Maximizing Direct Detection with HYPER Dark Matter

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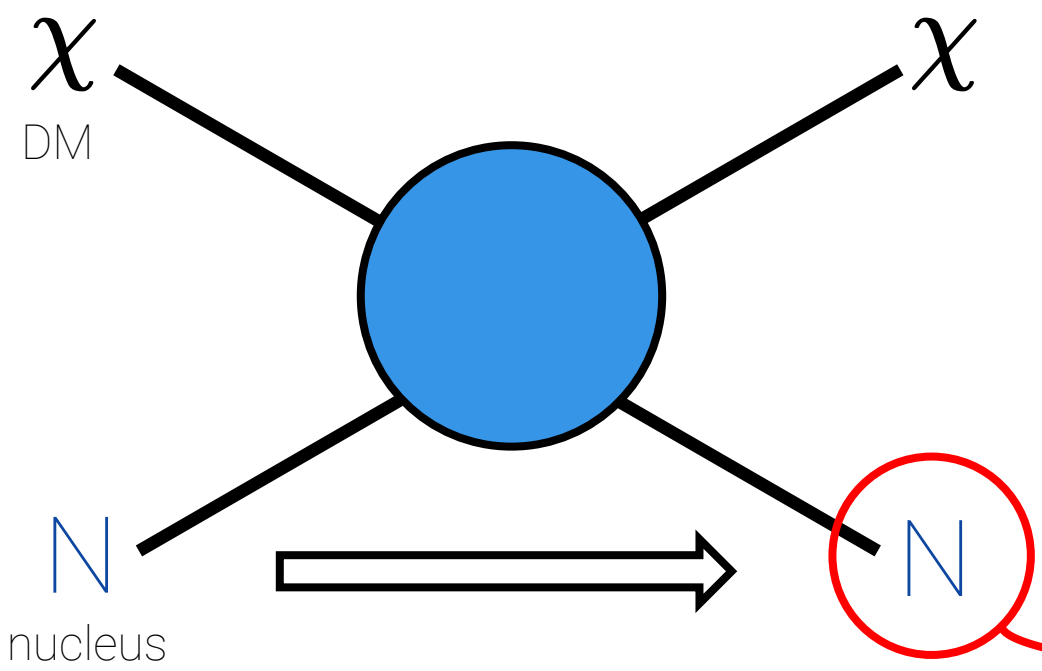
U.S. DEPARTMENT OF ENERGY | Office of Science

2112.03920

w/ Gilly Elor & Aaron Pierce

PHENO 22, 5/9/22

Direct Detection Refresher



Credit: The XENON Experiment

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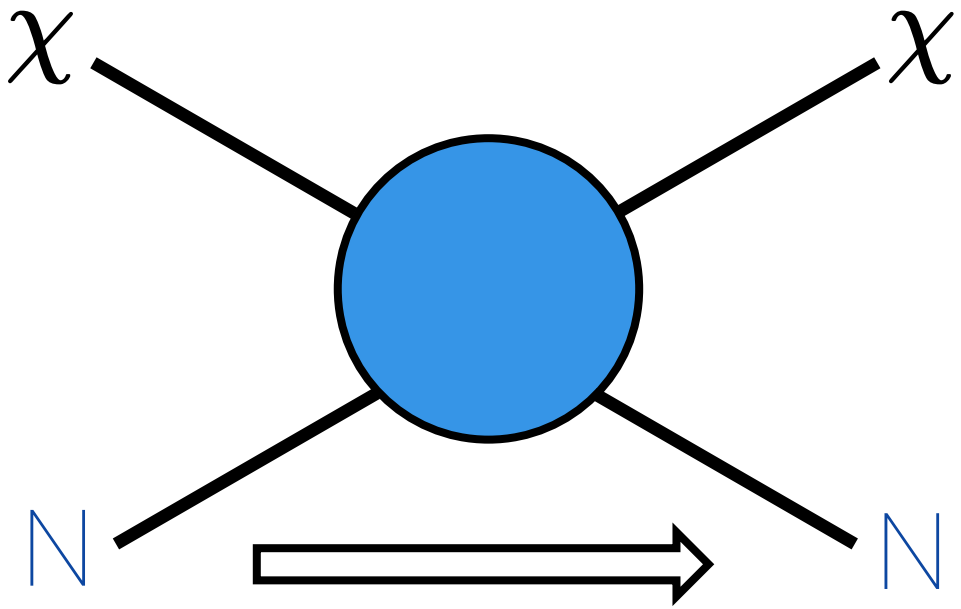
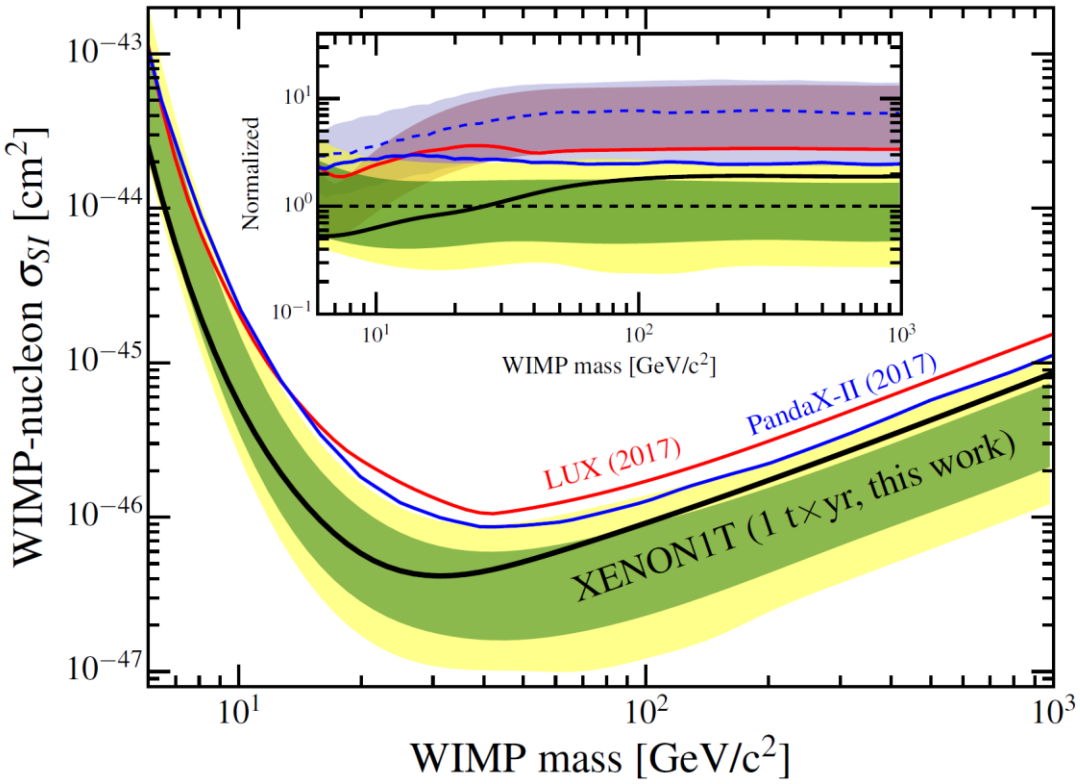
Direct Detection Refresher





XENON Collaboration [1805.12562]

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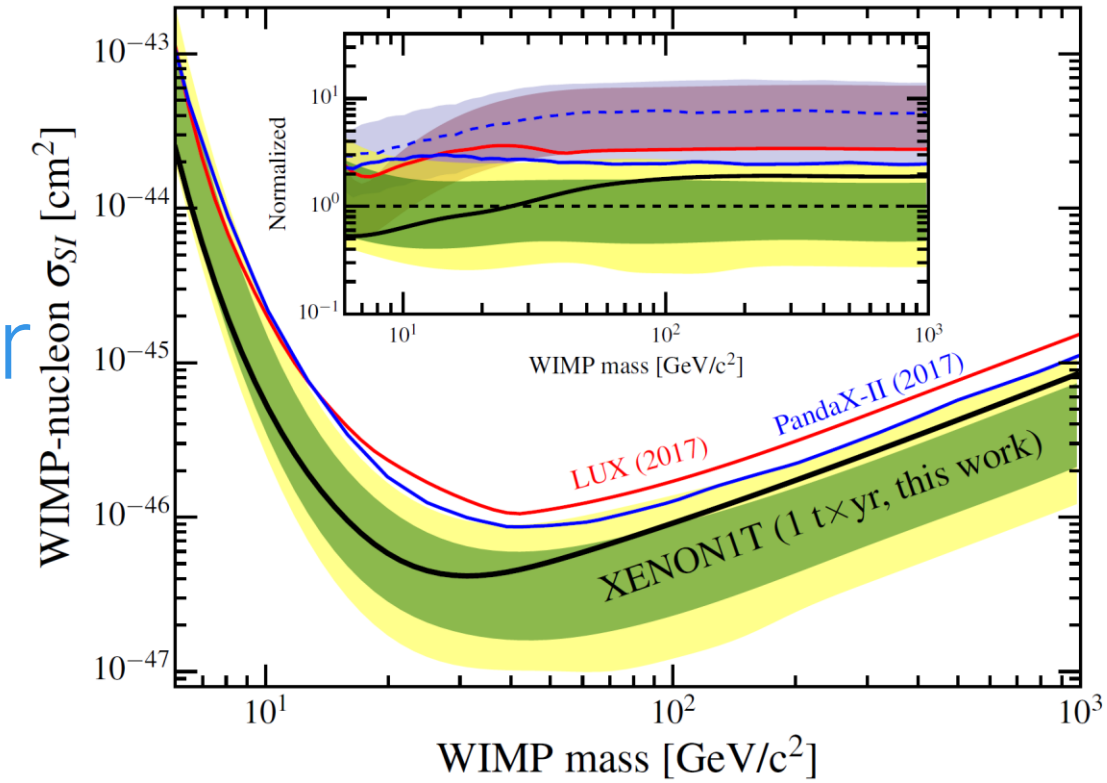
Direct Detection Future

Go higher?

