Bounds on Long-lived Dark Matter Mediators from Neutron Stars

Thong. T.Q. Nguyen[1,2],

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

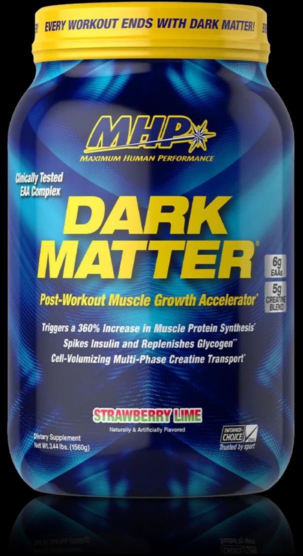
arXiv:2212.12547

1. Institute of Physics, Academia Sinica
2. Sorbonne University, Jussieu, Paris, France
3. Department of Physics and Astronomy, University of California, Irvine

TMEX-2023: Theory meets experiments

Outline

Preview: Dark Matter Detections

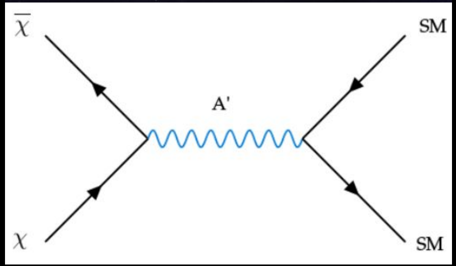


Available on Amazon!

→

Neutron Stars in Galactic Center.

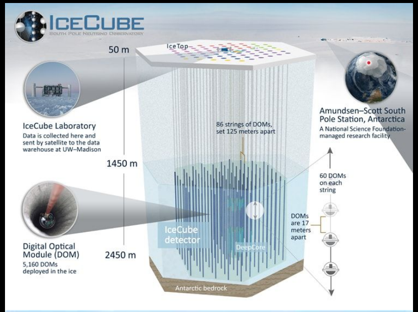
Free High Energy Colliders!!

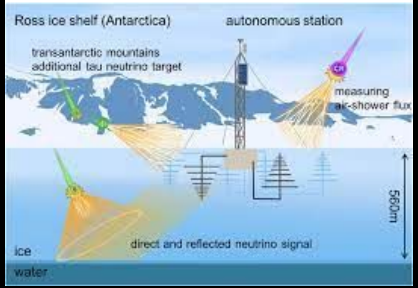


The DM model.

→

IceCube





ARIA

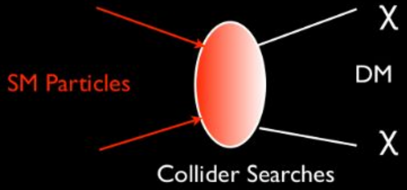
→ New bounds:

$$\sigma_{\chi n}(m_\chi)$$

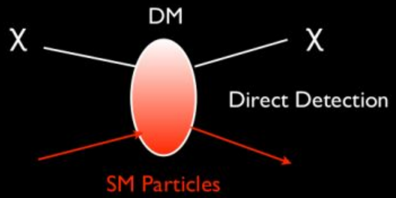
arXiv:2212.12547

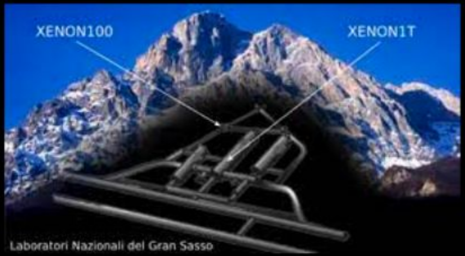
Dark Matter Detection Methods

Signature: radiations.



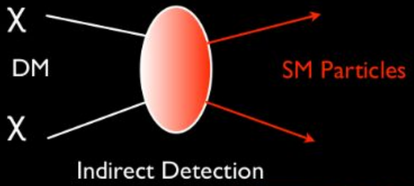
Signature: recoiled energies.





$\sigma_{\chi n}$

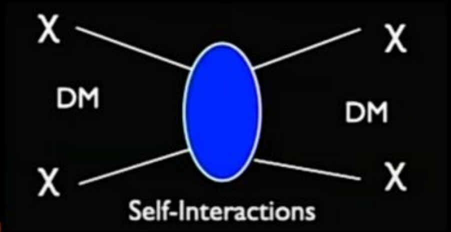
Signature: stable SM $(e^+, p, \gamma, \nu, \dots)$.



