Maximizing Direct Detection with HYPER Dark Matter

Gilly Elor

MITP, JGU

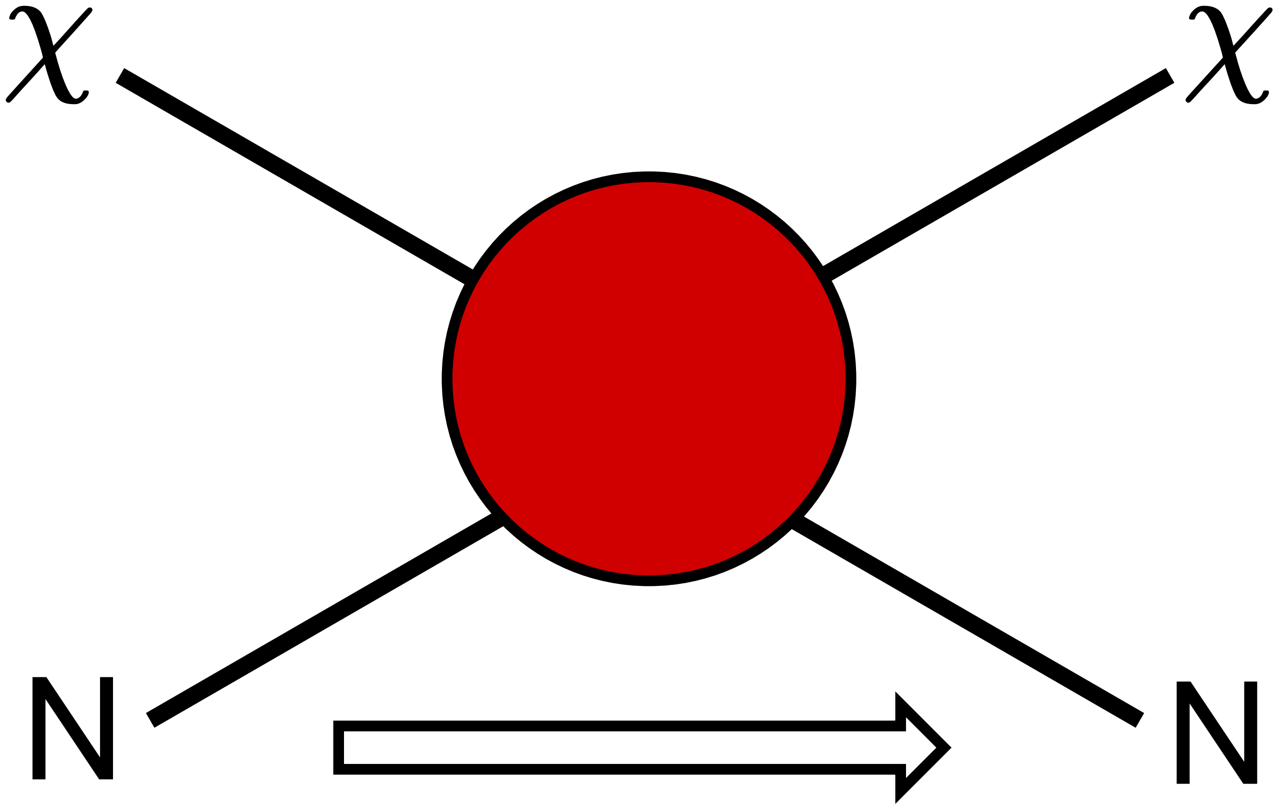
Based on:

soon to be posted work with Robert McGehee and Aaron Pierce

Dark Matter Direct Detection

Credit: The XENON Experiment

Dark Matter Direct Detection



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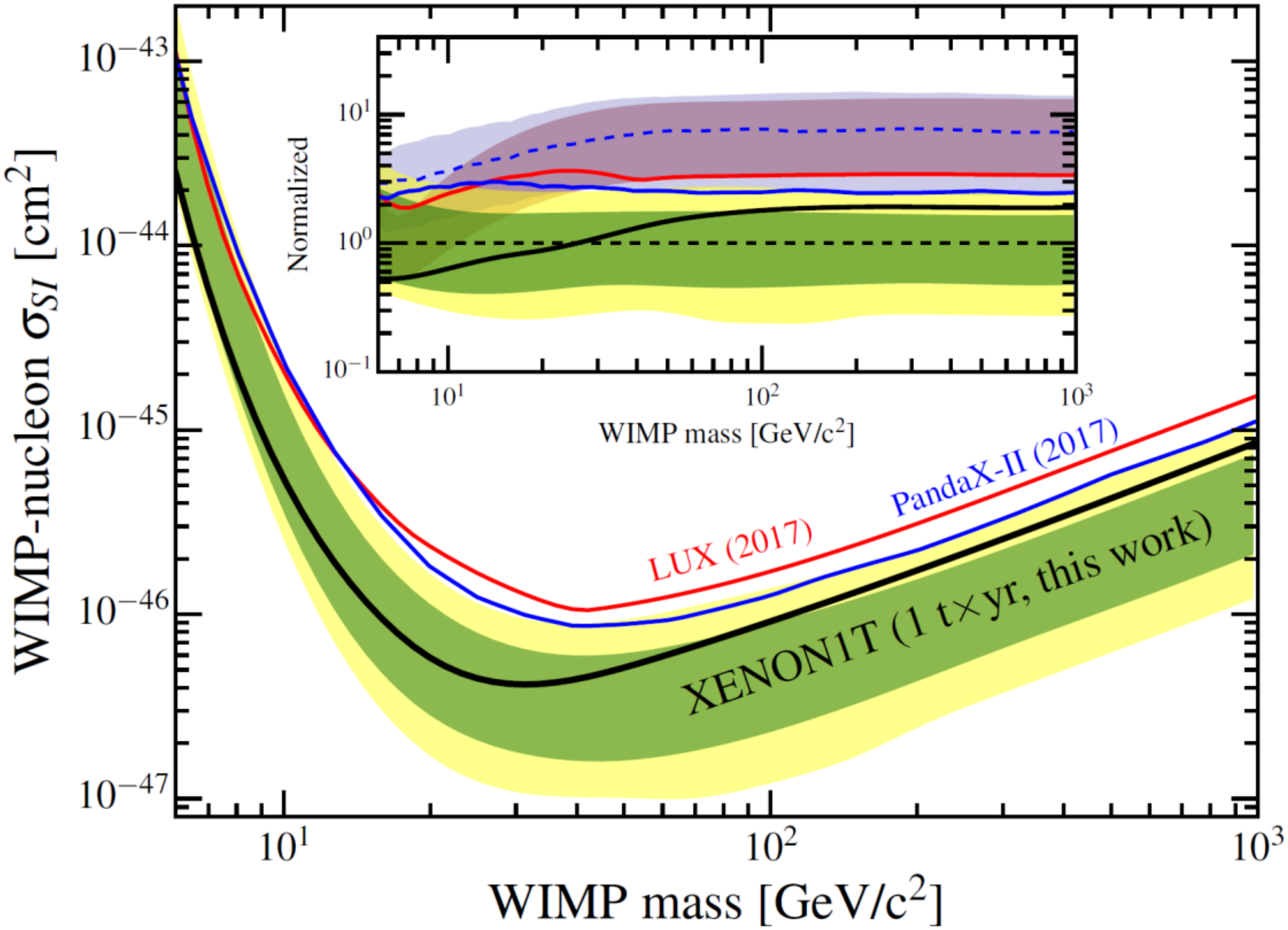
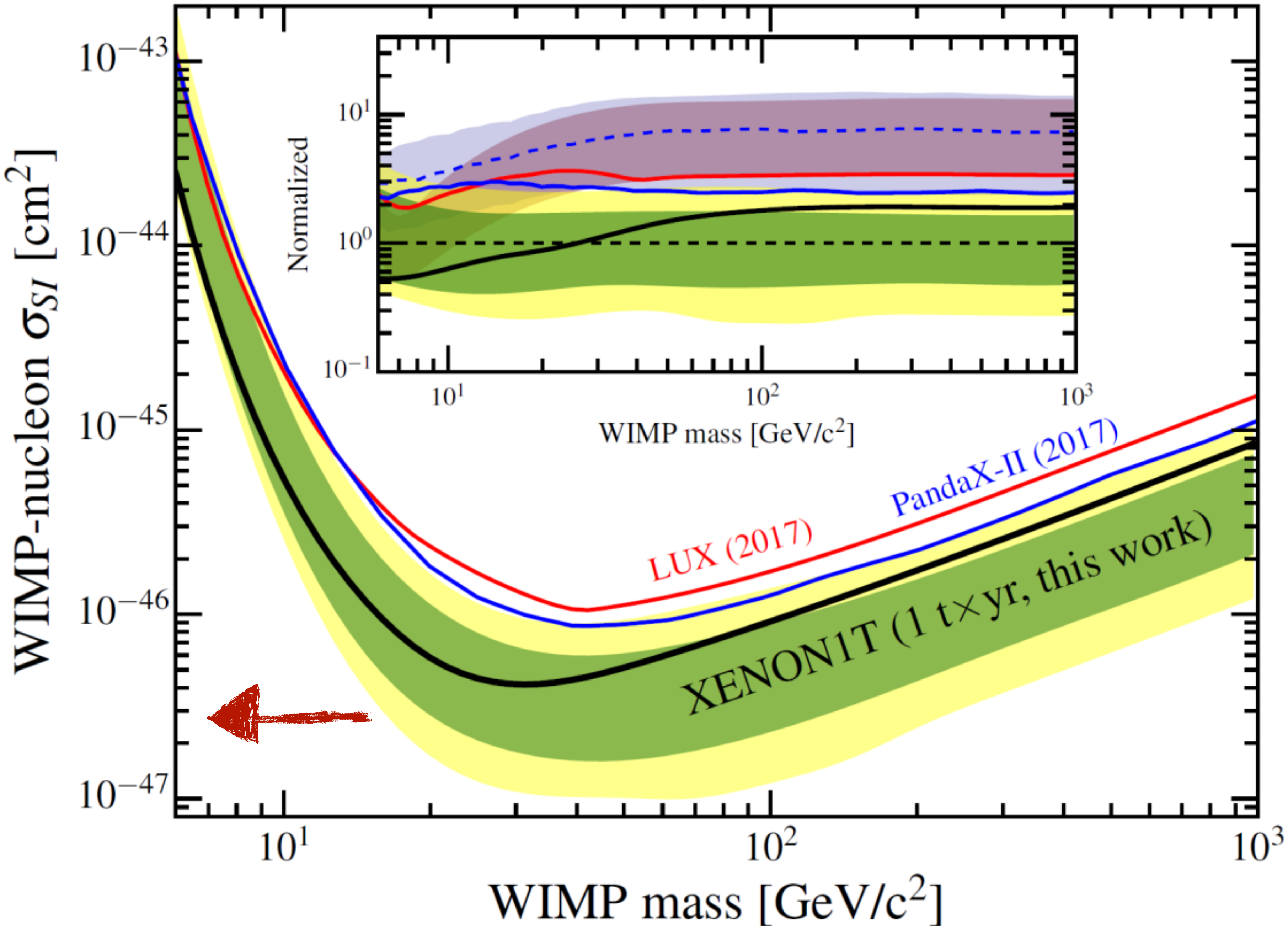
WIMP Dark Matter



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

G. Elor

Sub-GeV Dark Matter



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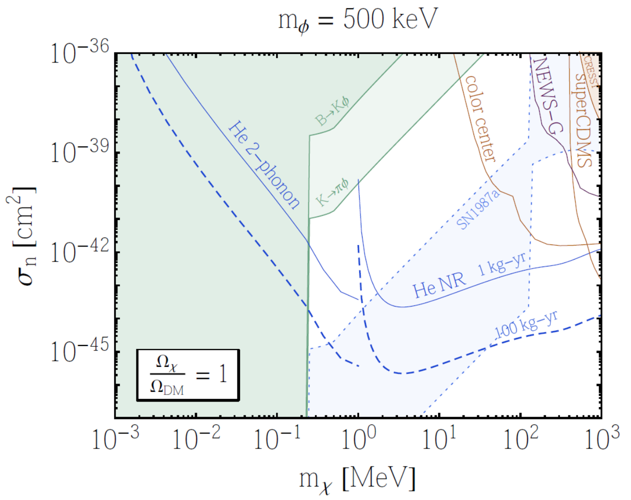
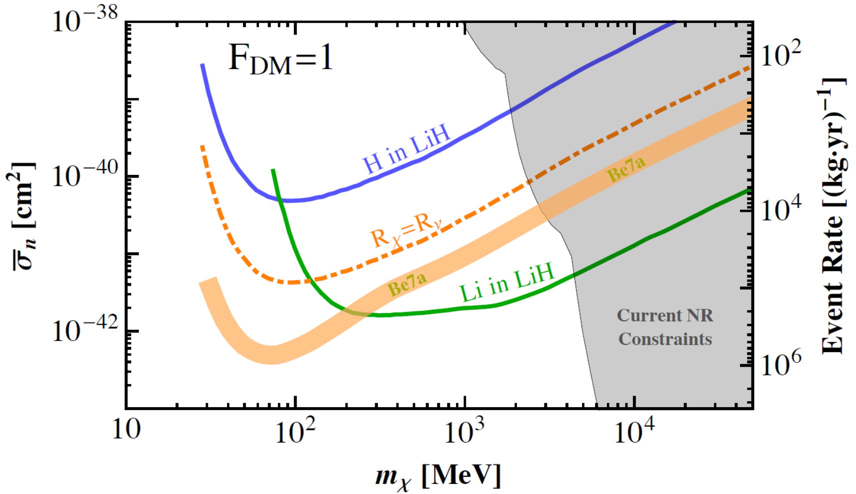
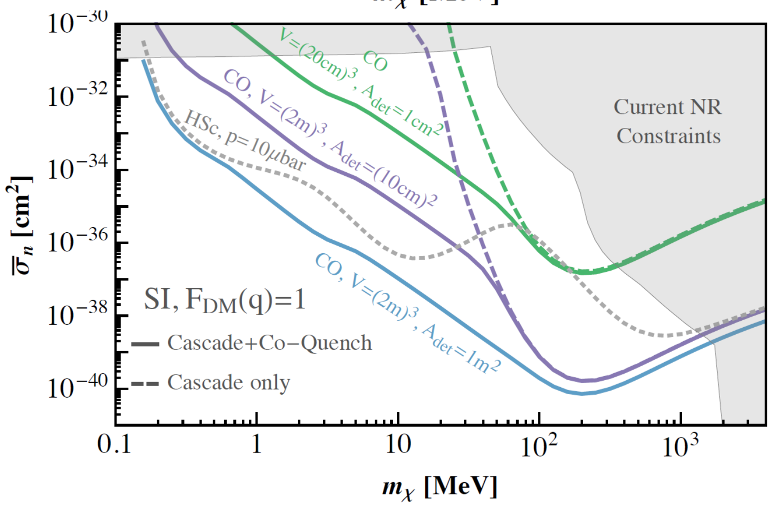


Superfluid Helium
[1611.06228, 1709.07882]



Color Center
Production in
Crystals
[1705.03016]



Molecular
Excitations
[1907.07682]

