# Scattering meets absorption in dark matter detection

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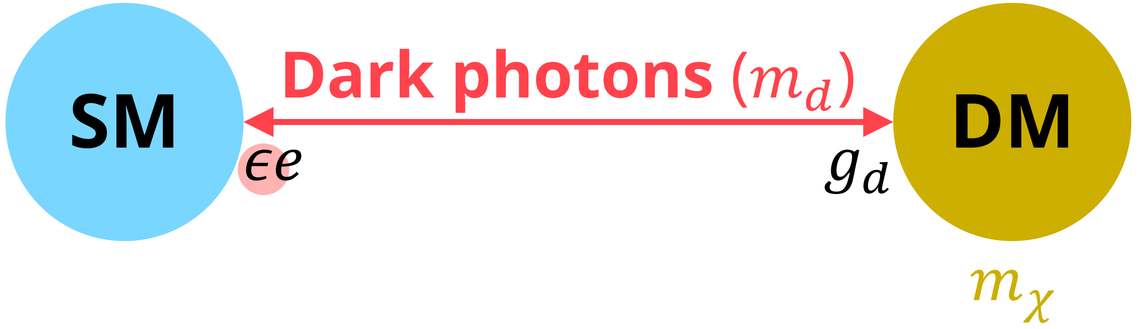
Based on JHEP 07 (2025) 143
Light Dark World 2025

Radboud University
Nikhef

# DARK PHOTON MEDIATED DARK MATTER

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \epsilon e j_{EM}^{\mu} A_{d,\mu} + \frac{m_d^2}{2} A_d^{\mu} A_{d,\mu} + \bar{\chi}(i\gamma^{\mu}\partial_{\mu} - m_{\chi})\chi - g_d \bar{\chi}\gamma^{\mu}\chi A_{d,\mu}$$



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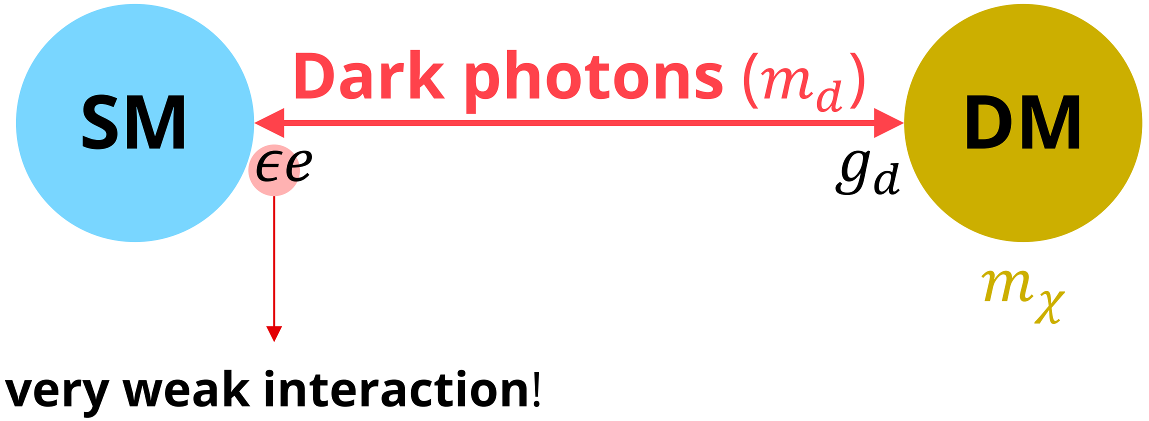
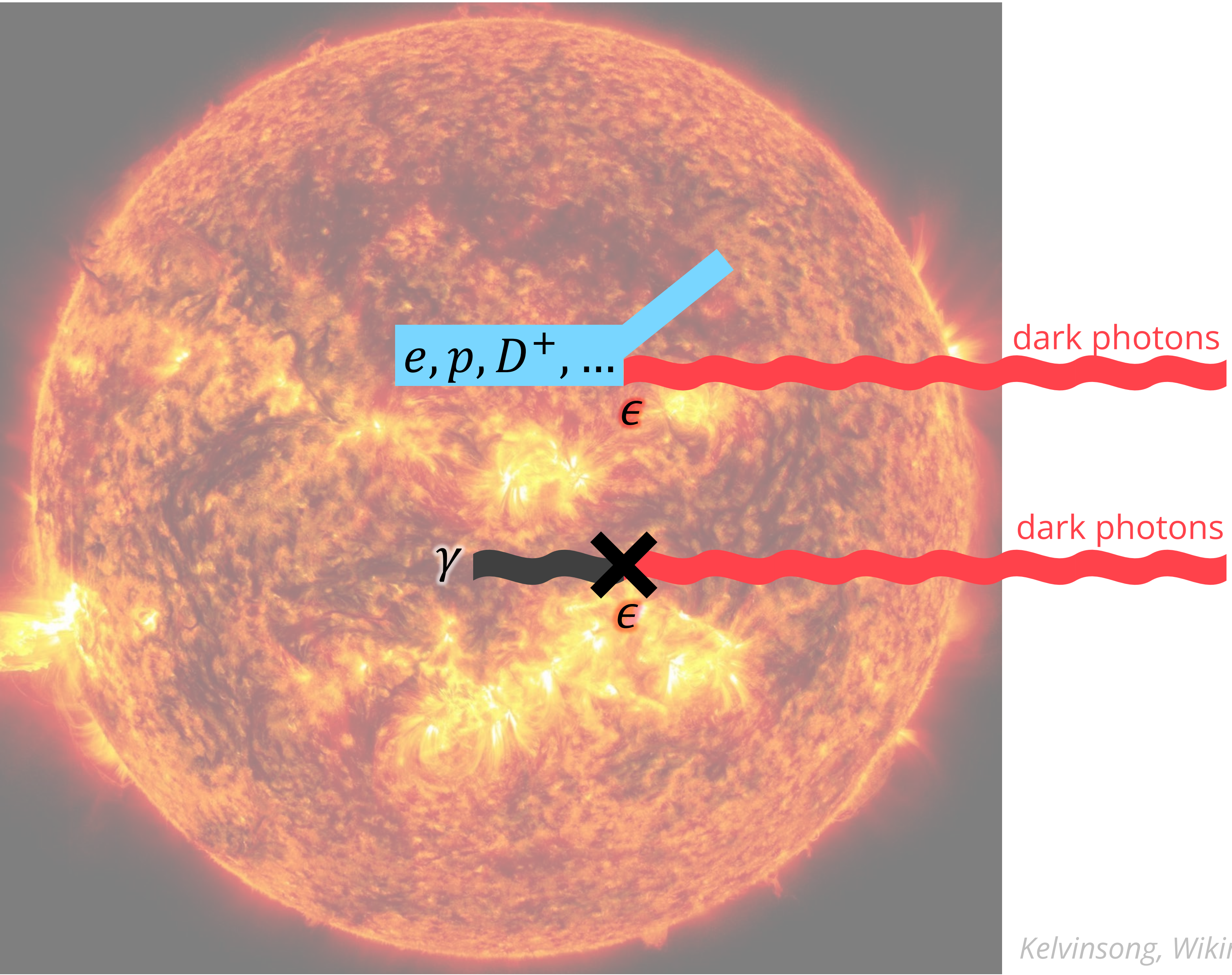



Both dark photons and dark matter can be observed at direct detection experiments.

# SOLAR DARK PHOTONS




Kelvinsong, Wikimedia

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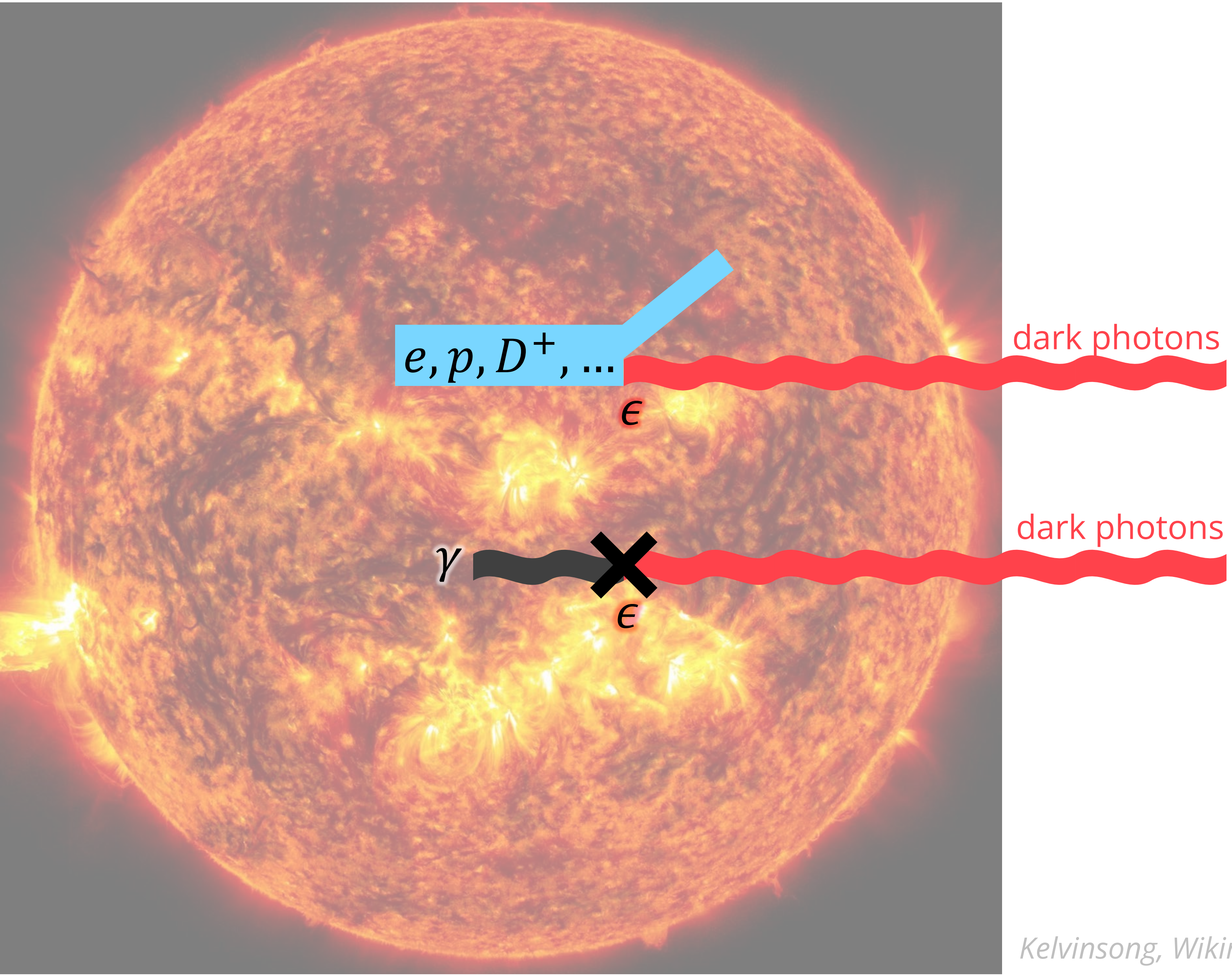
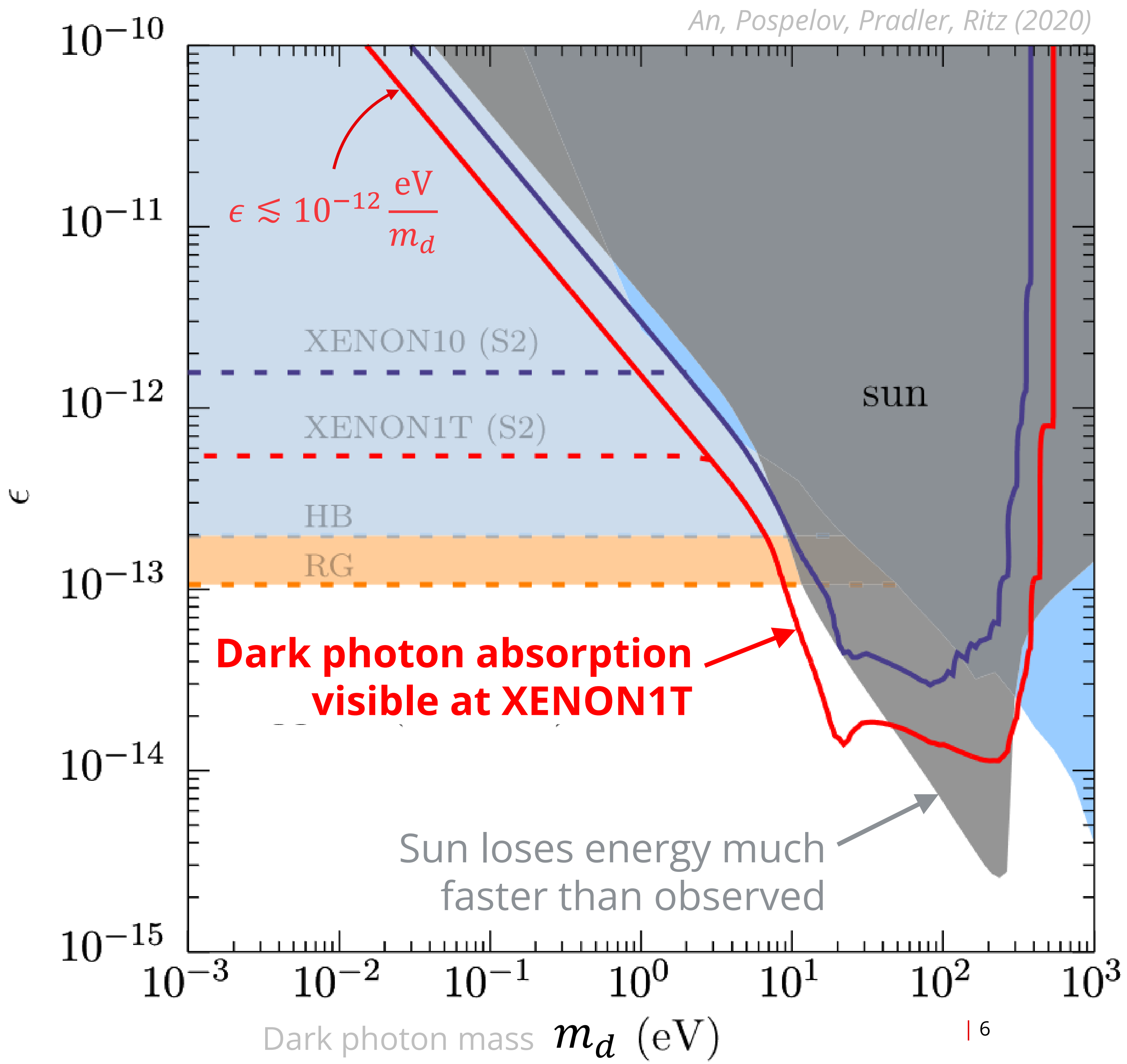



