Nuclear structure with exotic beams

Lecture 1:

Physics Topics of Current Interest

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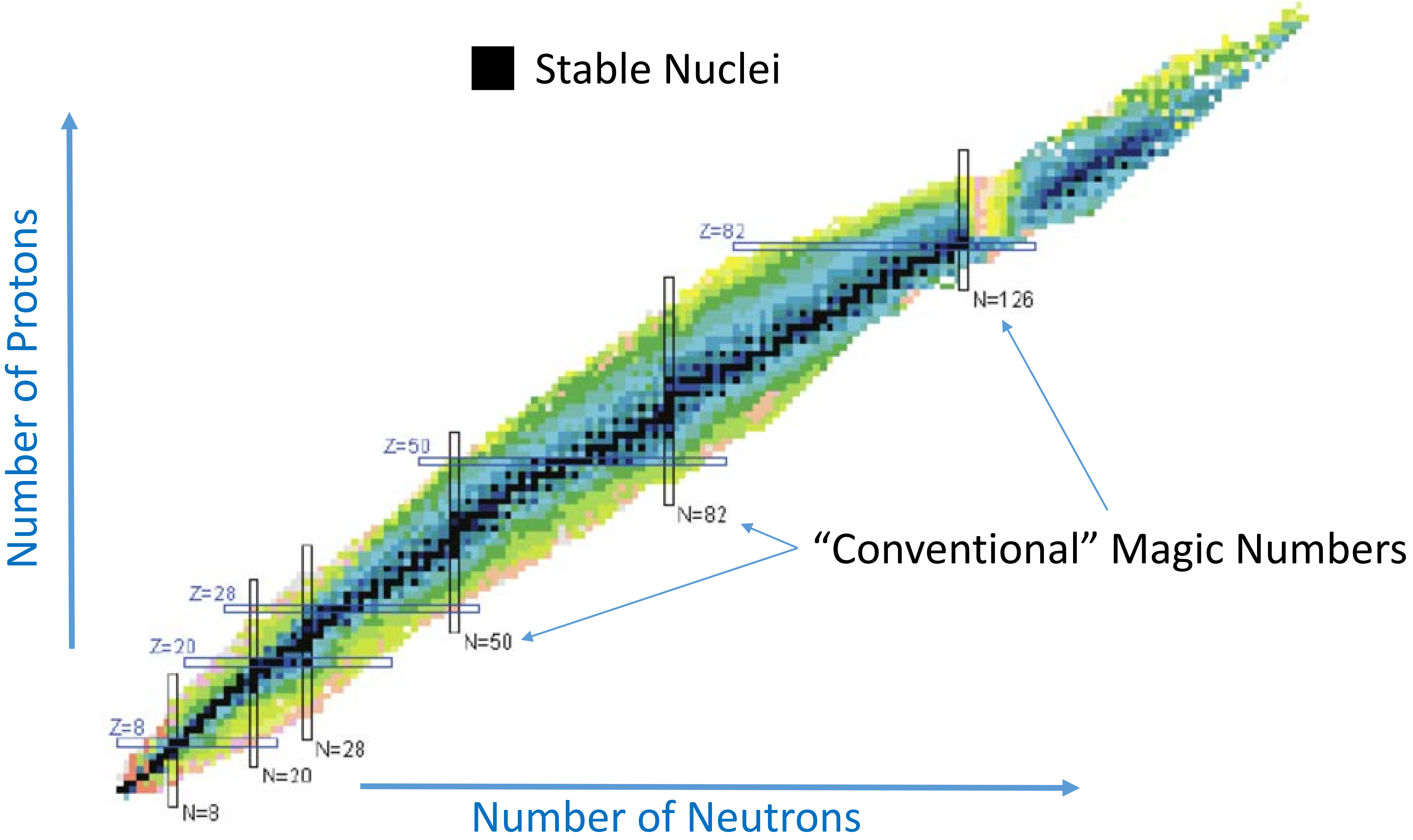
Global Outline

- Lecture 1: Physics Topics: What is interesting today?
- Lecture 2: Nuclear Reactions 1: Elastic and inelastic scattering
- Lecture 3: Nuclear Reactions 2: Transfer reactions
- Lecture 4: Techniques: Production and Detection

- Warning: there is far too much to be covered in this subject than can fit into 4 lectures, so some topics will be partially or completely omitted. I will present a personal perspective based on what I know better. I will not discuss nuclear masses, or relevance to fundamental interactions (covered elsewhere).

The Nuclear Landscape

Approximately 3000 known nuclei



MARIA GOEPPERT MAYER

The shell model

Nobel Lecture, December 12, 1963

At that time Enrico Fermi had become interested in the magic numbers. I had the great privilege of working with him, not only at the beginning, but also later. One day as Fermi was leaving my office he asked: « Is there any indication of spin-orbit coupling? » Only if one had lived with the data as long as I could one immediately answer: « Yes, of course and that will explain everything. » Fermi was skeptical, and left me with my numerology.

The shell model has initiated a large field of research. It has served as the starting point for more refined calculations. There are enough nuclei to investigate so that the shell modellists will not soon be unemployed.

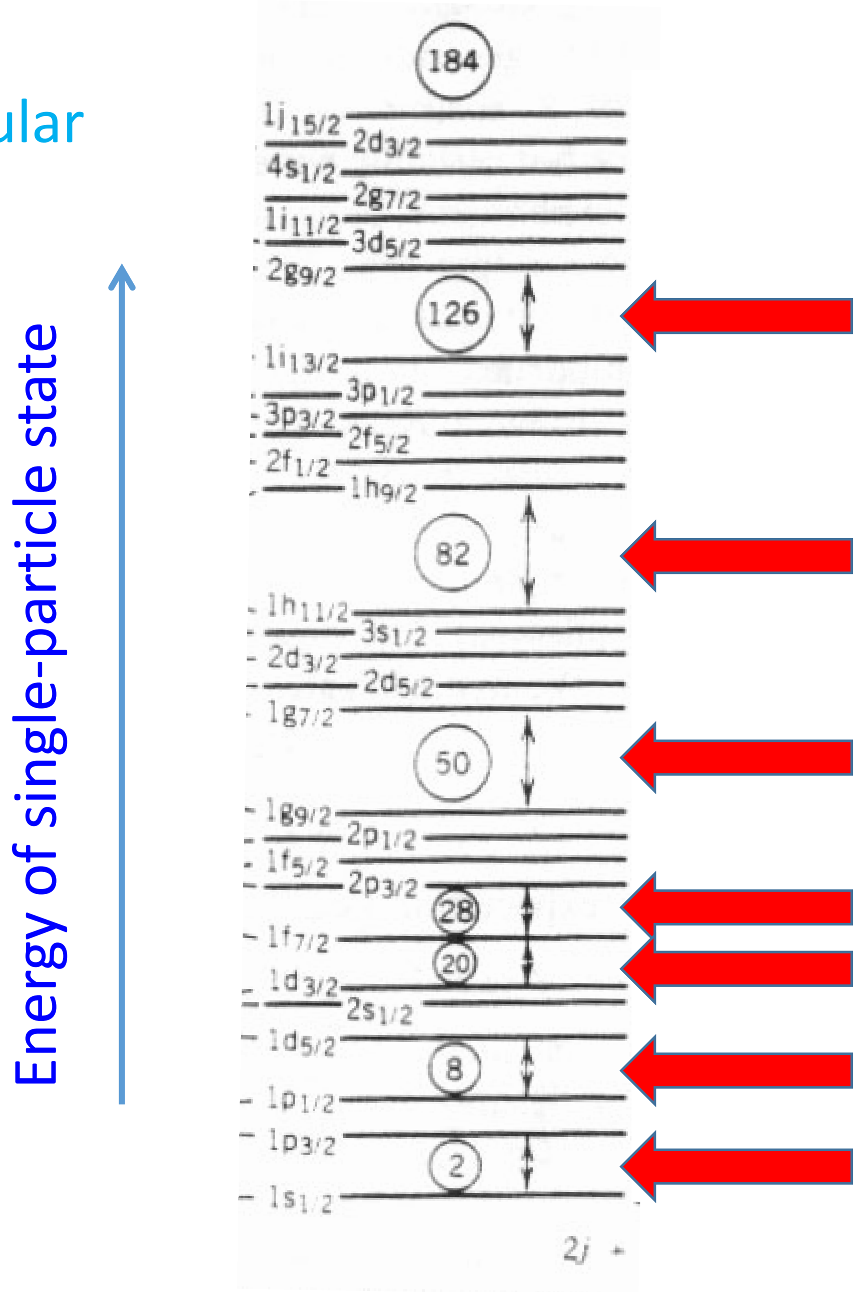
Understanding nuclear structure far from stability

of nodes+1

Orbital Angular Momentum

$N\ell_j$

Total Angular Momentum



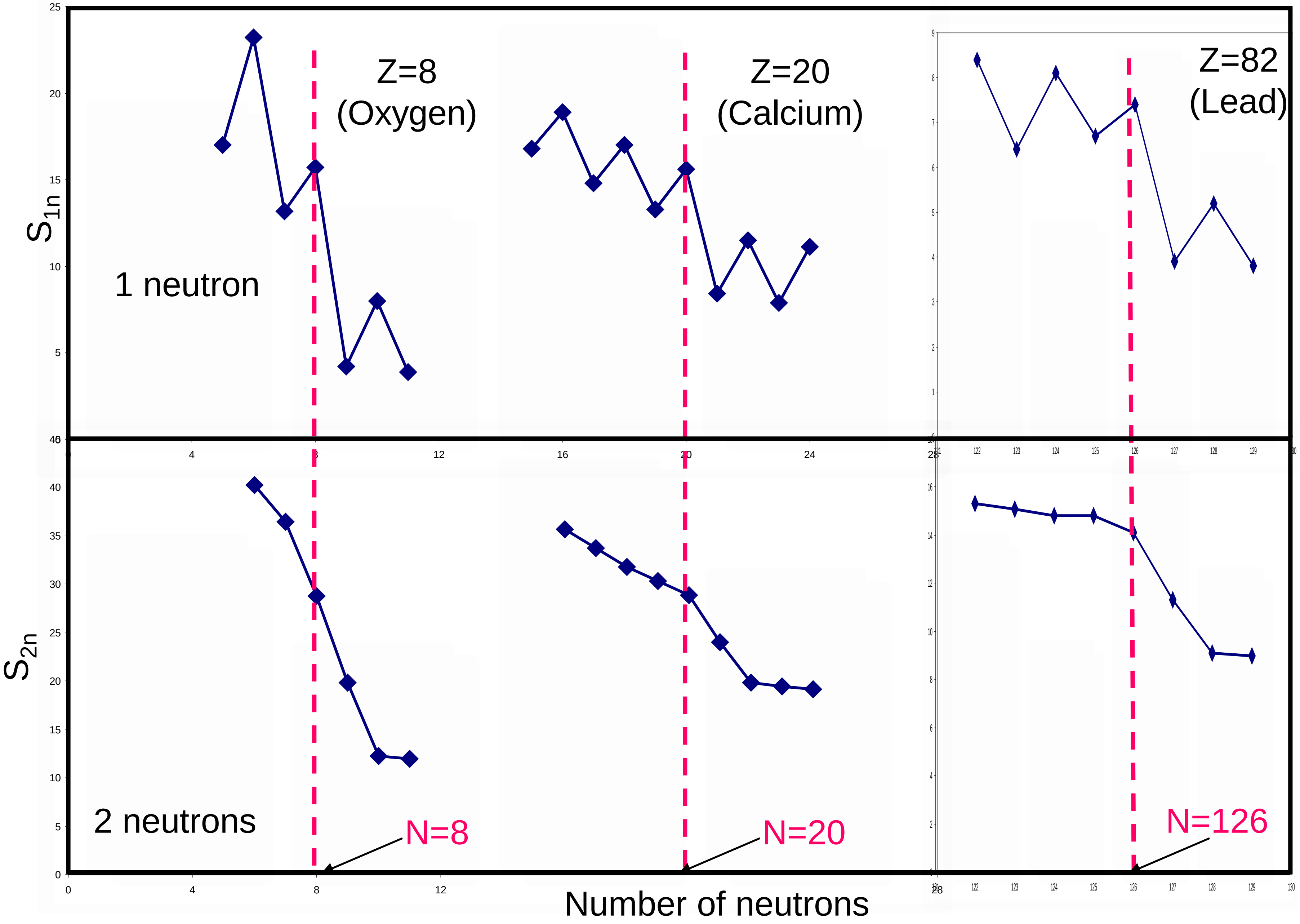
Energy gaps are responsible for many nuclear properties

