II. Models and mediators for dark sectors

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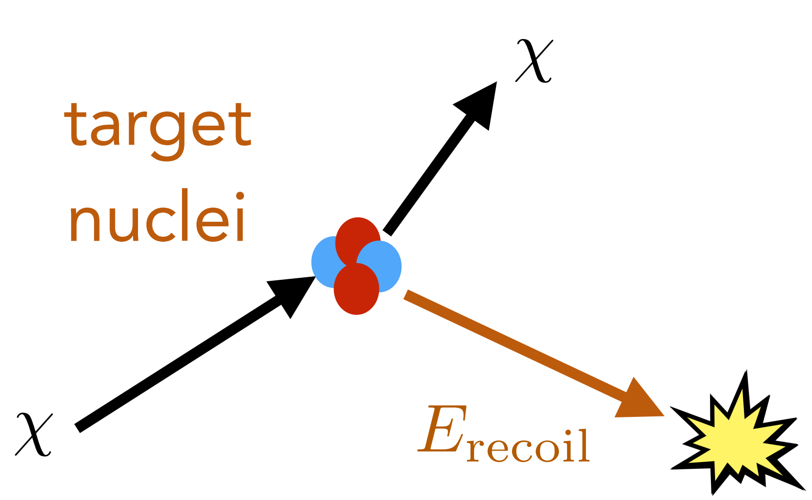
Summer Institute 2019, Korea

Dark sectors

Today: consider minimal sub-GeV dark sectors and implications mainly for **direct detection.**

nuclear recoils



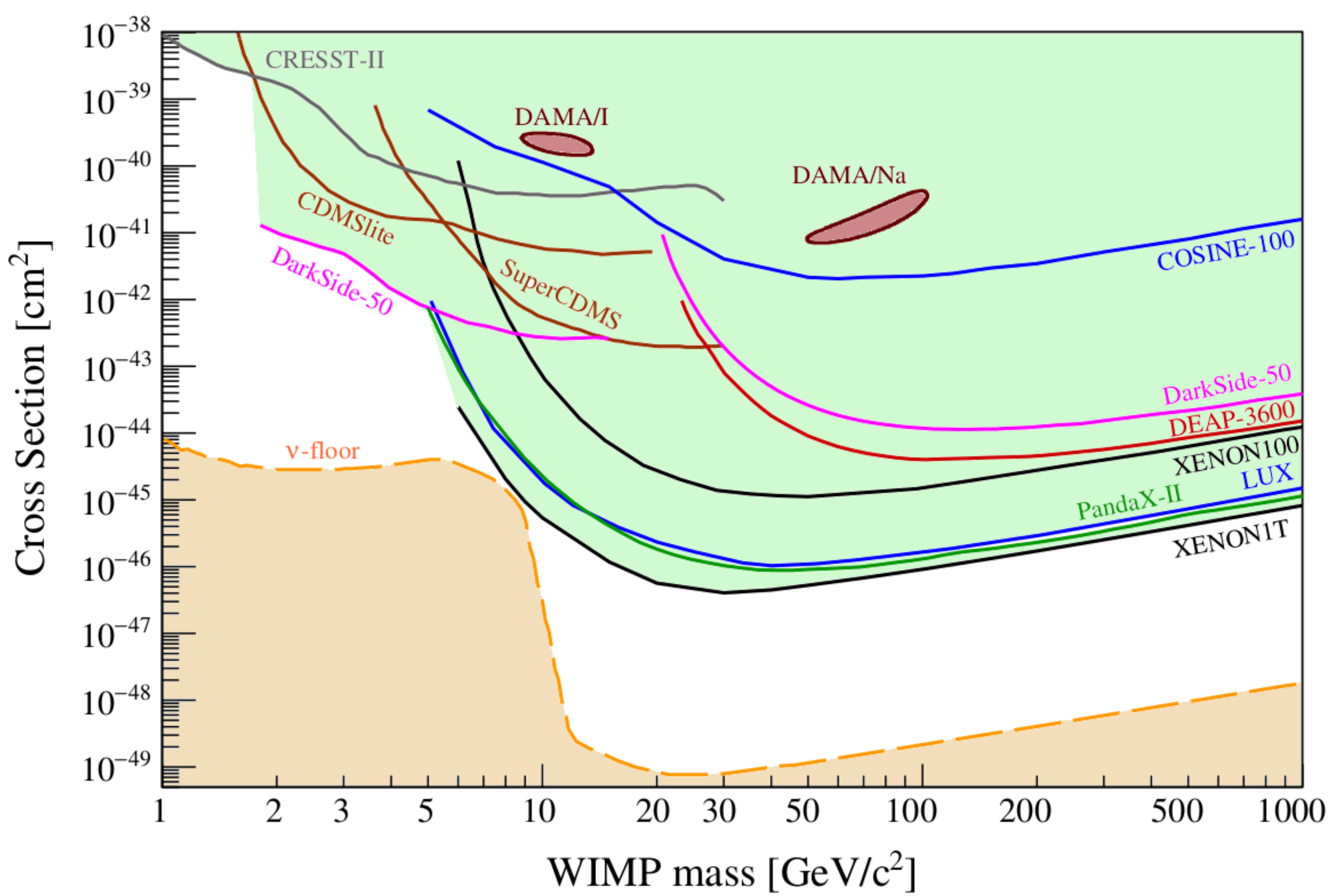


Fig from Schumann 2019

Outline

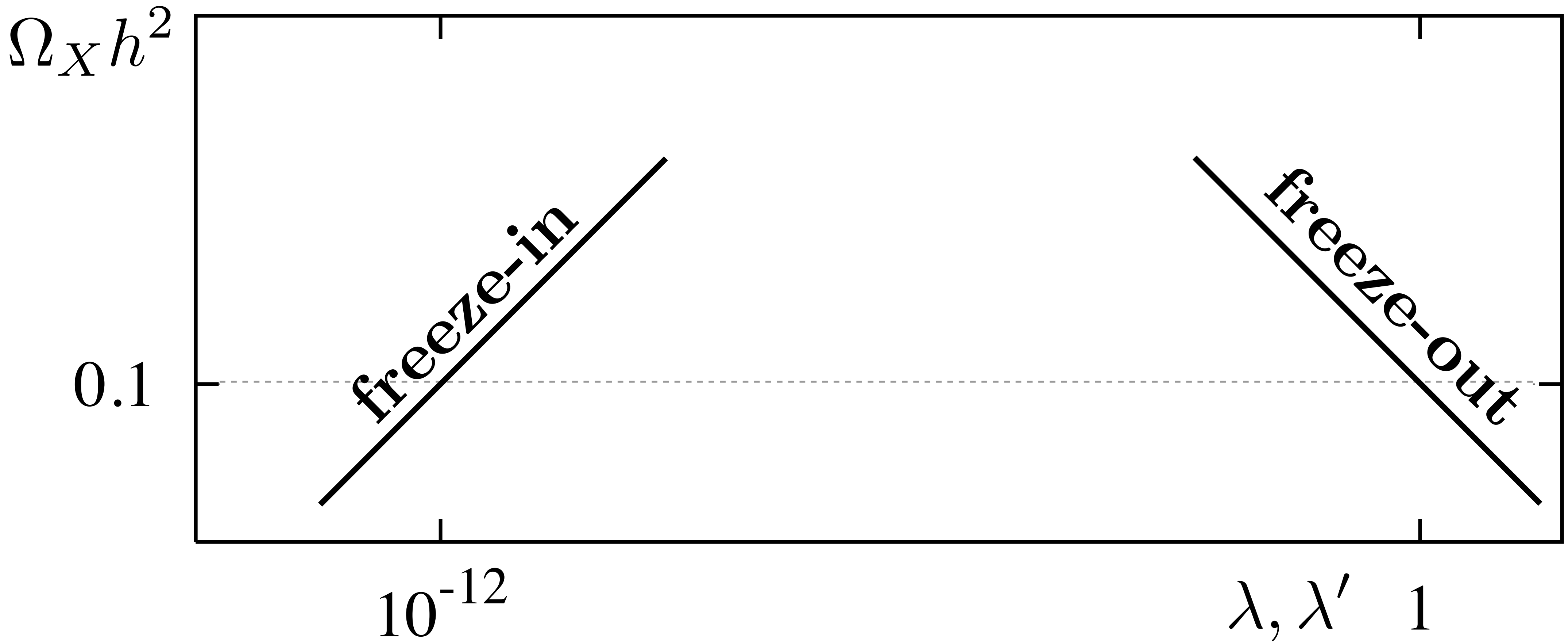
Scalar mediators & implications for direct detection

Dark-photon mediated models

Cosmology of sub-MeV freeze-in DM

Based on Knapen, TL, Zurek 2017;
Dvorkin, TL, Schutz 2019; TL 2019;
additional refs throughout

Freeze-in and freeze-out



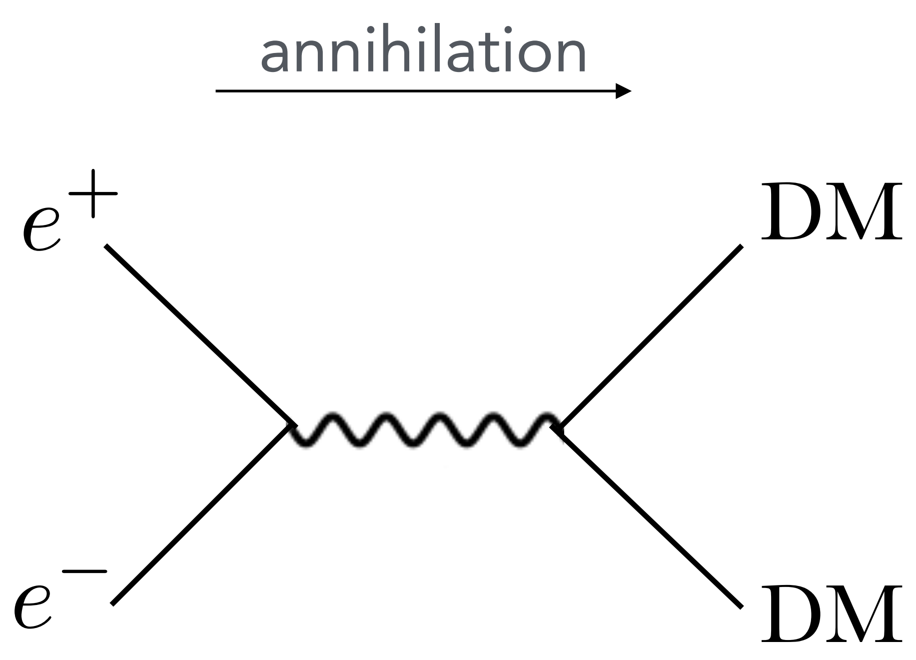
From Hall, Jedamzik, March-Russell, West 2009

In general, couplings depend on mediator and DM masses, but this gives a rough idea of effective coupling range needed.

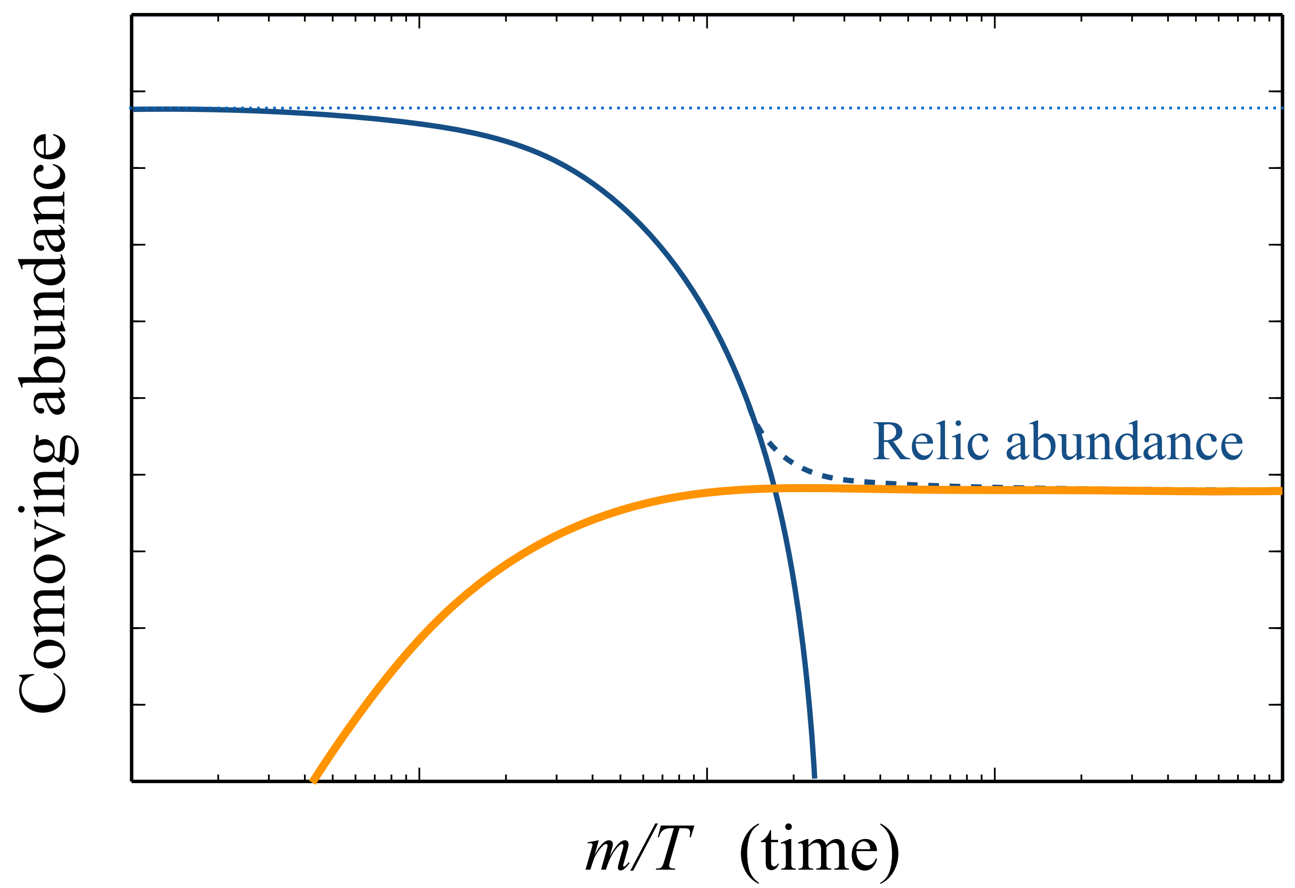
See also: Bernal et al. 2017
Chu, Hambye, Tytgat 2011

Freeze-in

Not just thermal freeze-out for light DM!



See also: sterile neutrino



Dark matter *only* populated by out-of-equilibrium annihilations of SM into dark sector

Dodelson and Widrow 1993
Hall et al. 2009
Chu, Hambye, Tytgat 2011
Essig, Mardon, Volansky 2011
Bernal et al. 2017 (review)

Freeze-in

UV freeze-in: $$Y_{\rm DM} \sim \frac{\Gamma}{H} \simeq \frac{\alpha_f \alpha_X T^3 M_{\rm pl}}{\Lambda^4}$$

Dominated by highest temperatures, reheating

Freeze-in

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IR freeze-in: $$Y_{\rm DM} \sim \frac{\Gamma}{H} \simeq \frac{\alpha_f \alpha_X M_{\rm pl}}{T}$$

Dominated by lowest temperatures (m_f or m_{DM})

Freeze-in

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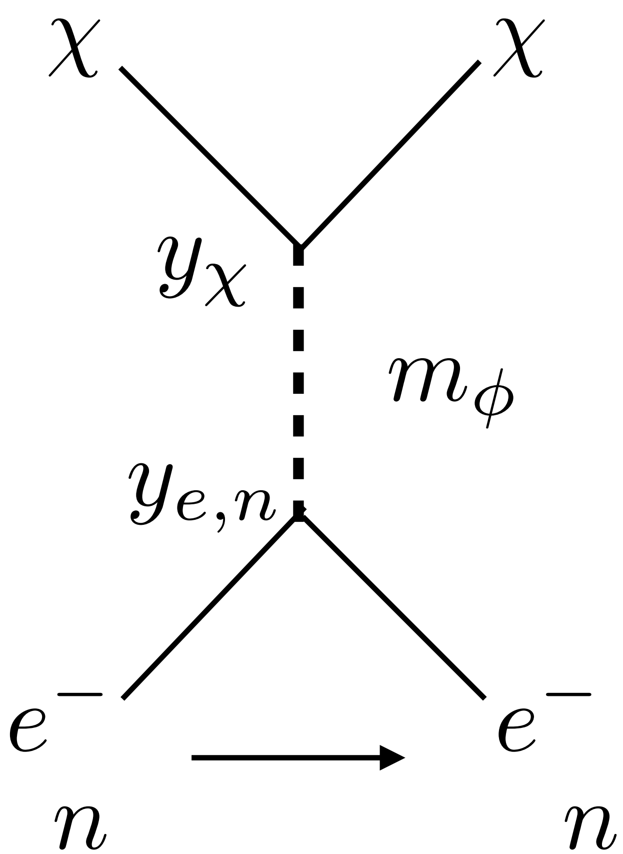
IR freeze-in: $$Y_{\rm DM} \sim \frac{\Gamma}{H} \simeq \frac{\alpha_f \alpha_X M_{\rm pl}}{T}$$

Dominated by lowest temperatures (m_f or m_{DM})

For correct relic abundance: $$g_X g_f \sim 10^{-12} \times \min(1, \sqrt{m_f/m_{\rm DM}})$$

Freeze-in through a light mediator reproduces some appealing features of thermal freeze-out. Many freeze-in variations.

