NCTS Annual Meeting 2019, Hsinchu, Taiwan
Yen-Hsun Lin (林彥勳)
Institute of Physics, Academia Sinica

Probing the isospin violation of self-interacting dark matter through old neutron stars

Outline

- **Part I:**

  Motivation for introducing dark matter (DM) self-interaction

- **Part II:**
  - Neutron star (NS) capture of isospin violation DM
  - Black hole (BH) formation in the NS

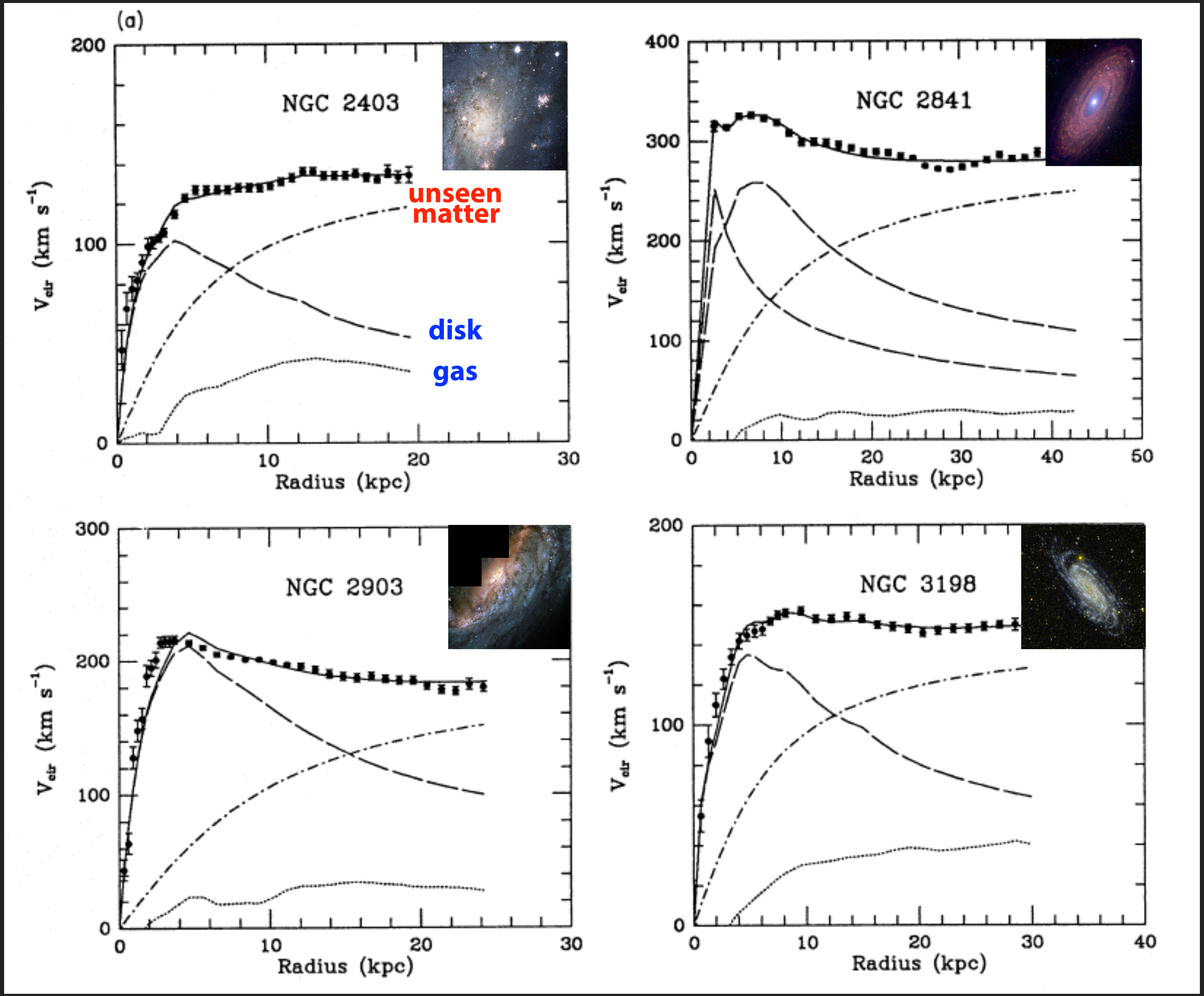
- **Part III:**

  NS sensitivities on DM-baryon cross section and isospin violation

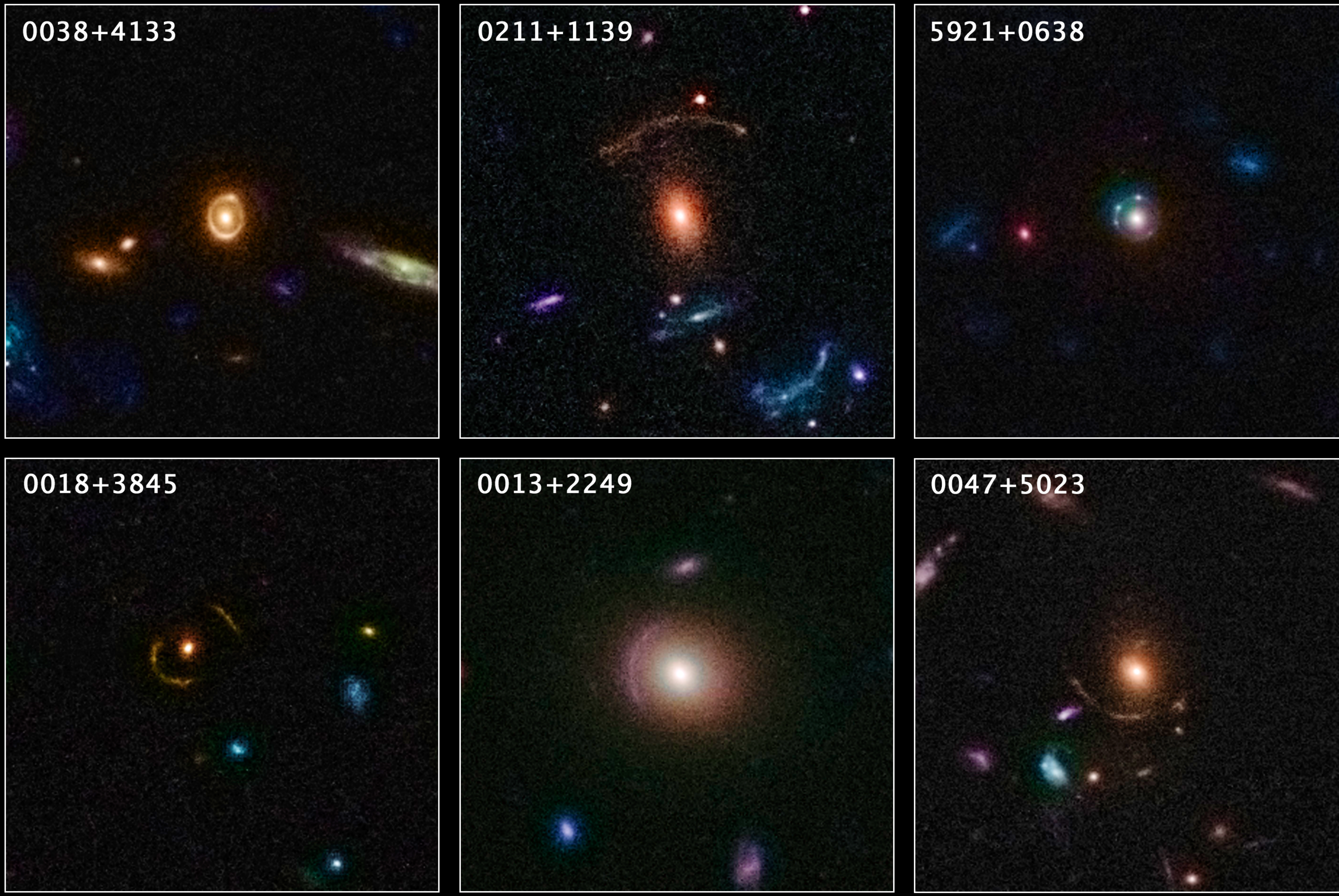
- **Summary**

Part I

DM in the Universe



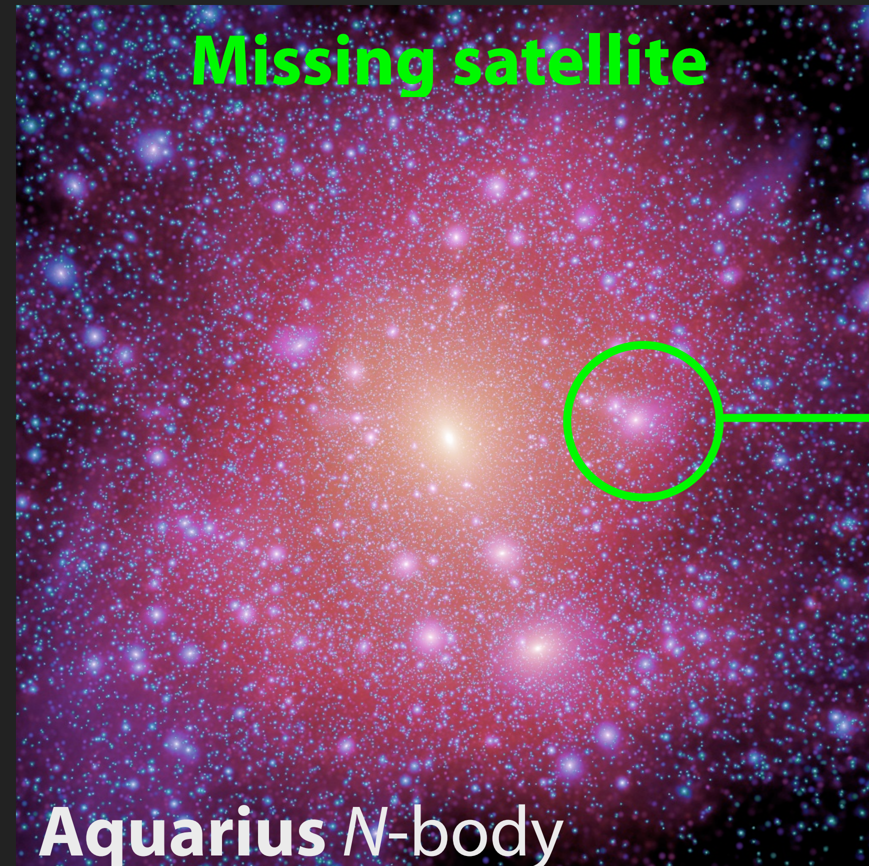
K. G. Begeman *et al., MNRAS* **249**, 523 (1991)



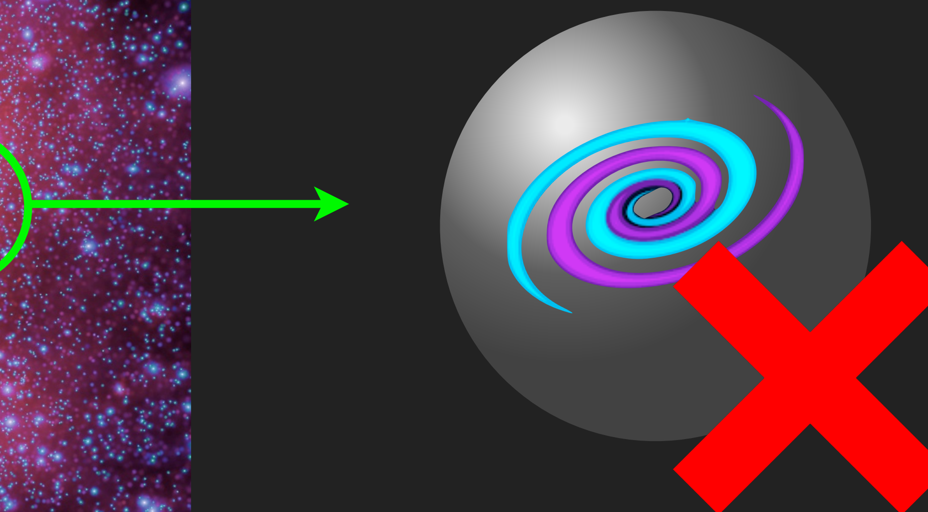
Gravitational Lenses in the COSMOS Survey
Hubble Space Telescope ▪ ACS/WFC

