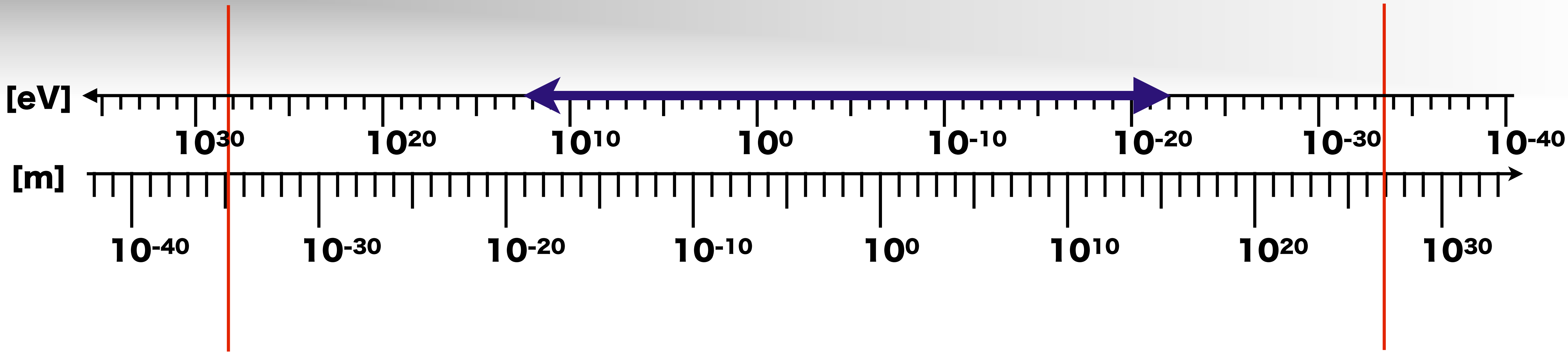
Neutron Fundamental Physics

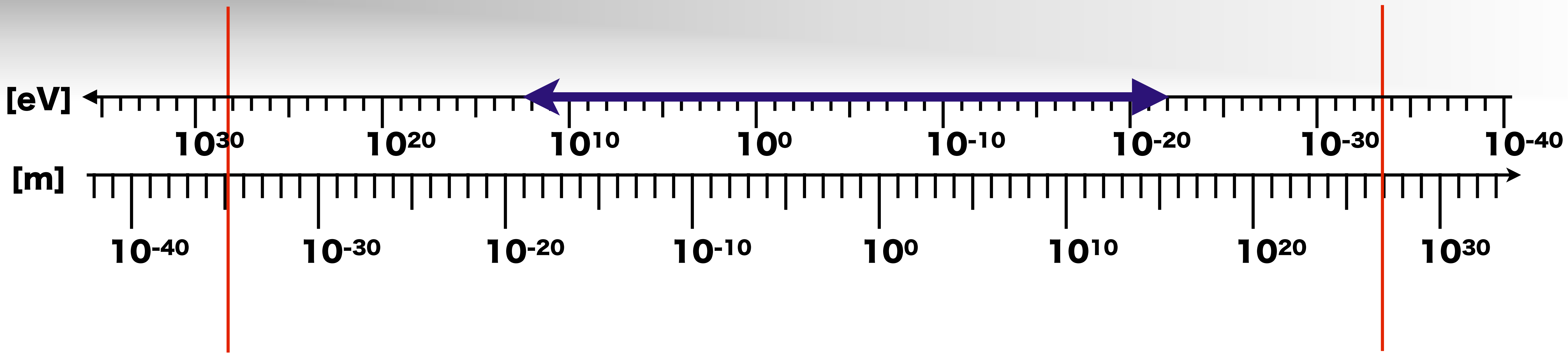
Hirohiko SHIMIZU

shimizu@phi.phys.nagoya-u.jp

Department of Physics, Nagoya University

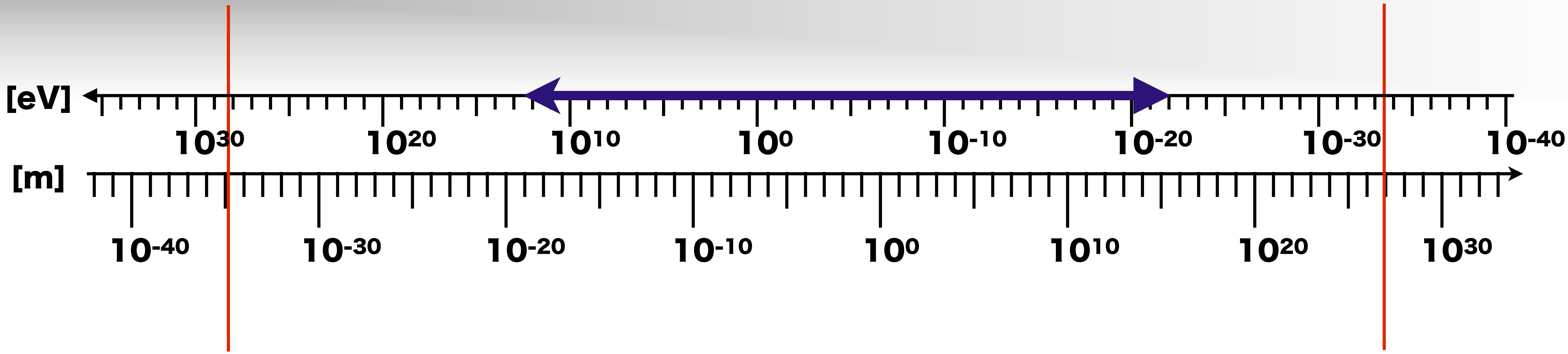
Introduction


[eV]
10^{30}
10^{20}
10^{10}
10^{0}
10^{-10}
10^{-20}
10^{-30}
10^{-40}
[m]
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}



Planck length
1.6×10^{-35}m
1.2×10^{28}eV (2×10^{9}J)

co-moving distance
8.8×10^{26}m = 880Ym
2.3×10^{-34}eV (3.6×10^{-53}J)



Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

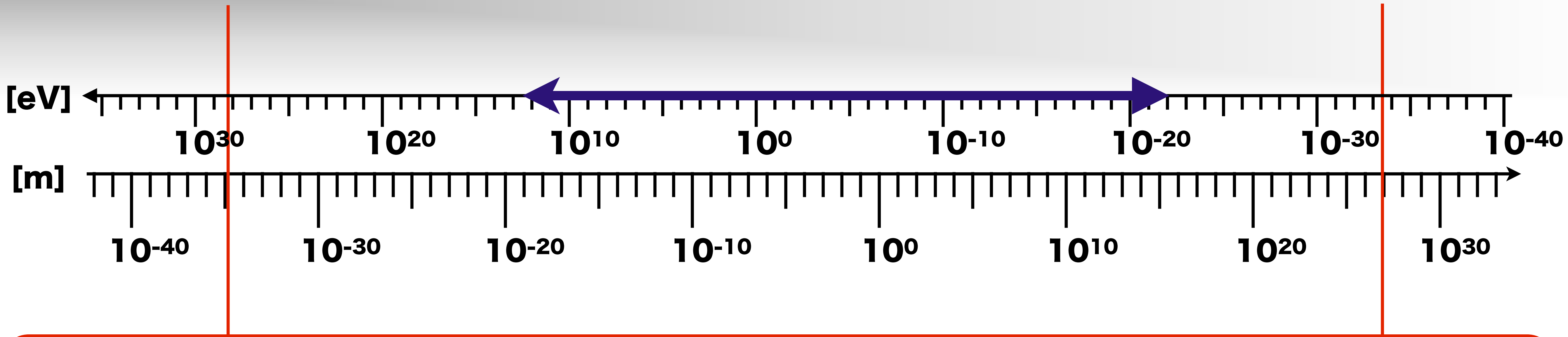
Why can't the Standard Model predict a particle's mass?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons?

How does gravity fit into all of this?

http://particleadventure.org/index.html



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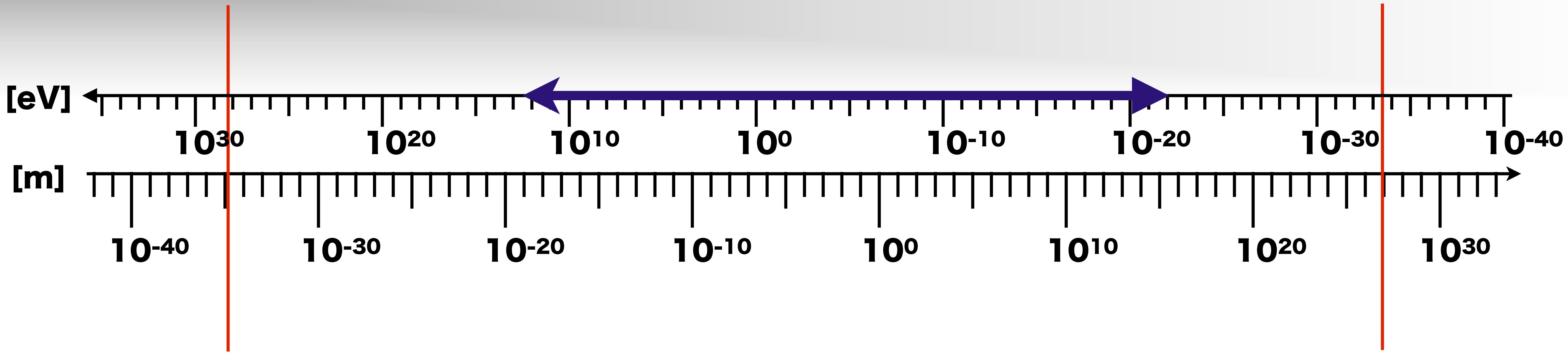
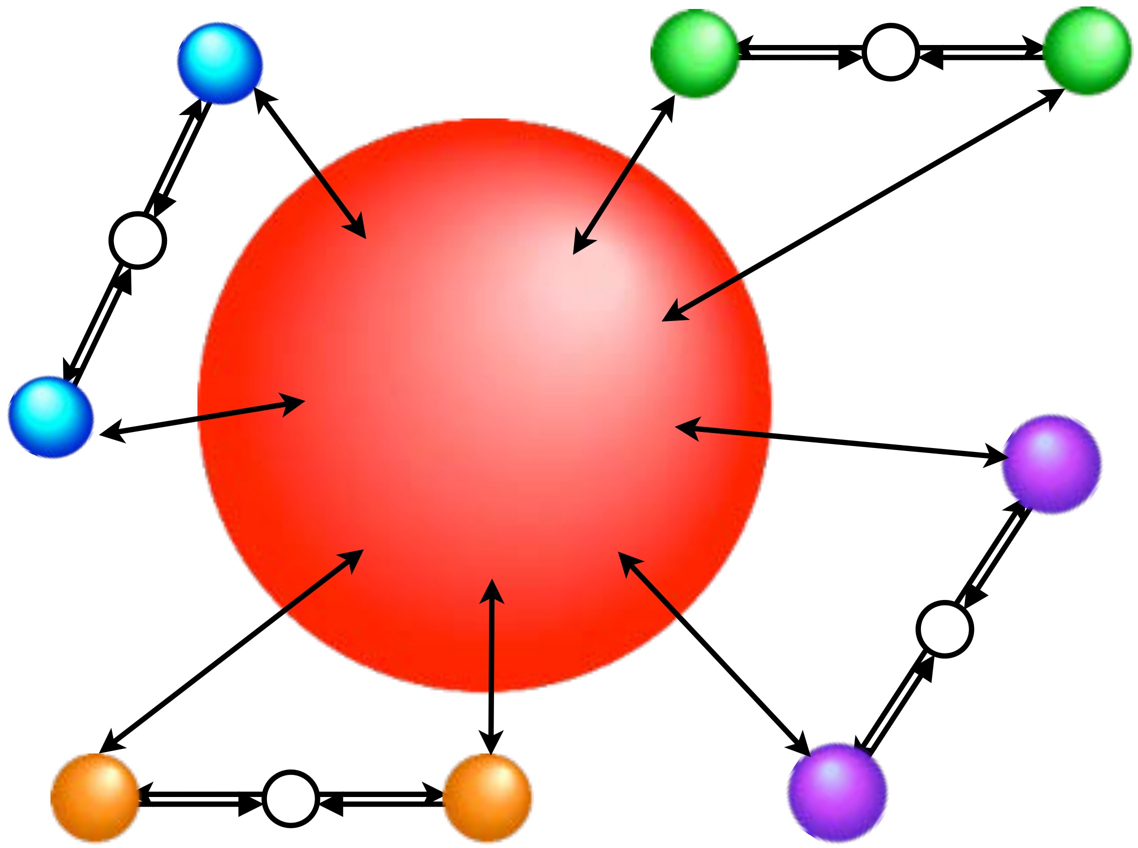


Study of High Energy Phenomena through Quantum Loops (Radiative Correction)

$$\delta_{\rm NEW} = \frac{\Delta O_{\rm NEW}}{O}$$

$$\sim \frac{\alpha}{\pi}\left(\frac{M}{M'}\right)^2$$



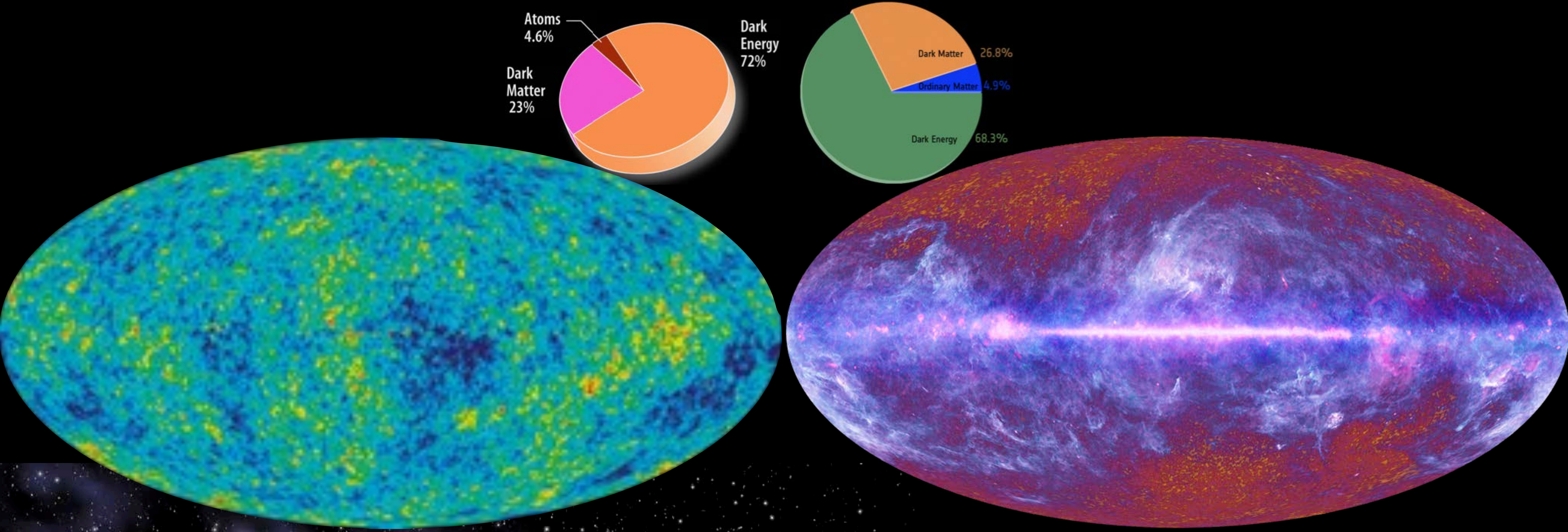
If O is known precisely, ...

If $\Delta O_{\rm NEW}$ is known in various systems, ...

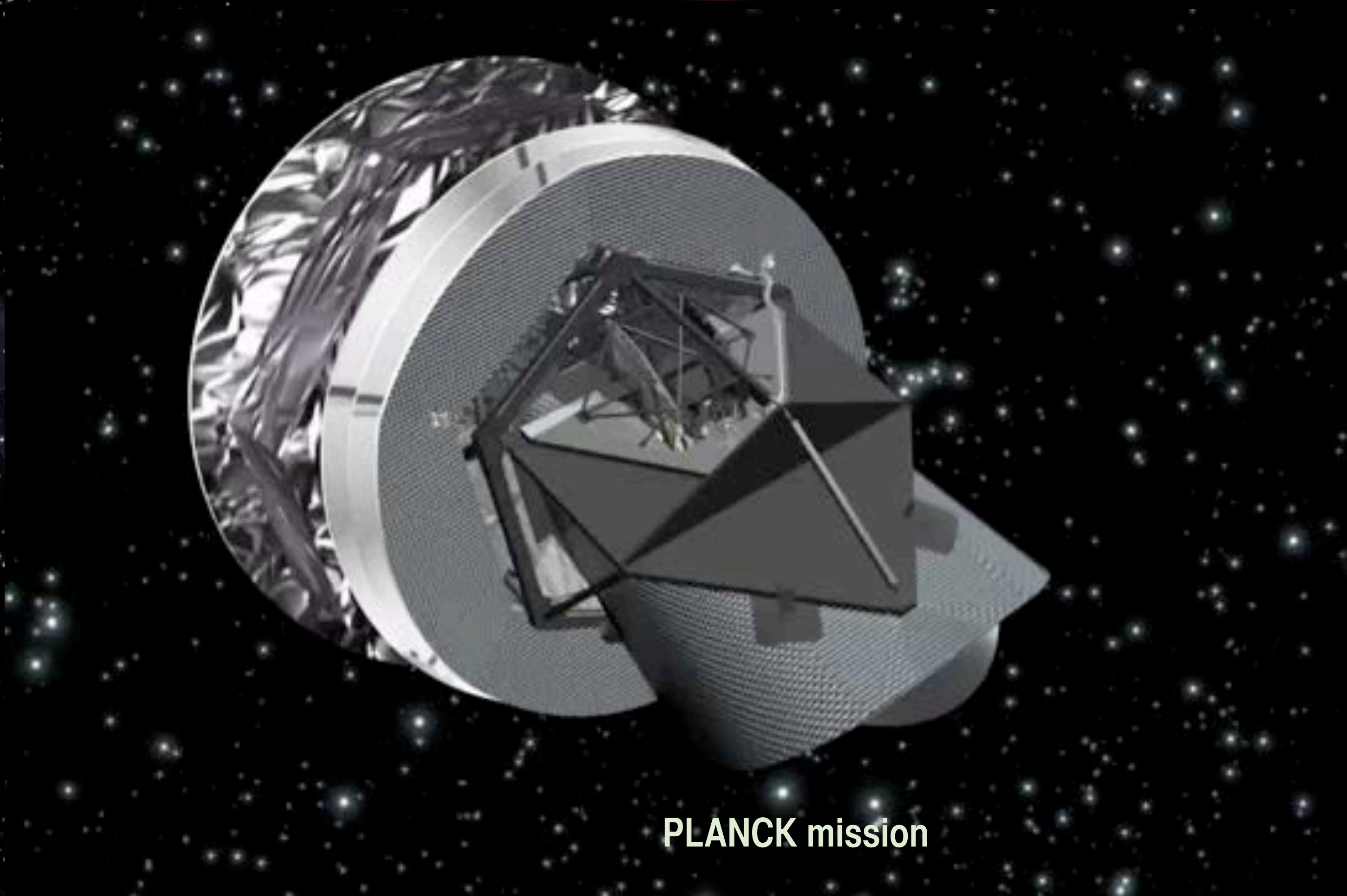
If $\Delta O_{\rm NEW}$ is strongly excluded in existing frameworks, ...

Anisotropy of Cosmic Microwave Background

WMAP&PLANCK → Constituents of the Universe



WMAP: Wilkinson Microwave Anisotropy Probe



PLANCK mission

Anisotropy of Cosmic Microwave Background

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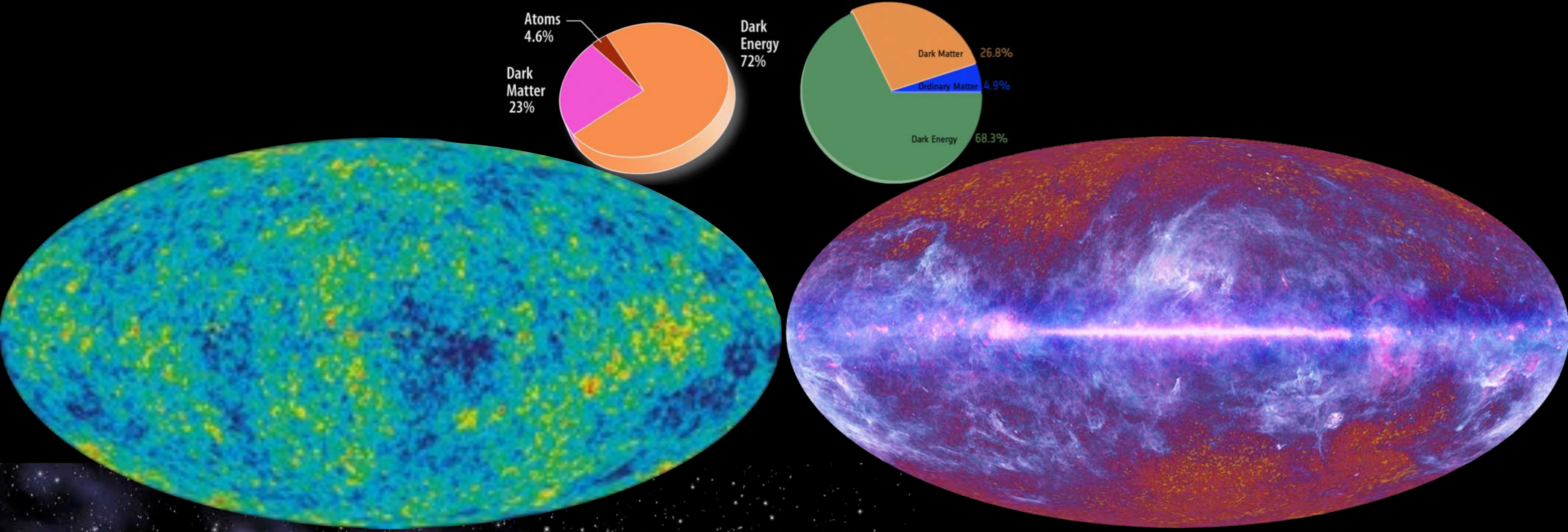

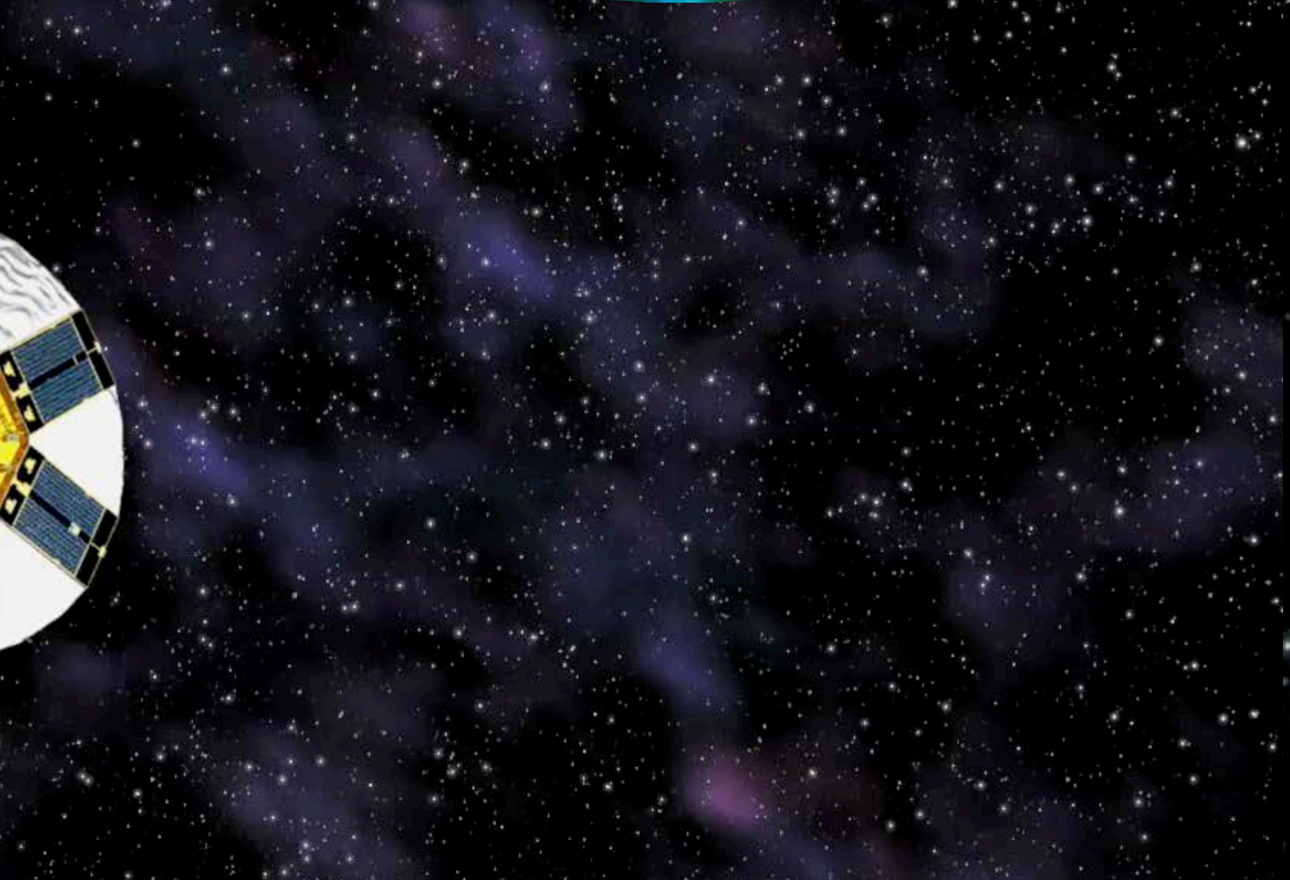

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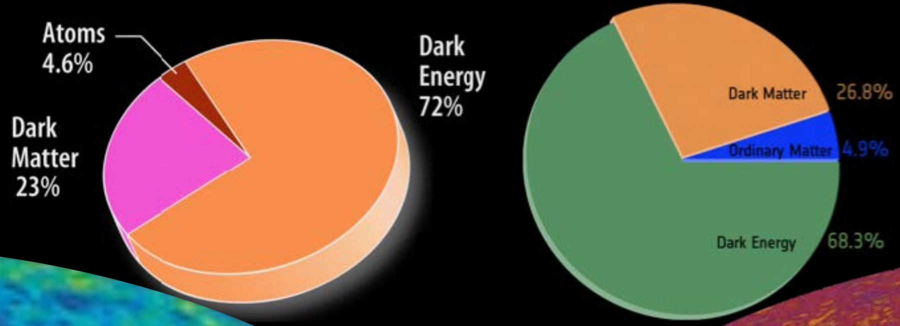
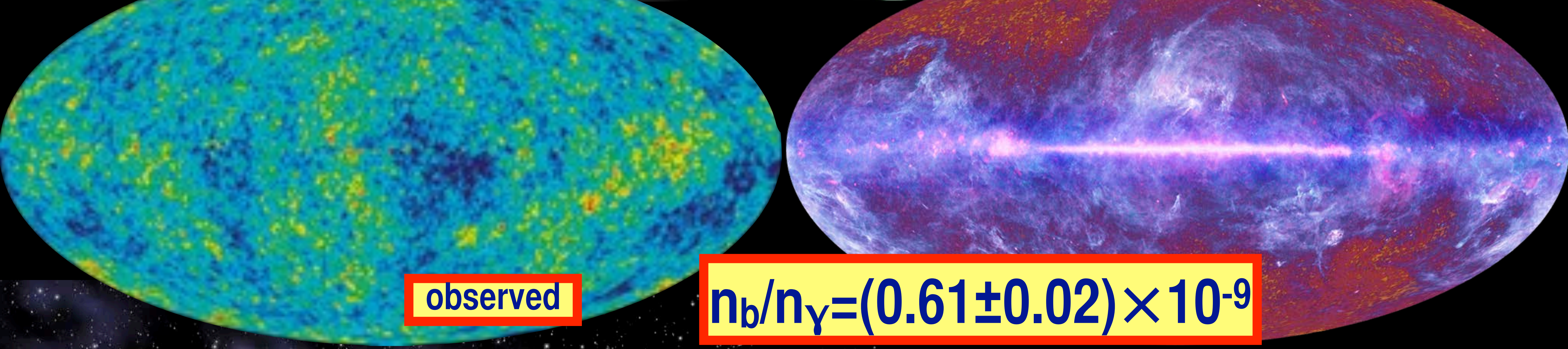
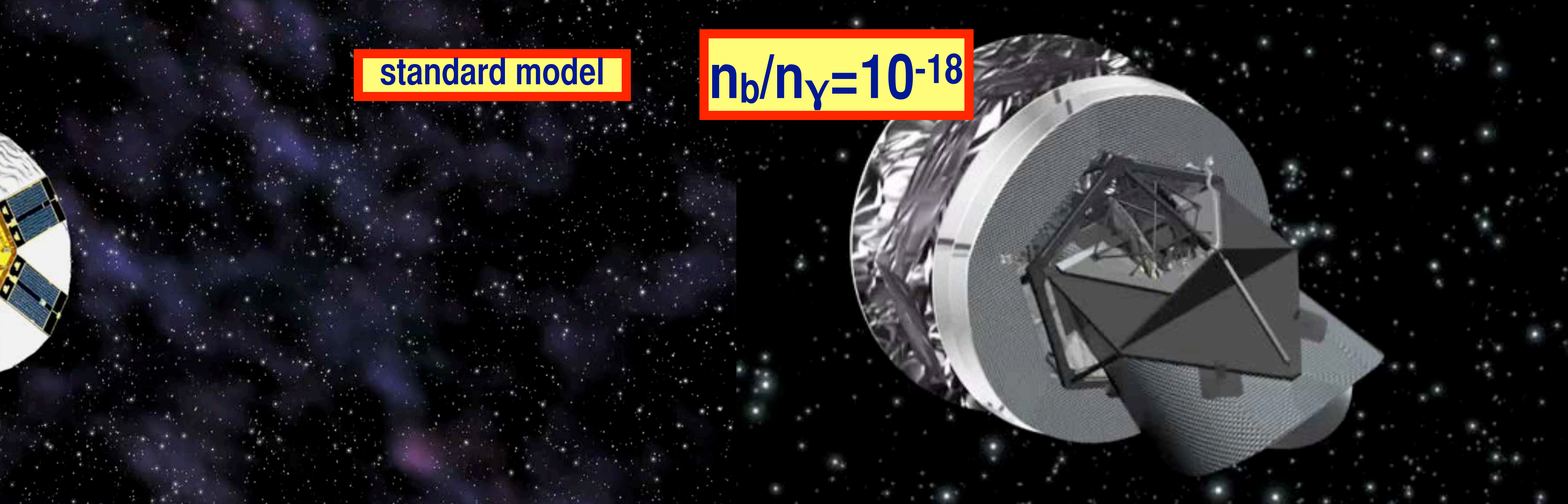




observed $n_b/n_\gamma=(0.61\pm0.02)\times10^{-9}$

standard model $n_b/n_\gamma=10^{-18}$



WMAP: Wilkinson Microwave Anisotropy Probe

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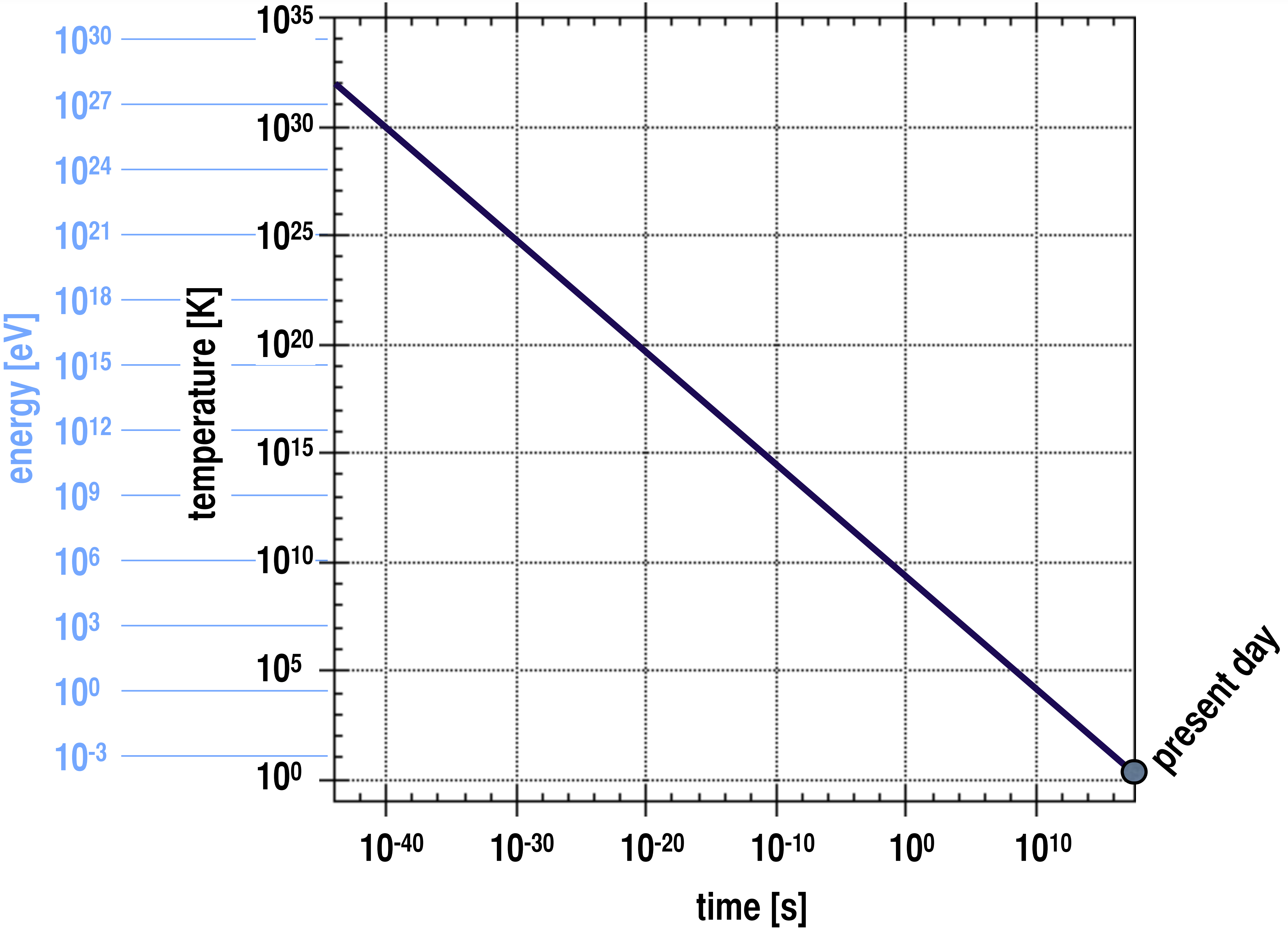
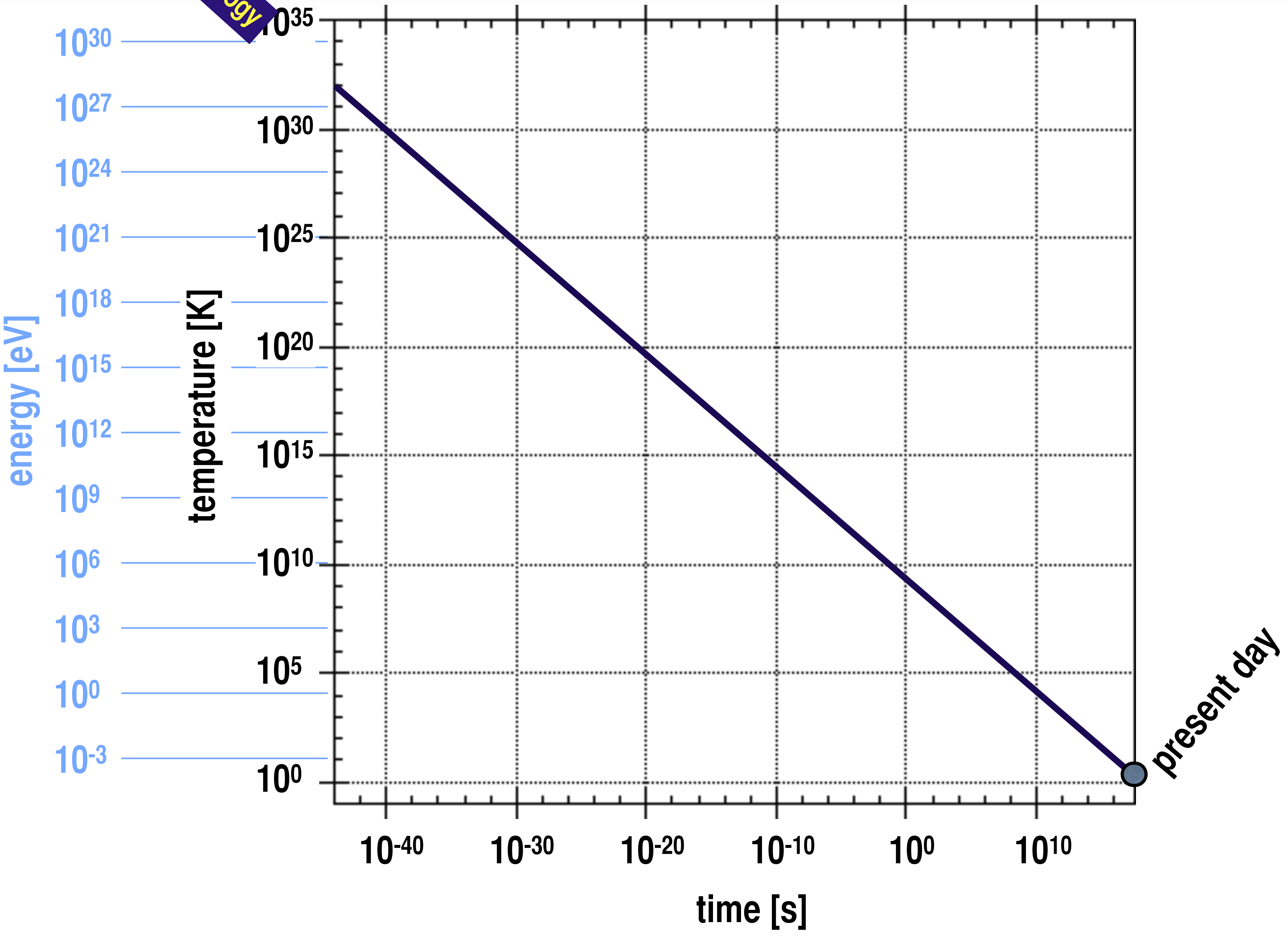

energy [eV]
10^30
10^27
10^24
10^21
10^18
10^15
10^12
10^9
10^6
10^3
10^0
10^-3
temperature [K]
10^35
10^30
10^25
10^20
10^15
10^10
10^5
10^0
10^-40
10^-30
10^-20
10^-10
10^0
10^10
time [s]
present day

cosmology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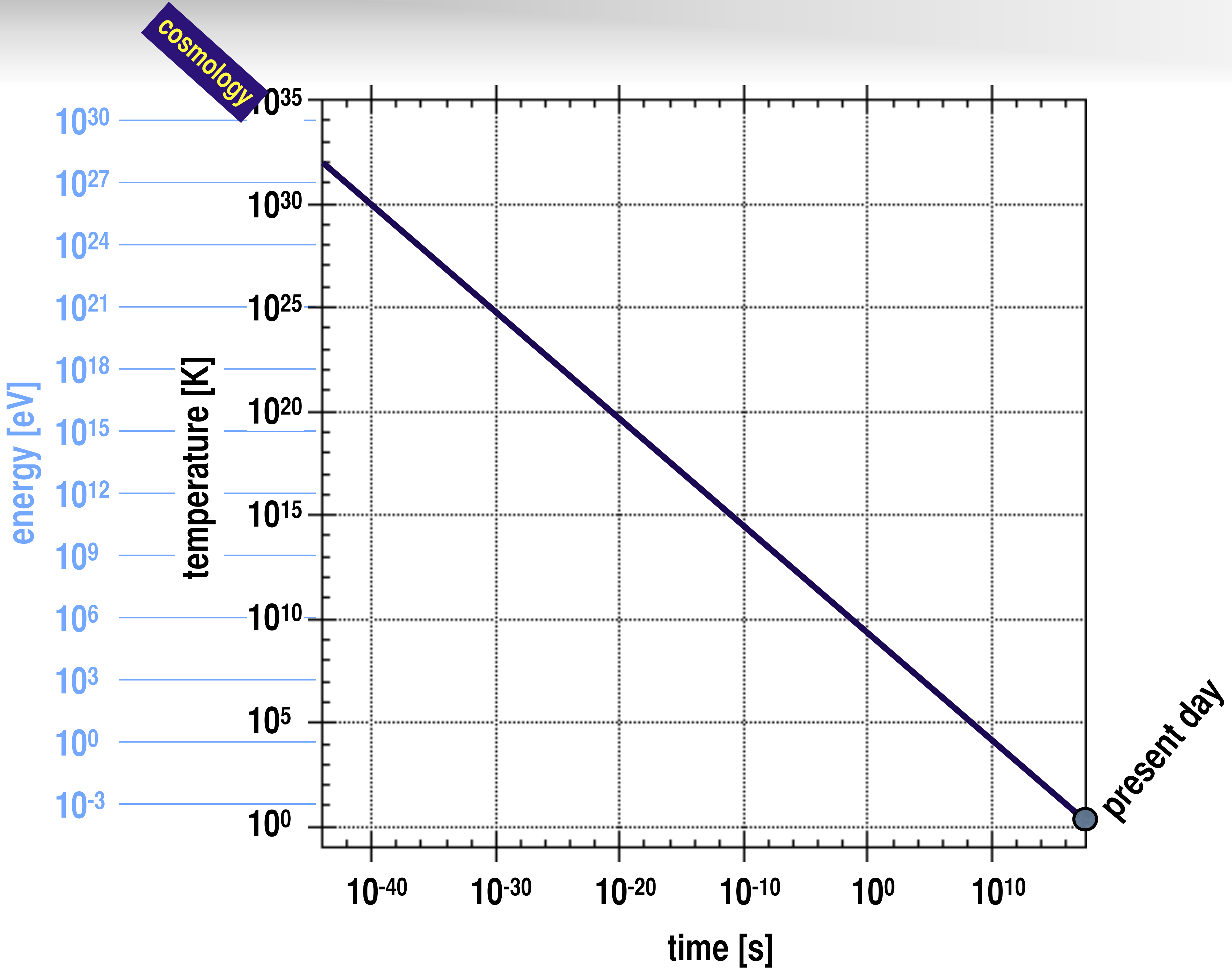
present day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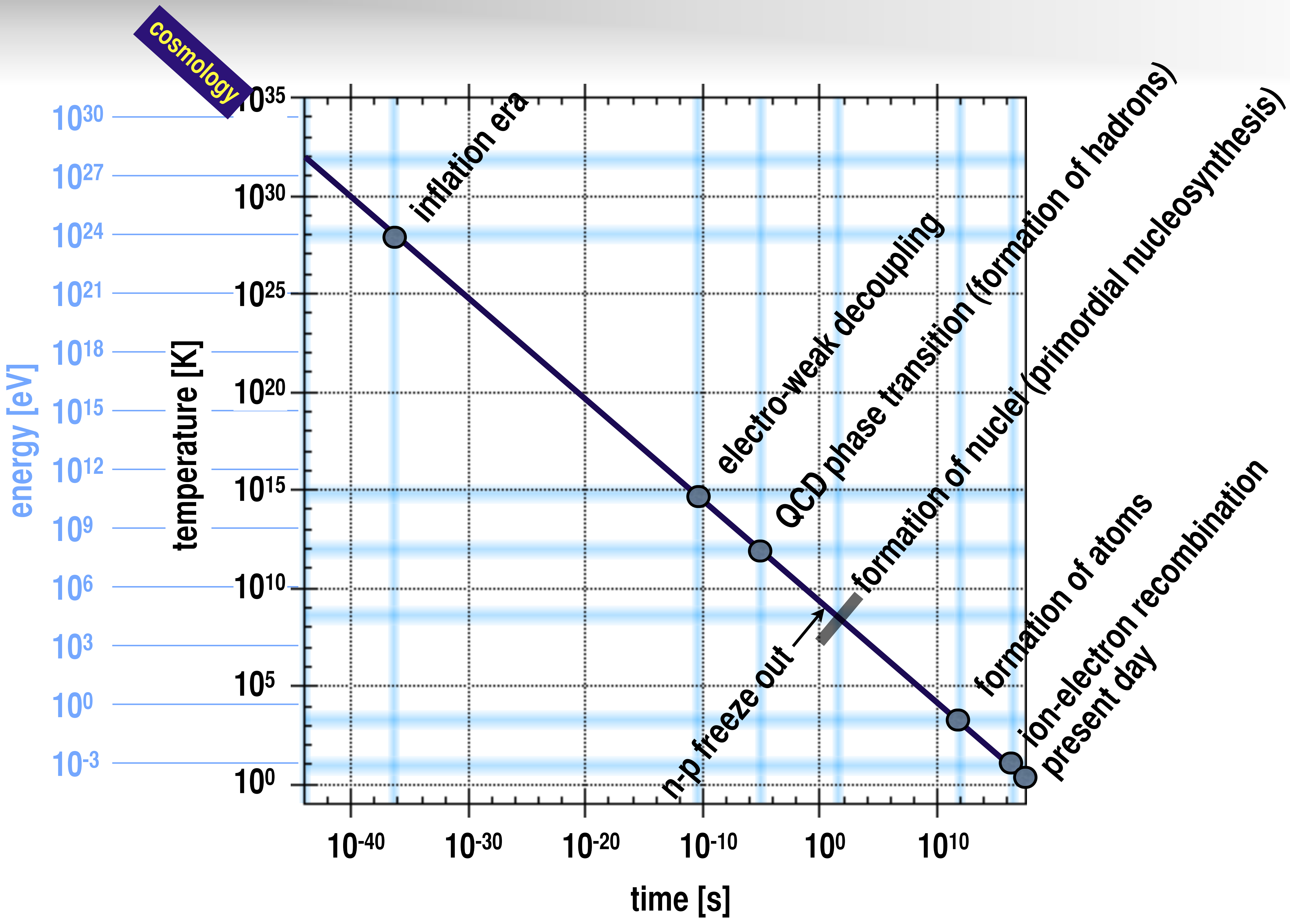
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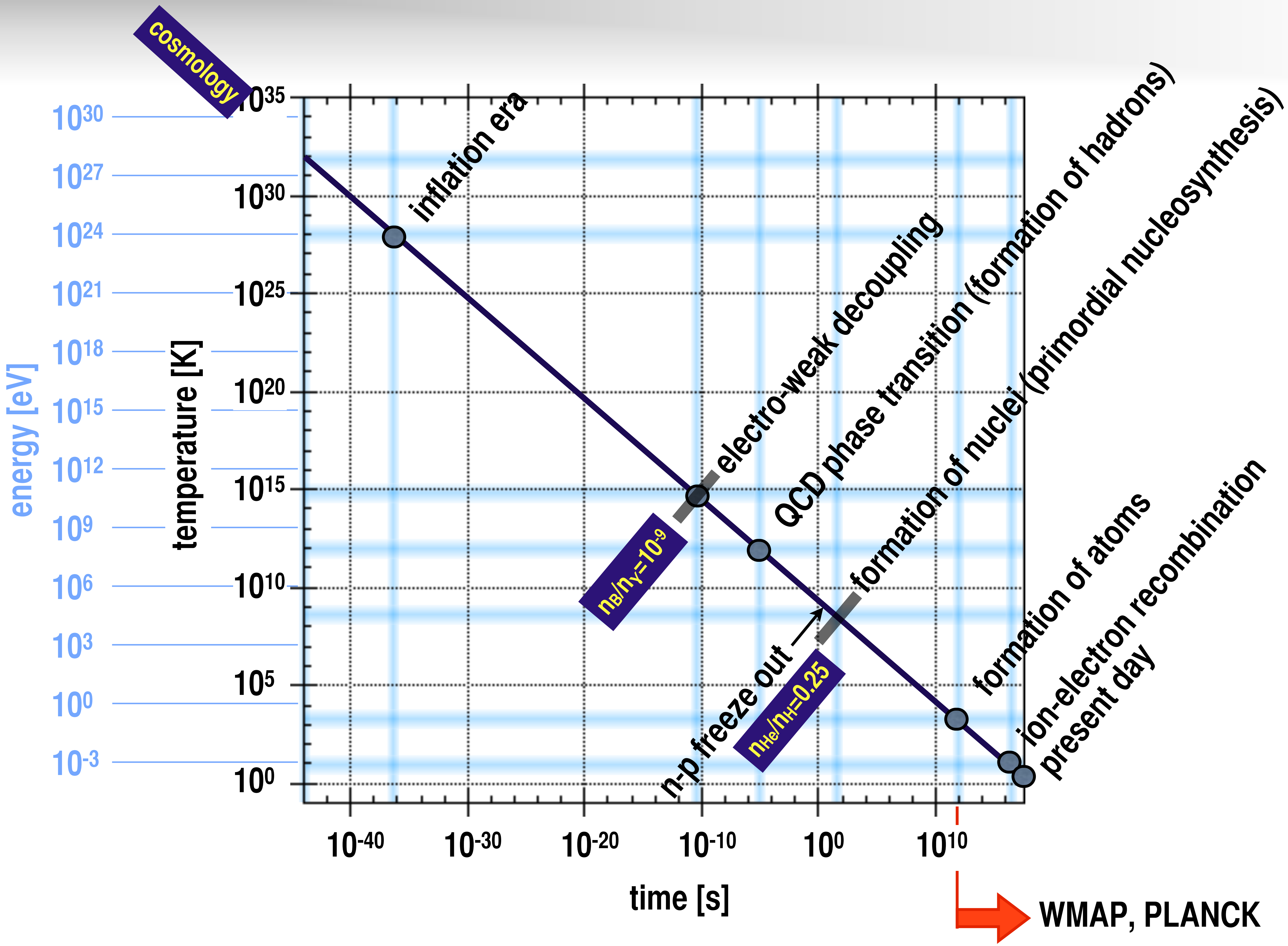
10^{15}
10^{10}
10^{5}
10^{0}
time [s]
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
inflation era
electro-weak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
n-p freeze out
formation of atoms
ion-electron recombination
present day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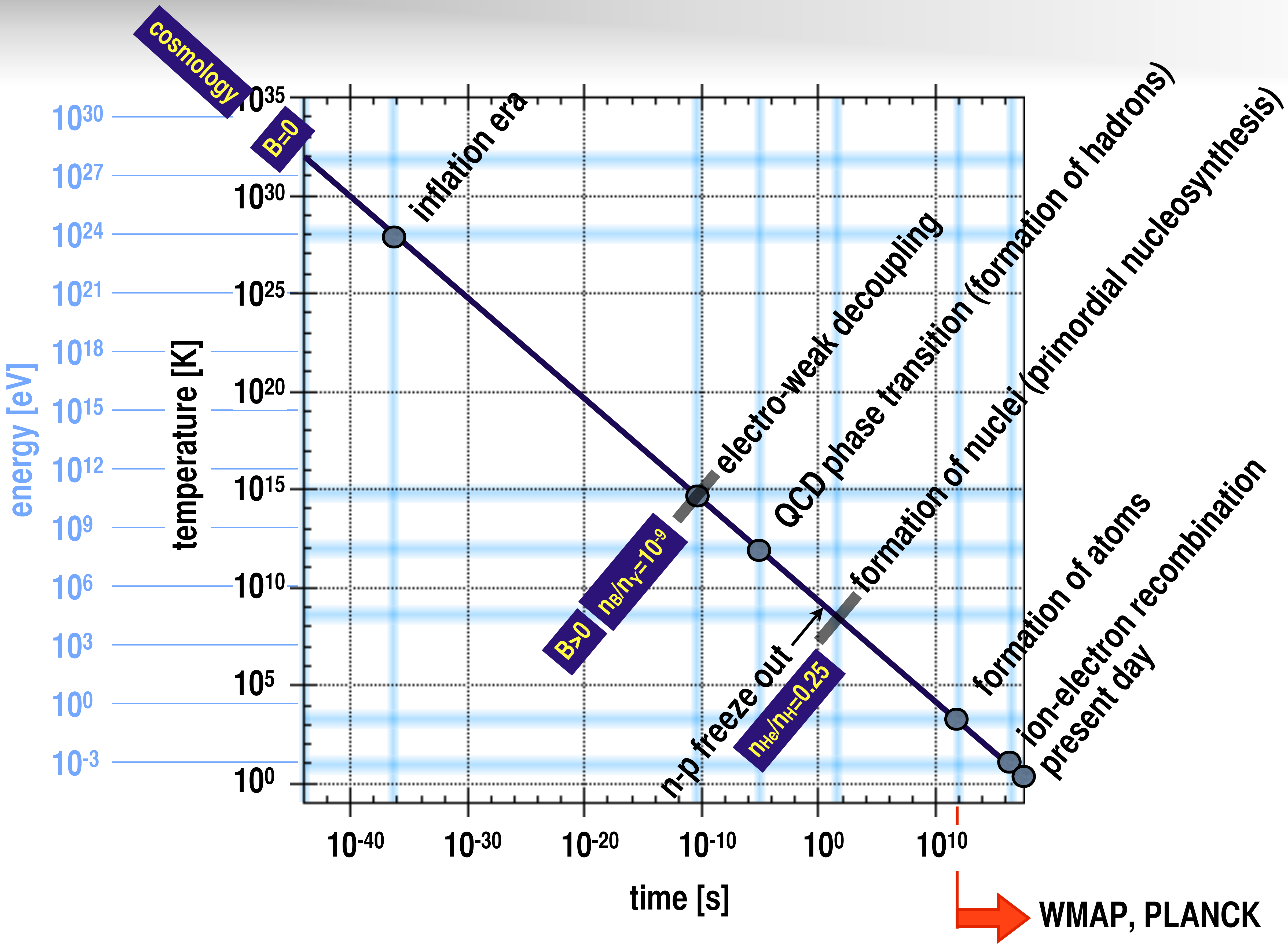
present day
n_B/n_γ=10^{-9}
n-p freeze out
n_{He}/n_H=0.25
WMAP, PLANCK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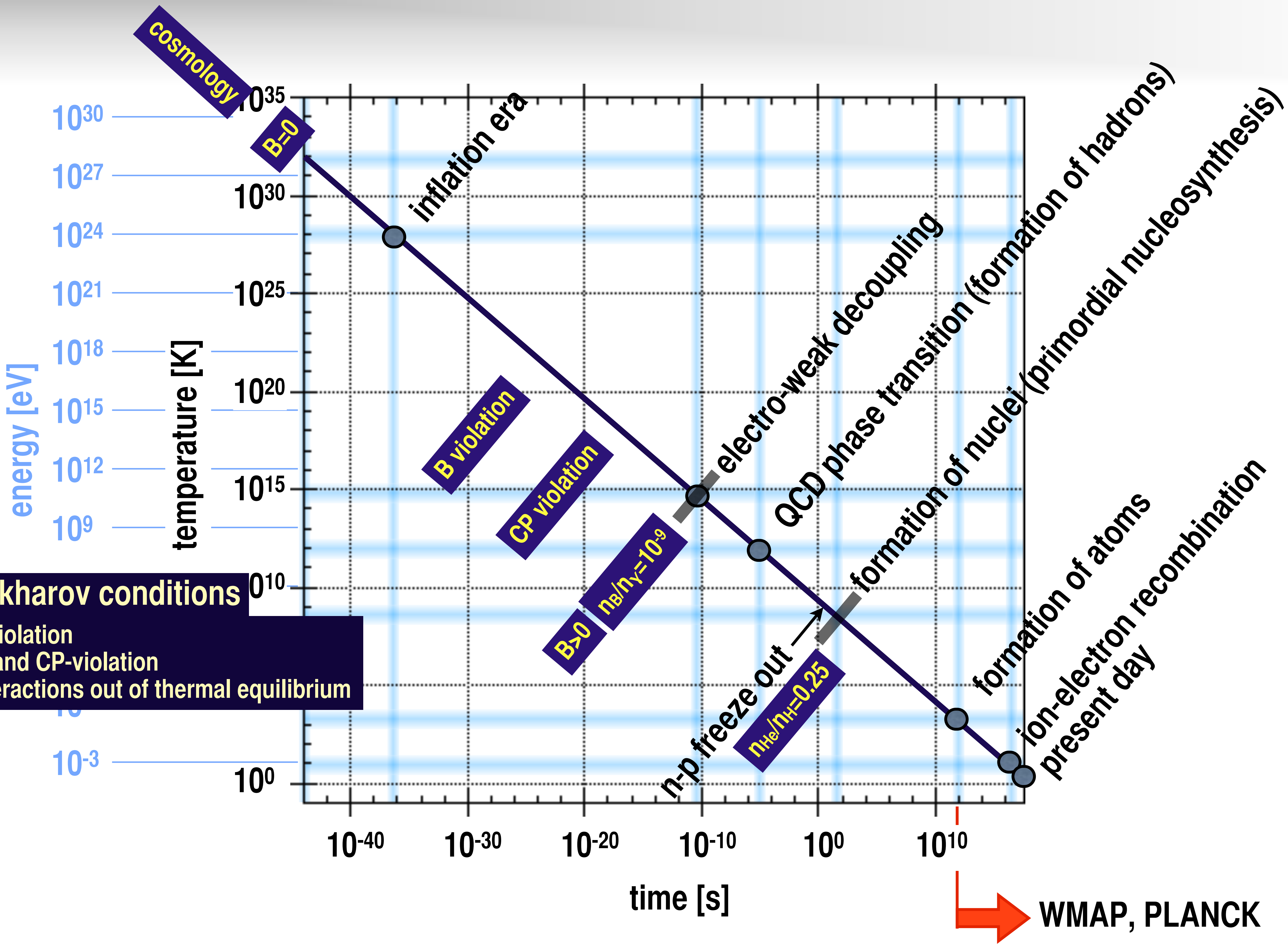
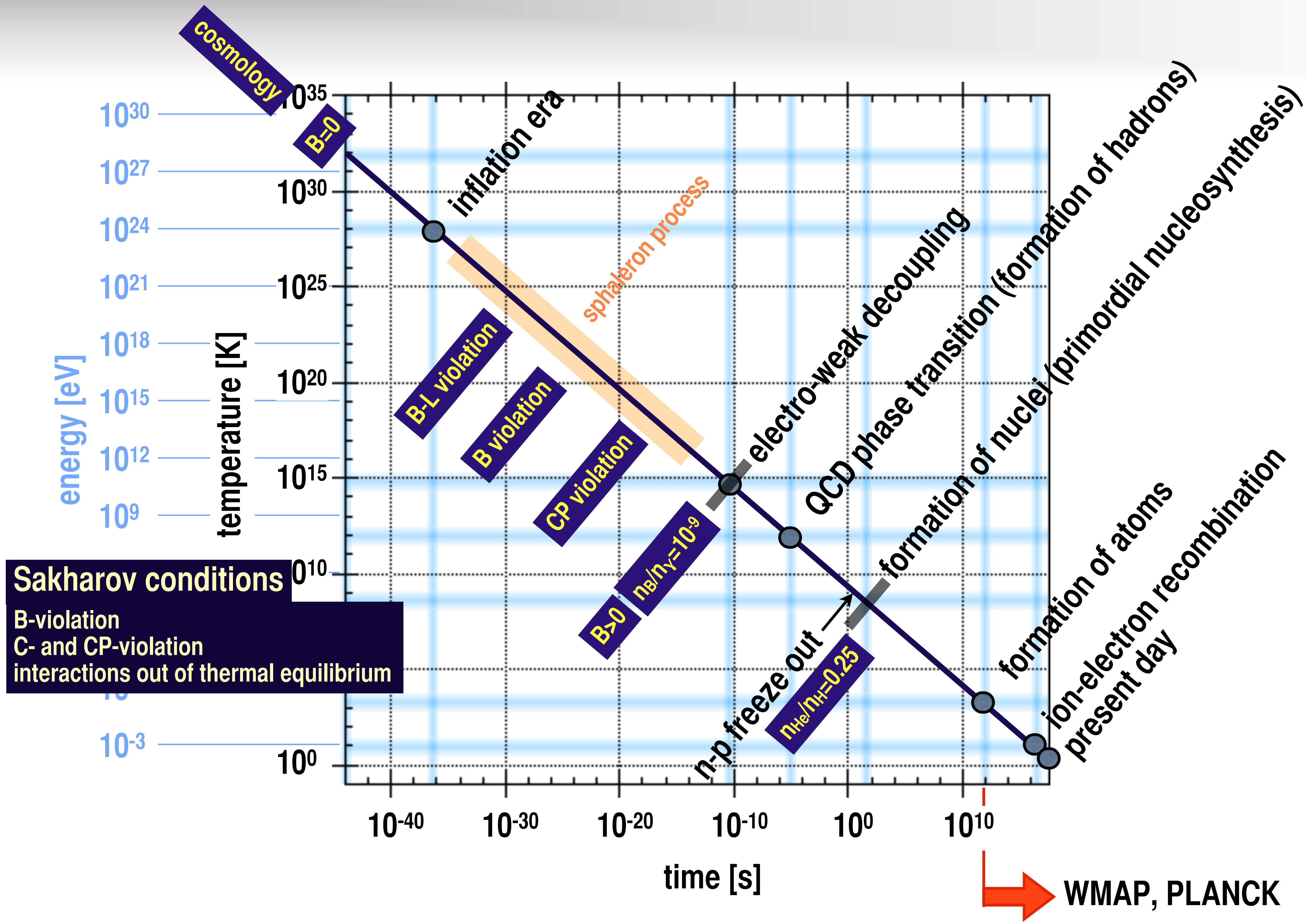
WMAP, PLANCK



Sakharov conditions

B-violation
C- and CP-violation
interactions out of thermal equilibrium



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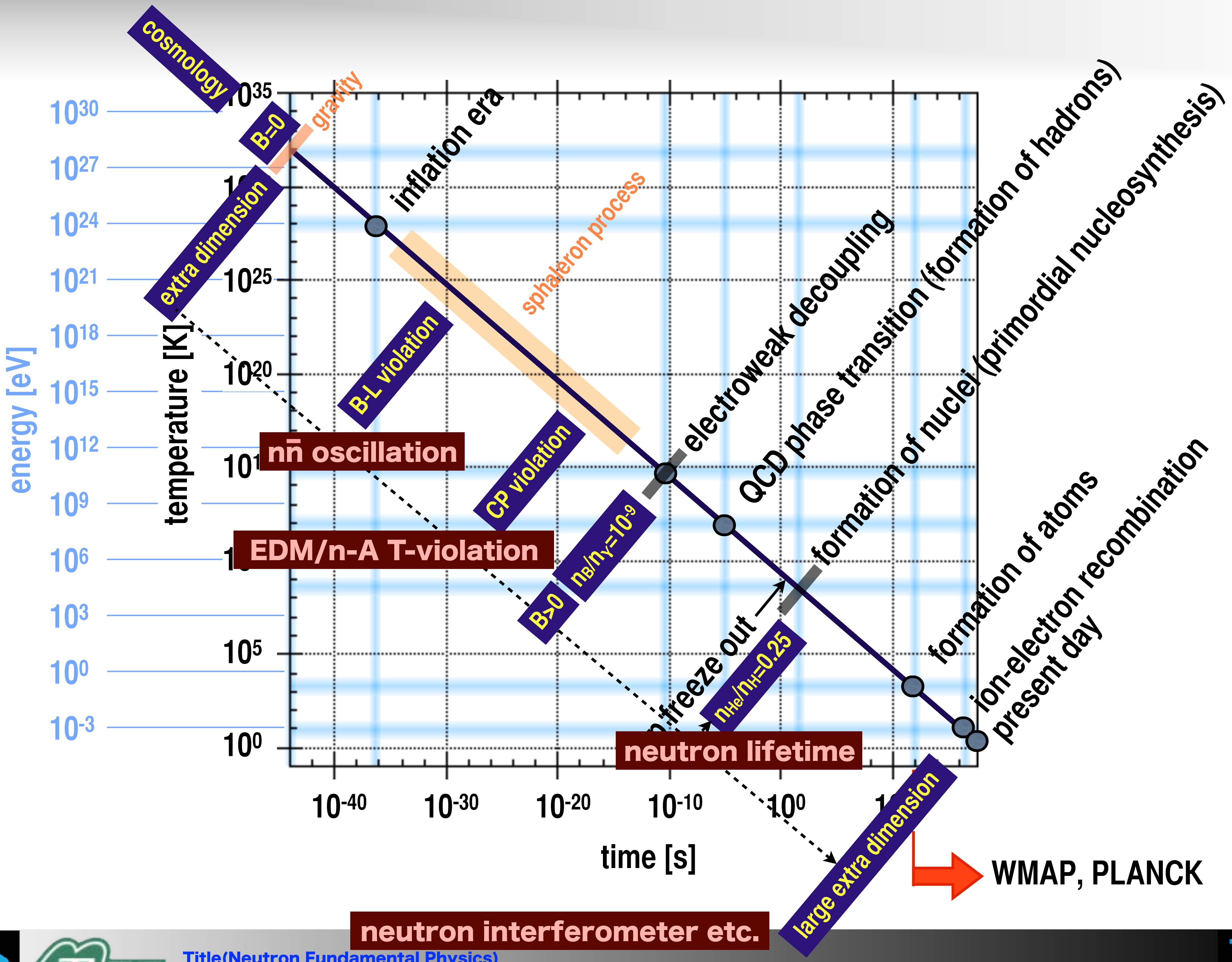
cosmology
gravity
B=0
extra dimension
inflation era
sphaleron process
B-L violation
nn̄ oscillation
CP violation
electroweak decoupling
QCD phase transition (formation of hadrons)
formation of nuclei (primordial nucleosynthesis)
EDM/n-A T-violation
n_B/n_γ=10-9
B>0
n freeze out
n_{He}/n_H=0.25
formation of atoms
ion-electron recombination
present day
neutron lifetime
large extra dimension
neutron interferometer etc.
WMAP, PLANCK
energy [eV]
10^{30}
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
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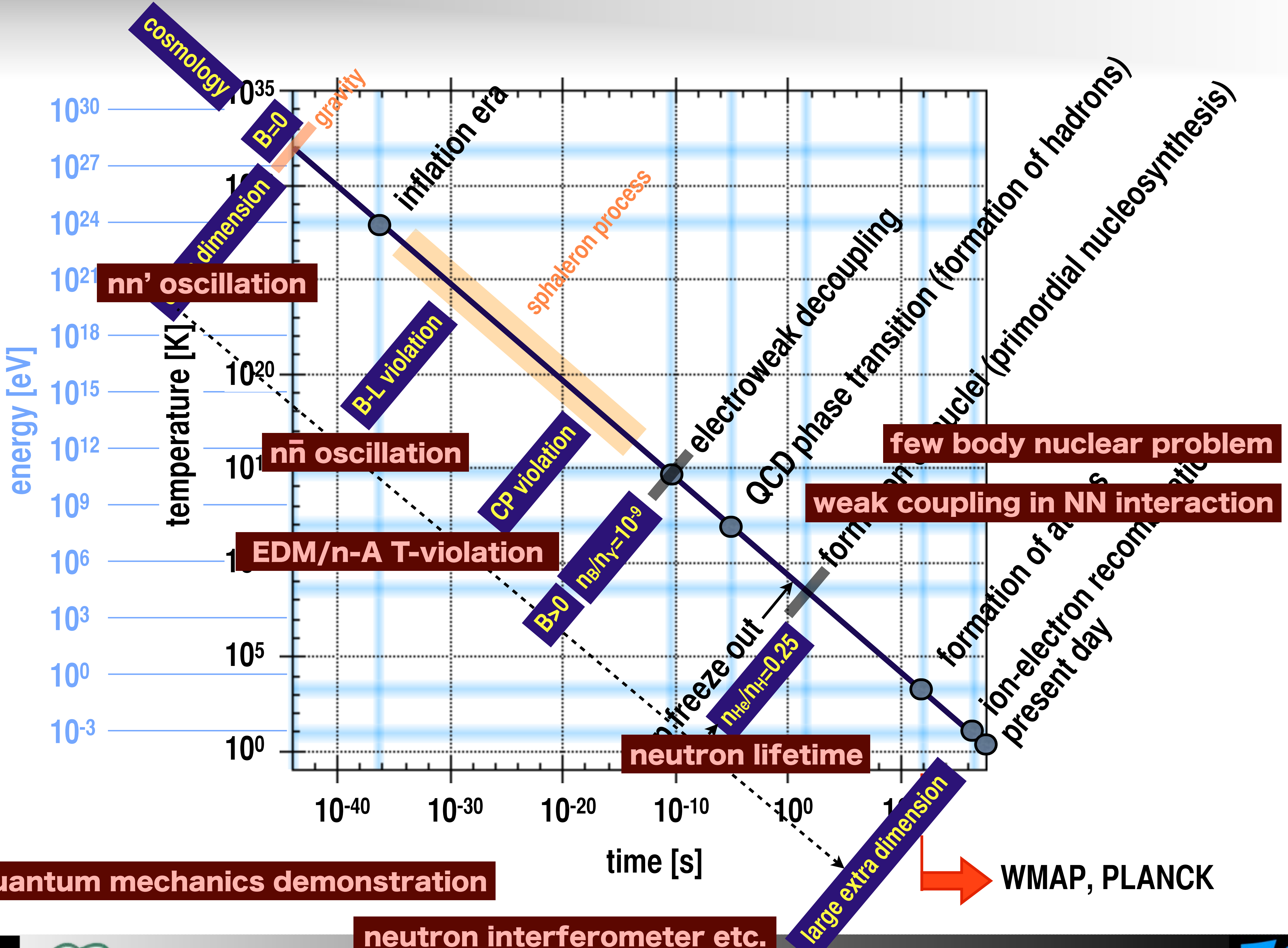


nn’ oscillation

nn̄ oscillation

EDM/n-A T-violation

few body nuclear problem

weak coupling in NN interaction

neutron lifetime

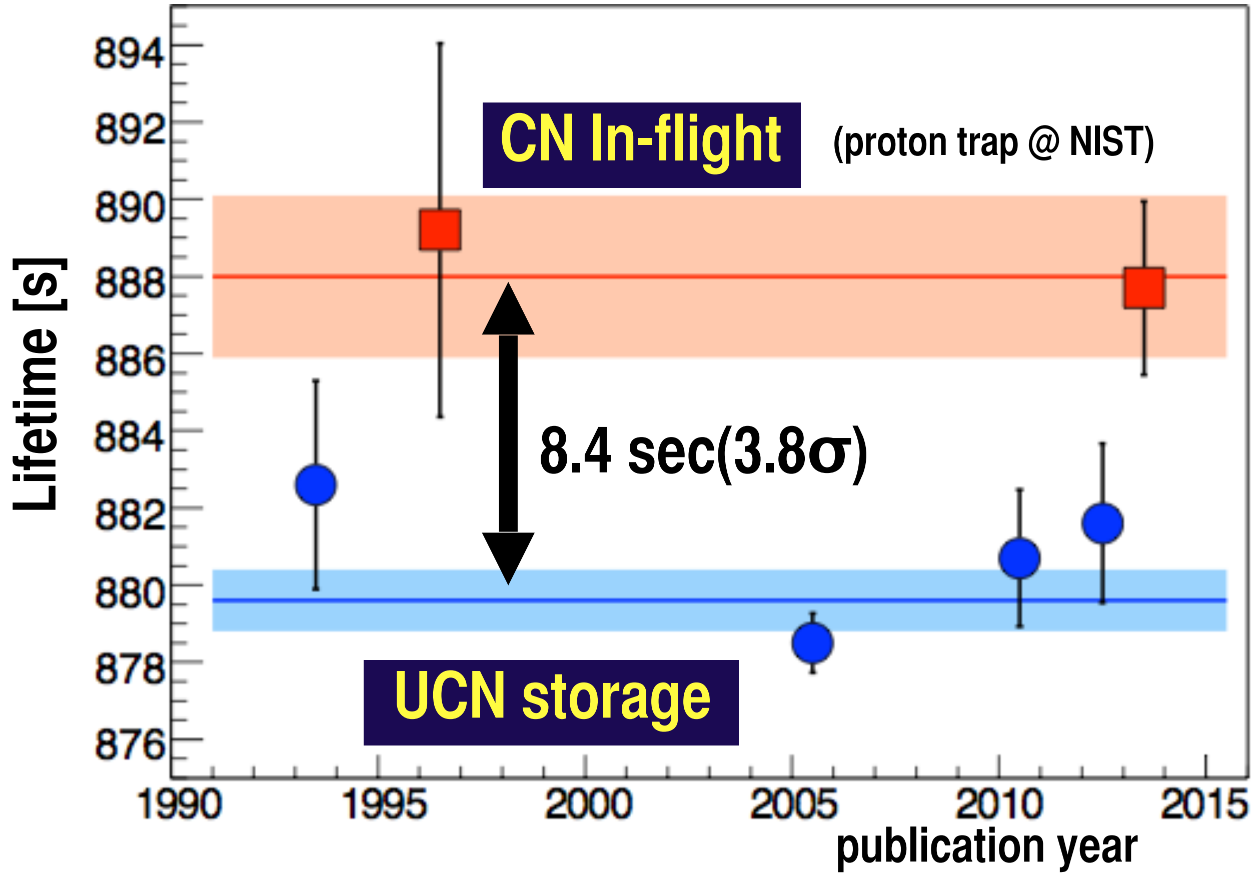
quantum mechanics demonstration

neutron interferometer etc.

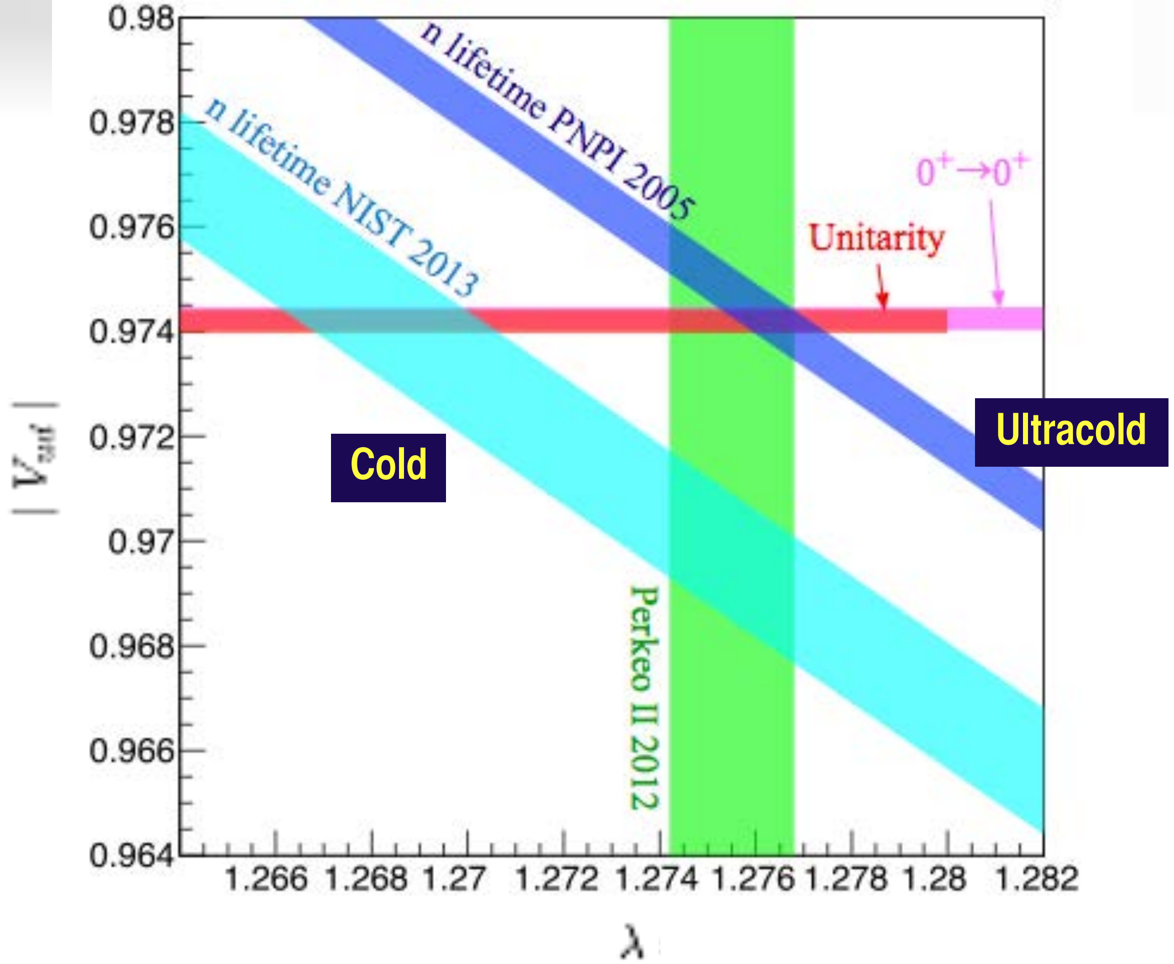
physical reality of electromagnetic potential

general relativity

Neutron Lifetime



A.T. Yue et. al., PRL 111, 222501 (2013)



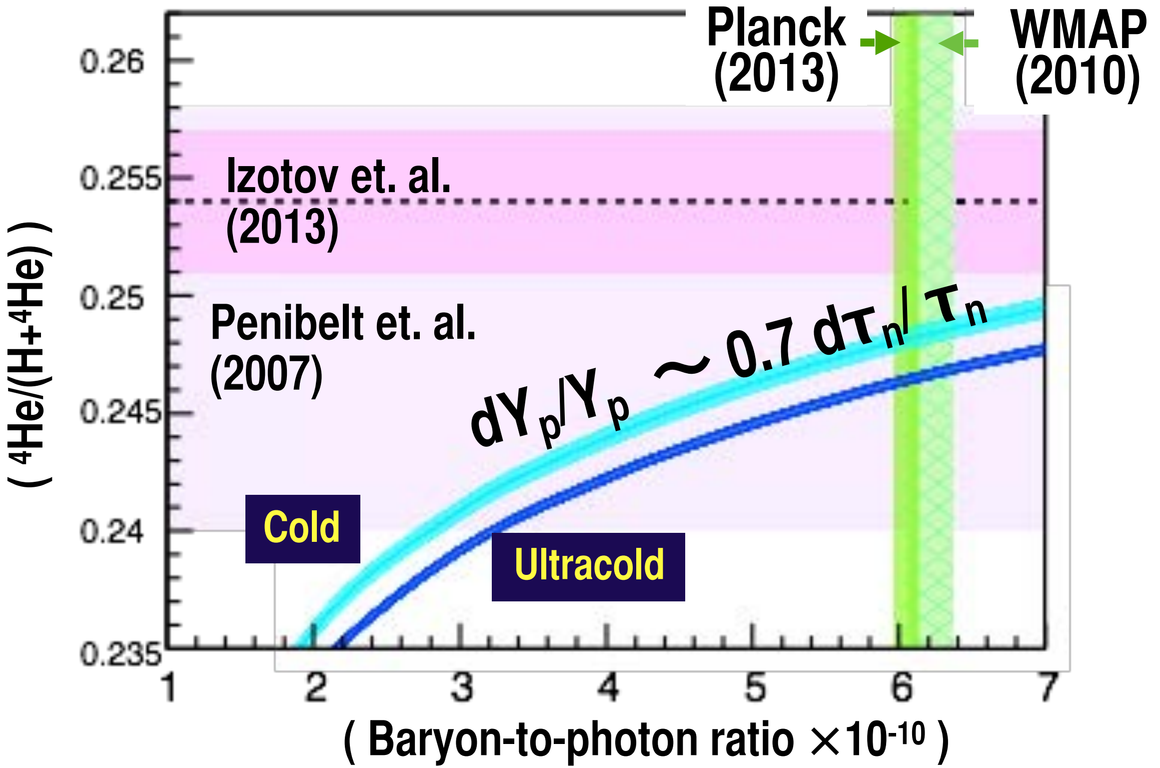
Improvment of in-flight cold neutron lifetime at

$$\Delta\tau_n \leq 1\,[\mathrm{s}]$$

τ_n is meaured relative to the cross section of ^{3}He(n,p)

largest uncertainty common
to in-flight measurements

$$\frac{\partial \tau_n}{\partial \sigma_{^3\mathrm{He}}}\Delta\sigma_{^3\mathrm{He}} \gtrsim 1\,[\mathrm{s}]$$



Test of Effective Field Theory in Neutron β-decay

Nagoya Univ., RIKEN, KEK

$$w\ dE_e\, d\Omega_e\, d\Omega_{\bar{\nu}_e} = \frac{1}{(2\pi)^5}\, p_e E_e\,(E_0 - E_e)^2\, dE_e\, d\Omega_e\, d\Omega_{\bar{\nu}_e}\, \xi$$

$$\times\left[1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_{\bar{\nu}_e}}{E_e E_{\bar{\nu}_e}} + b\frac{m_e}{E_e} + \frac{\mathbf{J}}{J}\cdot\left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_{\bar{\nu}_e}}{E_{\bar{\nu}_e}} + D\frac{\mathbf{p}_e\times\mathbf{p}_{\bar{\nu}_e}}{E_e E_{\bar{\nu}_e}}\right)\right]$$

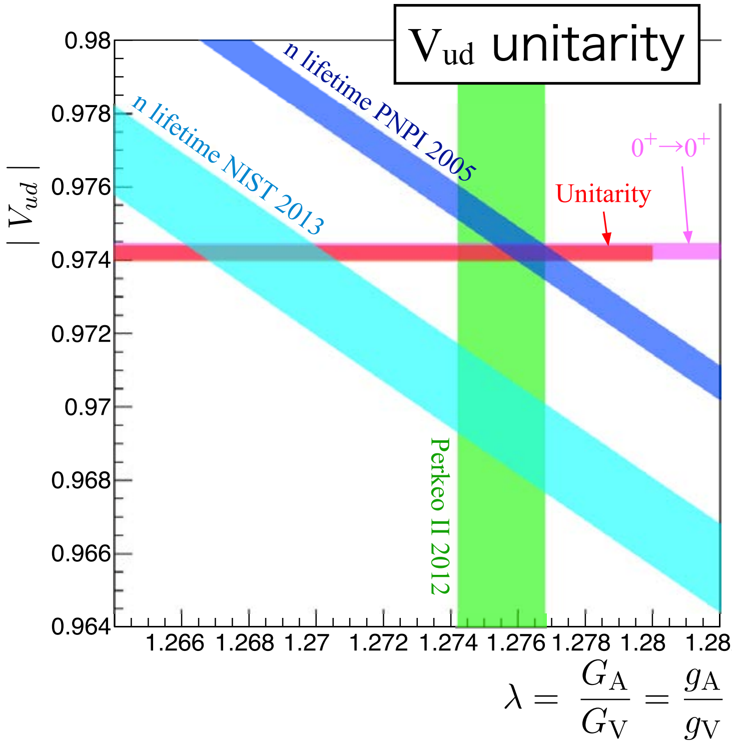
$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}\,,\ b=0\,,\ A = -2\frac{|\lambda|\cos\phi+|\lambda|^2}{1+3|\lambda|^2}\,,\ B = -2\frac{|\lambda|\cos\phi-|\lambda|^2}{1+3|\lambda|^2}\,,\ D = 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$

Precision Test of Standard Theory

Check of the unitarity of CKM-matrix

→ **A：Electron Asymmetry**

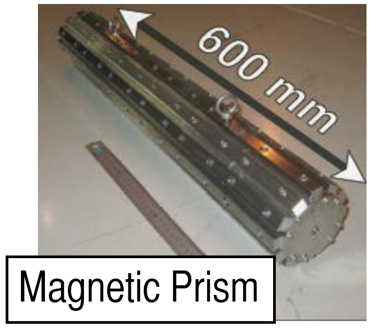
$$|V_{ud}|^2 = \frac{1}{\tau_n}\frac{(4908.7 \pm 1.9)\ \mathrm{s}}{(1+3\lambda^2)}$$



Next Leading Order

→ **a：Proton Electron Correlation**

Supercondcuting Detector to Measure Proton Energy



Magnetic Prism

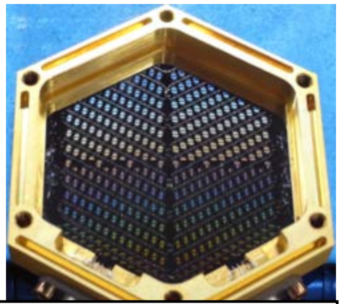
Search for New Physics beyond the Standard Model

New physics may affect Next-Leading-Order terms

→ **B：Neutrino Asymmetry**

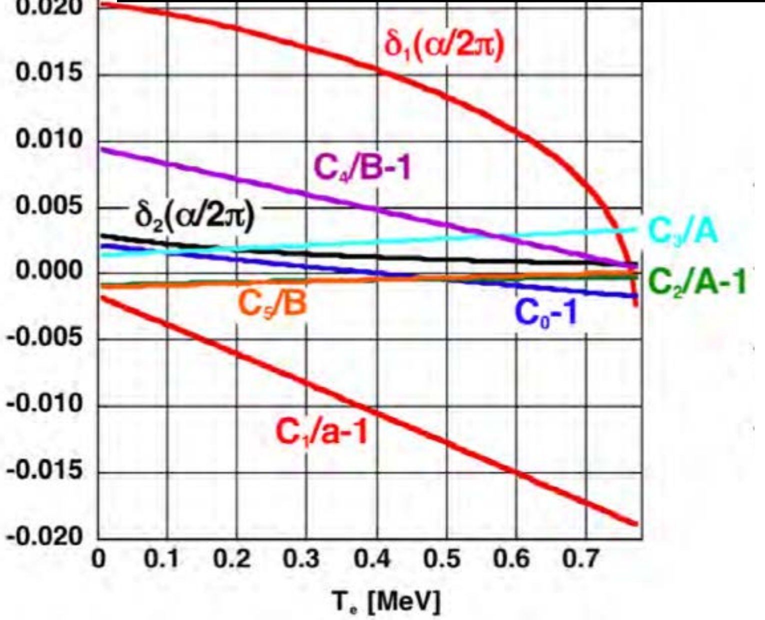
D is T-odd term prohibited in the Standard Model

→ **D：Triple-vector Correlation**



Superconduting Kinetic Inductance Detector

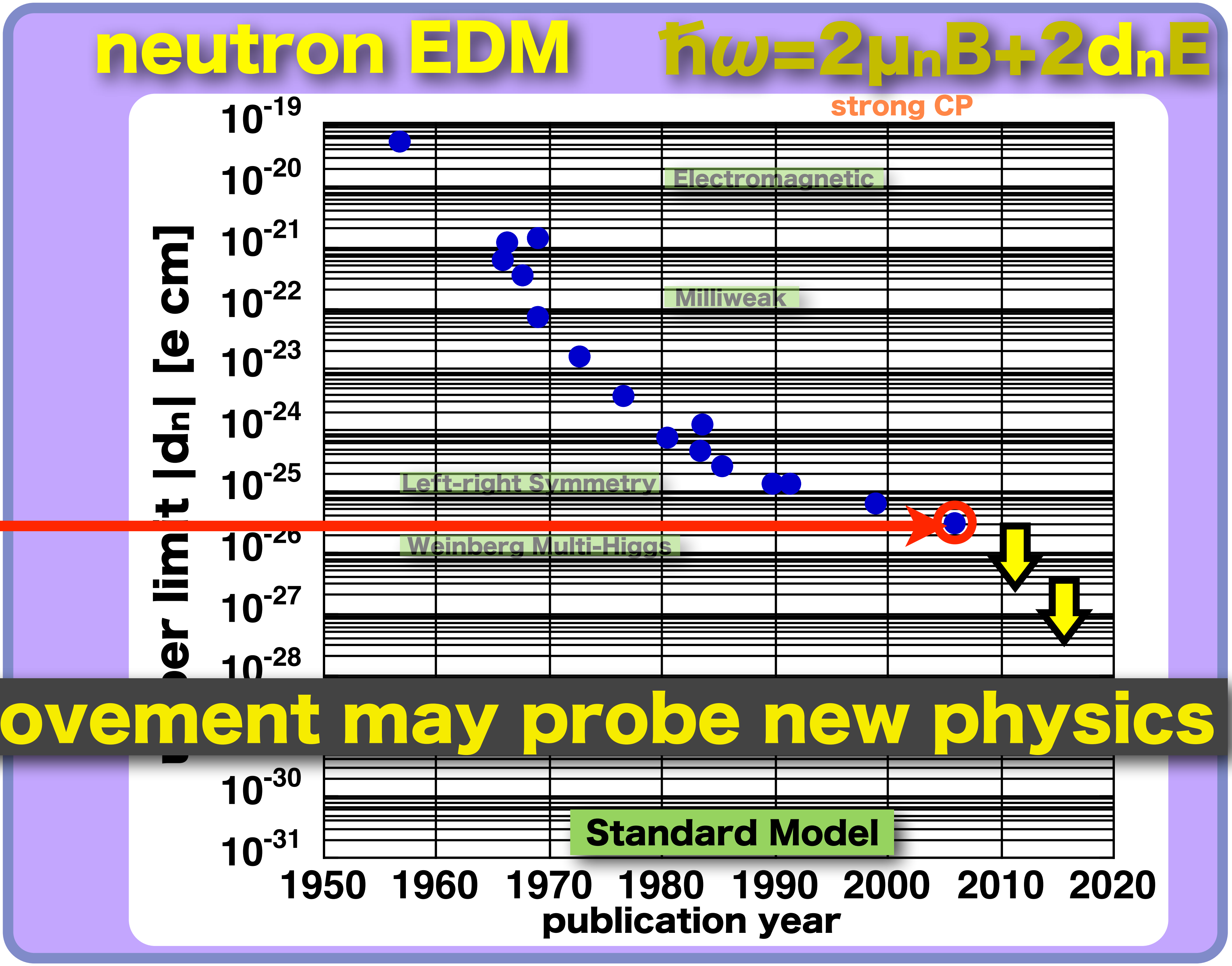
Energy Dependence of Correlation Terms



CP-violation in Electric Dipole Moment

$|d_n|<2.9\times10^{-26}$ e cm
(90%C.L.)

Baker et al., PRL97 (2006)131801

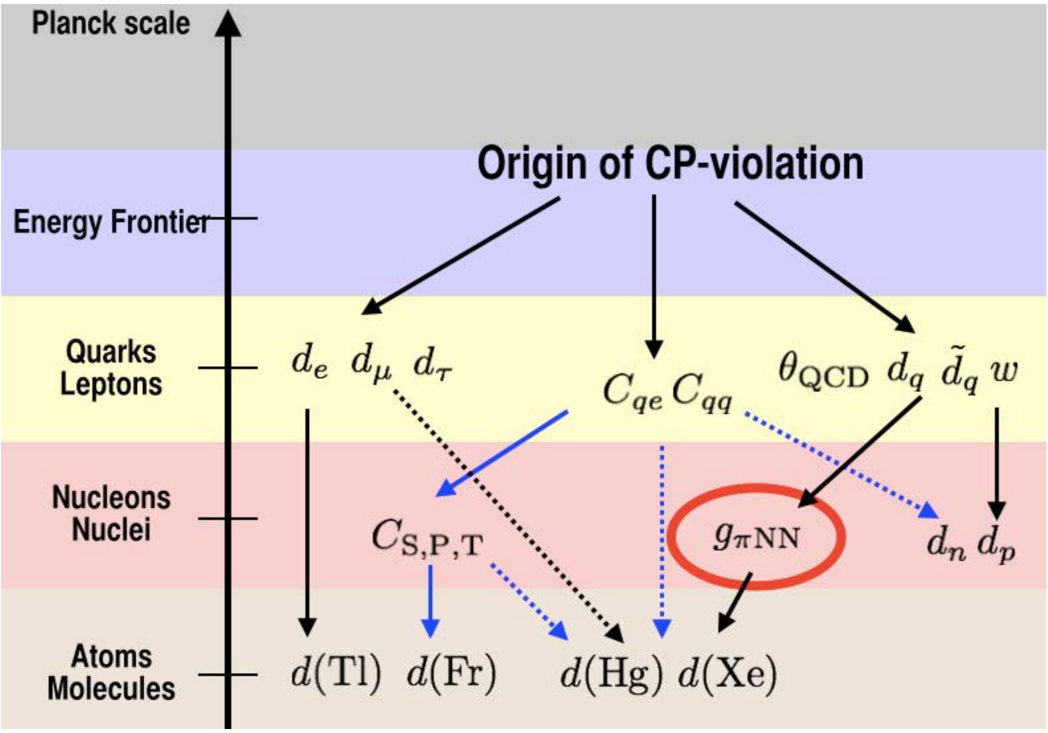


1-2 order improvement may probe new physics

CP-violation in Epithermal Neutron Optics

Application of 10^6-times enhancement of parity violating effects in compound resonances to the search of T-violating (CP-violating) effects beyond the Standard Model

Nagoya Univ., KEK, JAEA, RIKEN, RCNP, Kyoto Univ., British Columbia Univ., Indiana Univ., Oak Ridge National Lab., South Carolina Univ., Yamagata Univ., Tokyo Inst. Tech., Tohoku Univ., Hokkaido Univ.



Existing upper bound may be achievable in a few days using J-PARC

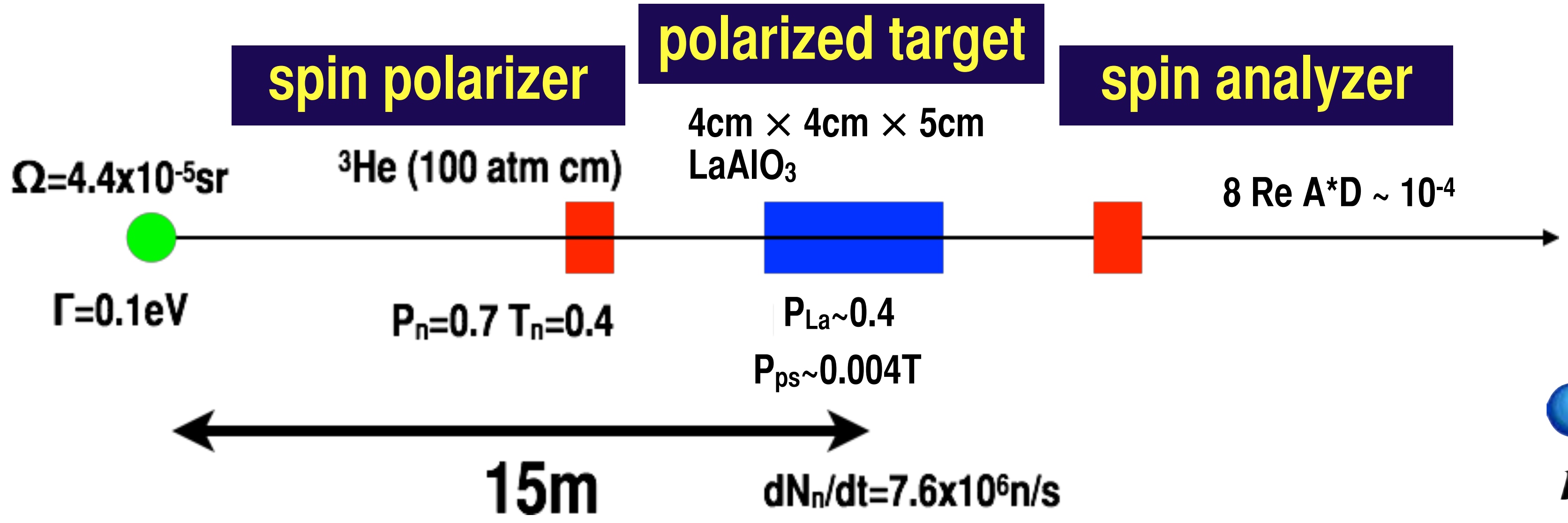
$$\left|\Delta\sigma_{\mathrm{T}}^{nA}\right| < 2.5\times10^{-4}[\mathrm{b}]\times\kappa(J)$$

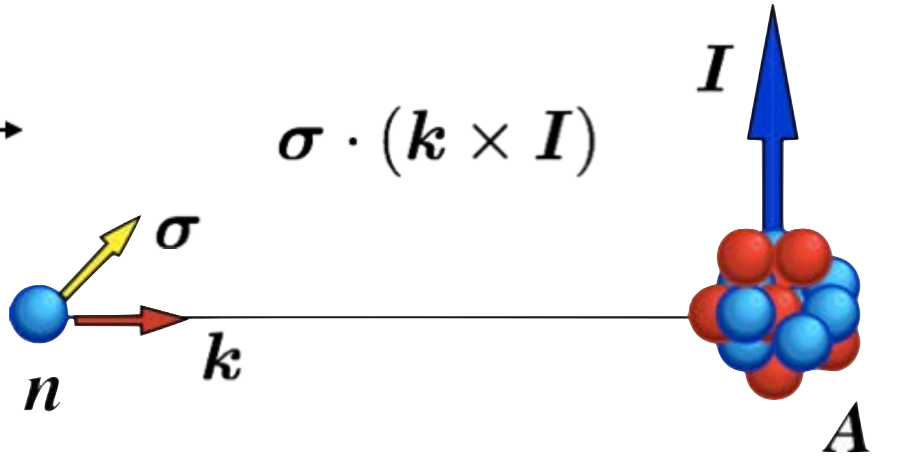
T-violation

Upper limit of nEDM

Angular Factor(P⇄T)

T.Okudaira-Phys. Rev. C97 (2018) 034622





Medium-range Force Search

C.C.Haddock, Phys. Rev. D 97 (2018) 062002

Kyushu Univ., Nagoya Univ., KEK, Indiana Univ.

Precision Measurement of Angular Distribution of Neutron Scattering

Yukawa-type interaction causes a peak in angular distribution

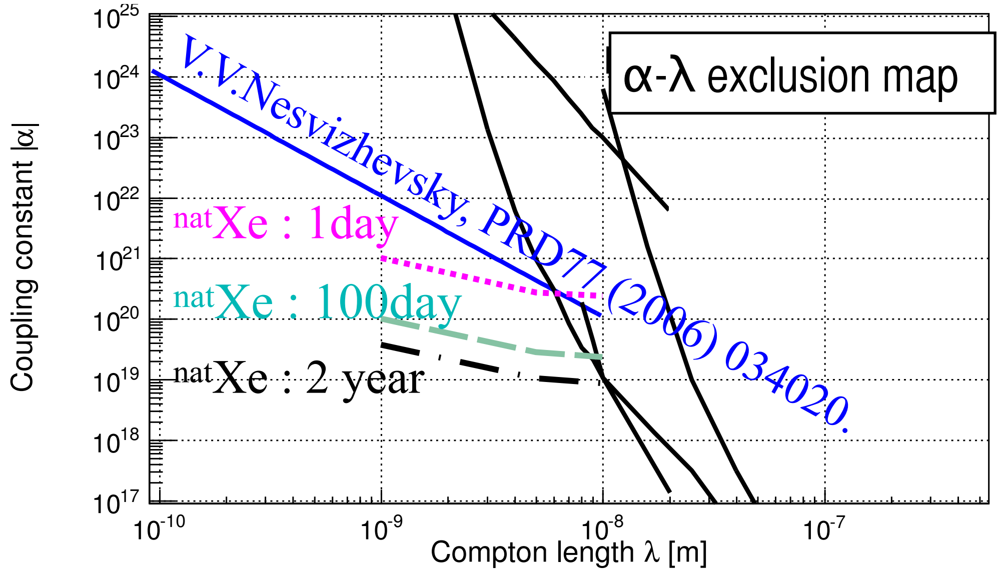
$$V(r) = G\frac{m_1 m_2}{r}(1+\alpha e^{-r/\lambda})$$

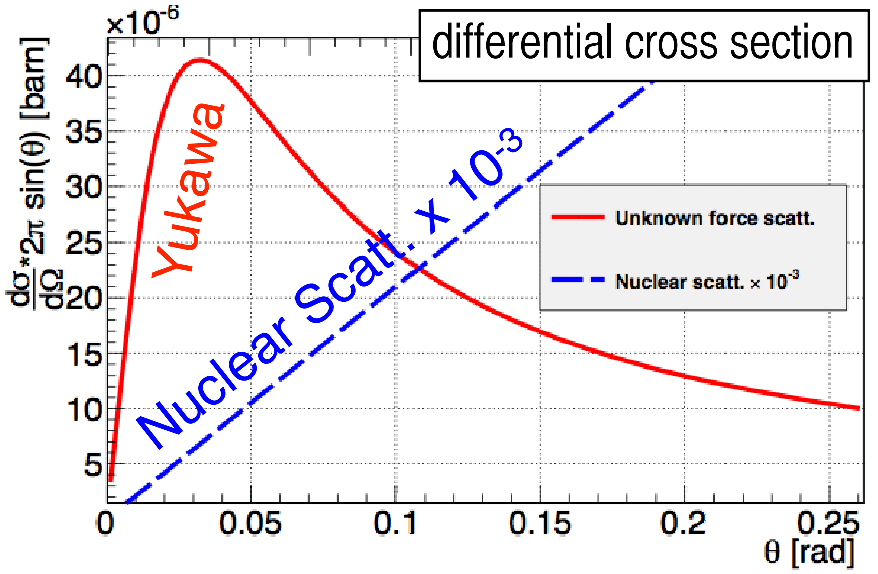
$$\frac{d\sigma_G(\theta)}{d\Omega} = 2\cdot\sigma_N^{1/2}\cdot\alpha\cdot\left(\frac{G\cdot m_n\cdot M}{4}\right)\left(\frac{1}{\frac{1}{m_n c^2}\left(\frac{\hbar c}{\lambda}\right)^2 + 8E_n\sin^2\frac{\theta}{2}}\right)$$

➡ **measurement of scattering cross section of noble gas**

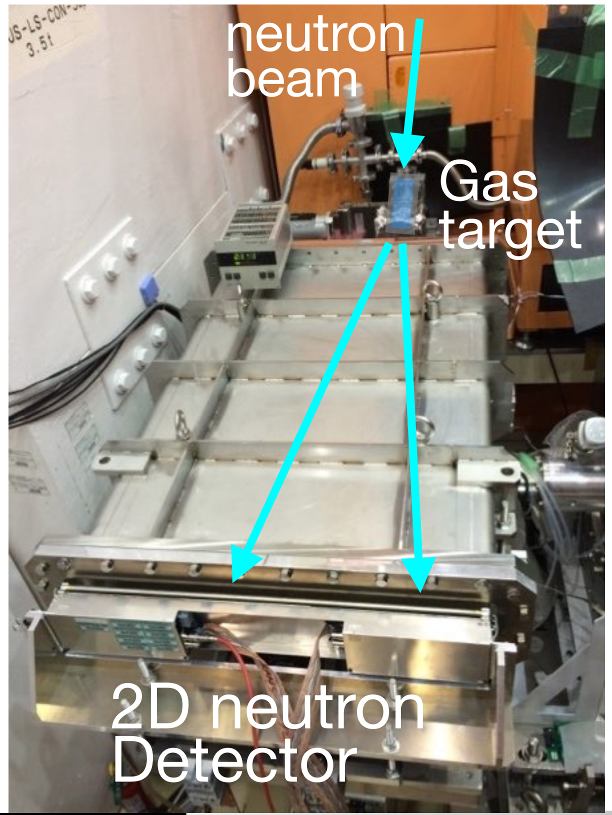
Pulsed beam on Xe target

→ accessible to $\alpha=10^{20}$ in 100days

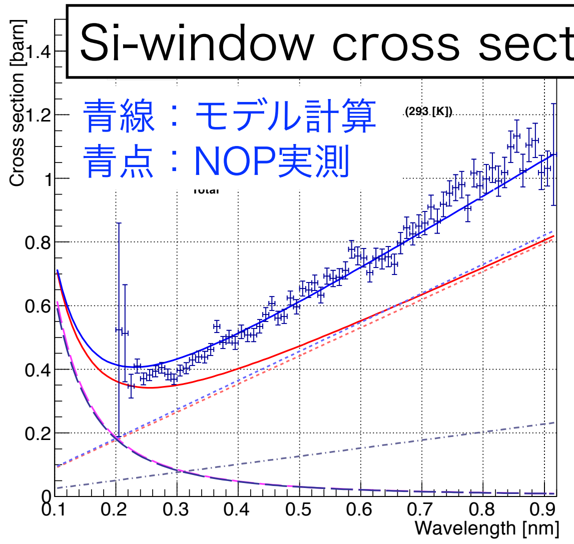




$\alpha=10^{23}$ $\lambda=0.5$ nm $E_n=20$ meV



Phase-1 in progress



Checking Si-window of gas chamber

Neutron Interferometry

RIKEN, Nagoya Univ.

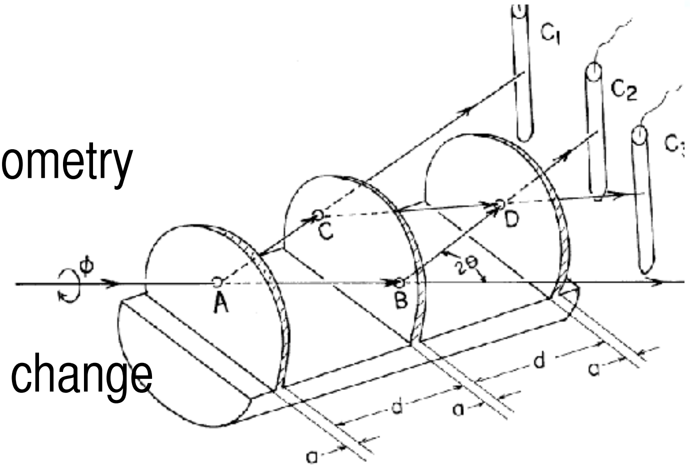
Laboratory study of general relativity

Search for post-Newtonian terms

1m^2 long-wavelength interferometry

↓

Lense-Thiring effect
corresponds to 1μrad phase change



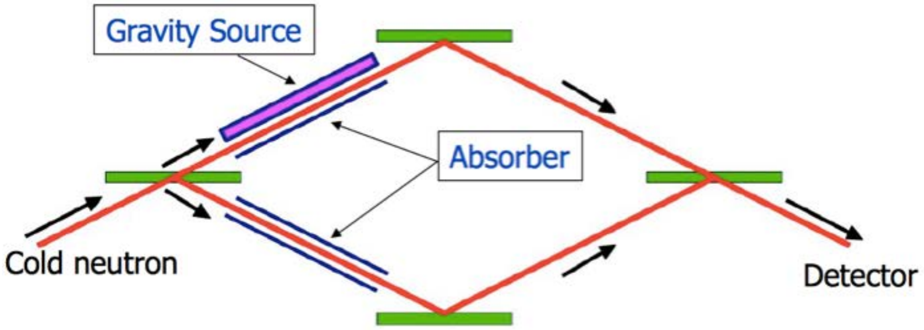
$$\mathcal{H} = \frac{\boldsymbol{p}}{2m_n} + \overset{\text{COW}}{\underline{m\phi}} + \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S}) + \frac{1}{c^2}\left(\underbrace{\frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})}_{\text{Lense-Thiring}} - \frac{\boldsymbol{p}^4}{8m^3} + \frac{m\phi^2}{2} + \frac{3\boldsymbol{p}\cdot\phi\boldsymbol{p}}{2m} + \frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \frac{6GMR^3}{5r^5}\boldsymbol{S}\cdot[r\times(r\times\Omega)]\right)$$

post-Newtonian terms

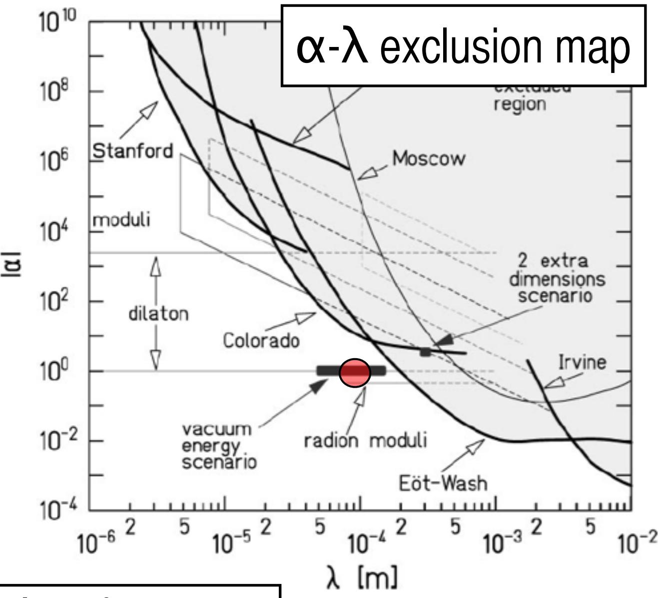
μm-order new-force search

$$V(r) = G\frac{m_1 m_2}{r}(1+\alpha e^{-r/\lambda})$$

put source close to one of paths



α-λ exclusion map



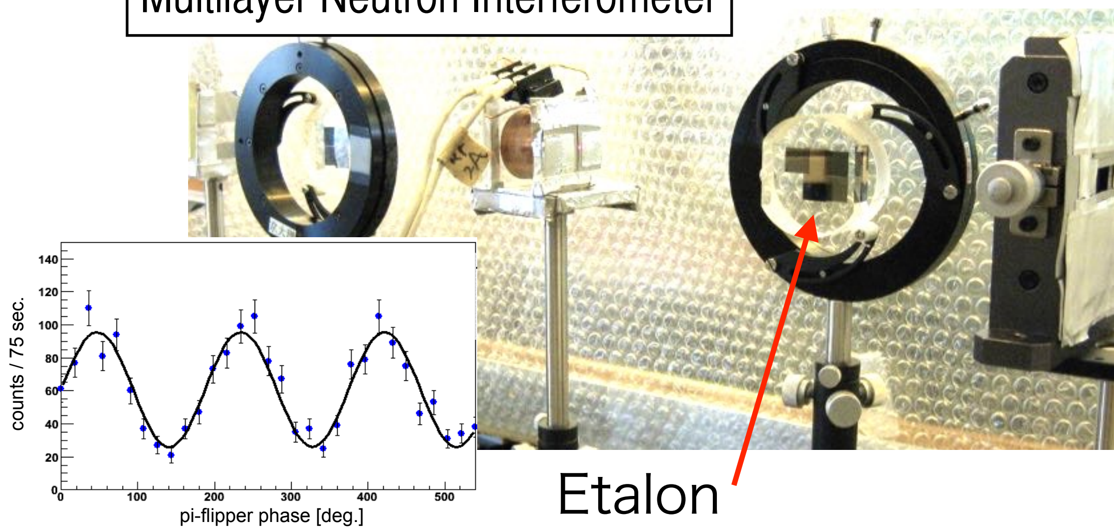
Precision measurement of scattering length

for few-body nucleon system

and for neutron scattering data

put material on one of paths

Multilayer Neutron Interferometer



Etalon

Neutron Optics

Neutron Spin Optics

magnetic moment

Neutron

Neutron

$$J^{\pi} = \frac{1}{2}^{+}$$

fermion

$$J^\pi = \frac{1}{2}^+$$

fermion

$$J^{\pi} = \frac{1}{2}^{+}$$

Dirac's equation

$$\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$$

Classical Mechanics

Quantum Mechanics

Classical Mechanics

$$E = \frac{\boldsymbol{p}^2}{2m} + V$$

Quantum Mechanics

Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}\psi = \left(-\frac{\hbar}{2m}\boldsymbol{\nabla}^2 + V\right)\psi$$

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correspondance

number operator

$$E \to i\hbar\frac{\partial}{\partial t}$$

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$$c = \hbar = 1$$

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correspondance

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relativistic quantum mechanics

fermion

$$J^{\pi} = \frac{1}{2}^{+}$$

Dirac's equation

$$\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$$

Lagrangian

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi$$

fermion

$$J^\pi = \frac{1}{2}^+$$

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Lagrangian

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$$F^{\mu\nu} = \partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu}$$

$$A^{\mu} = (\phi, \boldsymbol{A})$$

Electromagnetic tensor

$$F^{\mu\nu} = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{pmatrix}$$

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gauge invariance

$$\mathcal{L} = \bar{\psi}\left\{i\gamma^\mu\left(\partial_\mu - ieA_\mu\right) - m\right\}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$g\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$$

fermion

$$J^{\pi}=\frac{1}{2}^{+}$$

Dirac's equation

$$\left(i\gamma^{\mu}\partial_{\mu}-m\right)\psi=0$$

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$$\cancel{g\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}}$$

minimal coupling

fermion

$$J^{\pi} = \frac{1}{2}^{+}$$

Dirac's equation

$$(i\gamma^{\mu}\partial_{\mu} - m)\,\psi = 0$$

Lagrangian

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi$$

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$$H_{\mathrm{int}} = -\boldsymbol{\mu}_{\mathrm{e}} \cdot \boldsymbol{B} \qquad \boldsymbol{\mu}_{\mathrm{e}} = \mathrm{g}\,\mu_{\mathrm{B}}\boldsymbol{s} \qquad \mu_{\mathrm{B}} = \frac{e\hbar}{2m_{\mathrm{e}}}$$

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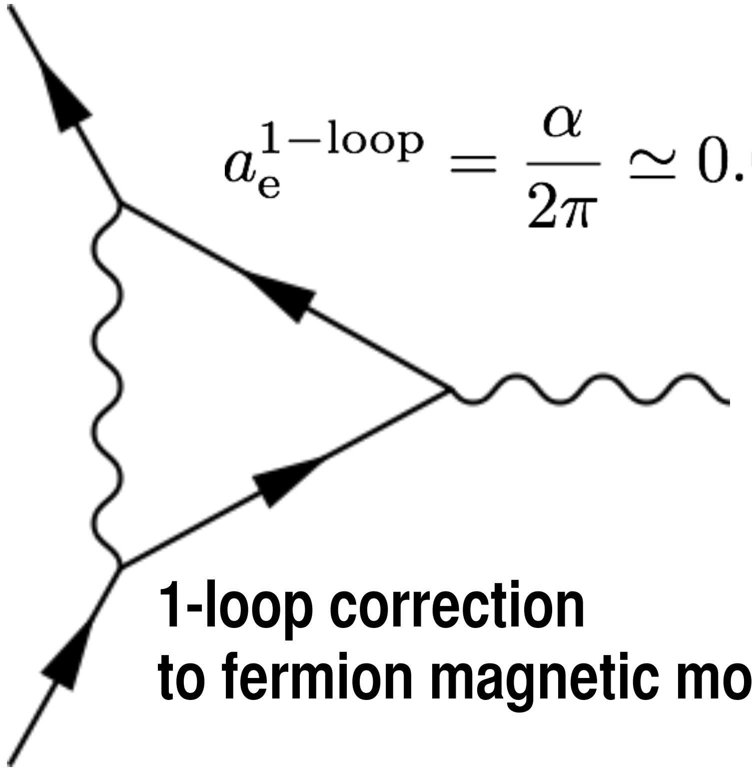

$$a_{\mathrm{e}}^{1-\mathrm{loop}} = \frac{\alpha}{2\pi} \simeq 0.001\,161\,4$$

1-loop correction
to fermion magnetic moment

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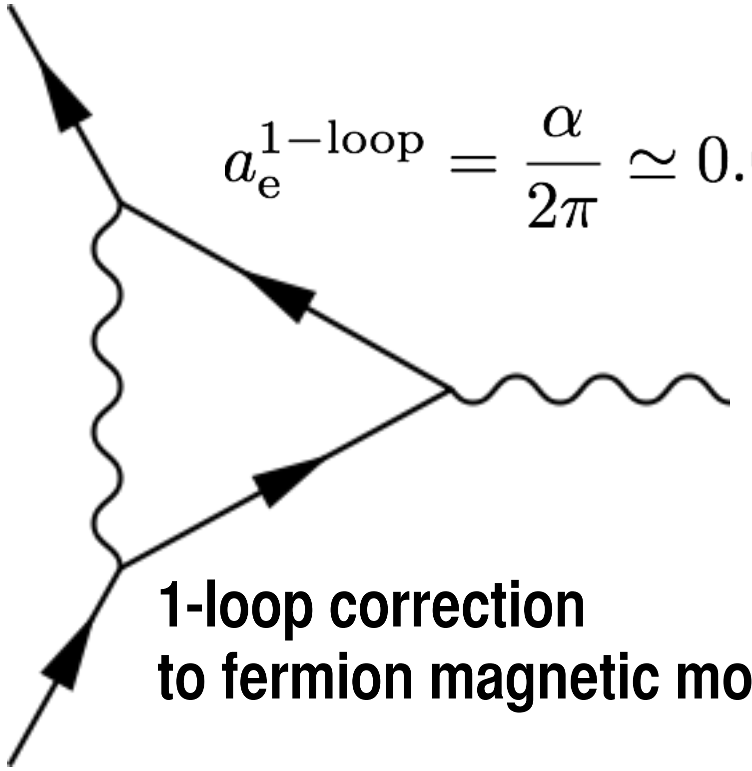
anomalous magnetic moment

electron

$$a_{\mathrm{e}} = \frac{\mathrm{g}_{\mathrm{e}} - 2}{2}$$



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anomalous magnetic moment

electron

$$a_{\mathrm{e}} = \frac{\mathrm{g_e} - 2}{2}$$

$$a_{\mathrm{e}}^{\mathrm{exp}} = 0.001\,159\,652\,180\,76(27)$$

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$$a_{\mathrm{e}}^{\mathrm{exp}} - a_{\mathrm{e}}^{\mathrm{theory}} = -0.91(0.82) \times 10^{-12}$$

fermion

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$$g = 2$$

point-like fermion

$$H_{\mathrm{int}} = -\boldsymbol{\mu}_{\mathrm{e}} \cdot \boldsymbol{B}$$

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muon

$$a_{\mu} = \frac{g_{\mu} - 2}{2}$$

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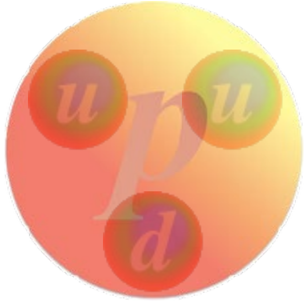
$$a_{\text{p}} = \frac{\text{g}_{\text{p}} - 2}{2}$$



$$\boldsymbol{\mu}_{\text{p}} = \text{g}_{\text{p}}\,\mu_{\text{N}}\,\boldsymbol{s}$$

$$\text{g}_{\text{p}} = 5.5858$$

$$a_{\text{p}} = 2.792\,847\,356(23)$$

$$\mu_{\text{N}} = \frac{e\hbar}{2m_{\text{p}}}$$

fermion

$$J^\pi = \frac{1}{2}^+$$

$$\mathrm{g} = 2$$

point-like fermion

$$H_{\mathrm{int}} = -\boldsymbol{\mu}_{\mathrm{e}} \cdot \boldsymbol{B}$$

$$\boldsymbol{\mu}_{\mathrm{e}} = \mathrm{g}\,\mu_{\mathrm{B}}\,\boldsymbol{s}$$

$$\mu_{\mathrm{B}} = \frac{e\hbar}{2m_{\mathrm{e}}}$$

anomalous magnetic moment

electron

$$a_{\mathrm{e}} = \frac{\mathrm{g_e} - 2}{2}$$

$$a_{\mathrm{e}}^{\mathrm{exp}} = 0.001\,159\,652\,180\,76(27)$$

$$a_{\mathrm{e}}^{\mathrm{theory}} = 0.001\,159\,652\,181\,13(11)(37)(02)(77)$$

$$a_{\mathrm{e}}^{\mathrm{exp}} - a_{\mathrm{e}}^{\mathrm{theory}} = -0.91(0.82) \times 10^{-12}$$

muon

$$a_\mu = \frac{\mathrm{g}_\mu - 2}{2}$$

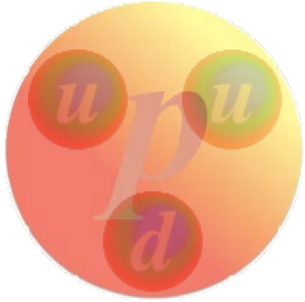
$$a_\mu^{\mathrm{exp}} = 0.001\,165\,920\,91(63)$$

$$a_\mu^{\mathrm{theory}} = 0.001\,165\,918\,03(49)$$

$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{theory}} = 2.88(0.80) \times 10^{-9}$$

proton

$$a_{\mathrm{p}} = \frac{\mathrm{g_p} - 2}{2}$$



$$\mathrm{g_p} = 5.5858$$

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$$\boldsymbol{\mu}_{\mathrm{p}} = \mathrm{g_p}\,\mu_{\mathrm{N}}\,\boldsymbol{s}$$

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fermion

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$$a_{\mathrm{p}} = \frac{\mathrm{g}_{\mathrm{p}} - 2}{2}$$

