Bounds on Long-lived Dark Matter Mediators from Neutron Stars

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in collaboration with Tim. M.P. Tait[3]

(In preparation)

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"The Future is Illuminating"", NCTS, June 30, 2022, Taiwan.

Outline

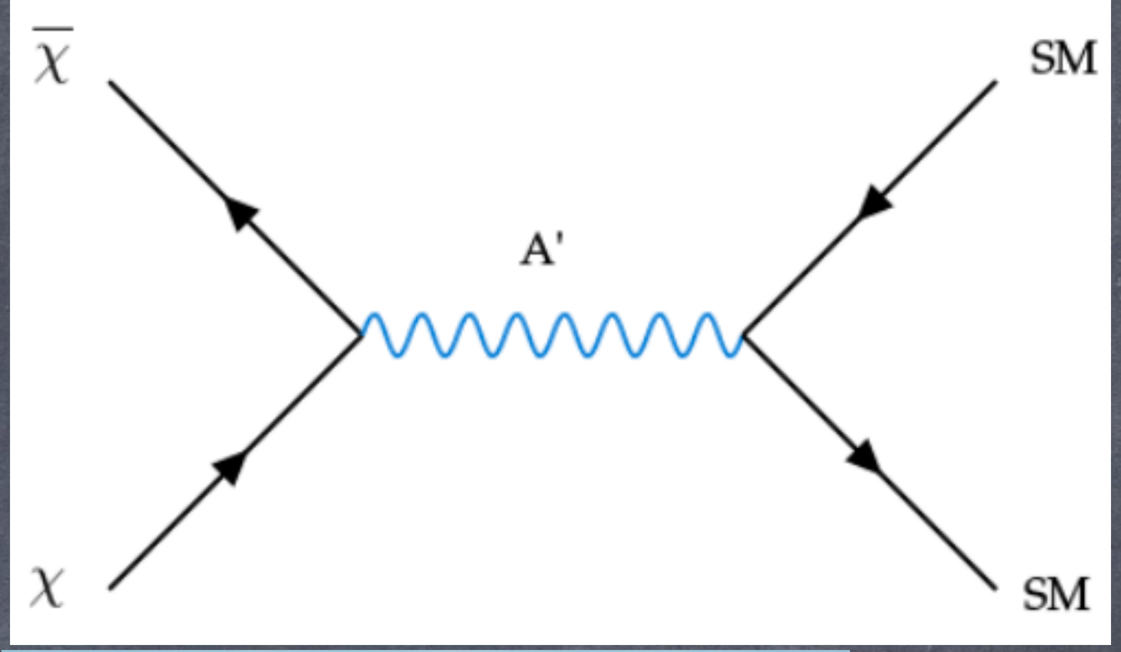
Preview: Dark Matter Detections

Available on Amazon,
Come with different flavors.

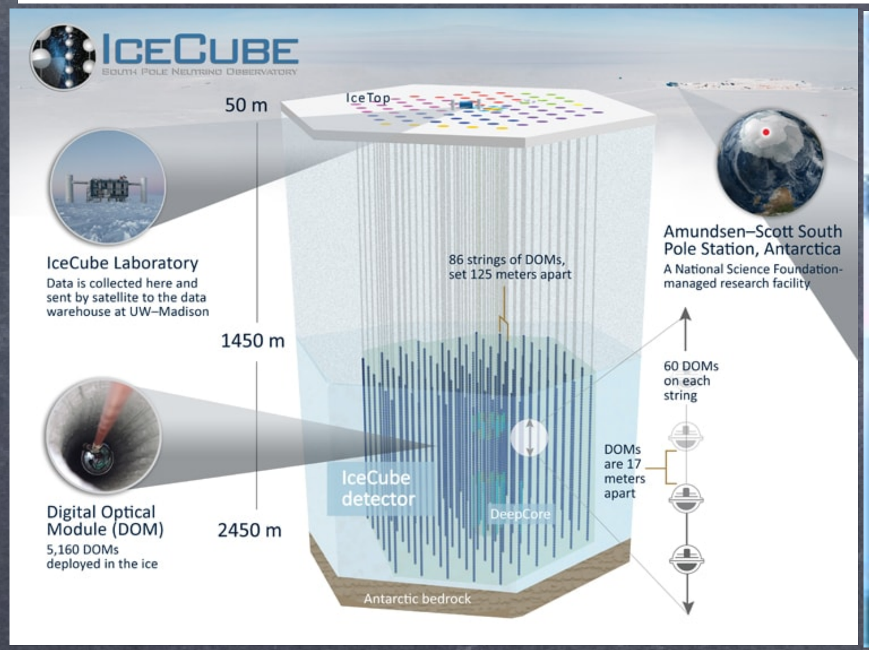
Neutron Stars in Galactic Center.

Free High Energy Colliders!!

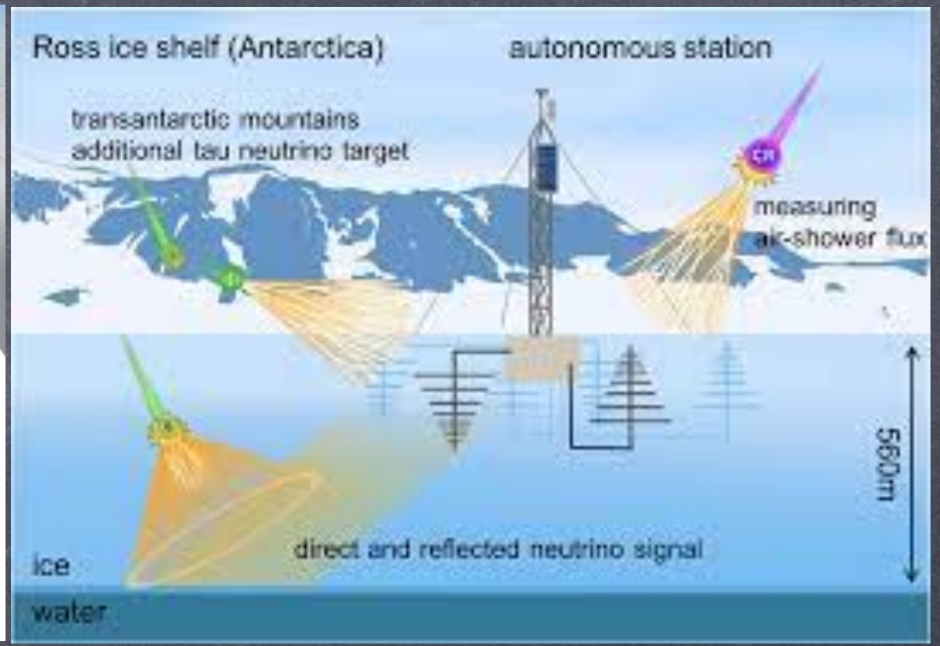
The DM model.



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



IceCube.



ARIANNA (Projections).

Experimental results

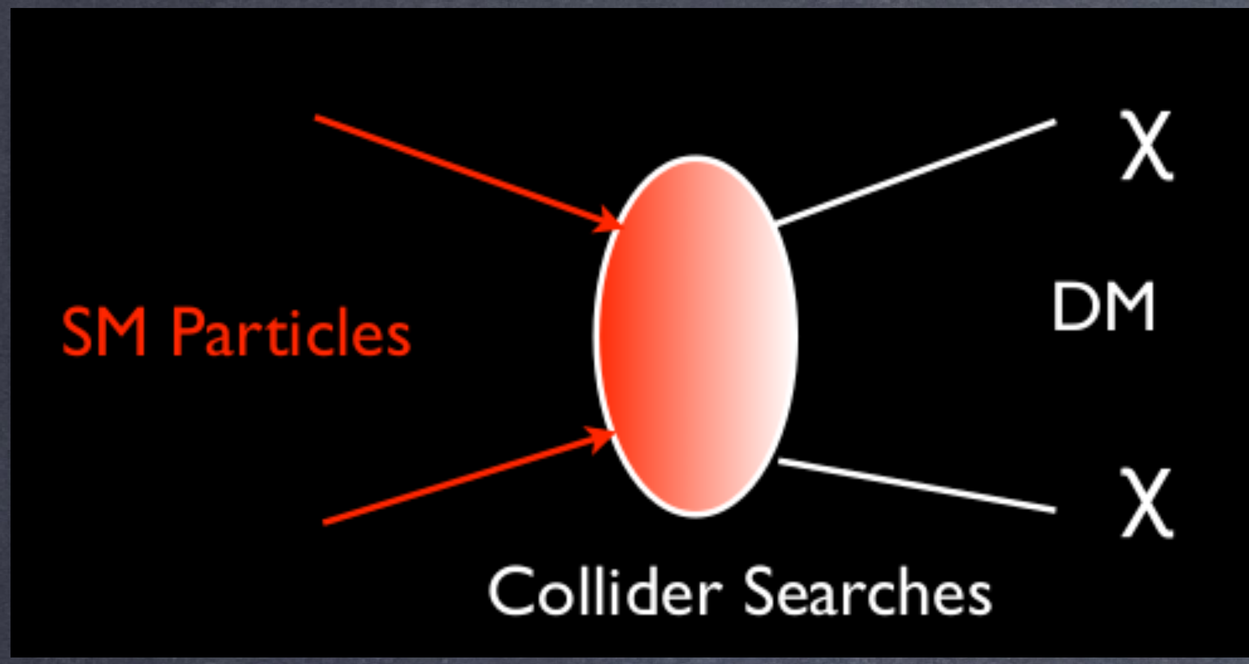
Dark matter Detection methods

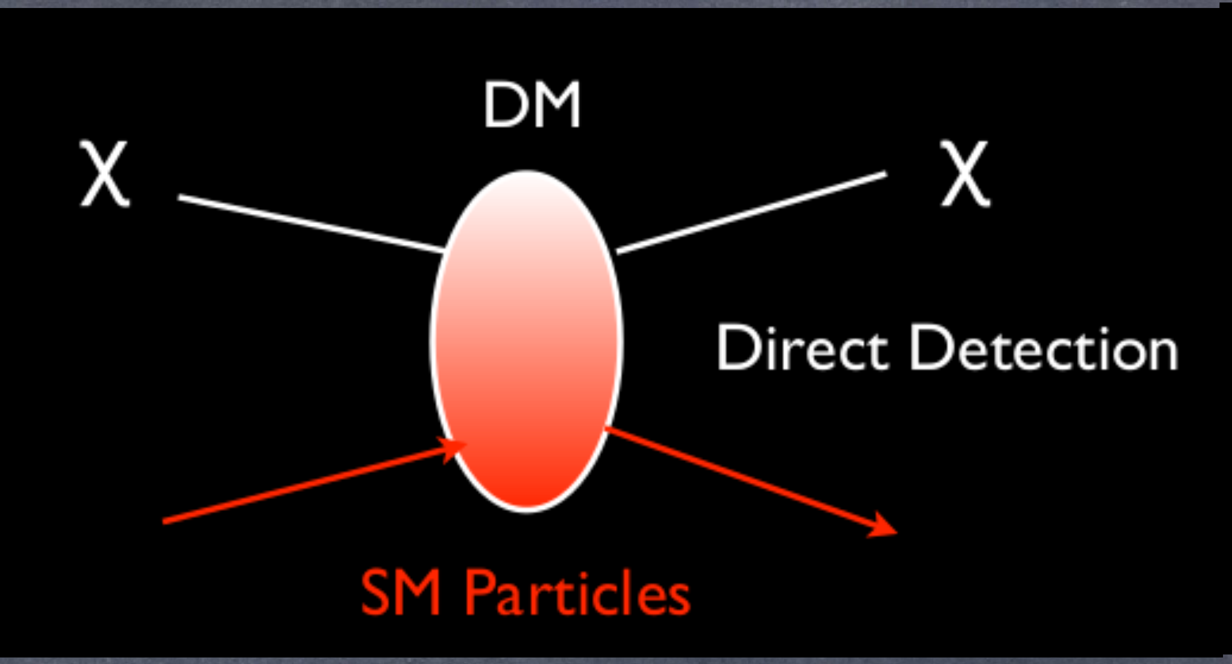
Signature: radiations.

