The Power of the Dark Sink

Robert McGehee

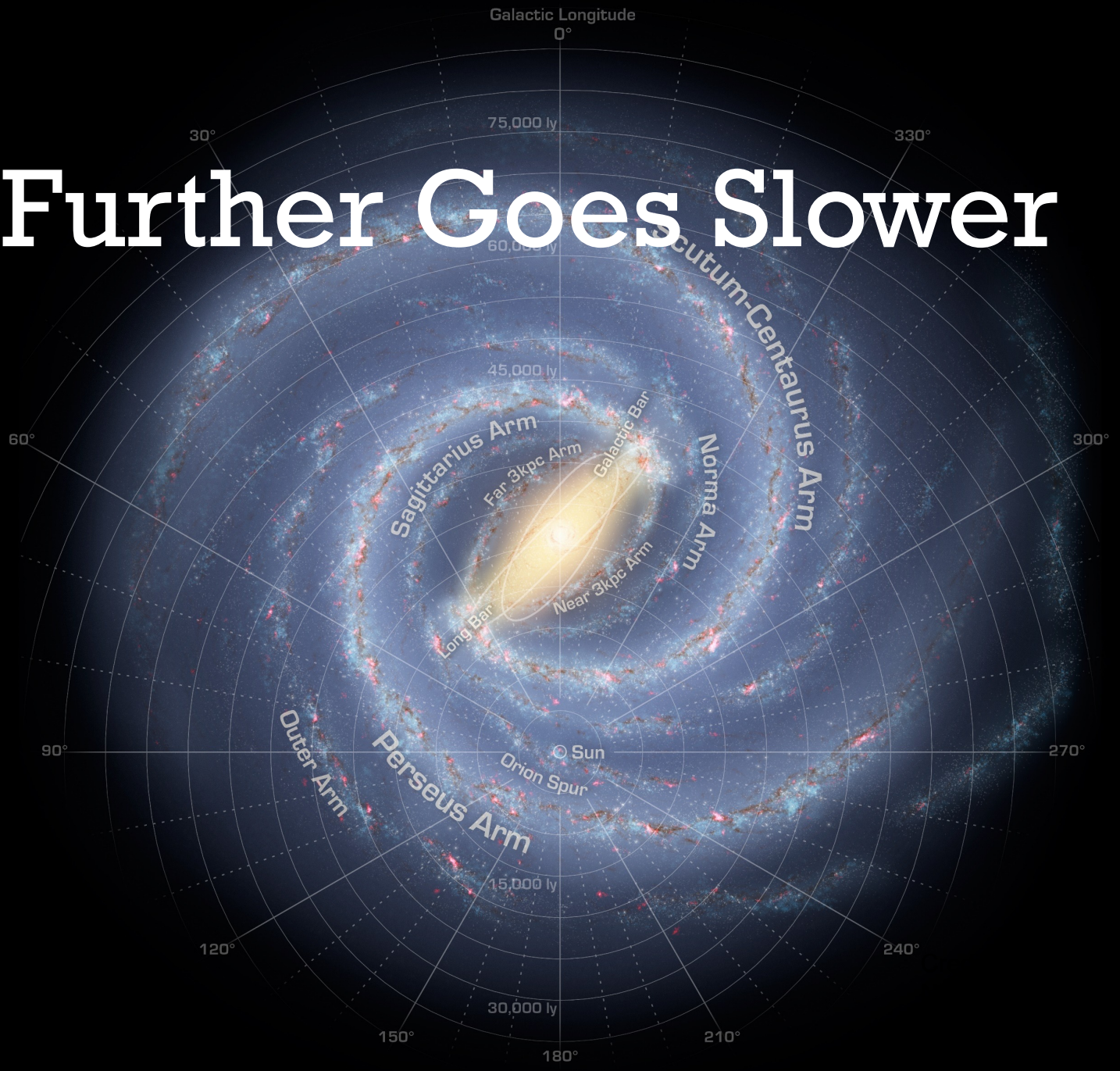
University of Minnesota

CETUP* 2024 6/24

“The” Dark Matter Slide

R McGehee

Further Goes Slower

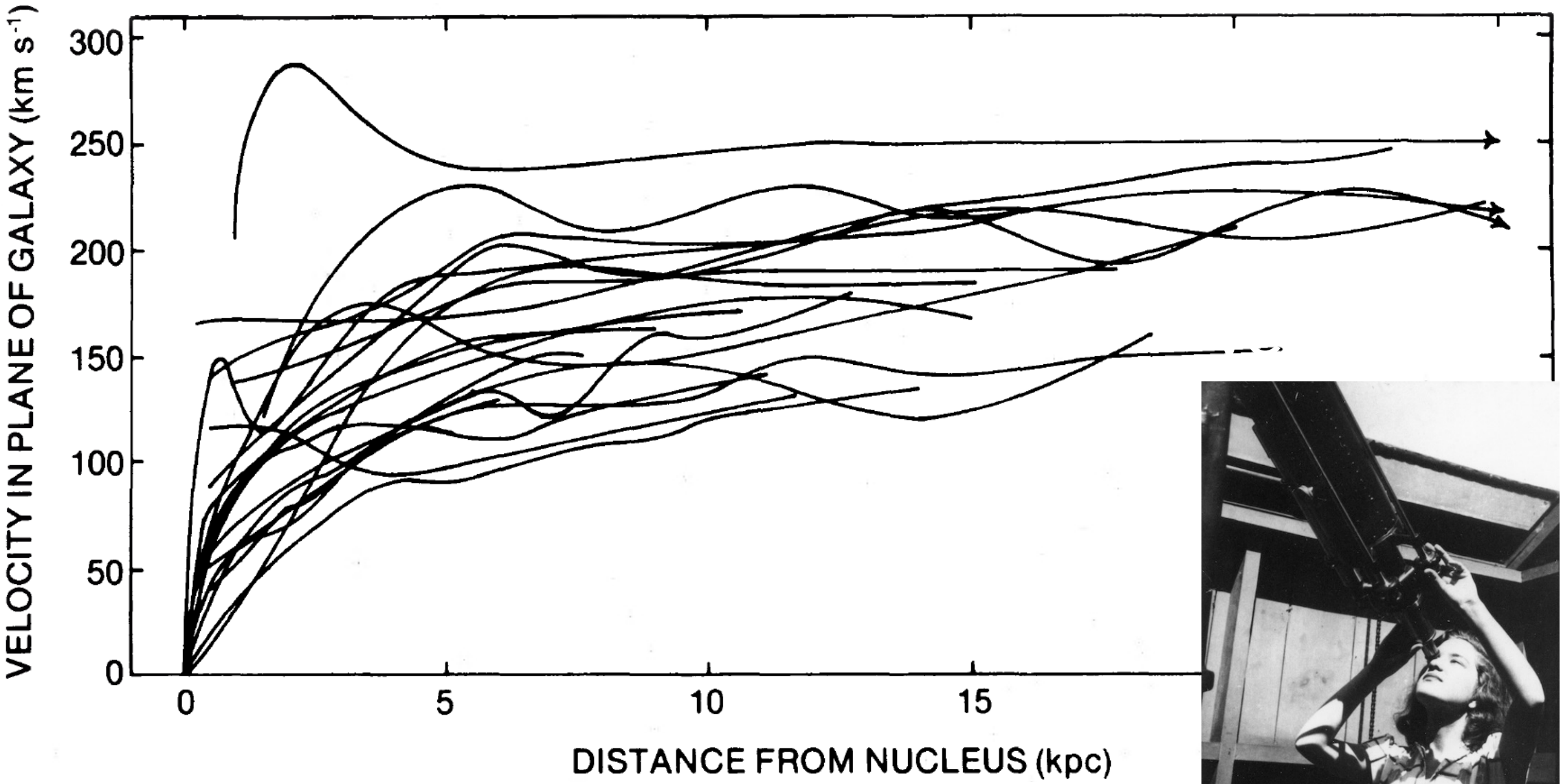


Further Goes Slower

Further Goes Similar!

Credit: Vassar College, courtesy AIP Emilio Segrè Visual Archives

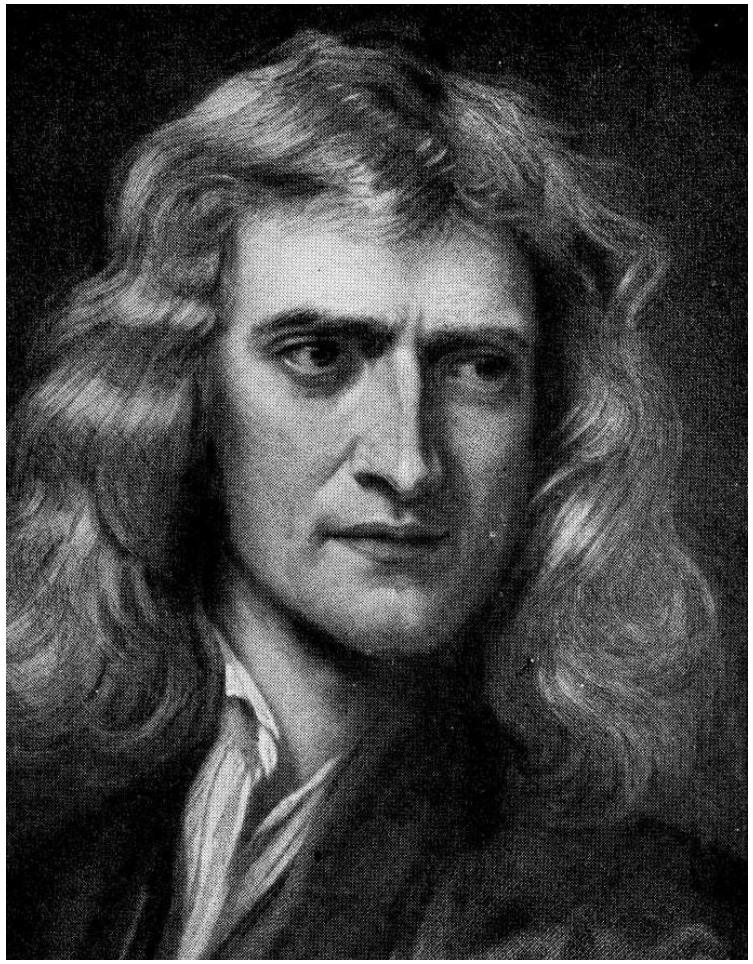
Vera Rubin

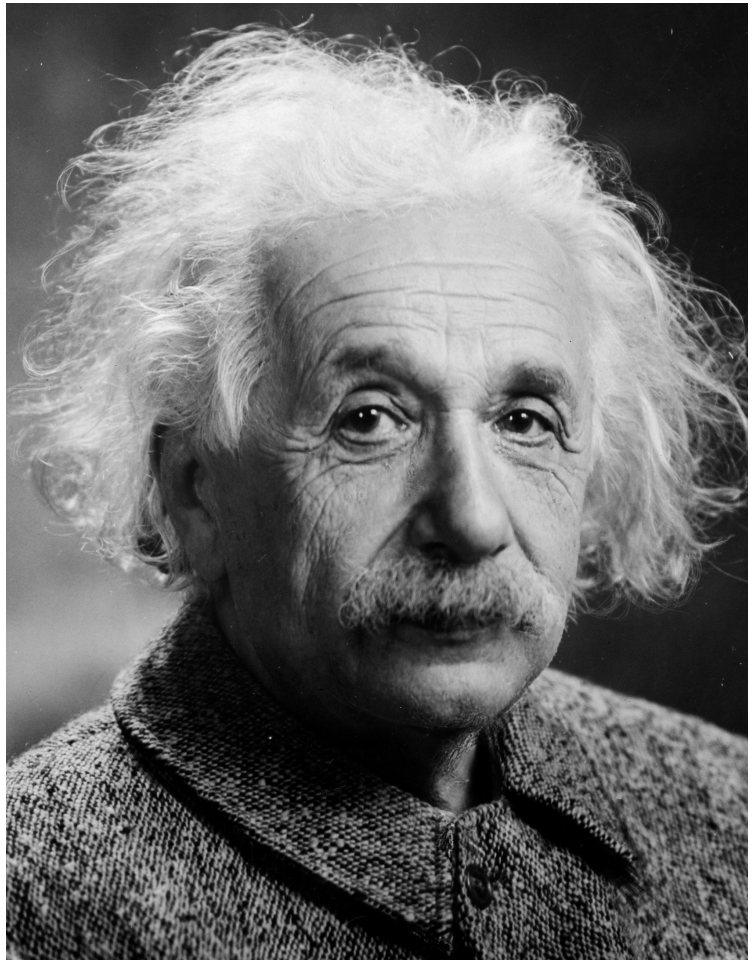


V.C. Rubin, N. Thonnard, W.K. Ford, Jr. Astrophys. J. 238 (1980) 471

Credit: Vassar College, courtesy AIP Emilio Segrè Visual Archives

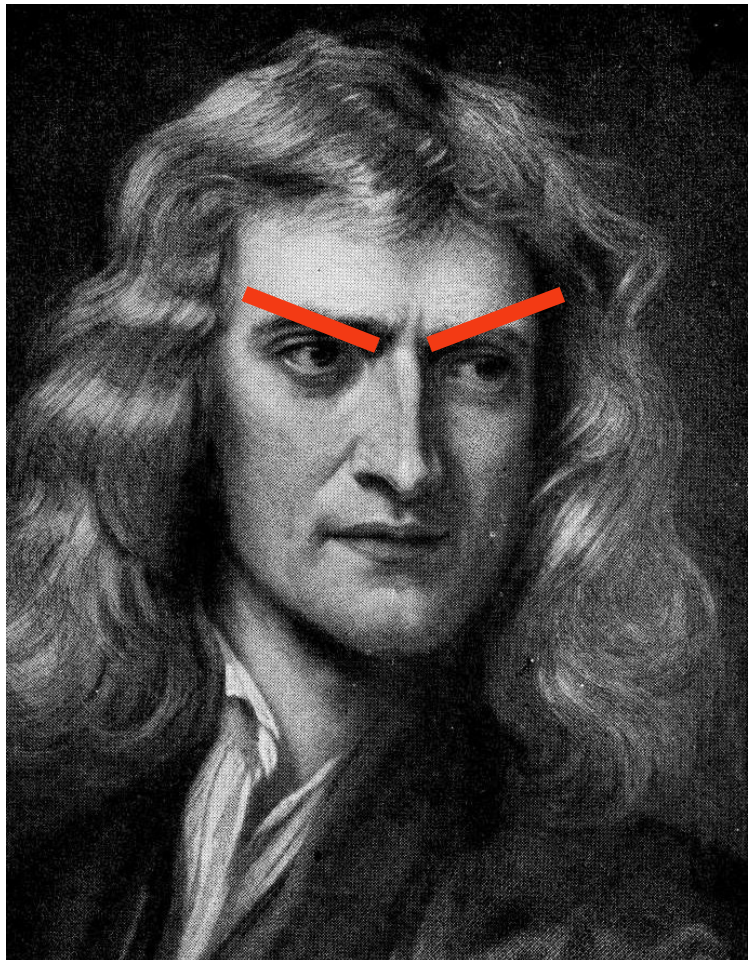
Oops?

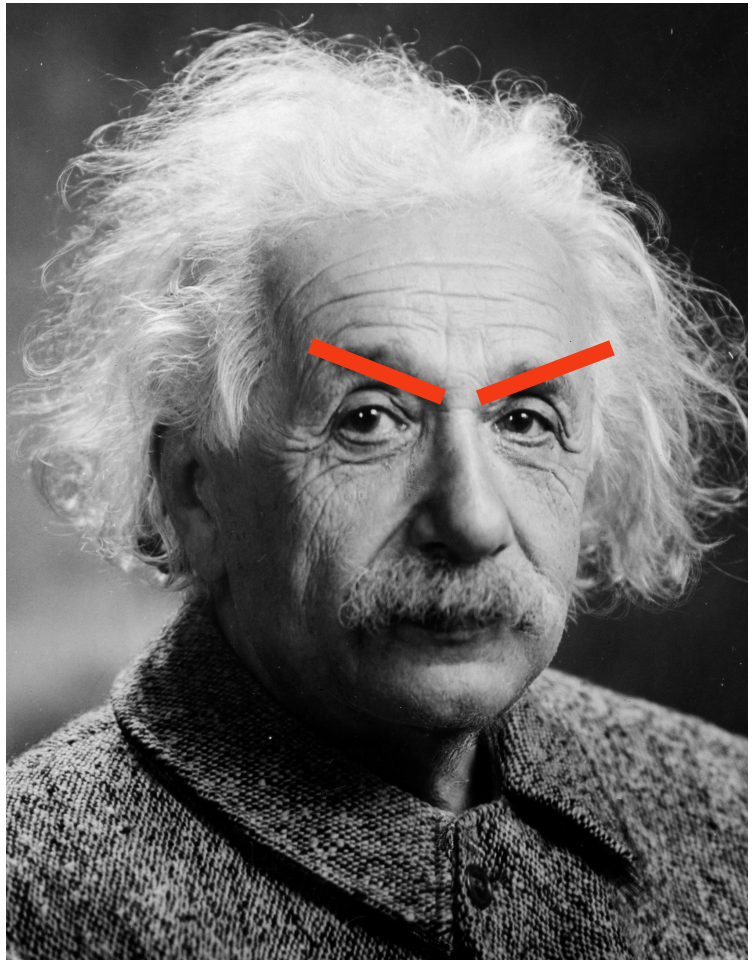




R McGehee

Blasphemer!





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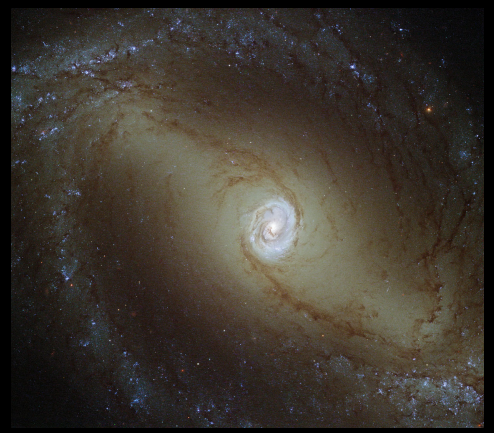
Credit: NASA, ESA, and T. Brown and J. Tumlinson (STScI)




Credit: NASA

So…what do we know?

R McGehee

So…what do we know?

there's lots of it

$$\Omega_{\mathrm{DM}} \approx 5\Omega_{\mathrm{b}}$$

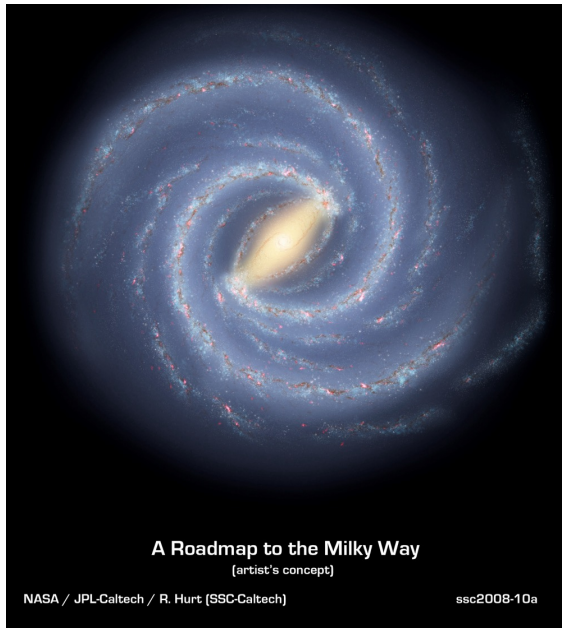
R McGehee

So…what do we know?

there's lots of it

$$\Omega_{\rm DM} \approx 5\Omega_{\rm b}$$

it's in galaxies, including ours



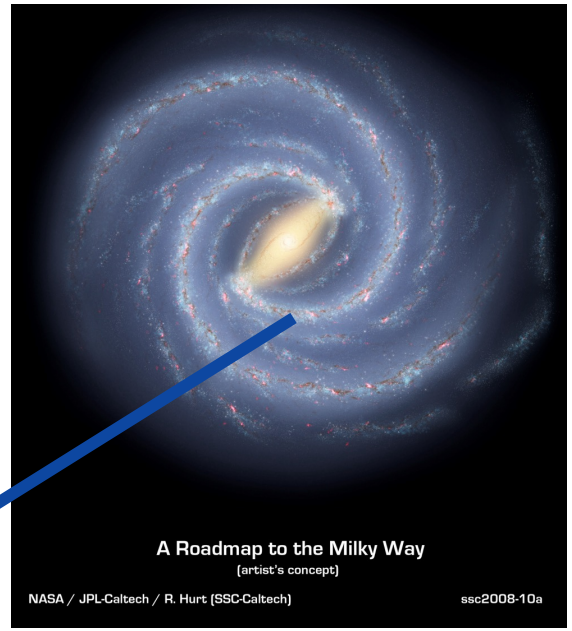
R McGehee

So…what do we know?

there's lots of it

$$\Omega_{\mathrm{DM}} \approx 5\Omega_{\mathrm{b}}$$

it's in galaxies, including ours



maybe it (very rarely) bumps into stuff on Earth

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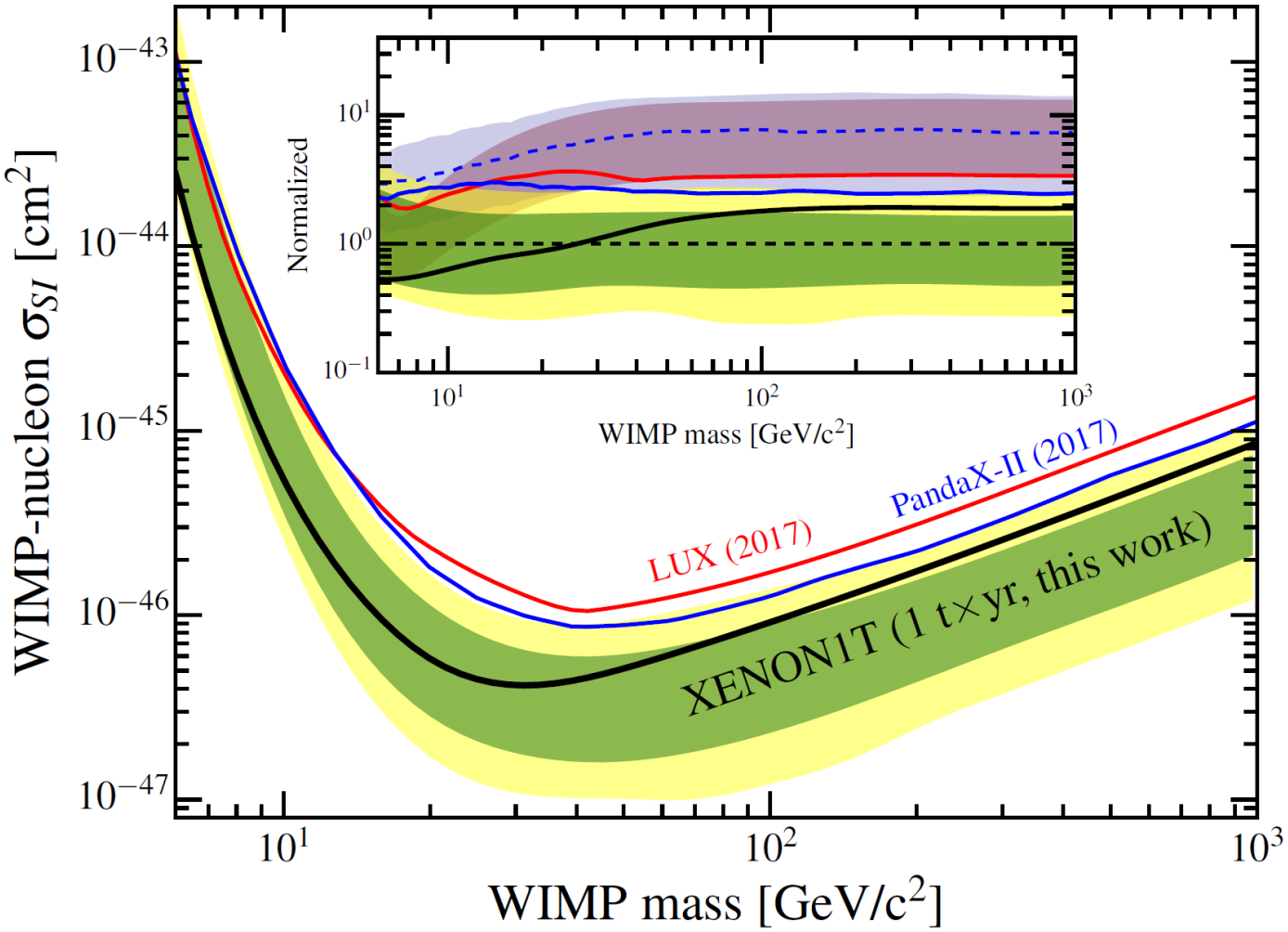
Direct Detection Today



