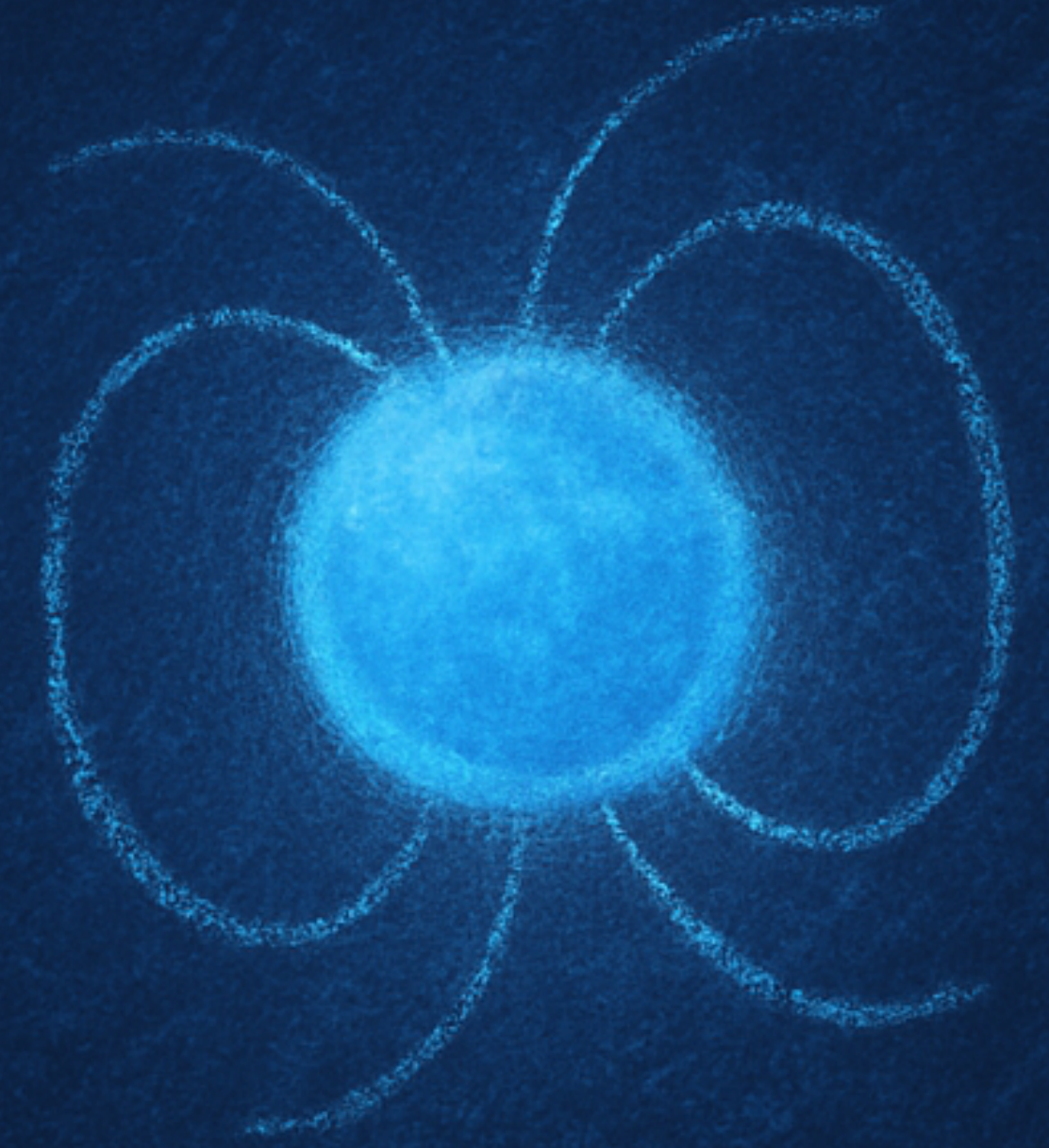
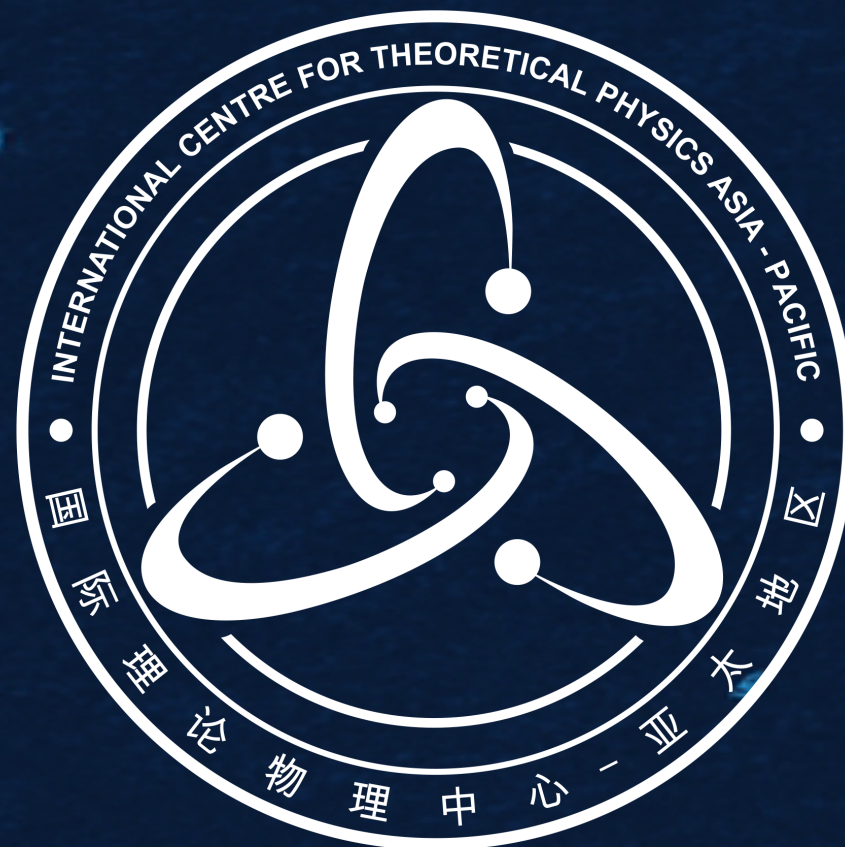


