Bounds on Long-lived Dark Matter Mediators from Neutron Stars

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(In preparation)

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Dark Interactions
New Perspectives from Theory and Experiment
Brookhaven National Laboratory

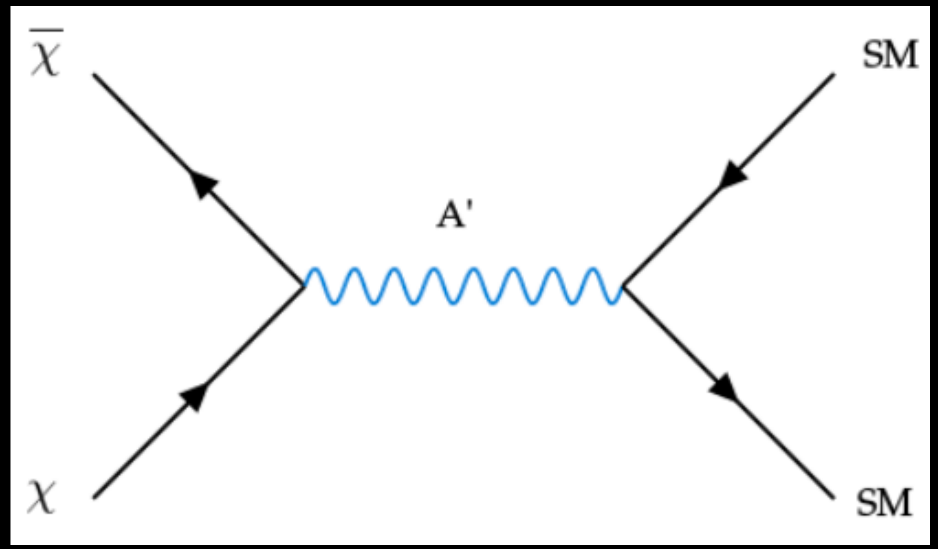
Outline

Available on Amazon,
Come with different flavors.

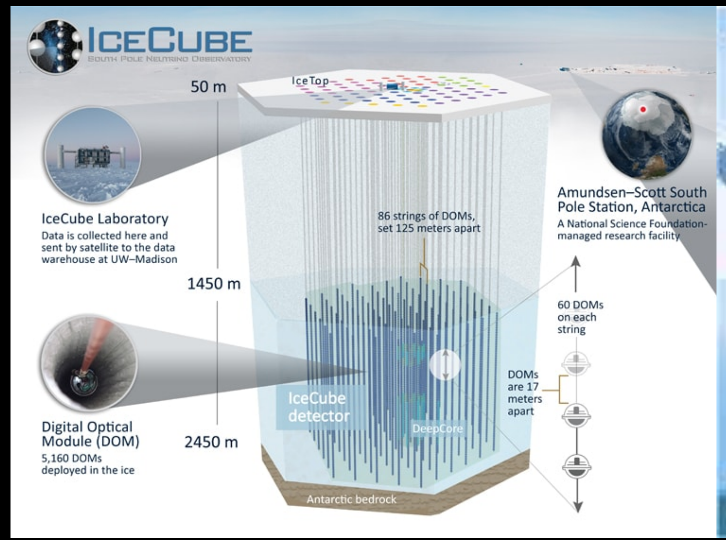
Neutron Stars in
Galactic Center.

Free High Energy Colliders!!

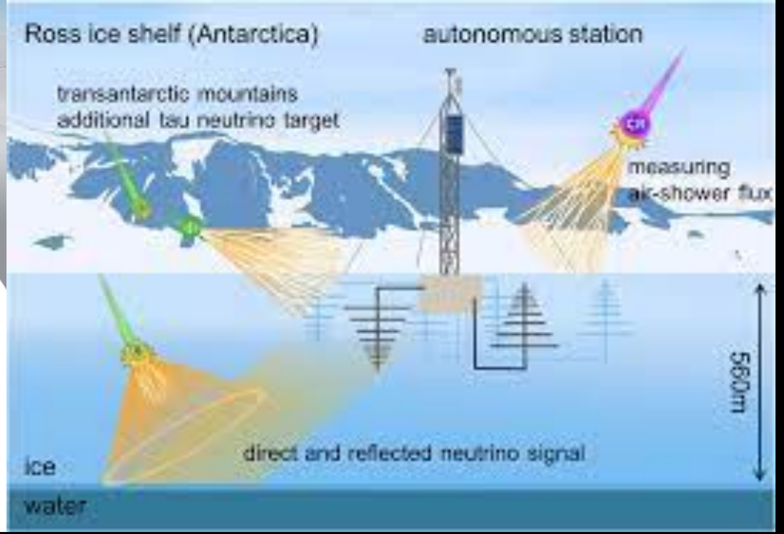
The DM model.



Bounds of
$\sigma_{\chi n}^{\rm SI}(m_\chi)$.