XENON Collaboration [1805.12562]

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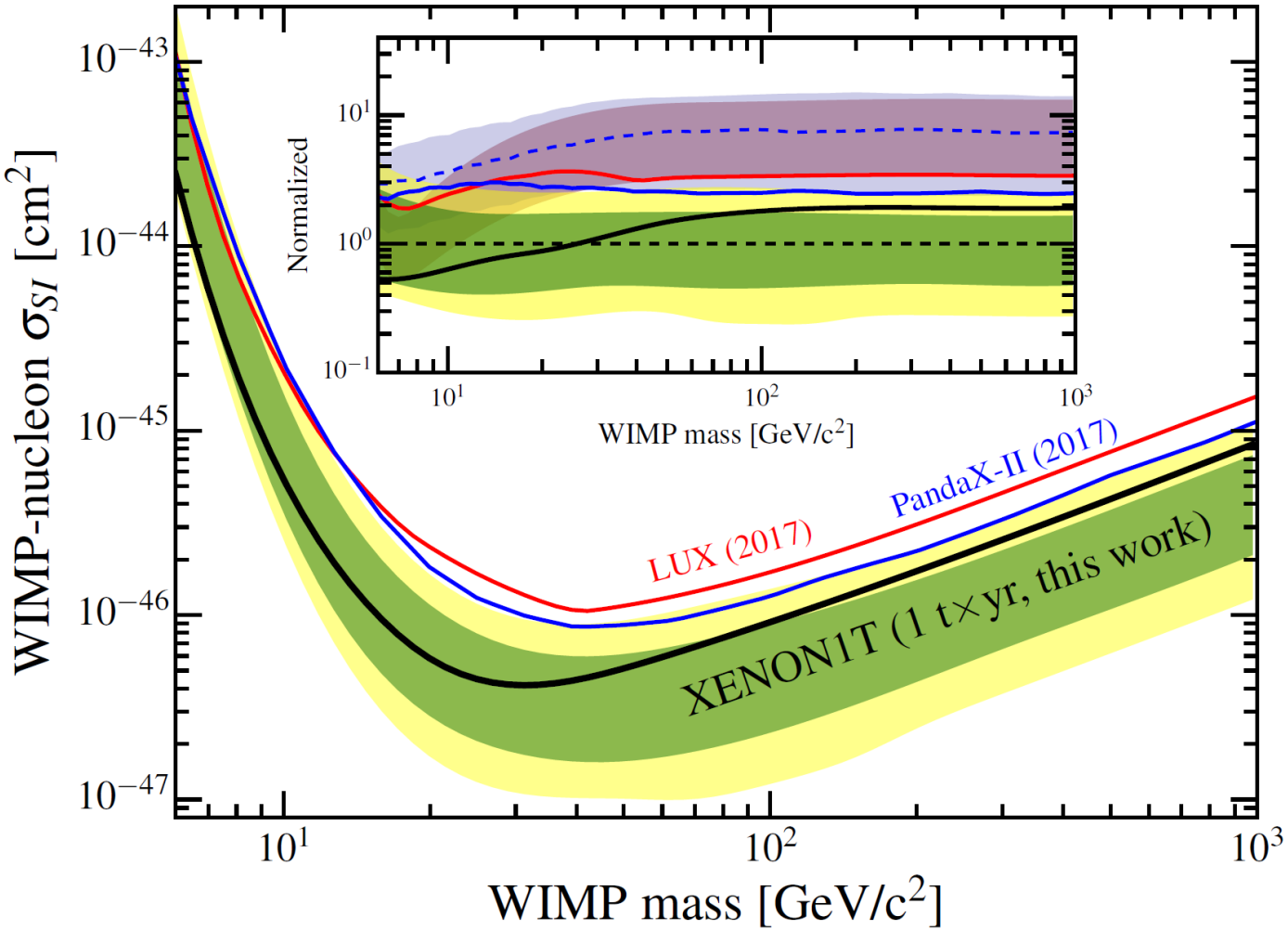
Direct Detection Future

Go lighter

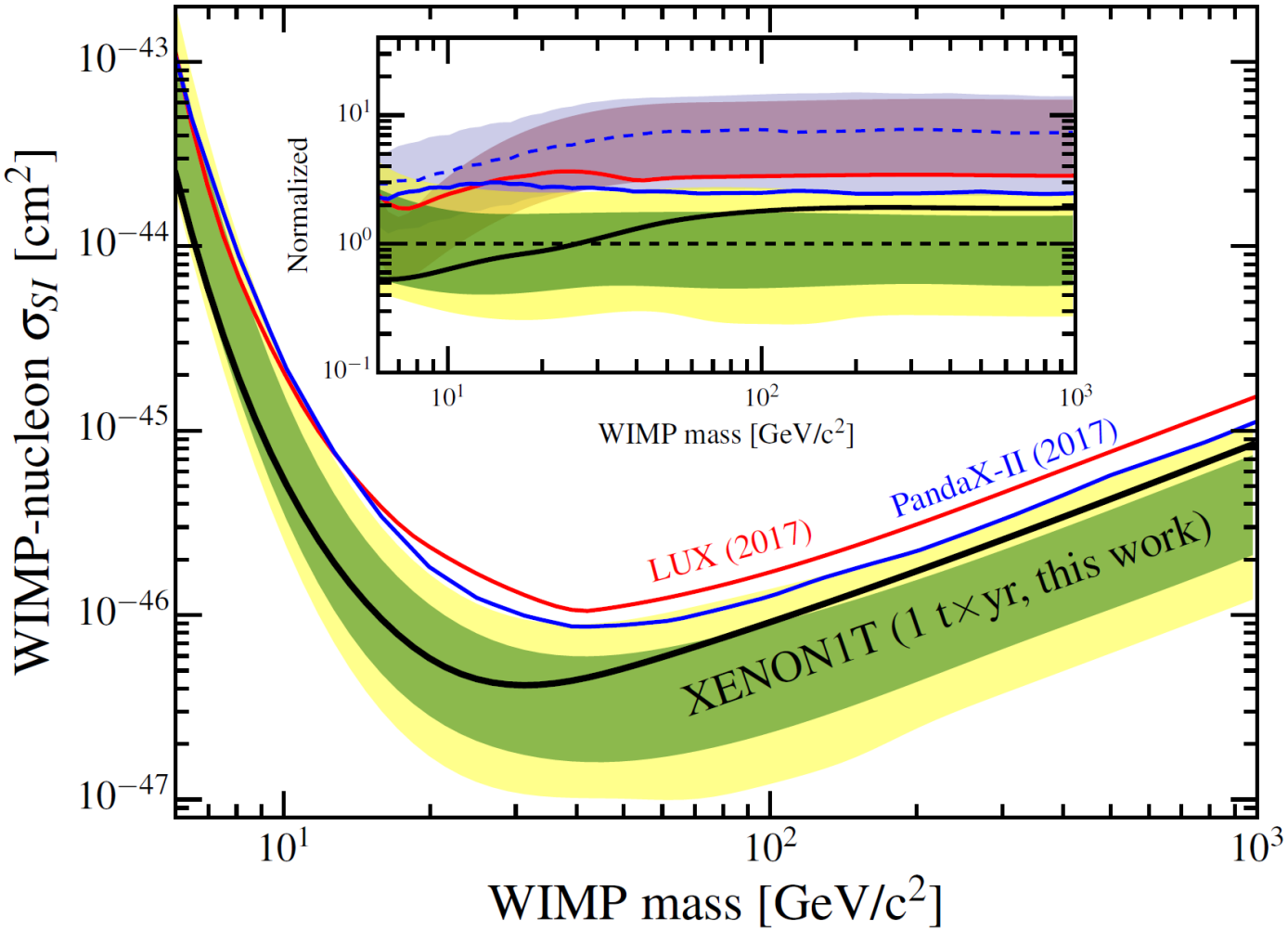


Go lower

R McGehee

Direct Detection Future

Go lighter



Go lower

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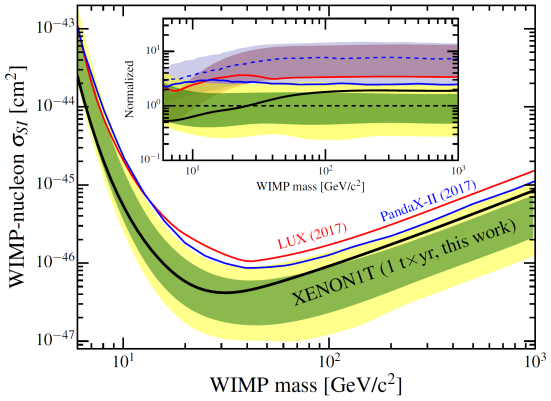
Direct Detection Future
Full Steam Ahead!

2018

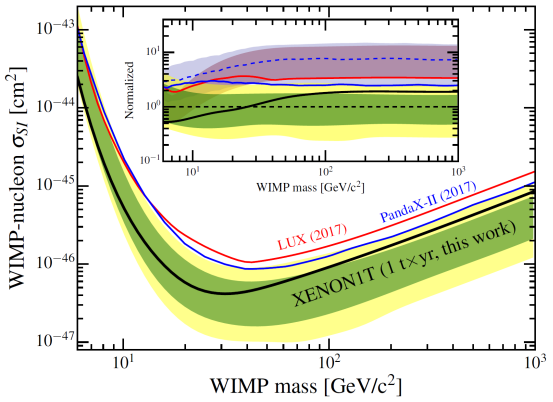


XENON Collaboration
[1805.12562]

R McGehee

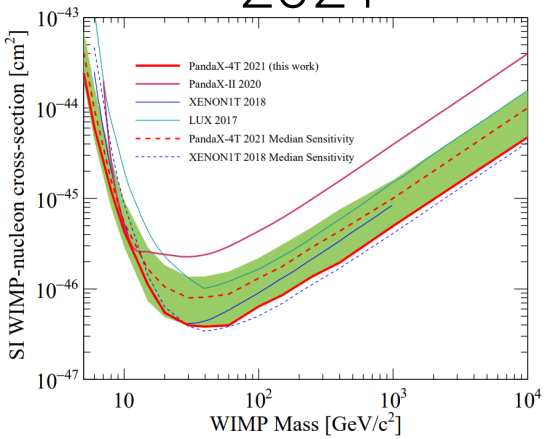
Direct Detection Future
Full Steam Ahead!

2018

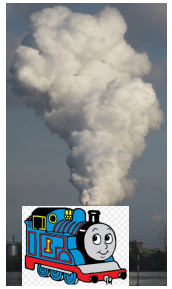


XENON Collaboration
[1805.12562]

2021



PandaX Collaboration
[2107.13438]



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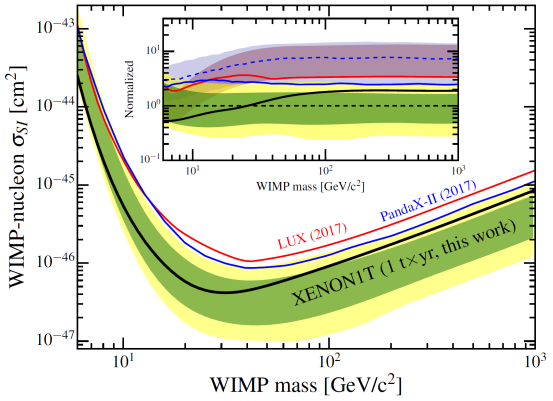
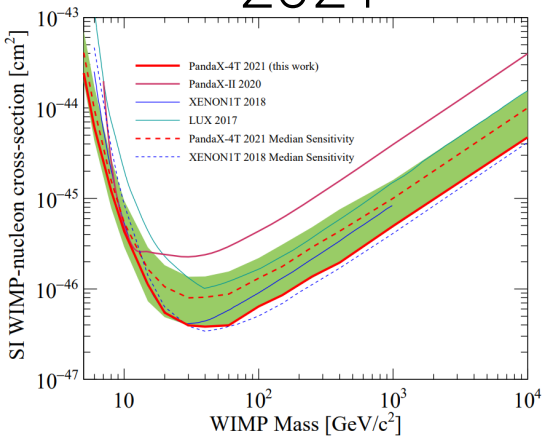
Direct Detection Future
Full Steam Ahead!

2018



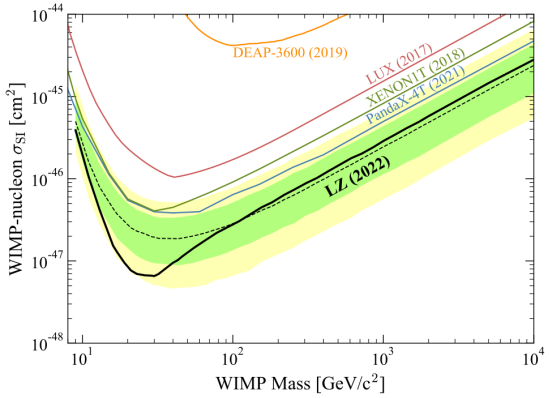
XENON Collaboration
[1805.12562]

2021

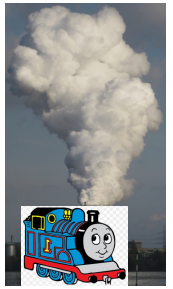


PandaX Collaboration
[2107.13438]

2022



LZ Collaboration
[2207.03764]



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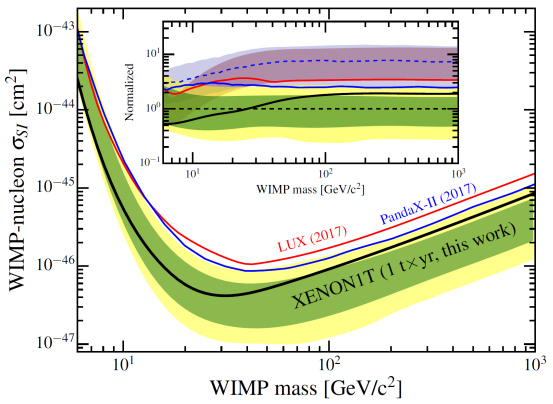
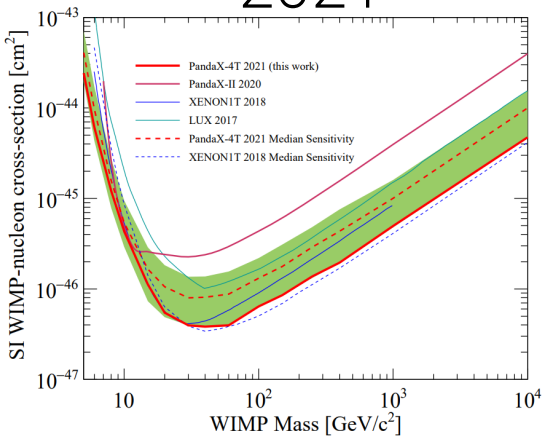
Direct Detection Future
Full Steam Ahead!

2018



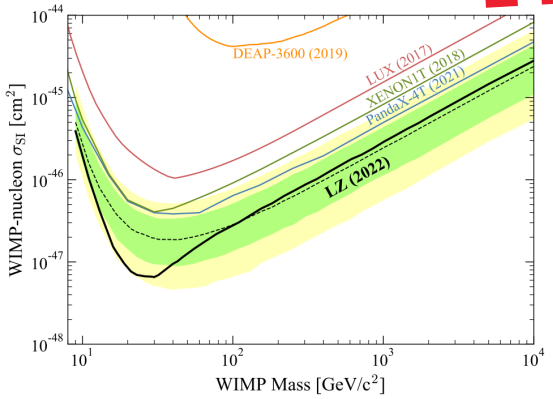
XENON Collaboration
[1805.12562]

2021



PandaX Collaboration
[2107.13438]

2022



LZ Collaboration
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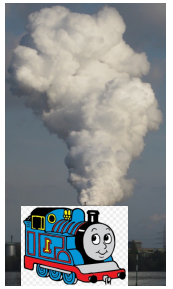

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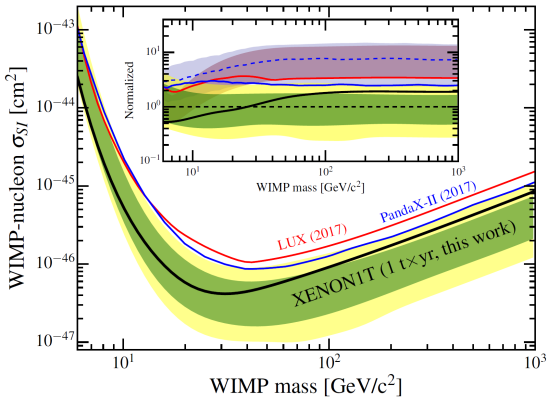
Direct Detection Future
Full Steam Ahead!

2018



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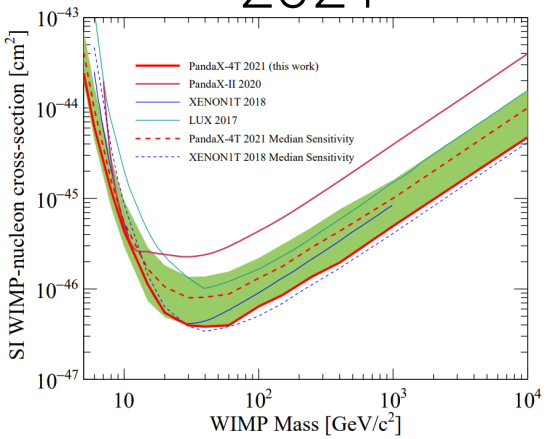

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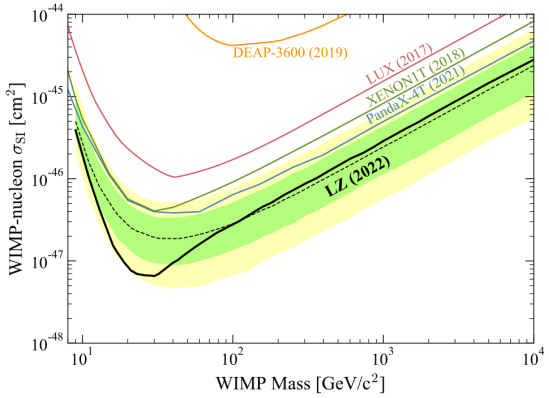

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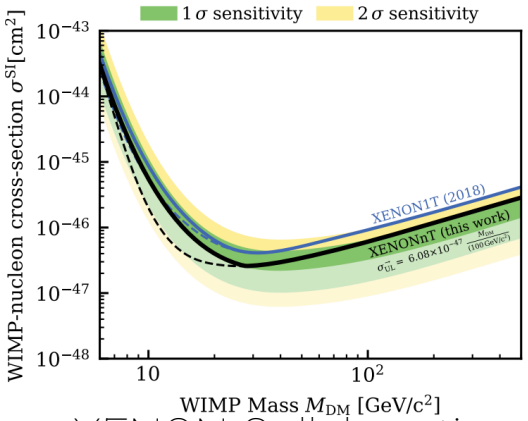
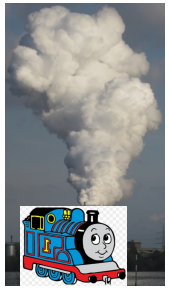


XENON Collaboration
[2303.14729]



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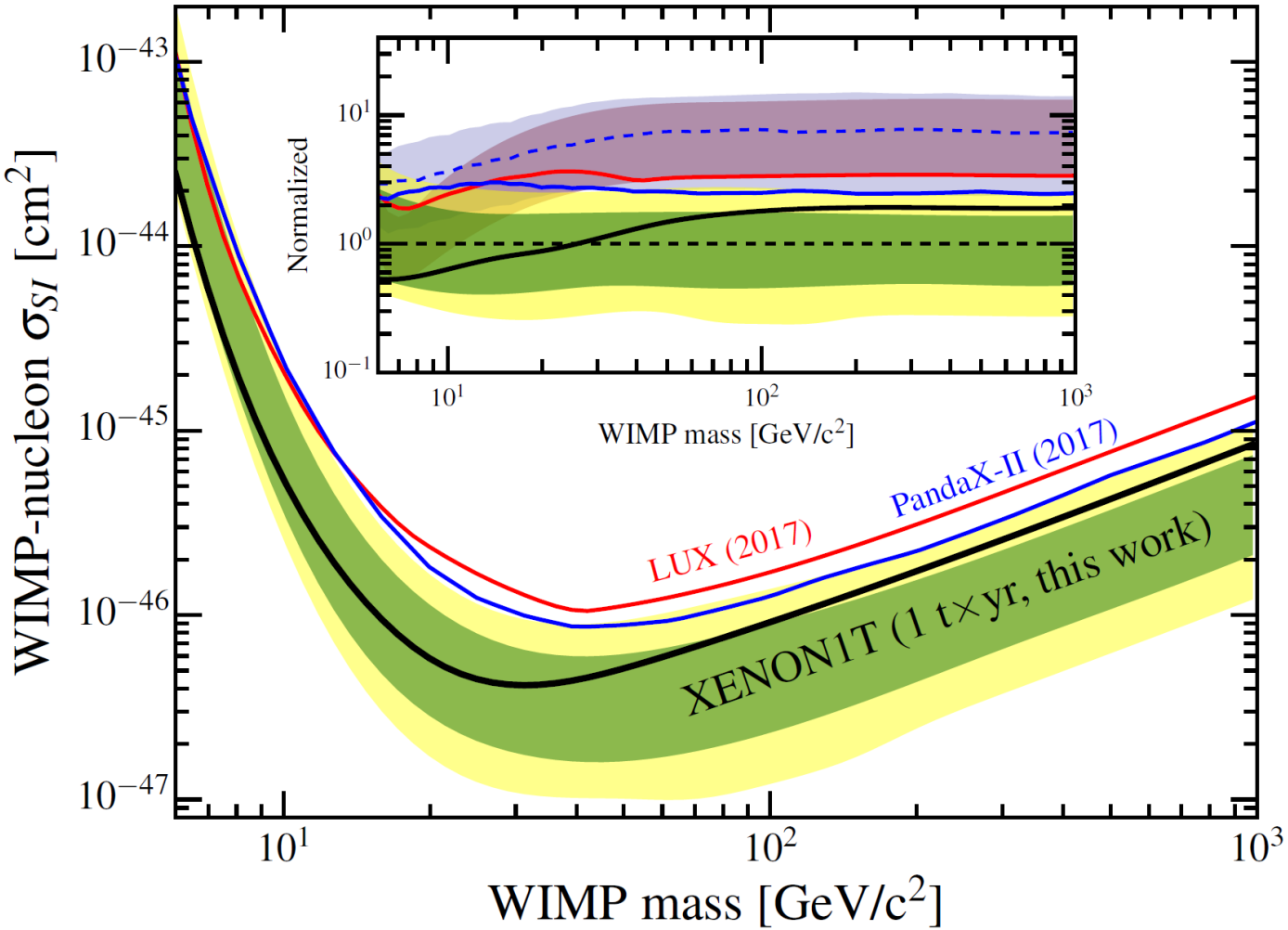
Direct Detection Future

