Maximizing Detection Rates with HYPER Dark Matter

with Gilly Elor & Aaron Pierce

2110.XXXXX

Robert McGehee

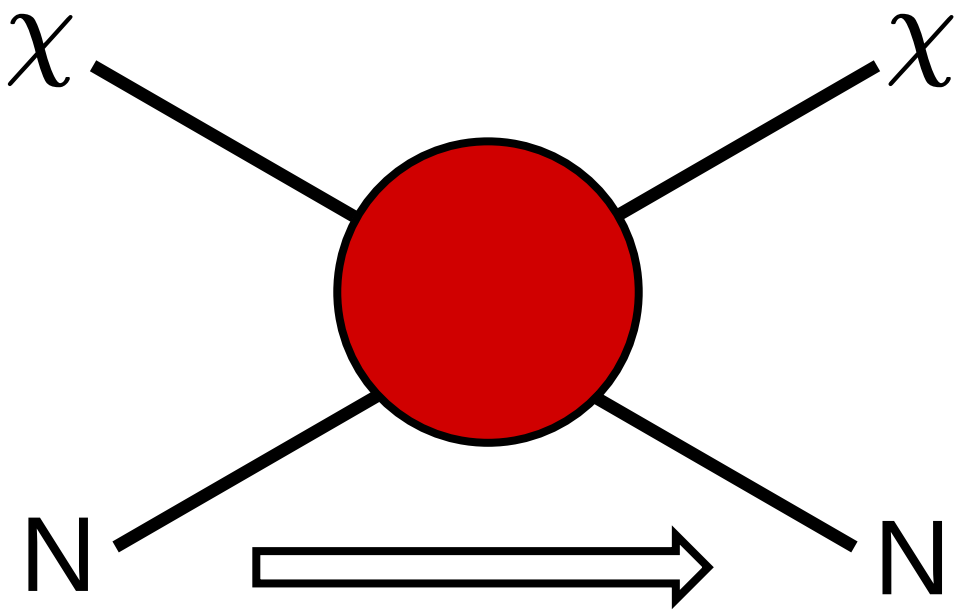
MITP, 29/9/21

Direct Detection Refresher: WIMPs

Fermion

~10 GeV-10 TeV

Stable

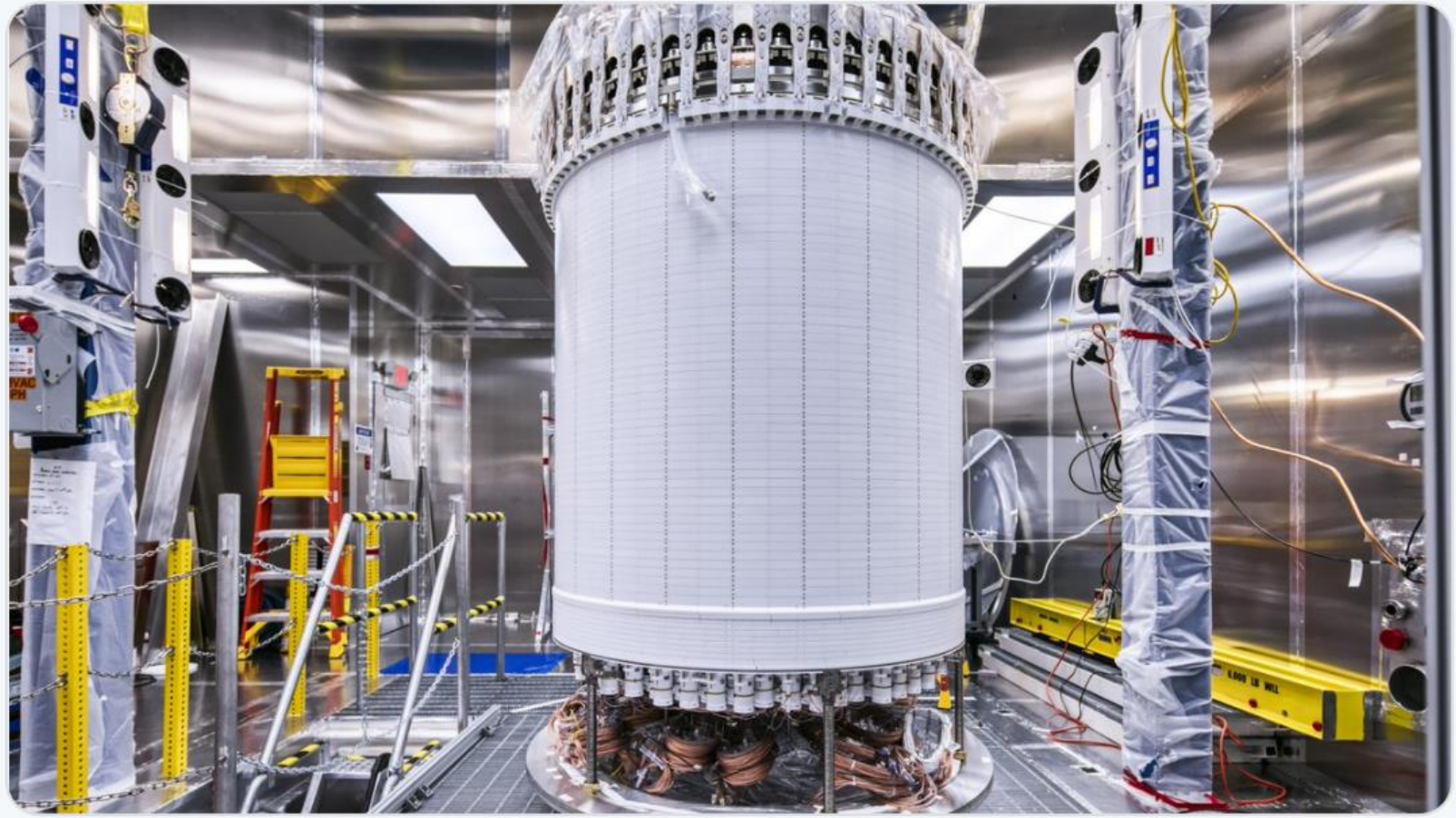


Berkeley Lab @BerkeleyLab · Oct 29

Q: How do you get a 5,000-pound, 9-foot-tall particle detector, designed to hunt for #darkmatter, nearly a mile underground? 🤔

A: Very carefully. 🤓

Now begins the next stage of work on the LUX-ZEPLIN @LZdarkmatter experiment. bit.ly/DrkMttrDeepDive @LBNLphysics @LZdeepdive



Credit: The XENON Experiment

27 institutions
160 scientists

Direct Detection Refresher: WIMPs

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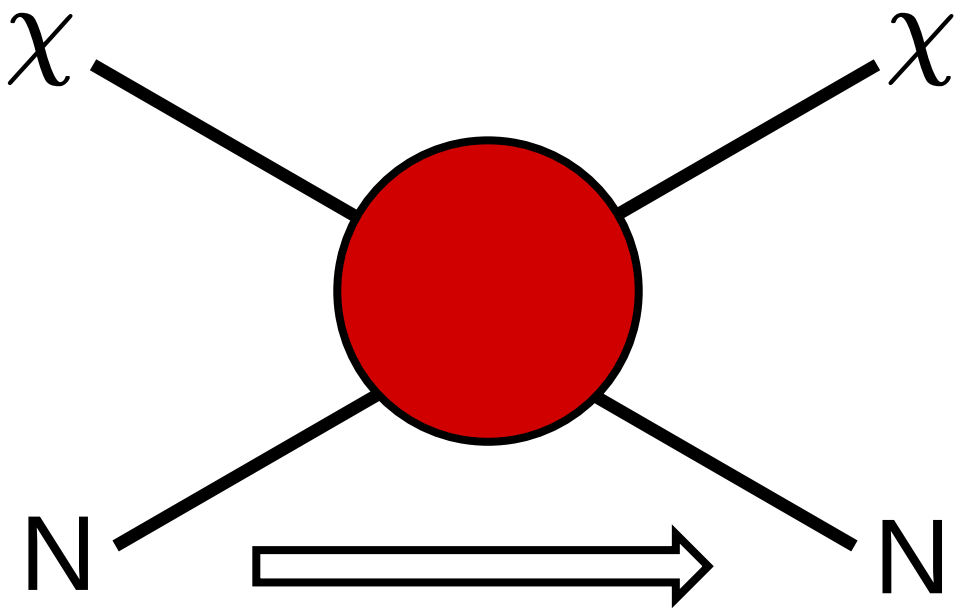
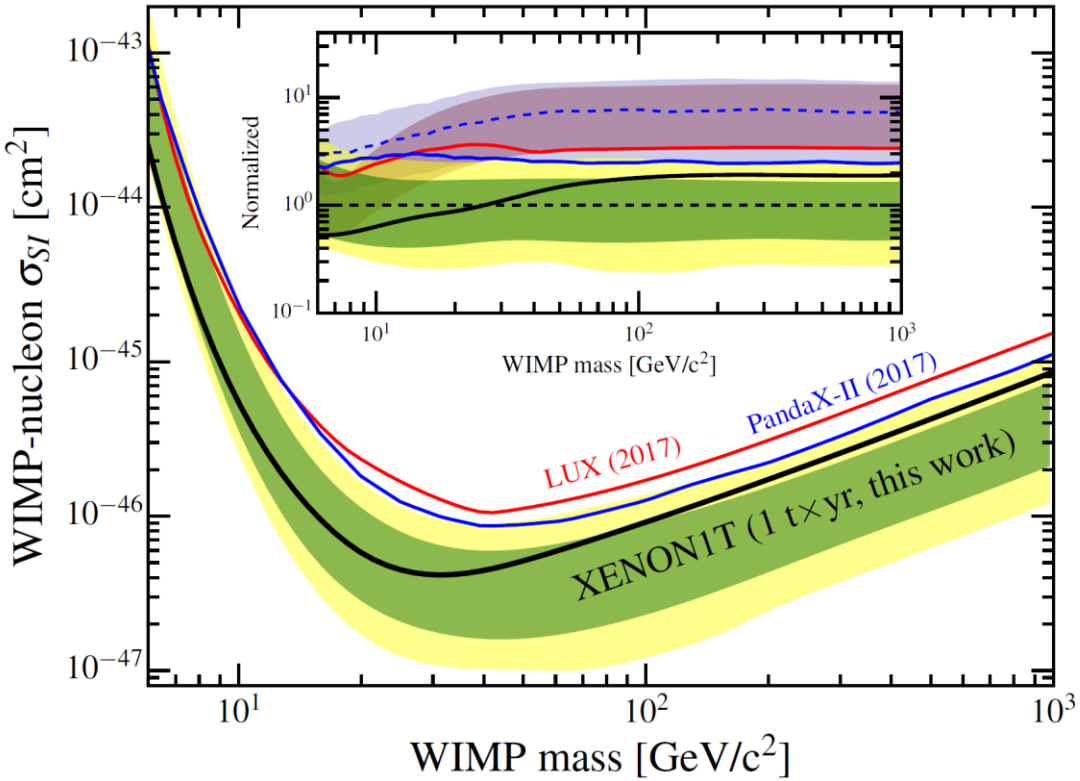




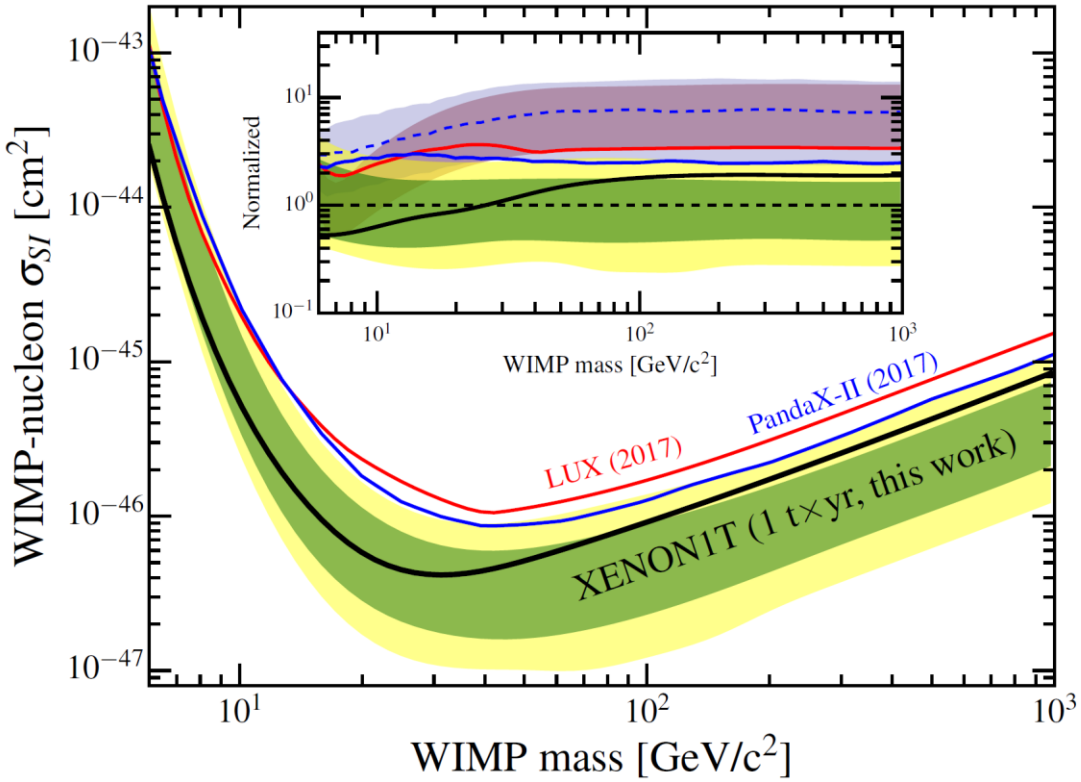
XENON Collaboration, E. Aprile *et al.*, "Dark Matter Search Results from a One Ton-Year Exposure of XENON1T", *Phys. Rev. Lett.* **121** (2018), no. 11, 111302

Robert McGehee

Direct Detection Future

Go higher?

Go lighter

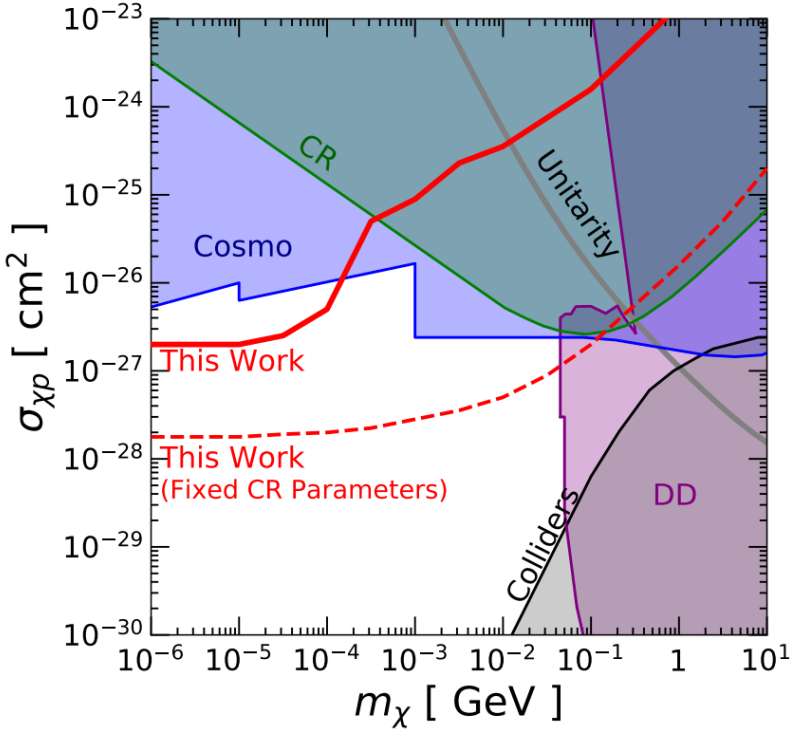


Go lower

Robert McGehee

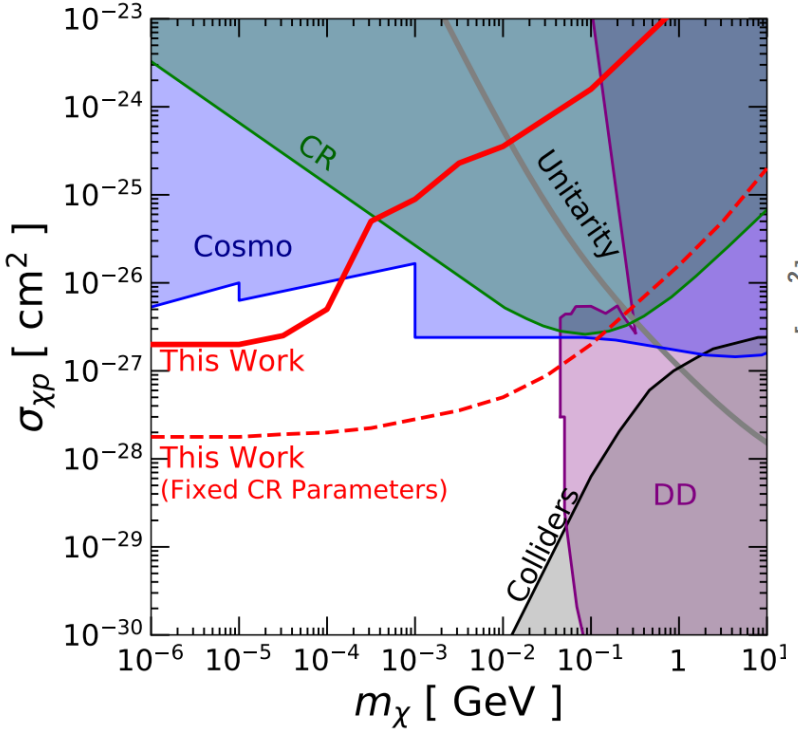
Going higher?

Bounds from Cosmic Ray Scattering



1810.07705

Bounds from Cosmic Ray Scattering



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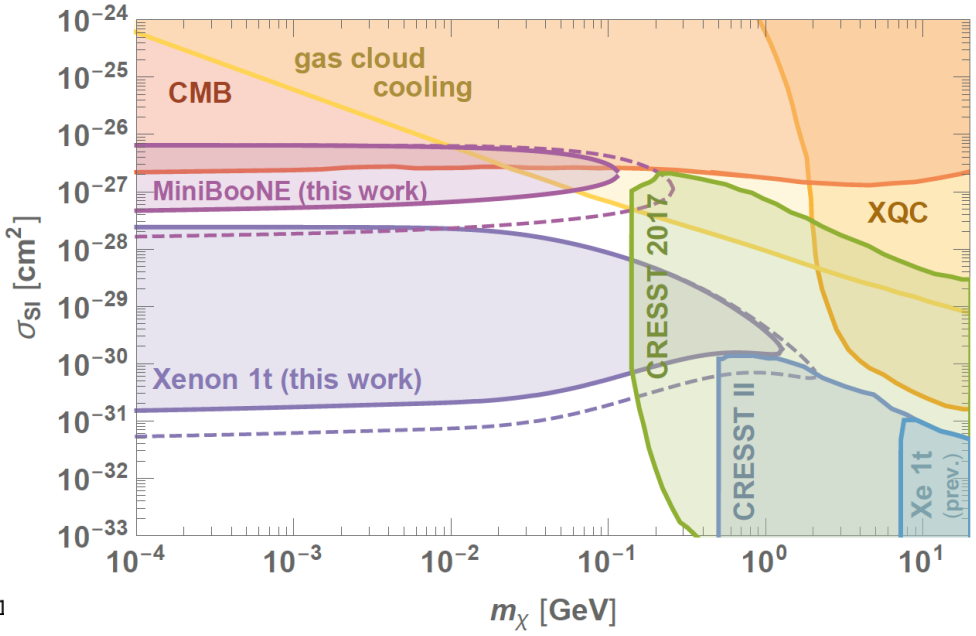
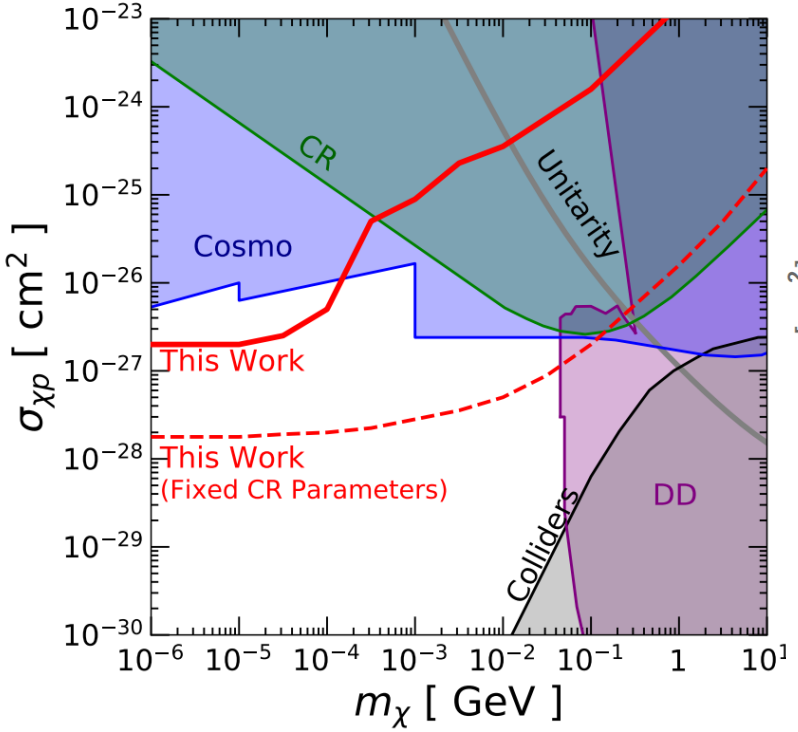


1810.10543

Bounds from Cosmic Ray Scattering



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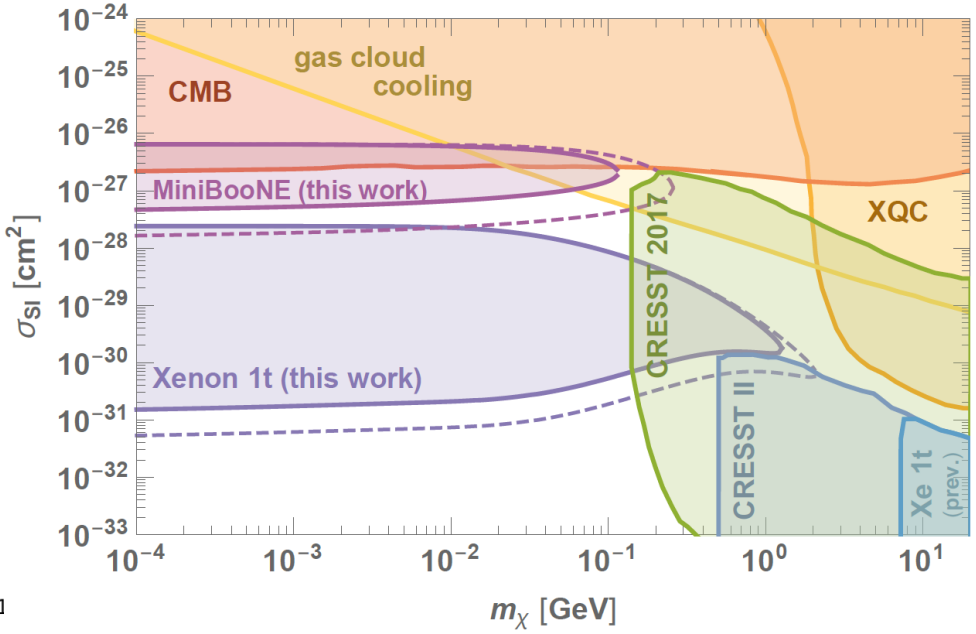