Go lighter



Go lower

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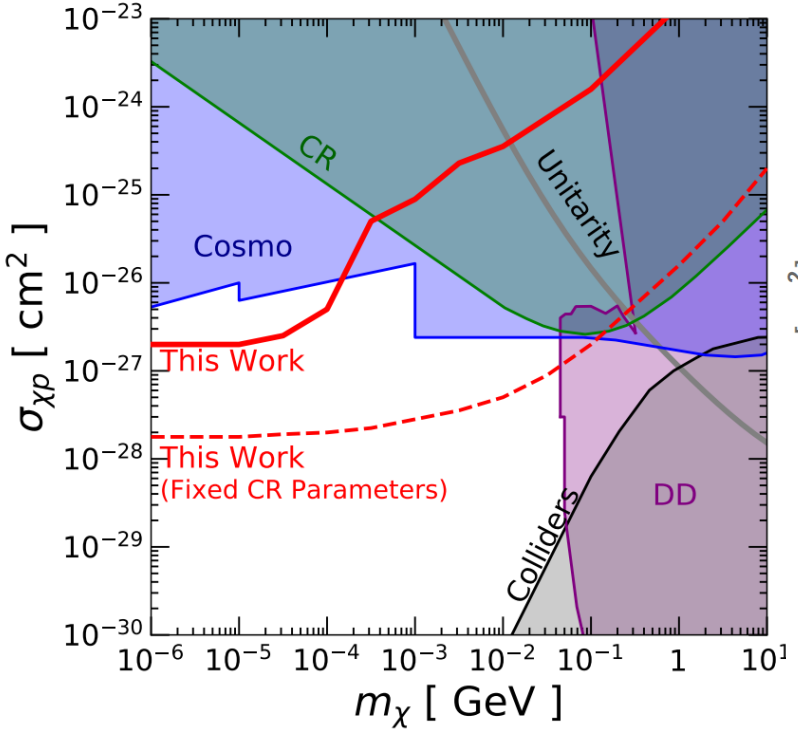
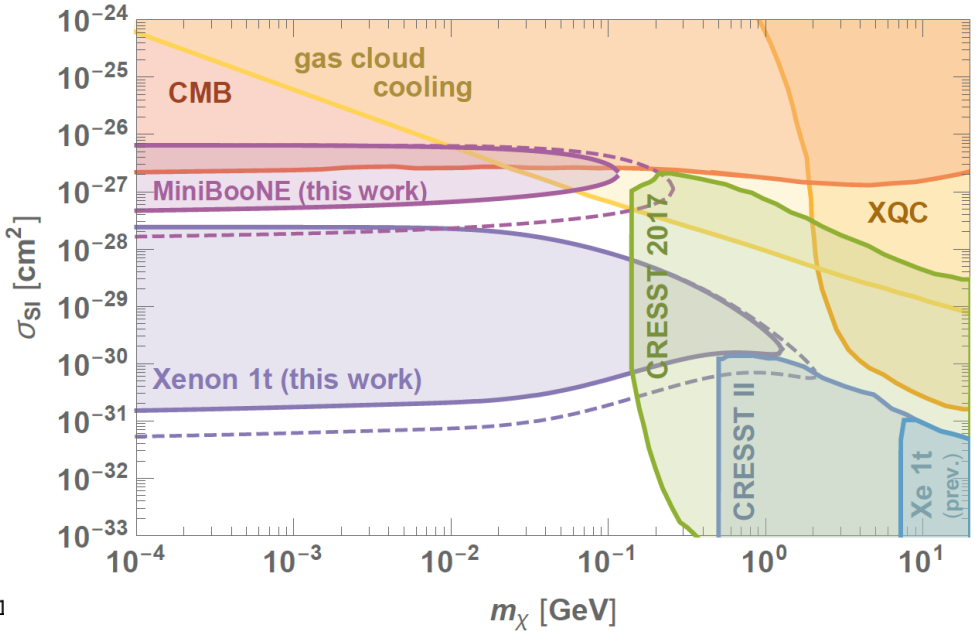
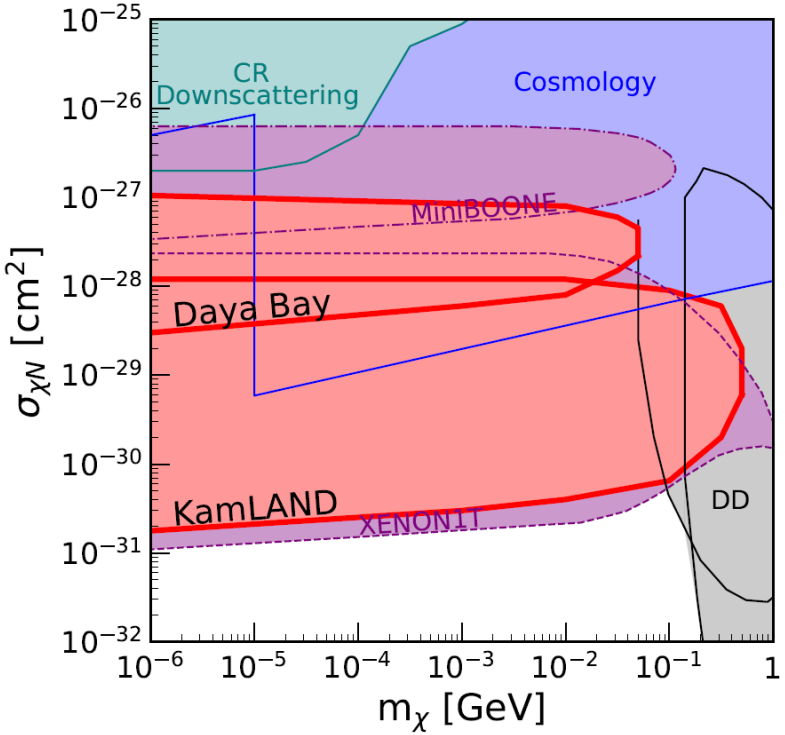
Bounds from Cosmic Ray Scattering



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



T. Bringmann, M. Pospelov
[1810.10543]



C. Cappiello, J. Beacom
[1906.11283]

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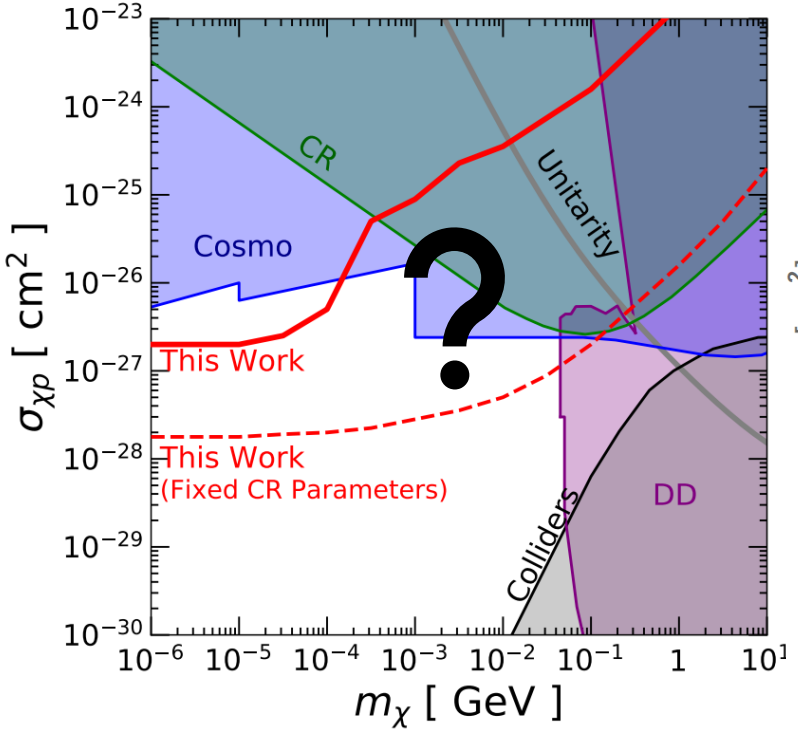
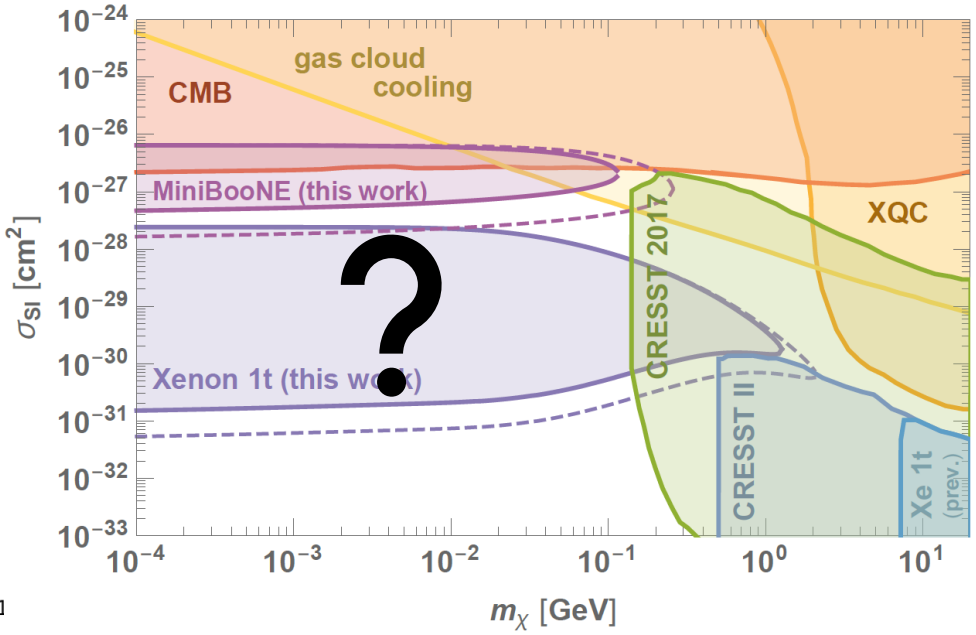
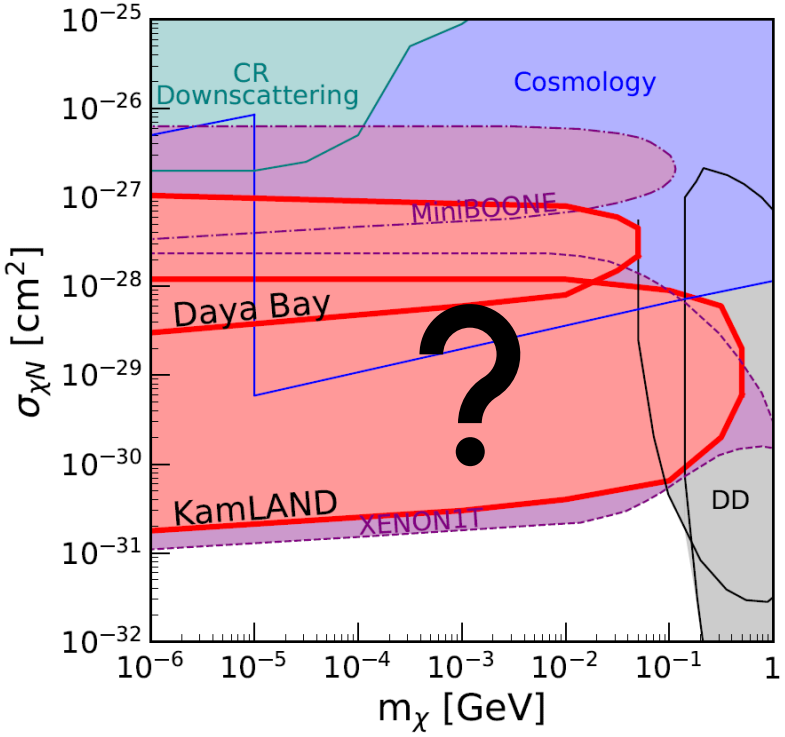
Is Dark Matter here?







