# Maximizing Direct Detection with HYPER Dark Matter

Gilly Elor

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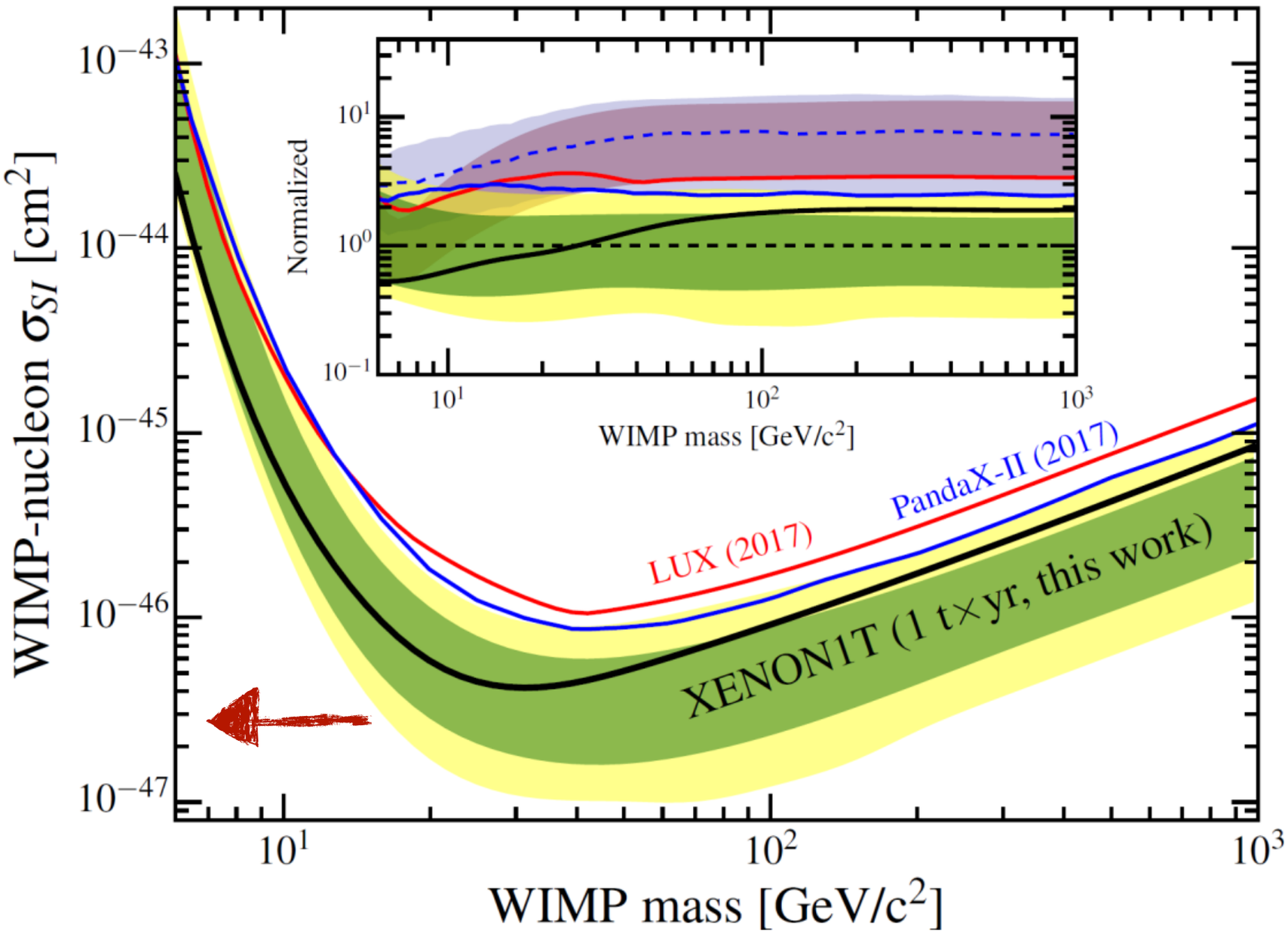
Based on:
[arXiv:2112.03920] with Robert McGehee and Aaron Pierce

# Sub-GeV Dark Matter




XENON Collaboration PRL 121 (2018) no. 11, 111302

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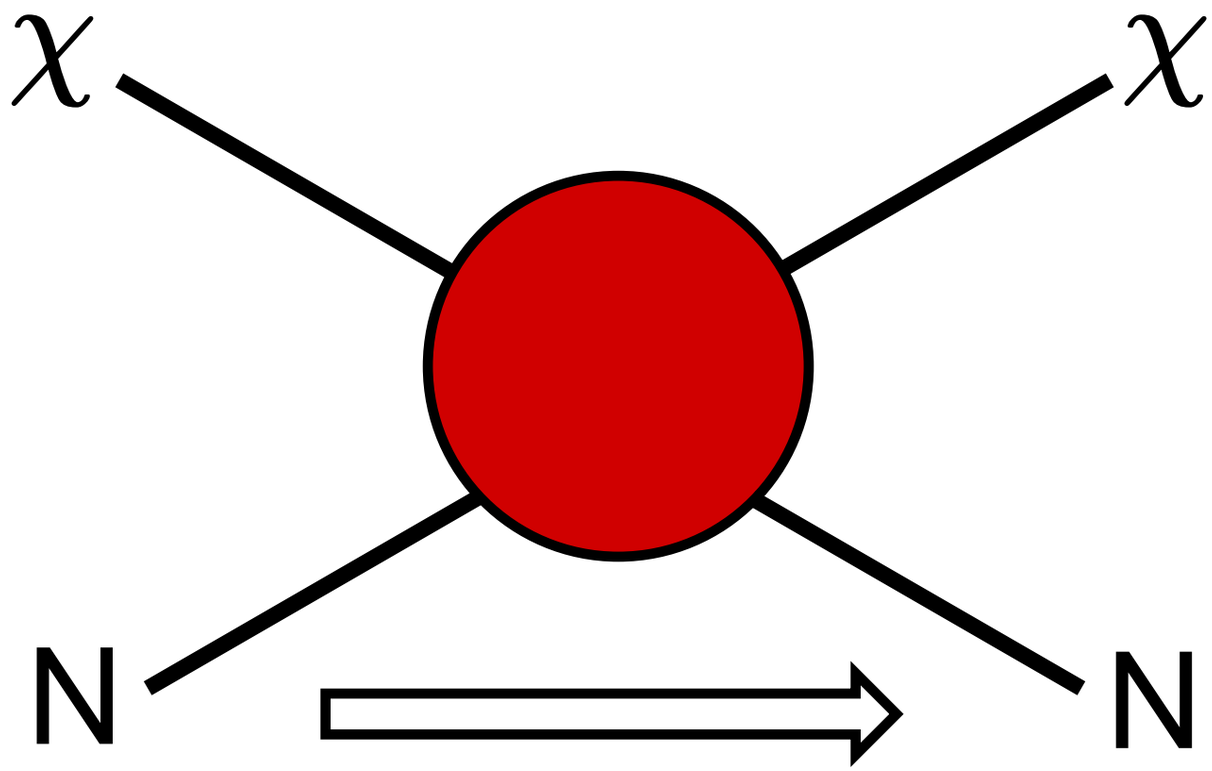
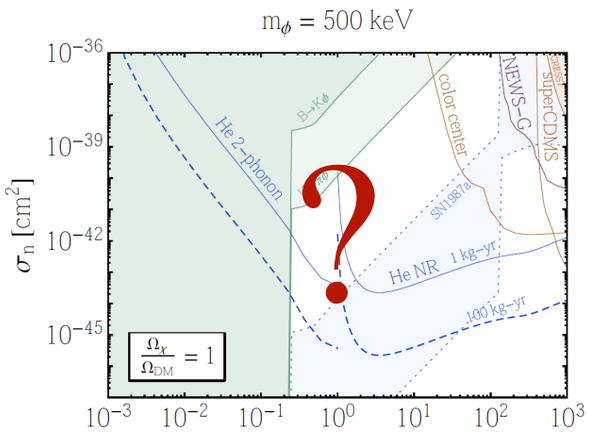
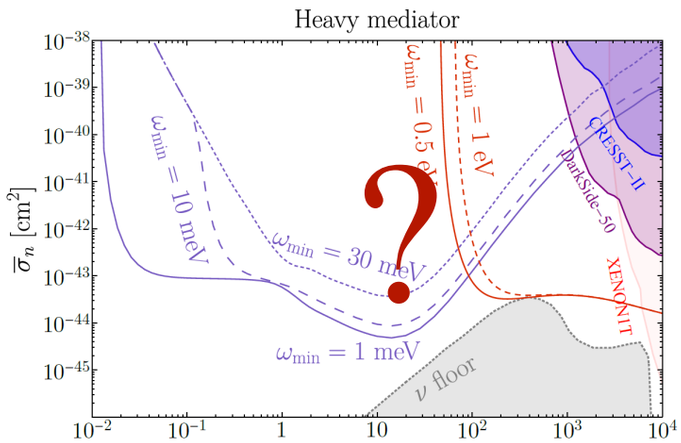
# Dark Matter Direct Detection



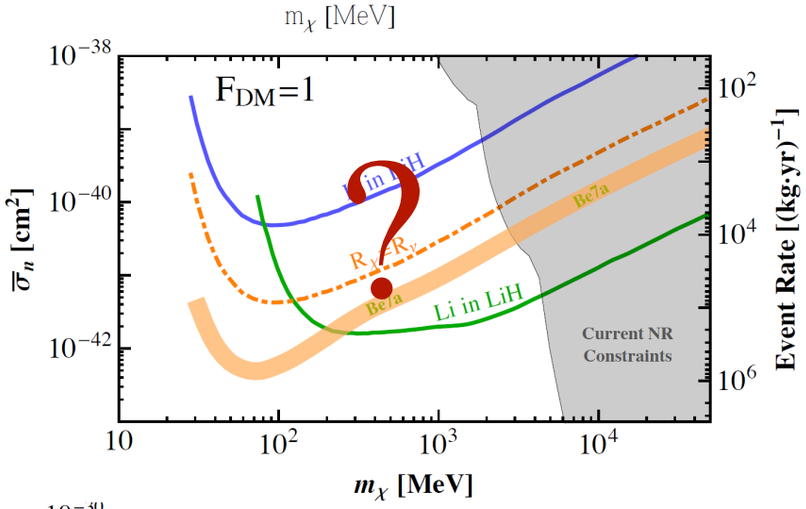
# Where is the Dark Matter?