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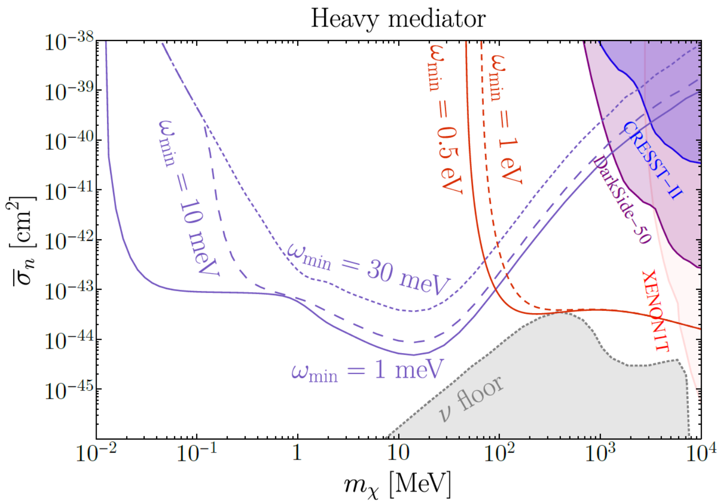
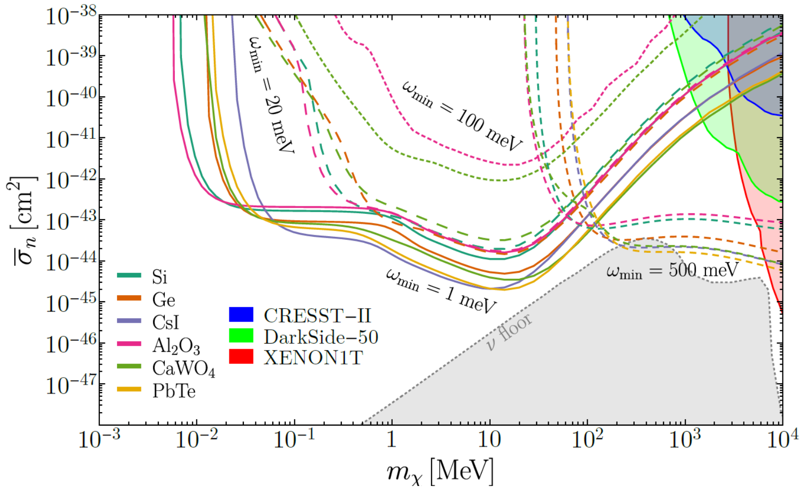
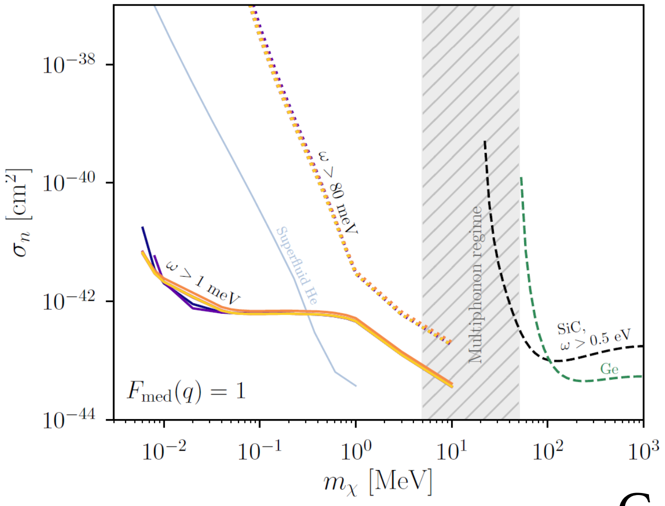
[1910.08092,
1910.10716]





Silicon Carbide
[2008.08560]



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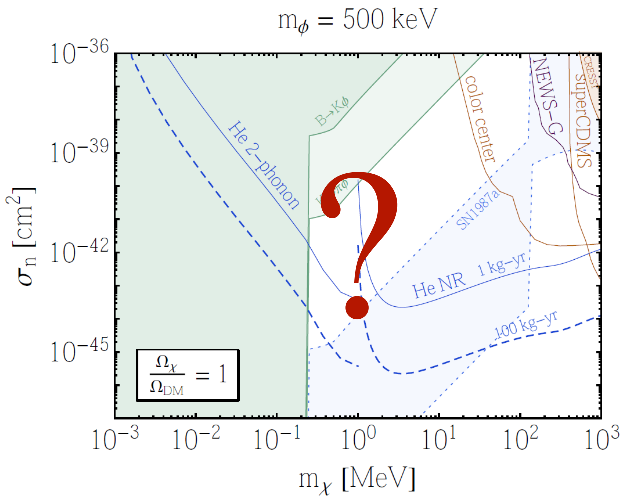
Where is the Dark Matter?



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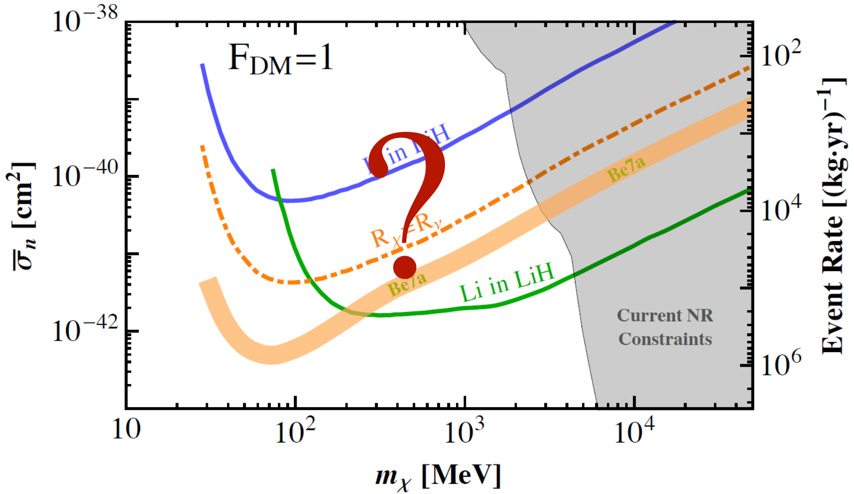

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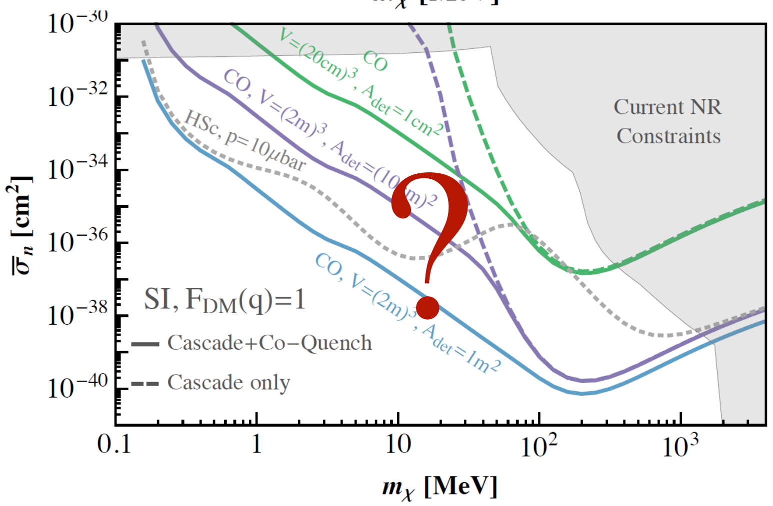

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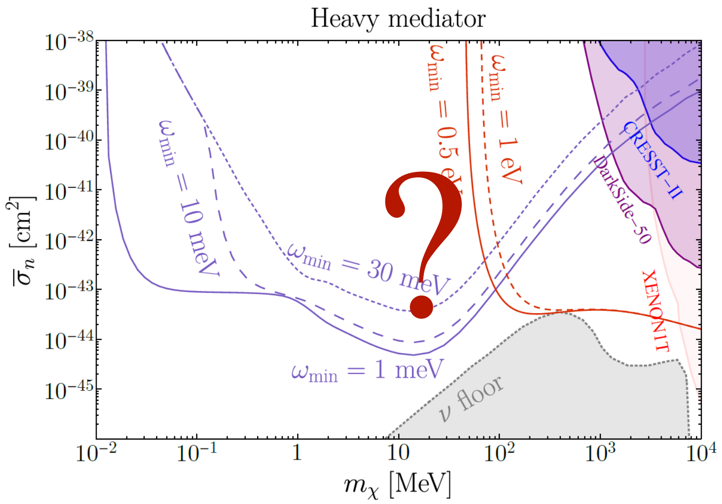

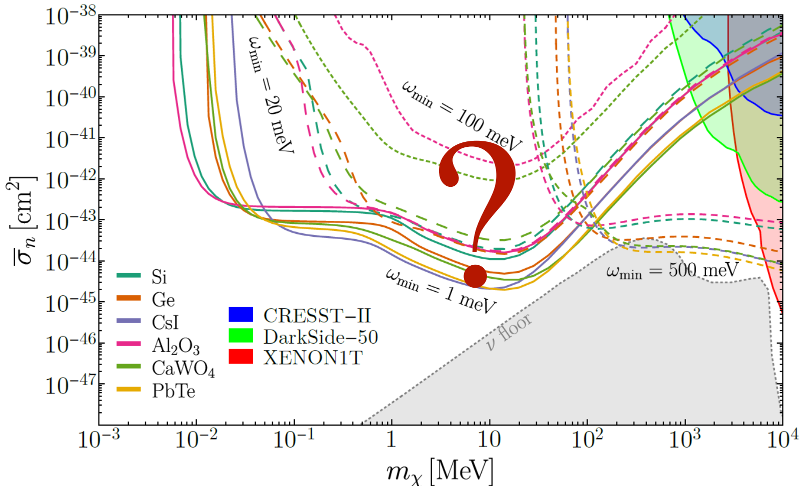

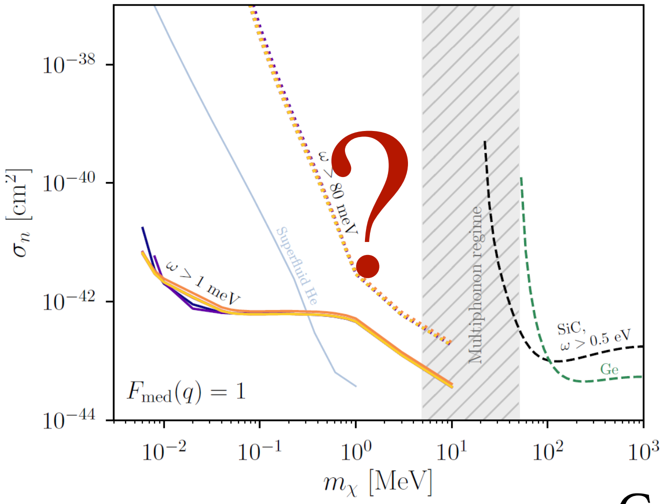

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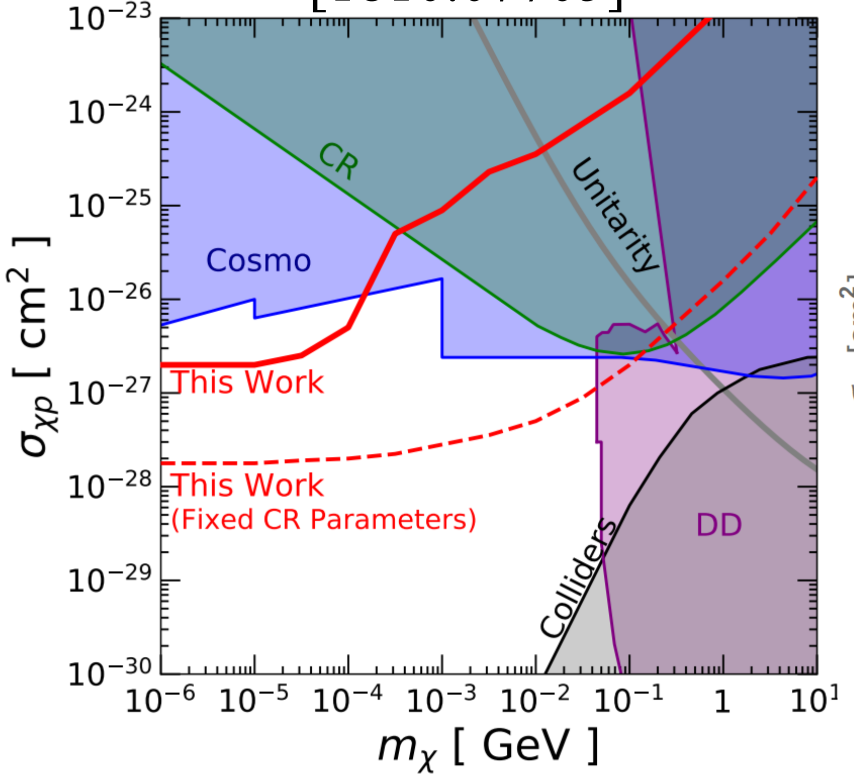
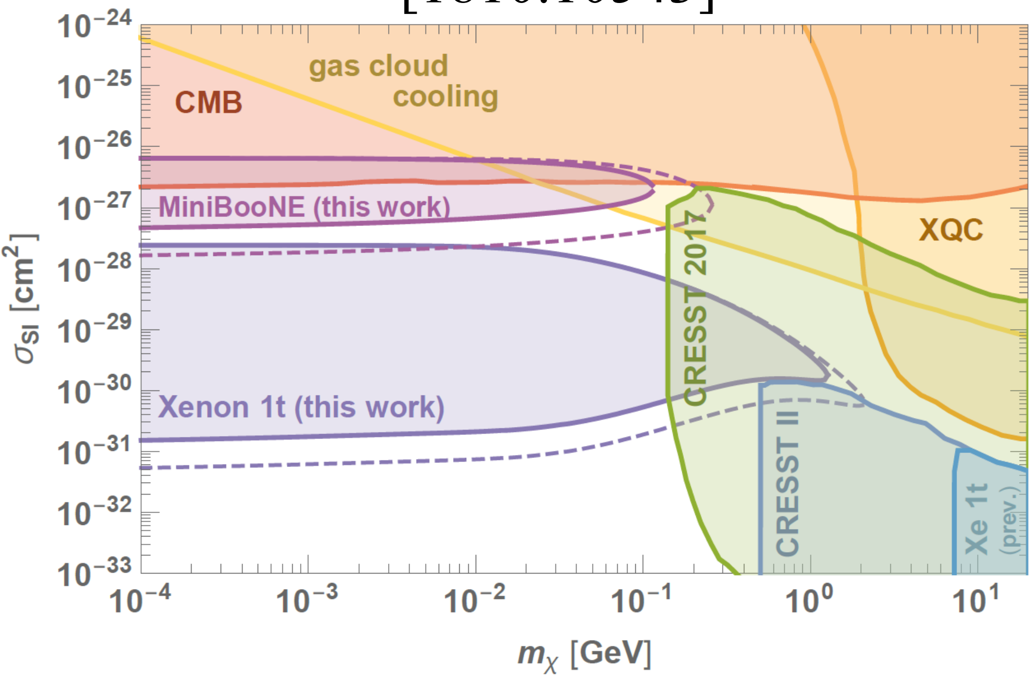
Bounds from Cosmic Ray Upscattering

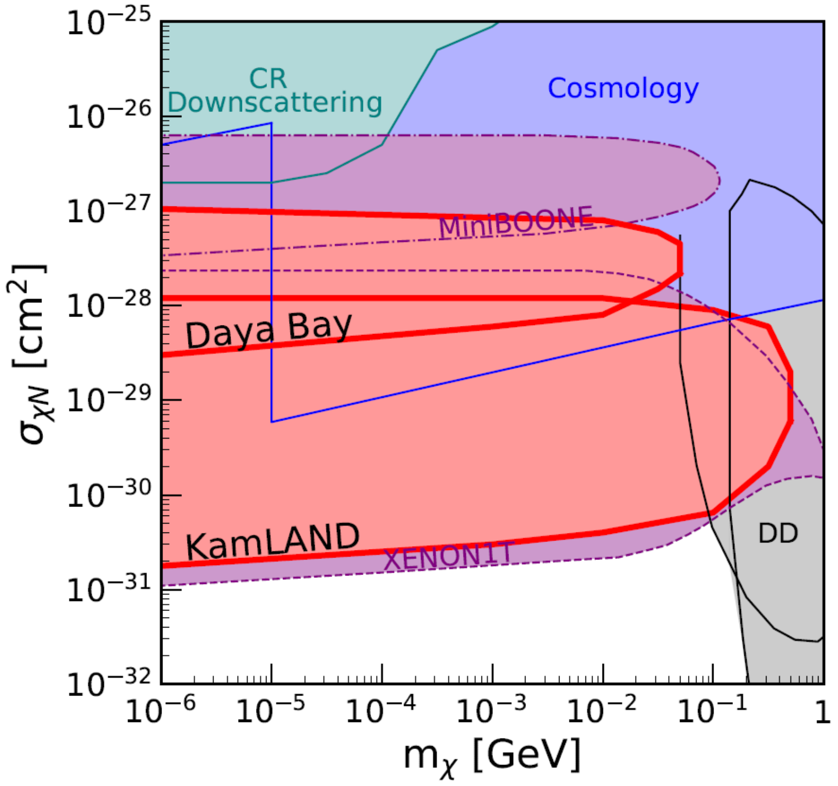
[1810.07705]



[1810.10543]



[1906.11283]



Is such a large cross section even feasible?
Is there a maximum cross section for DM nucleon scattering given present day constraints?