$\langle \sigma_{\chi\chi} \rangle$

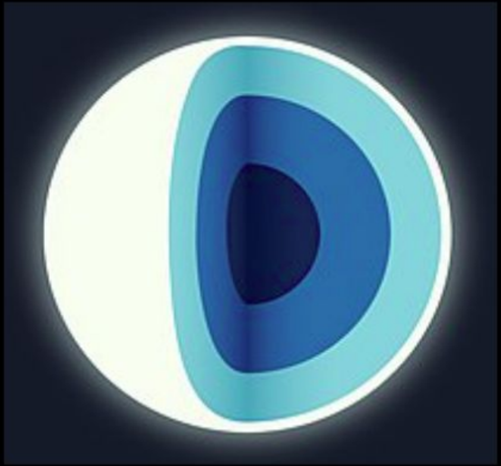
$\sigma_{\chi n}$ arXiv:2212.12547

Astrophysical structure of the Universe.



Van Que Tran, Thong T.Q. Nguyen, Tim M.P. Tait, Tzu-Chiang Yuan, in preparation

Neutron Stars in Galactic Center



$m_{\rm n} = 1 \text{ GeV} \qquad M \simeq 1.5 M_\odot \qquad R_\star \simeq 10 \text{ km}$

Escape velocity: $v_{\rm esc} \simeq 2 \times 10^5 \text{ km/s}$

Saturation Cross Section:

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

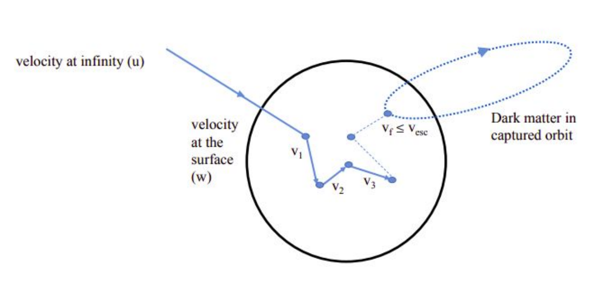
Neutron Star's number density[1] in Galactic Center:

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

A. Generozov, N.C. Stone, B.D. Metzger, J.P. Ostriker, *Mon.Not.Roy.Astron.Soc.* 478 (1804.01543)

Dark matter captured by neutron stars

Basudeb Dasgupta, Arita Gupta, Anupam Ray, *JCAP* 08 (1906.04204)



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

Dark Matter Capture Rate after Nth times [GeV]:

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

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

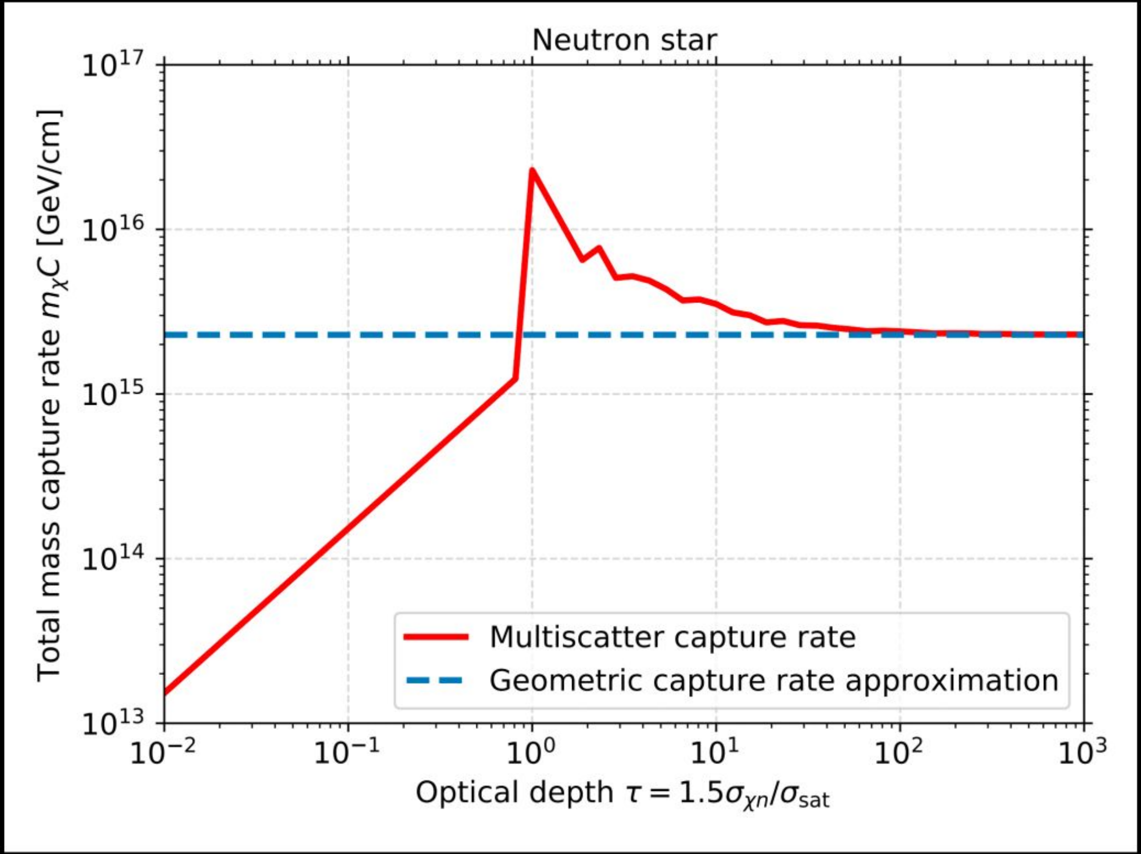
$\sigma_{\chi n}$ ⟶ DM model.

