Bounds on Long-lived Dark Matter Mediators from Neutron Stars

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

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

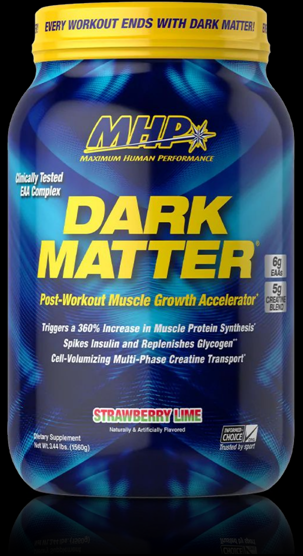
arXiv:2212.12547 and 23xx.xxxx

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

Workshop on Very Light Dark Matter 2023

Outline

Preview: Dark Matter Detections

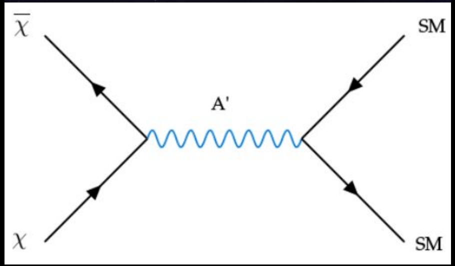


Available on Amazon!

→

Neutron Stars in Galactic Center.

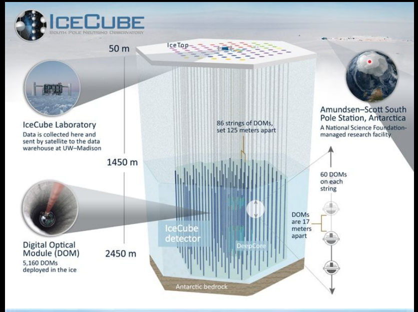
Free High Energy Colliders!!

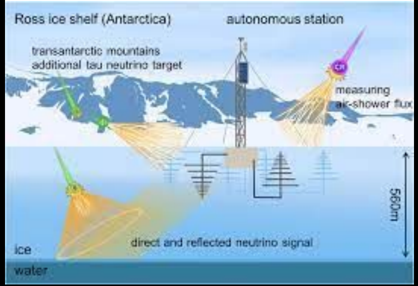


The DM model.

