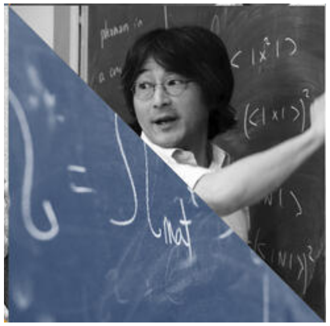
# Will we see light dark matter?

**Aaron Pierce**
**Leinweber Center for Theoretical Physics**
**University of Michigan**



Bhattiprolu, McGehee, Petrosky, AP, 2408.07744 [hep-ph];
Bhattiprolu, McGehee, AP, *Phys.Rev.D* 110 (2024) 3, L031702 2312.14152;
Bhattiprolu, Elor, McGehee, AP *JHEP* 01 (2023) 128 2210.15653;
see also: Elor, McGehee, AP,
*Phys.Rev.Lett.* 130 (2023) 3, 031803 2112.03920;

**in Celebration of Lawrence and Hitoshi**

Work supported via DoE

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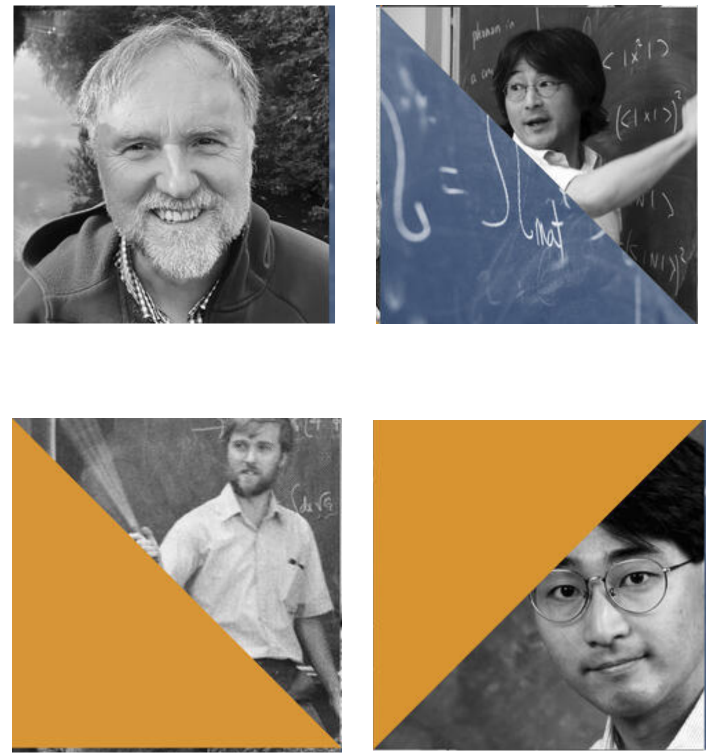

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# Topics in Berkeley Grad school

- Neutralino Dark Matter
- SUSY GUTs and flavor
- SUSY Proton Decay
- Anomaly Mediation
- MSSM Baryogenesis
- Leptogenesis
- mu-problem (with Lawrence + Yasunori)
- Extra  Dimensions!

# The LBL lunch crowd

- Neal Weiner
- David Tucker-Smith
- Jay Wacker
- Takemichi Okui
- Thomas Gregoire
- Brent Nelson (MKG)
- Roni Harnik
- C. Grojean
- W. Goldberger
- Yasunori Nomura
- M. Perelstein
- G. Burdman
- Z. Chacko

Hitoshi Promotion party: We should have a party, because after this, there may not be any more milestones to celebrate….

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"I firmly believe that basic scientific research is a true peacemaker for humankind."

2014

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P5

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IPMU — 2007


"I firmly believe that basic scientific research is a true peacemaker for humankind."

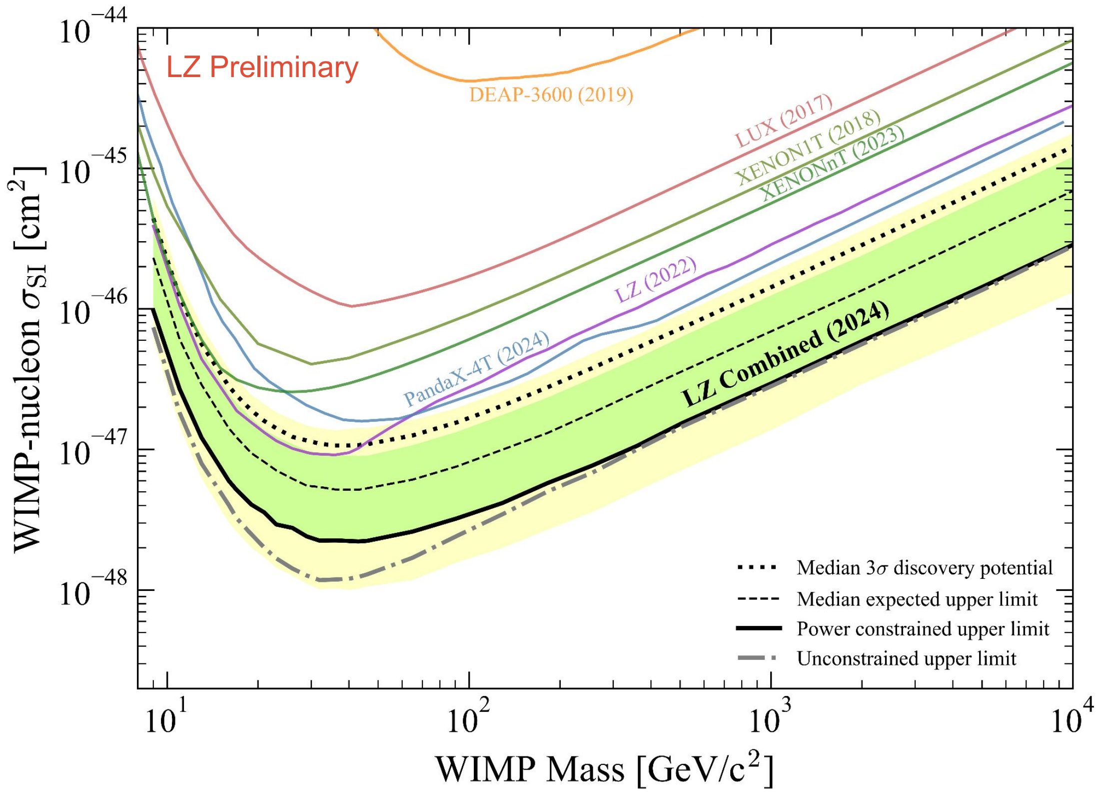
2014

P5

# Outline

- Light(er) Dark Matter
- Dark Matter Freeze-in
- Modifying Freeze-in
  - Low-reheat temperatures
  - Dark Sinks

# WIMP bounds very strong
## LZ (TevPA)

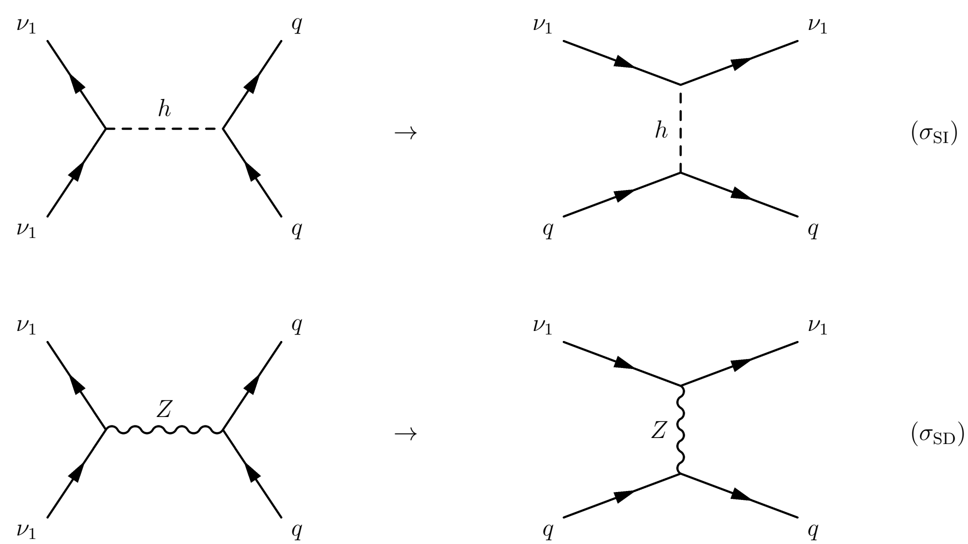



Scott Haselschwardt
LBL-> UMich

# “Wimps with a capital W”

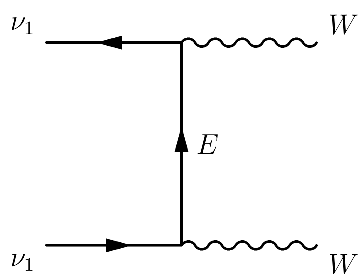
## Singlet-Doublet Model (binos+higgsinos)

$$\Delta\mathcal{L} = -\lambda DHS - \lambda' D^c \tilde{H} S - M_D D D^c - \frac{1}{2} M_S S^2 + \text{ h.c.},$$

