Direct Detection of sub-GeV Hadrophilic Dark Matter

Robert McGehee

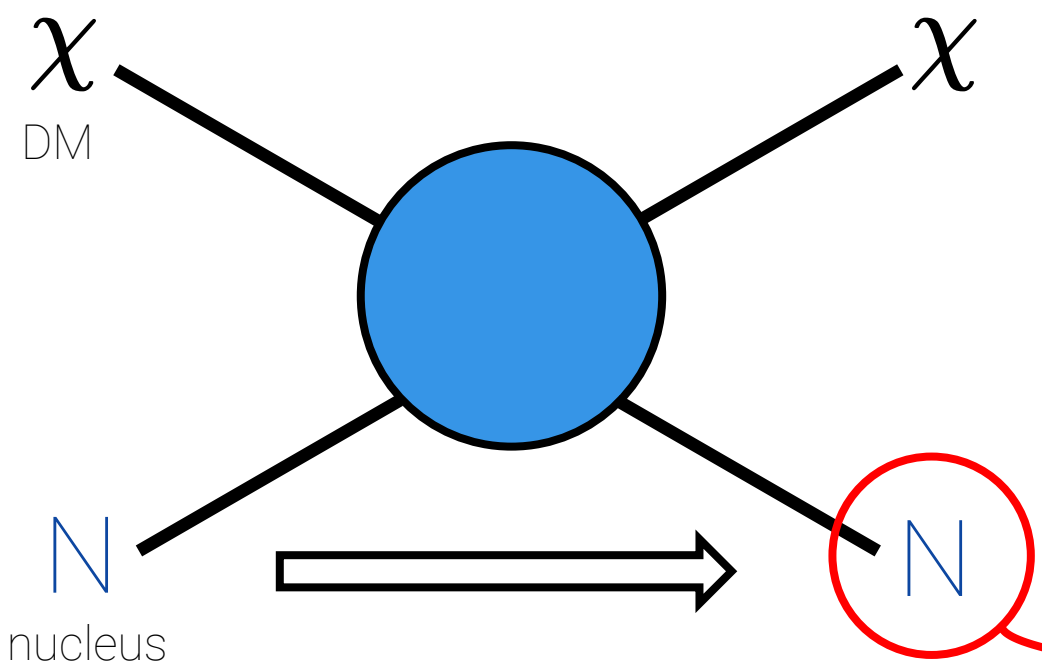
UNIVERSITY OF MICHIGAN

U.S. DEPARTMENT OF ENERGY | Office of Science

2112.03920 w/ Gilly Elor & Aaron Pierce
2210.15653 + Prudhvi N. Bhattiprolu

Dark Interactions, 11/14/22

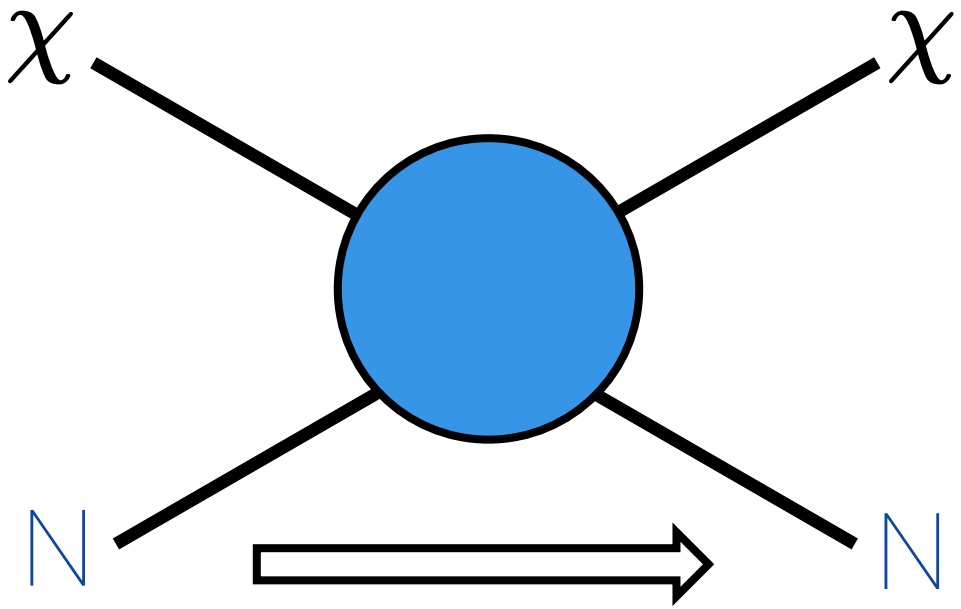
Direct Detection Refresher

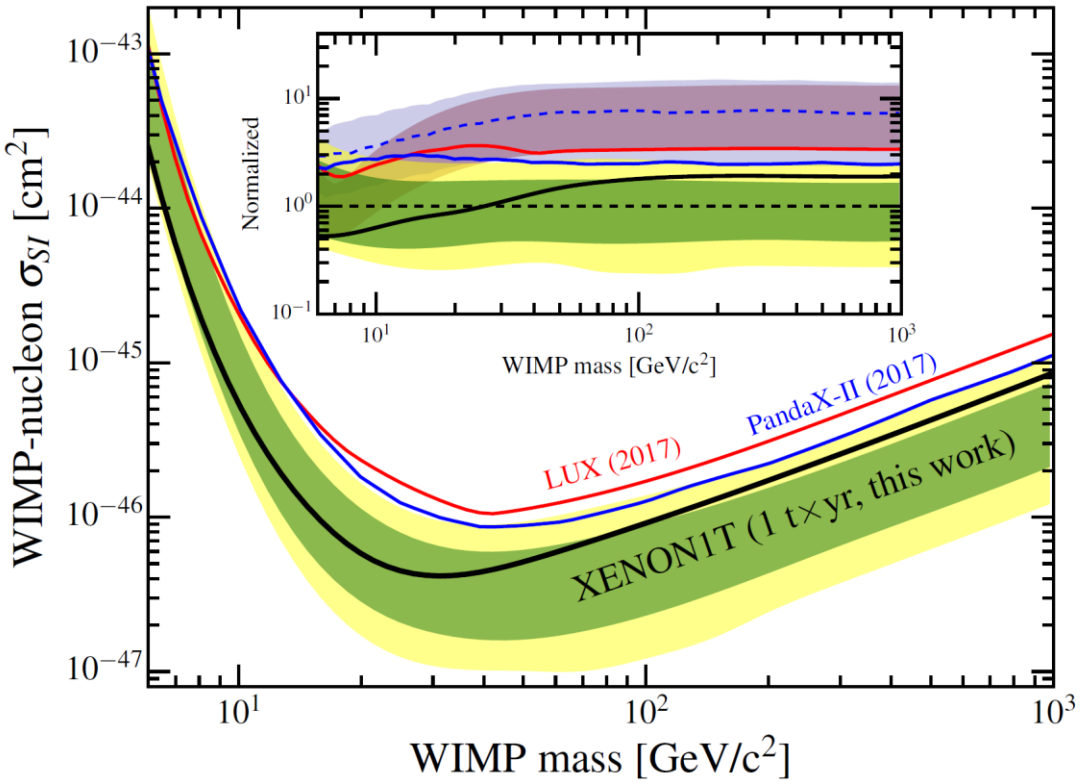


Credit: The XENON Experiment

R McGehee

Direct Detection Refresher



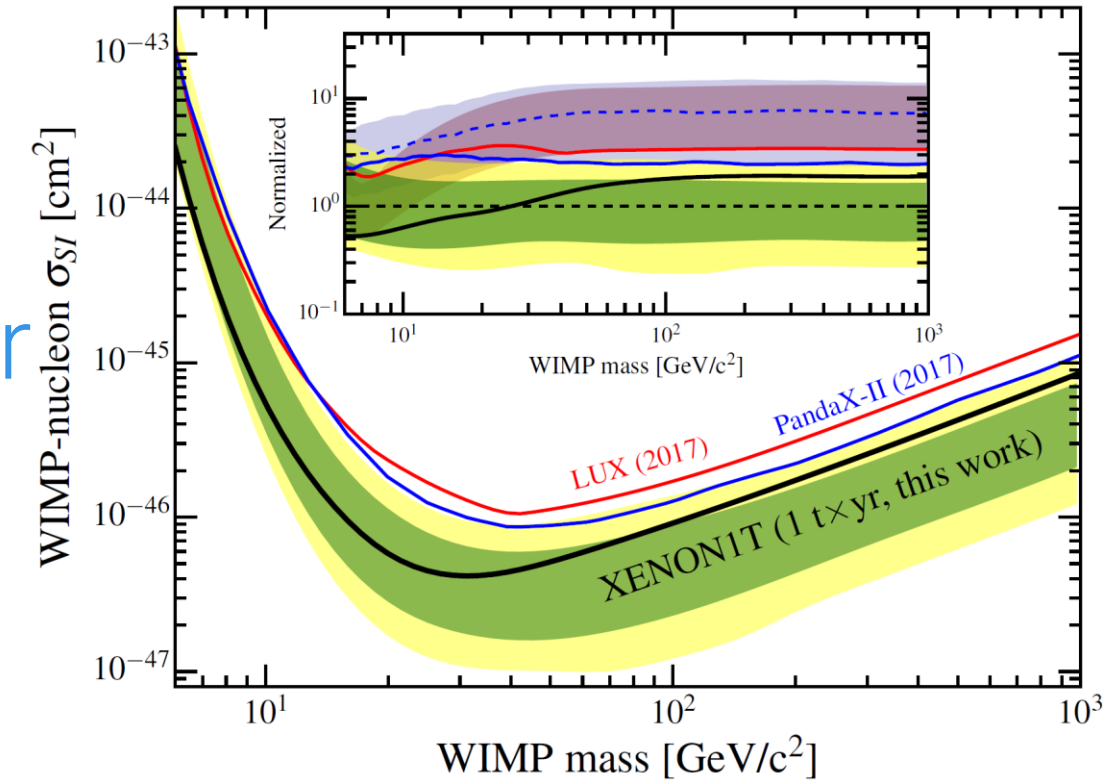


XENON Collaboration [1805.12562]