*Kelvinsong, Wikimedia*

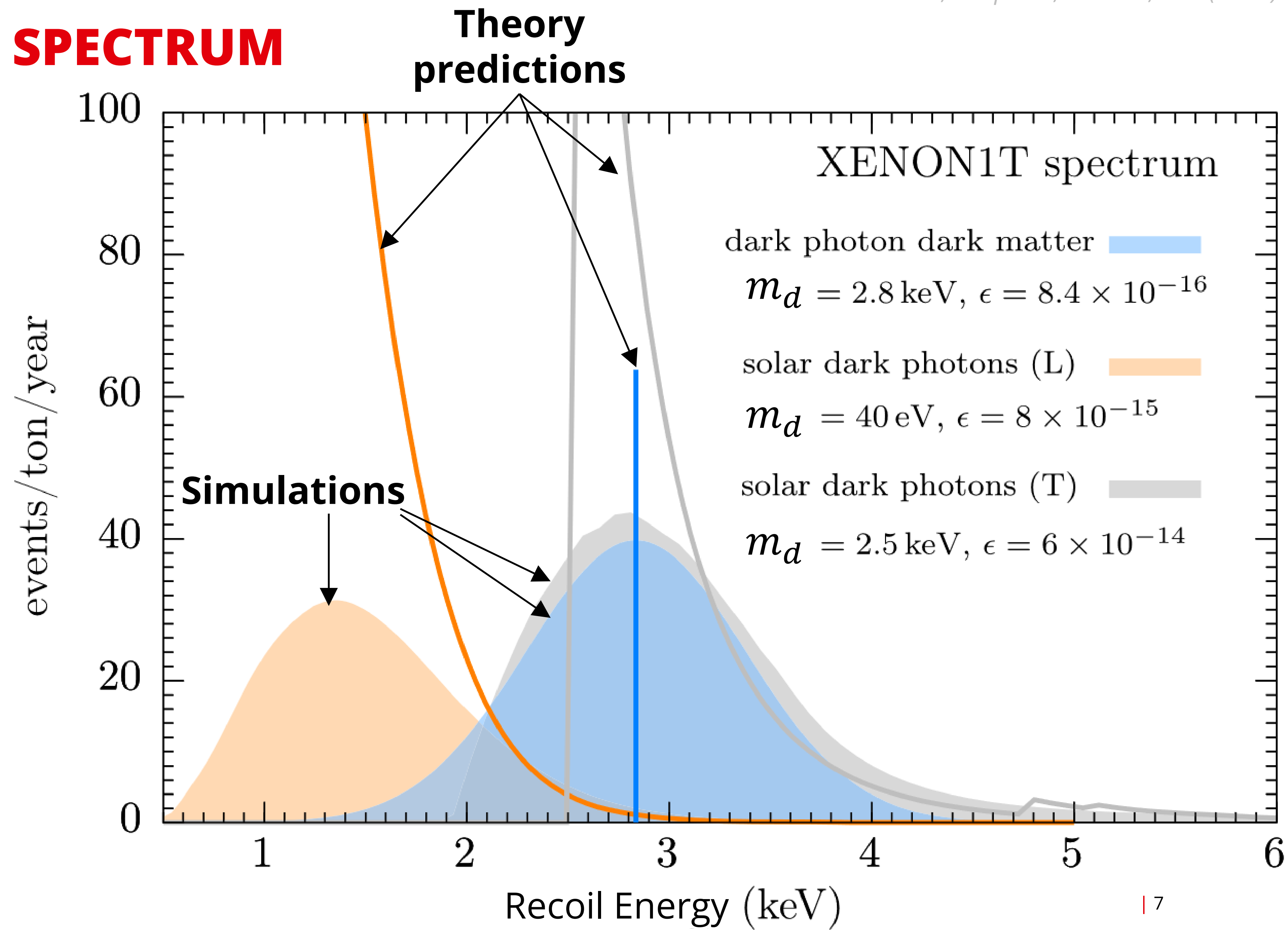
Two observable effects:

- Sun loses energy much faster than observed
- Dark photons can be absorbed in detectors

# SOLAR DARK PHOTONS



# RECOIL ENERGY SPECTRUM



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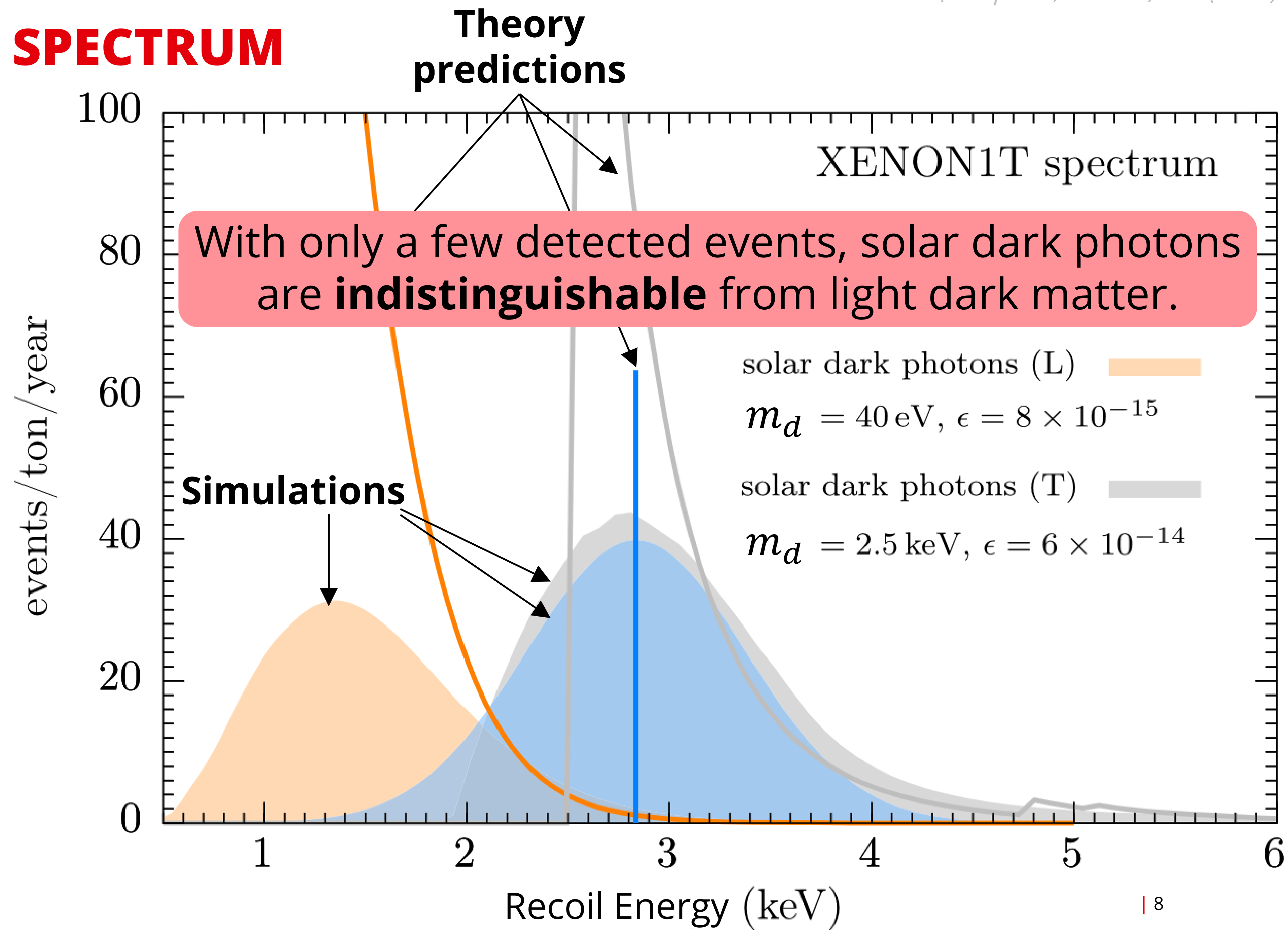


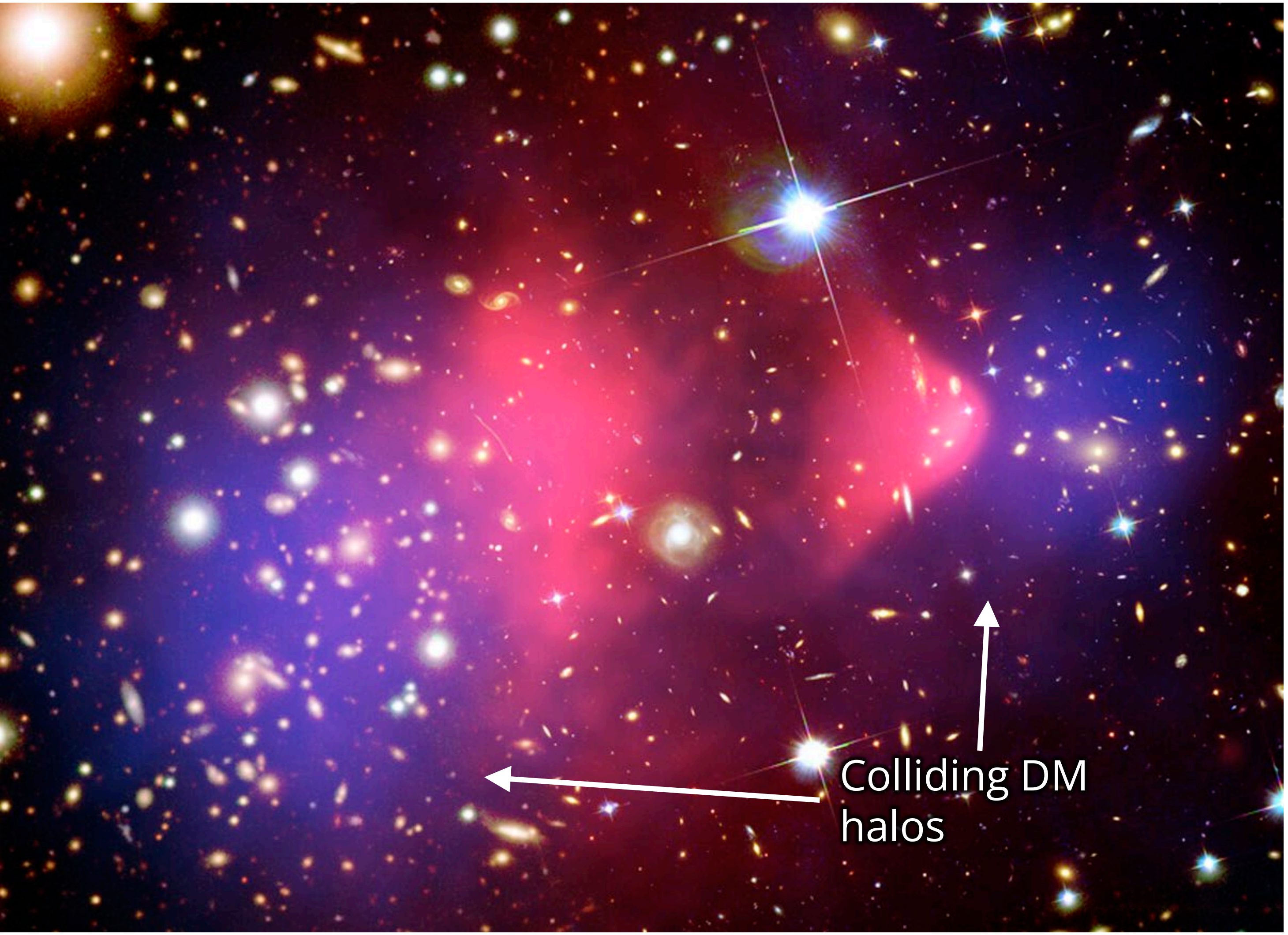
# DARK MATTER SELF-INTERACTION

Adhikari et al. (2022)
Zavala, Lovell, Vogelsberger, Burger (2019)
Correa (2021)