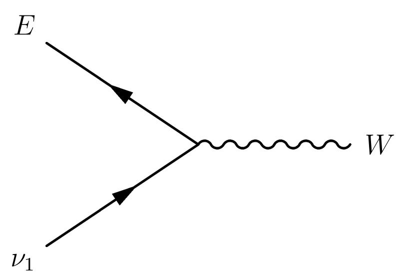



Arkani-Hamed, Dimopoulos, Kachru,
hep-th/0501082

# Other options




$\rightarrow$ No tree-level direct detection analog

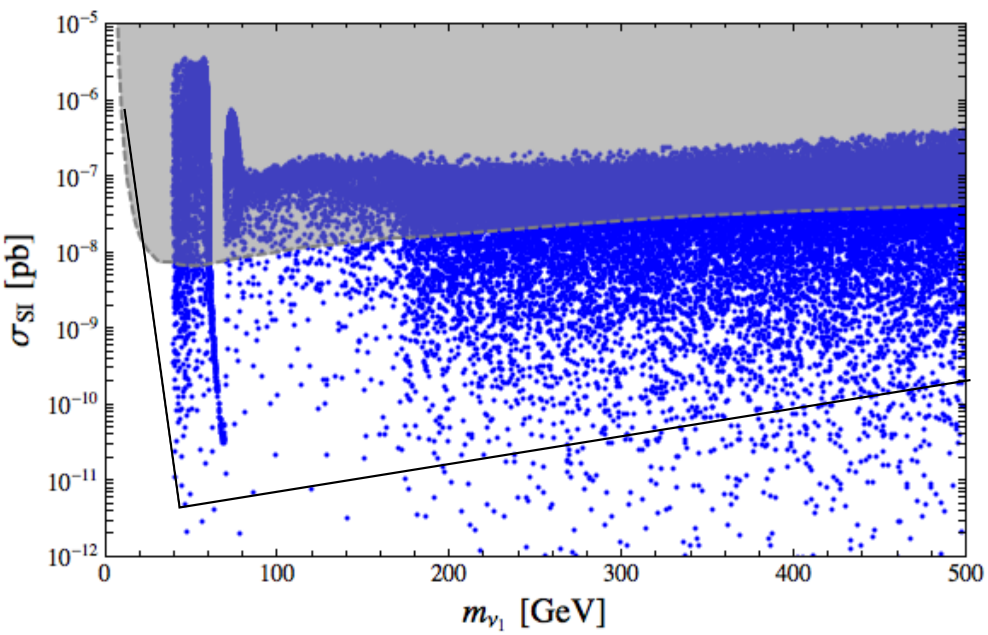


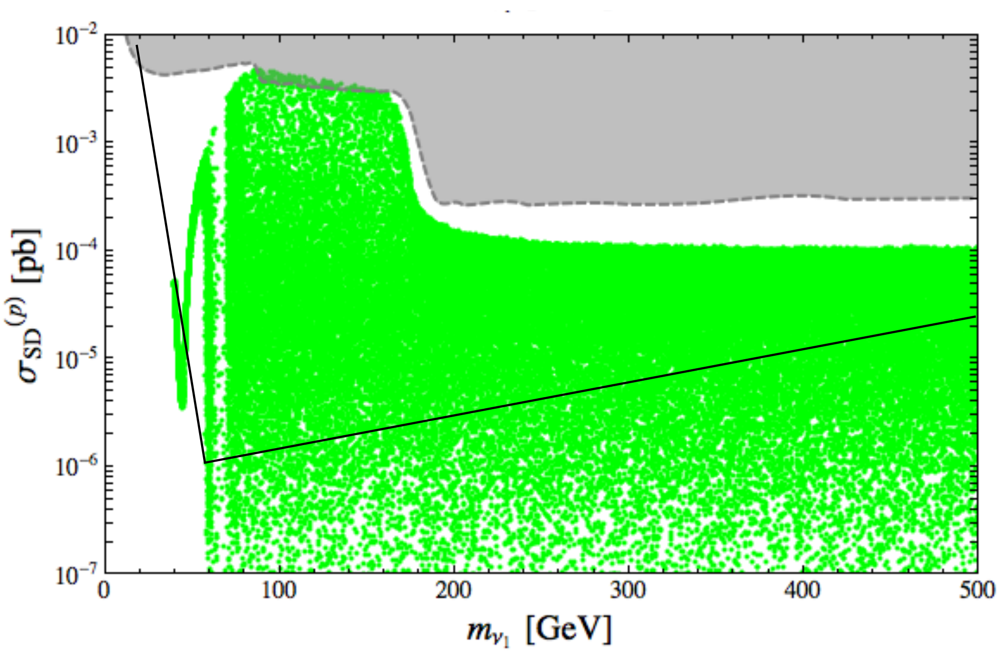

$\rightarrow$ No tree-level direct detection analog

# Singlet-Doublet Model

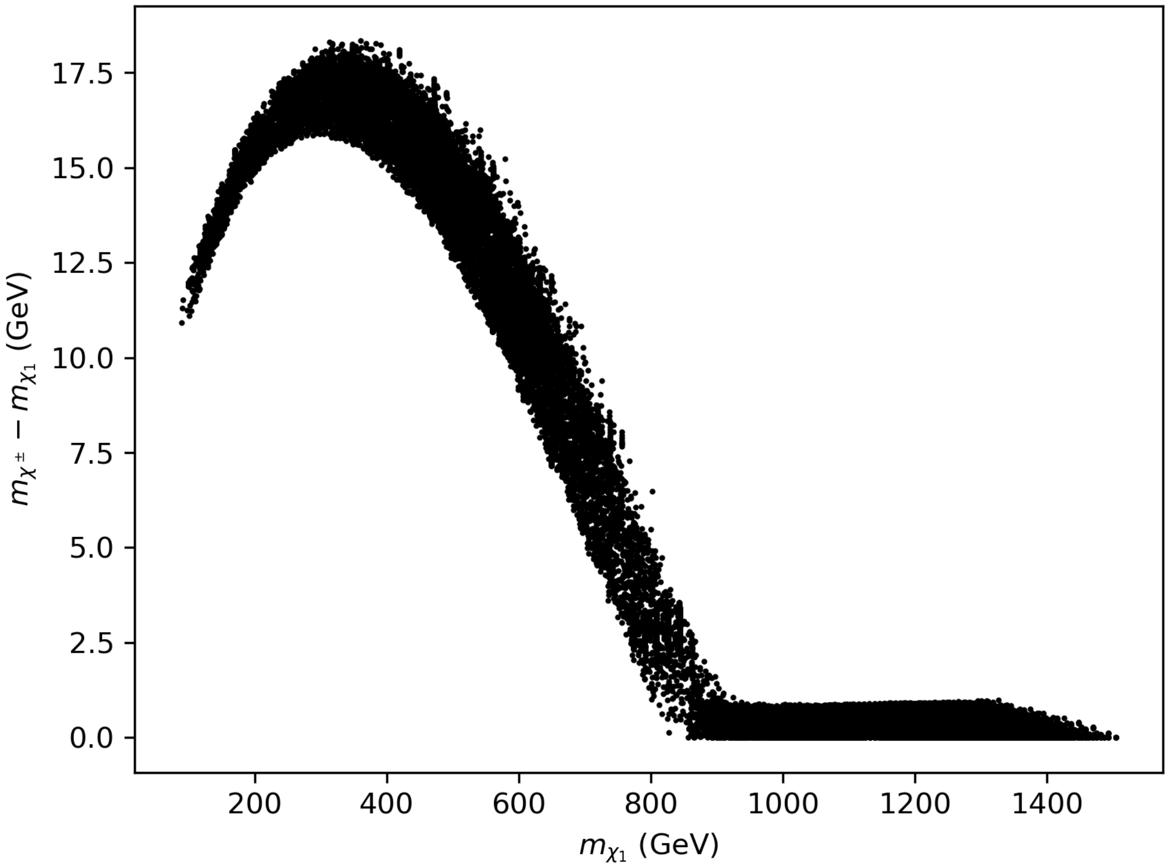
Cohen, Kearney, AP, David Tucker-Smith, *Phys.Rev.D* 85 (2012) 075003

$$\Delta\mathcal{L} = -\lambda DHS - \lambda' D^c \tilde{H} S - M_D D D^c - \frac{1}{2} M_S S^2 + \text{ h.c.},$$



# Last refuge of WIMPS?




Bhattiprolu, Petrosky, AP

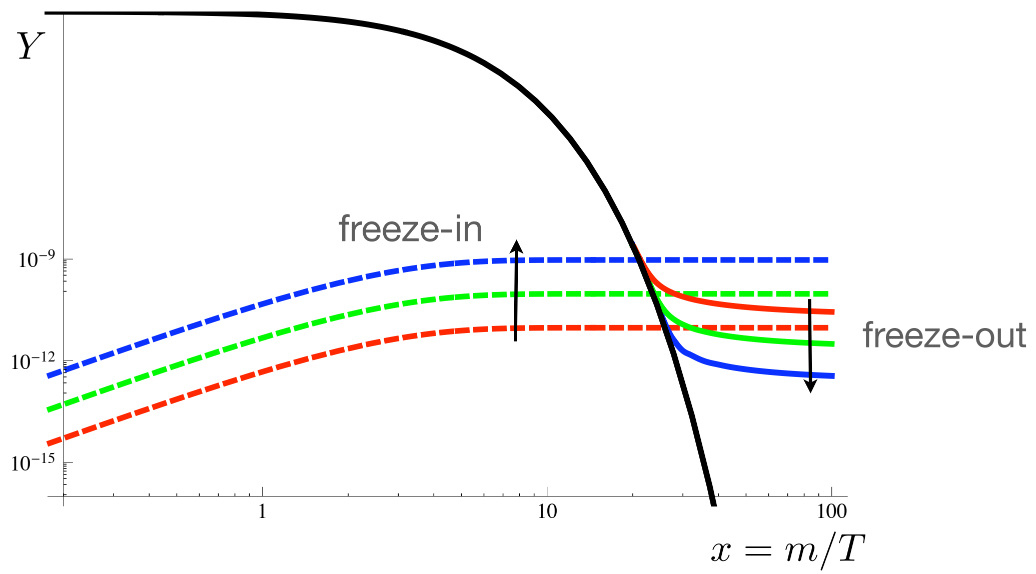
Preliminary

# Light dark matter?

- In response to the downward march of these limits, a lot of effort has been put in to thinking about dark matter in the sub-GeV regime.

| Experimental side | Theory side |
|---|---|
| Nuclear recoils: Light Hadrophilic DM<br><br>Electron Recoils: take advantage of mass matching | How would sub-GeV dark matter come to be? |

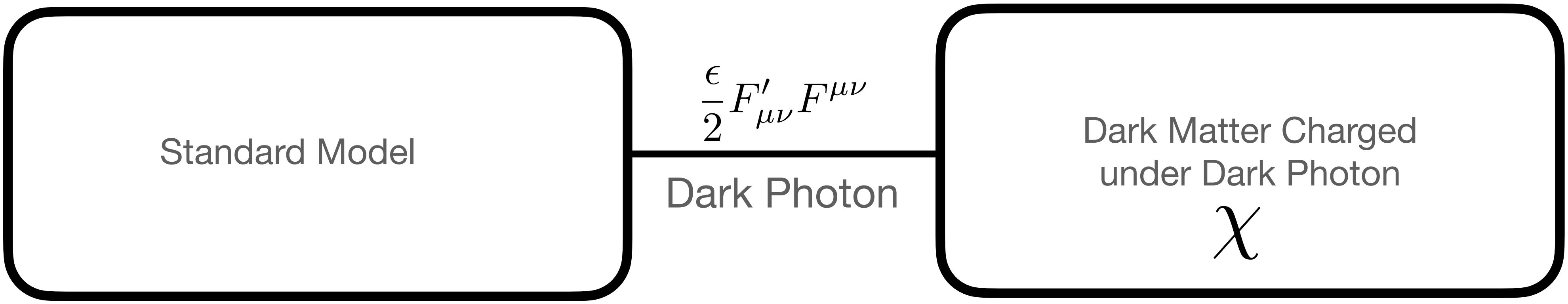
# Freeze-in of Dark Matter




- Hall, et al, JHEP 1003:080,2010.

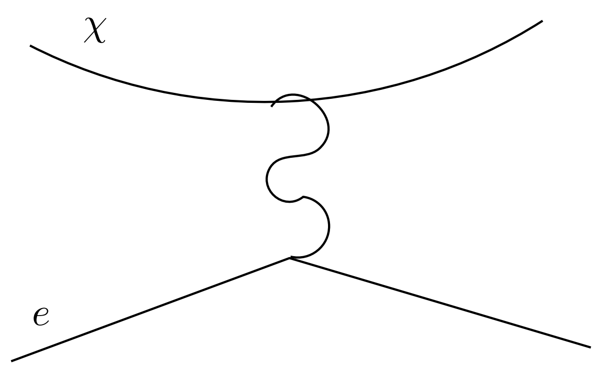
# Freeze In Model:

- Dark Matter communicates via kinetic mixing portal

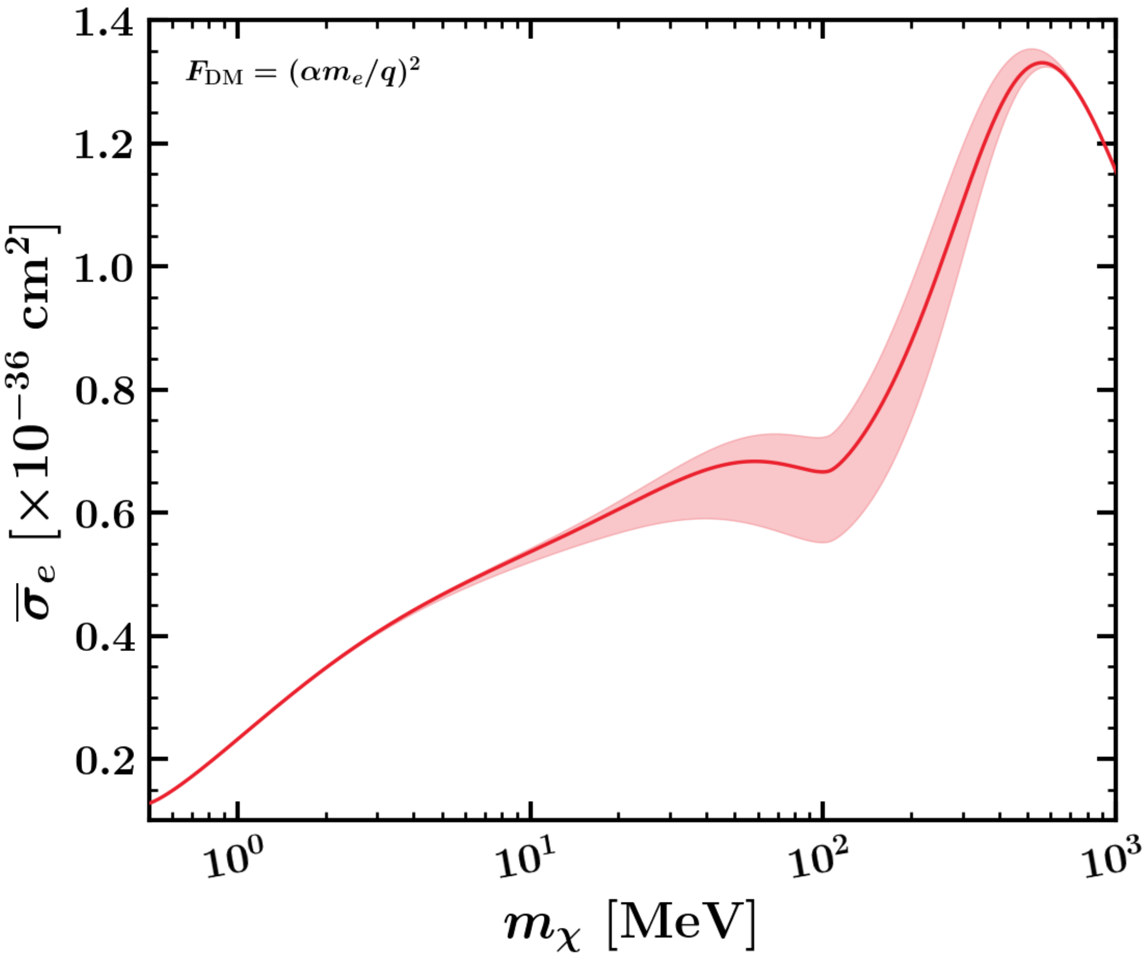


# Direct Detection

$$\overline{\sigma}_e = \frac{16\pi\mu_{\chi e}^2\alpha^2\kappa^2}{(\alpha m_e)^4} \qquad \kappa \equiv \epsilon\sqrt{\frac{\alpha'}{\alpha}}$$



# Freeze-in Benchmark



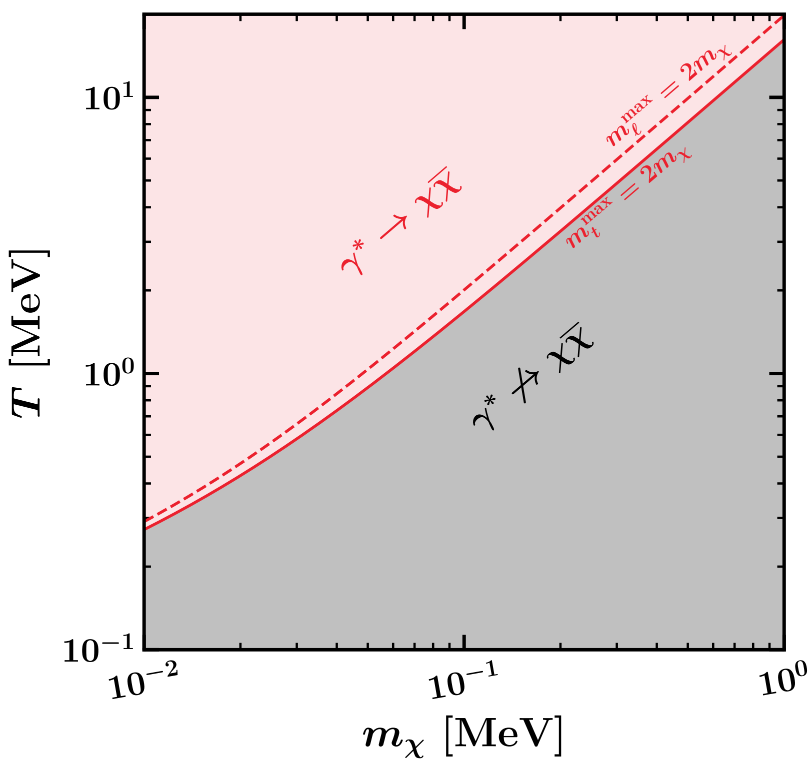

P. N. Bhattiprolu, R. McGehee, A. Pierce, "A Dark Sink Enhances the Direct Detection of Freeze-in Dark Matter," arXiv: 2312.14152 [hep-ph].

- S. Heeba, T. Lin, K. Schutz, *Phys.Rev.D* 108 (2023) 9, 095016

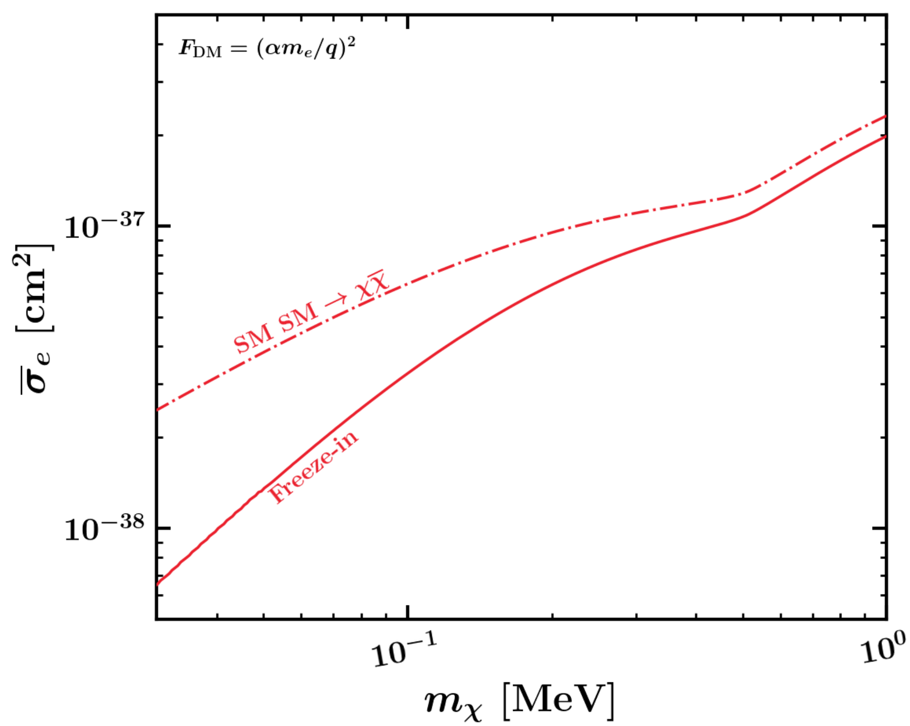
X. Chu, T. Hambye, and M. H. G. Tytgat, JCAP 05, 034 (2012), arXiv:1112.0493 [hep-ph].
R. Essig, J. Mardon, and T. Volansky, Phys. Rev. D 85, 076007 (2012), arXiv:1108.5383 [hep-ph].

https://github.com/prudhvibhattiprolu/FreezeIn

# Plasmons are important for sub-MeV DM




P. N. Bhattiprolu, R. McGehee, E. Petrosky, AP, "Sub-MeV Dark Sink Dark Matter," arXiv: 2408.07744 [hep-ph].



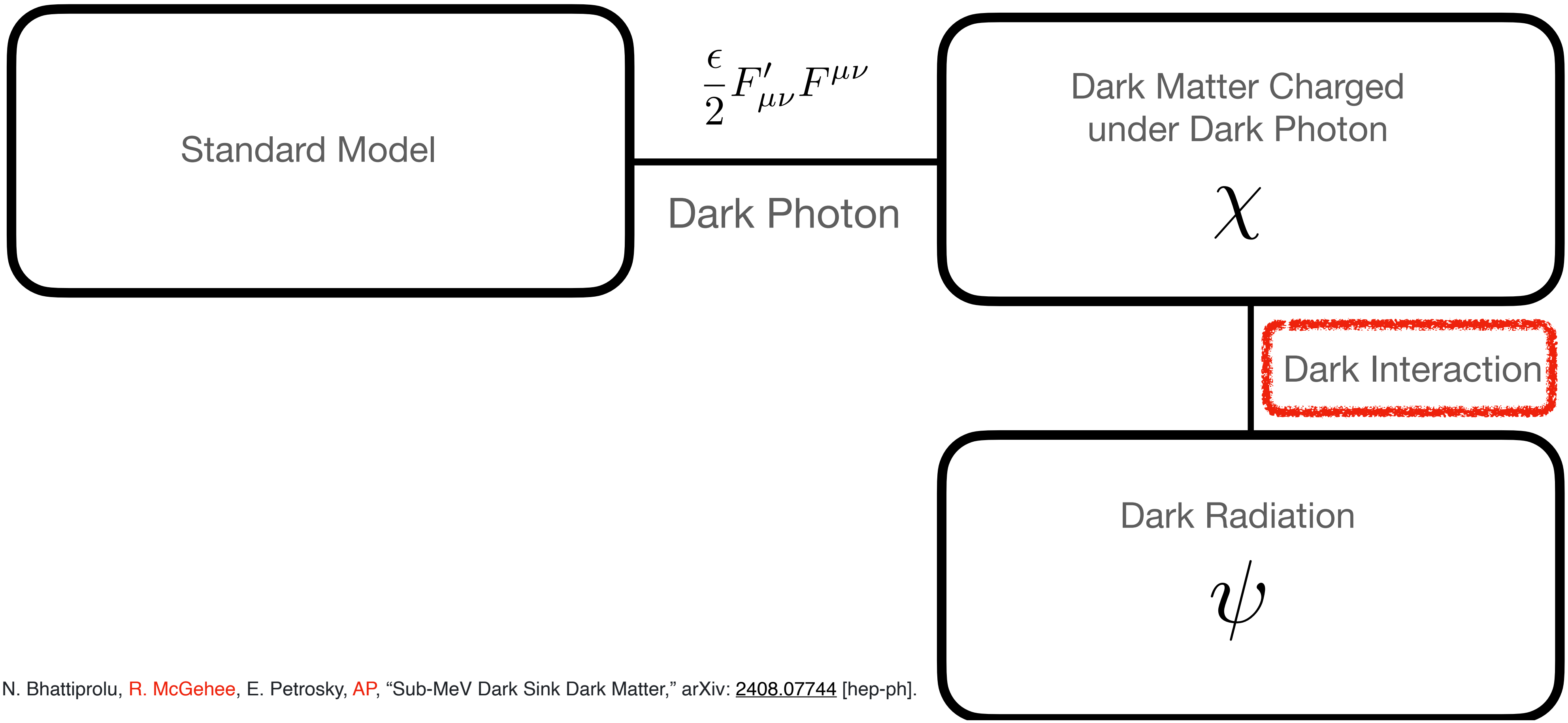

- *See: Dvorkin, Lin and Schutz Phys.Rev.D* 99 (2019) 11, 115009, *Phys. Rev.D* 105 (2022) 11, 119901 (erratum)