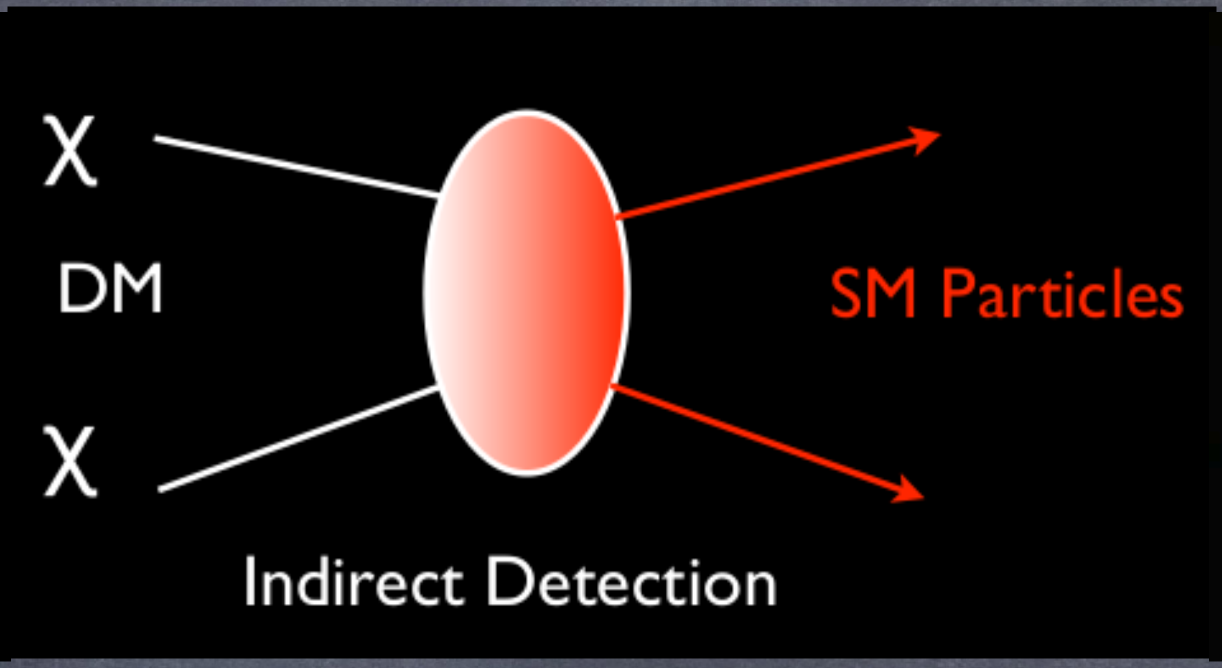
Signature: recoiled energies.

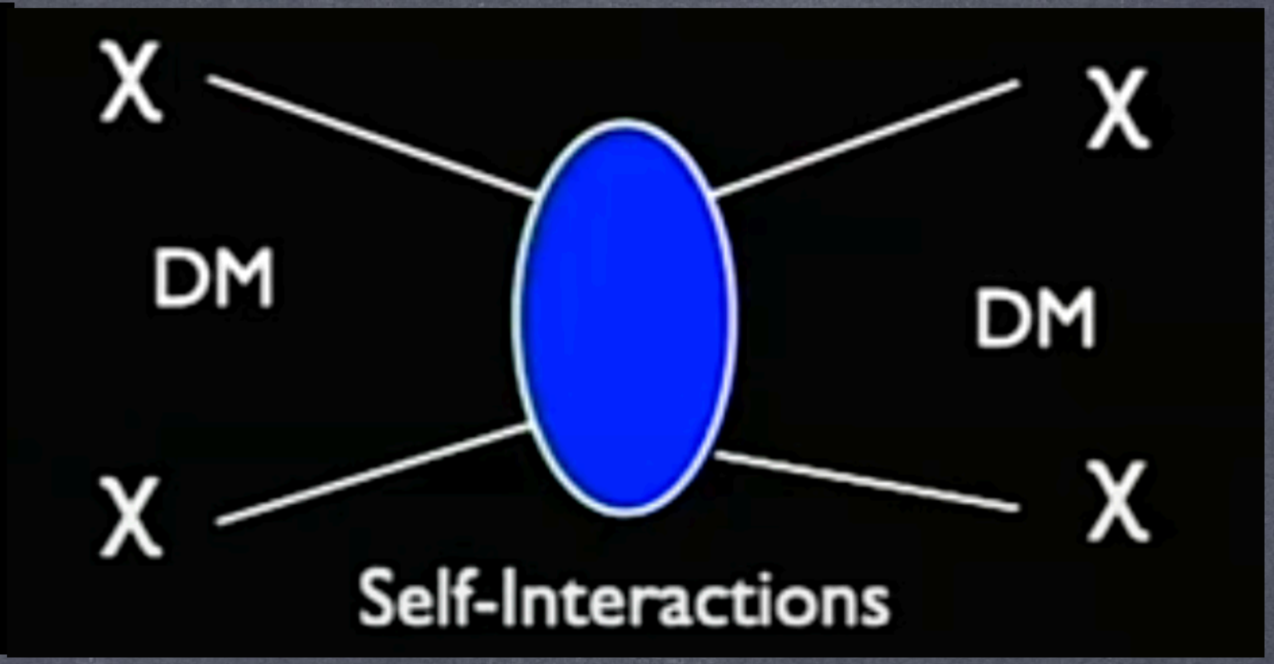
Signature: stable SM $(e^+, p, \gamma, \nu, \ldots)$.

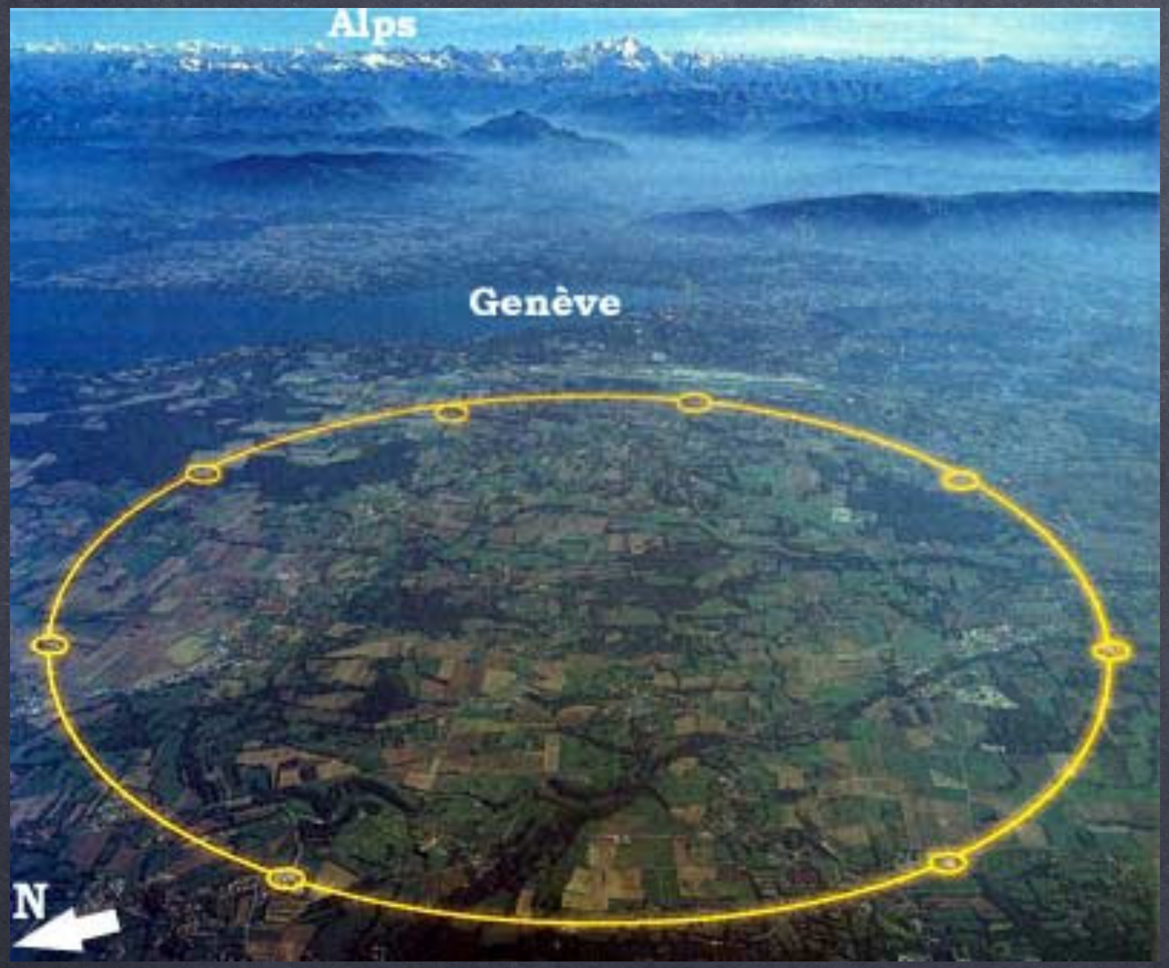
Astrophysical structure of the Universe.