Simplified portal setup



For the moment, consider all scalars

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

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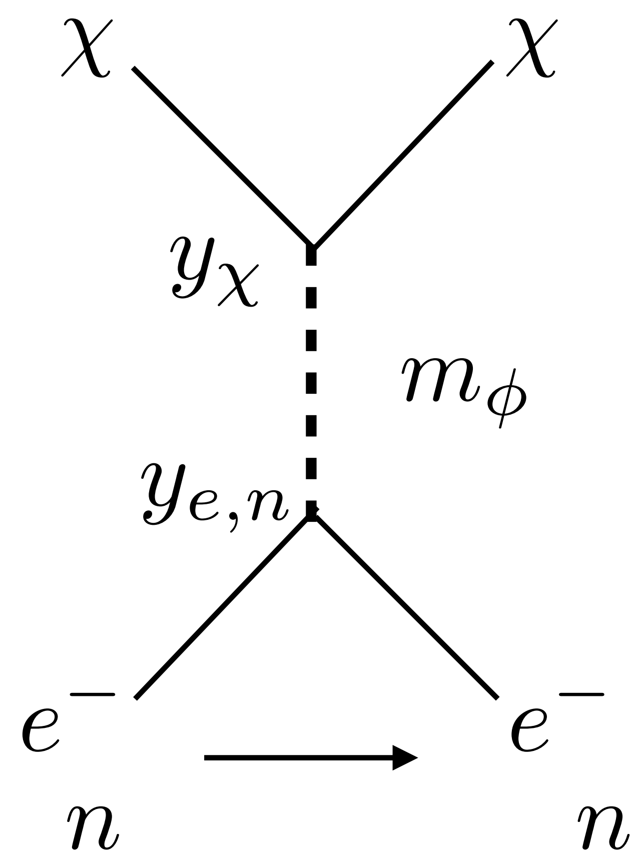

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Scattering in direct detection:

$$\bar{\sigma}_e \equiv \frac{y_\chi^2 y_e^2}{4\pi}\frac{\mu_{\chi e}^2}{(m_\phi^2 + \alpha^2 m_e^2)^2} \qquad q_{\rm typical} \simeq \alpha m_e$$

$$\sigma_n \equiv \frac{y_n^2 y_\chi^2}{4\pi}\frac{\mu_{\chi n}^2}{(m_\phi^2 + v_{DM}^2 m_\chi^2)^2} \qquad q_{\rm typical} \simeq m_\chi v_{DM}$$

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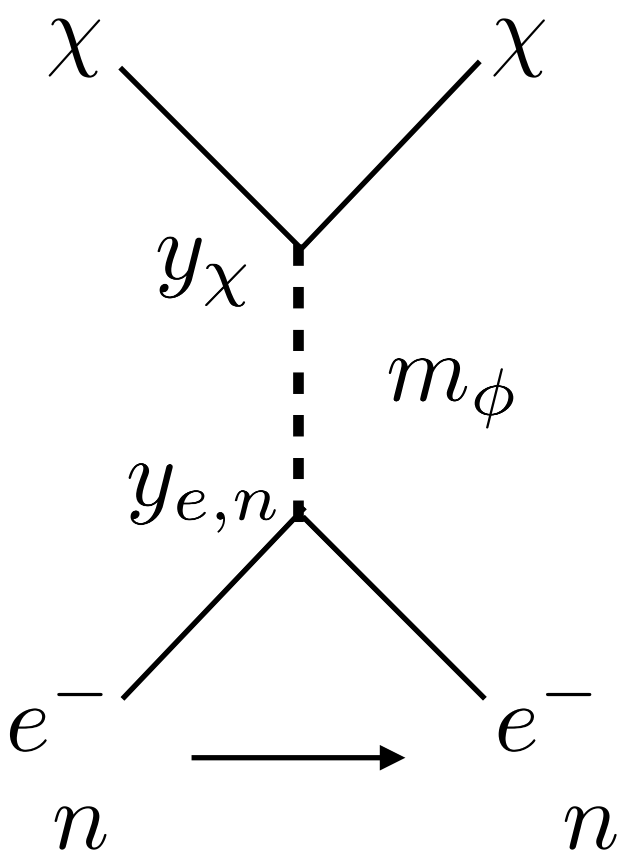

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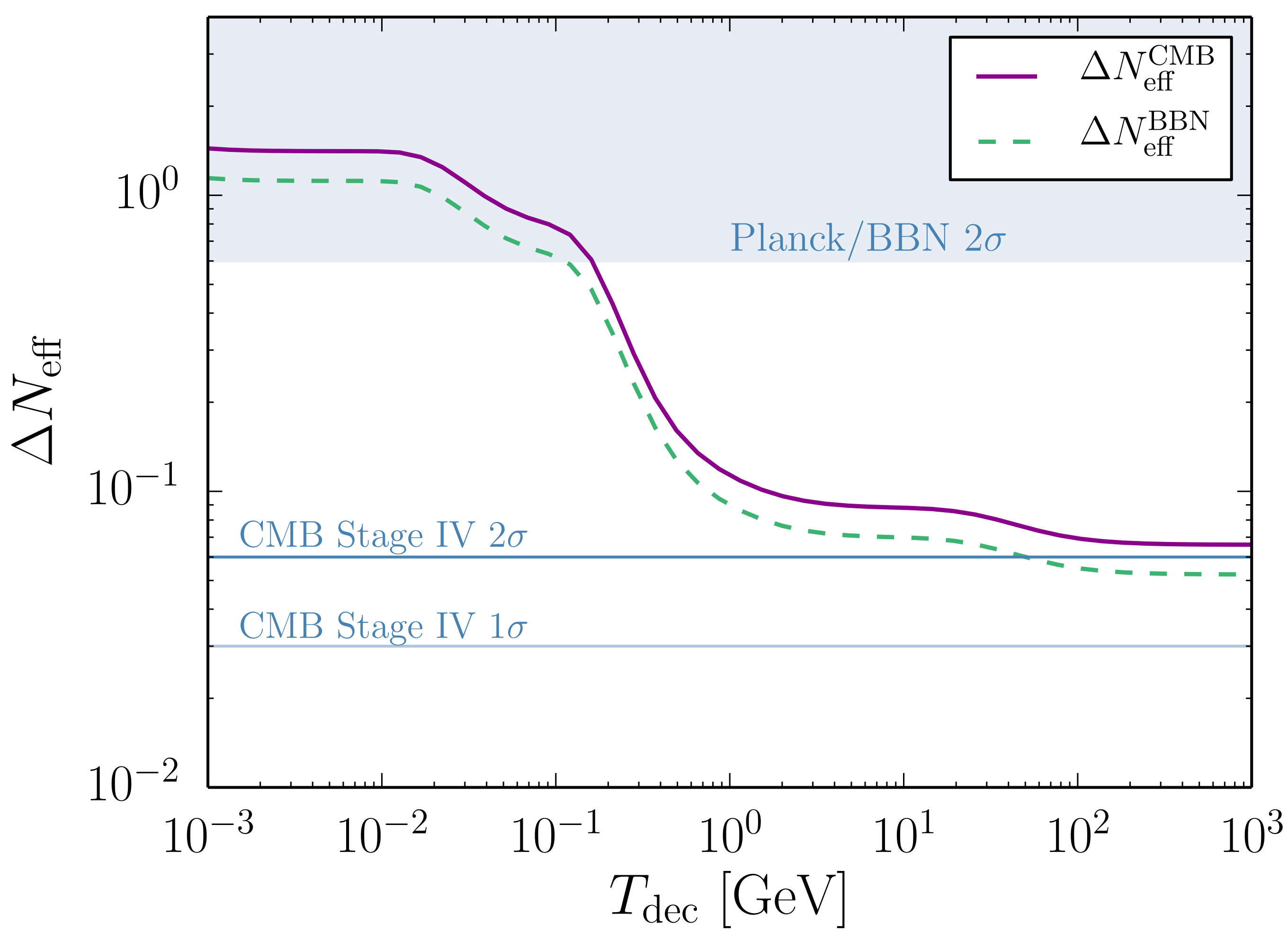
Depending on the mass scales, DM annihilation to SM or mediator not allowed. Introduce dark radiation states for relic abundance:

$$\mathcal{L} \supset -\frac{1}{2}m_a a^2 - \frac{1}{2}y_a m_a \phi a^2 - \frac{1}{4}\lambda\chi^2 a^2$$

Sub-GeV model considerations

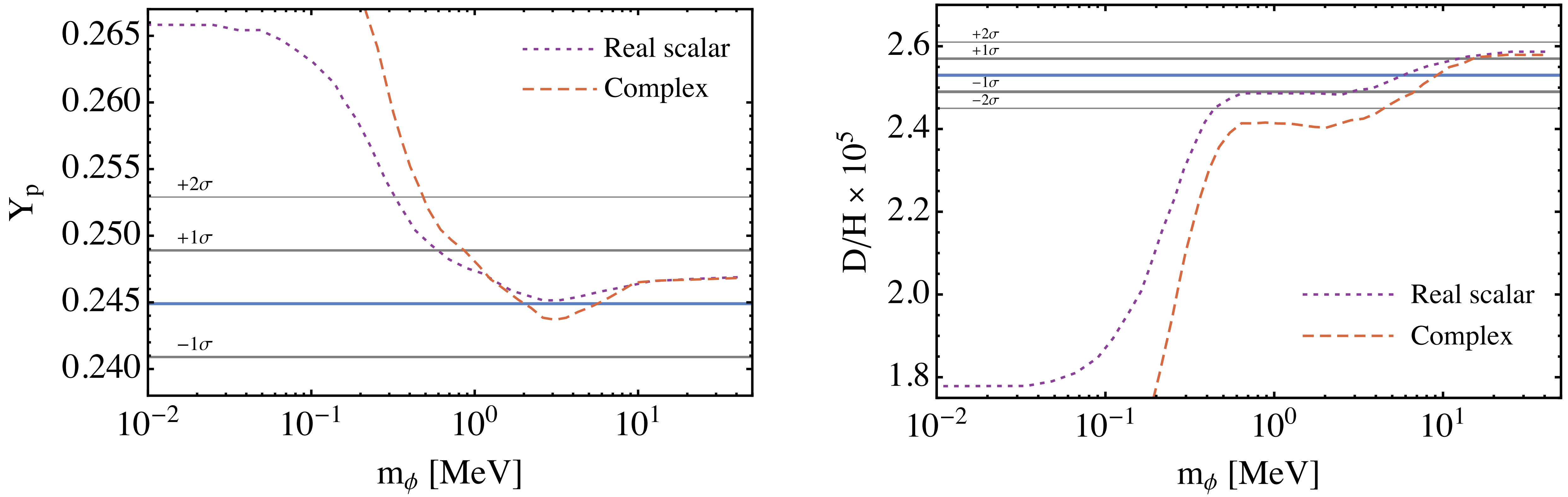
- Direct constraints on mediators (stellar production, lab bounds)
- Constraints on secluded mediator & DM sector from CMB, BBN (consider real fields to minimize effect)



BBN-epoch effect is to increase helium fraction (Yp) and deuterium (D/H)

Sub-GeV model considerations

- If DM or mediator is in equilibrium with the SM photons/electrons, this can effectively change the baryon-to-photon ratio and modify BBN abundances

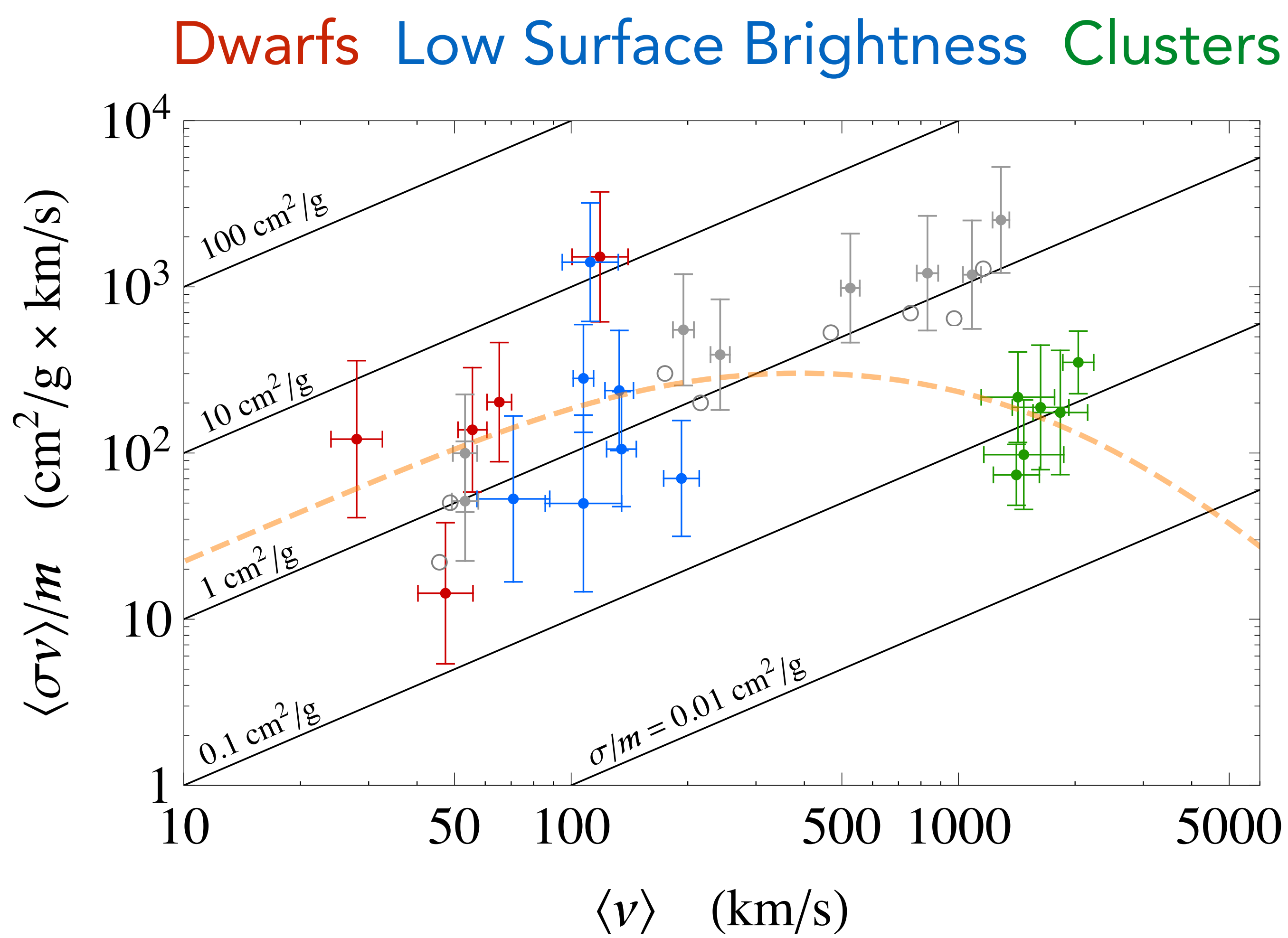


For detailed discussion:
Nollett & Steigman 2014; Boehm et al. 1303.6270
See also Berlin, Blinov, Li 1904.04256

Sub-GeV model considerations

Low-mass dark sectors also affect late-time gravitational clustering on small scales.

$$\Gamma \approx \frac{\rho_{\rm DM}}{m_\chi}\sigma v \approx \frac{1}{10^9\ {\rm year}}$$



From Kaplinghat, Tulin, Yu 2015

Sub-GeV model considerations

Fit to data with
$m_\chi = 15\ \mathrm{GeV}$
$m_V = 17\ \mathrm{MeV}$

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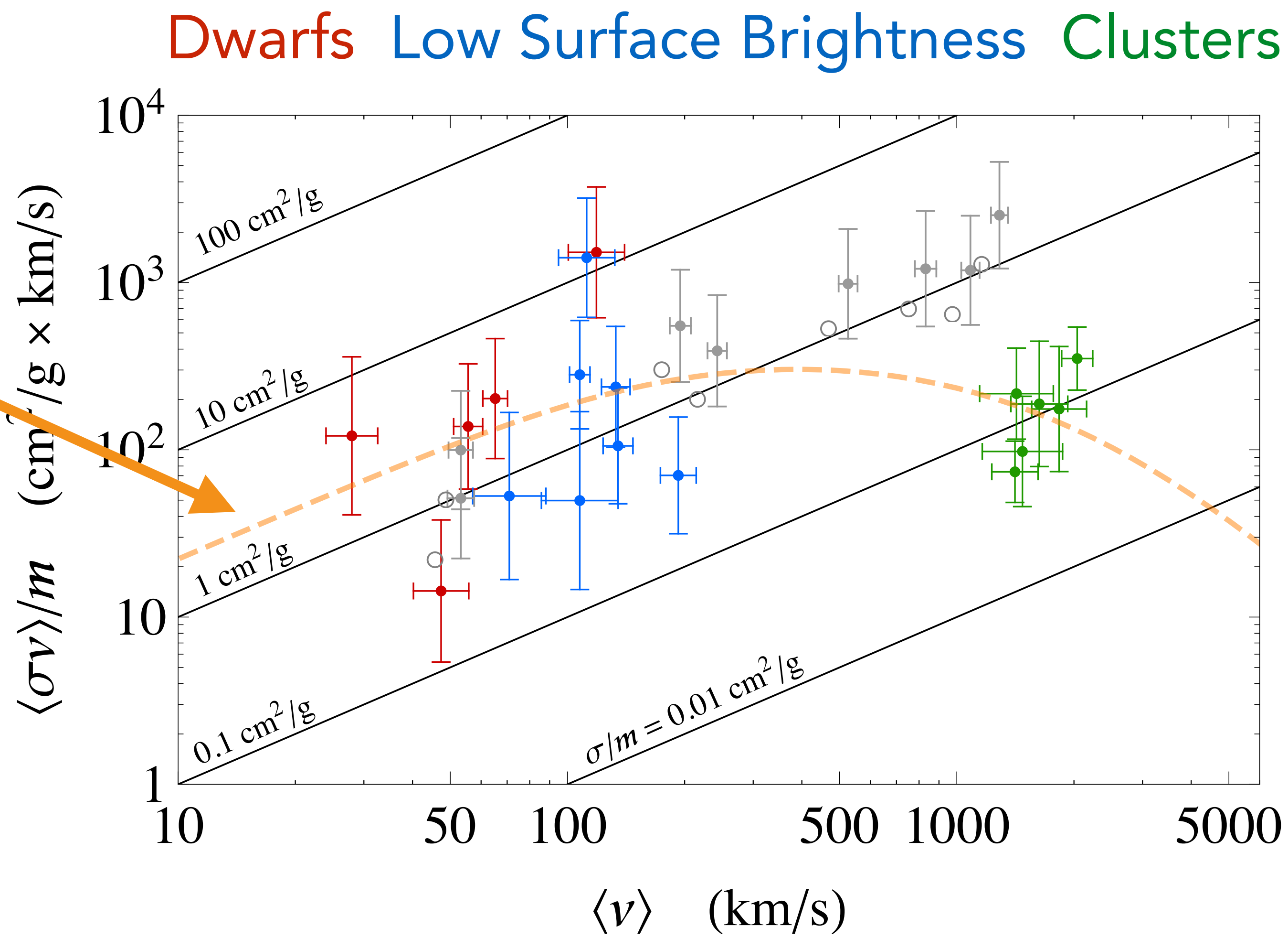

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Sub-GeV model considerations

