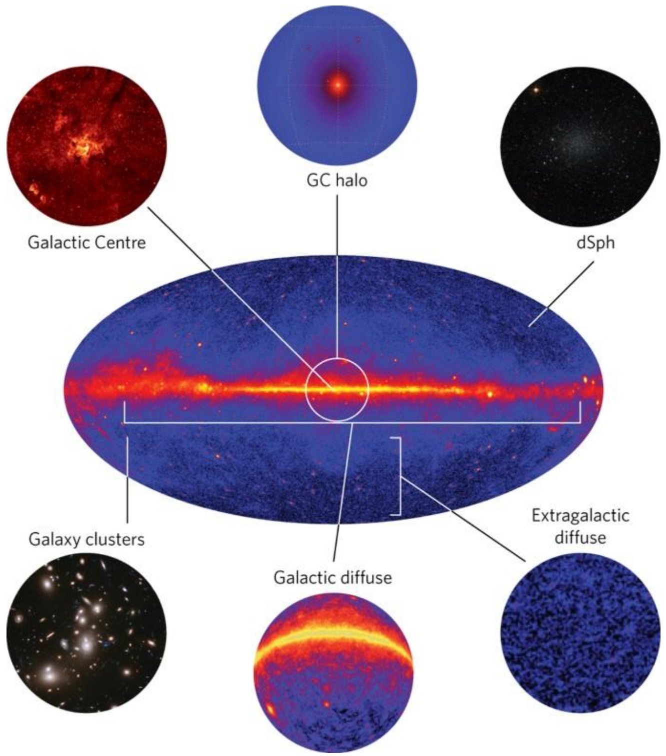
Neutron Star Heating by Inelastic DM

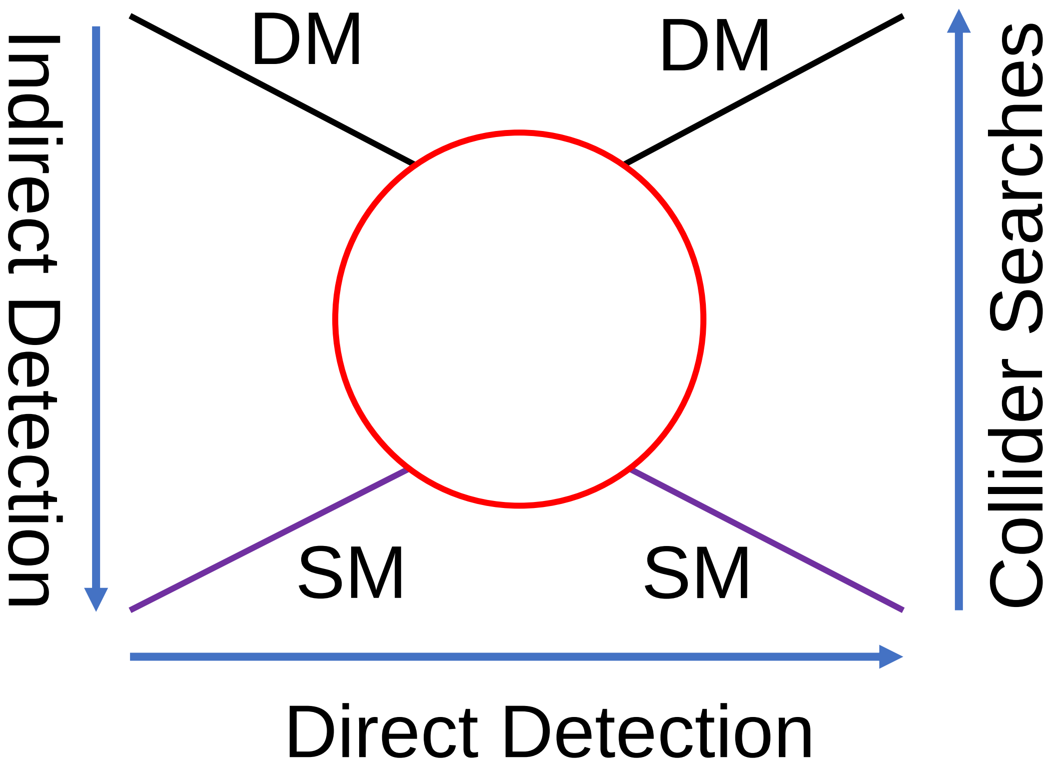
Aniket Joglekar

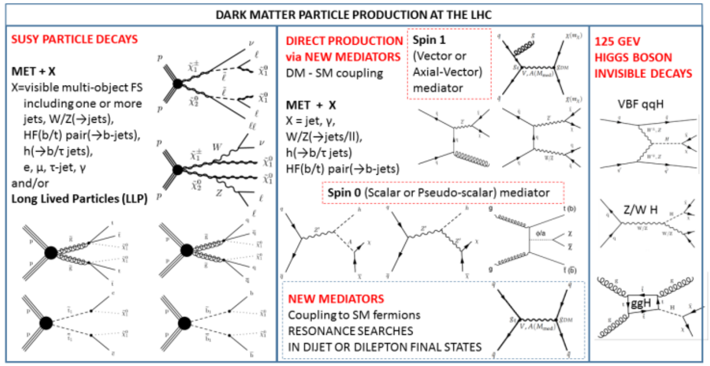
CHEP Frontiers in Particle Physics
10 August 2024

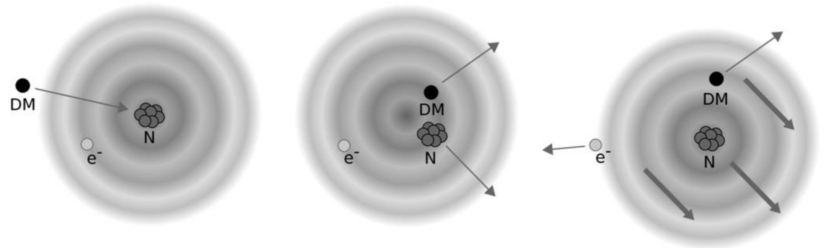
भारतीय प्रौद्योगिकी संस्थान तिरुपति
TIRUPATI

Probing the Nature of Dark Matter









Direct Detection of Dark Matter

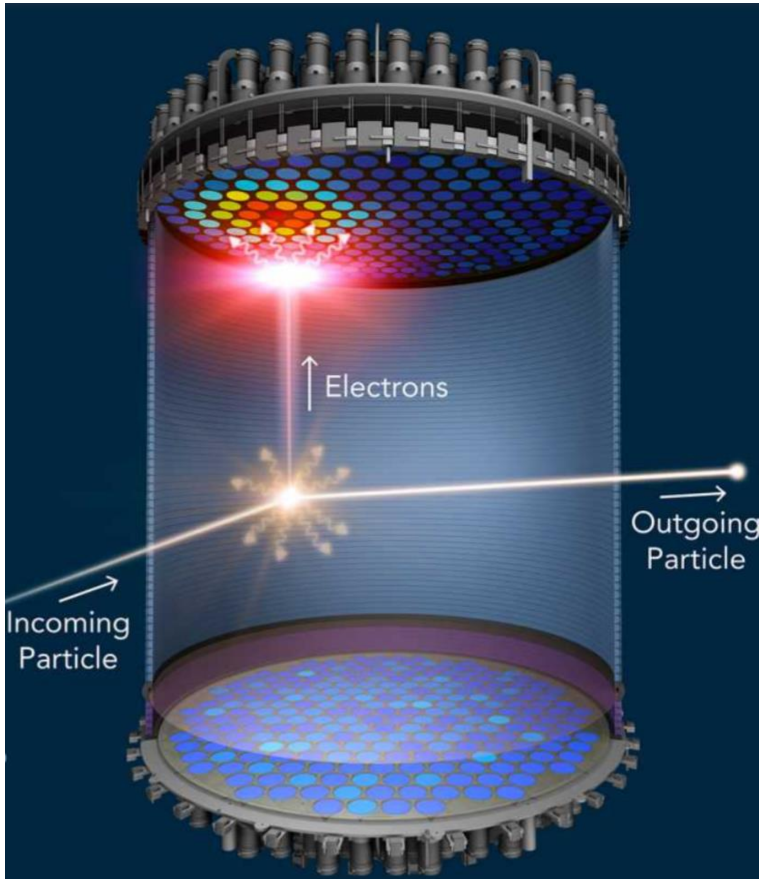


Image: Lux-LZ

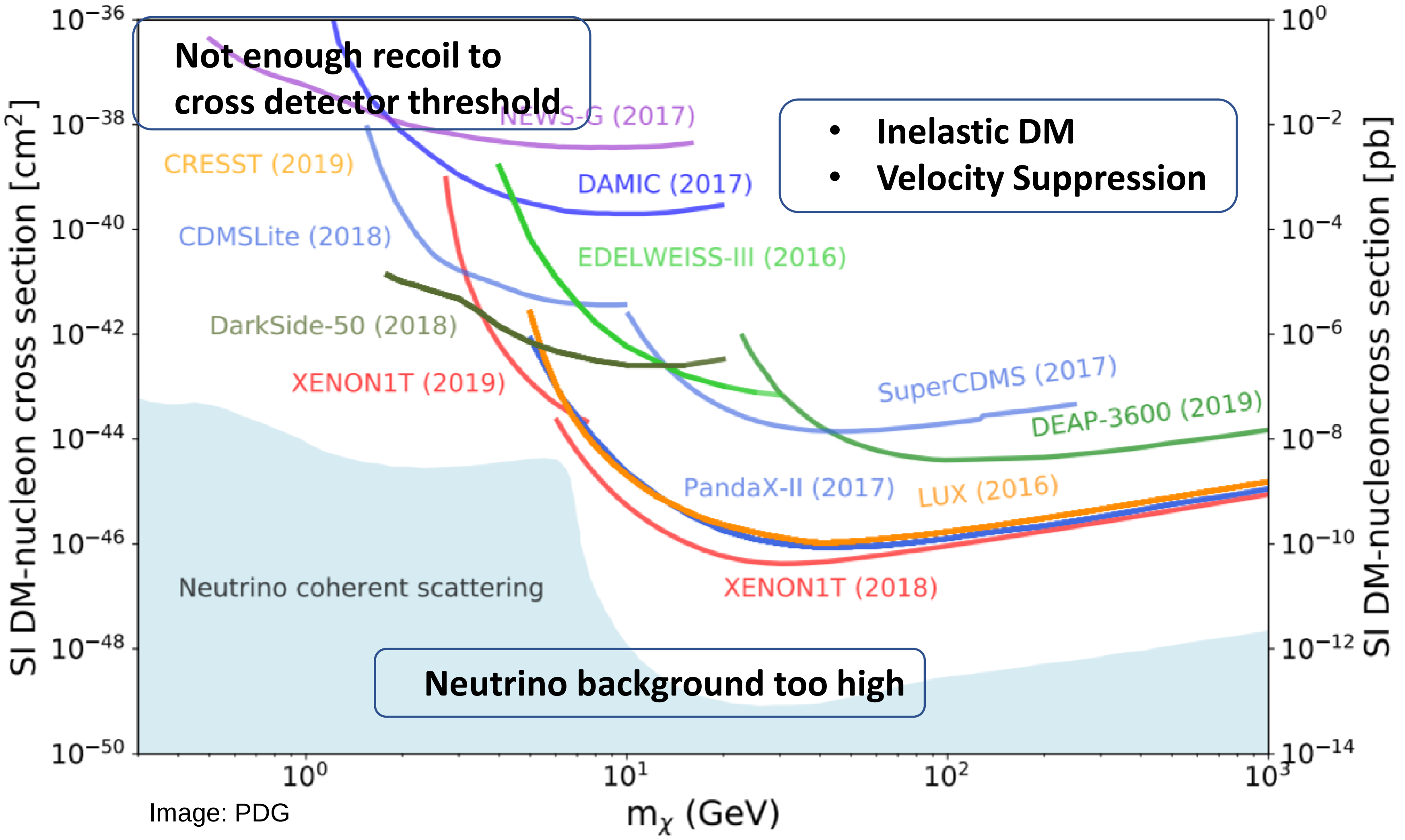
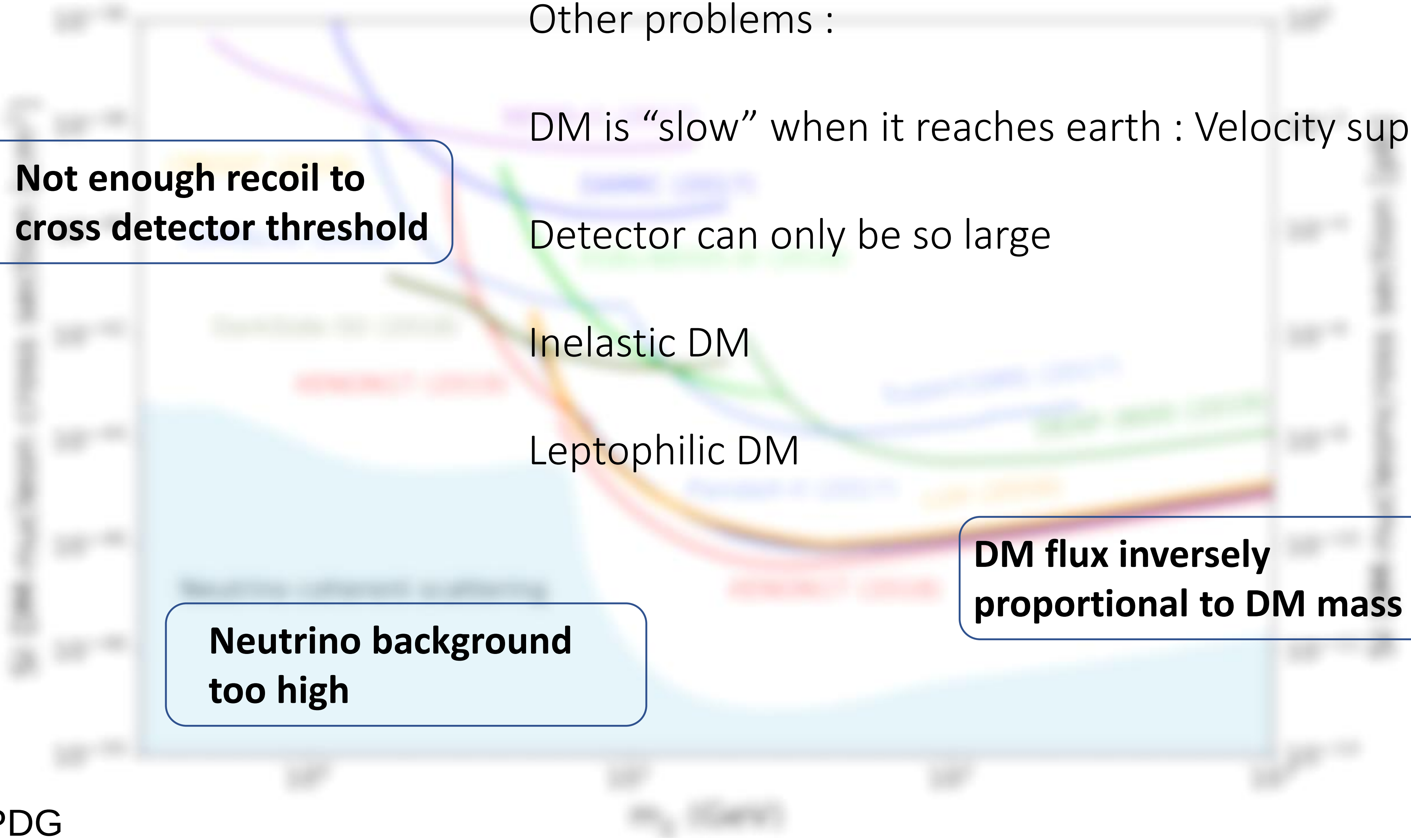


Image: PDG

Challenges



Other problems :

DM is “slow” when it reaches earth : Velocity suppression

Detector can only be so large

Inelastic DM

Leptophilic DM

Not enough recoil to cross detector threshold

Neutrino background too high

DM flux inversely proportional to DM mass

Image: PDG

Dark Matter in Heavy Compact Objects

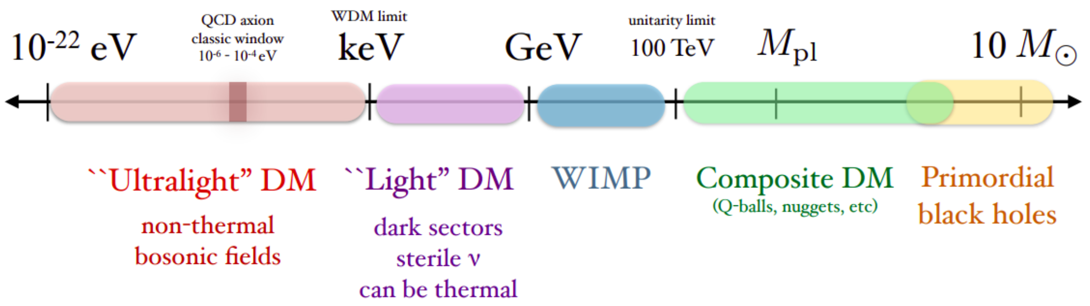


Image : https://arxiv.org/abs/1904.07915 TASI Lecture by Tongyan Lin

Huge range of masses for candidates

Neutron star Kinetic Heating

e.g. Baryakhtar, Bramant , Li, Linden, Raj Phys.Rev.Lett 119 (2017)13, 131801

Radio Signals from Nautron Star Magnetosphere

e.g. Hook, Kahn, Safdi , Sun Phys.Rev.Lett 121 (2018), 24, 241102

BH Super-radiance

e.g. Baryakhter, Lasenby, Teo *Phys.Rev.D* 96 (2017) 3, 035019

Heating of exoplanets and brown dwarfs

e.g. Leane, Smirnov *Phys.Rev.Lett.* 126 (2021)

Existence of old neutron stars

e.g. Kouvaris, *Phys.Rev.Lett.* 108 (2012) 191301

Many more….