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

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

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

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

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

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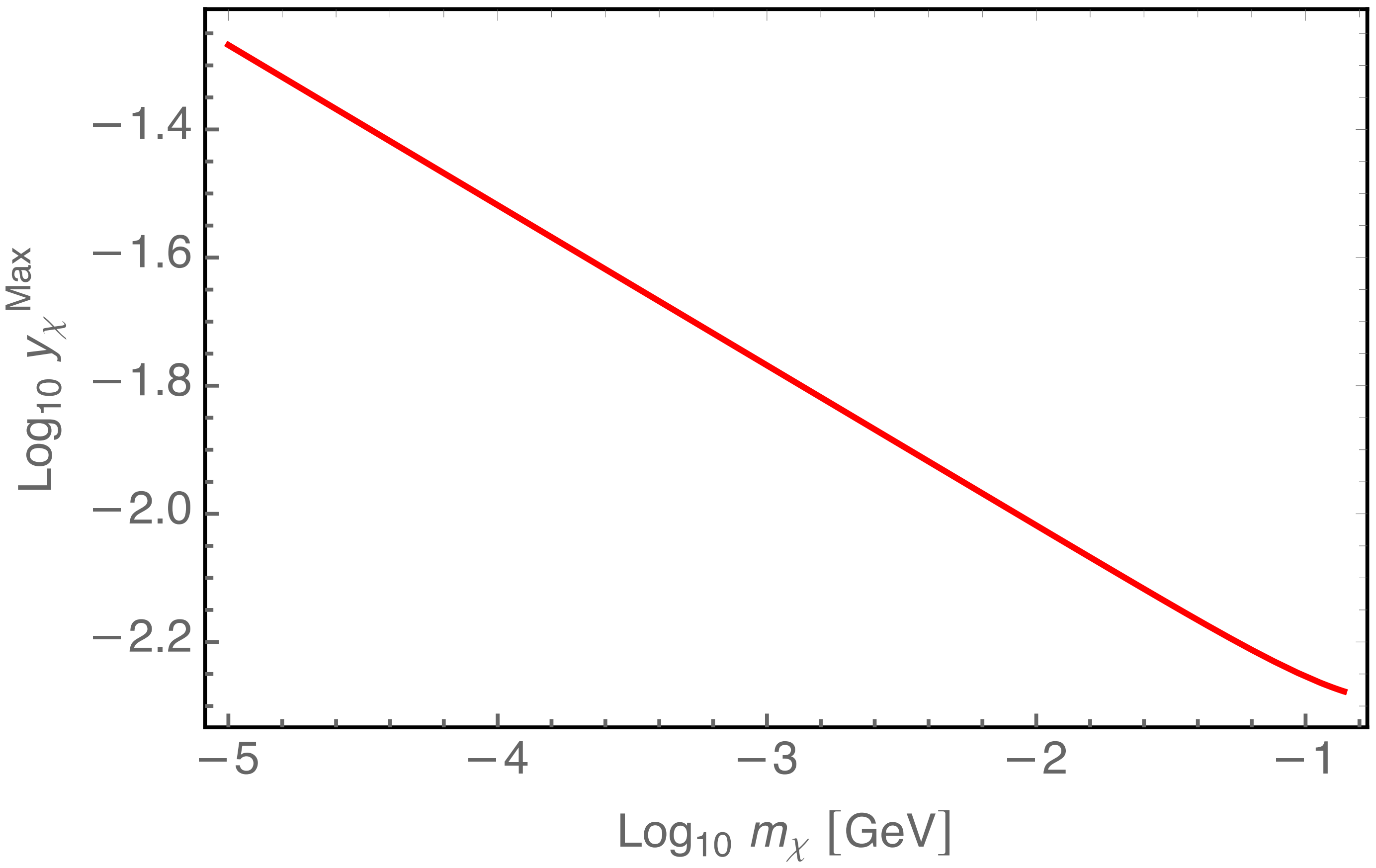
$$\boxed{\sigma_{\chi n}^{\max} \equiv \frac{\left(y_n^{\max} y_\chi^{\max}\right)^2}{4\pi} \frac{\mu_{\chi n}^2}{\left[\left(m_\phi^{\min}\right)^2 + v_{\rm DM}^2 m_\chi^2\right]^2}}$$

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

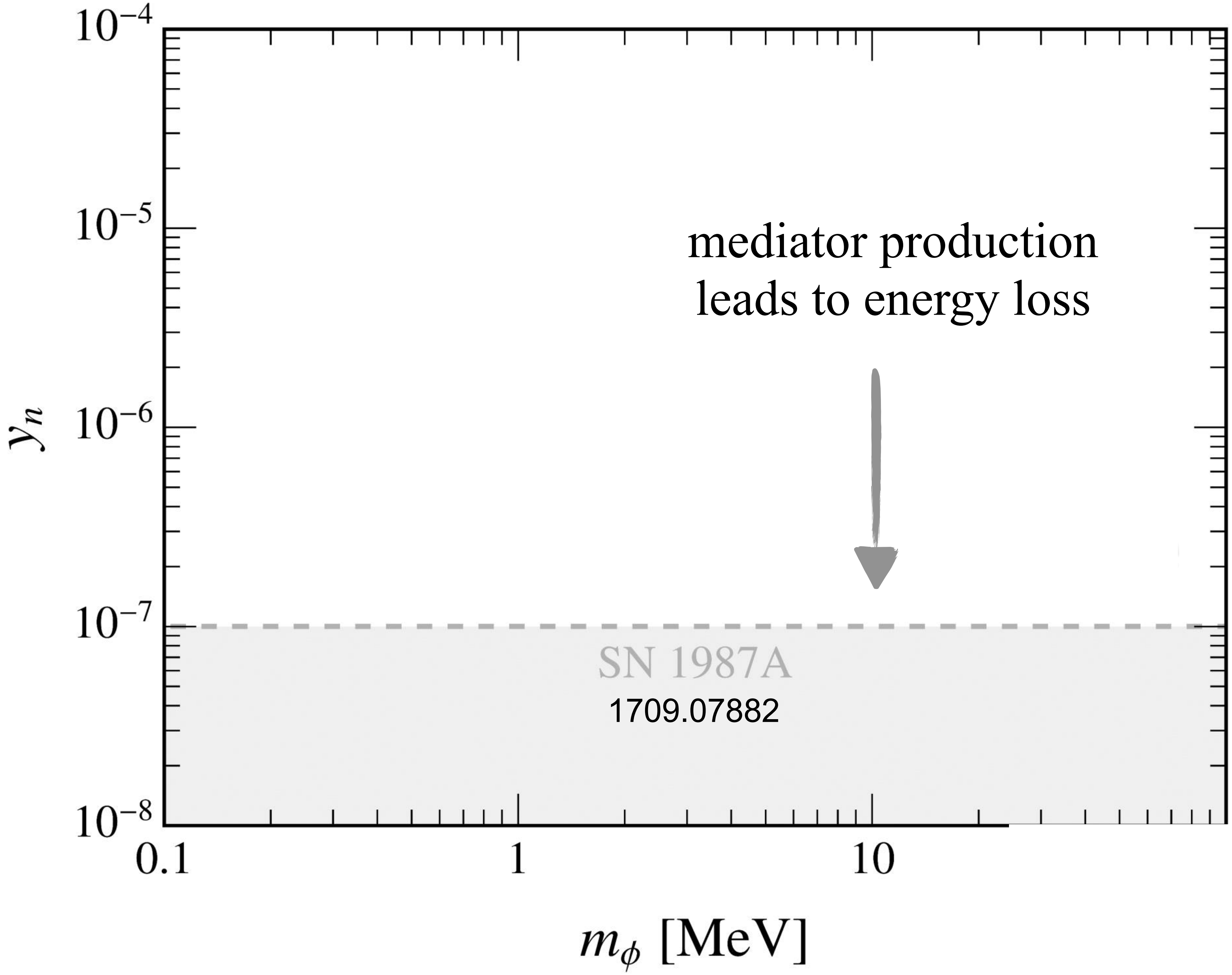
Dark Matter Self Interactions: $\sigma_T^{\text{born}} \approx \frac{8\pi\alpha_\chi^2}{m_\chi^2 v^4}\left[\log(1+R^2) - R^2/(1+R^2)\right]$ $\qquad R \equiv m_\chi v/m_\phi$



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

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

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



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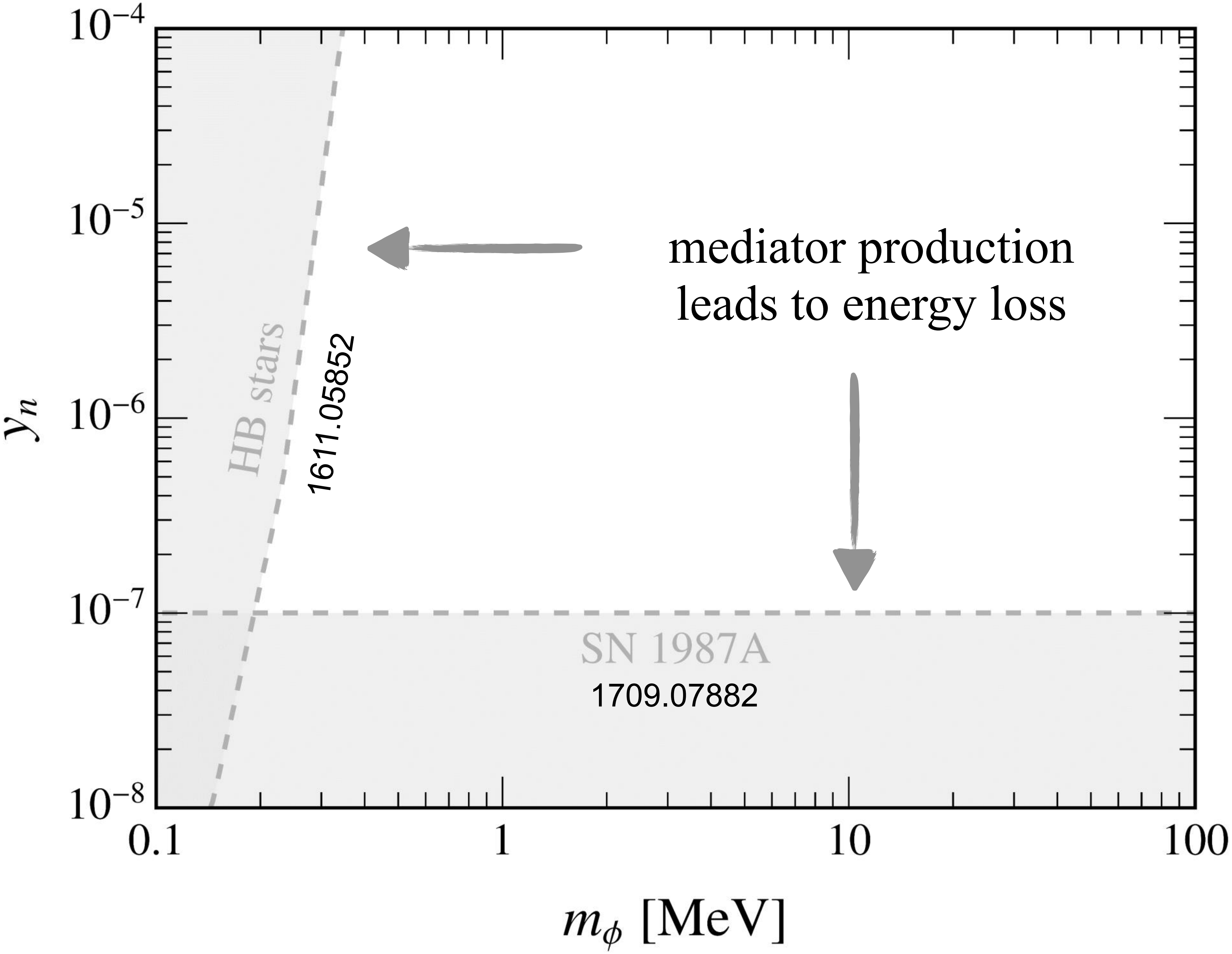
Estimating $\sigma_{n\chi}^{\max}$



mediator production
leads to energy loss

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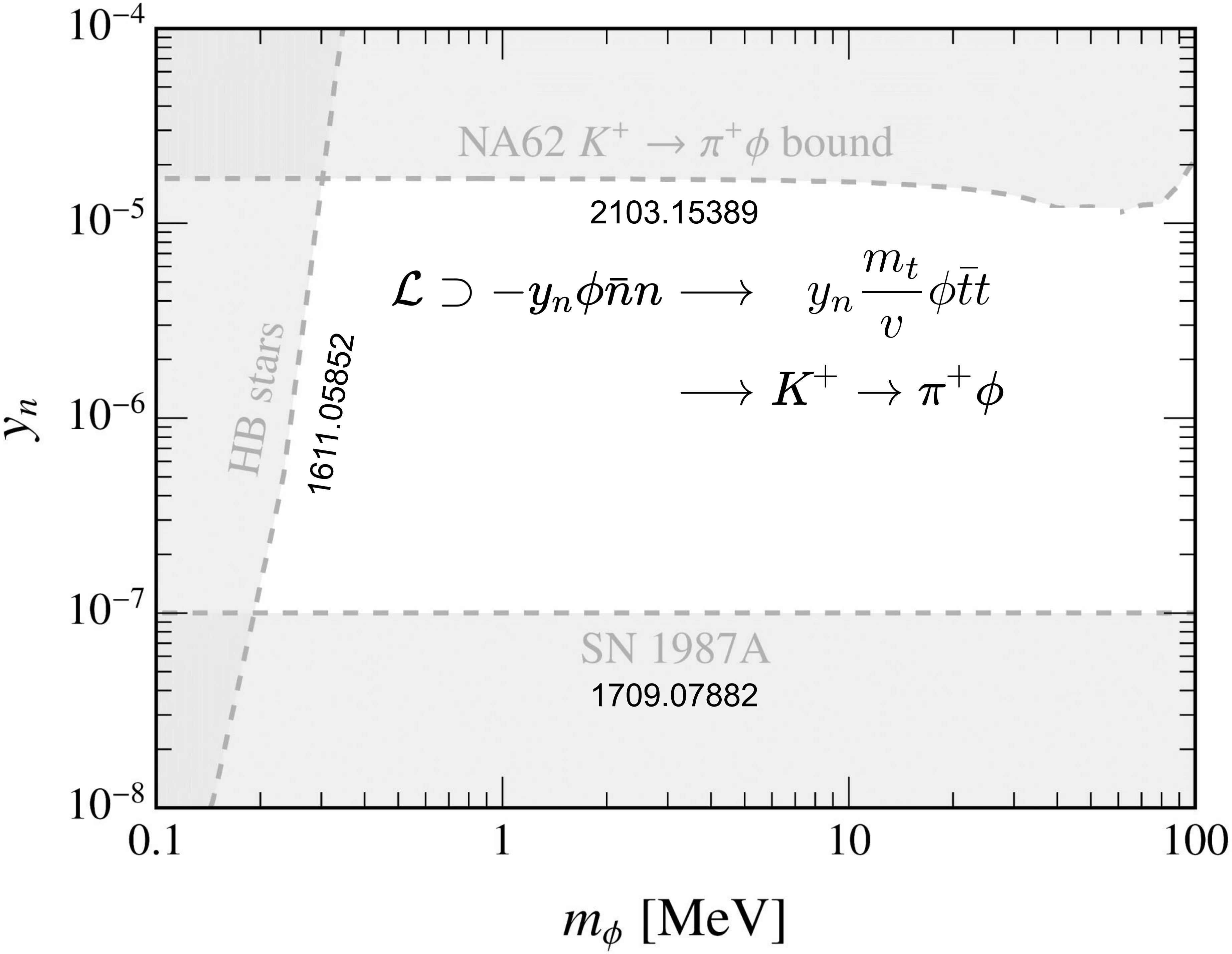
Estimating $\sigma_{n\chi}^{\mathrm{max}}$