NASA, ESA, C. Faure (Zentrum für Astronomie, University of Heidelberg) and J.-P. Kneib (Laboratoire d'Astrophysique de Marseille)

STScI-PRC08-09

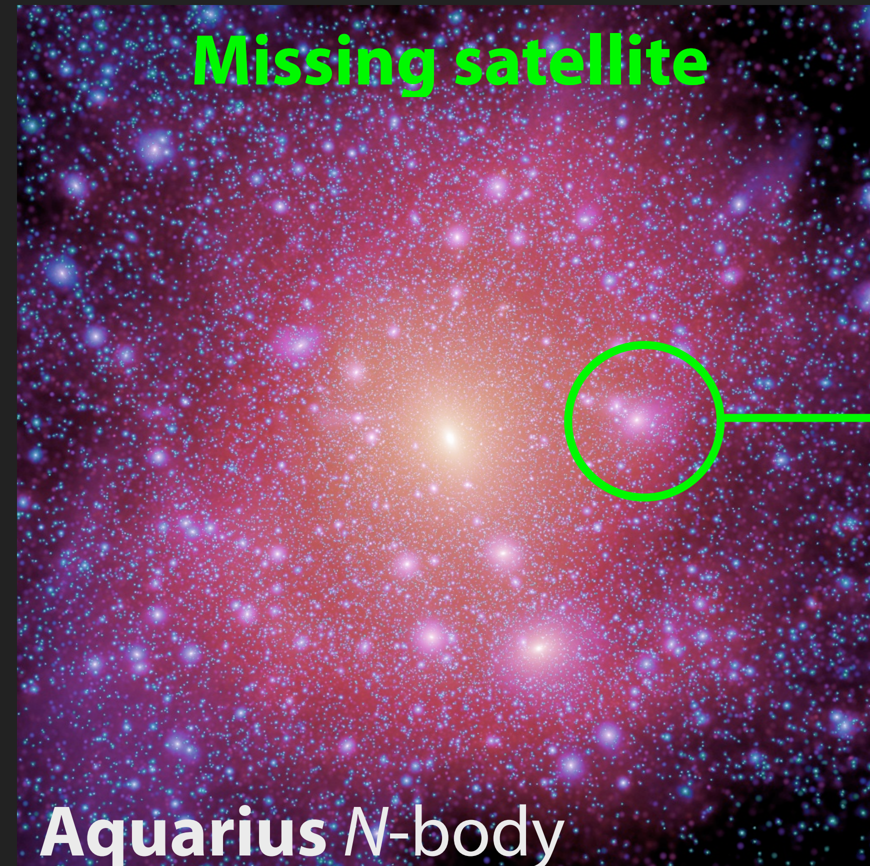


Too-big-to-fail



We didn’t see any satellite as massive as predicted by the *N*-body sim.

J. S. Bullock *et al.*, *Ann. Rev. Astron. Astrophys.* **55**, 343 (2017)
S. Tulin *et al.*, *Phys. Rept.* **730**, 1 (2018)



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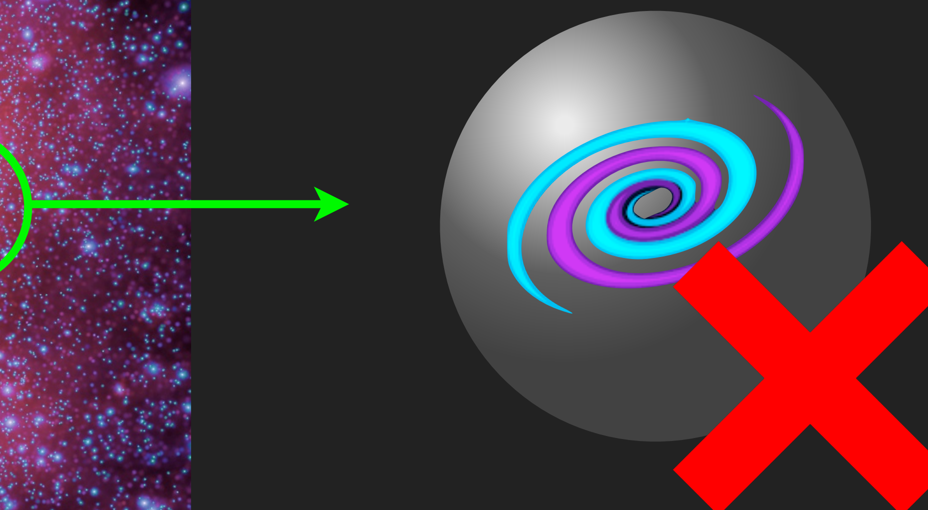

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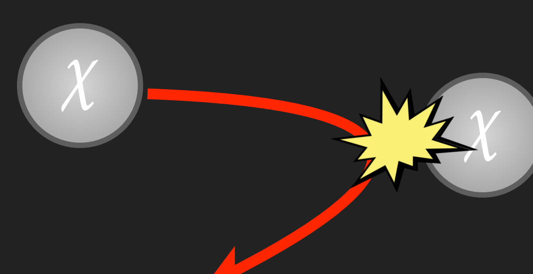
To alleviate these small-scale problem:

DM self-interaction is introduced

$$10^{-25}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}} \leq \frac{\sigma_{\chi\chi}}{m_\chi} \leq 10^{-23}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}}$$



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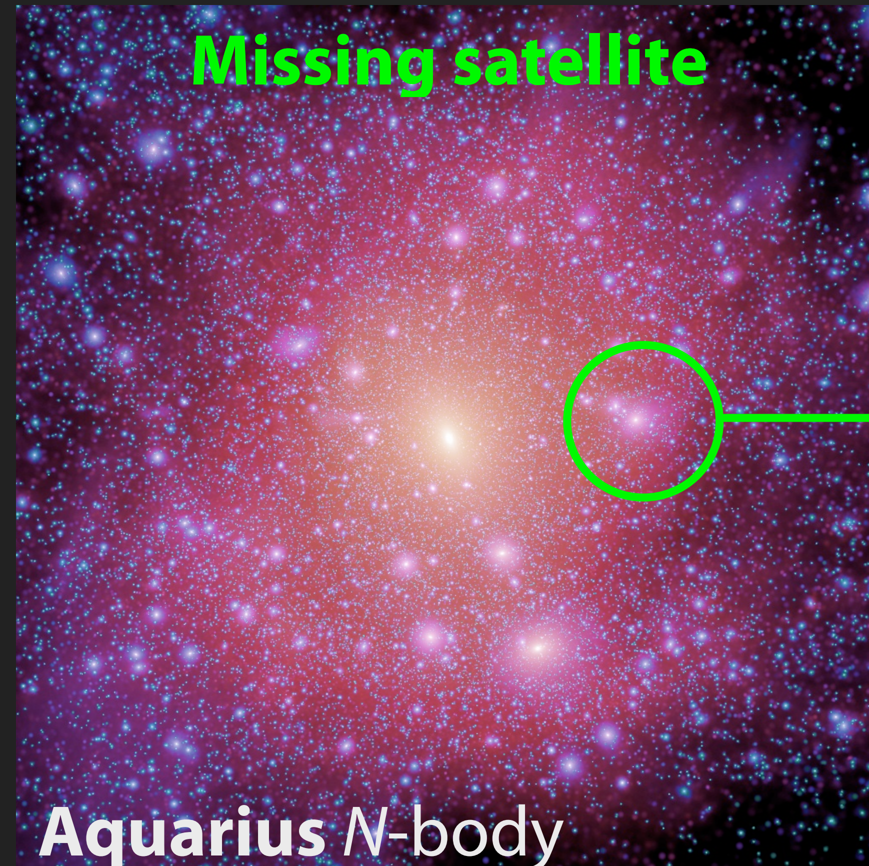

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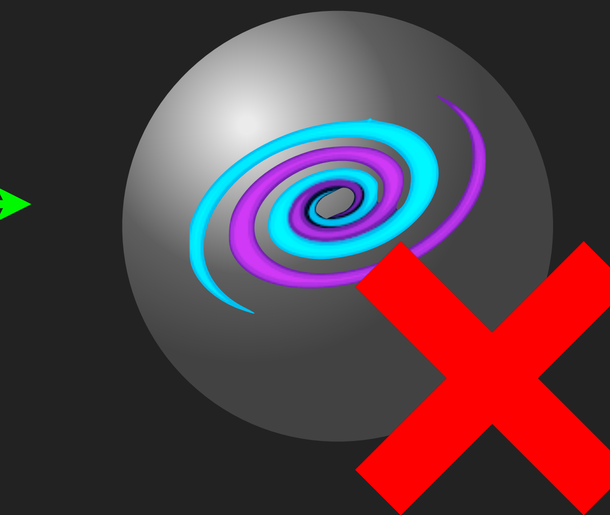

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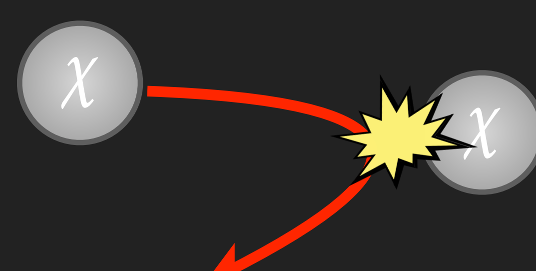
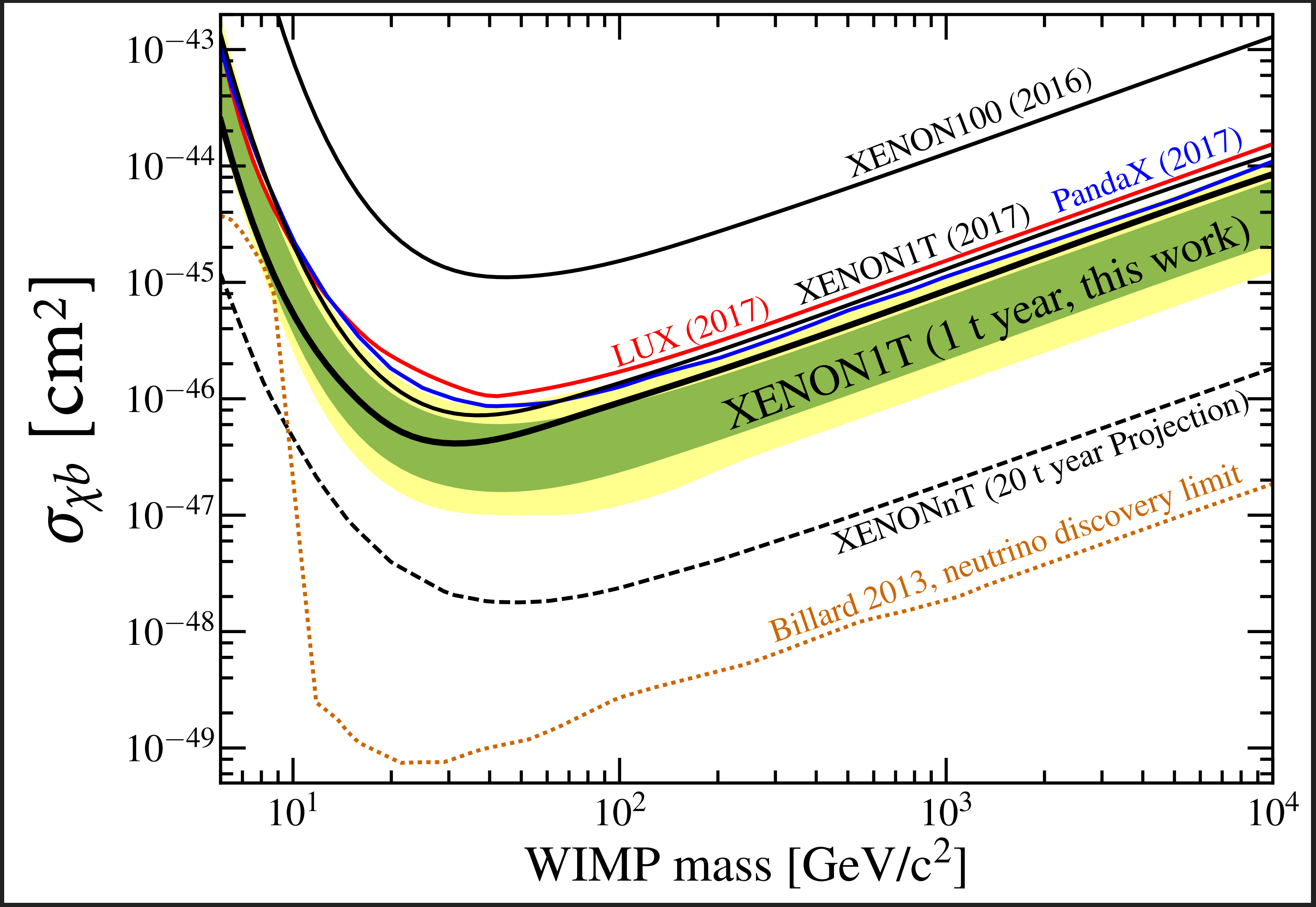