R McGehee

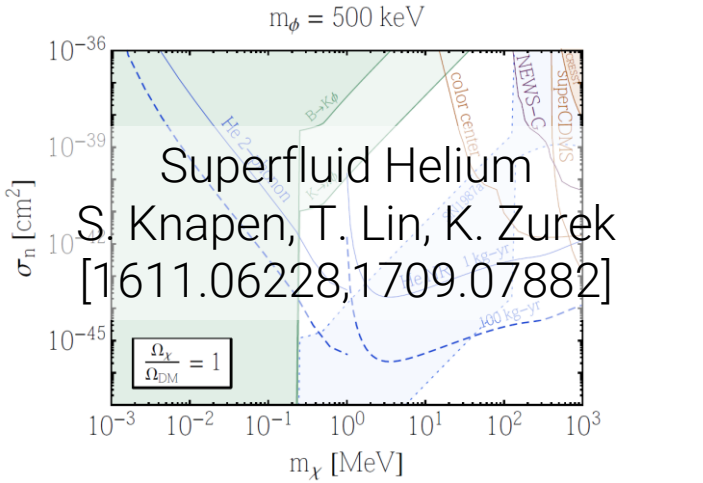
Direct Detection Future

Go lighter

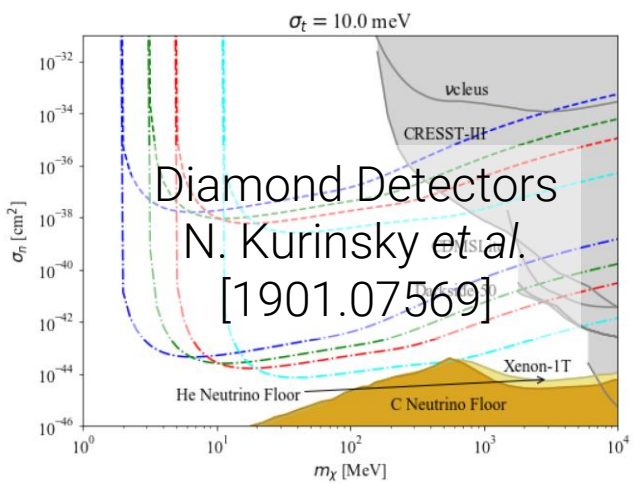


Go lower

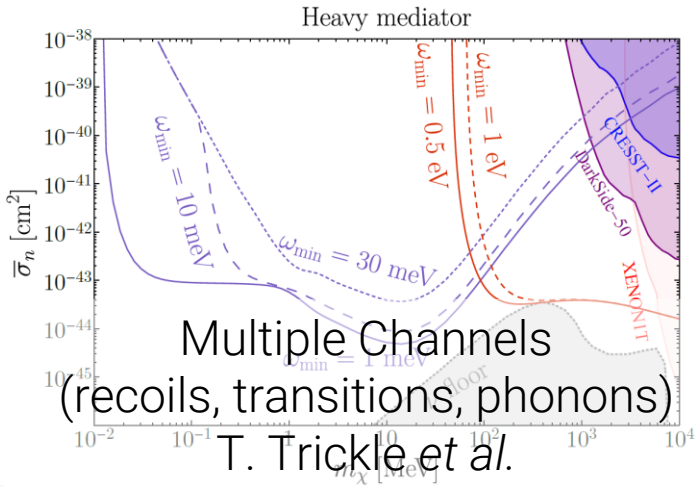
R McGehee



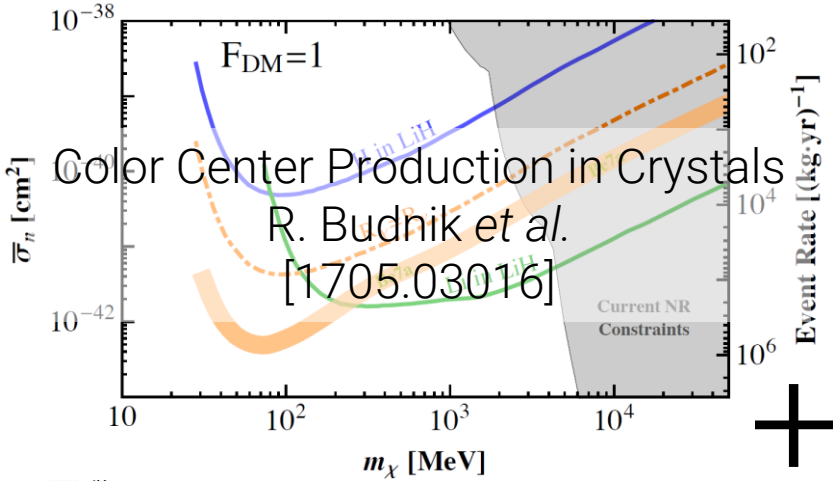
Superfluid Helium
S. Knapen, T. Lin, K. Zurek
[1611.06228,1709.07882]



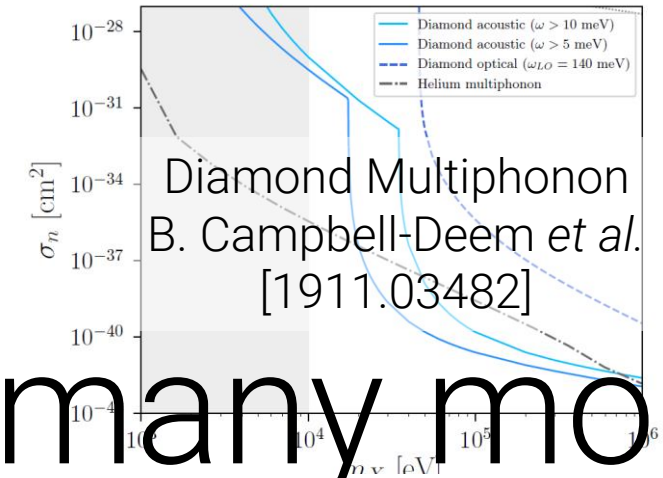
Diamond Detectors
N. Kurinsky *et al.*
[1901.07569]



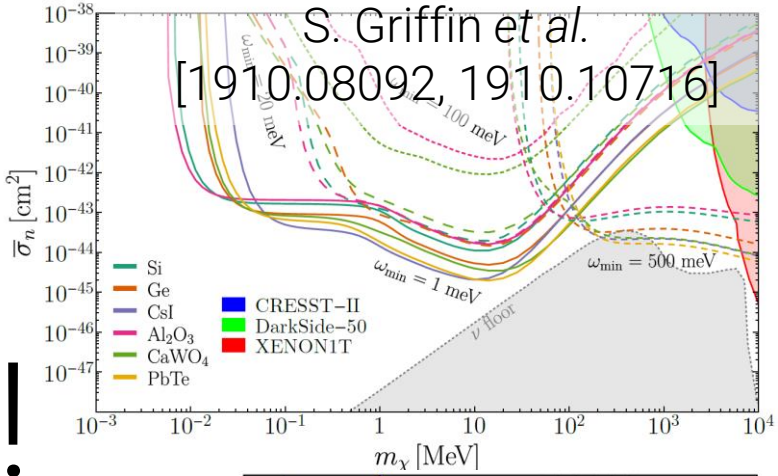
Multiple Channels
(recoils, transitions, phonons)
T. Trickle *et al.*
S. Griffin *et al.*
[1910.08092, 1910.10716]