$$\mathcal{L} \supset -y_n \phi \bar{n} n \longrightarrow \quad y_n \frac{m_t}{v} \phi \bar{t} t$$

$$\longrightarrow K^+ \to \pi^+ \phi$$

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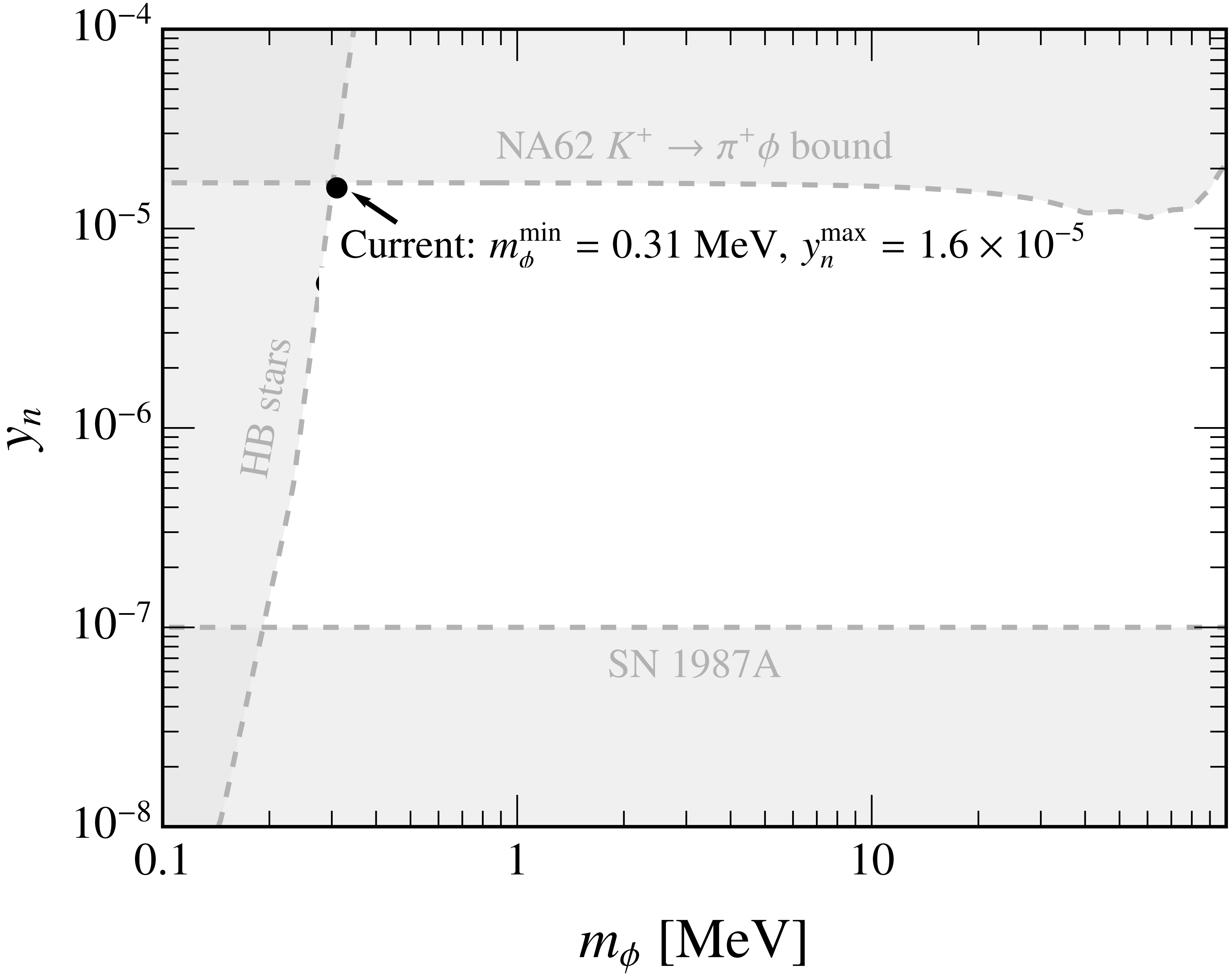
Estimating $\sigma_{n\chi}^{\max}$



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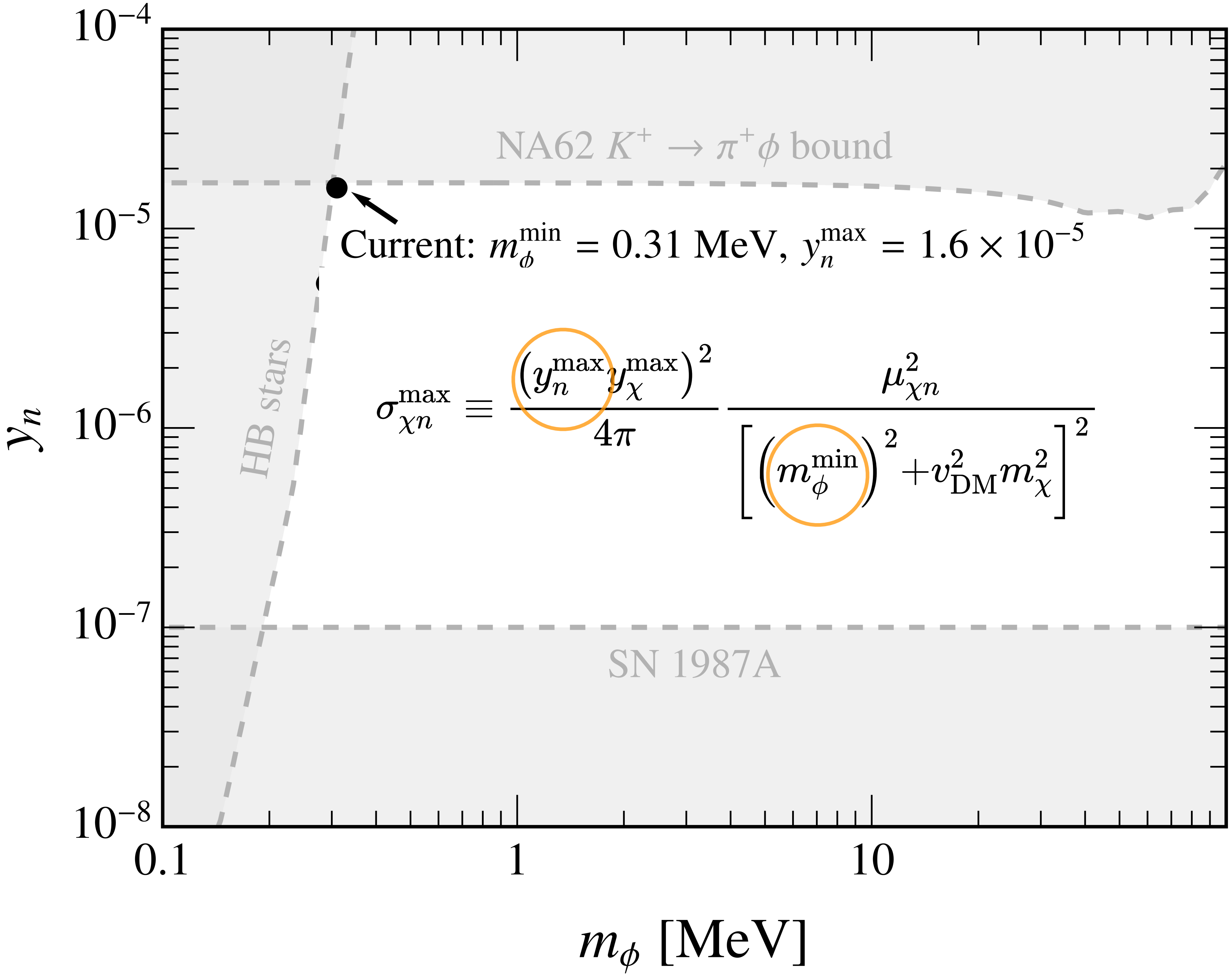
Estimating $\sigma_{n\chi}^{\max}$



Current: $m_\phi^{\min} = 0.31$ MeV, $y_n^{\max} = 1.6 \times 10^{-5}$

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

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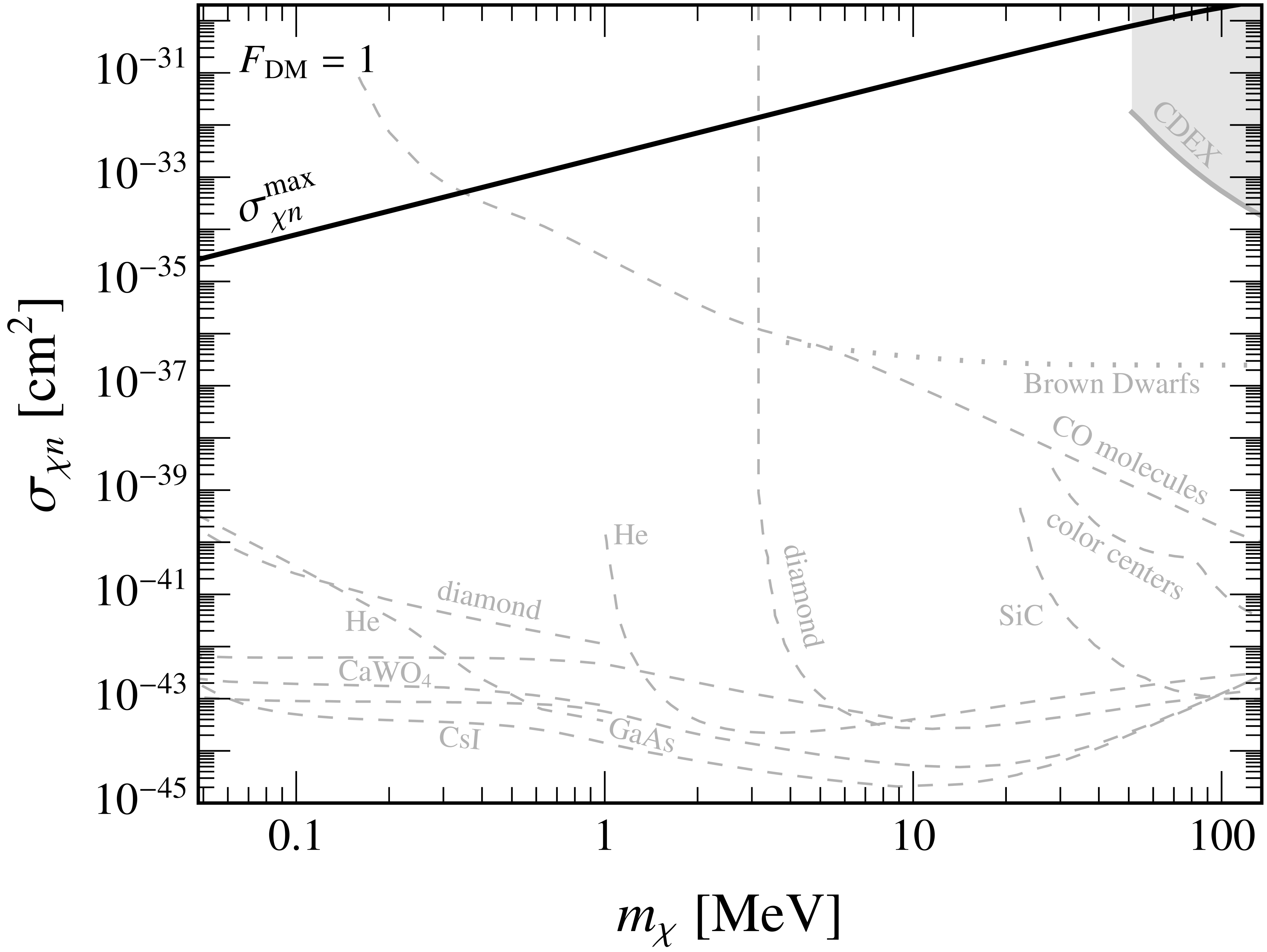
Estimating $\sigma_{n\chi}^{\max}$



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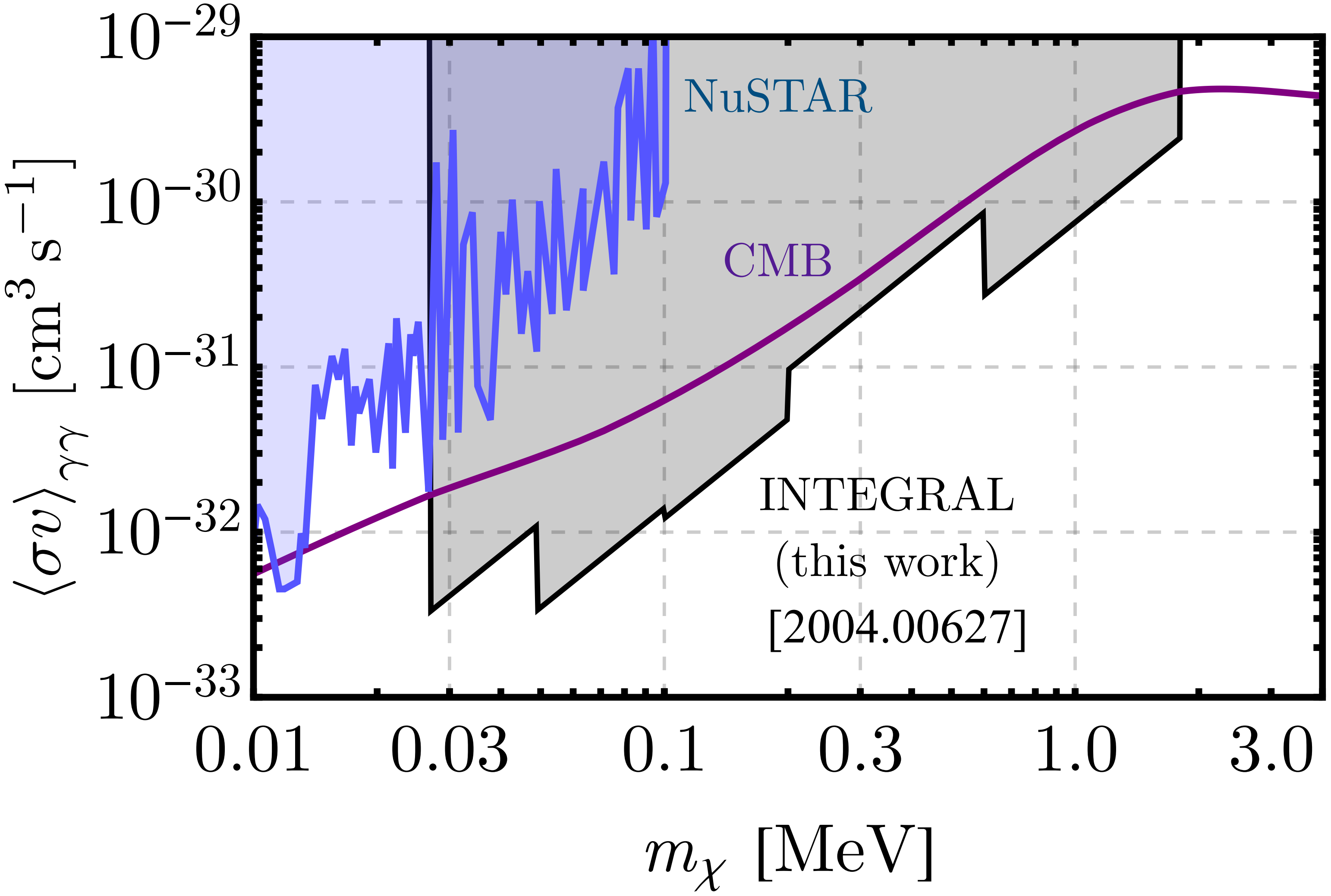
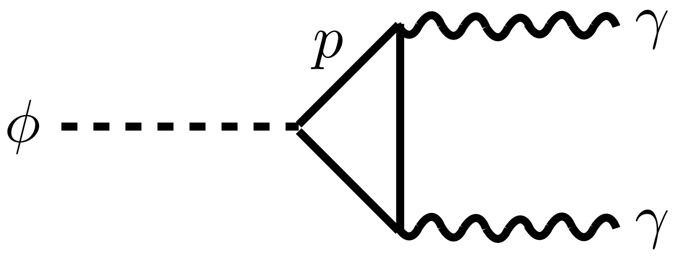
Indirect Detection $\chi\bar{\chi} \to \gamma\gamma$



