Maximizing Direct Detection with HYPER Dark Matter

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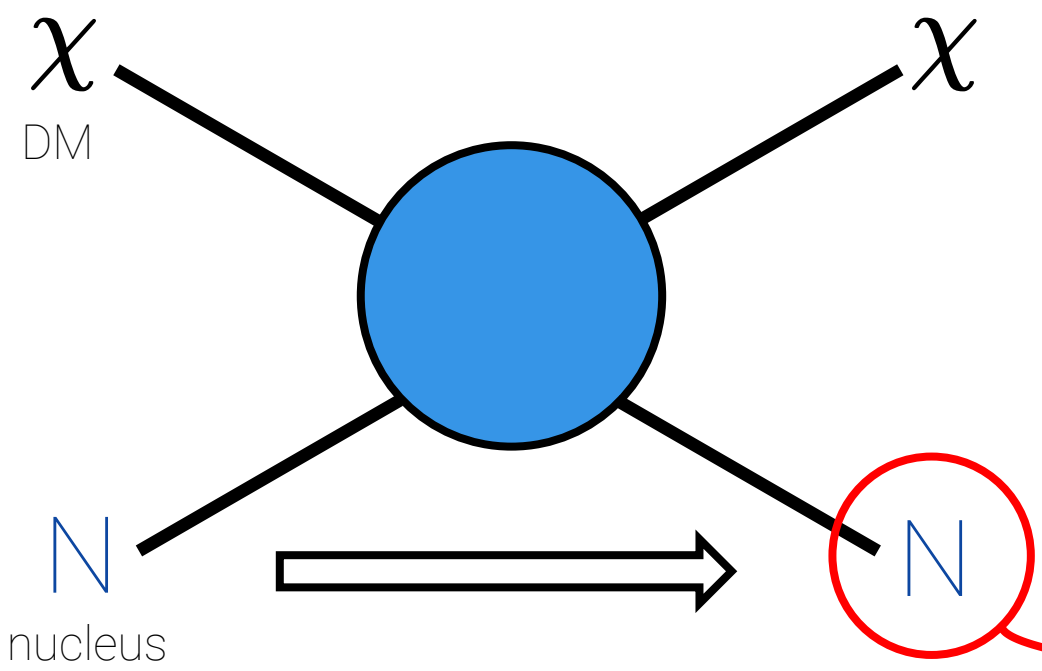
UNIVERSITY OF MICHIGAN

2112.03920

w/ Gilly Elor & Aaron Pierce

PIKIMO 12 @ Notre Dame, 4/30/22

Direct Detection Refresher



Credit: The XENON Experiment

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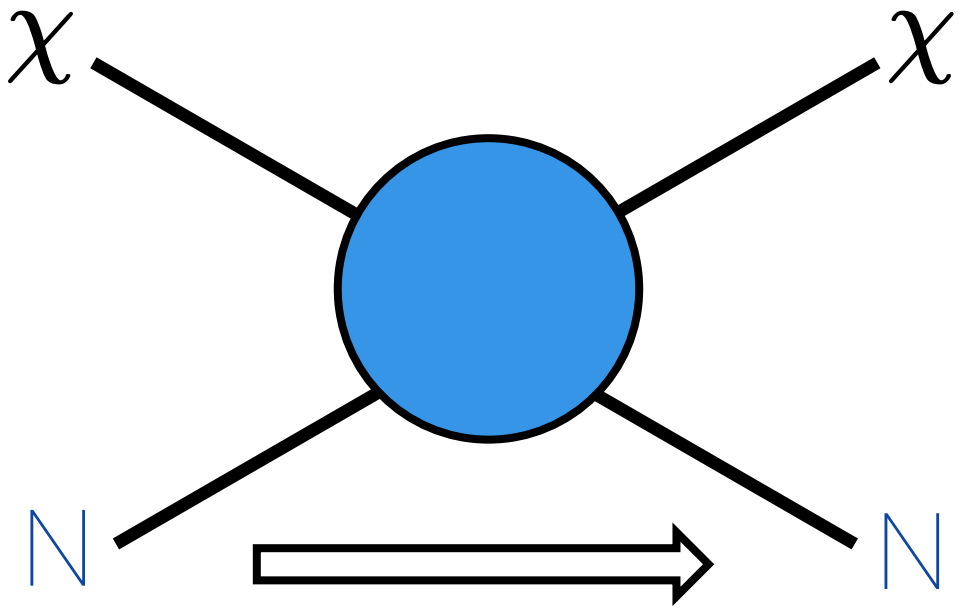
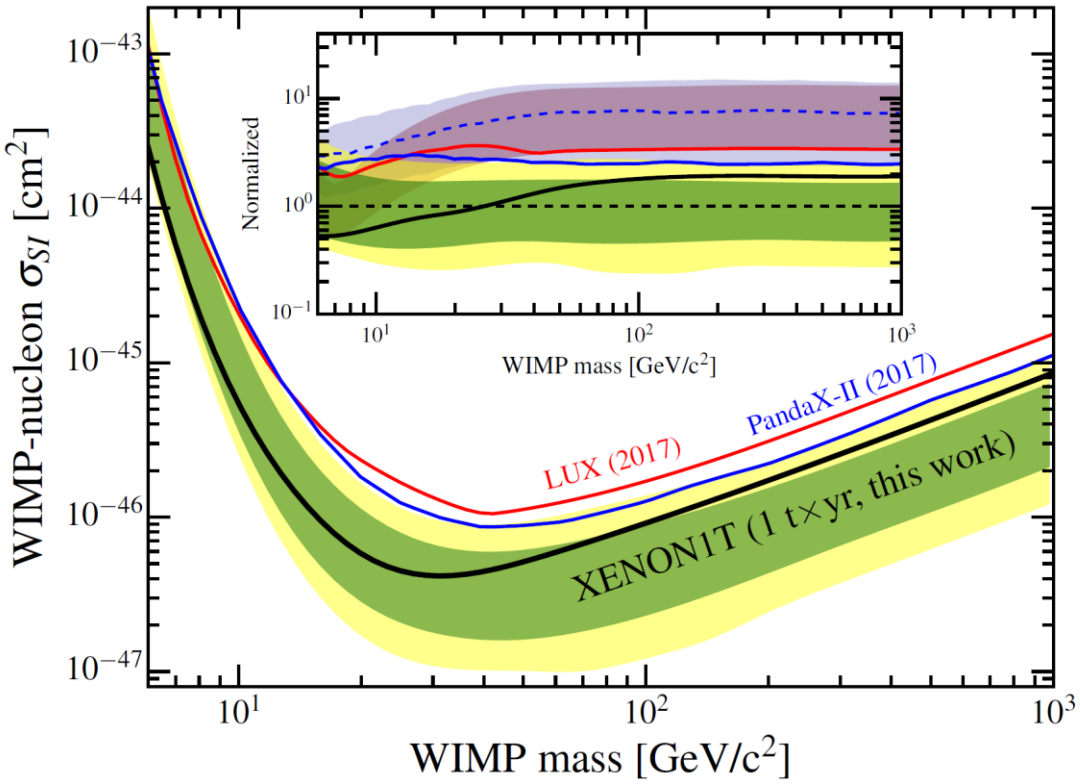
Direct Detection Refresher





XENON Collaboration [1805.12562]

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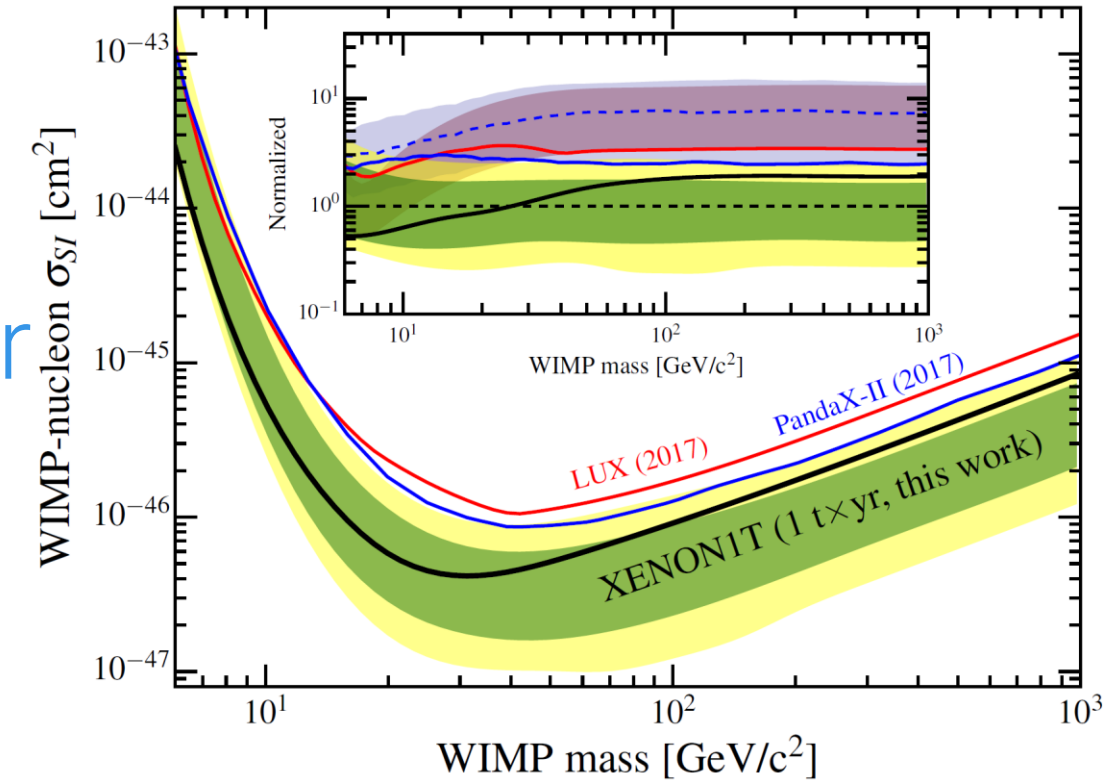
Direct Detection Future

Go higher?

Go lighter



Go lower

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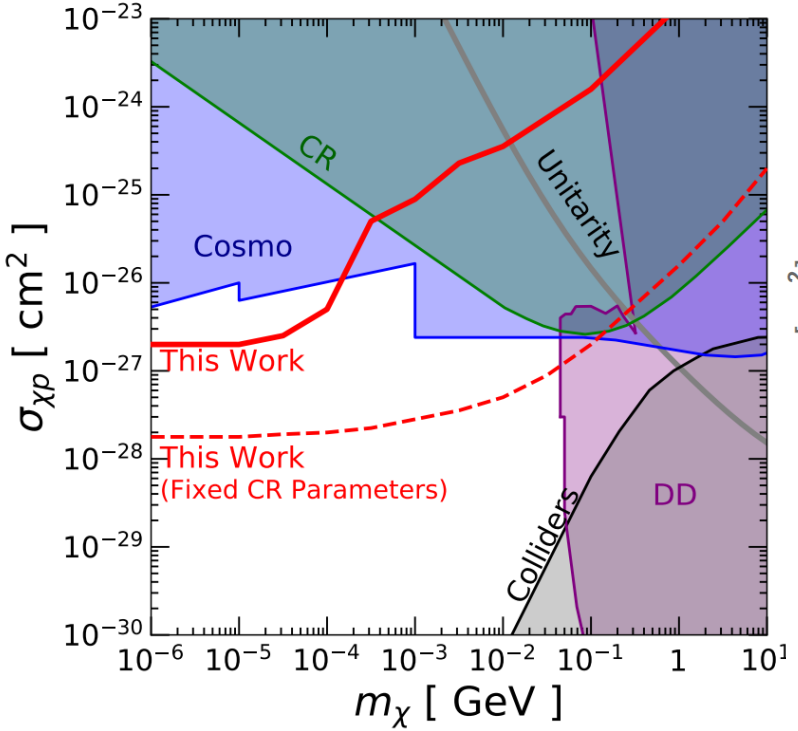
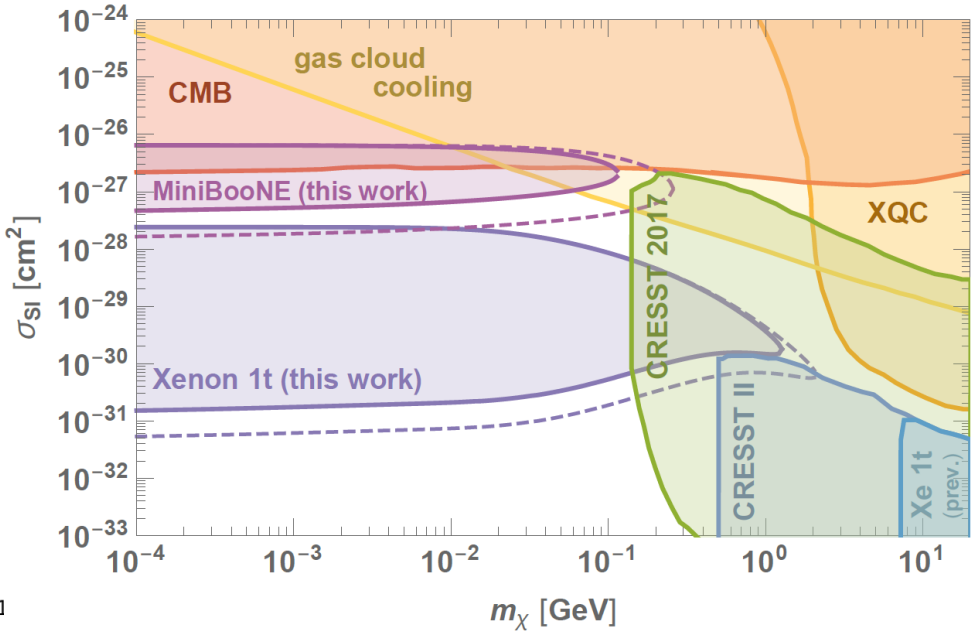
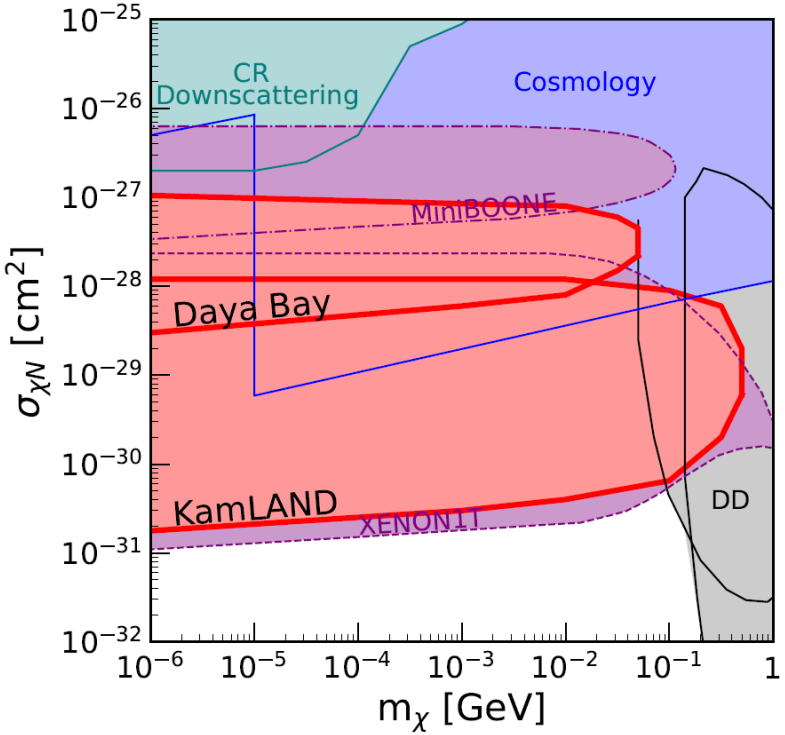
Bounds from Cosmic Ray Scattering