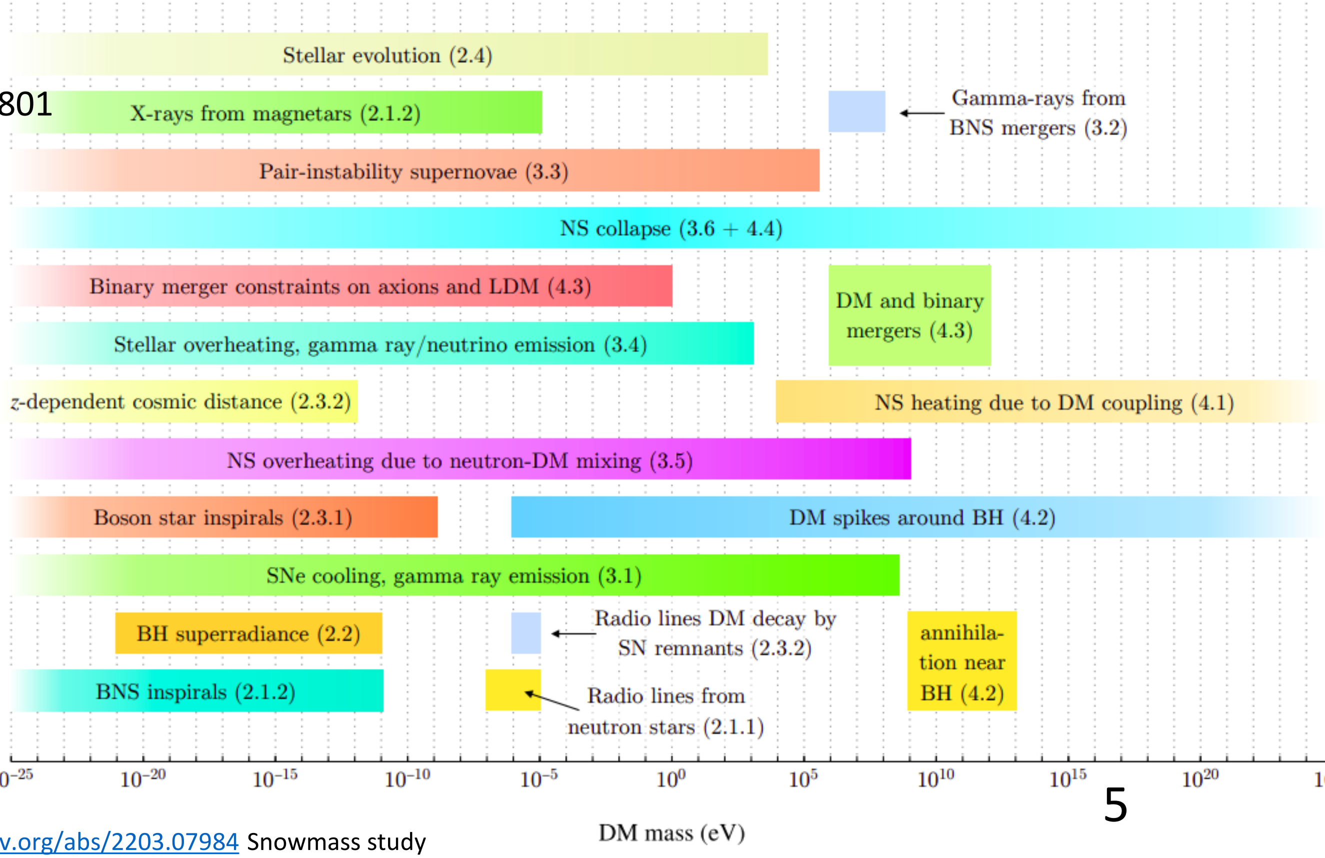
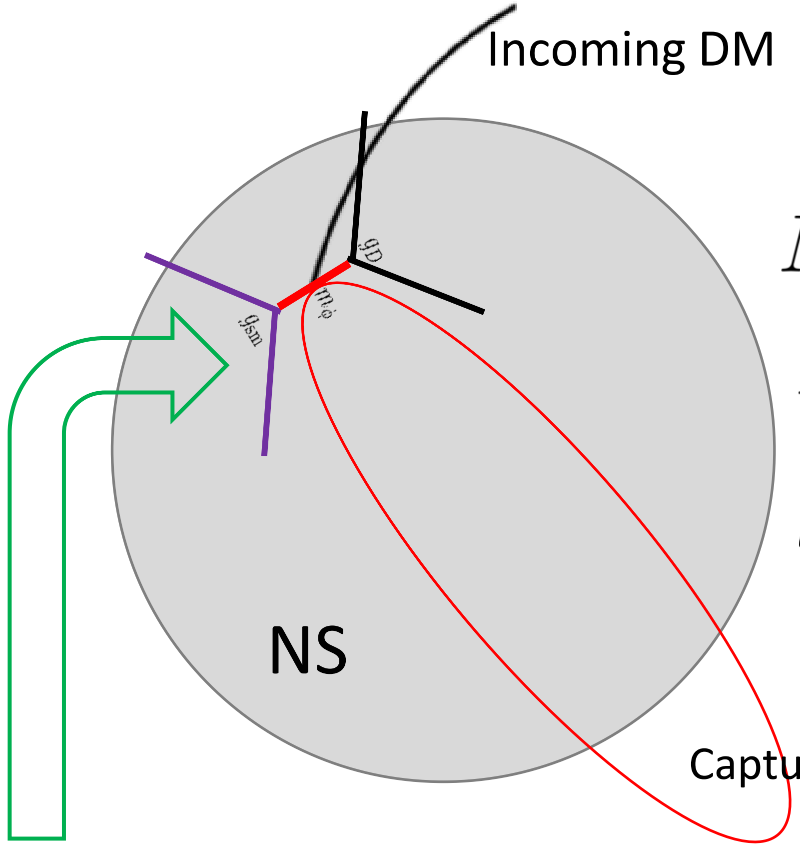