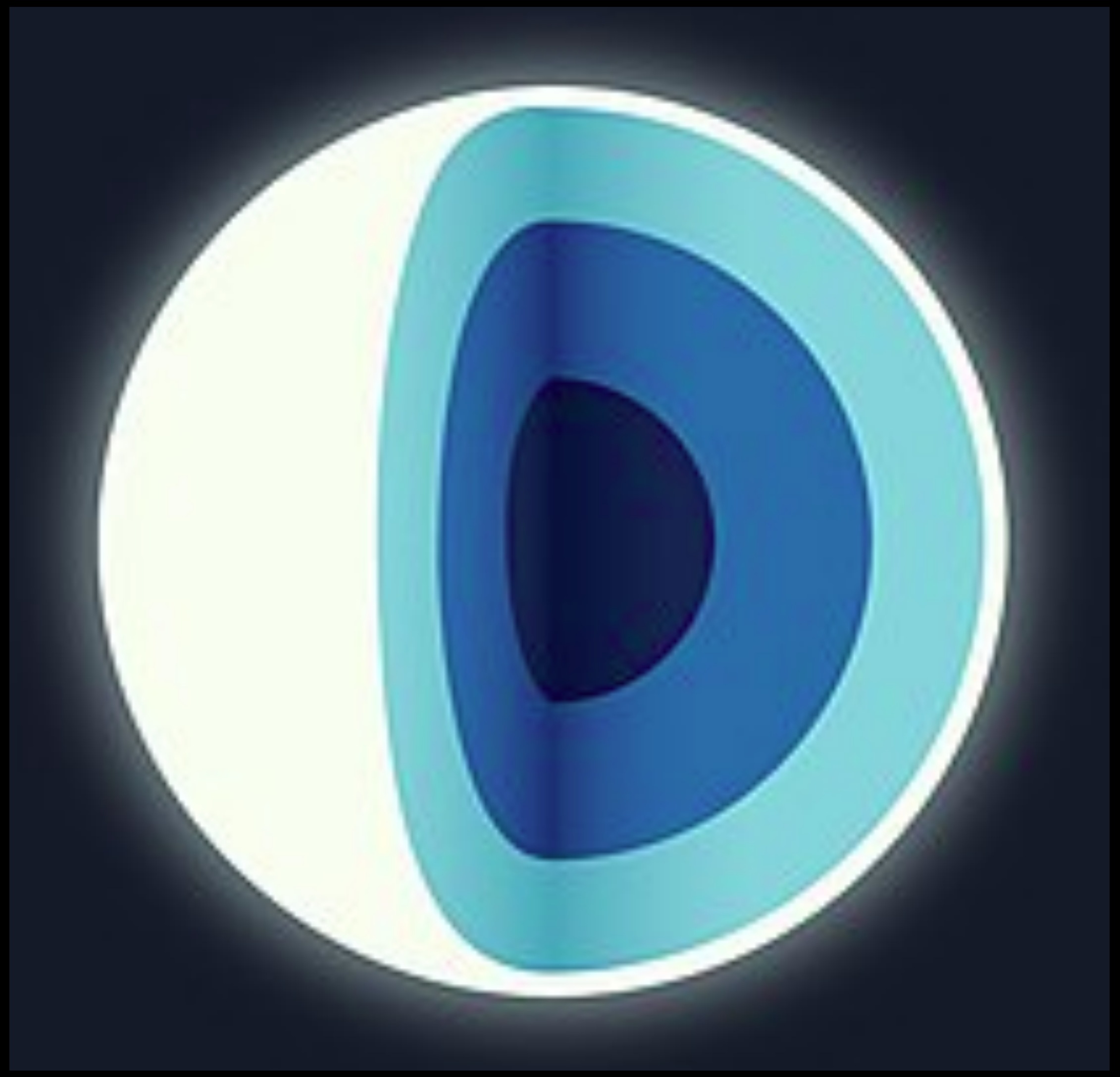
IceCube



ARIANNA
(Projections).

Experimental results

Neutron Stars in Galactic Center



- Make from neutrons: $m_n = 1.0\ \mathrm{GeV}$.
- Mass: $M_{\mathrm{ns}} \approx 1.5\ M_{\odot}$, Radius: $R_{\mathrm{ns}} \approx 10\ \mathrm{km}$.
- (Blueshift) Escape velocity:

  $$v_{\mathrm{esc}} \approx 2.1 \times 10^5\ \mathrm{km/s},$$
- Saturation Cross Section:

  $$\sigma_{\mathrm{sat}} = \pi R_{\mathrm{n}}^2 / N_n \approx 1.87 \times 10^{-45}\ \mathrm{cm}^2.$$

Neutron Star's number density in Galactic Center:[1]

$$n_{\mathrm{ns}}(r) = 5.98 \times 10^3 \left(\frac{r}{1\mathrm{pc}}\right)^{-1.7} \mathrm{pc}^{-3}\ (0.1\mathrm{pc} < r < 2\mathrm{pc})$$

$$= 2.08 \times 10^4 \left(\frac{r}{1\mathrm{pc}}\right)^{-3.5} \mathrm{pc}^{-3}\ (r > 2\mathrm{pc})\,.$$

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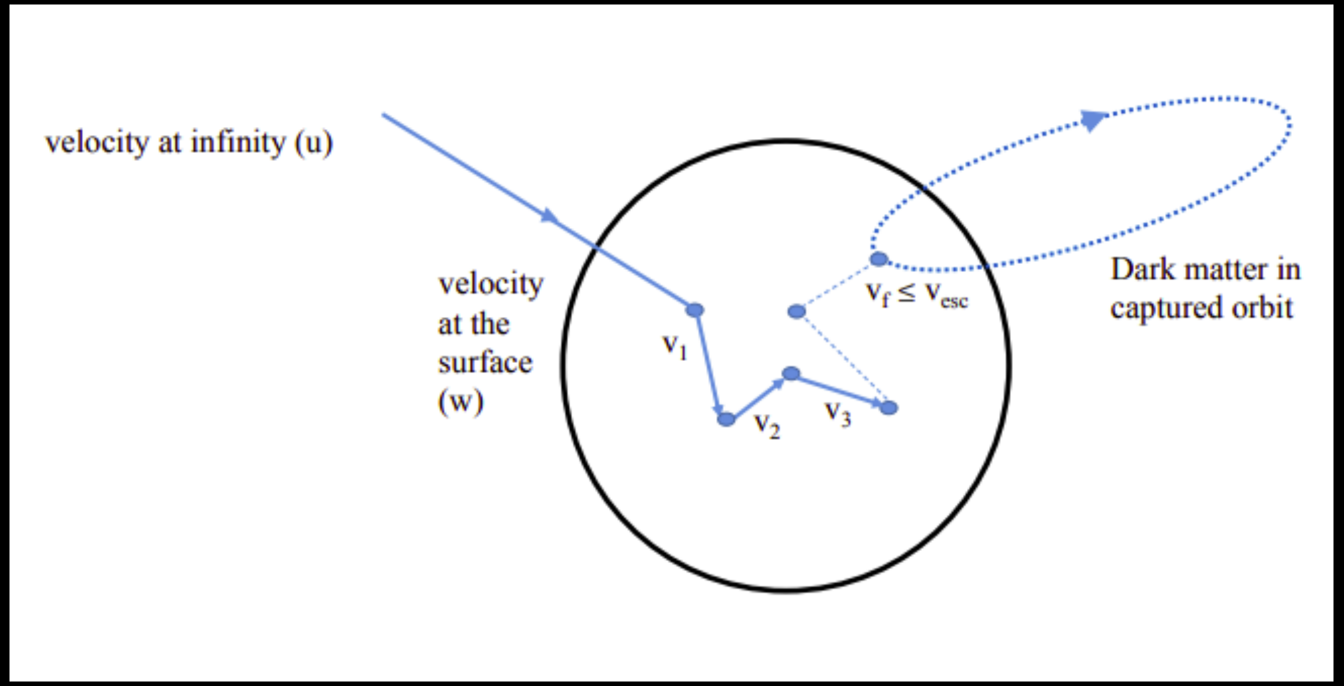
[1] This density is extracted from Fig. 2 of arXiv:1804.01543.