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fermion

$$J^{\pi} = \frac{1}{2}^{+}$$

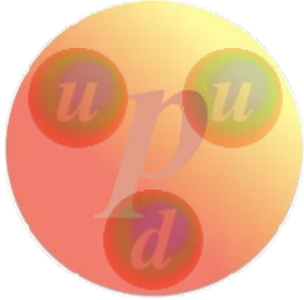
$$\mathrm{g} = 2$$

point-like fermion

anomalous magnetic moment

proton

$$a_{\mathrm{p}} = \frac{\mathrm{g_p} - 2}{2}$$



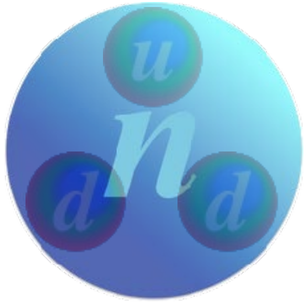
$$\mathrm{g_p} = 5.5858$$
$$a_{\mathrm{p}} = 2.792\,847\,356(23)$$

$$\boldsymbol{\mu}_{\mathrm{p}} = \mathrm{g_p}\,\mu_{\mathrm{N}}\,\boldsymbol{s}$$

$$\mu_{\mathrm{N}} = \frac{e\hbar}{2m_{\mathrm{p}}}$$

proton

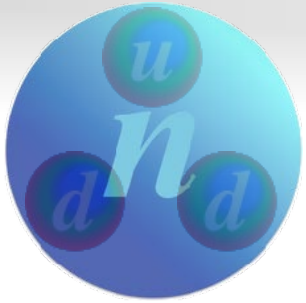
$$a_{\mathrm{n}} = \frac{\mathrm{g_n} - 2}{2}$$



$$\mathrm{g_n} = -3.8263$$
$$a_{\mathrm{n}} = -1.913\,042\,73(45)$$

Neutron

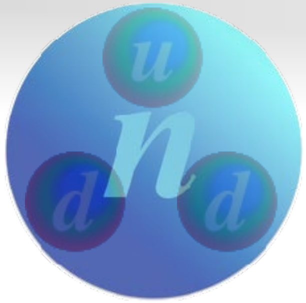
$$J^{\pi} = \frac{1}{2}^{+}$$



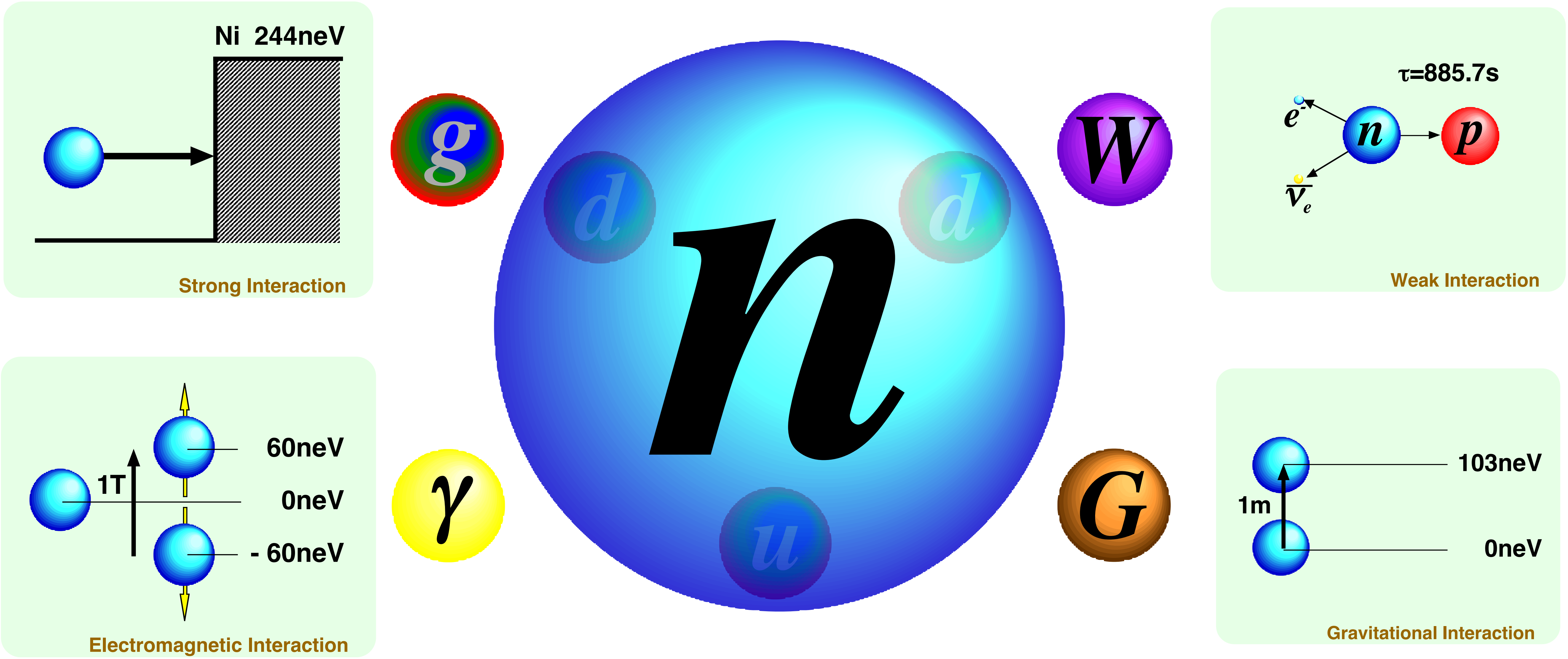
$$\begin{aligned} H_{\text{int}} &= -\boldsymbol{\mu}_{\text{n}} \cdot \boldsymbol{B} \\ &= 1.913\mu_{\text{N}}\, \boldsymbol{\sigma} \cdot \boldsymbol{B} \\ &\simeq \pm 60\,\text{neV T}^{-1} \end{aligned}$$

Neutron

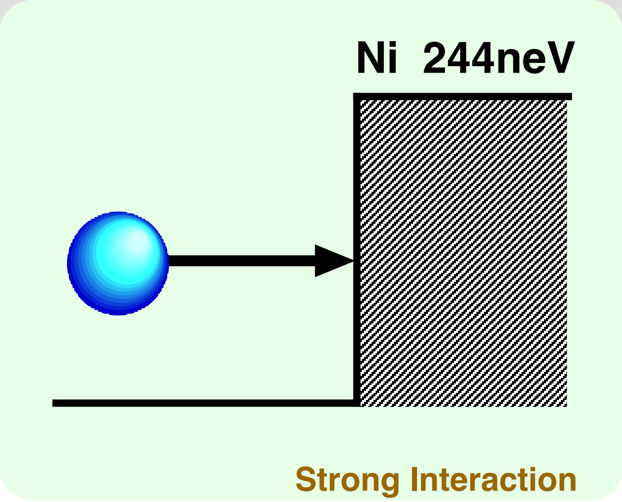
$$J^{\pi} = \frac{1}{2}^{+}$$



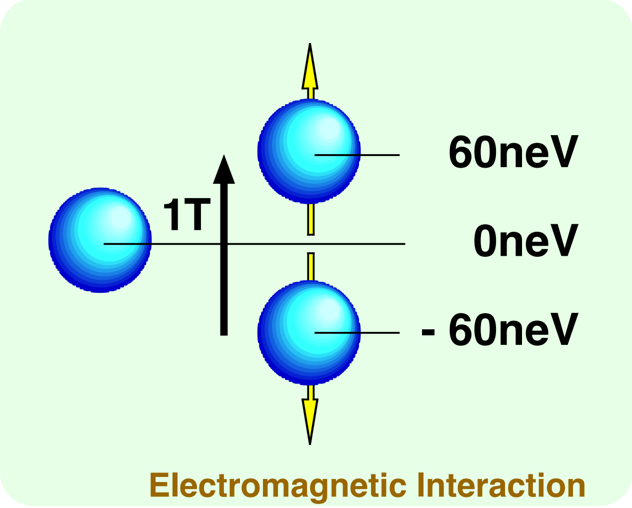
$$\begin{aligned} H_{\rm int} &= -\boldsymbol{\mu}_{\rm n}\cdot\boldsymbol{B} \\ &= 1.913\mu_{\rm N}\,\boldsymbol{\sigma}\cdot\boldsymbol{B} \\ &\simeq \pm 60\,{\rm neV\,T^{-1}} \end{aligned}$$



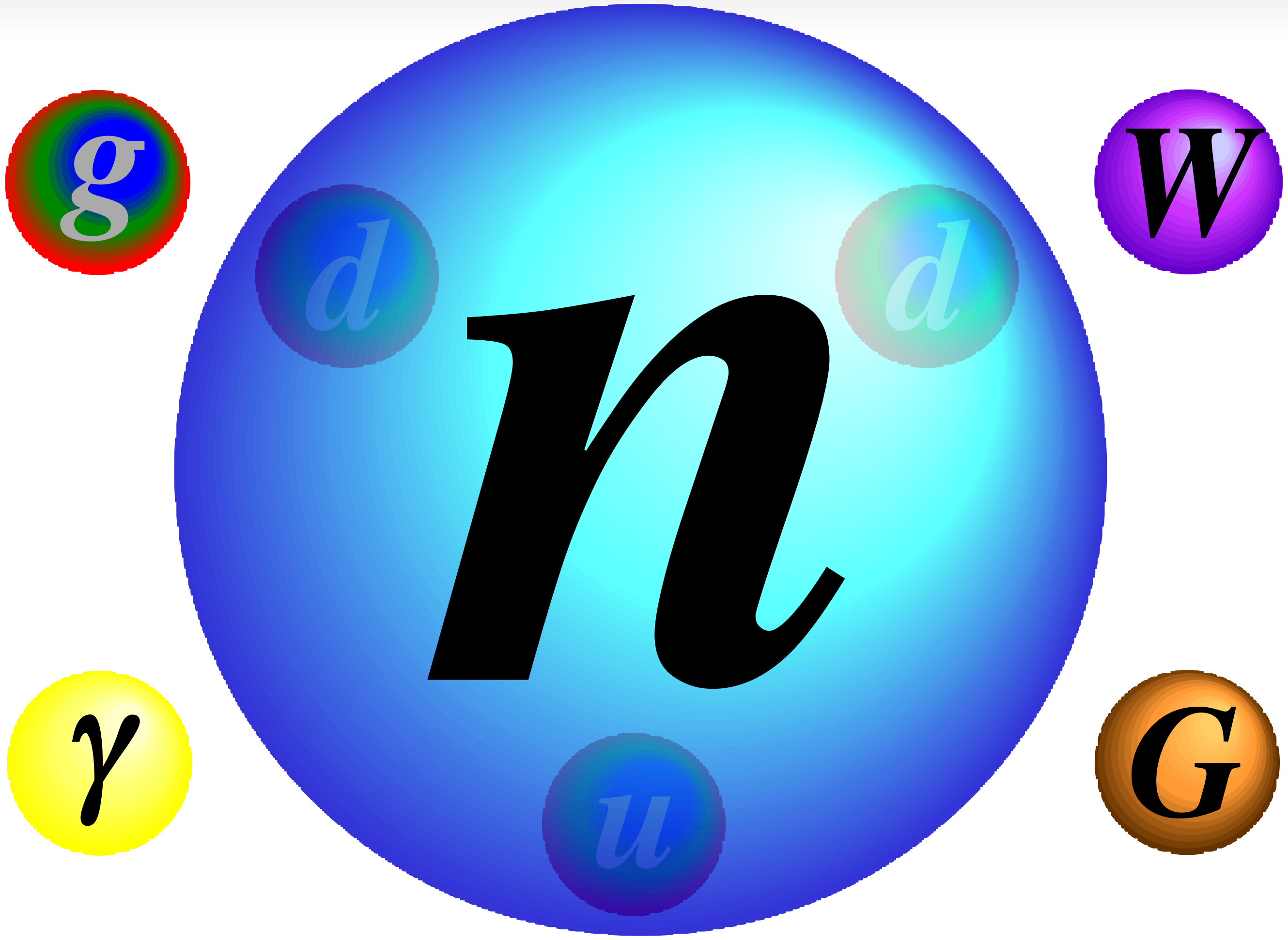
Neutron

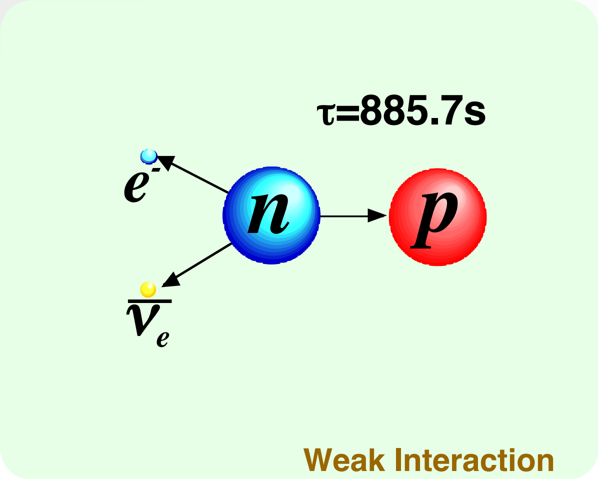


Strong Interaction

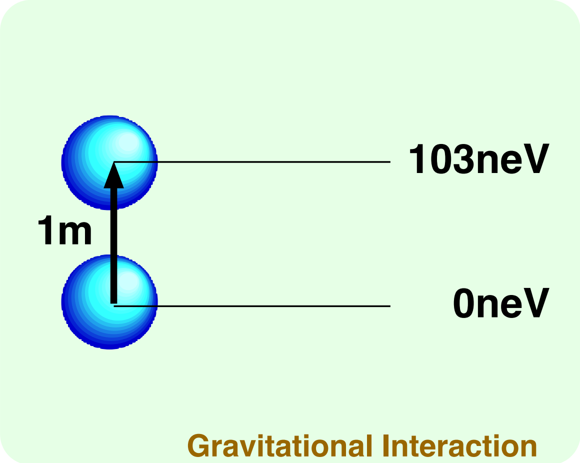


Electromagnetic Interaction



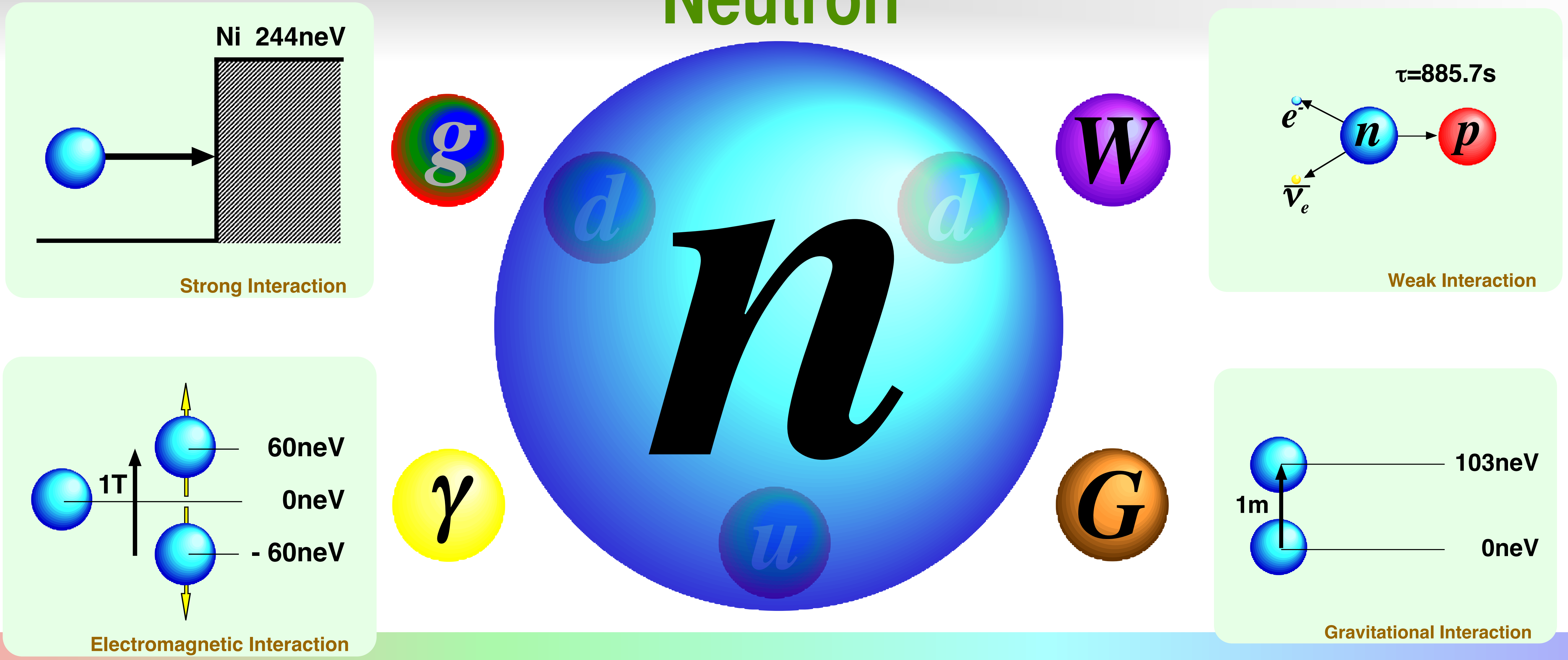


Weak Interaction



Gravitational Interaction

Neutron

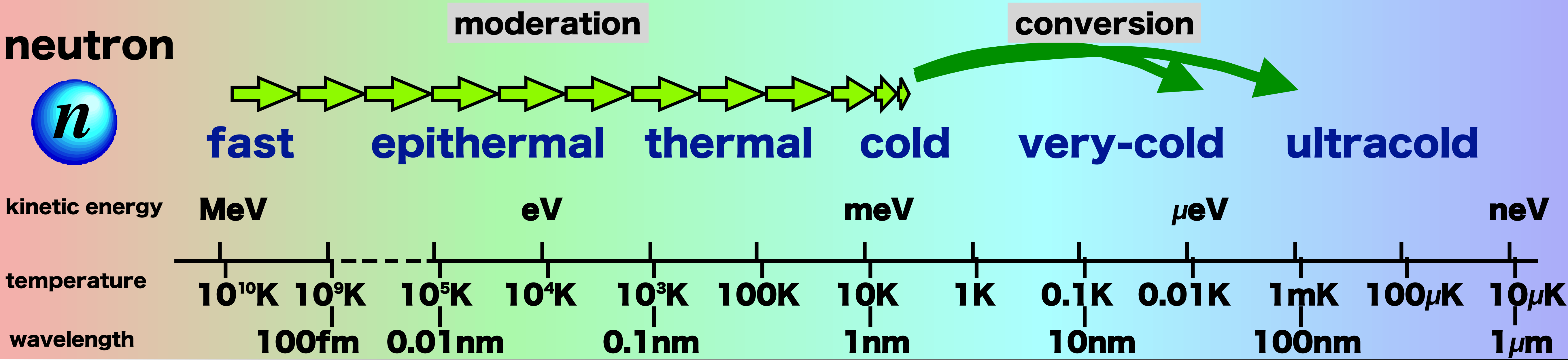


Strong Interaction

Weak Interaction

Electromagnetic Interaction

Gravitational Interaction



neutron

moderation

conversion

fast epithermal thermal cold very-cold ultracold

kinetic energy MeV eV meV μeV neV

temperature 10^{10}K 10^{9}K 10^{5}K 10^{4}K 10^{3}K 100K 10K 1K 0.1K 0.01K 1mK 100μK 10μK

wavelength 100fm 0.01nm 0.1nm 1nm 10nm 100nm 1μm

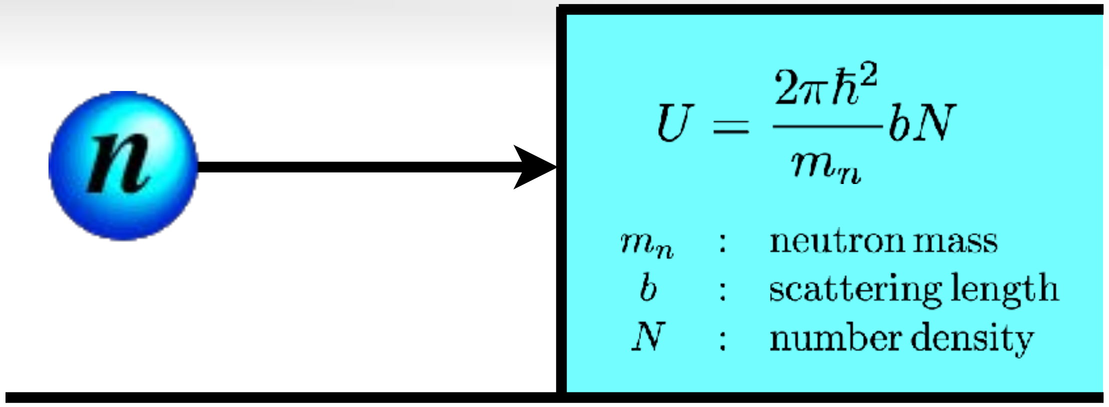
Devices

Devices

Magnetic Supermirror

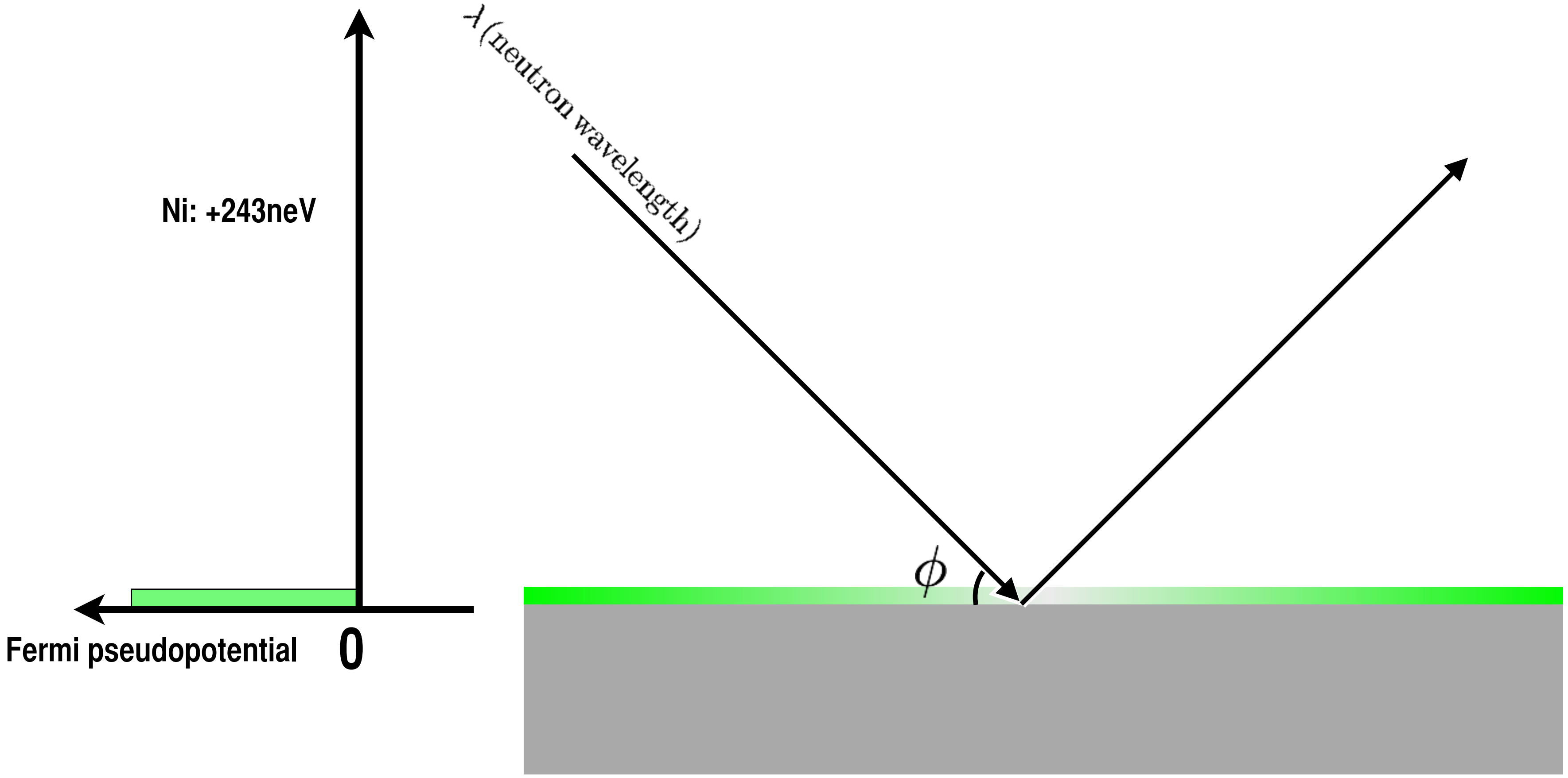
Neutron Reflection

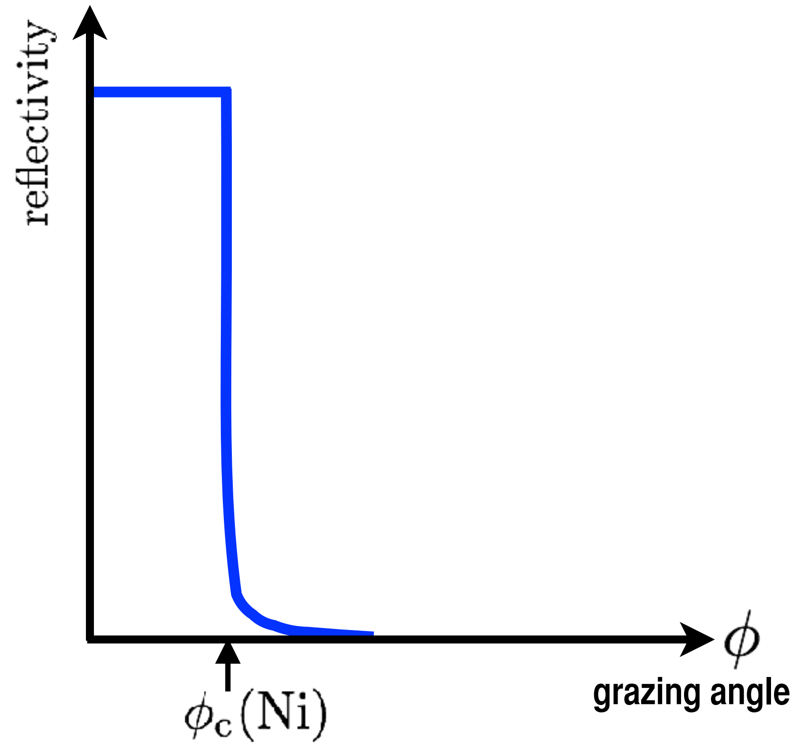
Fermi pseudopotential



$$U = \frac{2\pi\hbar^2}{m_n} bN$$

m_n : neutron mass
b : scattering length
N : number density

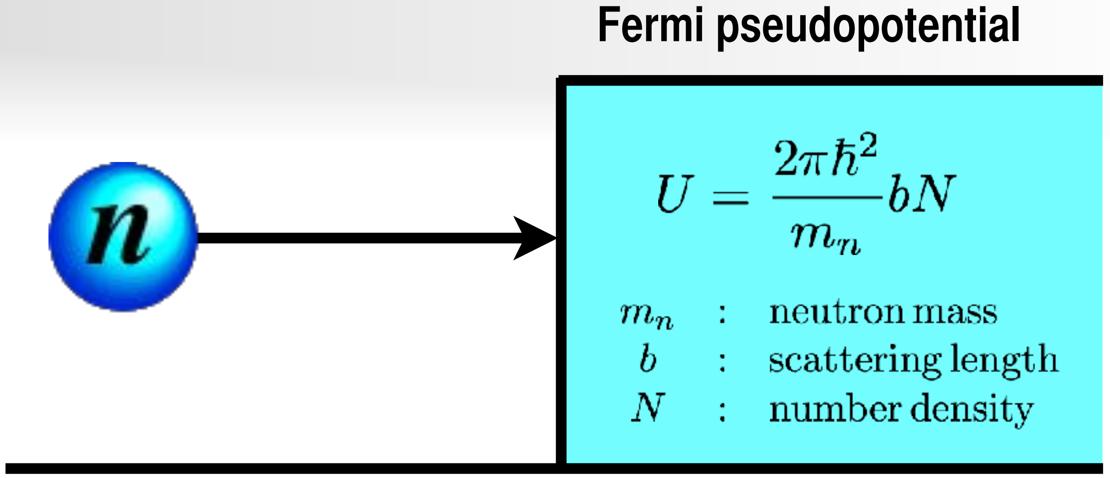




$$\frac{\phi_c(\mathrm{Ni})}{\lambda} = 1.7\,\mathrm{mrad}\,\mathrm{Å}^{-1}$$

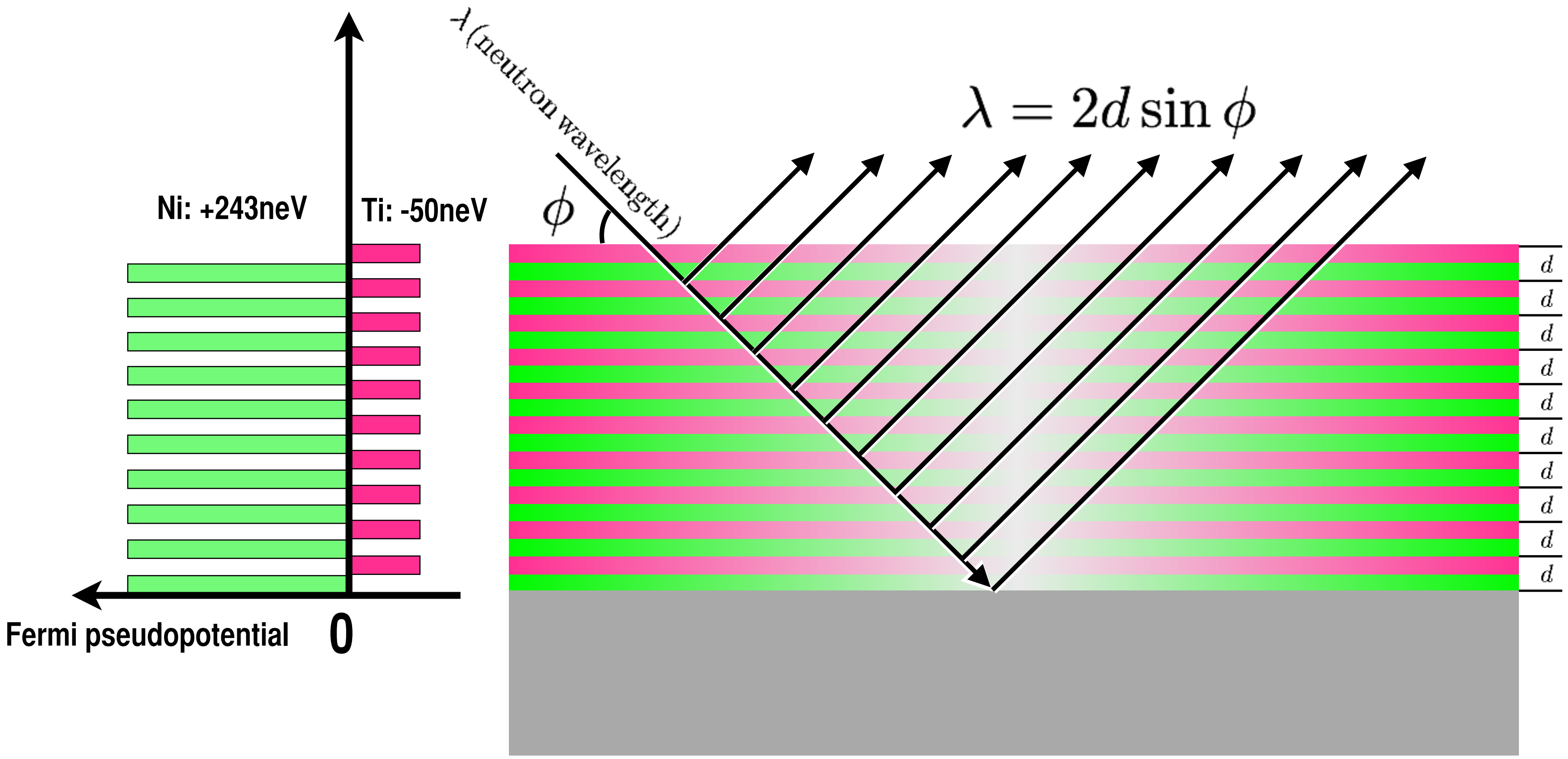
$$v_\perp(\mathrm{Ni}) = 7\,\mathrm{m/s}$$

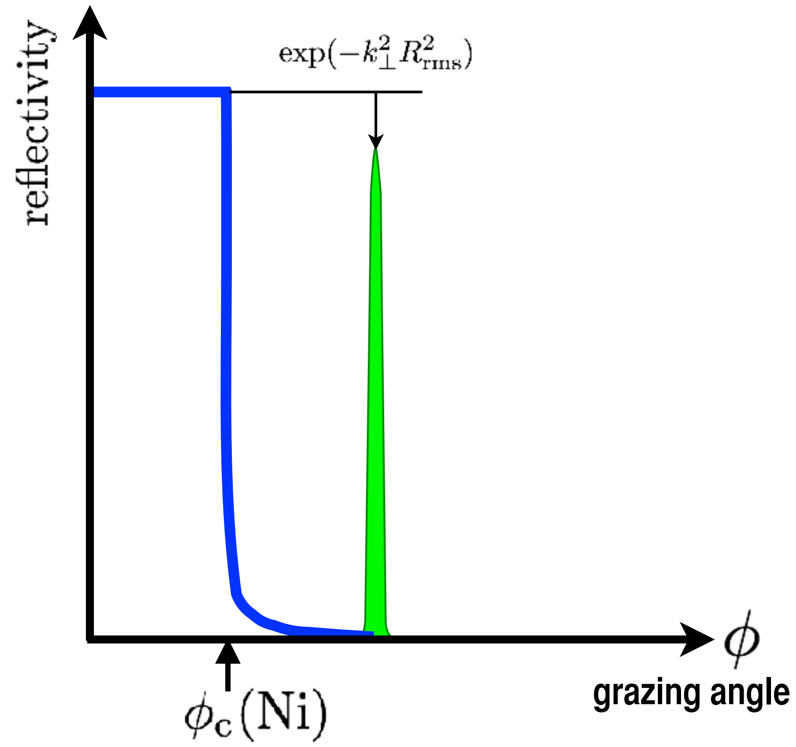
Multilayer Mirror (Monochromatic)



$$U = \frac{2\pi\hbar^2}{m_n} bN$$

m_n : neutron mass
b : scattering length
N : number density

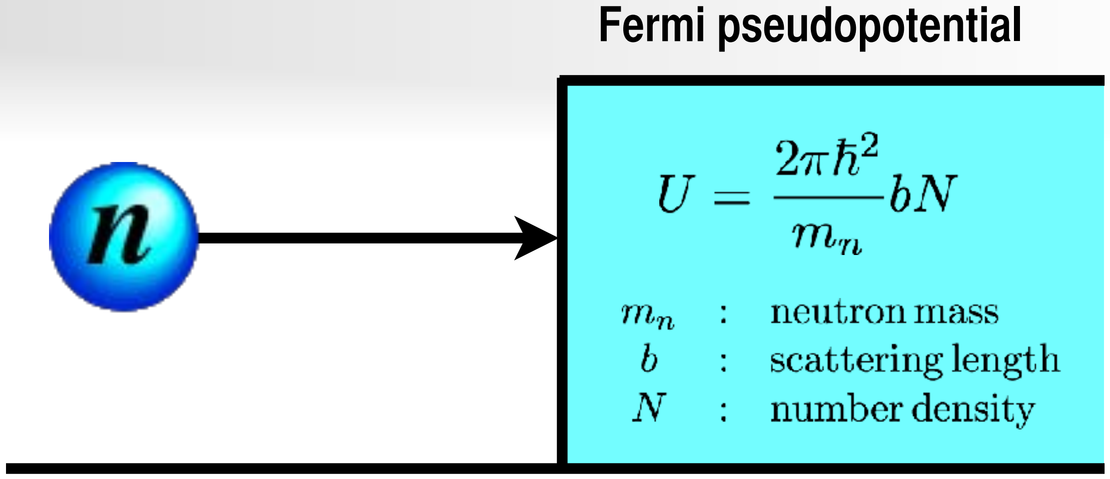




$$\frac{\phi_c(\mathrm{Ni})}{\lambda} = 1.7\,\mathrm{mrad}\,\mathrm{\AA}^{-1}$$

$$v_\perp(\mathrm{Ni}) = 7\,\mathrm{m/s}$$

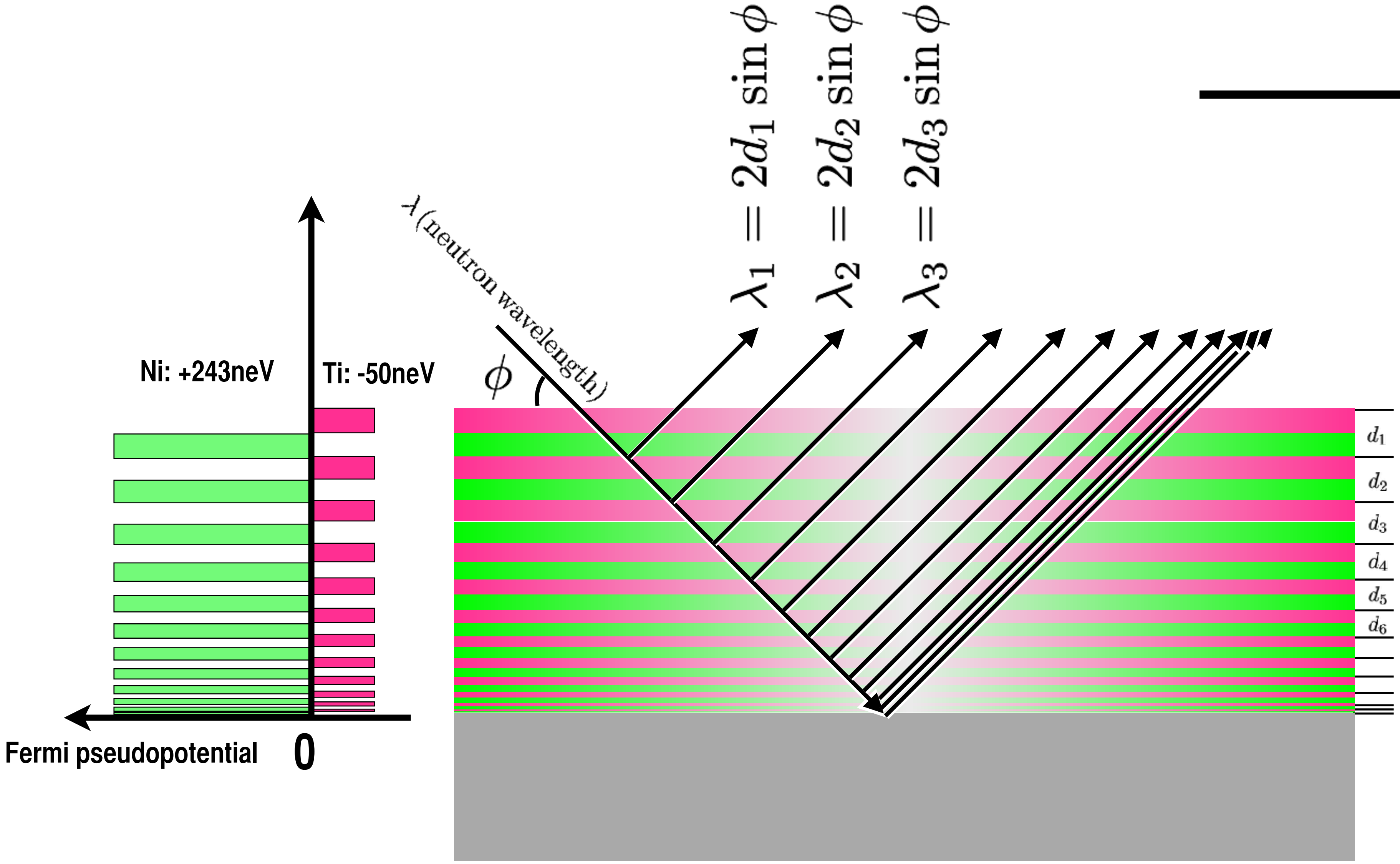
Supermirror

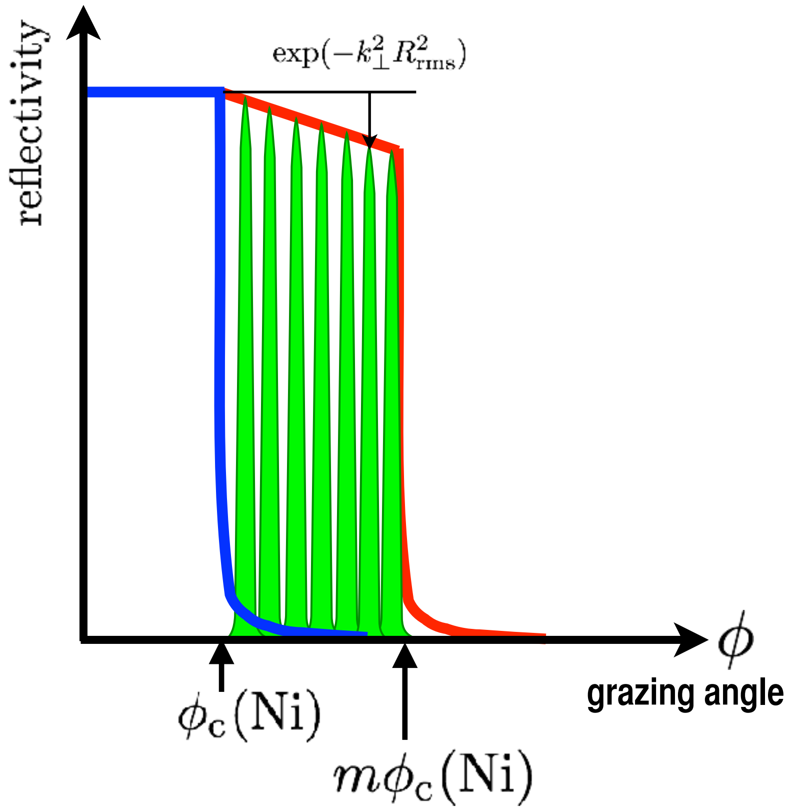


Fermi pseudopotential

$$U = \frac{2\pi\hbar^2}{m_n} bN$$

m_n : neutron mass
b : scattering length
N : number density





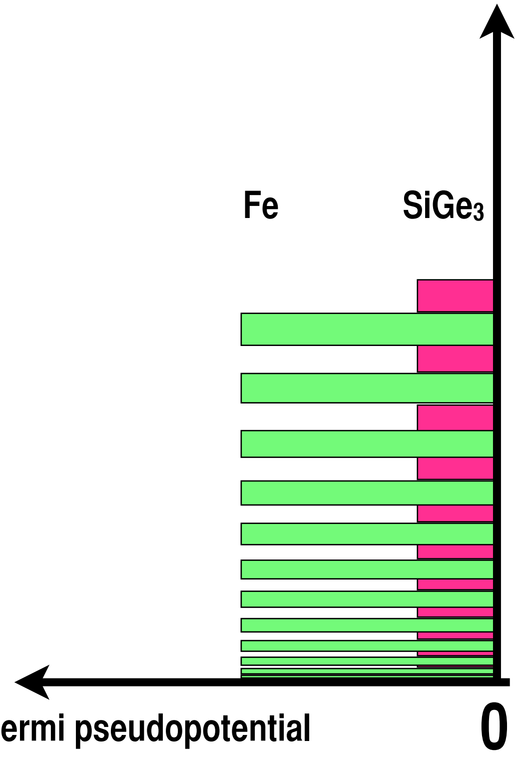
$$\frac{\phi_c(\mathrm{Ni})}{\lambda} = 1.7\,\mathrm{mrad}\,\mathrm{\mathring{A}}^{-1}$$

$$v_\perp(\mathrm{Ni}) = 7\,\mathrm{m/s}$$

Magnetic Supermirror

Magnetic layers

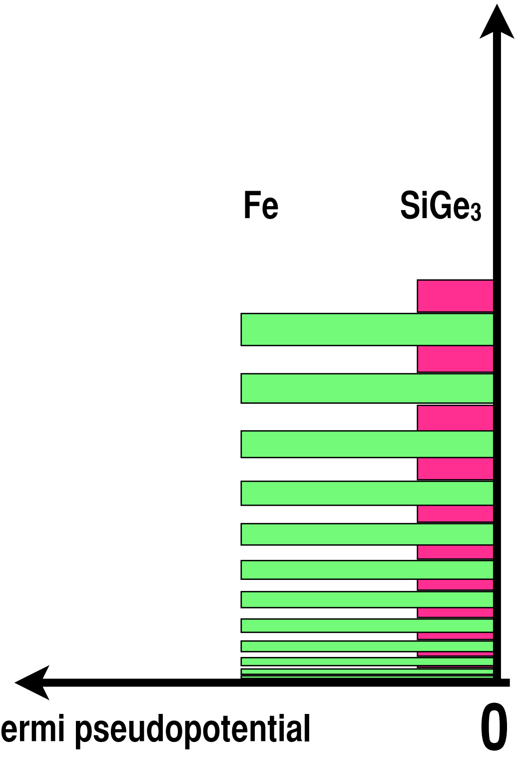
Non-magnetic layers



Magnetic Supermirror

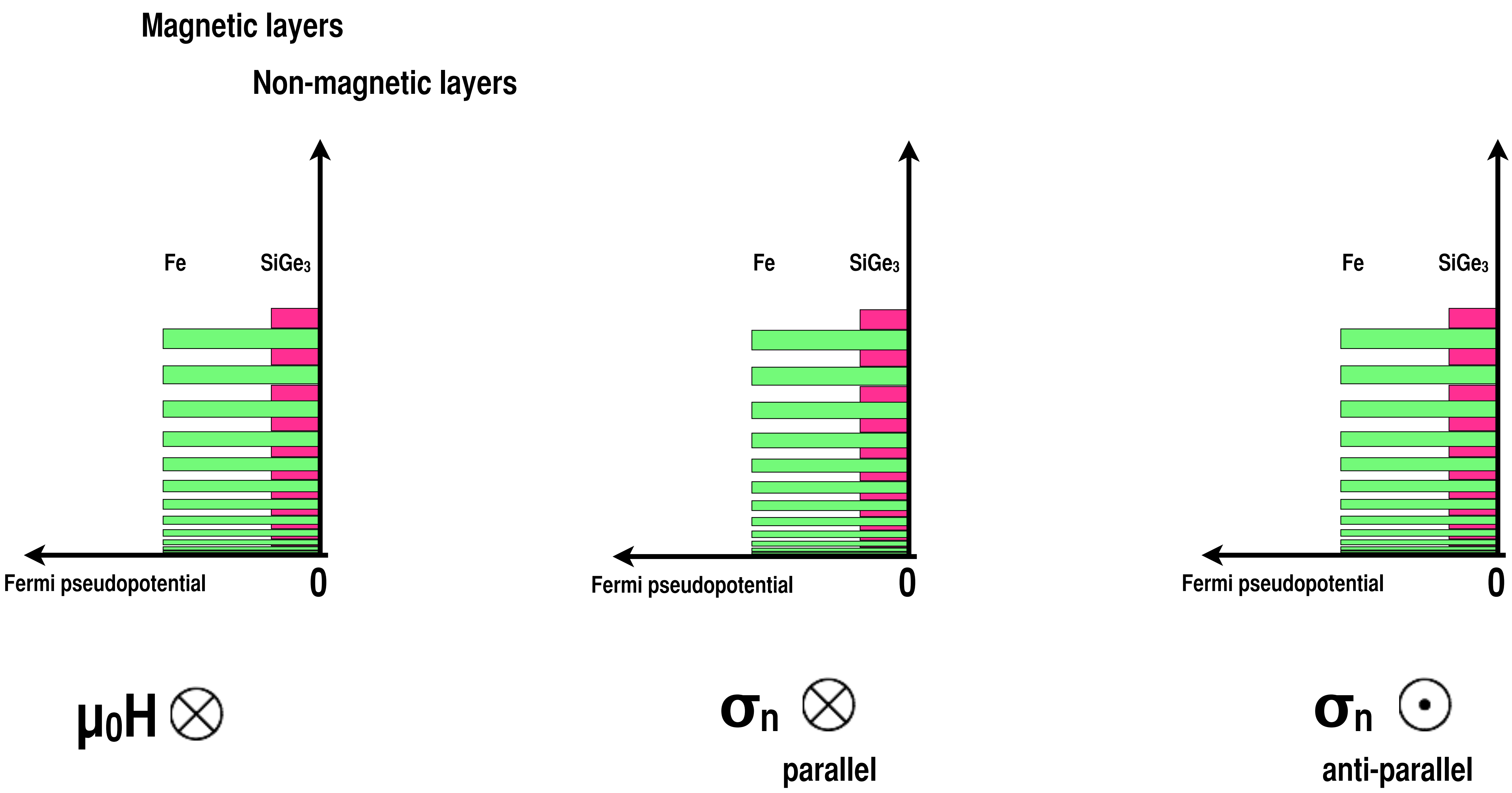
Magnetic layers

Non-magnetic layers



$\mu_0 H \otimes$

Magnetic Supermirror



Magnetic layers

Non-magnetic layers

$\mu_0 H \otimes$

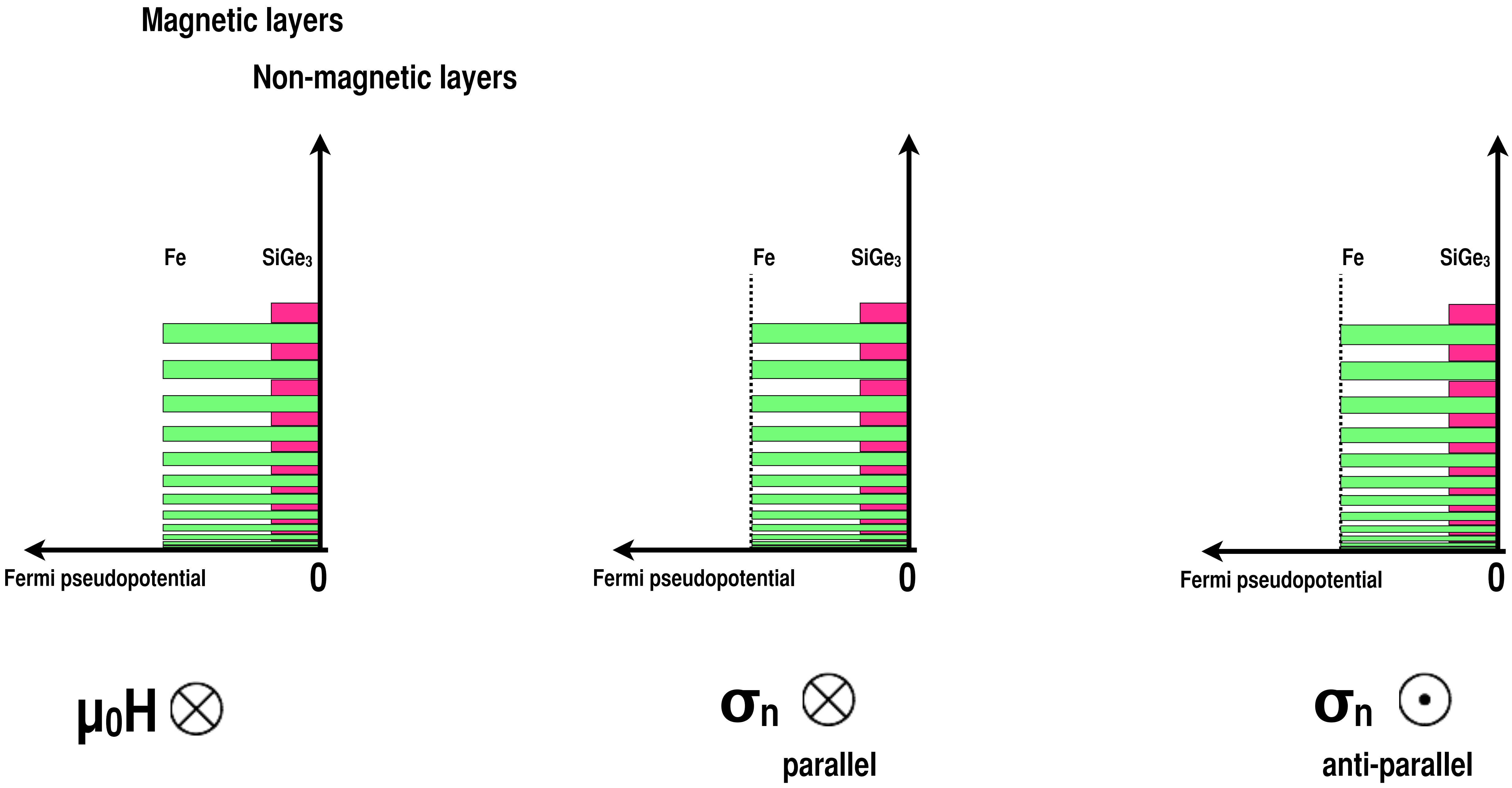
$\sigma_n \otimes$

parallel

$\sigma_n \odot$

anti-parallel

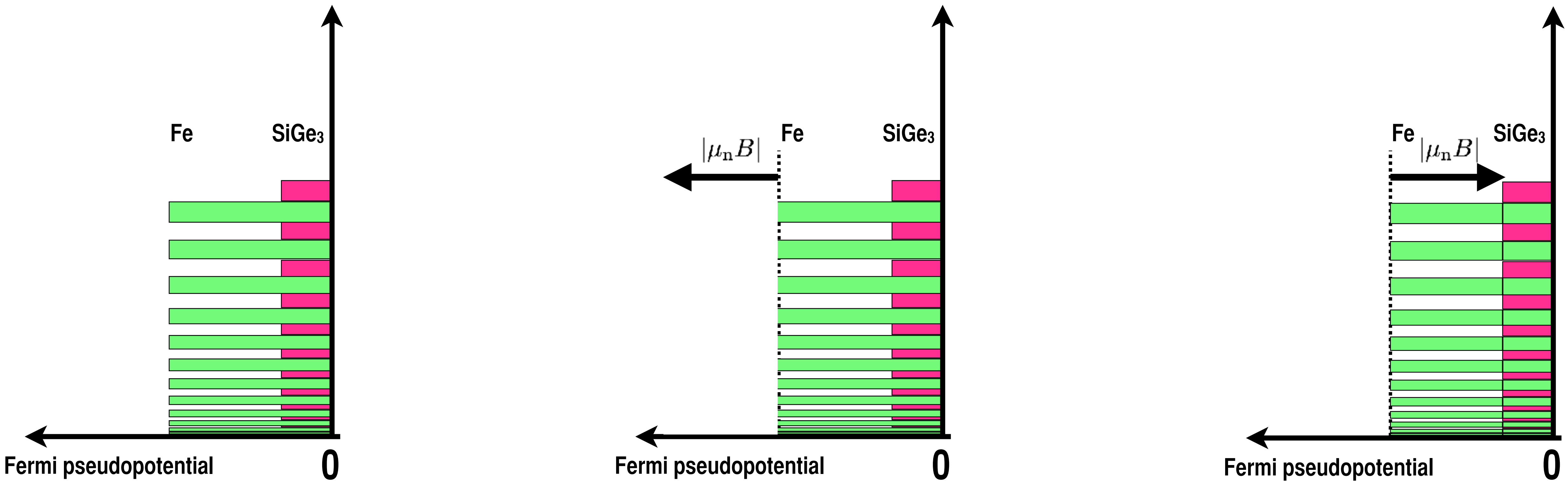
Magnetic Supermirror



Magnetic Supermirror

Magnetic layers

Non-magnetic layers



$\mu_0 H$ ⊗

σ_n ⊗

parallel

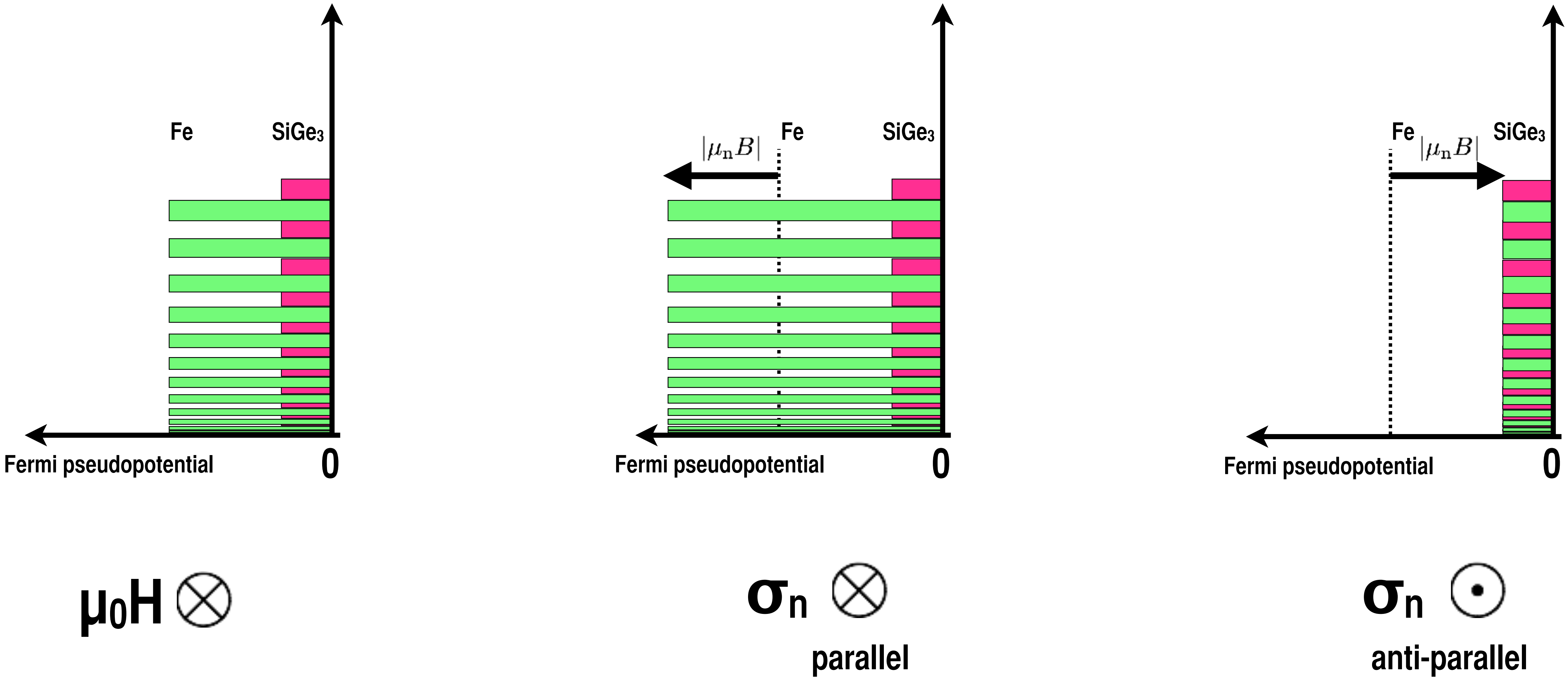
σ_n ⊙

anti-parallel

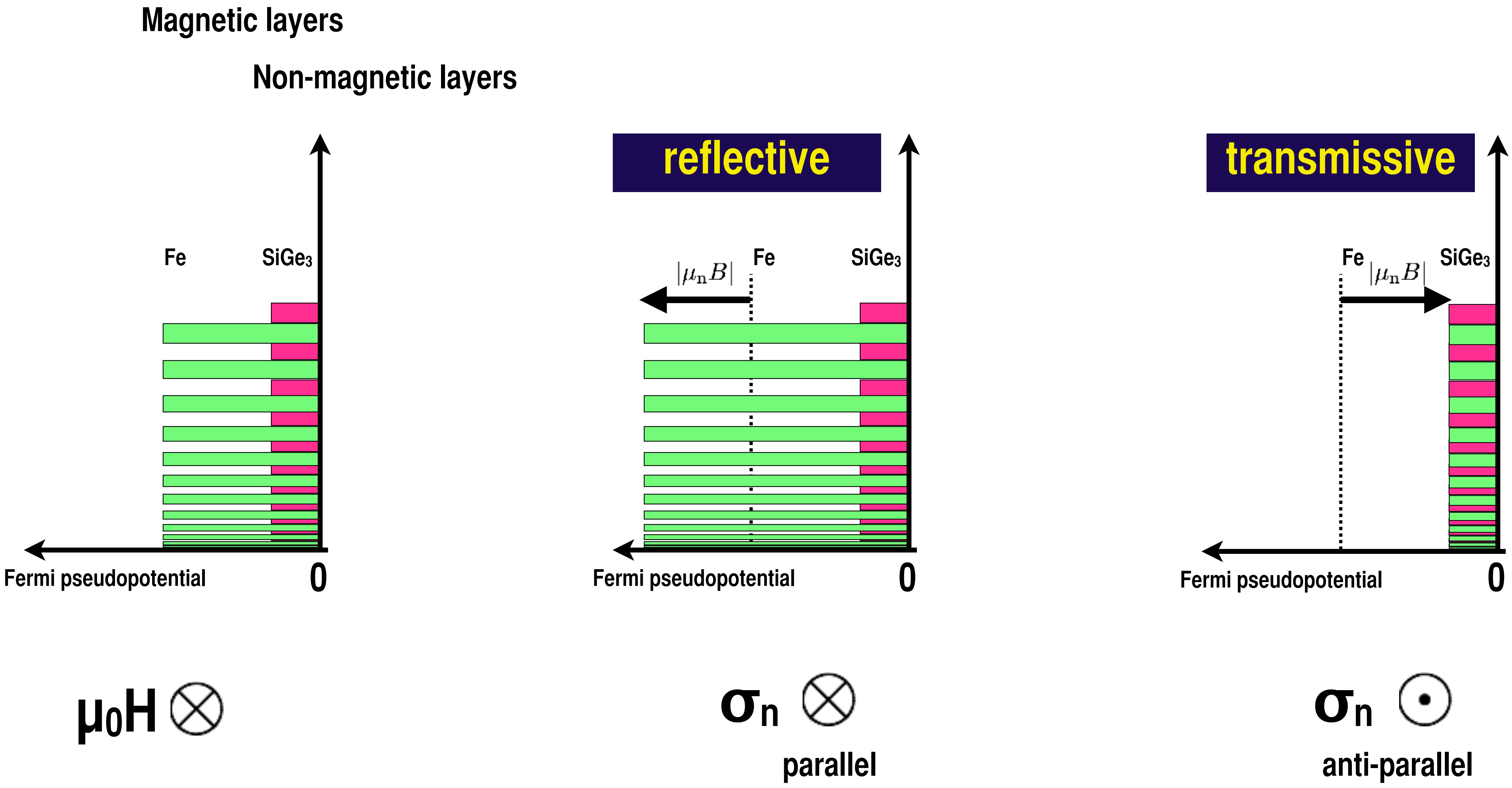
Magnetic Supermirror

Magnetic layers

Non-magnetic layers



Magnetic Supermirror



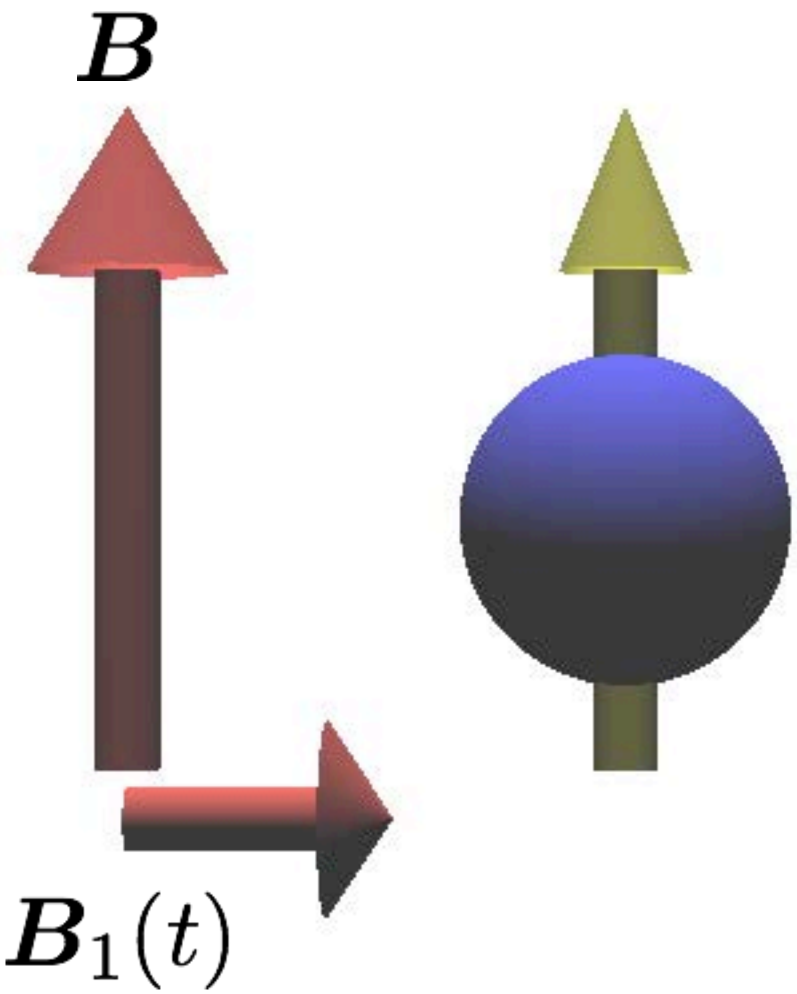
Spin Flipper

Spin Flipper

Spin Flipper

$$U = -\mu B$$

Spin Flipper



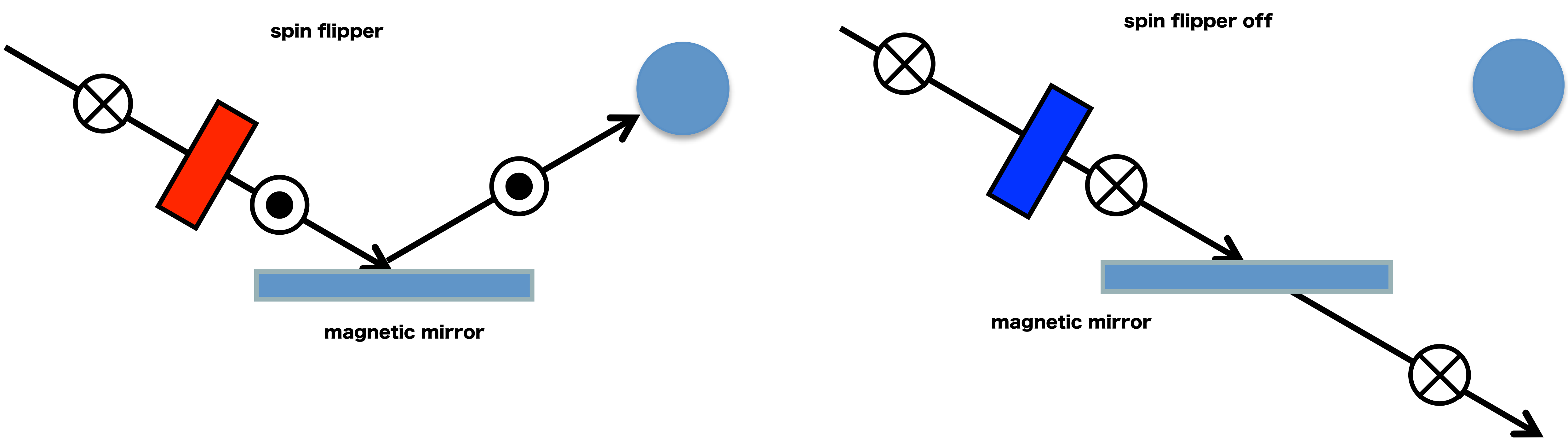
$$U = -\mu B$$

$$\leftarrow \quad \Delta U = +2\mu B$$

$$U = \mu B$$

Spin Flip Chopper

electromagnetic steering

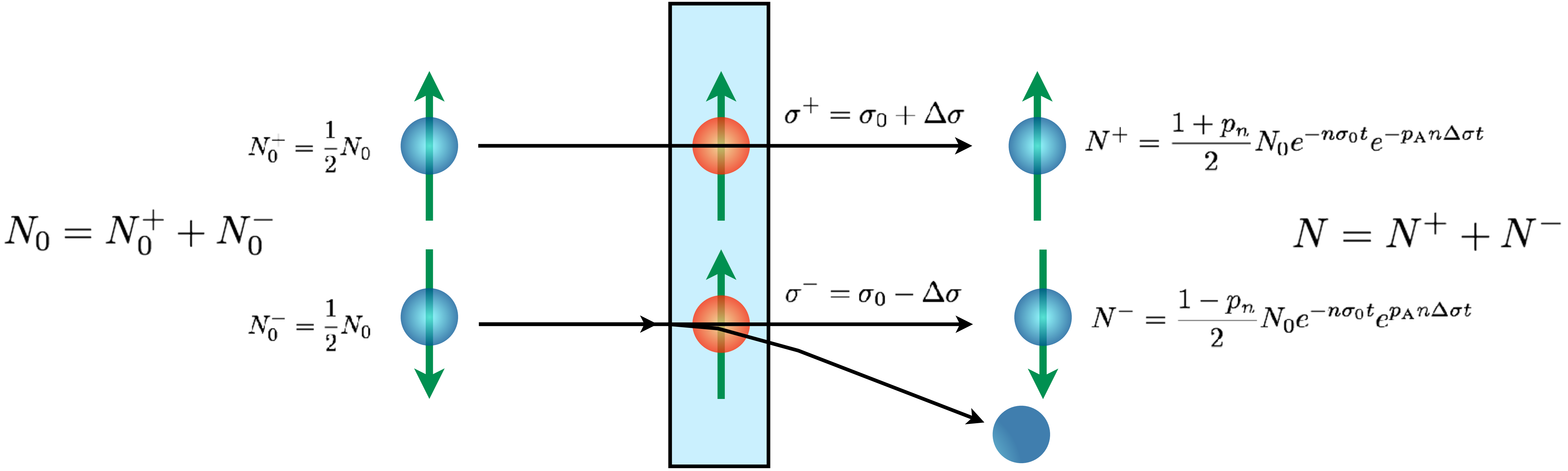


Devices

Spin Filter

Neutron Polarizer (Spin Filter)

n : nuclear number density
p_{A} : target nuclear polarization
t : target thickness



$N_0^+ = \frac{1}{2}N_0$

$N_0 = N_0^+ + N_0^-$

$N_0^- = \frac{1}{2}N_0$

$\sigma^+ = \sigma_0 + \Delta\sigma$

$\sigma^- = \sigma_0 - \Delta\sigma$

$N^+ = \frac{1+p_n}{2} N_0 e^{-n\sigma_0 t} e^{-p_{\mathrm{A}} n\Delta\sigma t}$

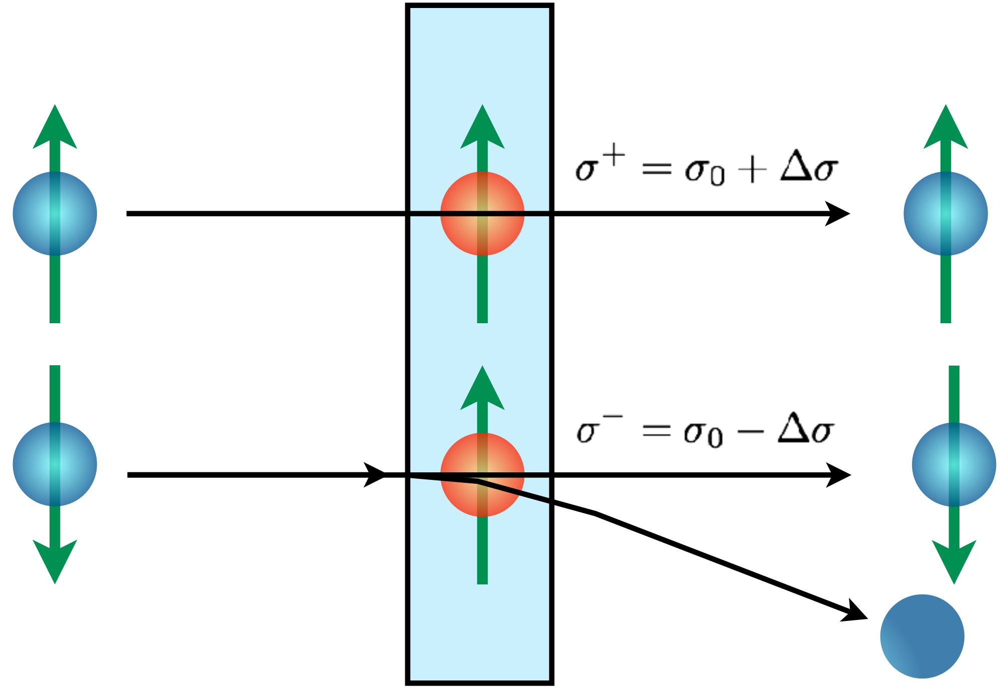
$N = N^+ + N^-$

$N^- = \frac{1-p_n}{2} N_0 e^{-n\sigma_0 t} e^{p_{\mathrm{A}} n\Delta\sigma t}$

スピンフリップ無視

Neutron Polarizer (Spin Filter)

n : nuclear number density
p_A : target nuclear polarization
t : target thickness



$N_0^+ = \frac{1}{2} N_0$

$N_0 = N_0^+ + N_0^-$

$N_0^- = \frac{1}{2} N_0$

$\sigma^+ = \sigma_0 + \Delta\sigma$

$\sigma^- = \sigma_0 - \Delta\sigma$

$N^+ = \frac{1+p_n}{2} N_0 e^{-n\sigma_0 t} e^{-p_A n \Delta\sigma t}$

$N = N^+ + N^-$

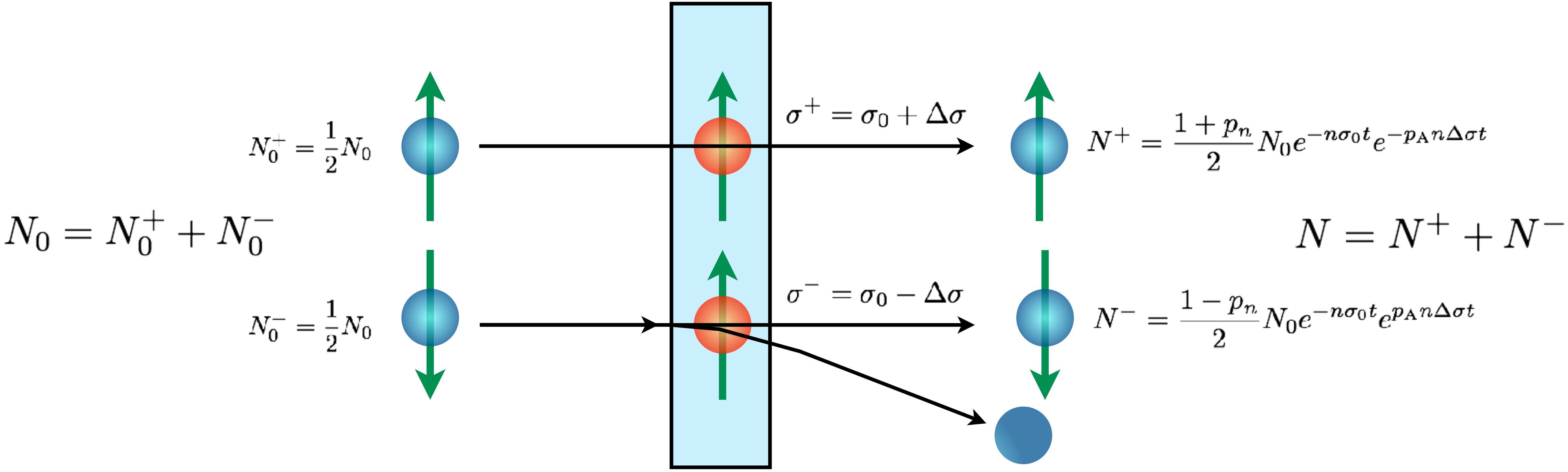
$N^- = \frac{1-p_n}{2} N_0 e^{-n\sigma_0 t} e^{p_A n \Delta\sigma t}$

スピンフリップ無視

$$T = \frac{N}{N_0} = e^{-n\sigma_0 t} \cosh(p_A n \Delta\sigma t)$$

Neutron Polarizer (Spin Filter)

n : nuclear number density
p_{A} : target nuclear polarization
t : target thickness



$N_0^+ = \frac{1}{2}N_0$

$N_0 = N_0^+ + N_0^-$

$N_0^- = \frac{1}{2}N_0$

$\sigma^+ = \sigma_0 + \Delta\sigma$

$\sigma^- = \sigma_0 - \Delta\sigma$

$N^+ = \frac{1+p_n}{2}N_0 e^{-n\sigma_0 t}e^{-p_{\mathrm{A}}n\Delta\sigma t}$

$N = N^+ + N^-$

$N^- = \frac{1-p_n}{2}N_0 e^{-n\sigma_0 t}e^{p_{\mathrm{A}}n\Delta\sigma t}$

スピンフリップ無視

$$T = \frac{N}{N_0} = e^{-n\sigma_0 t}\cosh(p_{\mathrm{A}}n\Delta\sigma t)$$

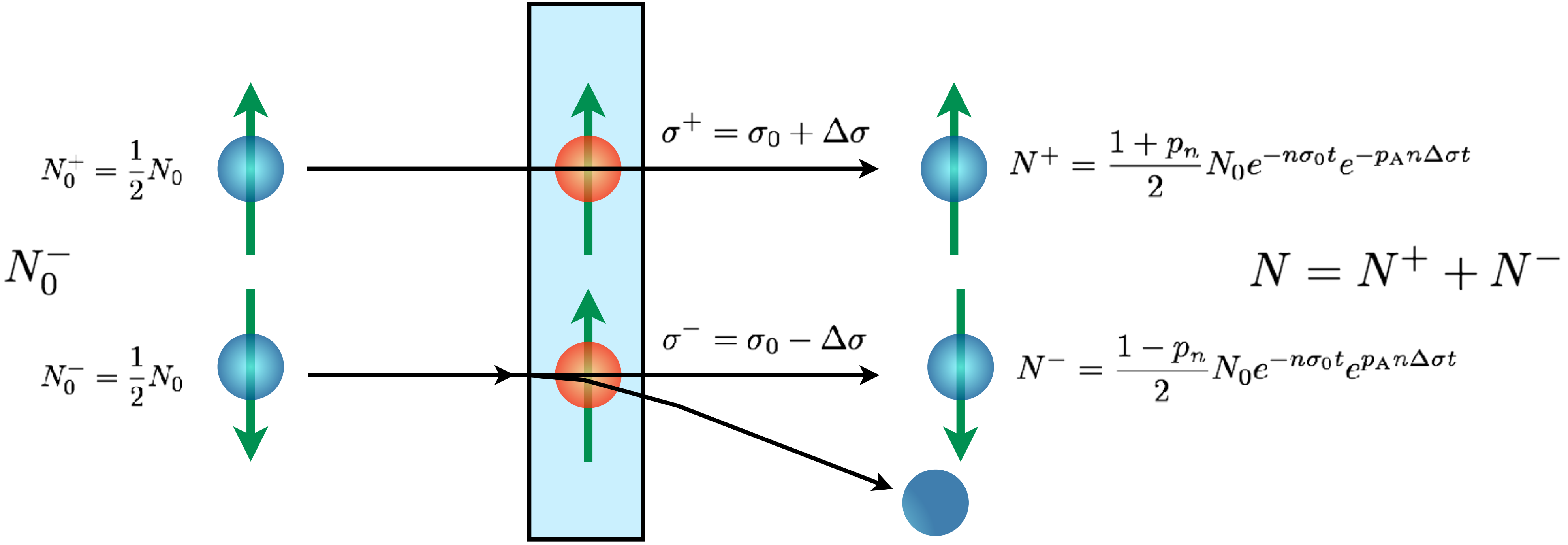
$$p_n = \frac{N^+ - N^-}{N^+ + N^-} = -\tanh(p_{\mathrm{A}}n\Delta\sigma t)$$

Neutron Polarizer (Spin Filter)

n : nuclear number density

p_{A} : target nuclear polarization

t : target thickness



$N_0^+ = \frac{1}{2}N_0$

$N_0 = N_0^+ + N_0^-$

$N_0^- = \frac{1}{2}N_0$

$\sigma^+ = \sigma_0 + \Delta\sigma$

$\sigma^- = \sigma_0 - \Delta\sigma$

$N^+ = \frac{1+p_n}{2}N_0 e^{-n\sigma_0 t}e^{-p_{\mathrm{A}}n\Delta\sigma t}$

$N = N^+ + N^-$

$N^- = \frac{1-p_n}{2}N_0 e^{-n\sigma_0 t}e^{p_{\mathrm{A}}n\Delta\sigma t}$

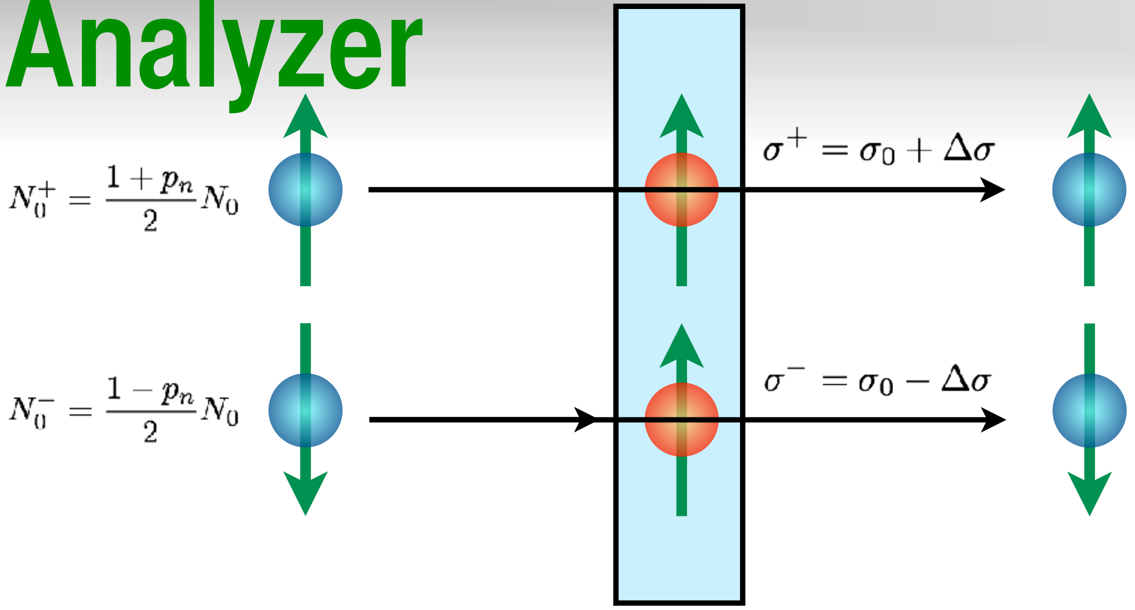
スピンフリップ無視

$$T = \frac{N}{N_0} = e^{-n\sigma_0 t}\cosh(p_{\mathrm{A}}n\Delta\sigma t)$$

$$p_n = \frac{N^+ - N^-}{N^+ + N^-} = -\tanh(p_{\mathrm{A}}n\Delta\sigma t)$$

$$(\mathrm{F_{igure}O_fM_{erit}})_{\mathrm{pol}} = p_n^2 T$$

Spin Analyzer



$N_0^+ = \frac{1+p_n}{2} N_0$

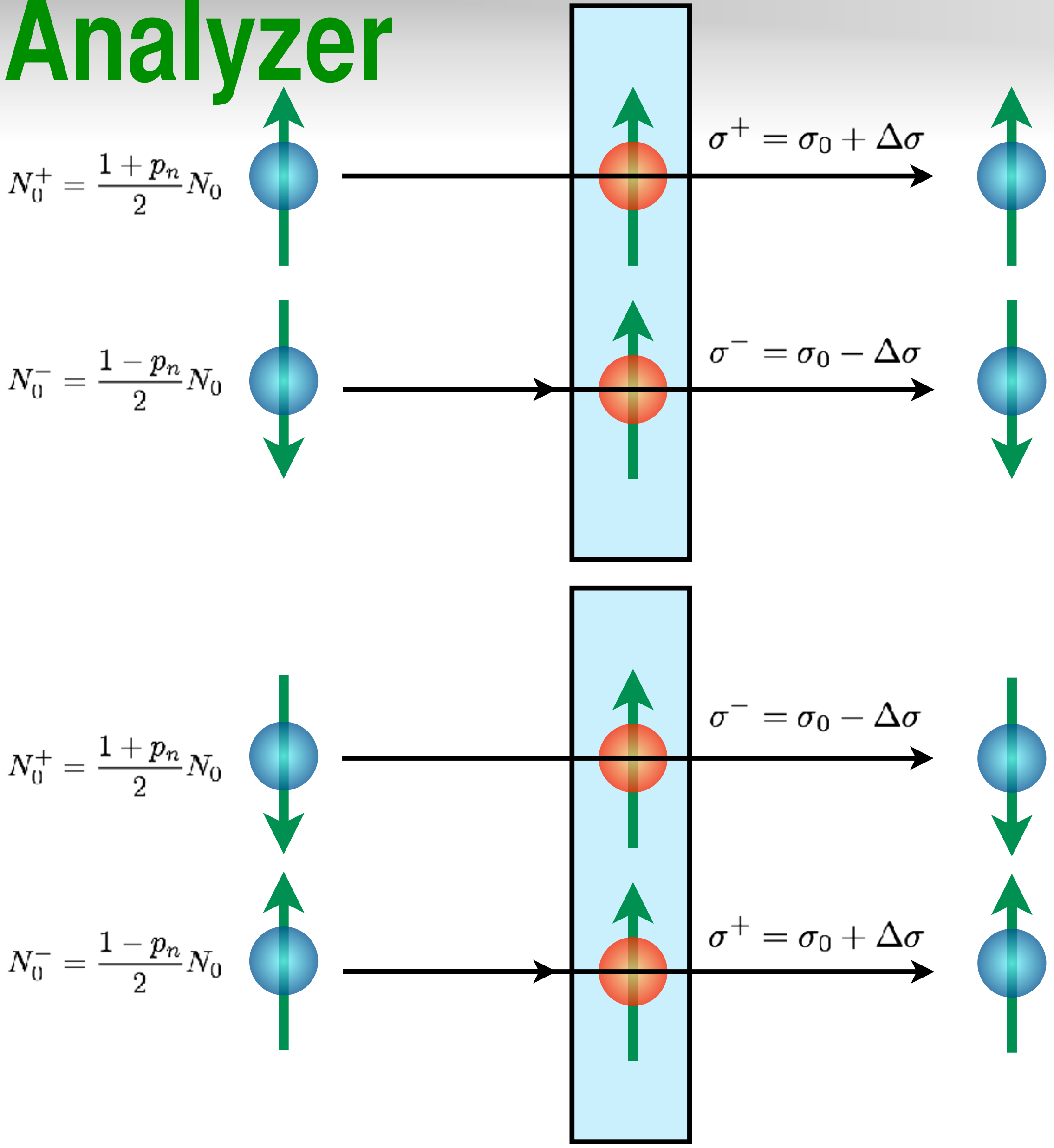
$N_0^- = \frac{1-p_n}{2} N_0$

$\sigma^+ = \sigma_0 + \Delta\sigma$

$\sigma^- = \sigma_0 - \Delta\sigma$

$$N_1 = N_0 e^{-n\sigma_0 t} \left(\cosh(p_{\mathrm{A}} n \Delta\sigma t) - p_n \sinh(p_{\mathrm{A}} n \Delta\sigma t)\right)$$

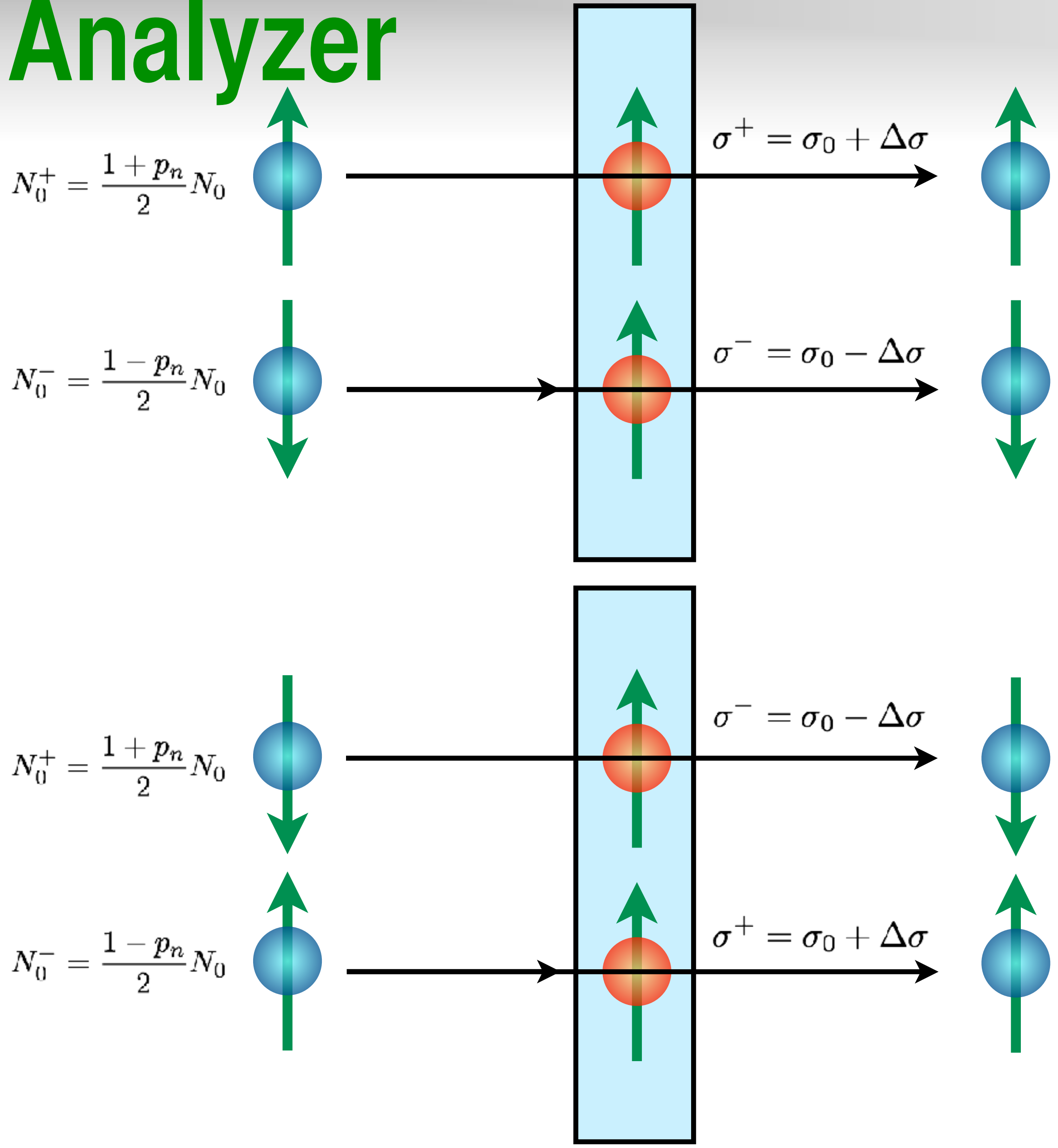
Spin Analyzer



$$N_1 = N_0 e^{-n\sigma_0 t} \left(\cosh(p_\mathrm{A} n \Delta\sigma t) - p_n \sinh(p_\mathrm{A} n \Delta\sigma t)\right)$$

$$N_2 = N_0 e^{-n\sigma_0 t} \left(\cosh(p_\mathrm{A} n \Delta\sigma t) + p_n \sinh(p_\mathrm{A} n \Delta\sigma t)\right)$$

Spin Analyzer



$N_0^+ = \frac{1+p_n}{2}N_0$

$\sigma^+ = \sigma_0 + \Delta\sigma$

$N_0^- = \frac{1-p_n}{2}N_0$

$\sigma^- = \sigma_0 - \Delta\sigma$

$N_0^+ = \frac{1+p_n}{2}N_0$

$\sigma^- = \sigma_0 - \Delta\sigma$

$N_0^- = \frac{1-p_n}{2}N_0$

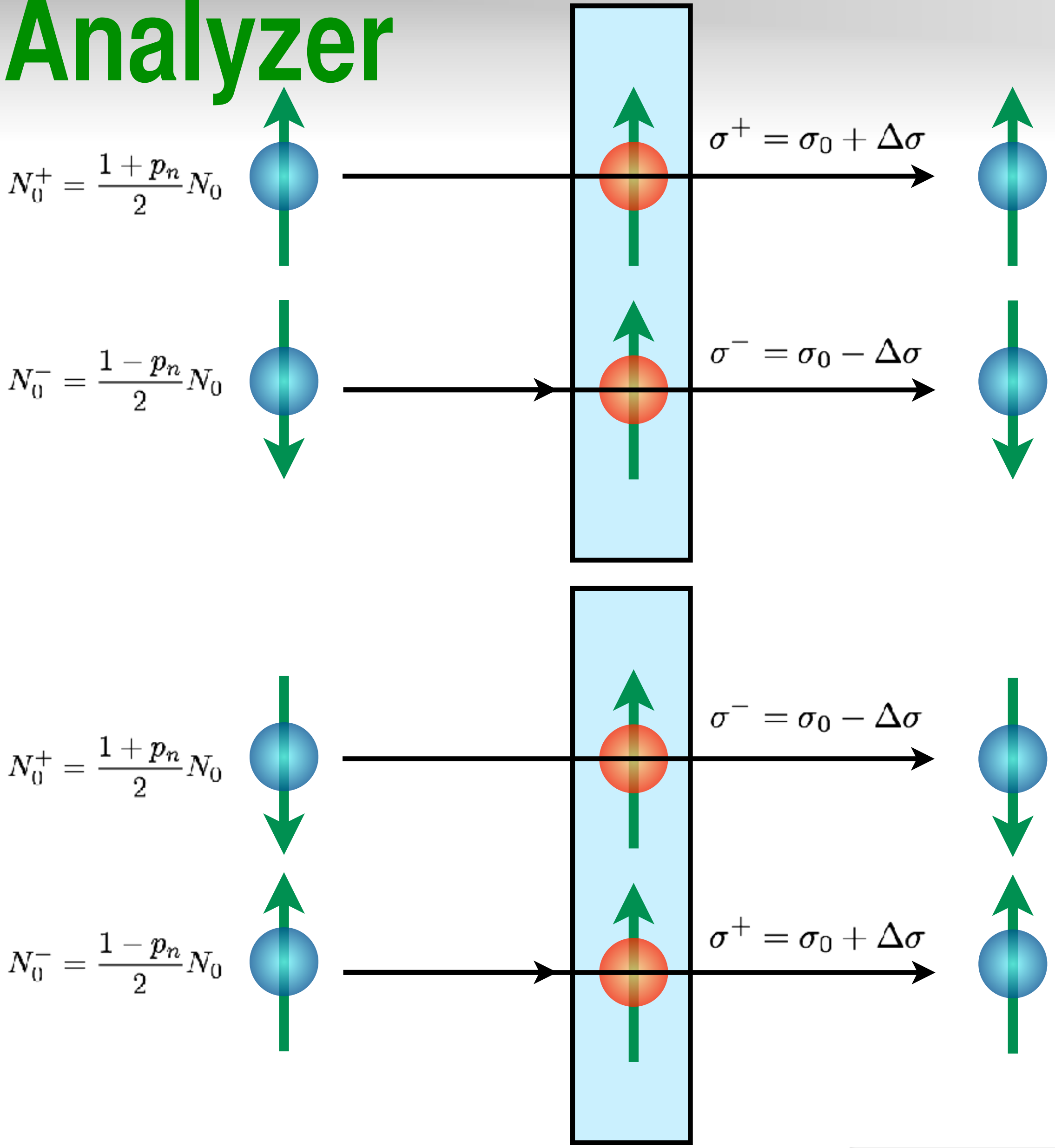
$\sigma^+ = \sigma_0 + \Delta\sigma$

$$N_1 = N_0 e^{-n\sigma_0 t}\left(\cosh(p_A n\Delta\sigma t) - p_n \sinh(p_A n\Delta\sigma t)\right)$$

$$\frac{N_1 - N_2}{N_1 + N_2} = -p_n \tanh(p_A n\Delta\sigma t)$$

$$N_2 = N_0 e^{-n\sigma_0 t}\left(\cosh(p_A n\Delta\sigma t) + p_n \sinh(p_A n\Delta\sigma t)\right)$$

Spin Analyzer



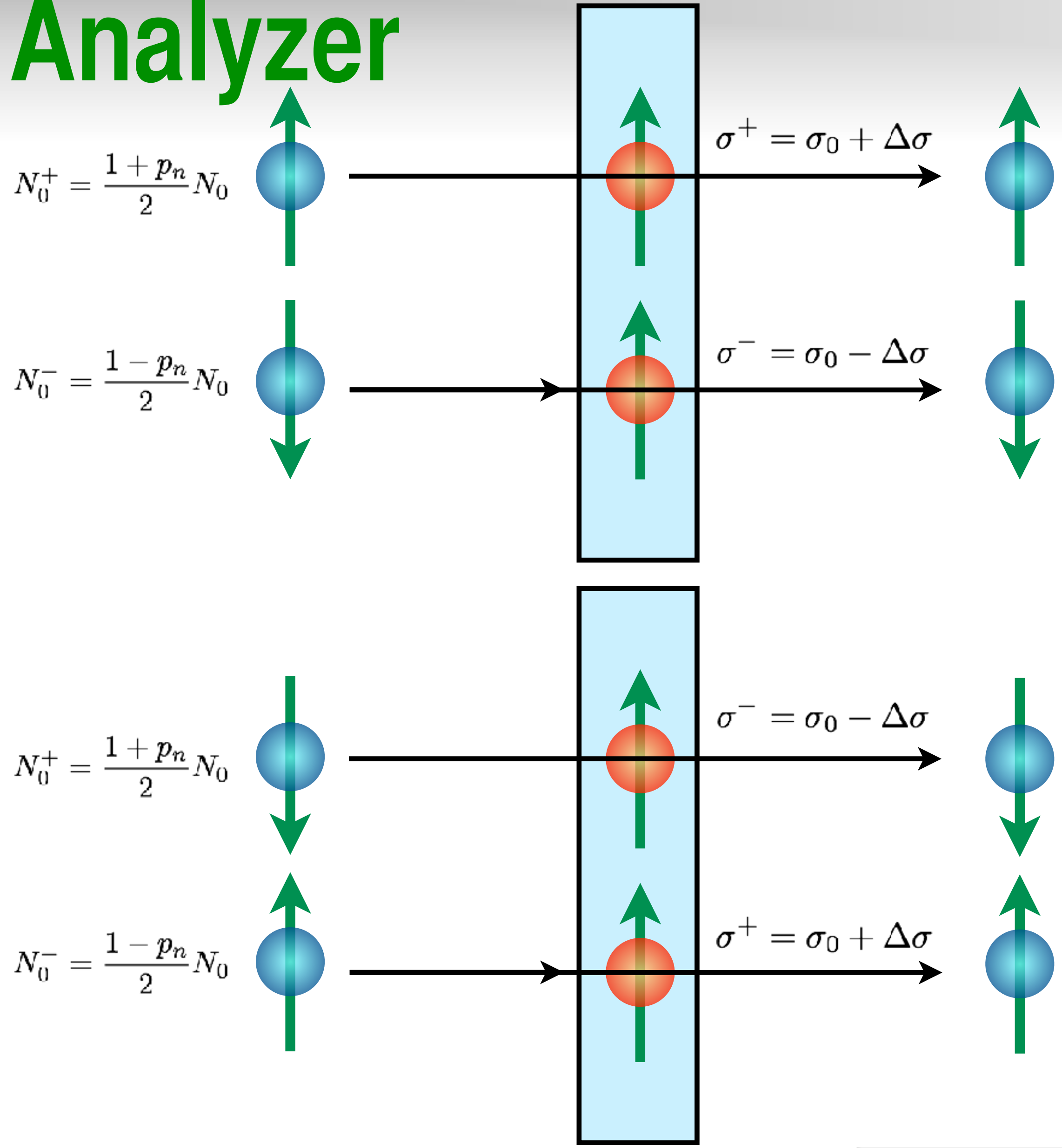
$$N_1 = N_0 e^{-n\sigma_0 t} \left(\cosh(p_A n \Delta\sigma t) - p_n \sinh(p_A n \Delta\sigma t)\right)$$

$$\frac{N_1 - N_2}{N_1 + N_2} = -p_n \tanh(p_A n \Delta\sigma t)$$

$$N_2 = N_0 e^{-n\sigma_0 t} \left(\cosh(p_A n \Delta\sigma t) + p_n \sinh(p_A n \Delta\sigma t)\right)$$

$$\Delta p_n = \frac{1}{\sqrt{N_0}} \frac{e^{n\sigma_0 t/2}}{\sqrt{2}} \sqrt{\frac{1 - p_n^2 \tanh^2(p_A n \Delta\sigma t)}{\tanh(p_A n \Delta\sigma t) \sinh(p_A n \Delta\sigma t)}}$$

Spin Analyzer



$$N_1 = N_0 e^{-n\sigma_0 t} \left(\cosh(p_{\mathrm{A}} n \Delta\sigma t) - p_n \sinh(p_{\mathrm{A}} n \Delta\sigma t)\right)$$

$$\frac{N_1 - N_2}{N_1 + N_2} = -p_n \tanh(p_{\mathrm{A}} n \Delta\sigma t)$$

$$N_2 = N_0 e^{-n\sigma_0 t} \left(\cosh(p_{\mathrm{A}} n \Delta\sigma t) + p_n \sinh(p_{\mathrm{A}} n \Delta\sigma t)\right)$$

$$\Delta p_n = \frac{1}{\sqrt{N_0}} \frac{e^{n\sigma_0 t/2}}{\sqrt{2}} \sqrt{\frac{1 - p_n^2 \tanh^2(p_{\mathrm{A}} n \Delta\sigma t)}{\tanh(p_{\mathrm{A}} n \Delta\sigma t) \sinh(p_{\mathrm{A}} n \Delta\sigma t)}}$$

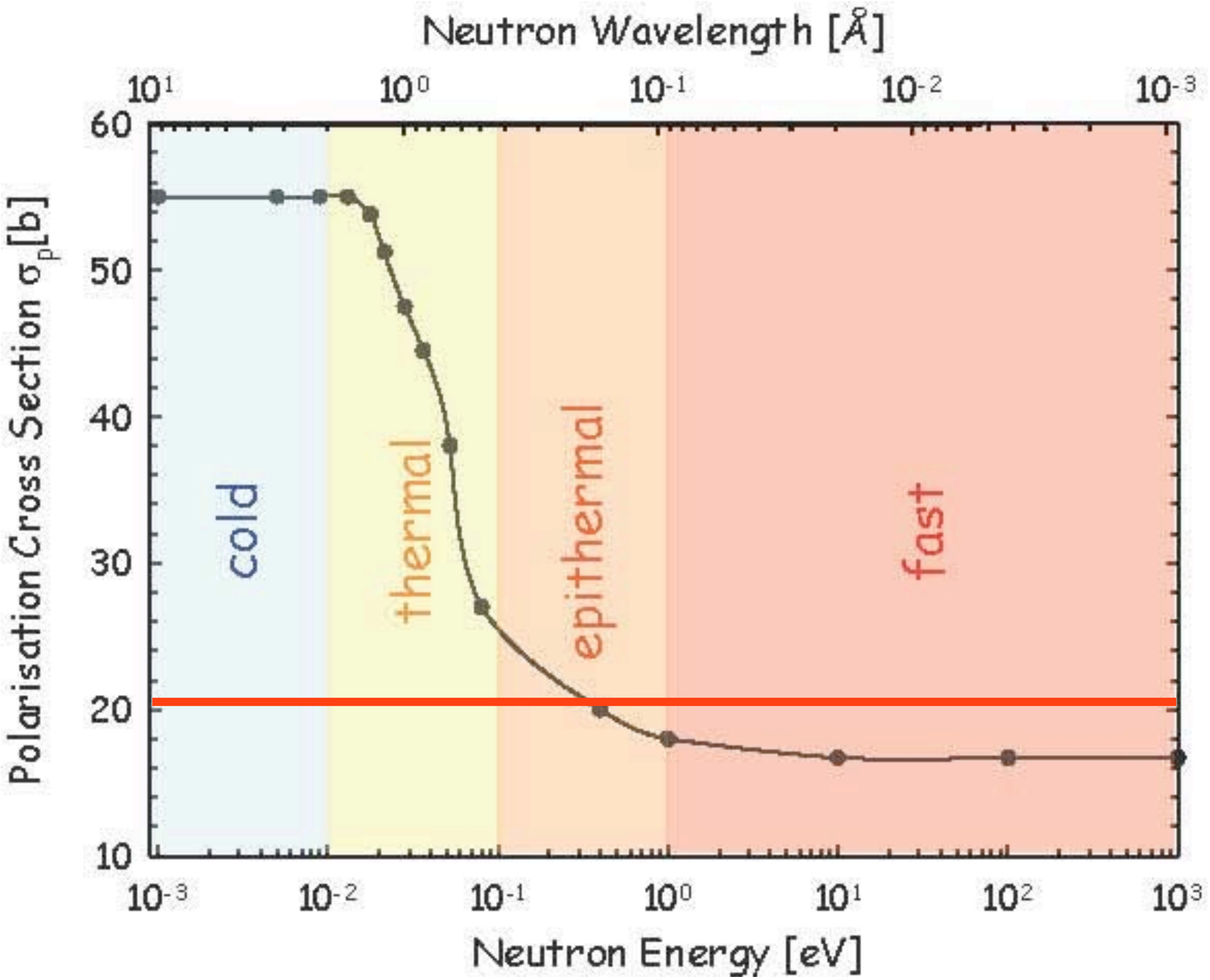
$$(\mathrm{FOM})_{\mathrm{ana}} = \left(\frac{\Delta p_n}{p_n} \sqrt{N_0}\right)^{-1} = \sqrt{2} p_n e^{-n\sigma_0 t/2} \sqrt{\frac{\tanh(p_{\mathrm{A}} n \Delta\sigma t) \sinh(p_{\mathrm{A}} n \Delta\sigma t)}{1 - p_n^2 \tanh^2(p_{\mathrm{A}} n \Delta\sigma t)}}$$

Polarization Cross Section

^{3}He

$$\Delta\sigma \simeq \sigma_{\mathrm{tot}} \simeq 5333[\mathrm{b}] \times \sqrt{\frac{\mathbf{0.025eV}}{E}}$$

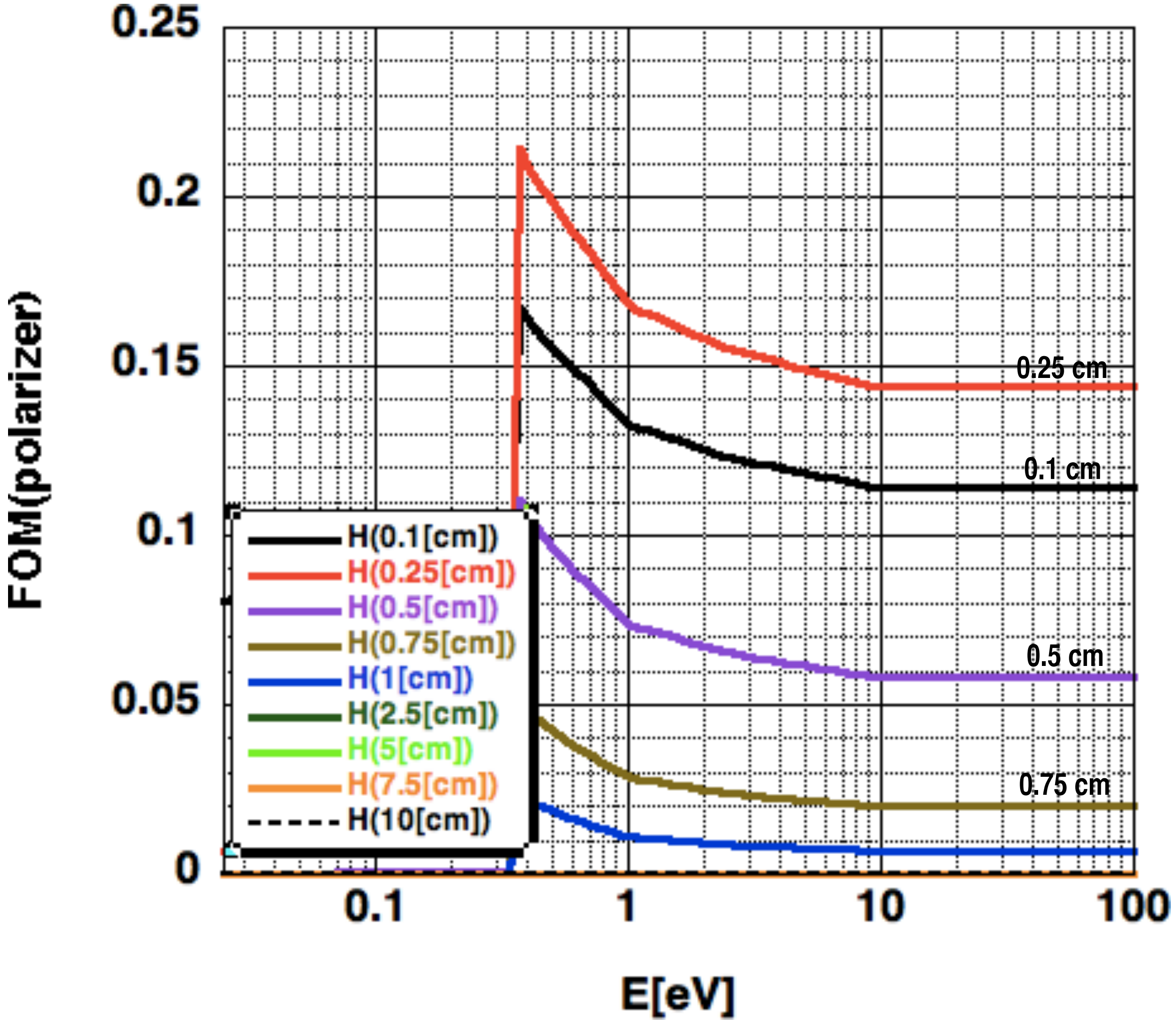
H



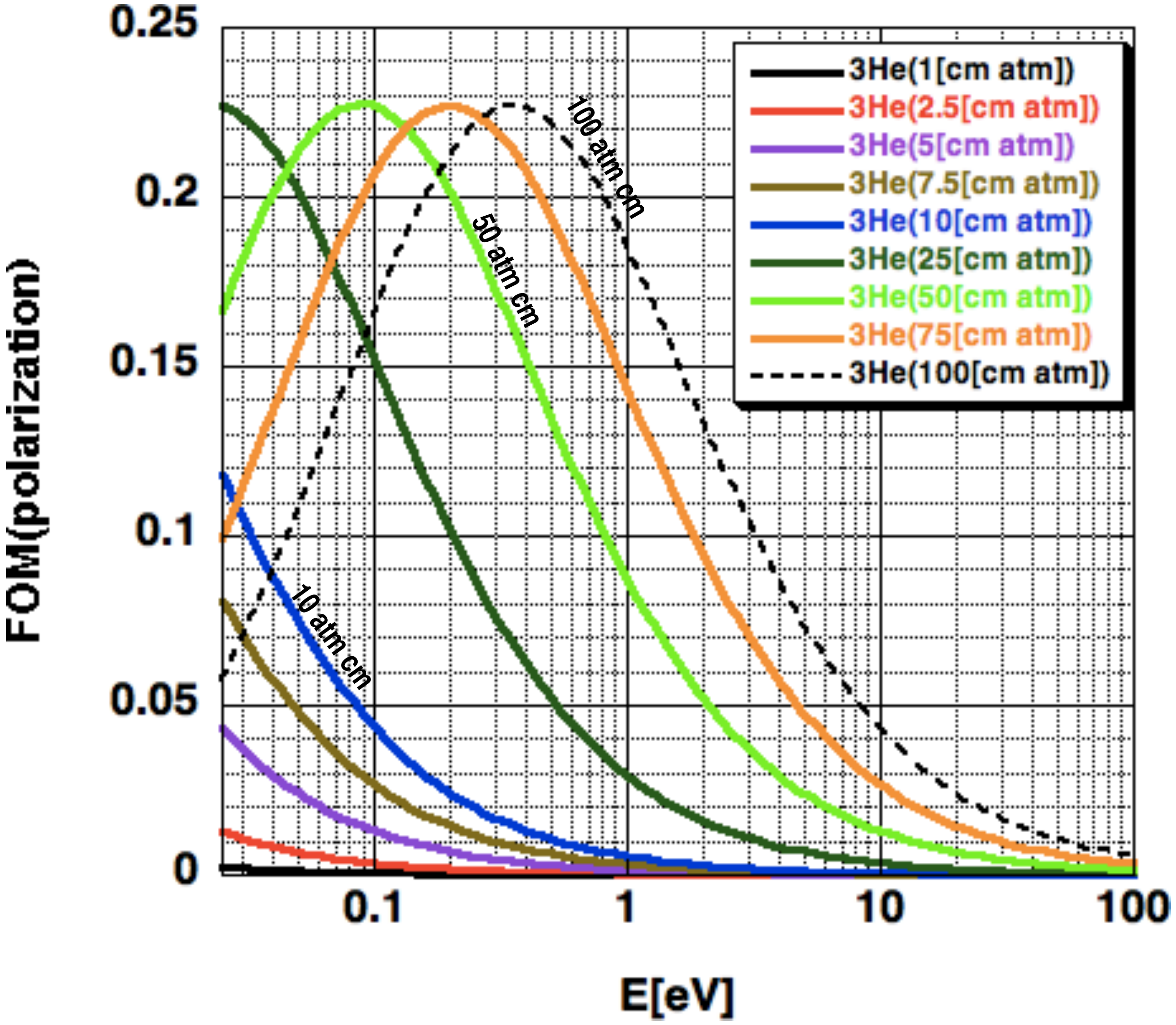
by courtesy of Patrick Hautle

$$(\mathrm{FOM})_{\mathrm{pol}} = p_n^2 T$$

H



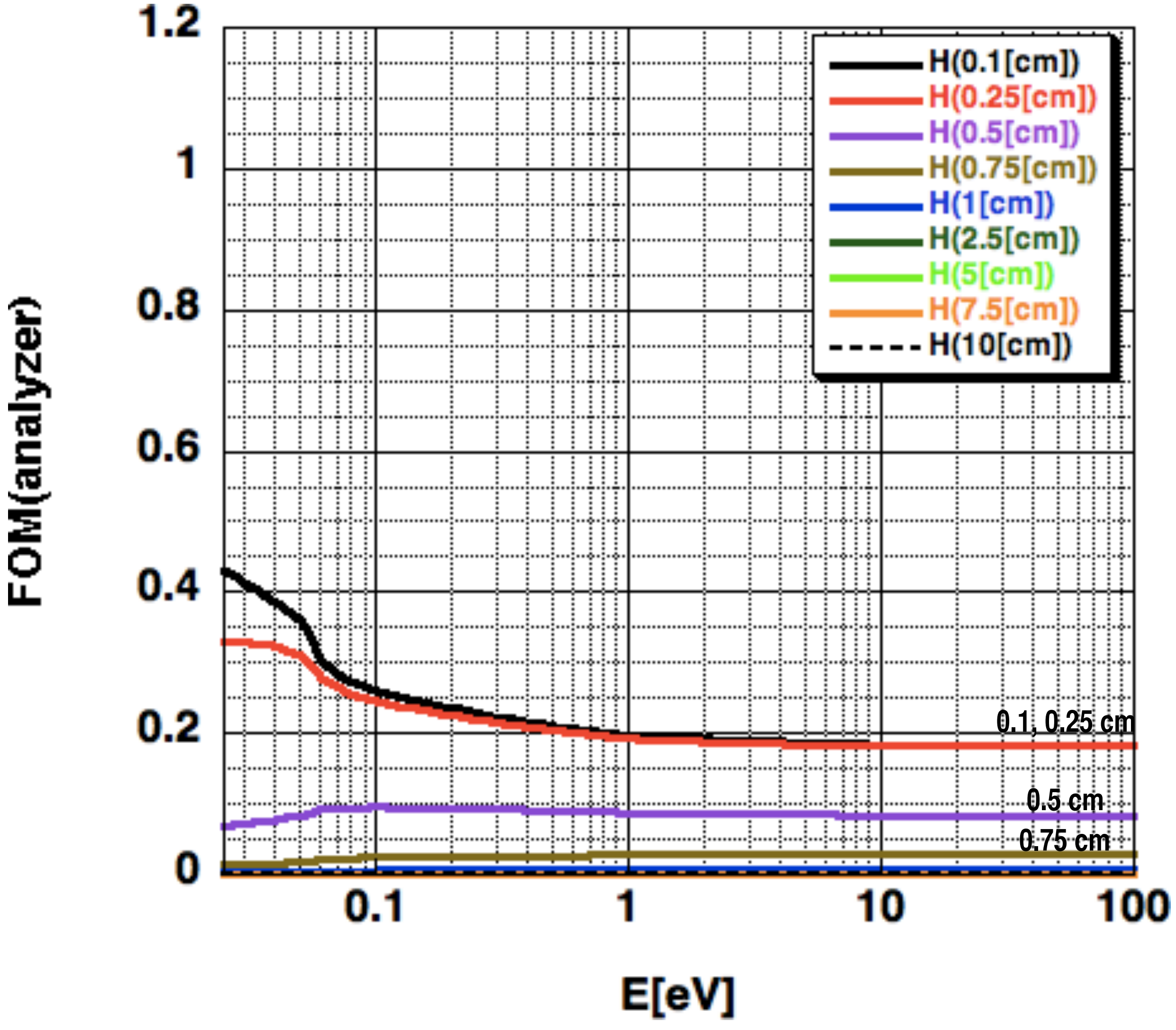
^{3}He



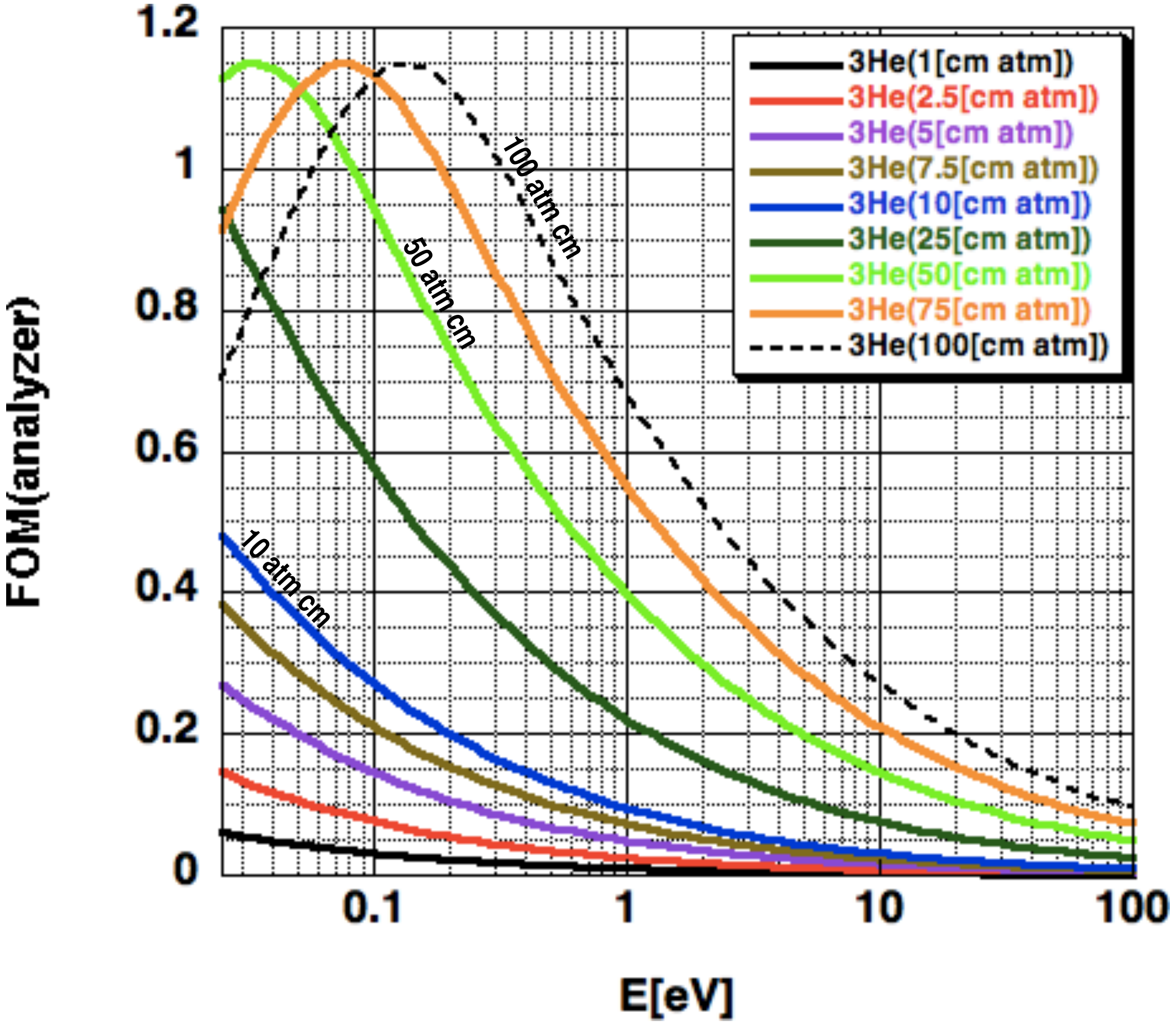
$p_{\mathrm{H}} = 0.7$ $p_n = 0.9$ $p_{^3\mathrm{He}} = 0.7$

$$(\mathrm{FOM})_{\mathrm{ana}} = \sqrt{2}p_n e^{-n\sigma_0 t/2}\sqrt{\frac{\tanh(p_{\mathrm{A}}n\Delta\sigma t)\sinh(p_{\mathrm{A}}n\Delta\sigma t)}{1-p_n^2\tanh^2(p_{\mathrm{A}}n\Delta\sigma t)}}$$

H



^{3}He



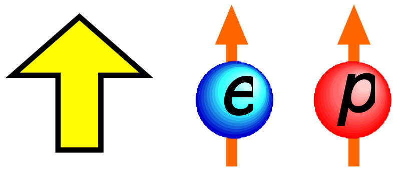
$p_{\mathrm{H}} = 0.7$ $p_n = 0.9$ $p_{^3\mathrm{He}} = 0.7$

Polarized Target (solid)

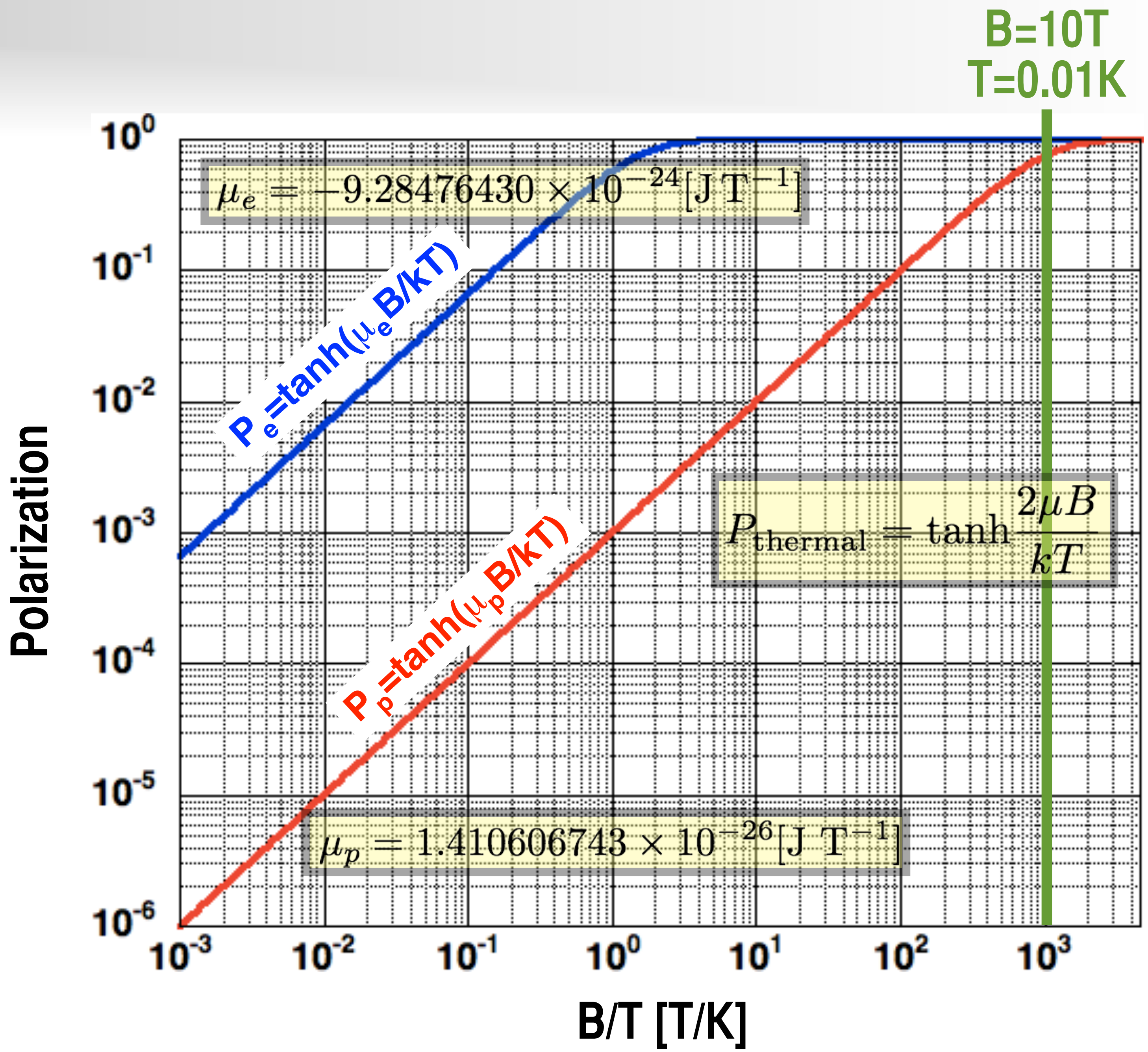
Brute-force Method

B~10T

T≤0.1K



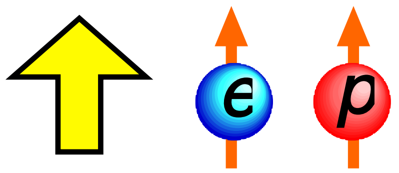
thermal equilibrium



Polarized Target (solid)

Brute-force Method

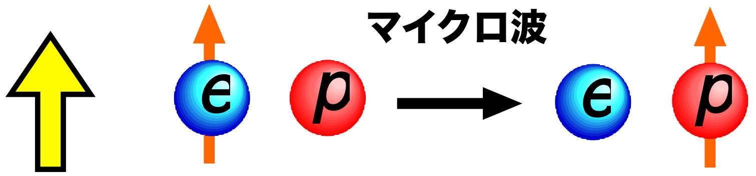
B~10T
T≤0.1K



thermal equilibrium

Dynamic Nuclear Polarization (DNP)

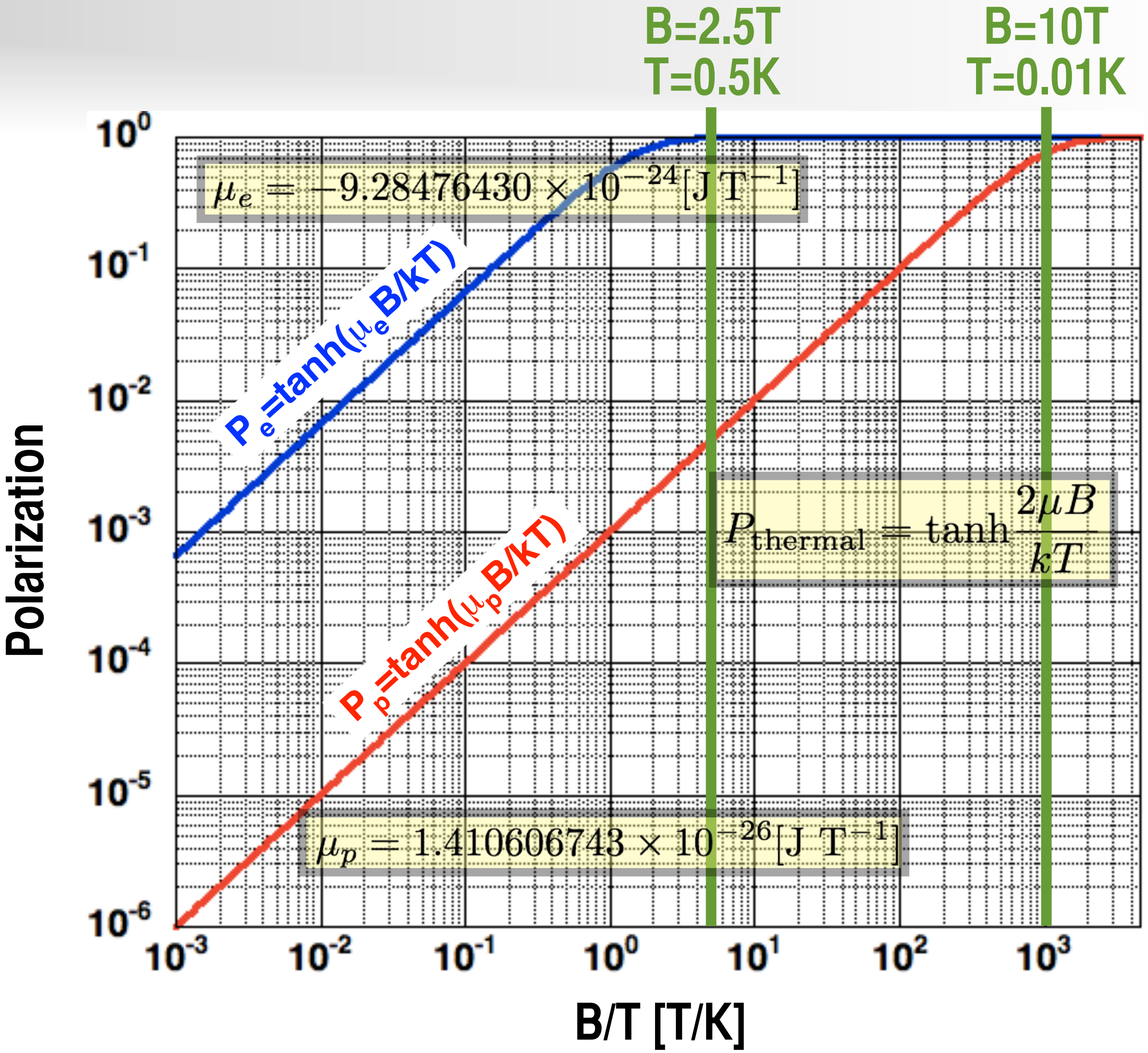
B~2-5T
T≲1K



常磁性中心

熱平衡

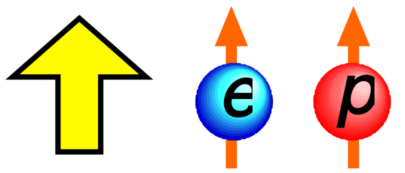
熱非平衡



Polarized Target (solid)

Brute-force Method

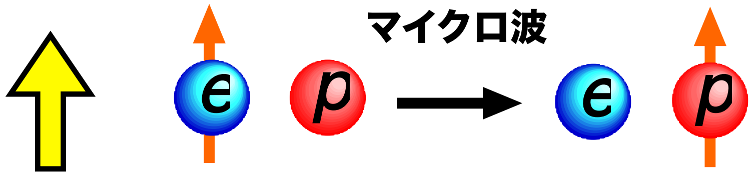
B~10T
T≤0.1K



thermal equilibrium

Dynamic Nuclear Polarization (DNP)

B~2-5T
T≤1K



マイクロ波

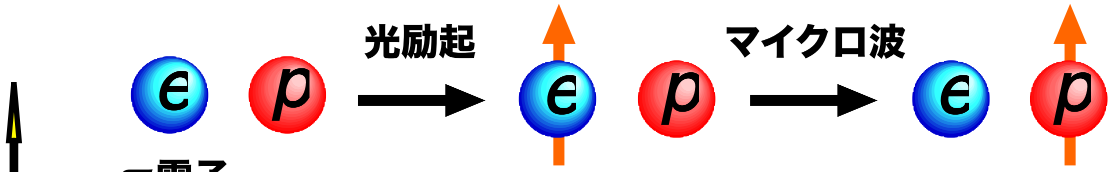
常磁性中心

熱平衡

熱非平衡

Microwave-Induced Optical Nuclear Polarization (MIONP)

B~0.3T
T≤77K
(↑ 300K)



光励起

マイクロ波

π電子

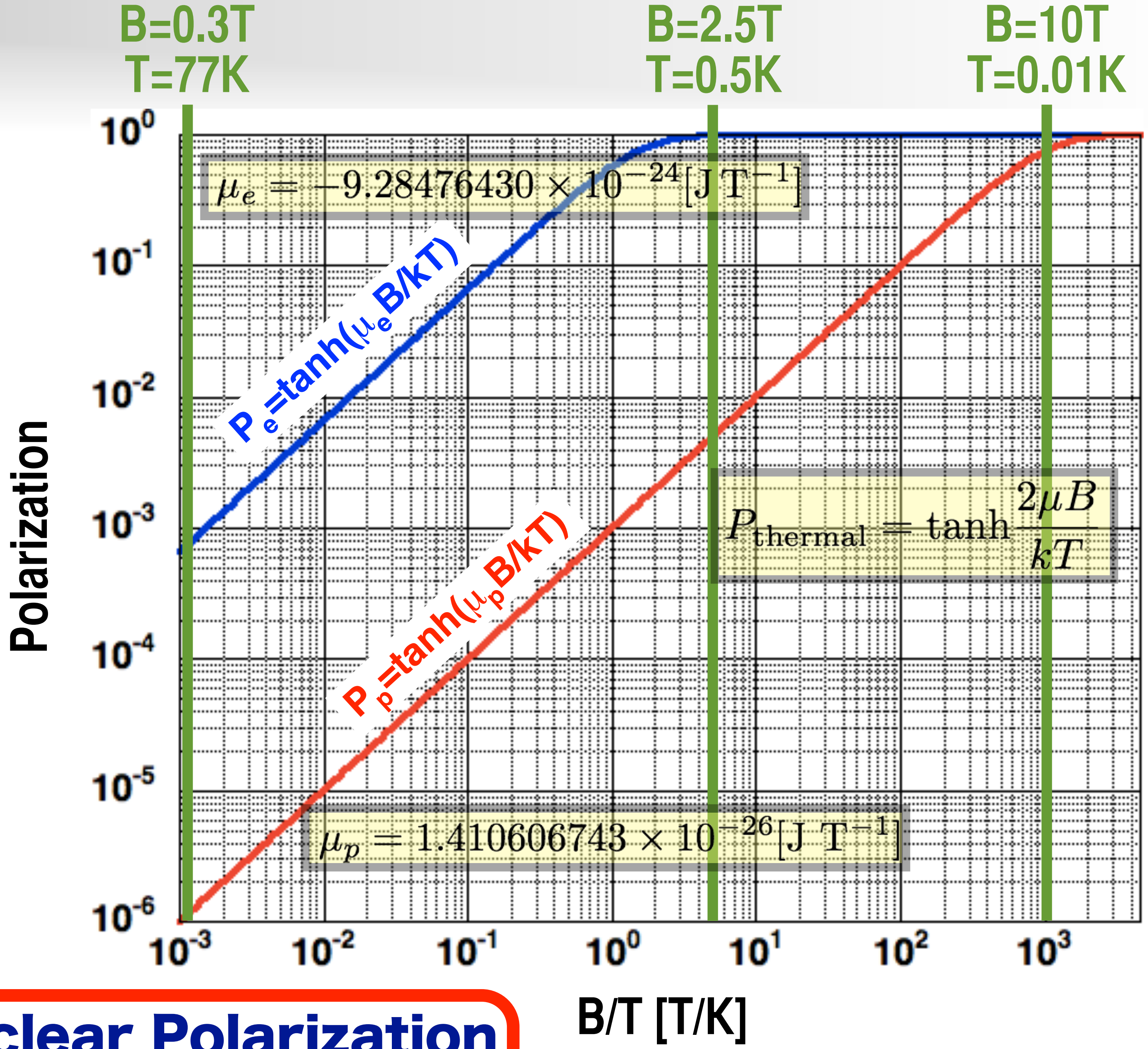
π電子の自発的スピン整列

熱非平衡

熱非平衡

M.Iinuma et al. (Kyoto Univ.)
K.Takeda et al. (Kyoto Univ.)

