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arXiv: 2004.05312 (*JCAP* accepted)

in collaboration with
Guey-Lin Lin (NCTU)

Analysis on the black hole formations inside old neutron stars by isospin-violating dark matter with self-interaction

Outline

- **Part I:**
  - Motivation for introducing DM self-interaction
  - Phenomenological model for DM-DM and DM-SM interactions
- **Part II:**

  Neutron star (NS) and the capture of DM
- **Part III:**

  Black hole formation of DM inside the NS
- **Part IV:**

  Sensitivity of Gyr-old NS on the particle nature of DM
- **Summary**

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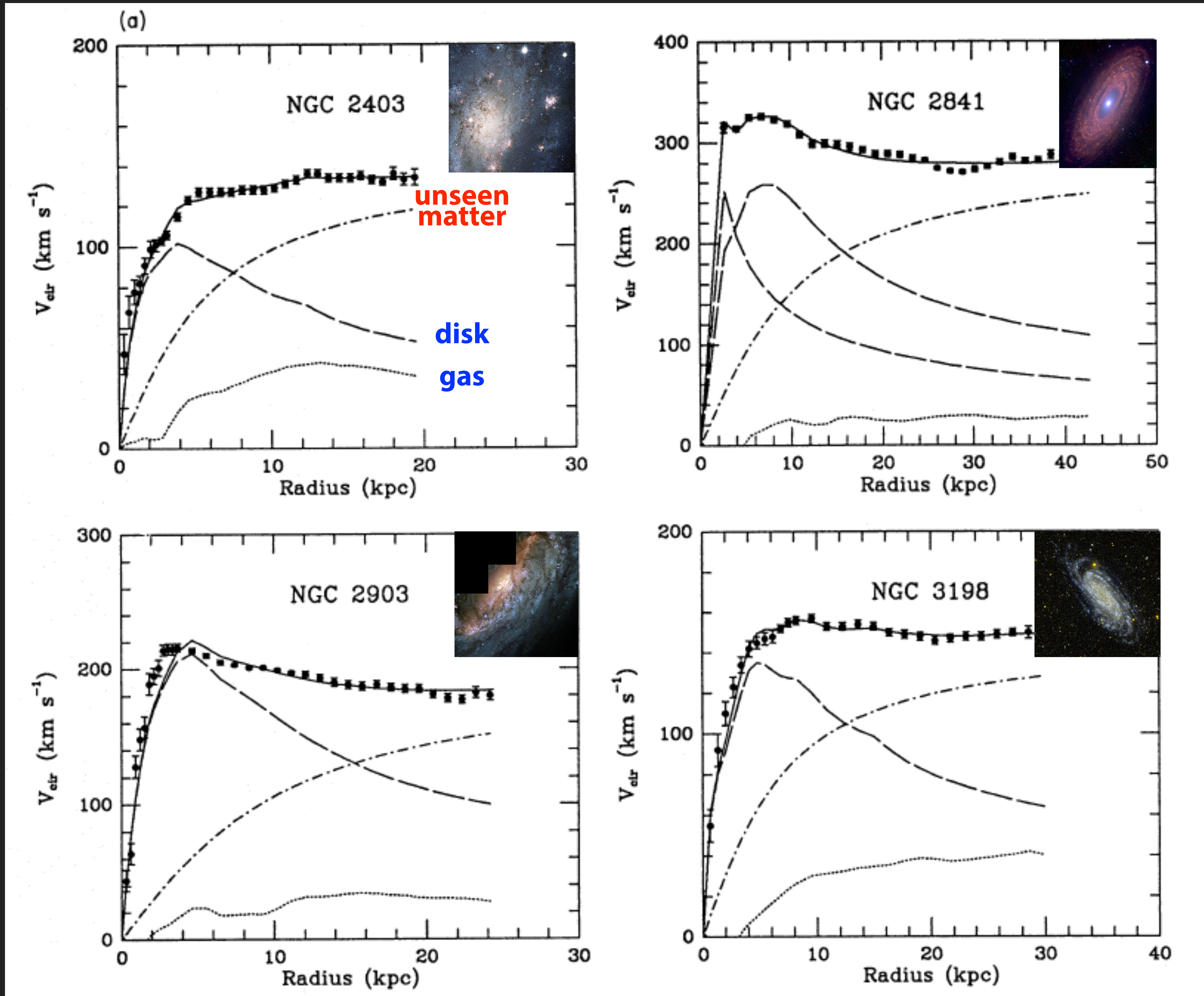
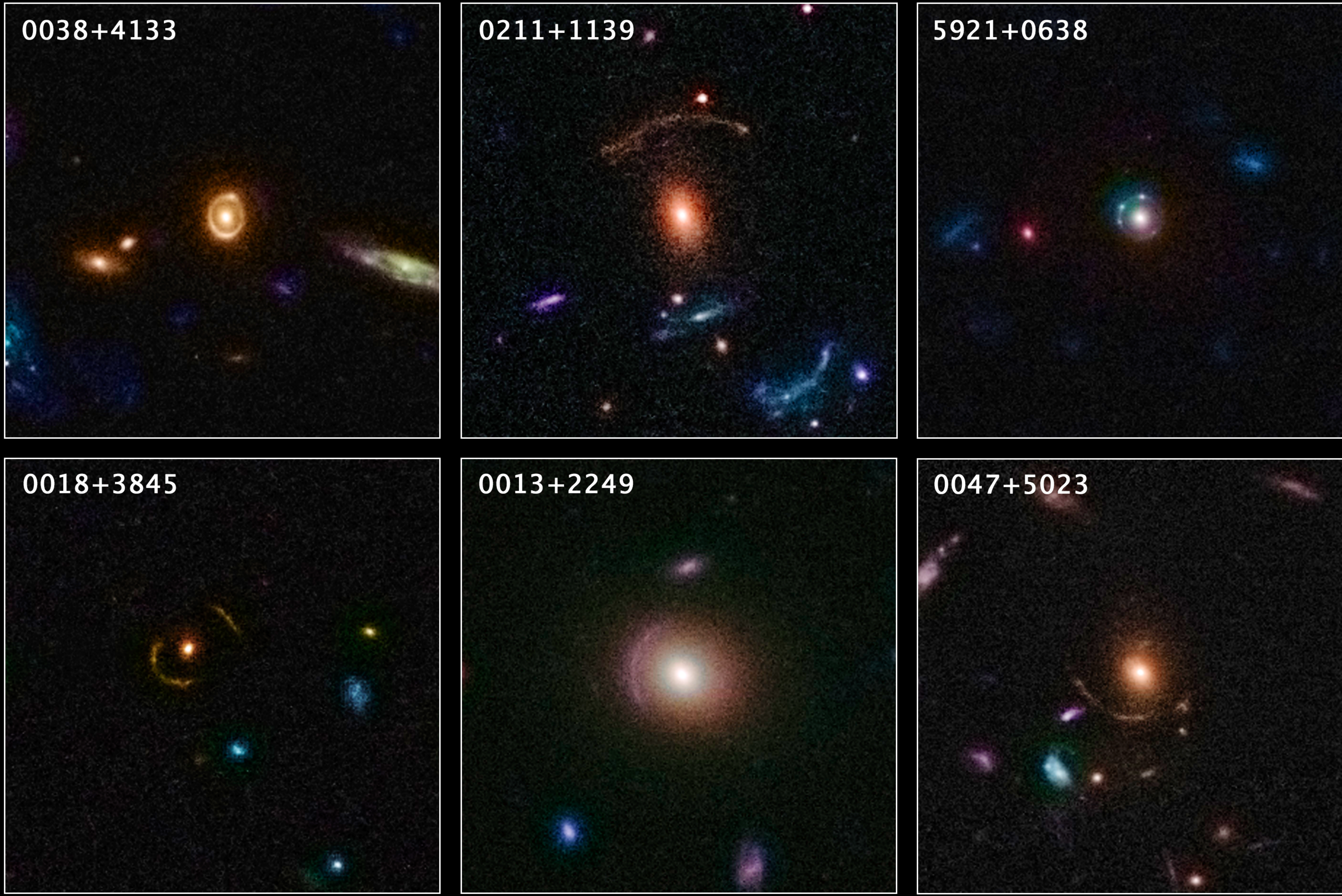


