Maximizing Direct Detection*
with HYPER Dark Matter

Gilly Elor

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TACOS

Based on:

[arXiv:2112.03920, PRL] **GE**, Robert McGehee and Aaron Pierce
[arXiv:2210.15653, JHEP] Prudhvi Bhattiprolu, **GE**, Robert McGehee and Aaron Pierce

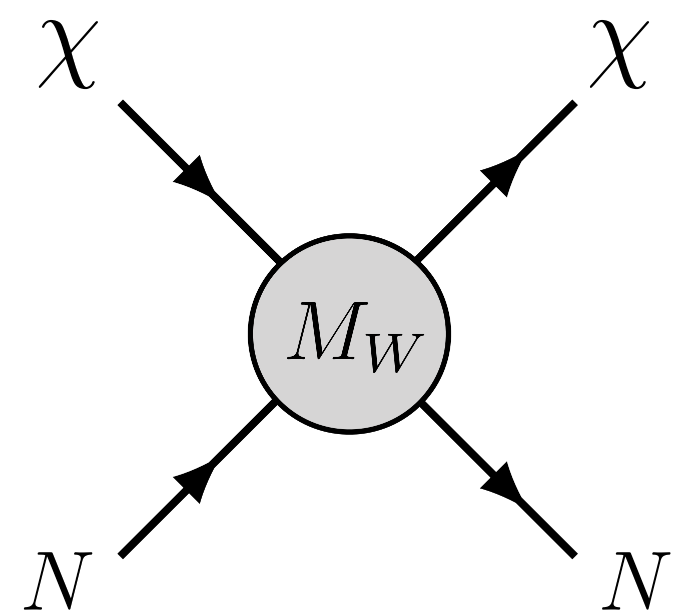
*Not a hardcore direct detection talk (there will be Cosmology and Astrophysics)

Dark Matter Direct Detection

"Vanilla" WIMP:

- Interacts via weak force
- $m_\chi \sim$ 10 GeV - 10 TeV

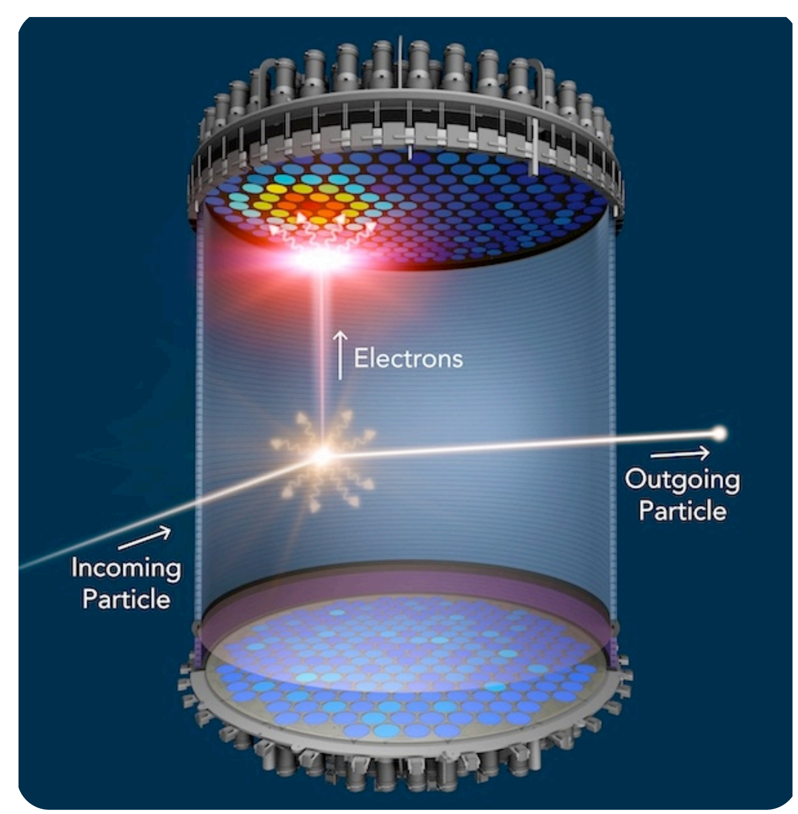
Searching for WIMP DM?



Direct Detection Searches:

- Elastic Scattering: DM imparts kinetic energy on nuclei
- Measure nuclear recoil

$$E_R \sim \frac{\mu^2 v^2}{M_N}$$



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Dark Matter Direct Detection

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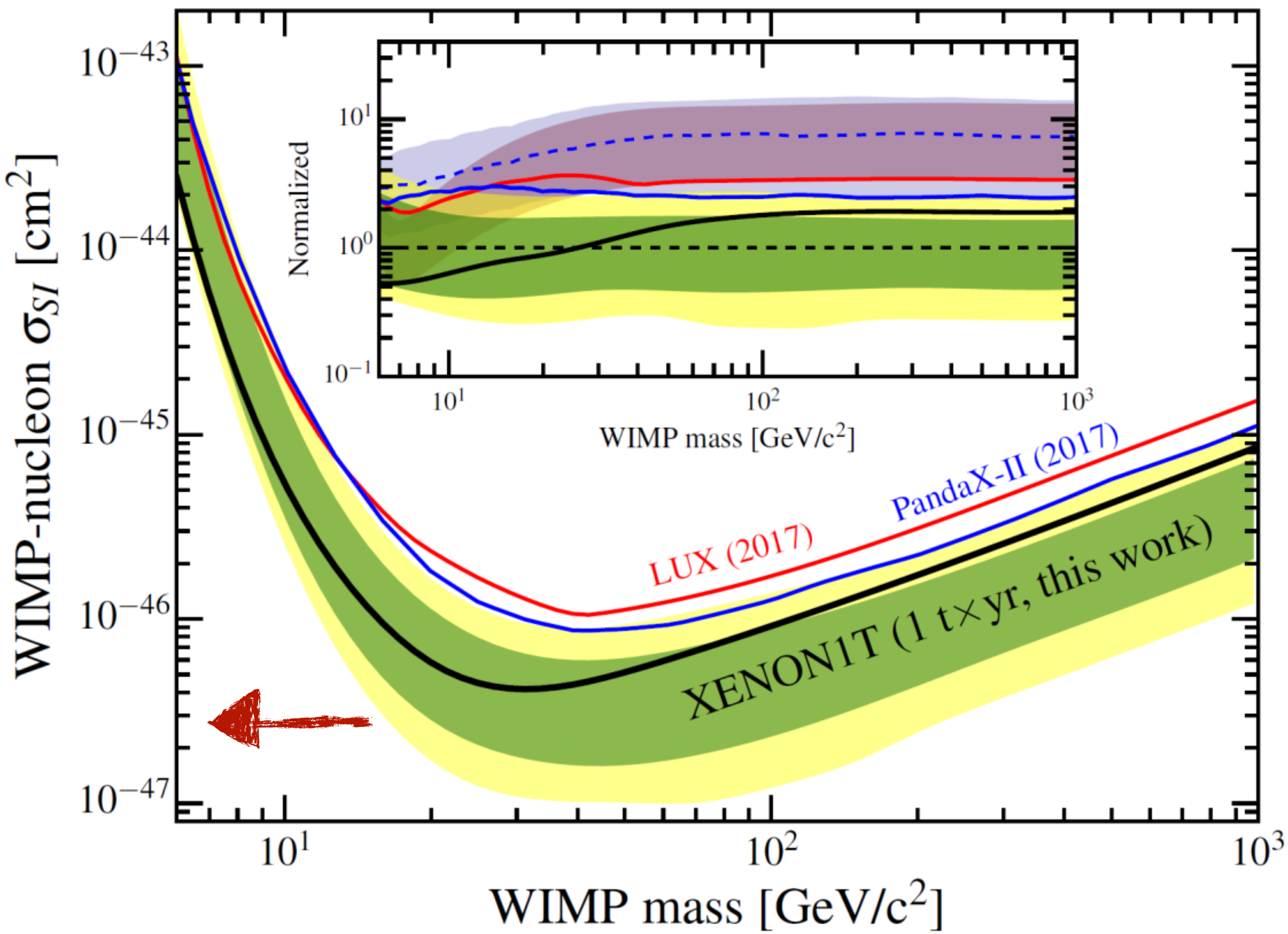
Searching for Dark Matter with Nuclear Scattering



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

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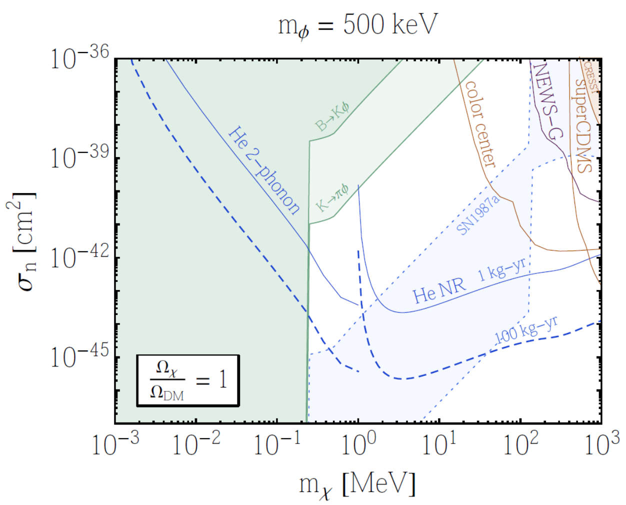
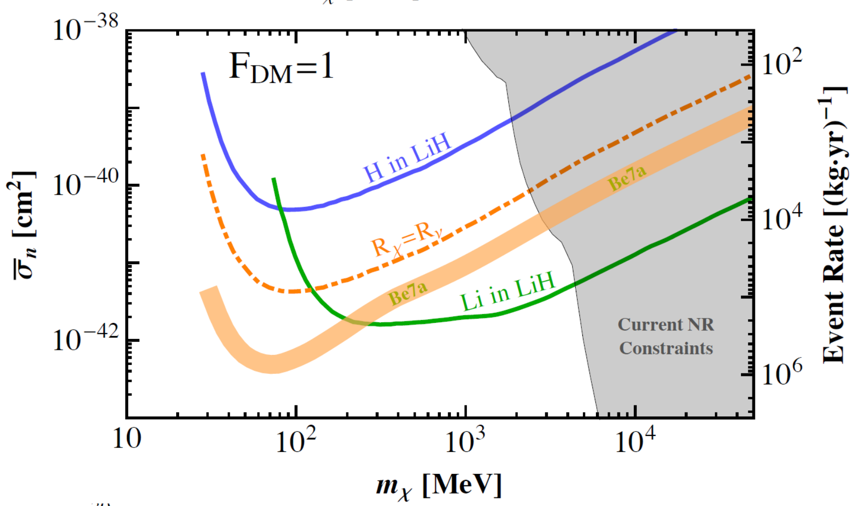
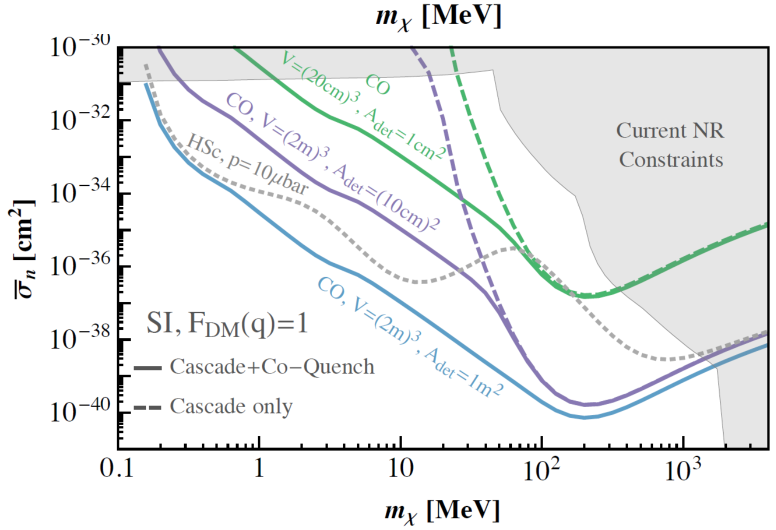
Proposed Experiments: Sub-GeV Dark Matter with Nuclear Scattering