Go lighter

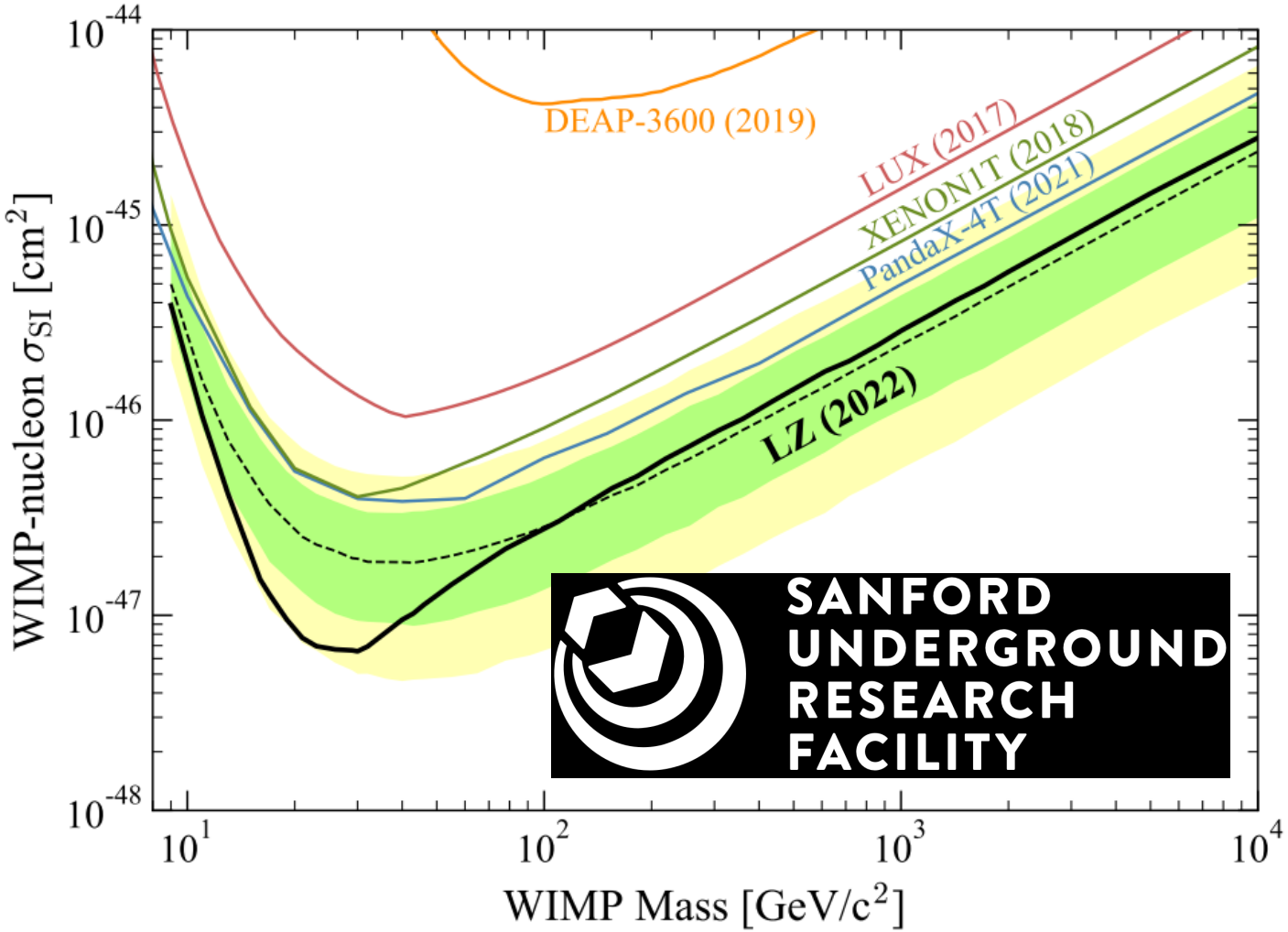


Go lower

R McGehee

Direct Detection Future

Go lighter



Go lower

R McGehee

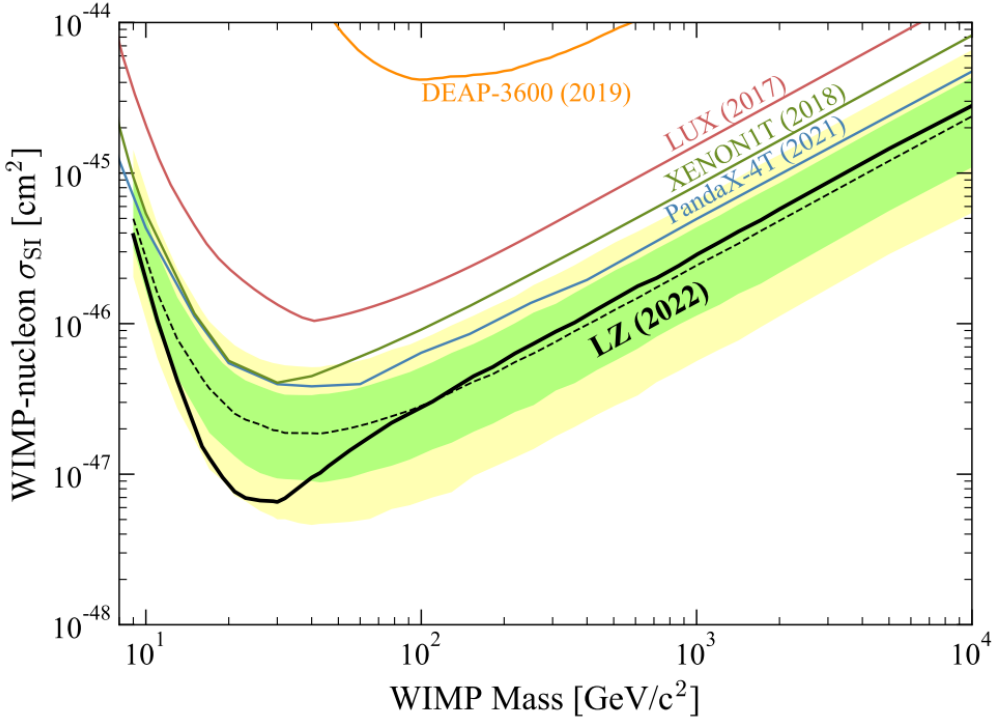
Directly Detecting *Light* Dark Matter

How?

R McGehee

Directly Detecting *Light* Dark Matter

How?



$$E_{\text{thresh}} \sim \text{keV}$$

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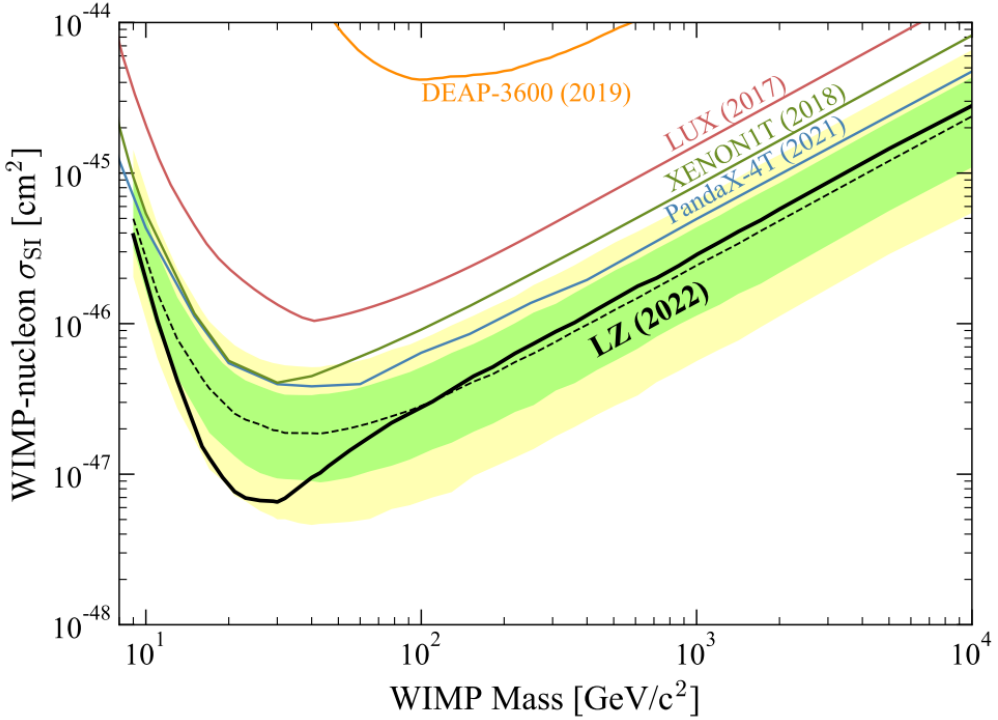
Directly Detecting *Light* Dark Matter

How?



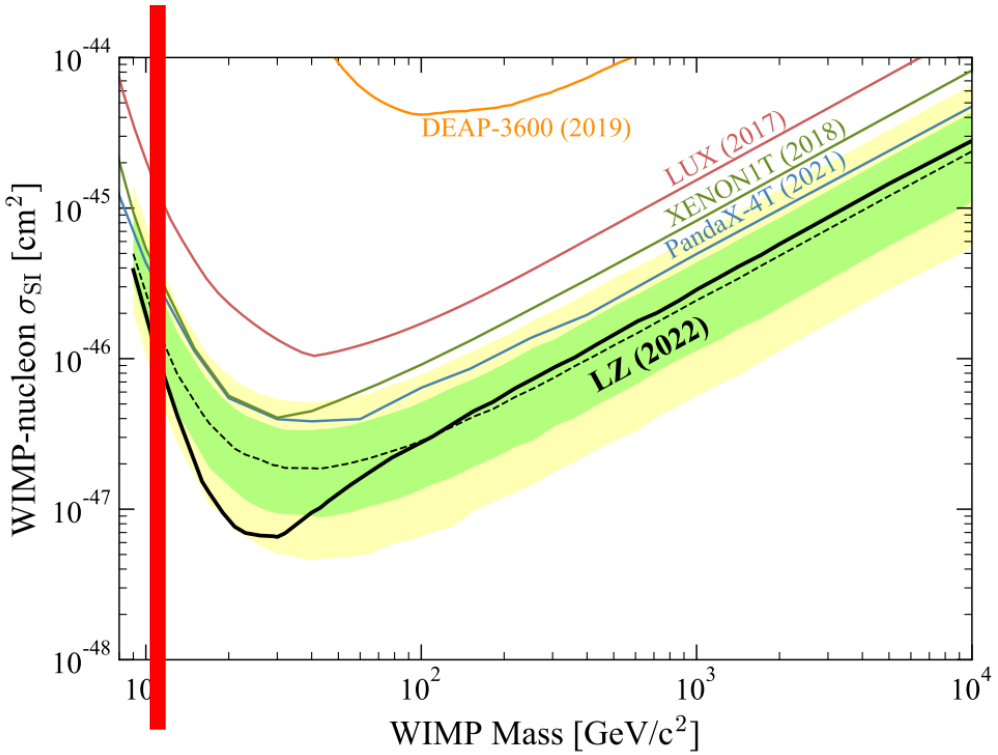
$$E_{\text{thresh}} \sim \text{keV}$$

$$E_{\text{NR}} \sim \frac{(m_{\text{DM}} v)^2}{m_N}$$

R McGehee

Directly Detecting *Light* Dark Matter

How?



$$E_{\text{thresh}} \sim \text{keV}$$

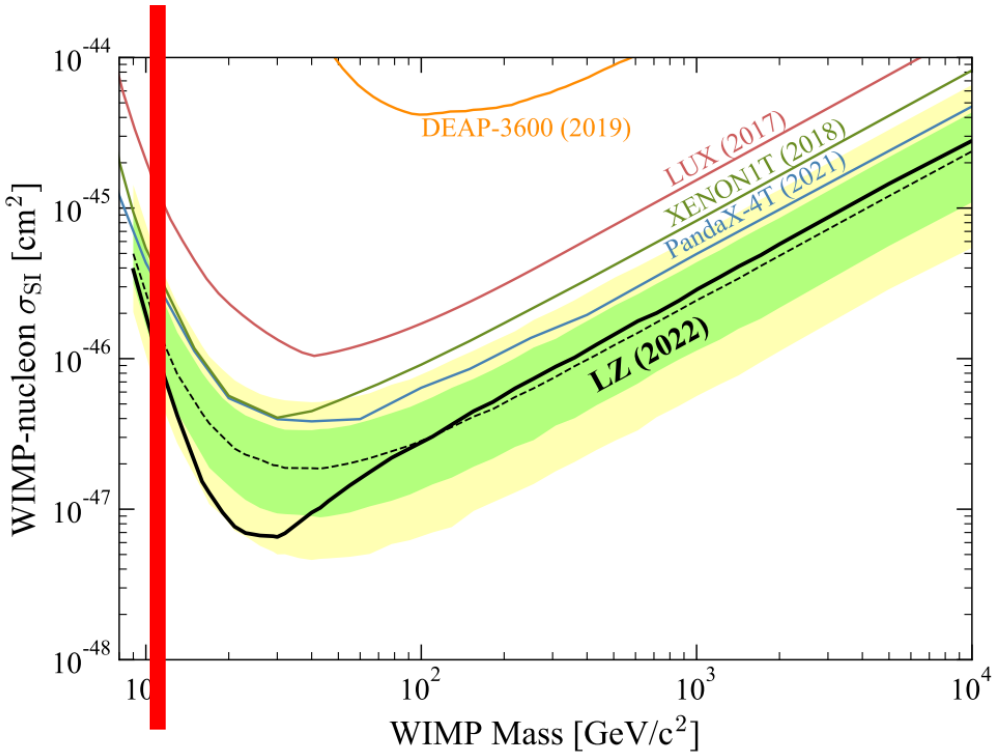
$$E_{\text{NR}} \sim \frac{(m_{\text{DM}} v)^2}{m_N}$$

$$v \sim 10^{-3}$$
$$m_{\text{DM}} \sim 10 \text{ GeV}$$
$$m_N \sim 100 \text{ GeV}$$

R McGehee

Directly Detecting *Light* Dark Matter

How?



$$E_{\rm thresh} \sim {\rm keV}$$

$$E_{\rm NR} \sim \frac{(m_{\rm DM} v)^2}{m_N} \sim {\rm keV}$$

$$v \sim 10^{-3}$$
$$m_{\rm DM} \sim 10\ {\rm GeV}$$
$$m_N \sim 100\ {\rm GeV}$$

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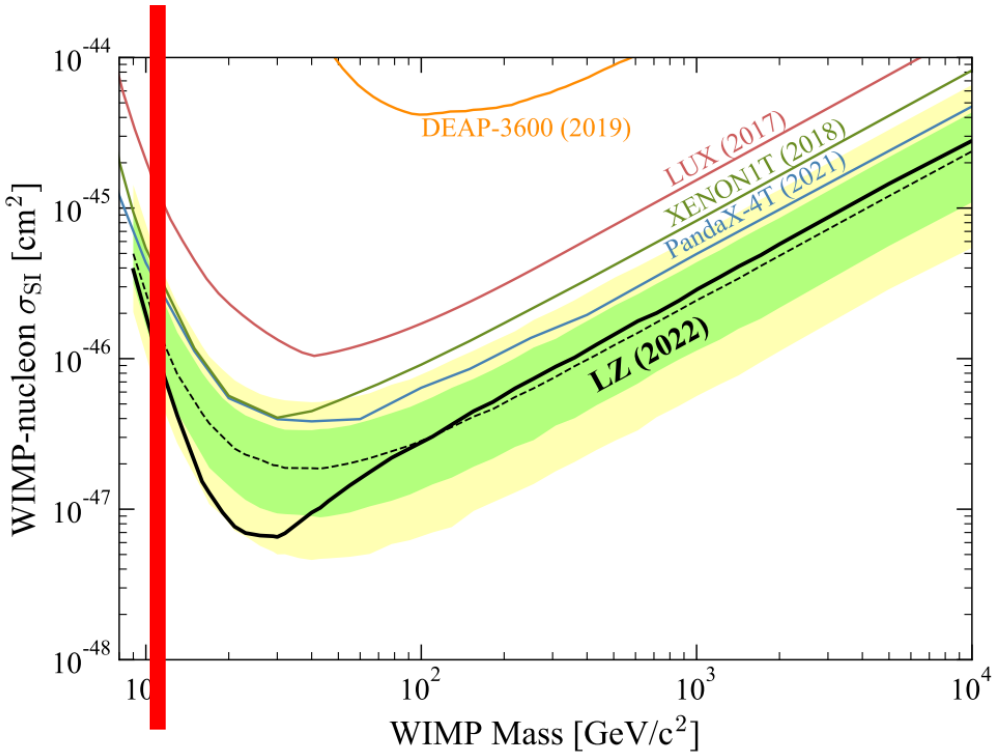
Directly Detecting *Light* Dark Matter

How?



$$v \sim 10^{-3}$$

$$E_{\rm thresh} \sim {\rm keV} \qquad m_{\rm DM} \sim 10\ {\rm GeV}$$

$$m_N \sim 100\ {\rm GeV}$$

$$E_{\rm NR} \sim \frac{(m_{\rm DM} v)^2}{m_N} \sim {\rm keV}$$

$$m_{\rm DM} \lesssim 10\ {\rm GeV}$$ requires new ideas!

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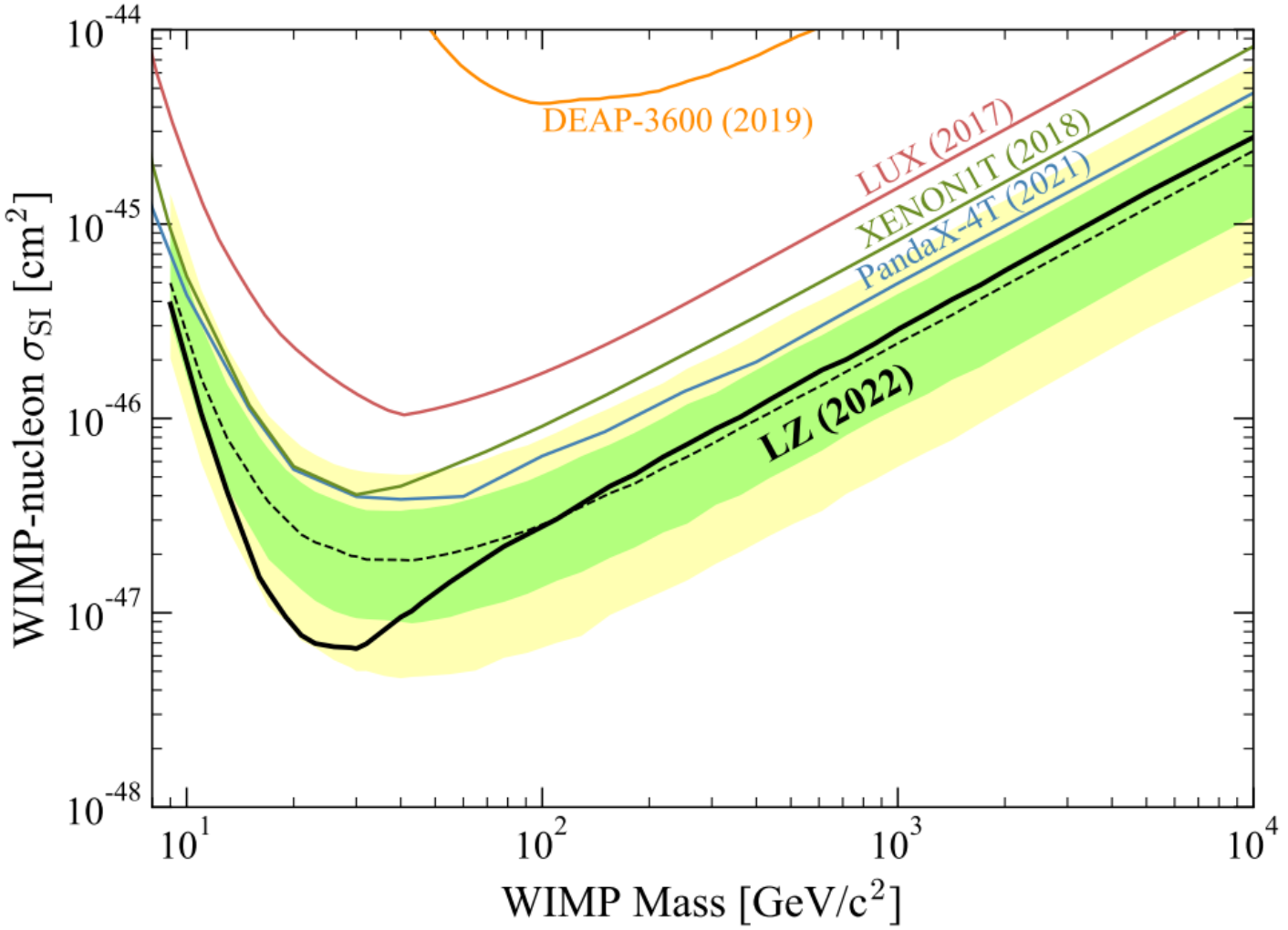
Direct Detection Future

Go lighter



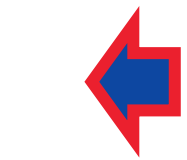
Go lower

R McGehee

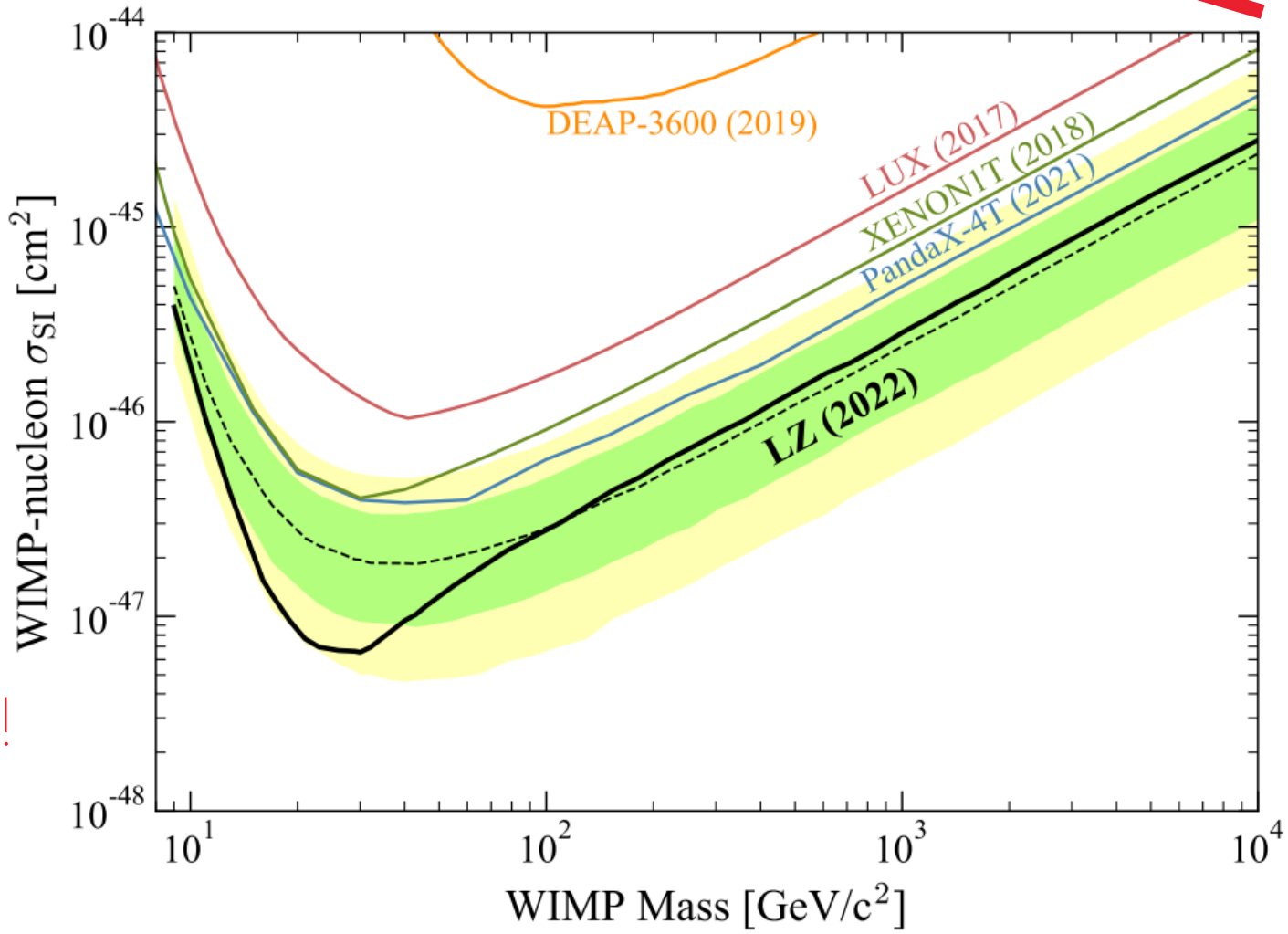
Today!

Direct Detection ~~Future~~

Go lighter



Use electrons!