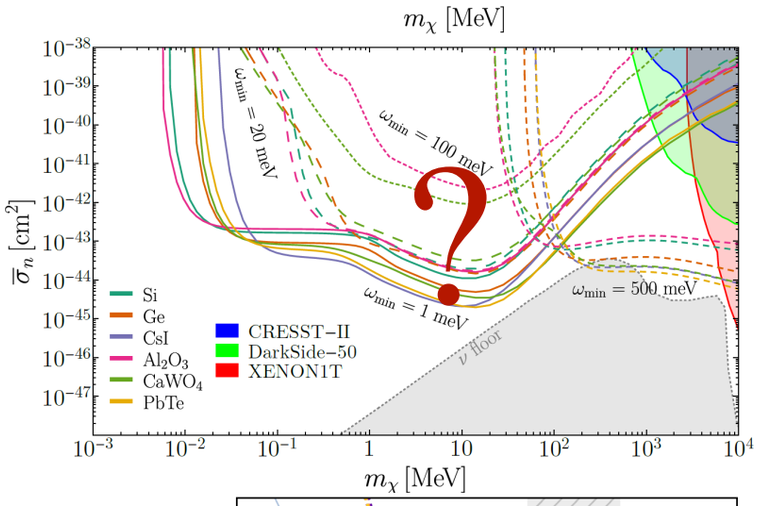

Superfluid Helium
[1611.06228, 1709.07882]

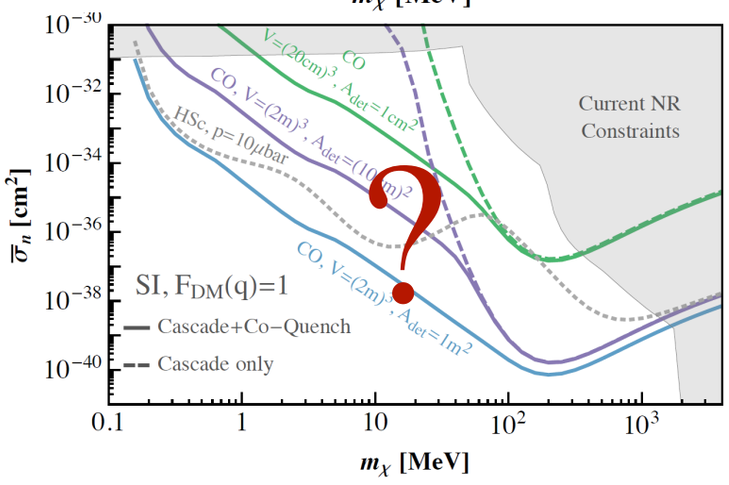



Multiple Channels (recoils, transitions, phonos) [1910.08092, 1910.10716]



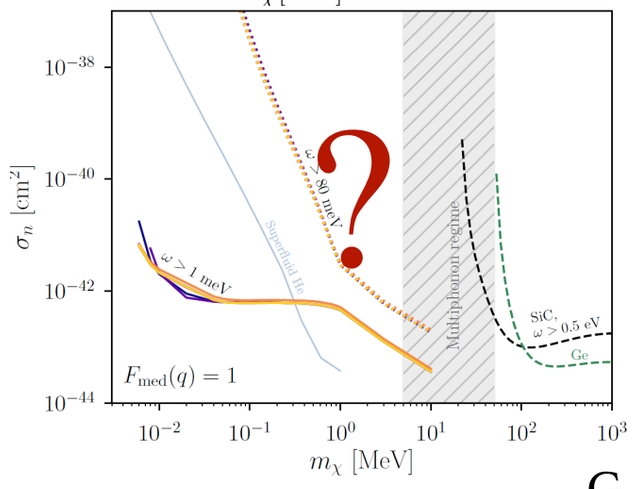

Color Center Production in Crystals [1705.03016]




Molecular Excitations [1907.07682]

Silicon Carbide [2008.08560]

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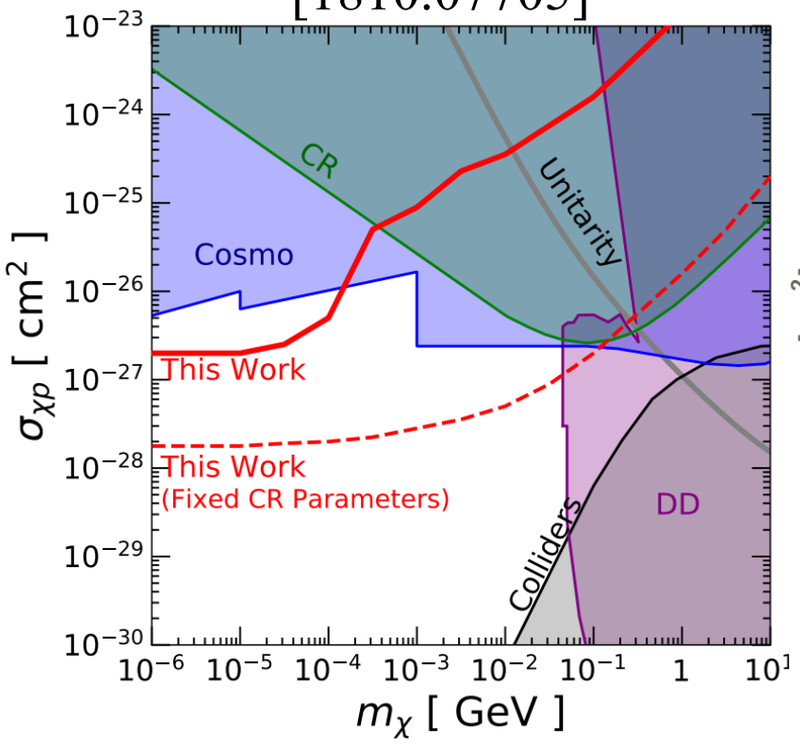
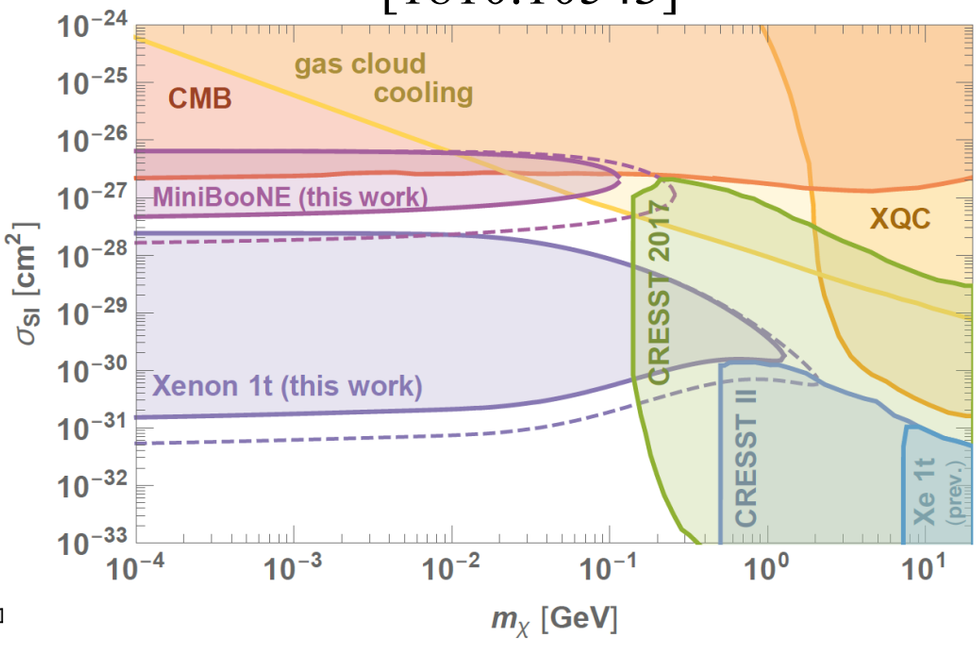
# Bounds from Cosmic Ray Upscattering

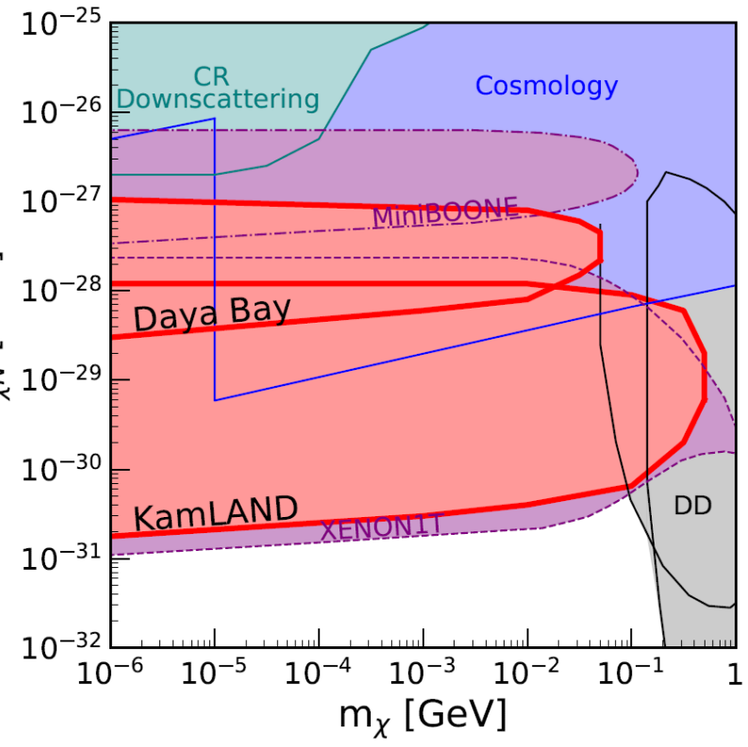
[1810.07705]




[1810.10543]




[1906.11283]




Is such a large cross section even feasible in light of other present day bounds?

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# Part I

# Maximizing Direct Detection

There exists a maximum cross section $\sigma_{\chi n}^{\max}$.

To design experiments targeting larger cross sections is not motivated.