Superfluid Helium
[1611.06228, 1709.07882]

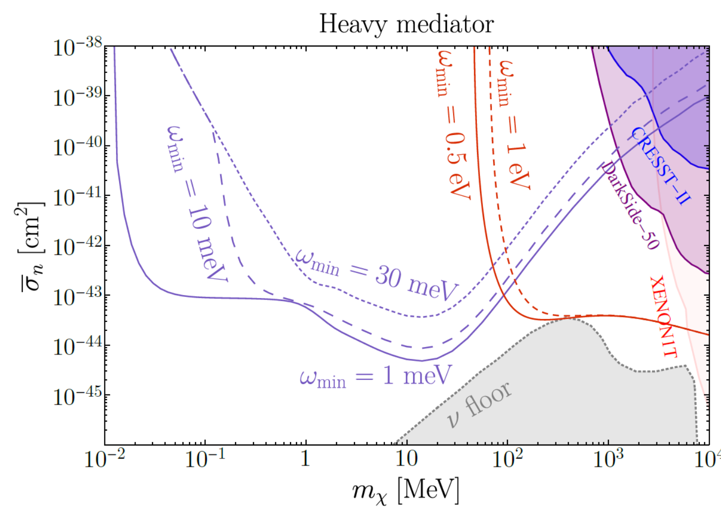


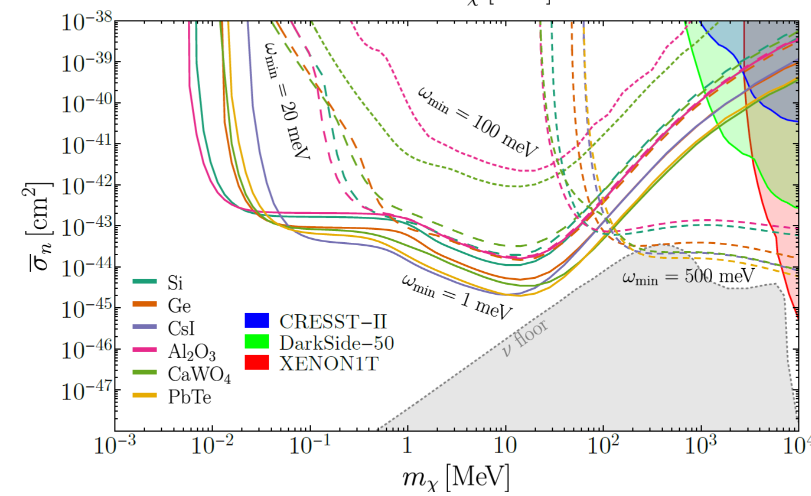
Color Center Production in Crystals
[1705.03016]



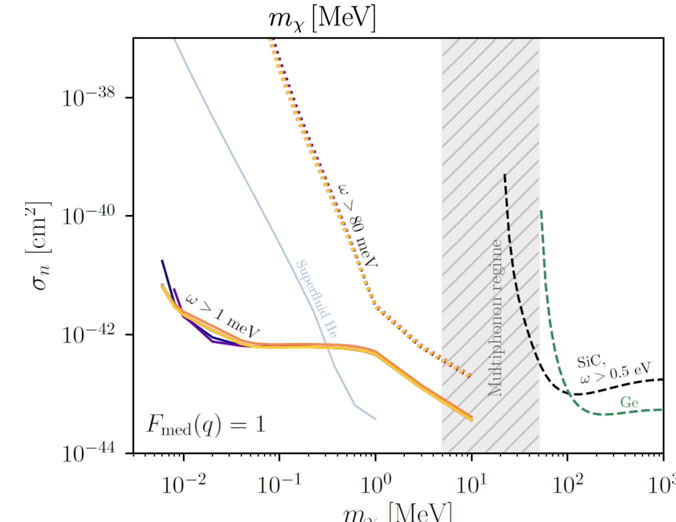
Molecular Excitations
[1907.07682]

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





Silicon Carbide
[2008.08560]



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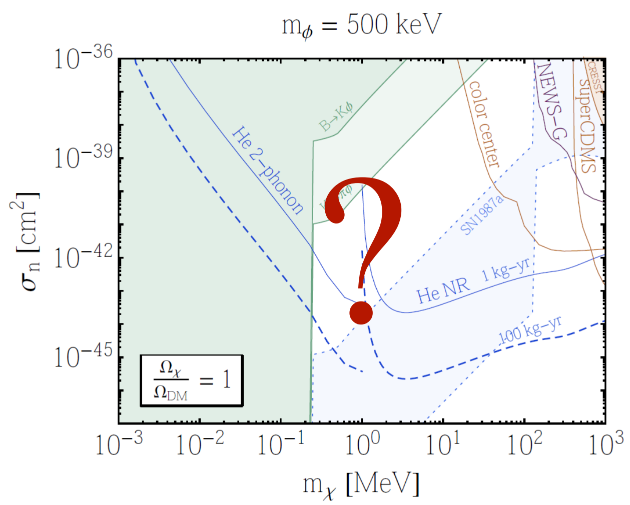
Where is the Dark Matter?



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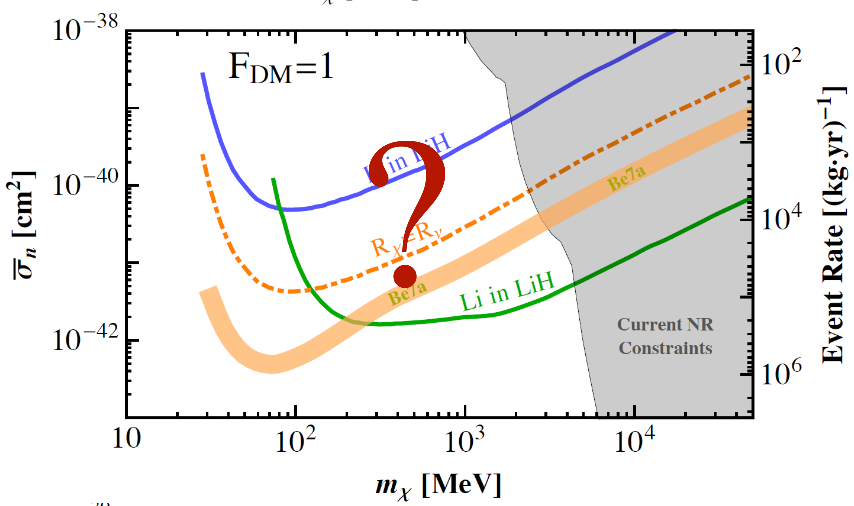

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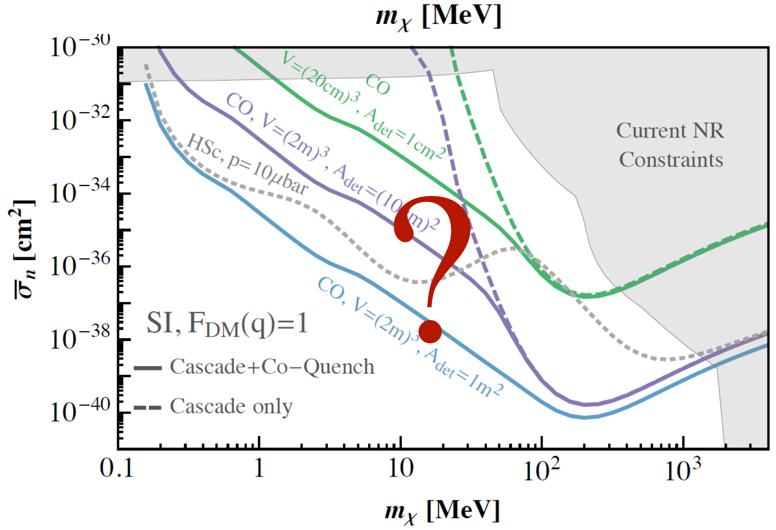