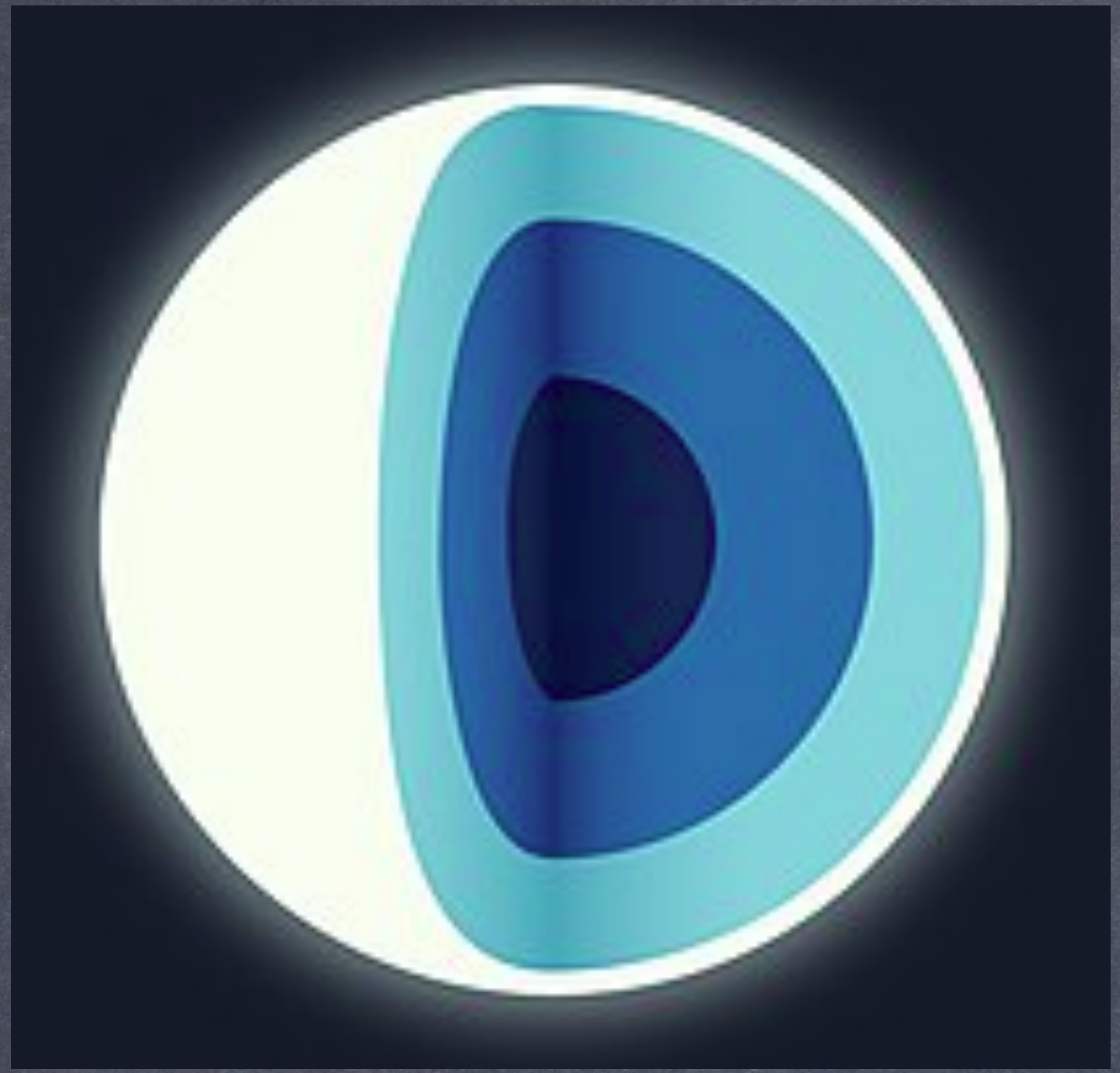




This project!

Pictures for the processes are taken from Tim Tait's slide of KITP Snowmass2022.

Neutron Stars in Galactic Center



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

$$v_{esc} = \sqrt{2\chi} \approx 2.1 \times 10^5\ \text{km/s}, \quad (1)$$

$$\text{with } \chi = 1 - \sqrt{1 - 2G_N M_{ns}/R_{ns}}. \quad (2)$$

- Saturation Cross Section:

$$\sigma_{sat} = \pi R_n^2 / N_n \approx 1.87 \times 10^{-45}\ \text{cm}^2. \quad (3)$$

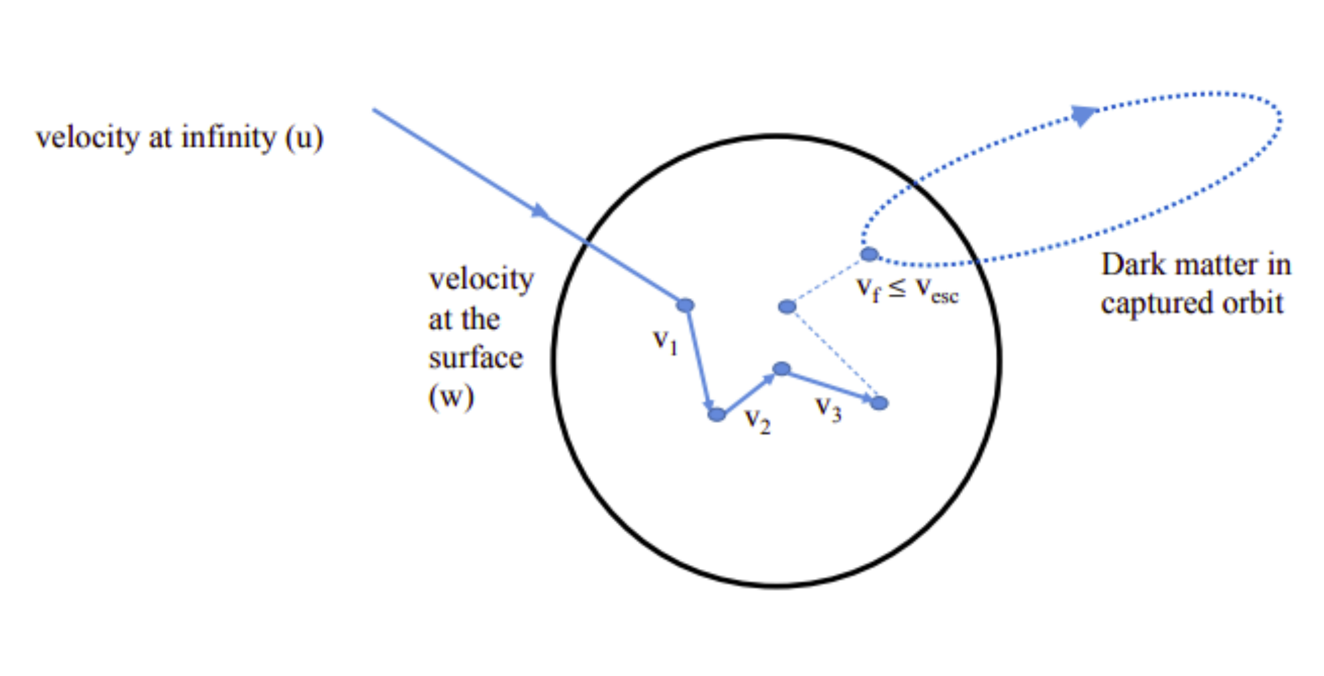
Neutron Star's number density[1] in Galactic Center:

$$n_{ns}(r) = 5.98 \times 10^3 \left(\frac{r}{1\text{pc}}\right)^{-1.7} \text{pc}^{-3}\ (0.1\text{pc} < r < 2\text{pc})$$
$$= 2.08 \times 10^4 \left(\frac{r}{1\text{pc}}\right)^{-3.5} \text{pc}^{-3}\ (r > 2\text{pc}). \quad (4)$$

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

Dark Matter capture by neutron stars

Figure from arXiv:1906.04204



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

Dark Matter Capture Rate after Nth times [GeV]:

$$C_N = \frac{\pi R_\star p_N(\tau)}{1 - 2G_N M_\star / R_\star} \frac{\sqrt{6} n_\chi}{3\sqrt{\pi}\bar{v}} \times \left[2\bar{v}^2 + 3v_{\rm esc}^2 - (2\bar{v}^2 + 3v_N^2)\exp\left(- \frac{3(v_N^2 - v_{\rm esc}^2)}{2\bar{v}^2} \right) \right]. \quad (5)$$

- Capture rate (1 NS): $C = \sum_{N=1}^{\infty} C_N$. (6)
- Total capture rate (All NSs): $C_{\rm tot} = 4\pi \int_{r_1=0.1{\rm pc}}^{r_2=100{\rm pc}} r^2 n_{\rm ns} C dr$. (7)

- DM velocity dispersion: $\bar{v}$.
- DM velocity (Nth-time scattering): v_N.
- DM density profile: n_χ.

- Probability scattering N-time:

$$p_N(\tau) = 2 \int_0^\infty dy \frac{y e^{-y\tau}(y\tau)^N}{N!}.$$

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

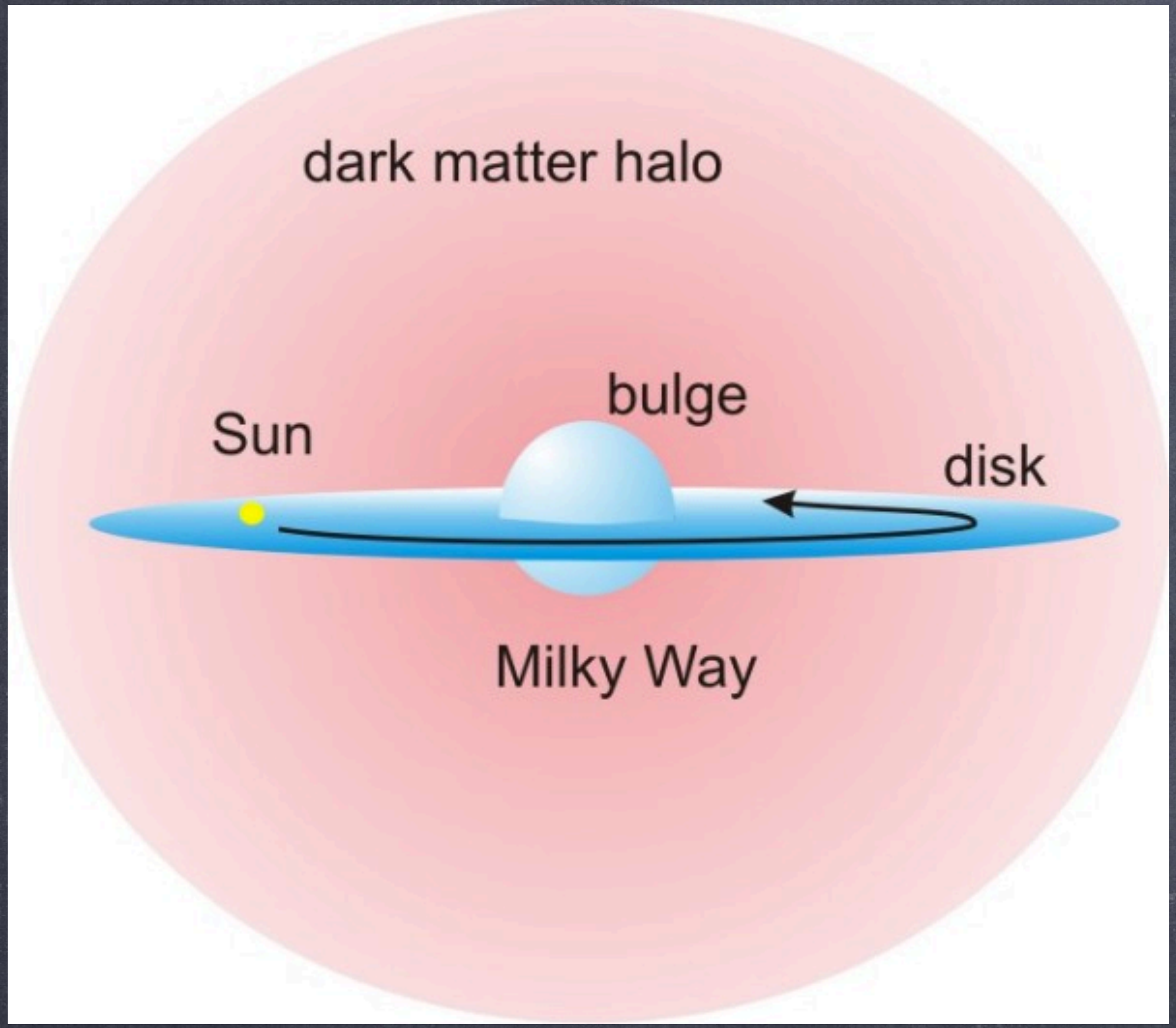
$\sigma_{\chi n}$ ⟶ DM model.

$\sigma_{\rm sat}$ ⟶ Celestial object.