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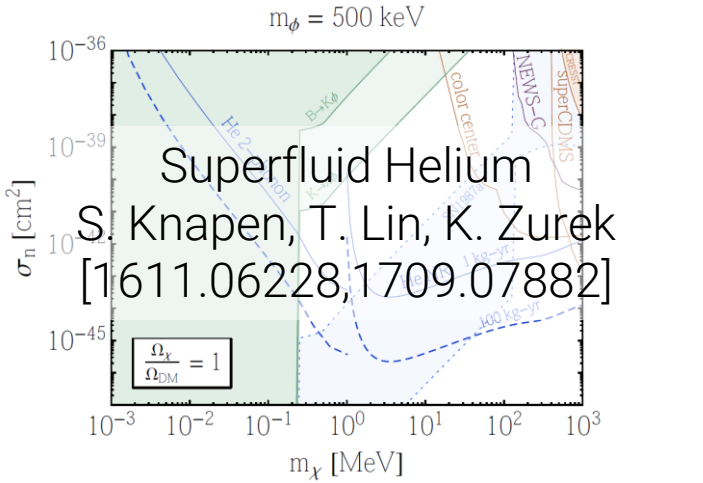
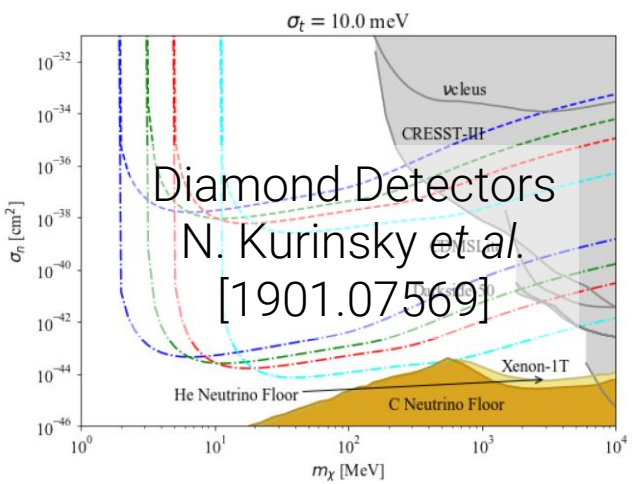
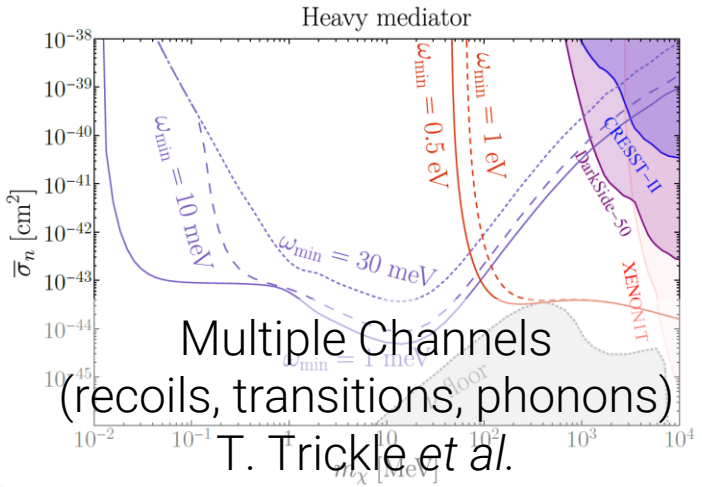
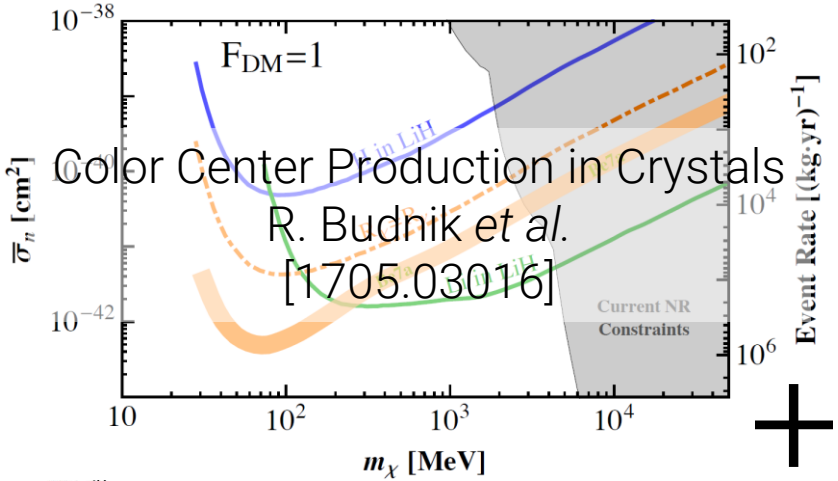
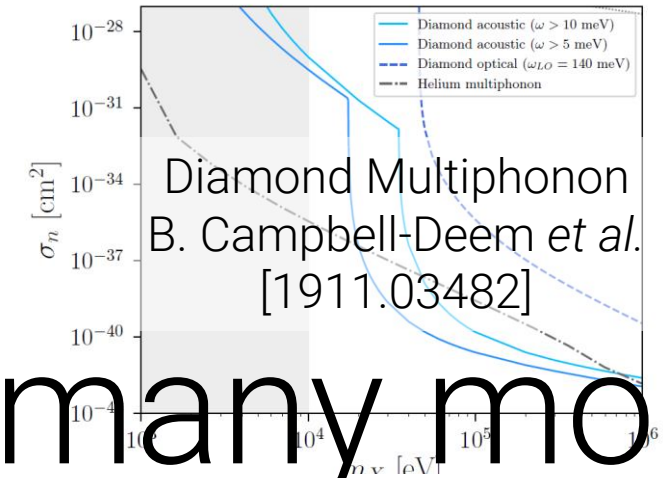
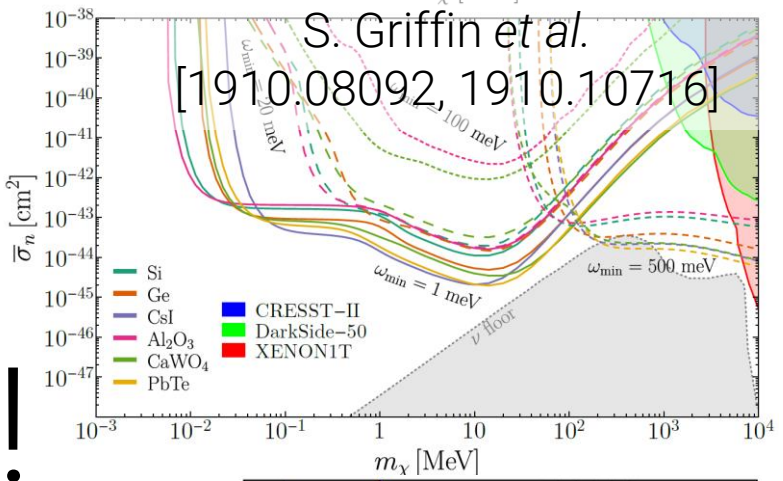

m_ϕ = 500 keV
Superfluid Helium
S. Knapen, T. Lin, K. Zurek
[1611.06228,1709.07882]
σ_n [cm^2]
m_χ [MeV]


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]

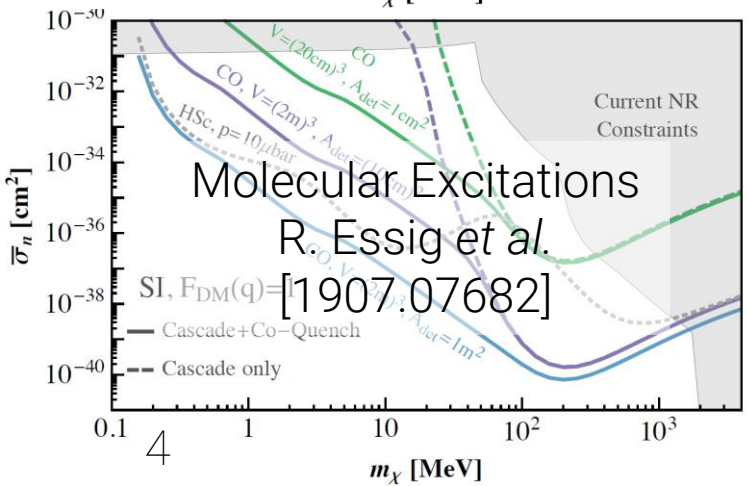

Heavy mediator
Multiple Channels
(recoils, transitions, phonons)
T. Trickle *et al.*
S. Griffin *et al.*
[1910.08092, 1910.10716]
ω_{min} = 10 meV
ω_{min} = 30 meV
ω_{min} = 0.5 eV
ω_{min} = 1 eV
CRESST-II
DarkSide-50
XENON1T
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

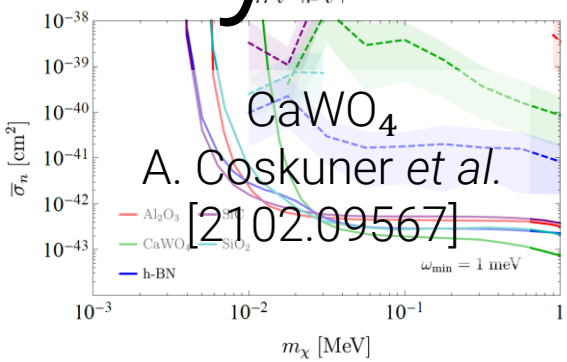

F_{DM}=1
Color Center Production in Crystals
R. Budnik *et al.*
[1705.03016]
Current NR Constraints
Event Rate [(kg·yr)$^{-1}$]
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

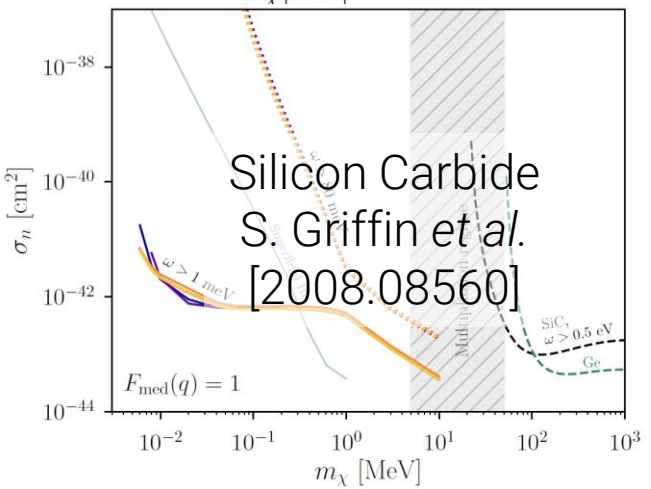

Diamond acoustic (ω > 10 meV)
Diamond acoustic (ω > 5 meV)
Diamond optical (ω_{LO} = 140 meV)
Helium multiphonon
Diamond Multiphonon
B. Campbell-Deem *et al.*
[1911.03482]
σ_n [cm^2]

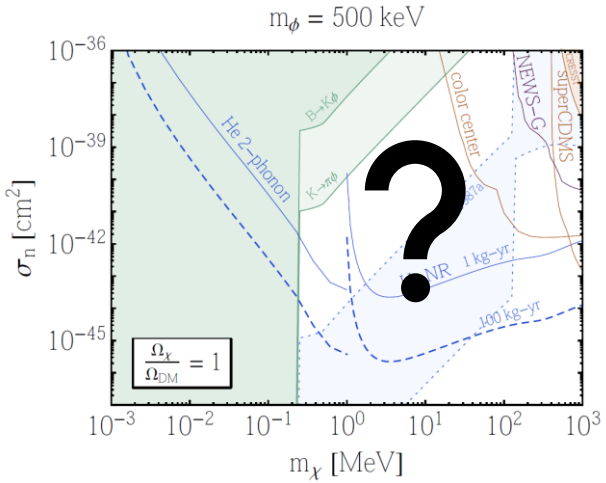

Si
Ge
CsI
Al_2O_3
$CaWO_4$
PbTe
CRESST-II
DarkSide-50
XENON1T
ω_{min} = 1 meV
ω_{min} = 500 meV
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

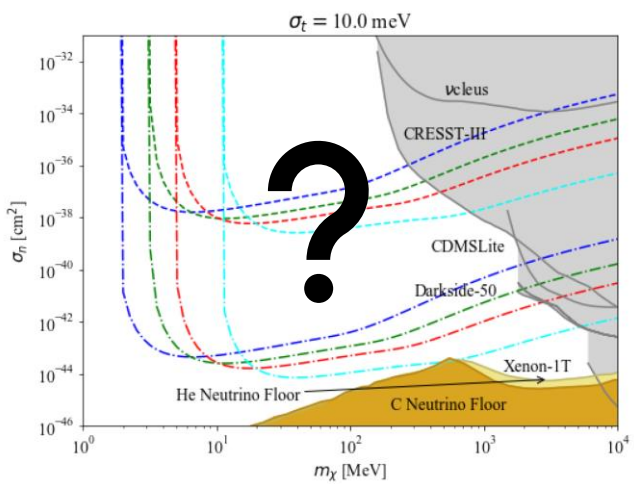
+ many more!

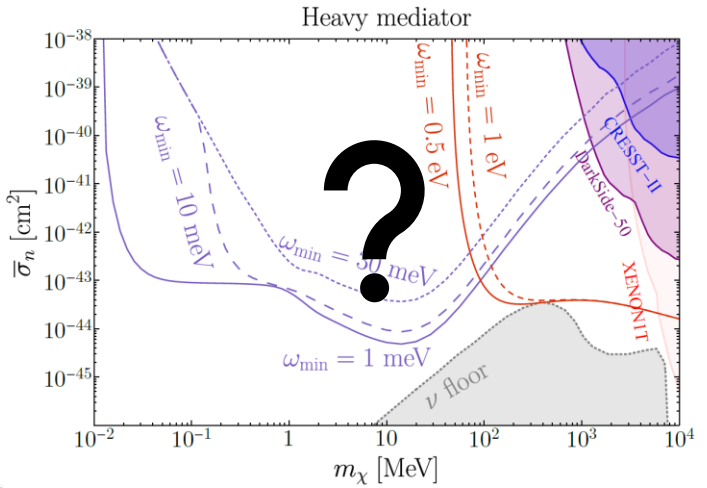

Molecular Excitations
R. Essig *et al.*
[1907.07682]
Current NR Constraints
SI, $F_{DM}(q)=1$
Cascade+Co-Quench
Cascade only
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

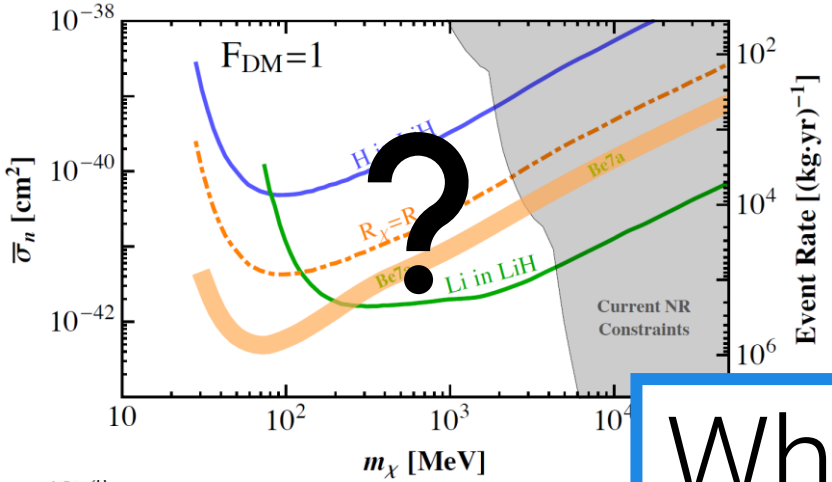

$CaWO_4$
A. Coskuner *et al.*
[2102.09567]
Al_2O_3
$CaWO_4$
SiO_2
h-BN
ω_{min} = 1 meV
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

