The Power of the Dark Sink

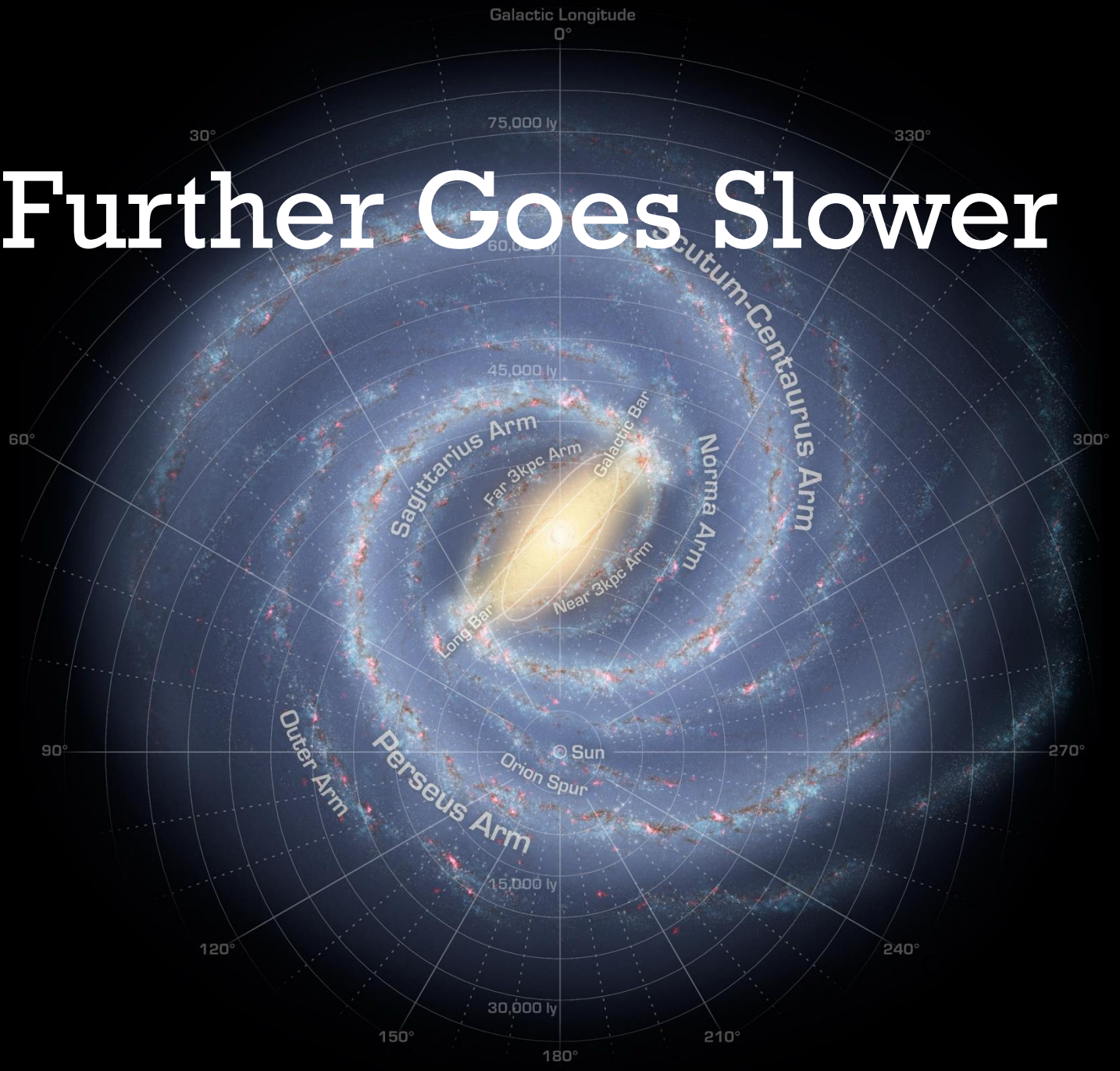
Robert McGehee

University of Minnesota

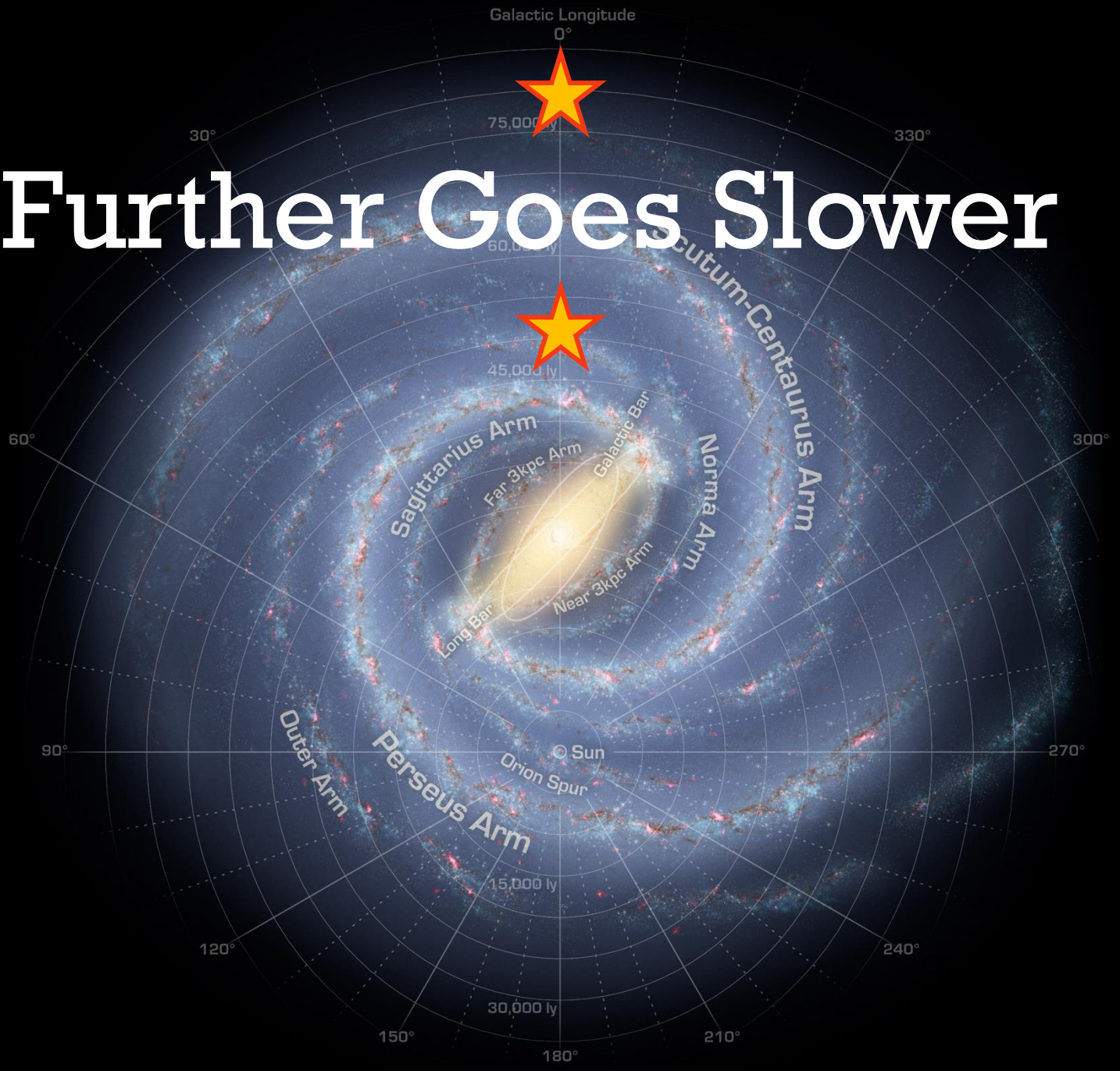
“The” Dark Matter Slide

R McGehee

Further Goes Slower



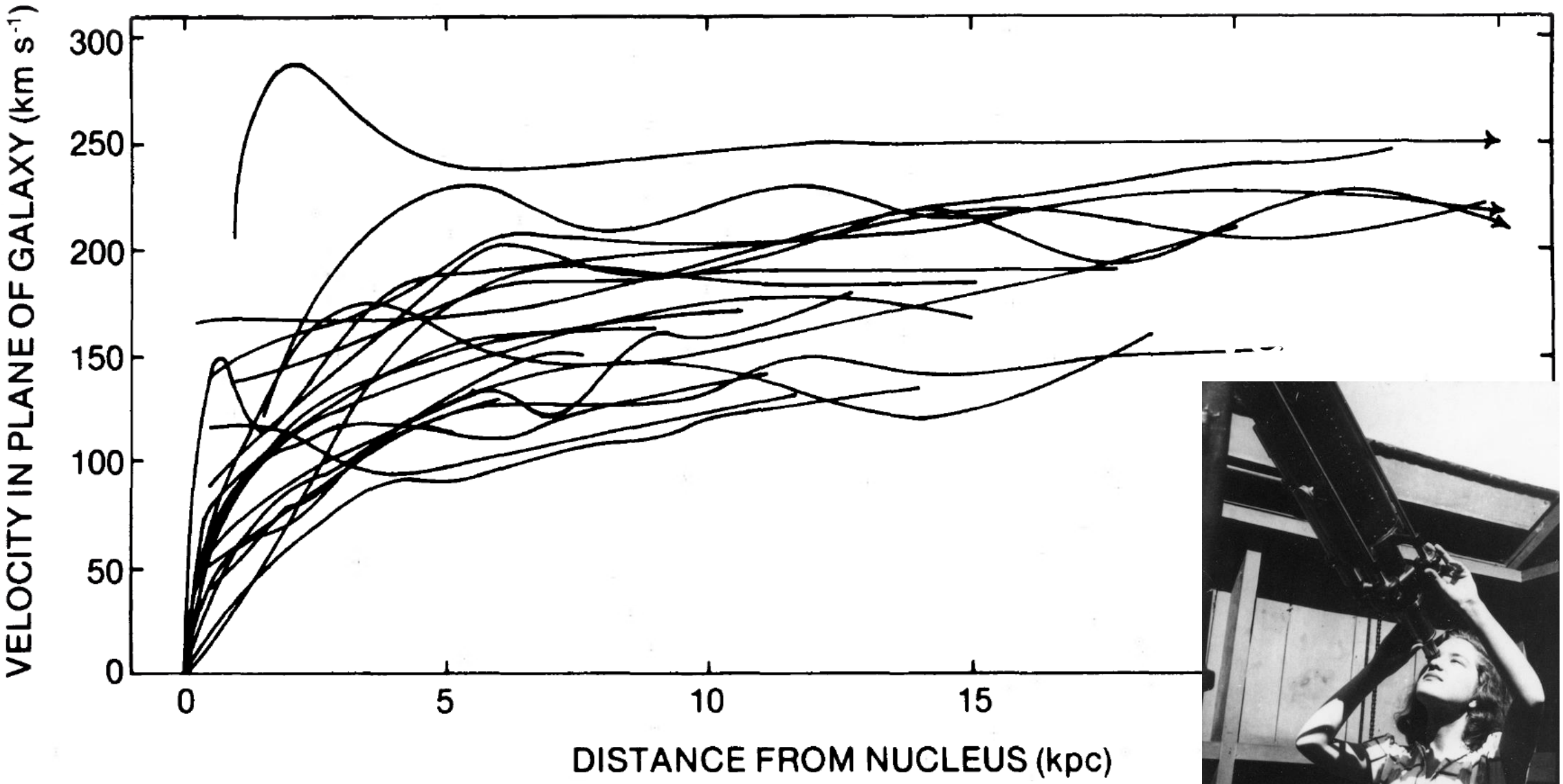
Further Goes Slower



Further Goes Similar!

Credit: Vassar College, courtesy AIP Emilio Segrè Visual Archives

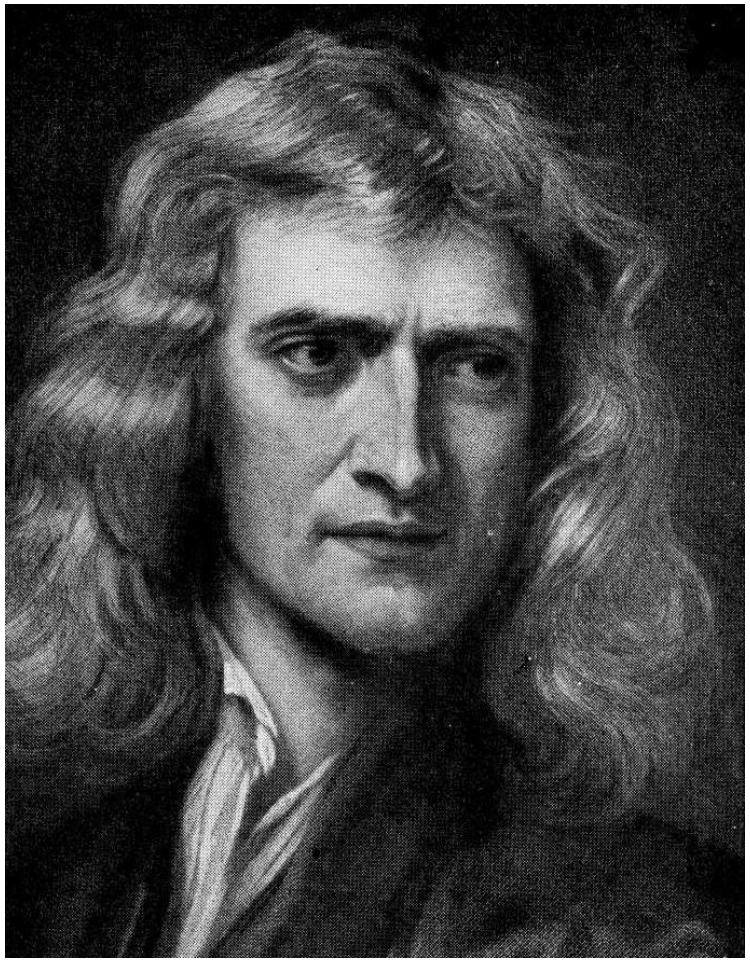
Vera Rubin

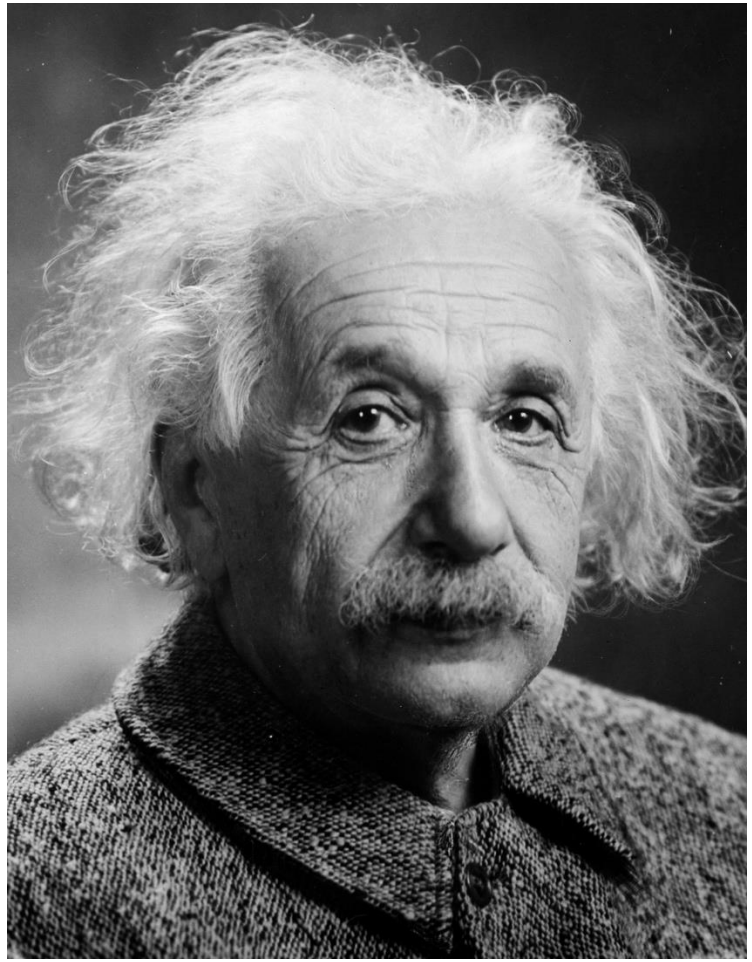


V.C. Rubin, N. Thonnard, W.K. Ford, Jr. Astrophys. J. 238 (1980) 471

Credit: Vassar College, courtesy AIP Emilio Segrè Visual Archives

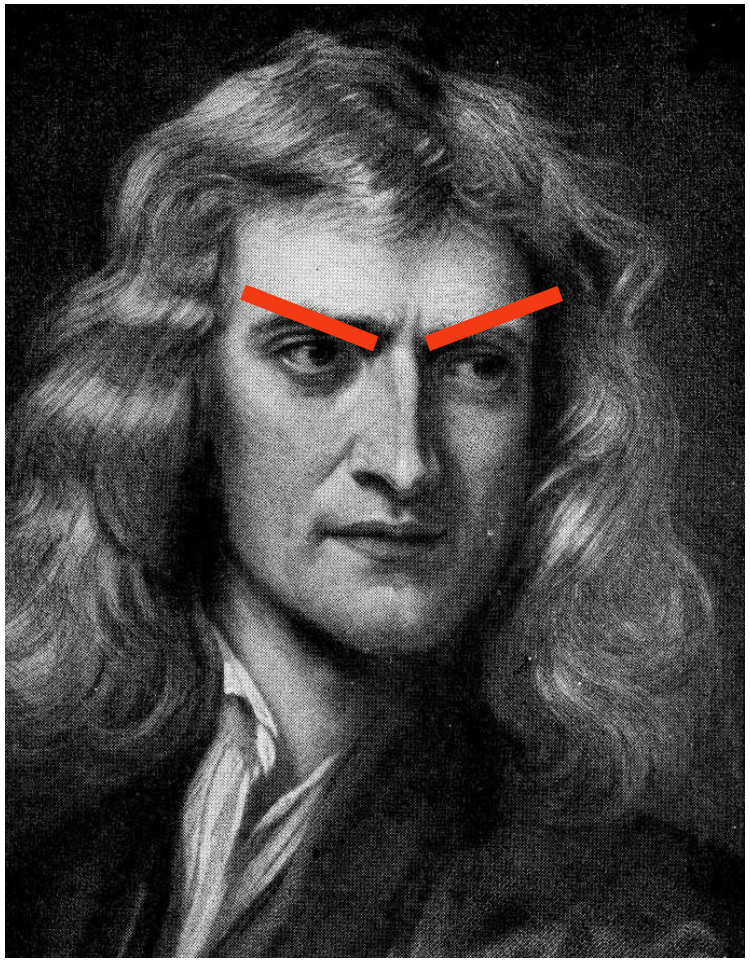
Oops?

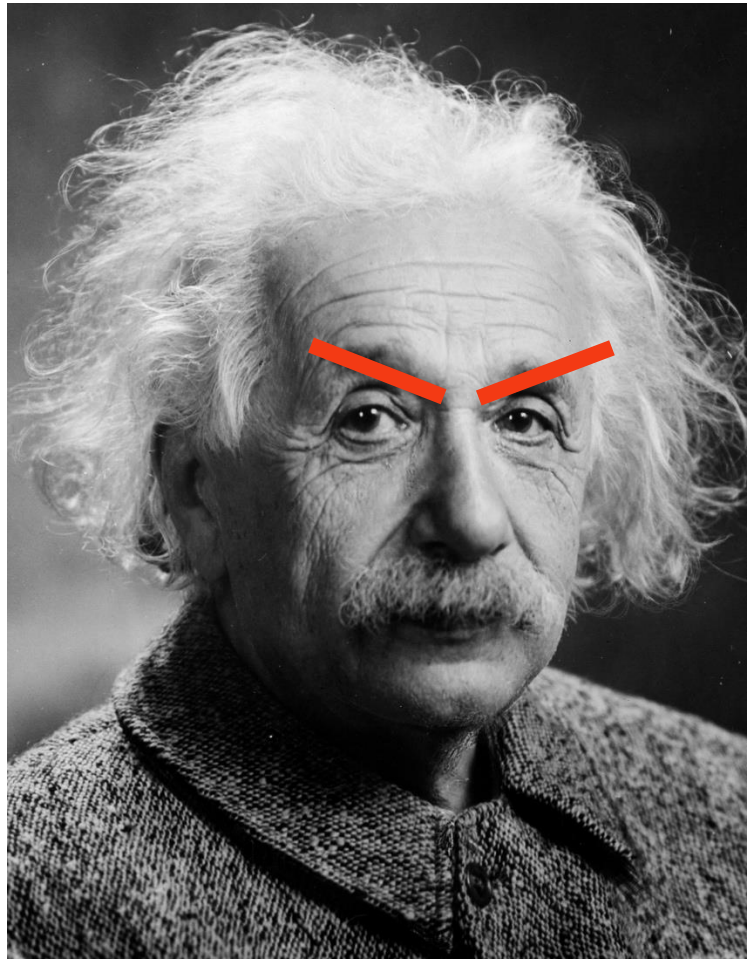




R McGehee

Blasphemer!





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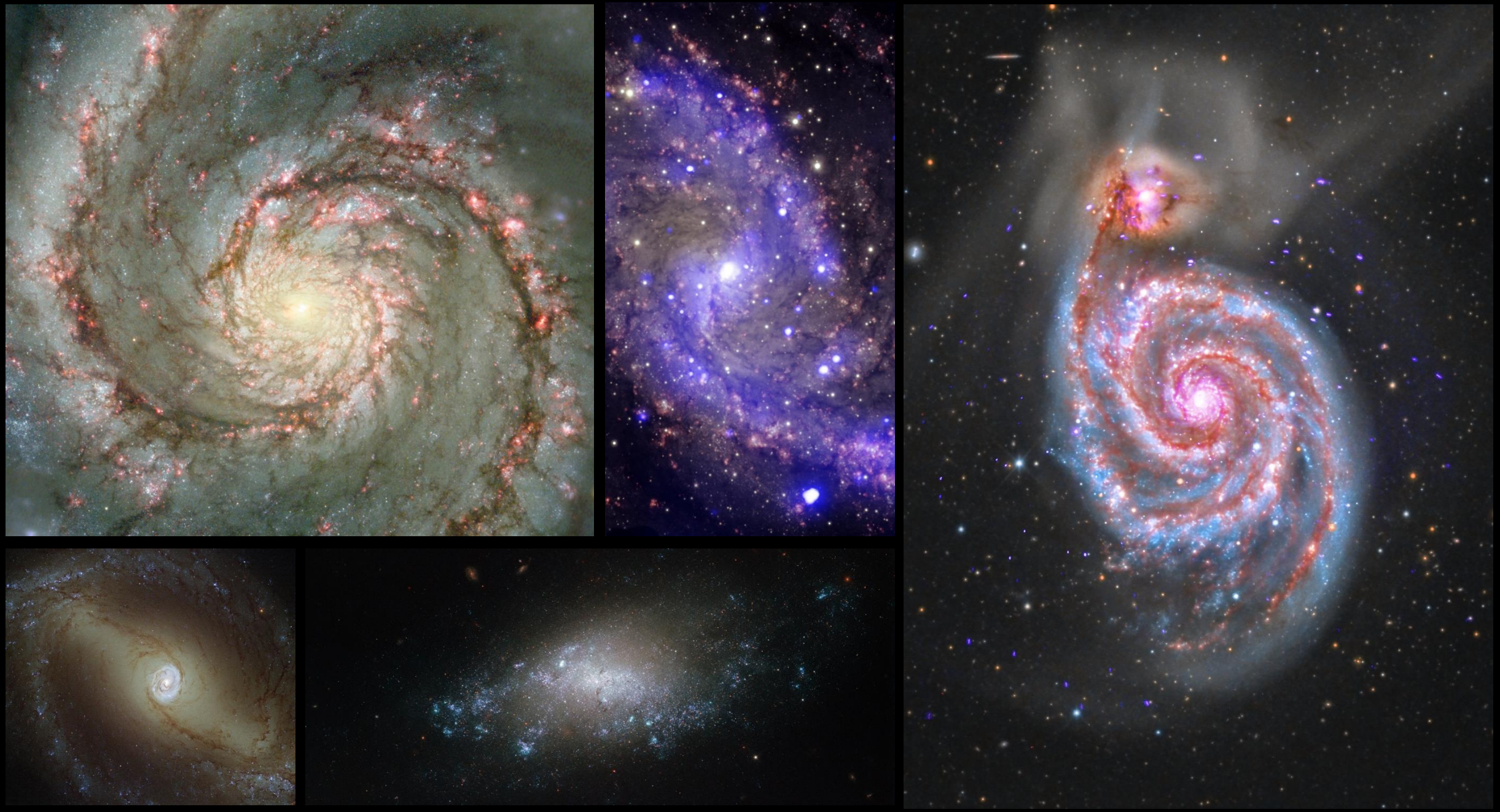
Credit: NASA, ESA, and T. Brown and J. Tumlinson (STScI)



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

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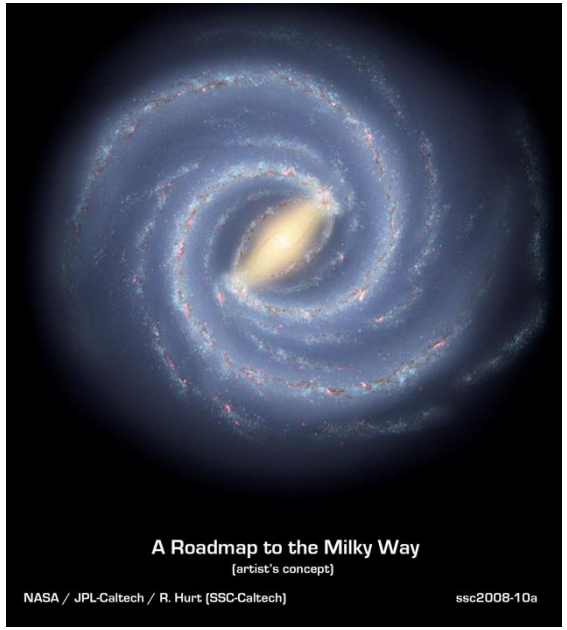
it's in galaxies, including ours



R McGehee

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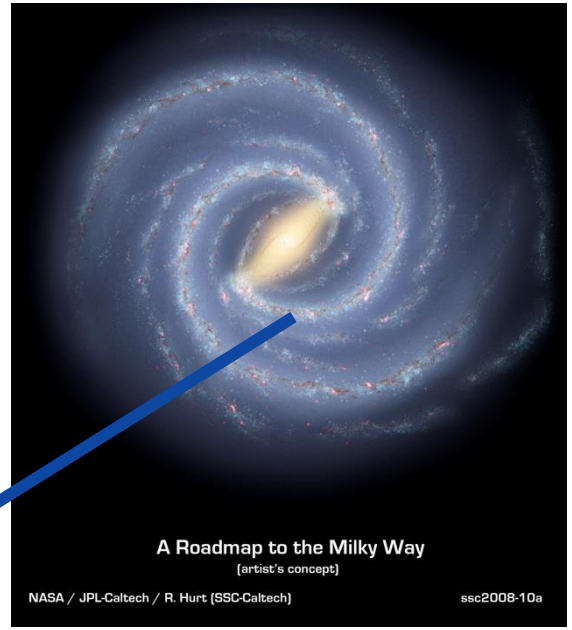
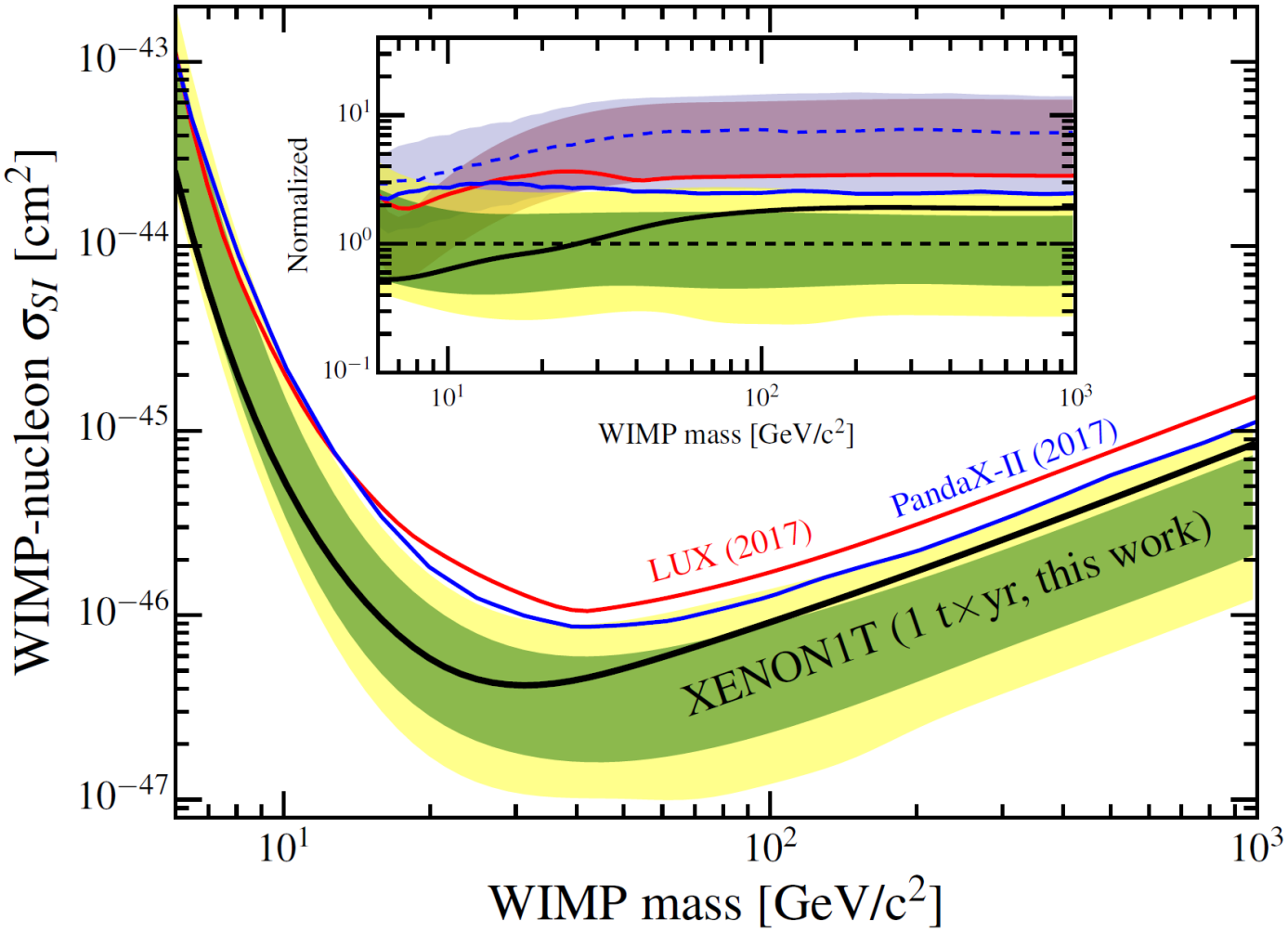


maybe it (very rarely) bumps into stuff on Earth

R McGehee

Direct Detection Today

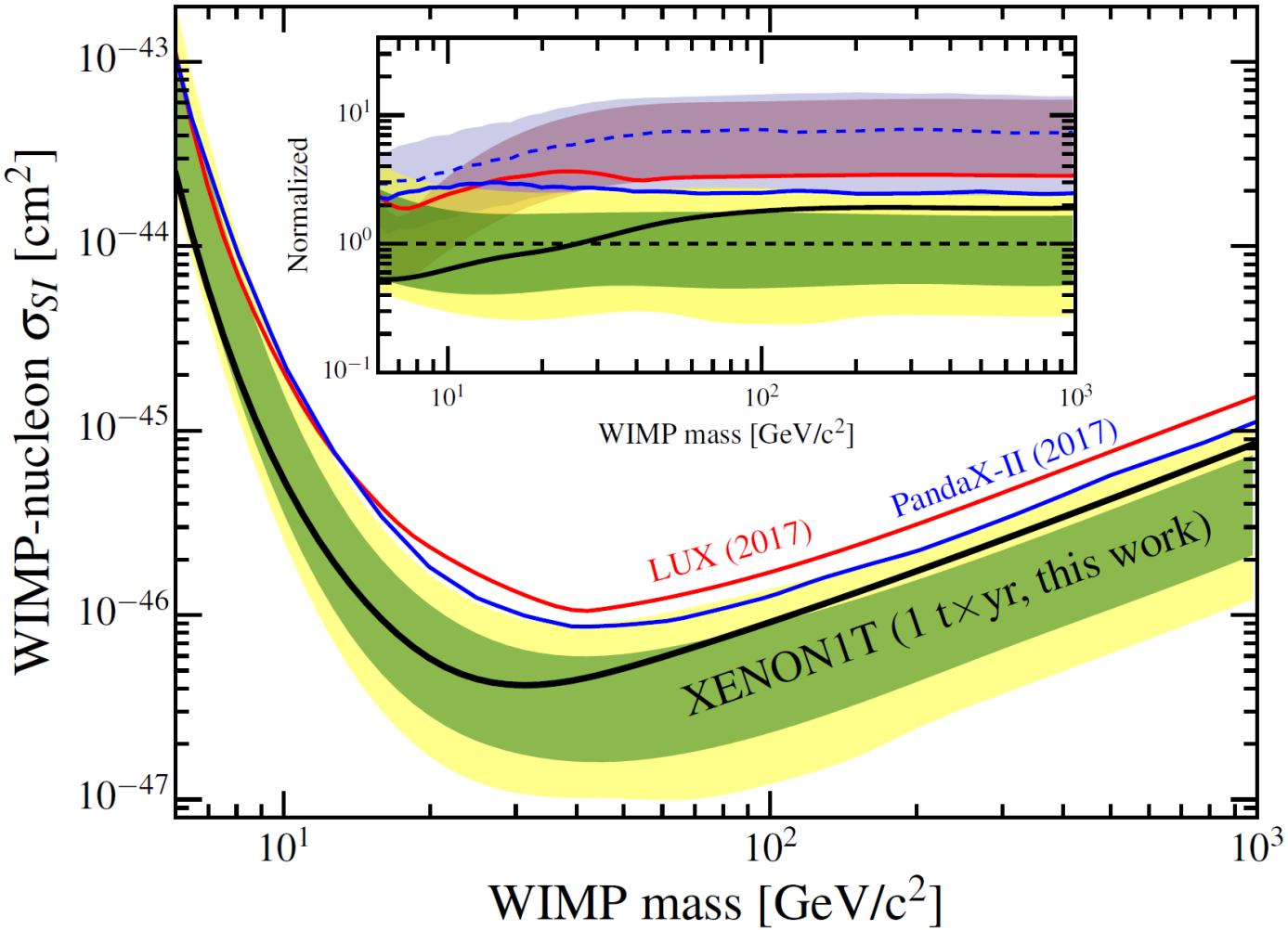


XENON Collaboration [1805.12562]