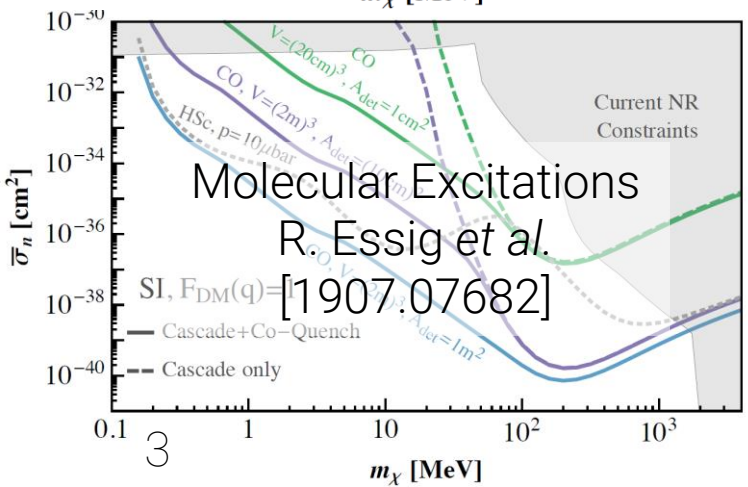
Color Center Production in Crystals
R. Budnik *et al.*
[1705.03016]



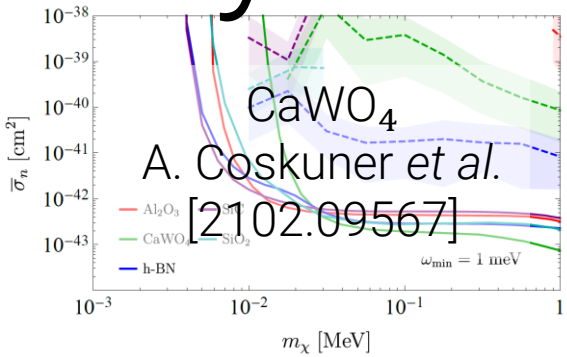
Diamond Multiphonon
B. Campbell-Deem *et al.*
[1911.03482]



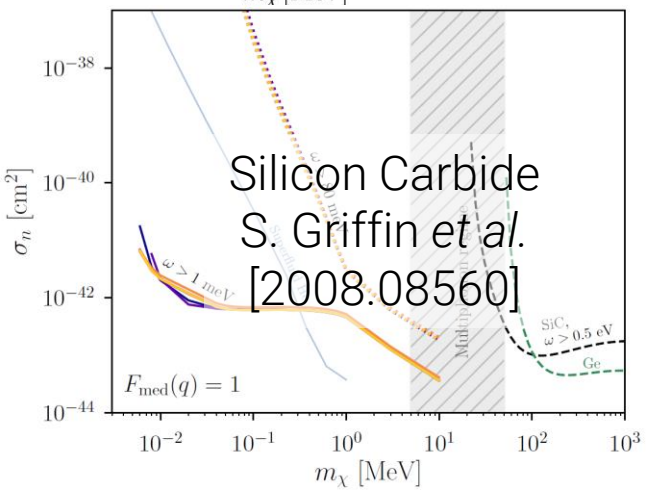
+ many more!



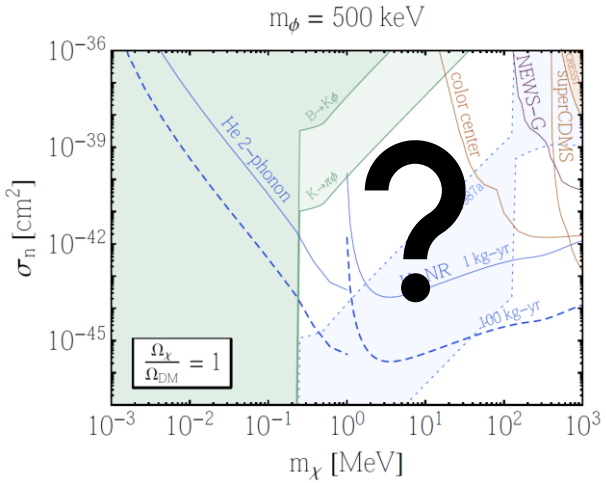
Molecular Excitations
R. Essig *et al.*
[1907.07682]

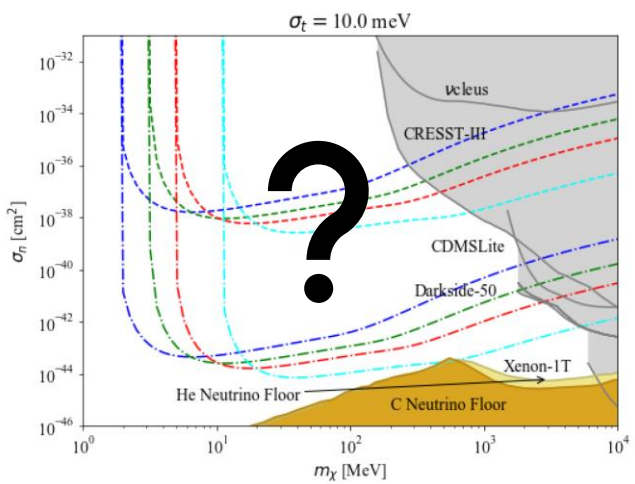


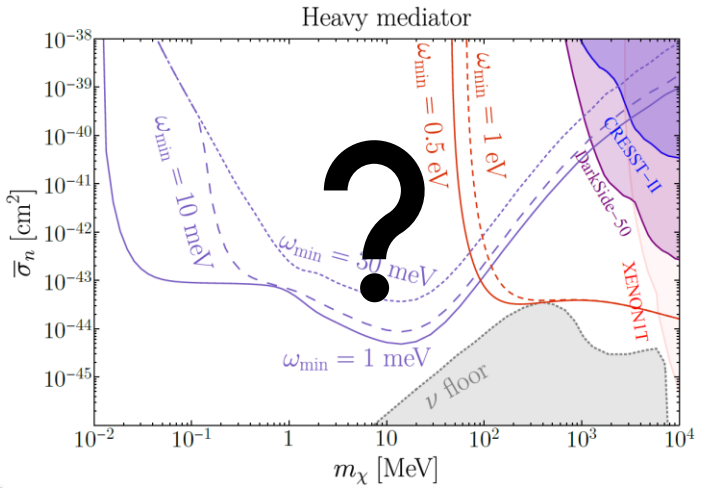
$CaWO_4$
A. Coskuner *et al.*
[2102.09567]

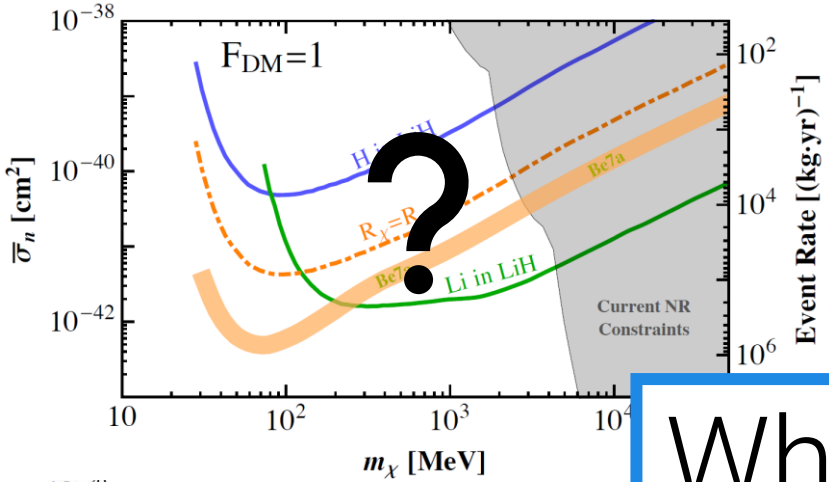


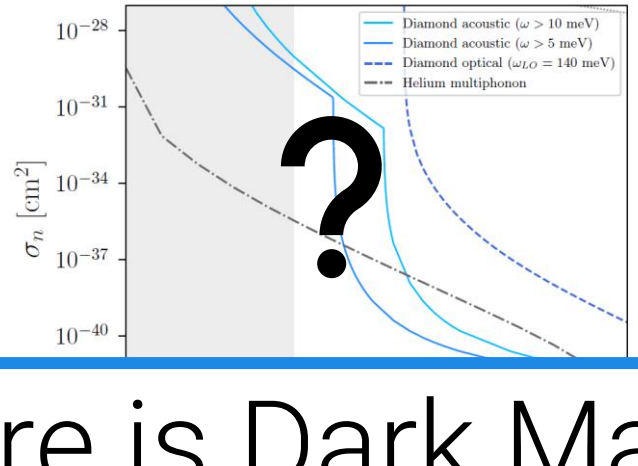
Silicon Carbide
S. Griffin *et al.*
[2008.08560]