→

IceCube





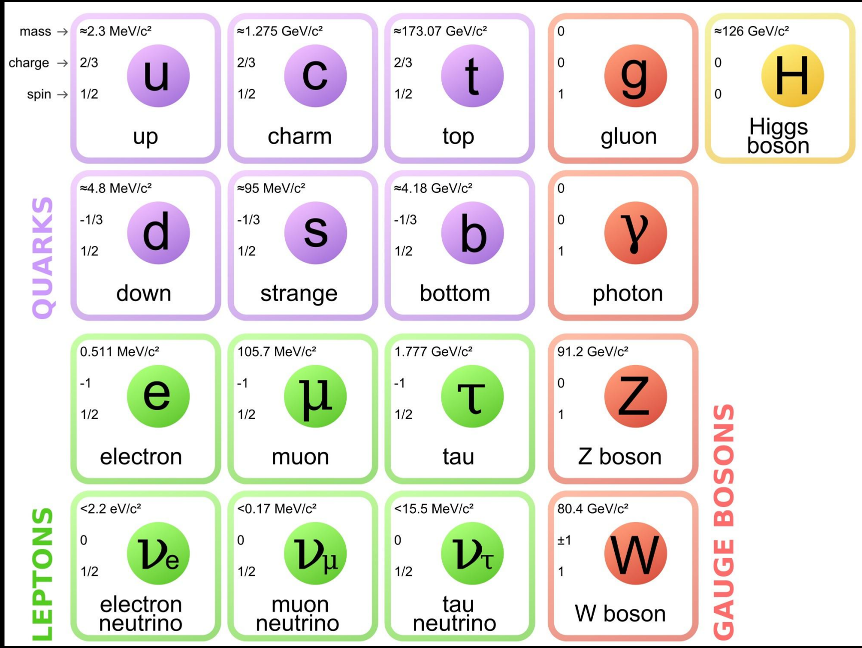
ARIA

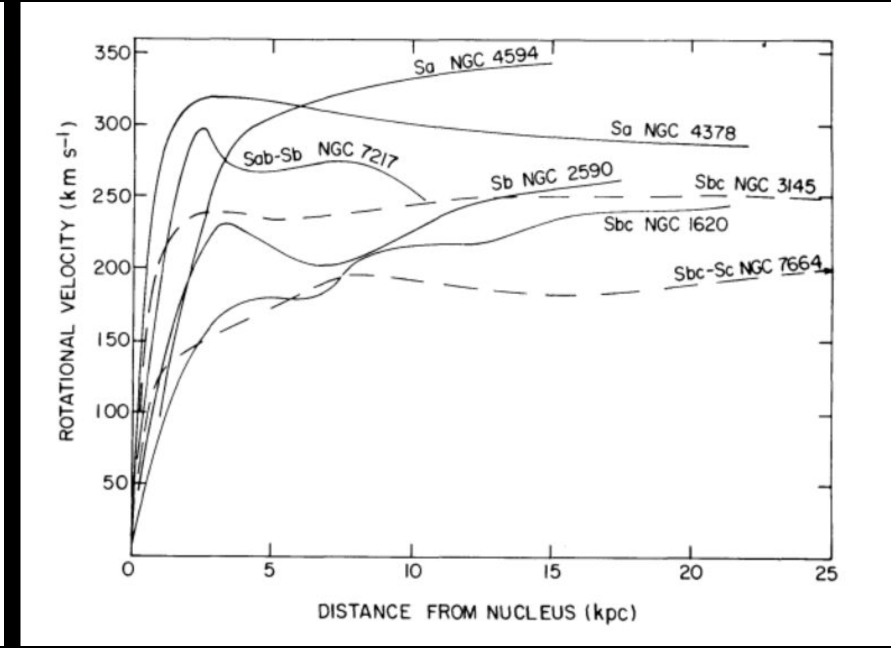
→ New bounds:

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

arXiv:2212.12547

Why Dark Matter?



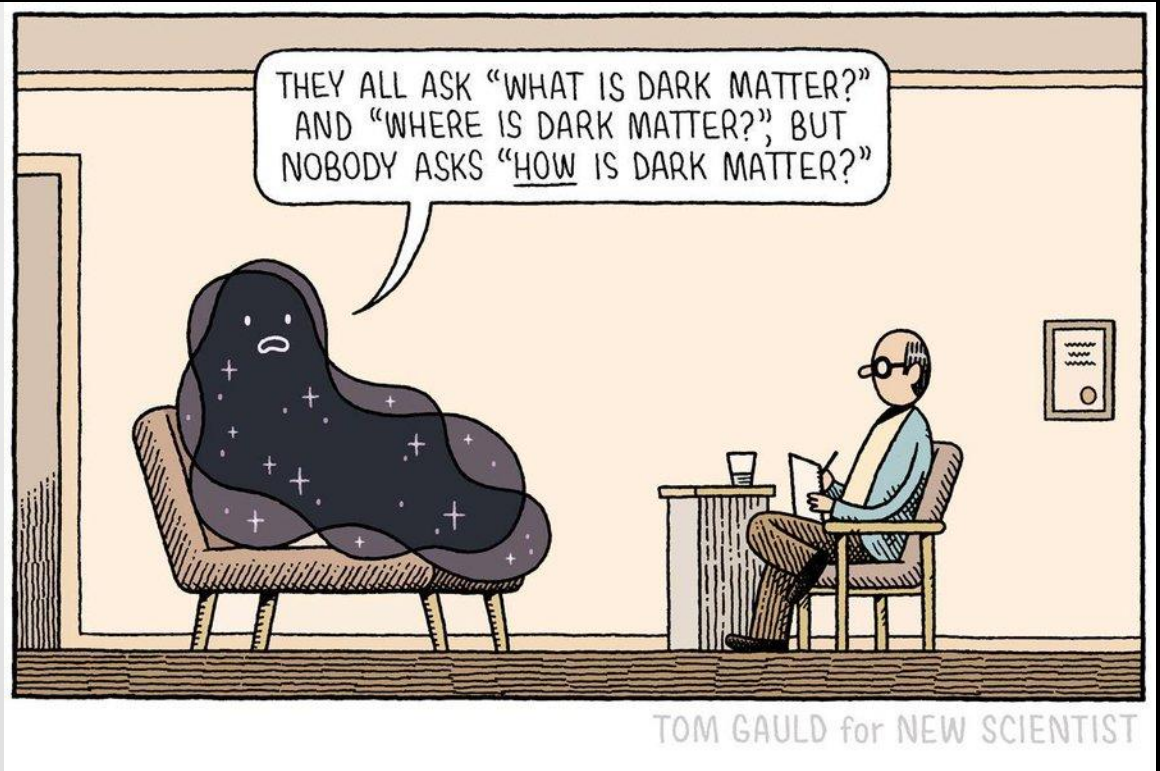


$$v(r) = \sqrt{\frac{G_N M(r)}{r}}$$

Dark Matter interactions: via Gravity and ???

