Direct Detection of sub-GeV Hadrophilic Dark Matter

Robert McGehee
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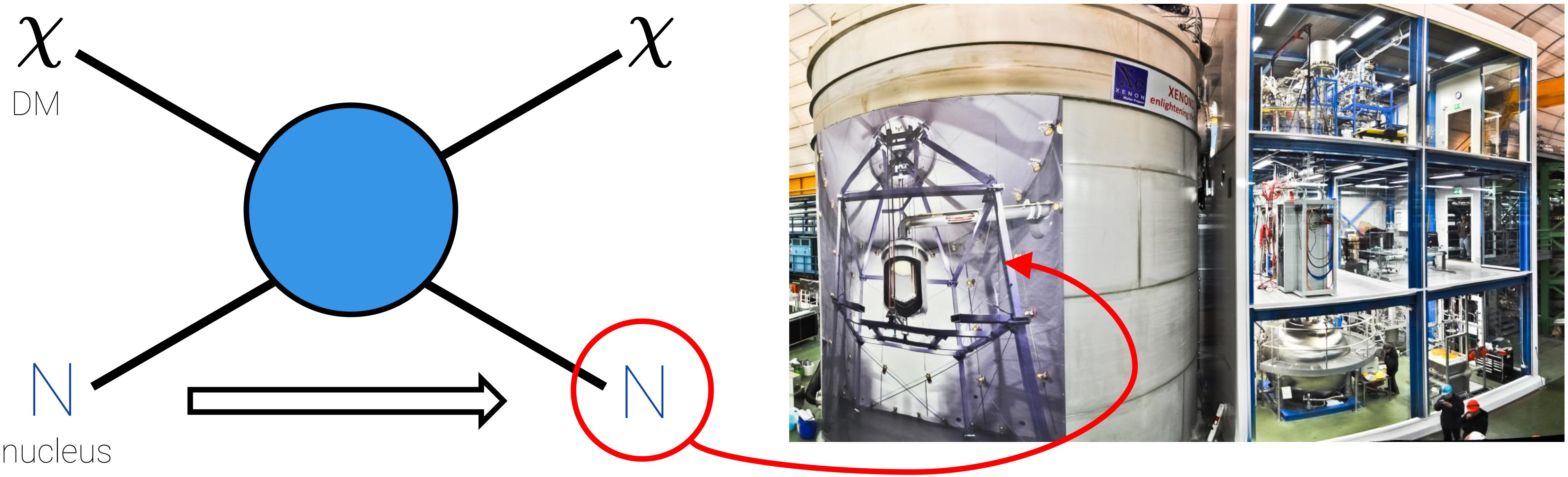
2112.03920 w/ Gilly Elor & Aaron Pierce
22XX.XXXXX + Prudhvi N. Bhattiprolu

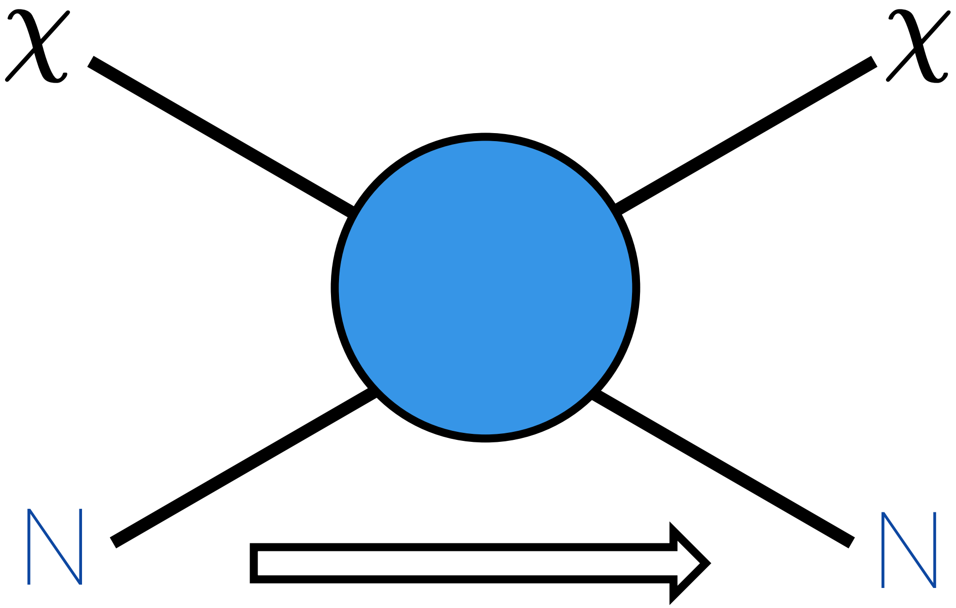
UW INT, 8/15/22

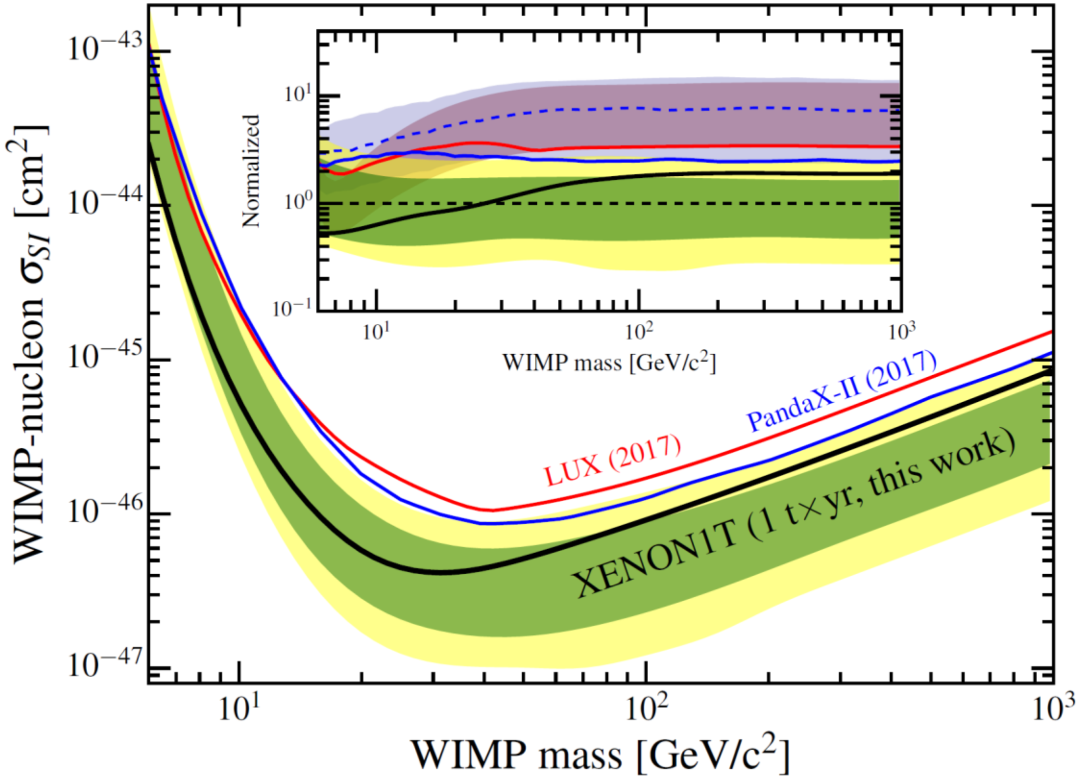
Direct Detection Refresher

Credit: The XENON Experiment



Direct Detection Refresher





XENON Collaboration [1805.12562]

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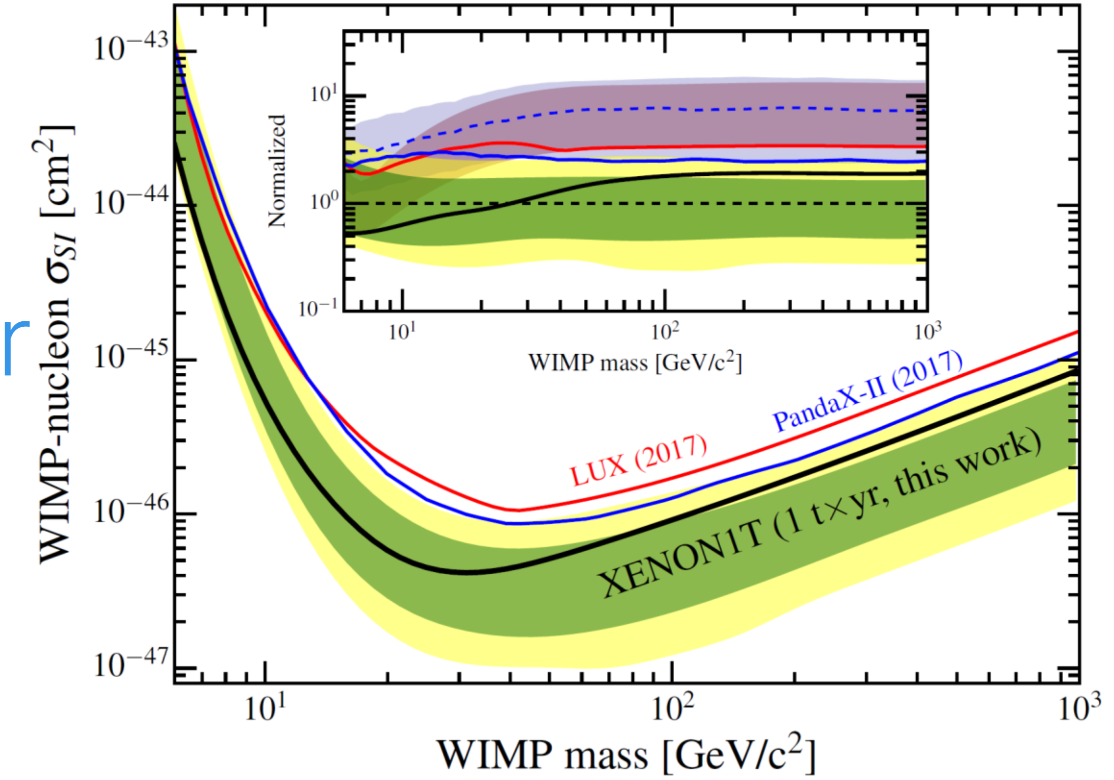
Direct Detection Future

Go higher?

Go lighter



Go lower

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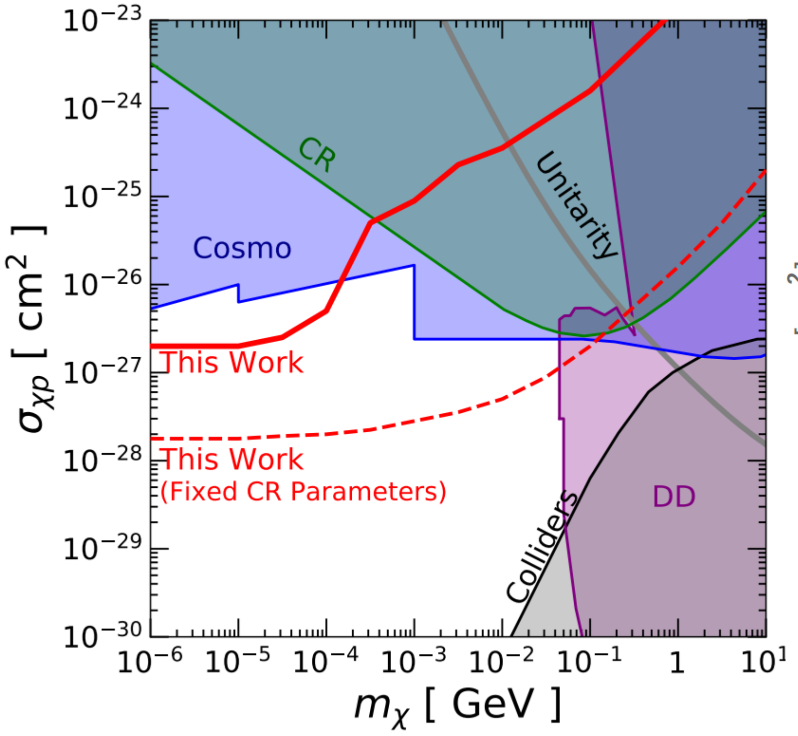
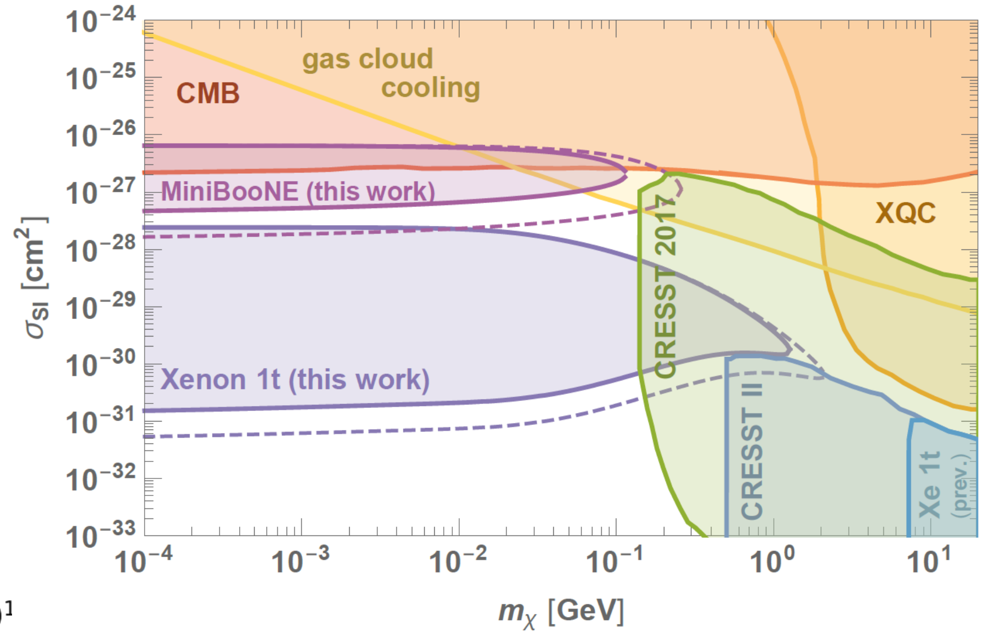
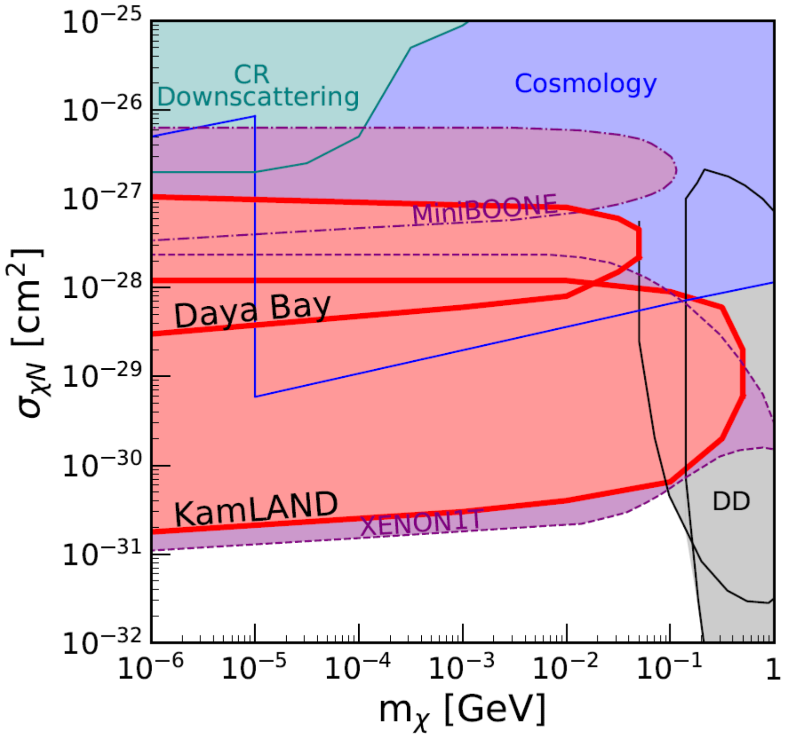
Bounds from Cosmic Ray Scattering