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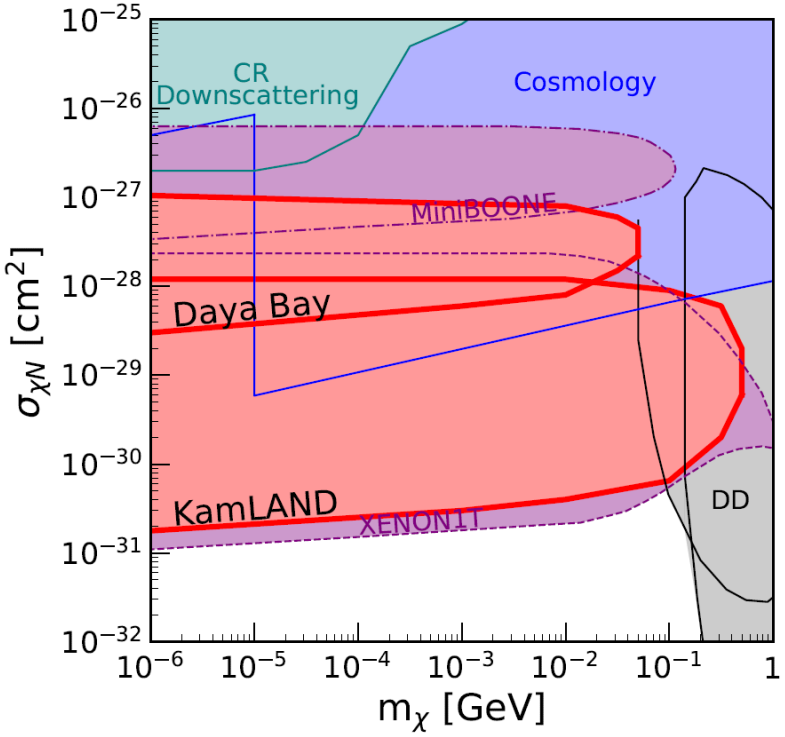
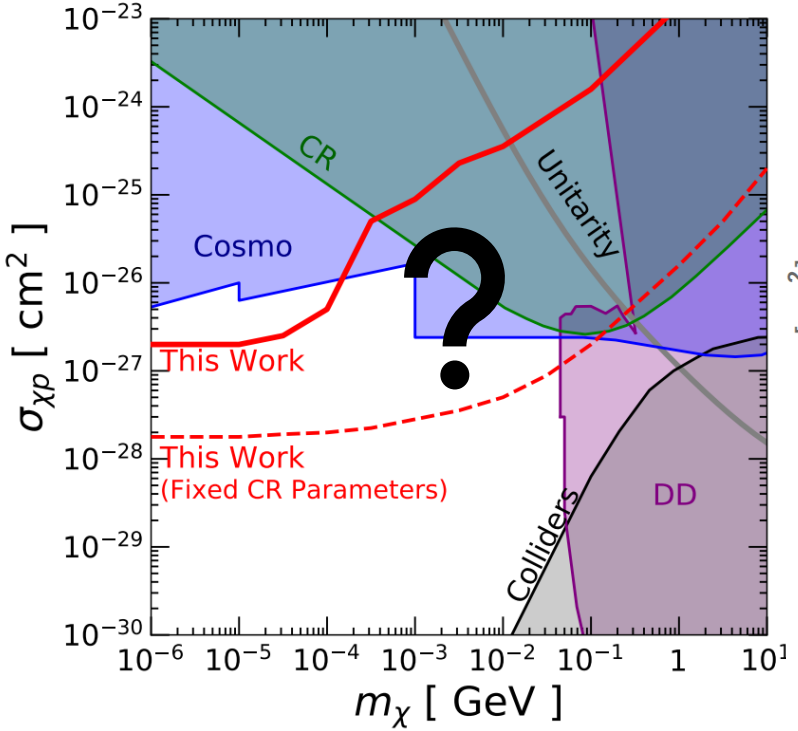


1906.11283

Robert McGehee

Is Dark Matter here?



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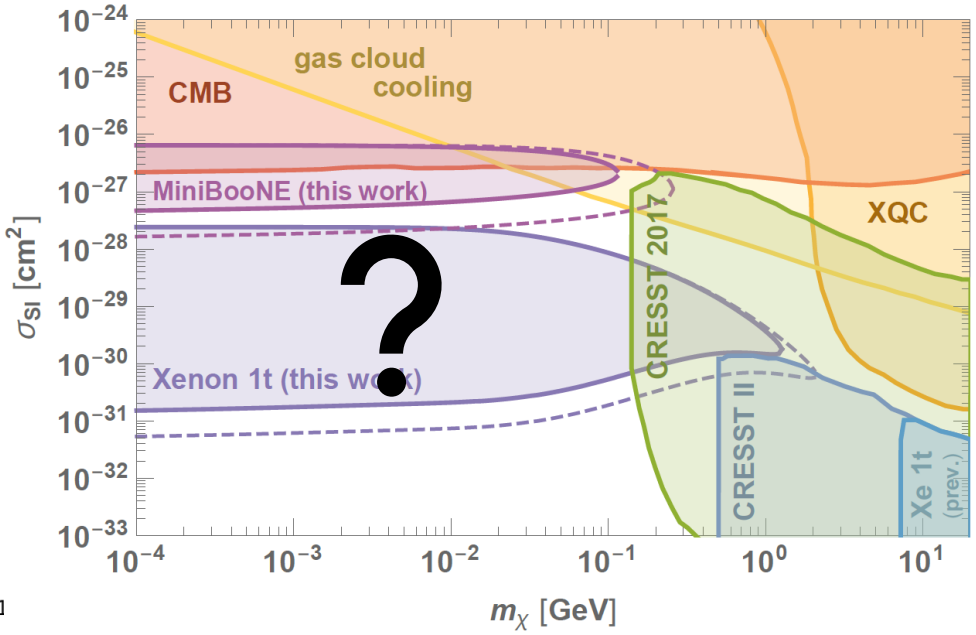

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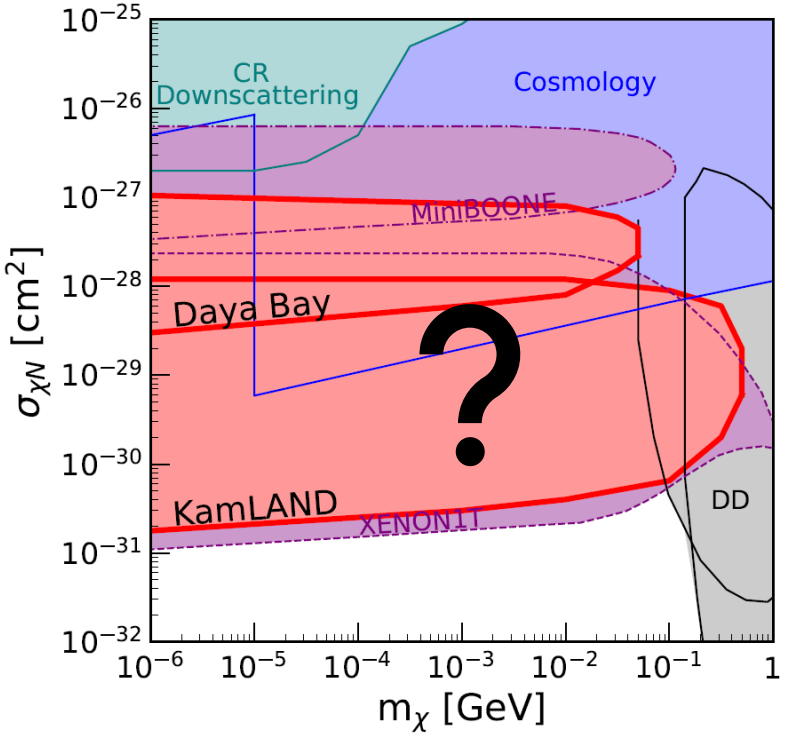

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Going lighter…

Direct Detection Future

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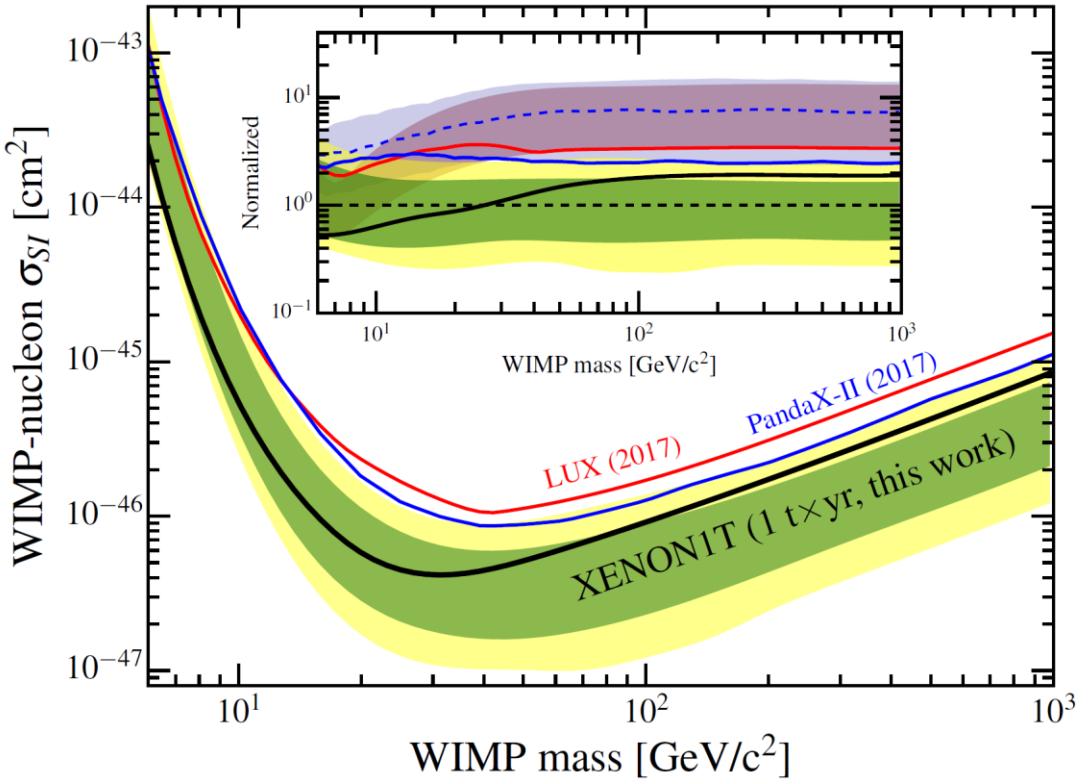
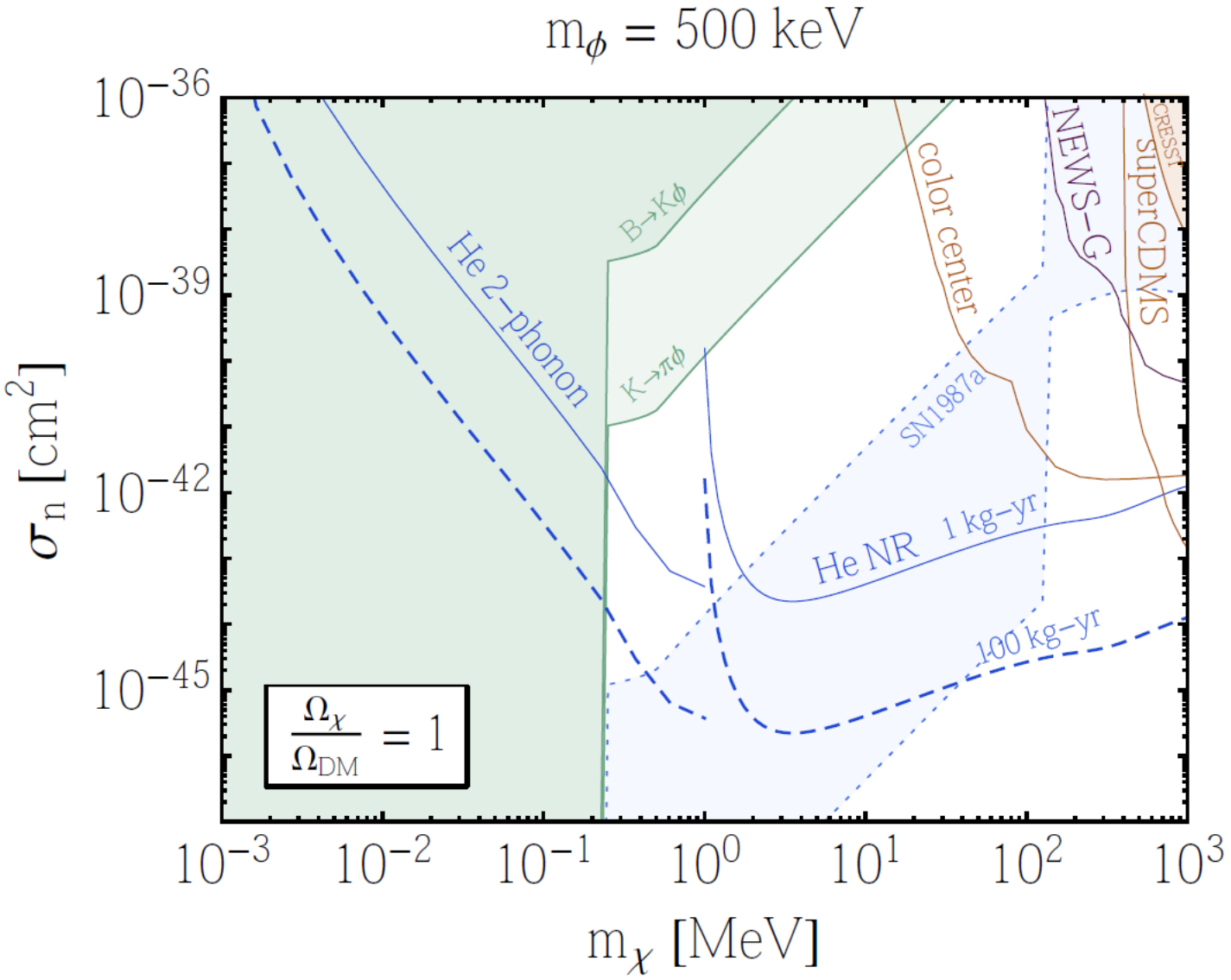
$$E_R \sim \frac{\mu^2 v^2}{2M_N}$$



Go lower

Robert McGehee

Superfluid Helium (1611.06228,1709.07882)



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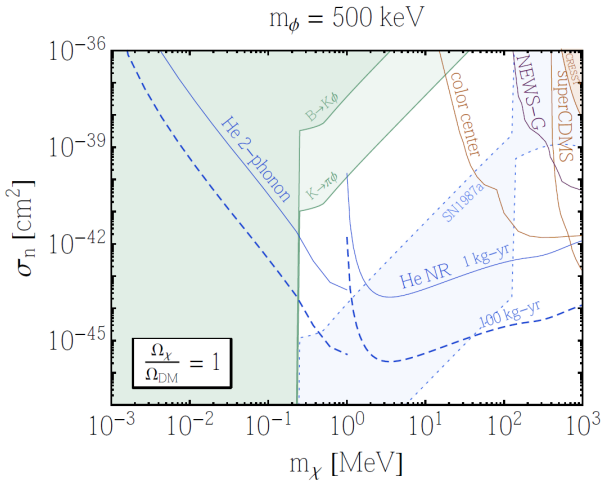

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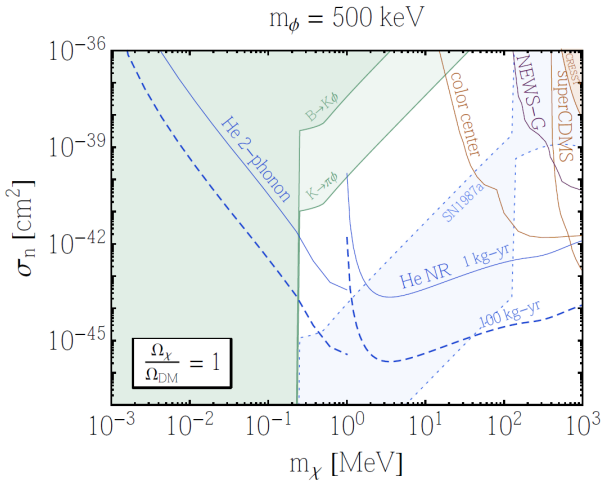

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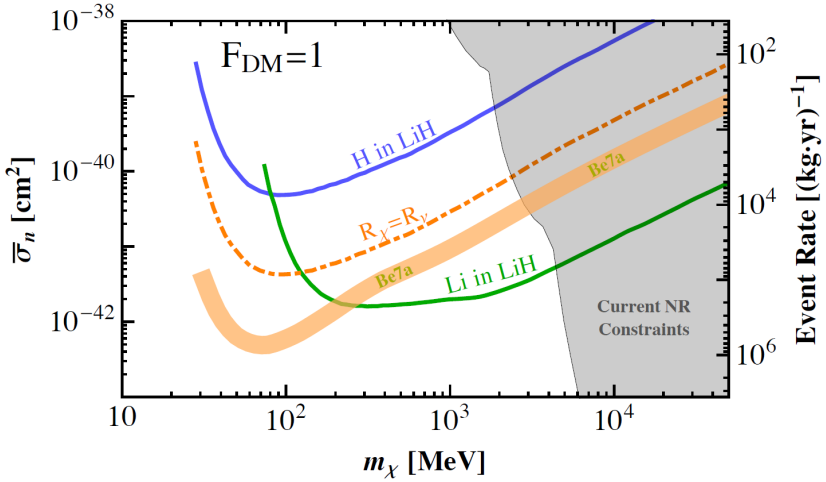
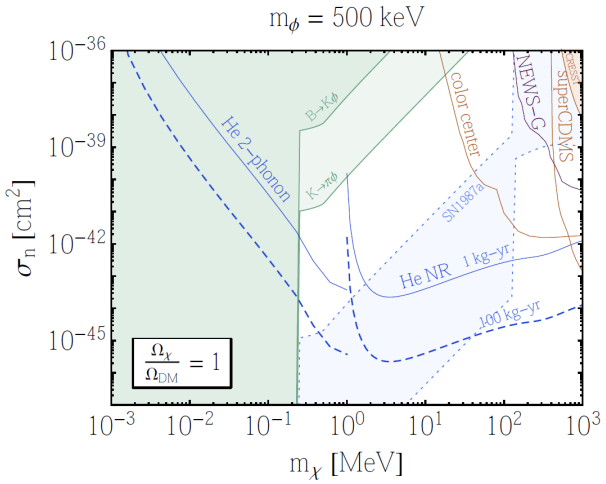


Color Center Production in Crystals
1705.03016



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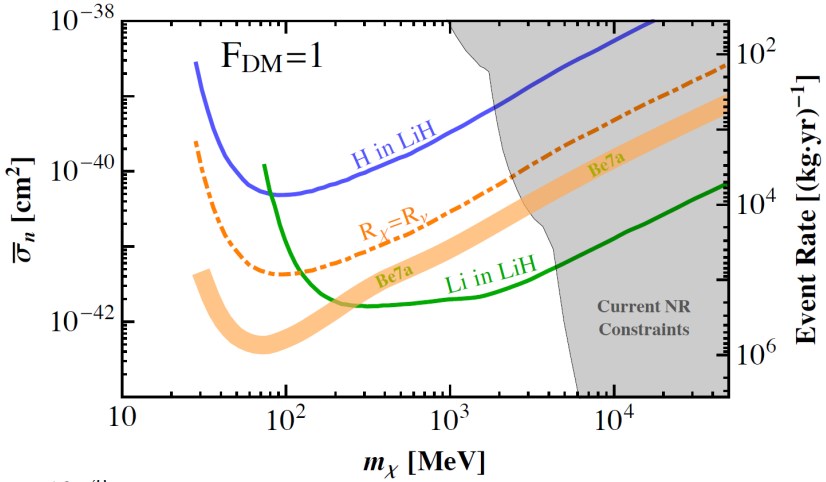

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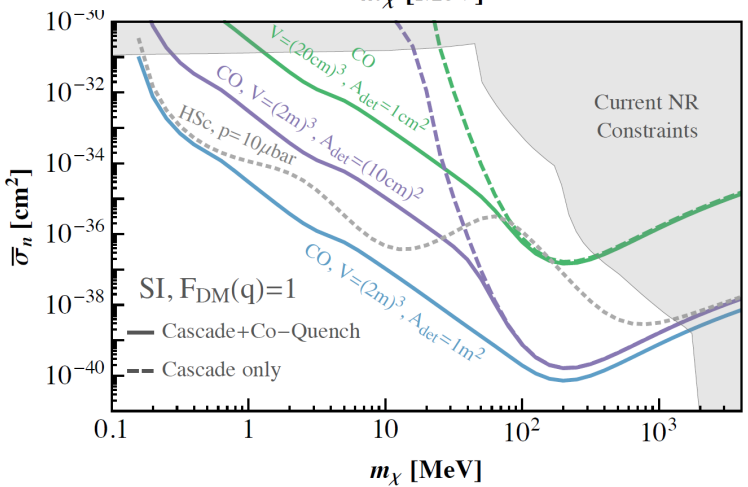
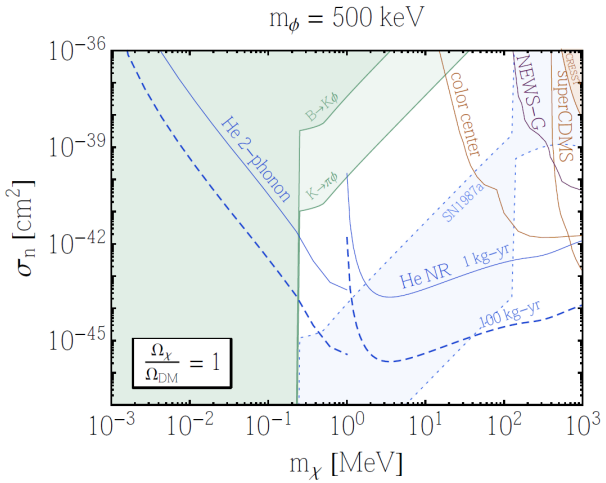