- Self-interaction bounds

Heavy mediator limit

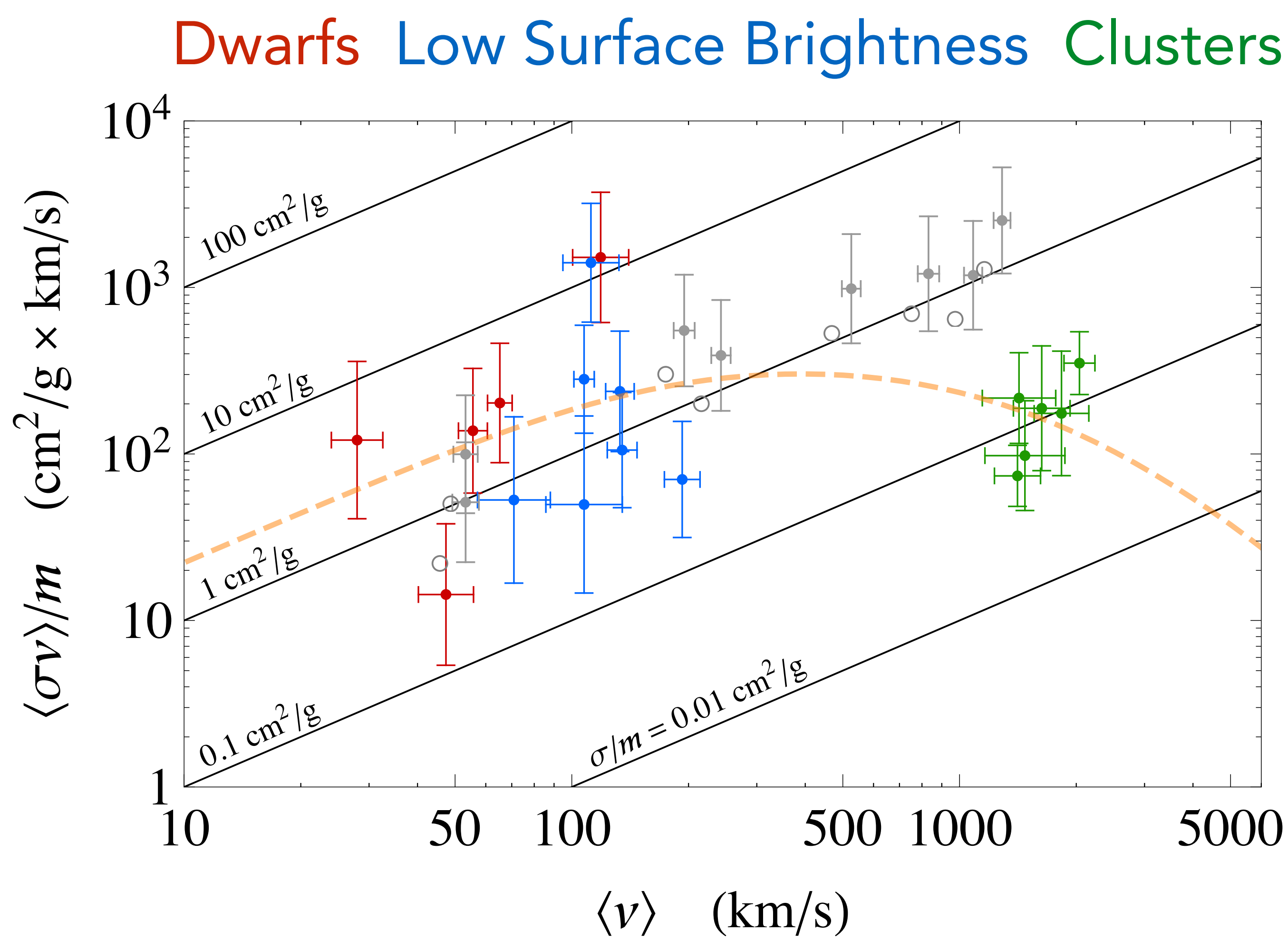
$$m_\phi \gg 10^{-3} m_\chi$$

$$\alpha_\chi \lesssim 0.025 \left(\frac{1\ \text{keV}}{m_\chi}\right)^{1/2} \left(\frac{m_\phi}{1\ \text{MeV}}\right)^2$$

Light mediator limit

$$m_\phi \lesssim 10^{-3} m_\chi$$

$$\alpha_\chi \lesssim 6 \times 10^{-10} \times \left(\frac{m_\chi}{1\ \text{MeV}}\right)^{3/2}$$



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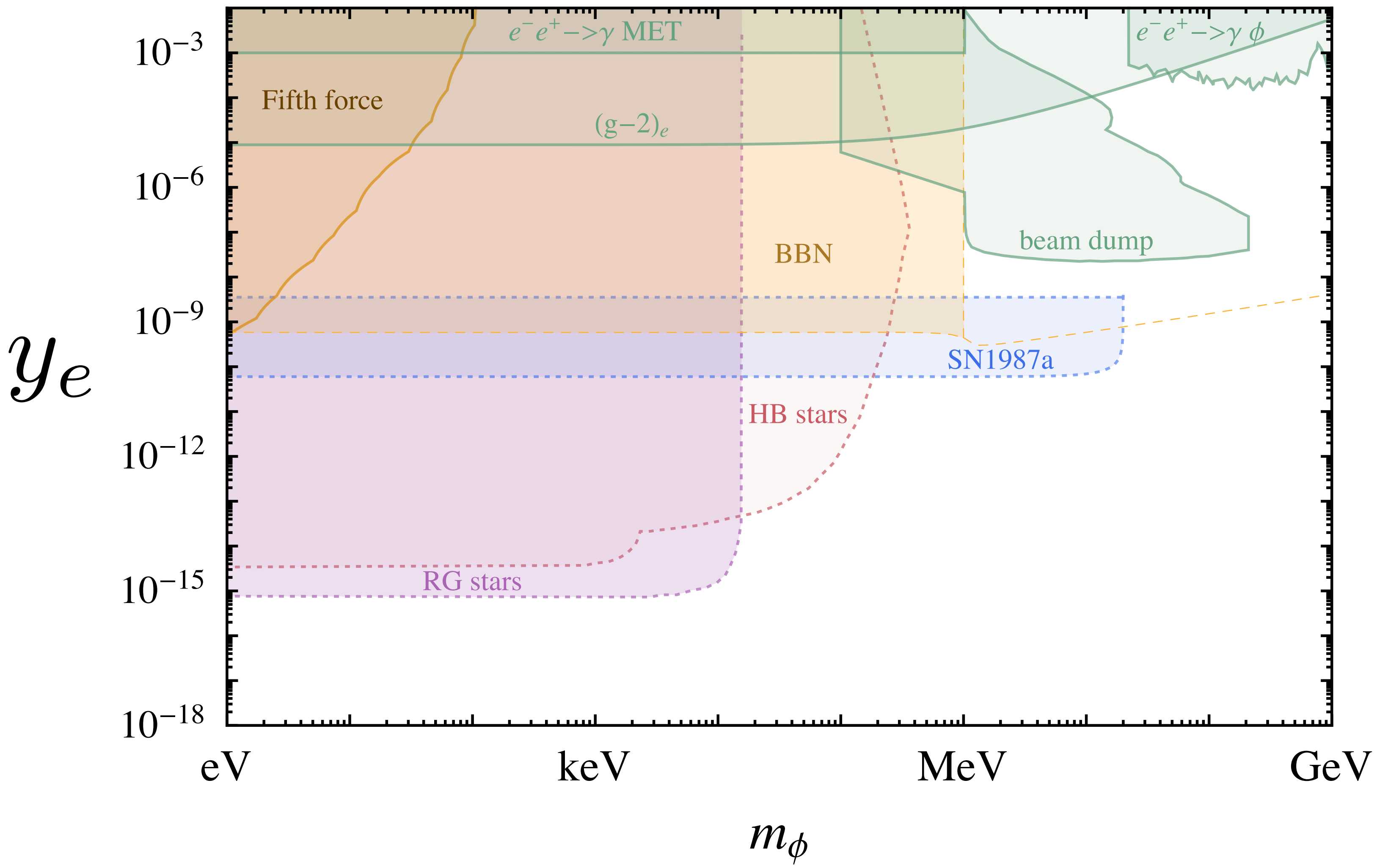
Leptophilic scalar

Couplings to a light mediator are strongly constrained
by stellar emission and fifth force searches on the low mass end



Scalar coupled to electron

From Knapen, TL, Zurek 2017
See also Krnjaic 2017

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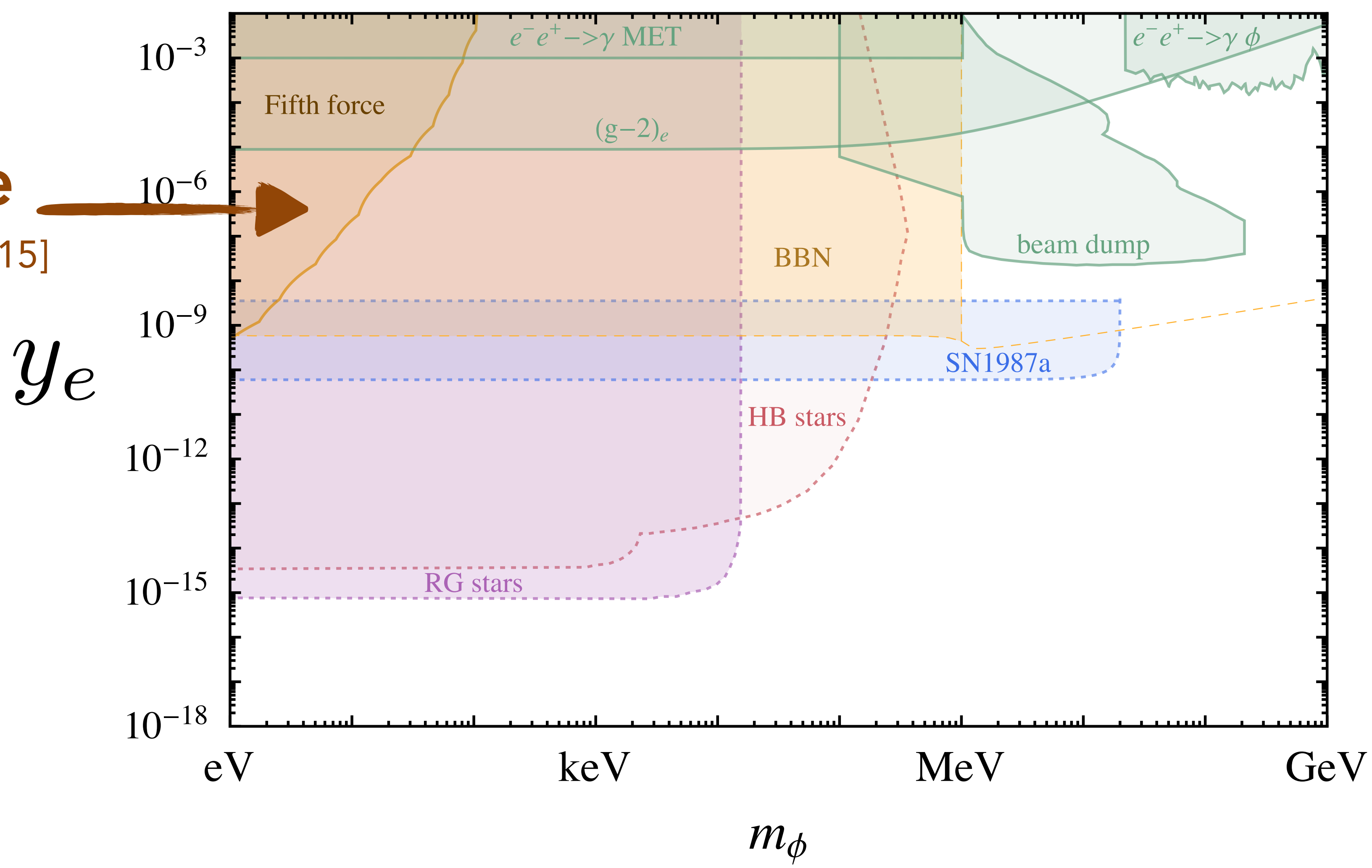
Fifth force

[Murata & Tanaka 2015]



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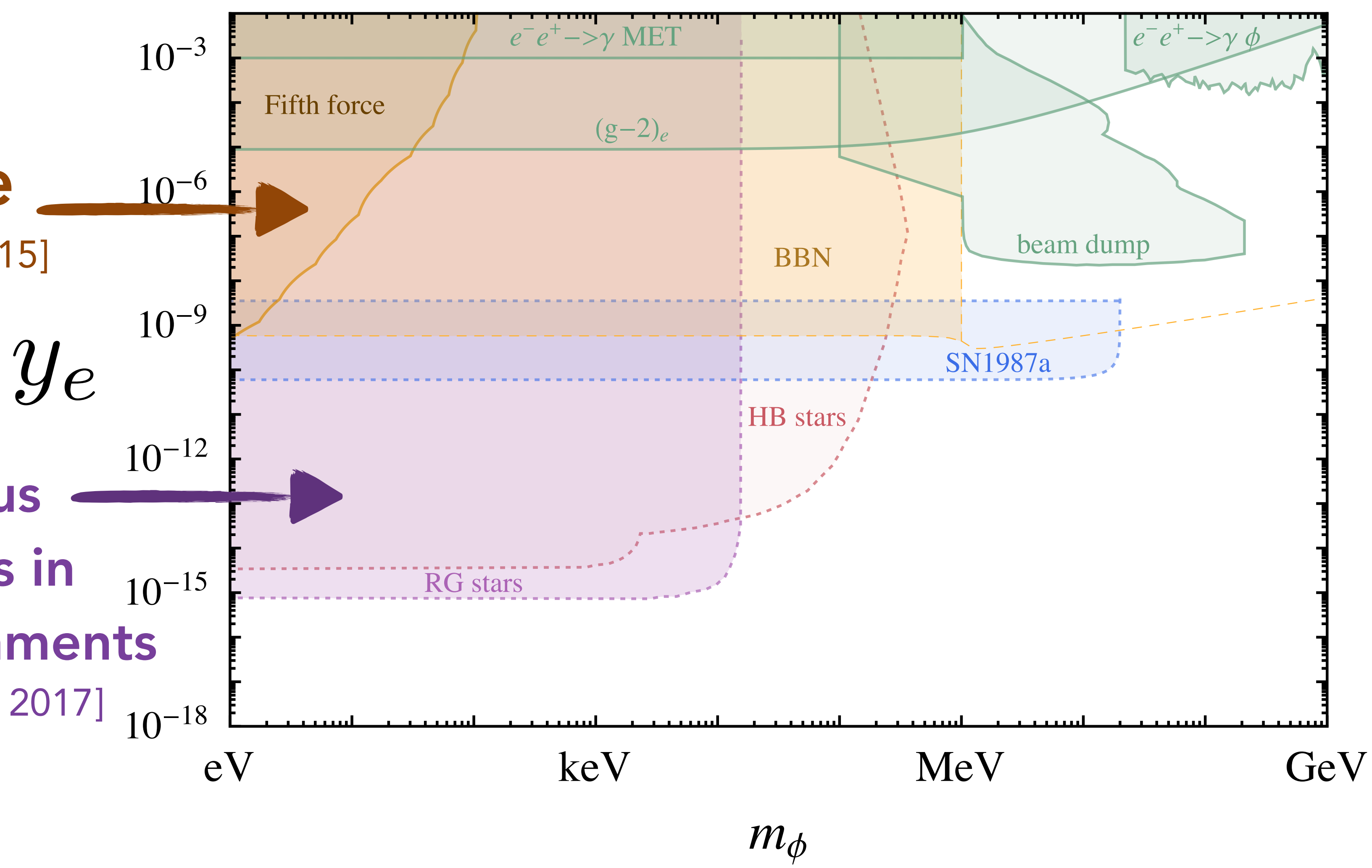
[Murata & Tanaka 2015]

Anomalous energy loss in stellar environments
[Hardy & Lasenby 2017]



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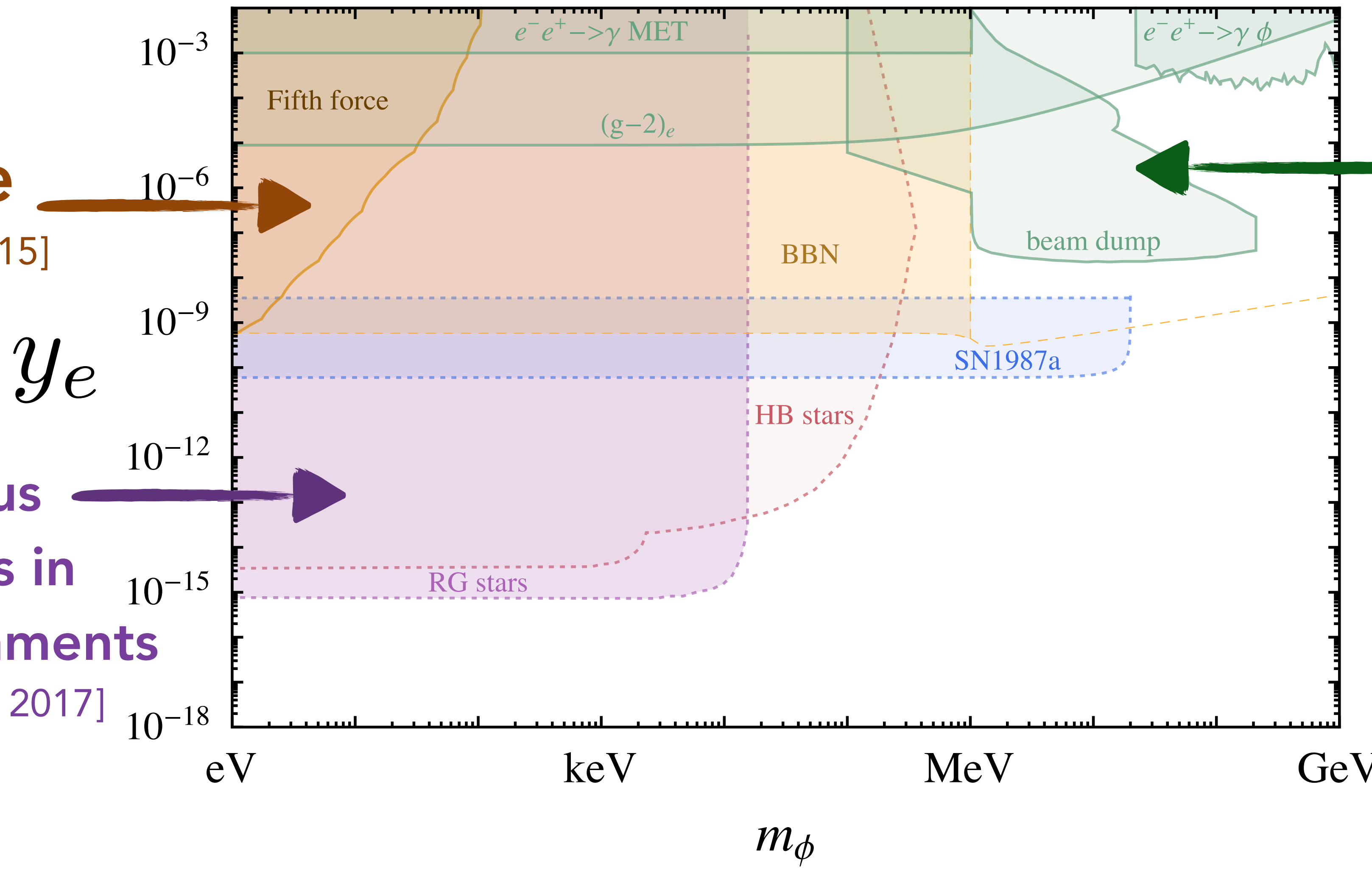