C. Cappiello, K. Ng, J. Beacom
[1810.07705]



T. Bringmann, M. Pospelov
[1810.10543]



C. Cappiello, J. Beacom
[1906.11283]

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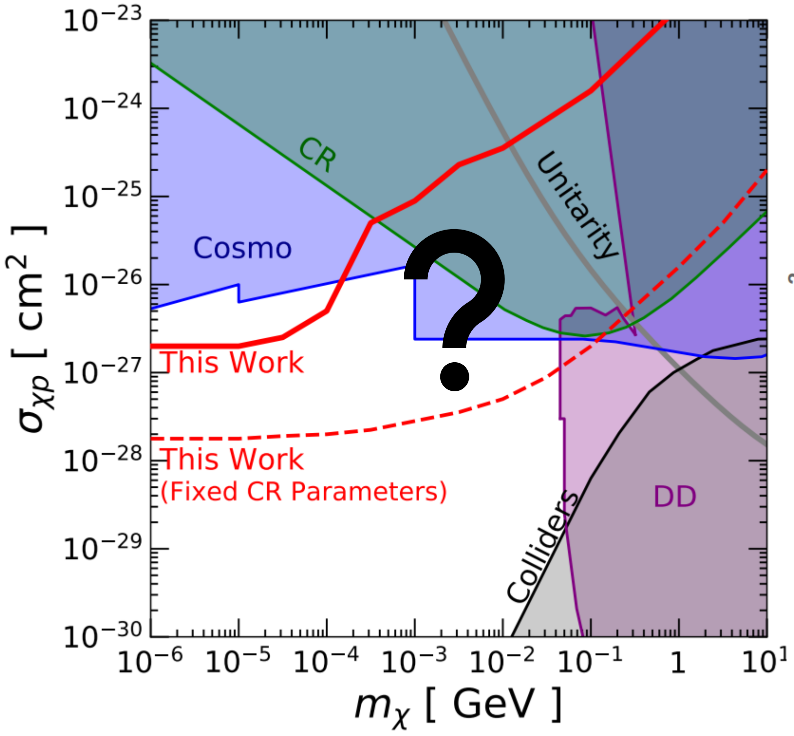
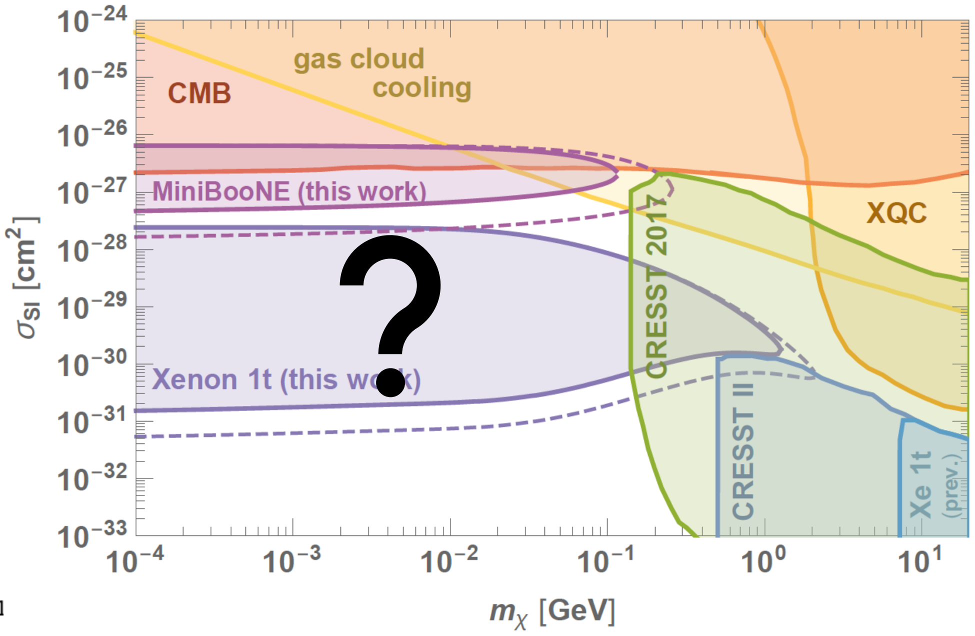
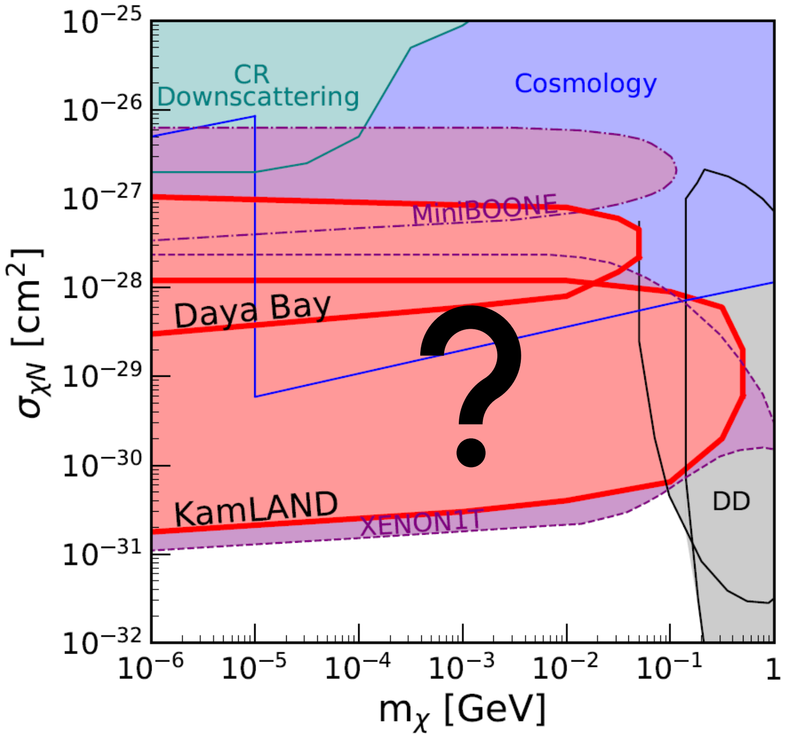
Is Dark Matter here?







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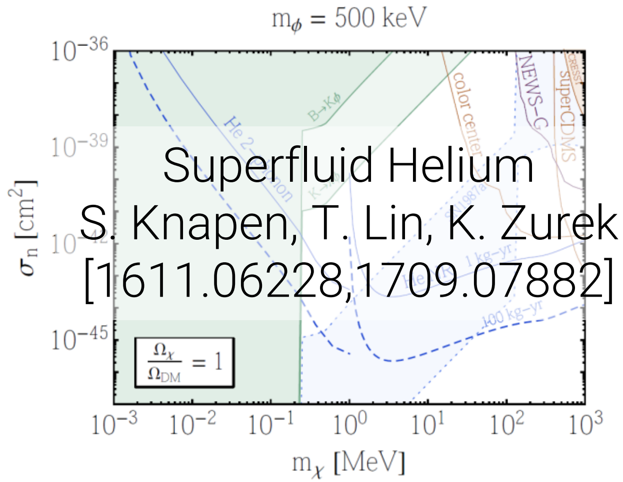
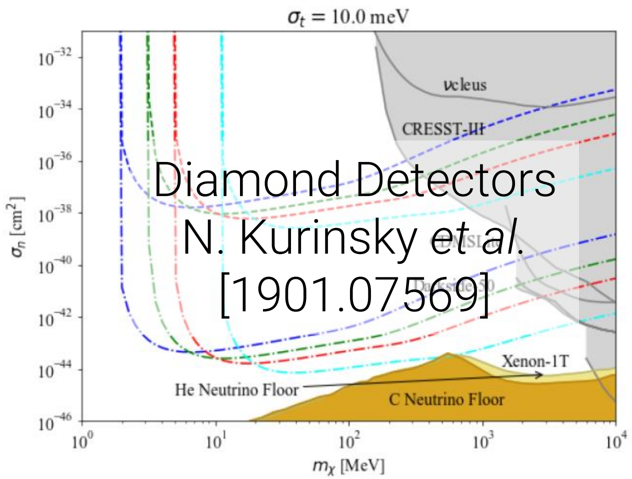
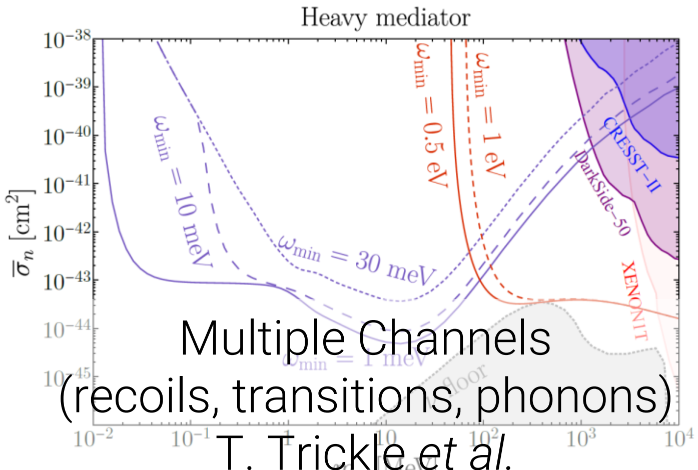


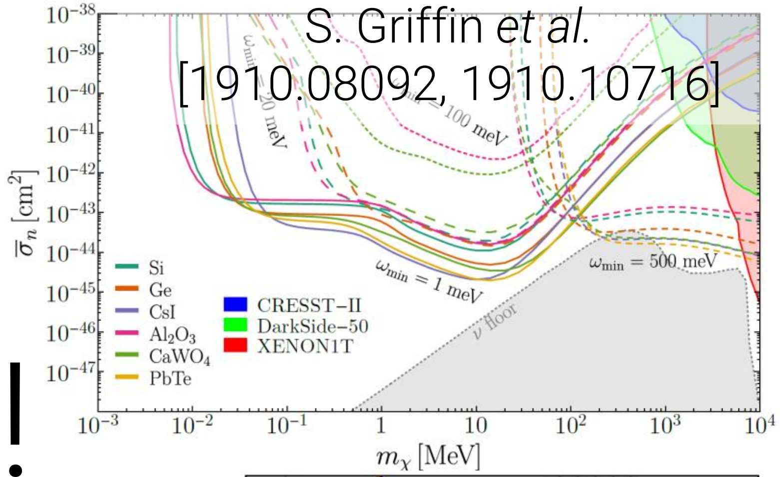
Superfluid Helium
S. Knapen, T. Lin, K. Zurek
[1611.06228,1709.07882]