2. Rebecca K. Leane, Tim Linden, Payel Mukhopadhyay, Natalia Toro (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} ($r \leq h$)	$h = 12.0$	$\rho_0 = 0.011$

$$M(r) = M_{\mathrm{BH}} + 4\pi \int_0^r (\rho_{\mathrm{inner}} + \rho_{\mathrm{outer}} + \rho_{\mathrm{disk}} + \rho_\chi) r^2 dr. \quad (8)$$

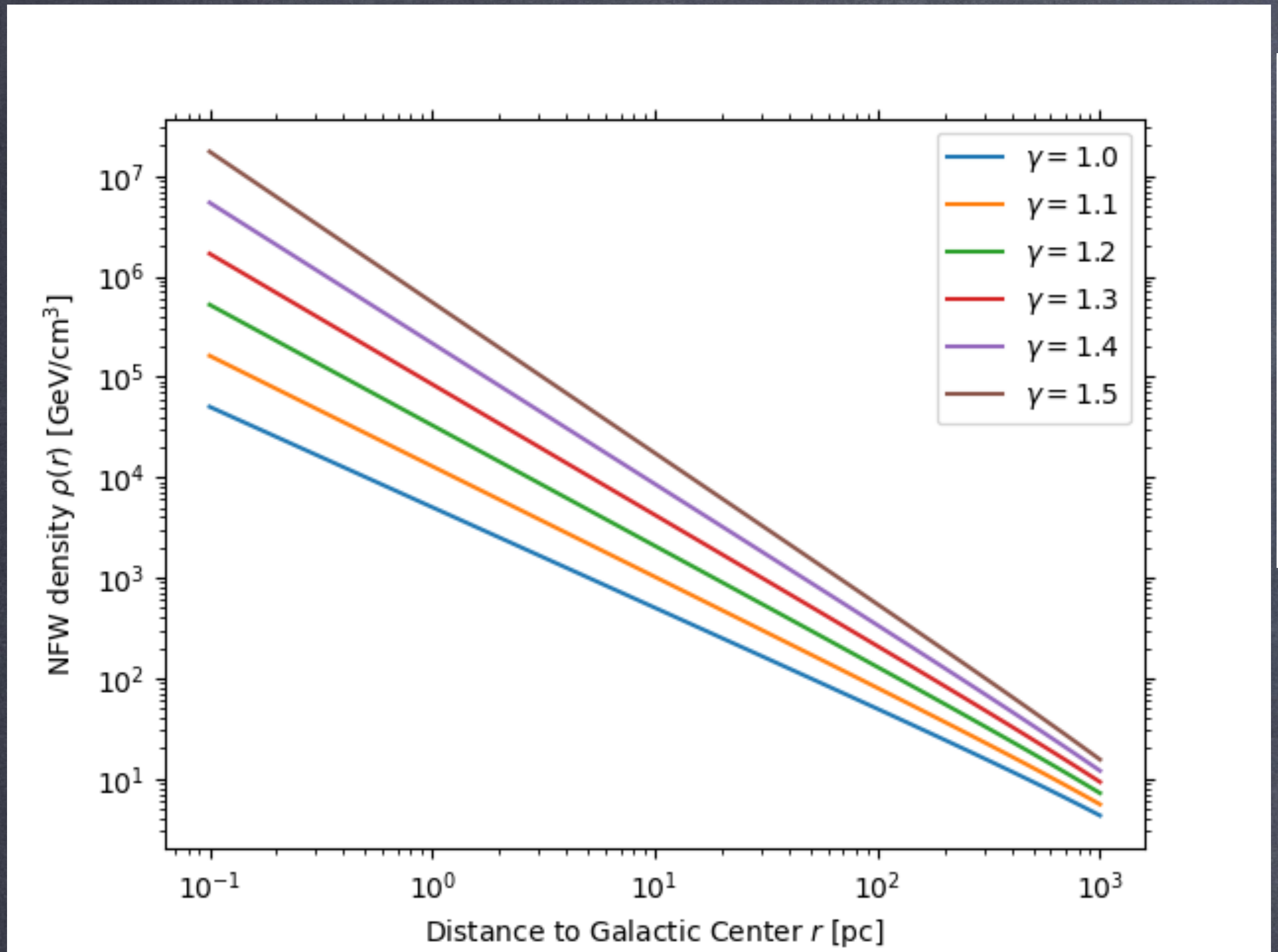
$$\rho_\chi(r) = \rho_{\mathrm{NFW}}(r) = m_\chi n_\chi(r) = \frac{\rho_0}{(r/r_s)^\gamma (1 + r/r_s)^{3-\gamma}} .$$

(arXiv:9508025)

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

Milky Way Galaxy

(arXiv:1301.8241)



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$$M(r) = M_{\rm BH} + 4\pi \int_0^r (\rho_{\rm inner} + \rho_{\rm outer} + \rho_{\rm disk} + \rho_\chi) r^2 dr. \quad (8)$$

DM velocity dispersion: $\bar{v}(r) = \sqrt{\frac{3}{2}} v_c(r) = \sqrt{\frac{3}{2}} \sqrt{\frac{G_N M(r)}{r}}$. (9)

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

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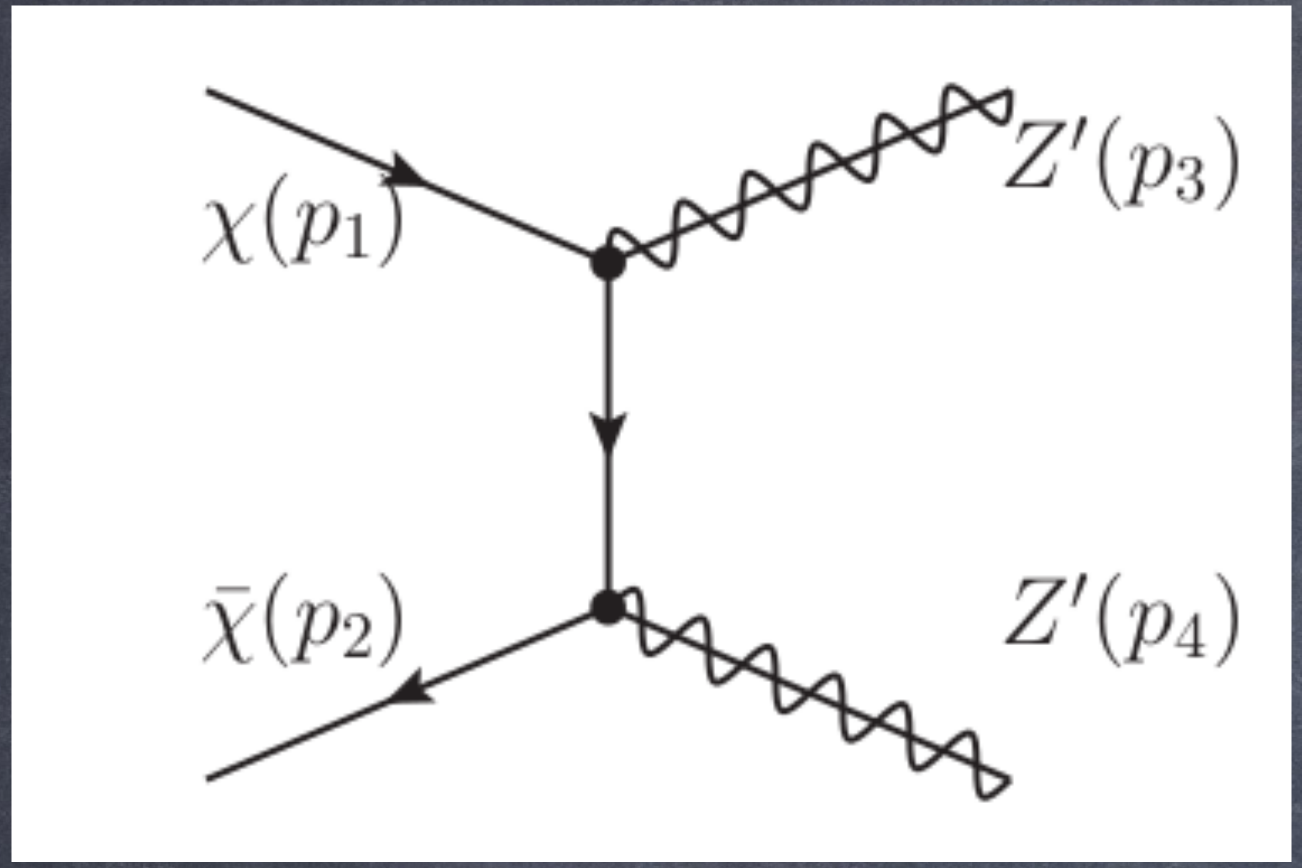
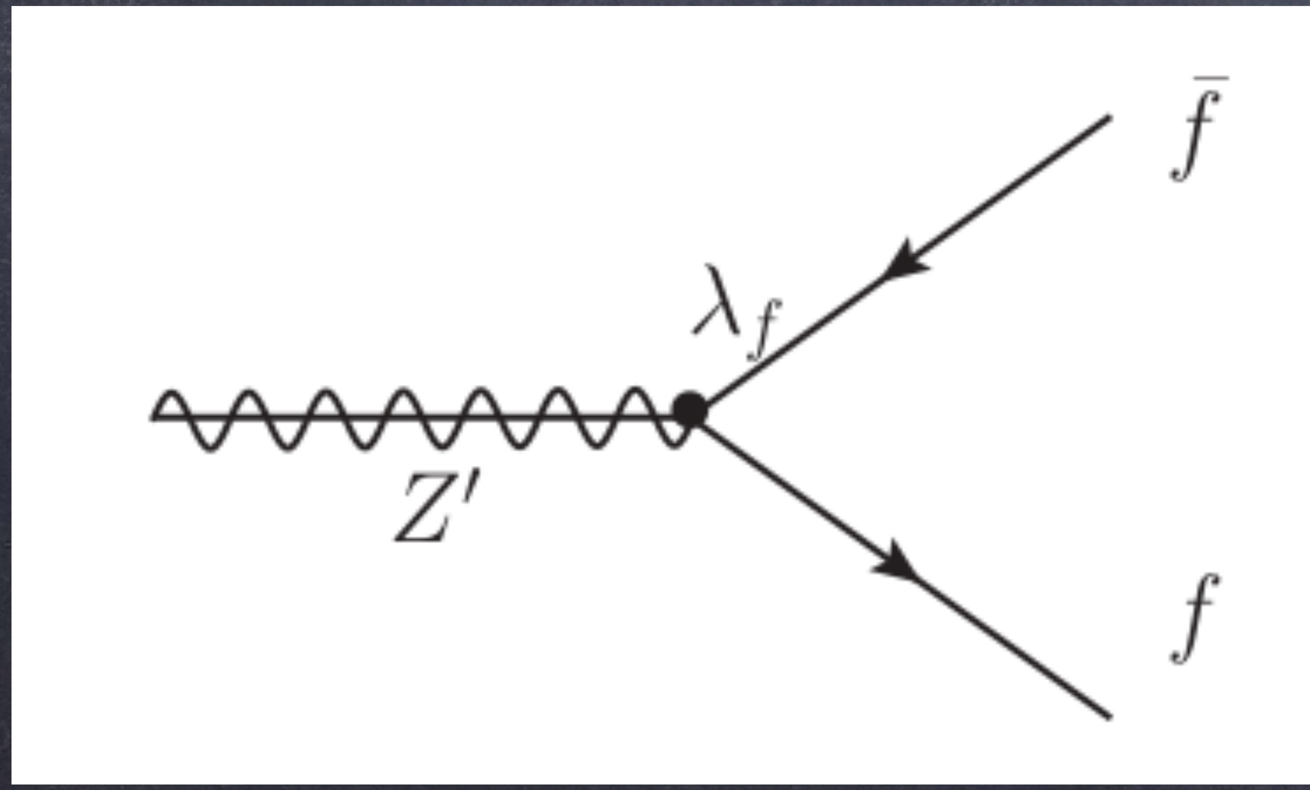
Signal from DM annihilation in NS