Accelerator bounds
[Liu et al. 1605.04612, Babar dark photon searches **assuming mϕ < 2 mX**]

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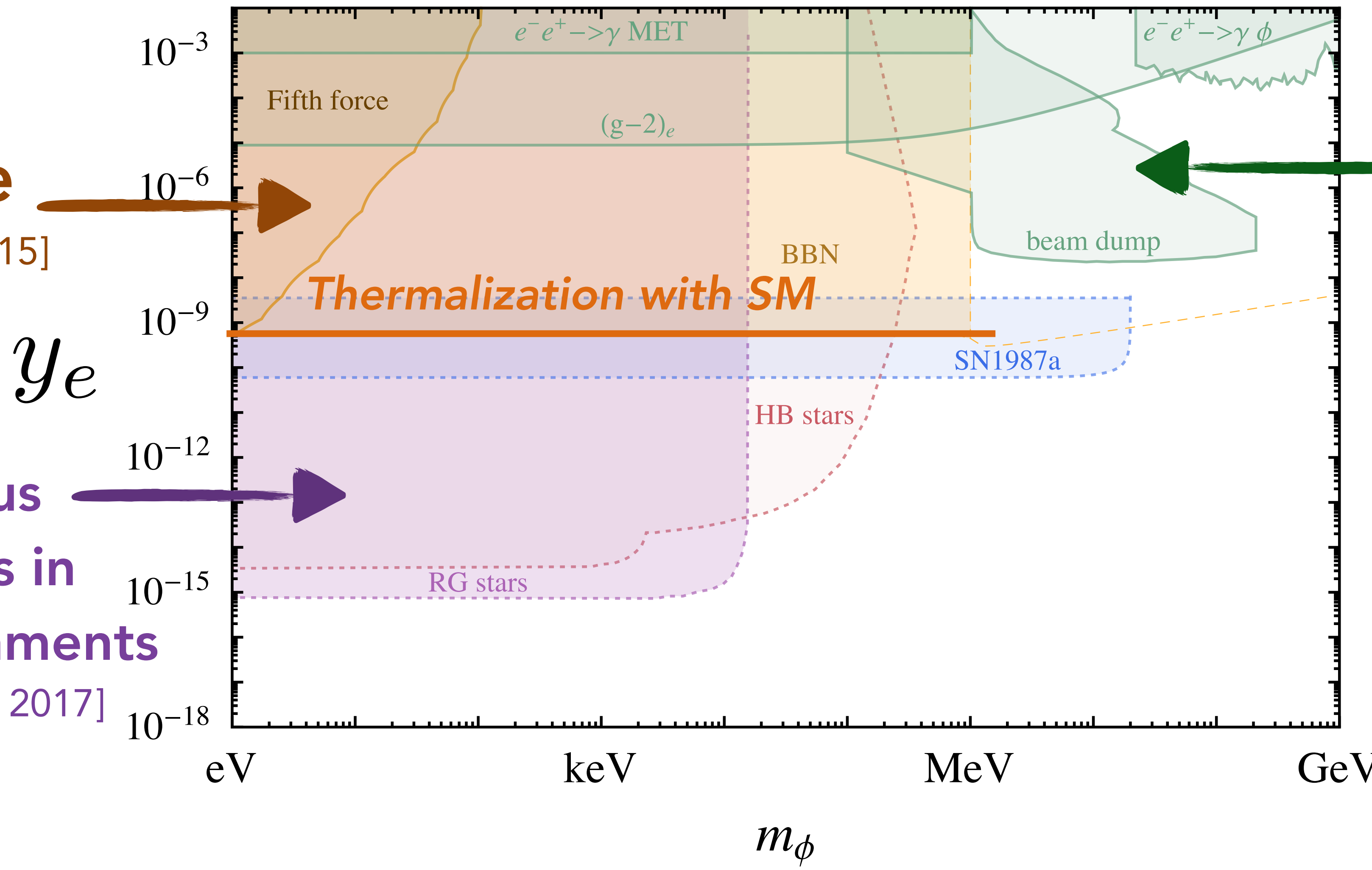

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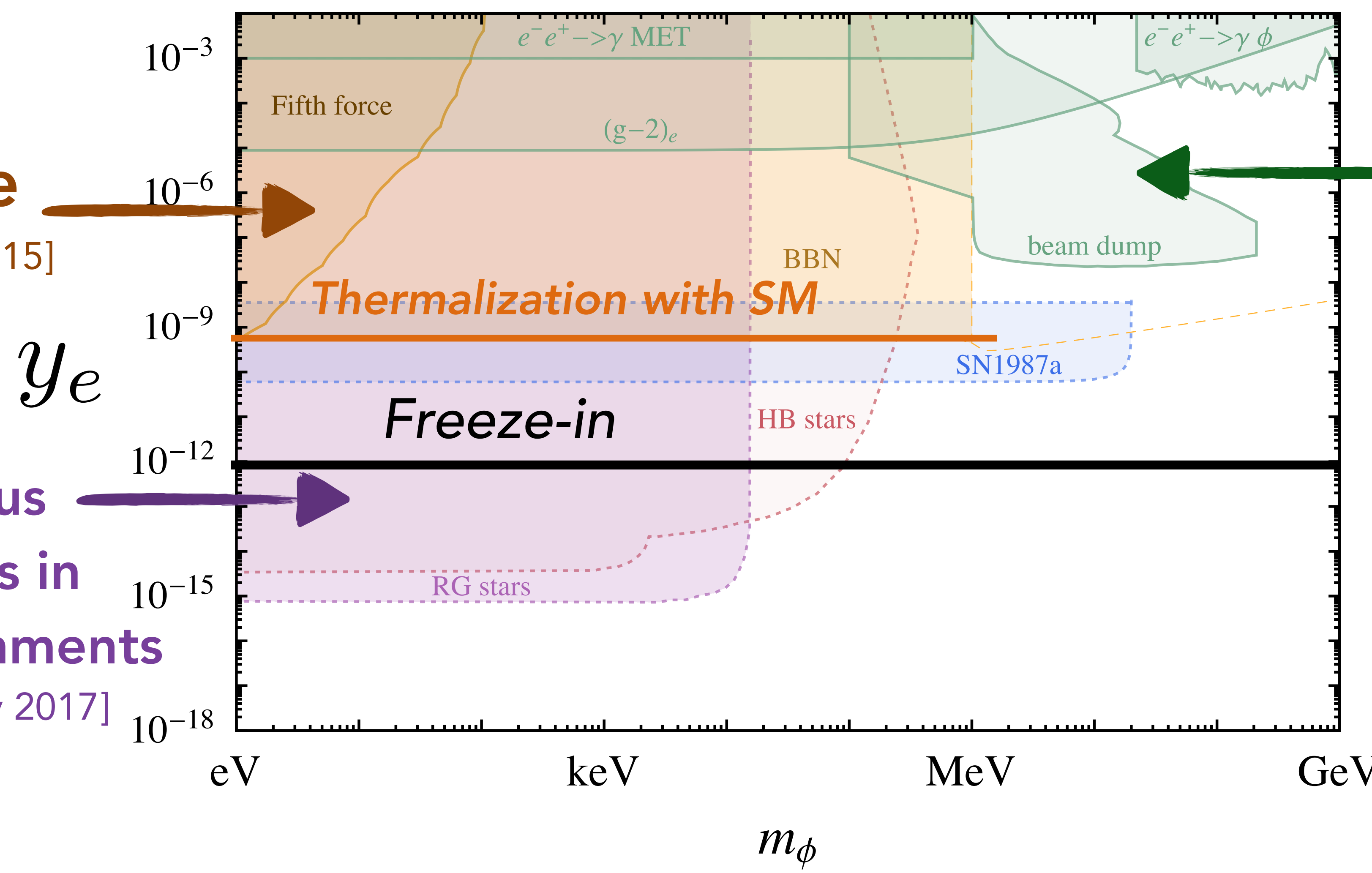

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Electron scattering

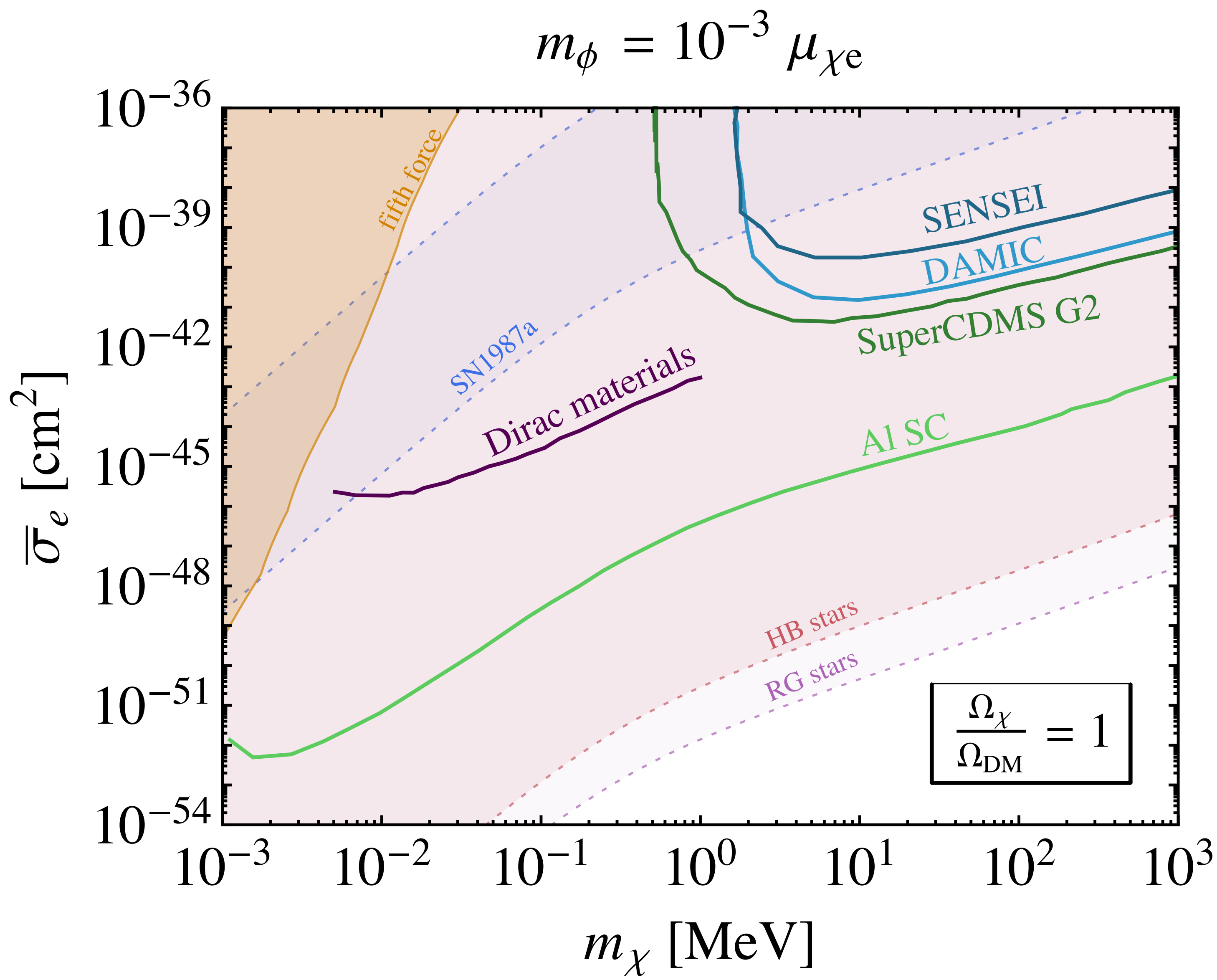
$$\bar{\sigma}_e \equiv \frac{y_\chi^2 y_e^2}{4\pi} \frac{\mu_{\chi e}^2}{(m_\phi^2 + \alpha^2 m_e^2)^2}$$

Typical momentum transfer^2 for electron scattering in target

Combination of stellar+SIDM constraints severely limits open parameter space.

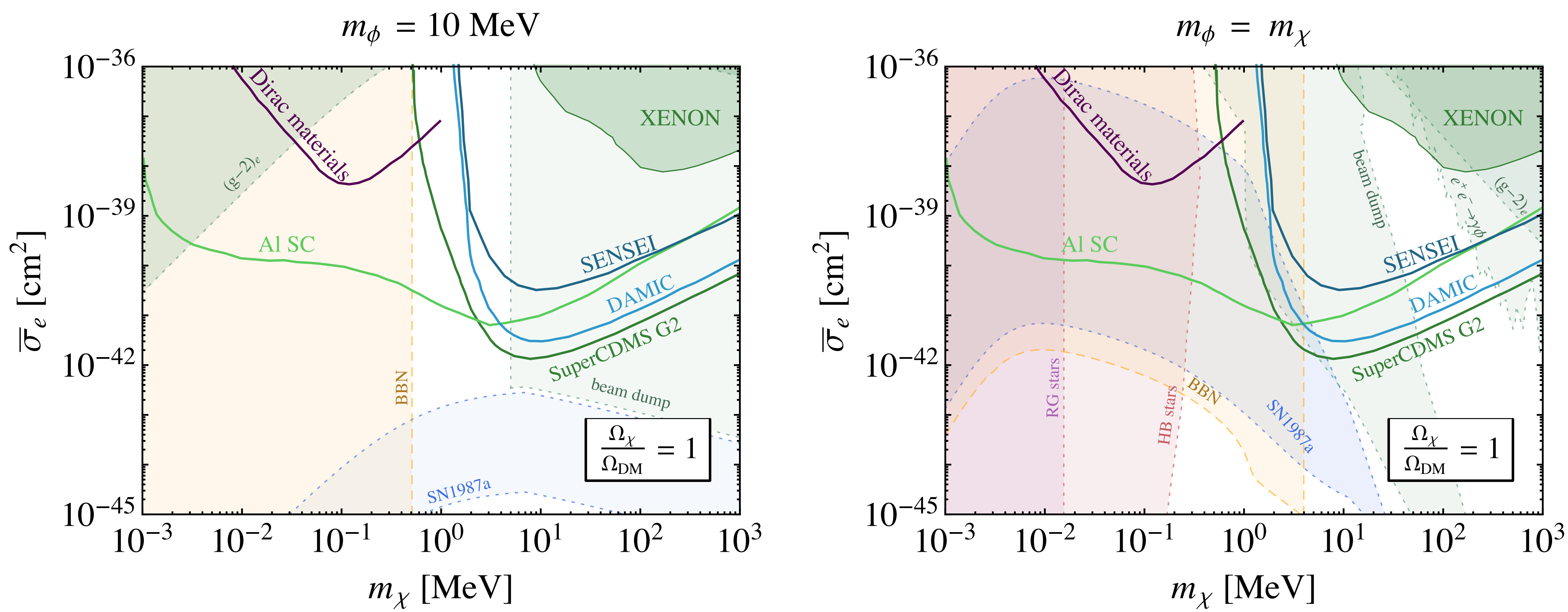
Considering sub-component DM can open things up a little.

``Light" mediator case



Electron scattering

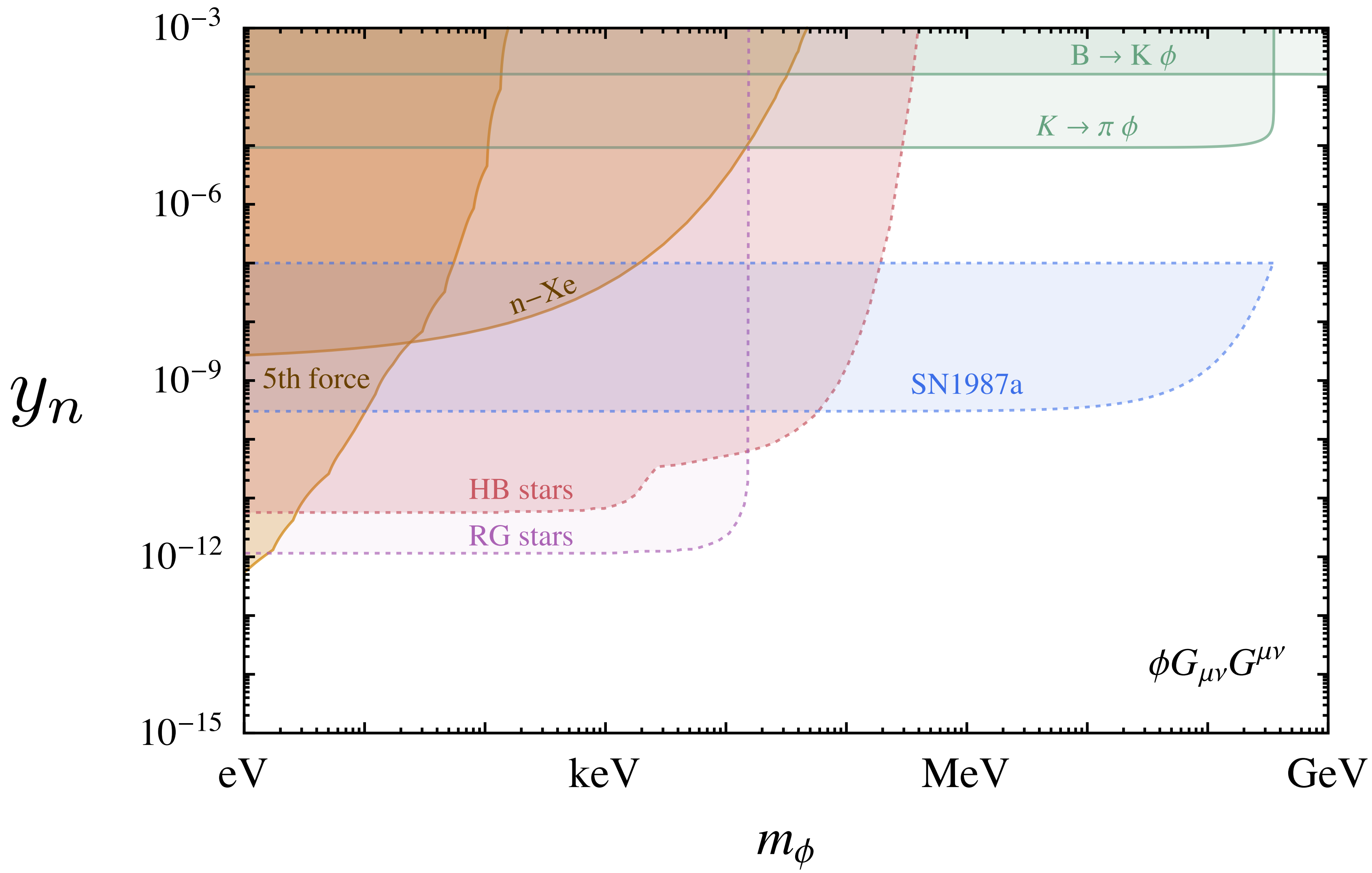
``Heavy” mediator case



DM masses below MeV are strongly constrained by BBN measurements of ΔNeff.