Image : https://arxiv.org/abs/2203.07984 Snowmass study

Capture in Neutron Stars

Continuous dark matter flux incident on the NS



$$M_\star = 1.5\, M_\odot$$

$$R_\star = 12.6\,\mathrm{km}$$

$$\sim 5 \times 10^{57}$$

Targets

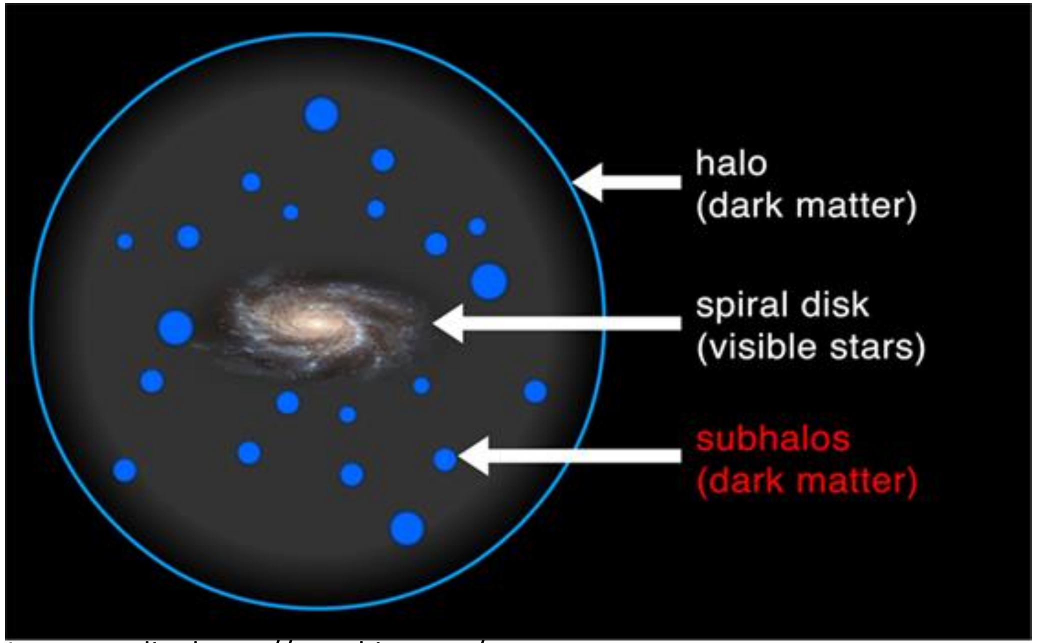


Image credit : https://astrobites.org/

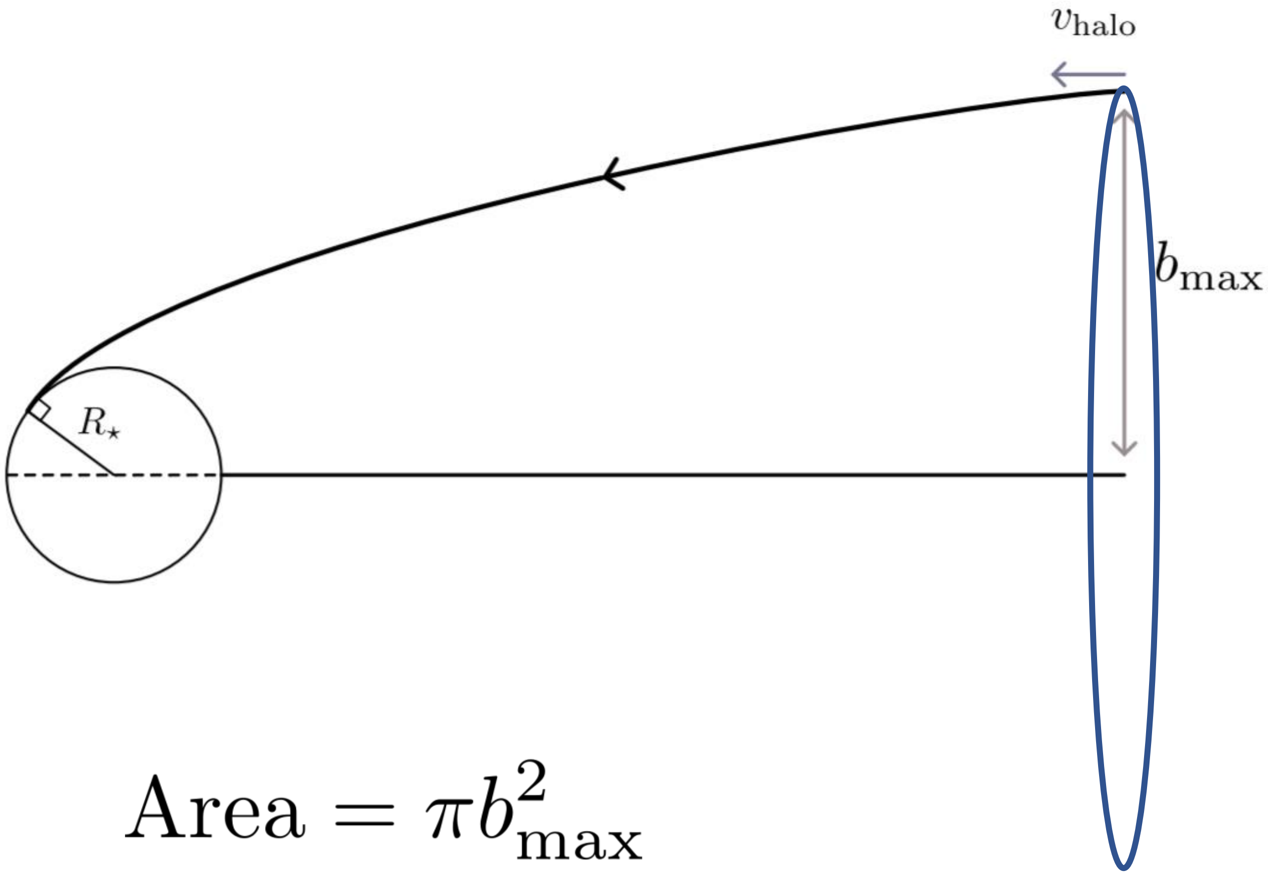
Densely Packed

Interaction where DM loses more energy than its Halo KE

Accelerates DM to $v \sim 0.6\, c$

Flux

Continuous dark matter flux incident on the NS



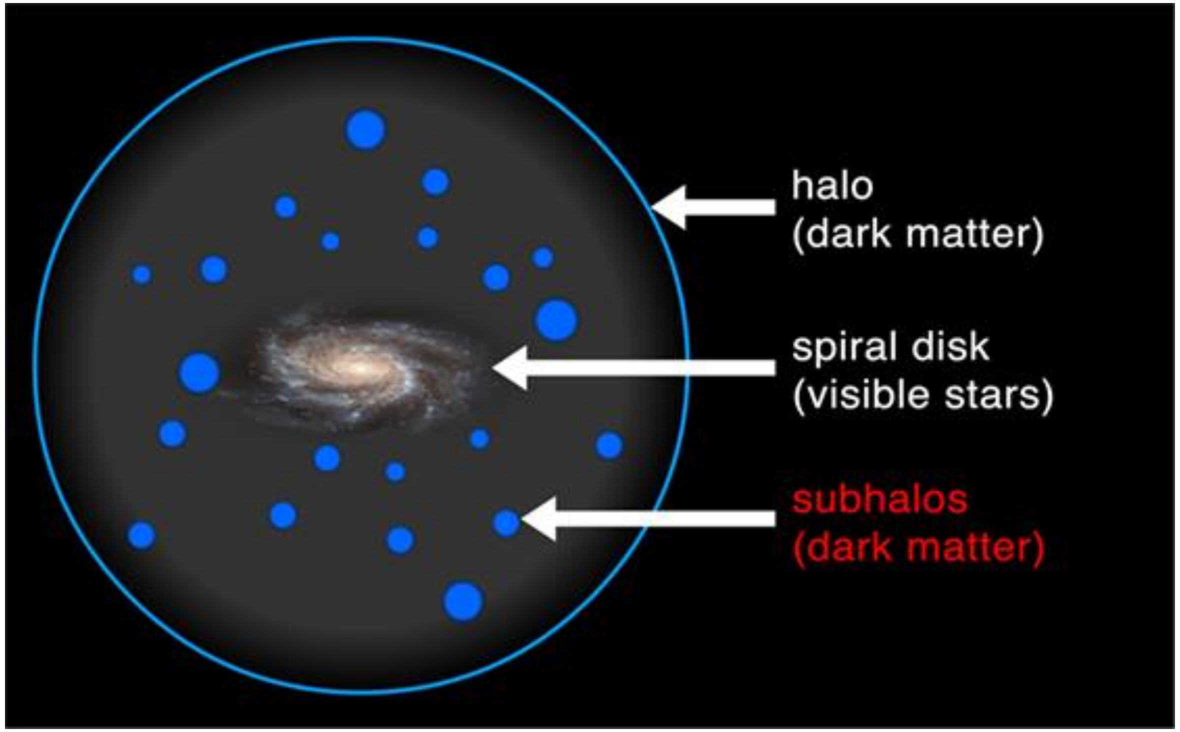


Image credit : https://astrobites.org/

$$\text{Area} = \pi b_{\rm max}^2$$

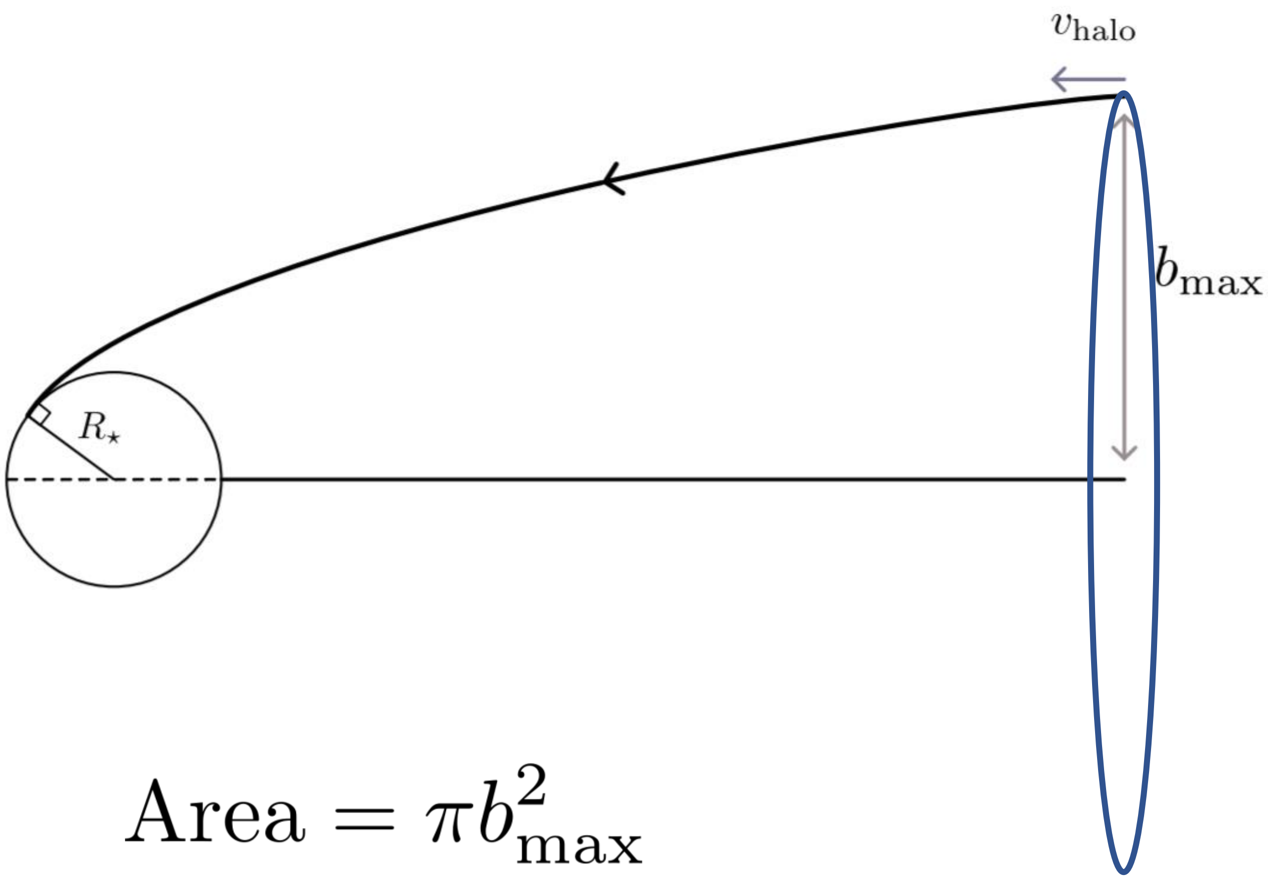
$$v_{\rm halo} = 8 \times 10^{-4},\ \rho_\chi = 0.3\ \text{GeV/cc}$$

$$M_\star = 1.5\, M_\odot,\ R_\star = 12.6\,\text{km}$$

Being fed to NS with velocity $v_{\rm halo}$

Flux

Continuous dark matter flux incident on the NS



We take:

$$v_{\mathrm{halo}} = 8 \times 10^{-4},\ \rho_\chi = 0.3\ \mathrm{GeV/cc}$$

$$M_\star = 1.5\, M_\odot,\ R_\star = 12.6\,\mathrm{km}$$

This means :

$$b_{\max} = \frac{R_\star}{v_{\mathrm{halo}}} \sqrt{\frac{2GM}{R}} \left(1 - \frac{2GM}{R}\right)^{-1/2}$$

$$\frac{2GM_\star}{R_\star} \sim 0.35 \qquad b_{\max} \sim 10^3\, R_\star$$

$$\mathrm{Area} = \pi b_{\max}^2$$

DM Flux is : $\pi b_{\max}^2 \rho_\chi v_{\mathrm{halo}}$

Large compared to $R_\star$!

Capture & Heating in Other Celestial Bodies?

Image credit : Arttist's impression of WD CC

Density less by factor 10^8

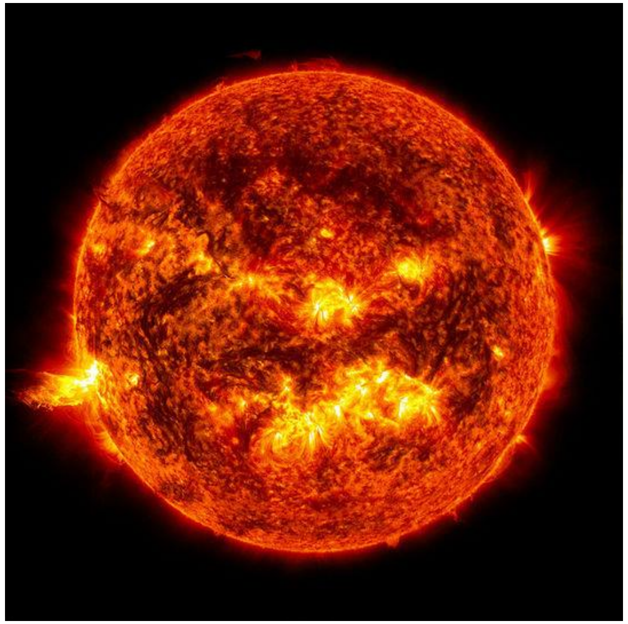


Image : NAsA

by factor 10^{14}

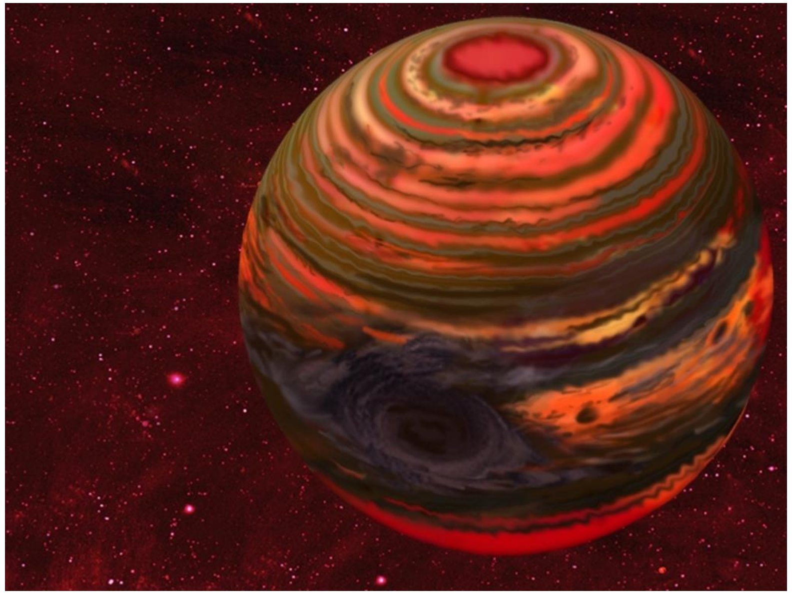


Image : Art by Jon Lomberg

by factor 10^{11} - 10^{13}

$$\text{capture} \propto \text{density} \times \text{flux}$$

Neutron Stars $\sim 10^{-45}\,\text{cm}^2$

Other stuff $\sim 10^{-35}\,\text{cm}^2$

Generally too hot for anomalous heating

NS Kinetic Heating

$$\text{Flux} = \pi b_{\text{max}}^2 v_{\text{halo}} \rho \sim \frac{4 \times 10^{25}}{m_\chi \, (\text{GeV})} \, s^{-1}$$

$$\text{KE} = (\gamma - 1) m_\chi$$

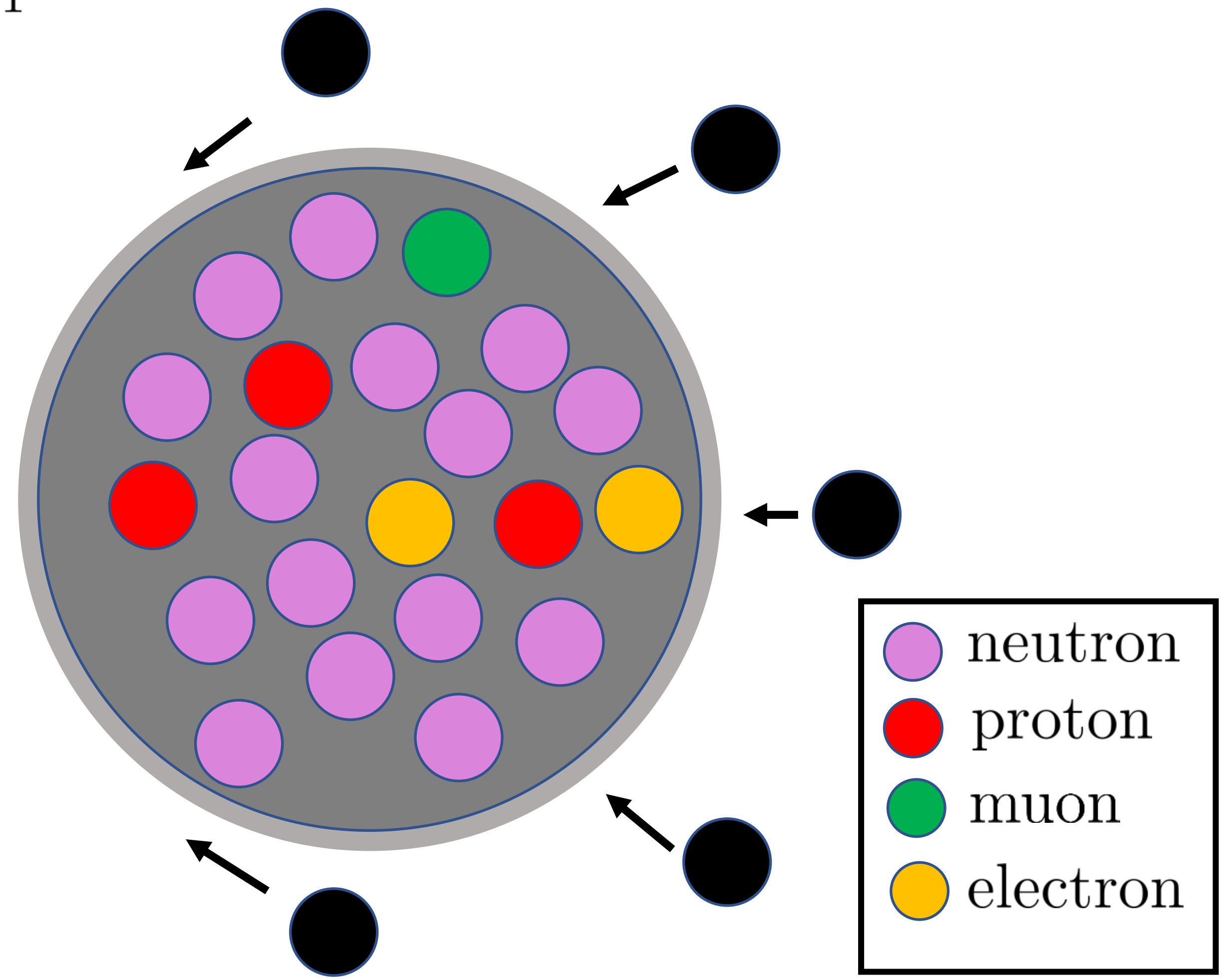
$$\dot{E} = f \times \text{flux} \times \text{KE}$$

$$= f \times (\gamma_{\text{esc}} - 1) \times 4 \times 10^{25} \, s^{-1}$$

Capture efficiency

$$\dot{E} = 4\pi R_\star^2 \sigma_{\text{SB}} T^4$$

$$T \sim 1600 f^{1/4} \, K$$



NS Kinetic Heating

$$\text{Flux} = \pi b_{\max}^2 v_{\text{halo}} \rho \sim \frac{4 \times 10^{25}}{m_\chi \,(\text{GeV})} \, s^{-1}$$

$$\text{KE} = (\gamma - 1) m_\chi$$

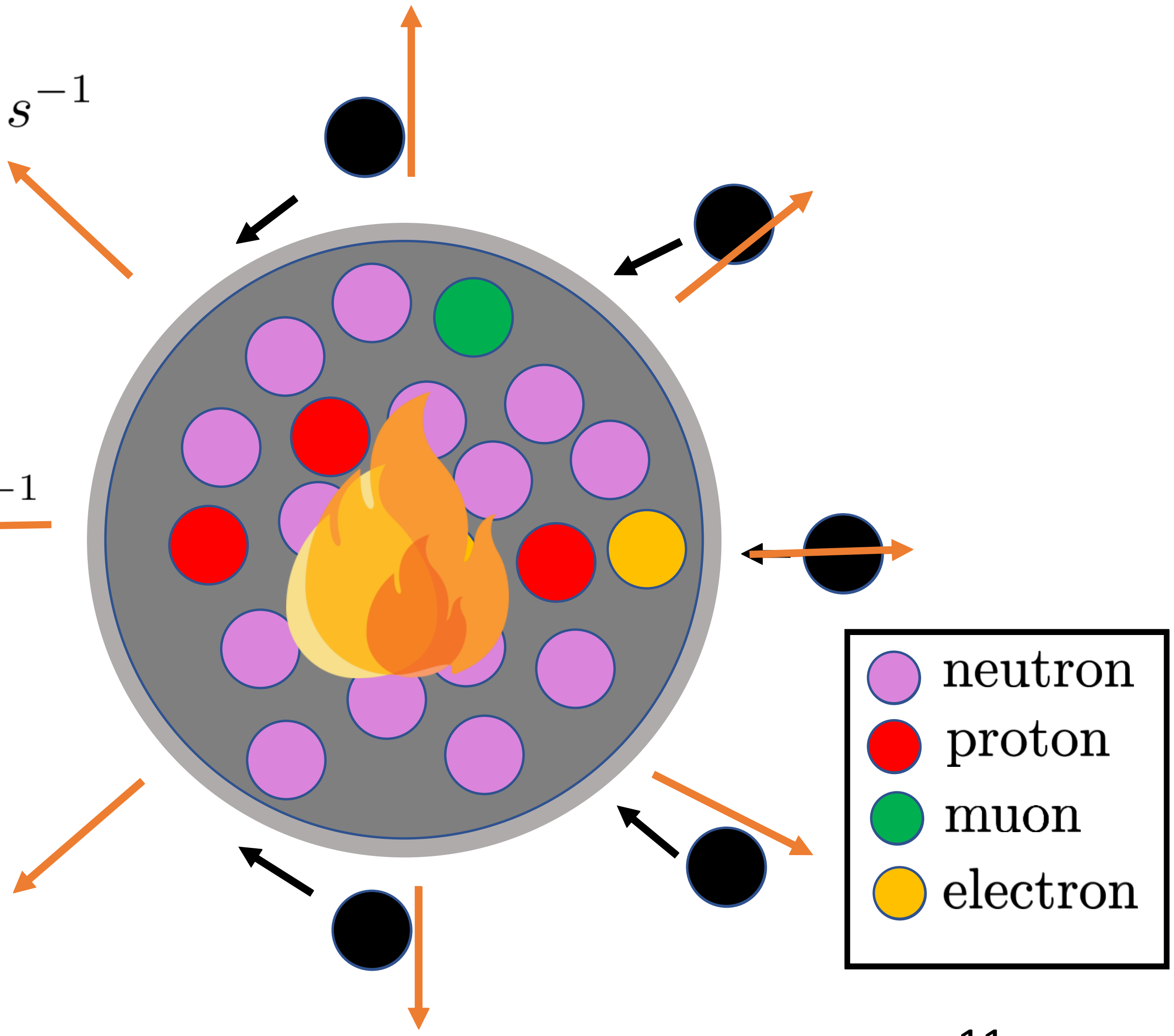
$$\dot{E} = f \times \text{flux} \times \text{KE}$$