K. G. Begeman *et al., MNRAS* **249**, 523 (1991)

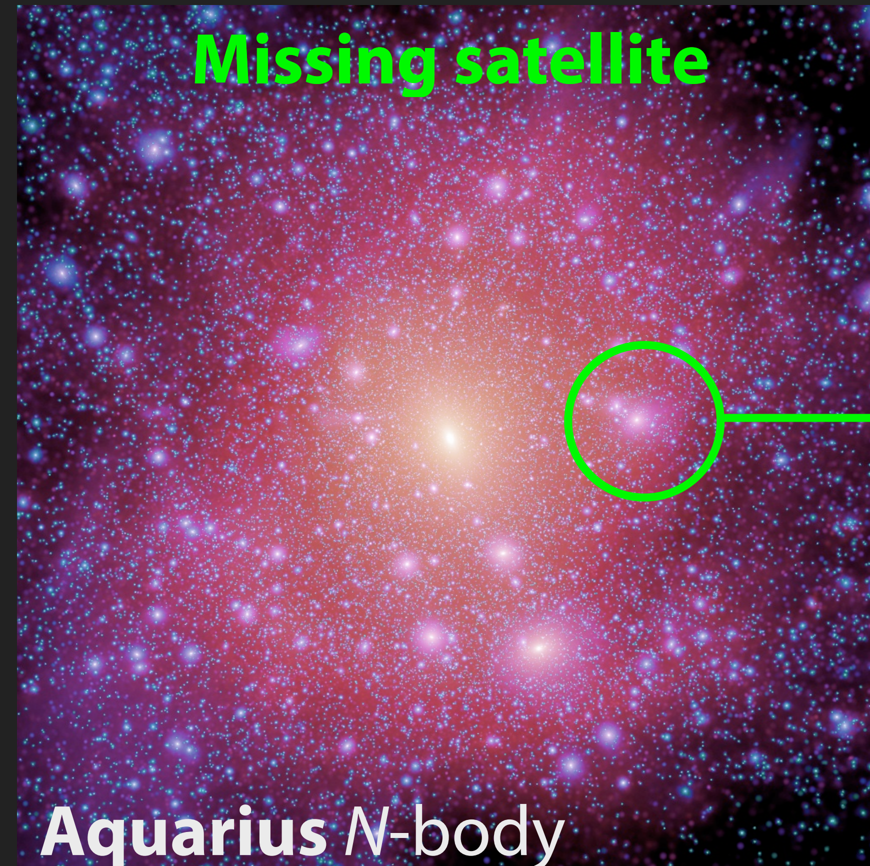


Gravitational Lenses in the COSMOS Survey

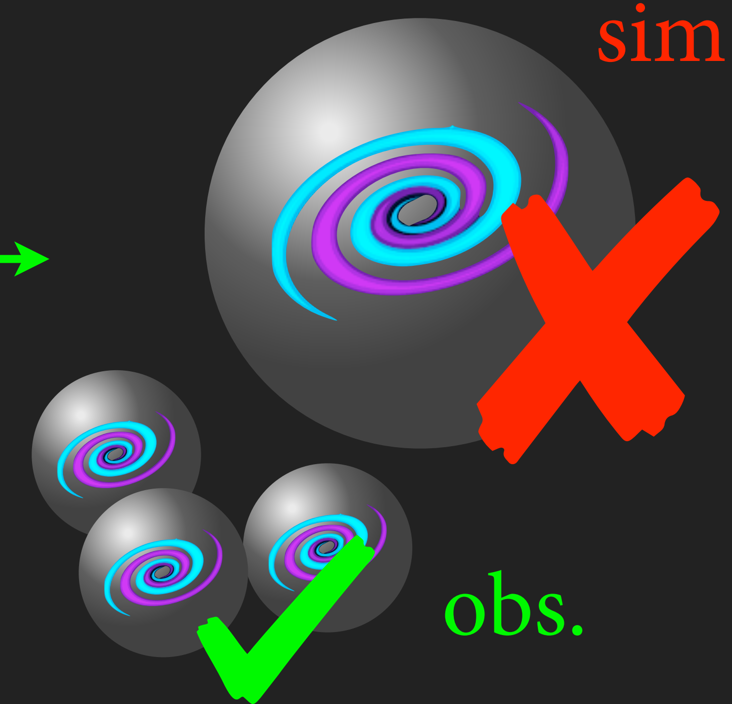
Hubble Space Telescope ▪ ACS/WFC

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

STScI-PRC08-09



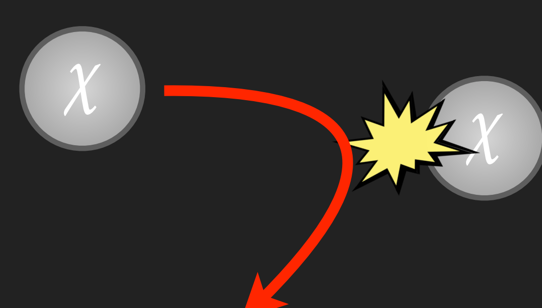
Too-big-to-fail



To alleviate these small-scale problem:

DM self-interaction is introduced

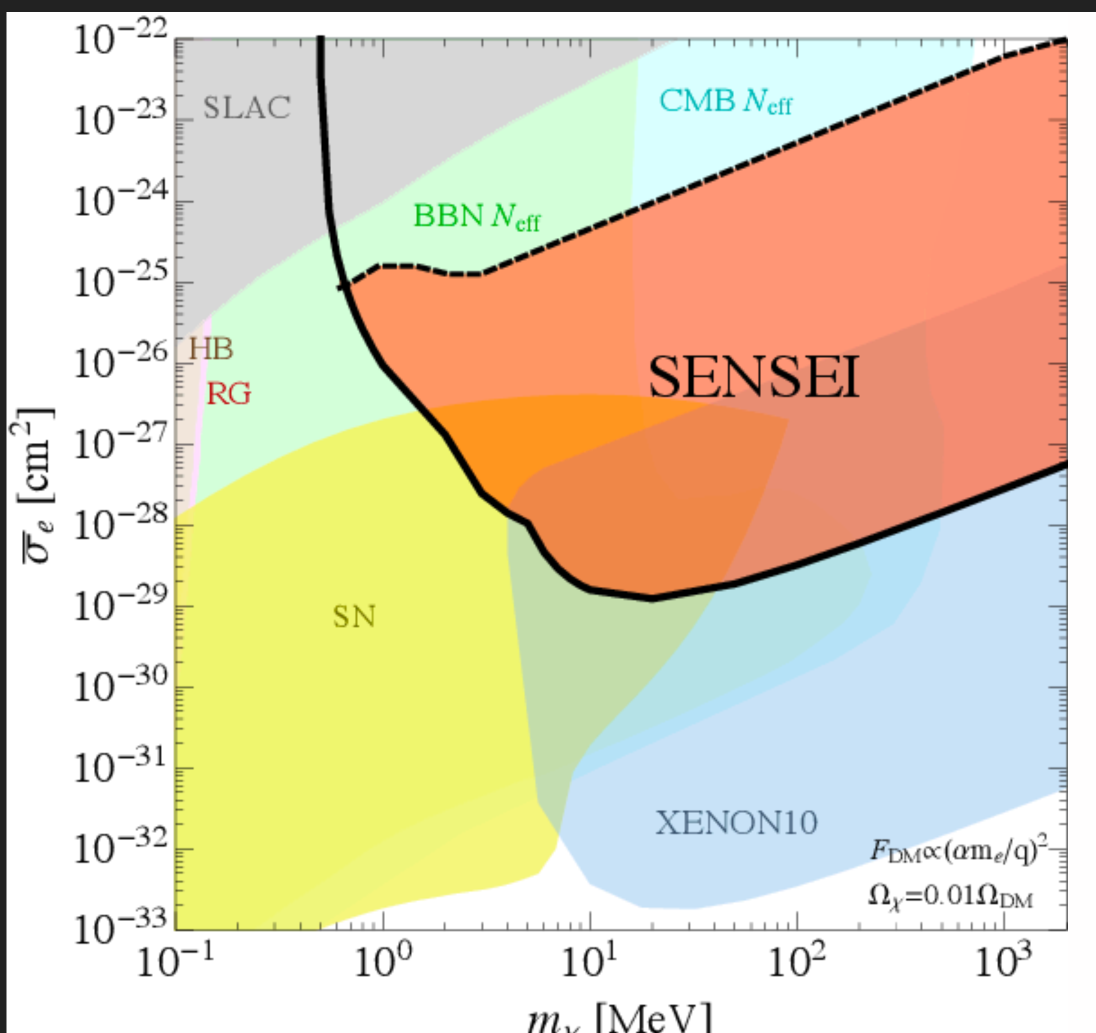
$$10^{-25}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}} \le \frac{\sigma_{\chi\chi}}{m_\chi} \le 10^{-23}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}}$$