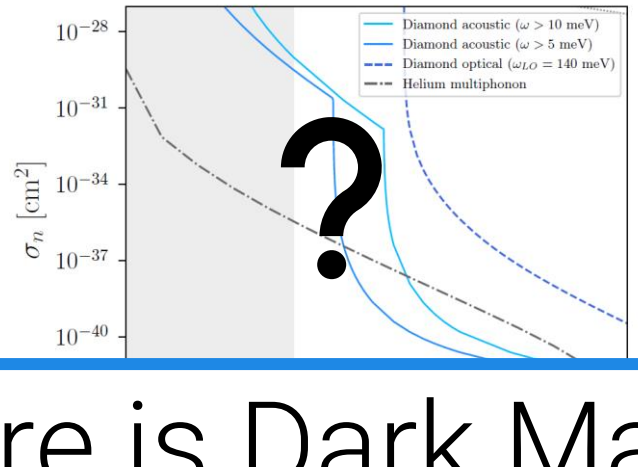

Silicon Carbide
S. Griffin *et al.*
[2008.08560]
ω > 1 meV
SiC, ω > 0.5 eV
Ge
$F_{med}(q) = 1$
σ_n [cm^2]
m_χ [MeV]

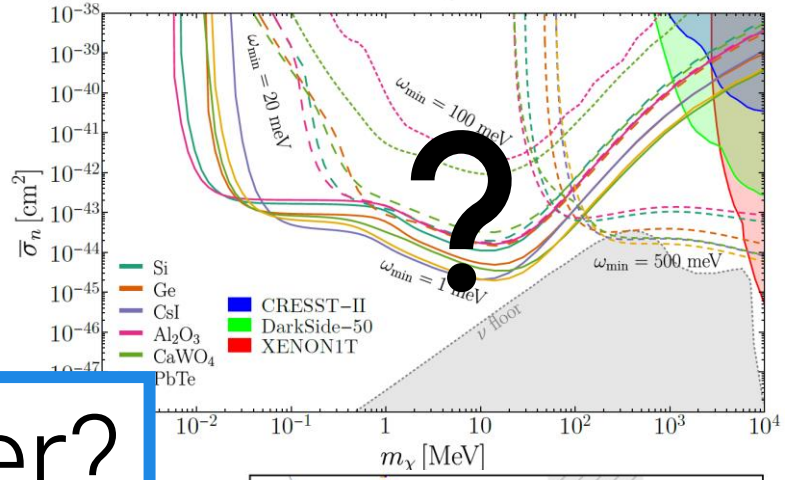


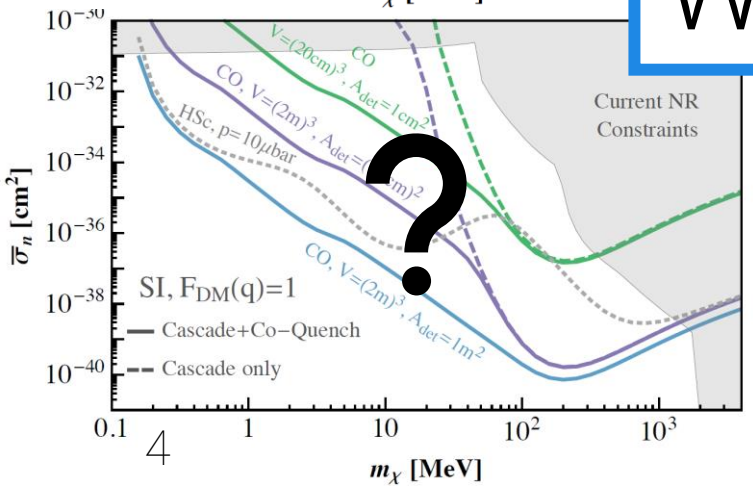


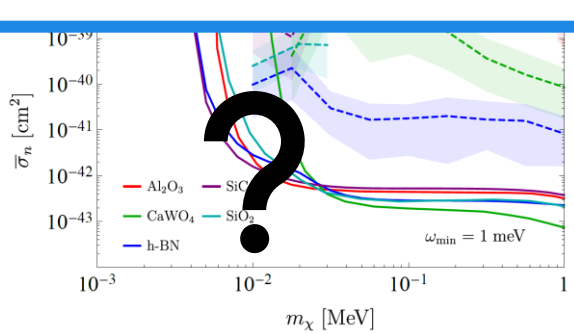


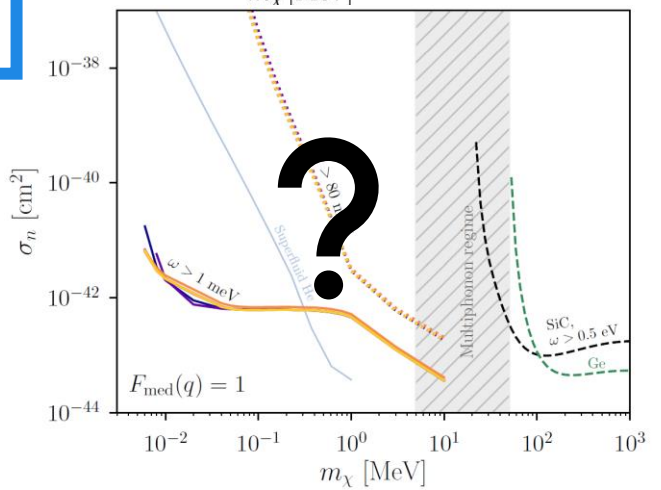












Where is Dark Matter?

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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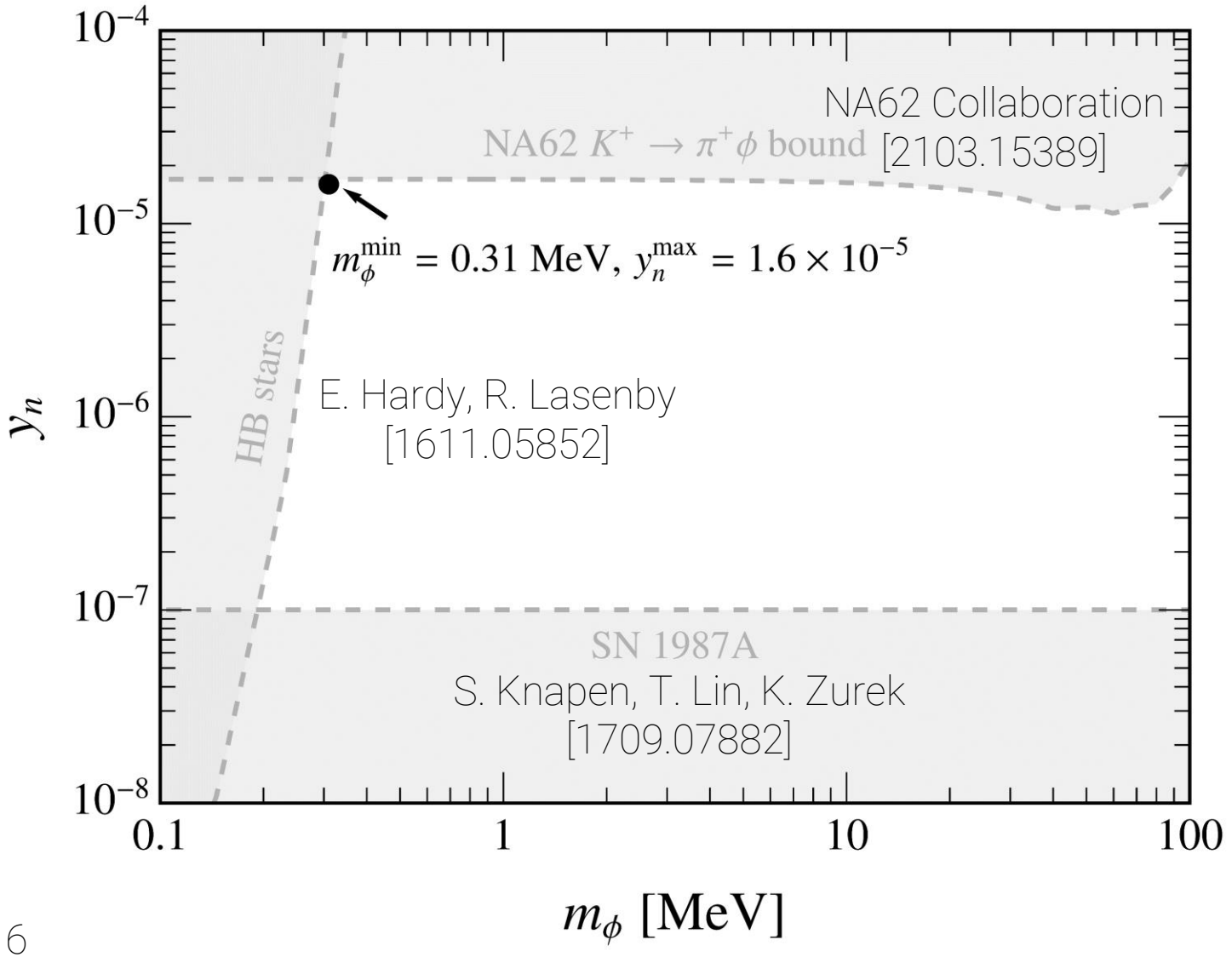
The Basics



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

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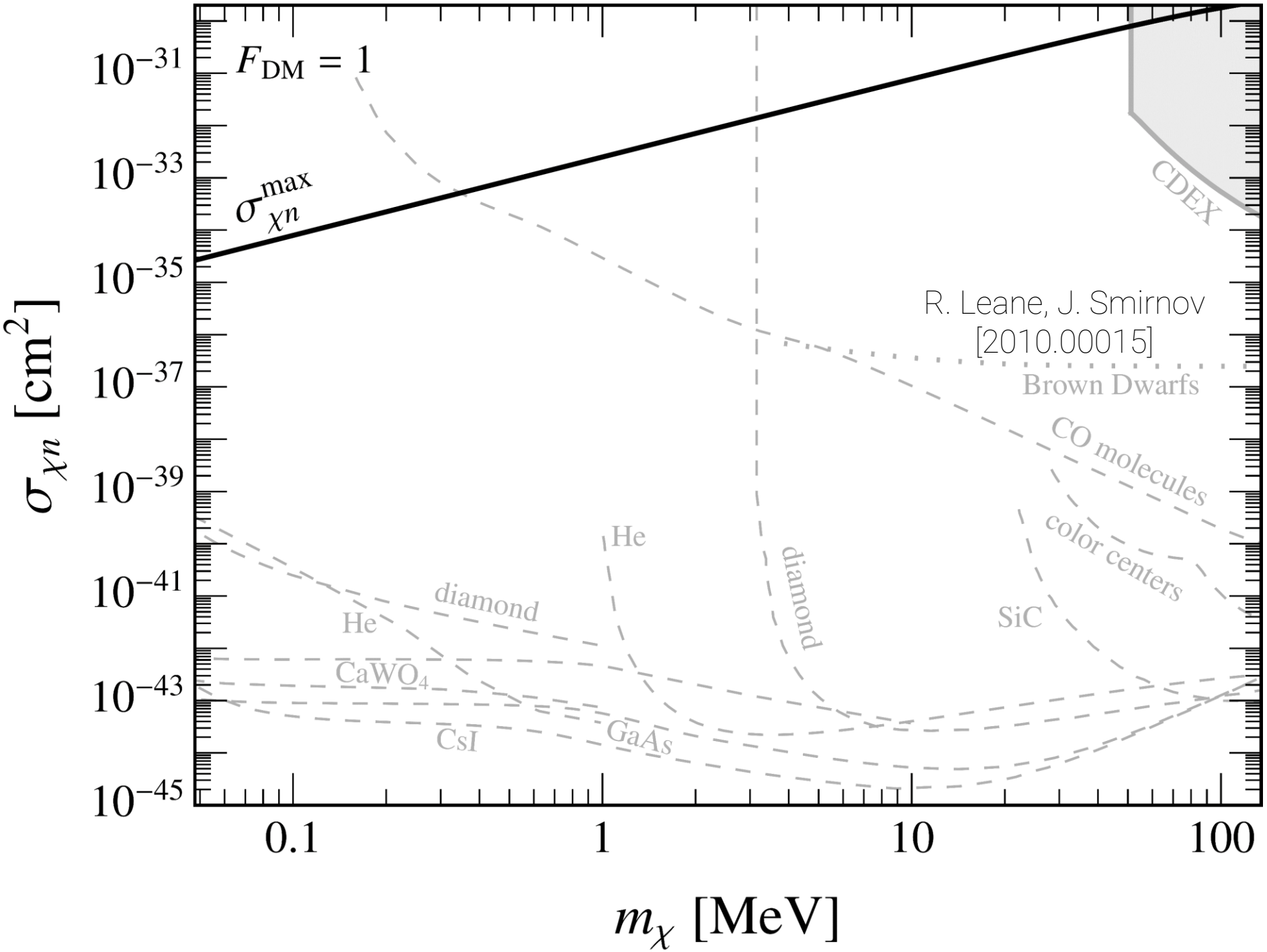
$F_{\rm DM} = 1$
$\sigma_{\chi n}^{\rm max}$
CDEX
R. Leane, J. Smirnov
[2010.00015]
Brown Dwarfs
CO molecules
color centers
SiC
diamond
He
diamond
He
$CaWO_4$
CsI
GaAs
$\sigma_{\chi n}$ [cm^2]
m_χ [MeV]
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
0.1
1
10
100