Similar pictures for neutrons and protons

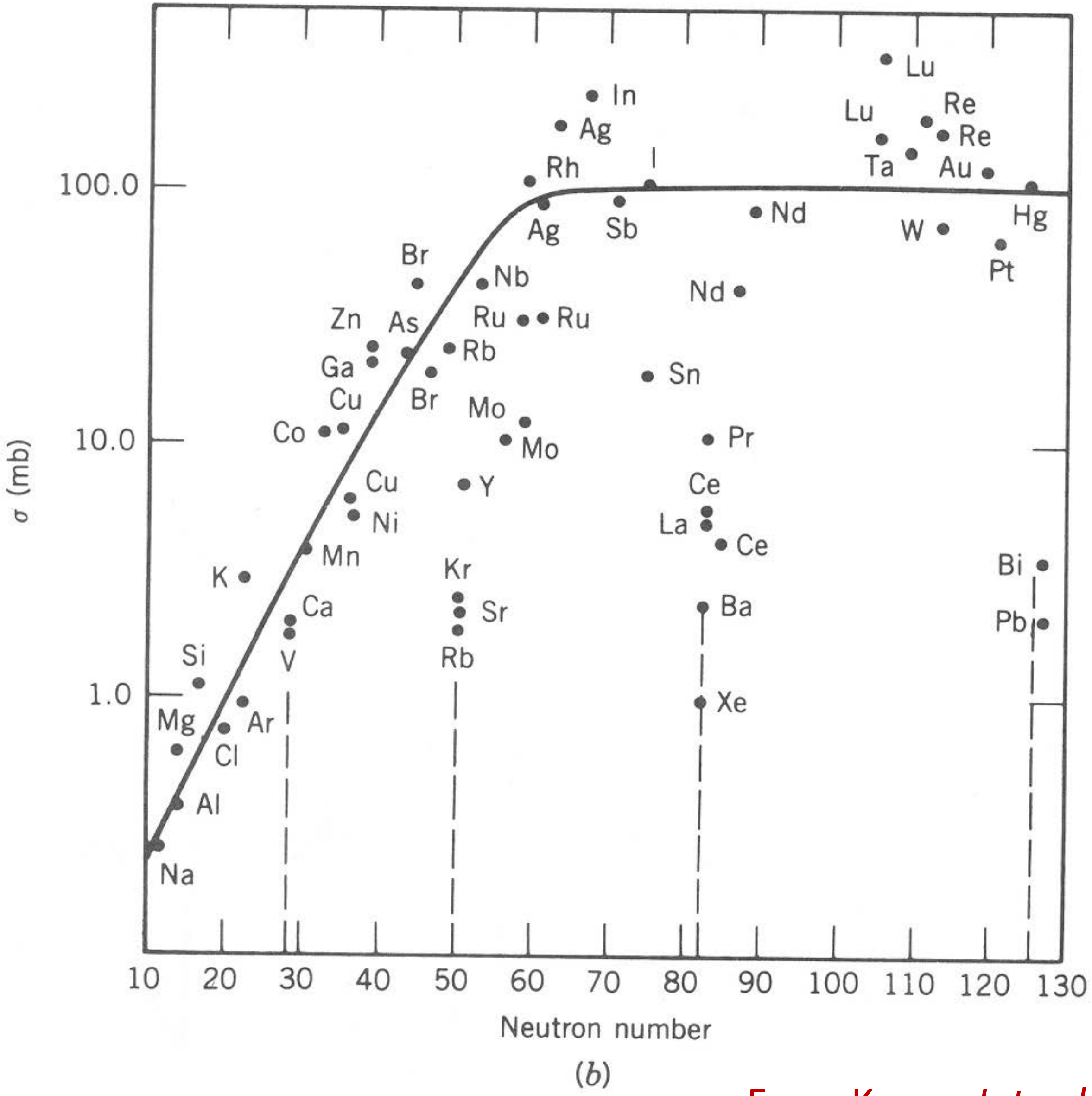
BUT: the number of neutrons can affect the order of the proton levels, and vice-versa!

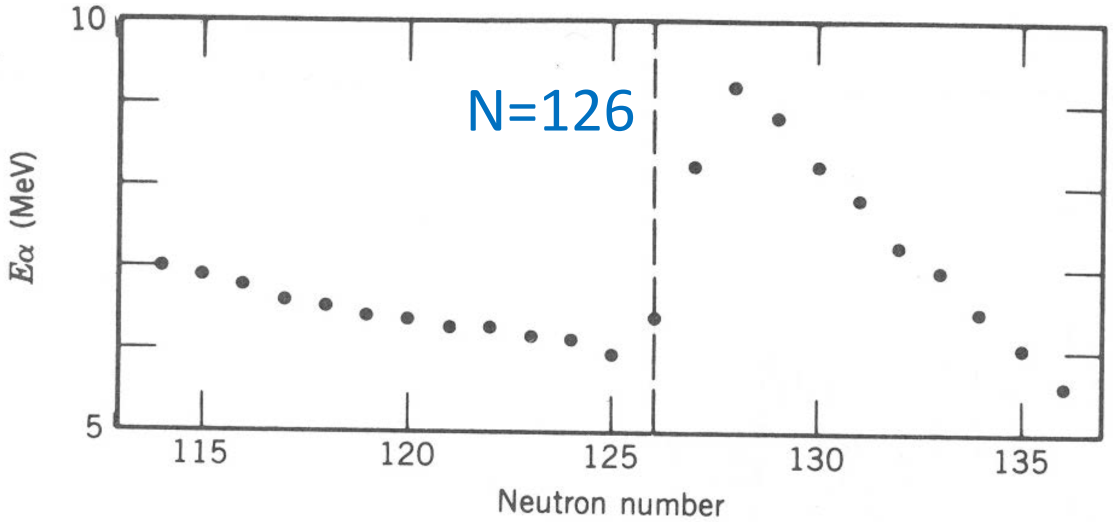
The energy gaps can change with changing N and Z!

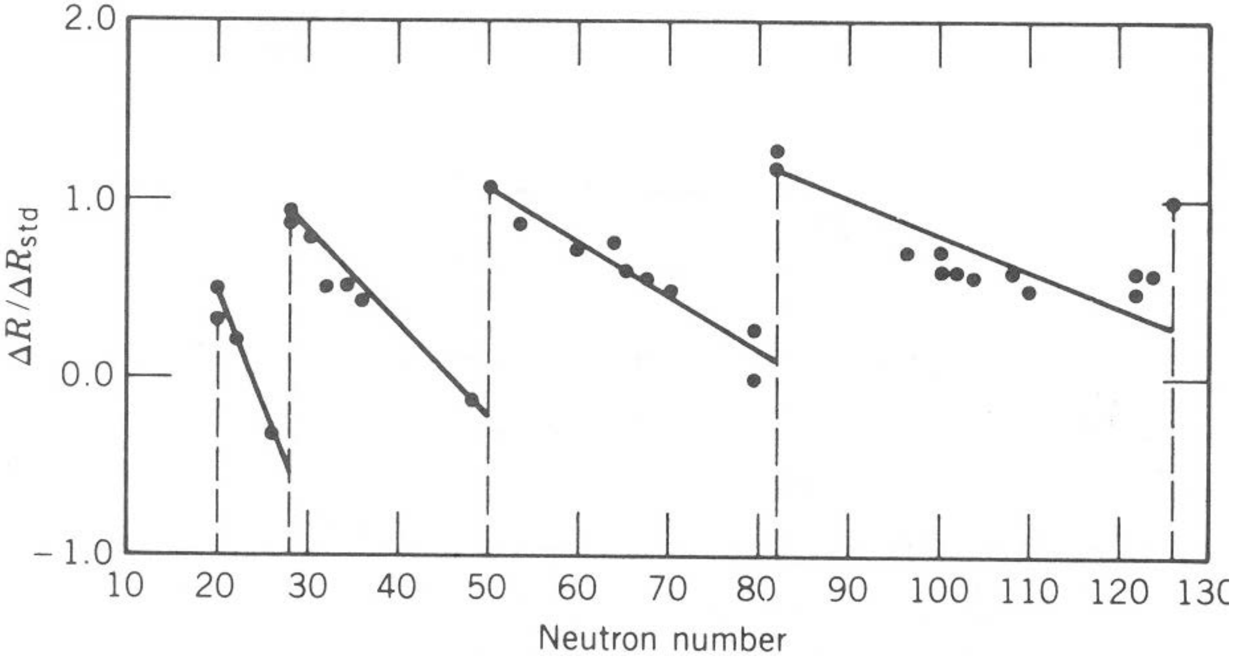
Evidence for shells: Neutron separation Energies