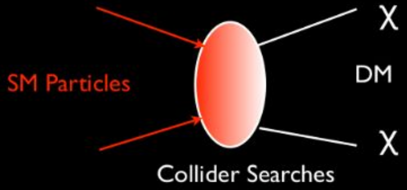
Assumption!!!


DARK
MATTER
MATTERS

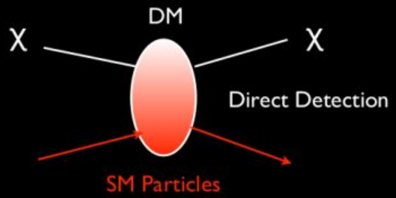

THEY ALL ASK "WHAT IS DARK MATTER?" AND "WHERE IS DARK MATTER?", BUT NOBODY ASKS "HOW IS DARK MATTER?"
TOM GAULD for NEW SCIENTIST

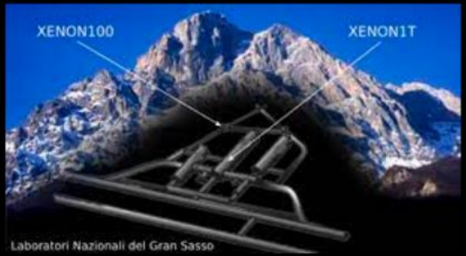
Dark Matter Detection Methods

Signature: radiations.



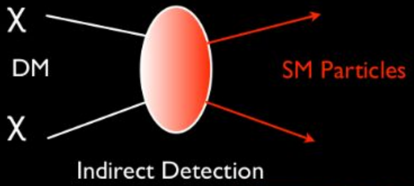
Signature: recoiled energies.





$\sigma_{\chi n}$

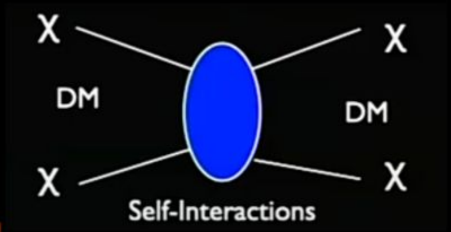
Signature: stable SM $(e^+, p, \gamma, \nu, \ldots)$.



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

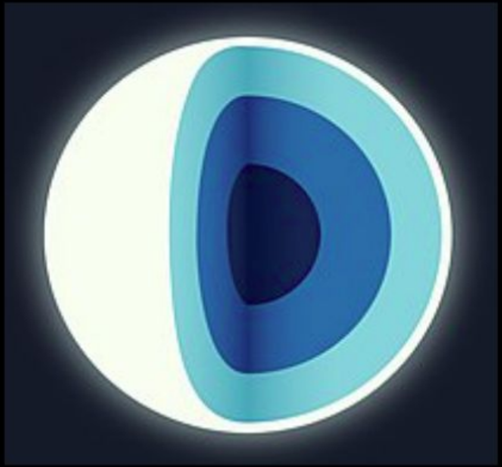
$\sigma_{\chi n}$ arXiv:2212.12547

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:

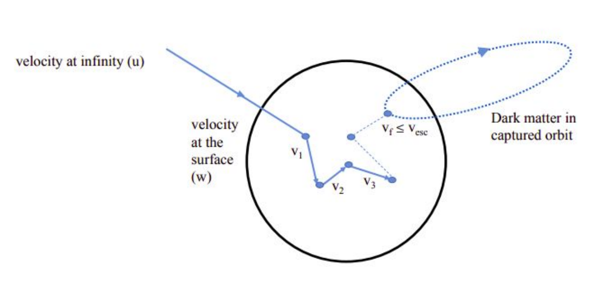
$$n_{\rm ns}(r) = 5.98 \times 10^3 \left(\frac{r}{1\text{pc}}\right)^{-1.7} \text{pc}^{-3} \ (0.1\text{pc} < r < 2\text{pc})$$