Molecular
Excitations
1907.07682



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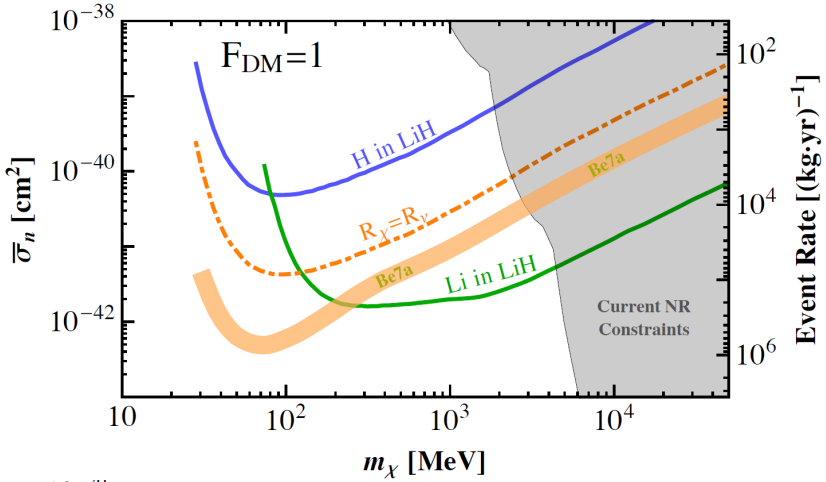

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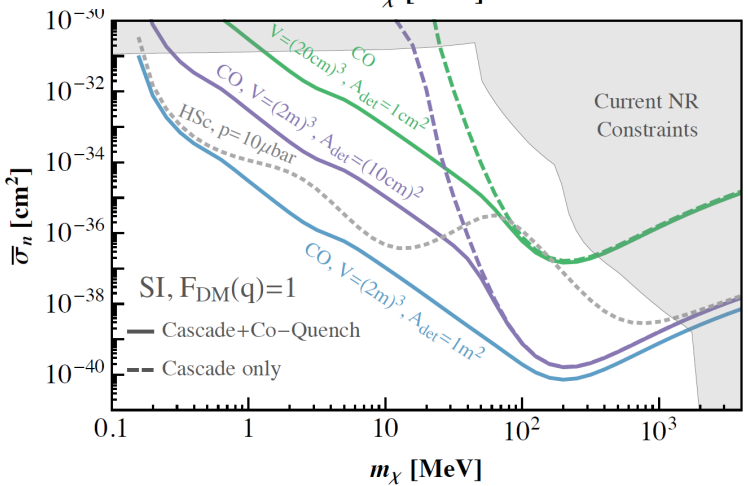

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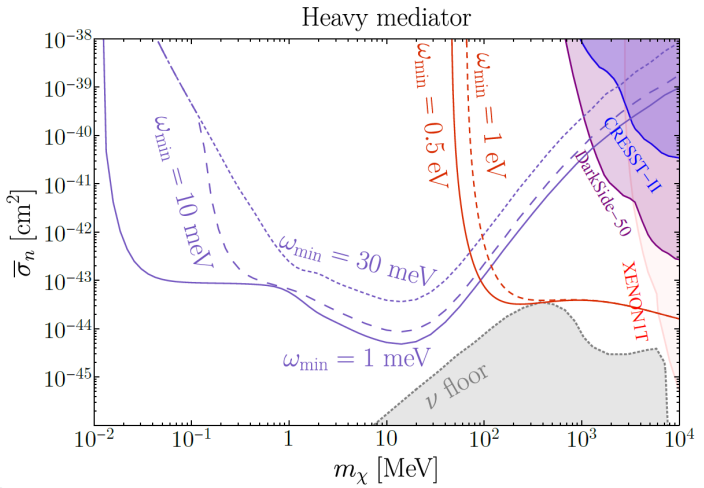
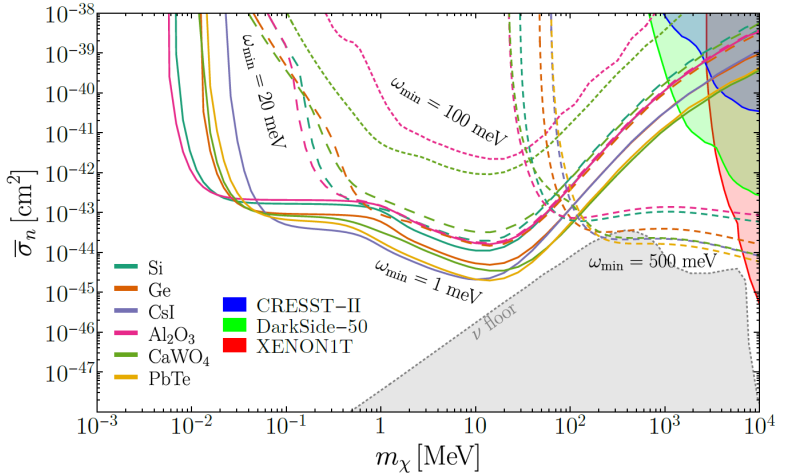
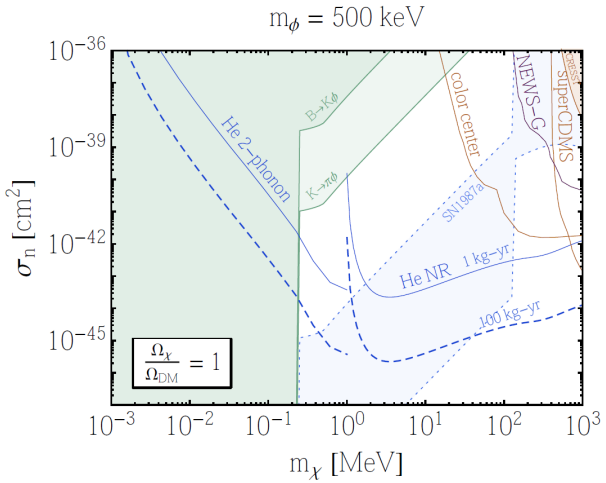
Multiple Channels (recoils, transitions, phonons)
1910.08092
1910.10716







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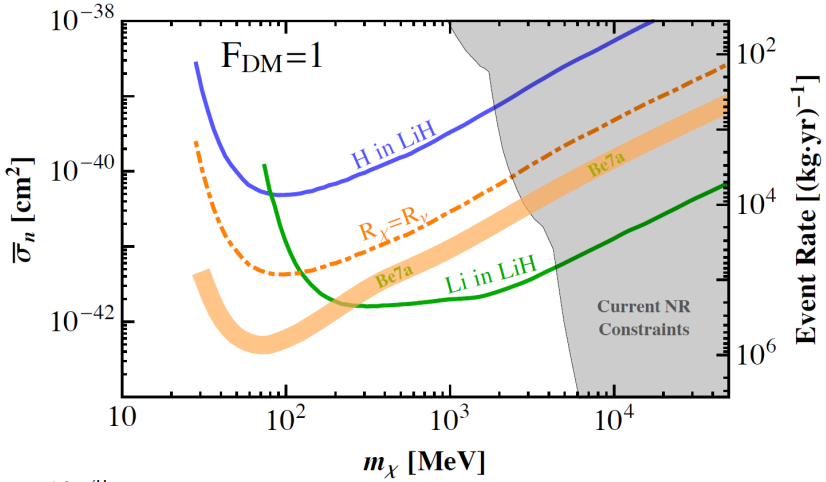

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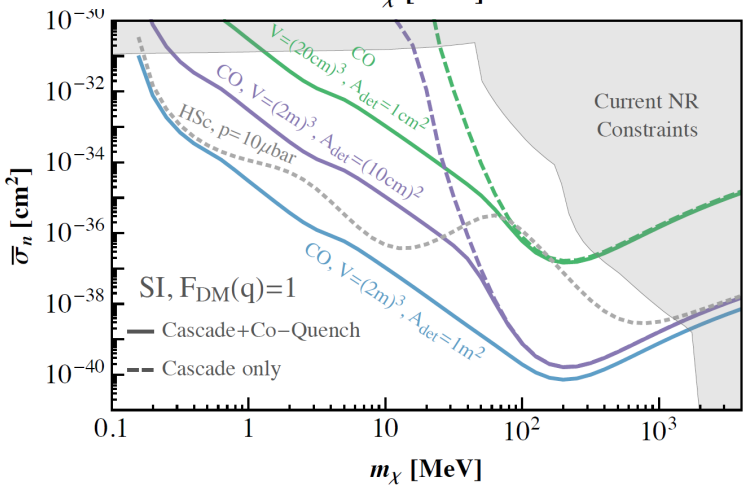

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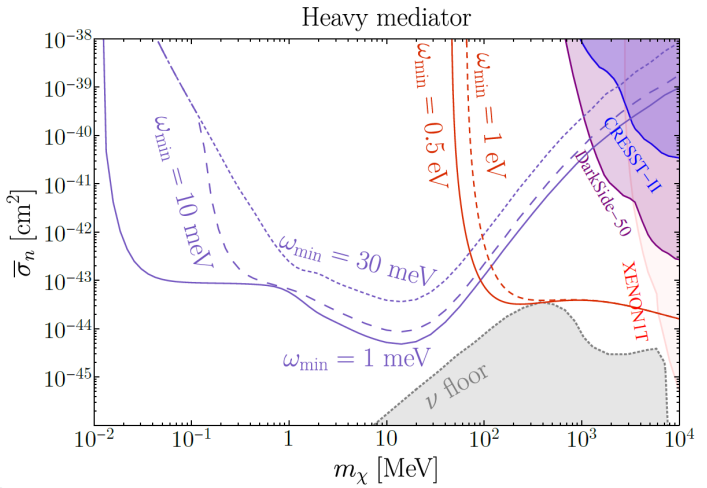
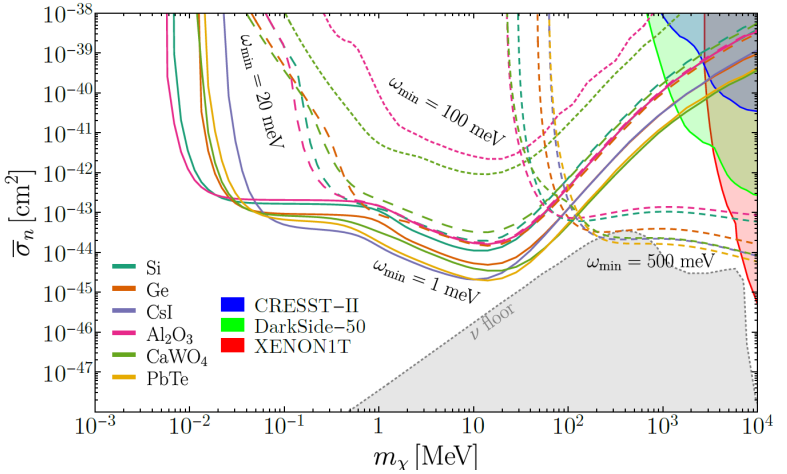
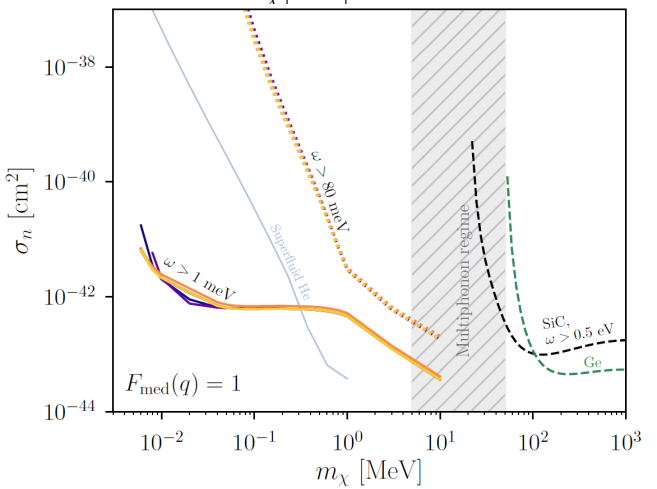
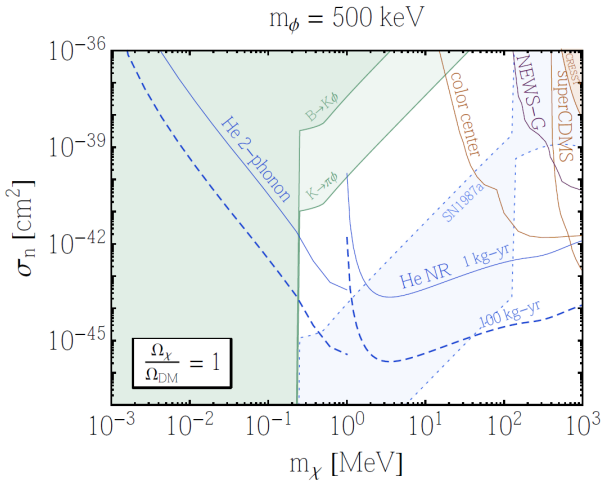




Silicon Carbide
2008.08560





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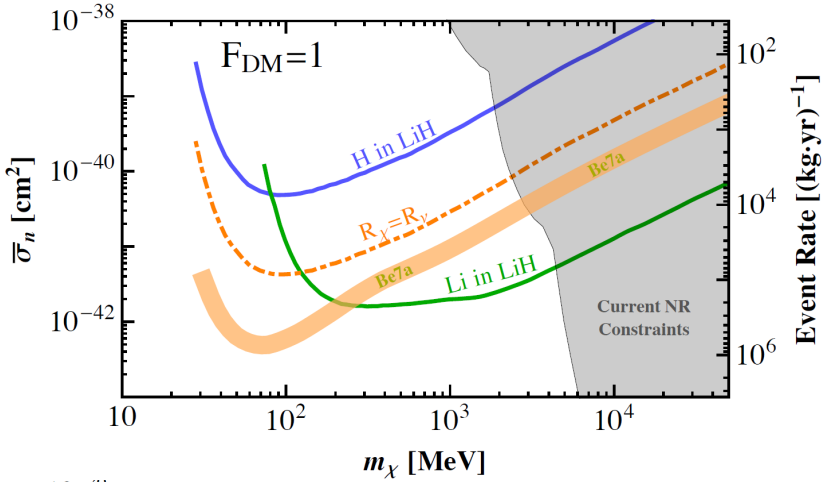

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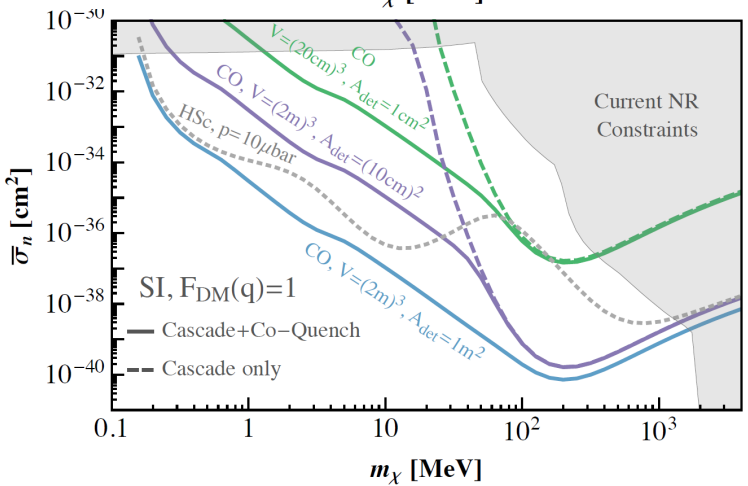
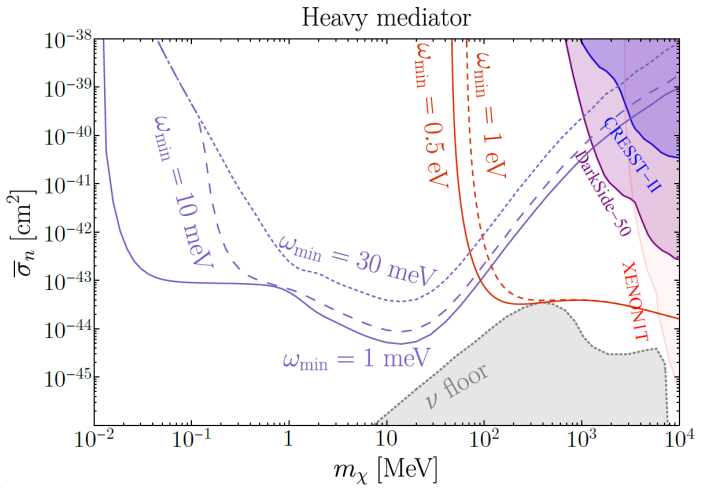


Molecular Excitations
1907.07682

+ many more!



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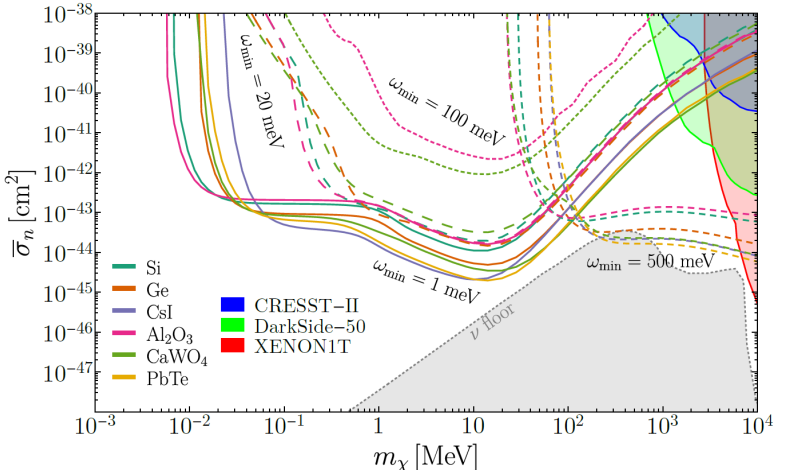
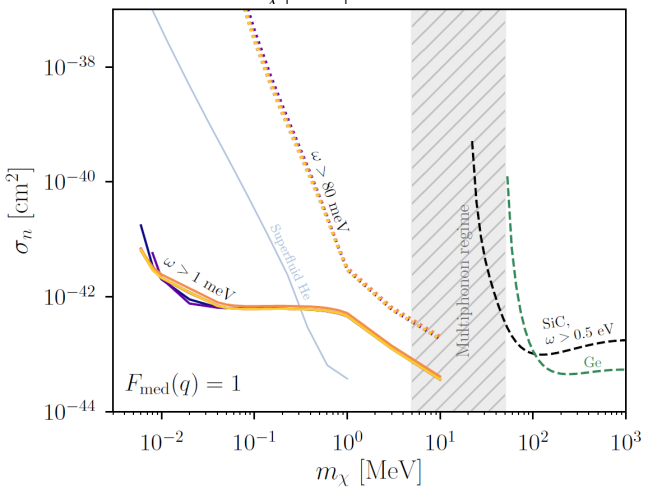
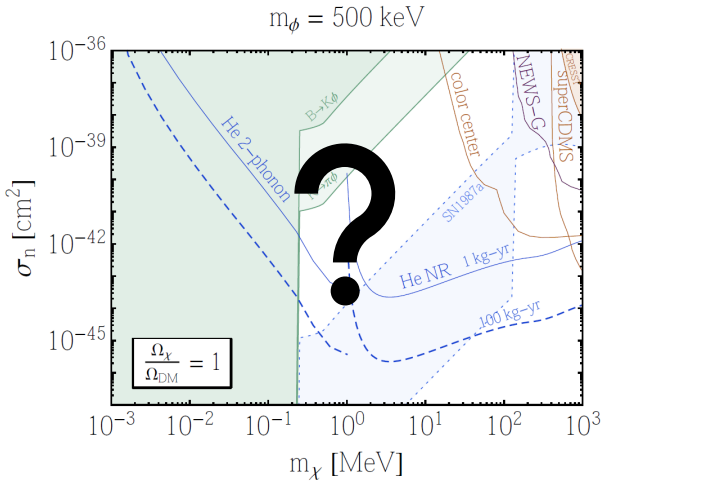
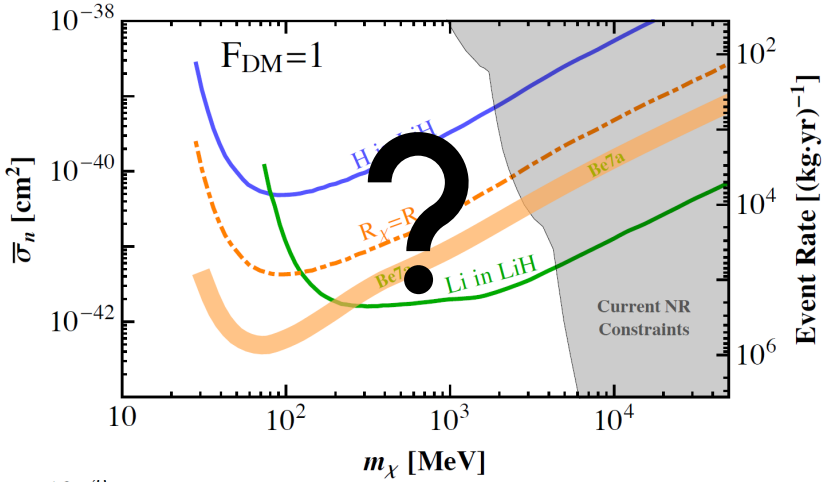
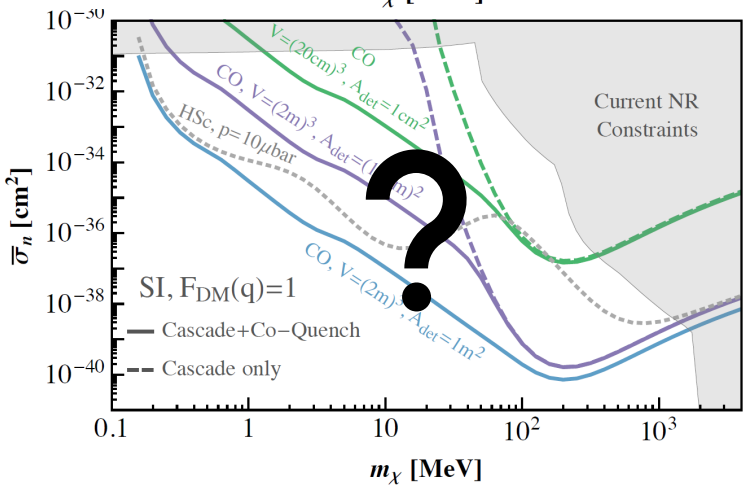




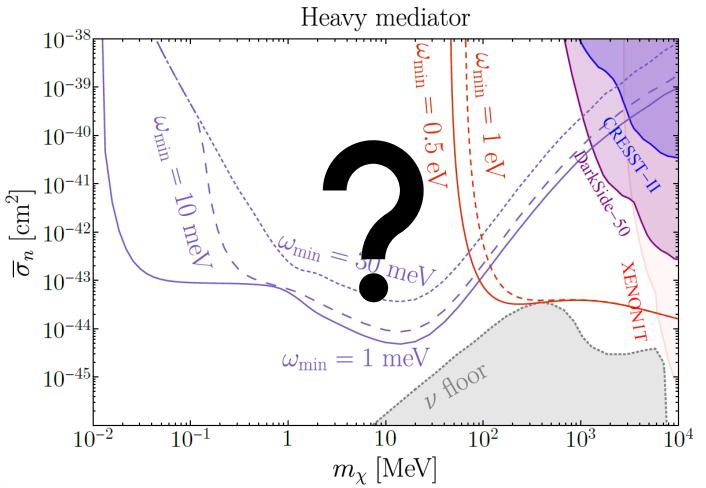
Silicon Carbide
2008.08560

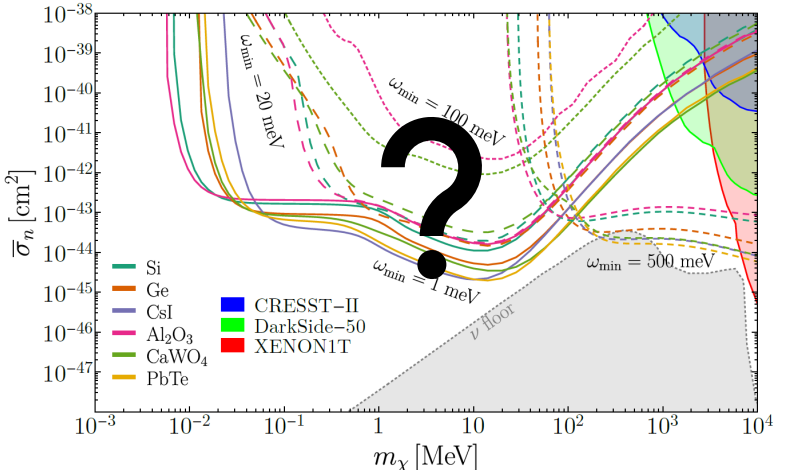


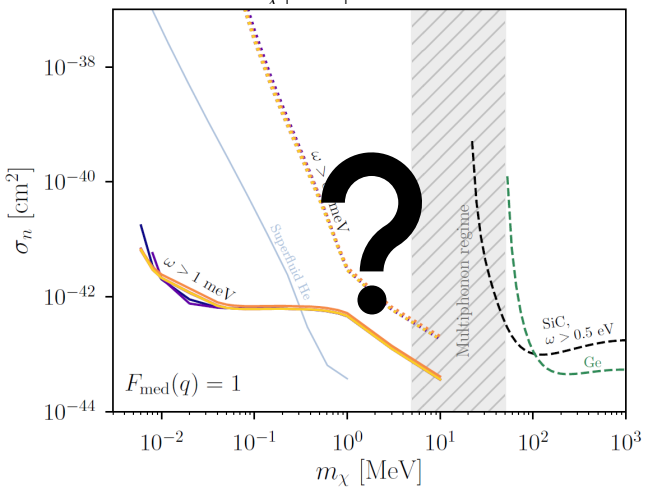




Where is the Dark Matter?