Evidence for shells: *n* capture, α decay, radii

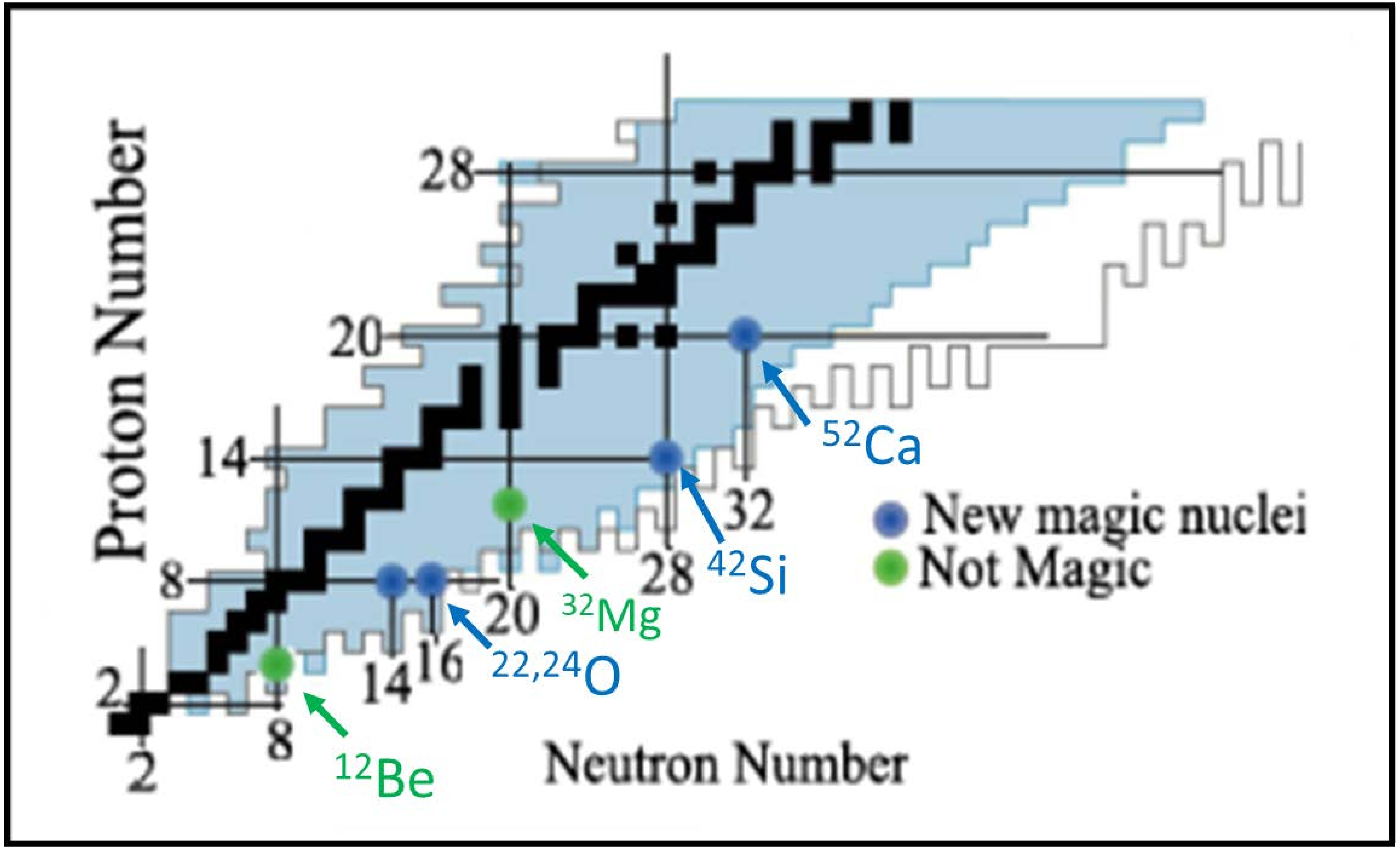






From Krane, *Introduction to Nuclear Physics*

Unexpected behavior far from stability



New understanding developed from exotic-beam experiments

http://www.riken.jp/en/research/rikenresearch/highlights/7240/

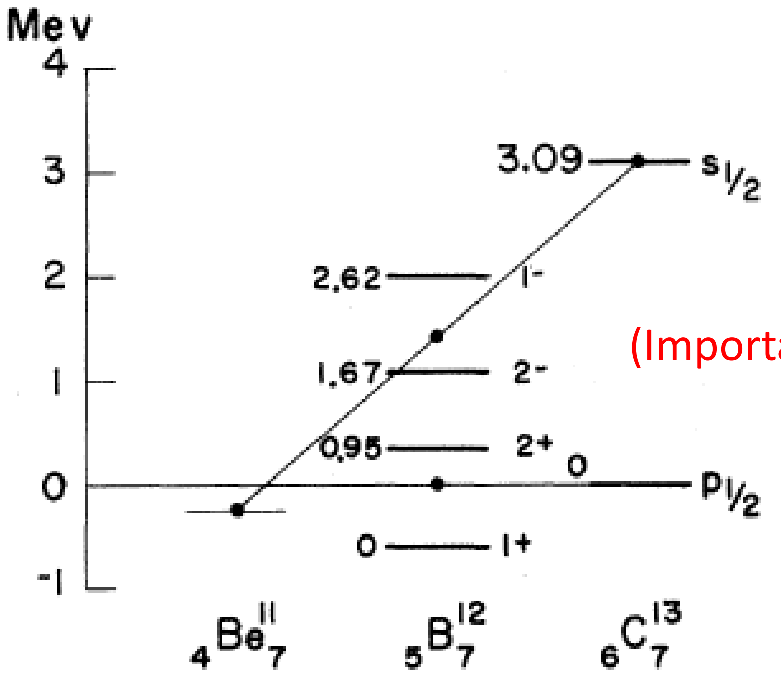
Early understanding in light nuclei

VOLUME 4, NUMBER 9 PHYSICAL REVIEW LETTERS MAY 1, 1960

ORDER OF LEVELS IN THE SHELL MODEL AND SPIN OF Be^{11*}

I. Talmi and I. Unna

For example, the order of filling of neutron shells may depend on the proton configuration.



(Important for ^{11}Li)

FIG. 1. Competition between $s_{1/2}$ and $p_{1/2}$ levels.

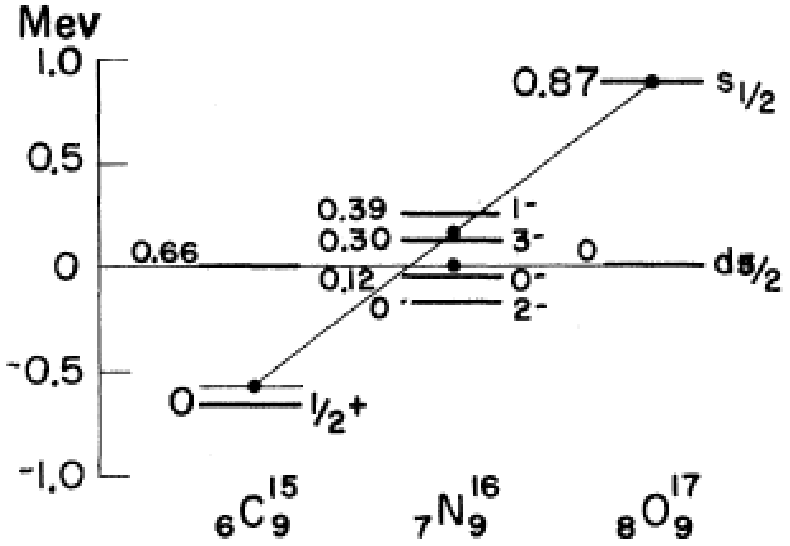
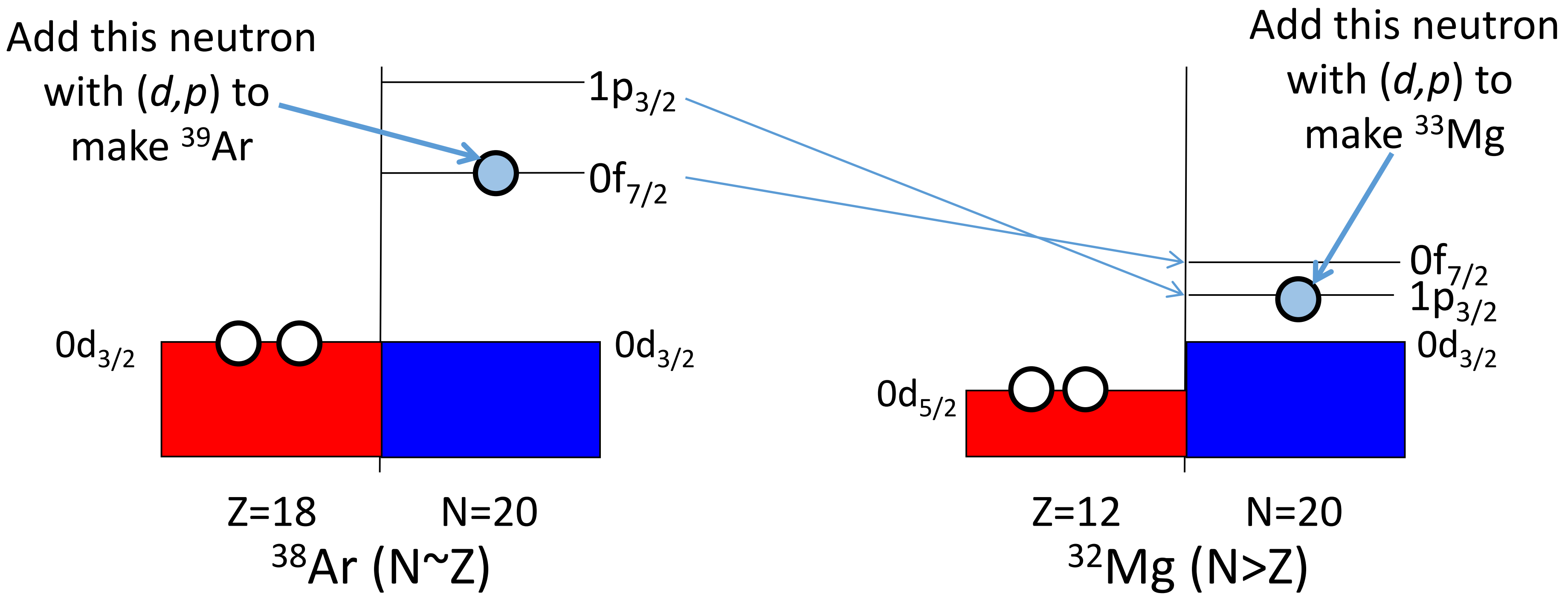


FIG. 2. Competition between $d_{5/2}$ and $s_{1/2}$ levels.

Simple effect: decreased neutron-proton interaction with fewer protons

Predicted ^{11}Be ground-state spin and explained ^{15}C-^{17}O $1s_{1/2}$-$0d_{5/2}$ inversion

…The order of filling of neutron shells …



^{38}Ar(2^+): 3.167 MeV
^{39}Ar($J^{\pi}_{g.s.}$)=$7/2^-$
^{39}Ar($3/2^-$): 1.267 MeV

^{32}Mg(2^+): 0.885 MeV
^{33}Mg($J^{\pi}_{g.s.}$)=$3/2^-$
^{33}Mg($7/2^-$): 0.484 MeV

N=20: large gaps!

N=20: Inversion and small gaps!

(Schematic picture)

More recent understanding

PRL 95, 232502 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Evolution of Nuclear Shells due to the Tensor Force

Takaharu Otsuka,[1,2,3,*] Toshio Suzuki,[4] Rintaro Fujimoto,[1] Hubert Grawe,[5] and Yoshinori Akaishi[6]

$j_< = l - 1/2$ $j_> = l + 1/2$

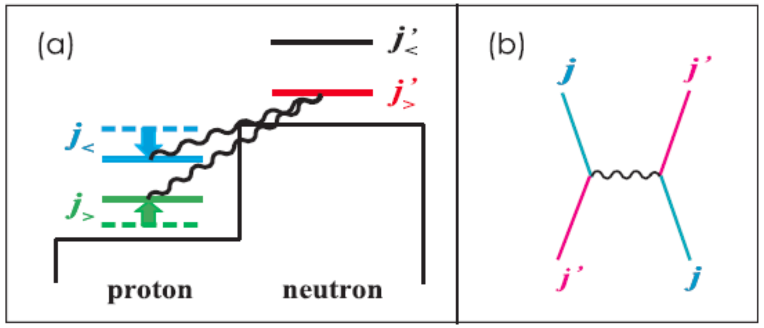


FIG. 1 (color). (a) Schematic picture of the monopole interaction produced by the tensor force between a proton in $j_{>,<} = l \pm 1/2$ and a neutron in $j'_{>,<} = l' \pm 1/2$. (b) Exchange processes contributing to the monopole interaction of the tensor force.

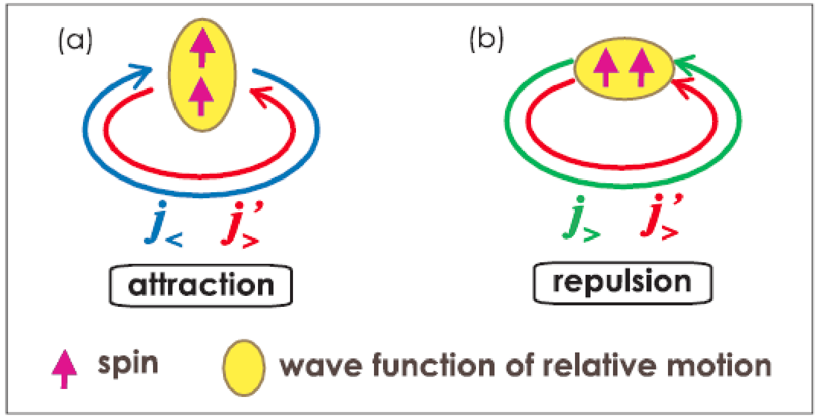


FIG. 2 (color). Intuitive picture of the tensor force acting two nucleons on orbits j and j'.

$$V_T(r) = f(r)(3\sigma_1 \cdot \hat{r}\sigma_2 \cdot \hat{r} - \sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$$

Tensor force from pion exchange

important for large neutron-proton imbalance

More recent understanding

PRL **95,** 232502 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

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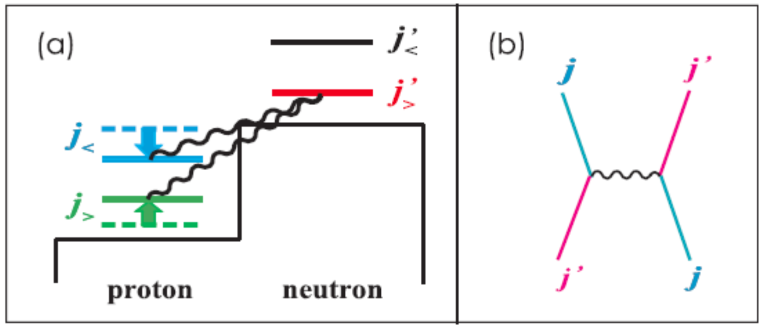
$j_<=l-1/2$ $j_>=l+1/2$