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

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:

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

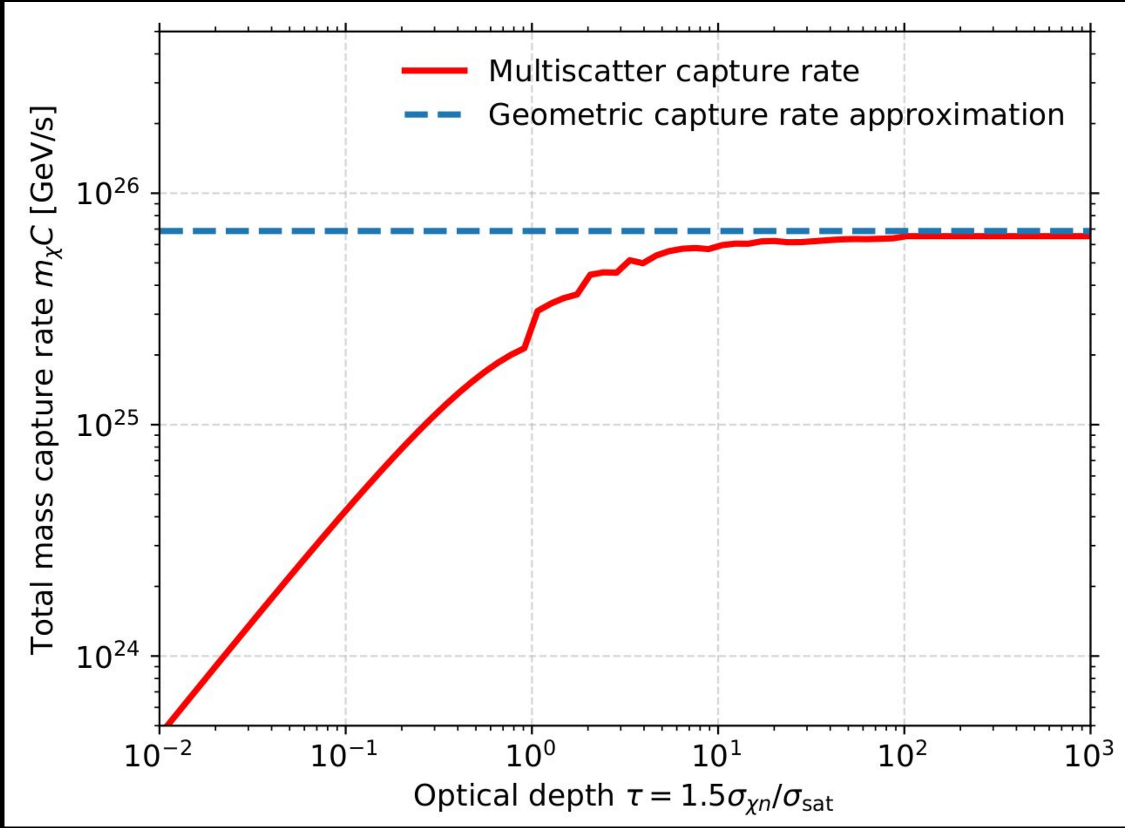
Optical Depth: $\tau = 1.5 \frac{\sigma_{\chi n}}{\sigma_{\rm sat}}$

$\sigma_{\chi n}$ ⟶ DM model.

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

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

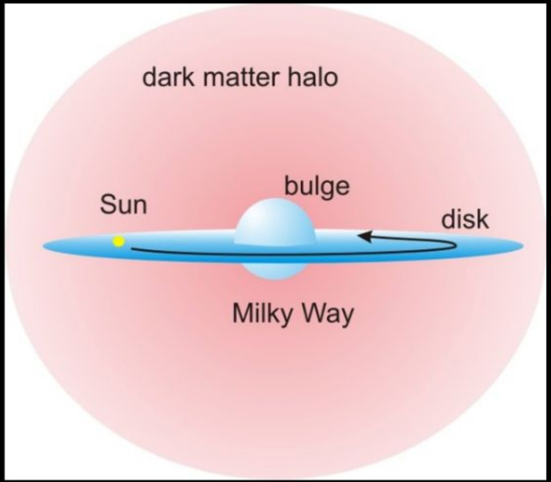
Total capture rate (All NSs): $C_{\rm tot} = 4\pi \int_{r_1=0.1{\rm pc}}^{r_2=100{\rm pc}} r^2 n_{\rm ns} C dr$.