Outline

Is Dark Matter here?

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

Outline

Is Dark Matter here?

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

Where is the 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?

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?

Disclaimer

If I have:

- typos

Please forgive me! I am jetlagged.

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If I have:

- typos
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- slides with too much text
- broken the known laws of physics

Please forgive me! I am jetlagged.

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

The Basics

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

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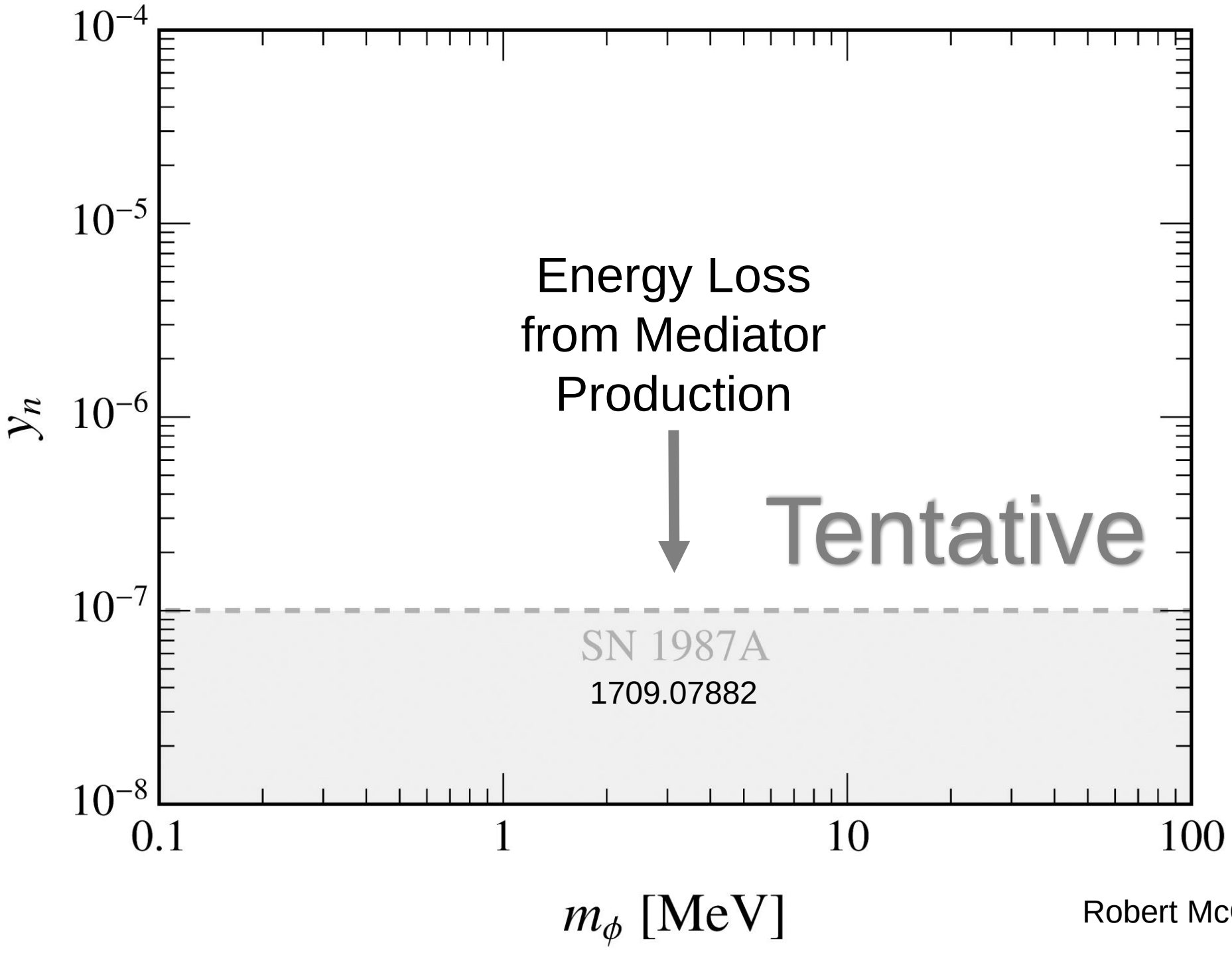

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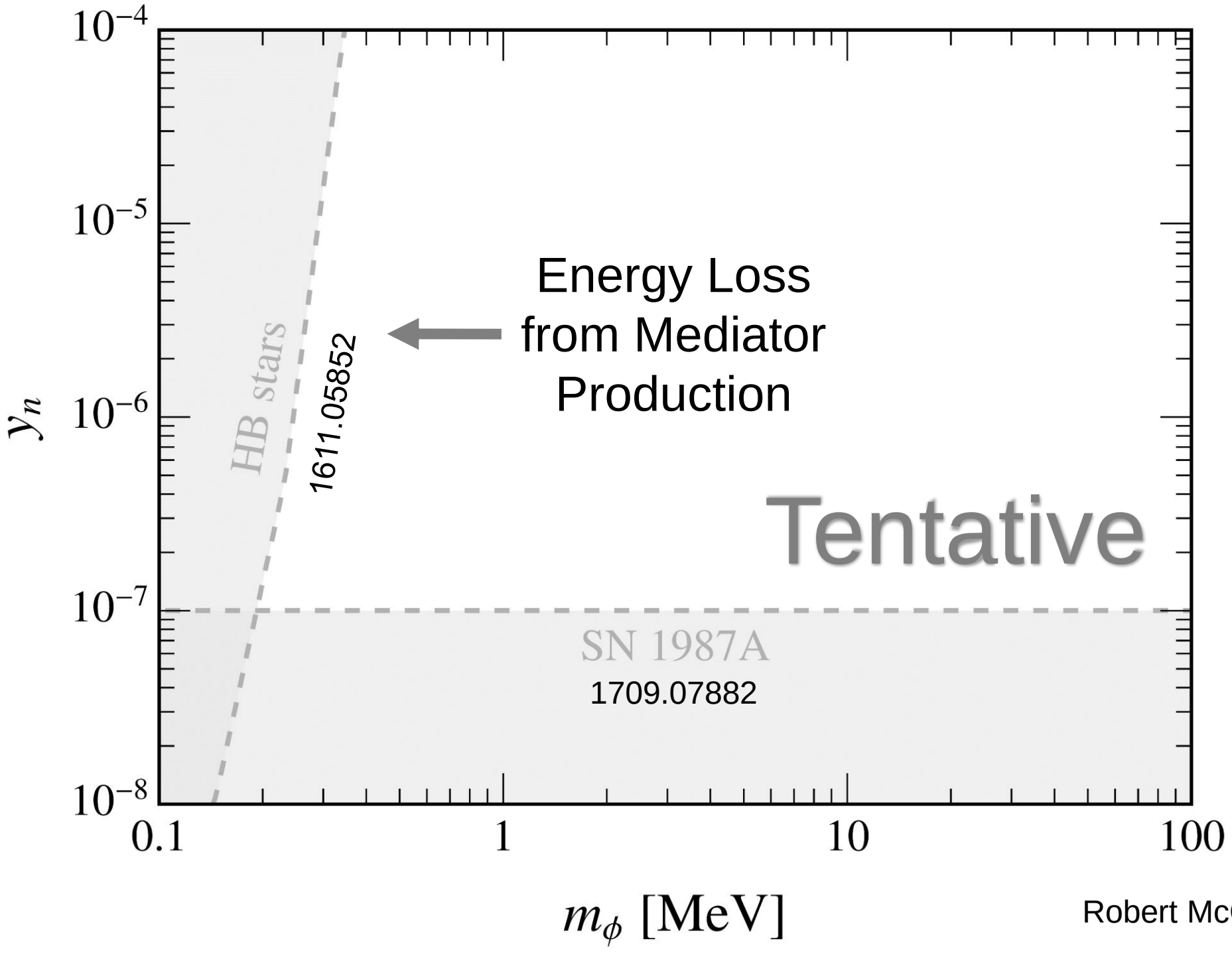

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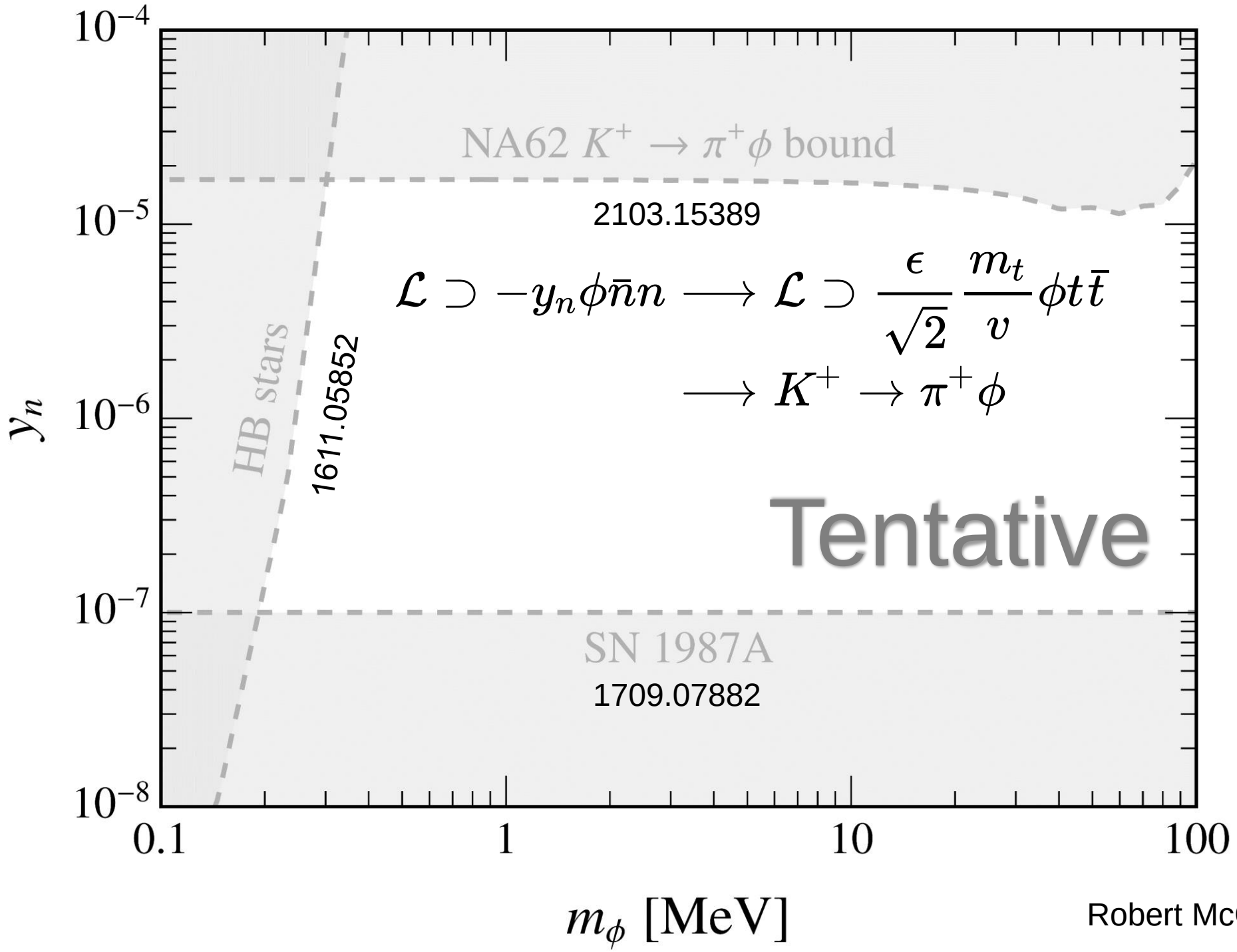

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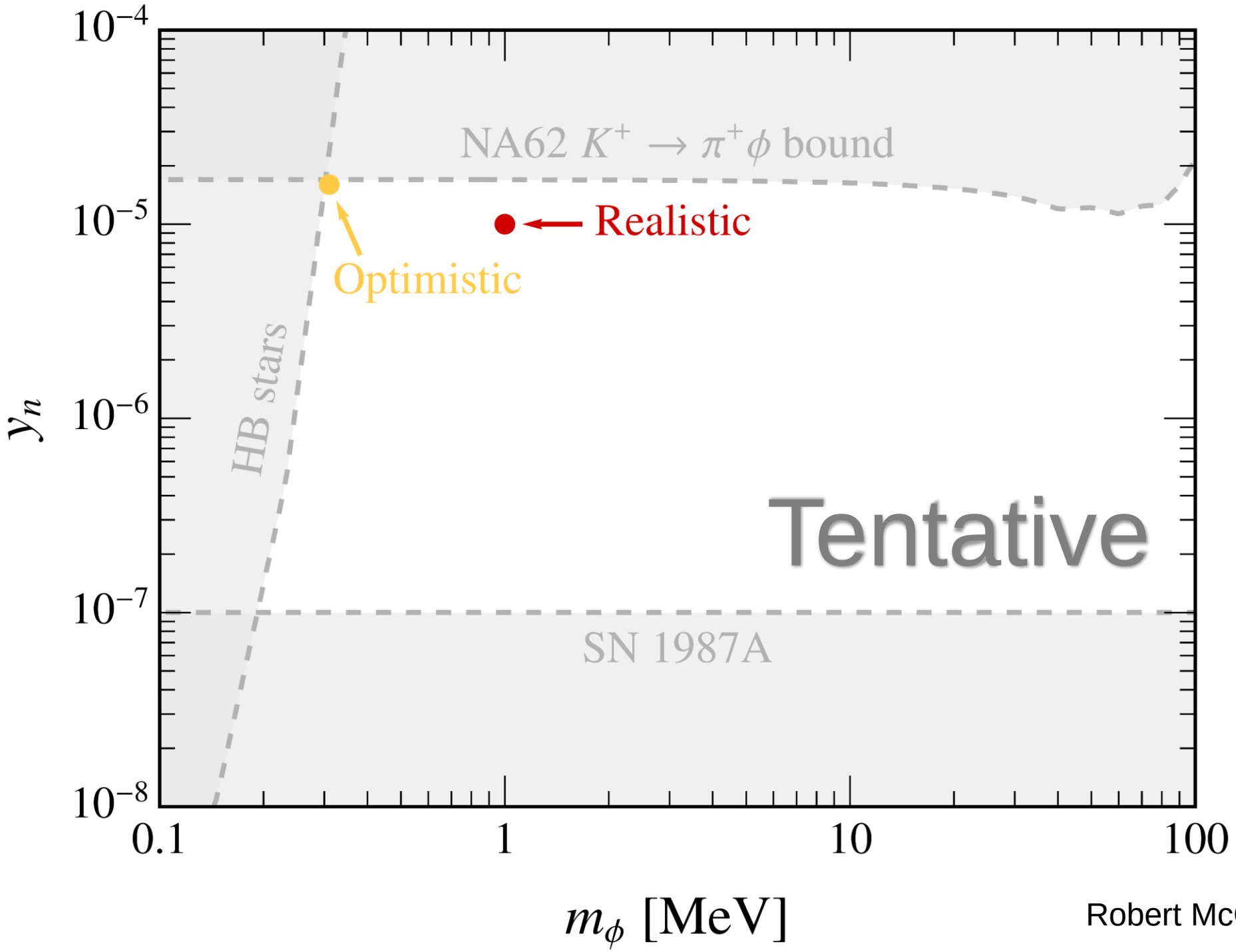

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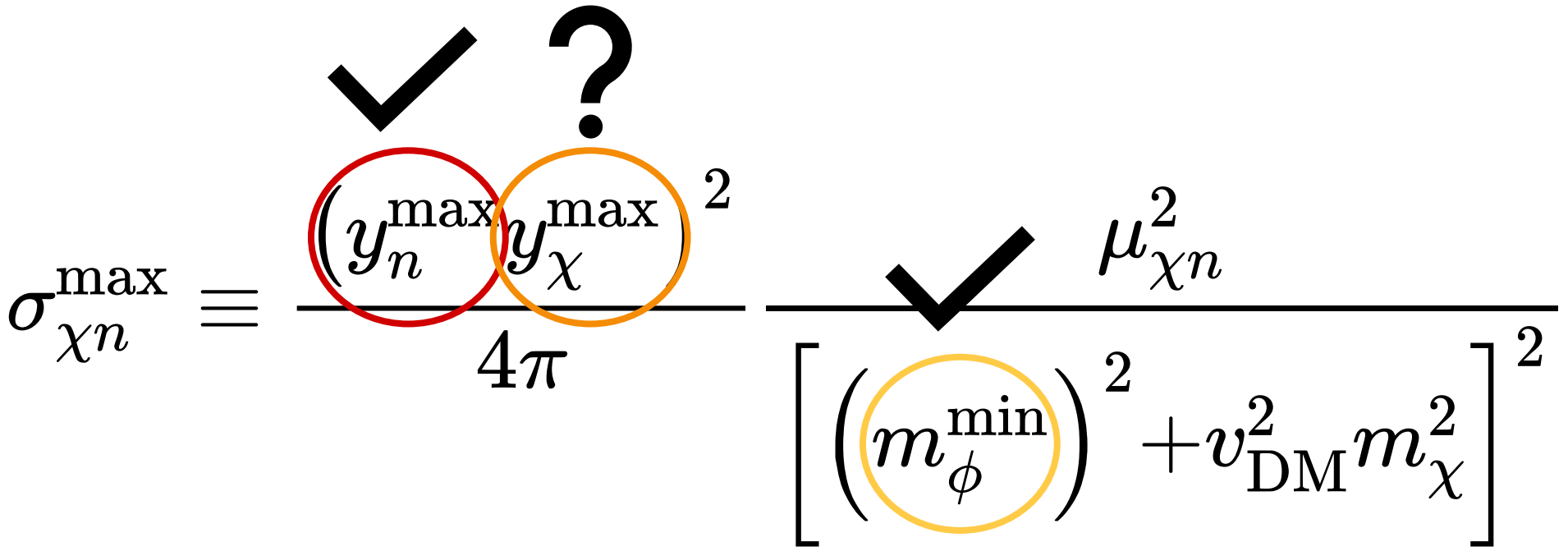