Assuming attractive Yukawa int.

$$V(r) = \alpha_\chi \frac{e^{-m_\phi r}}{r}$$

J. S. Bullock *et al.*, *Ann. Rev. Astron. Astrophys.* **55**, 343 (2017)
S. Tulin *et al.*, *Phys. Rept.* **730**, 1 (2018)

Constraints from DM direct searches

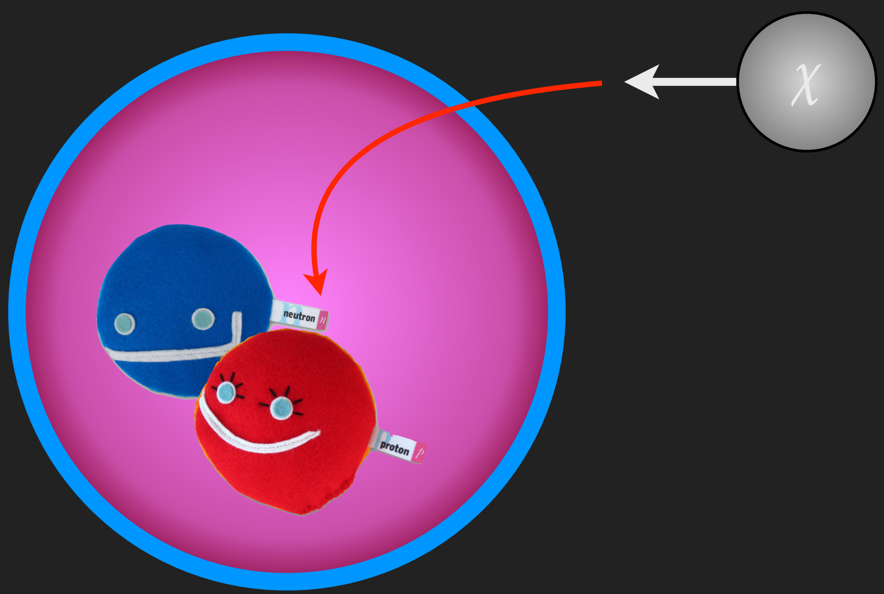


S. A. Malik *et al.*, *Phys. Dark Univ.* **9-10,** 51 (2015)
O. Buchmueller *et al.*, *JHEP* 01, **037** (2015)
J. Aalbers *et al.* [DARWIN], *JCAP* **11**, 017 (2016)
D. S. Akerib *et al.* [LUX] *PRL* **118**, 021303 (2017)
C. Amole *et al.* [PICO], *PRL* **118**, 251301 (2017)
E. Aprile *et al.* [XENON] *PRL* **119**, 181301 (2017)

Part II

DM captured by the neutron star

Capturing DM particles



NS capture rate C_c:
DM-baryon interaction $\sigma_{\chi b}$
$b = n, p$ for neutron and proton

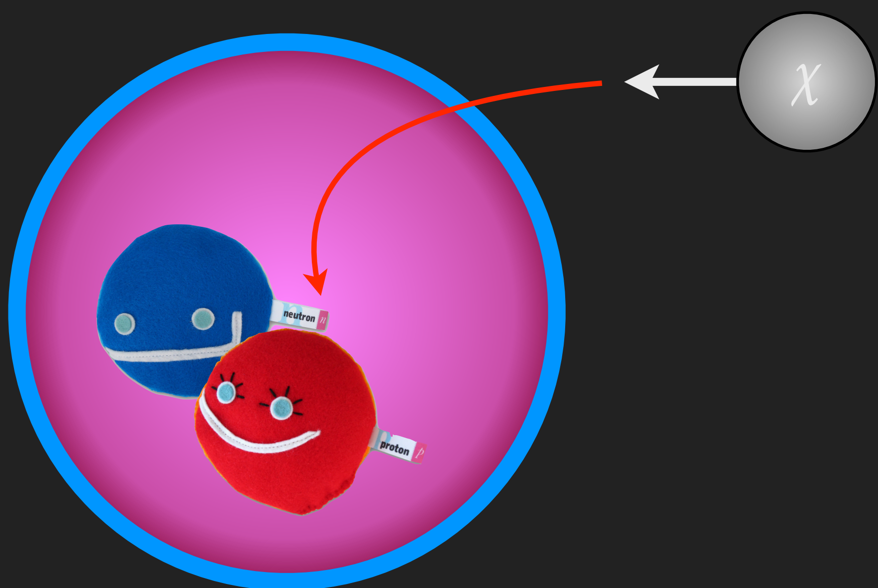
R. Garani *et al.*, *JCAP* **05**, 035 (2019)

$$C_c \propto \left(\frac{\rho_\chi}{m_\chi}\right) \int_0^\infty \frac{f(u)}{u} w(r) du \int_0^{v_{\rm esc}(r)} R^-(w \to v) dv$$

$$R^-(w \to v) = \int \zeta_b(r) \rho_u \frac{d\sigma_{\chi b}}{dv} |w - u| f_b(E_b, r)[1 - f_{b'}(E_b + q_0, r)] d^3u$$

Not-to-scale

Capturing DM particles



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differential scattering rate

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Not-to-scale

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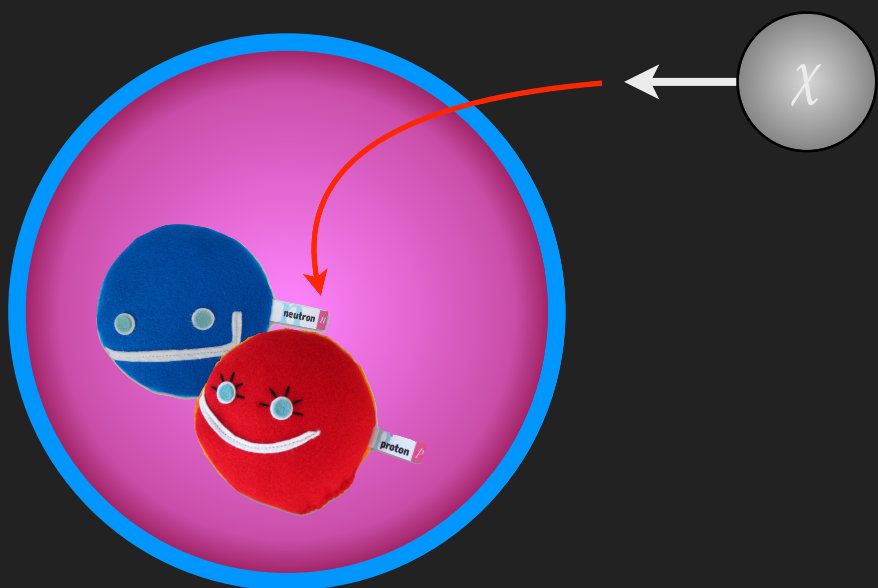

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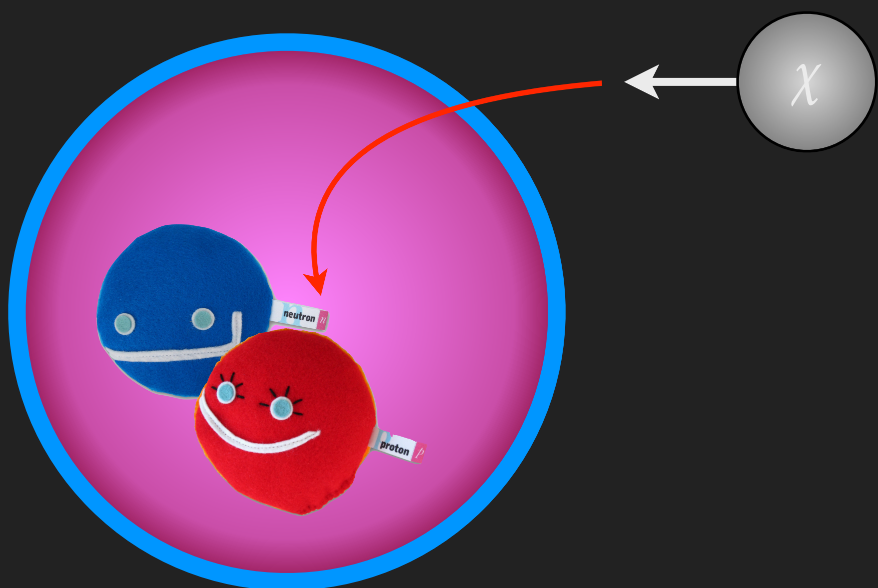
baryon
density dist.

Not-to-scale

Capturing DM particles



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differential scattering rate

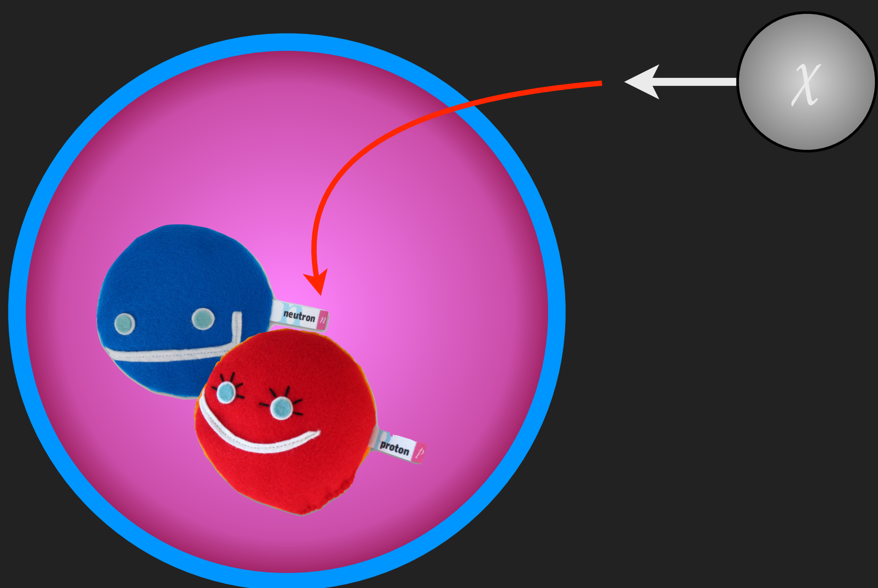
DM-baryon cross section

$$R^-(w \to v) = \int \boxed{\zeta_b(r) \rho_u} \boxed{\frac{d\sigma_{\chi b}}{dv}} |w - u| f_b(E_b, r)[1 - f_{b'}(E_b + q_0, r)] d^3u$$

baryon density dist.