Constraints on Symmetric Dark Matter from Neutron Star Capture and Collapse

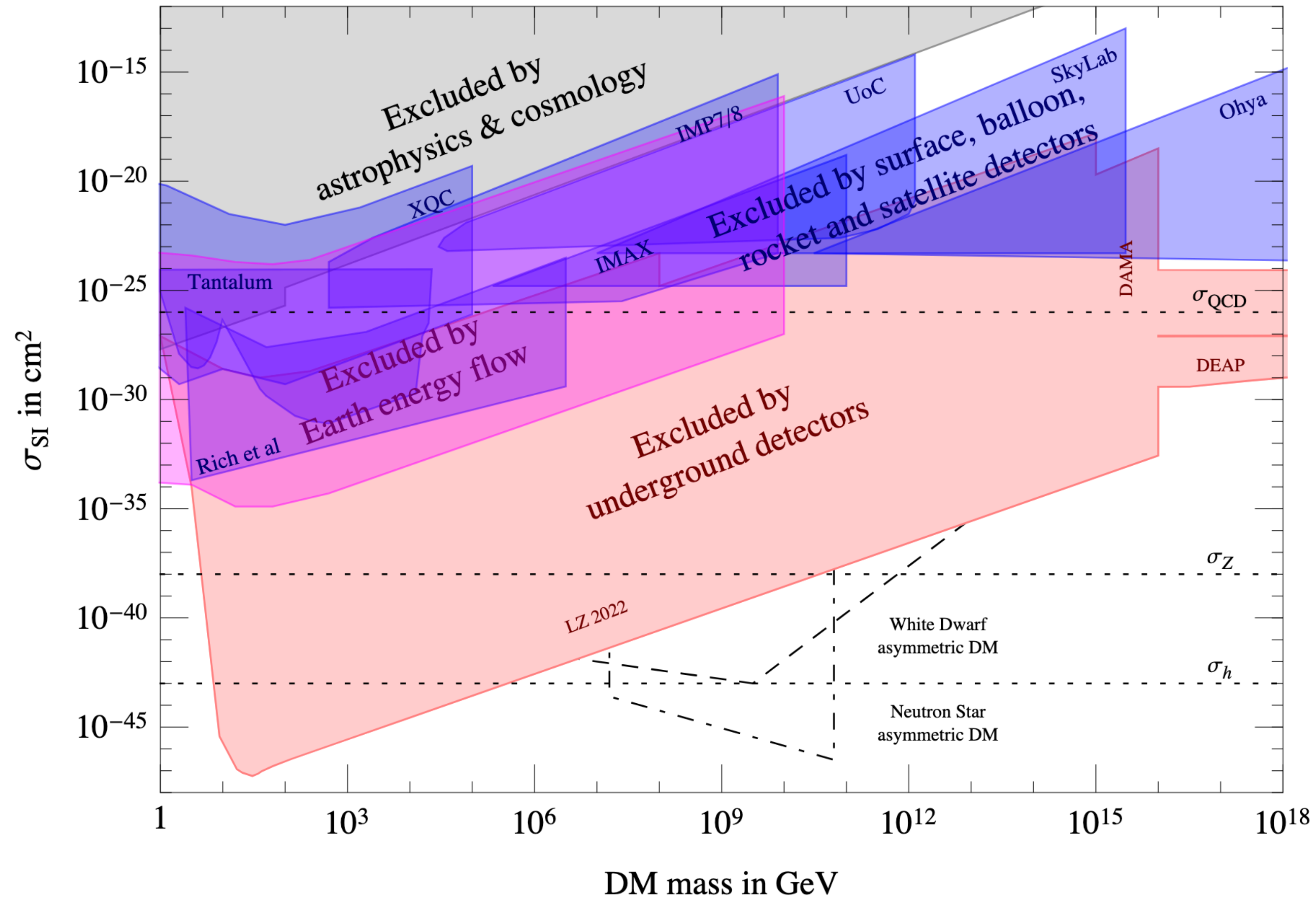


Yuxin Liu

Aug. 24th, 2026 @2nd New Horizons for Ψ



DM (collisional) searches

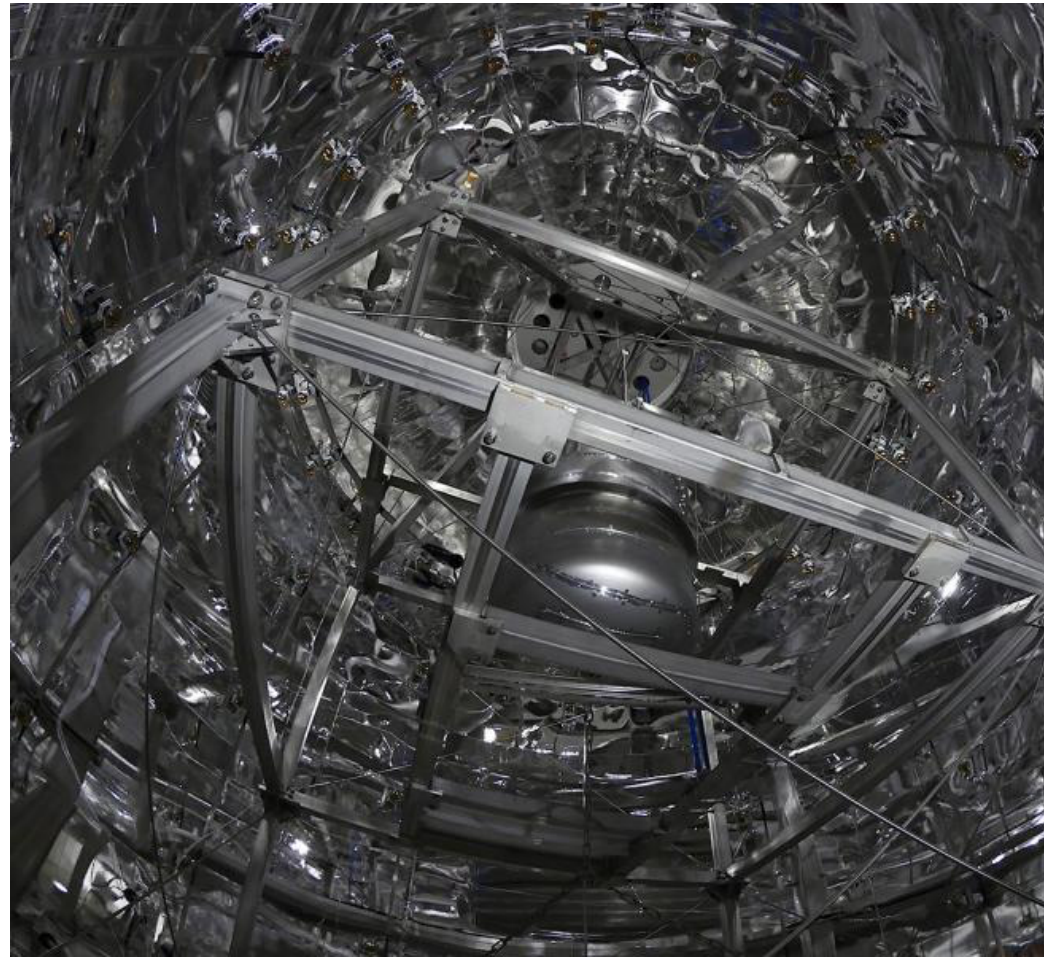


Dark Matter (2024)
Cirelli, Strumia, Zupan

Direct Detection constraints on SI scattering

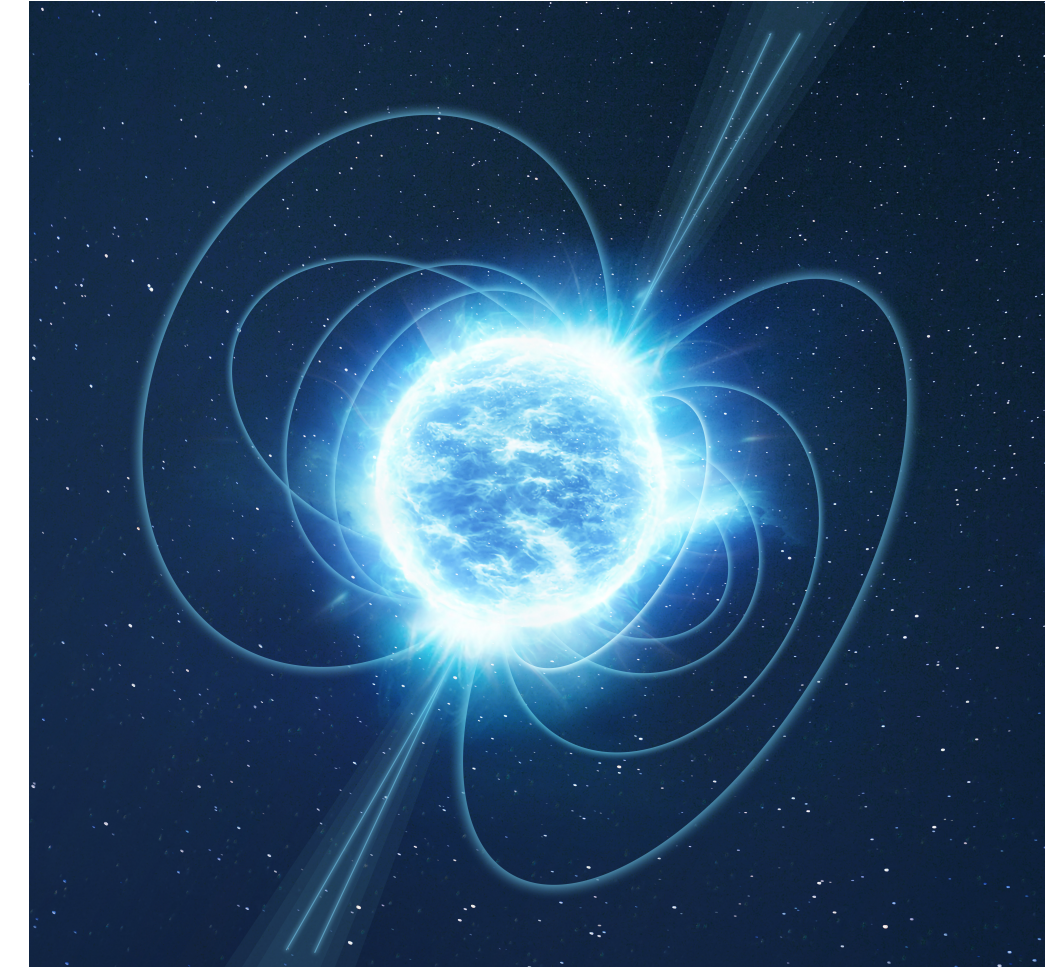
DM direct (collisional) searches

Exposure = Sensitivity



Xenon-1T

- Test Mass: ~ 1000 kg
- Test time: ~ 1000 day
- Exposure: $\sim 10^6$ kg day

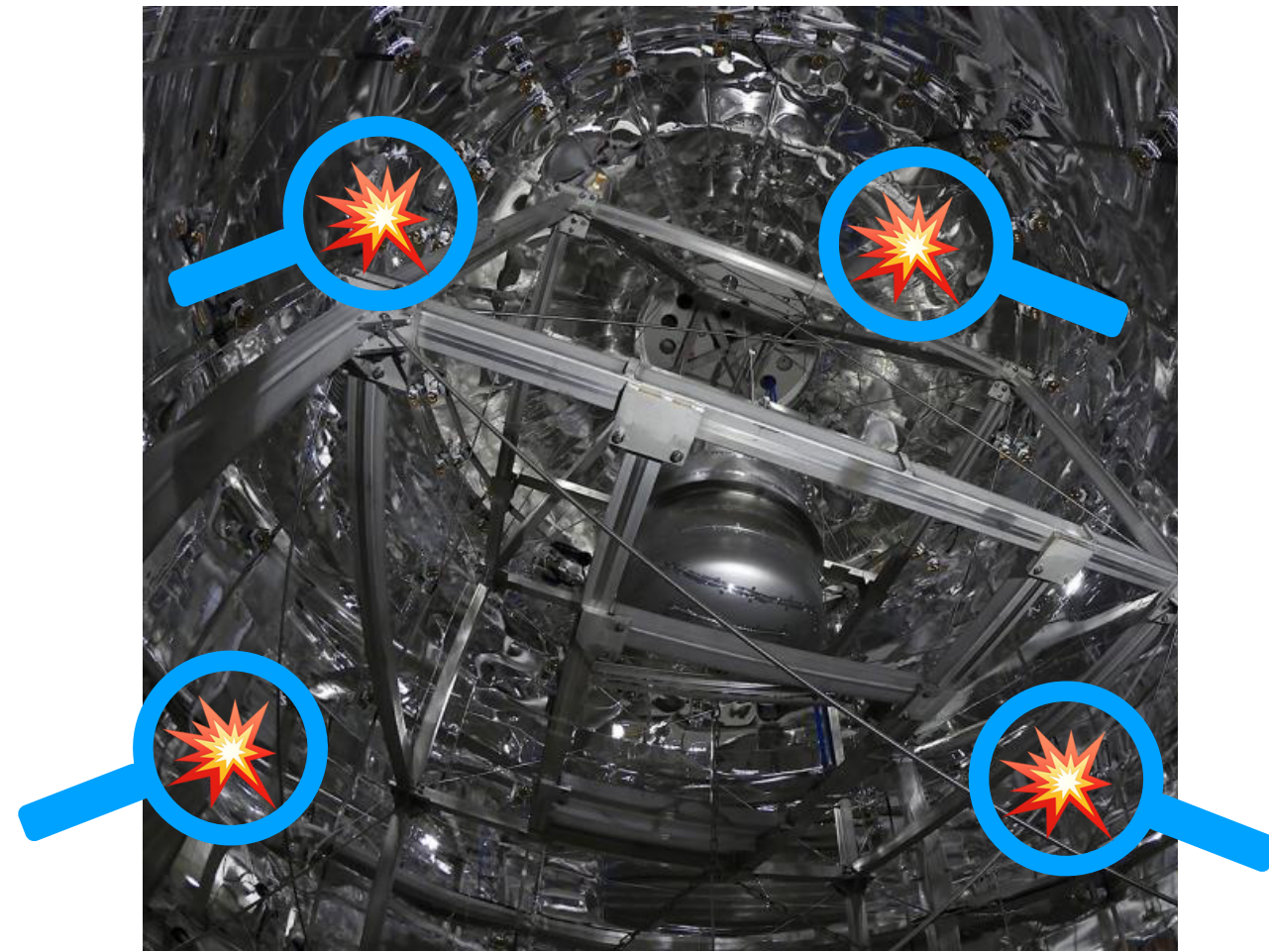


Solar-Mass Neutron Star

- Test Mass: $\sim 2 \times 10^{30}$ kg
- Test time: $\sim 5.84 \times 10^{12}$ day
- Exposure: $\sim 1.2 \times 10^{43}$ kg day

DM direct (collisional) searches

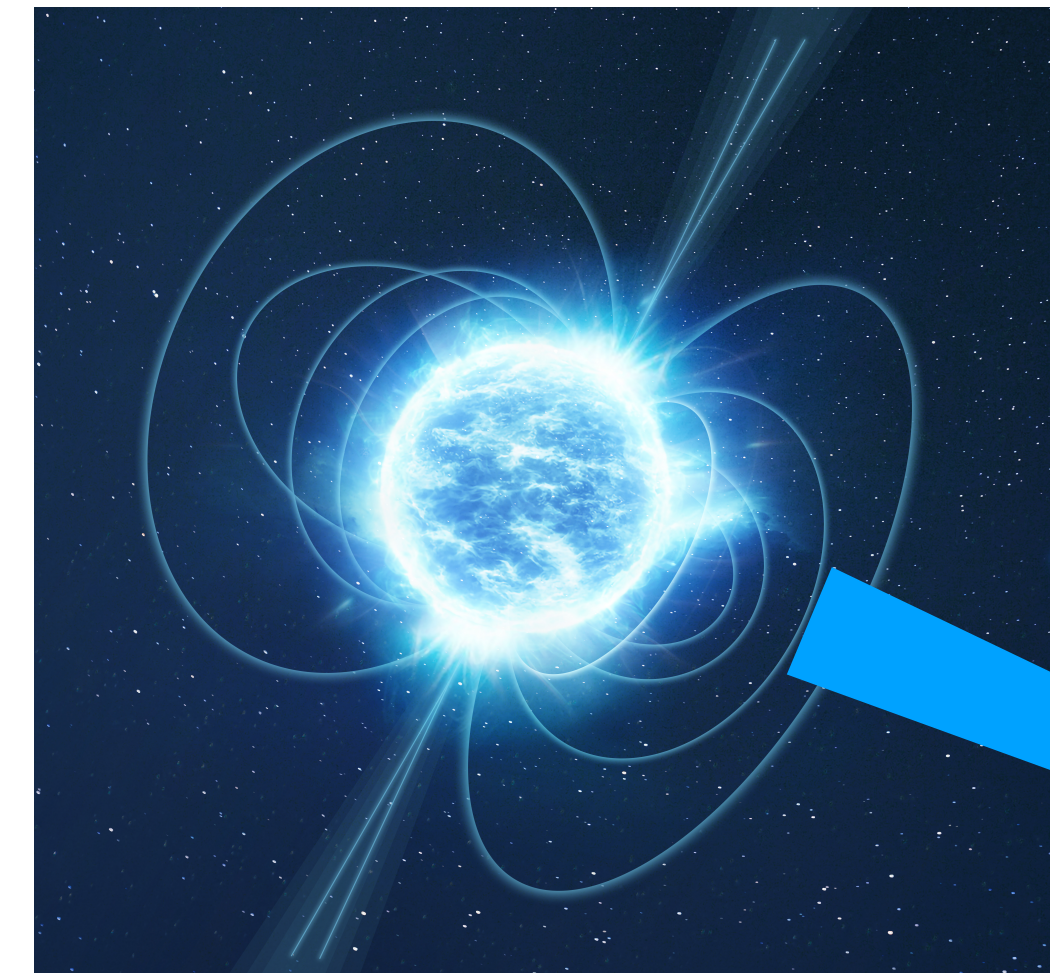
We “see” and count **every** event



Xenon-1T

- Test Mass: ~ 1000 kg
- Test time: ~ 1000 day
- Exposure: $\sim 10^6$ kg day

We see only the total flux: $\propto 1/r^2$

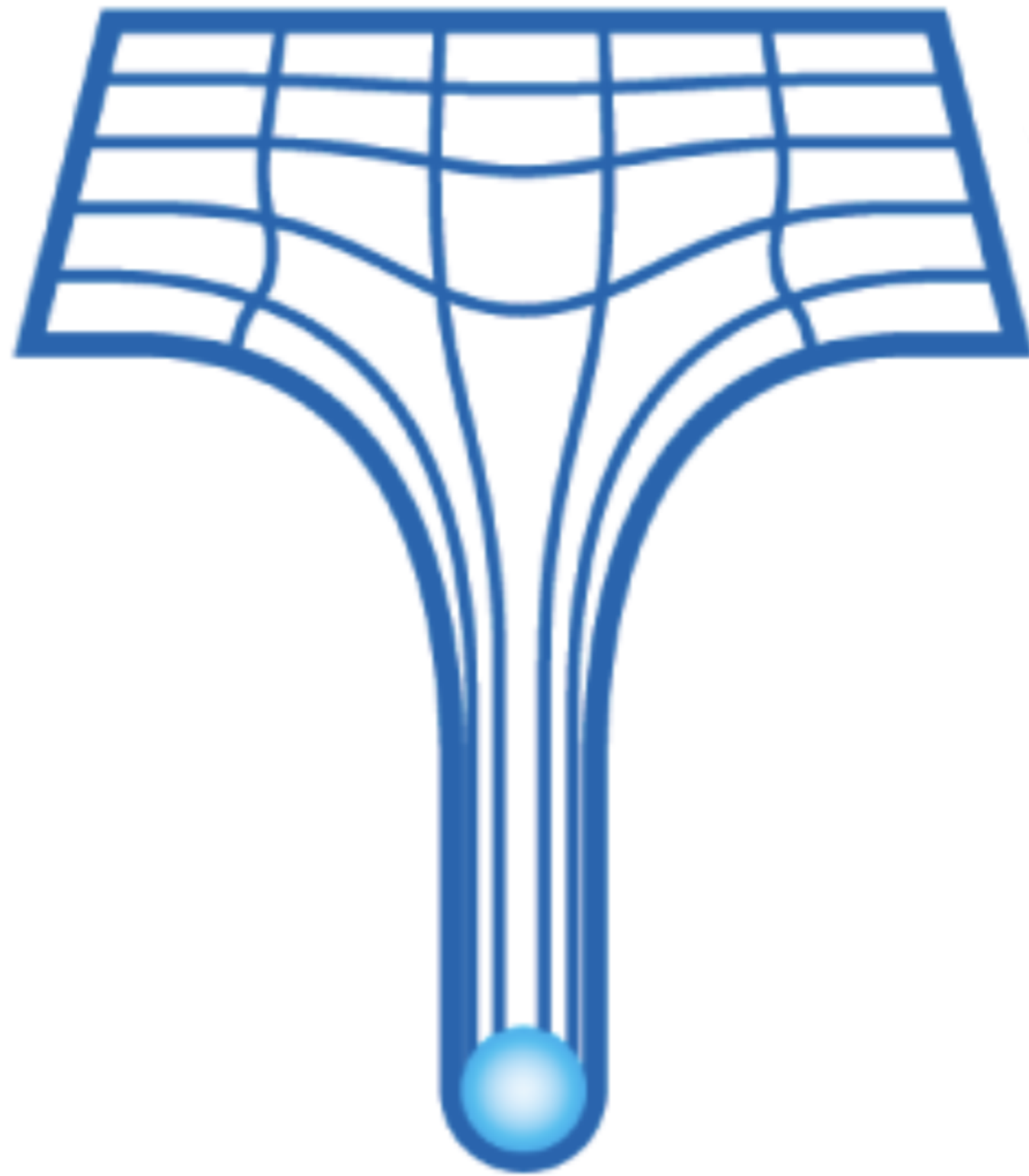


A “point” on the sky

Solar-Mass Neutron Star

- Test Mass: $\sim 2 \times 10^{30}$ kg
- Test time: $\sim 5.84 \times 10^{12}$ day
- Exposure: $\sim 1.2 \times 10^{43}$ kg day