Go lower

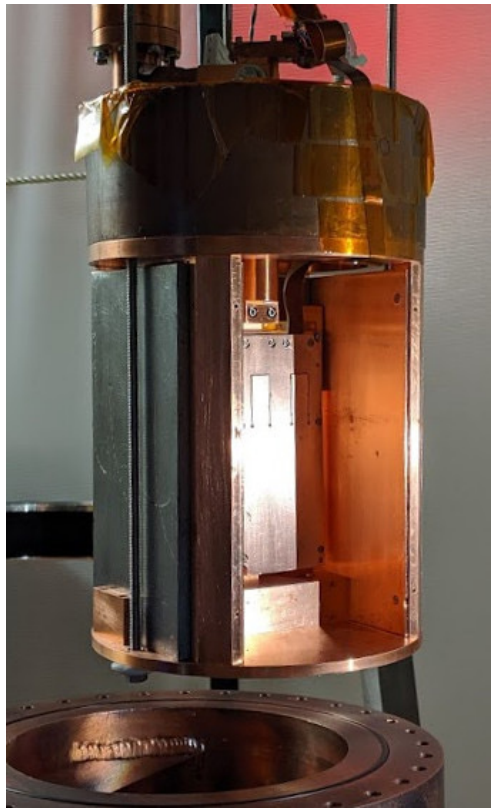
R McGehee

Direct Detection ~~Future~~ Today!

New technology

Go lighter

Use electrons!



SENSEI

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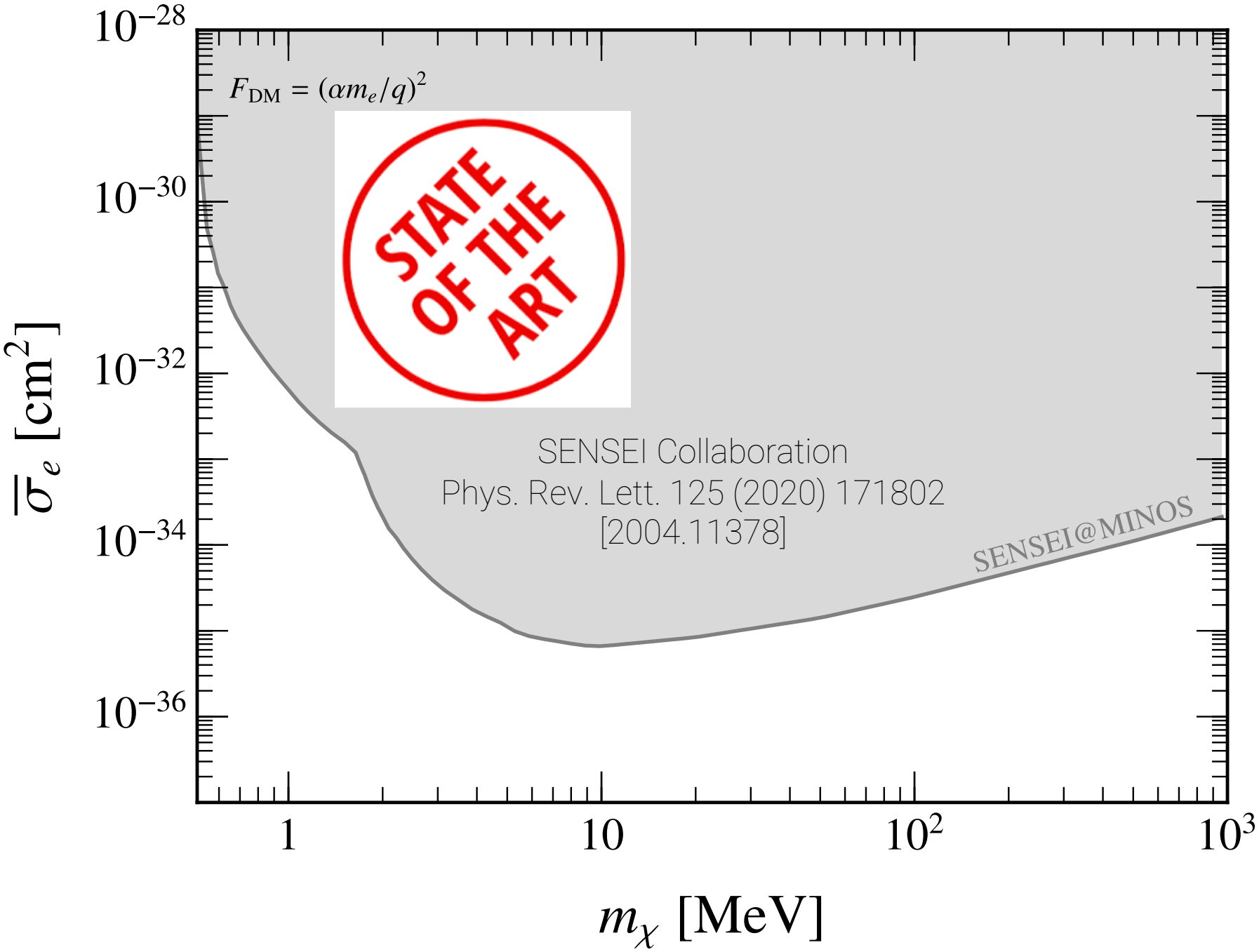
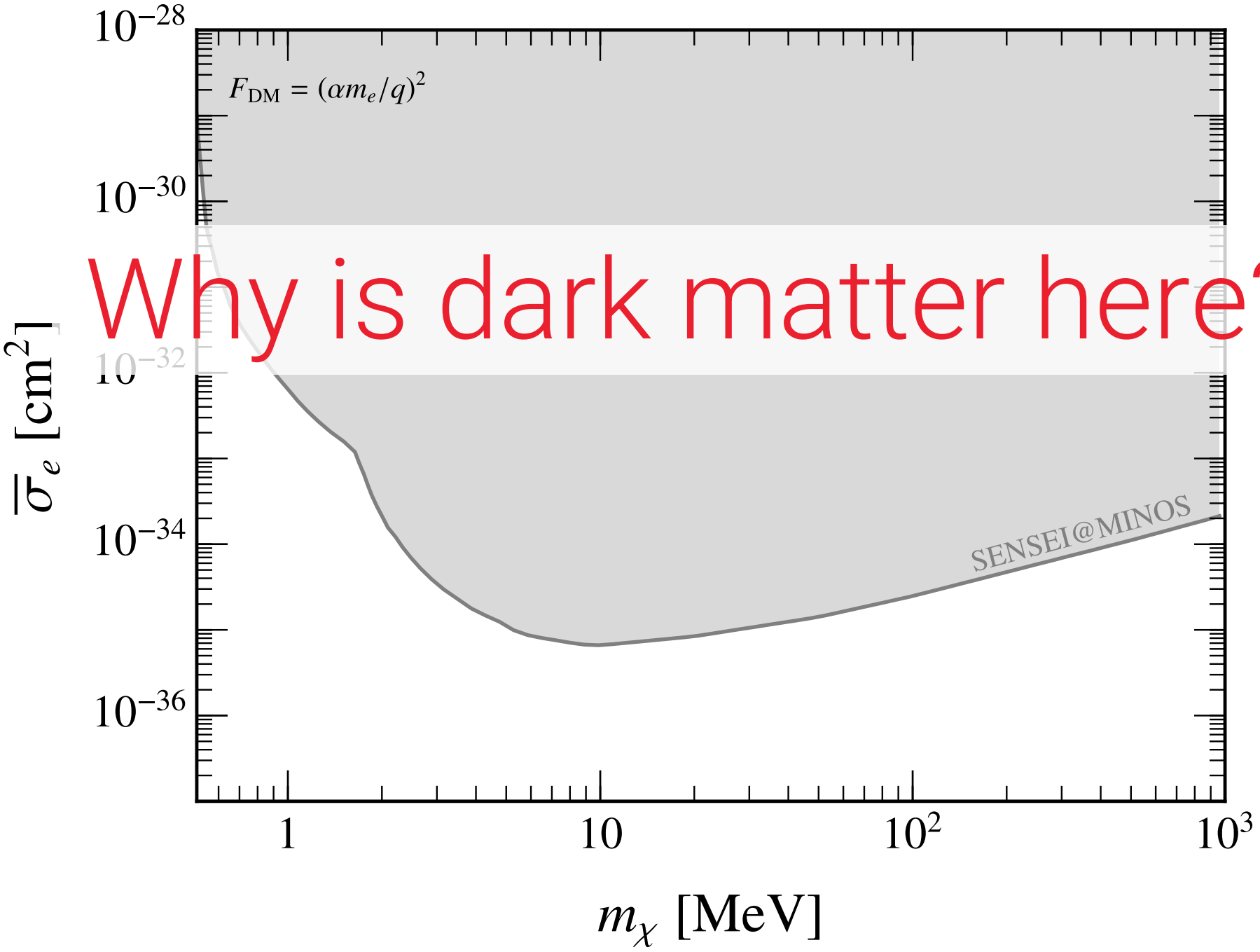

$F_{\rm DM} = (\alpha m_e/q)^2$
STATE OF THE ART
SENSEI Collaboration
Phys. Rev. Lett. 125 (2020) 171802
[2004.11378]
SENSEI@MINOS
$\overline{\sigma}_e$ [cm^2]
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
1
10
10^2
10^3
m_χ [MeV]

R McGehee



Why is dark matter here?

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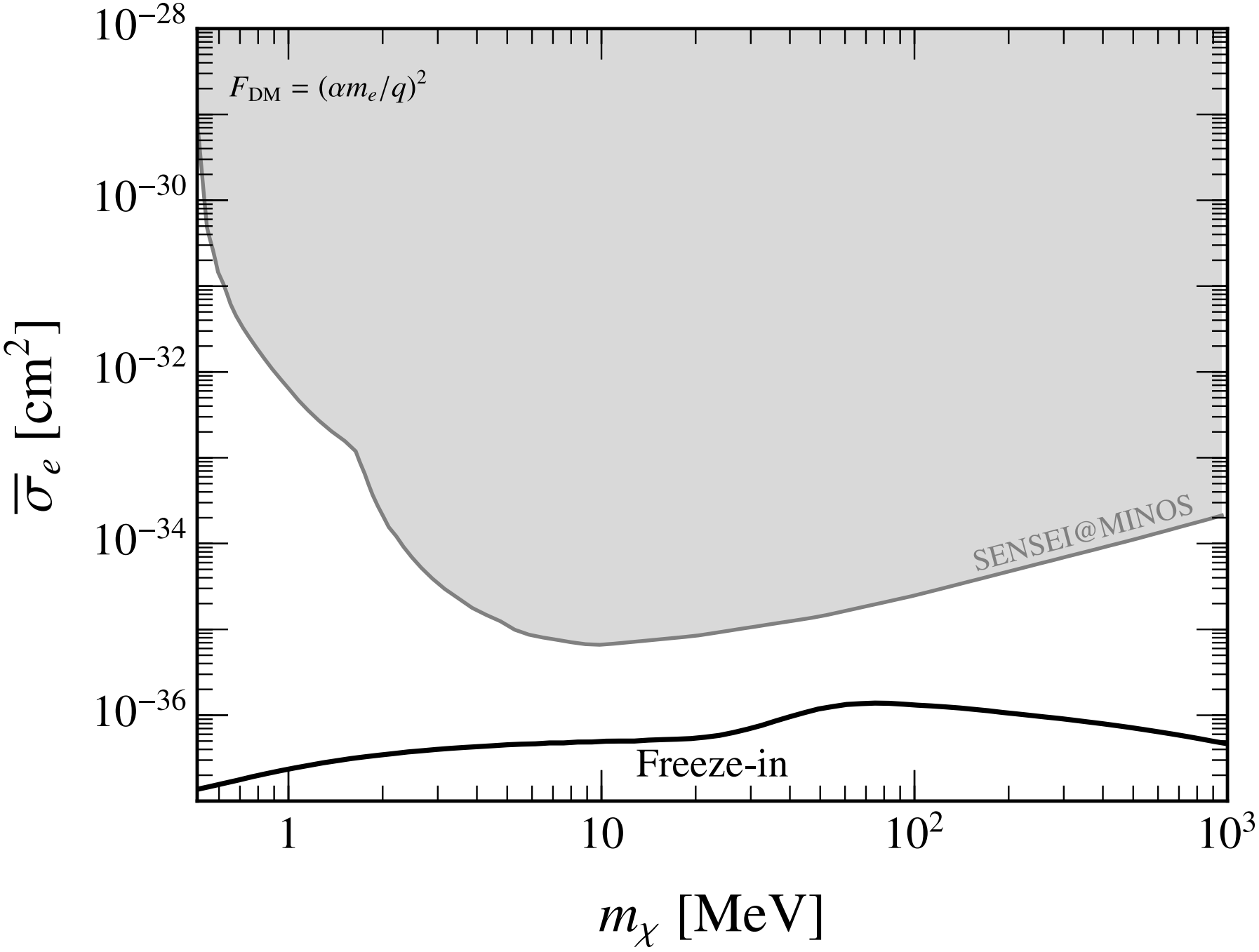
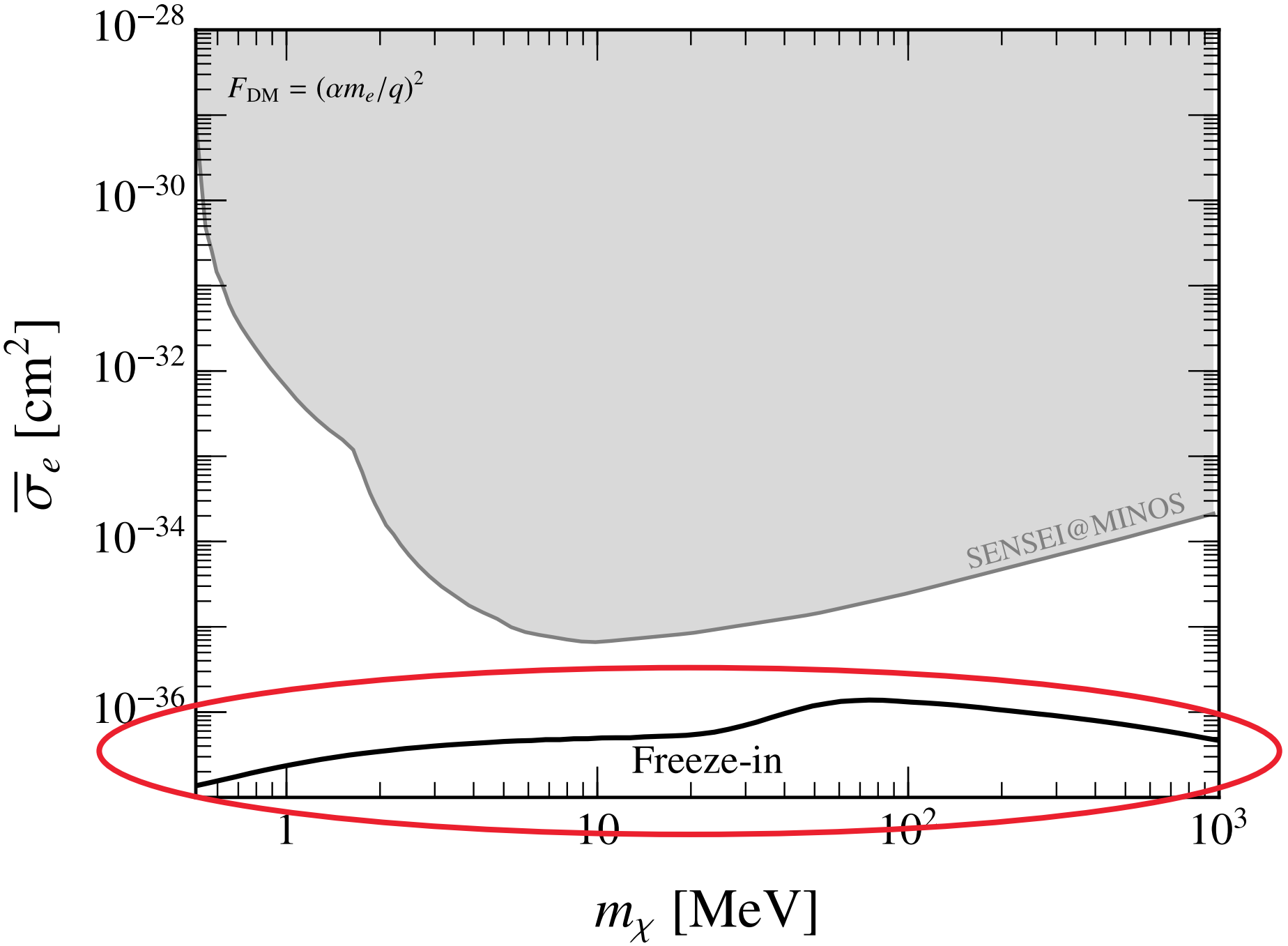

10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
$\overline{\sigma}_e$ [cm^2]
$F_{\rm DM} = (\alpha m_e/q)^2$
SENSEI@MINOS
Freeze-in
1
10
10^2
10^3
m_χ [MeV]

R McGehee


10^{-28}
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10^{-36}
$F_{\rm DM} = (\alpha m_e/q)^2$
SENSEI@MINOS
Freeze-in
1
10
10^2
10^3
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]

R McGehee

Freeze-In

L. J. Hall, K. Jedamzik,
J. March-Russell, & S. M. West
JHEP 03 (2010) 080
[0911.1120]

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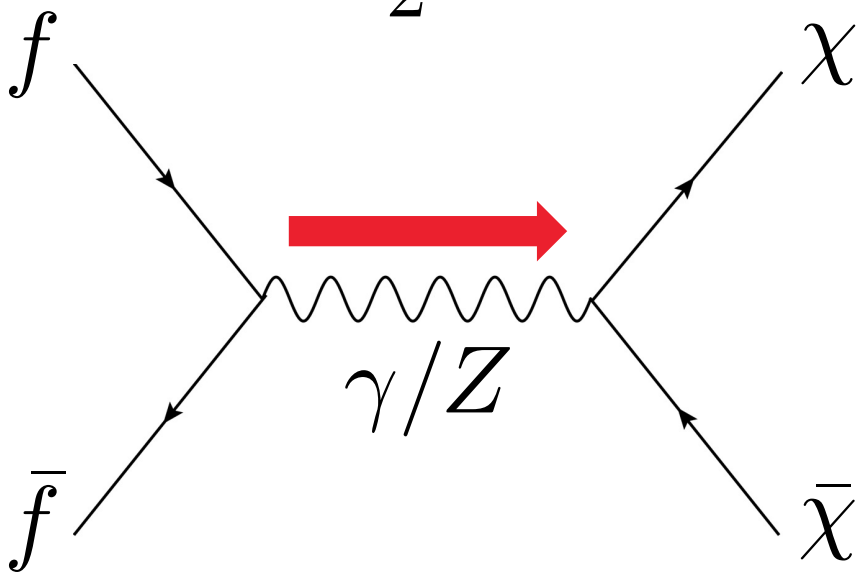
Freeze-In

$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

R McGehee

Freeze-In

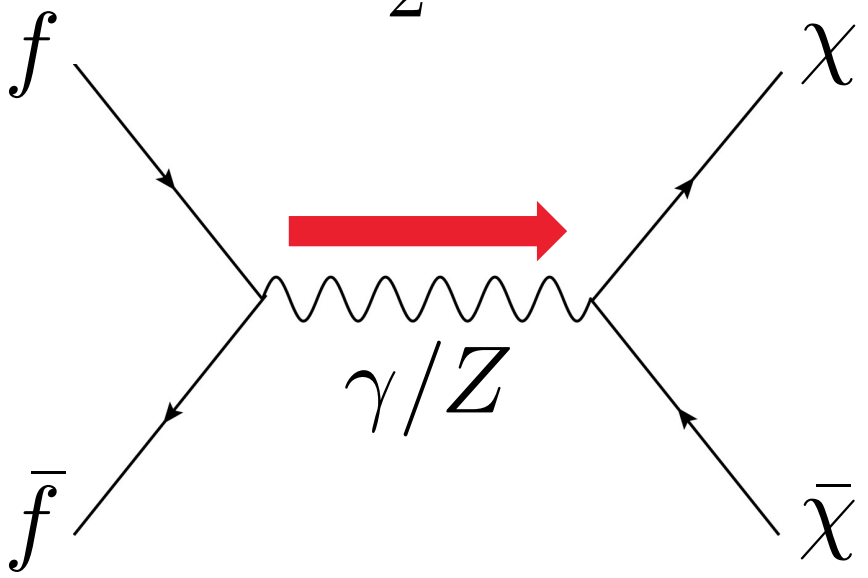
$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$



R McGehee

Freeze-In

$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$



$$\kappa \equiv \epsilon \sqrt{\alpha'/\alpha} \approx \mathcal{O}(10^{-11})$$

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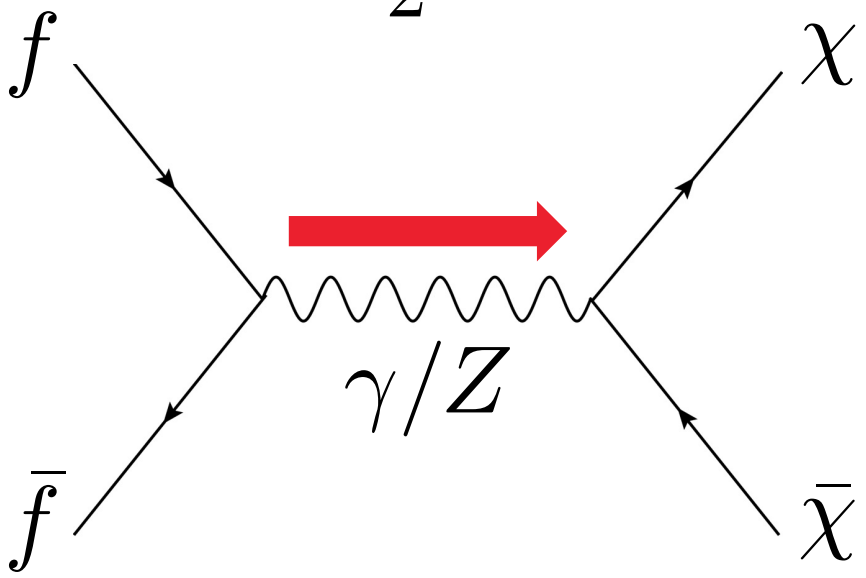
Freeze-In

$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

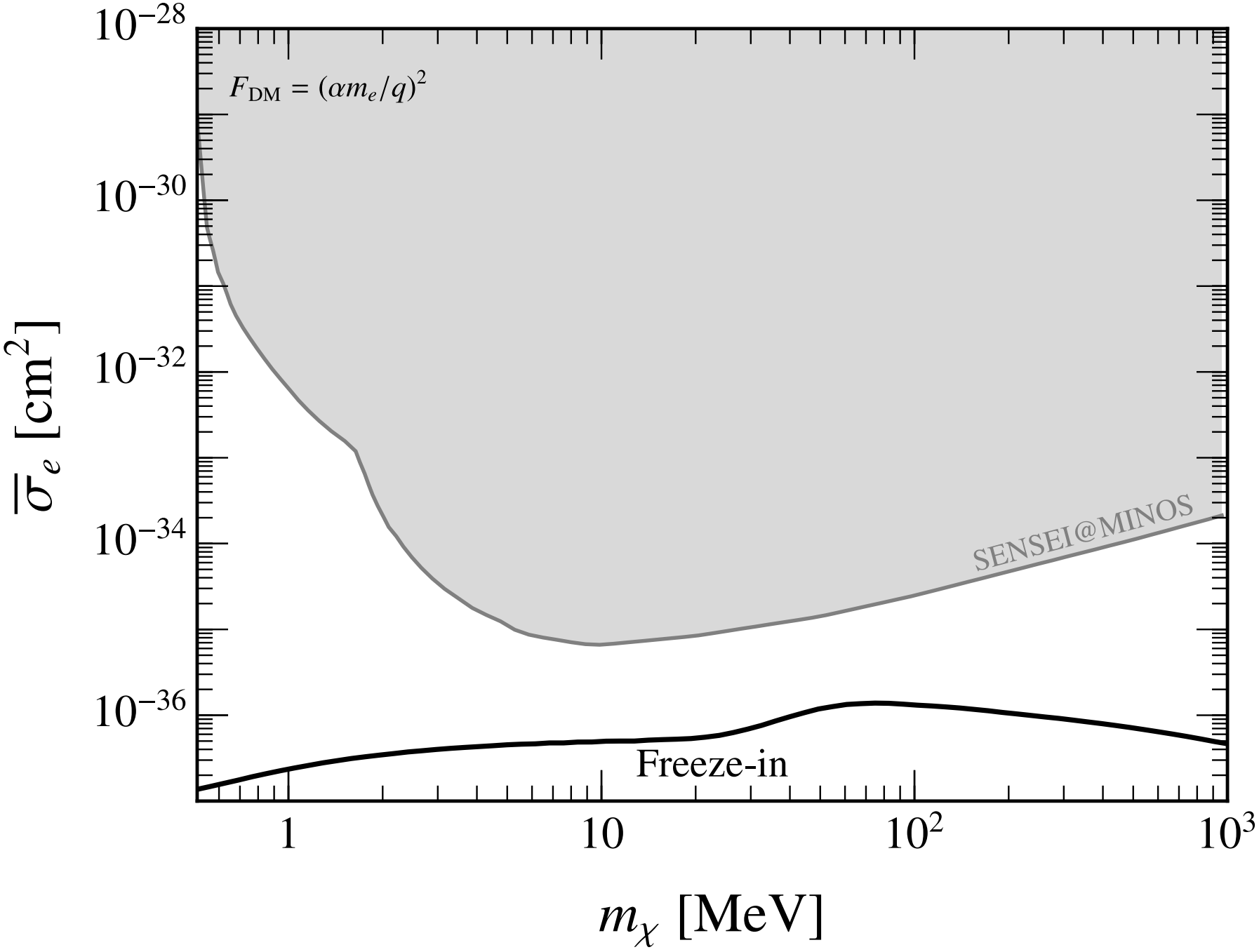


$$\kappa \equiv \epsilon \sqrt{\alpha'/\alpha} \approx \mathcal{O}(10^{-11})$$

$$\bar{\sigma}_e \approx \frac{16\pi \mu_{\chi e}^2 \kappa^2 \alpha^2}{(\alpha m_e)^4}$$