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

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}	$h = 12.0$	$\rho = 0.011$

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

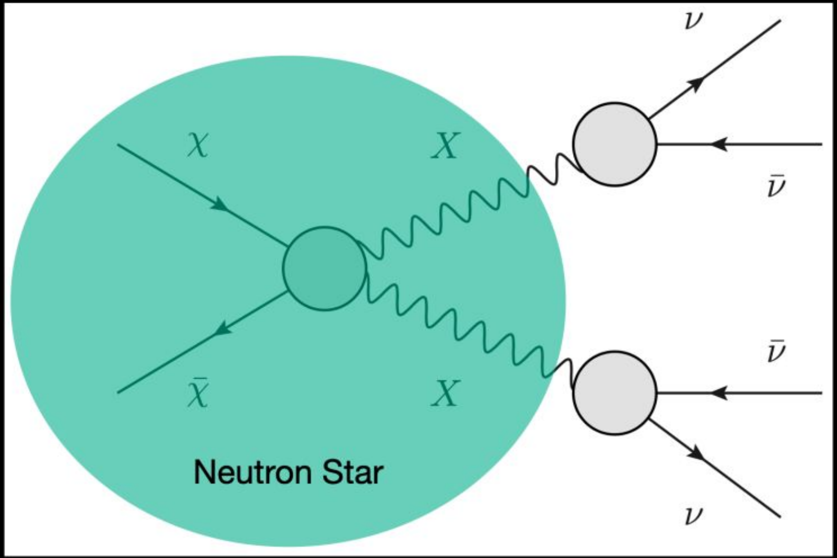
DM velocity dispersion: $\bar{v}(r) = \sqrt{\frac{3}{2}} v_c(r) = \sqrt{\frac{3}{2}} \sqrt{\frac{G_N M(r)}{r}}.$

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

- $\rho_0 = 0.42$ 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: $\Gamma_{\text{ann}} \rightarrow \frac{\Gamma_{\text{cap}}}{2} = \frac{C_{total}}{2}$

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

Observable: Differential Energy Flux

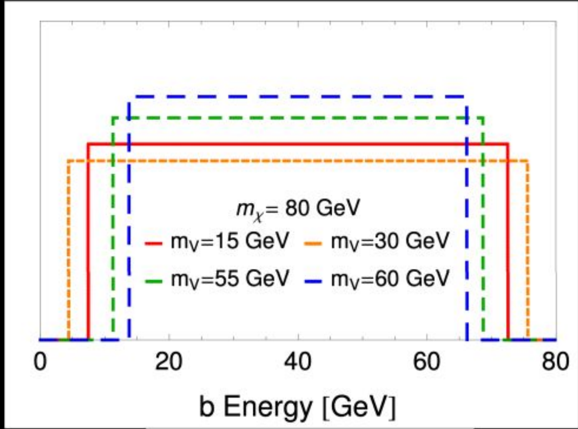
Differential Energy Flux (measured by ID Experiments):