# A Hadrophilic Scalar Mediator

$$\mathcal{L} \supset -m_\chi \bar{\chi}\chi - y_n \phi \bar{n} n - y_\chi \phi \bar{\chi}\chi$$

UV Model: new vector-like quarks at the TeV scale

S. Knapen, T. Lin, K. Zurek [1790.07882]

$$\mathcal{L} \supset \lambda \phi \bar{\psi} \psi \quad \longrightarrow \quad \frac{\alpha_s}{\Lambda} \phi G^{\mu\nu} G_{\mu\nu} \qquad \frac{1}{\Lambda} = \frac{\lambda}{M_\psi} \leftrightarrow \frac{y_n}{m_n}$$

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$$\sigma_{\chi n}^{\max} \equiv \frac{\left(y_n^{\max} y_\chi^{\max}\right)^2}{4\pi} \frac{\mu_{\chi n}^2}{\left[\left(m_\phi^{\min}\right)^2 + v_{\rm DM}^2 m_\chi^2\right]^2}$$

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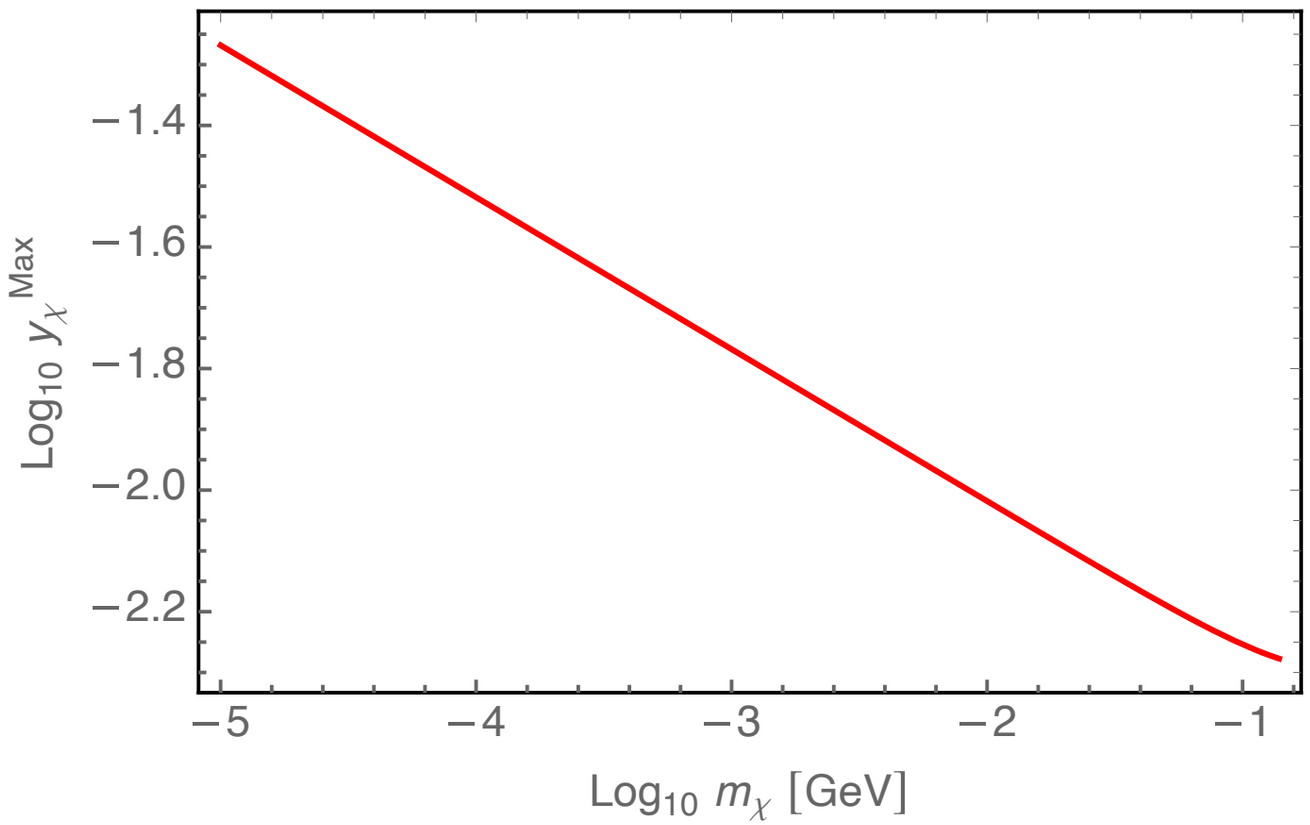
# Estimating $\sigma_{n\chi}^{\max}$

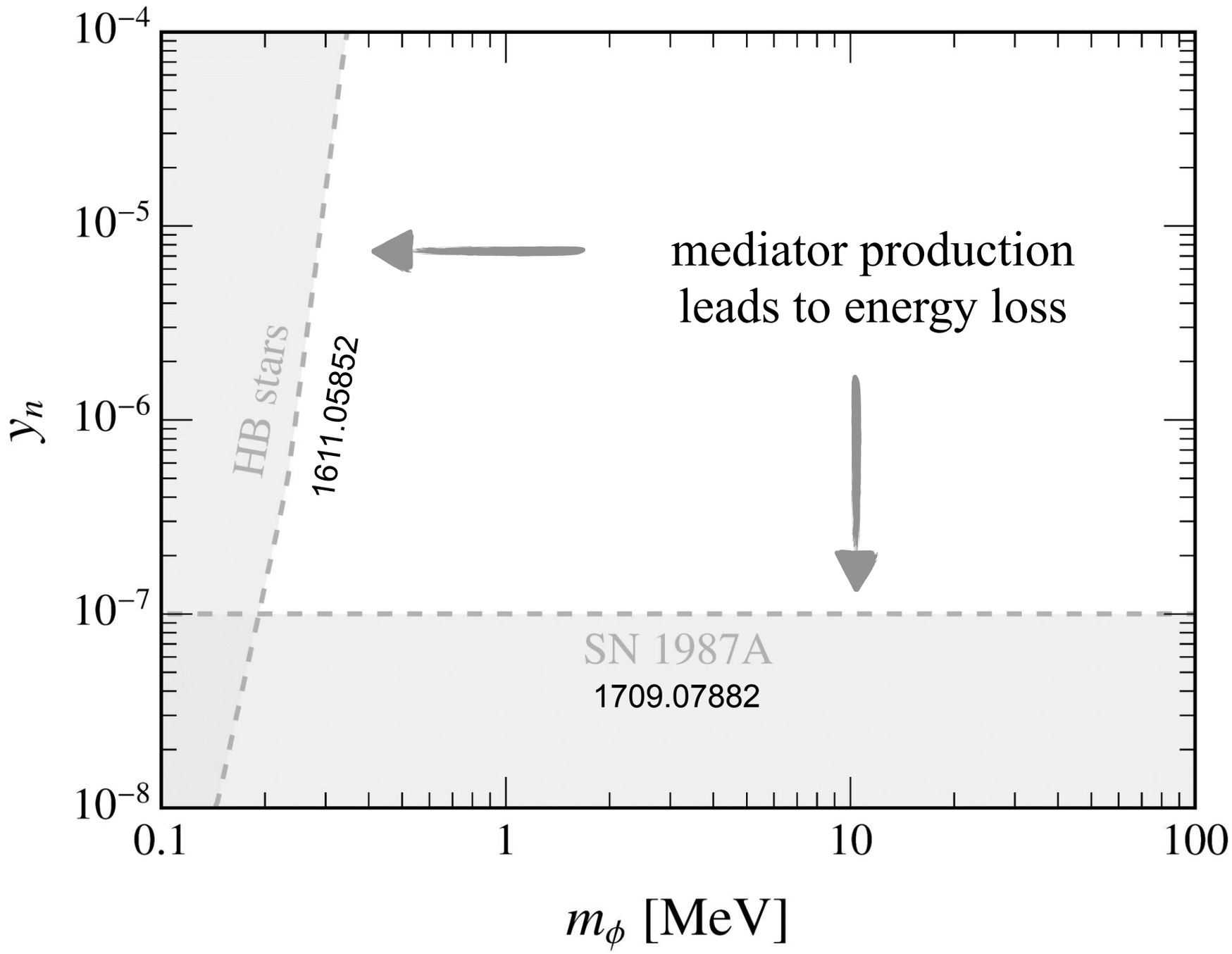
Dark Matter Self Interactions: $\sigma_T^{\rm born} \approx \frac{8\pi\alpha_\chi^2}{m_\chi^2 v^4}\left[\log(1+R^2) - R^2/(1+R^2)\right]$ $\qquad R \equiv m_\chi v/m_\phi$




$\sigma_{\chi\chi}/m_\chi \lesssim 1\ {\rm cm}^2/{\rm g}$
at $v \sim 10^{-3}$

$$\sigma_{\chi n}^{\max} \equiv \frac{\left(y_n^{\max} y_\chi^{\max}\right)^2}{4\pi} \frac{\mu_{\chi n}^2}{\left[\left(m_\phi^{\min}\right)^2 + v_{\rm DM}^2 m_\chi^2\right]^2}$$