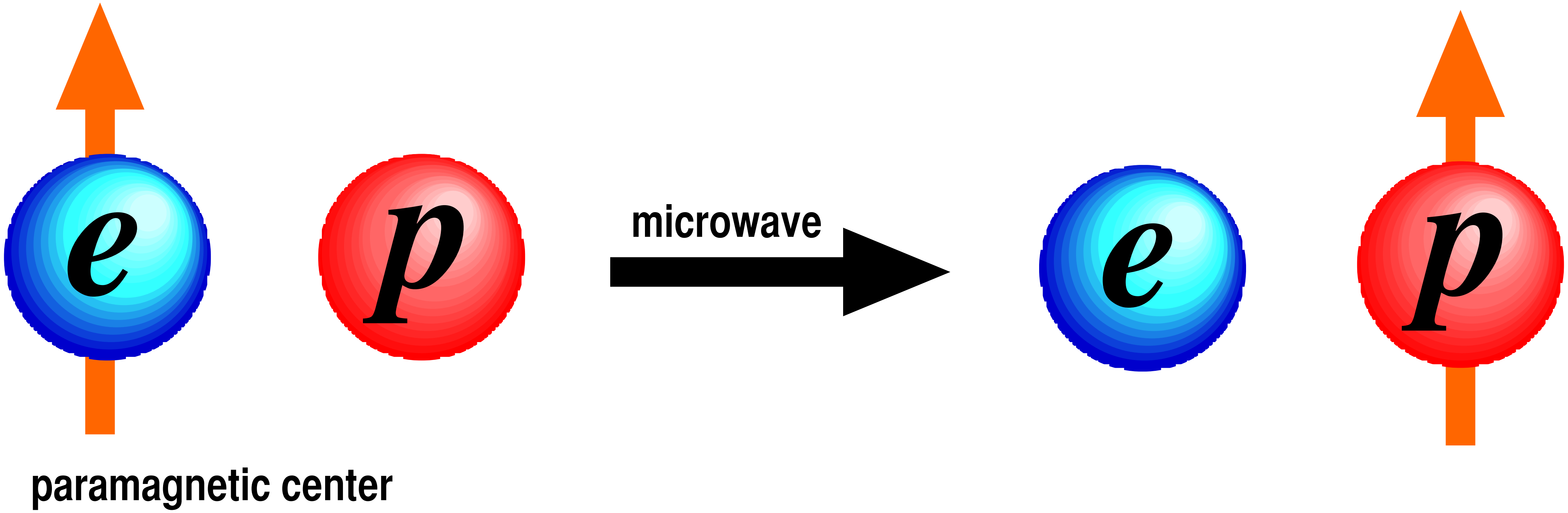
P~0.4 in bulk at LN2 temp. and B=3kG
P~0.7 in bulk at 105K and B=3.2kG



Polarized Target (solid)

method	electron	proton
Brute-force	thermal equilibrium	thermal equilibrium
DNP	thermal equilibrium	thermal non-equilibrium
MIONP	thermal non-equilibrium	thermal non-equilibrium

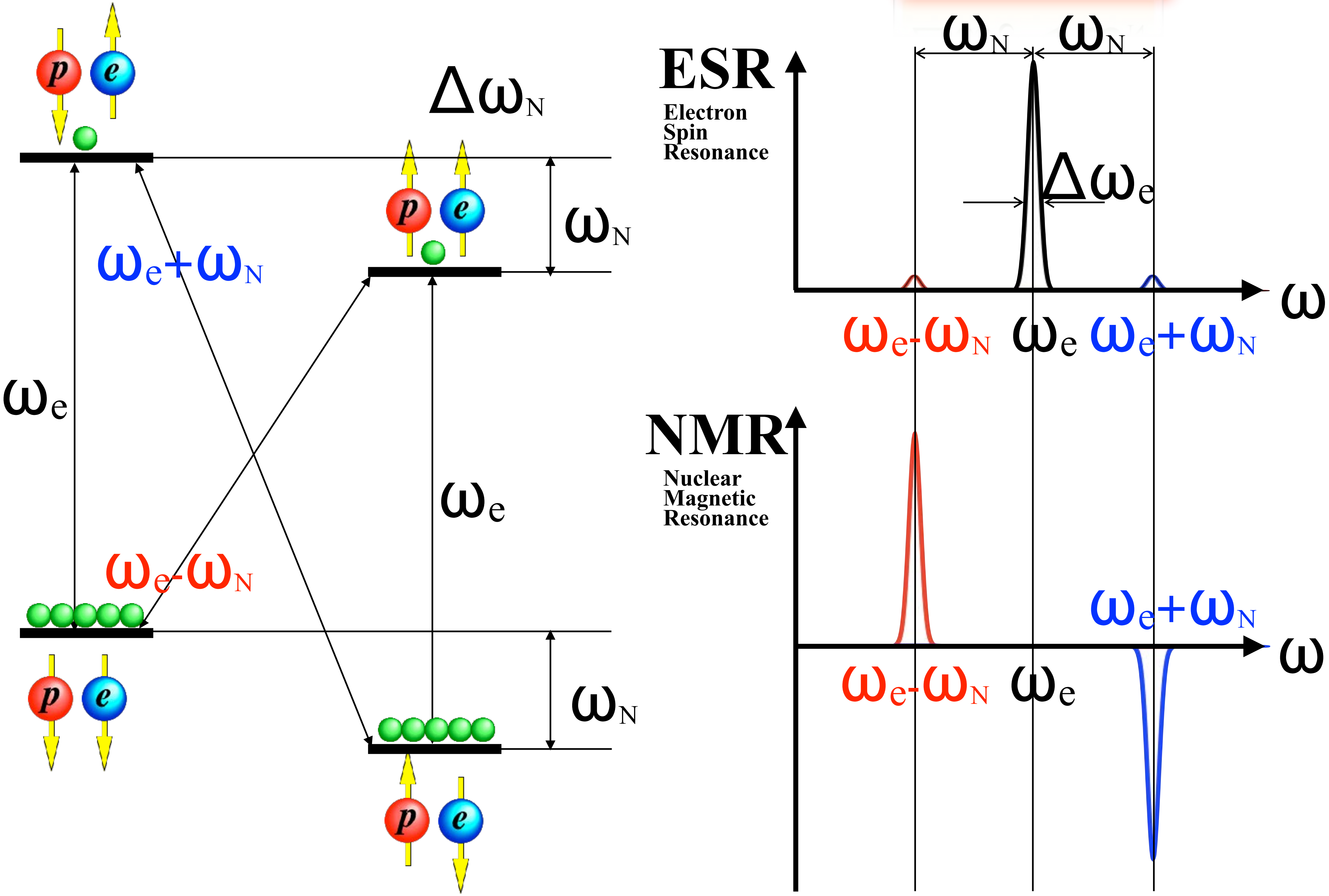
Dynamic Nuclear Polarization (DNP)



(Differential) Solid Effect

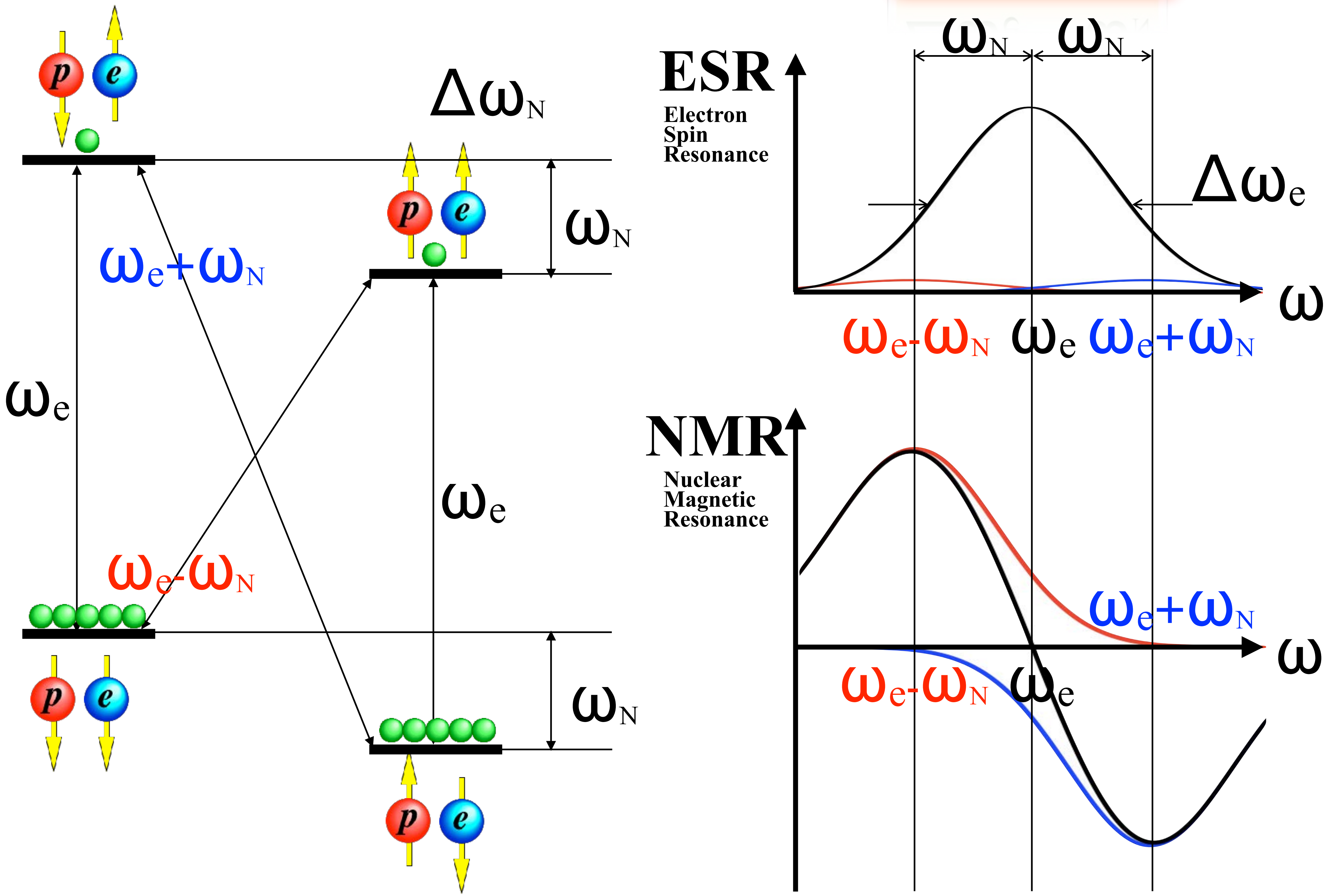
narrow ESR

$\Delta\omega_e < \omega_N$



(Differential) Solid Effect

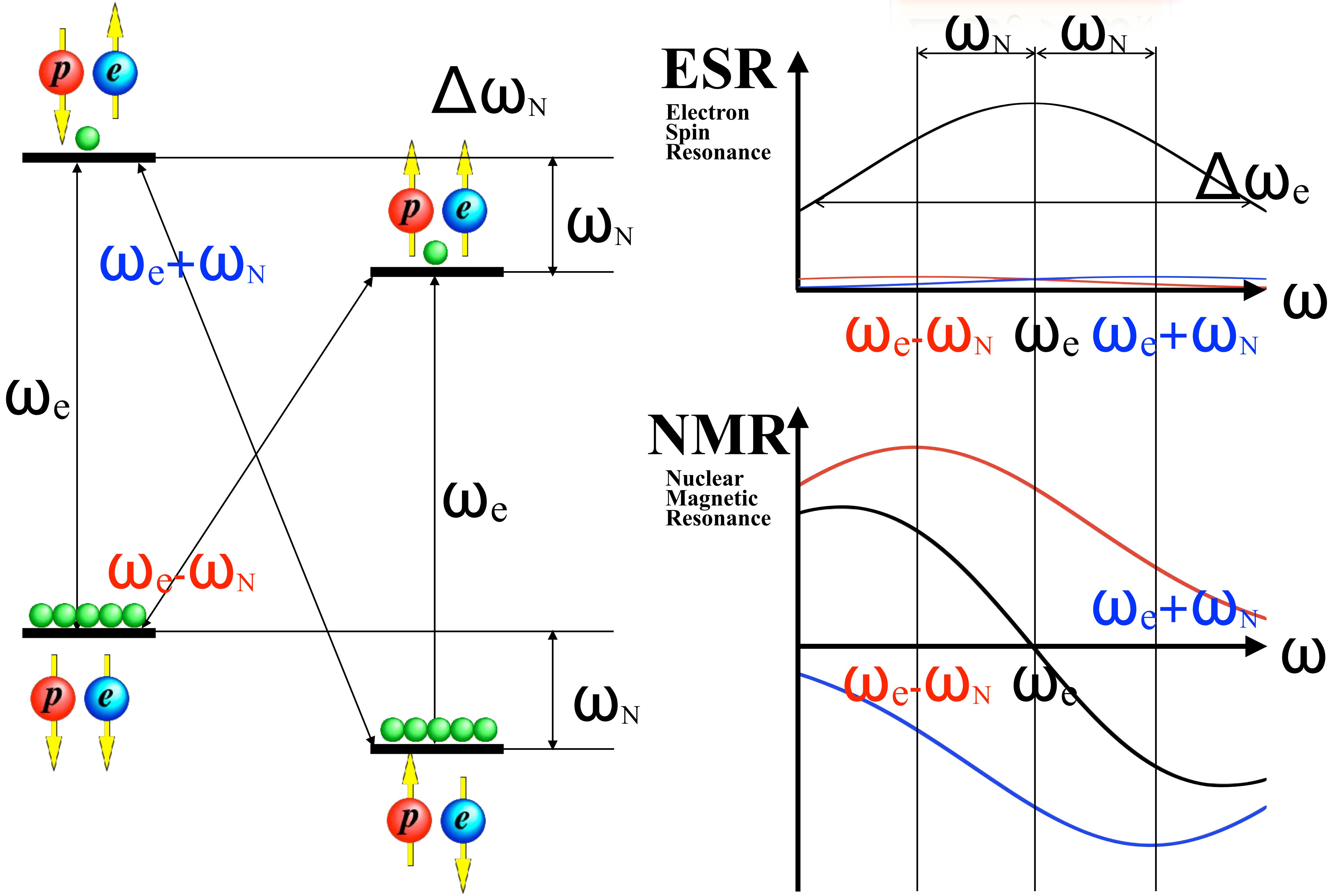
$\Delta\omega_e \sim \omega_N$



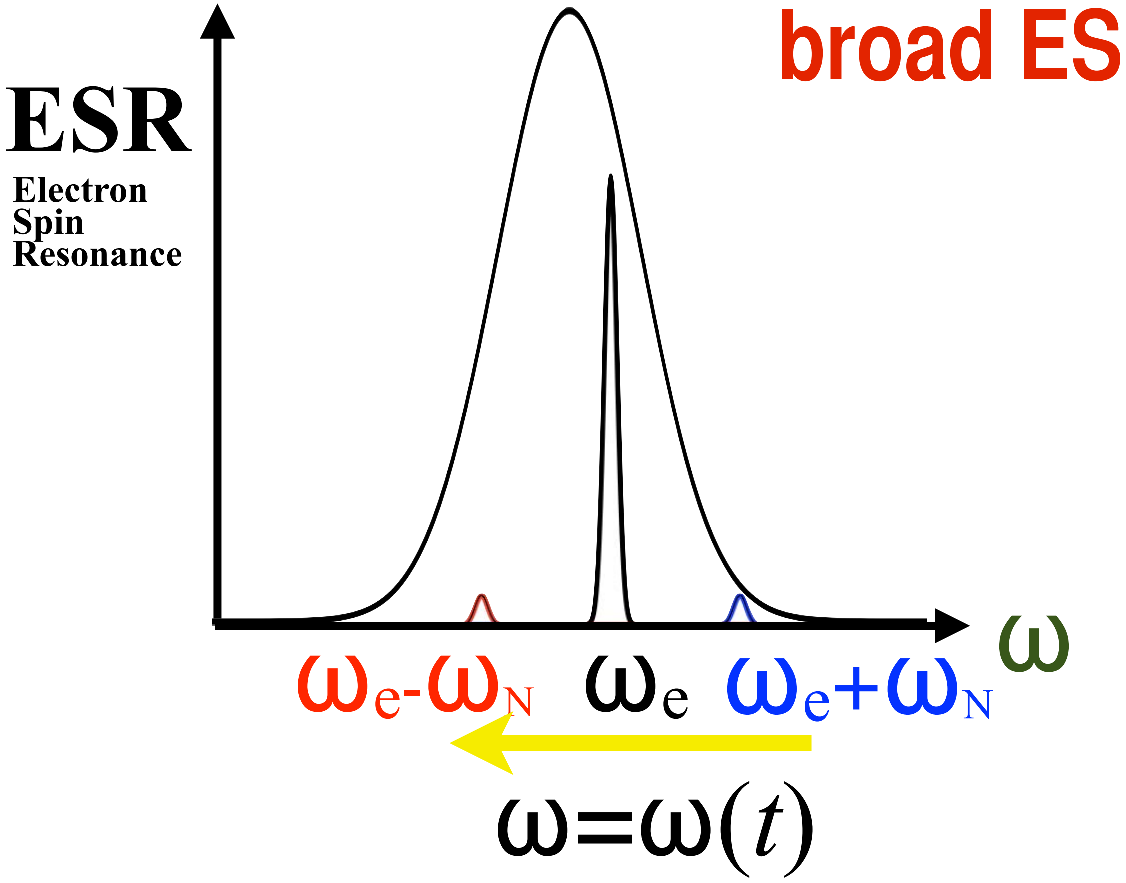
~~(Differential) Solid Effect~~

broad ESR

$\Delta\omega_e > \omega_N$



Integrated Solid Effect

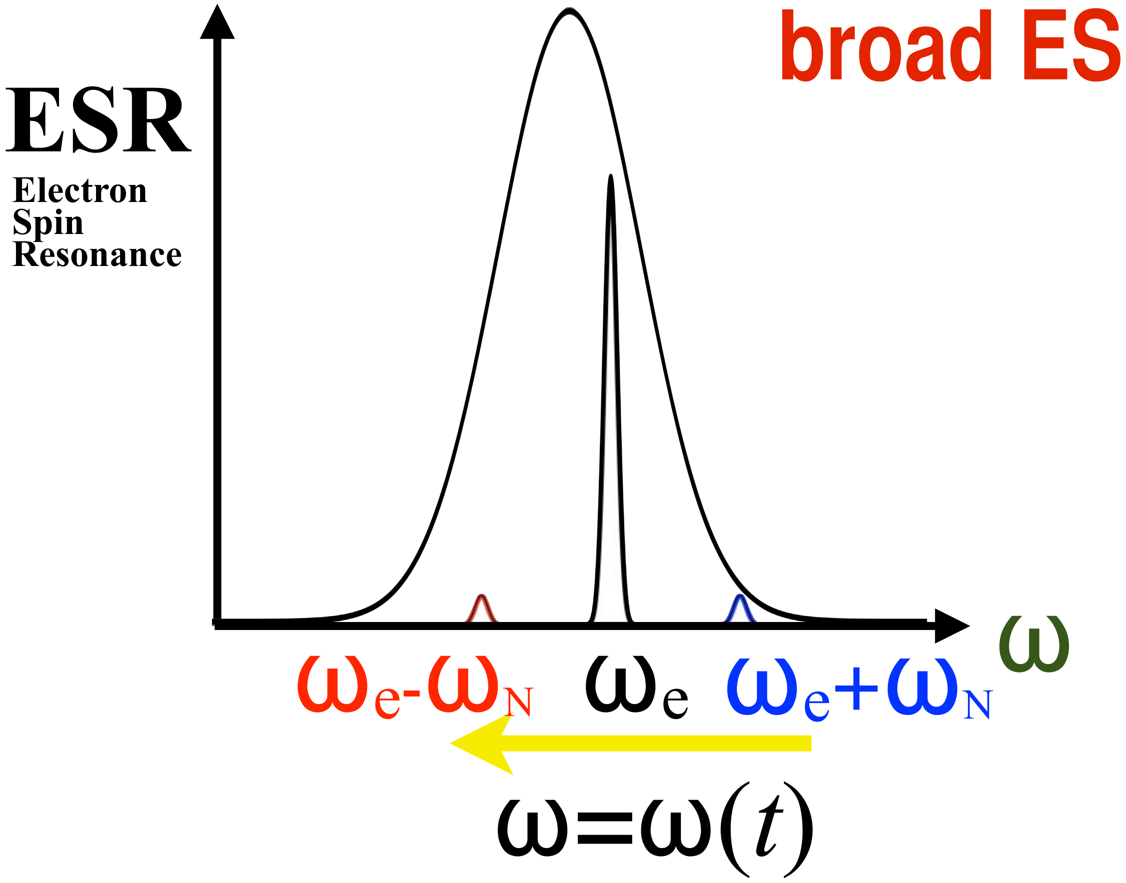


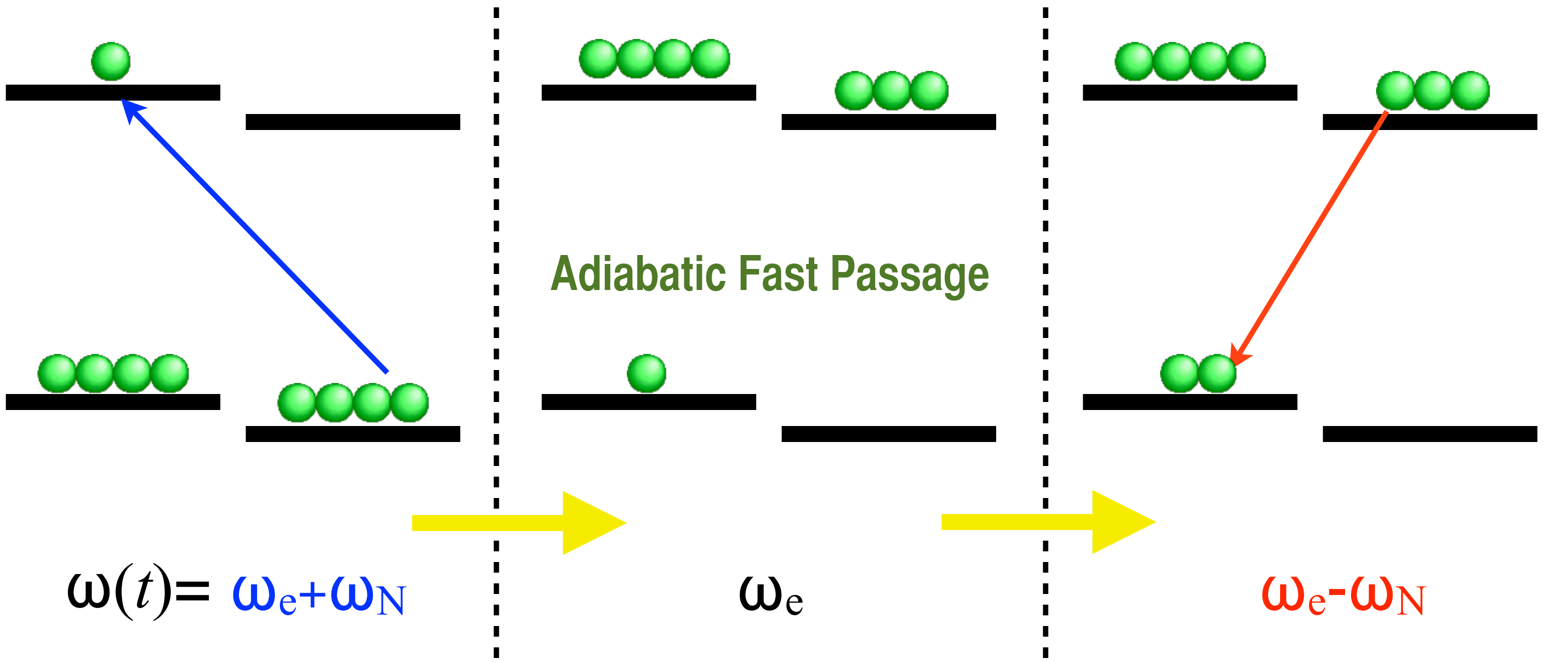
$\Delta\omega_e > \omega_N$

Integrated Solid Effect

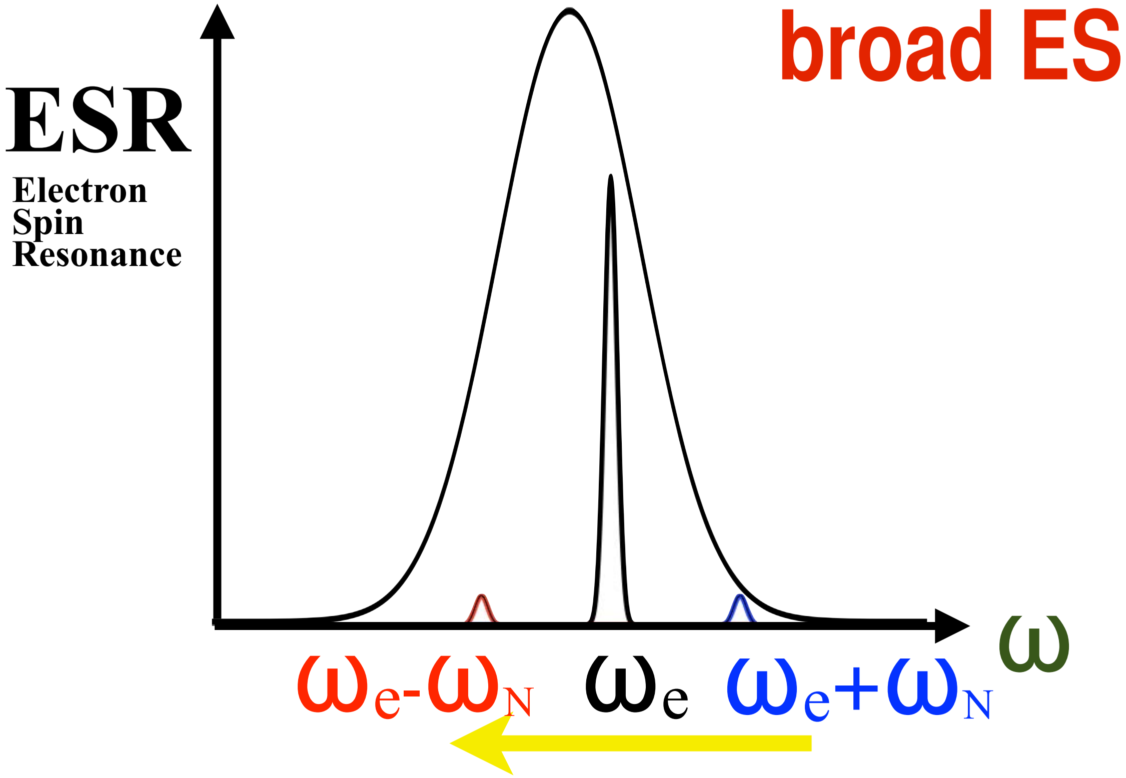
$\Delta\omega_e > \omega_N$

broad ESR





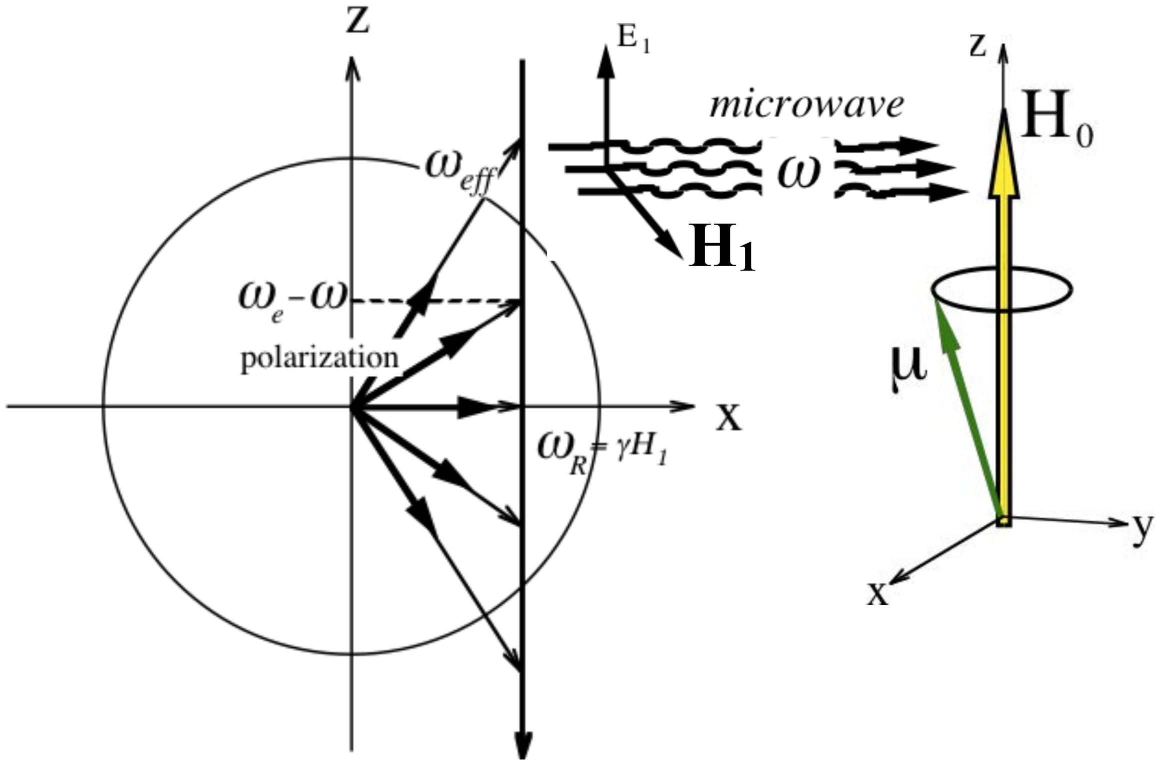
Integrated Solid Effect



$\omega = \omega(t)$

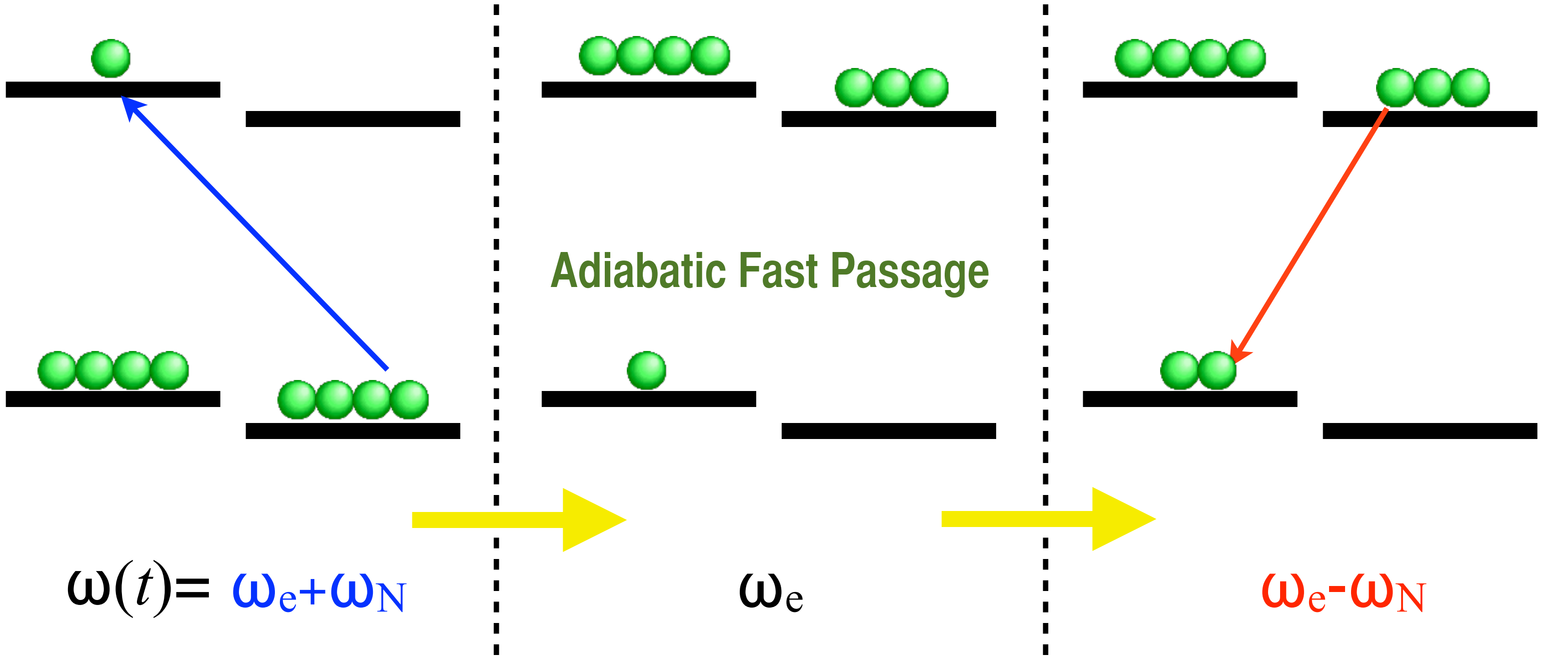
$\Delta\omega_e > \omega_N$

Adiabatic Fast Passage

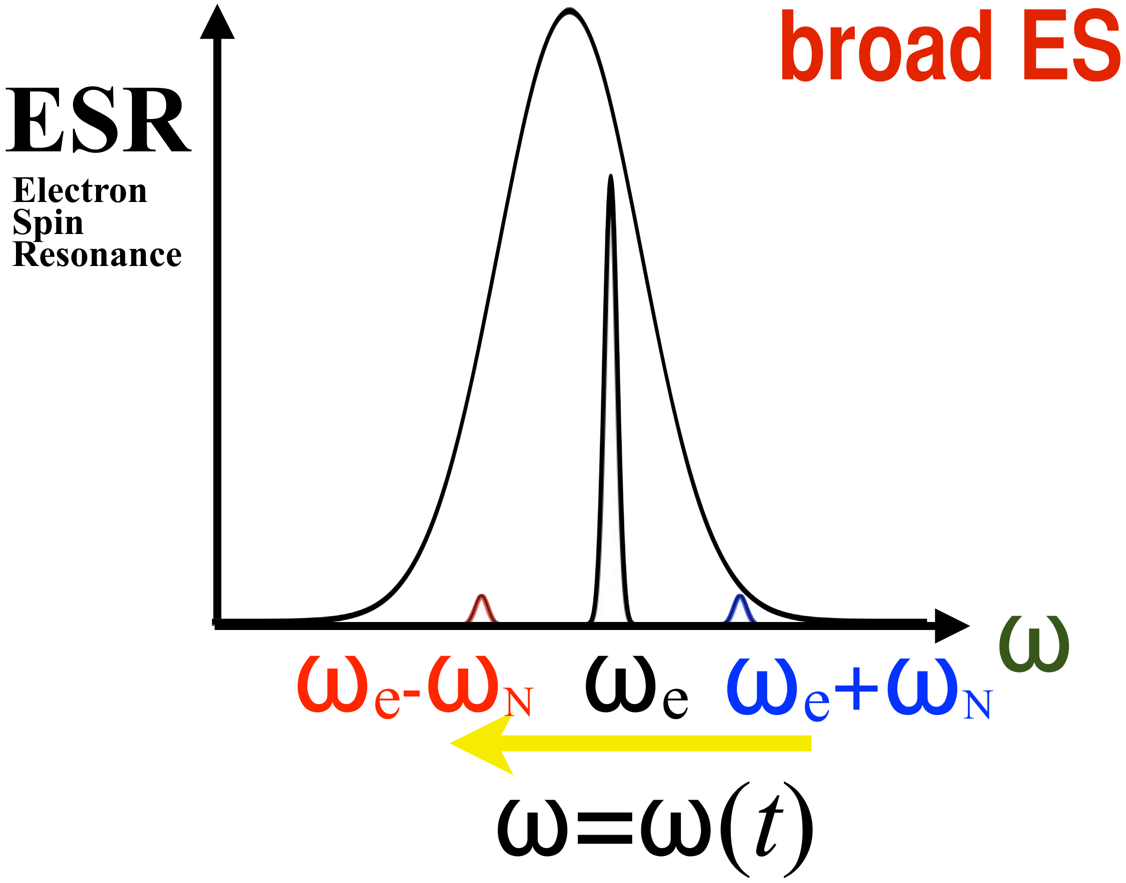


Adiabatic: rotation of w_{eff} < Larmor precession

Fast: rotation of w_{eff} > spin-lattice relaxation

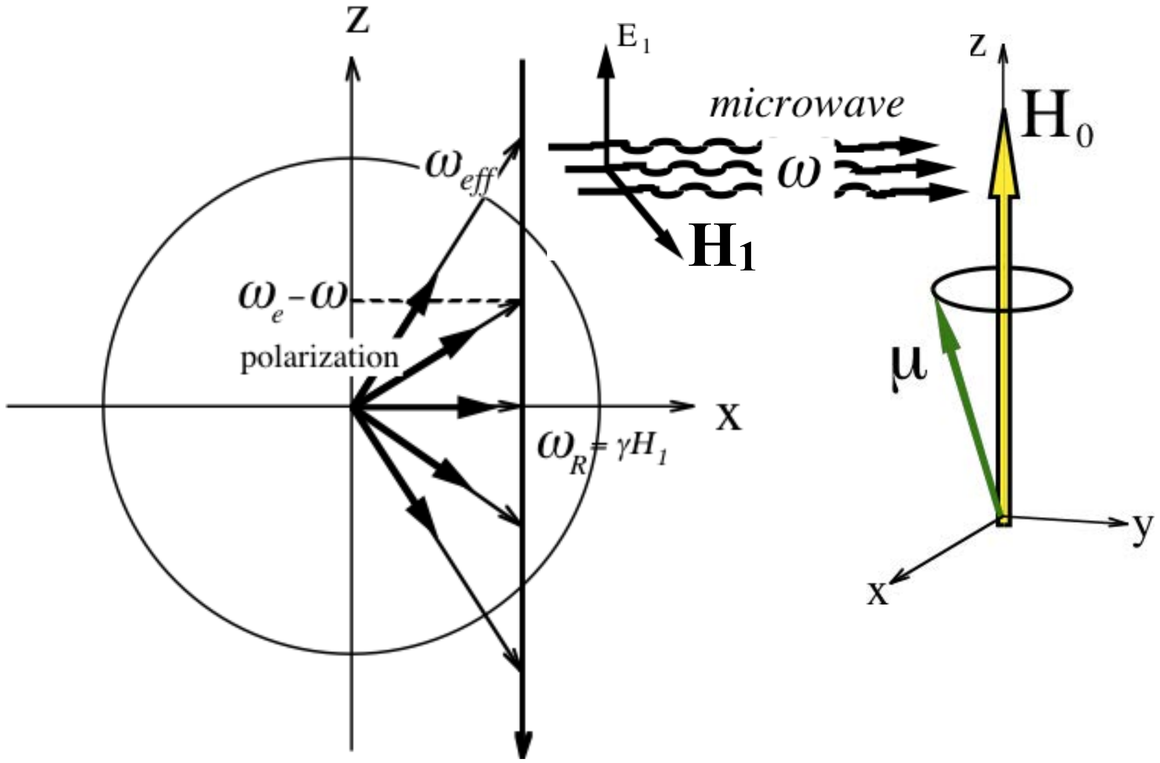


Integrated Solid Effect



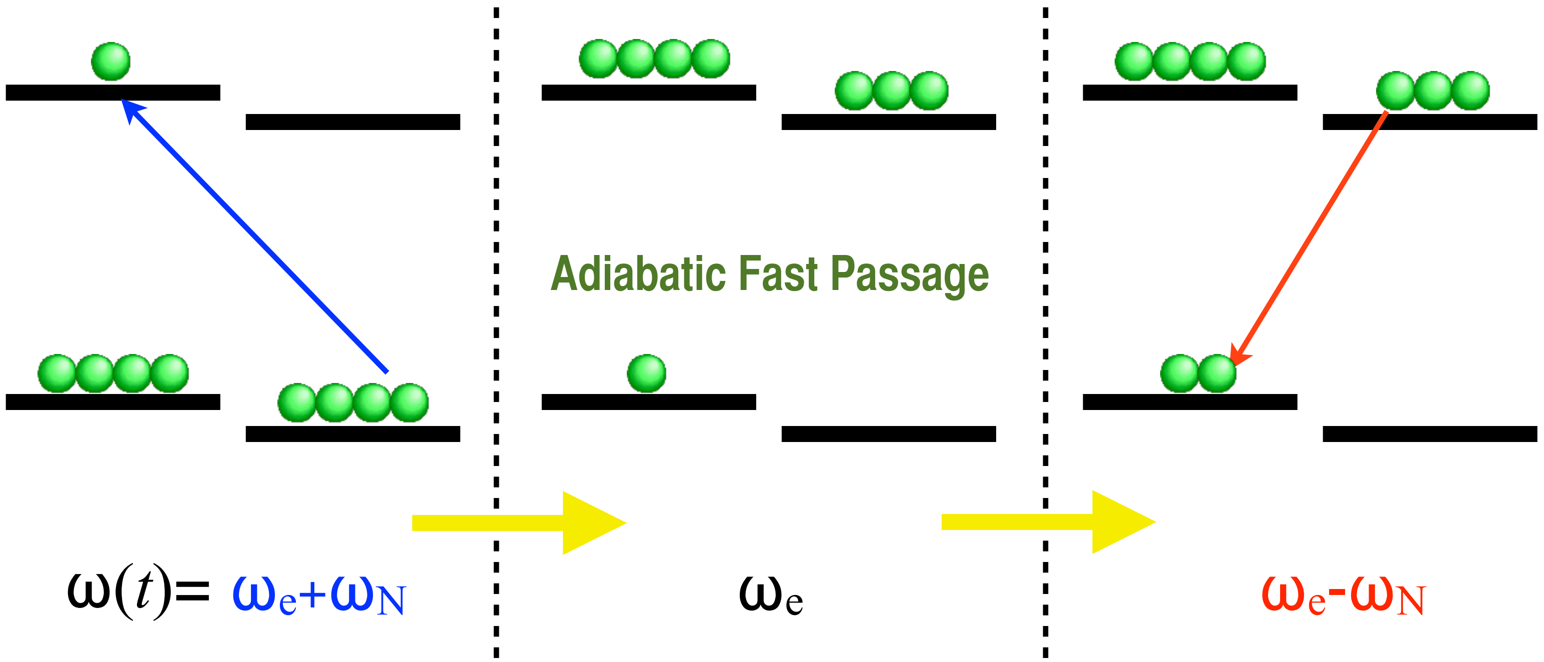
$\Delta\omega_e > \omega_N$

Adiabatic Fast Passage



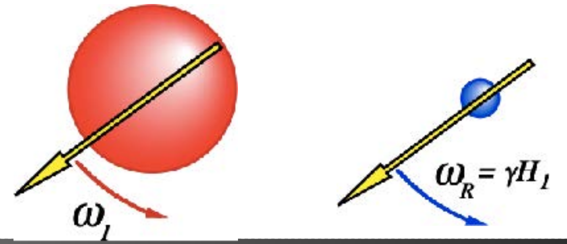
Adiabatic: rotation of w_{eff} < Larmor precession

Fast: rotation of w_{eff} > spin-lattice relaxation



NOVEL

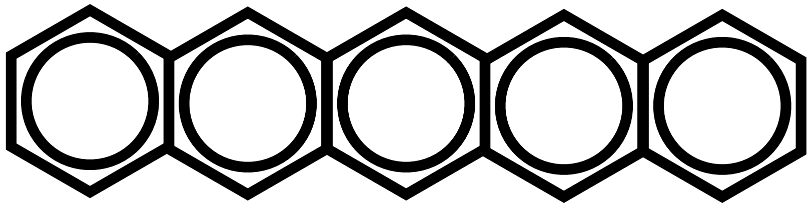
Nuclear-spin Orientation Via Electron-spin Locking



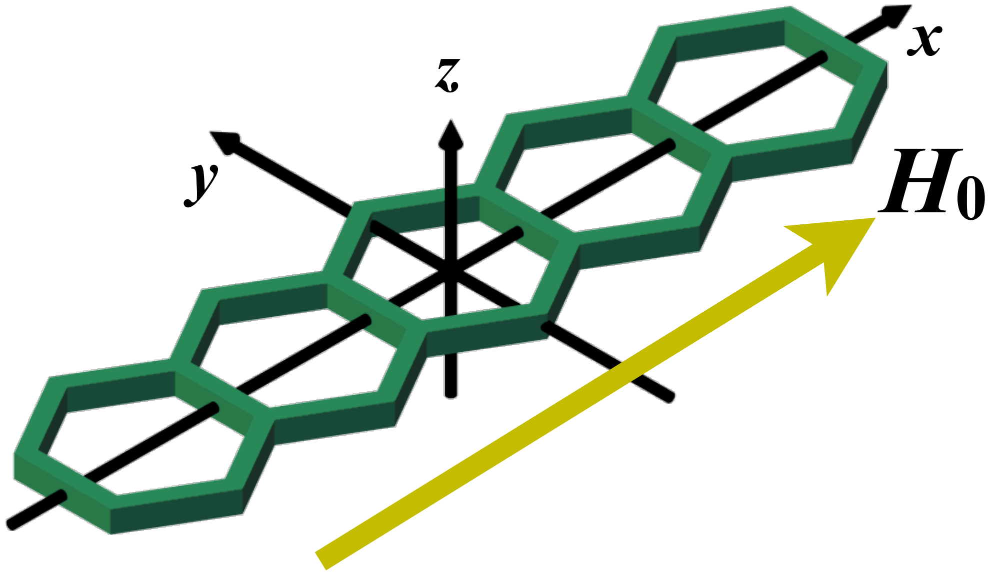
$\omega_I = \omega_e$

Pentacene $C_{22}H_{14}$

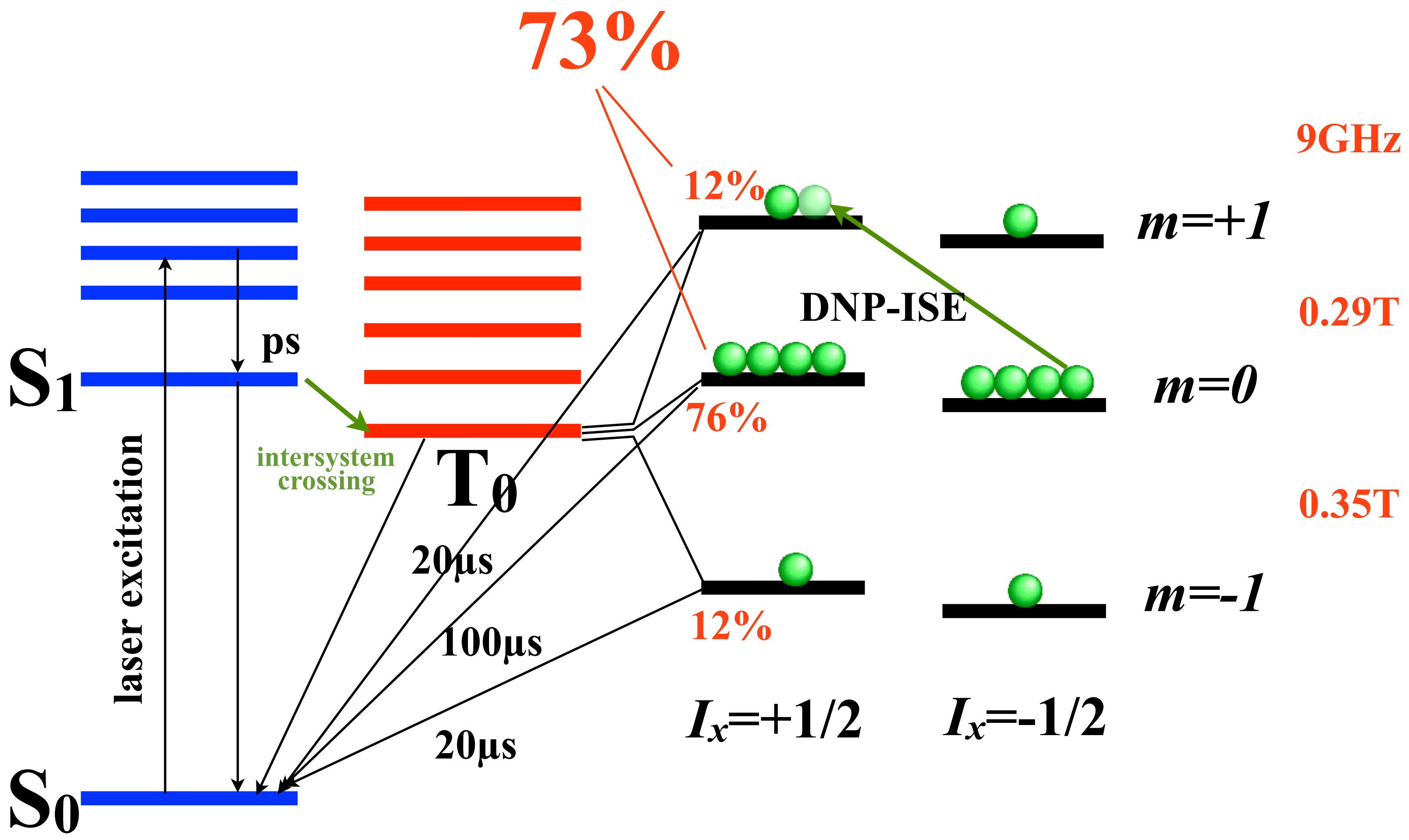
Chem. Phys. Lett. 165 (1990) 6



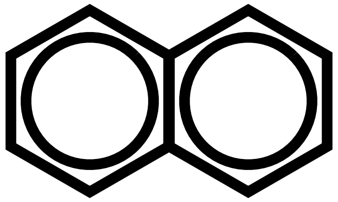
m.p.=270°C



	H_0 // x	H_0 // y	H_0 // z
m=+1	12%	45%	46%
m=0	76%	16%	8%
m=-1	12%	39%	46%



Naphthalene $C_{10}H_8$

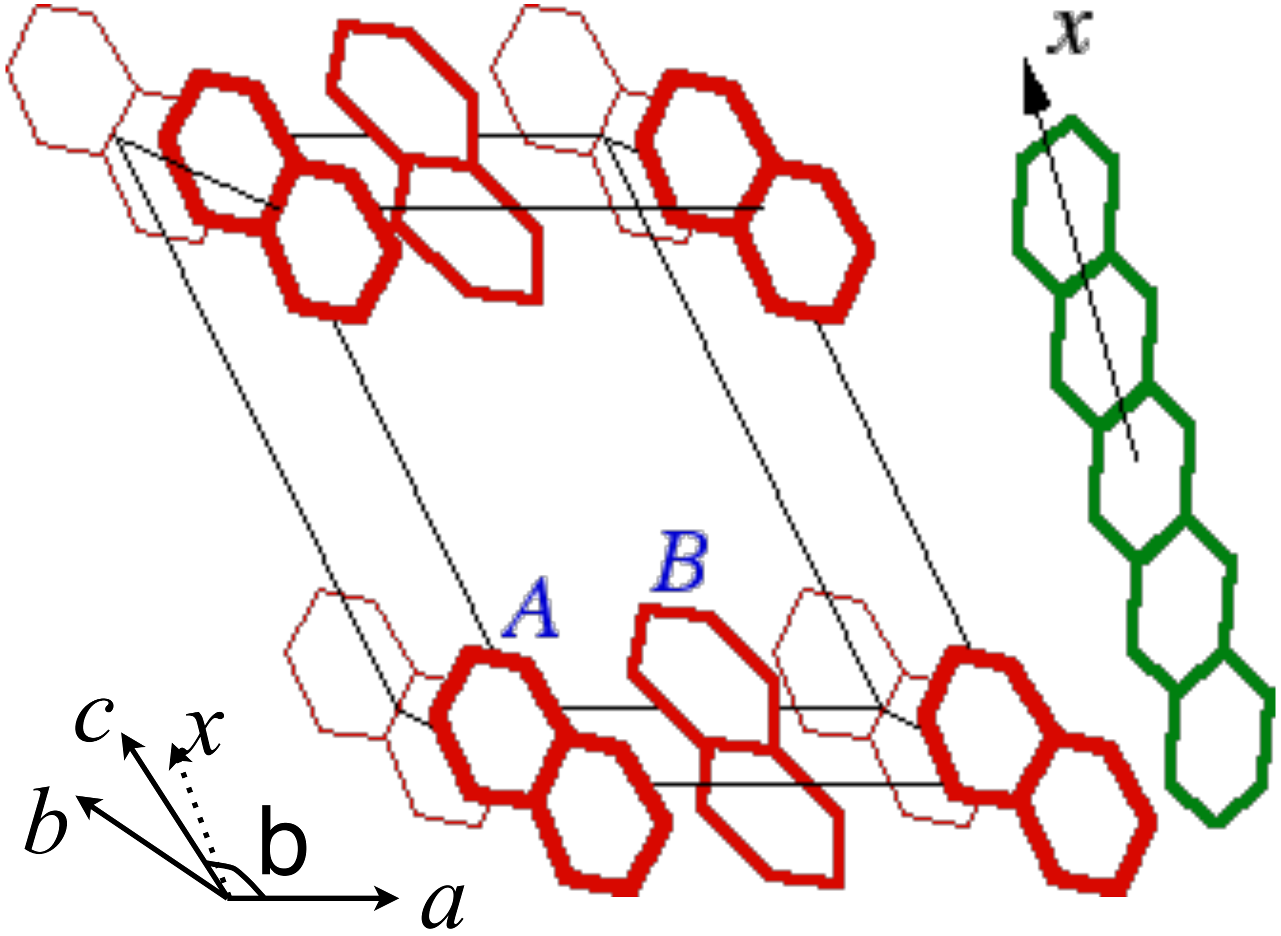


m.p.=80°C

2 naphthalene molecules

1 pentacene molecule

Pentacene < 0.01 mol%



a=0.82nm
b=0.6nm
c=0.87nm

a=g=90°
b=123°

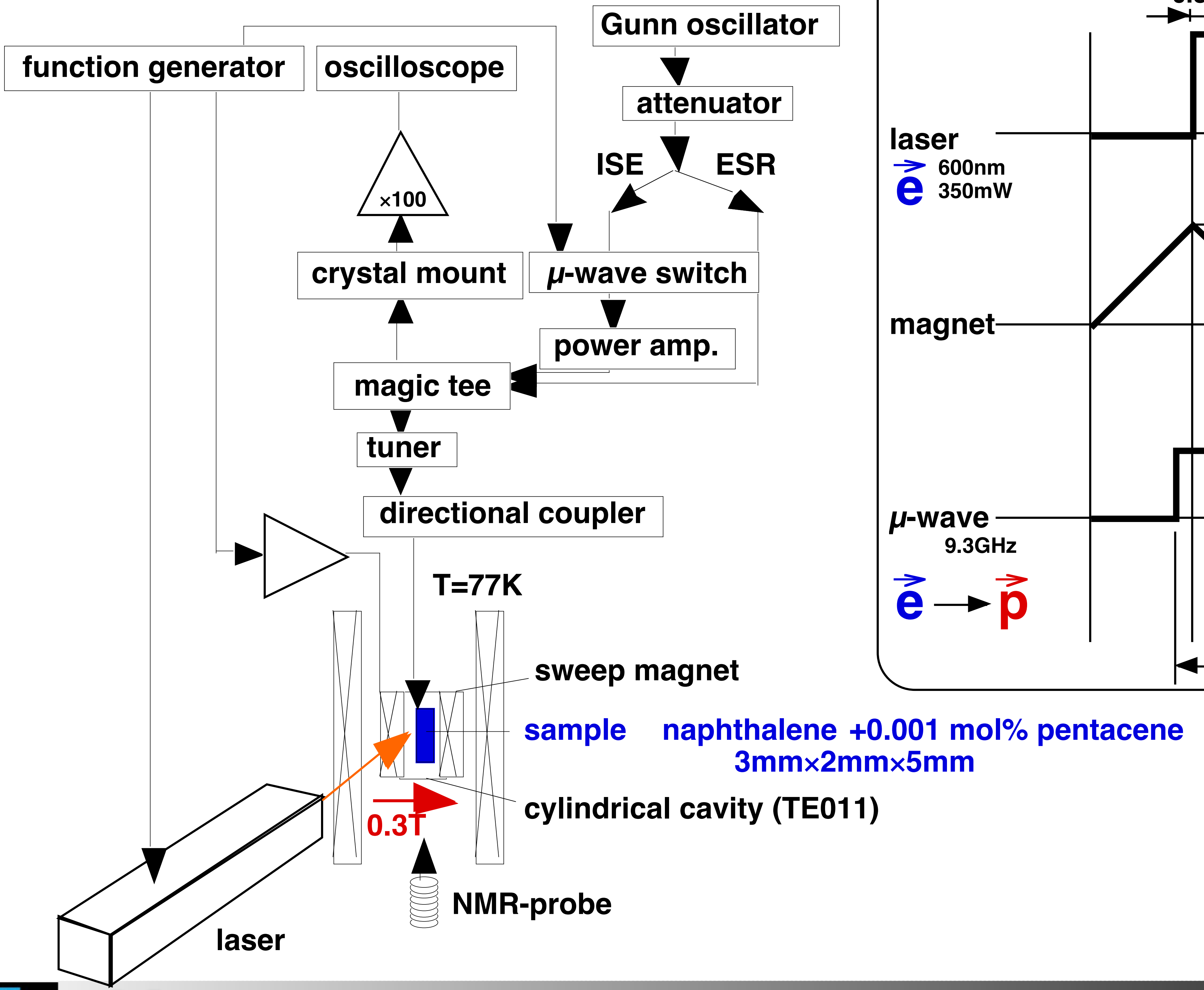
$P2_1/a$ (monoclinic)

The x-axis of pentacene is aligned in host crystals.

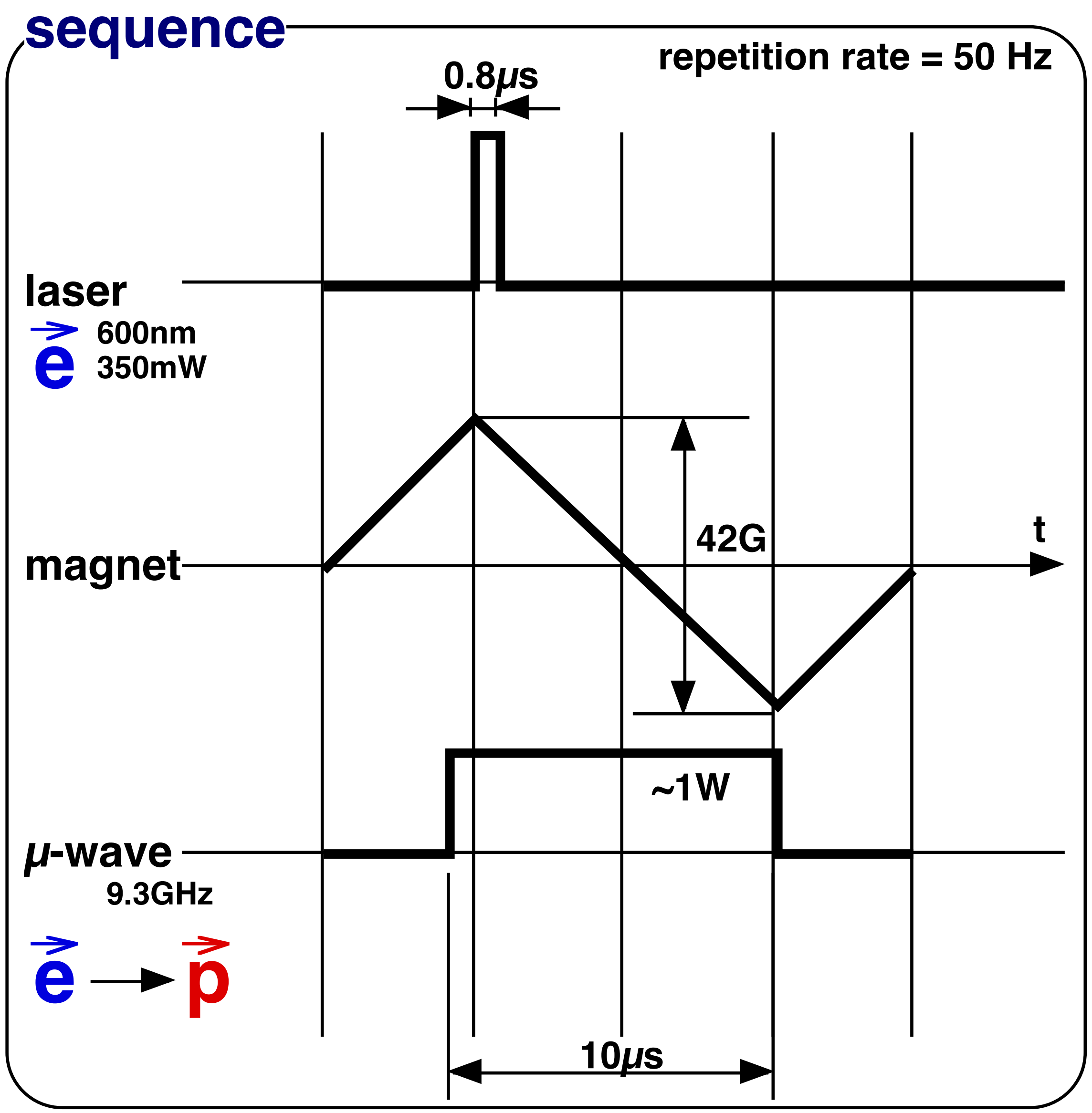
Experimental Setup

M.Iinuma et al., Phys. Rev. Lett. 84 (2000) 171

Microwave Induced Optical Nuclear Polarization



sequence

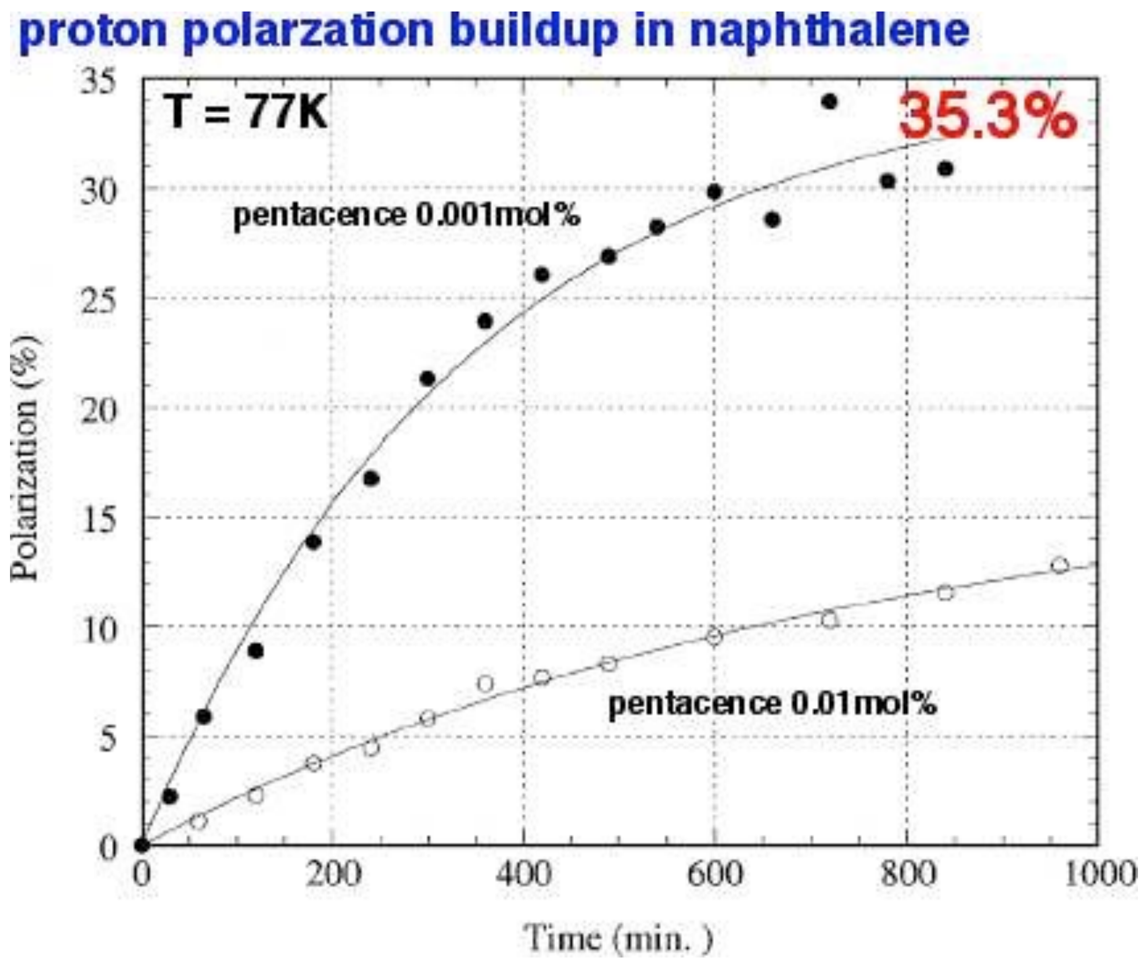


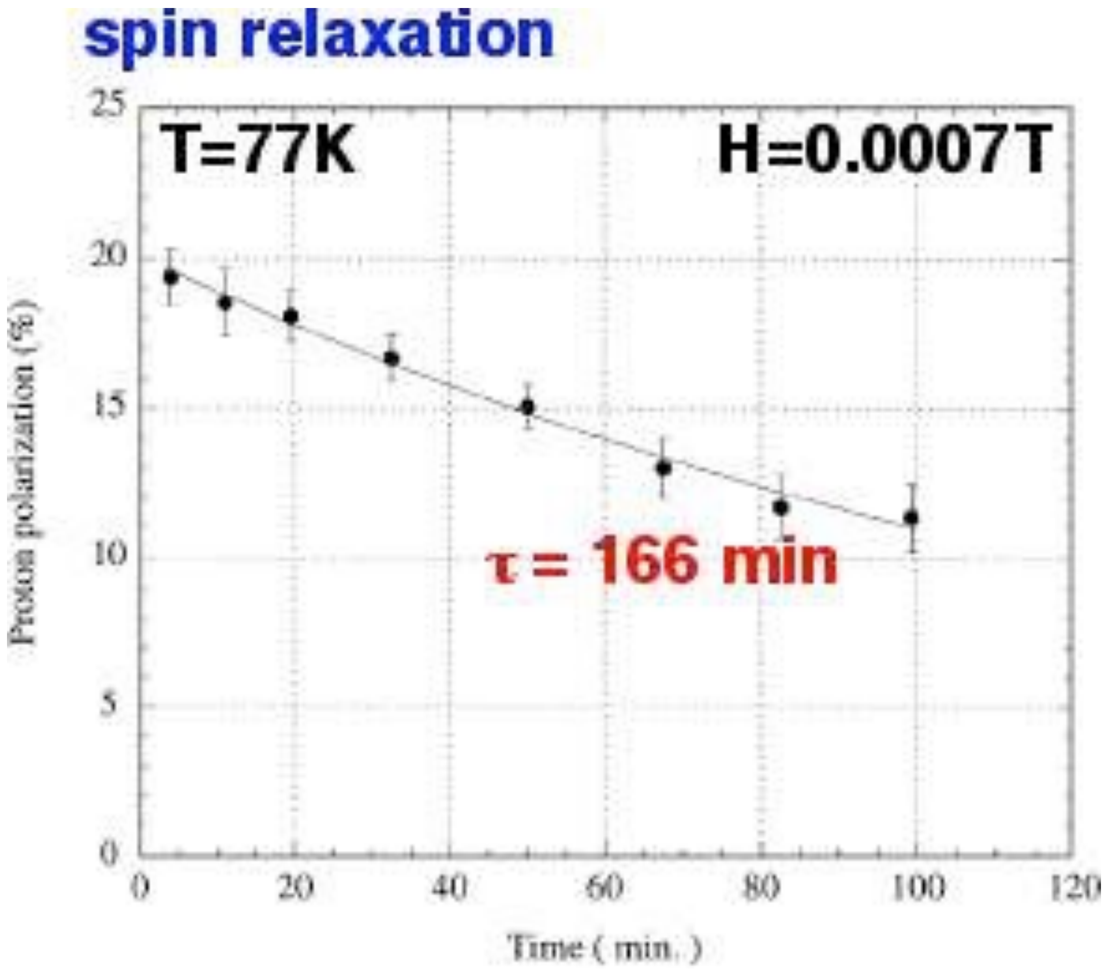
M.Iinuma et al., Phys. Rev. Lett. 84 (2000) 171

Experimental Result (MIONP, triplet-DNP)

P_p~0.35 T=77K B=0.3T

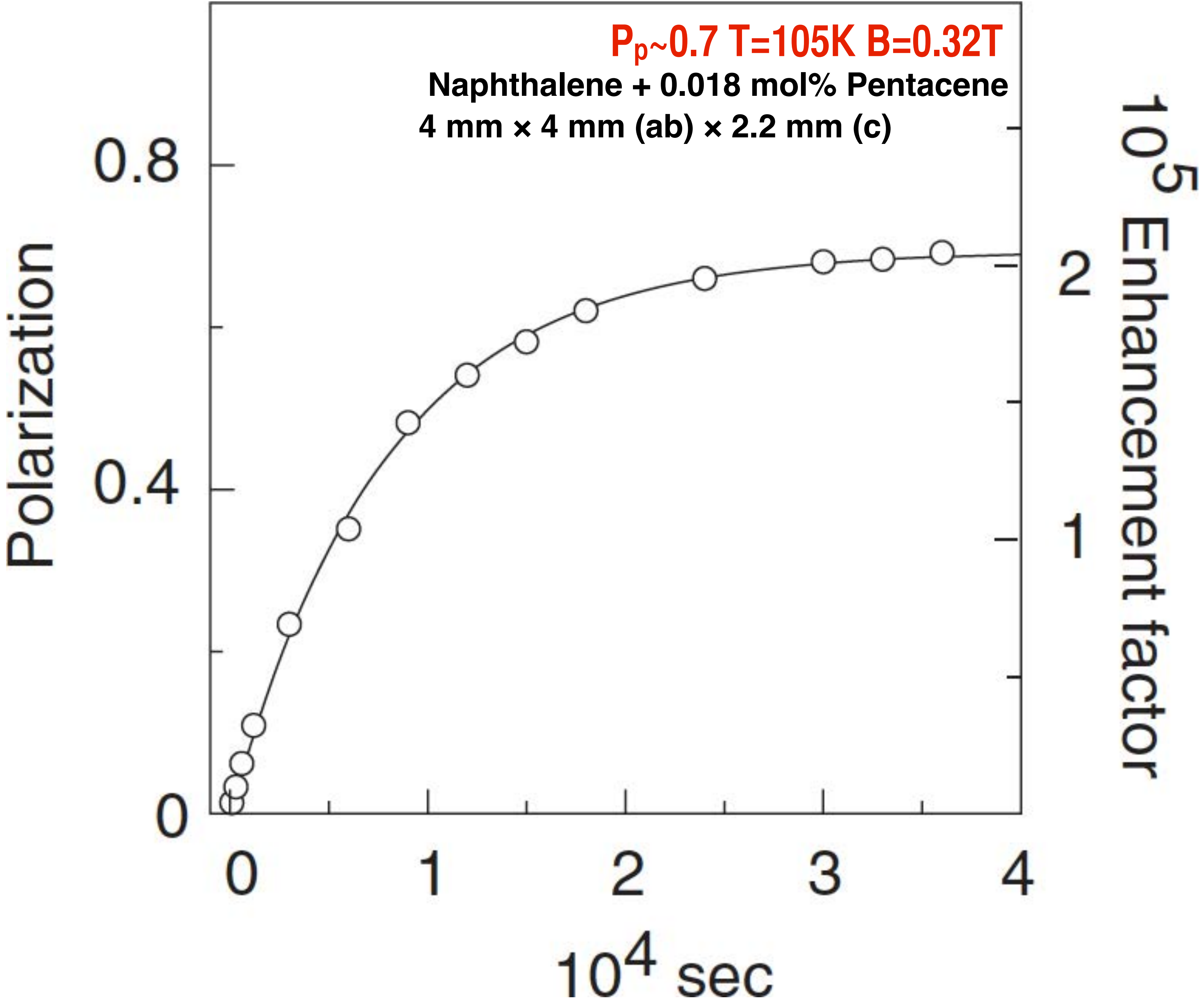
Naphthalene + 0.001 mol% Pentacene
3 mm × 2 mm (ab) × 5 mm


proton polarzation buildup in naphthalene

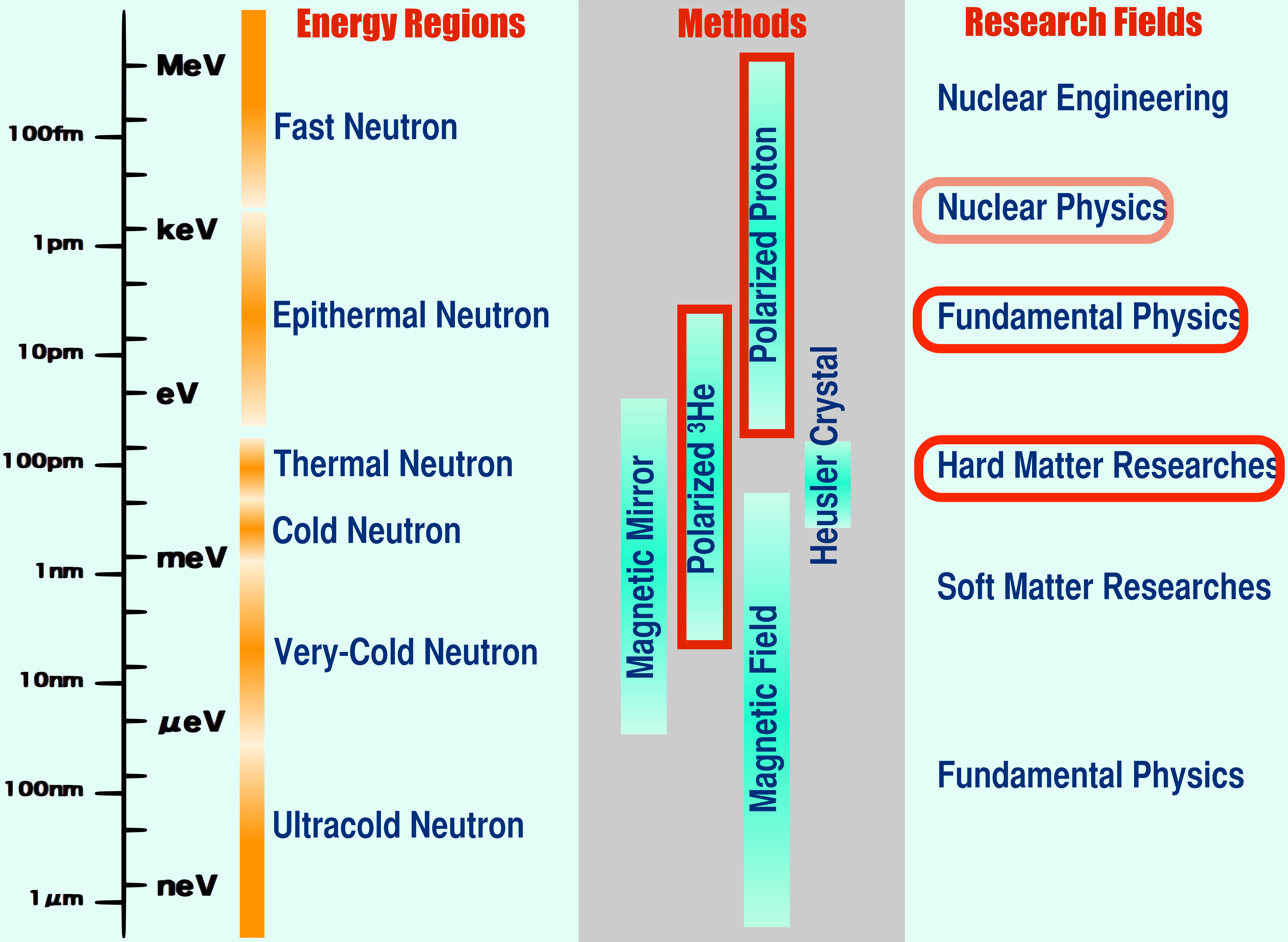

spin relaxation

Experimental Result (MIONP, triplet-DNP)

K.Takeda et al., J. Phys. Soc. Jpn. 73 (2004) 2313



Neutron Polarizer/Analyzer



Energy Regions

- Fast Neutron
- Epithermal Neutron
- Thermal Neutron
- Cold Neutron
- Very-Cold Neutron
- Ultracold Neutron

Methods

- Magnetic Mirror
- Polarized ³He
- Polarized Proton
- Magnetic Field
- Heusler Crystal

Research Fields

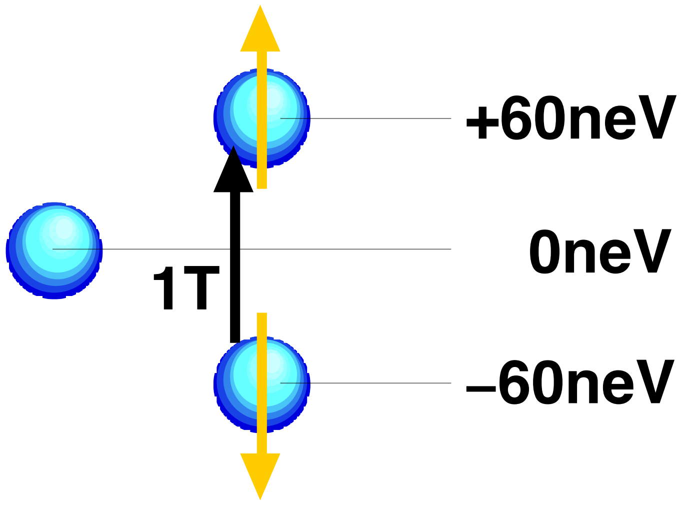
- Nuclear Engineering
- Nuclear Physics
- Fundamental Physics
- Hard Matter Researches
- Soft Matter Researches
- Fundamental Physics

Neutron Accelerator/Decelerator

Y.Arimoto et al., Phys. Rev. A 86 (2012) 023843

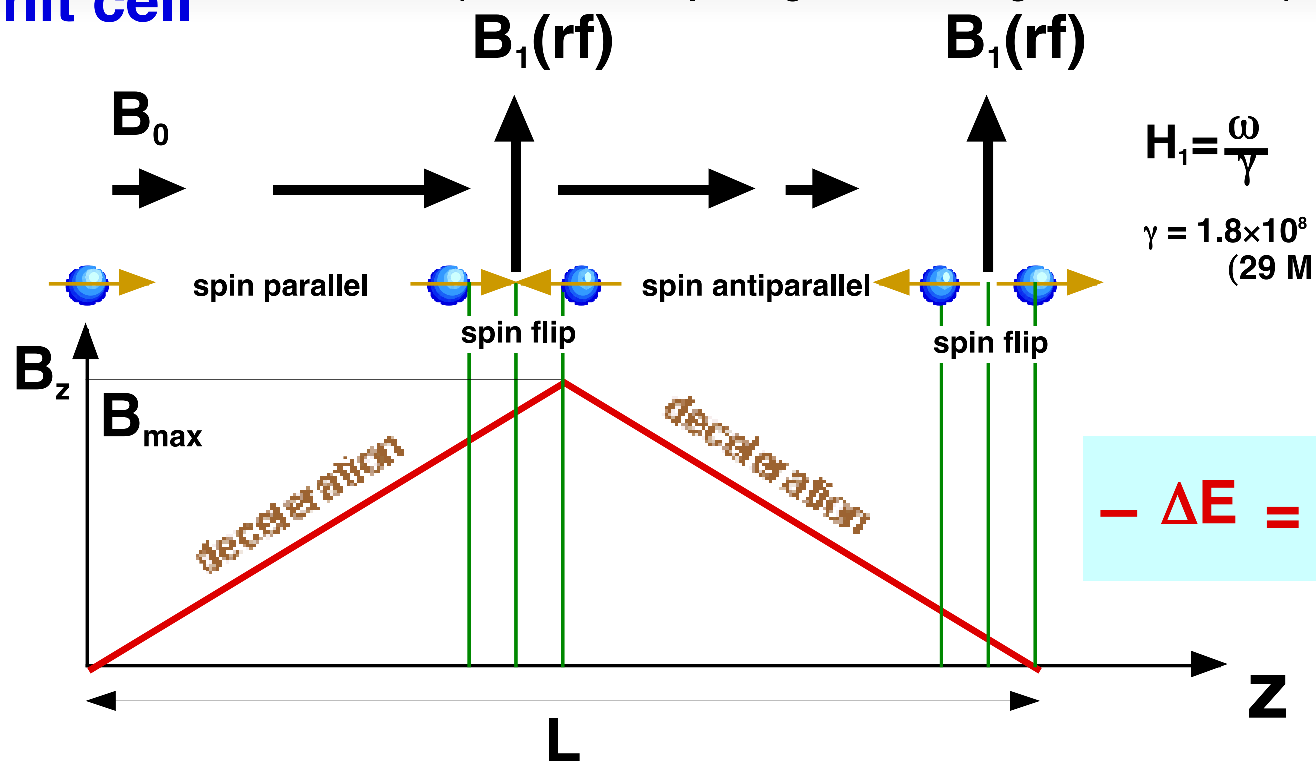
Neutron Decelerator by Successive Spin Flip

magnetic dipole interaction



unit cell

AFP-NMR (adiabatic fast passage nuclear magnetic resonance)



$H_1 = \frac{\omega}{\gamma}$

$\gamma = 1.8\times10^{8}$ rad s^{-1} T^{-1}
(29 MHz/T)

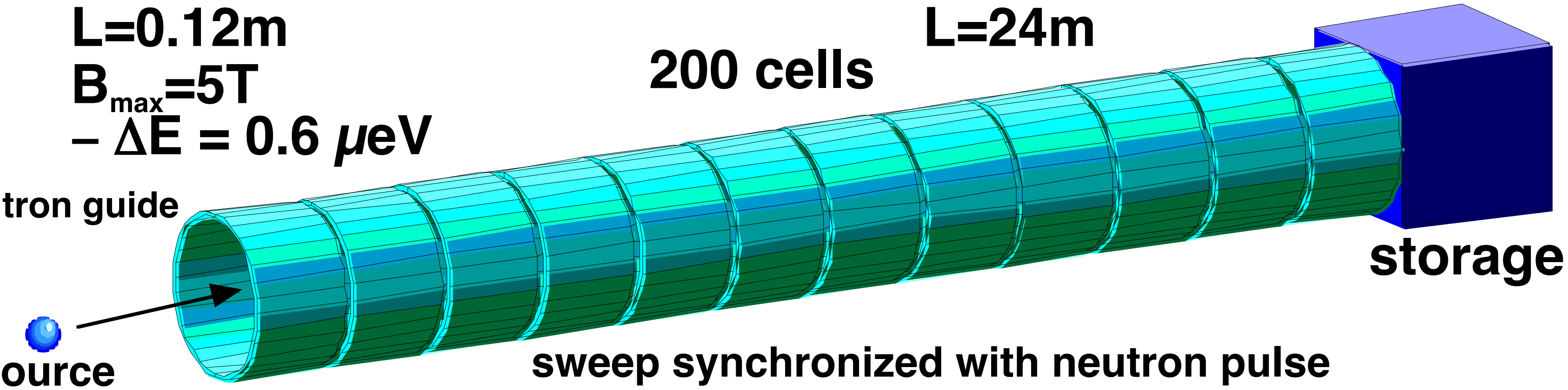
$$-\Delta E = 120 \frac{B_{max}}{1\ T} \text{neV}$$

---

cell
L=0.12m
B_{max}=5T
$-\Delta E = 0.6\ \mu eV$

total $-\Delta E = 120\ \mu eV$
200 cells
L=24m

$J = 1.5\times10^{4}\ cm^{-2} s^{-1}$
LANSCE



inner surface = neutron guide

pulsed neutron source

sweep synchronized with neutron pulse

storage time = 50sec

neutron density

$3\times10^{4}\ cm^{-3}$
LANSCE
$3\times10^{5}\ cm^{-3}$
JSNS

$(0.9948)^{172}$=0.41 reflection loss
0.32 spin flip loss
0.54 phase mismatch due to neutron pulse width

$2\times10^{3}\ cm^{-3}$
LANSCE
$2\times10^{4}\ cm^{-3}$
JSNS

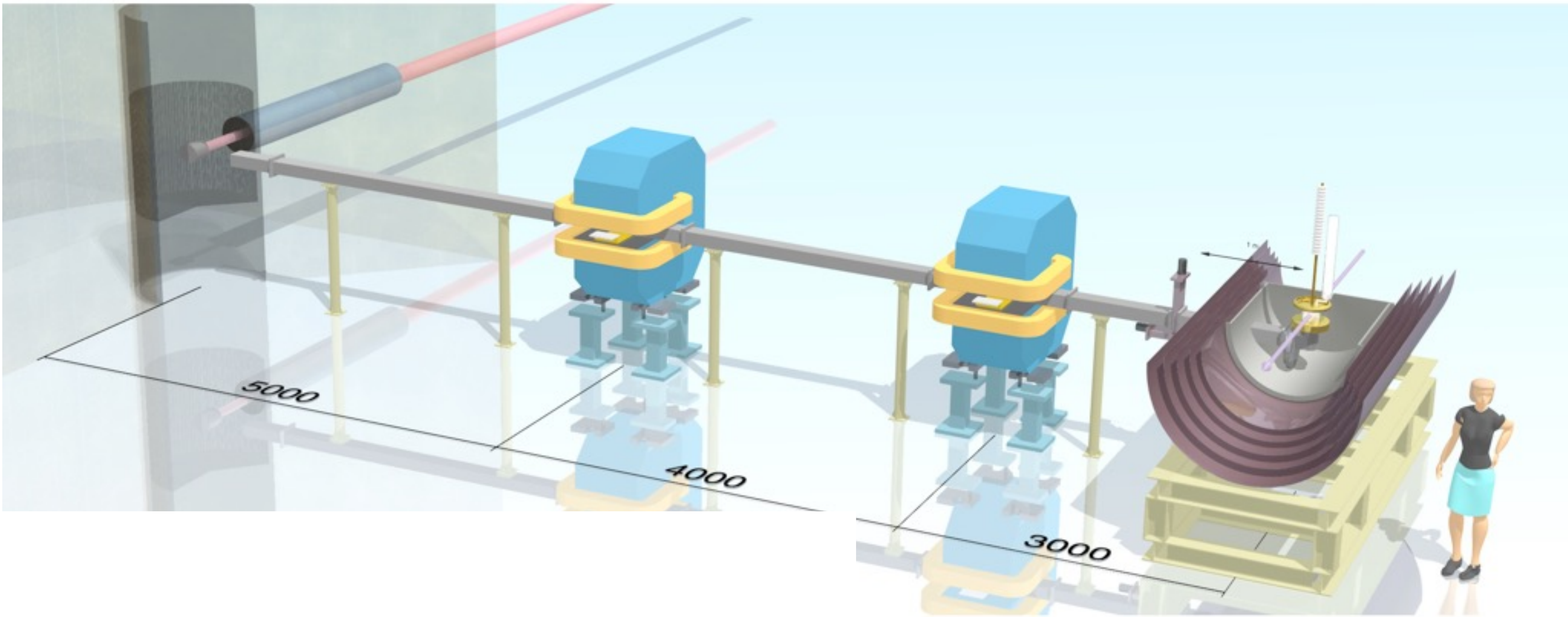
Neutron Accelerator/Decelerator

rebuncher

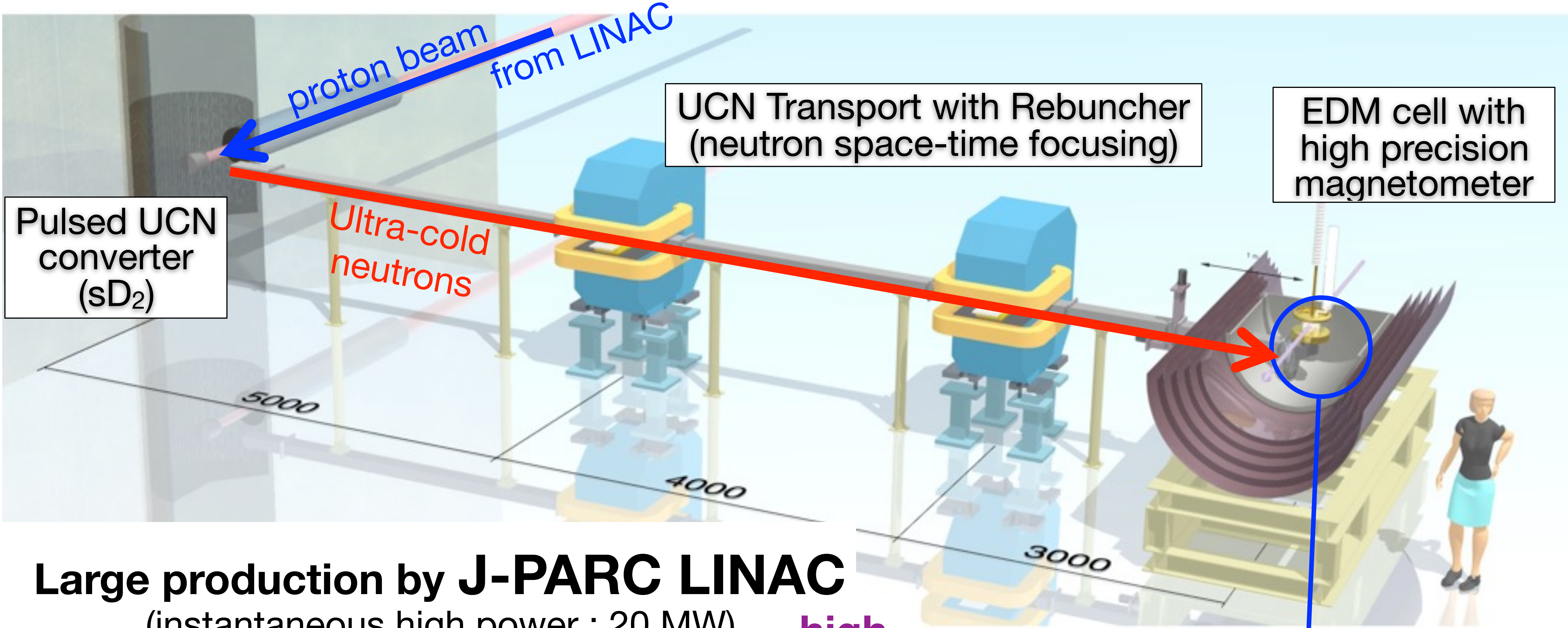
Y,Arimoto, Phys. Rev. A 86 (2012) 023843

S.Imajo, Prog. Theor. Exp. Phys. (2016) 013C02

Motivation nEDM at J-PARC (P33)



Motivation   nEDM at J-PARC (P33)



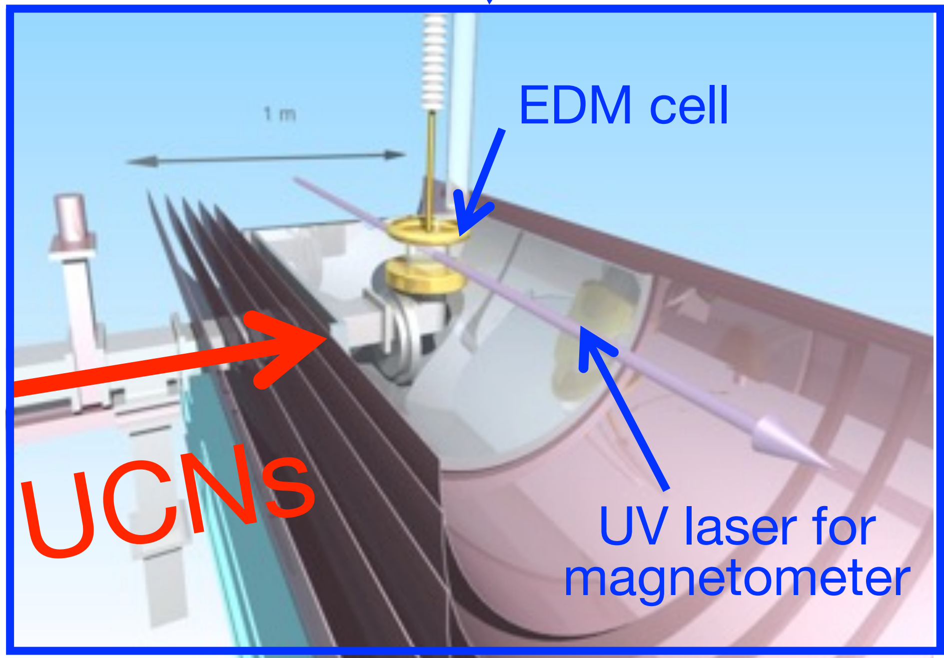
Large production by J-PARC LINAC
(instantaneous high power : 20 MW)
+
Transport optics
(focusing with pulsed neutron decelerator)
+
High precision measurement
(magnetometer using UV laser)

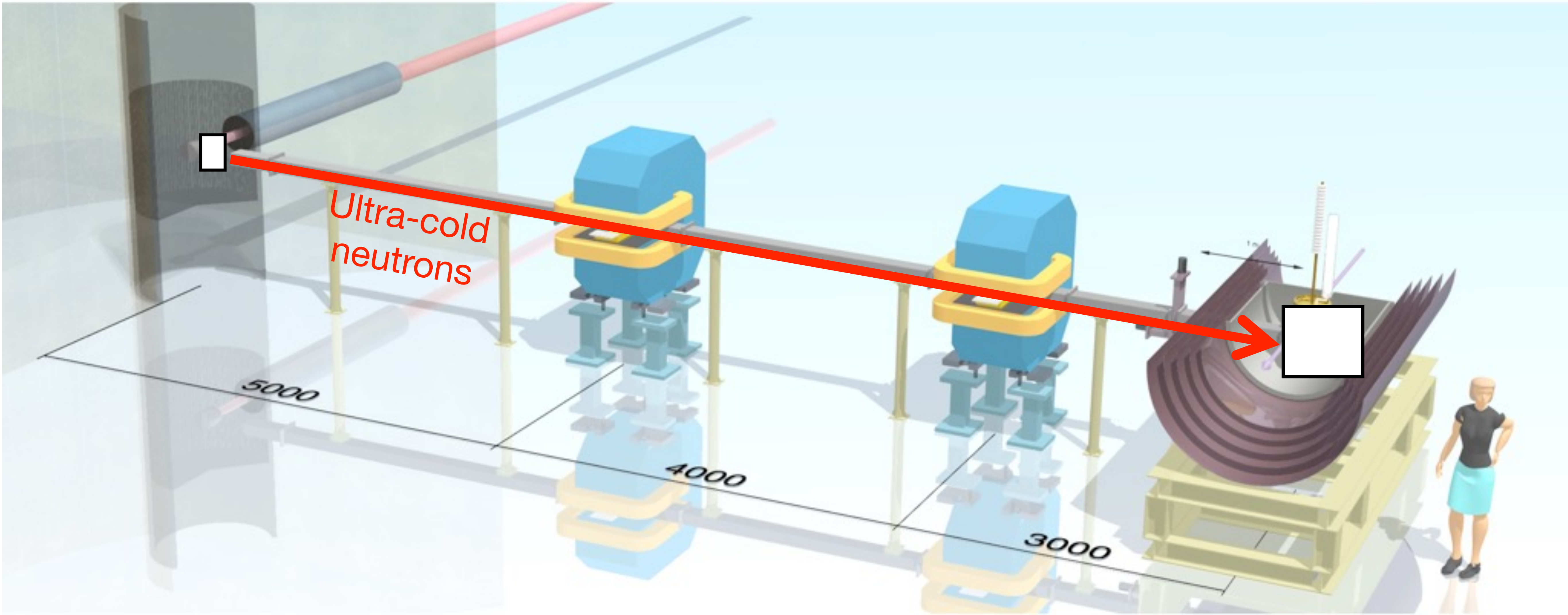
high density

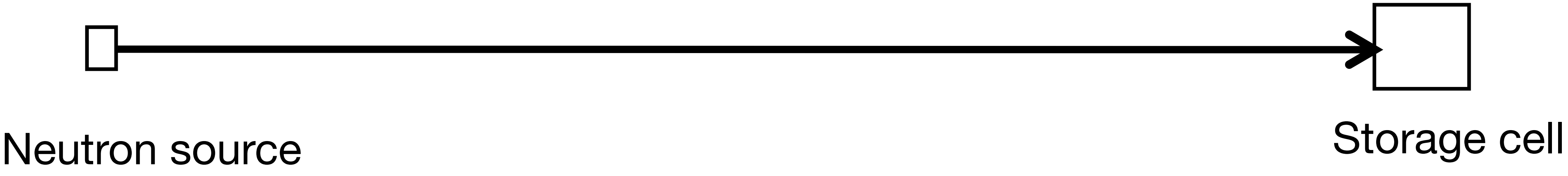
small systematic errors

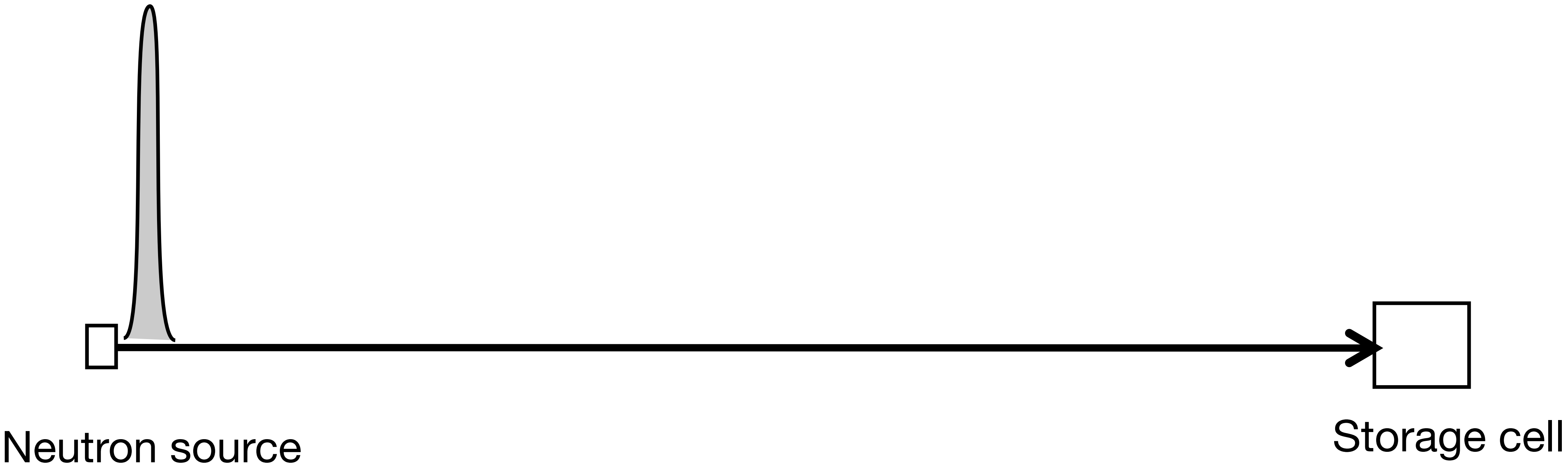
⇨ **10^{-27} e cm (phase1, 5 years)**

⇨ **10^{-28} e cm (phase2)**

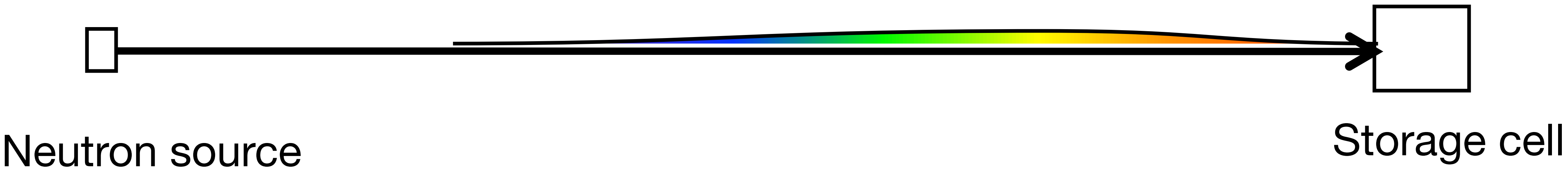



Ultra-cold neutrons
5000
4000
3000


Neutron source
Storage cell

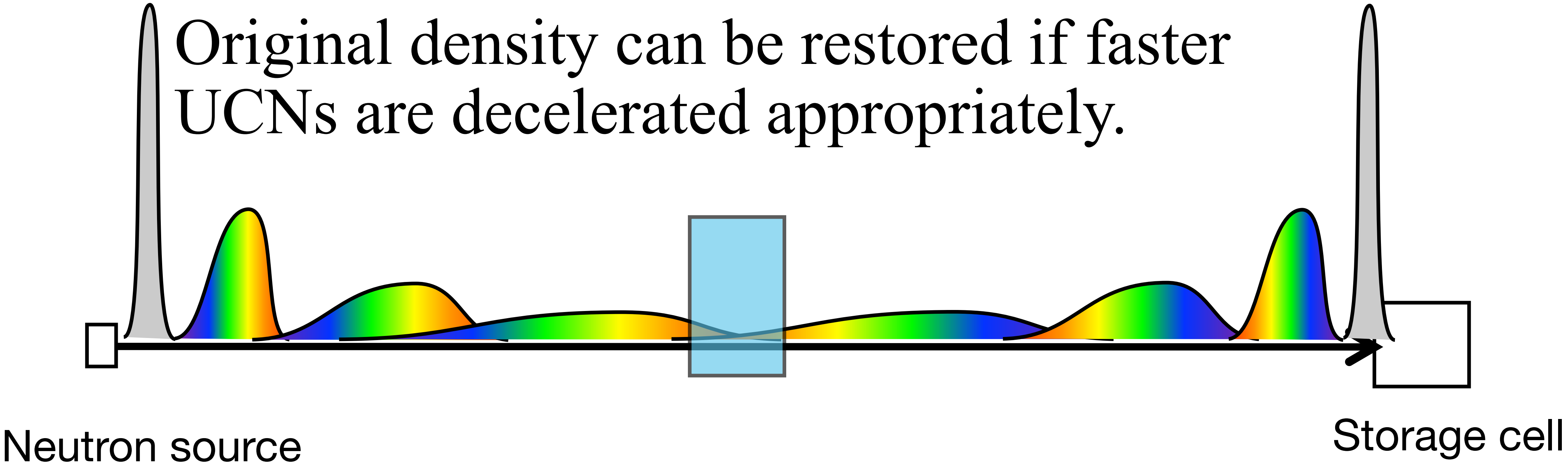


Neutron source
Storage cell



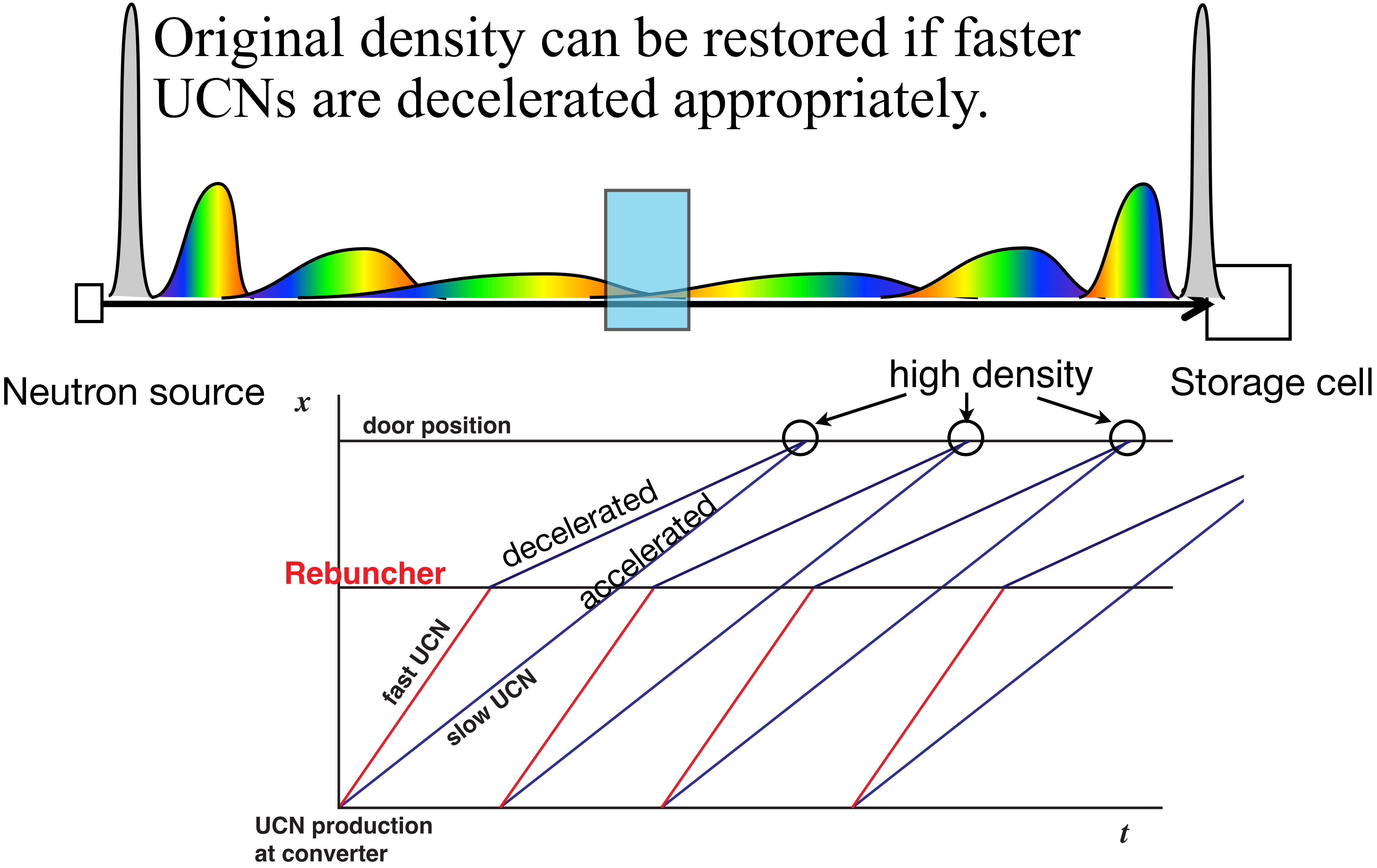
Pulsed UCNs spread spatially,
Density decreases quickly
without any treatment.

Transport without loss of density!



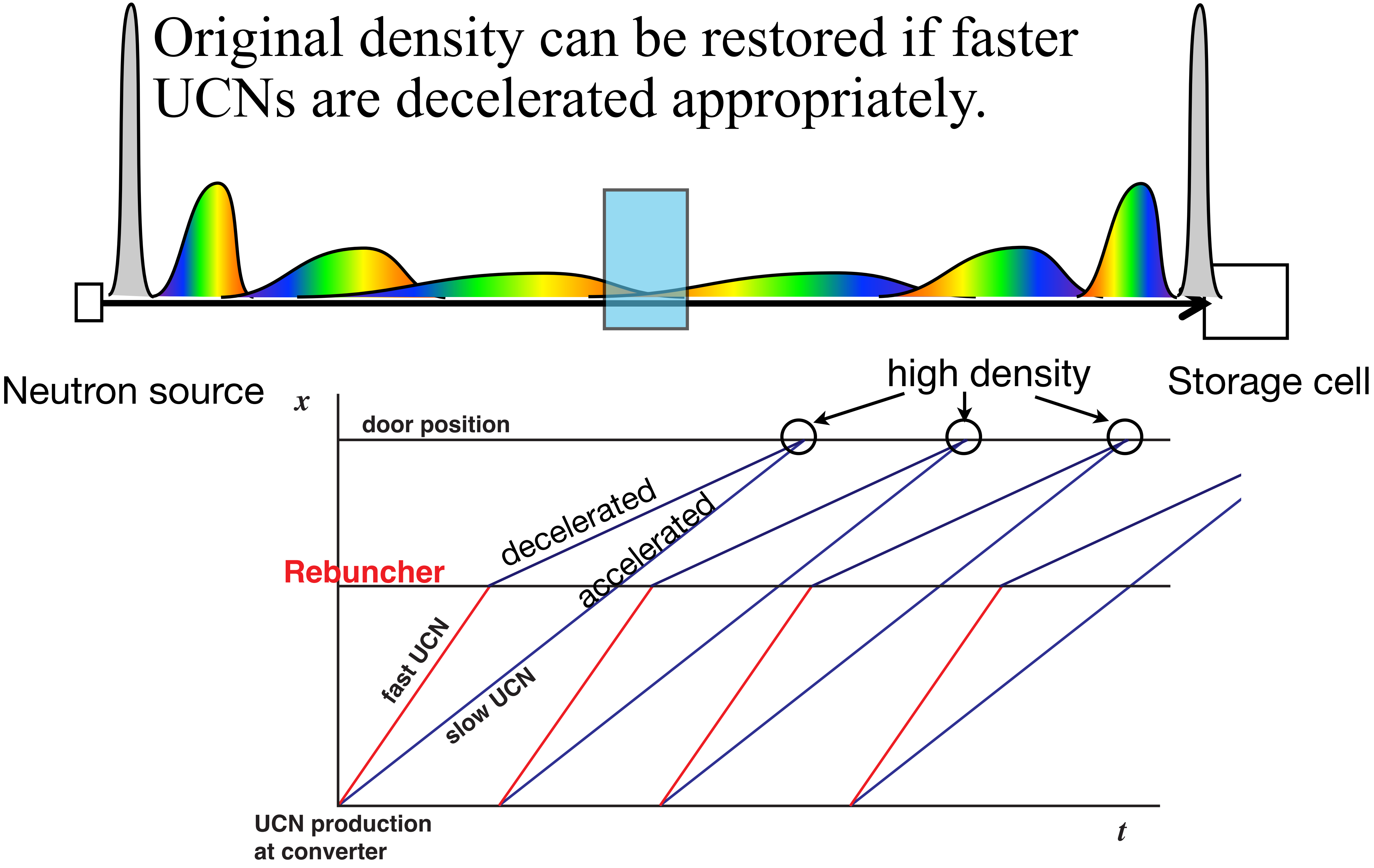
Original density can be restored if faster UCNs are decelerated appropriately.

Original density can be restored if faster UCNs are decelerated appropriately.

