Dark matter effect on the neutron star equation of state

The 22nd CNS International Summer School (A3F-CNSSS23)

7th Aug. 2023, Nishina Hall, RIKEN

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collaborator : Prof. Myung-Ki Cheoun

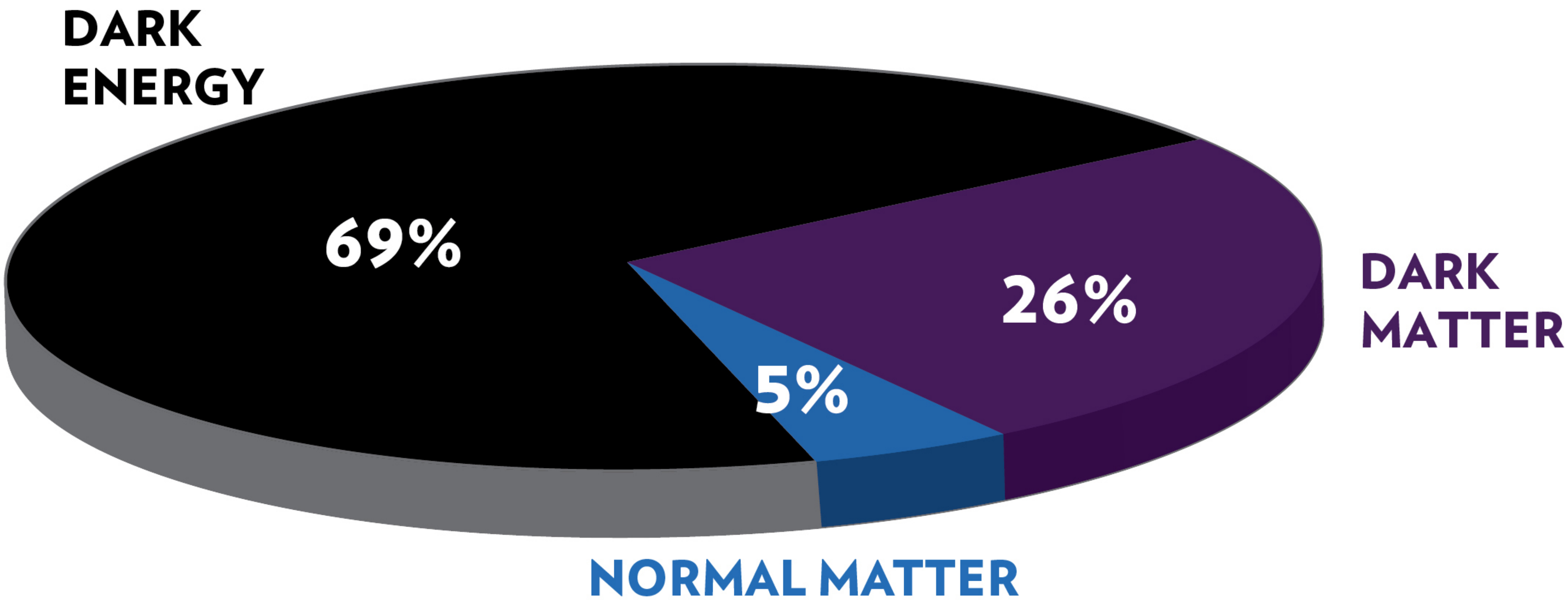
References: 1. JCAP10(2021)086 (ArXiv ePrint: 2104.01540), Wasif Husain and A. W. Thomas
https://doi.org/10.1088/1475-7516/2021/10/086
2. PRD 96, 083004 (2017), Grigorios Panotopoulos and Ilidio Lopes
3. ``THE RELATIVISTIC NUCLEAR MANY-BODY PROBLEM ", Brian D. Serot and John Dirk Walecka

Content

- Brief introduction about the dark matter and Higgs particle
- Model setup – in particular, Higgs and fermionic dark matter
- Equation of State(EOS) of hadronic matter without dark matter
- EOS with dark matter
- M versus R
- Conclusion

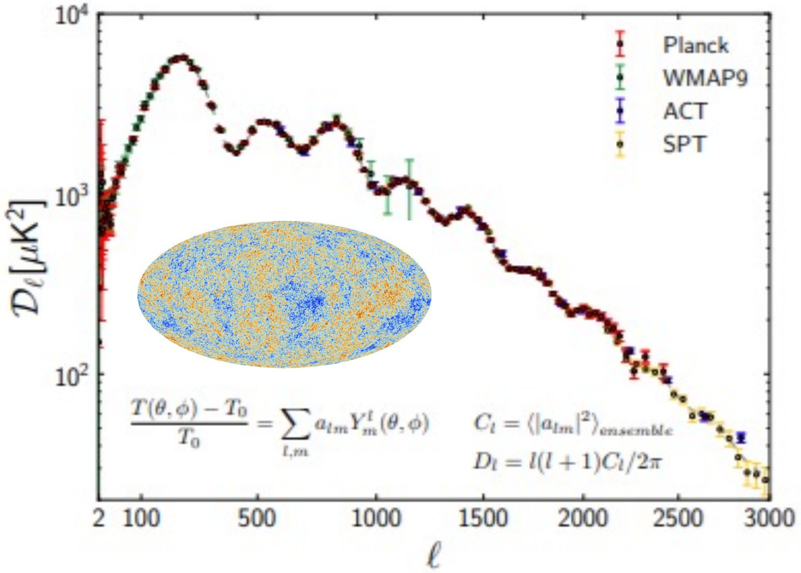
https://chandra.harvard.edu/resources/illustrations/darkmatter.html

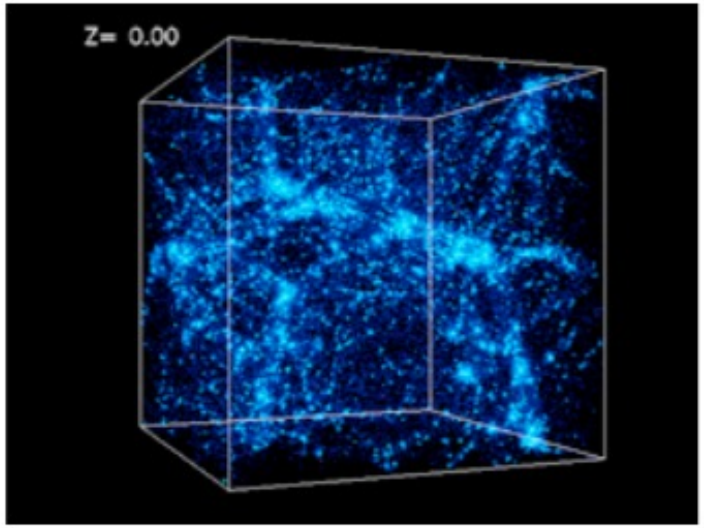
ENERGY DISTRIBUTION OF THE UNIVERSE

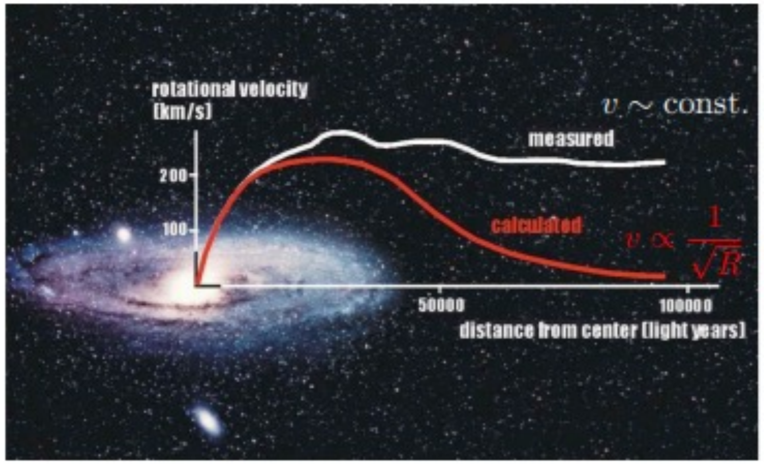


Why do we need the dark matter ?