$$= f \times (\gamma_{\text{esc}} - 1) \times 4 \times 10^{25} \, s^{-1}$$

f: Capture efficiency

$$\dot{E} = 4\pi R_\star^2 \sigma_{\text{SB}} T^4$$

$$T \sim 1600 f^{1/4} \, K$$



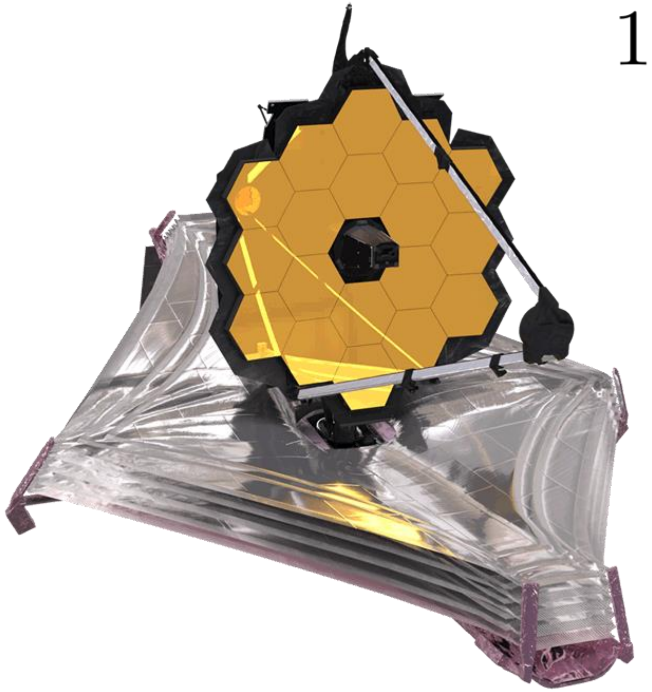
How to Detect Excess Heating?

Find an old "nearby" NS with radio telescope
with expected temp $\mathcal{O}(10 - 100)\,\mathrm{K}$

Credit: Ou Dongqu/Xinhua/ZUMA

Exposure time for SNR 2 :

$$10^5 \left(\frac{d}{10\,\mathrm{pc}}\right)^4 \mathrm{s}$$



Observe it with JWST

NIRCam on JWST ~ 0.6-5 μm imager

Good sensitivity around few `000 K

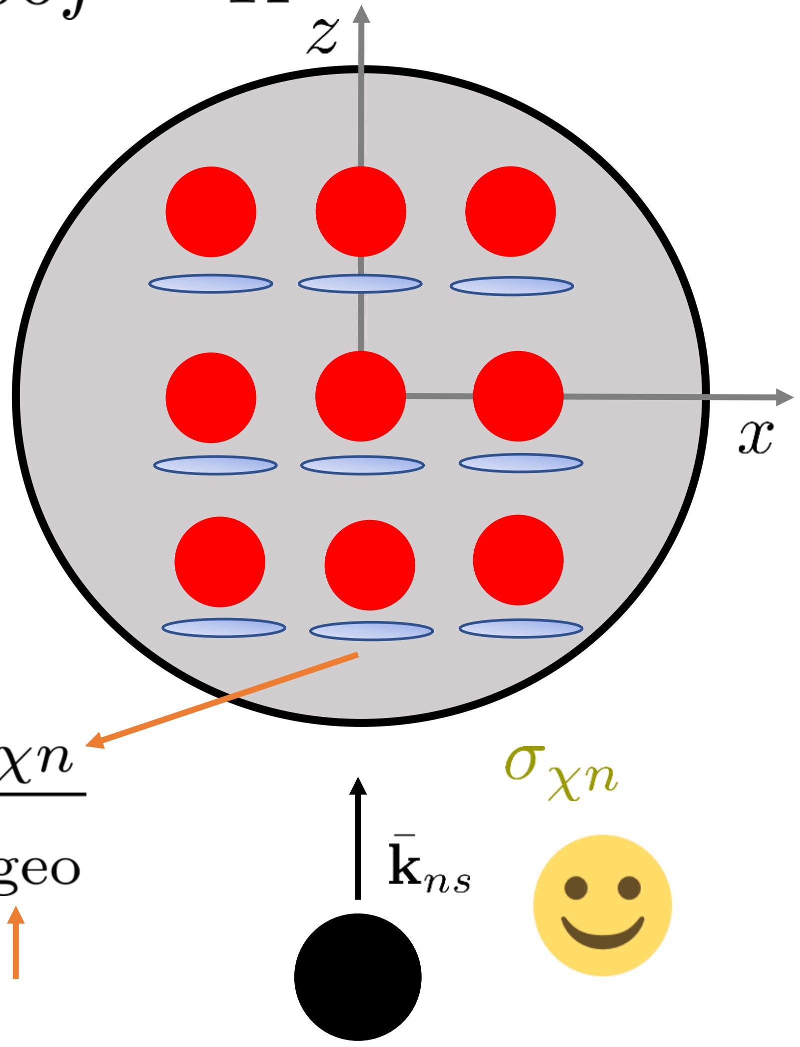
See for details, scope, limitations :

Baryakhtar, Bramant , Li, Linden, Raj
Phys.Rev.Lett 119 (2017)13, 131801

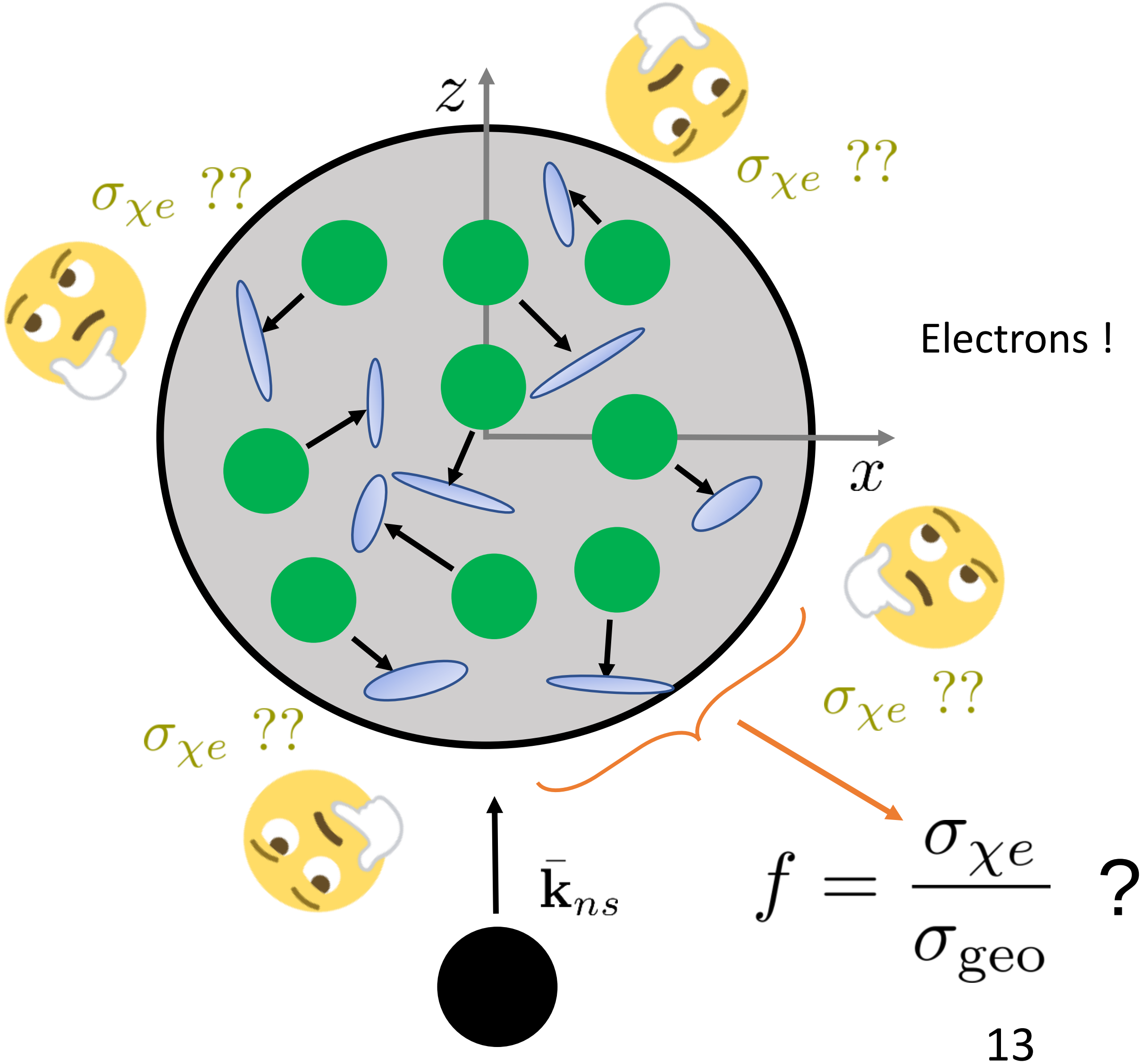
Chatterjee, Garani, Jain, Kanodia, Kumar,
Vempati *Phys.Rev.D* 108 (2023) L021301

Relativistic Capture Efficiency

$T \sim 1600 f^{1/4}\,\mathrm{K}$



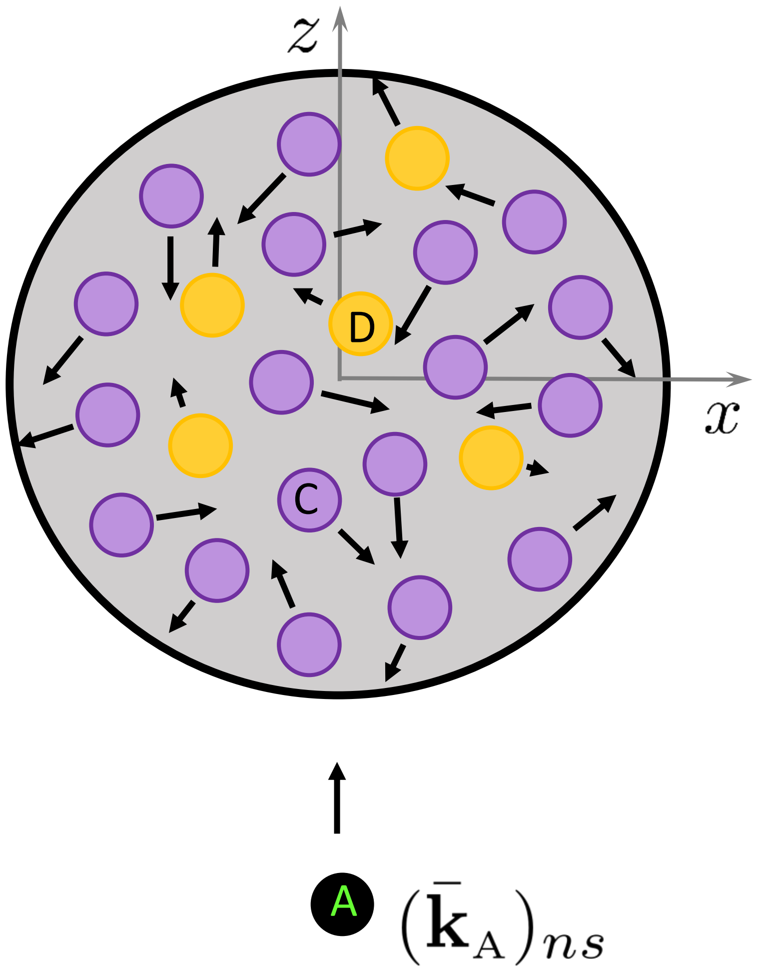
$$f = \frac{\sigma_{\chi n}}{\sigma_{\rm geo}}$$



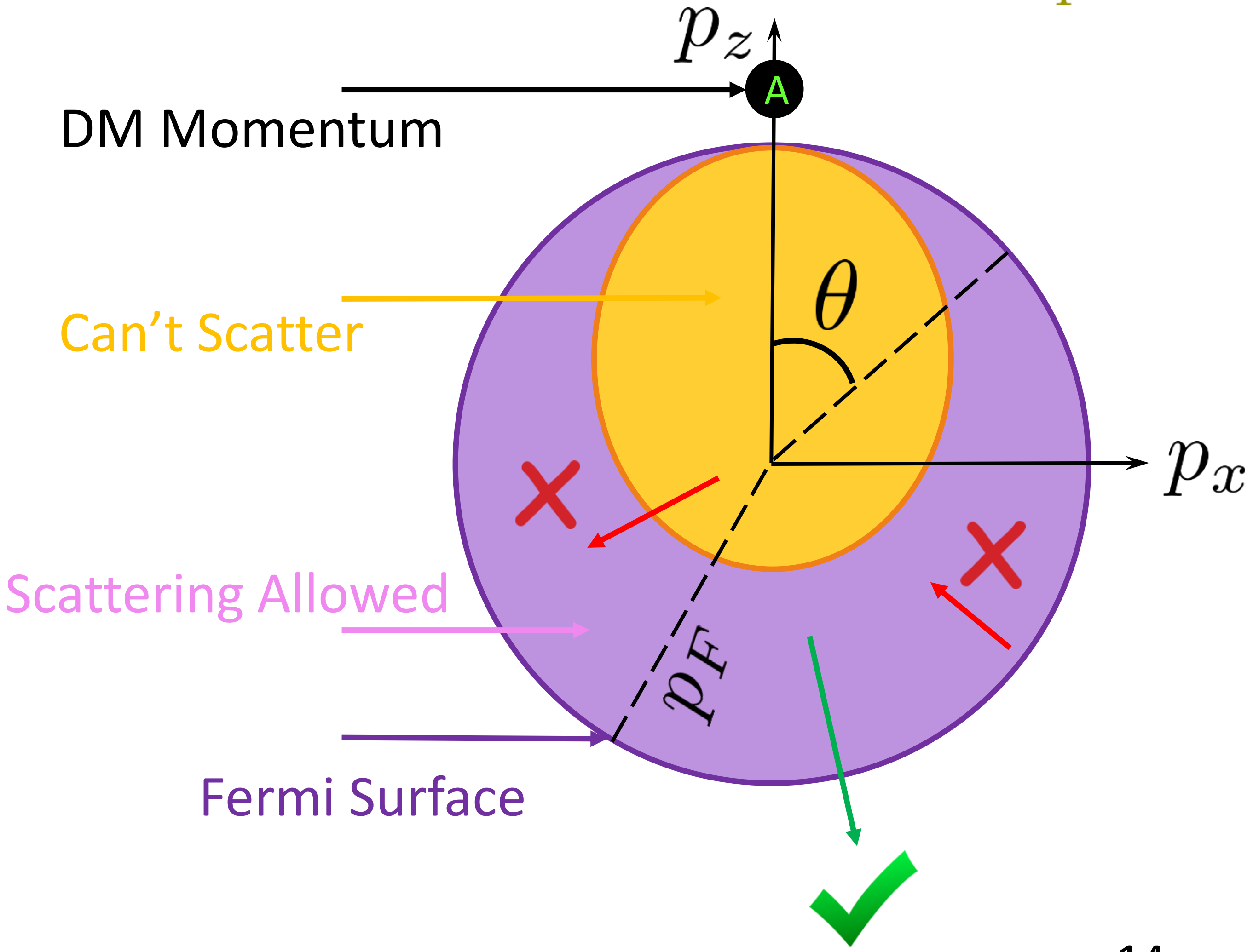
$$f = \frac{\sigma_{\chi e}}{\sigma_{\rm geo}} \quad ??$$