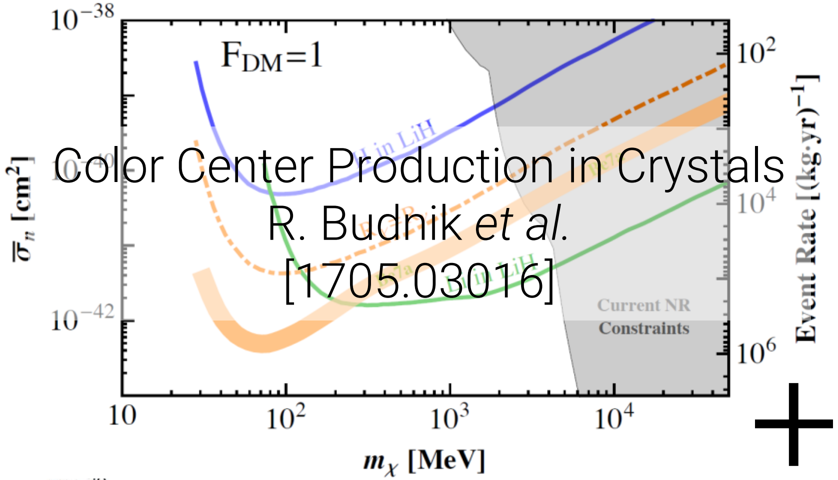


Diamond Detectors
N. Kurinsky *et al.*
[1901.07569]

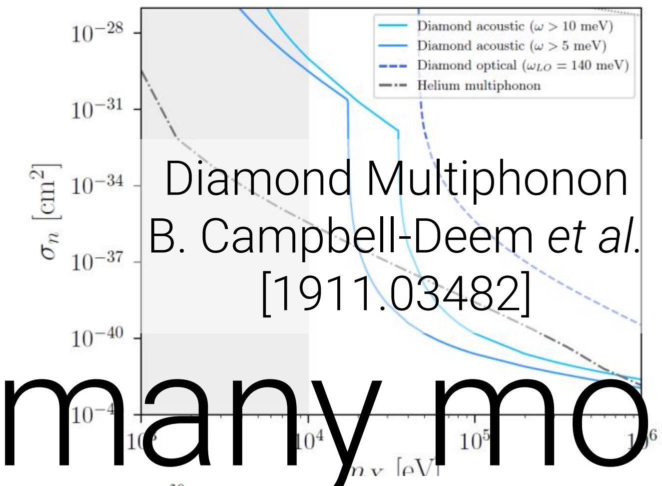


Multiple Channels
(recoils, transitions, phonons)
T. Trickle *et al.*
S. Griffin *et al.*
[1910.08092, 1910.10716]



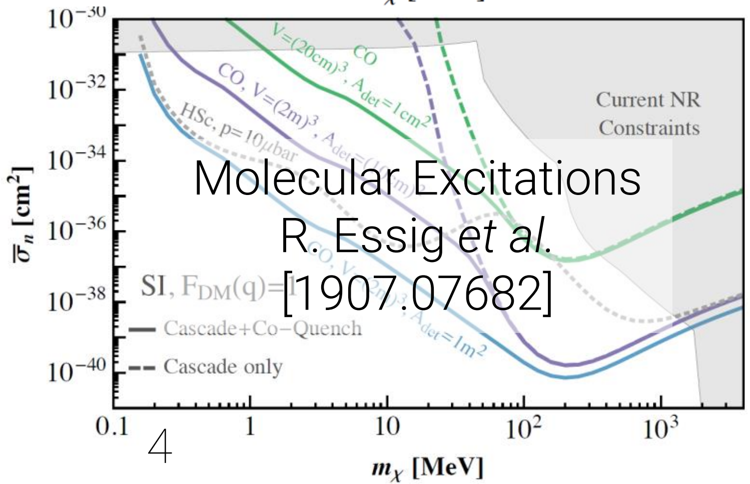


Color Center Production in Crystals
R. Budnik *et al.*
[1705.03016]

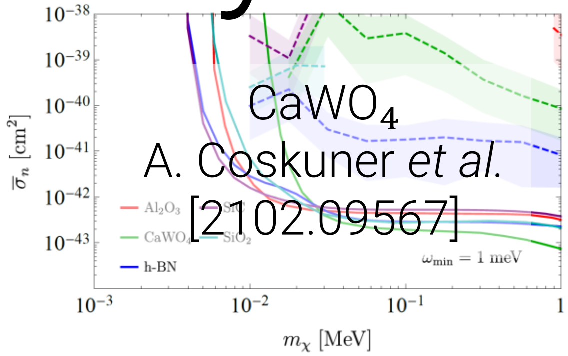


Diamond Multiphonon
B. Campbell-Deem *et al.*
[1911.03482]

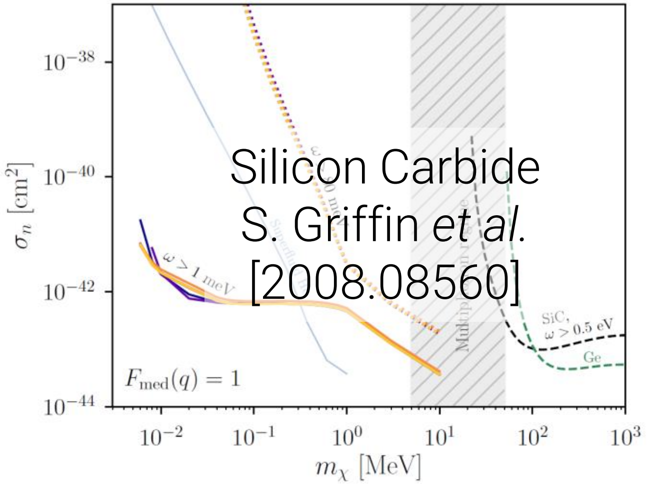
+ many more!



Molecular Excitations
R. Essig *et al.*
[1907.07682]

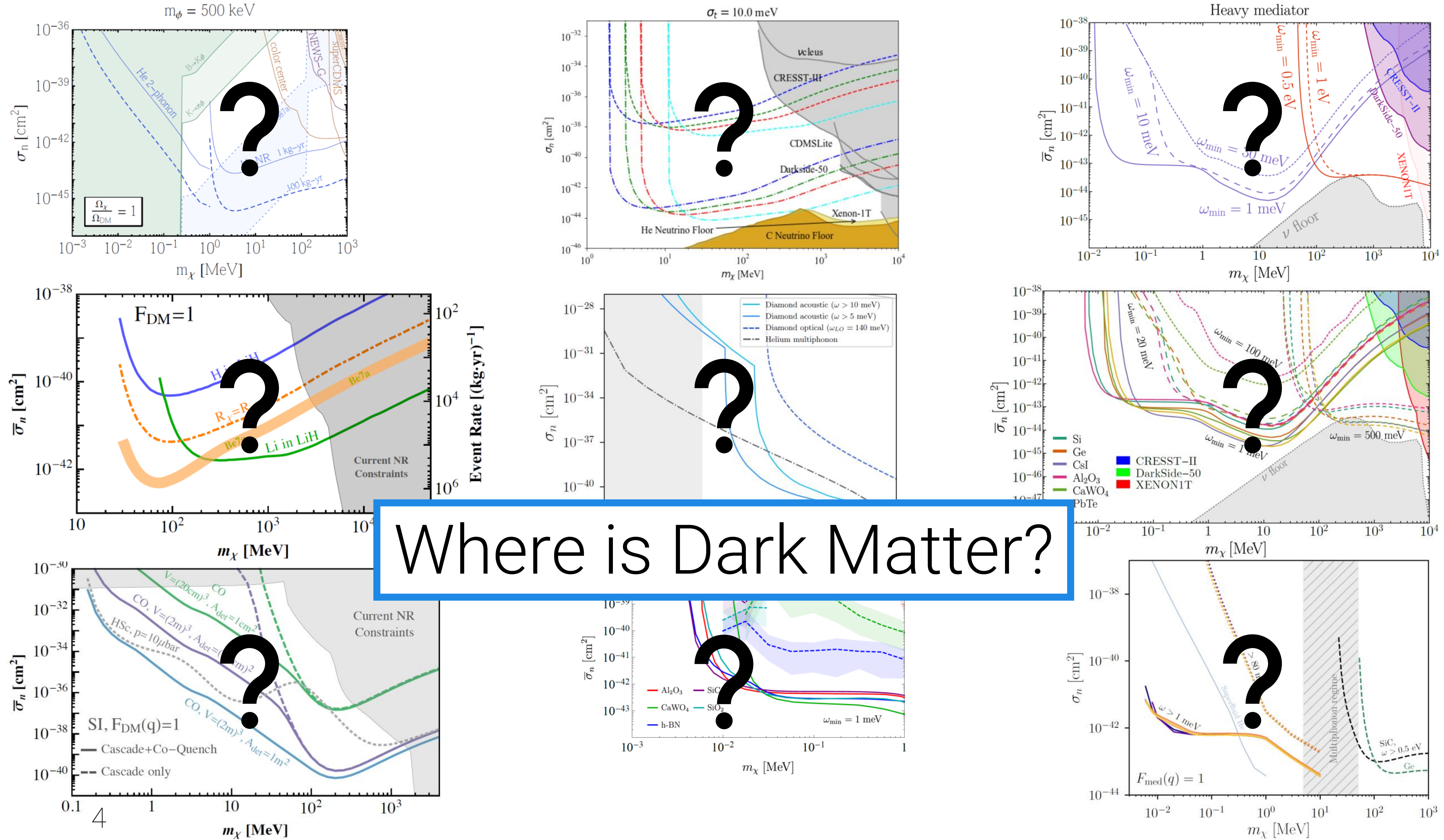


$CaWO_4$
A. Coskuner *et al.*
[2102.09567]



Silicon Carbide
S. Griffin *et al.*
[2008.08560]

Where is Dark Matter?



Outline

Is Dark Matter here?

↳ What is the max cross section of sub-GeV DM scattering off nucleons?

Where is the Dark Matter?

↳ Is there a sub-GeV DM candidate which

1. may be detected at proposed experiments?
2. may approach such a max cross section?

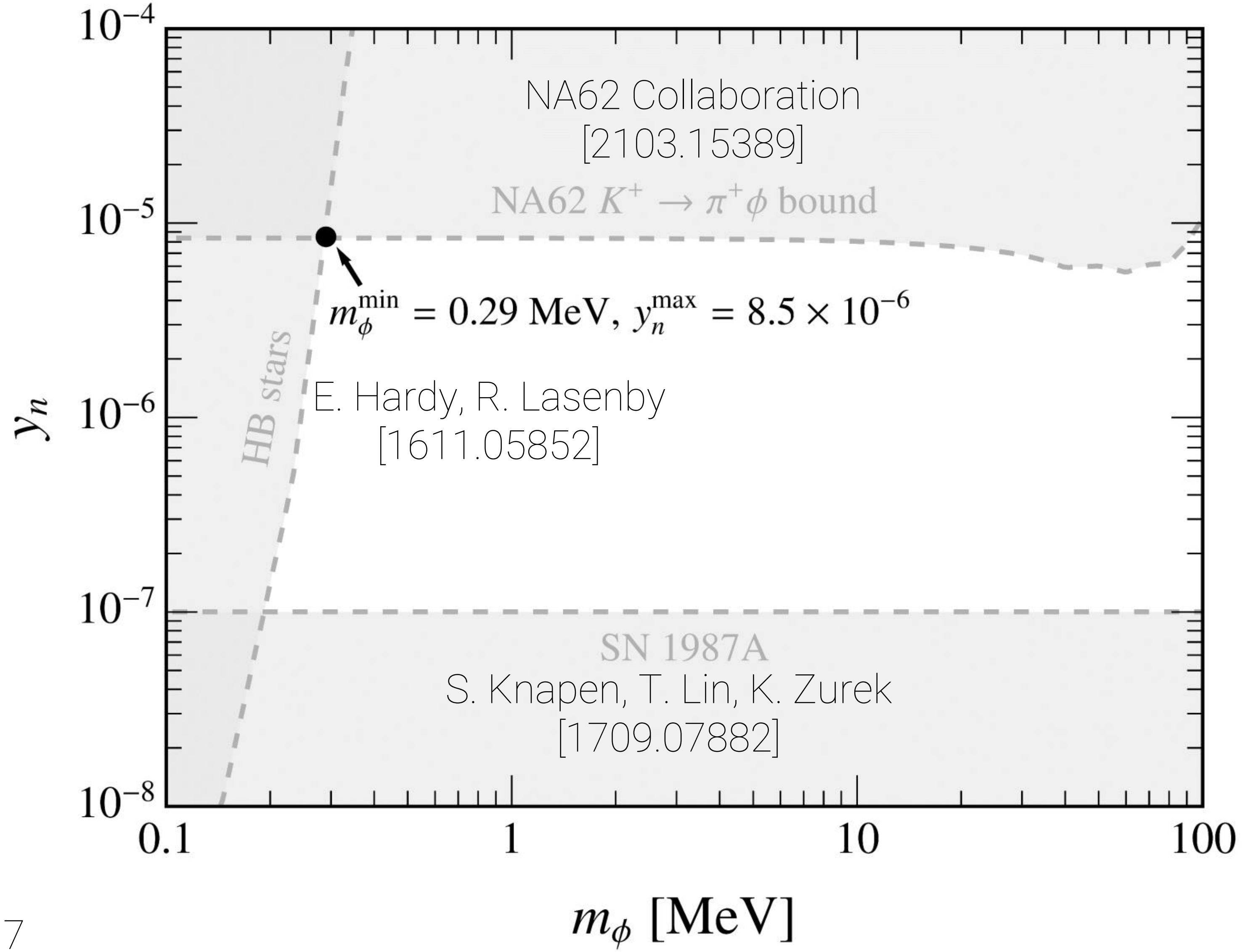
What is the max cross section of sub-GeV DM scattering off nucleons?