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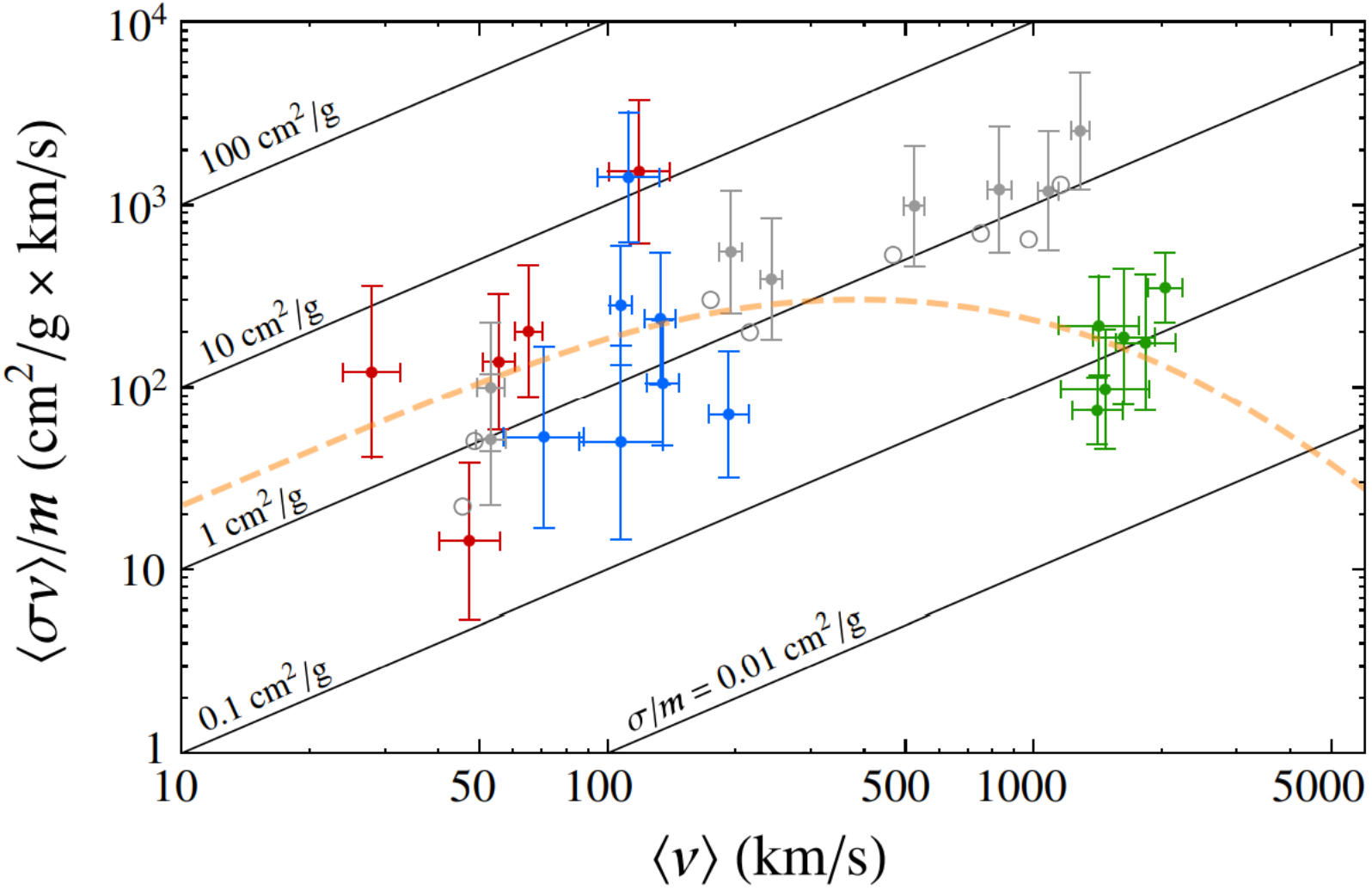
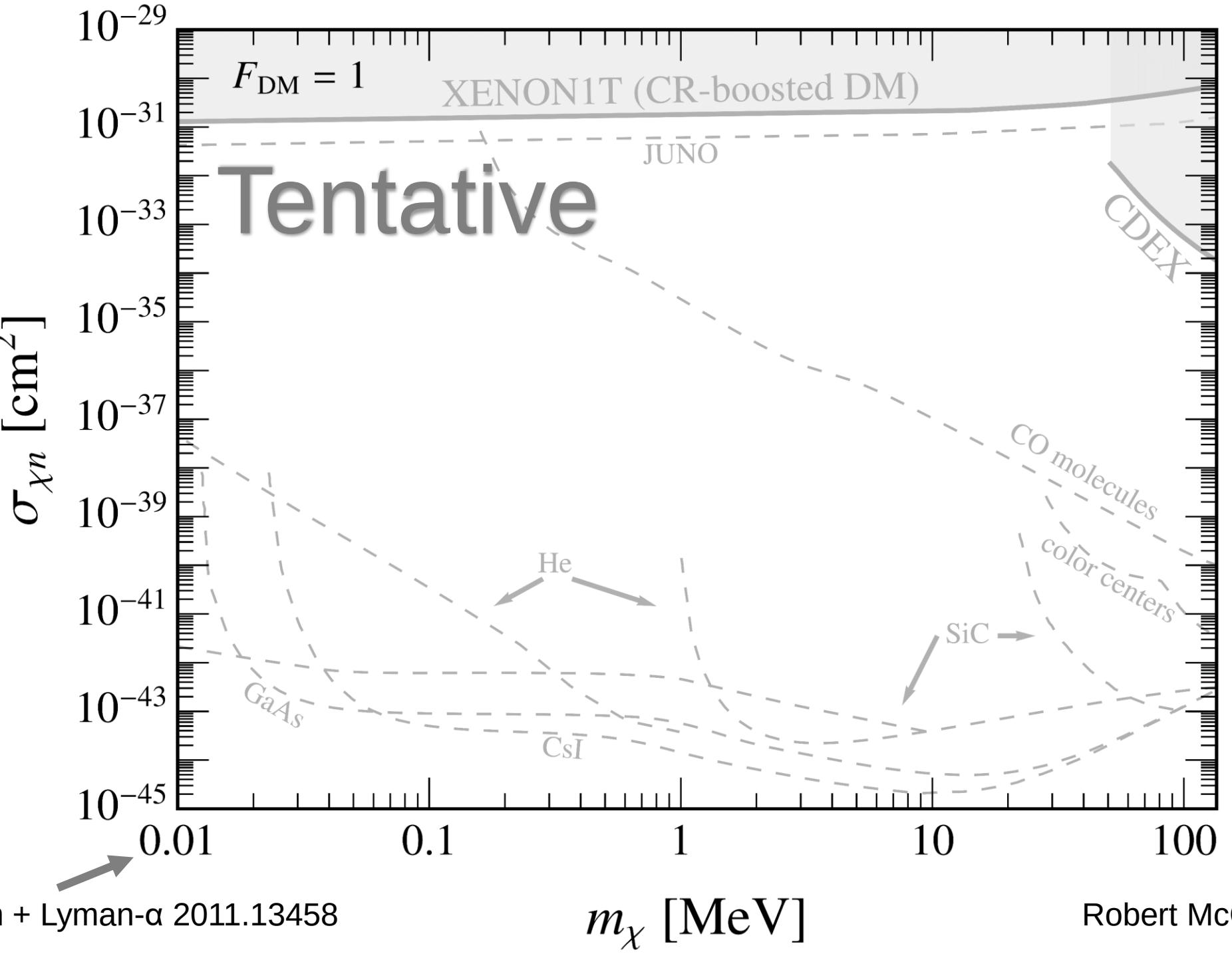
DM Self Interactions



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

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

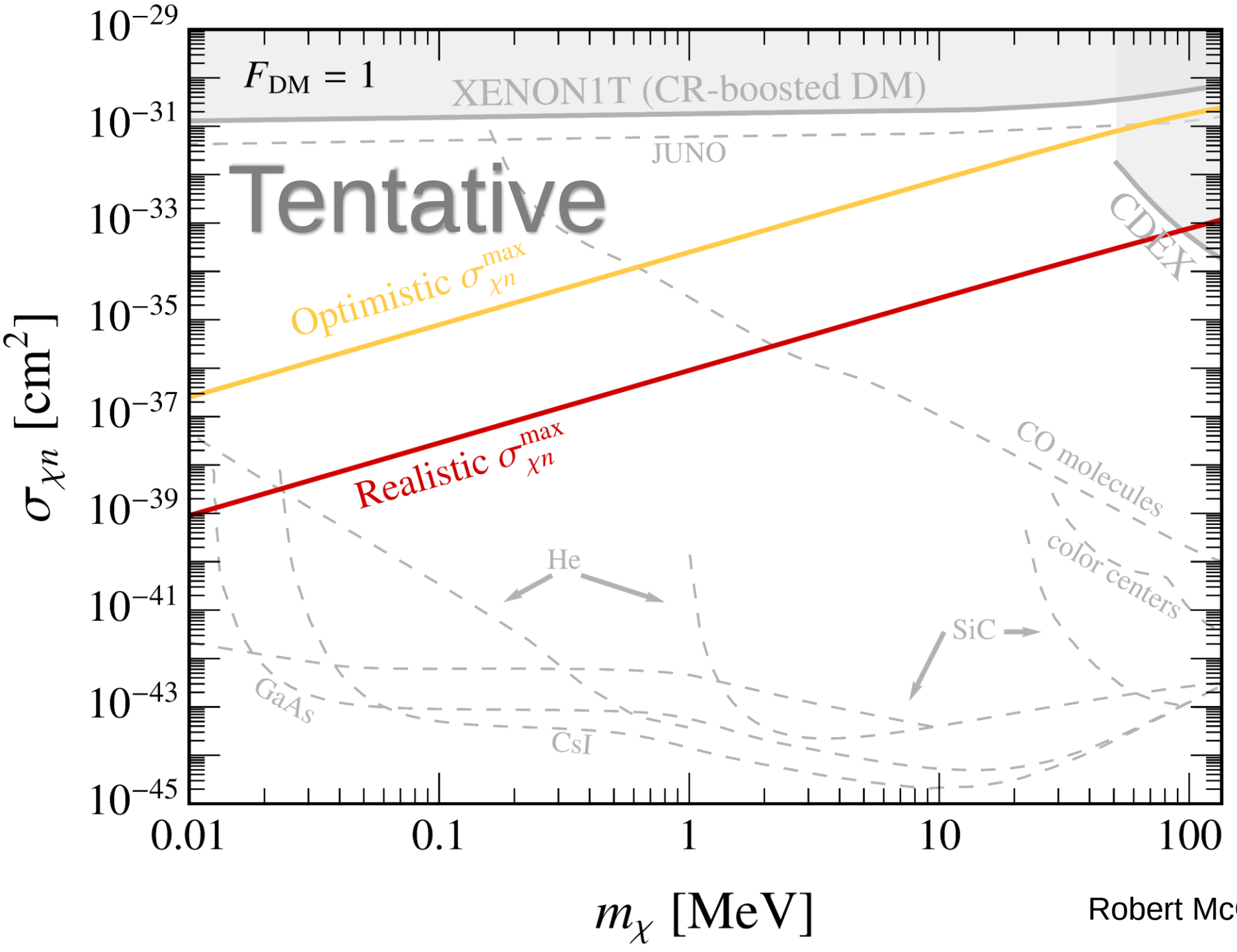
1508.03339



Tentative

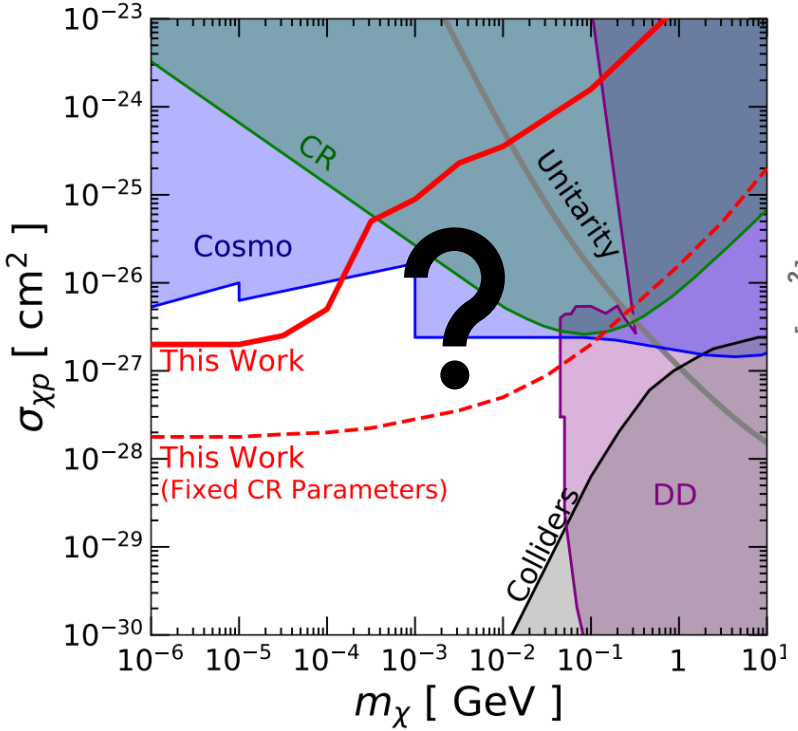
power spectrum + Lyman-α 2011.13458

Robert McGehee

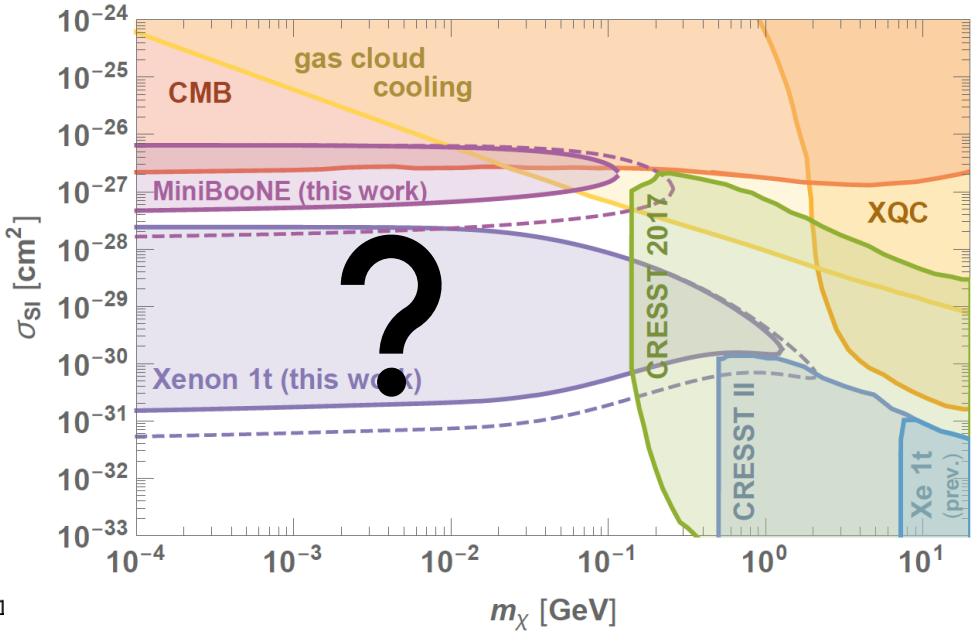


Robert McGehee

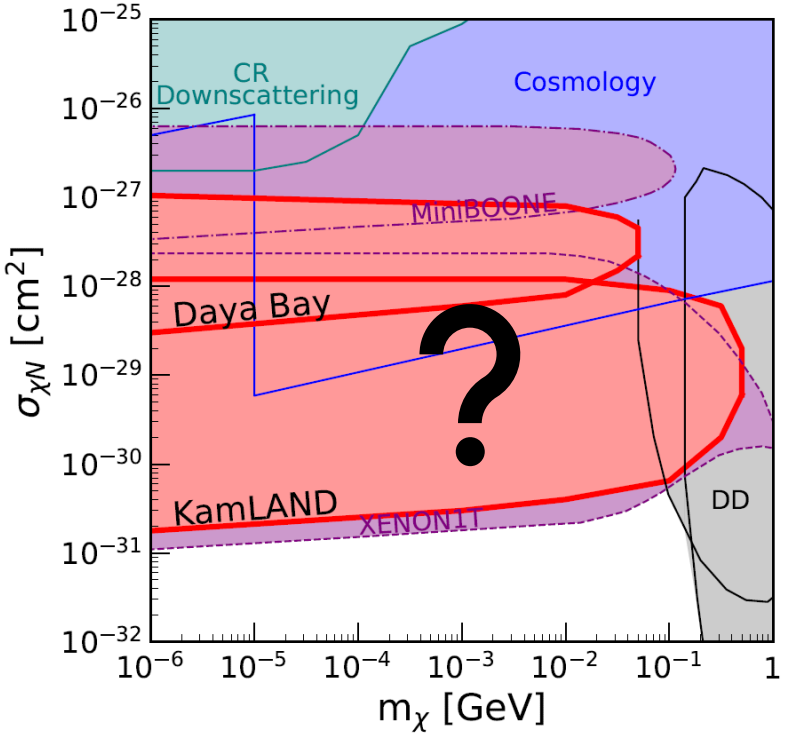
Is Dark Matter here?



1810.07705



1810.10543

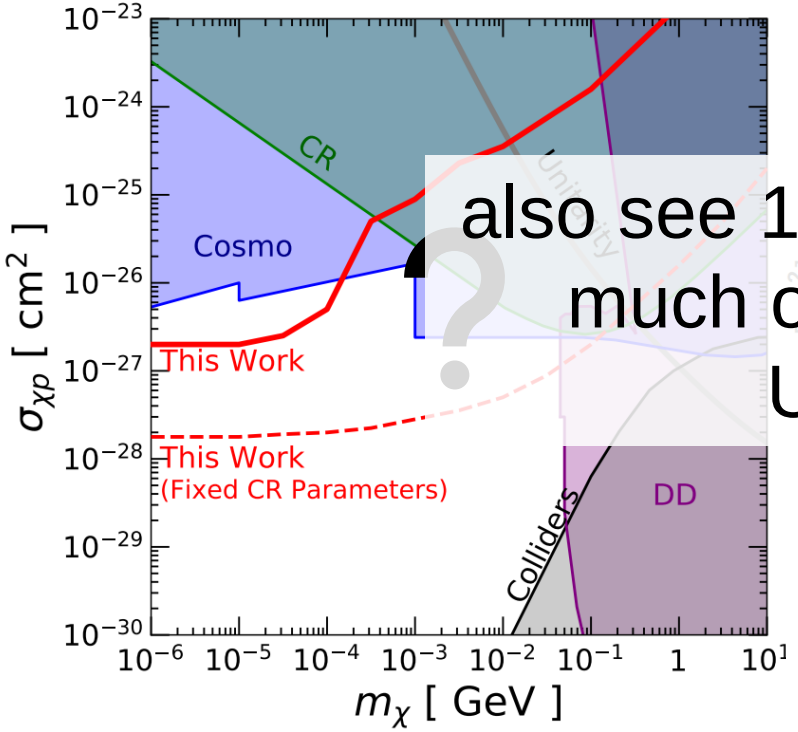


1906.11283

Robert McGehee

Is Dark Matter here?

nope. don't bother.



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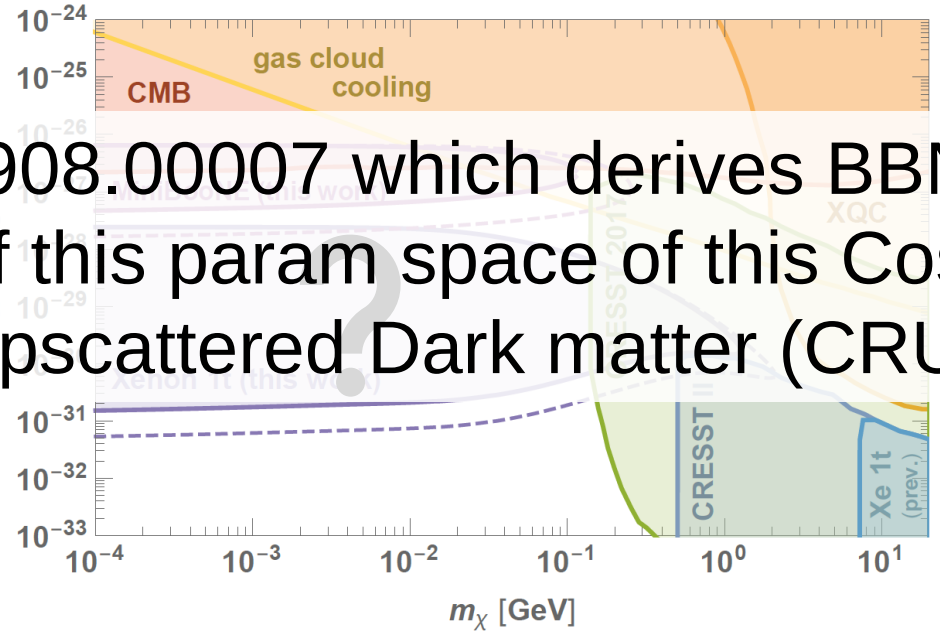

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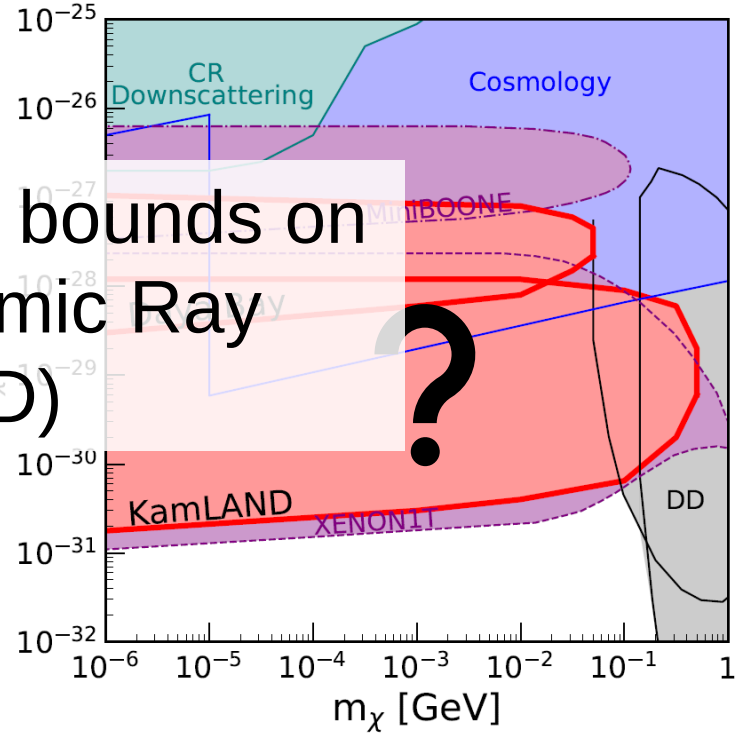


1906.11283

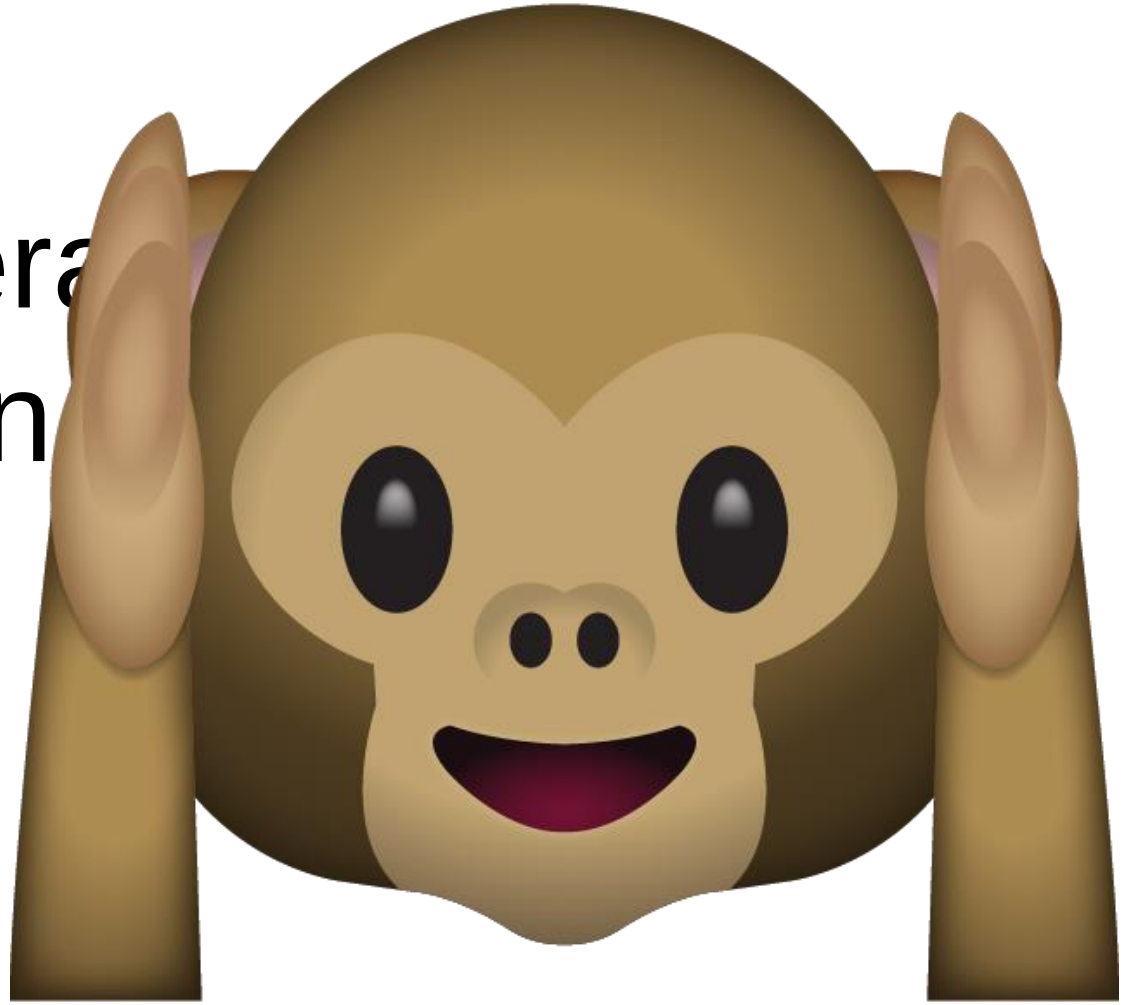
also see 1908.00007 which derives BBN bounds on much of this param space of this Cosmic Ray Upscattered Dark matter (CRUD)

And Now for Something Completely Different

How did the weakly interacting massive particle best Mad Max in a fight?