NS is BETTER at capturing particles



Dark matter get accelerated when falling into the NS:

$$E_k \approx \frac{1}{2} m_{\text{DM}} v_{\text{esc}}^2 \sim m_{\text{DM}}, \quad v_{\text{esc}} \approx \mathcal{O}(0.6)c$$

Colliding with colder NS, they typically lose energy:

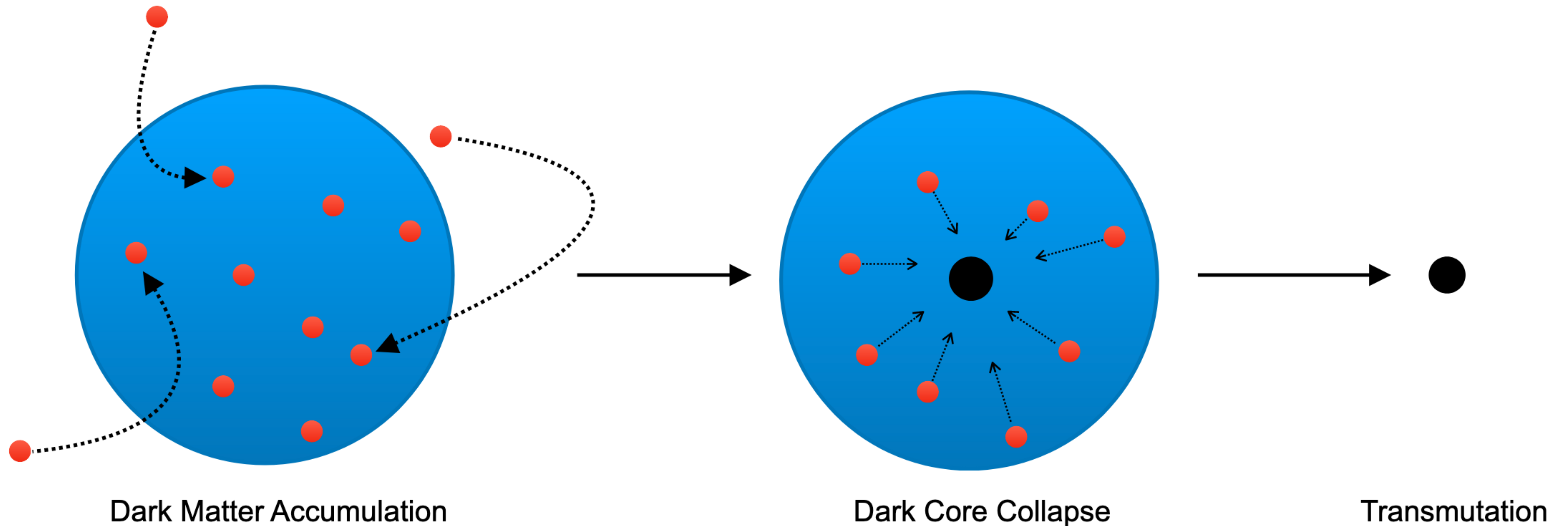
$$\Delta E \approx \mu E_k \approx m_n v_{\text{esc}}^2 \sim m_n,$$

The amount of energy DM needed to lose to be trapped:

$$\Delta E^{\text{needed}} \approx \frac{1}{2} m_{\text{DM}} v_{\text{vir}}^2 \sim 10^{-6} m_{\text{DM}},$$

Image from sciencenews.org

Stringent constraints from existing NSs



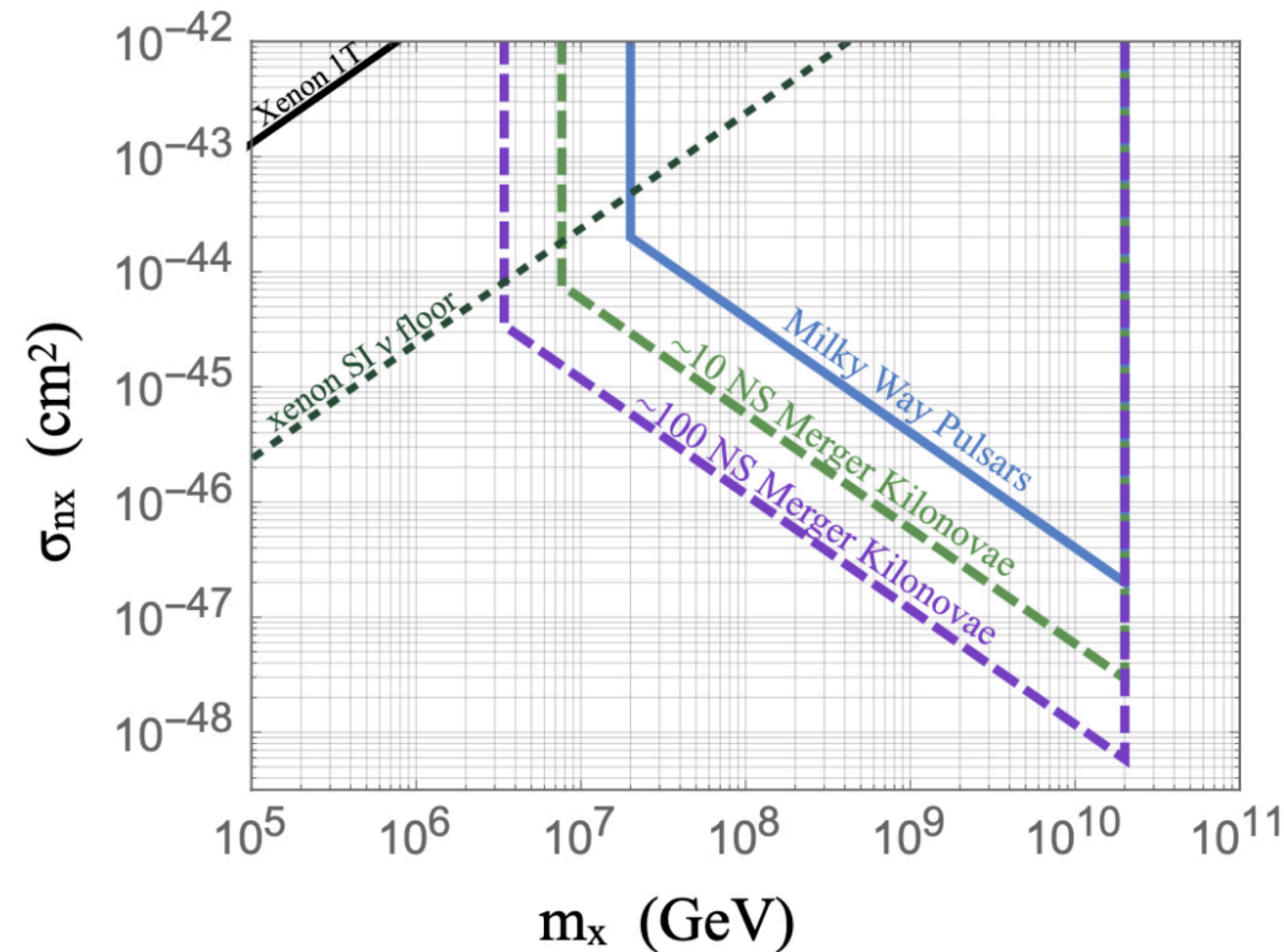
Anupam Ray.(2023)

Stringent constraints from existing NSs

For **asymmetric** DM, collected DM do not self-annihilate.

- Core temperature is **low**.
- Small equilibrium velocity
- Small equilibrium orbit radius
- Strongly confined in a small region

Virial
Theorem

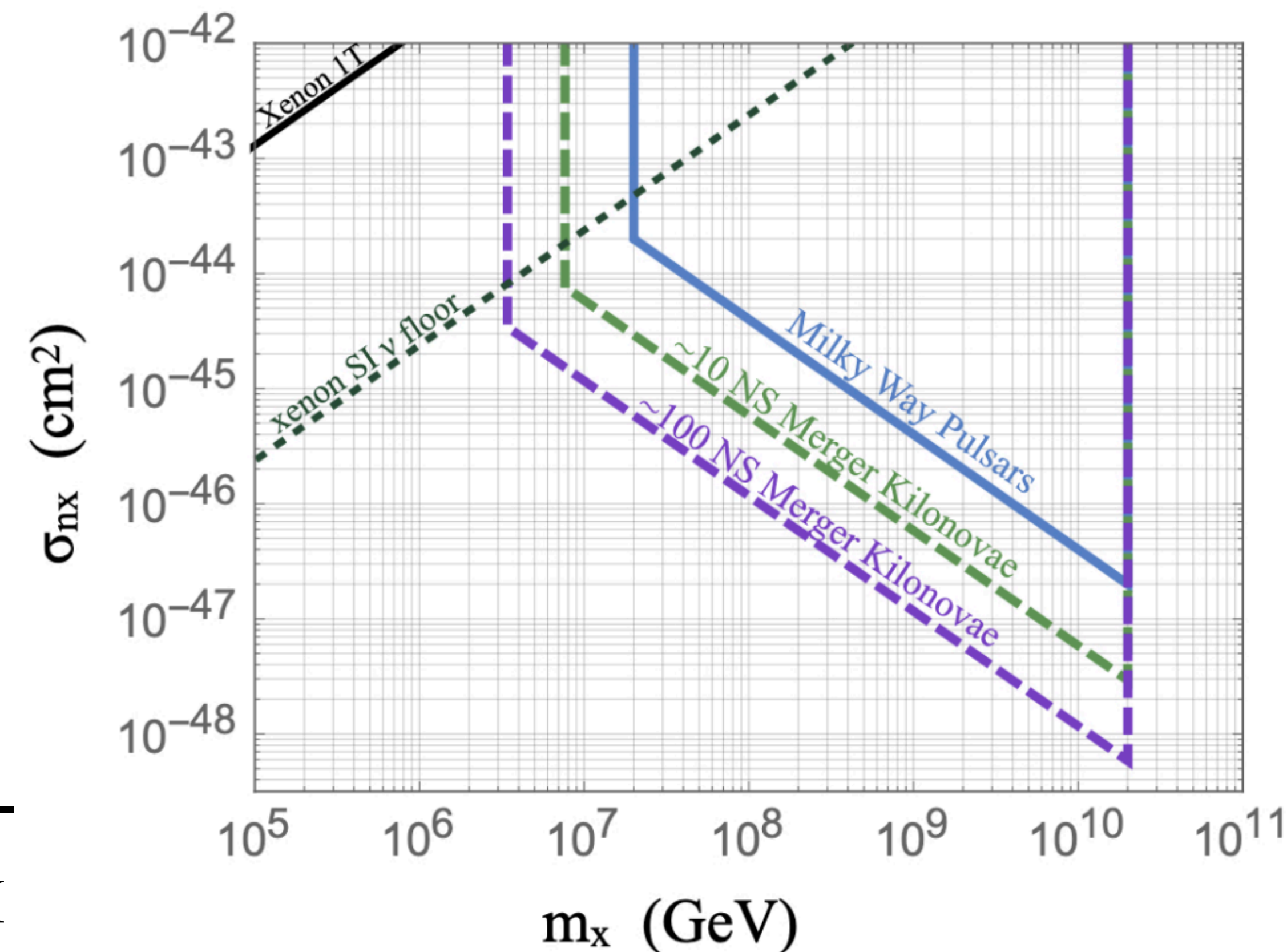


J. Bramante et al.(2017)

Stringent constraints from existing NSs

For **asymmetric** DM, collected DM do not self-annihilate.

- Core temperature is **low**.
- Quantum pressure **dominate**,
- over thermal pressure—Jeans Instability,
- crossing gravity instability.
- Reaching Chandrasekhar limit, $M_{\text{ch}} \sim \frac{m_{\text{pl}}^3}{m_{\text{DM}}^2}$

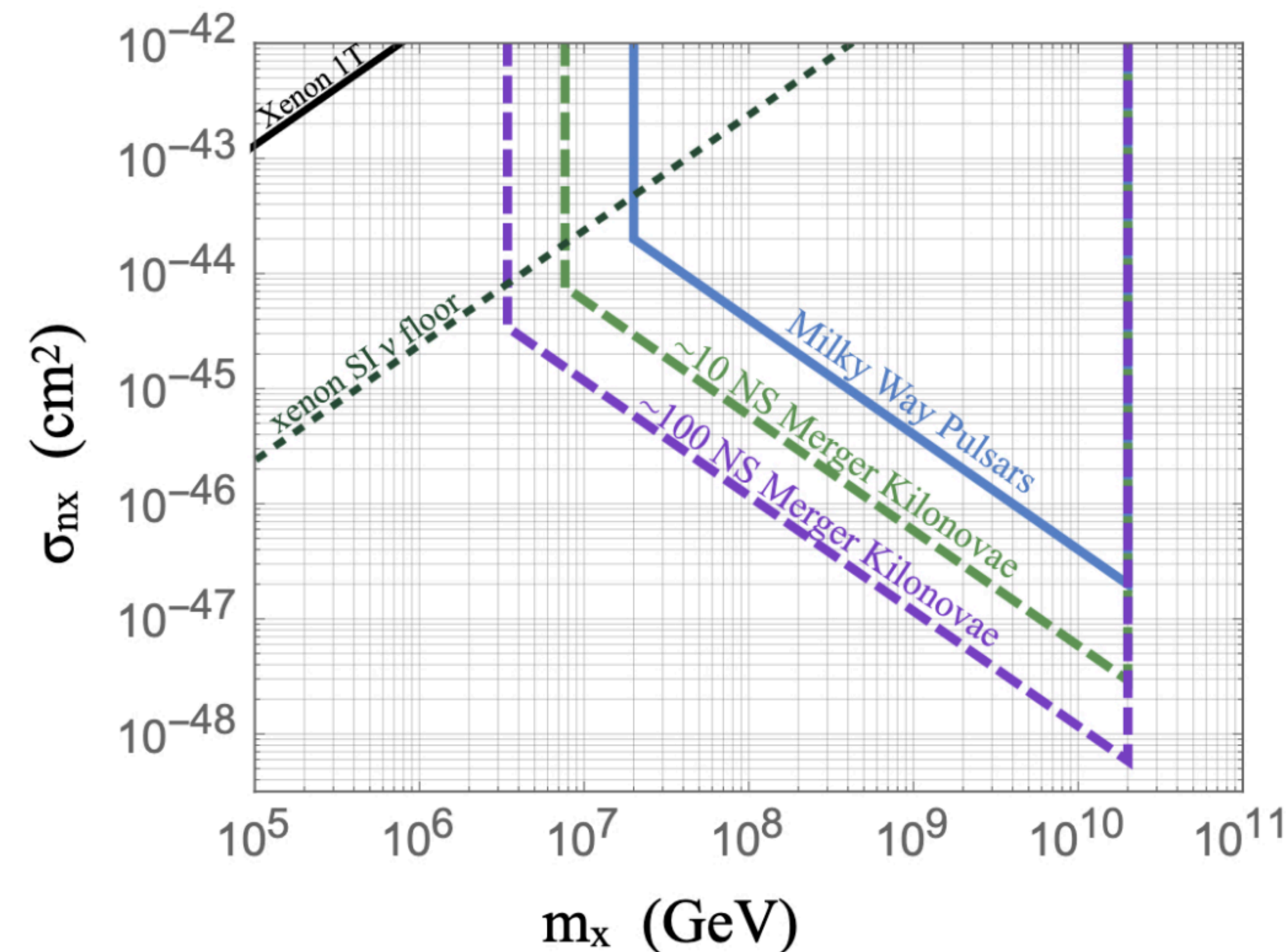


J. Bramante et al.(2017)

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- Core temperature is **low**.
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- BH growth is faaaaaast! Negligible growth time
- Can probe extremely low cross-sections