$$V_{\mathrm{DM-DM}} = \pm \frac{\alpha_d}{r} e^{-m_d r}$$

*Randall, Markevitch, Clowe, Gonzalez, Bradac (2008)*
*Markevitch et al. (2004)*

# BOUNDS ON DARK MATTER SELF-INTERACTION




**Bullet Cluster**
Observation of colliding DM halos

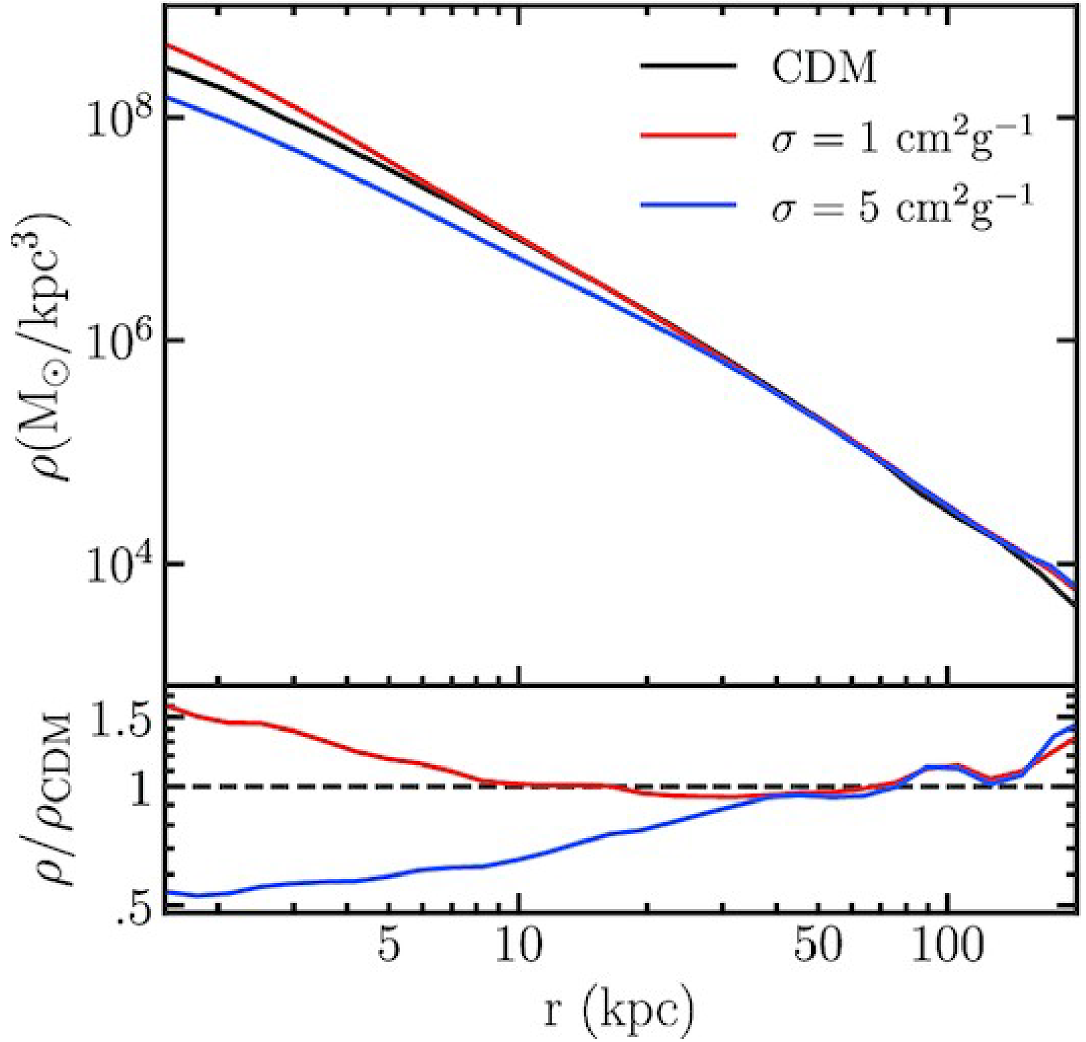
$$\frac{\sigma_T}{m_{DM}} \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$$

for $v = 1000$ km/s

# BOUNDS ON DARK MATTER SELF-INTERACTION

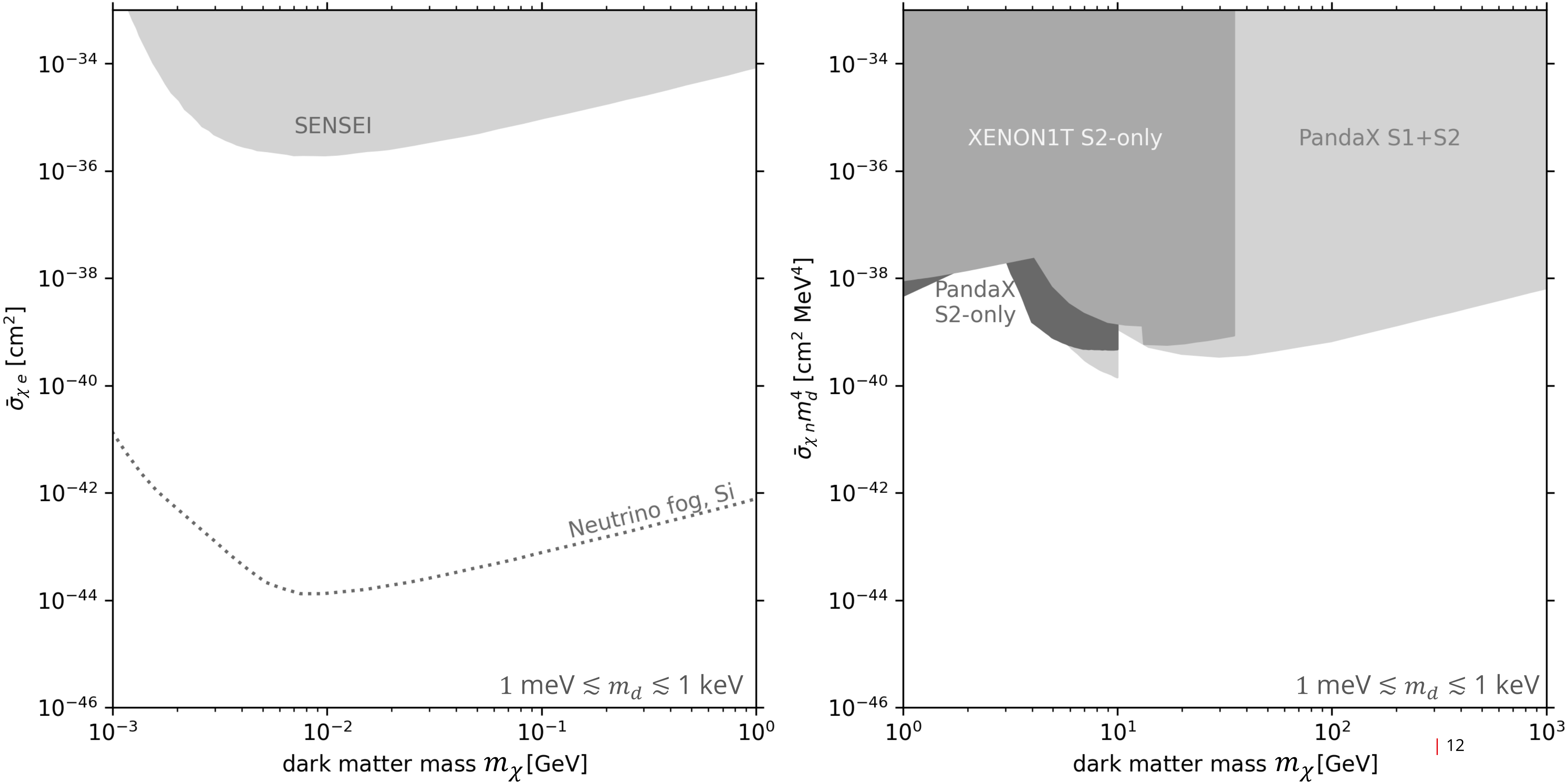
DM self-interaction affects matter distribution

*Silverman et al. (2022)*




$$\frac{\sigma_T}{m_{DM}} \lesssim 100\ \mathrm{cm^2/g} \quad \text{for } v = 10\ \text{km/s}$$

# DIRAC DARK MATTER



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SENSEI (2023), XENON (2019), PandaX (2018,2023)
Carew, Caddell, Maity, O'Hare (2024)
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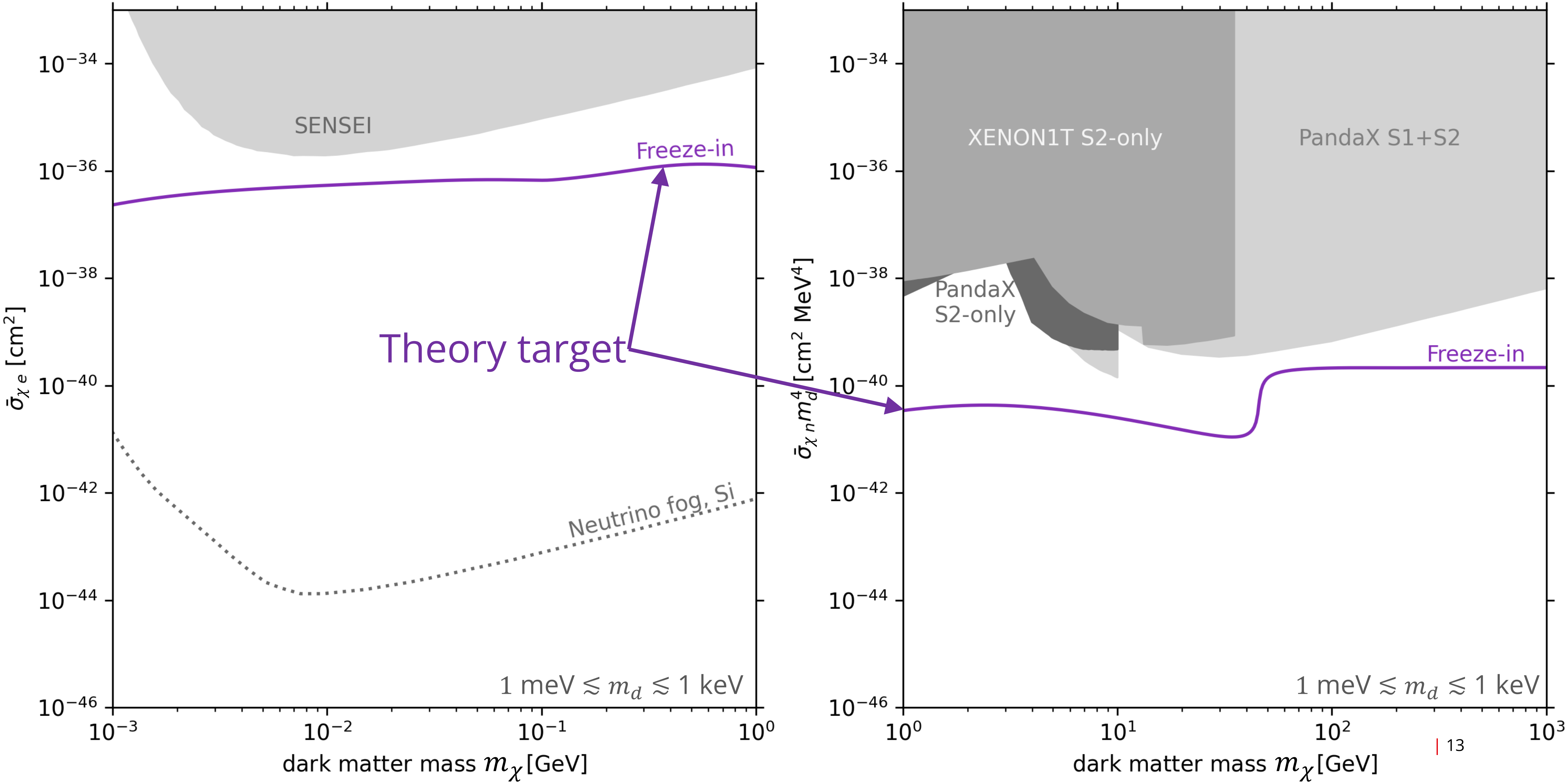