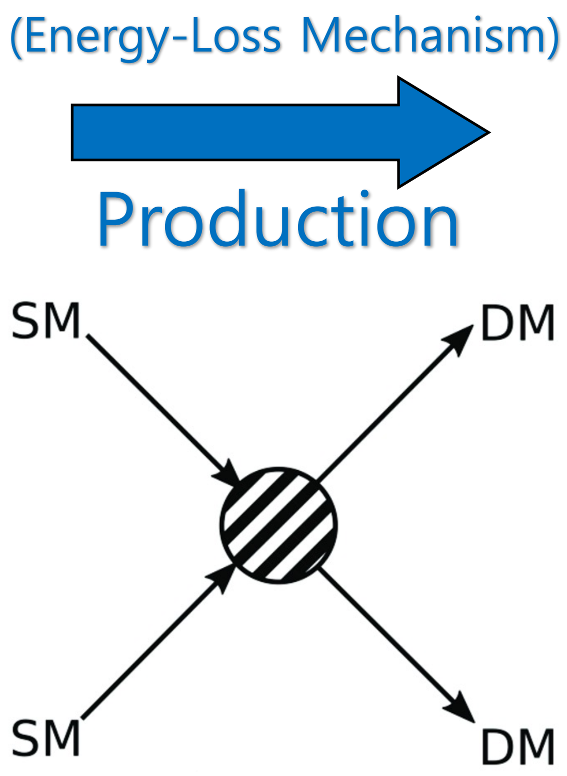
- Dark Matter in the CMB temperature perturbation

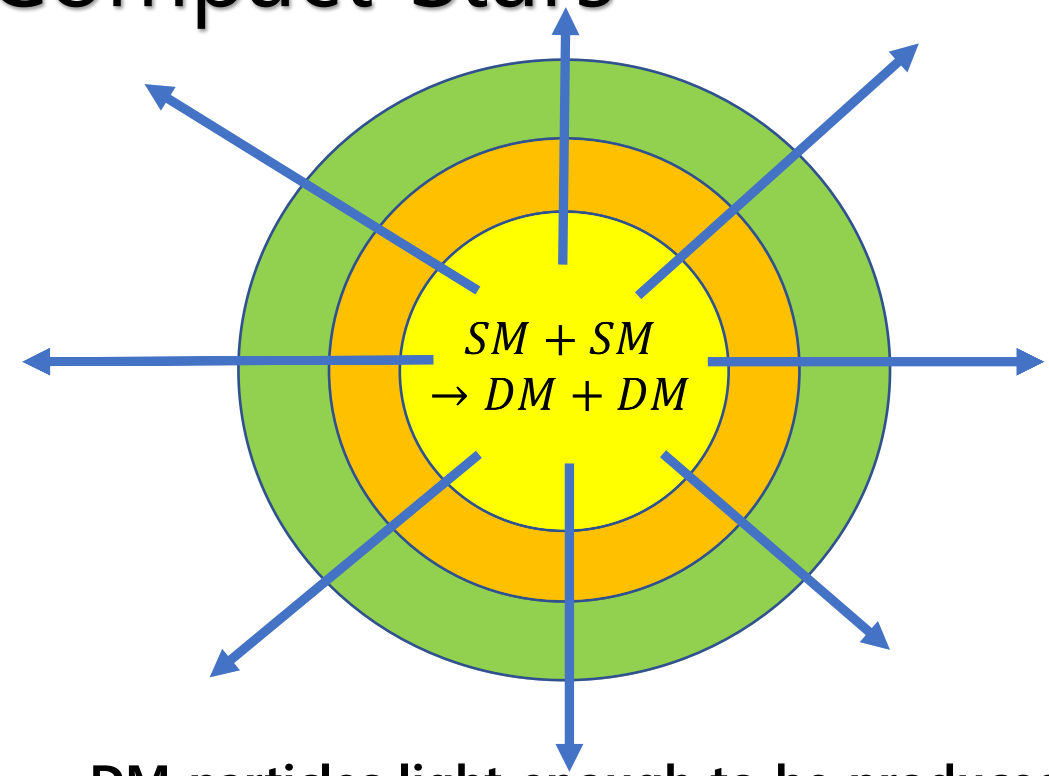






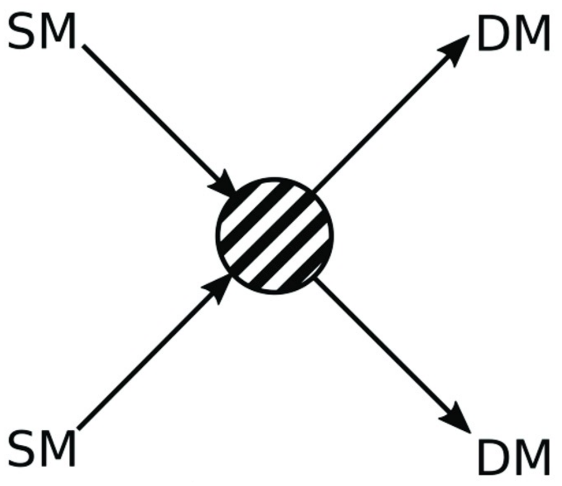
Dark Matter Effects inside Compact Stars





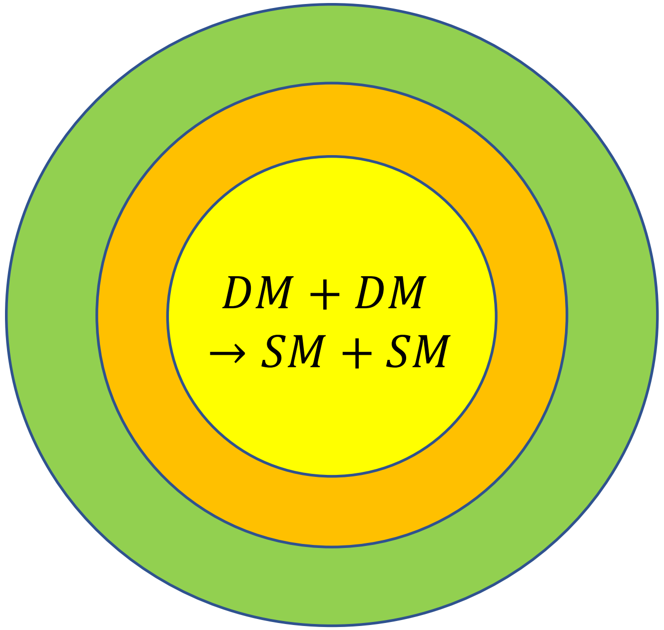
DM particles light enough to be produced in collisional processes inside stars, with typically temperatures in the keV,
or supernovae, with energy scales in the MeV,
lead to an additional energy-loss mechanism, if capable of escaping the system.

Dark Matter Effects inside Compact Stars



Annihilation

(Energy-Production Mechanism)



DM annihilation can even have fueled early stages of stellar evolution, perhaps with measurable consequences

Higgs particle in the Standard Model (SM)

- Higgs field (h) : responsible for
  ① the spontaneous EW symmetry breaking
  ② the generation of masses of all the SM particle

- The potential is characterized by **only two parameters** :
  ① **vacuum expectation value** v
  ② **the Higgs mass** m_H

$$v = \frac{1}{\sqrt{\sqrt{2}\, G_F}} \approx 246 \text{ GeV} \qquad V_{SM}(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

Higgs trilinear and quartic self-coupling

$$\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2\,v^2}$$

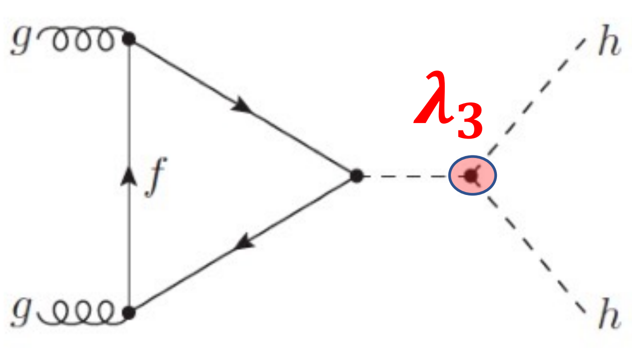
New Physics can affect the Higgs potential form