# Estimating $\sigma_{n\chi}^{\max}$

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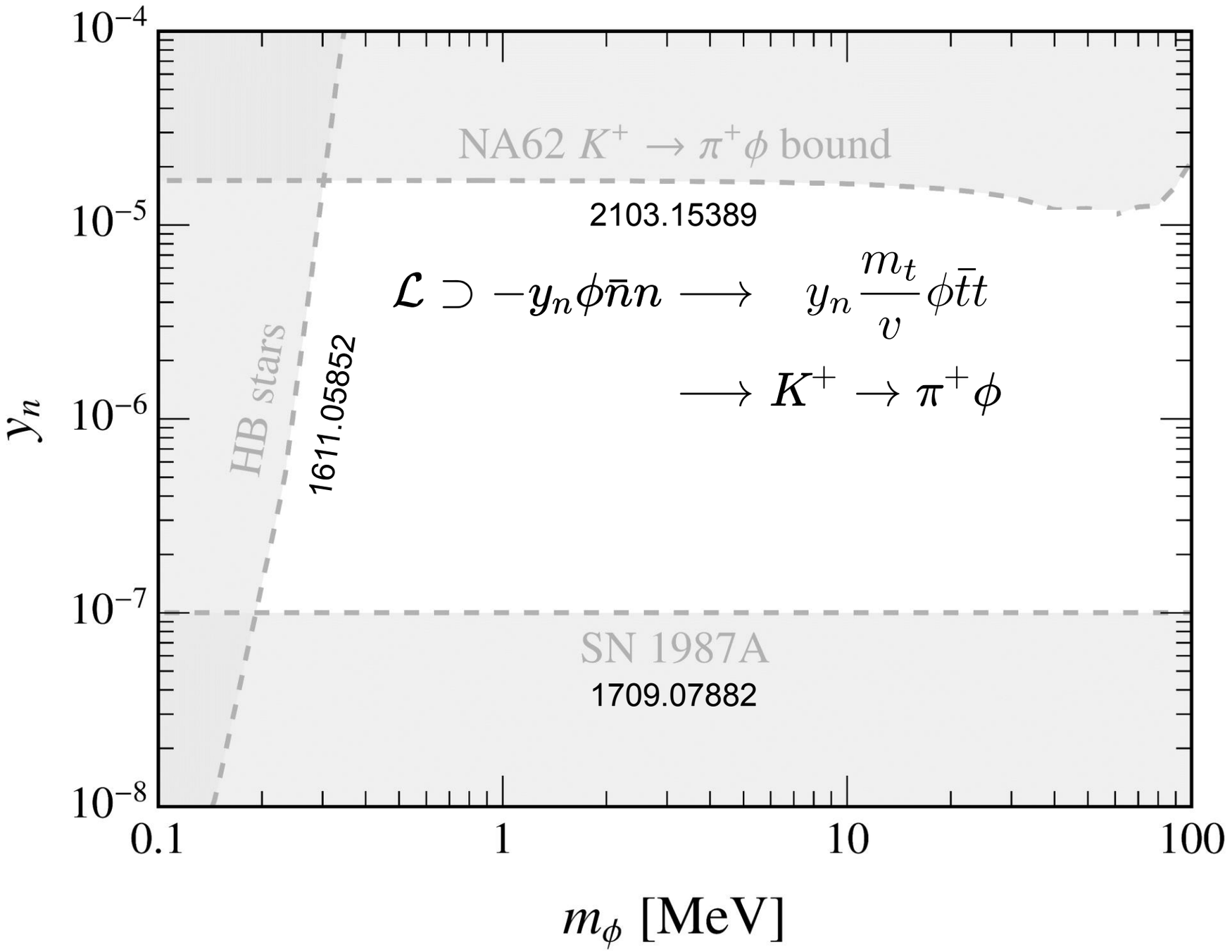

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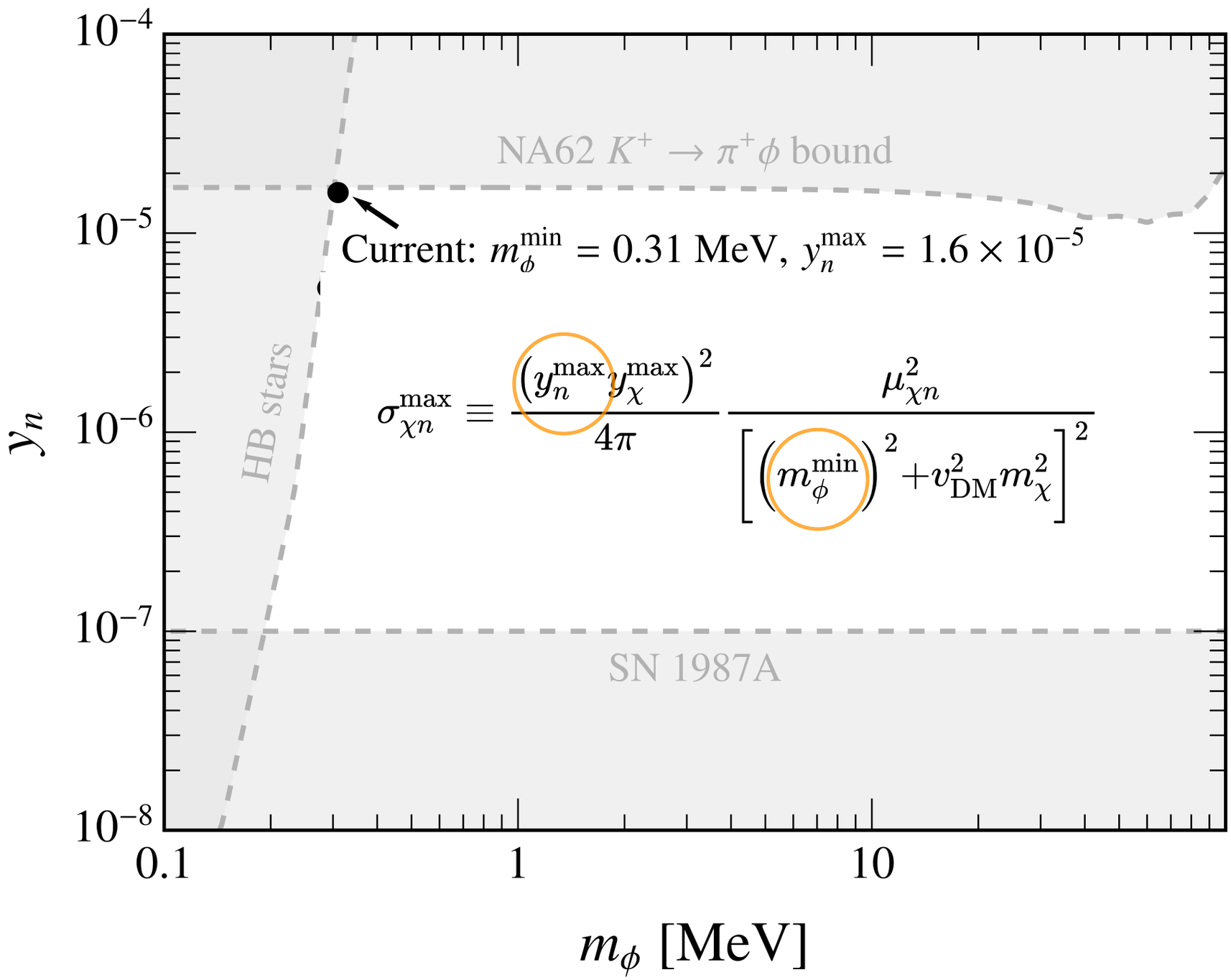


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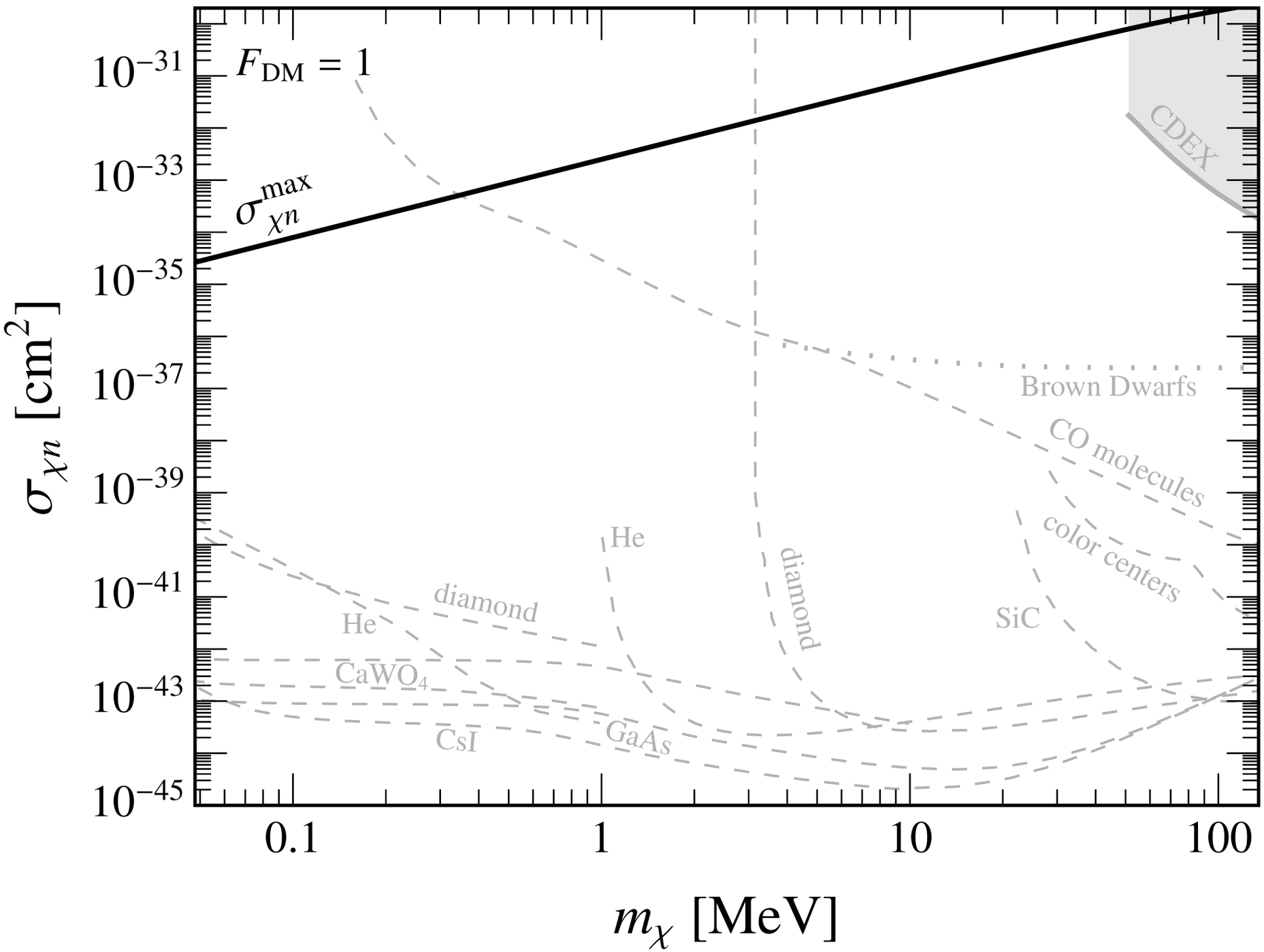