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

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

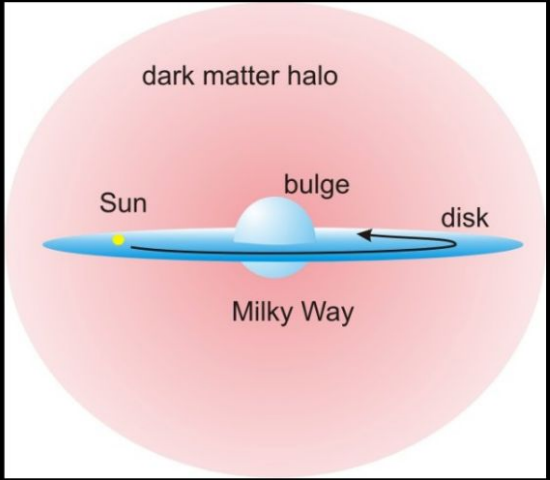
Total capture rate (All NSs): $C_{\rm tot} = 4\pi \int_{r_1 = 0.1\rm pc}^{r_2 = 100\rm pc} r^2 n_{\rm ns} C dr$.

$$C_{\max} = \pi R^2 n_\chi(r) v_0 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{\bar{v}(r)^2}\right)\xi(v_p, \bar{v}(r)),$$



Milky Way Galaxy

(Credit: https://scienceblogs.com)



Y. Sofue, *Publ.Astron.Soc.Jap.* 65 (1307.8241)

Mass Component	Total mass ($M_\odot$)	Scale radius (kpc)	Center density ($M_\odot$ pc^{-3})
Black hole	4×10^6	—	—
Inner bulge (core)	5×10^7	0.0038	3.6×10^4
Main Bulge	8.4×10^9	0.12	1.9×10^2
Disk	4.4×10^{10}	3.0	15
Dark halo	5×10^{10}	$h = 12.0$	$\rho = 0.011$

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

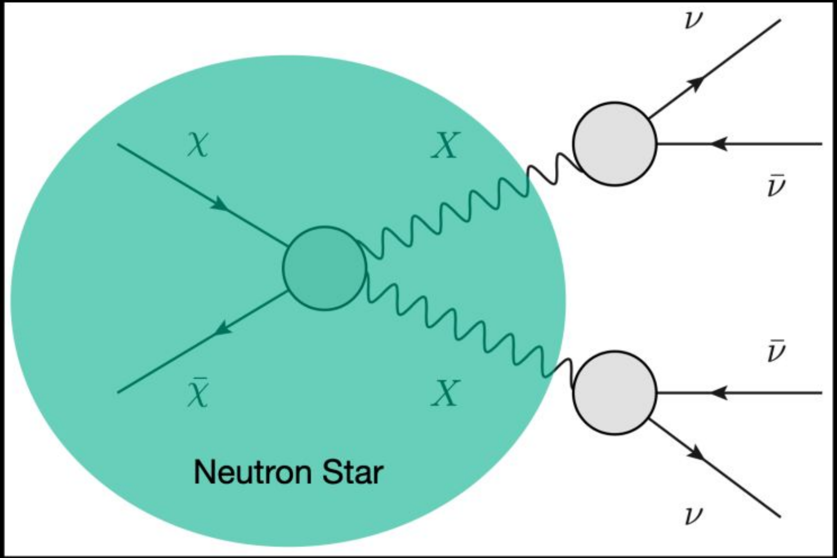
DM velocity dispersion: $\bar{v}(r) = \sqrt{\frac{3}{2}} v_c(r) = \sqrt{\frac{3}{2}} \sqrt{\frac{G_N M(r)}{r}}.$