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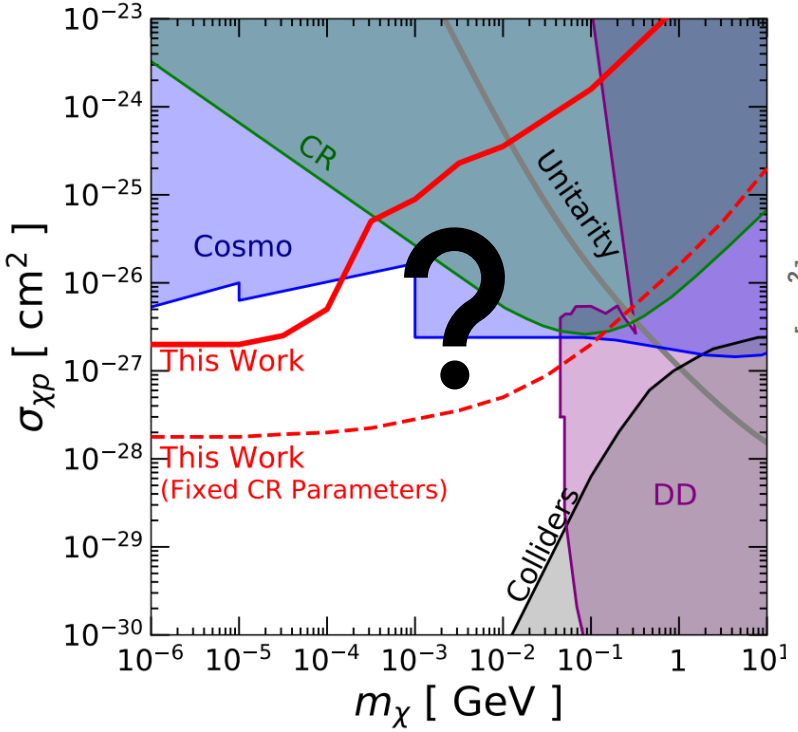
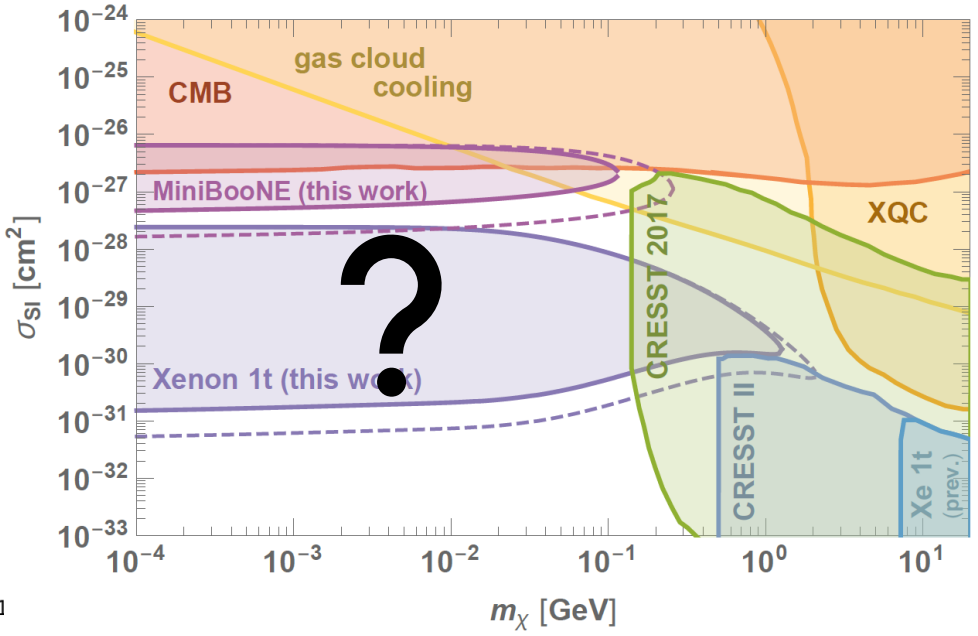
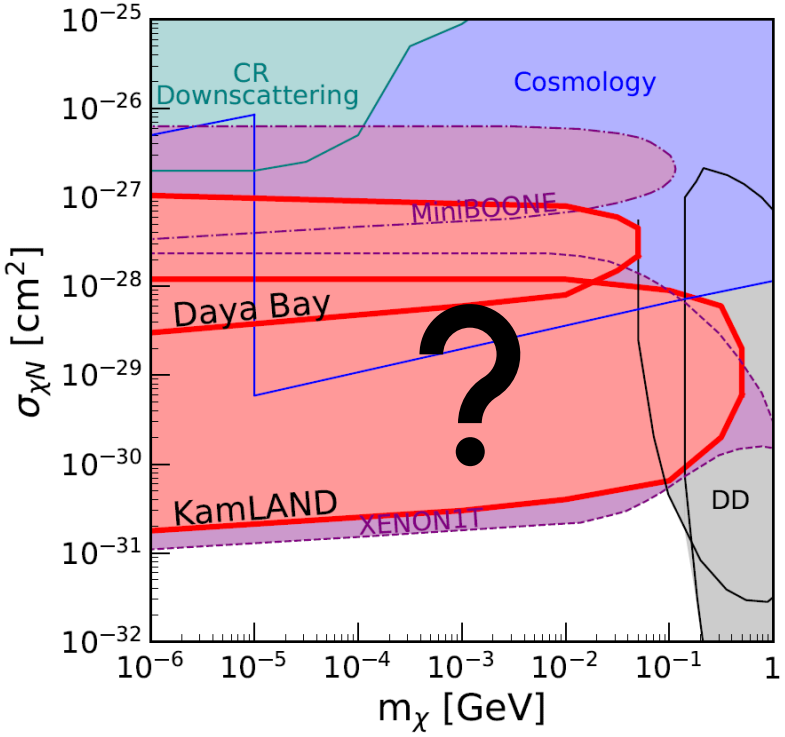
Is Dark Matter here?







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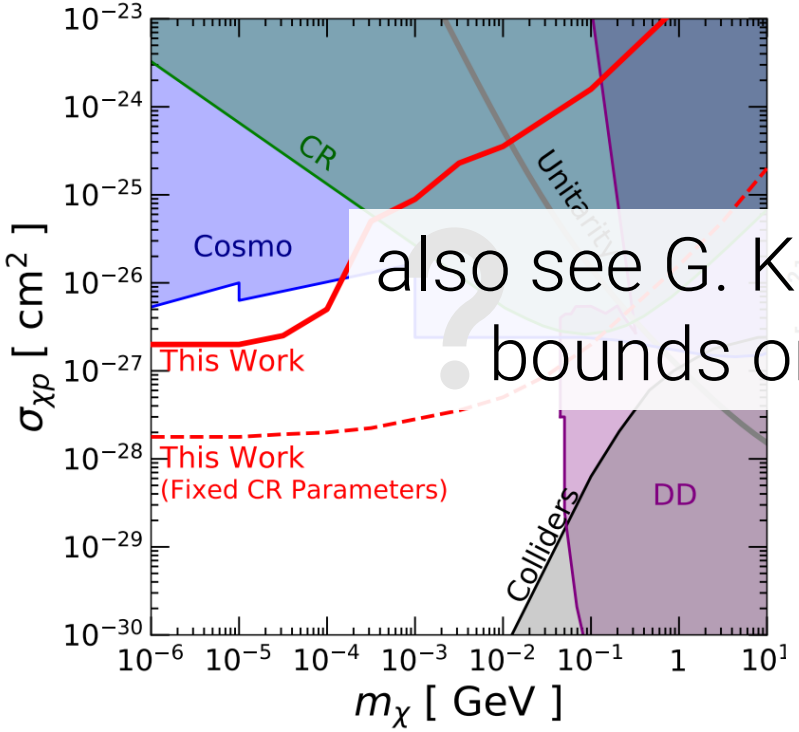
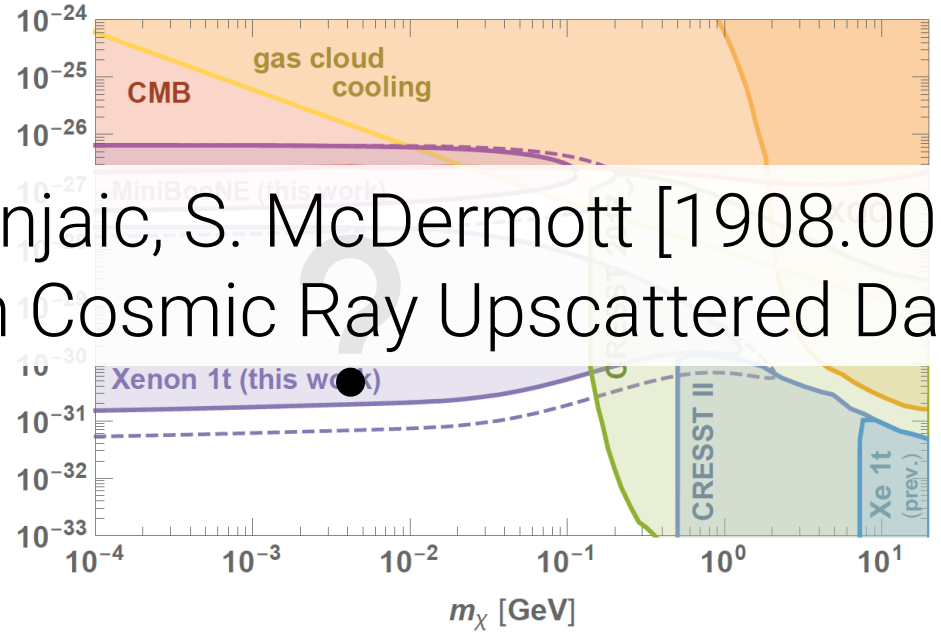
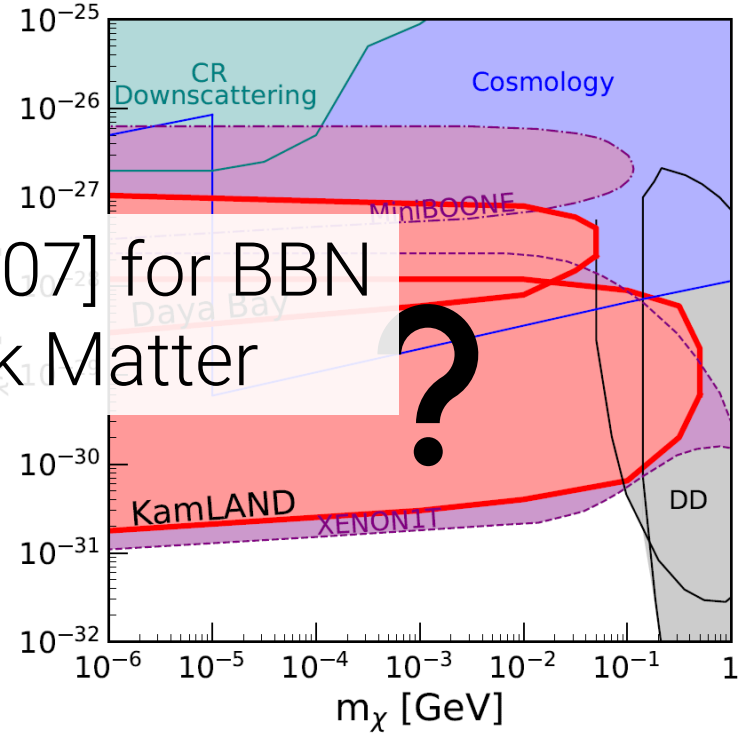
Is Dark Matter here?