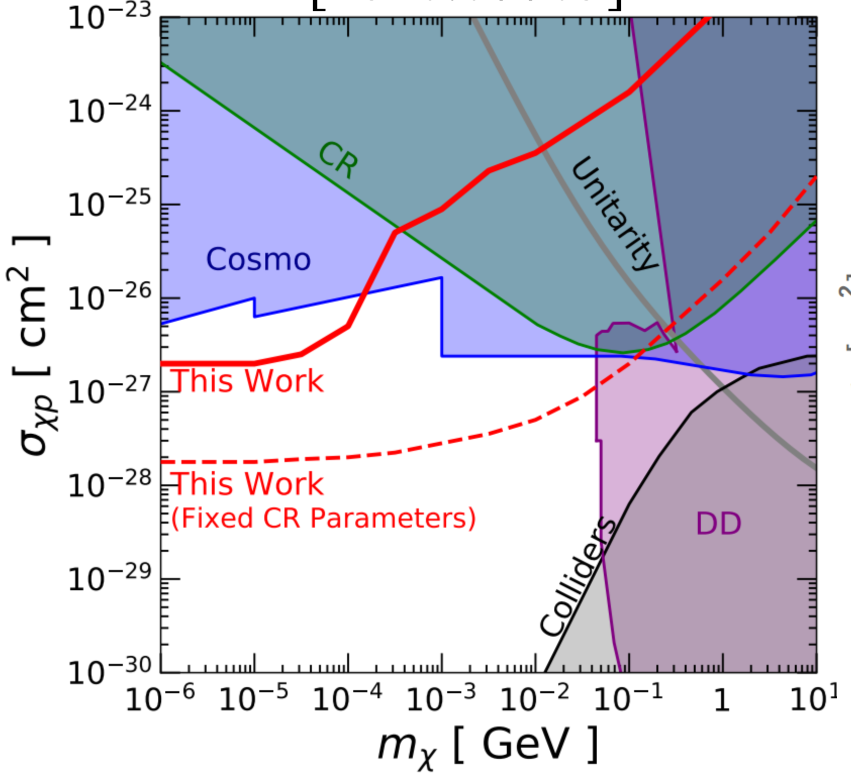


$$\mathcal{L} \supset \frac{\alpha y_n}{6\pi m_p}\phi F_{\mu\nu}F^{\mu\nu}$$

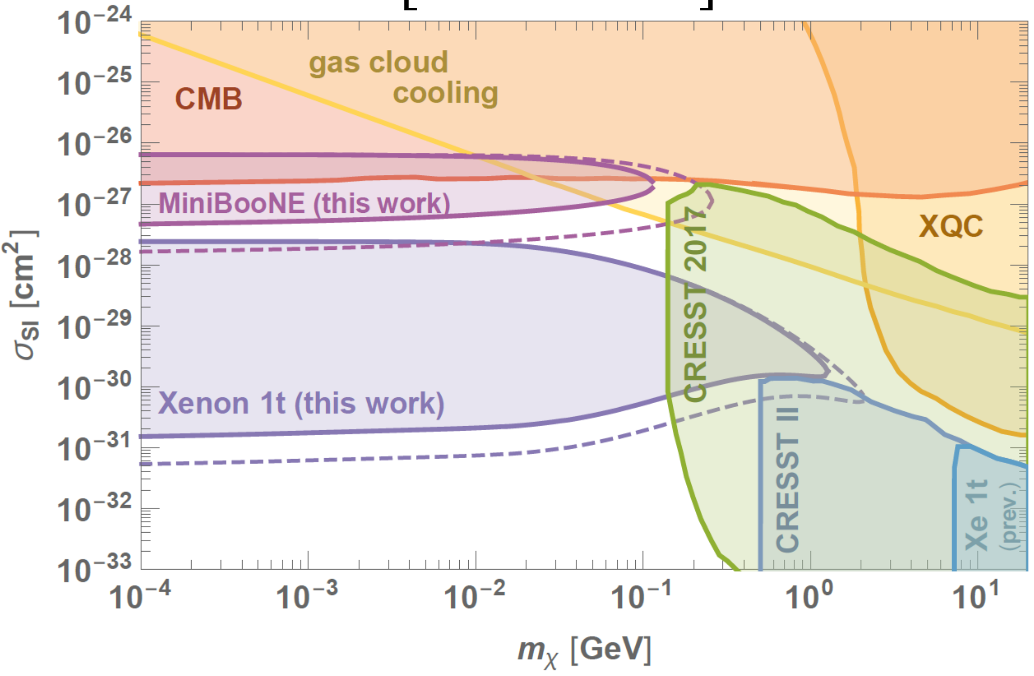
$$\sigma v_{\rm ann} = \frac{1}{32\pi}\left(\frac{2\alpha y_n^{\rm max} y_\chi^{\rm max}}{3\pi m_p}\right)^2 \frac{s\left(s-4m_\chi^2\right)}{\left(s-(m_\phi^{\rm min})^2\right)^2} \sim 10^{-44}{\rm cm}^3{\rm s}^{-1}$$

Bounds from Cosmic Ray Upscattering

[1810.07705]



[1810.10543]



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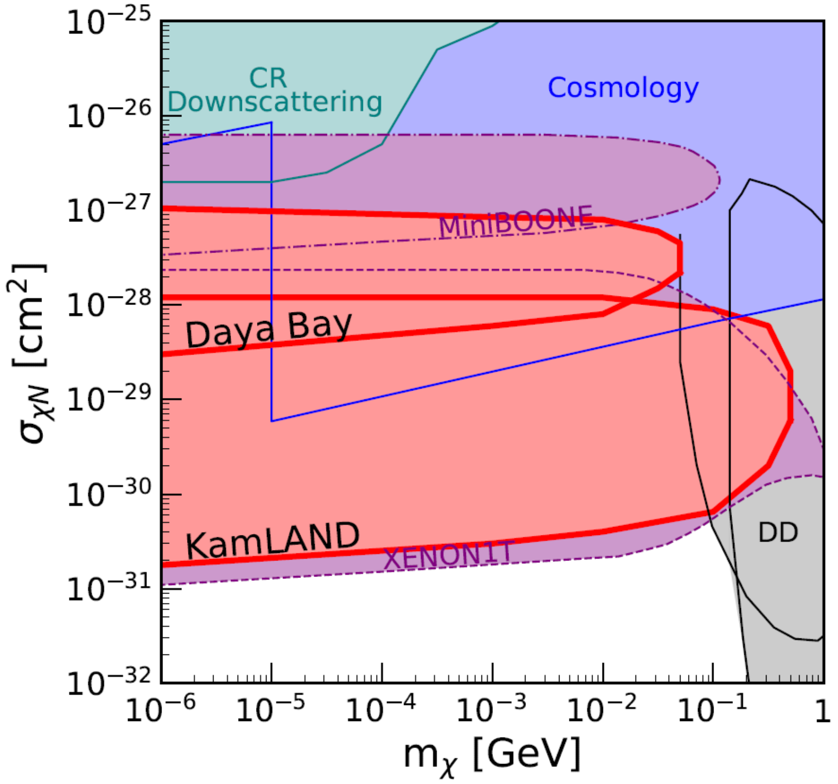

Is such a large cross section even feasible?

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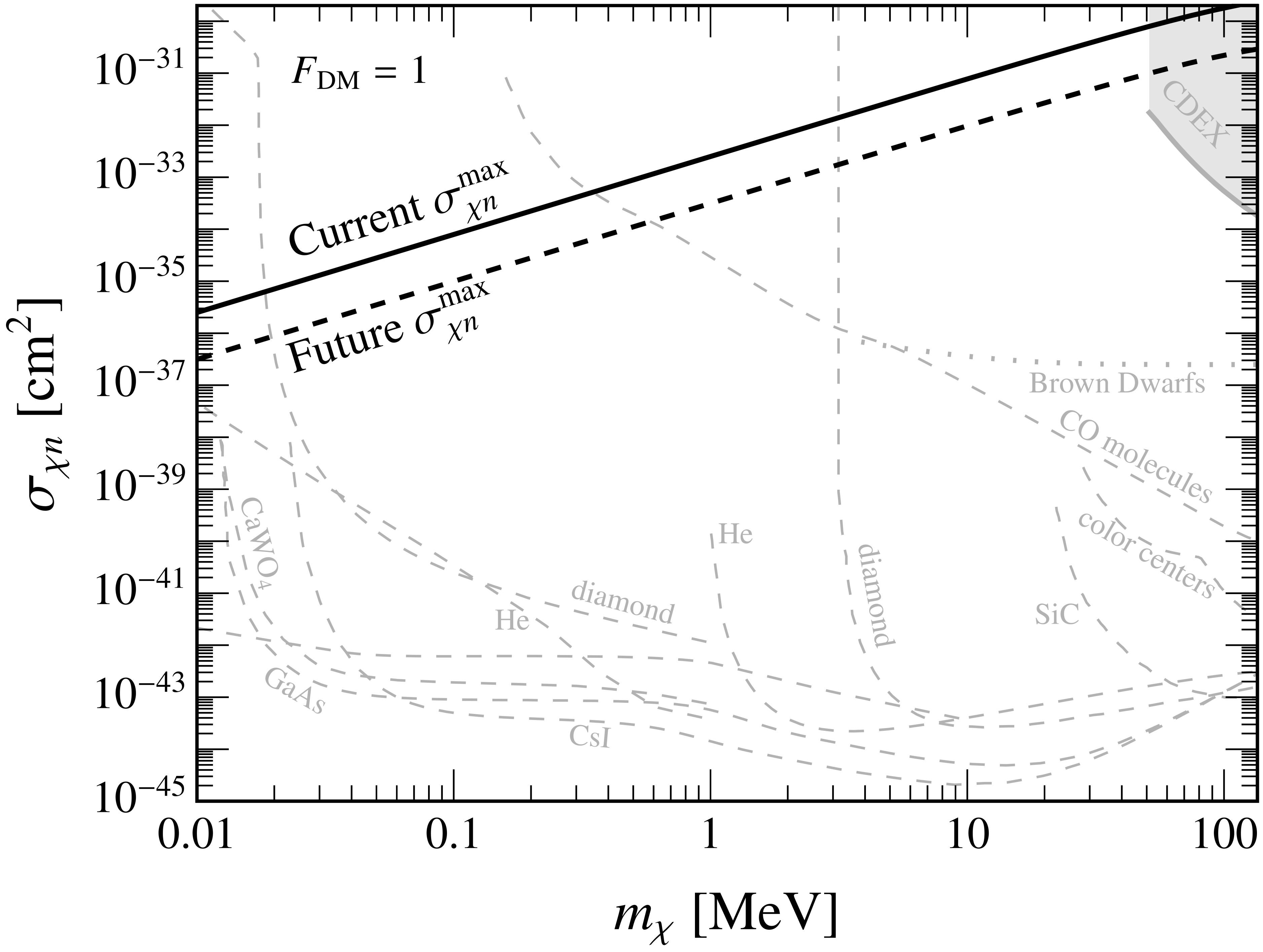
Bounds from Cosmic Ray Upscattering



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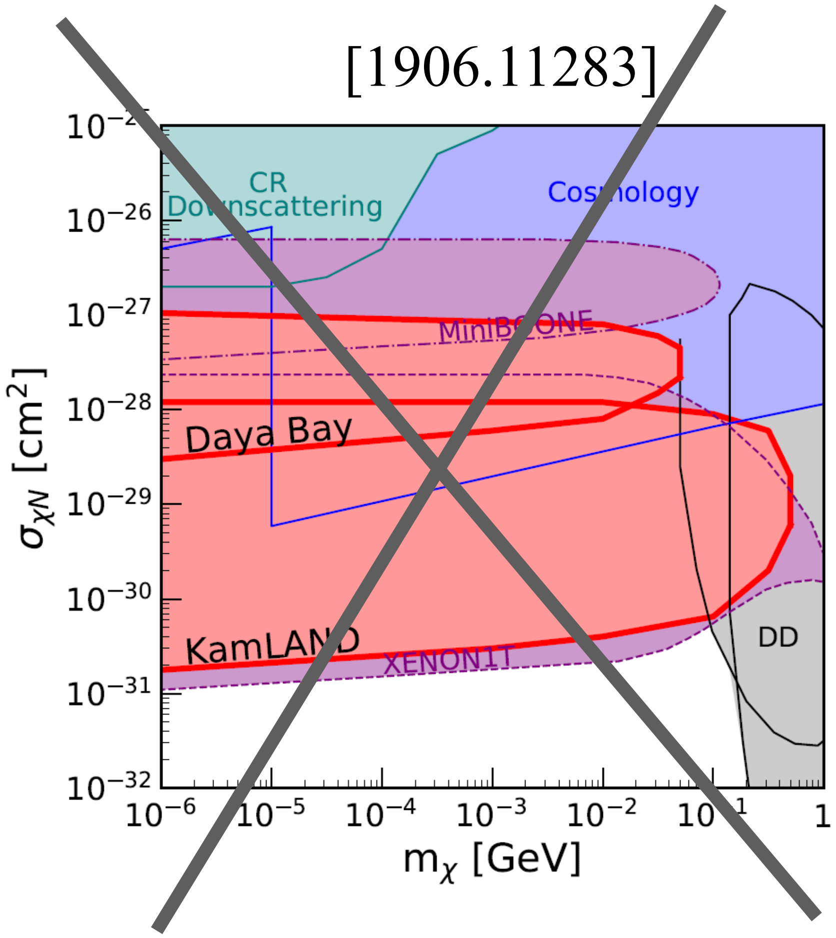

Probably not!

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

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

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

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

- 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 $\sigma_{n\chi}^{\max}$?

Is there a sub-GeV dark matter candidate that:
1) may be detected at proposed experiments?
2) may have such a large cross section?

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

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?

- 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_{eff} constraints.

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.