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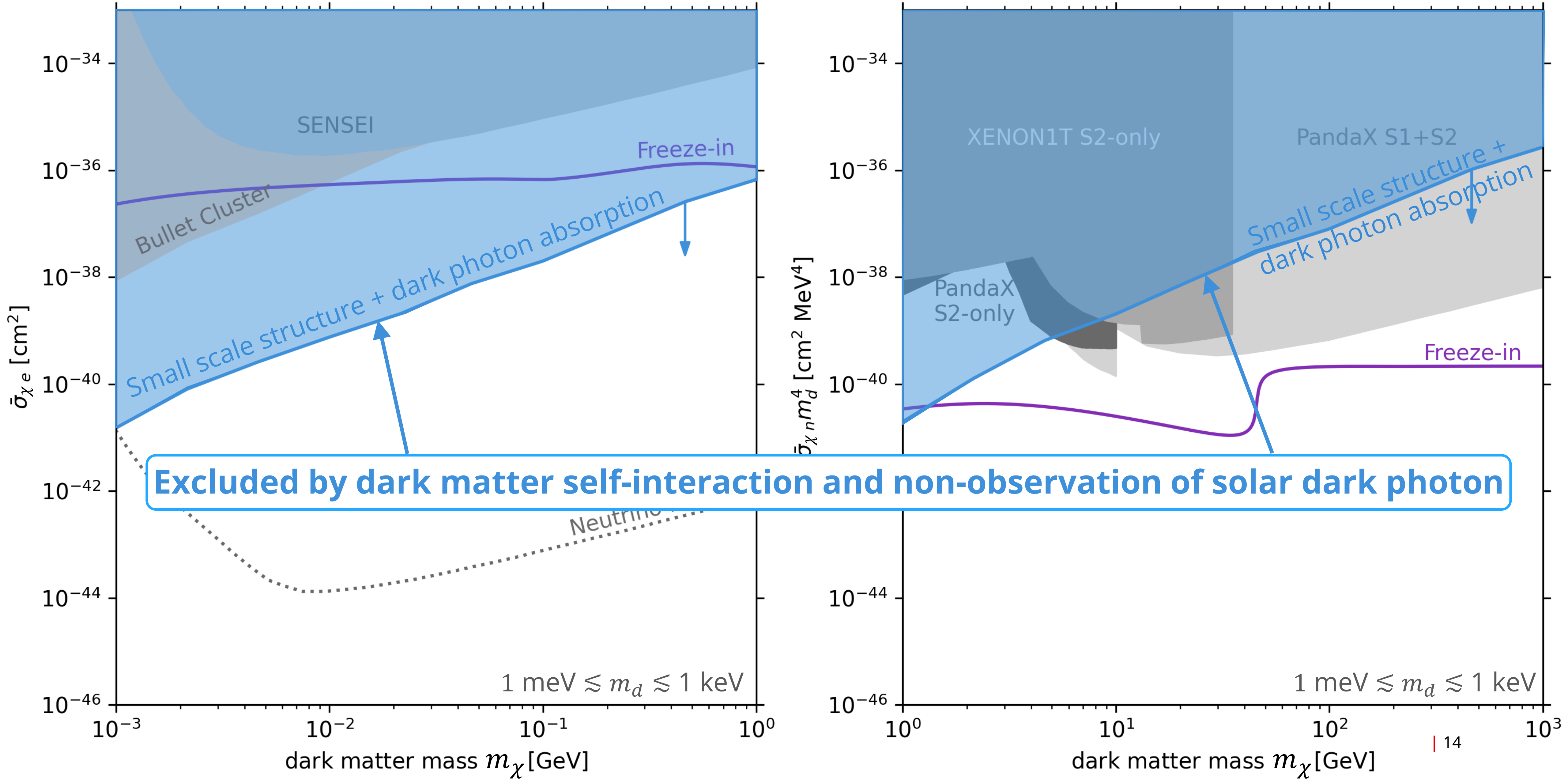

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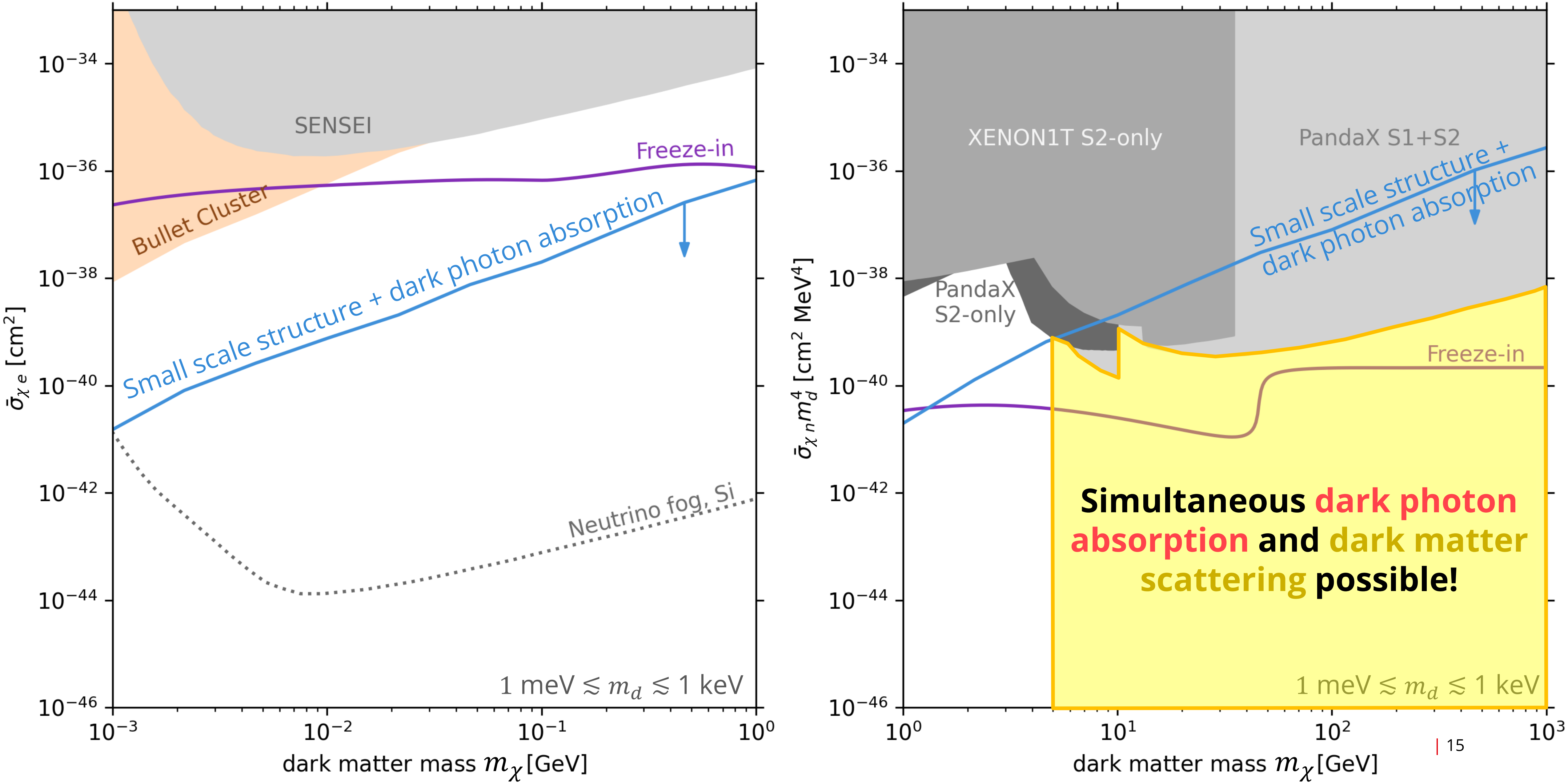
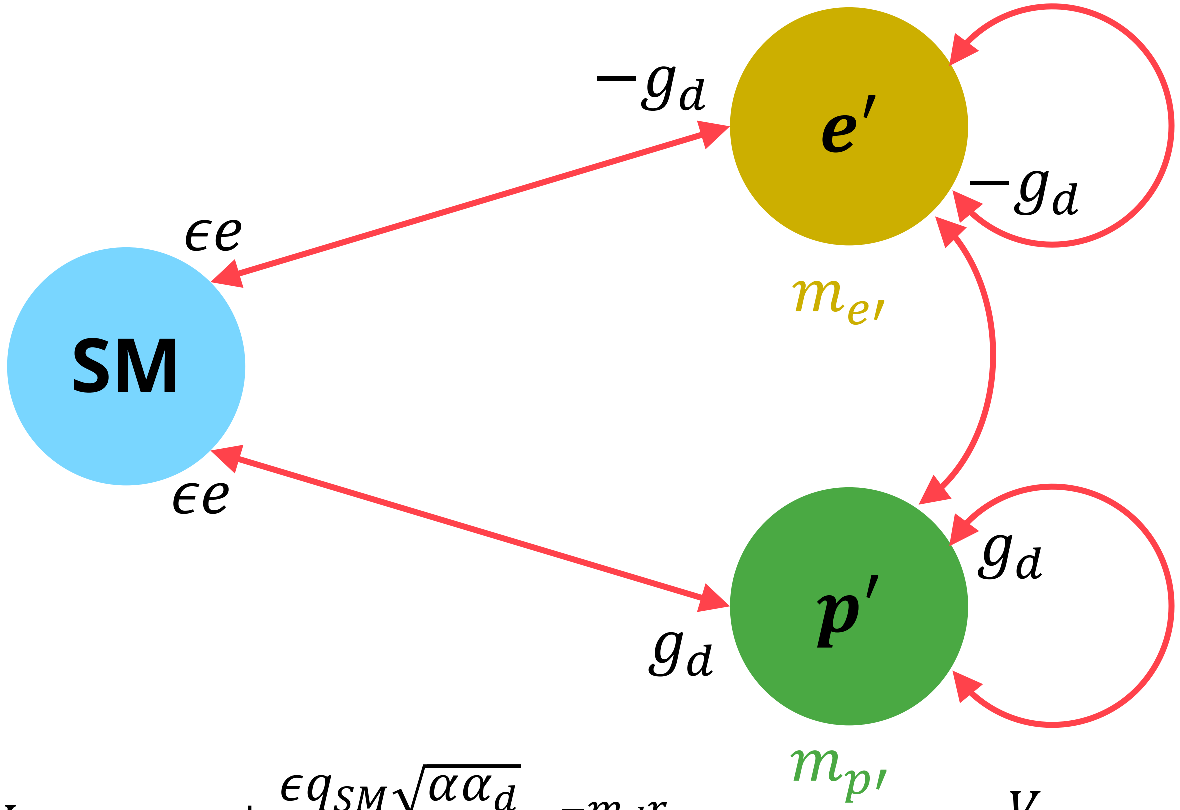


# ATOMIC DARK MATTER

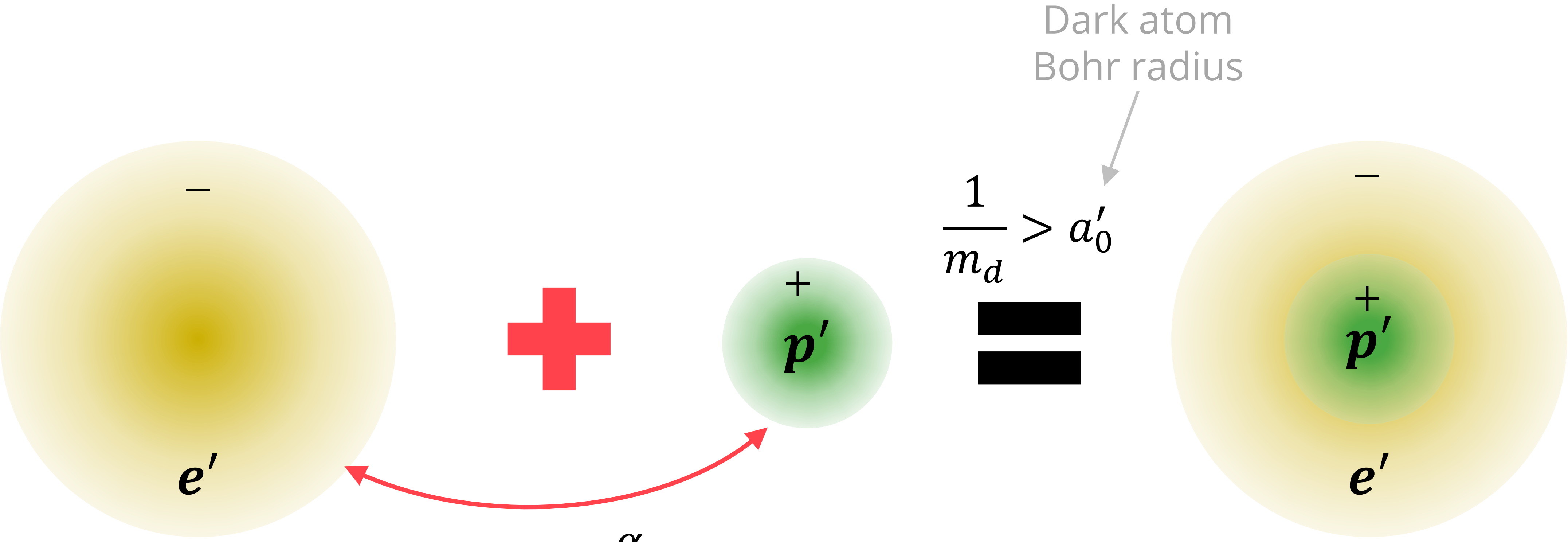
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \epsilon e j_{EM}^{\mu} A_{d,\mu} + \frac{m_d^2}{2} A_d^{\mu} A_{d,\mu} + \bar{e}'(i\gamma^{\mu}\partial_{\mu} - m_{e'})e' - g_d \bar{e}'\gamma^{\mu} e' A_{d,\mu}$$
$$+\bar{p}'(i\gamma^{\mu}\partial_{\mu} - m_{p'})p' + g_d \bar{p}'\gamma^{\mu} p' A_{d,\mu}$$




$$V_{\text{SM}-\text{DM}} = \pm \frac{\epsilon q_{SM}\sqrt{\alpha\alpha_d}}{r} e^{-m_d r}$$

$$V_{\text{DM}-\text{DM}} = \pm \frac{\alpha_d}{r} e^{-m_d r}$$

# ATOMIC DARK MATTER




$$V_{\mathrm{DM-DM}} = \pm \frac{\alpha_d}{r} e^{-m_d r}$$

Neutral dark atom

We require that neutral dark atoms dominate the DM abundance today

# COSMOLOGICAL EVOLUTION

*Kaplan, Krnjaic, Rehermann, Wells (2010)*
*Cyr-Racine, Sigurdson (2013)*
*Cline, Liu, Moore, Xue (2014)*
*Cline (2022)*