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

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

J.F. Navarro, C.S. Frenk, S.D.M. White, *Astrophys.J.* 462 (9508025)

Dark Matter annihilation in NS



$$\eta = m_\chi / m_X$$

$$L = \eta c \tau_X \geq R_\star$$

Number of DM e.o.m:

$$\frac{dN(t)}{dt} = C_{total} - C_A N(t)^2$$

Solution:

$$N(t) = \sqrt{C_{total}/C_A} \tanh \frac{t}{t_{eq}}$$

Equilibrium time scale:

$$t_{eq} = 1/\sqrt{C_A C_{total}} \qquad C_A = \frac{\langle \sigma_A v \rangle}{V_\star}$$

Neutron Stars in GC are expected to be old!!

Annihilation rate: $\Gamma_{\rm ann} \rightarrow \frac{\Gamma_{\rm cap}}{2} = \frac{C_{total}}{2}$

R.K. Leane, T. Linden, P. Mukhopadhyay, N. Toro, *Phys.Rev.D* 103 (2101.12213)

Observable: Differential Energy Flux

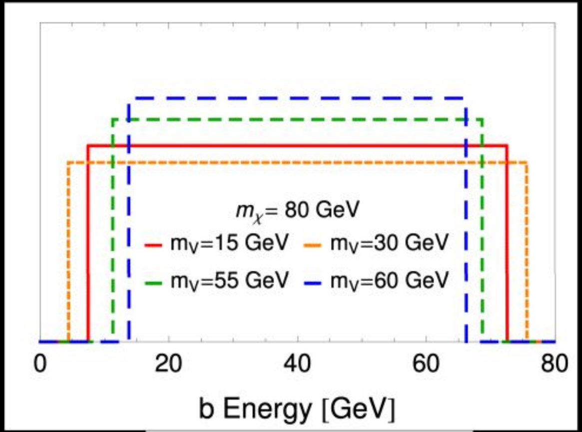
Differential Energy Flux (measured by ID Experiments):