R McGehee

Direct Detection Future

Go lighter

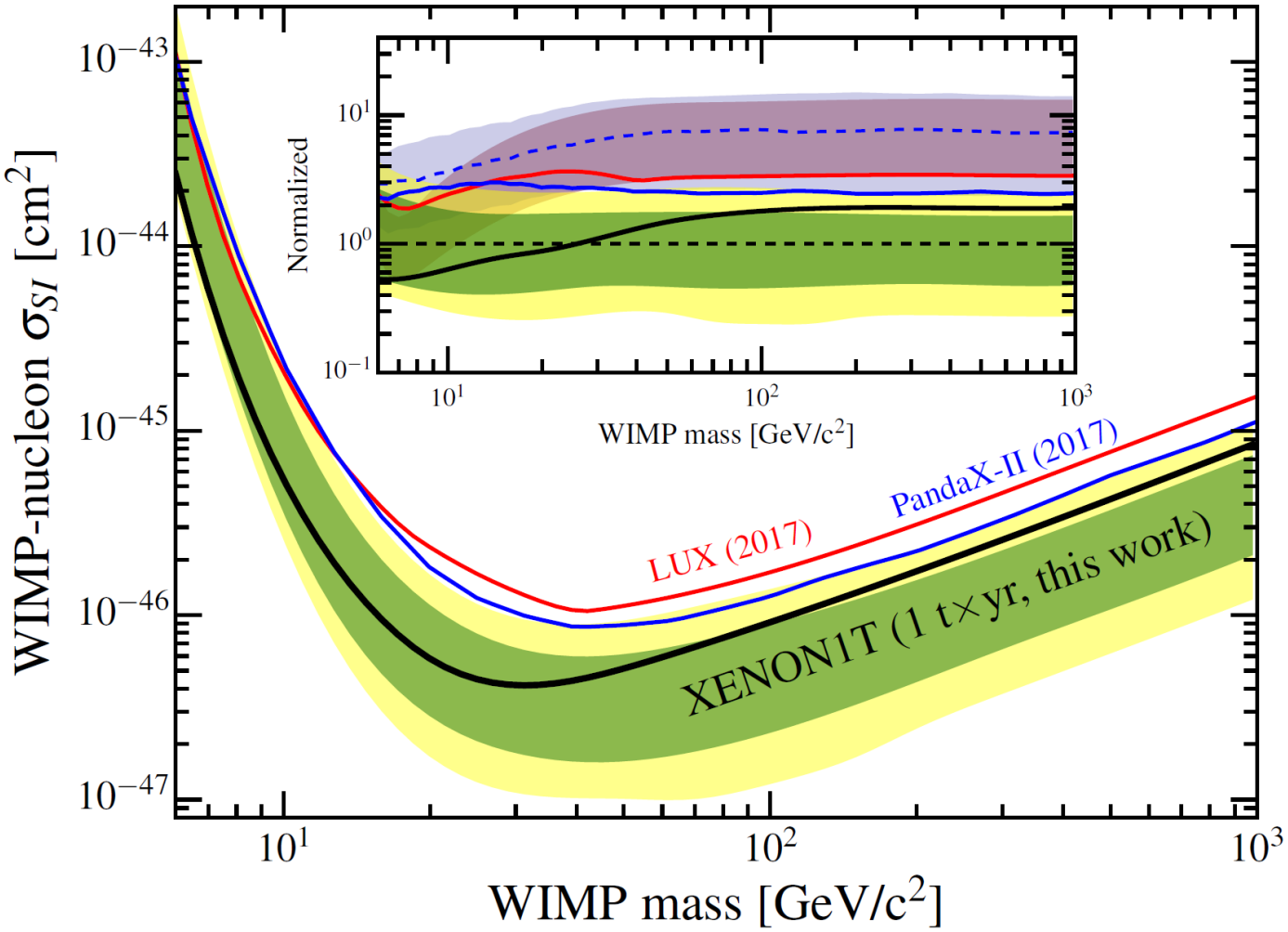


Go lower

R McGehee

Direct Detection Future

Go lighter



Go lower

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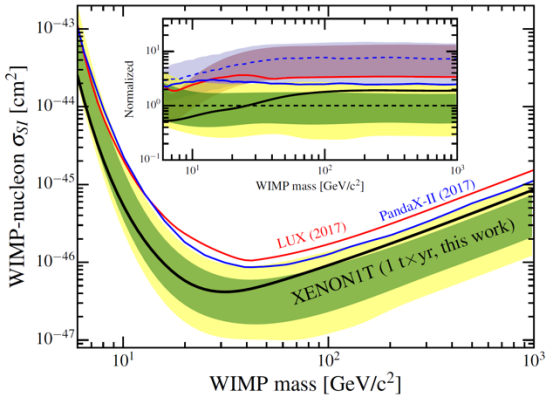
Direct Detection Future
Full Steam Ahead!

2018



XENON Collaboration
[1805.12562]

R McGehee

Direct Detection Future
Full Steam Ahead!

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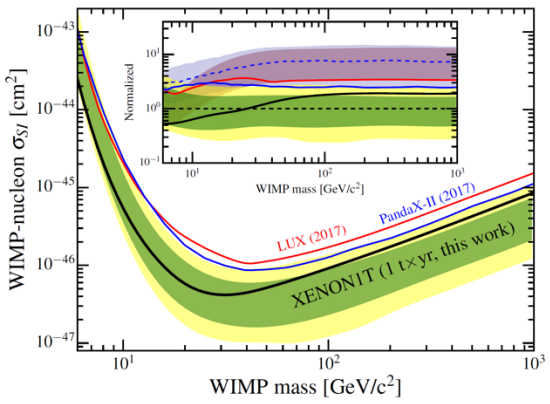
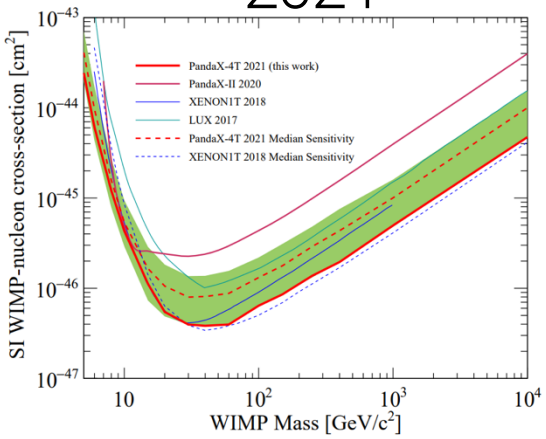


XENON Collaboration
[1805.12562]

2021

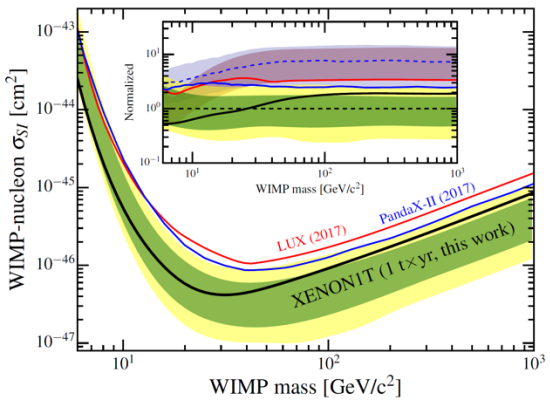


PandaX Collaboration
[2107.13438]

R McGehee

Direct Detection Future
Full Steam Ahead!

2018



XENON Collaboration
[1805.12562]

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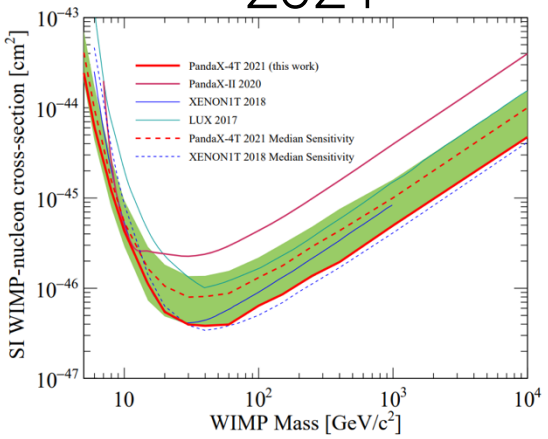
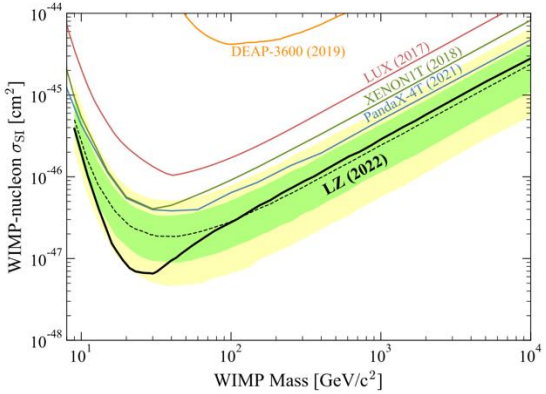
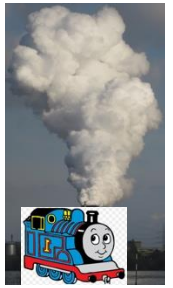


PandaX Collaboration
[2107.13438]

2022



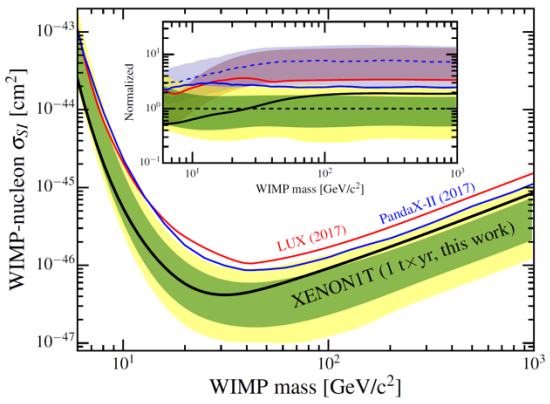
LZ Collaboration
[2207.03764]



R McGehee

Direct Detection Future
Full Steam Ahead!

2018



XENON Collaboration
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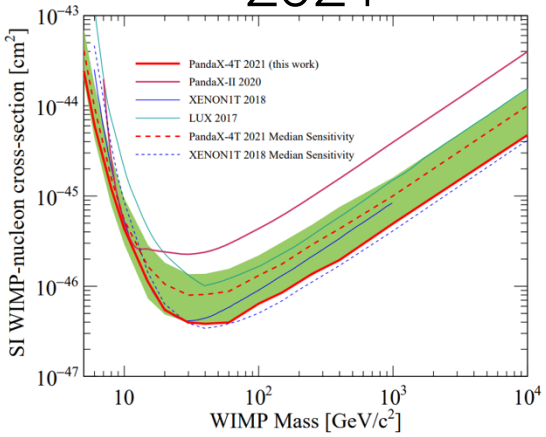
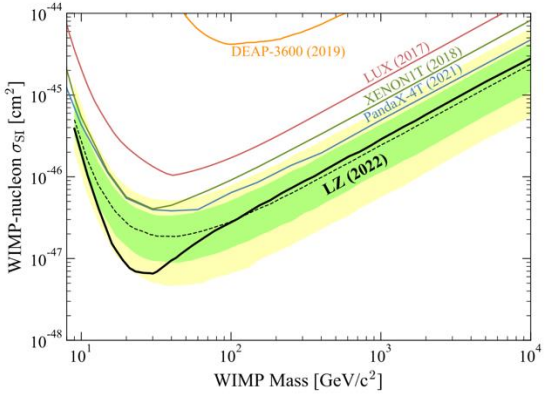
2021



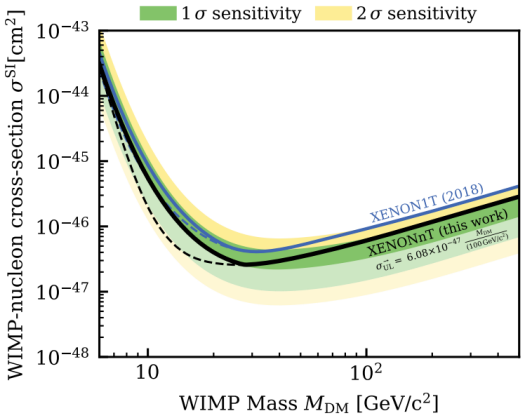
PandaX Collaboration
[2107.13438]

2022



LZ Collaboration
[2207.03764]

2023



XENON Collaboration
[2303.14729]

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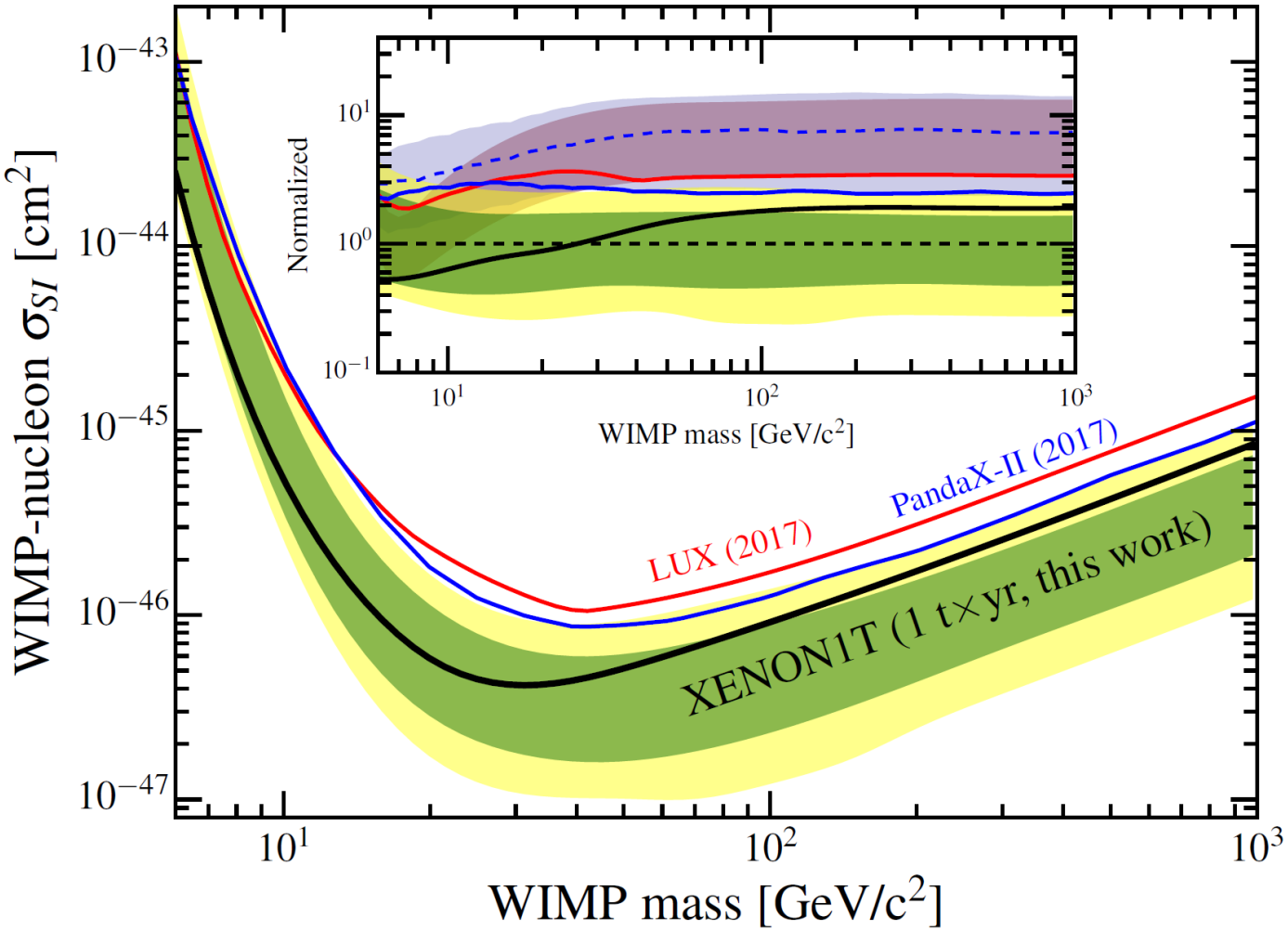
Direct Detection Future

Go lighter

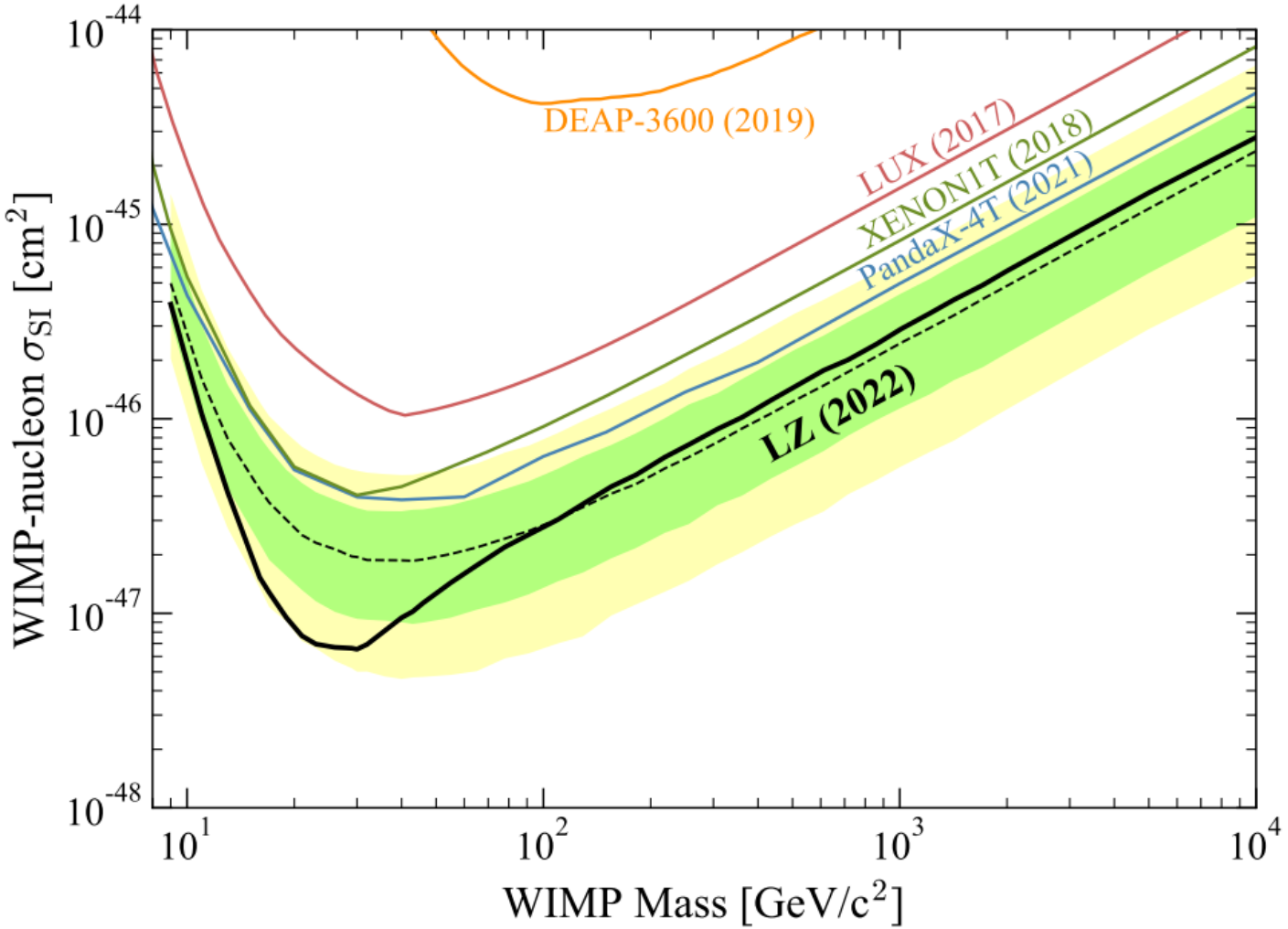


Go lower

R McGehee

Direct Detection Future

Go lighter



Go lower

R McGehee

Directly Detecting *Light* Dark Matter

How?

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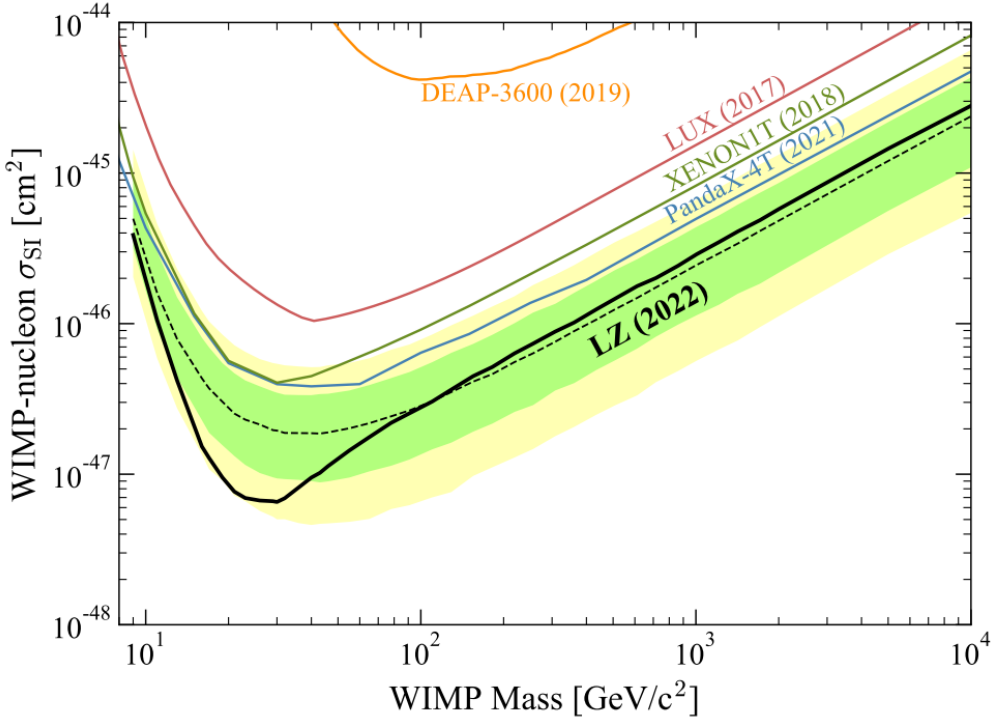
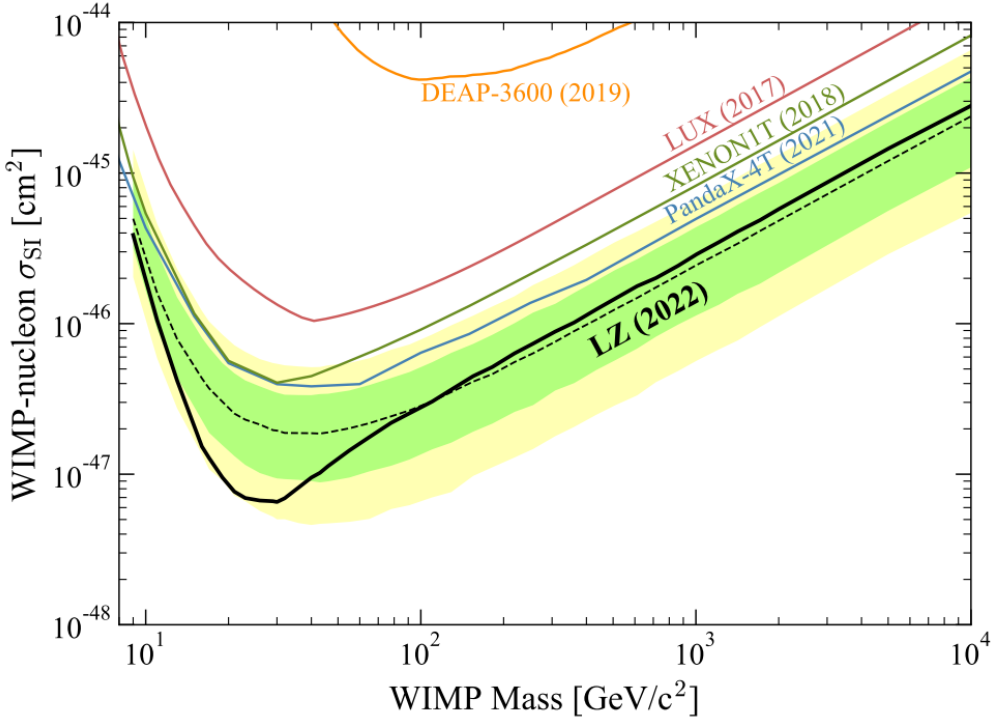


$$E_{\text{thresh}} \sim \text{keV}$$

R McGehee

Directly Detecting *Light* Dark Matter

How?



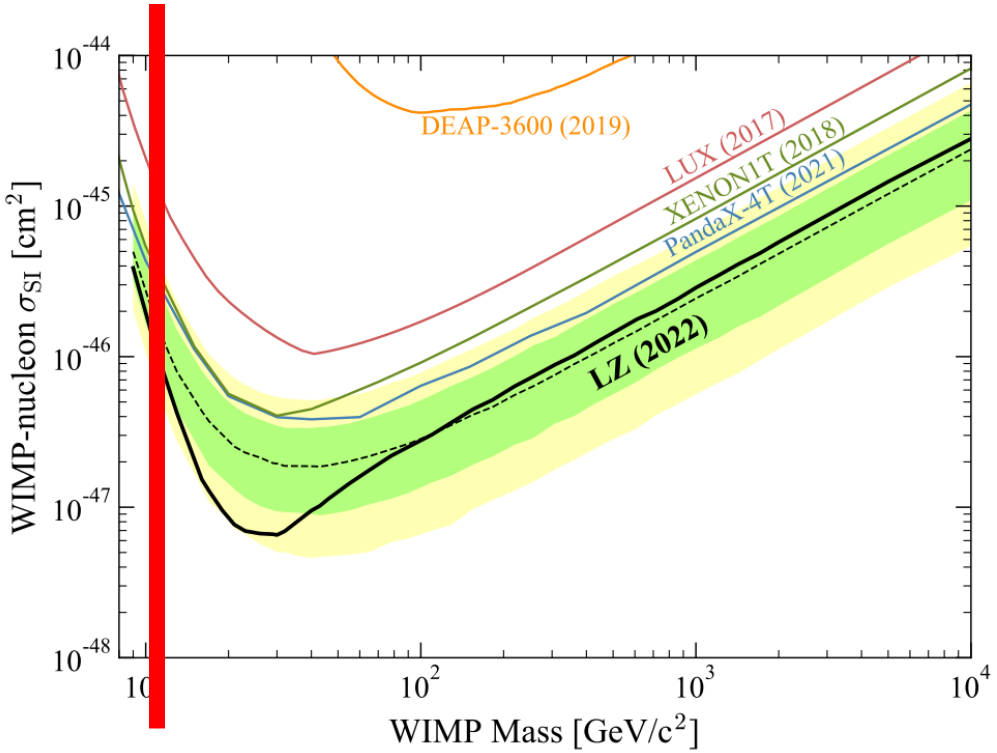
$$E_{\rm thresh} \sim {\rm keV}$$

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

R McGehee

Directly Detecting *Light* Dark Matter

How?



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

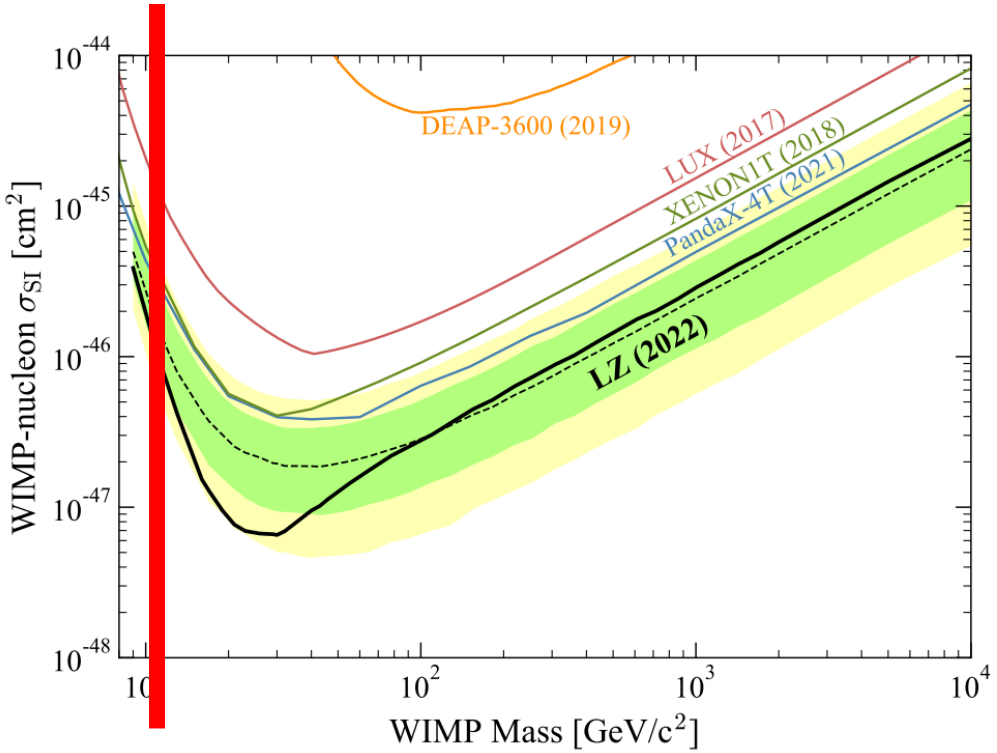
$$E_{\rm NR} \sim \frac{(m_{\rm DM} v)^2}{m_N}$$

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

R McGehee

Directly Detecting *Light* Dark Matter

How?