Dark atom binding energy

Hubble parameter

$T \sim m_{p'}/20$ | $T \sim m_{e'}/20$ | $T \sim B_{H'}$ | $\Gamma_{e'p' \to H' A_d} \lesssim H$ | time

Dark sector in thermal equilibrium

$e'\bar{e}' \leftrightarrow A_d A_d$

$p'\bar{p}' \leftrightarrow A_d A_d$

$p'$ freezes-out

$p'\bar{p}' \to A_d A_d$

$e'$ freezes-out

$e'\bar{e}' \to A_d A_d$

$e'$ and $p'$ "re"combine

$e' + p' \to H' + A_d$

$H'$ freezes-out

Ionization fraction $\quad f_i \equiv \dfrac{n_{e'}}{n'_e + n_{H'}} \approx \min\left[1, 10^{-10} \dfrac{T_{\text{dark}}}{T_{\text{CMB}}} \alpha_d^{-4} \dfrac{m_{e'}}{m_{p'}} \left(\dfrac{m_{H'}}{\text{GeV}}\right)^2\right]$

Ghalsasi, McQuinn (2018)
Cline (2022)

# REIONIZATION

- Dark atoms can be ionized at late time due to virialization → strong self-interaction
- We require no reionization at late time

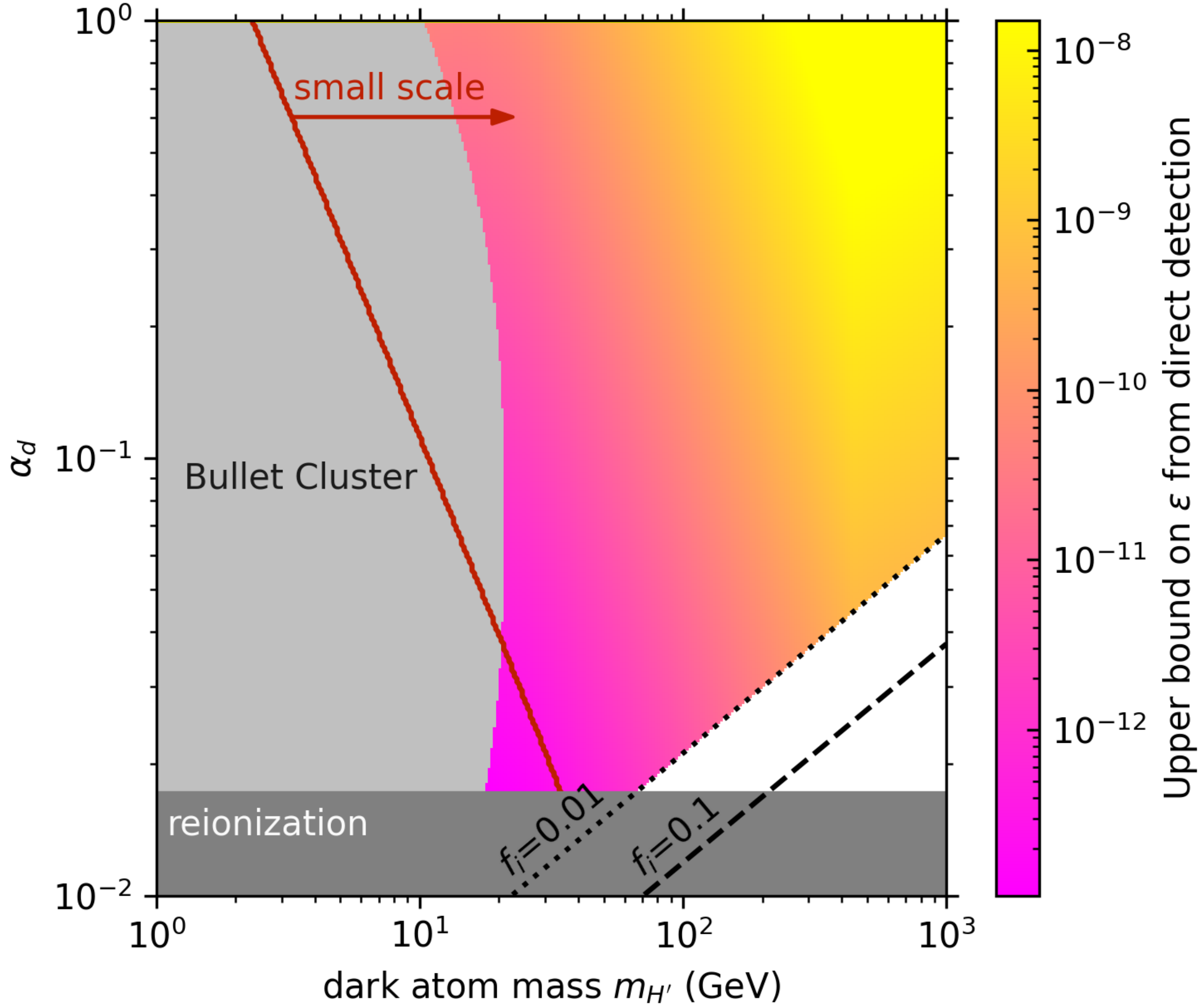
$$T_{\text{virial}} \sim G M_{\text{halo}}^{2/3} \rho_{DM}^{1/3} m_{H'} (1+z) \lesssim 0.1\, B_{H'}$$

$$\Big\downarrow$$

$$\alpha_d \gtrsim 1.4 \times 10^{-3} \sqrt{\frac{m_{p'}}{m_{e'}}}$$

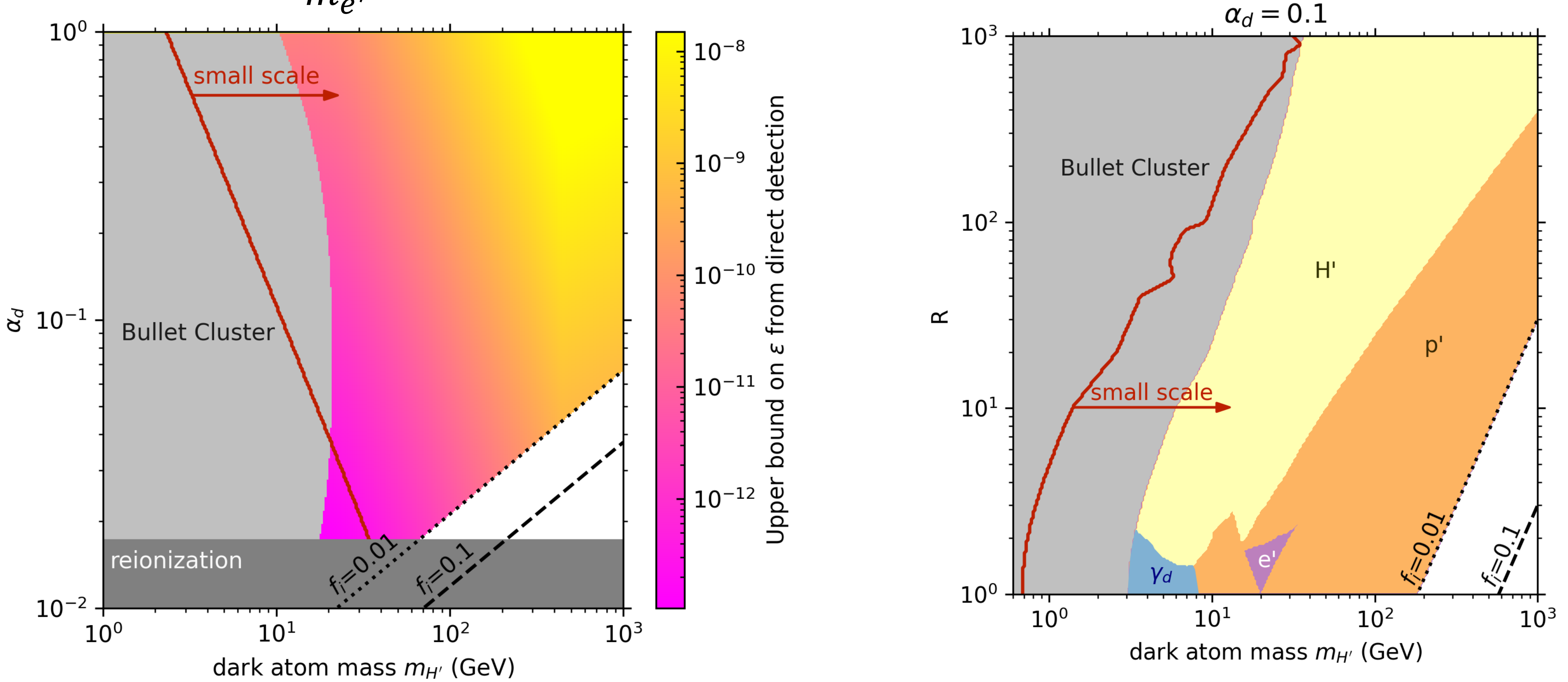
# RESULTS

$$\frac{m_{p'}}{m_{e'}} = 150$$



# RESULTS

$$R = \frac{m_{p'}}{m_{e'}} = 150$$



# RESULTS

## Electron scattering

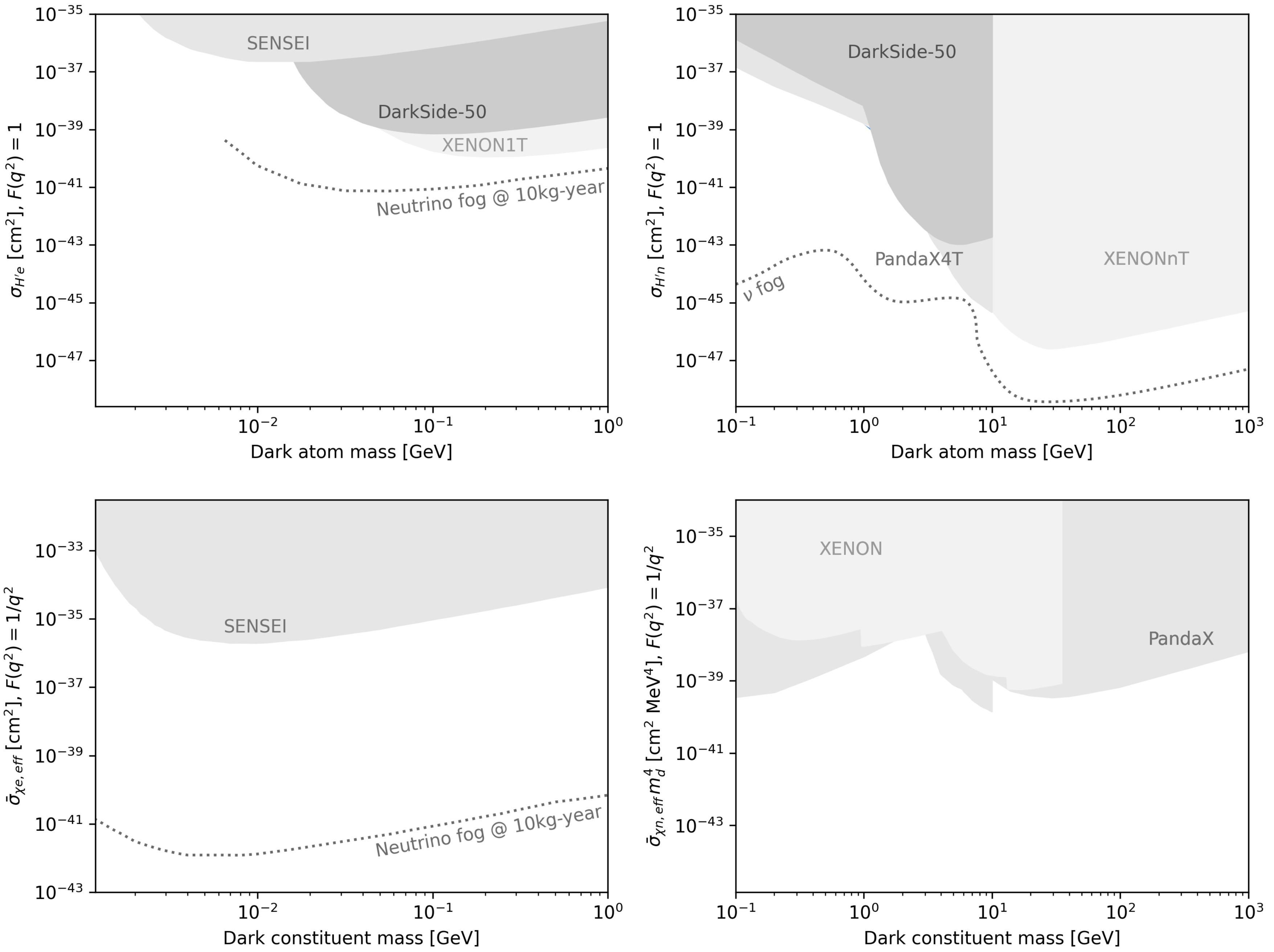
## Nucleon scattering

## Dark atom searches

(Point-like interaction)