Not-to-scale

Capturing DM particles



Not-to-scale

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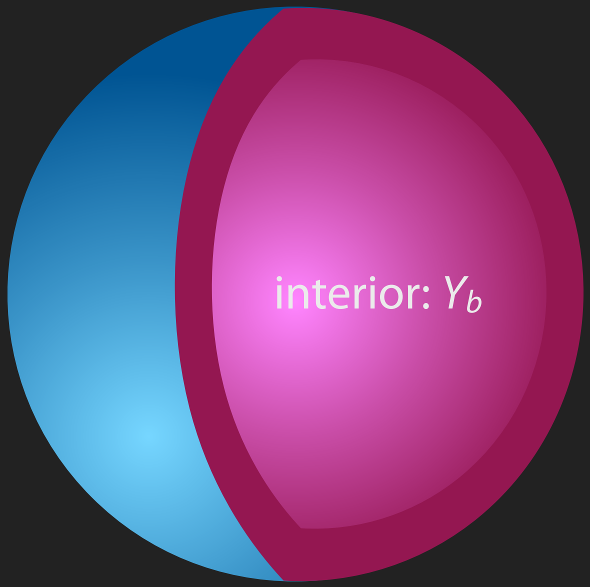
baryon density dist.

Fermi-Dirac dist. of baryons

Baryons in the NS



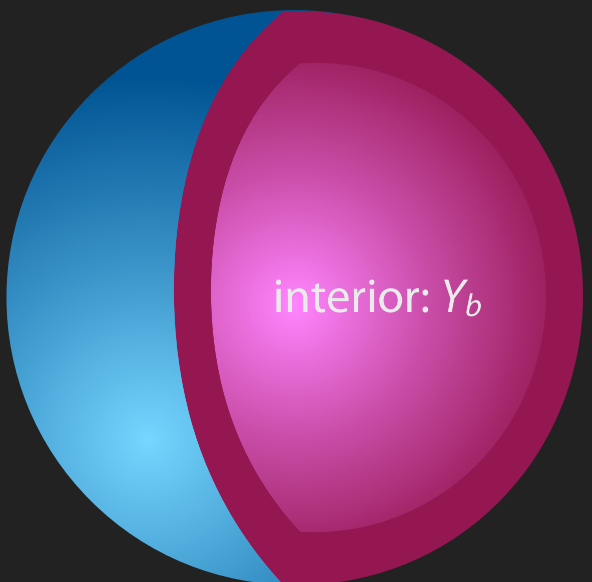
- Density distributions
- Chemical potentials

not identical for n and p

A. Y. Potekhin *et al.*, *AA* **560**, A48 (2013)
S. Goriely *et al.*, *PRC* **88**, 024303 (2013)
R. Garani *et al.*, *JCAP* **05**, 035 (2019)

Not-to-scale

Baryons in the NS



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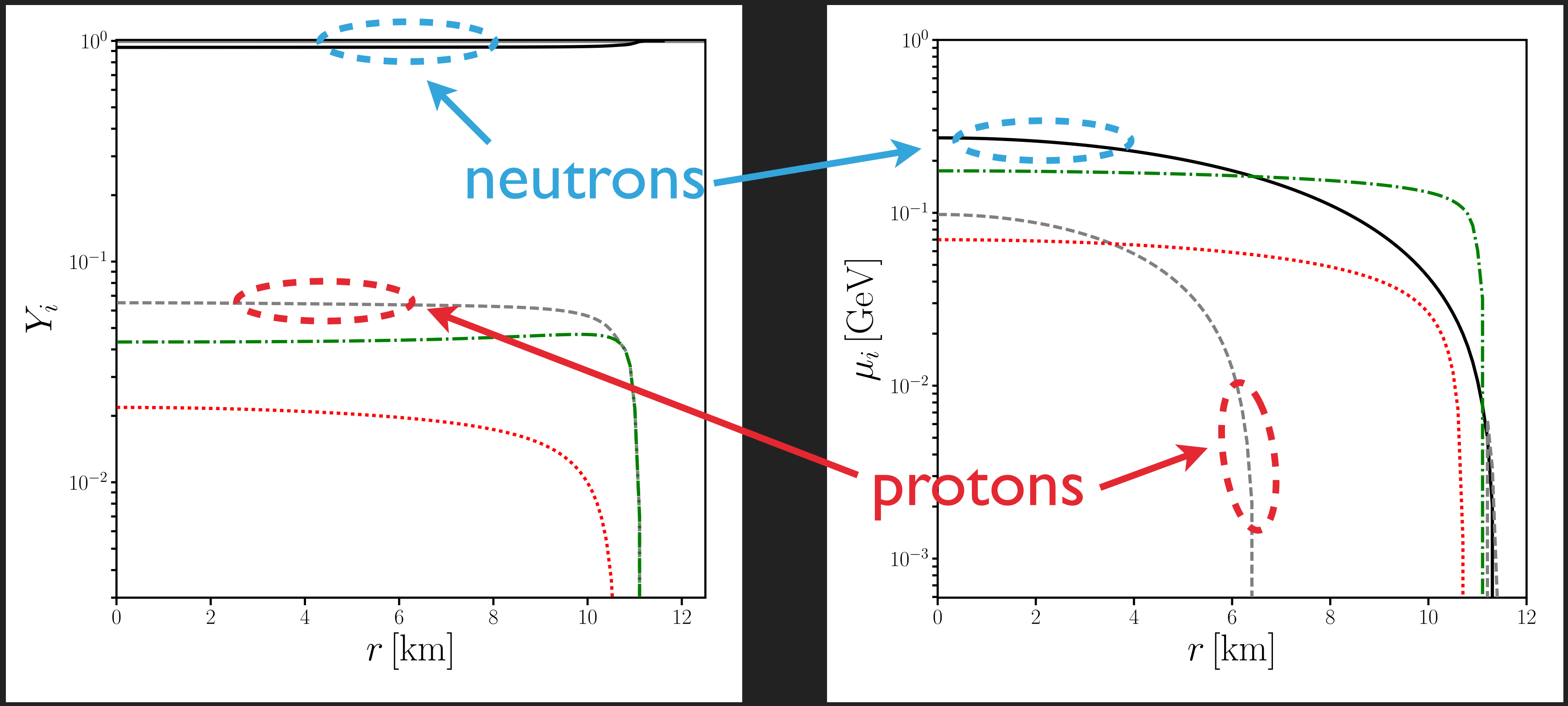
baryonic yields | chemical potentials



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Not-to-scale

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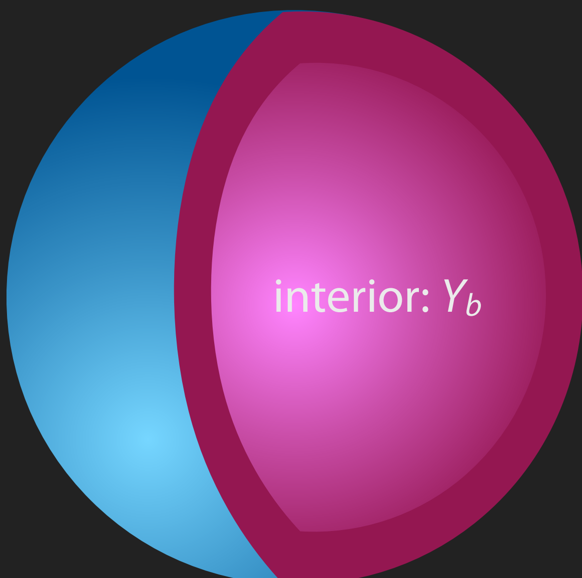

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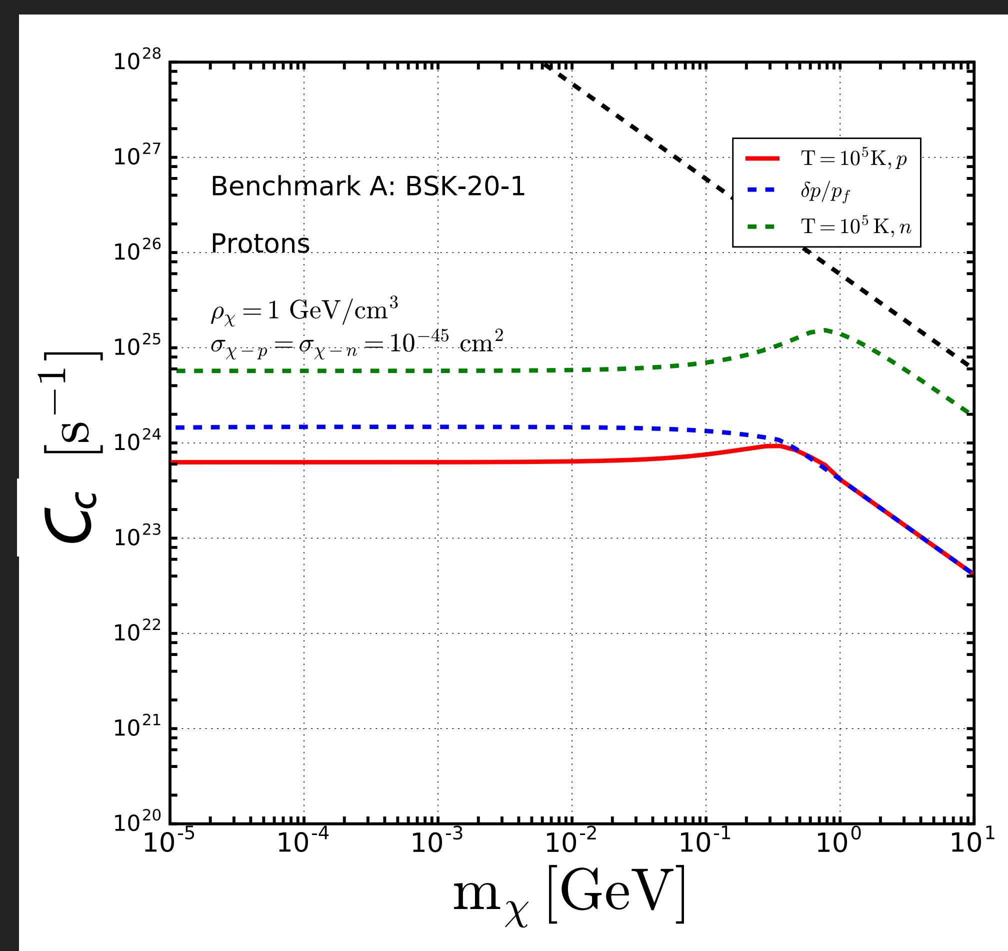
Capture rate C_c : $\sigma_{\chi n} = \sigma_{\chi p} = 10^{-45}$ cm^2