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R McGehee

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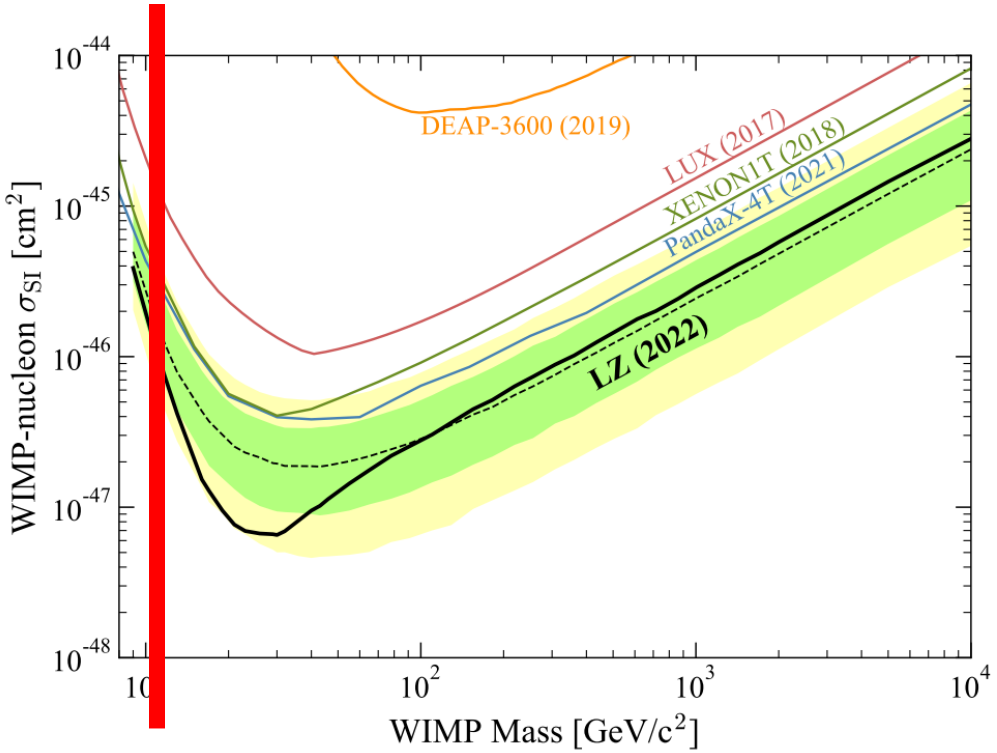

$$E_{\rm thresh} \sim {\rm keV}$$

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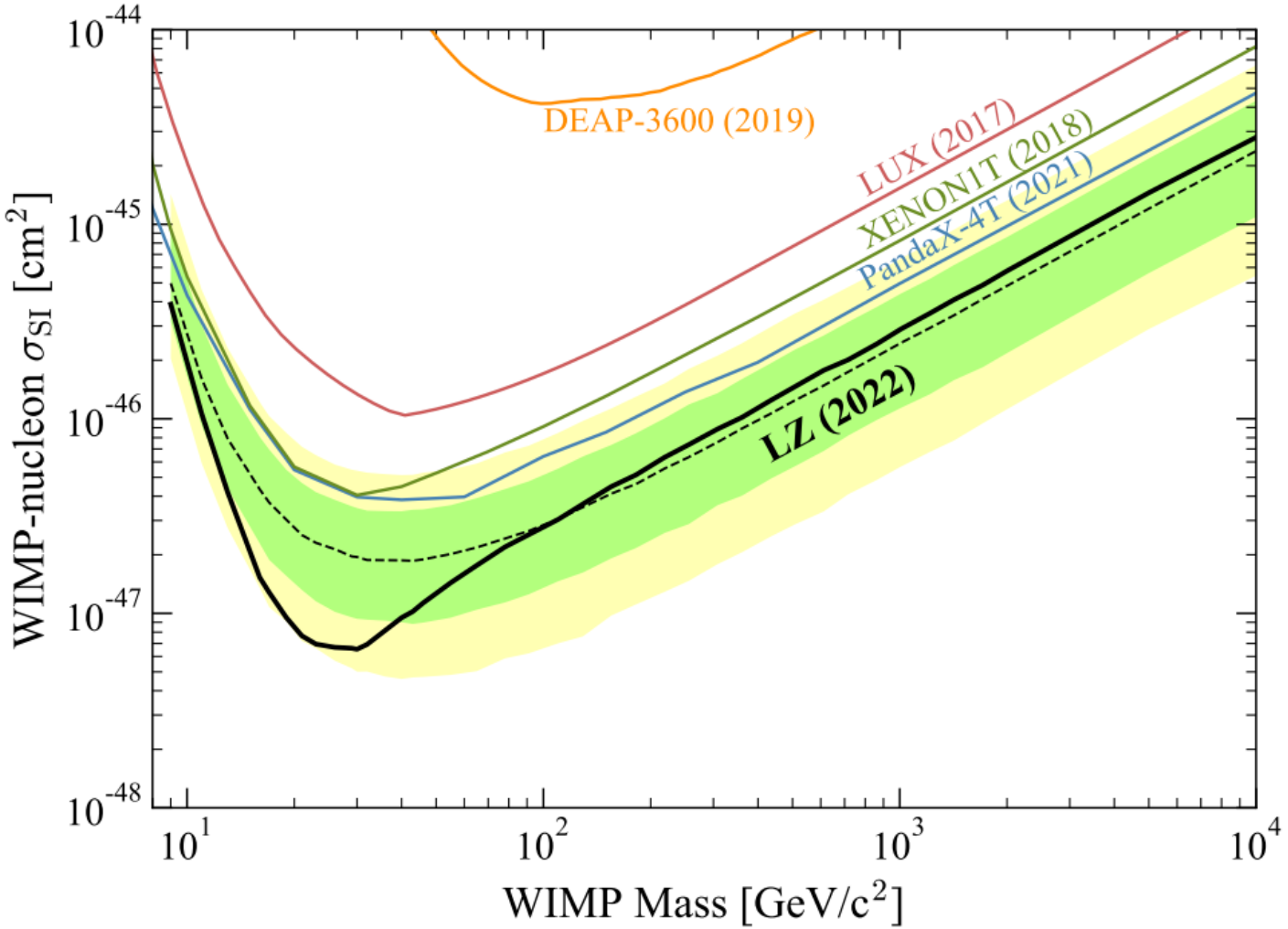
$$v \sim 10^{-3}$$
$$m_{\rm DM} \sim 10\ {\rm GeV}$$
$$m_N \sim 100\ {\rm GeV}$$

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

R McGehee

Direct Detection Future

Go lighter



Go lower

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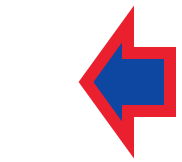
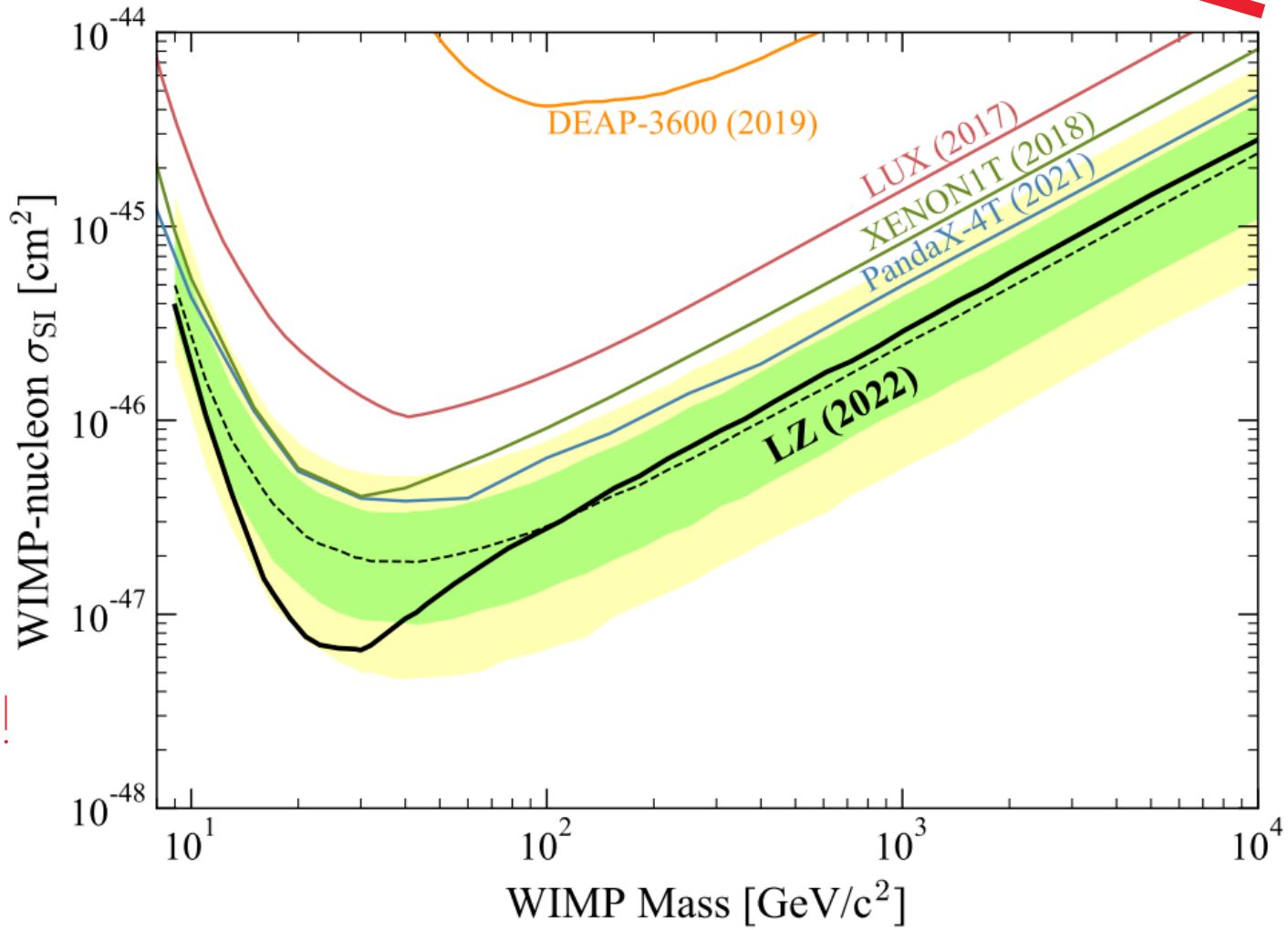
Direct Detection ~~Future~~ Today!

Go lighter



Use electrons!



Go lower

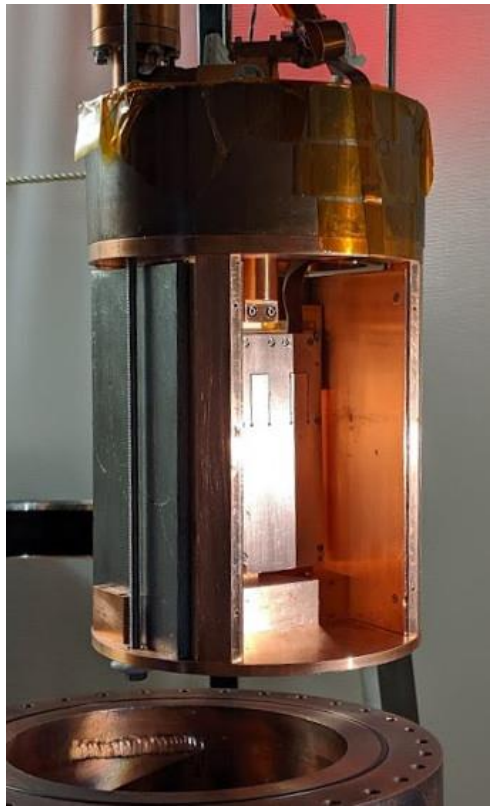
R McGehee

Direct Detection ~~Future~~ Today!

New technology

Go lighter

Use electrons!



SENSEI

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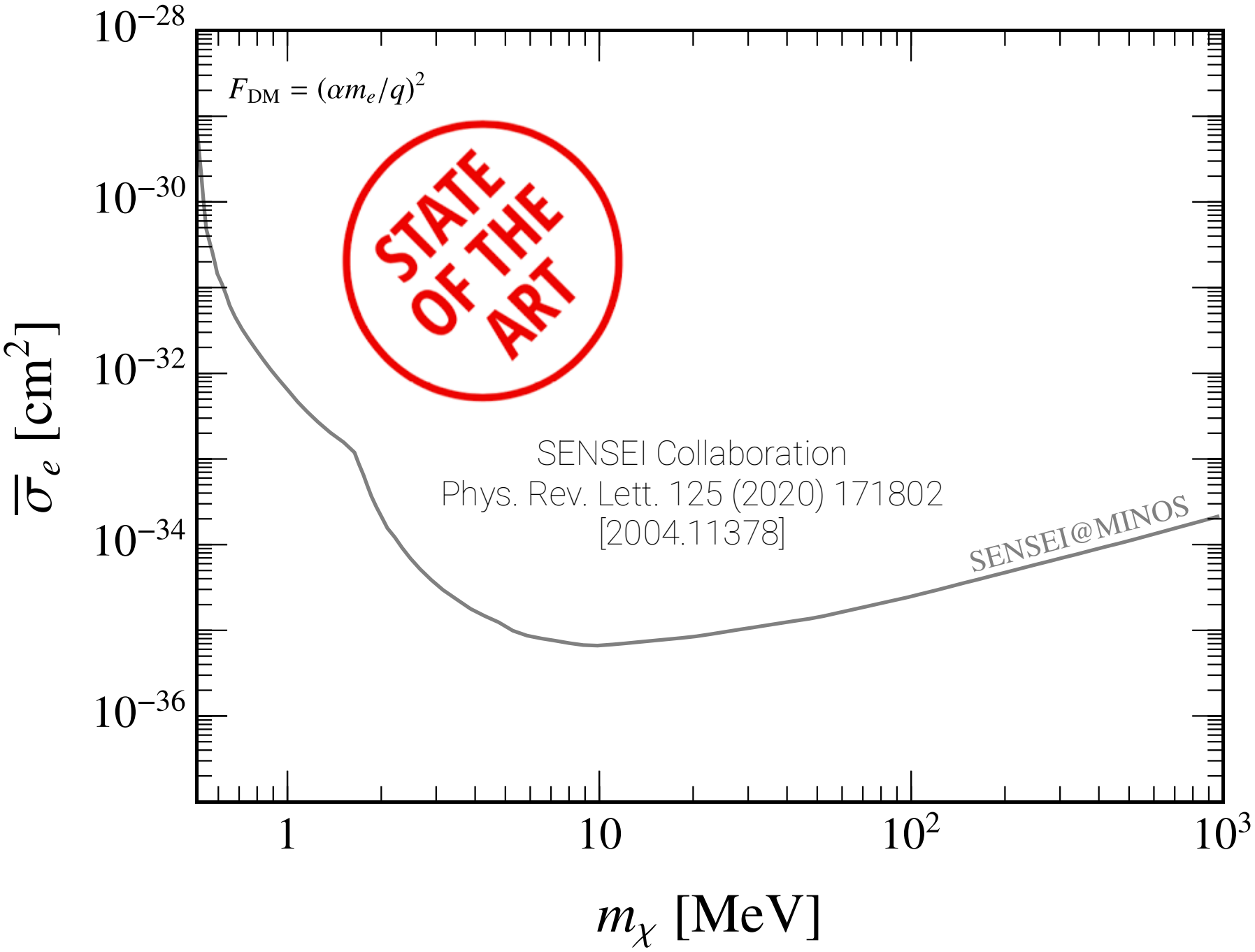
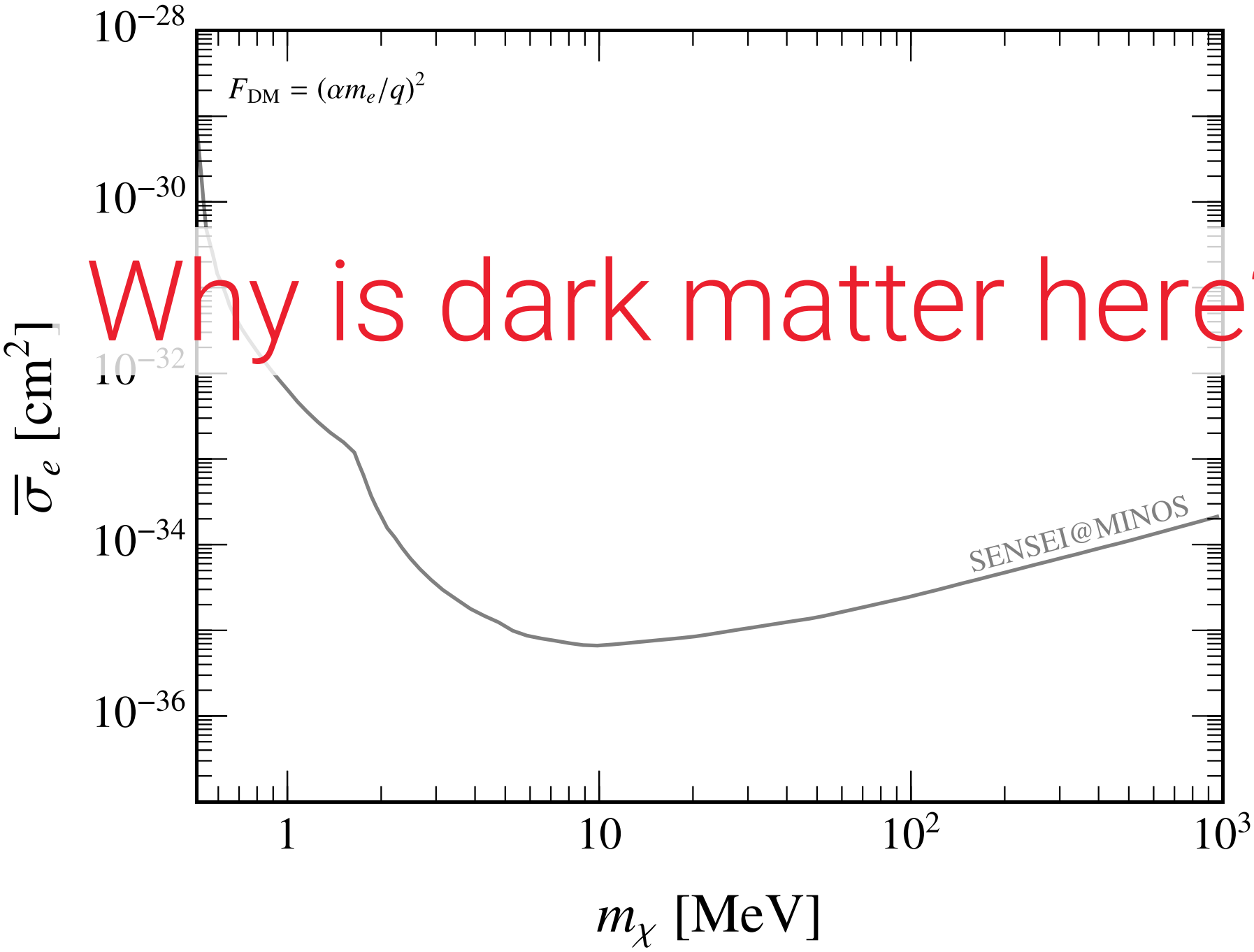
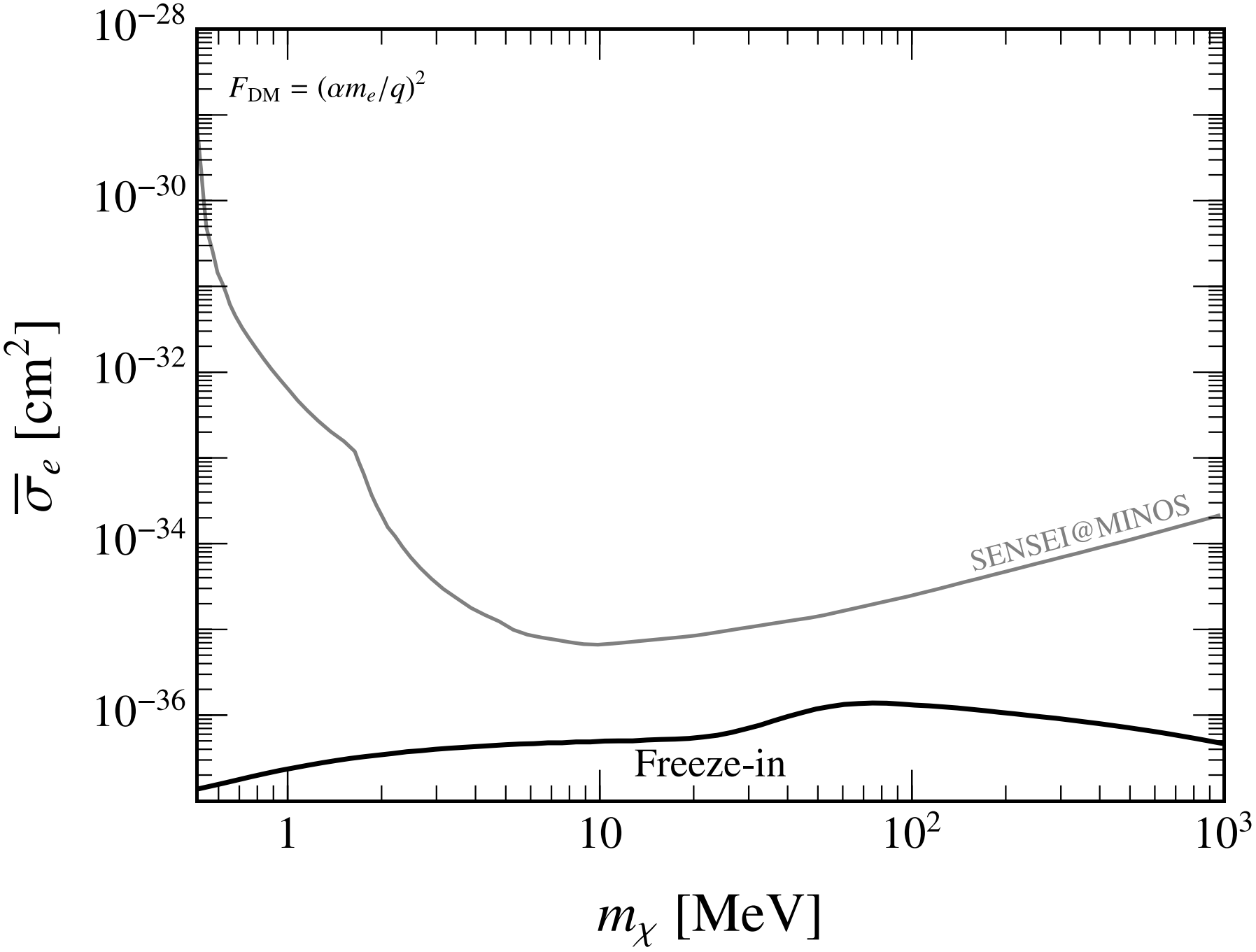

$F_{\rm DM} = (\alpha m_e/q)^2$
STATE OF THE ART
SENSEI Collaboration
Phys. Rev. Lett. 125 (2020) 171802
[2004.11378]
SENSEI@MINOS
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
$\overline{\sigma}_e$ [cm^2]
1
10
10^2
10^3
m_χ [MeV]

R McGehee



Why is dark matter here?

R McGehee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10^{-32}
10^{-34}
10^{-36}
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SENSEI@MINOS
Freeze-in
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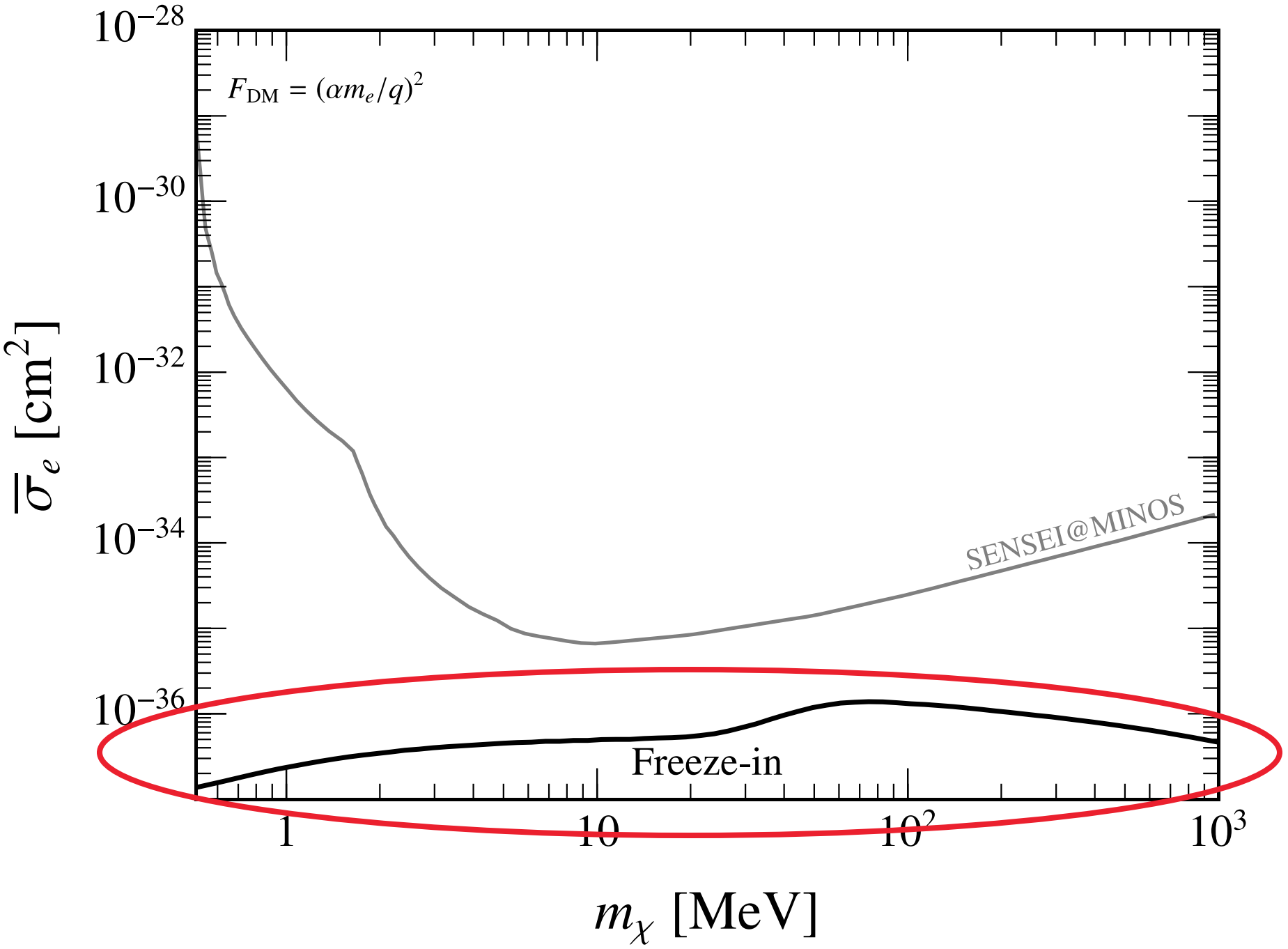
R McGehee


10^{-28}
10^{-30}
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SENSEI@MINOS
Freeze-in
1
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10^2
10^3
m_χ [MeV]

R McGehee

Freeze-In

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

R McGehee

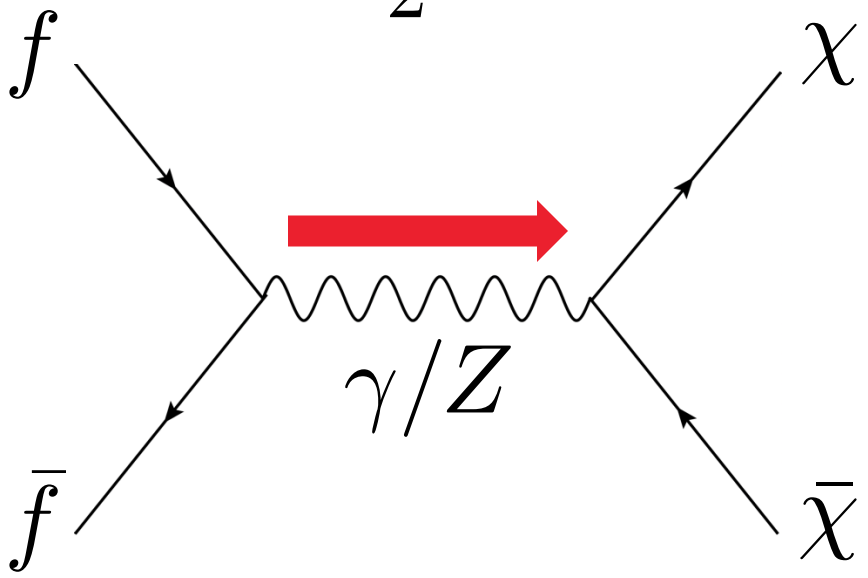
Freeze-In

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

R McGehee

Freeze-In

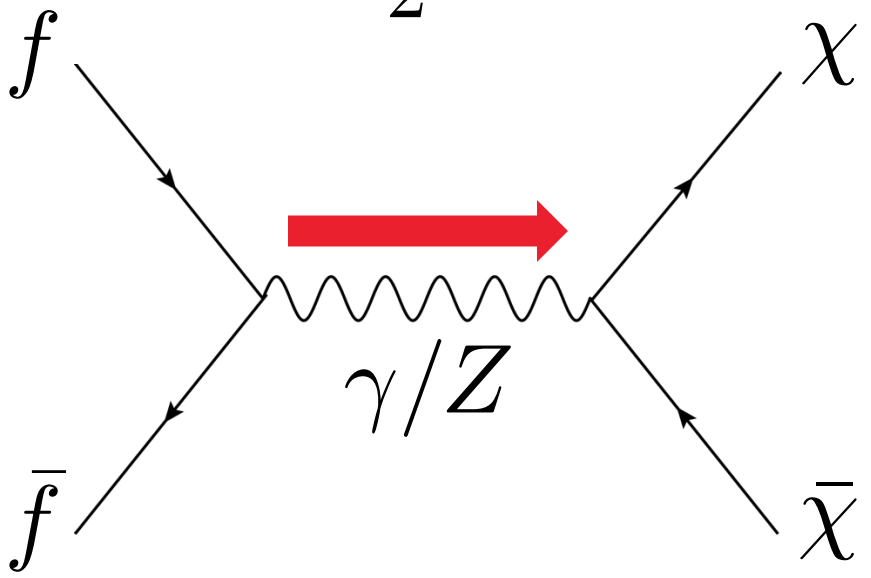
$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$