How did the weakly intera
particle best Mad Max in

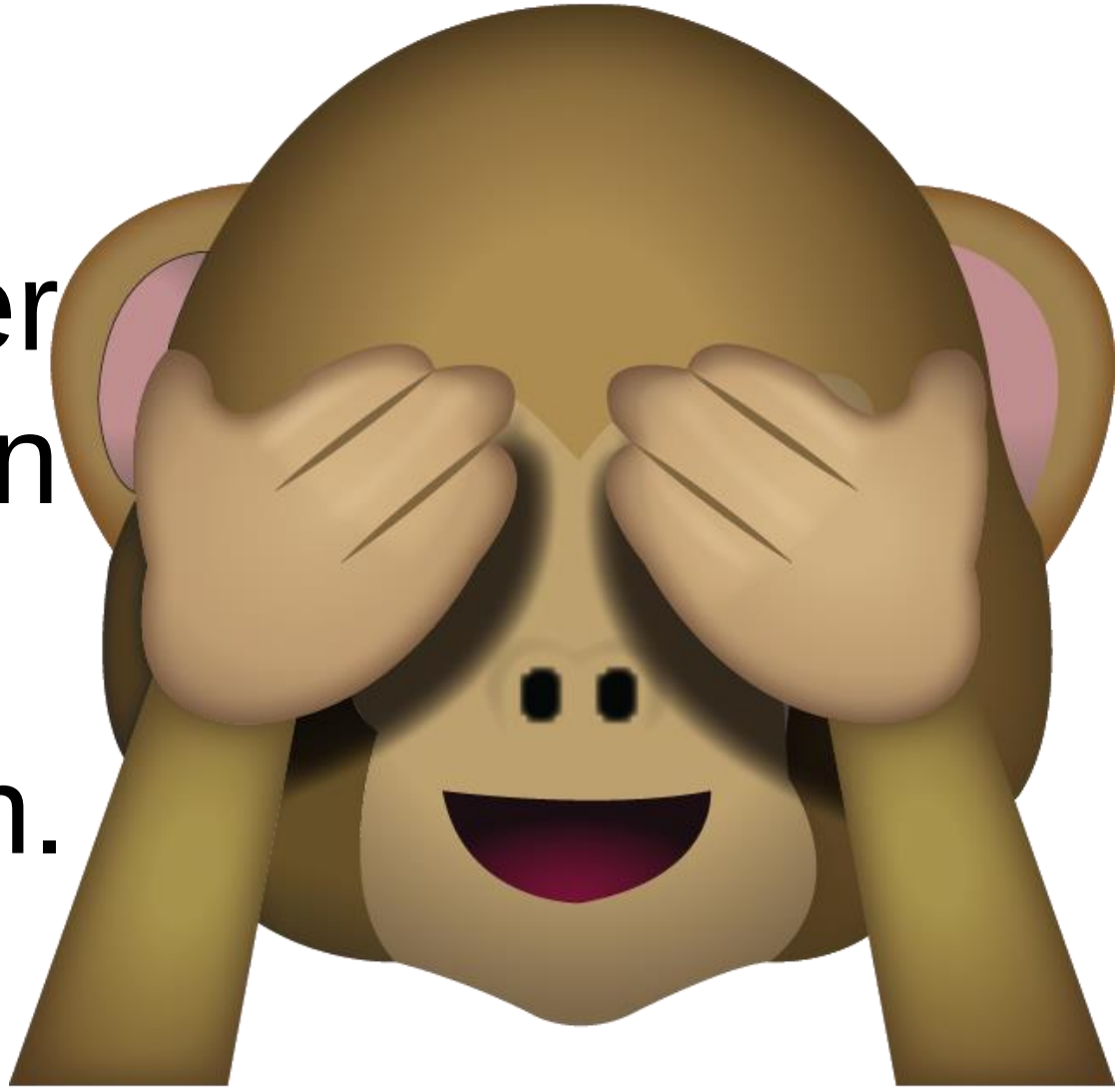
It was madder.



How did the weakly inter particle best Mad Max in

It was madder.

JK. It couldn’t touch him.



Is there a sub-GeV DM candidate which

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

Is there a sub-GeV DM
candidate which
HYPERs
naximal cross section?

HighlY interactive
ParticlE Relics (HYPERs)

HYPER's Origin Story

Ch. 1 UV freeze-in → the relic abundance is set early and depends on the otherwise uninteresting reheat temperature

HYPER's Origin Story

Ch. 1 UV freeze-in

Ch. 2 Dark Sector Phase Transition

Robert McGehee

HYPER's Origin Story

Ch. 1 UV freeze-in

Ch. 2 Dark Sector Phase Transition → other interesting uses of DS PTs, *e.g.* 1608.07578 1912.02830 by Joachim Kopp & co.

HYPER's Origin Story

Ch. 1 UV freeze-in

Ch. 2 Dark Sector Phase Transition

Ch. 3 Mediator Mass Drop

Robert McGehee

HYPER's Origin Story

Ch. 1 UV freeze-in

Ch. 2 Dark Sector Phase Transition

Ch. 3 Mediator Mass Drop

Ch. 4 Cross Section Grows!

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

HYPER's Origin Story

Ch. 1 UV freeze-in

Ch. 2 Dark Sector Phase Transition

Ch. 3 Mediator Mass Drop

Ch. 4 Cross Section Grows!

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

- Changes relic abundance?
- BBN bounds?
- CMB bounds?

🚩Changes relic abundance?

$$\bar{\chi}\chi \to \text{hadrons}$$

🚩Changes relic abundance?

$$m_\chi < m_{\pi^0} \longrightarrow \bar{\chi}\chi \not\to \text{hadrons}$$

🚩Changes relic abundance?

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

$$\text{hadrons} \to \bar{\chi}\chi$$

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

🚩Changes relic abundance? ☑

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

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

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

🚩BBN bounds? CMB bounds?

🚩BBN bounds? ☑ CMB bounds?

$$1\ \mathrm{MeV} \lesssim T_{\mathrm{PT}} \longrightarrow \mathrm{BBN\ OK}$$

🚩BBN bounds? ☑ CMB bounds? ☑

$$1\ \mathrm{MeV} \lesssim T_{\mathrm{PT}} \longrightarrow \mathrm{BBN\ OK}$$

$$m_\chi < m_{\pi^0} \longrightarrow \bar{\chi}\chi \not\rightarrow \mathrm{hadrons}$$

Robert McGehee

HYPER's Origin Story

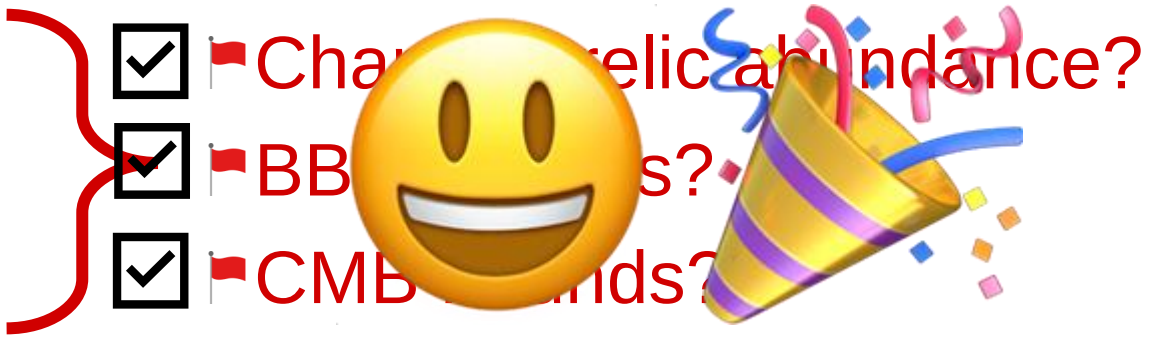
Ch. 1 UV freeze-in

Ch. 2 Dark Sector Phase Transition

Ch. 3 Mediator Mass Drop

Ch. 4 Cross Section Grows!

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



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

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

Possible if

$$m_\chi > m_\phi$$

$$T_{\rm PT} > m_\phi$$

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

Possible if

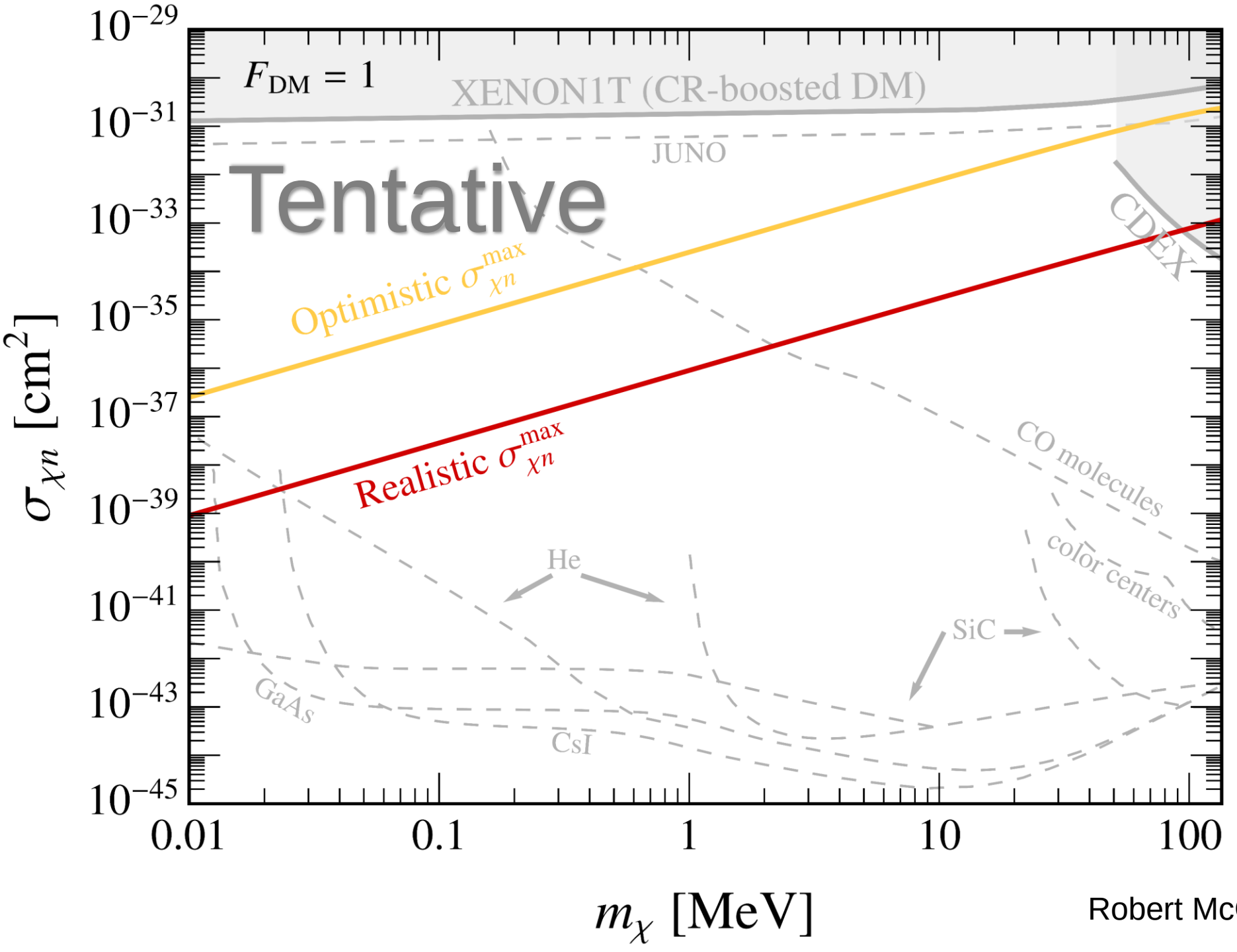
$$m_\chi > m_\phi$$

$$T_{\rm PT} > m_\phi$$

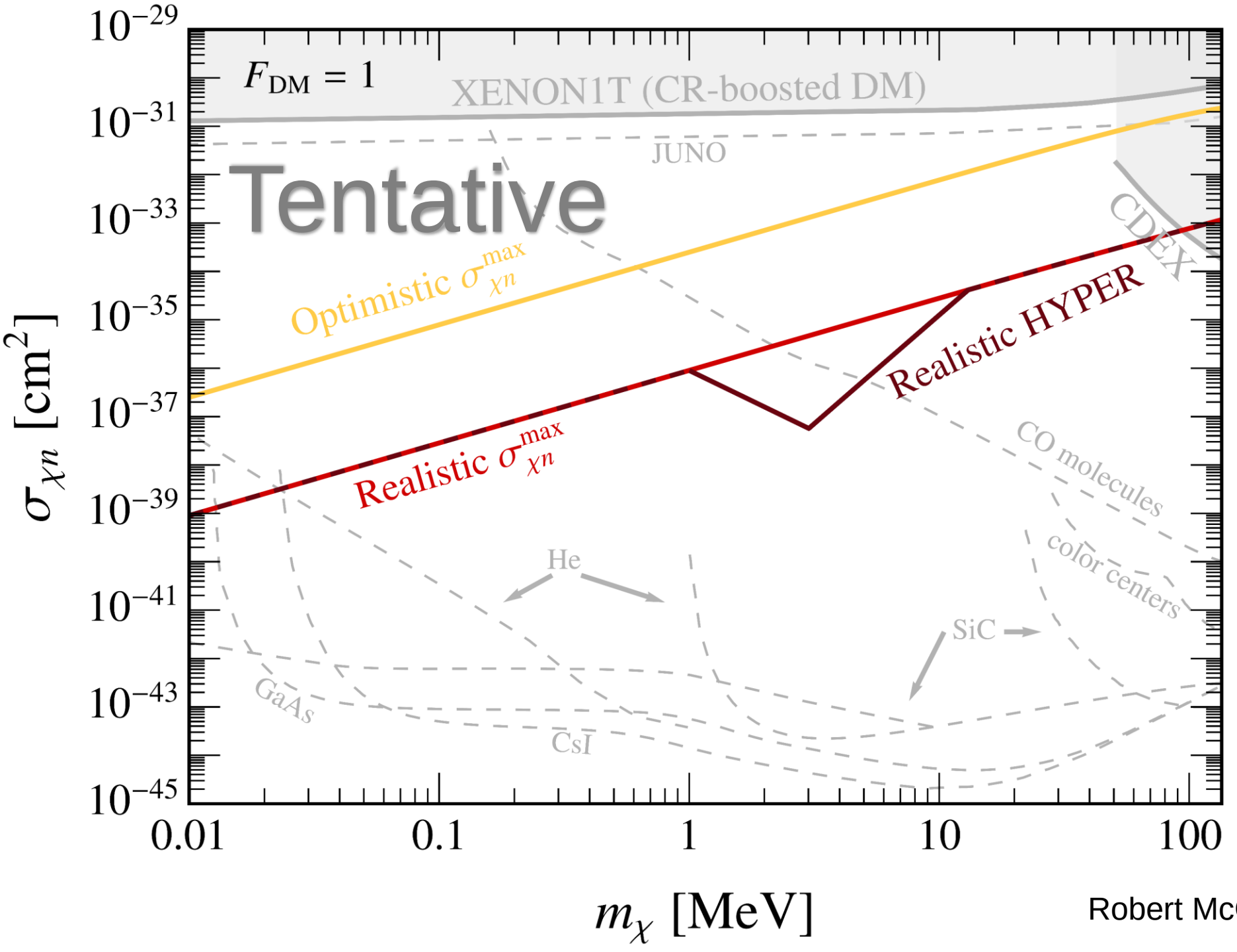
Require that

$$(\sigma v)_{\chi\bar{\chi}\to\phi\phi} n_\chi \Big|_{T_{\rm PT}} < H\Big|_{T_{\rm PT}}$$