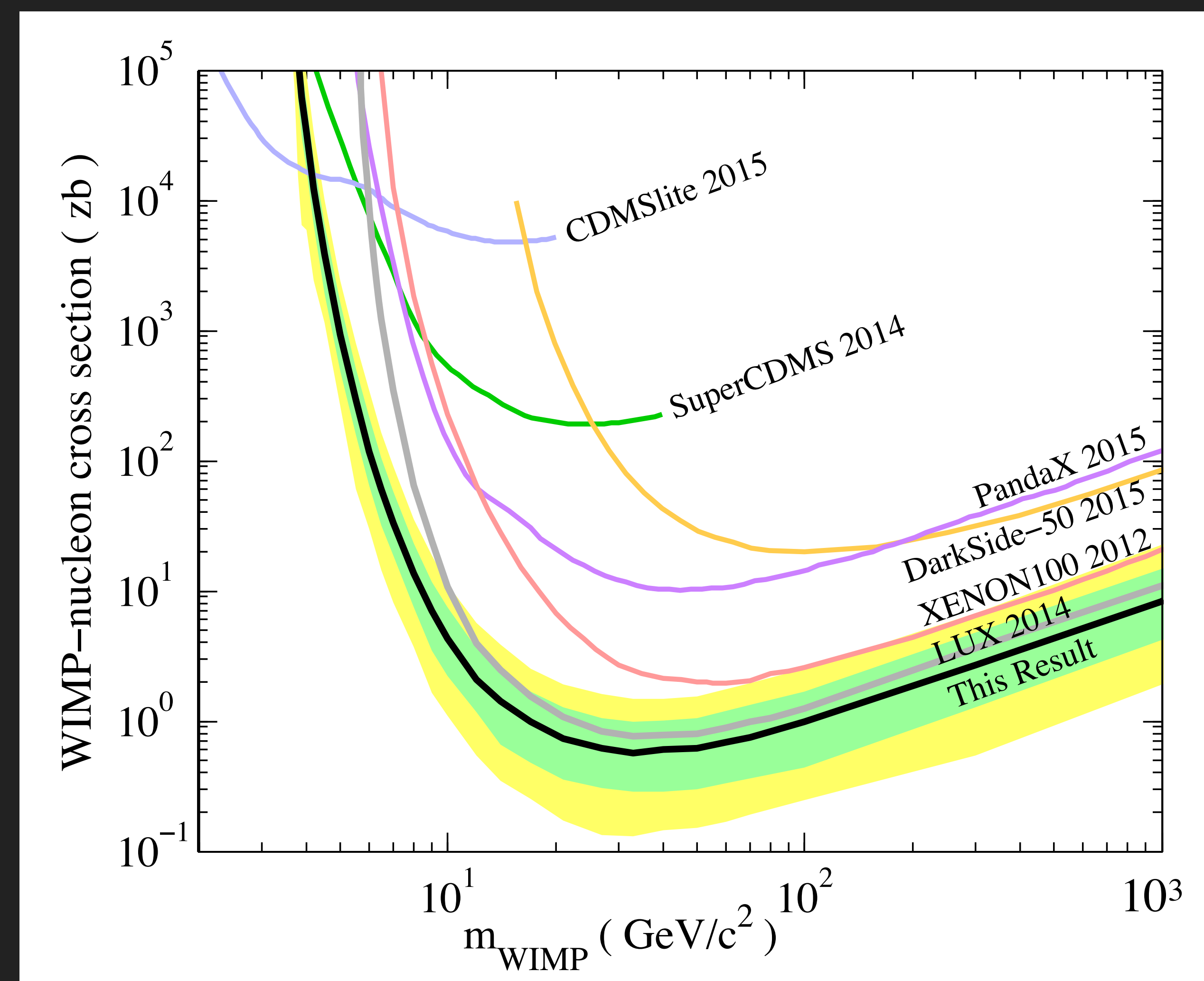
J. S. Bullock *et al.*, *Ann. Rev. Astron. Astrophys.* **55**, 343 (2017)
S. Tulin *et al.*, *Phys. Rept.* **730**, 1 (2018)

Constraints from DM direct searches

sub-GeV DM



GeV DM



M. Crisler *et al.* [SENSEI], *PRL* **121**, 061803 (2018)
(and refs. therein)

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)

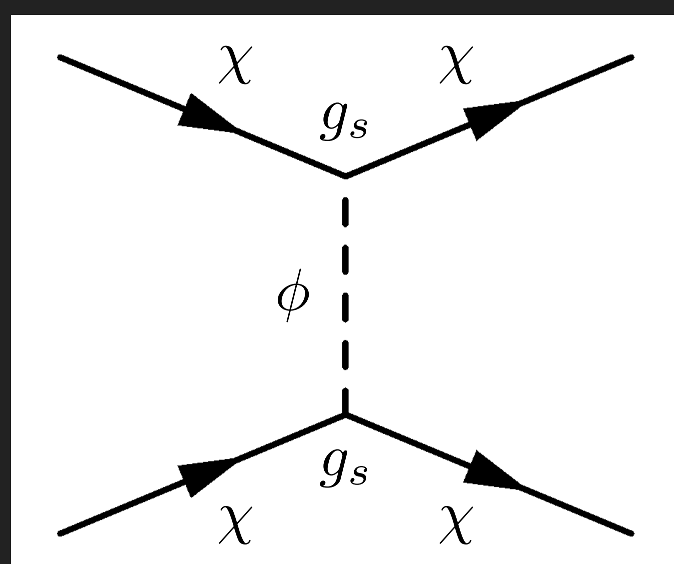
H. Davoudiasl, *et al.*, *PRD* **85**, 115019 (2013)

Dark matter self-interaction

- Introducing a dark scalar ϕ and a massive $U(1)_d$ gauge boson Z_d in the dark sector and both couple to the fermionic asymmetric DM χ

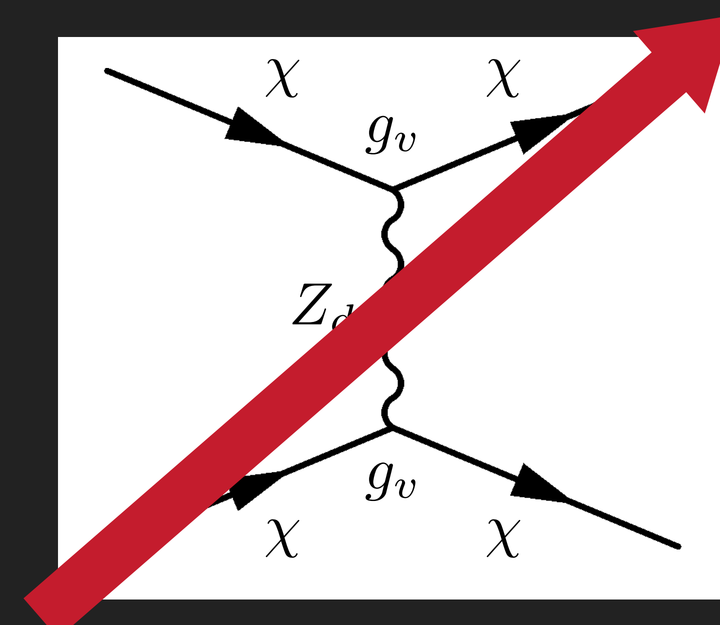
$$\mathcal{L}_S = g_s \phi \bar{\chi} \chi \qquad \mathcal{L}_V = g_v \bar{\chi} \gamma_\mu \chi Z_d^\mu$$

$$\mathcal{M}_S \sim \frac{g_s^2}{m_\phi^2}$$



attractive

$$\gg$$



repulsive

$$\mathcal{M}_V \sim \frac{g_v^2}{m_{Z_d}^2}$$

$$g_s^2 \gg g_v^2 \frac{m_\phi^2}{m_{Z_d}^2}$$

H. Davoudiasl *et al.*, *PRD* **85**, 115019 (2013)
M. Kaplinghat *et al.*, *PRD* **89**, 035009 (2014)

DM-SM interaction and isospin violation

- The $U(1)_d$ gauge boson Z_d can couple to SM photon via kinetic mixing ε_γ and Z boson via mass mixing ε_Z

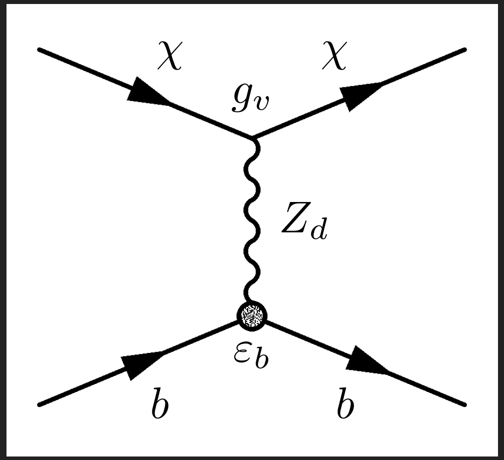
$$\mathcal{L}_{\rm mix} = \frac{\varepsilon_\gamma}{2} F_{\mu\nu} Z_d^{\mu\nu} + \varepsilon_Z m_Z^2 Z_\mu Z_d^\mu$$

- The mixing can provide portals for interacting with SM EM current $J_\mu^{\rm EM}$ and weak neutral current $J_\mu^{\rm NC}$
- Effectively, the DM-baryon (neutron & proton) interaction can be recasted as

$$\mathcal{L}_{\rm int} = \sum_{b=n,p} \varepsilon_b \bar{b} \gamma_\mu Z_d^\mu b$$

$$\varepsilon_n \approx -0.6 \varepsilon_Z$$
$$\varepsilon_p \approx \varepsilon_\gamma + 0.05 \varepsilon_Z$$

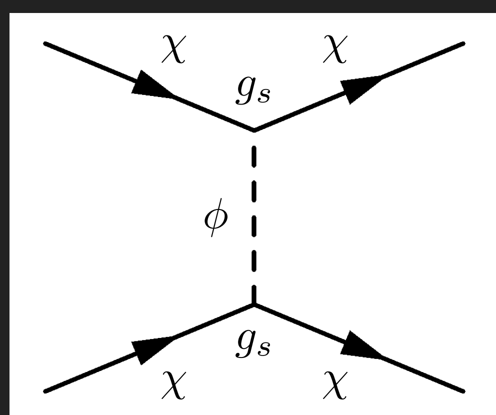
DM couples to *n* & *p* in an asymmetric way → isospin violation effect



What interactions we have so far?

