Directly Detecting Light Dark Matter

Robert McGehee

UNIVERSITY OF MICHIGAN

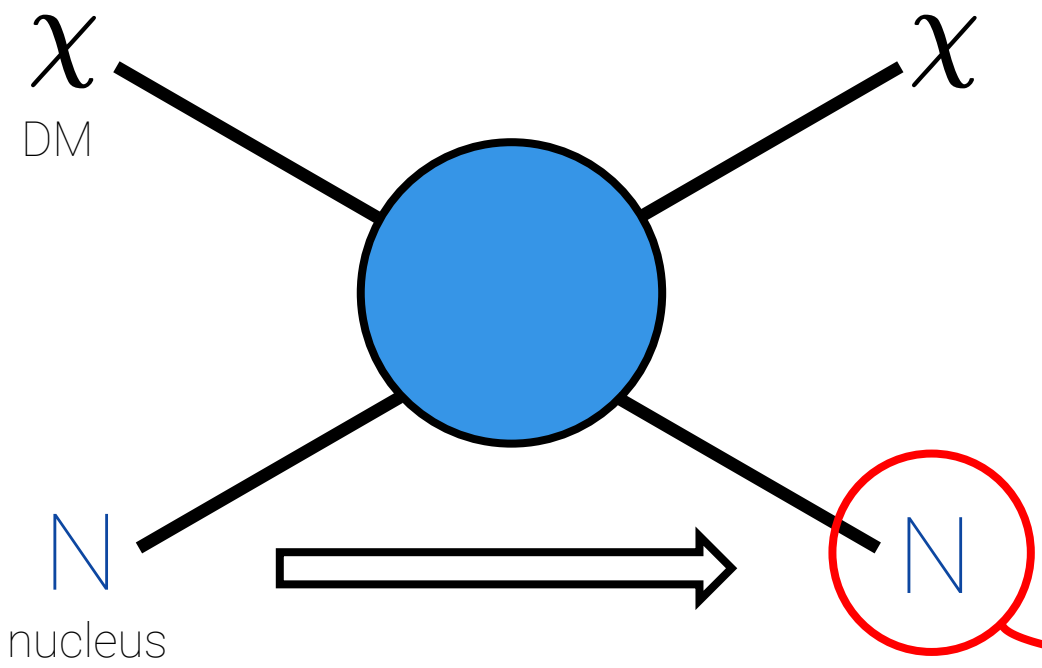
U.S. DEPARTMENT OF ENERGY | Office of Science

PRL 130 (2023) 3, 031803
JHEP 01 (2023) 128

w/ Gilly Elor & Aaron Pierce
+ Prudhvi N. Bhattiprolu

PIKIMO @ The OSU, 4/29/23

Direct Detection Refresher



Credit: The XENON Experiment

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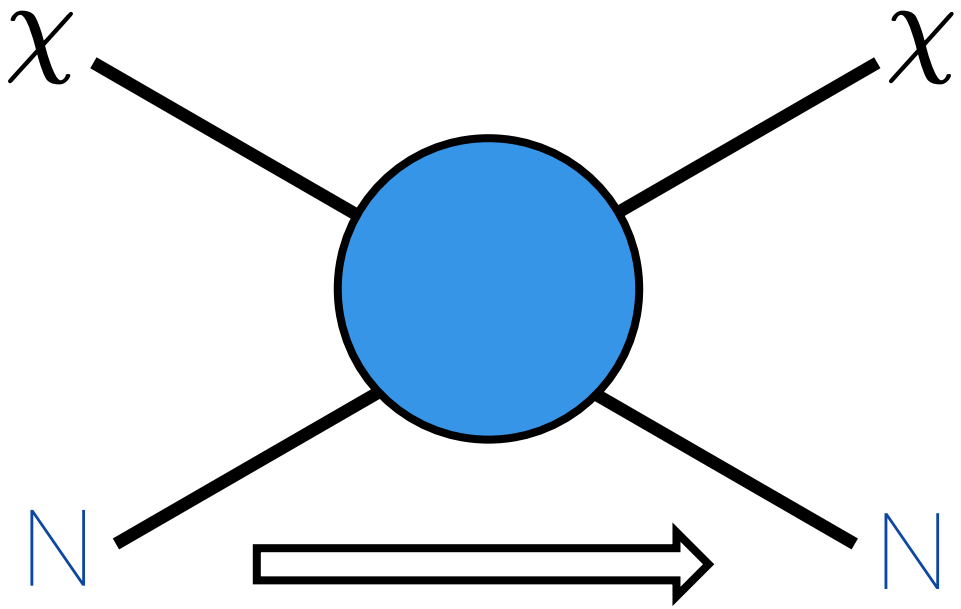
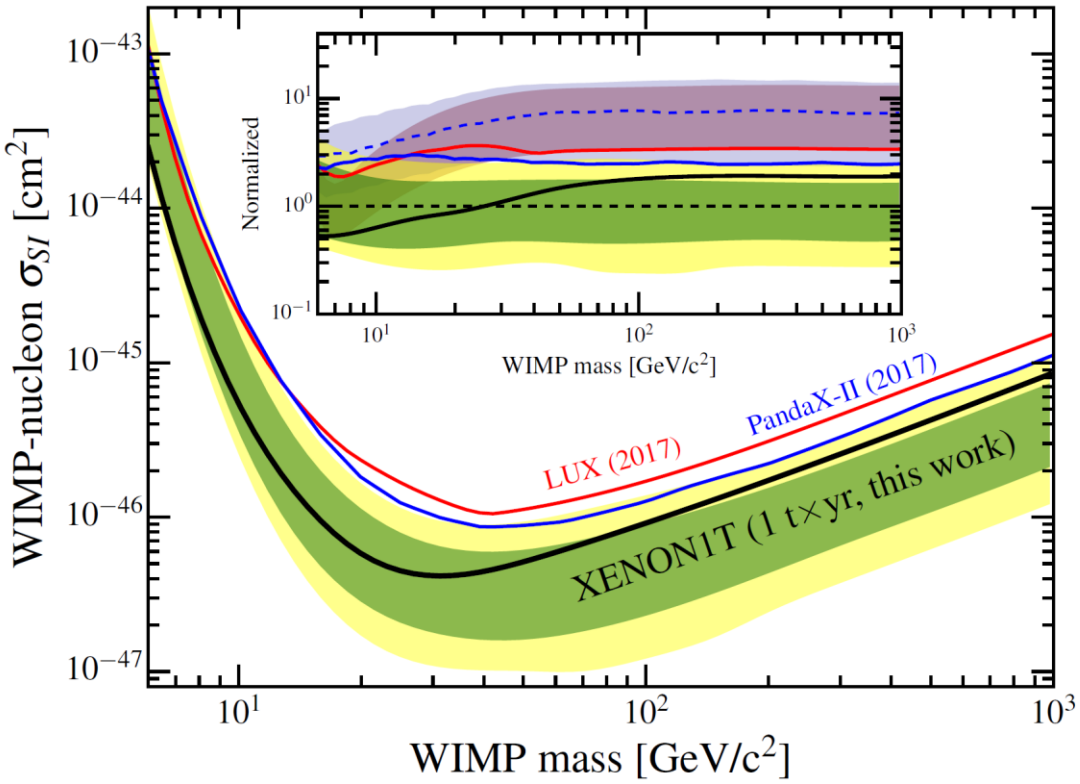
Direct Detection Refresher





XENON Collaboration [1805.12562]

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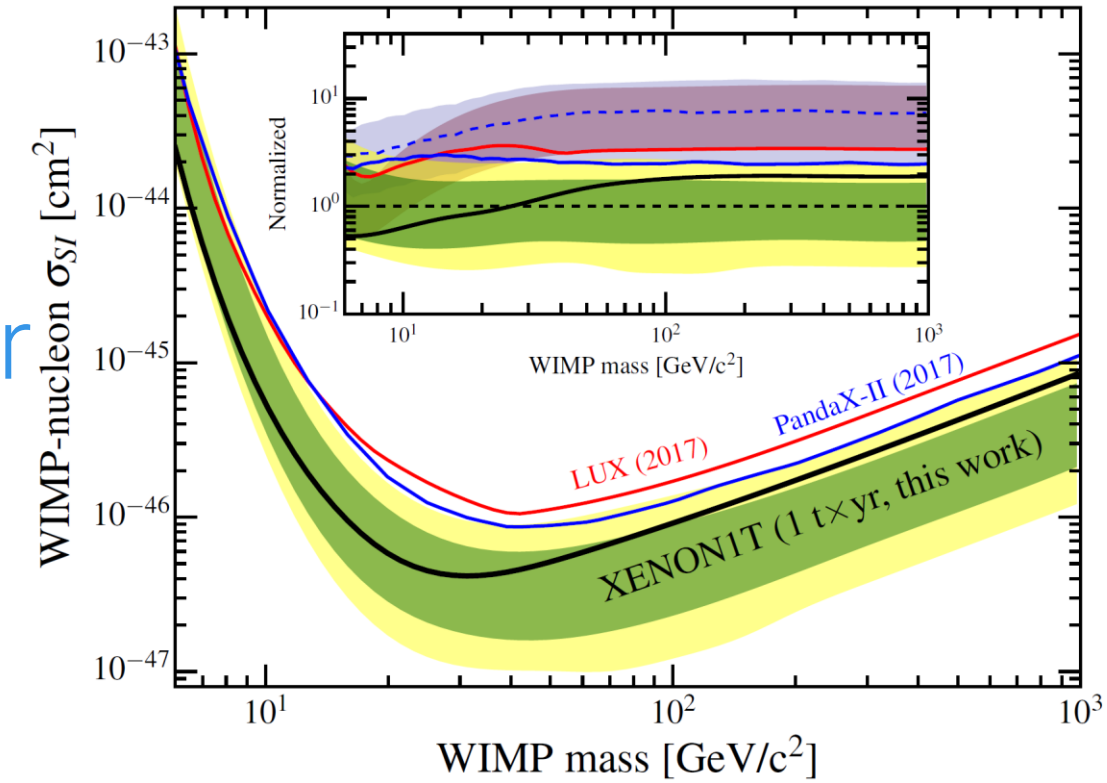
Direct Detection Future