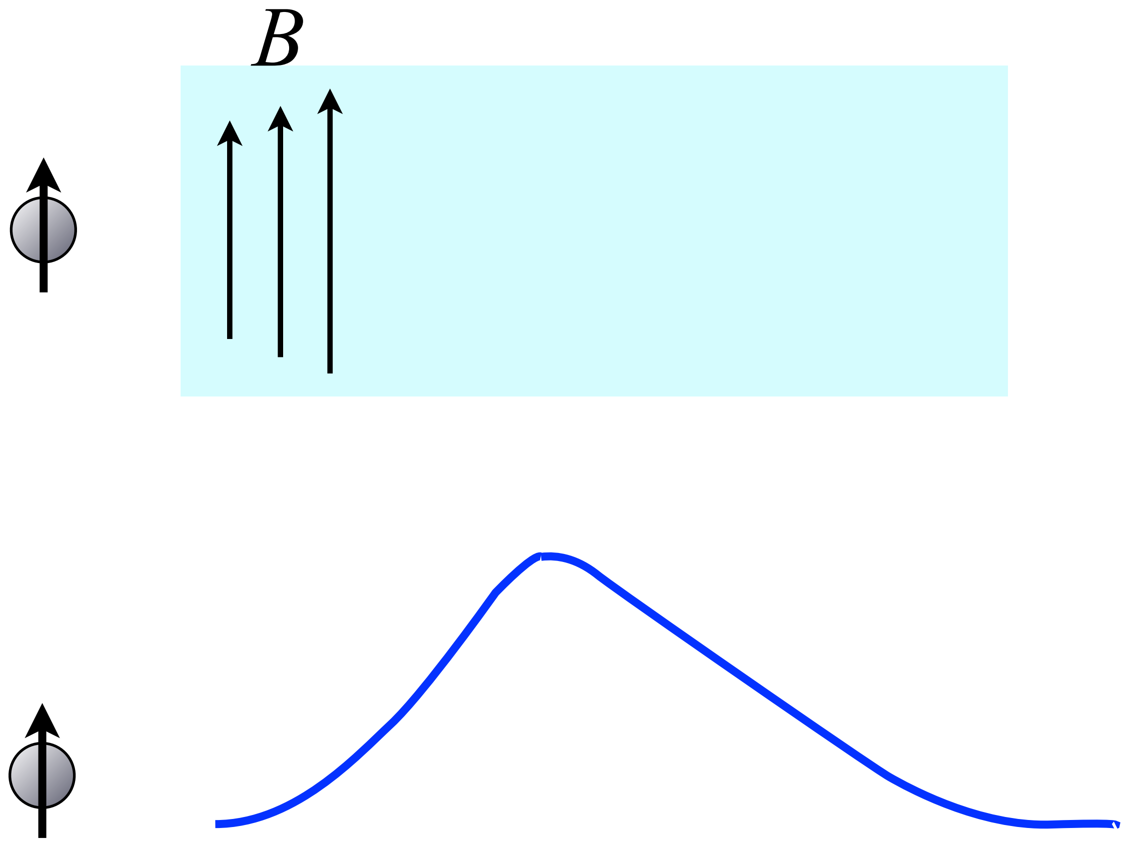


UCN Rebuncher = Neutron Accelerator

Original density can be restored if faster UCNs are decelerated appropriately.



Adiabatic Fast Passage (AFP) spin flipper is used for control of the neutron energy.



RF magnetic field in gradient field gives/removes the energy with spin flip.

$$2\mu B = \hbar\omega$$

30 MHz = 1T = 120 neV

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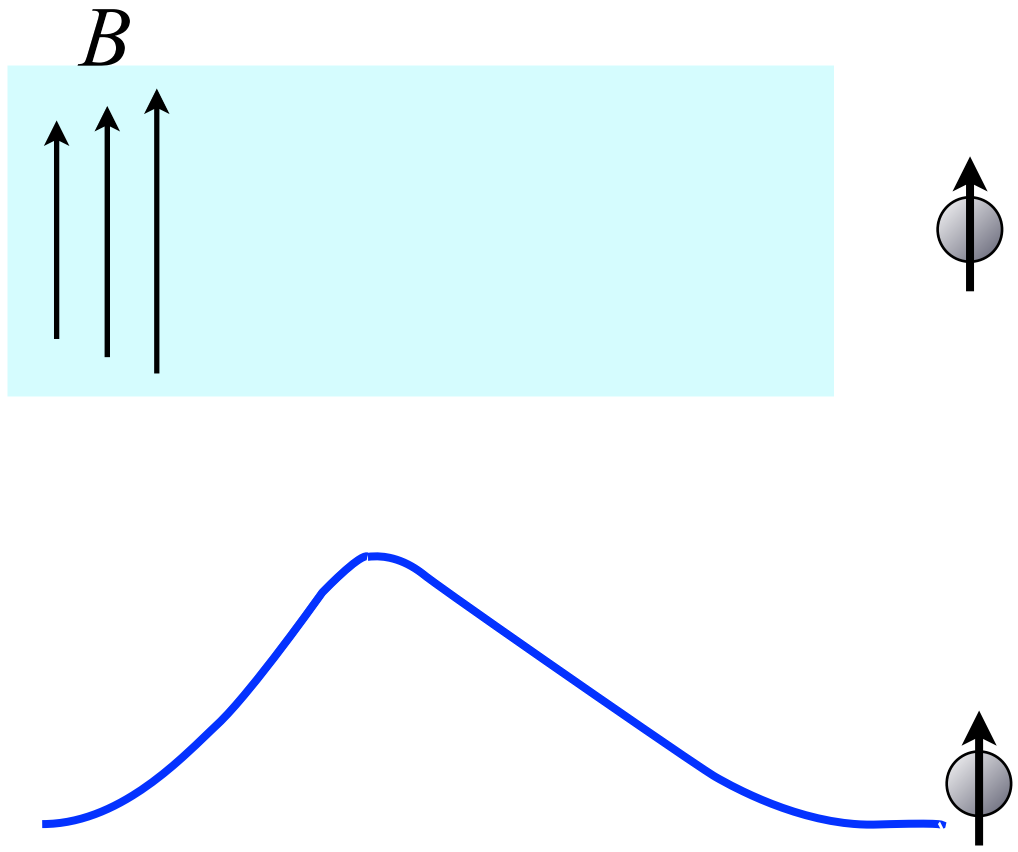

RF magnetic field in gradient field gives/removes the energy with spin flip.

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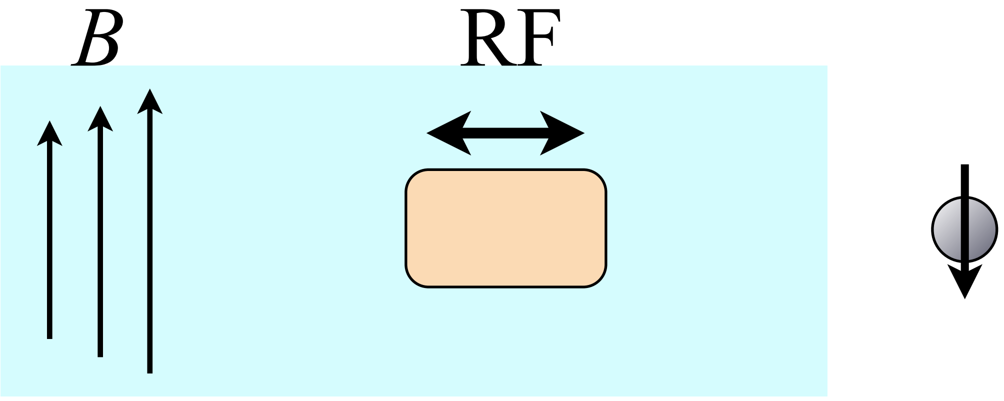
30 MHz = 1T = 120 neV

Adiabatic Fast Passage (AFP) spin flipper is used for control of the neutron energy.



RF magnetic field in gradient field gives/removes the energy with spin flip.

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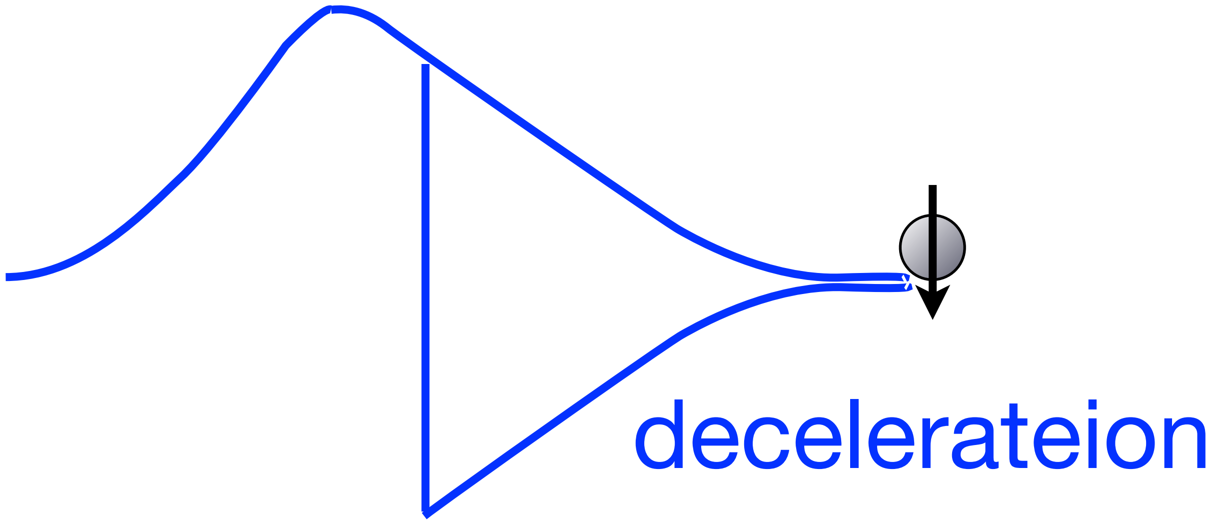
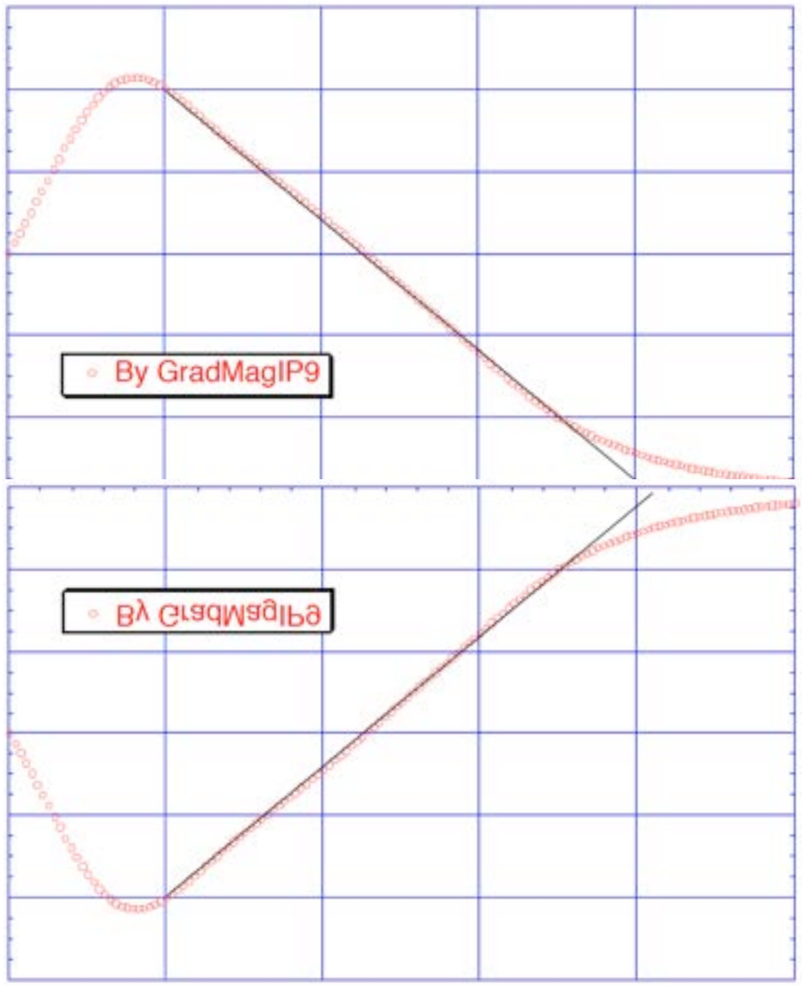


Opposite-spin neutrons are accelerated.

Adiabatic Fast Passage (AFP) spin flipper



RF magnetic field in gradient field gives/removes the energy with spin flip.

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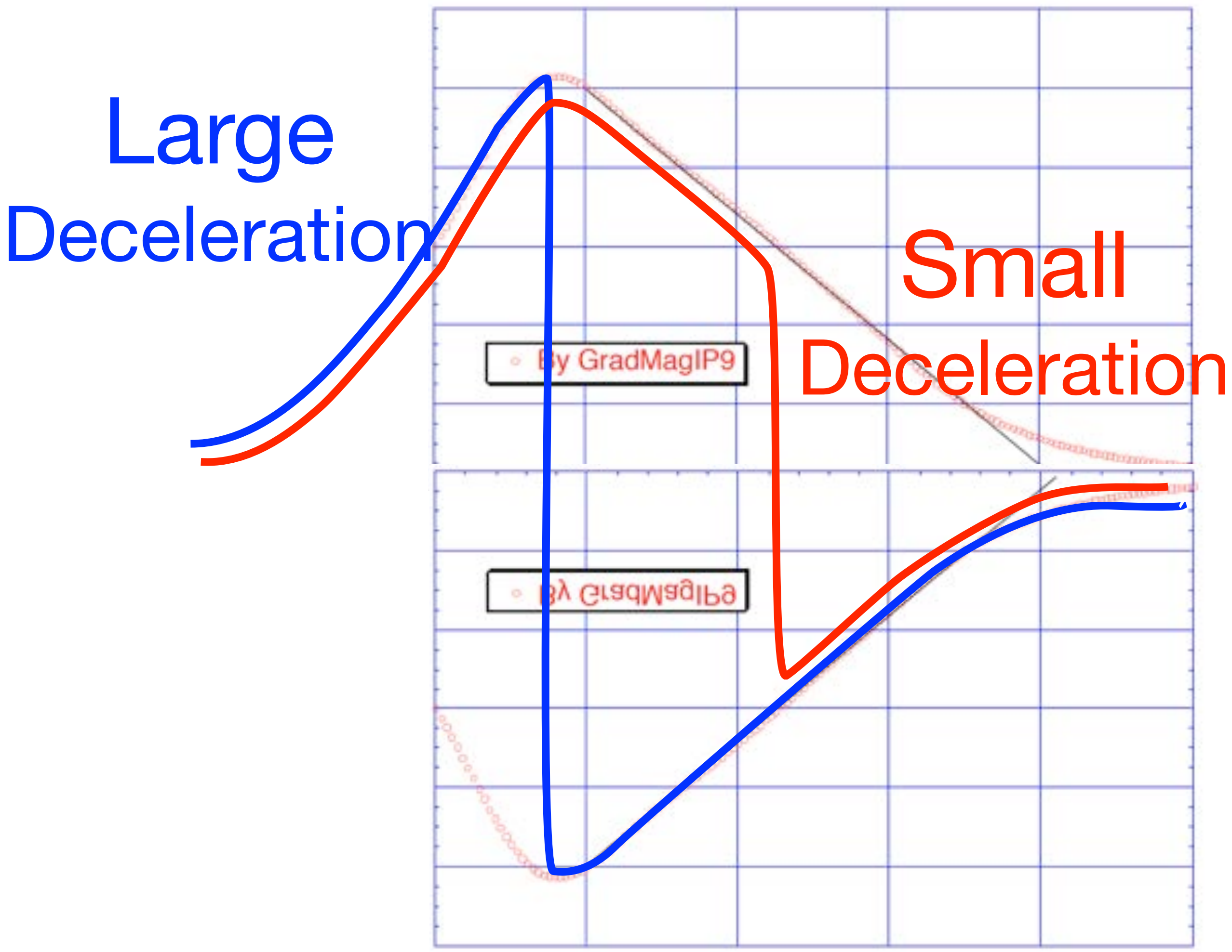


RF magnetic field in gradient field gives/ removes the energy with spin flip.

$$2\mu B = \hbar\omega$$

30 MHz = 1T = 120 neV

Faster neutrons arrive earlier.

Large deceleration = High Freq. RF

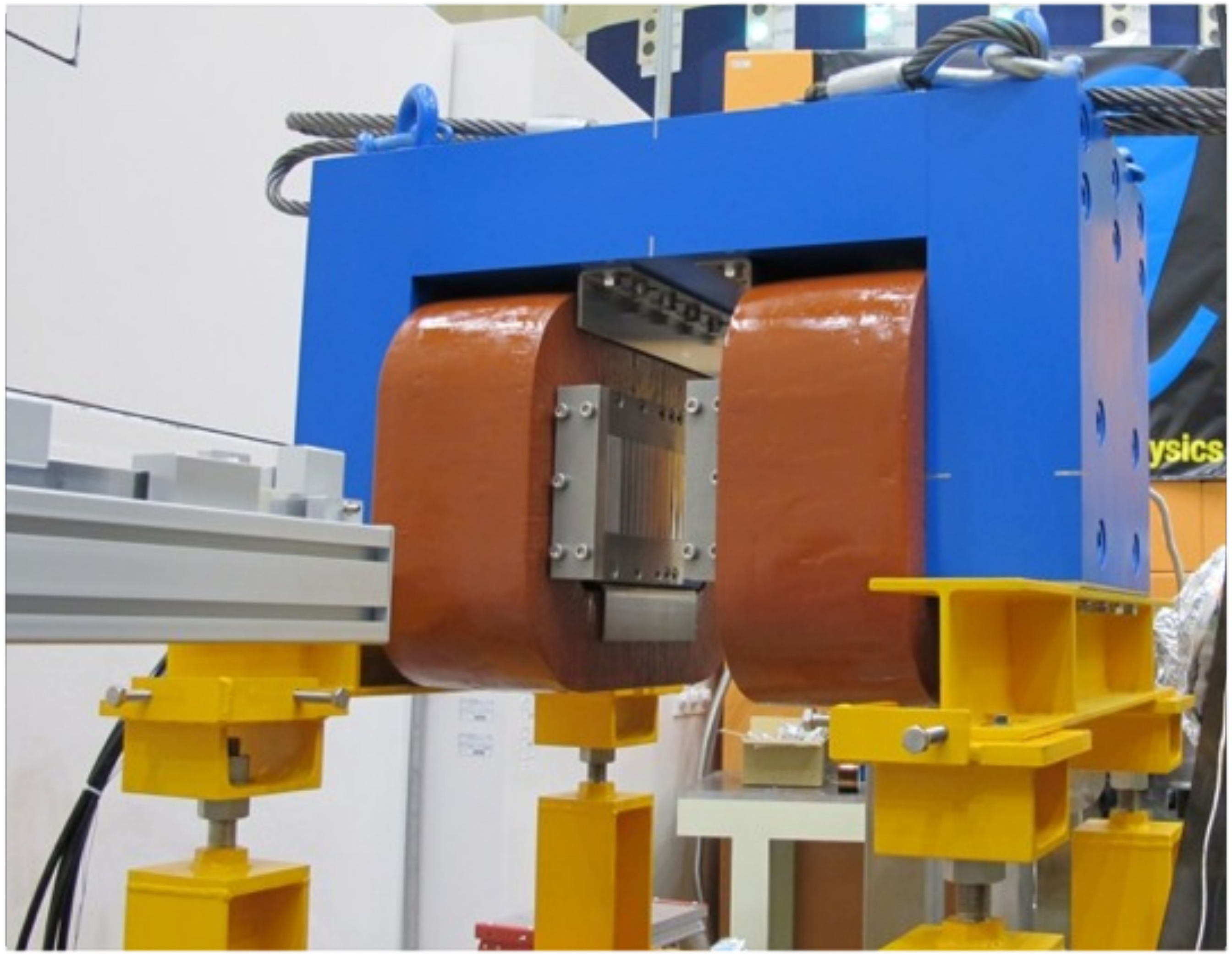
Slower neutrons arrive later.

Small deceleration = Low Freq. RF

Energy exchange is proportional to the RF frequency.

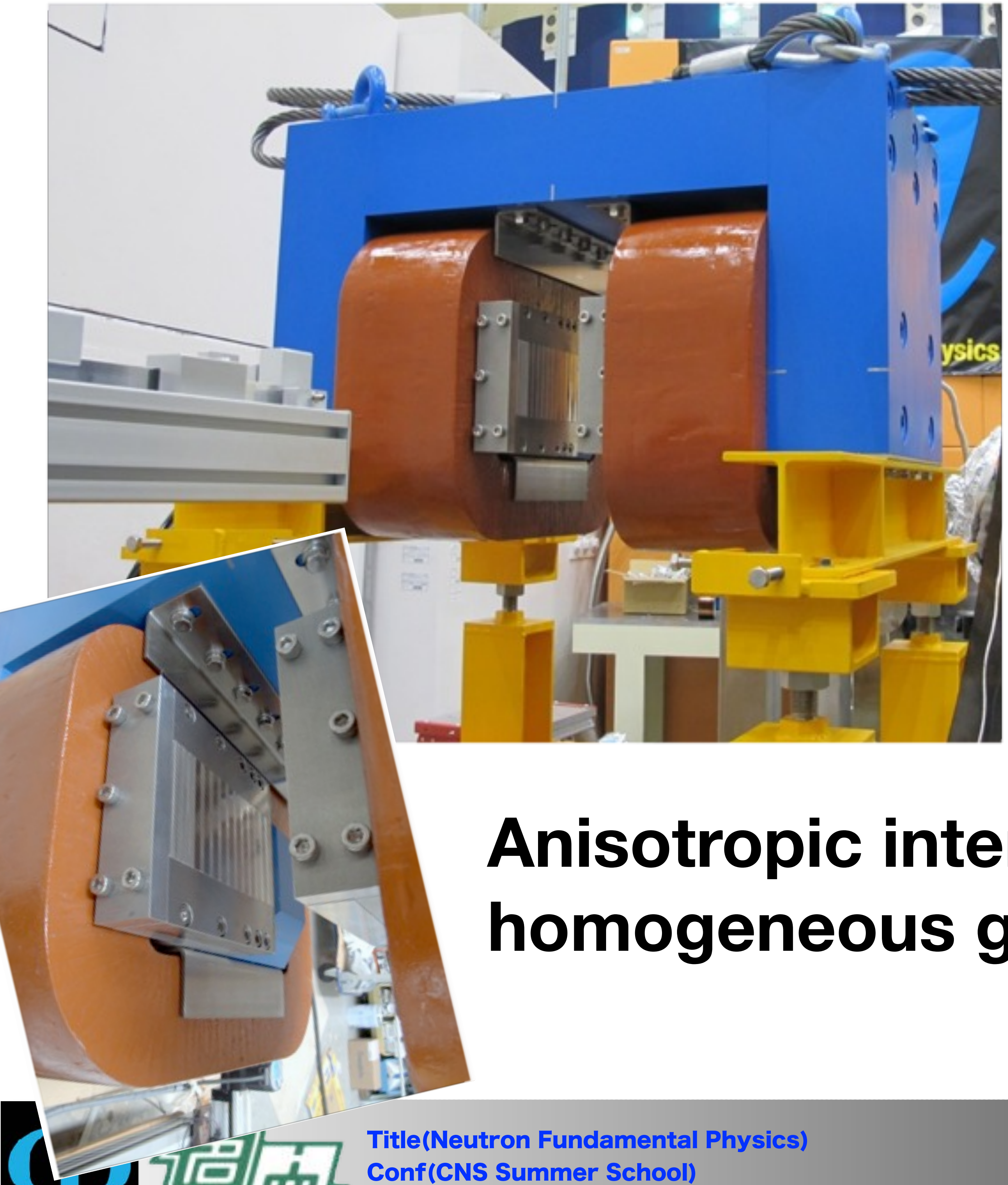
Sweeping frequency matching to the arrival time

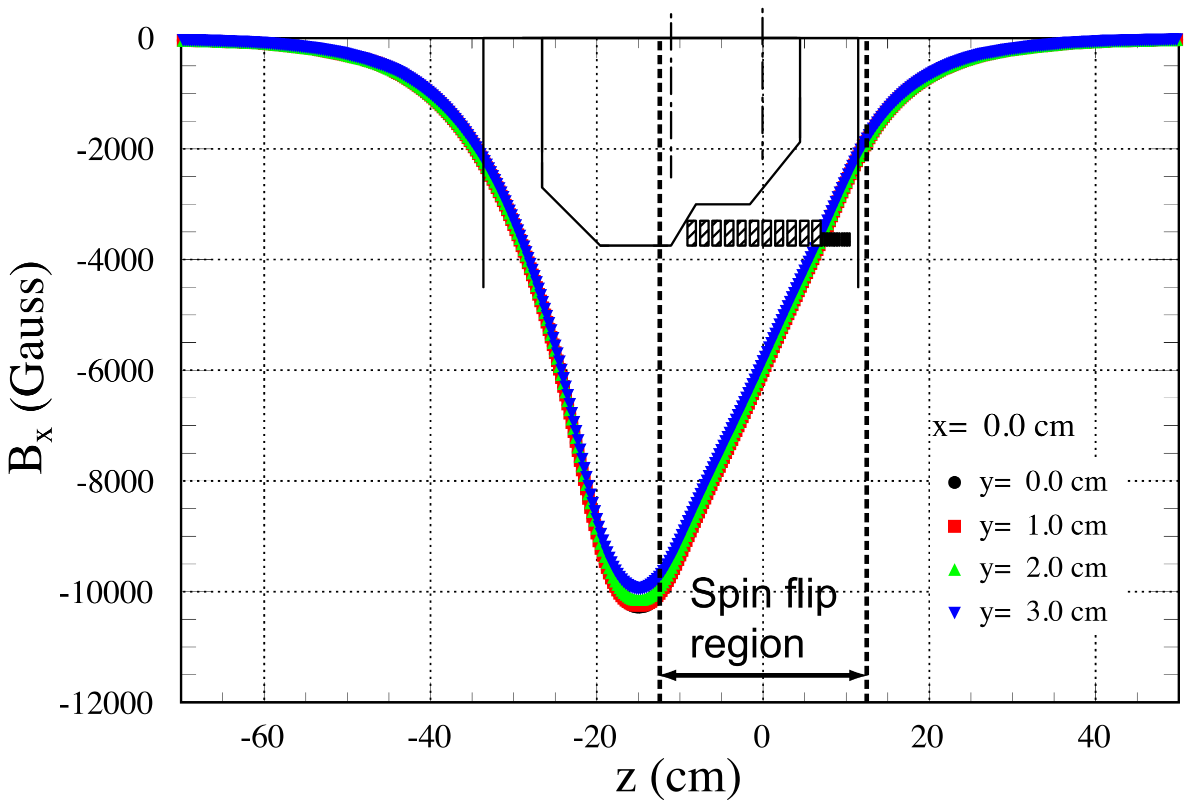
Prototype **Static Magnet**



Y.Arimoto, et. al.,IEEE Trans. Appl. Supercond. 22, 4500704 (2012).

Prototype Static Magnet

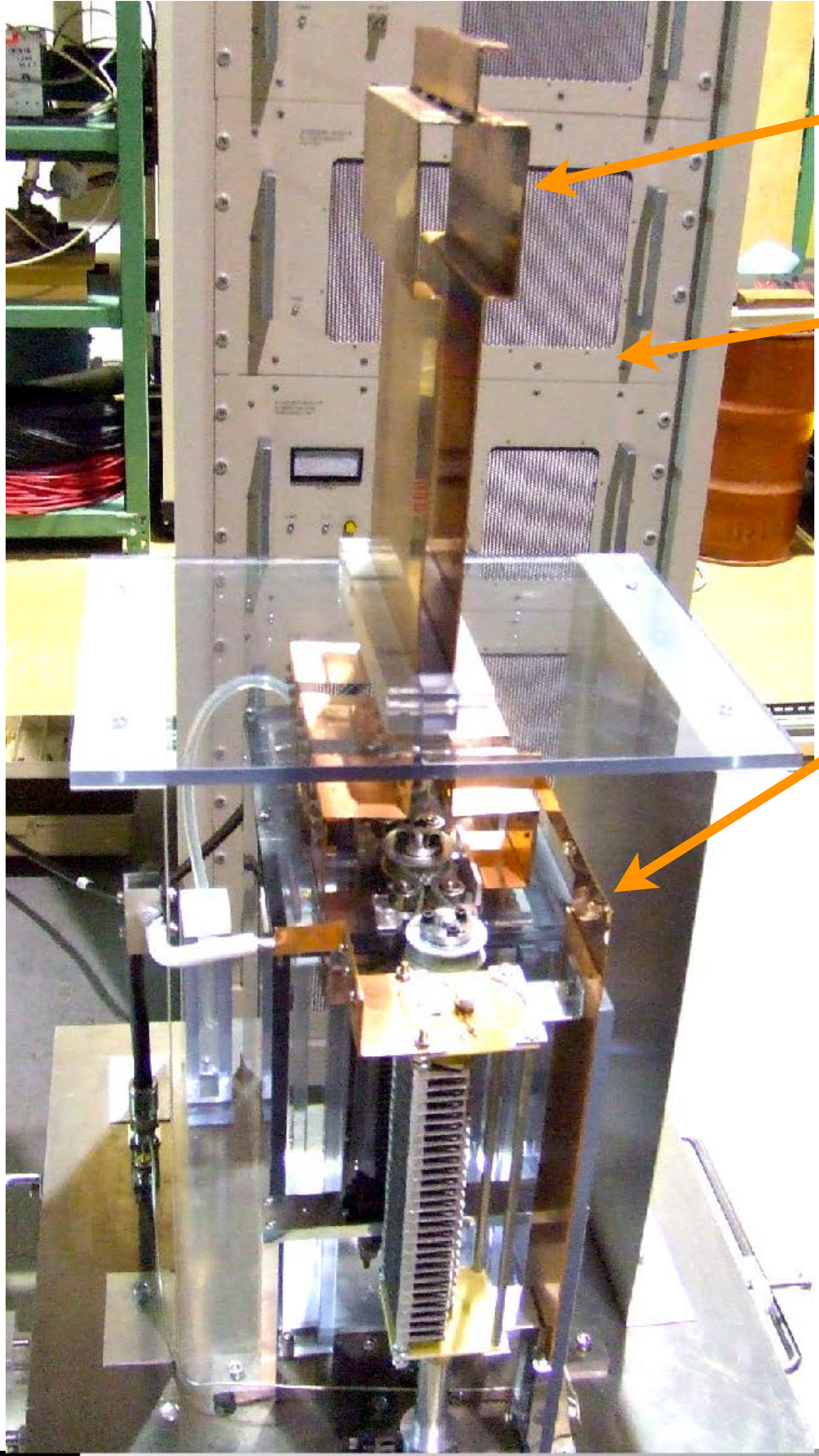




Y.Arimoto, et. al.,IEEE Trans. Appl. Supercond. 22, 4500704 (2012).

Anisotropic inter-poles make homogeneous gradient field.

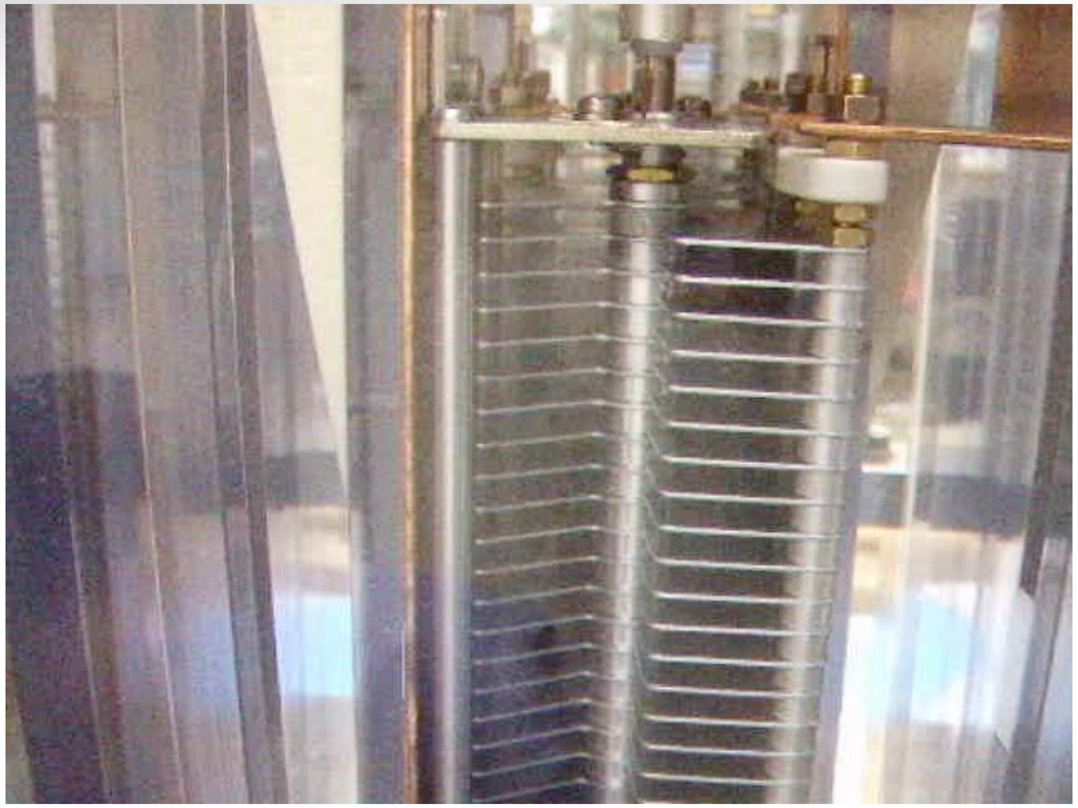
Prototype RF



RF coil (one-turn)

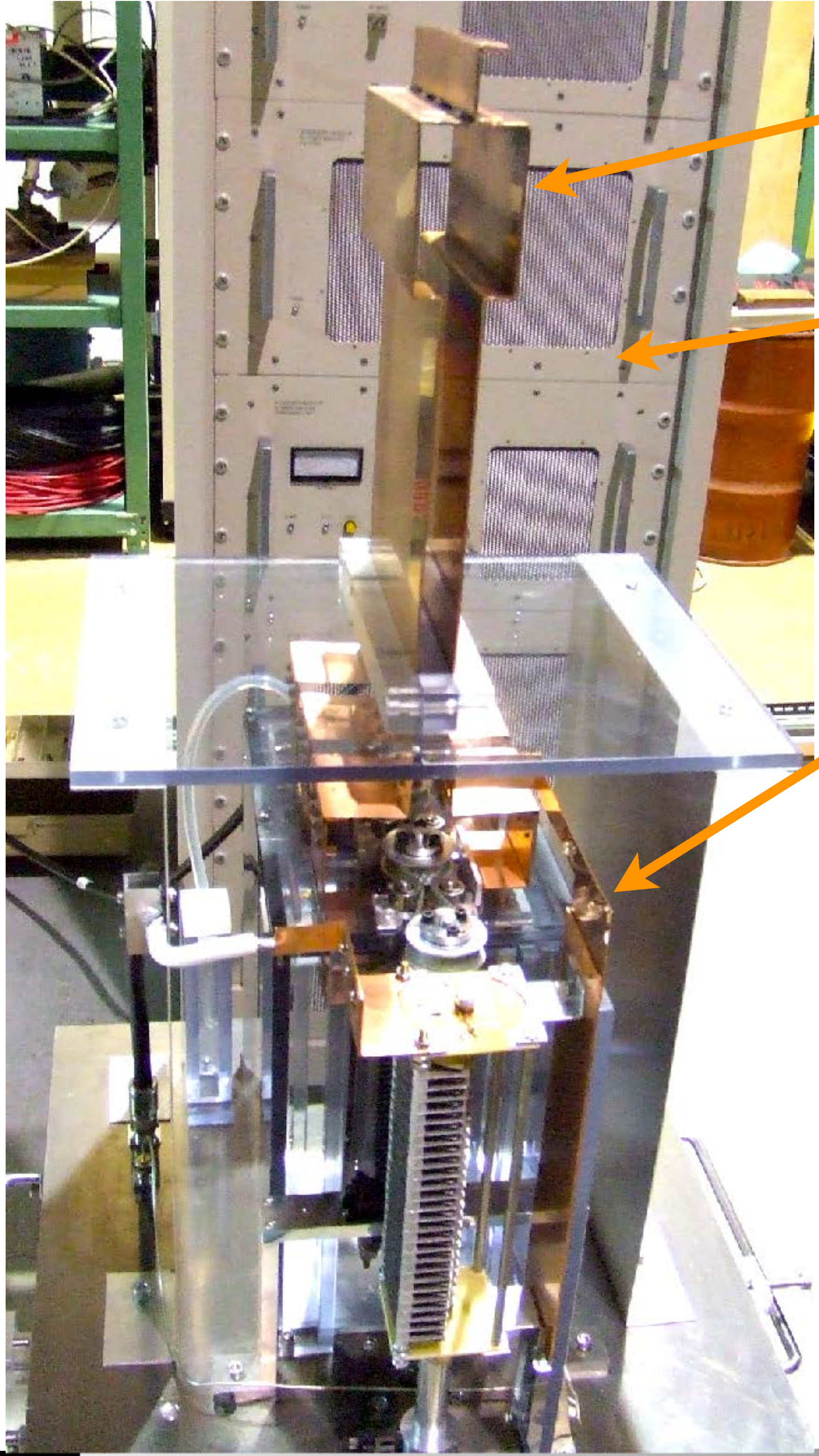
RF Amp 1kW

Resonance circuit (Variable capacitor)



RF matching
15 - 30 MHz

Prototype RF



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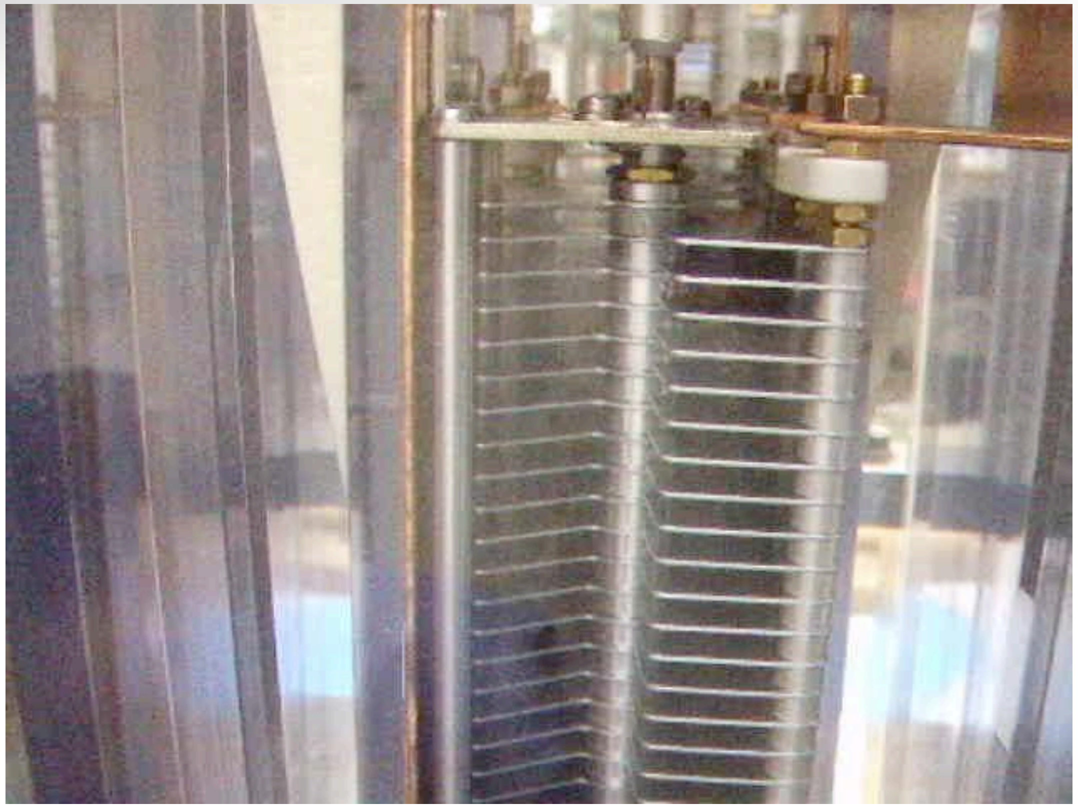
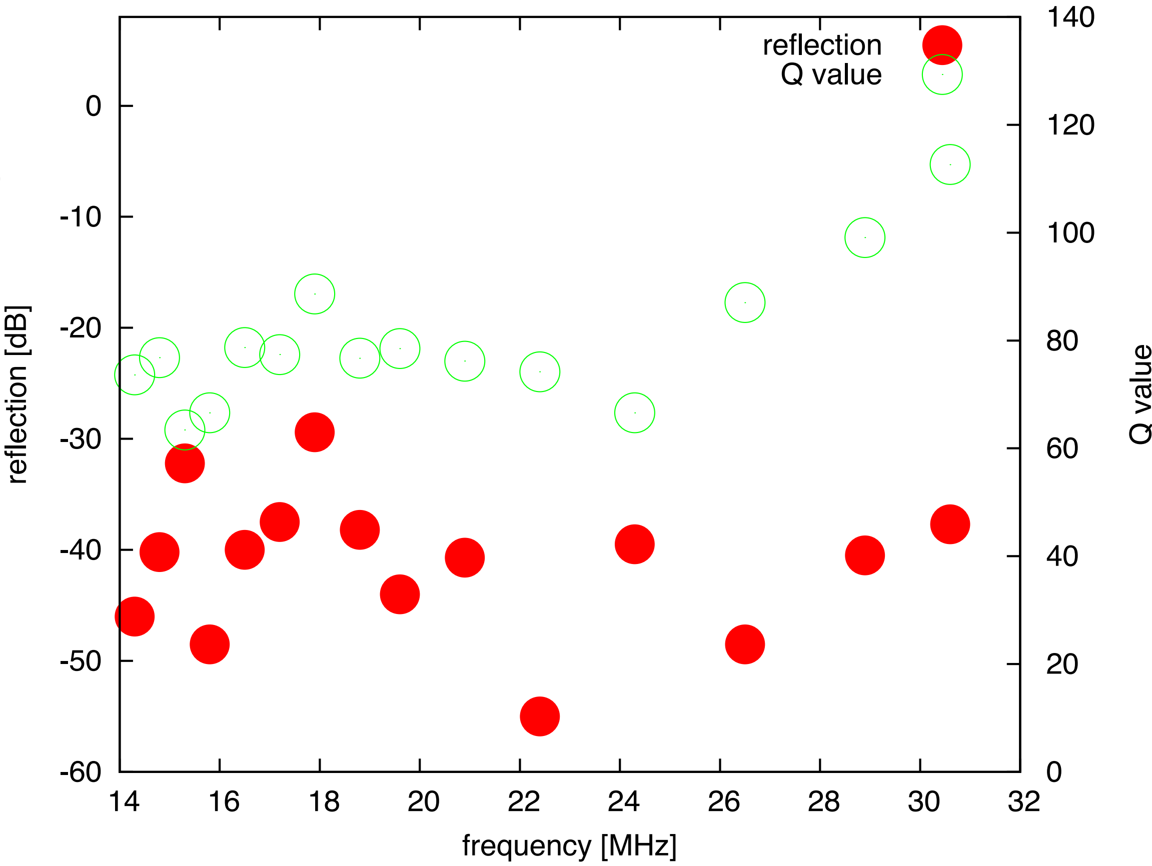
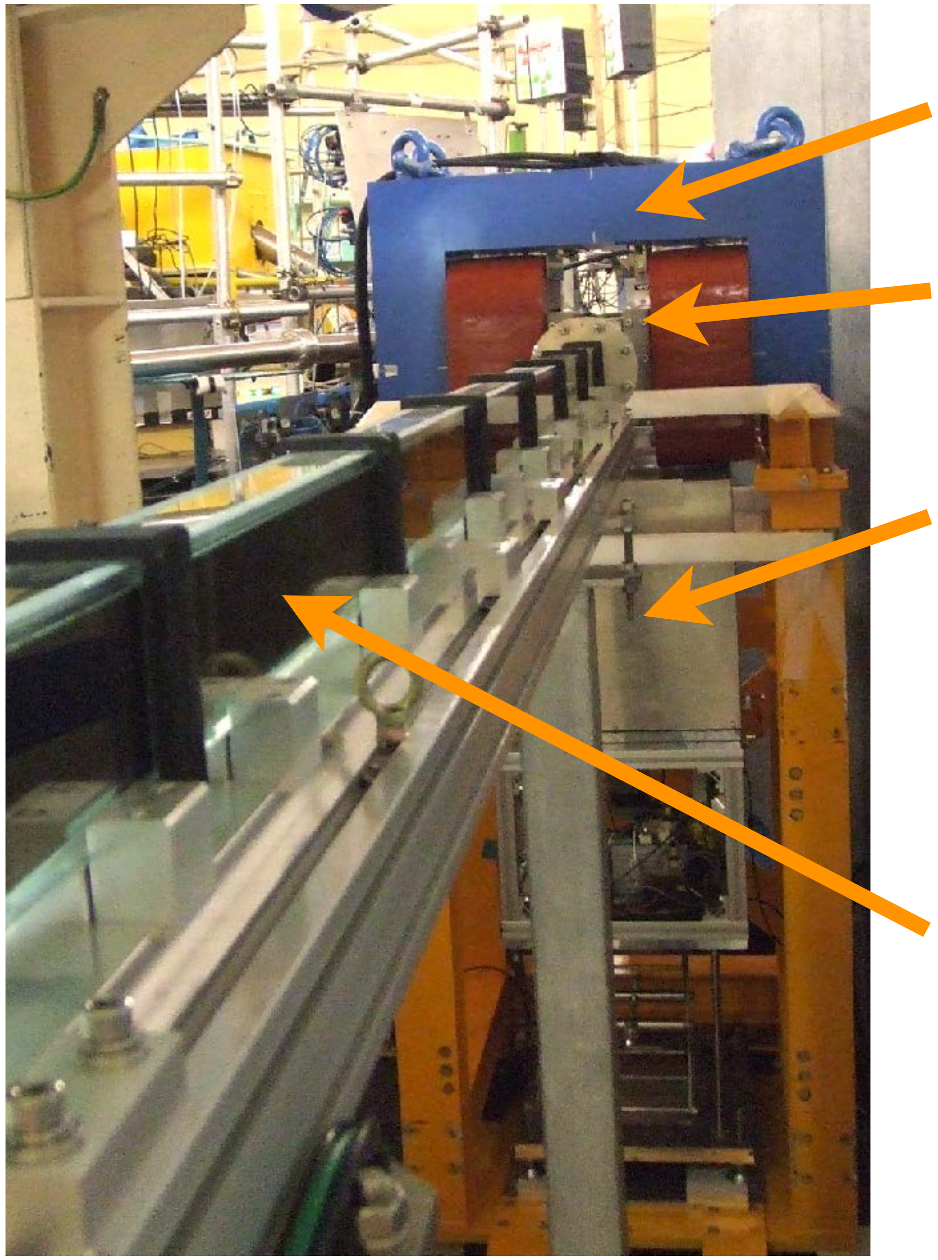




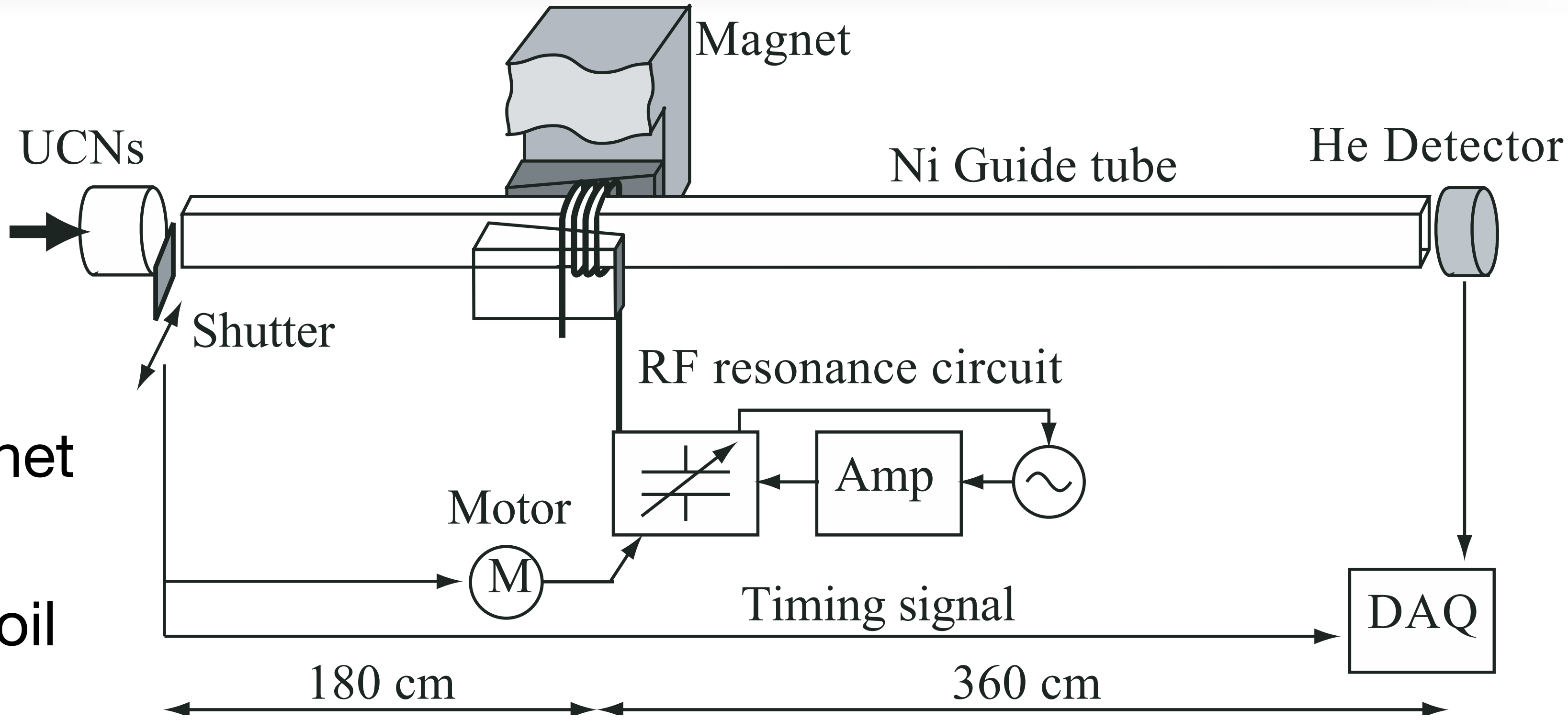
UCN beam line PF2 High Flux Reactor ILL, France


Magnet

RF coil

Resonance circuit

Ni guide tube
(consists of
neutron mirrors)



Continuous UCN beam was chopped by shutter to simulate pulsed source.

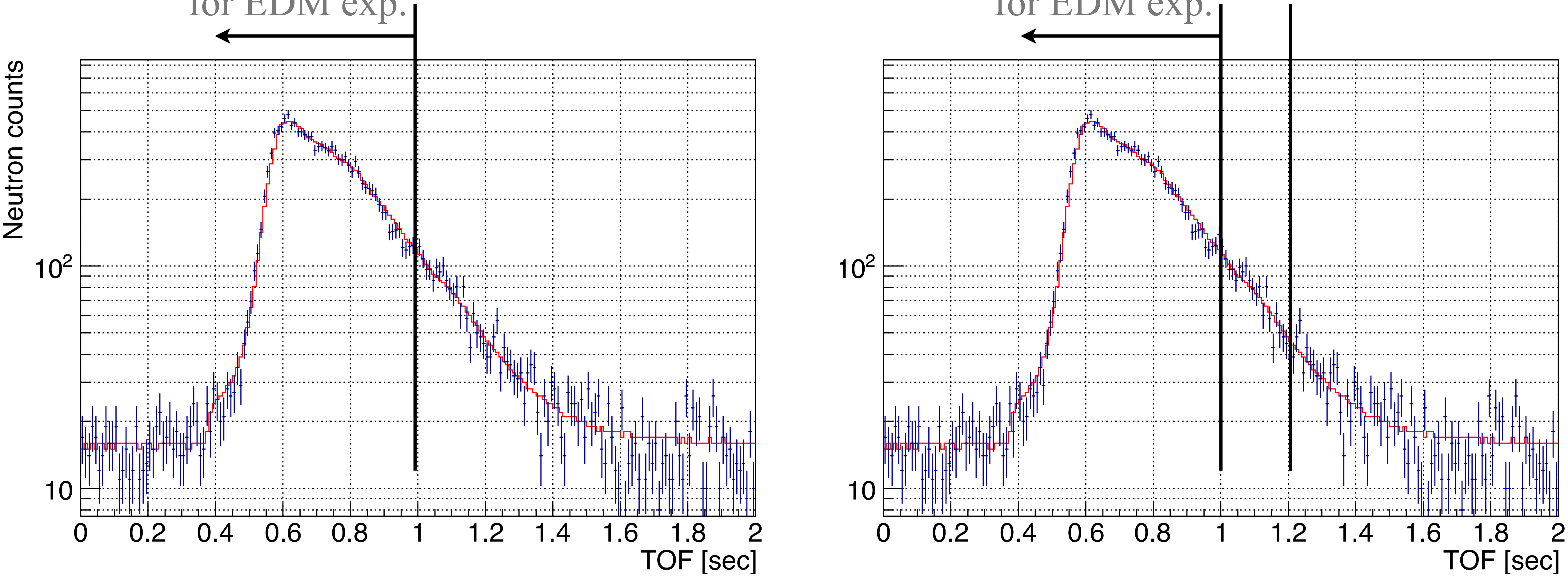
Sweeping RF frequency is synchronized with the shutter.

Results

RF OFF

Too fast
for EDM exp.

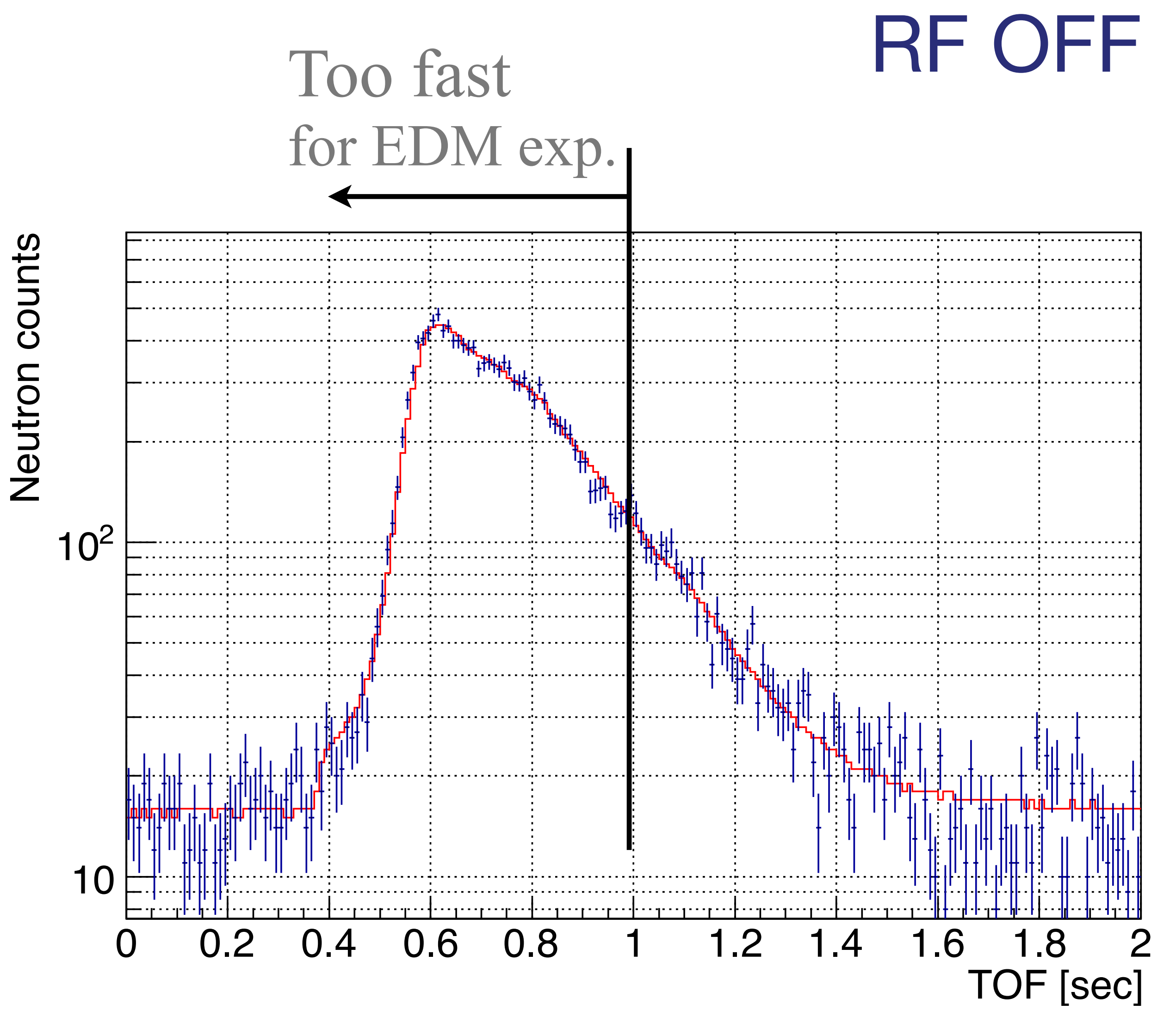
Too fast
for EDM exp.

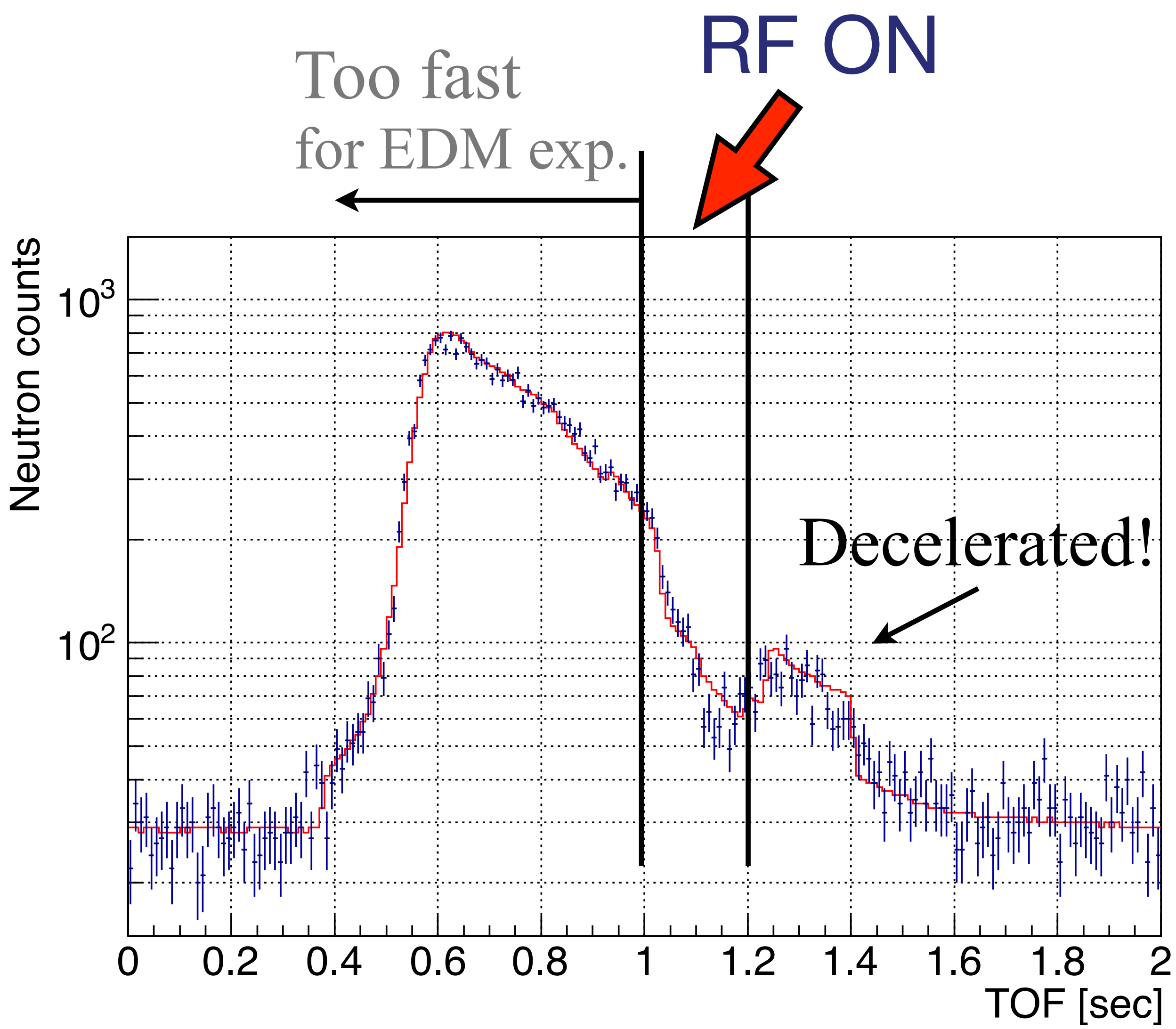


Blue : Exp. Data
Red : Simulation

Y. Arimoto, et., al.,
Phys. Rev. A 86, 023843 (2012).

Results





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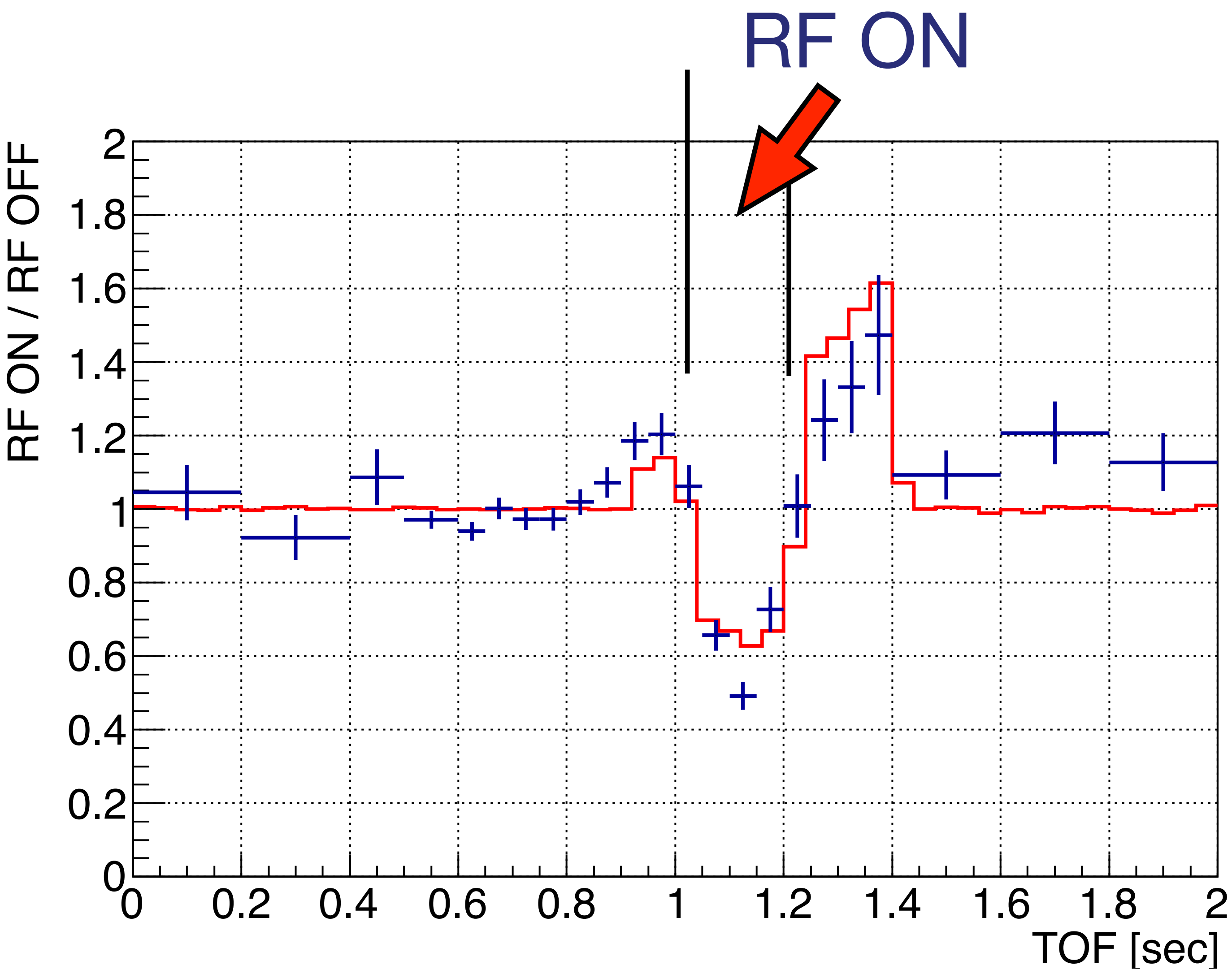

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Rebunching of UCNs
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Y. Arimoto, et., al.,
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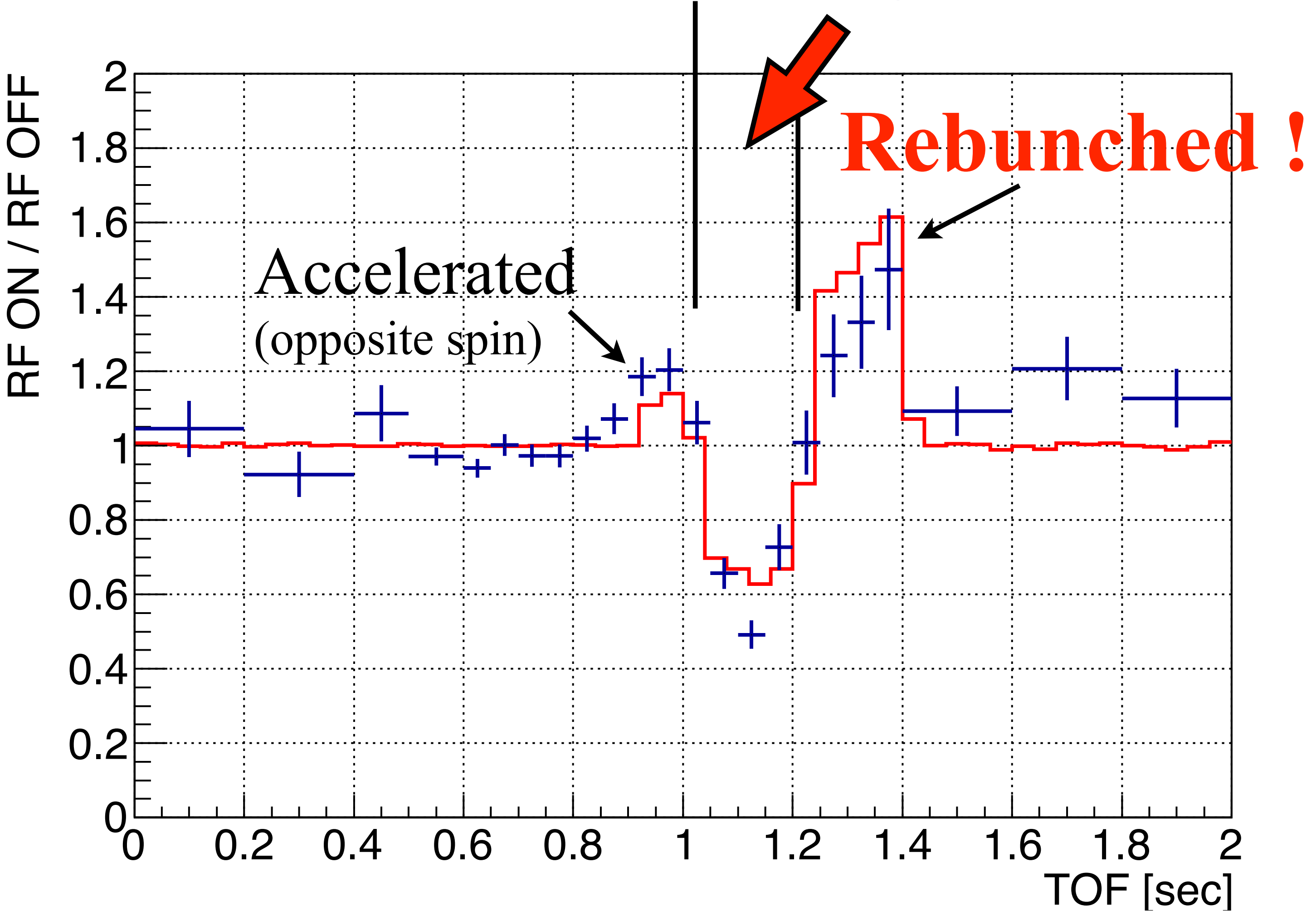
Results



RF ON

Rebunched !

Accelerated
(opposite spin)

Blue : Exp. Data
Red : Simulation

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Y. Arimoto, et., al.,
Phys. Rev. A 86, 023843 (2012).

Neutron Accelerator/Decelerator

velocity concentrator

M.Kitaguchi, Prog. Theor. Exp. Phys. (2017) 043D01

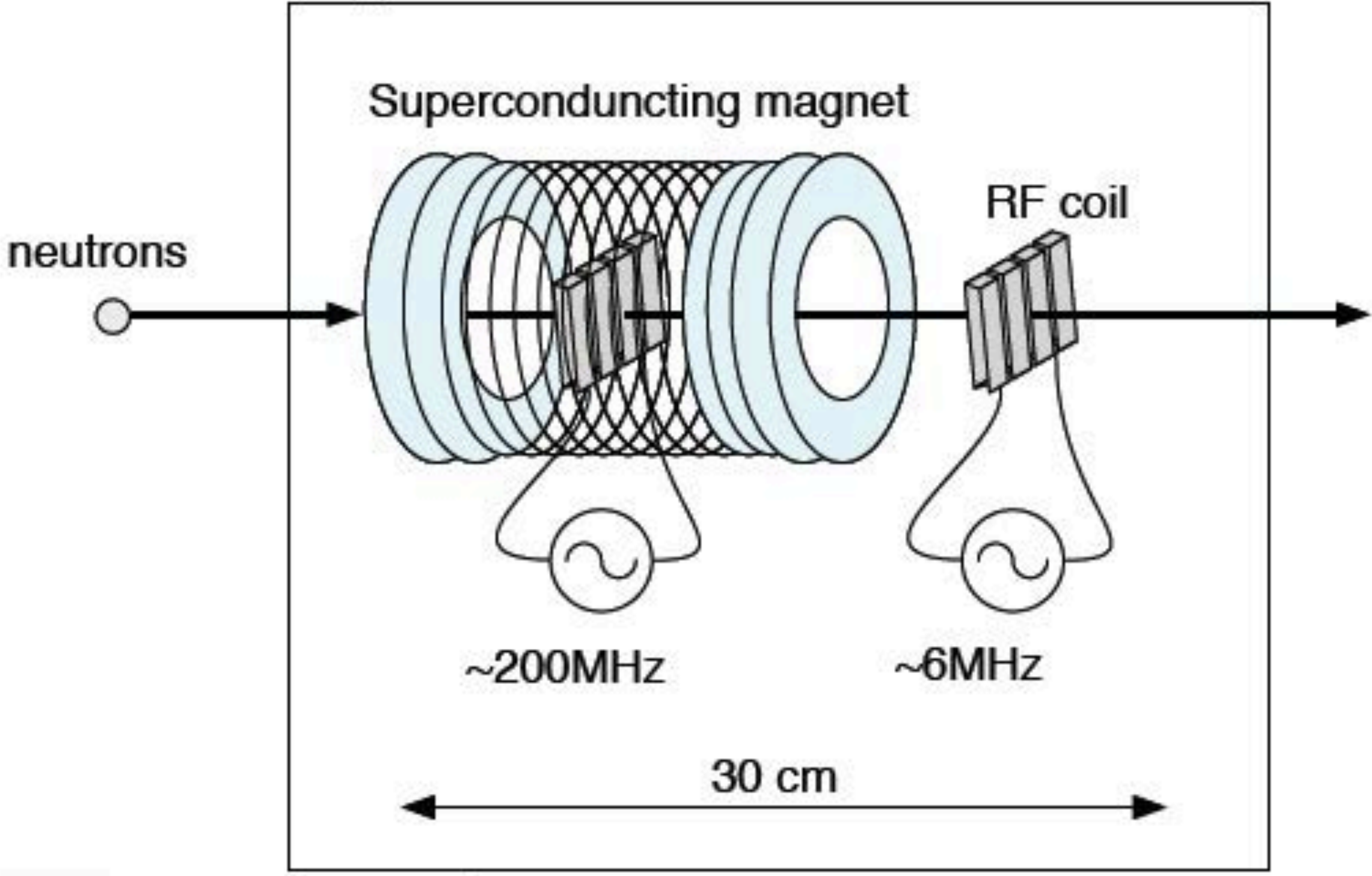
Deceleration and acceleration by spin flip

RF spin flipper

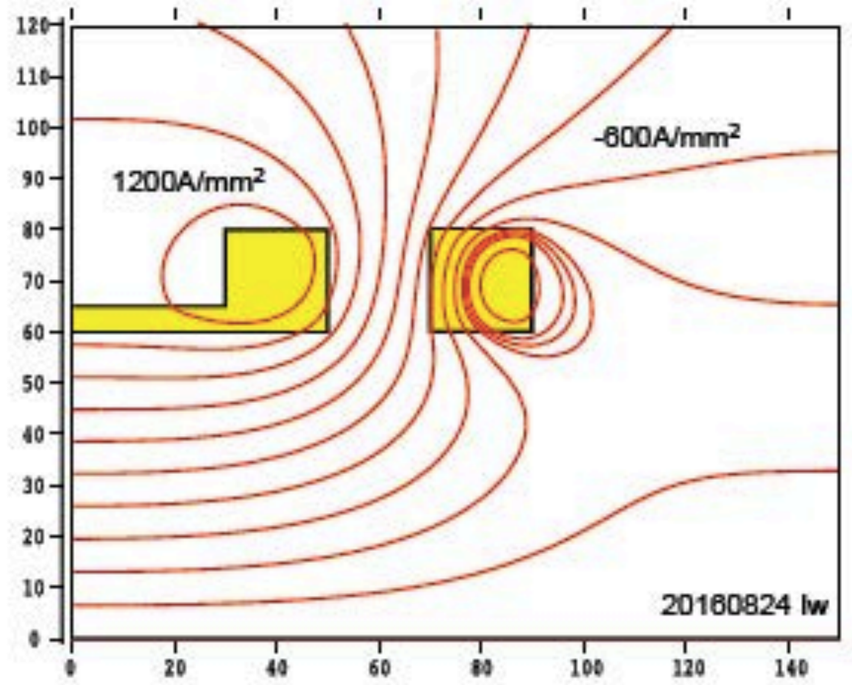
RF spin flipper (RSF) can decelerate and / or accelerate the neutrons.

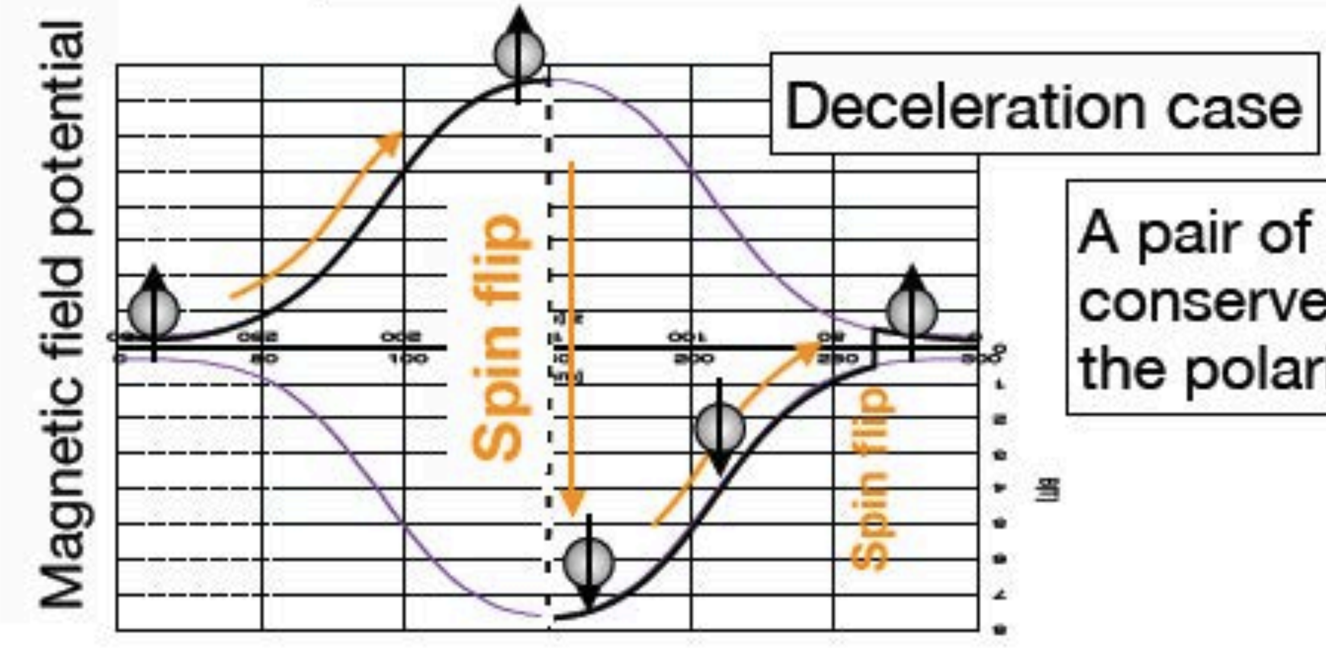
RSF in 7.5 T magnetic field changes the energy of 0.9 μeV.

Flipper unit



Calculation of magnetic field





A pair of flips conserves the polarity.

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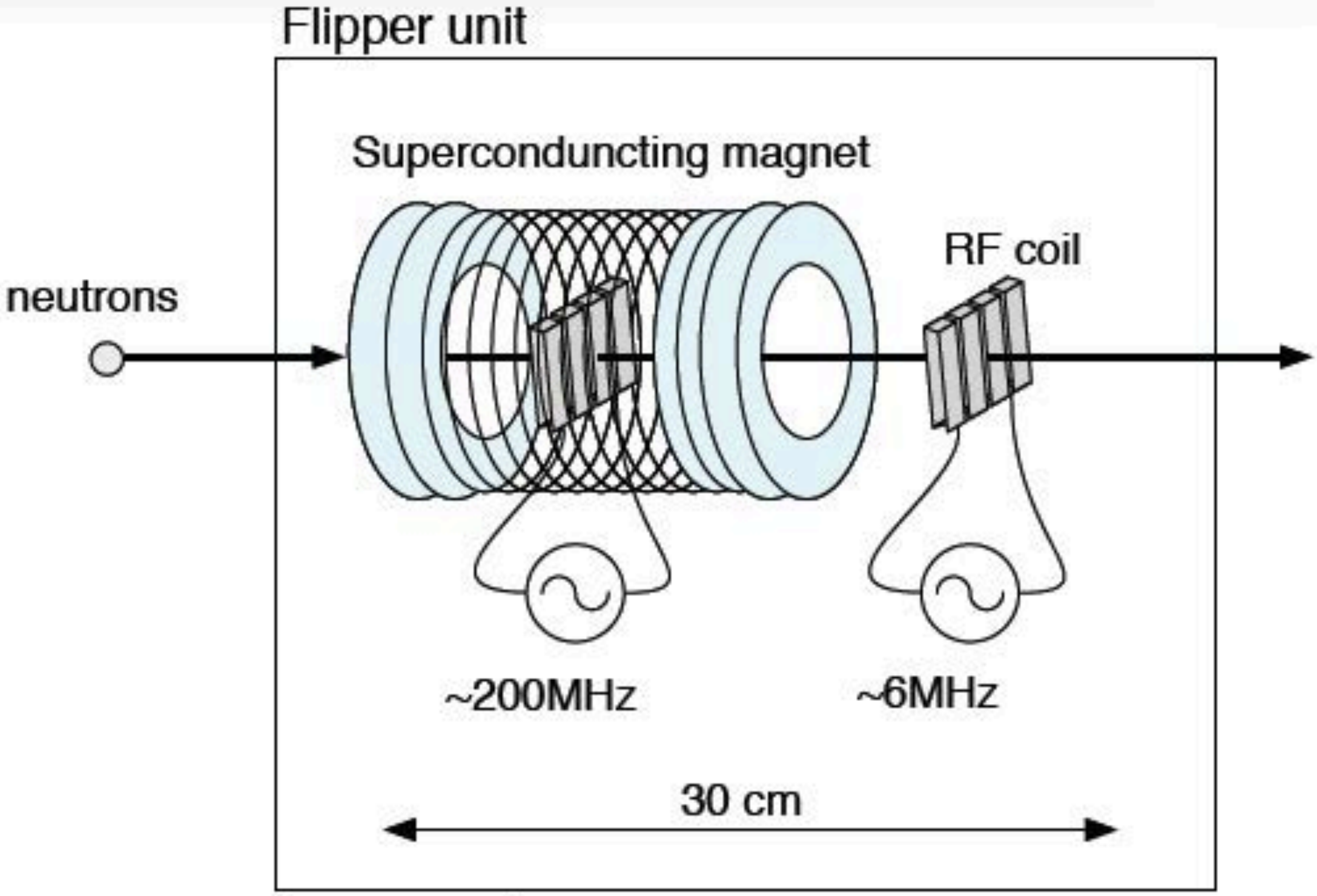

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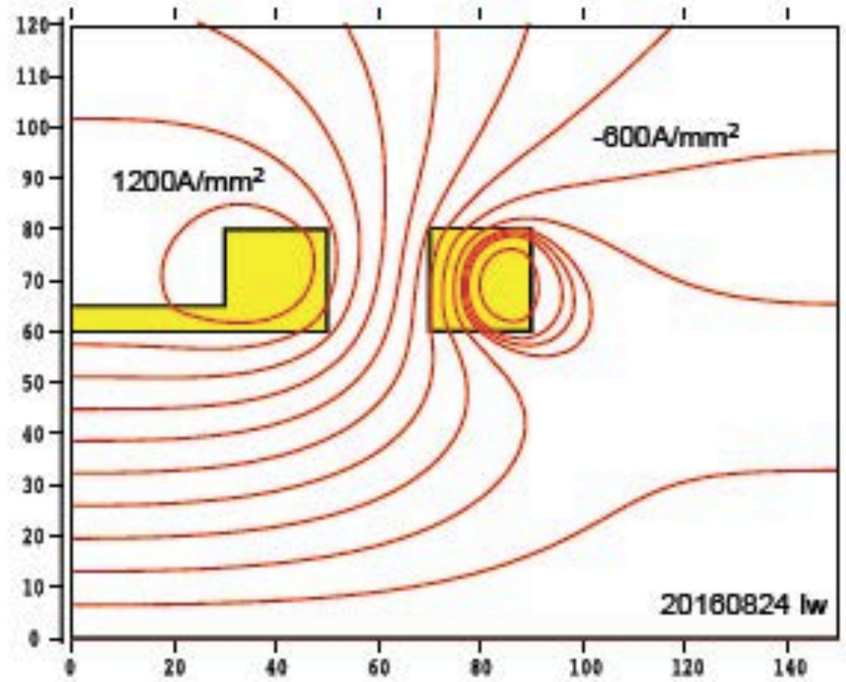

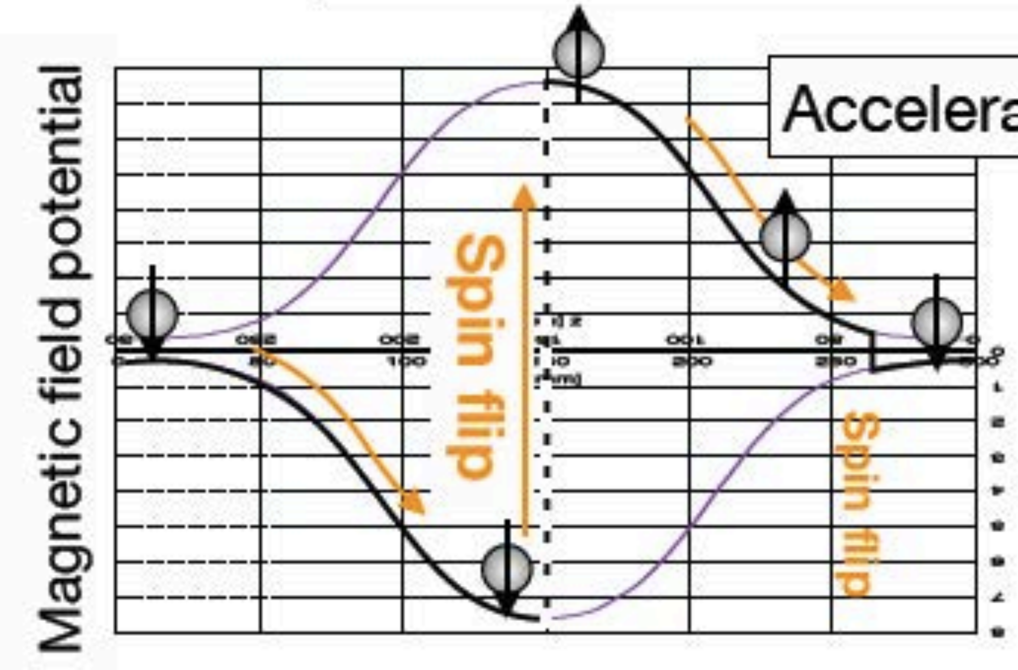

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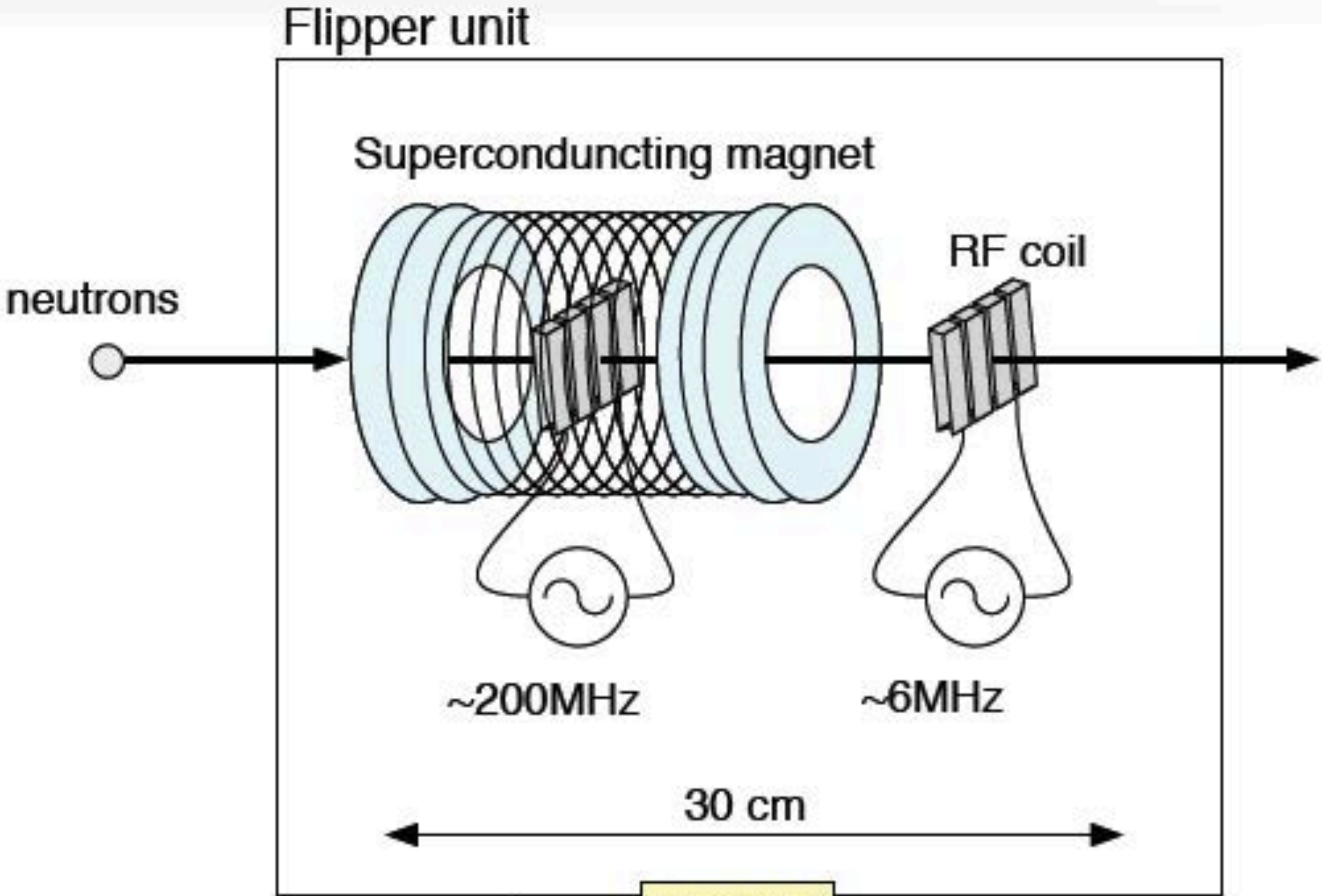

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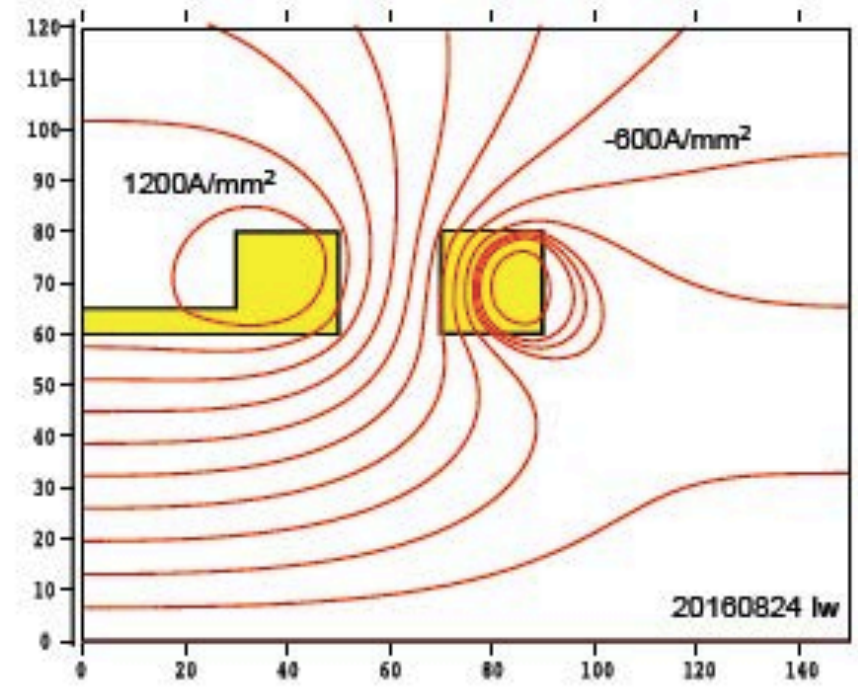
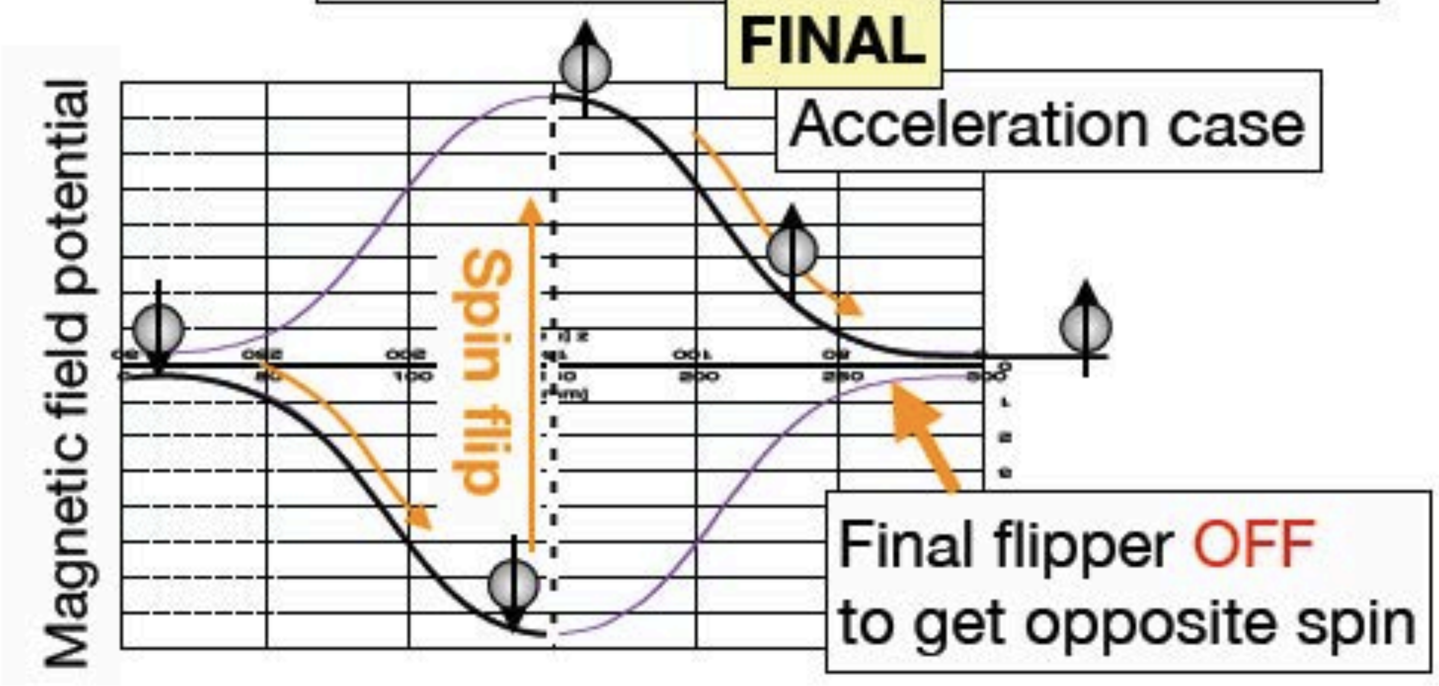




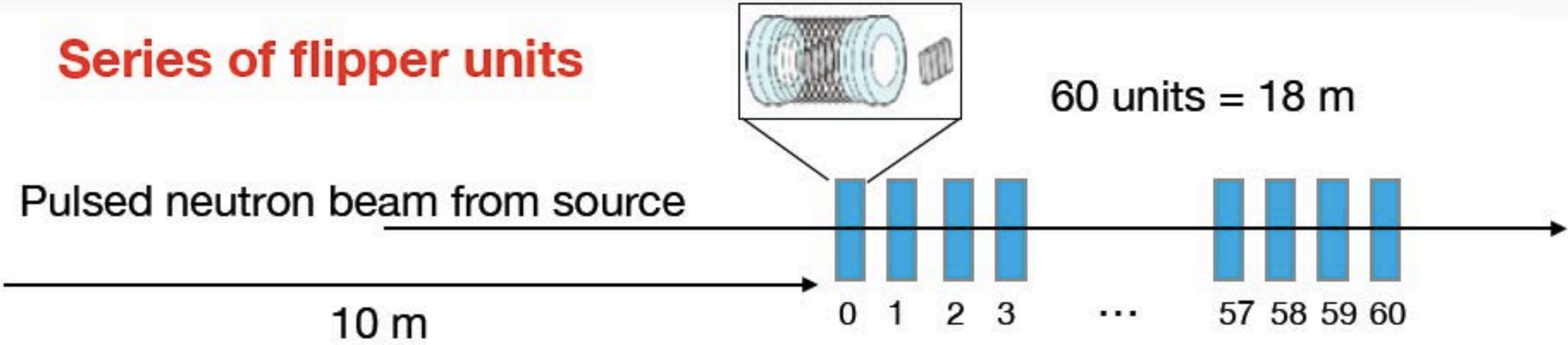
FINAL

Acceleration case

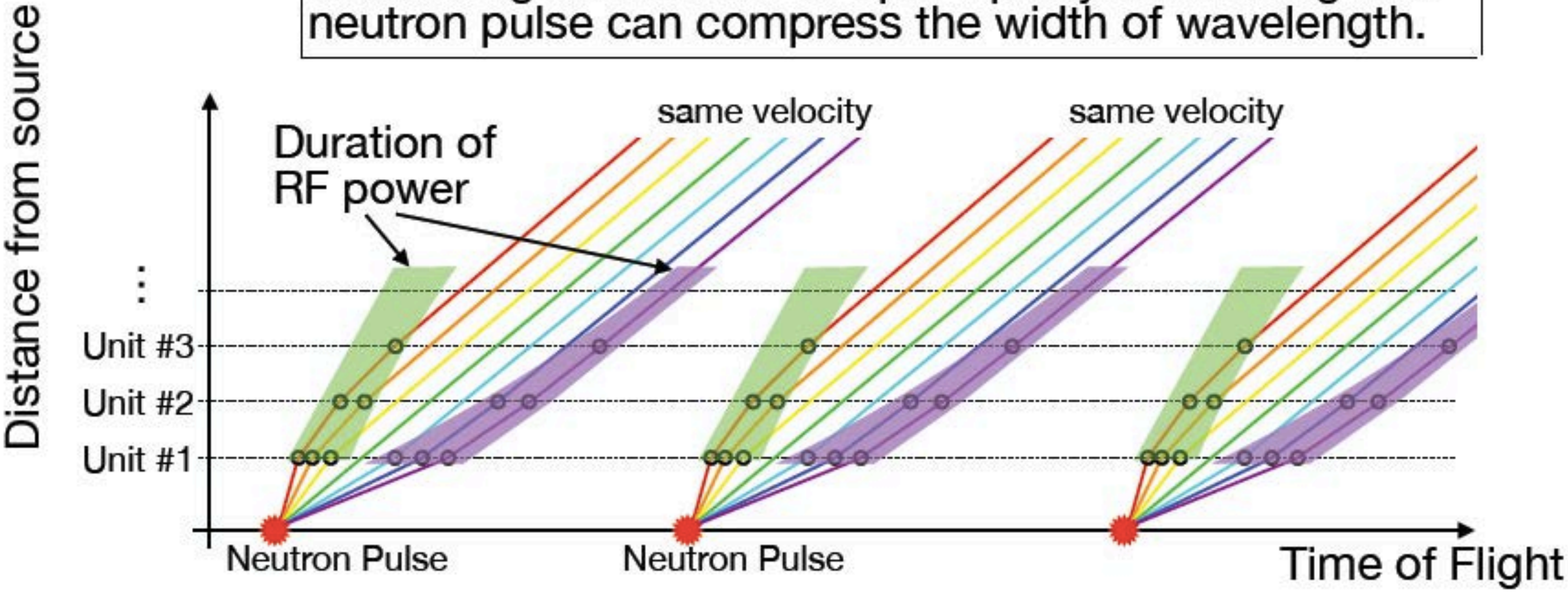
Final flipper OFF to get opposite spin

Neutron Velocity Concentrator

Series of flipper units



Controlling the number of spin flips synchronizing with neutron pulse can compress the width of wavelength.

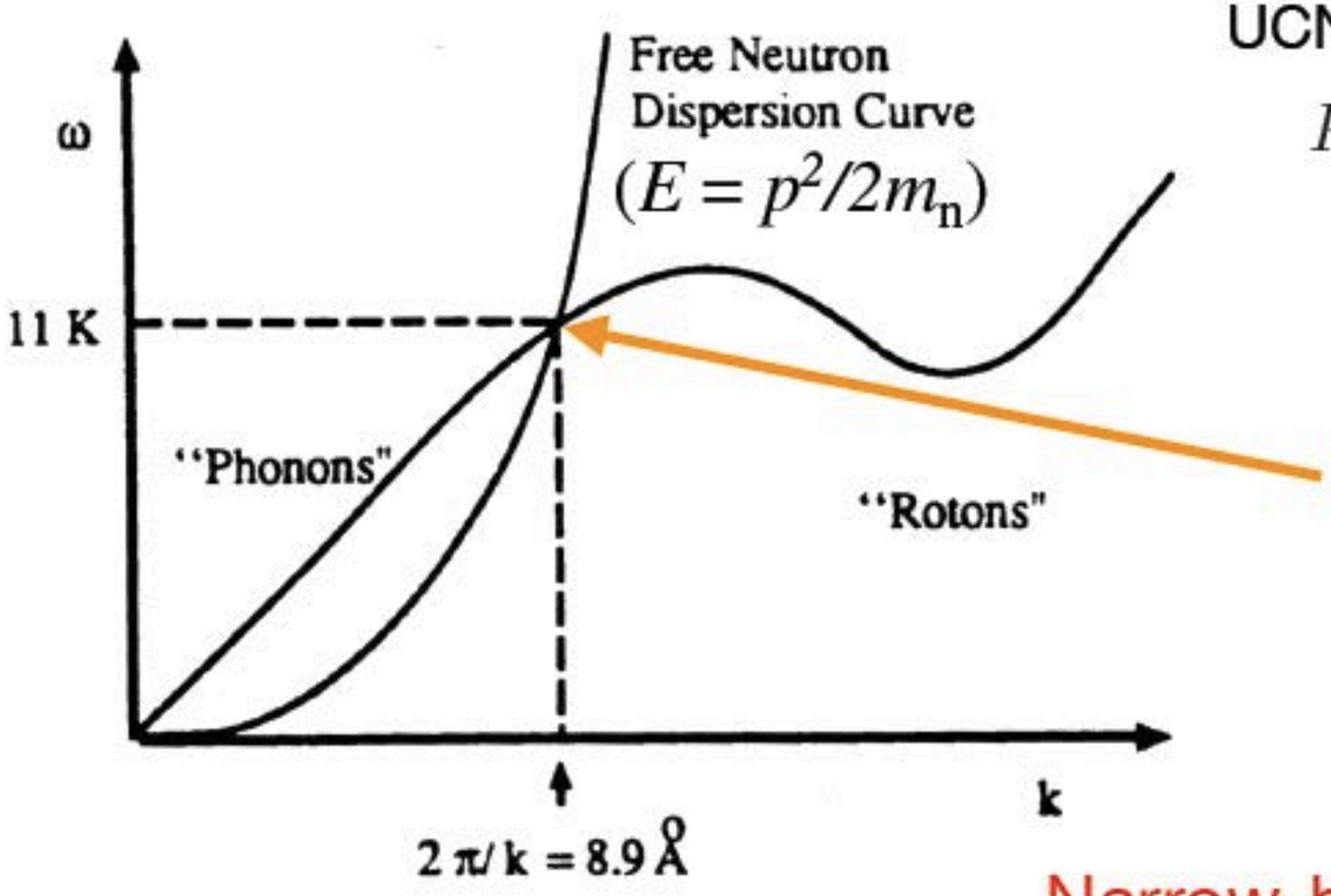


UCN production by superfluid He converter

Superthermal source

Neutron with 1 meV transfers all energy and momentum to phonon and down-scatters to UCNs in superfluid He.

Dispersion curve



UCN production

$$P_{\mathrm{UCN}}(V_c) = N\,\sigma V_c \frac{k_c}{3\pi}\int_0^\infty \frac{d\phi}{d\lambda}\, s(\lambda)\,\lambda\, d\lambda$$

$$s(\lambda) = \hbar \int S(q,\hbar\omega)\delta(\hbar\omega - \hbar^2k^2/2m_n)d\omega$$

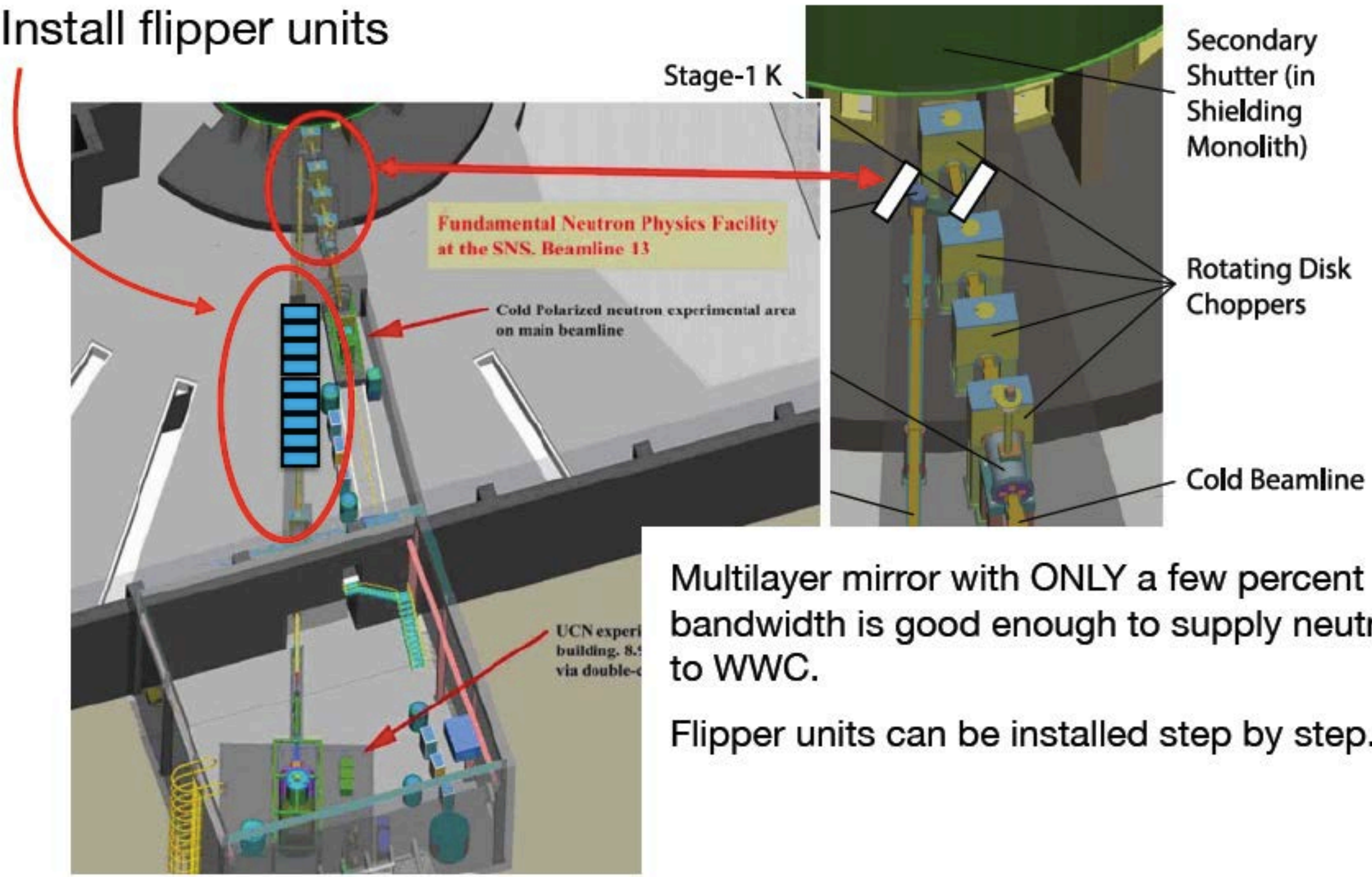
Single phonon excitation

$$s_I(\lambda) = \underline{S^*\delta(\lambda^* - \lambda)}$$

where $\lambda^* = 2\pi/q^*$

Narrow-bandwidth neutrons are required.

Possible setup for SNS-UCN beamline

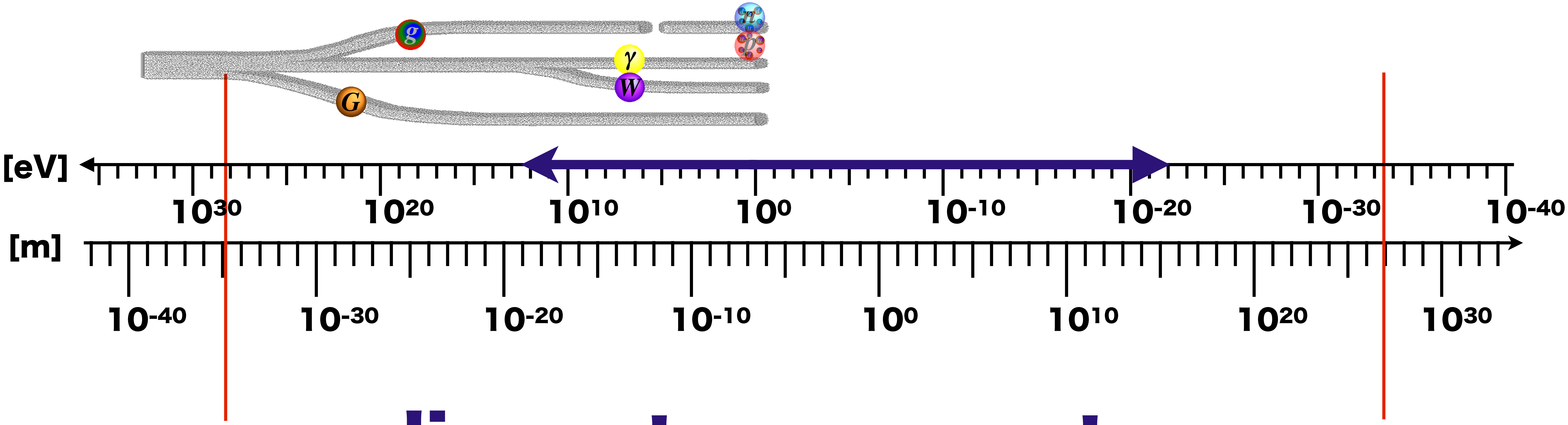


N. Fomin et al. / Nuclear Instruments and Methods in Physics Research A 773 (2015) 45–51

Multilayer mirror with ONLY a few percent bandwidth is good enough to supply neutrons to WWC.

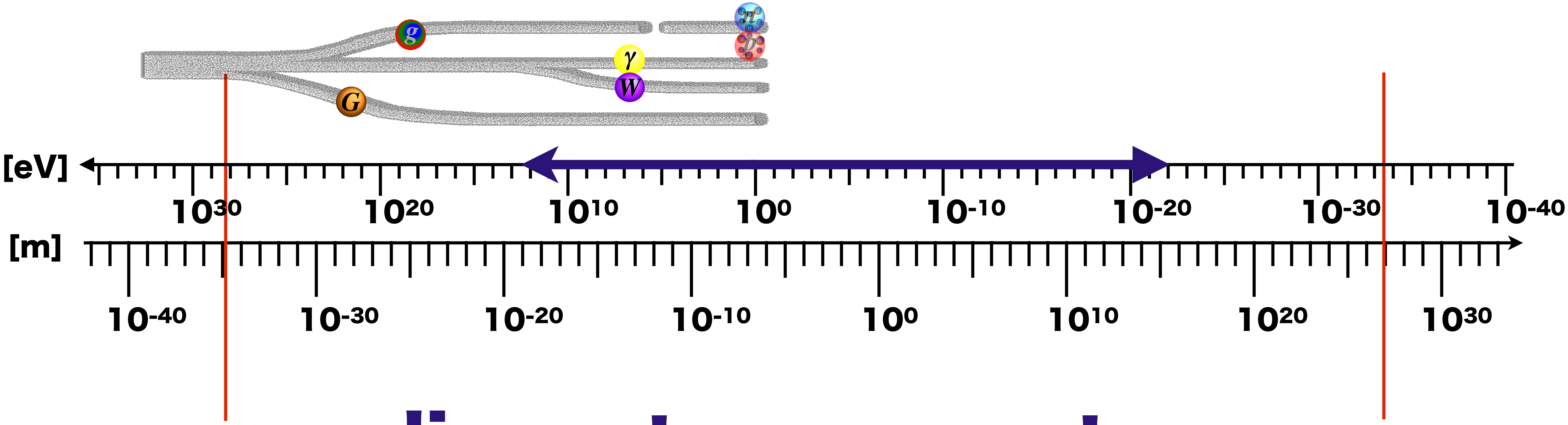
Flipper units can be installed step by step.