- DM self-interactions

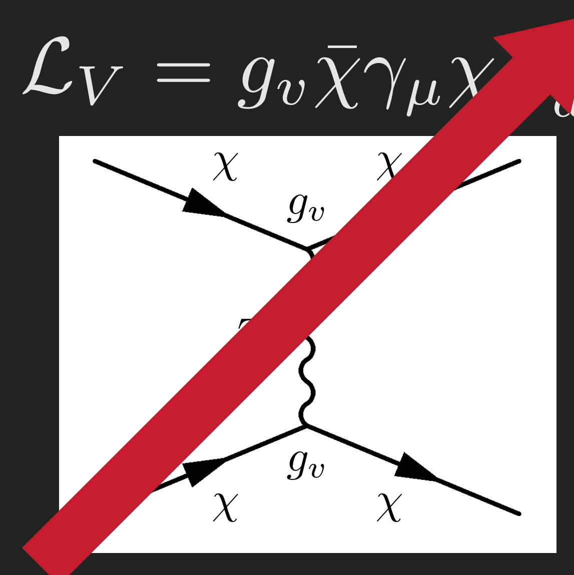
$$\mathcal{L}_S = g_s \phi \bar{\chi}\chi$$



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

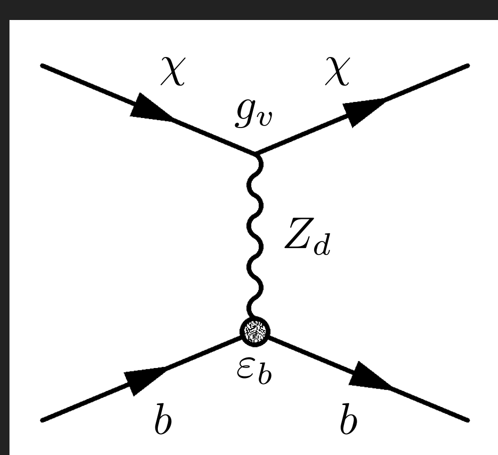
$$\alpha_\chi = \frac{g_s^2}{4\pi}$$

$$\mathcal{L}_V = g_v \bar{\chi}\gamma_\mu \chi Z_d^\mu$$



- DM-SM interactions

$$\mathcal{L}_{\text{int}} = \varepsilon_b \bar{b}\gamma_\mu Z_d^\mu b$$



$$\sigma_{\chi n} = \frac{C_n^2}{m_{Z_d}^4}\varepsilon_n^2$$

$$\sigma_{\chi p} = \frac{C_p^2}{m_{Z_d}^4}\varepsilon_p^2$$

not necessary equals 1

isospin violation

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

$$C_{n,p} = \frac{e g_v \mu_{n,p}}{\sqrt{\pi}}, \quad C_n \approx C_p$$

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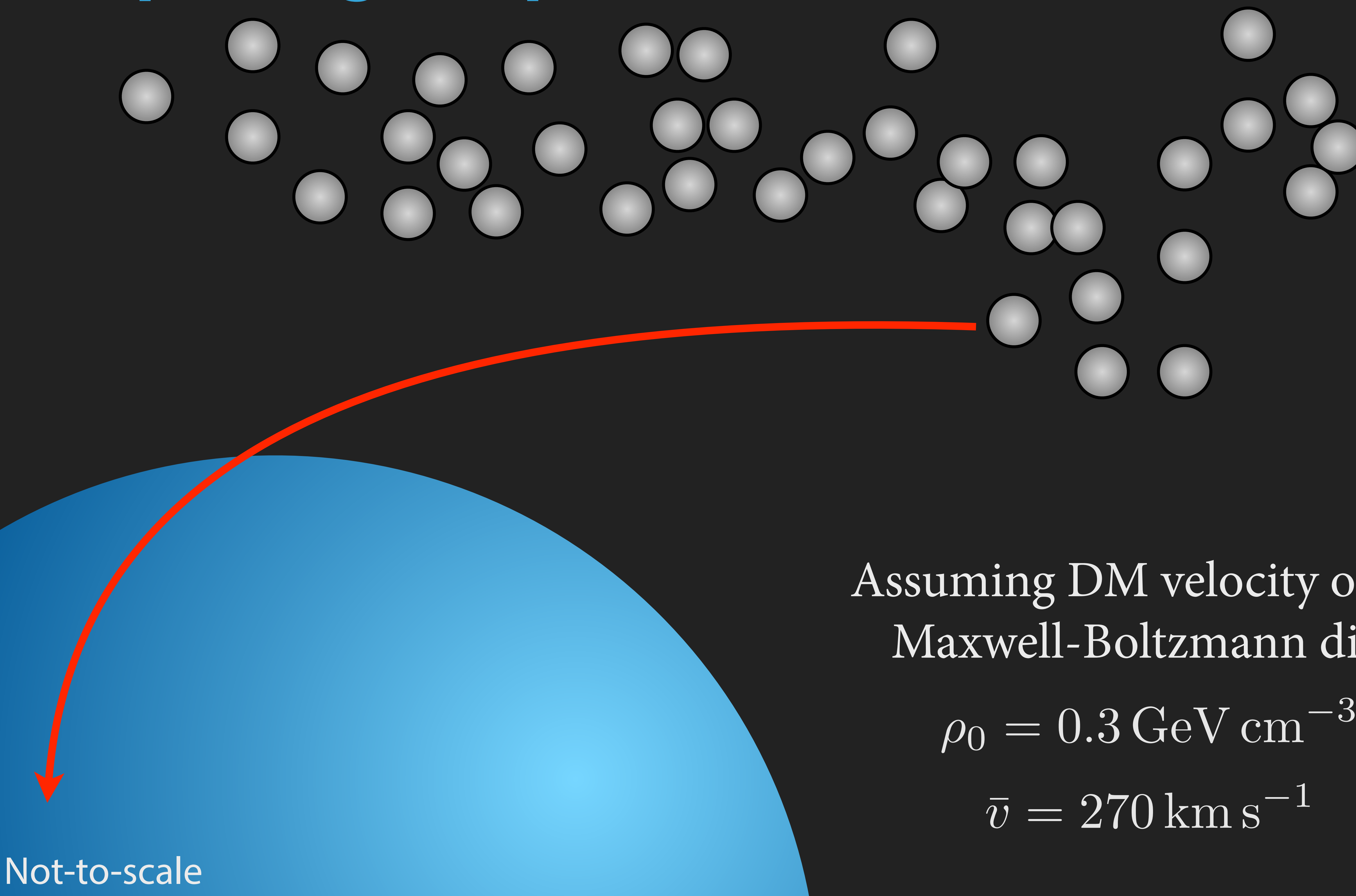
Capturing DM particles



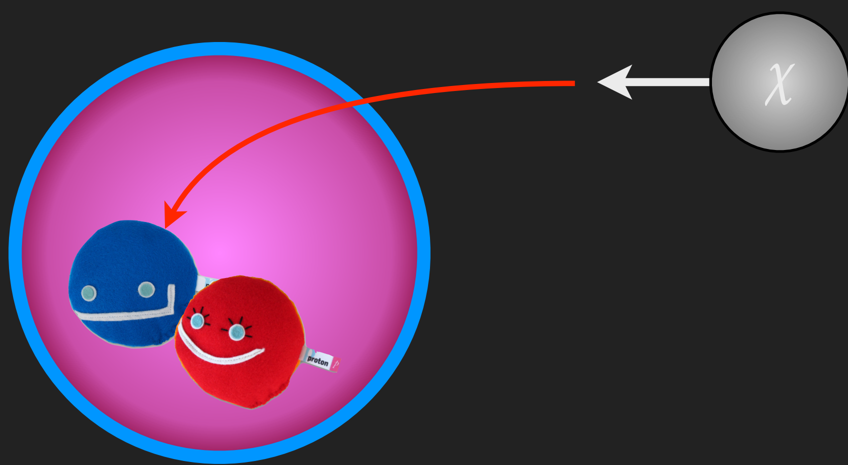
Assuming DM velocity obeys Maxwell-Boltzmann dist.