R McGehee

Freeze-In

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

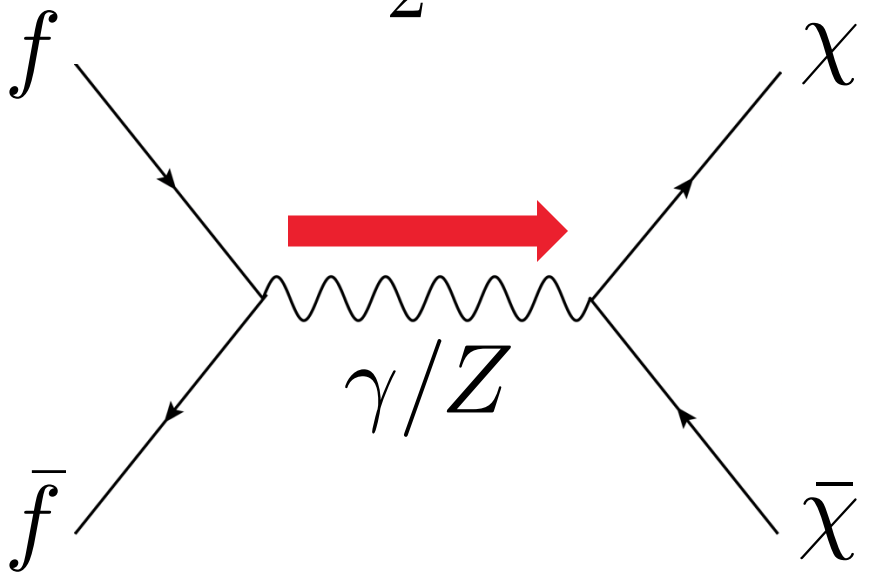


$$\kappa \equiv \epsilon \sqrt{\alpha'/\alpha} \approx \mathcal{O}(10^{-11})$$

R McGehee

Freeze-In

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

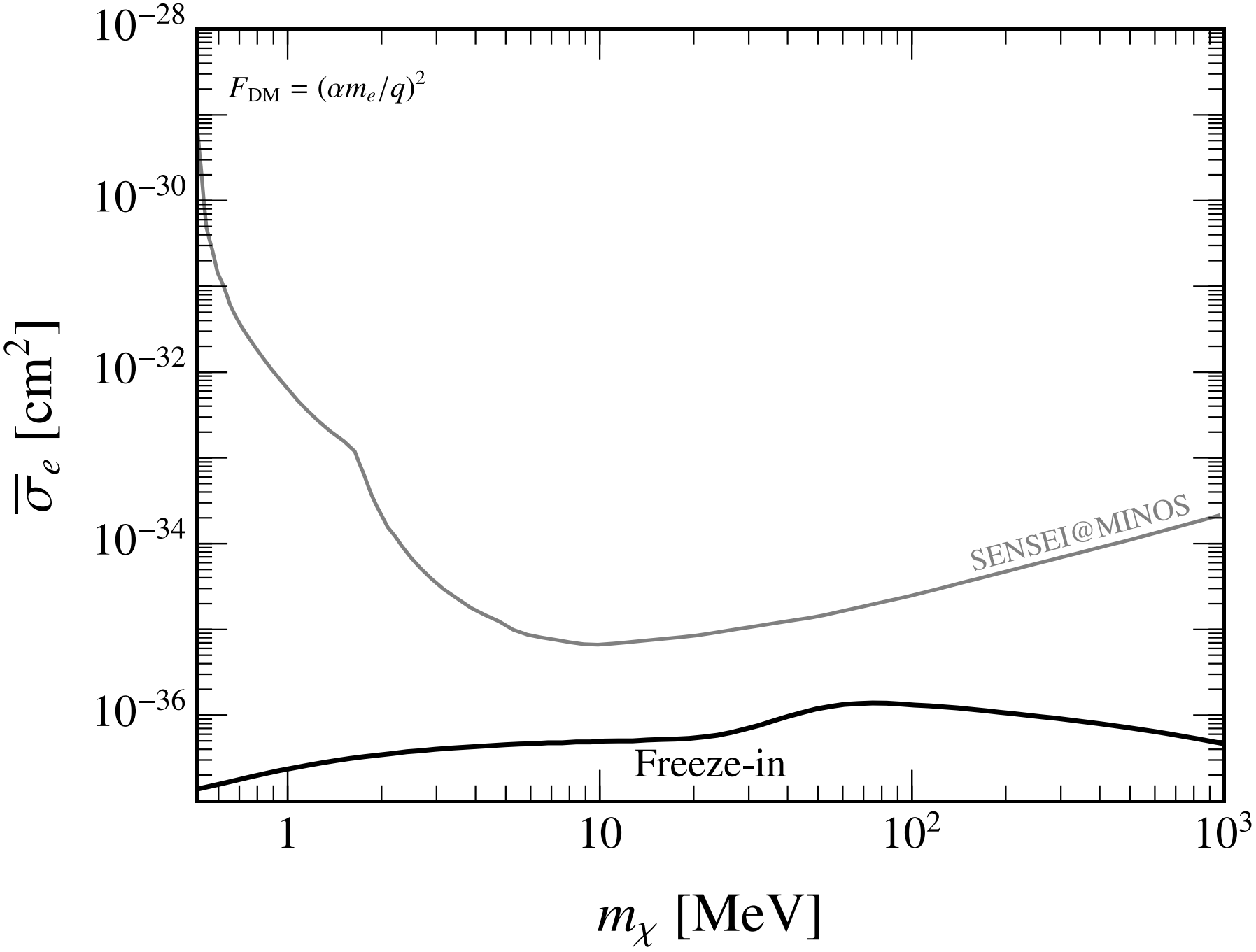


$$\kappa \equiv \epsilon \sqrt{\alpha'/\alpha} \approx \mathcal{O}(10^{-11})$$

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

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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SENSEI@MINOS
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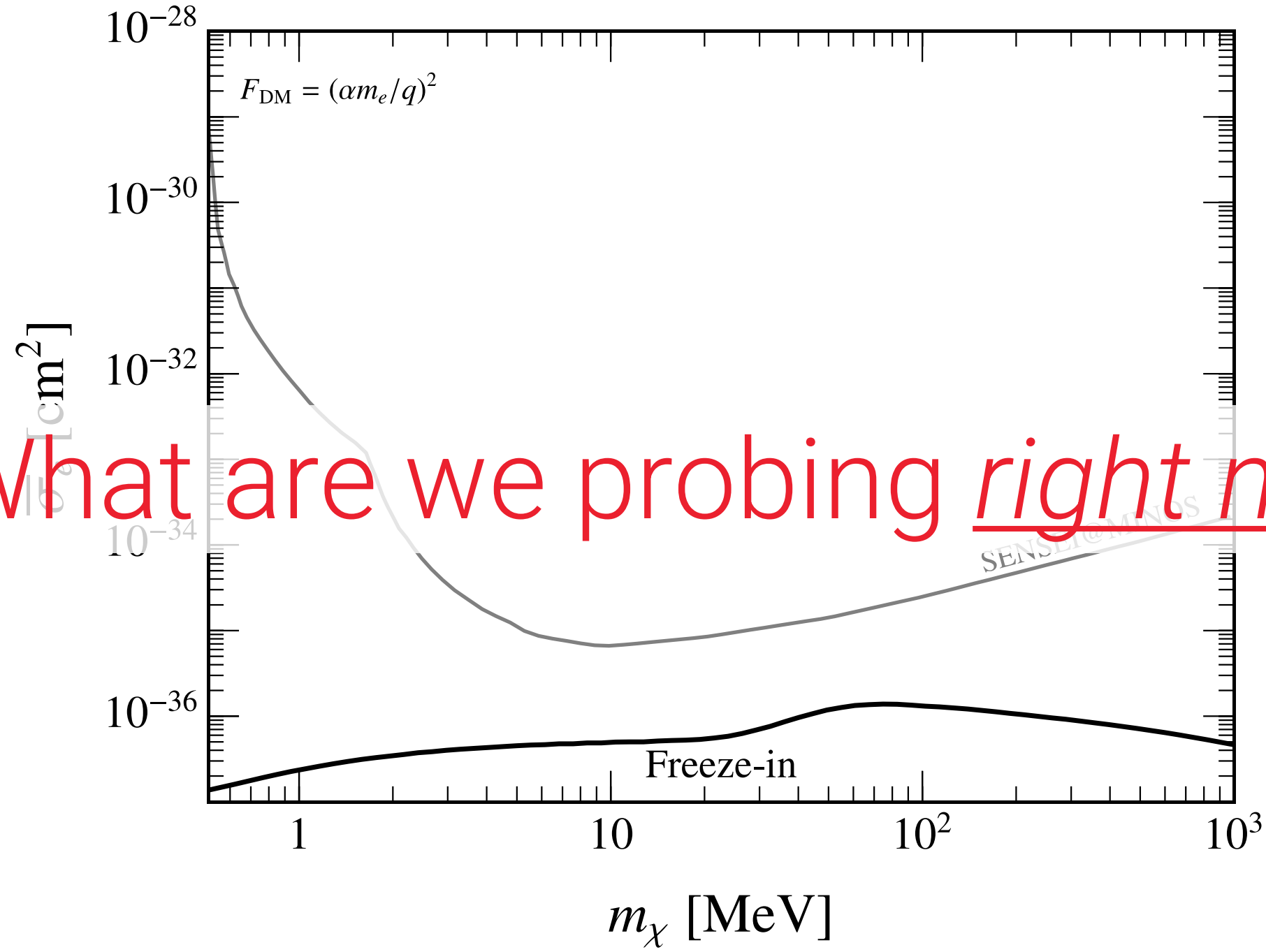
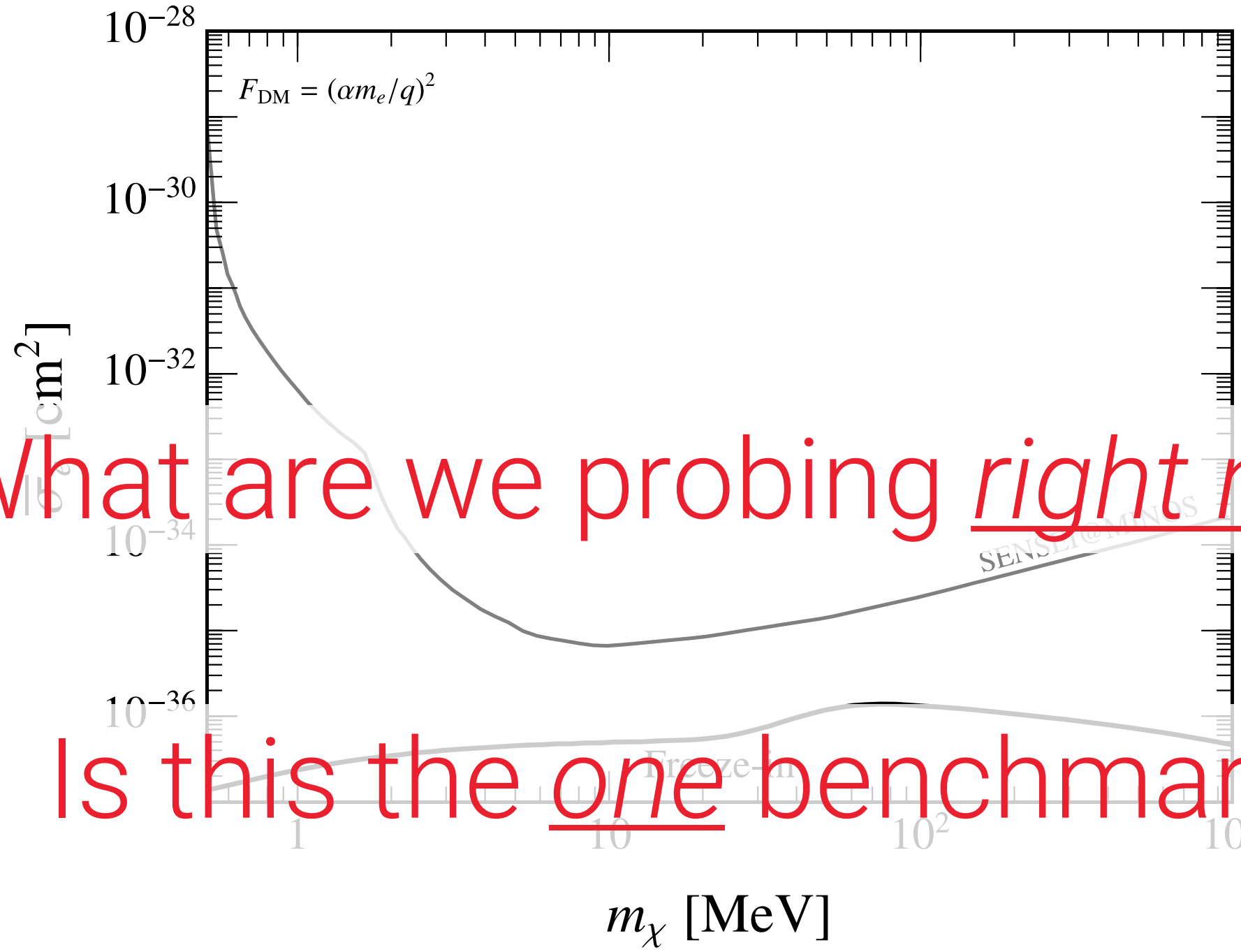
m_χ [MeV]

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

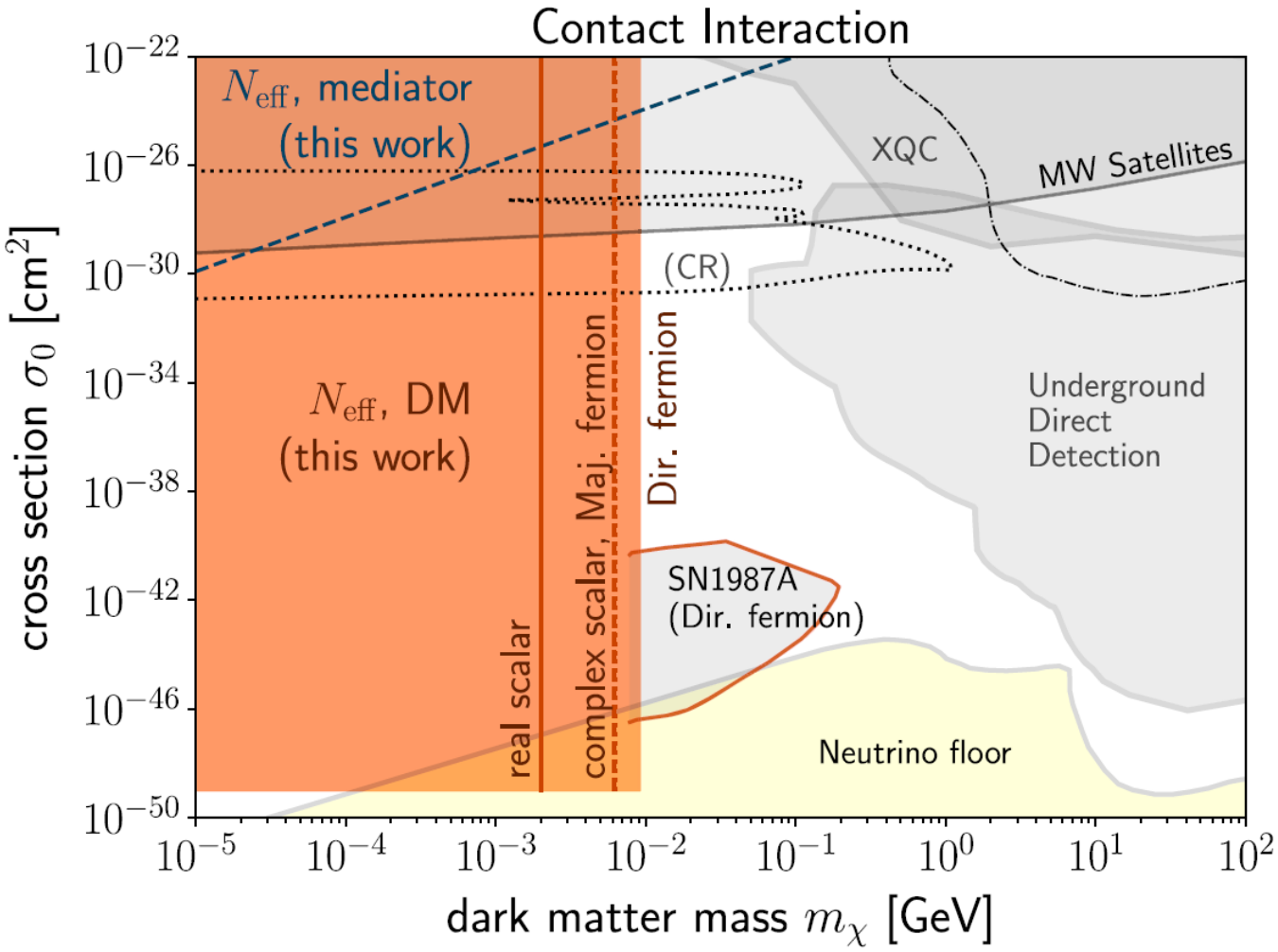
The Real Challenge: BBN

BBN “measures” the energy density of the Universe

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

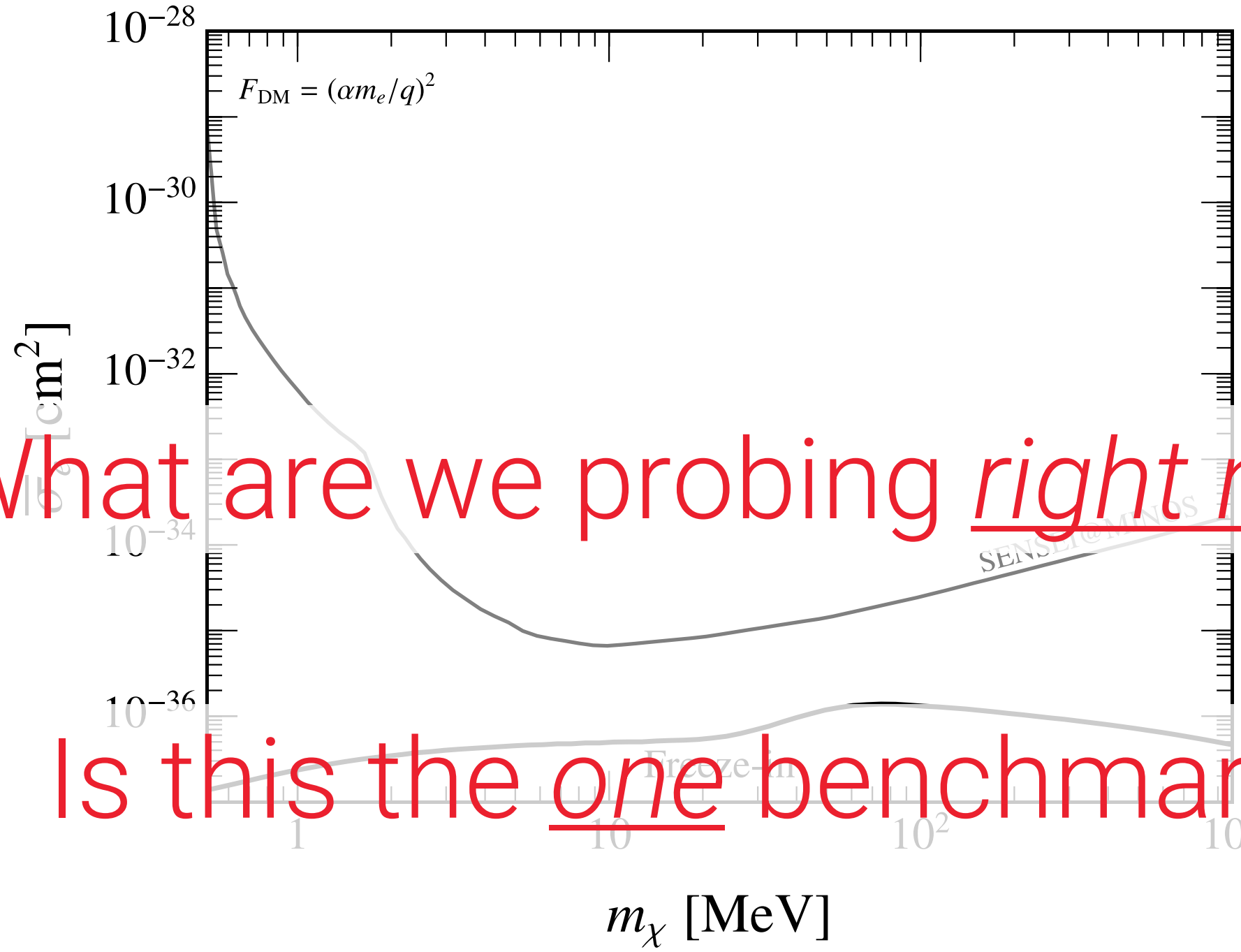
R McGehee

The Real Challenge: BBN



G. Krnjaic and S. McDermott [1908.00007]

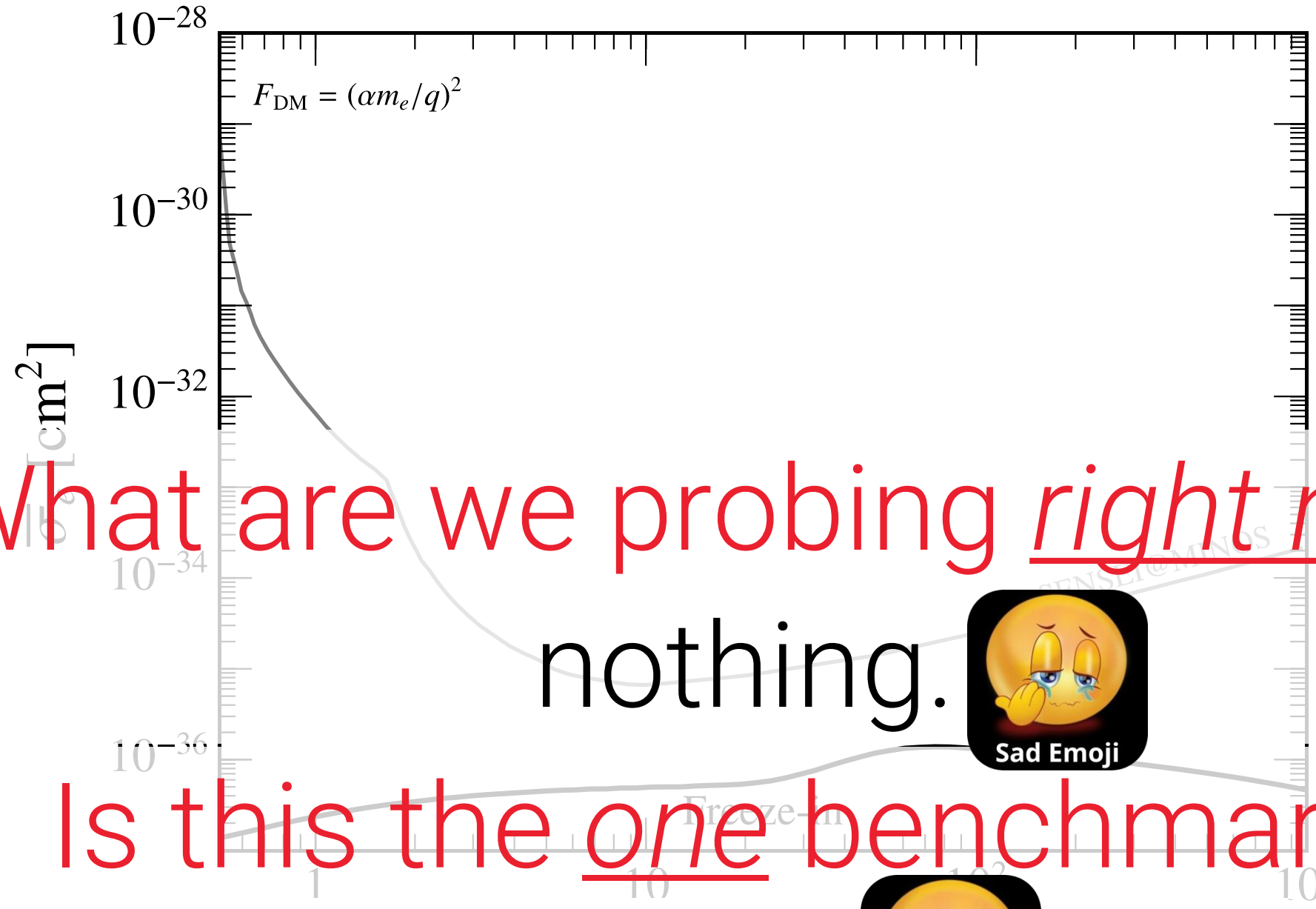
R McGehee



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

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

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

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

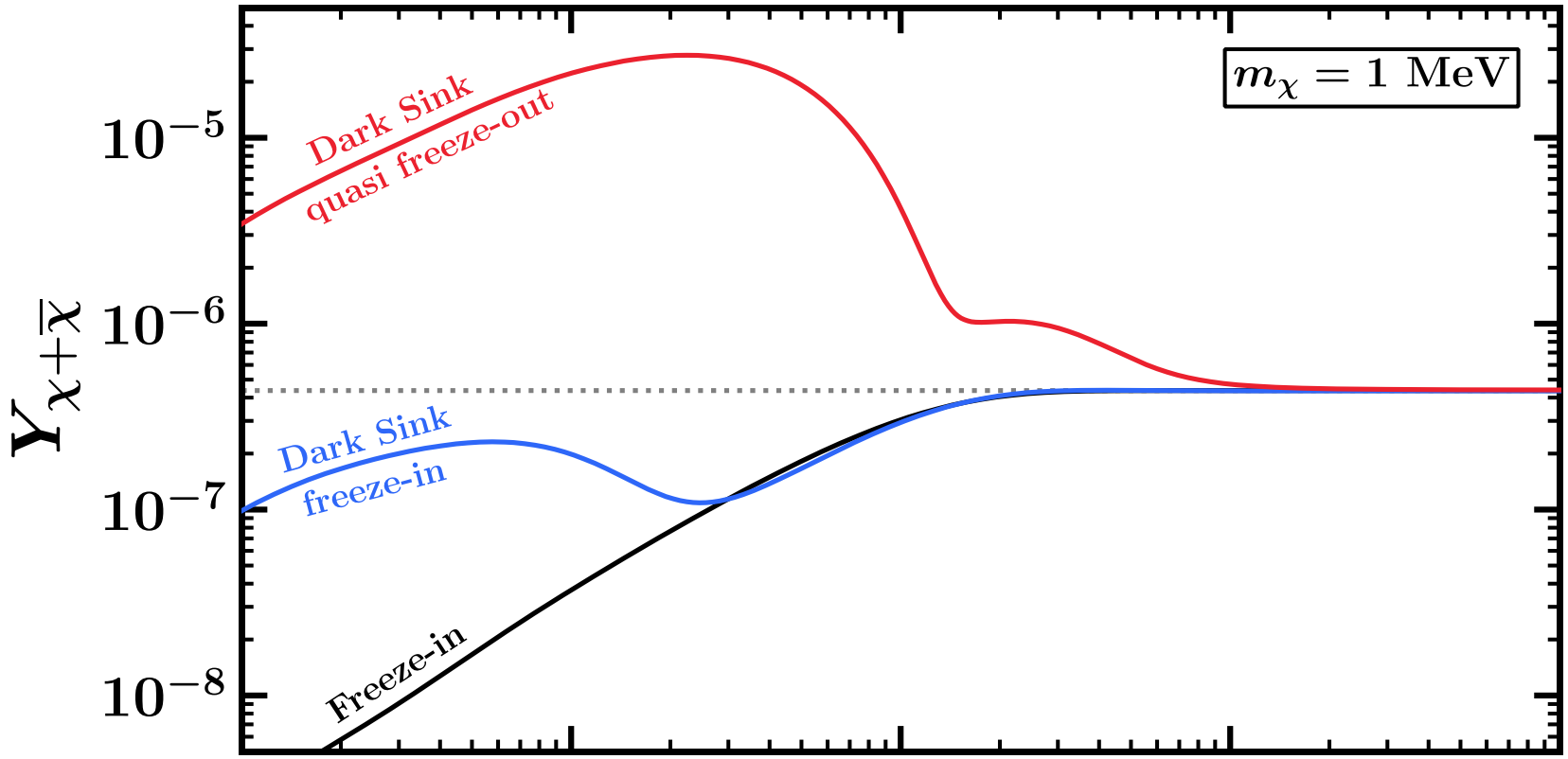
R McGehee

Temperature

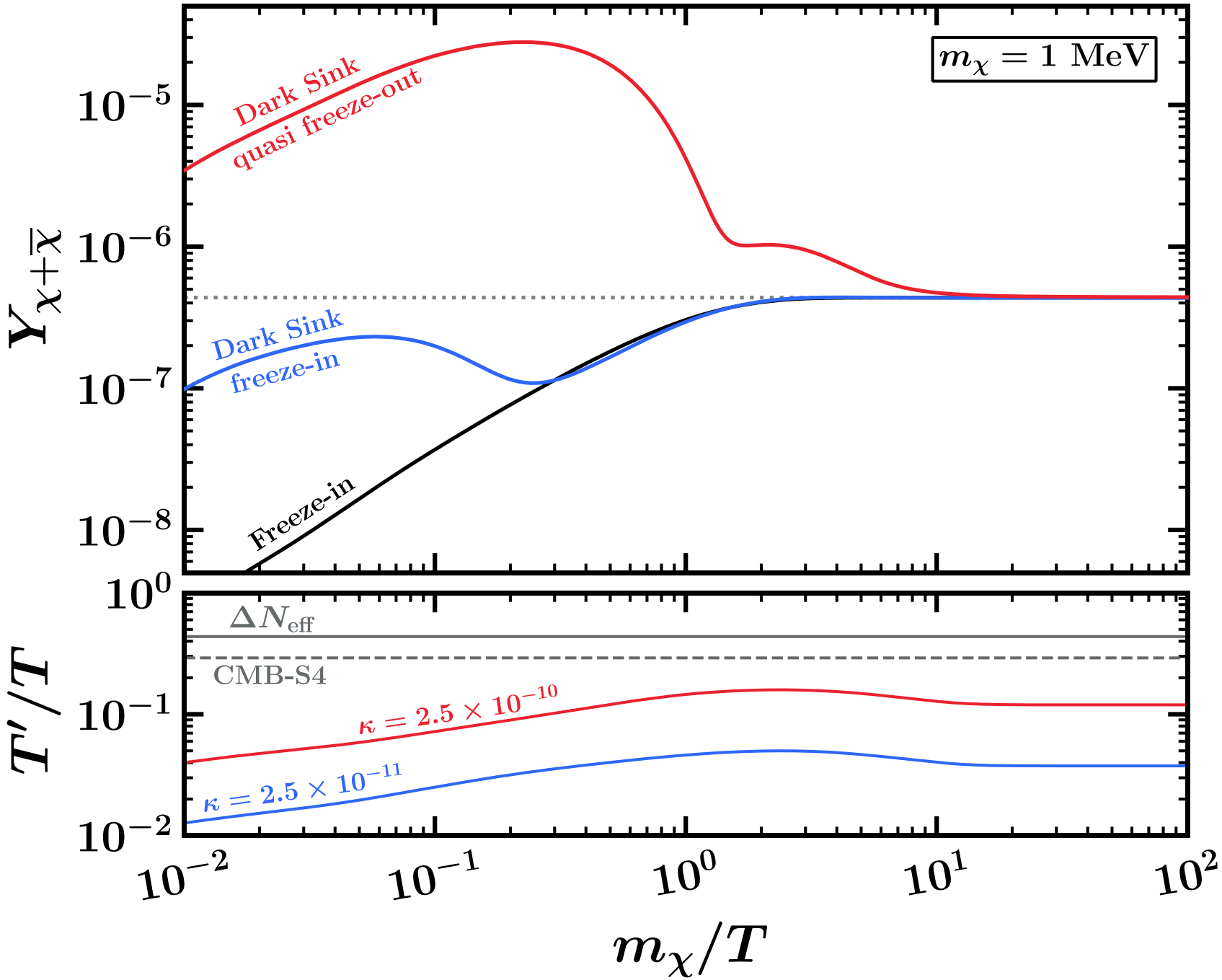
The Story

- 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

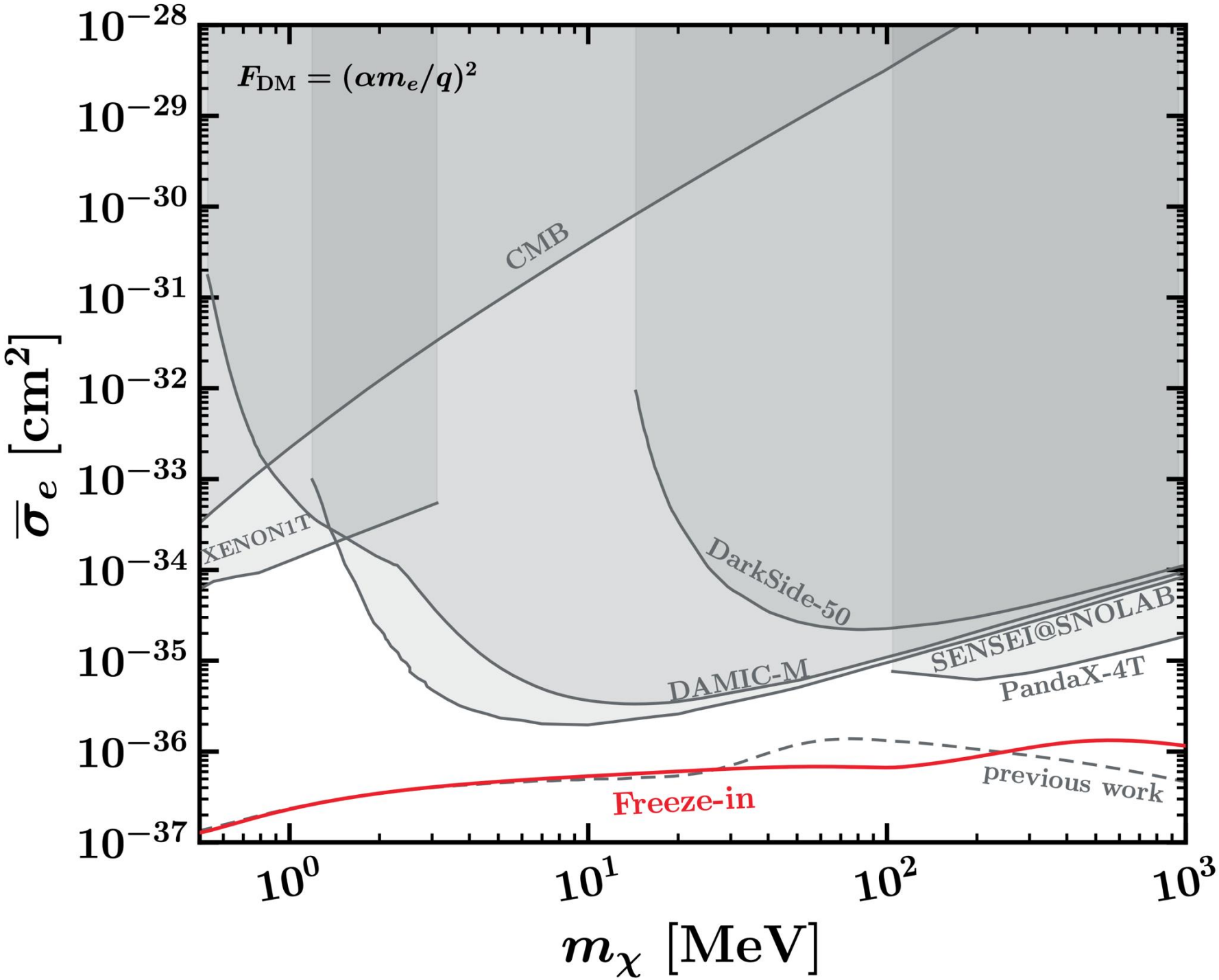
R McGehee


$m_\chi = 1$ MeV
Dark Sink
quasi freeze-out
Dark Sink
freeze-in
Freeze-in
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$Y_{\chi+\bar{\chi}}$
m_χ/T