Physics



discrete symmetry

C	Charge Conjugation
P	Spatial Inversion
T	Time Reversal



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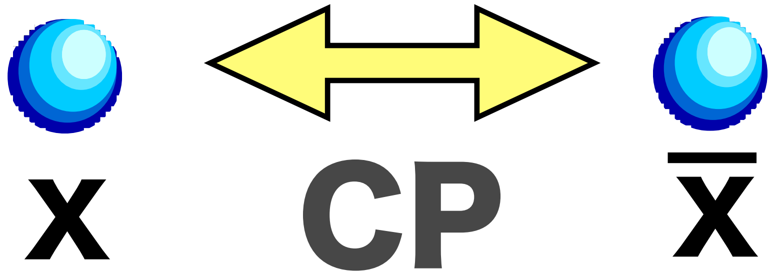
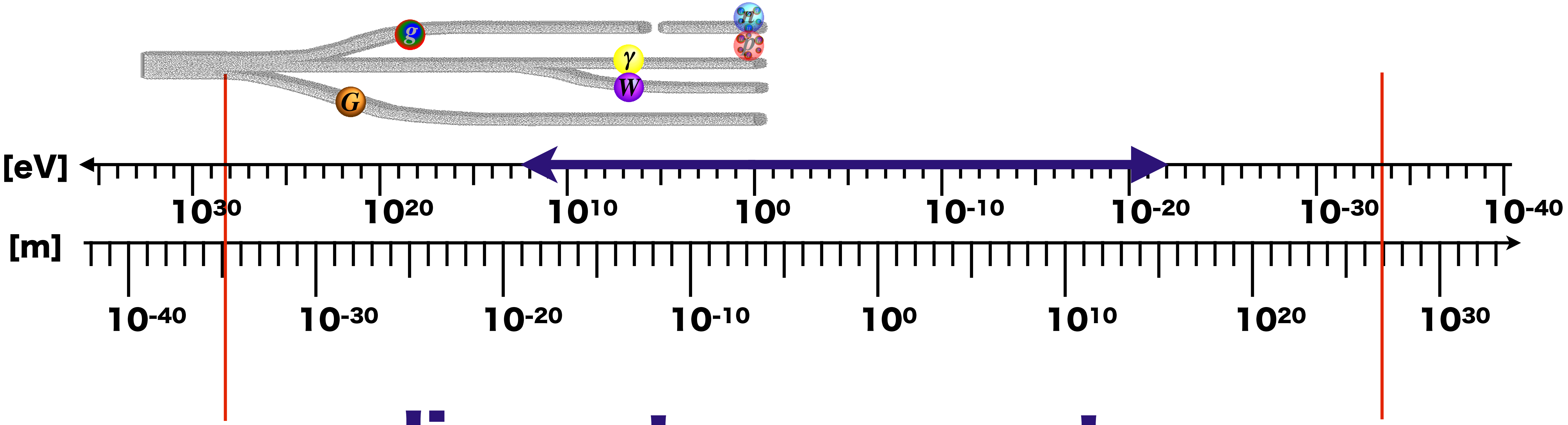


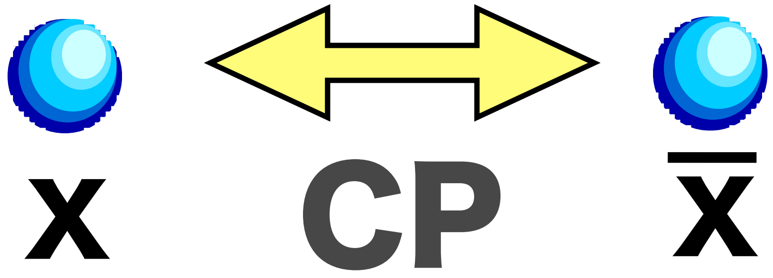


discrete symmetry

C Charge Conjugation

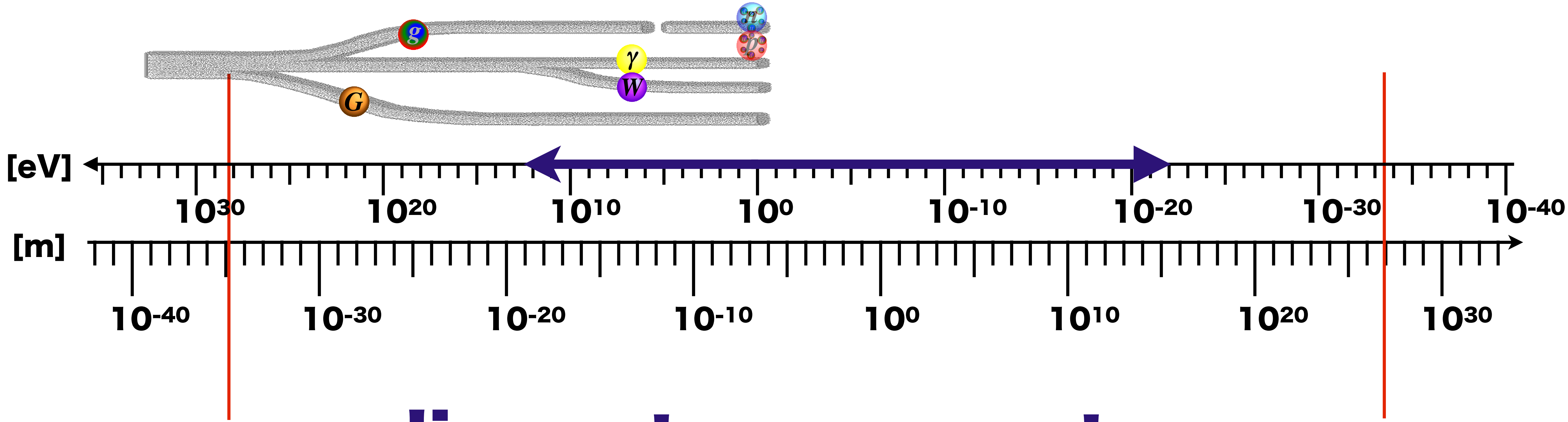
P Spatial Inversion

T Time Reversal



CPT theorem CPT=1

Equations of fields hold valid also for CPT-inverted states.



discrete symmetry

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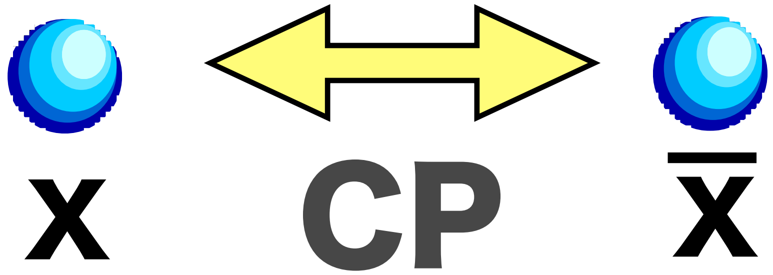


CPT theorem $\mathbf{CPT=1}$

Equations of fields hold valid also for CPT-inverted states.

$$CP \neq 1 \Leftrightarrow T \neq 1$$

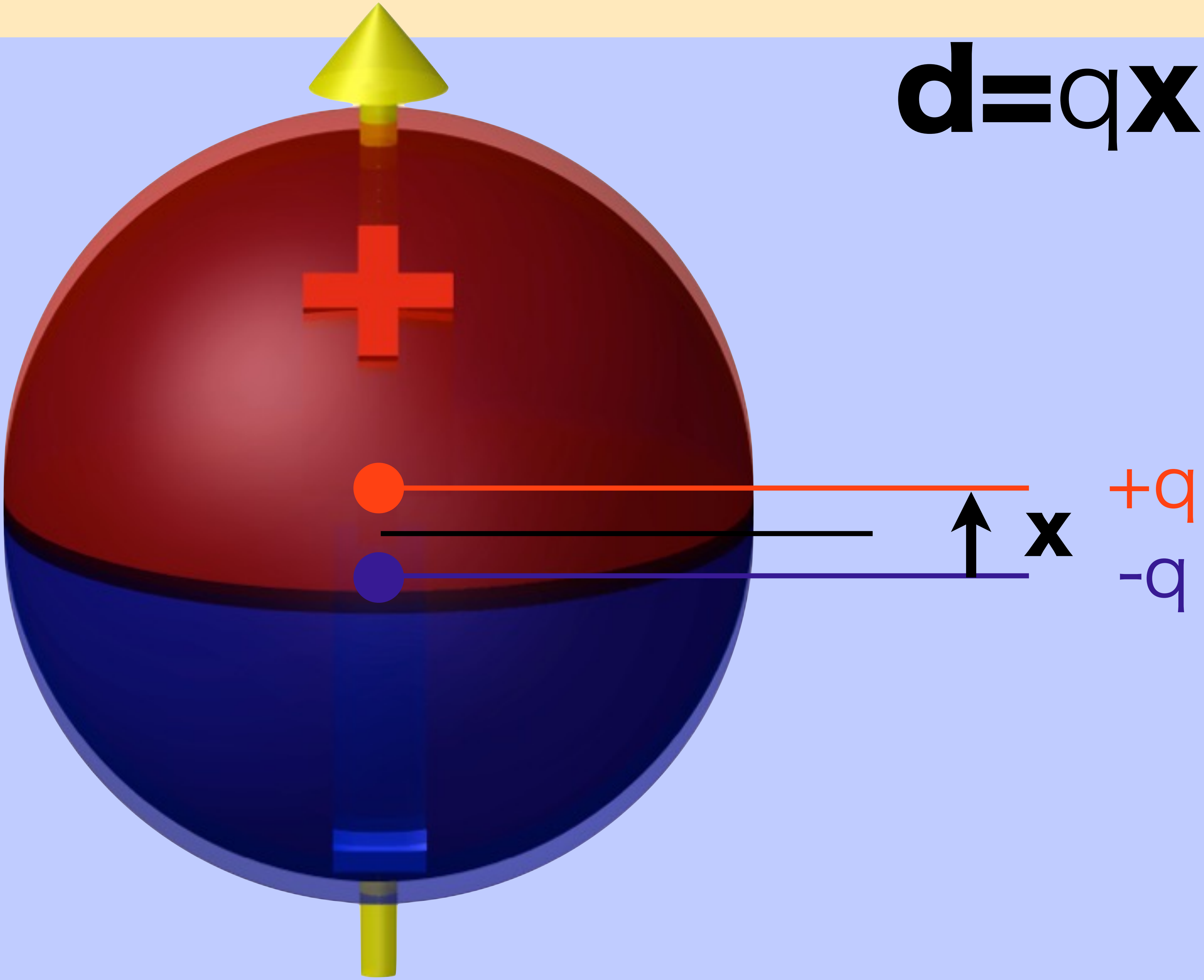
CP-violation **T-violation**

Physics

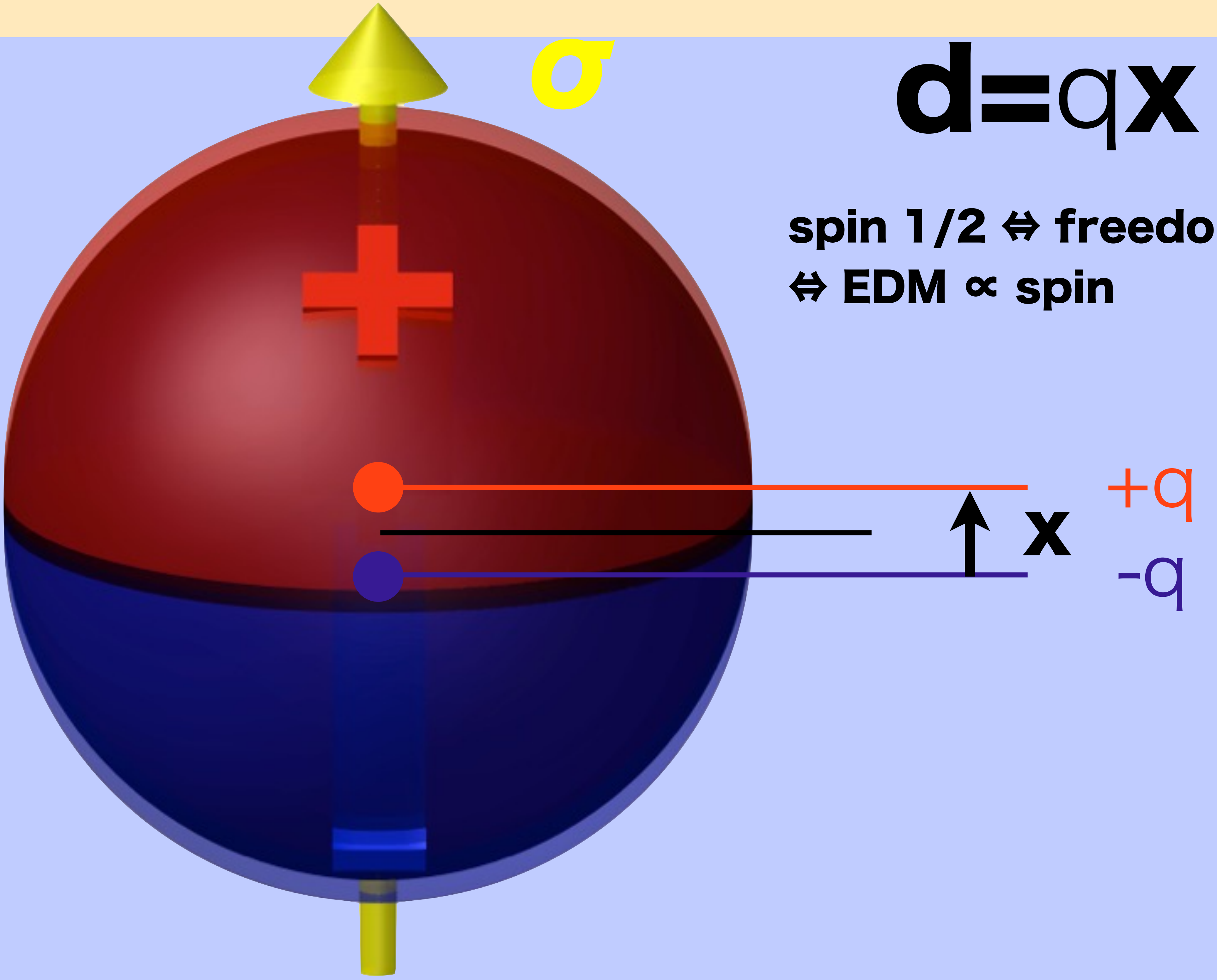
Electric Dipole Moment

Neutron Electric Dipole Moment

$\mathbf{d} = q\mathbf{x}$



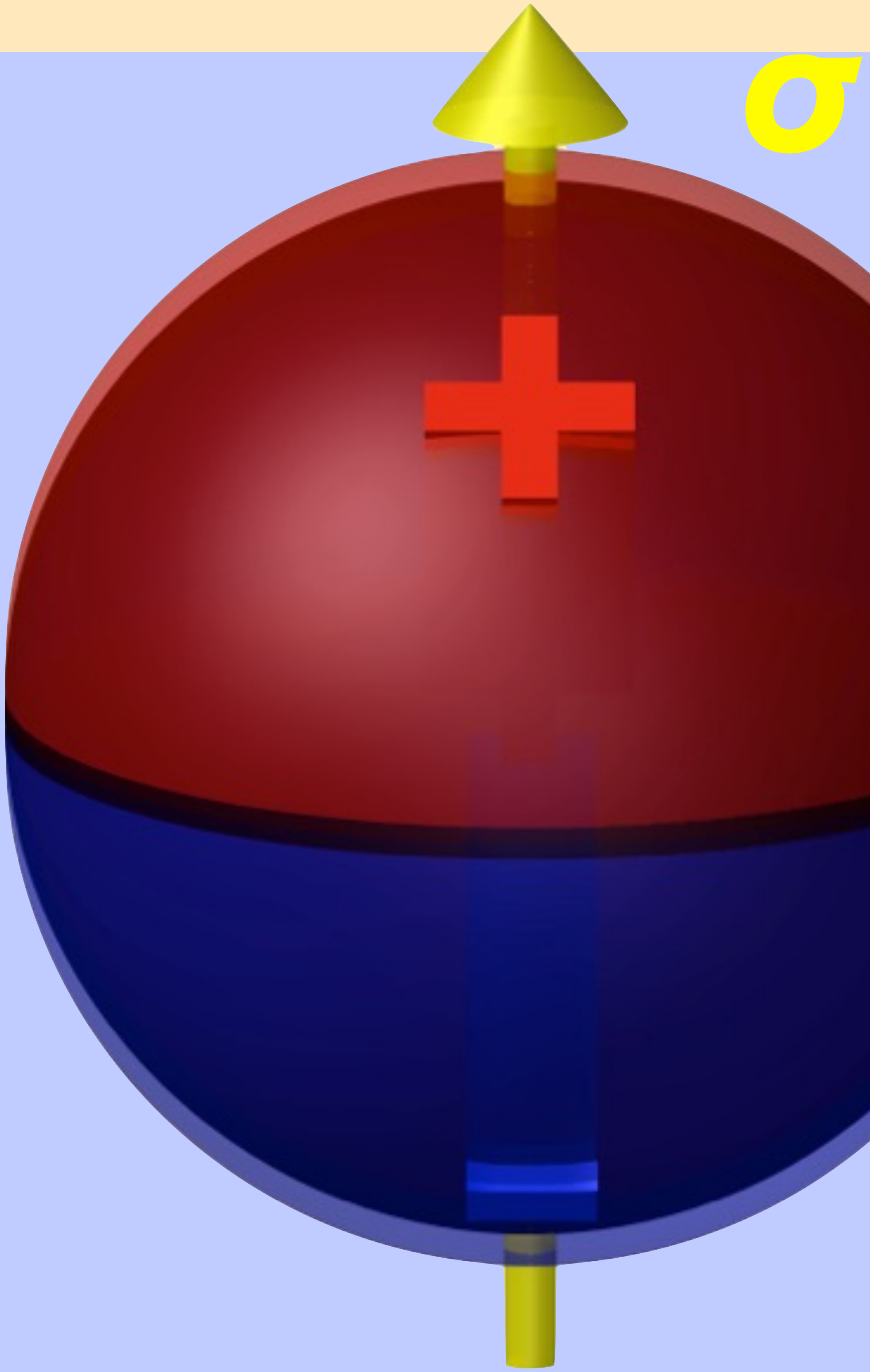
Neutron Electric Dipole Moment



$$d=qx$$

spin 1/2 ⇔ freedom=2
⇔ EDM ∝ spin

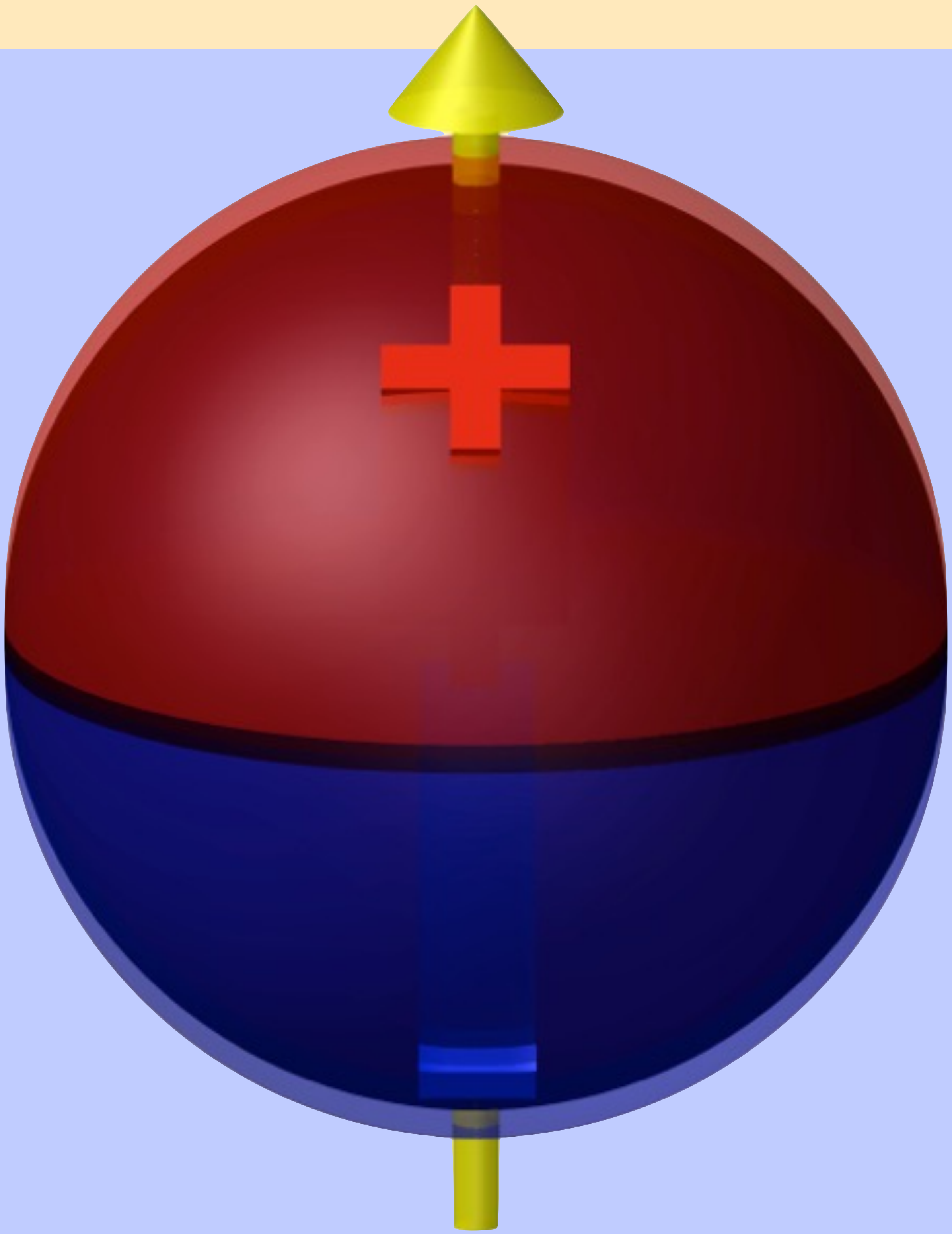
Neutron Electric Dipole Moment



$\boldsymbol{d}=\boldsymbol{\sigma}d$

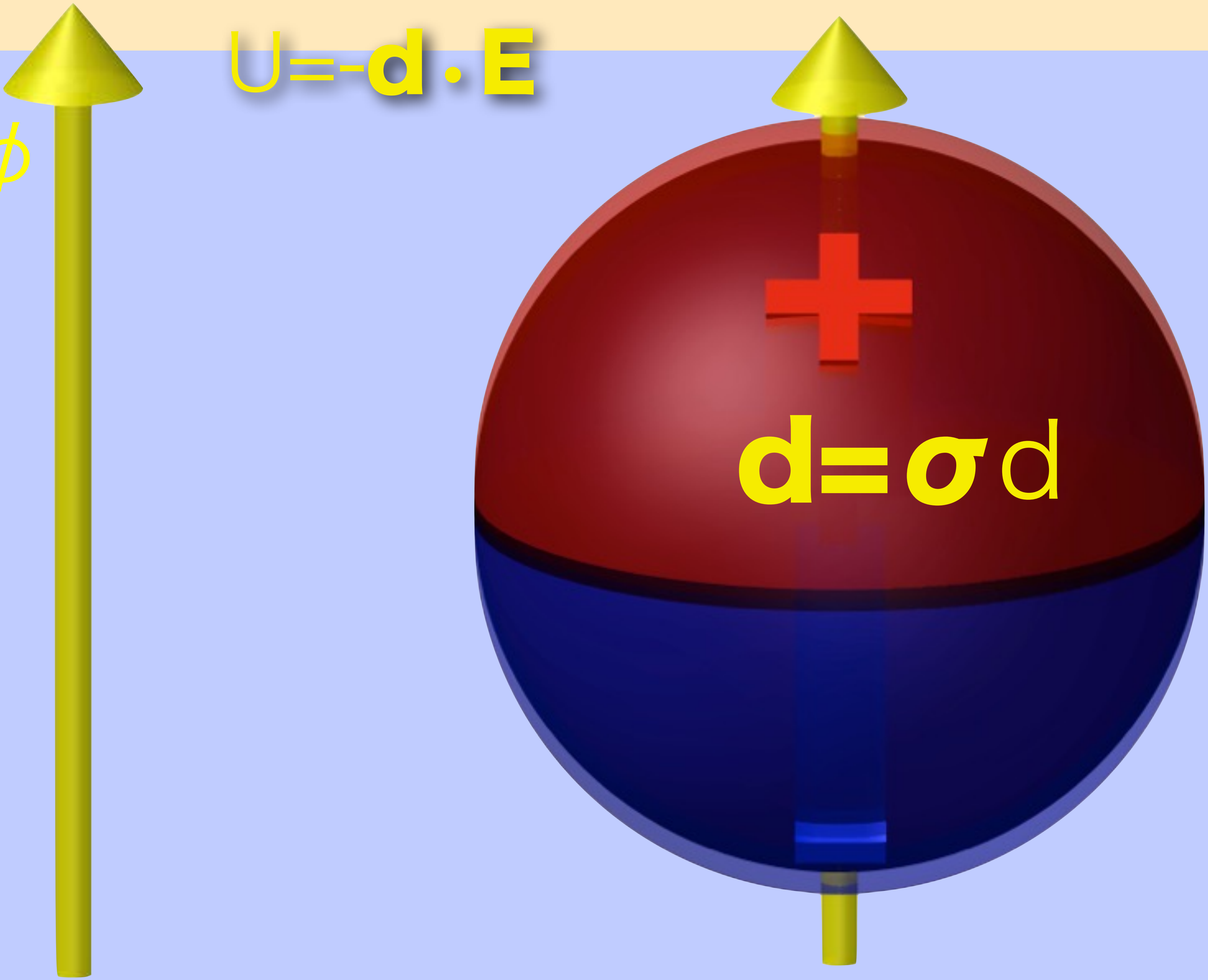
spin 1/2 ⇔ freedom=2
⇔ EDM ∝ spin

Neutron Electric Dipole Moment



$\mathbf{d} = \boldsymbol{\sigma} d$

Neutron Electric Dipole Moment



$U = -\mathbf{d} \cdot \mathbf{E}$

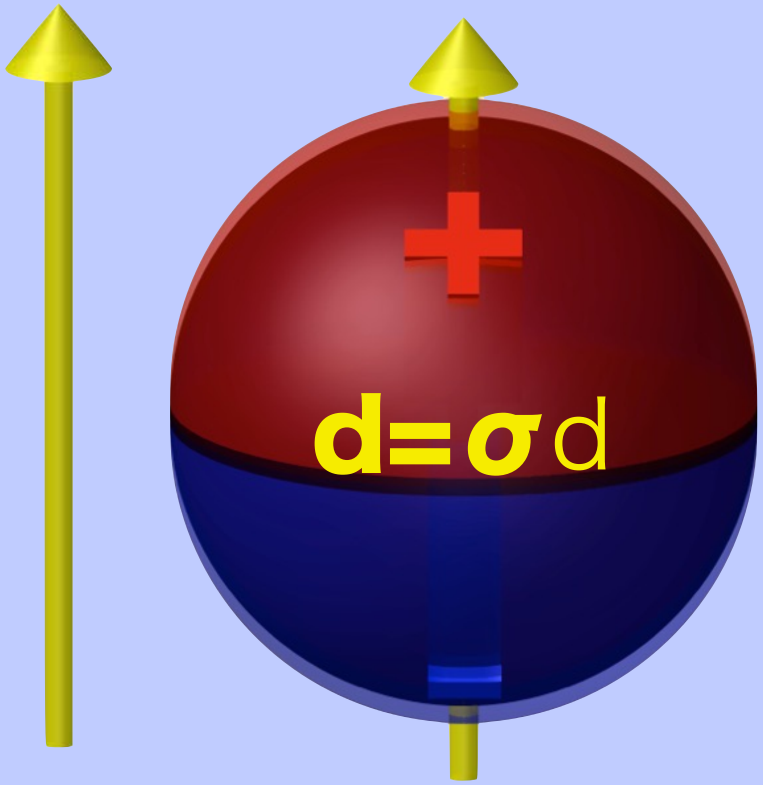
$\mathbf{E} = -\nabla \phi$

$\mathbf{d} = \boldsymbol{\sigma} d$

Neutron Electric Dipole Moment

$U=-\mathbf{d}\cdot\mathbf{E}$

$\mathbf{E}=-\nabla\phi$ $\boldsymbol{\sigma}$



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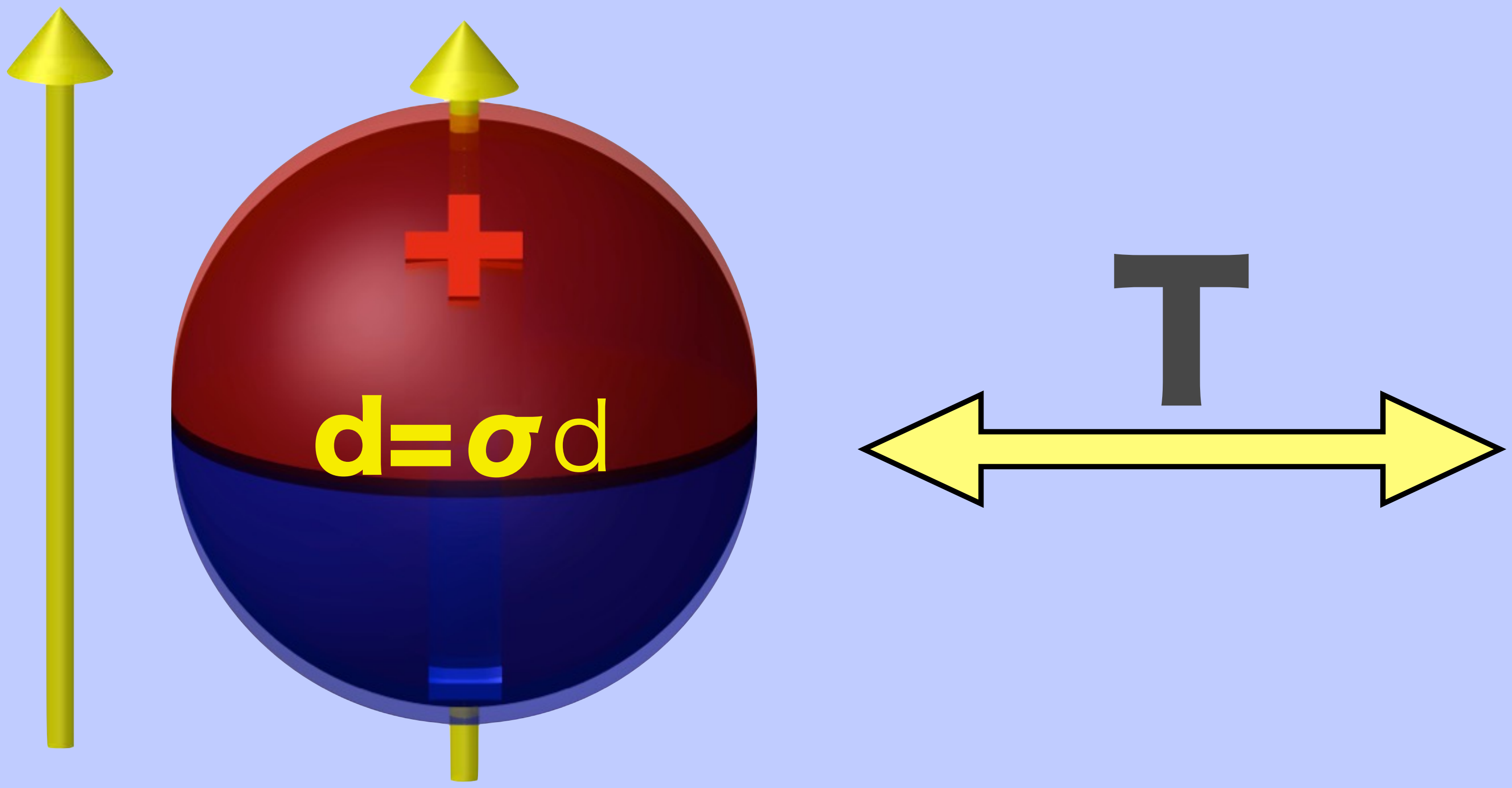
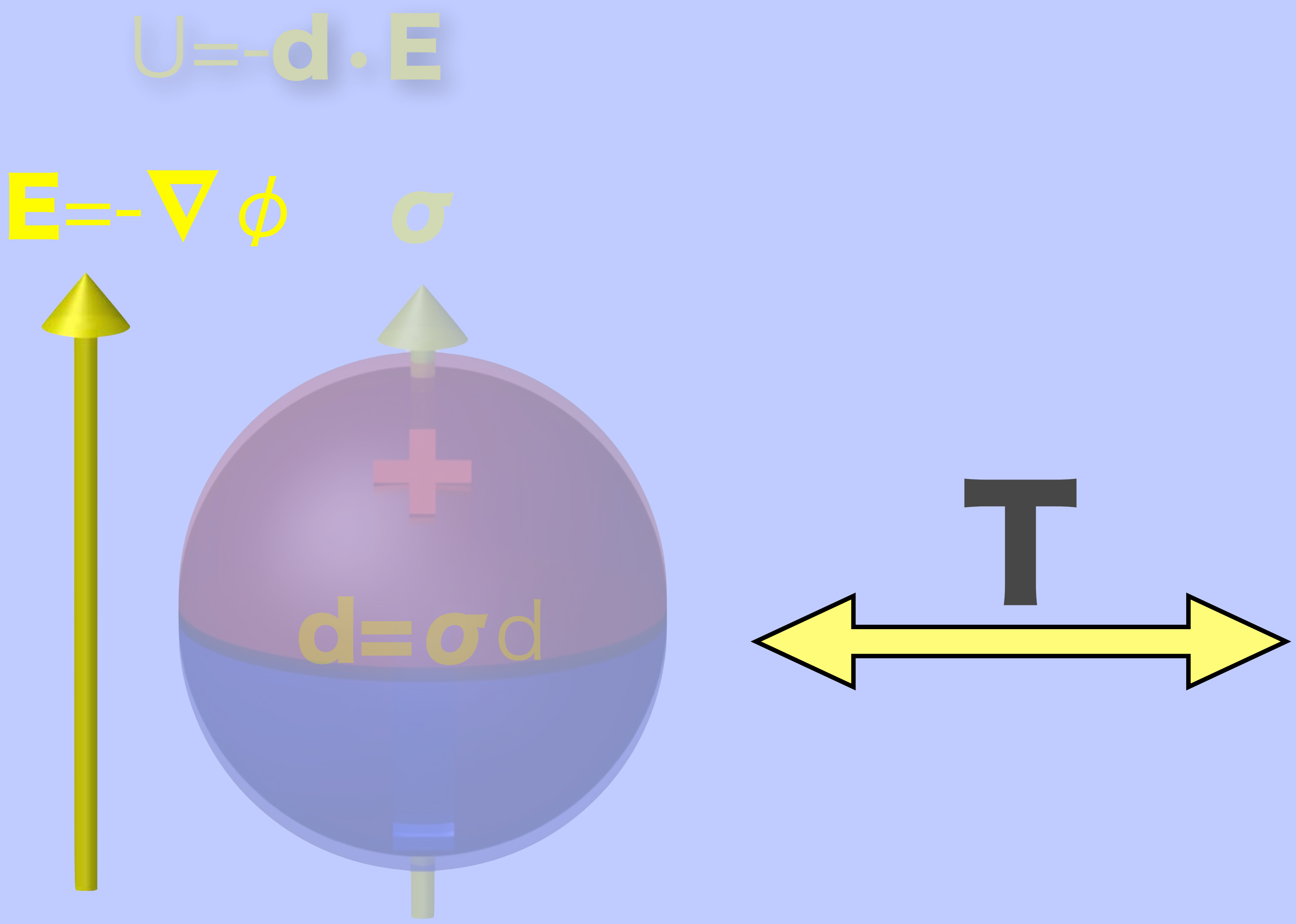
$\mathbf{E}=-\nabla\phi$ $\boldsymbol{\sigma}$

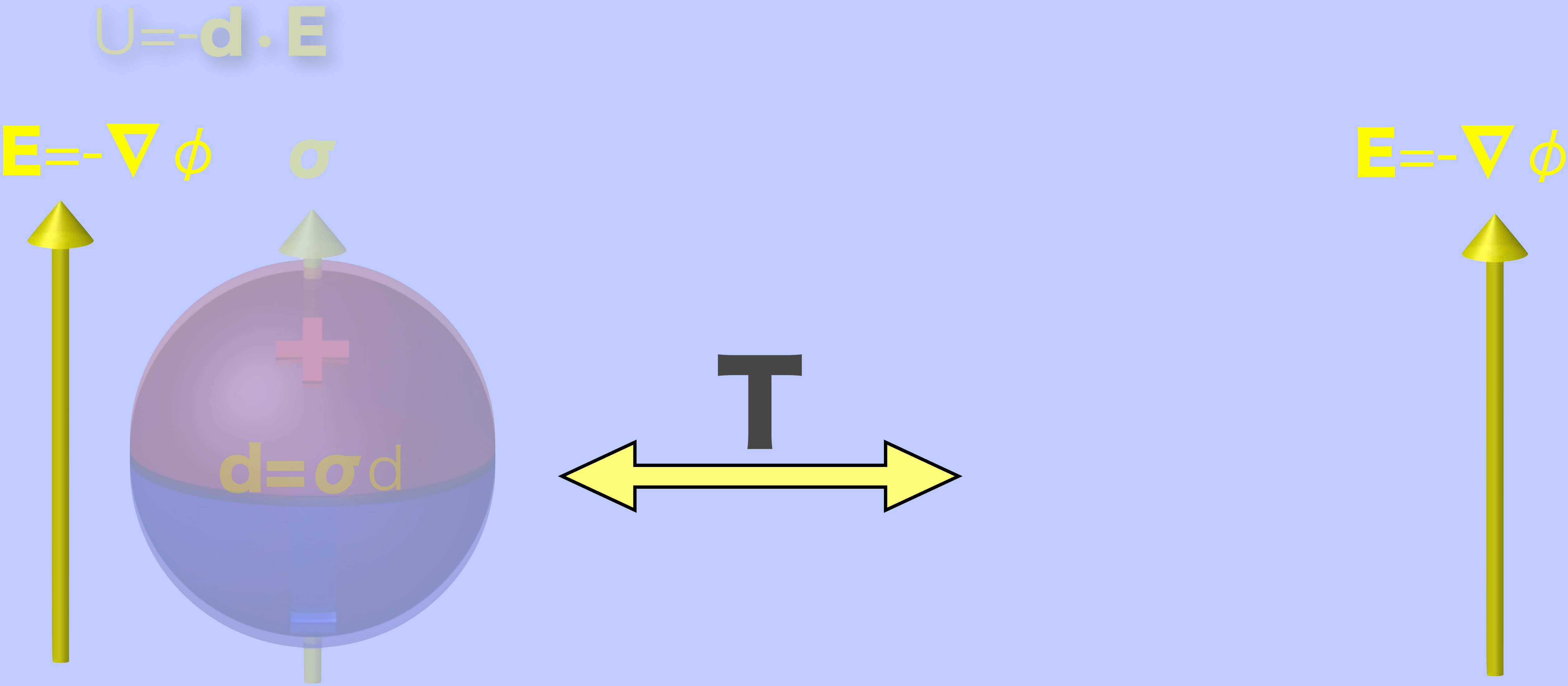


Neutron Electric Dipole Moment



$$m\frac{\mathrm{d}^2\vec{r}}{\mathrm{d}t^2} = \vec{F} = q\vec{E}$$

Neutron Electric Dipole Moment



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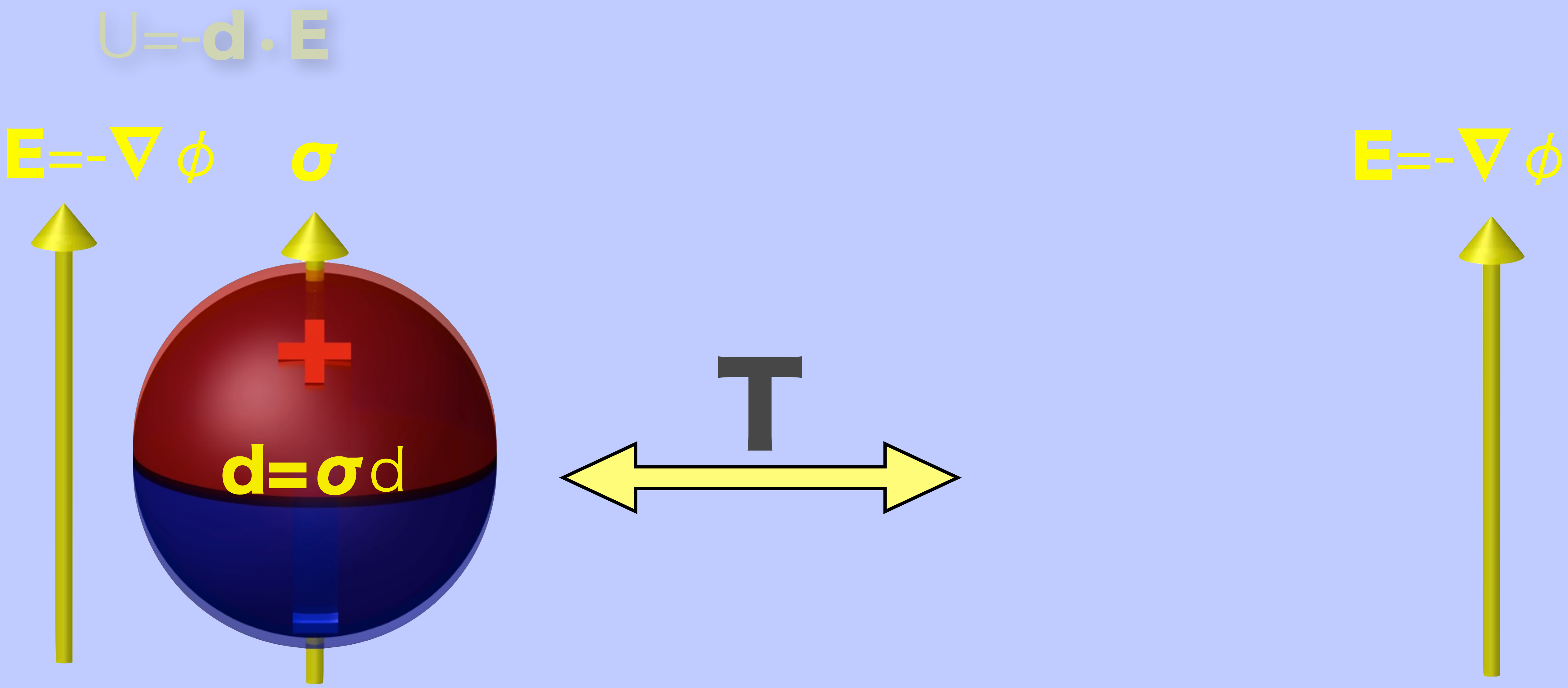


$U=-\mathbf{d}\cdot\mathbf{E}$

$\mathbf{E}=-\nabla\phi$ $\boldsymbol{\sigma}$

$\mathbf{d}=\boldsymbol{\sigma}d$

T

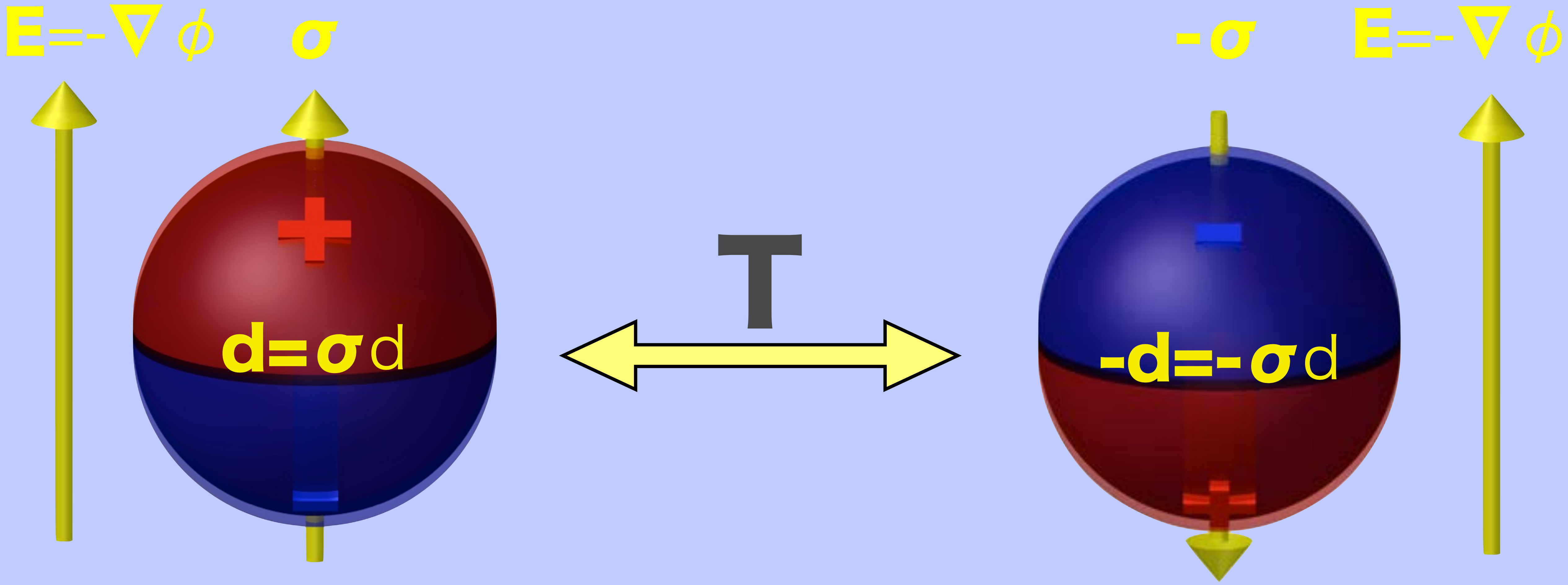
$\mathbf{E}=-\nabla\phi$

ref. orbital angular momentum

$$\vec{L}=\vec{r}\times\vec{p}=\vec{r}\times m\frac{\mathrm{d}\vec{r}}{\mathrm{d}t}$$

Neutron Electric Dipole Moment

$U=-\mathbf{d}\cdot\mathbf{E}$



$\mathbf{E}=-\nabla\phi$

$\boldsymbol{\sigma}$

$\mathbf{d}=\boldsymbol{\sigma}d$

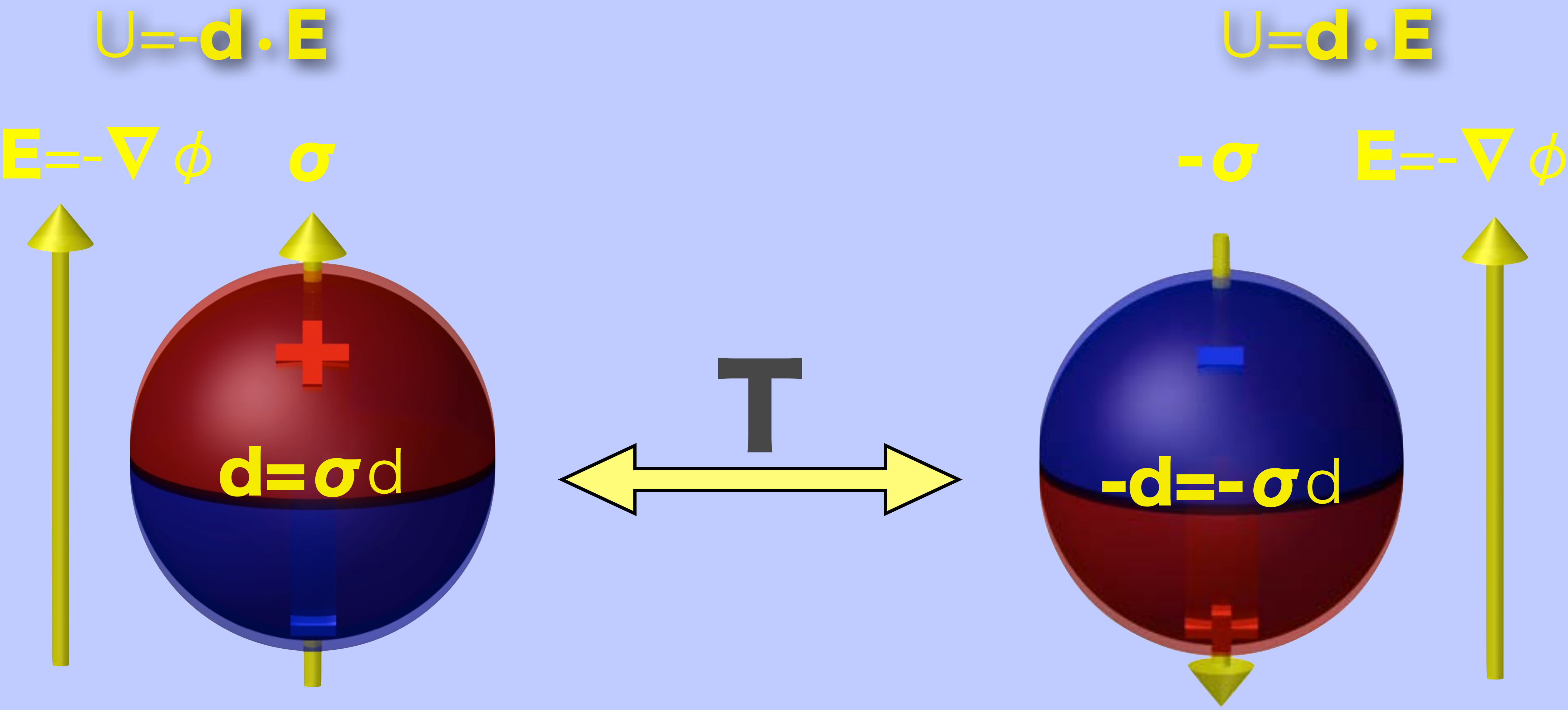
T

$-\boldsymbol{\sigma}$

$-\mathbf{d}=-\boldsymbol{\sigma}d$

$\mathbf{E}=-\nabla\phi$

Neutron Electric Dipole Moment



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$\mathbf{E}=-\nabla\phi$ $\boldsymbol{\sigma}$

$-\boldsymbol{\sigma}$ $\mathbf{E}=-\nabla\phi$

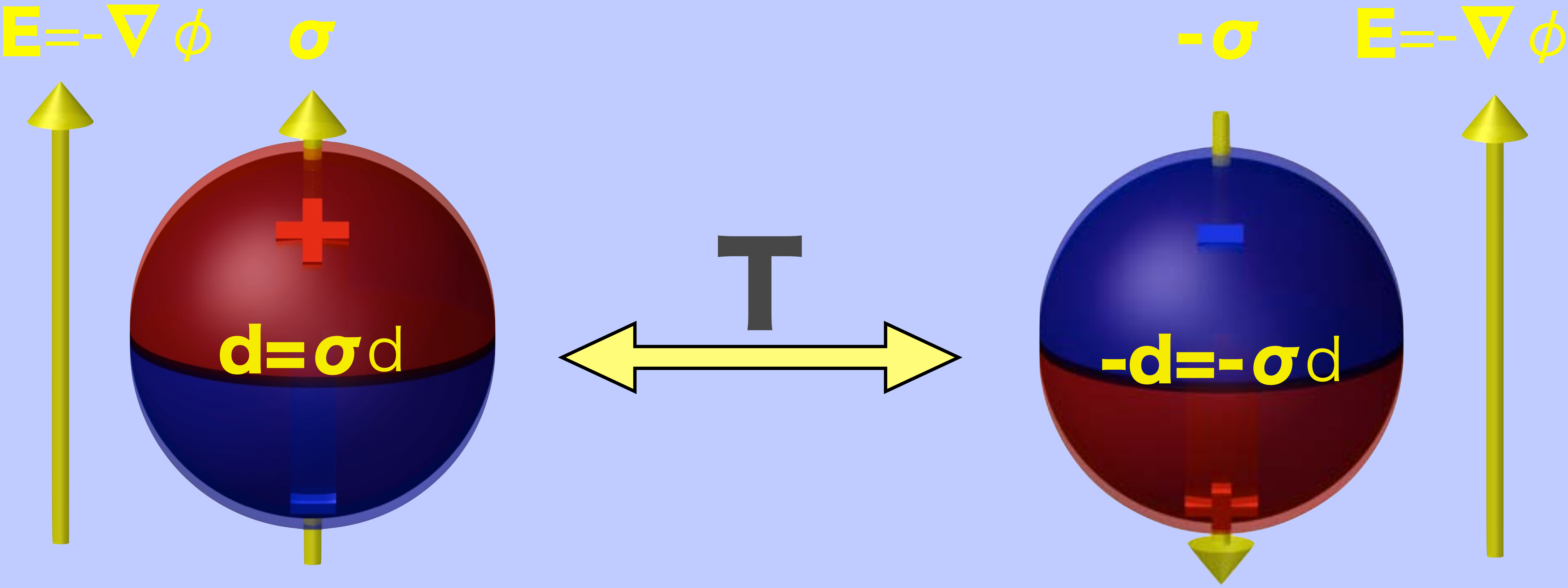
$\mathbf{d}=\boldsymbol{\sigma}d$

T

$-\mathbf{d}=-\boldsymbol{\sigma}d$

Neutron Electric Dipole Moment

$U=-\mathbf{d}\cdot\mathbf{E}$ $\quad = \quad$ $U=\mathbf{d}\cdot\mathbf{E}$



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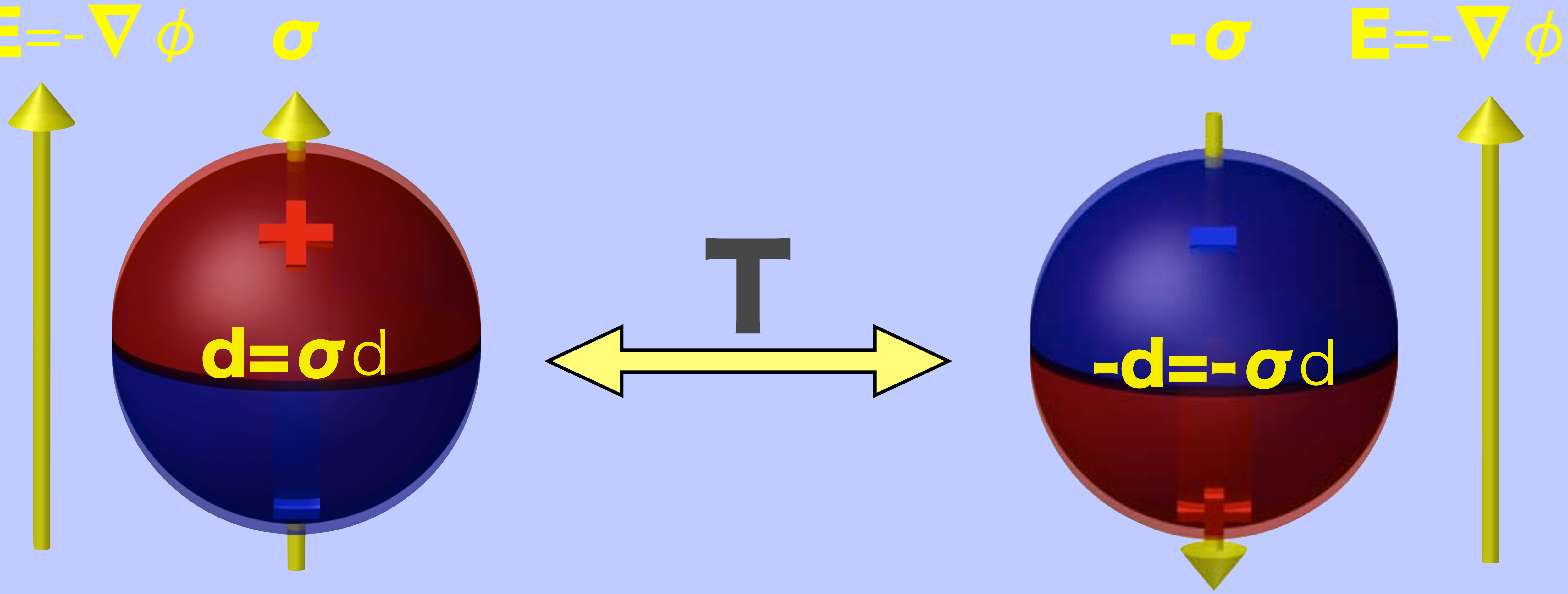

$\mathbf{E}=-\nabla\phi$ $\quad \boldsymbol{\sigma}$ $\qquad\qquad$ $-\boldsymbol{\sigma}$ $\quad \mathbf{E}=-\nabla\phi$

$\mathbf{d}=\boldsymbol{\sigma}d$ $\quad \xleftrightarrow{\mathbf{T}} \quad$ $-\mathbf{d}=-\boldsymbol{\sigma}d$

$$\mathbf{d=0}$$

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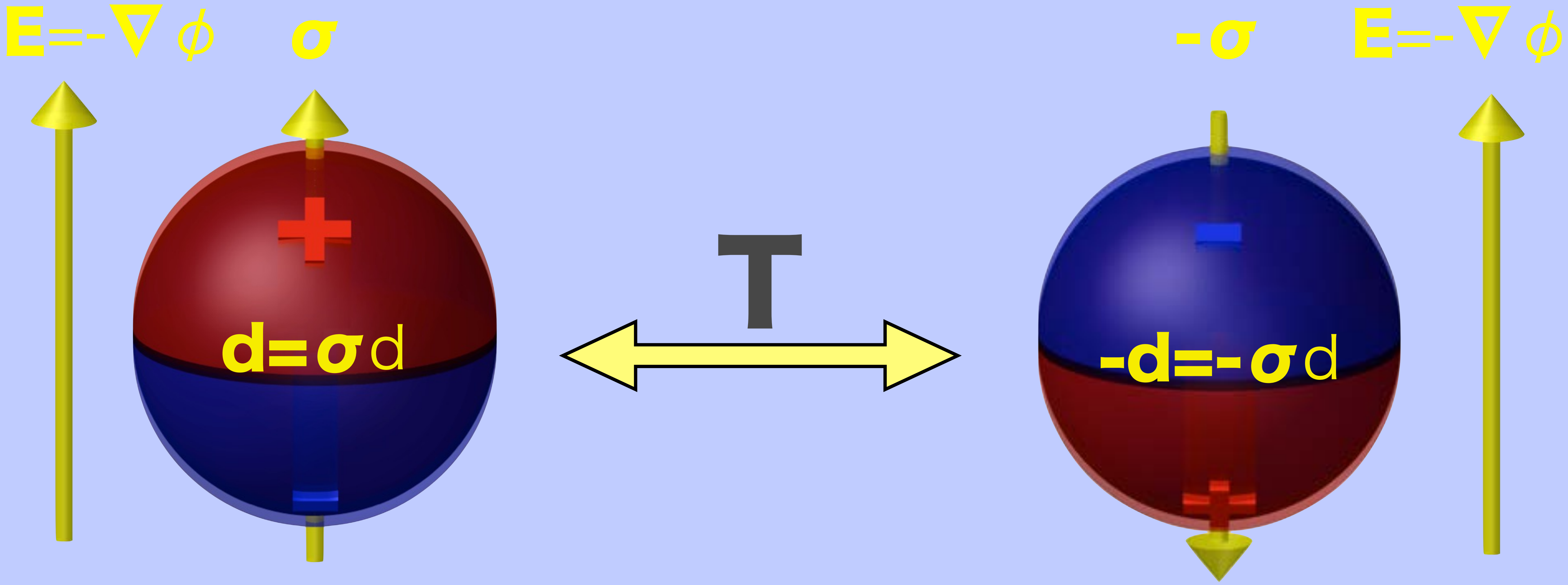


$\mathbf{E}=-\nabla\phi$ $\boldsymbol{\sigma}$

$\mathbf{d}=\boldsymbol{\sigma}d$

T

$-\boldsymbol{\sigma}$ $\mathbf{E}=-\nabla\phi$

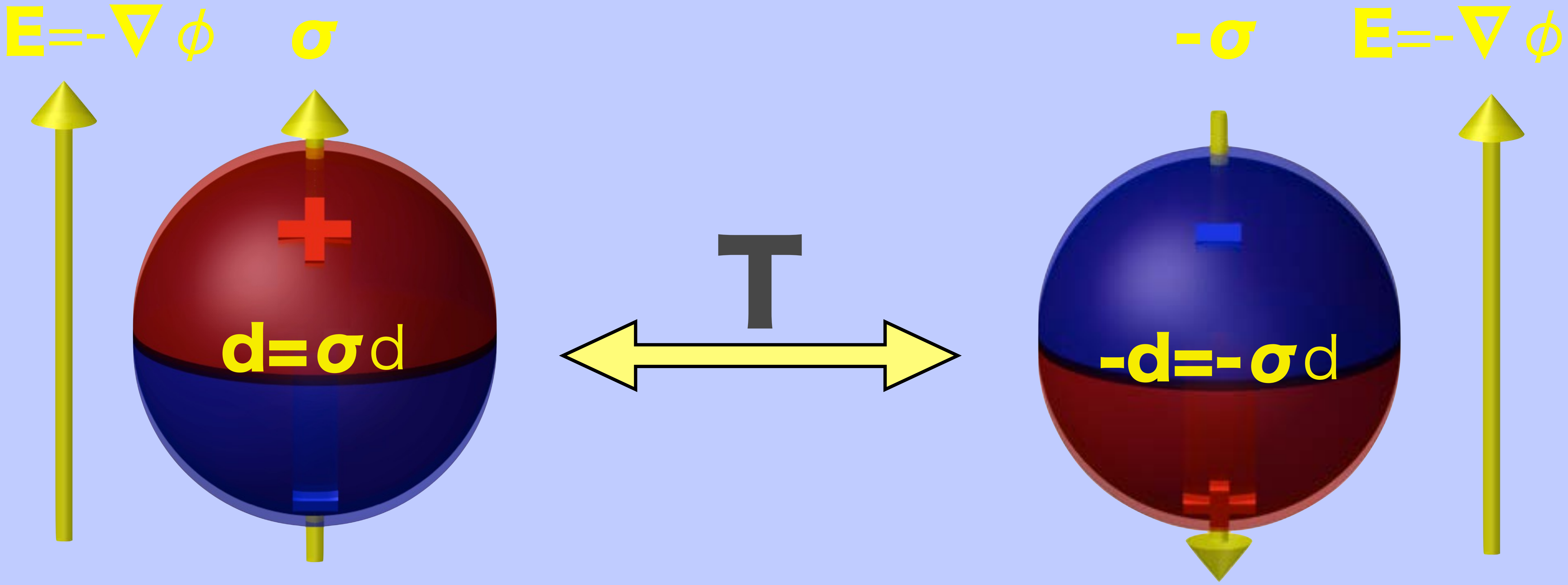
$-\mathbf{d}=-\boldsymbol{\sigma}d$

If the system is symmetric under time reversal, then d=0.

- contraposition -

Neutron Electric Dipole Moment

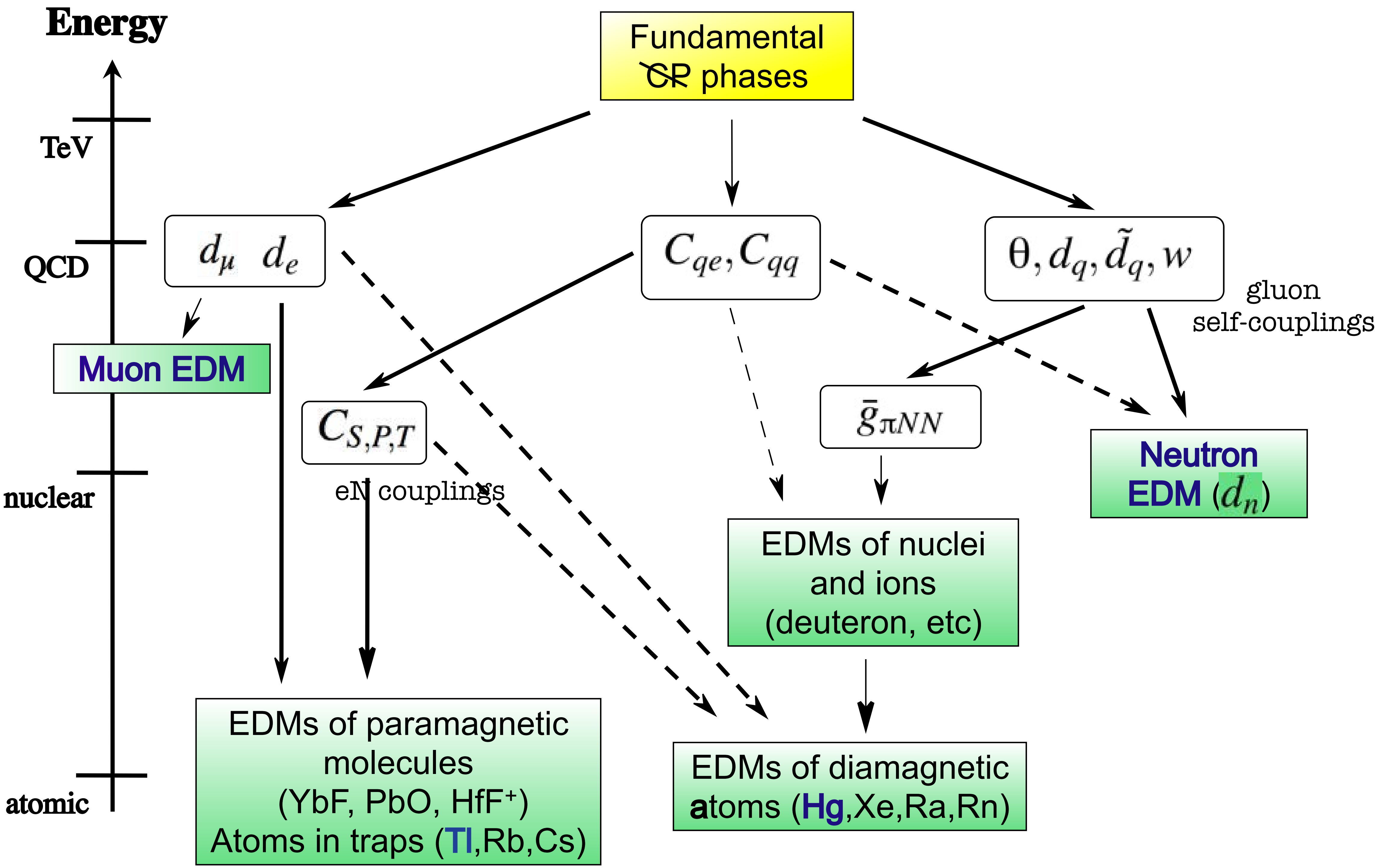
$$U=-\mathbf{d}\cdot\mathbf{E} \quad \neq \quad U=\mathbf{d}\cdot\mathbf{E}$$



If d≠0, then the system is not symmetric under time reversal.

- contraposition -

CP-violation in Low Energy Phenomena



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TeV

QCD

nuclear

atomic

Fundamental
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C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

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Pospelov Ritz, Ann Phys 318 (05) 119

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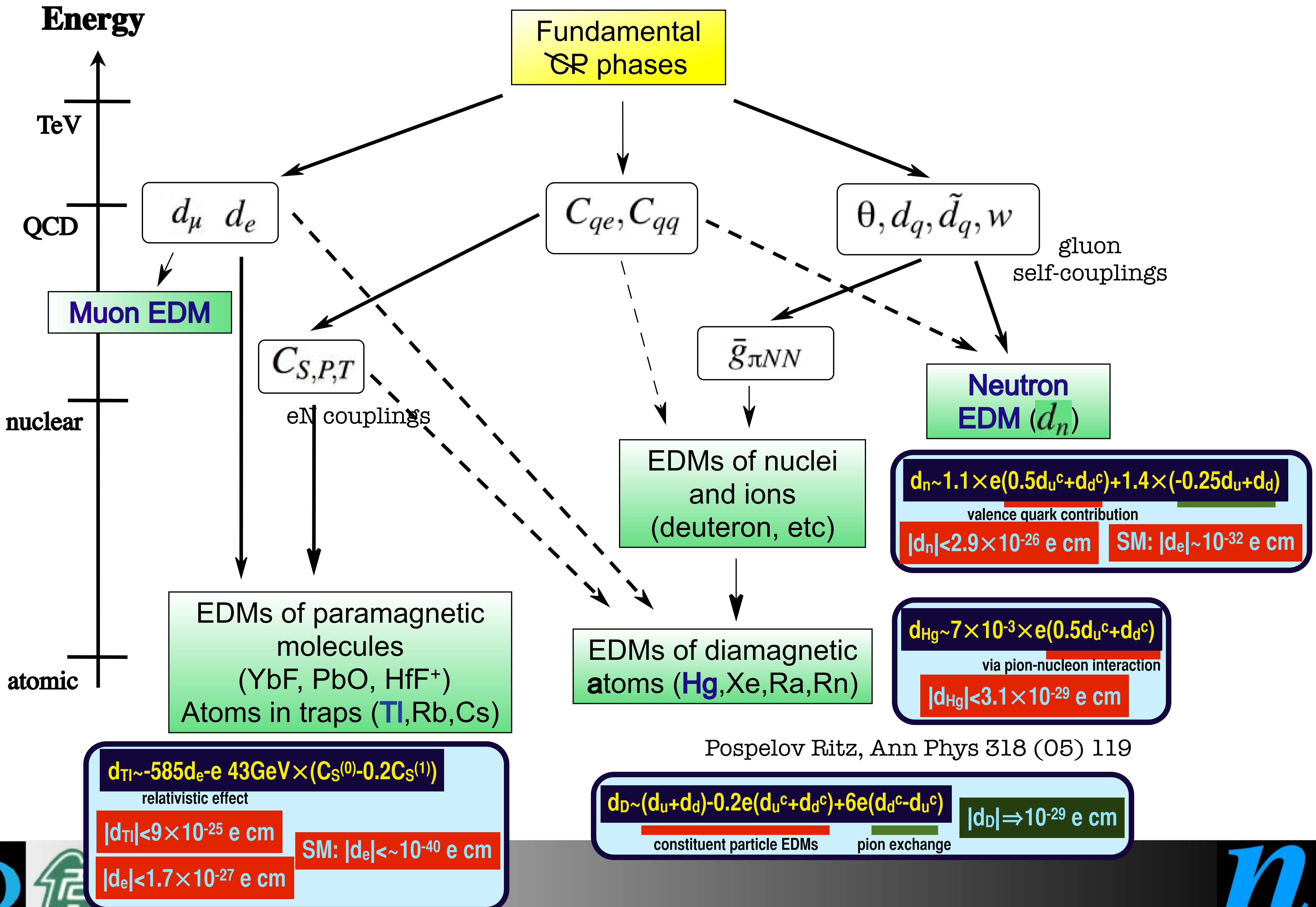

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$|d_n| < 2.9 \times 10^{-26}$ e cm

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$d_D \sim (d_u + d_d) - 0.2e(d_u^c + d_d^c) + 6e(d_d^c - d_u^c)$

constituent particle EDMs

pion exchange

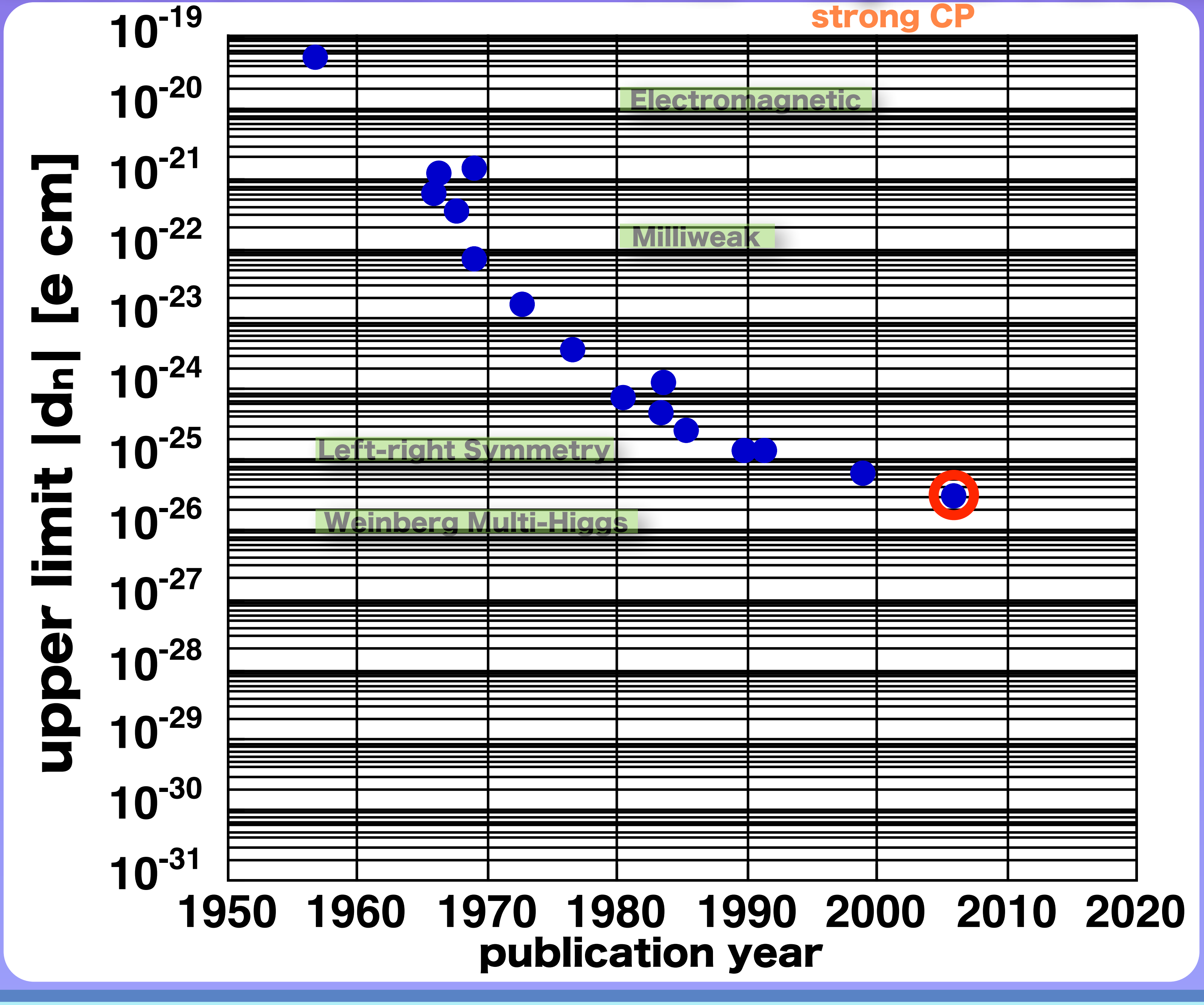
$|d_D| \Rightarrow 10^{-29}$ e cm

Neutron Electric Dipole Moment

$|d_n|<2.9\times10^{-26}$ e cm
(90%C.L.)

Baker et al., PRL97 (2006)131801

neutron EDM $\hbar\omega=2\mu_nB+2d_nE$



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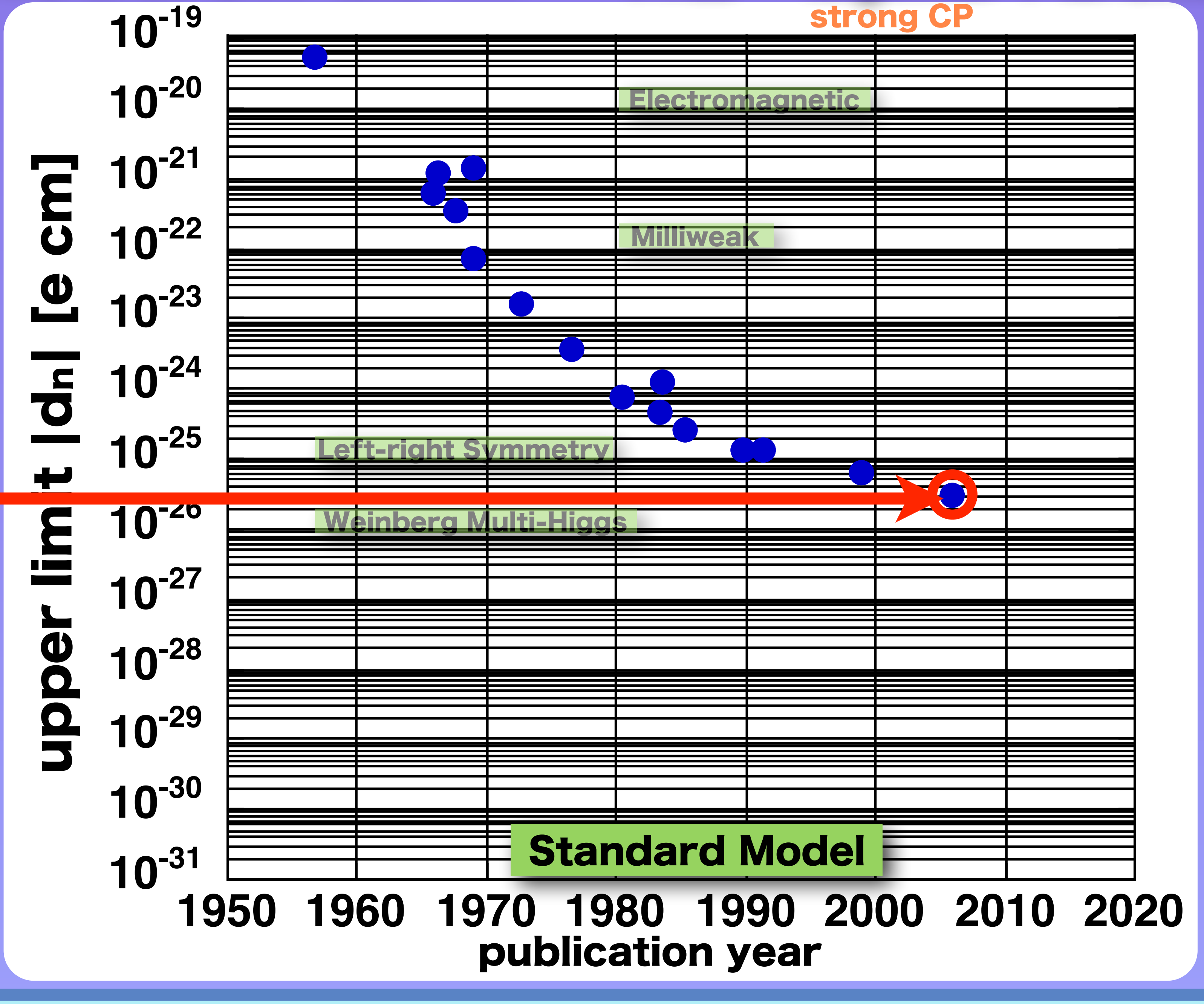

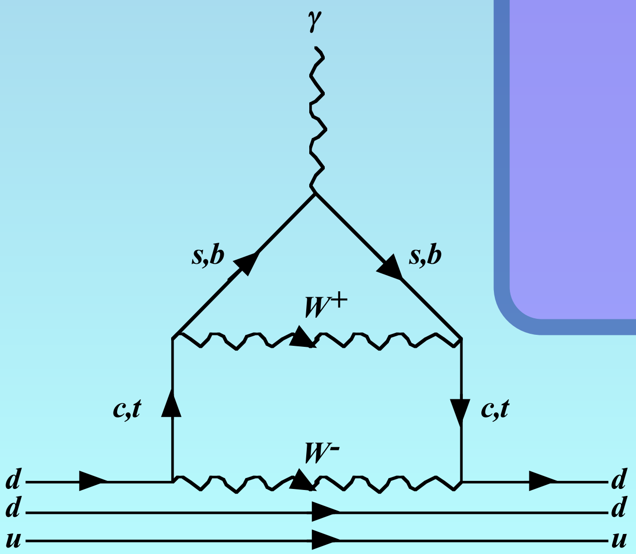

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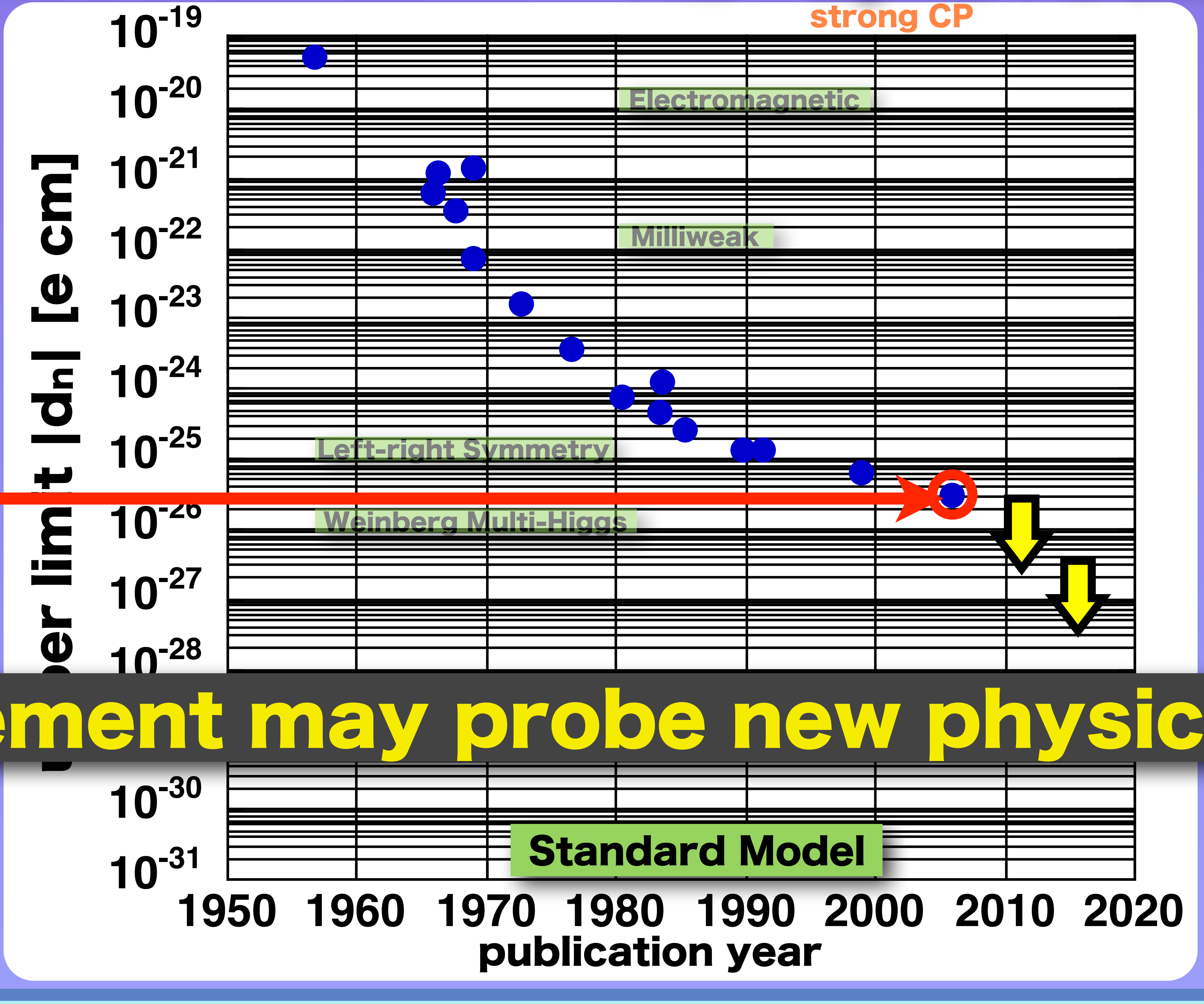
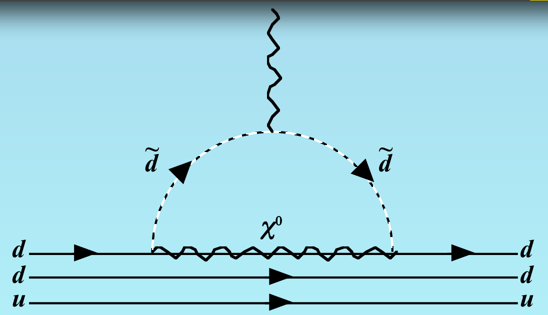
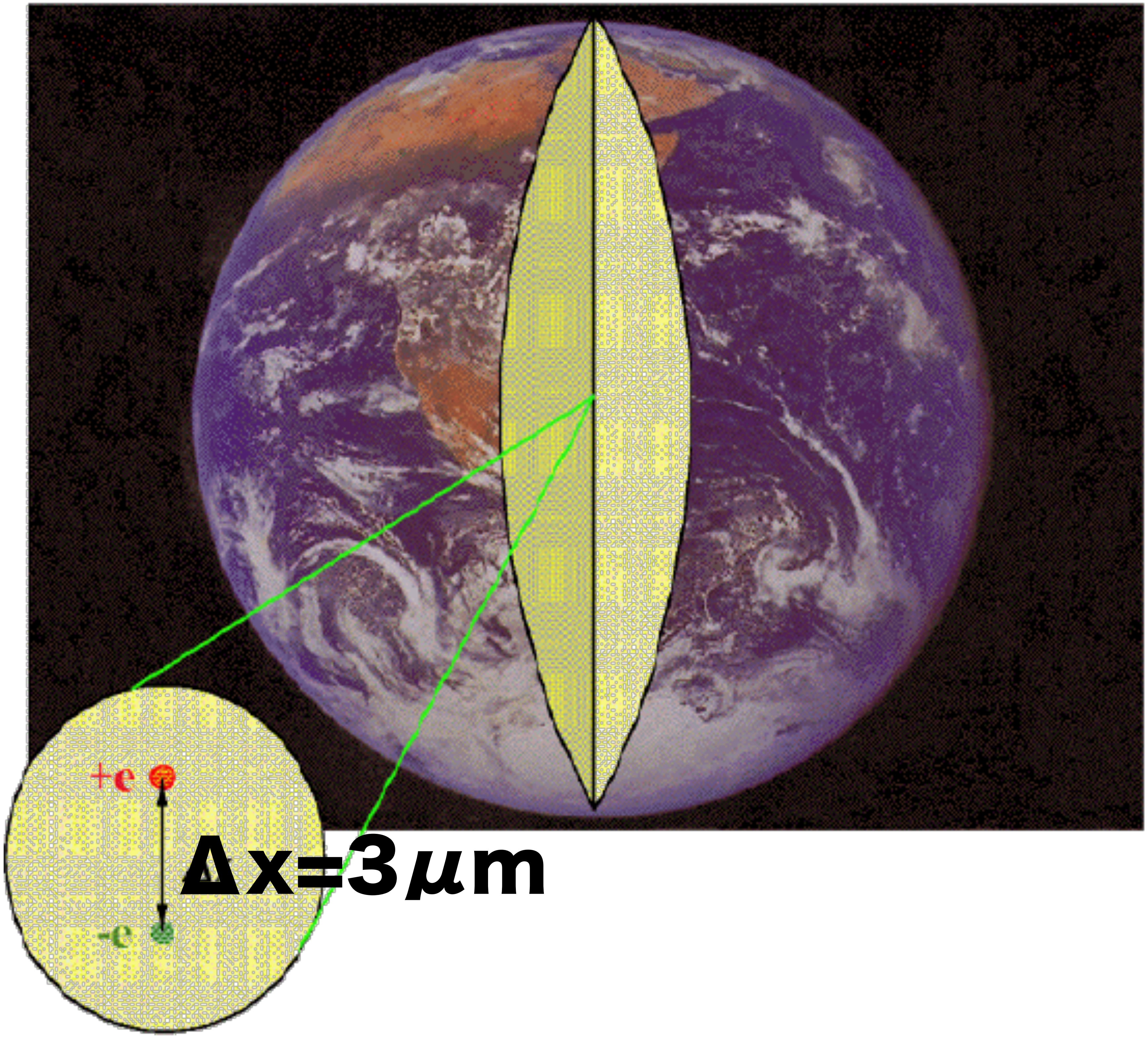


1-2 order improvement may probe new physics



$|d_n| < 2.9\times10^{-26}$ e cm (90%CL)

The moment corresponds to 3μm difference of charge centers in the earth.

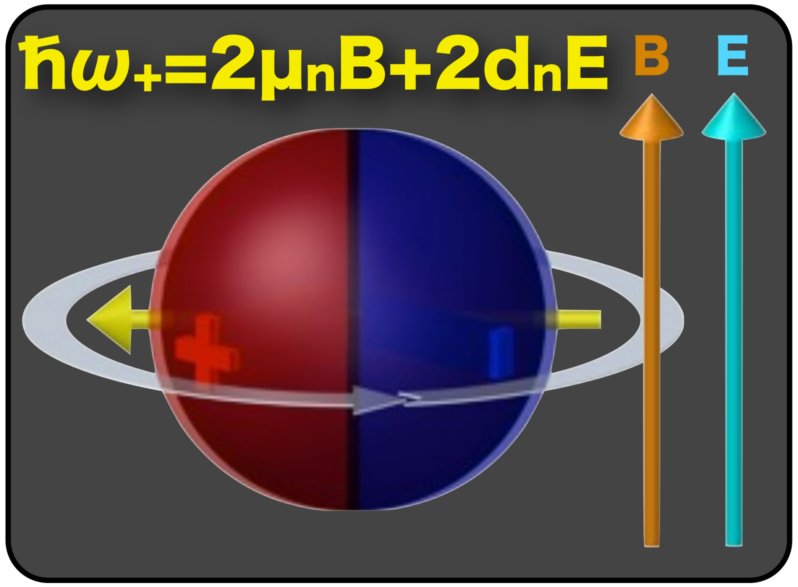


Measurement of Neutron Electric Dipole Moment

search for the phase change when the electric field is reversed

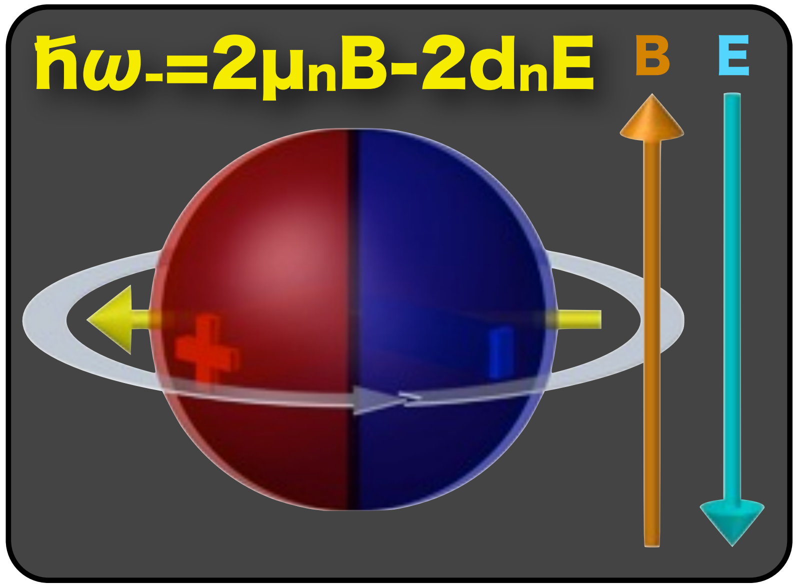
$$\hbar\omega_+ = 2d_nE + 2\mu_nB$$

$$\hbar\omega_- = 2d_nE - 2\mu_nB$$



$$\Delta\phi = \int(\omega_+ - \omega_-)\mathrm{d}t = \frac{2d_nET}{\hbar}$$

$$\Delta d_n = \frac{\hbar/2}{ET\sqrt{N}}$$



long precession time

Confined Ultracold Neutron

$E=10^4$ V/cm, T=100s

$$ET \sim 10^6[\mathrm{s\,V/cm}]$$

strong electric field

Cold Neutron Diffraction by Single Crystal

$E=10^9$ V/cm, T=1ms

resolved systematics

Guided Cold Neutron

$E=10^5$ V/cm, T=0.1s

long precession time

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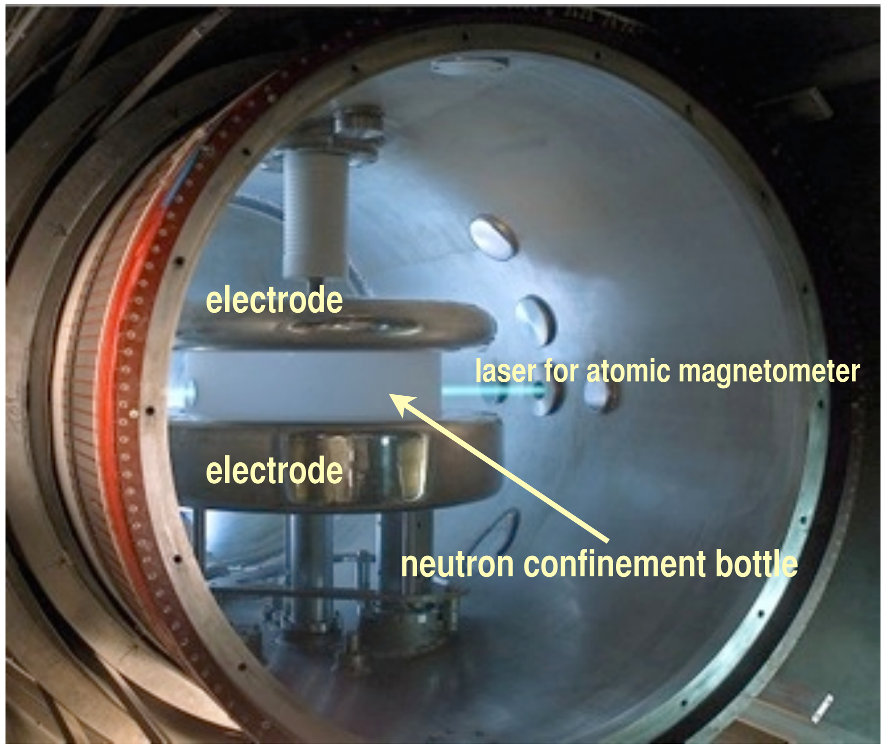
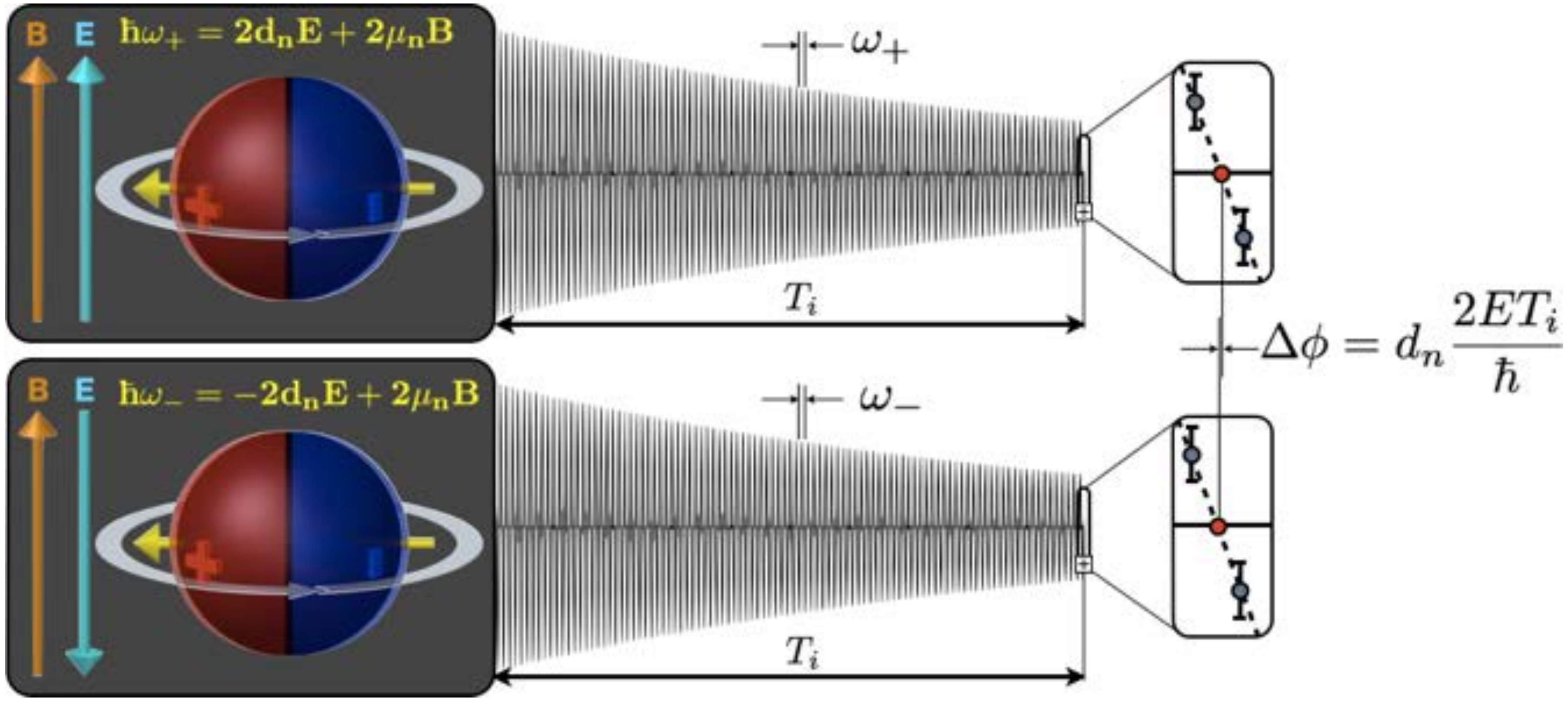
Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency





$$\frac{\omega_\pm}{2\pi} = \boxed{30[\mathrm{Hz}]\frac{B}{1\,[\mu\mathrm{T}]}} \pm \boxed{5\times 10^{-8}[\mathrm{Hz}]\frac{d_n}{10^{-26}\,[\mathrm{e\cdot cm}]}\frac{E}{10\,[\mathrm{kV/cm}]}}$$

magnetic field **1μT**

electric field **1fT equiv.**

$$\frac{\omega_\pm}{2\pi} = 3 \times 10^1 \frac{B}{1\mu T} \pm 5 \times 10^{-8} \frac{d_n}{10^{-26}\mathrm{e\cdot cm}} \frac{E}{10\mathrm{kV/cm}}$$

$$\begin{aligned} \Delta U = U_+ - U_- = 2d_nE &= 2 \times 10^{-26}[\mathrm{e\cdot cm}] \times 10[\mathrm{kV/cm}] \\ &= 2 \times 10^{-22}[\mathrm{eV}] \end{aligned}$$

Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency

$$\frac{\omega_\pm}{2\pi} = \boxed{30[\mathrm{Hz}]\frac{B}{1\,[\mu\mathrm{T}]}} \pm \boxed{5\times 10^{-8}[\mathrm{Hz}]\frac{d_n}{10^{-26}\,[\mathrm{e}\cdot\mathrm{cm}]}\frac{E}{10\,[\mathrm{kV/cm}]}}$$

magnetic field **1μT**

electric field **1fT equiv.**

precision control of magnetic field

density of confined neutrons

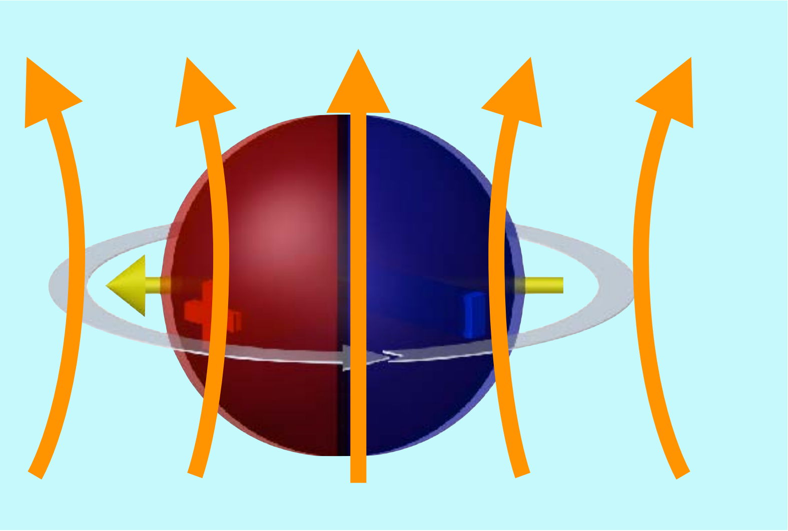
- superthermal production of ultracold neutron
- transport optics with minimum density decrease

control of the motion of confined neutrons

- optical properties of neutron reflectors

accuracy of the magnetic field measurement

- atomic magnetometry



long precession time

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strong electric field

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$E=10^9$ V/cm, T=1ms

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Guided Cold Neutron

$E=10^5$ V/cm, T=0.1s

Measurement of Neutron Electric Dipole Moment

Cold Neutron Diffraction in Single Crystal

$$f(\boldsymbol{q}) = \underbrace{f_0}_{a} + \underbrace{f_{\mathrm{Schw}}(\boldsymbol{q})}_{i\frac{2e\mu_n}{\hbar c}(Z-F(q))\frac{\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{q})}{q^2}} + \underbrace{f_{\mathrm{EDM}}(\boldsymbol{q})}_{i\frac{2med_n}{\hbar^2}(Z-F(q))\frac{\boldsymbol{\sigma}\cdot\boldsymbol{q}}{q}}$$

$$F(\boldsymbol{q}) = \int \rho(\boldsymbol{q})e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\mathrm{d}\boldsymbol{r}$$ atomic form factor

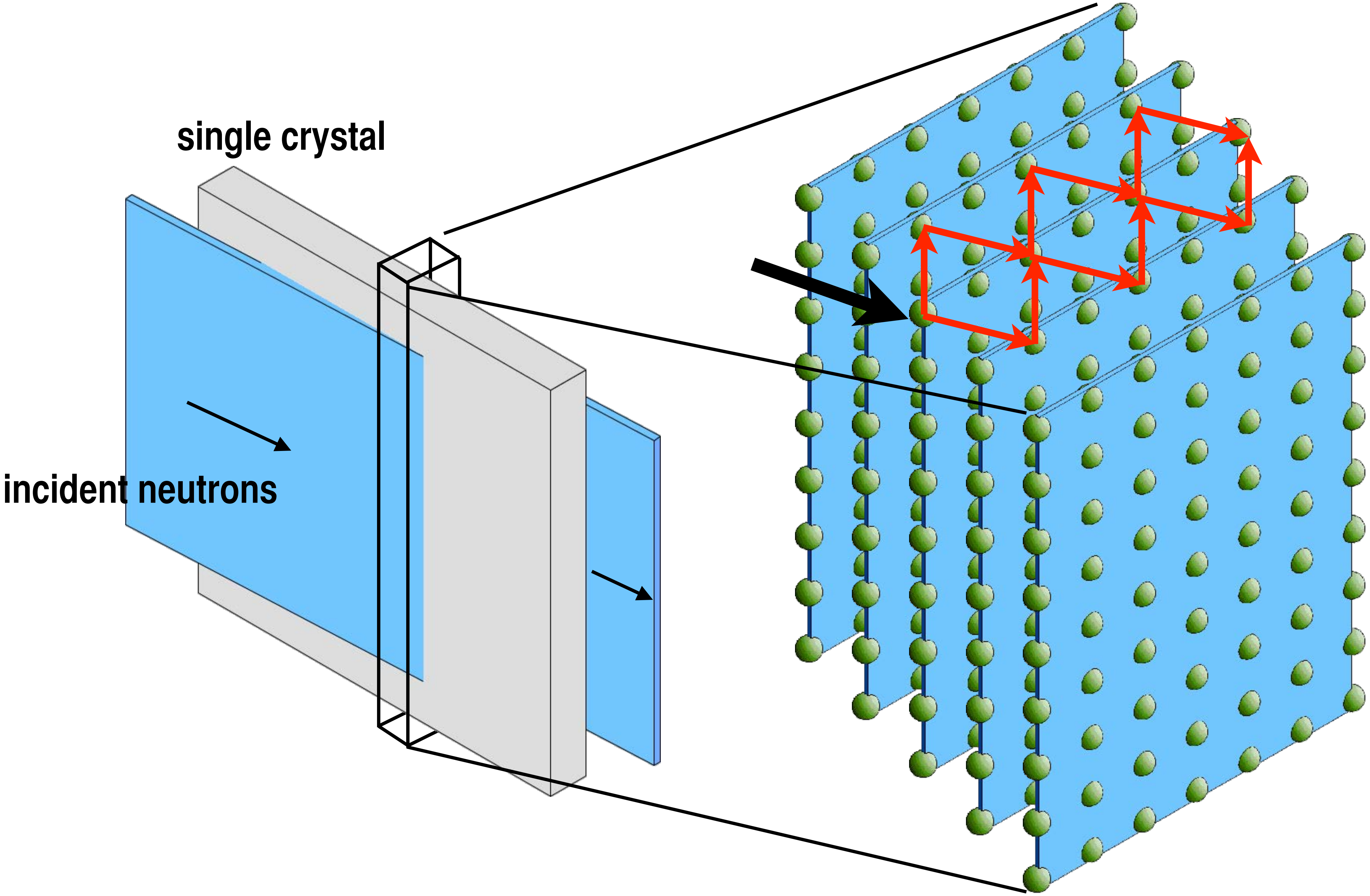
α-quartz (SiO_2)

$$d_n = (2.5 \pm 6.5_{\mathrm{stat}} \pm 5.5_{\mathrm{syst}}) \times 10^{-24}\ [\mathrm{e\,cm}]$$

V.V.Fedorov et al., Phys. Lett. B694 (2010) 22

→ 10^{-26} e cm / 100 days

Neutron-wave Propagation in Single Crystal



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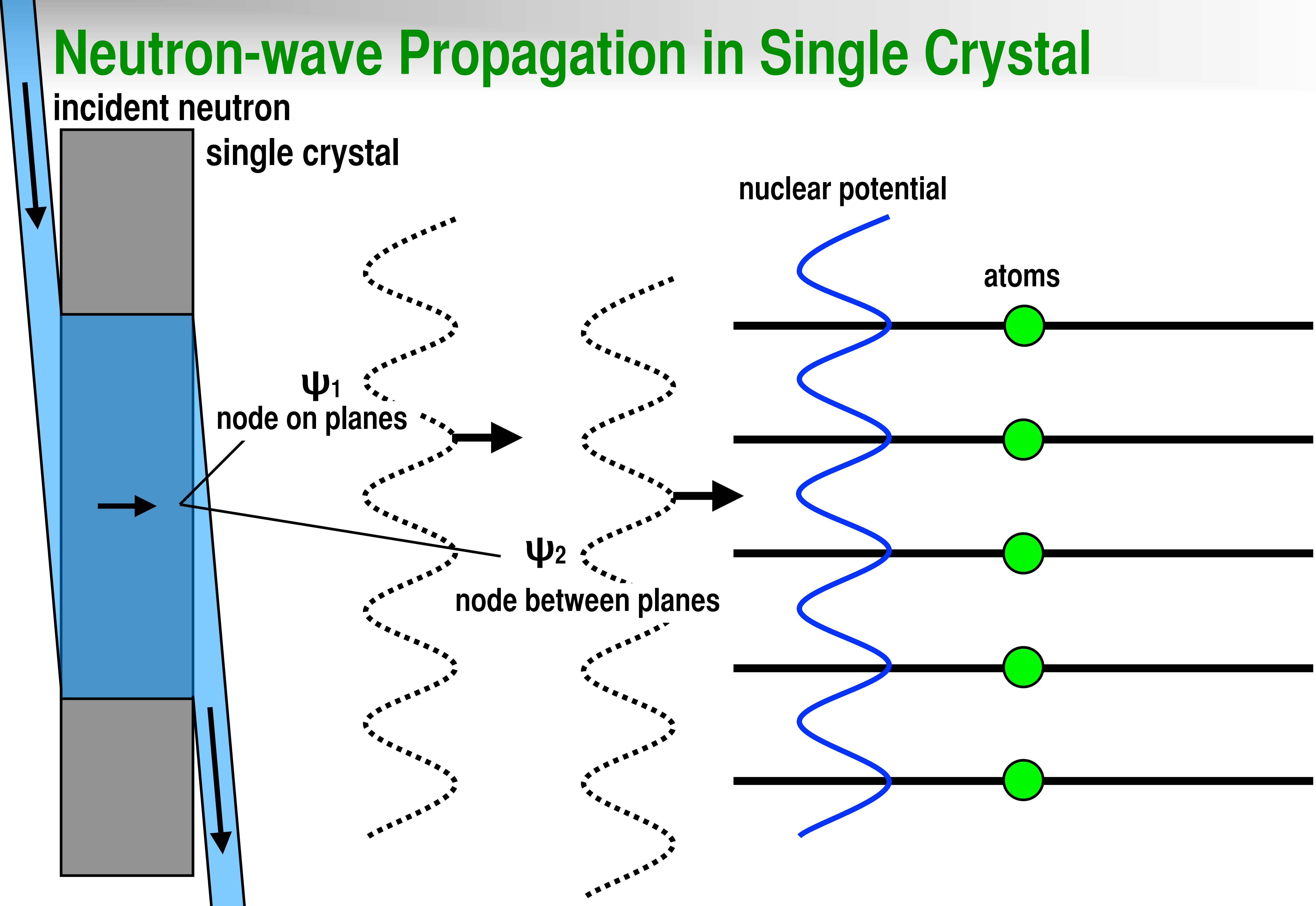

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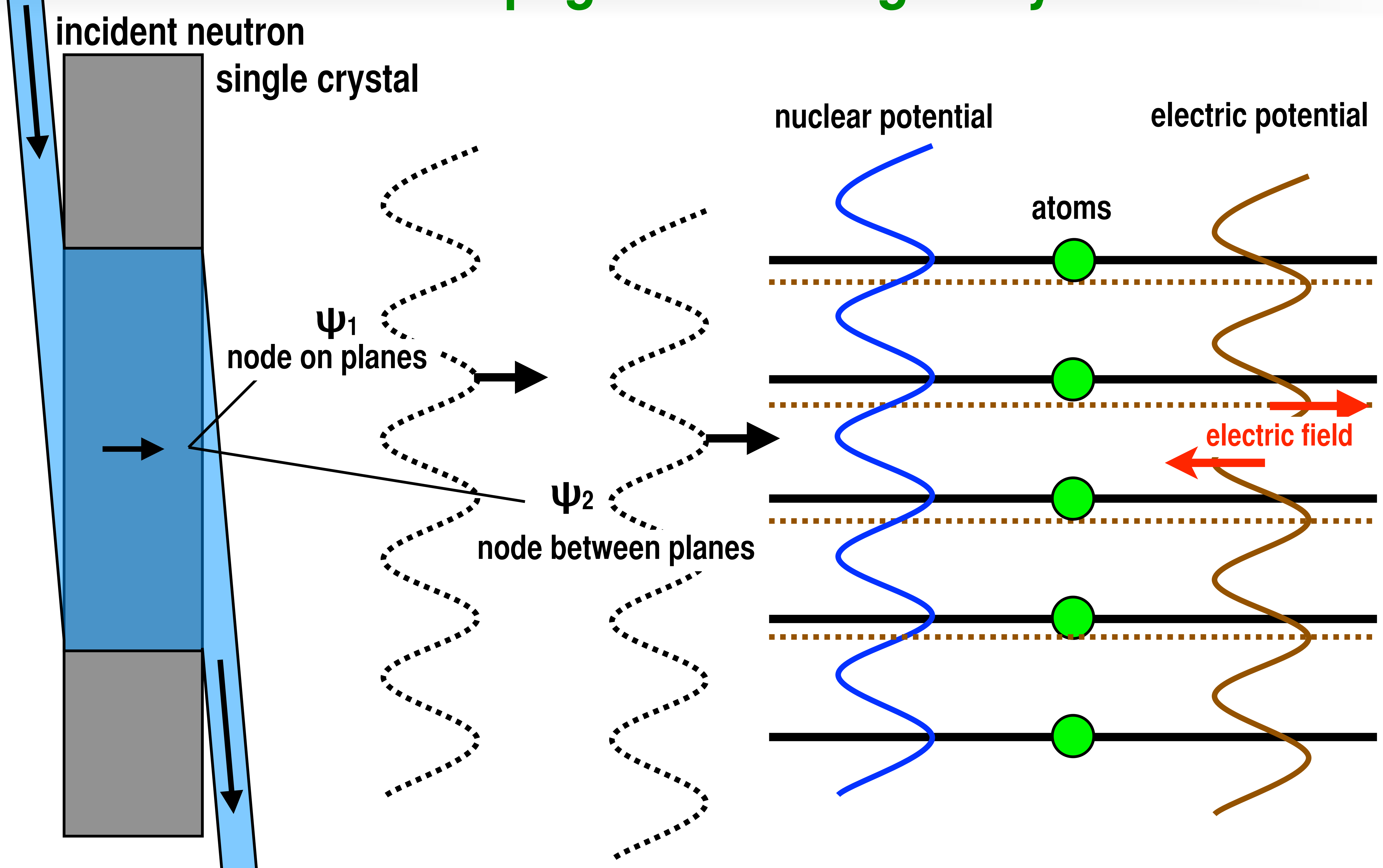
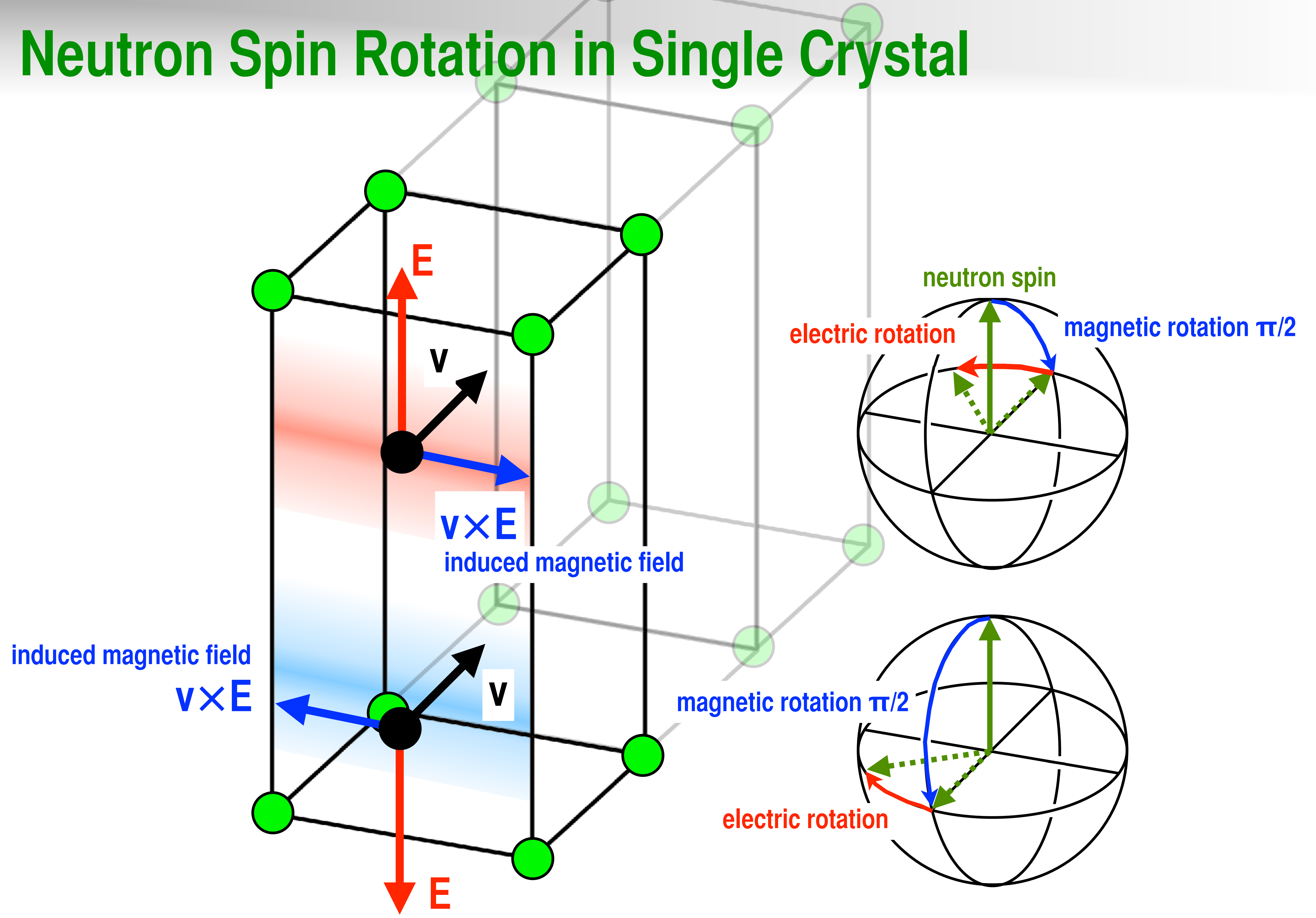


Neutron Spin Rotation in Single Crystal



Measurement of Neutron Electric Dipole Moment

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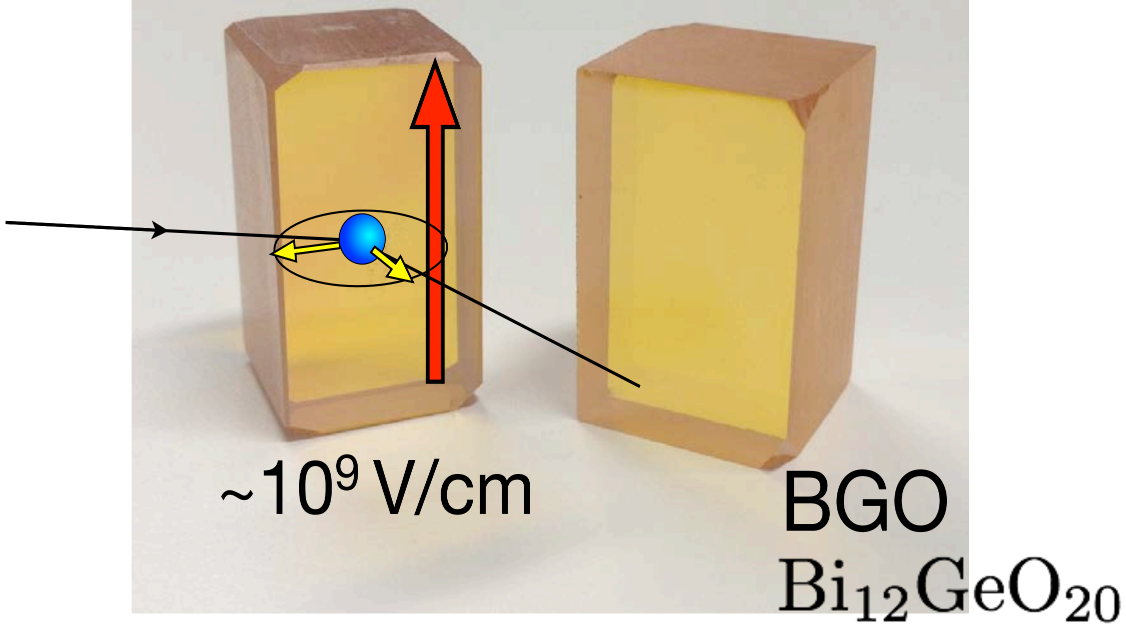
completeness of crystal is under study



by S.Itoh, M.Kitaguchi, …

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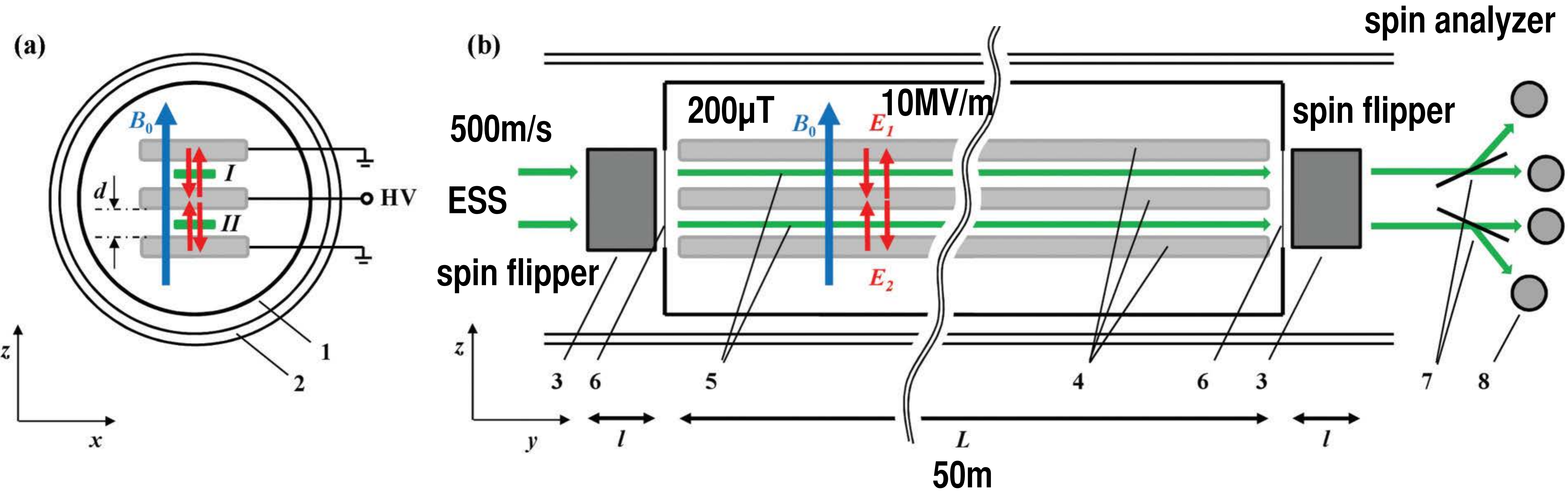
In-flight Measurement
of Neutron Electric Dipole Moment

F.Piegsa, Phys. Rev. C 88 (2013) 045502

$|d_n| \sim 5x10^{-28}$ e cm / 100 days



Physics

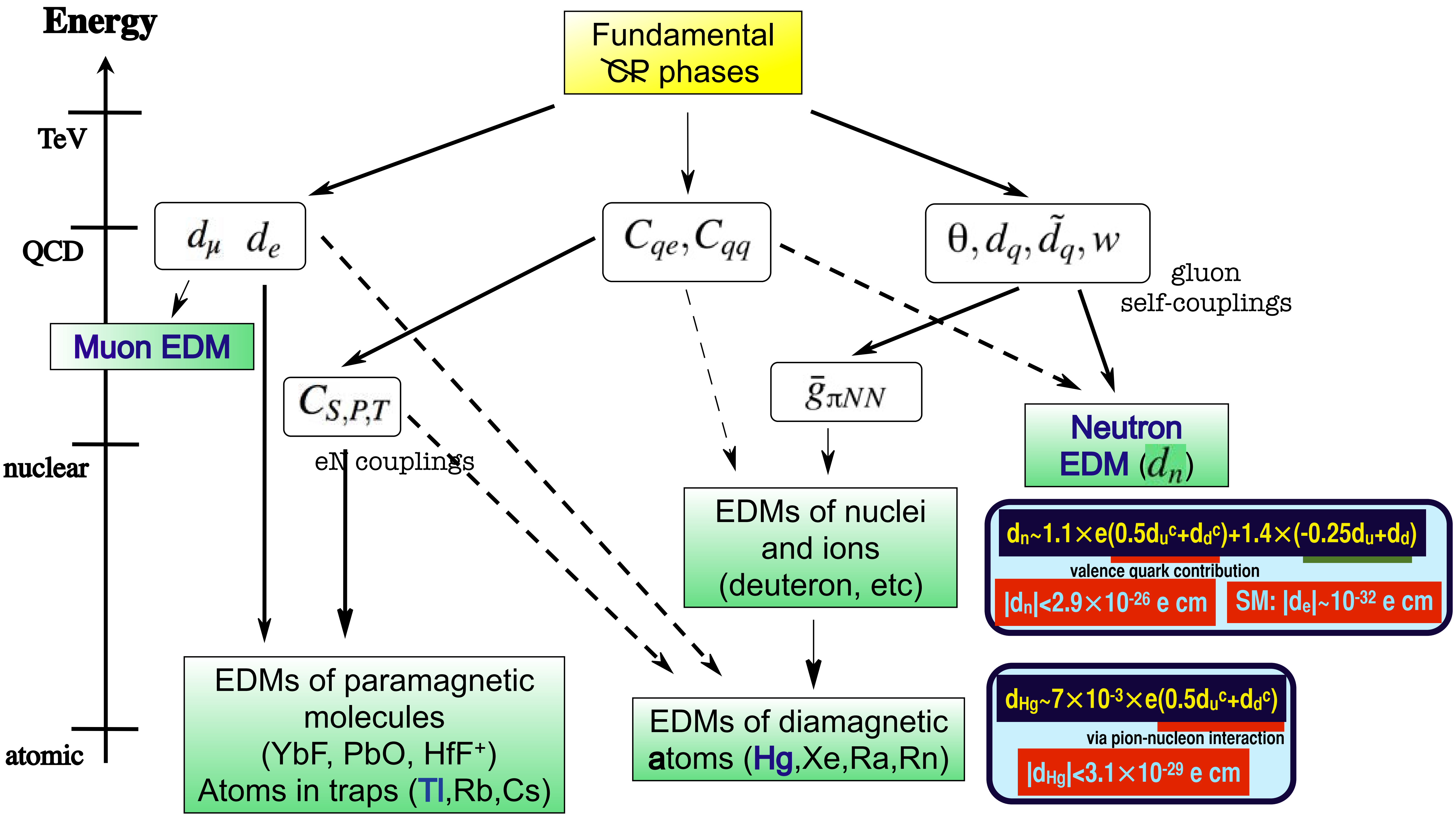
Discrete Symmetry Violation
in Neutron-induced Compound States

KEK 2018S12

NOPTREX Collaboration

Neutron Optics for Parity and Time Reversal EXperiment

CP-violation in Low Energy Phenomena



Energy

TeV

QCD

nuclear

atomic

Fundamental $\cancel{CP}$ phases

$d_\mu \quad d_e$

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

gluon self-couplings

Muon EDM

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Neutron EDM (d_n)

EDMs of nuclei and ions (deuteron, etc)

EDMs of paramagnetic molecules (YbF, PbO, HfF⁺) Atoms in traps (**Tl**,Rb,Cs)

EDMs of diamagnetic atoms (**Hg**,Xe,Ra,Rn)

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Pospelov Ritz, Ann Phys 318 (05) 119

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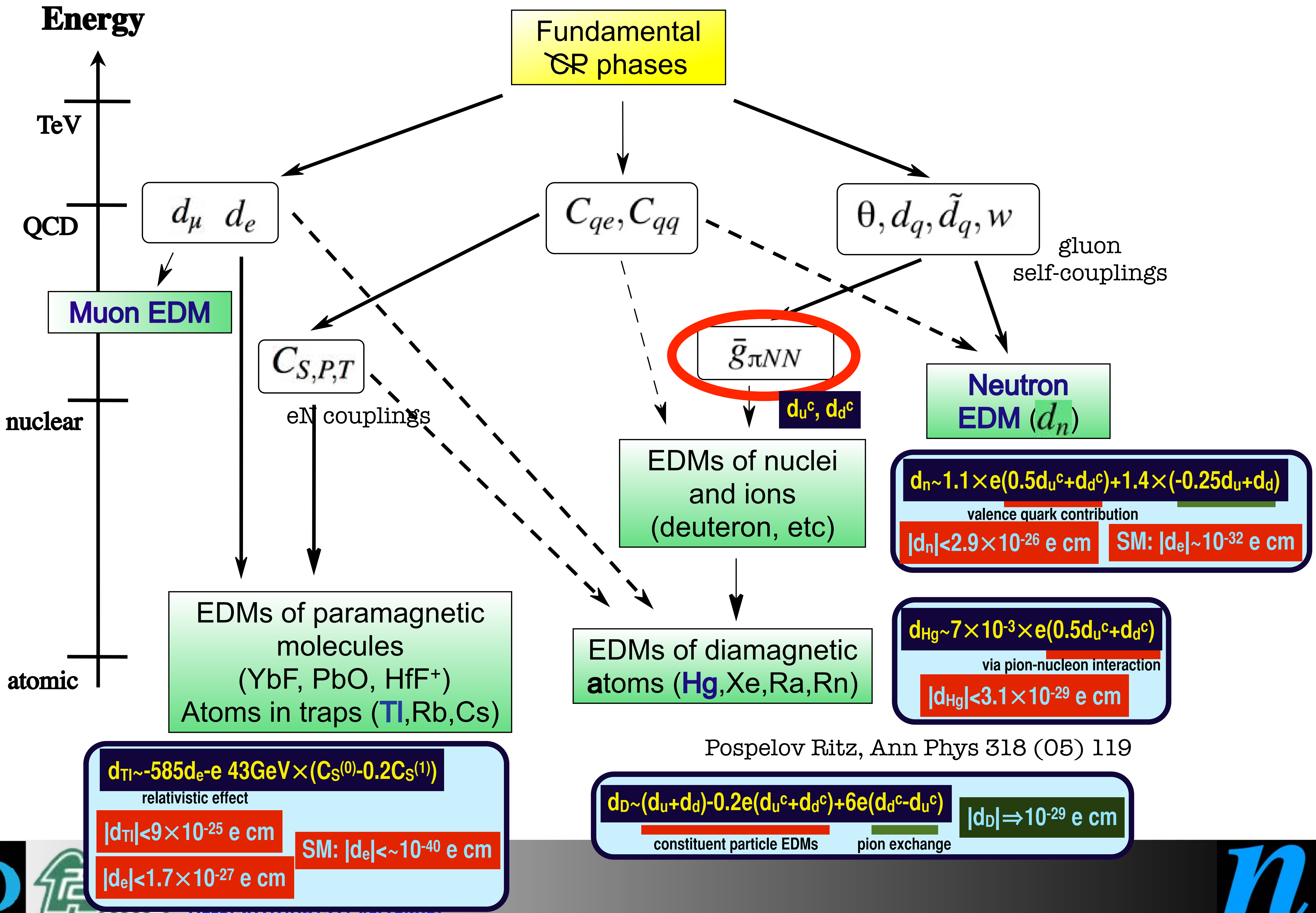

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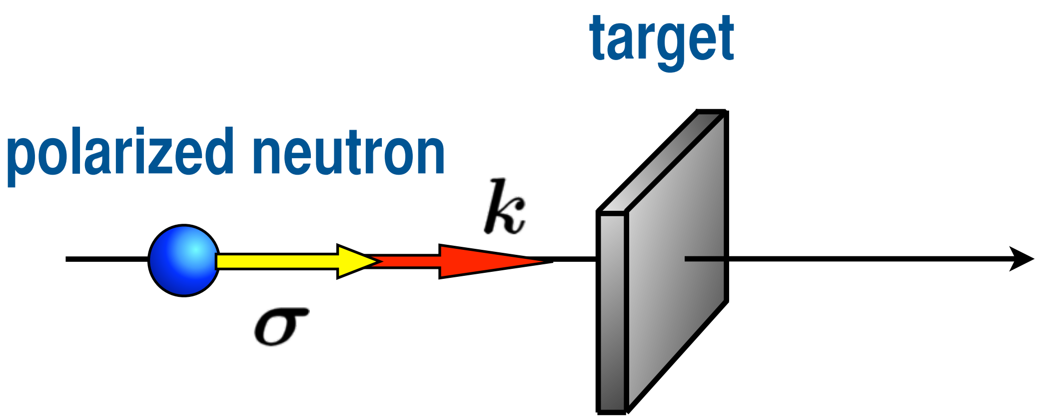
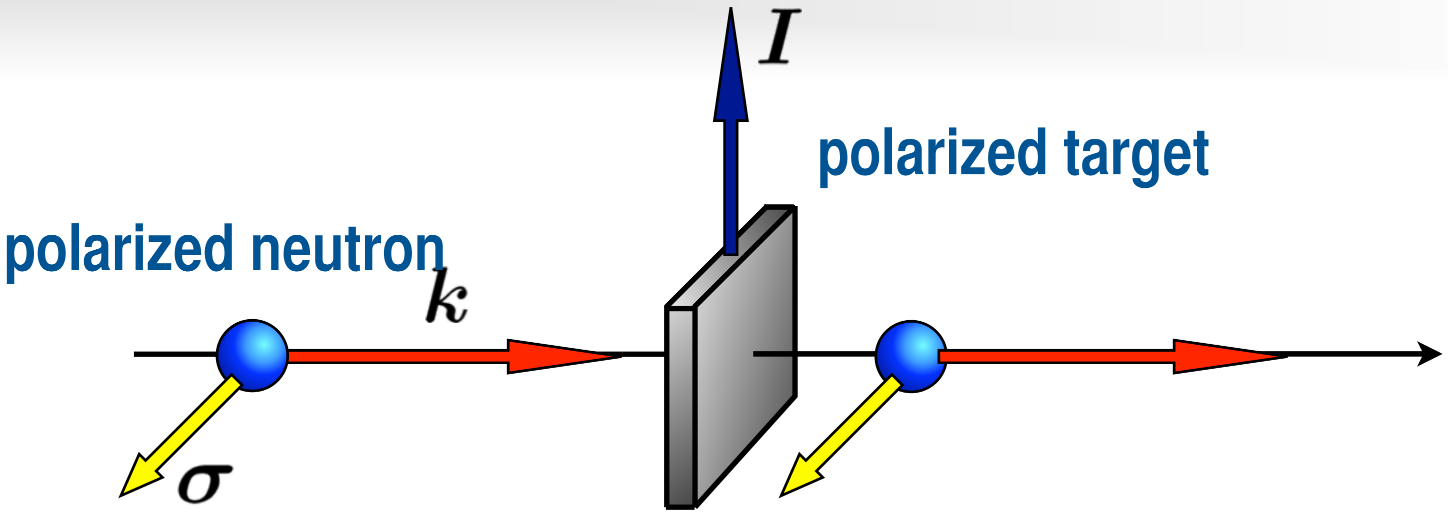


$$\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}$$

$$P:\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}\rightarrow\boldsymbol{\sigma}\cdot(-\hat{\boldsymbol{k}})$$

P-odd

$\cancel{P}$



$$\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{k}}\times\hat{\boldsymbol{I}})$$

$$P:\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{k}}\times\hat{\boldsymbol{I}})\rightarrow\boldsymbol{\sigma}\cdot((-\hat{\boldsymbol{k}})\times\hat{\boldsymbol{I}})$$

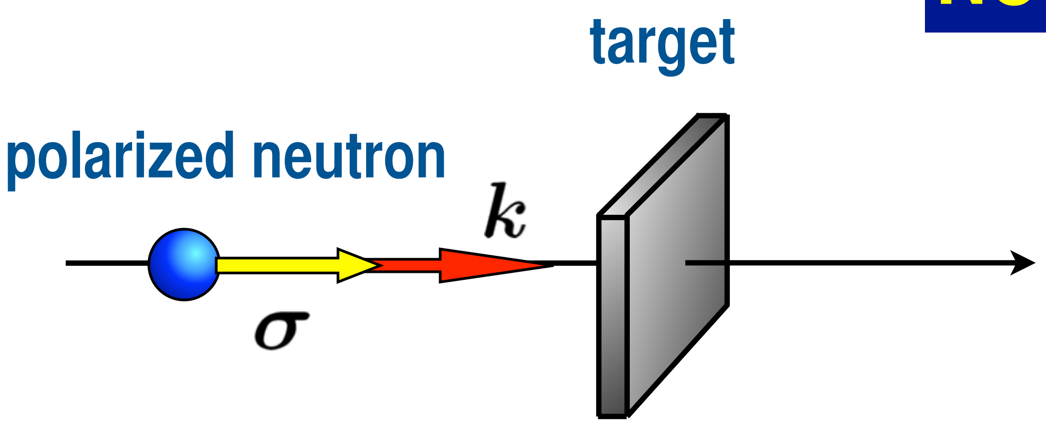
$$T:\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{k}}\times\hat{\boldsymbol{I}})\rightarrow(-\boldsymbol{\sigma})\cdot((-\hat{\boldsymbol{k}})\times(-\hat{\boldsymbol{I}}))$$

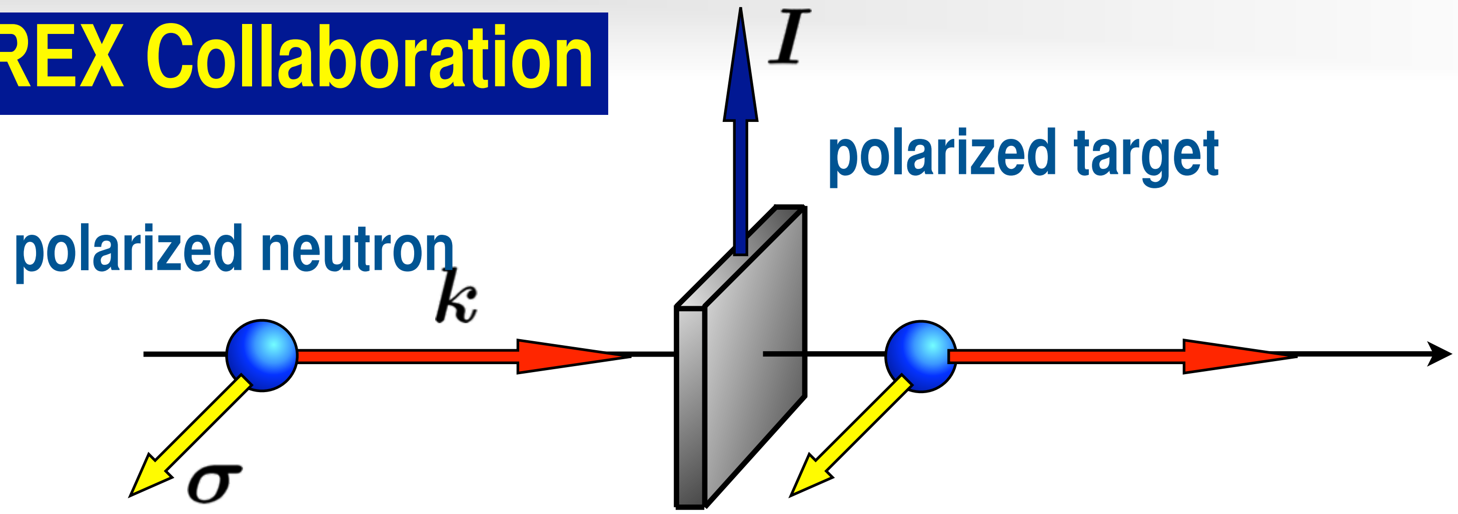
P-odd T-odd

$\cancel{T}$

Neutron Optics for Parity and Time Reversal EXperiment

NOPTREX Collaboration





$$\boldsymbol{\sigma} \cdot \hat{\boldsymbol{k}}$$

$$\boldsymbol{\sigma} \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}})$$

$$P : \boldsymbol{\sigma} \cdot \hat{\boldsymbol{k}} \rightarrow \boldsymbol{\sigma} \cdot (-\hat{\boldsymbol{k}})$$

$$P : \boldsymbol{\sigma} \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}}) \rightarrow \boldsymbol{\sigma} \cdot ((-\hat{\boldsymbol{k}}) \times \hat{\boldsymbol{I}})$$

$$T : \boldsymbol{\sigma} \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}}) \rightarrow (-\boldsymbol{\sigma}) \cdot ((-\hat{\boldsymbol{k}}) \times (-\hat{\boldsymbol{I}}))$$

P-odd

P-odd T-odd

$\cancel{P}$

$\cancel{T}$

KEK 2018S12

Neutron Optics for Parity and Time Reversal EXperiment

NOPTREX Collaboration

Nagoya University

H.M.Shimizu, M.Kitaguchi, K.Hirota, T.Yamamoto, K.Ishizaki, S.Endoh, T.Sato, Y.Niinomi, T.Morishima, G.Ichikawa, Y.Kiyanagi, J.Hisano, N,Wada, T.Matsushita

Kyushu University

T.Yoshioka, S.Takada, J.Koga, S.Makise

JAEA

T.Okudaira, K.Sakai, A.Kimura, H.Harada

KEK

T.Ino, S.Ishimoto, K.Taketani, K.Mishima, C.C.Haddock

Hiroshima Univ.