# Dark Sink Idea

# Dark Sink Idea


# Freeze In Model with a Sink

- Dark Matter communicates via kinetic mixing portal




P. N. Bhattiprolu, R. McGehee, E. Petrosky, AP, "Sub-MeV Dark Sink Dark Matter," arXiv: 2408.07744 [hep-ph].

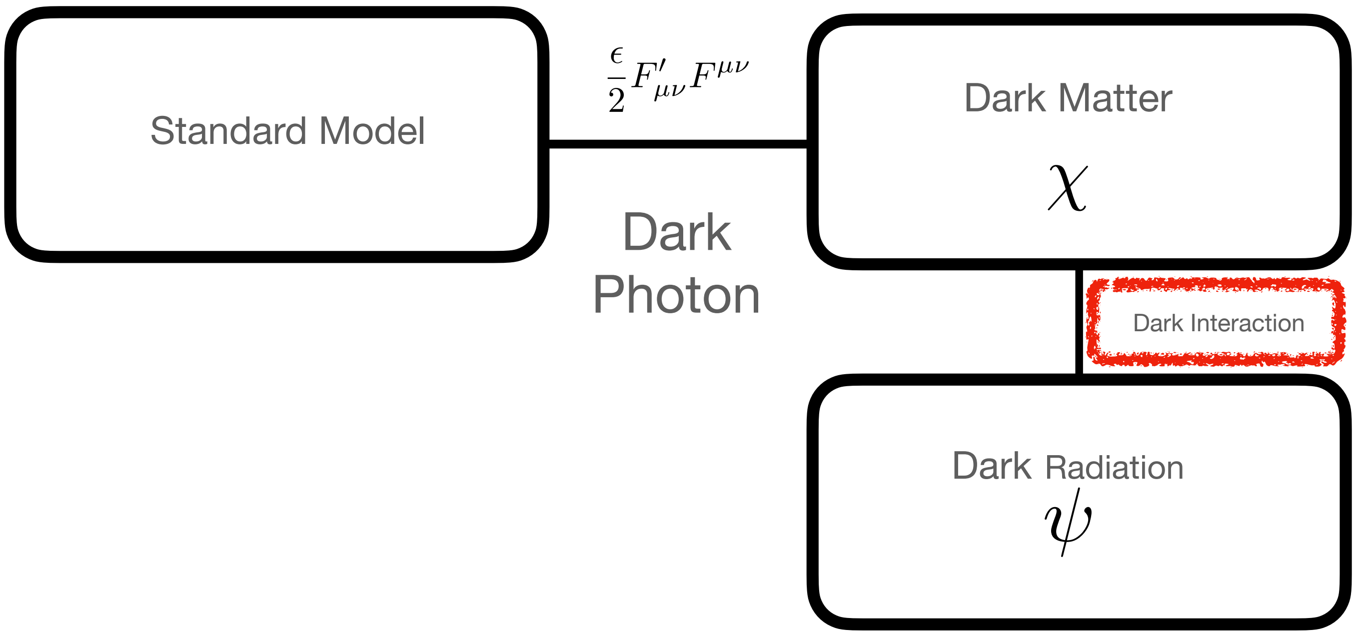
# Dark Interaction

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

$$\langle\sigma v\rangle' \approx \frac{3}{4\pi}\frac{y_\chi^2 y_\psi^2}{m_\Phi^4} m_\chi T'. \qquad m_\chi/T' \gg 1$$

# Dark Matter Production

- Produce dark matter
- Dark Sector Thermalizes at a temperature T’<T



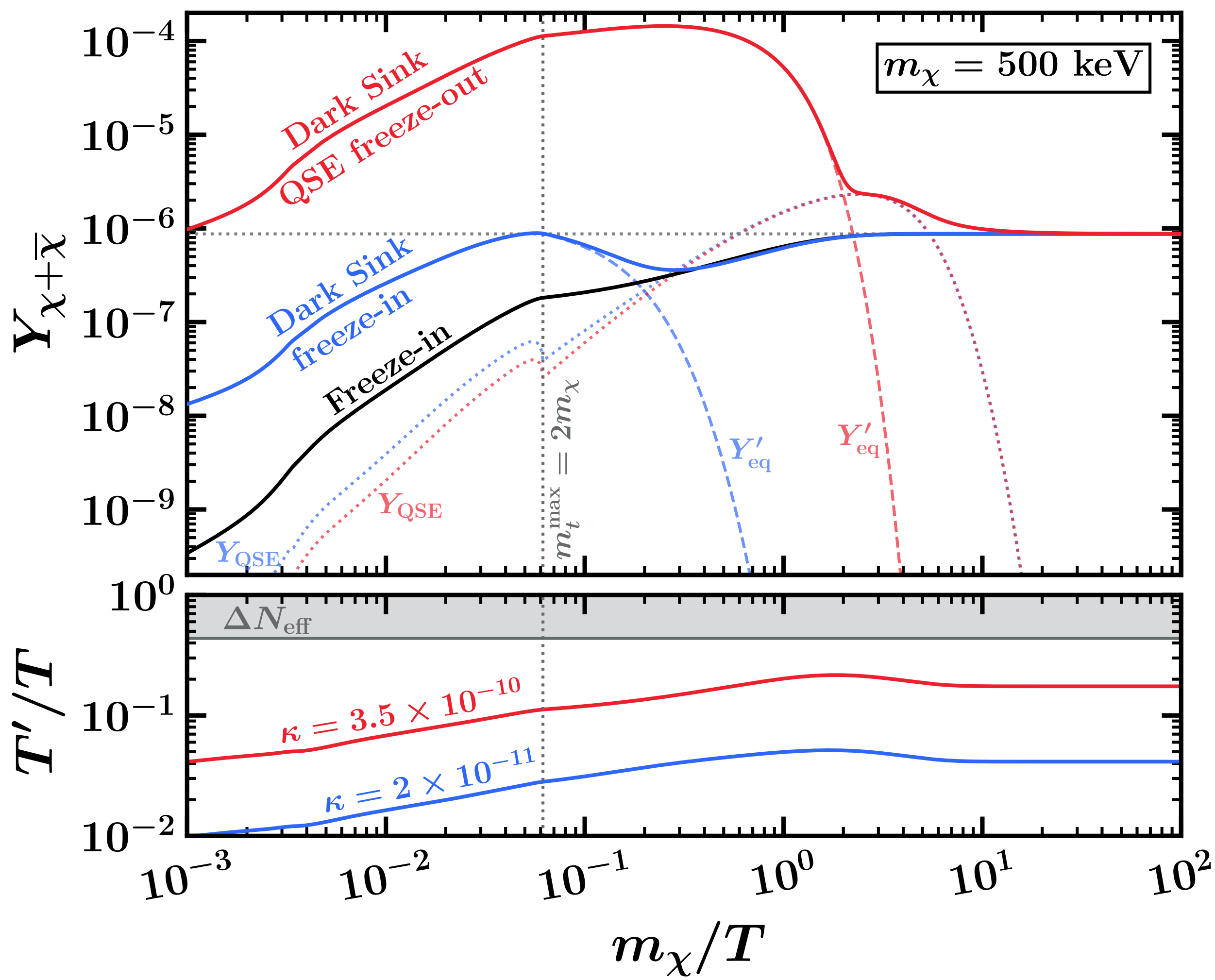
# Dark Matter Production

$$-\overline{H}T\frac{d\rho'}{dT}+3H(\rho'+p')=\sum_{(i,j)}\frac{4g_i^2}{(4\pi)^5}\int_{s_{\min}}^{\infty}ds\;\overline{|\mathcal{M}|}^2_{ij\to\chi\overline{\chi}}\sqrt{s-4m_i^2}\sqrt{s-4m_\chi^2}\left(TK_2\left(\frac{\sqrt{s}}{T}\right)-T'K_2\left(\frac{\sqrt{s}}{T'}\right)\right),$$

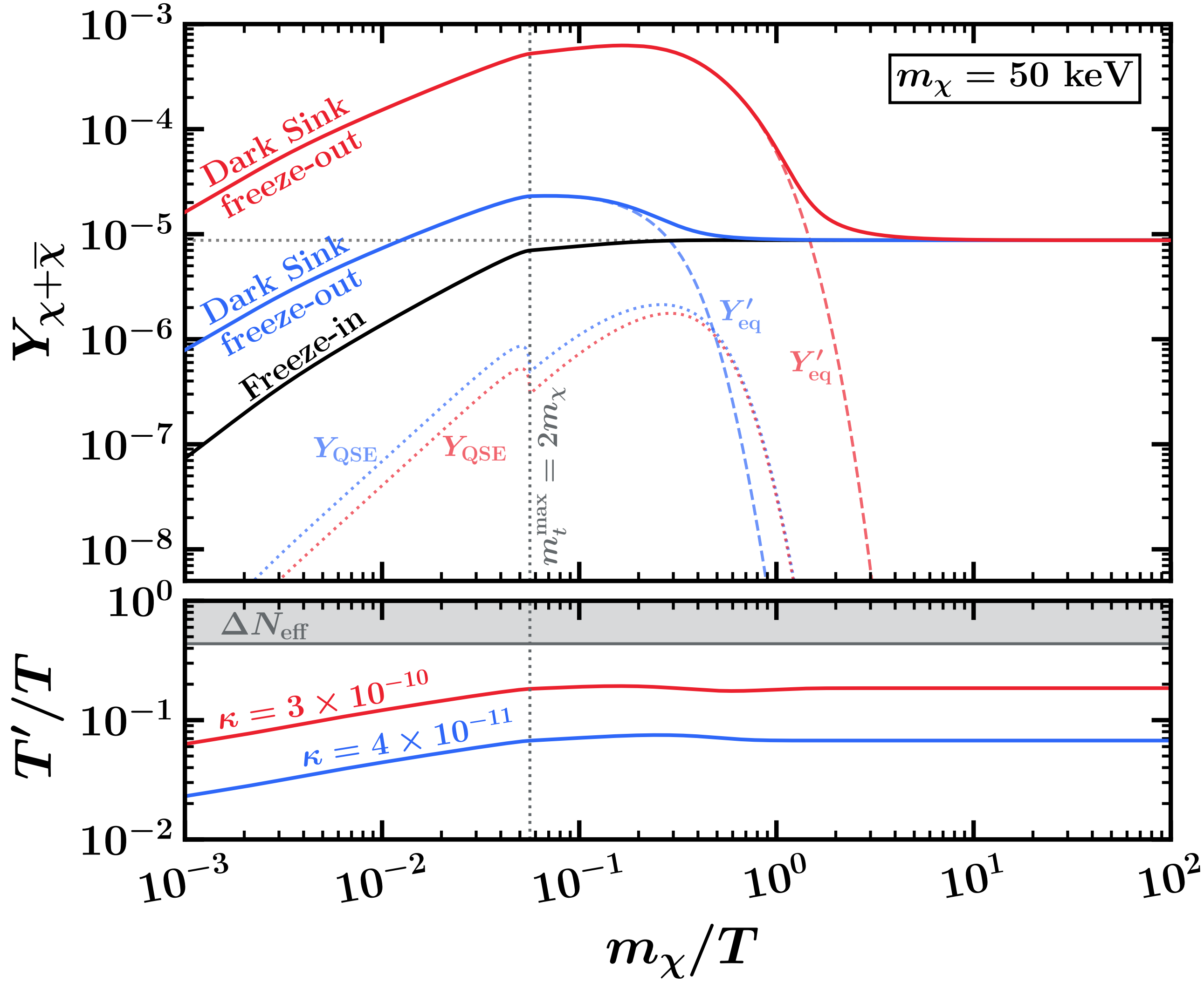
$$\text{with}\quad H/\overline{H}=1+\frac{1}{3}\frac{d\ln g_{*,s}}{d\ln T}+\frac{1}{3}\frac{d\ln g_{*,s}}{d\ln T'}\frac{T}{T'}\frac{dT'}{dT}\quad\text{and}\quad p'=\frac{\rho'}{3}-\frac{m_\chi^3T'}{3\pi^2}K_1\left(\frac{m_\chi}{T'}\right),$$

$$-\frac{\overline{H}T}{s}\frac{dY}{dT}=\langle\sigma v\rangle'\left[{Y'_{eq}}^2+\left(1-\frac{Y^2}{Y_{eq}^2}\right)Y_{QSE}^2-Y^2\right]$$