Dark Matter capture by neutron stars

Figure from arXiv:1906.04204



$v_f \leq v_{\text{esc}} \Rightarrow$ Captured!

Dark Matter Capture Rate after Nth times [GeV]:

$$C_N = \frac{\pi R_\star p_N(\tau)}{1 - 2G_N M_\star / R_\star} \frac{\sqrt{6} n_\chi}{3\sqrt{\pi}\bar{v}} \times \left[2\bar{v}^2 + 3v_{\text{esc}}^2 - (2\bar{v}^2 + 3v_N^2)\exp\left(-\frac{3(v_N^2 - v_{\text{esc}}^2)}{2\bar{v}^2} \right) \right].$$

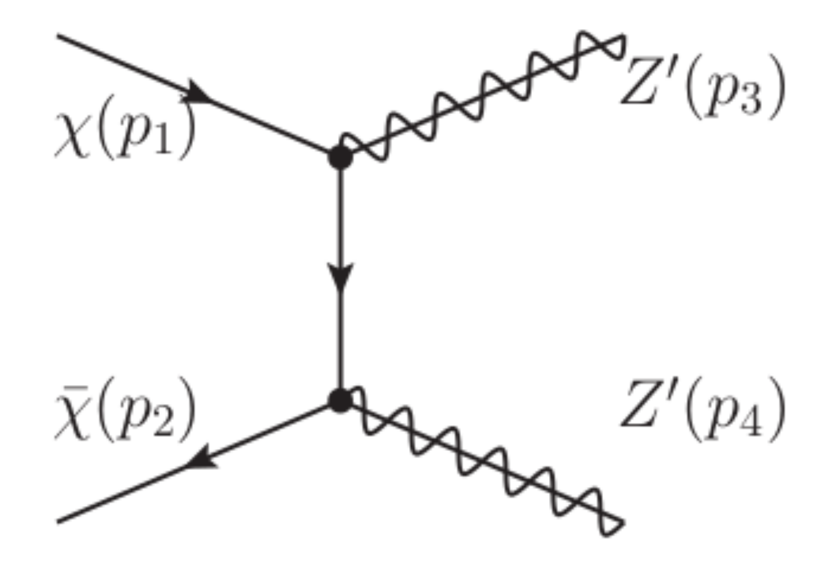
- Capture rate (1 NS): $C = \sum_{N=1}^{\infty} C_N.$

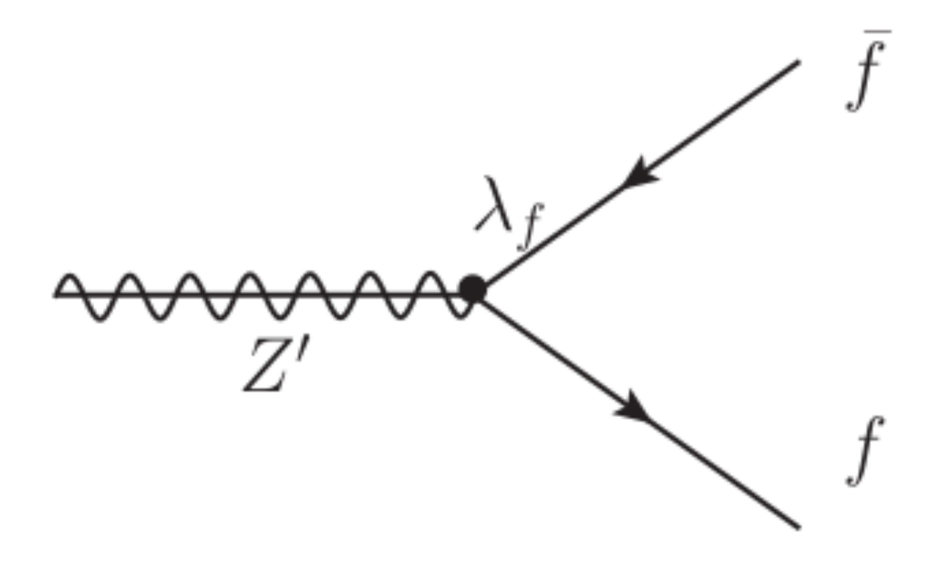
Optical Depth: $\tau = 1.5 \frac{\sigma_{\chi n}}{\sigma_{\text{sat}}}$

$\sigma_{\chi n}$ → DM model.

σ_{sat} → Celestial object.

- Total capture rate (All NSs): $C_{\text{tot}} = 4\pi \int_{r_1=0.1\text{pc}}^{r_2=100\text{pc}} r^2 n_{\text{ns}} C dr.$





Equilibrium: $\Gamma_{\text{ann}} = \frac{\Gamma_{\text{cap}}}{2} = \frac{C_{\text{tot}}}{2}.$

Differential Energy Flux (measured by ID Experiments):

$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\text{ann}}}{4\pi D^2} \times E^2 \frac{dN}{dE} \times \text{BR}(X \to \text{SM}) \times P_{\text{surv}} \quad [\text{GeV cm}^{-2}\ \text{s}^{-1}]$$