DM annihilation in NS



Mediator live long enough! 🖐



Mediator decays to SM particles

Equilibrium: $\Gamma_{\rm ann} = \frac{\Gamma_{\rm cap}}{2} = \frac{C_{\rm tot}}{2}$. (10)

- Lorentz Boost: $\eta \approx m_\chi / m_{Z'}$. (11)
- Escaping condition: $L = \eta\beta\tau_m \approx \eta c\tau_m > R_\star$. (12)

Differential Energy Flux (measured by ID Experiments):

$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\rm ann}}{4\pi D^2} \times E^2 \frac{dN}{dE} \times {\rm BR}(X \to {\rm SM}) \times P_{\rm surv}\,.. \quad (13)$$

$$[{\rm GeV\ \ cm^{-2}\ \ s^{-1}}]$$

- D: Average distance from GC to detectors (Earth).
- dN/dE: Signal (neutrino) spectrum.
- Signal surviving probability: $P_{\rm surv} = e^{-R_\star/L} - e^{-D/L}$. (14)
- Limit: $L \leq D \approx 8.0$ kpc. (15)

Neutrinos experimental results

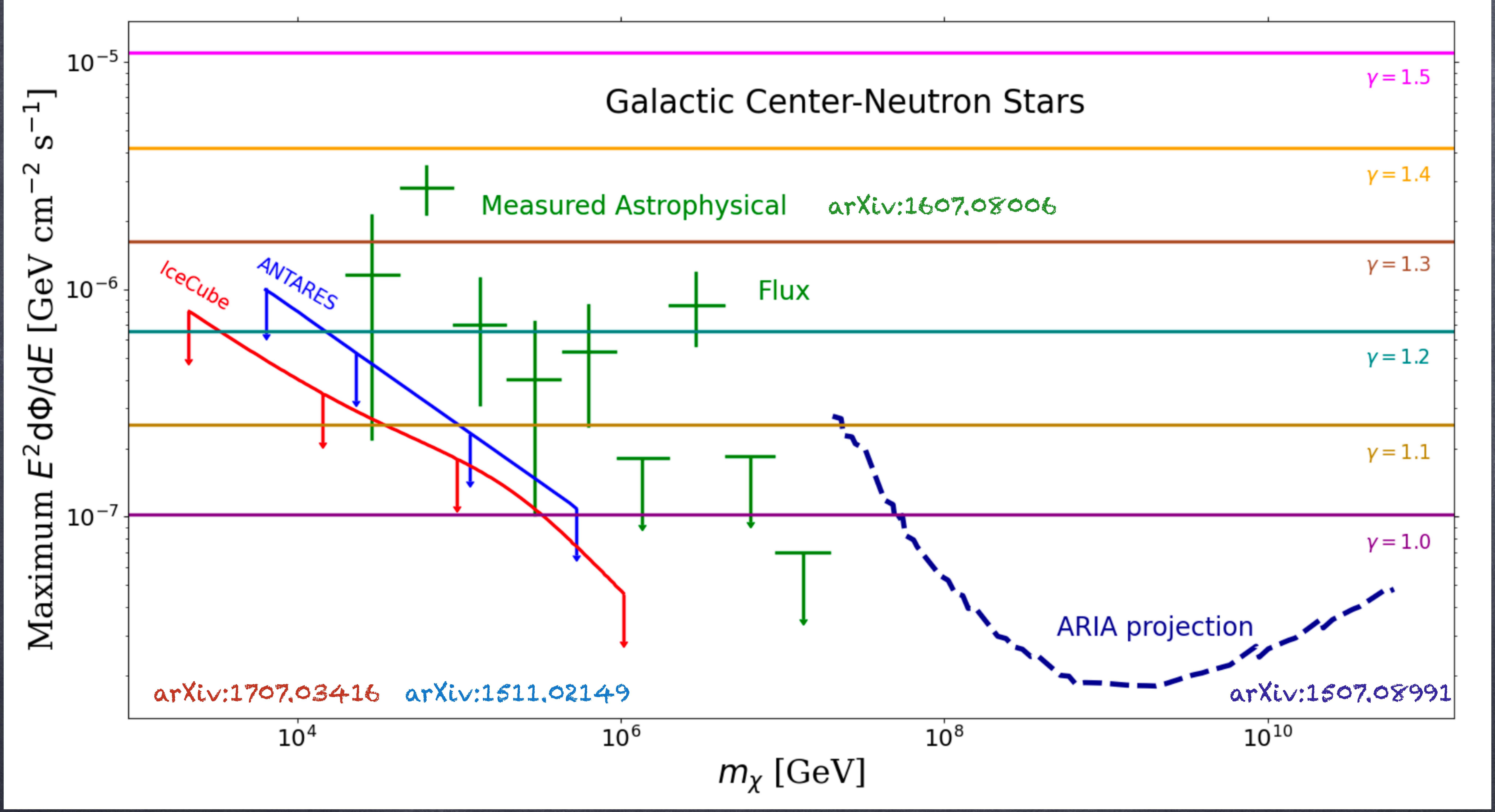
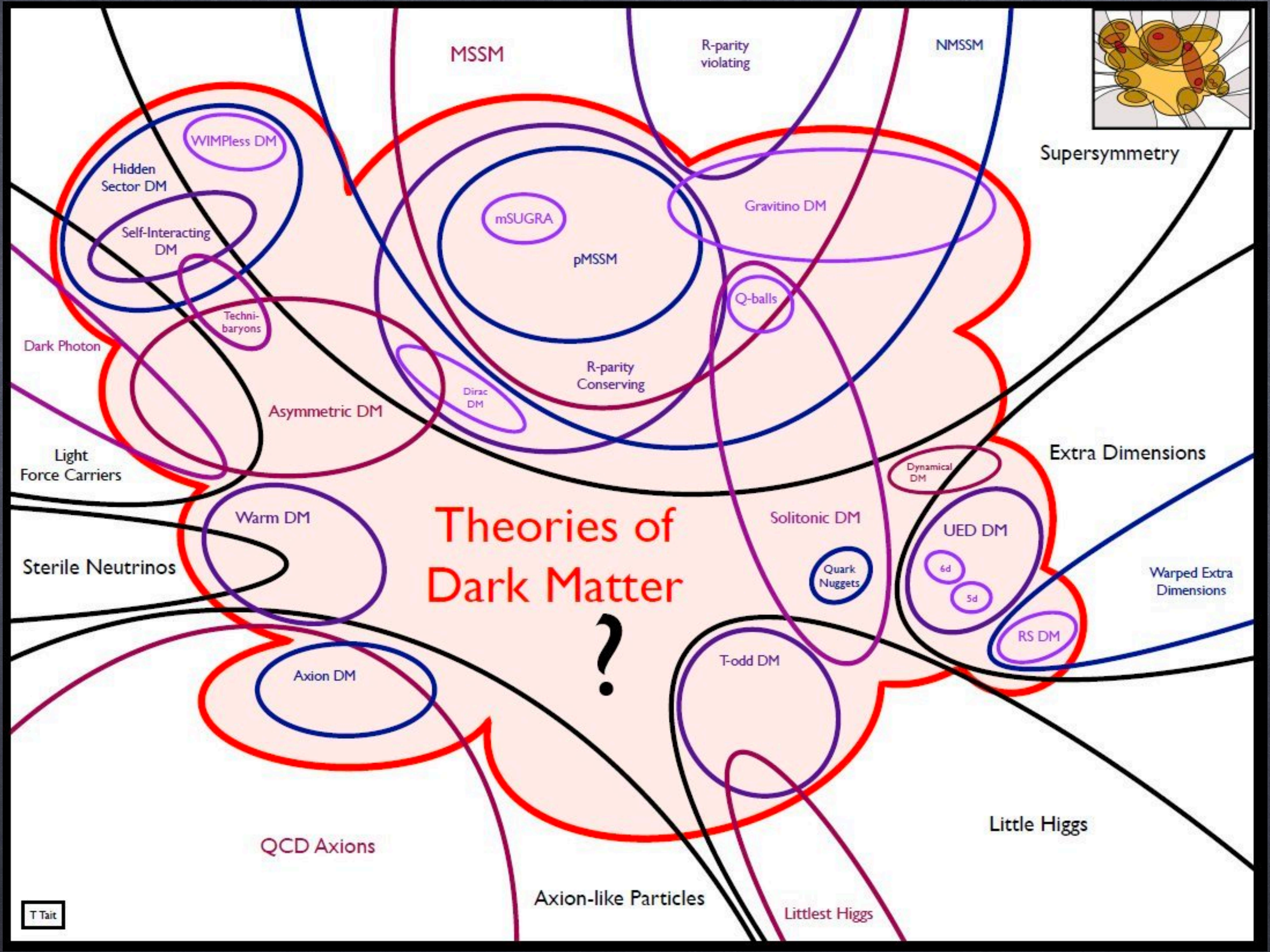


Fig. 1: Differential Energy Flux of muon neutrino: Experimental upper limits and data. The horizontal lines for maximum fluxes from NS in GC after integrate all over the sky.

Which DM model?

Our consideration



Dark Matter model

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

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

- Kinetic mixing coupling: ϵ
- Dark photon:

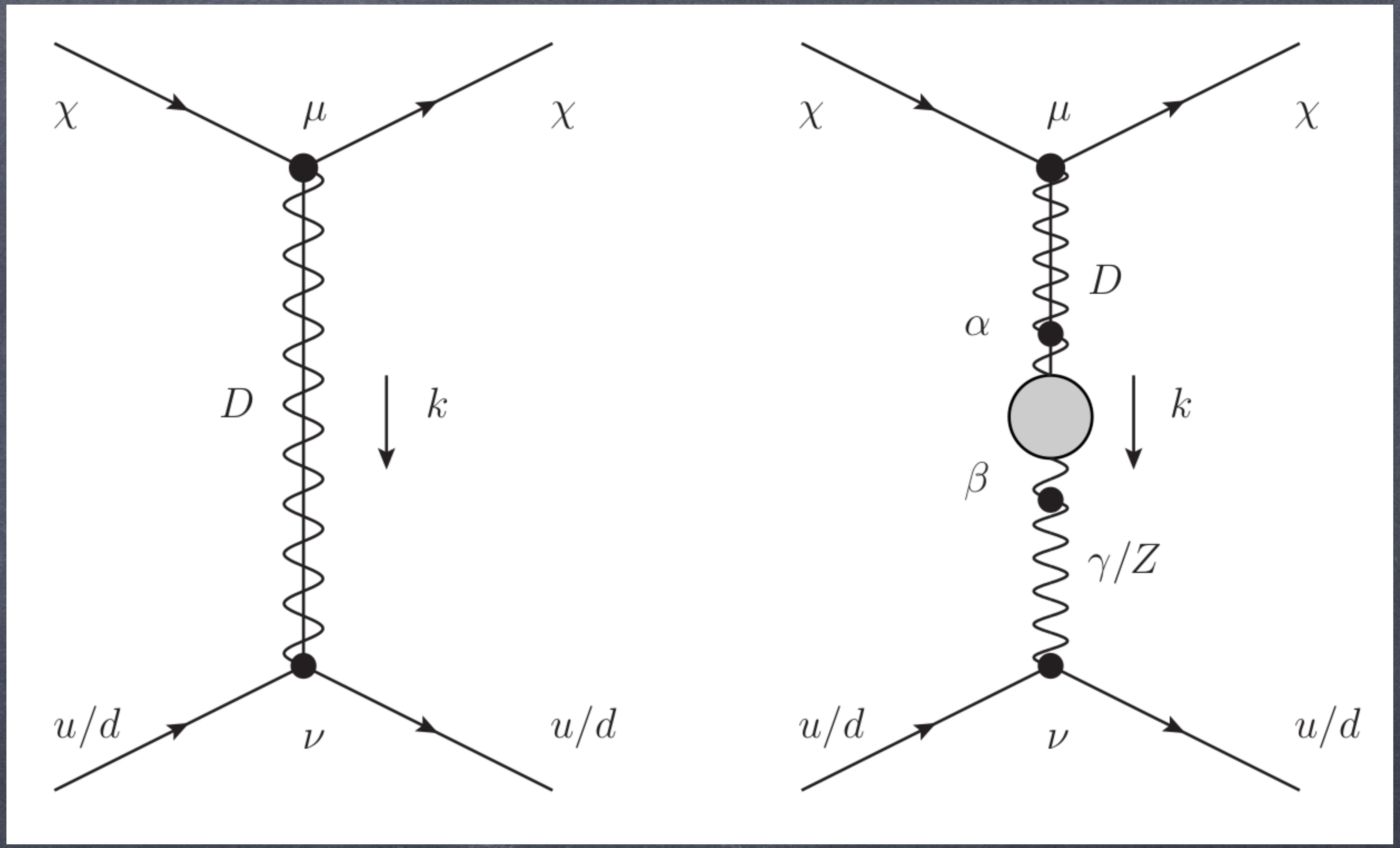
$$\mathscr{D}_{\mu\nu} = \partial_\mu \mathscr{D}_\nu - \partial_\nu \mathscr{D}_\mu .$$