# Bounds from Cosmic Ray Upscattering

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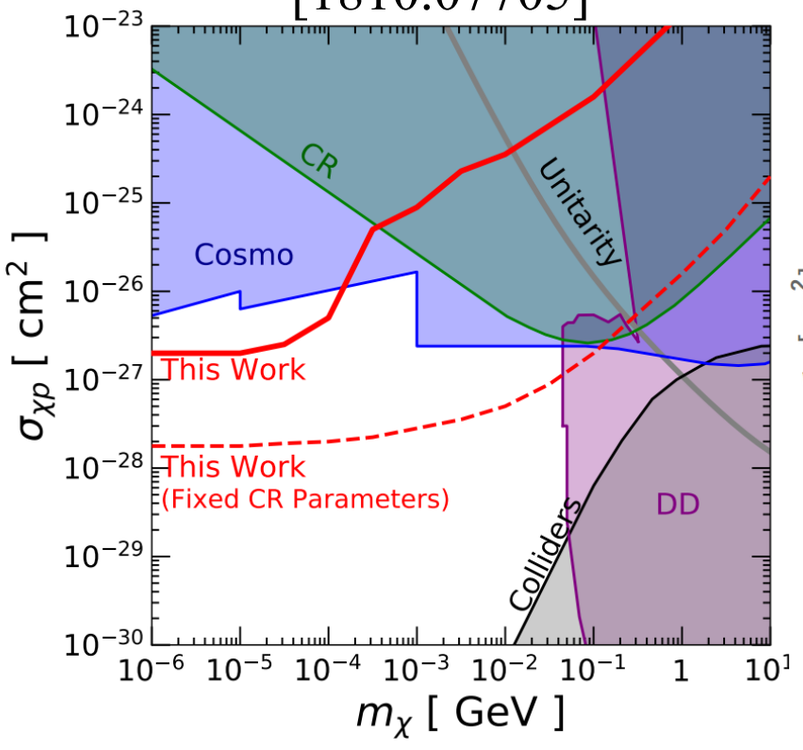


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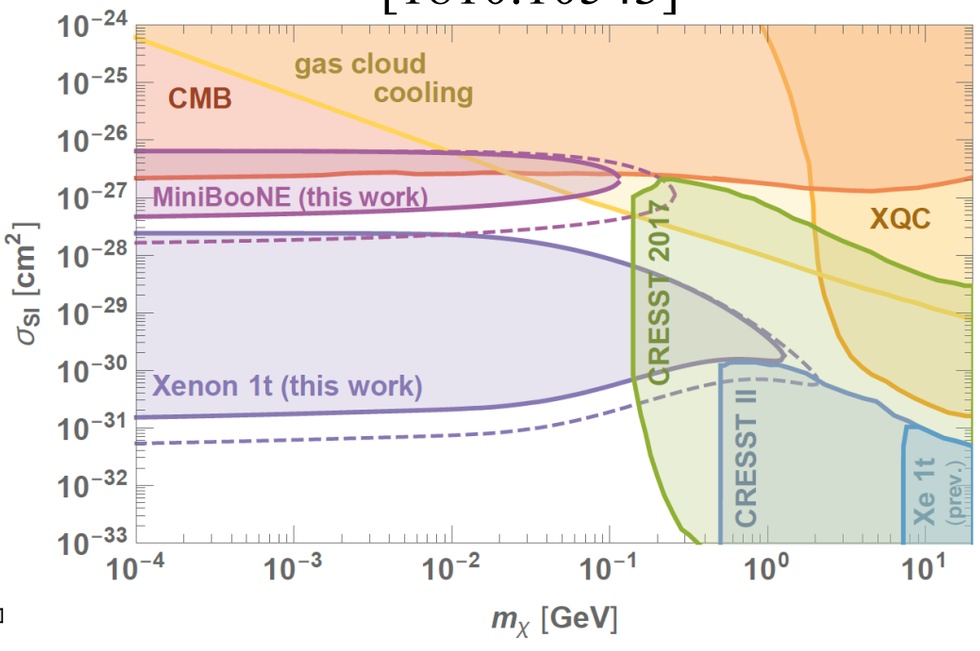


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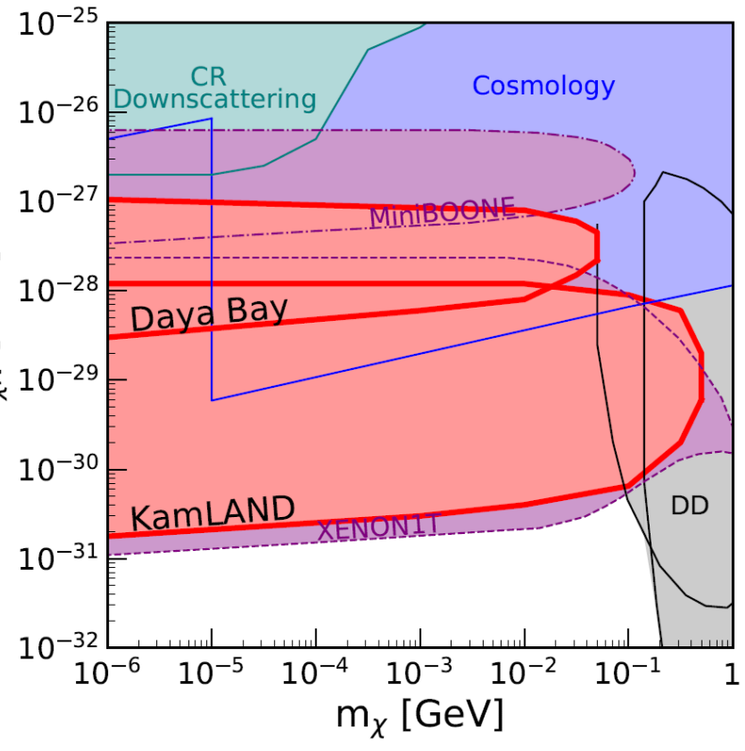


Is such a large cross section even feasible?

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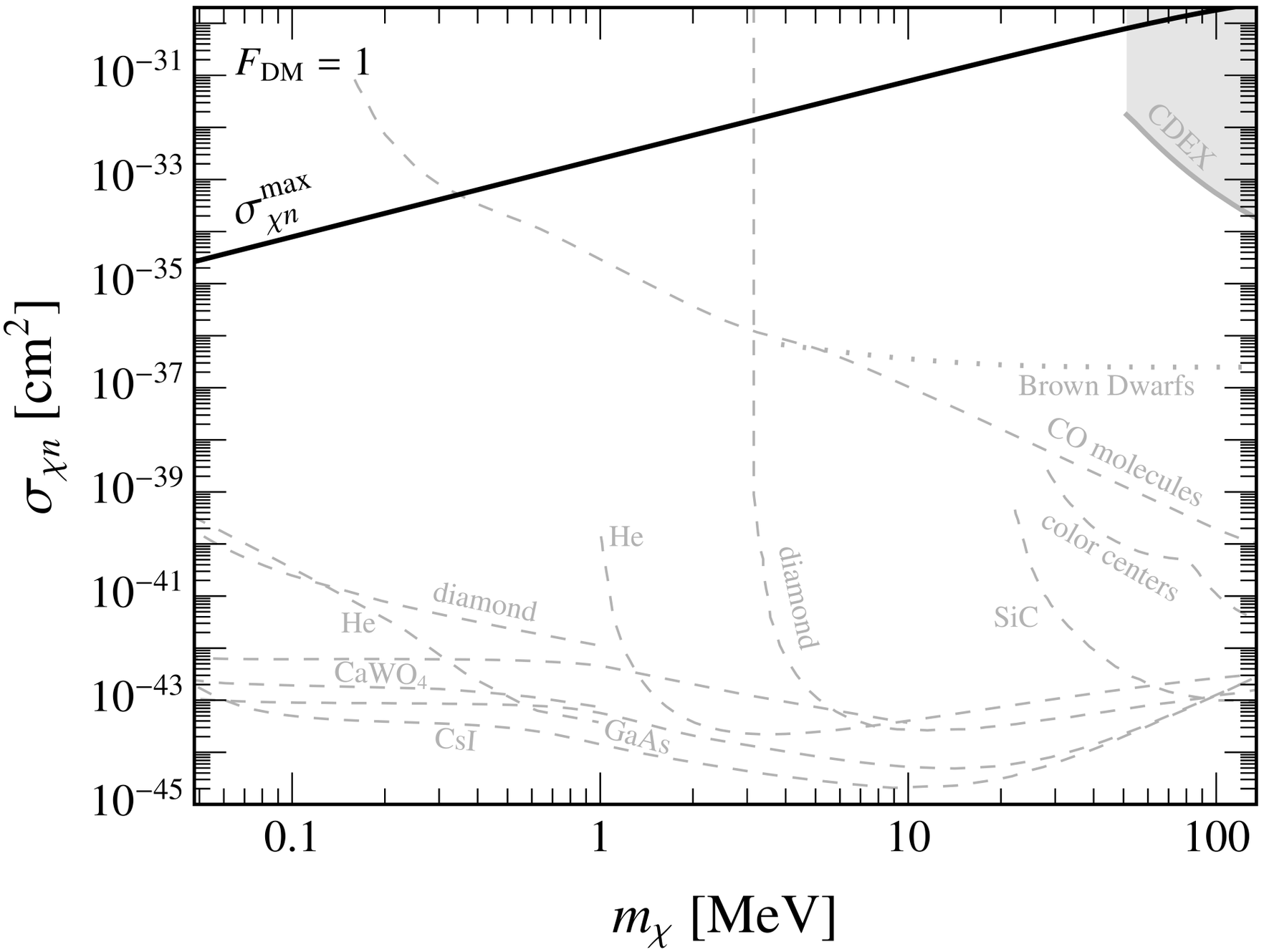
# Bounds from Cosmic Ray Upscattering