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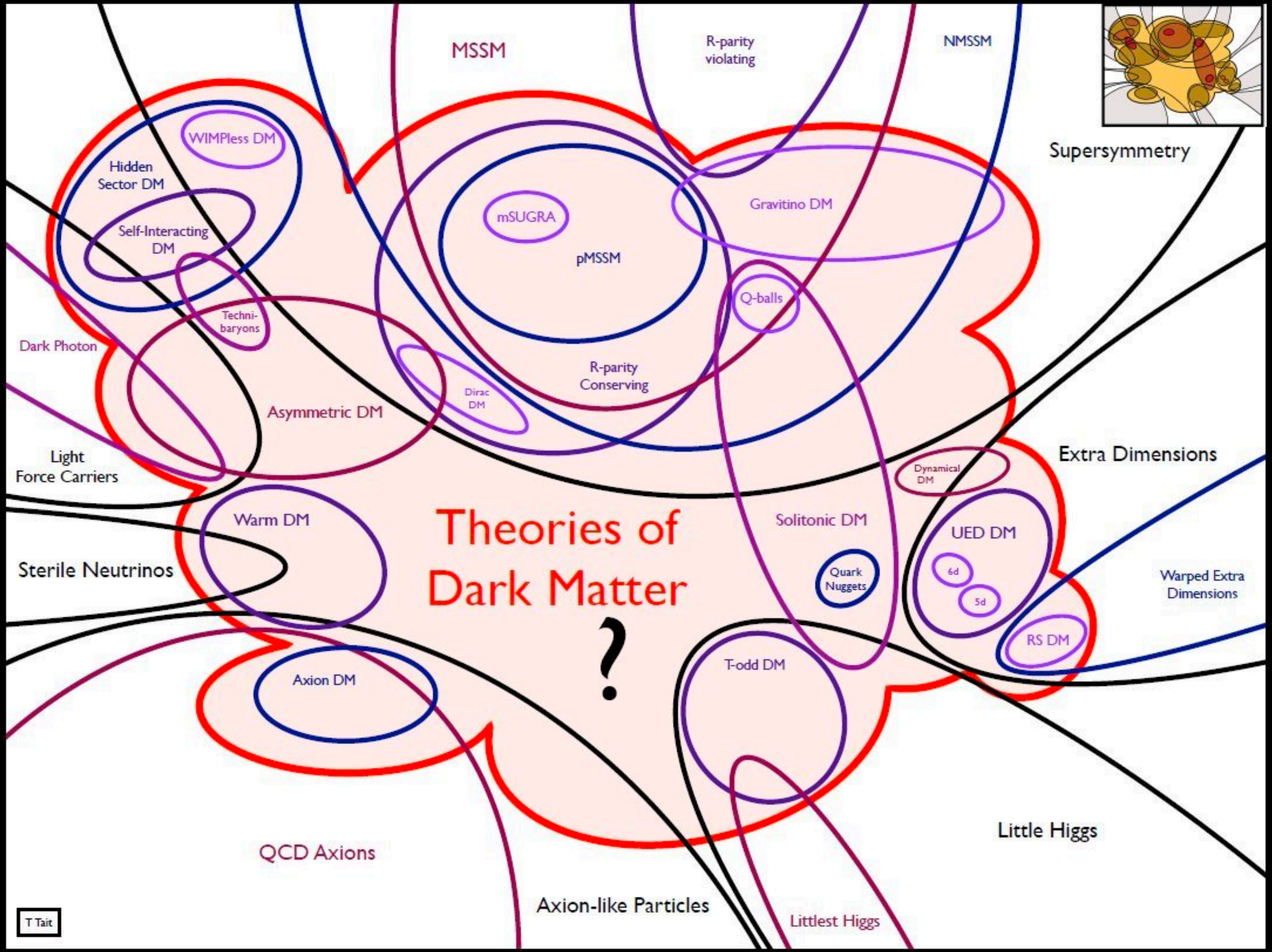
2. Rebecca K. Leane, Tim Linden, Payel Mukhopadhyay, Natalia Toro (arXiv:2101.12213).

Which DM model?

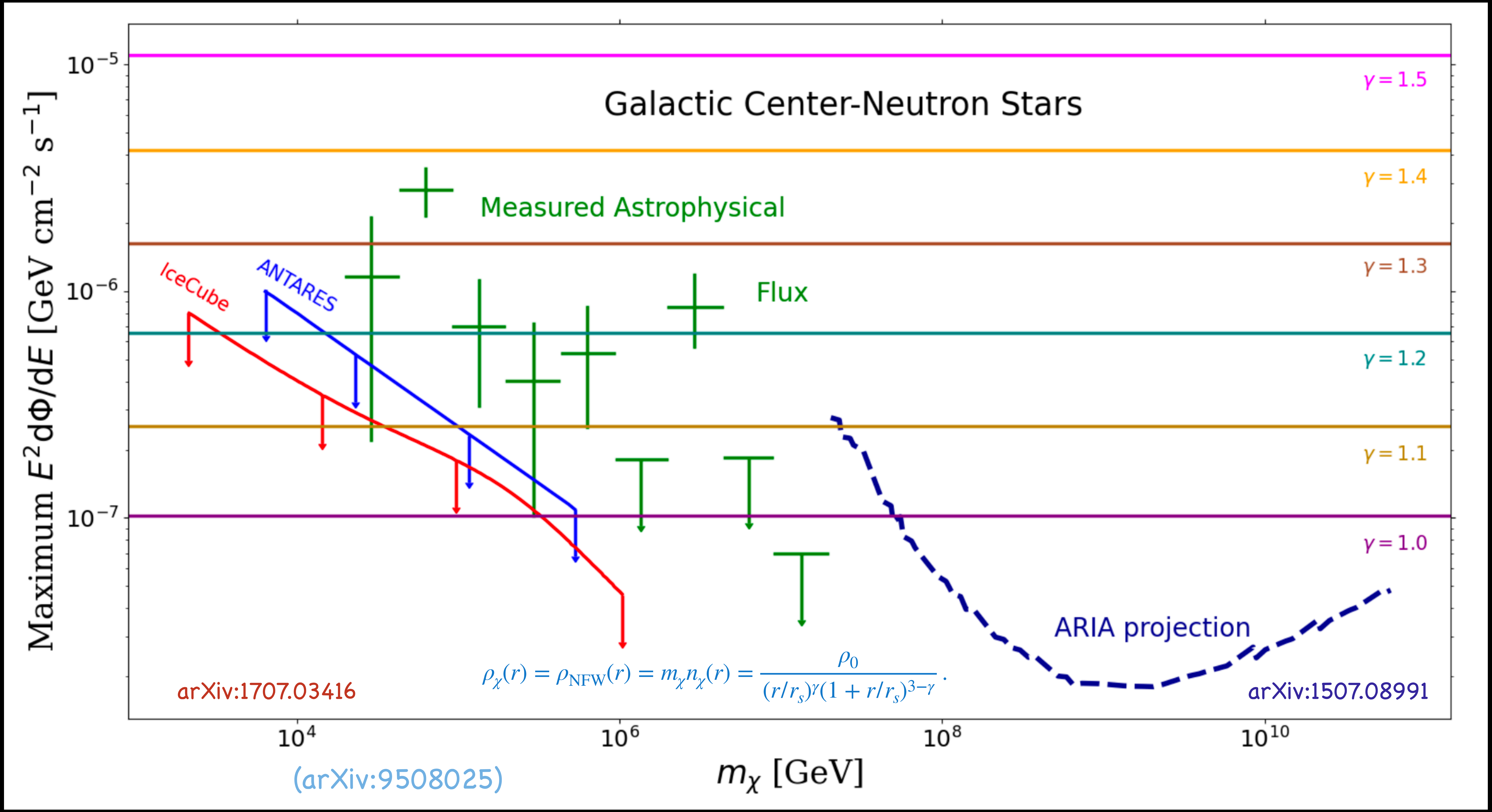
Our
consideration

$$SU(2)_L \times U(1)_Y \times U(1)_X$$

$$\mathscr{L} \supset -\frac{1}{4}\mathscr{D}_{\mu\nu}\mathscr{D}^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}\mathscr{D}^{\mu\nu}$$
$$+\bar{\chi}(i\gamma^{\mu}D_{\mu} - m_{\chi})\chi\,.$$