Go lighter



Go lower

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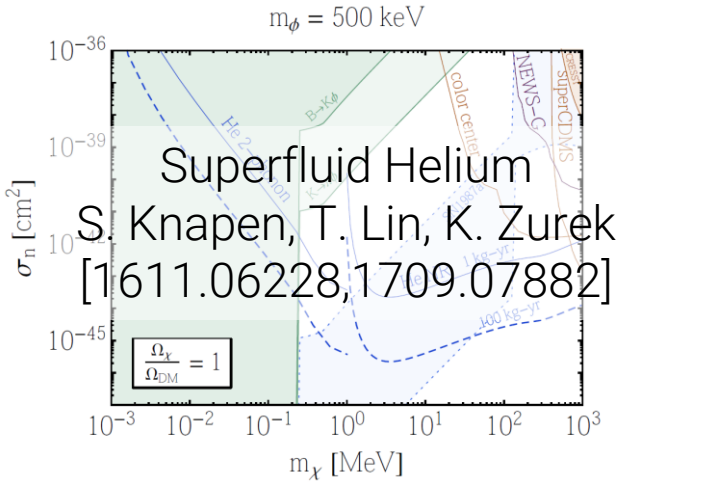
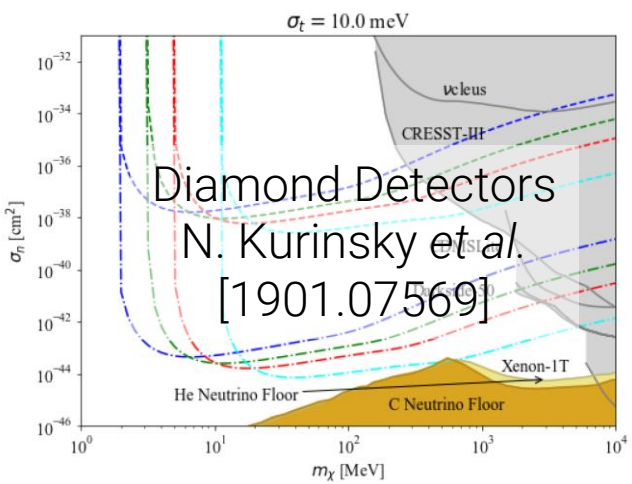
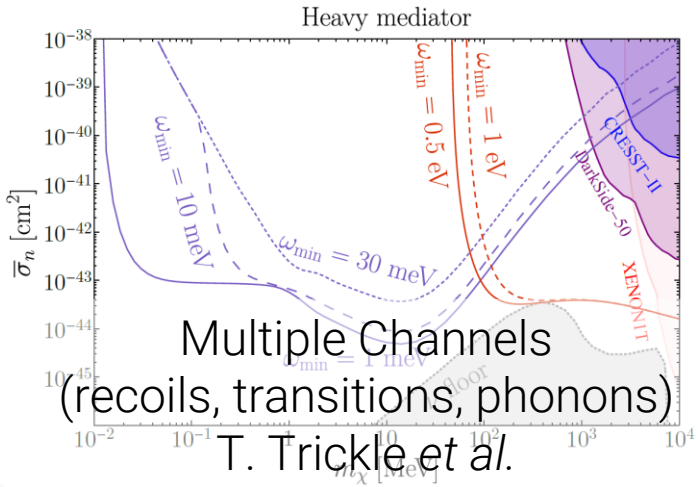
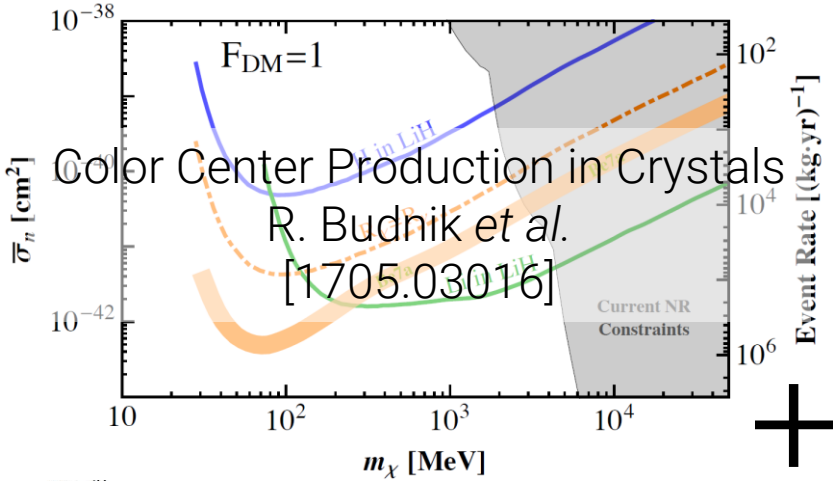
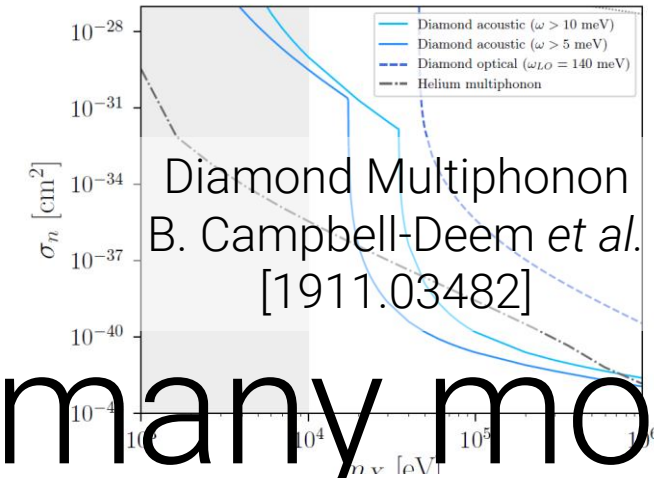
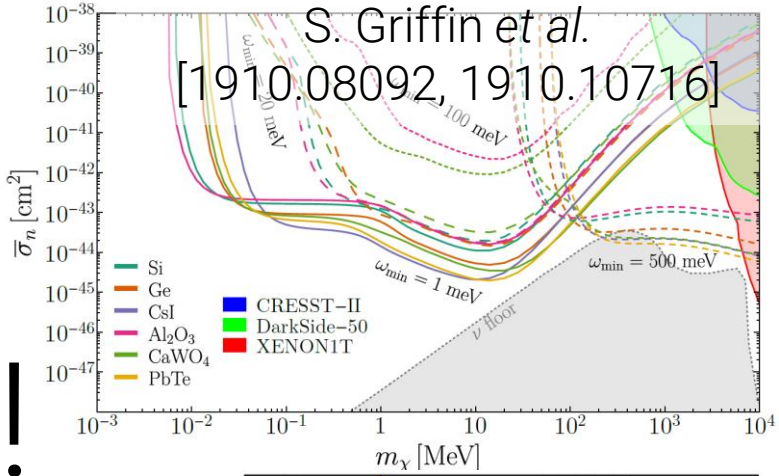

m_ϕ = 500 keV
Superfluid Helium
S. Knapen, T. Lin, K. Zurek
[1611.06228,1709.07882]
σ_n [cm^2]
m_χ [MeV]


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]

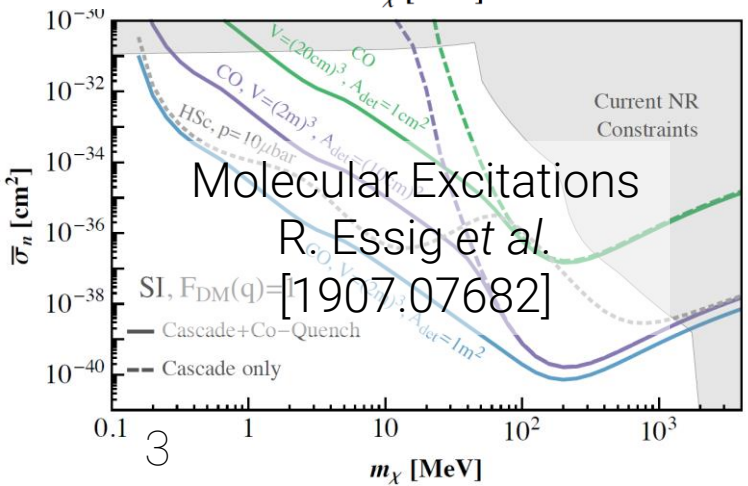

Heavy mediator
Multiple Channels
(recoils, transitions, phonons)
T. Trickle *et al.*
S. Griffin *et al.*
[1910.08092, 1910.10716]
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

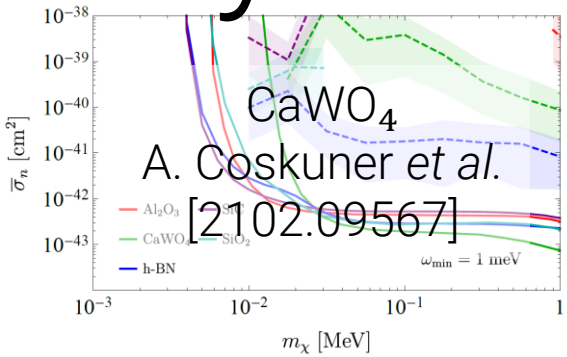

F_{DM}=1
Color Center Production in Crystals
R. Budnik *et al.*
[1705.03016]
Current NR Constraints
Event Rate [(kg·yr)$^{-1}$]
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

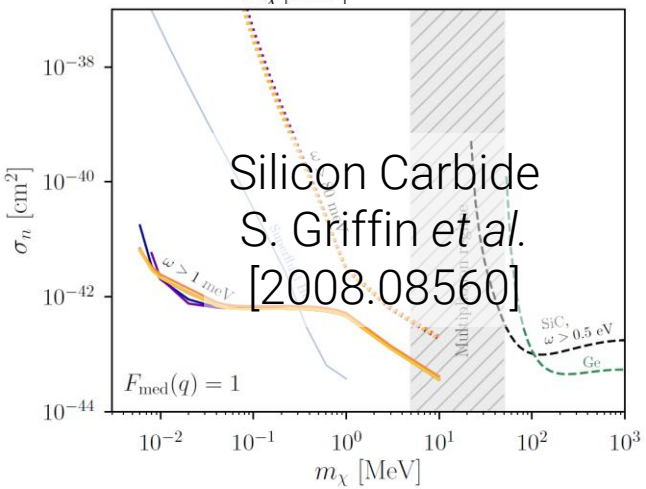

Diamond acoustic (ω > 10 meV)
Diamond acoustic (ω > 5 meV)
Diamond optical (ω$_{LO}$ = 140 meV)
Helium multiphonon
Diamond Multiphonon
B. Campbell-Deem *et al.*
[1911.03482]
σ_n [cm^2]

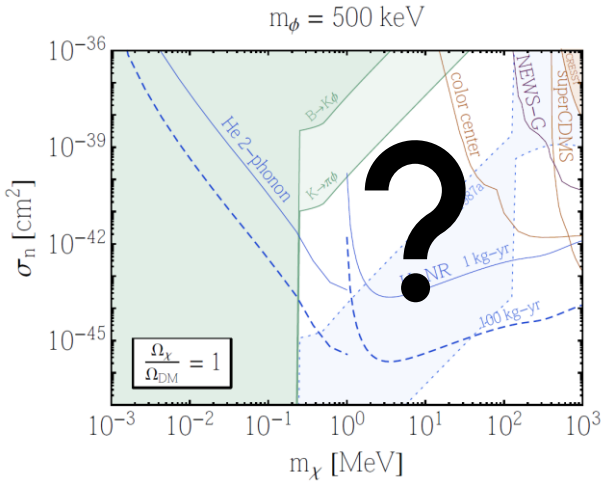

Si
Ge
CsI
Al_2O_3
$CaWO_4$
PbTe
CRESST−II
DarkSide−50
XENON1T
ω_{min} = 1 meV
ω_{min} = 500 meV
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

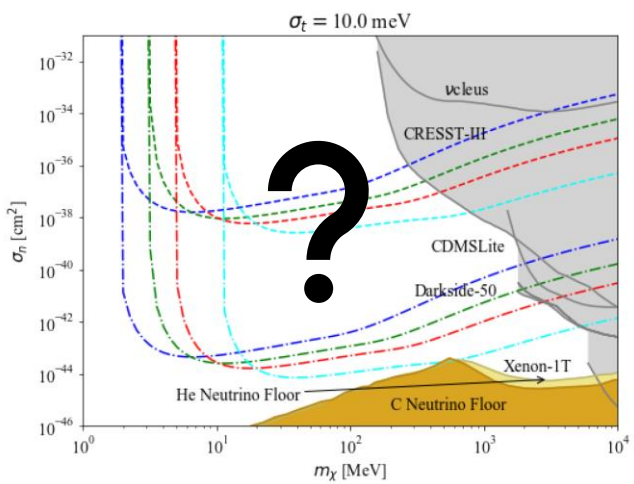
+ many more!

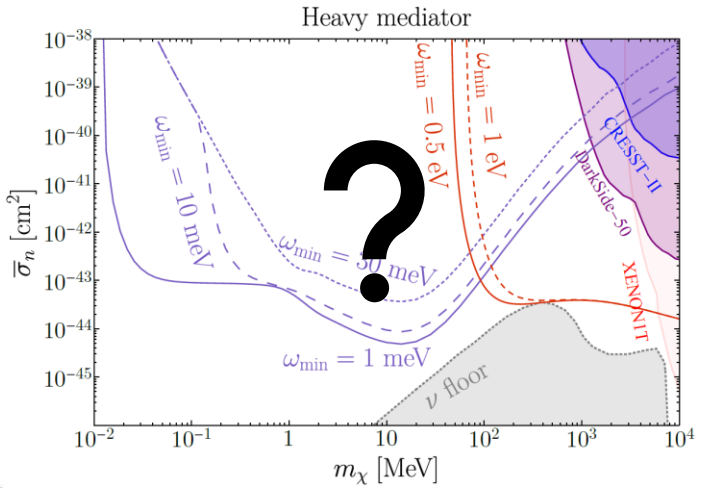

Molecular Excitations
R. Essig *et al.*
[1907.07682]
Current NR Constraints
SI, $F_{DM}(q)=1$
Cascade+Co−Quench
Cascade only
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

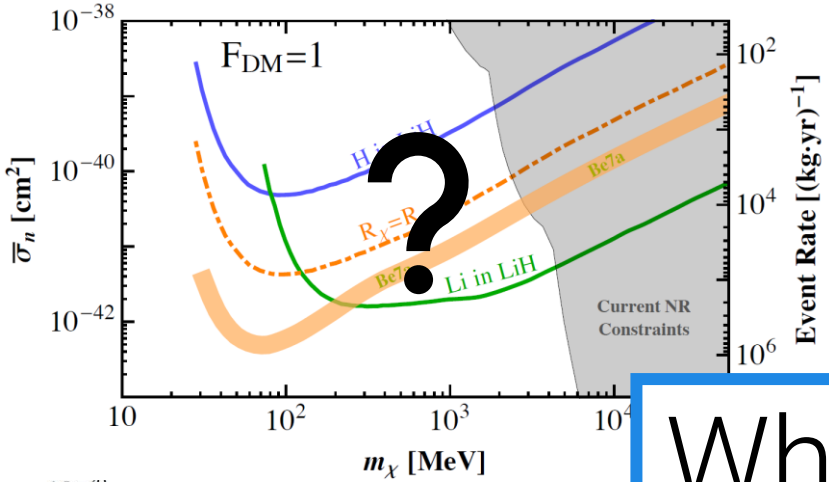

$CaWO_4$
A. Coskuner *et al.*
[2102.09567]
Al_2O_3
$CaWO_4$
SiO_2
h-BN
ω_{min} = 1 meV
$\overline{\sigma}_n$ [cm^2]
m_χ [MeV]