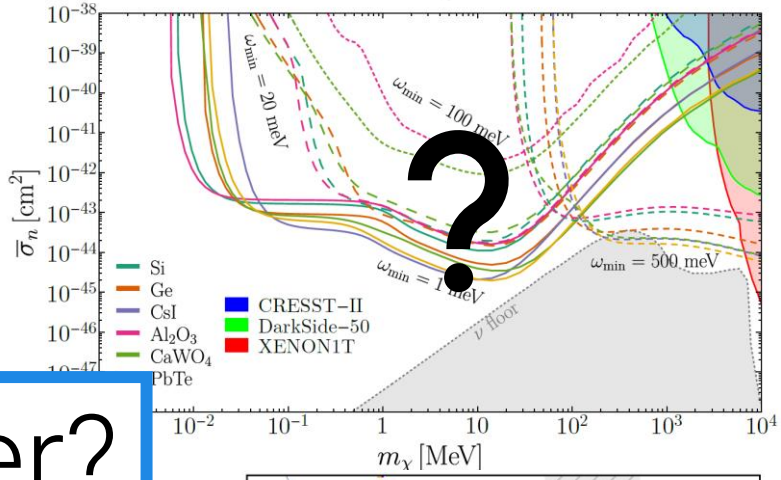




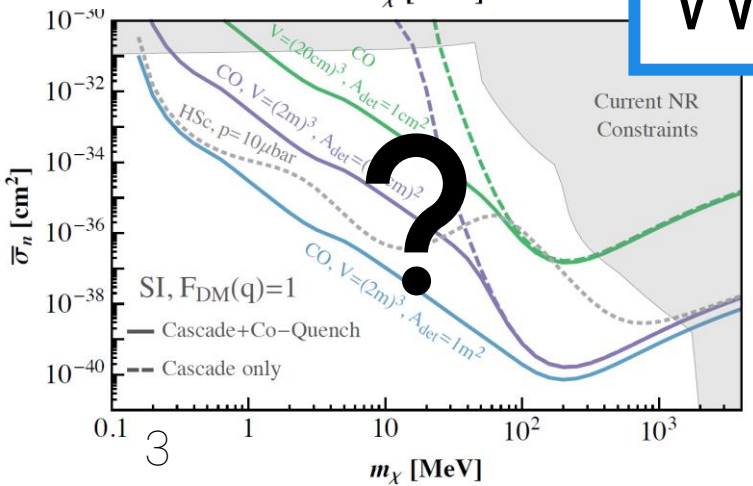


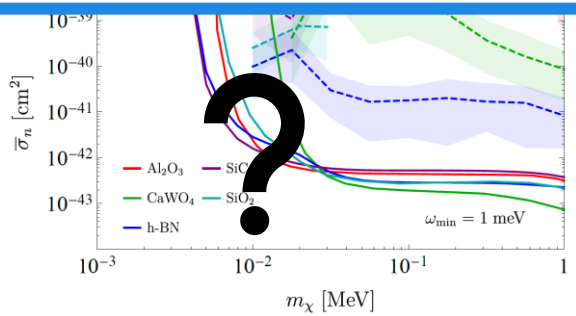


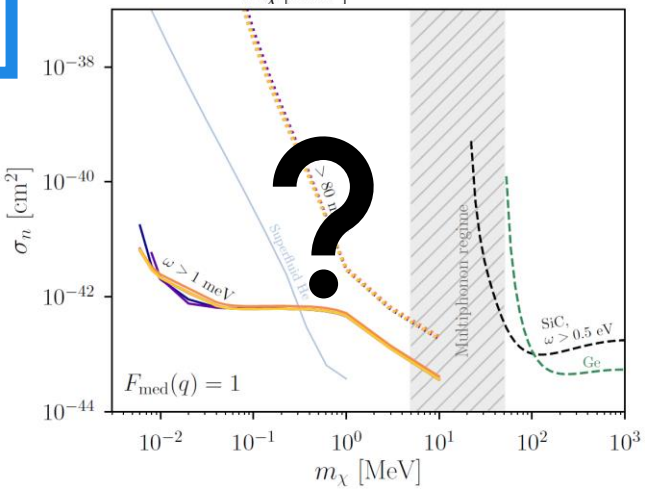




Where is Dark Matter?







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

R McGehee

The Basics

UV Freeze-In

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

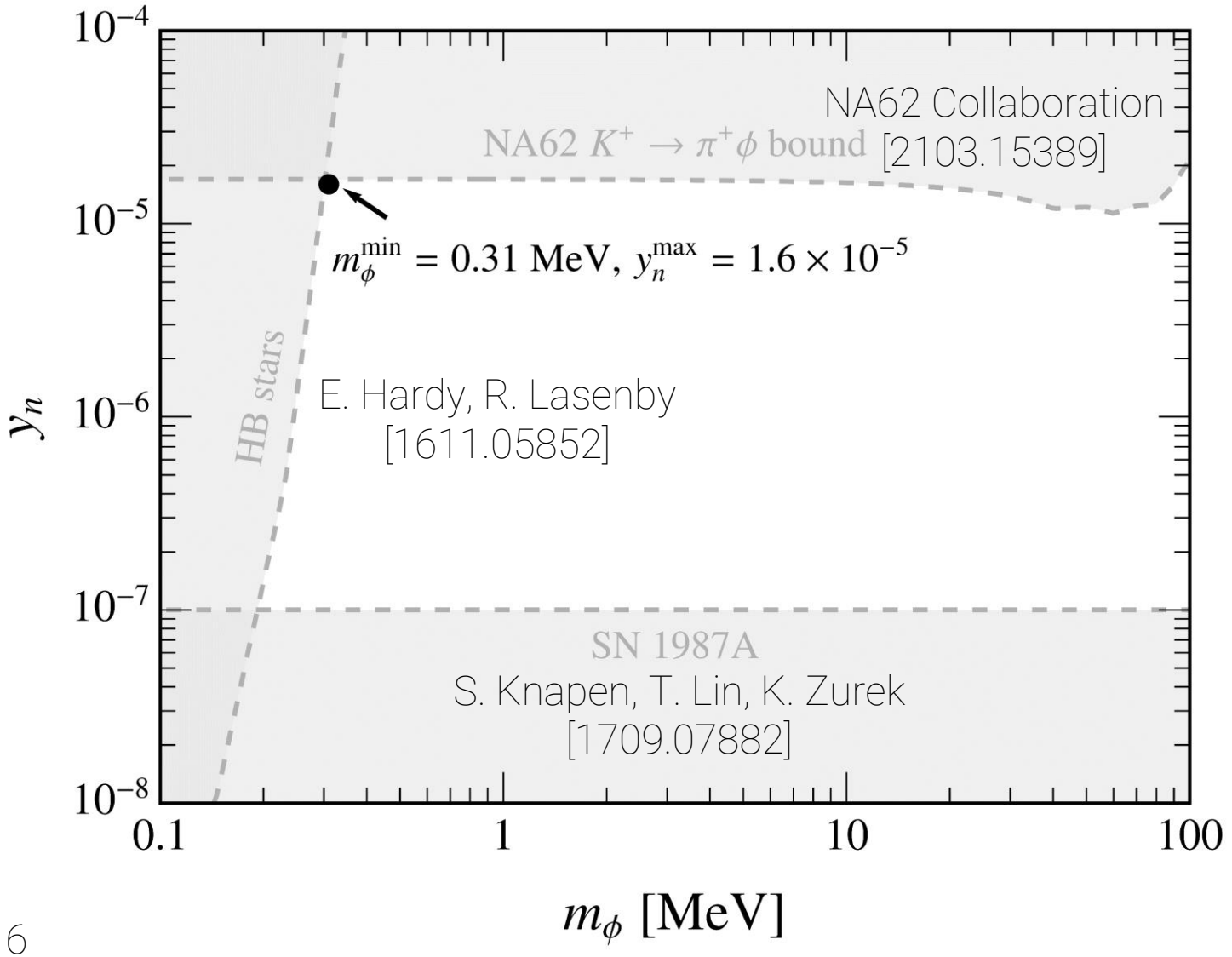
$$\sigma_{\chi n} = \frac{(y_n y_\chi)^2}{\pi} \frac{\mu_{\chi n}^2}{m_\phi^4}$$

R McGehee

1) HighlY interactive ParticlE Relics (HYPERs)