$$Y_{QSE}=Y_{eq}\sqrt{\frac{\langle\sigma v\rangle}{\langle\sigma v\rangle'}}$$

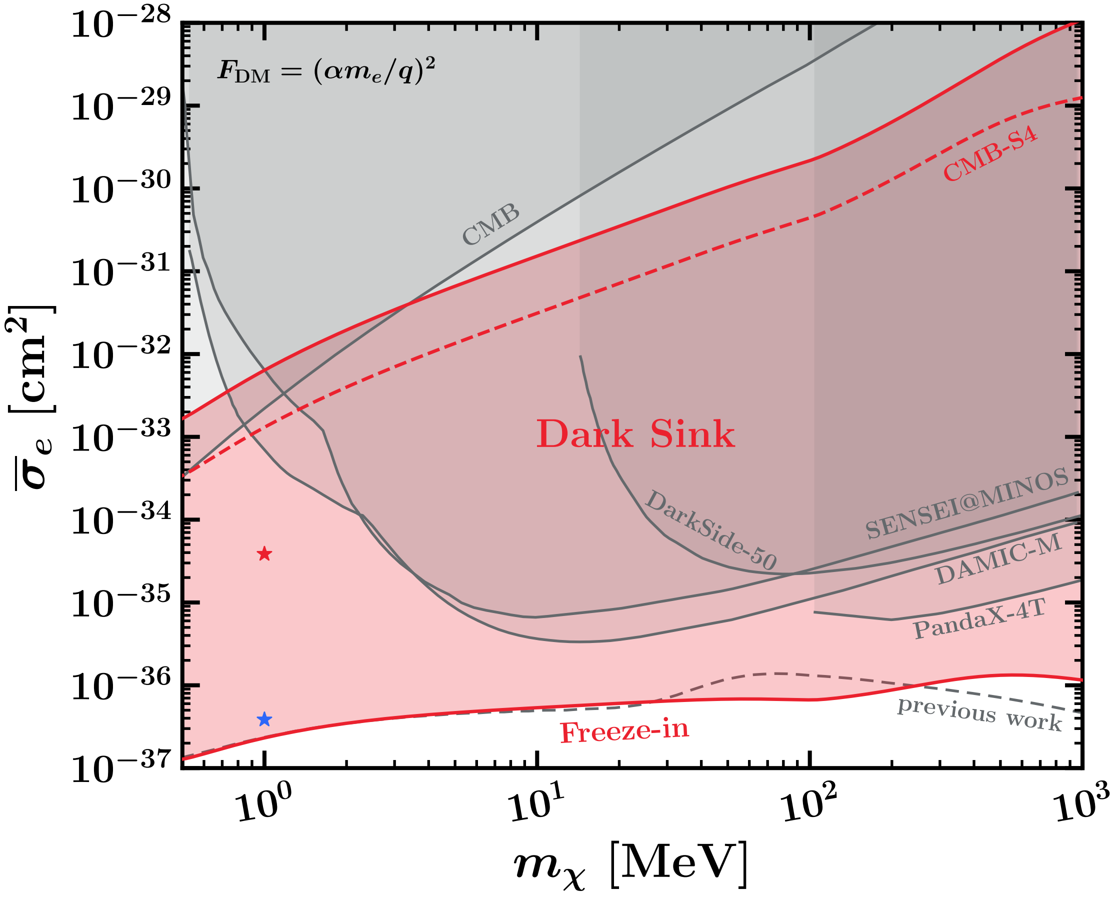


$m_\chi = 500$ keV
Dark Sink
QSE freeze-out
Dark Sink
freeze-in
Freeze-in
$Y_{\rm QSE}$
$Y_{\rm QSE}$
$m_t^{\rm max} = 2m_\chi$
$Y'_{\rm eq}$
$Y'_{\rm eq}$
$Y_{\chi+\overline{\chi}}$
$\Delta N_{\rm eff}$
$\kappa = 3.5 \times 10^{-10}$
$\kappa = 2 \times 10^{-11}$
$T'/T$
$m_\chi/T$



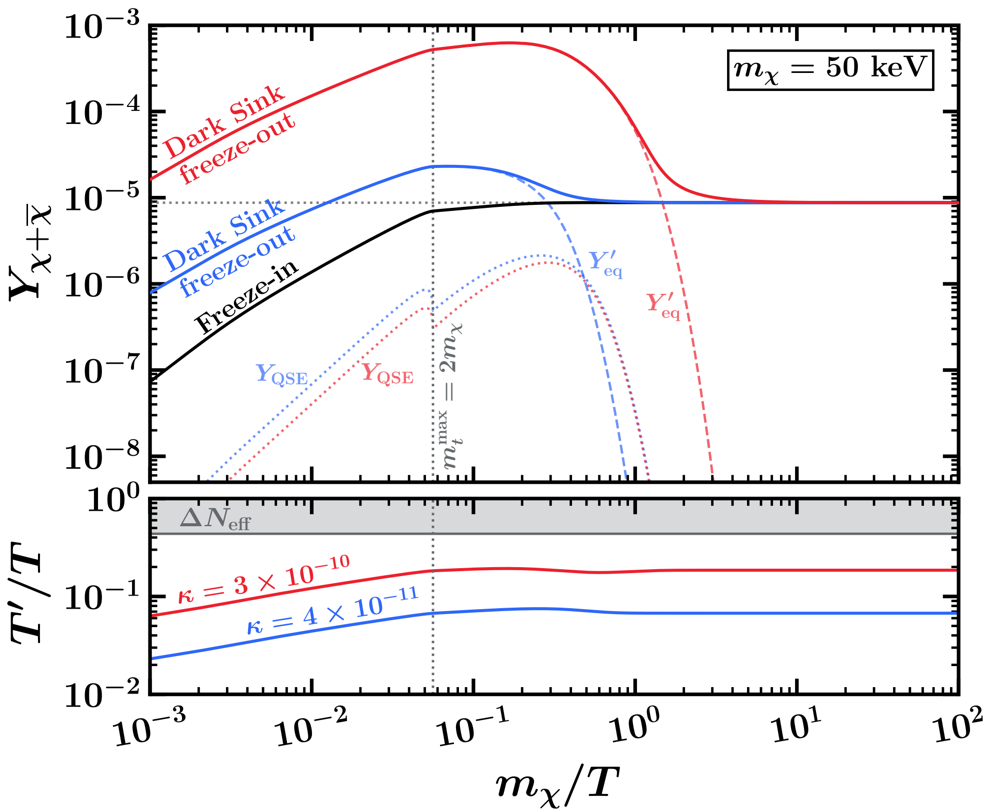
$m_\chi = 50$ keV
Dark Sink freeze-out
Dark Sink freeze-out
Freeze-in
$Y'_{\rm eq}$
$Y'_{\rm eq}$
$Y_{\rm QSE}$
$Y_{\rm QSE}$
$m_t^{\rm max} = 2m_\chi$
$\Delta N_{\rm eff}$
$\kappa = 3 \times 10^{-10}$
$\kappa = 4 \times 10^{-11}$
$Y_{\chi+\overline{\chi}}$
$T'/T$
$m_\chi/T$

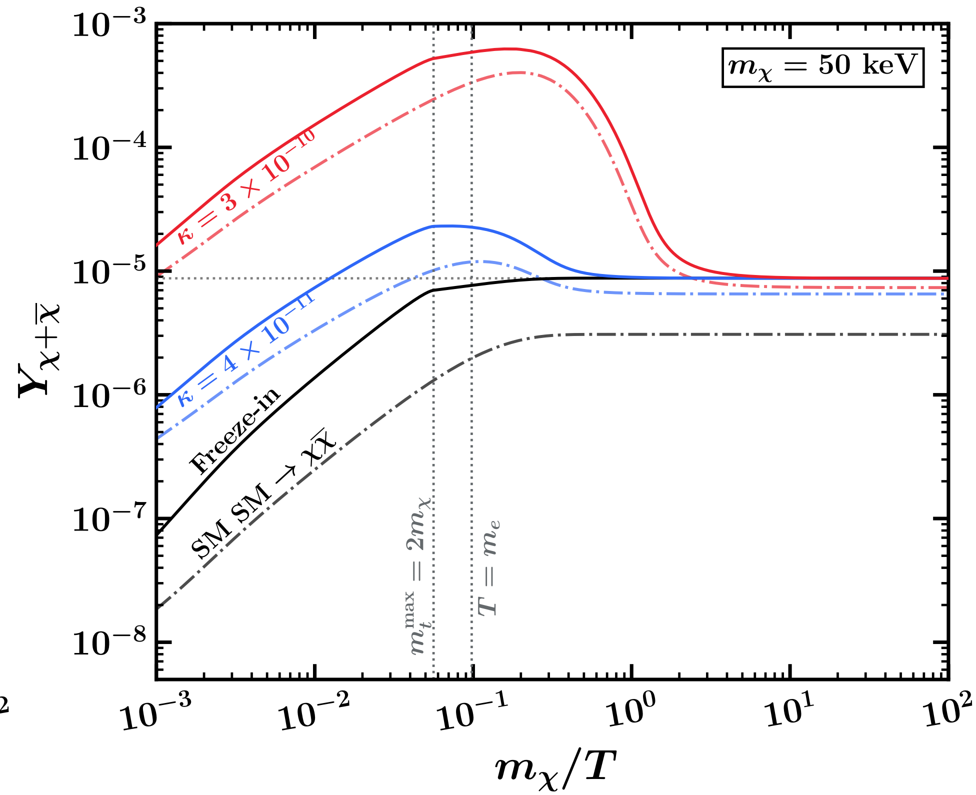
# Dark Sink



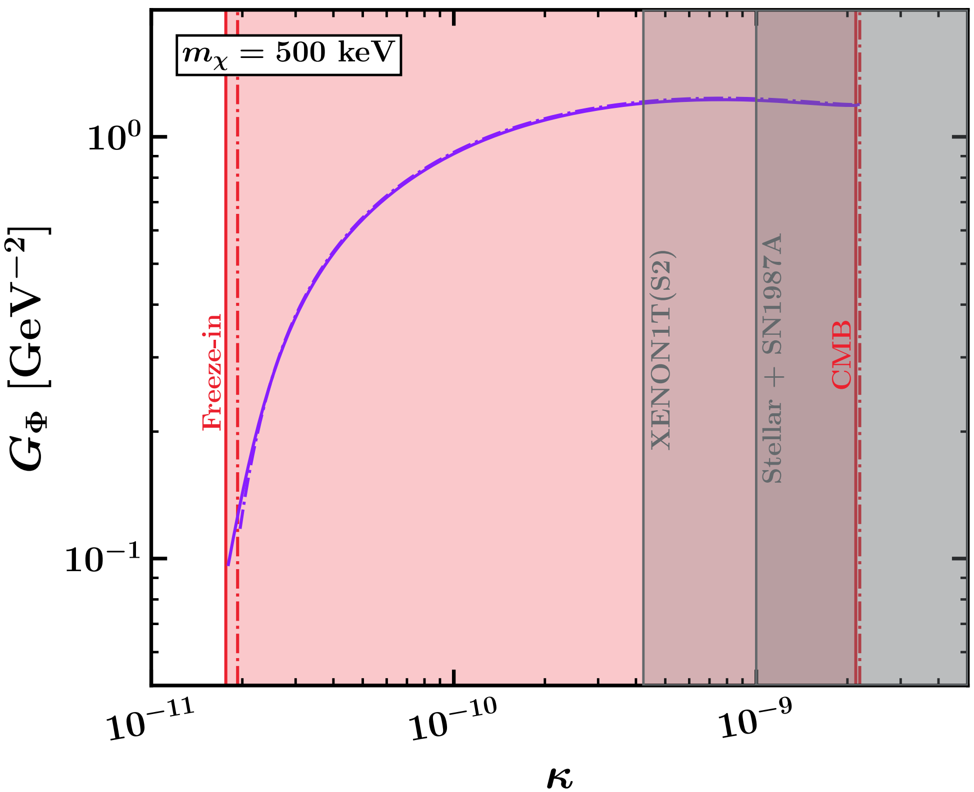
$F_{\rm DM} = (\alpha m_e/q)^2$
CMB
CMB-S4
Dark Sink
DarkSide-50
SENSEI@MINOS
DAMIC-M
PandaX-4T
previous work
Freeze-in
$10^{-28}$
$10^{-29}$
$10^{-30}$
$10^{-31}$
$10^{-32}$
$10^{-33}$
$10^{-34}$
$10^{-35}$
$10^{-36}$
$10^{-37}$
$10^0$
$10^1$
$10^2$
$10^3$
$\overline{\sigma}_e$ [cm$^2$]
$m_\chi$ [MeV]