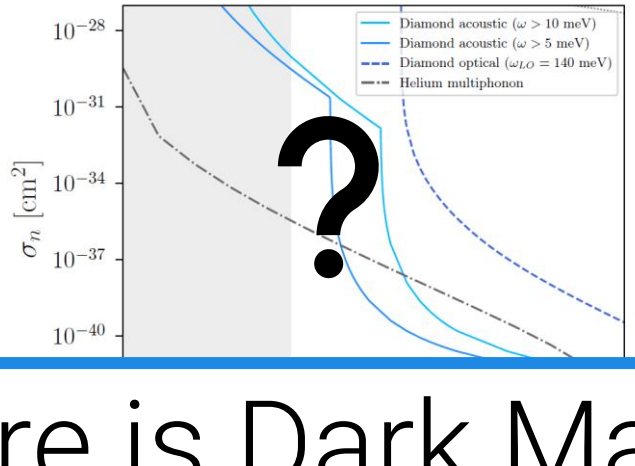

Silicon Carbide
S. Griffin *et al.*
[2008.08560]
$F_{med}(q) = 1$
σ_n [cm^2]
m_χ [MeV]

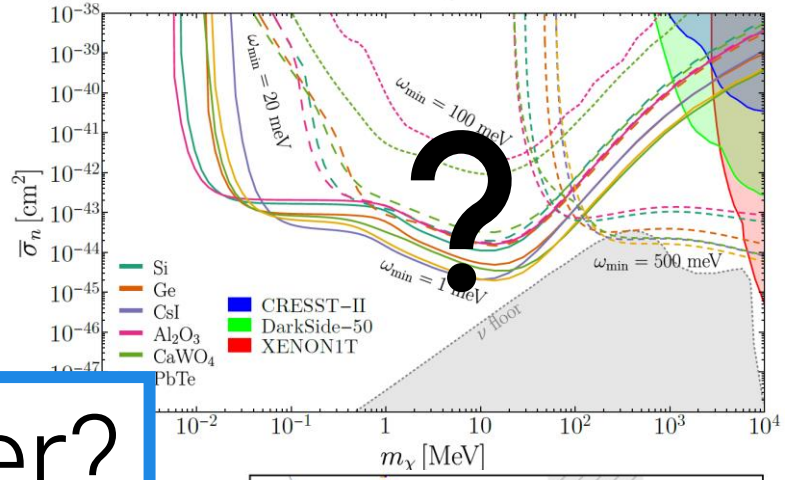




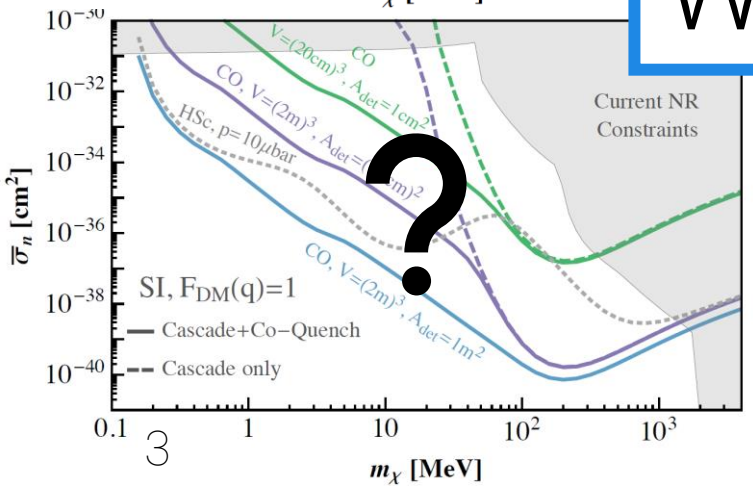


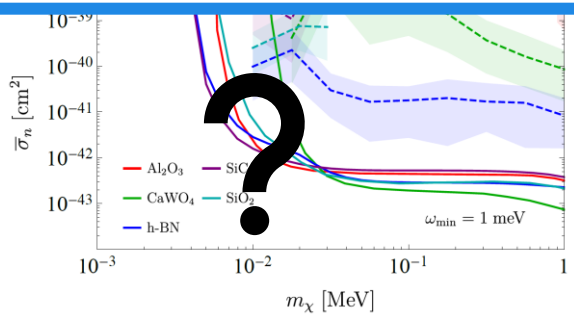


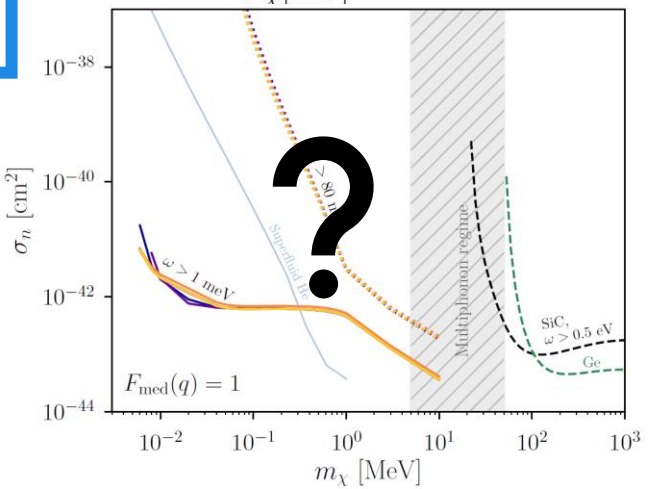


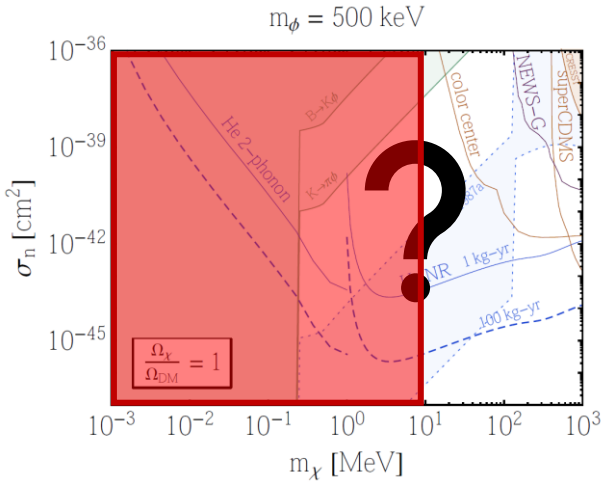


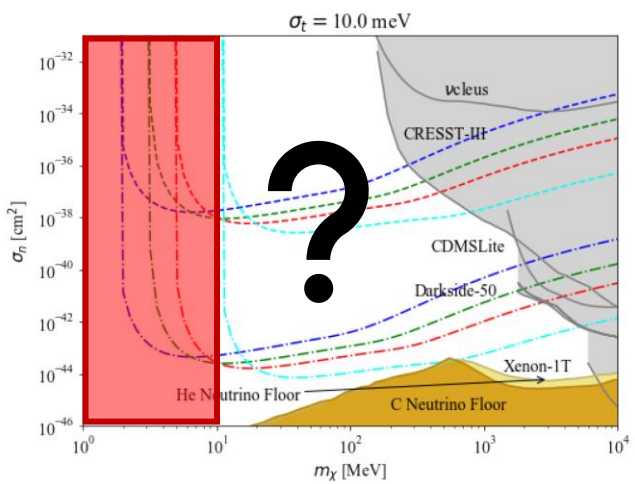
Where is Dark Matter?