2112.03920 Gilly Elor, RM, & Aaron Pierce

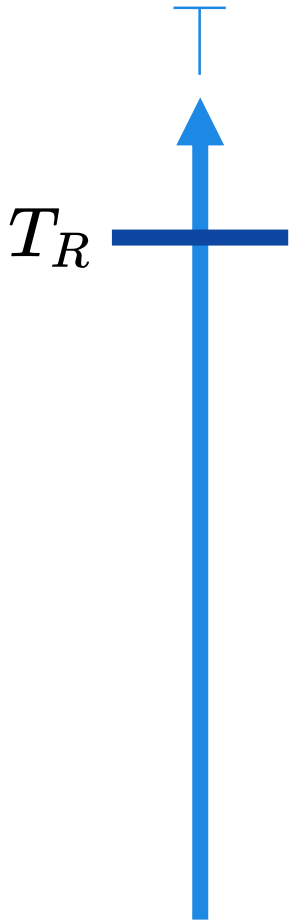
Constraints for HYPERs



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

R McGehee

HYPER History

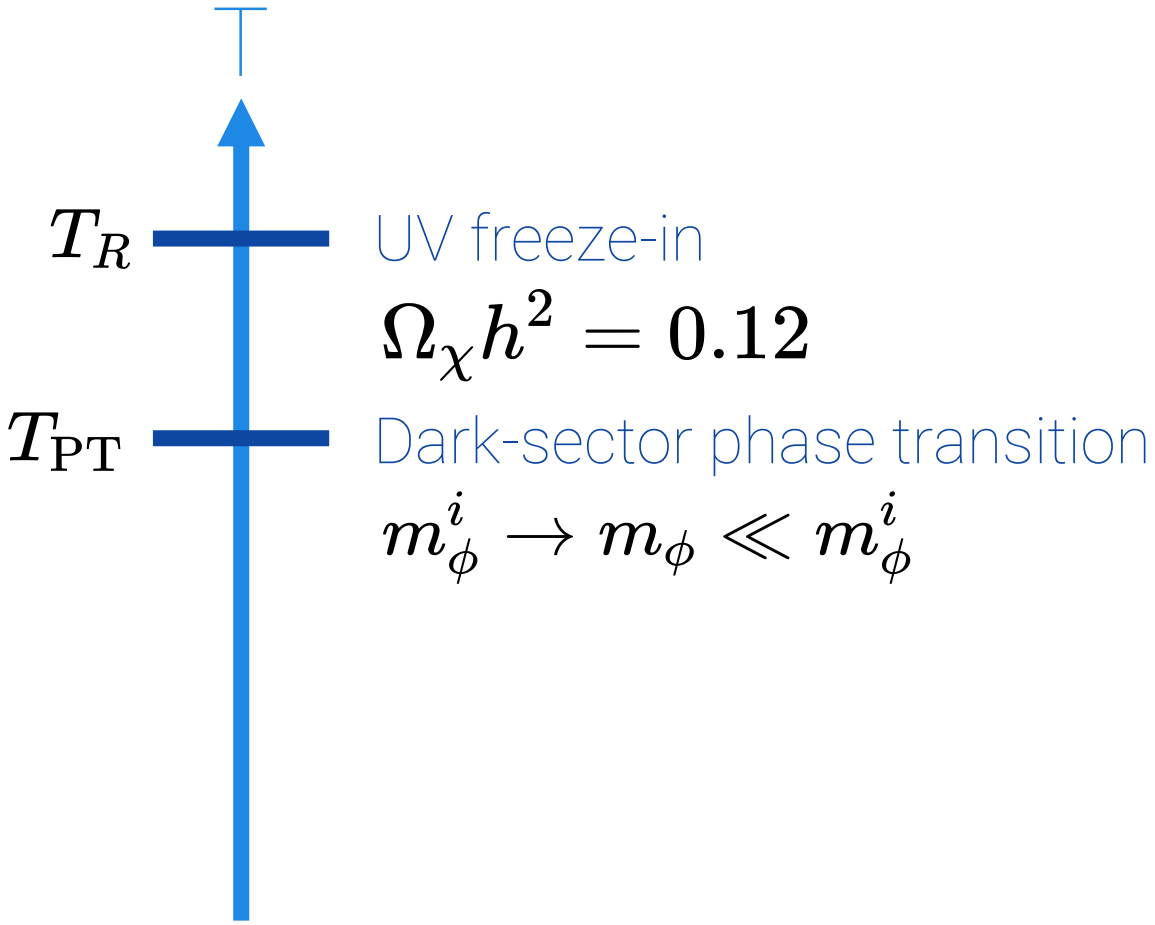


UV freeze-in → relic abundance set early and depends on T_R and m_ϕ^i

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

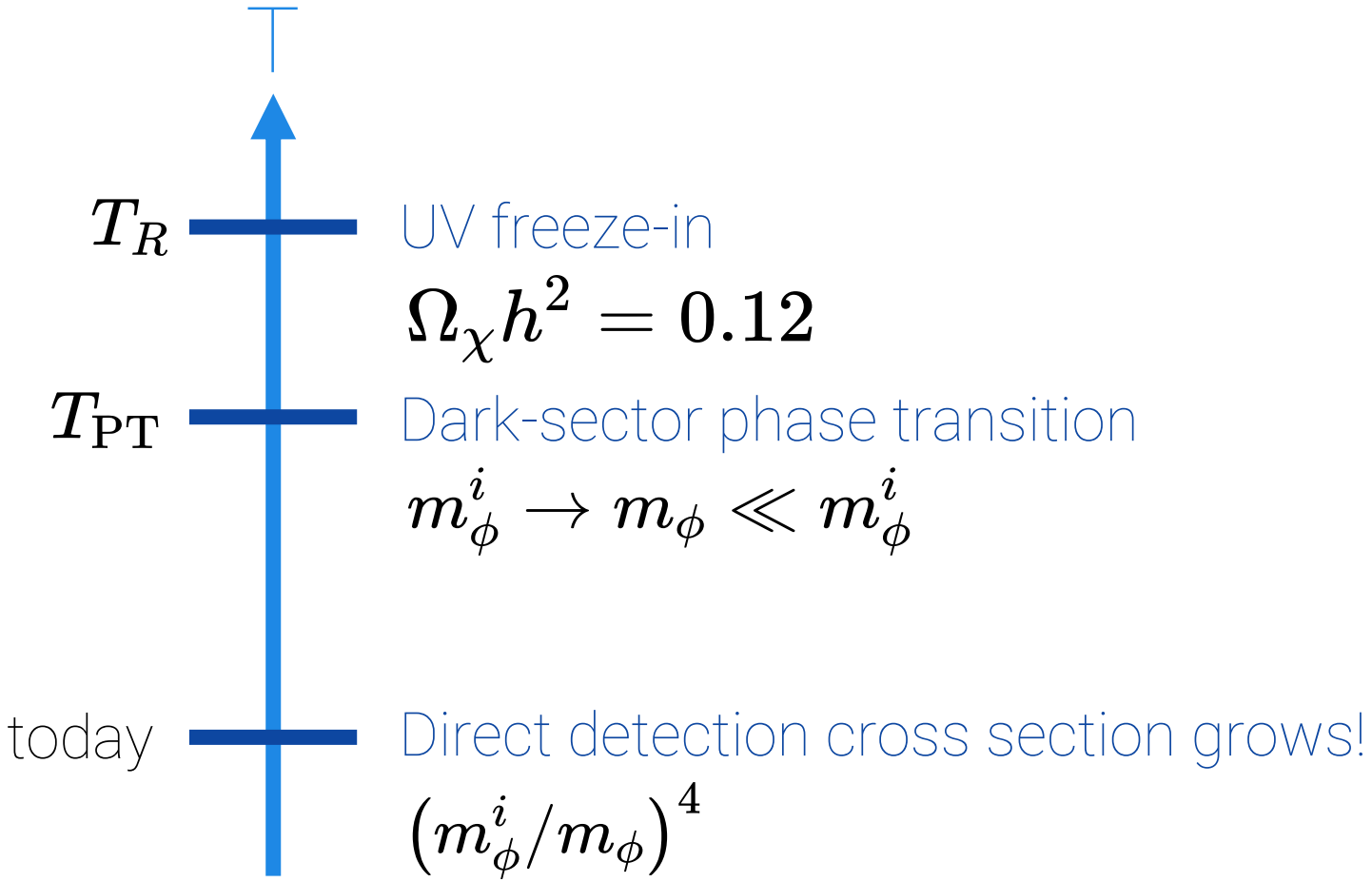
R McGehee

HYPER History



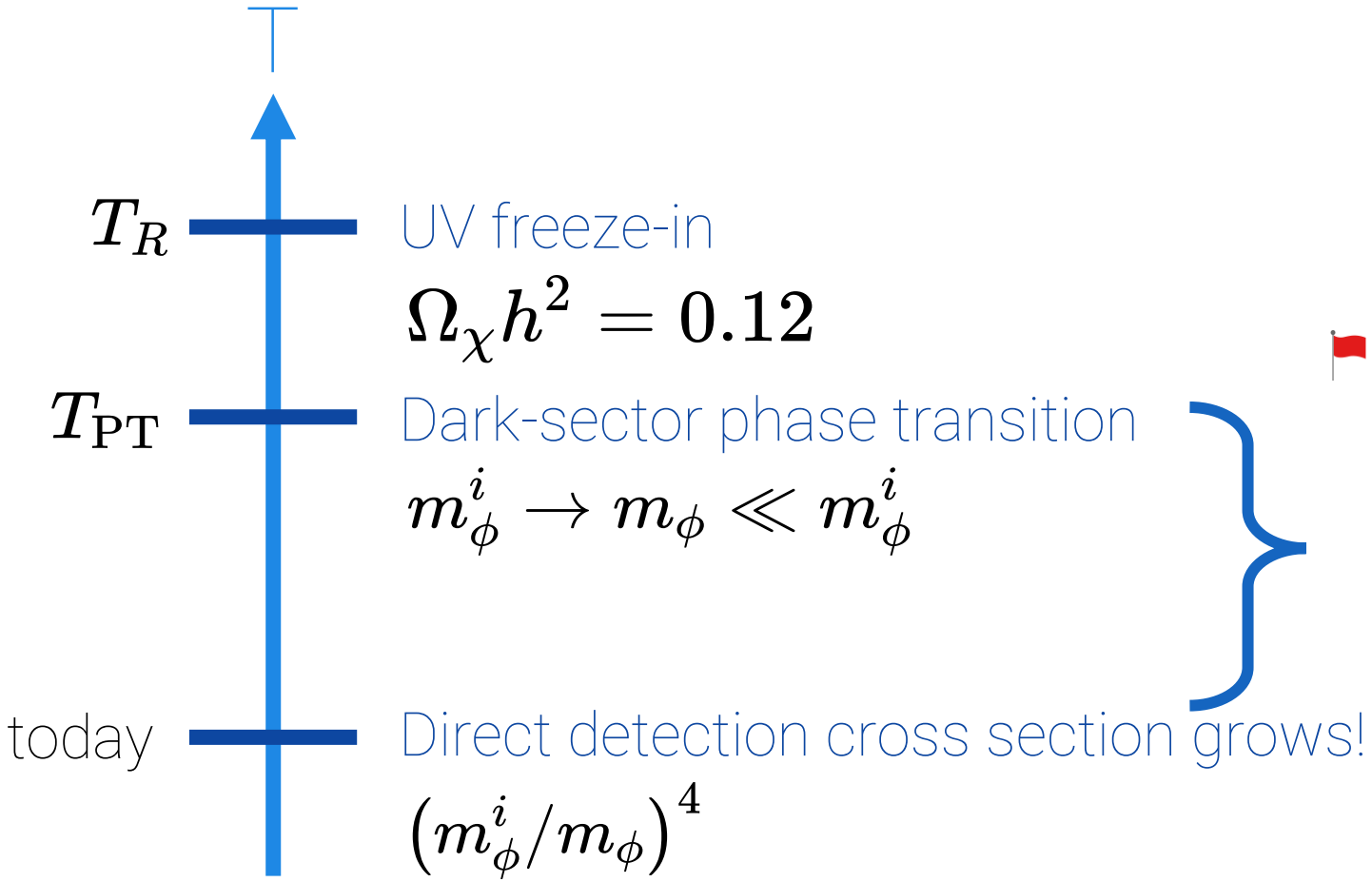
R McGehee

HYPER History



R McGehee

HYPER History

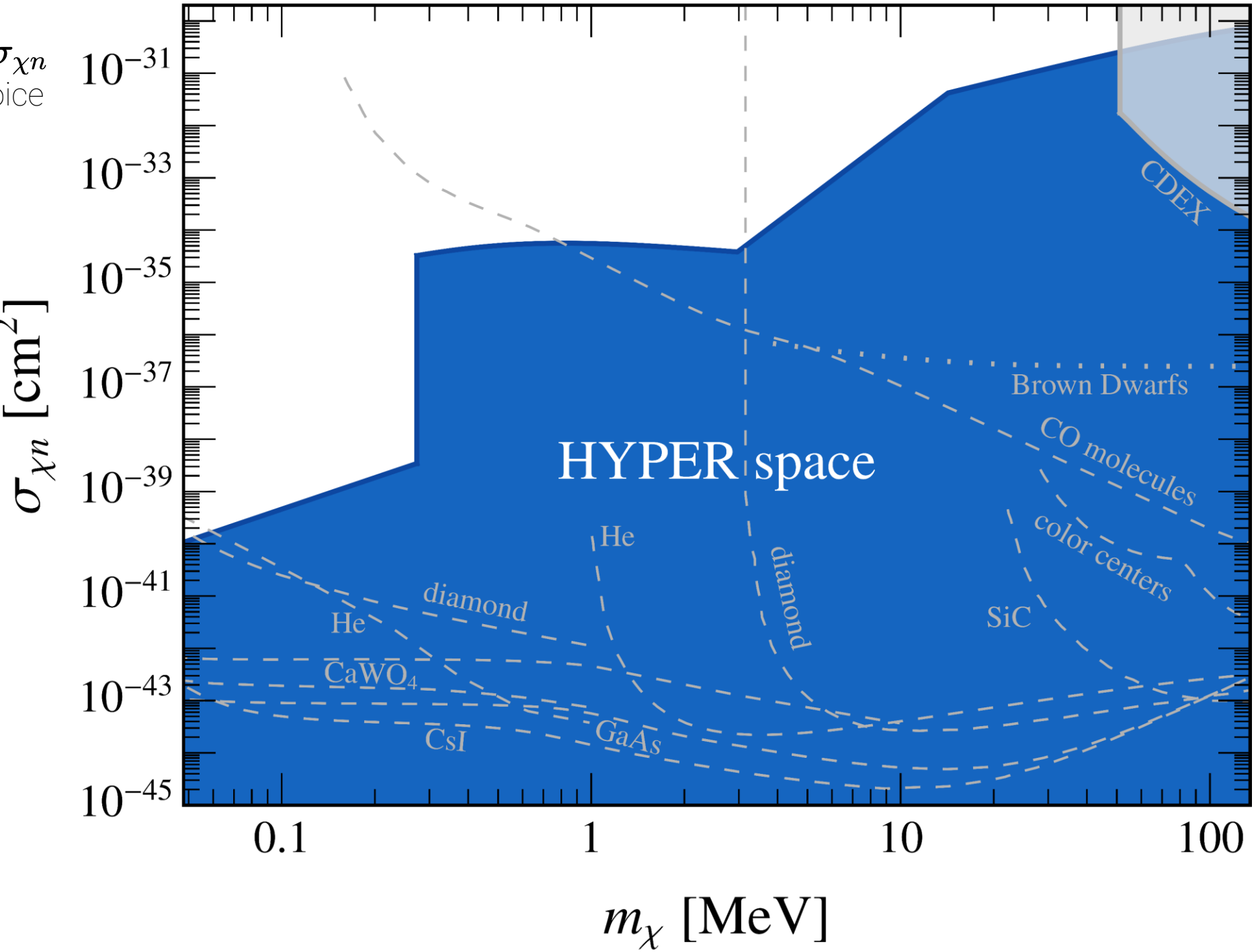


🚩What if this changes the relic abundance?

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

R McGehee

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



R McGehee

2) Freezing-in at low reheating temperatures

2210.15653 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

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

R McGehee

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

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

R McGehee

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

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

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

R McGehee

Freezing-In @ Low Reheating

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

$$Y_{\rm DM} \approx \frac{3888\sqrt{10}}{\pi^8} \frac{M_{\rm Pl}}{g_{s,*}\sqrt{g_*}} \left(\frac{17 y_n y_\chi \alpha}{4\pi m_n m_\phi^2} \right)^2 T_{\rm R}^5$$