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



T. Bringmann, M. Pospelov
[1810.10543]



C. Cappiello, J. Beacom
[1906.11283]

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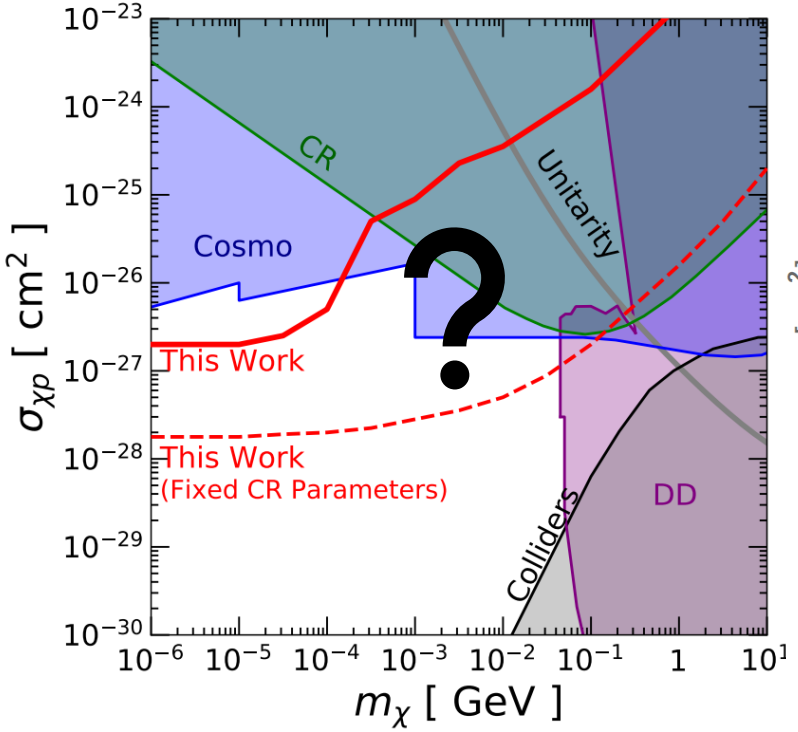
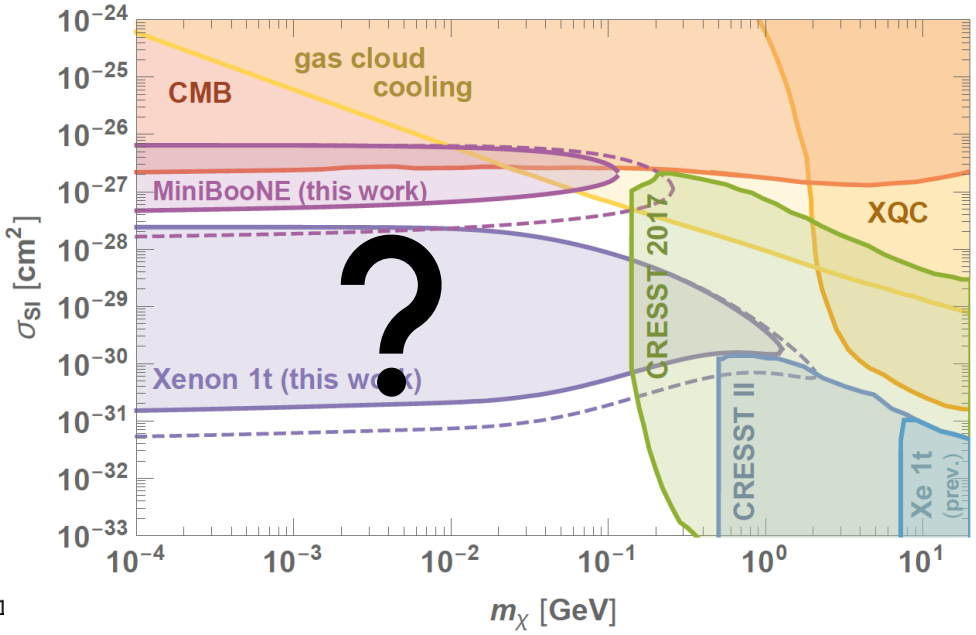
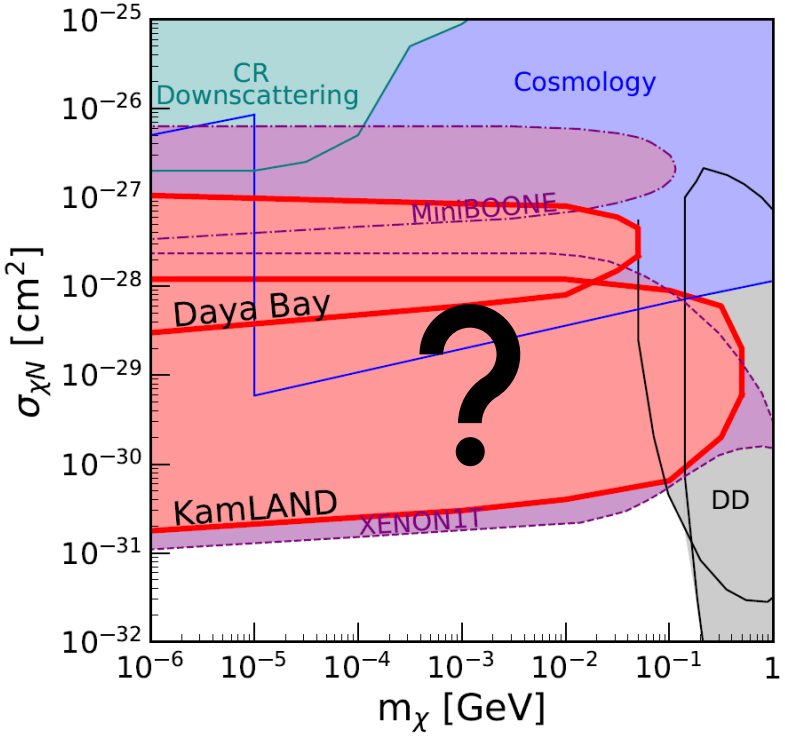
Is Dark Matter here?







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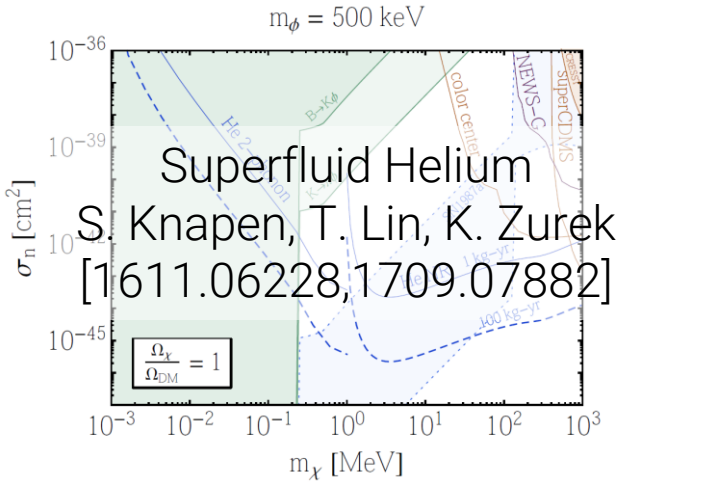
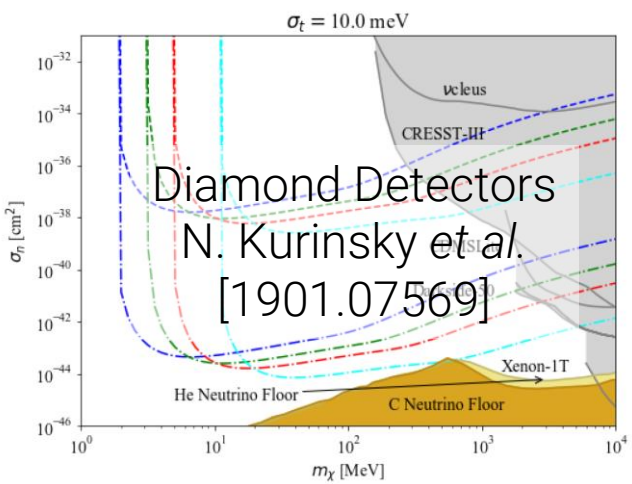
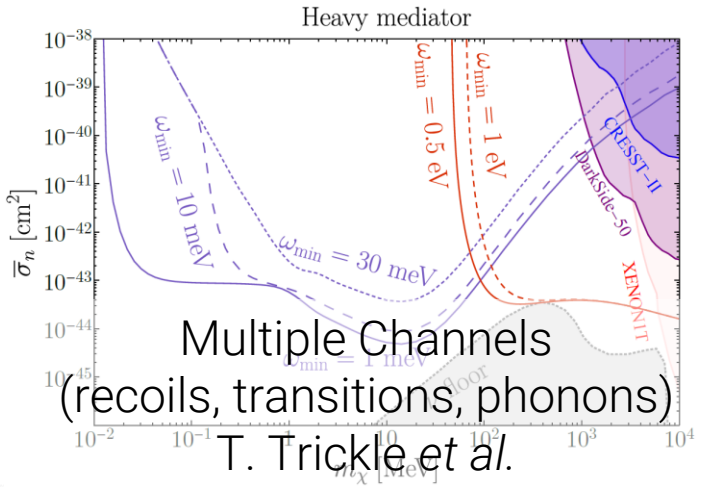
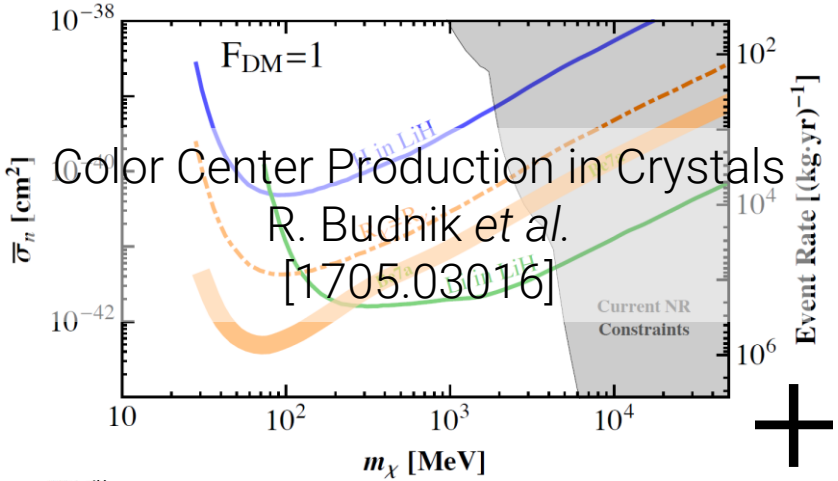
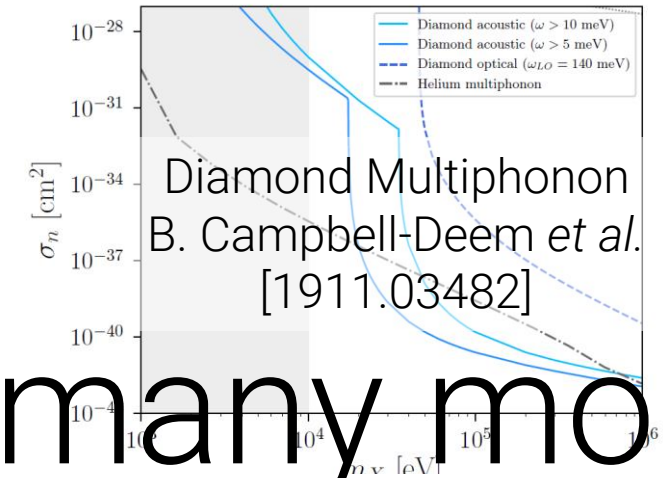
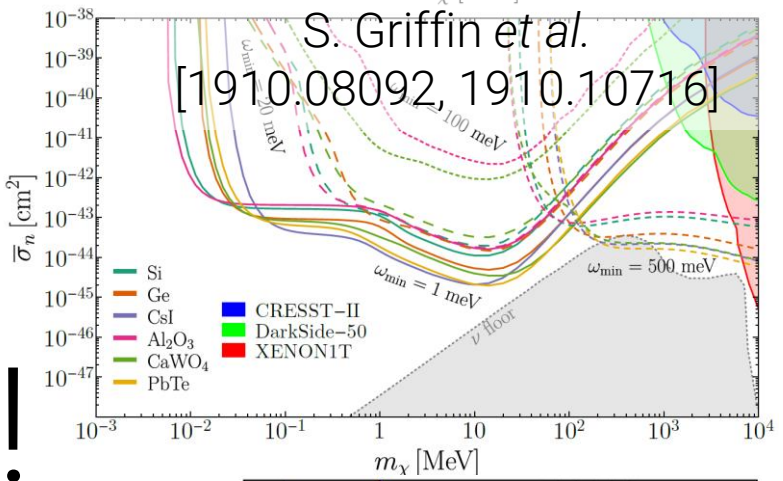

m_ϕ = 500 keV
Superfluid Helium
S. Knapen, T. Lin, K. Zurek
[1611.06228,1709.07882]
σ_n [cm^2]
m_χ [MeV]


σ_t = 10.0 meV
Diamond Detectors
N. Kurinsky *et al.*
[1901.07569]
Xenon-1T
He Neutrino Floor
C Neutrino Floor
σ_n [cm^2]
m_χ [MeV]

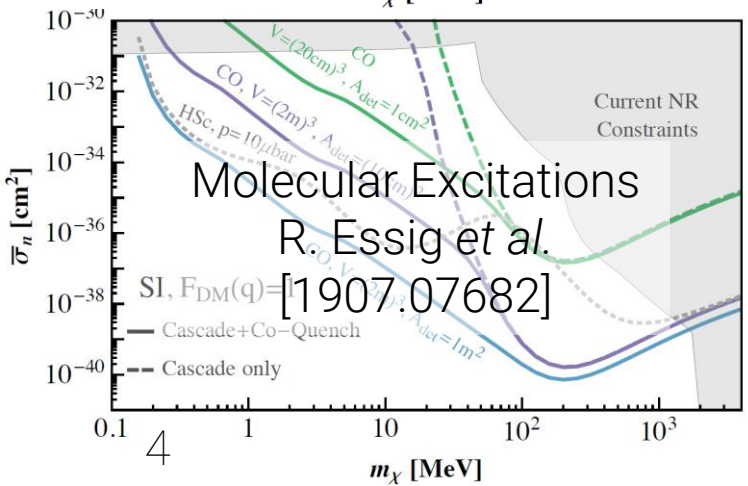

Heavy mediator
Multiple Channels
(recoils, transitions, phonons)
T. Trickle *et al.*
S. Griffin *et al.*
[1910.08092, 1910.10716]
ω_{min} = 10 meV
ω_{min} = 30 meV
ω_{min} = 0.5 eV
ω_{min} = 1 eV
CRESST-II
DarkSide-50
XENON1T
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

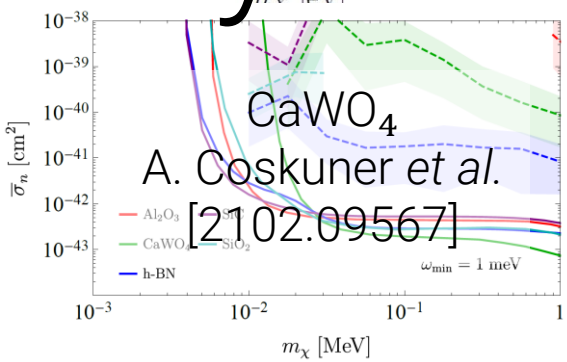

F_{DM}=1
Color Center Production in Crystals
R. Budnik *et al.*
[1705.03016]
Current NR Constraints
Event Rate [(kg·yr)$^{-1}$]
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

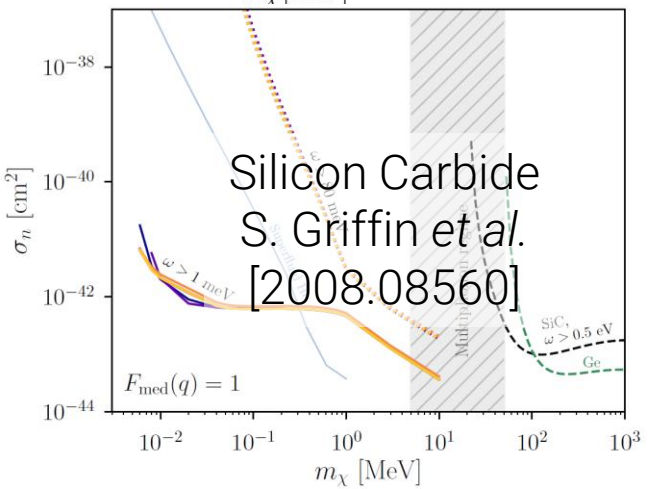

Diamond acoustic (ω > 10 meV)
Diamond acoustic (ω > 5 meV)
Diamond optical (ω_{LO} = 140 meV)
Helium multiphonon
Diamond Multiphonon
B. Campbell-Deem *et al.*
[1911.03482]
σ_n [cm^2]

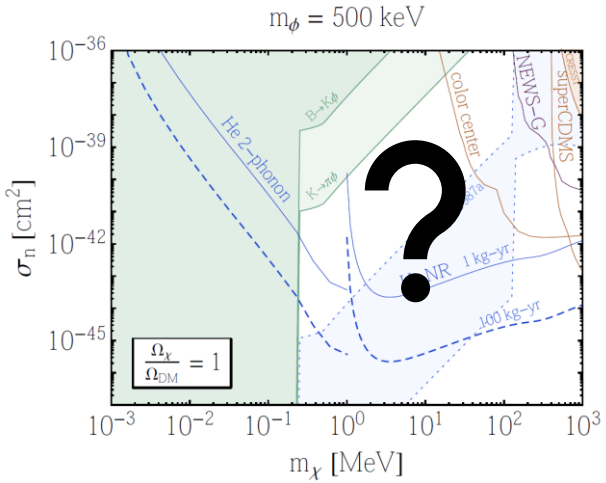

Si
Ge
CsI
Al_2O_3
$CaWO_4$
PbTe
CRESST-II
DarkSide-50
XENON1T
ω_{min} = 1 meV
ω_{min} = 500 meV
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

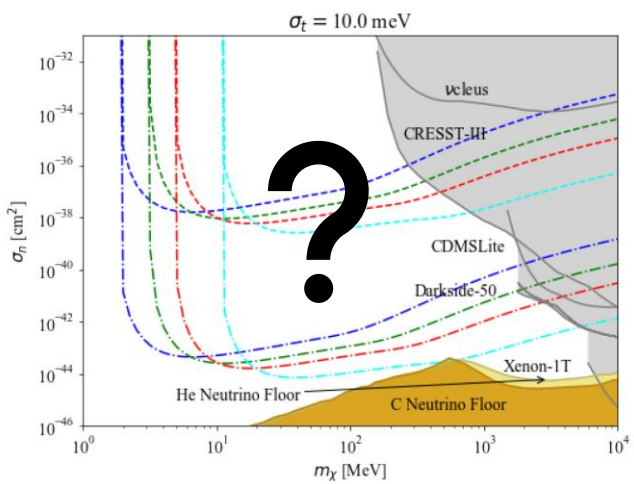
+ many more!