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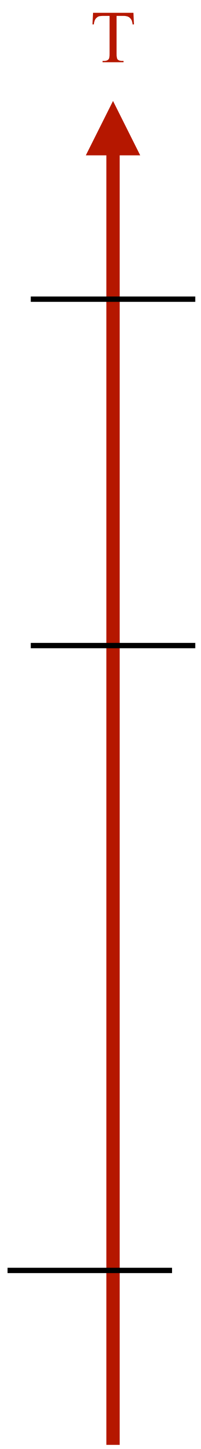
HYPERs :

HighlY interactive ParticlE Relics



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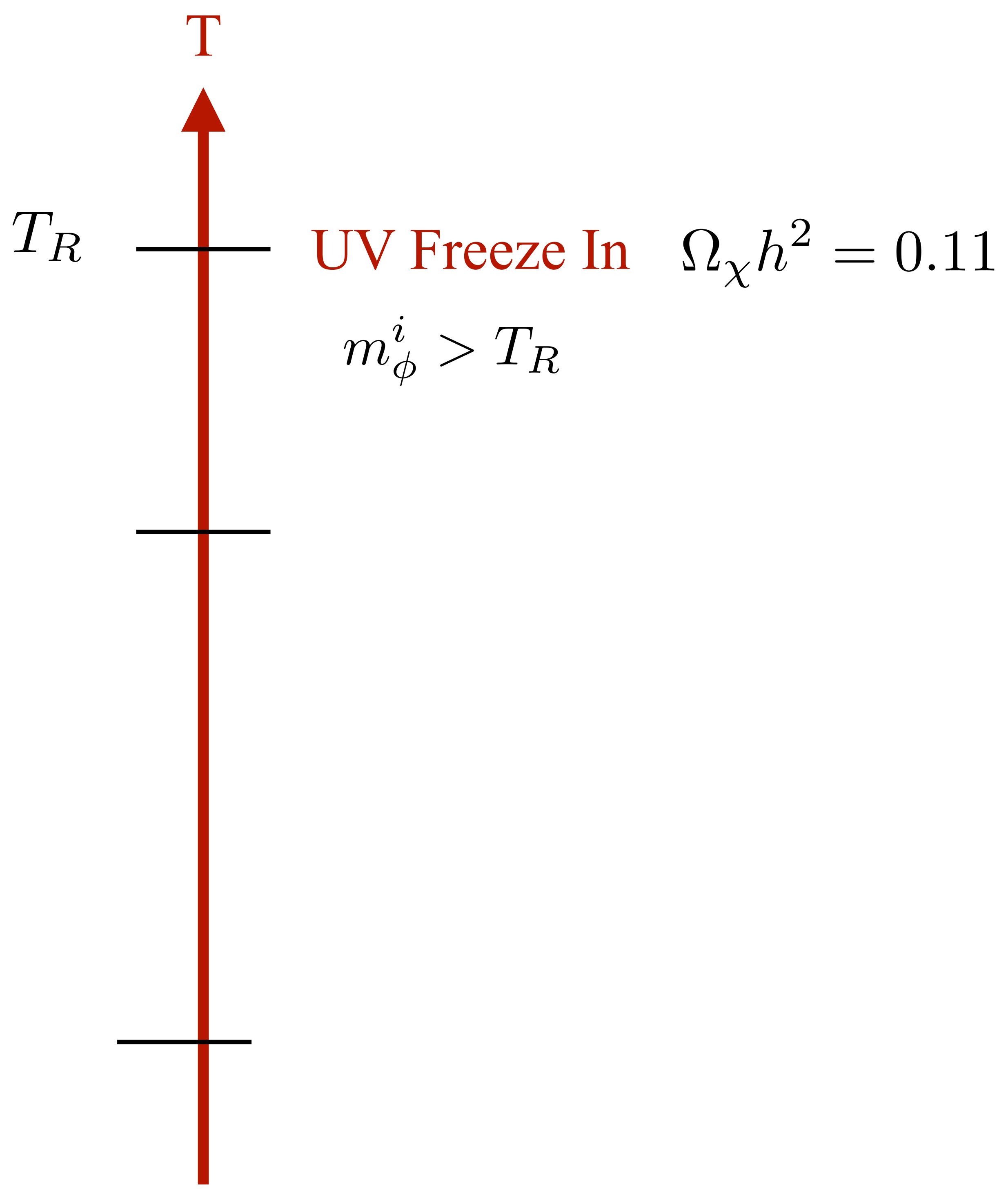

T_R

UV Freeze In $\Omega_\chi h^2 = 0.11$

$m_\phi^i > T_R$

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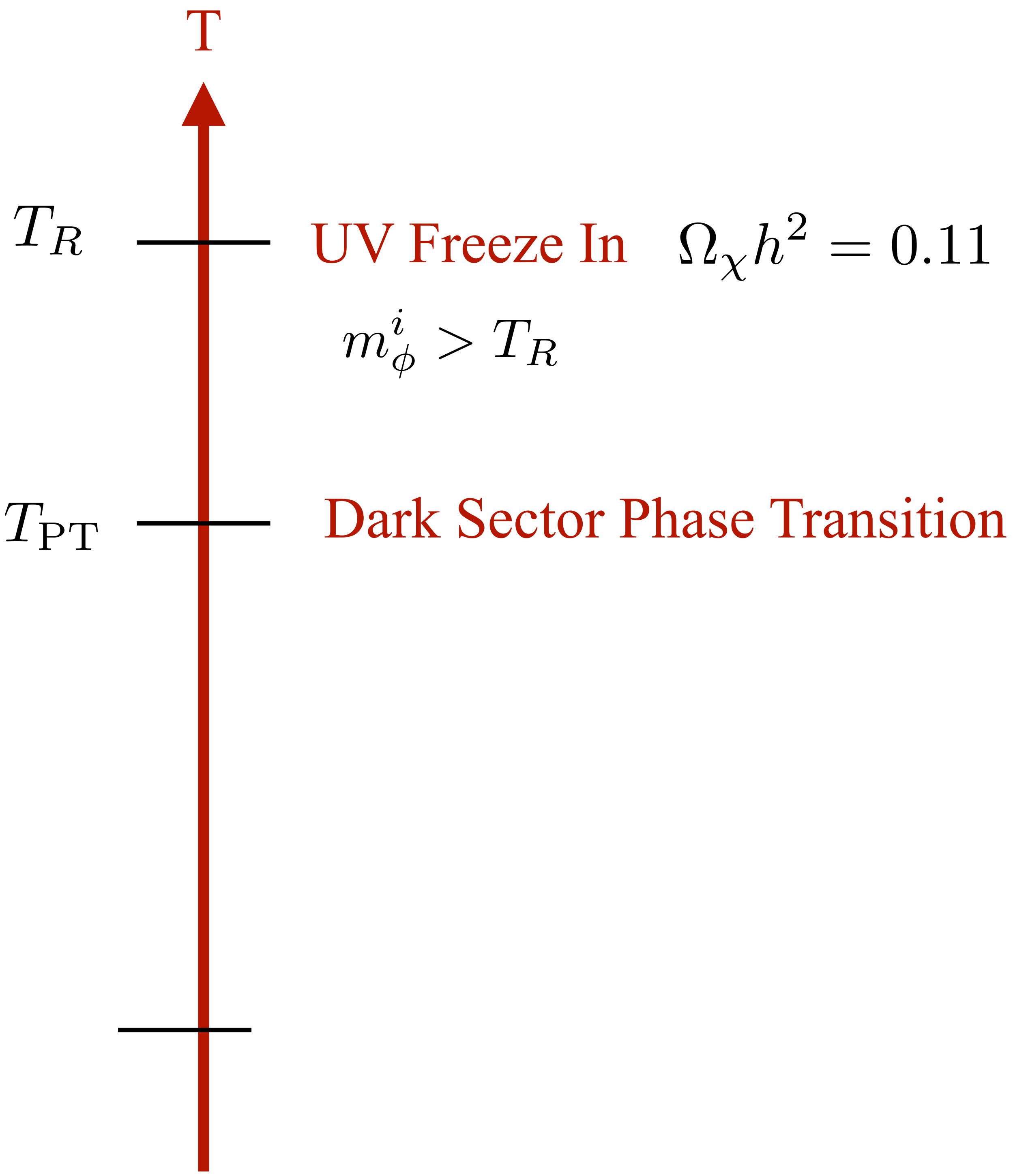
T

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

HYPERs :
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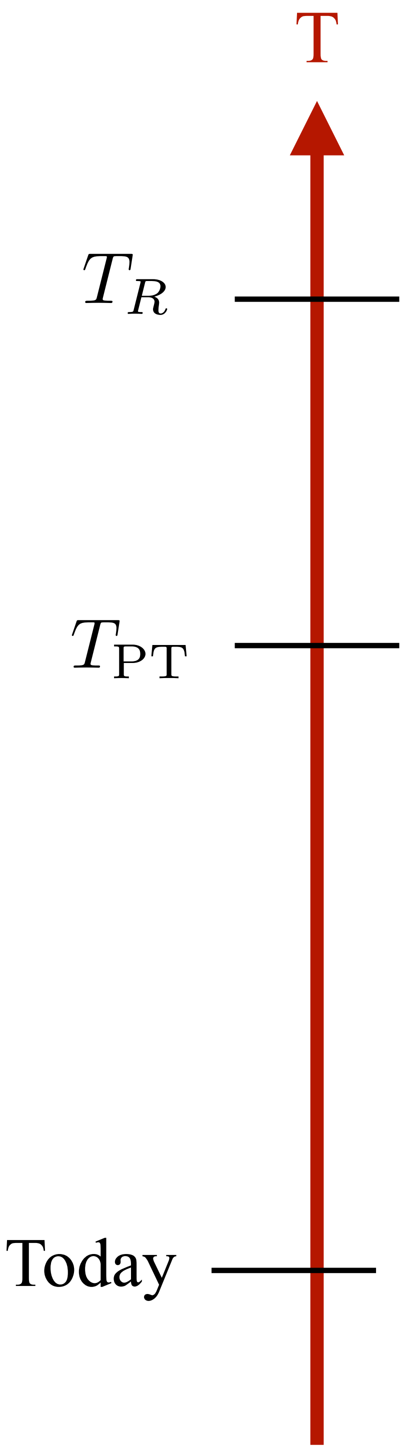


UV Freeze In $\Omega_\chi h^2 = 0.11$

$m_\phi^i > T_R$

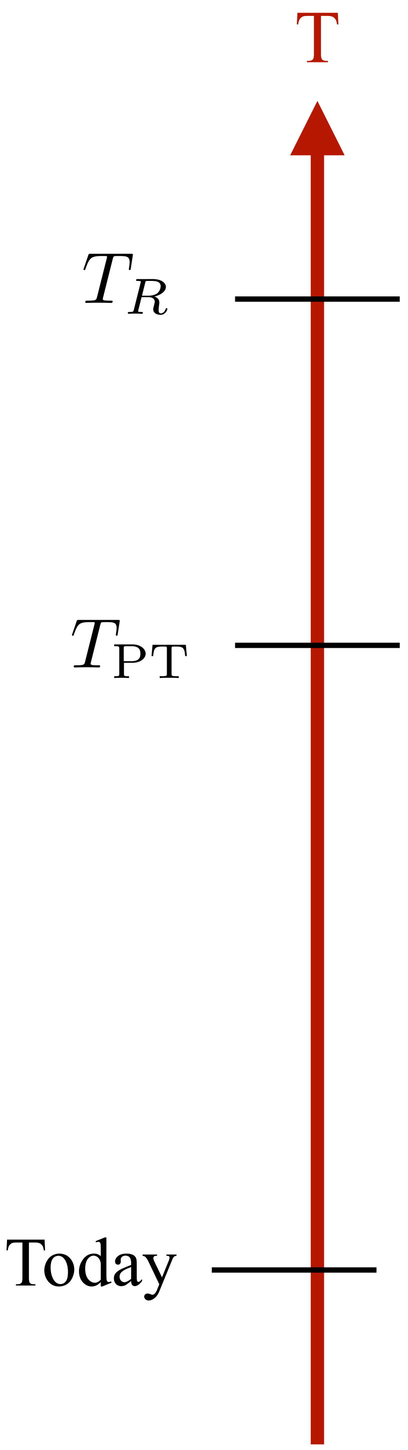
Dark Sector Phase Transition

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]
And many more

G. Elor

HYPERs :
HighlY interactive ParticlE Relics



T

T_R

UV Freeze In $\Omega_\chi h^2 = 0.11$

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$T_{\rm PT}$

Dark Sector Phase Transition

For HYPERs the *mediator* mass changes

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

Today

G. Elor

HYPERs :
HighlY interactive ParticlE Relics

T

T_R UV Freeze In $\Omega_\chi h^2 = 0.11$

$m_\phi^i > T_R$

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

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

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

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HYPERs :

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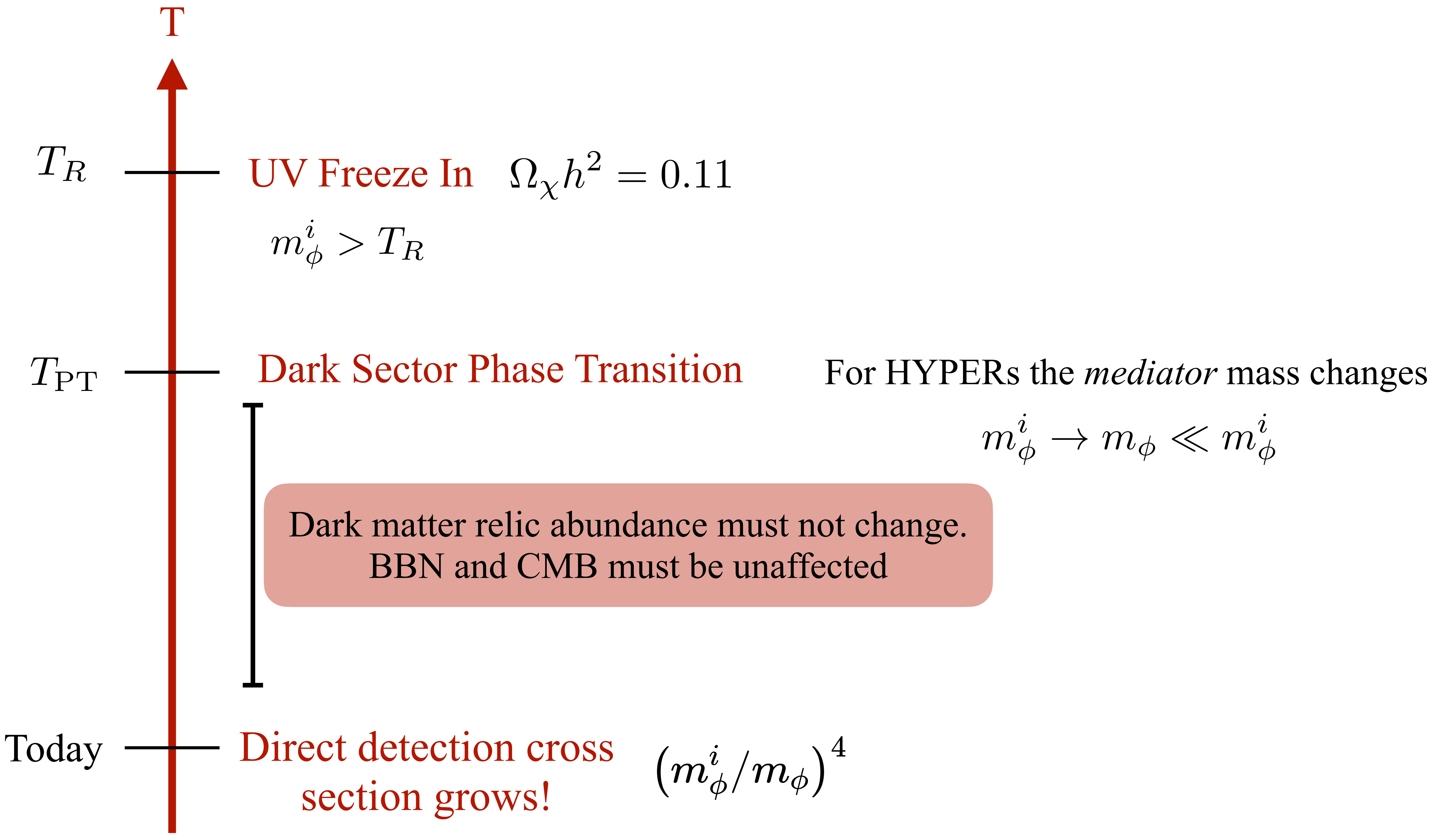

T_R UV Freeze In $\Omega_\chi h^2 = 0.11$

$m^i_\phi > T_R$

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

For HYPERs the *mediator* mass changes

$$m^i_\phi \to m_\phi \ll m^i_\phi$$

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

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

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UV Freeze-In

At high scales, integrating out initially heavy mediator and heavy vector like quarks:

$$\mathcal{L} \supset \lambda\phi\bar{\psi}\psi \longrightarrow \frac{\alpha_s}{\Lambda}\phi G^{\mu\nu}G_{\mu\nu} \longrightarrow \boxed{\frac{\alpha_s y_\chi y_n}{2.6\, m_n (m_\phi^i)^2}\chi\bar{\chi}G^{a,\,\mu\nu}G^a_{\mu\nu}}$$

UV Freeze-In

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UV Freeze In: $T_R < \mathrm{Min}\left[m_\phi^i/20\,,\, m_\psi/20\right]$ $\quad Y_\chi \simeq 4\times 10^{-5}\left(\frac{y_n y_\chi \alpha_s}{m_n (m_\phi^i)^2}\right)^2 \frac{M_{\rm Pl}T_R^5}{g_{s,*}\sqrt{g_*}}$

We can adjust $T_{\rm R}$ and m_ϕ^i to yield the correct relic abundance.