- Covariant derivative:

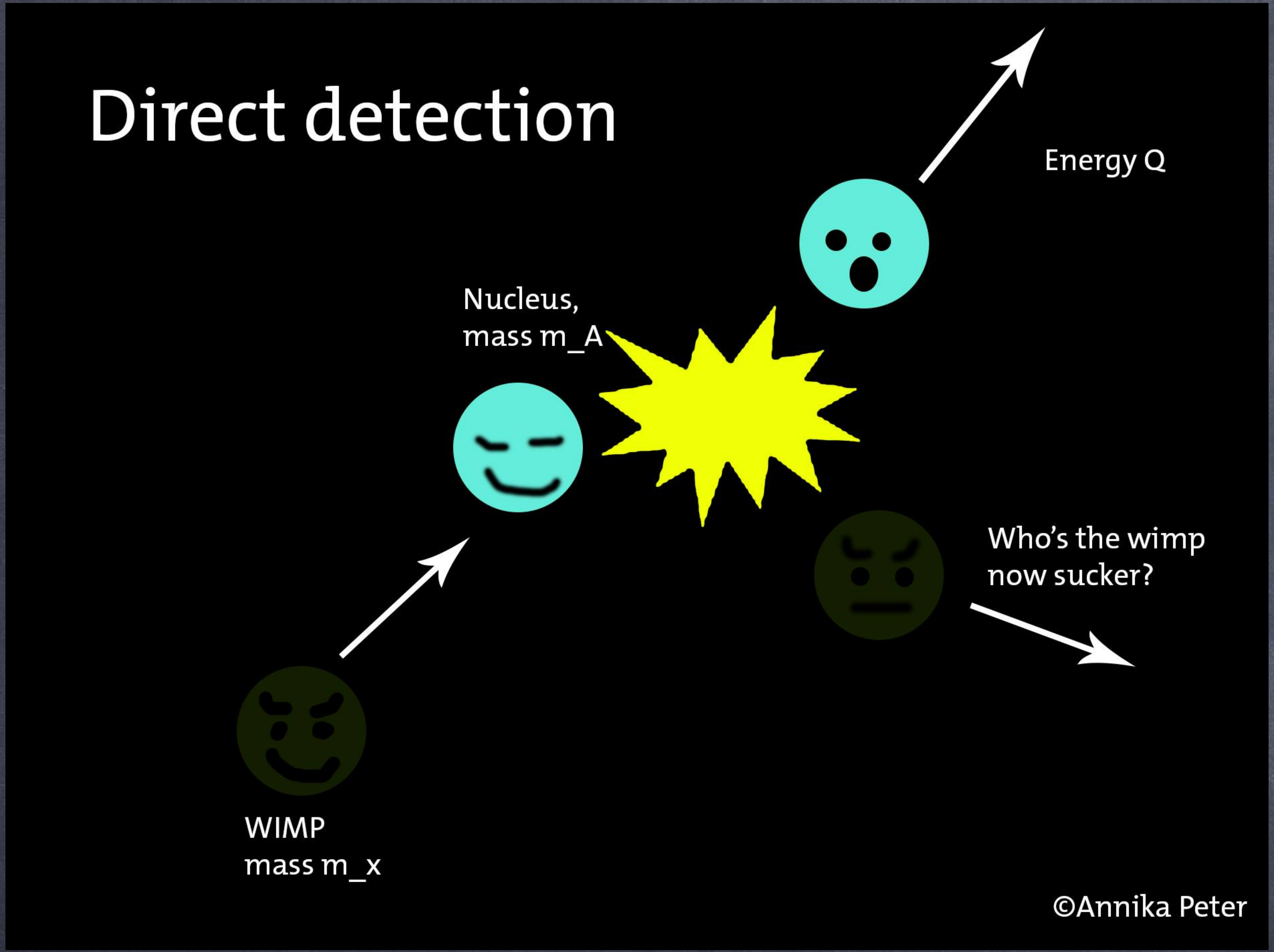
$$D_\mu = \partial_\mu - ig_2 \sum_{a=1}^{3} T^a W^a_\mu - ig_1 \frac{Y}{2} B_\mu - ig_x \frac{X}{2} \mathscr{D}_\mu \,.$$

Only acts on SM

Mediator can interact with DM and SM



Dark Matter-nucleon cross section



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.

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

(SI) Cross Section Limits

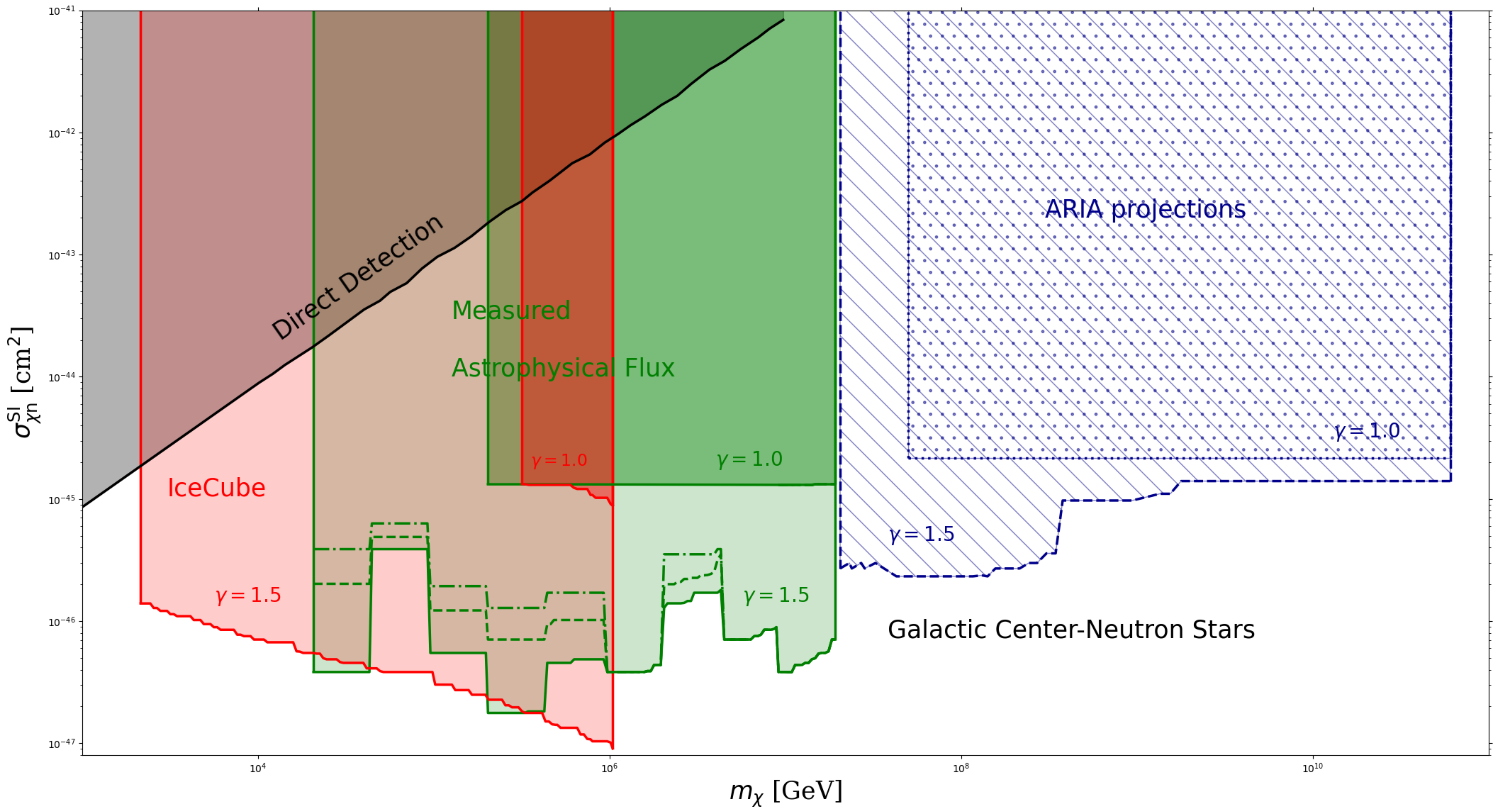


Fig. 2: SI Cross Section limits, using IceCube, Measured Astrophysical (muon) Neutrino, and ARIA projection.

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, ...

Acknowledgements

We would like to thanks:

- Rebecca Leane, Payel Mukhopadhyay, Natalie Toro (SLAC, Stanford) and Tim Linden (Stockholm U., OKC): capture rate calculation.
- Nicholas Rodd (CERN): neutrino spectrum.
- Meng-Ru Wu (IoP, Academia Sinica): neutrino flavor ratios.


Thank you for listening!
I'm searching for
Dog-Matter too!!
NCTS
ntqthonghep@gate.sinica.edu.tw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BACKUP SLIDES ARE COMING
memegenerator.net

What is the optical depth?