R. Essig, J. Mardon,T. Volansky
Phys. Rev. D 85 (2012) 076007
[1108.5383]
X. Chu, T. Hambye, M. H. G. Tytgat
JCAP 05 034 (2012)
[1112.0493]

R McGehee


10^{-28}
10^{-30}
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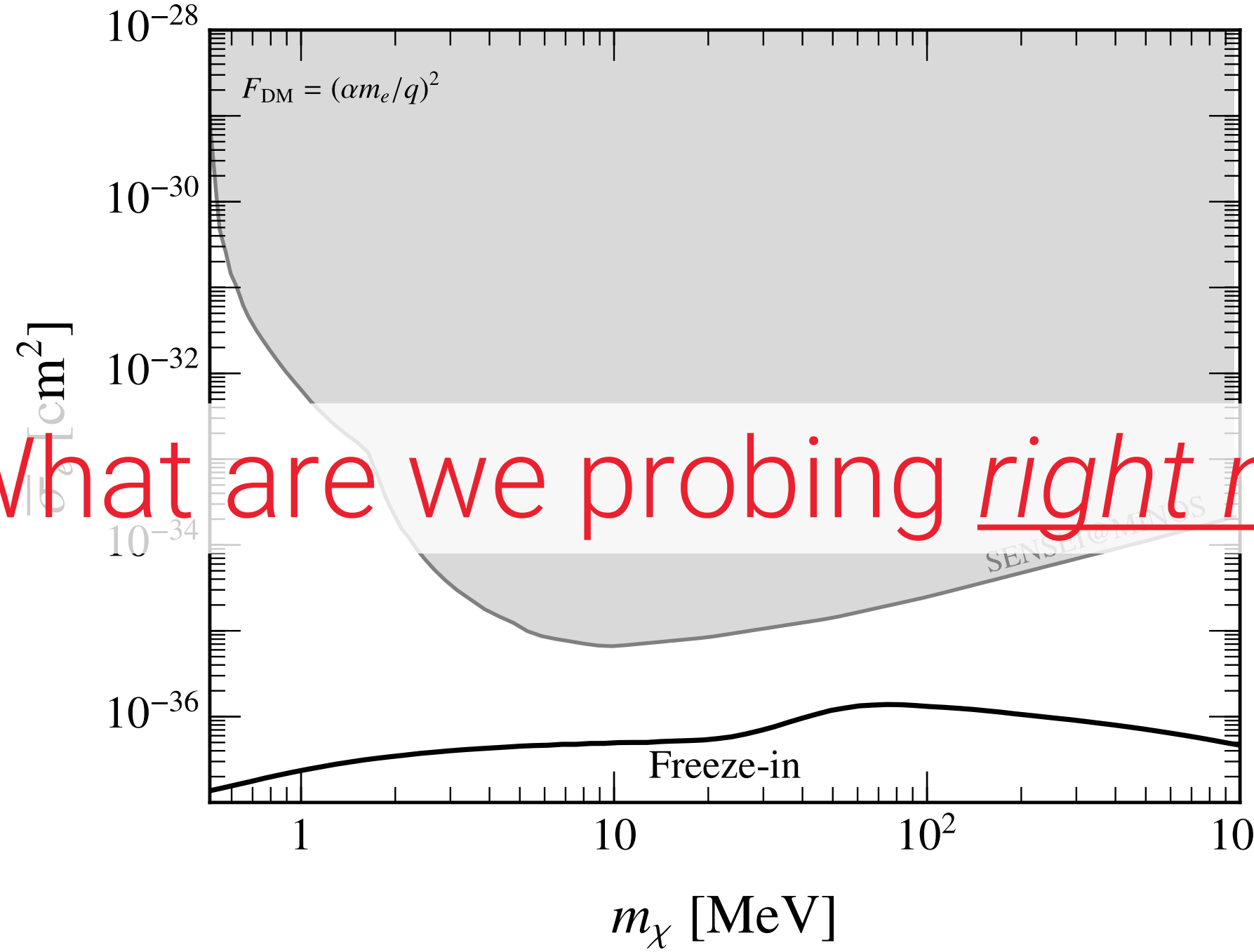
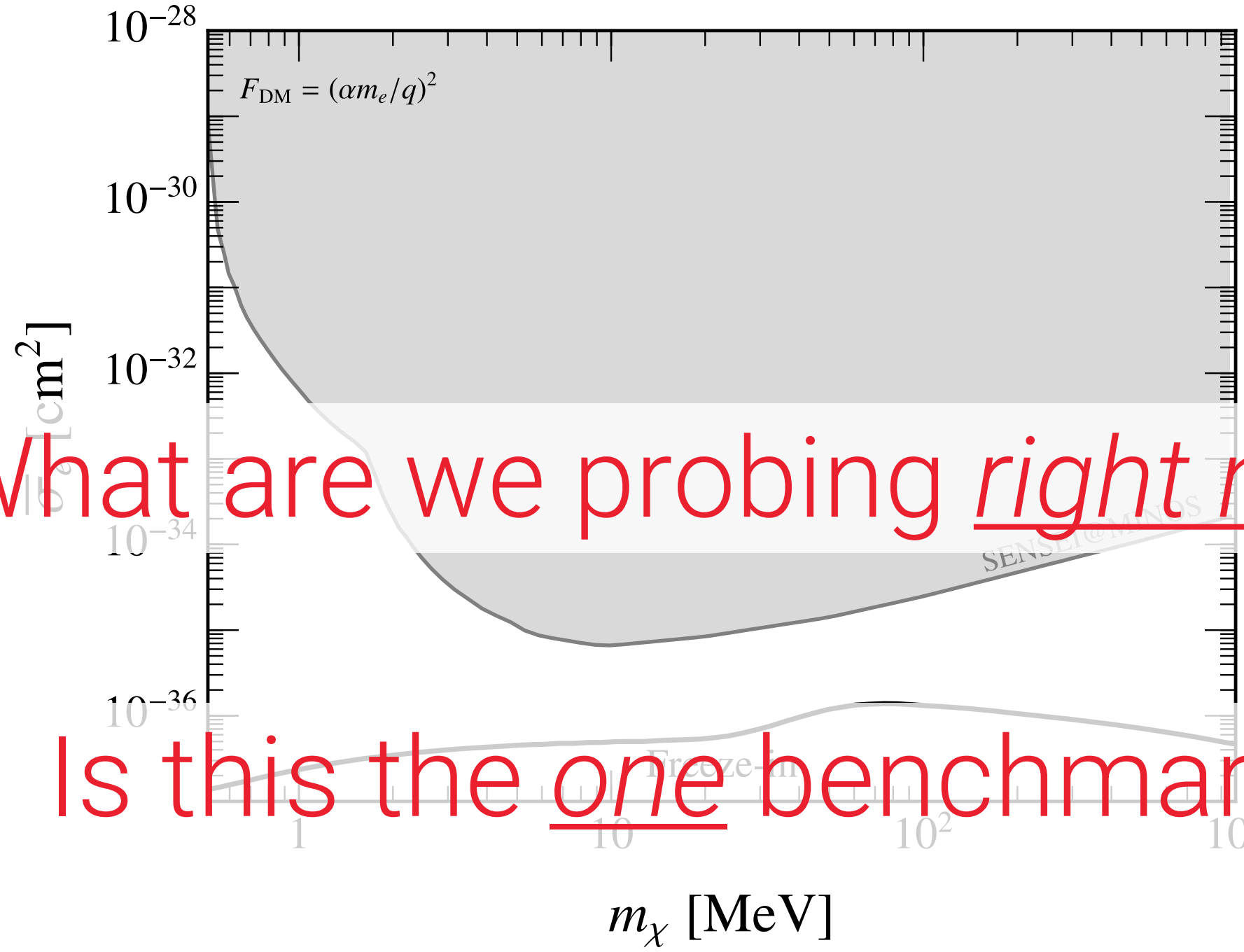
10^{-36}
$\overline{\sigma}_e$ [cm^2]
$F_{\rm DM} = (\alpha m_e/q)^2$
SENSEI@MINOS
Freeze-in
1
10
10^2
10^3
m_χ [MeV]

R McGehee



What are we probing *right now*?

R McGehee



What are we probing *right now*?

Is this the *one* benchmark?

R McGehee

The Challenges of Model Building

Want a realistic model with a “large” cross section

R McGehee

The Challenges of Model Building

Want a realistic model with a “large” cross section

- Light mediators coupled to SM are constrained

R McGehee

The Challenges of Model Building

Want a realistic model with a “large” cross section

- Light mediators coupled to SM are constrained
- Large couplings to DM may mess up relic abundance

R McGehee

The Challenges of Model Building

Want a realistic model with a “large” cross section

- Light mediators coupled to SM are constrained
- Large couplings to DM may mess up relic abundance

Big Bang Nucleosynthesis (BBN)

R McGehee

The Real Challenge: BBN

BBN “measures” the energy density of the Universe

R McGehee

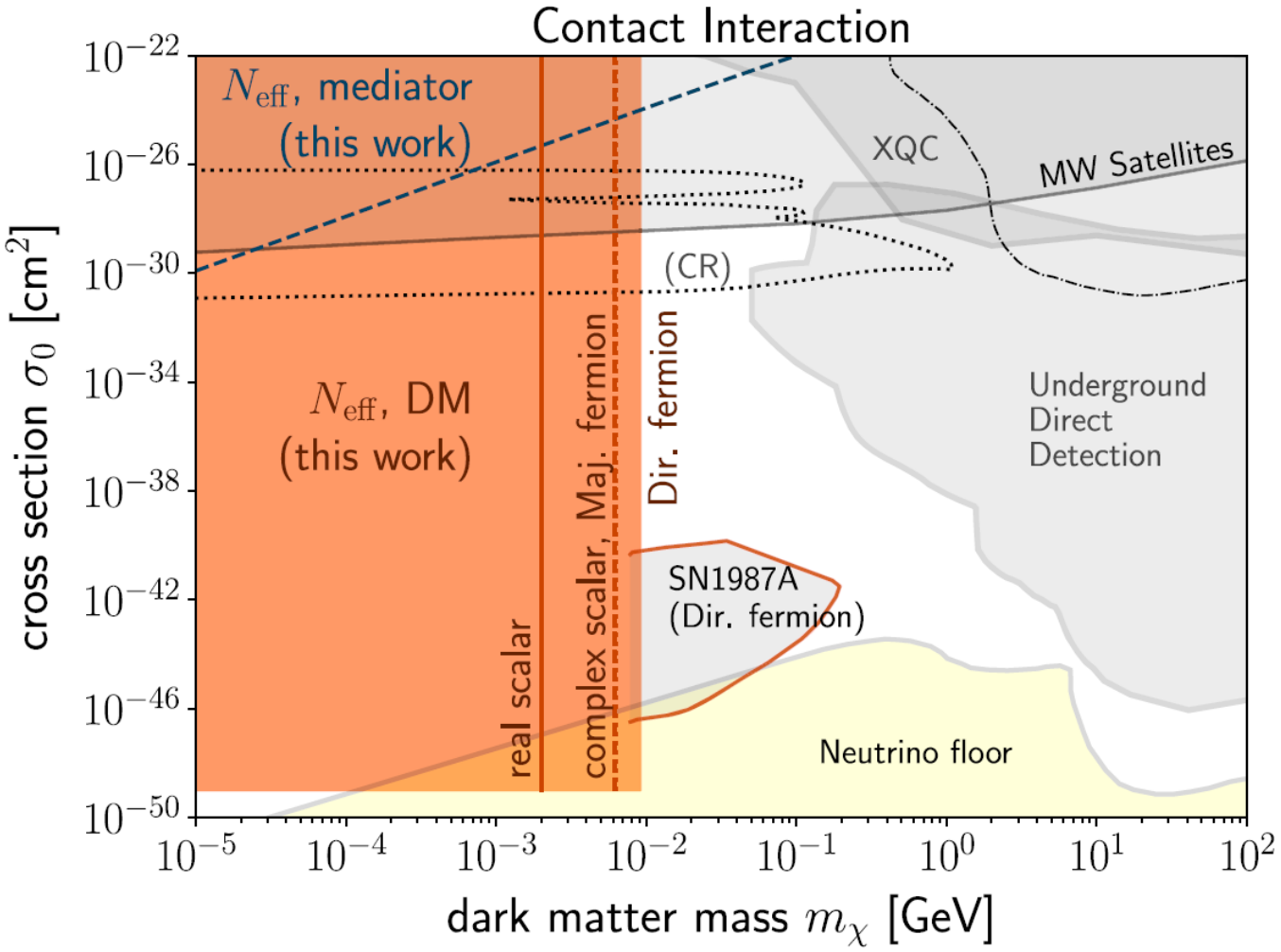
The Real Challenge: BBN

BBN “measures” the energy density of the Universe

if DM is *light* and *interacts too much*, it will have too much energy density

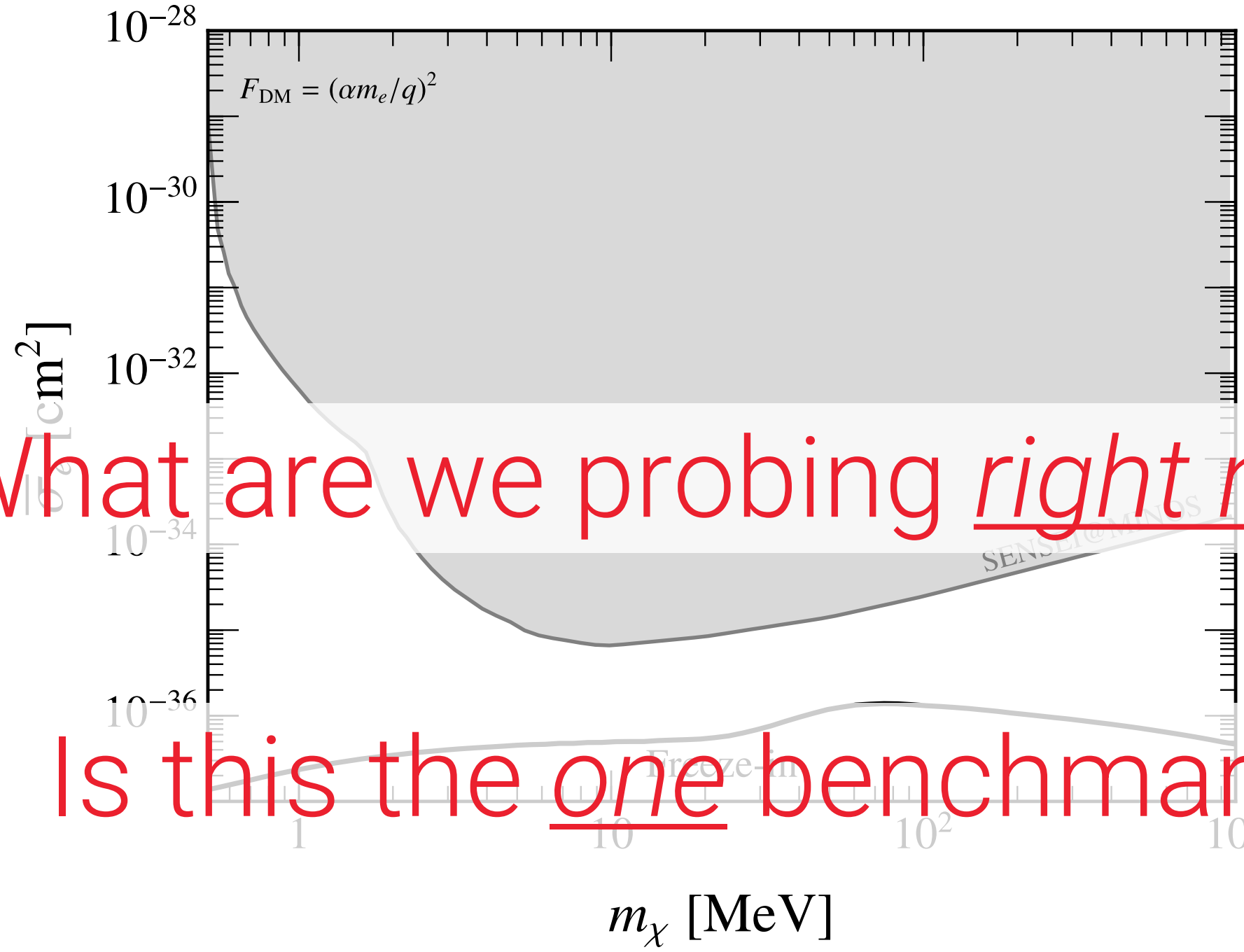
R McGehee

The Real Challenge: BBN



G. Krnjaic and S. McDermott [1908.00007]

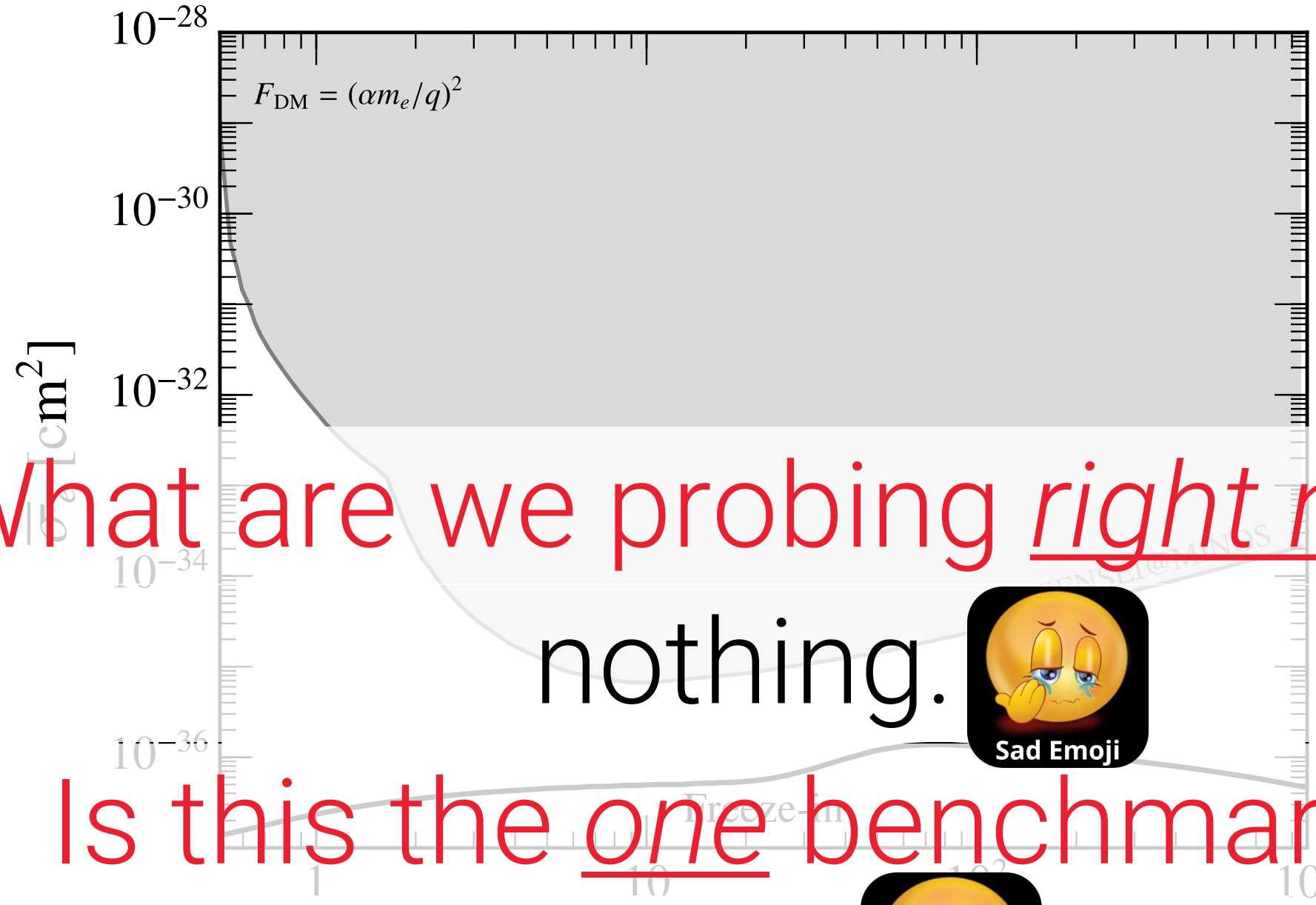
R McGehee



What are we probing *right now*?

Is this the *one* benchmark?

R McGehee



What are we probing *right now*?

nothing.

Is this the *one* benchmark?

yes.