The Basics

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

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

The Basics



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

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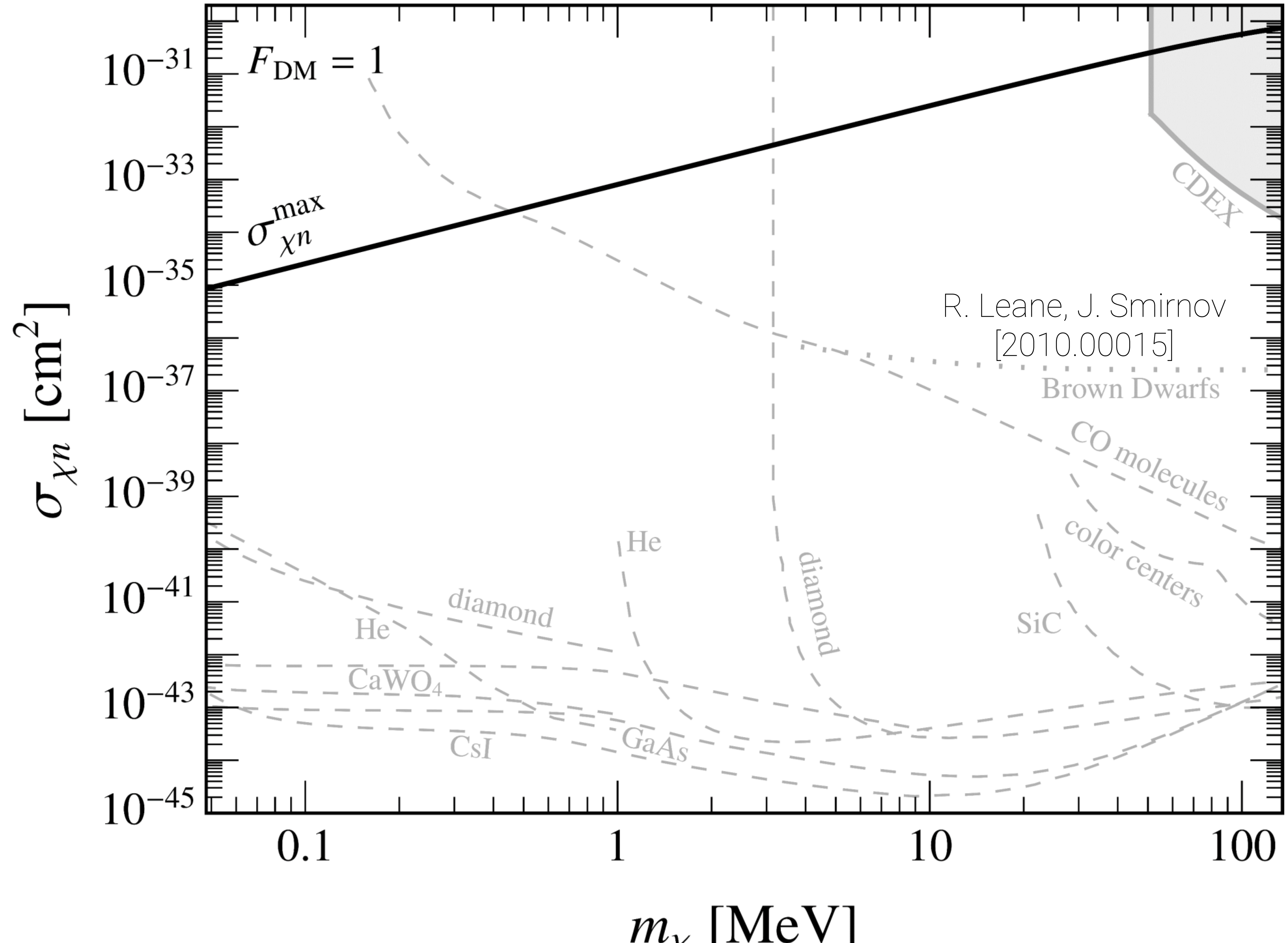

$F_{\rm DM} = 1$
$\sigma_{\chi n}^{\rm max}$
CDEX
R. Leane, J. Smirnov
[2010.00015]
Brown Dwarfs
CO molecules
color centers
SiC
diamond
He
diamond
He
CaWO$_4$
CsI
GaAs
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
$\sigma_{\chi n}$ [cm^2]
0.1
1
10
100
m_χ [MeV]

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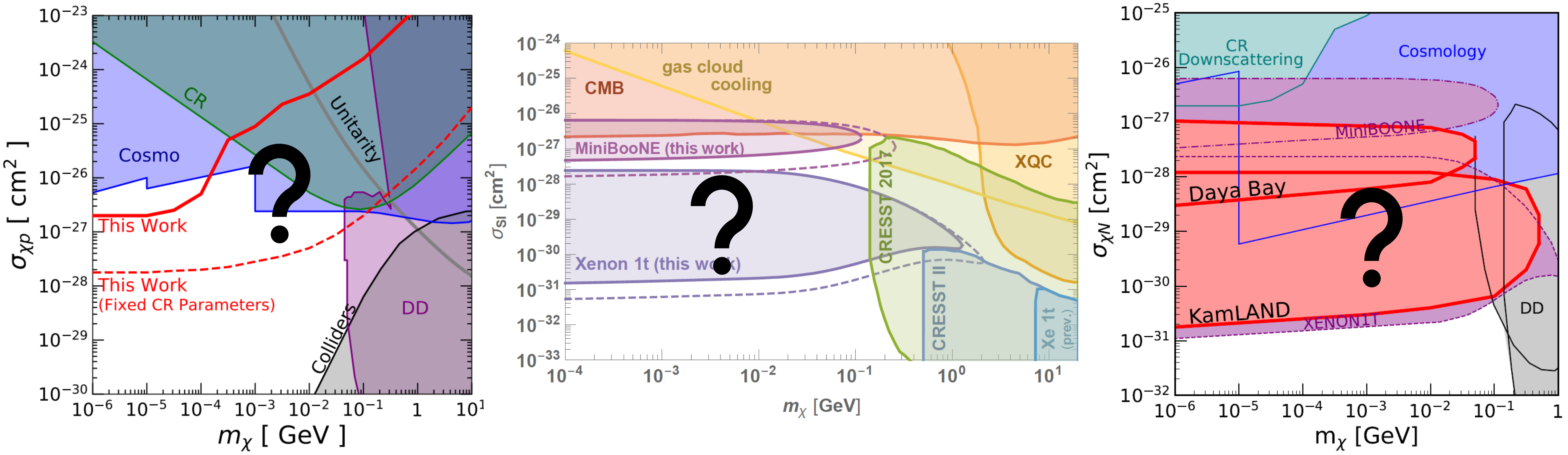
Is Dark Matter here?



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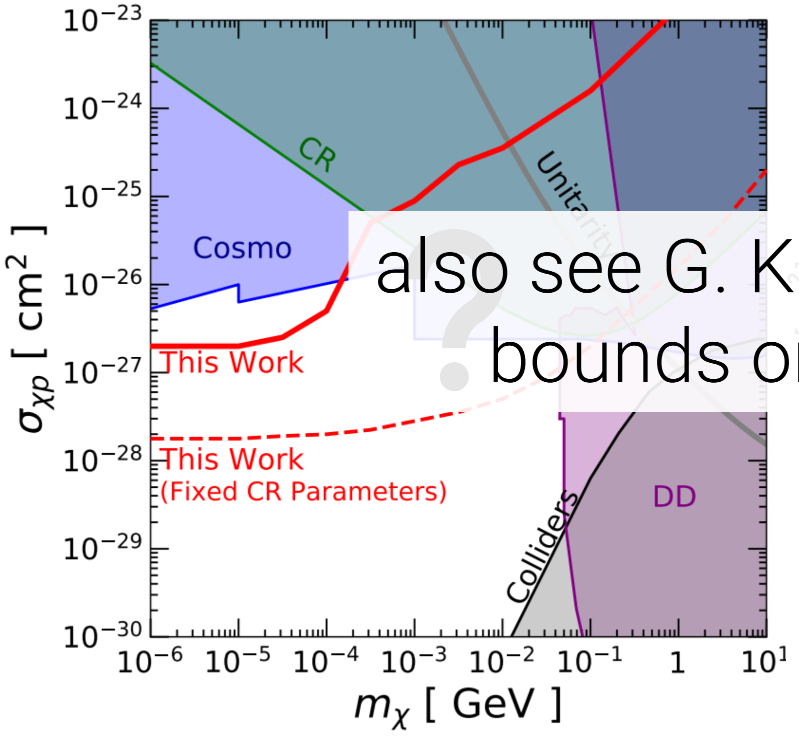
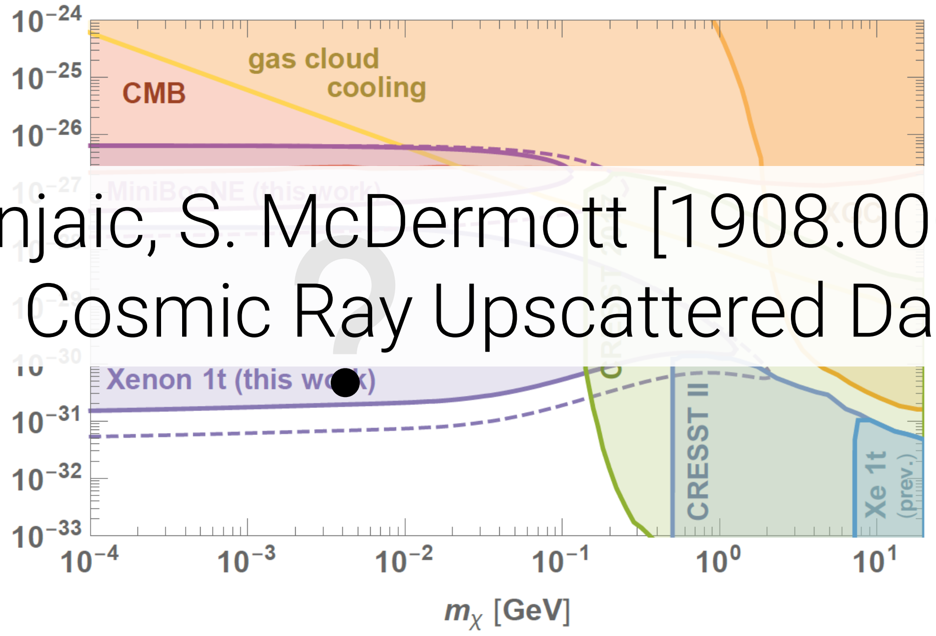
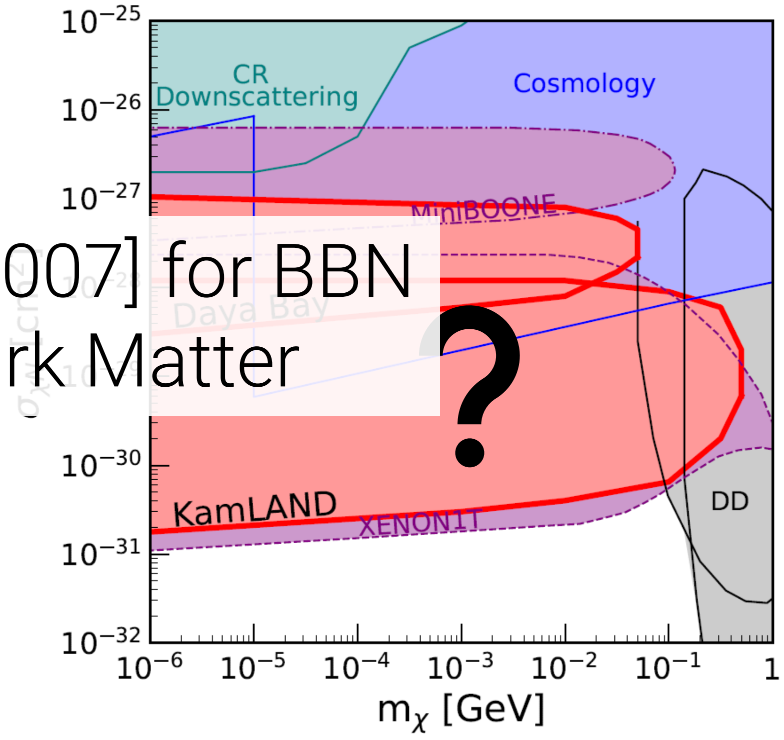
Is Dark Matter here?

Probably not.







also see G. Krnjaic, S. McDermott [1908.00007] for BBN bounds on Cosmic Ray Upscattered Dark Matter

Challenges for Achieving $\sigma_{\chi n}^{\mathbf{max}}$

A light ϕ with sizable couplings to DM and nuclei

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

fast annihilations deplete relic abundance

constrained by indirect detection

Thermalization of ϕ increases N_{eff}

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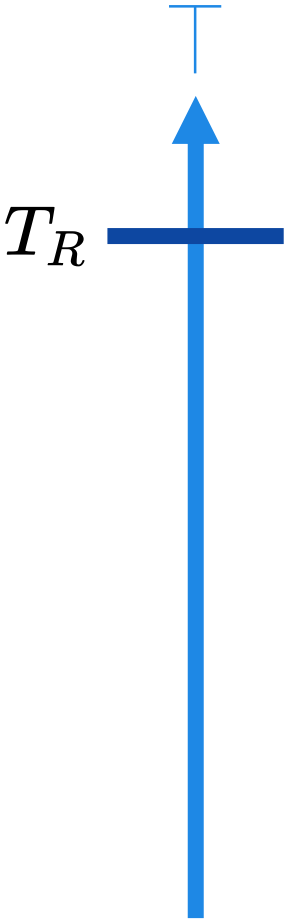
Is there a sub-GeV DM candidate which

1. may be detected at proposed experiments?
2. may approach such a max cross section?