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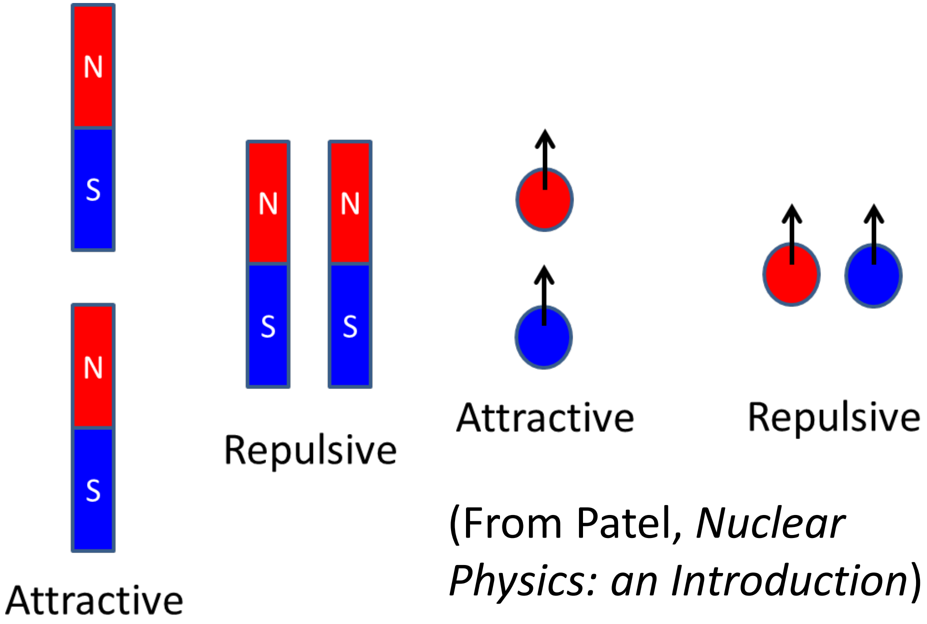

(From Patel, *Nuclear Physics: an Introduction*)

$$V_T(r) = f(r)(3\sigma_1 \cdot \hat{r}\sigma_2 \cdot \hat{r} - \sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$$

Tensor force from pion exchange

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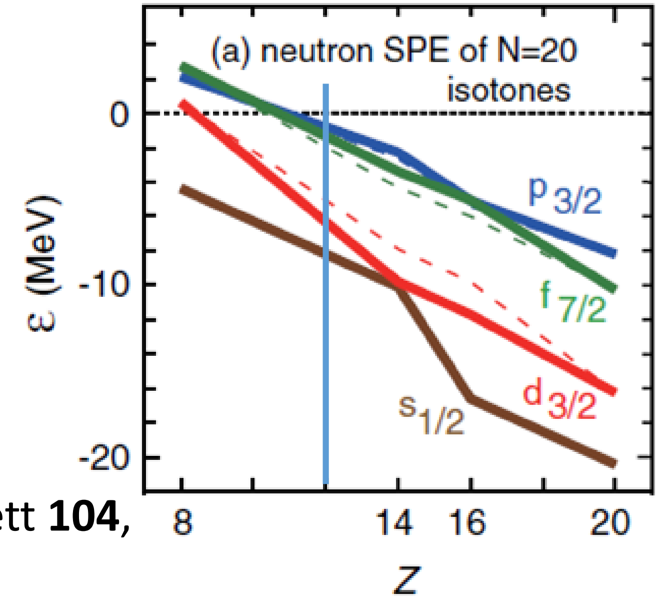
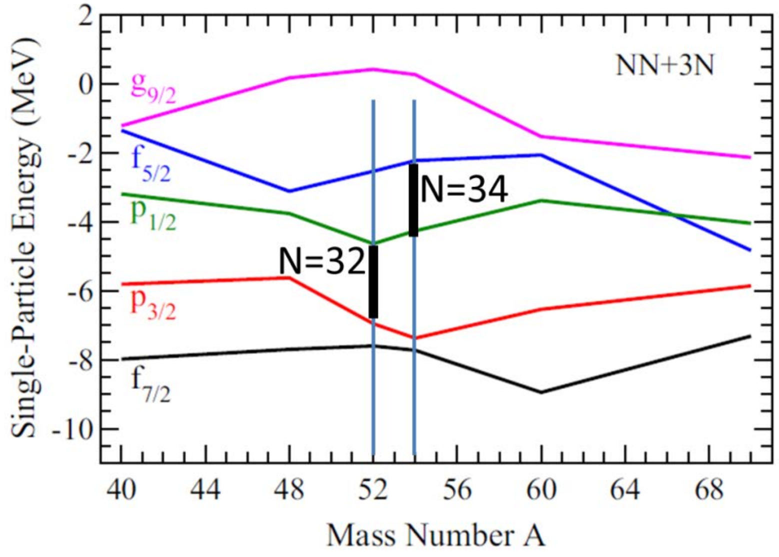
Effect of Tensor Interaction

- Near ^{32}Mg: Disappearance of N=20 magic number and *sd*-$f_{7/2}$ gap driven by tensor force and pairing; (*sd*)-(*fp*) mixing



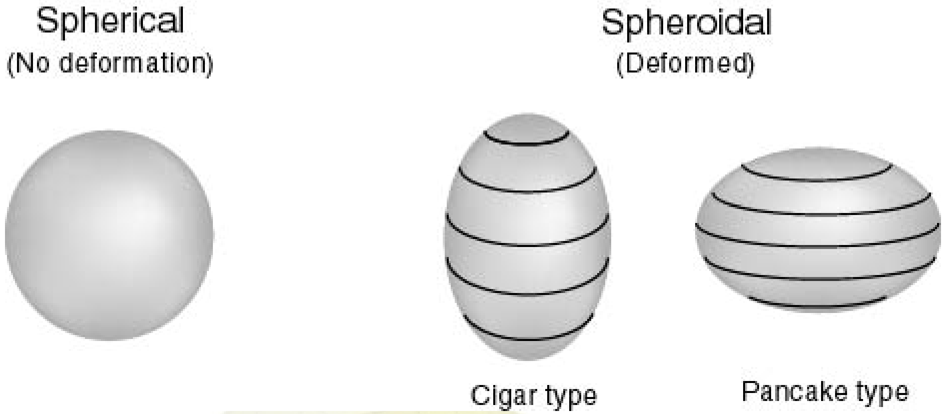
T. Otsuka et al., Phys Rev Lett **104**, 012501 (2010)

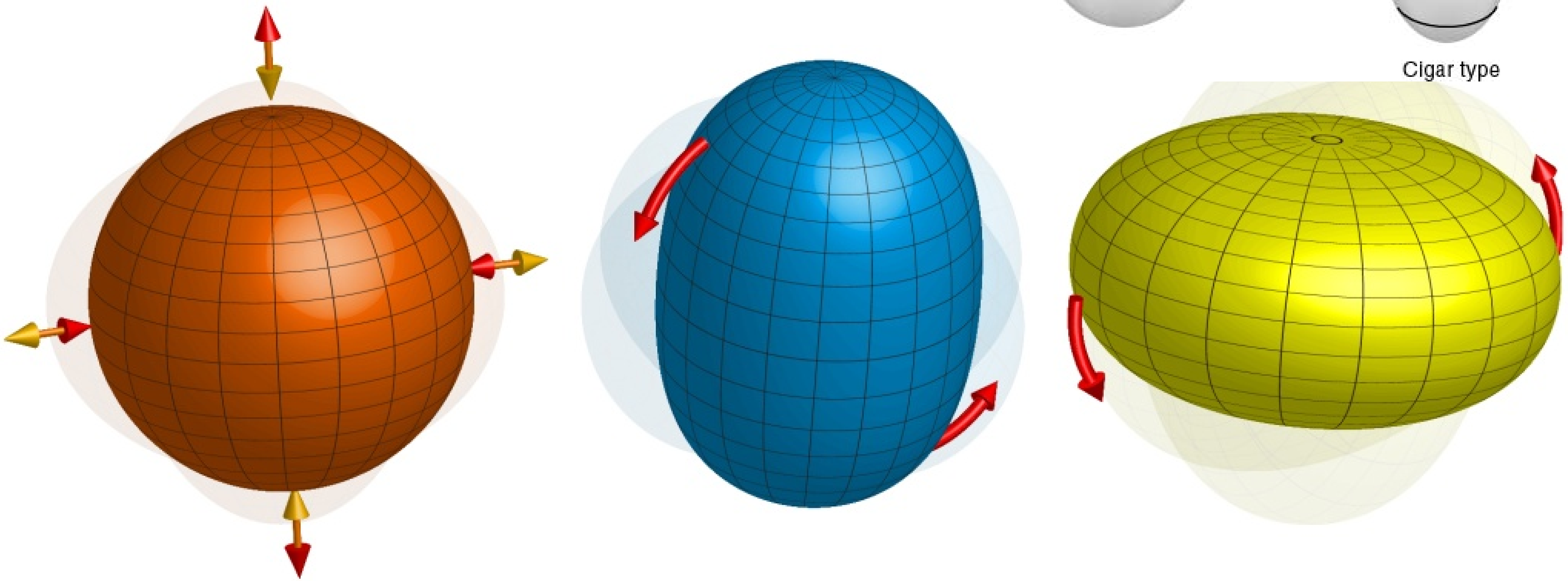
- ^{52}Ca (^{54}Ca?): Appearance of N=32 (and N=34?) magic no. from decreased $\pi 0f_{7/2}$- $\nu 0f_{5/2}$ interaction as $\pi 0f_{7/2}$ is emptied