M.Iinuma

Tokyo Inst. Tech.

H.Fujioka

Univ. British Columbia

T.Momose

Osaka Univ.

K.Ogata, H.Kohri, M.Yosoi, T.Shima, H.Yoshikawa

Tohoku Univ.

M.Fujita

RIKEN

Y.Yamagata, T.Uesaka, K.Tateishi, H.Ikegami

Yamagata Univ.

T.Iwata, Y.Miyachi

Ashikaga Univ.

D.Takahashi

Japan Women's Univ.

R.Ishiguro

Kyoto Univ.

Y.I.Takahashi, M.Hino

Indiana University

W.M.Snow, J.Curole, J.Carini

Univ. South Carolina

V.Gudkov

Oak Ridge National Lab.

J.D.Bowman, S.Penttila, X.Tong, P.Jiang

Kentucky Univ.

B.Plaster, D.Schaper, C.Crawford

Paul Scherrer Institut

P.Hautle

Southern Illinois University

B.M.Goodson

Univ. California Berkeley

A.S.Tremsin

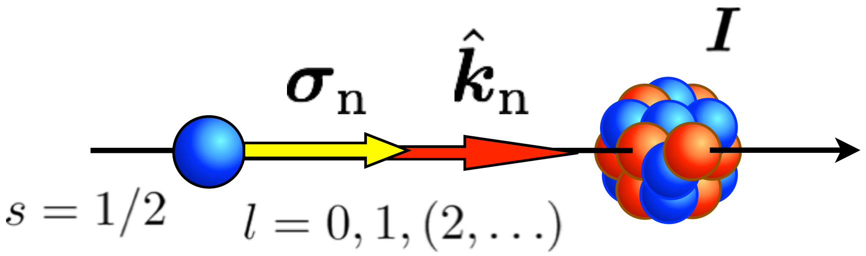
Berea College

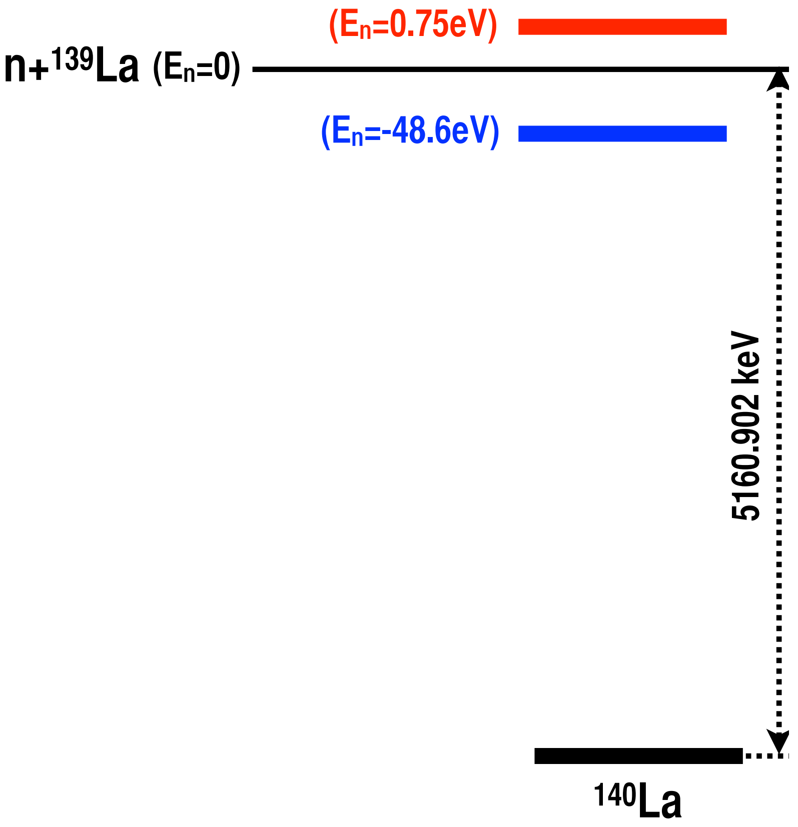
M.Veillette

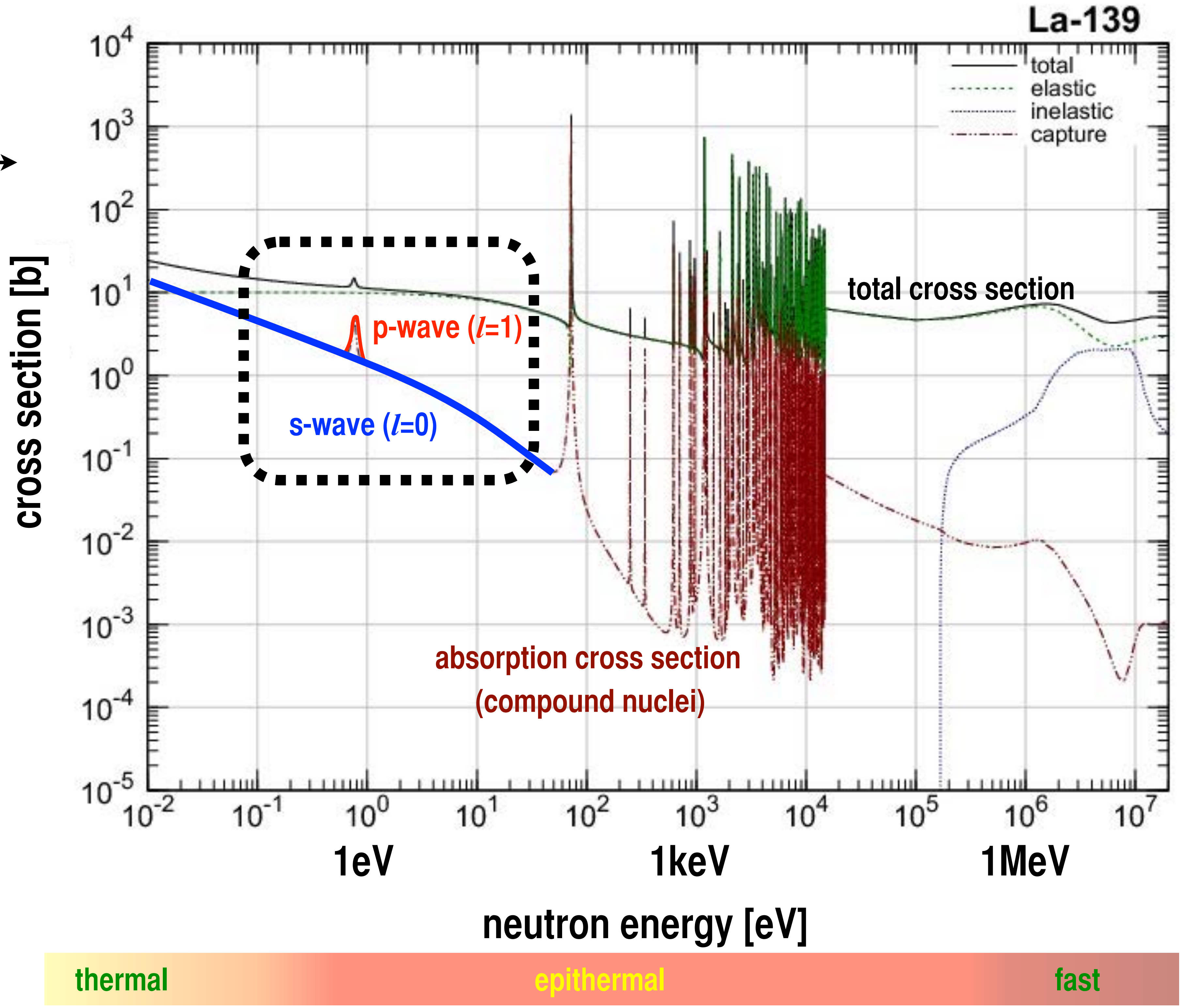
Compound States

P-violation

$$\sigma = \sigma_0 + \boxed{\Delta\sigma}(\boldsymbol{\sigma}_{\rm n} \cdot \hat{\boldsymbol{k}}_{\rm n})$$



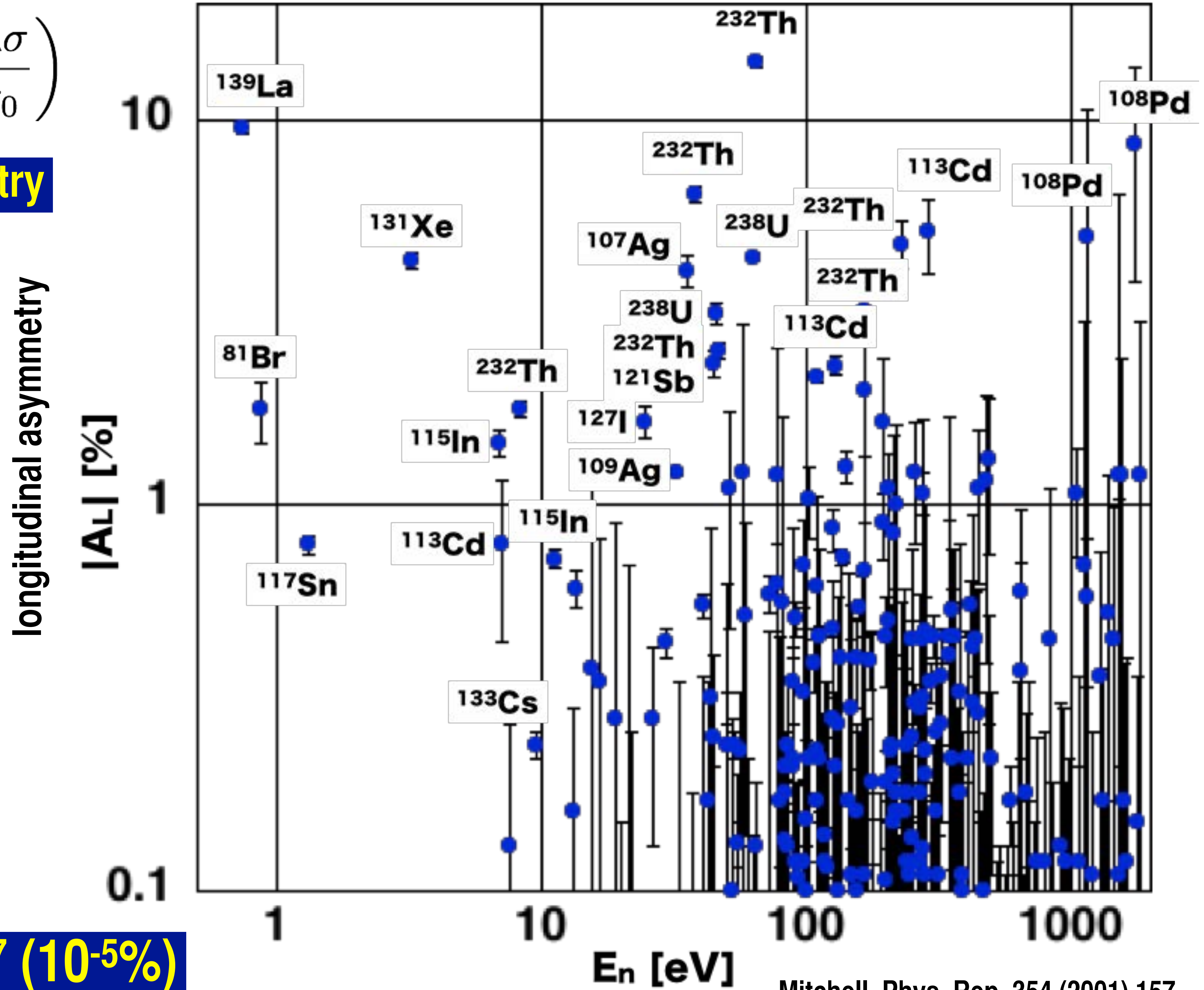




Enhanced P-violation in Compound States

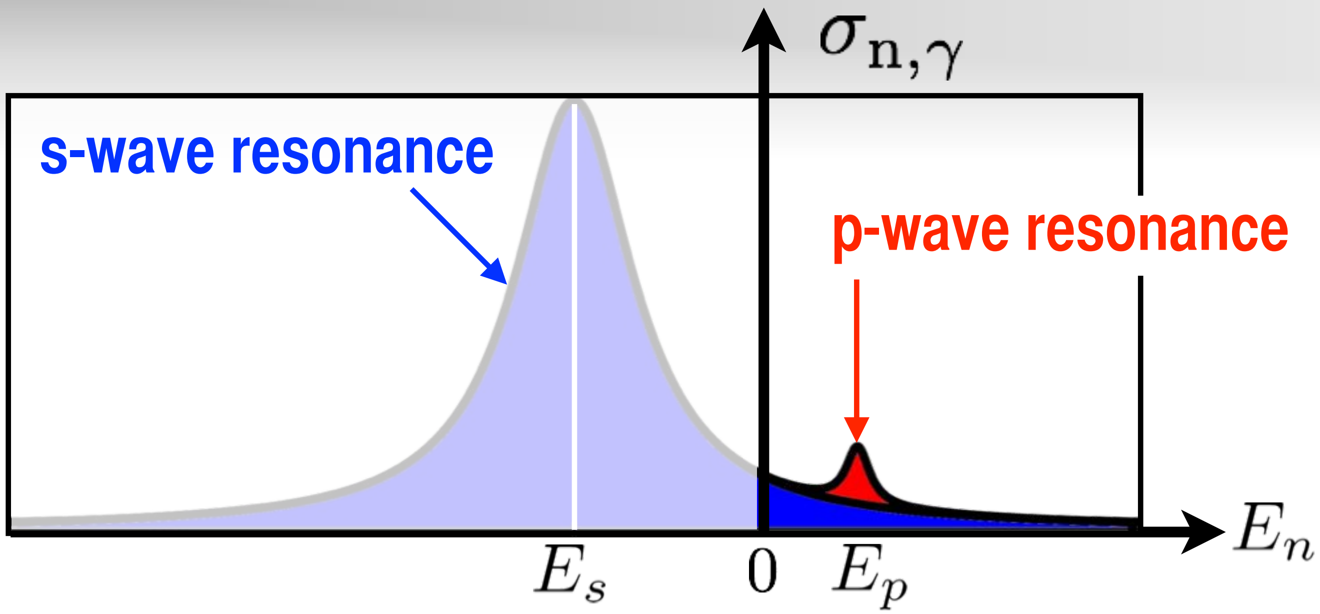
$$A_{\mathrm{L}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \left(= \frac{\Delta\sigma}{\sigma_0} \right)$$

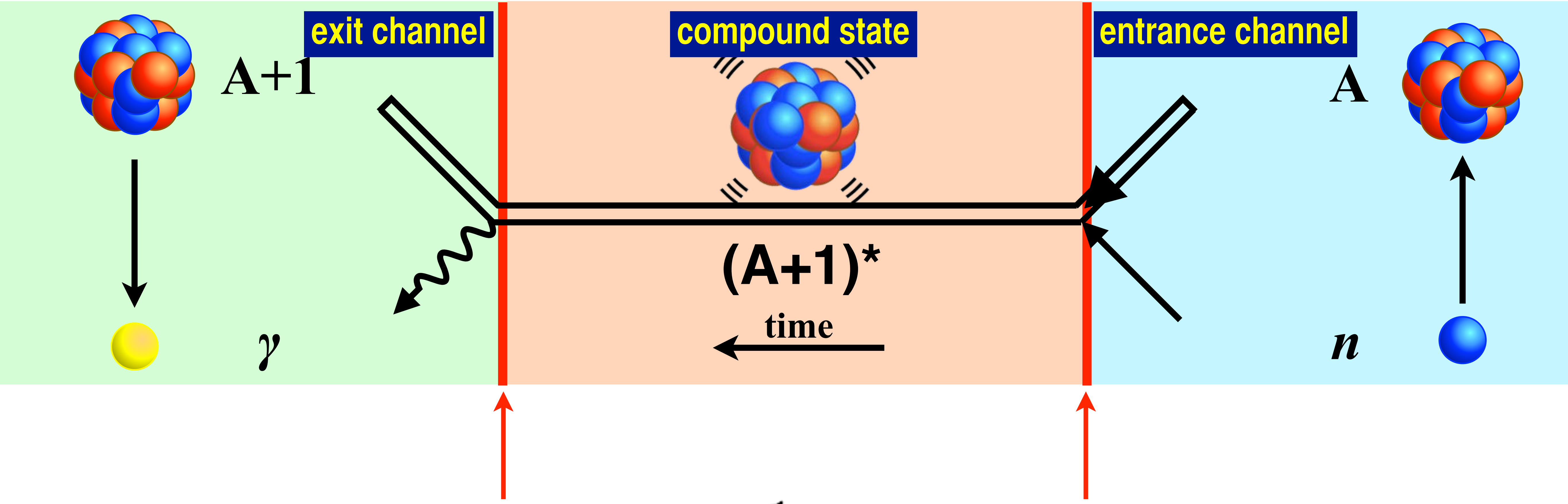
Longitudinal Asymmetry



Mitchell, Phys. Rep. 354 (2001) 157

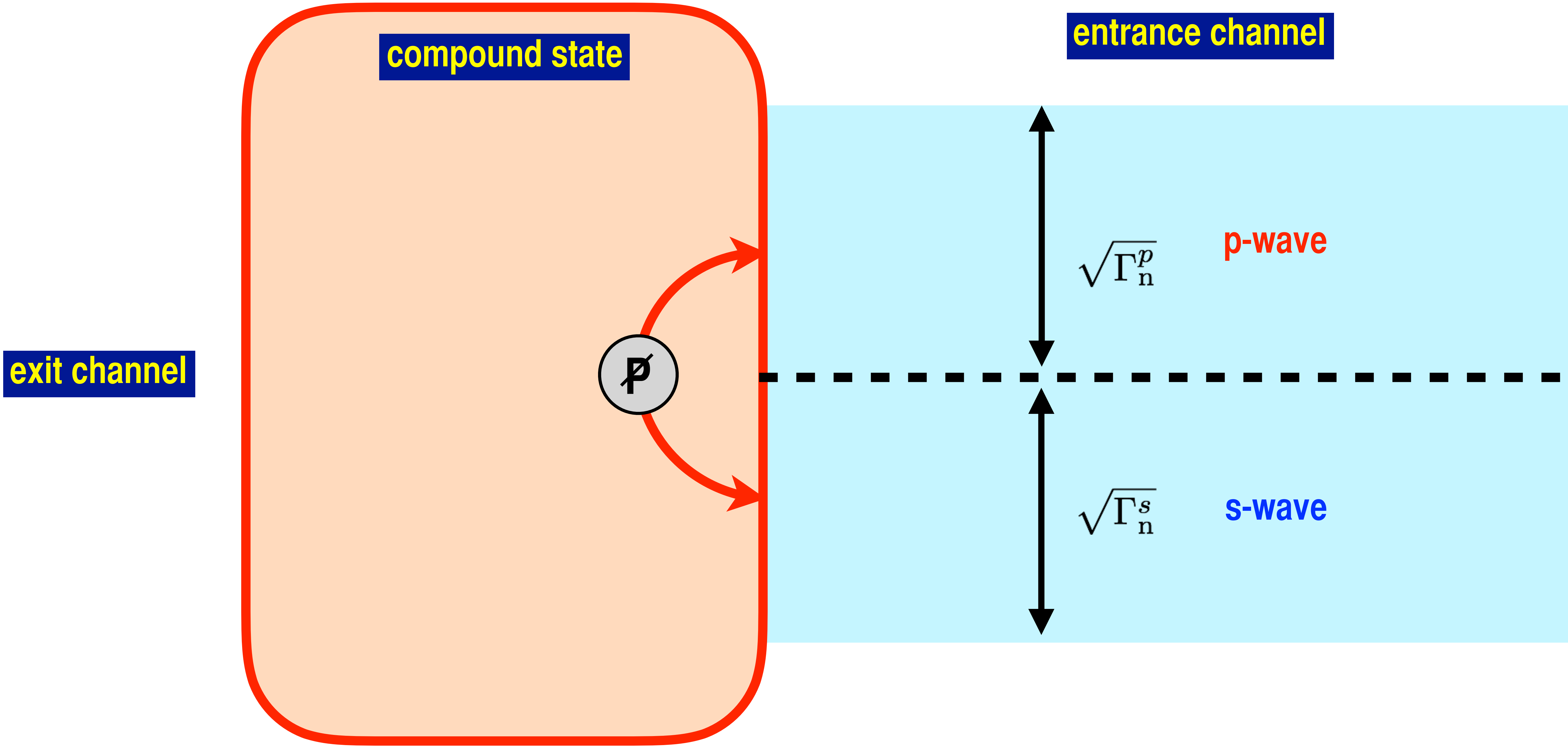
NN-interaction 10^{-7} (10^{-5}%)



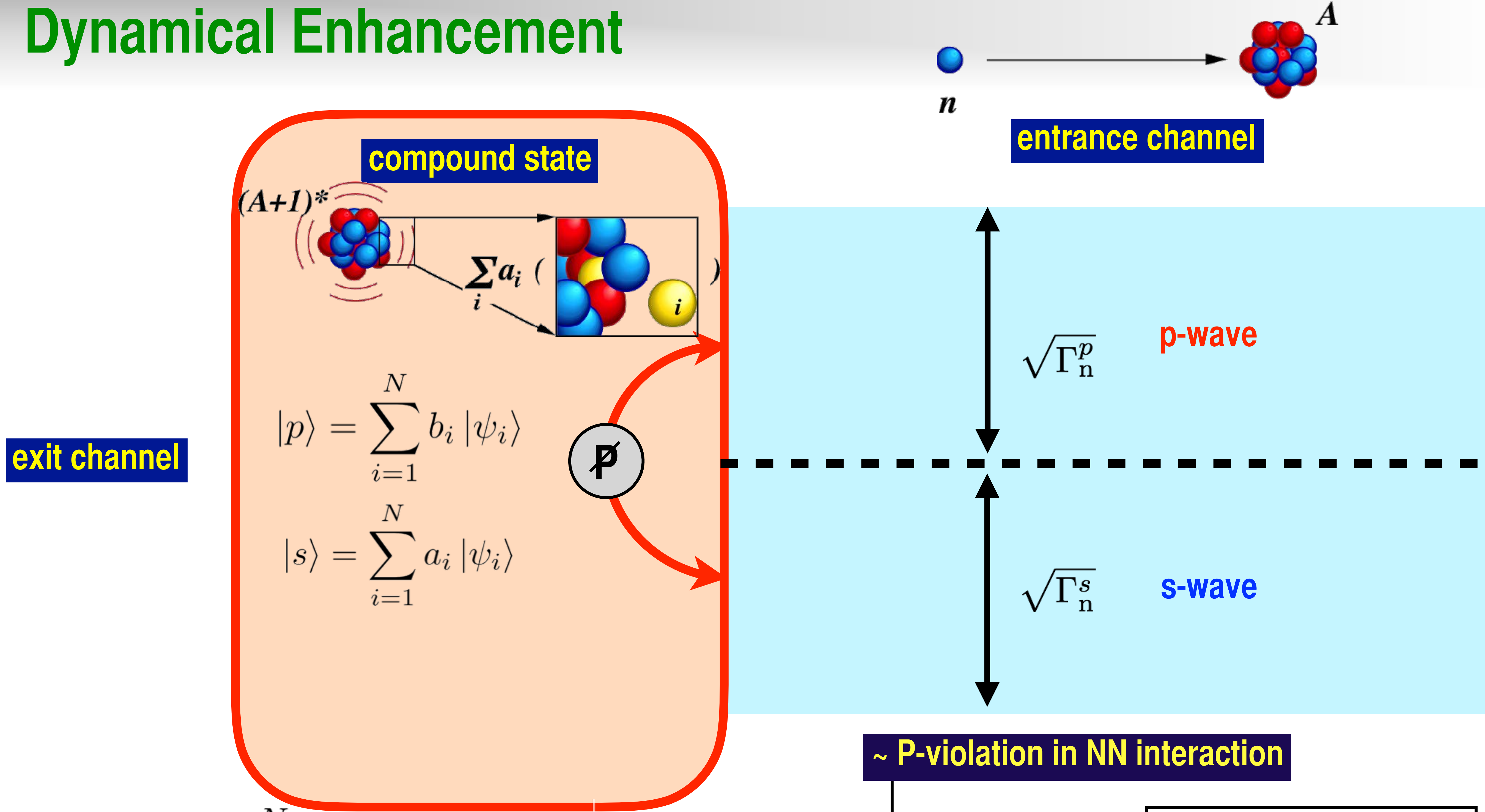


$$\sqrt{\Gamma_\gamma}\frac{1}{E-E_0+i\Gamma/2}\sqrt{\Gamma_\mathrm{n}}$$

Dynamical Enhancement



Dynamical Enhancement



entrance channel

compound state

exit channel

$$|p\rangle = \sum_{i=1}^{N} b_i \, |\psi_i\rangle$$

$$|s\rangle = \sum_{i=1}^{N} a_i \, |\psi_i\rangle$$

p-wave

s-wave

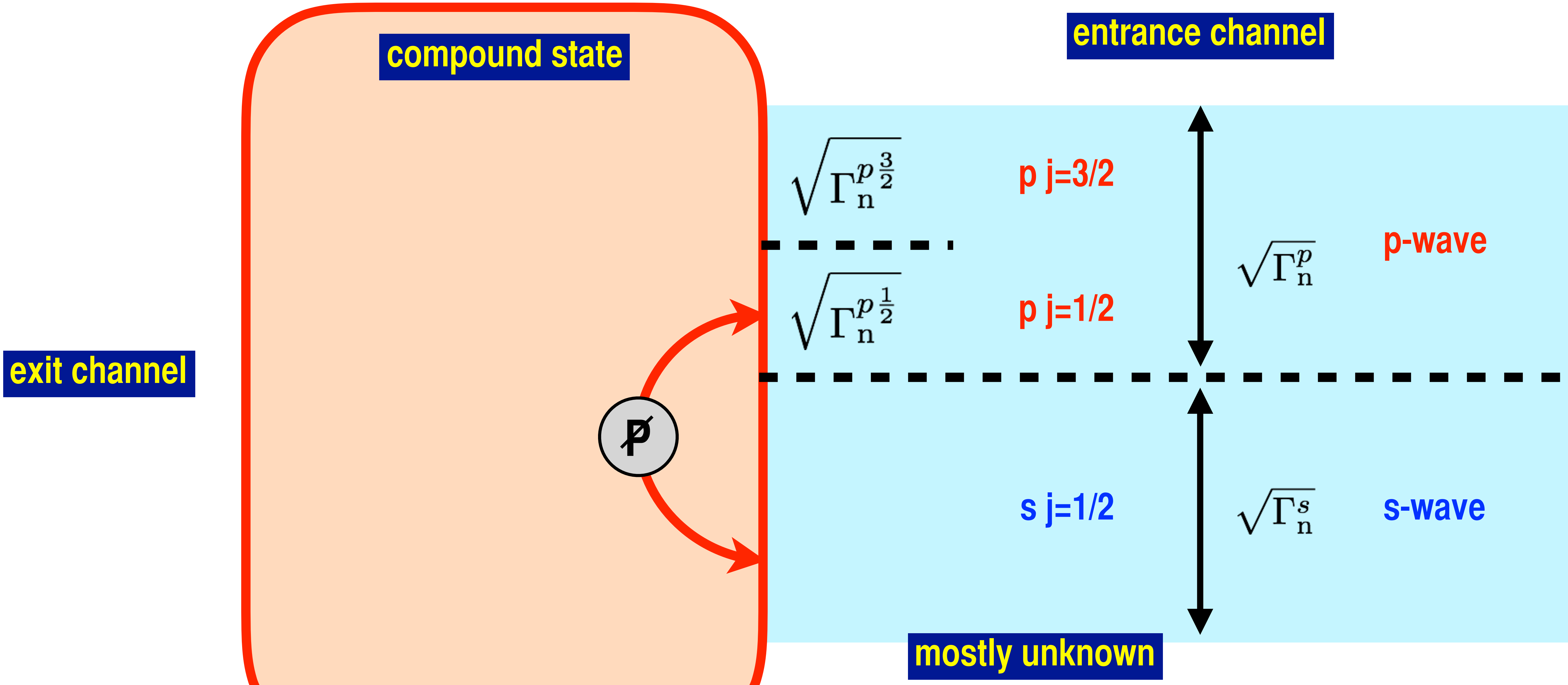
~ P-violation in NN interaction

$$\langle s|W|p\rangle = \sum_{i,j}^{N} a_i^* b_j \langle \psi_i|W|\psi_j\rangle \sim \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N}} \langle W\rangle \sqrt{N}$$

randomness of expansion coefficients

$$N \sim \frac{\overset{10^6\text{ eV}}{\Delta E}}{\underset{10\text{ eV}}{D}} \sim 10^5$$

Universality Check



$$x$$

$$A_{\mathrm{L}} = -\frac{2W}{E_{\mathrm{p}} - E_{\mathrm{s}}}\sqrt{\frac{\Gamma_{\mathrm{n}}^{s}}{\Gamma_{\mathrm{n}}^{p}}}\sqrt{\frac{\Gamma_{\mathrm{n}}^{p\frac{1}{2}}}{\Gamma_{\mathrm{n}}^{p}}}$$

$$x = \sqrt{\frac{\Gamma_{\mathrm{n}}^{p\frac{1}{2}}}{\Gamma_{\mathrm{n}}^{p}}} \quad y = \sqrt{\frac{\Gamma_{\mathrm{n}}^{p\frac{3}{2}}}{\Gamma_{\mathrm{n}}^{p}}}$$

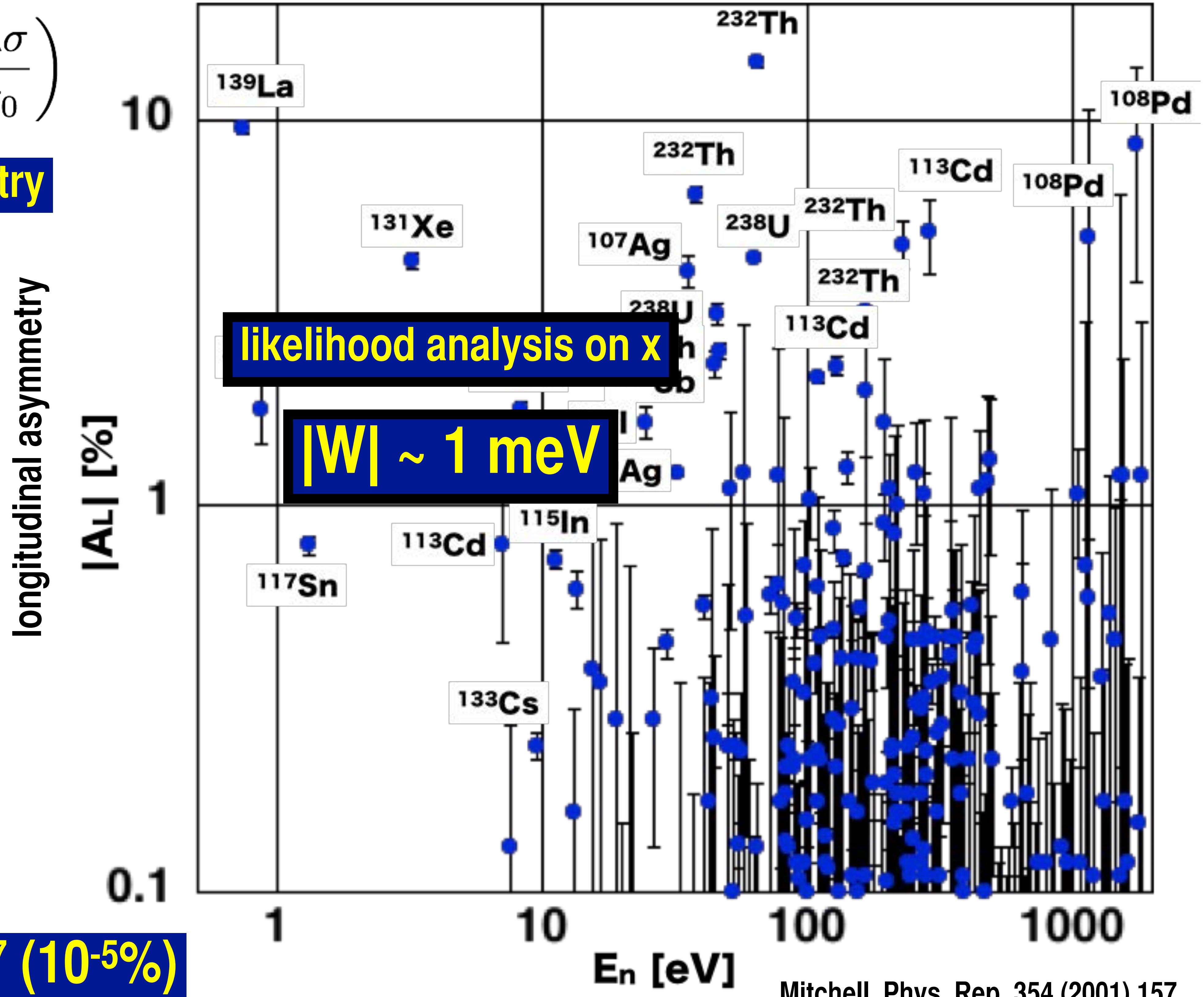
$$x^2 + y^2 = 1$$

$$x = \cos\phi \quad y = \sin\phi$$

Enhanced P-violation in Compound States

$$A_{\mathrm{L}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \left(= \frac{\Delta\sigma}{\sigma_0} \right)$$

Longitudinal Asymmetry

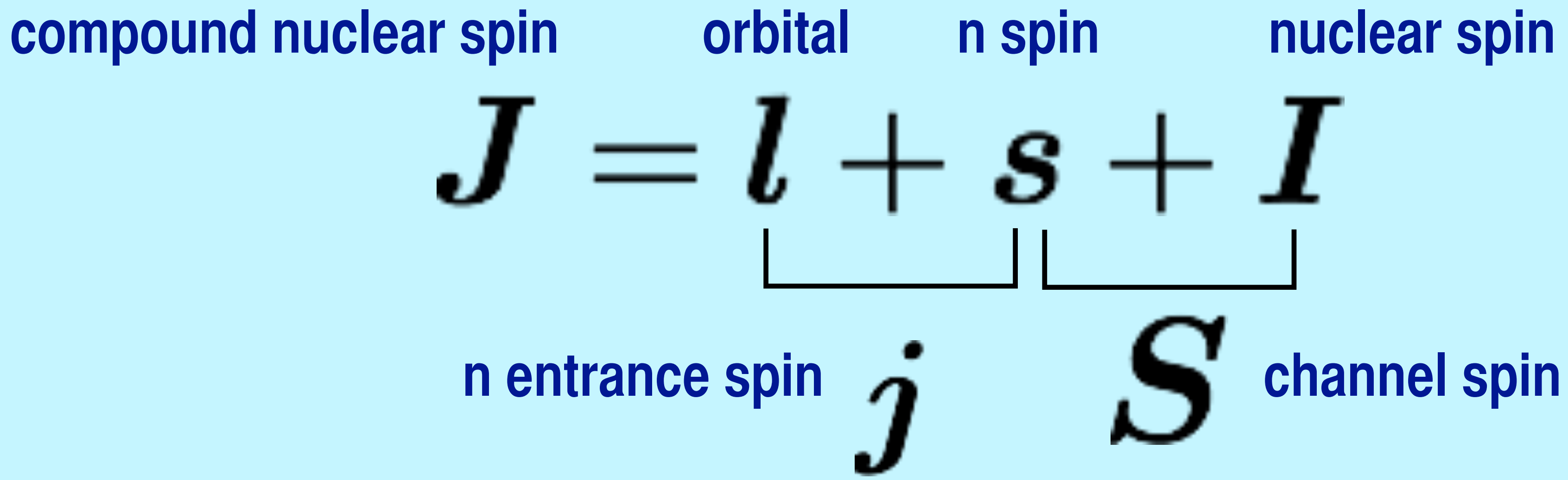


likelihood analysis on x

|W| ~ 1 meV

NN-interaction 10^{-7} (10^{-5}%)

Mitchell, Phys. Rep. 354 (2001) 157



$$\boldsymbol{J} = \boldsymbol{l} + \boldsymbol{s} + \boldsymbol{I}$$

$$\boldsymbol{j} \qquad \boldsymbol{S}$$

$$|((Is)S,l)J\rangle = \sum_j \langle (I,(sl)j)J|((Is)S,l)J\rangle \, |(I,(sl)j)J\rangle$$

$$= \sum_j (-1)^{l+s+I+J} \sqrt{(2j+1)(2S+1)} \left\{ \begin{array}{ccc} I & s & l \\ J & S & j \end{array} \right\} |(I,(sl)j)J\rangle$$

$$x = \sqrt{\frac{\Gamma^p_{\mathrm{n}}(j=1/2)}{\Gamma^p_{\mathrm{n}}}} \qquad y = \sqrt{\frac{\Gamma^p_{\mathrm{n}}(j=3/2)}{\Gamma^p_{\mathrm{n}}}} \qquad x_S = \sqrt{\frac{\Gamma^p_{\mathrm{n}}(S=I-\frac{1}{2})}{\Gamma^p_{\mathrm{n}}}} \qquad y_S = \sqrt{\frac{\Gamma^p_{\mathrm{n}}(S=I+\frac{1}{2})}{\Gamma^p_{\mathrm{n}}}}$$

$$z_j = \left\{ \begin{array}{ll} x & (j=1/2) \\ y & (j=3/2) \end{array} \right. , \quad \tilde{z}_S = \left\{ \begin{array}{ll} x_S & (S=I-1/2) \\ y_S & (S=I+1/2) \end{array} \right. \qquad \tilde{z}_S = \sum_j (-1)^{l+I+j+S} \sqrt{(2j+1)(2S+1)} \left\{ \begin{array}{ccc} l & s & j \\ I & J & S \end{array} \right\} z_j$$

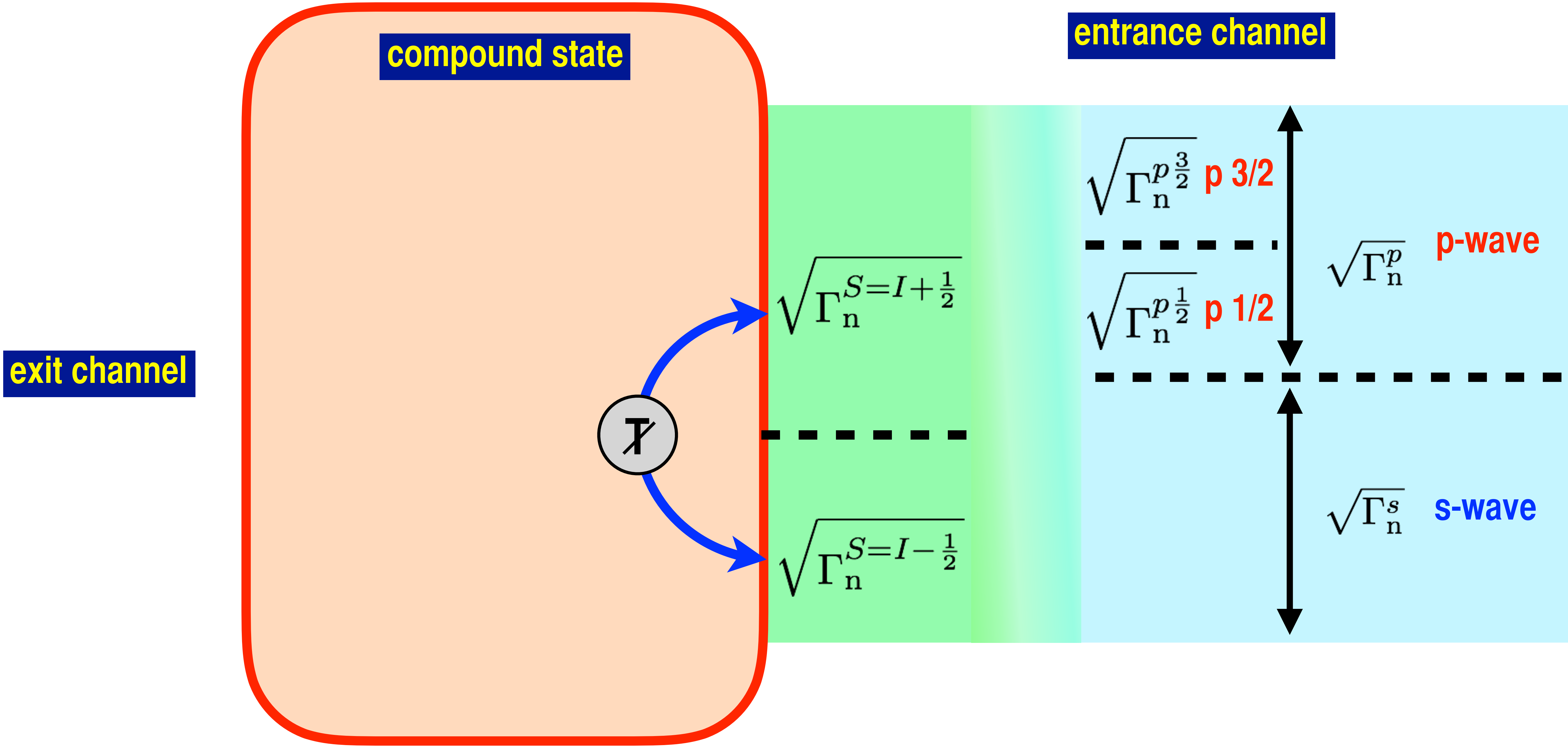
s-p interference ⇔ channel-spin interference

$$P : |lsI\rangle \rightarrow (-1)^l |lsI\rangle \qquad T : |lsI\rangle \rightarrow (-1)^{i\pi S_y} K |lsI\rangle$$

$l = 0, 1$ **P-odd**

$S = I \pm 1/2$ **T-odd**

T-odd ➡ Channel-spin Interference



T-violation in Neutron Optics

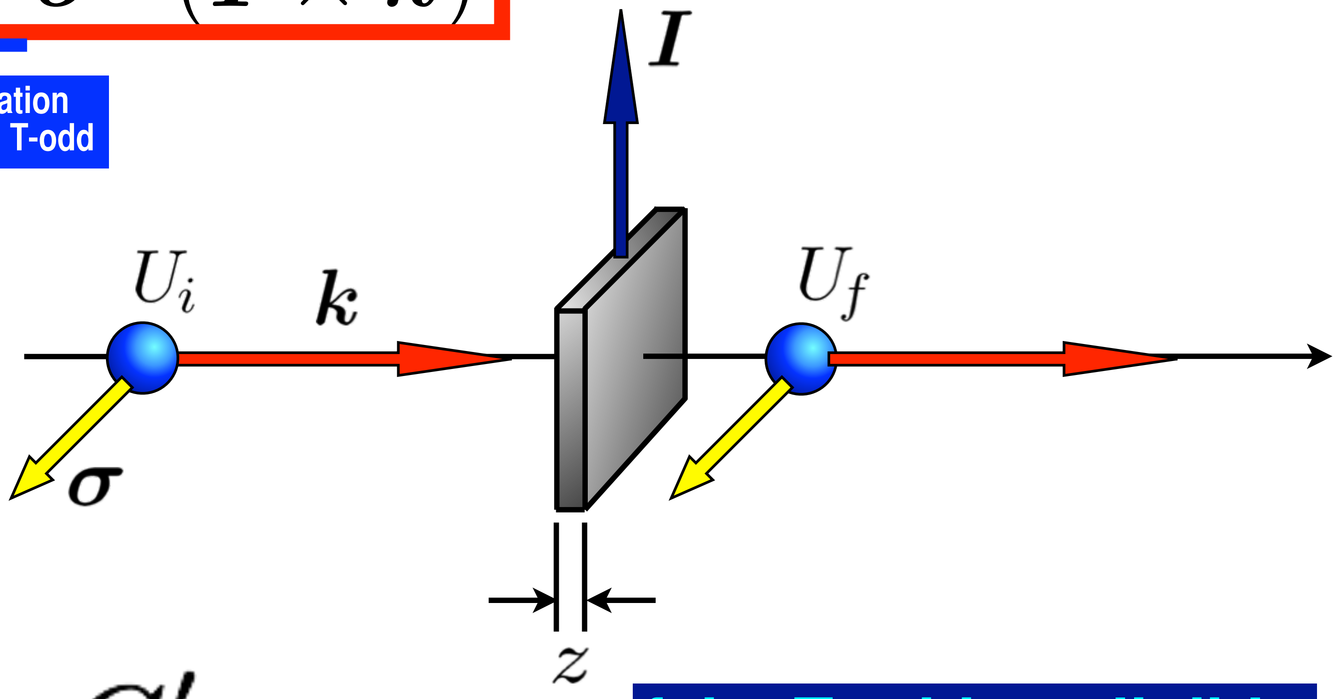
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})}$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd



fake T-odd negligible

T-violating matrix element

C'

$$D' \; \boxed{\Delta\sigma_{\mathrm{CP}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\Delta\sigma_{\mathrm{P}}}$$

Gudkov, Phys. Rep. 212 (1992) 77

T-violation

angular momentum factor

P-violation

P-violating matrix element

T-violation in Neutron Optics

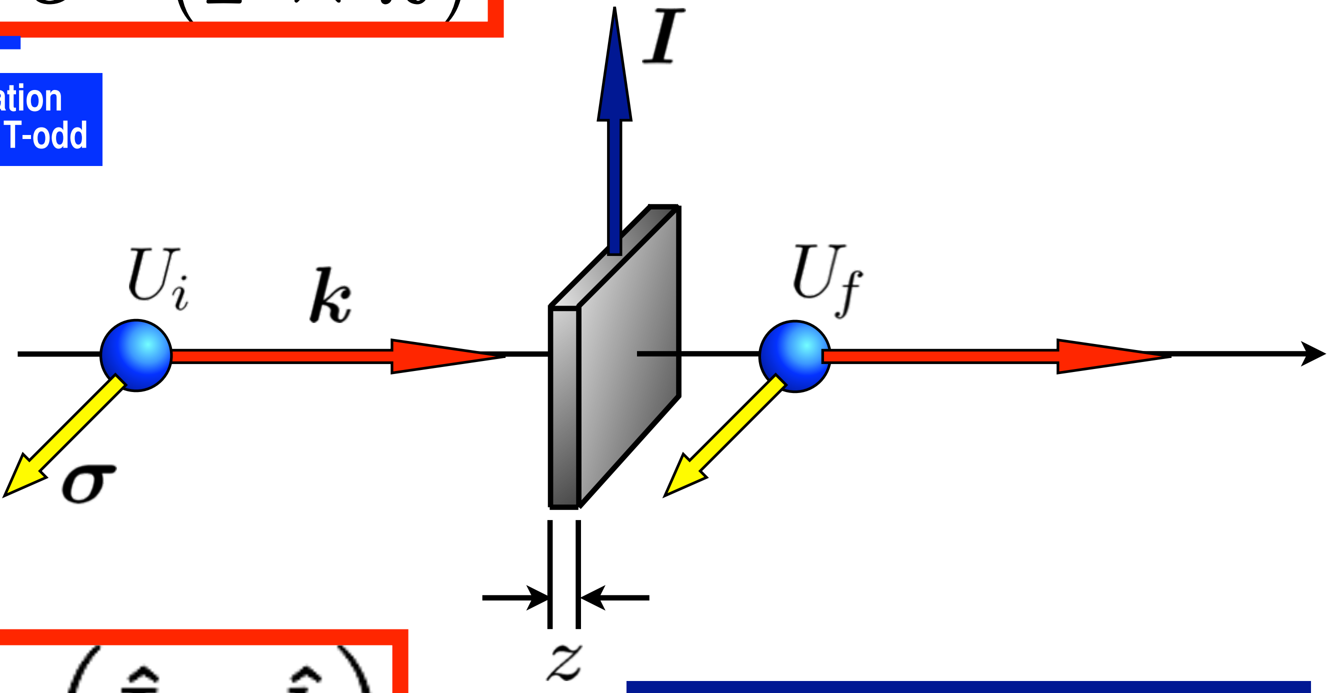
$$f = \underbrace{A'}_{} + \underbrace{B'}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D'}_{}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})}$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd



$$U_f = \delta U_i$$

$$\delta = e^{i(n-1)kz} \qquad n = 1 + \frac{2\pi\rho}{k^2} f$$

$$\delta = \underbrace{A}_{} + \underbrace{B}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C}_{}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \boxed{\underbrace{D}_{}\boldsymbol{\sigma}\cdot\left(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}}\right)}$$

Spin Independent
P-even T-even

Spin Dependent
P-even T-even

P-violation
P-odd T-even

T-violation
P-odd T-odd

fake T-odd negligible

$$A = e^{iZA'}\cos b \qquad B = ie^{iZA'}\frac{\sin b}{b}ZB'$$

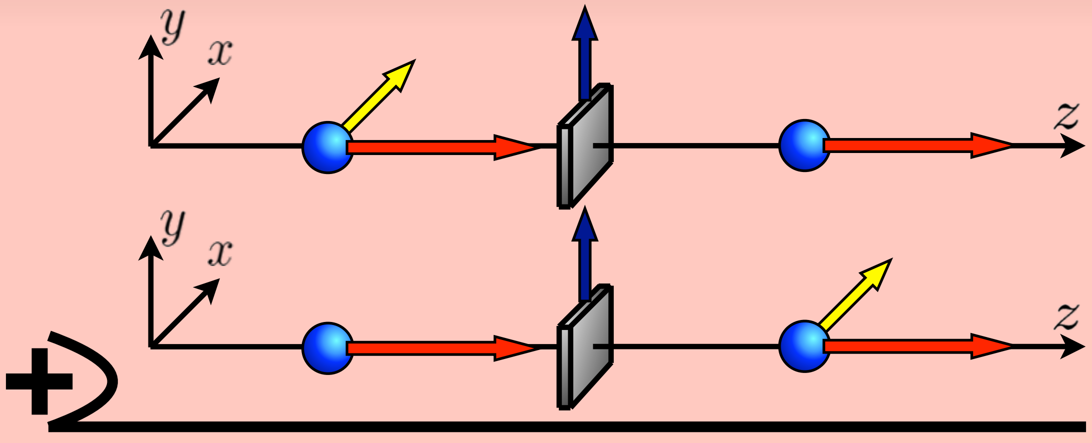
$$Z = \frac{2\pi\rho}{k}z \qquad C = ie^{iZA'}\frac{\sin b}{b}ZC'$$

$$b = Z(B'^2 + C'^2 + D'^2)^{1/2} \qquad D = ie^{iZA'}\frac{\sin b}{b}ZD'$$

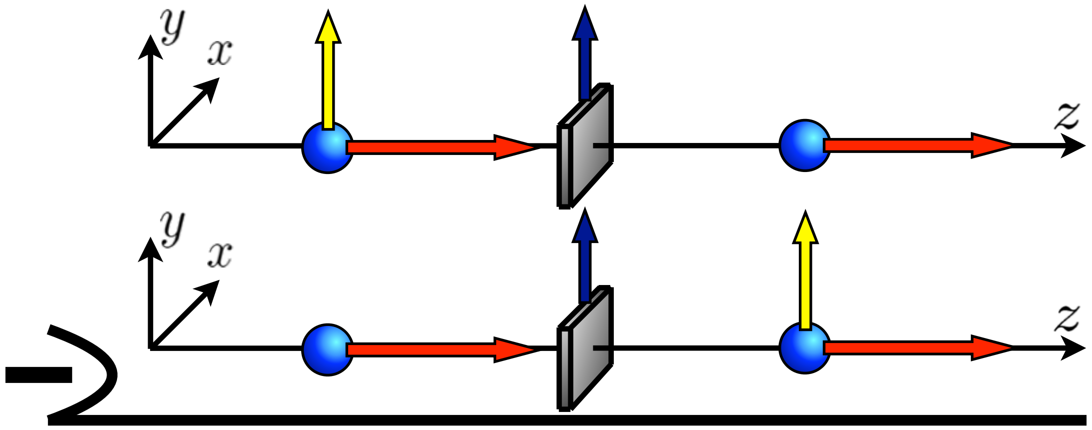
D≠0 ➡ D’≠0

validity of this description can be checked via the consistency among A, B, C

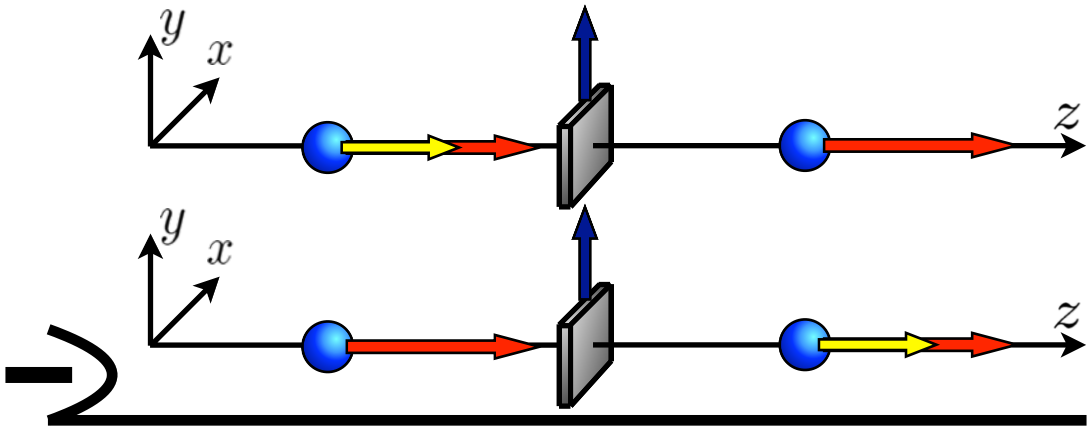
Analyzing Power and Polarization



$$A_x + P_x = 8\mathrm{Re}\, A^* D$$

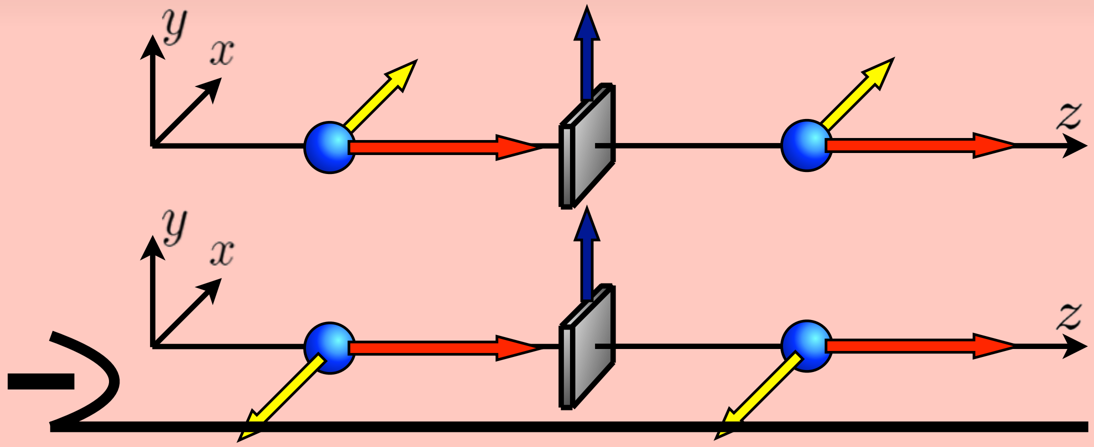


$$A_y - P_y = 8\mathrm{Im}\, C^* D$$

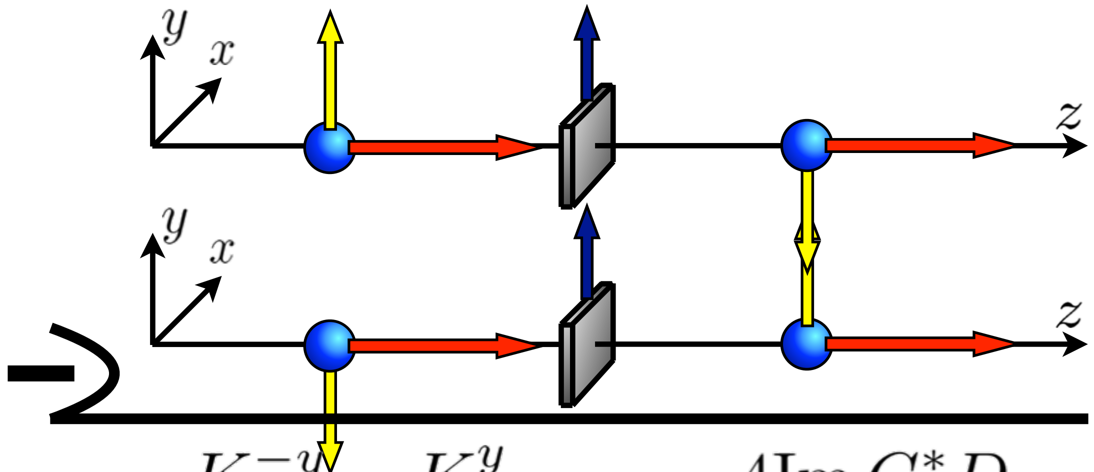


$$A_z - P_z = 8\mathrm{Im}\, D^* B$$

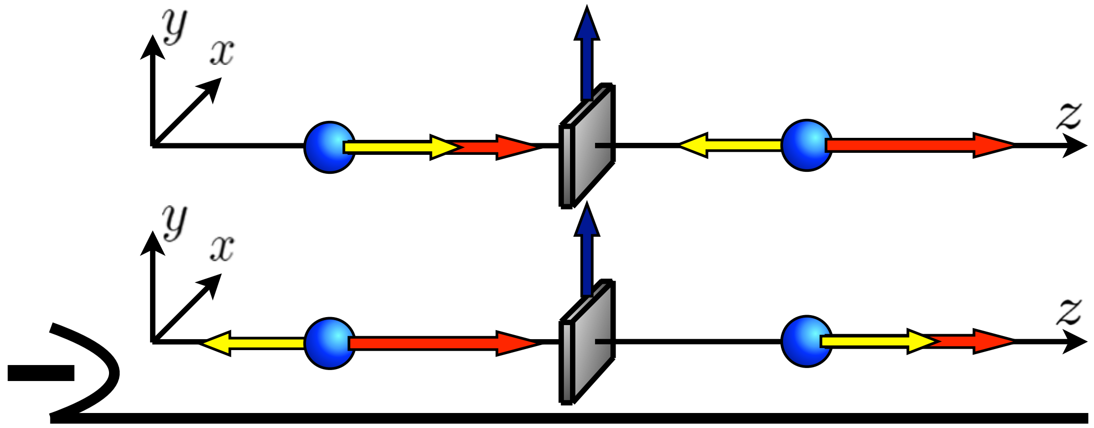
Polarization Transfer Coefficient



$$K_x^x - K_{-x}^{-x} = 4\mathrm{Re}\, A^* D$$

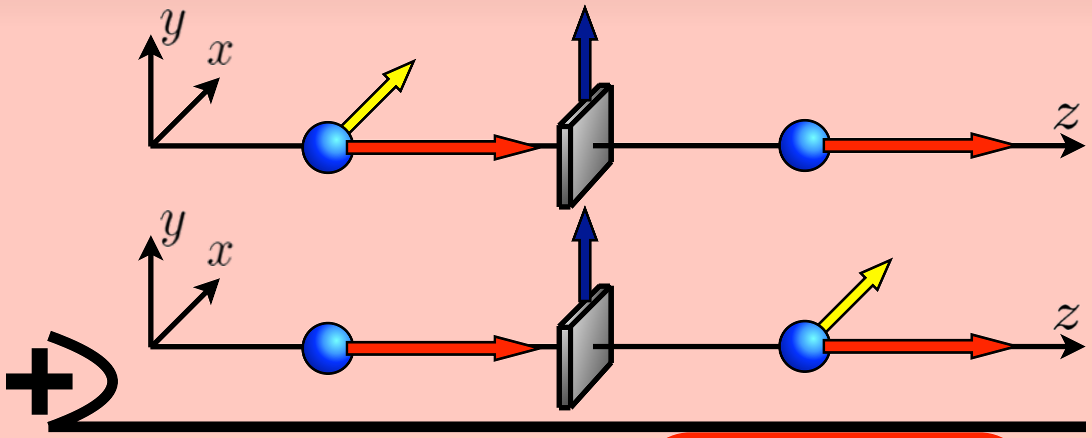


$$K_y^{-y} - K_{-y}^{y} = 4\mathrm{Im}\, C^* D$$

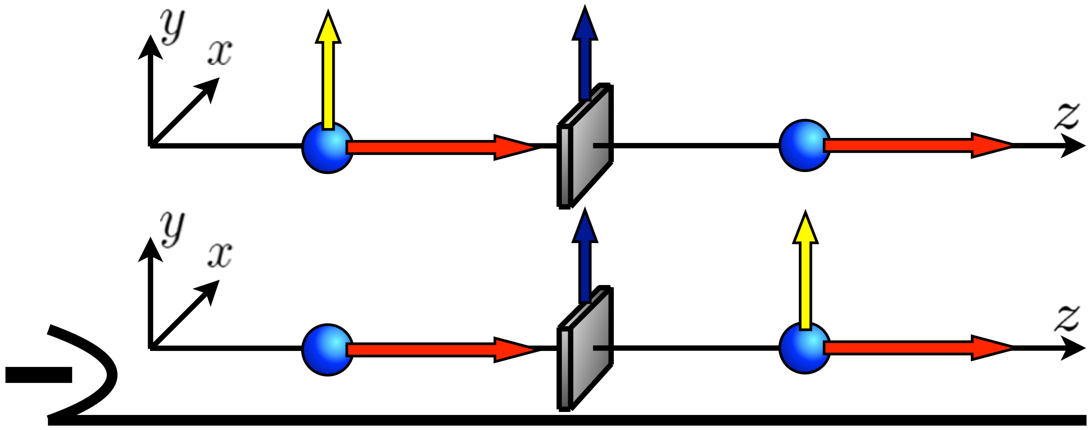


$$K_z^{-z} - K_{-z}^{z} = 4\mathrm{Im}\, D^* B$$

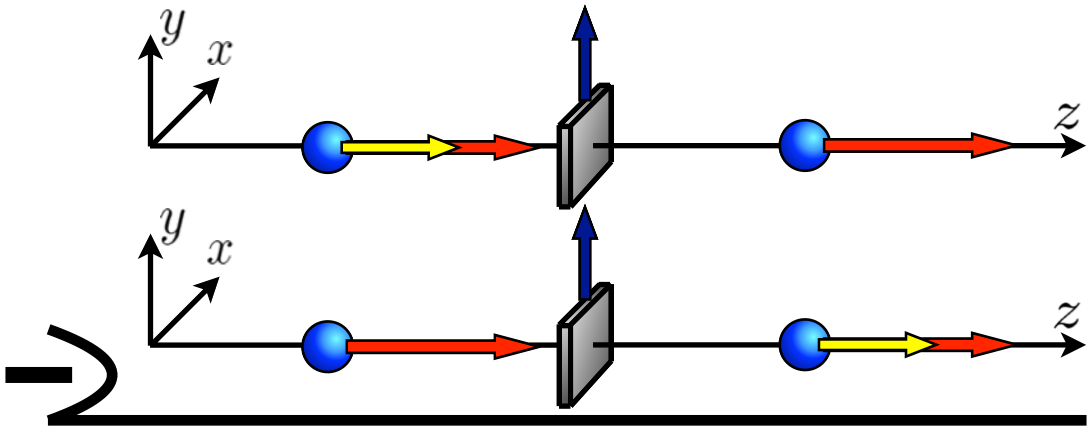
Analyzing Power and Polarization



$$A_x + P_x = \boxed{8\mathrm{Re}\, A^* D}$$



$$A_y - P_y = 8\mathrm{Im}\, C^* D$$



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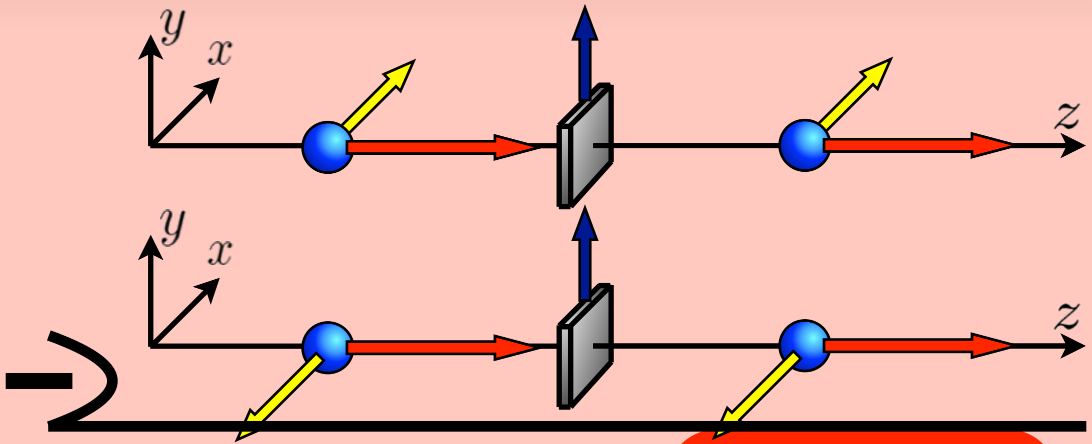
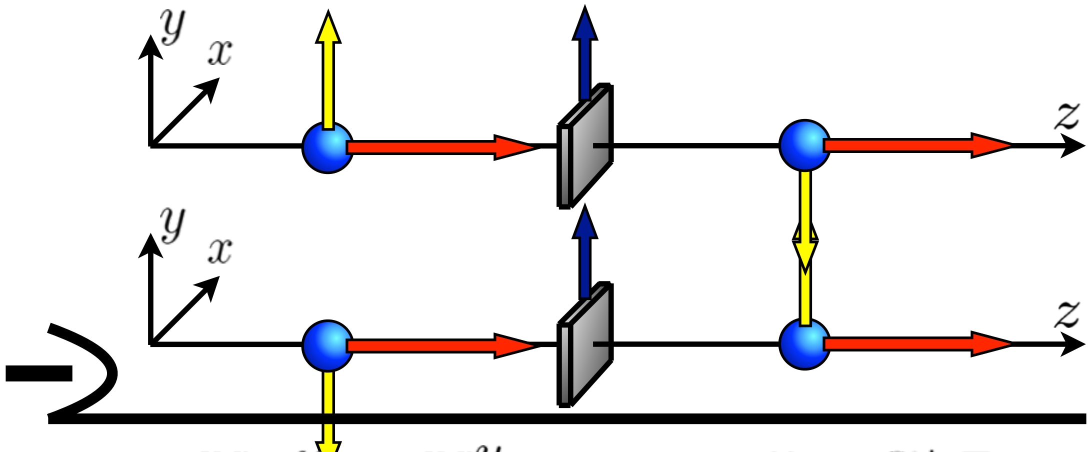
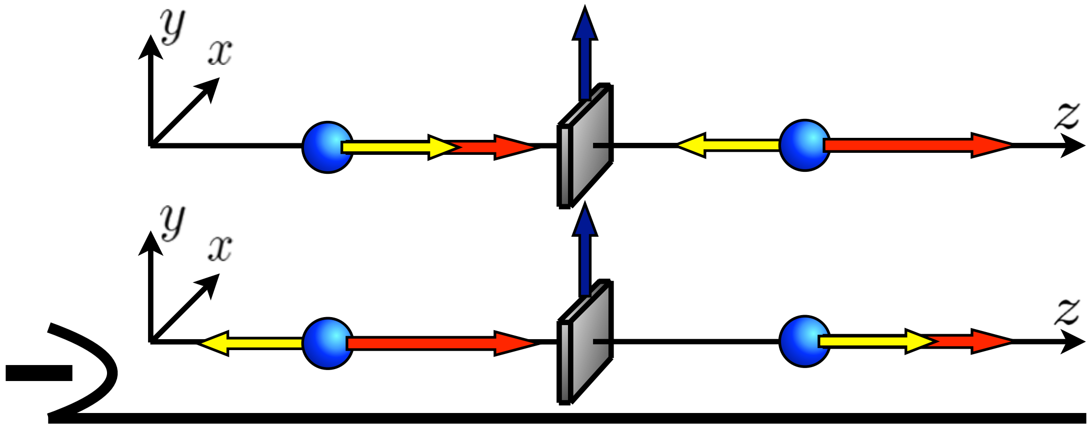
Polarization Transfer Coefficient



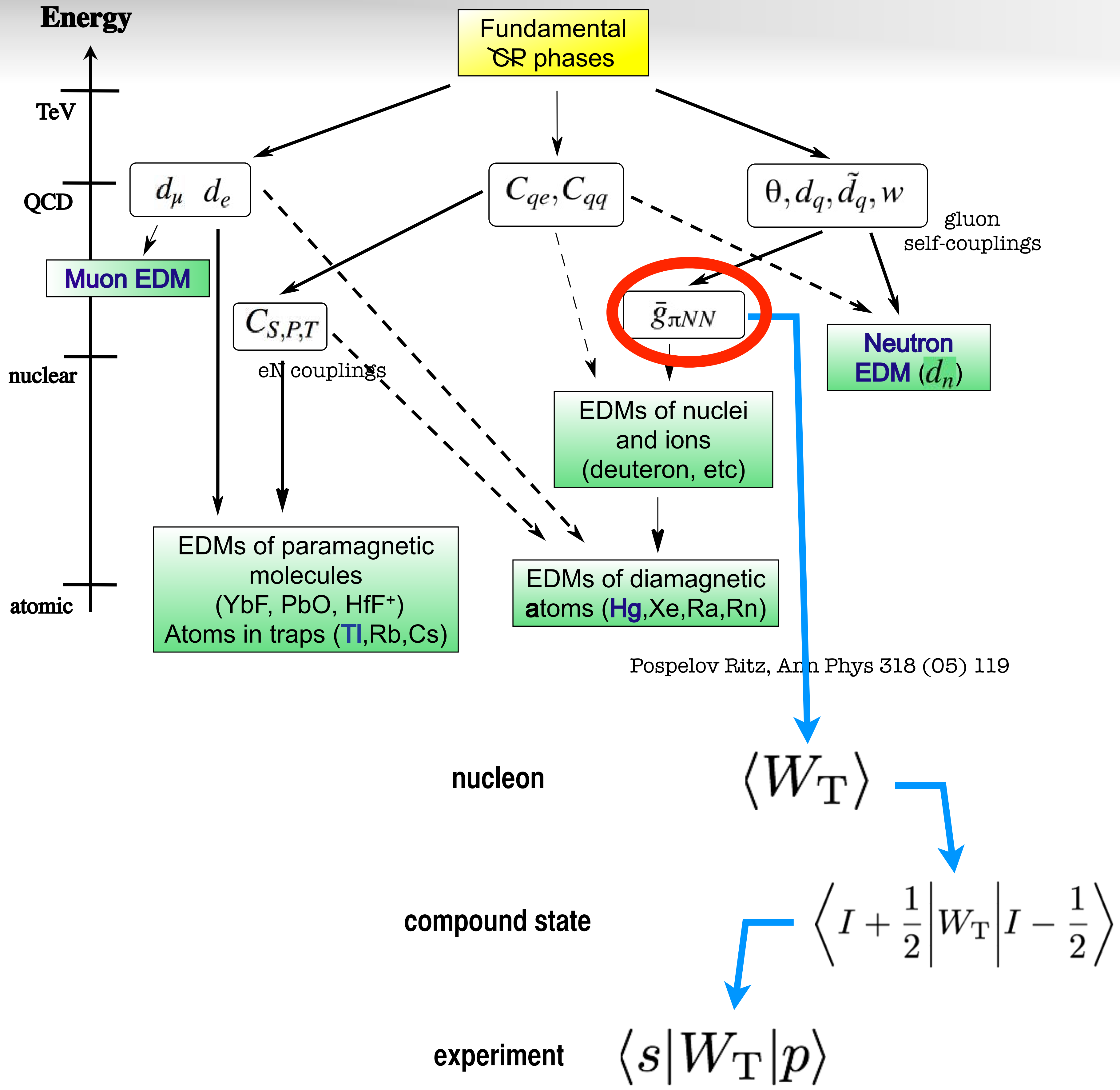
$$K_x^{x} - K_{-x}^{-x} = \boxed{4\mathrm{Re}\, A^* D}$$



$$K_y^{-y} - K_{-y}^{y} = 4\mathrm{Im}\, C^* D$$



$$K_z^{-z} - K_{-z}^{z} = 4\mathrm{Im}\, D^* B$$



Energy

TeV

QCD

nuclear

atomic

Fundamental $\cancel{CP}$ phases

$d_\mu \quad d_e$

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

gluon self-couplings

Muon EDM

$C_{S,P,T}$

eN couplings

$\bar{g}_{\pi NN}$

Neutron EDM (d_n)

EDMs of nuclei and ions (deuteron, etc)

EDMs of paramagnetic molecules (YbF, PbO, HfF⁺) Atoms in traps (Tl,Rb,Cs)

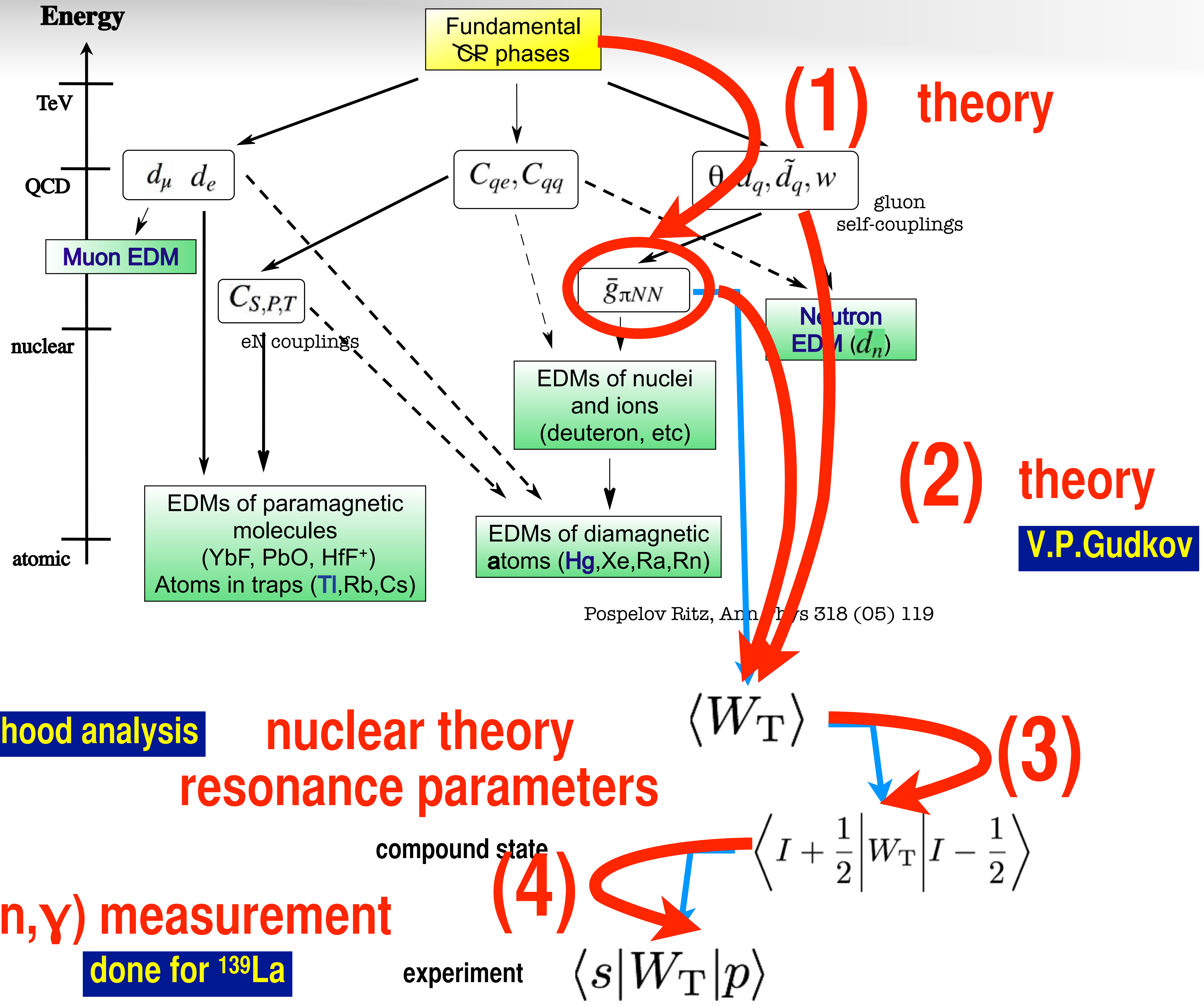
EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn)

Pospelov Ritz, Ann Phys 318 (05) 119

nucleon $\langle W_{\mathrm{T}} \rangle$

compound state $\left\langle I+\frac{1}{2} \middle| W_{\mathrm{T}} \middle| I-\frac{1}{2} \right\rangle$

experiment $\langle s | W_{\mathrm{T}} | p \rangle$



Energy

TeV

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nuclear

atomic

Fundamental $\not{CP}$ phases

(1) theory

$d_\mu \quad d_e$

C_{qe}, C_{qq}

$\theta, d_q, \tilde{d}_q, w$

gluon self-couplings

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EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn)

Pospelov Ritz, Ann Phys 318 (05) 119

(2) theory

V.P.Gudkov

$\langle W_{\mathrm{T}} \rangle$

done via likelihood analysis

nuclear theory
resonance parameters

(3)

compound state

$\left\langle I+\frac{1}{2} \middle| W_{\mathrm{T}} \middle| I-\frac{1}{2} \right\rangle$

(4)

(n,γ) measurement

done for ^{139}La

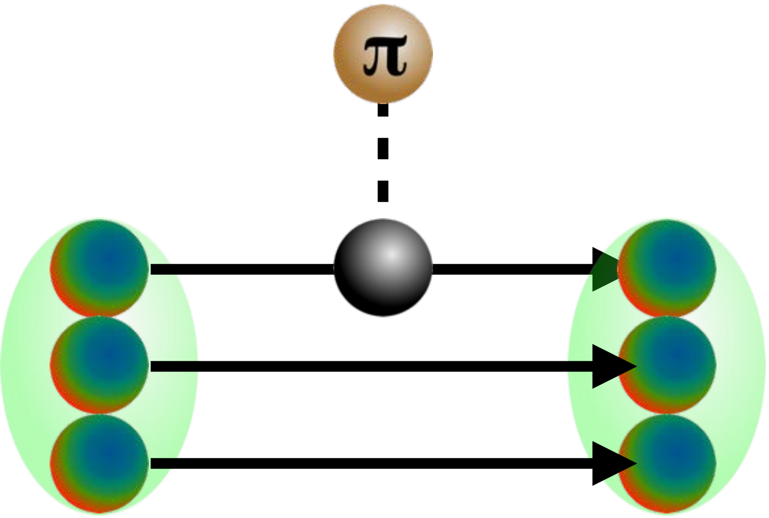
experiment

$\langle s | W_{\mathrm{T}} | p \rangle$

(1), (2) Estimation in Effective Field Theory

Y.-H.Song et al., Phys. Rev. C83 (2011) 065503

T-odd P-odd meson couplings



$$\boldsymbol{\sigma}_{\pm} = \boldsymbol{\sigma}_1 \pm \boldsymbol{\sigma}_2 \qquad \boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2 \qquad x_a = m_a r$$

$$T^z_{12} = 3\tau^z_1\tau^z_2 - \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2 \qquad Y_1(x) = \left(1+\frac{1}{x}\right)\frac{e^{-x}}{x}$$

$$g_\pi = 13.07, \quad g_\eta = 2.24, \quad g_\rho = 2.75, \quad g_\omega = 8.25$$

$$\begin{aligned}
V_{\mathrm{CP}} = & \left[-\frac{\bar{g}^{(0)}_\eta g_\eta}{2m_N}\frac{m^2_\eta}{4\pi}Y_1(x_\eta) + \frac{\bar{g}^{(0)}_\omega g_\omega}{2m_N}\frac{m^2_\omega}{4\pi}Y_1(x_\omega)\right]\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}} \\
& + \left[-\frac{\bar{g}^{(0)}_\pi g_\pi}{2m_N}\frac{m^2_\pi}{4\pi}Y_1(x_\pi) + \frac{\bar{g}^{(0)}_\rho g_\rho}{2m_N}\frac{m^2_\rho}{4\pi}Y_1(x_\rho)\right]\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}} \\
& + \left[-\frac{\bar{g}^{(2)}_\pi g_\pi}{2m_N}\frac{m^2_\pi}{4\pi}Y_1(x_\pi) + \frac{\bar{g}^{(2)}_\rho g_\rho}{2m_N}\frac{m^2_\rho}{4\pi}Y_1(x_\rho)\right]T^z_{12}\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}} \\
& + \left[-\frac{\bar{g}^{(1)}_\pi g_\pi}{2m_N}\frac{m^2_\pi}{4\pi}Y_1(x_\pi) + \frac{\bar{g}^{(1)}_\eta g_\eta}{2m_N}\frac{m^2_\eta}{4\pi}Y_1(x_\eta) + \frac{\bar{g}^{(1)}_\rho g_\rho}{2m_N}\frac{m^2_\rho}{4\pi}Y_1(x_\rho) + \frac{\bar{g}^{(1)}_\omega g_\omega}{2m_N}\frac{m^2_\omega}{4\pi}Y_1(x_\omega)\right]\tau_+\boldsymbol{\sigma}_-\cdot\hat{\boldsymbol{r}} \\
& + \left[-\frac{\bar{g}^{(1)}_\pi g_\pi}{2m_N}\frac{m^2_\pi}{4\pi}Y_1(x_\pi) - \frac{\bar{g}^{(1)}_\eta g_\eta}{2m_N}\frac{m^2_\eta}{4\pi}Y_1(x_\eta) - \frac{\bar{g}^{(1)}_\rho g_\rho}{2m_N}\frac{m^2_\rho}{4\pi}Y_1(x_\rho) + \frac{\bar{g}^{(1)}_\omega g_\omega}{2m_N}\frac{m^2_\omega}{4\pi}Y_1(x_\omega)\right]\tau_+\boldsymbol{\sigma}_+\cdot\hat{\boldsymbol{r}}
\end{aligned}$$

➡

$$\tilde{d}_n \simeq 0.14\left(\bar{g}^{(0)}_\pi - \bar{g}^{(2)}_\pi\right)$$

➡

$$\frac{\Delta\sigma_{\mathrm{CP}}}{2\sigma_{\mathrm{tot}}} = \frac{-0.185[\mathrm{b}]}{2\sigma_{\mathrm{tot}}}\left(\bar{g}^{(0)}_\pi + 0.26\bar{g}^{(1)}_\pi\right)$$

(1), (2) Estimation in Effective Field Theory

$$\frac{\langle s|W_\mathrm{T}|p\rangle}{\langle s|W|p\rangle} \simeq (1-0.1) \times \frac{\langle W_\mathrm{T}\rangle}{\langle W\rangle}$$

Gudkov, Phys. Rep. 212 (1992) 77

Flambaum, Phys. Rev. C51 (1995) 2914

$$\frac{W_\mathrm{T}}{W} \simeq -0.47\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + 0.26\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right)$$

Y.H.Song et al., Phys. Rev. C83(2011) 065503

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Y.H.Song et al., Phys. Rev. C83(2011) 065503

$$\bar{g}_{\pi}^{(0)} < 2.5 \times 10^{-10}$$

$$|d_{\mathrm{n}}| < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

(1), (2) Estimation in Effective Field Theory

$$\frac{\langle s|W_{\mathrm{T}}|p\rangle}{\langle s|W|p\rangle} \simeq (1-0.1) \times \frac{\langle W_{\mathrm{T}}\rangle}{\langle W\rangle}$$

Gudkov, Phys. Rep. 212 (1992) 77

Flambaum, Phys. Rev. C51 (1995) 2914

$$\frac{W_{\mathrm{T}}}{W} \simeq -0.47\left(\frac{\overline{g}_{\pi}^{(0)}}{h_{\pi}^{1}} + 0.26\frac{\overline{g}_{\pi}^{(1)}}{h_{\pi}^{1}}\right)$$

Y.H.Song et al., Phys. Rev. C83(2011) 065503

$$\overline{g}_{\pi}^{(0)} < 2.5 \times 10^{-10} \qquad |d_{\mathrm{n}}| < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

$$\overline{g}_{\pi}^{(1)} < 0.5 \times 10^{-11} \qquad \left|d({}^{199}\mathrm{Hg})\right| < 3.1 \times 10^{-29}\, e\,\mathrm{cm}$$

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Gudkov, Phys. Rep. 212 (1992) 77

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Y.H.Song et al., Phys. Rev. C83(2011) 065503

$$\bar{g}_{\pi}^{(0)} < 2.5 \times 10^{-10} \qquad |d_{\mathrm{n}}| < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

$$\bar{g}_{\pi}^{(1)} < 0.5 \times 10^{-11} \qquad \left|d(^{199}\mathrm{Hg})\right| < 3.1 \times 10^{-29}\, e\,\mathrm{cm}$$

$$h_{\pi}^{1} \sim 3 \times 10^{-7} \qquad \mathrm{n} + \mathrm{p} \to \mathrm{d} + \gamma$$

(1), (2) Estimation in Effective Field Theory

$$\frac{\langle s|W_{\mathrm{T}}|p\rangle}{\langle s|W|p\rangle} \simeq (1-0.1) \times \frac{\langle W_{\mathrm{T}}\rangle}{\langle W\rangle}$$

Gudkov, Phys. Rep. 212 (1992) 77

Flambaum, Phys. Rev. C51 (1995) 2914

$$\frac{W_{\mathrm{T}}}{W} \simeq -0.47\left(\frac{\overline{g}_\pi^{(0)}}{h_\pi^1} + 0.26\frac{\overline{g}_\pi^{(1)}}{h_\pi^1}\right)$$

Y.H.Song et al., Phys. Rev. C83(2011) 065503

$\overline{g}_\pi^{(0)} < 2.5 \times 10^{-10}$ $\quad |d_{\mathrm{n}}| < 3 \times 10^{-26}\, e\,\mathrm{cm}$

$\overline{g}_\pi^{(1)} < 0.5 \times 10^{-11}$ $\quad \left|d(^{199}\mathrm{Hg})\right| < 3.1 \times 10^{-29}\, e\,\mathrm{cm}$

$h_\pi^1 \sim 3 \times 10^{-7}$ $\quad \mathrm{n} + \mathrm{p} \to \mathrm{d} + \gamma$

$$\left|\frac{W_{\mathrm{T}}}{W}\right| < 3.9 \times 10^{-4}$$

(1), (2) Estimation in Effective Field Theory

$$\frac{\langle s|W_{\mathrm{T}}|p\rangle}{\langle s|W|p\rangle} \simeq (1-0.1) \times \frac{\langle W_{\mathrm{T}}\rangle}{\langle W\rangle}$$

Gudkov, Phys. Rep. 212 (1992) 77

Flambaum, Phys. Rev. C51 (1995) 2914

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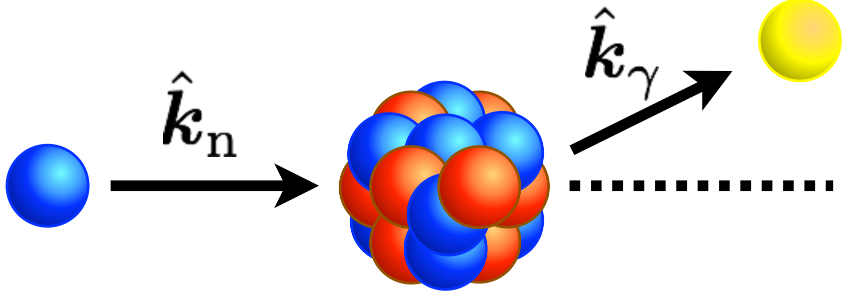
$\left|\frac{W_{\mathrm{T}}}{W}\right| < 3.9 \times 10^{-4}$ ←**discovery potential corresponding to the present nEDM upper limit**

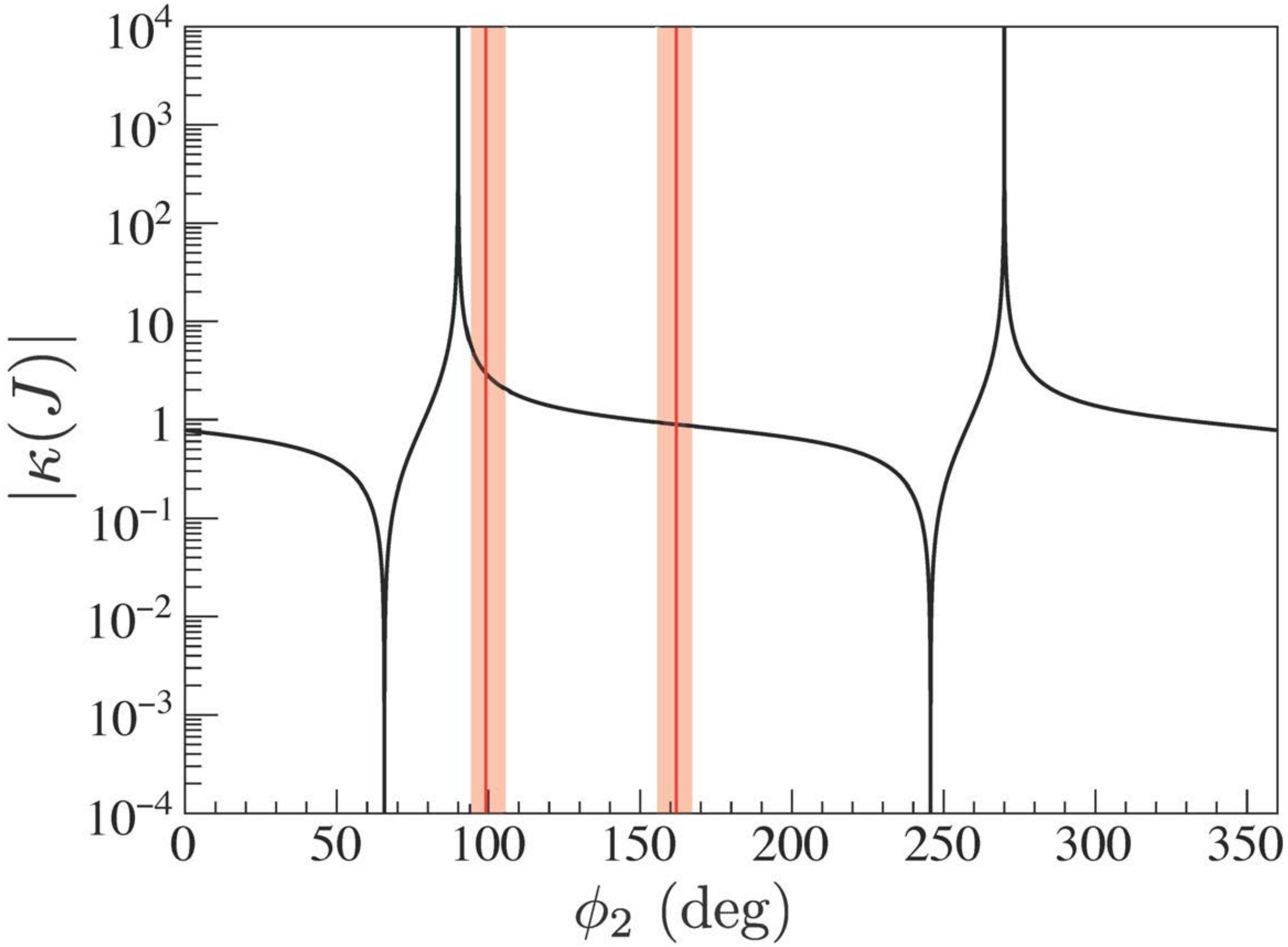
(4) Details of Entrance Channel

$$\frac{d\sigma_{n\gamma}}{d\Omega_\gamma} = \frac{1}{2}\left(a_0 + a_1 \cos\theta_\gamma + a_3(\cos^2\theta_\gamma - \frac{1}{3})\right)$$



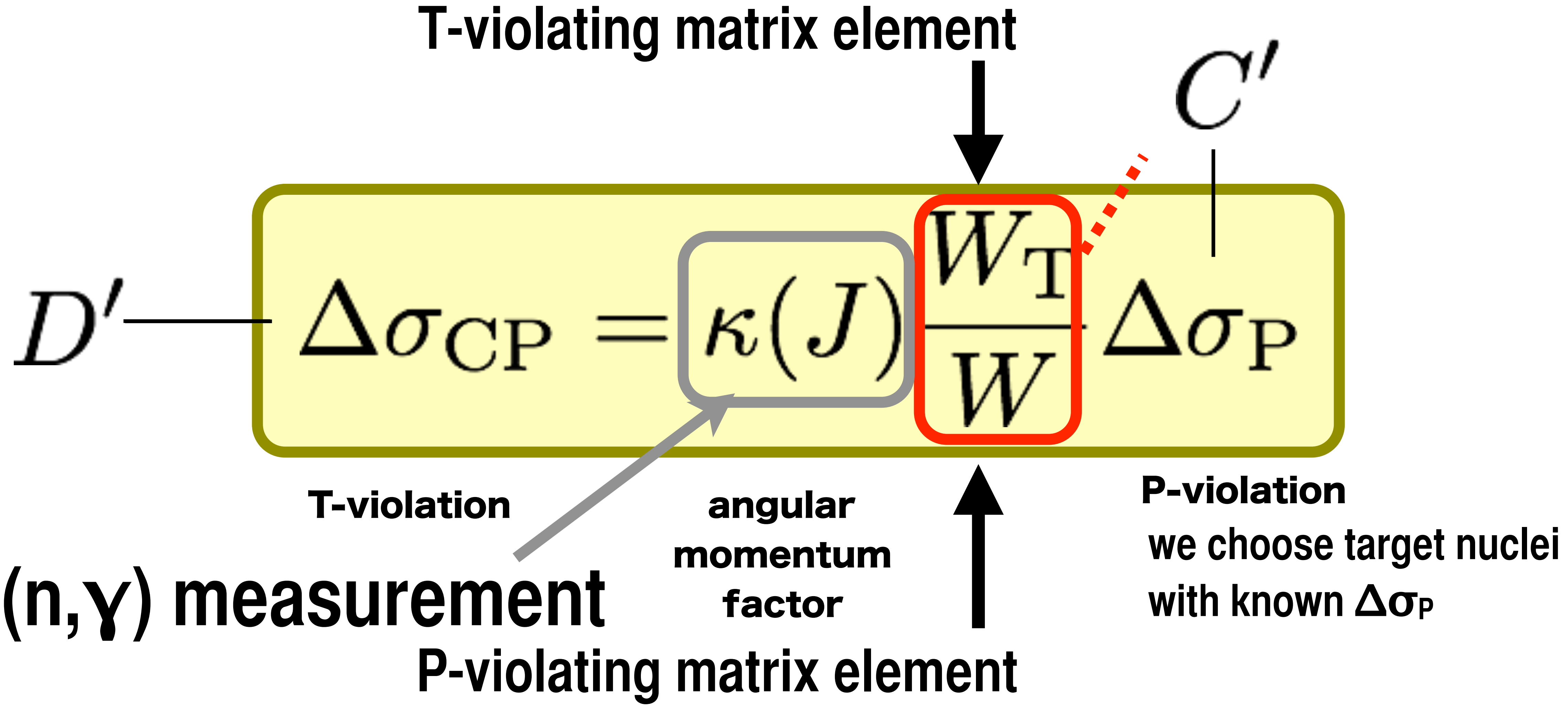
T.Okudaira et al., Phys. Rev. C97 (2018) 034622

$$\kappa(J) = 0.99^{+0.88}_{-0.07},\ 4.84^{+5.58}_{-1.69}$$



Order Estimation of T-violation Sensitivity

Gudkov, Phys. Rep. 212 (1992) 77



T-violating matrix element

C'

D'

$$\Delta\sigma_{\rm CP} = \boxed{\kappa(J)}\,\boxed{\frac{W_{\rm T}}{W}}\,\Delta\sigma_{\rm P}$$

T-violation

angular momentum factor

P-violation

we choose target nuclei with known $\Delta\sigma_P$

(n,γ) measurement

P-violating matrix element

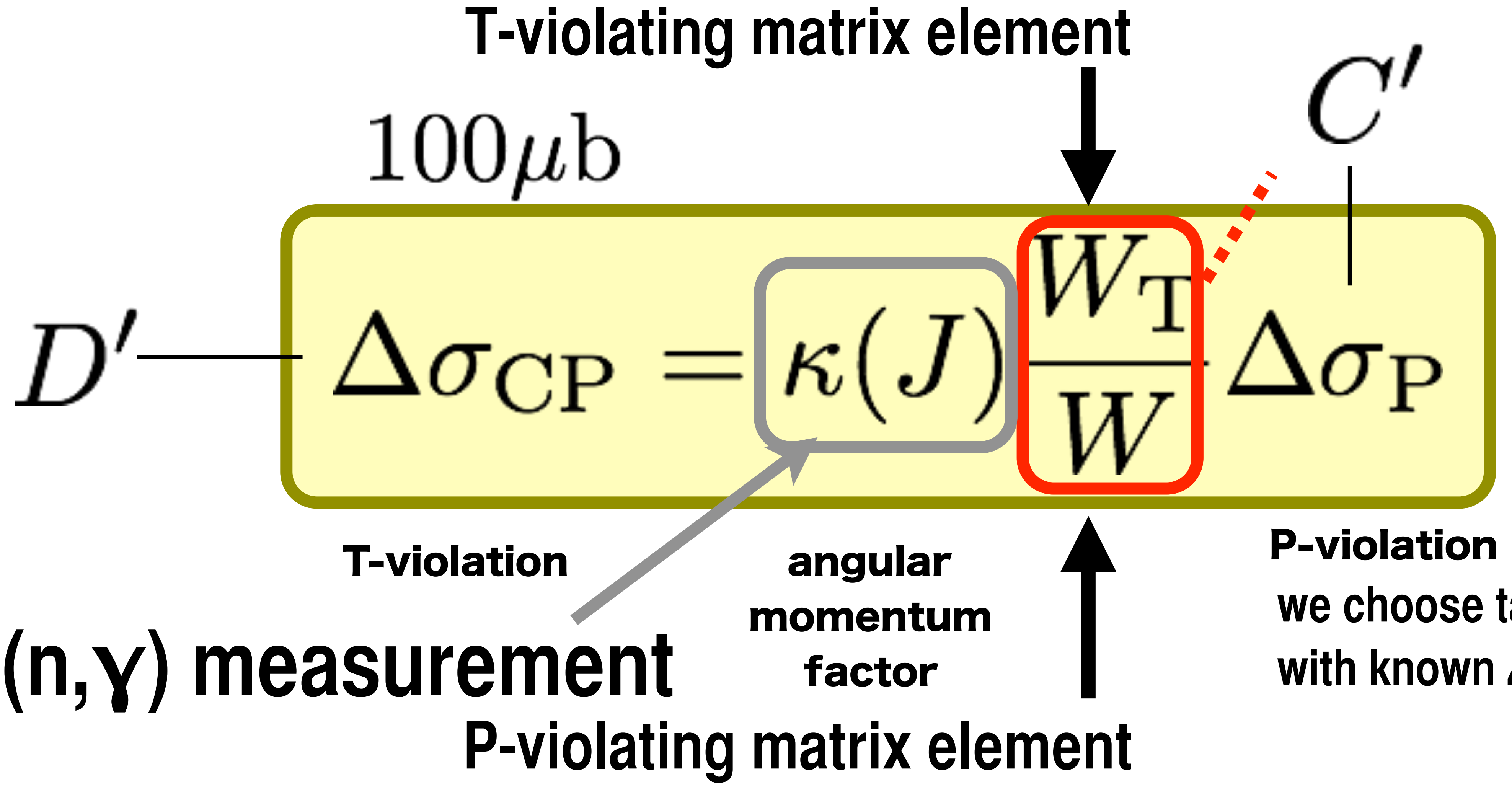
$$\kappa(J) = 0.99^{+0.88}_{-0.07},\ 4.84^{+5.58}_{-1.69}$$

$$\left|\frac{W_{\rm T}}{W}\right| < 3.9\times10^{-4}$$

discovery potential

Order Estimation of T-violation Sensitivity

Gudkov, Phys. Rep. 212 (1992) 77



T-violating matrix element

$100\mu\mathrm{b}$

C'

D'

$$\Delta\sigma_{\mathrm{CP}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\Delta\sigma_{\mathrm{P}}$$

T-violation

angular momentum factor

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we choose target nuclei with known $\Delta\sigma_{\mathrm{P}}$

(n,γ) measurement

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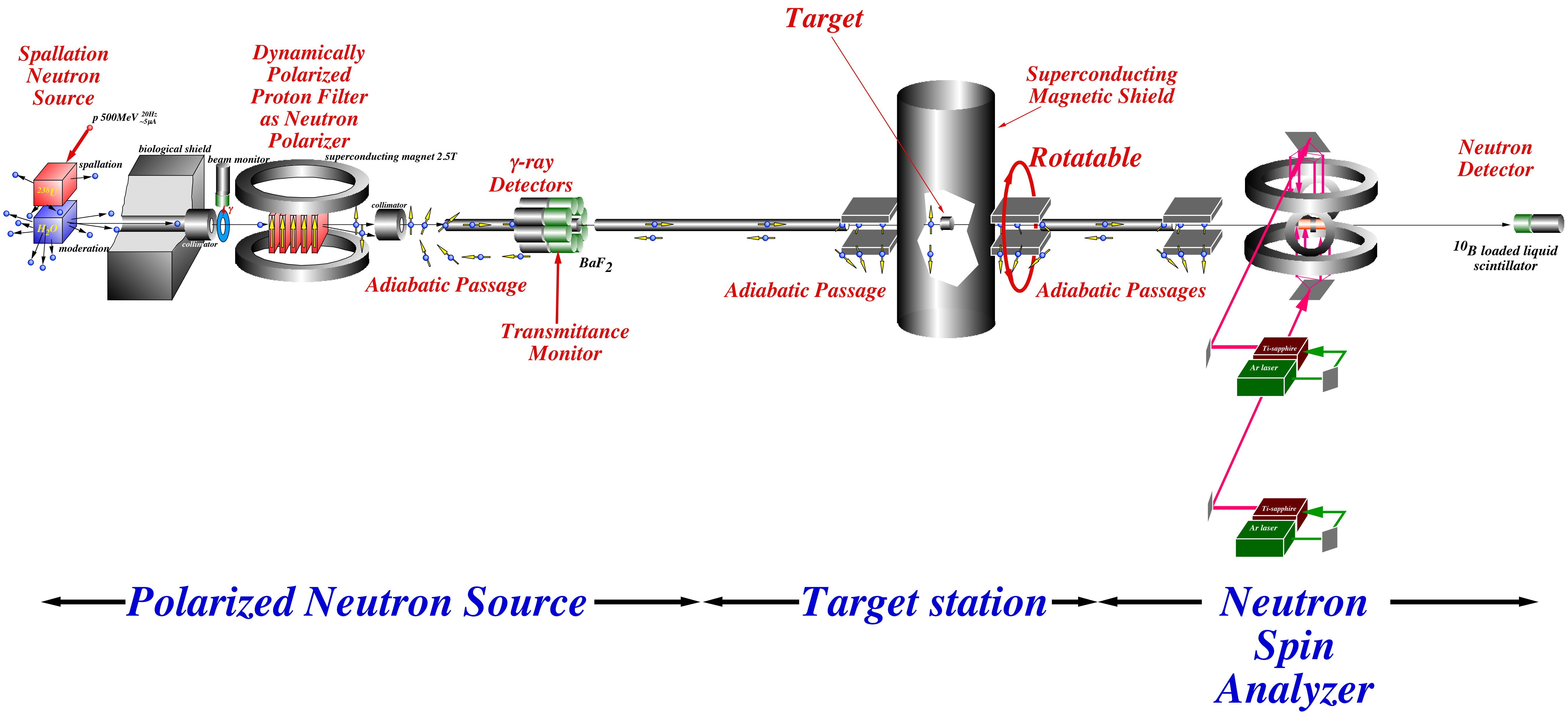
discovery potential

KEK 2018S12

Neutron Optics for Parity and Time Reversal EXperiment

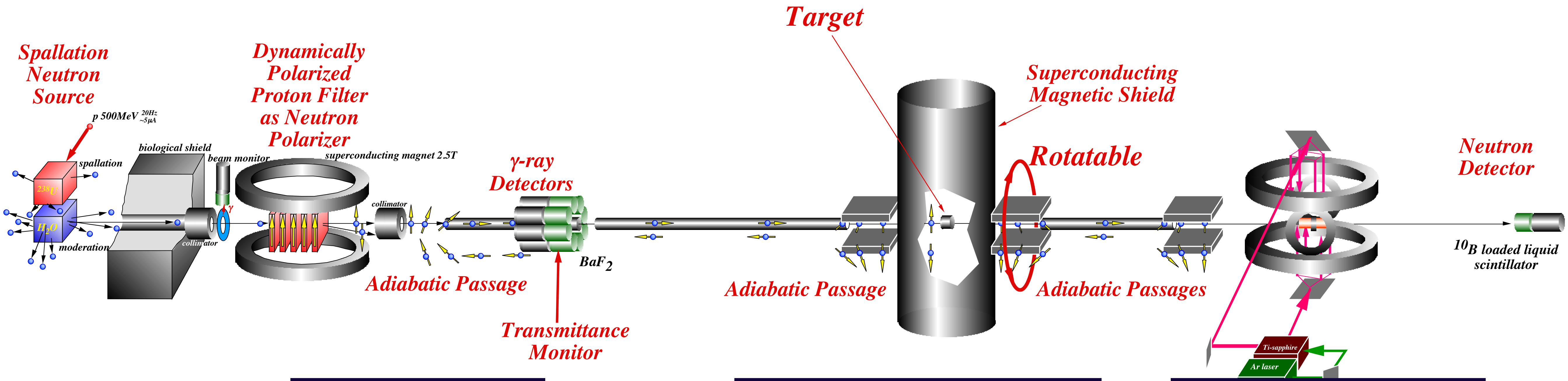
NOPTREX Collaboration



KEK 2018S12

Neutron Optics for Parity and Time Reversal EXperiment

NOPTREX Collaboration



epithermal neutron polarizer

polarized target

spin control

epithermal neutron spin analyzer

←Polarized Neutron Source→ ←Target station→ ←Neutron Spin Analyzer→

KEK 2018S12

Neutron Optics for Parity and Time Reversal EXperiment

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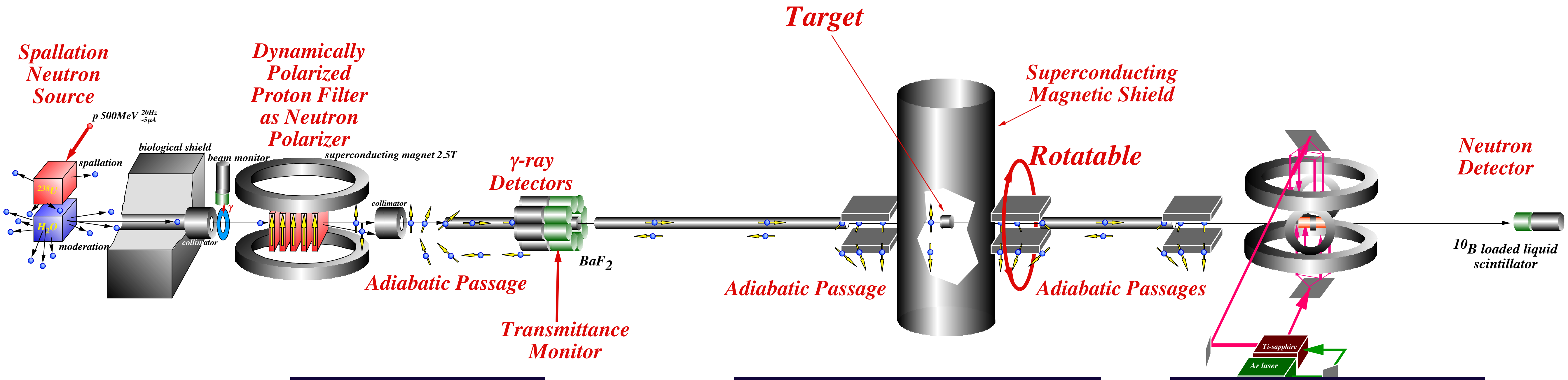

epithermal neutron polarizer

polarized target

spin control

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Polarized Neutron Source ← → *Target station* ← → *Neutron Spin Analyzer*

$\overrightarrow{^3\mathrm{He}}$ $\vec{\mathrm{p}}$

$\overrightarrow{^{139}\mathrm{La}}$ $\overrightarrow{^{131}\mathrm{Xe}}$

$\overrightarrow{^{81}\mathrm{Br}}, \overrightarrow{^{117}\mathrm{Sn}}, \overrightarrow{^{115}\mathrm{In}}, \overrightarrow{^{127}\mathrm{I}}, \overrightarrow{^{133}\mathrm{Cs}}, \overrightarrow{^{81}\mathrm{Br}}, \ldots$

$\overrightarrow{^3\mathrm{He}}$ $\vec{\mathrm{p}}$

KEK 2018S12

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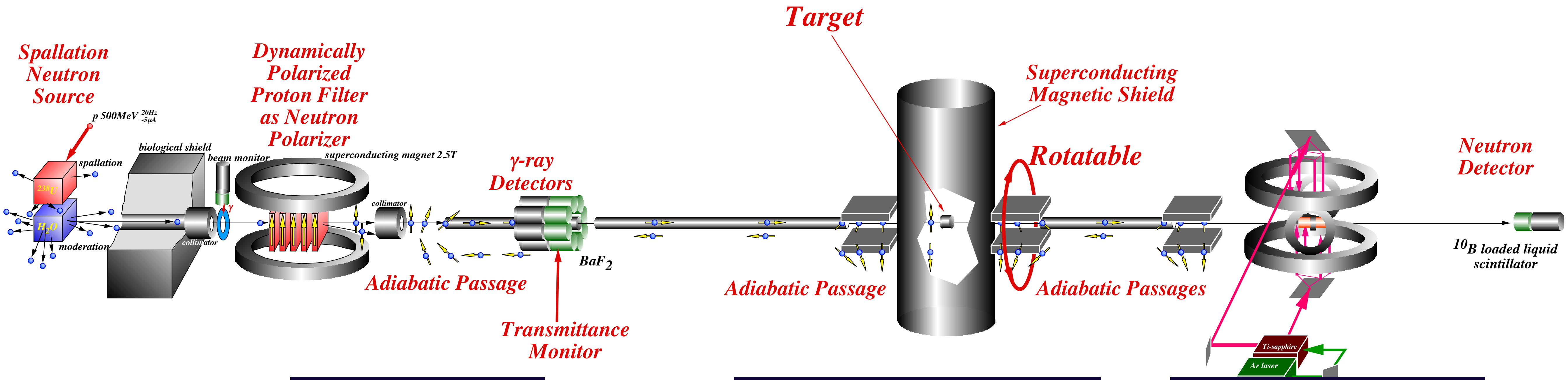

epithermal neutron polarizer

polarized target

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←*Polarized Neutron Source*→ ←*Target station*→ ←*Neutron Spin Analyzer*→

$\overrightarrow{{}^{3}\mathrm{He}}$ $\overrightarrow{{}^{139}\mathrm{La}}$ $\overrightarrow{{}^{3}\mathrm{He}}$

$\overrightarrow{{}^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

$\overrightarrow{{}^{139}\mathrm{La}}$

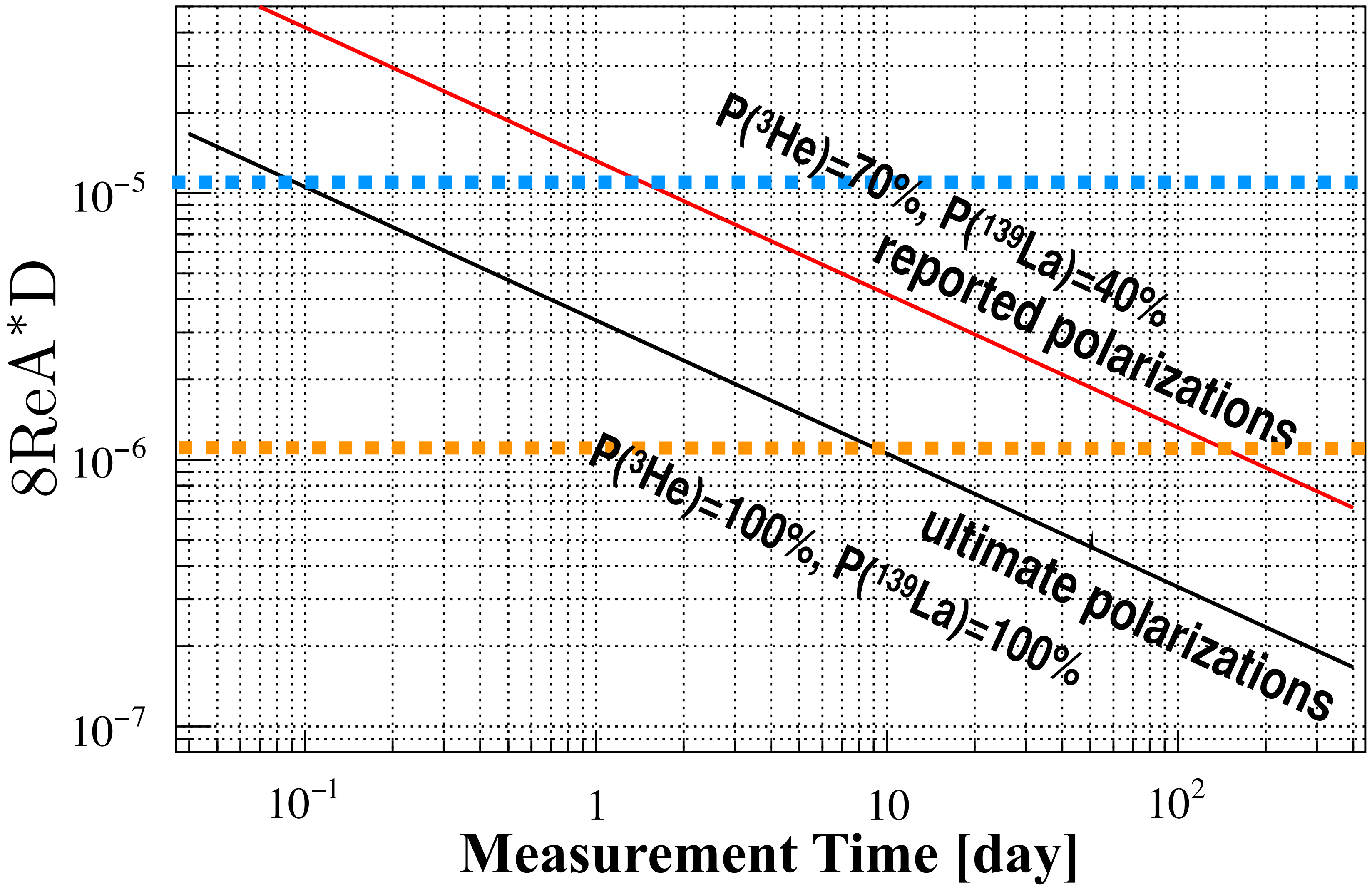
$\mathrm{LaAlO_3}$

$P(^{139}\mathrm{La})\geq 0.4$, $V\geq 4\mathrm{cm}\times 4\mathrm{cm}\times 6\mathrm{cm}$

$B_0\leq 0.1\mathrm{T}$

$\overrightarrow{{}^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

$P(^{139}La) \geq 0.4$, $V \geq 4cm \times 4cm \times 6cm$
$B_0 \leq 0.1T$



corresponding to $d_n = 3.0 \times 10^{-26}$ e cm

corresponding to $d_n = 3.0 \times 10^{-27}$ e cm

$\overrightarrow{^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

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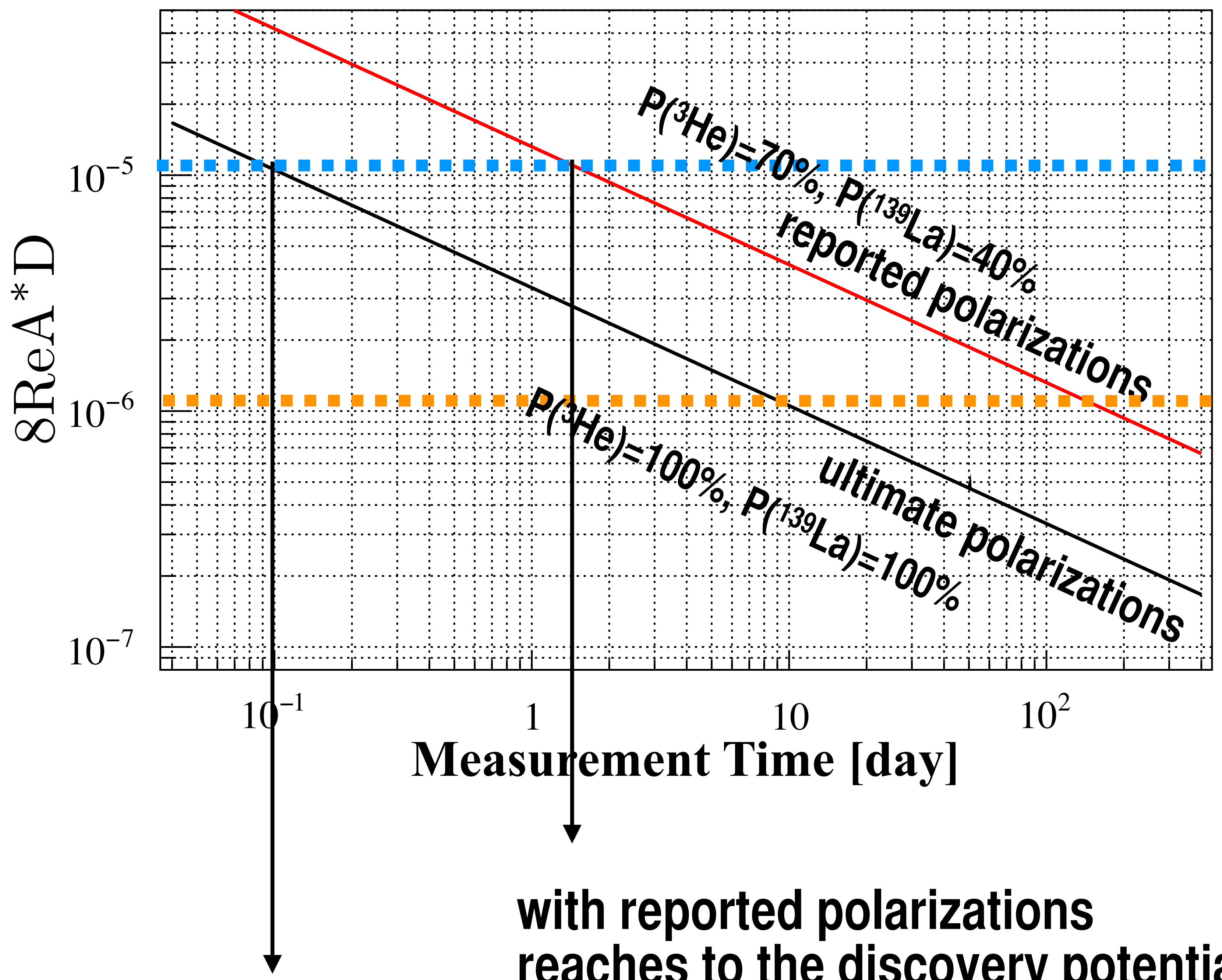


corresponding to
$d_n = 3.0 \times 10^{-26}$ e cm

corresponding to
$d_n = 3.0 \times 10^{-27}$ e cm

with reported polarizations
reaches to the discovery potential in 1.4 days

with ultimate polarizations
reaches the discovery potential in 2.2 hours

$\overrightarrow{{}^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

$P({}^{139}\mathrm{La}) \geq 0.4$, $V \geq 4\mathrm{cm} \times 4\mathrm{cm} \times 6\mathrm{cm}$
$B_0 \leq 0.1\mathrm{T}$