$$\rho_0 = 0.3\,\mathrm{GeV\,cm^{-3}}$$

$$\bar{v} = 270\,\mathrm{km\,s^{-1}}$$

R. Garani *et al.*, *JCAP* **05**, 035 (2019)
N.F. Bell *et al.*, 2004.14888 (2020)

Capturing DM particles



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

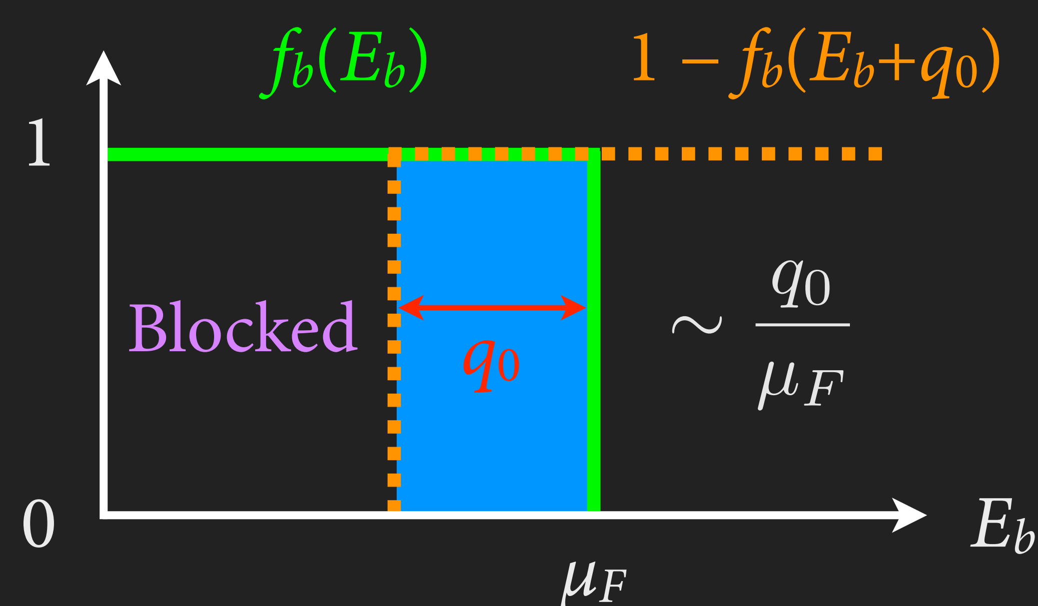
$$C_c = \int_0^{R_\star} 4\pi r^2 dr \left(\frac{\rho_\chi}{m_\chi}\right) \int_0^\infty \frac{f(u)}{u} w(r) du \int_0^{v_{\rm esc}(r)} \Omega^-(w \to v) dv$$

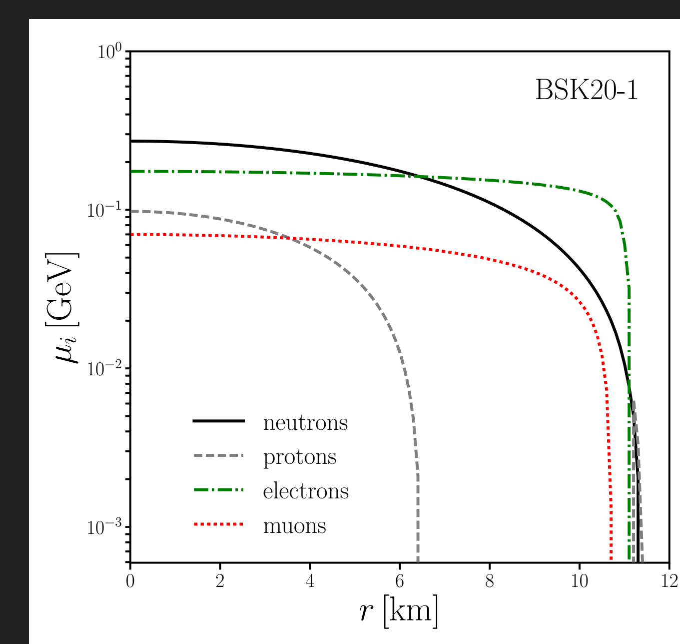
Pauli blocking of baryons

$$\Omega^-(w \to v) = \int n_b(r) \frac{d\sigma_{\chi b}}{dv} |w - u| \underbrace{f_b(E_b, r)}_{\text{before}} \underbrace{[1 - f_{b'}(E_b + q_0, r)]}_{\text{after}} d^3u$$