Probably not.







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

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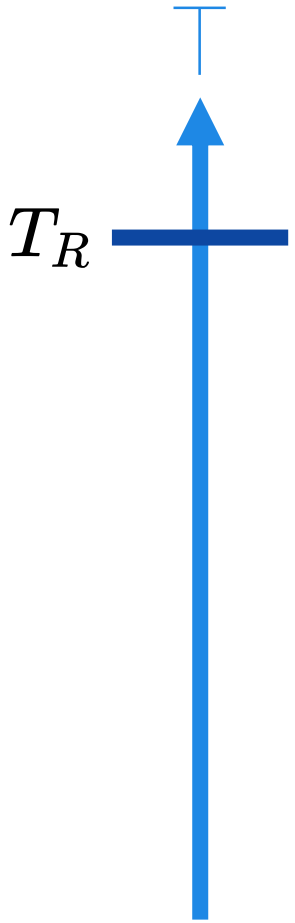
Is there a sub-GeV DM candidate which

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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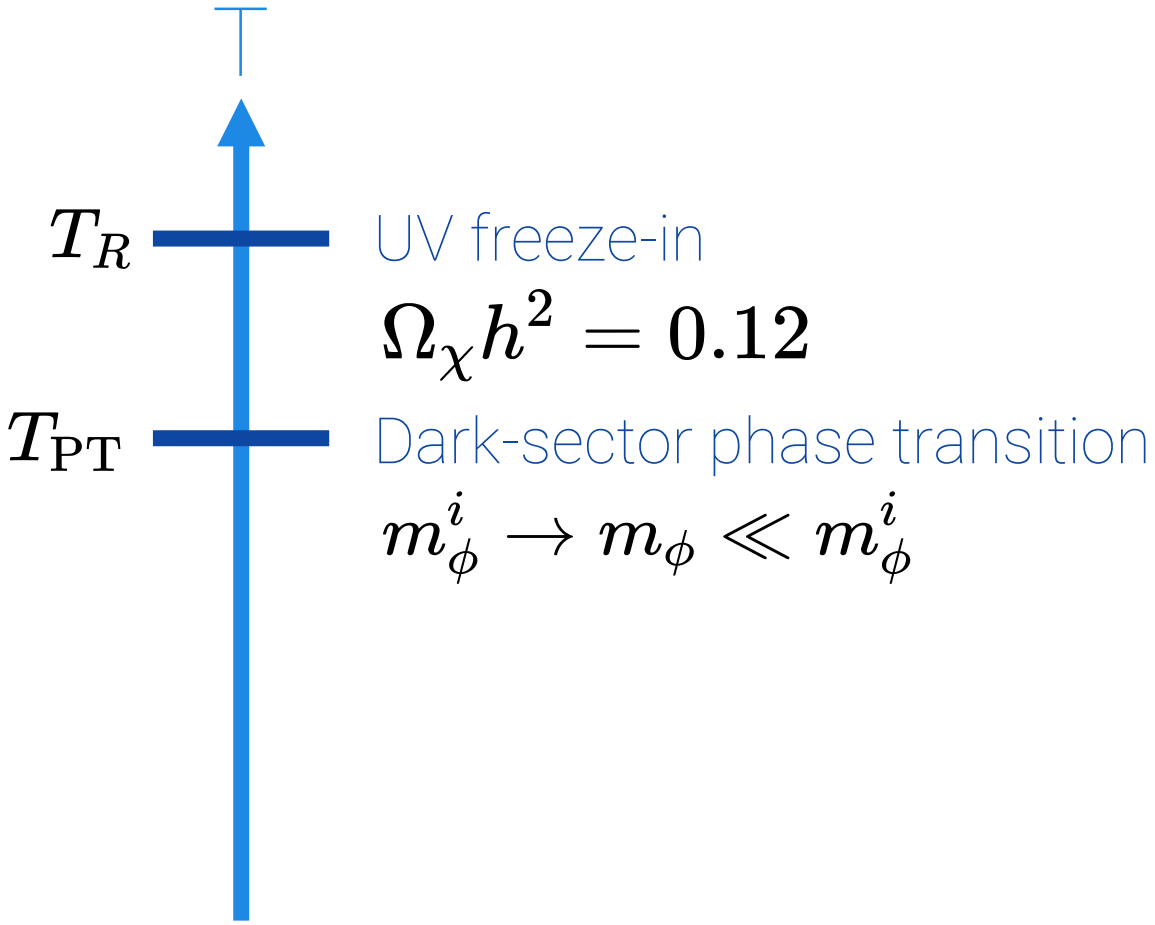
HYPER History



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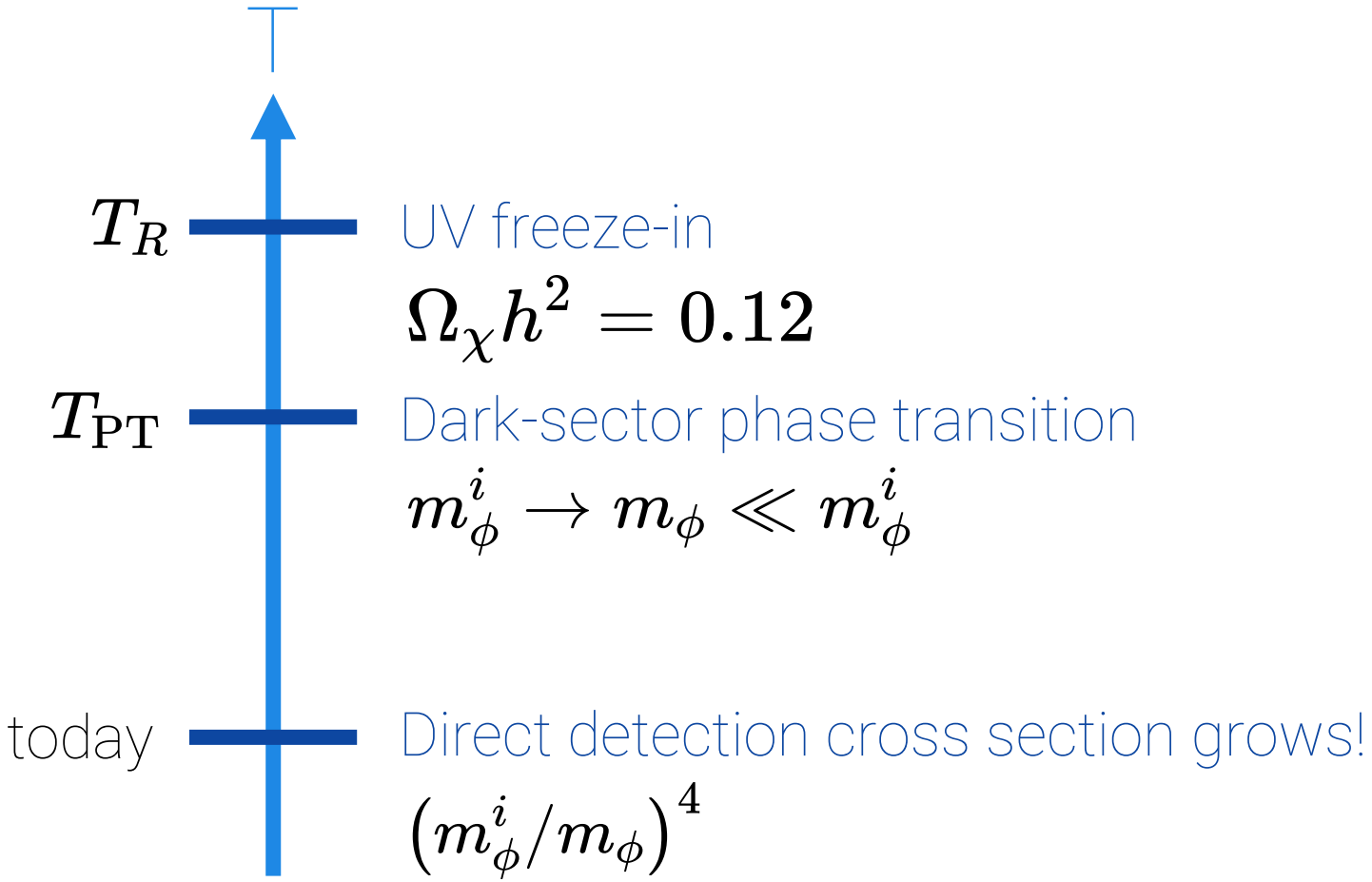
HYPER History



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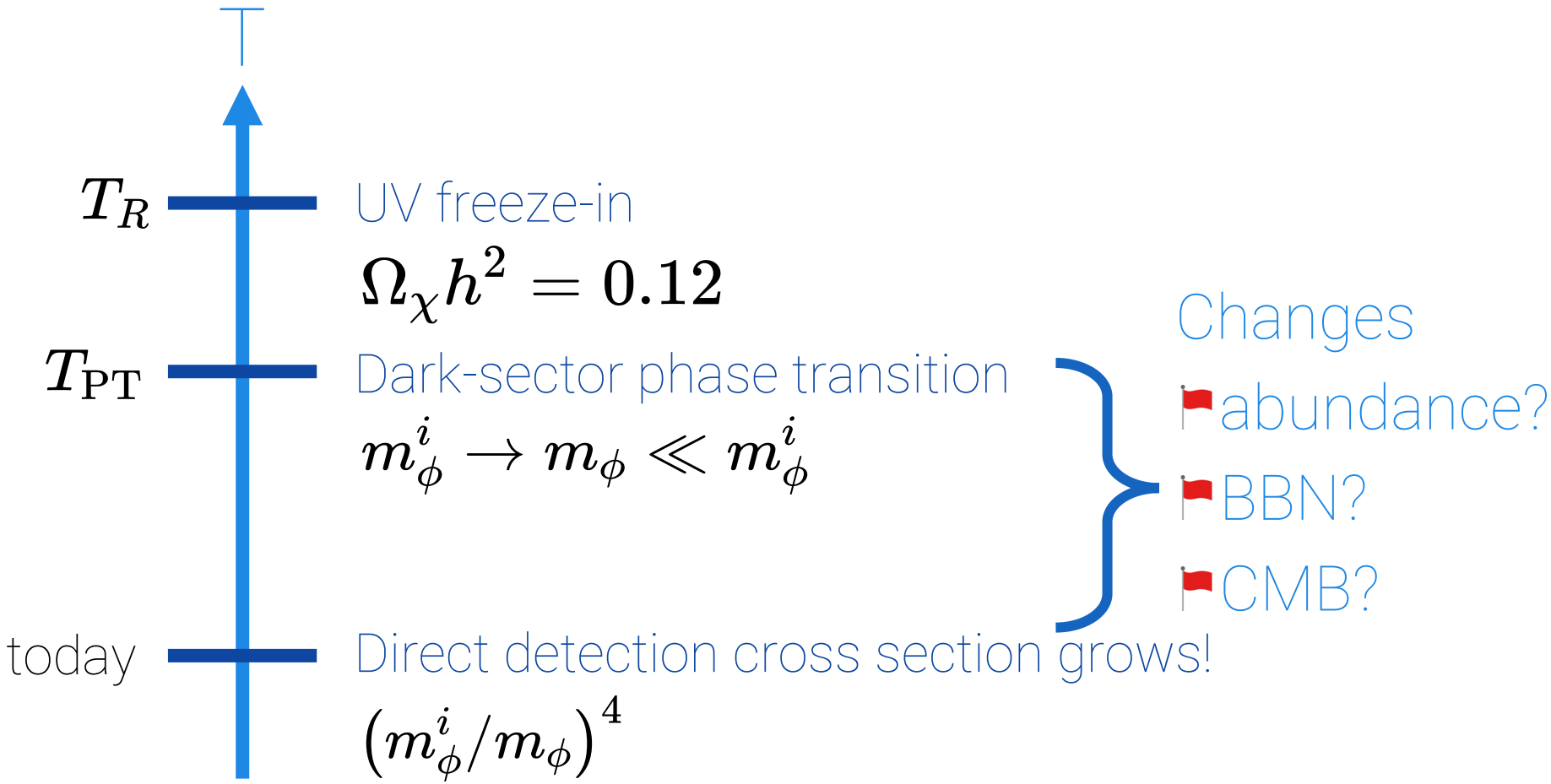
HYPER History