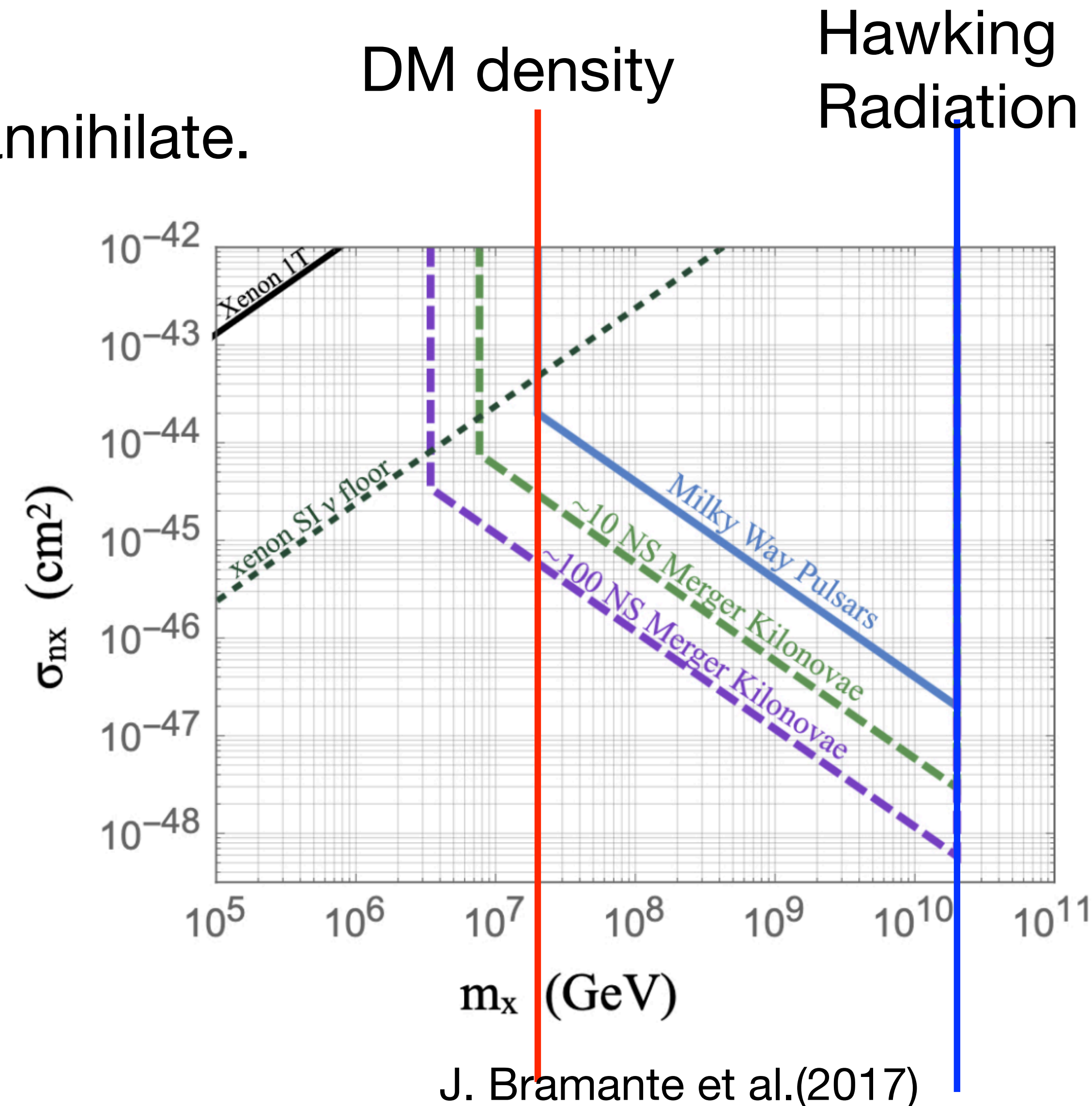


J. Bramante et al.(2017)

Stringent constraints from existing NSs

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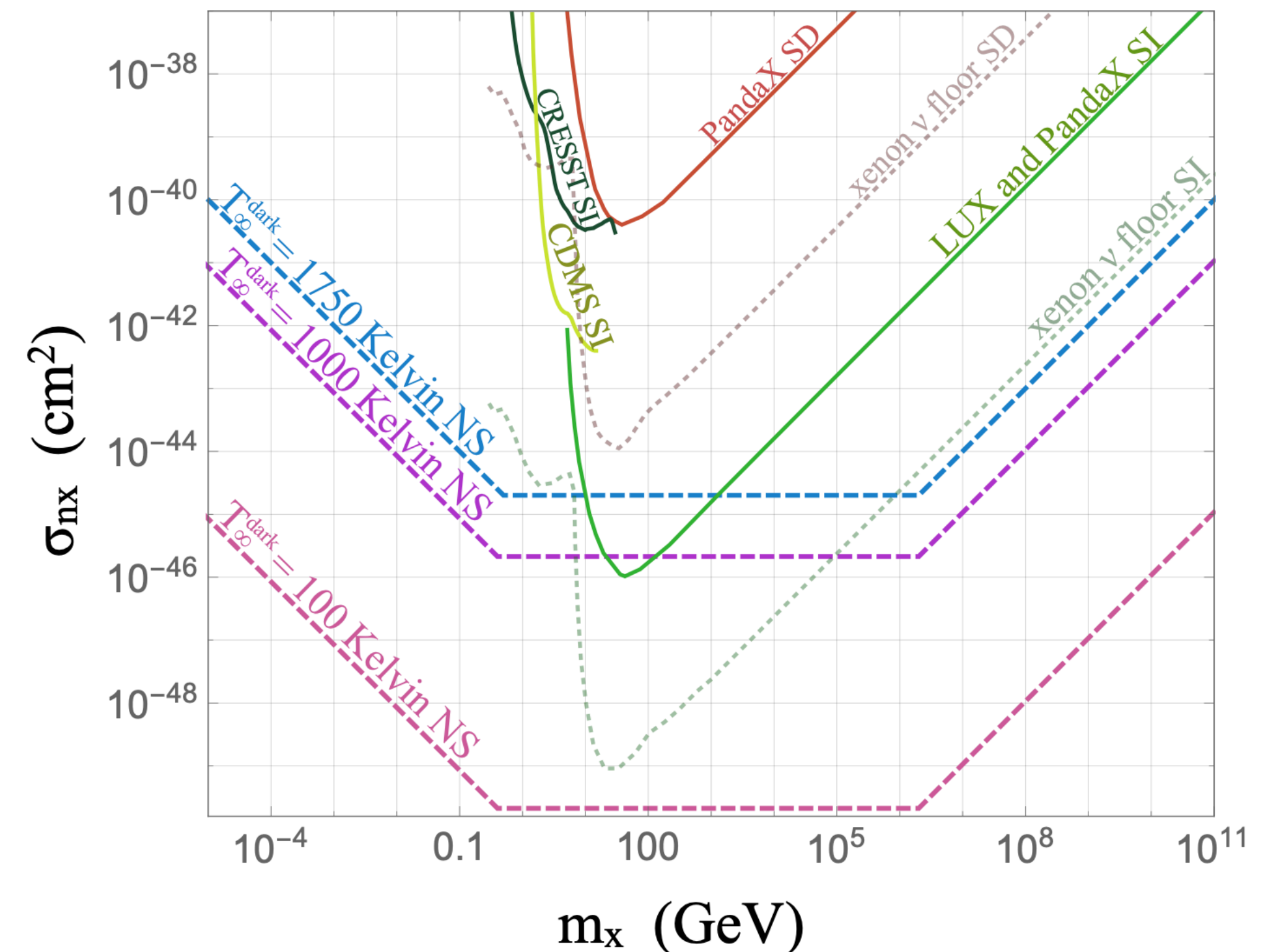
Stringent constraints from existing NSs

For **symmetric** DM $\rightarrow$ much easier to model

- **Symmetric** DM get evenly trapped and thermalized at the core of NS, high densities.
- DM annihilates, never reach extreme density.
- At equilibrium, DM capture $\Rightarrow$ Heating Rate.



Surface temperature $\Rightarrow$ Cooling Rate.



M. Baryakhtar et al.(2017)

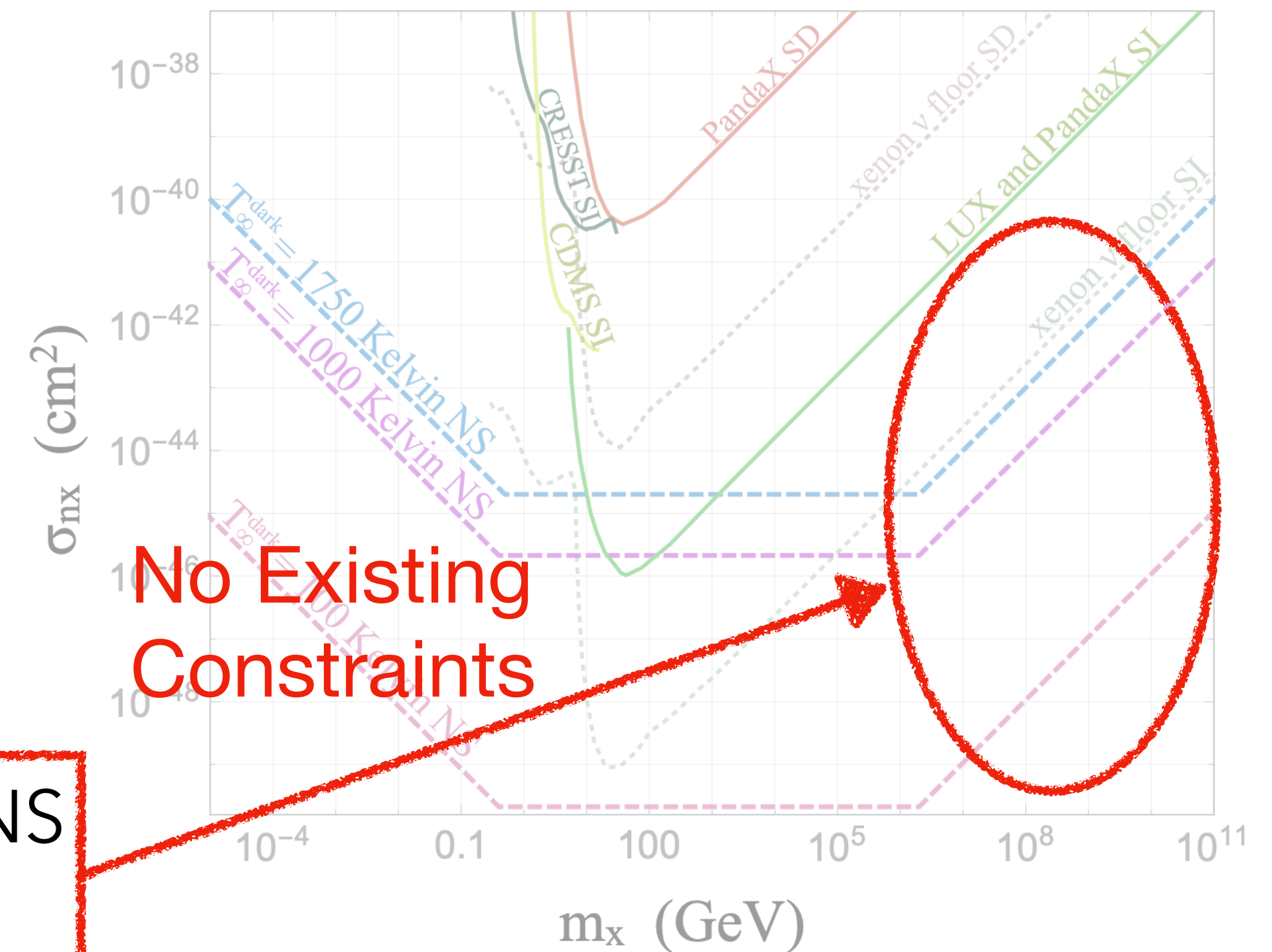
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- At equilibrium, DM capture $\Rightarrow$ Heating Rate.