Pauli Blocking

NS Frame: Position Space



NS Frame: Momentum Space



Formalism

$$df = \sum_{\mathrm{N_{hit}}} \frac{1}{N_{\mathrm{hit}}} d\Omega_{\mathrm{CM}} \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{CM}} \left(v_{\mathrm{mol}}\, dn_{\mathrm{T}} \Delta t\right)_{\mathrm{NS}}$$

$$\times \Theta\left(\Delta E - \frac{E_{\mathrm{halo}}}{N_{\mathrm{hit}}}\right) \Theta\left(\frac{E_{\mathrm{halo}}}{N_{\mathrm{hit}}+1} - \Delta E\right)$$ Multi Scatter Condition

$$\times \Theta\left(\Delta E + E_p - E_{\mathrm{F}}\right)$$ Pauli Blocking Condition

Joglekar, Raj, Tanedo, Yu *Phys.Lett.* B (2020) 135767, *Phys.Rev.D* 102 (2020) 12, 123002

Formalism

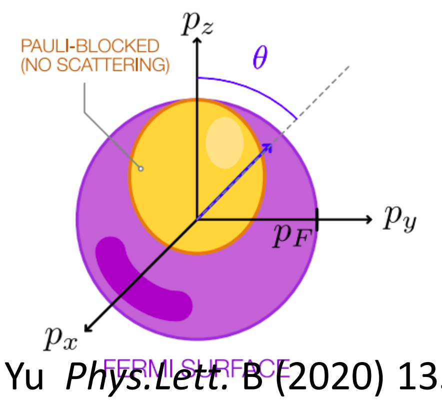
$$f = \sum_{\mathrm{N_{hit}}} \frac{\langle n_{\mathrm{T}}\rangle \Delta t}{N_{\mathrm{hit}}} \int d\Omega_{\mathrm{F}} \int \frac{p^2 dp}{V_{\mathrm{F}}} \int d\Omega_{\mathrm{CM}} \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{CM}} v_{\mathrm{mol}} \Theta^3(\Delta E)$$

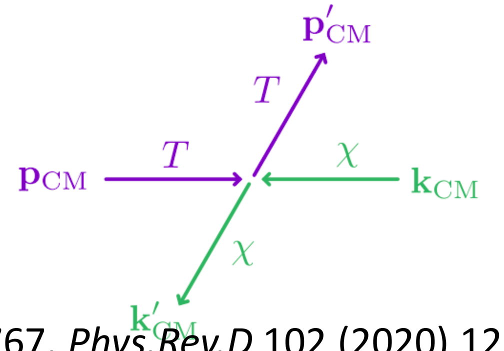
$$\Omega_{\mathrm{F}} = d\phi\, d(\cos\theta)$$

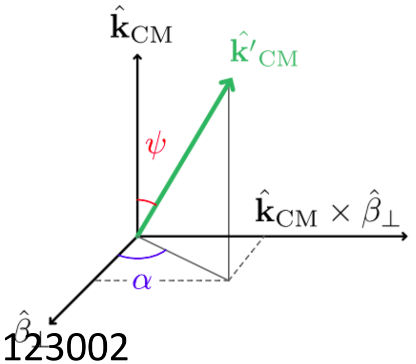
$$dn_{\mathrm{T}} = \langle n_{\mathrm{T}}\rangle \Omega_{\mathrm{F}} \frac{p^2 dp}{V_{\mathrm{F}}}$$

$$V_{\mathrm{F}} = \frac{4}{3}\pi p_{\mathrm{F}}^3$$

$$d\Omega = d\alpha\, d(\cos\psi)$$

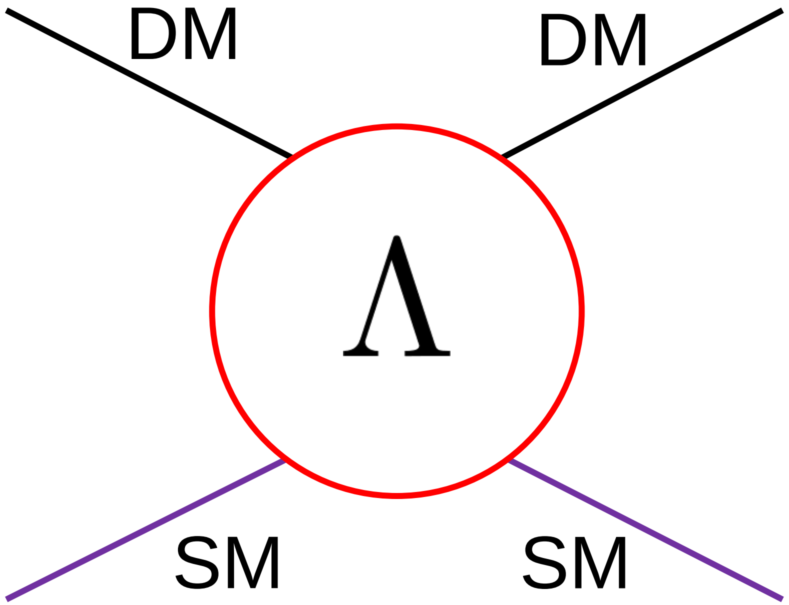




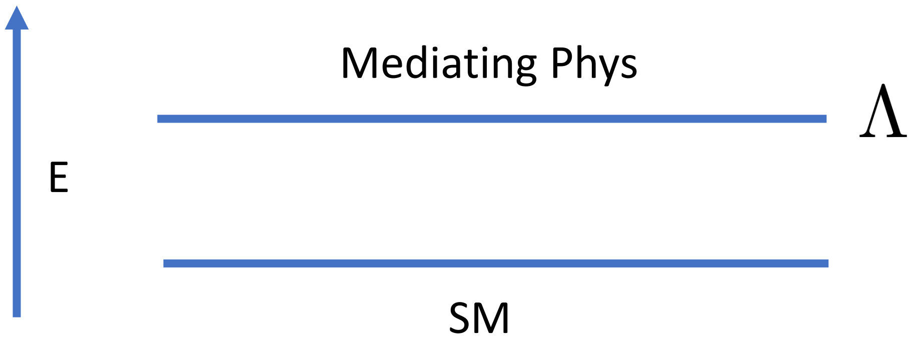


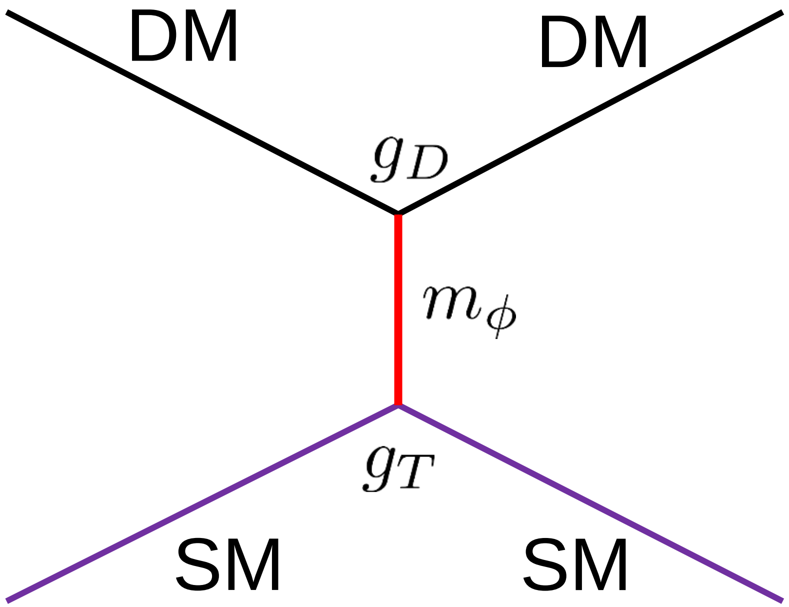
Joglekar, Raj, Tanedo, Yu *Phys.Lett.* B (2020) 135767, *Phys.Rev.D* 102 (2020) 12, 123002