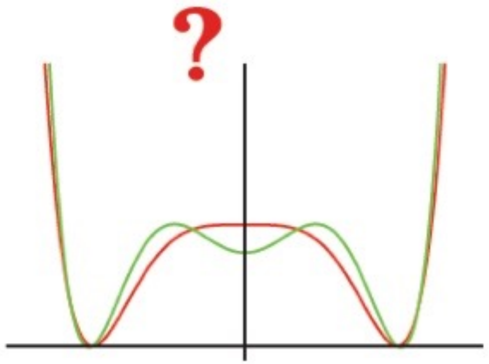
$\Longrightarrow$ Sizeable departures from the SM form

$\Longrightarrow$ $\lambda_3 = \lambda_3^{SM} + \delta\lambda_3^{SM}$, $\lambda_4 = \lambda_4^{SM} + \delta\lambda_4^{SM}$

Measuring the Higgs self coupling

Examine the Higgs potential





$$\lambda_3 = \lambda_3^{SM} + \delta\lambda_3^{SM}$$

Model setup

- Relativistic Mean Field Model (called Quantum Hydrodynamic s, QHDI)

$$\mathcal{L}_{\text{had}} = \bar{\psi}(i\gamma_\mu \partial^\mu - m_N + g_s\phi + g_v\gamma^\mu V_\mu)\psi + \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_s^2\phi^2) - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_\omega V_\mu V^\mu$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

$$m_s = 520 \text{ MeV}$$

$$m_\omega = 783 \text{ MeV}$$

$$g_s^2 = 109.6$$

$$g_v^2 = 190.4$$

$$m_N \simeq 1 \text{ GeV}$$

Higgs coupling and fermionic dark matter

$$\mathcal{L} = \mathcal{L}_{\text{had}} + \bar{\chi}(i\gamma_\mu\partial^\mu - M + yh)\chi + \frac{1}{2}\partial_\mu h\partial^\mu h - V(h) + \frac{f m_N}{v}\bar{\psi}h\psi$$

Fermionic dark matter

a DM mass $M = 200$ GeV

$M_h = 125$ GeV

A nucleon-Higgs Yukawa coupling y ~ f m_N / v, with v = 246 GeV is the Higgs vacuum expectation value and f parameterizes the Higgs-nucleon coupling.

Following the lattice computations [33]~[35], we shall consider the central value f ~ 0.3 in agreement with Ref. [32].

[32] J. M. Cline, K. Kainulainen, P. Scott, and C. Weniger, Phys. Rev. D **88**, 055025 (2013); **92**, 039906(E) (2015).

[33] J. M. Alarcon, J. Martin Camalich, and J. A. Oller, Ann. Phys. (Berlin) **336**, 413 (2013).

[34] R. D. Young, *Proc. Sci.*, LATTICE2012 (2012) 014, arXiv:1301.1765.

[35] L. Alvarez-Ruso, T. Ledwig, J. Martin Camalich, and M. J. Vicente-Vacas, Phys. Rev. D **88**, 054507 (2013).

Equation of State(EOS) of hadronic matter without dark matter

Effective mass via the interaction of scalar meson

$$m_* = m_N - g_s\phi_0$$

After taking the mean fields of two mesons

$$V_0 = \frac{g_v n}{m_\omega^2} \qquad n = \frac{k_F^3}{3\pi^2}$$

$$\phi_0 = \frac{g_s n_s(m_*)}{m_s^2} \qquad n_s = \frac{\partial \epsilon_{st}(m_*)}{\partial m_*} = \frac{2}{(2\pi)^3}\int_0^{k_F} d^3\vec{k}\,\frac{m_*}{\sqrt{k^2+m_*^2}}$$

to be useful later on, and it is given by

$$n_s = \frac{m_*^3}{2\pi^2}\left[x_F\sqrt{1+x_F^2} - ln\left(x_F + \sqrt{1+x_F^2}\right)\right]$$

$$\epsilon_{st} = \frac{2}{(2\pi)^3}\int_0^{k_F} d^3\vec{k}\,\sqrt{k^2+m_*^2}$$

$$p_{st} = \frac{1}{3}\frac{2}{(2\pi)^3}\int_0^{k_F} d^3\vec{k}\,\frac{k^2}{\sqrt{k^2+m_*^2}}$$

$$\epsilon_{st} = \frac{m_*^4}{8\pi^2}((x_F + 2x_F^3)\sqrt{1+x_F^2} - \sin h^{-1}(x_F))$$

$$p_{st} = \frac{m_*^4}{24\pi^2}((-3x_F + 2x_F^3)\sqrt{1+x_F^2} + 3\sin h^{-1}(x_F))$$

where we have defined $x_F = k_F/m_*$.

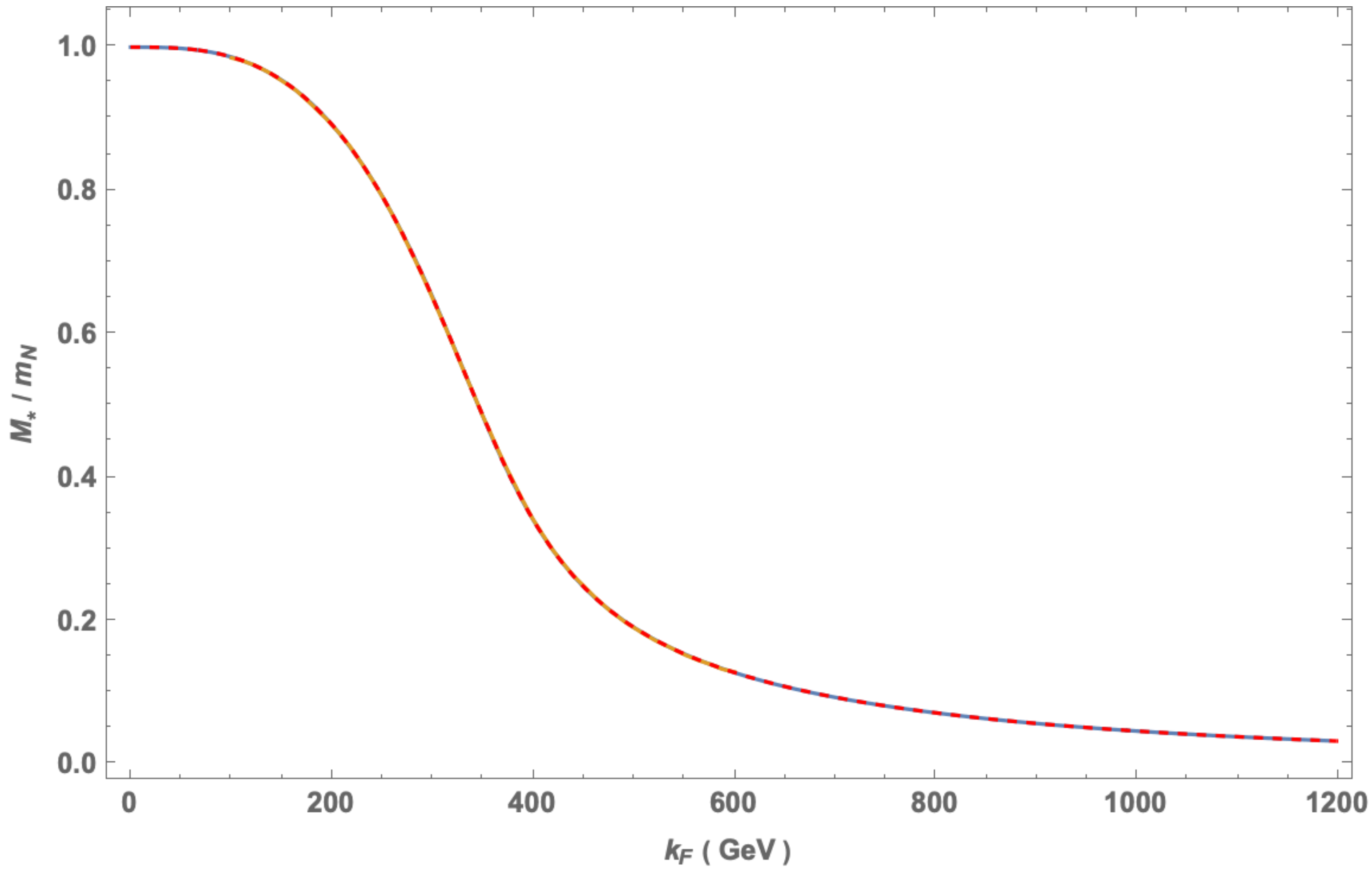


FIG. 1 Neutron effective mass versus wave number (in GeV) without dark matter in the σ − ω model.