R McGehee


$m_\chi = 1$ MeV
Dark Sink
quasi freeze-out
Dark Sink
freeze-in
Freeze-in
$Y_{\chi+\bar{\chi}}$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$\Delta N_{\rm eff}$
CMB-S4
$\kappa = 2.5 \times 10^{-10}$
$\kappa = 2.5 \times 10^{-11}$
T'/T
10^{0}
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m_χ/T

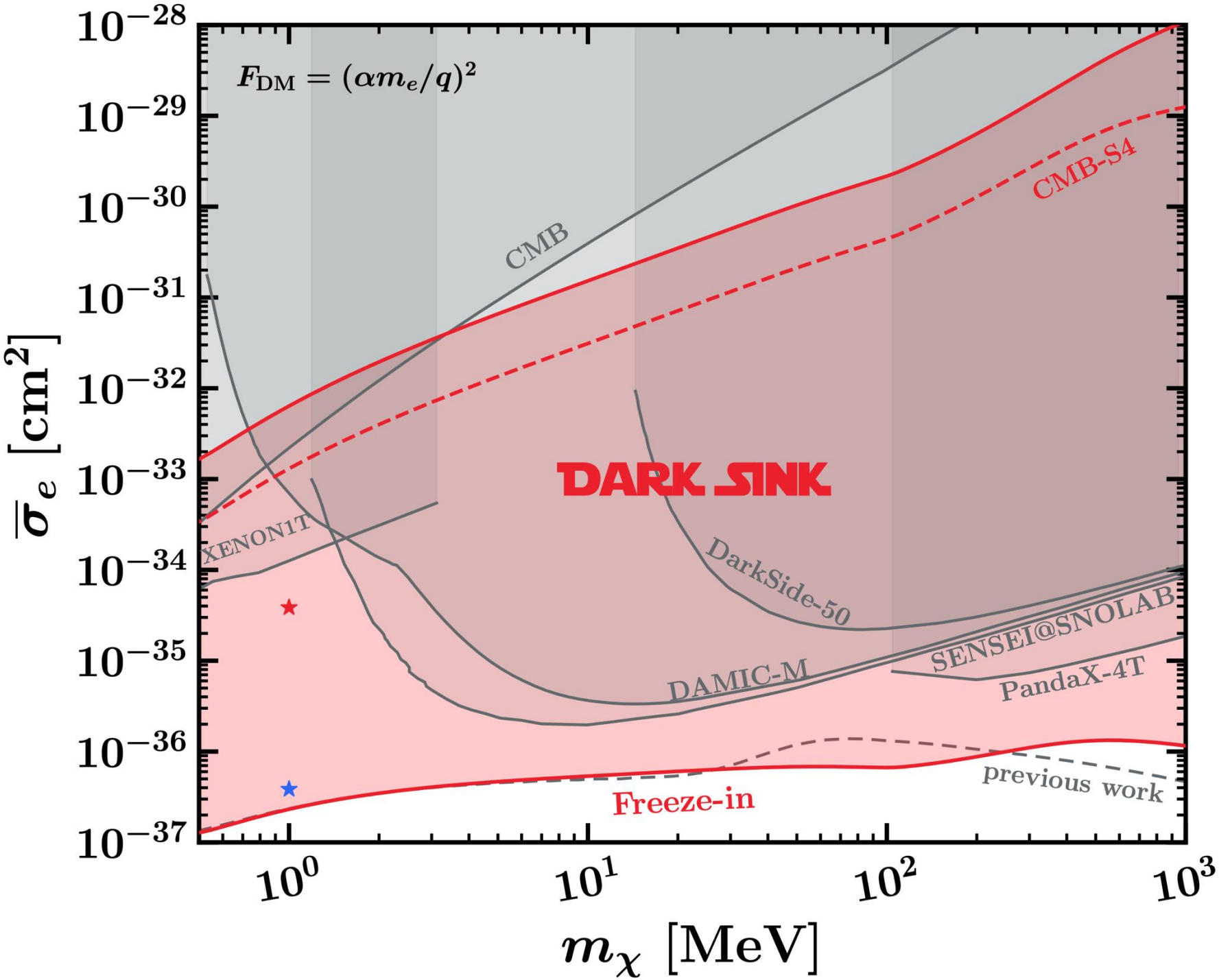
R McGehee



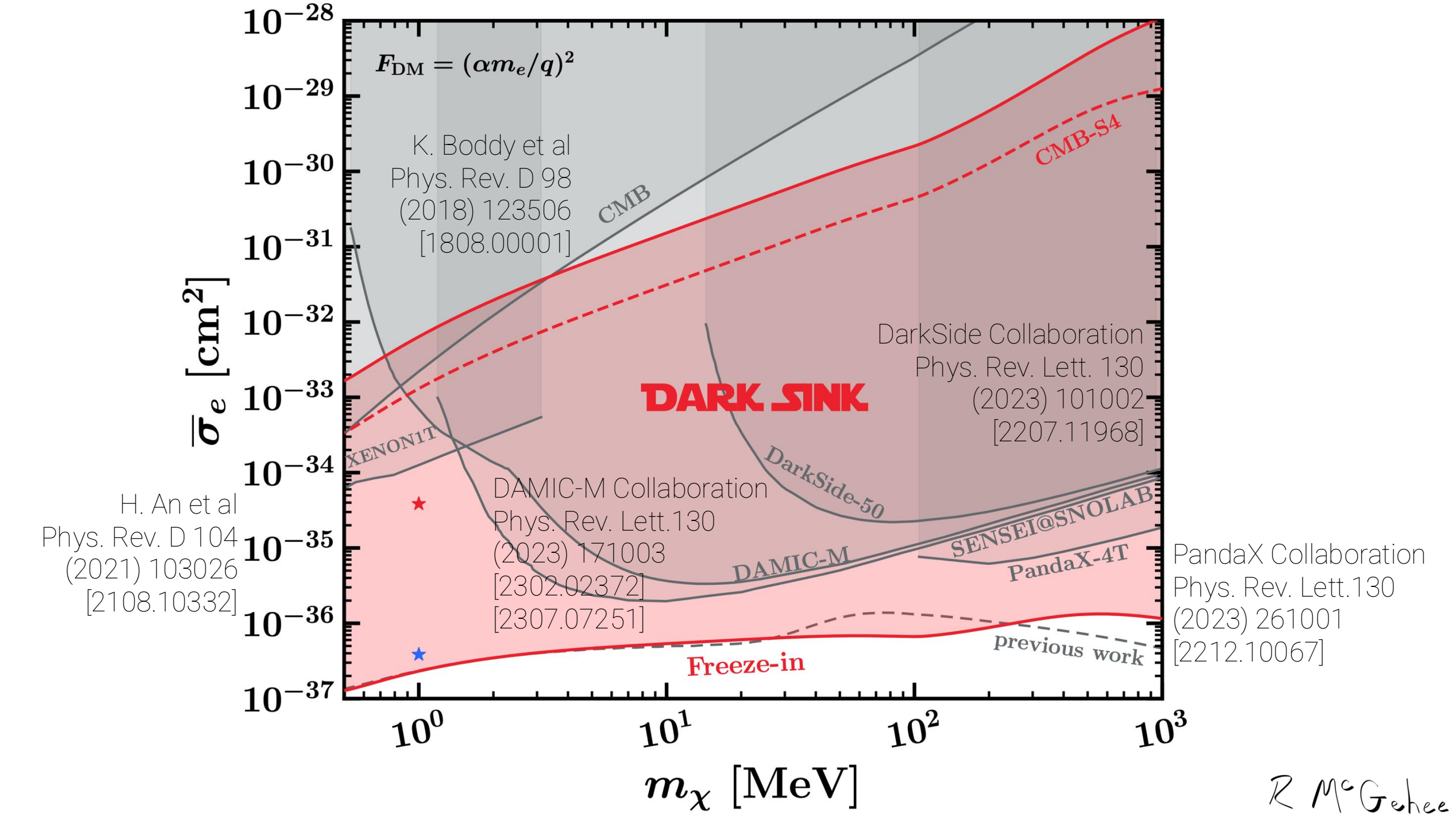
R. Essig, J. Mardon,T. Volansky Phys. Rev. D 85 (2012) 076007 [1108.5383]

SENSEI Collaboration [2312.13342]

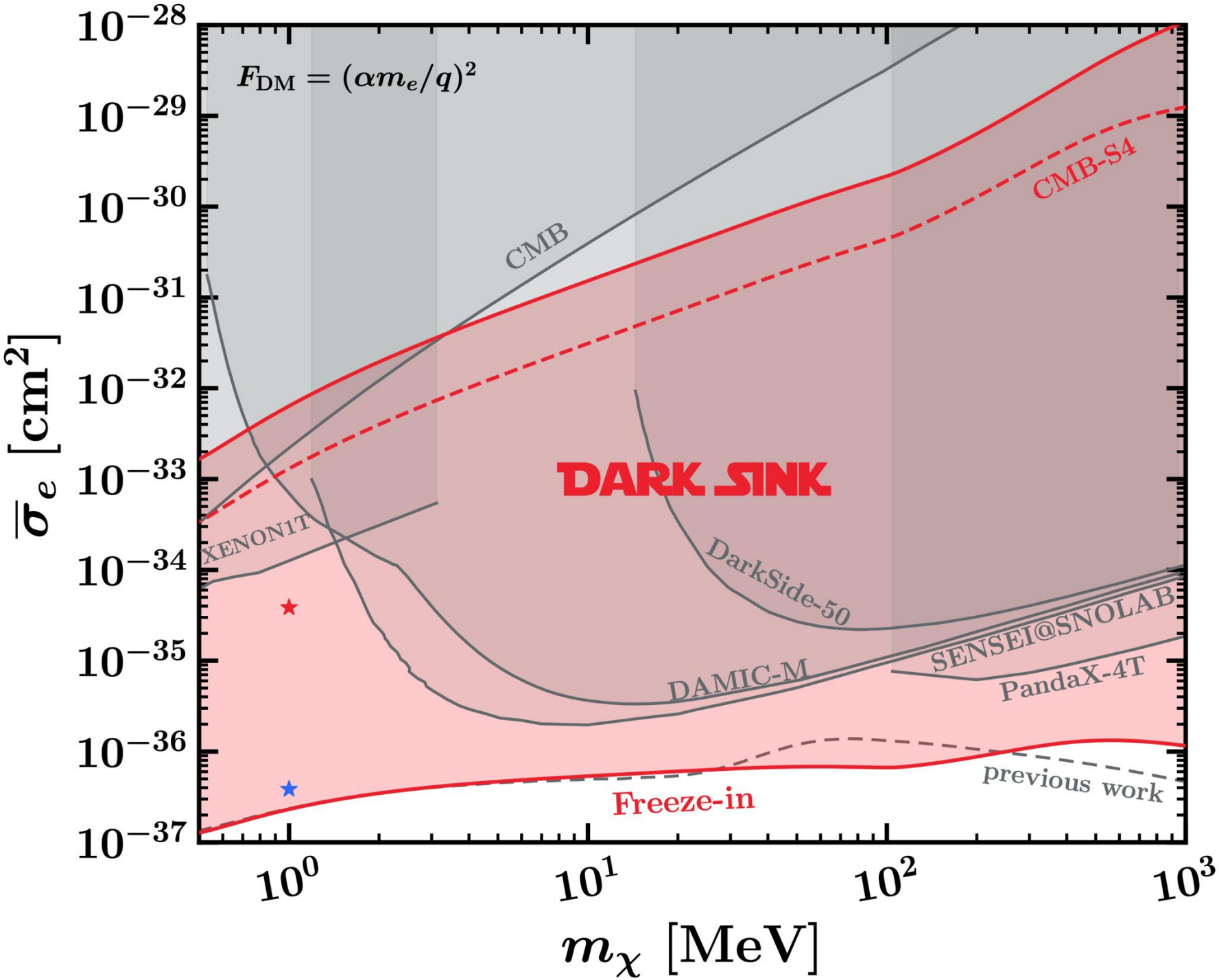
R McGehee


$F_{\rm DM} = (\alpha m_e/q)^2$
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

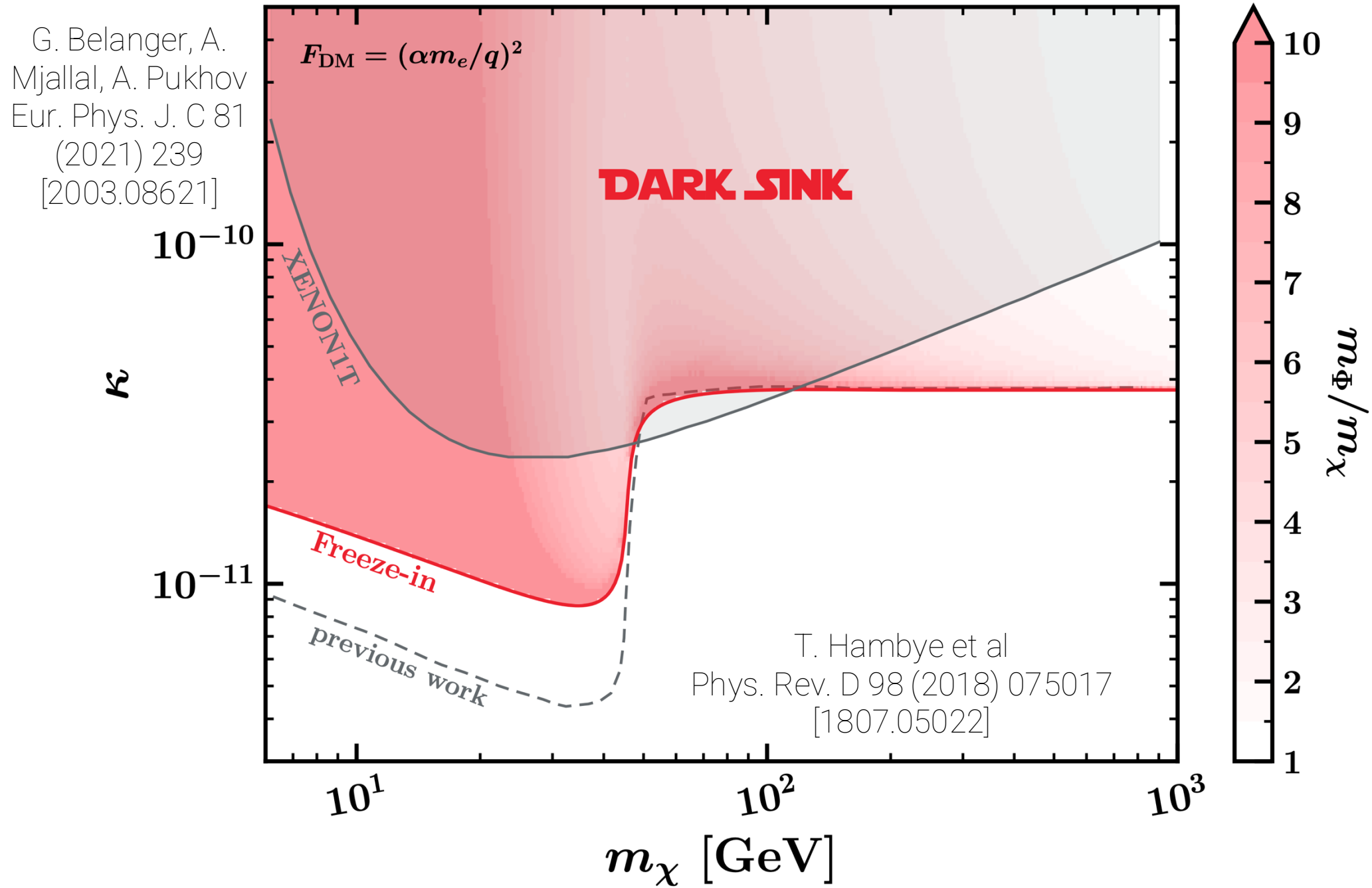

$F_{\rm DM} = (\alpha m_e/q)^2$
K. Boddy et al
Phys. Rev. D 98
(2018) 123506
[1808.00001]
CMB
CMB-S4
DARK SINK
DarkSide Collaboration
Phys. Rev. Lett. 130
(2023) 101002
[2207.11968]
XENON1T
DarkSide-50
DAMIC-M Collaboration
Phys. Rev. Lett.130
(2023) 171003
[2302.02372]
[2307.07251]
H. An et al
Phys. Rev. D 104
(2021) 103026
[2108.10332]
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
PandaX Collaboration
Phys. Rev. Lett.130
(2023) 261001
[2212.10067]
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


$F_{\rm DM} = (\alpha m_e/q)^2$
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

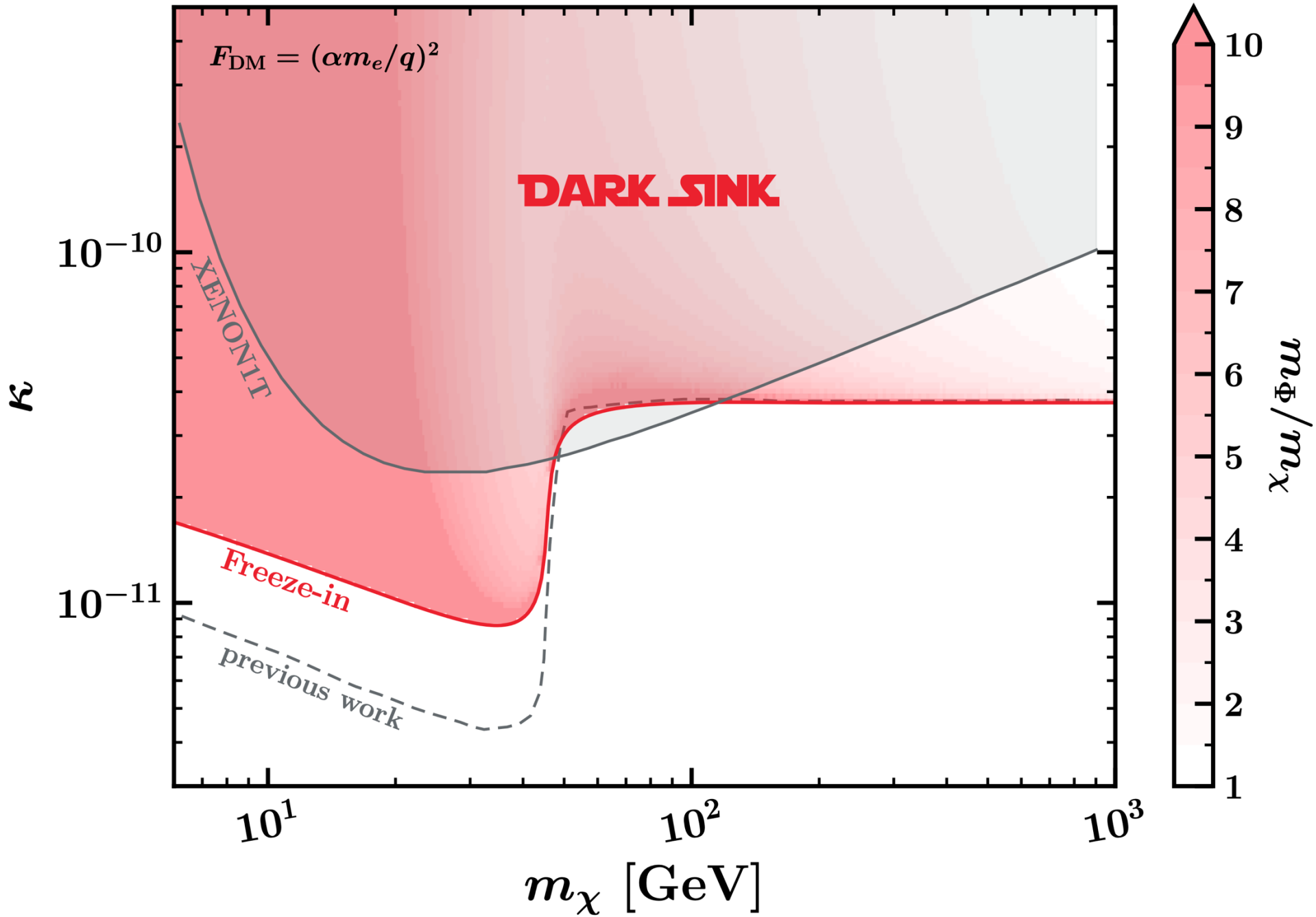
R McGehee

G. Belanger, A. Mjallal, A. Pukhov
Eur. Phys. J. C 81 (2021) 239
[2003.08621]

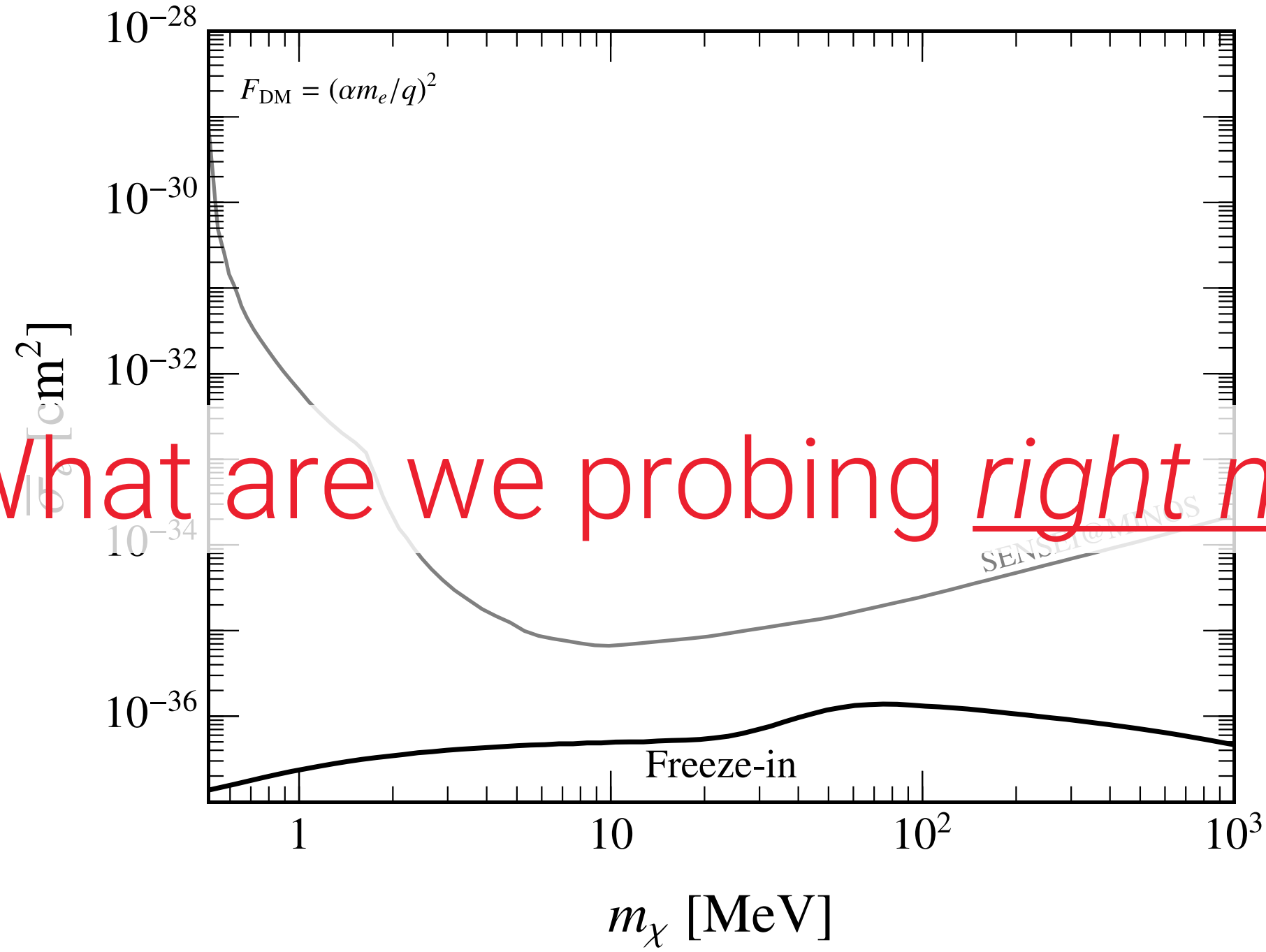


T. Hambye et al
Phys. Rev. D 98 (2018) 075017
[1807.05022]

R McGehee

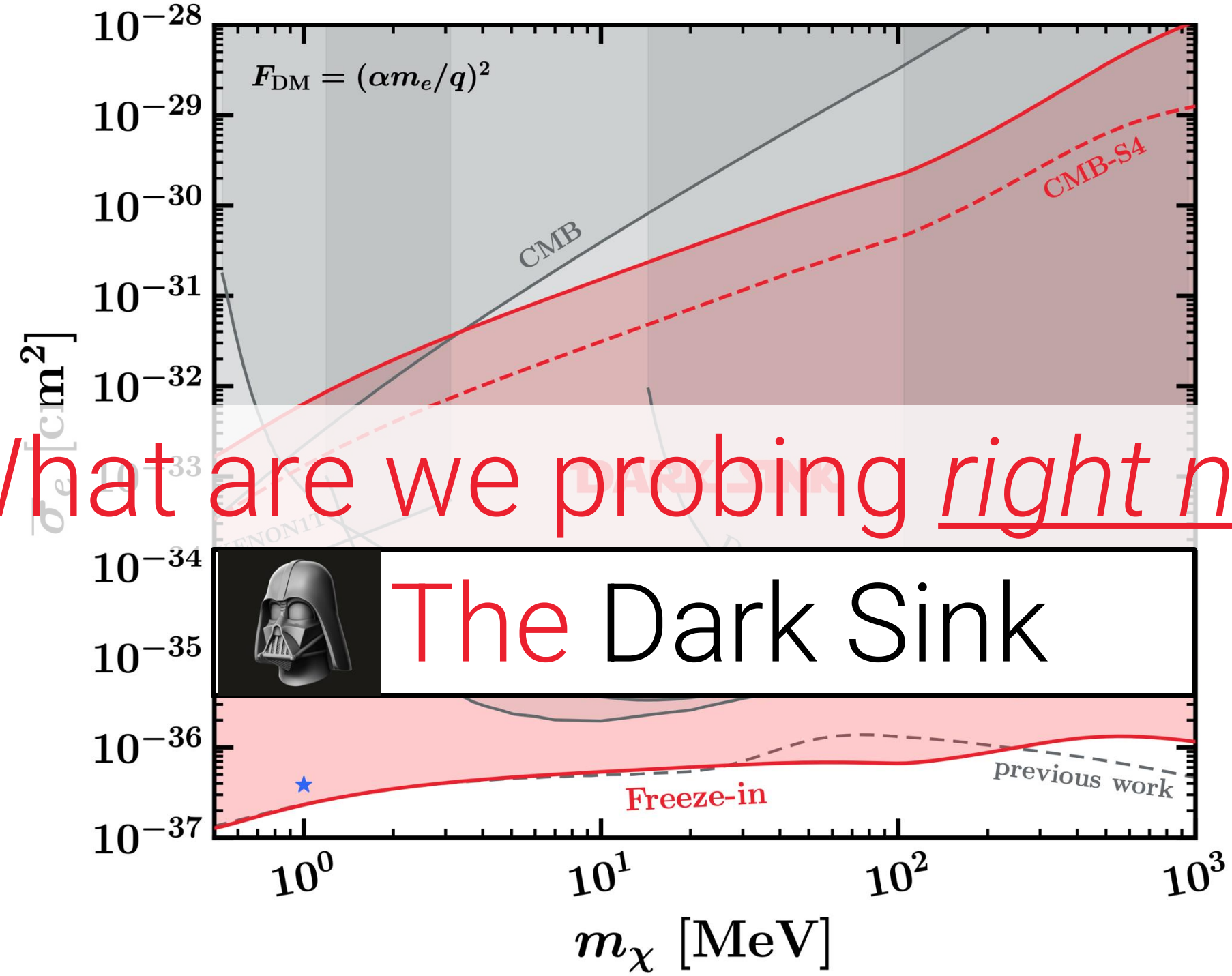

$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
XENON1T
Freeze-in
previous work
κ
10^{-10}
10^{-11}
10^1
10^2
10^3
m_χ [GeV]
χ_{nu}/Φ_{nu}
10
9
8
7
6
5
4
3
2
1

R McGehee



What are we probing *right now*?

R McGehee



What are we probing *right now*?