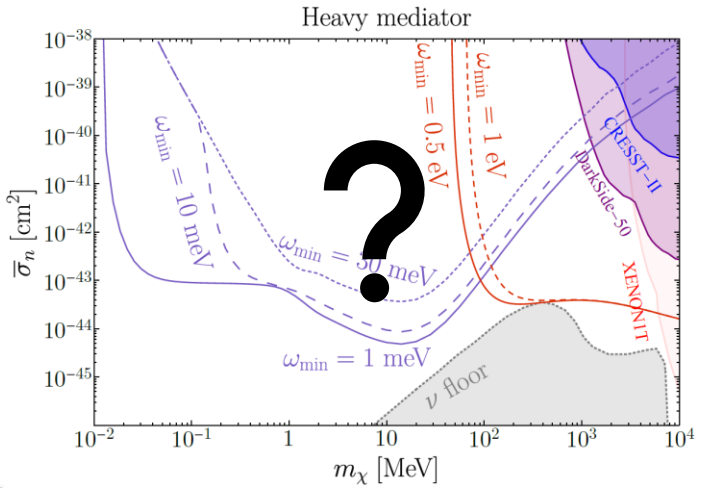

Molecular Excitations
R. Essig *et al.*
[1907.07682]
Current NR Constraints
SI, $F_{DM}(q)=1$
Cascade+Co-Quench
Cascade only
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

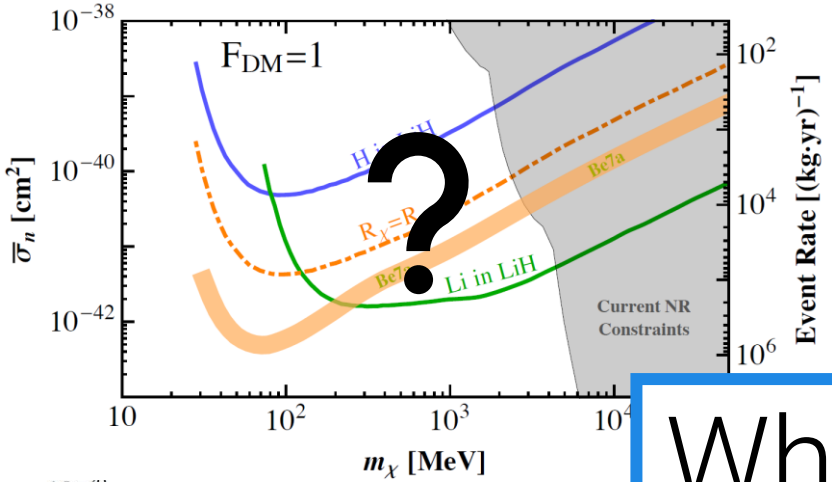

$CaWO_4$
A. Coskuner *et al.*
[2102.09567]
Al_2O_3
$CaWO_4$
SiO_2
h-BN
ω_{min} = 1 meV
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

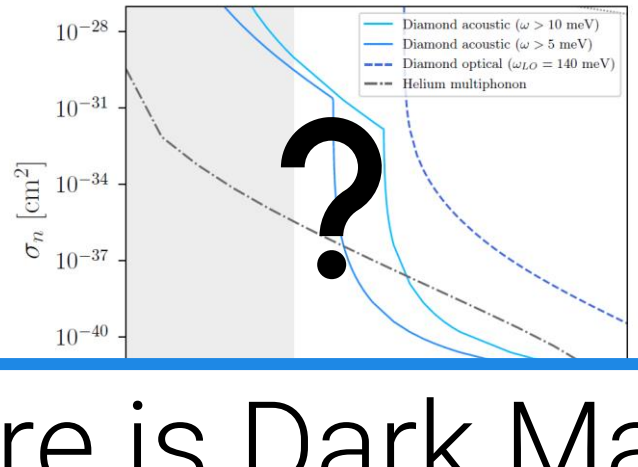

Silicon Carbide
S. Griffin *et al.*
[2008.08560]
ω > 1 meV
SiC, ω > 0.5 eV
Ge
$F_{med}(q) = 1$
σ_n [cm^2]
m_χ [MeV]

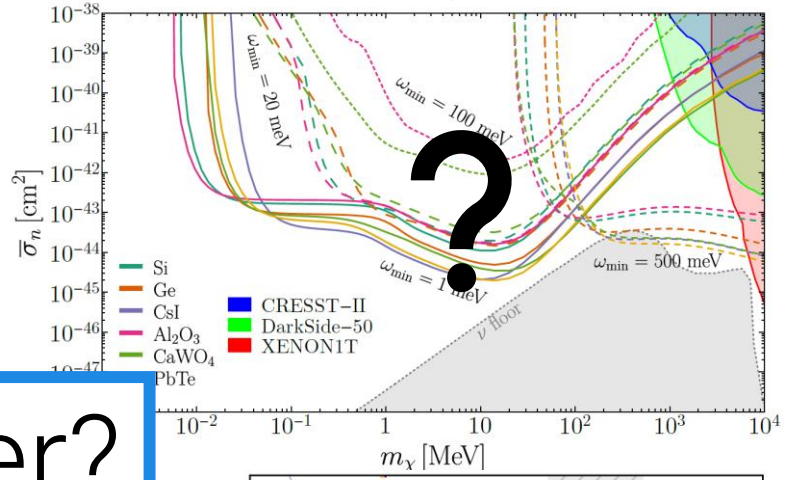


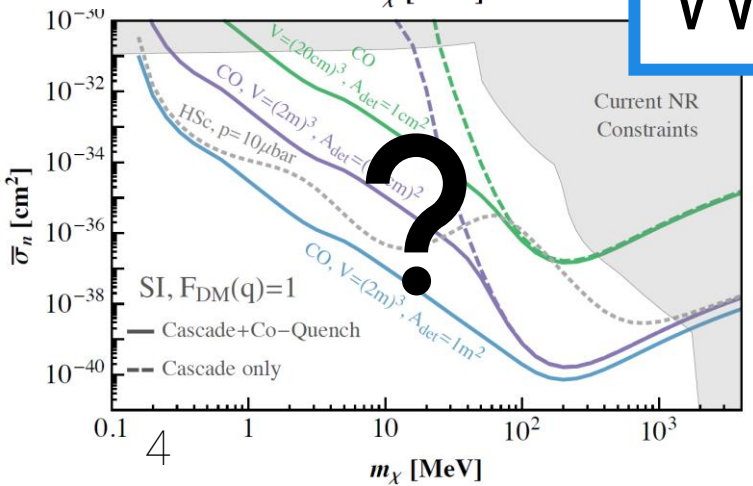


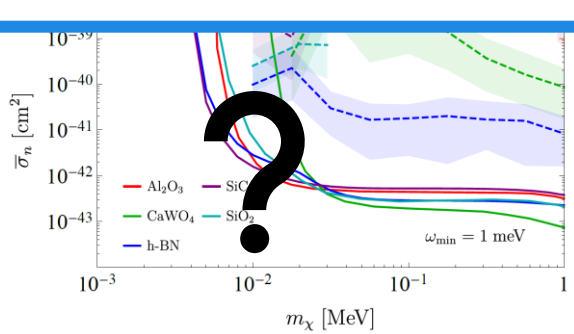


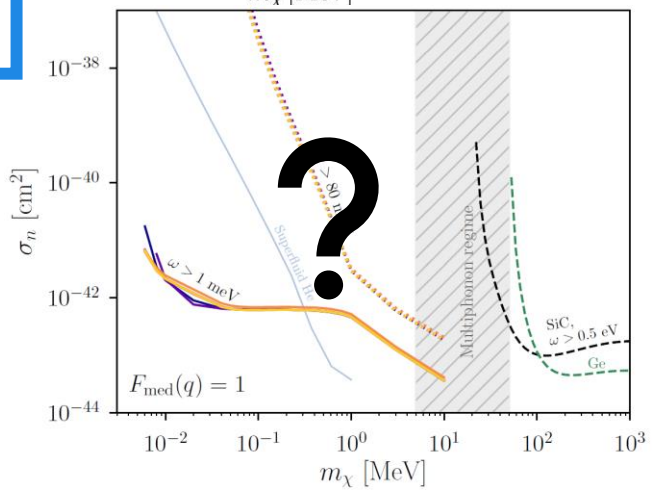












Where is Dark Matter?

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?

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

The Basics

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

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

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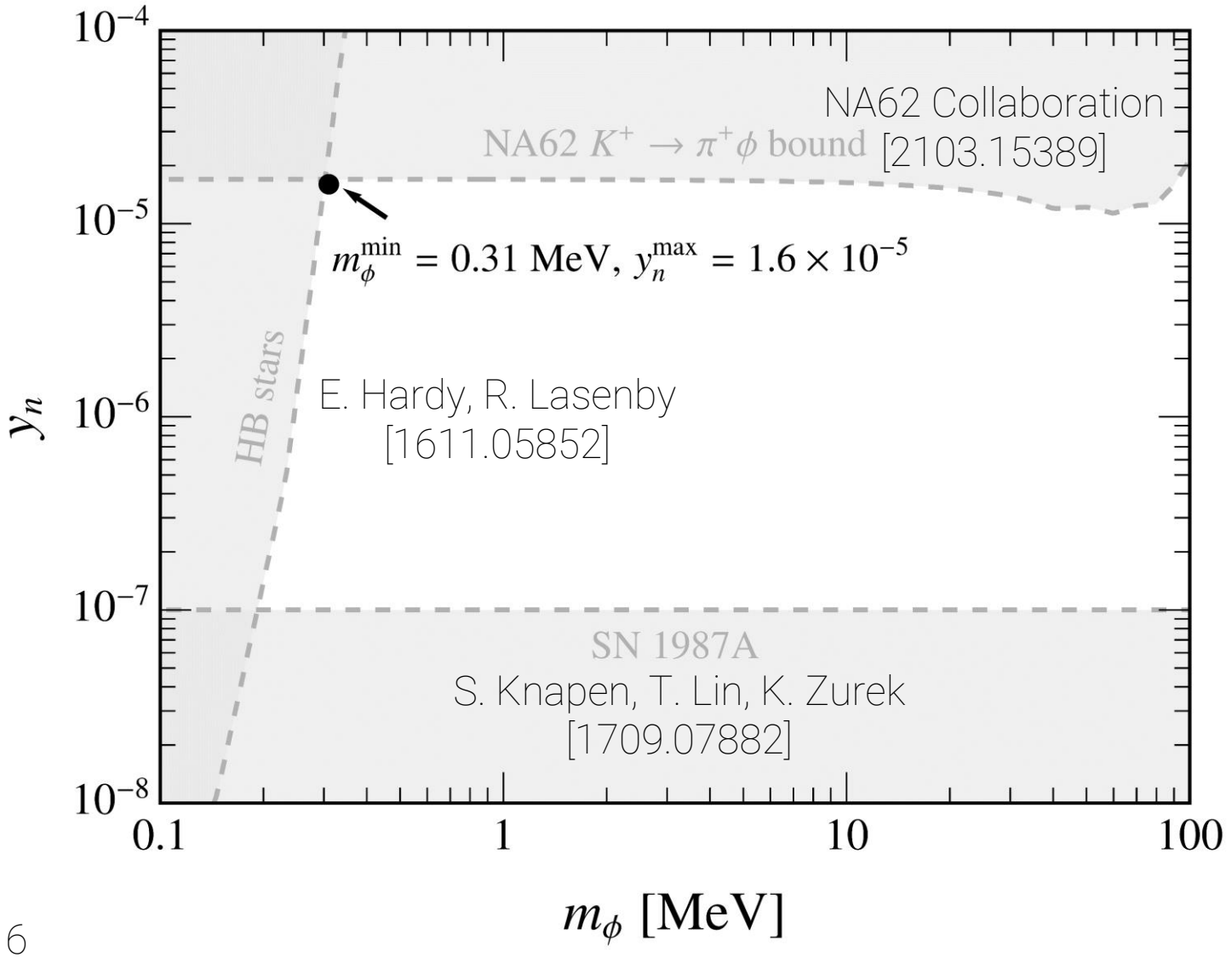
The Basics



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

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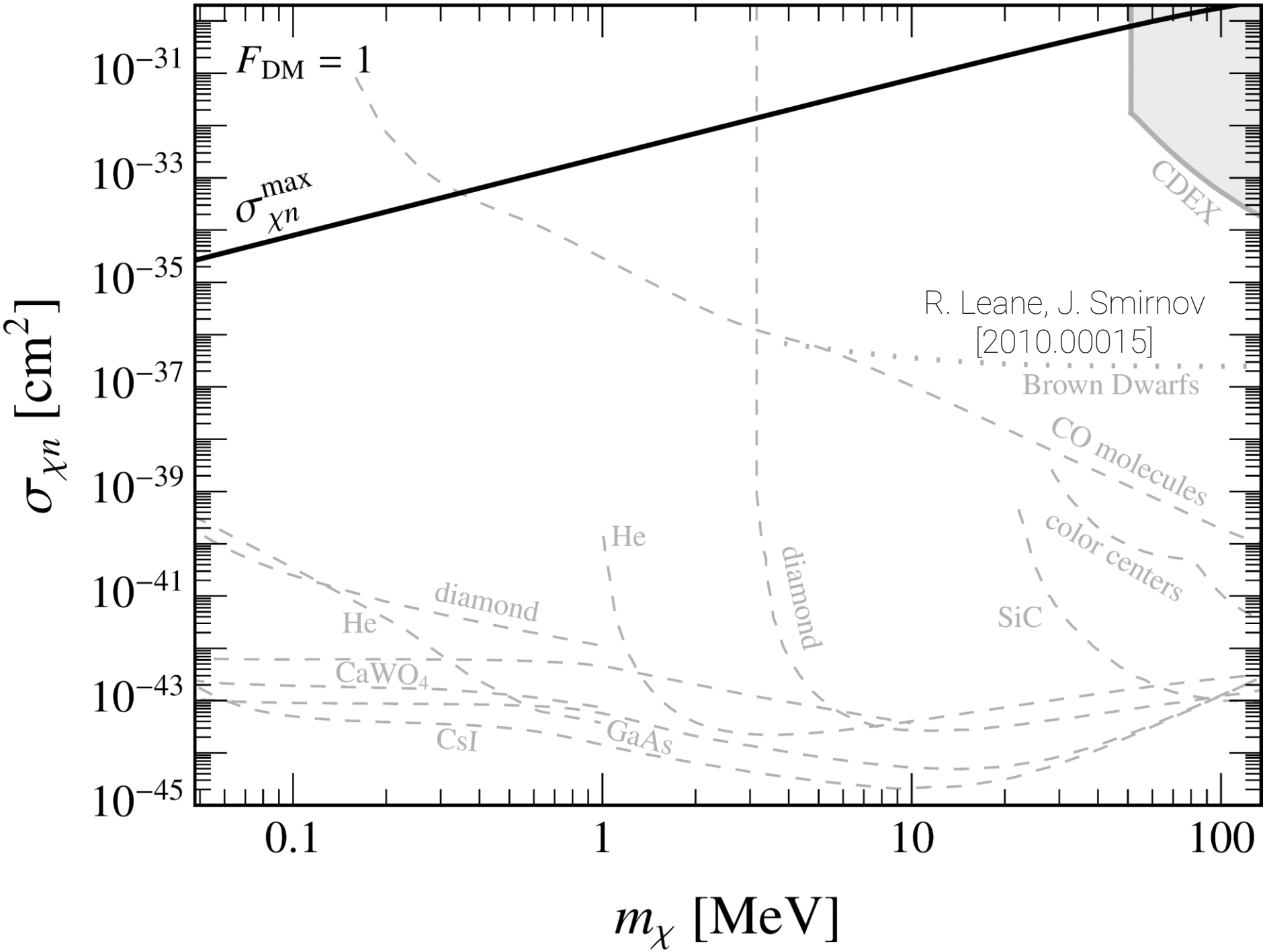
$F_{\rm DM} = 1$
$\sigma_{\chi n}^{\rm max}$
CDEX
R. Leane, J. Smirnov
[2010.00015]
Brown Dwarfs
CO molecules
color centers
SiC
diamond
He
diamond
He
$CaWO_4$
CsI
GaAs
$\sigma_{\chi n}$ [cm^2]
m_χ [MeV]
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
0.1
1
10
100

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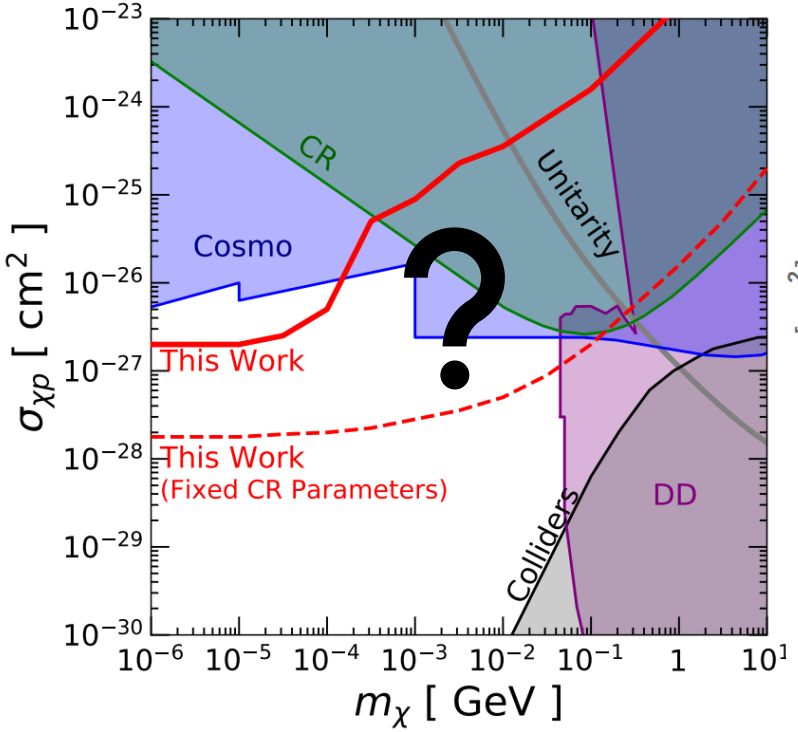
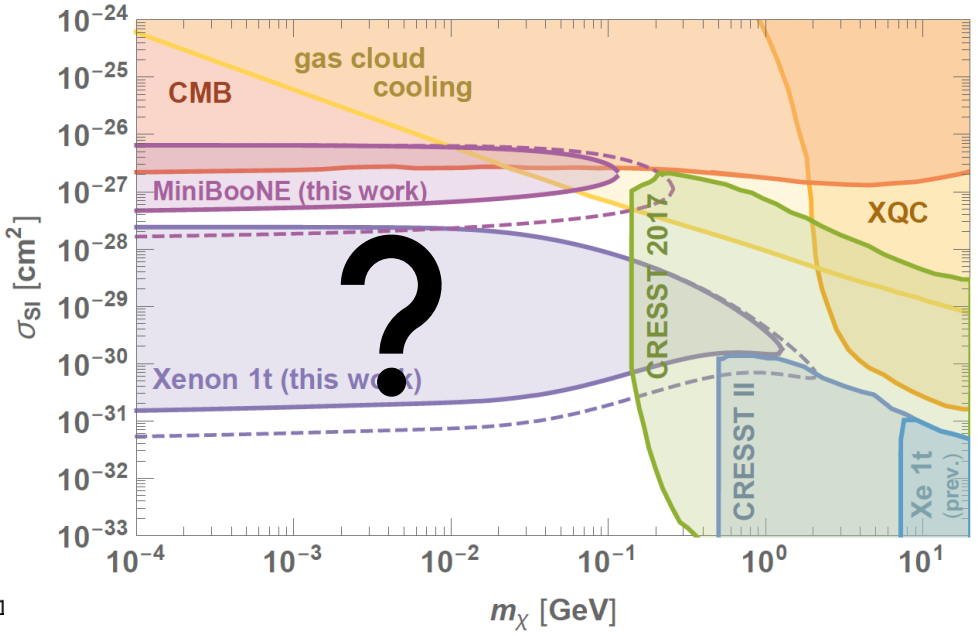
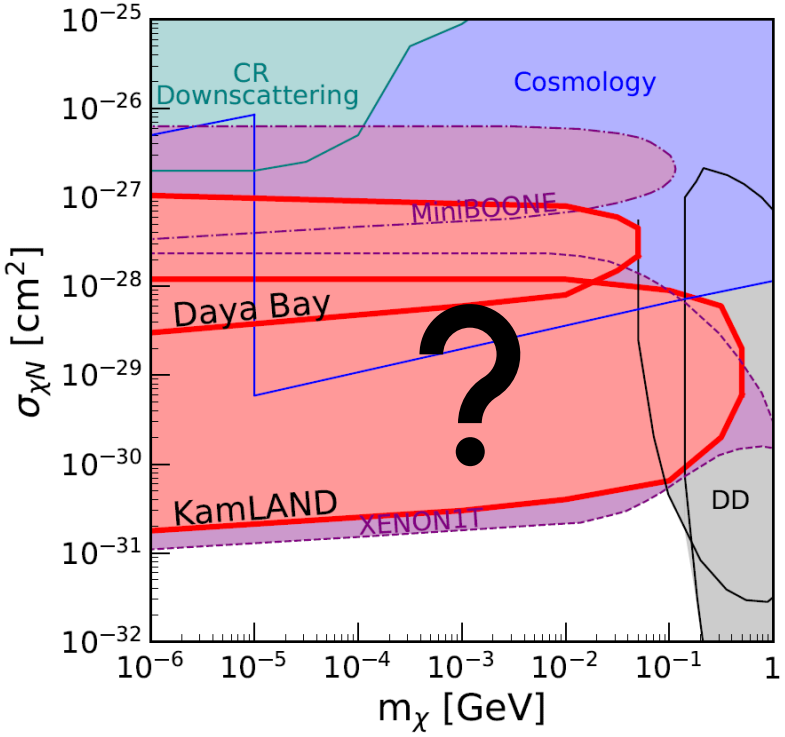
Is Dark Matter here?