HighlY interactive ParticlE Relics (HYPERs)

HYPER History



UV freeze-in

$$\Omega_\chi h^2 = 0.12$$

relic abundance set early and depends on T_R and m_ϕ^i

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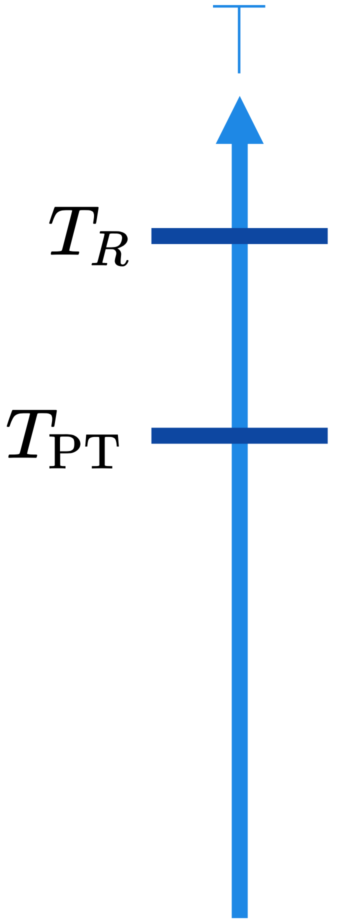
HYPER History



UV freeze-in

$$\Omega_\chi h^2 = 0.12$$

Dark-sector phase transition

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

HYPER History

T

T_R — UV freeze-in

$$\Omega_\chi h^2 = 0.12$$

$T_{\rm PT}$ — Dark-sector phase transition

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

today — Direct detection cross section grows!

$$\left(m_\phi^i / m_\phi\right)^4$$

HYPER History

T

T_R — UV freeze-in

$$\Omega_\chi h^2 = 0.12$$

$T_{\rm PT}$ — Dark-sector phase transition

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

Changes
- 🚩abundance?
- 🚩BBN?
- 🚩CMB?

today — Direct detection cross section grows!

$$\left(m_\phi^i / m_\phi\right)^4$$

🚩Changes relic abundance? ☑

$$m_\chi < m_{\pi^0} \longrightarrow \bar{\chi}\chi \to \text{hadrons}$$

$$T_{\text{PT}} \ll m_{\pi^0} \longrightarrow \text{hadrons} \to \bar{\chi}\chi$$

$$\longrightarrow \gamma\gamma \to \phi(\phi)$$

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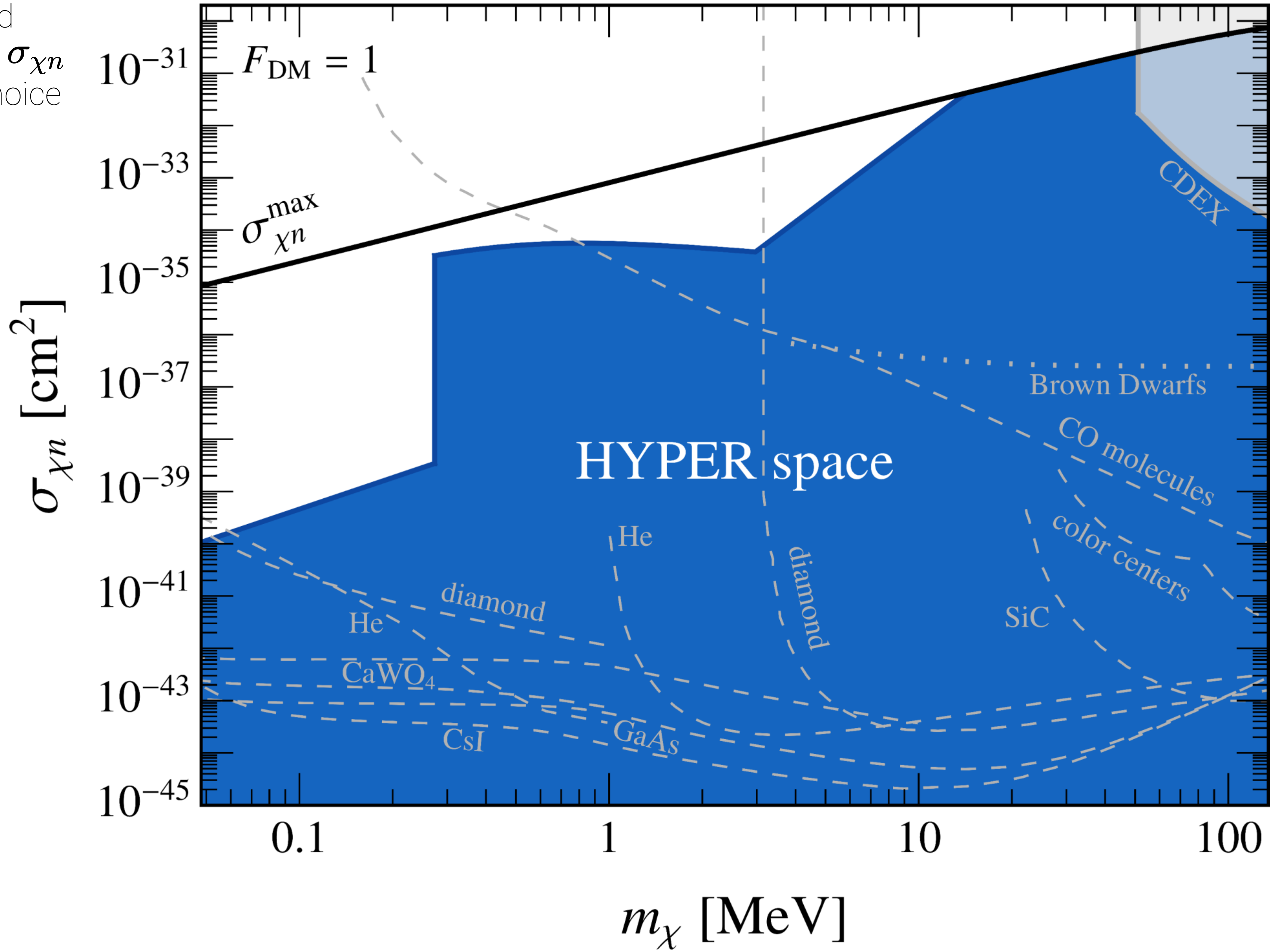
What about $\bar{\chi}\chi \to \phi\phi$?

Have to suppress → HYPERs can't always have max direct detection

Results

Boundary found by maximizing $\sigma_{\chi n}$ via judicious choice of (m_ϕ, y_χ)



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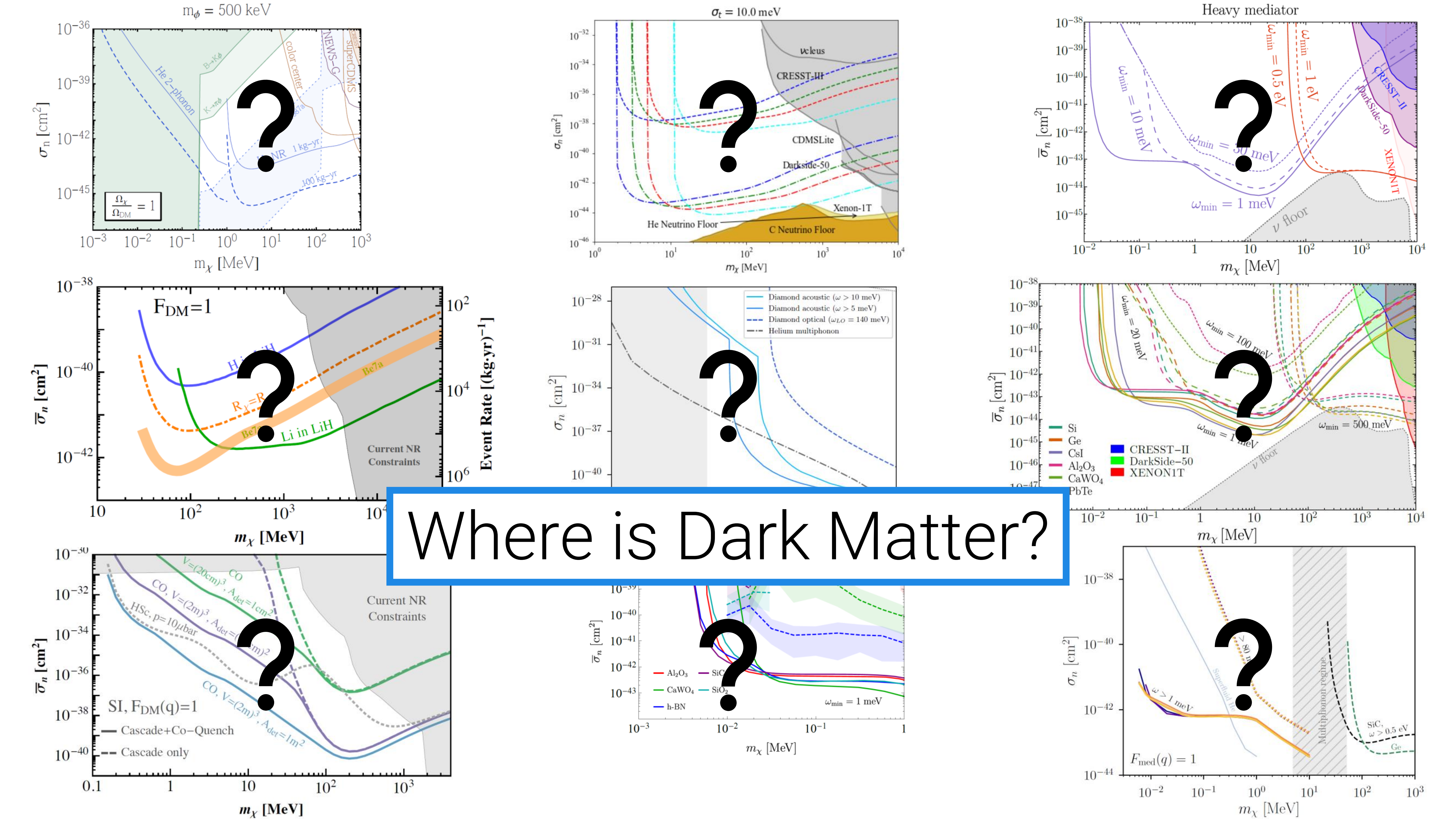
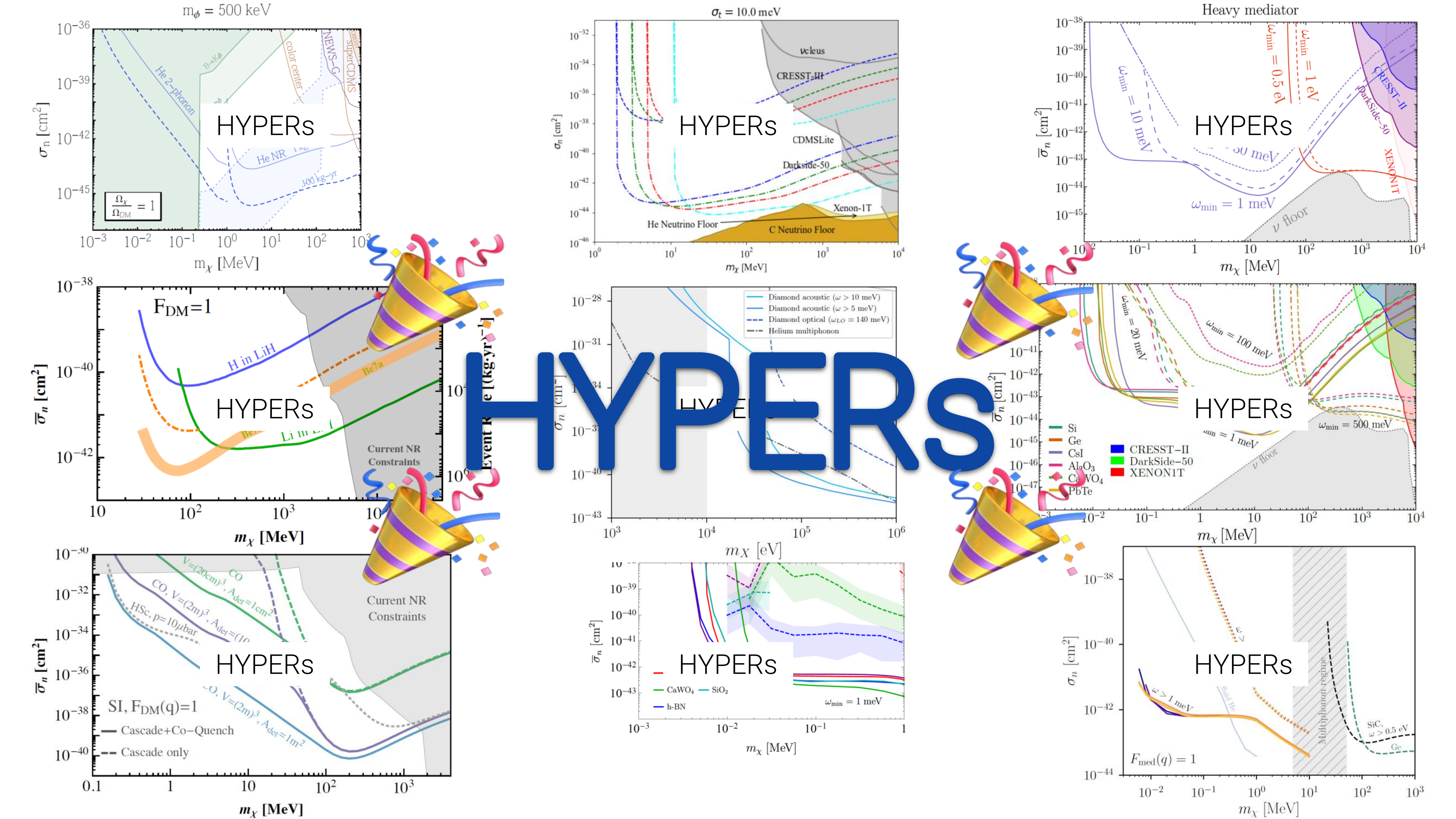

Where is Dark Matter?
m_φ = 500 keV
σ_t = 10.0 meV
Heavy mediator


HYPERs
HYPERs
HYPERs
HYPERs
HYPERs
HYPERs
HYPERs
m_ϕ = 500 keV
σ_n [cm^2]
m_χ [MeV]
He 2-phonon
He NR
color center
NEWS-G
superCDMS
$\frac{\Omega_\chi}{\Omega_{DM}} = 1$
σ_t = 10.0 meV
νcleus
CRESST-III
CDMSLite
Darkside-50
Xenon-1T
He Neutrino Floor
C Neutrino Floor
Heavy mediator
ω_{min} = 0.5 eV
ω_{min} = 1 eV
ω_{min} = 10 meV
ω_{min} = 1 meV
ν floor
CRESST-II
DarkSide-50
XENON1T
F_{DM}=1
H in LiH
Be7a
Current NR Constraints
Diamond acoustic (ω > 10 meV)
Diamond acoustic (ω > 5 meV)
Diamond optical (ω_{LO} = 140 meV)
Helium multiphonon
m_X [eV]
ω_{min} = 100 meV
ω_{min} = 20 meV
ω_{min} = 500 meV
Si
Ge
CsI
Al_2O_3
$CaWO_4$
PbTe
$V=(20cm)^3$, $A_{det}=1cm^2$
CO, $V=(2m)^3$
HSc, p=10μbar
SI, $F_{DM}(q)$=1
Cascade+Co-Quench
Cascade only
Current NR Constraints
$CaWO_4$
SiO_2
h-BN
ω_{min} = 1 meV
ω > 1 meV
Multiphonon regime
SiC, ω > 0.5 eV
$F_{med}(q) = 1$

Is Dark Matter here?