The Dark Sink

R McGehee

R McGehee

What about sub-MeV?

R McGehee

What about sub-MeV?

plasmons...

2408.07744
w/ Prudhvi N. Bhattiprolu, Evan Petrosky, & Aaron Pierce

R McGehee

So, what do plasmons do?

R McGehee

So, what do plasmons do?

They decay!

$$n_{\gamma_t^*}\langle\Gamma\rangle_{\gamma_t^*\to\chi\overline{\chi}} = \frac{\alpha\kappa^2}{\pi^2}\int_0^\infty \frac{k^2\,dk}{3} Z_t \frac{m_t^2}{\omega_t(e^{\omega_t/T}-1)}\left(1+\frac{2m_\chi^2}{m_t^2}\right)\sqrt{1-\frac{4m_\chi^2}{m_t^2}}$$

$$n_{\gamma_\ell^*}\langle\Gamma\rangle_{\gamma_\ell^*\to\chi\overline{\chi}} = \frac{\alpha\kappa^2}{2\pi^2}\int_0^{k_{\max}} \frac{k^2\,dk}{3} Z_\ell \frac{\omega_\ell}{e^{\omega_\ell/T}-1}\left(1+\frac{2m_\chi^2}{m_\ell^2}\right)\sqrt{1-\frac{4m_\chi^2}{m_\ell^2}}$$

R McGehee

So, what do plasmons do?

They decay!

$$n_{\gamma_t^*}\langle\Gamma\rangle_{\gamma_t^*\to\chi\overline{\chi}} = \frac{\alpha\kappa^2}{\pi^2}\int_0^\infty \frac{k^2\,dk}{3} Z_t \frac{m_t^2}{\omega_t(e^{\omega_t/T}-1)}\left(1+\frac{2m_\chi^2}{m_t^2}\right)\sqrt{1-\frac{4m_\chi^2}{m_t^2}}$$

$$n_{\gamma_\ell^*}\langle\Gamma\rangle_{\gamma_\ell^*\to\chi\overline{\chi}} = \frac{\alpha\kappa^2}{2\pi^2}\int_0^{k_{\max}} \frac{k^2\,dk}{3} Z_\ell \frac{\omega_\ell}{e^{\omega_\ell/T}-1}\left(1+\frac{2m_\chi^2}{m_\ell^2}\right)\sqrt{1-\frac{4m_\chi^2}{m_\ell^2}}$$

Kinda a pain...

R McGehee

How does this change the story?

R McGehee

How does this change the story?

Just another term in ye old Boltzmann equations…

$$-\overline{H}Ts\frac{dY}{dT} = n_e^2\langle\sigma v\rangle_{e^+e^-\to\chi\overline{\chi}}\left(1-\frac{Y^2}{Y_{\rm eq}^2}\right)$$

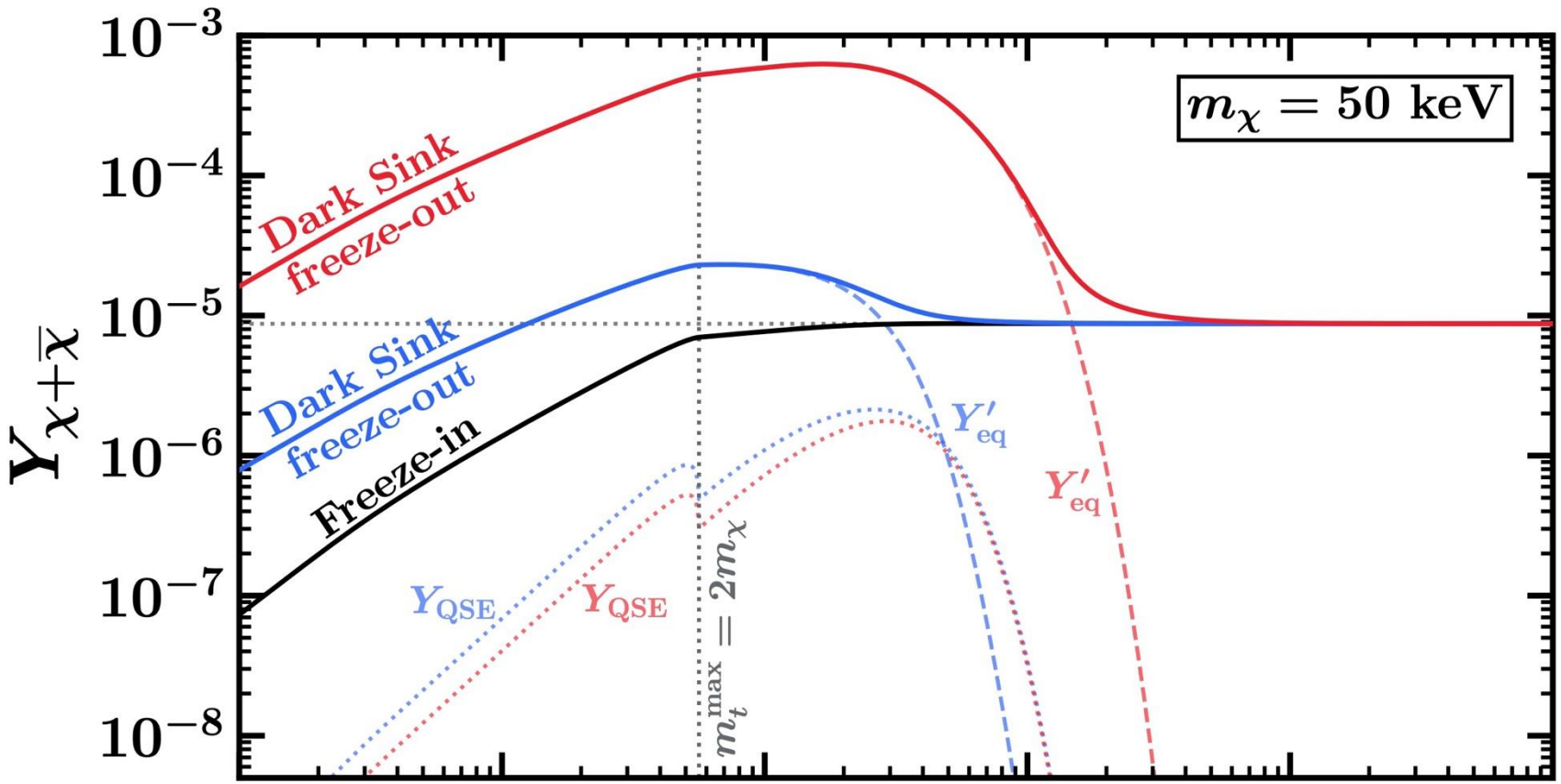
R McGehee

How does this change the story?

Just another term in ye old Boltzmann equations…

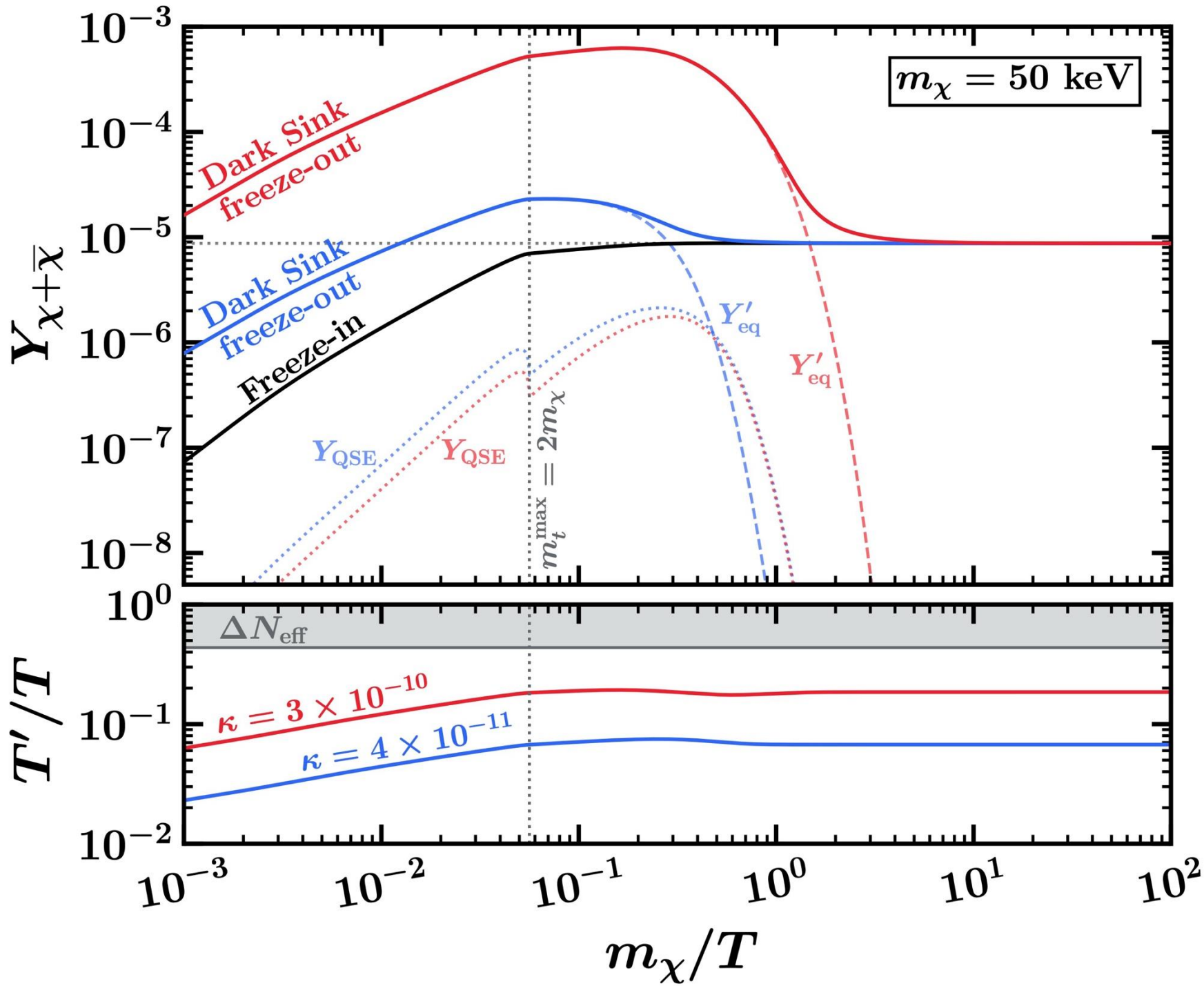
$$-\overline{H}Ts\frac{dY}{dT} = n_e^2\langle\sigma v\rangle_{e^+e^-\to\chi\overline{\chi}}\left(1-\frac{Y^2}{Y_{\rm eq}^2}\right) + n_{\gamma^*}\langle\Gamma\rangle_{\gamma^*\to\chi\overline{\chi}}\left(1-\frac{Y^2}{Y_{\rm eq}^2}\right)$$

R McGehee

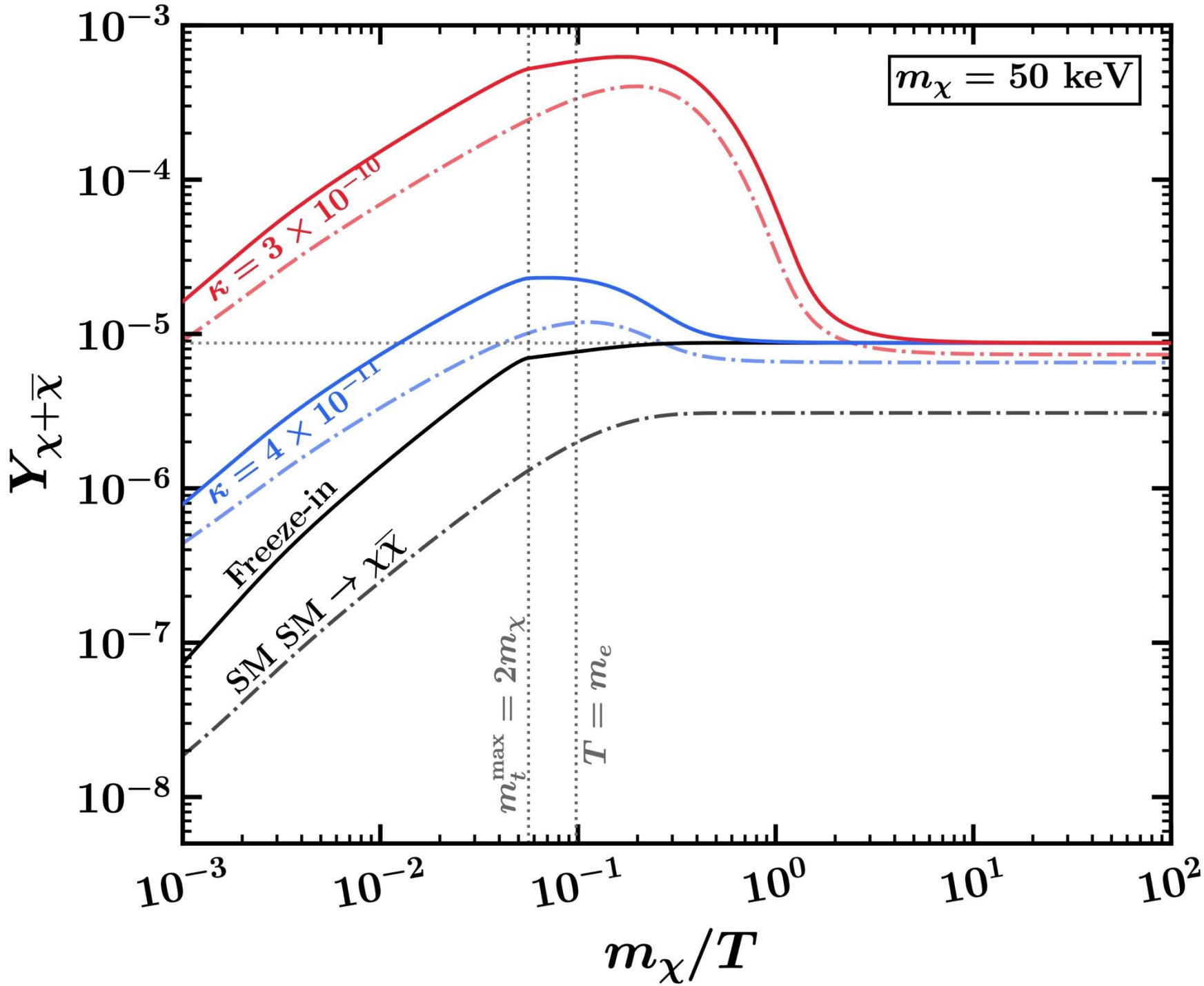


m_χ/T

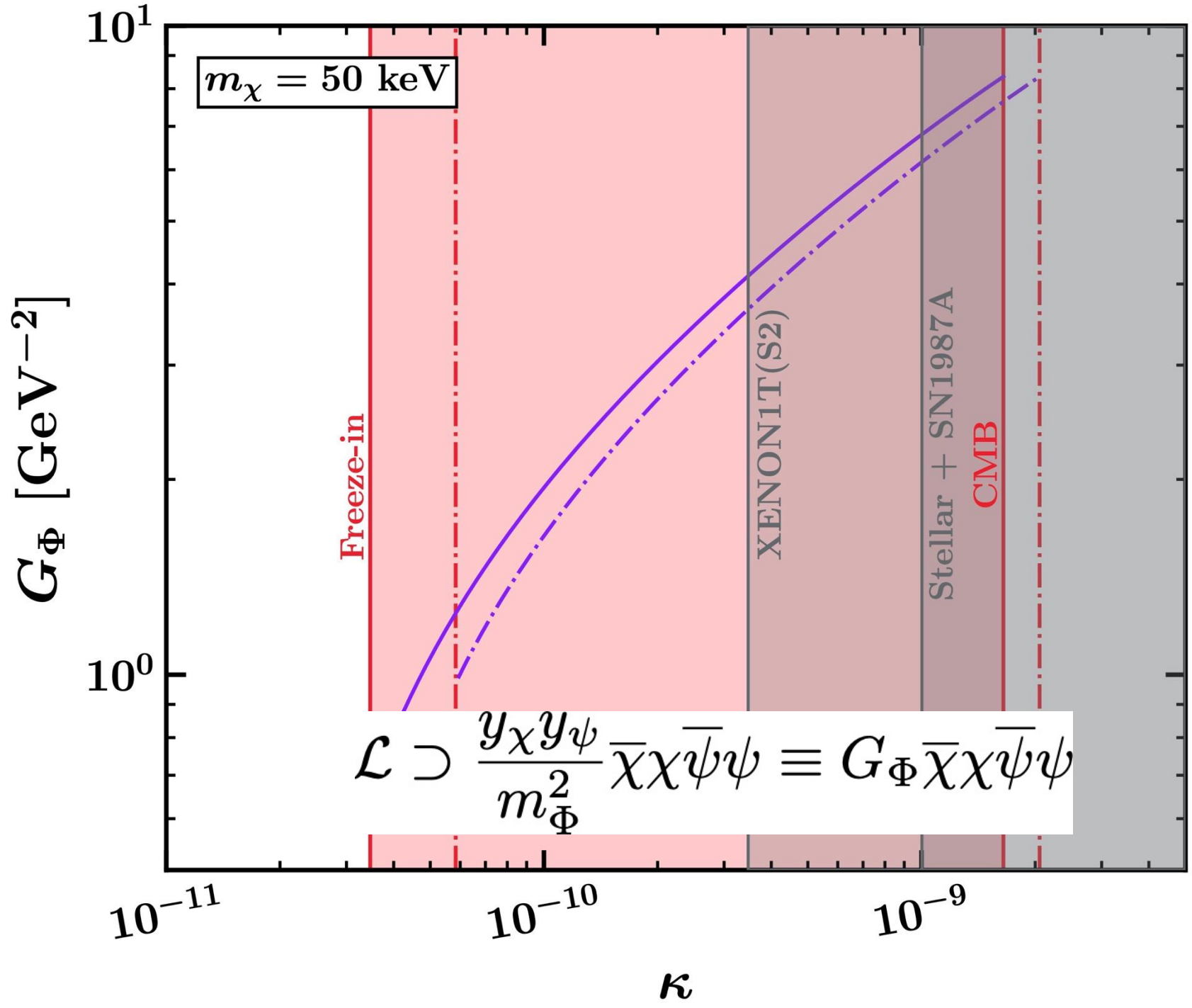
R McGehee


$m_\chi = 50$ keV
Dark Sink freeze-out
Dark Sink freeze-out
Freeze-in
$Y_{\chi+\bar{\chi}}$
$Y_{\rm QSE}$
$Y_{\rm QSE}$
$Y'_{\rm eq}$
$Y'_{\rm eq}$
$m_t^{\rm max} = 2m_\chi$
$\Delta N_{\rm eff}$
$\kappa = 3 \times 10^{-10}$
$\kappa = 4 \times 10^{-11}$
T'/T
m_χ/T

R McGehee

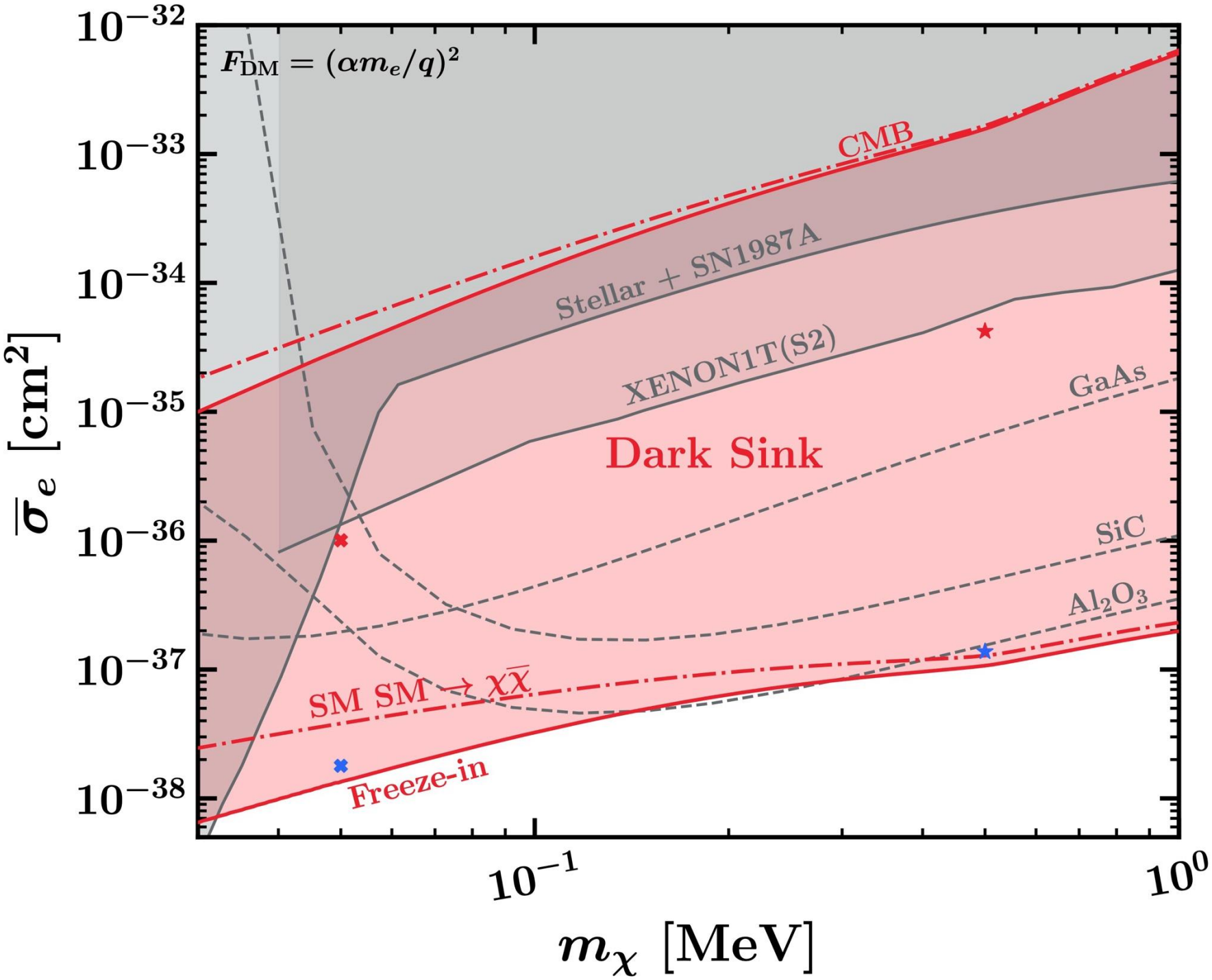

$m_\chi = 50$ keV
$\kappa = 3 \times 10^{-10}$
$\kappa = 4 \times 10^{-11}$
Freeze-in
SM SM $\to \chi\bar{\chi}$
$m_t^{\rm max} = 2m_\chi$
$T = m_e$
$Y_{\chi+\bar{\chi}}$
m_χ/T
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

R McGehee

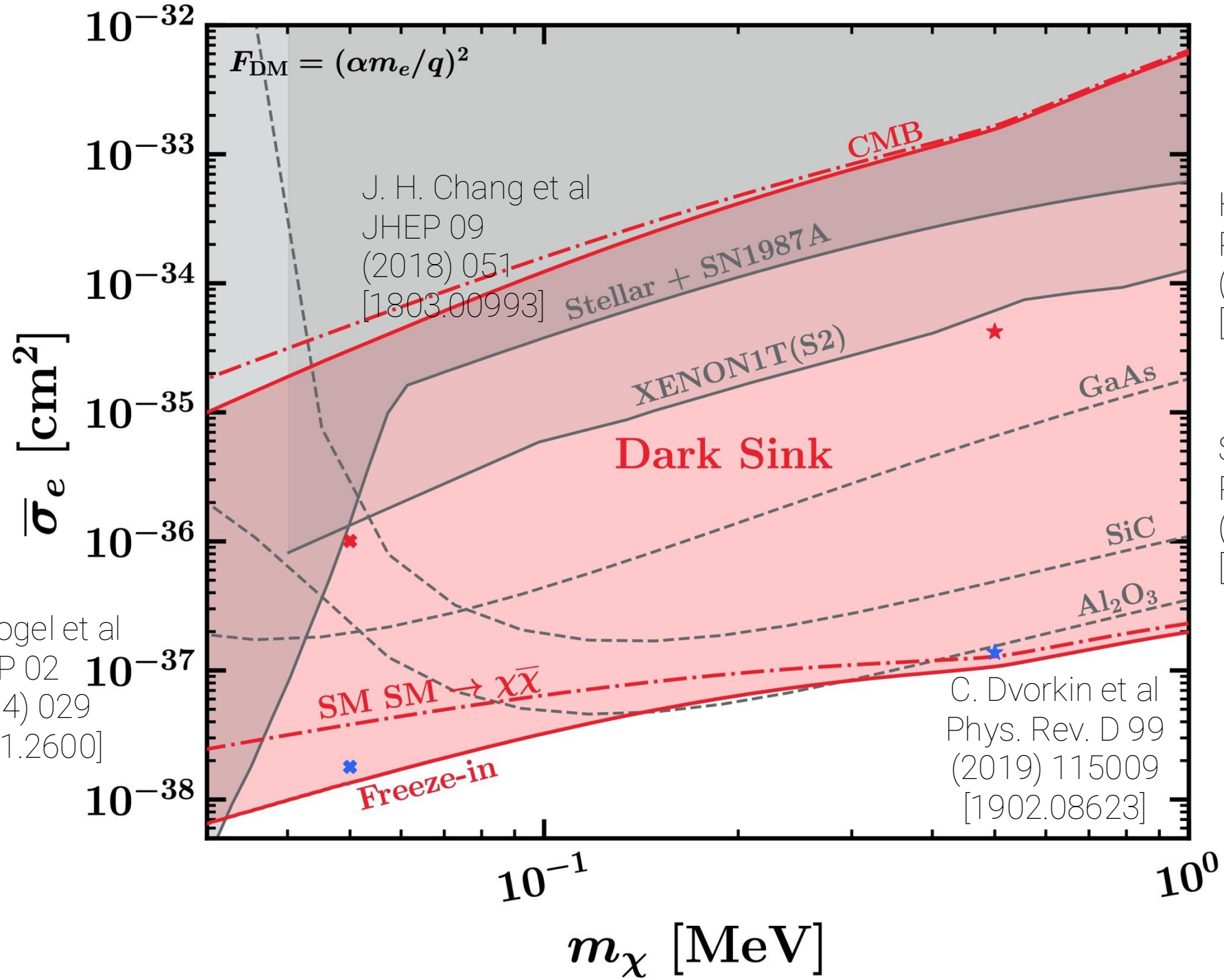


$$\mathcal{L} \supset \frac{y_\chi y_\psi}{m_\Phi^2}\overline{\chi}\chi\overline{\psi}\psi \equiv G_\Phi \overline{\chi}\chi\overline{\psi}\psi$$

R McGehee


$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
Stellar + SN1987A
XENON1T(S2)
GaAs
Dark Sink
SiC
Al_2O_3
SM SM $\to \chi\bar{\chi}$
Freeze-in
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-1}
10^{0}

R McGehee



J. H. Chang et al
JHEP 09
(2018) 051
[1803.00993]

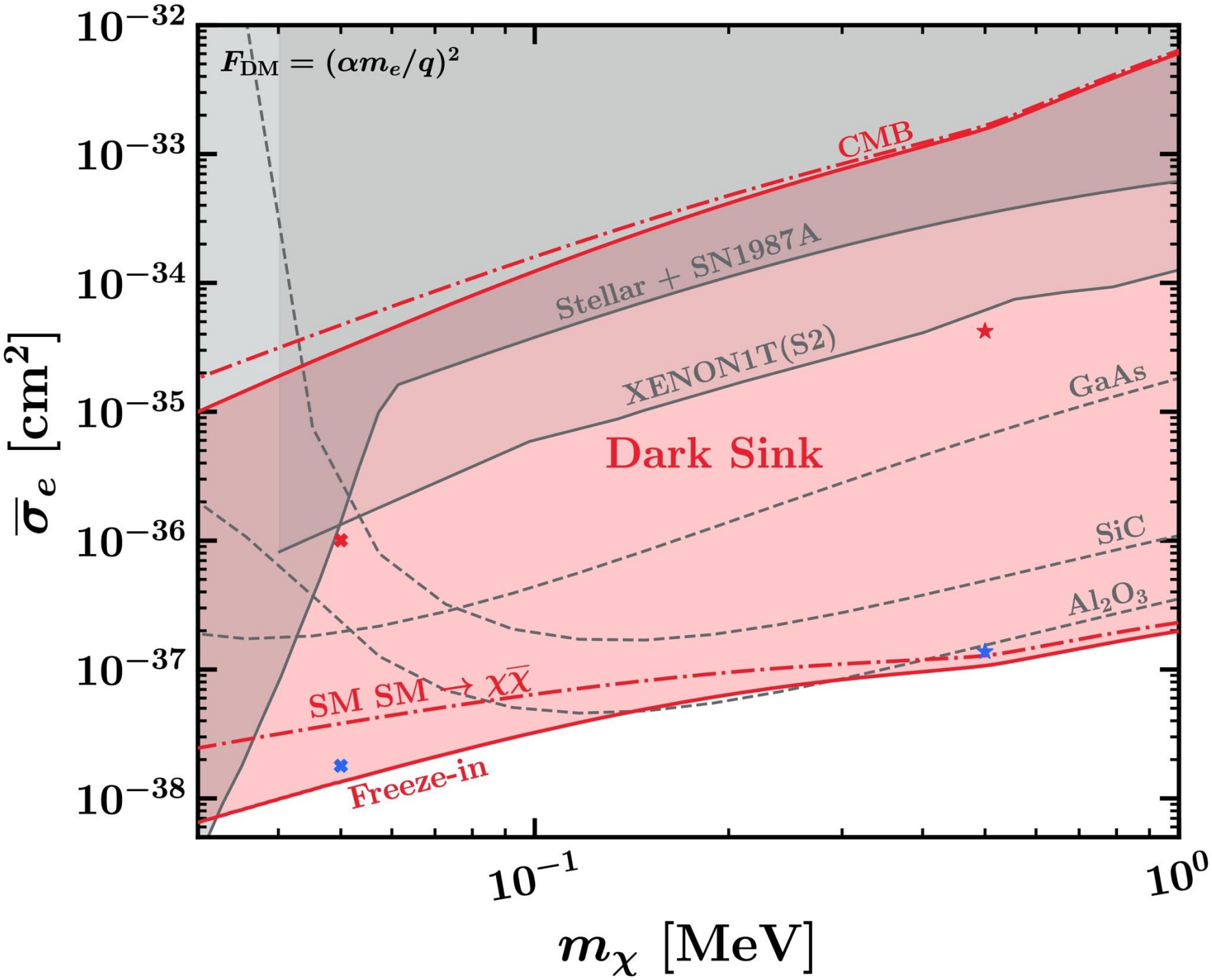
H. An et al
Phys. Rev. D 104
(2021) 103026
[2108.10332]