Star Cooling constraints need observation of cold NS

Current coolest temperature $\sim 4 \times 10^4$ Kelvin



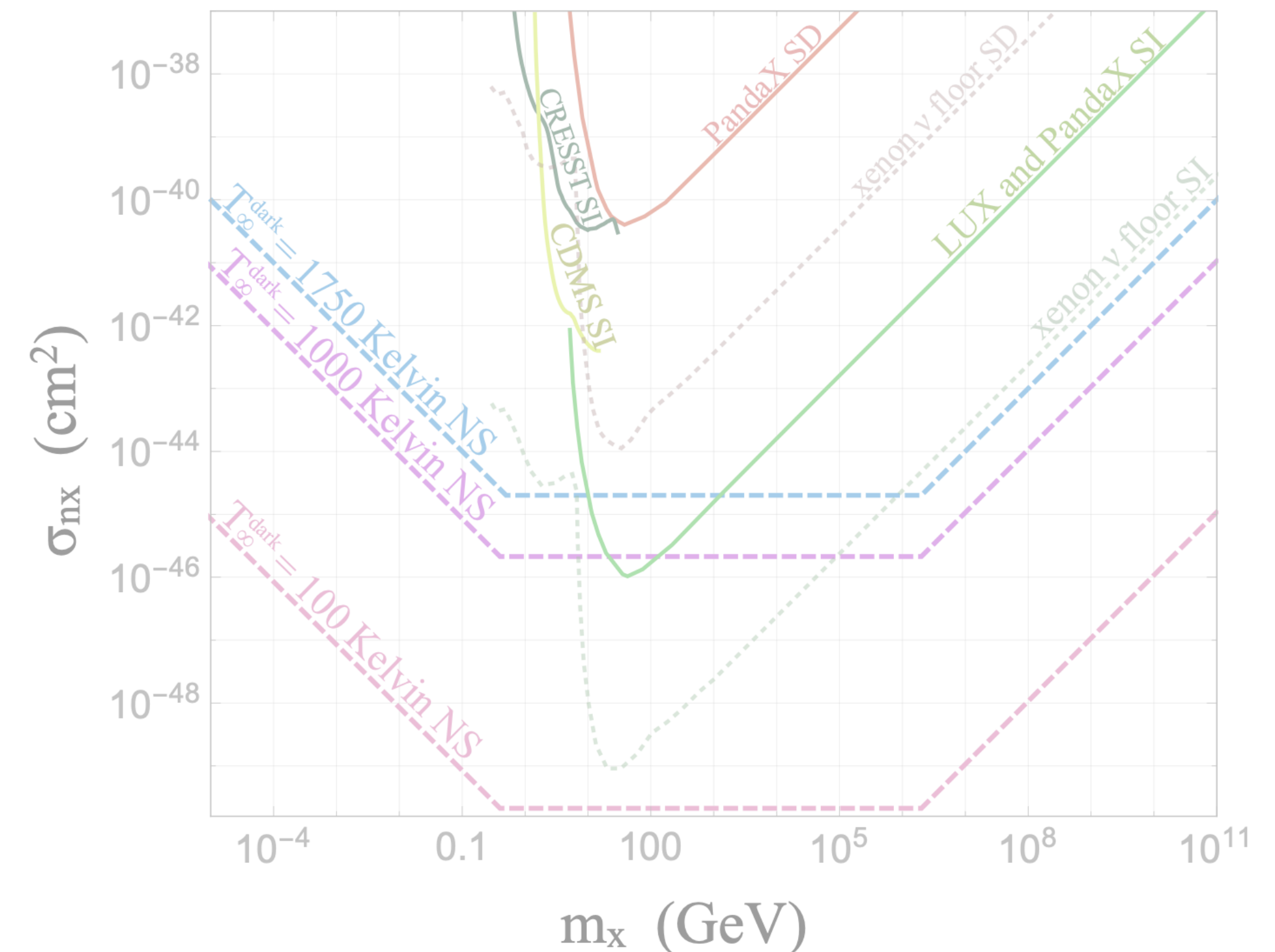
M. Baryakhtar et al.(2017)

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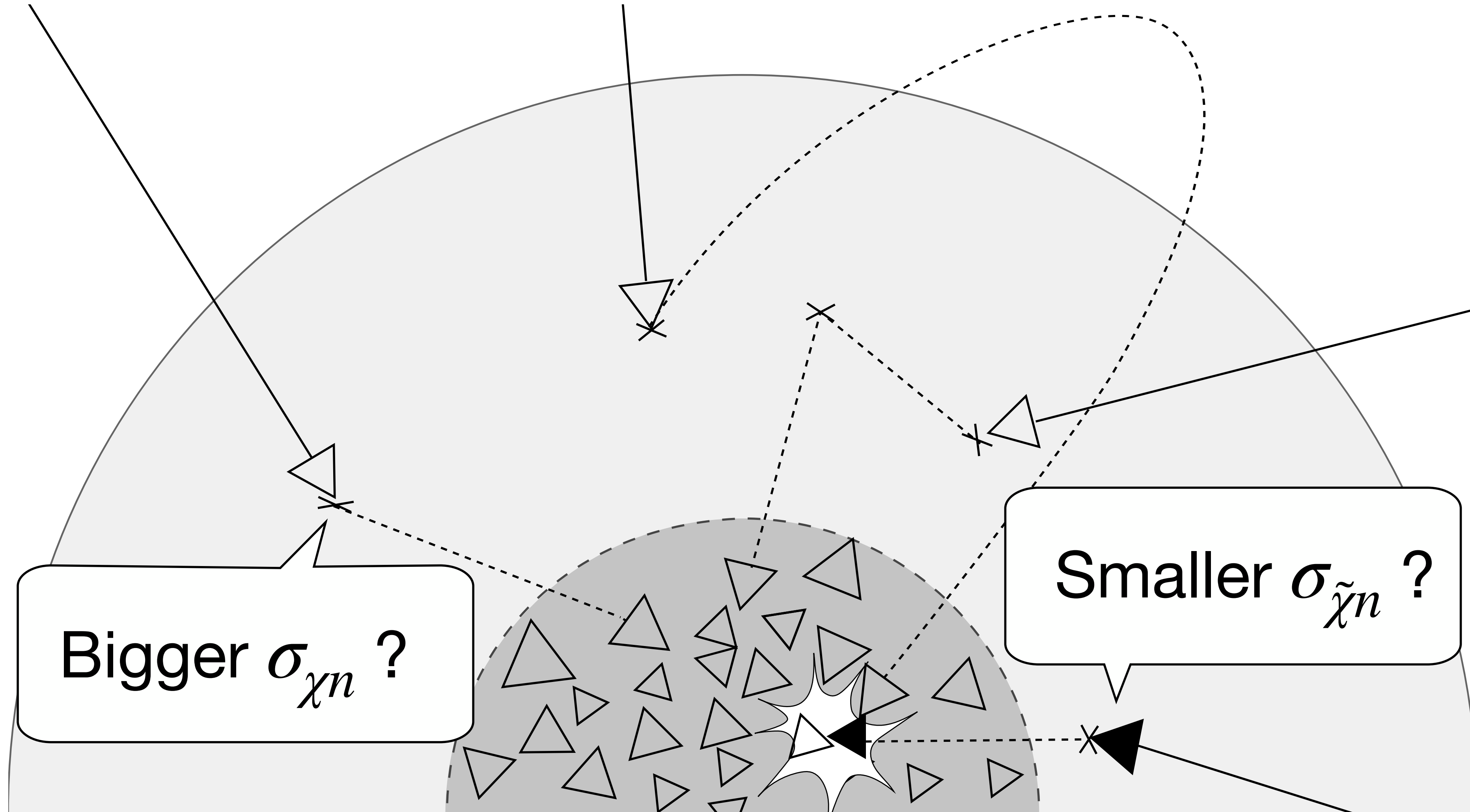
Not Necessarily True!



M. Baryakhtar et al.(2017)

Let's allow an Asymmetric capture rate

For **symmetric** DM $\rightarrow$ much easier to model

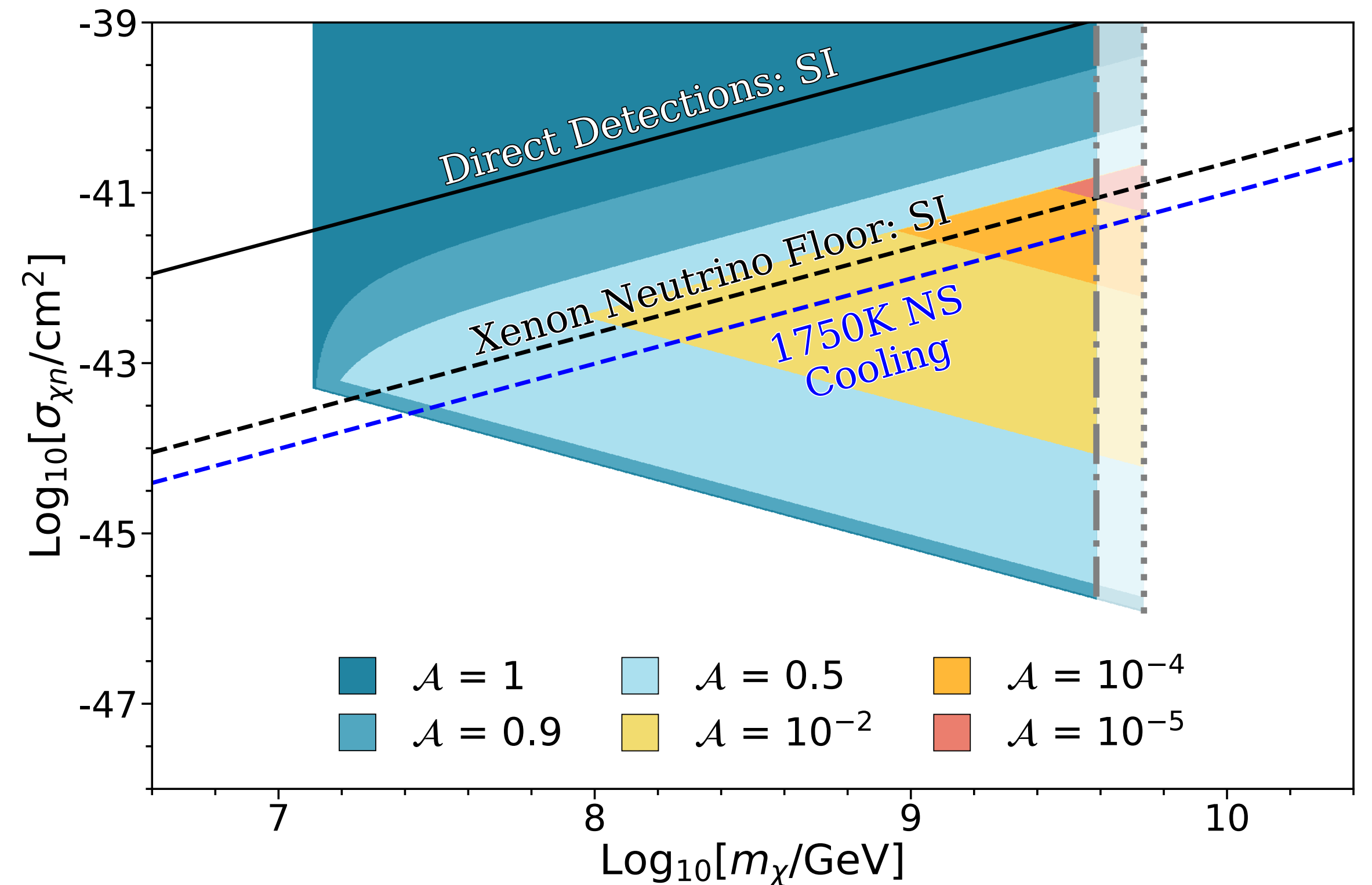


Sym-DM Asym-captured

Enabling Constraints for **Symmetric** Dark Matter

$$\mathcal{A} = \frac{\sigma_{\chi n} - \sigma_{\tilde{\chi} n}}{\sigma_{\chi n} + \sigma_{\tilde{\chi} n}}$$

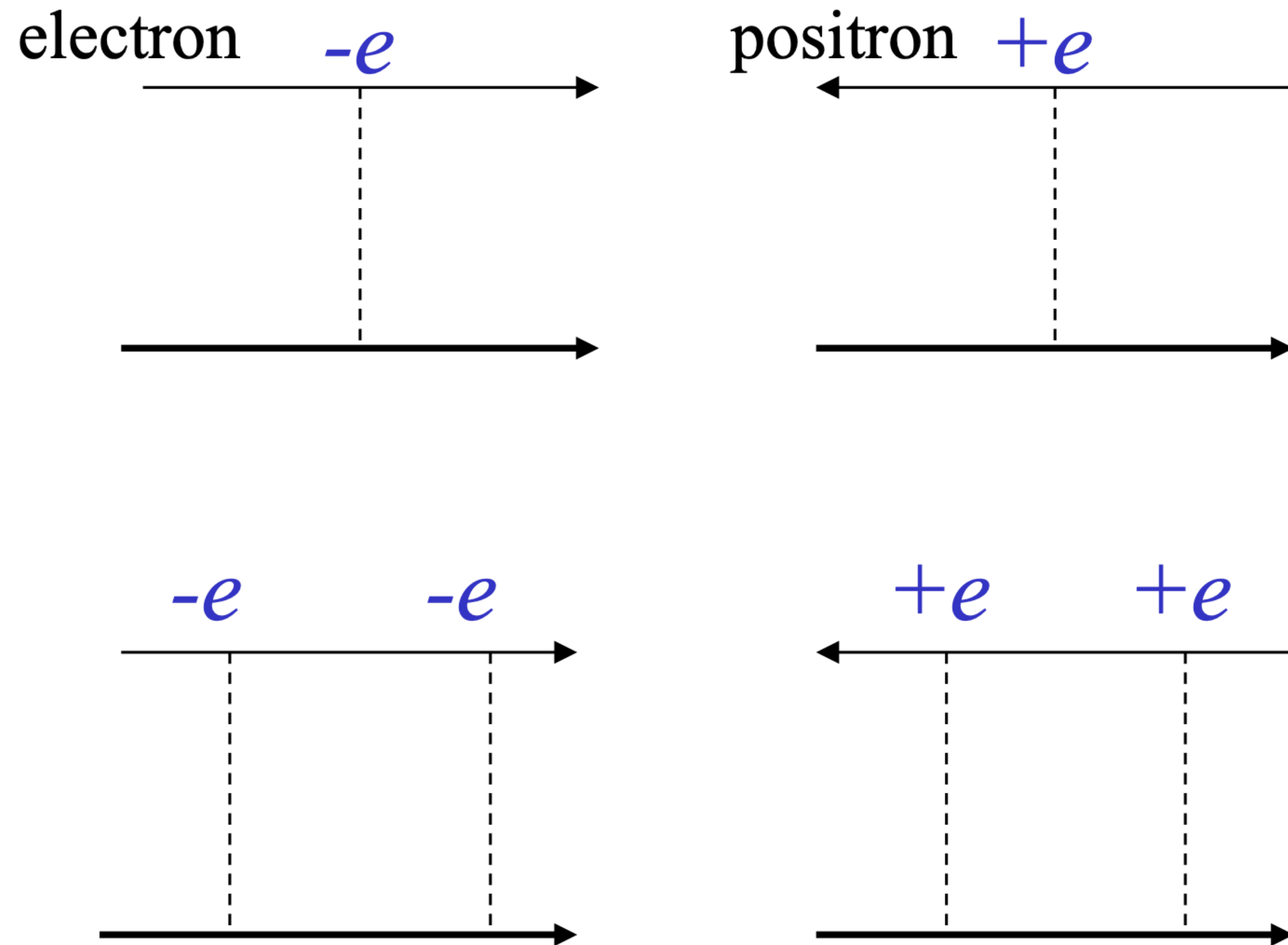
- Capture rate: $\frac{dN}{dt} \propto \sigma_{\chi n} - \sigma_{\tilde{\chi} n}$
 - Thermalization time
 - Gravitationally collapsing time
 - Black hole growth time
- $\left. \begin{array}{l} \text{Capture rate} \\ \text{Thermalization time} \\ \text{Gravitationally collapsing time} \\ \text{Black hole growth time} \end{array} \right\} < t_{\text{age}}$