Nucleo-philic scalar

Thermalization of mediator is more dangerous here because fewer SM states to go back to…



Scalar coupled to gluons

From Knapen, TL, Zurek 2017
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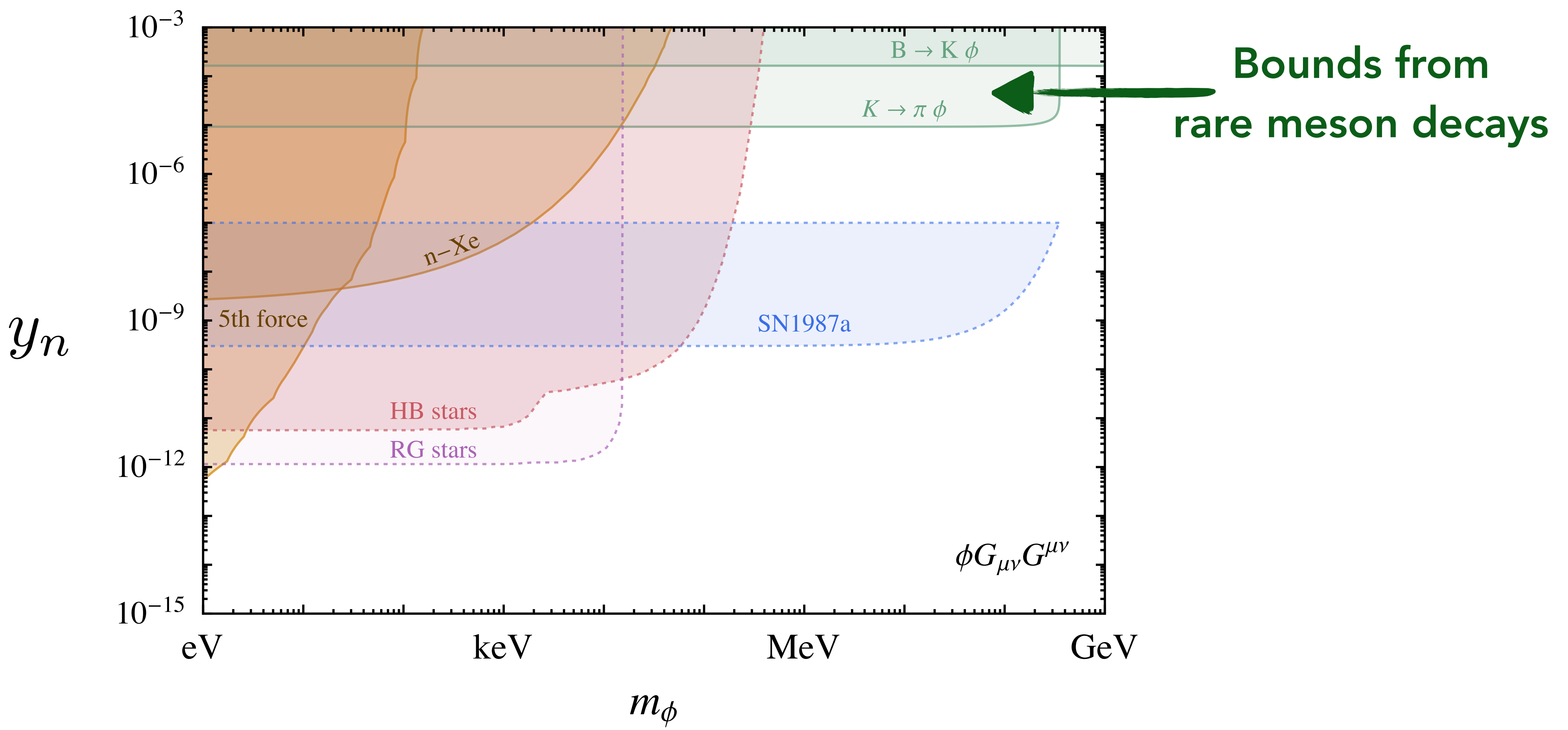

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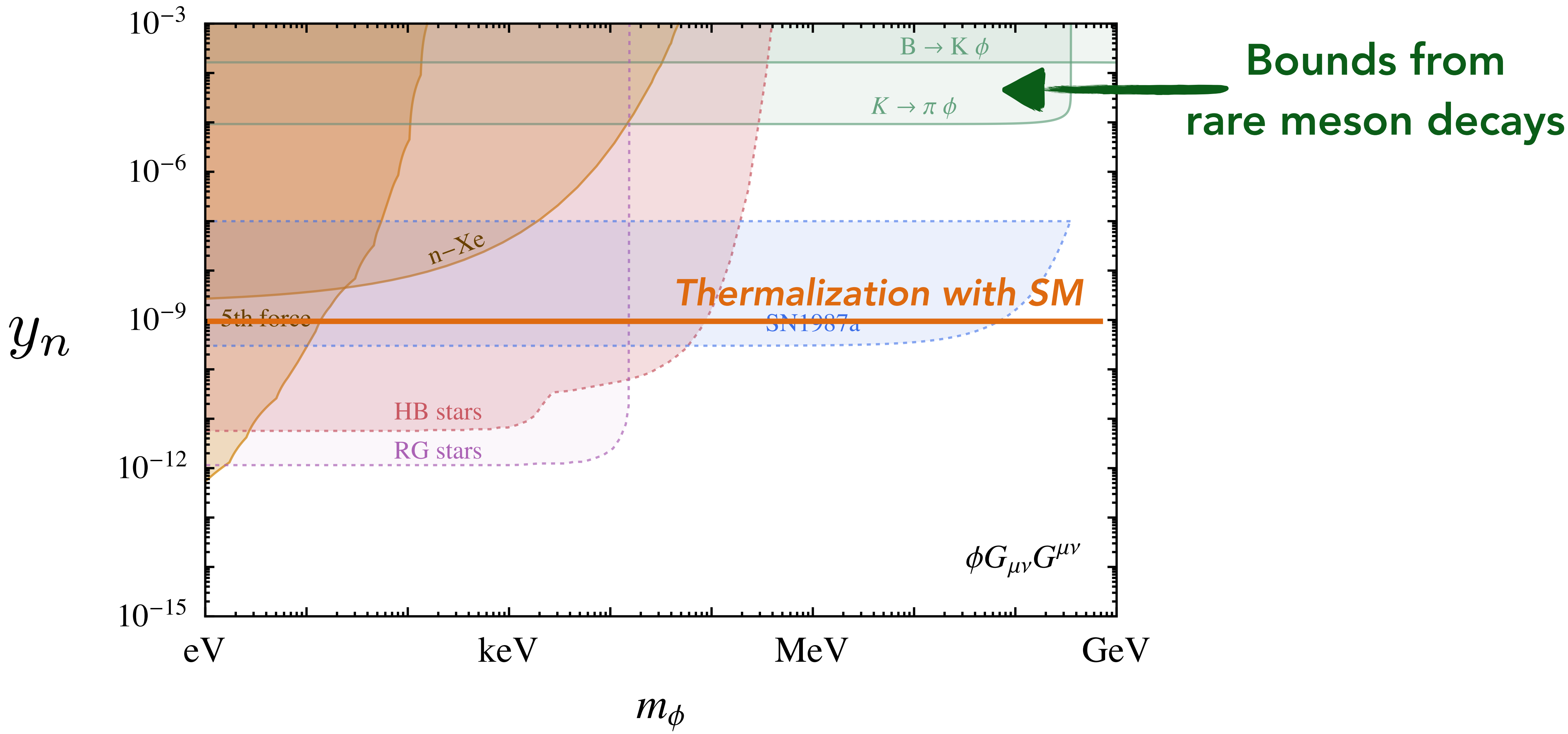

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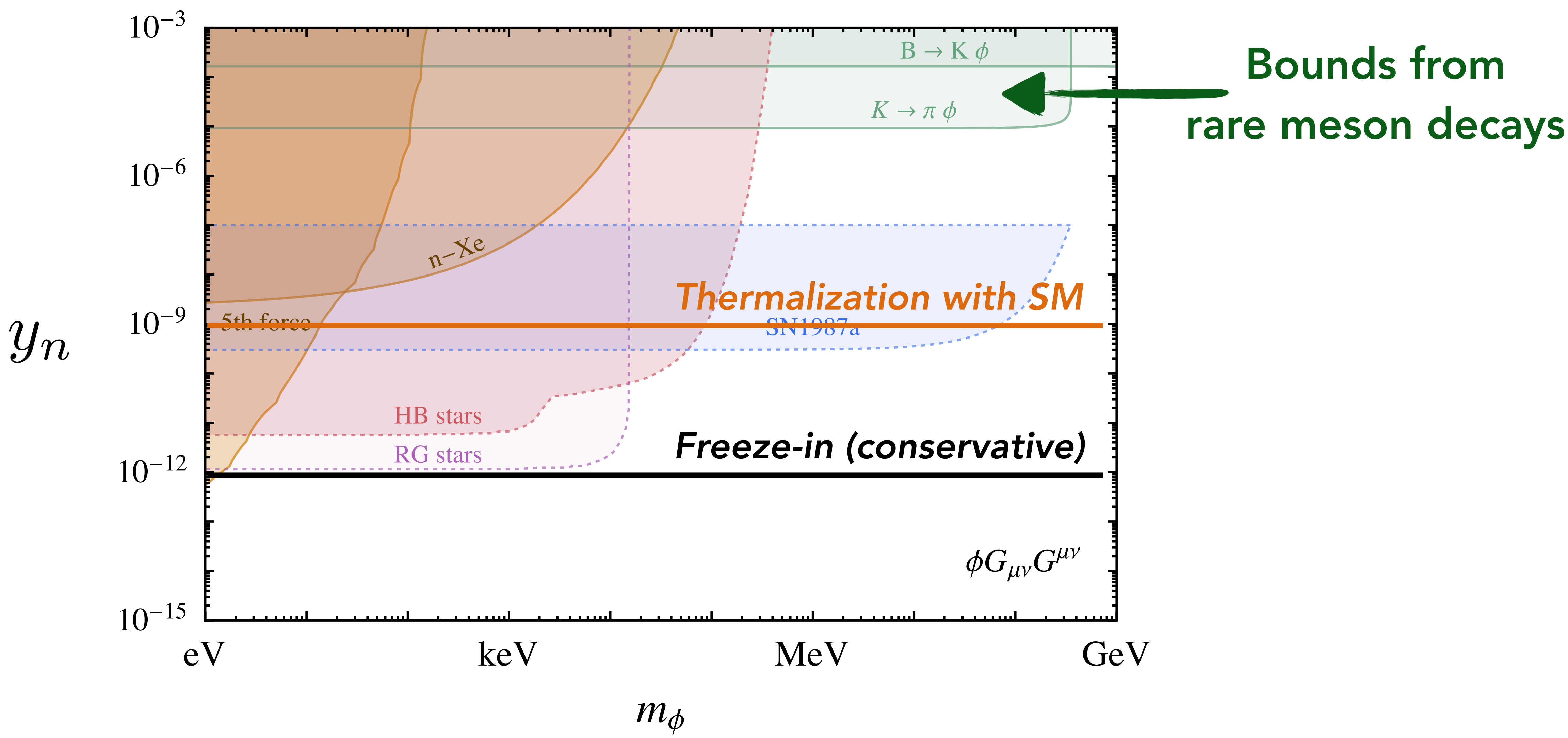

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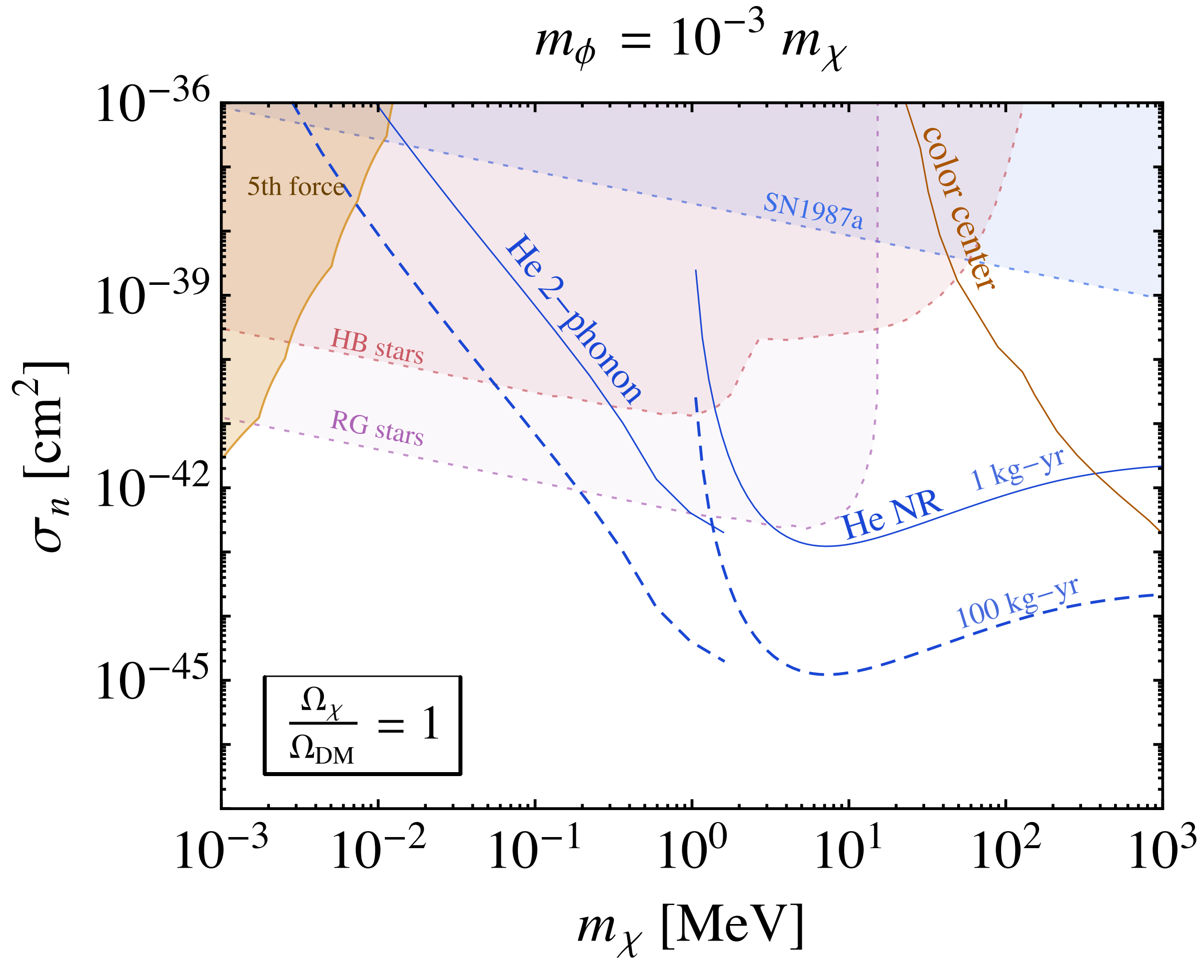
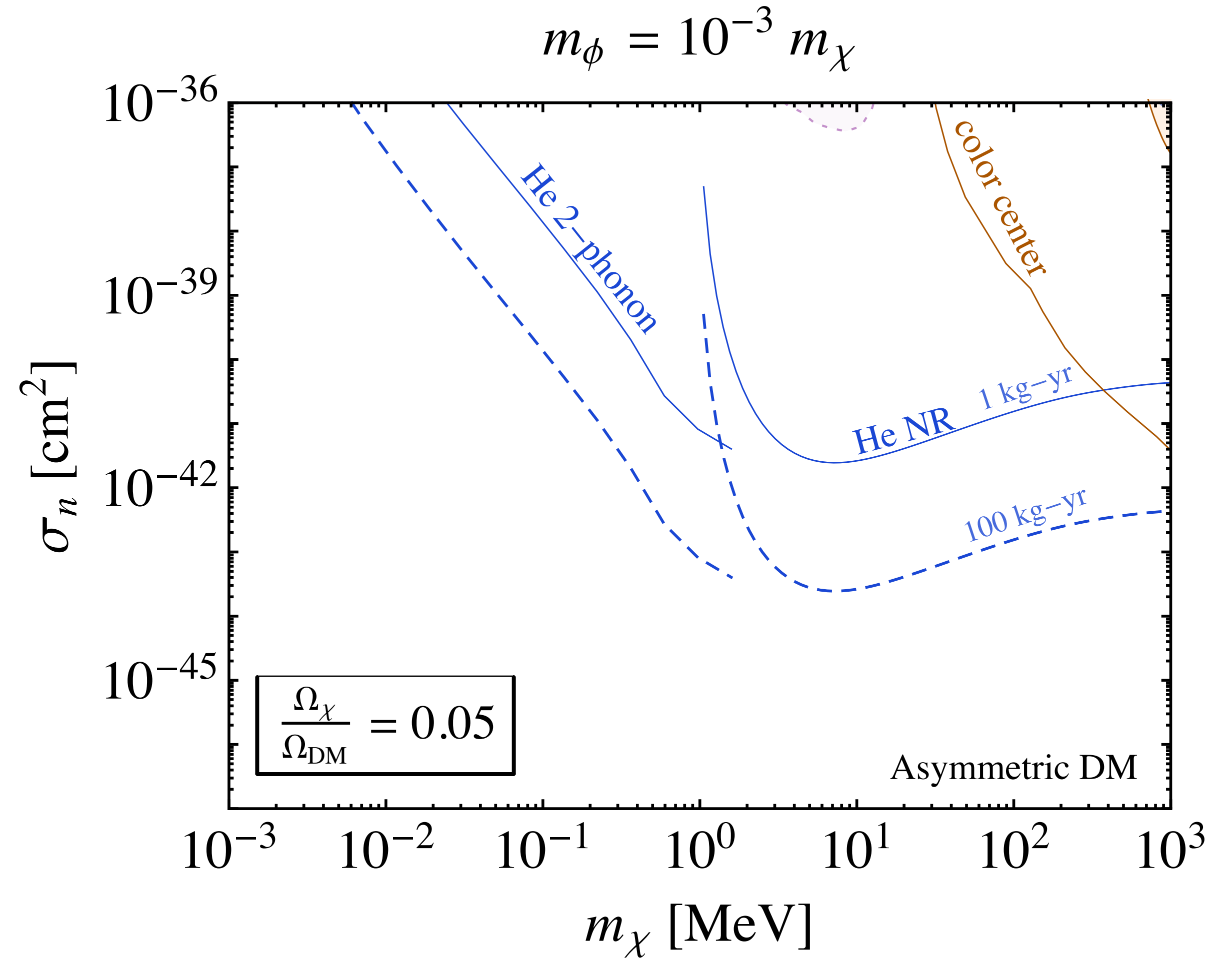
Nuclear recoils