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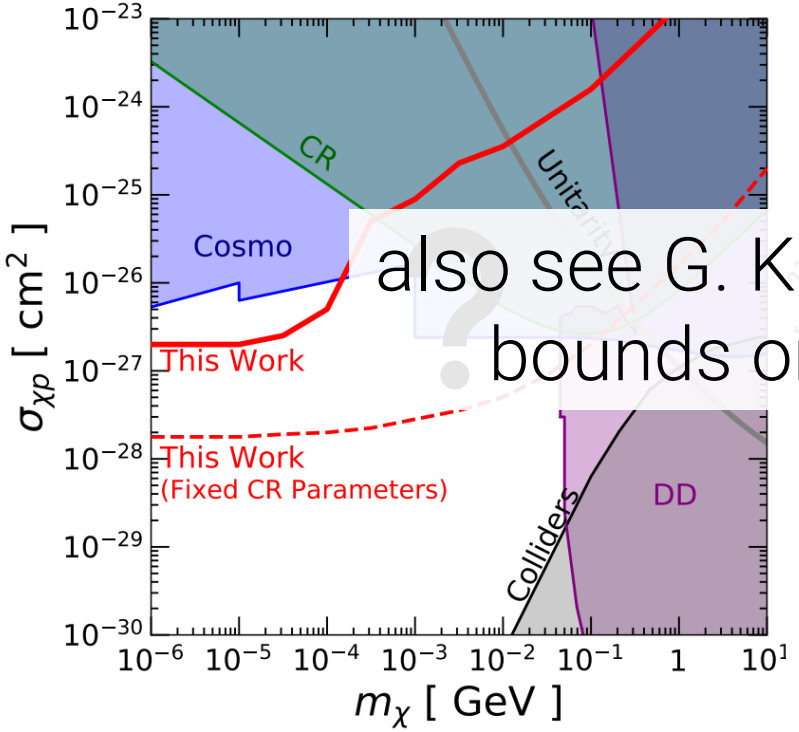
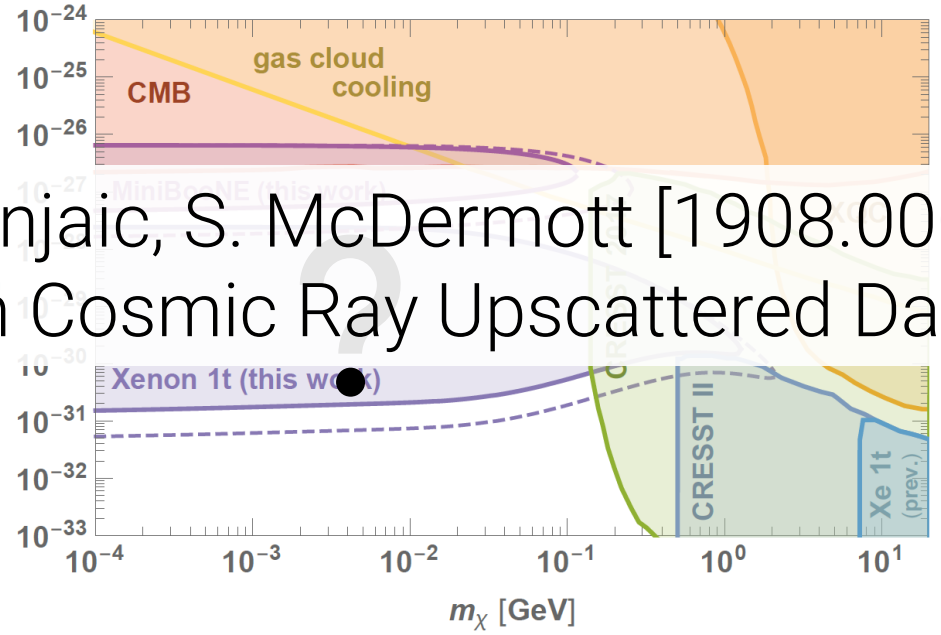
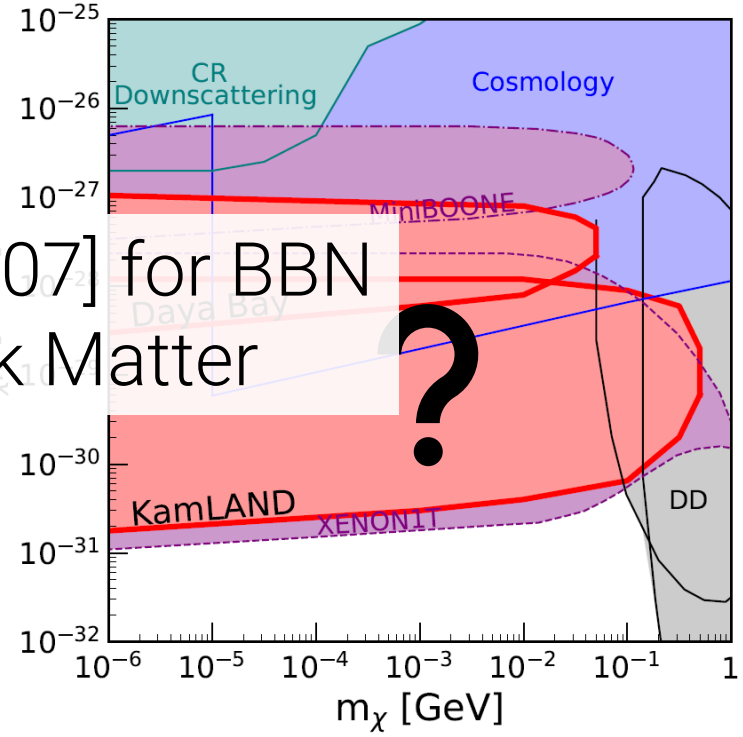
Is Dark Matter here?

Probably not.







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

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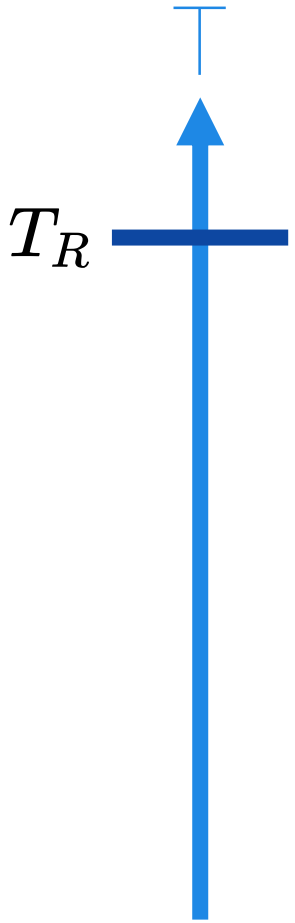
Is there a sub-GeV DM candidate which

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

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

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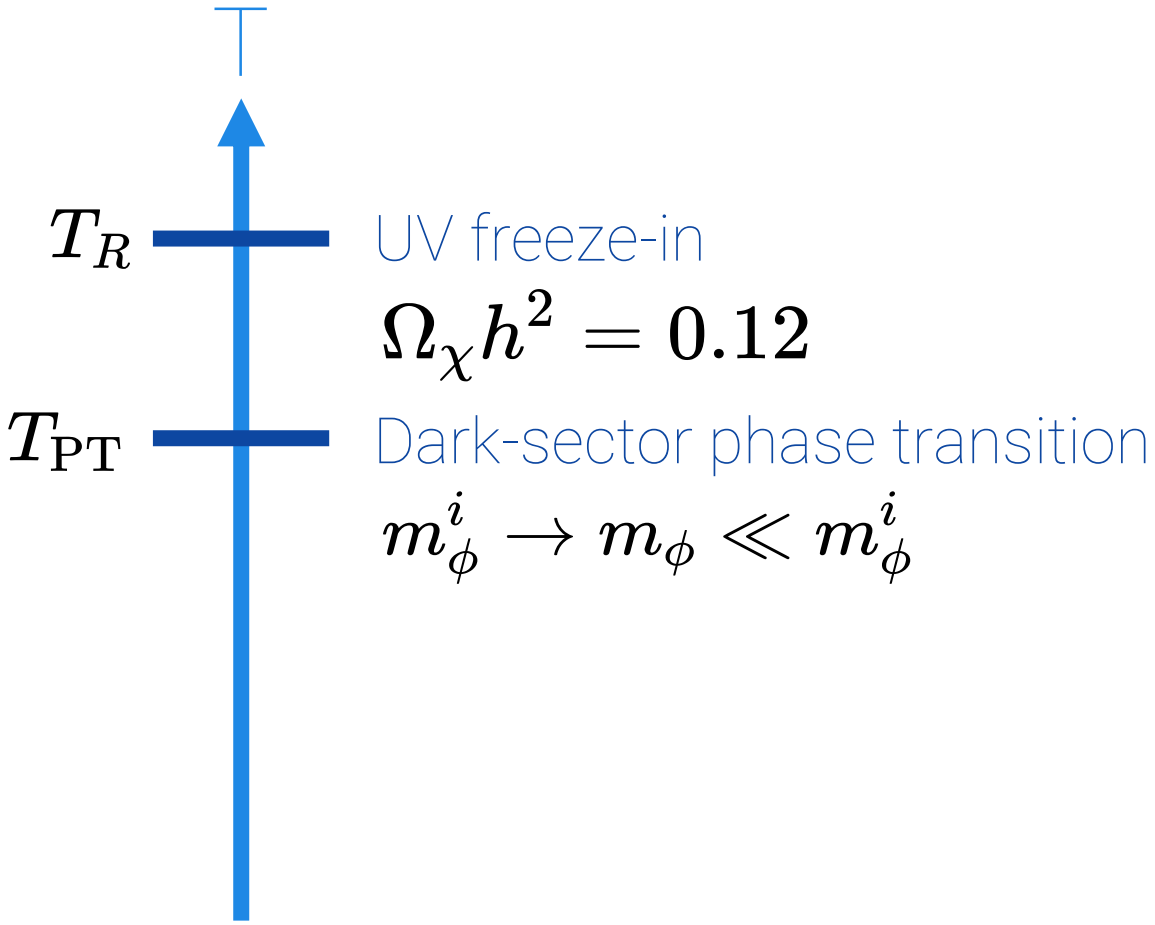
HYPER History



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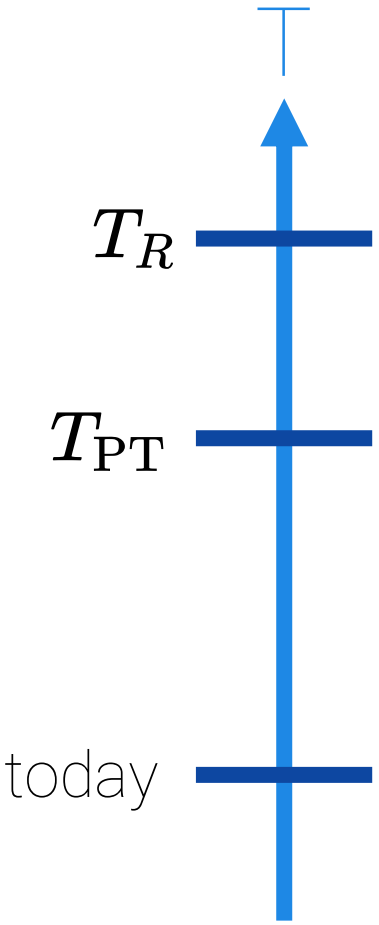
HYPER History



UV freeze-in

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

Dark-sector phase transition

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

Direct detection cross section grows!

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

K. Boddy, S. Carroll, M. Trodden [1208.4376]

→ Interactions much stronger today than when relic abundance was set

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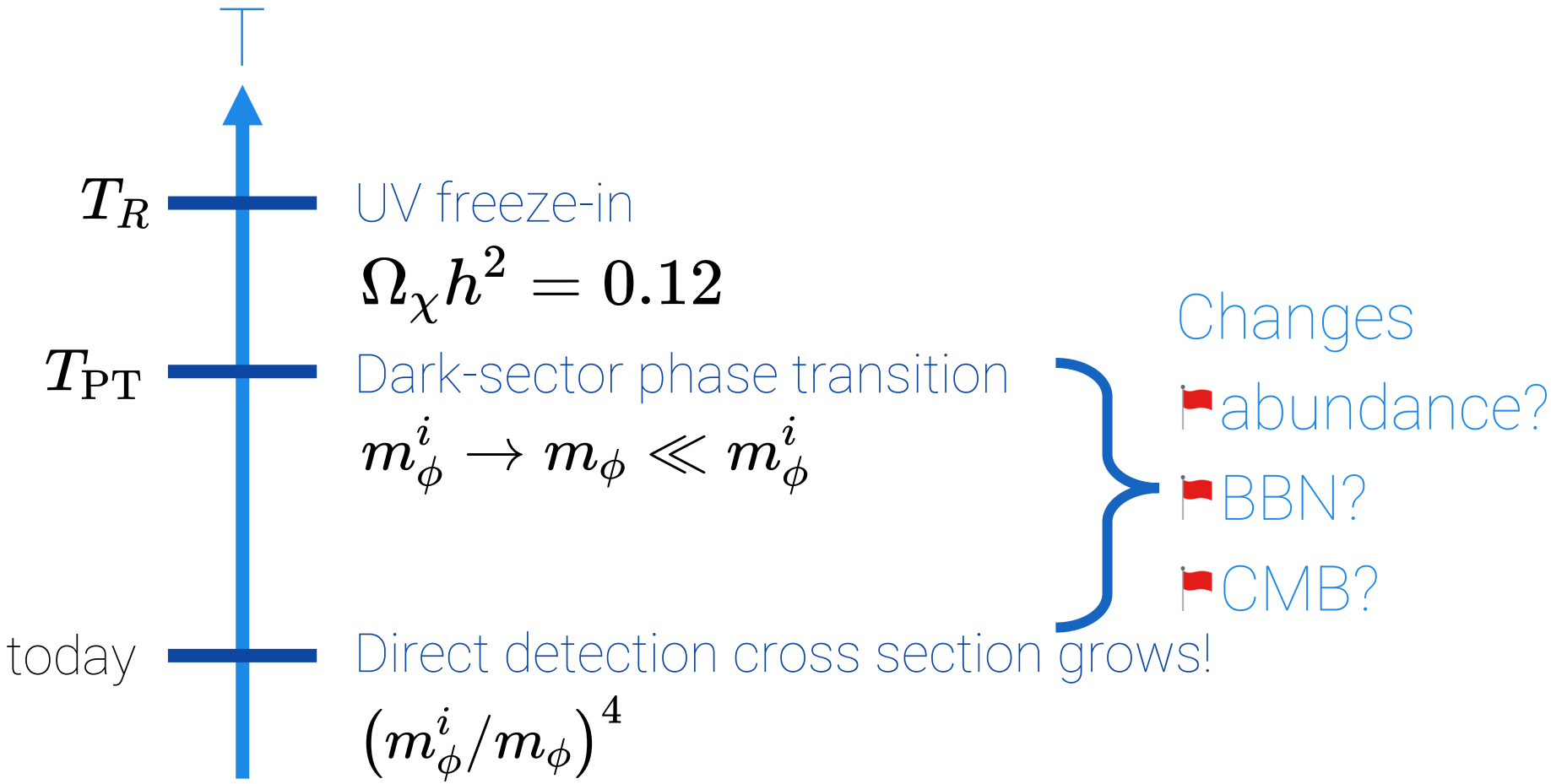
HYPER History



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🚩Changes relic abundance?

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

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

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

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🚩Changes relic abundance?