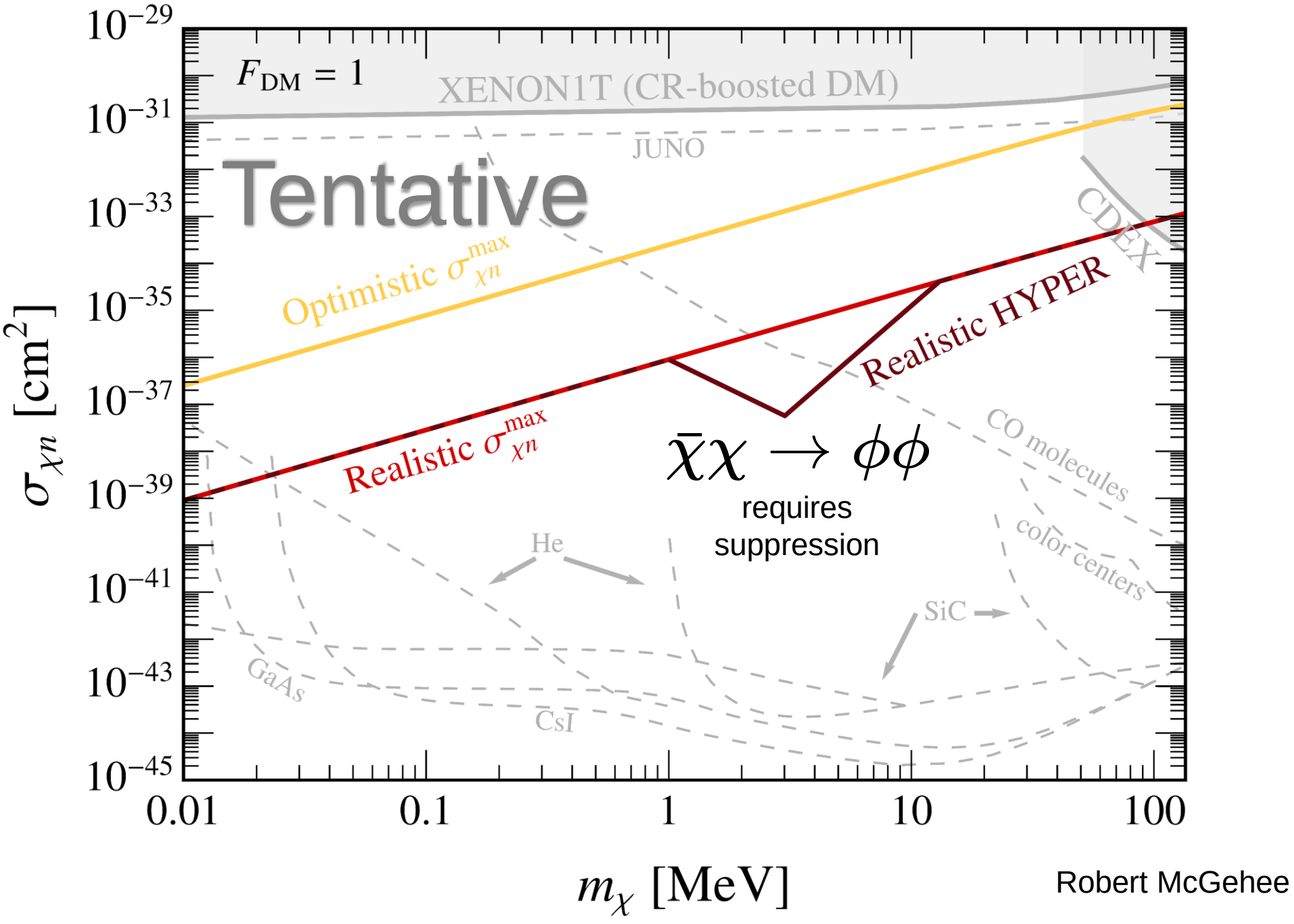
Results



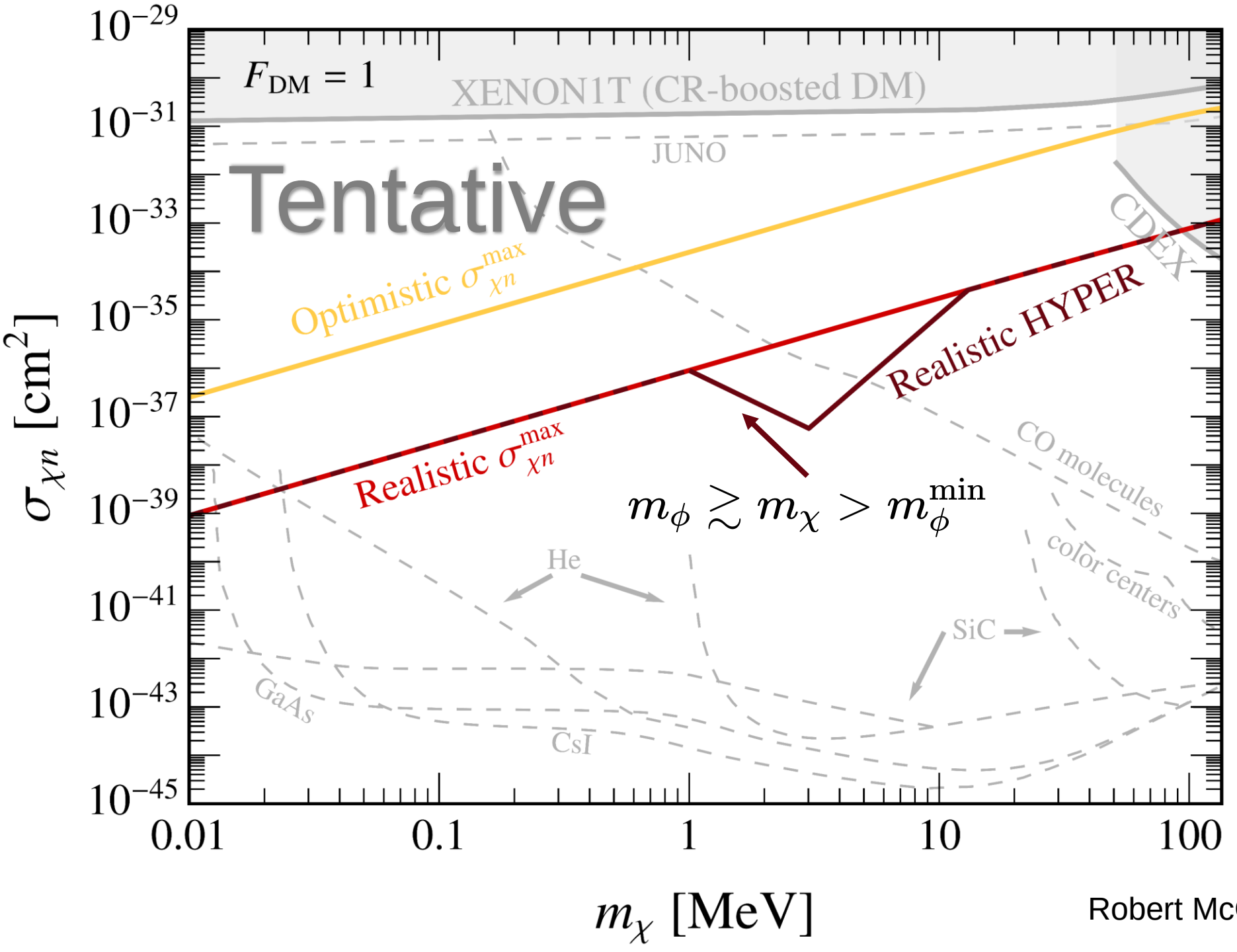
Robert McGehee



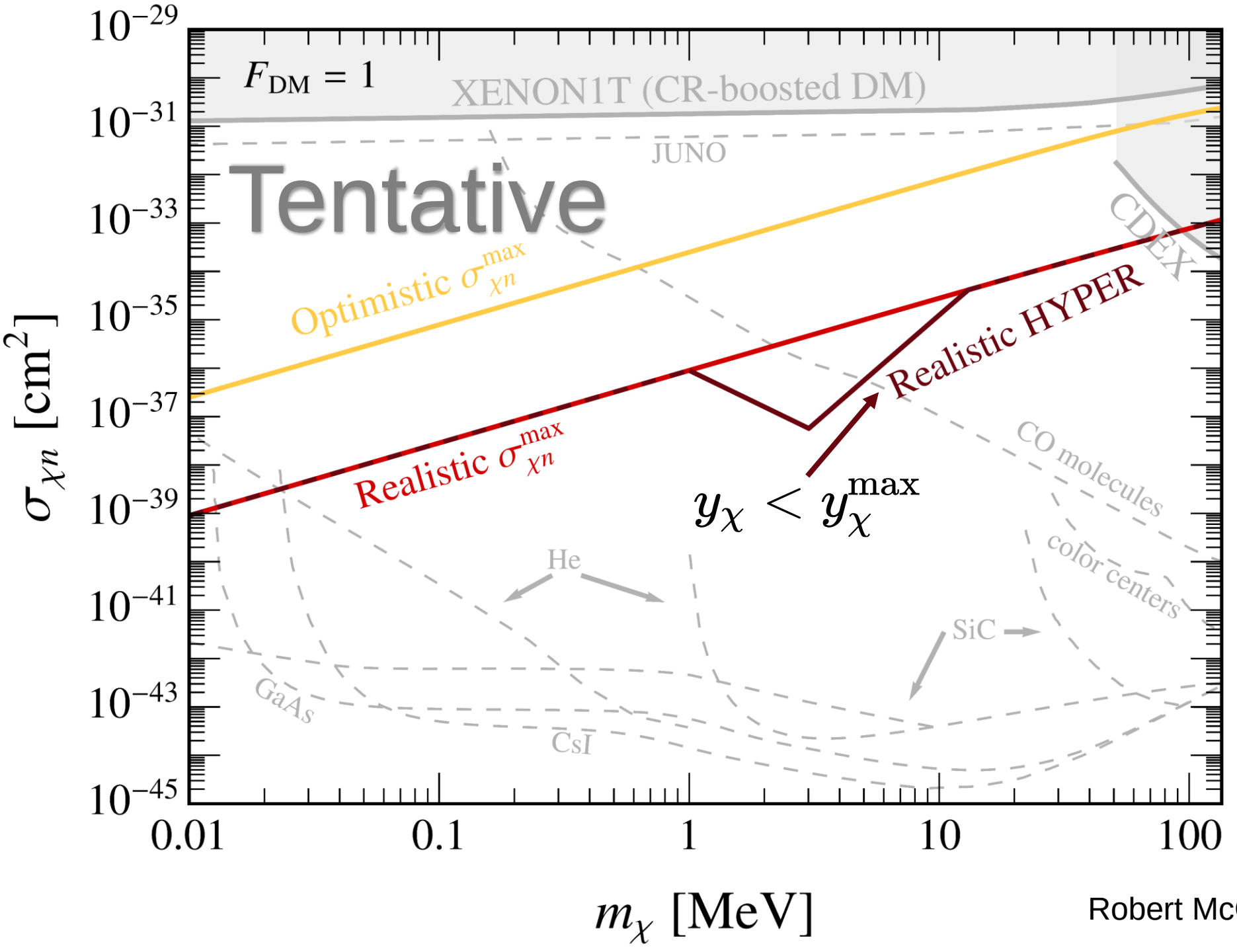
Robert McGehee



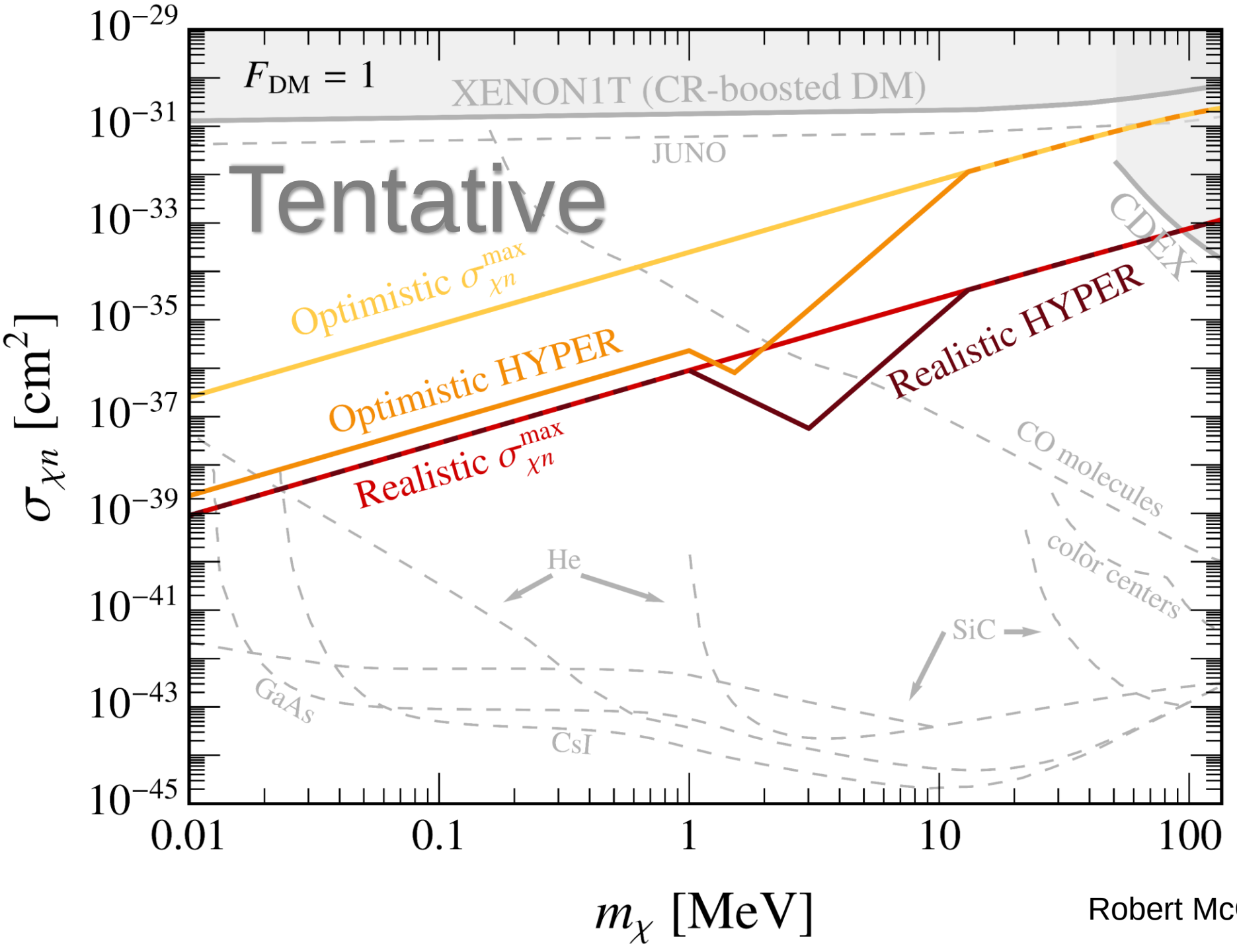
Robert McGehee



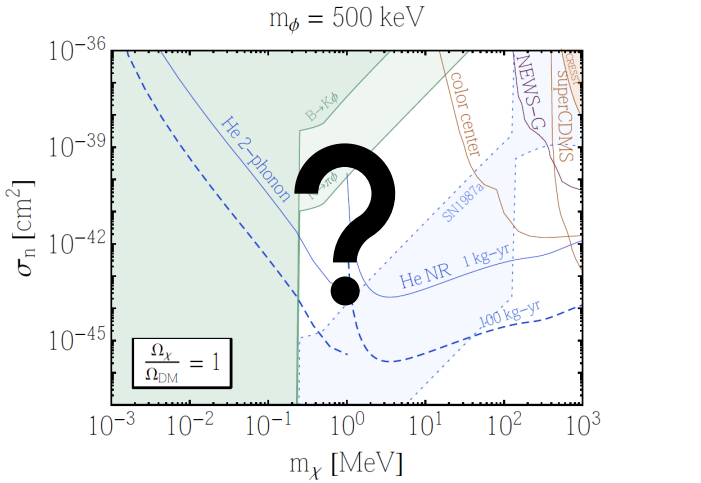
Robert McGehee

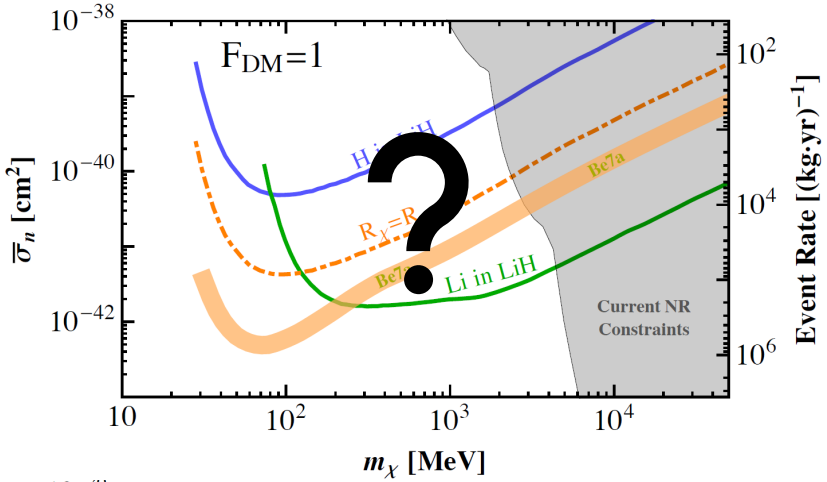


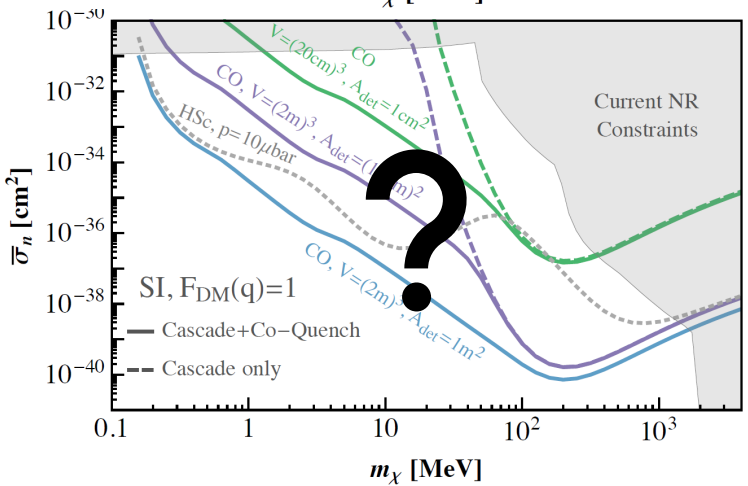
Robert McGehee



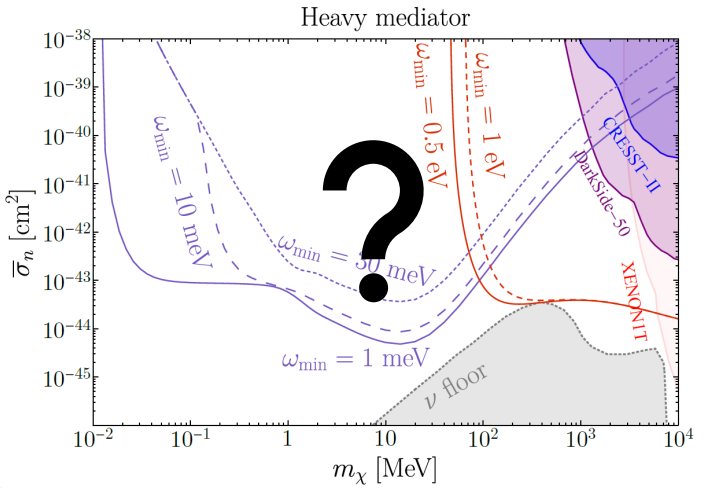
Robert McGehee

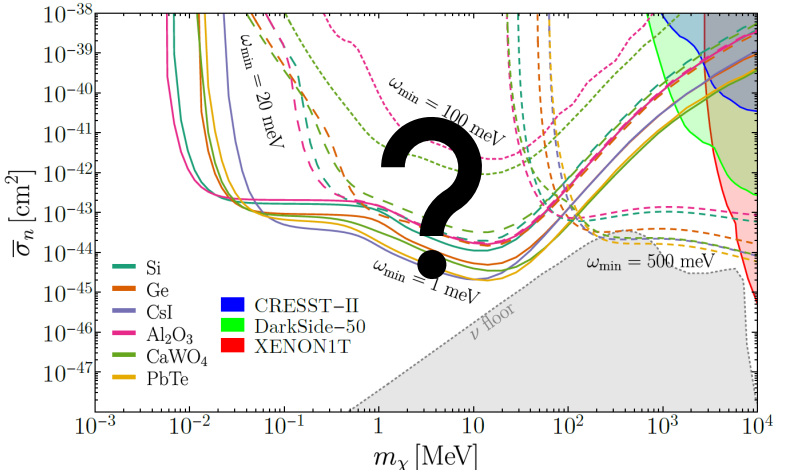


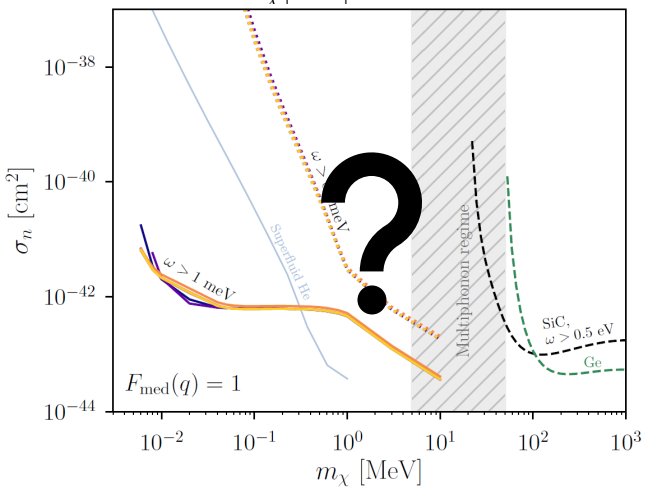


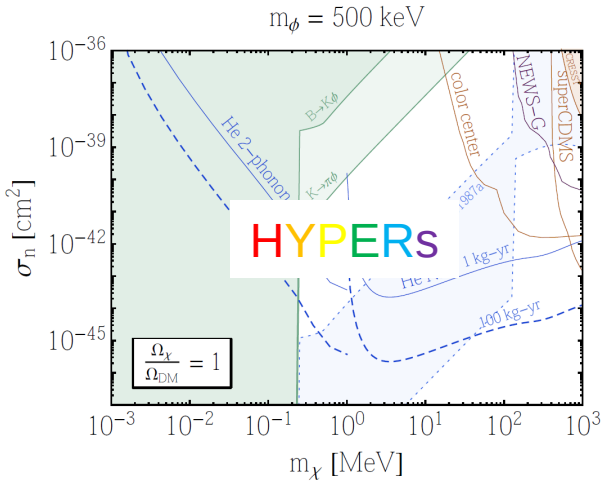


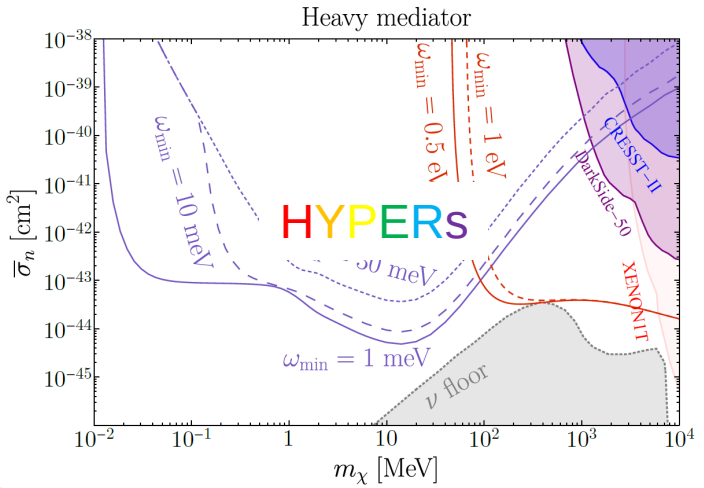
Where is the Dark Matter?

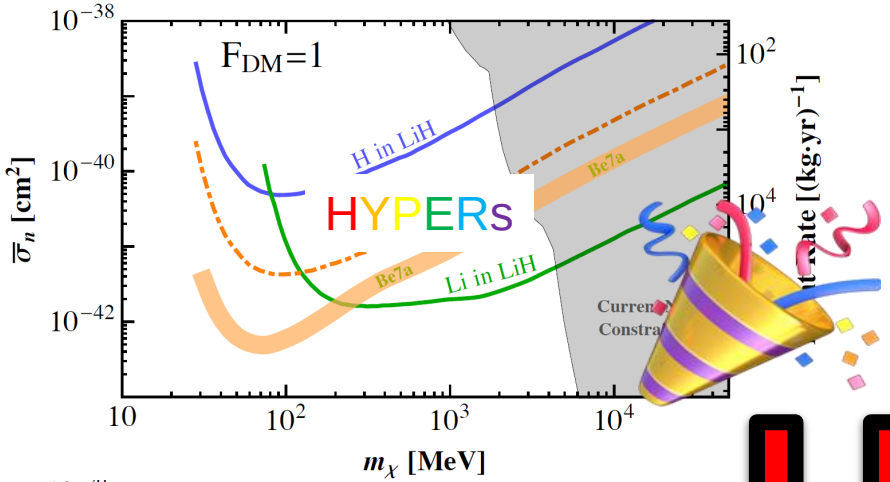


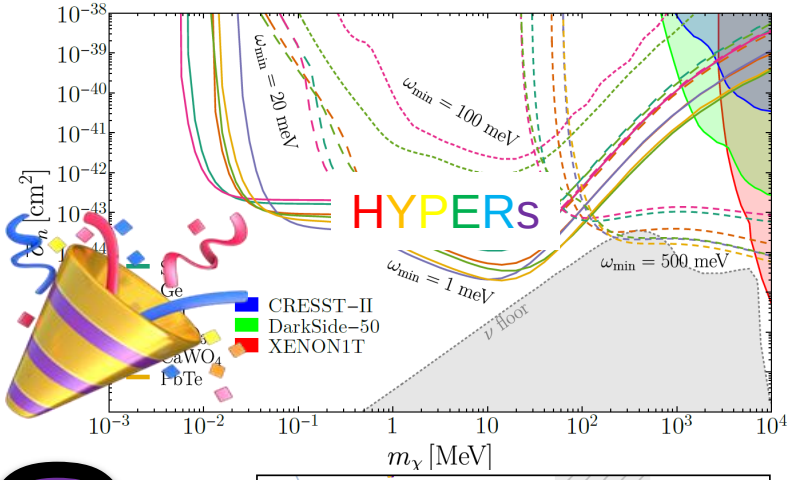






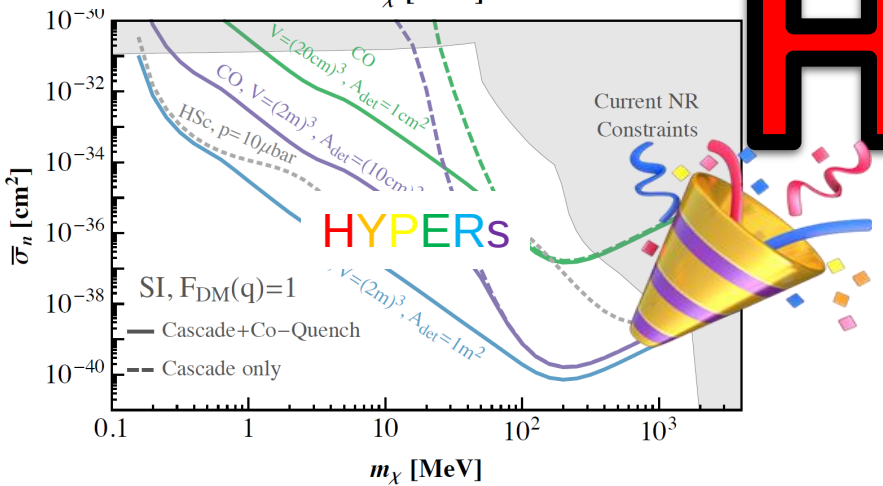


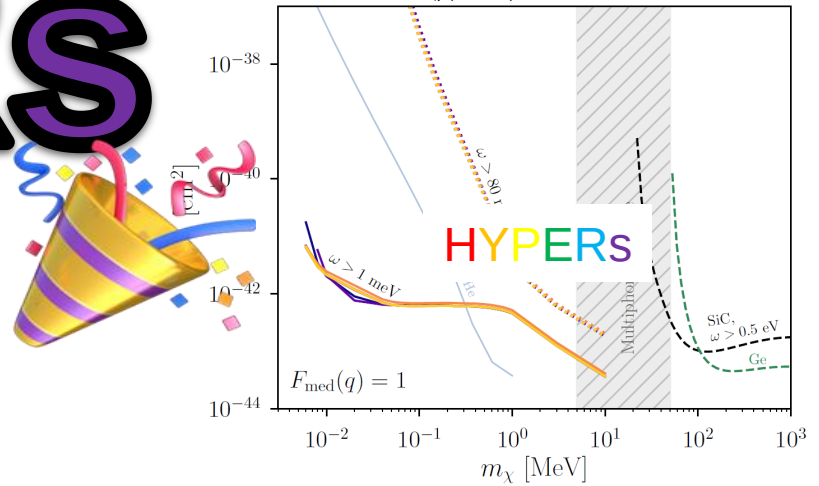




Where is the Dark Matter?