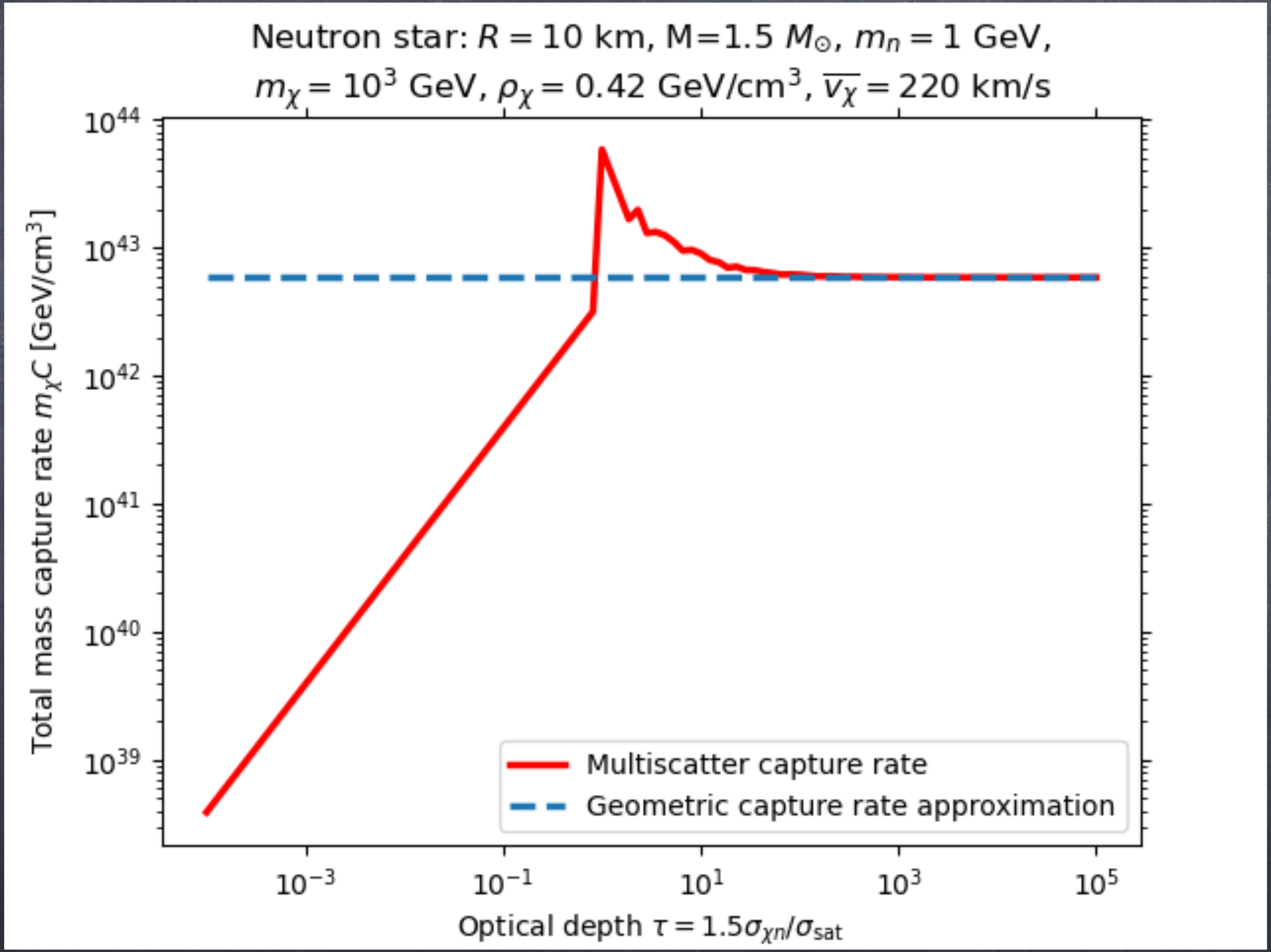
- For multiscatter capture it is convenient to define the optical depth, the average number of times a dark matter particle with dark matter - nuclear cross section $\sigma_{\chi n}$ will scatter when traversing the star.

- To understand the 3/2 factor in the optical depth, observe that the cross section for which 1 scatter occurs over a distance of 2R, (where R is the radius of the star) is:

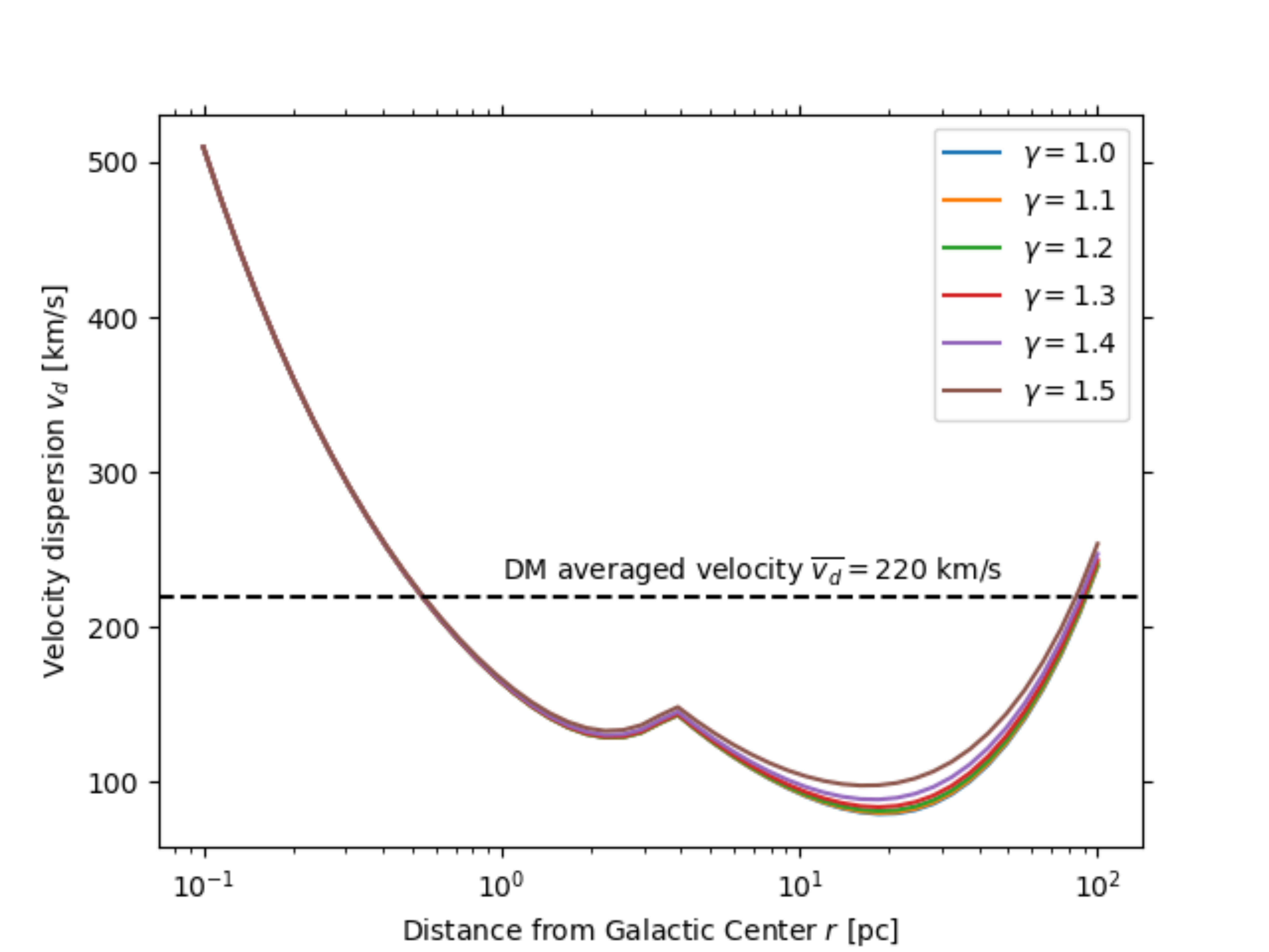
$$1 = n\,\sigma\,(2R) = \frac{N_n}{(4/3)\pi R^3}\sigma\,(2R) = \frac{3\,N_n}{2\pi\,R^2}\sigma$$
$$\rightarrow \sigma = \frac{2}{3}\left(\frac{\pi R^2}{N_n}\right) = \frac{2}{3}\sigma_{\rm sat}\,,$$

arXiv:1703.04043

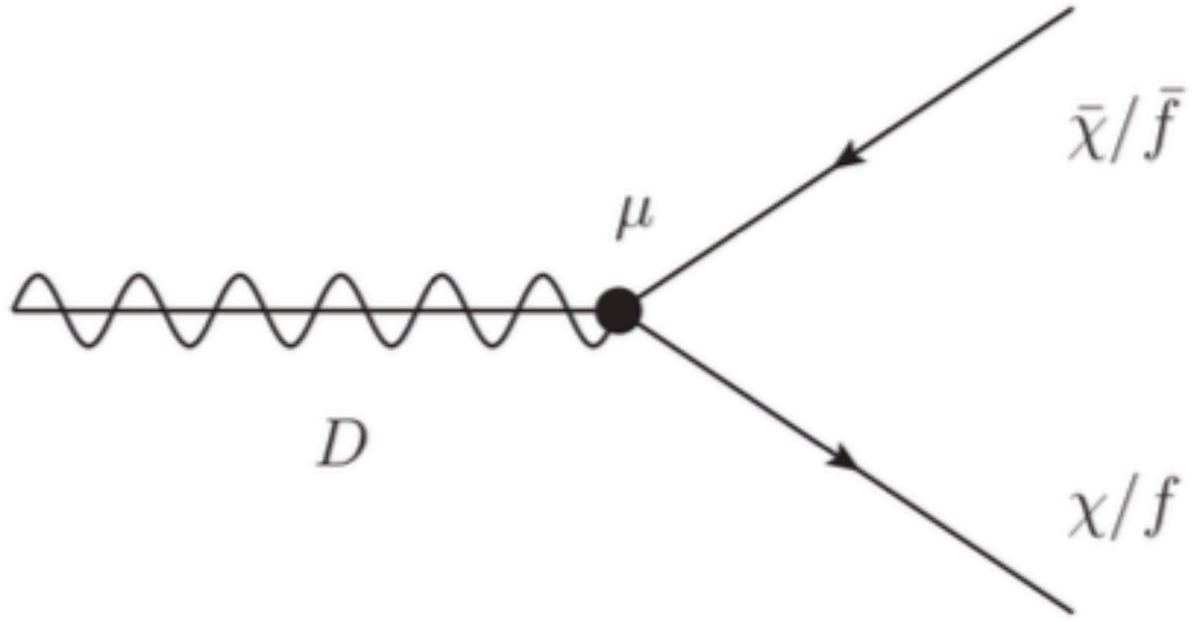
Capture Rate



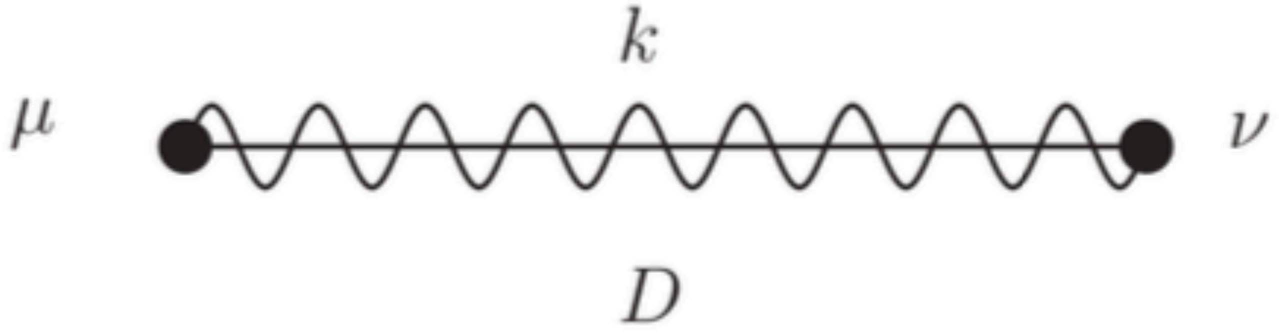
Velocity Dispersions of NS in Galactic Center