Work with Zhen Liu, Maxim Pospelov, Sanjay Reddy. arXiv: 2508.04961

Sym-DM Asym-captured

Example: proton-electron/positron interaction



$$\mathcal{M}_{e^-}^{\text{tree}} = - \mathcal{M}_{e^+}^{\text{tree}}$$

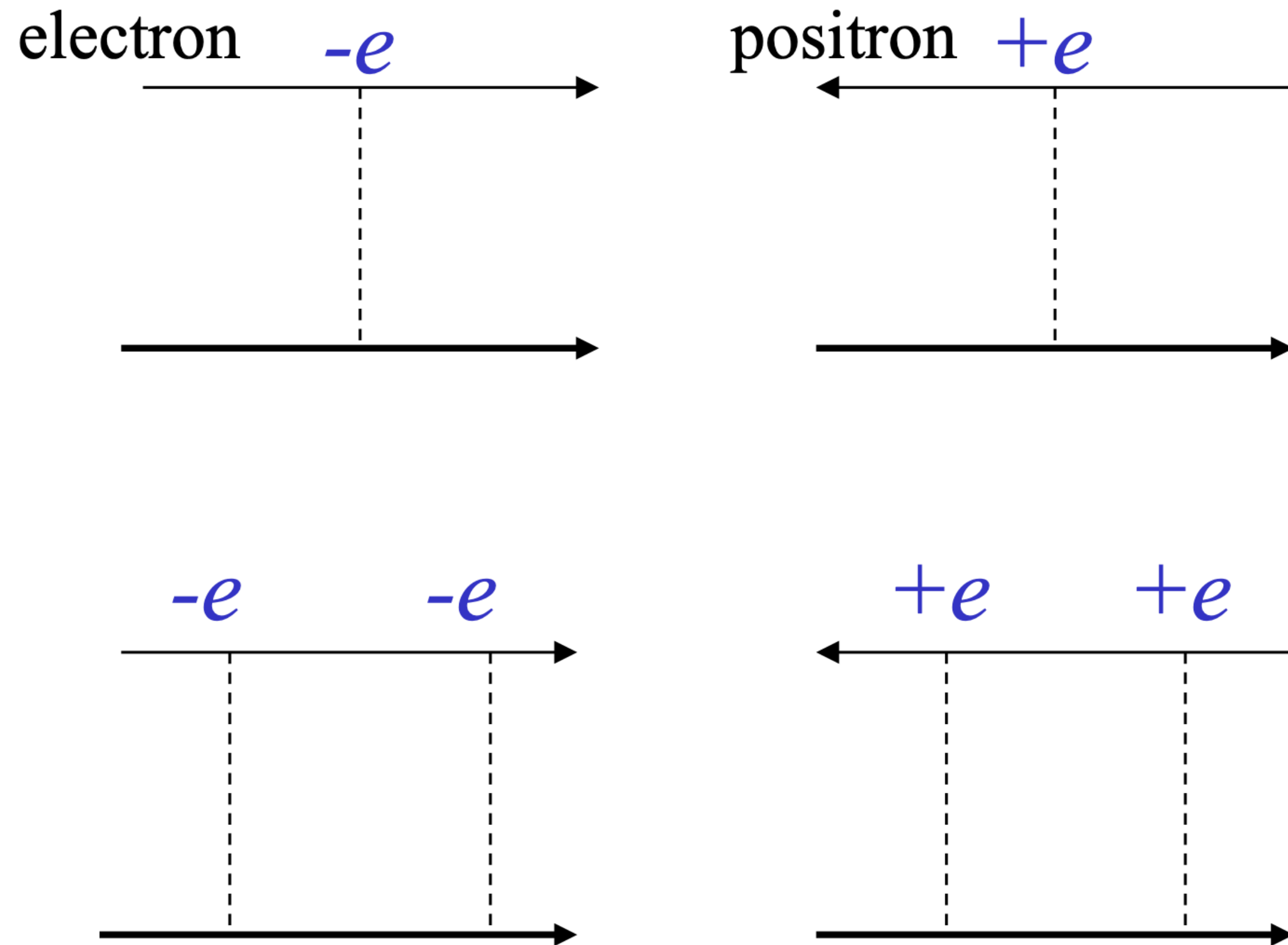
$$\mathcal{A} = \frac{\sigma(p^+e^-) - \sigma(p^+e^+)}{\sigma(p^+e^-) + \sigma(p^+e^+)} = \frac{\mathcal{M}_{e^-}^{\text{tree}} \mathcal{M}_{e^-}^{1\text{-loop}}}{(\mathcal{M}_{e^-}^{\text{tree}})^2}$$

$$\mathcal{M}_{e^-}^{1\text{-loop}} = \mathcal{M}_{e^+}^{1\text{-loop}}$$

Sym-DM Asym-captured

Example: proton-electron/positron interaction

Low energy EFT analysis!



$$\mathcal{M}_{e^-}^{\text{tree}} = -\mathcal{M}_{e^+}^{\text{tree}}$$

$$\mathcal{A} = \frac{\sigma(p^+e^-) - \sigma(p^+e^+)}{\sigma(p^+e^-) + \sigma(p^+e^+)} = \frac{\mathcal{M}_{e^-}^{\text{tree}} \mathcal{M}_{e^-}^{1\text{-loop}}}{(\mathcal{M}_{e^-}^{\text{tree}})^2}$$

$$\mathcal{M}_{e^-}^{1\text{-loop}} = \mathcal{M}_{e^+}^{1\text{-loop}}$$

Other examples include: $\nu/\bar{\nu}$ -nucleon interaction, asymmetry for hadrons, ...

EFT basis for asymmetries

For symmetric DM-nucleon operator up to dim-6 $\mathcal{L}_{\text{int}} = \pm \left(g_1 \mathcal{O}_1^\chi \mathcal{O}_1^n \pm g_2 \mathcal{O}_2^\chi \mathcal{O}_2^n \right)$

$C_\chi / C_\chi P_{\chi+n}$	$\bar{\chi}\chi$	$i\bar{\chi}\gamma^5\chi$	$\chi_s^\dagger\chi_s$	$i\chi_s^\dagger\overleftrightarrow{\partial}_\mu\chi_s$	$\bar{\chi}\gamma_\mu\chi$	$\bar{\chi}\gamma_\mu\gamma^5\chi$	$\bar{\chi}\sigma_{\mu\nu}\chi$
$\bar{n}n$	+/+	+/-	+/+				
$i\bar{n}\gamma^5 n$	+/-	+/+	+/-				
$\bar{n}\gamma^\mu n$					-/-	-/-	+/-
$\bar{n}\gamma^\mu\gamma^5 n$					-/+	-/+	+/+
$\bar{n}\sigma^{\mu\nu} n$							-/-

[black+brown] or [blue+red] pairs give asymmetries.

EFT basis for asymmetries

For symmetric DM-nucleon operator up to dim-6 $\mathcal{L}_{\text{int}} = \pm \left(g_1 \mathcal{O}_1^\chi \mathcal{O}_1^n \pm g_2 \mathcal{O}_2^\chi \mathcal{O}_2^n \right)$

$C_\chi / C_\chi P_{\chi+n}$	$\bar{\chi}\chi$	$i\bar{\chi}\gamma^5\chi$	$\chi_s^\dagger\chi_s$	$i\chi_s^\dagger\overleftrightarrow{\partial}_\mu\chi_s$	$\bar{\chi}\gamma_\mu\chi$	$\bar{\chi}\gamma_\mu\gamma^5\chi$	$\bar{\chi}\sigma_{\mu\nu}\chi$
$\bar{n}n$	+/+	+/-	+/+				
$i\bar{n}\gamma^5 n$	+/-	+/+	+/-				
$\bar{n}\gamma^\mu n$				-/-	-/-	+/-	
$\bar{n}\gamma^\mu\gamma^5 n$				-/+	-/+	+/+	
$\bar{n}\sigma^{\mu\nu} n$							-/-

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EFT basis for asymmetries

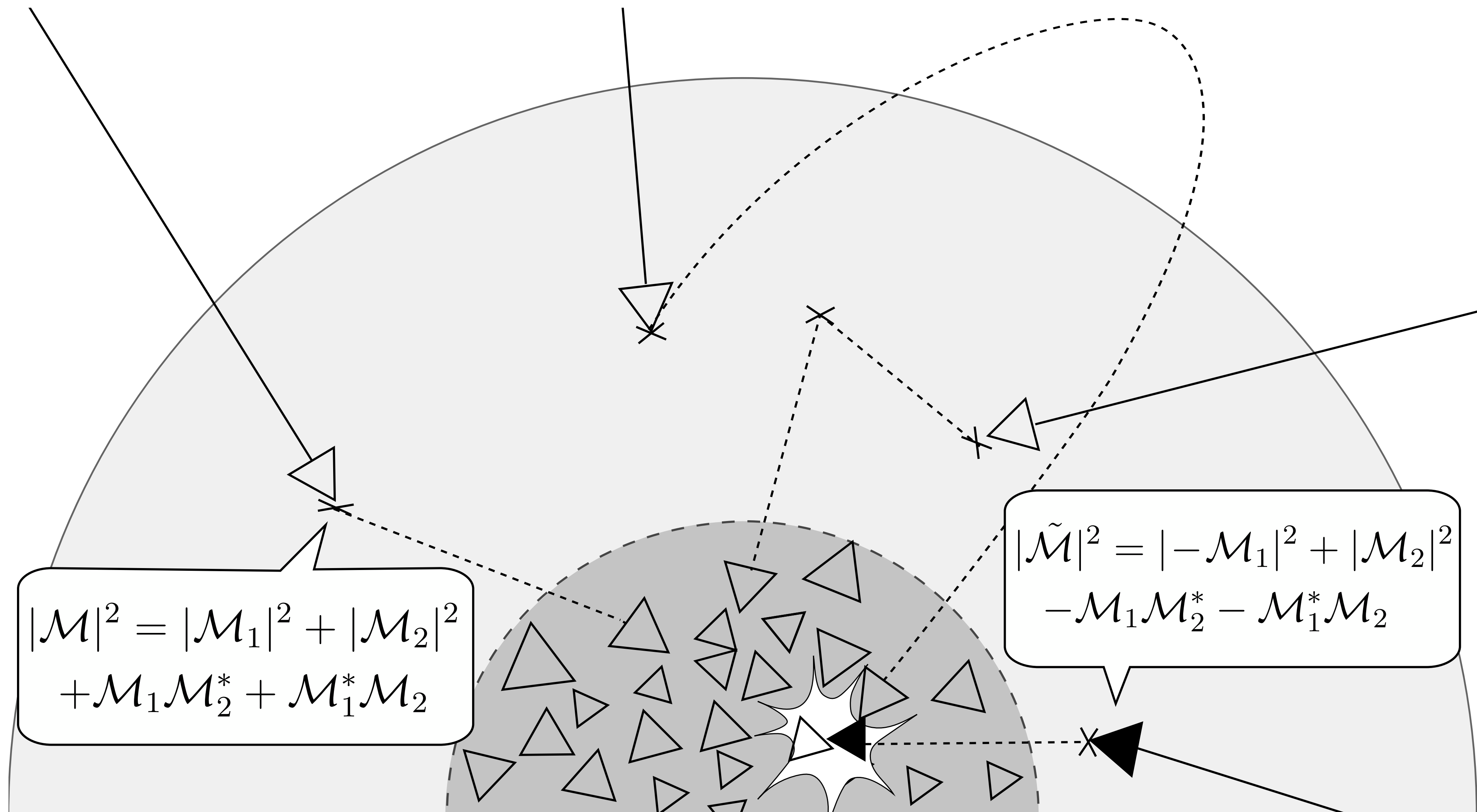
For symmetric DM-nucleon operator up to dim-8 $\mathcal{L}_{\text{int}} = \pm \left(g_1 \mathcal{O}_1^\chi \mathcal{O}_1^n \pm g_2 \mathcal{O}_2^\chi \mathcal{O}_2^n \right)$

$C_\chi / C_{\chi P}$	$\bar{n}n$	$i\bar{n}\gamma^5 n$	$\bar{n}\gamma_\mu n$	$\bar{n}\gamma_\mu \gamma^5 n$	$\bar{n}\sigma_{\mu\nu} n$	$i\bar{n}\overset{\leftrightarrow}{\partial}_\mu n$	$\bar{n}\overset{\leftrightarrow}{\partial}_\mu \gamma^5 n$	$i\bar{n}\overset{\leftrightarrow}{\partial}_{(\mu} \gamma_{\nu)} n$	$\bar{n}\overset{\leftrightarrow}{\partial}_{(\mu} \gamma_{\nu)} \gamma^5 n$
$\bar{\chi}\chi$	$+/+$	$+/-$							
$i\bar{\chi}\gamma^5 \chi$	$+/-$	$+/+$							
$\bar{\chi}\gamma^\mu \chi$			$-/-$	$-/+$		$-/-$	$-/+$		
$\bar{\chi}\gamma^\mu \gamma^5 \chi$			$+/-$	$+/+$		$+/-$	$+/+$		
$\bar{\chi}\sigma^{\mu\nu} \chi$					$-/-$			$-/-$	$-/+$
$i\bar{\chi}\overset{\leftrightarrow}{\partial}^\mu \chi$			$-/-$	$-/+$		$-/-$	$-/+$		
$\bar{\chi}\overset{\leftrightarrow}{\partial}^\mu \gamma^5 \chi$			$-/+$	$-/-$		$-/+$	$-/-$		
$i\bar{\chi}\overset{\leftrightarrow}{\partial}^{(\mu} \gamma^{\nu)} \chi$					$+/+$			$+/+$	$+/-$
$\bar{\chi}\overset{\leftrightarrow}{\partial}^{(\mu} \gamma^{\nu)} \gamma^5 \chi$					$-/+$			$-/+$	$-/-$
$\chi_s^\dagger \chi_s$	$+/+$	$+/-$							
$i\chi_s^\dagger \overset{\leftrightarrow}{\partial}^\mu \chi_s$			$-/-$	$-/+$		$-/-$	$-/+$		
$\chi_s^\dagger \overset{\leftrightarrow}{\partial}^\mu \overset{\leftrightarrow}{\partial}^\nu \chi_s$								$+/+$	$+/-$

[black+brown] or [blue+red]
pairs give asymmetries.