## $e', p'$ searches

(Long-range interaction)



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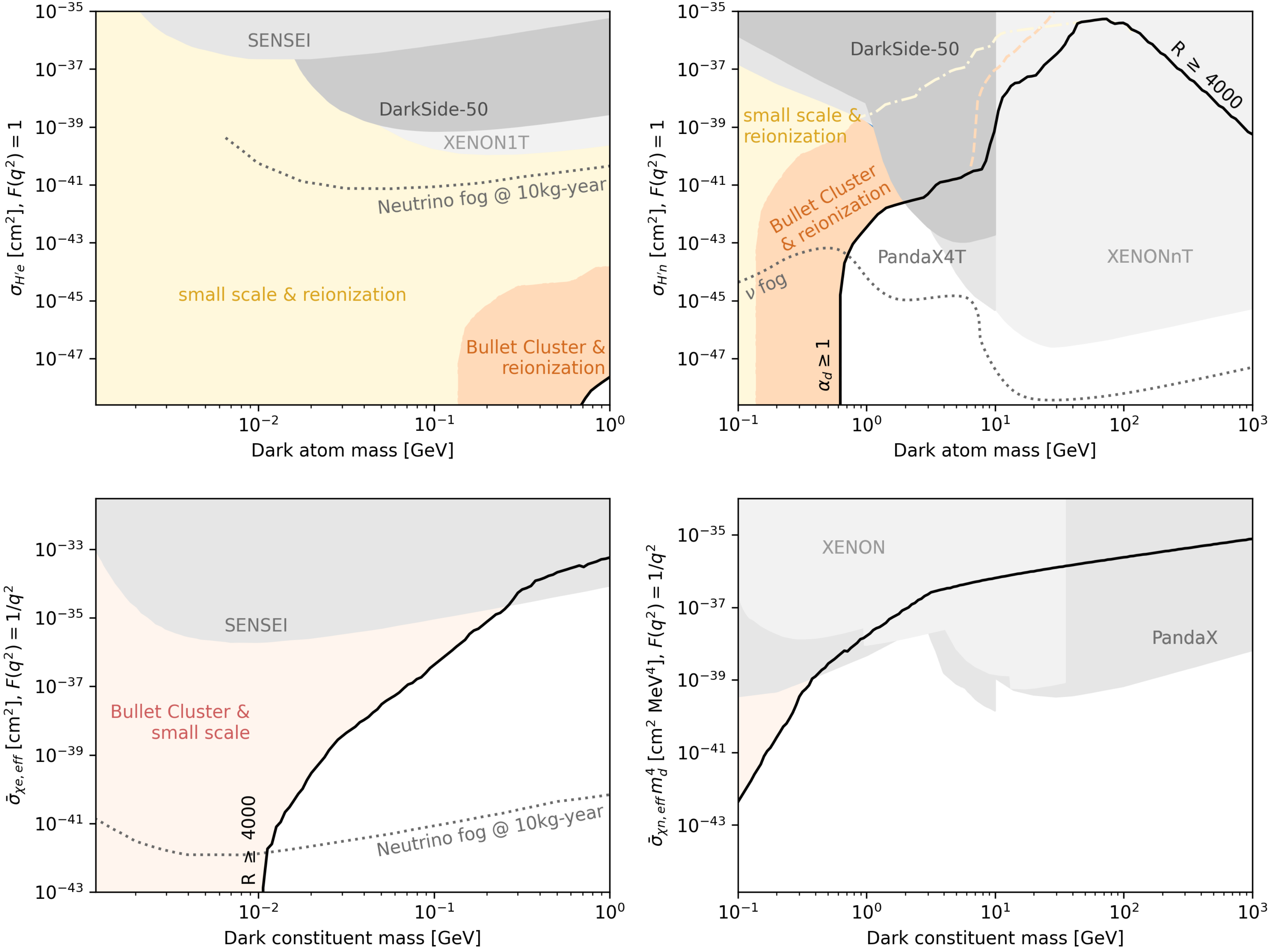

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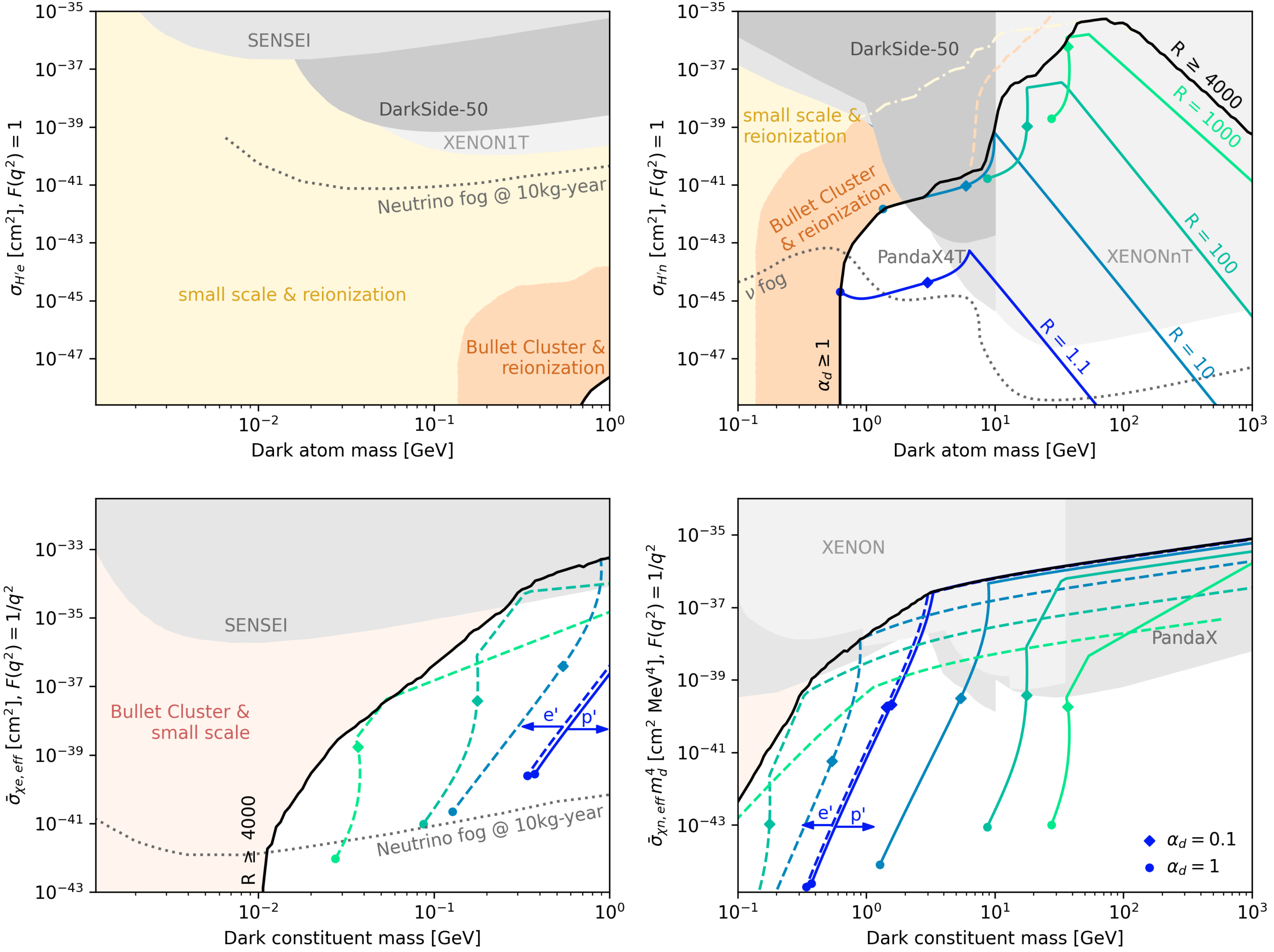

# Conclusions

- Astrophysics complements direct detection searches for dark matter with light mediators.
- For Dark Photon Mediated Dark Matter, **scattering and absorption can be observed simultaneously**. Astrophysics allows for freeze-in for $m_\chi \gtrsim 1$ GeV.
- Determining the underlying model from data requires care when interpreting the various signals.
- Detecting multiple signatures can help pinning down the dark matter model.

**Thank you for listening!**

# BACKUP SLIDES

# DIRAC DARK MATTER

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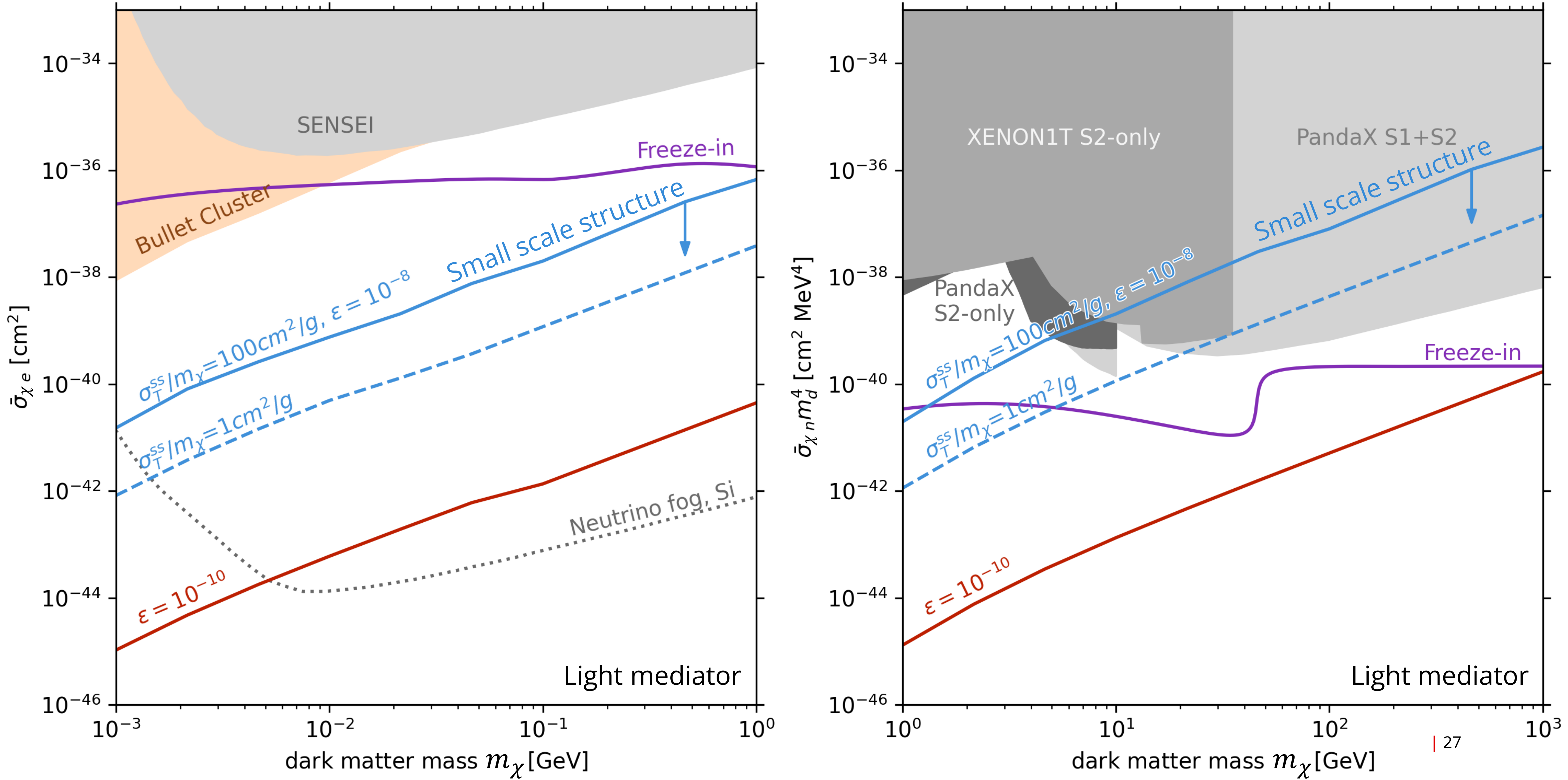