R McGehee

The Power of the Dark Sink

2312.14152
w/ Prudhvi N. Bhattiprolu & Aaron Pierce

~~Freeze In~~ Dark Sink

$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$ + Light fermion ψ

R McGehee

~~Freeze In~~ Dark Sink

$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$ + Light fermion ψ

$$\mathrm{SM}\ \mathrm{SM} \to \bar{\chi}\chi \qquad \bar{\chi}\chi \leftrightarrow \bar{\psi}\psi$$

R McGehee

~~Freeze In~~ Dark Sink

$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$ + Light fermion ψ

$$\mathrm{SM\ SM} \to \bar{\chi}\chi \qquad \bar{\chi}\chi \leftrightarrow \bar{\psi}\psi$$

$$\kappa \equiv \epsilon\sqrt{\alpha'/\alpha} \approx \mathcal{O}(10^{-11}) \qquad \kappa \lesssim \kappa_{\rm th} \approx 8 \times 10^{-7} \frac{\sqrt{m_\chi/\mathrm{GeV}}}{g_*(T = m_\chi)^{3/8}}$$

R McGehee

~~Freeze In~~ Dark Sink

$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$ + Light fermion ψ

$$\mathrm{SM\ SM} \to \bar{\chi}\chi \qquad \bar{\chi}\chi \leftrightarrow \bar{\psi}\psi$$

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Larger cross sections @ current direct detection exps

R McGehee

Temperature

The Story

- SM produces dark matter

R McGehee

Temperature

The Story

- SM produces dark matter
- Dark matter thermalizes with Dark Sink

R McGehee

Temperature

The Story

- SM produces dark matter
- Dark matter thermalizes with Dark Sink
- Dark Matter Annihilates away; SM continues to produce it

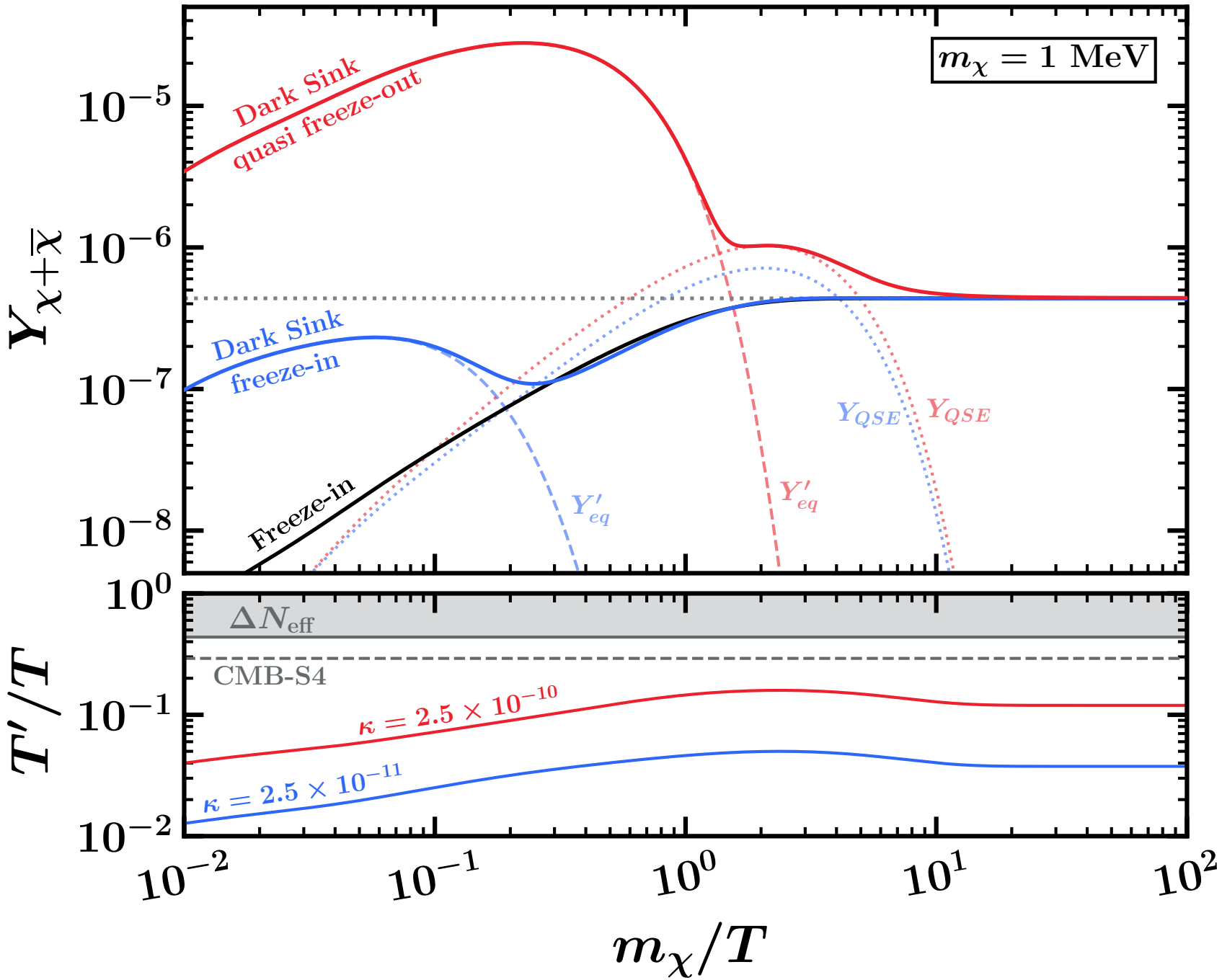
R McGehee

Temperature

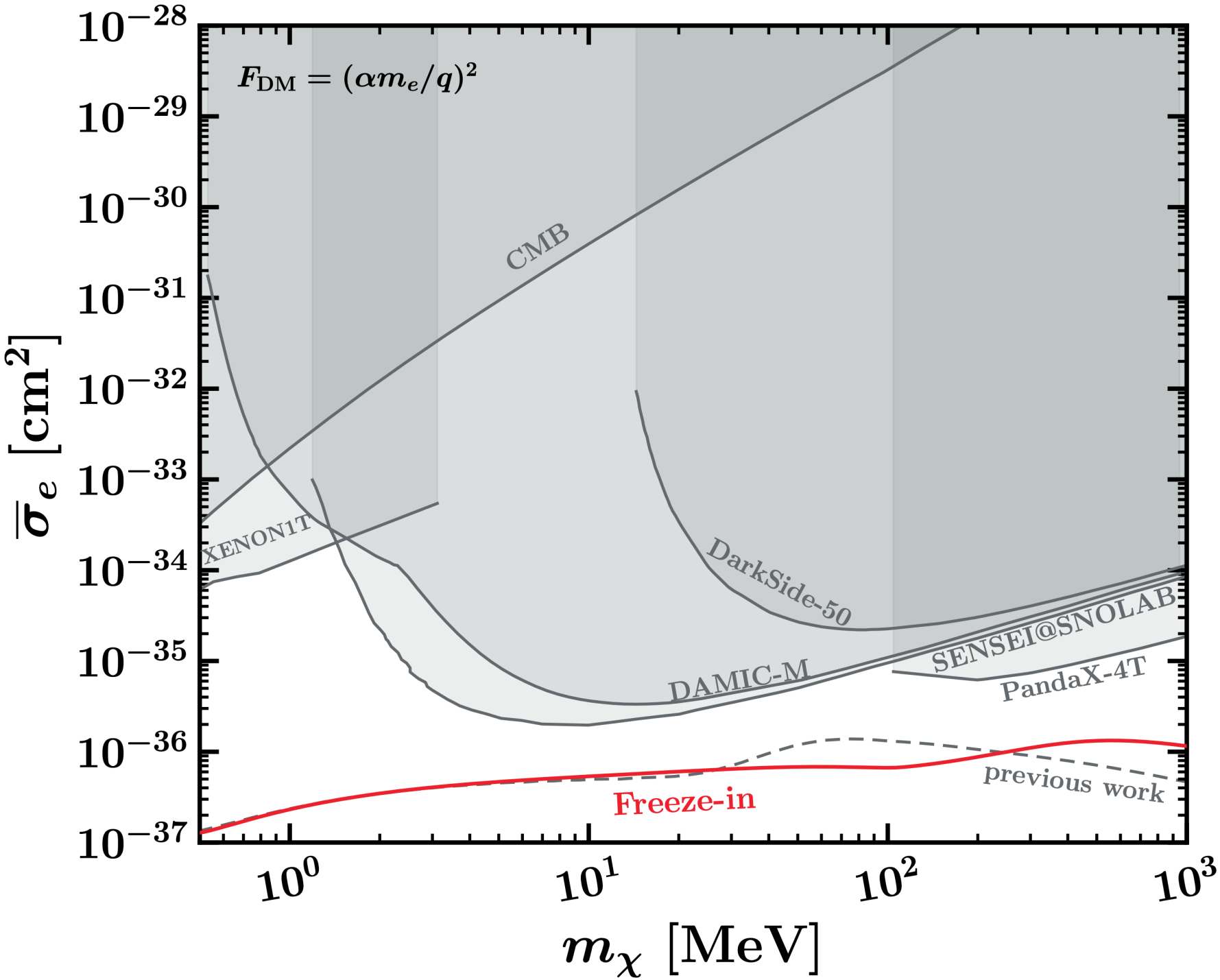
The Story

- SM produces dark matter
- Dark matter thermalizes with Dark Sink
- Dark Matter Annihilates away; SM continues to produce it
- Annihilations and SM freeze-in both lose to Hubble

R McGehee


$m_\chi = 1$ MeV
Dark Sink
quasi freeze-out
Dark Sink
freeze-in
Freeze-in
Y_{QSE}
Y_{QSE}
Y'_{eq}
Y'_{eq}
$Y_{\chi+\bar{\chi}}$
$\Delta N_{\rm eff}$
CMB-S4
$\kappa = 2.5 \times 10^{-10}$
$\kappa = 2.5 \times 10^{-11}$
T'/T
m_χ/T

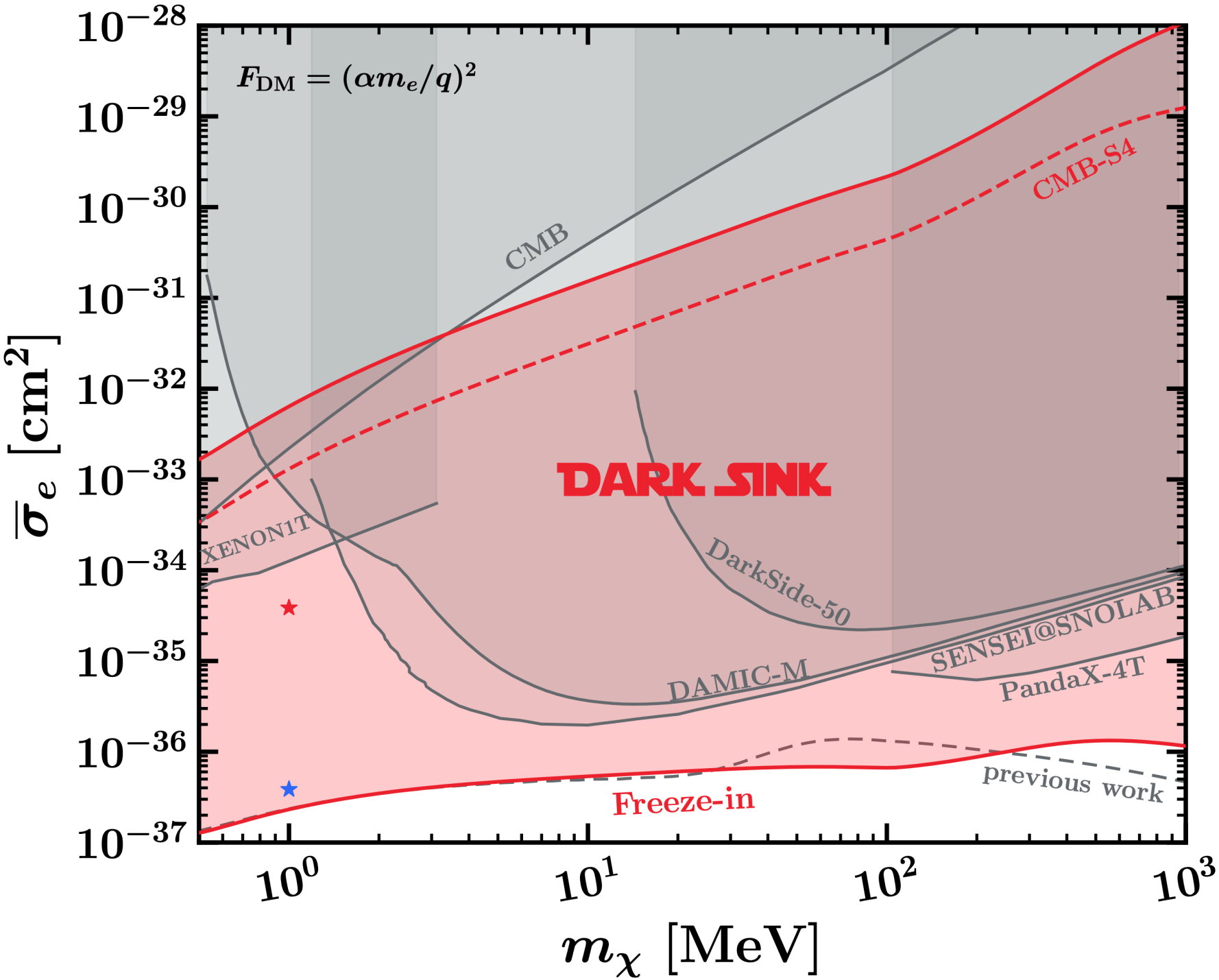
R McGehee



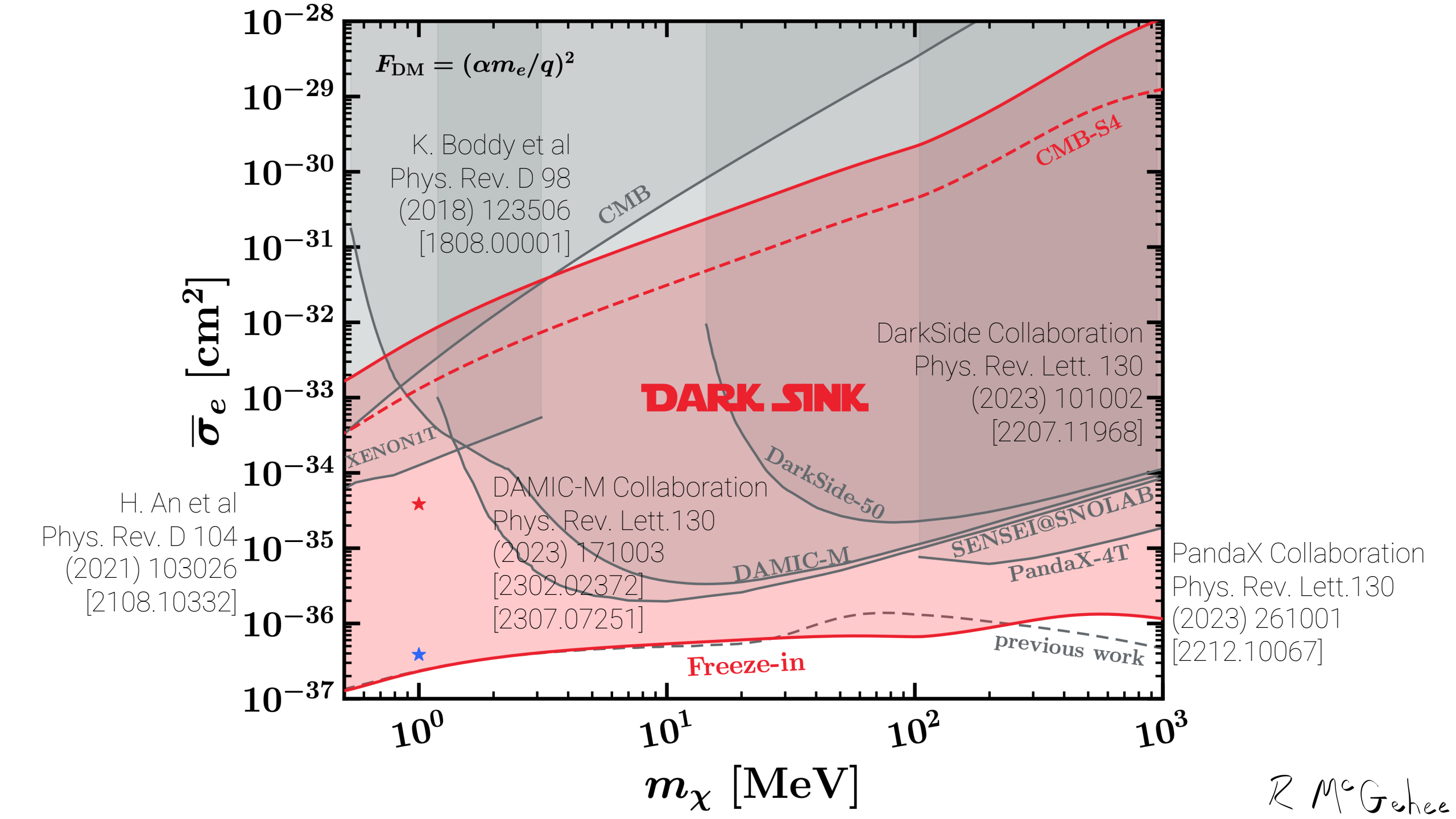
R. Essig, J. Mardon,T. Volansky Phys. Rev. D 85 (2012) 076007 [1108.5383]

SENSEI Collaboration [2312.13342]

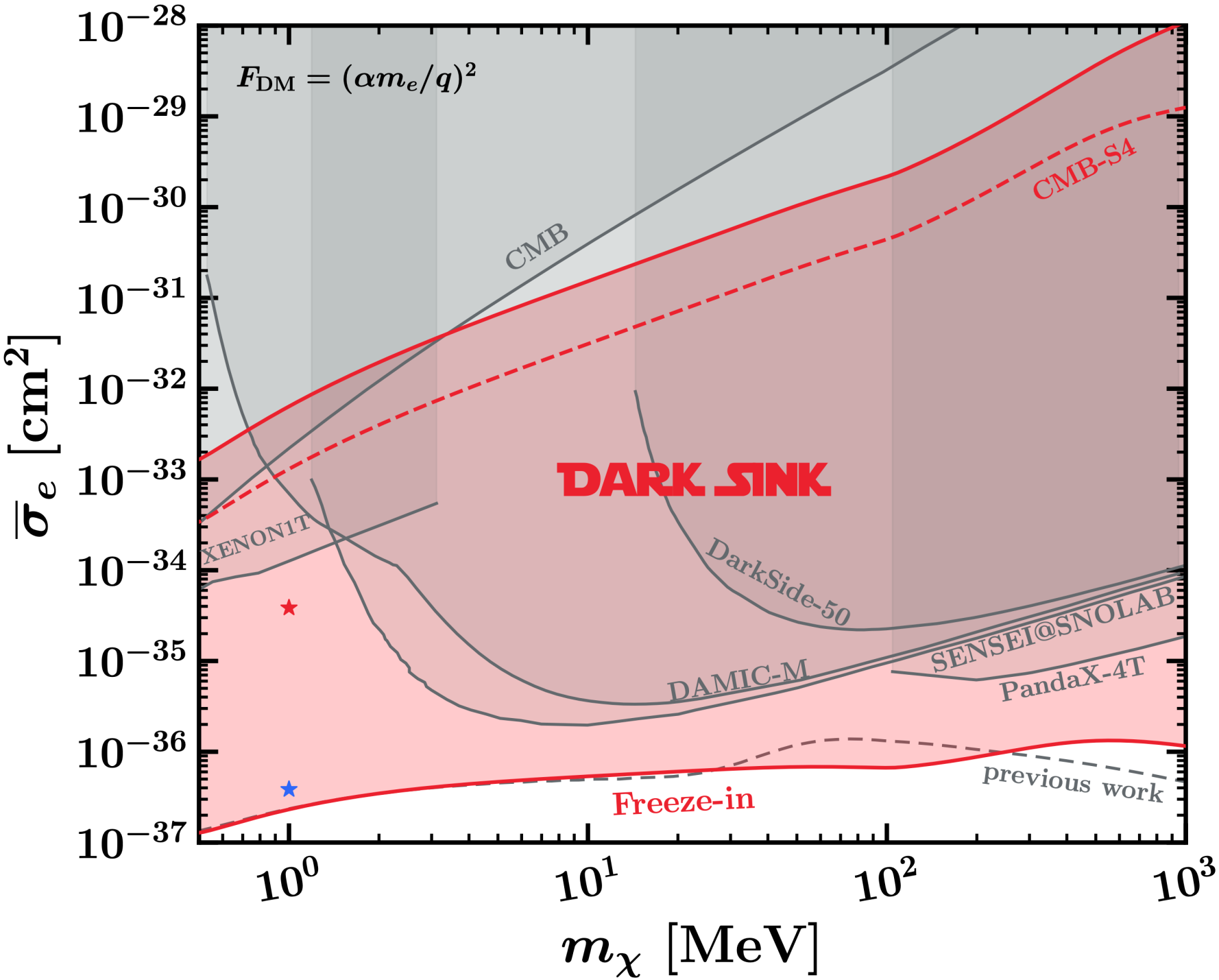
R McGehee


$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
CMB-S4
DARK SINK
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
previous work
Freeze-in
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^0
10^1
10^2
10^3

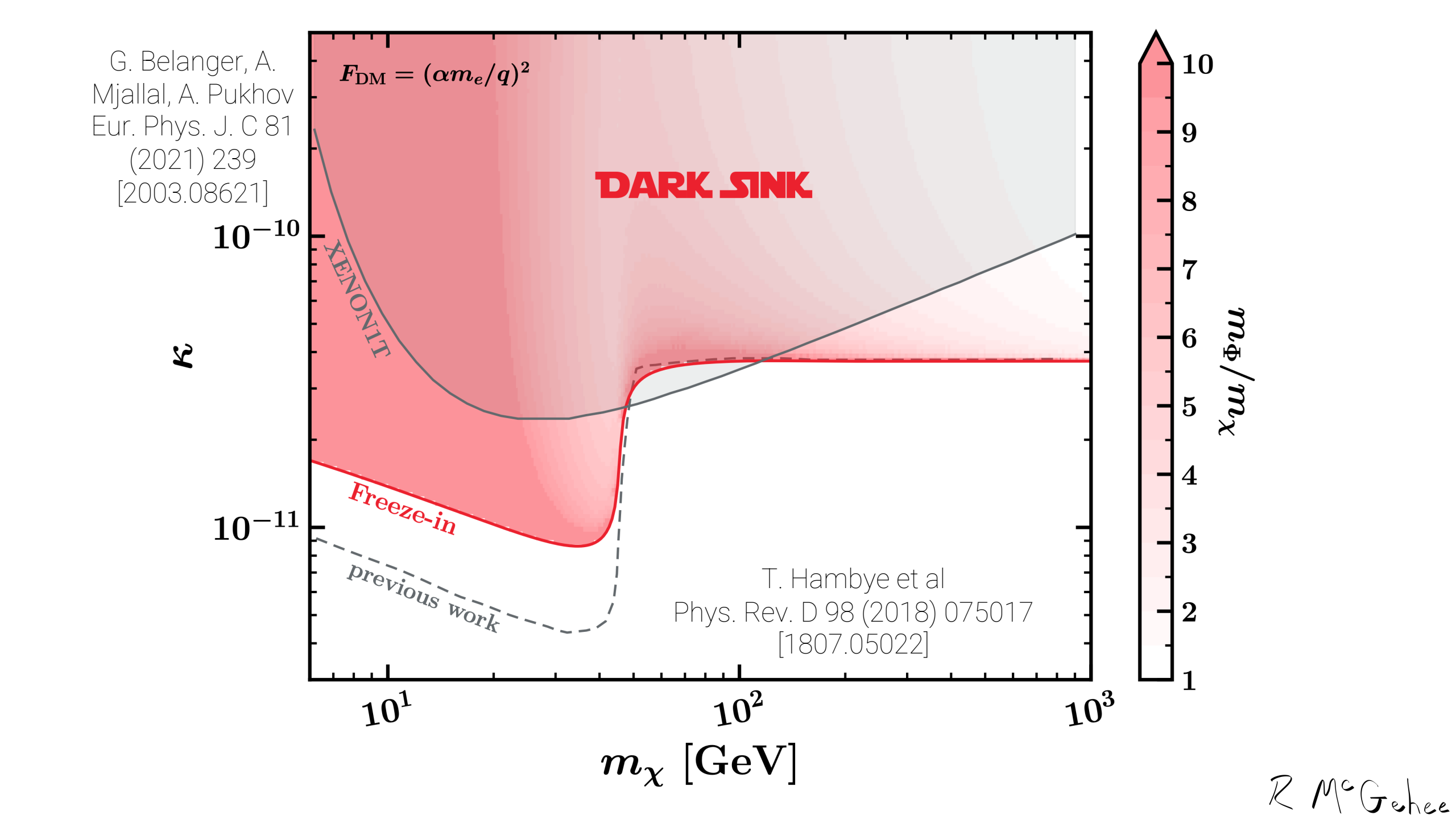
R McGehee

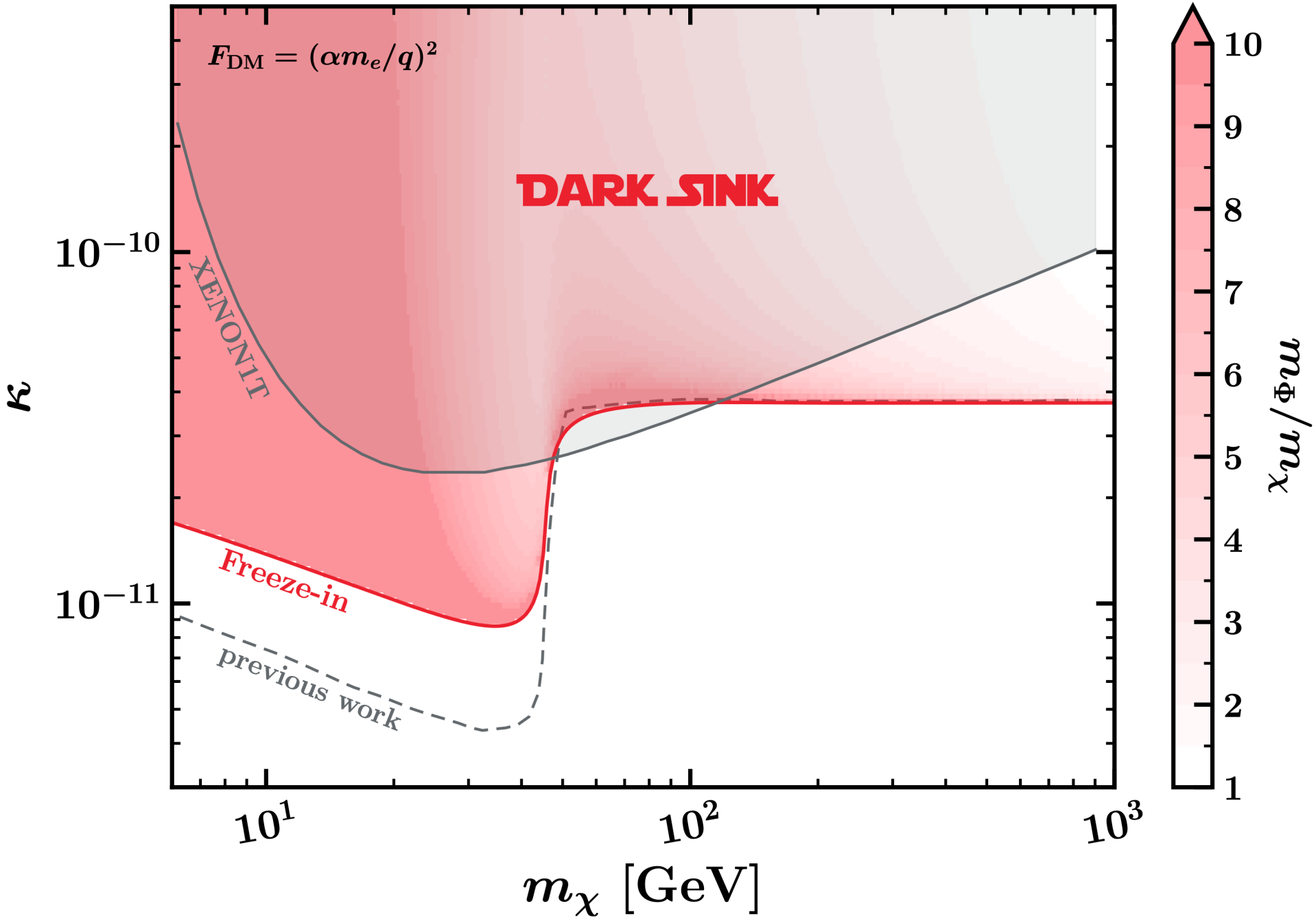

$F_{\rm DM} = (\alpha m_e/q)^2$
K. Boddy et al
Phys. Rev. D 98
(2018) 123506
[1808.00001]
CMB
CMB-S4
DARK SINK
DarkSide Collaboration
Phys. Rev. Lett. 130
(2023) 101002
[2207.11968]
XENON1T
DarkSide-50
SENSEI@SNOLAB
DAMIC-M
PandaX-4T
DAMIC-M Collaboration
Phys. Rev. Lett.130
(2023) 171003
[2302.02372]
[2307.07251]
H. An et al
Phys. Rev. D 104
(2021) 103026
[2108.10332]
Freeze-in
previous work
PandaX Collaboration
Phys. Rev. Lett.130
(2023) 261001
[2212.10067]
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^0
10^1
10^2
10^3