Let's allow an Asymmetric capture rate

For **symmetric** DM $\rightarrow$ much easier to model



Sym-DM asym-captured

Enabling constraints for Symmetric Dark Matter

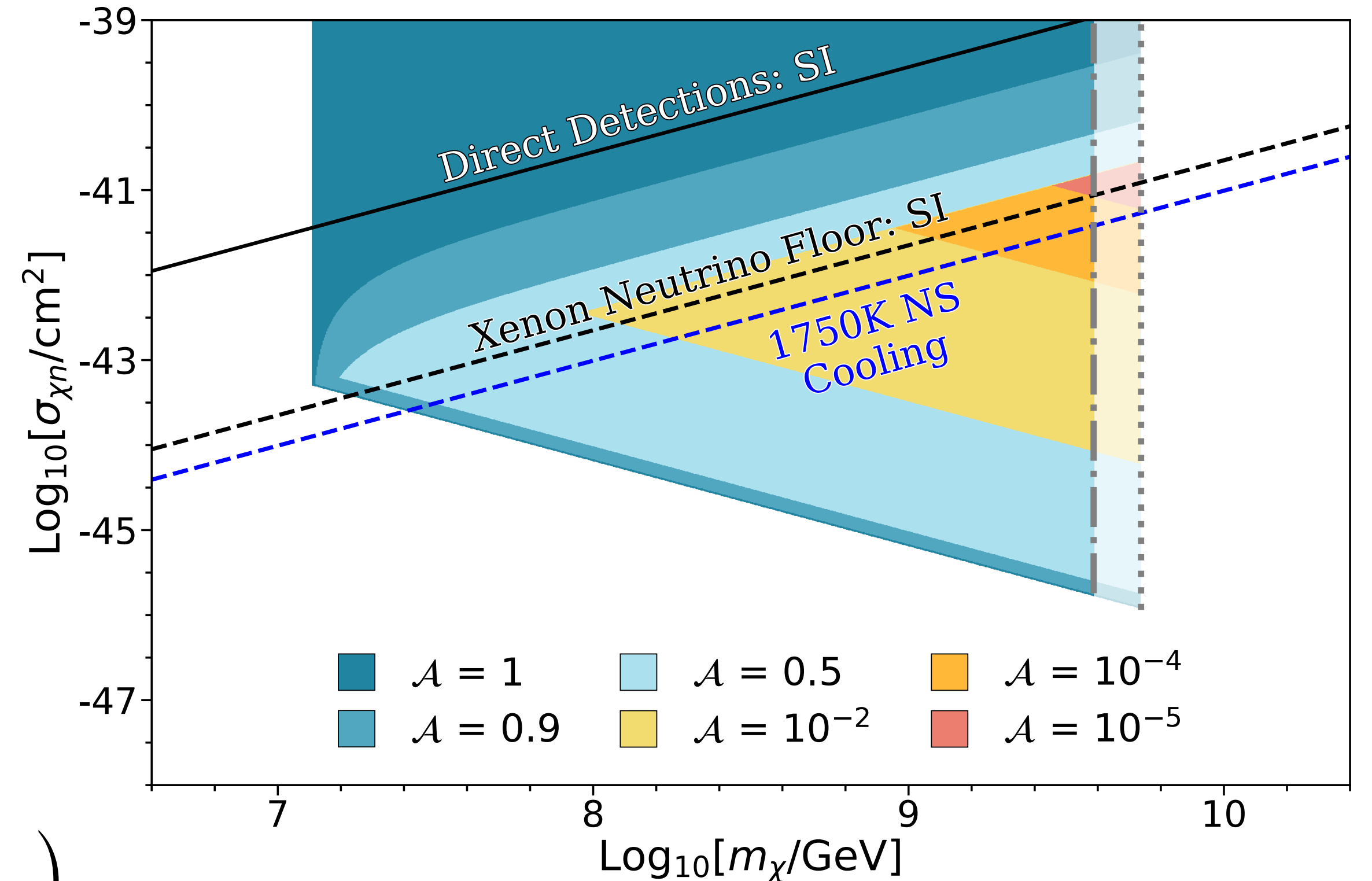
Scalar-Scalar vs Vector-Vector

$$\mathcal{A} \approx \frac{2g_{SS}g_{VV}}{g_{SS}^2 + g_{VV}^2}$$

Left-handed only

$$\begin{aligned} \mathcal{L} = \mathcal{L}_{LL} &= g_{LL} \mathcal{J}_{\chi L}^\mu \mathcal{J}_{nL\mu} \\ &= \frac{1}{4} \left(\left(\mathcal{J}_{\chi V} - \mathcal{J}_{\chi A} \right)^\mu \left(\mathcal{J}_{nV} - \mathcal{J}_{nA} \right)_\mu \right) \\ &= \frac{1}{4} g_{LL} \left(\mathcal{J}_{\chi V}^\mu \mathcal{J}_{nV\mu} - \mathcal{J}_{\chi V}^\mu \mathcal{J}_{nA\mu} - \mathcal{J}_{\chi A}^\mu \mathcal{J}_{nV\mu} + \mathcal{J}_{\chi A}^\mu \mathcal{J}_{nA\mu} \right) \end{aligned}$$

$$\mathcal{A} \approx \frac{(4 - \pi) |\mathbf{p}|^2}{4E_\chi E_n}$$



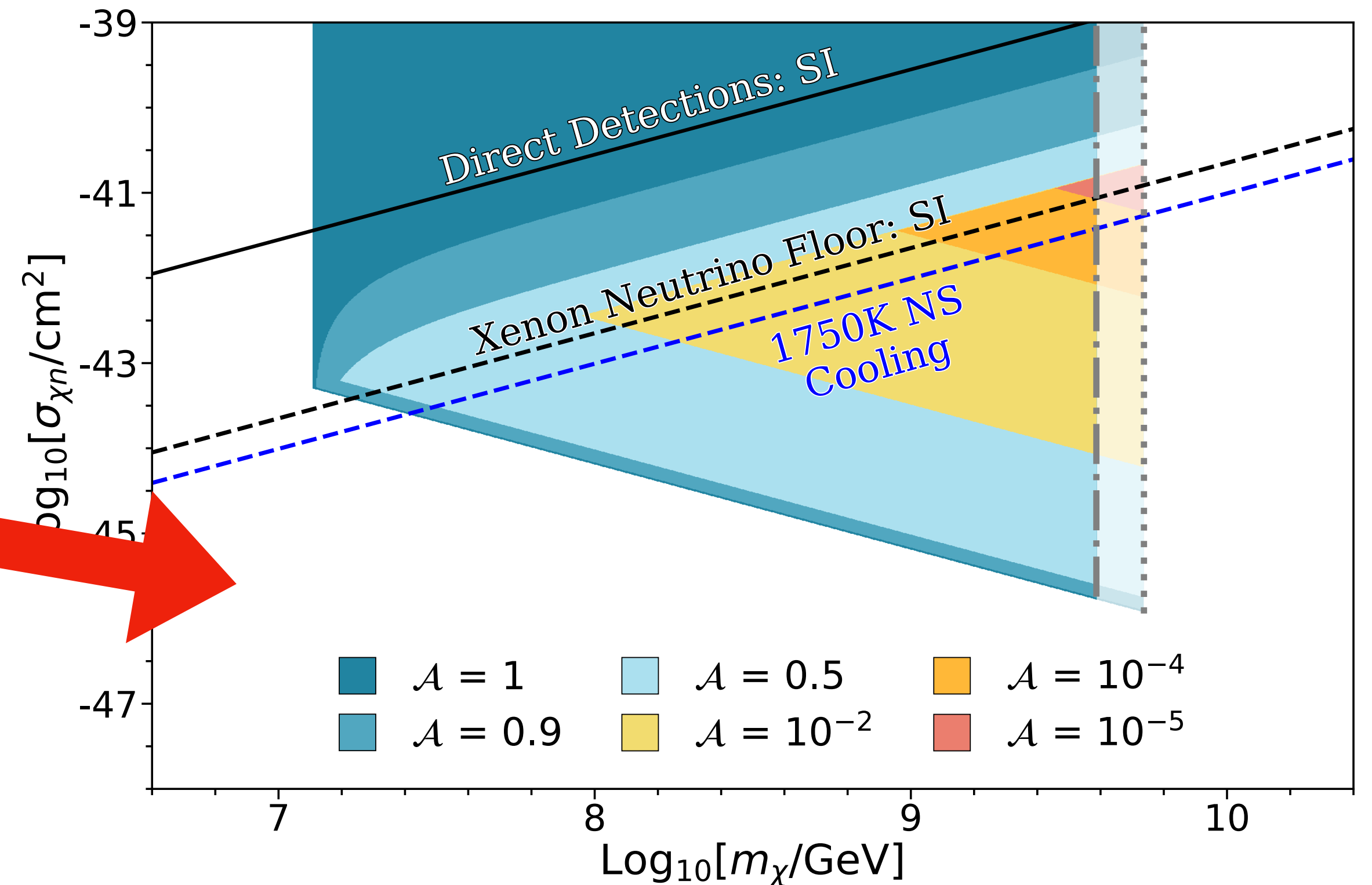
Work with Zhen Liu, Maxim Pospelov, Sanjay Reddy. arXiv: 2508.04961

Sym-DM Asym-captured

Enabling constraints for Symmetric Dark Matter

$$\mathcal{A} = \frac{\sigma_{\chi n} - \sigma_{\tilde{\chi} n}}{\sigma_{\chi n} + \sigma_{\tilde{\chi} n}}$$

Extend to lower mass and lower cross-sections,
with future observations of NS in the GC



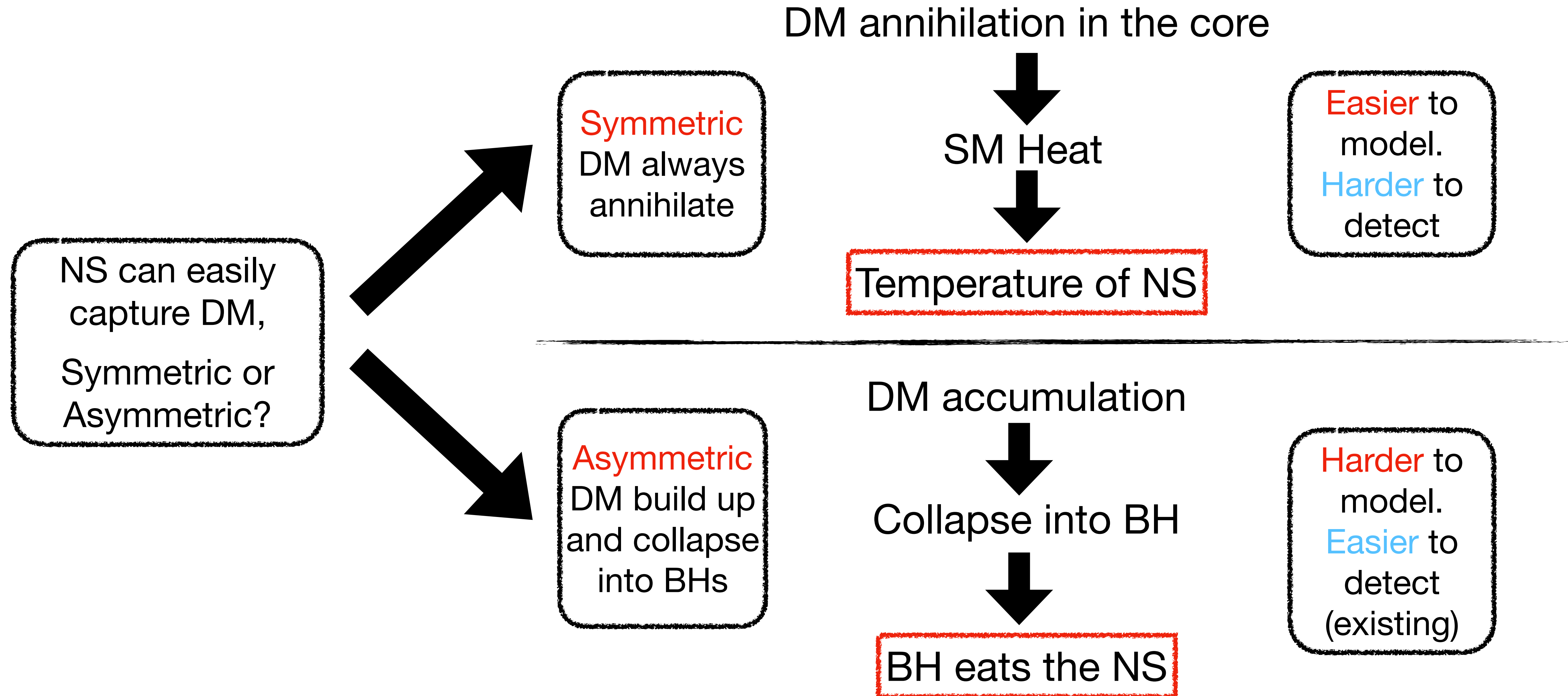
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Summary

- Neutron Stars are very good at capture DMs— —A Solar-mass Lab in our universe
- When too many DM get captured, they break the NS— —Black Hole formation
- **Sym-DM can now be constrained** through interference between two effective couplings:
 - DM/anti-DM generically have different cross-sections with neutron stars.
 - ‘unique’ constraints at heavy mass - weak cross section region.
 - A large variety of DM model can be tested.