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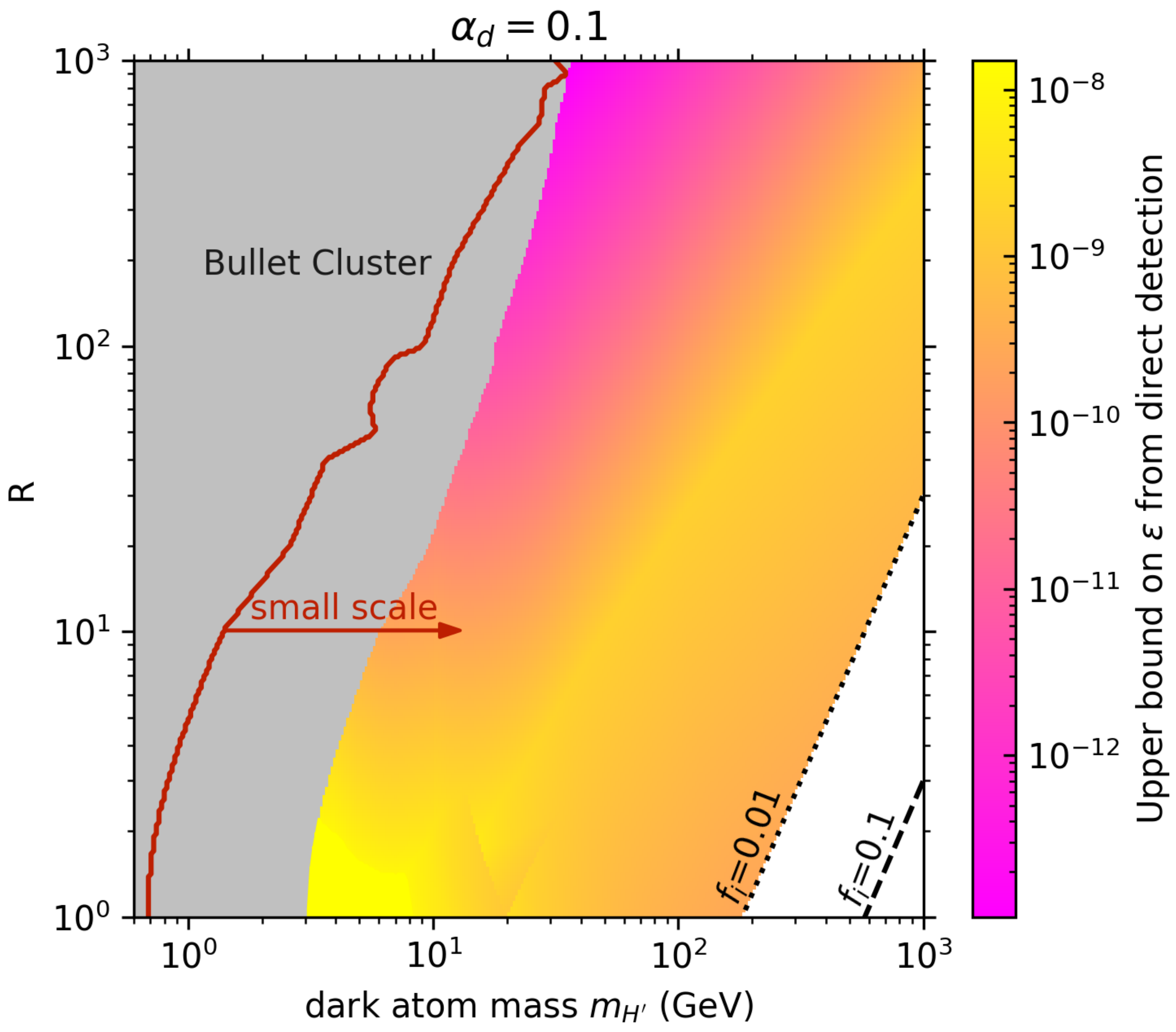
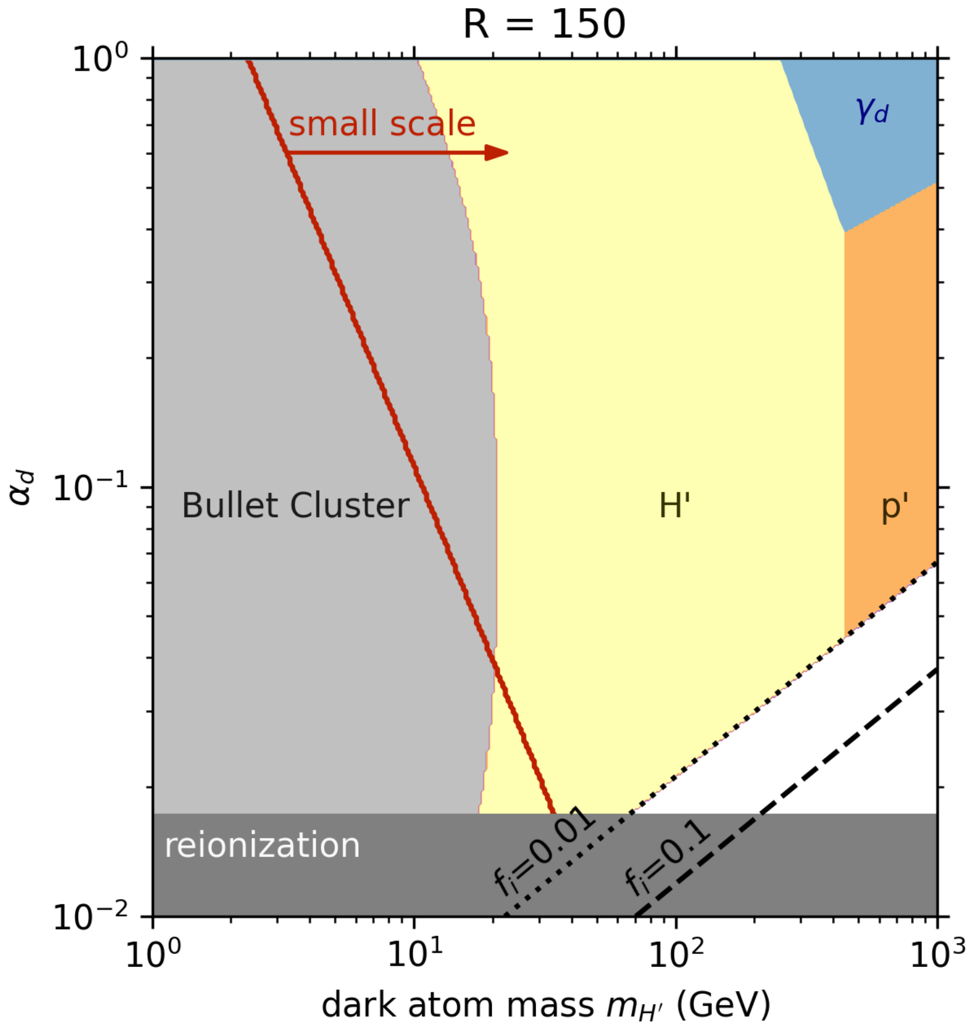


$\alpha_d = 0.1$
Bullet Cluster
small scale
$f_i$=0.01
$f_i$=0.1
R
dark atom mass $m_{H'}$ (GeV)
Upper bound on $\epsilon$ from direct detection

R = 150
small scale
$\gamma_d$
Bullet Cluster
H'
p'
reionization
$f_i$=0.01
$f_i$=0.1
$\alpha_d$
dark atom mass $m_{H'}$ (GeV)

# SCATTERING CROSS SECTIONS

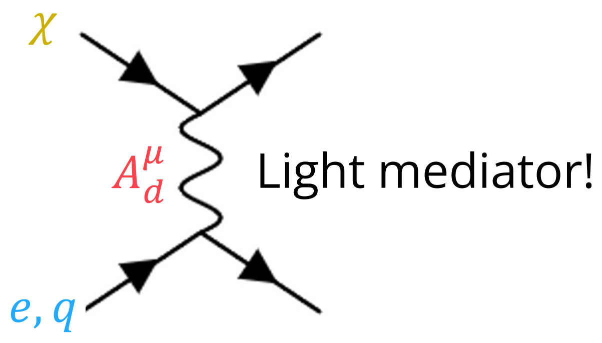
Dark constituents - nucleon scatterings

$$\bar{\sigma}_{\chi n,\mathrm{eff}} m_d^4 = 2.4 \times 10^{-34}\ \mathrm{cm}^2 \mathrm{MeV}^4 \left(\frac{\alpha_d}{0.1}\right) \left(\frac{\epsilon}{10^{-8}}\right)^2 \left(\frac{\mu_{\chi p}}{m_p}\right)^2 \left(\frac{m_\chi}{m_{H'}}\right) f_i(m_{H'}, R, \alpha_d)$$

Dark atom - nucleon scatterings

$$\sigma_{H'n}^{\mathrm{el}} = 7.8 \times 10^{-36}\ \mathrm{cm}^2 \left(\frac{R}{10^3}\right)^4 \left(\frac{0.04}{\alpha_d}\right)^3 \left(\frac{\epsilon}{10^{-8}}\right)^2 \left(\frac{50\ \mathrm{GeV}}{m_{H'}}\right)^4$$

# DARK MATTER DIRECT DETECTION




$$\mathcal{M} = \frac{e q_f \epsilon g_d}{q^2 - m_d^2} \bar{f} \gamma^\mu f \; \bar{\chi} \gamma_\mu \chi$$


$$\bar{\sigma}_e = 16 \pi \alpha \alpha_d \epsilon^2 \frac{\mu_{e\chi}^2}{\left(m_d^2 + q_{\mathrm{ref}}^2\right)^2}$$

$$q_{\mathrm{ref}} = \alpha m_e$$

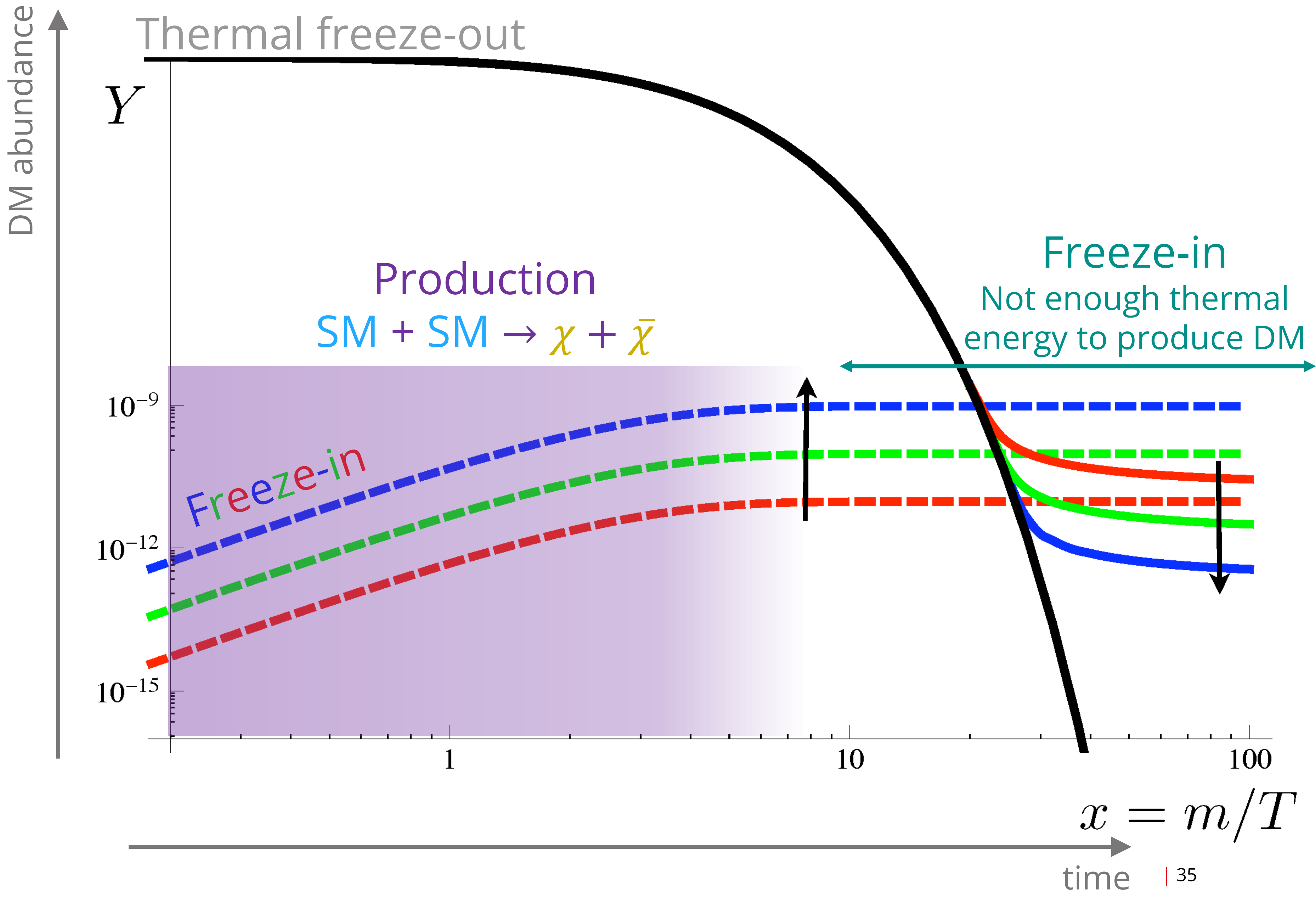
$$\mu_{f\chi} = \frac{m_f m_\chi}{m_f + m_\chi}$$

$$\alpha_d = g_d^2 / 4\pi$$


$$\bar{\sigma}_n = 16 \pi \alpha \alpha_d \epsilon^2 \frac{\mu_{p\chi}^2}{m_d^4} \left(\frac{Z}{A}\right)^2$$