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

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

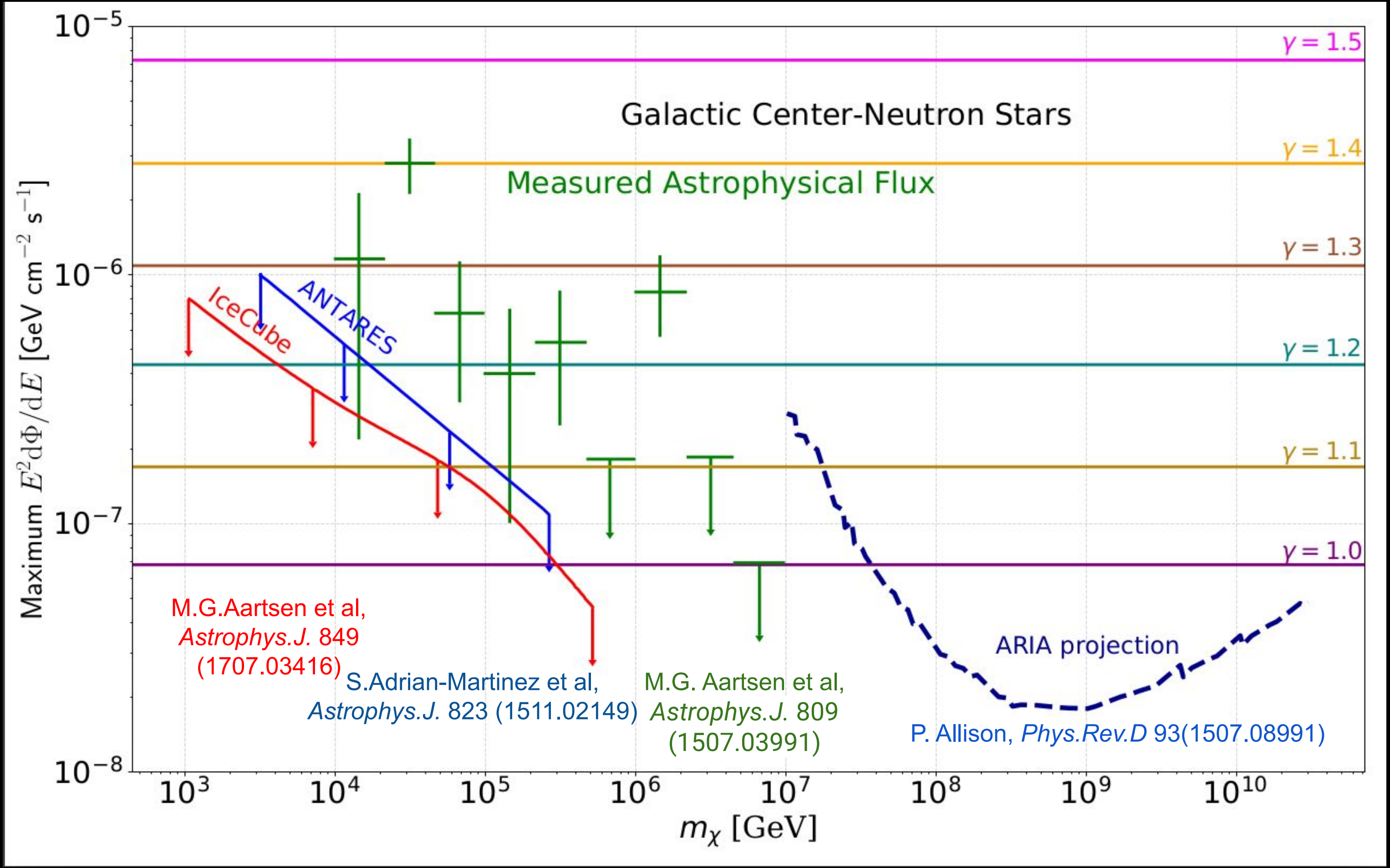
$$\frac{dN_\nu}{dE_\nu} = \frac{4}{m_\chi}\Theta\left(E_\nu\right)\Theta\left(m_\chi - E\right),$$