S. Knapen et al
Phys. Rev. D 105
(2022) 015014
[2104.12786]

H. Vogel et al
JCAP 02
(2014) 029
[1311.2600]

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

R McGehee

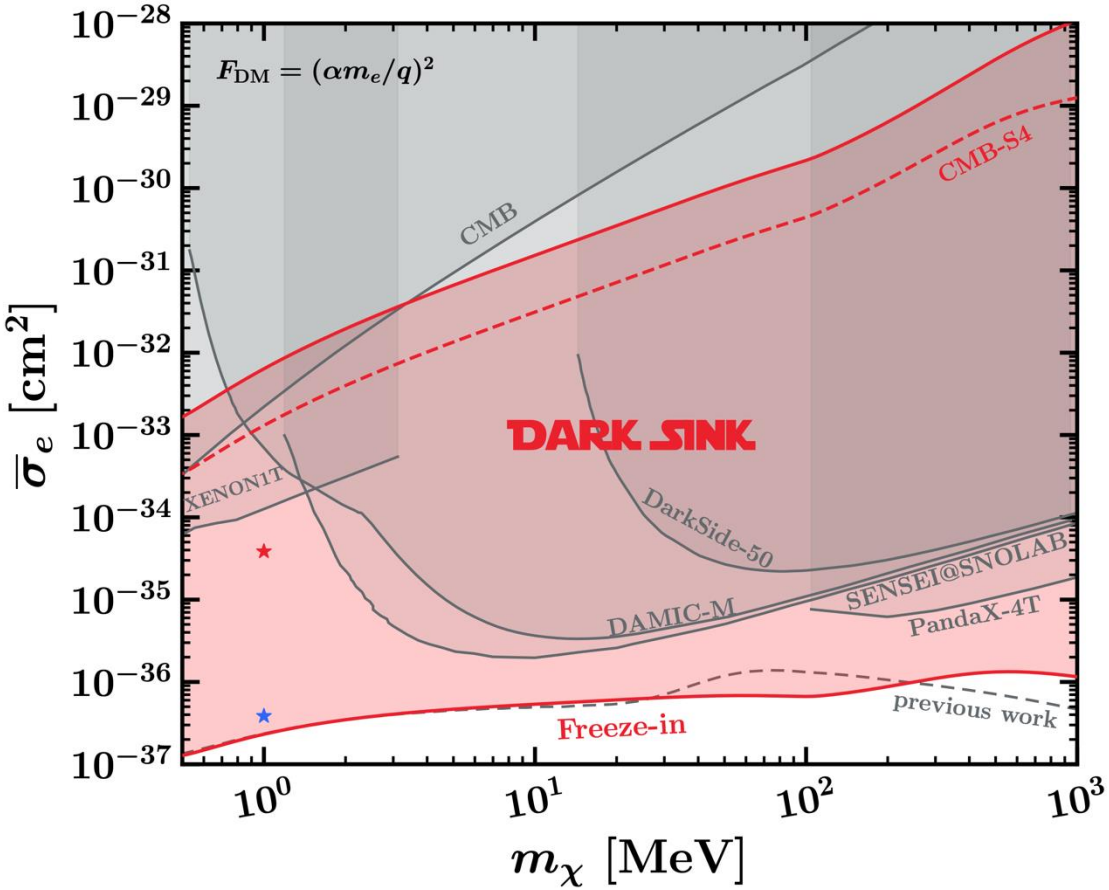

$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
Stellar + SN1987A
XENON1T(S2)
GaAs
Dark Sink
SiC
Al_2O_3
SM SM $\to \chi\bar{\chi}$
Freeze-in
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-1}
10^{0}

R McGehee

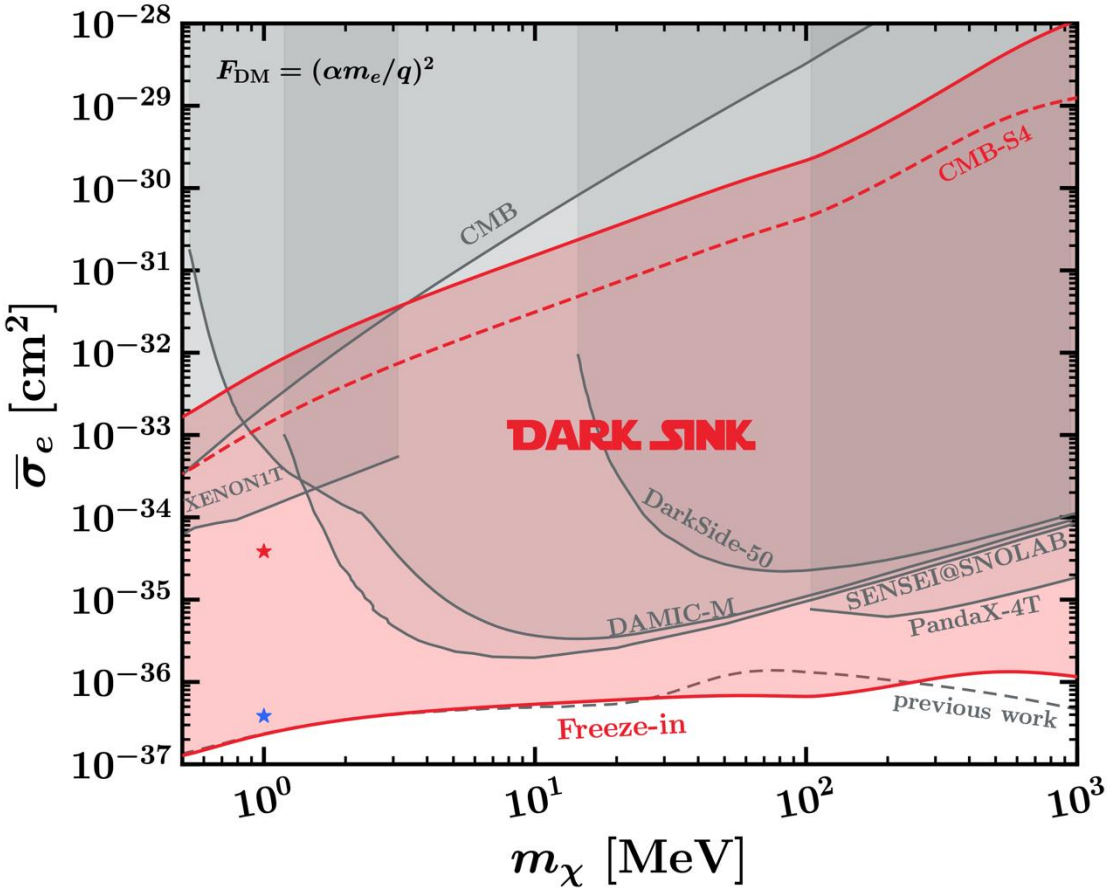
R McGehee

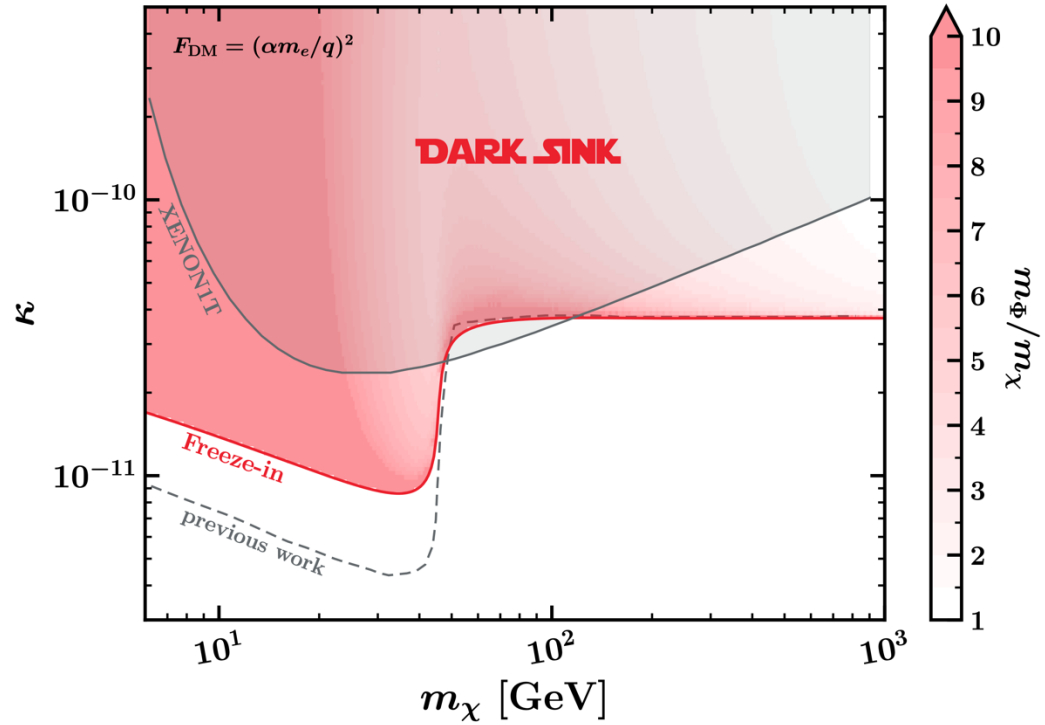
- How a Dark Sink could change other motivated freeze-in pheno:
  - Long-lived searches for FIMPs
  - Direct detection of UV freeze-in models

R McGehee

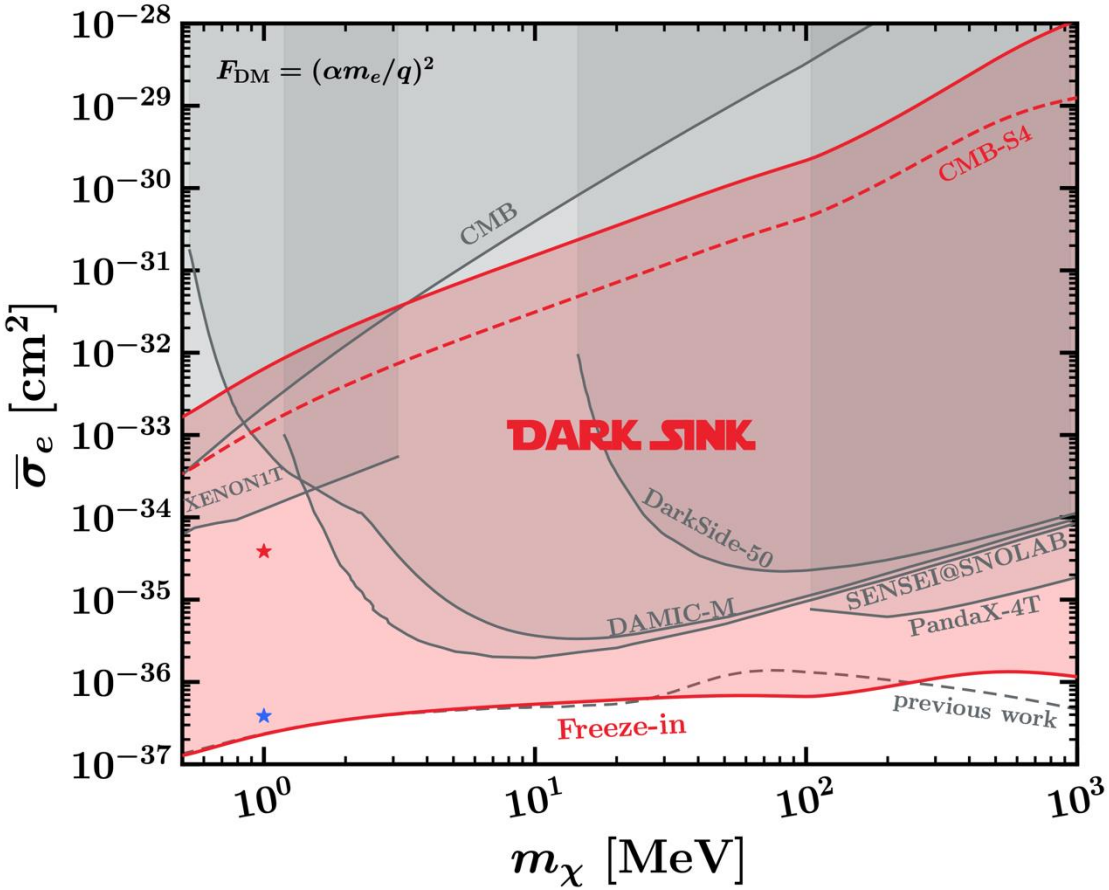

$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
CMB-S4
DARK SINK
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
Freeze-in
previous work
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^0
10^1
10^2
10^3

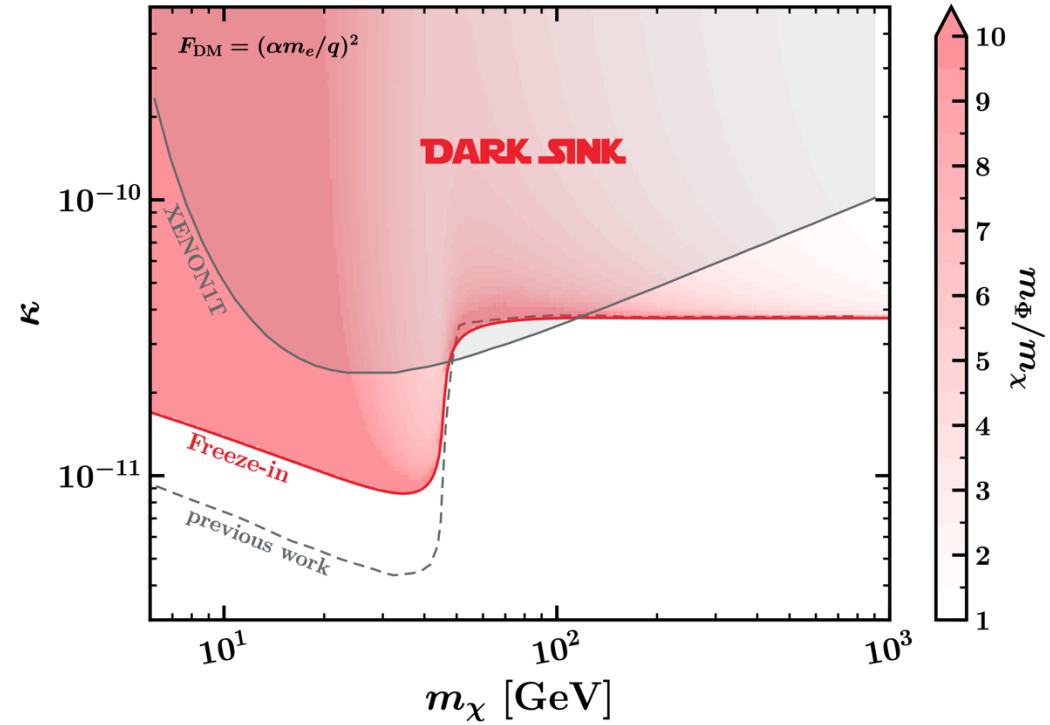
R McGehee

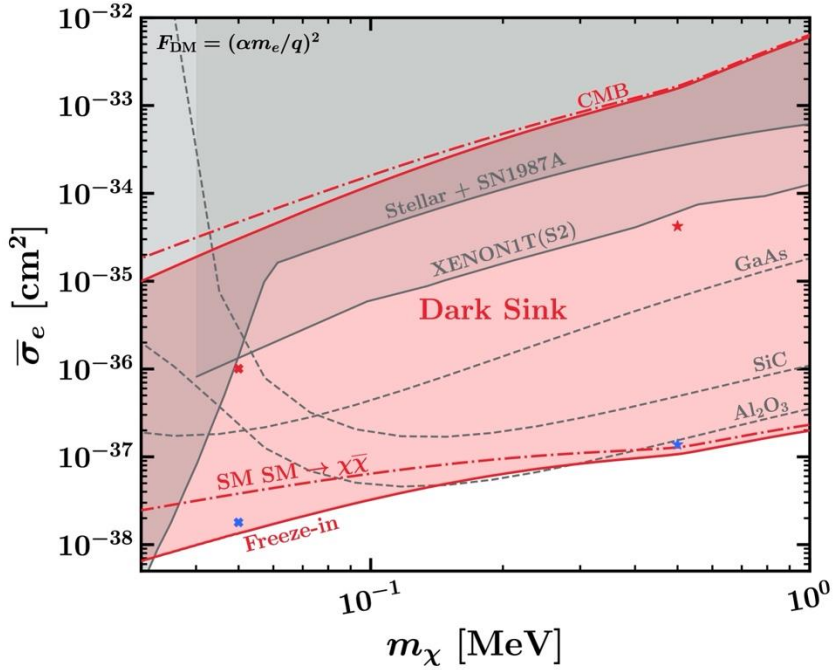

$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
CMB
CMB-S4
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
Freeze-in
previous work
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]


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

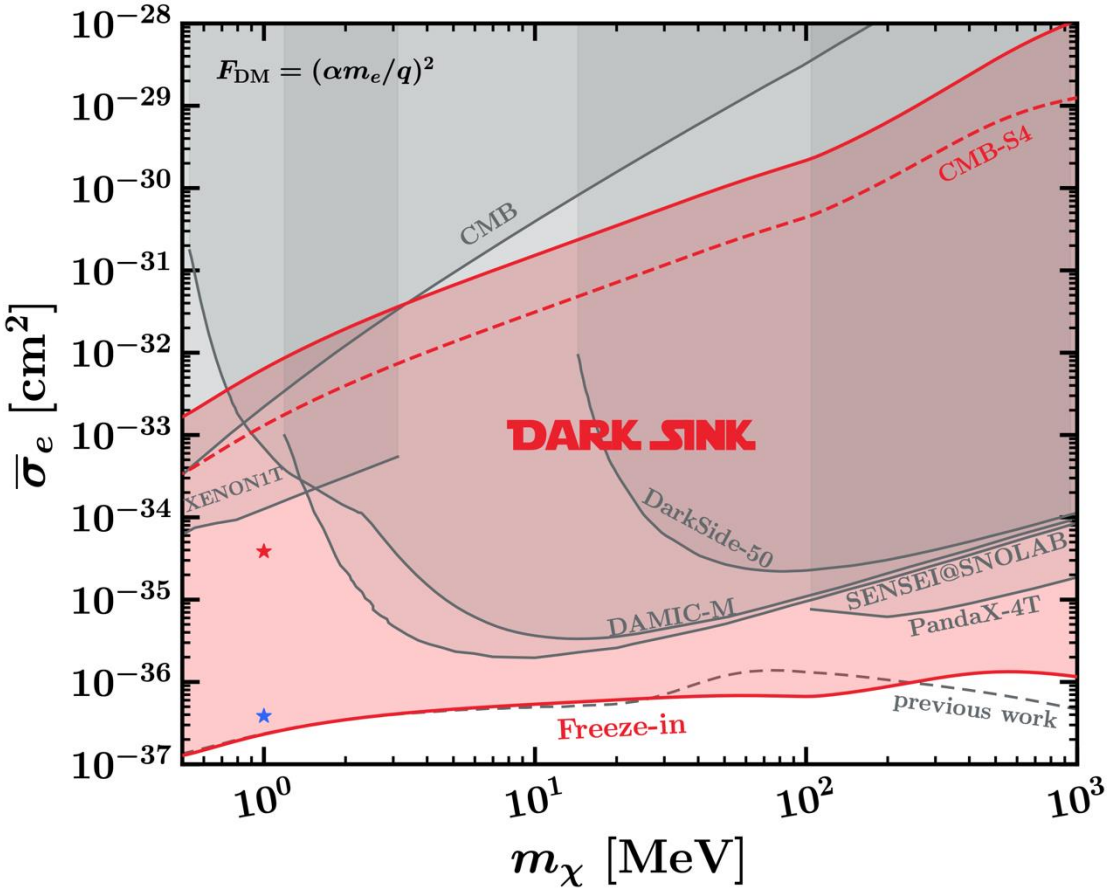
R McGehee

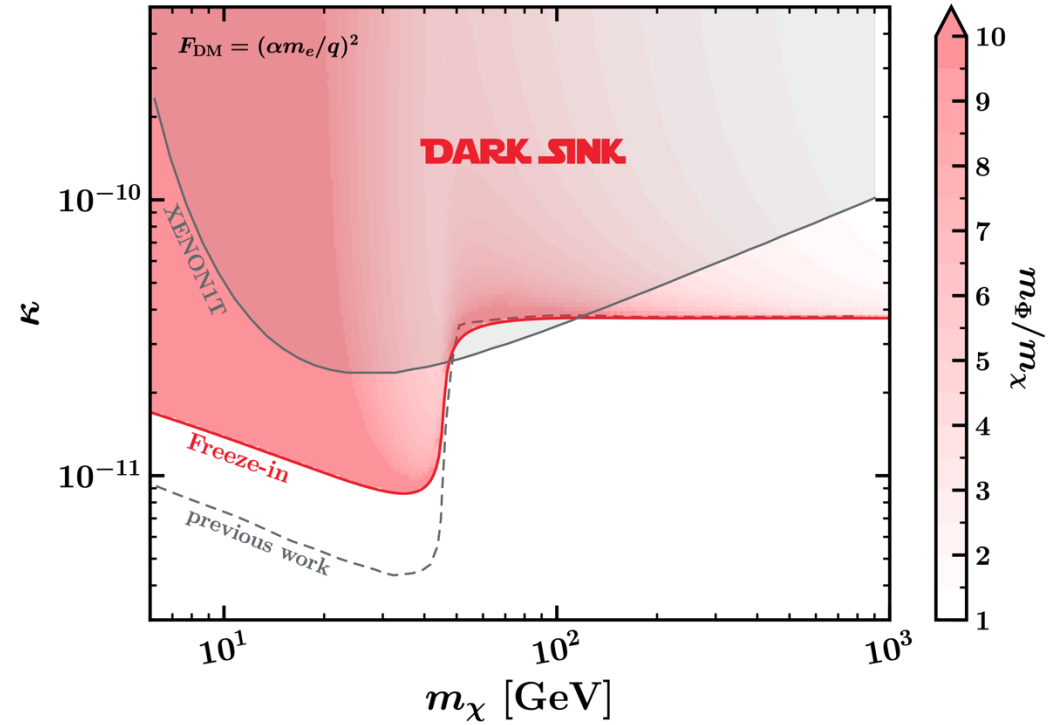

$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
CMB
CMB-S4
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
Freeze-in
previous work
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]

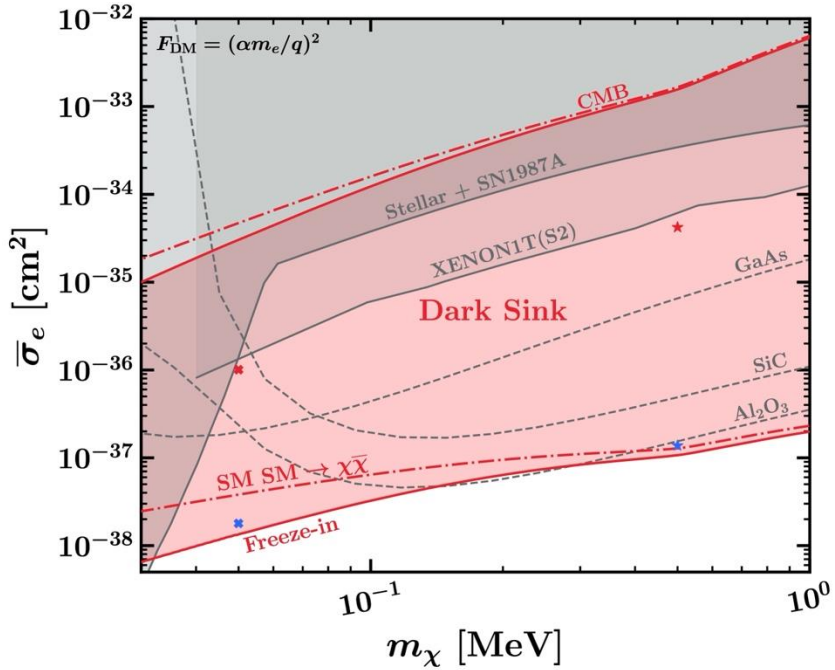

$F_{\rm DM} = (\alpha m_e/q)^2$
DARK SINK
XENON1T
Freeze-in
previous work
κ
m_χ [GeV]
$\chi u/\Phi u$


$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
Stellar + SN1987A
XENON1T(S2)
GaAs
Dark Sink
SiC
Al_2O_3
SM SM $\to \chi\bar{\chi}$
Freeze-in
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]

R McGehee

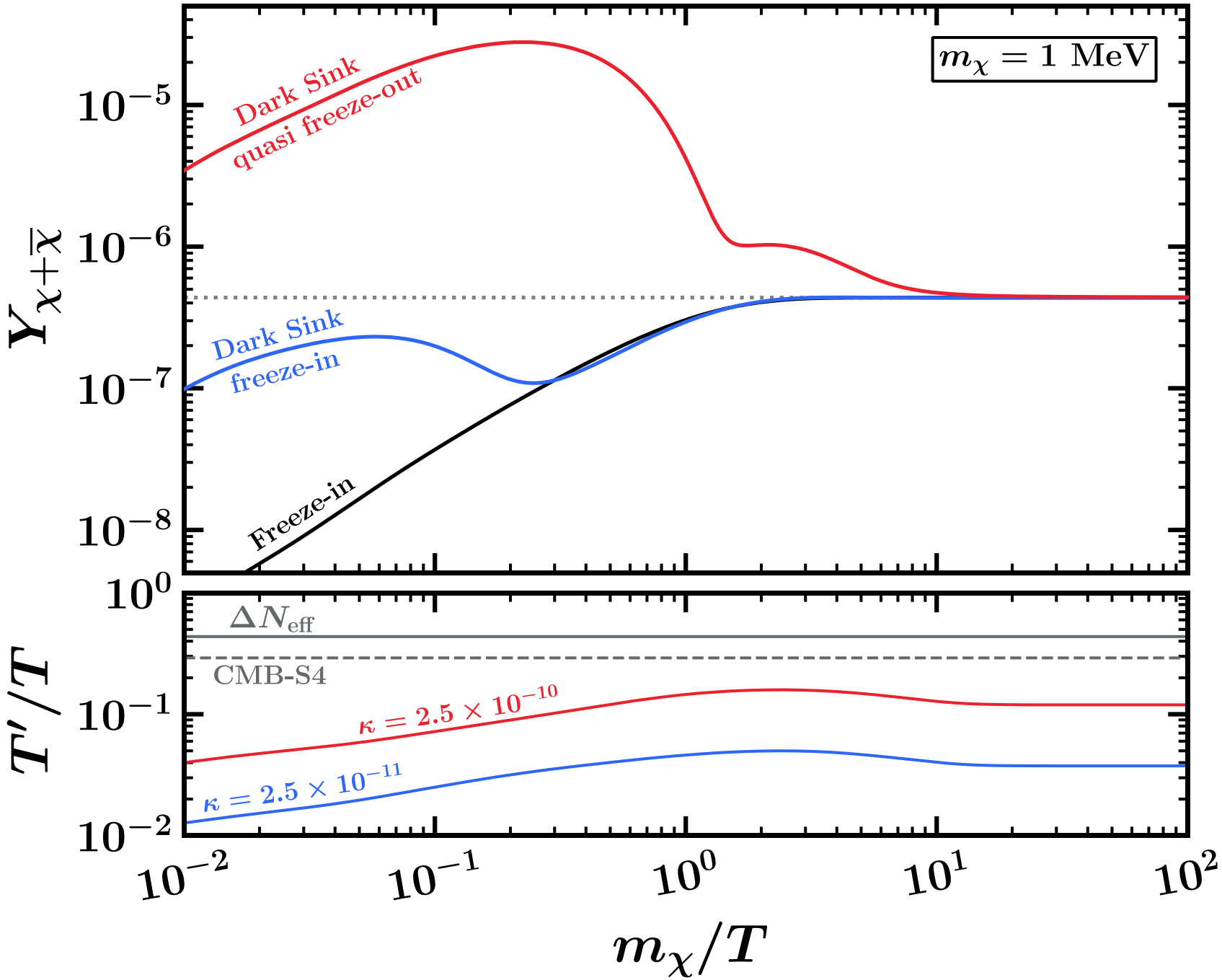

$F_{\rm DM} = (\alpha m_e/q)^2$
CMB-S4
CMB
DARK SINK
XENON1T
DarkSide-50
DAMIC-M
SENSEI@SNOLAB
PandaX-4T
Freeze-in
previous work
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]


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

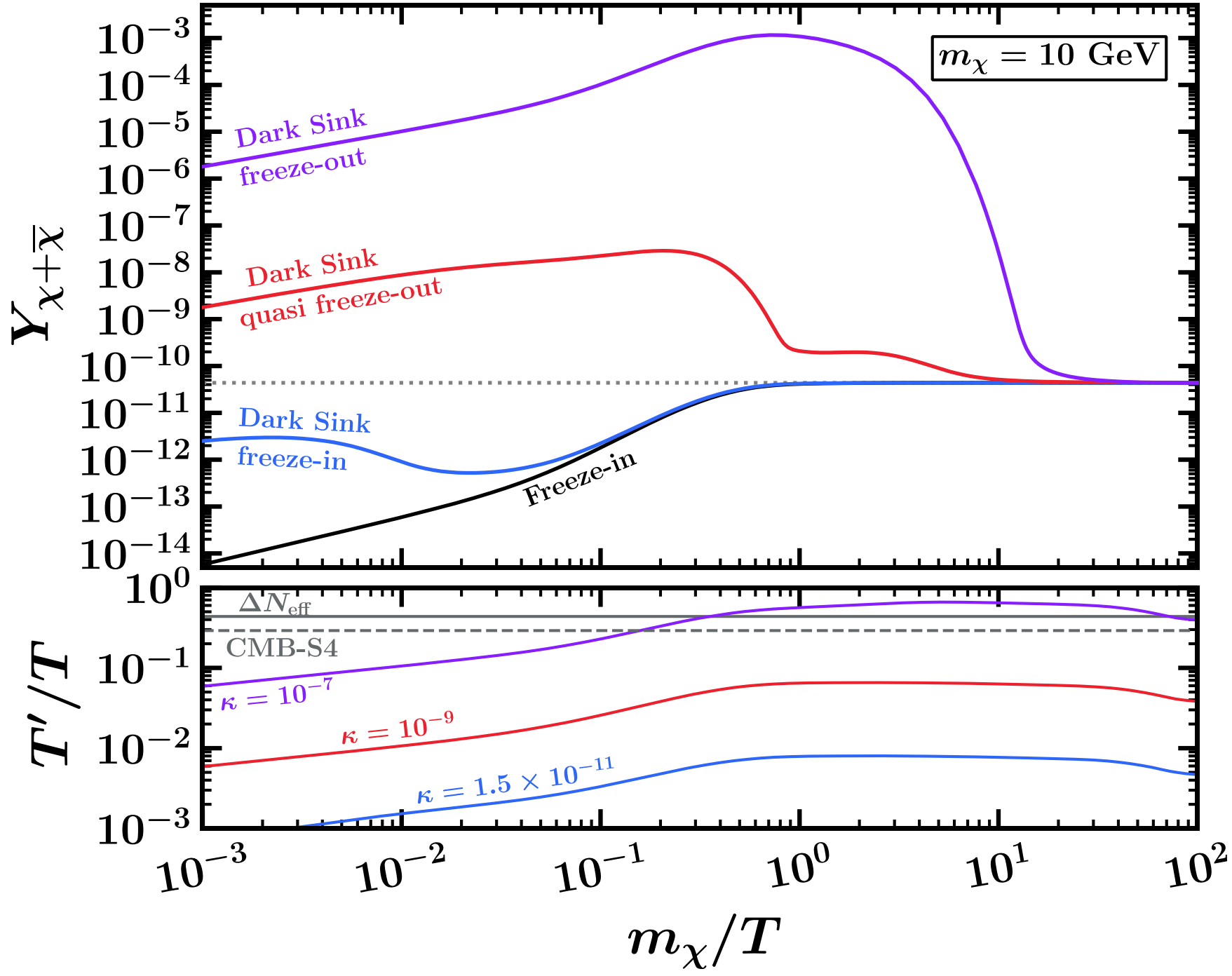

$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
Stellar + SN1987A
XENON1T(S2)
GaAs
Dark Sink
SiC
Al_2O_3
SM SM $\to \chi\bar{\chi}$
Freeze-in
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]