J. D. Holt et al., Phys Rev C **90**, 024312 (2014)

Deformation in nuclei – Collective Motion



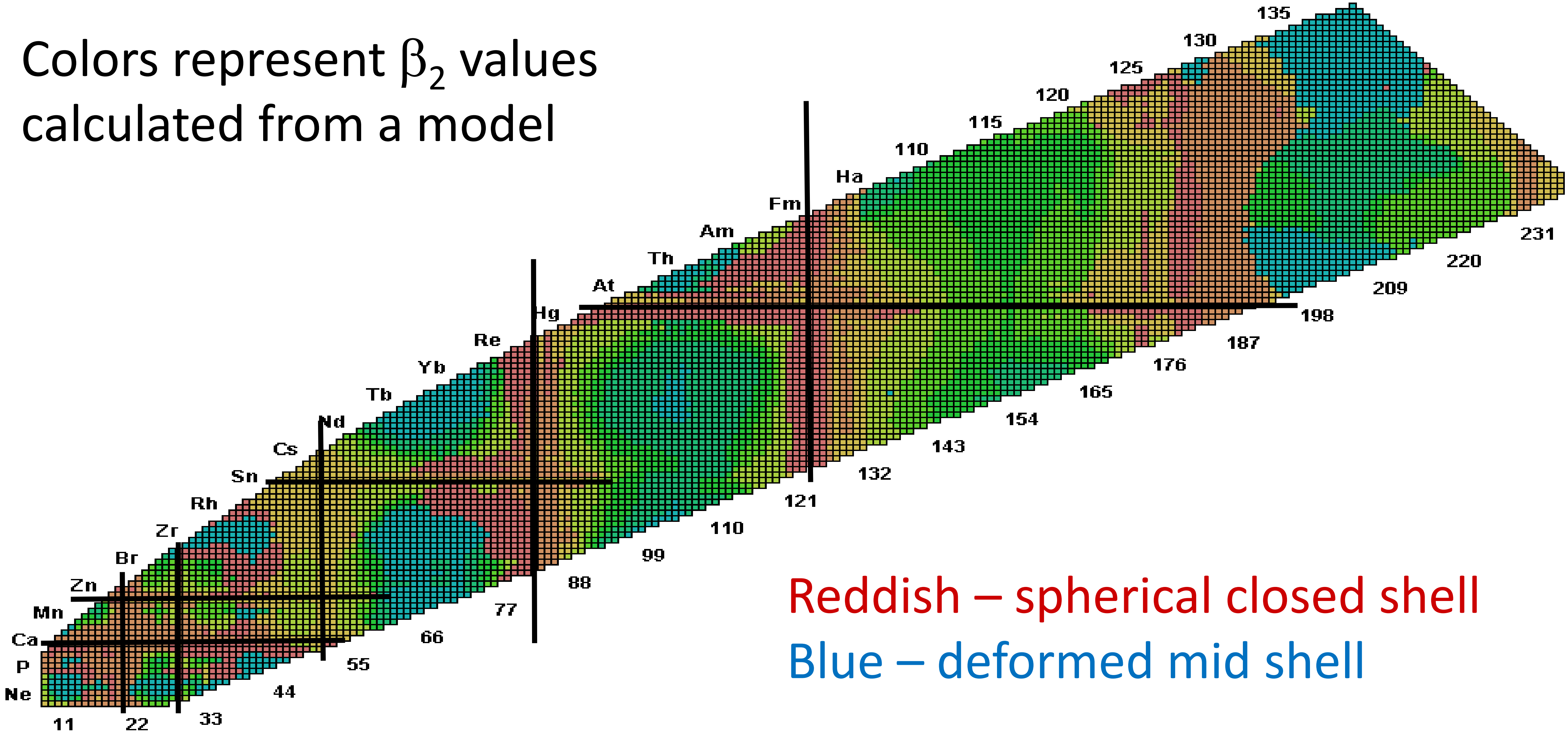


^{36}Si ^{38}Si ^{40}Si ^{42}Si

http://www.riken.jp/en/research/rikenresearch/highlights/7240/

Nuclear deformation – away from closed shells

Colors represent β_2 values calculated from a model



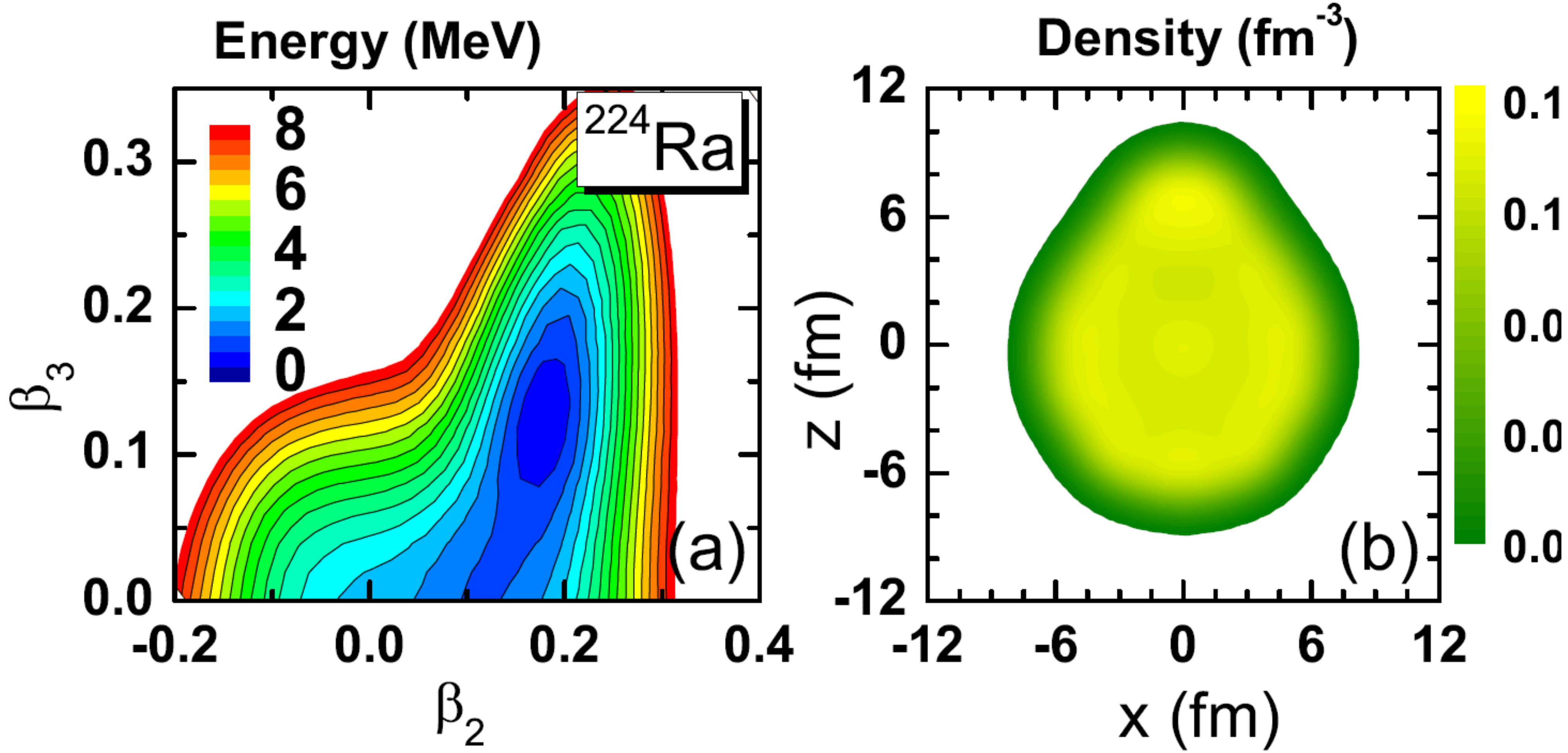
Reddish – spherical closed shell

Blue – deformed mid shell

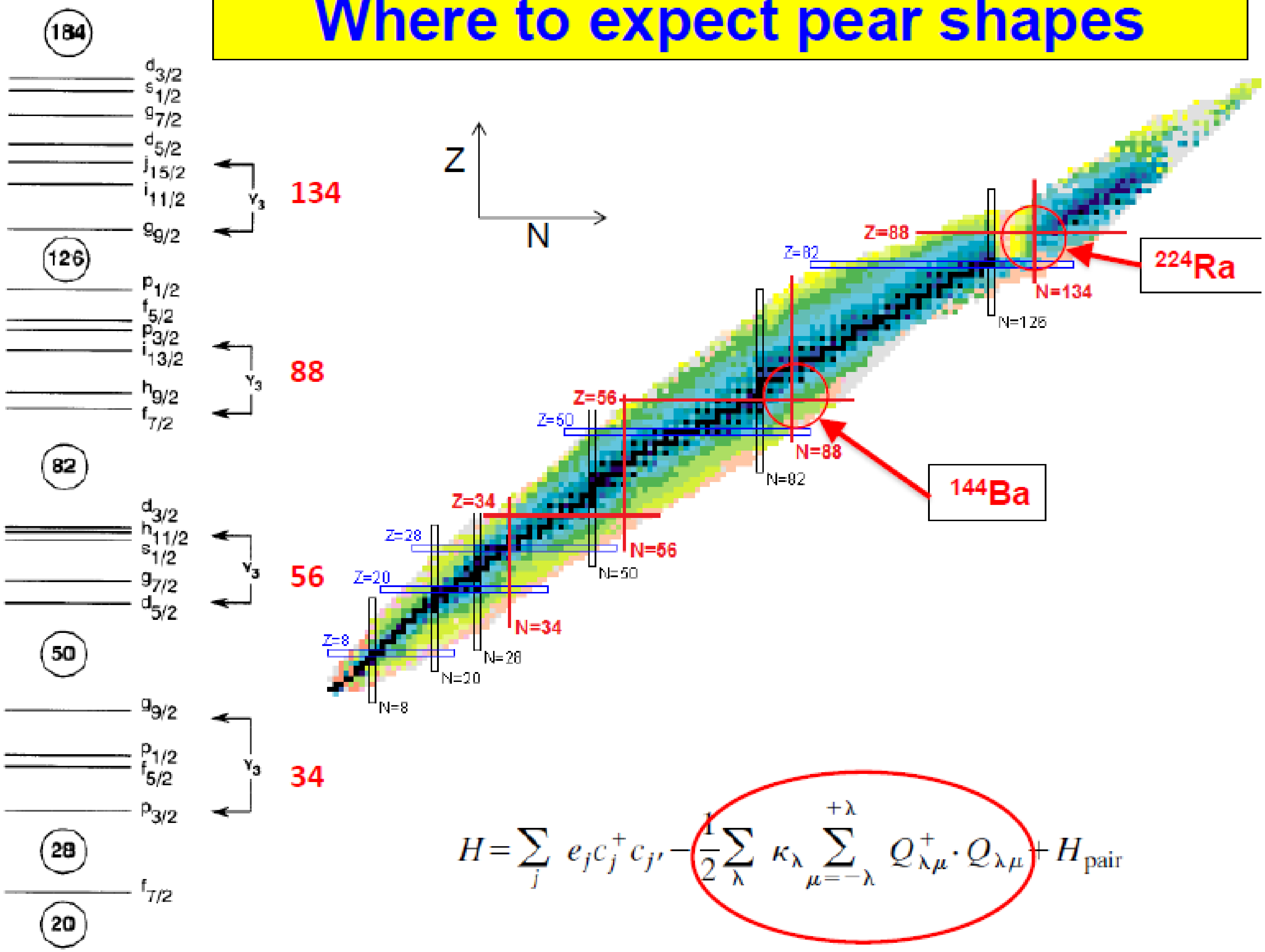
Octupole deformations

Interesting regions of nuclear structure

Also, β_3 deformation enhances effects of EDM



Where to expect pear shapes



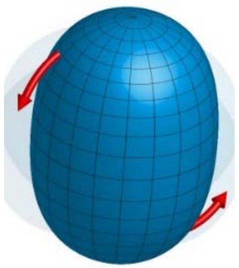
$$H = \sum_j e_j c_j^+ c_{j'} - \frac{1}{2} \sum_\lambda \kappa_\lambda \sum_{\mu=-\lambda}^{+\lambda} Q_{\lambda\mu}^+ \cdot Q_{\lambda\mu} + H_{\text{pair}}$$