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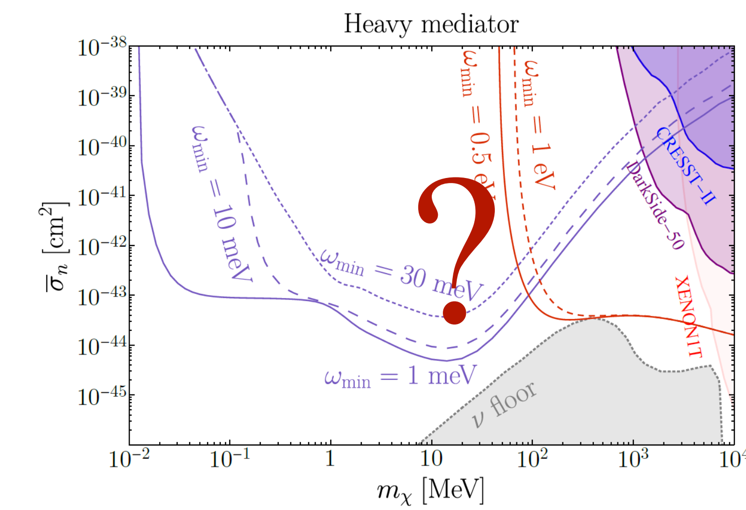

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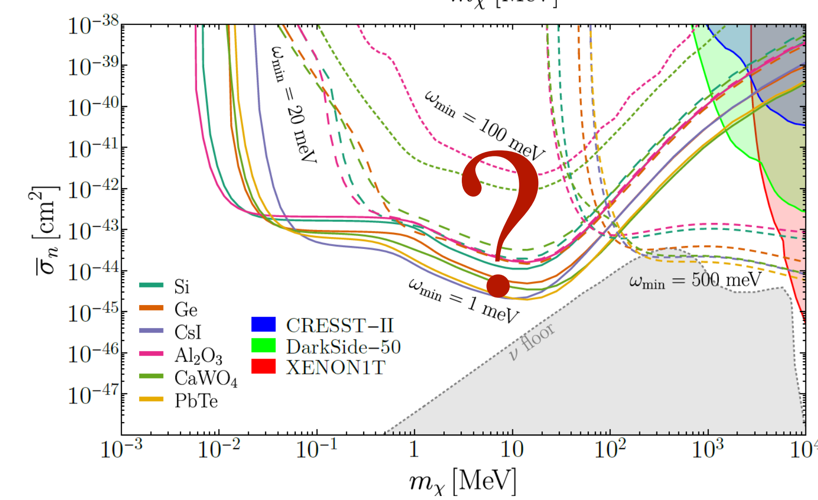

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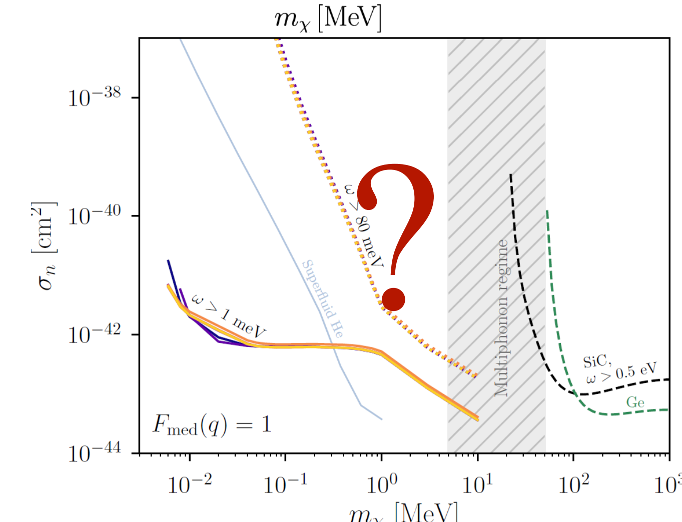

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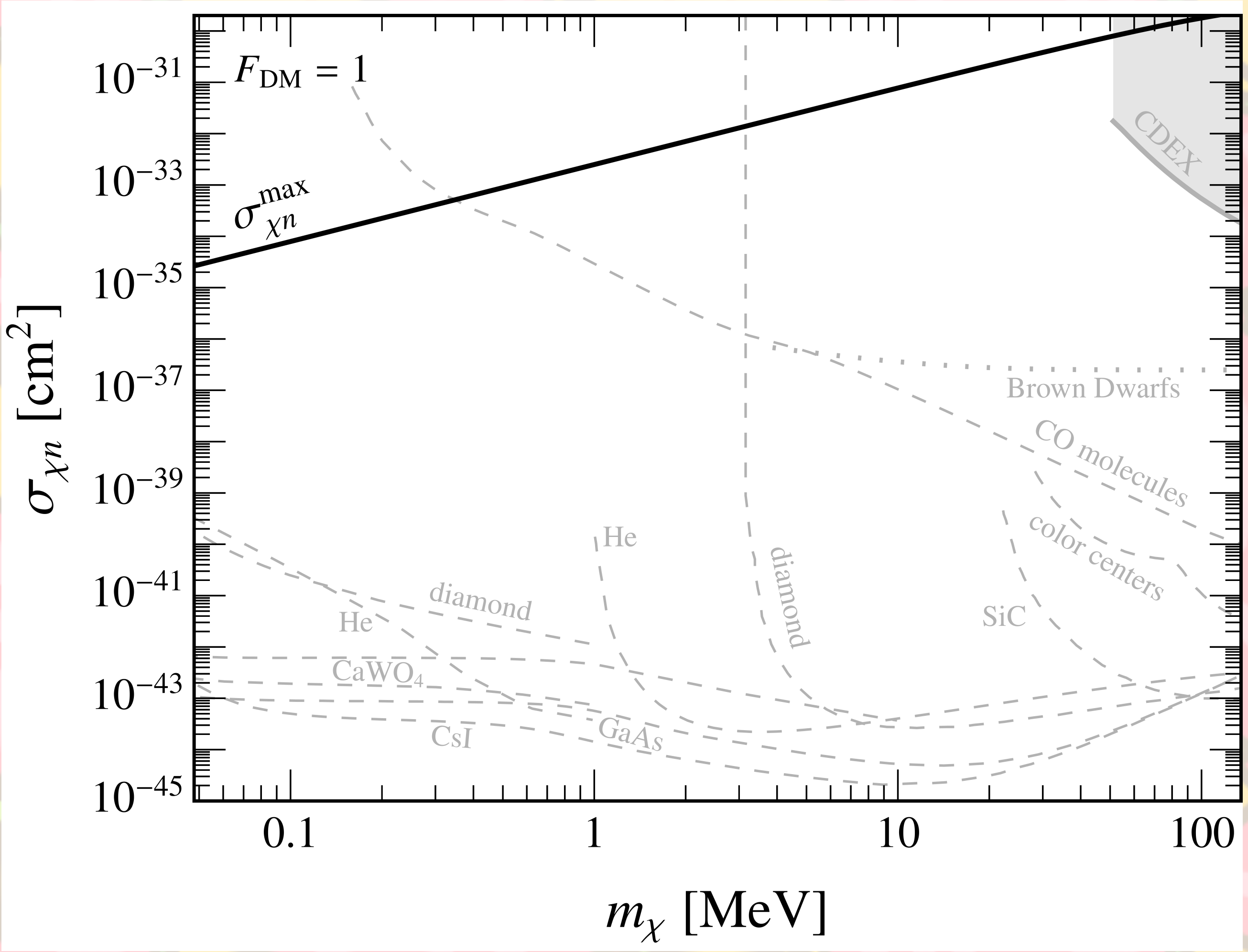
Maximizing Direct Detection

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

To design experiments targeting larger cross sections is not motivated.



[arXiv:2112.03920, PRL] **GE**, Robert McGehee and Aaron Pierce

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 $m_\psi \gtrsim 1.5\ \mathrm{TeV}$

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

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

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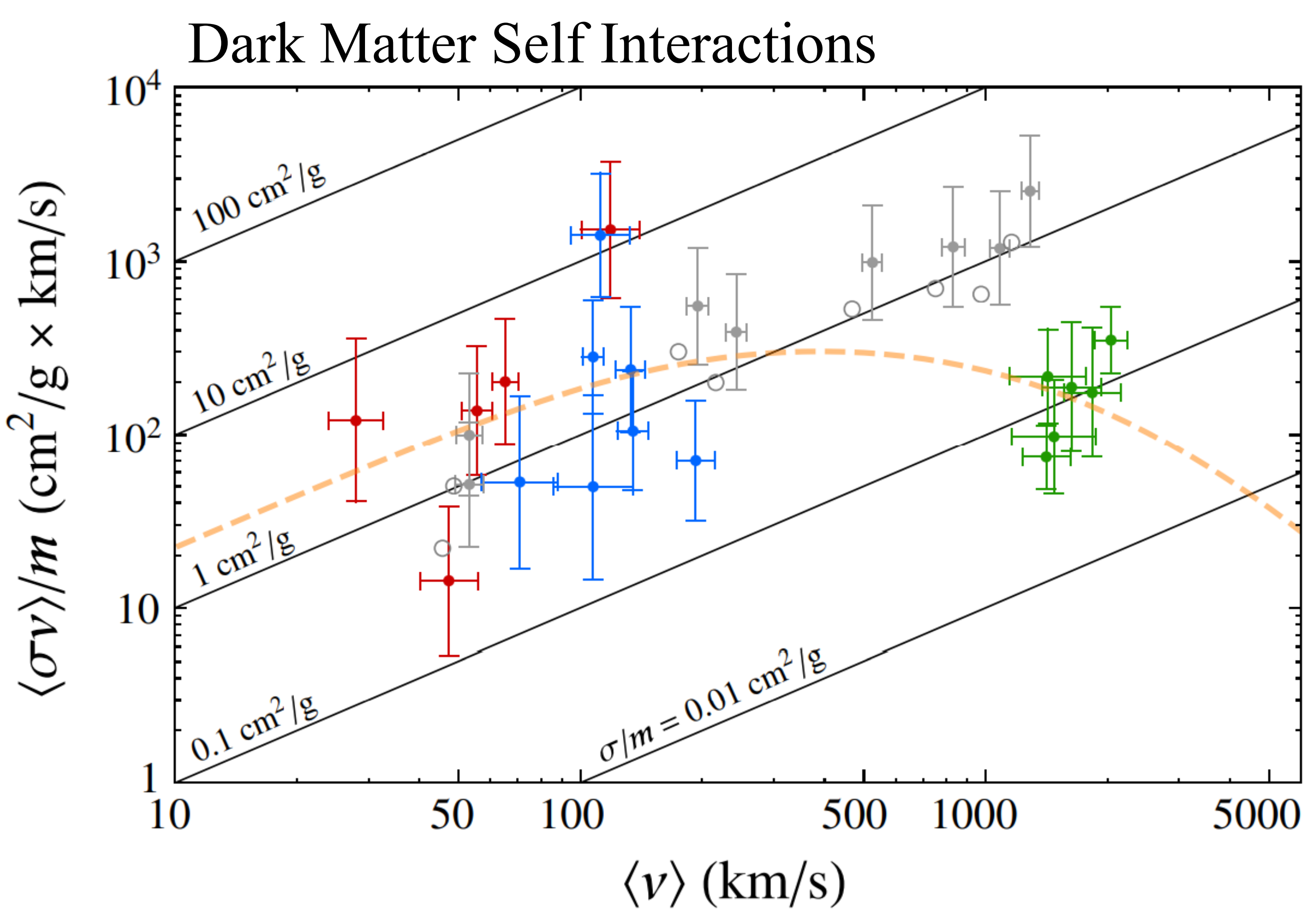
Estimating $\sigma_{n\chi}^{\max}$: Self Interactions