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

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

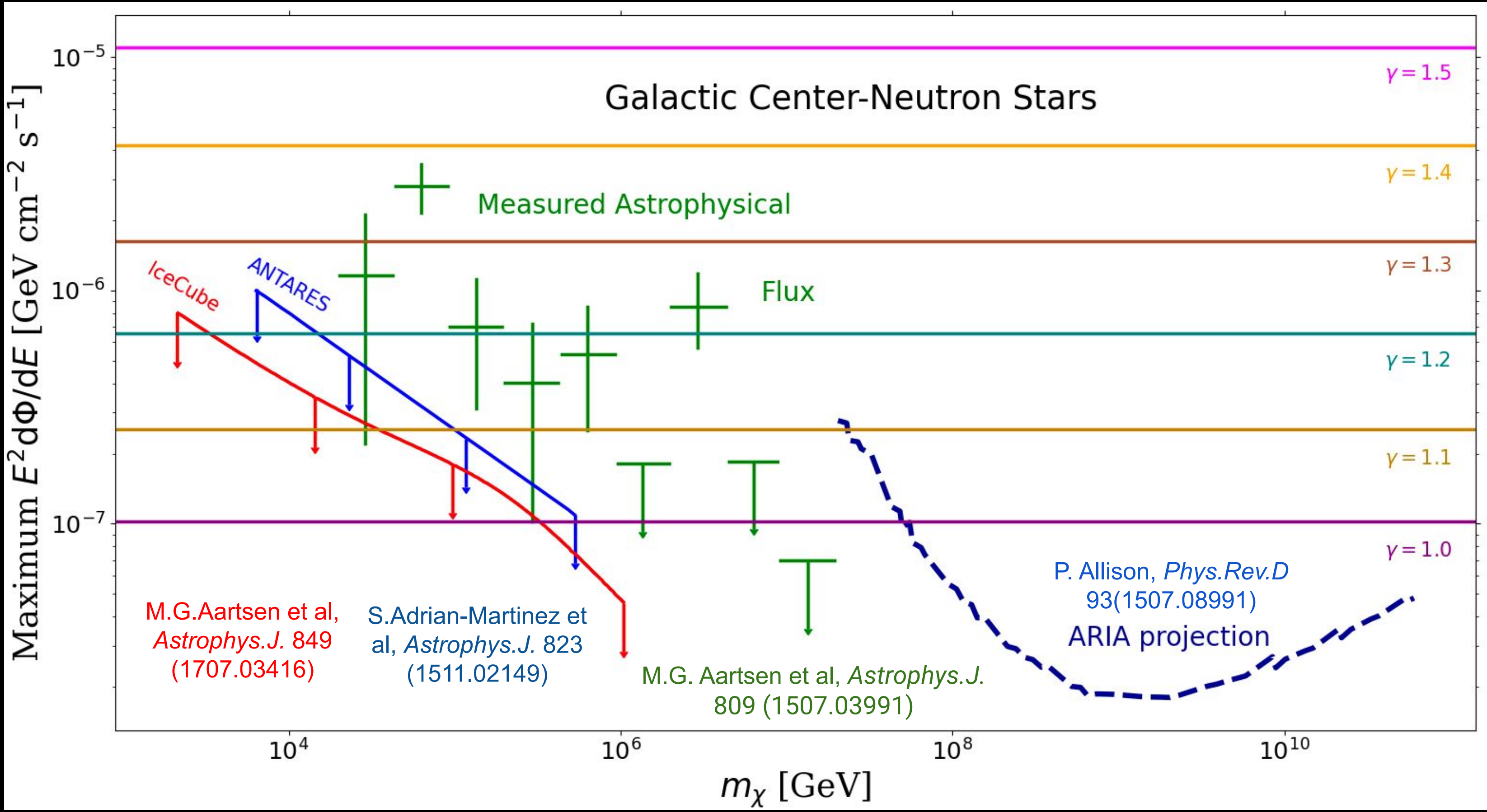
$$\frac{dN_\nu}{dE_\nu} = \frac{4}{m_\chi} \Theta(E_\nu) \Theta(m_\chi - E),$$