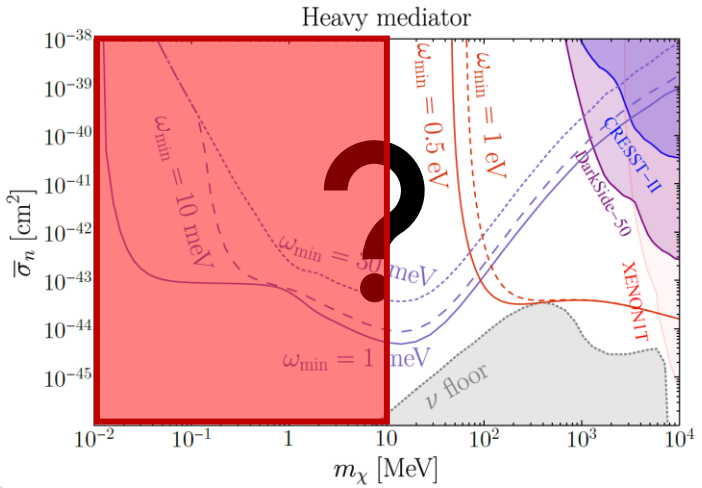


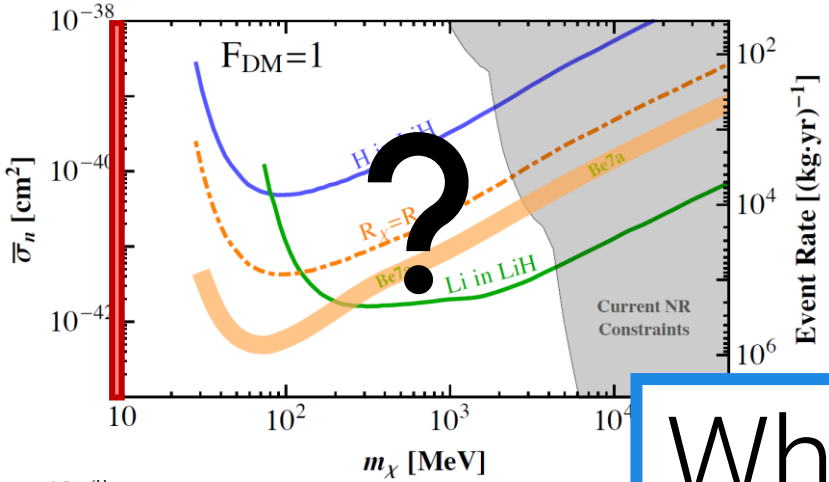


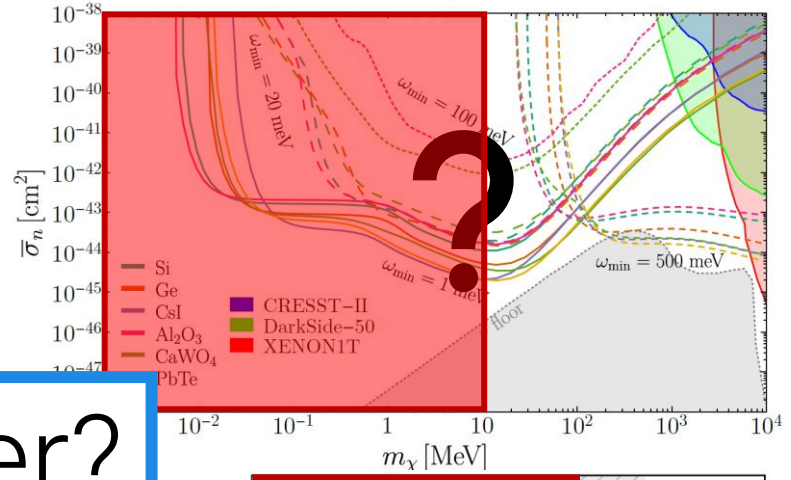


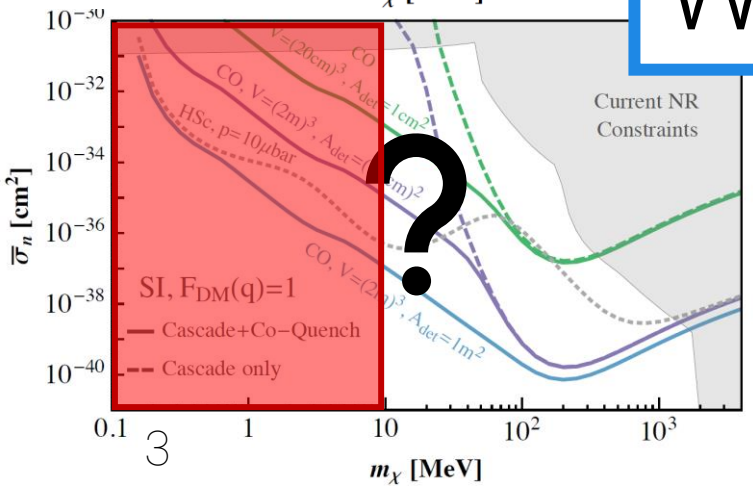


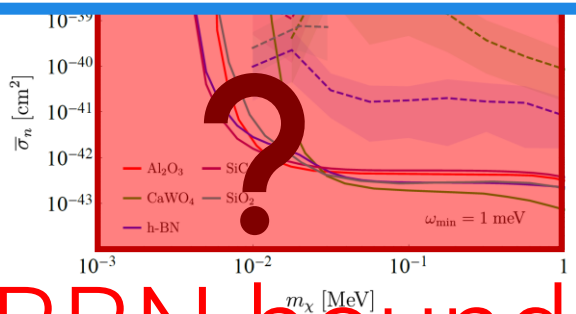


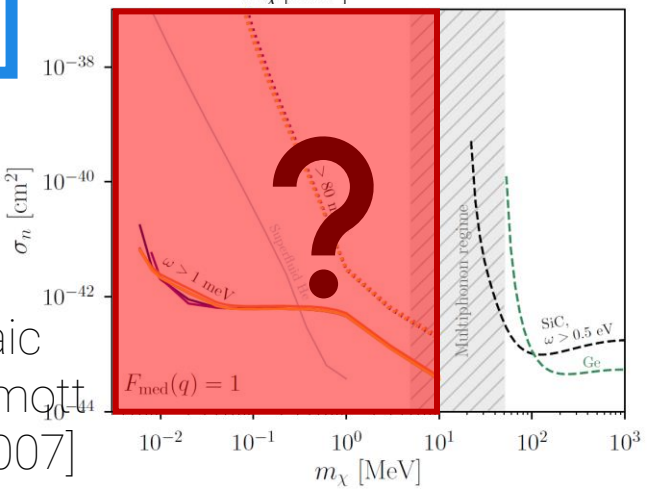








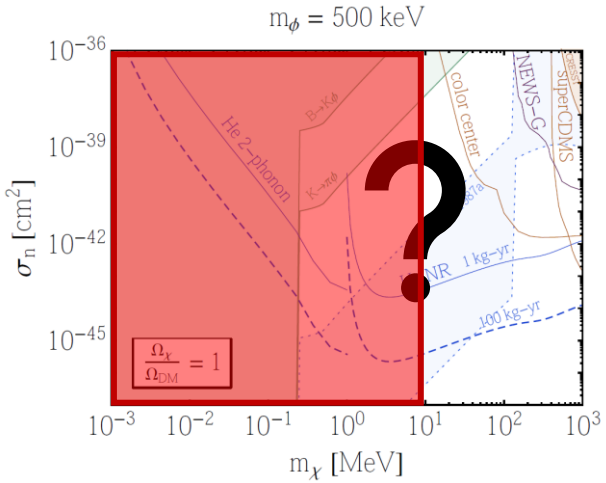


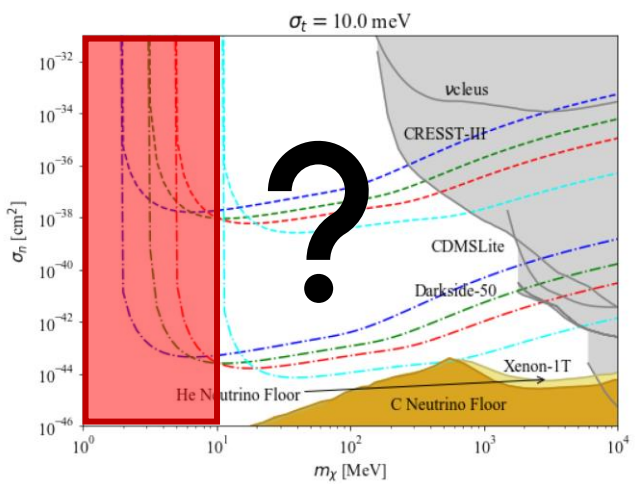


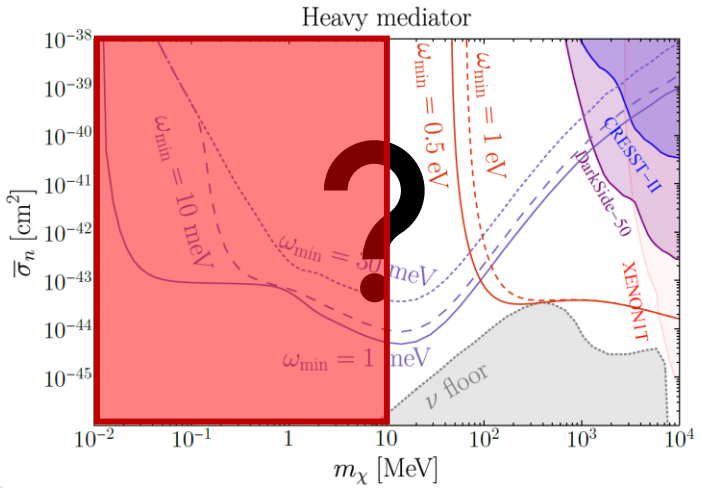
Where is Dark Matter?

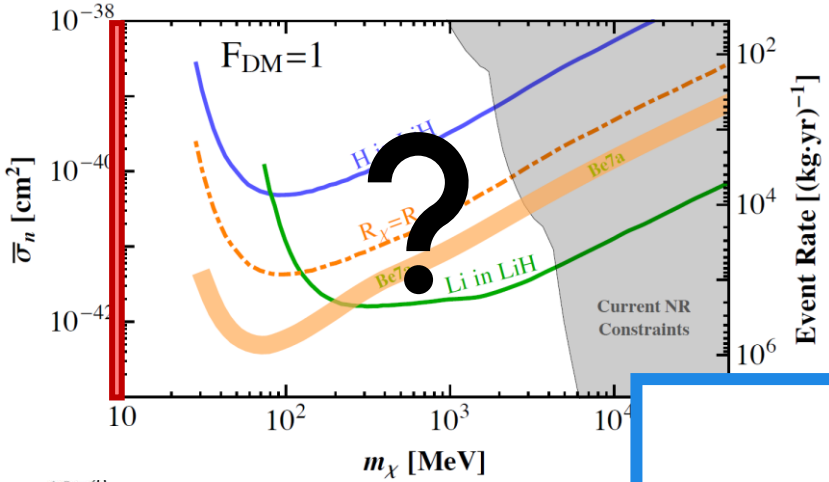
BBN bounds

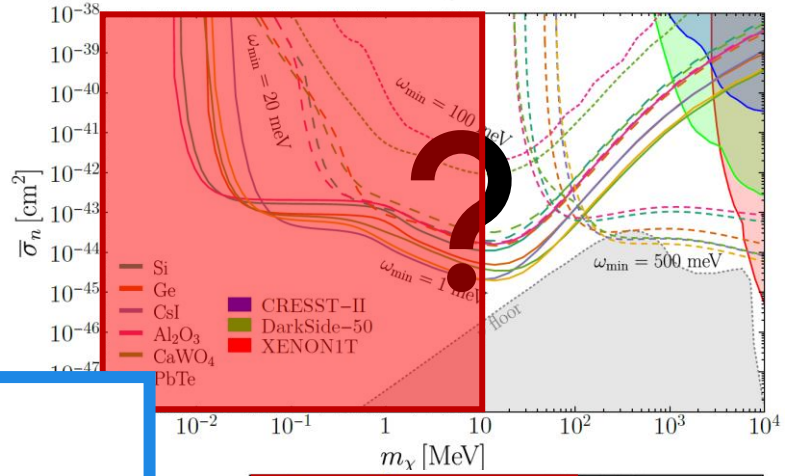
G. Krnjaic
S. McDermott
[1908.00007]

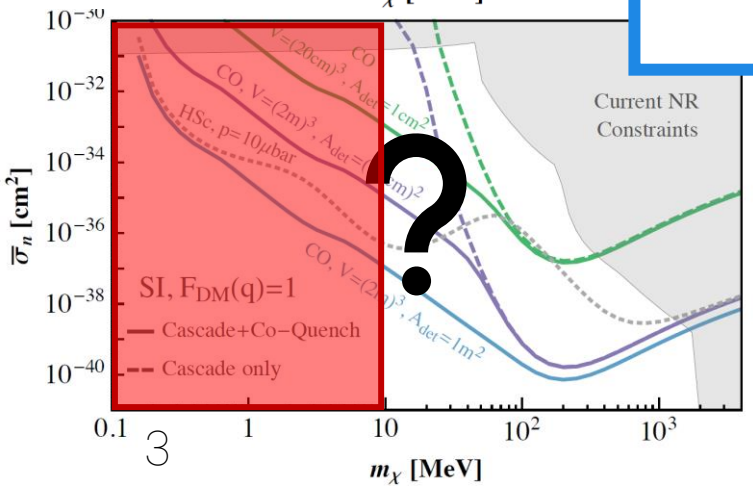


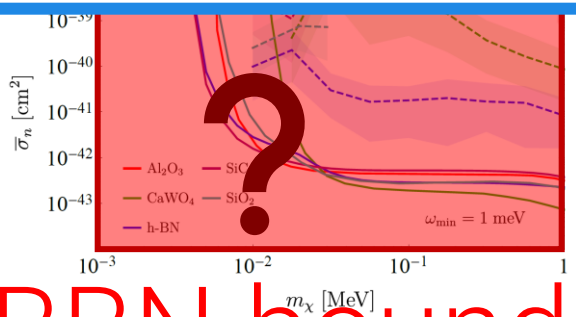


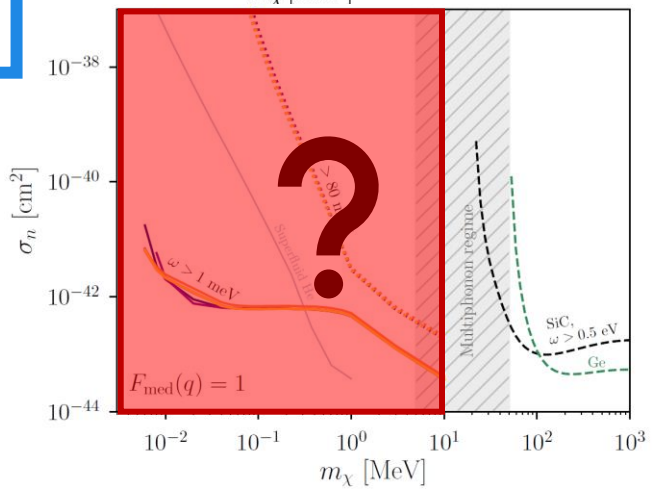












Not here?

BBN bounds

Two ways to get light, detectable DM

1) Dark phase transition at low temp. (HYPERs)

2) Freezing-in at low reheating temperatures

R McGehee

The Basics

UV Freeze-In F. Elahi, C. Kolda, J. Unwin [1410.6157]