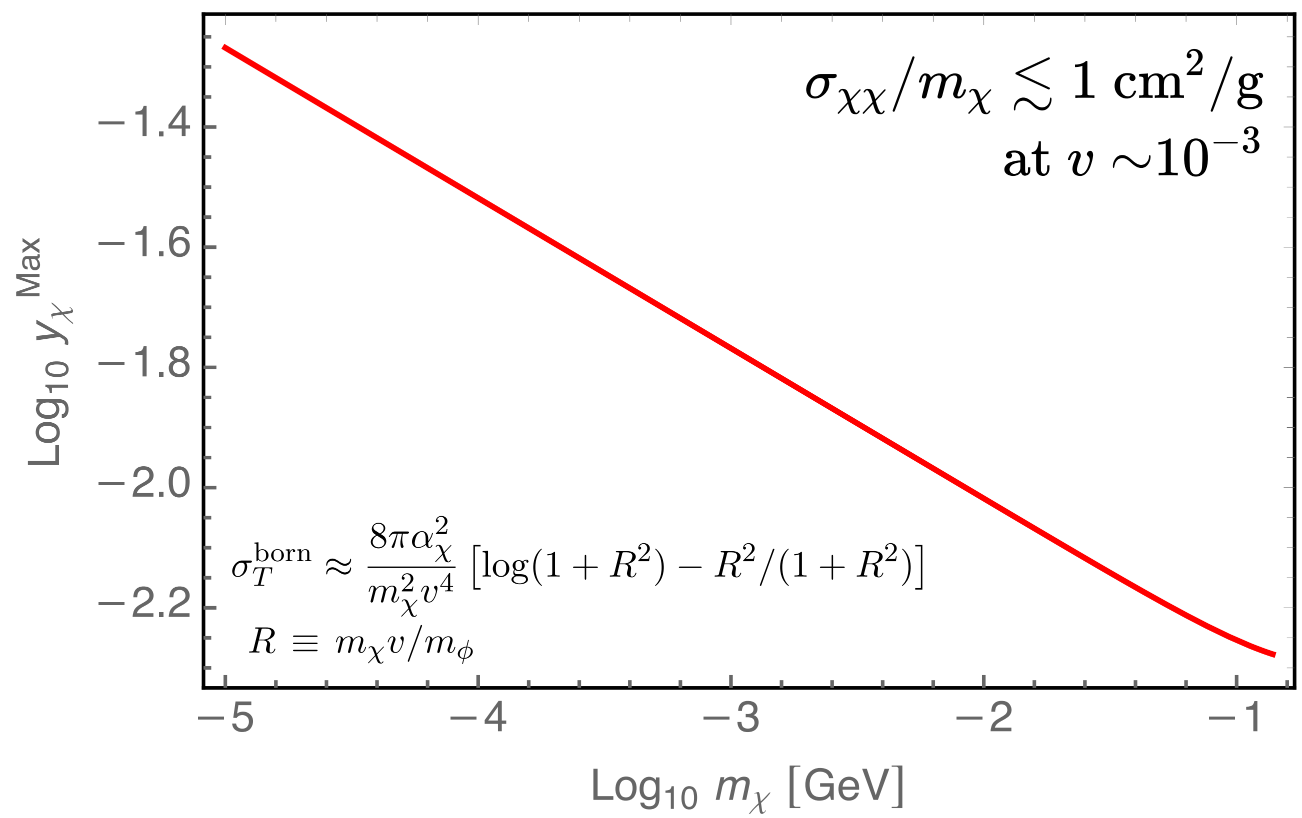
1508.03339

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

Self interactions constrained by shapes of halos

$$y_\chi \phi \bar{\chi} \chi$$

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



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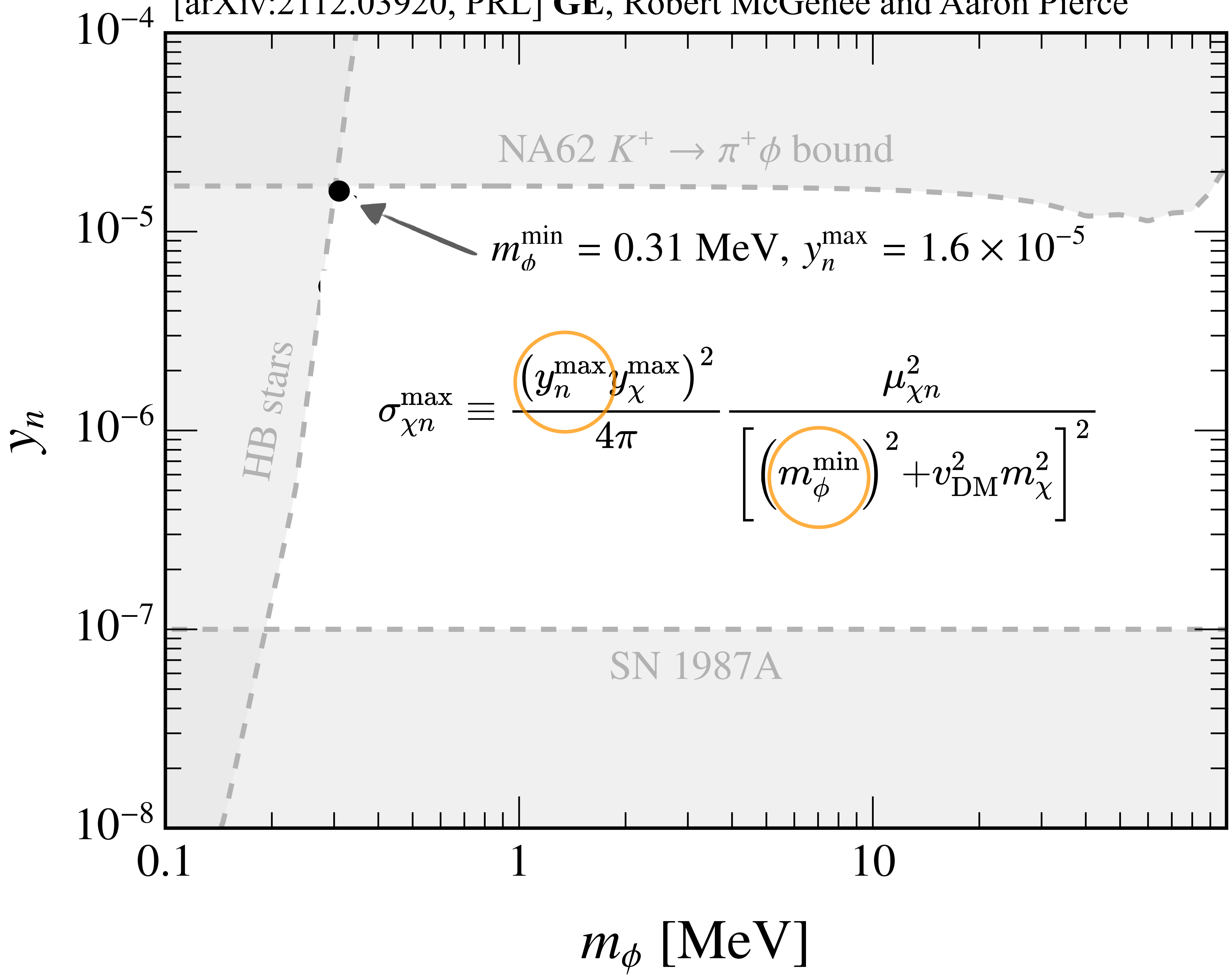
Estimating $\sigma_{n\chi}^{\max}$