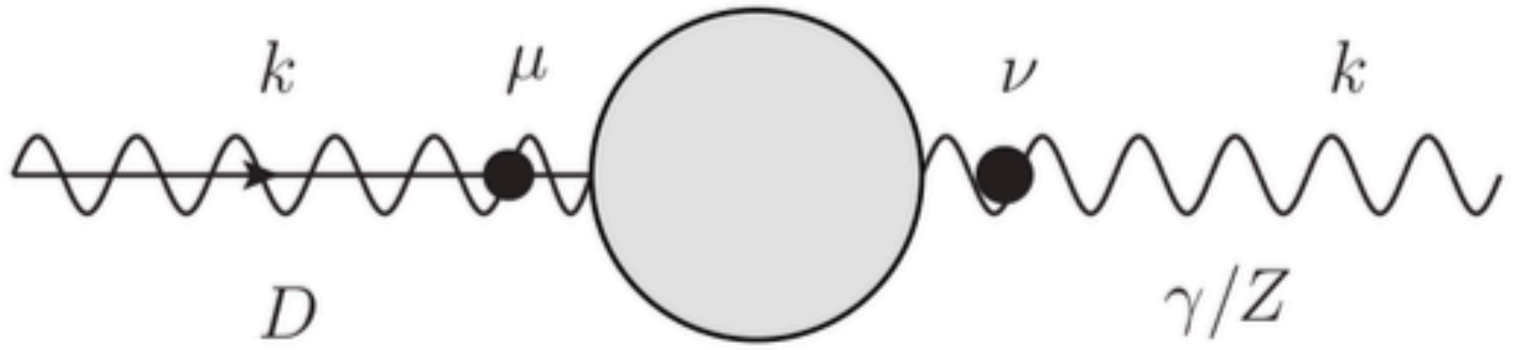
Feynman rules



$$= i\lambda_{\chi/f}\gamma^{\mu},$$



$$= \frac{-ig_{\mu\nu}}{k^2 - m_D^2 + im_D\Gamma_D},$$



$$= \begin{cases} \gamma: & -i\epsilon_{\text{mix}}\cos\theta_w(k^2 g^{\mu\nu} - k^{\mu}k^{\nu}), \\ Z: & i\epsilon_{\text{mix}}\sin\theta_w(k^2 g^{\mu\nu} - k^{\mu}k^{\nu}), \end{cases}$$

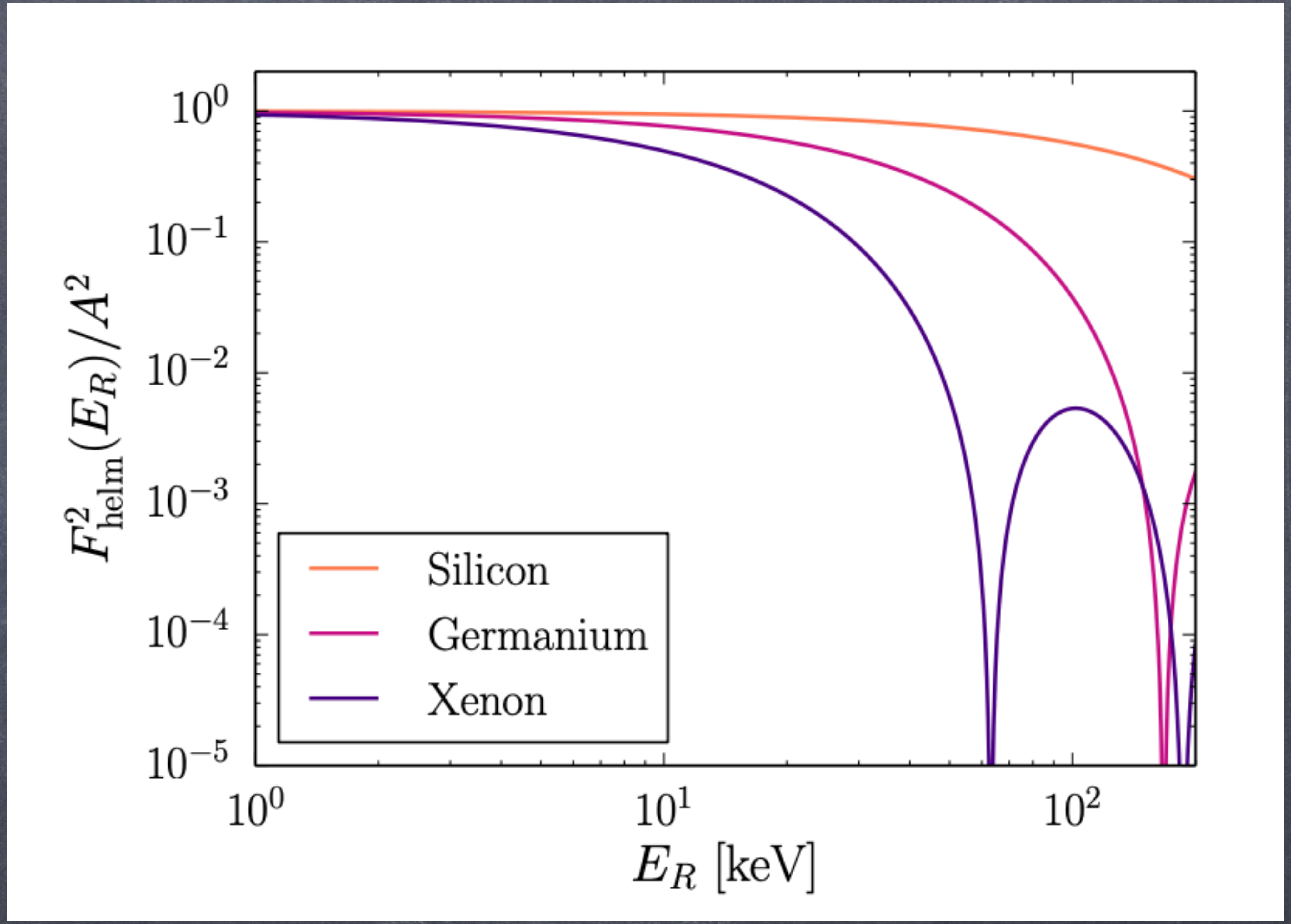
EFT: DM-nucleon scattering

$$\mathcal{M}_q^{\rm SI} = \frac{i\lambda_\chi}{k^2 - m_D^2}\left[\lambda_q - eQ_q\epsilon_{\rm mix}c_w + \frac{k^2}{k^2 - m_Z^2 + im_Z\Gamma_Z}\frac{es_w(I_3^q - 2Q_q s_w^2)}{2s_w c_w}\right]\times \left[\bar{u}^{s'}(p_3)\gamma^\mu u^s(p_1)\right]\times\left[\bar{u}^{t'}(p_4)\gamma_\mu u^t(p_2)\right],$$

$$\text{neutron: } \mathcal{M}_{\rm n} = \frac{\lambda_\chi(\lambda_u + 2\lambda_d)}{m_D^2}\times(4m_\chi m_{\rm n}) = b_{\rm n}\times(4m_\chi m_{\rm n}),$$

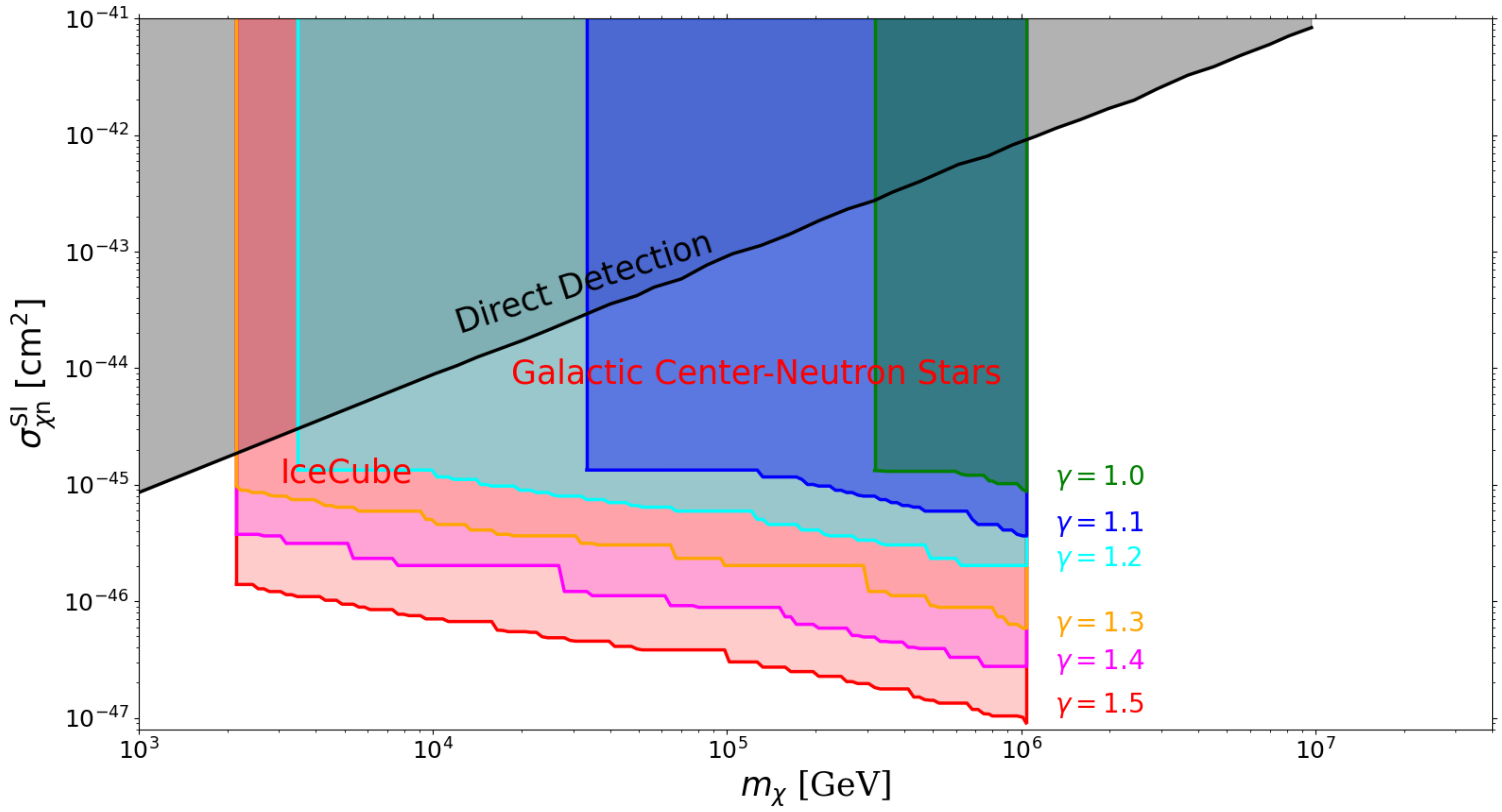
$$\text{proton: } \mathcal{M}_{\rm p} = \frac{\lambda_\chi(2\lambda_u + \lambda_d - ec_w\epsilon_{\rm mix})}{m_D^2}\times(4m_\chi m_{\rm p}) = b_{\rm p}\times(4m_\chi m_{\rm p}),$$

$$d\sigma_n = \frac{|\mathcal{M}_n|^2}{4m_\chi m_n v}\frac{d^3\vec{p}_3}{(2\pi)^3 2m_\chi}\frac{d^3\vec{p}_4}{(2\pi)^3 2m_n}(2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4) = \frac{b_n^2}{4\pi v^2}d|\vec{p}_4|^2 d\cos\theta\times\delta\left(\cos\theta - \frac{|\vec{p}_4|}{2\mu_{\chi n}v}\right),$$



Dark Photon mass	m_D	$10^{-9} - 10^{-3}$	GeV
Dark matter mass	m_χ	$10^{3} - 10^{11}$	GeV
Couplings	$\lambda_{\chi/f}$, ϵ	$10^{-15} - 10^{-3}$	

Bounds from IceCube



Bounds from Data