Neutrinos experimental results



$$\rho_\chi(r) = \rho_{\rm NFW}(r) = m_\chi n_\chi(r) = \frac{\rho_0}{(r/r_s)^\gamma(1+r/r_s)^{3-\gamma}}\,.$$

Fig. 1: Differential Energy Flux of muon neutrino: Experimental upper limits and data. The horizontal lines for maximum fluxes from NS in GC after integrate all over the sky.

(SI) Cross Section limits

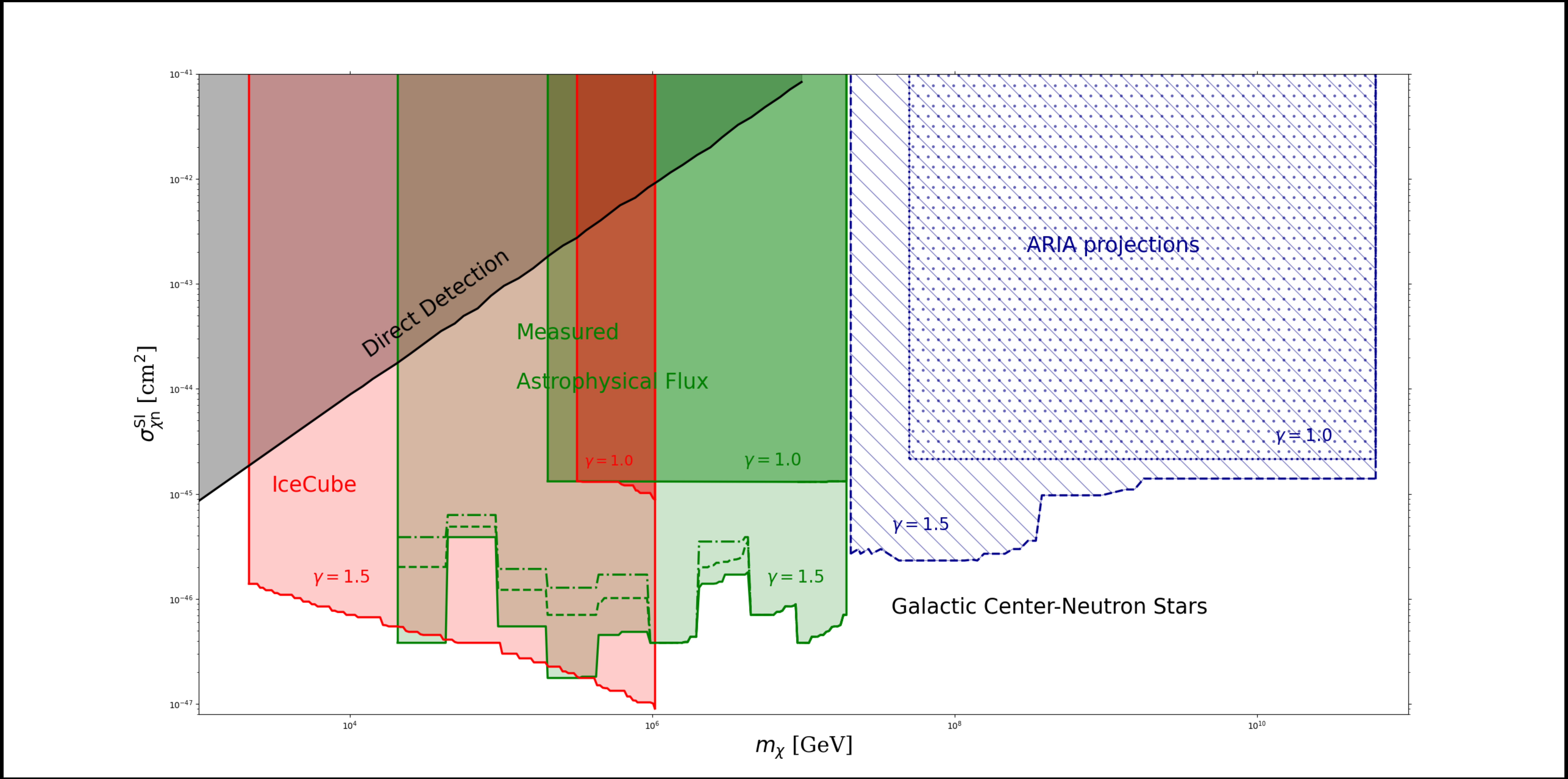


Fig. 2: SI Cross Section limits, using IceCube, Measured Astrophysical (muon) Neutrino, and ARIA projection.

Take home message

- Neutron Stars can help us investigate Long-lived Dark Matter Mediator models.
- With Light Z'-model and current IceCube result, the bounds for SI Cross Section of DM-neutron can be pushed down to $10^{-46} - 10^{-47}\ \mathrm{cm}^2$ (TeV - PeV mass range).
- Can use other celestial objects with large number in Galactic Center: Brown Dwarfs, White Dwarfs, …
- Motivation for experimental results: ARIANNA, K3MNet, IceCube Gen2, …