$$\mathbf{SM\ SM} \rightarrow \bar{\chi}\chi$$

Feeble couplings or heavy mediators

Much slower than Hubble

DM remains out-of-equilibrium

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The Basics

UV Freeze-In

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

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

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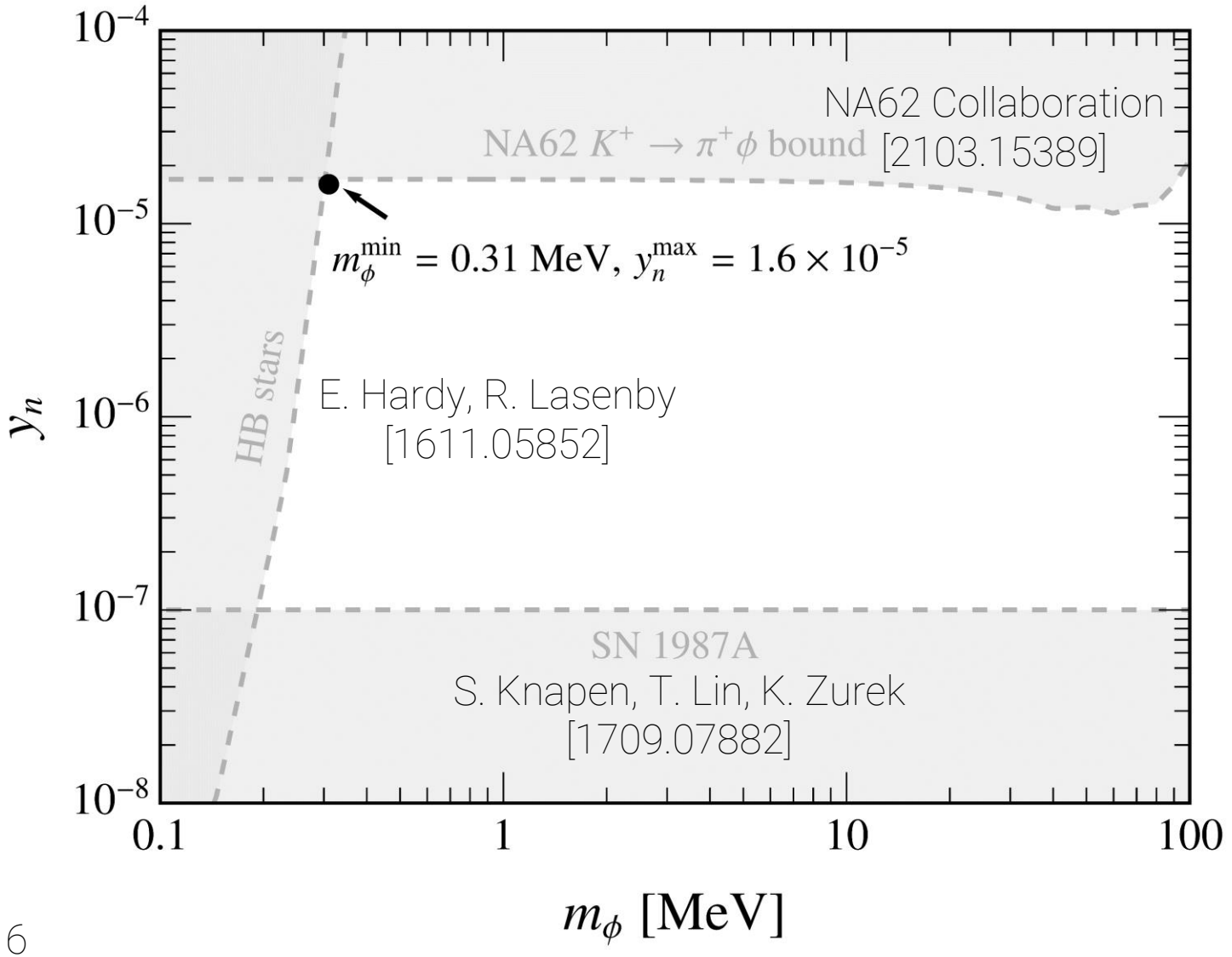
1) HighlY interactive ParticlE Relics (HYPERs)

PRL 130 (2023) 3, 031803 Gilly Elor, RM, & Aaron Pierce

Constraints for HYPERs



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

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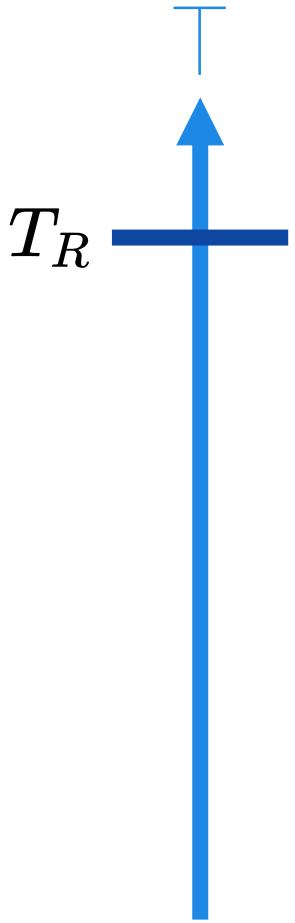
HYPER History



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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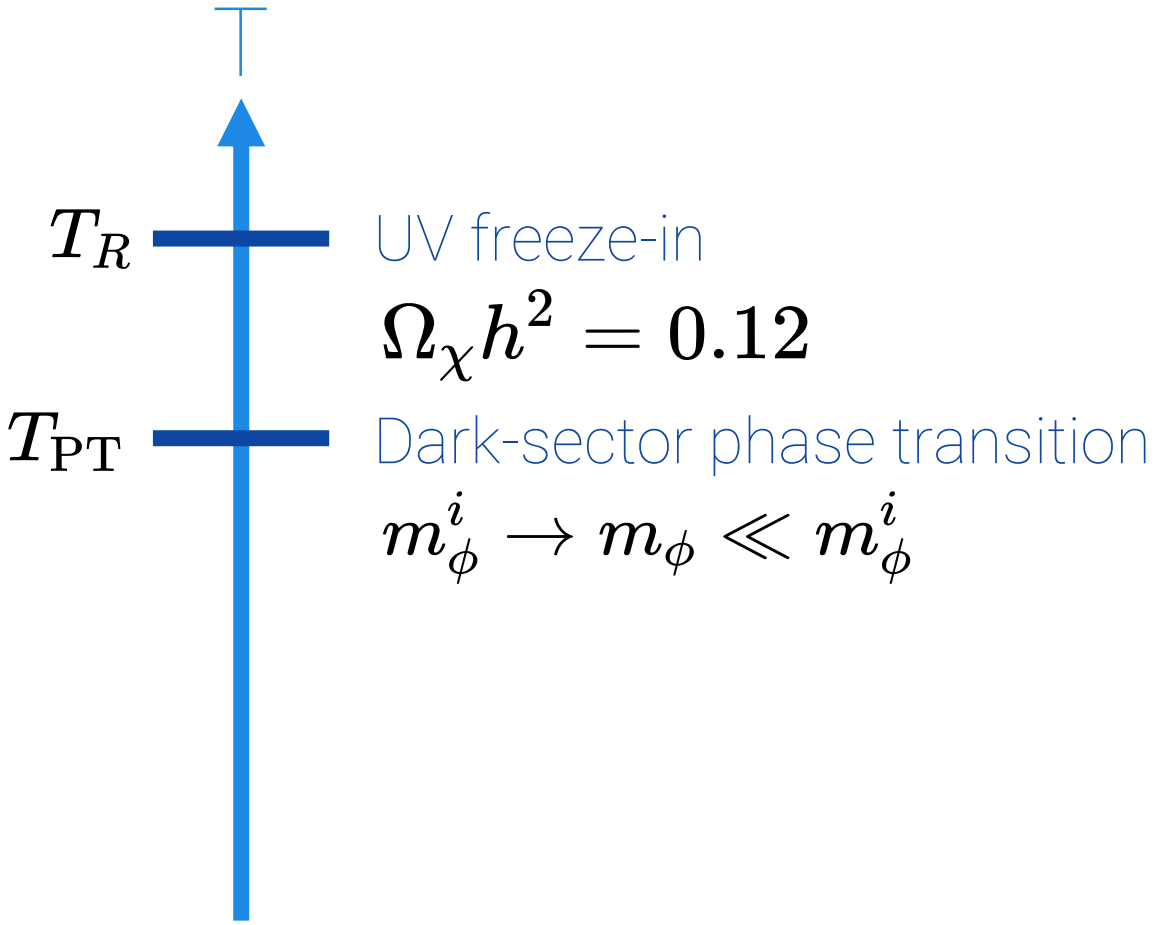
HYPER History



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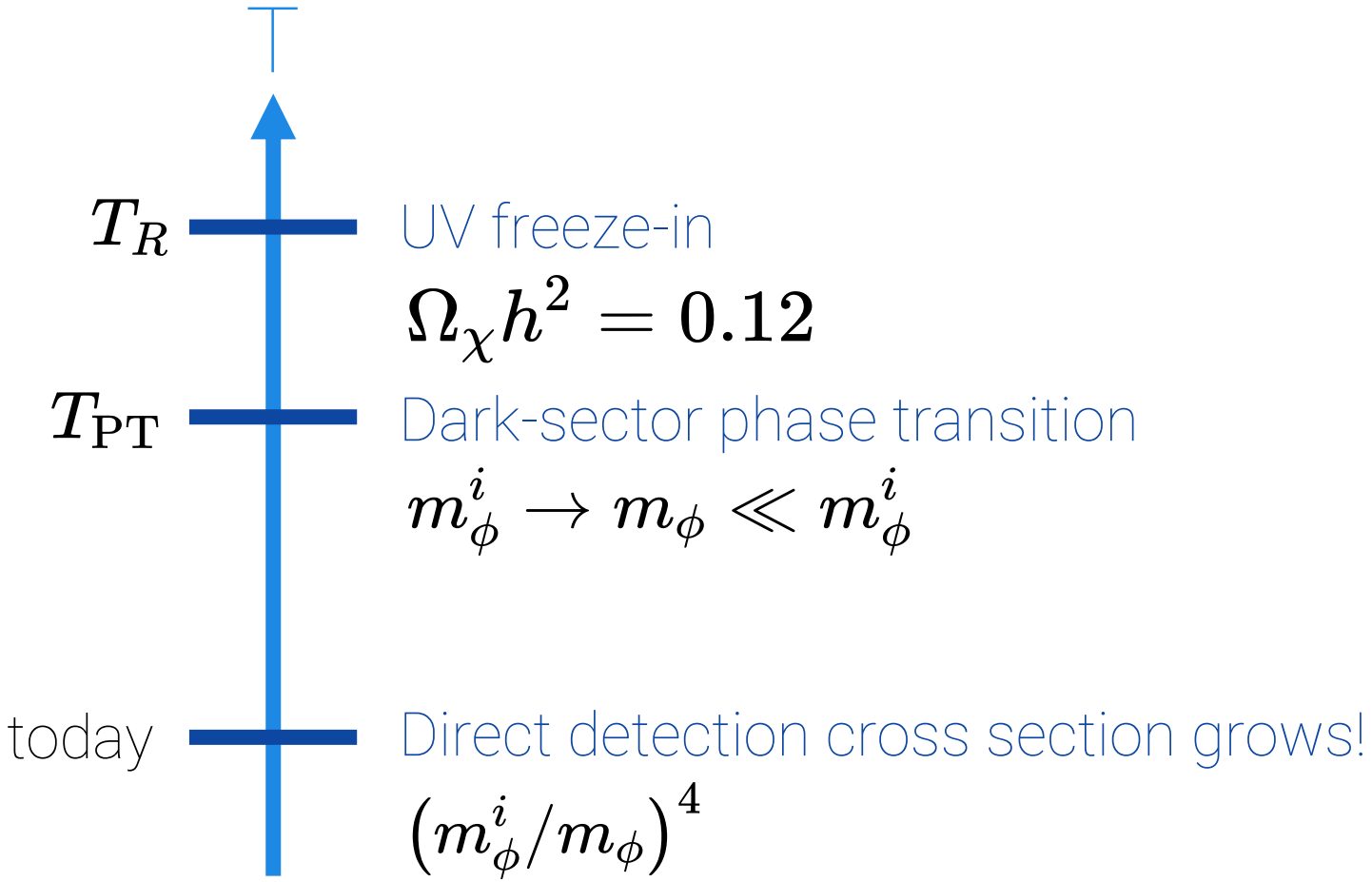
HYPER History