R McGehee

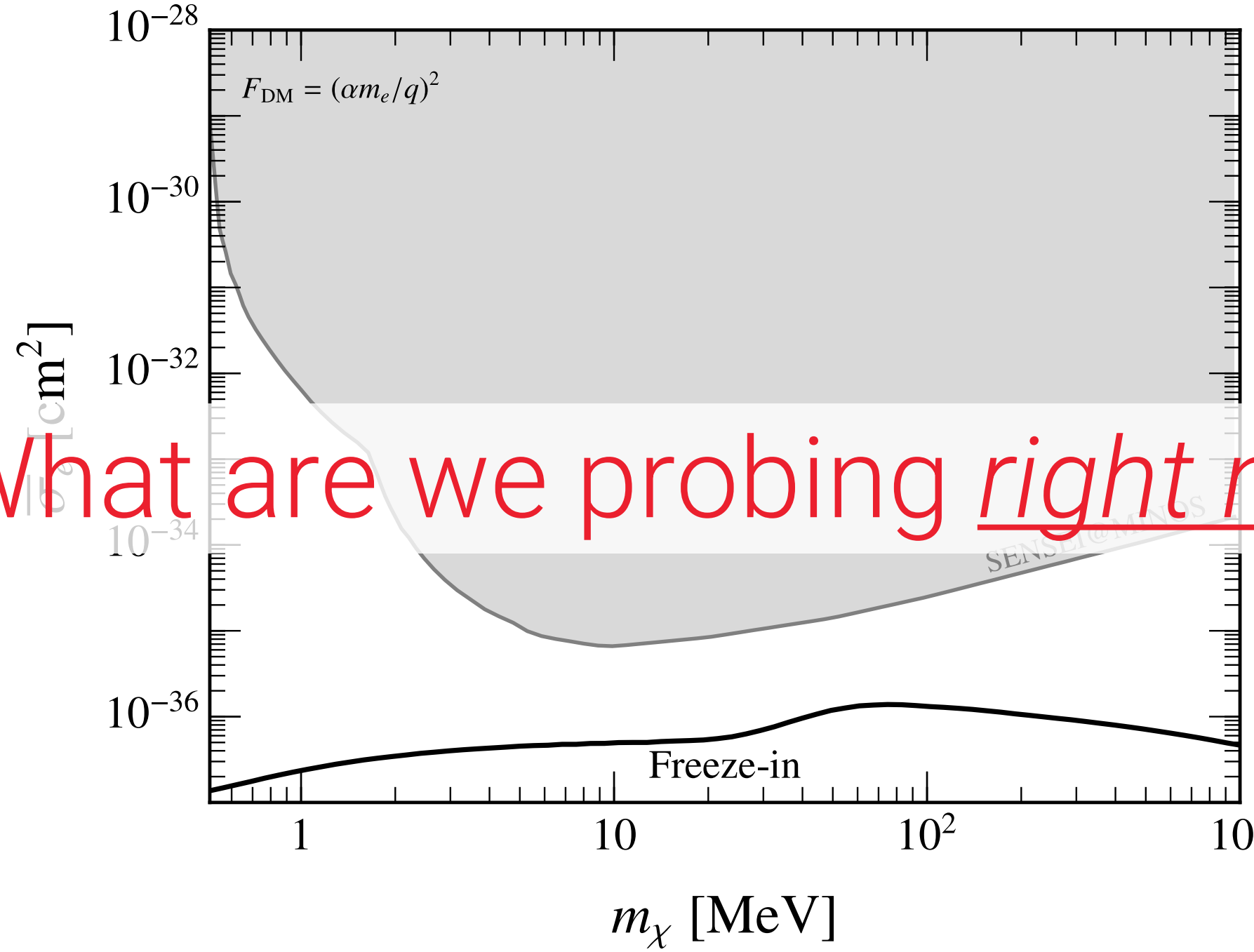

$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
CMB-S4
DARK SINK
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
previous work
Freeze-in
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^0
10^1
10^2
10^3

R McGehee


G. Belanger, A. Mjallal, A. Pukhov Eur. Phys. J. C 81 (2021) 239 [2003.08621]
$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
XENON1T
Freeze-in
previous work
T. Hambye et al Phys. Rev. D 98 (2018) 075017 [1807.05022]
κ
10^{-10}
10^{-11}
10^1
10^2
10^3
m_χ [GeV]
$\chi n/\Phi n$
10
9
8
7
6
5
4
3
2
1
R McGehee

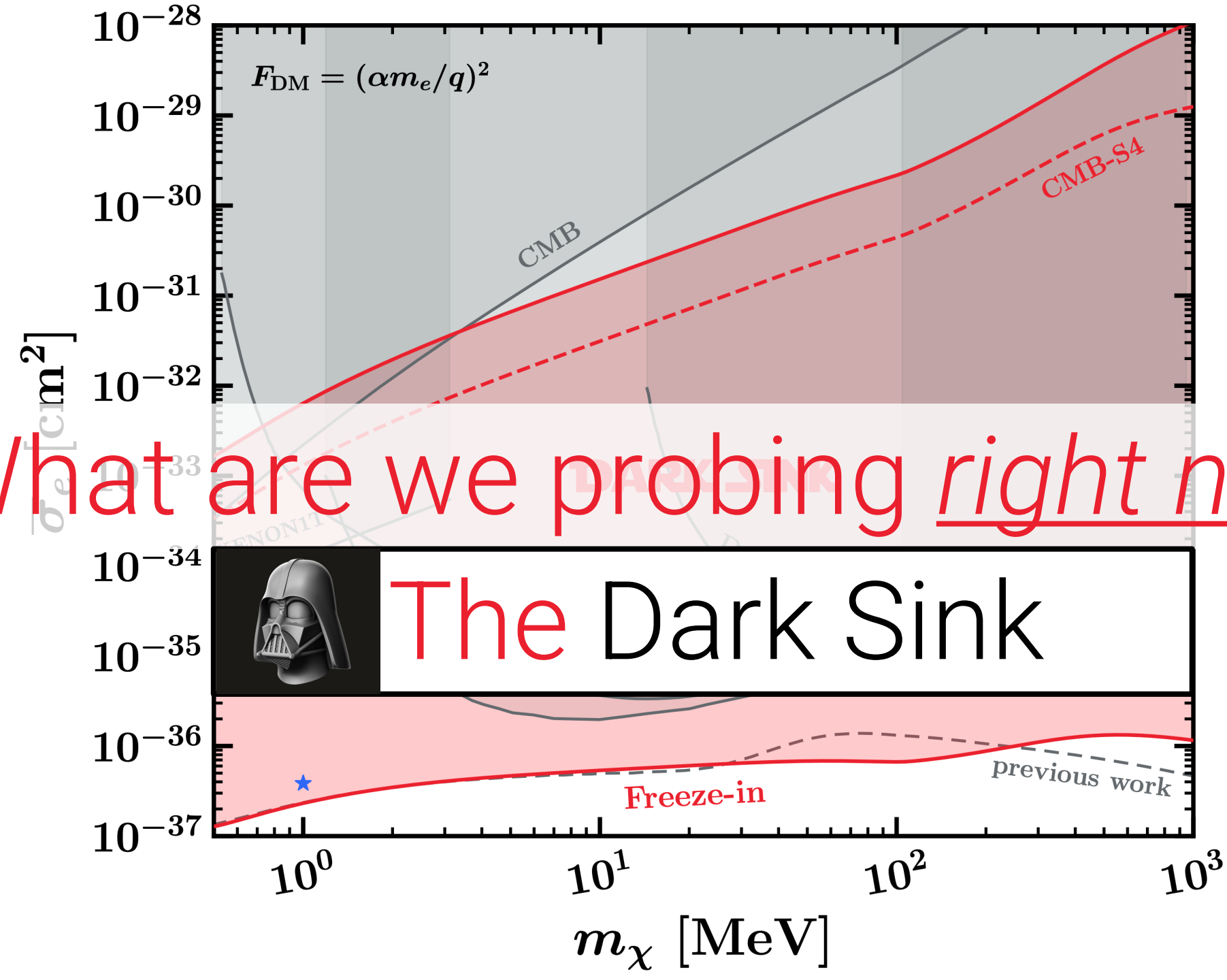

$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
XENON1T
Freeze-in
previous work
κ
10^{-10}
10^{-11}
10^1
10^2
10^3
m_χ [GeV]
χ_{nu}/Φ_{nu}
10
9
8
7
6
5
4
3
2
1

R McGehee



What are we probing *right now*?

R McGehee



What are we probing *right now*?

The Dark Sink

R McGehee

R McGehee

R McGehee

- Sub-MeV DM (plasmons start to matter)

R McGehee

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- How a Dark Sink could change other motivated freeze-in pheno:

R McGehee

- Sub-MeV DM (plasmons start to matter)
- How a Dark Sink could change other motivated freeze-in pheno:
  - Long-lived searches for FIMPs
  - Direct detection of UV freeze-in models

R McGehee

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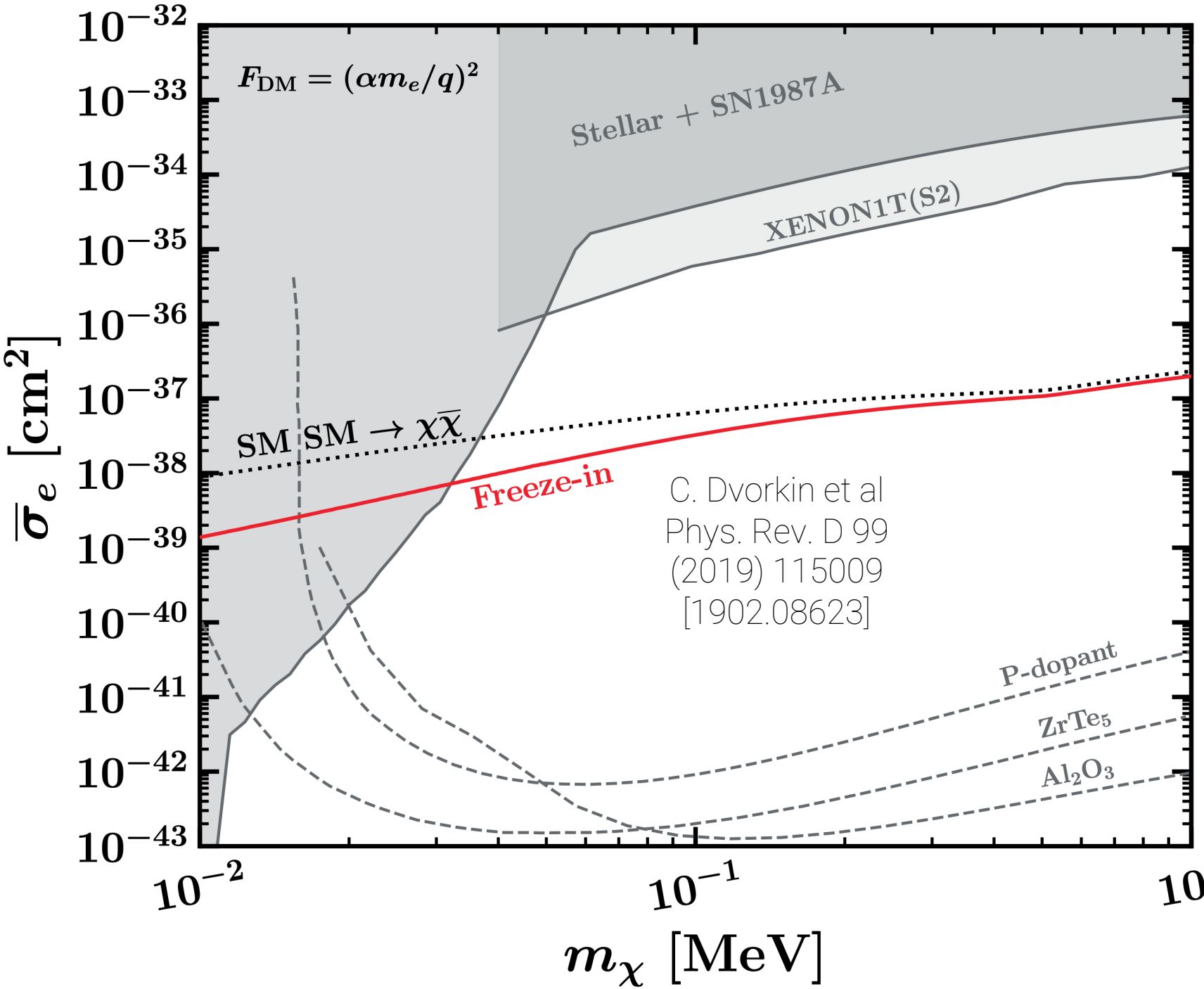
- How a Dark Sink could change other motivated freeze-in pheno:

  - Long-lived searches for FIMPs

  - Direct detection of UV freeze-in models

R McGehee



H. An et al
Phys. Rev. D 104
(2021) 103026
[2108.10332]

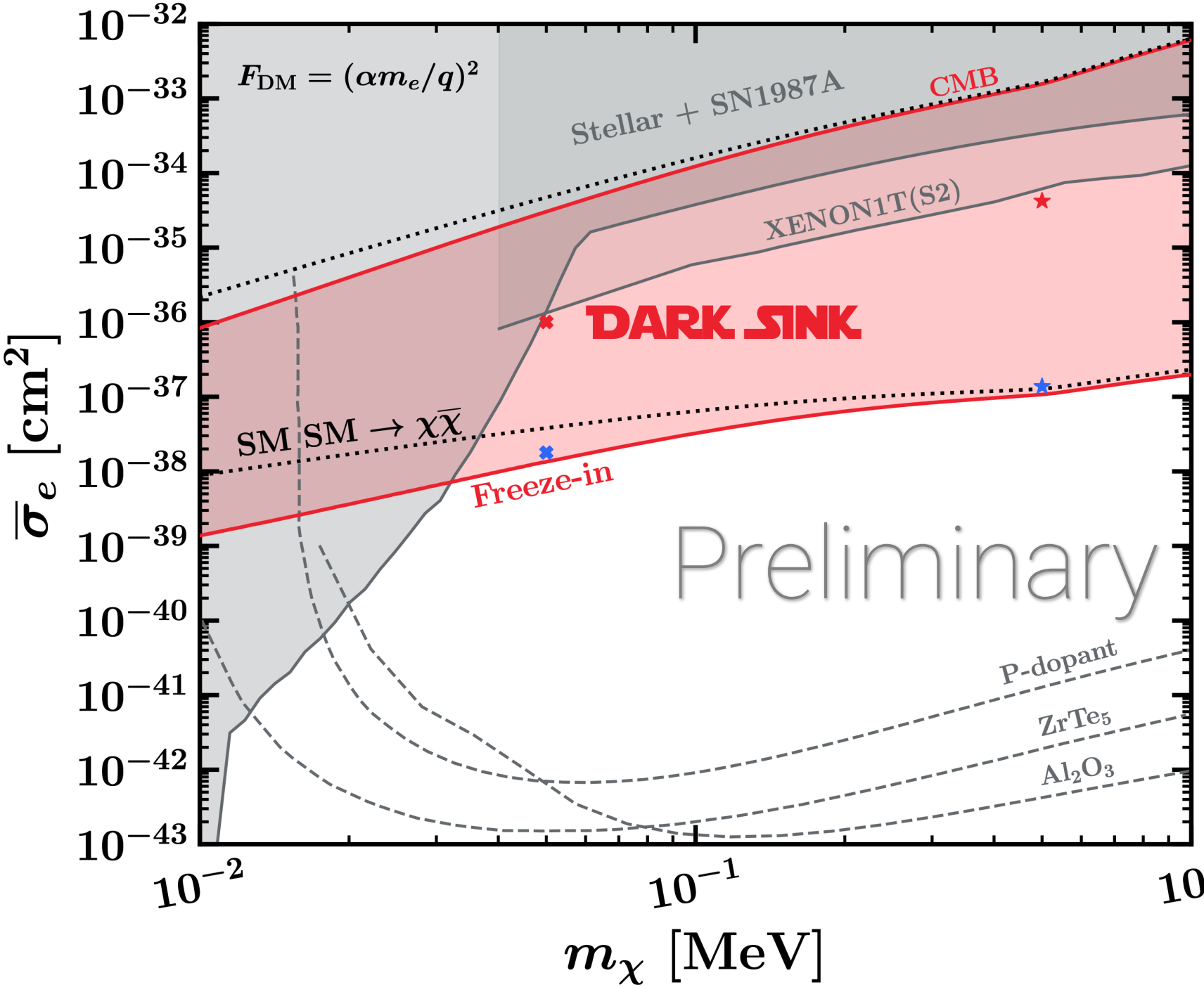
P. Du et al
Phys. Rev. D 109
(2024) 055009
[2212.04504]

C. Dvorkin et al
Phys. Rev. D 99
(2019) 115009
[1902.08623]

Y. Hochberg et al
Phys. Rev. D 97
(2018) 015004
[1708.08929]

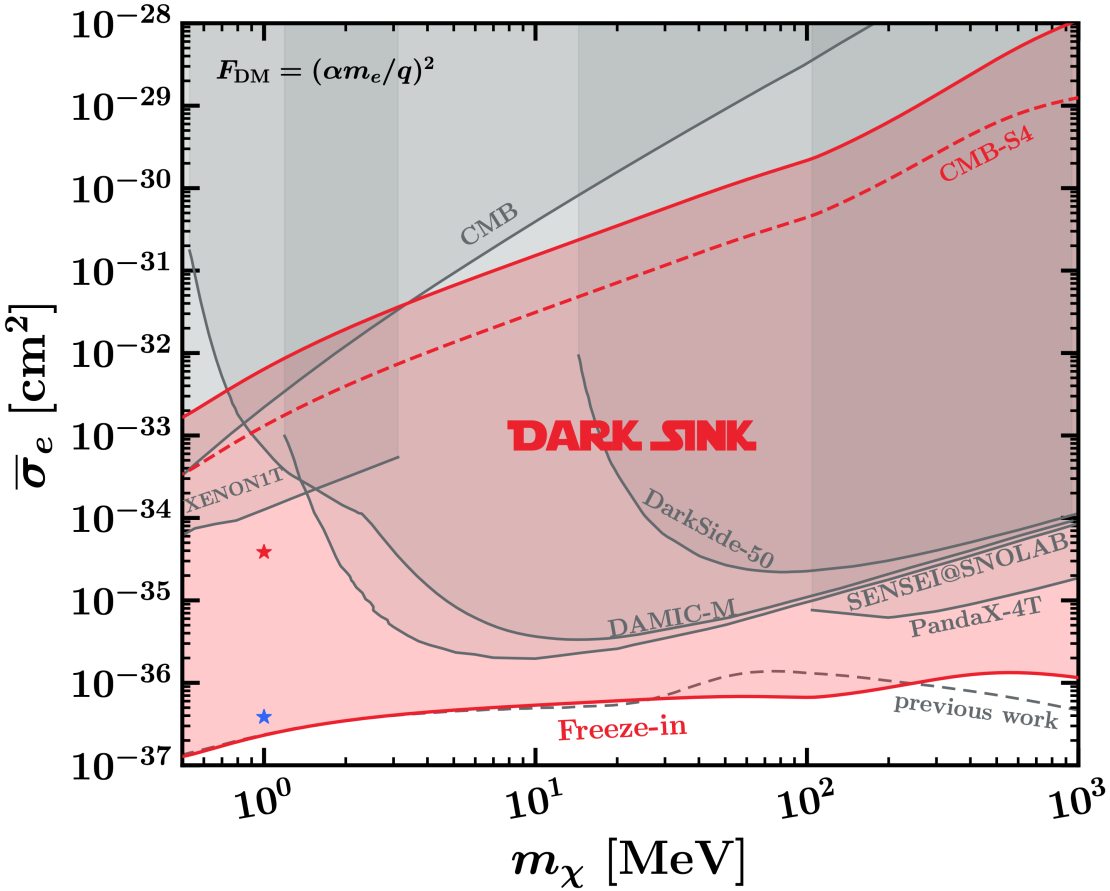
Y. Hochberg et al
JHEP 08
(2016) 057
[1512.04533]