``Light” mediator case $m_\phi \lesssim 10^{-3} m_\chi$



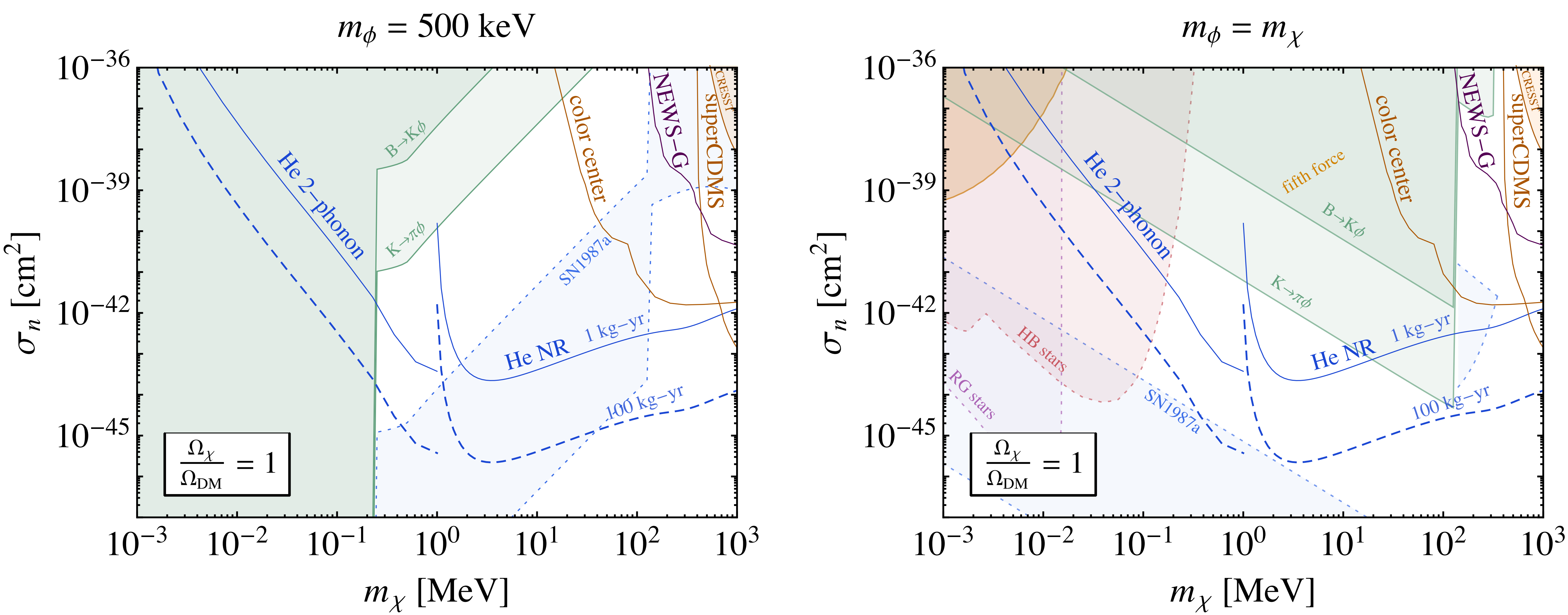
with SIDM bounds



without SIDM bounds

Nuclear recoils

``Heavy" mediator case

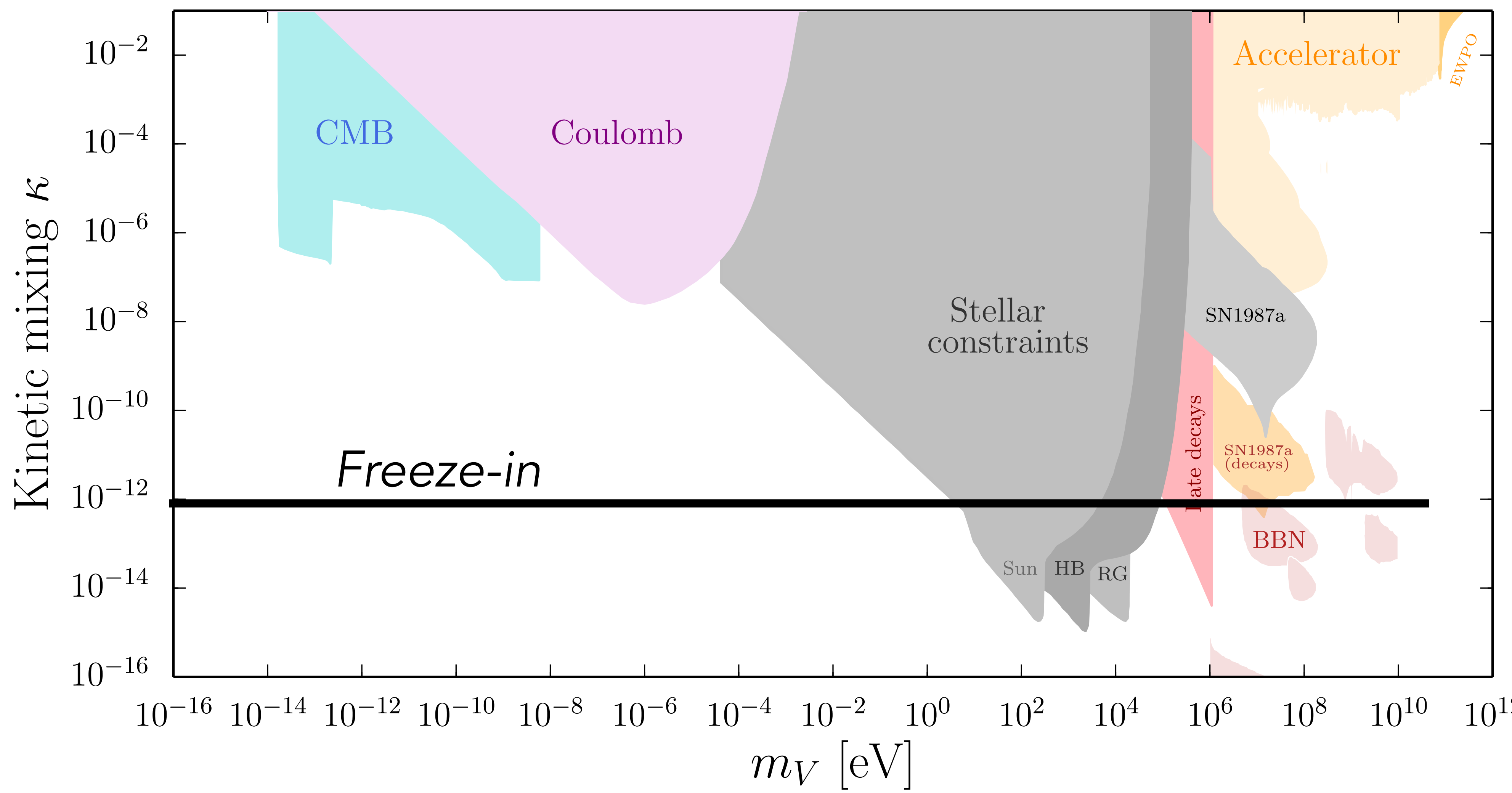


For mX < 100 MeV, mediator thermalizes with the SM bath after QCD phase transition and ΔNeff = 0.57!

Dark photon mediated models

Dark photon

Stellar and fifth force constraints are much weaker for dark photon mediators



Kinetically-mixed dark photon

In-medium dark photon couplings

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu_{\rm EM} + g_\chi V_\mu J^\mu_D$$

Usual (vacuum) interaction basis ↓ $A_\mu \to A_\mu + \kappa V_\mu$

$$e(A_\mu + \kappa V_\mu)J^\mu_{\rm EM} + g_\chi V_\mu J^\mu_D$$

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In-medium interactions ↓

$$\mathcal{L} \supset -\tfrac{1}{2}A_\mu \Pi^{\mu\nu} A_\nu - \kappa A_\mu \Pi^{\mu\nu} V_\nu$$

$$\Pi^{\mu\nu}(q) = \Pi_L(q)\eta^\mu_L\eta^\nu_L + \Pi_T(q)\,(\eta^\mu_+)^*\,\eta^\nu_+ + \Pi_T(q)\,(\eta^\mu_-)^*\,\eta^\nu_-$$

In-medium dark photon couplings

Diagonalizing quadratic terms gives effective in-medium couplings

↓

$$\mathcal{L} \supset -\frac{1}{4}\bar{F}^{+}_{\mu\nu}\bar{F}^{\mu\nu}_{+} - \frac{1}{4}\bar{V}^{+}_{\mu\nu}\bar{V}^{\mu\nu}_{+} + \frac{1}{2}\Pi_T(q)\bar{A}^{+}_{\mu}\bar{A}^{\mu}_{+} + \frac{1}{2}m_V^2\bar{V}^{+}_{\mu}\bar{V}^{\mu}_{+}$$
$$+ e\left(\bar{A}^{+}_{\mu} + \frac{\kappa m_V^2}{m_V^2 - \Pi_T(q)}\bar{V}^{+}_{\mu}\right)J^{\mu}_{\rm EM} + g_\chi\left(\bar{V}^{+}_{\mu} - \frac{\kappa\,\Pi_T(q)}{m_V^2 - \Pi_T(q)}\bar{A}^{+}_{\mu}\right)J^{\mu}_{D}$$

(similar result for longitudinal modes)

For $|\mathbf{q}| \sim \omega$ and non-relativistic plasma, $\Pi_T(q) \approx \omega_p^2$

In-medium dark photon couplings

$$e\left(\bar{A}^+_\mu + \frac{\kappa m_V^2}{m_V^2 - \Pi_T(q)}\bar{V}^+_\mu\right) J^\mu_{\mathrm{EM}} + g_\chi\left(\bar{V}^+_\mu - \frac{\kappa\,\Pi_T(q)}{m_V^2 - \Pi_T(q)}\bar{A}^+_\mu\right) J^\mu_D$$

Implications

In-medium dark photon couplings

$$e\left(\bar{A}^+_\mu + \frac{\kappa m_V^2}{m_V^2 - \Pi_T(q)}\bar{V}^+_\mu\right) J^\mu_{\rm EM} + g_\chi \left(\bar{V}^+_\mu - \frac{\kappa\,\Pi_T(q)}{m_V^2 - \Pi_T(q)}\bar{A}^+_\mu\right) J^\mu_D$$

Implications

Production of dark photon in stars is suppressed by $(mV/\omega_p)^2 \sim (mV/keV)^2$ for small mV. Resonant production is possible for $mV=\omega_p$

In-medium dark photon couplings

$$e\left(\bar{A}_\mu^+ + \frac{\kappa m_V^2}{m_V^2 - \Pi_T(q)}\bar{V}_\mu^+\right) J_{\rm EM}^\mu + g_\chi\left(\bar{V}_\mu^+ - \frac{\kappa\,\Pi_T(q)}{m_V^2 - \Pi_T(q)}\bar{A}_\mu^+\right) J_D^\mu$$

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In the ultralight mediator limit, dark matter coupled to V can be treated as effectively millicharged.

In-medium dark photon couplings

$$e\left(\bar{A}^+_\mu + \frac{\kappa m_V^2}{m_V^2 - \Pi_T(q)}\bar{V}^+_\mu\right) J^\mu_{\rm EM} + g_\chi\left(\bar{V}^+_\mu - \frac{\kappa\,\Pi_T(q)}{m_V^2 - \Pi_T(q)}\bar{A}^+_\mu\right) J^\mu_D$$

Implications

Production of dark photon in stars is suppressed by $(mV/\omega_p)^2 \sim (mV/keV)^2$ for small mV. Resonant production is possible for $mV = \omega_p$

In the ultralight mediator limit, dark matter coupled to V can be treated as effectively millicharged.

Benchmarks with dark matter coupling to massive mediators are mostly unaffected

Heavy mediator limit

Thermal freeze out with scalar DM or asymmetric fermion DM is viable above ~10 MeV

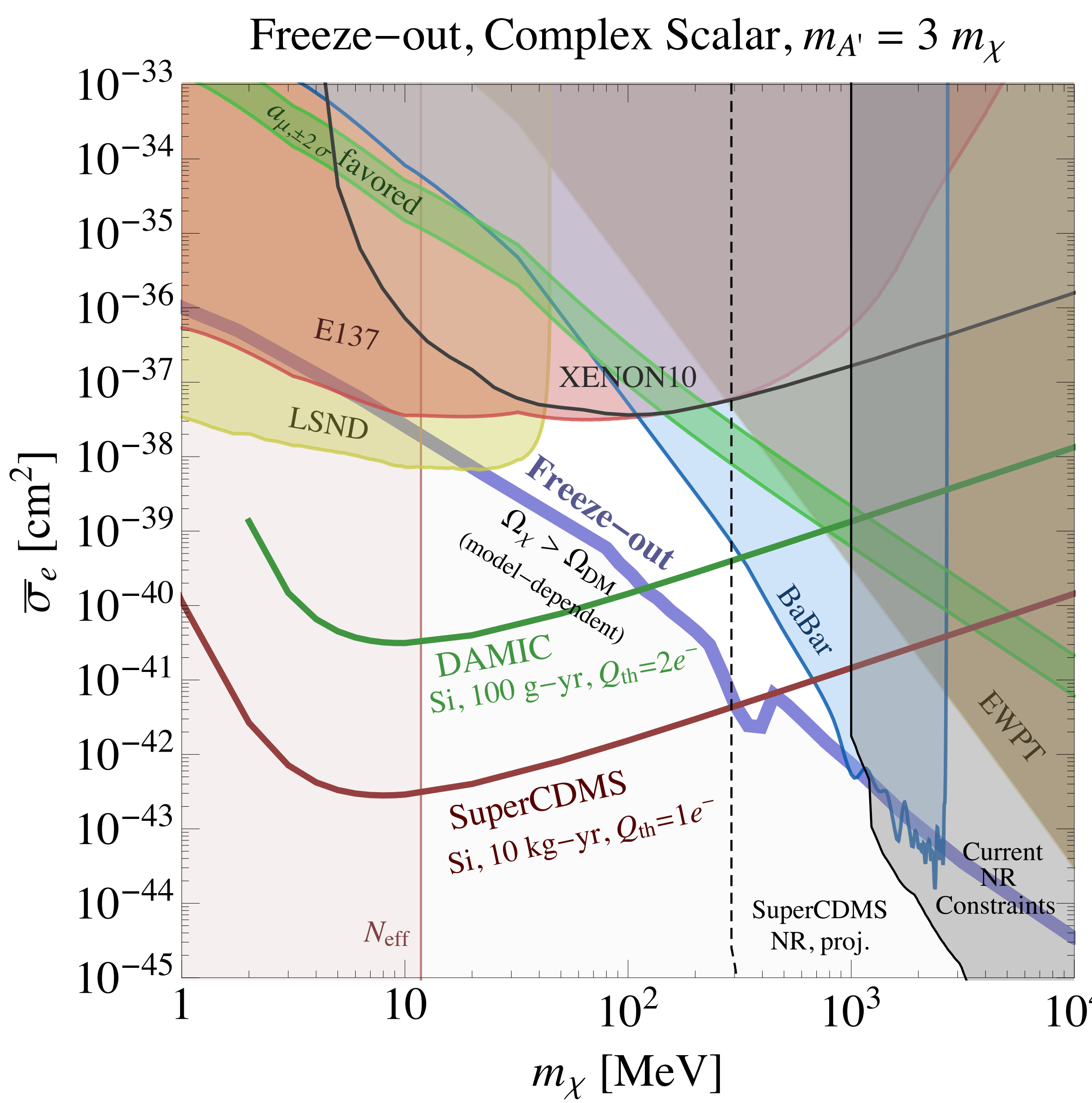
$$\bar{\sigma}_e \equiv \frac{16\pi\alpha_\chi\alpha_{em}\kappa^2\mu_{\chi e}^2}{\left(m_V^2+\alpha_{em}^2 m_e^2\right)^2}$$

Example parameters:

$m_\chi \simeq 20\ \mathrm{MeV}$ $\quad g_\chi \simeq 0.3$

$m_V \simeq 60\ \mathrm{MeV}$ $\quad \kappa \simeq 3\times 10^{-4}$

Accessible also with accelerator searches



From Essig et al. 2015

The ultralight mediator limit

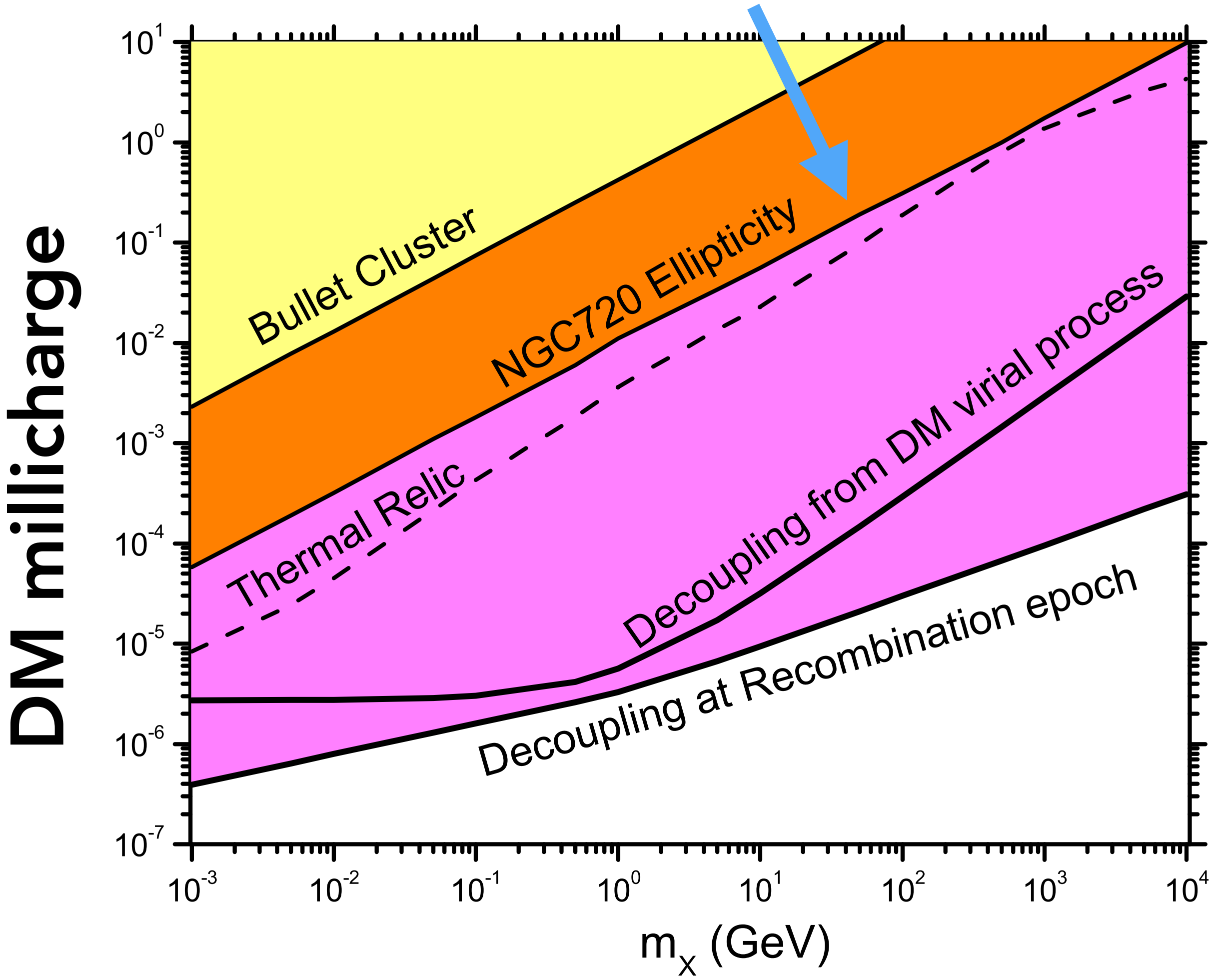
For dark photon masses below ~eV, define effective millicharge

$$Q = \frac{\kappa g_X}{e}$$

Self-interaction bounds on gX push us to large κ and thus to the ultralight mediator mass limit

—> Can be considered specific realization of millicharged DM

Couplings for thermal freezeout



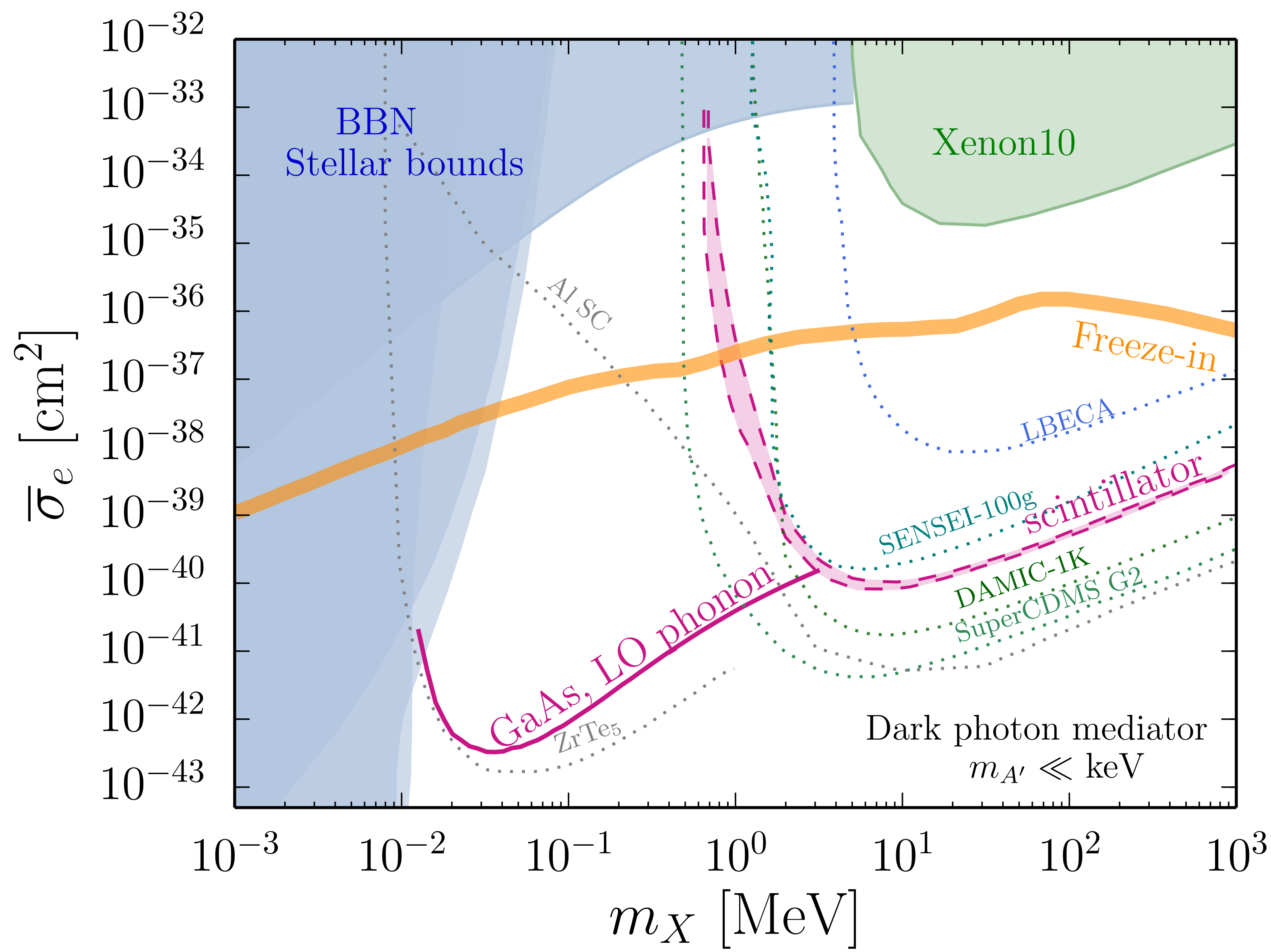
From McDermott, Yu, Zurek 2010

Thermal freeze-in benchmark

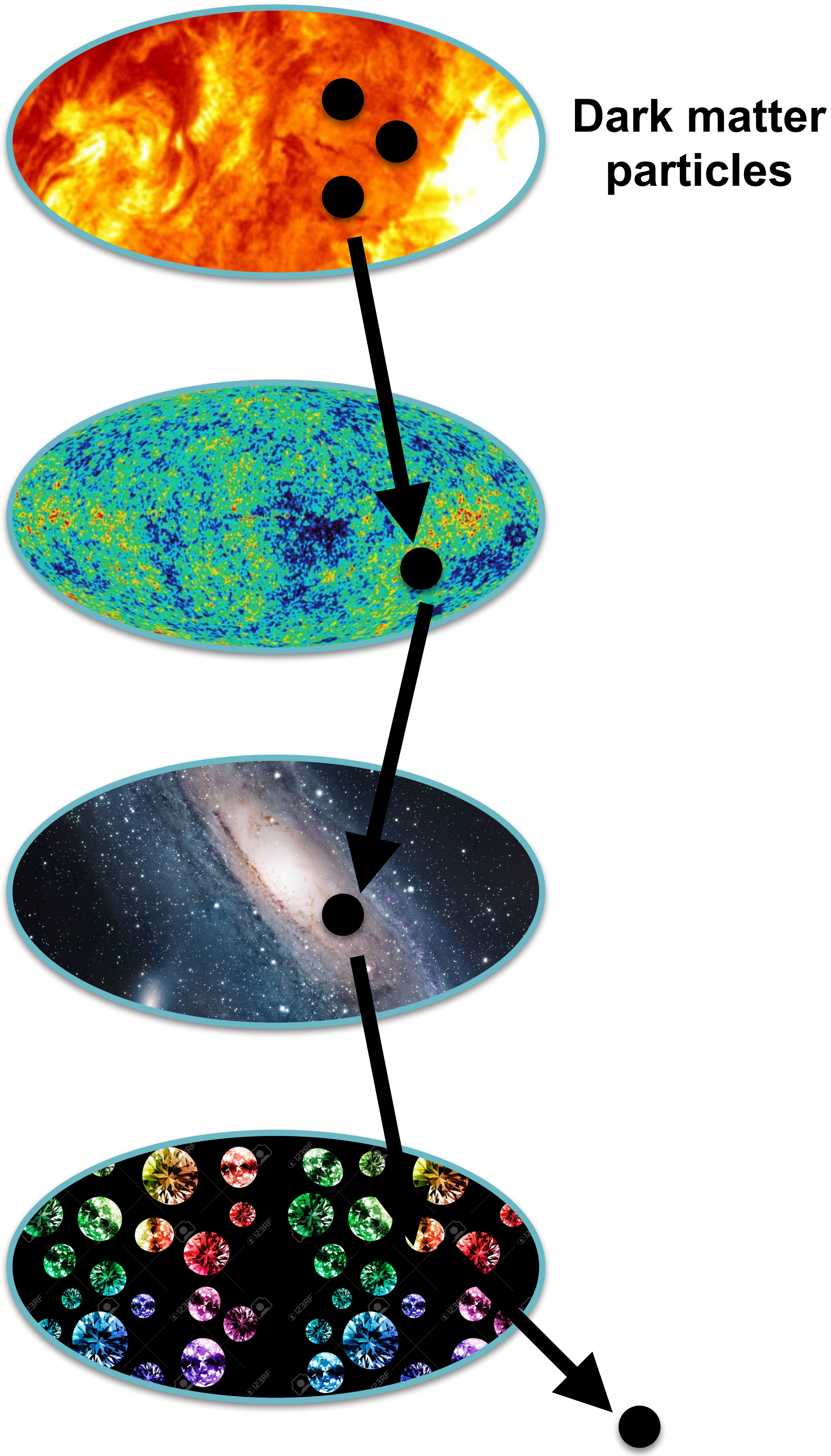
DM has millicharge $Q = \frac{\kappa g_X}{e} \sim 10^{-11}$

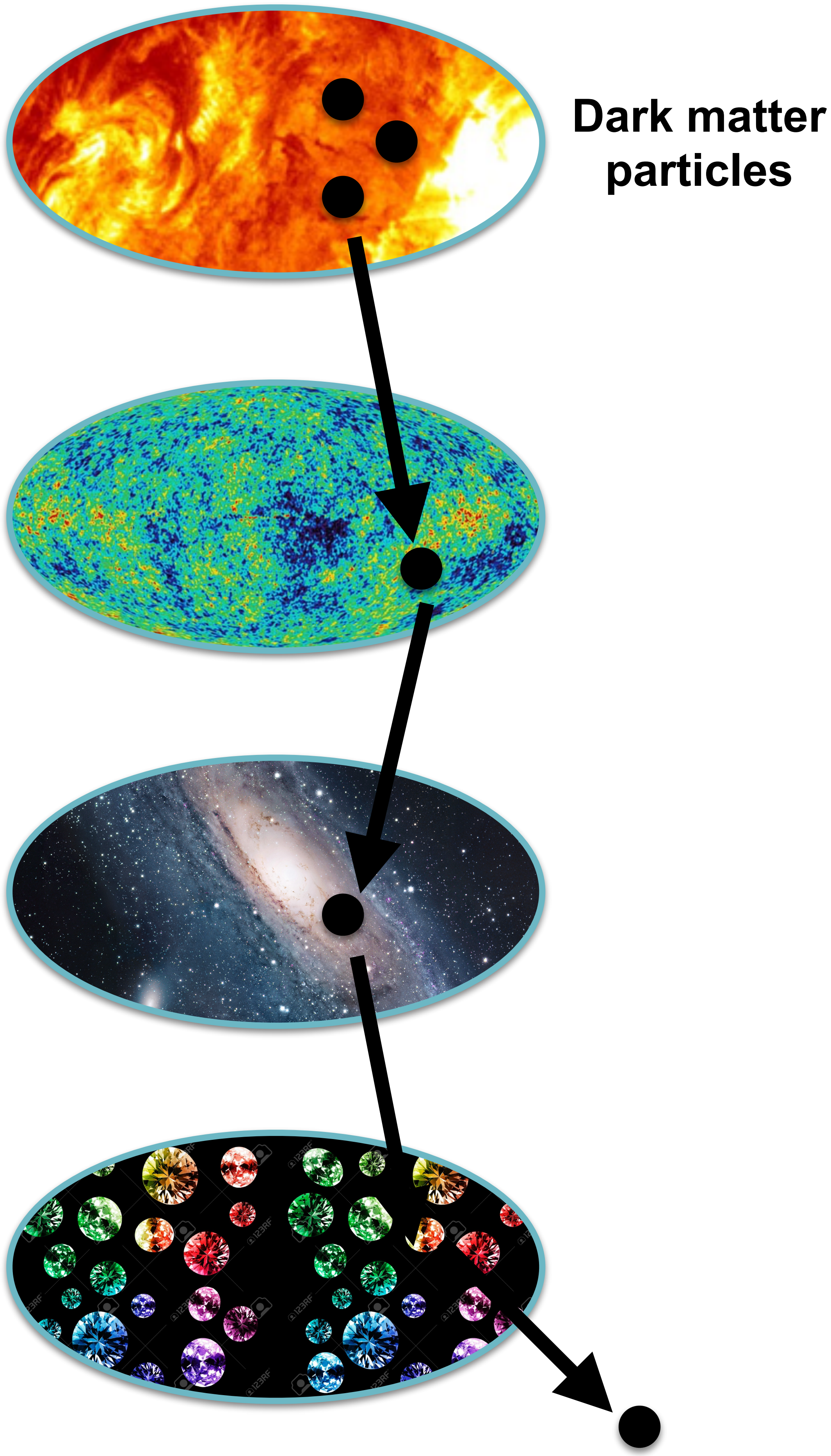
Electron scattering cross section is also maximized for freeze-in through a light mediator

$$\bar{\sigma}_e \equiv \frac{16\pi\alpha_\chi \alpha_{em} \kappa^2 \mu_{\chi e}^2}{\left(m_V^2 + \alpha_{em}^2 m_e^2\right)^2}$$