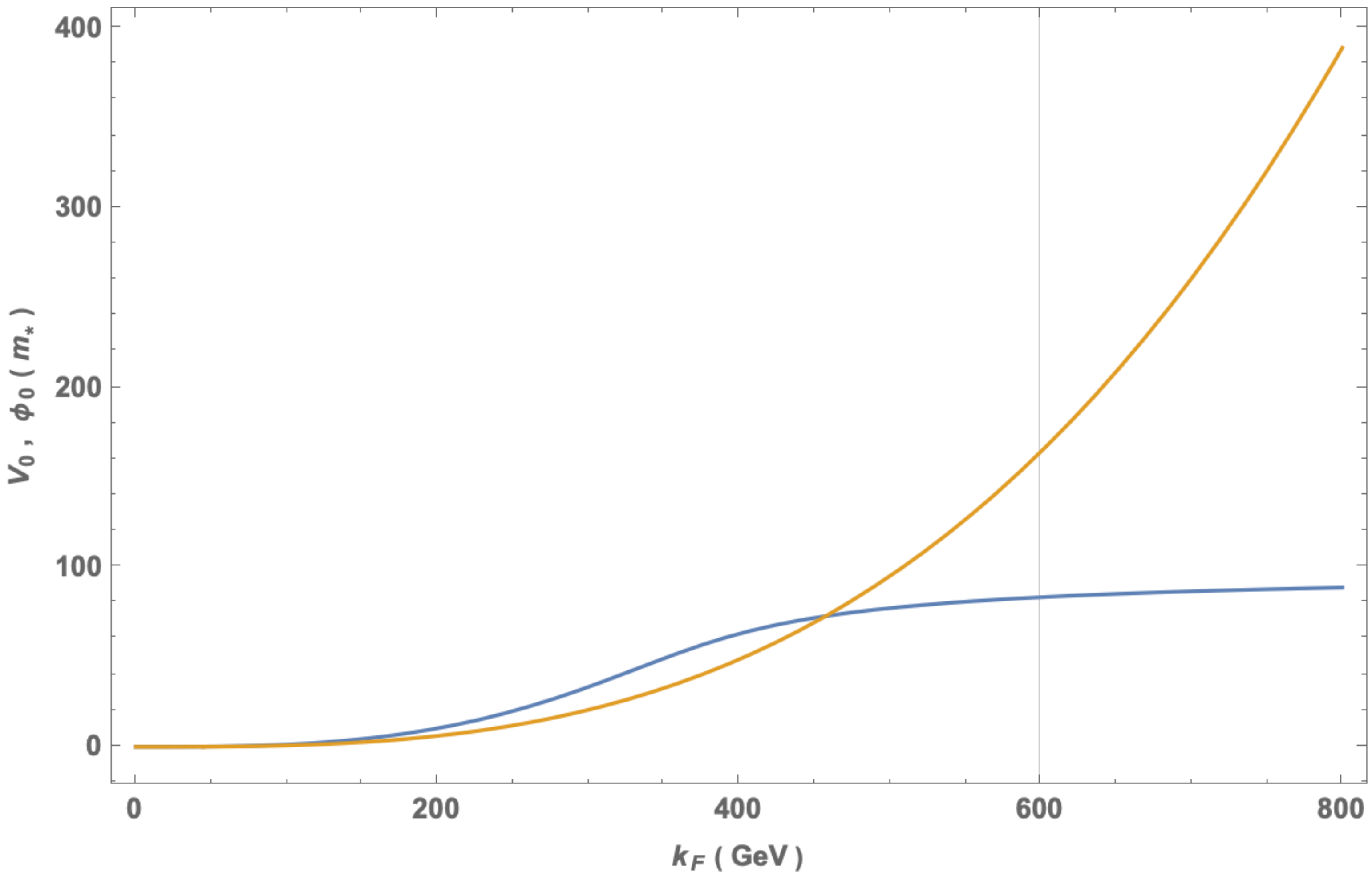


FIG. 2 vector and scalar mean fields versus wave number (in GeV) without dark matter in the σ − ω model.

EOS without dark matter

Depending on the values of the parameters the DM-Higgs coupling takes values in the range 0.001–0.1, and in the following we shall adopt the value $y \sim 0.07$.

We also assume that inside the neutron star the DM average number density is ∼1000 times smaller than the average neutron number density, which implies a DM mass fraction MDM=M ≃ 1=6 ≃ 0.17 [18], with M being the mass of the star.

[18] X. Li, F. Wang, and K. S. Cheng, J. Cosmol. Astropart. Phys. 10 (2012) 031.

Applying the mean-field approximation to this model, the system looks like an ideal Fermi gas consisting of two noninteracting fermions with effective masses