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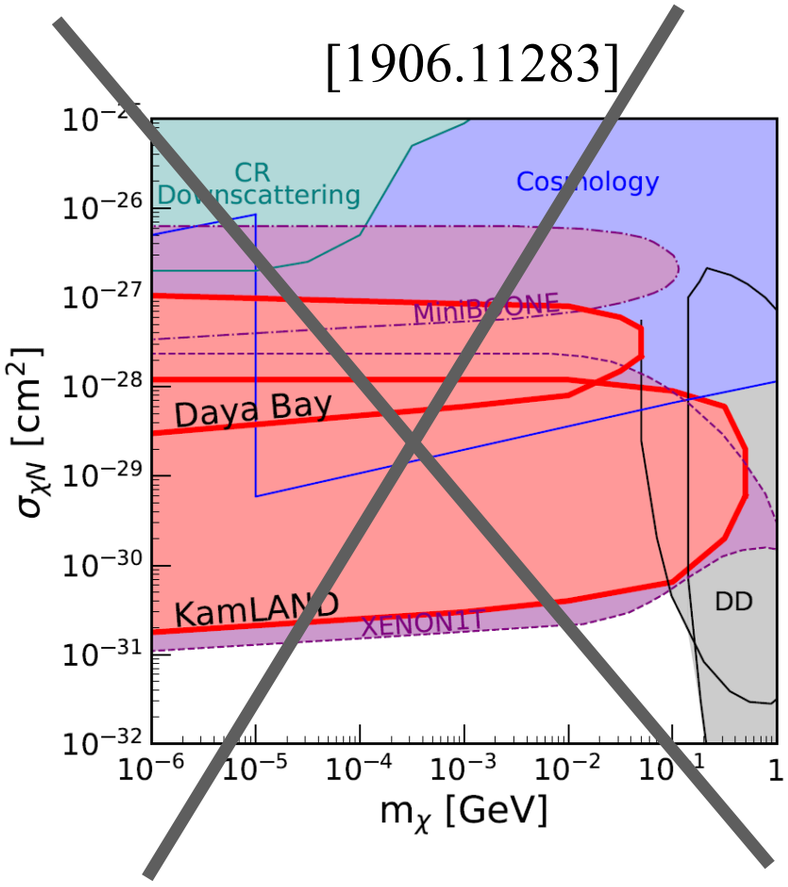


Probably not!

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# Achieving $\sigma_{n\chi}^{\max}$ ?

Is there a sub-GeV dark matter candidate that:

1) may be detected at proposed experiments?

2) may have such a large cross section?

?

$$\sigma_{\chi n}^{\max} \equiv \frac{\left(y_n^{\max} y_\chi^{\max}\right)^2}{4\pi} \frac{\mu_{\chi n}^2}{\left[\left(m_\phi^{\min}\right)^2 + v_{\rm DM}^2 m_\chi^2\right]^2} \qquad \text{and} \qquad \Omega_\chi h^2 = 0.11$$

?

- Large couplings could over-annihilate in the early Universe: $\chi\bar{\chi} \to \phi\phi$, leading to $\Omega_\chi h^2 < 0.1$
- BBN and CMB constrain sub-MeV dark matter with large cross sections.
- Dark matter (and mediators) with MeV mass and large interactions could thermalize the bath and lead to $N_{\rm eff}$ constraints.

# Part II

# Maximizing Direct Detection

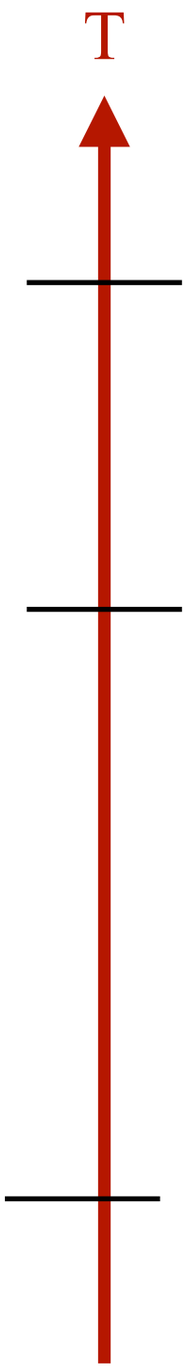
There exists a maximum cross section $\sigma_{\chi n}^{\max}$.
To design experiments targeting larger cross sections is not motivated.

# with HYPER Dark Matter

There exists a model of dark matter that can achieve $\sigma_{\chi n}^{\max}$,
and generally lives in a parameter space upcoming experiments will target.

# HYPERs :

# *HighlY interactive ParticlE Relics*



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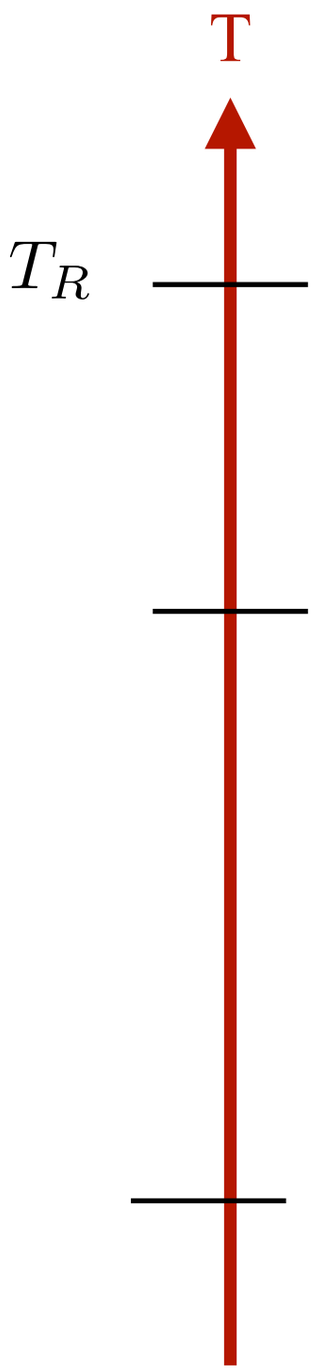


UV Freeze In $\quad \Omega_\chi h^2 = 0.11 \quad \frac{\alpha_s y_\chi y_n}{2.6\, m_n (m_\phi^i)^2} \chi\bar{\chi} G^{a,\,\mu\nu} G^a_{\mu\nu}$

$m_\phi^i > T_R$

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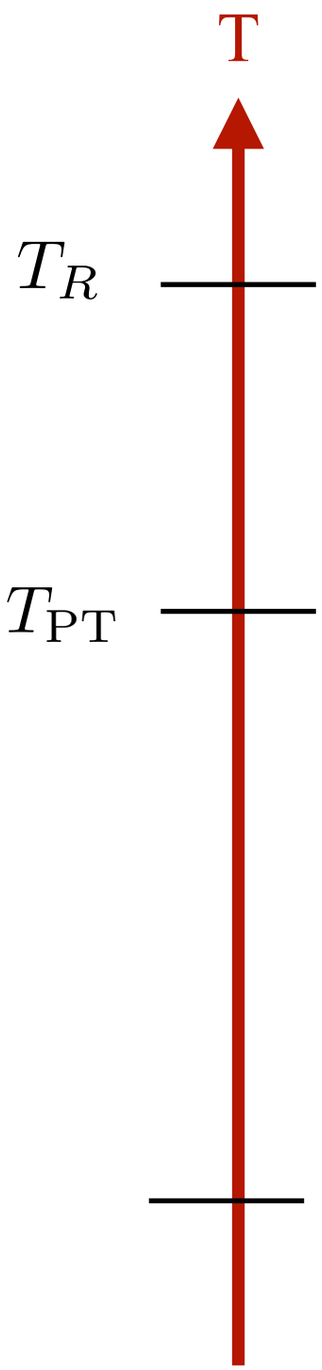


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Dark Sector Phase Transition

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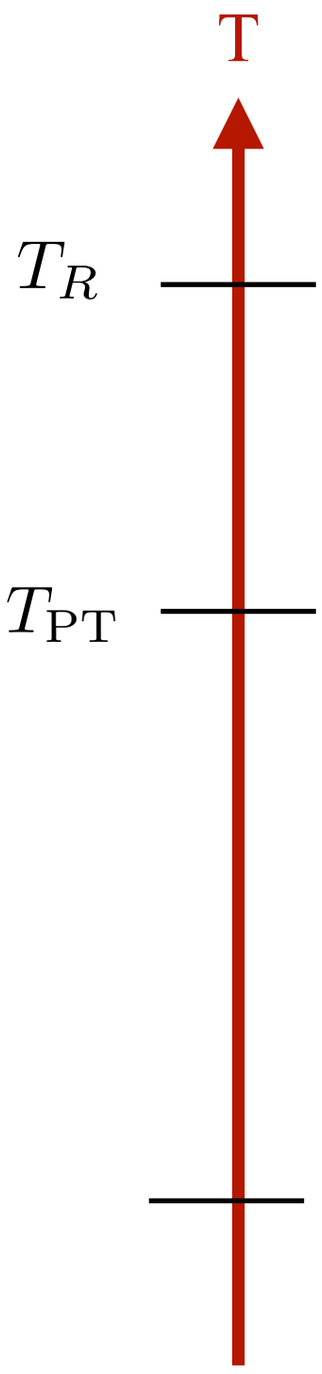


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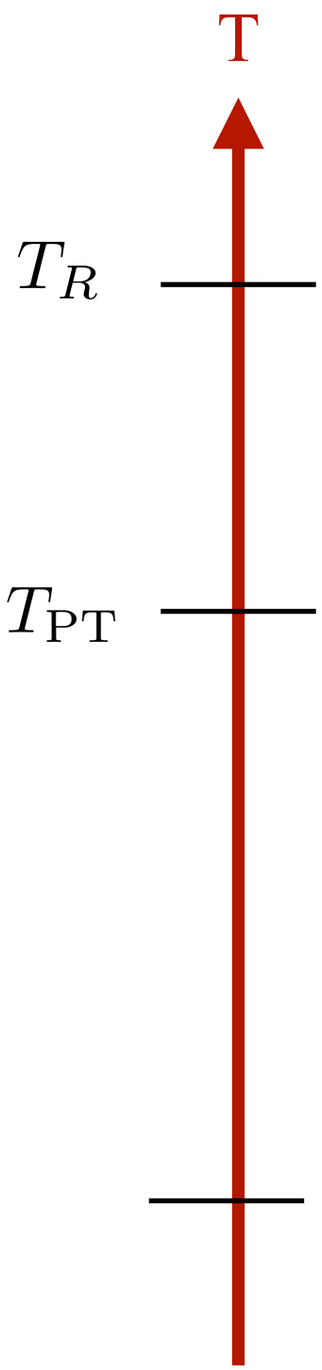
$m_\phi^i > T_R$