DM Models



$\Lambda >> \text{momentum transfer}$





Light mediator

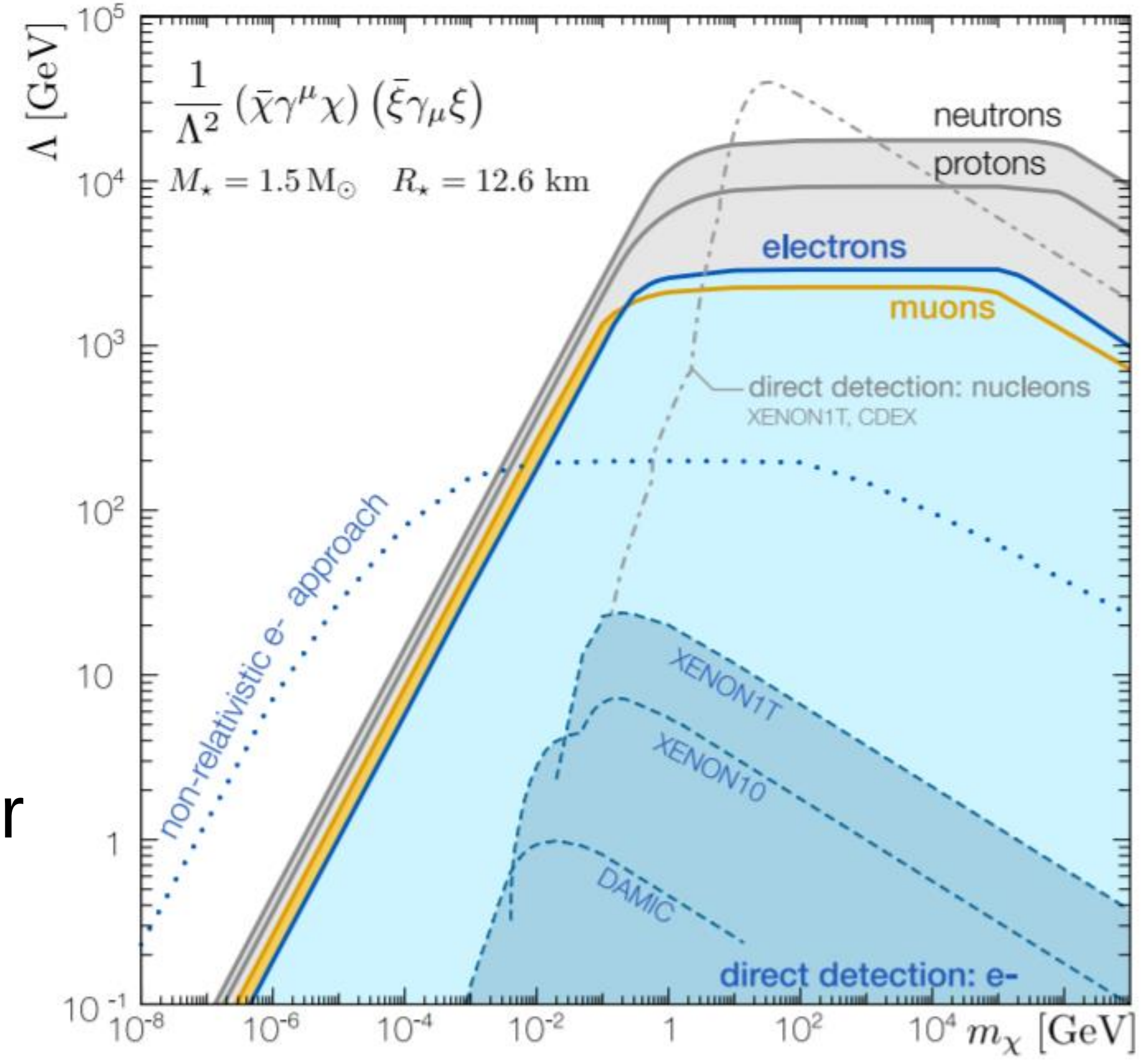
Reach

Recall : $T \sim 1600 f^{1/4}\, K$

$$f \propto |\mathcal{M}|^2 \propto \frac{1}{\Lambda^4};$$

$$T \propto \Lambda^{-1}$$

Shaded area corresponds to f ~ 1 or star temperature of ~ 1600 K



AJ, Raj, Tanedo, Yu *Phys.Lett.* B (2020) 135767

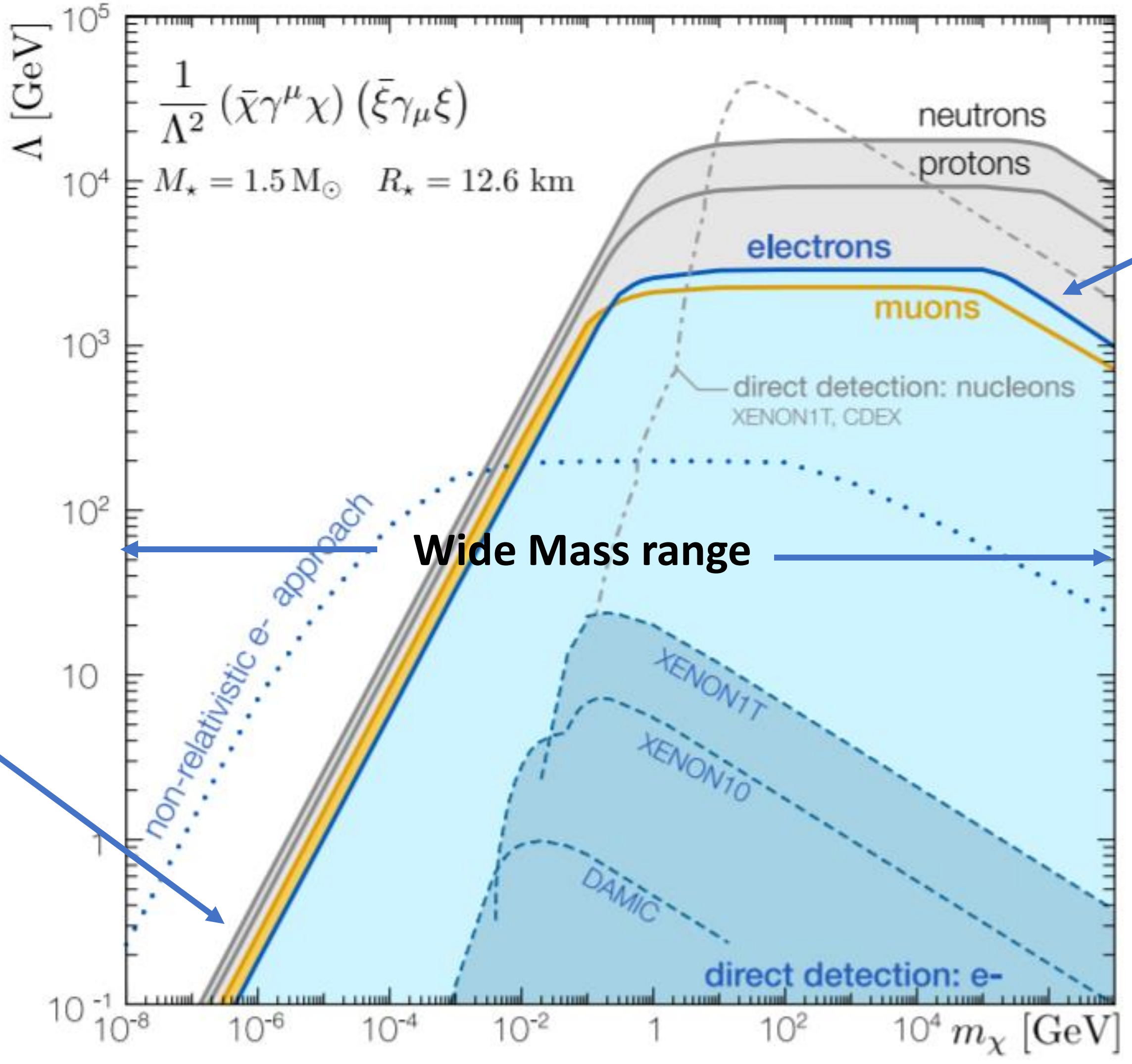
Reach

$$\text{cross sect} \propto \frac{m_\chi^2 \, E_p^2}{s\,\Lambda^4}$$

E_p : target energy

$$\text{capture} \propto m_\chi^3$$

Cross section + Pauli blocking

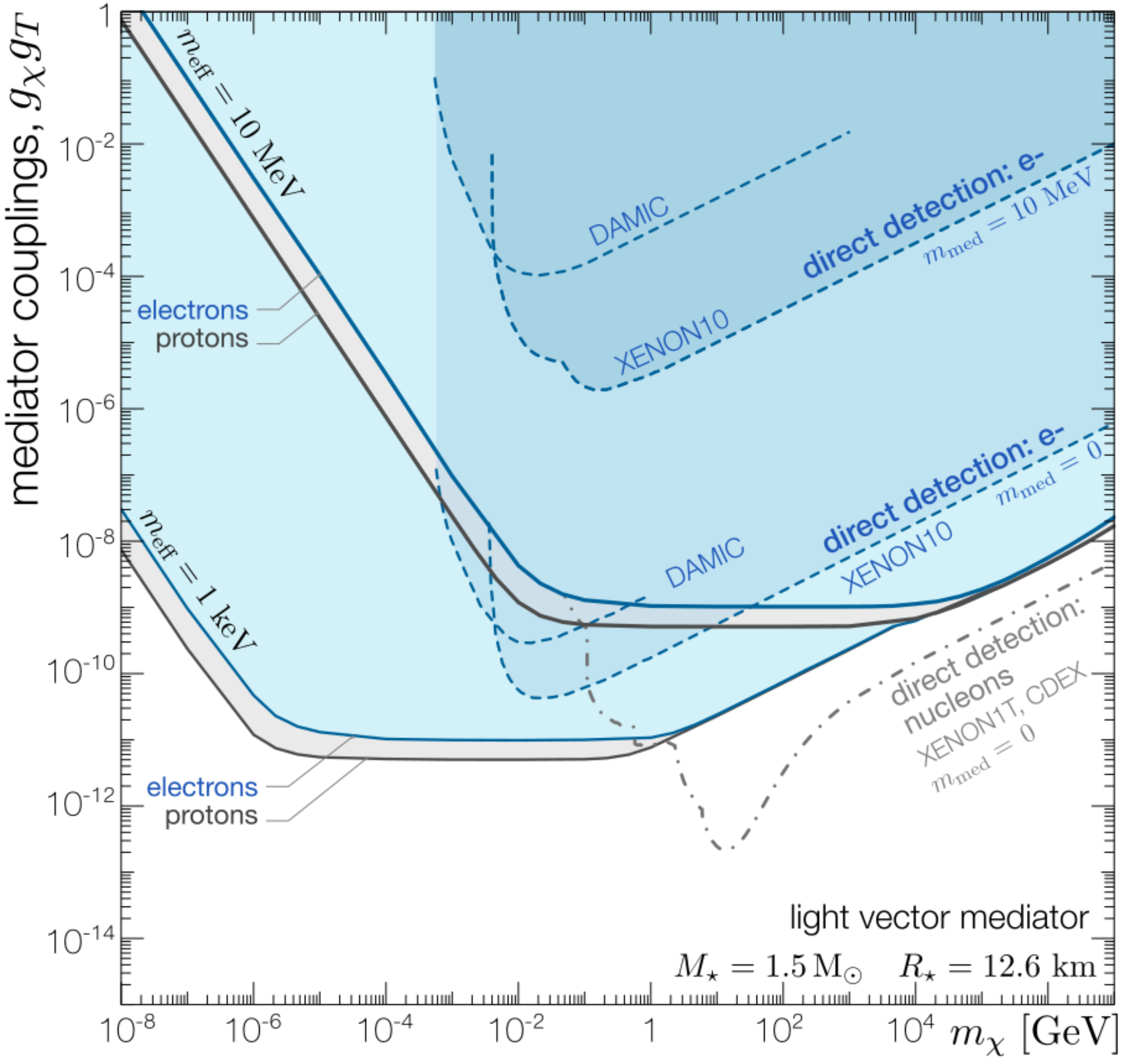


$$\text{capture} \propto \frac{1}{m_\chi}$$

Multiscatter needed to lose enough energy

AJ, Raj, Tanedo, Yu *Phys.Lett.* B (2020) 135767 and *Phys.Rev.D* 102 (2020) 12, 123002

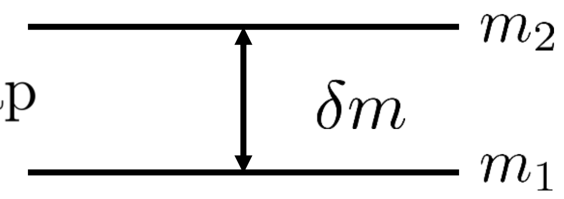
Reach



AJ, Raj, Tanedo, Yu *Phys.Lett.* B (2020) 135767

Inelastic Dark Matter

2 dark states split by a mass gap



$$\Delta = \frac{\delta m}{m_1}$$

Important class of models esp in the context of SIDM for explaining small scale structure problems

Hard to detect for terrestrial detectors above Δ values of 10^{-6}

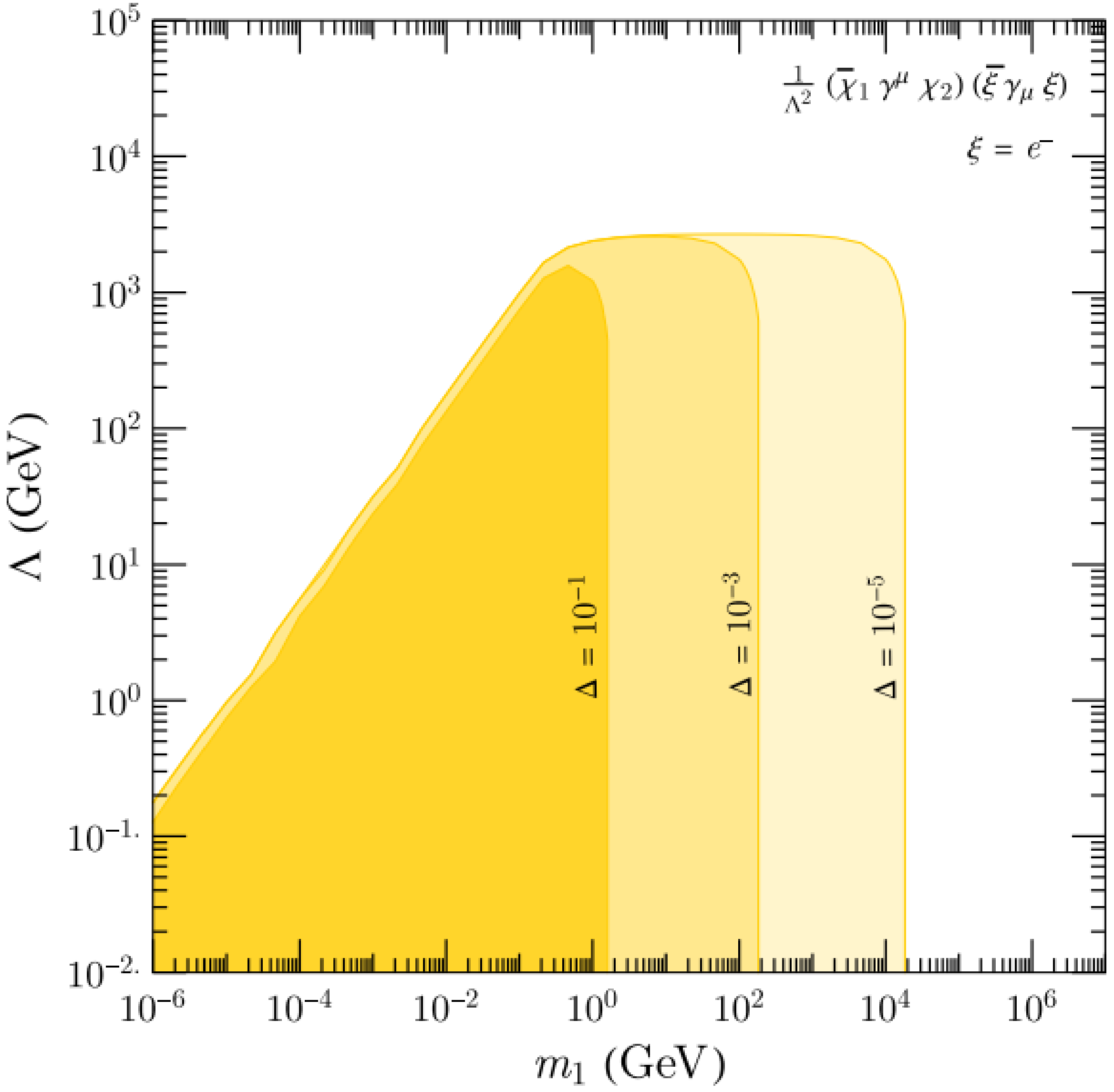
Velocity supressed $v \sim 10^{-3}$

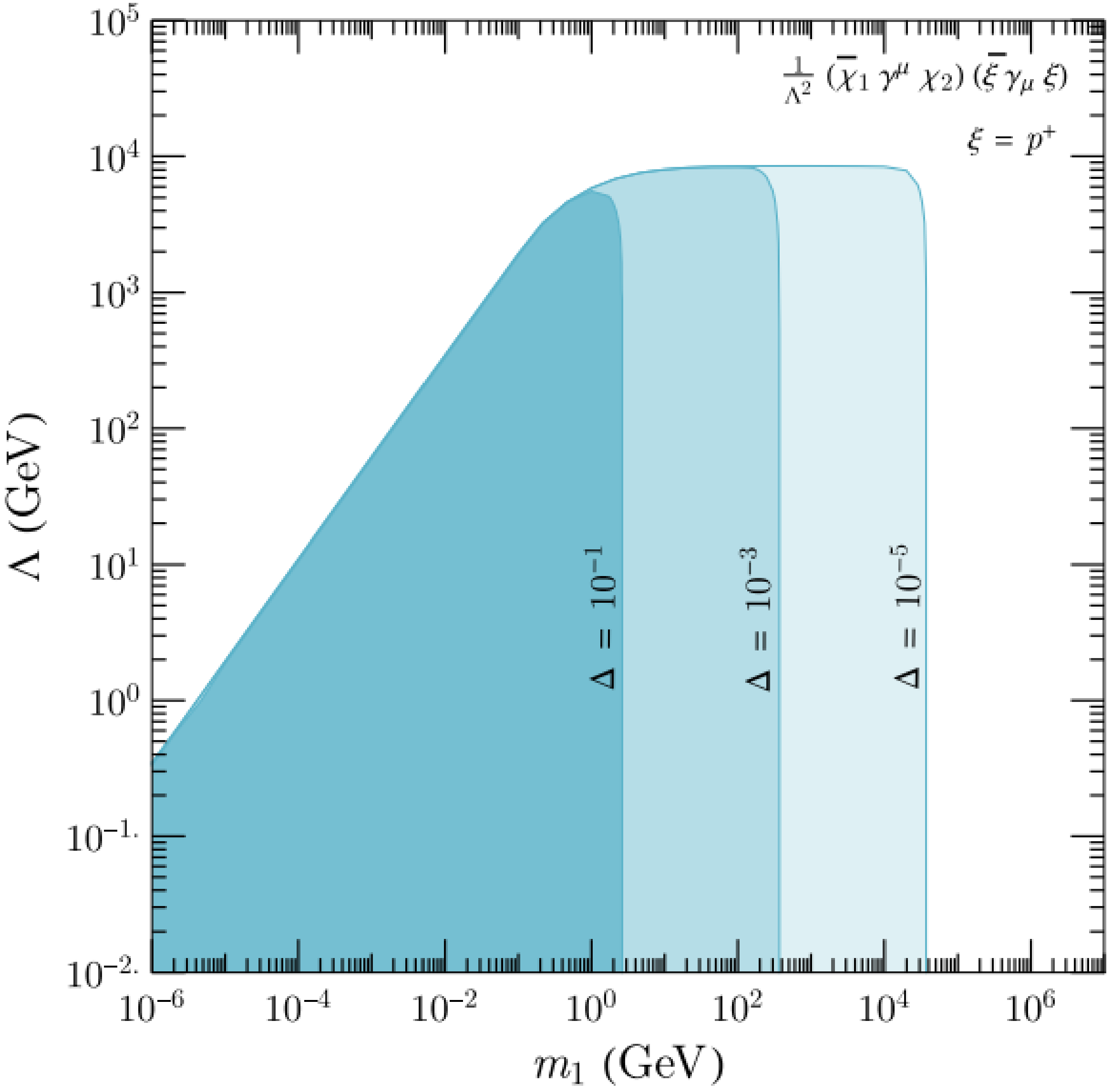
High gravity of NS means $v \sim 10^{-1}$

$\delta m < (\gamma - 1)\, m_T, (\gamma - 1)\, m_1$ For non-relativistic targets

$\delta m < \gamma \beta p_F, \left(\gamma^2 - 1\right) p_F$ For ultra-relativistic targets