$$m_*^n = m_N - g_s\phi_0 - fh_0$$

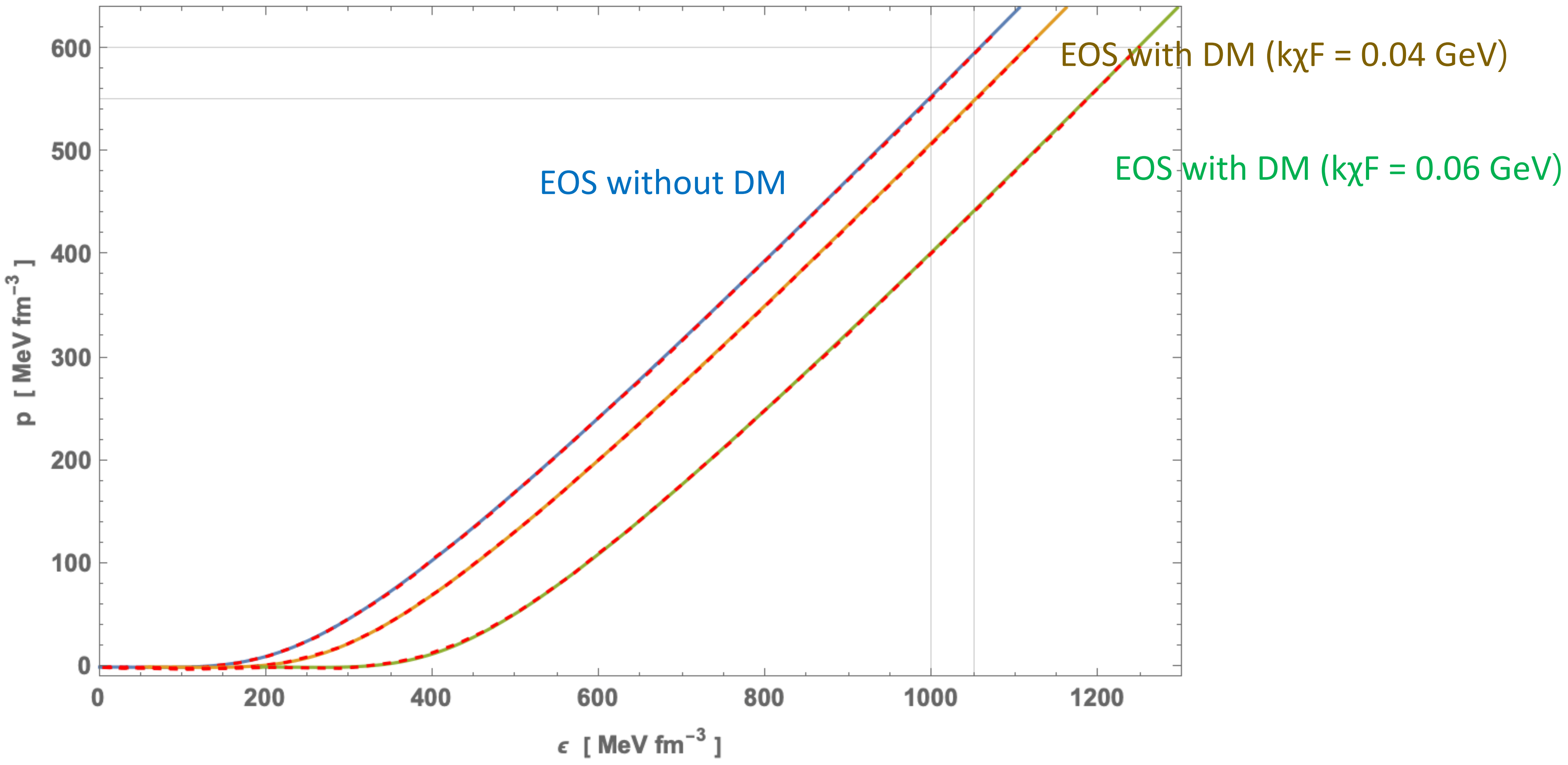
$$M_*^\chi = M - yh_0$$

$$h_0 = \frac{fn_s(m_*^n) + yn_s(M_*^\chi)}{M_h^2}$$

$$\phi_0 = \frac{g_s n_s(m_*^n)}{m_s^2}.$$

$$p = p_{st}(m_*^n) + p_{st}(M_*^\chi) - \frac{m_s^2\phi_0^2}{2} + \frac{m_\omega^2 V_0^2}{2} - \frac{M_h^2 h_0^2}{2}$$

$$\epsilon = \epsilon_{st}(m_*^n) + \epsilon_{st}(M_*^\chi) + \frac{m_s^2\phi_0^2}{2} + \frac{m_\omega^2 V_0^2}{2} + \frac{M_h^2 h_0^2}{2}$$



TOV equation and R versus M diagram

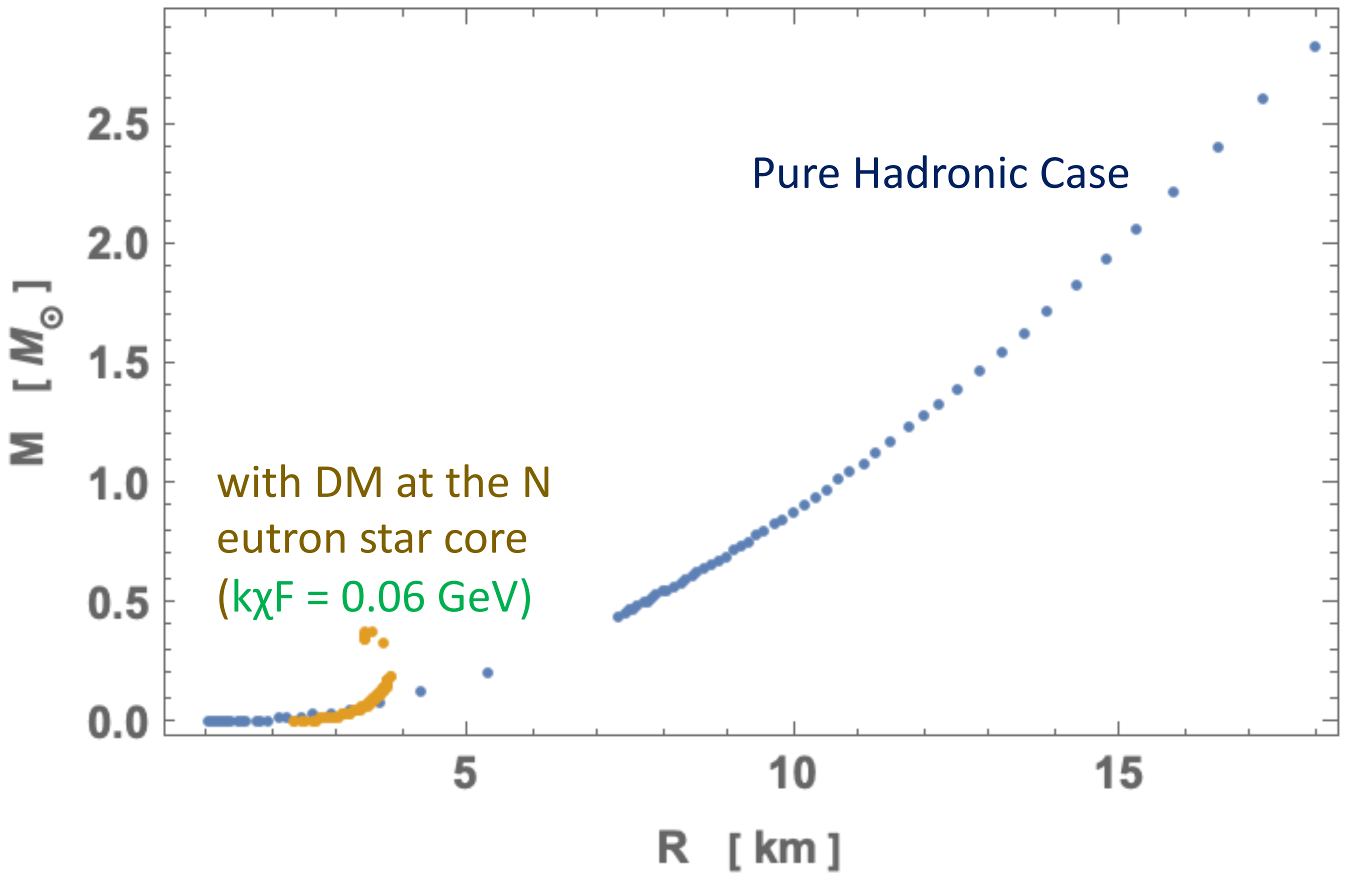
TOV equation :

$$m'(r) = 4\pi r^2 \epsilon(r)$$

$$p'(r) = -(\epsilon(r) + p(r)) \frac{m(r) + 4\pi p(r) r^3}{r^2(1 - 2m(r)/r)}$$

With these two initial conditions :

$$m(r=0) = 0, p(r=0) = p_c,$$



Conclusion

- We choose the simplest model (QHD-I) and introduce the Higgs and dark matter captured inside the neutron star.
- We calculate the EOSs w/wo the dark matter.
- We find that the dark matters at the neutron star core can make the EOS soft !
- We consider TOV equation including the relativistic corrections, and show the R vs. M relations w/wo the dark matter
- We are trying to check more the interesting and important effect of dark matter depending on the (relaxed) parameter spaces !