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

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

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

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

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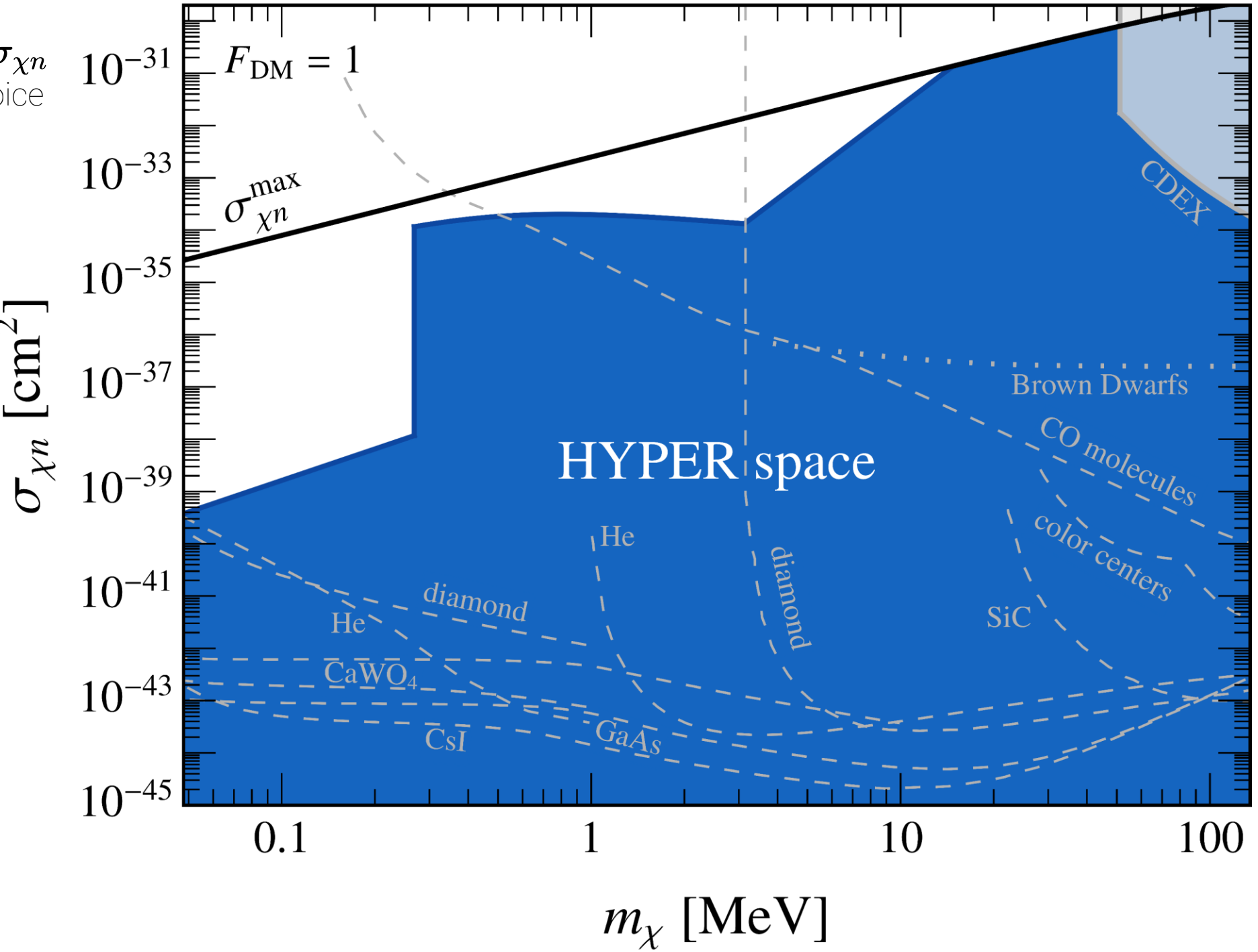
Results

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



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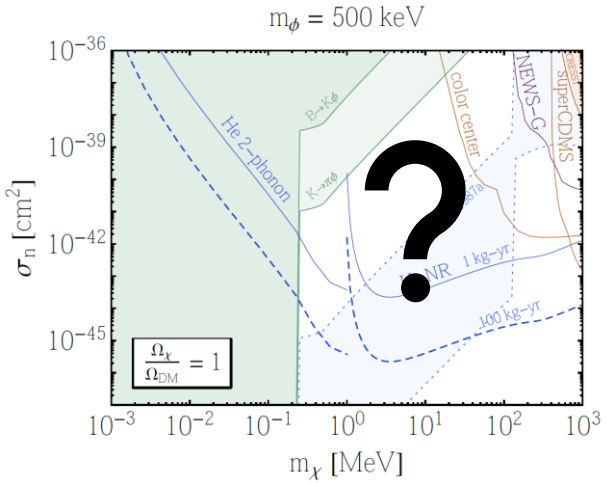
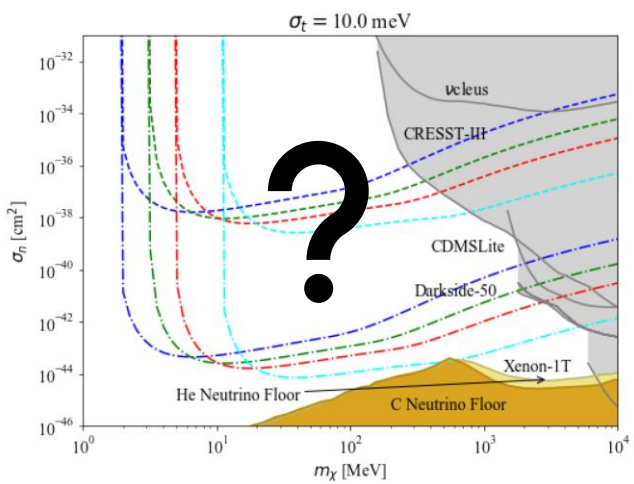
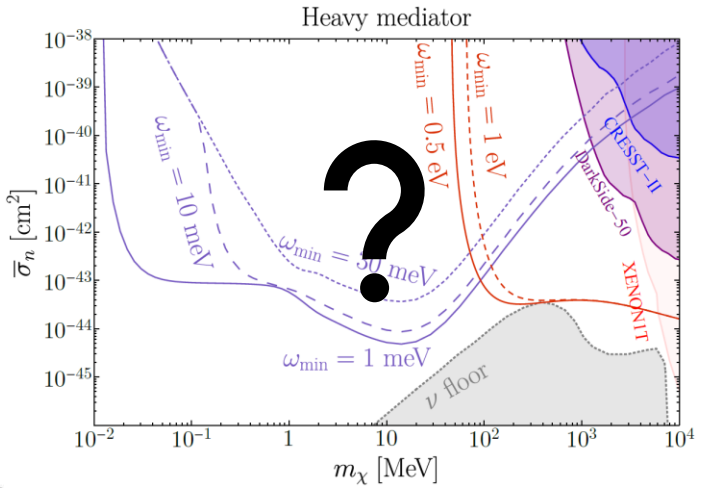
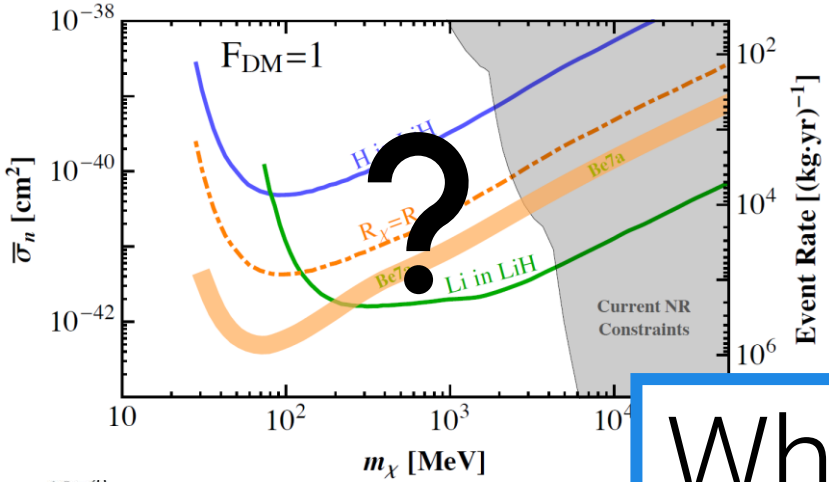
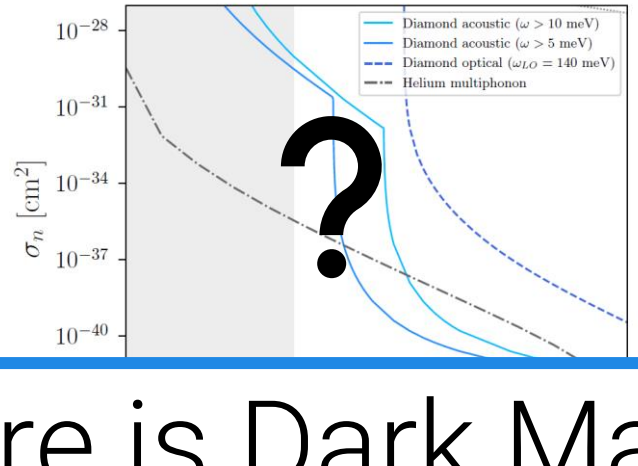
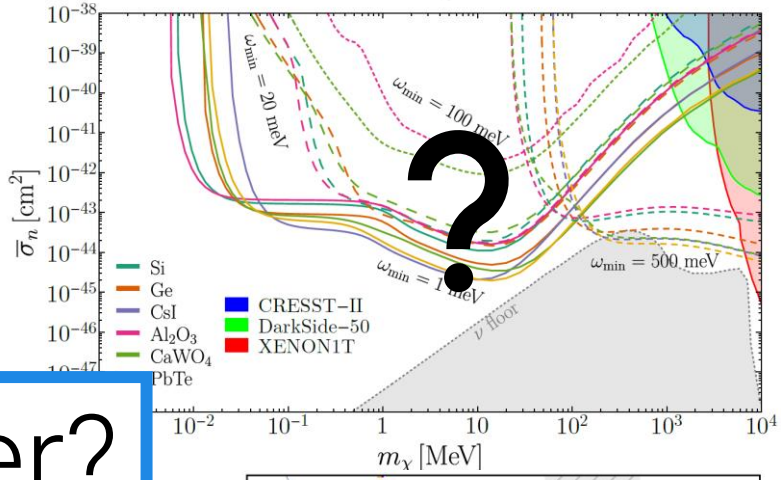




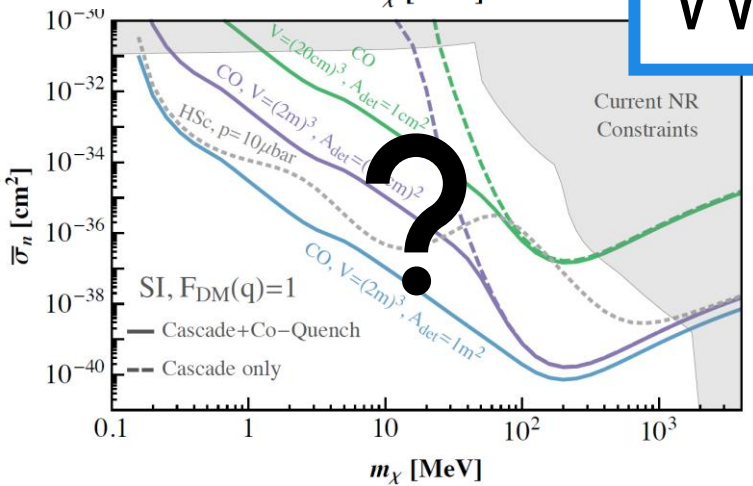


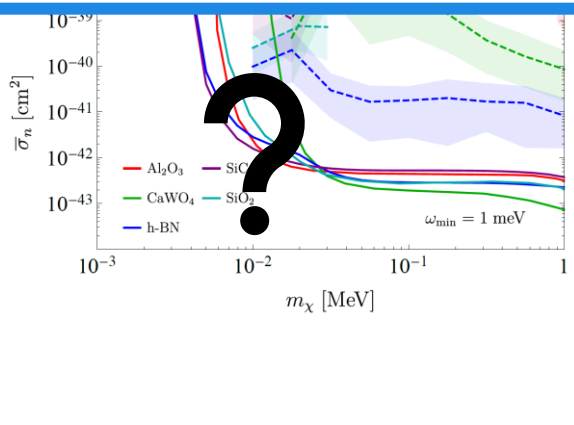


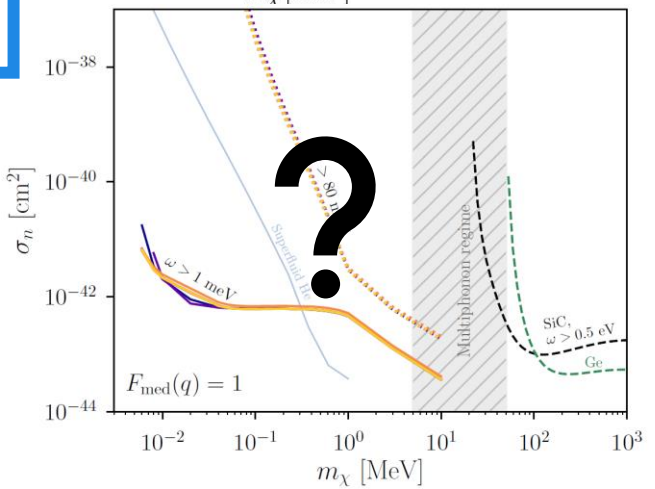


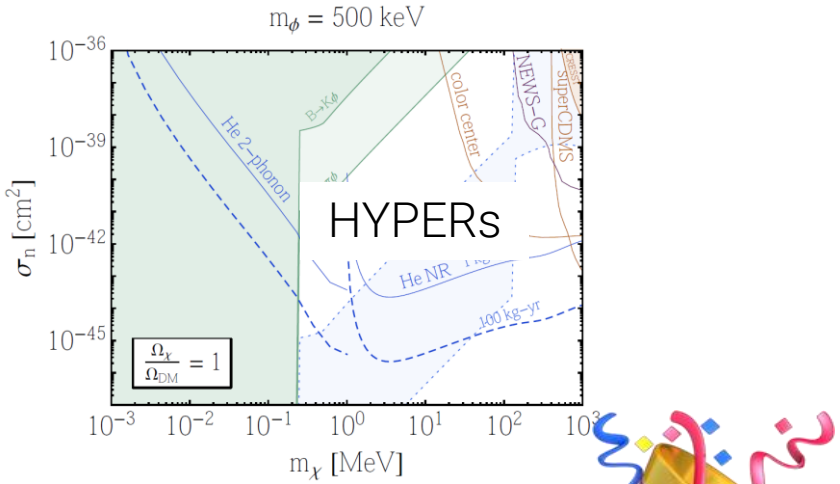


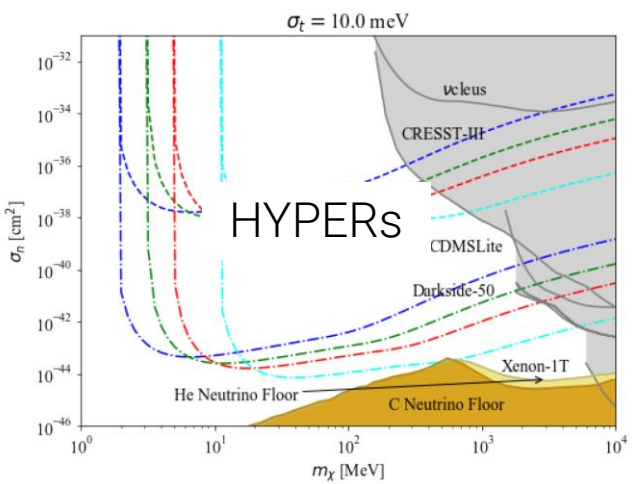
Where is Dark Matter?