Thanks!

How to utilize the NS observation we have?



Back up slides

Sym-DM Asym-captured

Properties of tree-level EFT

$$\mathcal{L}_{\text{int}} = \pm \left(g_1 \mathcal{O}_1^\chi \mathcal{O}_1^n \pm g_2 \mathcal{O}_2^\chi \mathcal{O}_2^n \right)$$

$$\mathcal{O}^\psi = \bar{\psi}[\text{anything}]\psi$$

C_χ : Charge conjugation of DM χ : taking $\chi \leftrightarrow \tilde{\chi}$

C_n : Charge conjugation of nucleon n : taking $n \leftrightarrow \tilde{n}$

P : Parity conjugation of DM and nucleon: taking $\psi_L \leftrightarrow \psi_R$

DM are virially unpolarized

Nucleons are thermally unpolarized

Sym-DM Asym-captured

C_χ and $C_\chi P$ -violation

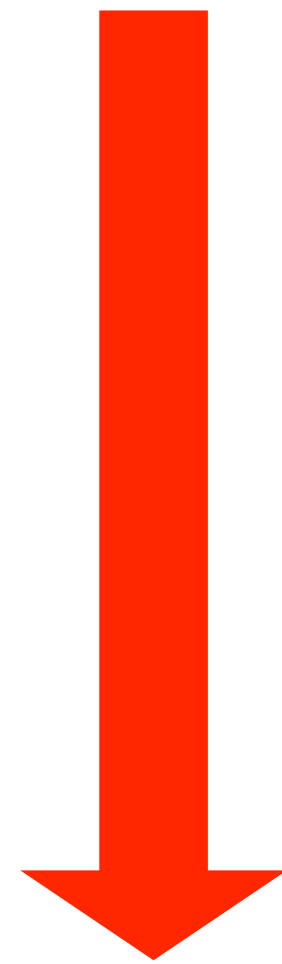
DM are virially unpolarized

Nucleons are thermally unpolarized

$$4\sigma(\chi + n) = \sigma(\chi_L + n_L) + \sigma(\chi_L + n_R) + \sigma(\chi_R + n_L) + \sigma(\chi_R + n_R)$$

$$4\sigma(\bar{\chi} + n) = \sigma(\bar{\chi}_L + n_L) + \sigma(\bar{\chi}_L + n_R) + \sigma(\bar{\chi}_R + n_L) + \sigma(\bar{\chi}_R + n_R).$$

$C_\chi P$



C_χ

$$4\sigma(\chi + n) = \sigma(\bar{\chi}_L + n_L) + \sigma(\bar{\chi}_L + n_R) + \sigma(\bar{\chi}_R + n_L) + \sigma(\bar{\chi}_R + n_R) = 4\sigma(\bar{\chi} + n),$$

$$4\sigma(\chi + n) = \sigma(\bar{\chi}_R + n_R) + \sigma(\bar{\chi}_R + n_L) + \sigma(\bar{\chi}_L + n_R) + \sigma(\bar{\chi}_L + n_L) = 4\sigma(\bar{\chi} + n).$$

Sym-DM Asym-captured

Properties of EFT

$$\mathcal{L}_{\text{int}} = \pm \left(g_1 \mathcal{O}_1^\chi \mathcal{O}_1^n \pm g_2 \mathcal{O}_2^\chi \mathcal{O}_2^n \right) \quad \mathcal{O}^\psi = \bar{\psi}[\text{anything}]\psi$$

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Breaking C_χ and $C_\chi P$ indicate **opposite** C_χ –parity and **same** P –parity between 1,2

Sym-DM Asym-captured

Properties of EFT

$$\mathcal{L}_{\text{int}} = \pm \left(g_1 \mathcal{O}_1^\chi \mathcal{O}_1^n \pm g_2 \mathcal{O}_2^\chi \mathcal{O}_2^n \right) \quad \mathcal{O}^\psi = \bar{\psi}[\text{anything}]\psi$$

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Breaking C_χ and $C_\chi P$ indicate **opposite** C_χ –parity and **same** P –parity between 1,2

One curious observation

Asymmetry from Lagrangian preserving C_n are either suppressed or vanishing.

- Group(1): vanishing asymmetry:

$$\mathcal{O}_P^\chi \mathcal{O}_P^n \otimes \mathcal{O}_V^\chi \mathcal{O}_V^n; \quad \mathcal{O}_V^\chi \mathcal{O}_A^n \otimes \mathcal{O}_P^\chi \mathcal{O}_S^n; \quad \mathcal{O}_V^\chi \mathcal{O}_A^n \otimes \mathcal{O}_S^\chi \mathcal{O}_P^n; \quad \mathcal{O}_T^\chi \mathcal{O}_T^n \otimes \mathcal{O}_A^\chi \mathcal{O}_V^n;$$

- Group(2): suppressed asymmetry:

$$\mathcal{O}_V^\chi \mathcal{O}_A^n \otimes \mathcal{O}_A^\chi \mathcal{O}_V^n; \quad \mathcal{O}_T^\chi \mathcal{O}_T^n \otimes \mathcal{O}_P^\chi \mathcal{O}_S^n; \quad \mathcal{O}_T^\chi \mathcal{O}_T^n \otimes \mathcal{O}_S^\chi \mathcal{O}_P^n,$$

$$\mathcal{O}_S^\chi \mathcal{O}_S^n \otimes \mathcal{O}_T^\chi \mathcal{O}_T^n; \quad \mathcal{O}_P^\chi \mathcal{O}_P^n \otimes \mathcal{O}_T^\chi \mathcal{O}_T^n; \quad \mathcal{O}_A^\chi \mathcal{O}_A^n \otimes \mathcal{O}_V^\chi \mathcal{O}_V^n;$$

Example UV model-1

Two additional “squark”

$$\mathcal{L}_{\text{int}} \supset y_L (\bar{u}_L \chi) \Phi_L^u + y_R (\bar{u}_R \chi) \Phi_R + B \tilde{H}^\dagger \begin{pmatrix} \Phi_L^u \\ \Phi_L^d \end{pmatrix} (\Phi_R)^* + \text{h.c.}$$

Integrate out the scalar mediator

$$\mathcal{L}_{\text{eff}}^{(u)} = \frac{|y_L|^2}{m_{\Phi_L^u} |\Delta m_L|} (\bar{u}_L \chi) (\bar{\chi} u_L) + \frac{|y_R|^2}{m_{\Phi_R} |\Delta m_R|} (\bar{u}_R \chi) (\bar{\chi} u_R) + \frac{y_L y_R^* B v}{m_{\Phi_L^u} m_{\Phi_R} |\Delta m_L \Delta m_R|} (\bar{u}_L \chi) (\bar{\chi} u_R) + \text{h.c.}$$

Example UV model-1

Fierz Transformation

$$\mathcal{L}_{\text{eff}}^{(u)} = \frac{y^2}{4m_\Phi |\Delta m|} \left[(\bar{u}\gamma_\mu\gamma_5 u)(\bar{\chi}\gamma^\mu\gamma_5\chi) - (\bar{u}\gamma_\mu u)(\bar{\chi}\gamma^\mu\chi) \right] +$$

$$\frac{y^2 B\nu}{4m_\Phi^2 |\Delta m|^2} \left[(\bar{u}u)(\bar{\chi}\chi) - (\bar{u}i\gamma_5 u)(\bar{\chi}i\gamma_5\chi) + \frac{1}{2}(\bar{u}\sigma_{\mu\nu}u)(\bar{\chi}\sigma^{\mu\nu}\chi) \right].$$

$$\mathcal{A} \approx \frac{(6c_A c_T + 2c_V c_S) \frac{B\nu}{m_\Phi |\Delta m|}}{3c_A^2 + c_V^2 + c_S^2 \left(\frac{B\nu}{m_\Phi |\Delta m|} \right)^2 + 3c_T^2 \left(\frac{B\nu}{m_\Phi |\Delta m|} \right)^2}.$$

Example UV model-2

$$\mathcal{A} \approx \frac{2g_{SS}g_{VV}}{g_{SS}^2 + g_{VV}^2}$$

A dark “Higgs” mixing with Higgs

$$V(H, S) = -\mu_H^2 |H|^2 + \frac{\lambda_H}{2} |H|^4 - \mu_S^2 |S|^2 + \frac{\lambda_S}{2} |S|^4 + \lambda_{HS} |H|^2 |S|^2.$$

$$\begin{aligned} \mathcal{L} \supset & g_X X_\mu \left(\bar{\chi}_1 \gamma^\mu \chi_1 + \sum_f q_f \bar{f} \gamma^\mu f \right) - \sum_{f_L, f_R} y_R \bar{f}_L H f_R - m_1 \bar{\chi}_1 \chi_1 - m_2 \bar{\chi}_2 \chi_2 \\ & - y_1 S \bar{\chi}_{1L} \chi_{2R} - y_2 S^* \bar{\chi}_{2L} \chi_{1R} + h.c. \quad , \end{aligned}$$

$$\begin{aligned} \mathcal{L} \supset & \frac{1}{2} g_X X_\mu \left(\bar{\chi}^{(\prime)} \gamma^\mu \chi^{(\prime)} + \sum_f q_f \bar{f} \gamma^\mu f \right) - \sum_f y_f (h \cos \theta + s \sin \theta) \bar{f} f + \frac{1}{\sqrt{2}} y_\chi (s \cos \theta + h \sin \theta) \bar{\chi} \chi \\ & - \frac{1}{\sqrt{2}} y_\chi (s \cos \theta + h \sin \theta) \bar{\chi}' \chi', \end{aligned}$$

$$\frac{g_{SS}}{g_{VV}} \approx \frac{c_S^{(n)}}{c_V^{(n)}} \frac{y_\chi y_f}{q_f} \frac{v_S^2 \sin 2\theta}{m_h^2}.$$

Example UV model-3

A heavy dark gauge

$$\mathcal{L} = \bar{\chi}[\gamma^\mu(i\partial_\mu + g_d A'_\mu) - m_\chi]\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{\varepsilon}{2}B^{\mu\nu}F'_{\mu\nu},$$

$$\frac{M_{1\text{-loop}}}{M_{\text{tree}}} \sim \pm \frac{\pi Q_q \varepsilon (\alpha \alpha_d)^{1/2} m_q}{16 m_X}.$$

$$\mathcal{A} \approx \frac{\pi \alpha \langle m_q \rangle}{16 m_X G_E^n} \approx 1 \times 10^{-3},$$

Example UV model-3

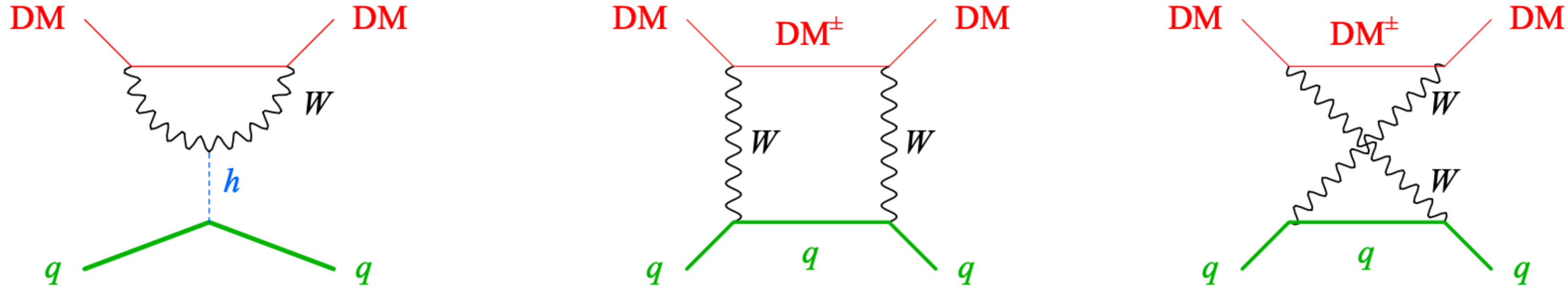


Figure 1: *One loop DM/quark scattering for fermionic MDM with $Y = 0$. Two extra graphs involving the four particle vertex exist in the case of scalar MDM.*

An elastic cross section on nuclei is generated at loop level via the diagrams in fig. 1. An explicit computation of the relevant one-loop diagrams is needed to understand qualitatively and quantitatively the result. We find that non-relativistic MDM/quark interactions of fermionic MDM with mass $M \gg M_W \gg m_q$ are described by the effective Lagrangian

$$\mathcal{L}_{\text{eff}}^W = (n^2 - (1 \pm 2Y)^2) \frac{\pi \alpha_2^2}{16 M_W} \sum_q \left[\left(\frac{1}{M_W^2} + \frac{1}{m_h^2} \right) [\bar{\mathcal{X}} \mathcal{X}] m_q [\bar{q} q] - \frac{2}{3M} [\bar{\mathcal{X}} \gamma_\mu \gamma_5 \mathcal{X}] [\bar{q} \gamma_\mu \gamma_5 q] \right] \quad (16)$$

Main Story

- Neutron Star is a very strong Dark Matter Collector.
- Collected DM can build up into extremely high densities.
- **Asymmetric (can't self-annihilate)** DM can turn NSs into Black Holes.
 - Strong constraints for heavy asymmetric dark matter
- **Symmetric** DM, however do self-annihilate
 - Also strong constraints for symmetric DM, with **asymmetric capture**.
 - Work with Zhen Liu, Maxim Pospelov, Sanjay Reddy. arXiv: 2508.04961