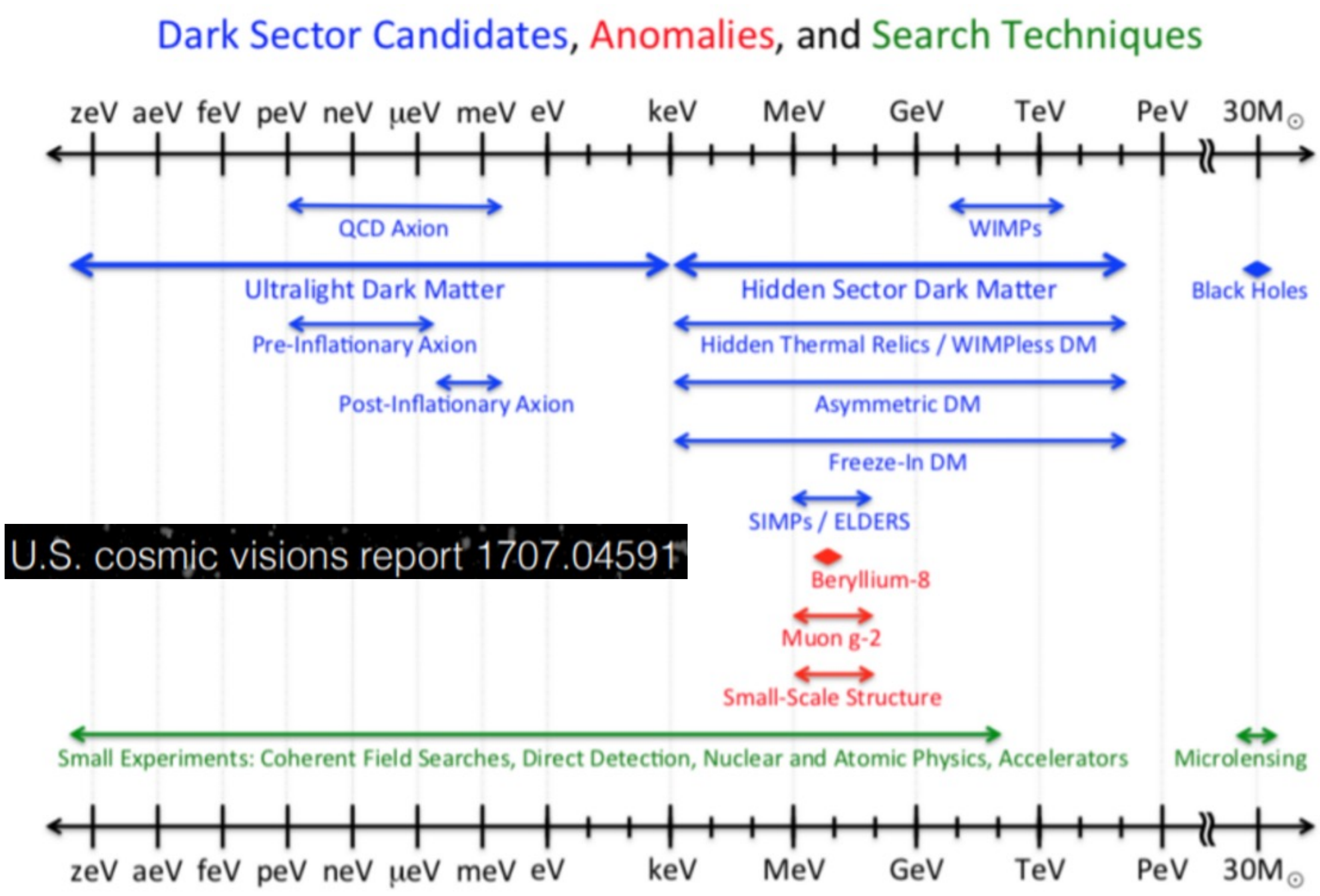
Thank you for your attention !!

ありがとうございます。

Others….

We will try to consider the self coupling of the Higgs boson, and extract some constraints(?) from the neutron star physics.