Both have no impact on $\sigma_{\chi n}^{\max}$.

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We can adjust $T_{\rm R}$ and m^i_ϕ to yield the correct relic abundance.

Both have no impact on $\sigma_{\chi n}^{\rm max}$.

$$\frac{\lambda}{M_\psi} \leftrightarrow \frac{y_n}{m_n} \rightarrow y_n^{\rm max} = 1.5 \times 10^{-5} \quad \leftrightarrow \quad m_\psi^{\rm max} \sim 40 \text{ TeV}$$

$$\boxed{T_R \lesssim 2 \text{ TeV}}$$

Dark Sector Phase Transition

$$\boxed{m_\phi^i \to m_\phi \ll m_\phi^i}$$

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

e.g. after the phase transition we must forbid or suppress processes such as

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$$\bar{\chi}\chi \to \text{hadrons}$$

$$\text{hadrons} \to \bar{\chi}\chi$$

$$\bar{\chi}\chi \to \phi\phi$$

$$\ldots.$$

G. Elor

Dark Sector Phase Transition

$$\boxed{m_\phi^i \to m_\phi \ll m_\phi^i}$$

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$$\xcancel{\bar{\chi}\chi \to \text{hadrons}}$$

$$\text{hadrons} \to \bar{\chi}\chi$$

$$\bar{\chi}\chi \to \phi\phi$$

$$\cdots\cdot$$

→

$$\mathcal{O}(10\text{ keV}) \lesssim m_\chi < m_{\pi^0}$$

G. Elor

Dark Sector Phase Transition

$$\boxed{m_\phi^i \to m_\phi \ll m_\phi^i}$$

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

e.g. after the phase transition we must forbid or suppress processes such as

$$\xcancel{\bar{\chi}\chi \to \text{hadrons}} \qquad\qquad \mathcal{O}(10\text{ keV}) \lesssim m_\chi < m_{\pi^0}$$

$$\xcancel{\text{hadrons} \to \bar{\chi}\chi} \qquad \longrightarrow \qquad 1\text{ MeV} \lesssim T_{\text{PT}} \lesssim m_{\pi^0}$$

$$\bar{\chi}\chi \to \phi\phi$$

$$\cdots\cdot$$

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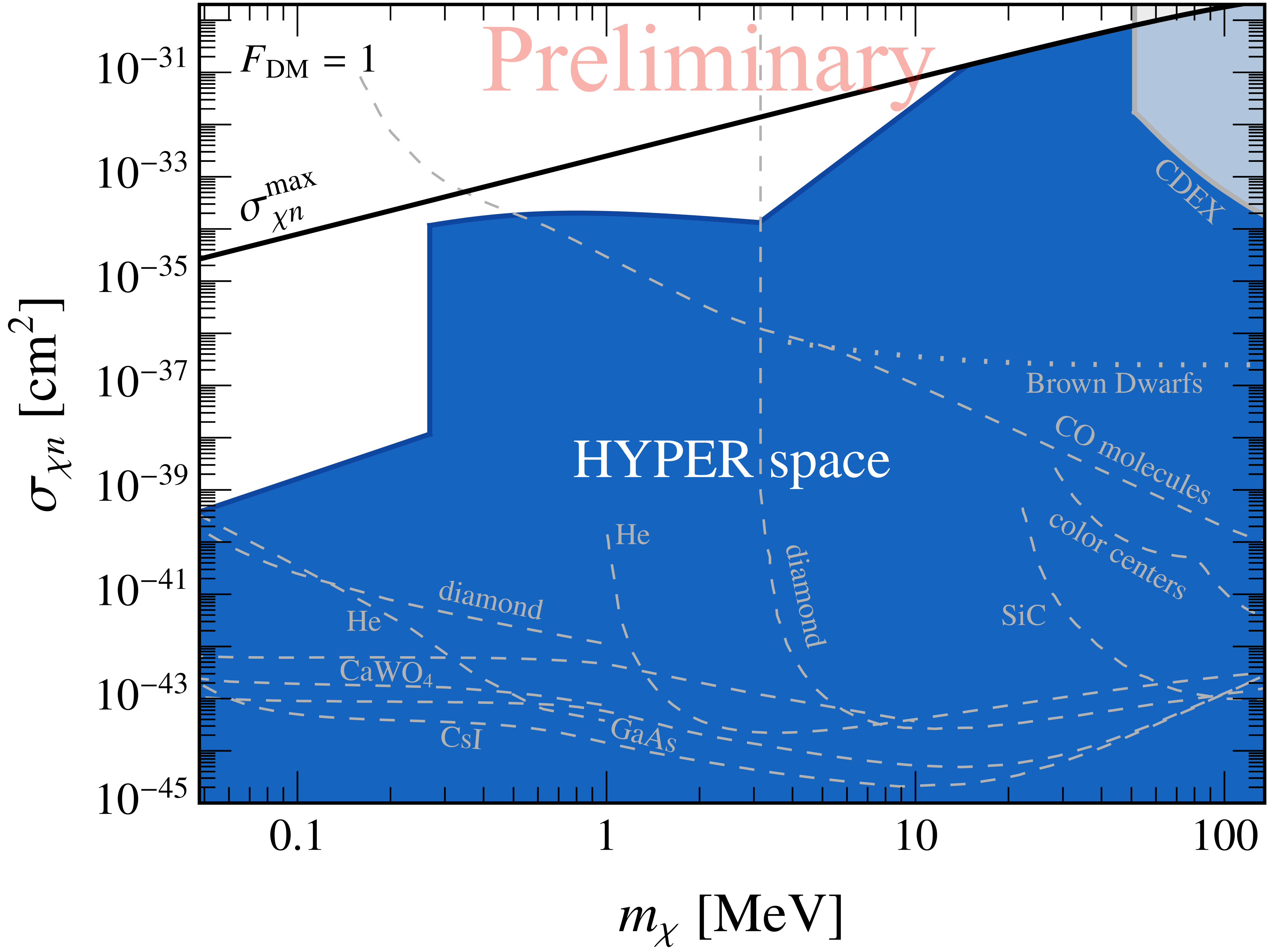
$$\bar{\chi}\chi \to \phi\phi \qquad \sigma v_{\chi\bar{\chi}\to\phi\phi} n_\chi < H$$

$$\cdots$$

G. Elor

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



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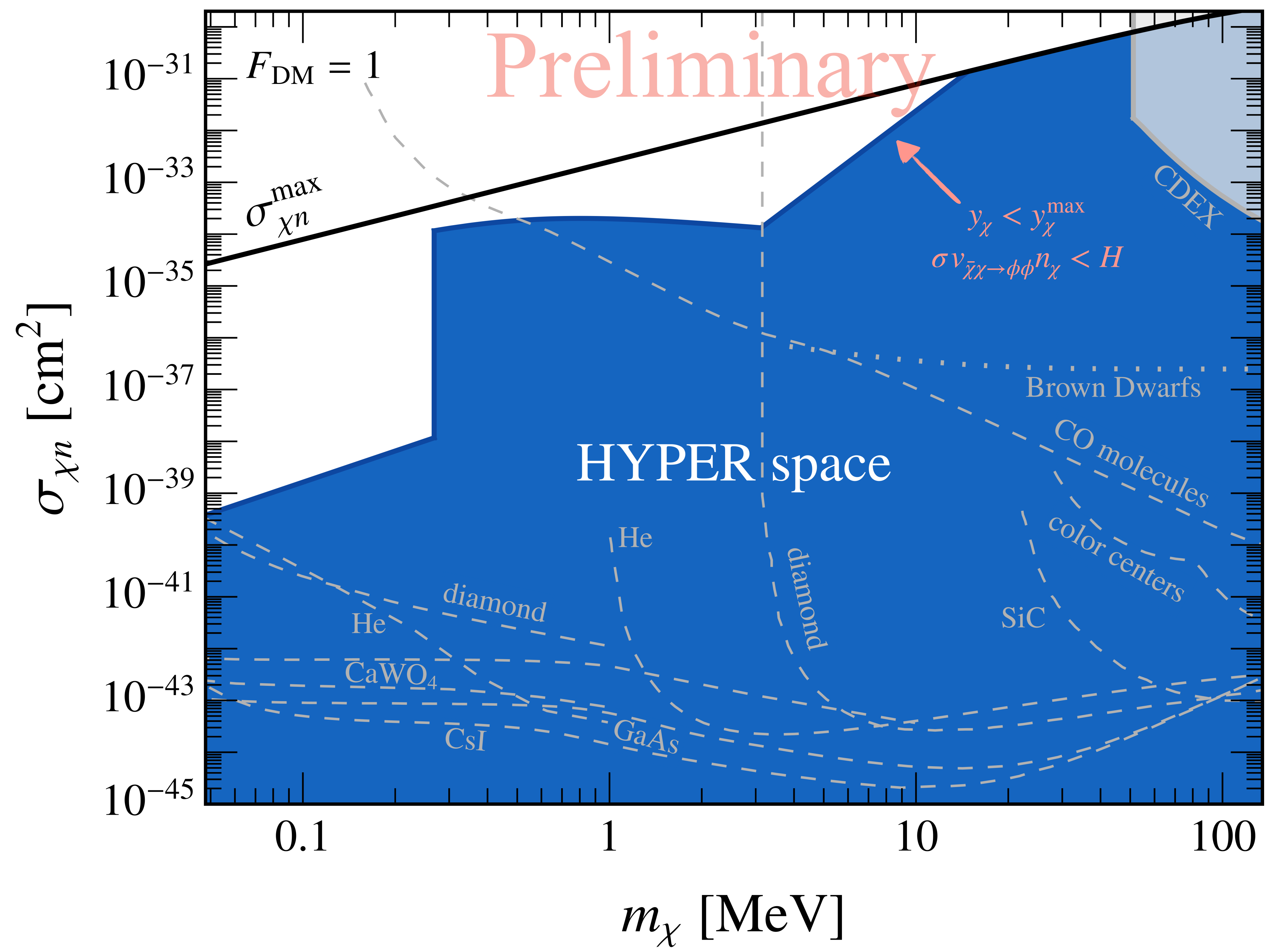

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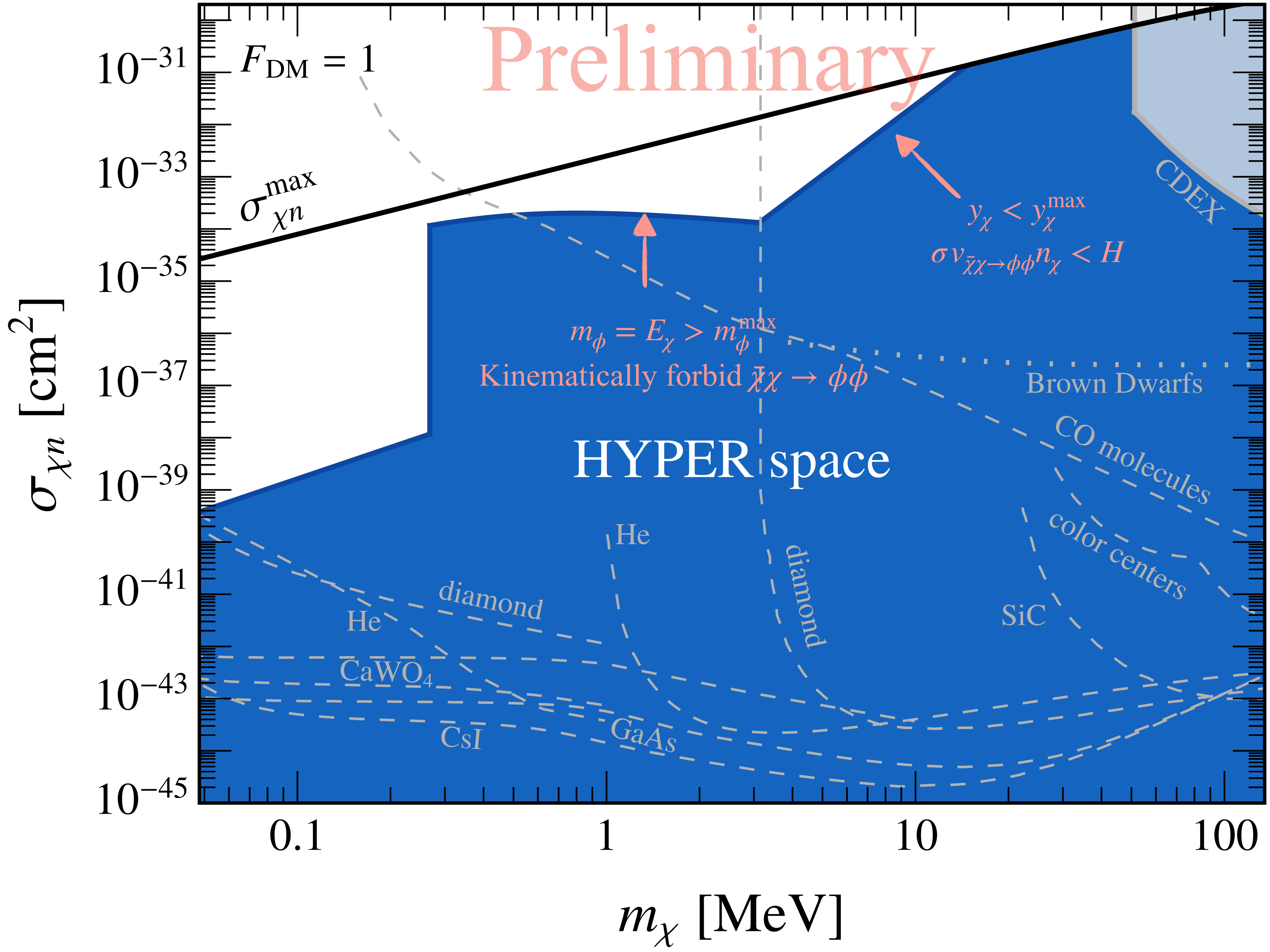