R McGehee

Freezing-In @ Low Reheating

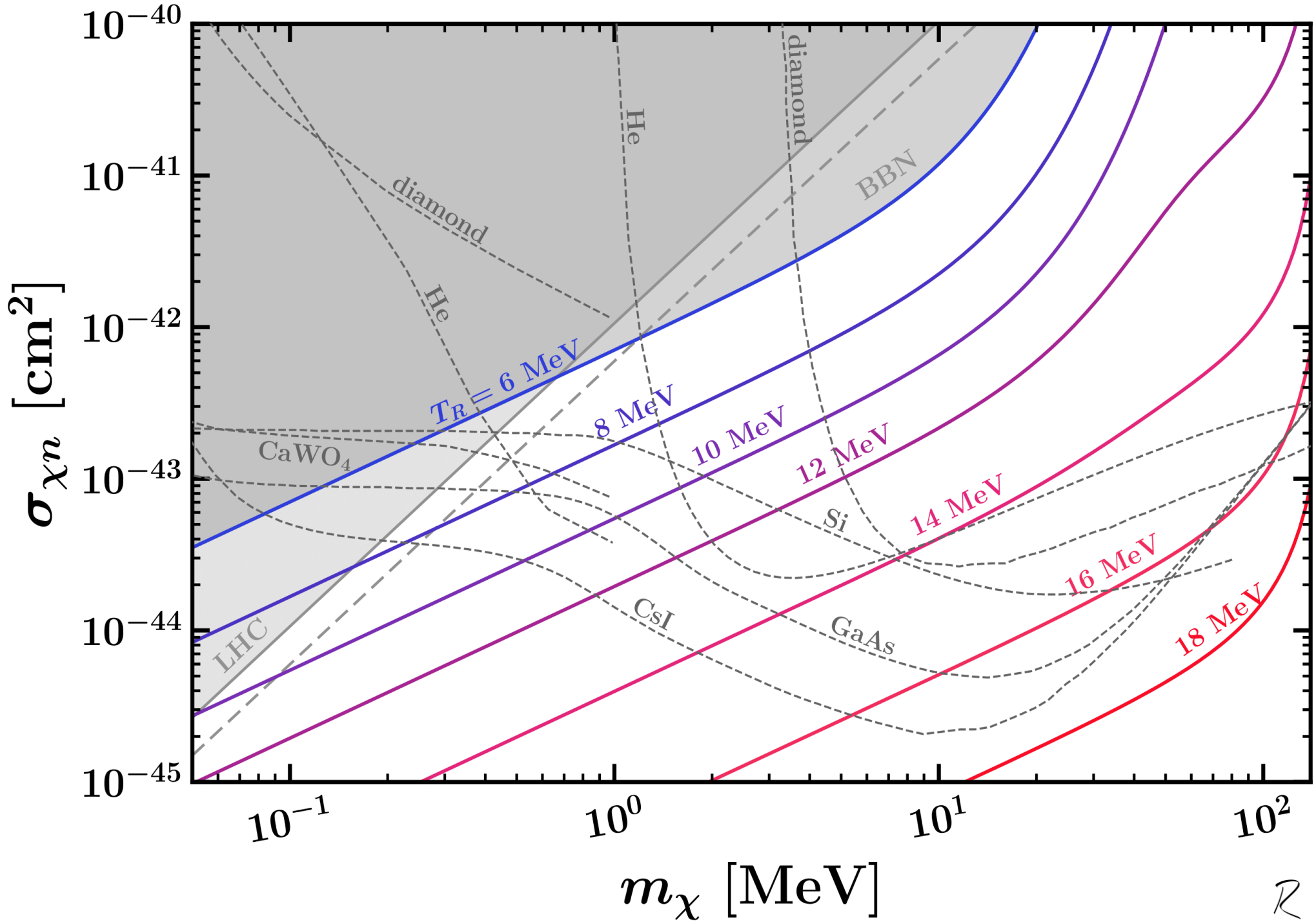
$$\gamma\gamma \to \bar{\chi}\chi$$

$$Y_{\rm DM} \approx \frac{3888\sqrt{10}}{\pi^8}\frac{M_{\rm Pl}}{g_{s,*}\sqrt{g_*}}\left(\frac{17 y_n y_\chi \alpha}{4\pi m_n m_\phi^2}\right)^2 T_{\rm R}^5$$

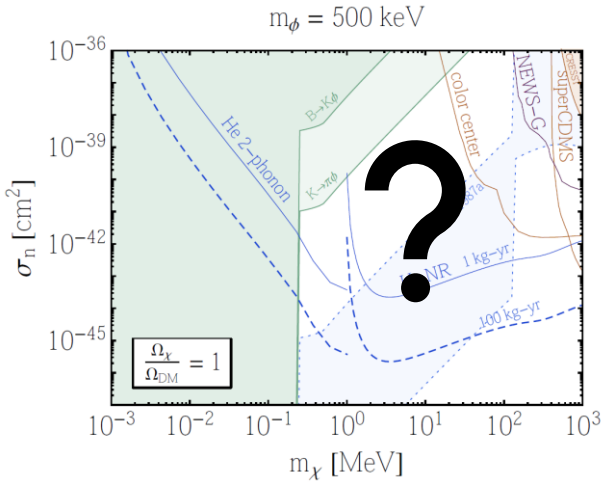
Relic abundance predicts a simple cross section

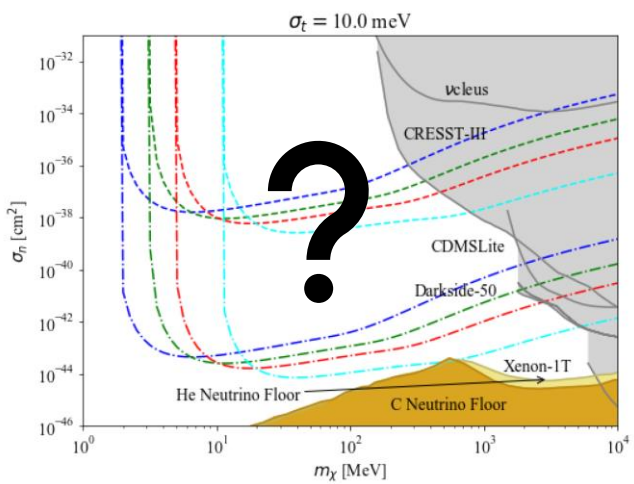
$$\sigma_{\chi n} \approx 5.5 \times 10^{-44}\ {\rm cm}^2 \left(\frac{g_{s,*}\sqrt{g_*}}{10.76^{3/2}}\right)\left(\frac{m_\chi}{1\ {\rm MeV}}\right)\left(\frac{10\ {\rm MeV}}{T_{\rm R}}\right)^5$$

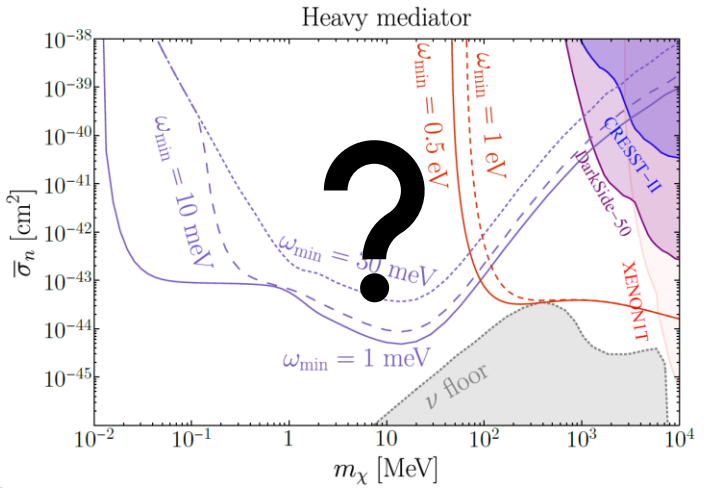
R McGehee

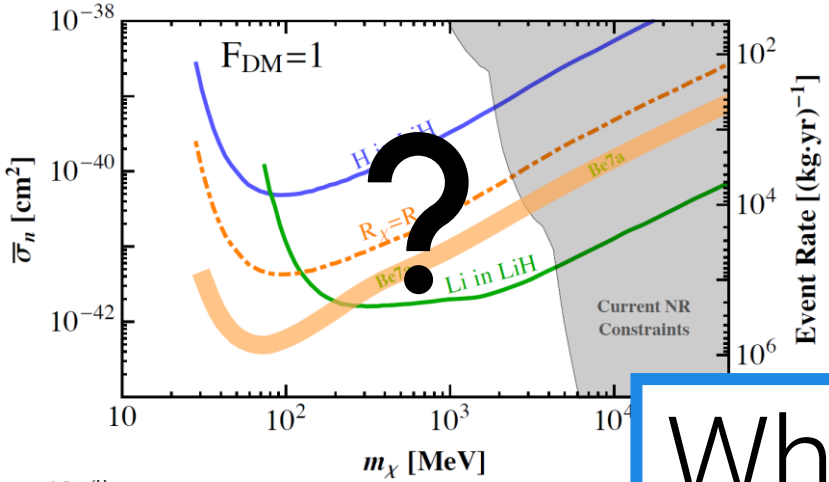

10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
$\sigma_{\chi n}$ [cm^2]
10^{-1}
10^{0}
10^{1}
10^{2}
m_χ [MeV]
diamond
He
He
diamond
BBN
$T_R = 6$ MeV
8 MeV
10 MeV
12 MeV
14 MeV
16 MeV
18 MeV
$CaWO_4$
Si
CsI
GaAs
LHC