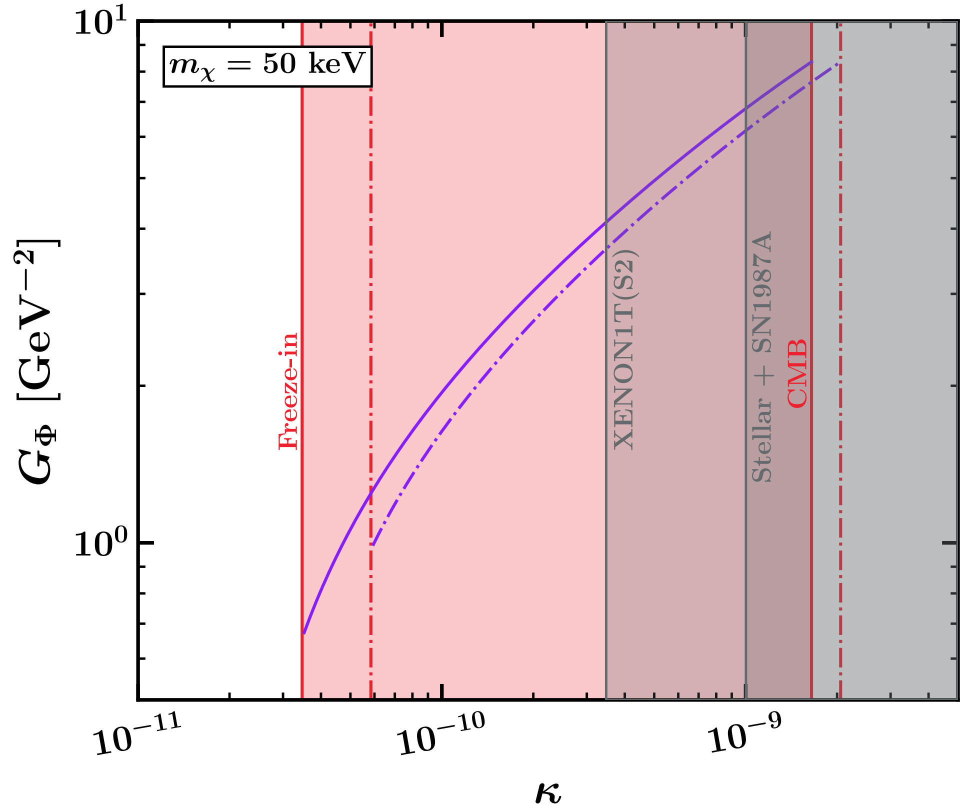
# The importance of plasmons

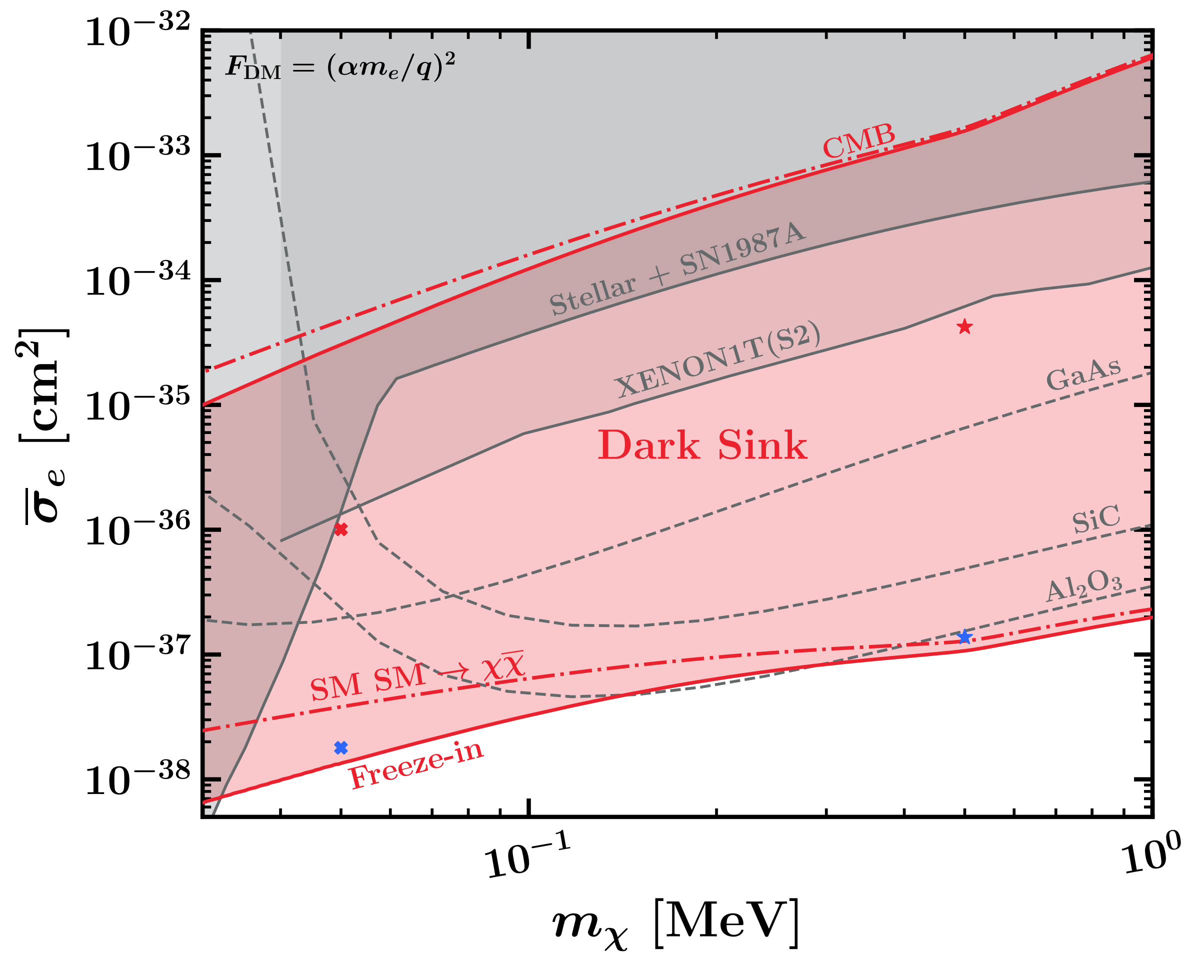


# Dark Sink Interactions





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

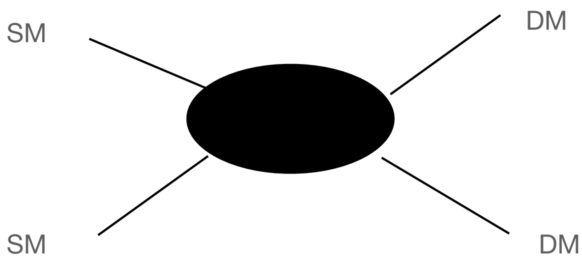
**What models nuclear recoil experiments probe at low DM masses?**

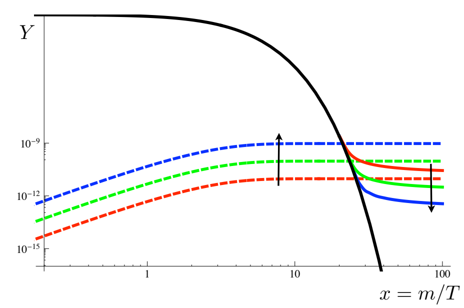
# Hadrophilic Dark Matter

## increasing cross section with a low reheating temperature

- Idea: UV freeze-in of dark matter will be suppressed for low reheating temperatures

$$T_{RH} \downarrow \qquad \Rightarrow \qquad \sigma_{DD} \uparrow$$



# Model of Hadrophilic Dark Matter

## Direct Detection

Mediator

$$\mathcal{L} \supset -m_\psi \overline{\psi}\psi - m_\chi \overline{\chi}\chi - \frac{1}{2} m_\phi^2 \phi^2 - y_\psi \phi \overline{\psi}\psi - y_\chi \phi \overline{\chi}\chi,$$

TeV-scale colored particle

DM

$$\mathcal{L} \supset \frac{y_\psi \alpha_s}{6\pi m_\psi} \phi G^a_{\mu\nu} G^{\mu\nu,a} \quad \Longrightarrow \quad \mathcal{L} \supset -y_n \phi \overline{n} n, \qquad y_n = y_\psi \frac{4 m_n}{27 m_\psi},$$

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

P. Bhattiprolu, G. Elor, R. McGehee, AP, *JHEP* 01 (2023) 128,
see also Kanpen, Lin, Zurek, *Phys.Rev.D* 96 (2017) 11, 115021

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TeV-scale colored particle

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$$\mathcal{L} \supset \frac{y_\psi \alpha_s}{6\pi m_\psi} \phi G^a_{\mu\nu} G^{\mu\nu,a} \Rightarrow \mathcal{L} \supset -y_n \phi \overline{n} n, \qquad y_n = y_\psi \frac{4 m_n}{27 m_\psi},$$

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# Model of Hadrophilic Dark Matter

## Dark Matter Production

$$\mathcal{L} \supset -m_\psi \overline{\psi}\psi - m_\chi \overline{\chi}\chi - \frac{1}{2}m_\phi^2\phi^2 - y_\psi \phi\overline{\psi}\psi - y_\chi \phi\overline{\chi}\chi,$$

$$\mathcal{L} \supset \frac{3y_n}{m_n}\phi\left(\frac{2}{3}\left|D^\mu\pi^+\right|^2 - m_\pi^2\pi^+\pi^-\right)$$

$$\mathcal{L}_{\phi FF} \sim \frac{17 y_n \alpha}{8\pi m_n}\phi F_{\mu\nu}F^{\mu\nu}$$

P. Bhattiprolu, G. Elor, R. McGehee, AP, *JHEP* 01 (2023) 128,
see also Kanpen, Lin, Zurek, *Phys.Rev.D* 96 (2017) 11, 115021

# A freeze-in model with low reheating

## Direct Detection

$$\mathcal{L} \supset -m_\psi \overline{\psi}\psi - m_\chi \overline{\chi}\chi - \frac{1}{2} m_\phi^2 \phi^2 - y_\psi \phi \overline{\psi}\psi - y_\chi \phi \overline{\chi}\chi,$$

$\psi$ = New colored fermion

$\chi$ = Dark Matter

$\phi$ = Mediator

$$\mathcal{L} \supset \frac{y_\psi \alpha_s}{6\pi m_\psi} \phi G^a_{\mu\nu} G^{\mu\nu,a}. \Rightarrow \mathcal{L} \supset -y_n \phi \overline{n} n, \quad y_n = y_\psi \frac{4 m_n}{27 m_\psi};$$

$$y_n = 9.3 \times 10^{-5} \left(\frac{y_\psi}{1}\right) \left(\frac{1.5\,\text{TeV}}{m_\psi}\right)$$

# A freeze-in model with low reheating

## Dark Matter Production

$$\mathcal{L} \supset \frac{3y_n}{m_n}\phi\left(\frac{2}{3}\left|D^\mu\pi^+\right|^2 - m_\pi^2\pi^+\pi^-\right)$$

$$\mathcal{L}_{\phi FF} \sim \frac{17 y_n \alpha}{8\pi m_n}\phi F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{L} \supset \frac{y_\chi}{m_\phi^2}\frac{17 y_n \alpha}{8\pi m_n}\overline{\chi}\chi F_{\mu\nu}F^{\mu\nu}$$