암흑물질 후보군

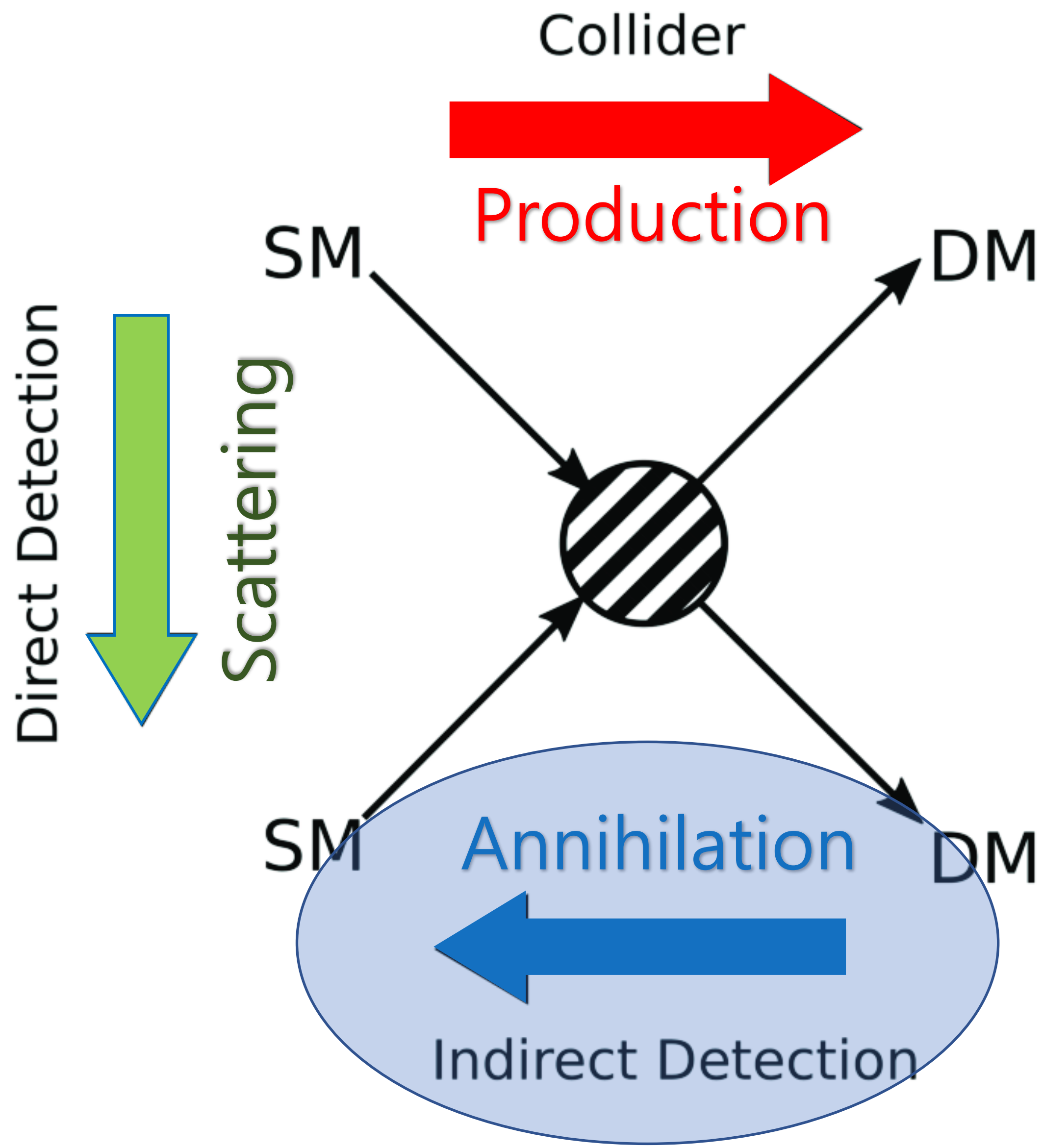


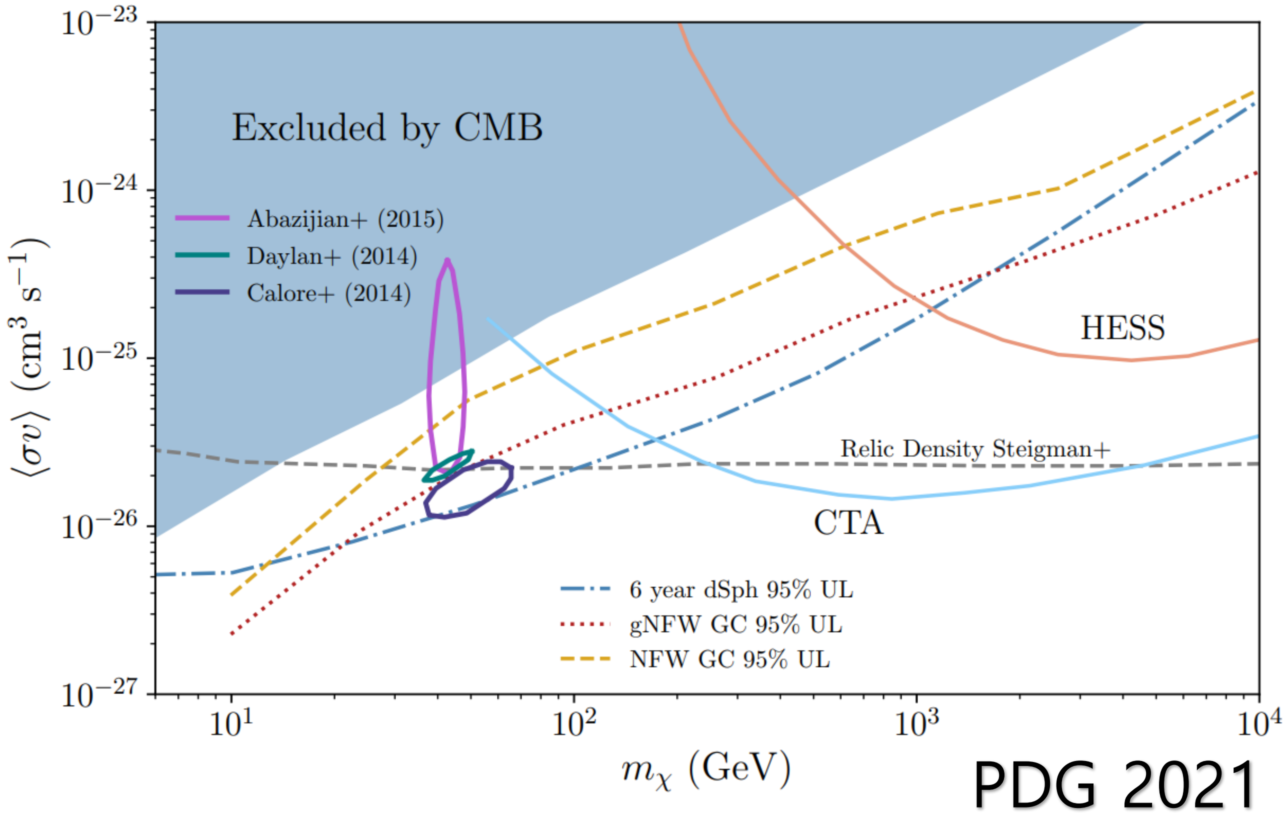
https://ko.wikipedia.org/wiki/암흑물질

일부 암흑물질 가설[86]

가벼운 보손	양자 색역학 액시온
	액시온 같은 입자
	퍼지 차가운 암흑물질(fuzzy cold dark matter)
중성미자	표준 모형
	비활성 중성미자
약작용 스케일(weak scale)	초대칭
	추가 차원
	작은 힉스(little Higgs)
	유효 이론
	단순화 모형
다른 입자들	약하게 상호작용하는 무거운 입자 (WIMP)
	자체 상호작용하는 암흑물질(Self-interacting dark matter)
	기묘체[87] Strangelet
초유체 진공 이론 (superfluid vacuum theory	
동적 암흑물질 (Dynamical Dark Matter)	
거시적	원시 블랙홀[88][89][90][91][92][93][94]
	거대하고 조밀한 헤일로 물체 (MaCHOs)
	거시적 암흑물질 (Macros)
일반 상대성이론의 대안 (MOG)	수정 뉴턴 역학 (MOND)
	텐서–벡터–스칼라 중력 (TeVeS)
	엔트로피 중력(entropic gravity)

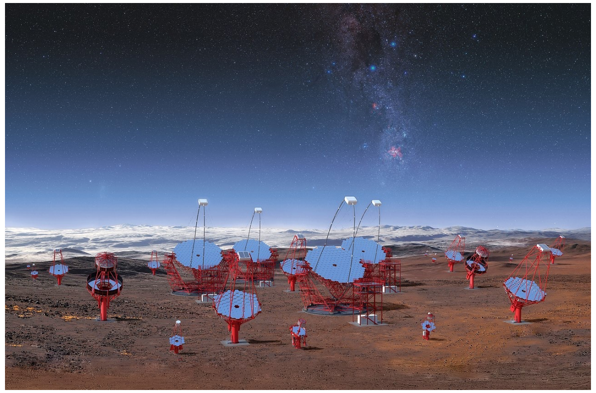
암흑물질 탐색





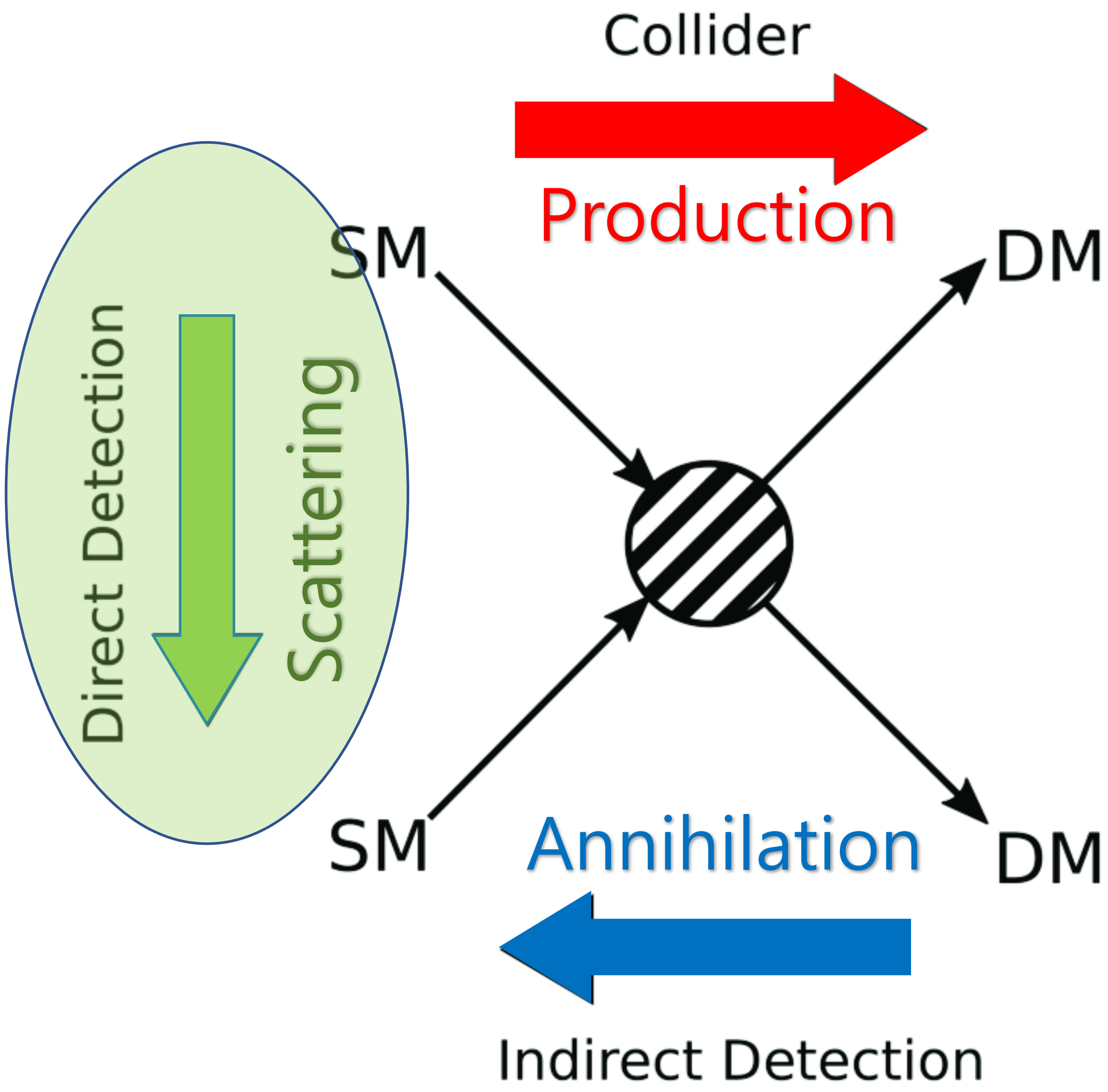
PDG 2021

Figure27.2: Upper limits and projected sensitivity from CTA(Cherenkov Telescope Array) on the pair-annihilation rate versus the DM mass from gamma-ray and CMB observations (figure courtesy of Logan Morrison).



https://en.wikipedia.org/wiki/Cherenkov_Telescope_Array#/media/File:CTA_Telescopes_in_Southern_Hemisphere.jpg