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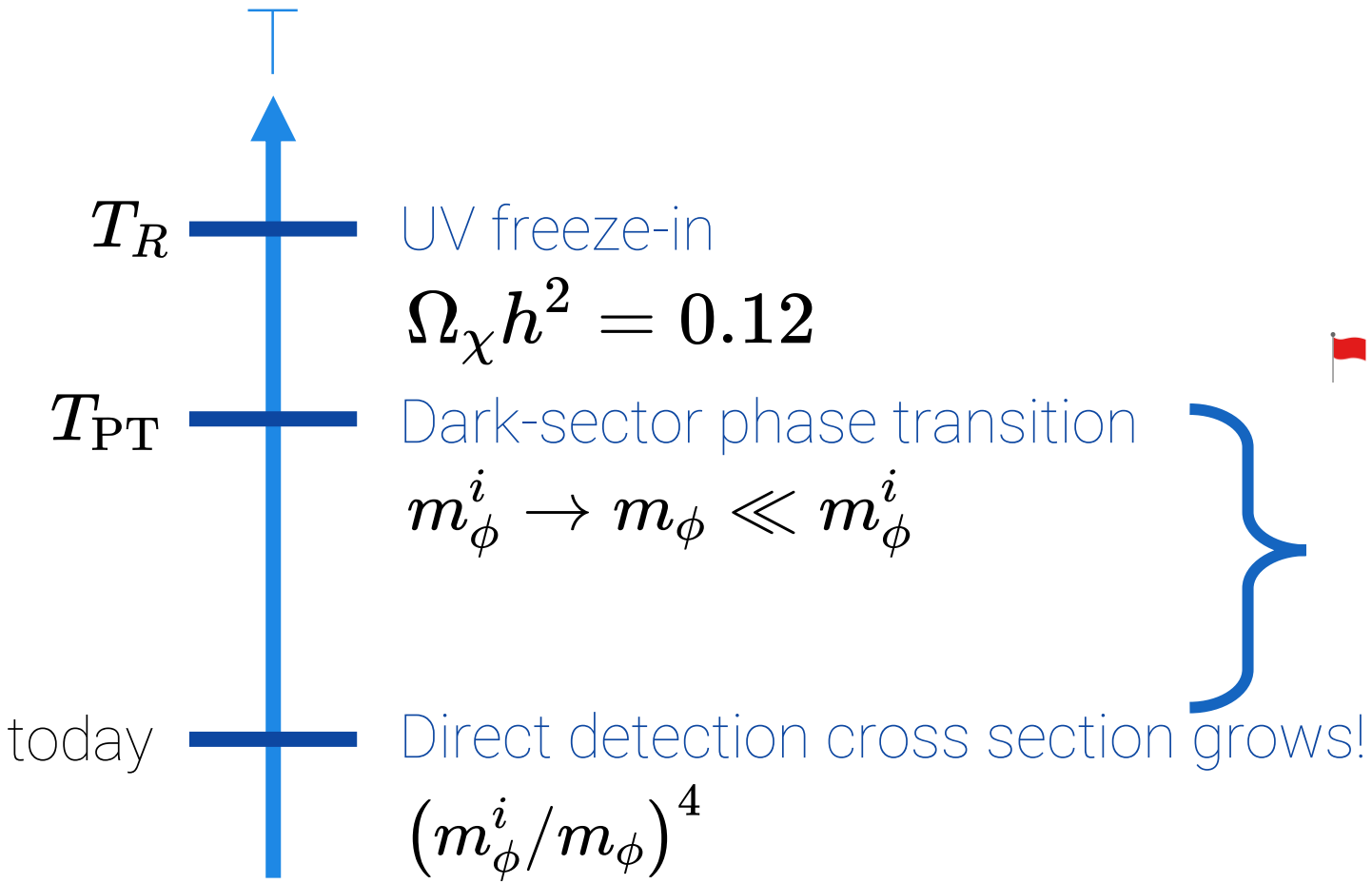
HYPER History



🚩What if this changes the relic abundance?

➢must prevent $\bar{\chi}\chi \to \phi\phi$

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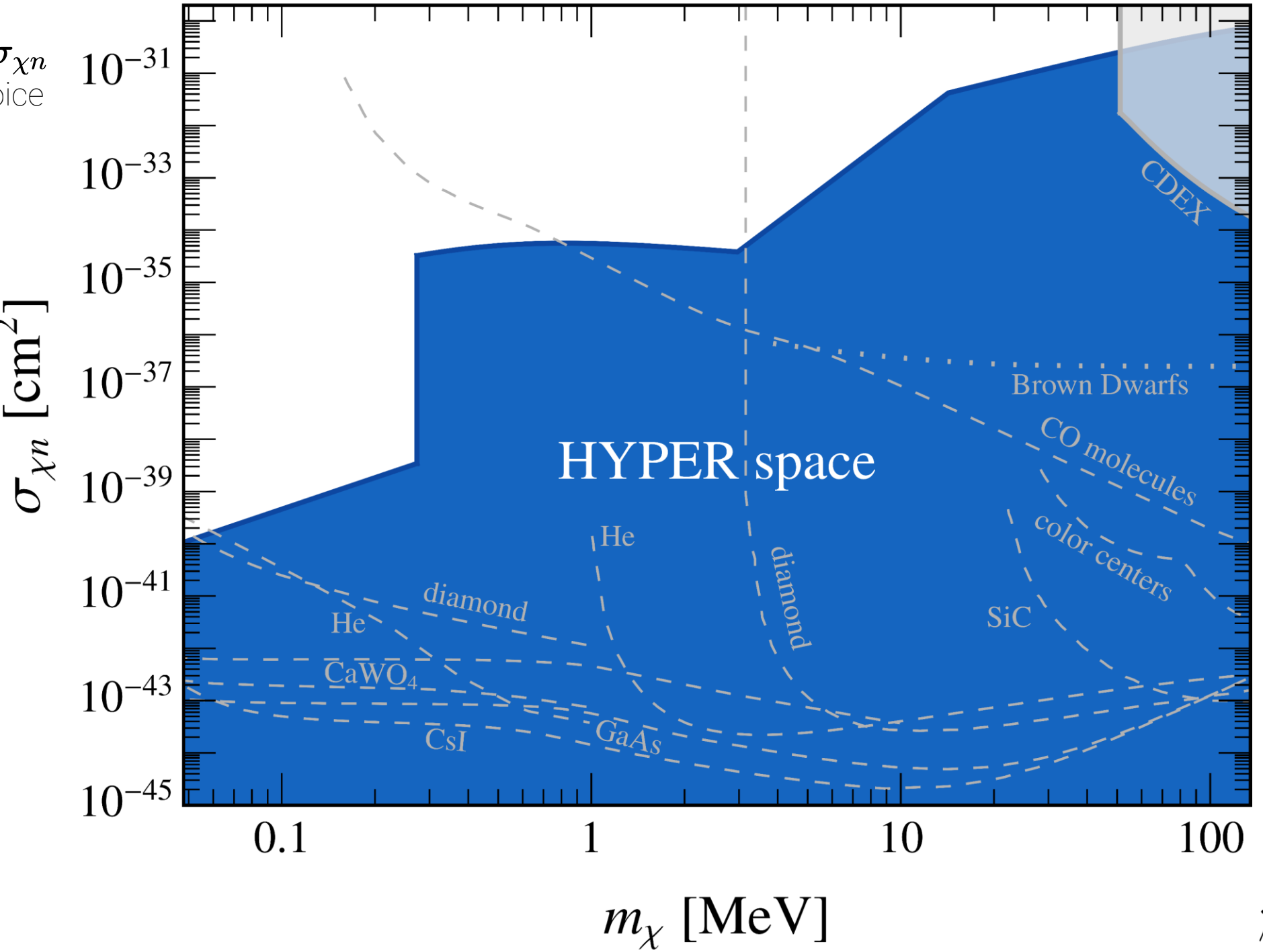
Boundary found by maximizing $\sigma_{\chi n}$ via judicious choice of (m_ϕ, y_χ)



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2) Freezing-in at low reheating temperatures

JHEP 01 (2023) 128 Prudhvi N. Bhattiprolu, Gilly Elor, RM, & Aaron Pierce

Low Reheating

$$5\ \mathrm{MeV} \lesssim T_R$$

BBN & CMB bounds

P.F. de Salas *et al* [1511.00672]

$$\mathcal{L}_{\phi FF} \sim \frac{17 y_n \alpha}{8\pi m_p} \phi F_{\mu\nu} F^{\mu\nu}$$

heavy mediator

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

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Low Reheating

$$5\ \mathrm{MeV} \lesssim T_R$$

BBN & CMB bounds

P.F. de Salas *et al* [1511.00672]

$$\mathcal{L}_{\phi FF} \sim \frac{17 y_n \alpha}{8\pi m_p} \phi F_{\mu\nu} F^{\mu\nu} \qquad \mathcal{L} \supset \frac{3y_n}{m_n}\phi\left(\frac{2}{3}\left|D^\mu \pi^+\right|^2 - m_\pi^2 \pi^+\pi^-\right)$$

heavy mediator

$$\gamma\gamma \to \bar{\chi}\chi \qquad \pi^+\pi^- \to \bar{\chi}\chi$$

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Low Reheating

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

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

reduce pion contribution to yield

$$\mathcal{L}_{\phi FF} \sim \frac{17 y_n \alpha}{8\pi m_p} \phi F_{\mu\nu} F^{\mu\nu}$$

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

heavy mediator

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

$$\pi^+\pi^- \to \bar{\chi}\chi$$

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Freezing-In @ Low Reheating

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

$$\hookrightarrow Y_{\rm DM} \propto \frac{M_{\rm Pl}\sigma_{\chi n} T_R^5}{\mu_{\chi n}^2 m_n^2}$$

R McGehee

Freezing-In @ Low Reheating

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

$$\hookrightarrow Y_{\rm DM} \propto \frac{M_{\rm Pl}\sigma_{\chi n}T_R^5}{\mu_{\chi n}^2 m_n^2}$$

Relic abundance predicts a simple cross section

$$\sigma_{\chi n} \approx 5.5 \times 10^{-44}\ {\rm cm}^2 \left(\frac{g_{s,*}\sqrt{g_*}}{10.76^{3/2}}\right)\left(\frac{m_\chi}{1\ {\rm MeV}}\right)\left(\frac{10\ {\rm MeV}}{T_{\rm R}}\right)^5$$

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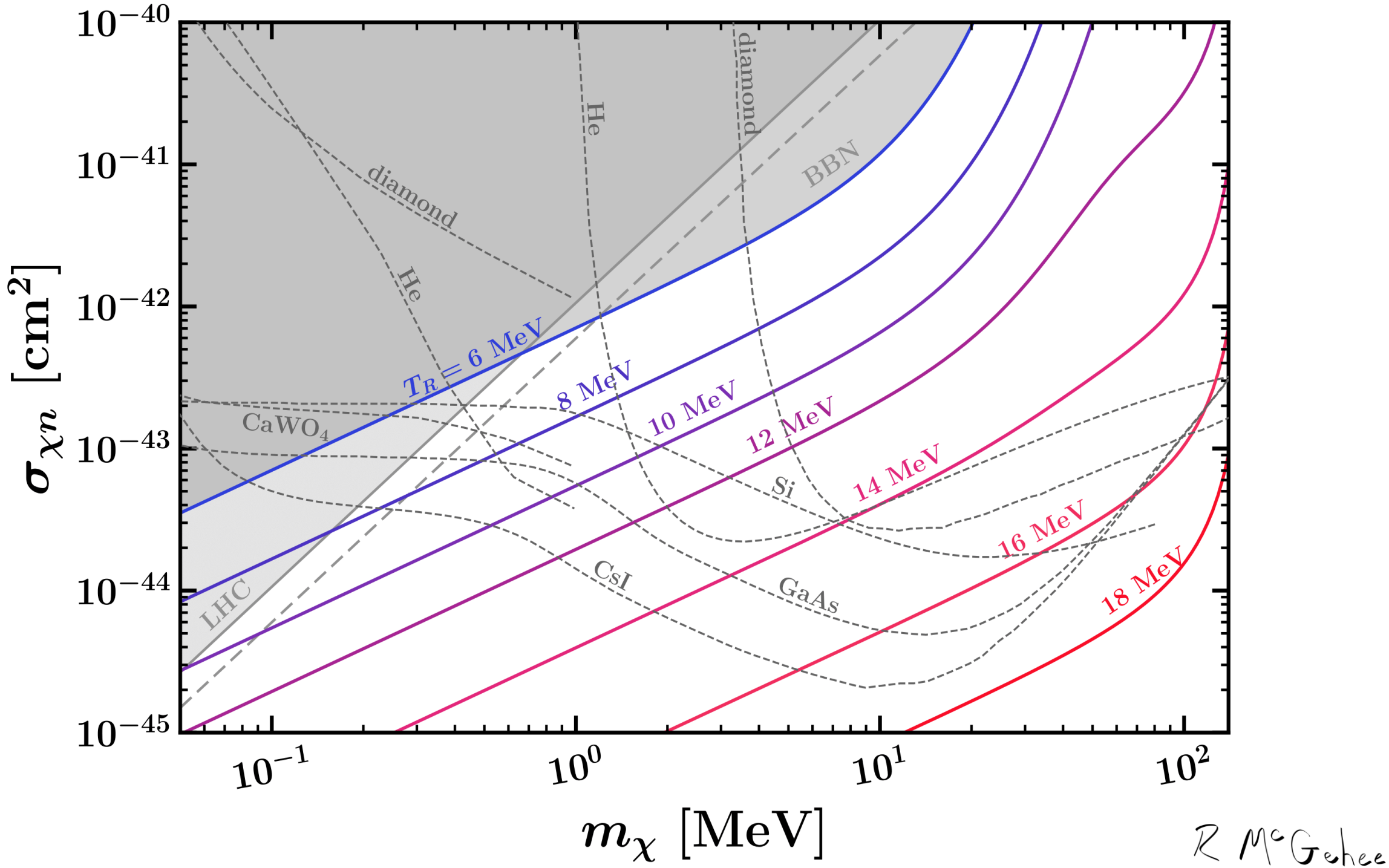
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
$\sigma_{\chi n}$ [cm^2]
10^{-1}
10^{0}
10^{1}
10^{2}
m_χ [MeV]
diamond
He
He
diamond
BBN
$T_R = 6$ MeV
8 MeV
10 MeV
12 MeV
14 MeV
16 MeV
18 MeV
$CaWO_4$
Si
CsI
GaAs
LHC