$$f_b(E_b, r) = \frac{1}{e^{(E_b - \mu_F(r))/T_{\rm NS}(r)} + 1}$$

zero-temp. limit

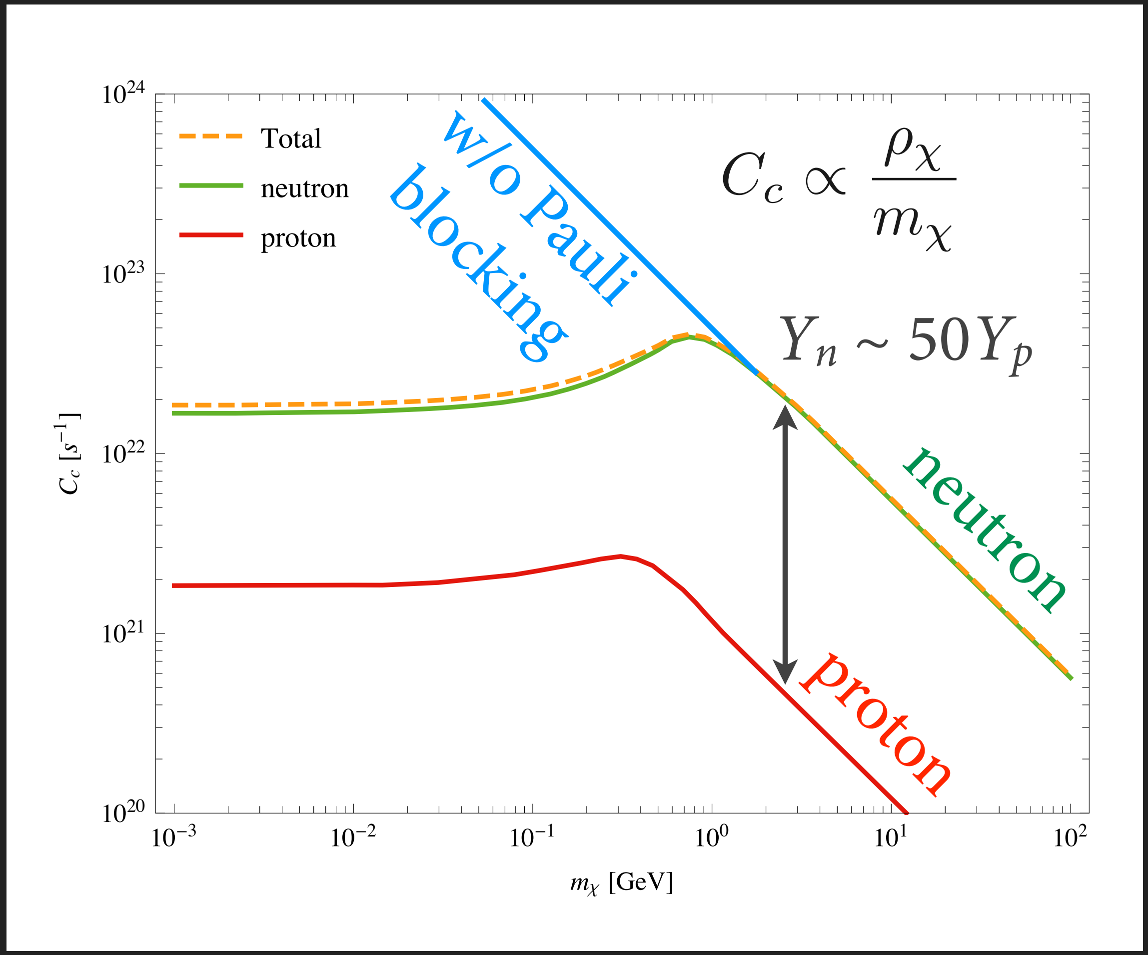




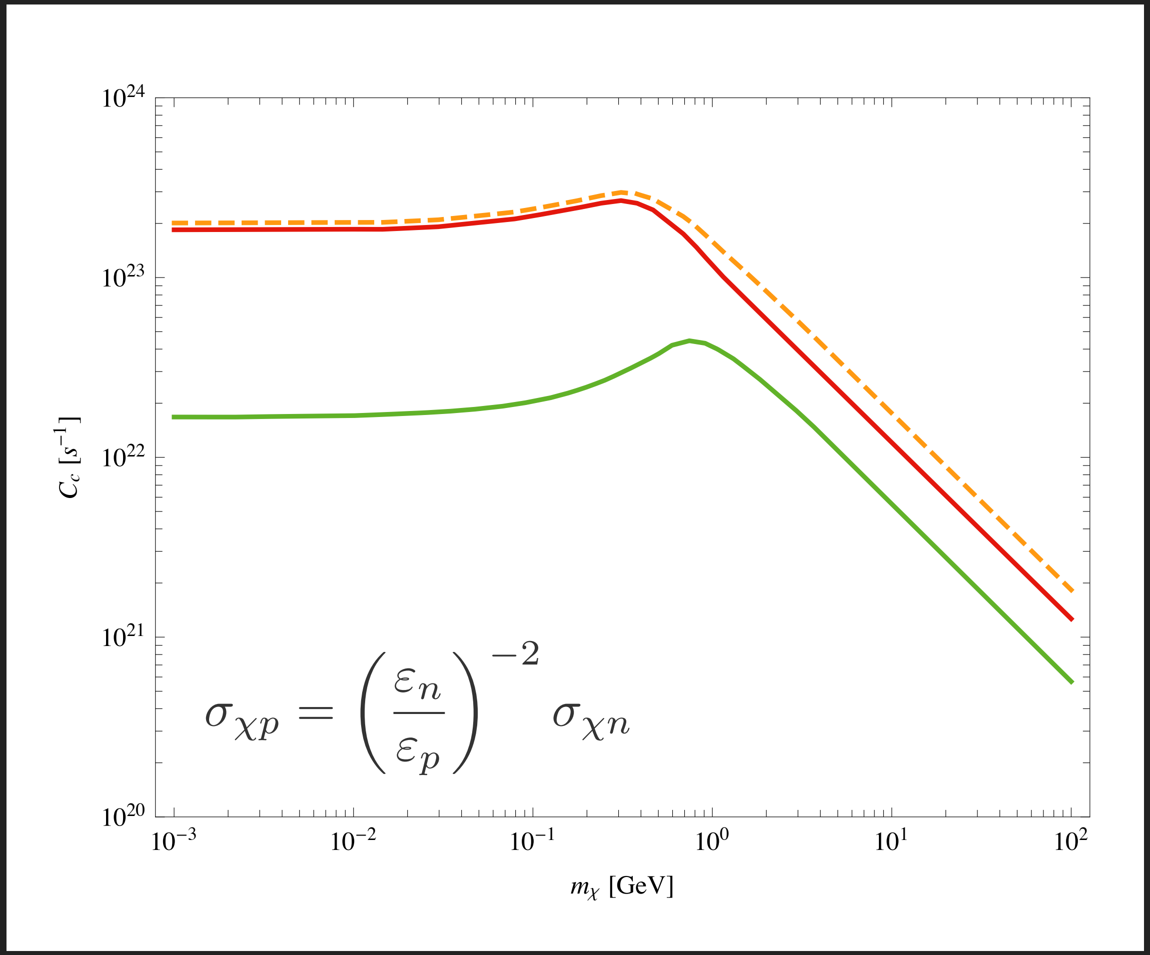
Not-to-scale

Capture rates: constant $\sigma_{\chi n} = 10^{-45}$ cm²

$\varepsilon_n/\varepsilon_p = 1,\ \sigma_{\chi p} = \sigma_{\chi n}$



$\varepsilon_n/\varepsilon_p = 0.1,\ \sigma_{\chi p} = 100\sigma_{\chi n}$



Due to isospin violation, the contribution from proton can become important!

S.D. McDermott *et al.*, *PRD* **85**, 023519 (2012)
Chen *et al.*, *JHEP* **08**, 069 (2018)

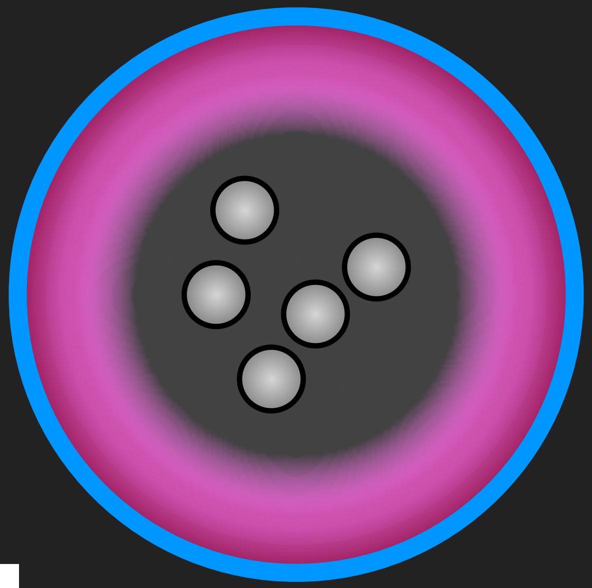
How much DM is inside the NS

- The number of DM particles N_χ

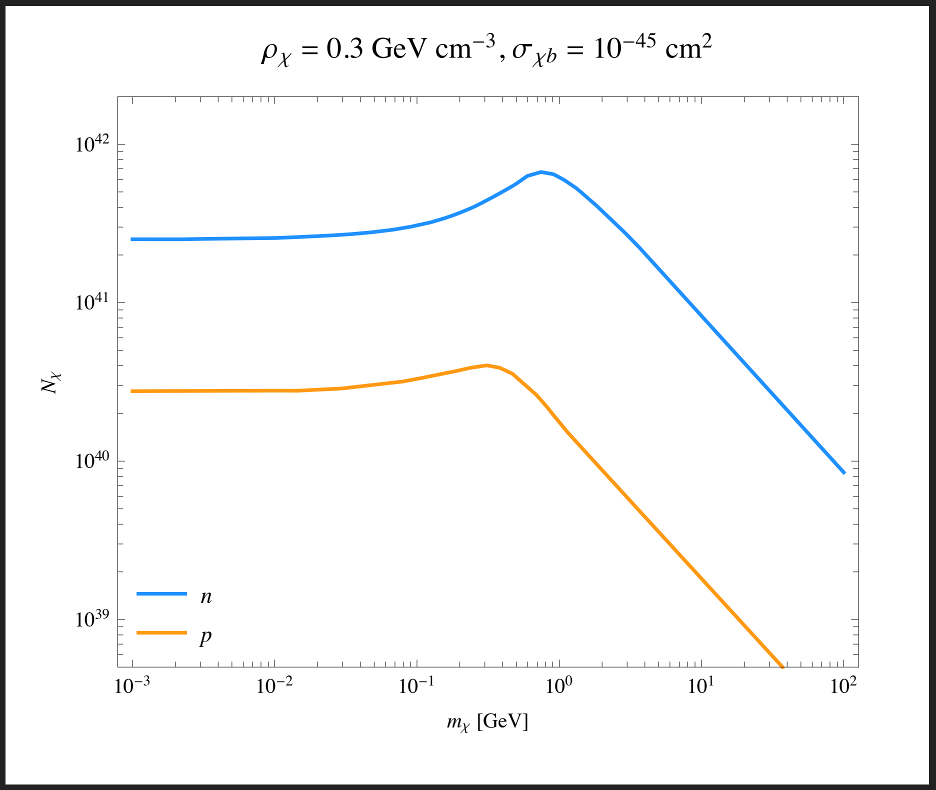
$$\frac{dN_\chi}{dt} = C_c + \cancel{C_s N_\chi}$$

small comparing to C_c

$$N_\chi(t) = C_c t$$



$t = 5$ Gyrs



Not-to-scale

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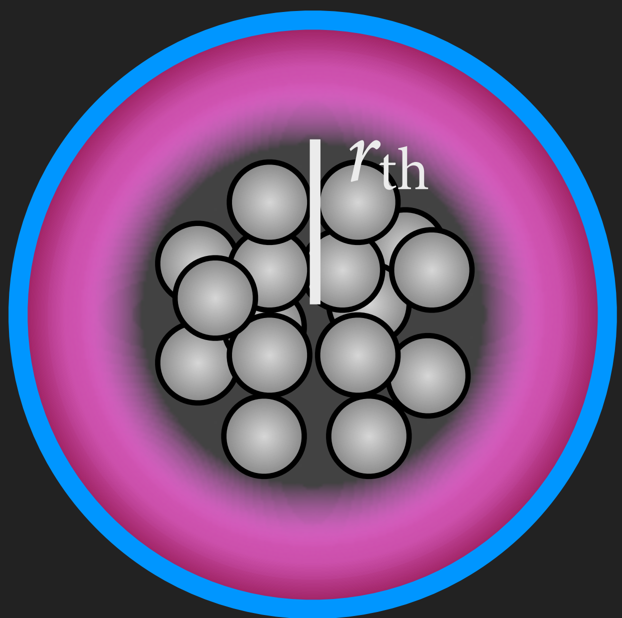
J. Bramante *et al.*, *PRD* **89**, 015010 (2014)

DM SELF-GRAVITATING

N_χ increases through time!



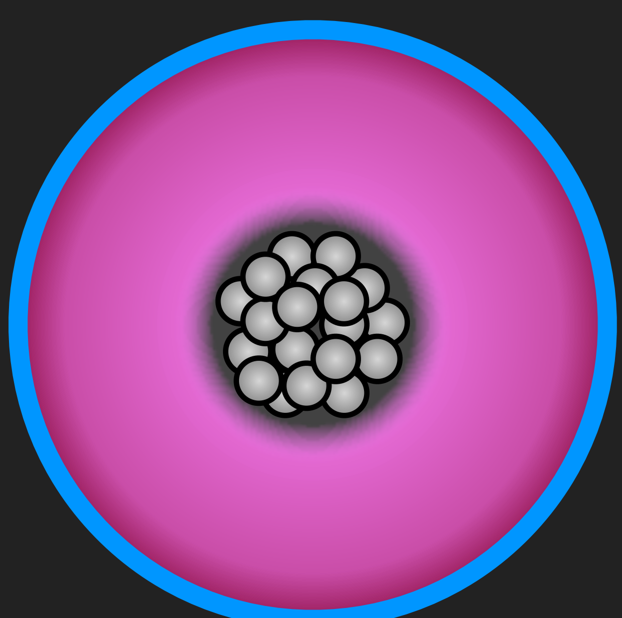
$$r_{\mathrm{th}} = \sqrt{\frac{9k_BT}{4\pi G\rho_b m_\chi}}$$

DM self-gravity

$$2\langle E_k\rangle = \underbrace{\frac{4\pi G\rho_b m_\chi r^2}{3}}_{} + \overbrace{\frac{GN_\chi m_\chi^2}{r}}^{U_{\mathrm{g,DM}}}$$

r_{th} holds when this equality holds

The virial equation will rebalance until r becomes smaller than r_{th}!