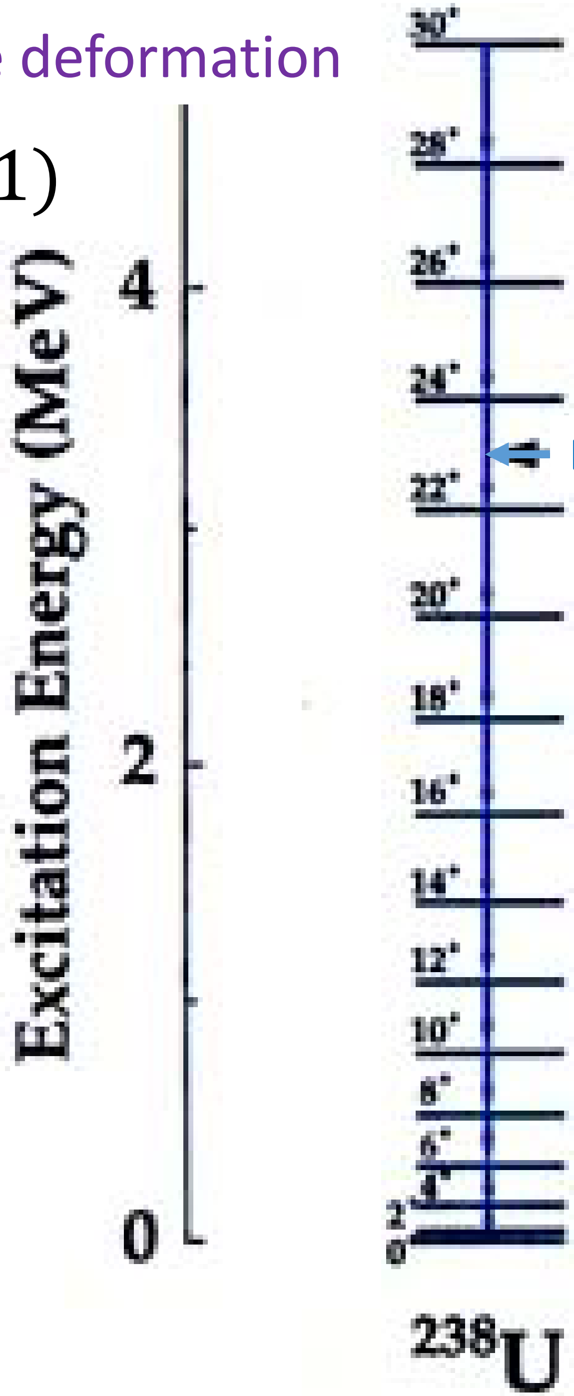
long range multipole-multipole force

Signatures of Deformed Nuclei

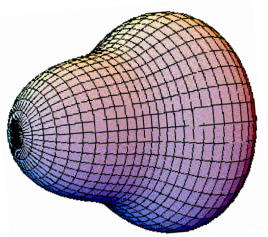
Quadrupole deformation

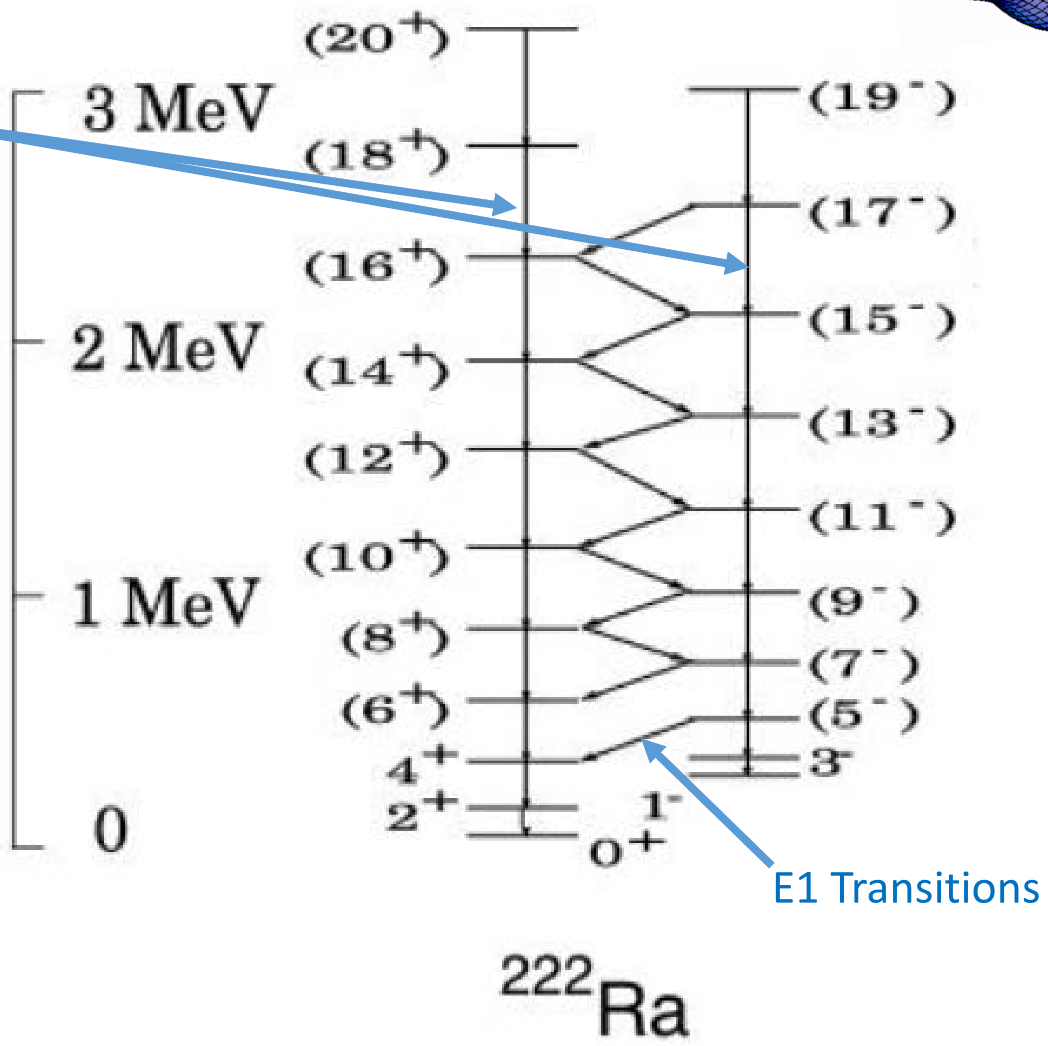
$$E_J \propto J(J+1)$$





Octupole deformation





Astrophysical environments and nucleo-synthesis

The chemical elements are produced in violent explosive environments in the cosmos:

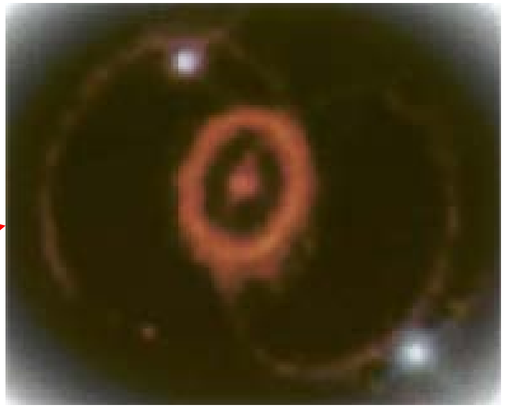
Such as:

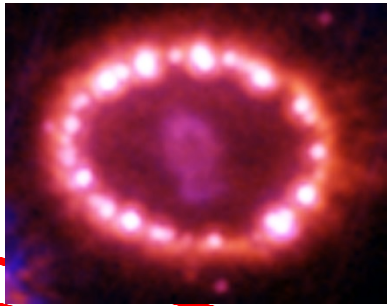
Novae

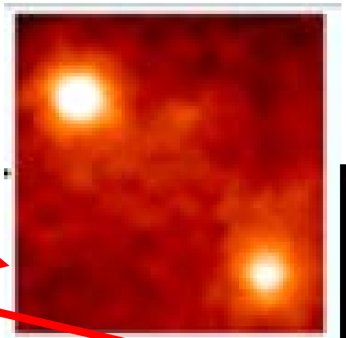
Supernovae

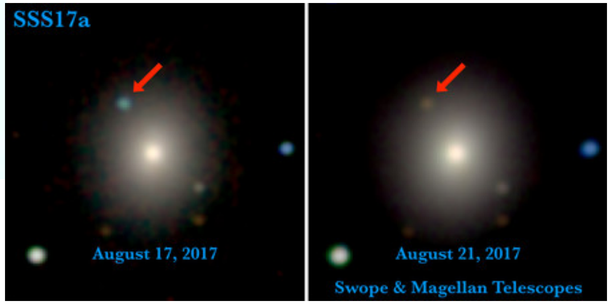
X-ray bursts

Neutron-star mergers



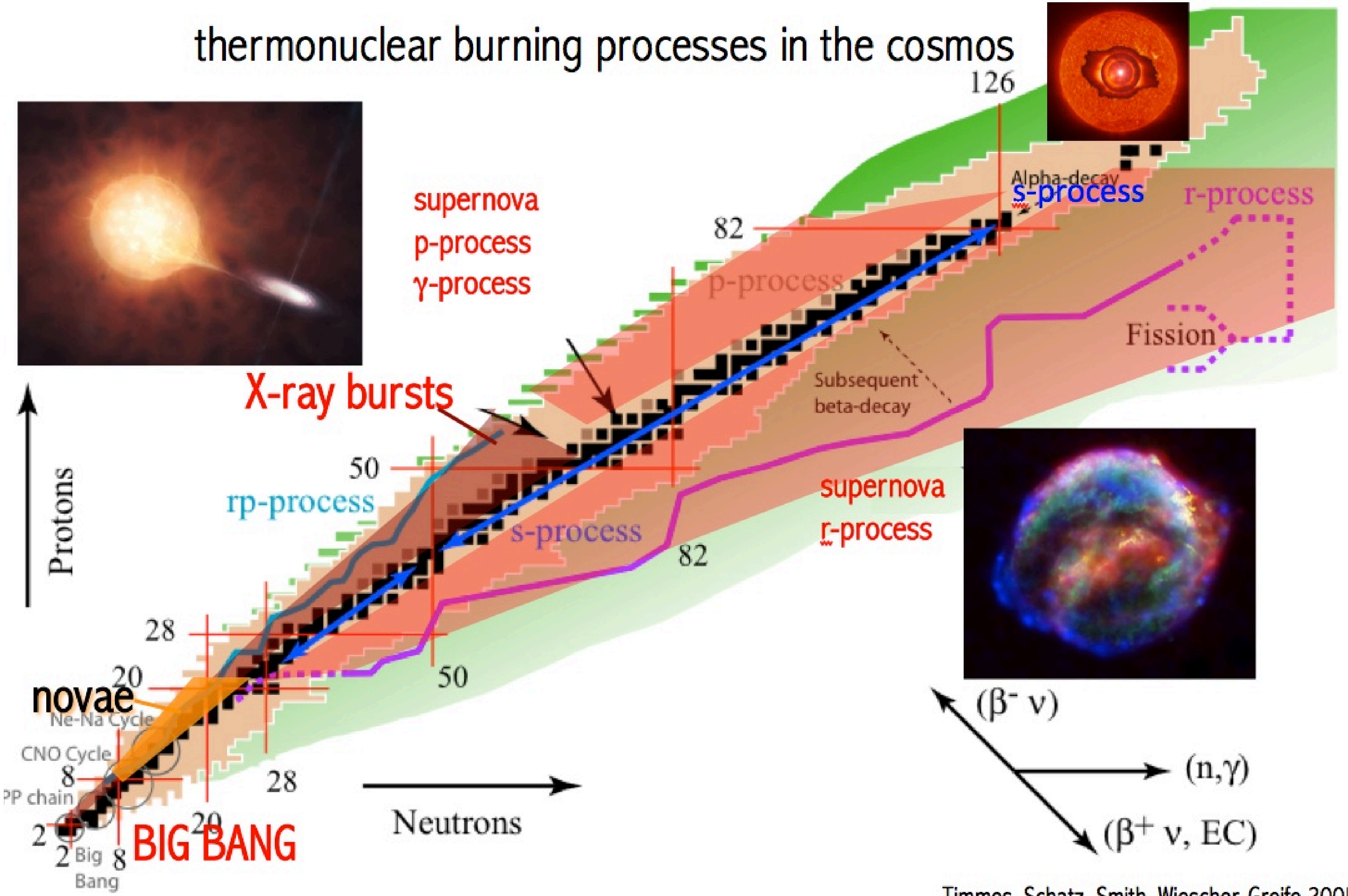






Nucleo-synthesis depends on nuclear structure, often far from stability

Nuclei in astrophysics



Timmes, Schatz, Smith, Wiescher, Greife 2005

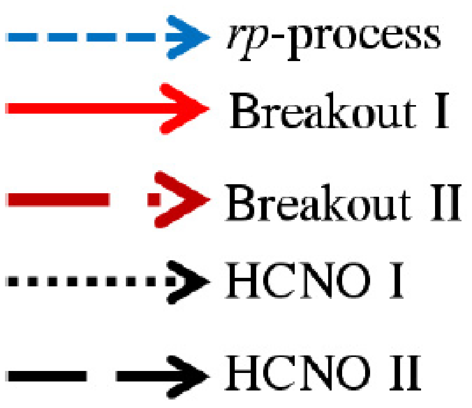
Around the HCNO Cycles

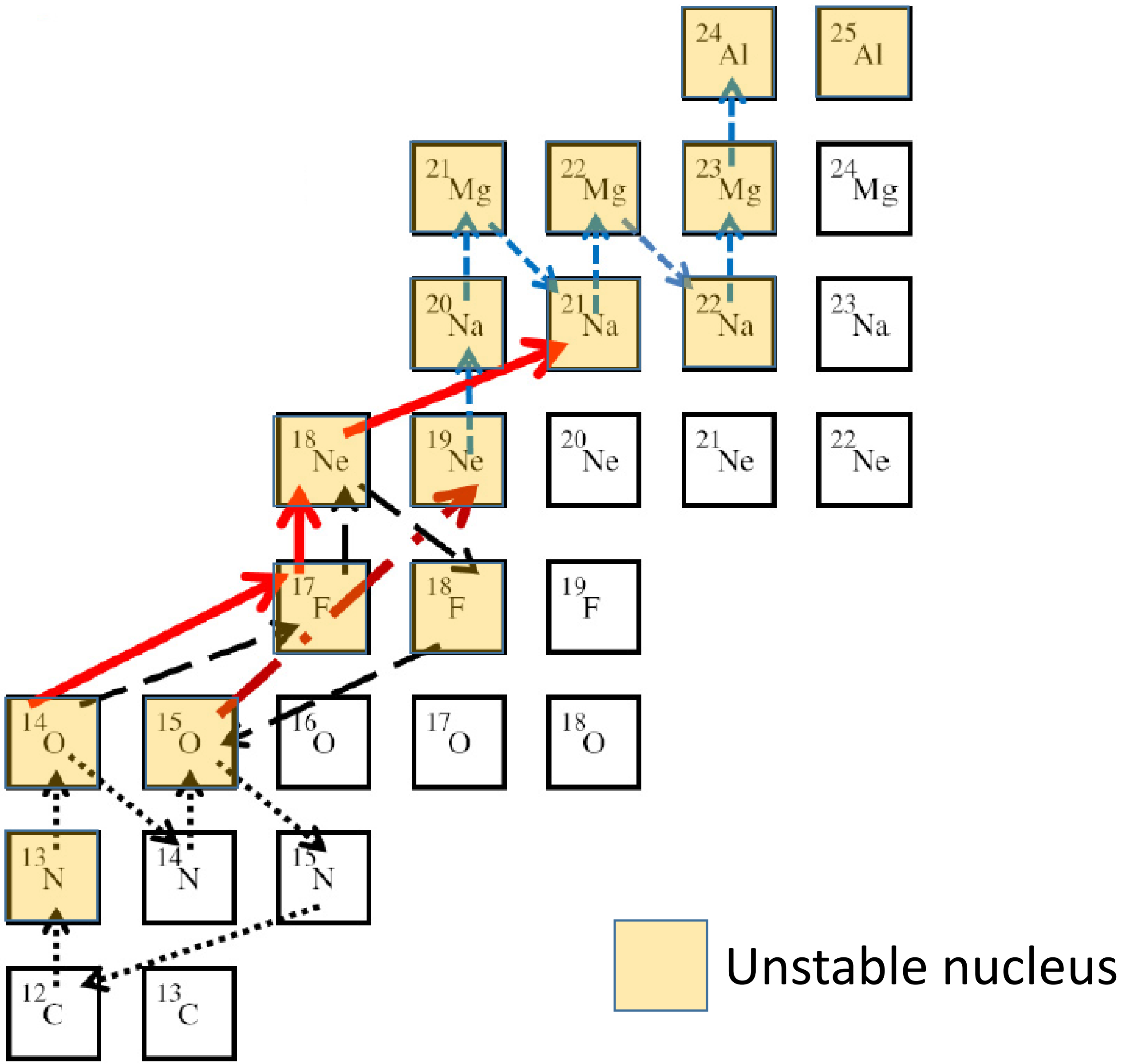
Important Reactions:

(α,p) e.g. $^{14}O(\alpha,p)^{17}F$

(α,γ) e.g. $^{15}O(\alpha,\gamma)^{19}Ne$

(p,γ) e.g. $^{13}N(p,\gamma)^{14}O$





Important reaction: $^{15}O(\alpha,\gamma)^{19}Ne$

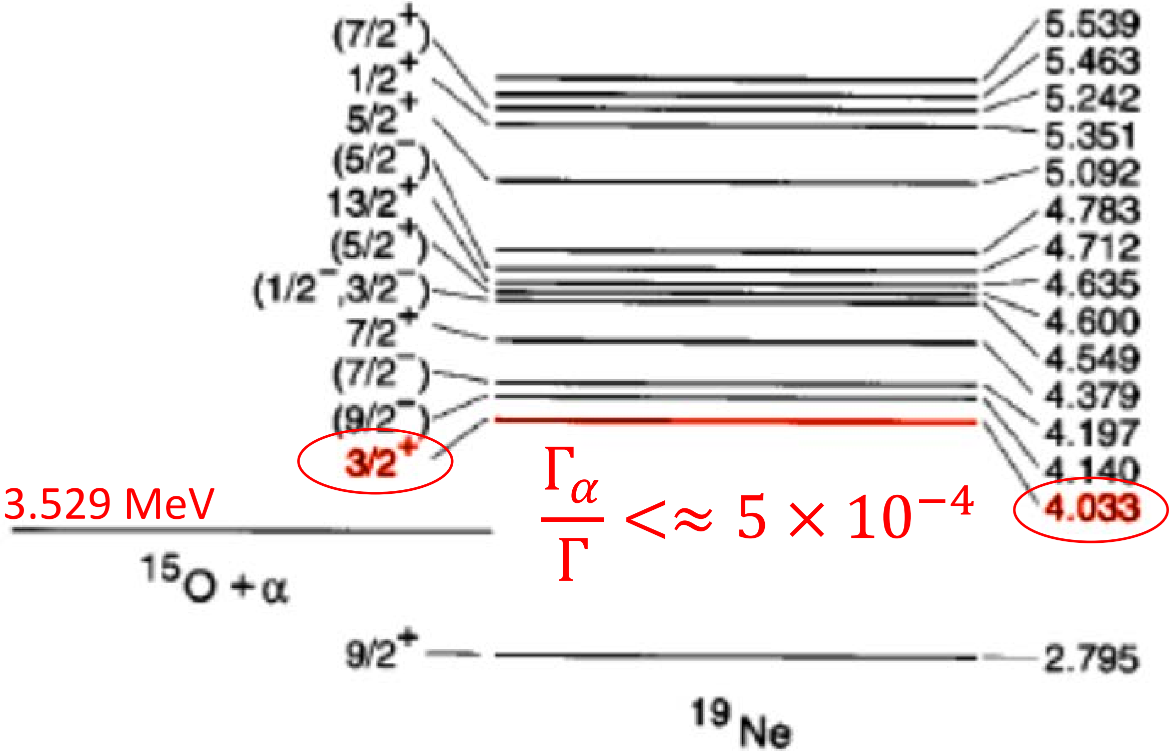
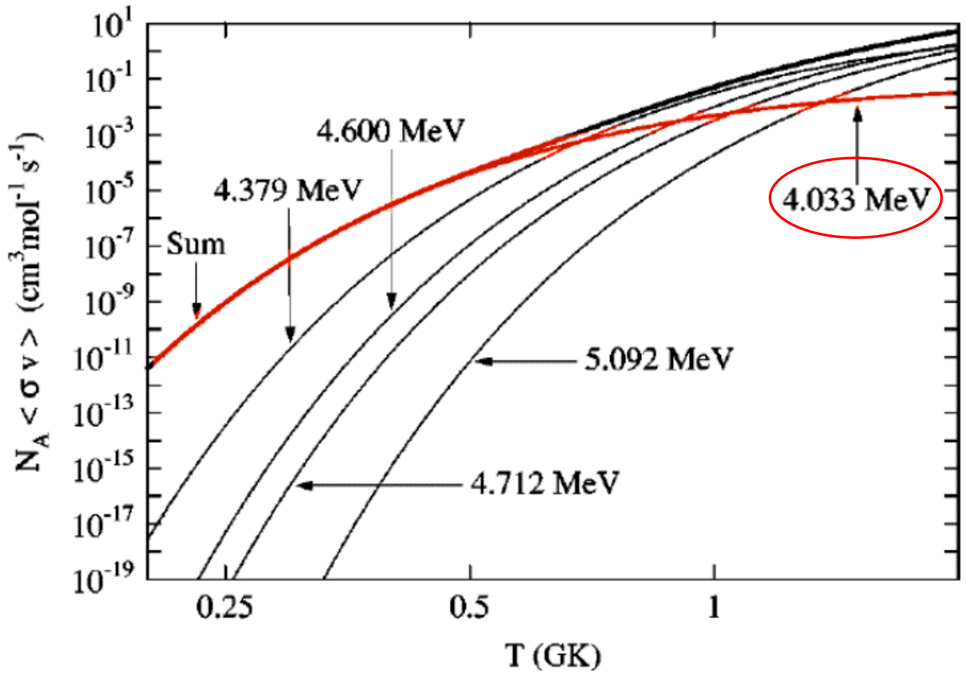
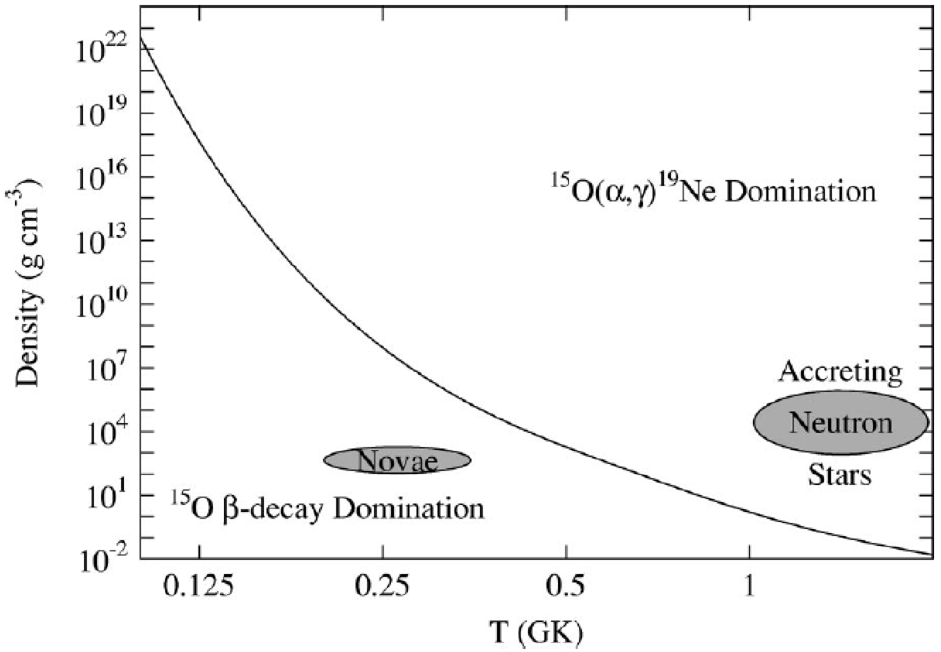


FIG. 1. Level scheme of ^{19}Ne in the vicinity of the (α) threshold.