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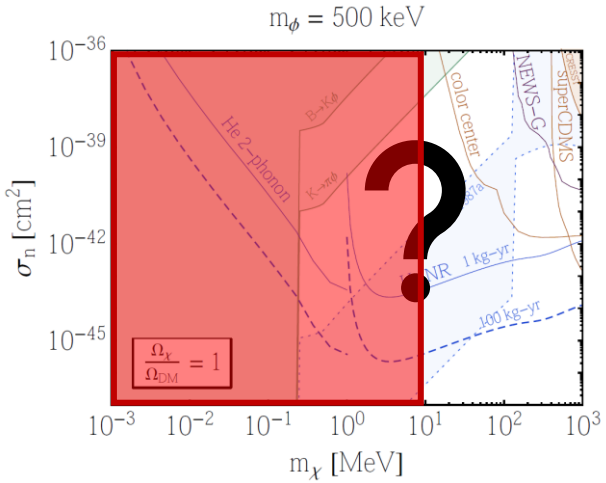
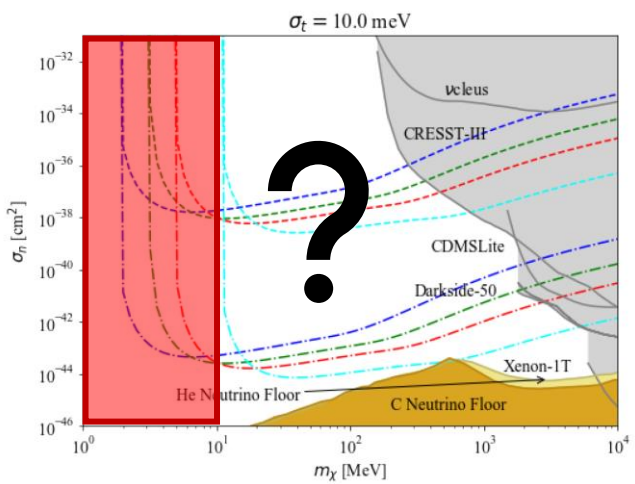
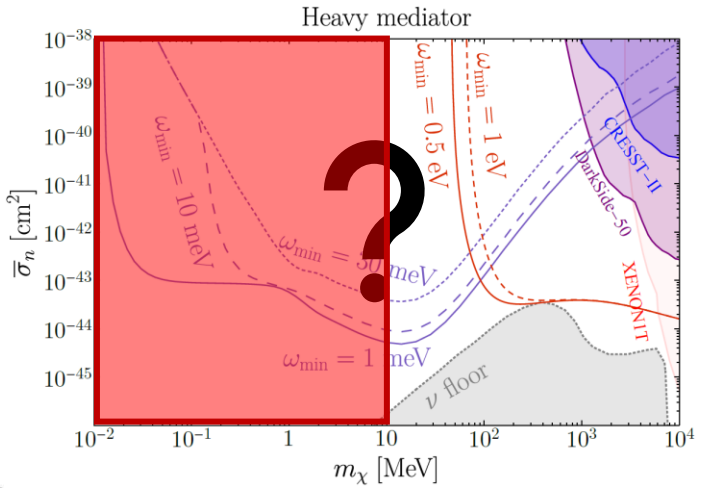
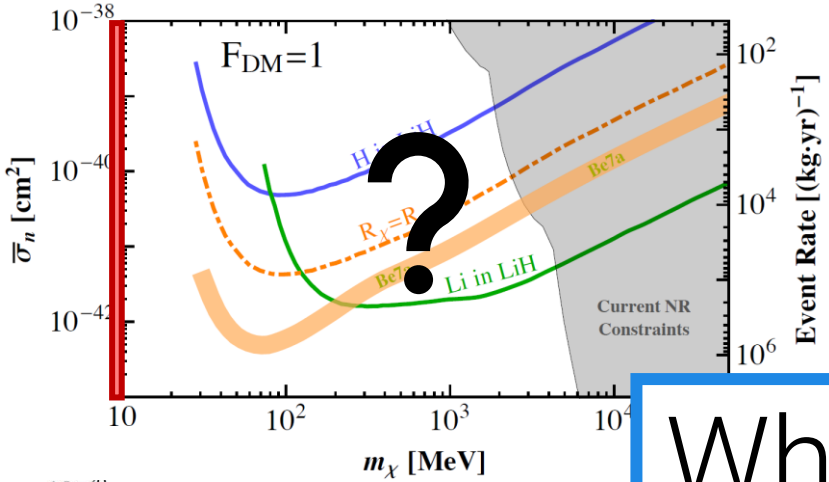
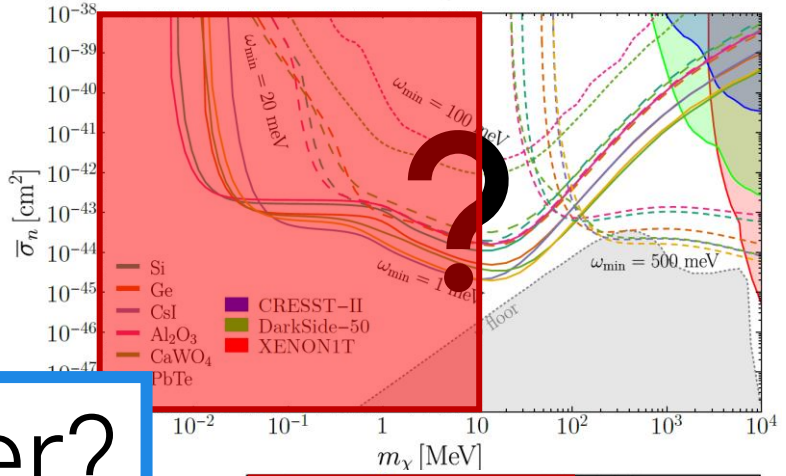


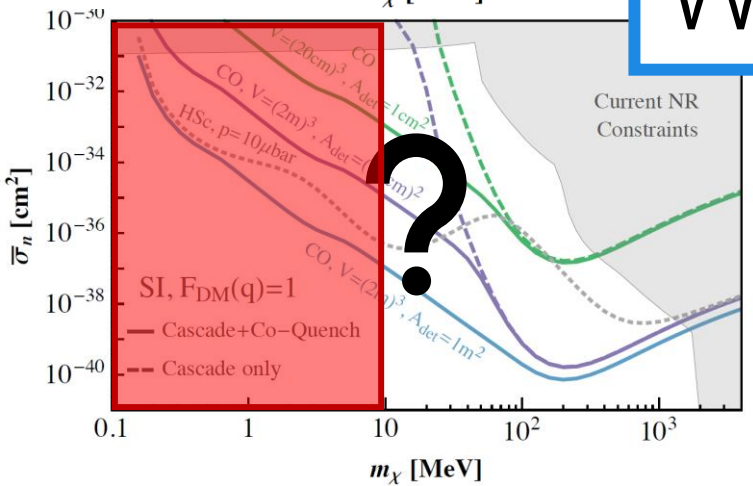


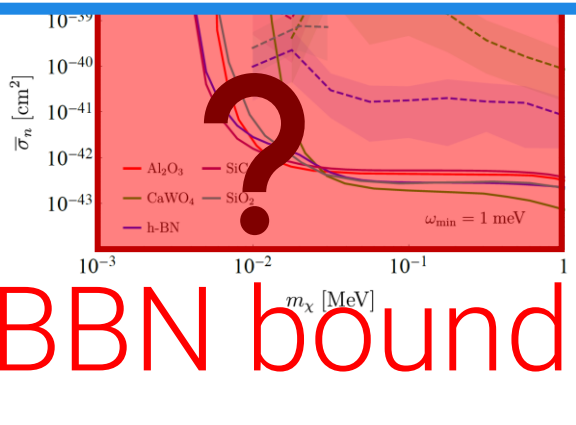




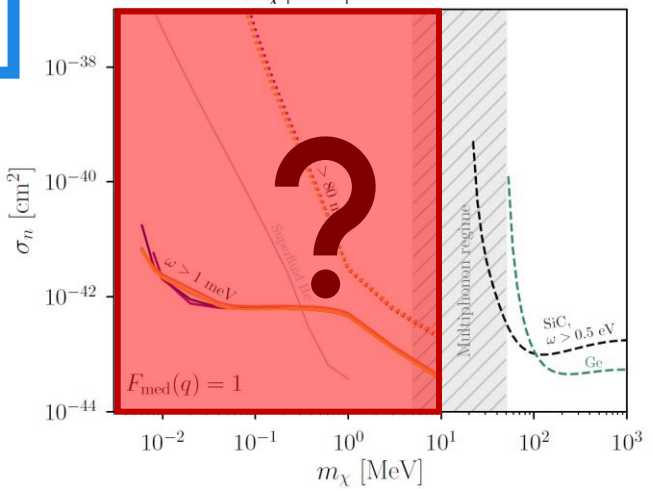


Where is Dark Matter?



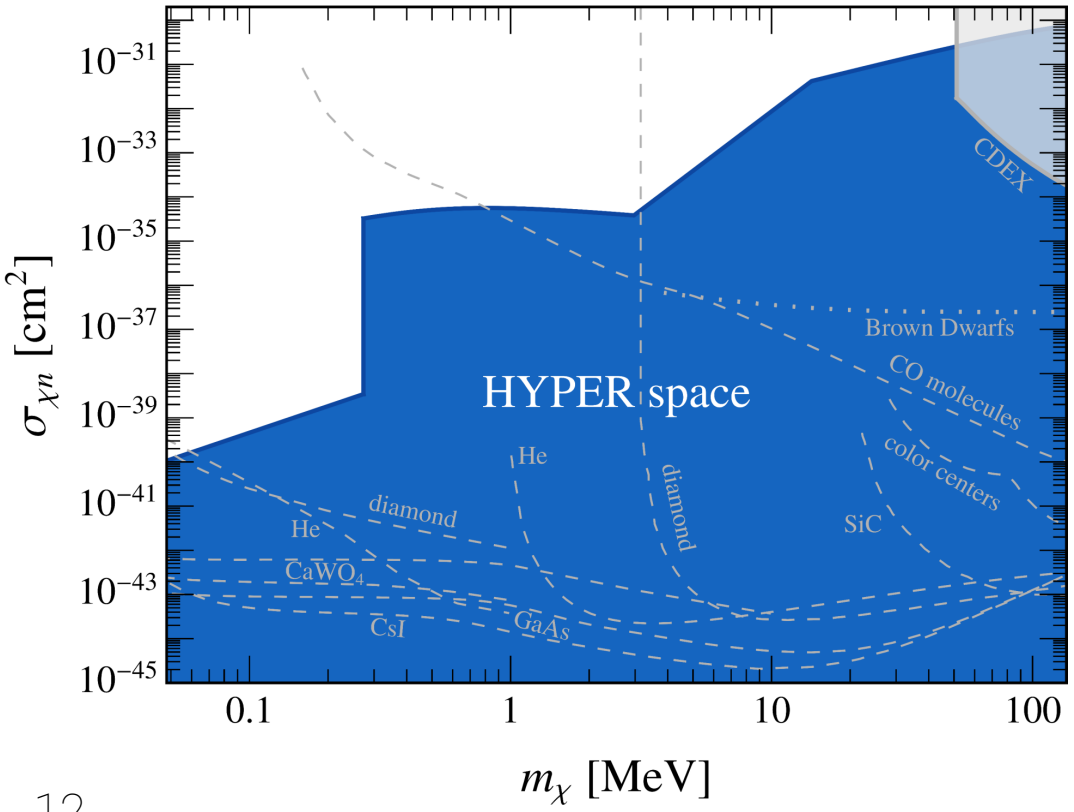


BBN bounds

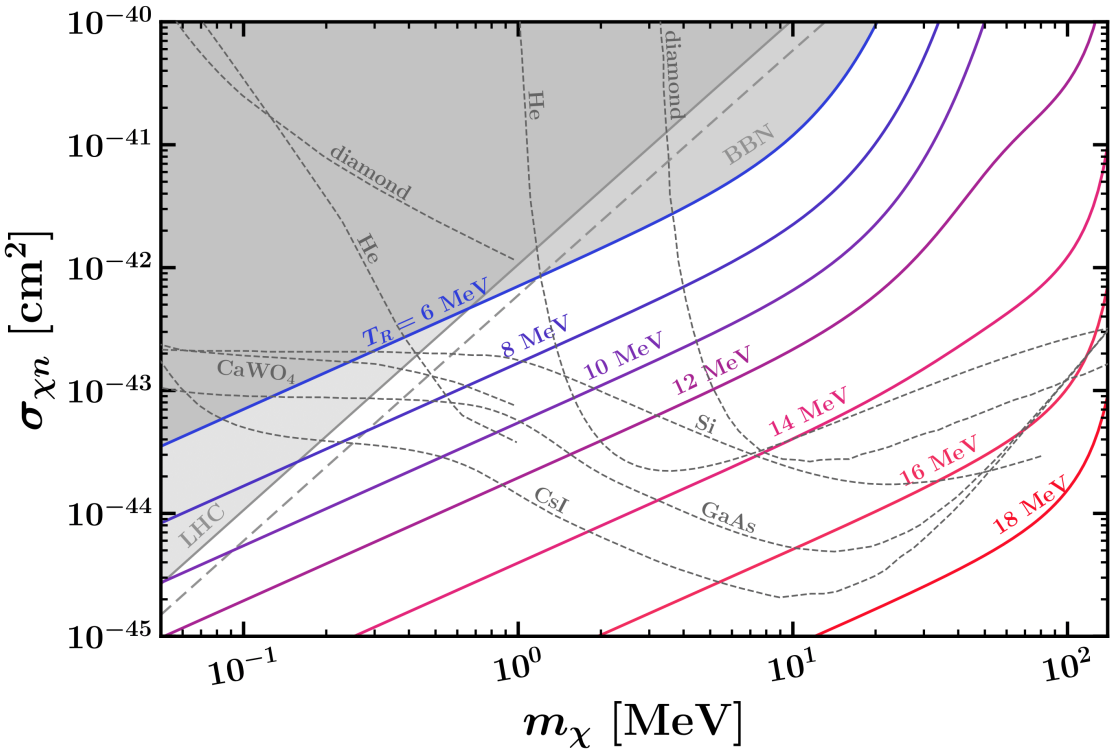


Two ways to get light, detectable DM

1) Dark phase transition at low temp. (HYPERs)