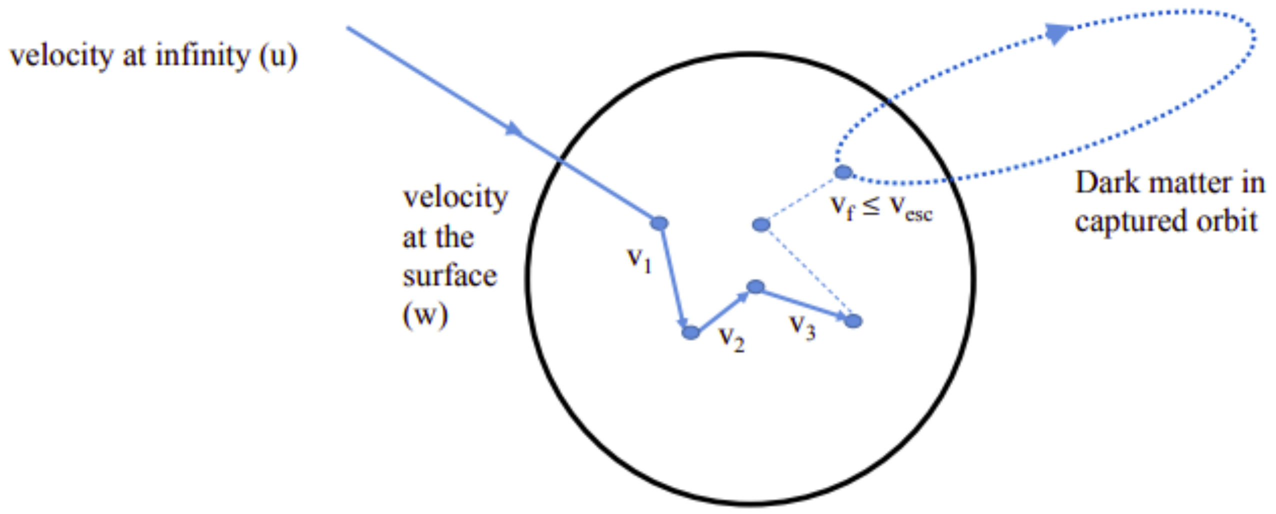
Thank you for listening!

I'm searching for
Dog-Matter too!!

BRACE YOURSELF
BACKUP SLIDES ARE COMING
memegenerator.net

Dark Matter capture by neutron stars

arXiv:1906.04204



Capture rate (1 NS): $C = \sum_{N=1}^{\infty} C_N.$ (6)

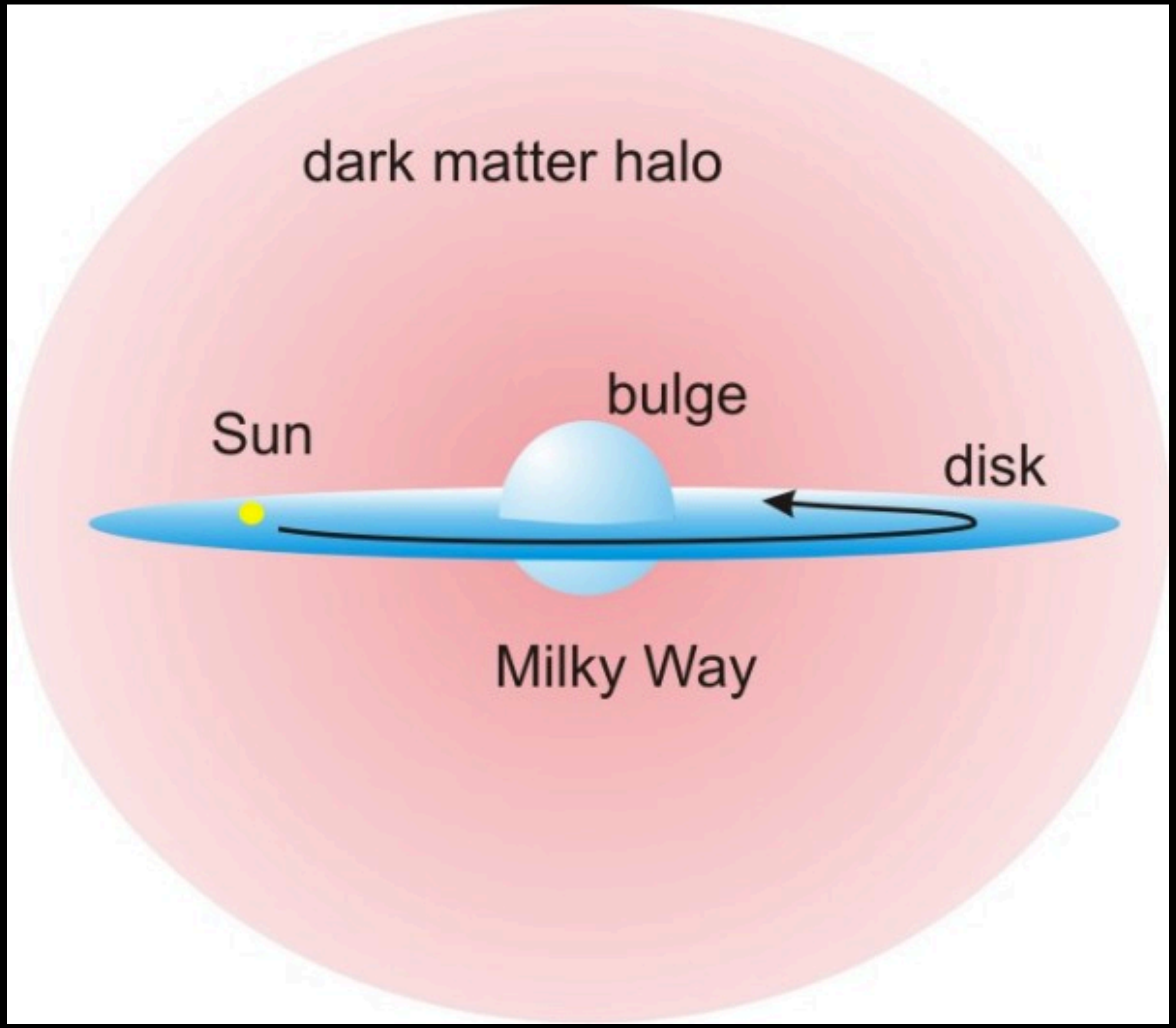
Total capture rate (All NSs): $C_{\text{tot}} = 4\pi \int_{r_1=0.1\text{pc}}^{r_2=100\text{pc}} r^2 n_{\text{ns}} C dr.$ (7)