→ What is the max cross section of sub-GeV DM scattering off nucleons?

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R McGehee

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A: HYPERs

What if there's no PT?
Can we still get a novel benchmark?

What if there's no PT?
Can we still get a novel benchmark?

Just make T_R low!

Low Reheating...

$$5\ \mathbf{MeV} \lesssim T_R \ll m_\pi$$

BBN & CMB bounds
P.F. de Salas *et al* [1511.00672]

only photons for production
(like HYPER story)

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$$\mathcal{L} \supset \frac{1}{\Lambda_F}\phi F^{\mu\nu}F_{\mu\nu} \Leftarrow \frac{1}{\Lambda_F} = \frac{y_n \alpha}{4\pi m_n}$$ for HYPER UV completion

Low Reheating...

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$$\mathcal{L} \supset \frac{y_\chi}{m_\phi^2 \Lambda_F}\bar{\chi}\chi F_{\mu\nu}F^{\mu\nu} \Leftarrow m_\phi \gtrsim 25 T_R$$ → E. Frangipane, S. Gori, B. Shakya [2110.10711]

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Freeze-In @ Low Reheating

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

$$Y_{\rm DM} \approx 2 \times \frac{7776\sqrt{10}}{\pi^8} \frac{M_{pl}}{g_{s,*}\sqrt{g_*}} \left(\frac{y_\chi}{\Lambda_F m_\phi^2} \right)^2 T_R^5$$

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Freeze-In @ Low Reheating

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Relic abundance predicts a simple cross section:

$$\sigma_{\chi n} \approx 8.9 \times 10^{-42}\ {\rm cm}^2 \frac{g_{s,*}\sqrt{g_*}}{10.76^{3/2}} \left(\frac{m_\chi}{1\ {\rm MeV}} \right) \left(\frac{10\ {\rm MeV}}{T_R} \right)^5$$

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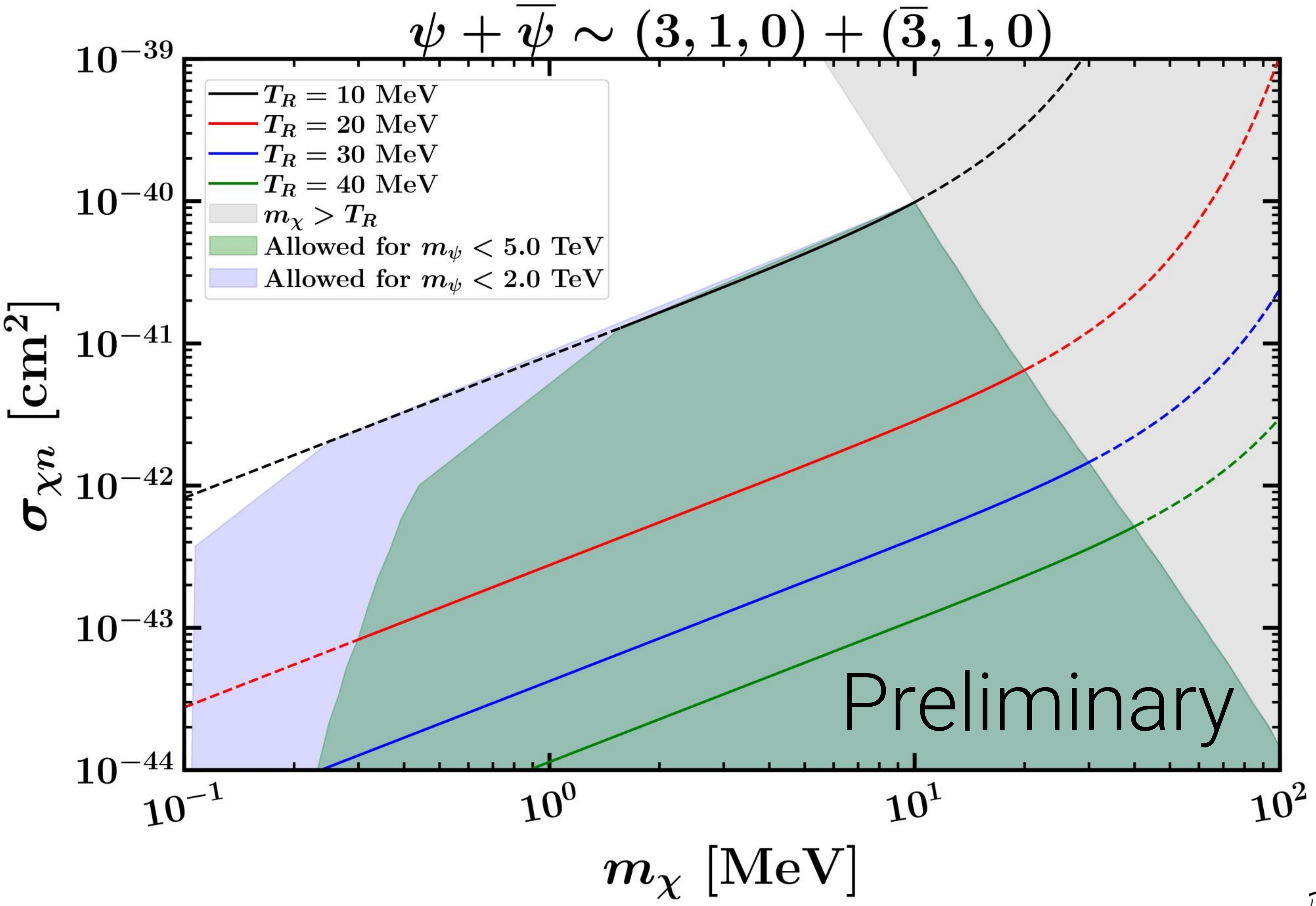
And now, for very preliminary results



$\psi + \overline{\psi} \sim (3, 1, 0) + (\overline{3}, 1, 0)$
$T_R = 10$ MeV
$T_R = 20$ MeV
$T_R = 30$ MeV
$T_R = 40$ MeV
$m_\chi > T_R$
Allowed for $m_\psi < 5.0$ TeV
Allowed for $m_\psi < 2.0$ TeV
Preliminary
$\sigma_{\chi n}$ [cm^2]
m_χ [MeV]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-1}
10^{0}
10^{1}
10^{2}

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A: HYPERs

What if no PT?

↳ A: Reheat @ low temperature for a simple benchmark

Backup Slides

The Basics

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

S. Knapen, T. Lin, K. Zurek
[1709.07882]

$$\mathcal{L} \supset \lambda \phi \bar{\psi} \psi \longrightarrow \frac{\alpha_s}{4\Lambda} \phi G^a_{\mu\nu} G^{a\mu\nu}$$

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Robustness of the Estimate

✓Chose "best" UV completion of nucleon coupling

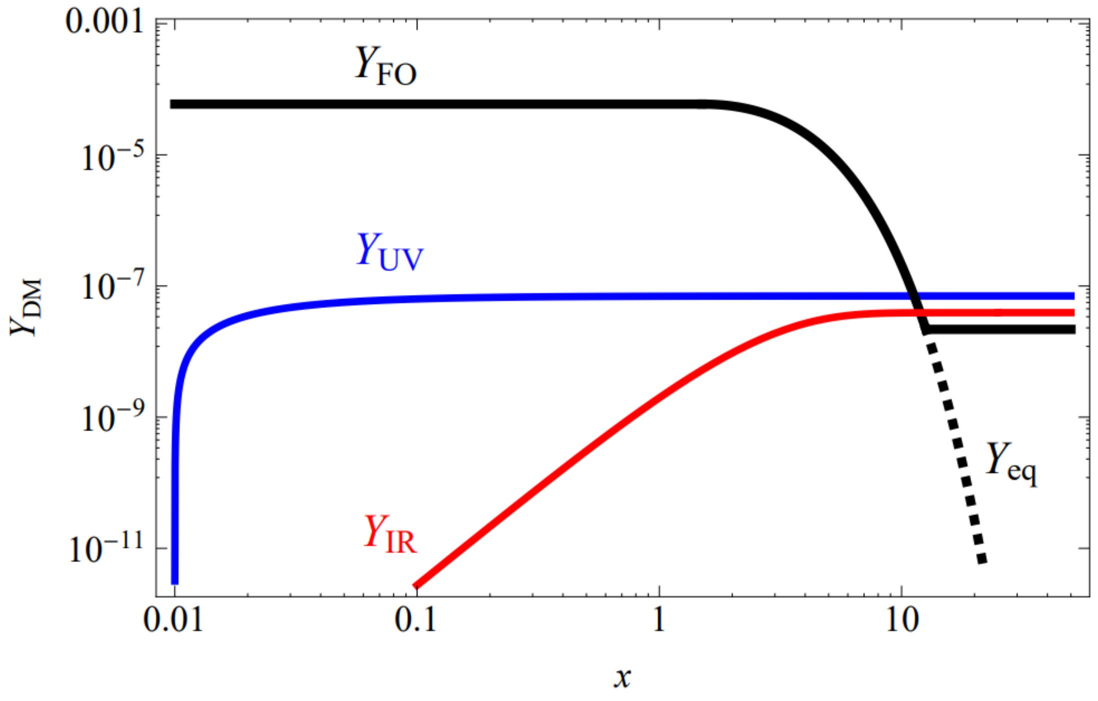
- ✓Coupling directly to tops gives a larger bound
- ✓Coupling directly to lighter quarks does too

✓Vector mediator? dark photon bounds much more stringent

Fine tuning the top coupling can reduce meson decay bounds

Large composite states of asymmetric DM may have a larger cross section C. Coskuner et al. [1812.07573]

UV Freeze-In



F. Elahi, C. Kolda, J. Unwin [1410.6157]

$$\mathcal{L} \supset \lambda\phi\bar{\psi}\psi \longrightarrow \frac{\alpha_s}{4\Lambda}\phi G^a_{\mu\nu}G^{a\mu\nu}$$

heavy ϕ

$$\frac{\alpha_s y_\chi y_n}{2.8\, m_n (m^i_\phi)^2}\bar{\chi}\chi G^{a,\mu\nu}G^a_{\mu\nu}$$