- NS keeps capturing DM particles, N_χ will continue growing

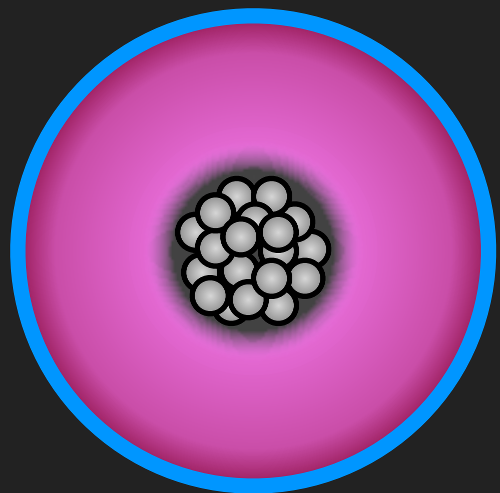
  $r \to$ smaller and smaller: **DM self-gravitating**

- Rough estimation

$$N_\chi^{\mathrm{sg}} > \frac{4\pi r_{\mathrm{th}}^3}{3}\frac{\rho_b}{m_\chi}$$

Not-to-scale

DM COLLAPSE



- When DM initiates self-gravitating, r becomes smaller and smaller

Yukawa potential

$$2\langle E_k\rangle = \frac{GN_\chi m_\chi^2}{r} + U_{\mathrm{Yuk}}$$

- E_k will be replaced by Fermi energy E_F when DM becomes too crowded in the star ($E_F < m_\chi$, *non-relativistic*)

$$\frac{GN_\chi m_\chi^2}{r_{\mathrm{deg}}} > 2E_F^{\mathrm{non-rel}} \Rightarrow N_\chi^{\mathrm{Fermi}} > \frac{3\sqrt{3(\pi G)^3\rho_b}}{2m_\chi^5} \approx 1.73\times 10^{56}\left(\frac{\mathrm{GeV}}{m_\chi}\right)^5$$

In general, NS **cannot** capture this much DM within $t_{\mathrm{Univ.}}$

- The attractive Yukawa interaction U_{Yuk} can reduce N^{Ch}

$$U_{\mathrm{Yuk}} = \sum_j^{N_\chi-1}\left(\frac{\alpha_\chi}{r_j}e^{-m_\phi r_j} + \alpha_\chi m_\phi e^{-m_\phi r_j}\right)$$

Coulomb-like

$$r_j < 1/m_\phi : \quad \frac{4\pi\alpha_\chi m_\phi}{y^3} \qquad y \equiv r_j m_\phi$$

$$r_j > 1/m_\phi : \quad 8\alpha_\chi\left(\frac{m_\phi e^{-y}}{y} + m_\phi e^{-y}\right)$$

short-distanced

Not-to-scale

BH formation in the NS

- To proceed collapse, $U_{\rm Yuk}$ must overcome the *relativistic* Fermi pressure in the final stage ($E_F \gtrsim m_\chi$)

non-relativistic $U_{\rm Yuk} > 2E_F^{\rm non-rel}$

relativistic $U_{\rm Yuk} > 2E_F^{\rm rel}$

→ $N_\chi^{\rm Fermi} \sim 10^{25}\alpha_\chi^{-6}\left(\frac{m_\phi}{\rm MeV}\right)^{12}\left(\frac{m_\chi}{\rm GeV}\right)^{-9}$

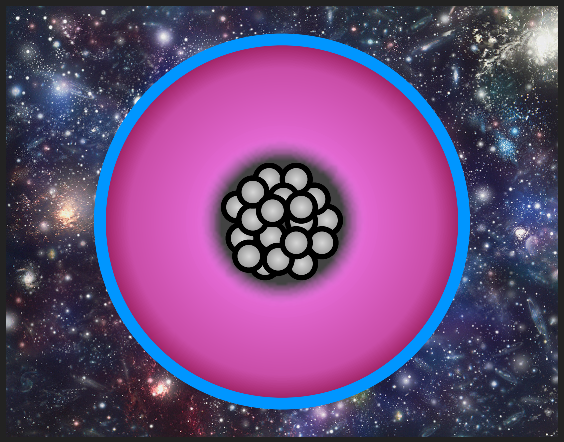
$\alpha_\chi > 4.7\frac{m_\phi^2}{m_\chi^2}$

- However, even a BH can form, it could suffer from Hawking radiation

$$\frac{dM_{\rm BH}}{dt} = \frac{4\pi(GM_{\rm BH})^2\rho_b}{v_s^3} - \frac{1}{15360\pi(GM_{\rm BH})^2}$$

accretion — Hawking radiation

→ $M_{\rm BH} \gtrsim 3\times10^{36}\,{\rm GeV}$



- When everything is setup:
  - $N_\chi > N_\chi^{\rm sg}$: DM self-gravitating
  - $N_\chi > N_\chi^{\rm Fermi}$: To overcome Fermi pressure
  - $N_\chi = \frac{M_{\rm BH}}{m_\chi} > 3\times10^{36}\left(\frac{\rm GeV}{m_\chi}\right)$: Avoiding BH evaporation

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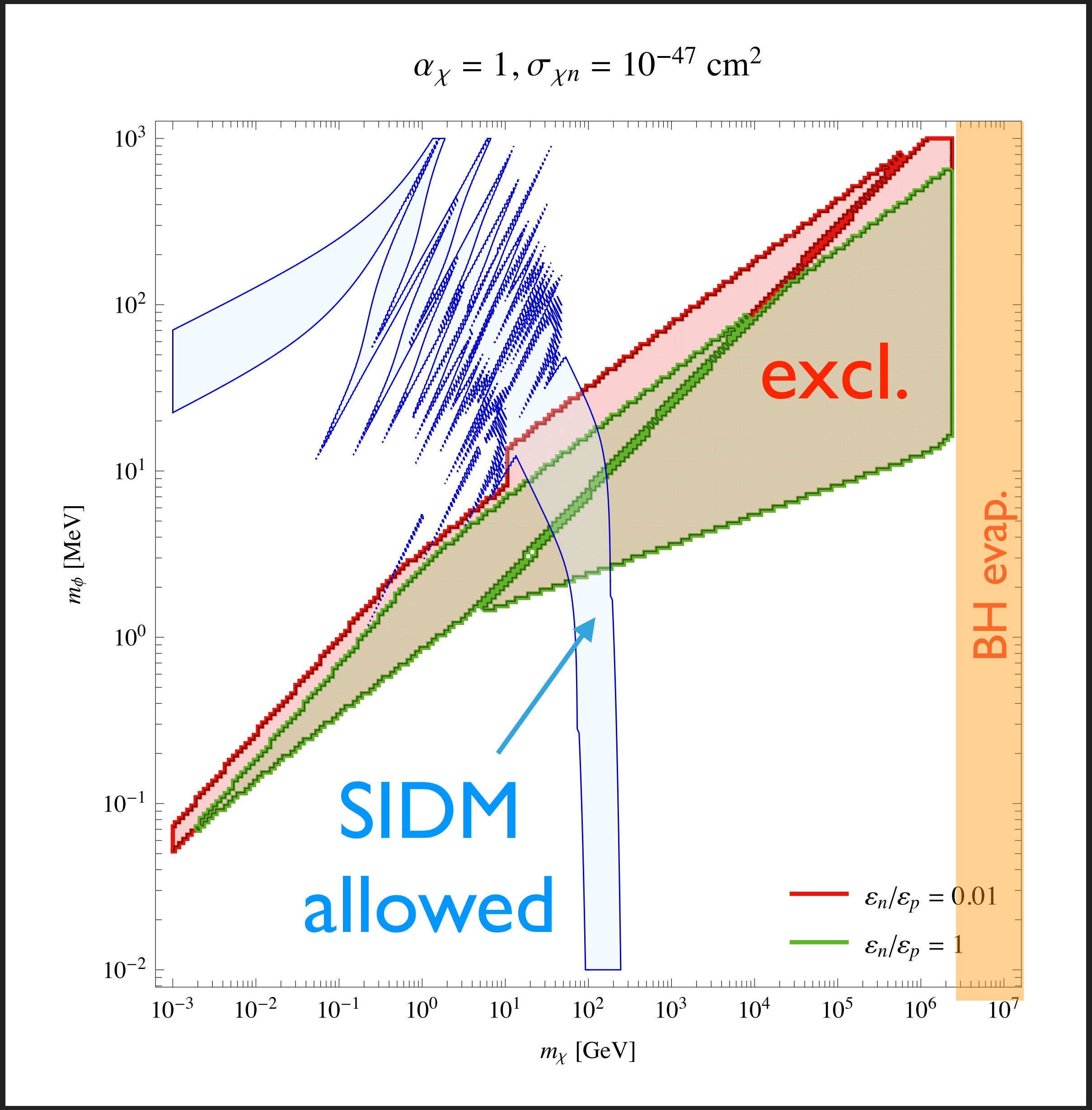
Exclusion plots for m_χ-m_φ plane