Optical Depth: $\tau = 1.5 \frac{\sigma_{\chi n}}{\sigma_{\text{sat}}}$

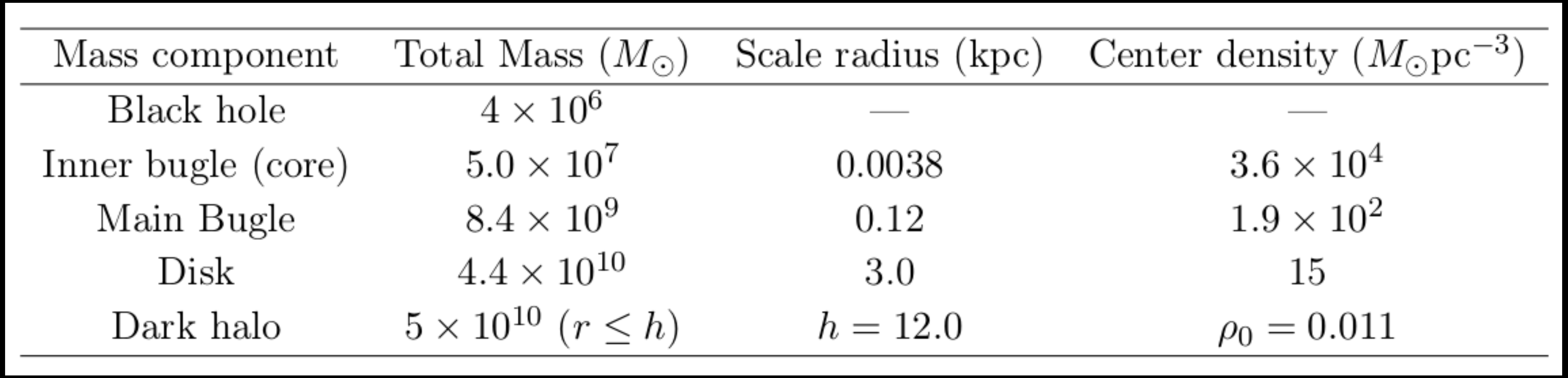
arXiv:2101.12213

Milky Way Galaxy

(Credit: https://scienceblogs.com)



(arXiv:1301.8241)



Mass component	Total Mass ($M_\odot$)	Scale radius (kpc)	Center density ($M_\odot \mathrm{pc}^{-3}$)
Black hole	4×10^6	—	—
Inner bugle (core)	5.0×10^7	0.0038	3.6×10^4
Main Bugle	8.4×10^9	0.12	1.9×10^2
Disk	4.4×10^{10}	3.0	15
Dark halo	5×10^{10} ($r \leq h$)	$h = 12.0$	$\rho_0 = 0.011$

$$M(r) = M_{\mathrm{BH}} + 4\pi \int_0^r (\rho_{\mathrm{inner}} + \rho_{\mathrm{outer}} + \rho_{\mathrm{disk}} + \rho_\chi) r^2 dr.$$

DM velocity dispersion: $\bar{v}(r) = \sqrt{\frac{3}{2}} v_c(r) = \sqrt{\frac{3}{2}} \sqrt{\frac{G_N M(r)}{r}}.$

$$\rho_\chi(r) = \rho_{\mathrm{NFW}}(r) = m_\chi n_\chi(r) = \frac{\rho_0}{(r/r_s)^\gamma (1 + r/r_s)^{3-\gamma}}.$$

(arXiv:9508025)

- $\rho_0 = 0.42\ \mathrm{GeV/cm^3}.$
- $r_s = 12.0\ \mathrm{kpc}.$
- γ : Inner Slope (1-1.5).

Dark Matter model

$$SU(2)_L \times U(1)_Y \times U(1)_X$$

$$\mathscr{L} \supset -\frac{1}{4}\mathscr{D}_{\mu\nu}\mathscr{D}^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}\mathscr{D}^{\mu\nu} + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi\,. \tag{16}$$

- Kinetic mixing coupling: ϵ
- Dark photon:

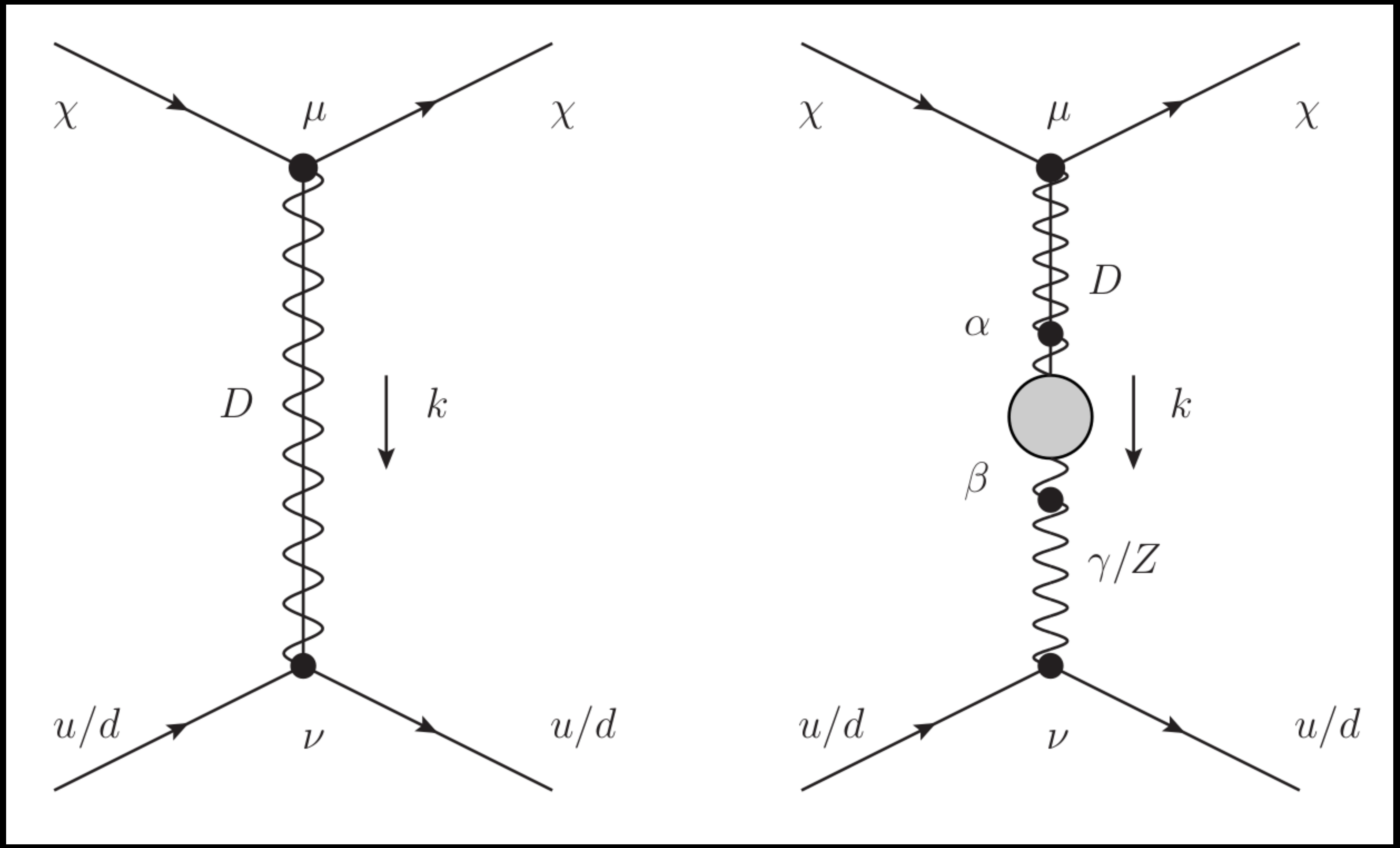
$$\mathscr{D}_{\mu\nu} = \partial_\mu \mathscr{D}_\nu - \partial_\nu \mathscr{D}_\mu.$$