[arXiv:2112.03920, PRL] **GE**, Robert McGehee and Aaron Pierce



$y_n \phi \bar{n} n$

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

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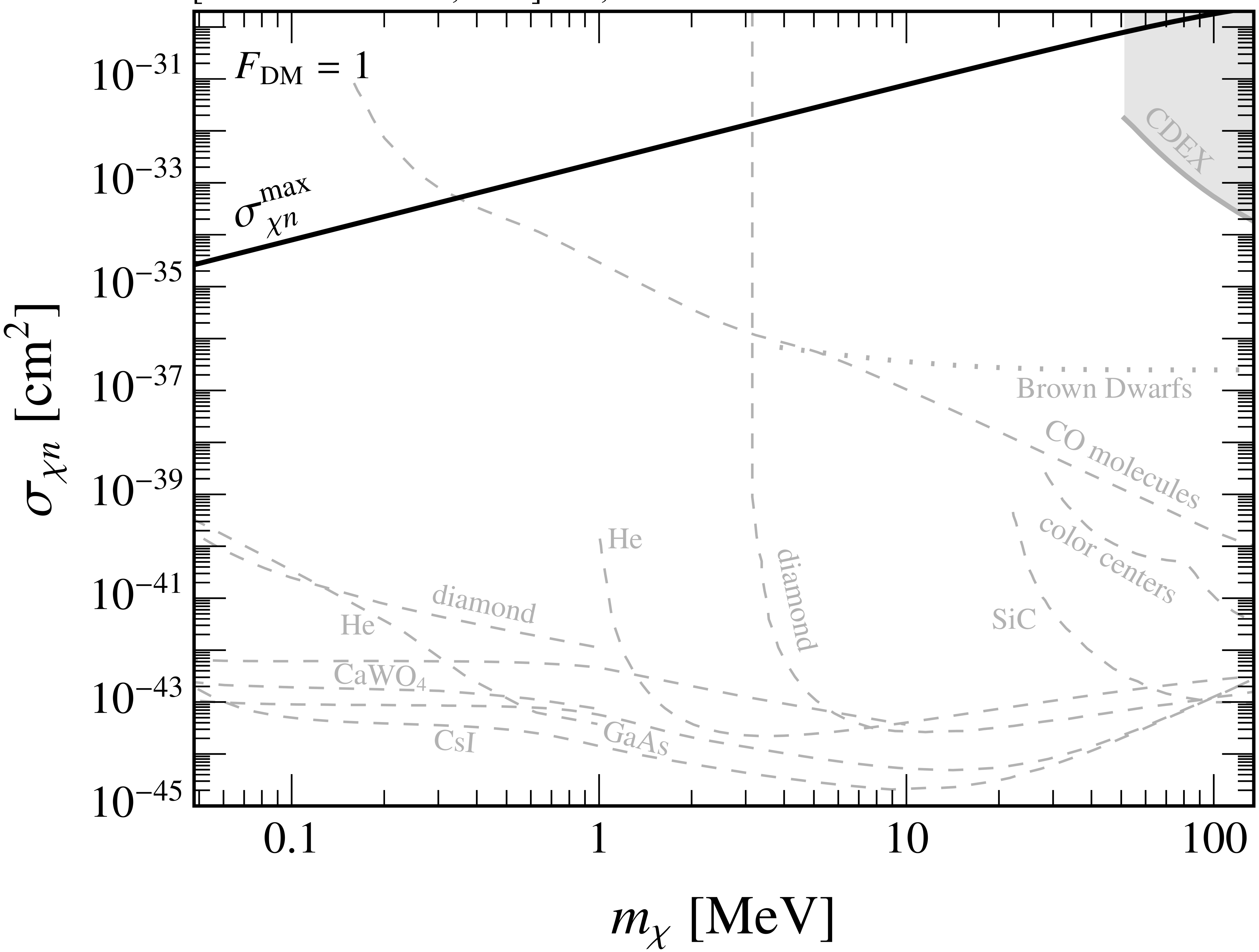

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Robustness of $\sigma_{n\chi}^{\max}$?

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

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

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

- Hadrophilic scalar with different UV completion e.g. mediator couples directly to quarks → Meson bounds are more constraining → smaller $\sigma_{n\chi}^{\max}$.
- Vector Mediator? e.g. visibly decaying dark photon: beam dump and collider constraints make $\sigma_{n\chi}^{\max}$ smaller.
- Composite asymmetric dark matter [1812.07573].

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?

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

- 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.

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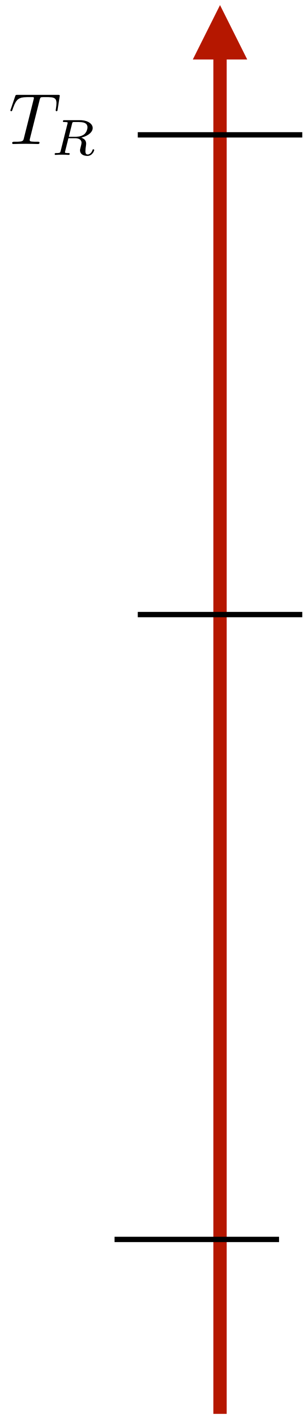
HYPERs :

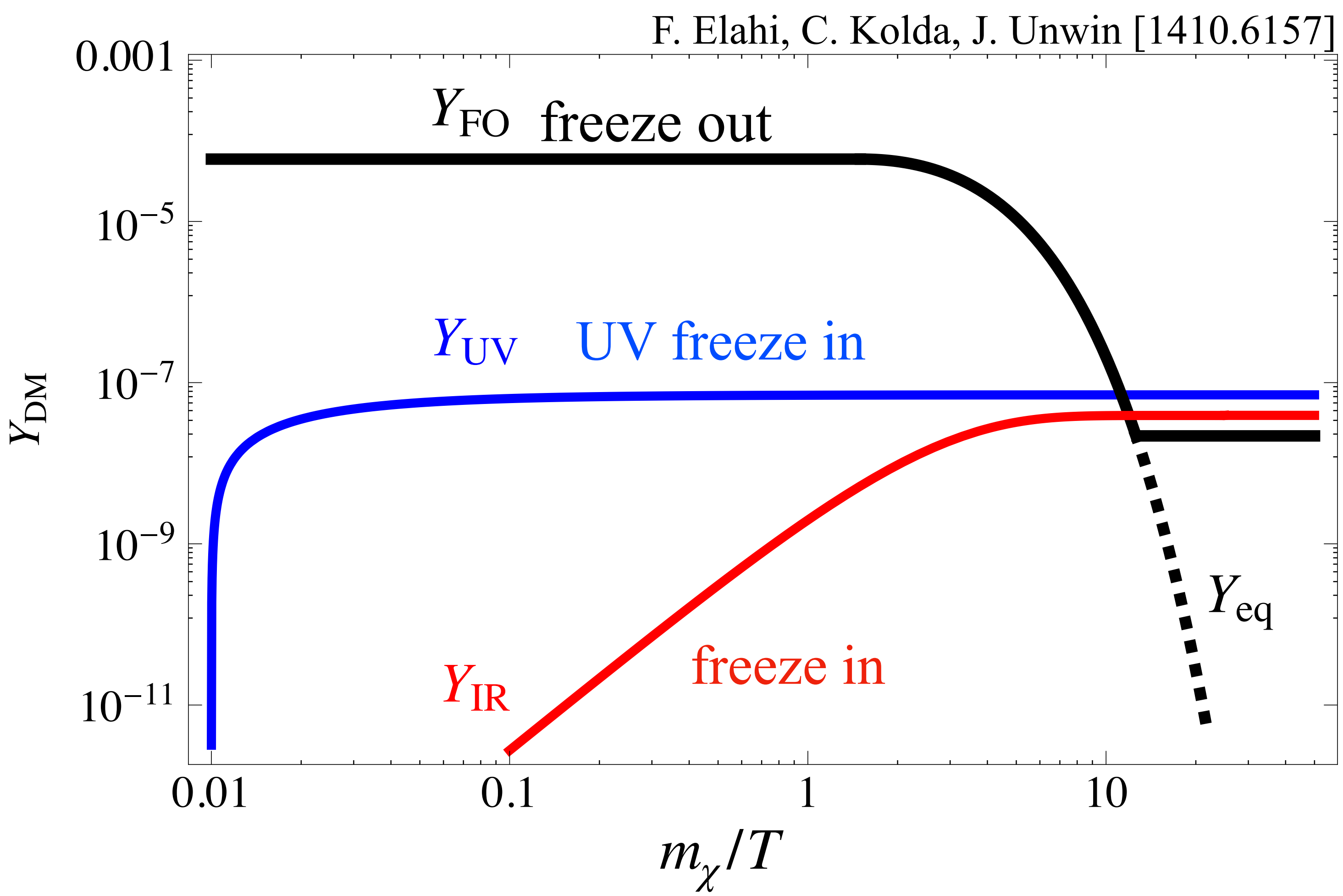
HighlY interactive ParticlE Relics



UV Freeze In $\quad \Omega_\chi h^2 = 0.11 \quad\quad \mathrm{SM\,SM} \to \phi \to \chi\bar{\chi} \quad\quad m_\phi^i > T_R$

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

$$10\,\mathrm{GeV} \lesssim T_R \lesssim 300\,\mathrm{GeV}$$



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HYPERs :
HighlY interactive ParticlE Relics

T_R — UV Freeze In $\Omega_\chi h^2 = 0.11$ $\quad \mathrm{SM\,SM} \to \phi \to \chi\bar{\chi}$ $\quad m_\phi^i > T_R$

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

$10\,\mathrm{GeV} \lesssim T_R \lesssim 300\,\mathrm{GeV}$

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

For HYPERs the *mediator* mass changes

$m_\phi^i \sim \mathcal{O}\,(10\,T_R) \to m_\phi \sim \mathcal{O}\,(\mathrm{MeV})$

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

$\bar{\chi}\chi \not\leftrightarrow \mathrm{dark}\,, \ \ \mathrm{dark} \leftrightarrow \gamma\gamma$