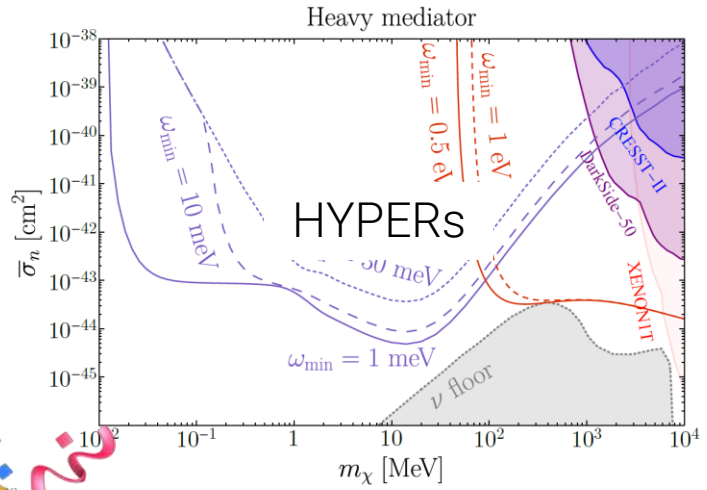


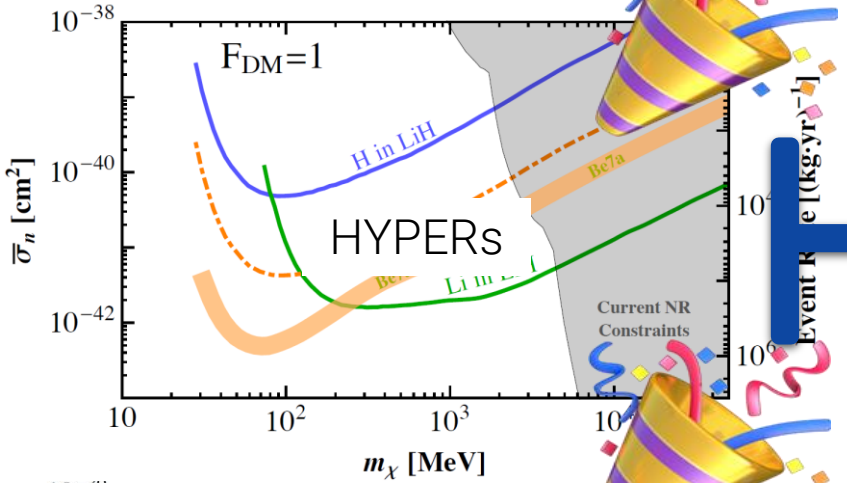


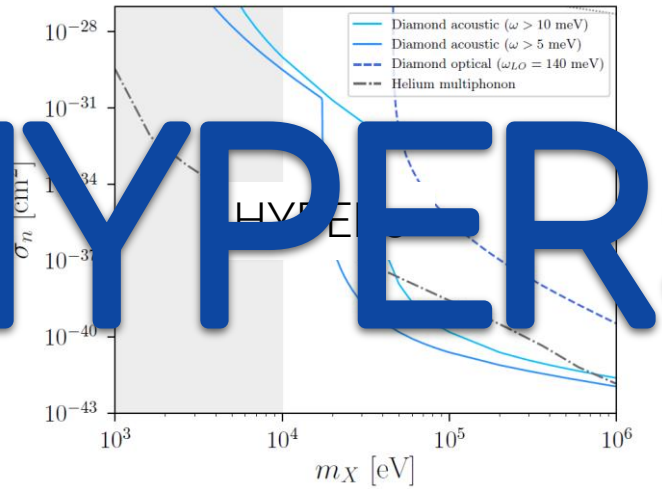


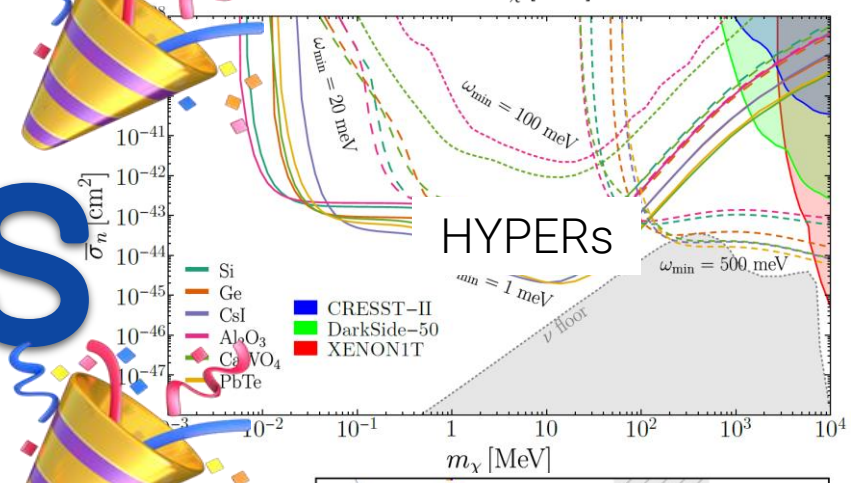

m_ϕ = 500 keV
HYPERs
He 2-phonon
color center
NEWS-G
SuperCDMS
He NR
100 kg-yr
$\frac{\Omega_\chi}{\Omega_{DM}} = 1$
σ_n [cm^2]
m_χ [MeV]

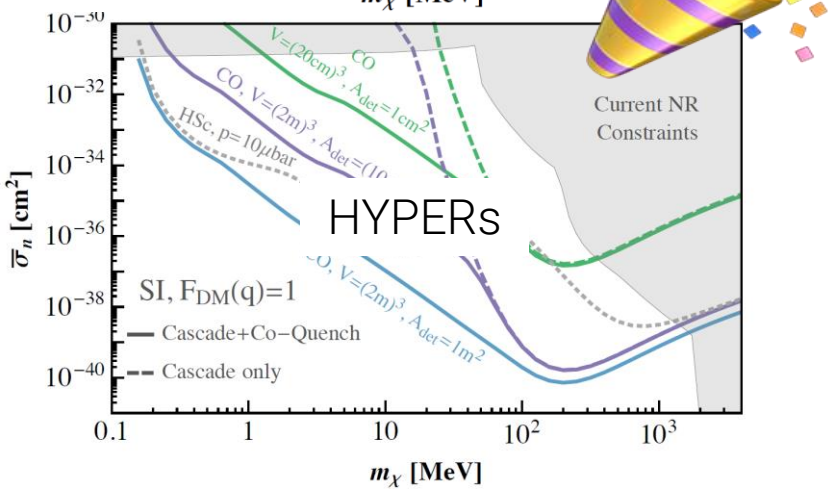

σ_t = 10.0 meV
HYPERs
ν-cleus
CRESST-III
CDMSLite
Darkside-50
Xenon-1T
He Neutrino Floor
C Neutrino Floor
σ_n [cm^2]
m_χ [MeV]

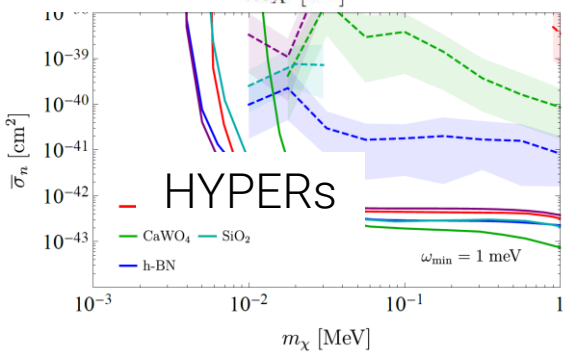

Heavy mediator
HYPERs
ω_{min} = 0.5 eV
ω_{min} = 1 eV
ω_{min} = 10 meV
ω_{min} = 1 meV
CRESST-II
DarkSide-50
XENON1T
ν floor
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

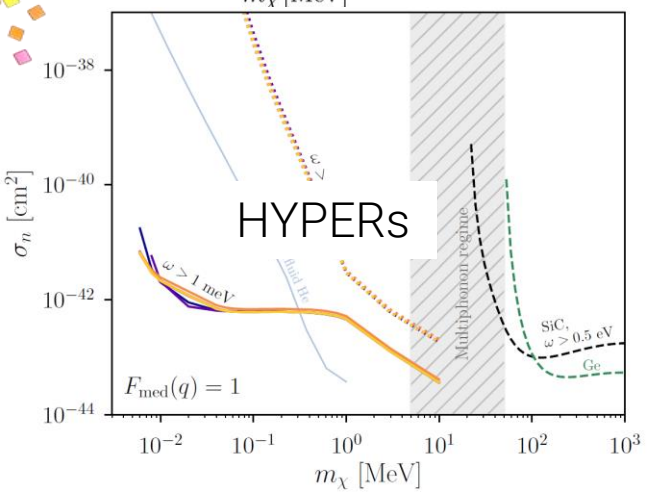

F_{DM}=1
HYPERs
H in LiH
Be7a
Current NR Constraints
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]


Diamond acoustic (ω > 10 meV)
Diamond acoustic (ω > 5 meV)
Diamond optical (ω_{LO} = 140 meV)
Helium multiphonon
HYPERs
σ_n [cm^2]
m_X [eV]


HYPERs
ω_{min} = 20 meV
ω_{min} = 100 meV
ω_{min} = 500 meV
ω_{min} = 1 meV
ν floor
Si
Ge
CsI
Al_2O_3
$CaWO_4$
PbTe
CRESST-II
DarkSide-50
XENON1T
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]


HYPERs
CO
CO, V=(2m)^3, A_{det}=1cm^2
HSc, p=10μbar
Current NR Constraints
SI, F_{DM}(q)=1
Cascade+Co-Quench
Cascade only
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]


HYPERs
$CaWO_4$
SiO_2
h-BN
ω_{min} = 1 meV
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]


HYPERs
ω > 1 meV
Multiphonon regime
SiC, ω > 0.5 eV
Ge
$F_{med}(q) = 1$
σ_n [cm^2]
m_χ [MeV]

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?

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Is Dark Matter here?

↳ What is the max cross section of sub-GeV DM scattering off nucleons? A: Not that big. Good to know.

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?

A: HYPERs

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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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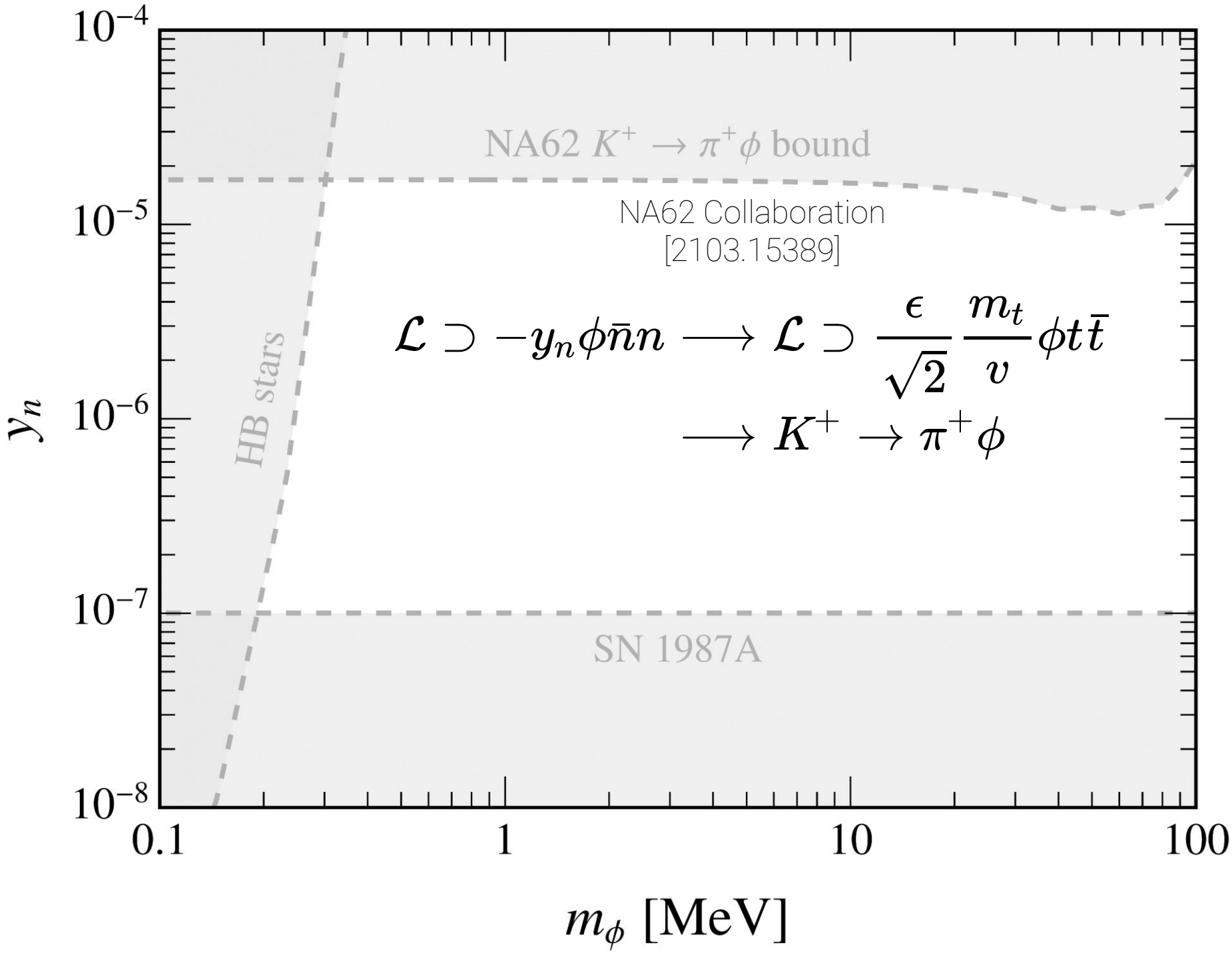
NA62 $K^+ \to \pi^+ \phi$ bound
NA62 Collaboration
[2103.15389]
HB stars
SN 1987A
$\mathcal{L} \supset -y_n \phi \bar{n} n \longrightarrow \mathcal{L} \supset \frac{\epsilon}{\sqrt{2}} \frac{m_t}{v} \phi t \bar{t}$
$\longrightarrow K^+ \to \pi^+ \phi$
y_n
m_ϕ [MeV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.1
1
10
100

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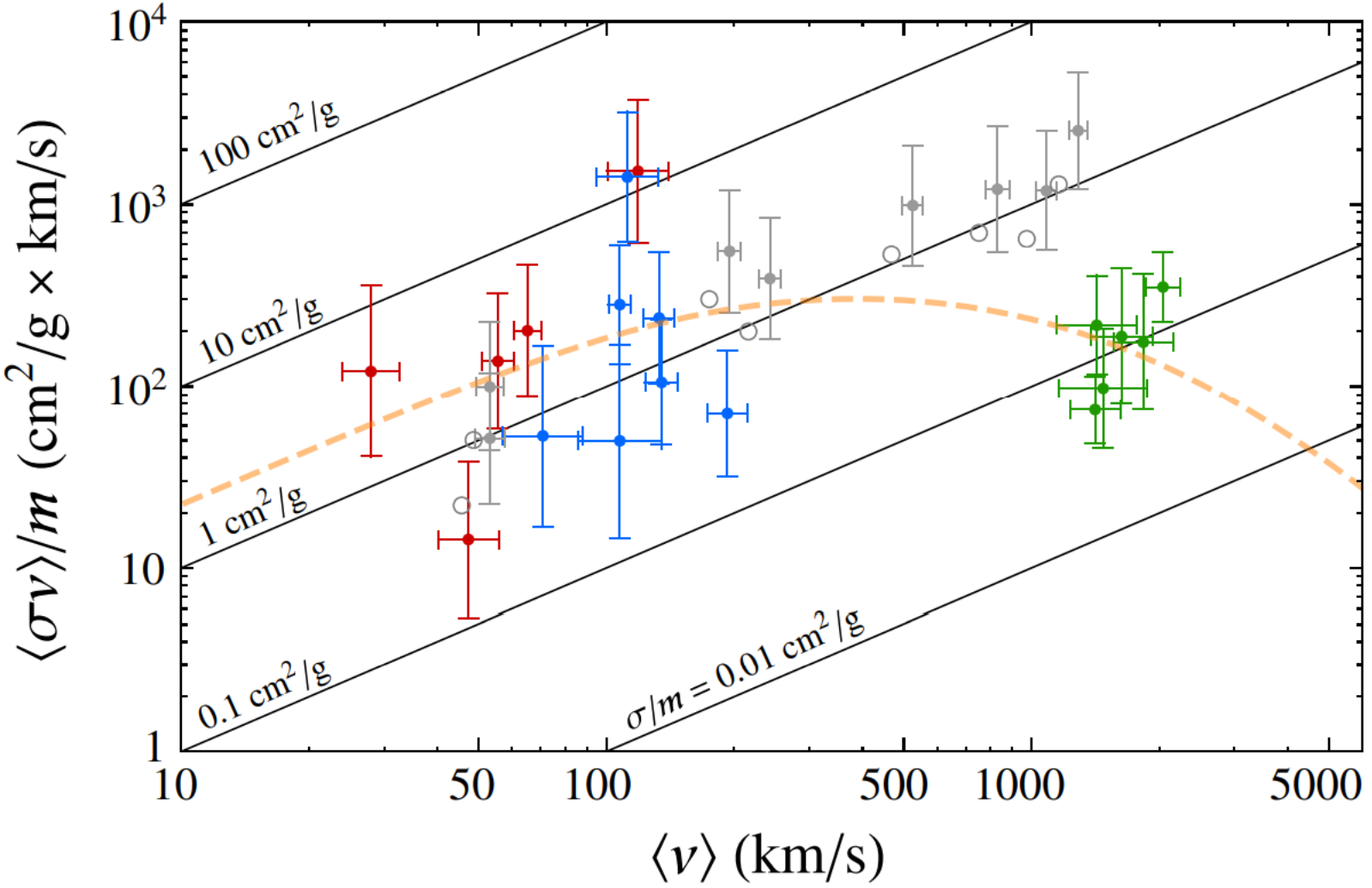
DM Self Interactions



M. Kaplinghat, S. Tulin, H. Yu [1508.03339]

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

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

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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]

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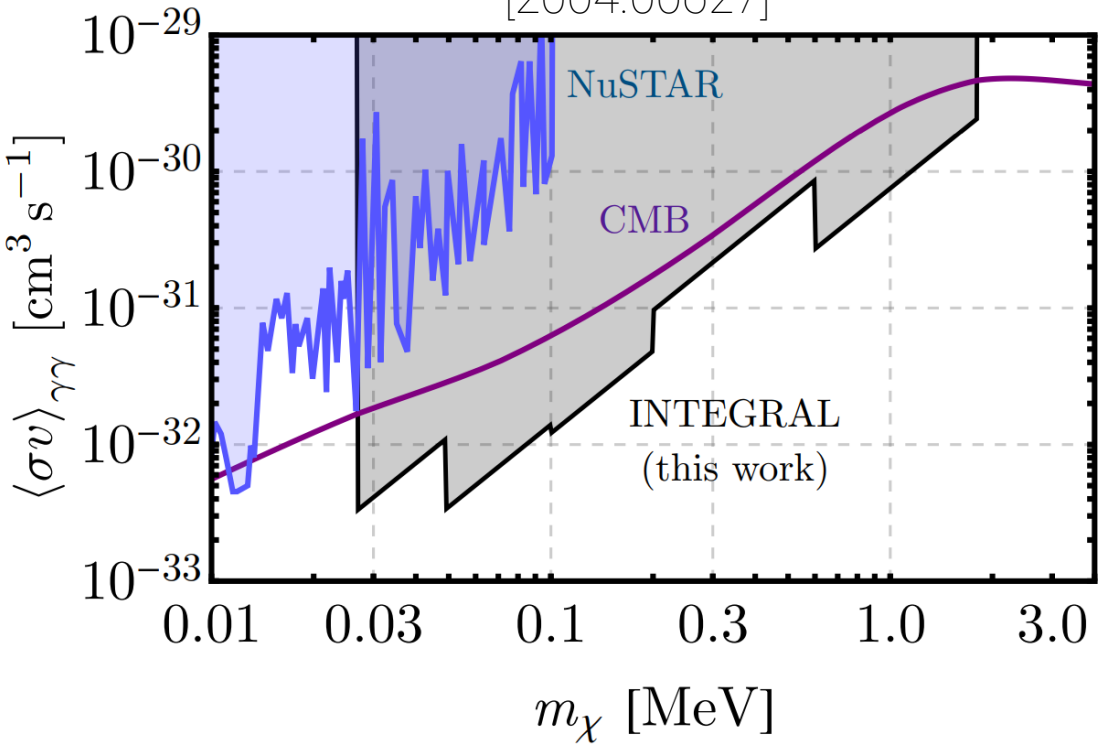
Indirect Detection