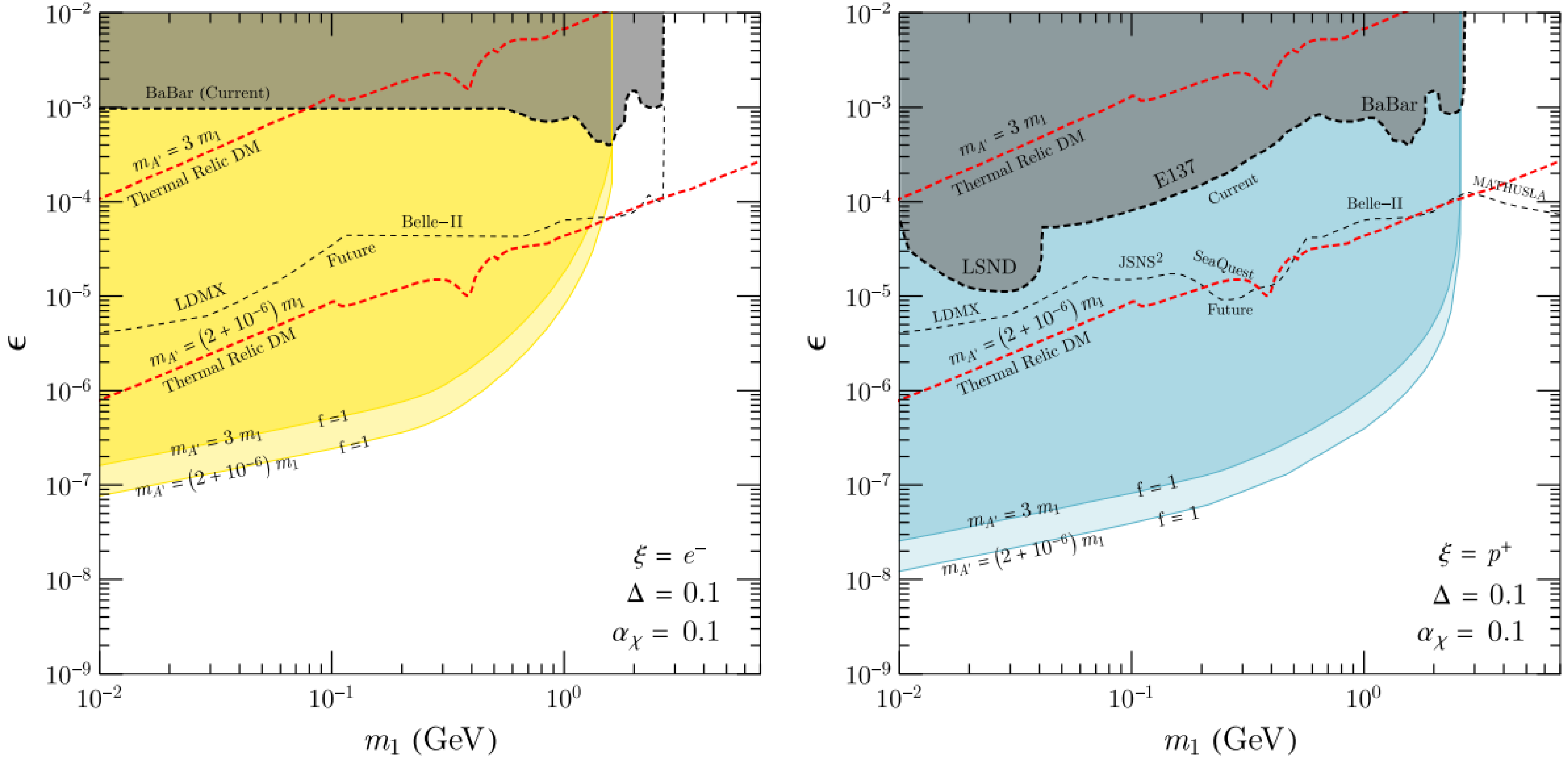
Inelastic Dark Matter





Alvarez, **AJ**, Mehr, Yu   Phys. Rev. D 107 (2023) 103024

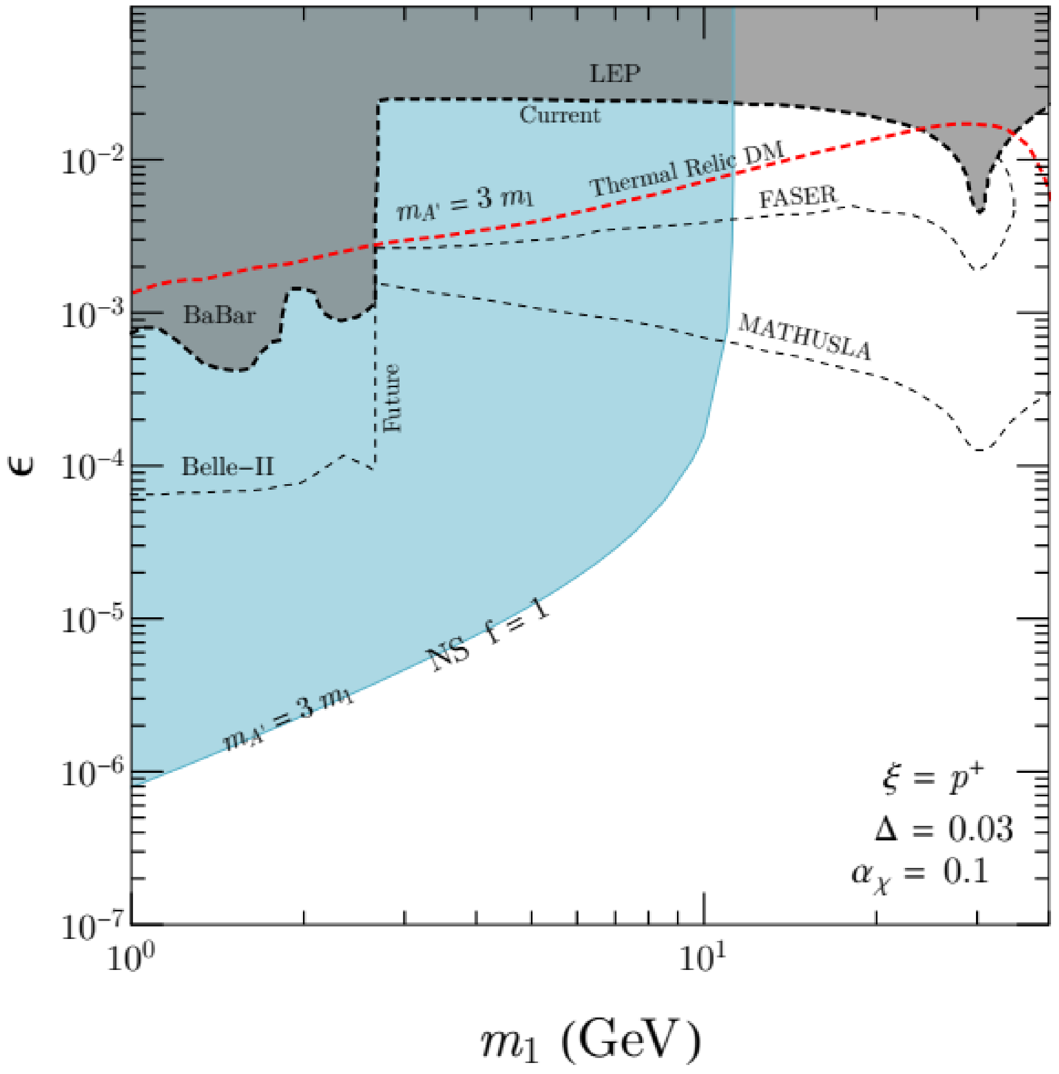
Inelastic Dark Matter : Heavy Dark Photons

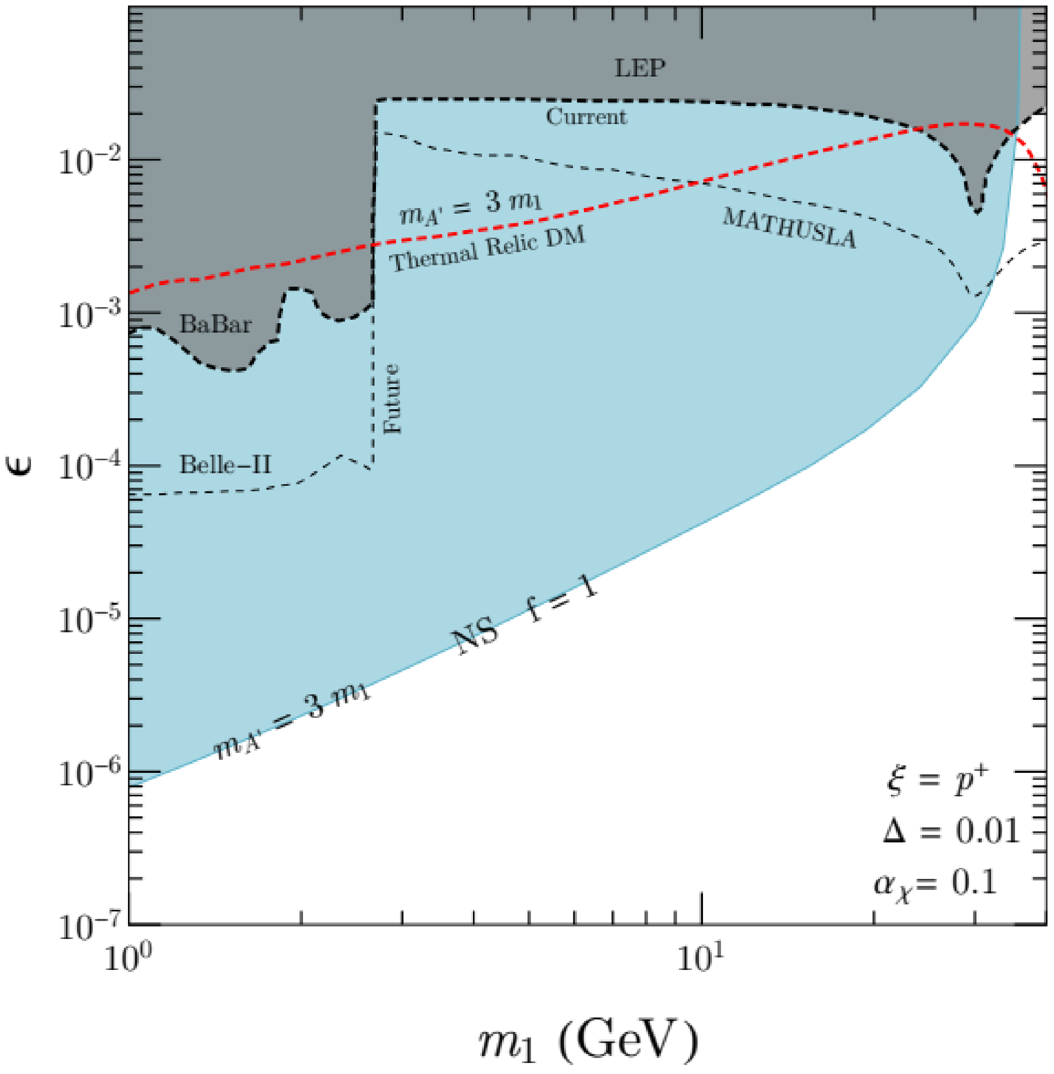


Alvarez, **AJ**, Mehr, Yu   Phys. Rev. D 107 (2023) 103024

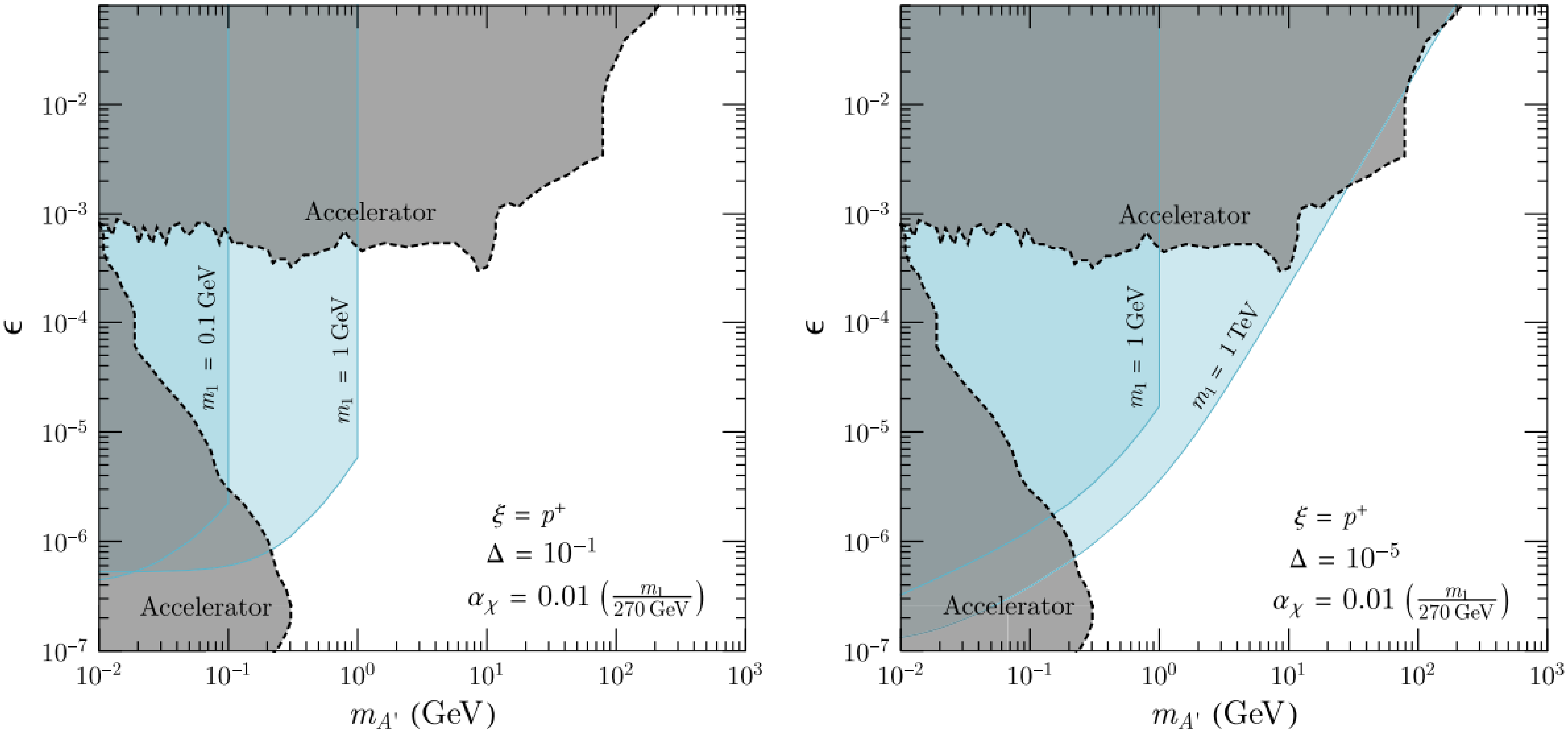
$$\mathcal{L}_{\rm int} \supset \frac{1}{2} m_{A'}^2 A'^\mu A'_\mu - \left(\frac{1}{2} g_\chi \bar{\chi}_2 \gamma^\mu \chi_1 A'_\mu + \text{H.c.} \right) + q\epsilon \bar{\zeta} \gamma^\mu \zeta A'_\mu$$