Dark Sector Phase Transition

Can change the dark matter mass e.g:

The Flip Flop vev [1608.07578,1912.02830]
D. Croon, G. Elor, R. Houtz, H. Murayama, G. White [2012.15284]
T. Cohen, D. Morrissey, A. Pierce [0808.3994]
And many more

# HYPERs :
# *HighlY interactive ParticlE Relics*

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$m_\phi^i > T_R$

Dark Sector Phase Transition

For HYPERs the *mediator* mass changes

$$m_\phi^i \to m_\phi \ll m_\phi^i$$

# HYPERs :

# *HighlY interactive ParticlE Relics*

T

$T_R$ — UV Freeze In $\Omega_\chi h^2 = 0.11$ $\frac{\alpha_s y_\chi y_n}{2.6\, m_n (m_\phi^i)^2} \chi\bar{\chi} G^{a,\,\mu\nu} G^a_{\mu\nu}$

$m_\phi^i > T_R$

$T_{\rm PT}$ — Dark Sector Phase Transition

For HYPERs the *mediator* mass changes

$$m_\phi^i \to m_\phi \ll m_\phi^i$$

Today — Direct detection cross section grows! $\left(m_\phi^i/m_\phi\right)^4$

G. Elor

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$T_R$ — UV Freeze In $\quad \Omega_\chi h^2 = 0.11 \quad \frac{\alpha_s y_\chi y_n}{2.6\, m_n (m_\phi^i)^2} \chi\bar{\chi} G^{a,\,\mu\nu} G^a_{\mu\nu}$

$m_\phi^i > T_R$

$T_{\rm PT}$ — Dark Sector Phase Transition

For HYPERs the *mediator* mass changes

$$m_\phi^i \to m_\phi \ll m_\phi^i$$

Dark matter relic abundance must not change.
BBN and CMB must be unaffected

Today — Direct detection cross section grows! $\quad \left(m_\phi^i / m_\phi\right)^4$

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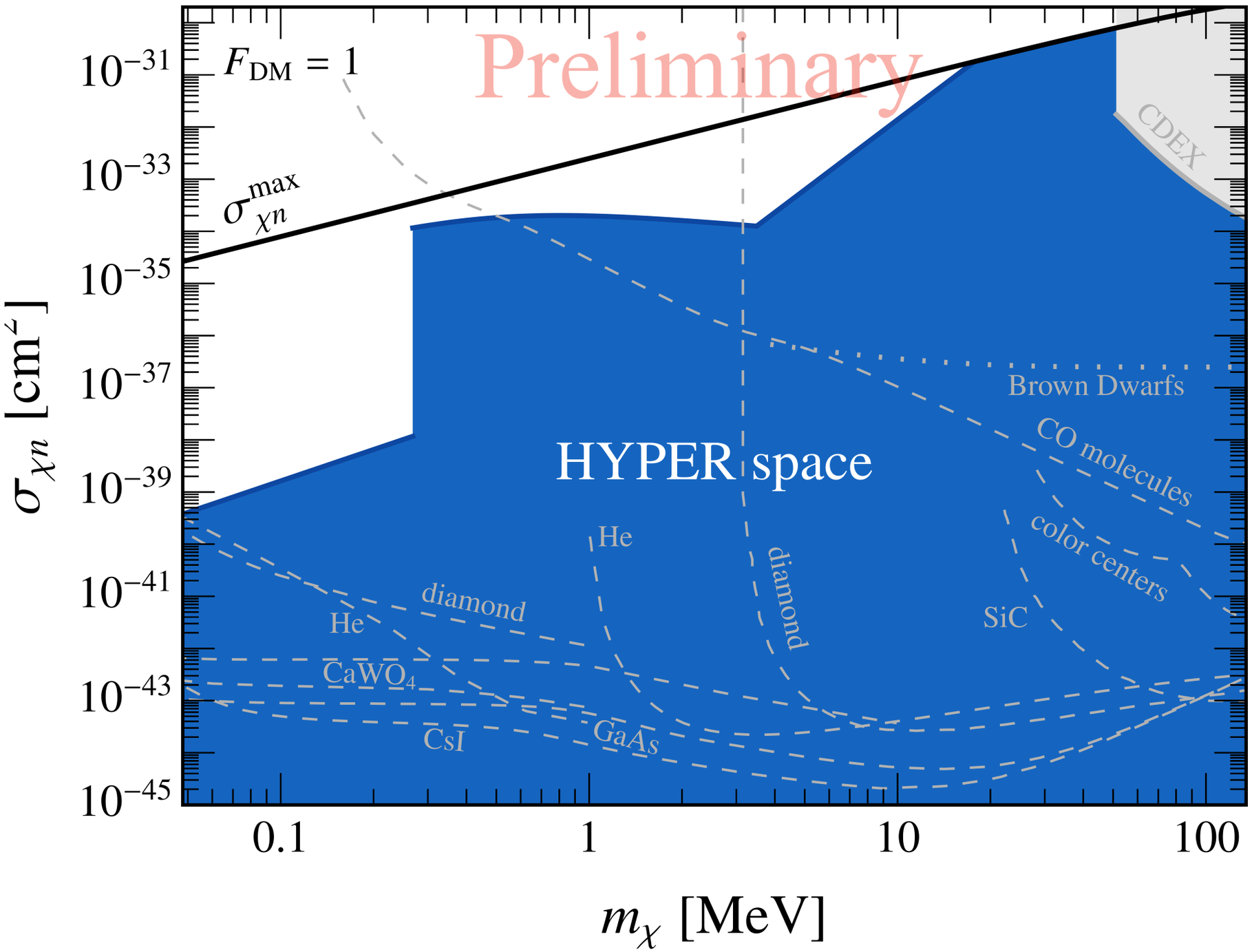
# Achieving $\sigma_{n\chi}^{\max}$ with HYPERs

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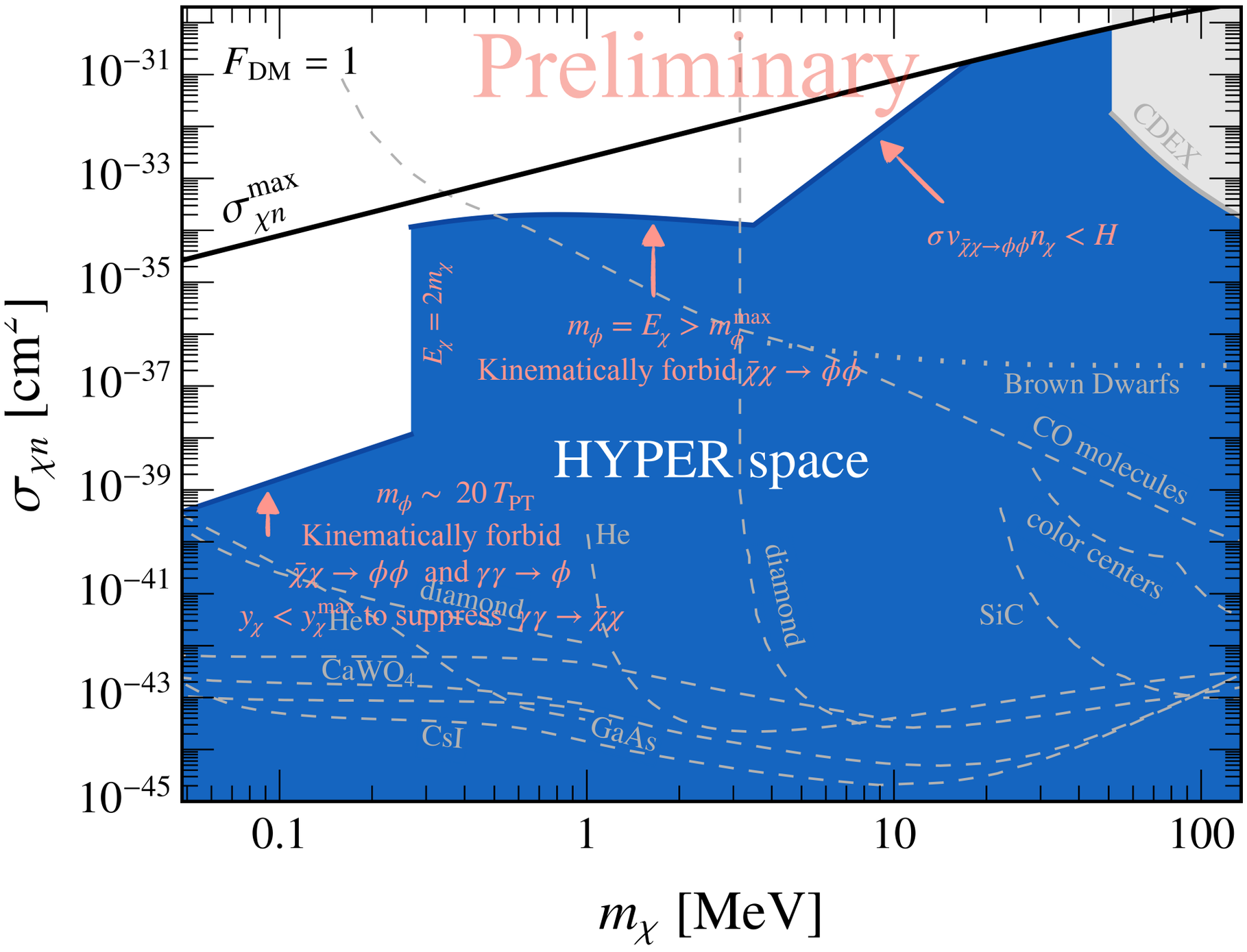


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# Summary

- Given present day constraints, it is unmotivated to think about cross sections larger than

$$\sigma_{\chi n} \lesssim 10^{-36} - 10^{-30}\,\mathrm{cm}^2 \qquad \text{for} \qquad 10\,\mathrm{keV} < m_\chi < 100\,\mathrm{MeV}$$

- It is not easy to find a dark matter model that realizes such large cross sections, or in general live in the parameter space of interest to proposed light dark matter direct detection experiments. However, HYPERs is one such candidate.