M. Abdullah, A. DiFanzo, A. Rajaraman, T.M.P. Tait, P. Tanedo, *Phys.Rev.D 90* (1404.6528)



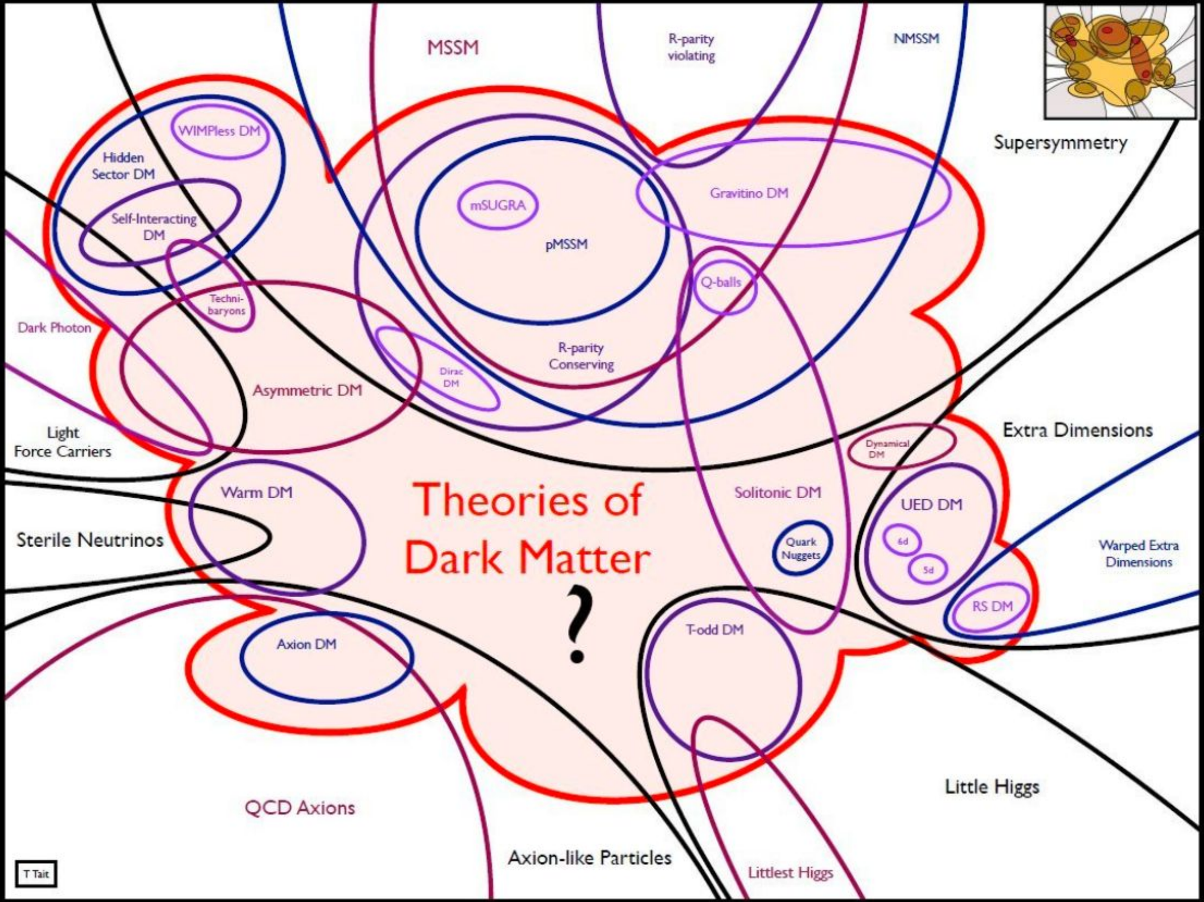
$$\chi\bar{\chi} \to VV \to 4b,$$

Experimental results



What DM model?