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



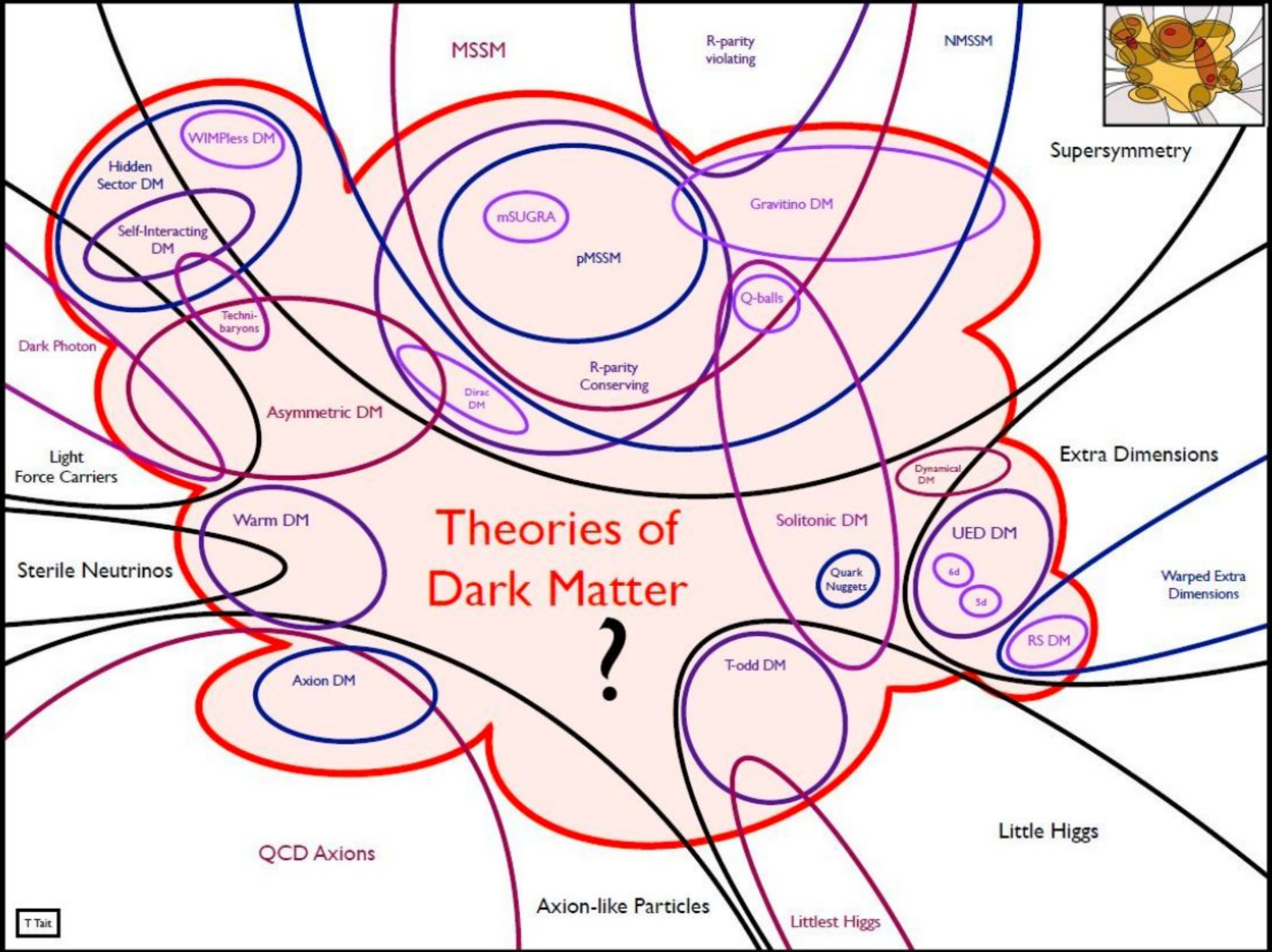
$$\chi\bar{\chi} \to VV \to 4b,$$

Experimental limits



What DM model?