Dynamic Nuclear Polarization

$$\mathrm{La_{1-\mathit{x}}Nd_{\mathit{x}}AlO_3}$$

$\overrightarrow{{}^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

$P(^{139}La) \geq 0.4$, $V \geq 4cm \times 4cm \times 6cm$

$B_0 \leq 0.1T$

Dynamic Nuclear Polarization **Brute-force**

$\mathrm{La}_{1-x}\mathrm{Nd}_x\mathrm{AlO}_3$ $\mathrm{LaAlO}_3 + (\pi(sp^2) \leftarrow h\nu)$

$\overrightarrow{{}^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

P(^{139}La)≥0.4, V≥4cm×4cm×6cm
B_0≤0.1T

Dynamic Nuclear Polarization **Brute-force**

$$\mathrm{La_{1-\mathit{x}}Nd_{\mathit{x}}AlO_3} \qquad \mathrm{LaAlO_3} + (\pi(sp^2)\leftarrow h\nu)$$

$\overrightarrow{{}^{131}\mathrm{Xe}}$ **Spin Exchange Optical Pumping**

$\overrightarrow{^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

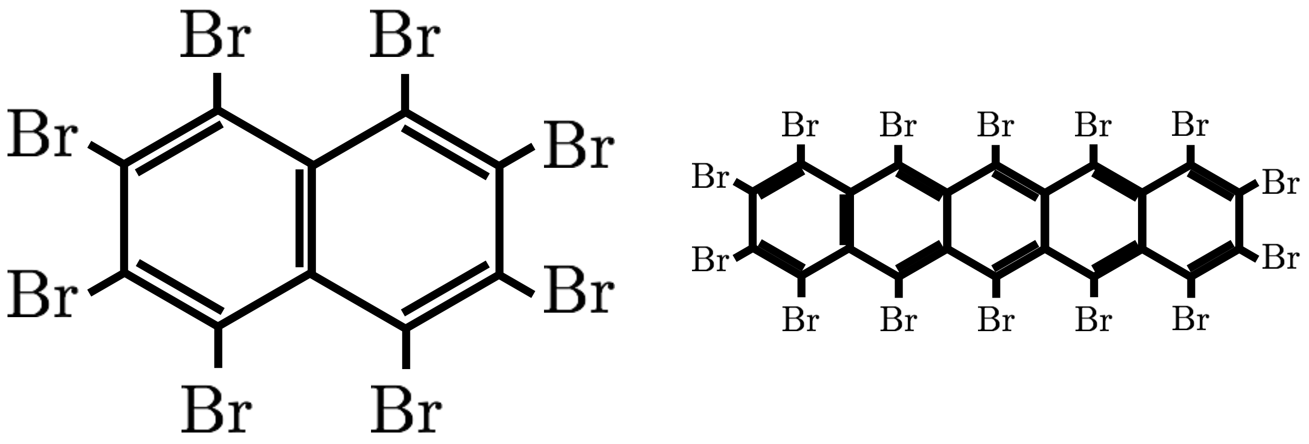
P(^{139}La)≥0.4, V≥4cm×4cm×6cm
B_0≤0.1T

Dynamic Nuclear Polarization **Brute-force**

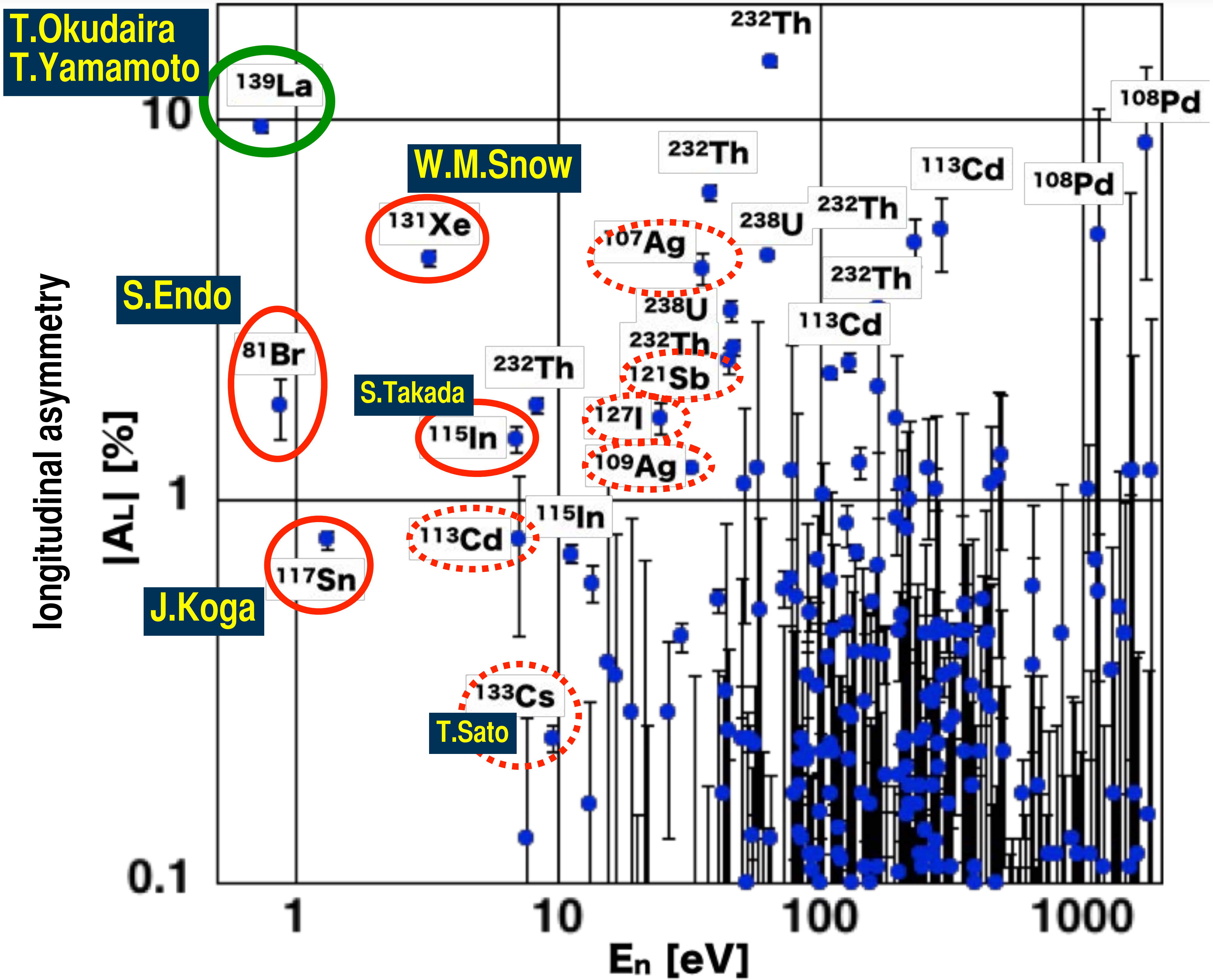
$$\mathrm{La}_{1-x}\mathrm{Nd}_x\mathrm{AlO}_3 \qquad \mathrm{LaAlO}_3 + (\pi(sp^2)\leftarrow h\nu)$$

$\overrightarrow{^{131}\mathrm{Xe}}$ **Spin Exchange Optical Pumping**

$\overrightarrow{^{81}\mathrm{Br}}$ **triple-DNP?**



Candidate Nuclei



Mitchell, Phys. Rep. 354 (2001) 157

NOPTREX Collaboration

KEK 2018S12

Enhanced Discrete Symmetry Violation in Compound States induced by Epithermal Neutron

has a discovery potential of new physics beyond the standard model

via $\overline{g}_{\pi\mathrm{NN}}$

development of polarized target in progress ← RCNP Project

basis of epithermal neutron optics
applicability of the random matrix theory
evaluation of systematic errors

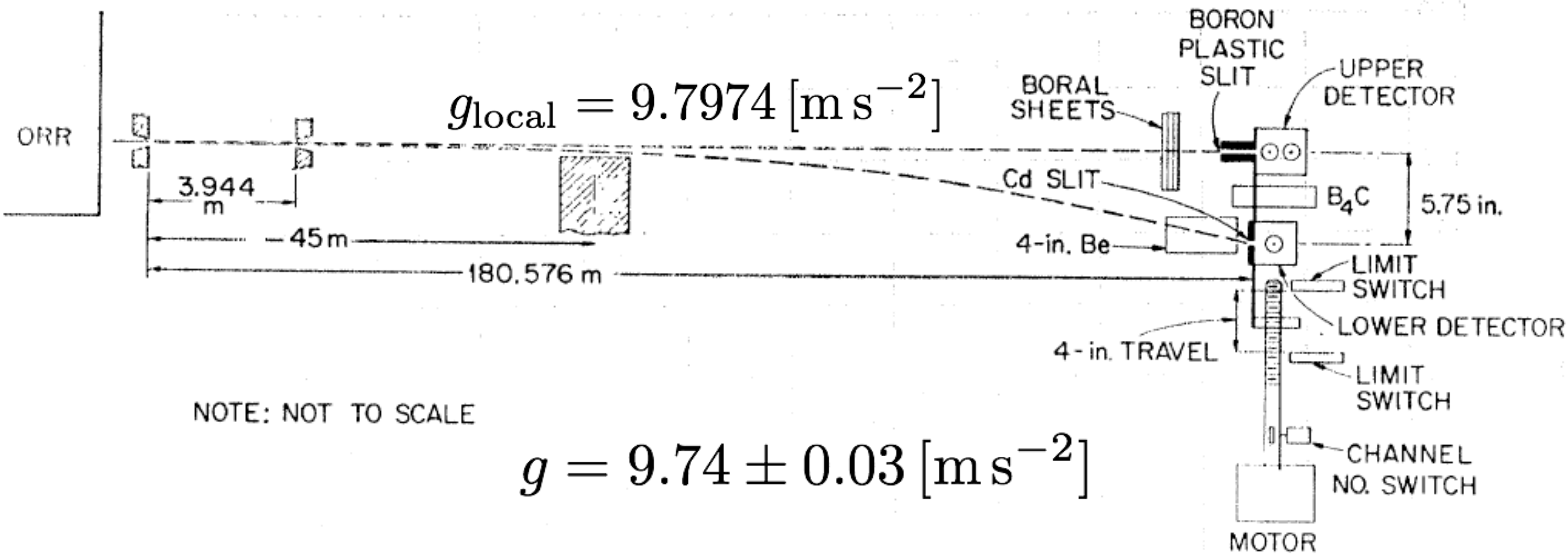
→ new physics

Physics

General Relativity

Gravitational Fall

Dabbs et al., Phys. Rev. 139 (1965) B756



$$g_{\mathrm{local}} = 9.7974\,[\mathrm{m\,s^{-2}}]$$

$$g = 9.74 \pm 0.03\,[\mathrm{m\,s^{-2}}]$$

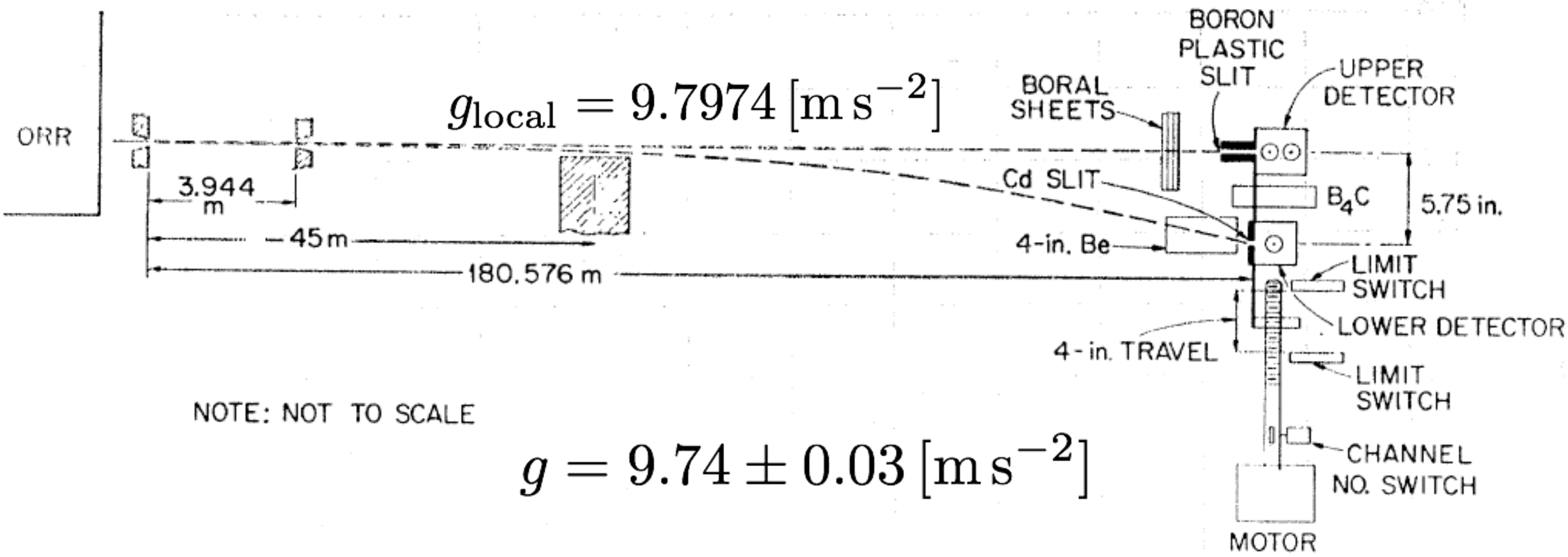
Gregoriev et al., Proc. 1st Int. Conf. Neutr. Phys., Kiev, 1 (1988) 60

$$g = 9.801 \pm 0.013\,[\mathrm{m\,s^{-2}}]$$

$$g_{\mathrm{local}} = 9.814\,[\mathrm{m\,s^{-2}}]$$

Gravitational Fall

Dabbs et al., Phys. Rev. 139 (1965) B756



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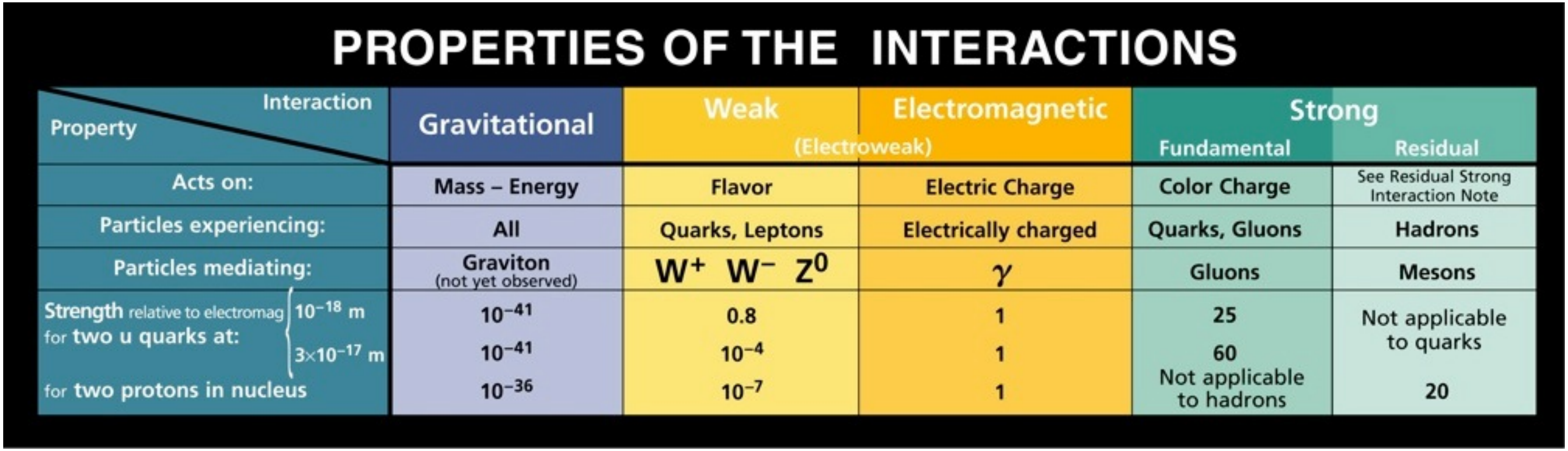
$$g_{\mathrm{local}} = 9.814\,[\mathrm{m\,s^{-2}}]$$

McReynolds, Bull. Am. Phys. Soc. 12 (1967) 105

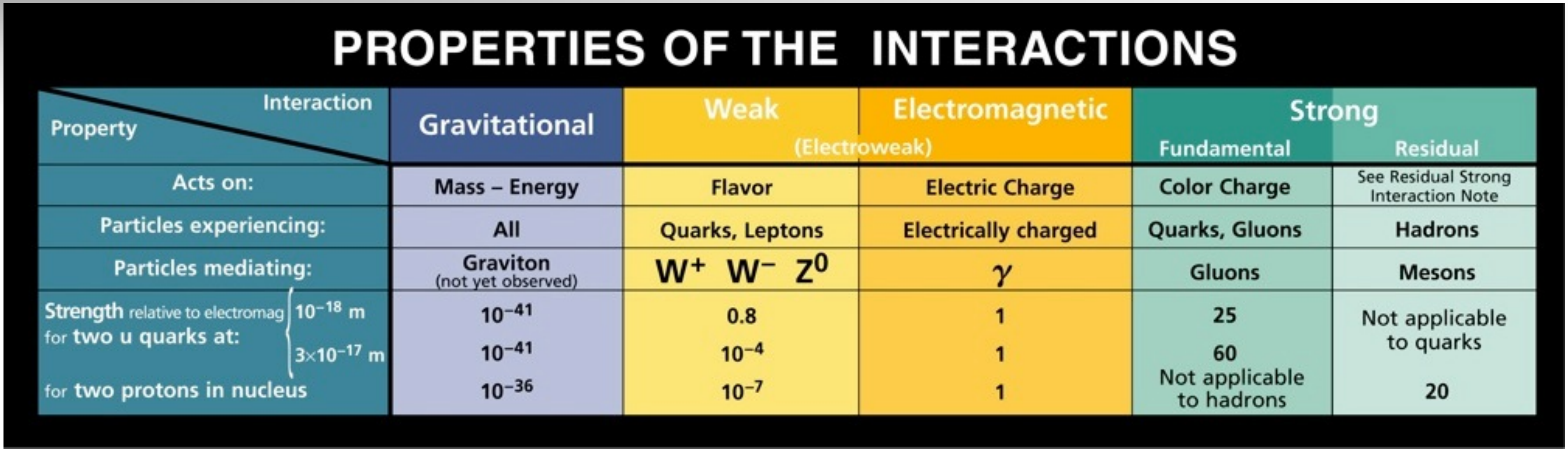
$$|\Delta g| < 5 \times 10^{-13} g_0 \qquad g = g_0 + \Delta g(\boldsymbol{\sigma} \cdot \boldsymbol{g})$$

Gravity is extremely weak.



PROPERTIES OF THE INTERACTIONS

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20



PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong Fundamental	Strong Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
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for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Why is the gravity so weak?

Gravity is not renormalizable.

Gravity is the nature of space time.

Gravity is essential at the Planck scale.

“hierarchy problem”: $M_{GUT}\sim10^{24}$eV ⇔ $M_{SU(2)\times U(1)}\sim10^{11}$eV

Phenomena out of the standard model is existing.

<u>Neutrino Oscillation, Dark Energy, Dark Matter</u>

Super-K, SNO, KamLAND **WMAP**

Gravity is extremely weak.

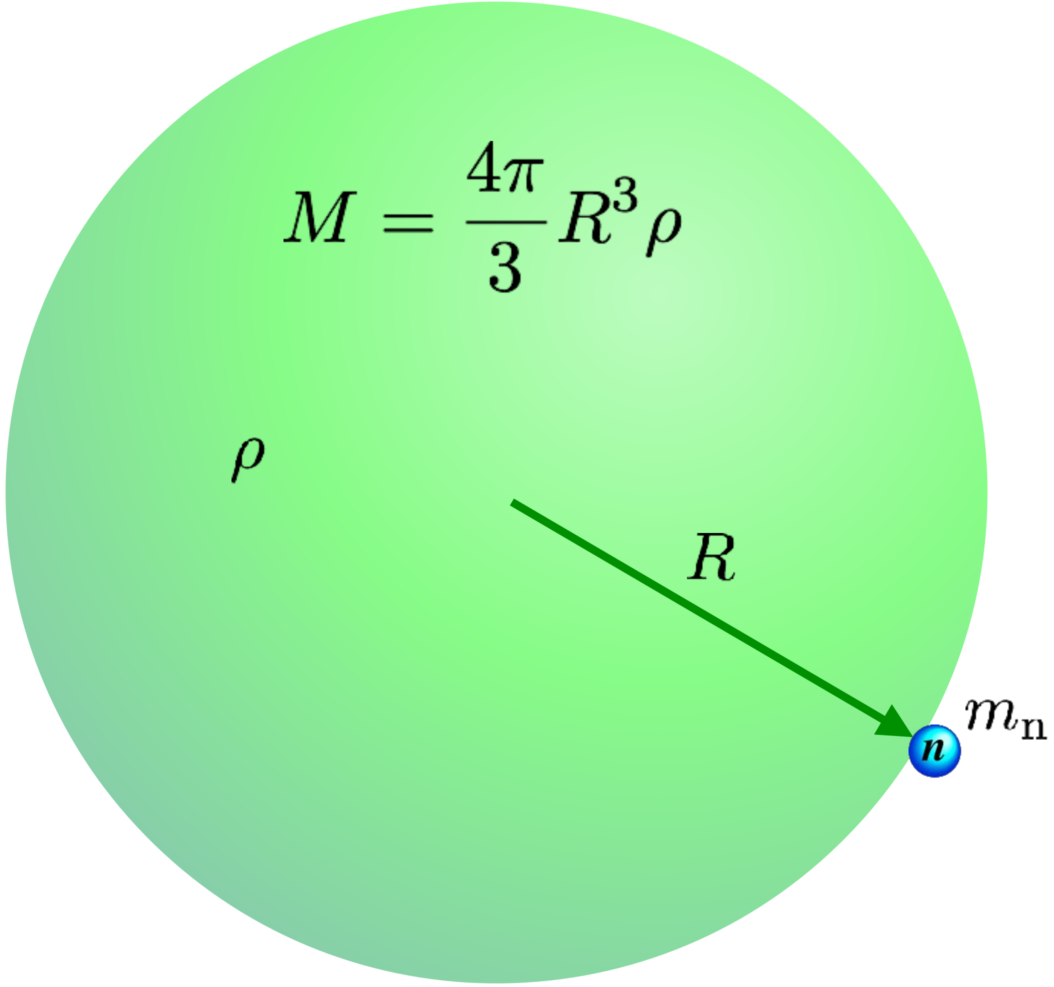
Gravity is extremely weak.

$$U = -G\frac{Mm_{\mathrm{n}}}{R}$$

Gravity is extremely weak.

$$U = -G\frac{Mm_{\mathrm{n}}}{R}$$

$$= -3.1 \times 10^{-15}[\mathrm{eV}] \times \left(\frac{R}{1\,\mathrm{m}}\right)^2 \left(\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}\right)$$



$$M = \frac{4\pi}{3}R^3\rho$$

Gravity is extremely weak.

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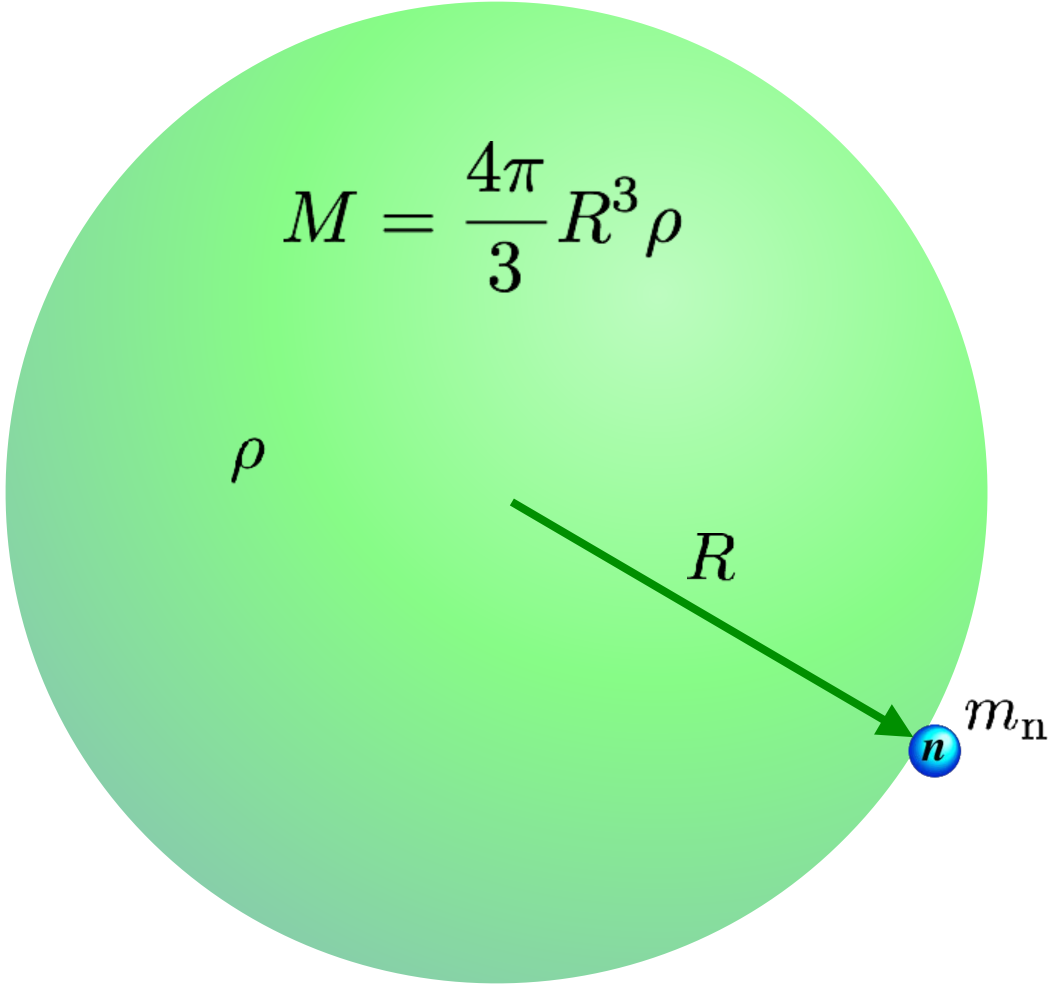
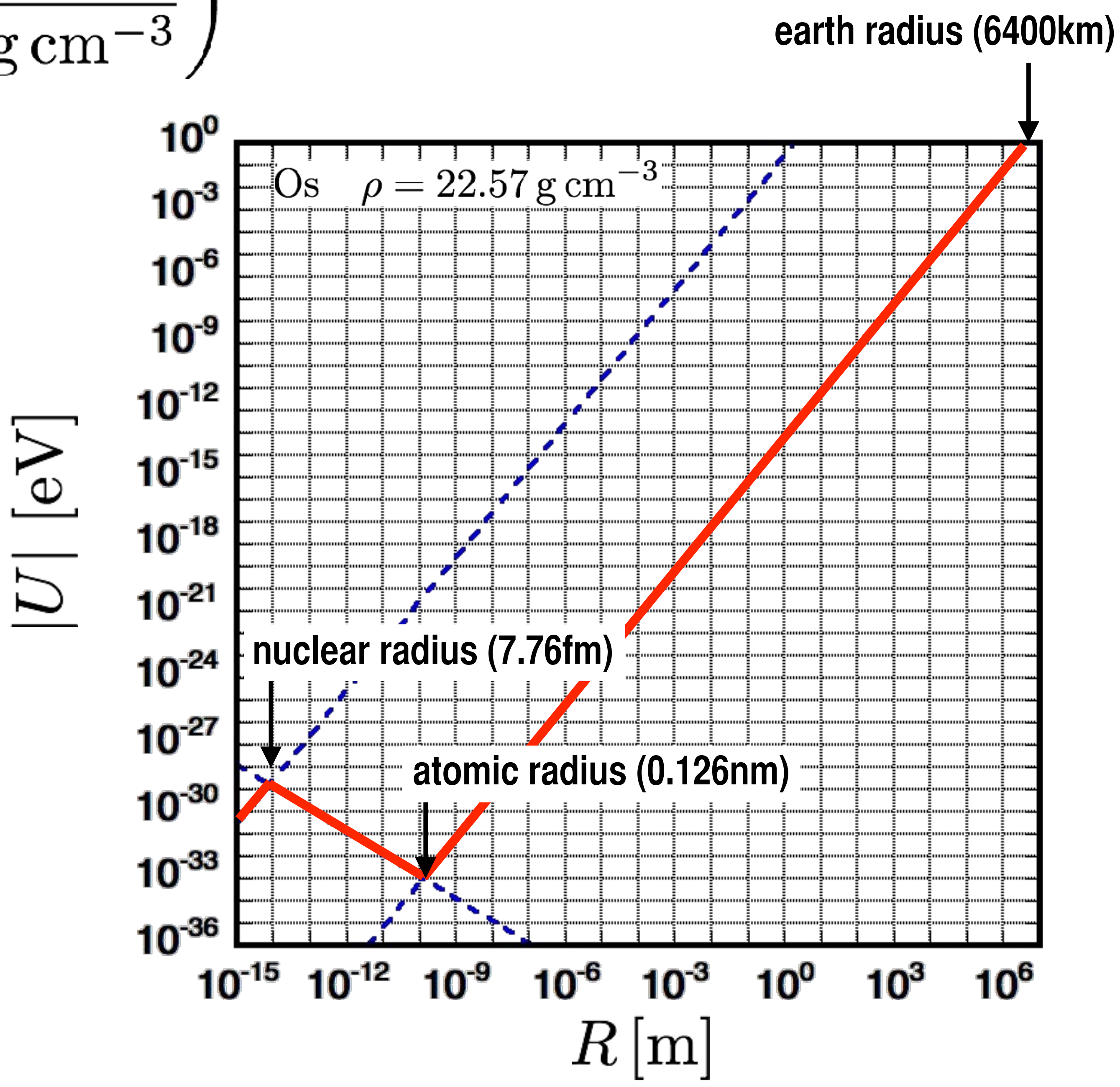
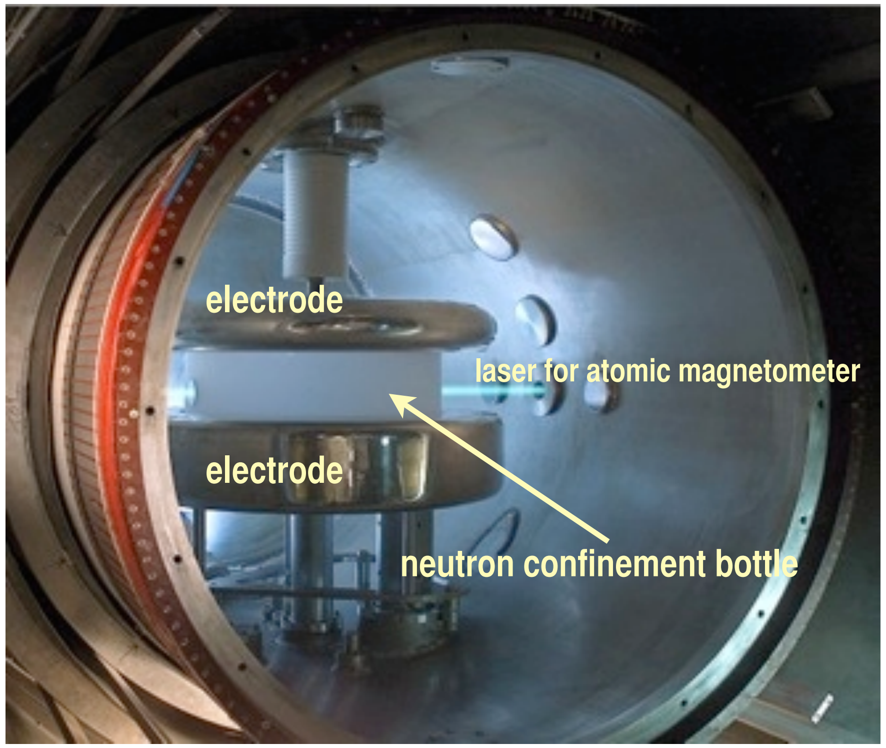
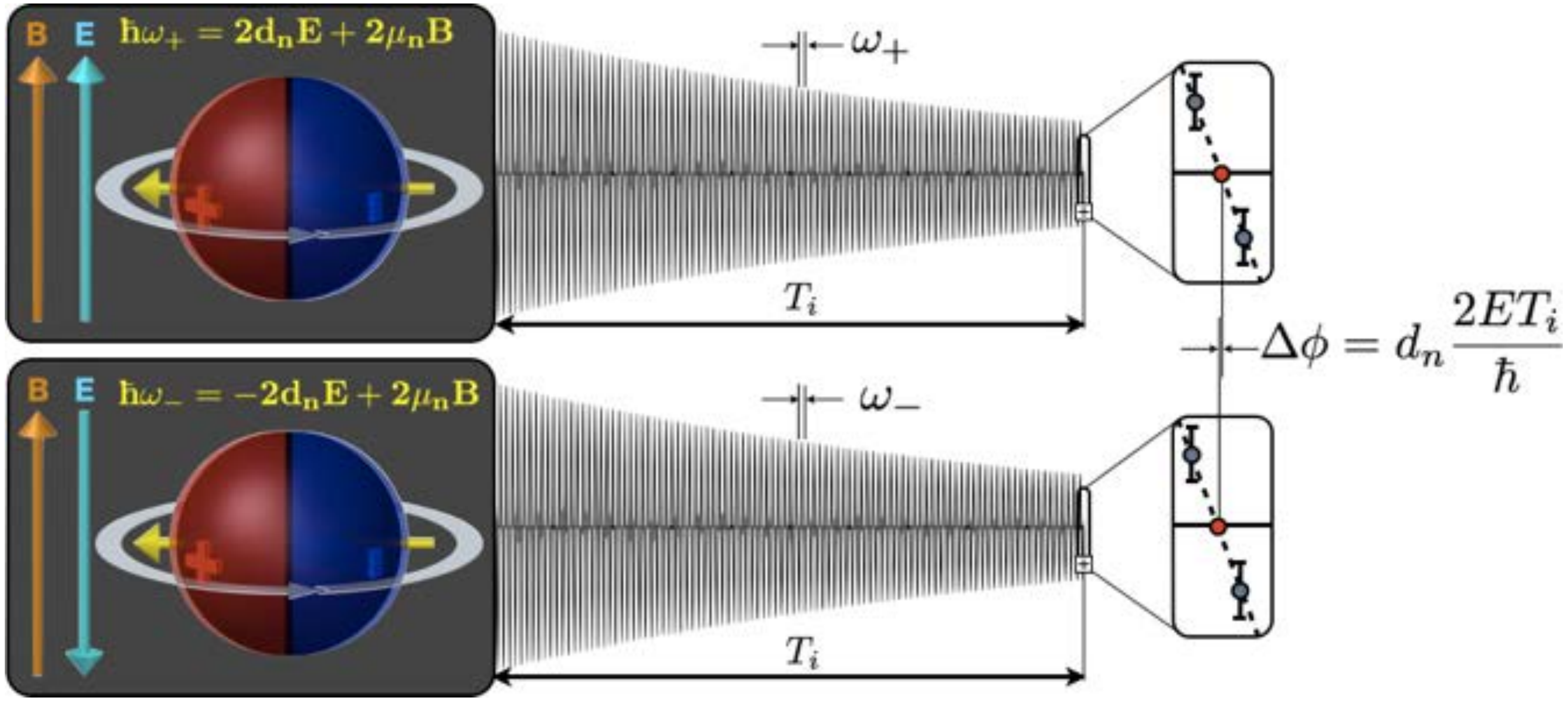




Measurement of Neutron Electric Dipole Moment

Confined Ultracold Neutron Spin Precession Frequency





$$\Delta U = 2d_n E = 2 \times (3 \times 10^{-26}\,[e \cdot \mathrm{cm}]) \times 10\,[\mathrm{kV/cm}]$$
$$= 6 \times 10^{-22}\,\mathrm{eV}$$

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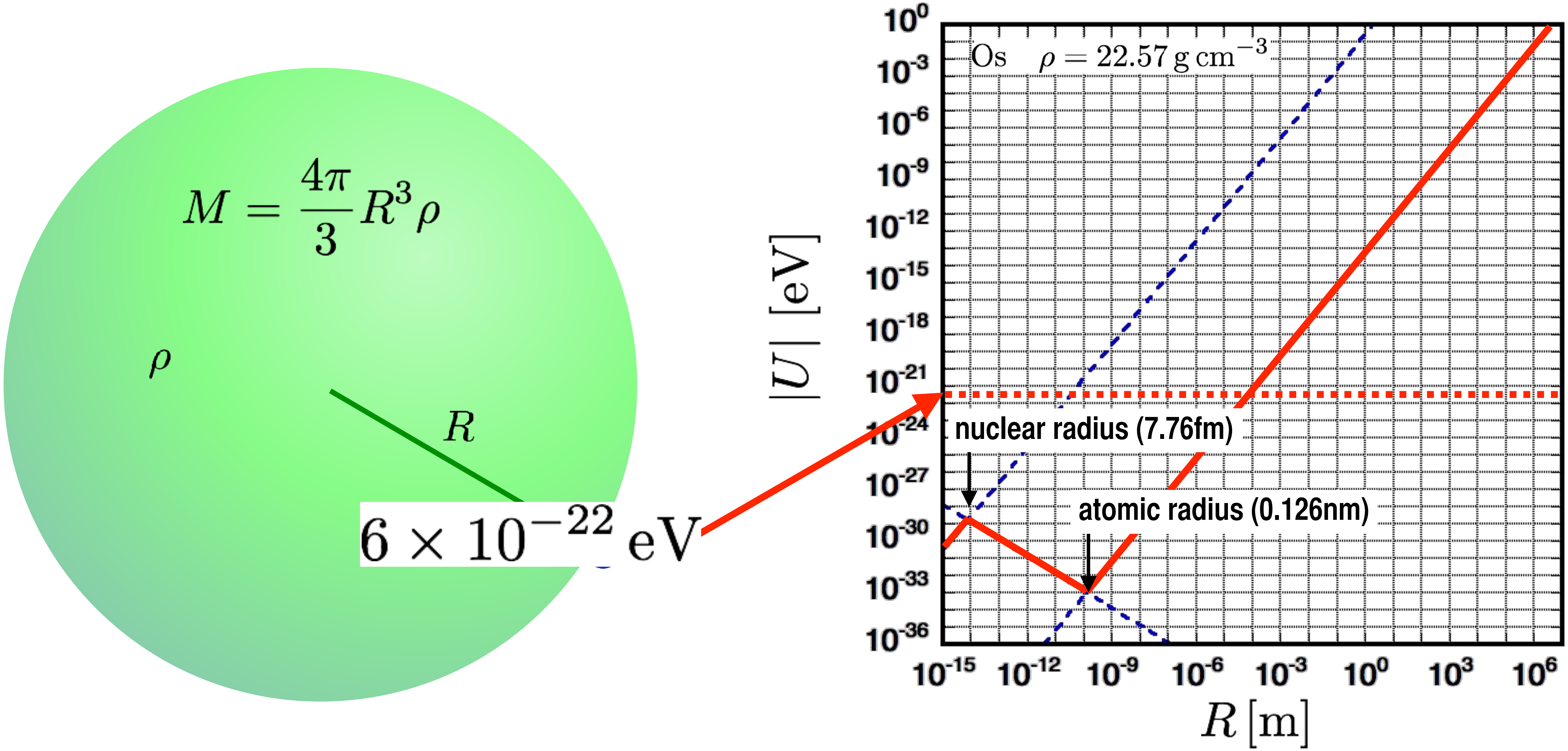

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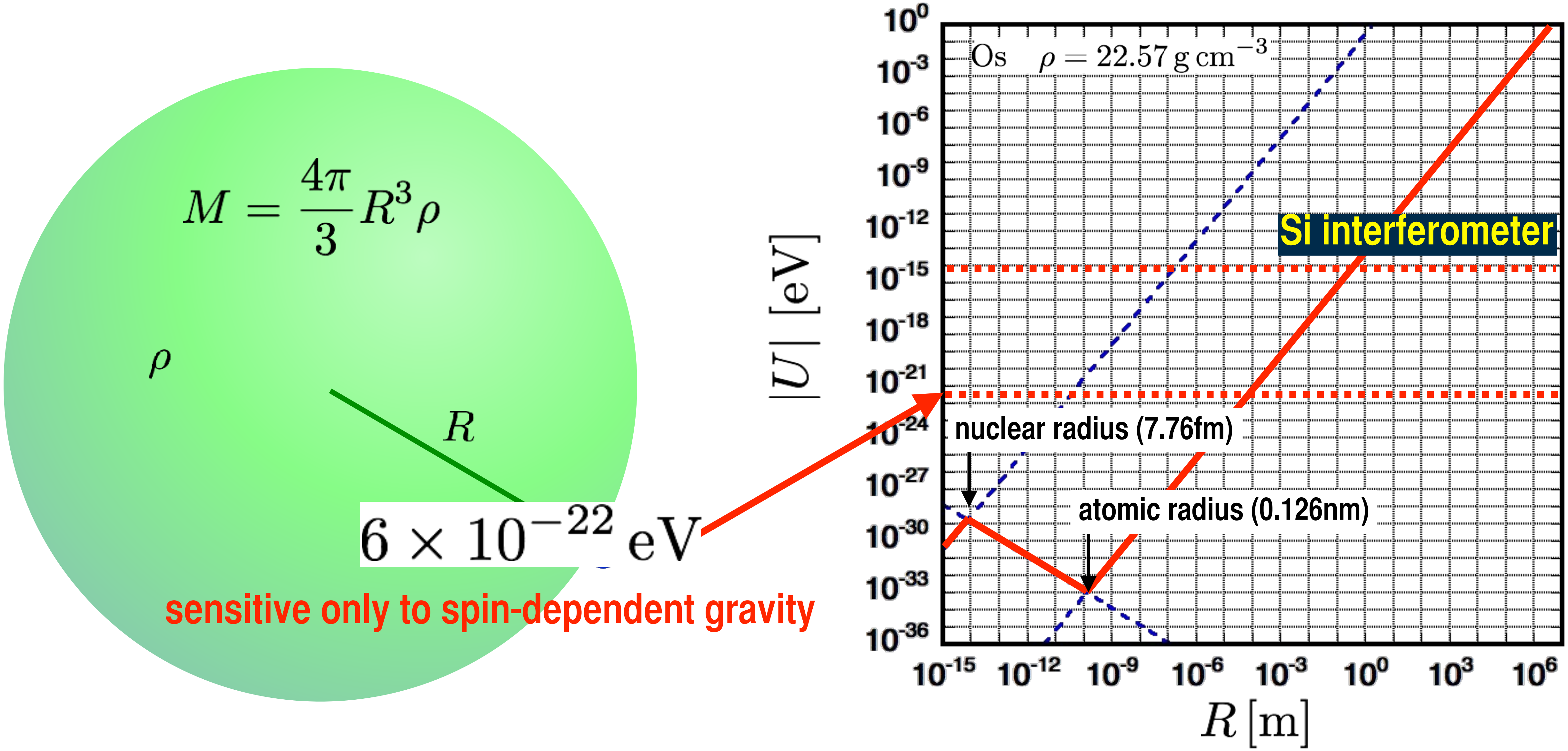


$6 \times 10^{-22}\,\mathrm{eV}$

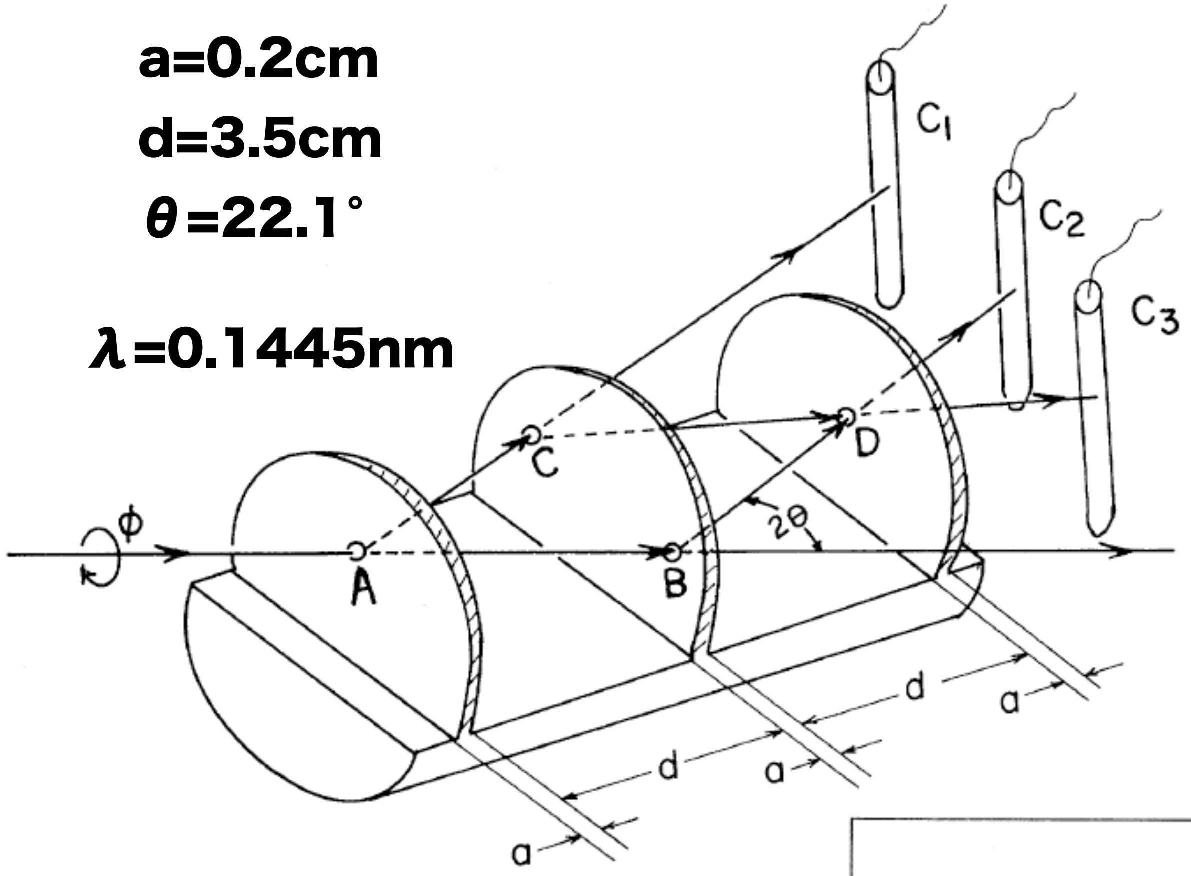
sensitive only to spin-dependent gravity

Neutron Phase induced by Earth’s Gravity

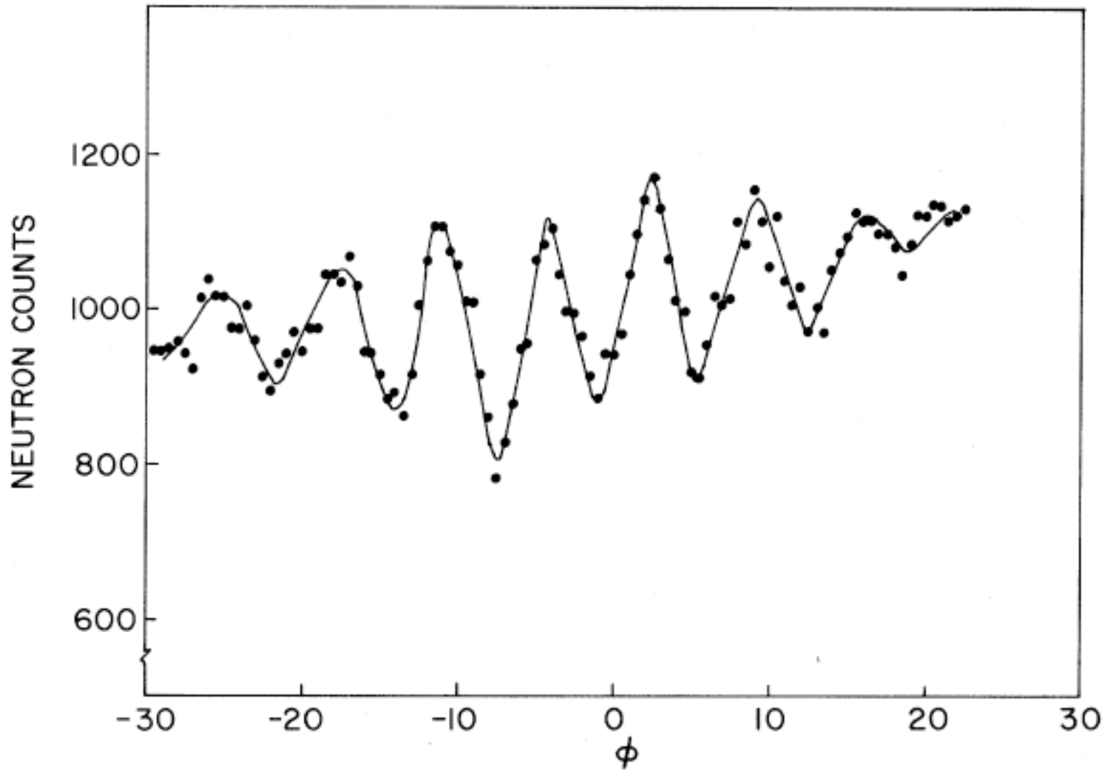
Collela, Overhauser, Werner, Phys. Rev. Lett. 34 (1975) 1472

a=0.2cm
d=3.5cm
θ=22.1°

λ=0.1445nm



COW expertment



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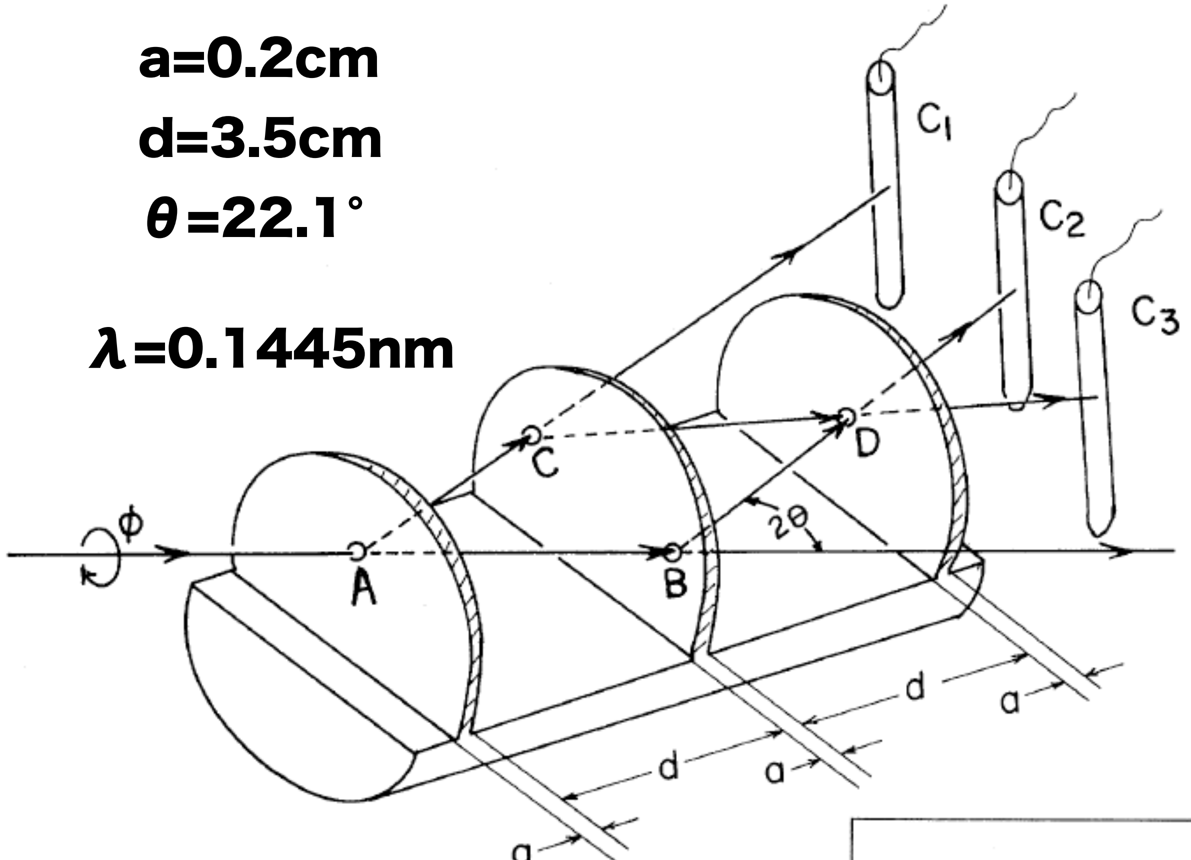

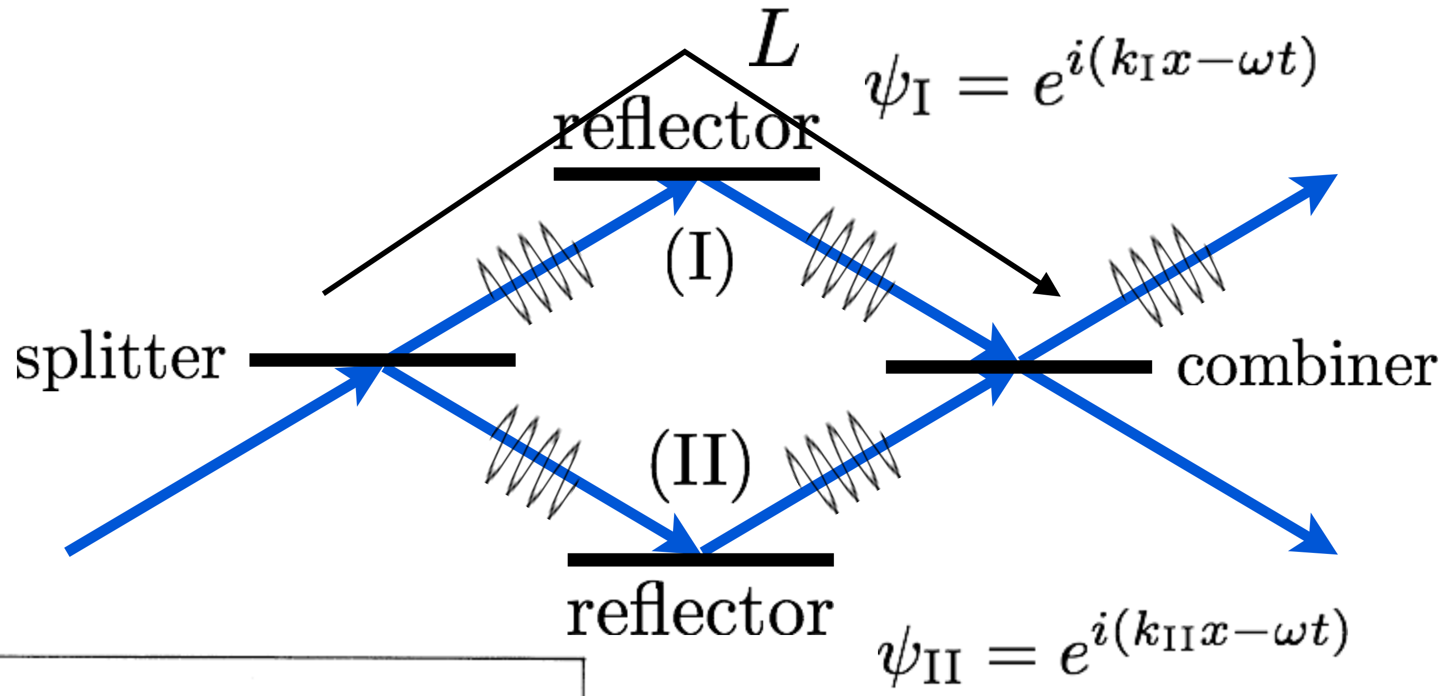

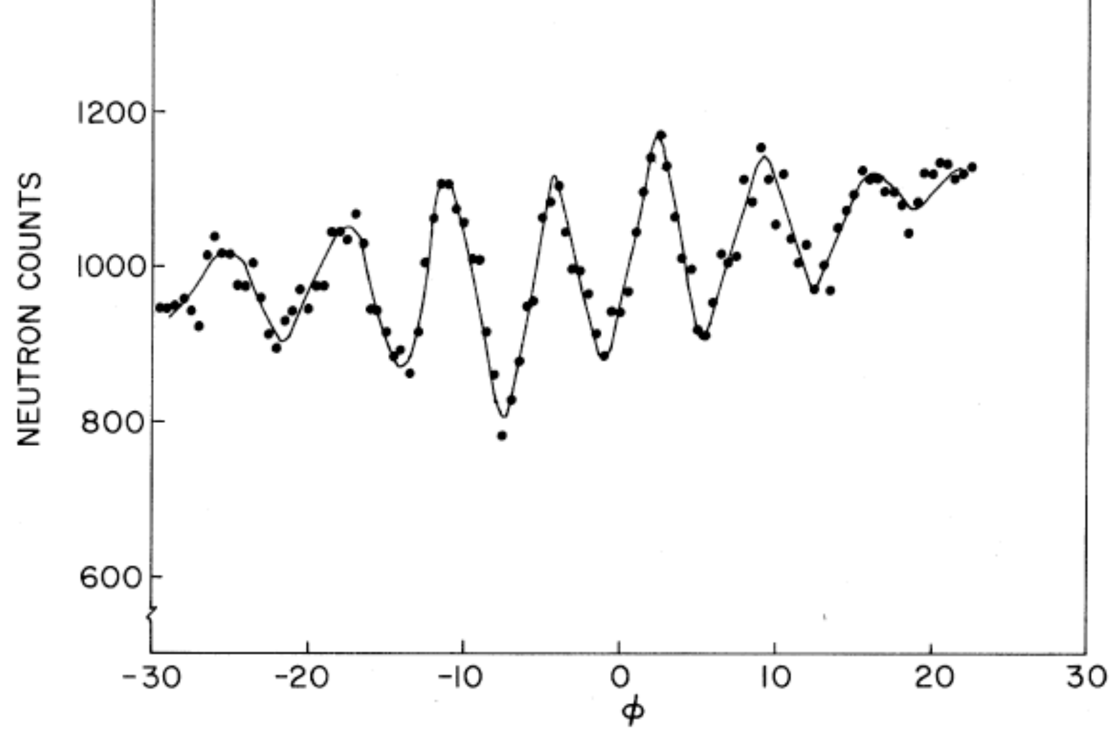

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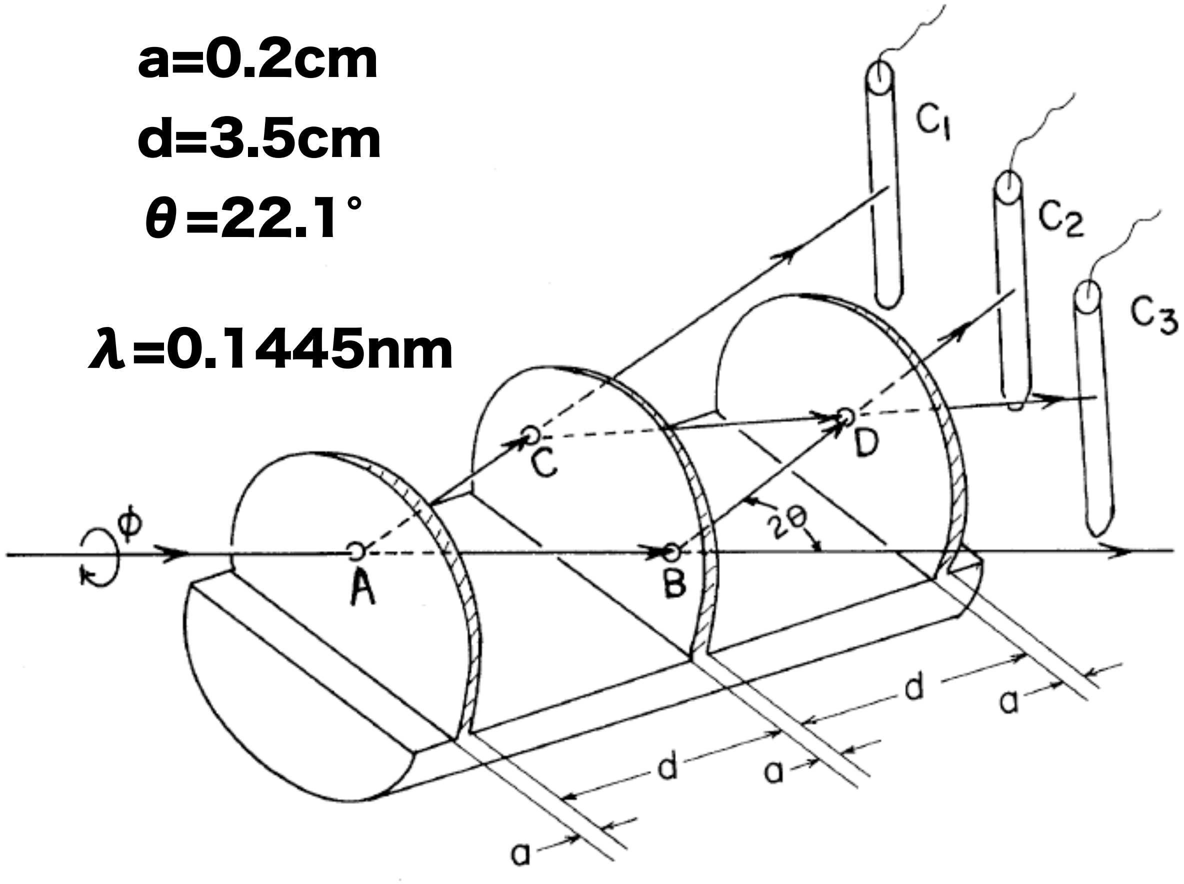

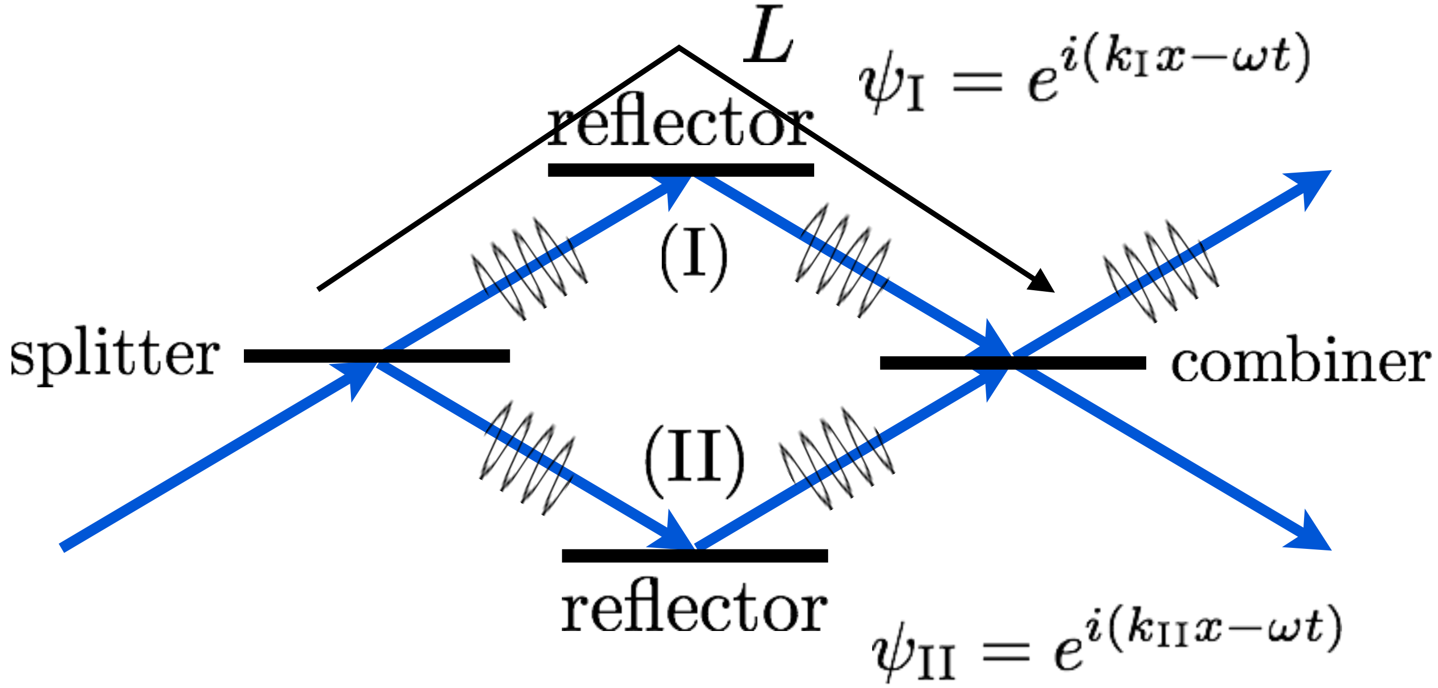

$$\psi_{\mathrm{I}} = e^{i(k_{\mathrm{I}}x-\omega t)}$$

$$\psi_{\mathrm{II}} = e^{i(k_{\mathrm{II}}x-\omega t)}$$

$$k_{\mathrm{I}} = \frac{\sqrt{2m_n(E_0+U)}}{\hbar} \qquad \phi_{\mathrm{I}} = k_{\mathrm{I}}L$$

$$k_{\mathrm{II}} = \frac{\sqrt{2m_n(E_0+U+\Delta U)}}{\hbar} \qquad \phi_{\mathrm{II}} = k_{\mathrm{II}}L$$

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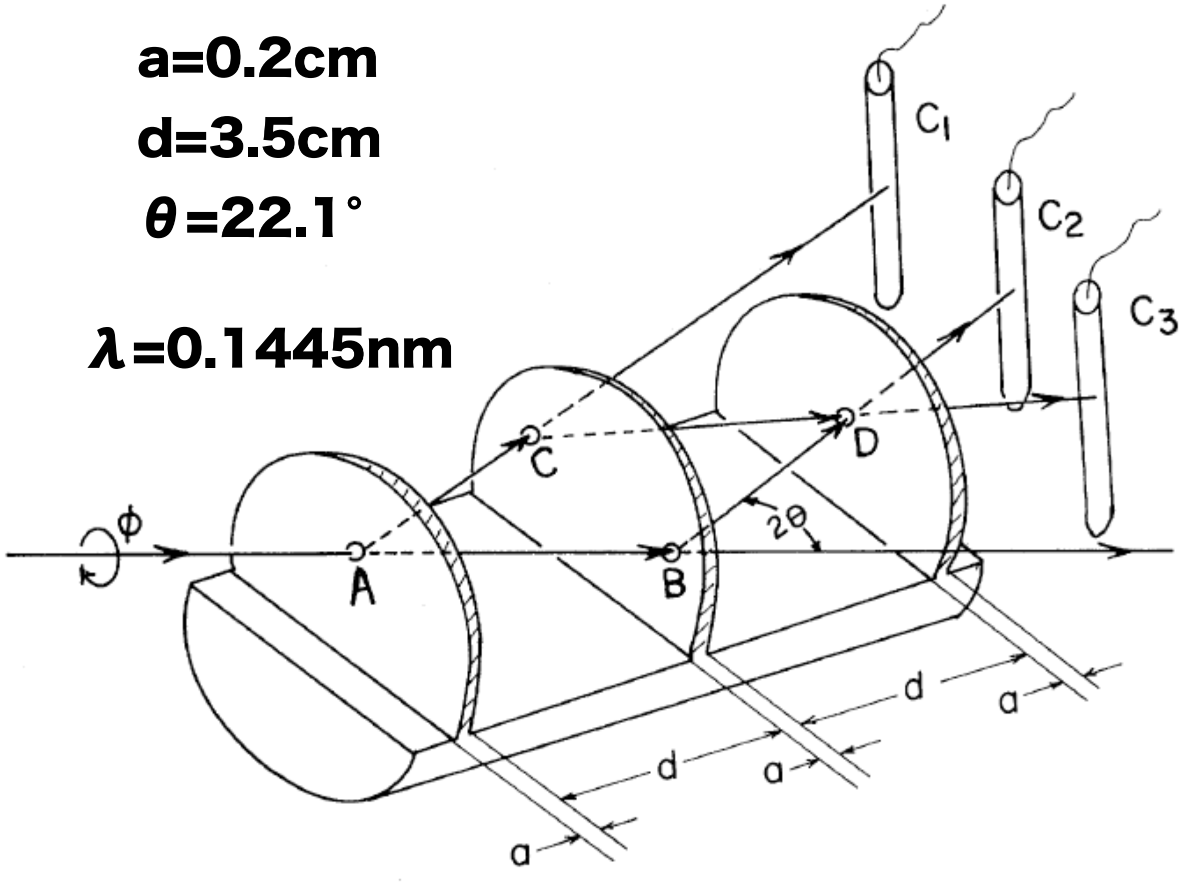

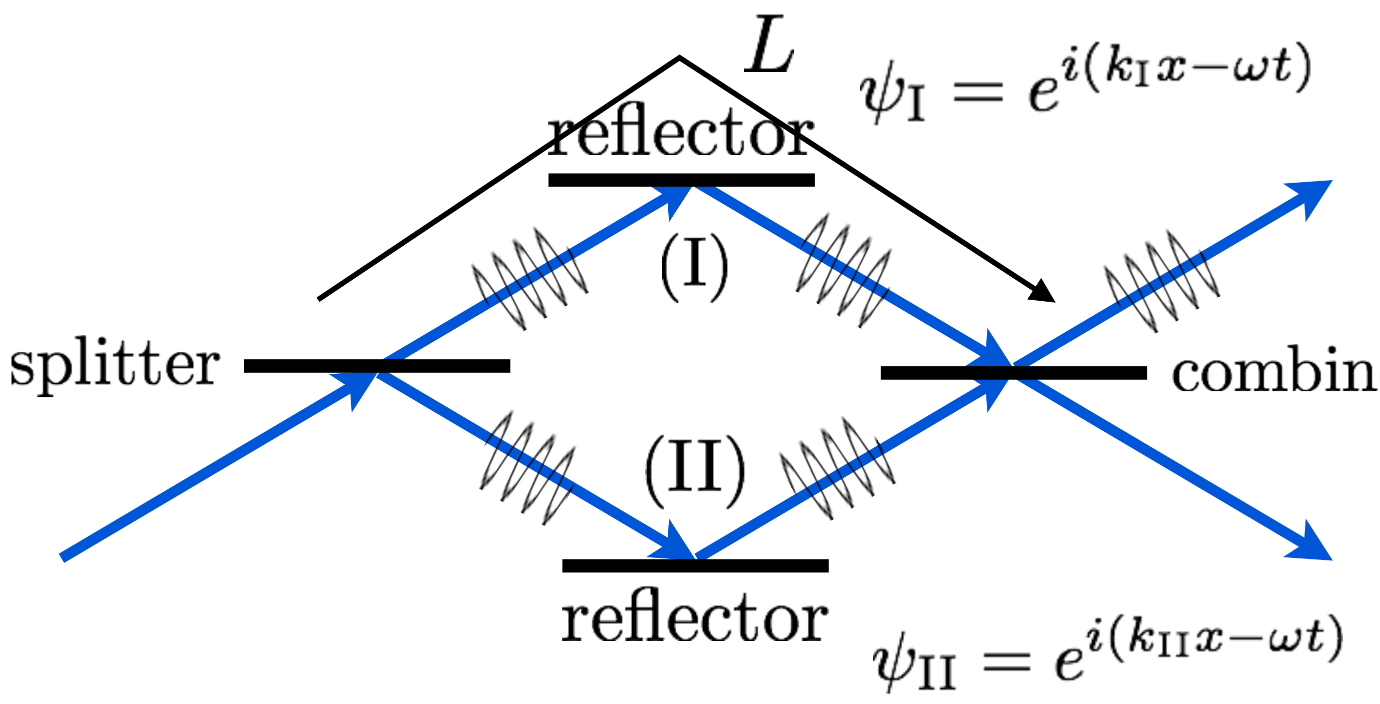

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larger interferometer

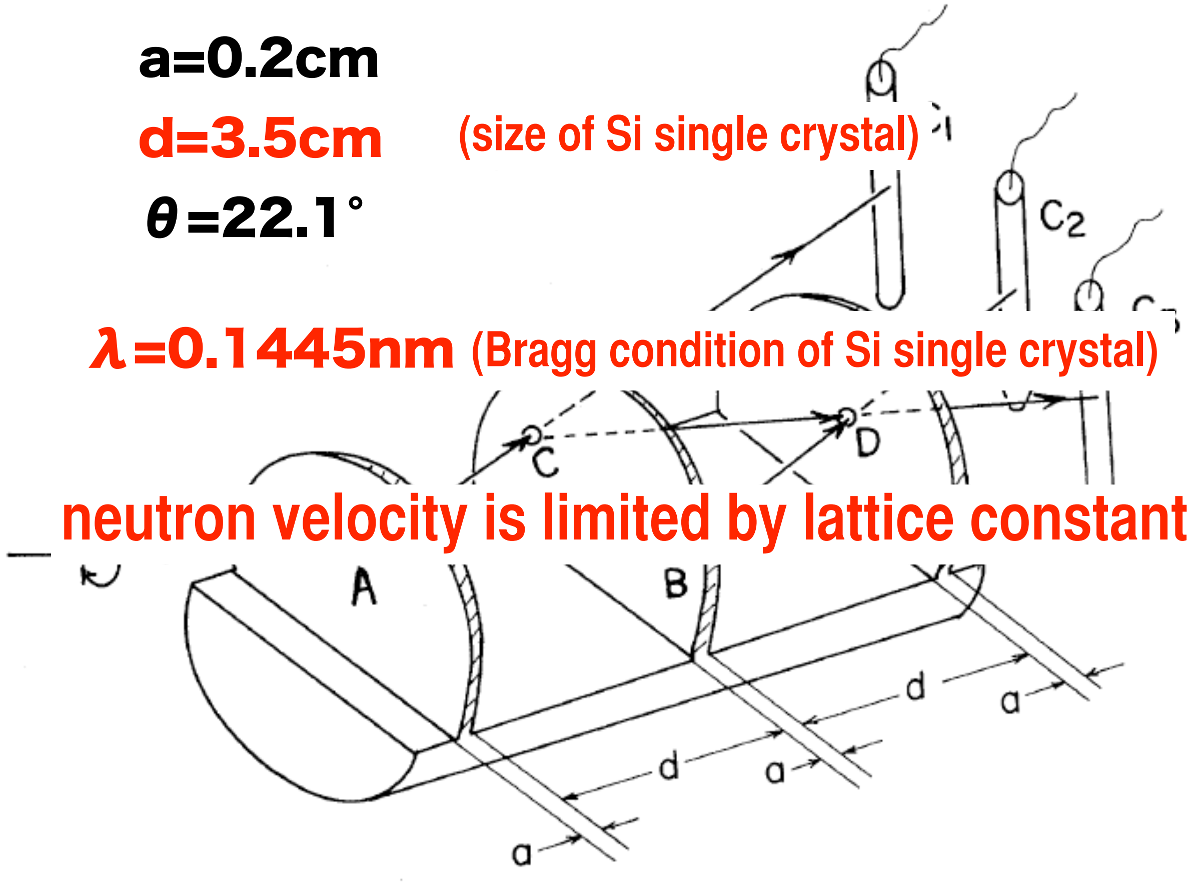
$$\boxed{\Delta\phi} = \phi_{\mathrm{II}} - \phi_{\mathrm{I}} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\,\frac{\boxed{L}\Delta U}{\hbar c}$$

better statistics

slower neutron

Neutron Phase induced by Earth’s Gravity

Collela, Overhauser, Werner, Phys. Rev. Lett. 34 (1975) 1472



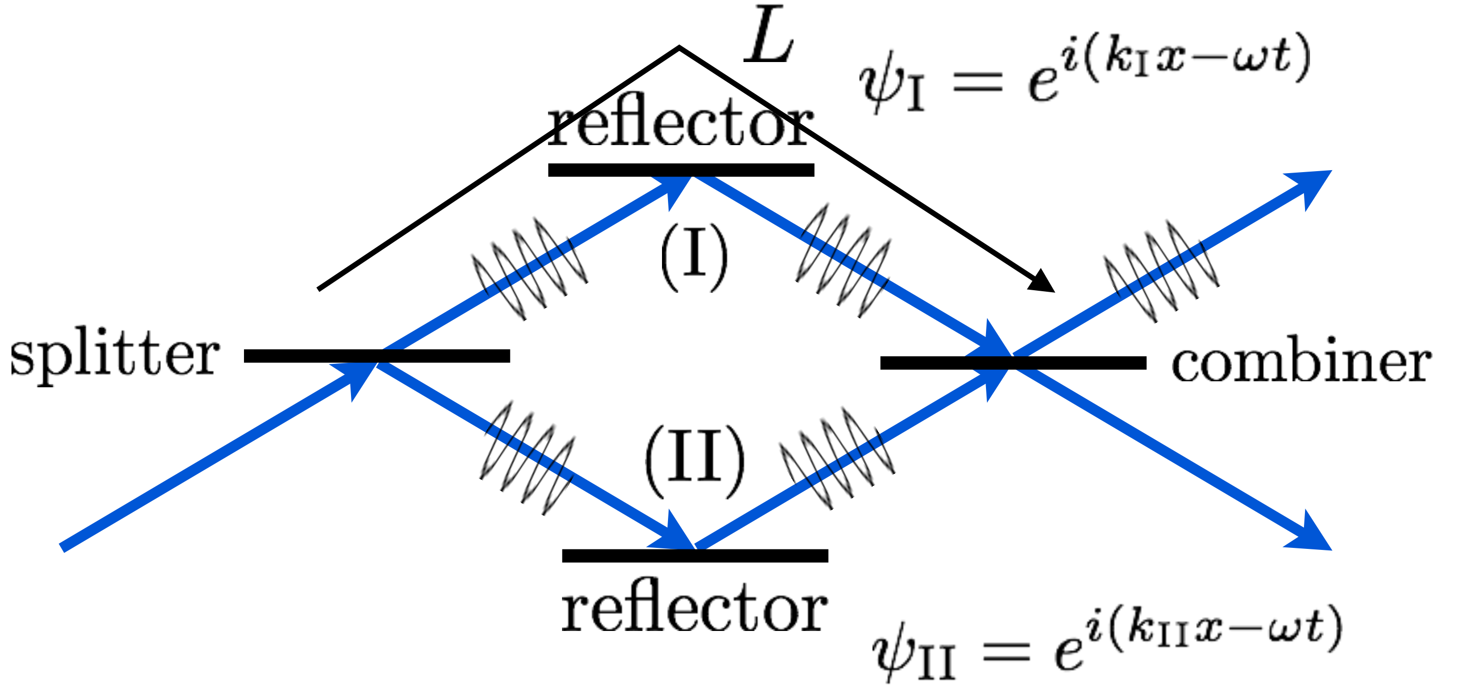
a=0.2cm

d=3.5cm (size of Si single crystal)

θ=22.1°

λ=0.1445nm (Bragg condition of Si single crystal)

neutron velocity is limited by lattice constant



$$k_{\mathrm{I}} = \frac{\sqrt{2m_n(E_0+U)}}{\hbar} \qquad \phi_{\mathrm{I}} = k_{\mathrm{I}}L$$

$$k_{\mathrm{II}} = \frac{\sqrt{2m_n(E_0+U+\Delta U)}}{\hbar} \qquad \phi_{\mathrm{II}} = k_{\mathrm{II}}L$$

larger interferometer

$$\boxed{\Delta\phi} = \phi_{\mathrm{II}} - \phi_{\mathrm{I}} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\,\frac{\boxed{L}\,\Delta U}{\hbar c}$$

better statistics

slower neutron

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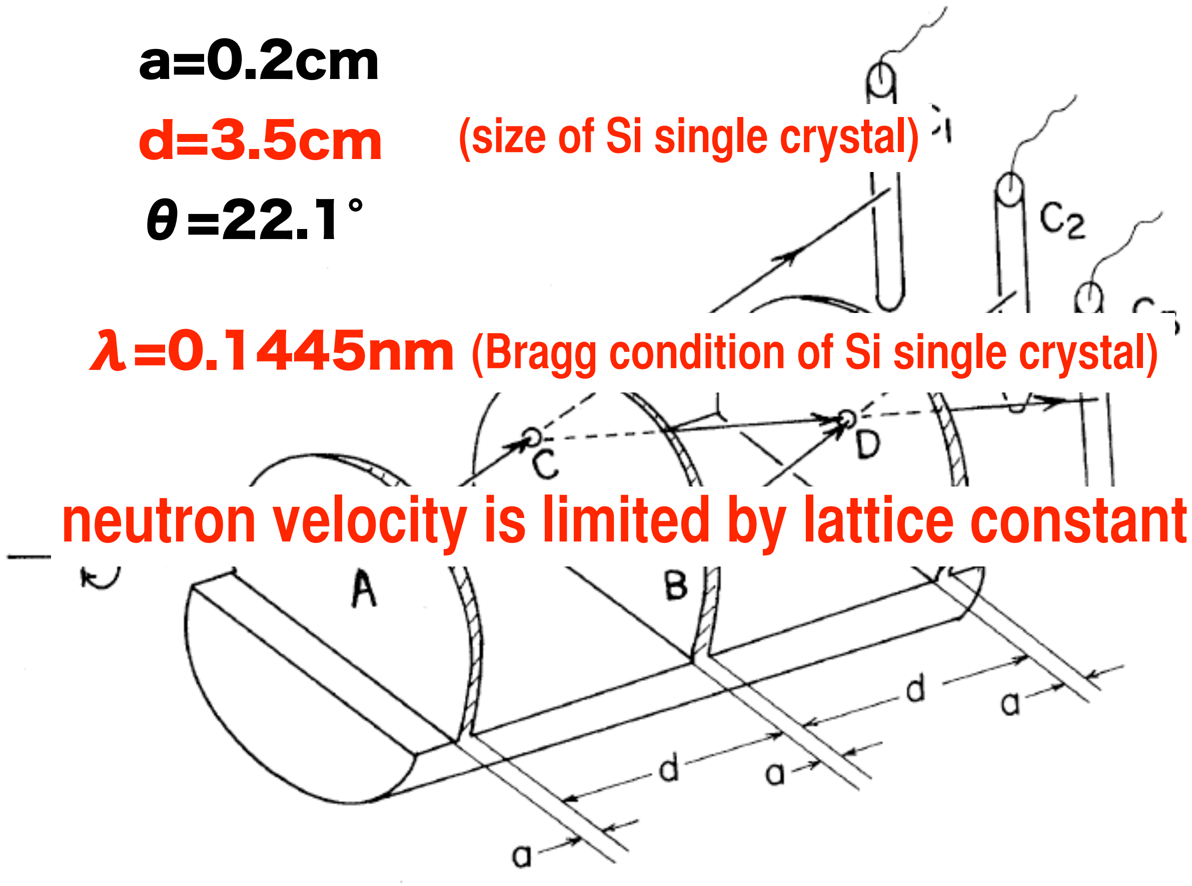

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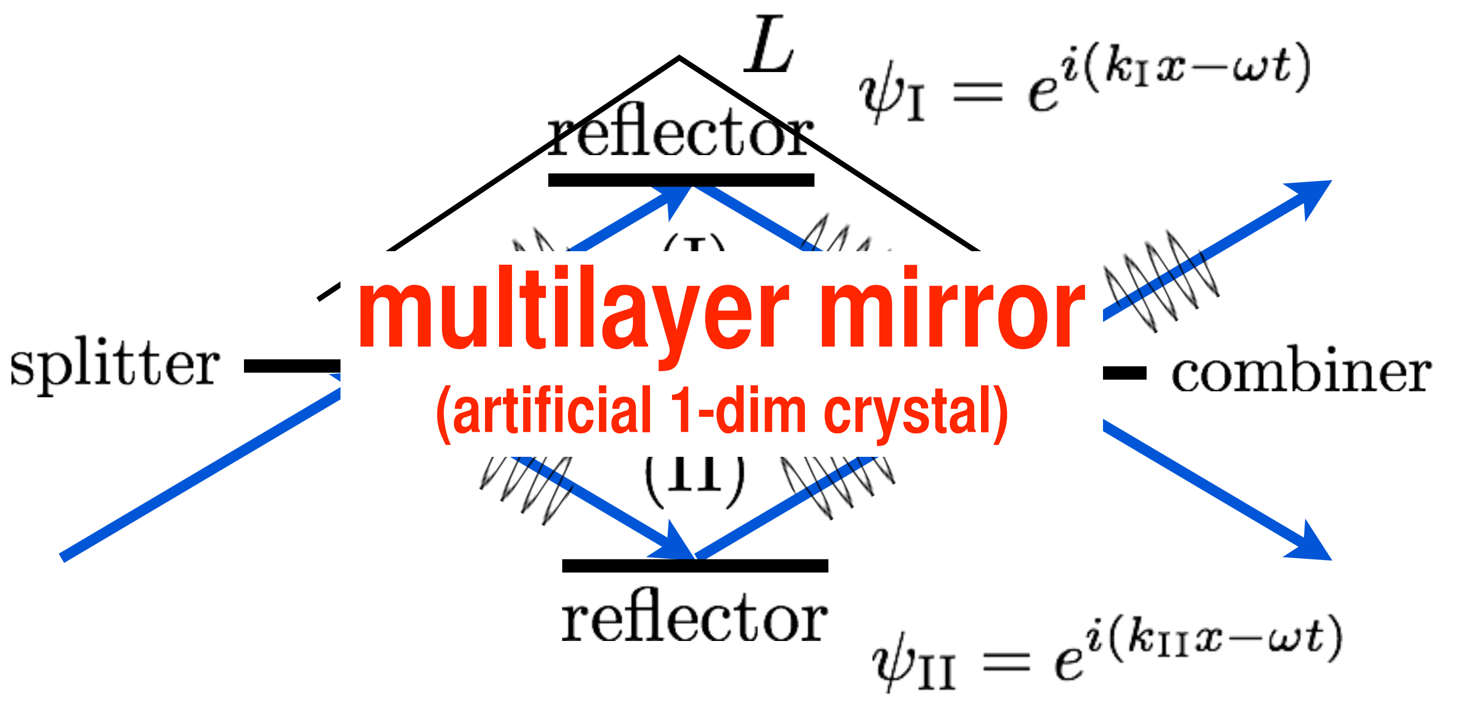


$\psi_{\rm I} = e^{i(k_{\rm I}x-\omega t)}$

$\psi_{\rm II} = e^{i(k_{\rm II}x-\omega t)}$

multilayer mirror

(artificial 1-dim crystal)

$$k_{\rm I} = \frac{\sqrt{2m_n(E_0+U)}}{\hbar} \qquad \phi_{\rm I} = k_{\rm I}L$$

$$k_{\rm II} = \frac{\sqrt{2m_n(E_0+U+\Delta U)}}{\hbar} \qquad \phi_{\rm II} = k_{\rm II}L$$

larger interferometer

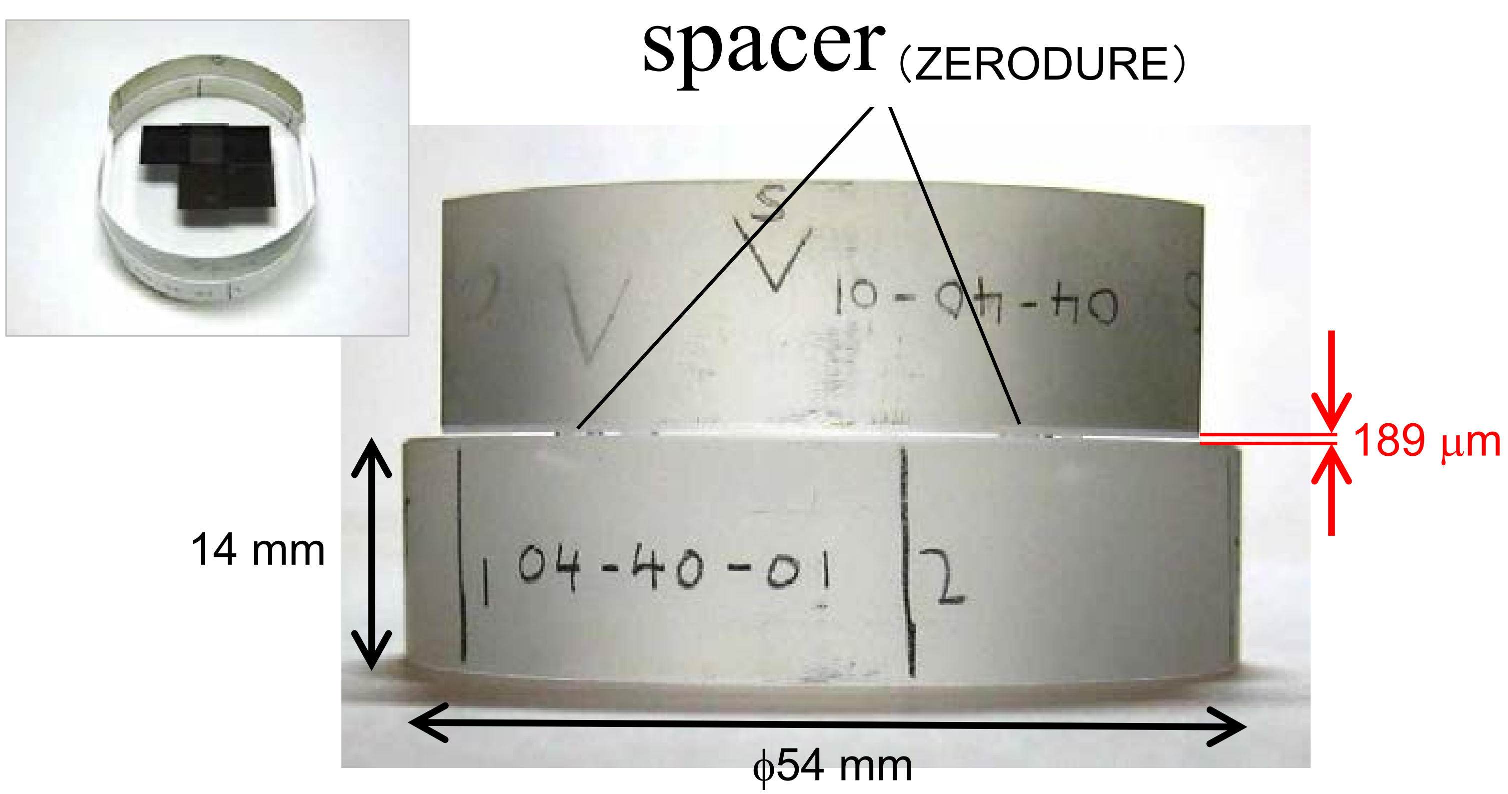
$$\boxed{\Delta\phi} = \phi_{\rm II} - \phi_{\rm I} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\,\frac{\boxed{L}\Delta U}{\hbar c}$$

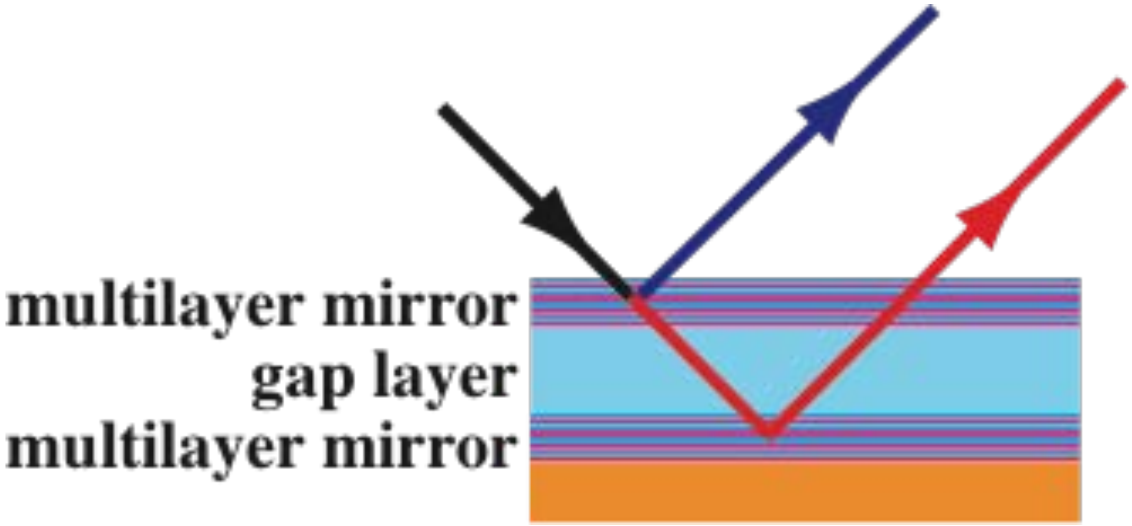
better statistics

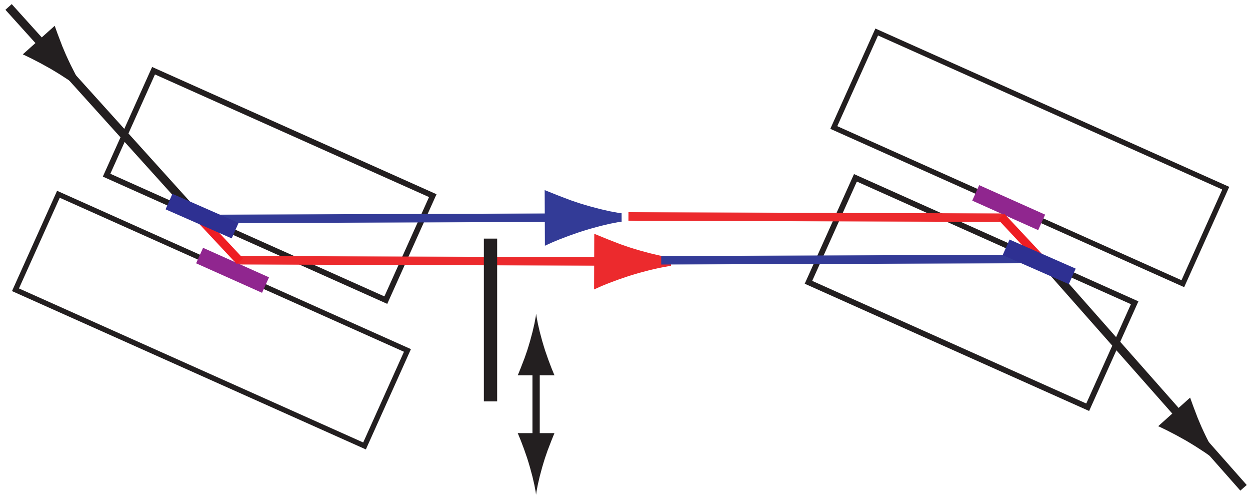
slower neutron

Mirror Alignment

Y. Seki et al., J. Phys. Soc. Jpn. 79 (2010) 124201.







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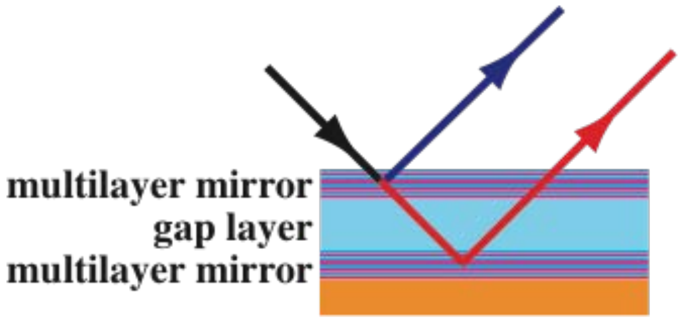

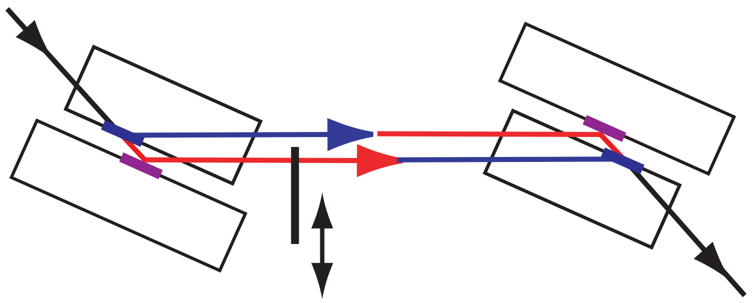

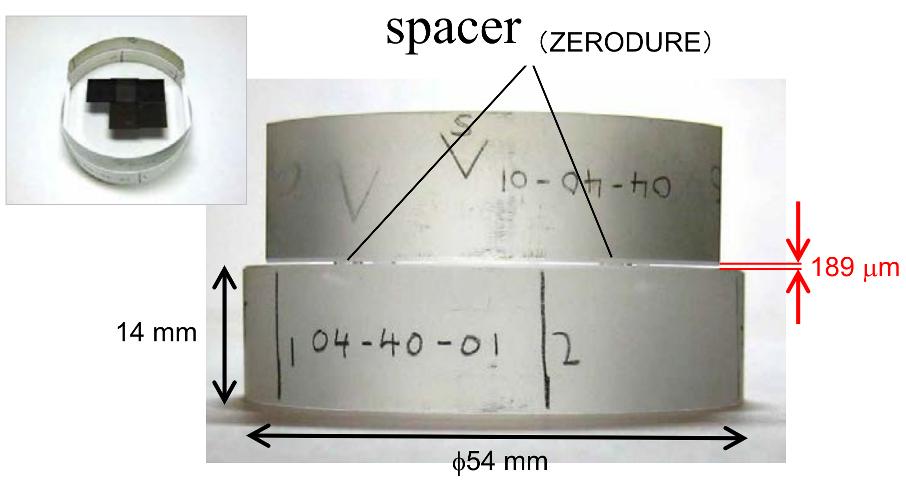

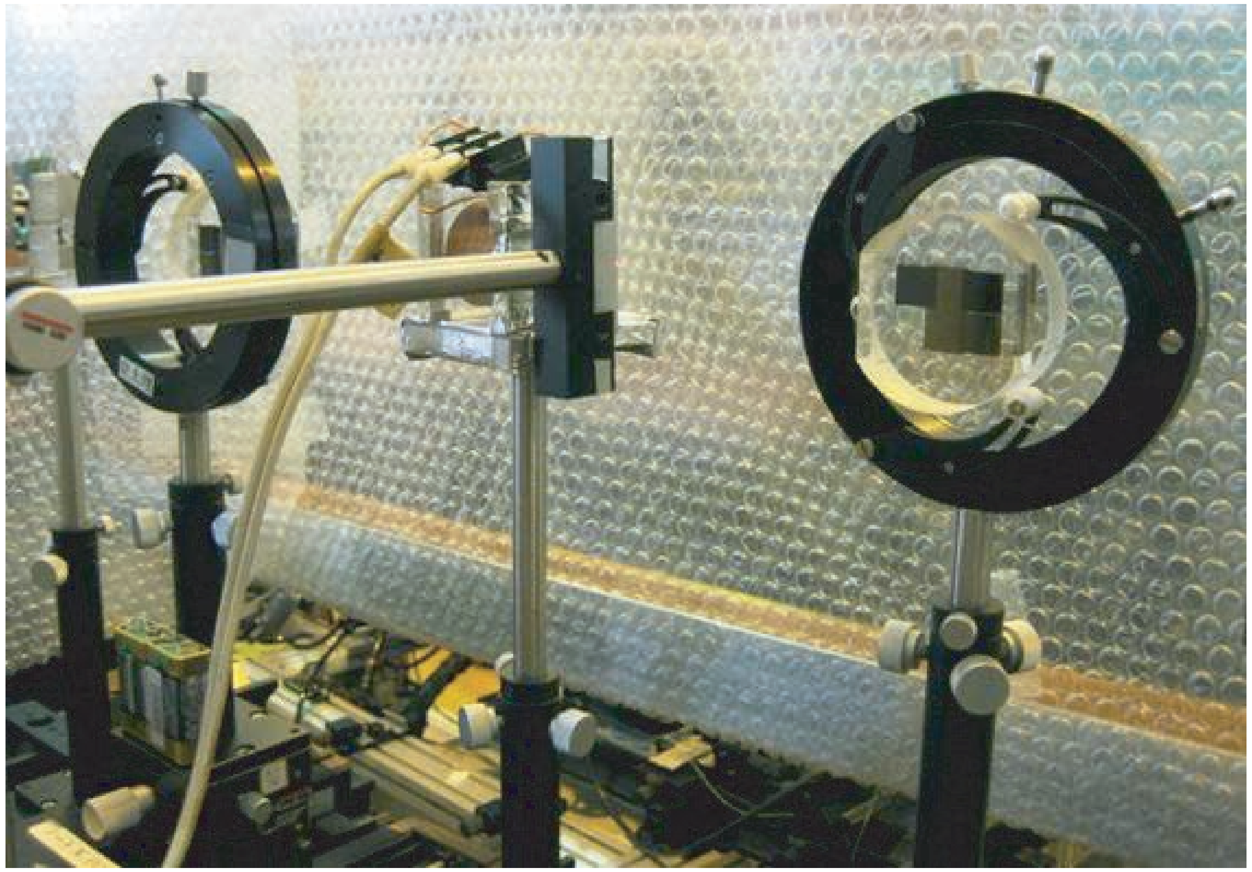

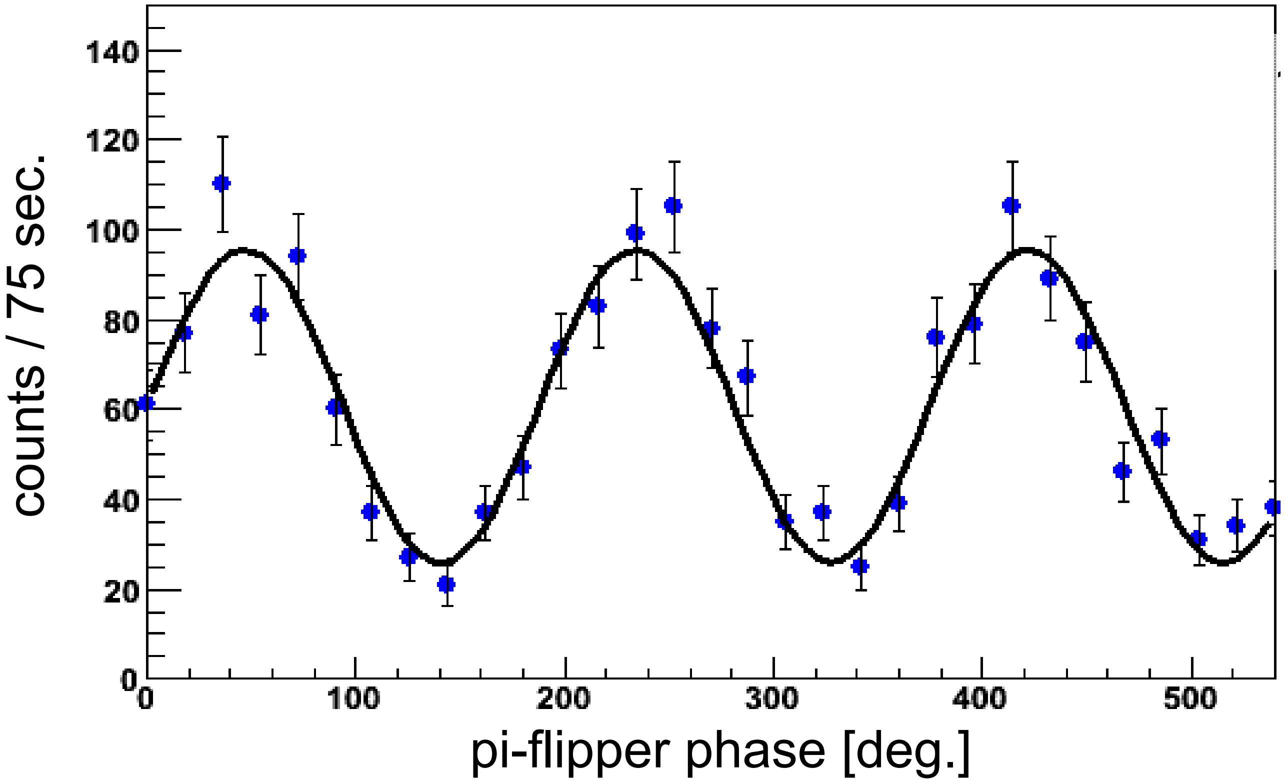

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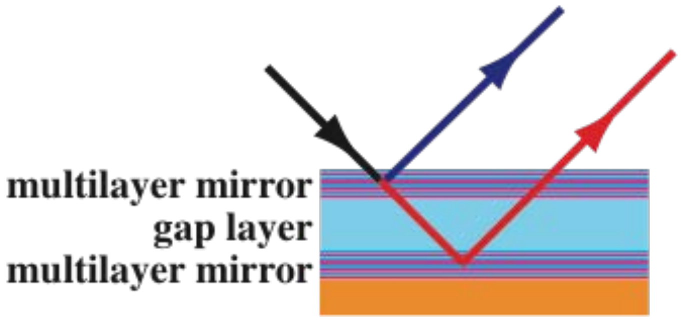
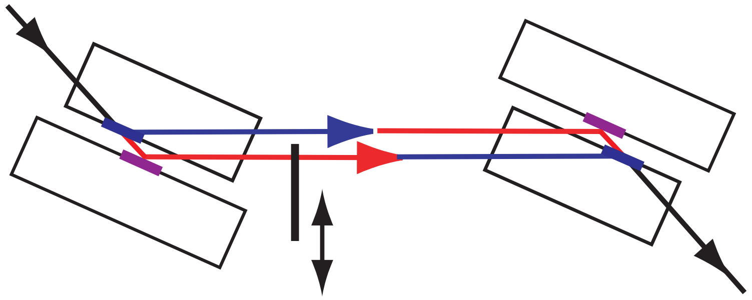
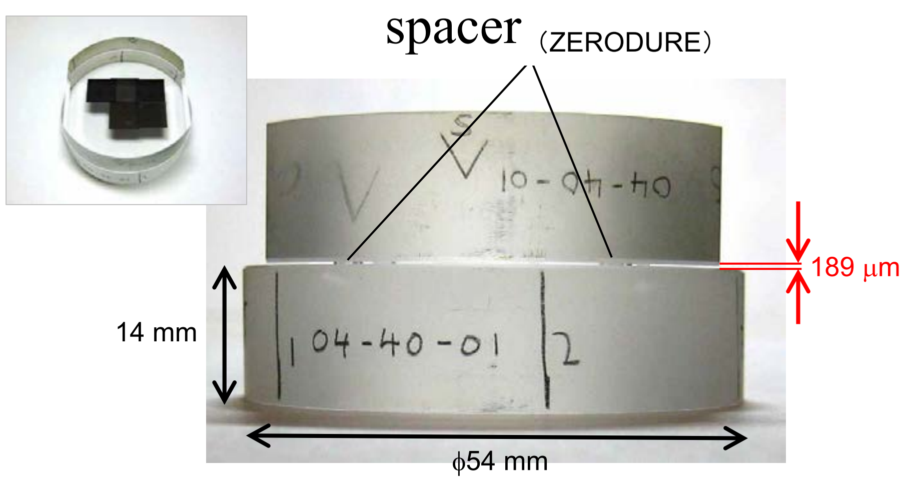
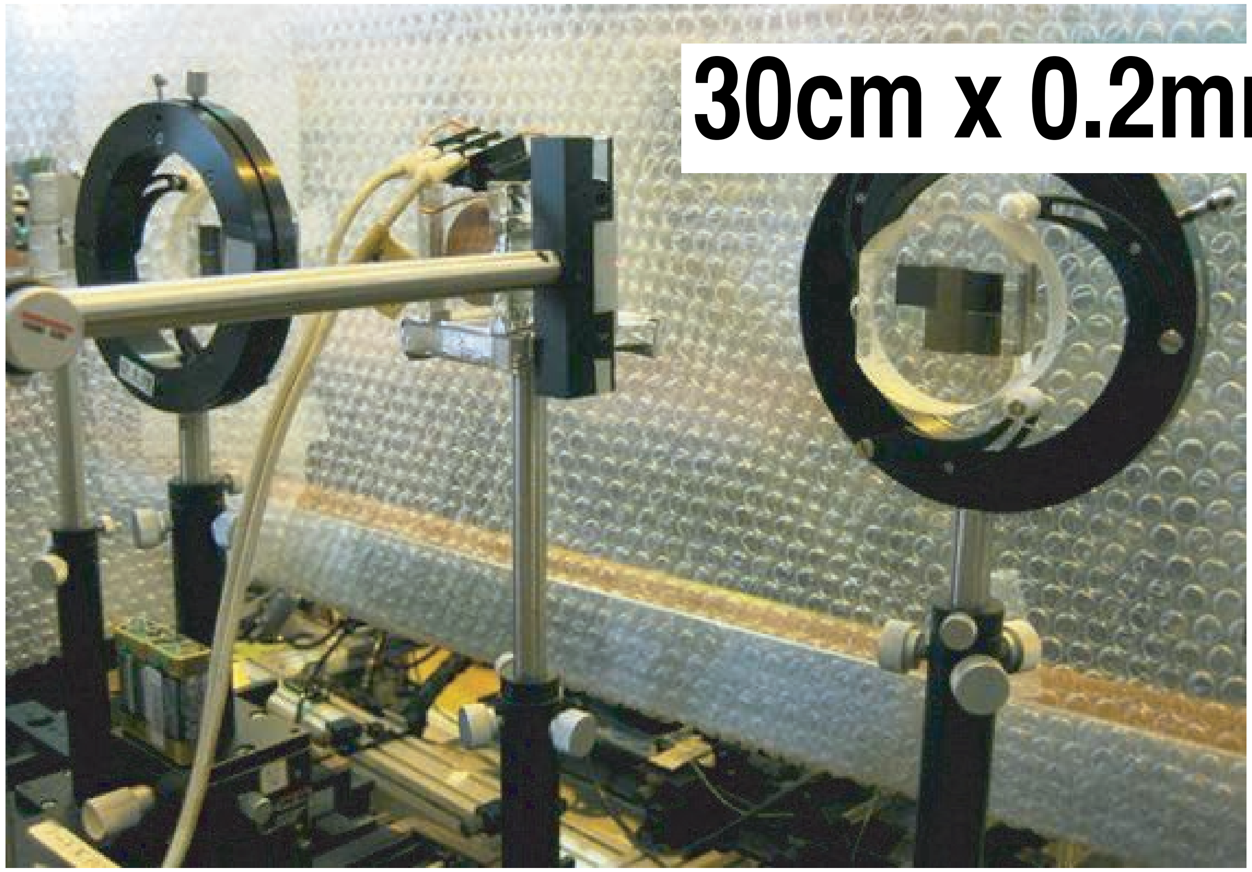
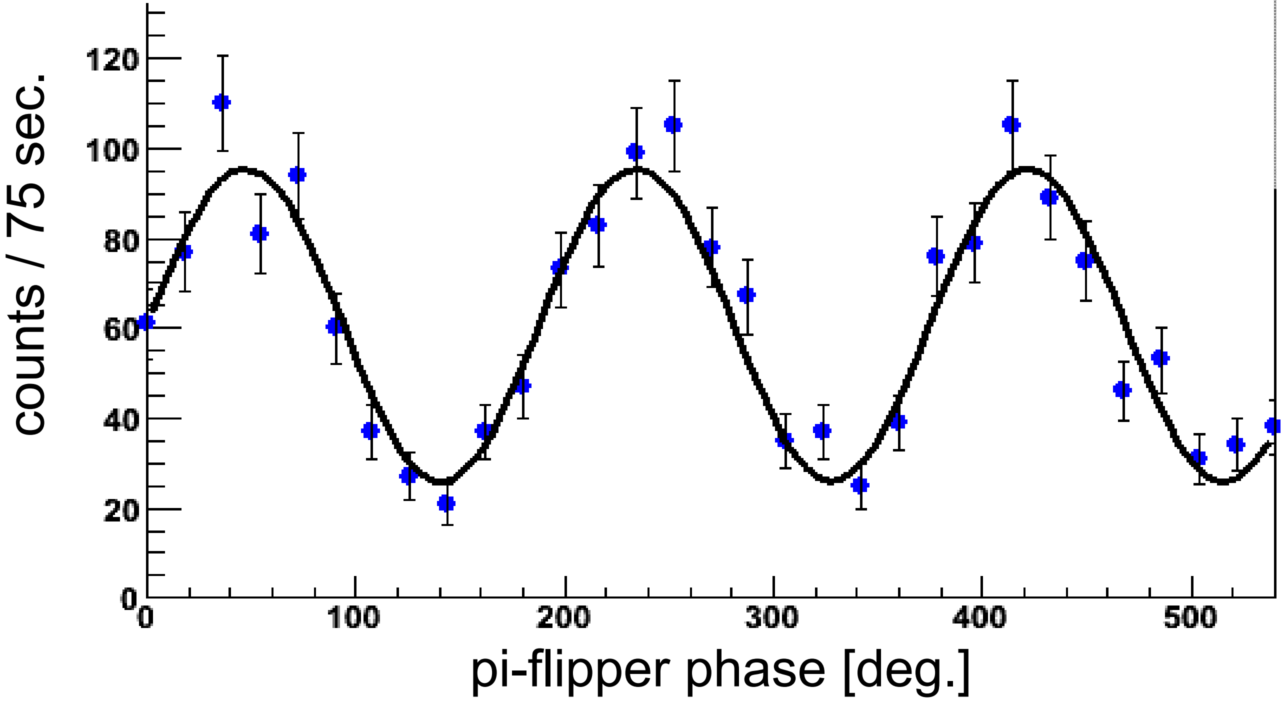




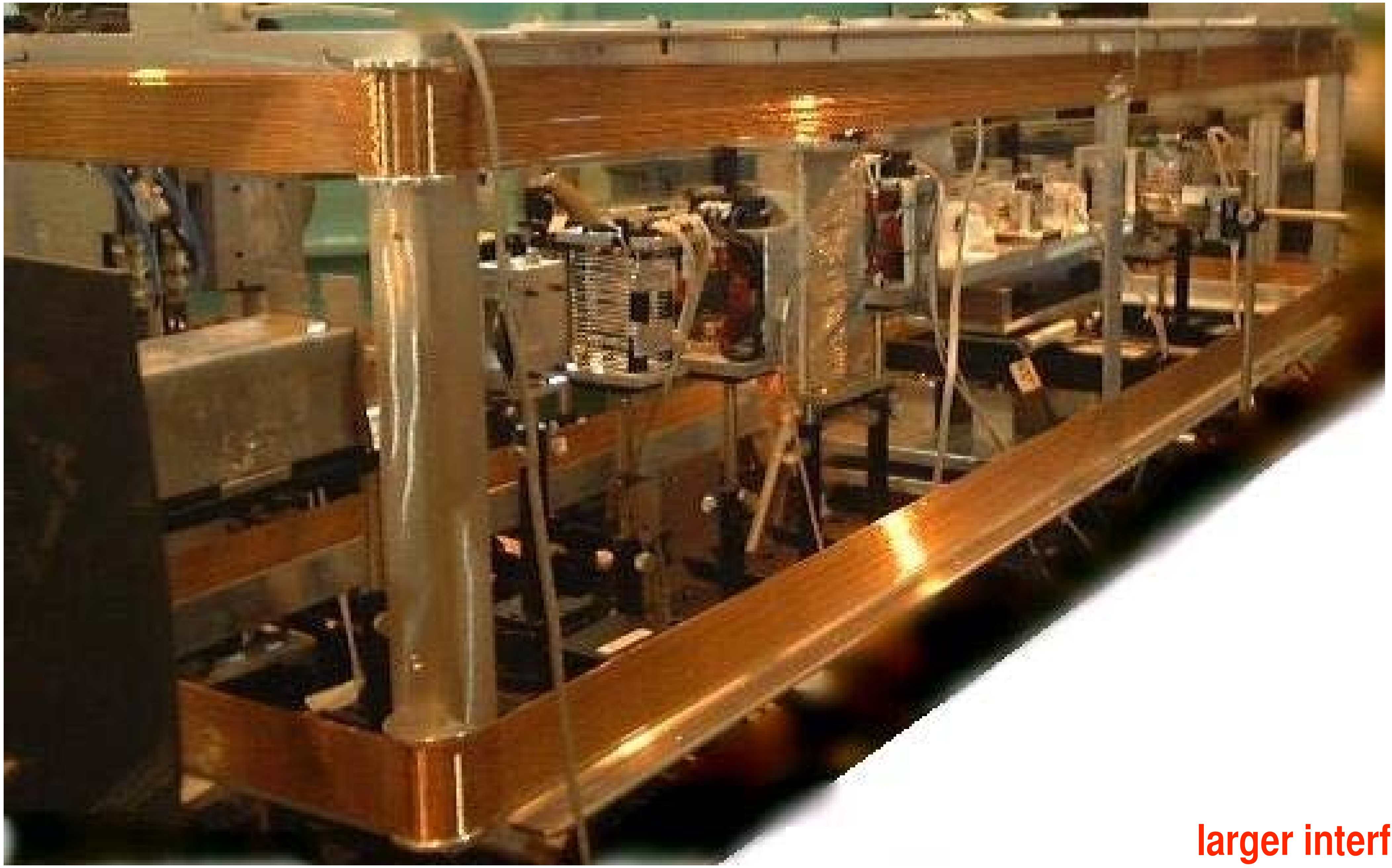




30cm x 0.2mm ~ 10^{-4} m^2



Multilayer Neutron Interferometer



larger interferometer

$$\boxed{\Delta\phi} = \phi_{\rm II} - \phi_{\rm I} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\,\frac{\boxed{L}\,\Delta U}{\hbar c}$$

better statistics

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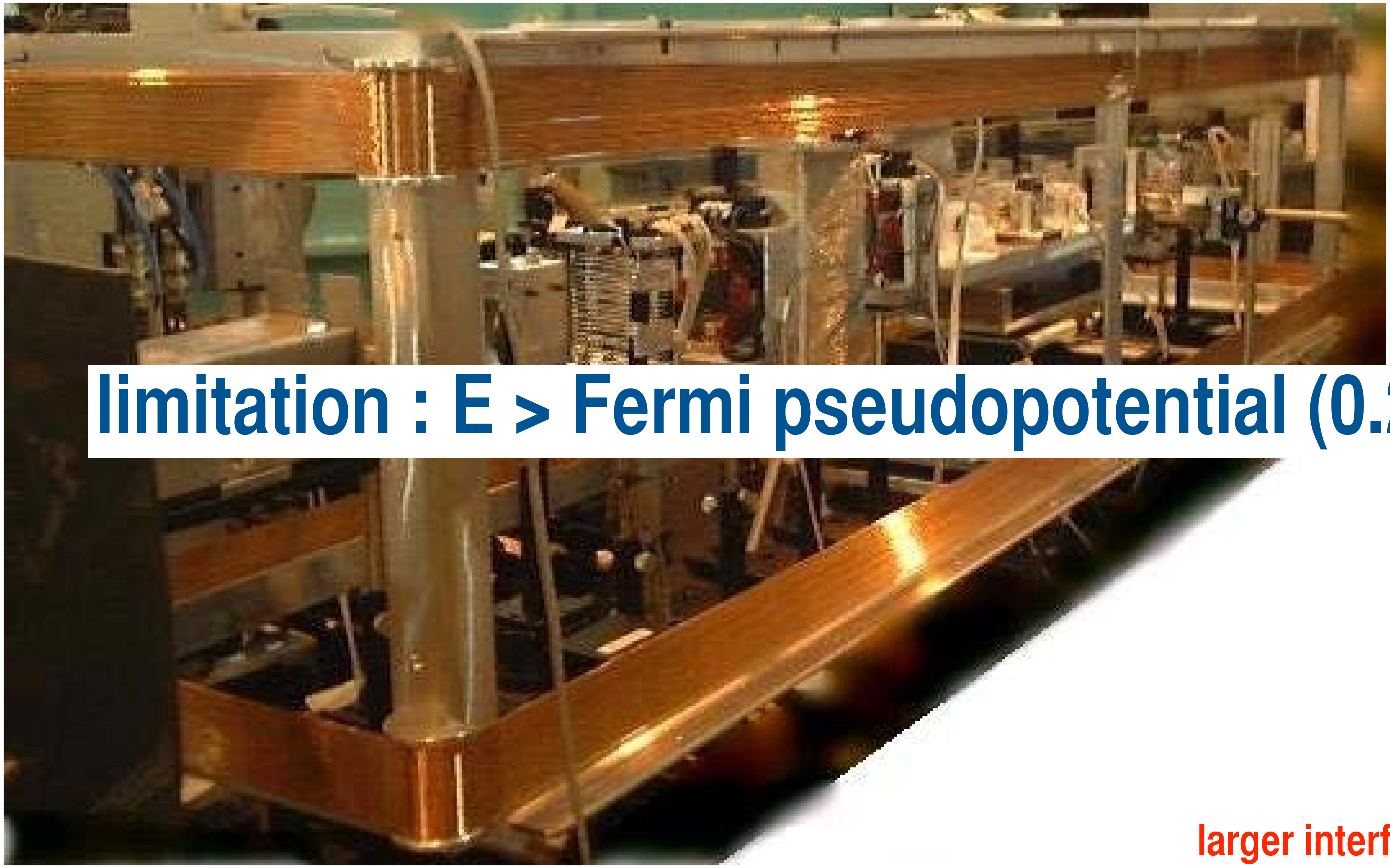

limitation : E > Fermi pseudopotential (0.25μeV)

$\lambda < 0.5\mathrm{nm}$

larger interferometer

$$\boxed{\Delta\phi} = \phi_{\mathrm{II}} - \phi_{\mathrm{I}} \simeq \sqrt{\frac{m_n c^2}{2\boxed{E}}}\,\frac{\boxed{L}\Delta U}{\hbar c}$$

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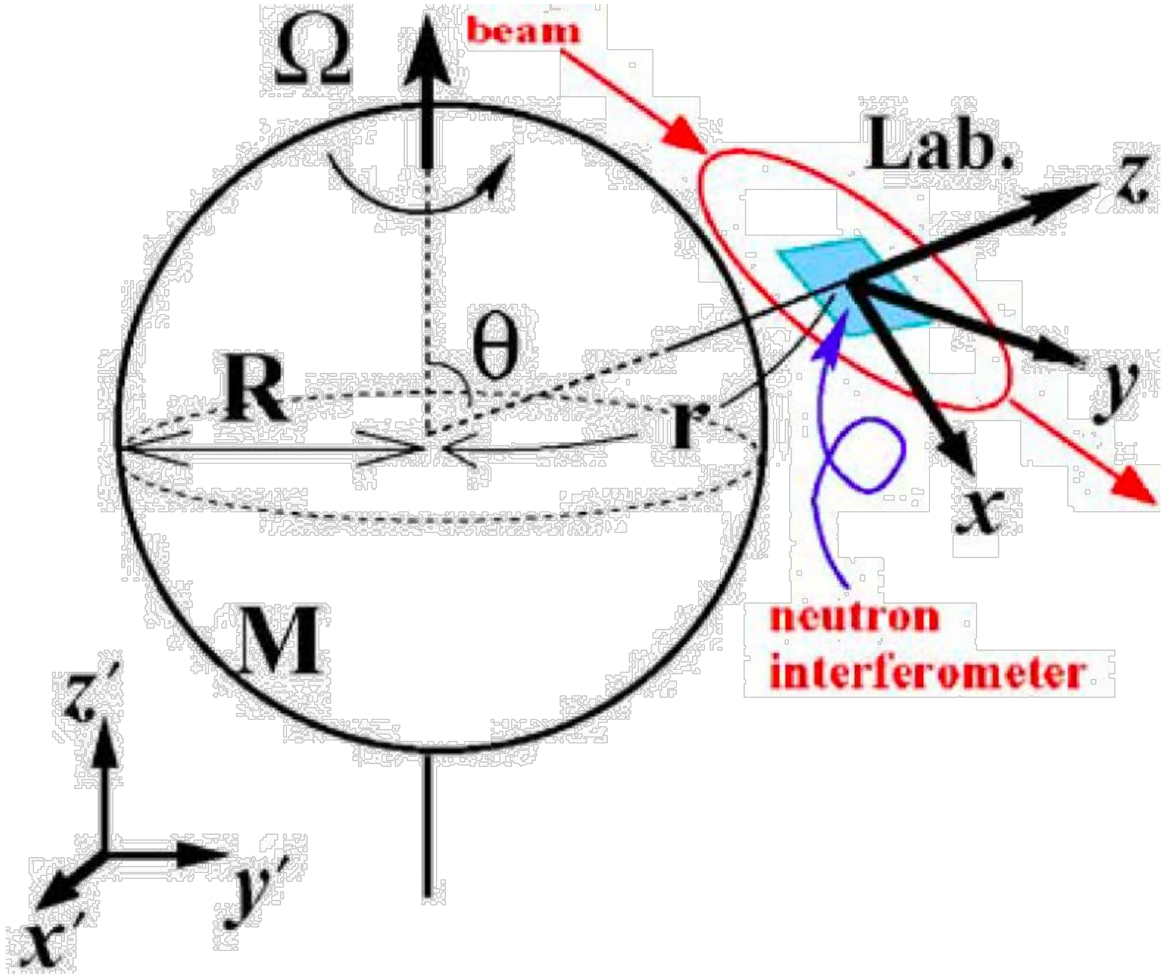
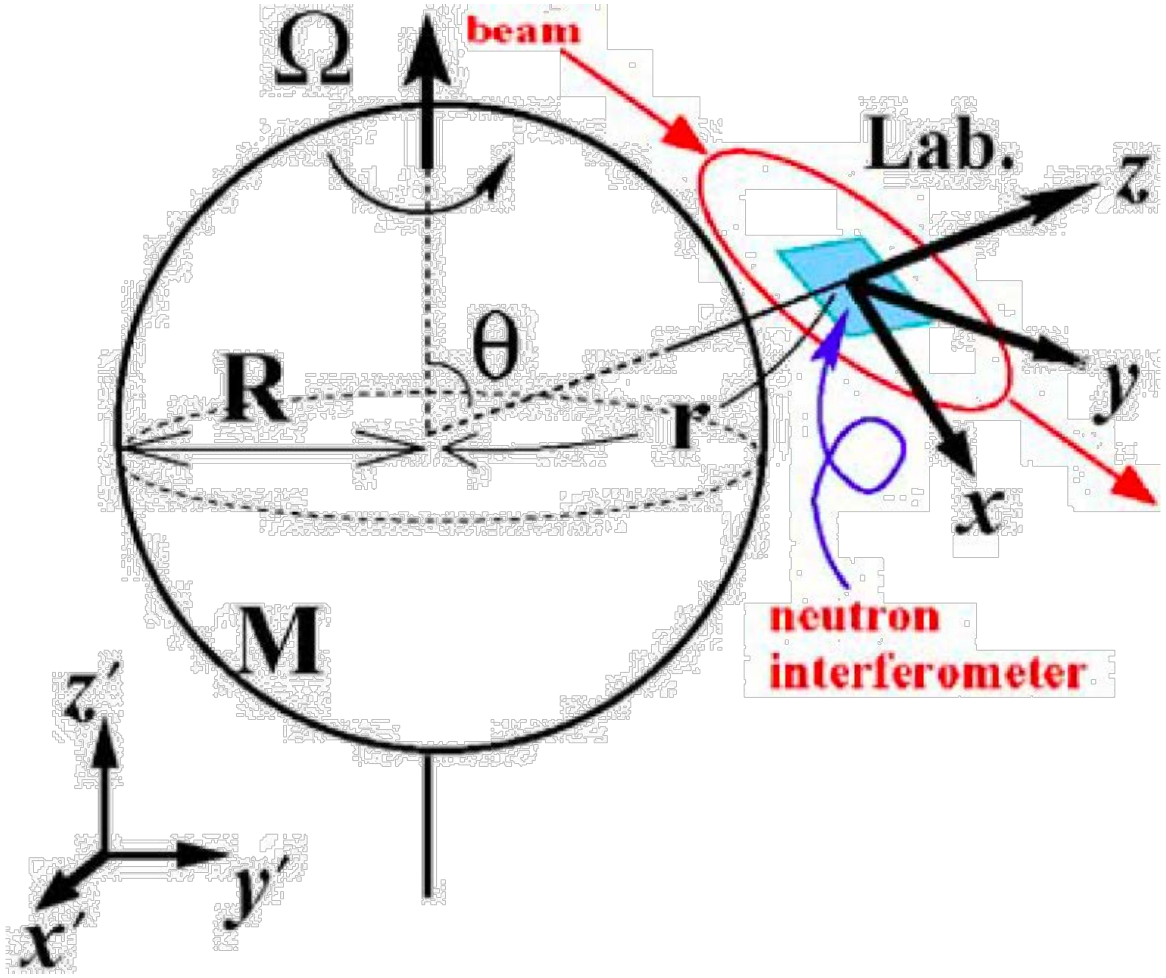
Neutrons for General Relativity

T.Morishima Nucl. Instrum. Methods A529 (2004) 187



Neutrons for General Relativity

T.Morishima Nucl. Instrum. Methods A529 (2004) 187



$$\phi = -\frac{GM}{r}$$

$$\boldsymbol{S} = \frac{\hbar}{2}\boldsymbol{\sigma}$$

$$\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$$

$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m} + m\phi - \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})$$

$$+\frac{1}{c^2}\left(-\frac{\boldsymbol{p}^4}{8m^3} + \frac{m}{2}\phi^2 + \frac{3}{2m}\boldsymbol{p}\cdot(\phi\boldsymbol{p}) + \frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S}) + \frac{6GMR^2}{5r^5}\boldsymbol{S}\cdot(\boldsymbol{r}\times(\boldsymbol{r}\times\boldsymbol{\Omega}))\right)$$

Neutrons for General Relativity

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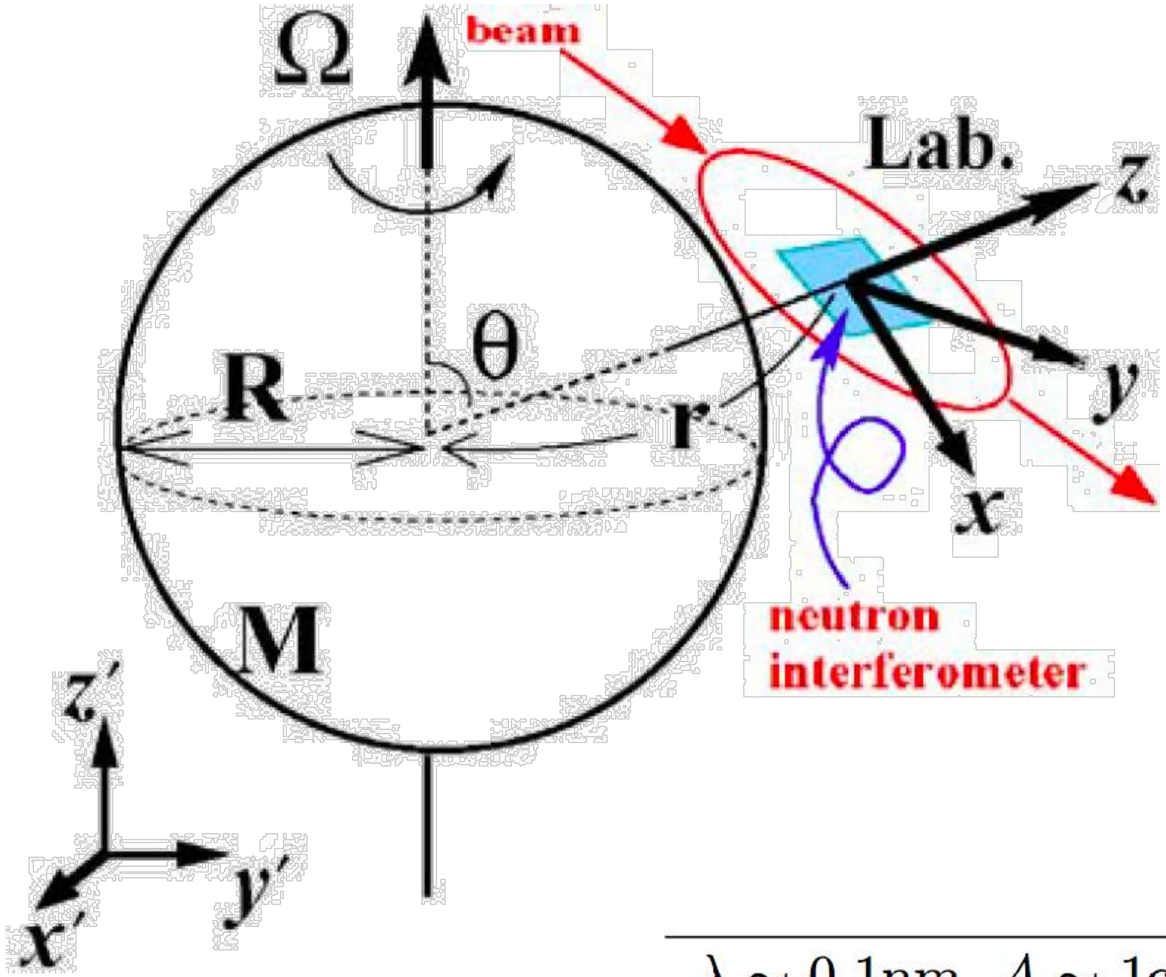

$$\phi = -\frac{GM}{r}$$

$$\boldsymbol{S} = \frac{\hbar}{2}\boldsymbol{\sigma}$$

$$\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$$

	$m\phi$	$4GMR^2\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})/5r^3c^2$
$\lambda \sim 0.1\text{nm},\ A \sim 1\text{cm} \times 1\text{cm}$	5	10^{-10}
$\lambda \sim 1.0\text{nm},\ A \sim 1\text{m} \times 1\text{m}$	10^5	10^{-6}

$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m} + \overset{\text{COW}}{\boxed{m\phi}} - \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})$$

$$+\frac{1}{c^2}\left(-\frac{\boldsymbol{p}^4}{8m^3} + \frac{m}{2}\phi^2 + \frac{3}{2m}\boldsymbol{p}\cdot(\phi\boldsymbol{p}) + \frac{3GM}{2mr^3}\boldsymbol{L}\cdot\boldsymbol{S} + \underset{\text{Lense-Thirring}}{\boxed{\frac{4GMR^2}{5r^3}\boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})}} + \frac{6GMR^2}{5r^5}\boldsymbol{S}\cdot(\boldsymbol{r}\times(\boldsymbol{r}\times\boldsymbol{\Omega}))\right)$$

Neutrons for General Relativity

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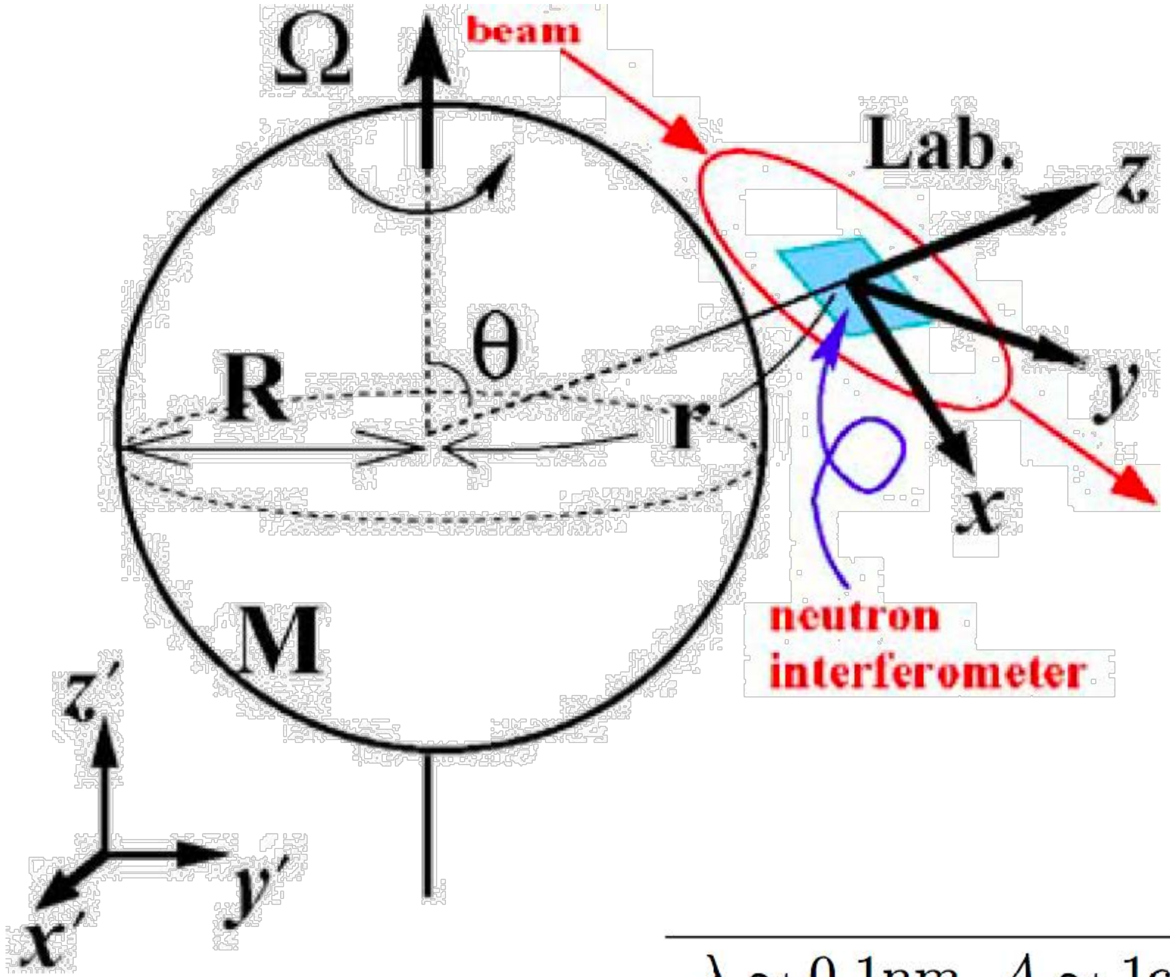

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accessible with J-PARC

$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m} + \overset{\text{COW}}{\boxed{m\phi}} - \boldsymbol{\Omega}\cdot(\boldsymbol{L}+\boldsymbol{S})$$

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Anomalous Gravity?