$^{15}O(\alpha,\gamma)^{19}Ne$ not yet feasible (σ ~ 100 pb)

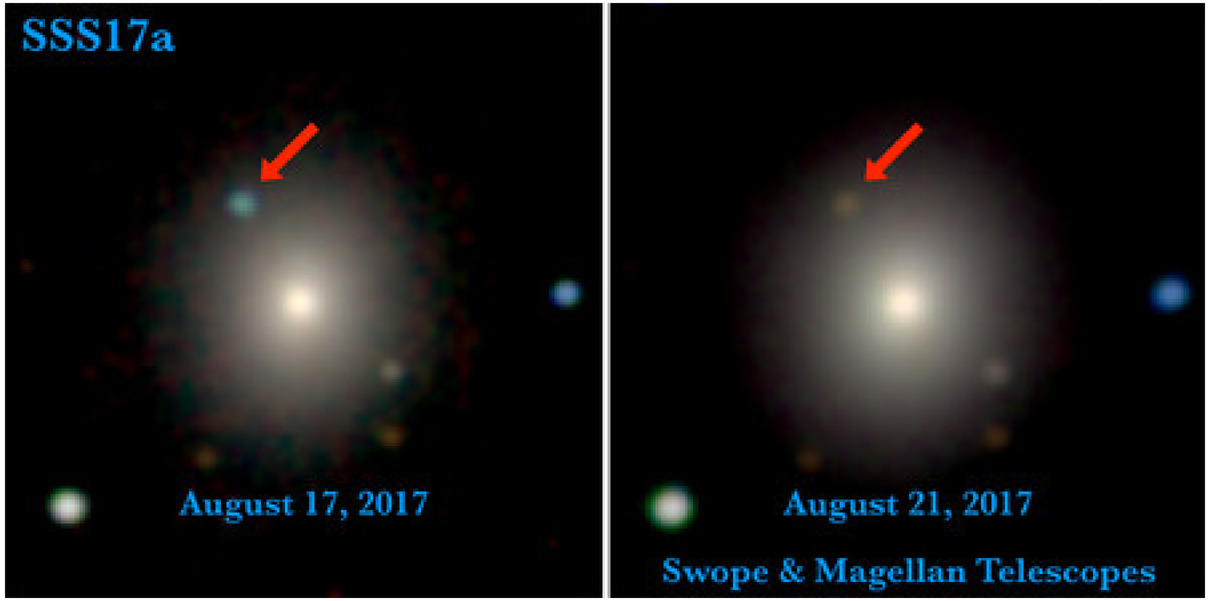
$^{20}Ne(^{3}He,\alpha)^{19}Ne(\alpha$ or $\gamma)$: K.E. Rehm et al., PRC **67** 065809 (2003)

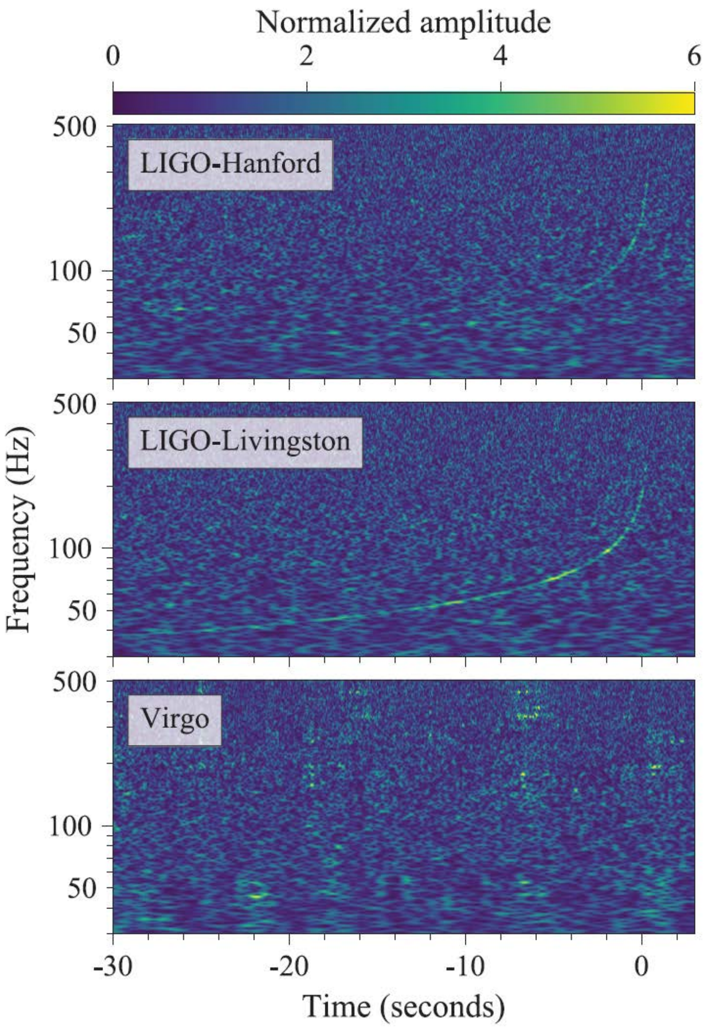
$^{21}Ne(p,t)^{19}Ne(\alpha$ or $\gamma)$: B. Davids et al., PRC **67** 012801 (2003)

$^{20}Mg(\beta p)^{19}Ne$: C. Wrede et al., PRC **96** 032801 (2017)

Also, you may have heard of this…

"GW170817"- neutron-star merger





It matters because…

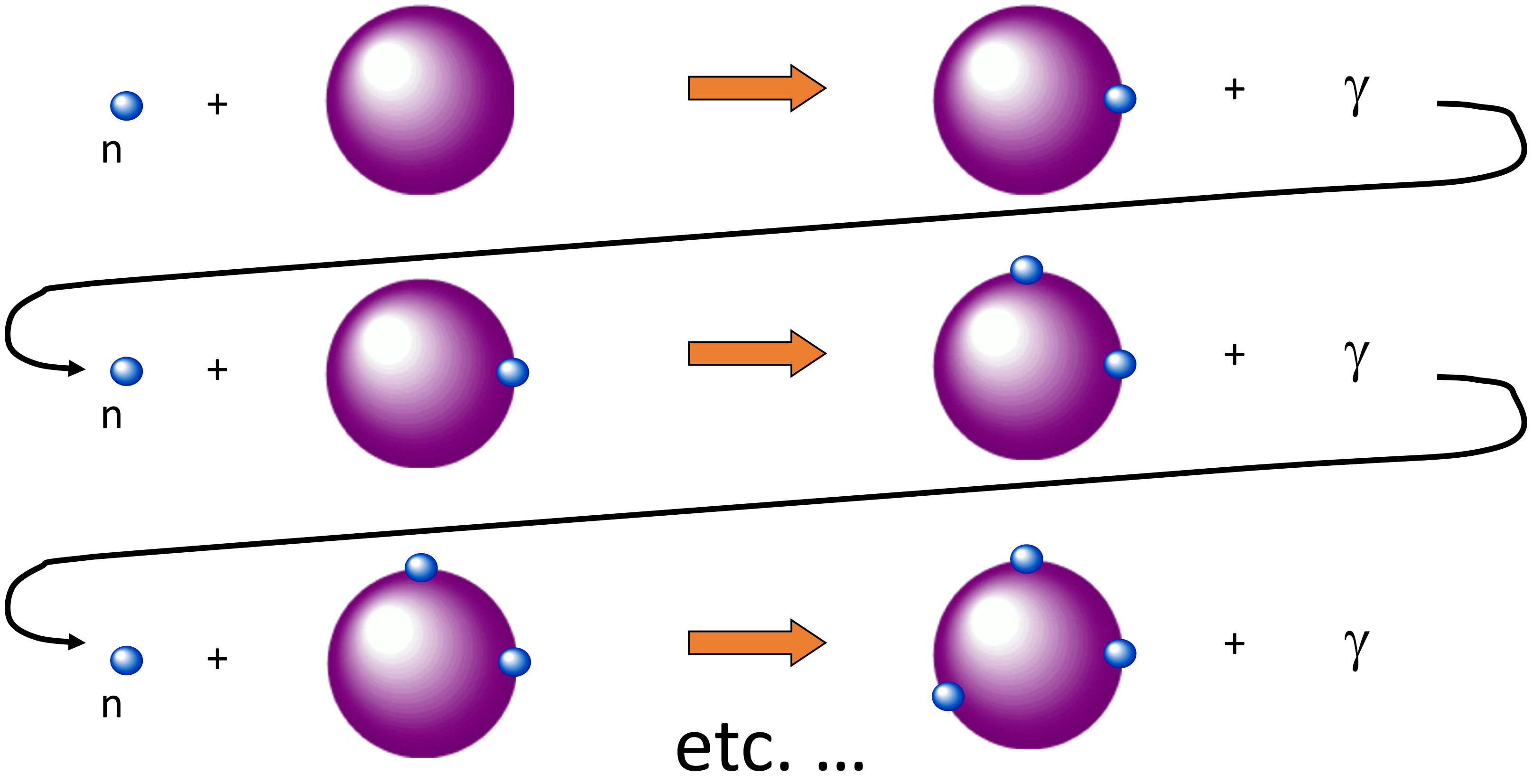
we like Gold.

This event made between 3 and 13 M_{earths} of it.

B. P. Abbott et al., PRL **119**, 161101 (2017)

"*r*-process" nucleo-synthesis

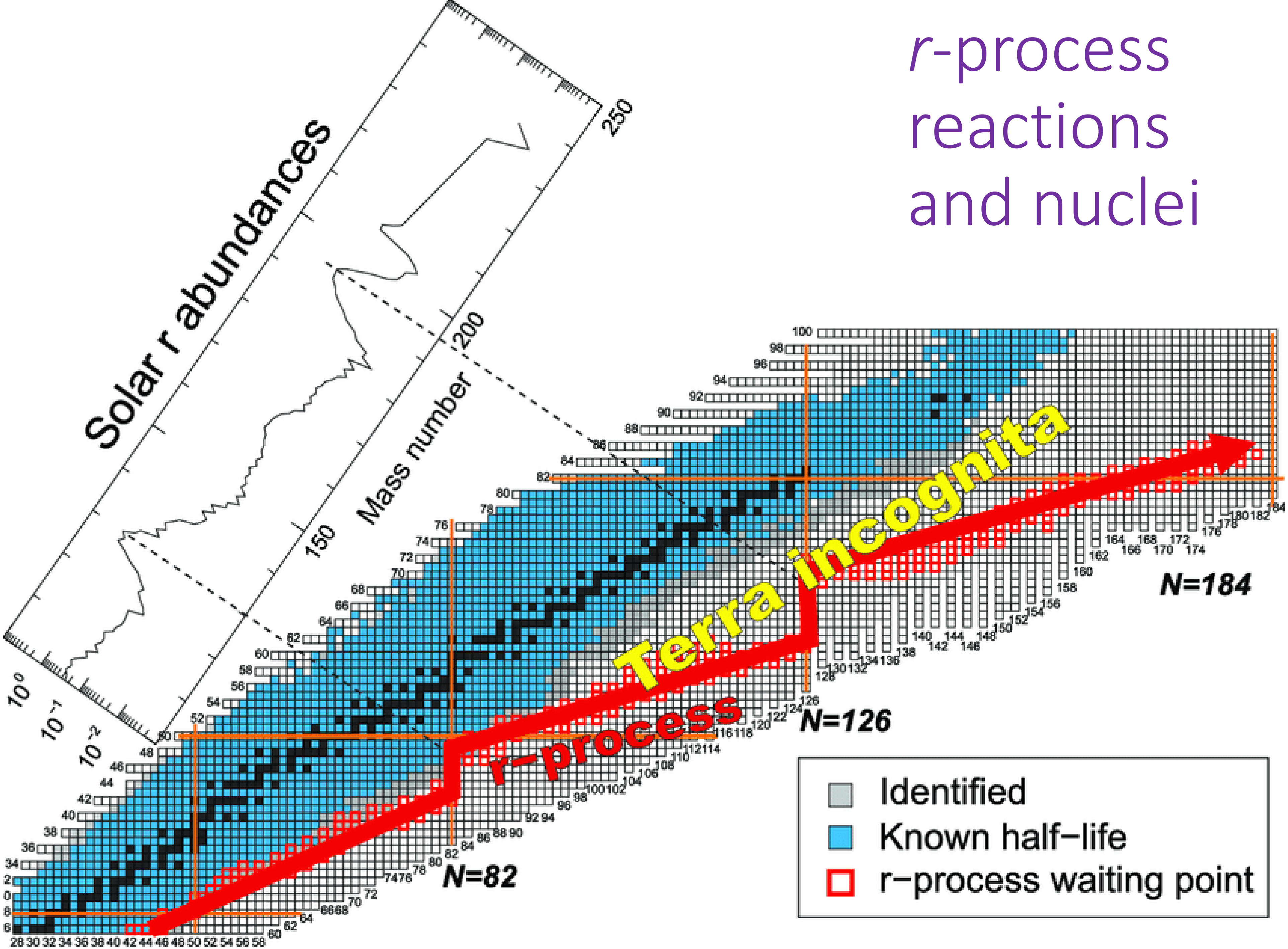
"*r*" – *r*apid neutron capture



$$\sigma_{DC}(E1) \propto \frac{k_\gamma^3}{k^2} \times \boldsymbol{S_n} \times \int u_l(r)\chi(r)r\,dr$$

From (*d*,*p*) reactions

r-process reactions and nuclei



Conclusions

- Many new topics of interest sound old, but…
- Our understanding has evolved a great deal and nuclear physics far from stability reveals many behaviors that are different from those near stability
- That evolution is crucial for understanding closely related topics such as nuclear astrophysics