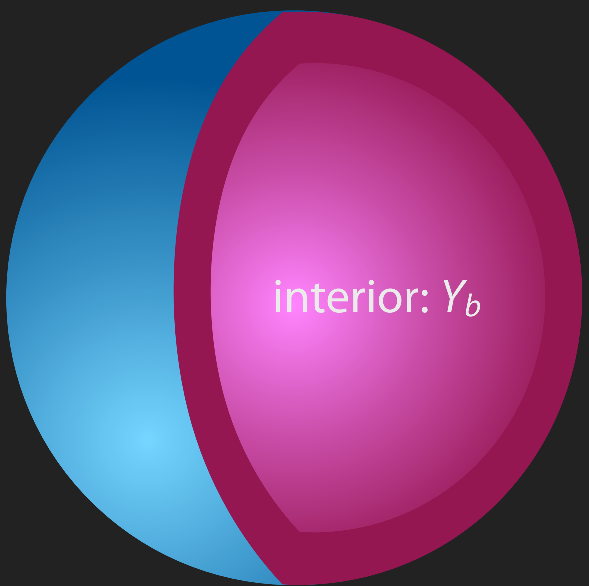


} $\mathcal{O}(10^{-2})$

R. Garani *et al.*, *JCAP* **05**, 035 (2019)
(*private communication*)

Not-to-scale

Baryons in the NS



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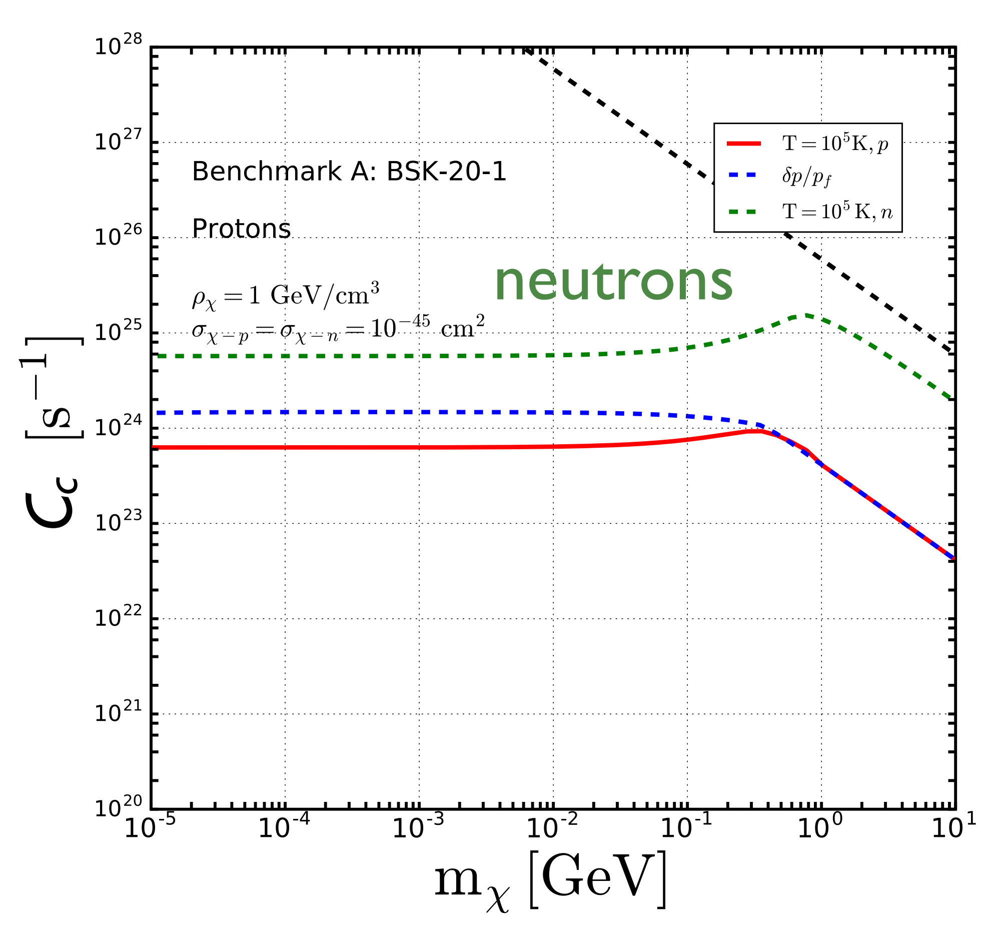

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(*private communication*)

Not-to-scale

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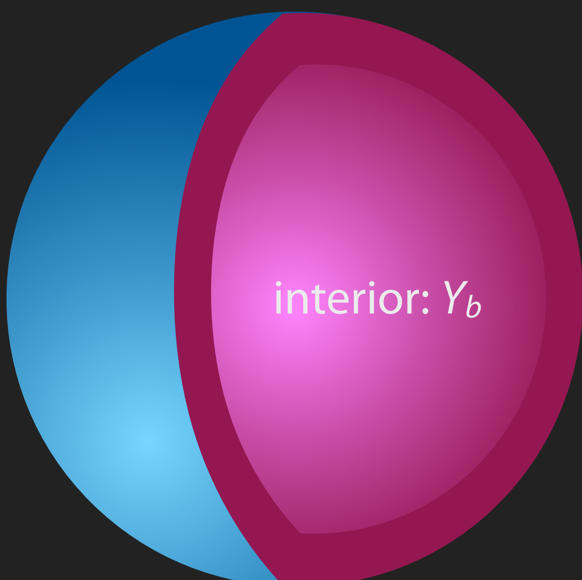

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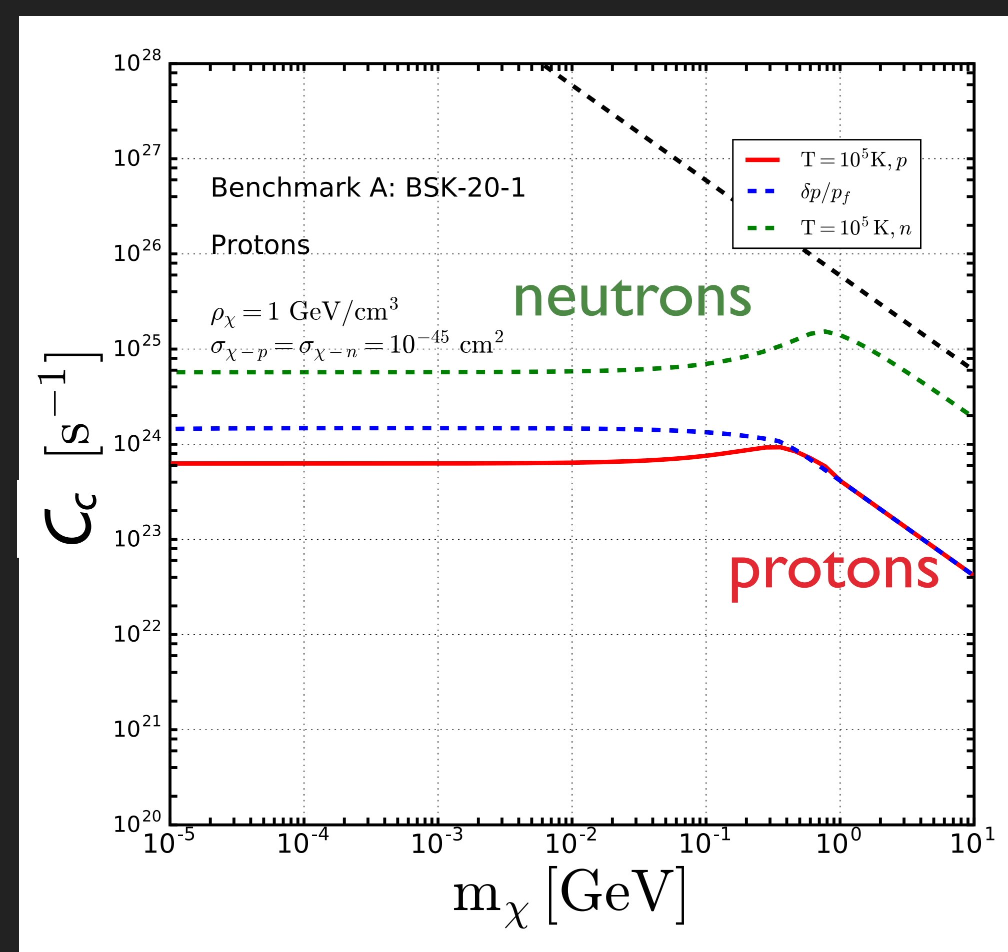

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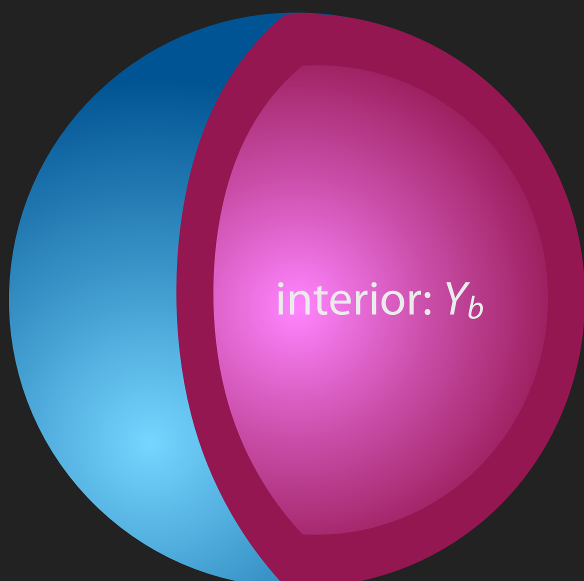
R. Garani *et al.*, *JCAP* **05**, 035 (2019)
(*private communication*)

Not-to-scale

Baryons in the NS



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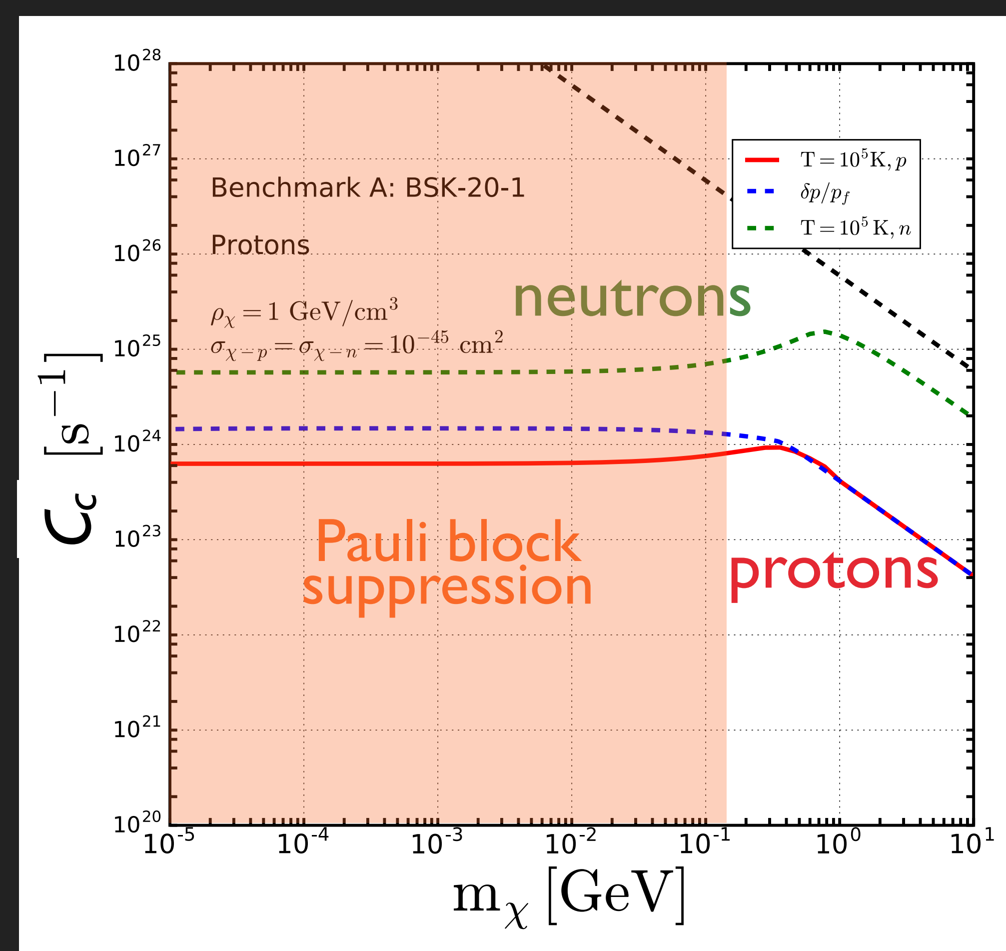