- Covariant derivative:

$$D_\mu = \partial_\mu - ig_2\sum_{a=1}^{3} T^a W_\mu^a - ig_1\frac{Y}{2}B_\mu - ig_X\frac{X}{2}\mathscr{D}_\mu\,.$$

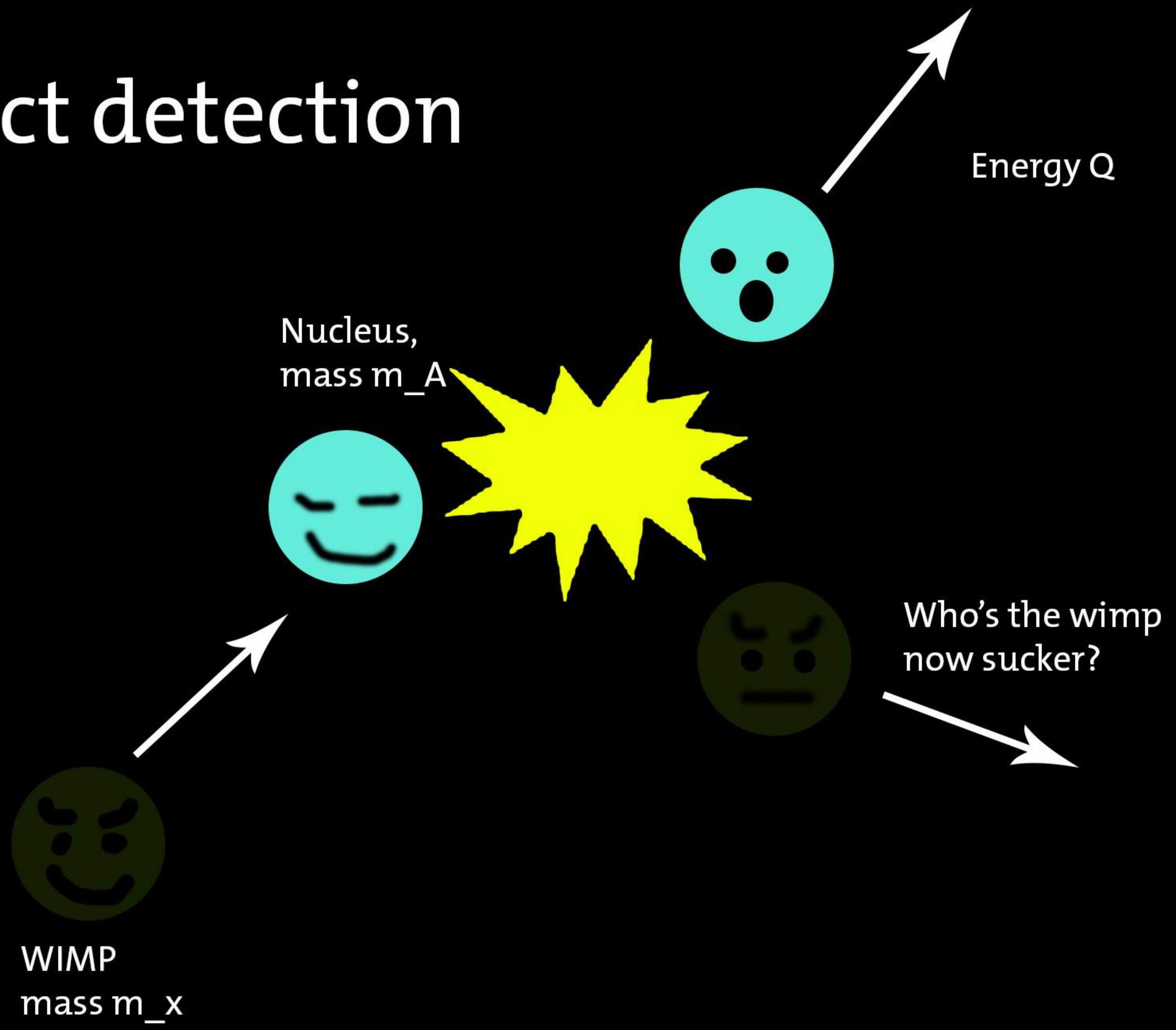
Only acts on SM

Mediator can interact with DM and SM



Dark Matter-nucleon cross section

Direct detection



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Non-relativistic Scattering

$$\sigma_{\chi n} = \frac{b_n^2 \mu_{\chi n}^2}{\pi} \quad \text{with} \quad \begin{cases} b_n & = \dfrac{\lambda\chi(\lambda_u + 2\lambda d)}{m_{Z'}^2} \\ \mu_{\chi n} & = \dfrac{m_\chi m_n}{m_\chi + m_n} \end{cases} \tag{17}$$

- $\lambda_{\chi/f}$: Mediator-DM/SM coupling.
- b_n: Mediator-neutron coupling.
- $m_{Z'}$: Mediator mass.
- $\mu_{\chi n}$: DM-neutron reduced mass.

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3. More detail in Prof. Tongyan Lin's lecture note (arXiv:1904.07915)