$$18\ \mathrm{GeV} \lesssim T_R \lesssim 75\ \mathrm{GeV}$$

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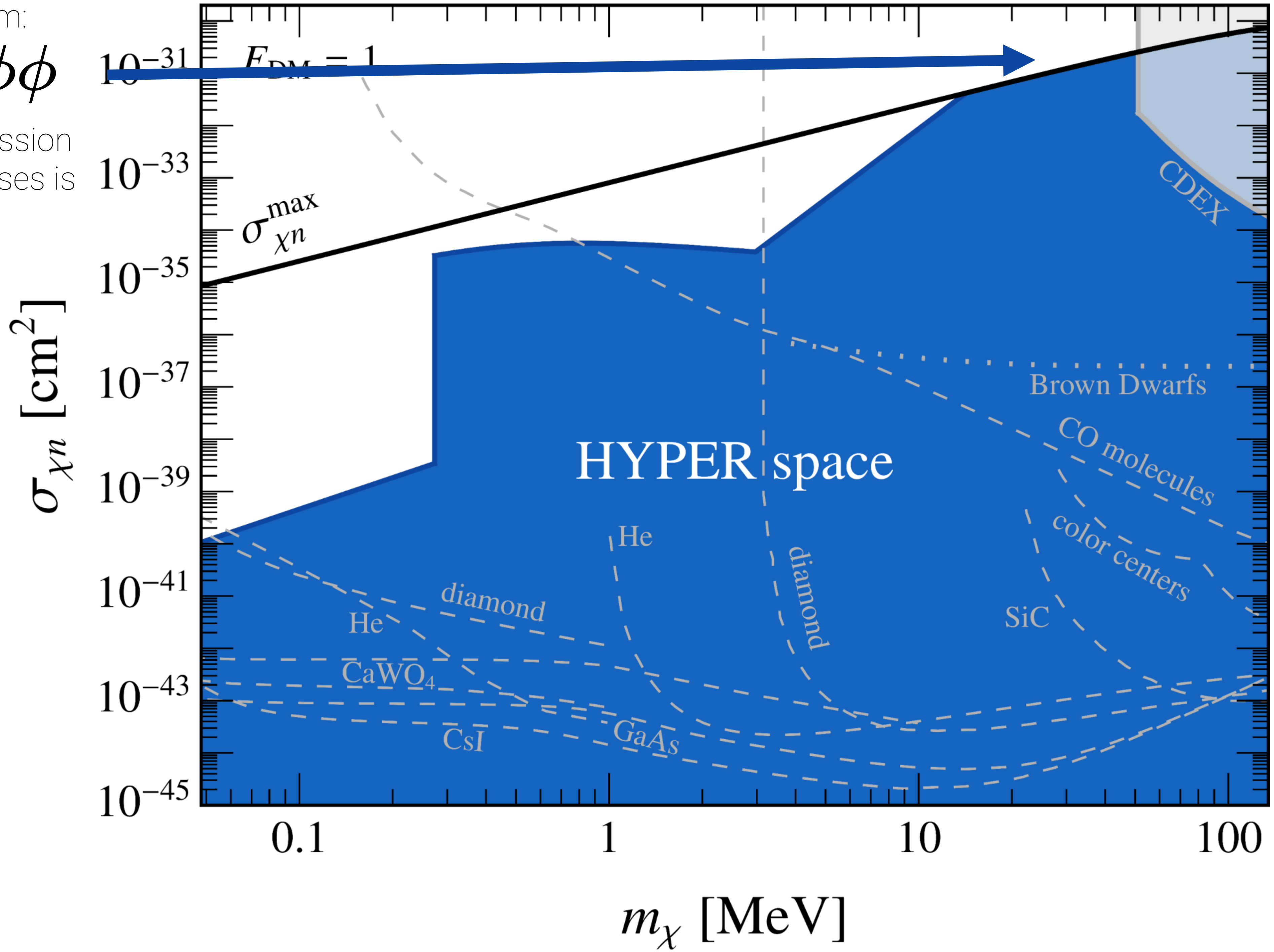
Biggest Problem:

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

P-wave suppression at heavier masses is sufficient

$$m_\phi = m_\phi^{\text{min}}$$

$$y_\chi = y_\chi^{\text{max}}$$



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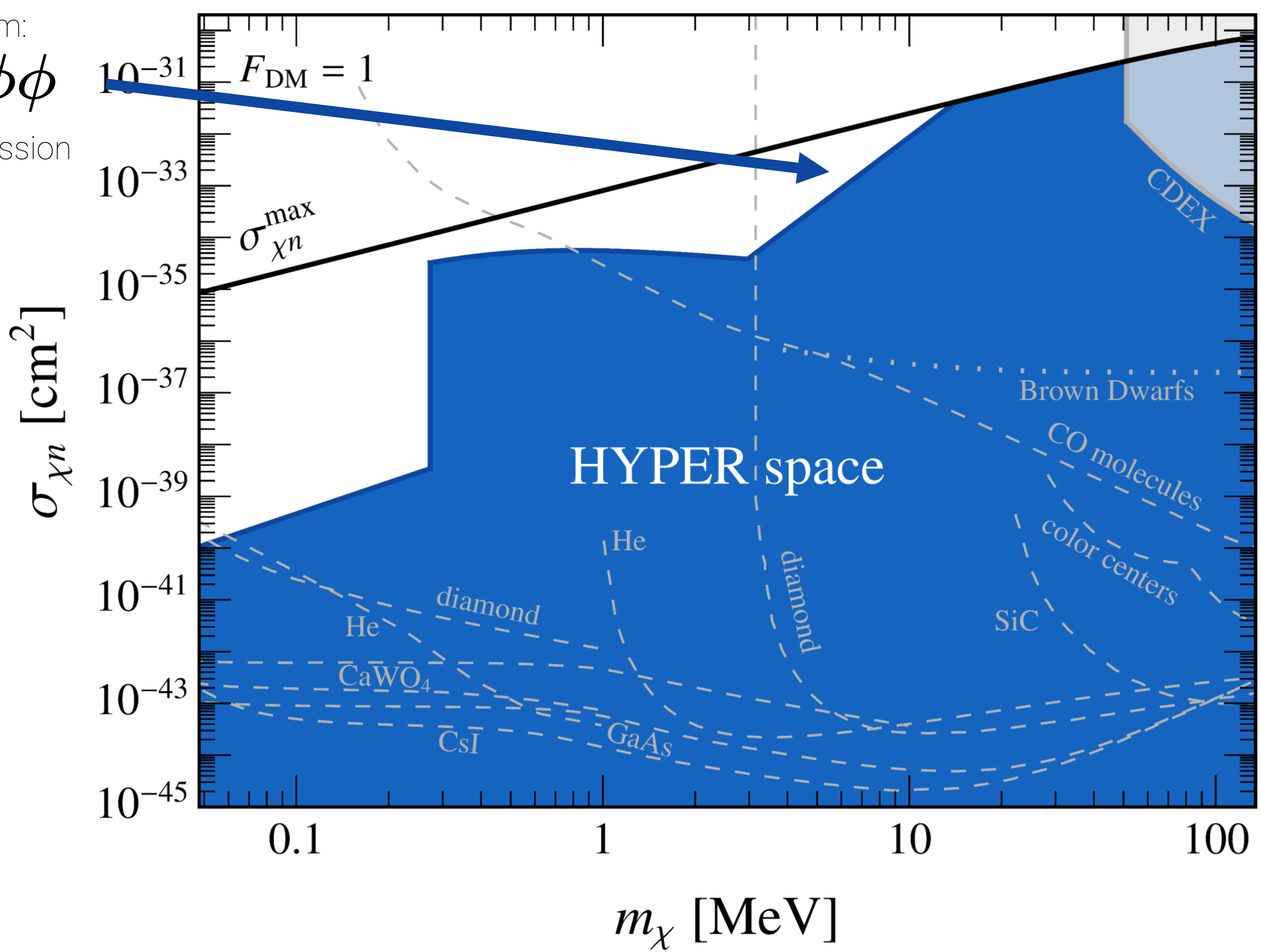
Biggest Problem:

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

P-wave suppression insufficient

$$m_\phi = m_\phi^{\text{min}}$$

$$y_\chi < y_\chi^{\text{max}}$$



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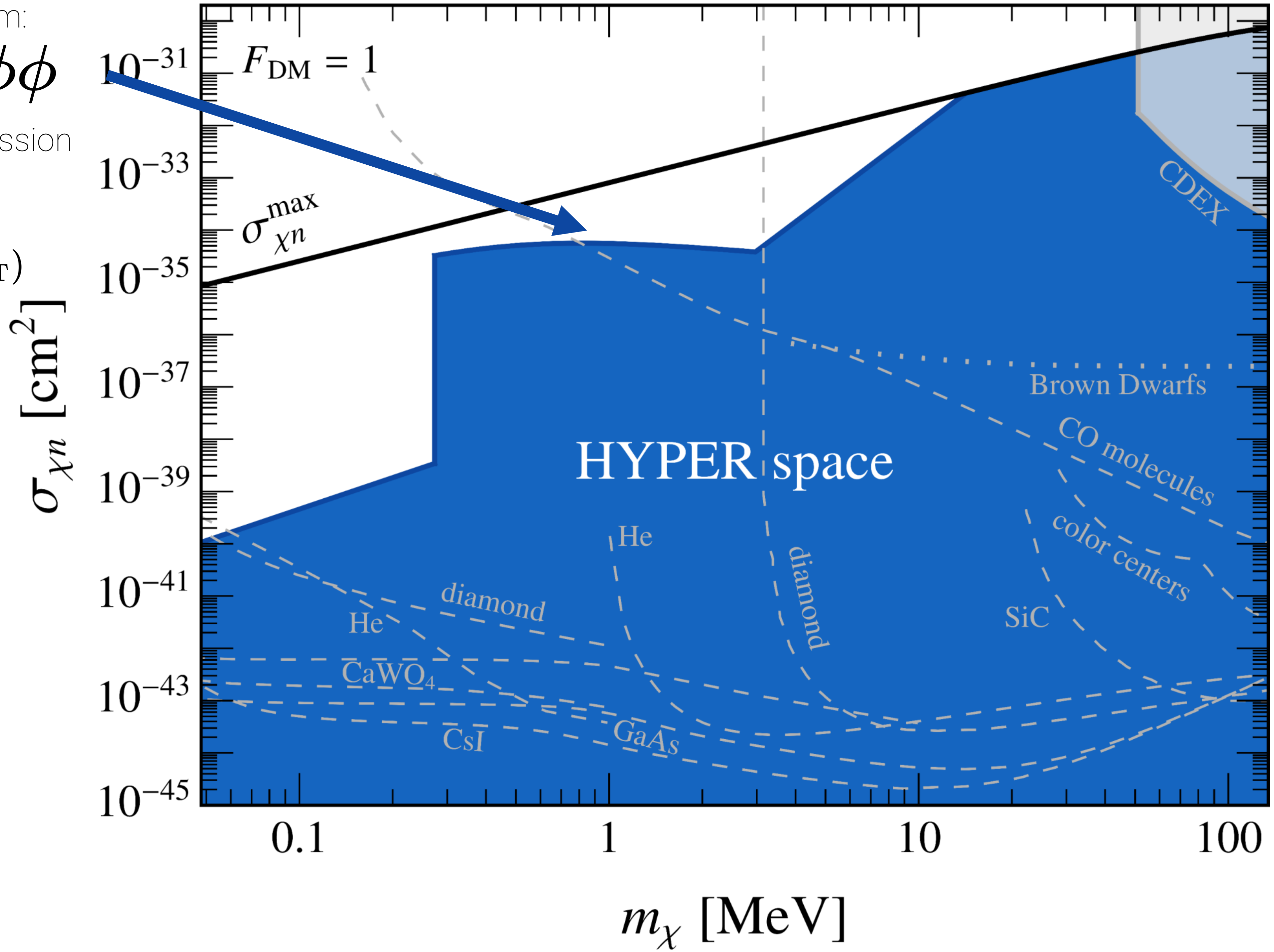
Biggest Problem:

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

P-wave suppression insufficient

$$m_\phi = E_\chi(T_{\rm PT})$$

$$y_\chi = y_\chi^{\rm max}$$



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Biggest Problem:

$$\gamma\gamma \to \phi$$

Setting

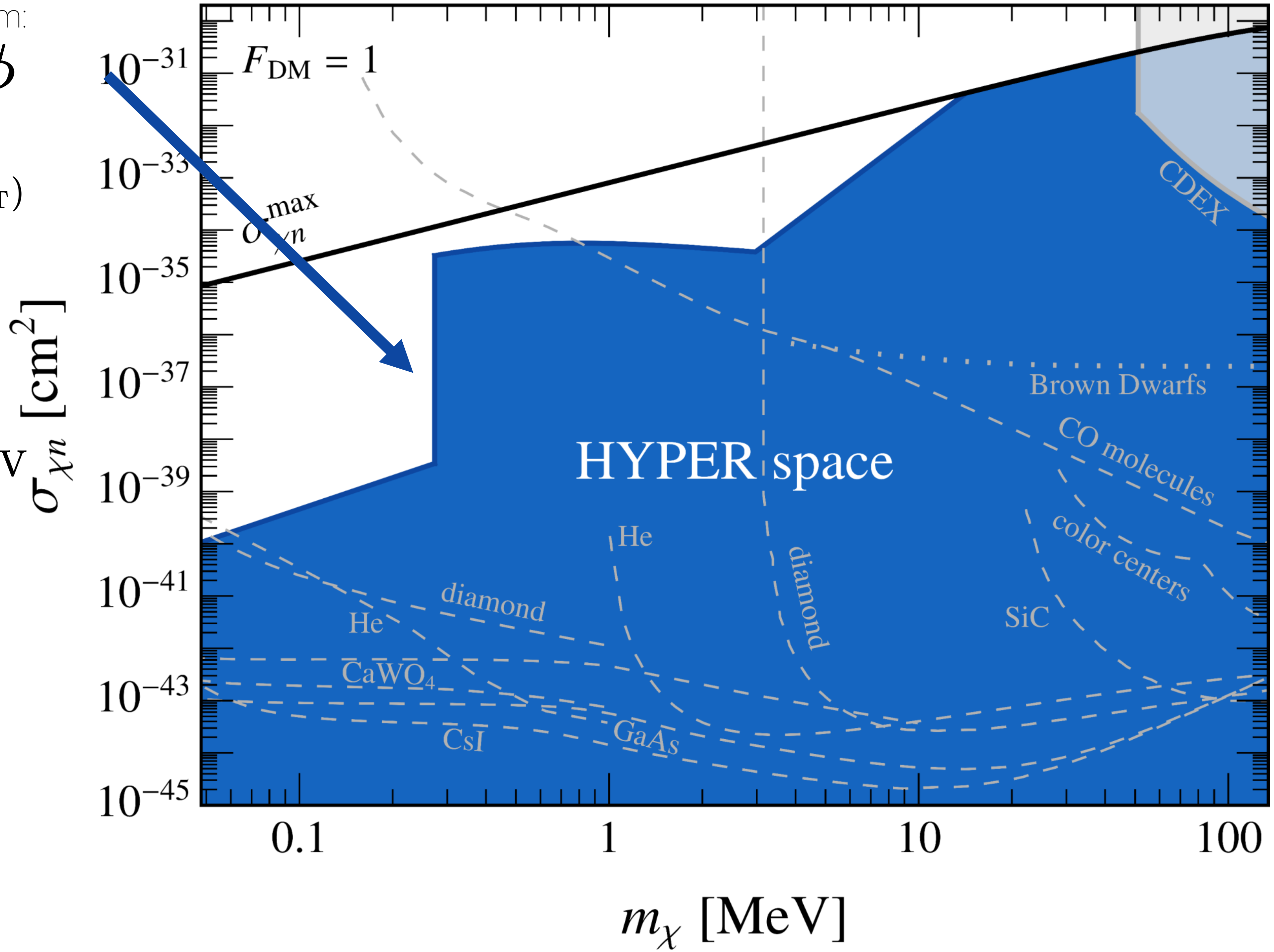
$m_\phi = E_\chi(T_{\rm PT})$

makes

$m_\phi \geq 2m_\chi$

Boltzmann suppress via

$m_\phi = 21\ \mathrm{MeV}$



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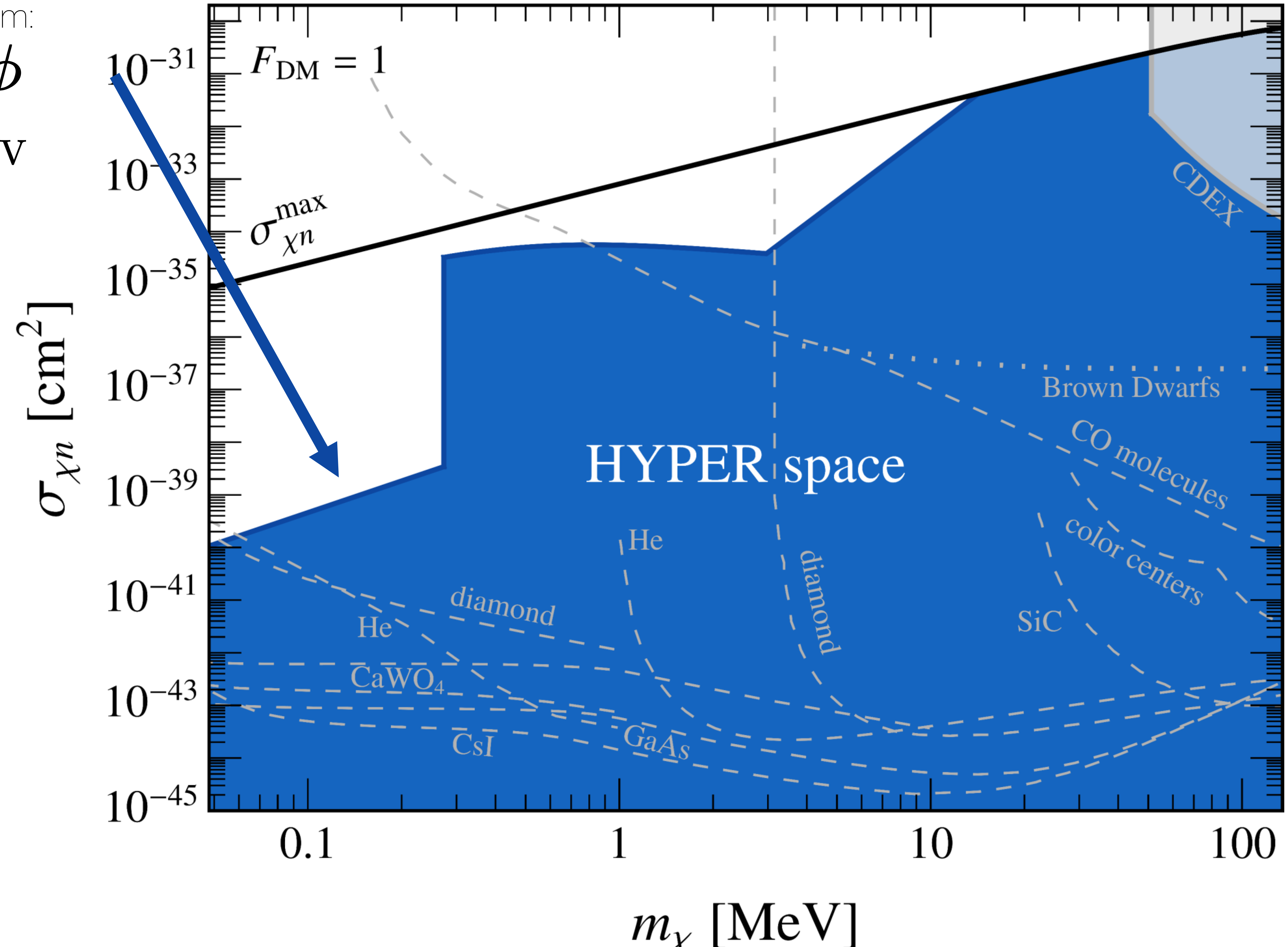
Biggest Problem:

$$\gamma\gamma \to \phi$$

$m_\phi = 21$ MeV

$y_\chi = y_\chi^{max}$



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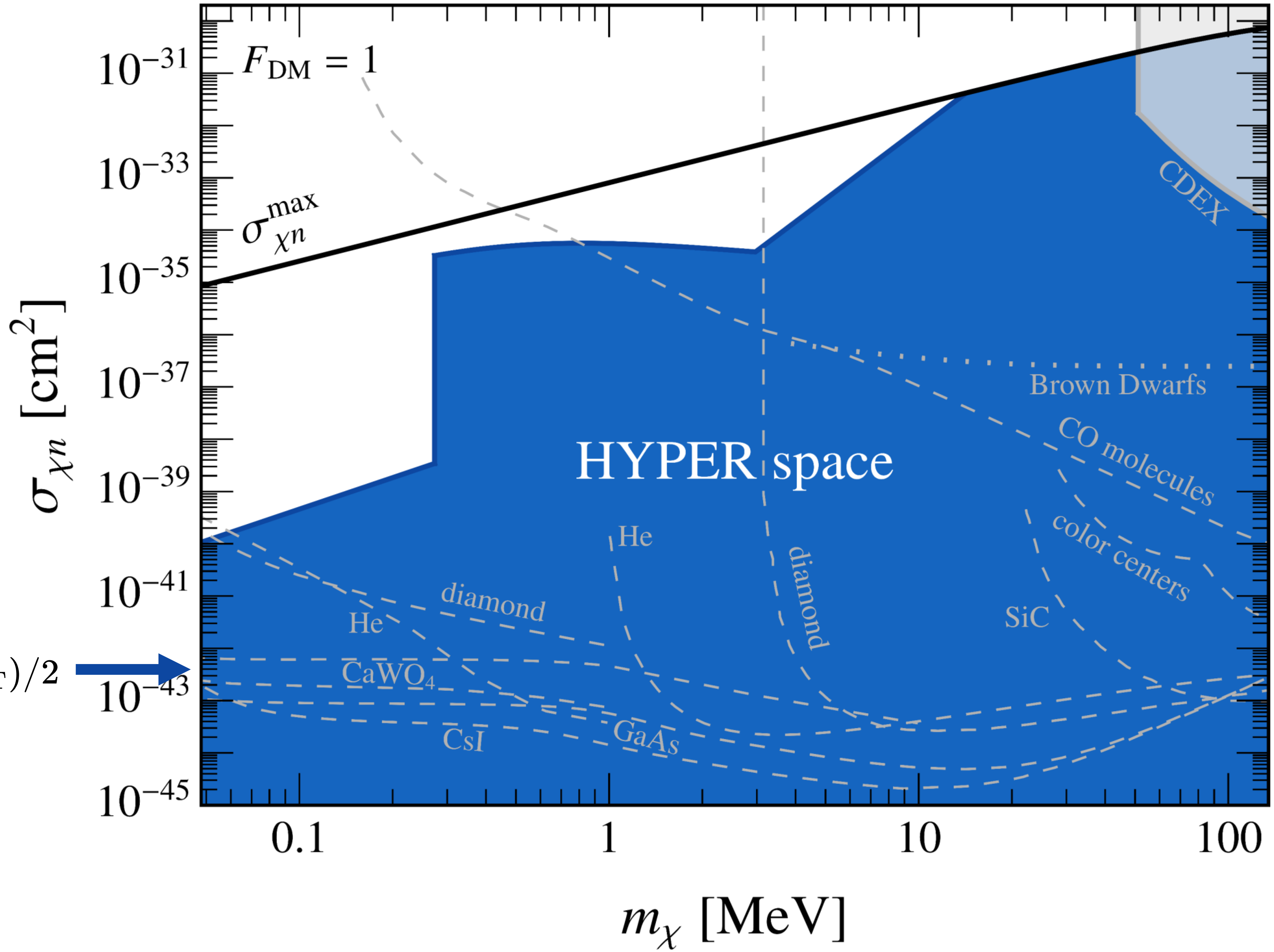

$m_\chi = \omega_p(T_{\rm PT})/2$

Longitudinal plasmons may decay

$\gamma^* \to \bar{\chi}\chi$

[1902.08623]

R McGehee

Earlier Phase Transition?

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

More problematic processes after PT

$$\pi\pi \to \phi\phi, \pi^+\pi^- \to \phi\gamma,$$
$$\pi^\pm\gamma \to \pi^\pm\phi, \pi^\pm\gamma \to \pi^\pm\phi\gamma, \cdots$$

$$\phi^{(*)} \to \bar{\chi}\chi$$

R McGehee

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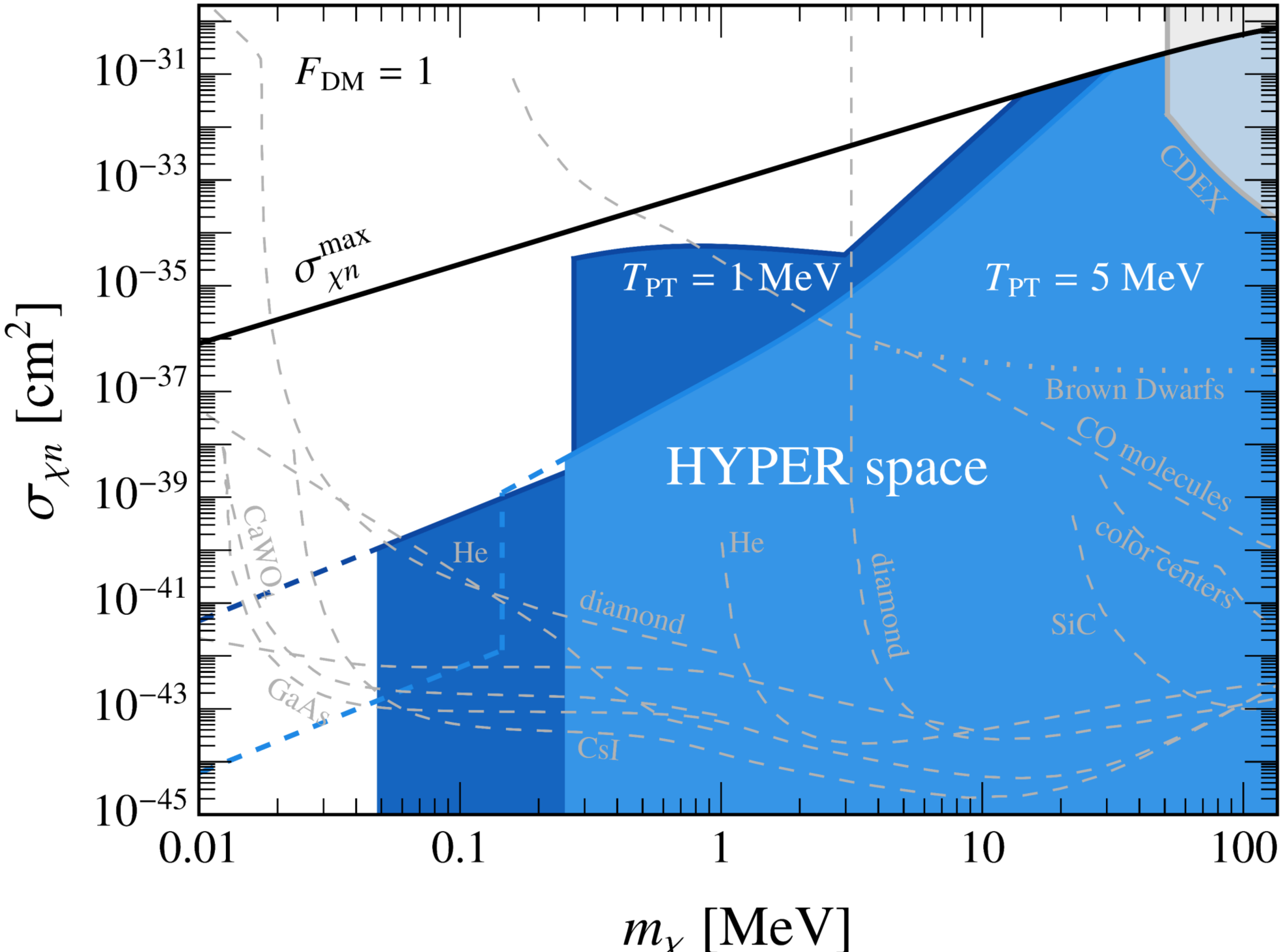
When do these start to matter?

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

$$T_{\text{PT}} \lesssim 5.2\ \text{MeV}$$

R McGehee



$F_{\mathrm{DM}} = 1$
$\sigma_{\chi n}^{\max}$
$T_{\mathrm{PT}} = 1$ MeV
$T_{\mathrm{PT}} = 5$ MeV
CDEX
Brown Dwarfs
CO molecules
color centers
HYPER space
He
He
diamond
diamond
SiC
$CaWO_4$
GaAs
CsI
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
0.01
0.1
1
10
100
$\sigma_{\chi n}$ [cm^2]
m_χ [MeV]

R McGehee