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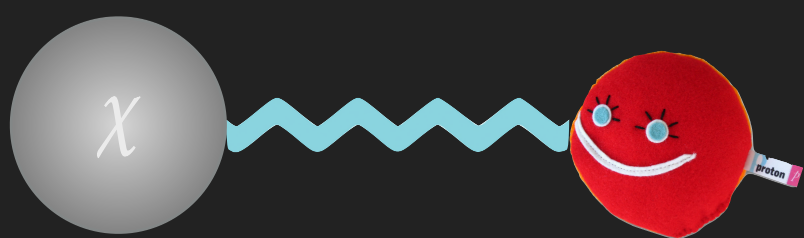
Not-to-scale

DM-baryon interactions

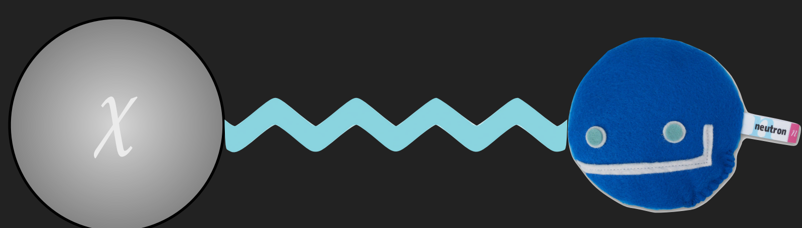
G. Jungman *et al.*, *Phys. Rept.* **267**, 195 (1995)

neutron



$$\sigma_{\chi n} = \frac{4\mu_n^2}{\pi} f_n^2$$

proton



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Not-to-scale

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G. Jungman *et al.*, *Phys. Rept.* **267**, 195 (1995)

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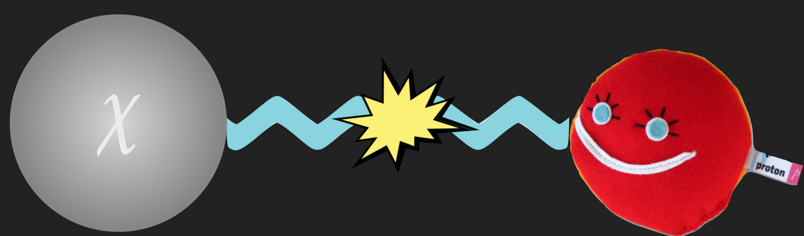
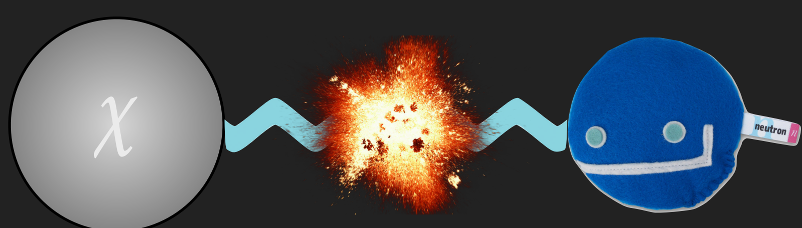


$$\sigma_{\chi n} = \frac{4\mu_n^2}{\pi} f_n^2$$

$$\nparallel$$

proton



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Not-to-scale

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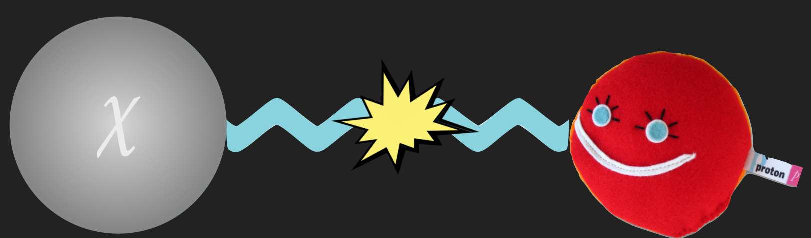
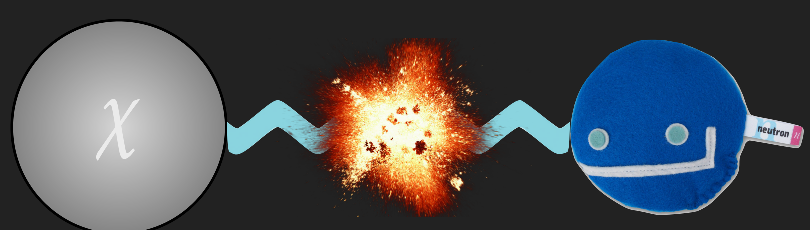


proton



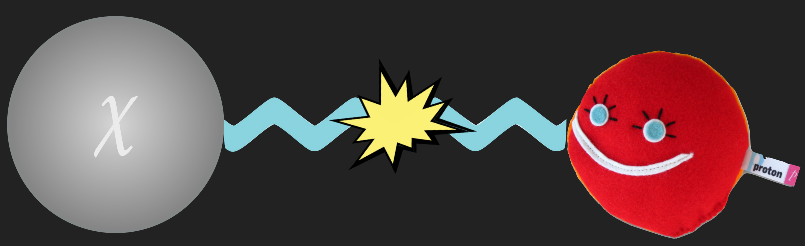
$$\left.\begin{array}{c} \sigma_{\chi n} = \dfrac{4\mu_n^2}{\pi} f_n^2 \\ \nparallel \\ \sigma_{\chi p} = \dfrac{4\mu_p^2}{\pi} f_p^2 \end{array}\right\} \text{isospin violation}$$

Not-to-scale

DM-baryon interactions

G. Jungman *et al.*, *Phys. Rept.* **267**, 195 (1995)

neutron



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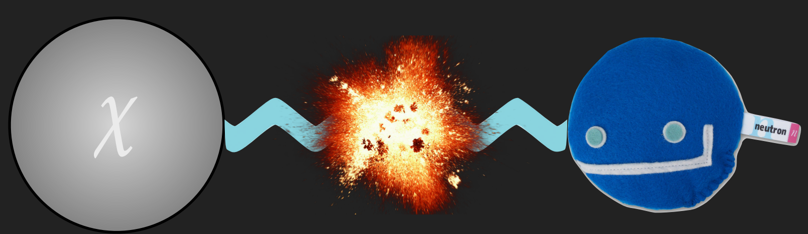
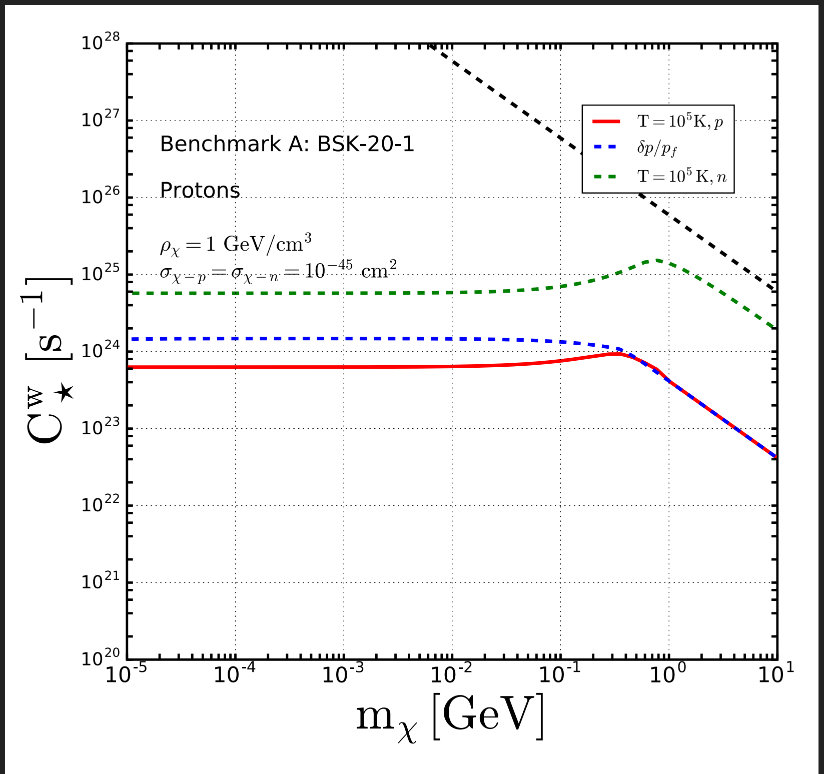


$$\sigma_{\chi p} = \frac{4\mu_p^2}{\pi} f_p^2$$

isospin violation

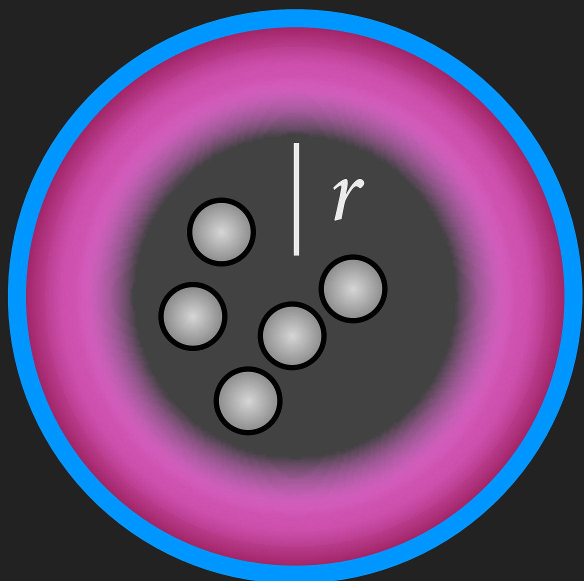
$$\sigma_{\chi p} = \left(\frac{f_n}{f_p}\right)^{-2} \sigma_{\chi n}$$



Not-to-scale

DM in the NS

C. Kouvaris, *PRL* **108**, 191301 (2012)
J. Bramante *et al.*, *PRD* **89**, 015010 (2014)



Virial theorem

$$\langle 2E_k \rangle = \frac{8}{3}\pi G \rho_b m_\chi r^2 + \frac{G N_\chi m_\chi^2}{r} + \sum_{j}^{N_\chi - 1} \left(\frac{\alpha e^{-m_\phi r_j}}{r_j} + \alpha m_\phi e^{-m_\phi r_j} \right)$$

Not-to-scale

C. Kouvaris, *PRL* **108**, 191301 (2012)
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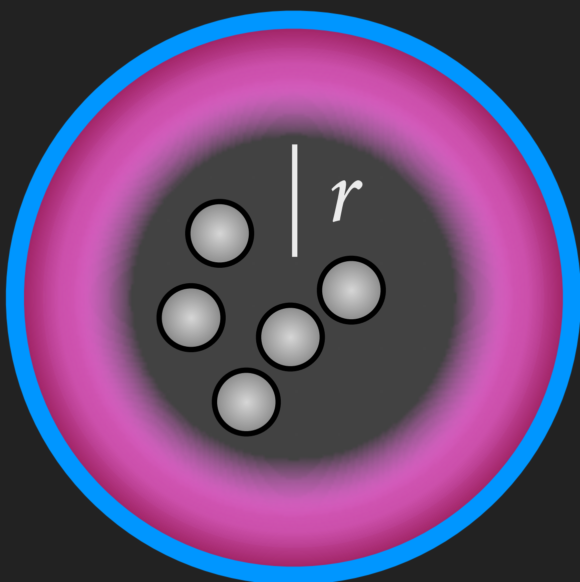

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Contribution from DM self-interaction
modeling by Yukawa potential

Not-to-scale

C. Kouvaris, *PRL* **108**, 191301 (2012)
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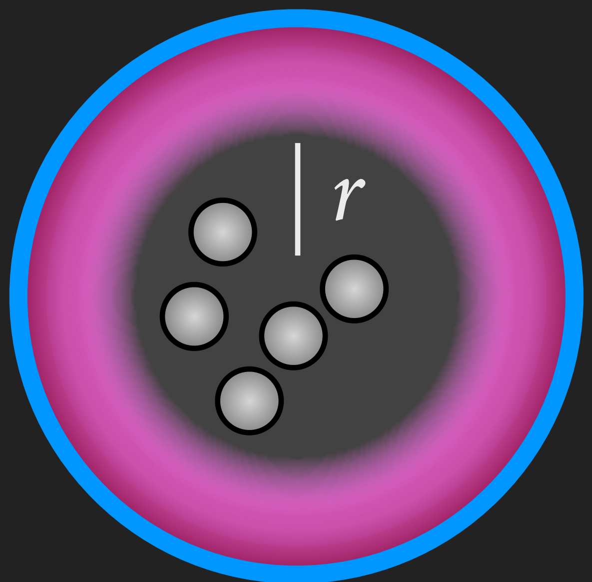
DM in the NS