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

$$\sigma v_{\bar{\chi}\chi\to\gamma\gamma} = \frac{1}{8\pi}\left(\frac{\alpha y_n^{\max} y_\chi^{\max}}{3\pi m_p}\right)^2 \frac{s\left(s-4m_\chi^2\right)}{\left[s-(m_\phi^{\min})^2\right]^2}$$

$$\sim 10^{-44}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

R. Laha, J. Muñoz, T. Slatyer
[2004.00627]



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

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 $N_{\rm eff}$

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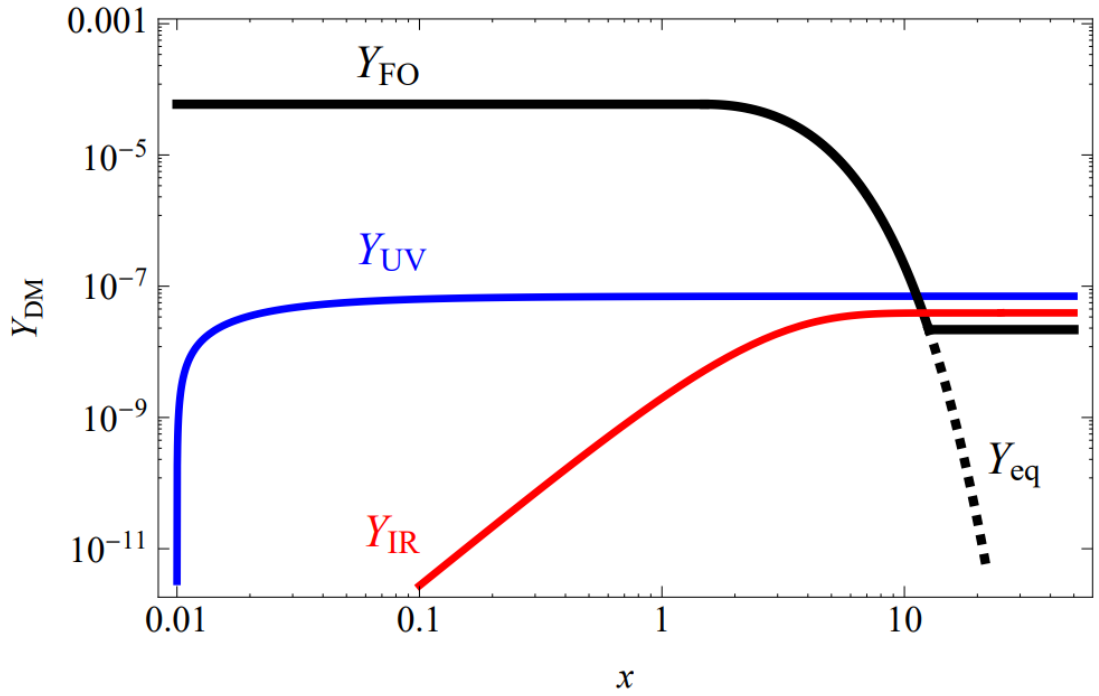
UV Freeze-In



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

$$\frac{\alpha_s y_\chi y_n}{2.6\, m_n (m^i_\phi)^2} \bar{\chi}\chi G^a_{\mu\nu} G^{a\mu\nu}$$

$$10\ \text{GeV} \lesssim T_R \lesssim 300\ \text{GeV}$$

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$$\Gamma_{K^+\to\pi^+\phi} = \frac{|C_{ds}|^2 f_0(m_\phi)^2}{16\pi m_{K^+}^3}\left(\frac{m_{K^+}^2 - m_{\pi^+}^2}{m_s - m_d}\right)^2 \times \sqrt{\left(m_{K^+}^2 - m_{\pi^+}^2 - m_\phi^2\right)^2 - 4m_{\pi^+}^2 m_\phi^2}$$

$$C_{ds} = \frac{3 m_s m_t^2 V_{td}^* V_{ts}}{16\pi^2 v^3}\epsilon$$

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$$\sigma_{\chi\chi} \approx \frac{y_\chi^4}{2\pi m_\chi^2 v_{\mathrm{DM}}^4}\left[\log\left(1+R^2\right) - \frac{R^2}{1+R^2}\right]$$

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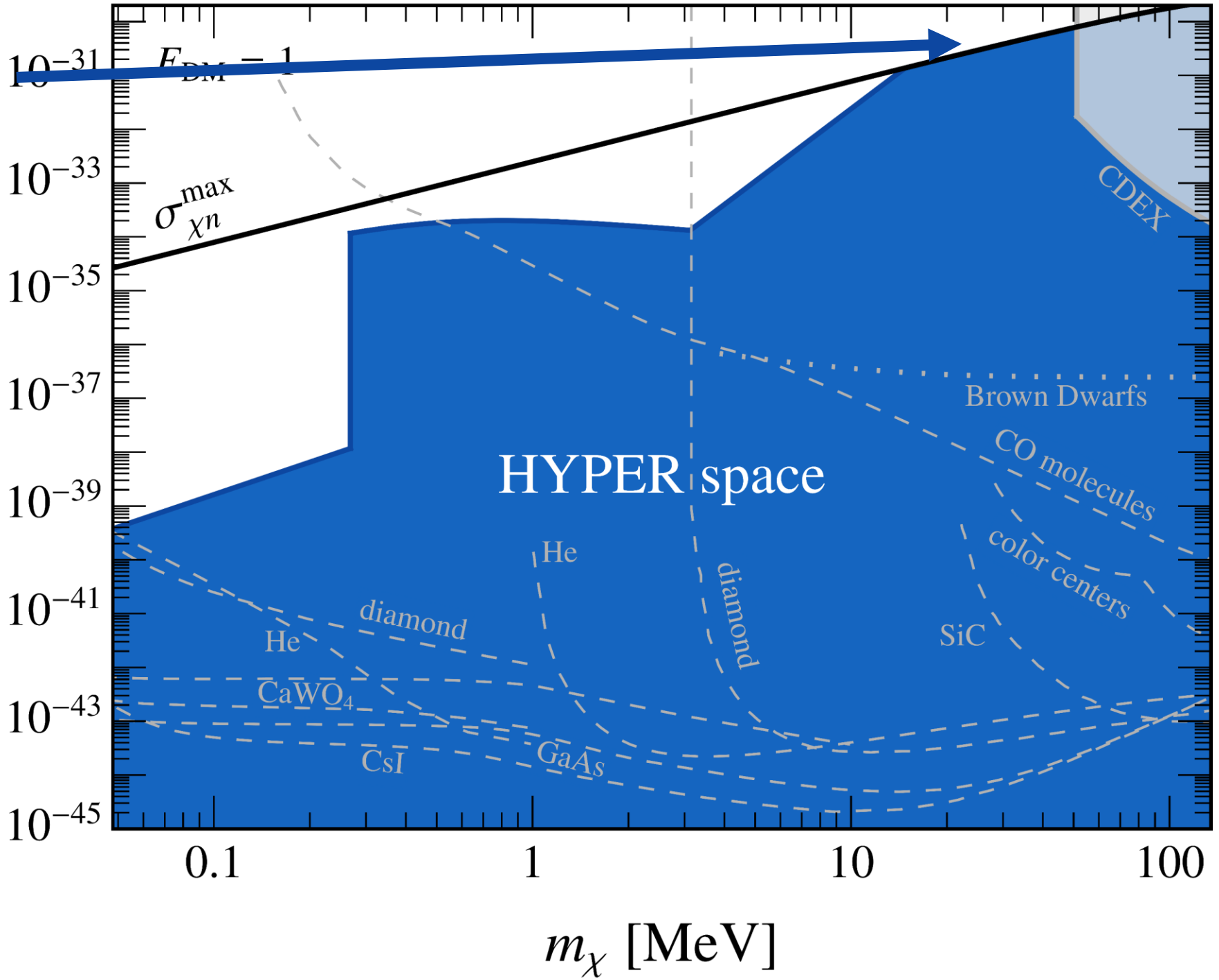
Biggest Problem:

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

P-wave suppression at heavier masses is sufficient

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

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



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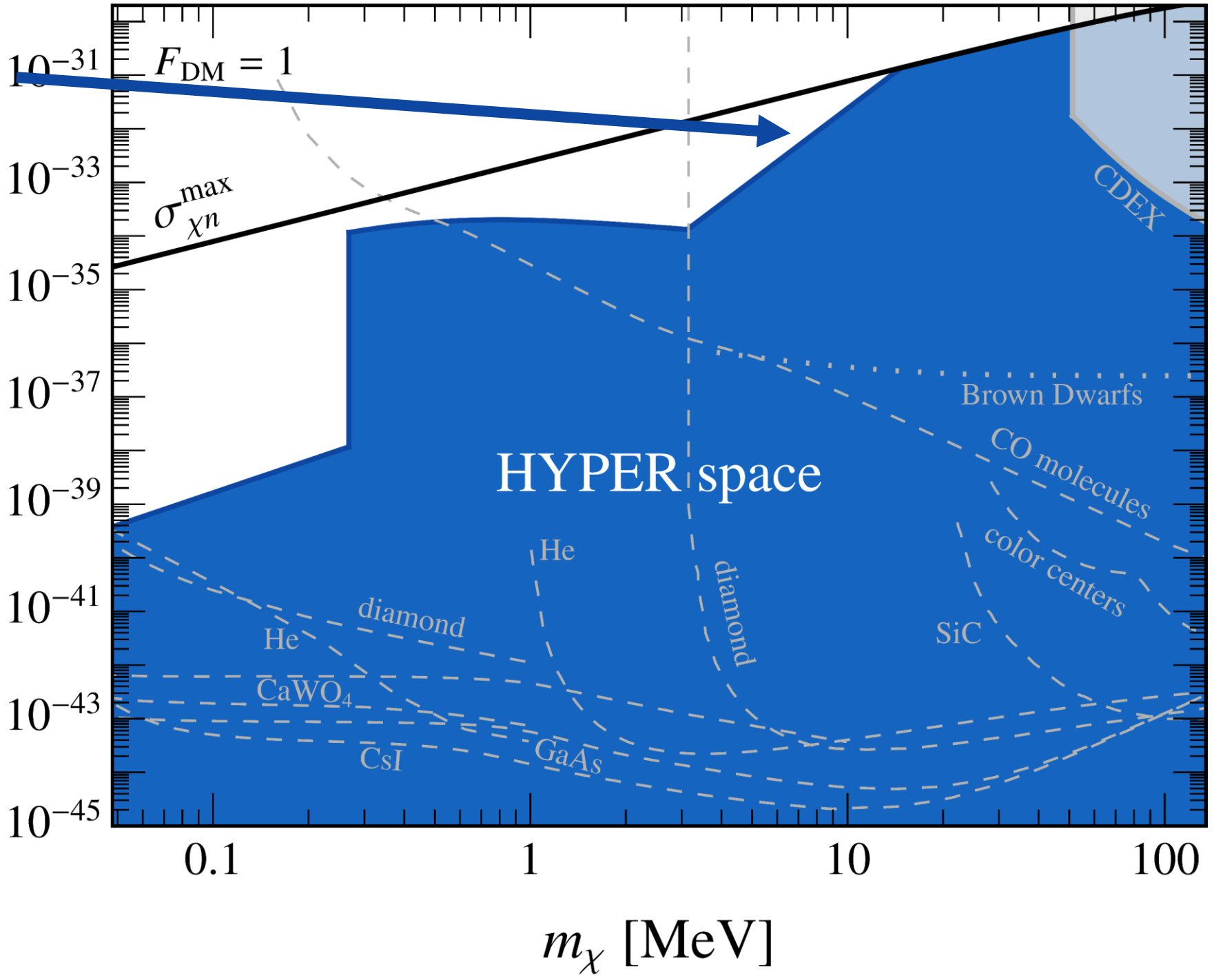
Biggest Problem:

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

P-wave suppression insufficient

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

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



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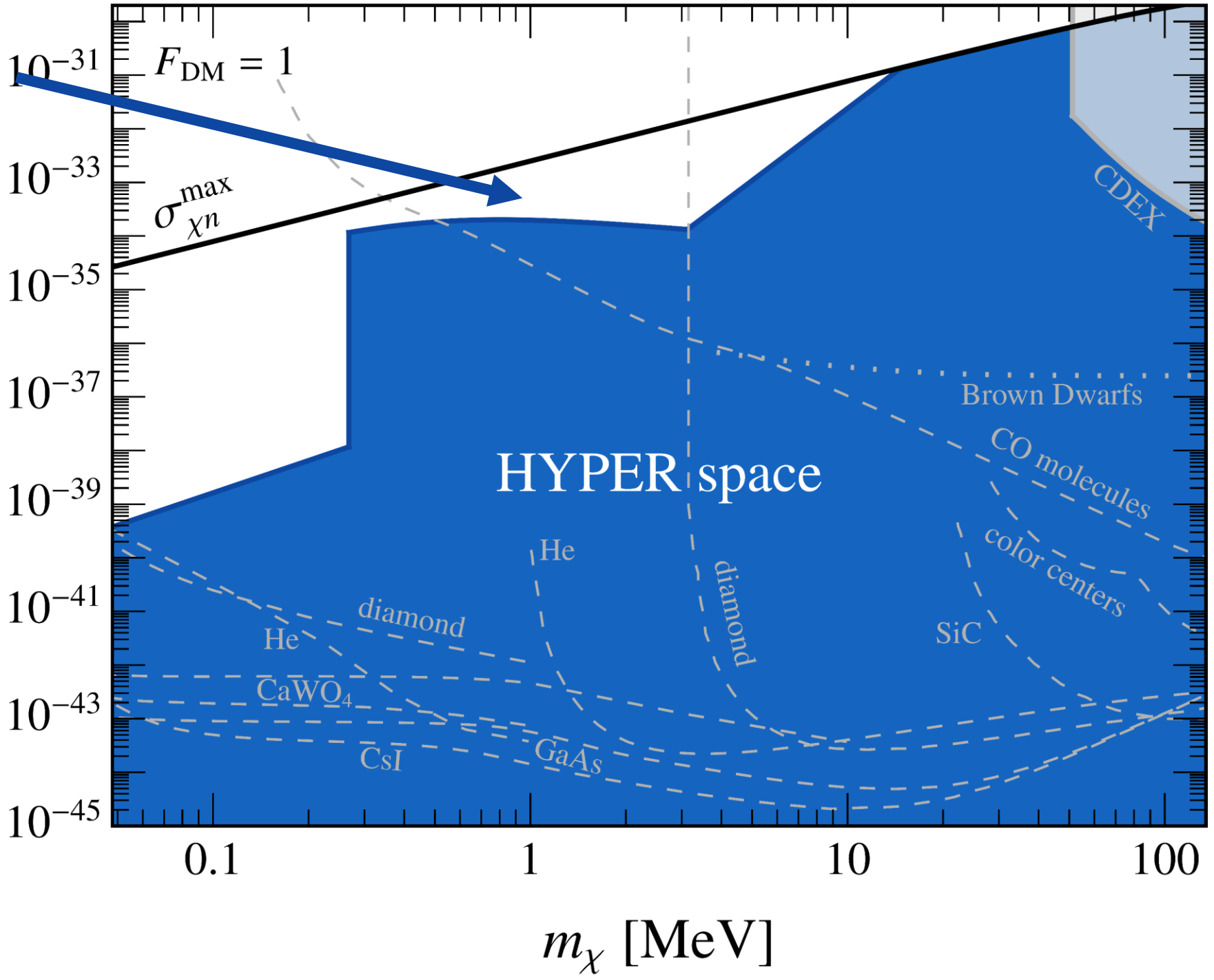
Biggest Problem:

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

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

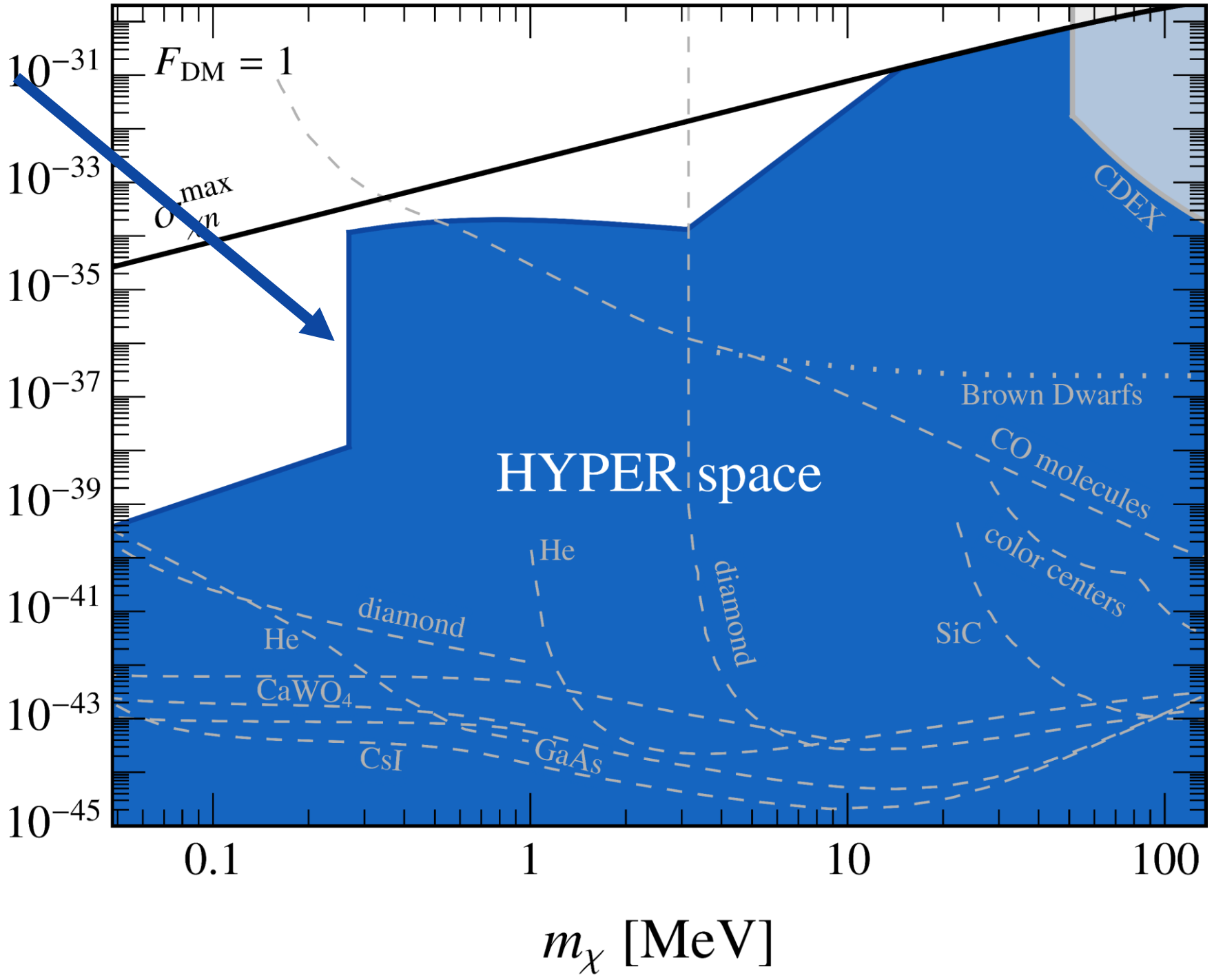
$m_\phi = E_\chi(T_{\rm PT})$

makes

$m_\phi \geq 2m_\chi$

Boltzmann suppress via

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



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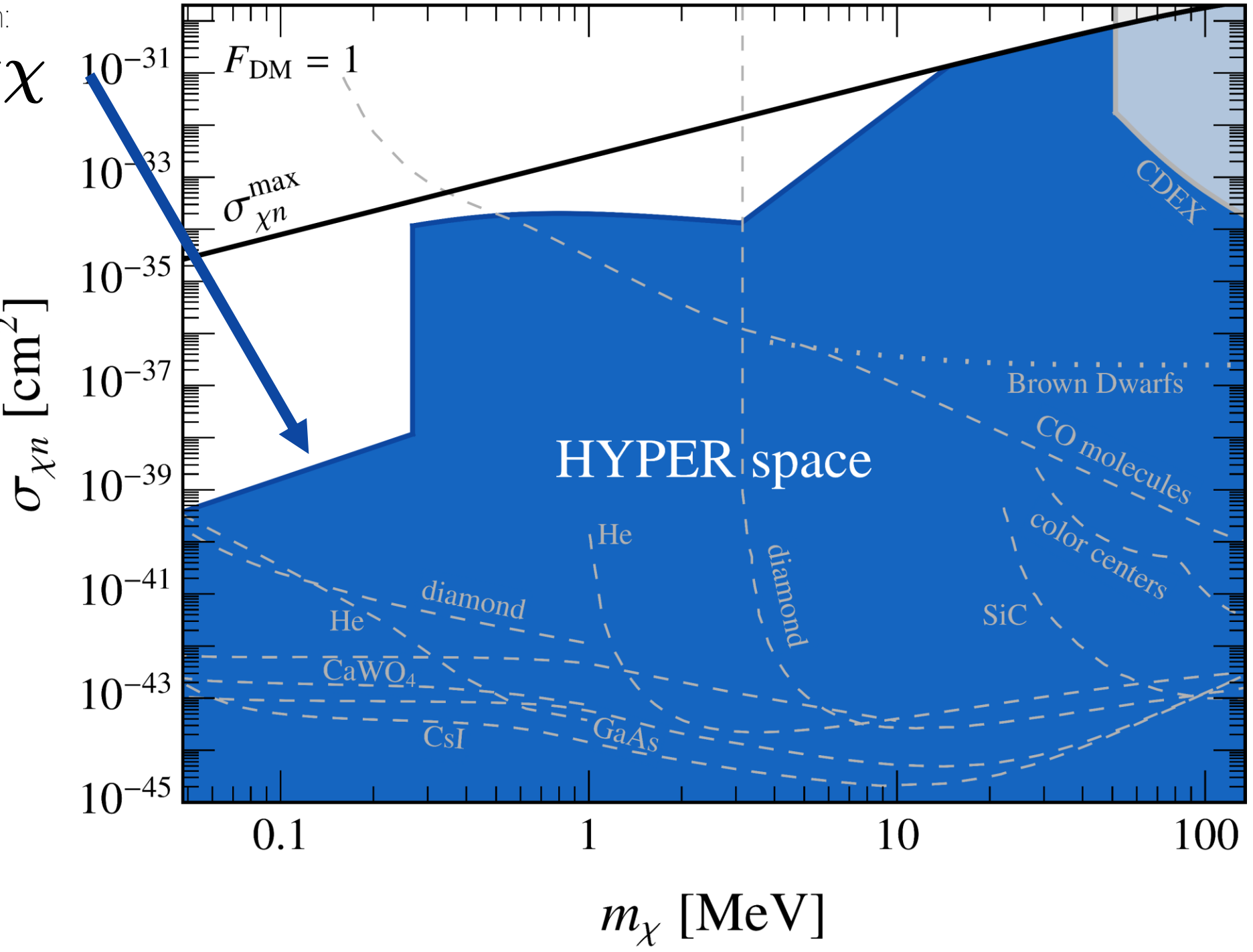
Biggest Problem:

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

$m_\phi = 21$ MeV

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



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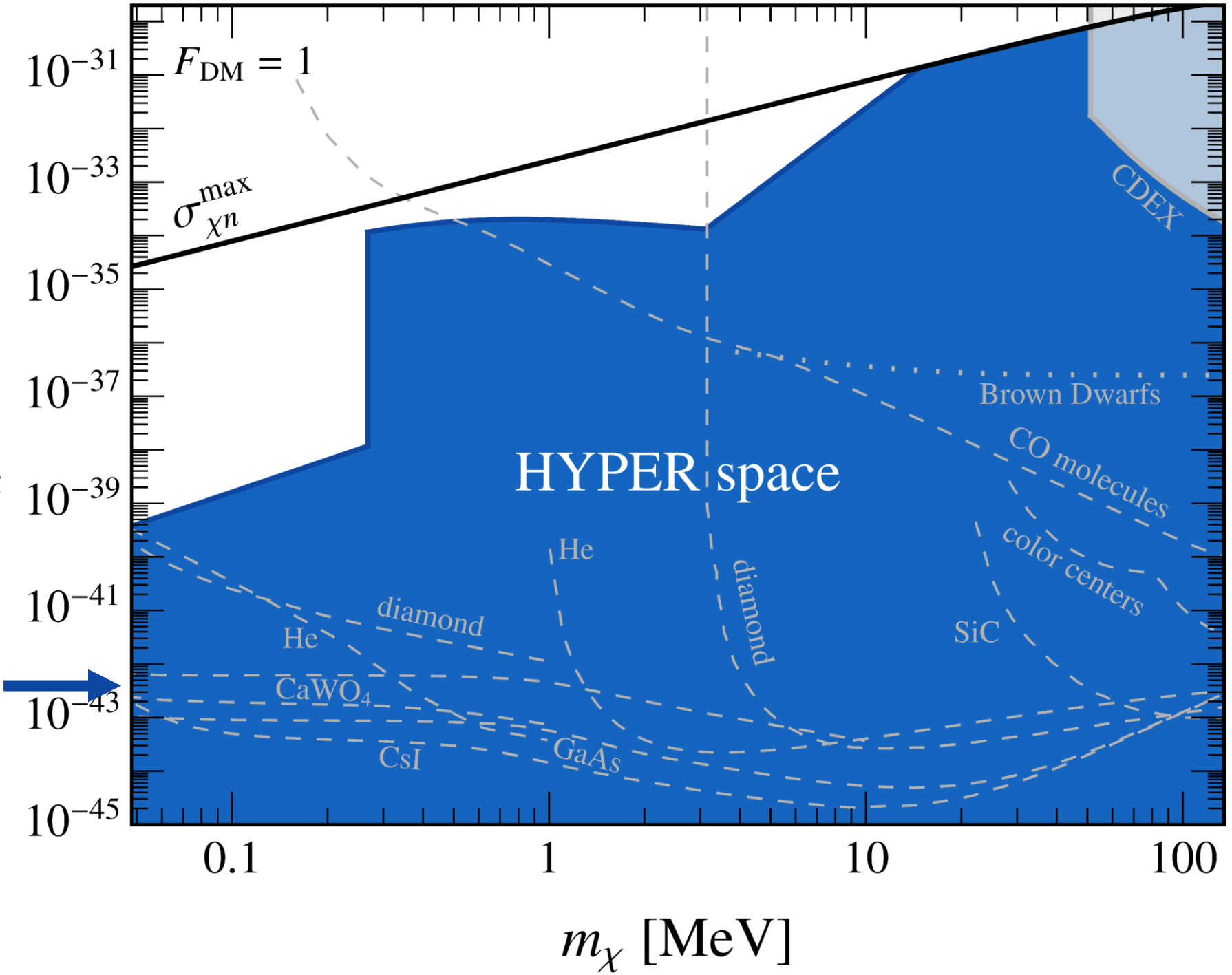

$m_\chi = \omega_p(T_{\rm PT})/2$

Longitudinal plasmons may decay

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

[1902.08623]

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Earlier Phase Transition?

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

More problematic processes after PT

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

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

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Earlier Phase Transition?

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

More problematic processes after PT

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

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

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

When do these start to matter?

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Earlier Phase Transition?

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

More problematic processes after PT

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

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

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

When do these start to matter?

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

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

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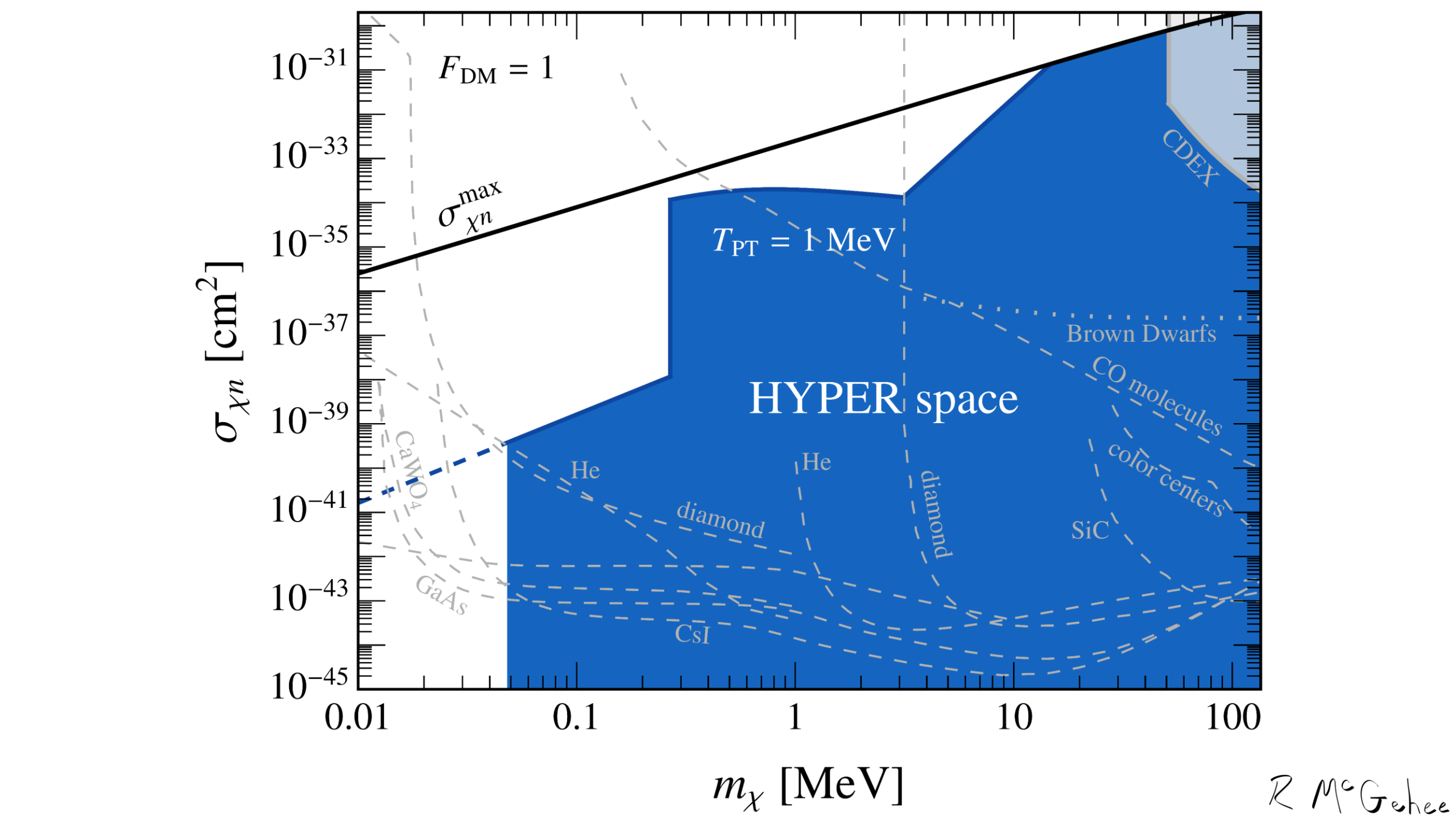
$F_{\rm DM} = 1$
$\sigma_{\chi n}^{\rm max}$
$T_{\rm PT} = 1$ MeV
HYPER space
CDEX
Brown Dwarfs
CO molecules
color centers
SiC
diamond
diamond
He
He
$CaWO_4$
GaAs
CsI
$\sigma_{\chi n}$ [cm^2]
m_χ [MeV]
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
0.01
0.1
1
10
100

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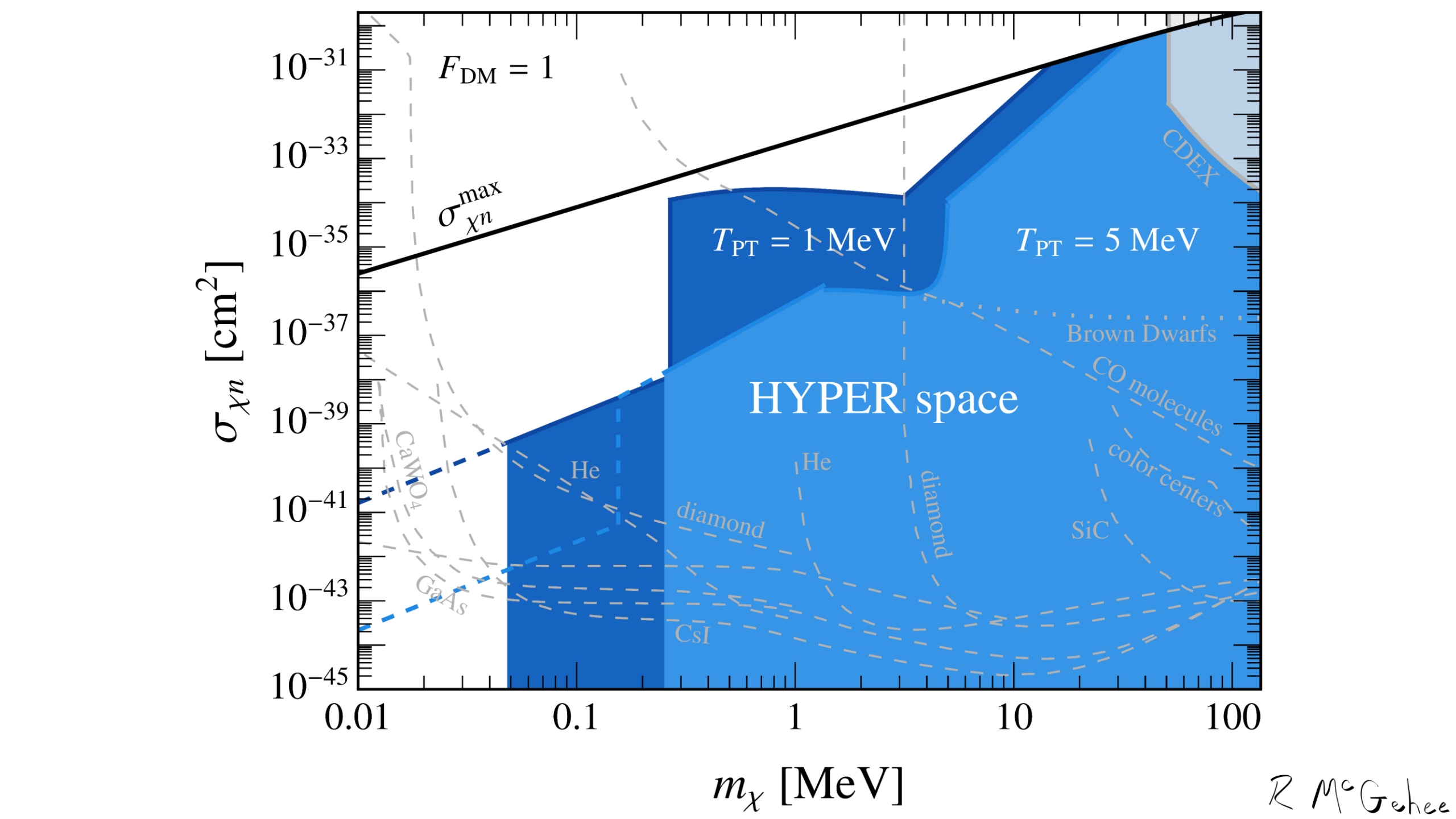
$F_{\rm DM} = 1$
$\sigma^{\rm max}_{\chi n}$
$T_{\rm PT} = 1$ MeV
$T_{\rm PT} = 5$ MeV
HYPER space
CDEX
Brown Dwarfs
CO molecules
color centers
SiC
diamond
He
diamond
He
CaWO$_4$
GaAs
CsI
$\sigma_{\chi n}$ [cm^2]
m_χ [MeV]
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
0.01
0.1
1
10
100

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Future Directions

Repeat for electron scattering; lower PT = interesting

Fully explore hadrophilic HYPER space
(e.g. vector mediator models)

Flesh out the dark sector PT

Many more!

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