→ $m_\phi > m_\phi^{\rm max}\,, \ \mathrm{and/or}\ y_\chi < y_\chi^{\rm max}$

$\bar{\chi}\chi \not\leftrightarrow$ hadrons

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

hadrons $\not\leftrightarrow \bar{\chi}\chi$

→ $1\ \mathrm{MeV} \lesssim T_{\rm PT} \lesssim m_{\pi^0}$

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

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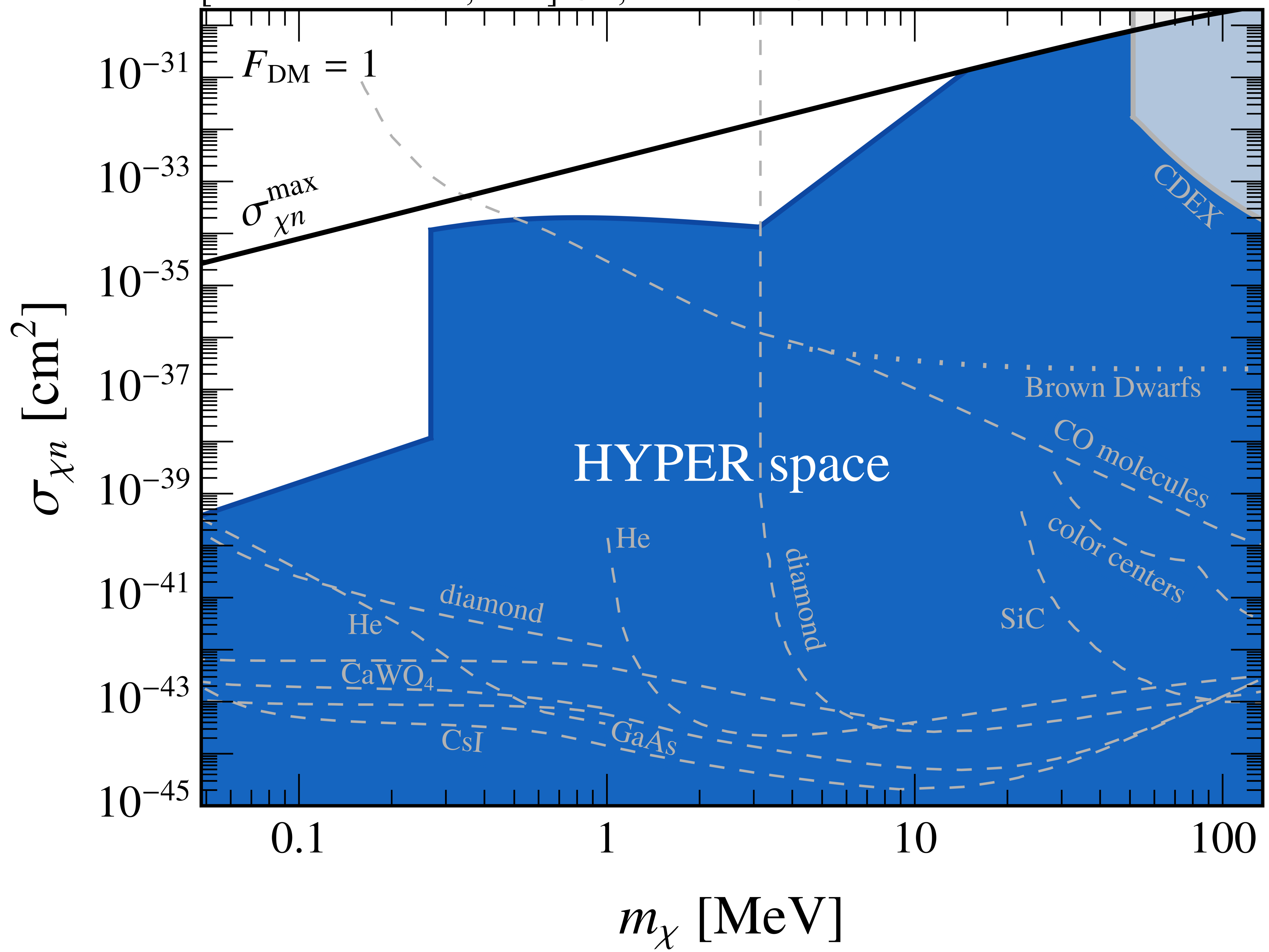
Achieving $\sigma_{n\chi}^{\max}$ with HYPERs

[arXiv:2112.03920, PRL] **GE**, Robert McGehee and Aaron Pierce



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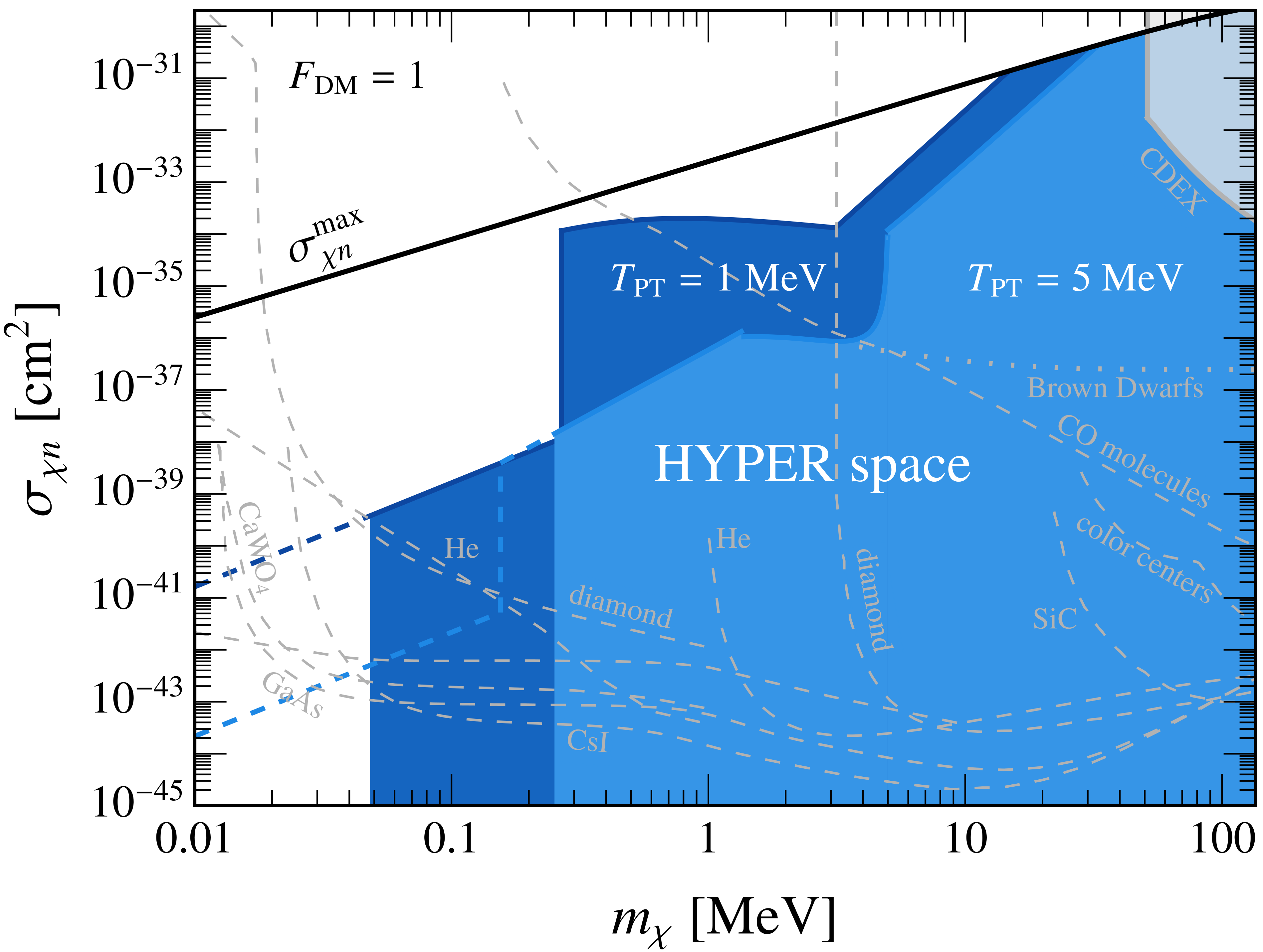
Going to higher $T_{\rm PT}$

Additional problematic process become possible e.g. $\pi^{\pm}\gamma \to \pi^{\pm}\phi$



$$\mathcal{L} \supset \frac{3y_n}{m_n}\phi\left(\frac{2}{3}\left|D^\mu\pi^+\right|^2 - m_\pi^2\pi^+\pi^-\right).$$

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

$$2\sigma v_{\pi^+\gamma\to\pi^+\phi}\, n_\gamma^{\rm eq} n_{\pi^+}^{\rm eq} \lesssim 0.15 H n_\chi$$

$\rightarrow$ $T_{\rm PT} \lesssim 6.7$ MeV.

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Other Cosmological Histories?

HYPERs

T

T_R — UV Freeze In

$$Y_\chi \simeq 4\times 10^{-5}\left(\frac{y_n y_\chi \alpha_s}{m_n (m_\phi^i)^2}\right)^2 \frac{M_{\rm Pl} T_R^5}{g_{s,*}\sqrt{g_*}}$$

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

Today — Direct detection $\sigma_{\chi n} = \frac{(y_n y_\chi)^2}{\pi}\frac{\mu_{\chi n}^2}{m_\phi^4}.$

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Low Scale Freeze-In

[arXiv:2210.15653, JHEP] Prudhvi Bhattiprolu, **GE**, Robert McGehee and Aaron Pierce

T

Decreasing T_R increases $y_n y_\chi / m_\phi^2$ for a fixed yield and increases the cross section at direct detection

$5\ \text{MeV} \lesssim T_\text{R} \lesssim 20\ \text{MeV}$

UV Freeze In

$$Y_\chi \simeq 4 \times 10^{-5} \left(\frac{y_n y_\chi \alpha_s}{m_n (m_\phi^i)^2} \right)^2 \frac{M_\text{Pl} T_R^5}{g_{s,*} \sqrt{g_*}}$$

Today

Direct detection $\sigma_{\chi n} = \frac{(y_n y_\chi)^2}{\pi} \frac{\mu_{\chi n}^2}{m_\phi^4}.$