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Increases as N_χ increasing

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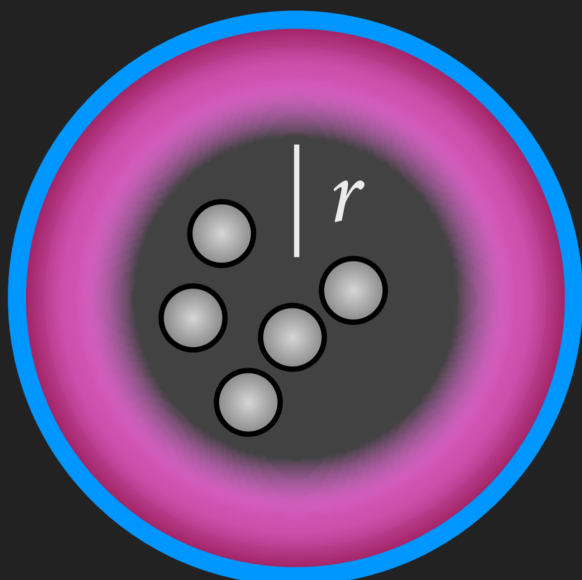

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$$+ \boxed{\sum_{j}^{N_\chi - 1} \left(\frac{\alpha e^{-m_\phi r_j}}{r_j} + \alpha m_\phi e^{-m_\phi r_j} \right)}$$

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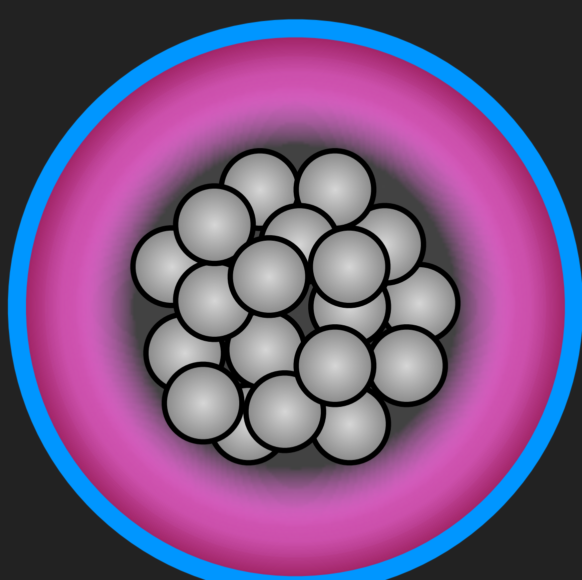

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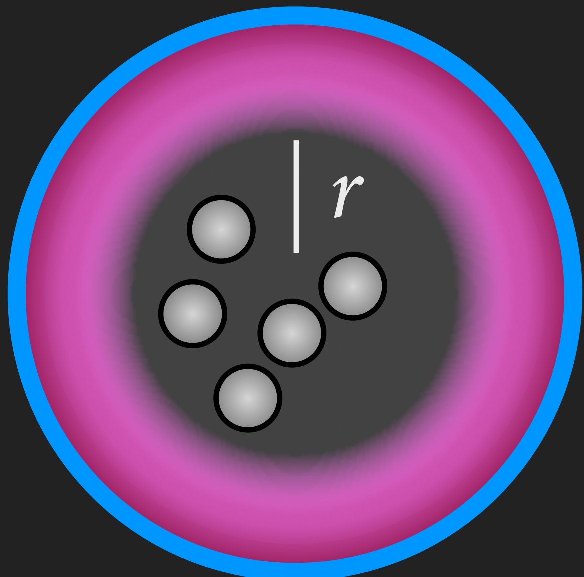
J. Bramante *et al.*, *PRD* **89**, 015010 (2014)

DM in the NS



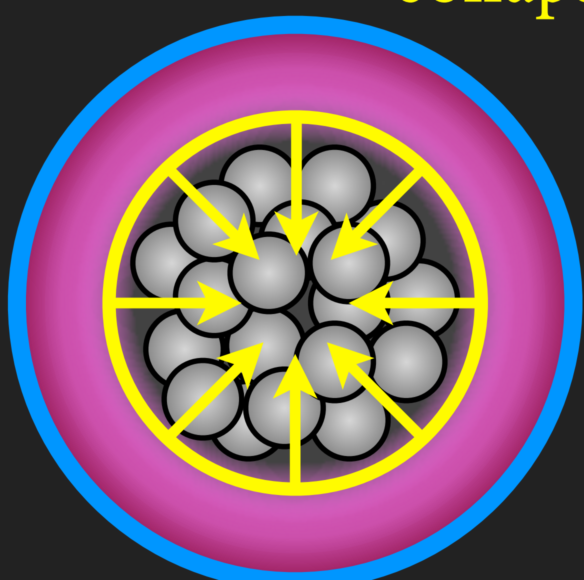
Virial theorem

$$\langle 2E_k \rangle = \frac{8}{3}\pi G \rho_b m_\chi r^2 + \boxed{\frac{G N_\chi m_\chi^2}{r}} + \boxed{\sum_j^{N_\chi - 1} \left(\frac{\alpha e^{-m_\phi r_j}}{r_j} + \alpha m_\phi e^{-m_\phi r_j} \right)}$$

Increases as N_χ increasing

Contribution from DM self-interaction modeling by Yukawa potential

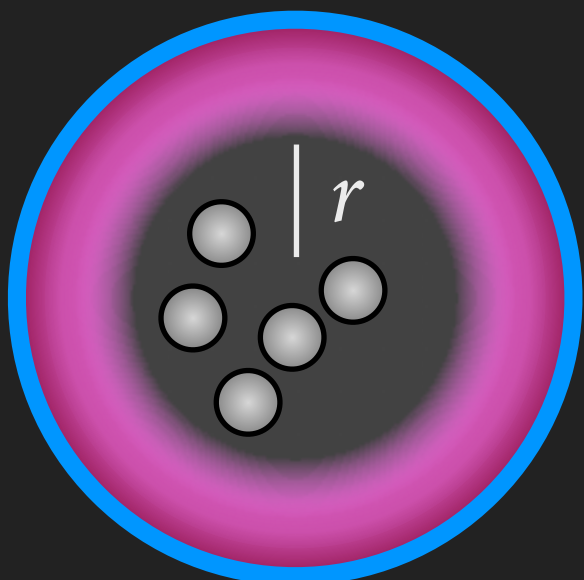
gravitational collapse $N_\chi > N_{\mathrm{crit}}$



Not-to-scale

C. Kouvaris, *PRL* **108**, 191301 (2012)
J. Bramante *et al.*, *PRD* **89**, 015010 (2014)

DM in the NS



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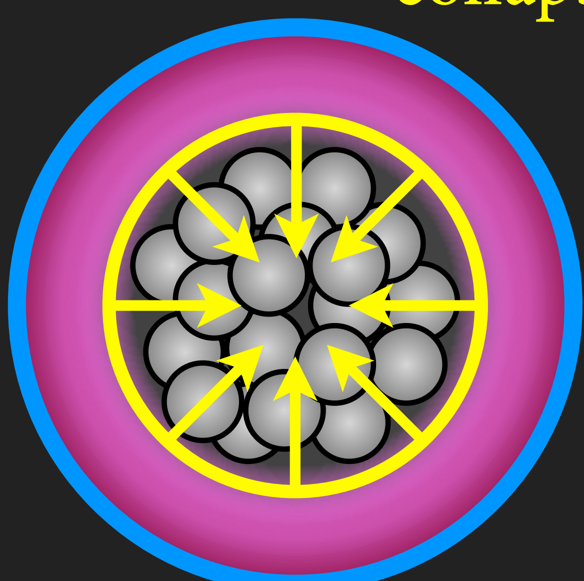
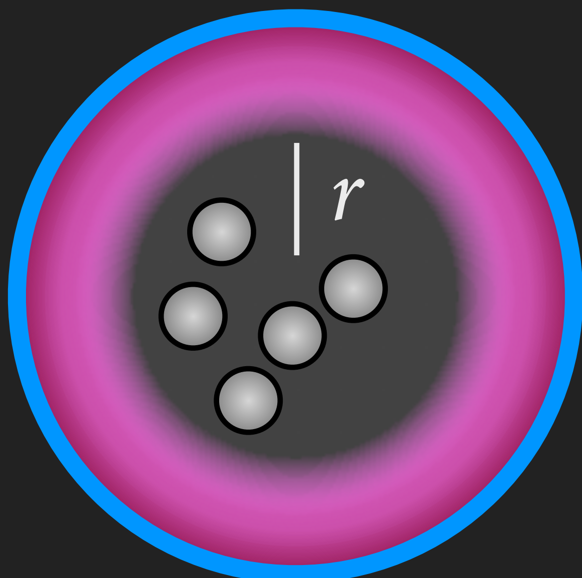


- Black hole formation
- Halted by Fermi pressure

Not-to-scale

C. Kouvaris, *PRL* **108**, 191301 (2012)
J. Bramante *et al.*, *PRD* **89**, 015010 (2014)

DM in the NS



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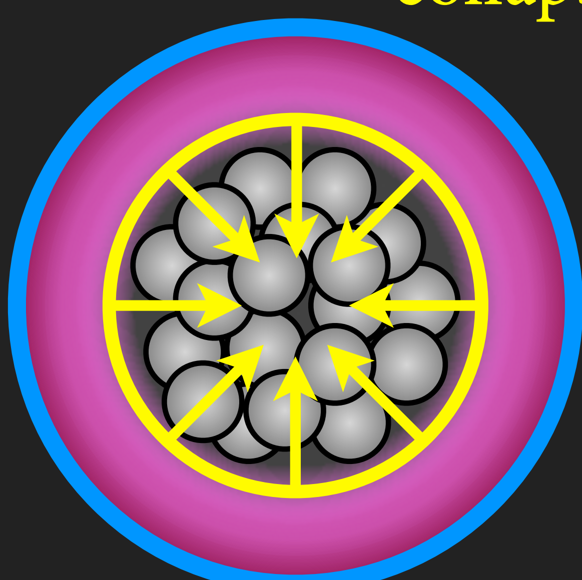
Contribution from DM self-interaction modeling by Yukawa potential

gravitational collapse $N_\chi > N_{\mathrm{crit}}$



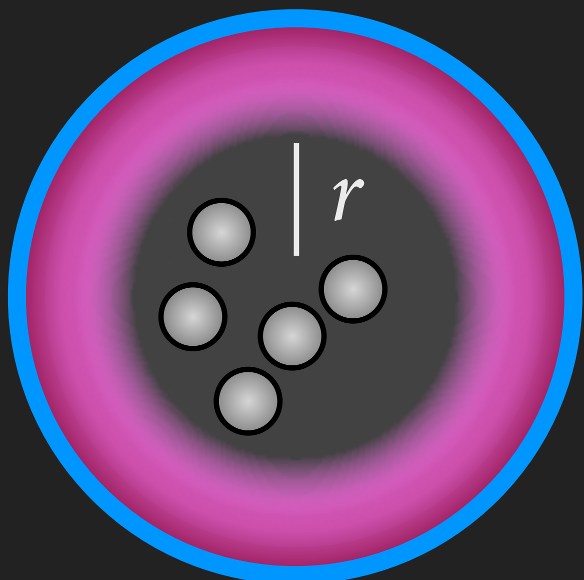
- Black hole formation
- Halted by Fermi pressure