R McGehee

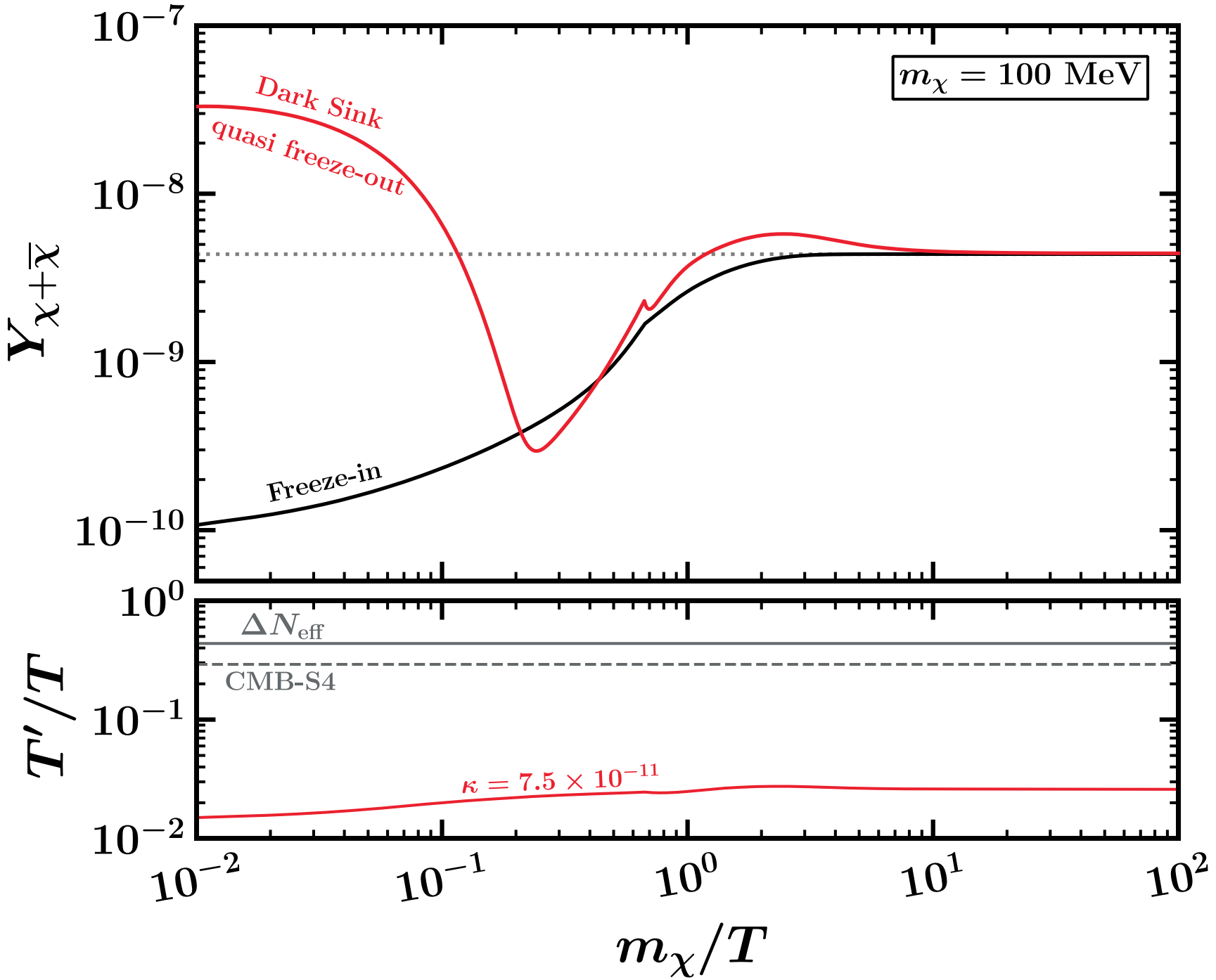
Backup Slides


$m_\chi = 1$ MeV
Dark Sink
quasi freeze-out
Dark Sink
freeze-in
Freeze-in
$Y_{\chi+\bar{\chi}}$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$\Delta N_{\rm eff}$
CMB-S4
$\kappa = 2.5 \times 10^{-10}$
$\kappa = 2.5 \times 10^{-11}$
T'/T
10^{0}
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m_χ/T

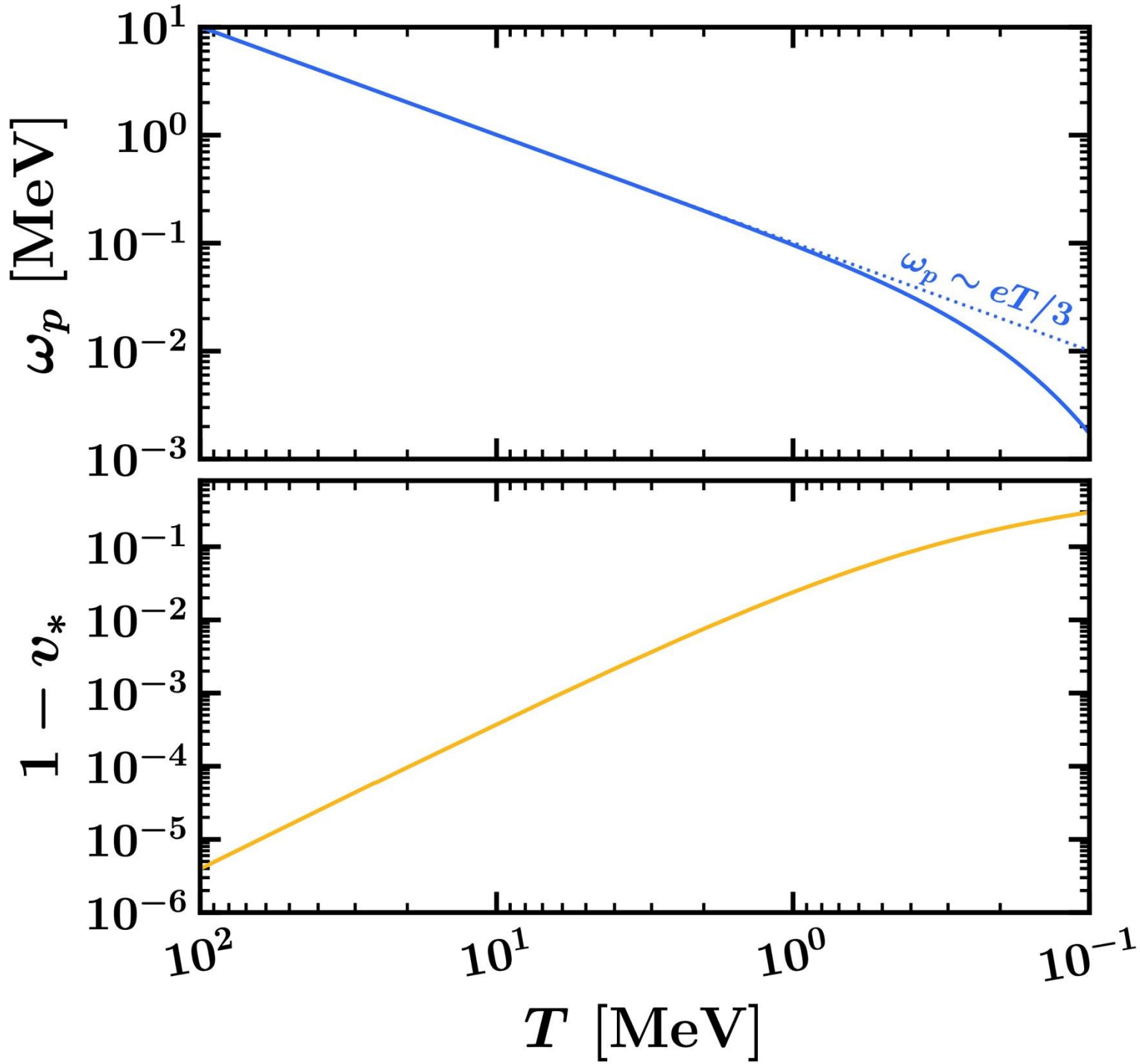
R McGehee


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

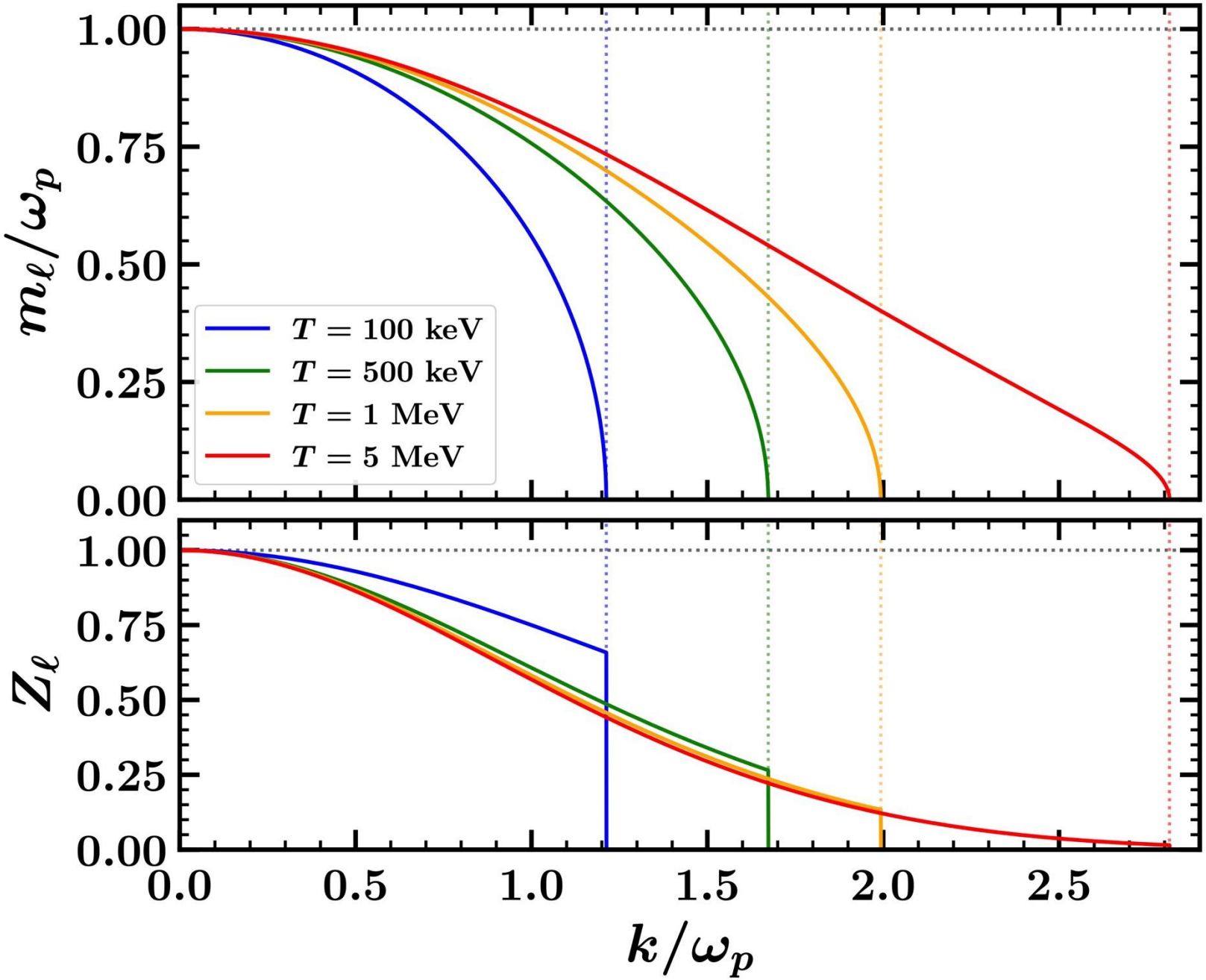
R McGehee


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

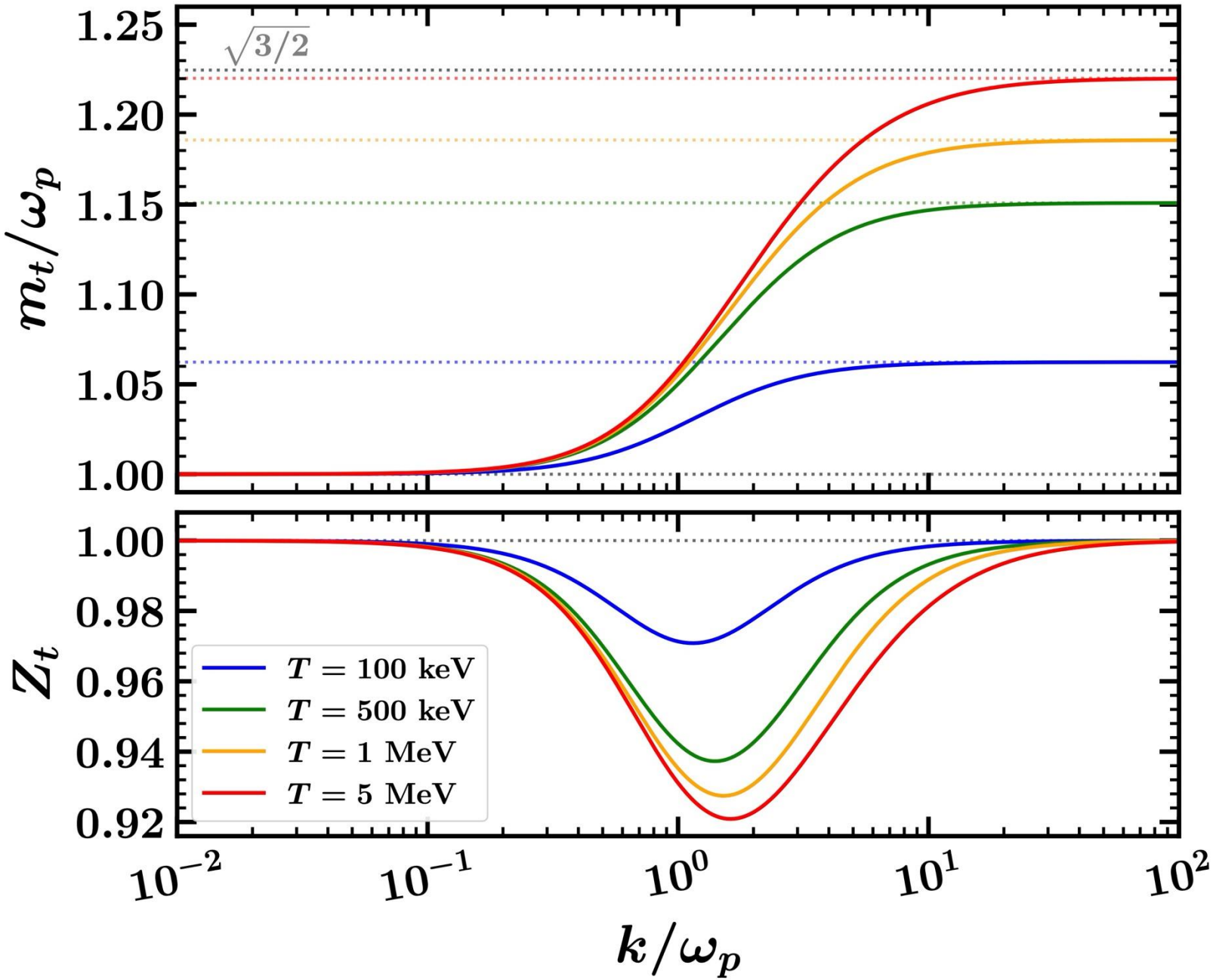
R McGehee


10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
ω_p [MeV]
$\omega_p \sim eT/3$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$1 - v_*$
10^{2}
10^{1}
10^{0}
10^{-1}
T [MeV]

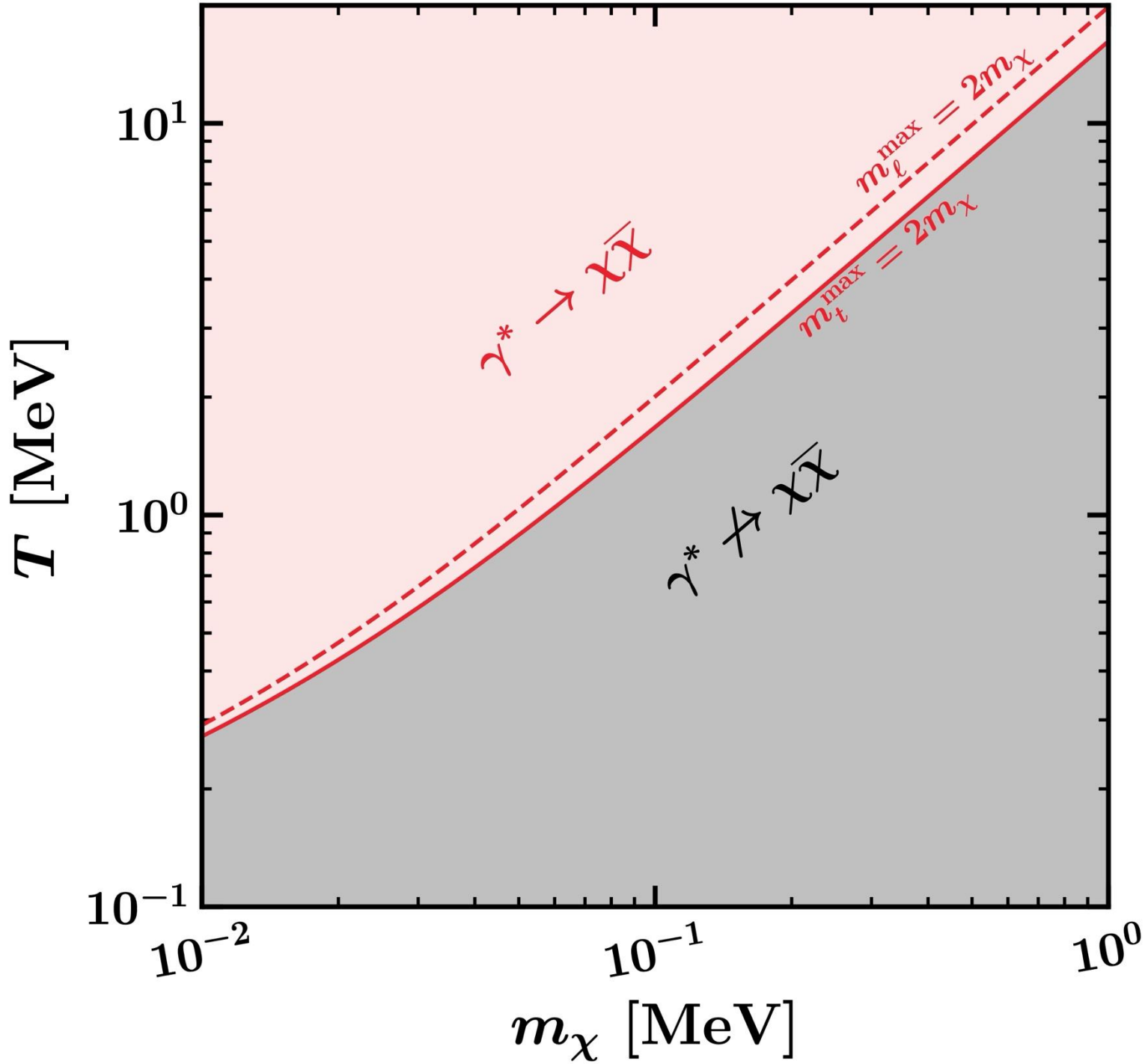
R McGehee


1.00
0.75
0.50
0.25
0.00
m_ℓ/ω_p
$T = 100$ keV
$T = 500$ keV
$T = 1$ MeV
$T = 5$ MeV
1.00
0.75
0.50
0.25
0.00
Z_ℓ
0.0
0.5
1.0
1.5
2.0
2.5
k/ω_p

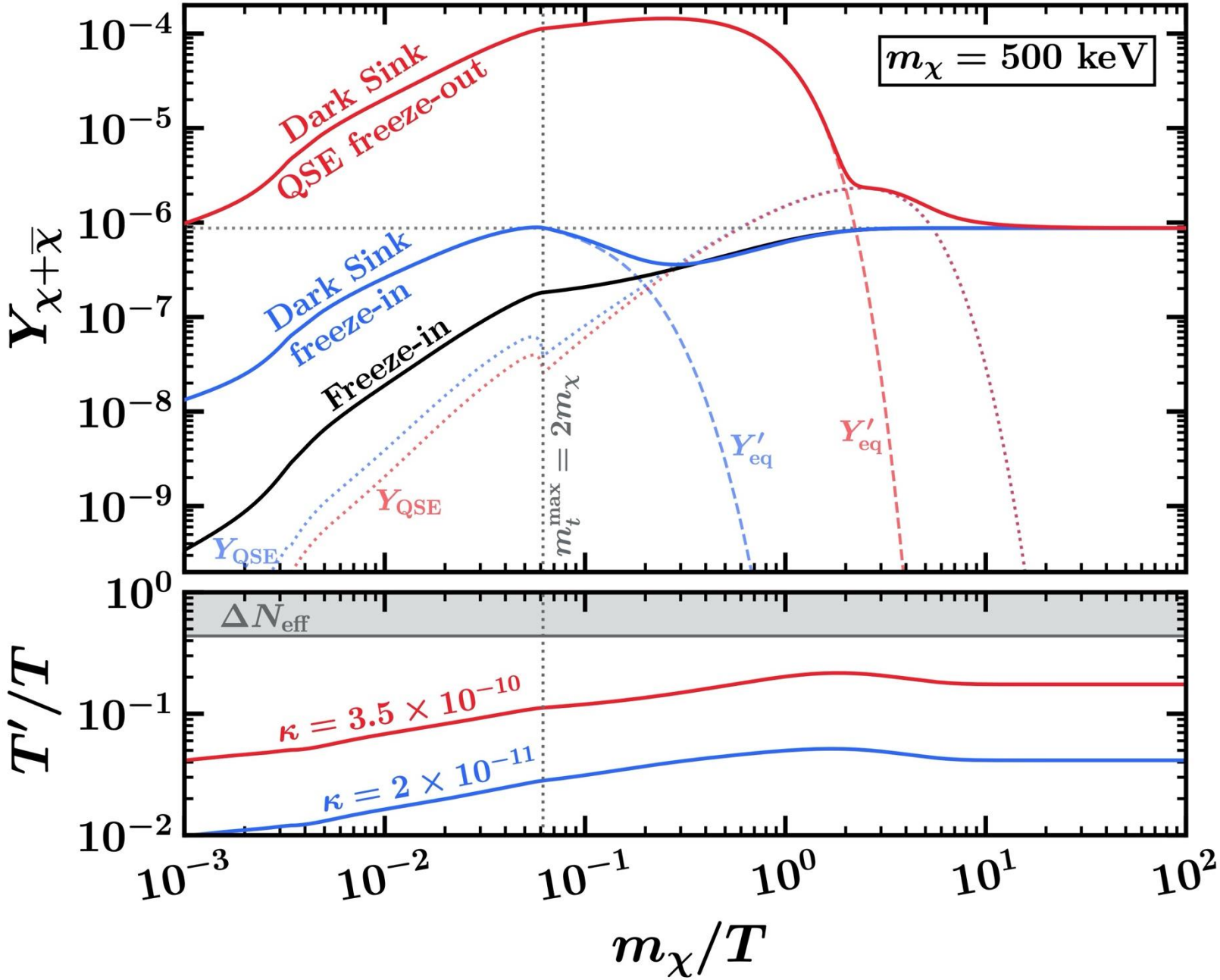
R McGehee


$\sqrt{3/2}$
m_t/ω_p
1.25
1.20
1.15
1.10
1.05
1.00
Z_t
1.00
0.98
0.96
0.94
0.92
$T = 100$ keV
$T = 500$ keV
$T = 1$ MeV
$T = 5$ MeV
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
k/ω_p

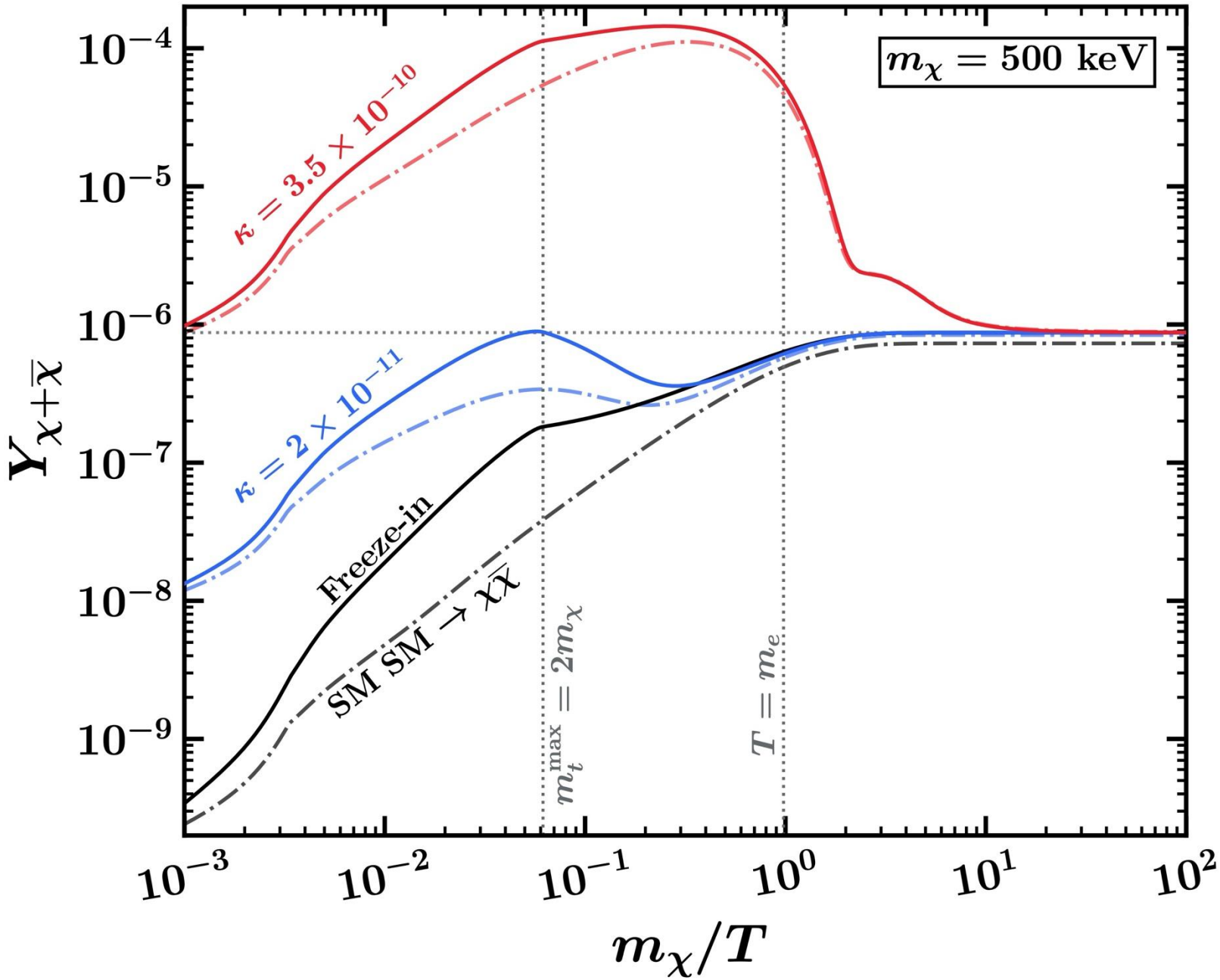
R McGehee


10^1
10^0
10^{-1}
T [MeV]
10^{-2}
10^{-1}
10^0
m_χ [MeV]
$\gamma^* \to \chi\bar{\chi}$
$\gamma^* \not\to \chi\bar{\chi}$
$m_\ell^{\max} = 2m_\chi$
$m_t^{\max} = 2m_\chi$

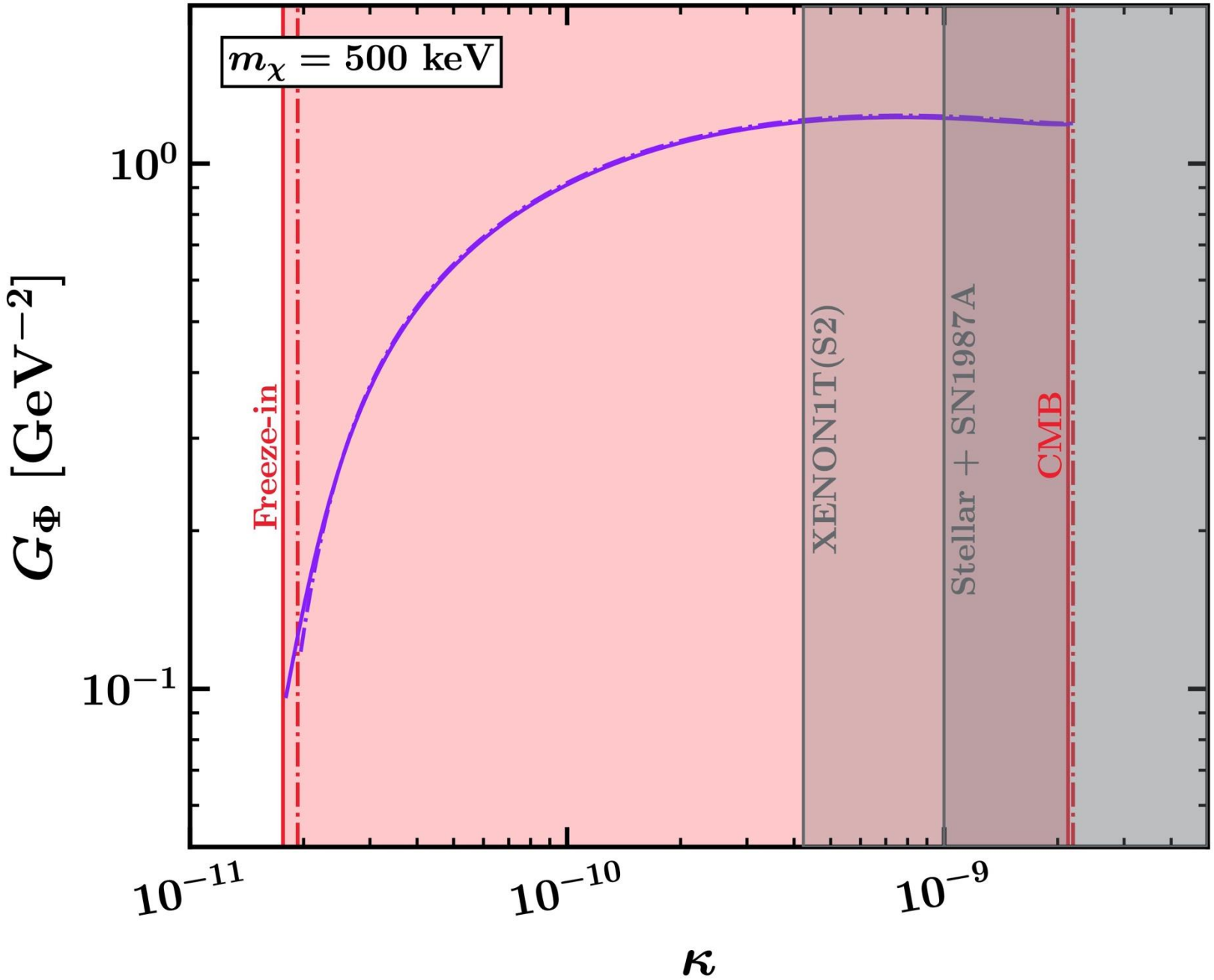
R McGehee


$m_\chi = 500$ keV
Dark Sink
QSE freeze-out
Dark Sink
freeze-in
Freeze-in
$Y_{\chi+\bar{\chi}}$
$Y_{\rm QSE}$
$Y_{\rm QSE}$
$m_t^{\rm max} = 2m_\chi$
$Y'_{\rm eq}$
$Y'_{\rm eq}$
$\Delta N_{\rm eff}$
$\kappa = 3.5 \times 10^{-10}$
$\kappa = 2 \times 10^{-11}$
T'/T
m_χ/T

R McGehee


$m_\chi = 500$ keV
$\kappa = 3.5 \times 10^{-10}$
$\kappa = 2 \times 10^{-11}$
Freeze-in
SM SM $\to \chi\bar{\chi}$
$m_t^{\max} = 2m_\chi$
$T = m_e$
$Y_{\chi+\bar{\chi}}$
m_χ/T
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

R McGehee


$m_\chi = 500$ keV
10^0
10^{-1}
G_Φ [GeV^{-2}]
Freeze-in
XENON1T(S2)
Stellar + SN1987A
CMB
10^{-11}
10^{-10}
10^{-9}
κ

R McGehee