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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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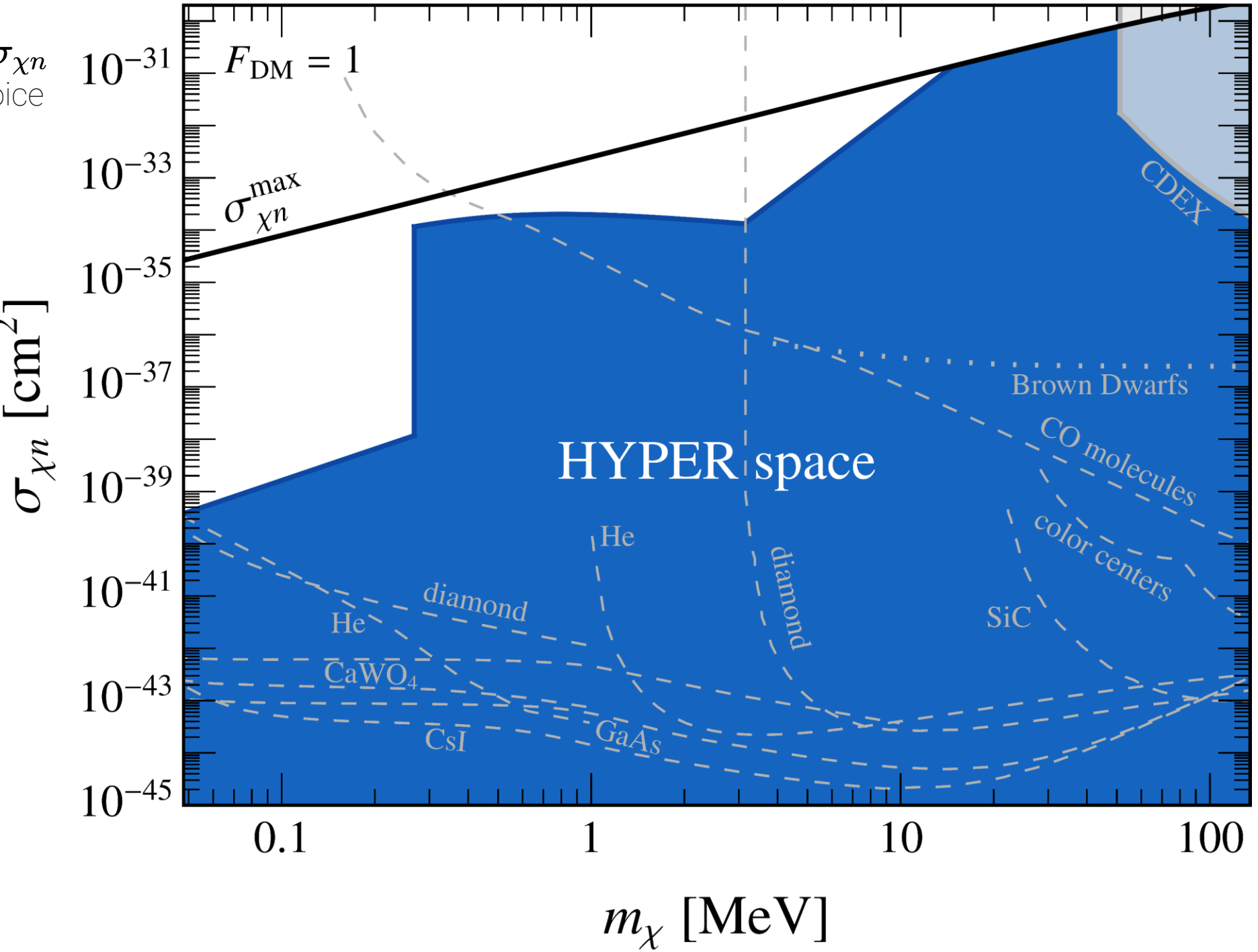
Results

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



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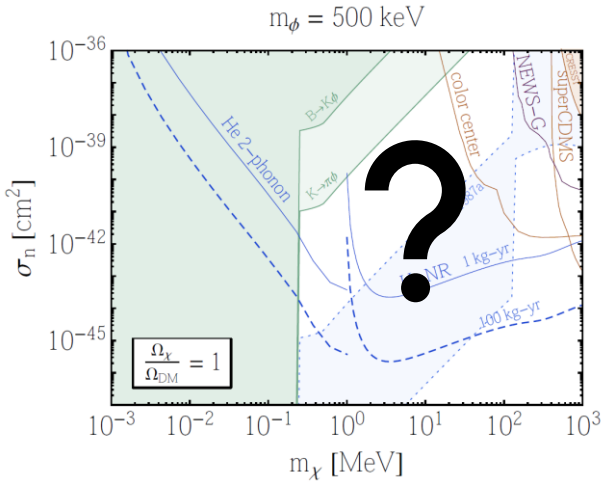
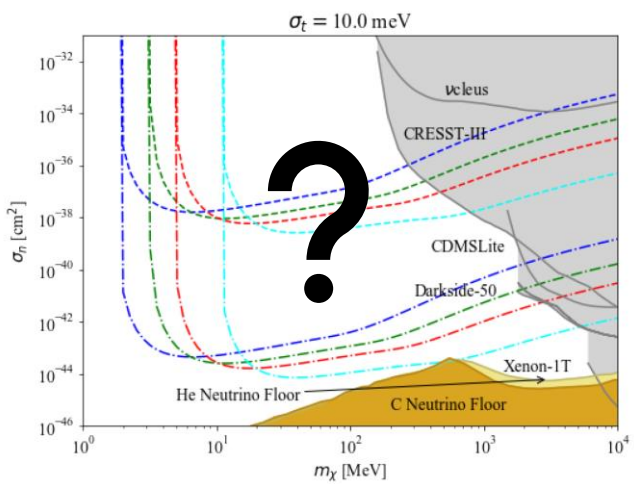
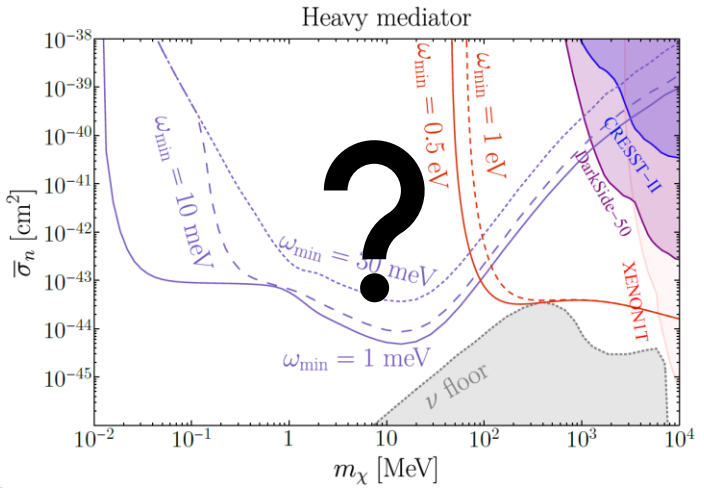
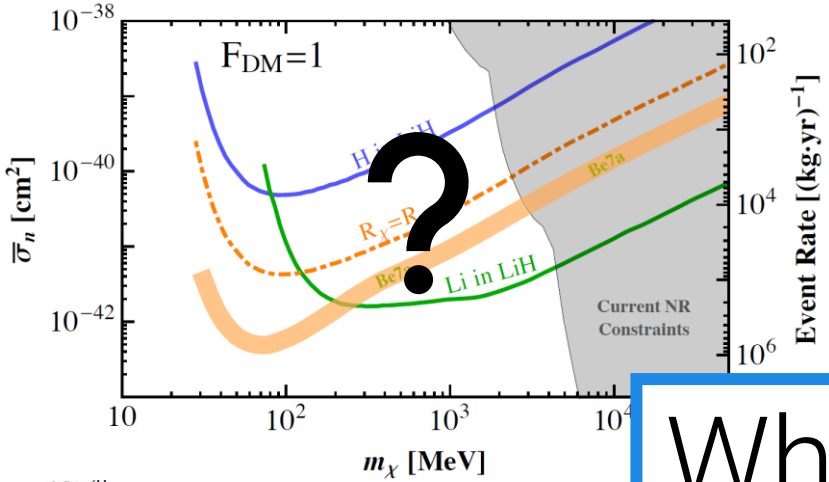
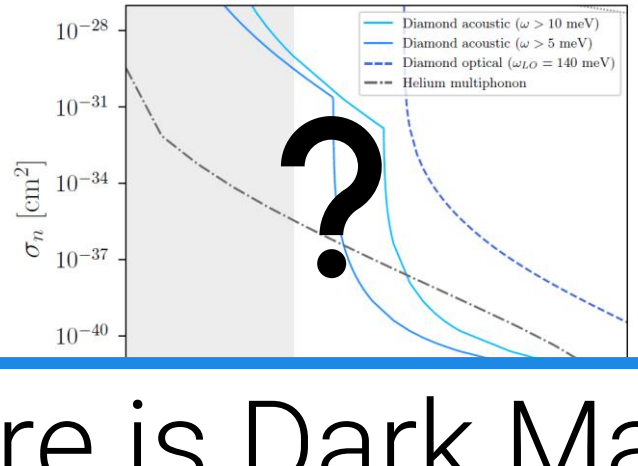
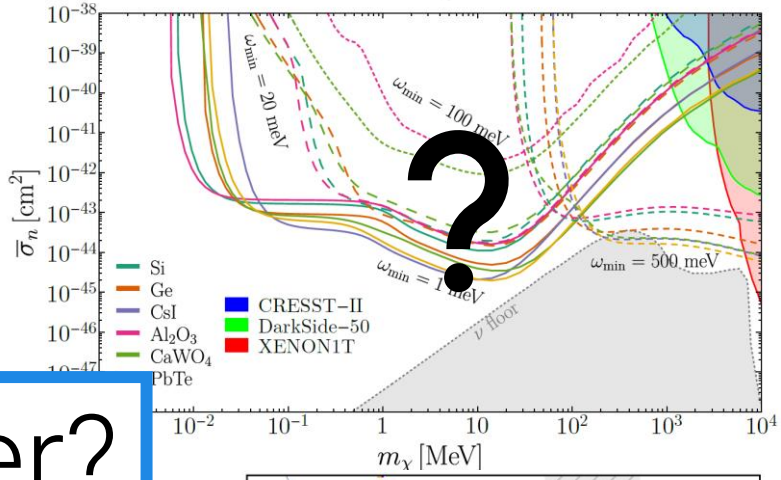