depending on α and m_ϕ

Not-to-scale

C. Kouvaris, *PRL* **108**, 191301 (2012)
J. Bramante *et al.*, *PRD* **89**, 015010 (2014)

DM in the NS



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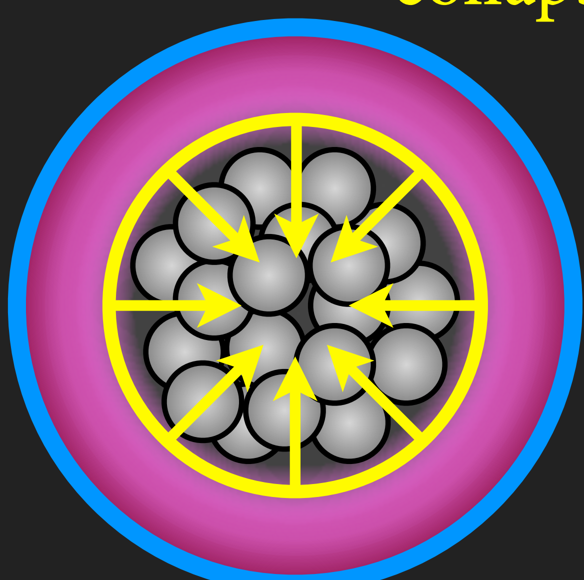
Contribution from DM self-interaction
modeling by Yukawa potential

gravitational
collapse $N_\chi > N_{\mathrm{crit}}$



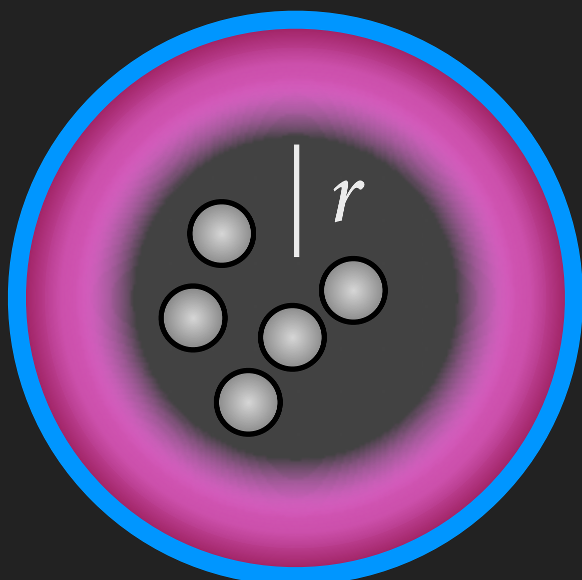
- Black hole formation
  - Star consumed
  - Evaporation
- Halted by Fermi pressure

depending on α and m_ϕ

Not-to-scale

C. Kouvaris, *PRL* **108**, 191301 (2012)
J. Bramante *et al.*, *PRD* **89**, 015010 (2014)

DM in the NS



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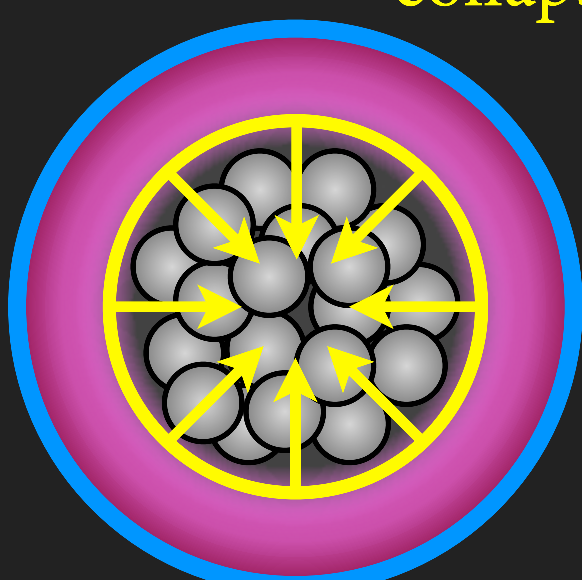
Contribution from DM self-interaction modeling by Yukawa potential

gravitational collapse $N_\chi > N_{\mathrm{crit}}$



- Black hole formation
  - Star consumed $N_{\mathrm{crit}} \gtrsim \frac{3 \times 10^{36}}{(m_\chi/\mathrm{GeV})}$
  - Evaporation
- Halted by Fermi pressure

depending on α and m_ϕ

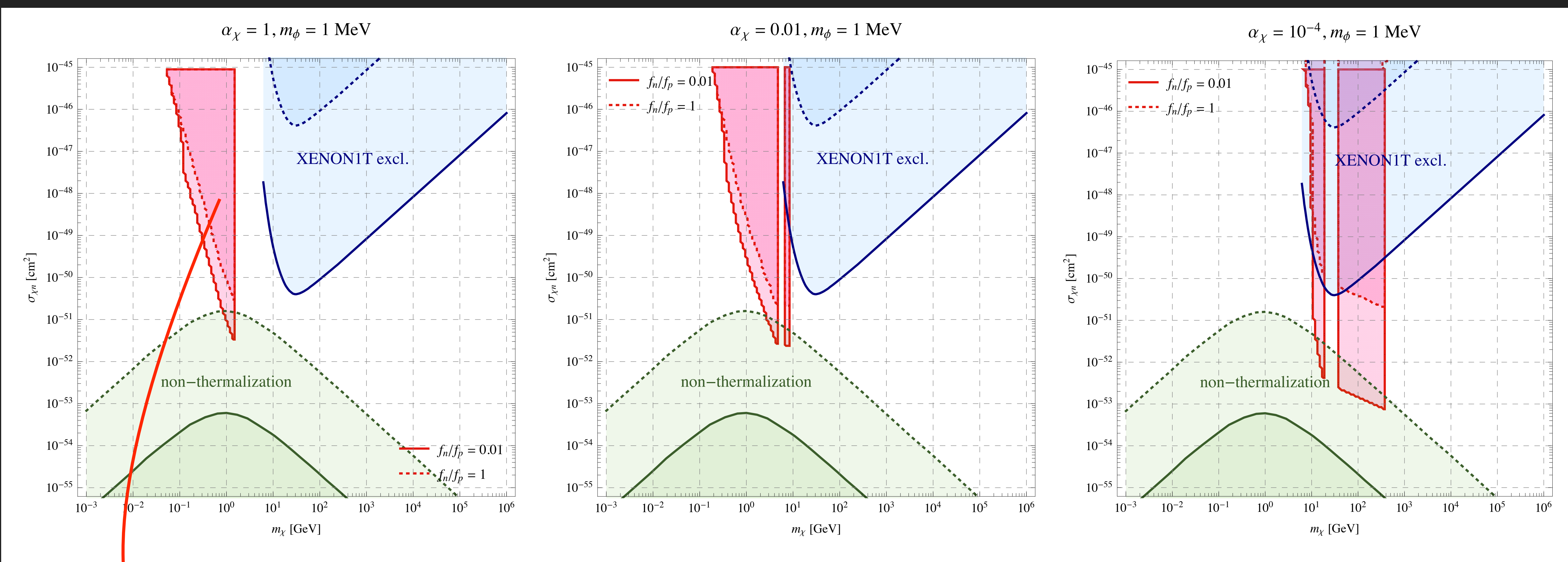
Not-to-scale

Part III

NS sensitivity on isospin violating $\sigma_{\chi b}$

DM-neutron cross section

age ~ Gyrs fixed $m_\phi = 1\ \mathrm{MeV}$ $V(r) = \alpha_\chi \frac{e^{-m_\phi r}}{r}$



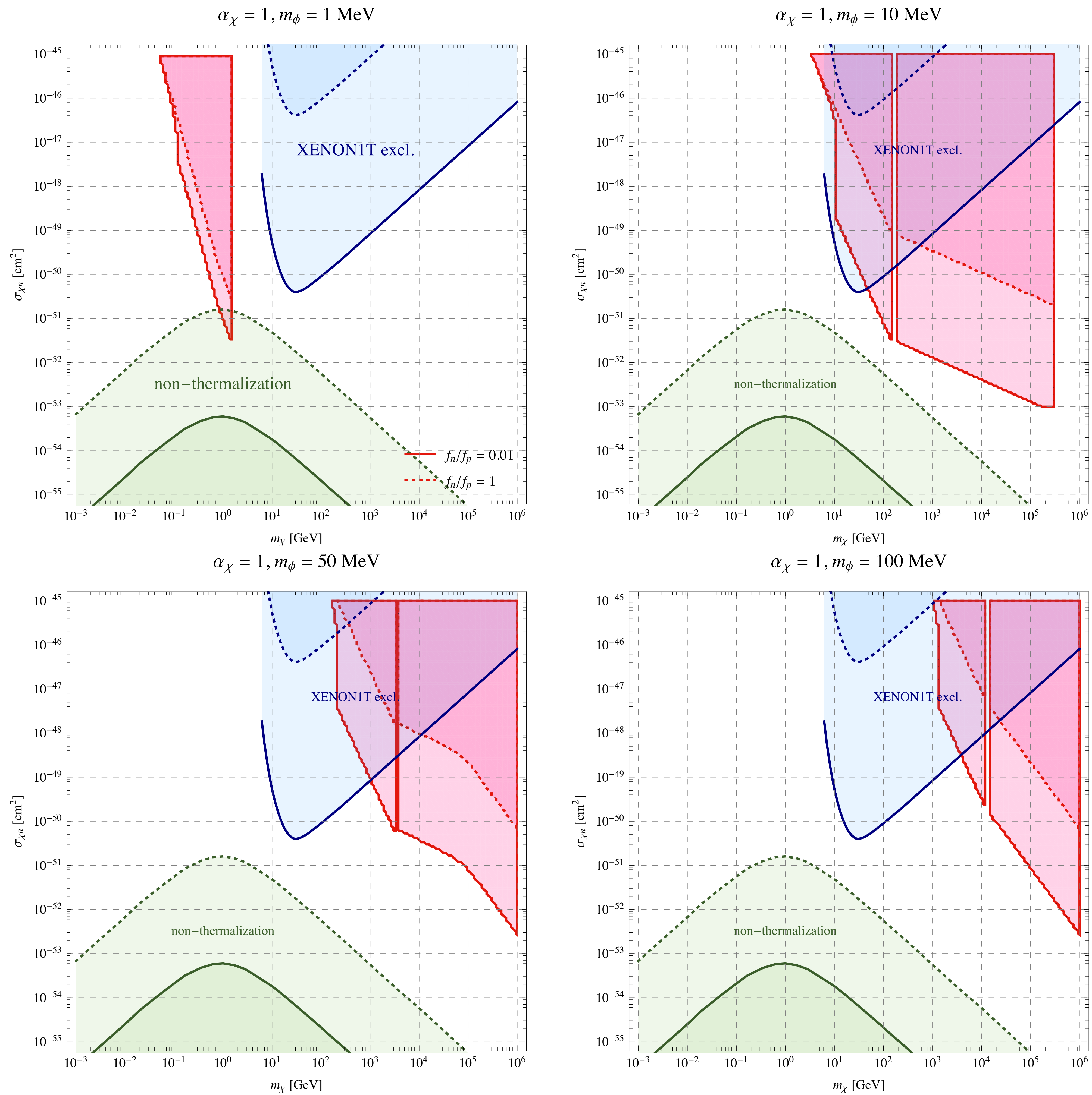
excluded

$f_n/f_p = 0.01$

$f_n/f_p = 1$

fixed $\alpha_\chi = 1$

$$V(r) = \alpha_\chi \frac{e^{-m_\phi r}}{r}$$



$f_n/f_p = 0.01$

$f_n/f_p = 1$

Part IV

Summary

Summary

- Isospin violation can affect the NS capture rate of DM
- Proton capture rate could be important if $f_p > f_n$
- With attractive self-interaction, fermionic DM could overcome the Fermi pressure and form a BH in the star
- For $m_\chi < 1$ GeV, the contributions from other light particles (e, μ…) to the capture rate in the NS could be important