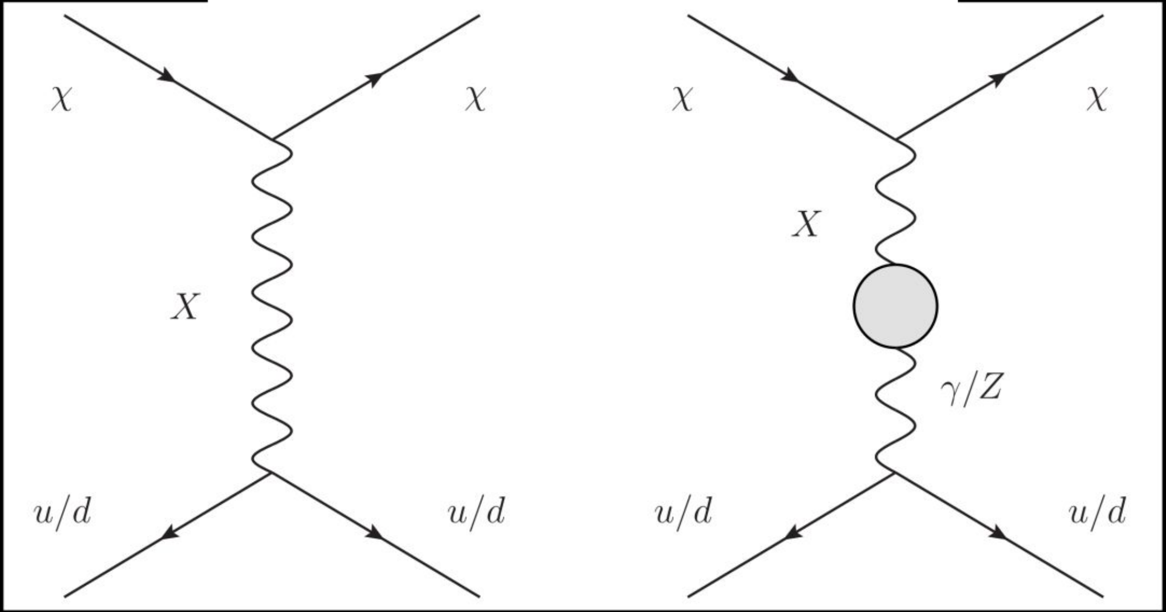
Our consideration



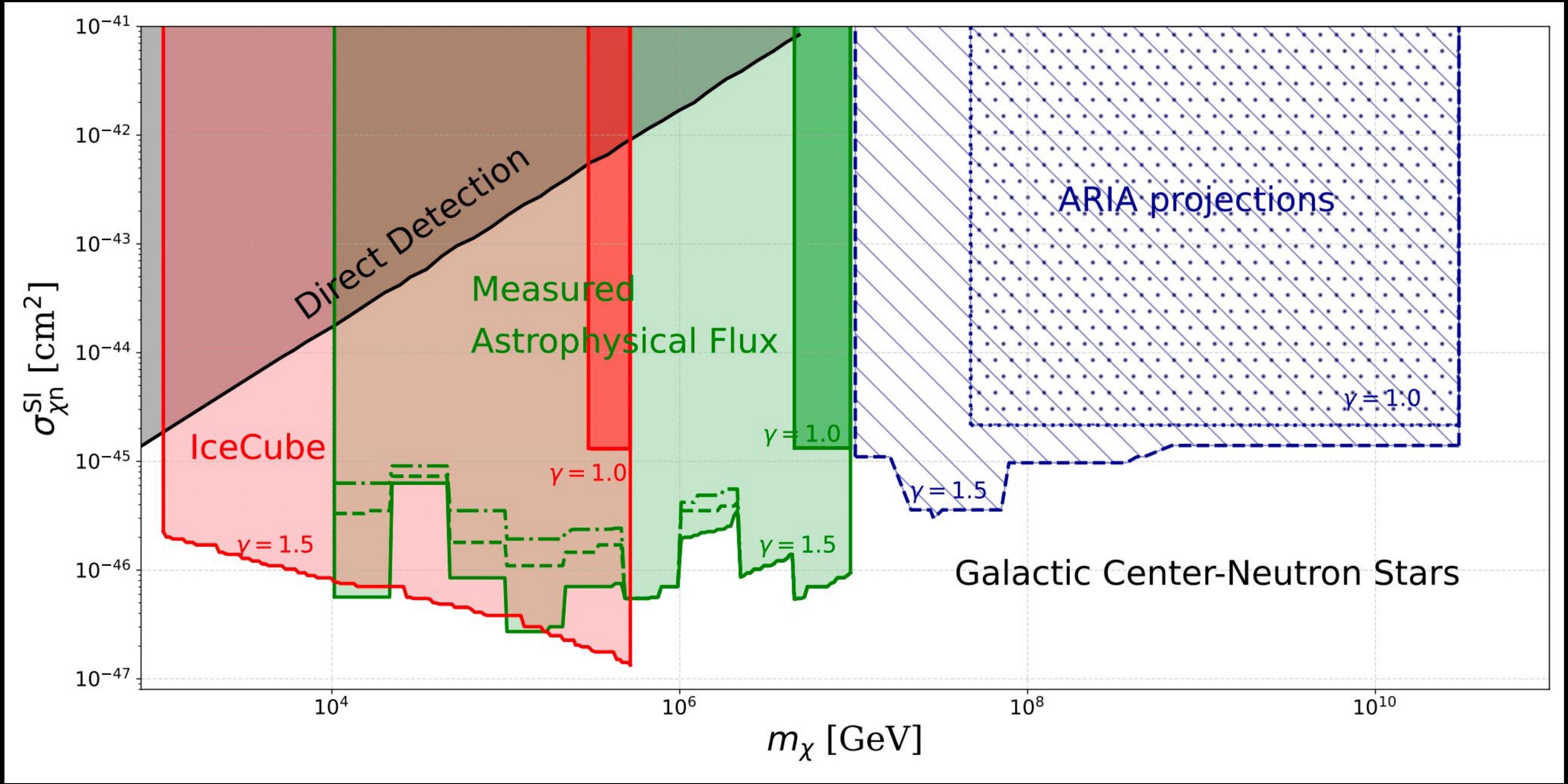
Dark Photon model

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

$$\mathcal{L} \supset -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}X_{\mu\nu}B^{\mu\nu} - \frac{1}{2}m_X^2 X_\mu X^\mu + \bar{\chi}(i\not{D}_{U(1)_X} - m_\chi)\chi,$$



Spin-Independent Cross Section limits



Take home message

- Neutron Stars can help us investigate Long-lived Dark Matter Mediator models.
- With Light Dark Photon 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, KM3Net, IceCube Gen2, ...


Thank you for listening!
Chiao is searching for Dog-matter too!