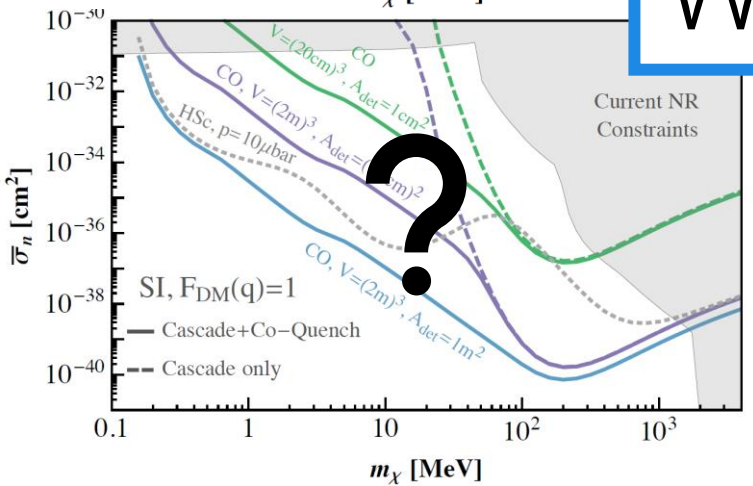


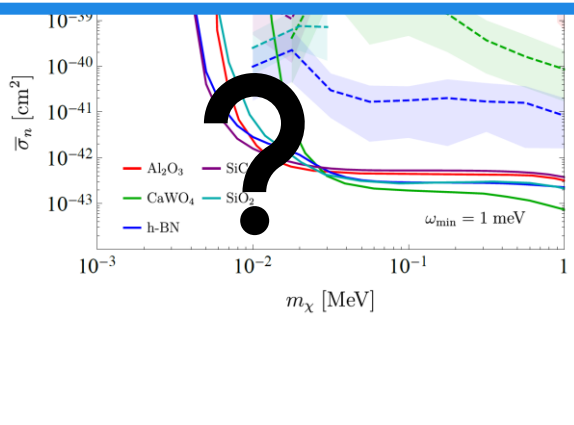


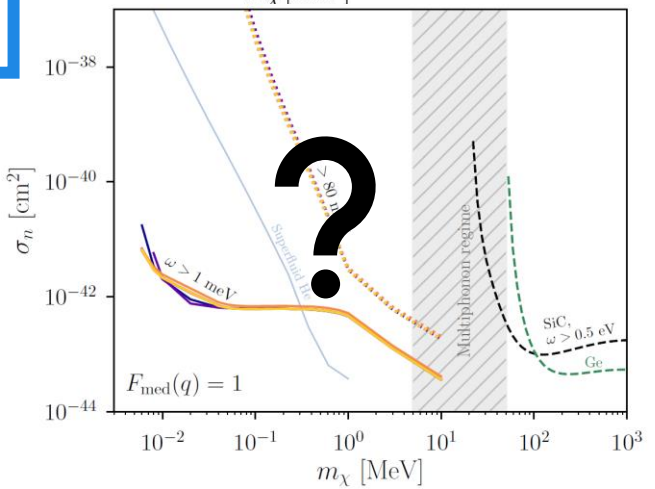


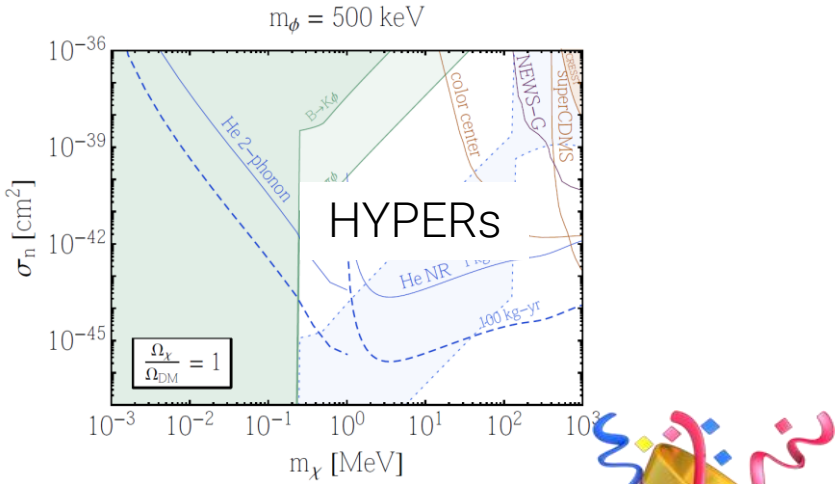


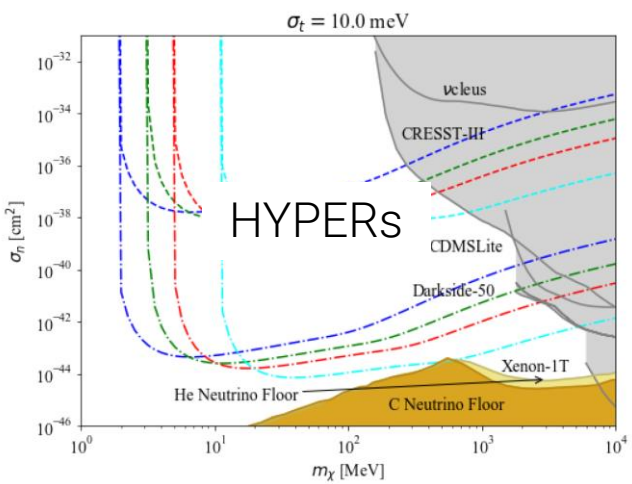
Where is Dark Matter?

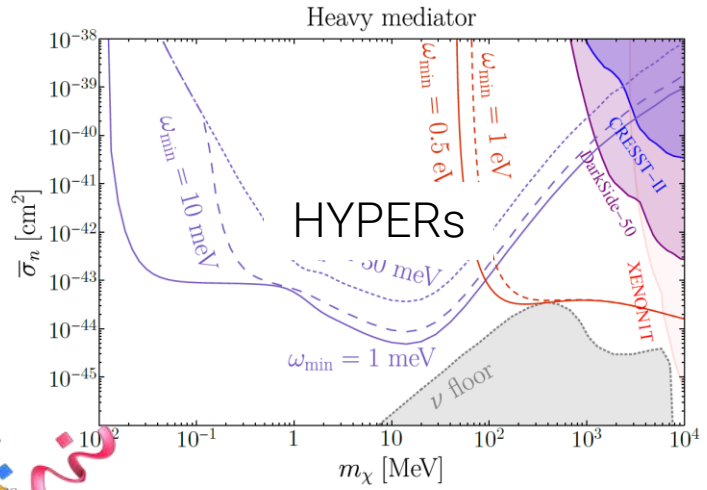


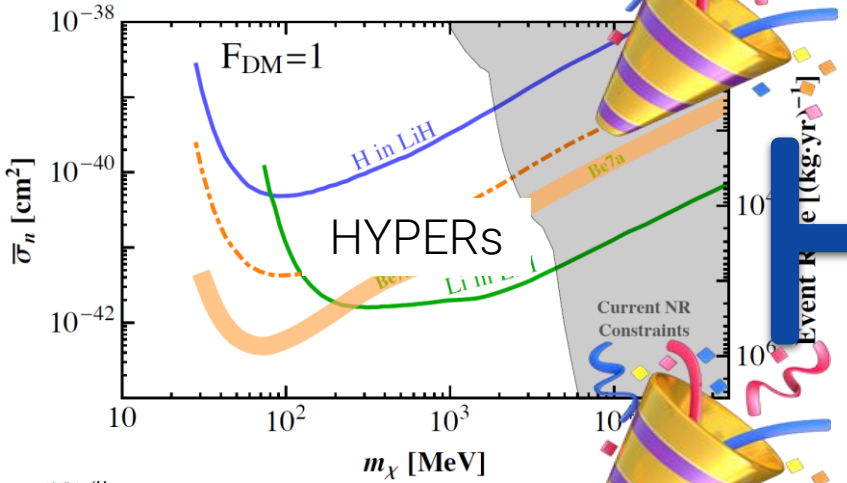


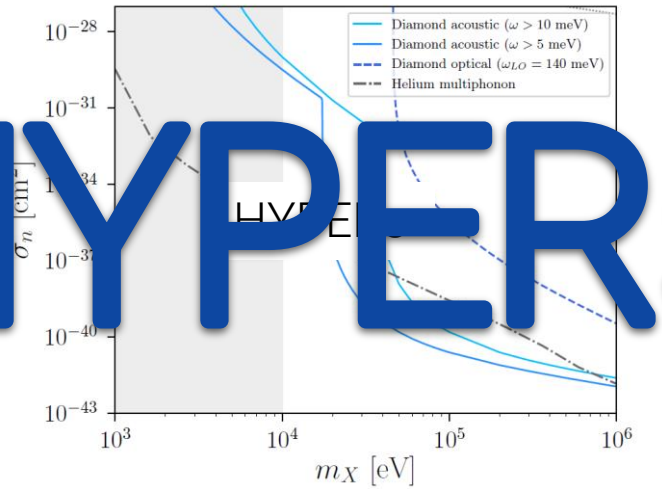


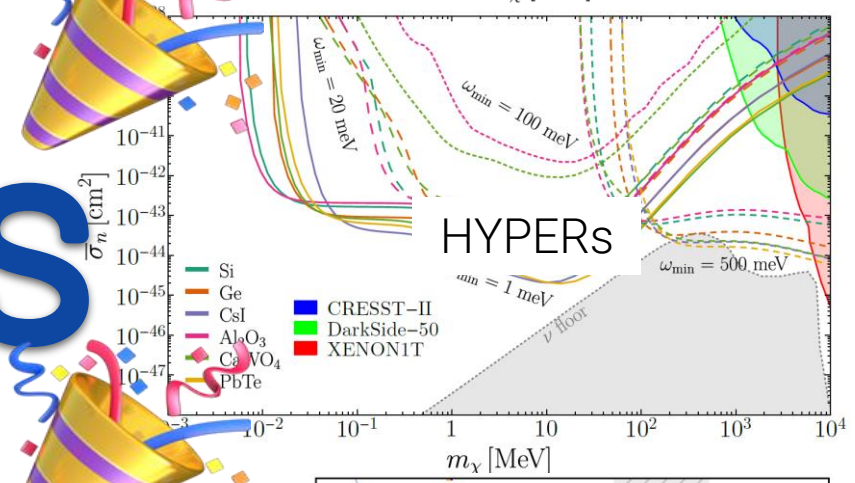

m_ϕ = 500 keV
HYPERs
He 2-phonon
color center
NEWS-G
SuperCDMS
He NR
100 kg-yr
$\frac{\Omega_\chi}{\Omega_{DM}} = 1$
σ_n [cm^2]
m_χ [MeV]

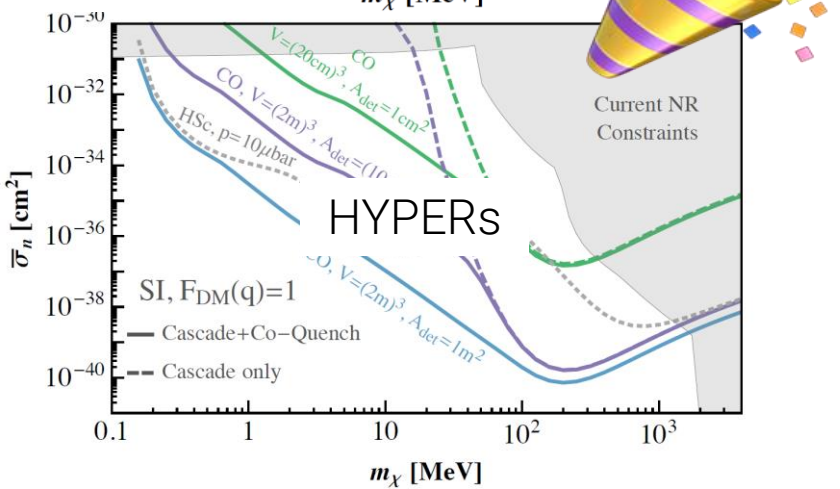

σ_t = 10.0 meV
HYPERs
ν-cleus
CRESST-III
CDMSLite
Darkside-50
Xenon-1T
He Neutrino Floor
C Neutrino Floor
σ_n [cm^2]
m_χ [MeV]

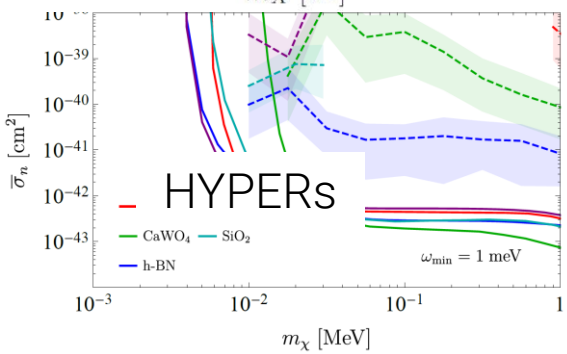

Heavy mediator
HYPERs
ω_{min} = 0.5 eV
ω_{min} = 1 eV
ω_{min} = 10 meV
ω_{min} = 1 meV
CRESST-II
DarkSide-50
XENON1T
ν floor
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

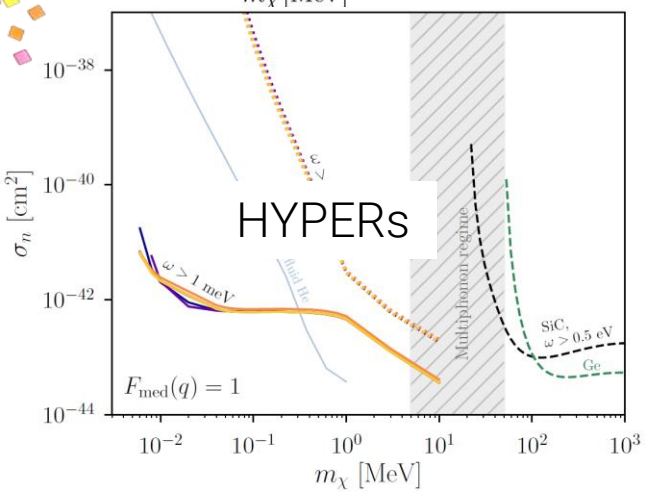

F_{DM}=1
HYPERs
H in LiH
Be7a
Current NR Constraints
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]


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?

R McGehee

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

R McGehee