3-dim. Gravity

$$F_3(r) = G_3 \frac{m_1 m_2}{r^2}$$

N-dim. Gravity

$$F_N(r) = G_N \frac{m_1 m_2}{r^{N-1}}$$

continuity at r=R*

$$\frac{G_3}{R*^2} = \frac{G_N}{R*^{N-1}} \Rightarrow G_3 = \frac{G_N}{R*^{N-3}}$$

If R* is longer than the Planck's length, G3 becomes smaller.

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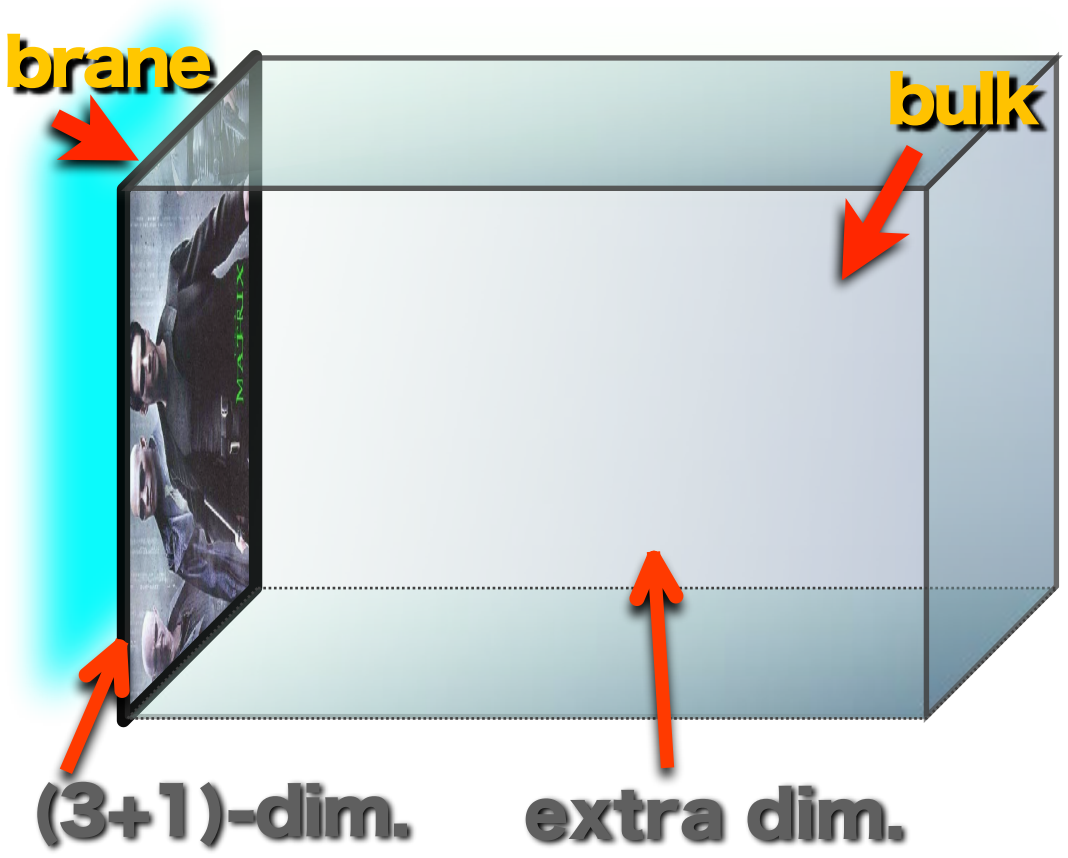

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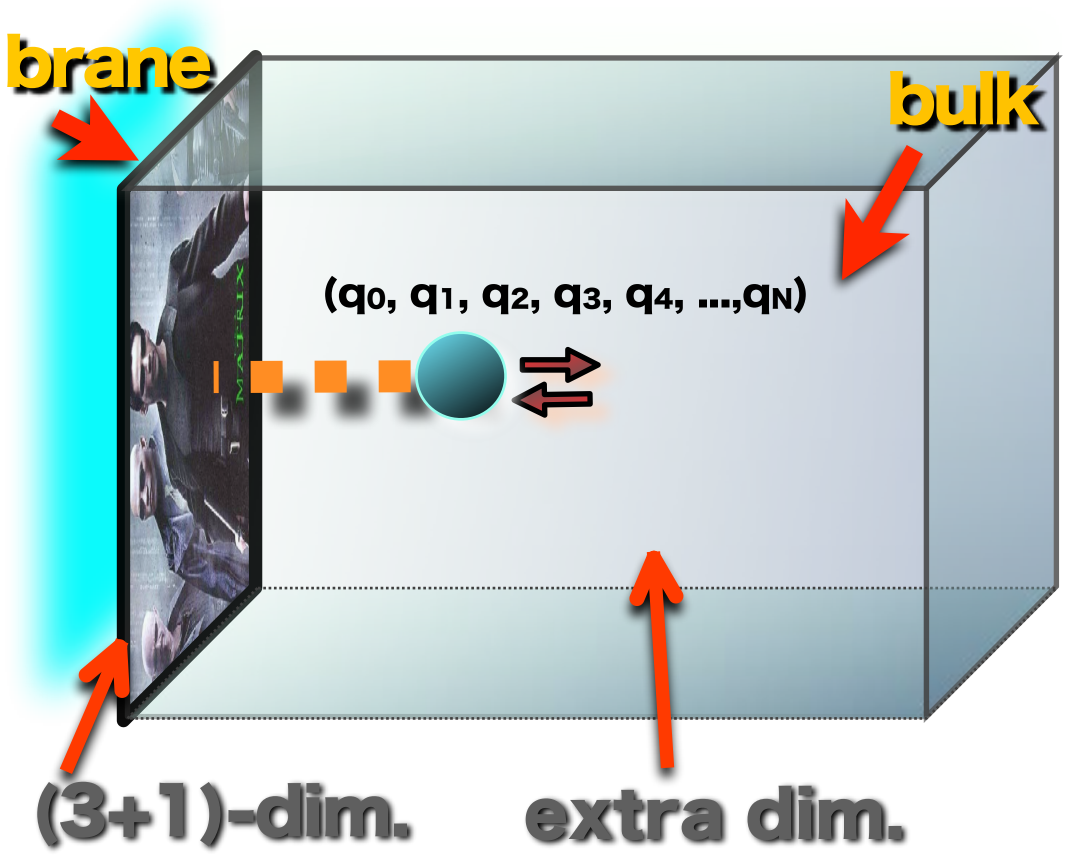

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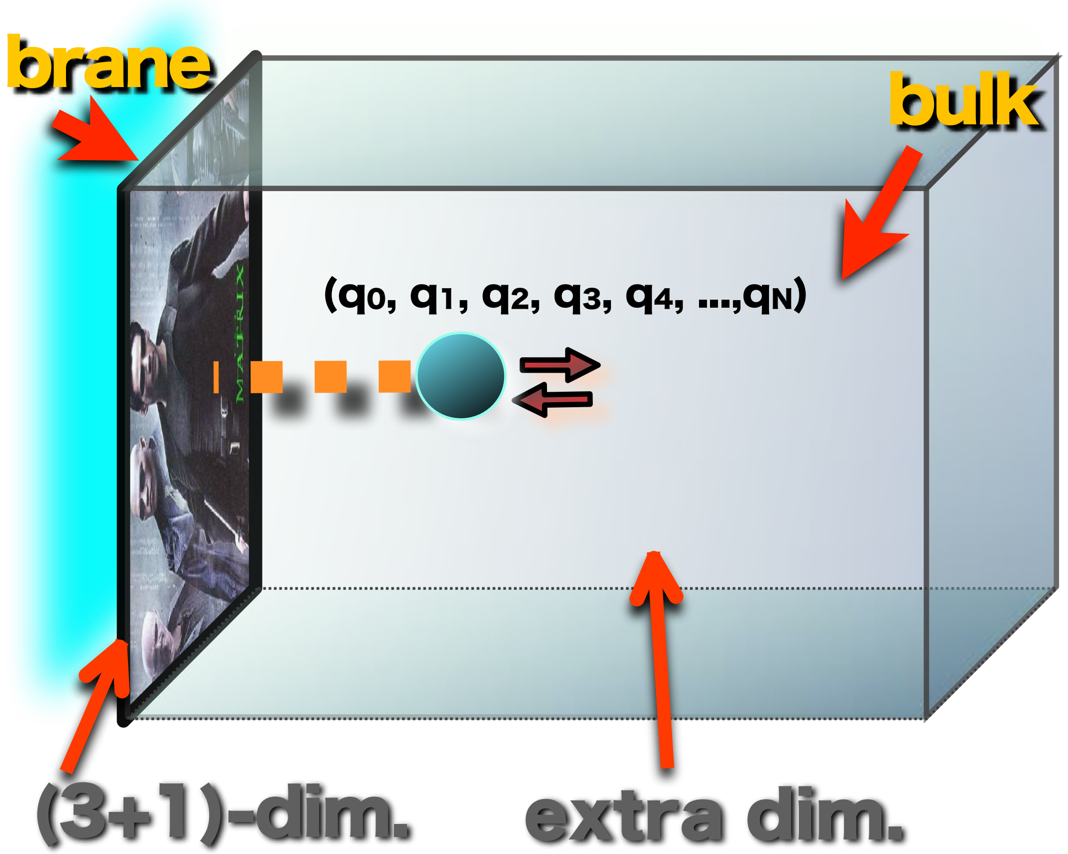

$$q_0^2 - q_1^2 - q_2^2 - \ldots - q_N^2 = 0$$

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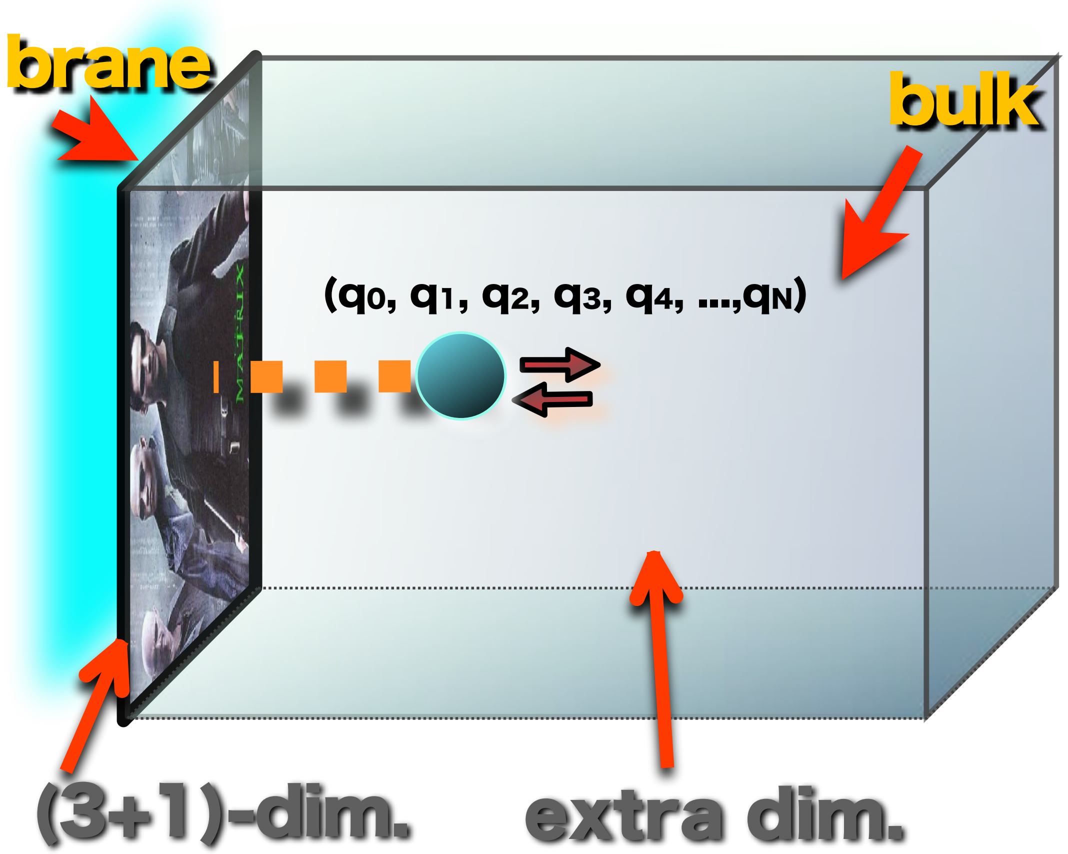

$$q_0^2 - q_1^2 - q_2^2 - \ldots - q_N^2 = 0$$

$$\Leftrightarrow \quad q_0^2 - q_1^2 - q_2^2 - q_3^2 = q_4^2 + \ldots + q_N^2$$

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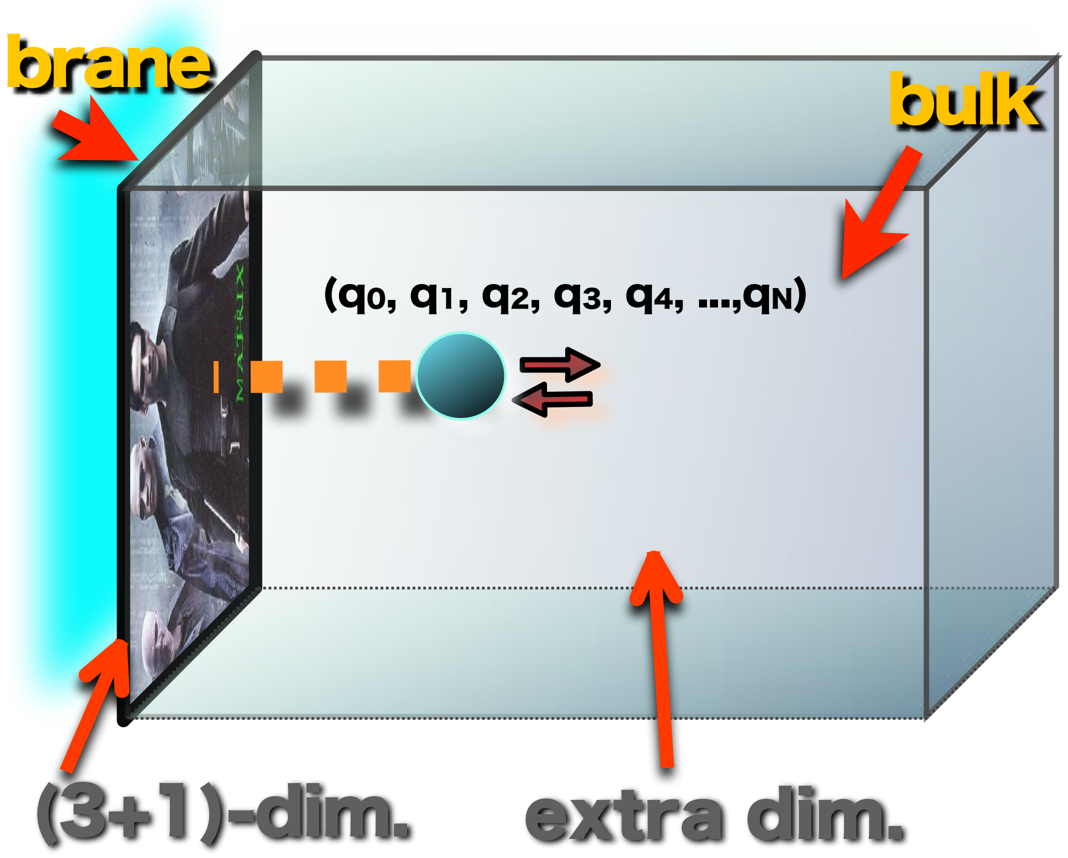

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$$q_0^2 - q_1^2 - q_2^2 - q_3^2 = \mu^2 > 0$$

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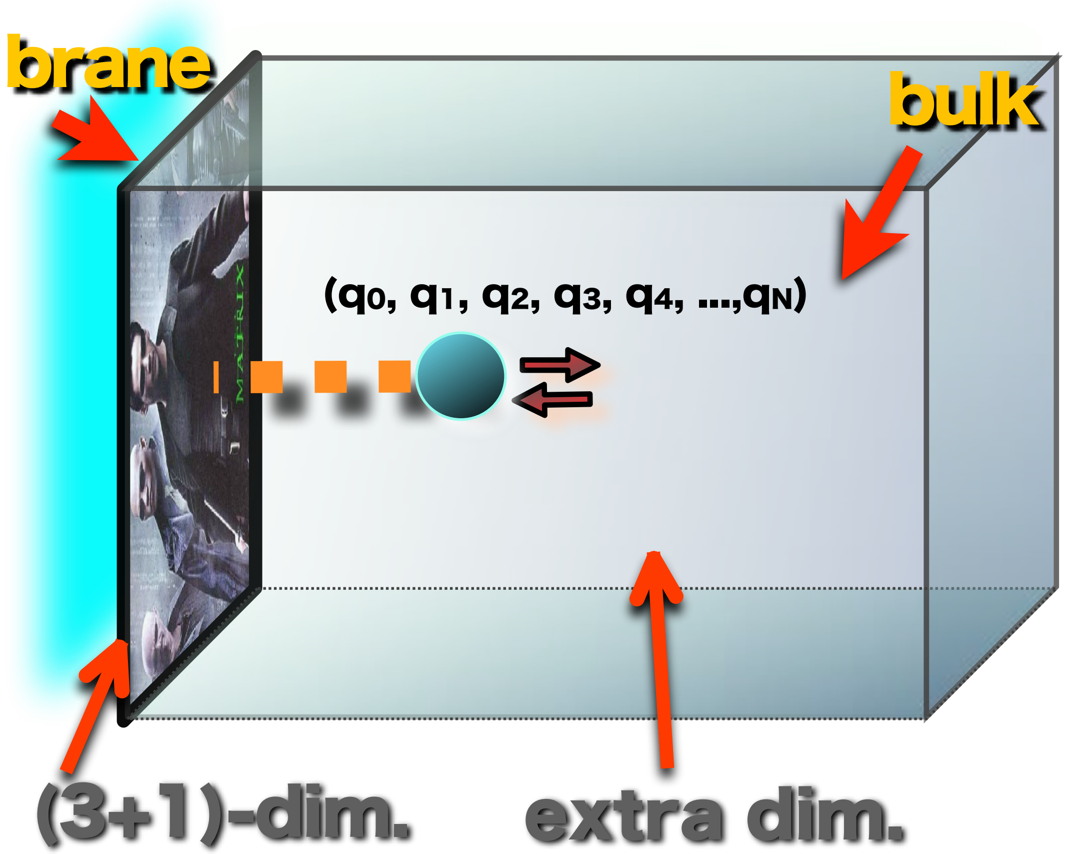

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$$q_0^2 - q_1^2 - q_2^2 - q_3^2 = \mu^2 > 0$$

$$V(r) = -\frac{Gm}{r} - \alpha G m \frac{e^{-r/\lambda}}{r}$$

Newtonian grvity
(μ=0)

N-dim gravity
(μ>0)
Yukawa potential

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If R* is longer than the Planck's length, G_3 becomes smaller.

Parametrization: $$V(r) = -\frac{GM}{r}\left(1 + \alpha\, e^{-r/\lambda}\right)$$

KK-graviton, which is emitted off our brane with the momentum (q_1, q_2, ...,q_n) along the extra-dimension, looks having the mass |q|.

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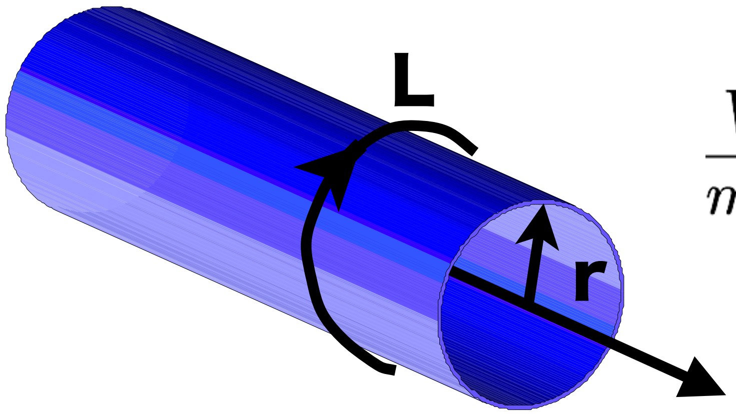
momentum is quantized in the unit of 2π/L in the extra-dimension



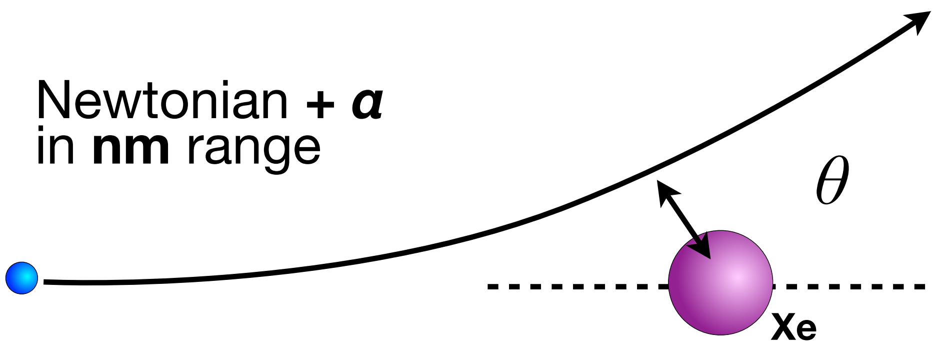
$$\frac{V(r)}{m_1 m_2} = G_3 \sum_{(k_1,\ldots,k_n)} \frac{e^{-\frac{2\pi|k|}{L}r}}{r} \xrightarrow[r \ll L]{} G_3 \frac{1}{r}\left(\frac{L}{2\pi r}\right)^n \int e^{-|u|} \mathrm{d}^n u$$

Scattering Experiment to study Intermediate-range Force

C.C.Haddock, Phys. Rev. D 97 (2018) 062002

Neutron Scattering by Noble Gas Atoms

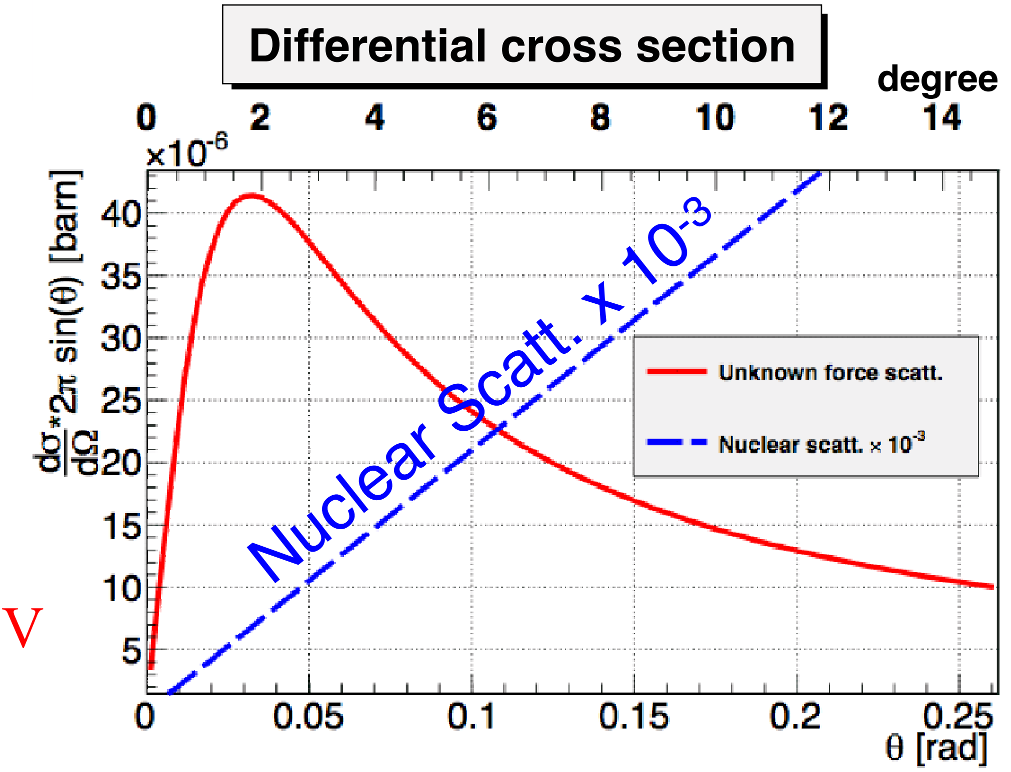
search for deviations from nuclear scattering

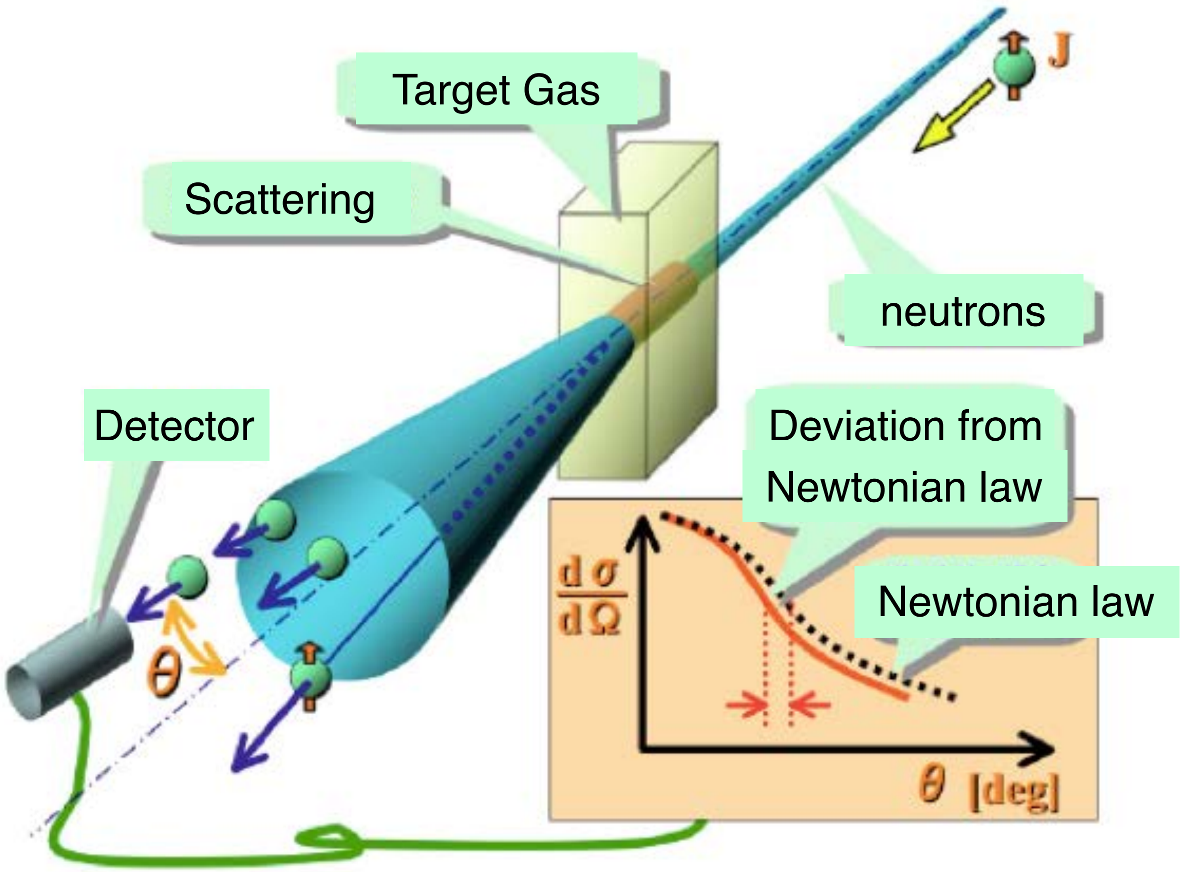


$\alpha=10^{23}$

$\lambda=0.5$ nm

$E_n=20$ meV





$$a_G \propto \alpha$$

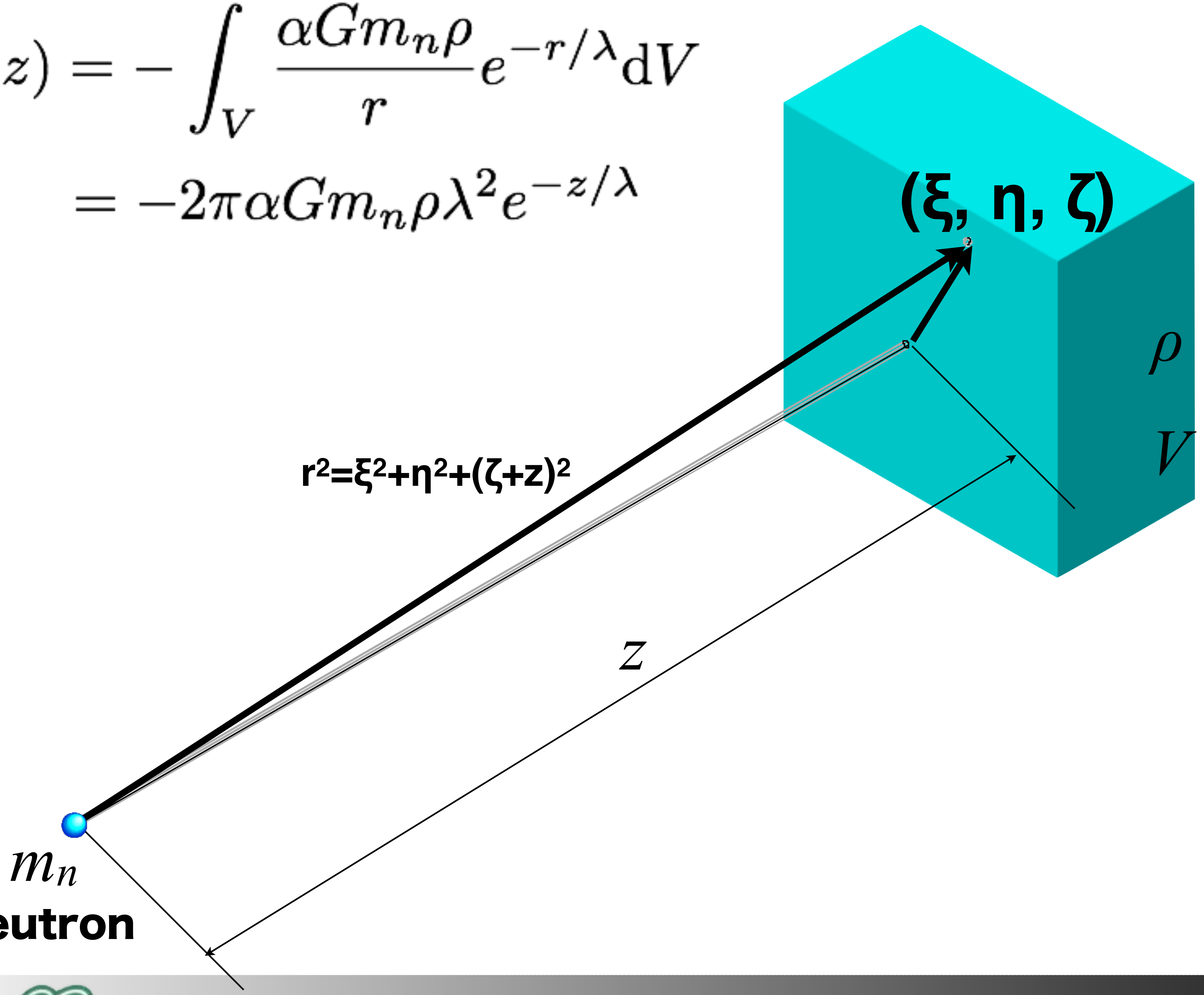
$$\frac{d\sigma(\theta)}{d\Omega}=\left[a_N+a_{ne}ZF_e(\theta)+a_GF_G(\theta)\right]^2$$

$$\simeq a_N{}^2+2a_Na_{ne}ZF_e(\theta)+a_{ne}{}^2Z^2F_e(\theta)^2+2a_Na_GF_G(\theta)$$

$$\frac{d\sigma_G(\theta)}{d\Omega}=2\cdot\sigma_N^{1/2}\cdot\alpha\cdot\left(\frac{G\cdot m_n\cdot M}{4}\right)\cdot\left(\frac{1}{\frac{1}{m_nc^2}\left(\frac{\hbar c}{\lambda}\right)^2+8E_n\sin^2\frac{\theta}{2}}\right)$$

Interferometric Search for Intermediate-range Forces

$$U(z) = -\int_V \frac{\alpha G m_n \rho}{r} e^{-r/\lambda} \mathrm{d}V$$
$$= -2\pi\alpha G m_n \rho \lambda^2 e^{-z/\lambda}$$



Interferometric Search for Intermediate-range Forces

$$U(z) = -2\pi\alpha G m_n \rho \lambda^2 e^{-z/\lambda}$$

N=2 α=16/3

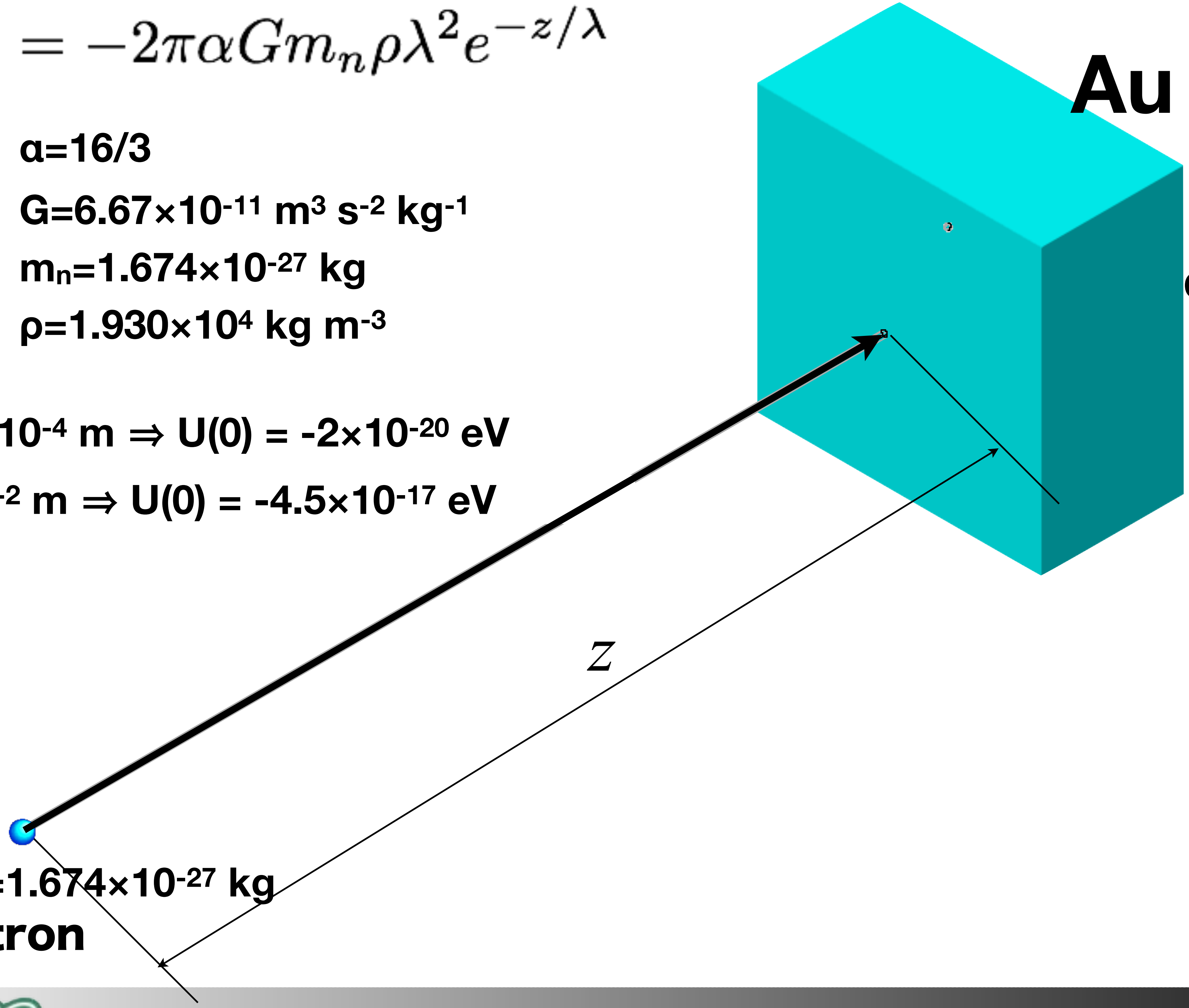
$G=6.67\times10^{-11}$ m^3 s^{-2} kg^{-1}

$m_n=1.674\times10^{-27}$ kg

$\rho=1.930\times10^{4}$ kg m^{-3}

$\lambda=2\times10^{-4}$ m ⇒ U(0) = -2×10^{-20} eV

$\lambda=10^{-2}$ m ⇒ U(0) = -4.5×10^{-17} eV



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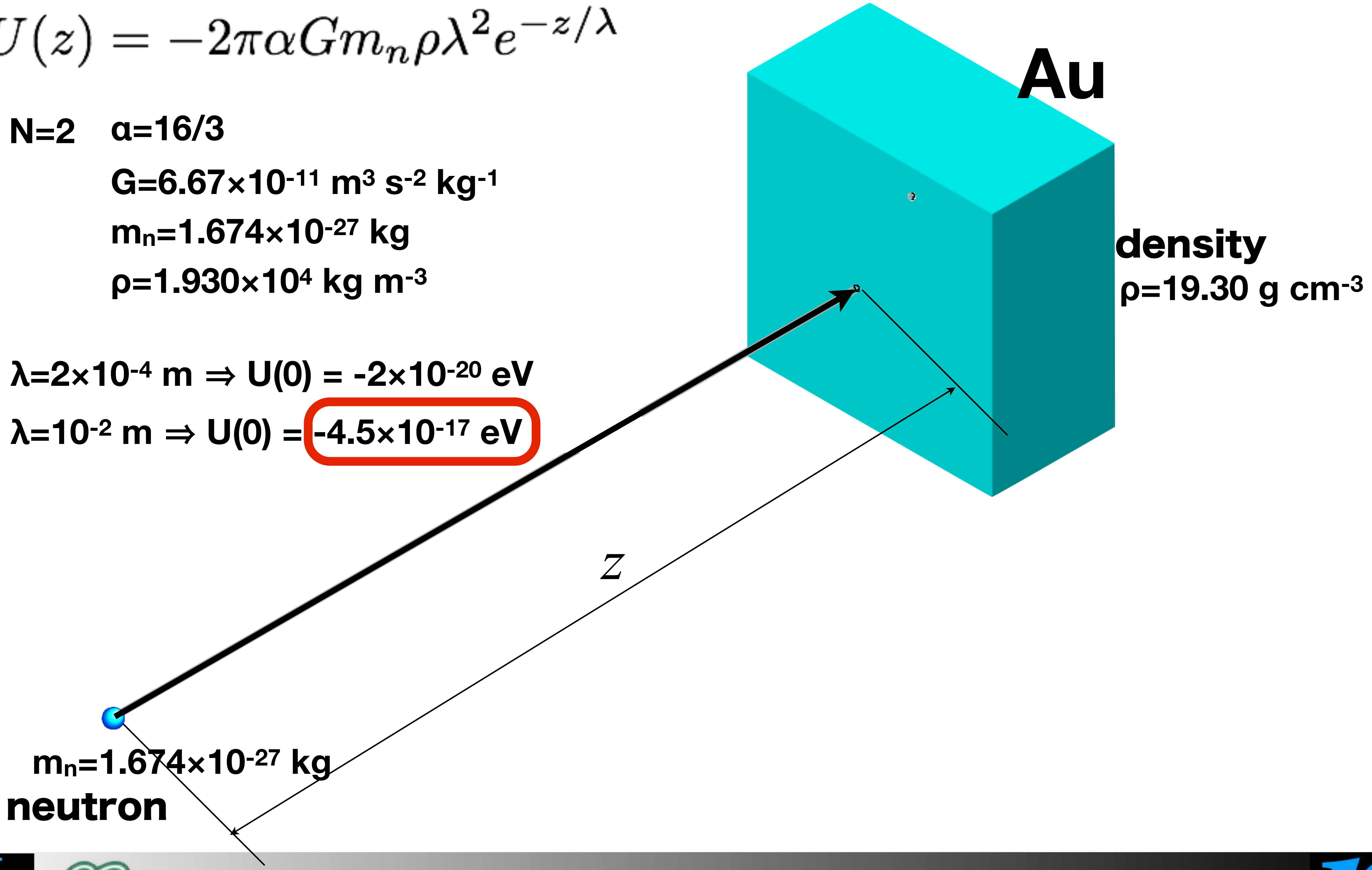
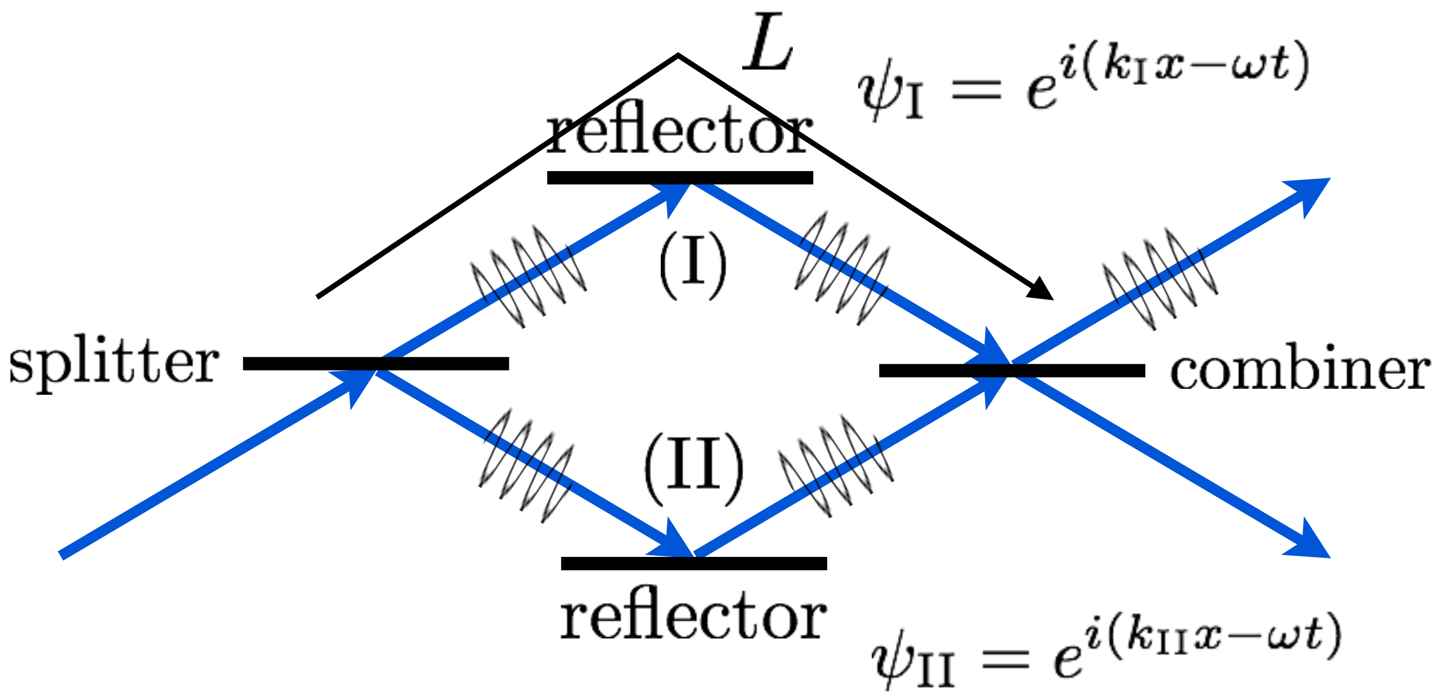


Interferometric Search for Intermediate-range Forces

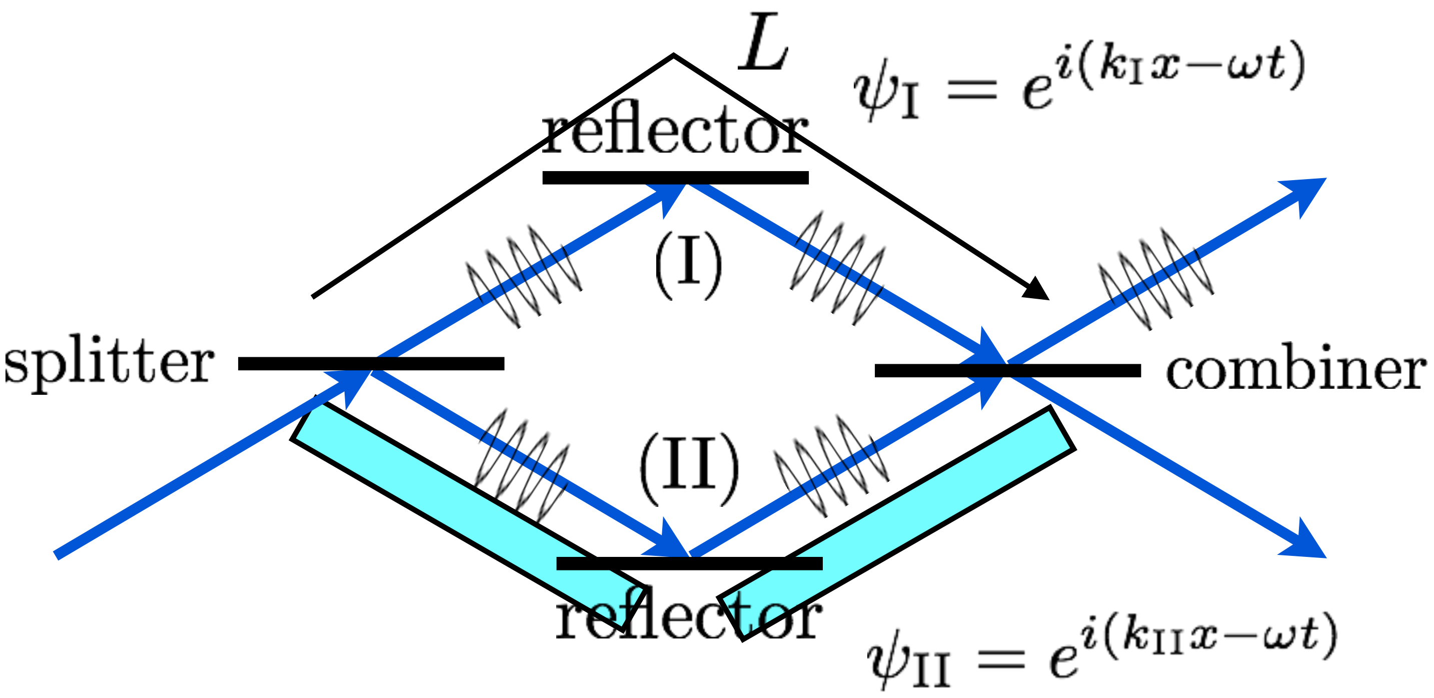


$$\Delta\phi = \phi_{\mathrm{II}} - \phi_{\mathrm{I}} \simeq \sqrt{\frac{m_n c^2}{2E}} \frac{L\Delta U}{\hbar c}$$

$1\mathrm{eV} = 1.6 \times 10^{-19}\mathrm{J}$
$m_n c^2 = 9.4 \times 10^8 \mathrm{eV}$
$\hbar c = 1.97 \times 10^{-7} \mathrm{eV\,m}\,(= 197\,\mathrm{MeV\,fm})$

E	L	Δφ	ΔU	$\Delta U/(m_n g)$
25 meV	0.1 m	1 rad	10^{-14} eV	1 mm

Interferometric Search for Intermediate-range Forces



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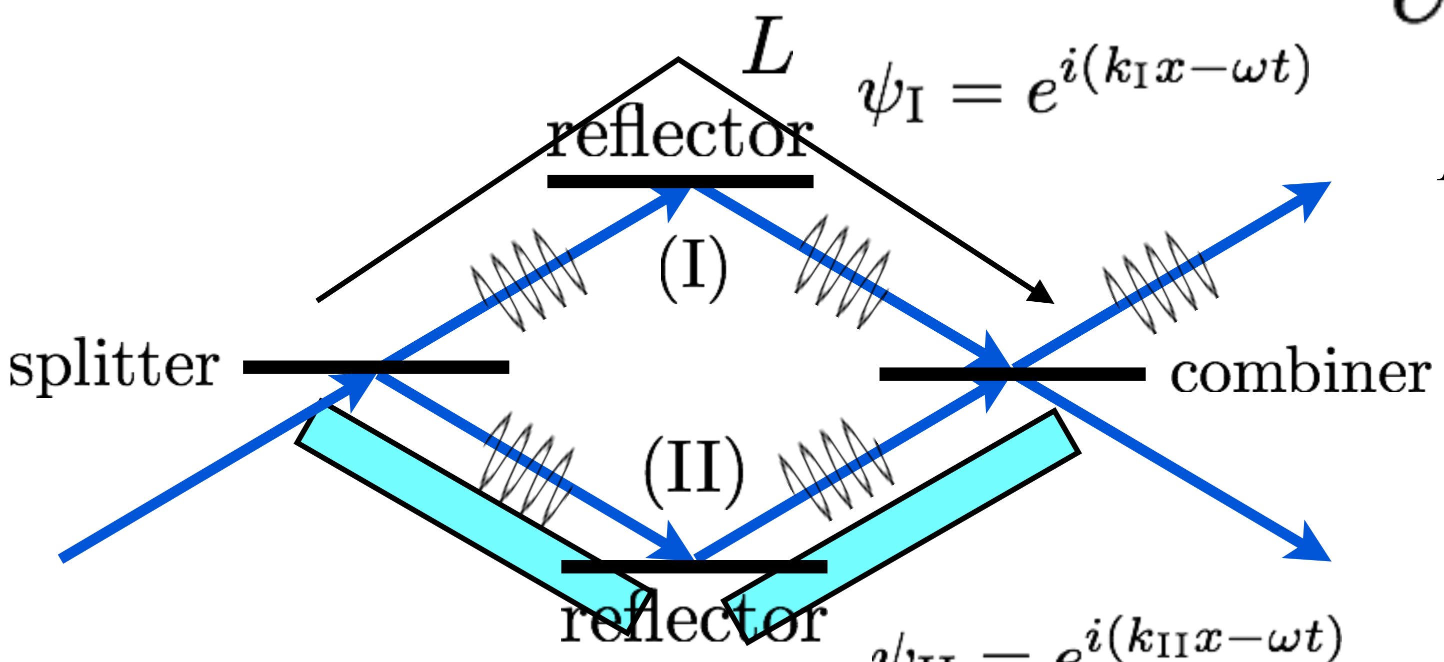

$$\psi_{\mathrm{I}} = e^{i(k_{\mathrm{I}}x-\omega t)}$$

$$\psi_{\mathrm{II}} = e^{i(k_{\mathrm{II}}x-\omega t)}$$

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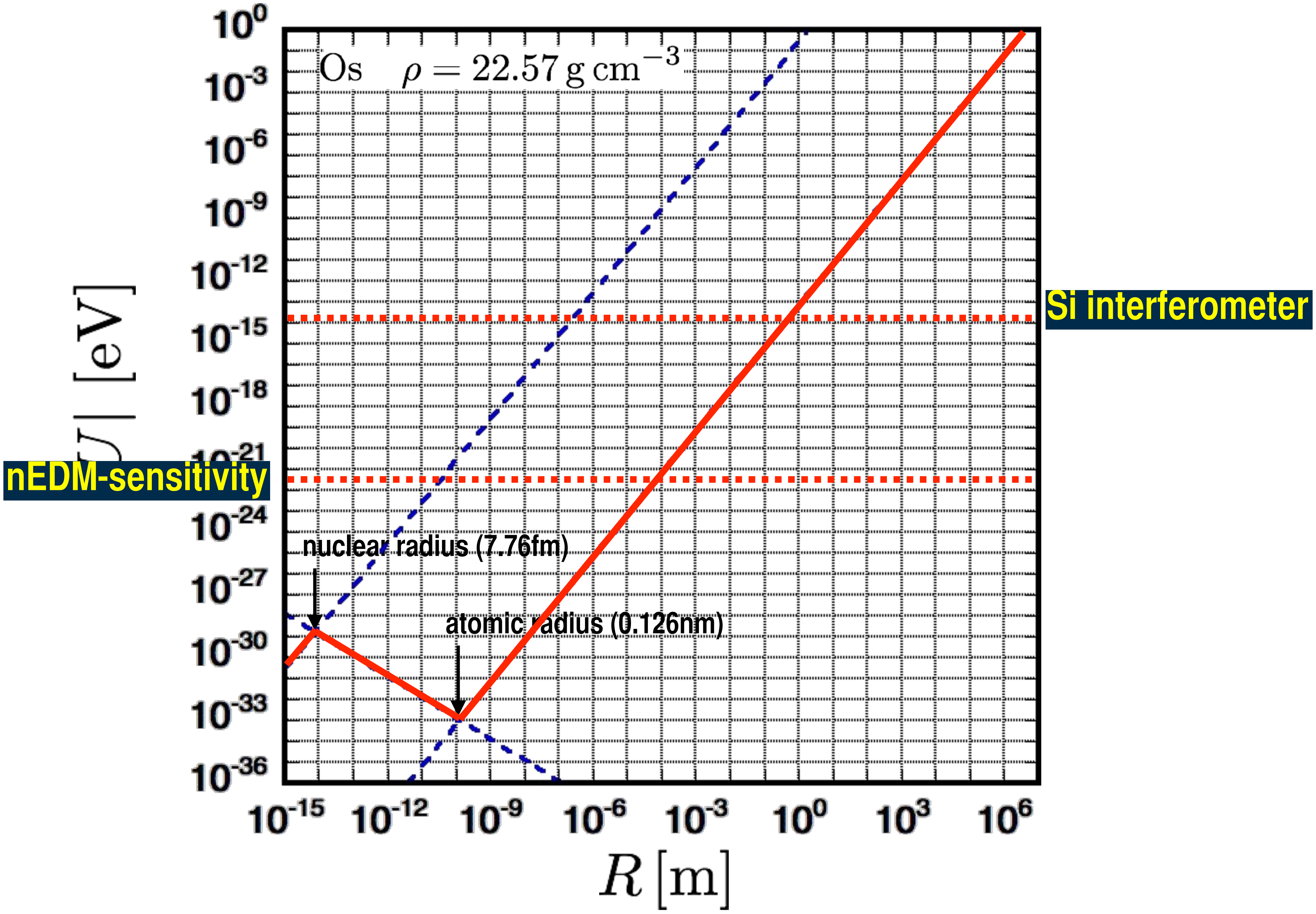
E	L	Δφ	ΔU	$\Delta U/(m_n g)$
25 meV	0.1 m	1 rad	10^{-14} eV	1 mm
10 meV	**1 m**	**10^{-3} rad**	**9×10^{-16} eV**	**9 nm**
250 neV	**1 m**	**10^{-3} rad**	**5×10^{-18} eV**	**40 pm**

$$U = -G\frac{Mm_{\rm n}}{R} = -3.1 \times 10^{-15}[\mathrm{eV}] \times \left(\frac{R}{1\,\mathrm{m}}\right)^2 \left(\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}\right)$$



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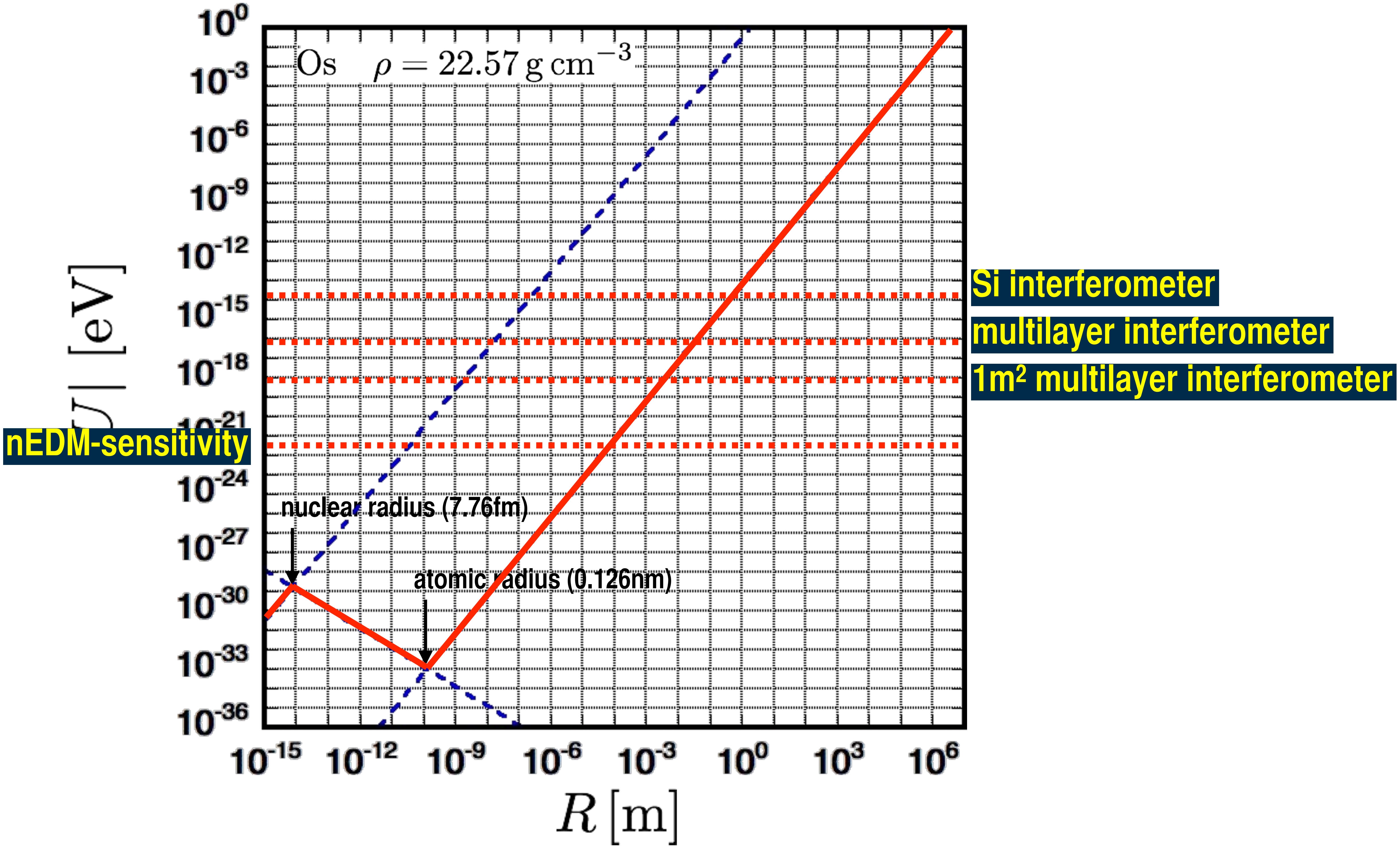


Summary of this chapter

Precise measurement of the spin precession of ultracold neutrons

for spin-dependent gravity $\boldsymbol{\sigma} \cdot \boldsymbol{g}$

Enlarged multilayer interferometer for pulsed cold and very-cold neutrons

for post-Newtonian terms

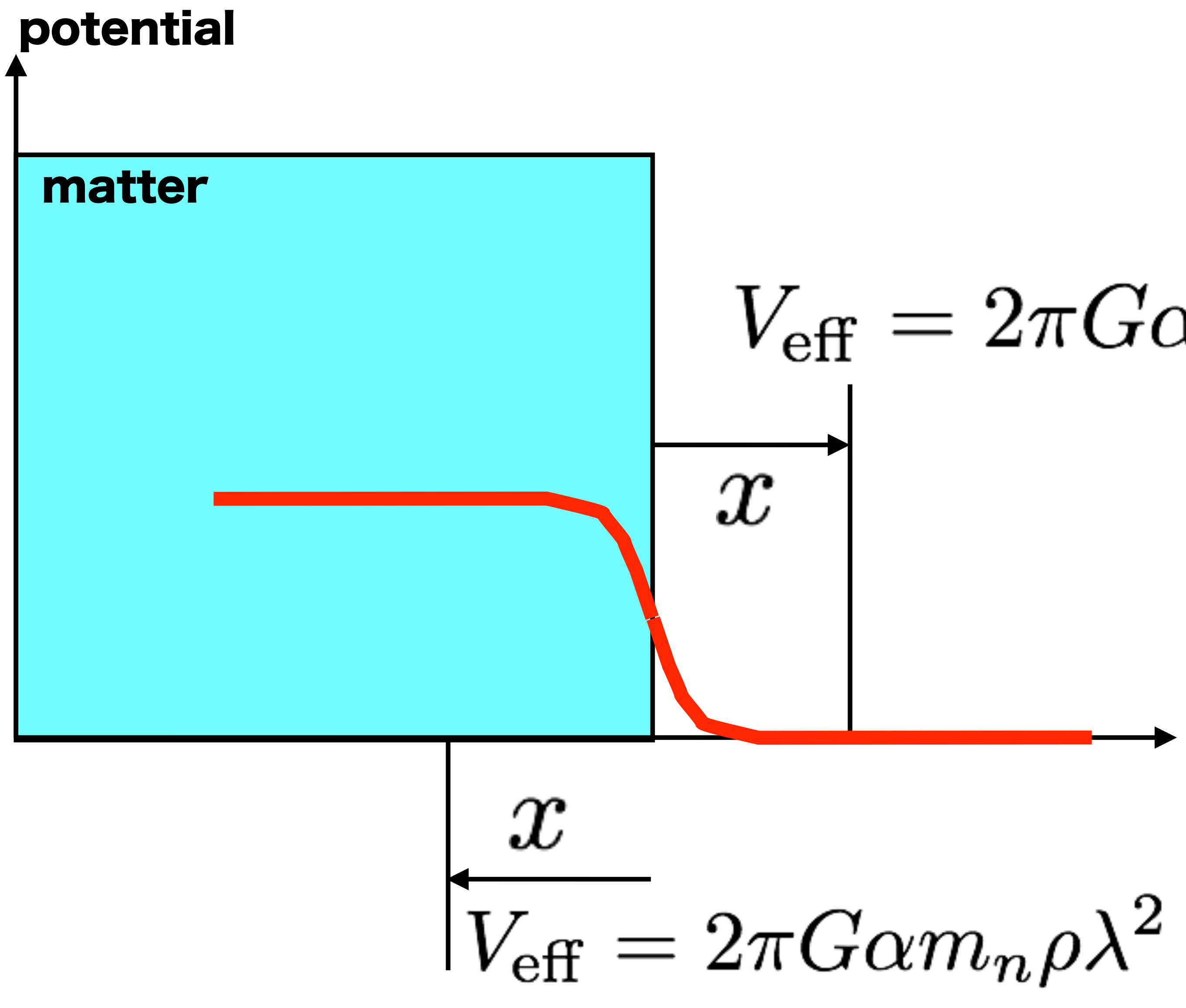
For anomalous gravity in short-distance

neutron scattering, neutron interferometry

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

$$V_G(r) = -\frac{GM}{r}\alpha e^{-r/\lambda}$$



$$V_{\text{eff}} = 2\pi G\alpha m_n \rho \lambda^2 e^{-x/\lambda}$$

$$V_{\text{eff}} = 2\pi G\alpha m_n \rho \lambda^2 \left(2 - e^{-x/\lambda}\right)$$

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

$$V_{\mathrm{G}}(r) = -\frac{GM}{r}\alpha e^{-r/\lambda}$$

$$V_{\mathrm{eff}} = k_0^2 + 2\alpha^2 e^{-L/2\lambda} \cosh\left(\frac{x}{\lambda}\right)$$

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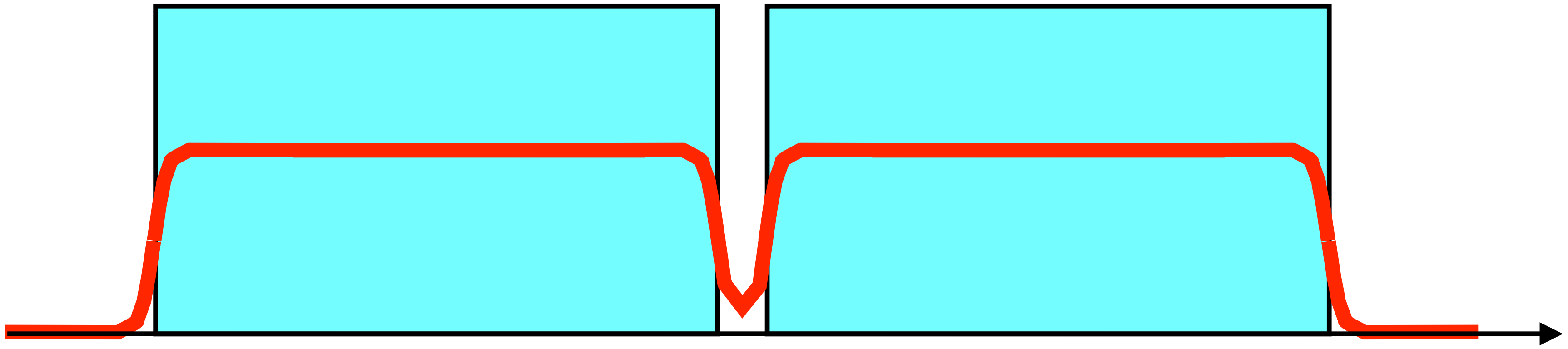

Anomalous Gravity in the vicinity of Material Surface

Phys. Rev. D59 (1999) 086004

$$V_{\text{eff}} = k_0^2 + 2\alpha^2 e^{-L/2\lambda} \cosh\left(\frac{x}{\lambda}\right)$$

$$\cosh\left(\frac{x}{\lambda}\right) = \frac{\sinh(L/\lambda)}{L/\lambda} + \sum_{n=1}^{\infty}\left[\frac{2(-1)^n(L/\lambda)\sinh(L/\lambda)}{(L/\lambda)^2+n^2\pi^2}\cos\left(\frac{n\pi x}{L}\right)\right]$$

pamametric resonance

$$\frac{2k_0}{1+\frac{2\alpha^2}{k_0^2}\exp(-L/\lambda)\frac{\sinh(L/\lambda)}{L/\lambda}} = \frac{n\pi}{L} \qquad \lambda_n \simeq \frac{4L}{n} \quad (\eta \to 0)$$

$$\gamma \simeq \frac{\alpha^2\lambda_n^2}{\pi^2}\frac{(L/\lambda)\sinh(L/\lambda)}{(L/\lambda)^2+16\pi^2(L/\lambda)^2}e^{-L/(2\lambda)}$$

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Phys. Rev. D59 (1999) 086004

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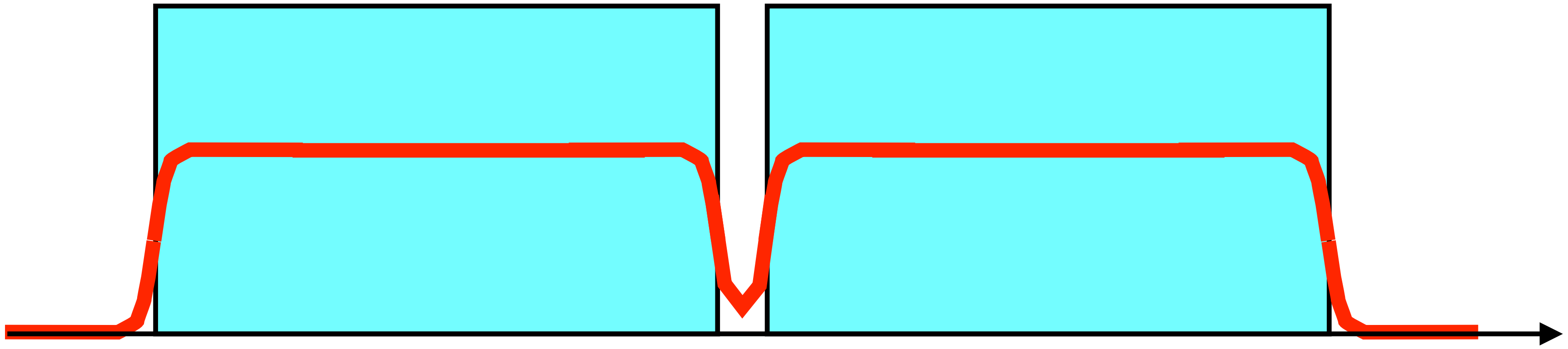
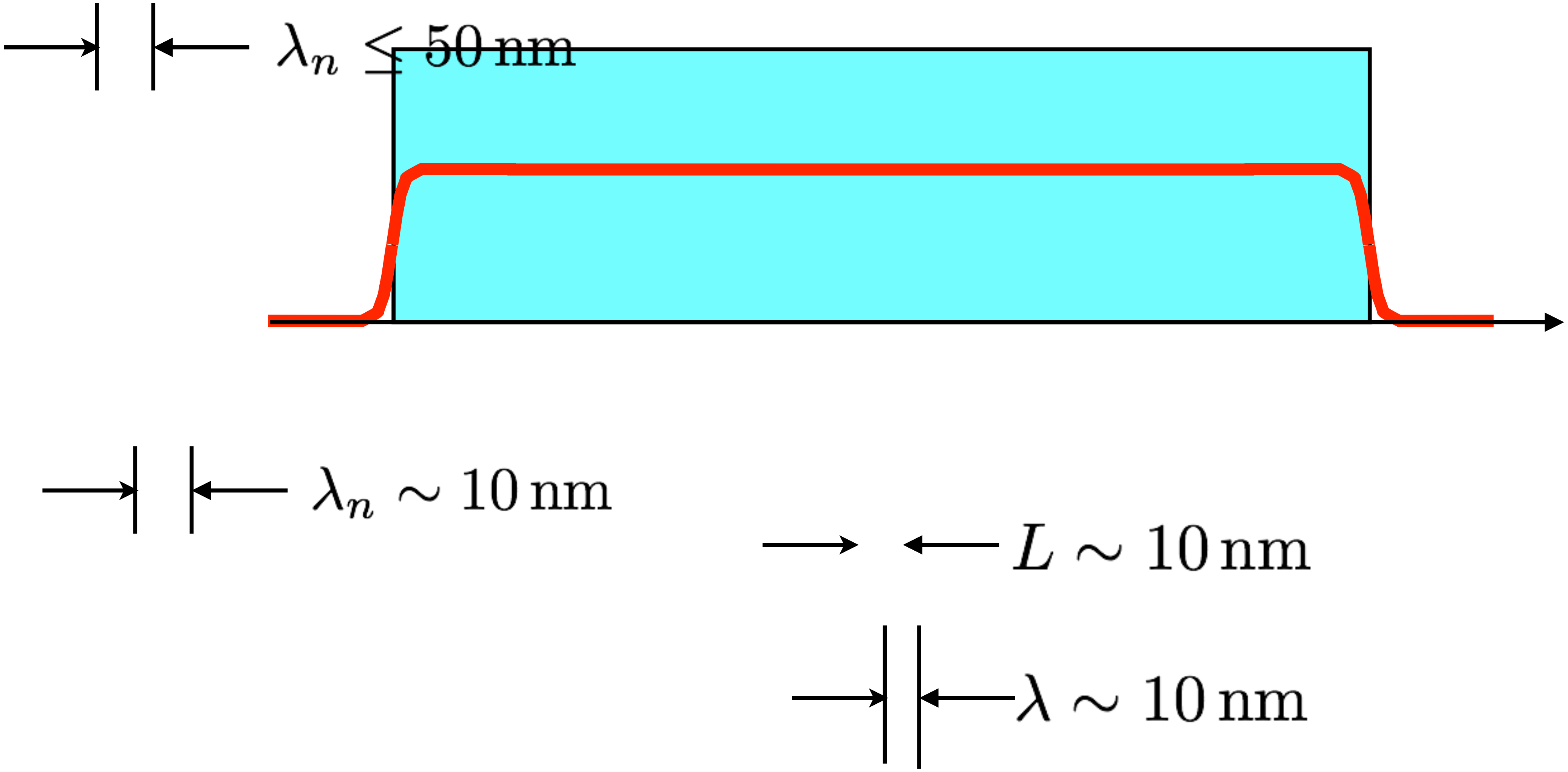


Parametric Resonance in 1-dim Potential

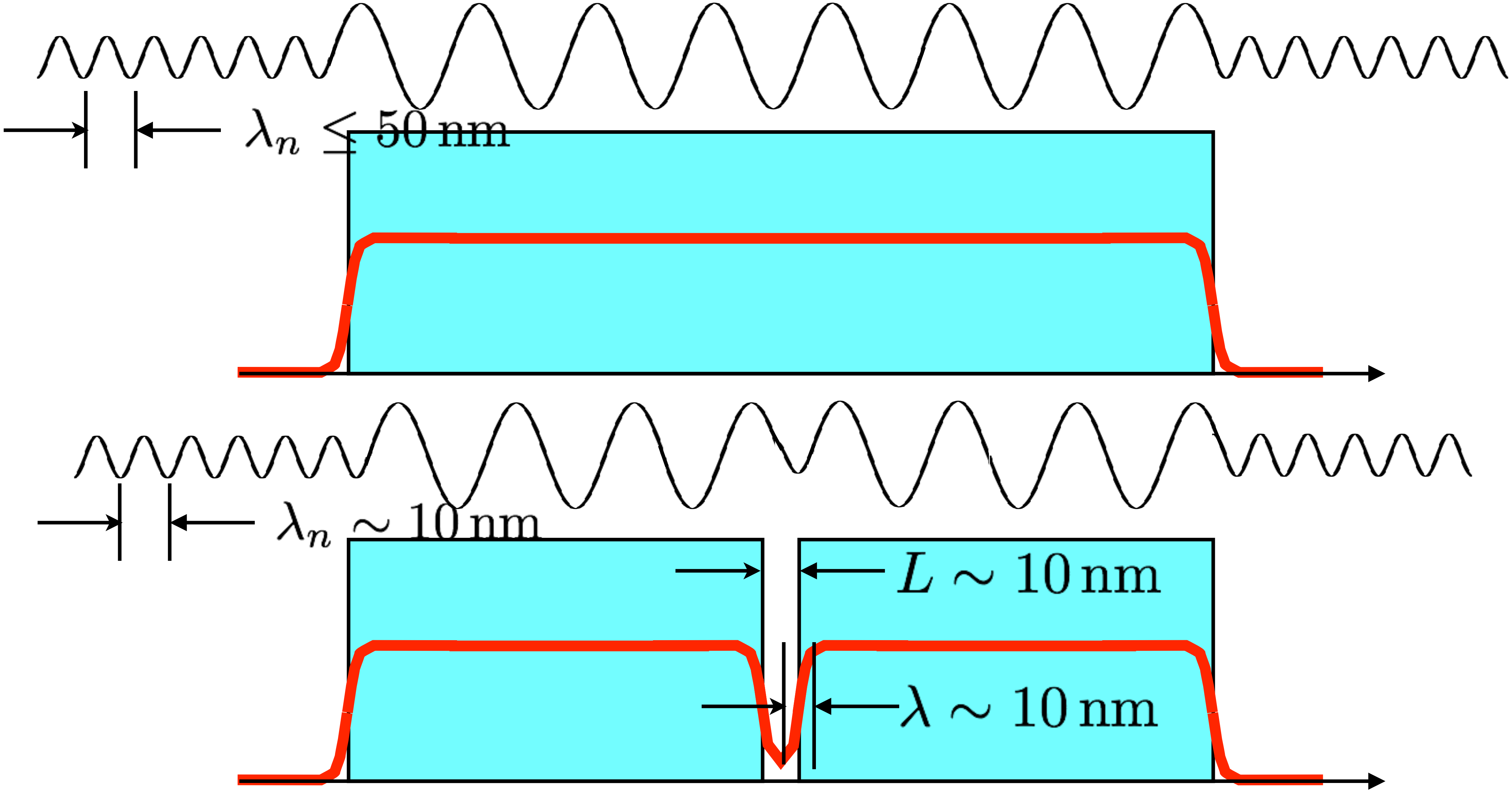
$$V_{\mathrm{G}}(r) = -\frac{GM}{r}\alpha e^{-r/\lambda}$$



Gudkov, Shimizu, Greene, PRC 83 (2011) 025501

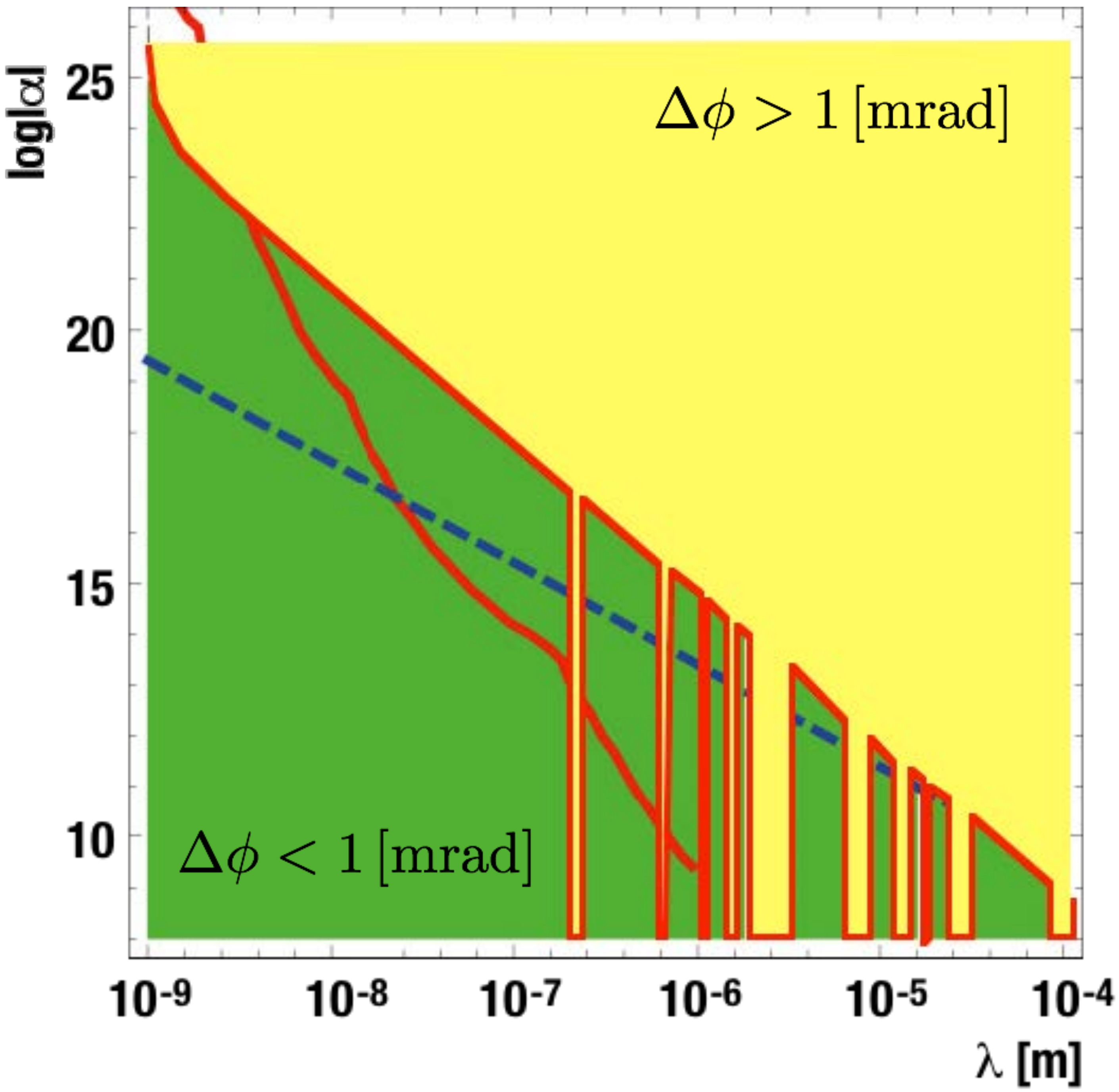
Parametric Resonance in 1-dim Potential

$$V_G(r) = -\frac{GM}{r}\alpha e^{-r/\lambda}$$



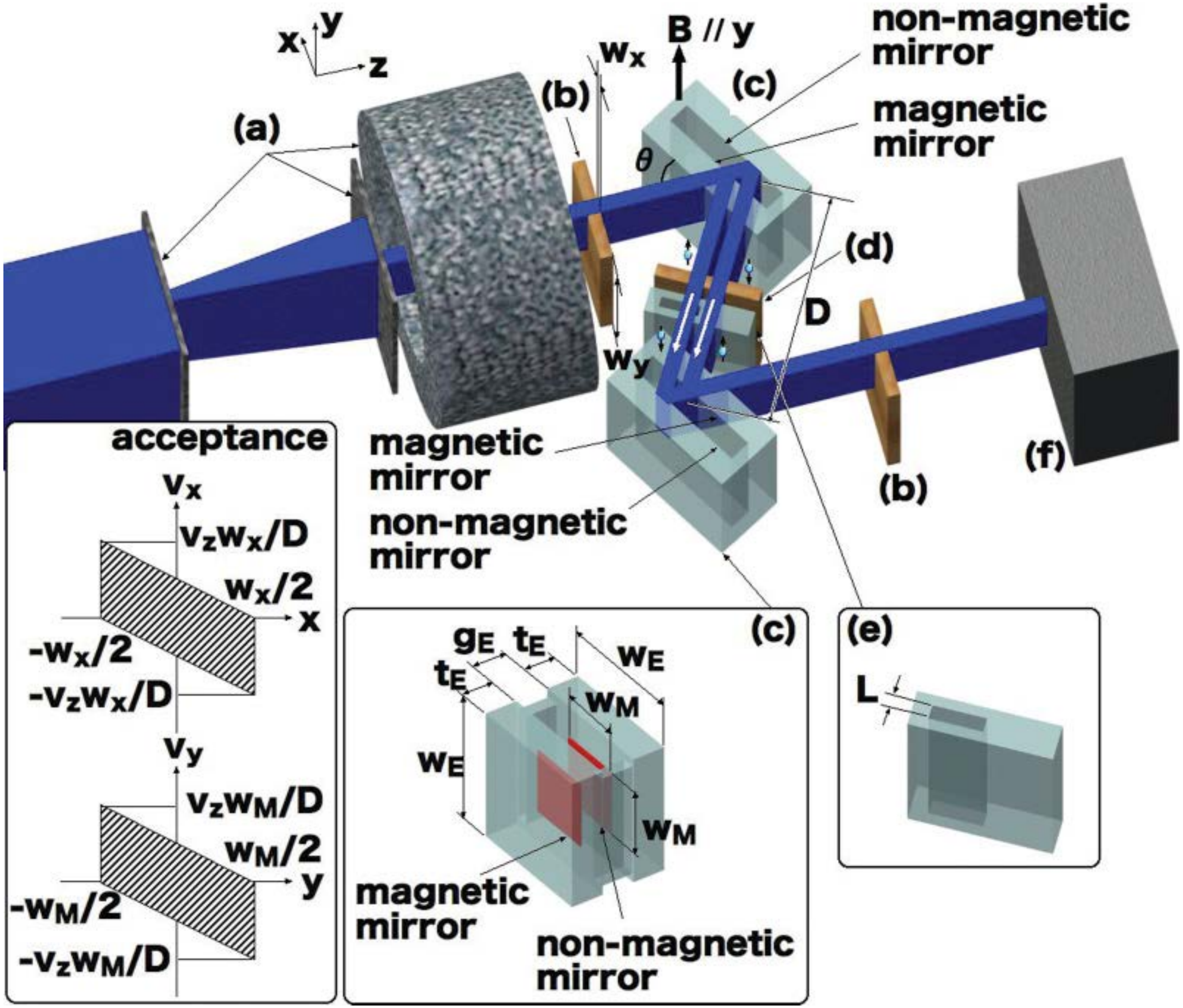
Gudkov, Shimizu, Greene, PRC 83 (2011) 025501

Parametric Resonance in 1-dim Potential



Gudkov, Shimizu, Greene, PRC 83 (2011) 025501

Experimental Apparatus of the Search for Parametric Resonance



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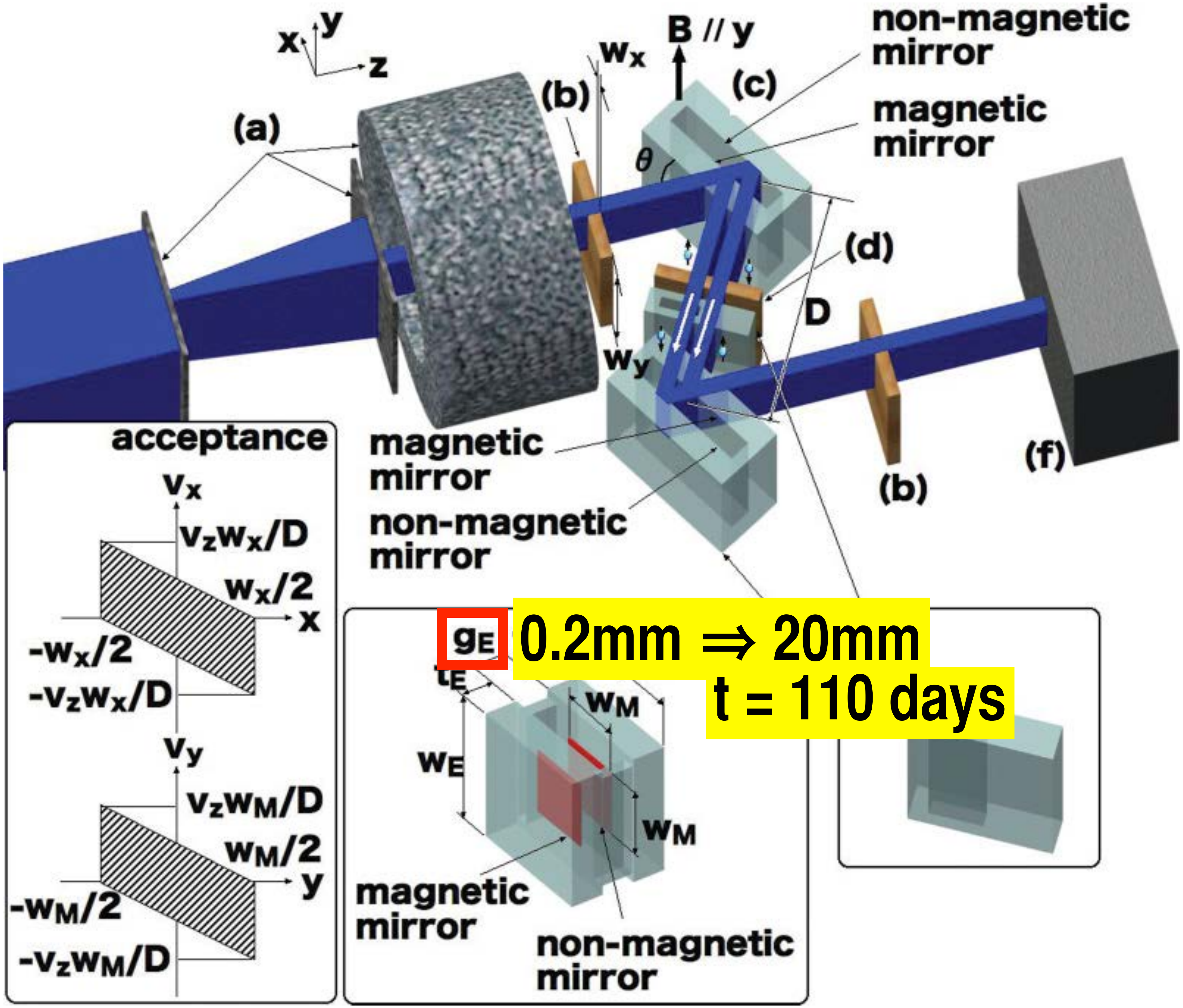
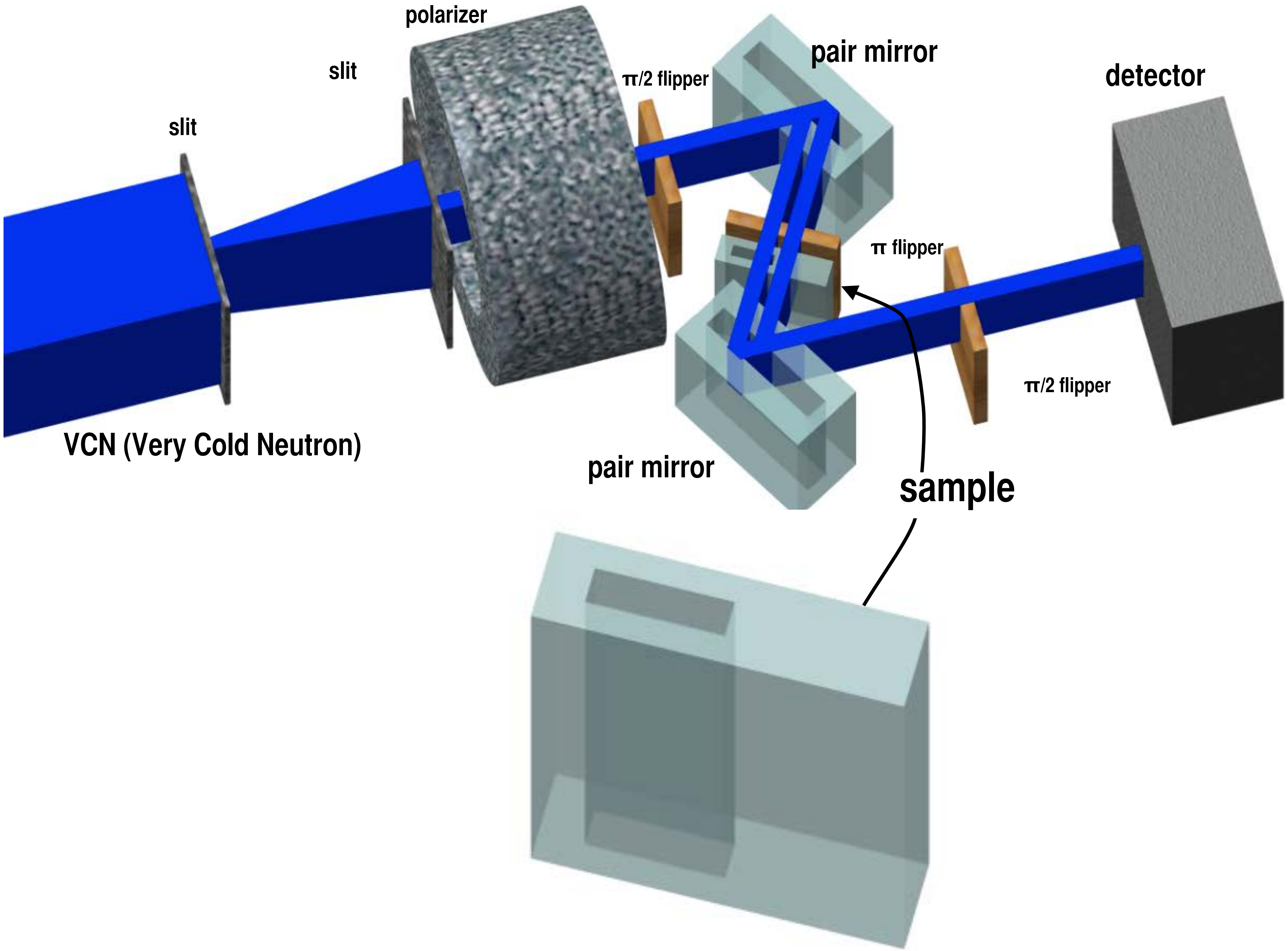


0.2mm ⇒ 20mm

t = 110 days

Experimental Apparatus of the Search for Parametric Resonance



Gudkov, Shimizu, Greene, PRC 83 (2011) 025

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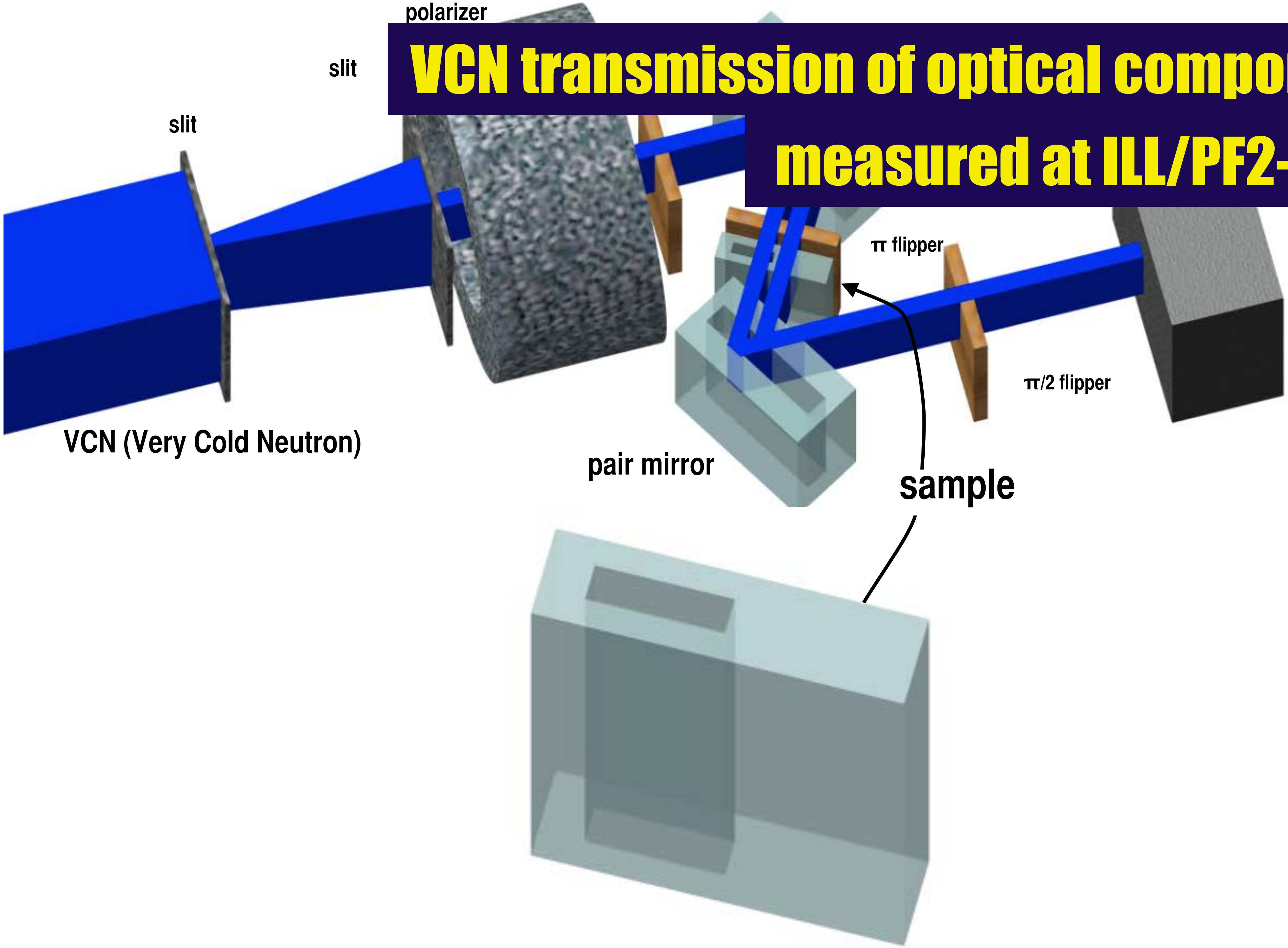

VCN transmission of optical component measured at ILL/PF2-VCN

Gudkov, Shimizu, Greene, PRC 83 (2011) 025

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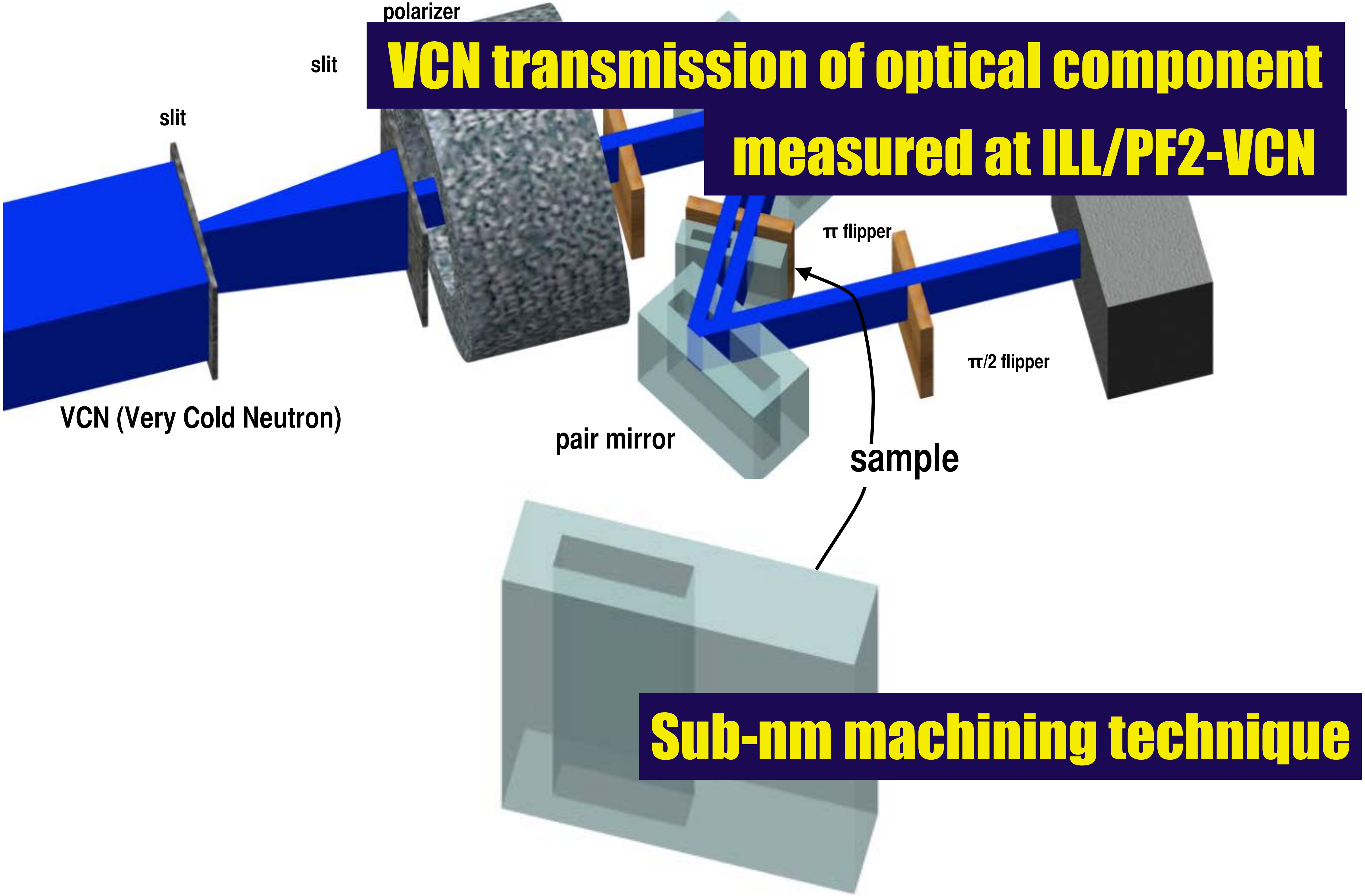

VCN transmission of optical component measured at ILL/PF2-VCN

Sub-nm machining technique

Gudkov, Shimizu, Greene, PRC 83 (2011) 025

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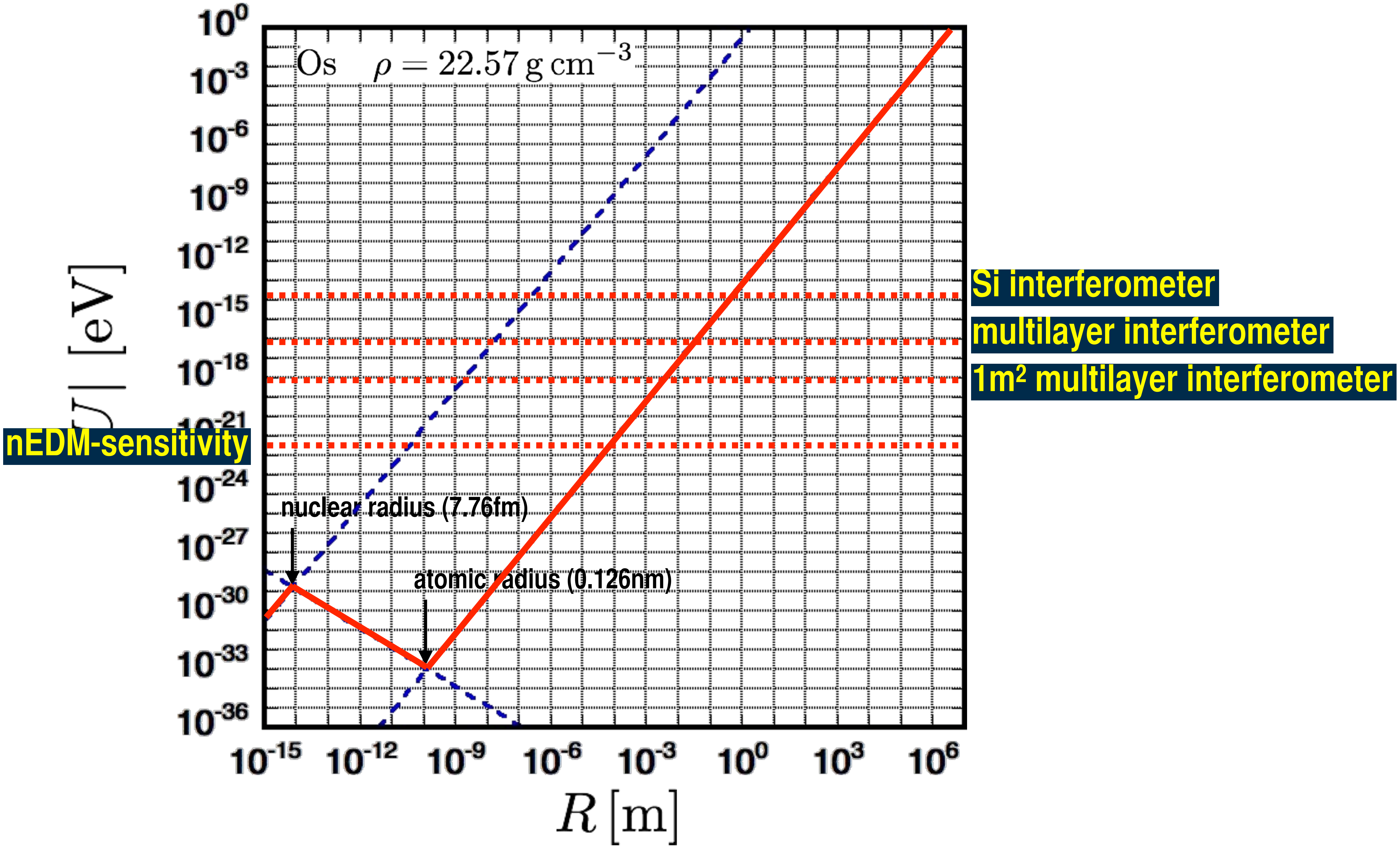

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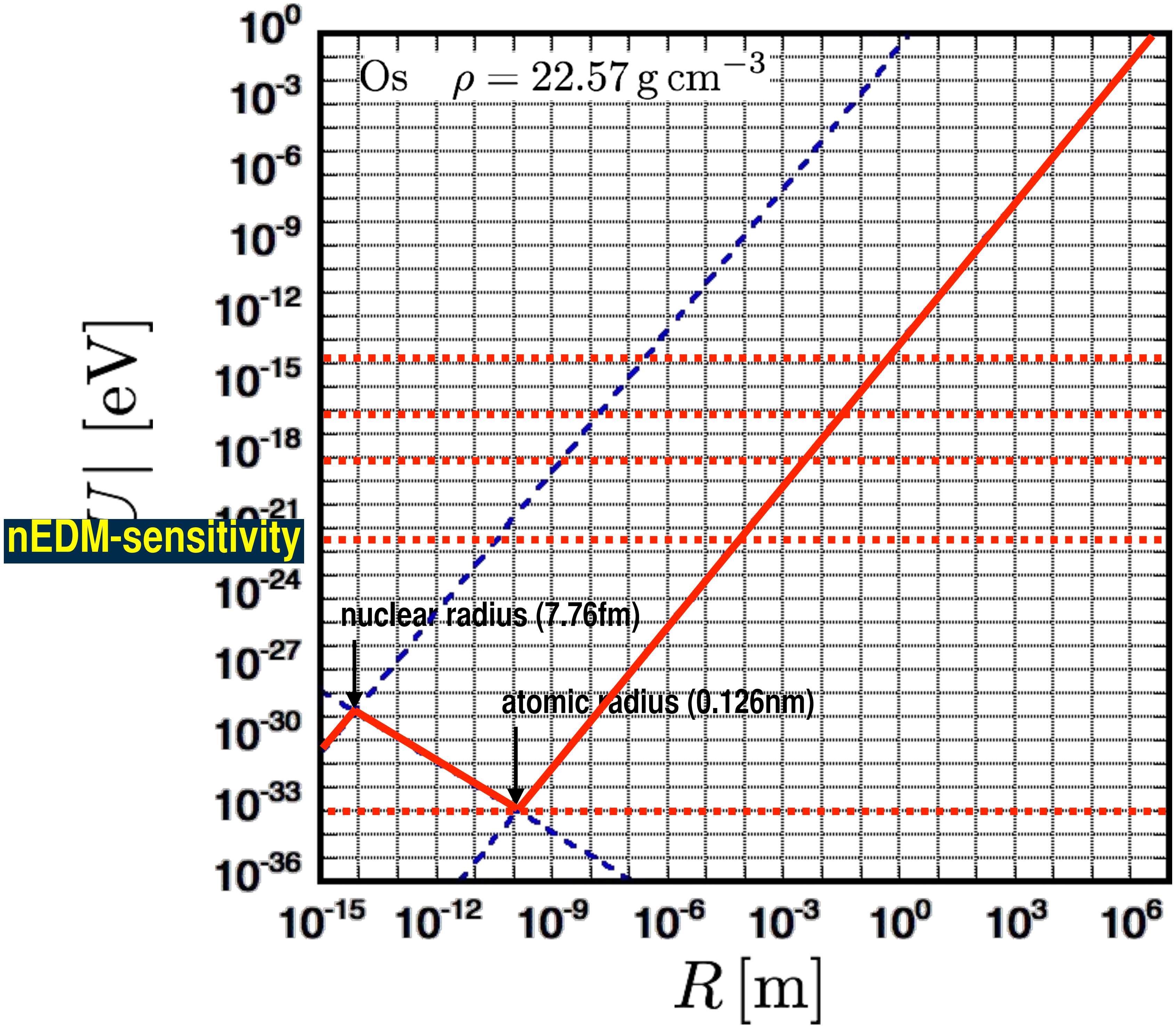

Si interferometer

multilayer interferometer

$1\mathrm{m}^2$ multilayer interferometer

multilayer interferometer
with parametric resonance?

Another summary of this chapter

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