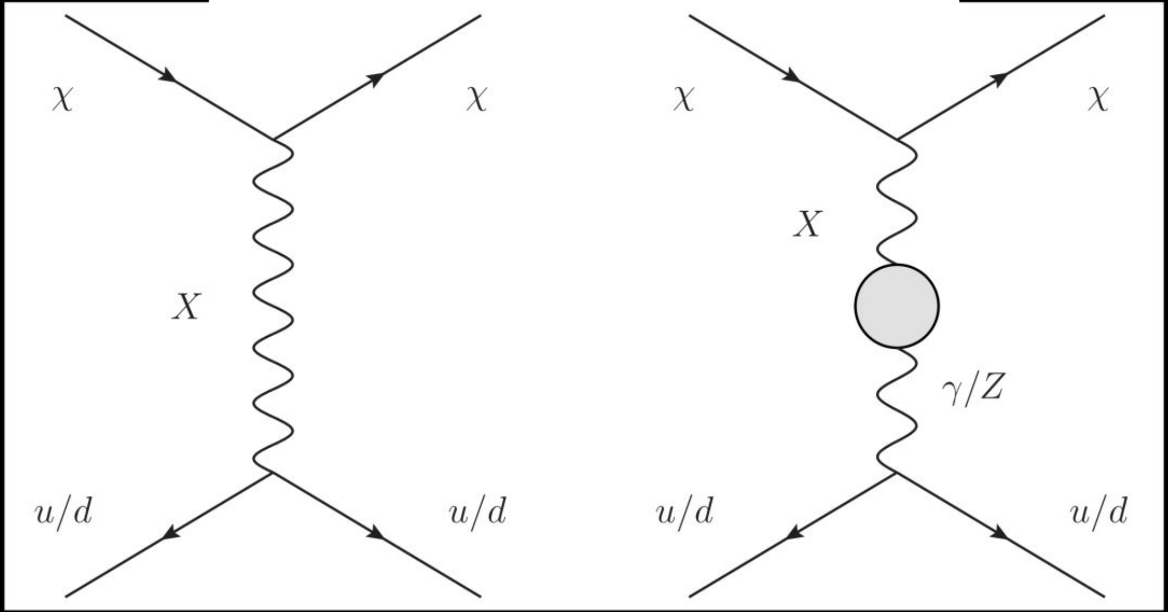
Our consideration



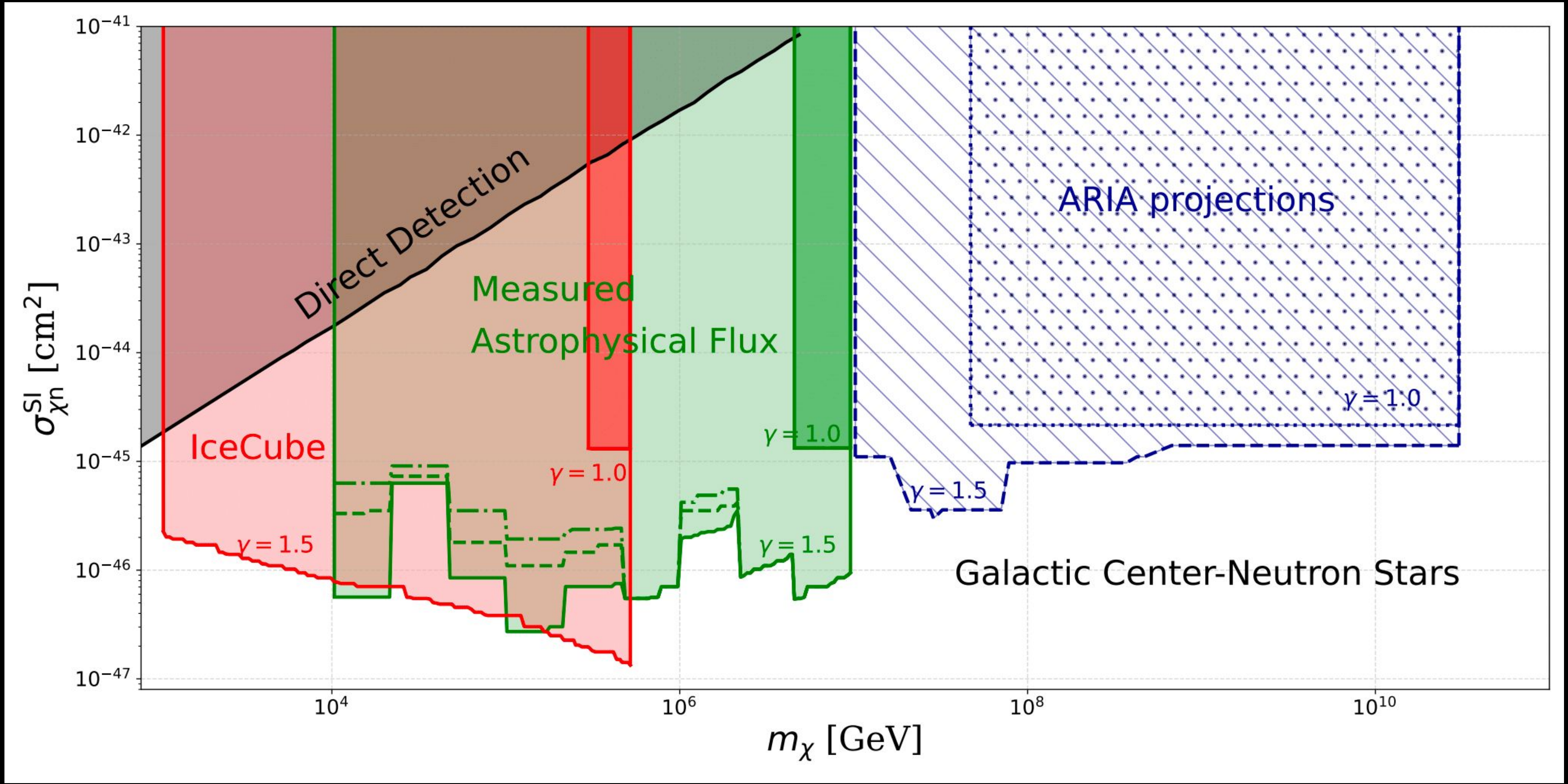
Dark Photon model

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

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



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!