$$\left(\frac{\varepsilon_n}{\varepsilon_p}\right)^{-2} \sigma_{\chi n}$$



- $N_\chi = C_c t \propto N_n \sigma_{\chi n} + N_p \sigma_{\chi p}$
- To trigger BH formation
  - $N_\chi > N^{sg}$ with the given time $t = 5$ Gyr

$$2\langle E_k \rangle = U_{\rm g,NS} + U_{\rm g,DM} + U_{\rm Yuk}$$

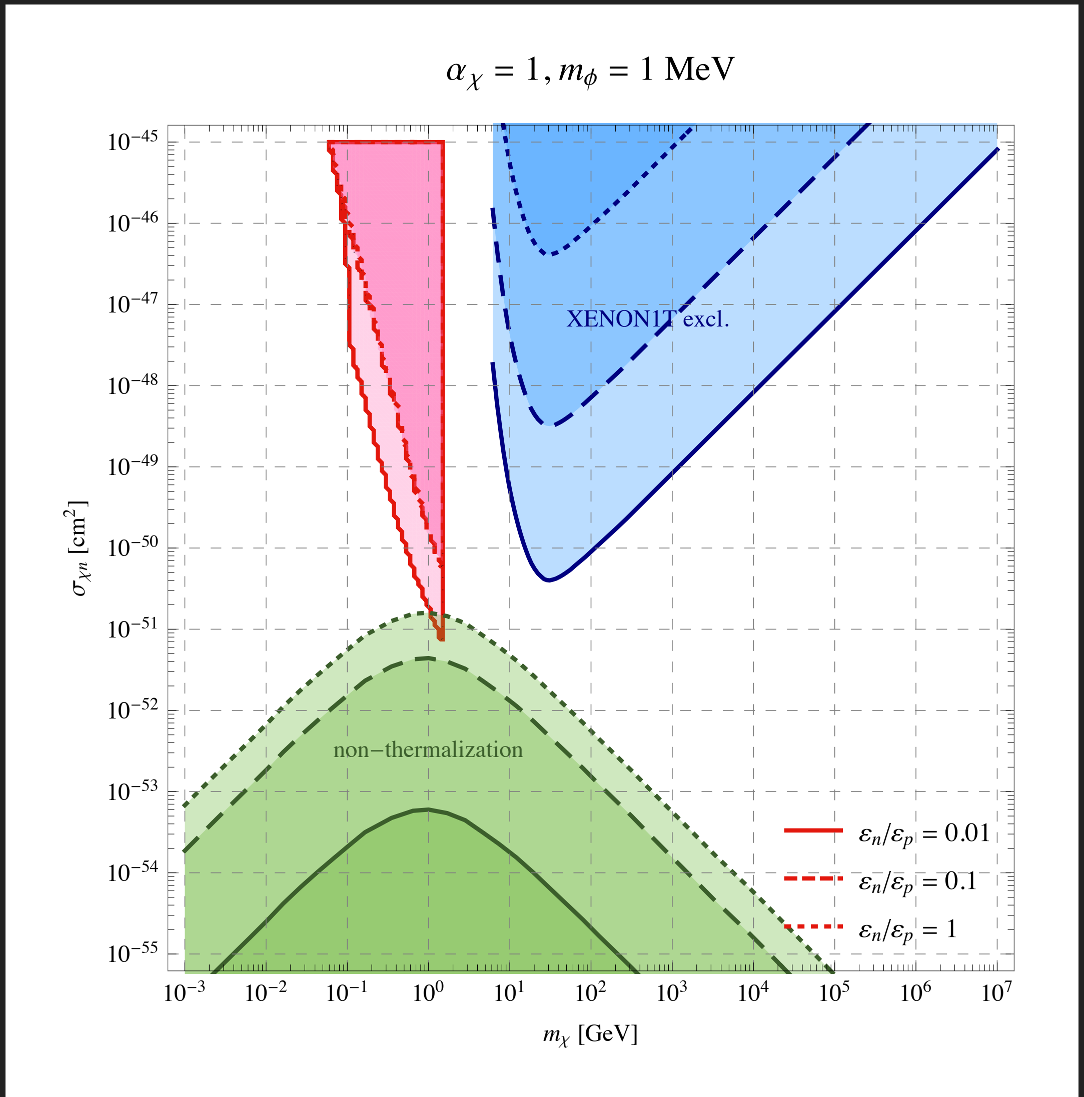
  - To overcome relativistic Fermi pressure

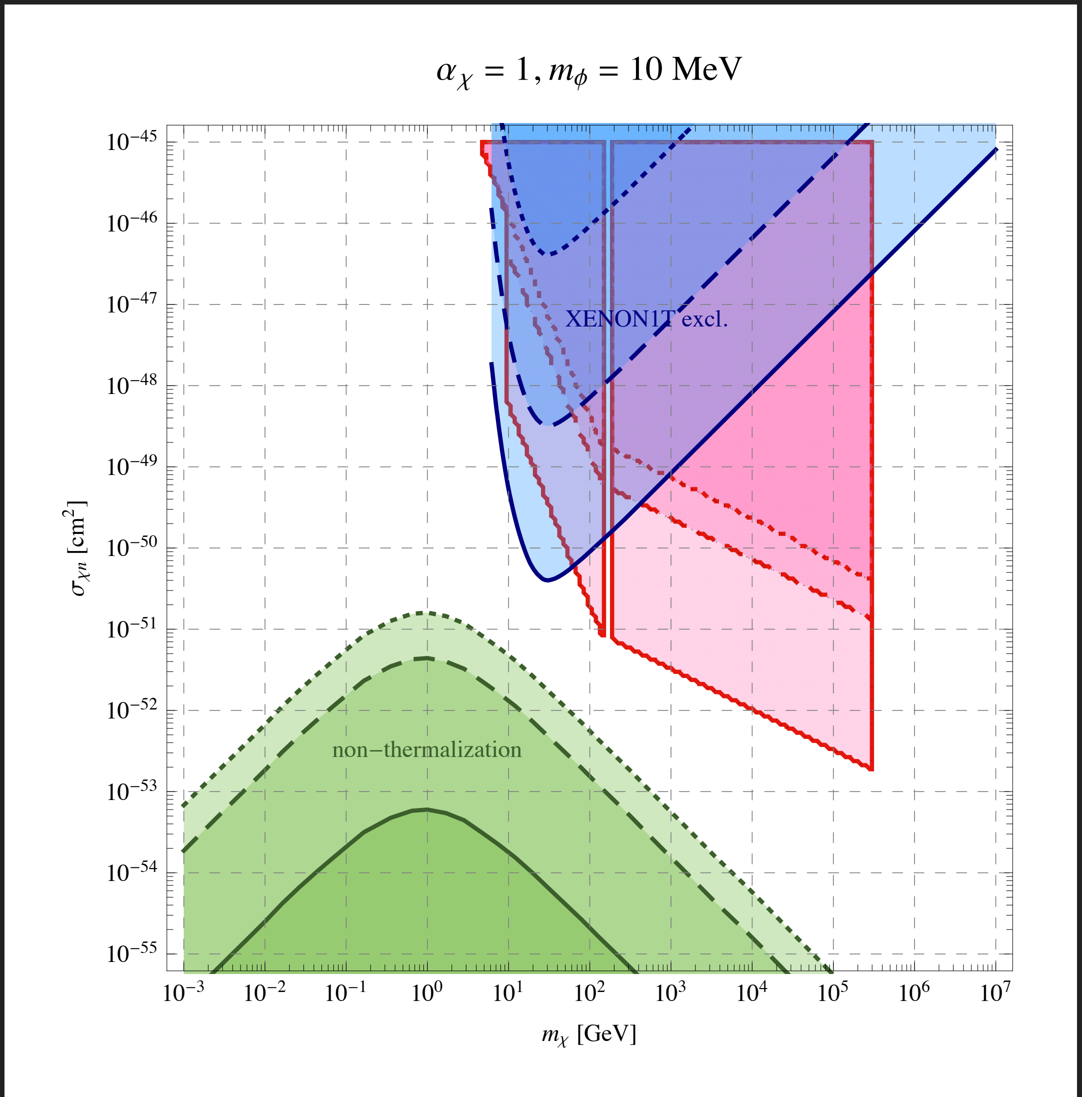
$$\alpha_\chi > 4.7 \frac{m_\phi^2}{m_\chi^2}$$

  - To avoid BH evaporation

$$N_\chi m_\chi = M_{\rm BH} > 3 \times 10^{36}\ {\rm GeV}$$

NS sensitivity on $\sigma_{\chi n}$ and $\varepsilon_n/\varepsilon_p$: $\alpha_\chi = 1$





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Summary

- NS acts as a complementary probe to other DM detections
- Proton can significantly contribute to DM capture rate in the presence of isospin violation
- If DM particles self-interact attractively, BH can form inside the NS
- By observing Gyr-old NS can set constraints on DM parameters α_χ, m_χ, m_ϕ, $\sigma_{\chi n,p}$
- Model-independent analysis with a well-motivated $U(1)_d$ pheno model to justify the way