2) Freezing-in at low reheating temperatures



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Two ways to get light, detectable DM

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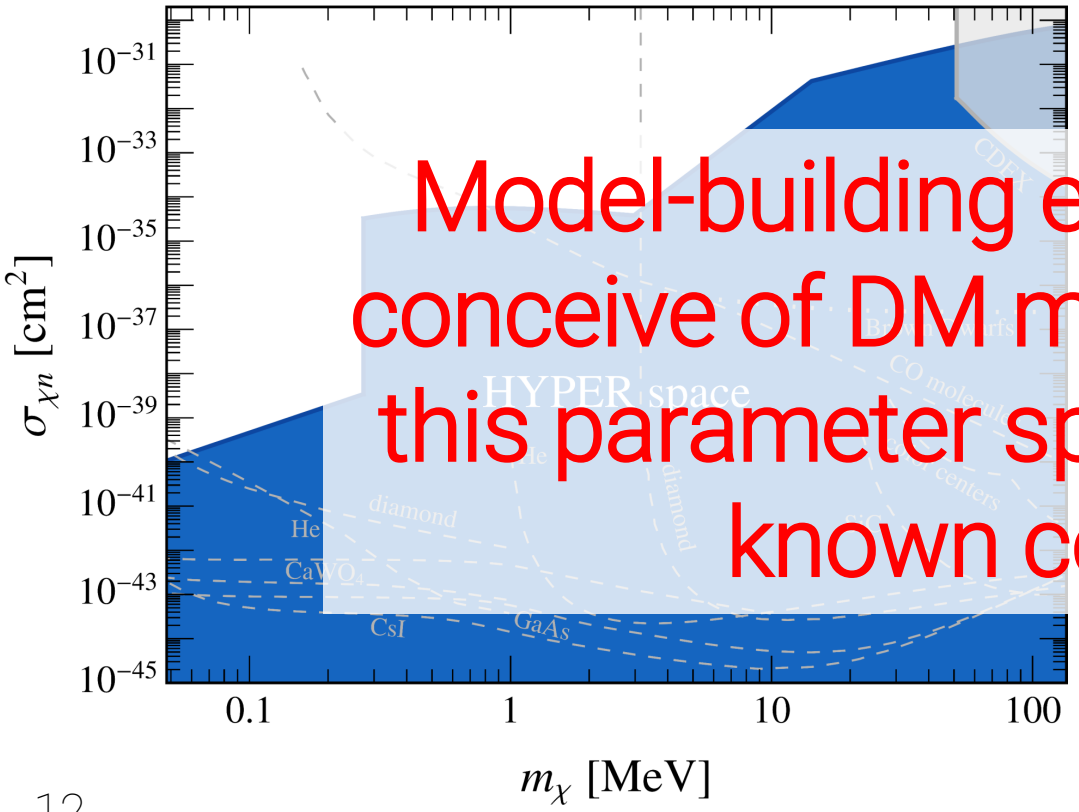
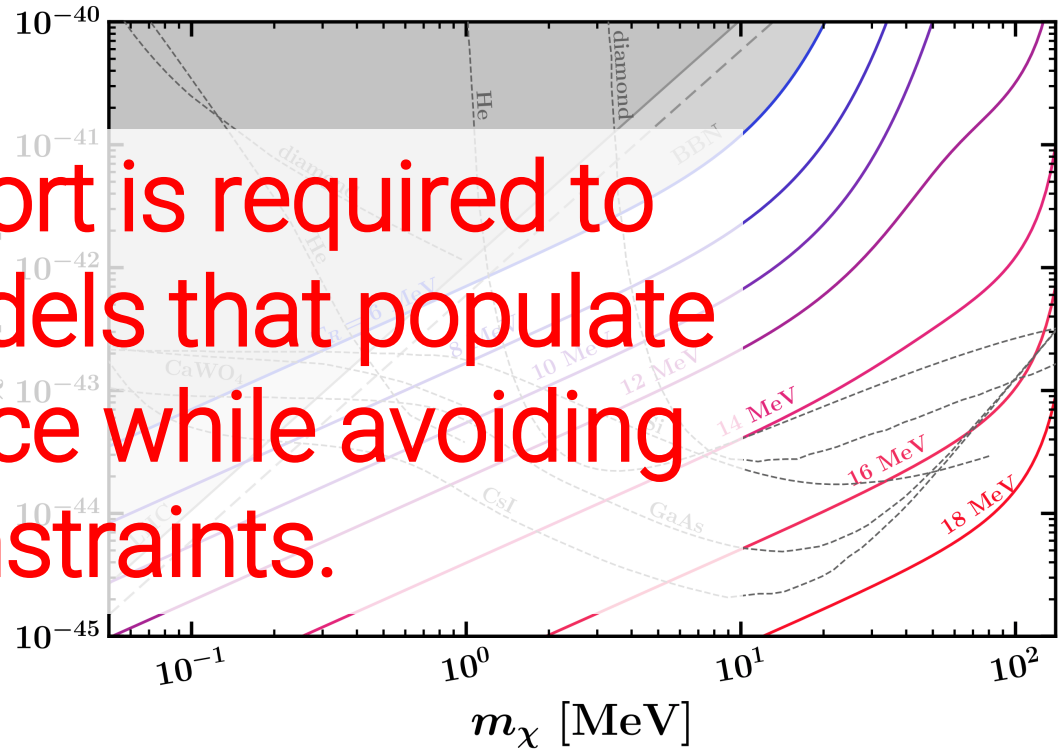


2) Freezing-in at low reheating temperatures



Model-building effort is required to conceive of DM models that populate this parameter space while avoiding known constraints.

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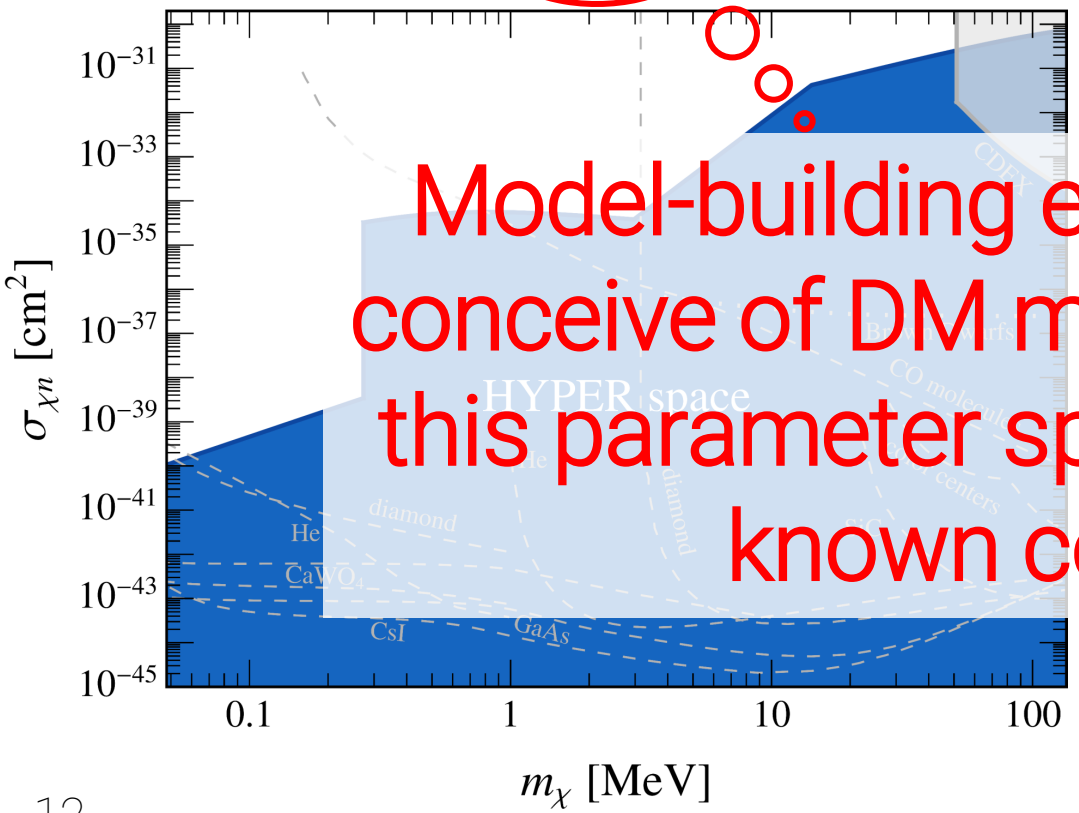
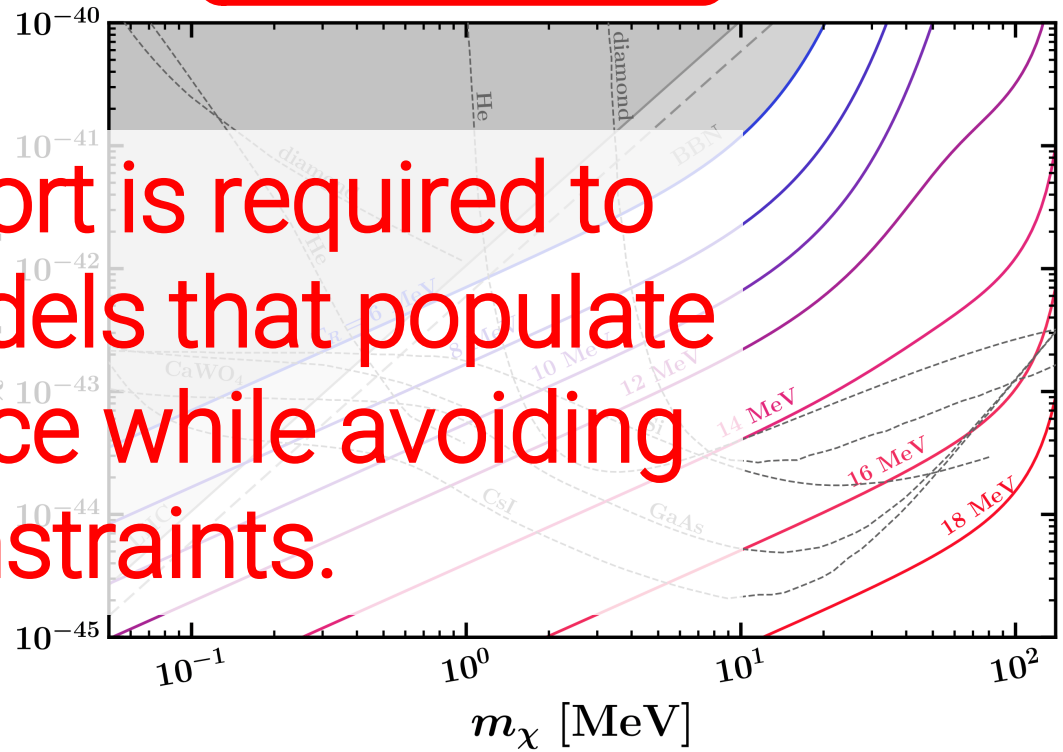
Two ways to get light, detectable DM

A word of caution...

A call to action!





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