R McGehee

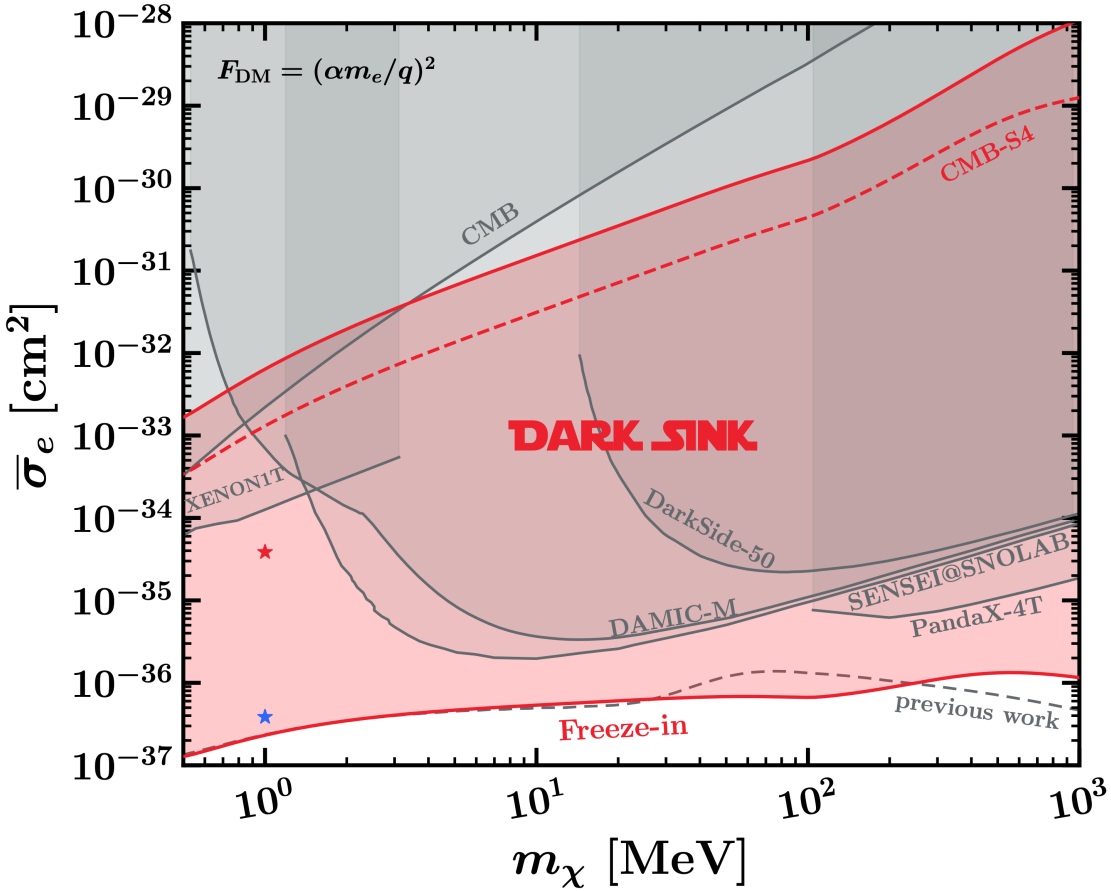


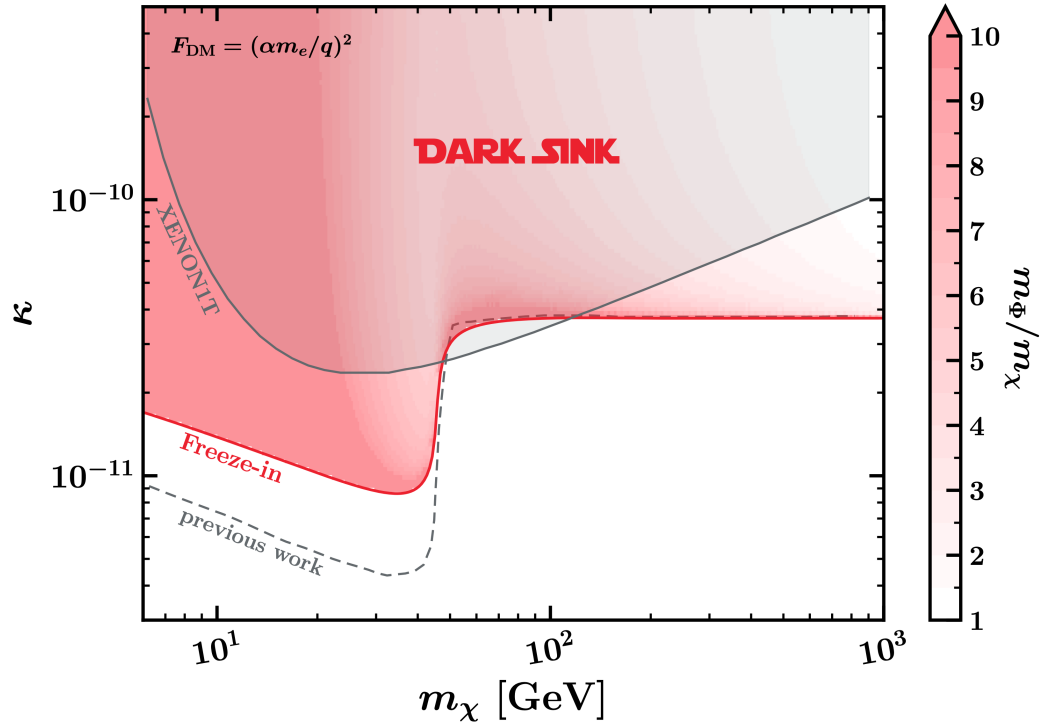
To appear w/ Prudhvi N. Bhattiprolu, Evan Petrosky, & Aaron Pierce

R McGehee

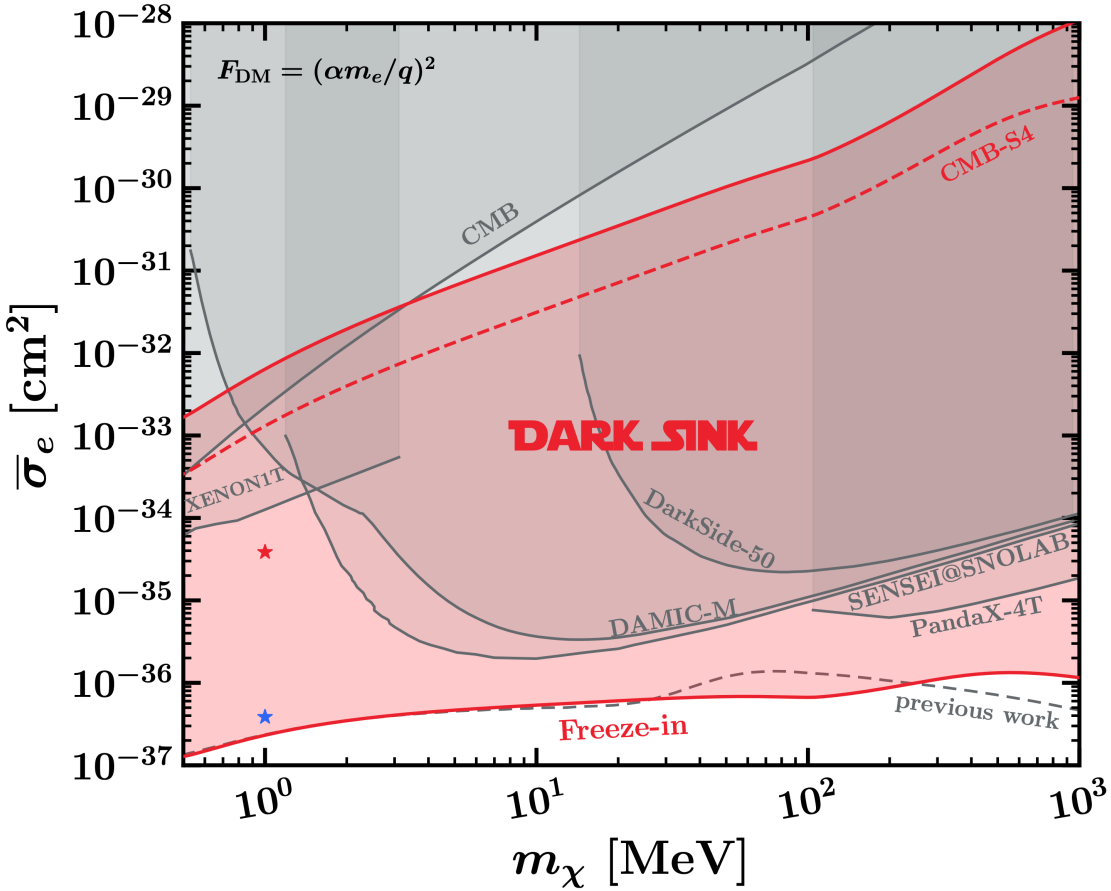

$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
CMB-S4
DARK SINK
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
Freeze-in
previous work
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^0
10^1
10^2
10^3

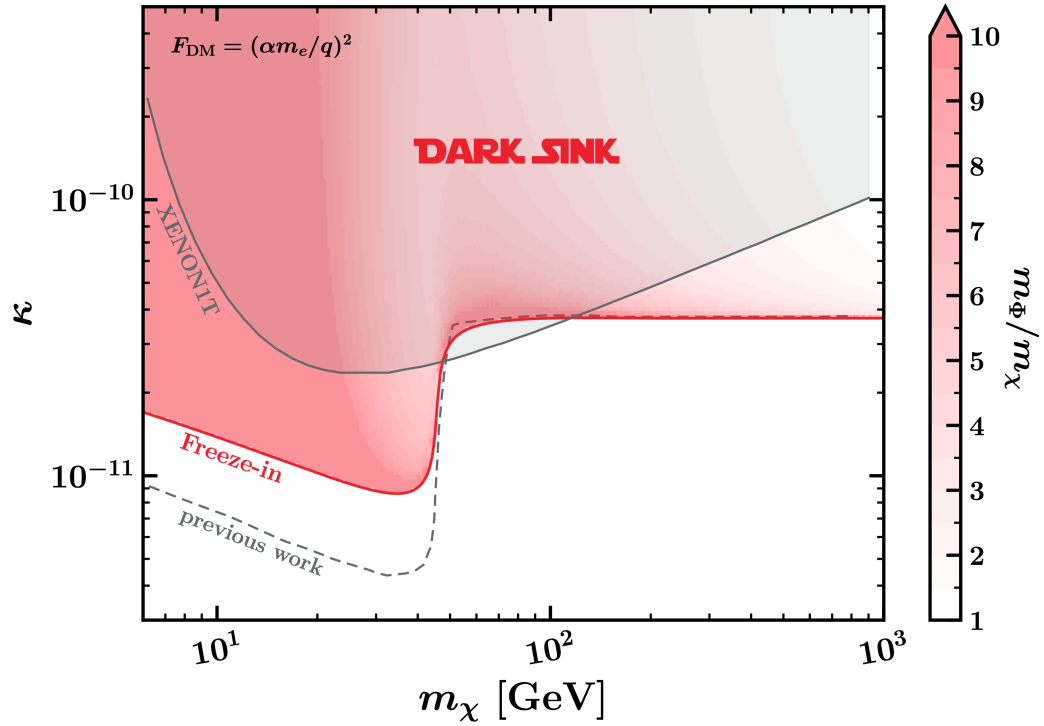
R McGehee

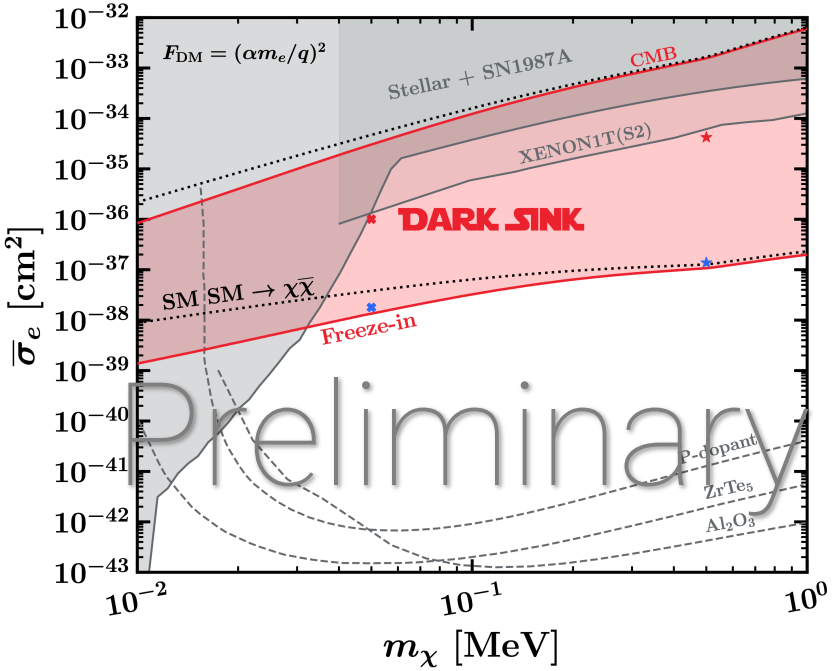

$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
CMB
CMB-S4
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
Freeze-in
previous work
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]


$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
XENON1T
Freeze-in
previous work
κ
m_χ [GeV]
$\chi u/\Phi u$

R McGehee

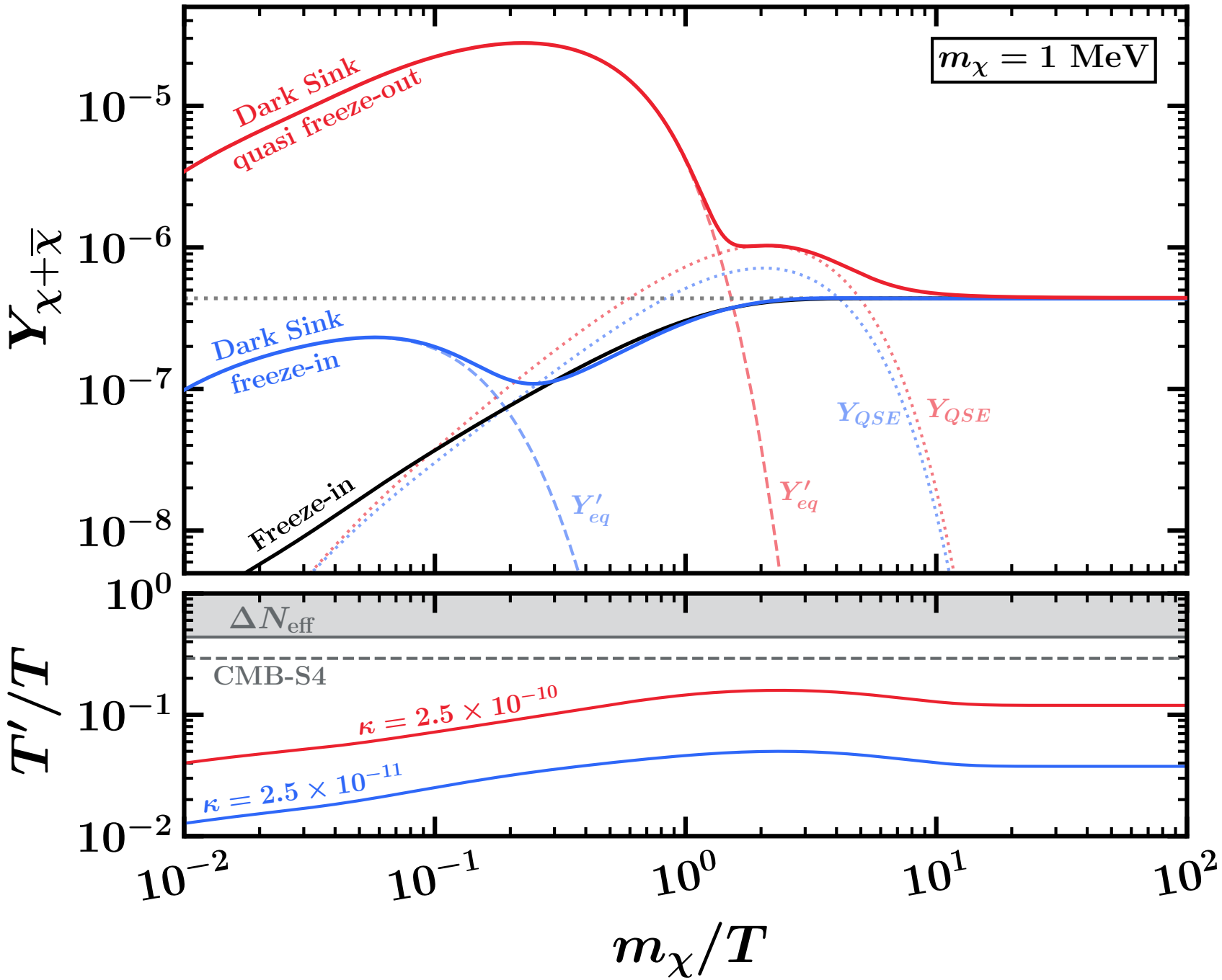

$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
CMB
CMB-S4
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
Freeze-in
previous work
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]


$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
XENON1T
Freeze-in
previous work
κ
m_χ [GeV]
$\chi u/\Phi u$

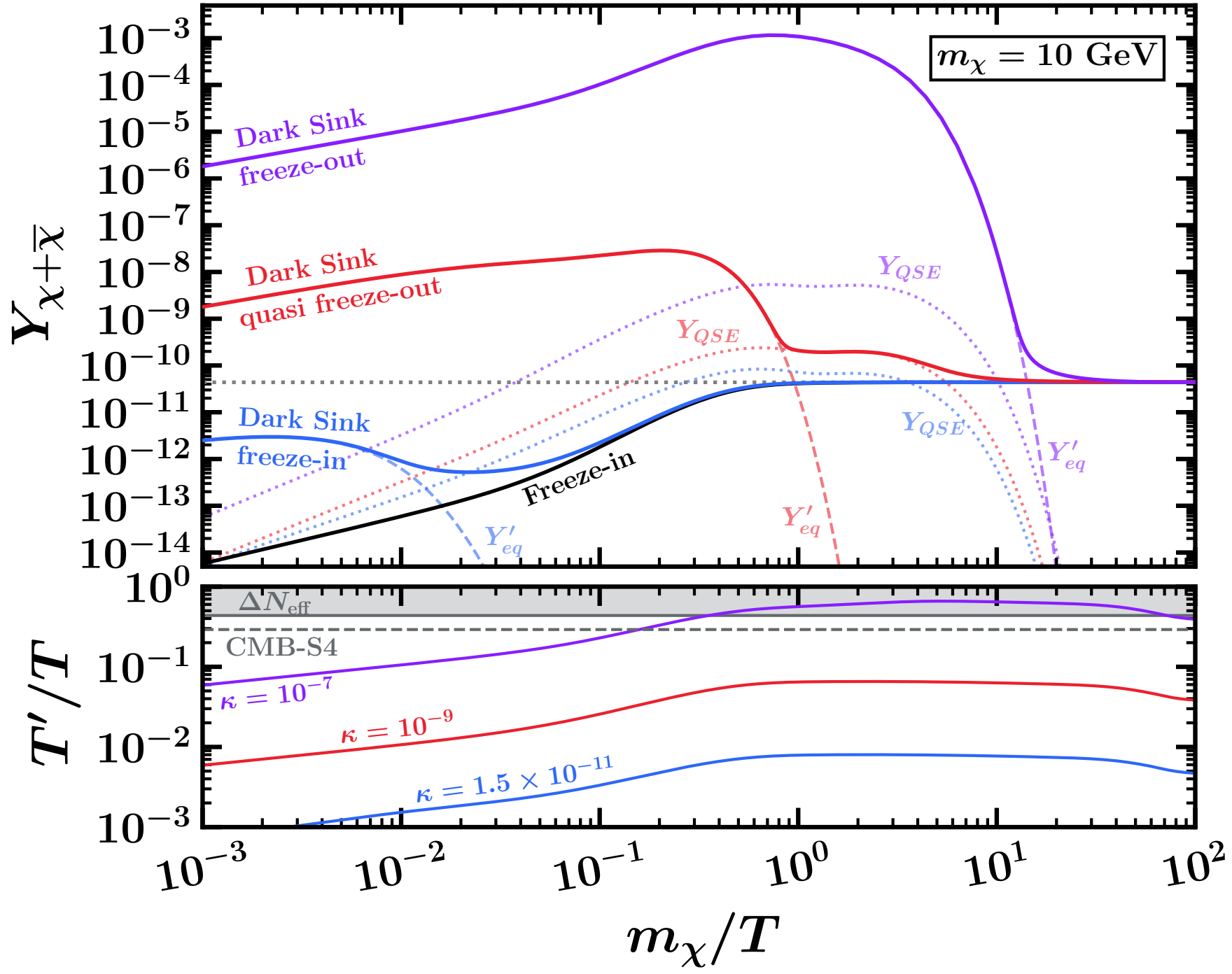

$F_{\rm DM} = (\alpha m_e/q)^2$
Stellar + SN1987A
CMB
XENON1T(S2)
DARK SINK
SM SM $\to \chi\overline{\chi}$
Freeze-in
Preliminary
P-dopant
$ZrTe_5$
Al_2O_3
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]

R McGehee

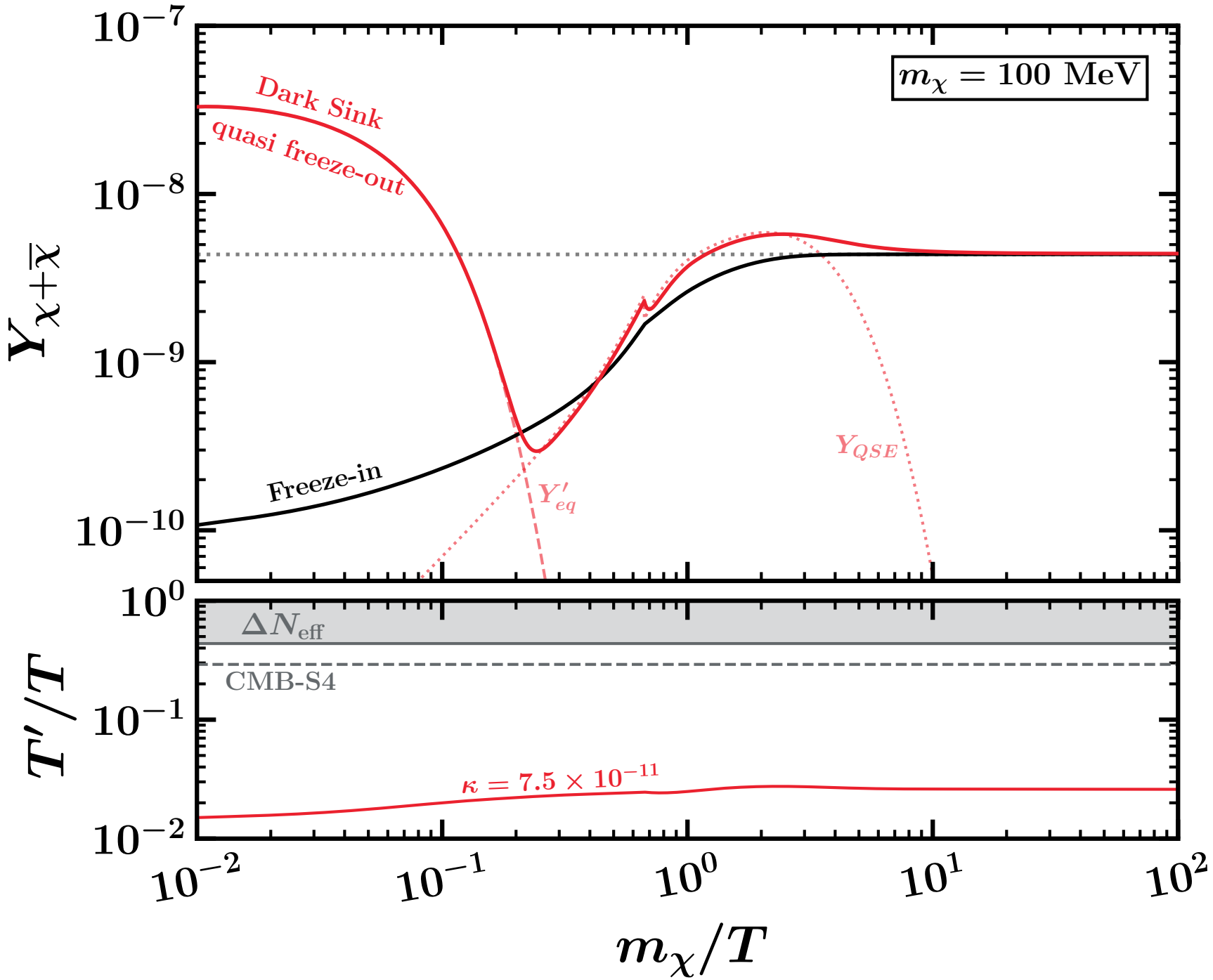
Backup Slides


$m_\chi = 1$ MeV
Dark Sink
quasi freeze-out
Dark Sink
freeze-in
Freeze-in
Y_{QSE}
Y_{QSE}
Y'_{eq}
Y'_{eq}
$Y_{\chi+\bar{\chi}}$
$\Delta N_{\rm eff}$
CMB-S4
$\kappa = 2.5 \times 10^{-10}$
$\kappa = 2.5 \times 10^{-11}$
T'/T
m_χ/T

R McGehee


$m_\chi = 10$ GeV
Dark Sink
freeze-out
Dark Sink
quasi freeze-out
Dark Sink
freeze-in
Freeze-in
Y_{QSE}
Y_{QSE}
Y_{QSE}
Y'_{eq}
Y'_{eq}
Y'_{eq}
$Y_{\chi+\bar{\chi}}$
$\Delta N_{\rm eff}$
CMB-S4
$\kappa = 10^{-7}$
$\kappa = 10^{-9}$
$\kappa = 1.5 \times 10^{-11}$
T'/T
m_χ/T

R McGehee


$m_\chi = 100$ MeV
Dark Sink
quasi freeze-out
Freeze-in
Y_{QSE}
Y'_{eq}
$Y_{\chi+\bar{\chi}}$
$\Delta N_{\rm eff}$
CMB-S4
$\kappa = 7.5 \times 10^{-11}$
T'/T
m_χ/T

R McGehee