# Solve a Boltzman equation

$$Y_{\mathrm{DM}} = \frac{y_n^2 y_\chi^2}{m_\phi^4 m_n^2} \frac{135\sqrt{10} M_{\mathrm{Pl}}}{(2\pi)^8} \sum_{j=\gamma,\pi^\pm} \kappa_j^2 \int_0^{T_{\mathrm{R}}} \frac{dT}{T^5} \frac{I(m_j)}{g_{s,*}(T)\sqrt{g_*(T)}},$$

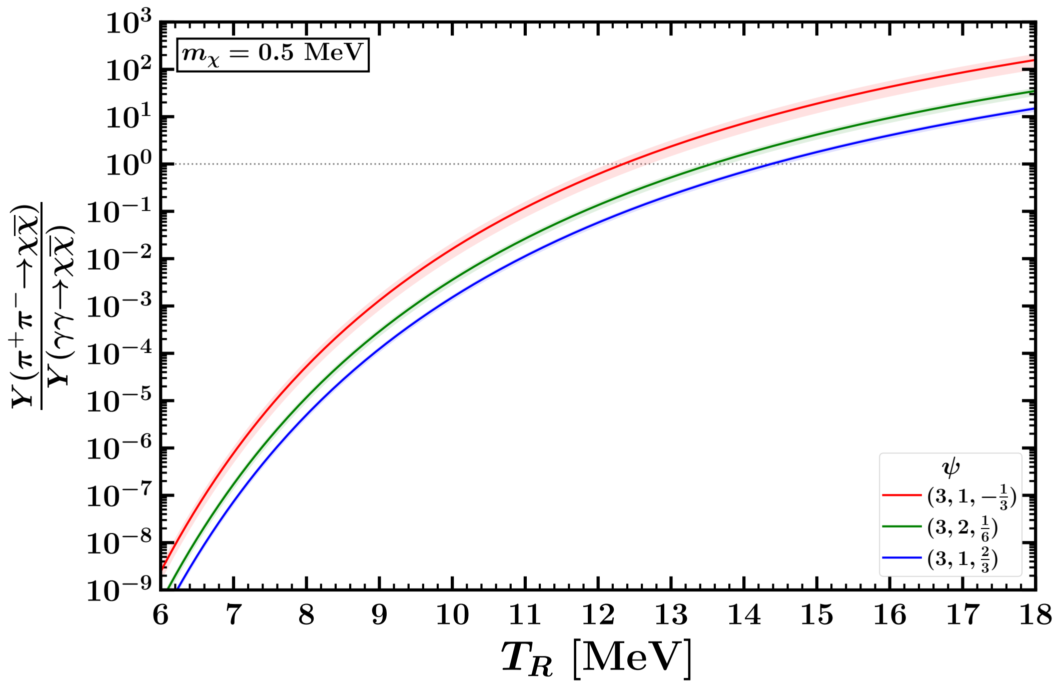
where

$$\kappa_j = \begin{cases} 1 \text{ for } j = \pi^\pm, \\ \frac{17\alpha}{4\pi} \text{ for } j = \gamma, \end{cases}$$

and

$$I(m) = \int_{\max(4m^2, 4m_\chi^2)}^{\infty} ds \frac{\left(s + m^2\right)^2}{\left(\frac{s}{m_\phi^2} - 1\right)^2 + \frac{\Gamma_\phi^2}{m_\phi^2}} \left(s - 4m_\chi^2\right)^{3/2} \sqrt{1 - \frac{4m^2}{s}} K_1\left(\frac{\sqrt{s}}{T}\right).$$

# Dark Matter Production

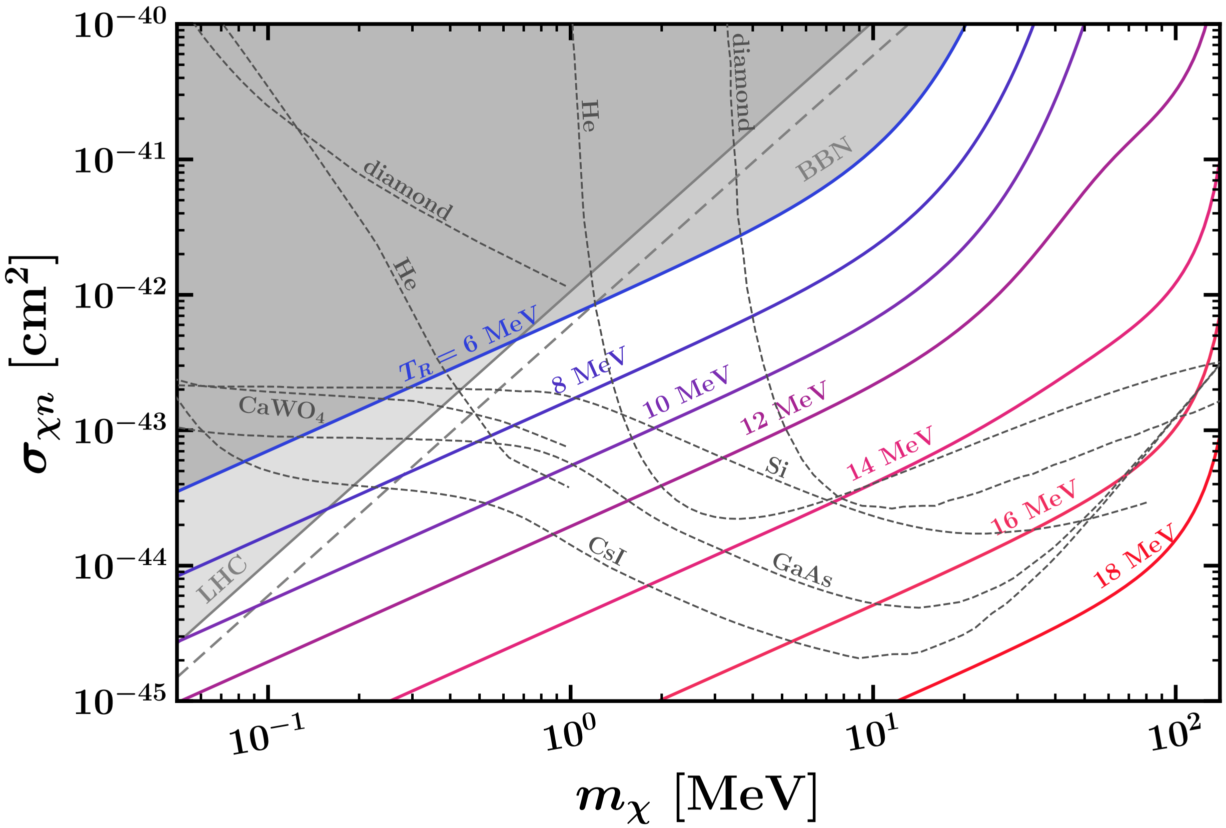


# Photon domination case (very low RH)

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

Direct detection depends on the choice of representation.