Low Scale Freeze-In

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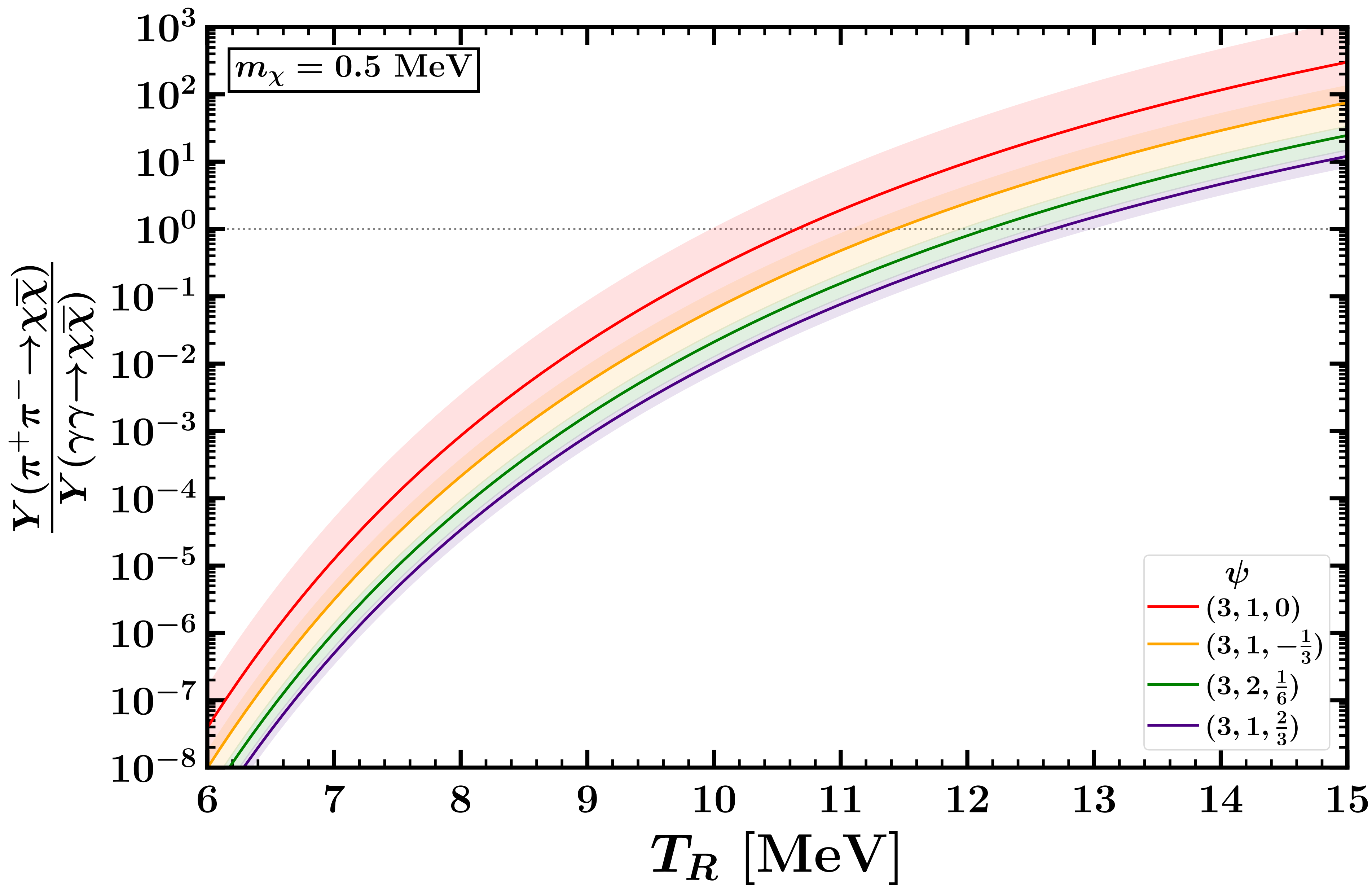
$$\mathcal{L} \supset \frac{3y_n}{m_n}\phi\left(\frac{2}{3}\left|D^\mu\pi^+\right|^2 - m_\pi^2\pi^+\pi^-\right). \qquad \mathcal{L}_{\phi FF} \sim \frac{7y_n\alpha}{8\pi m_p}\phi F_{\mu\nu}F^{\mu\nu}$$



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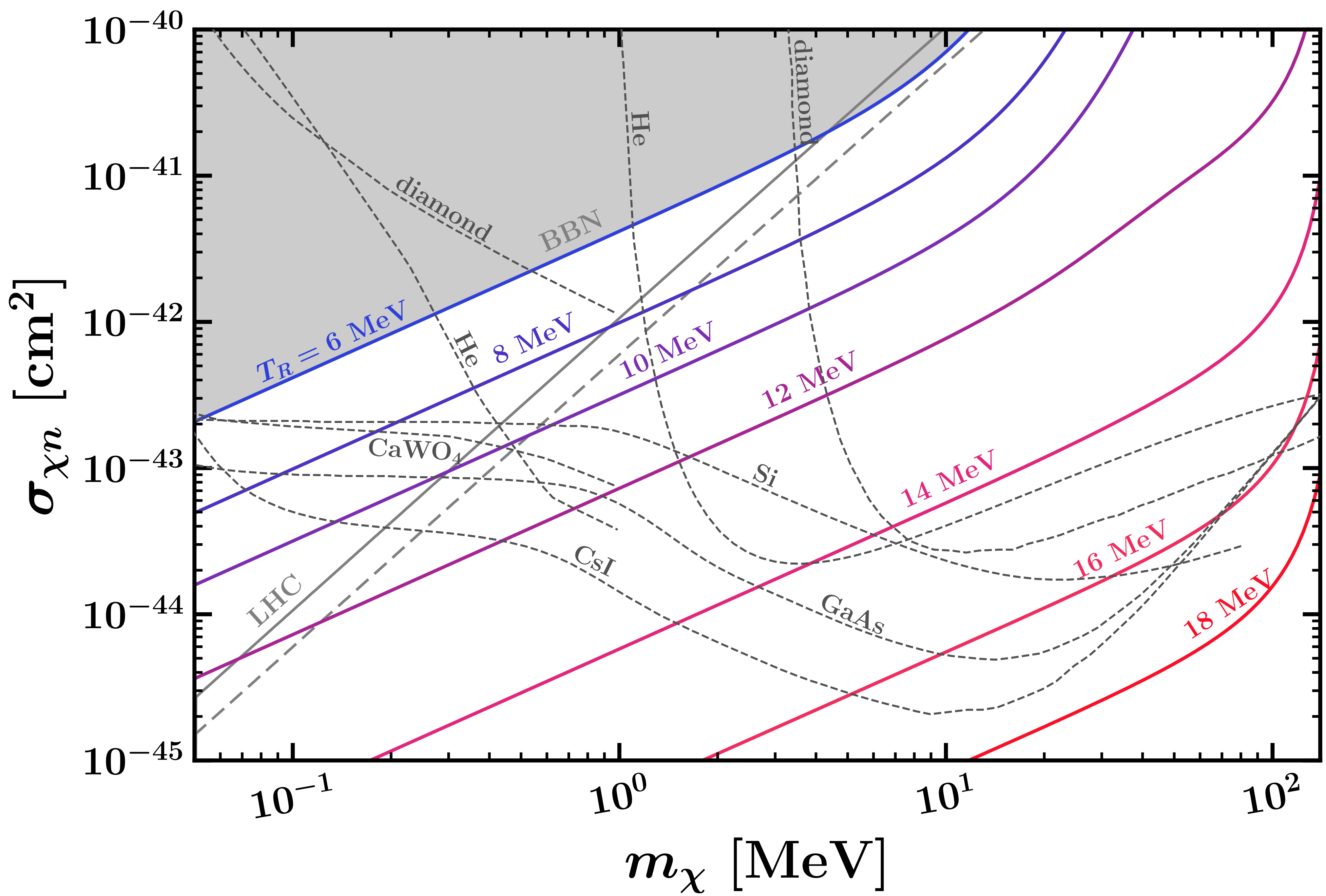
Detectable at Direct Detection

[arXiv:2210.15653, JHEP] Prudhvi Bhattiprolu, **GE**, Robert McGehee and Aaron Pierce



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Take Aways

- Given present day constraints, it is unmotivated to build experiments targeting DM-nuclear cross sections larger than:

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

- Even so, is not easy to find DM models that realizes such large cross sections. HYPERs involves a dark sector phase transition and can achieve $\sigma_{\chi n}^{\max}$.

- Freeze in with a hadrophilic mediator at very low reheating temperatures can also lead to detectable cross sections.

- Ongoing work: CMB and Supernova bounds on a late dark sector phase transition **GE**, Ryusuke Jinno, Soubhik Kumar, Robert McGehee, Yuhsin Tsai [arXiv:2310.xxxxx]

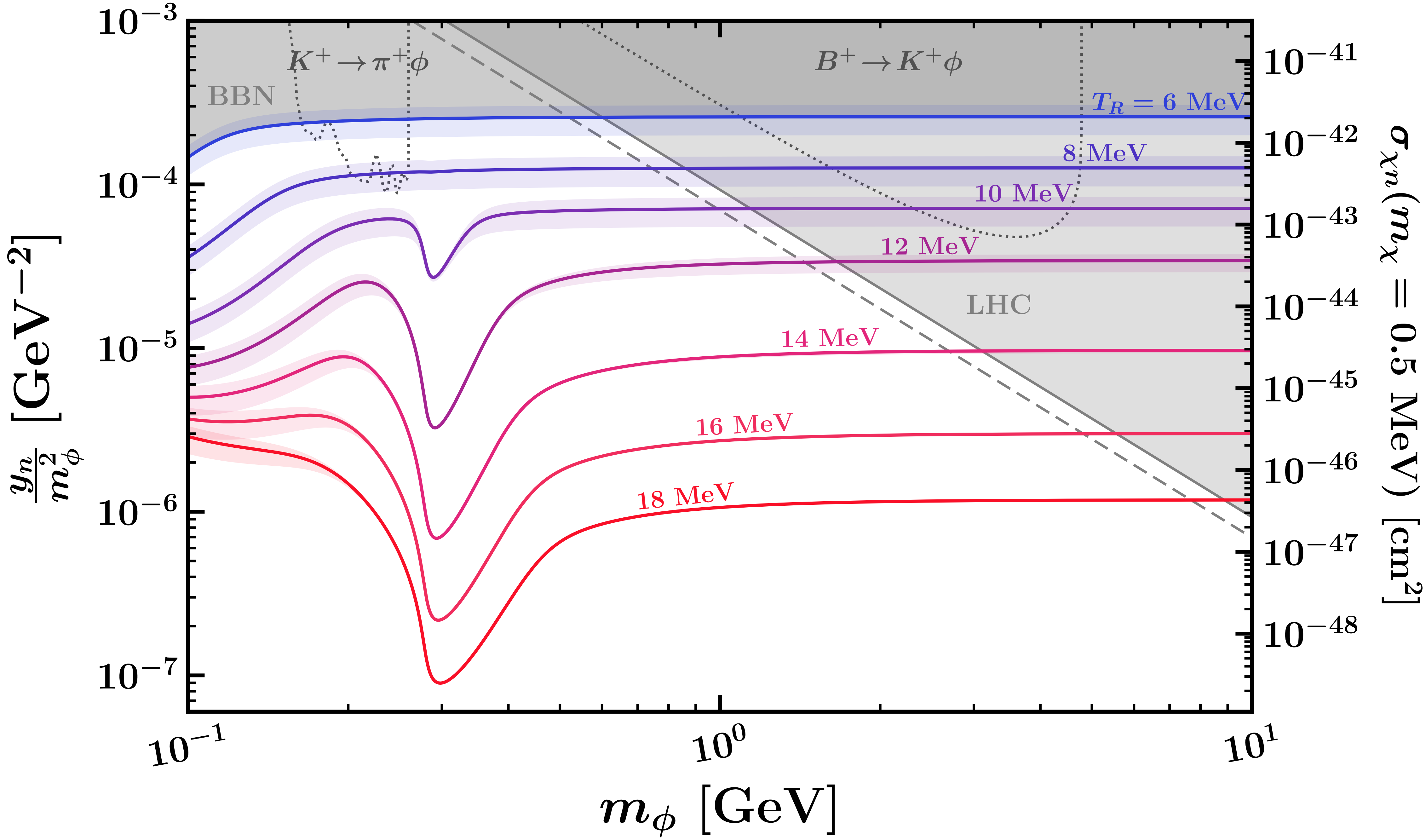
- Possible future work: model building (late time inflation, the phase transition…)