HYPERs





Future Directions

HYPER Building

Heavy HYPERs

>10 TeV

Larger Indirect detection at CTA

HYPER Building

Heavy HYPERs

- >10 TeV
- Larger Indirect detection at CTA

Leptophilic HYPERs

- electron-scattering experiments
- PT below electron mass

Robert McGehee

HYPER Building

Heavy HYPERs

- >10 TeV
- Larger Indirect detection at CTA

Leptophilic HYPERs

- electron-scattering experiments
- PT below electron mass

Vector Mediator

- different present-day bounds apply
- hadrophilic
- *B-L*

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Cosmology of Late(!) DS PTs

Necessary(?) for leptophilic HYPERs

Are there generic bounds?

Work arounds?

Interplay with stellar/SN bounds?

Is Dark Matter here?

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

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↳ Is there a sub-GeV DM candidate which

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A: HYPERs

Danke schön!

Robert McGehee

Backup Slides

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

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

$$f_0(q) = 0.33\left(1 - \frac{q^2}{38\ \mathrm{GeV}^2}\right).$$

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

An Antiwitz

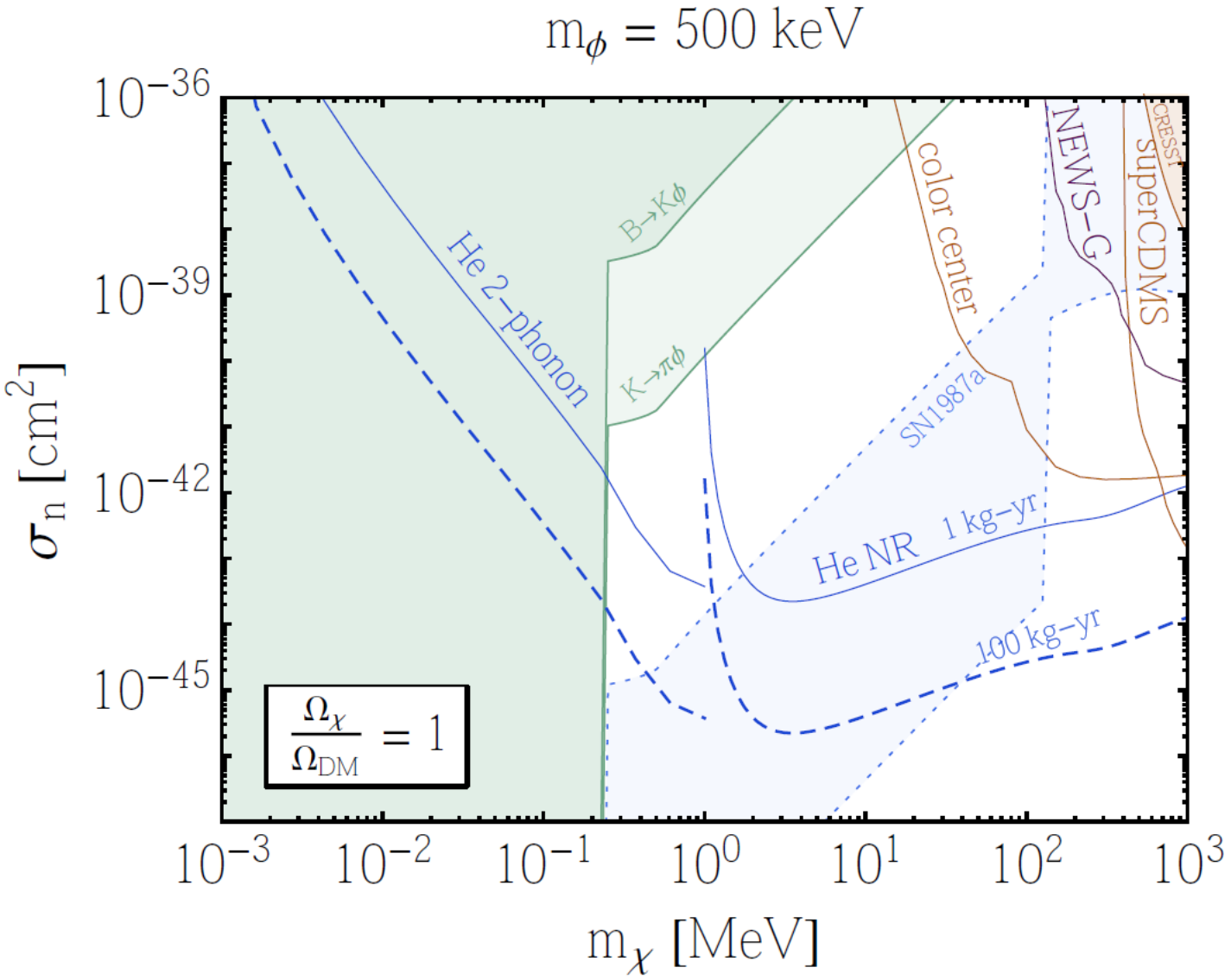
Two muffins are next to each other baking in the oven. Suddenly, one of them says, “Is it hot in here or is it just me?” to which the other muffin replies:

An Antiwitz

Two muffins are next to each other baking in the oven. Suddenly, one of them says, “Is it hot in here or is it just me?” to which the other muffin replies:

“Holy shit! It’s a talking muffin!”

Superfluid Helium (1611.06228,1709.07882)



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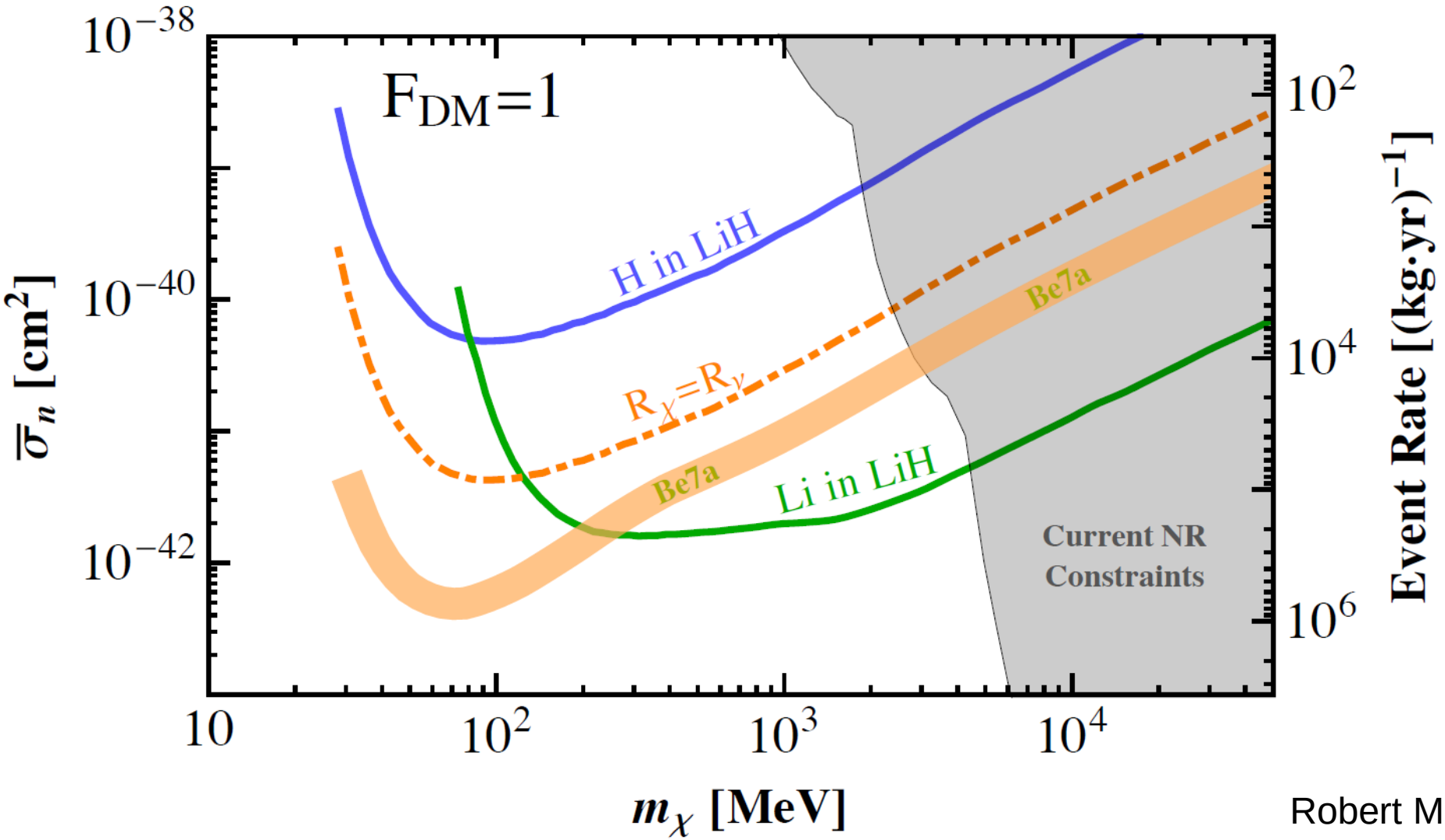
Color Center Production in Crystals

(1705.03016)



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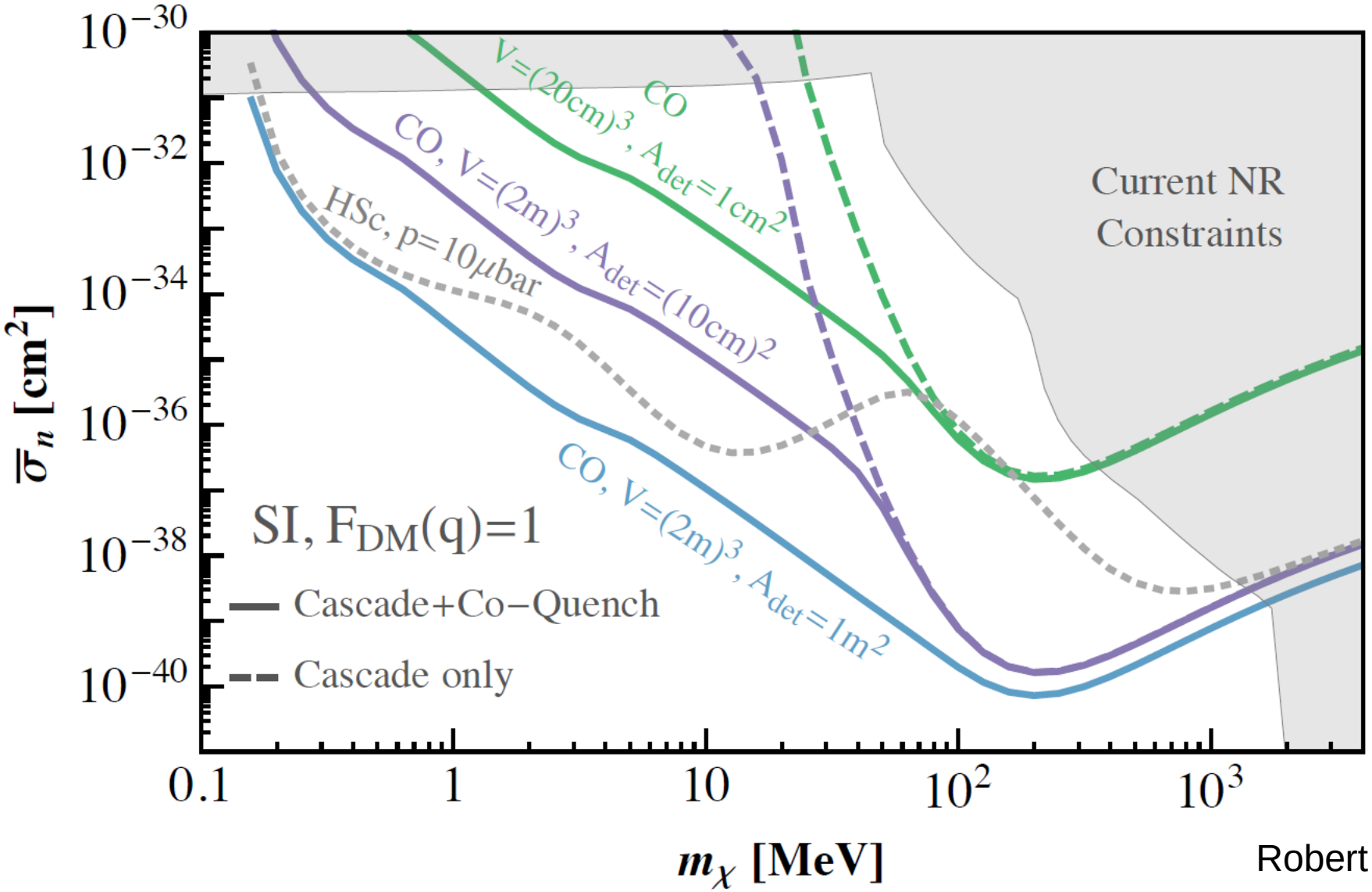
Molecular Excitations (1907.07682)



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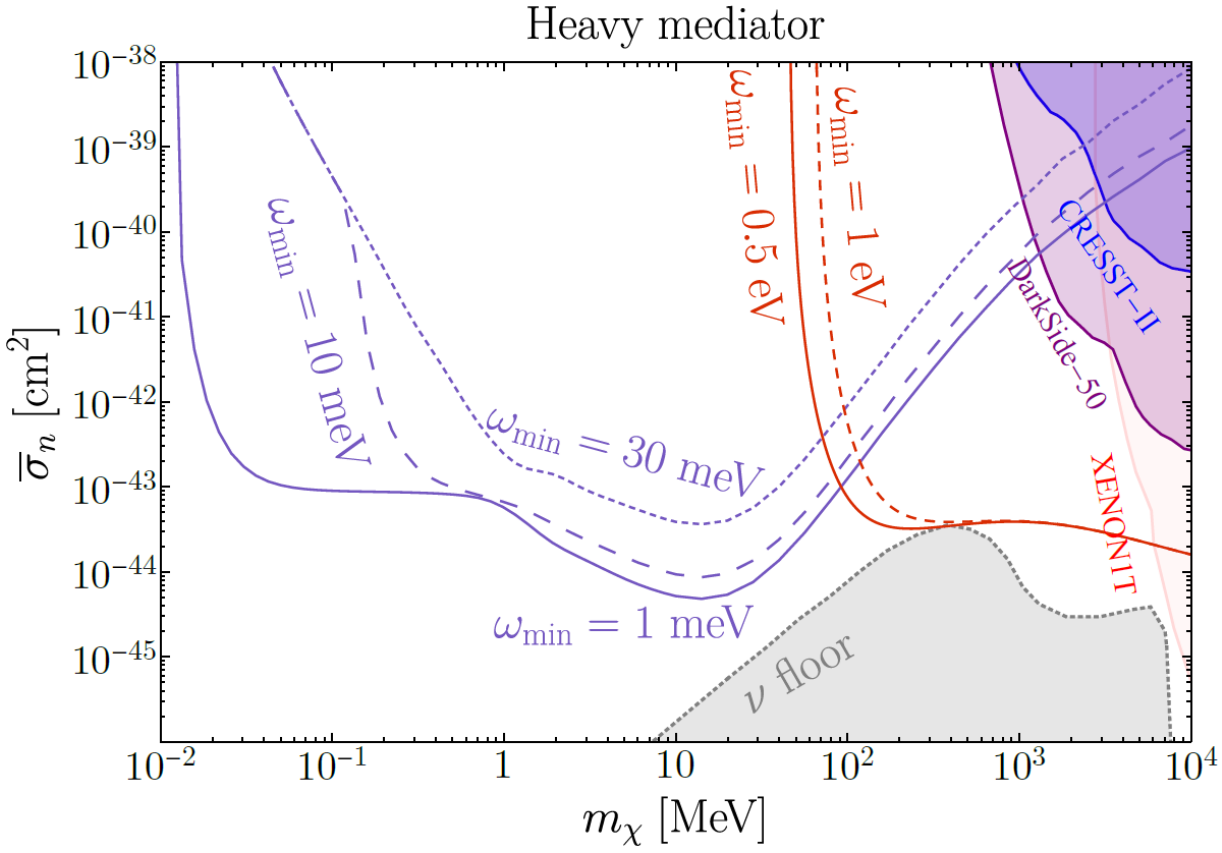
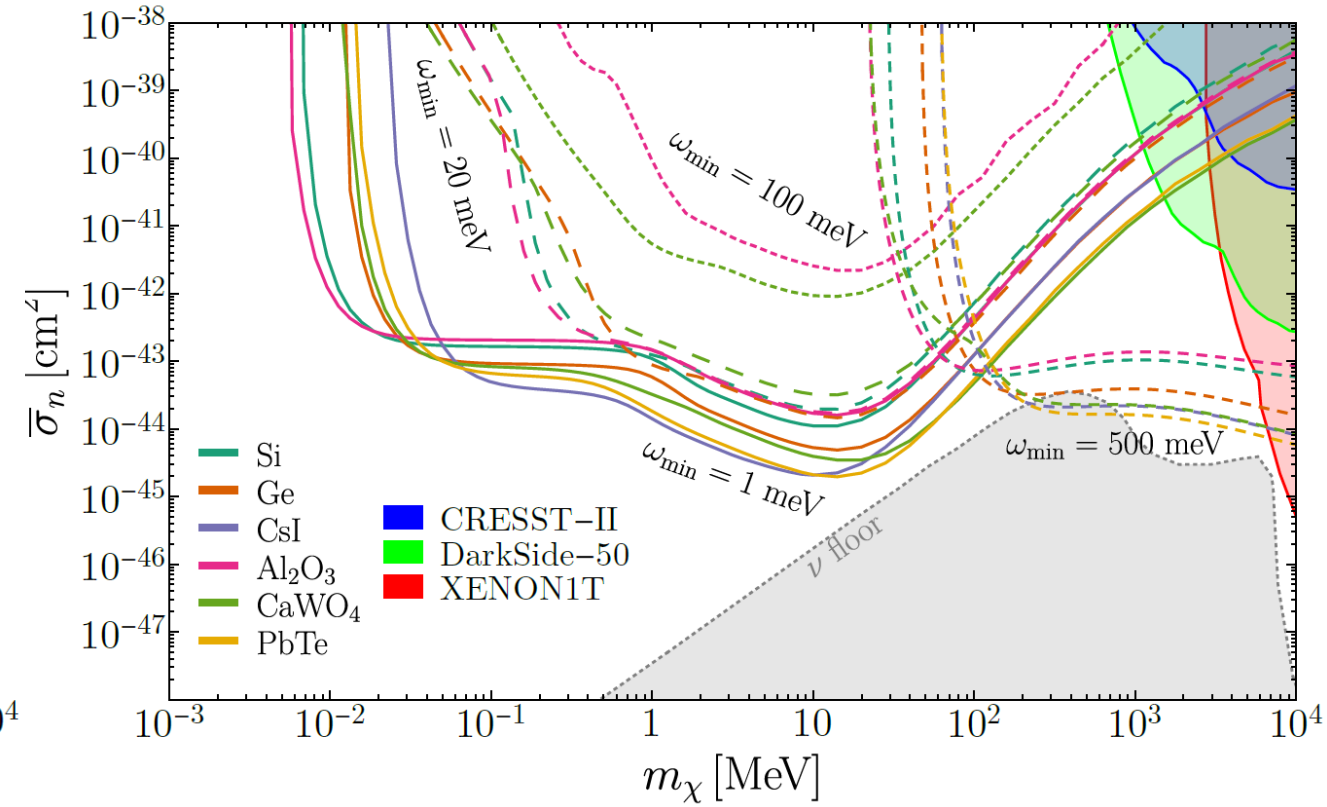
Multiple Channels (recoils, transitions, phonons)

(1910.08092, 1910.10716)





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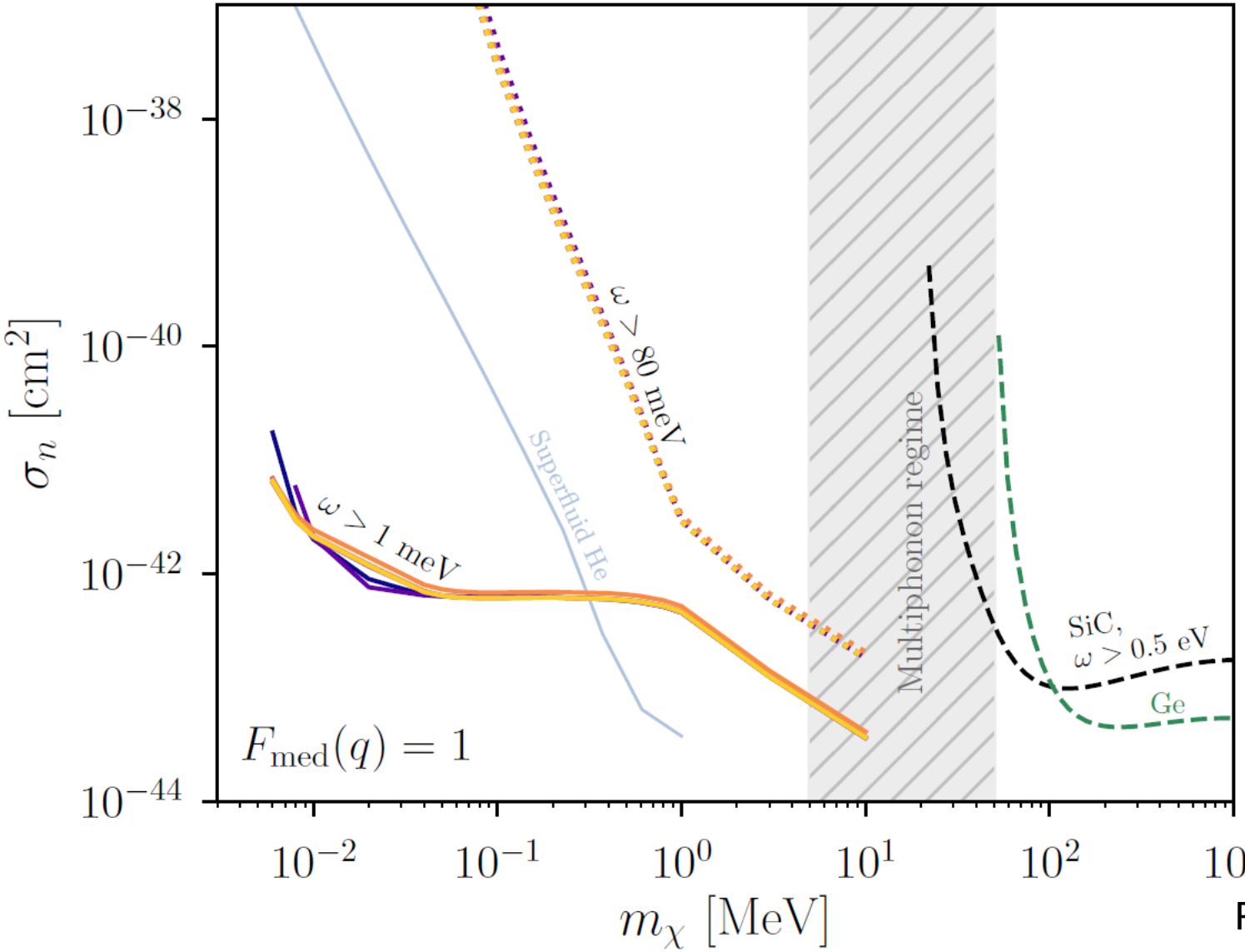
Silicon Carbide (SiC) (2008.08560)



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