# Predictions for direct detection

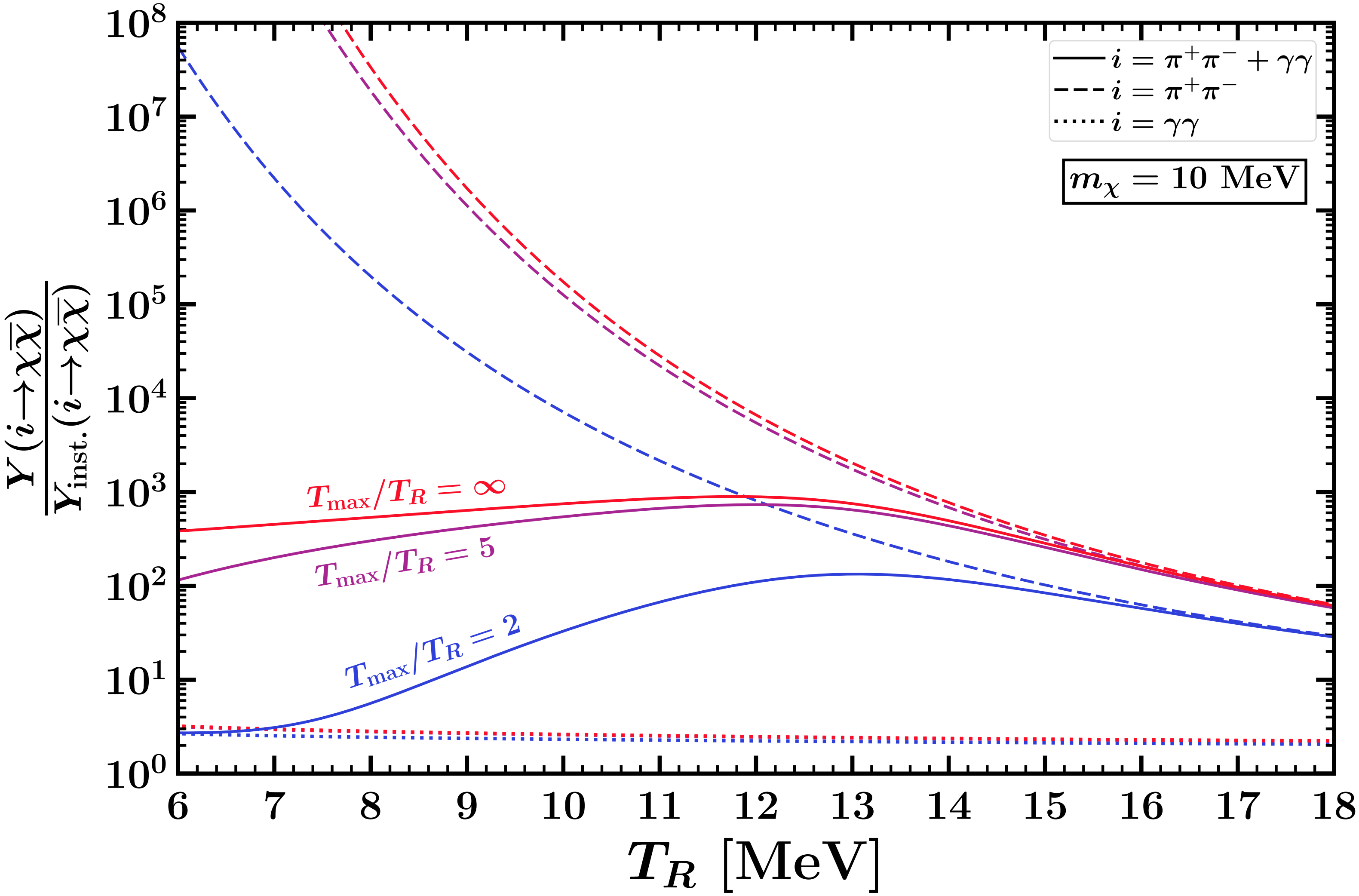


# Summary

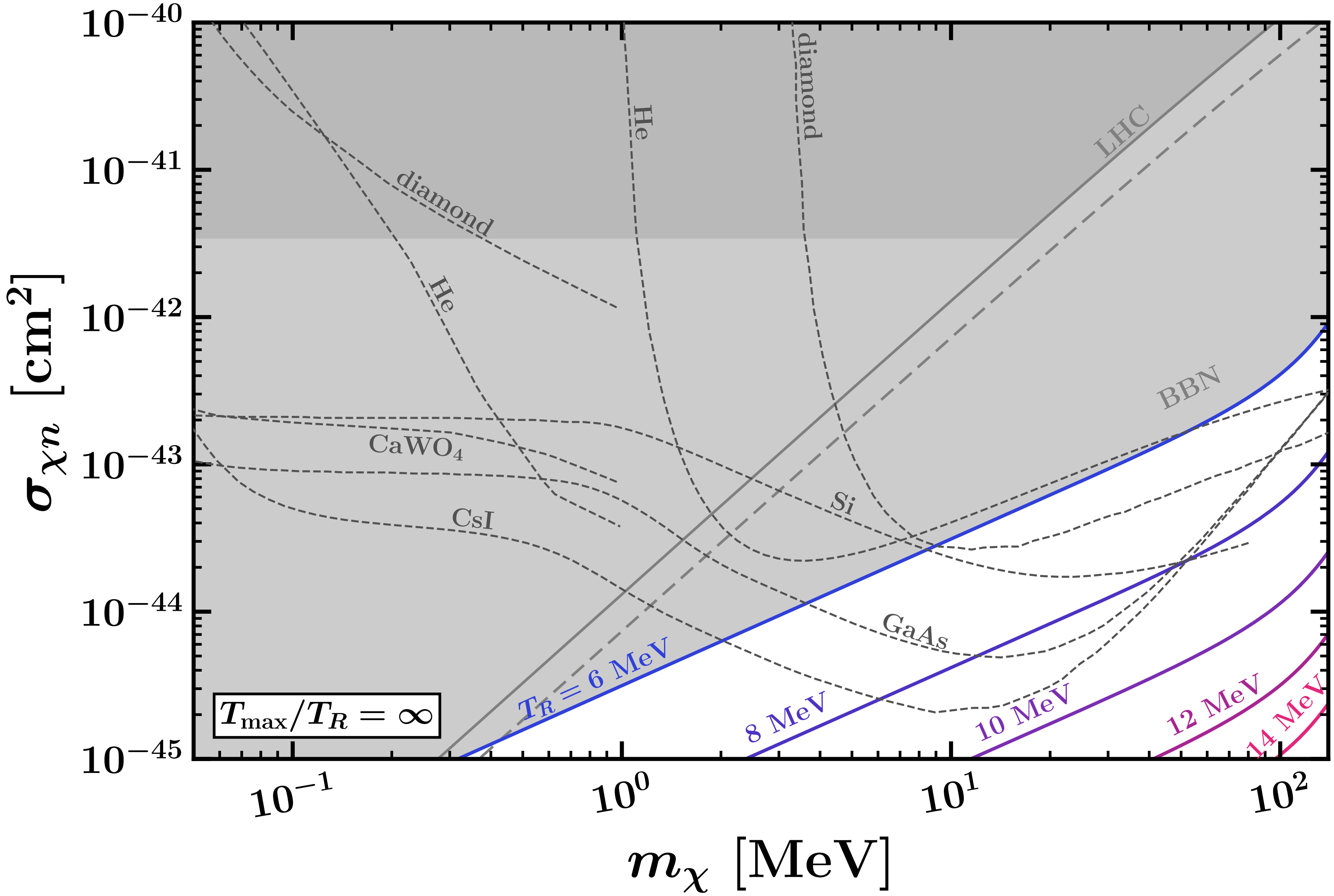
- Freeze-in represents an interesting target for direct detection at relatively low masses.
- Relatively minor modification of the freeze-in simplest story can give rise to a wide range of cross sections beyond the simplest benchmark, including ones that are being probed now!
- Detectable cross sections for nucleon scattering requires a bit more effort, but are possible, and low-reheat temperatures represents an existence proof.

# Thank you!

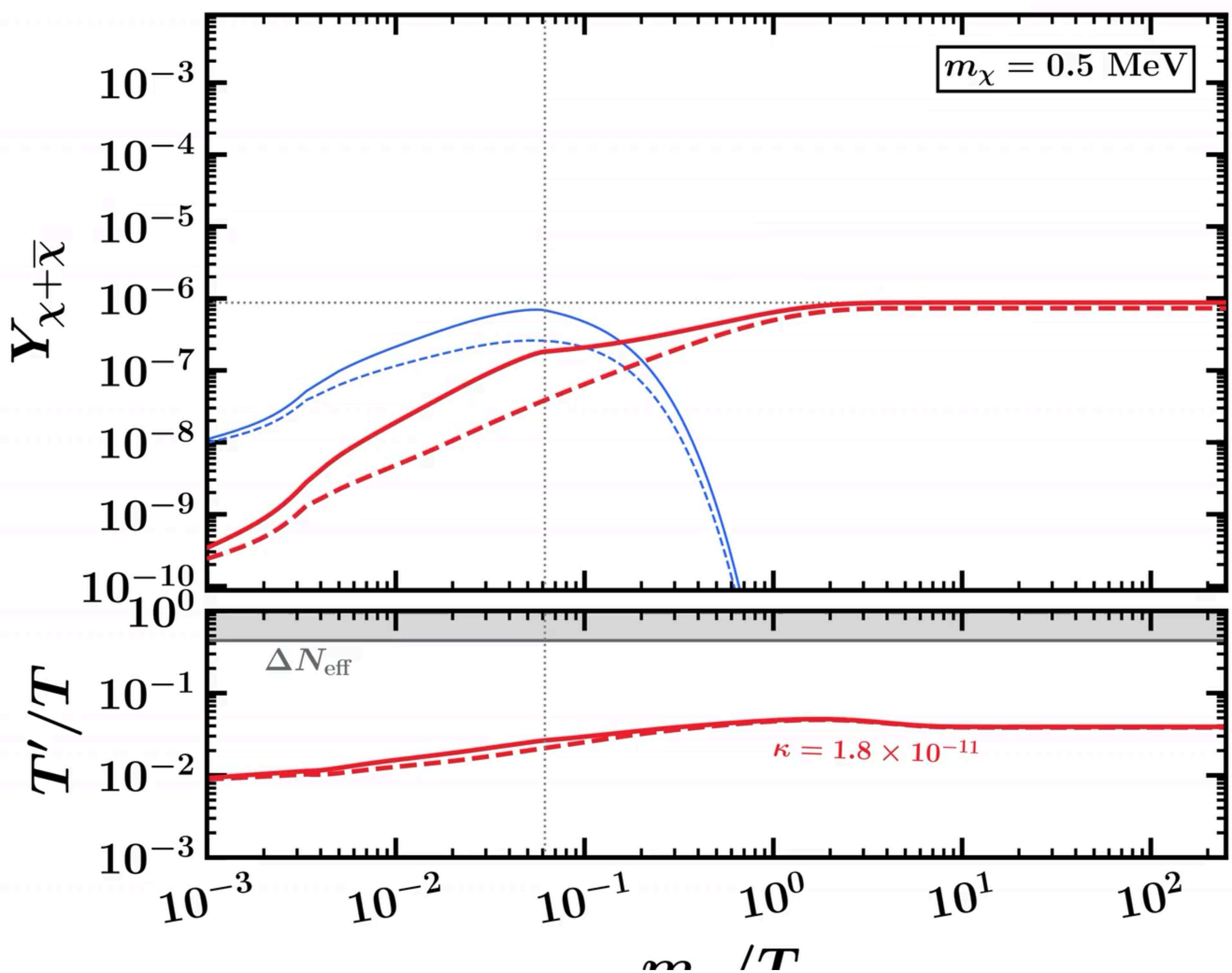
- Happy Birthday, Hitoshi and Lawrence!
- Your impact on the field through your science and your influence on generation(s!) of physicists is a remarkable legacy, and I know you are an inspiration to so many of us in this room.



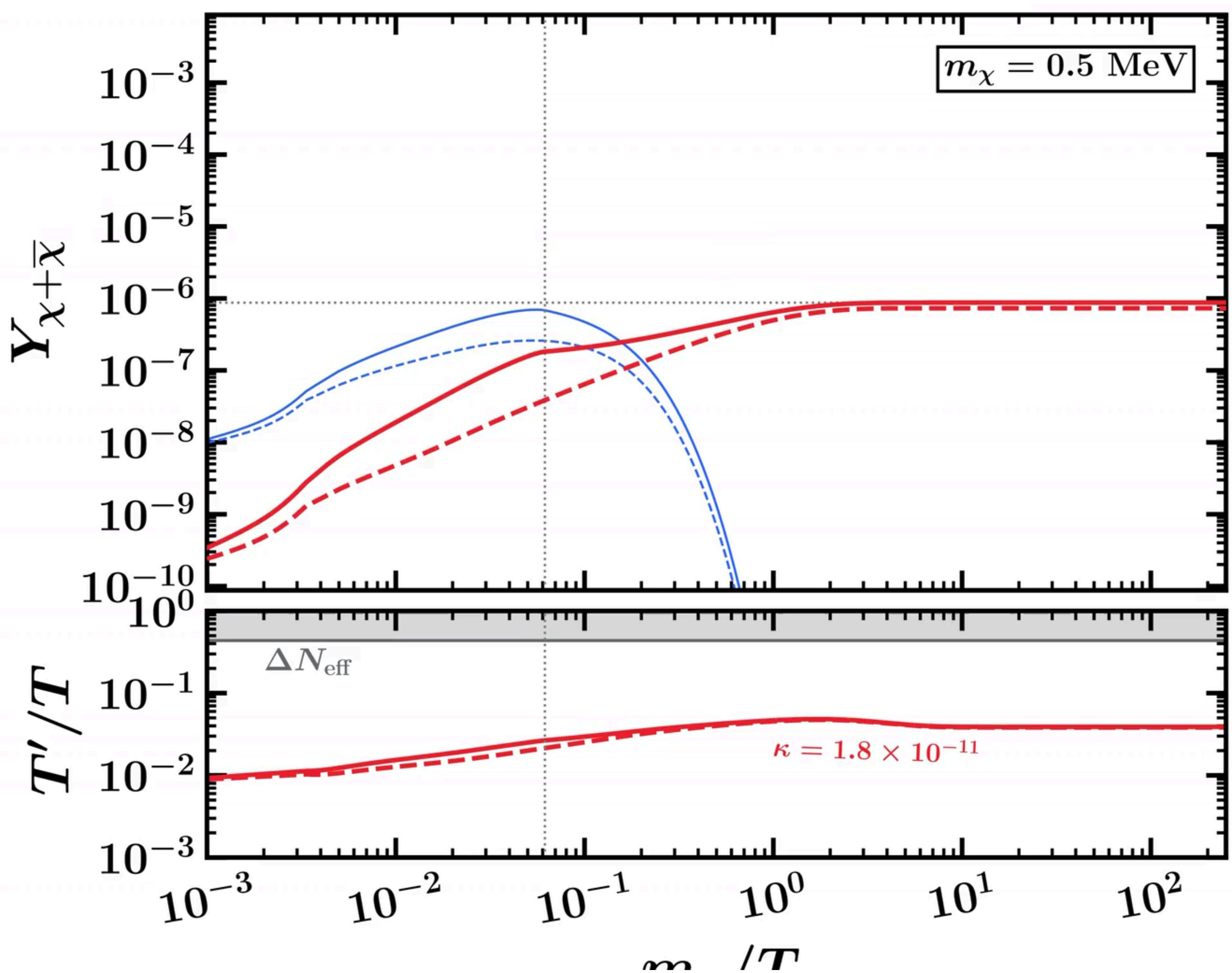
$i = \pi^+\pi^- + \gamma\gamma$
$i = \pi^+\pi^-$
$i = \gamma\gamma$
$m_\chi = 10$ MeV
$T_{\rm max}/T_R = \infty$
$T_{\rm max}/T_R = 5$
$T_{\rm max}/T_R = 2$
$\frac{Y(i\to\chi\overline{\chi})}{Y_{\rm inst.}(i\to\chi\overline{\chi})}$
$T_R$ [MeV]
$10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$
6 7 8 9 10 11 12 13 14 15 16 17 18



$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-44}$
$10^{-45}$
$\sigma_{\chi n}$ [cm$^2$]
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$m_\chi$ [MeV]
He
diamond
diamond
He
LHC
BBN
CaWO$_4$
CsI
Si
GaAs
$T_R = 6$ MeV
8 MeV
10 MeV
12 MeV
14 MeV
$T_{\rm max}/T_R = \infty$



$m_\chi = 0.5$ MeV
$Y_{\chi+\bar{\chi}}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{0}$
$\Delta N_{\rm eff}$
$T'/T$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$\kappa = 1.8 \times 10^{-11}$
$10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$



$m_\chi = 0.5$ MeV
$Y_{\chi+\bar{\chi}}$
$T'/T$
$\Delta N_{\rm eff}$
$\kappa = 1.8 \times 10^{-11}$