Back ups

Low Scale Freeze-In

[arXiv:2210.15653, JHEP] with Prudhvi Bhattiprolu, **GE**, Robert McGehee and Aaron Pierce

Decreasing T_R increases $y_n y_\chi / m_\phi^2$ for a fixed yield and increases the cross section at direct detection



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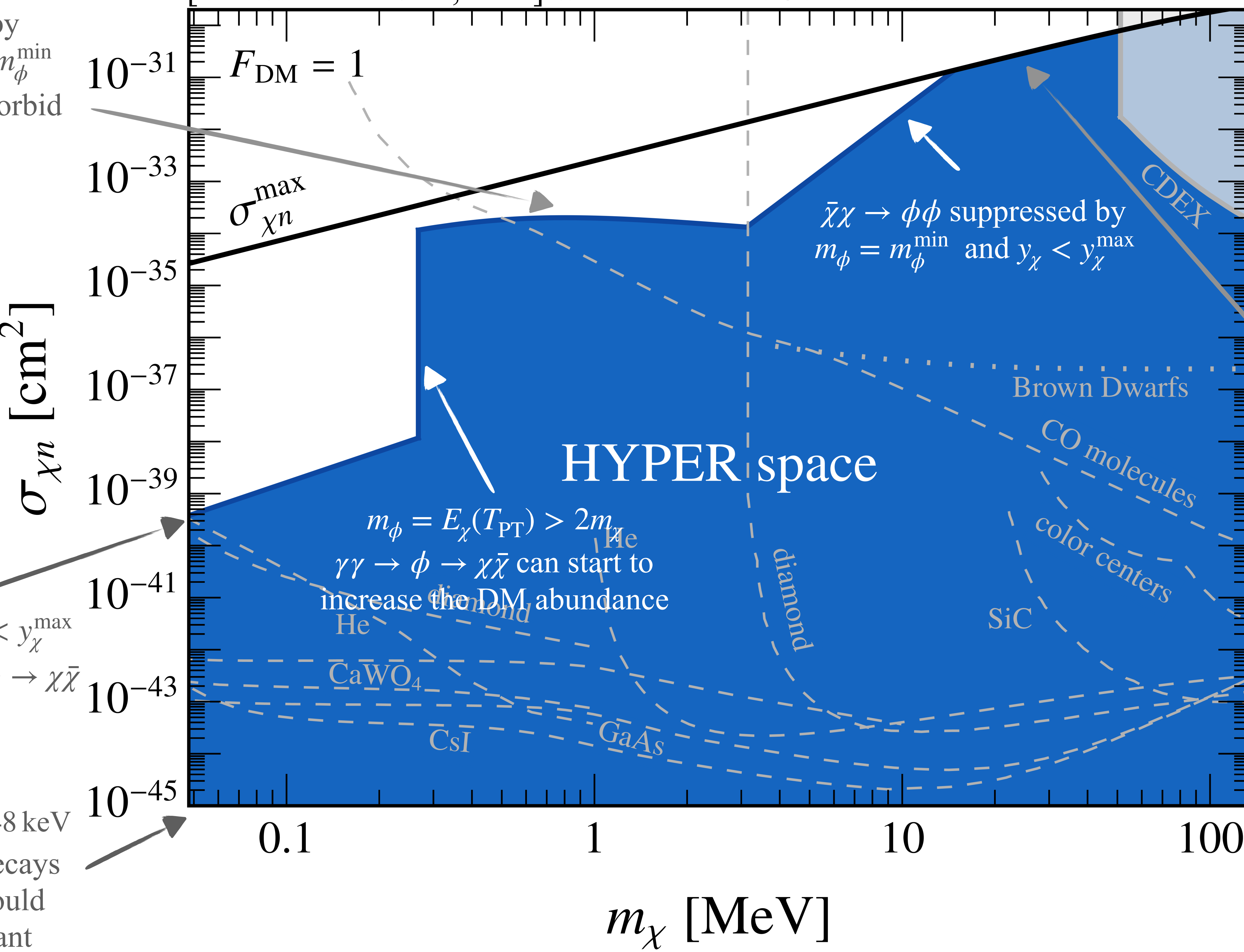
Achieving $\sigma_{n\chi}^{\max}$ with HYPERs

[arXiv:2112.03920, PRL] with Robert McGehee and Aaron Pierce

σ maximized by $m_\phi = E_\chi(T_{\rm PT}) > m_\phi^{\rm min}$ to kinematically forbid $\bar{\chi}\chi \to \phi\phi$



$\sigma v_{\bar{\chi}\chi}$ is p-wave suppressed so $\sigma v_{\bar{\chi}\chi \to \phi\phi} n_\chi < H$

$m_\phi > m_\phi^{\max}$ and $y_\chi < y_\chi^{\max}$ to suppress $\gamma\gamma \to \phi \to \chi\bar{\chi}$

$m_\chi = \omega_p(T_{\rm PT})/2 = 48$ keV below plasmon decays to dark matter could become important

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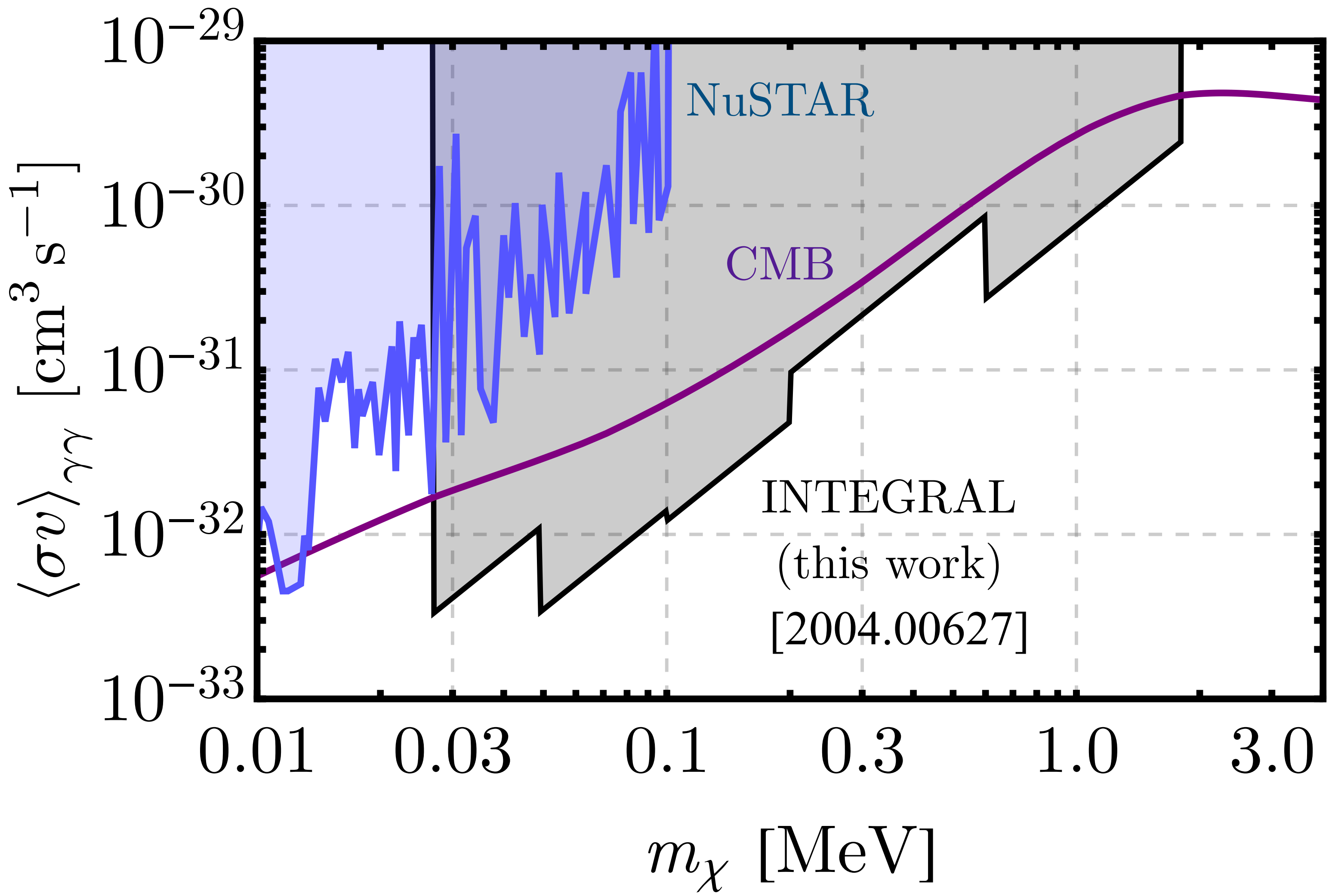
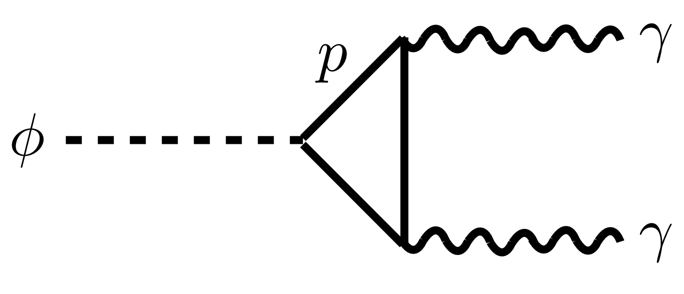
Indirect Detection $\chi\bar{\chi} \to \gamma\gamma$





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

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