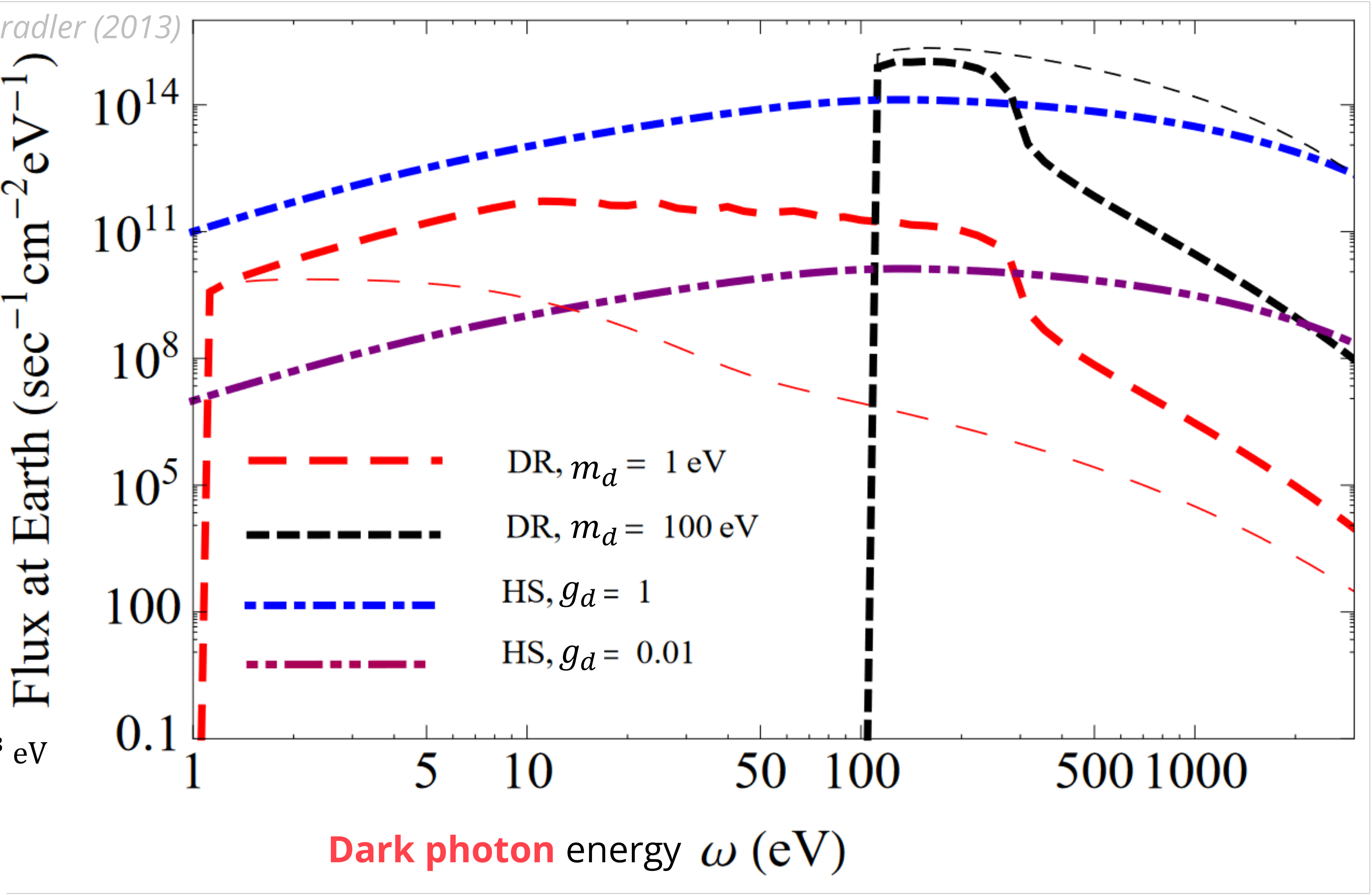
Hall, Jedamzik, March-Russell, West (2010)
Lin (2019)

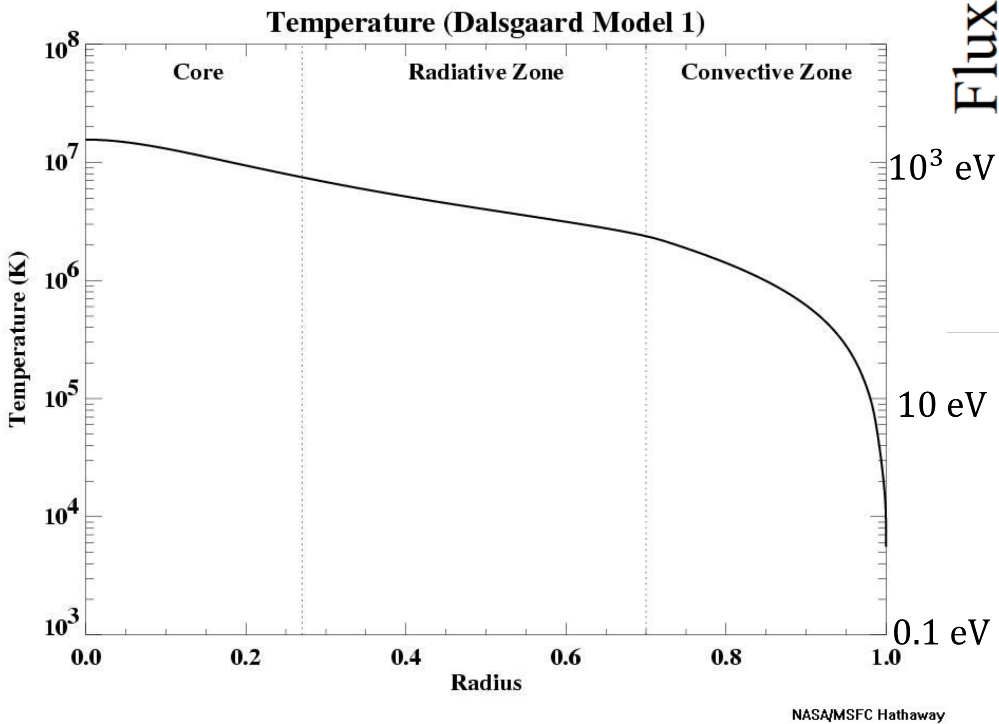
# DARK MATTER FREEZE-IN



# STELLAR PRODUCTION

An, Pospelov, Pradler (2013)



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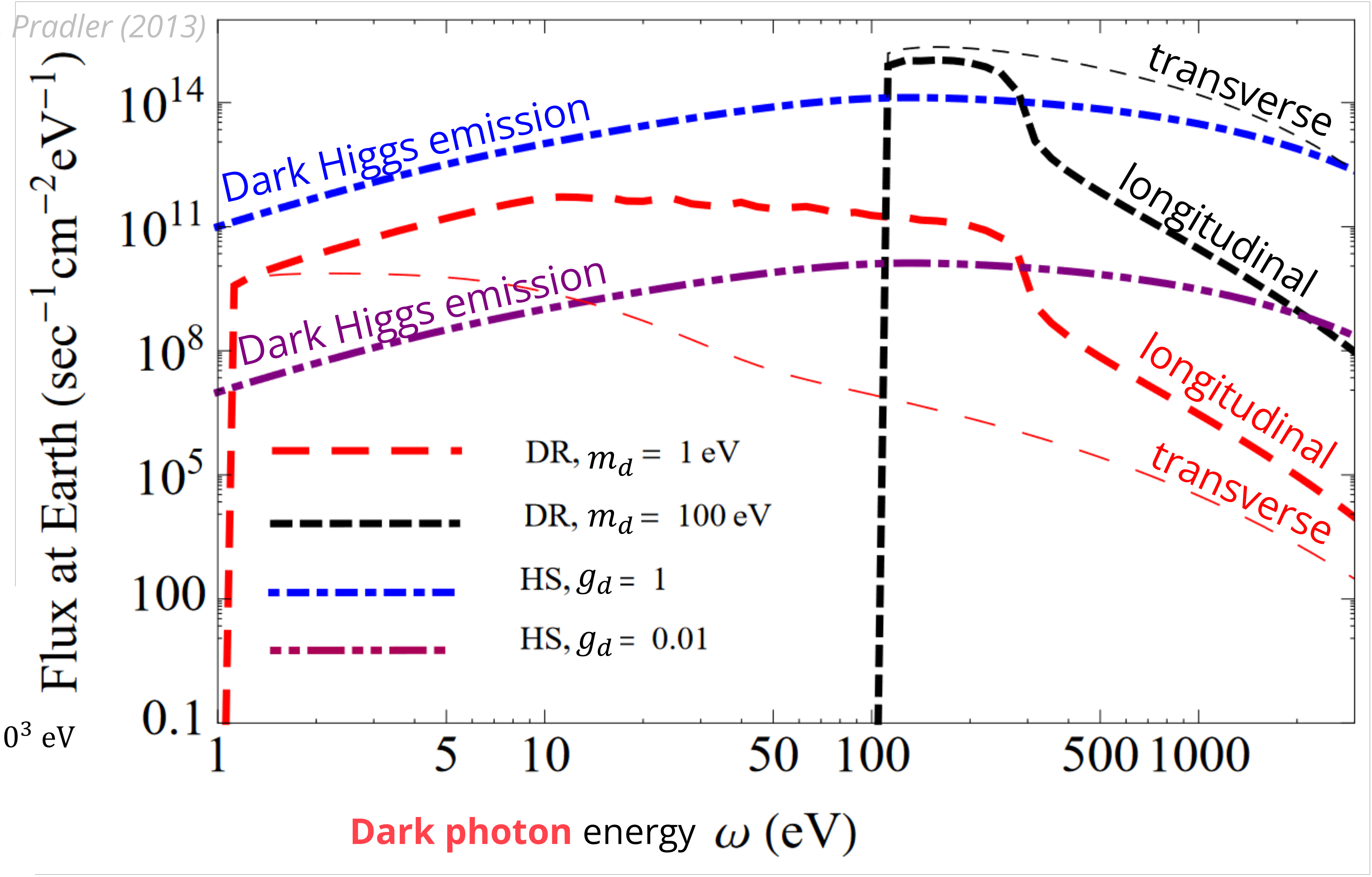


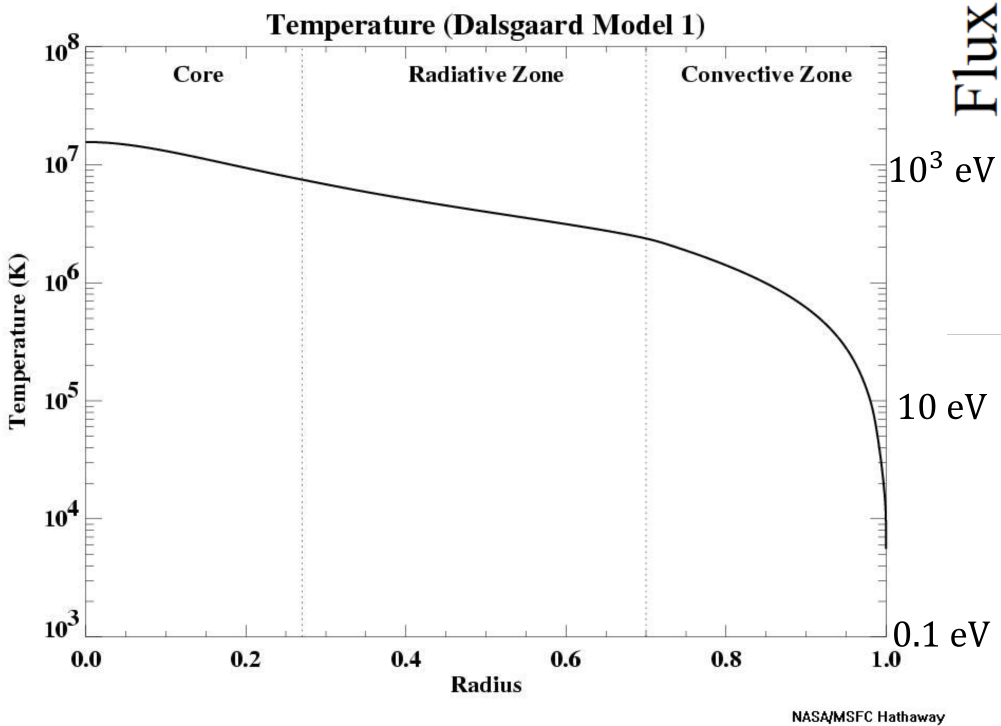


with dark Higgs: $\text{Rate}_{A_d h_d} \propto \alpha_d \epsilon^2$

transverse: $\text{Rate}_{A_{d,T}} \propto \begin{cases} \epsilon^2 m_d^4 \omega_p^{-4} & \text{if } m_d \ll \omega_p \\ \epsilon^2 & \text{if } m_d \gg \omega_p \end{cases}$

longitudinal: $\text{Rate}_{A_{d,T}} \propto \epsilon^2 m_d^2 \omega^{-2}$