암흑물질 탐색



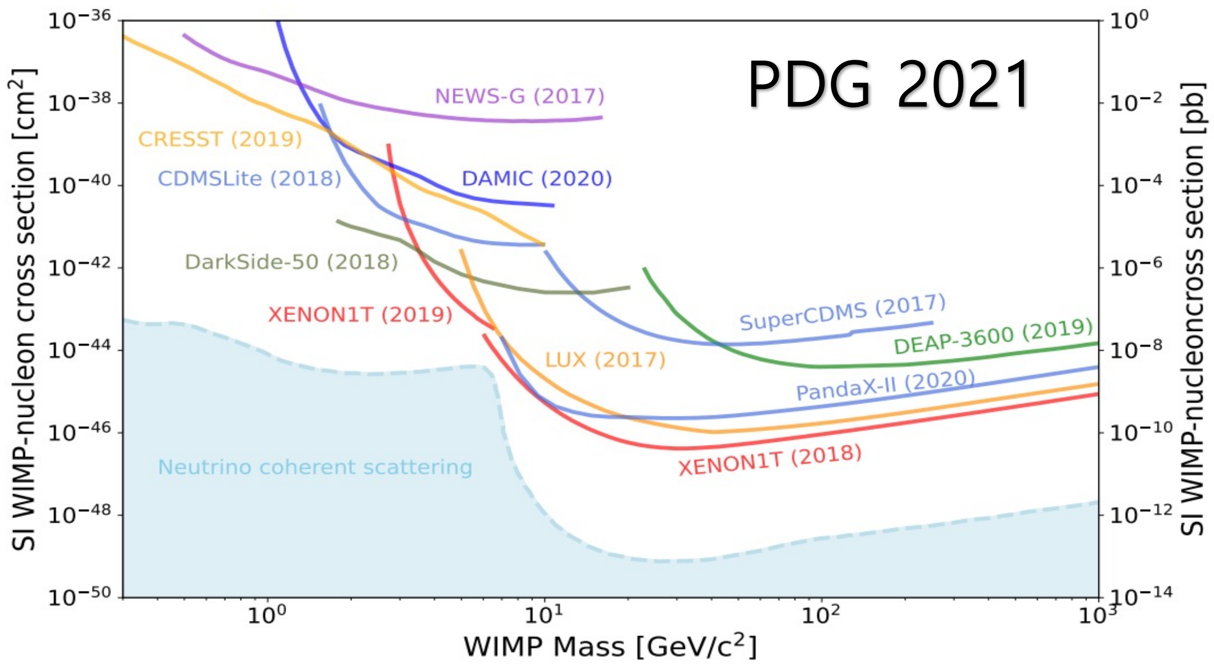
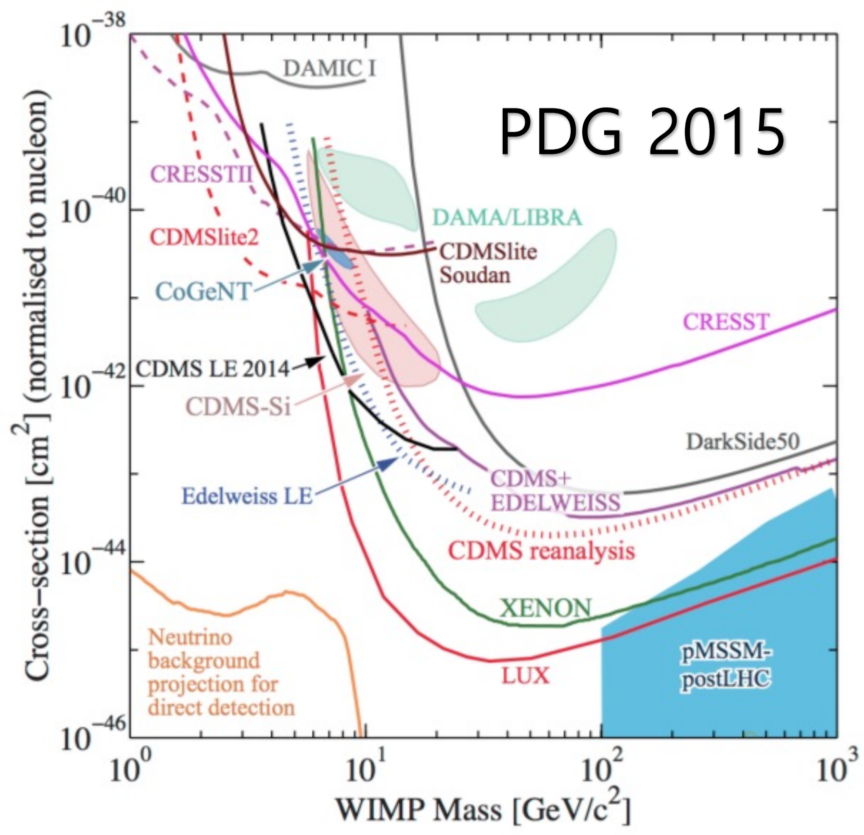
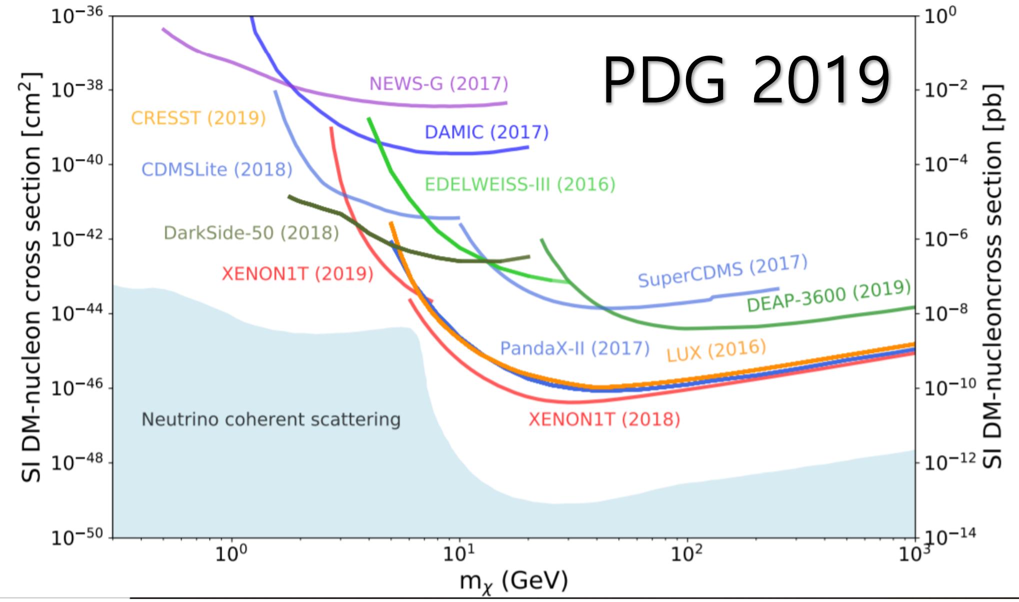
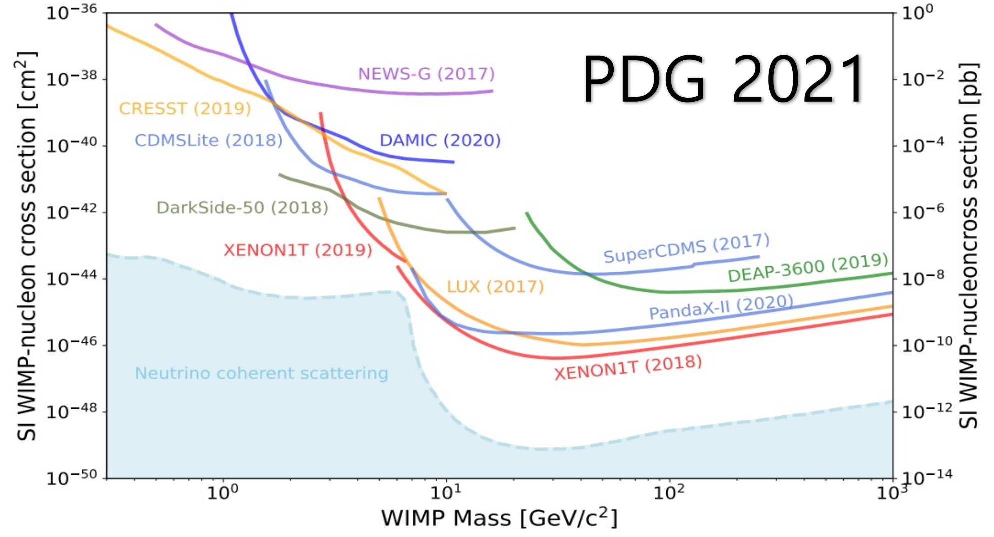


Figure 27.1: Upper limits on the SI DM-nucleon cross section as a function of DM mass.







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