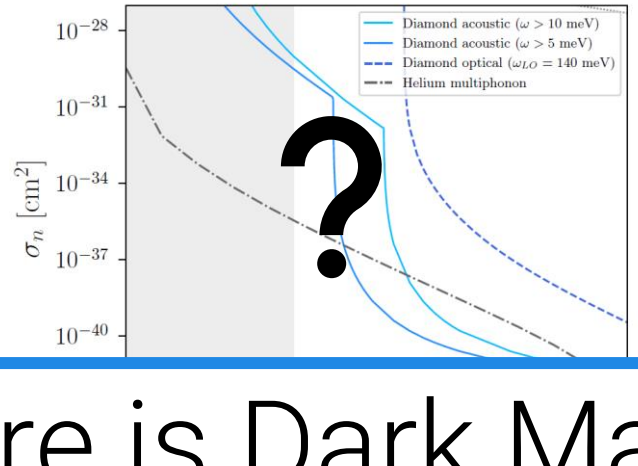
R McGehee

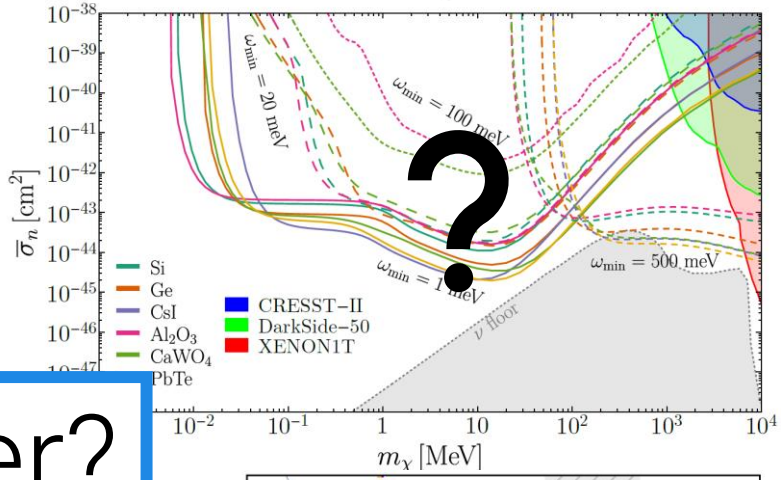




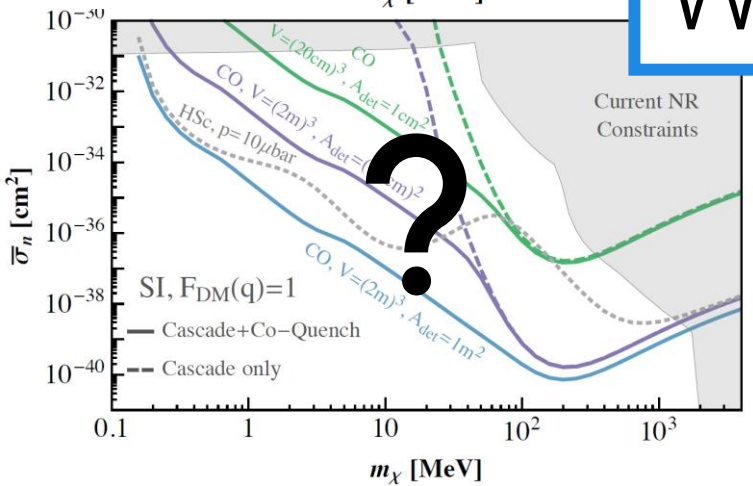


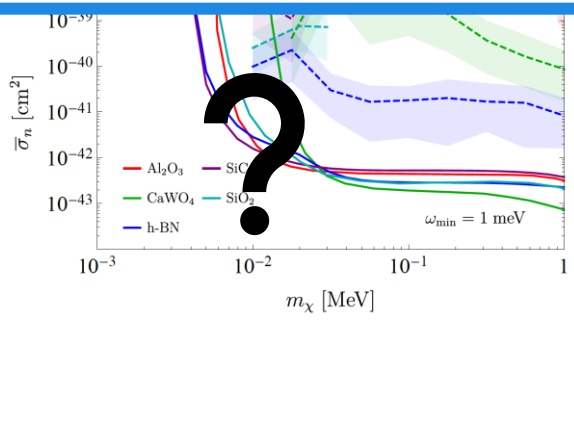


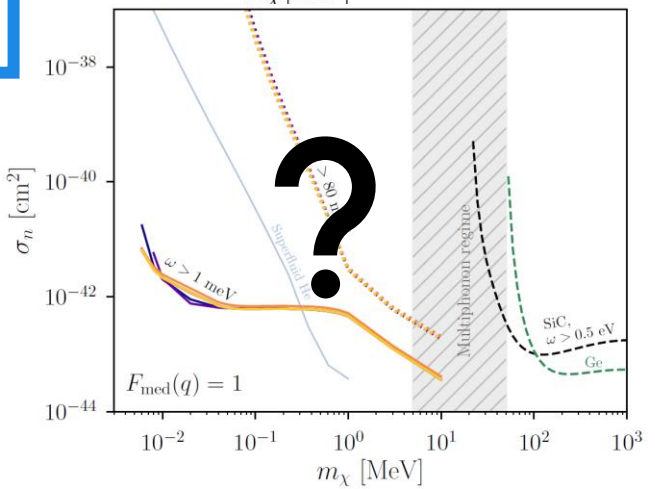




Where is Dark Matter?

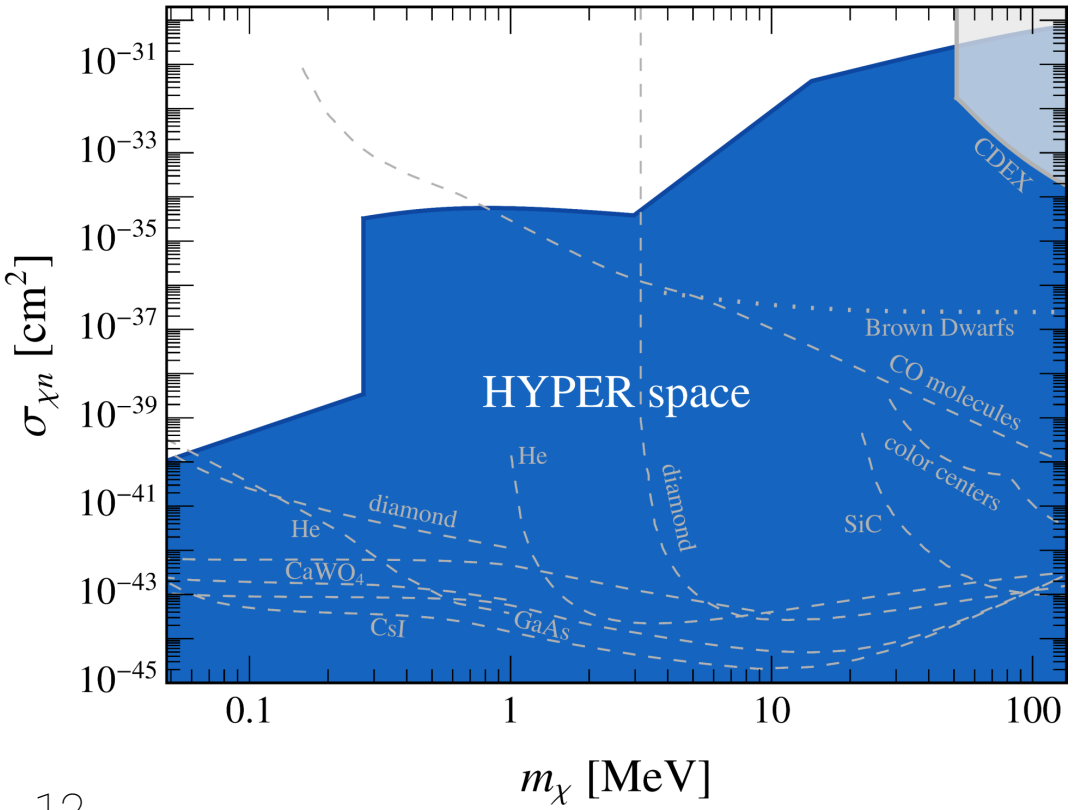




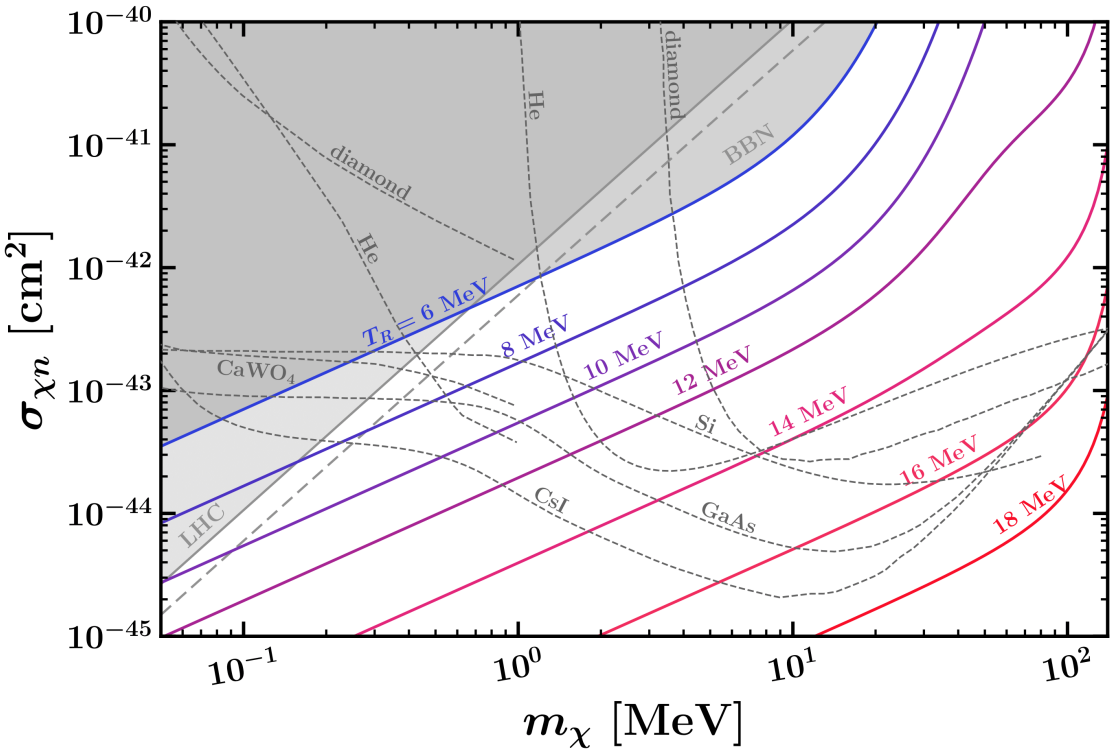


Two ways to get light, detectable DM

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



2) Freezing-in at low reheating temperatures



R McGehee