Inelastic Dark Matter : Heavy Dark Photons





Inelastic Dark Matter : Light Dark Photons

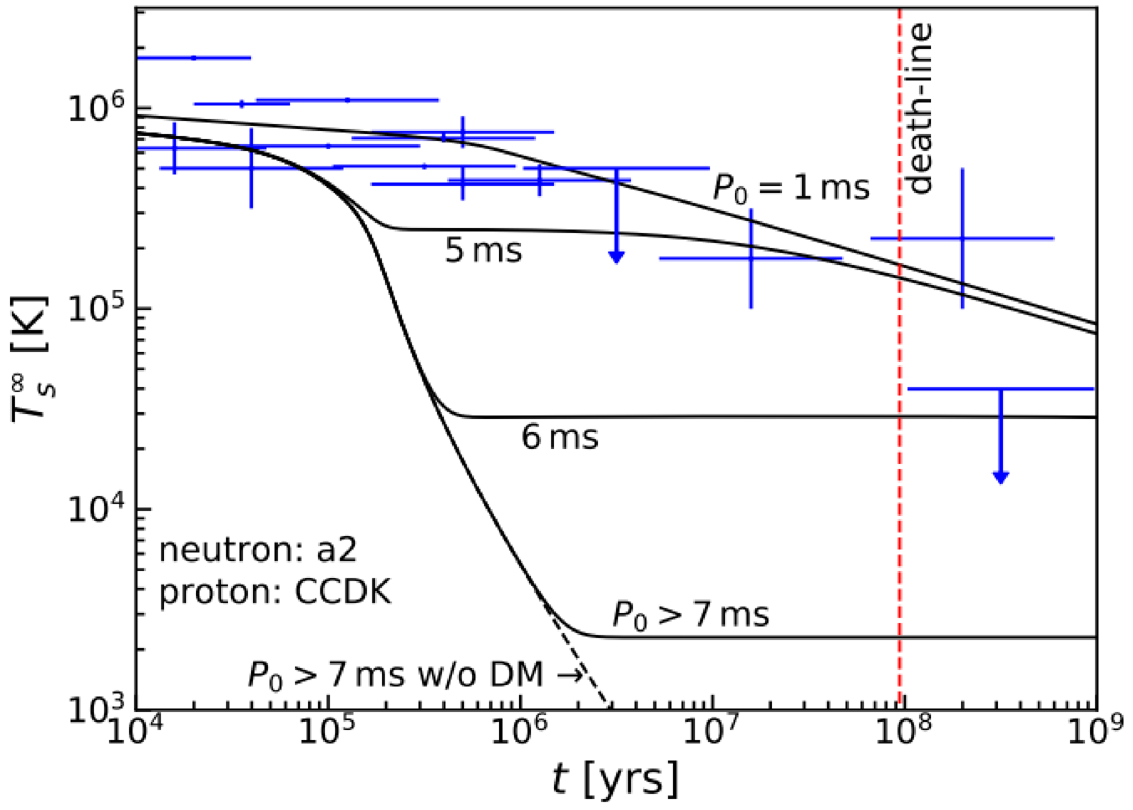


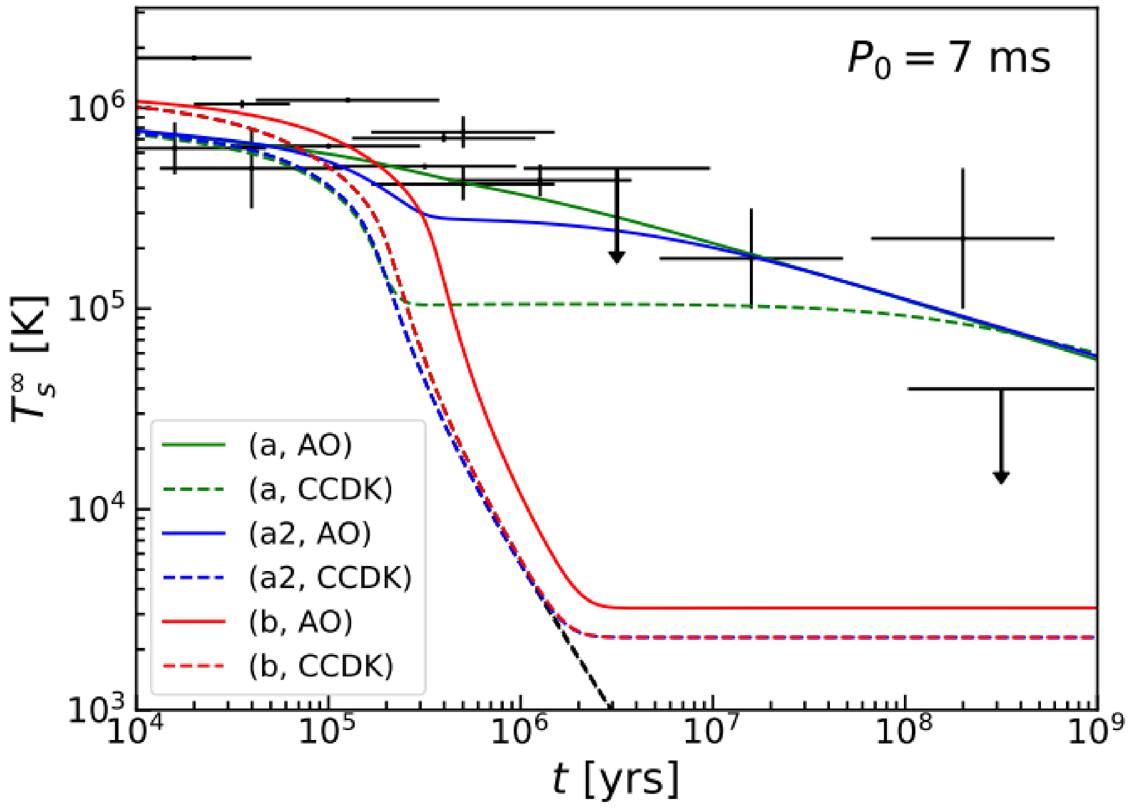
Alvarez, **AJ**, Mehr, Yu   Phys. Rev. D 107 (2023) 103024

Summary

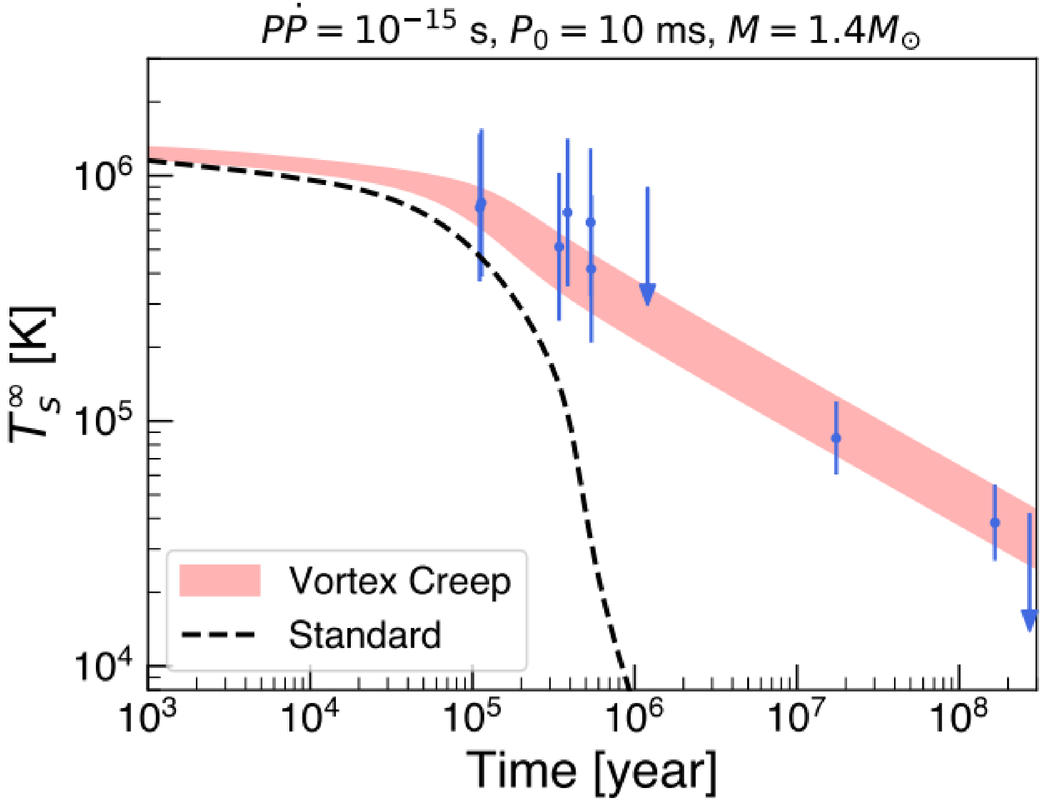
- Neutron stars are great for learning more about the nature of DM
- Can complement or exceed terrestrial searches
- Kinetic heating particularly shines in probing models like inelastic DM
- Particularly stronger compared to beam dump, long lived particle searches for sub-GeV DM

Thank You!

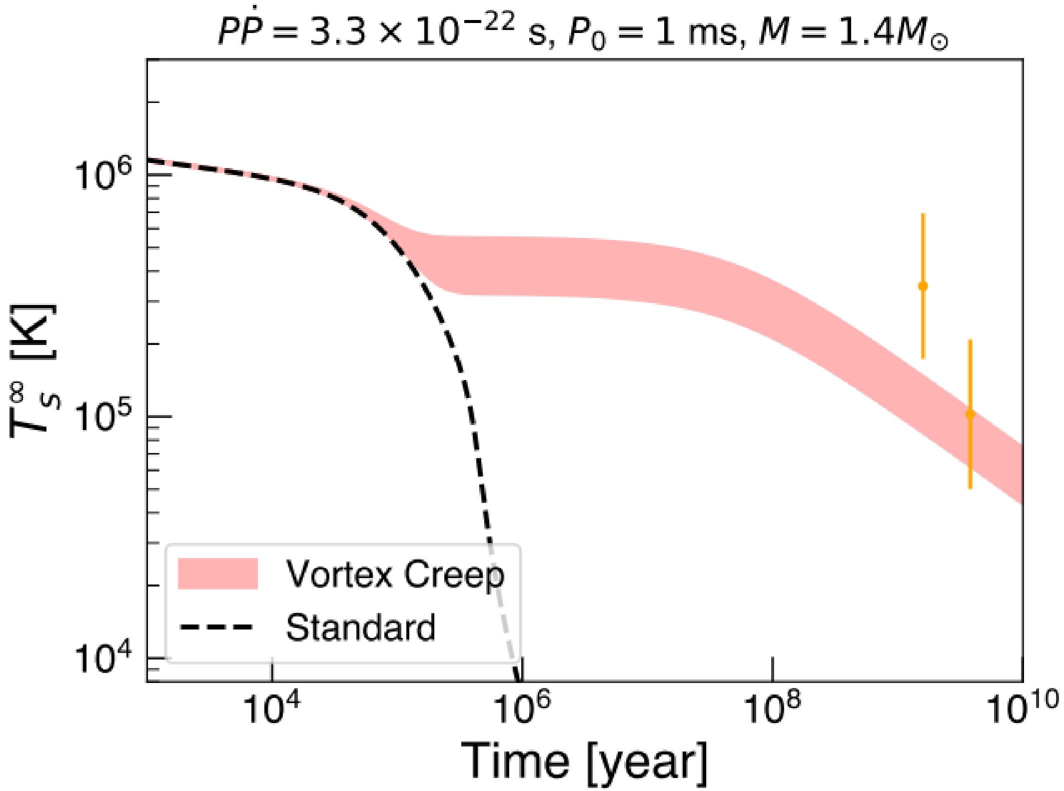




Hamaguchi, Nagata, Yanagi *Phys.Lett.B* 795 (2019) 484-489



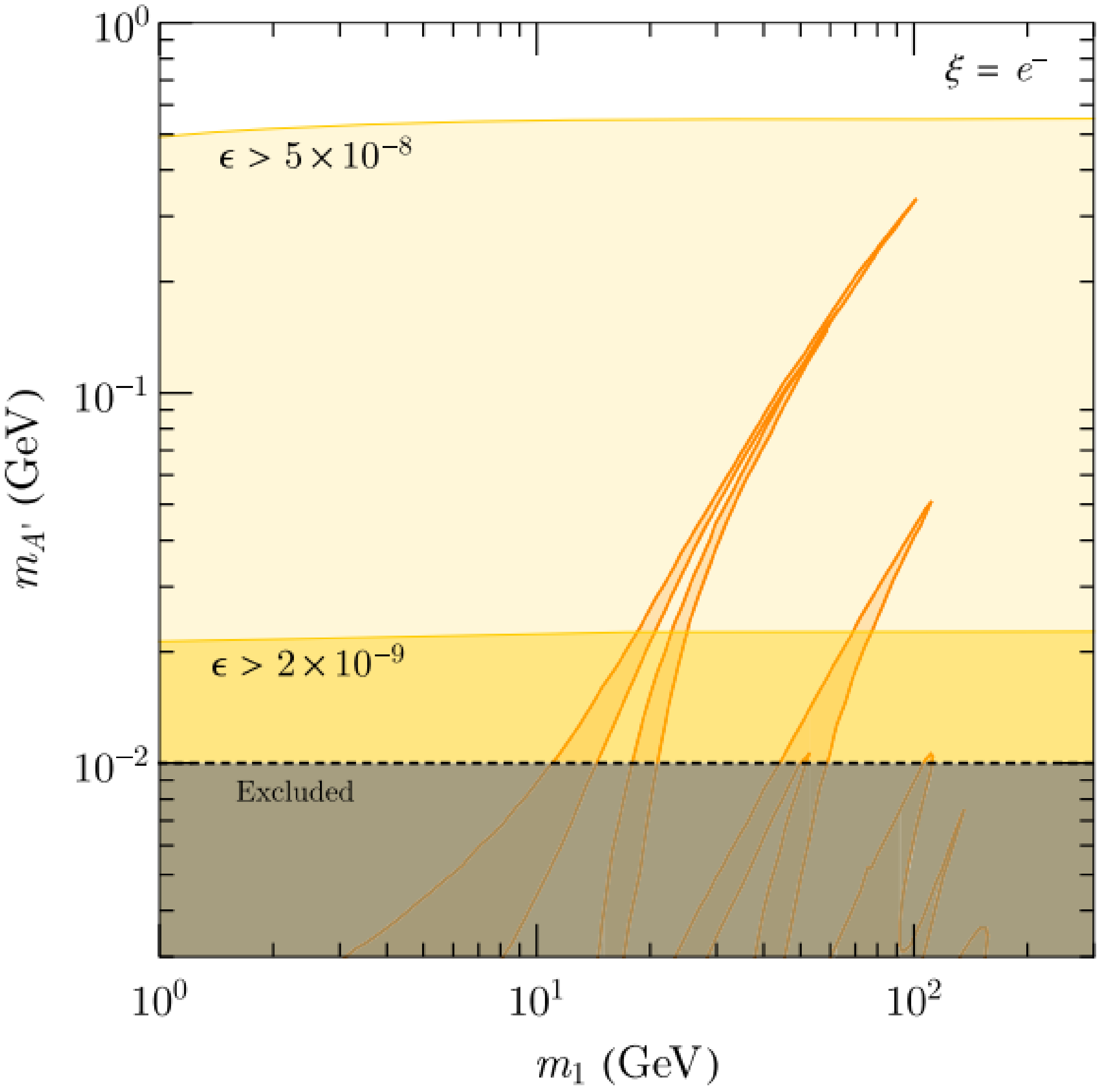
(a) Ordinary pulsars

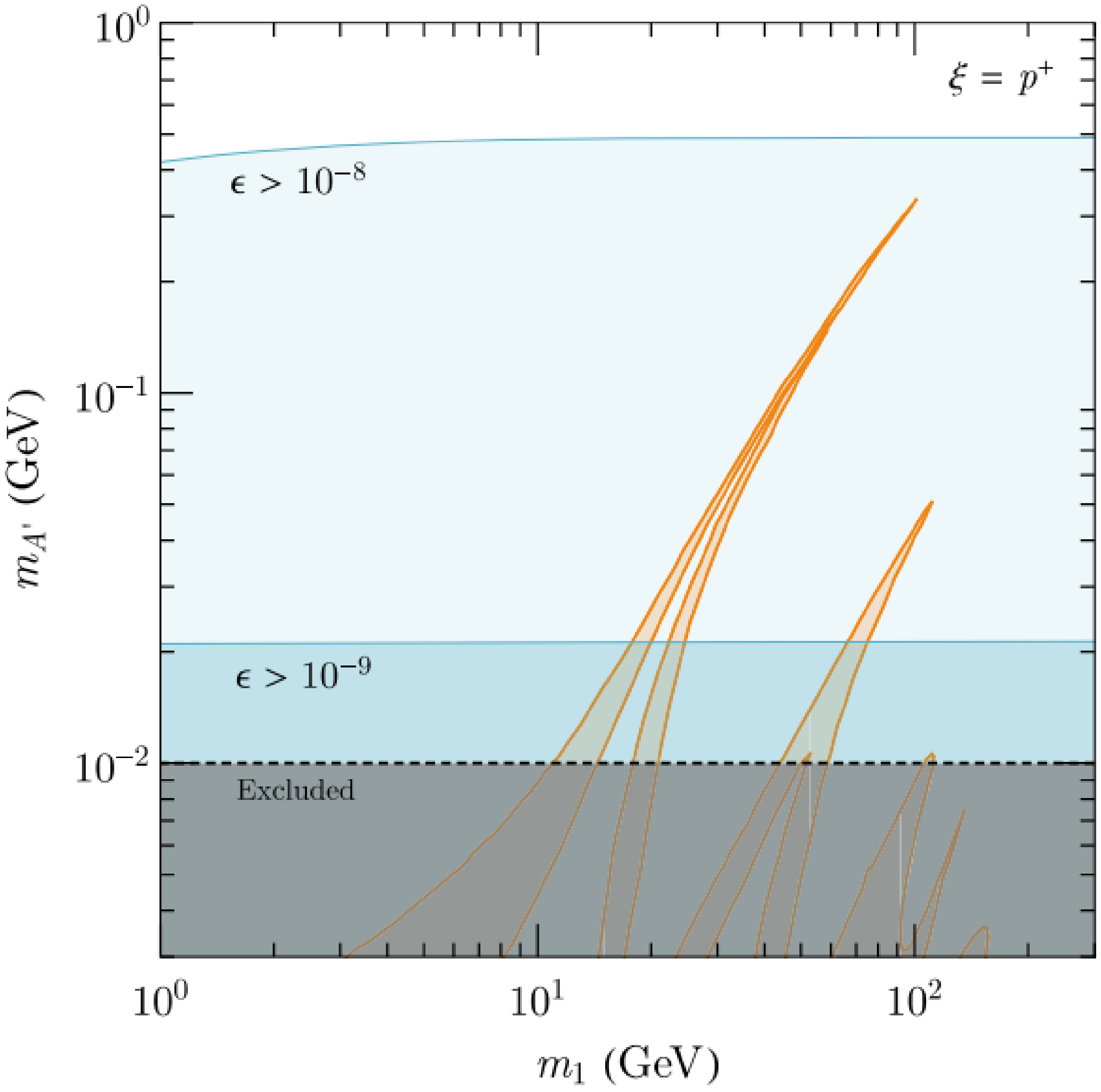


(b) Millisecond pulsars

Fujiwara, Hamaguchi, Nagata, Ramirez-Quezada *JCAP* 03 (2024) 051

Inelastic Dark Matter : Light Dark Photons





Alvarez, **AJ**, Mehr, Yu   Phys. Rev. D 107 (2023) 103024