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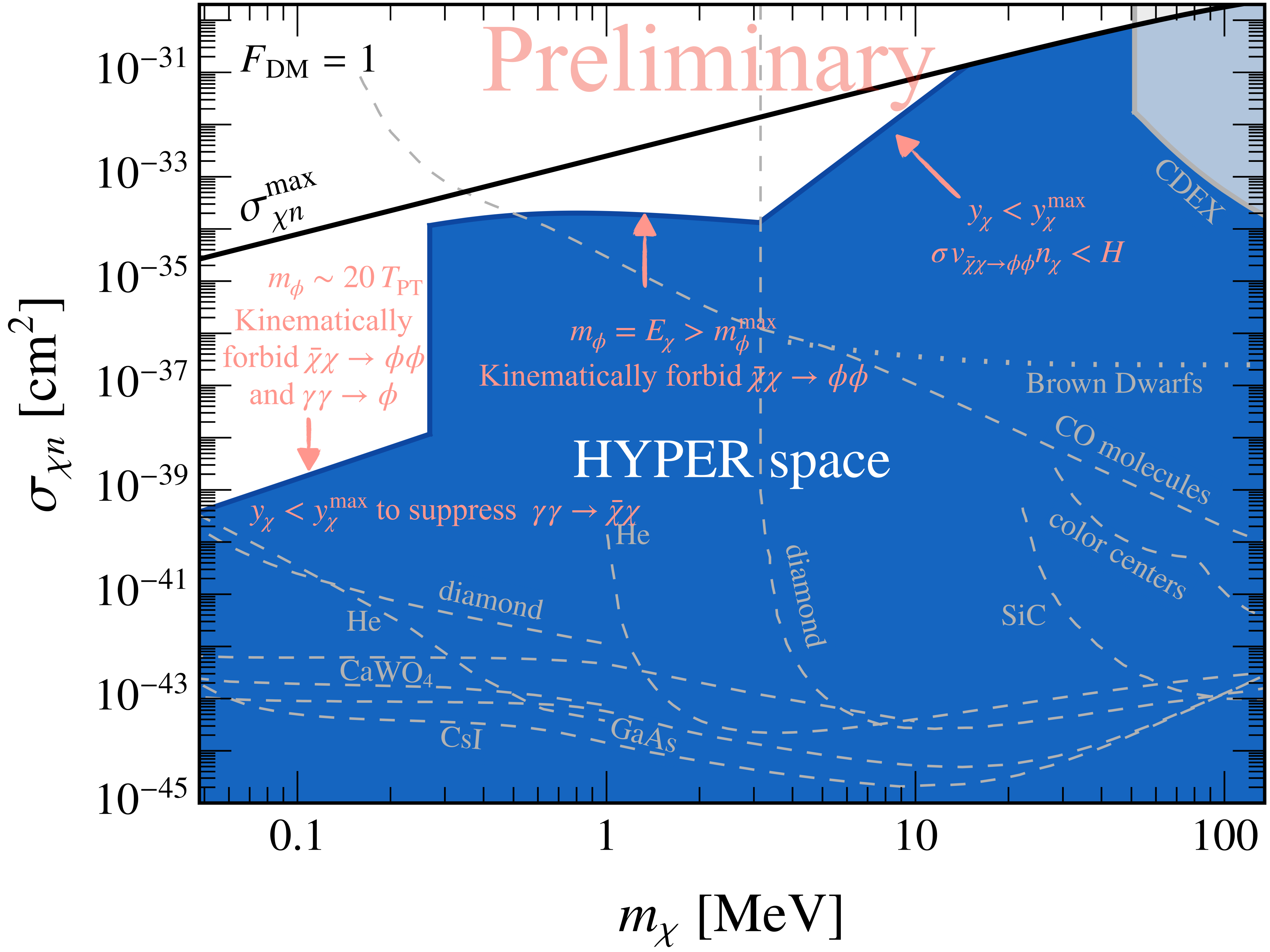

G. Elor

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.

Outlook/Future Directions

- Derive $\sigma_{\chi e}^{\max}$ and leptophilic HYPER models! Would likely require $T_{\mathrm{PT}} \lesssim m_e$
- 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

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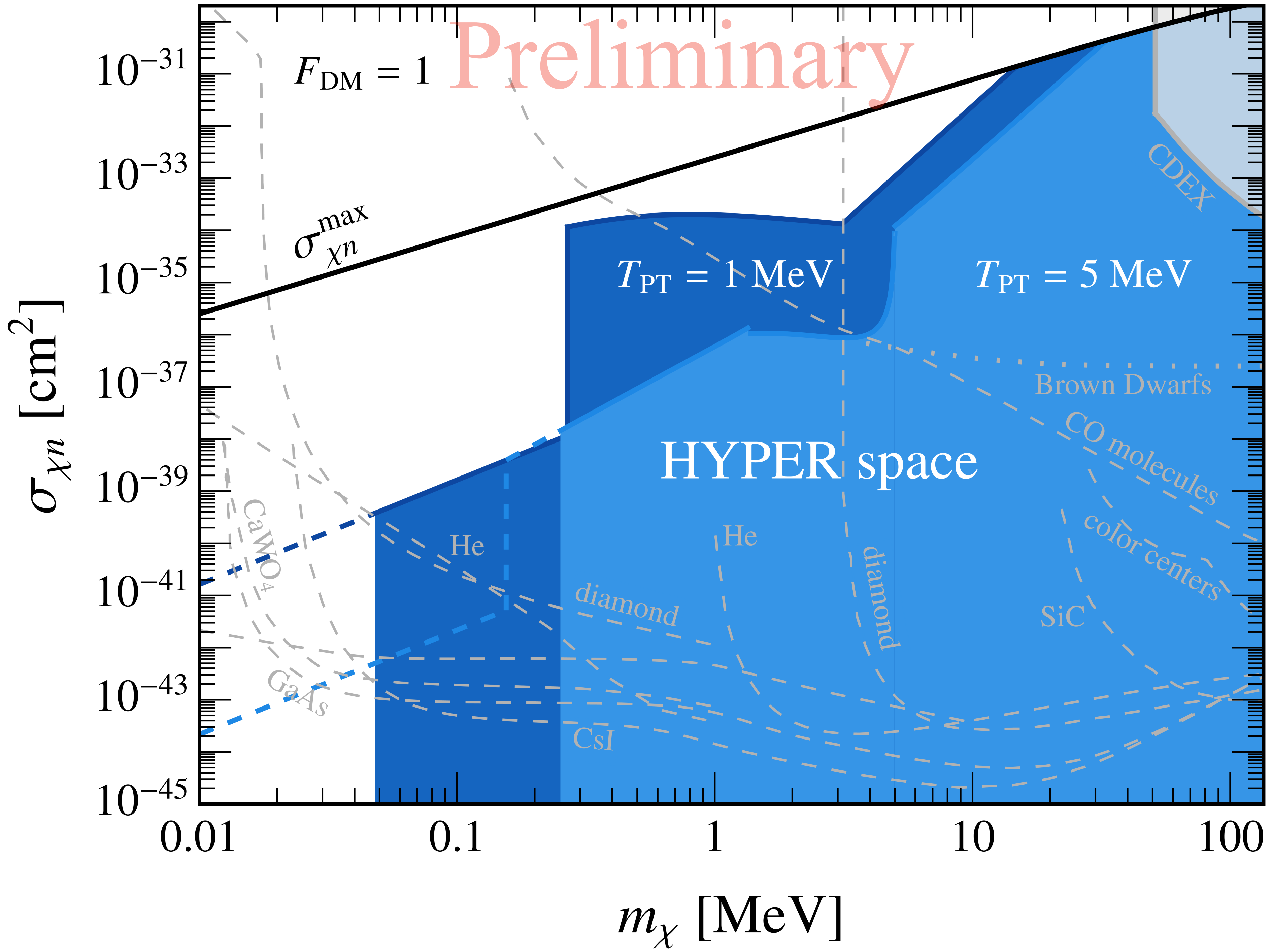
Thanks!

Back ups

Higher Temperatures



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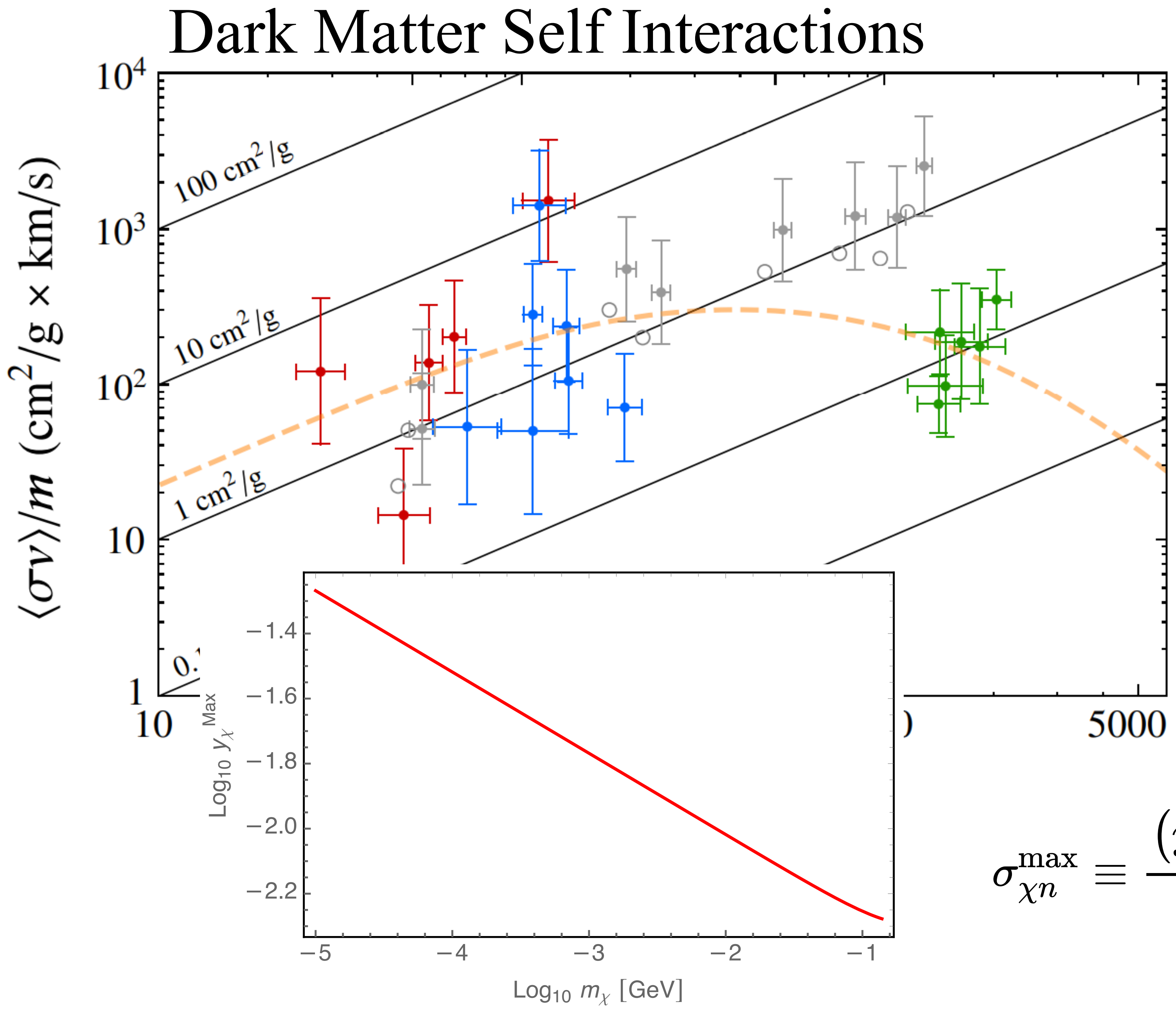
Estimating $\sigma_{n\chi}^{\max}$



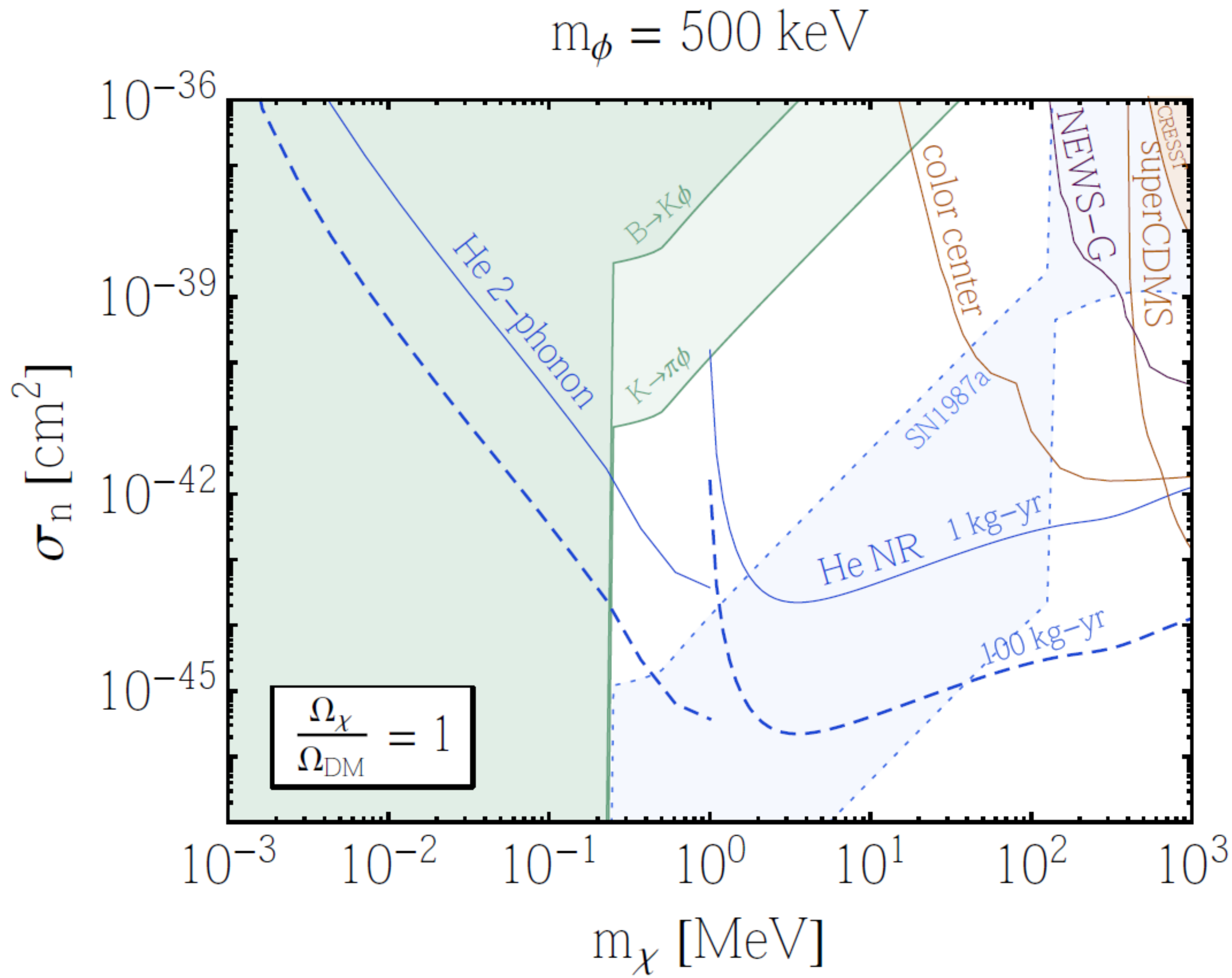
Dwarf, LSB,
SIDM *N*-body,
cluster data

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

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

G. Elor

Sub-GeV DM Detetors



Superfluid Helium [1611.06228, 1709.07882]