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# Thanks!

# Back ups

# Outlook/Future Directions

- Derive $\sigma_{\chi e}^{\max}$ and leptophilic HYPER models! Would likely require $T_{\rm PT} \lesssim m_e$
- Fully explore the HYPER space of the hadrophilic hyper model. Perhaps considering vector mediators as well.
- Details of the dark sector phase transition.
- And many more

# Robustness of $\sigma_{n\chi}^{\max}$ ?

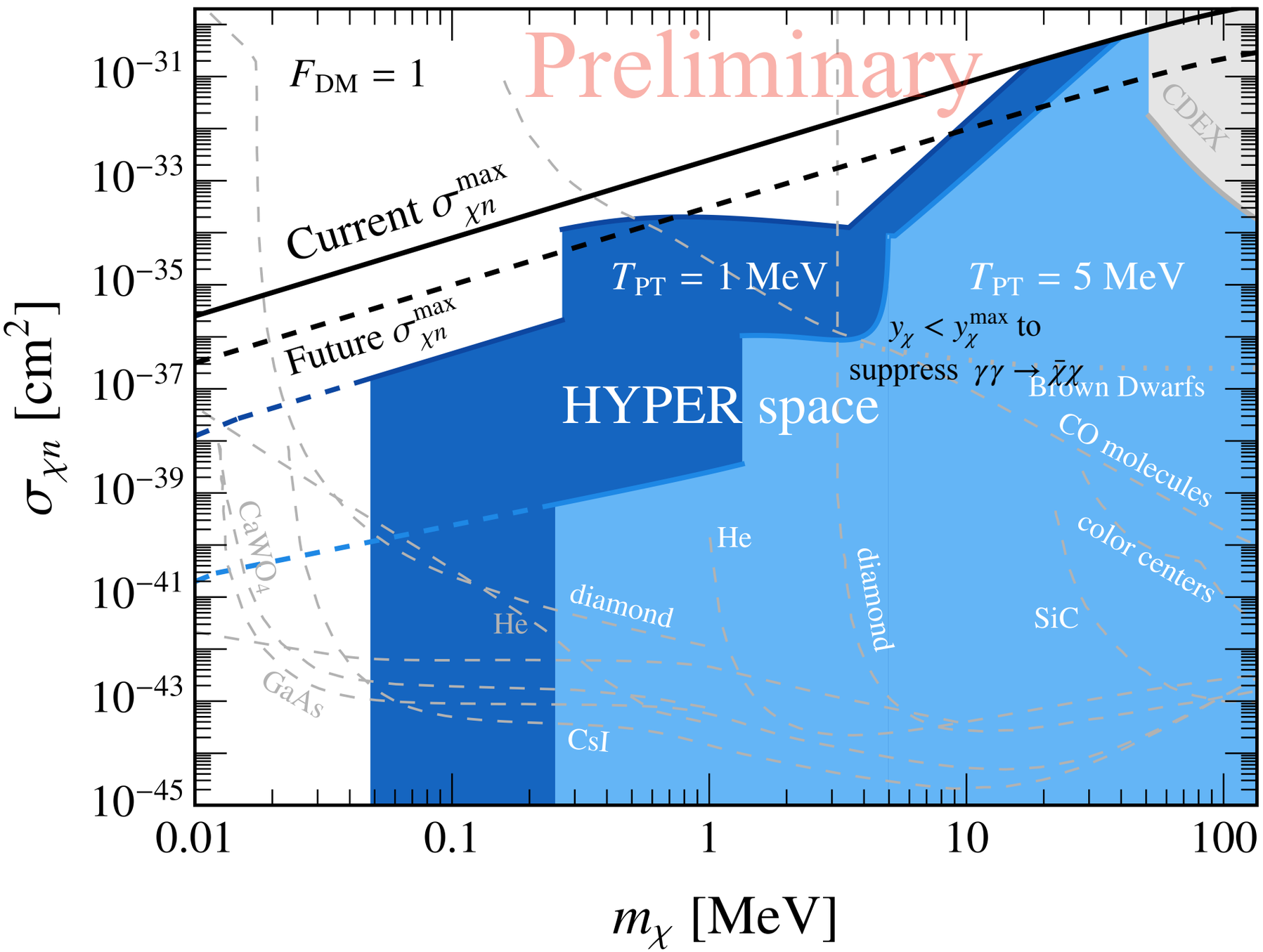
Is $\sigma_{n\chi}^{\max}$ for the Hydrophilic scalar model the $\sigma_{n\chi}^{\max}$ ?

$$\mathcal{L} \supset \lambda \phi \bar{\psi} \psi \quad \rightarrow \quad \frac{\alpha_s}{\Lambda} \phi G^{\mu\nu} G_{\mu\nu}$$

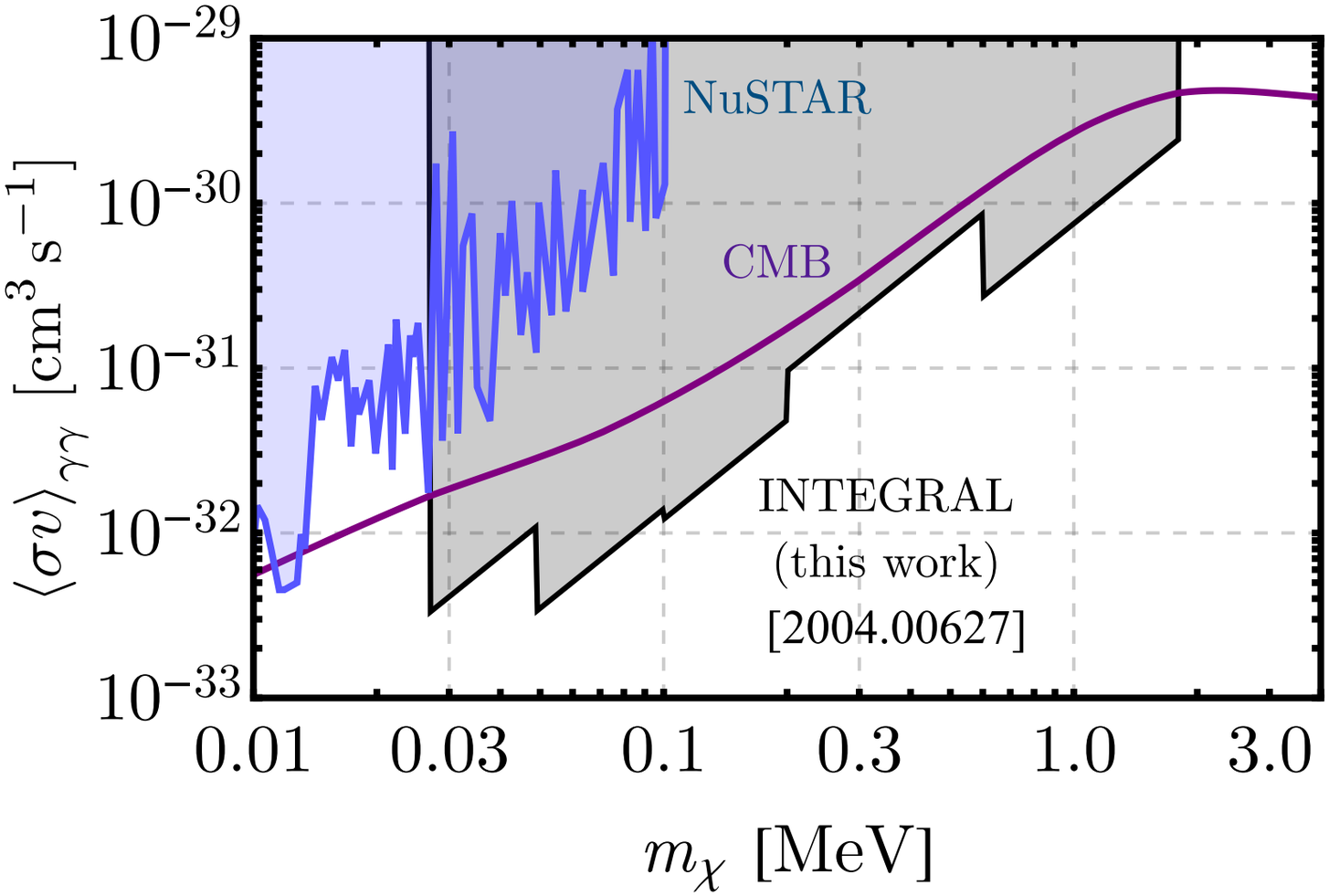
$$\rightarrow \quad \mathcal{L} \supset \; - m_\chi \bar{\chi} \chi - y_n \phi \bar{n} n - y_\chi \phi \bar{\chi} \chi$$

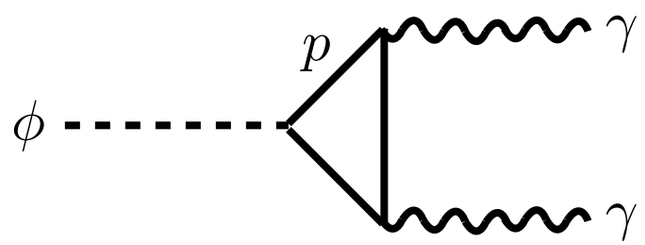
- Hadrophilic scalar with different UV completion e.g. mediator couples directly to quarks → Meson bounds are more constraining → smaller $\sigma_{n\chi}^{\max}$.
- Visibly decaying dark photon? Beam dump and collider constraints make $\sigma_{n\chi}^{\max}$ smaller.

# Achieving $\sigma_{n\chi}^{\max}$ with HYPERs



# Indirect Detection $\chi\bar{\chi} \to \gamma\gamma$




$$\mathcal{L} \supset \frac{\alpha y_n}{6\pi m_p}\phi F_{\mu\nu}F^{\mu\nu}$$

$$\sigma v_{\rm ann} = \frac{1}{32\pi}\left(\frac{2\alpha y_n^{\rm max} y_\chi^{\rm max}}{3\pi m_p}\right)^2 \frac{s\left(s-4m_\chi^2\right)}{\left(s-(m_\phi^{\rm min})^2\right)^2} \sim 10^{-44}{\rm cm}^3{\rm s}^{-1}$$