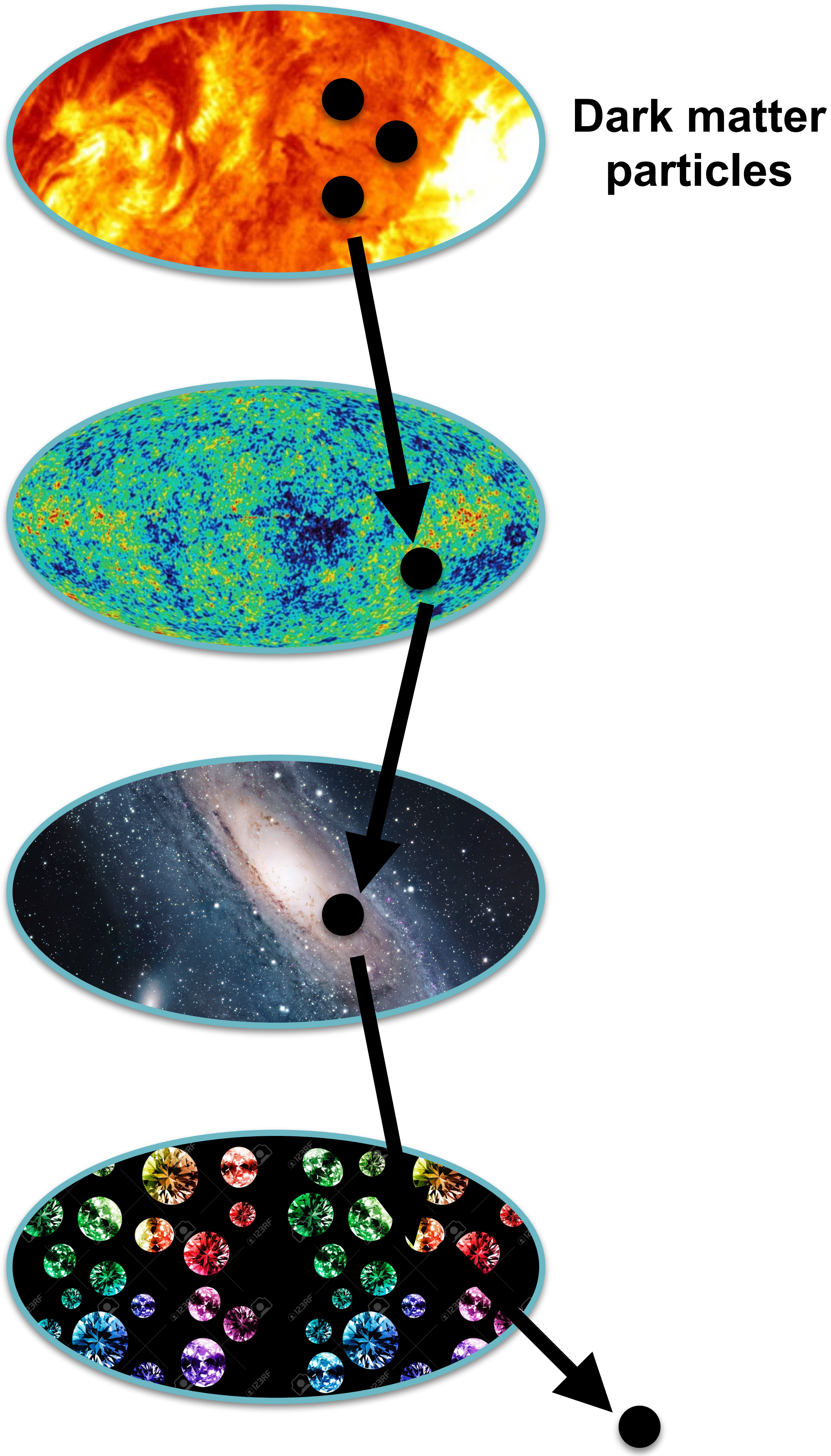


Cosmology of sub-MeV freeze-in DM


Dark matter
particles



First minute: In-medium photon decays to DM, which can then free-stream



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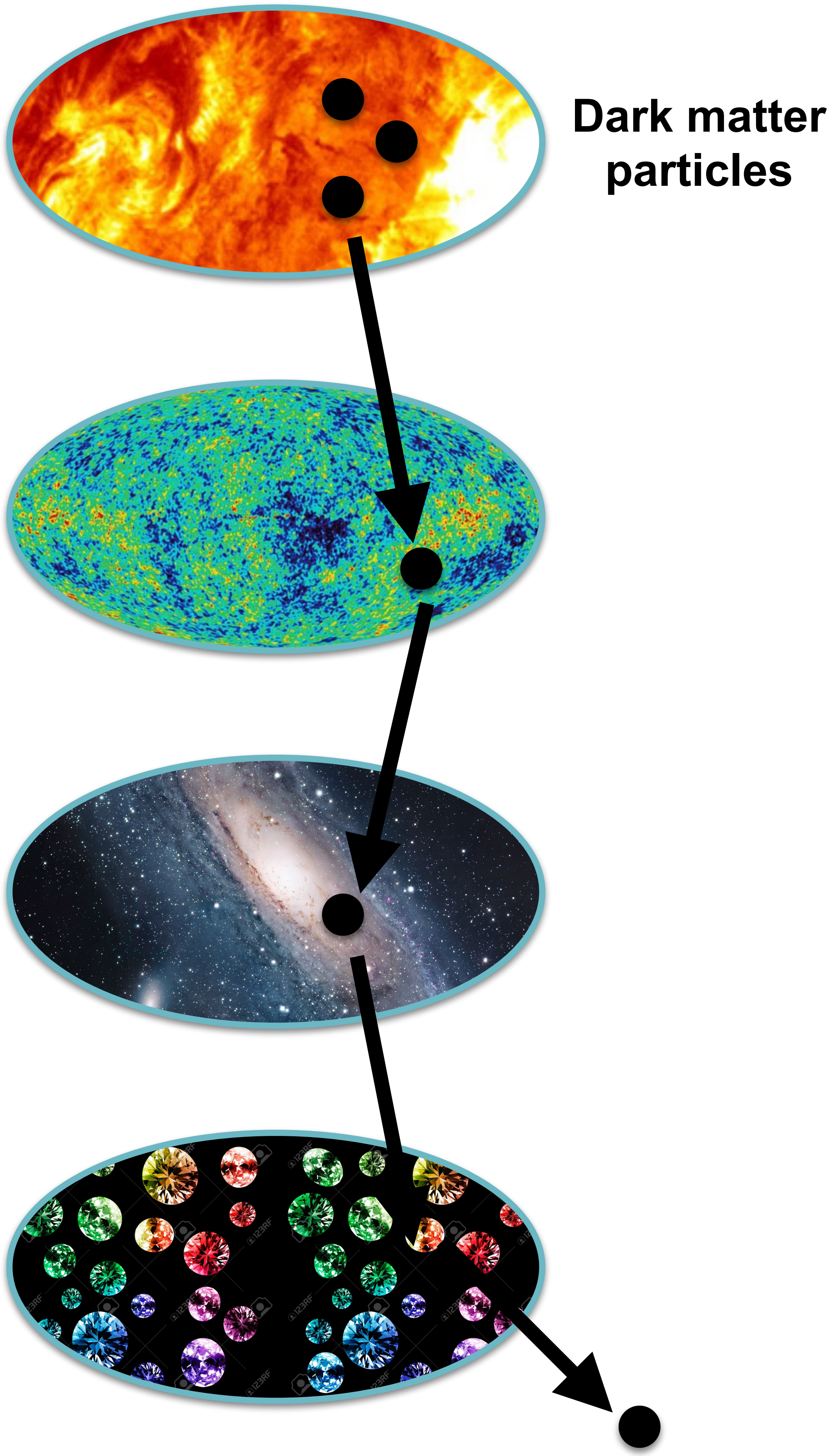

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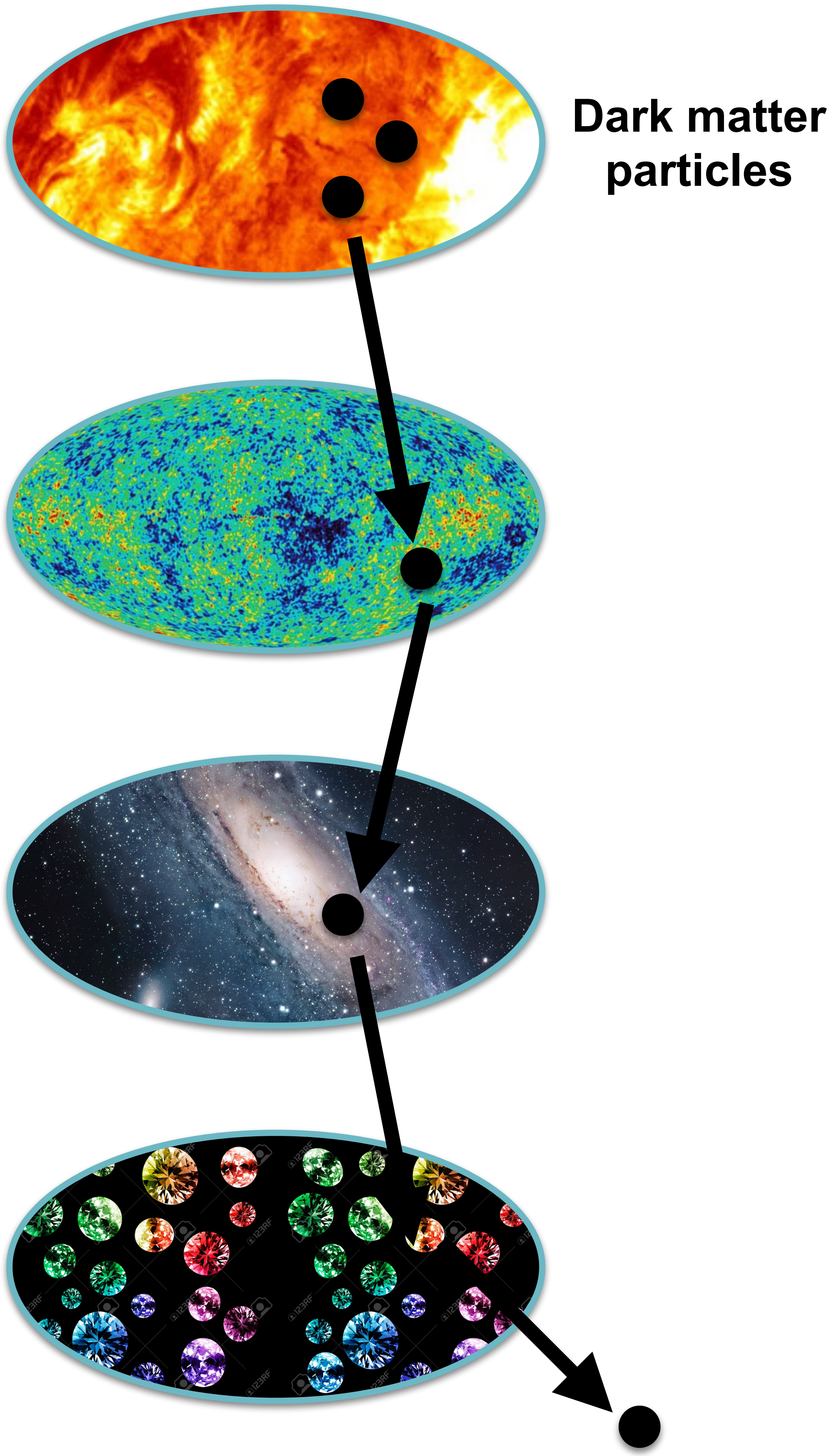
Galactic dynamics: Dark matter interacts with particles, fields within galaxies



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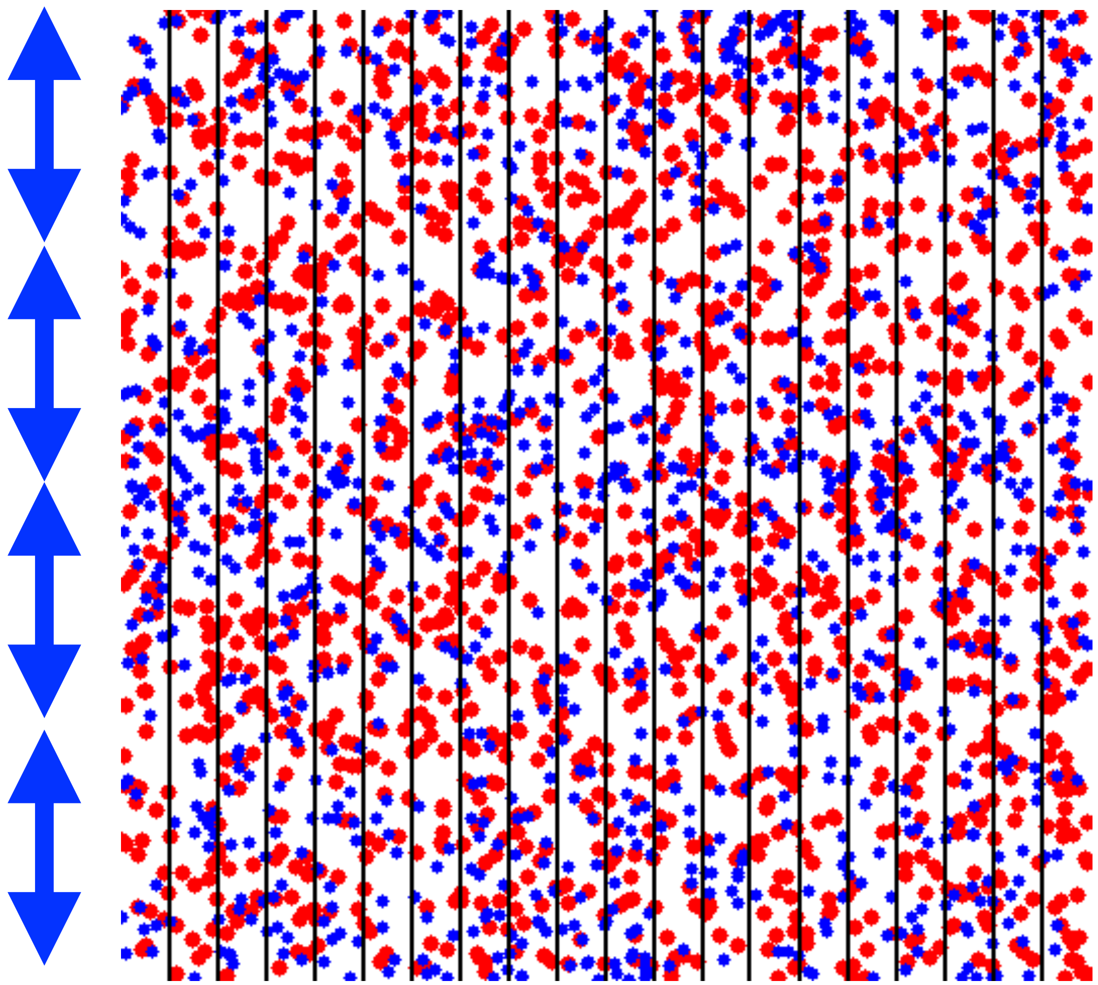
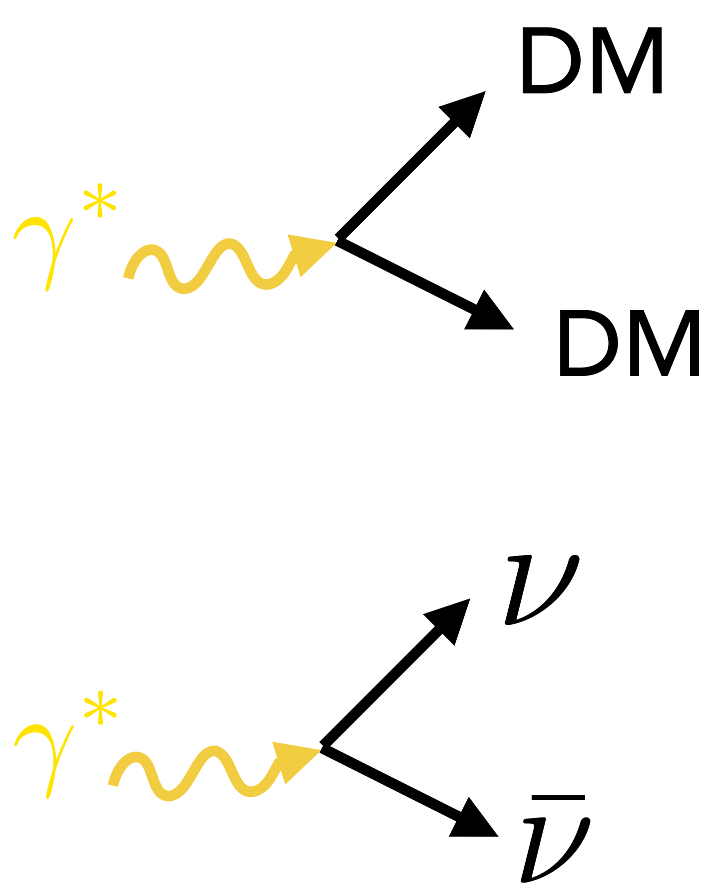
Plasma oscillations



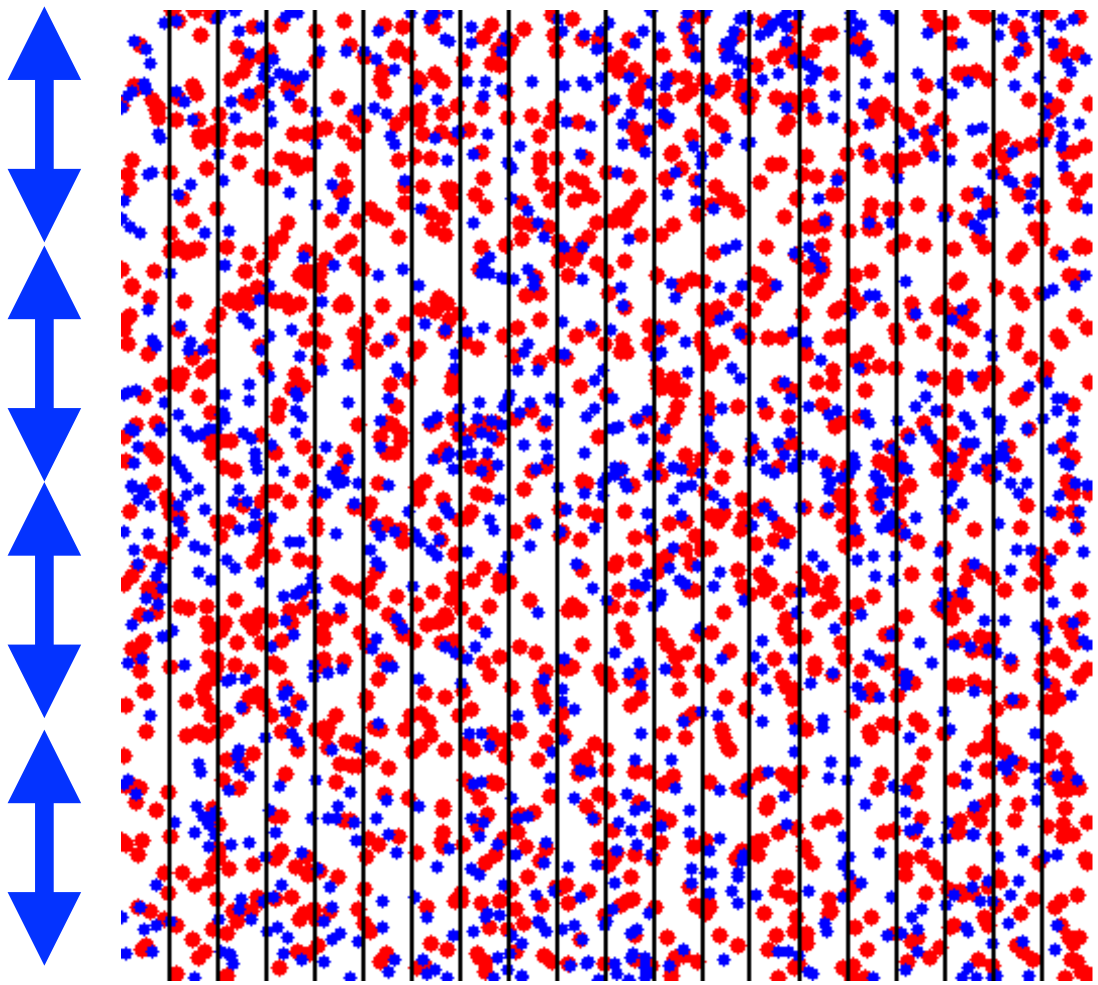
red: ion blue: electron



Dark matter created from plasma oscillations as long as plasma frequency $\omega_p \approx 0.1 k_B T$ is greater than $2m_{DM}$

Dvorkin, TL, Schutz 2019

Plasma oscillations



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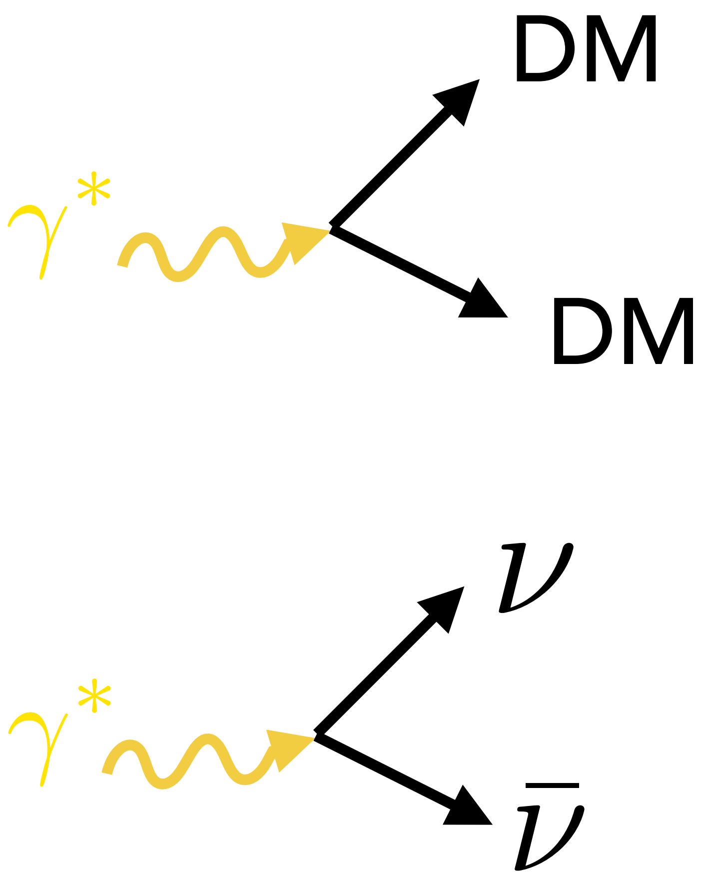

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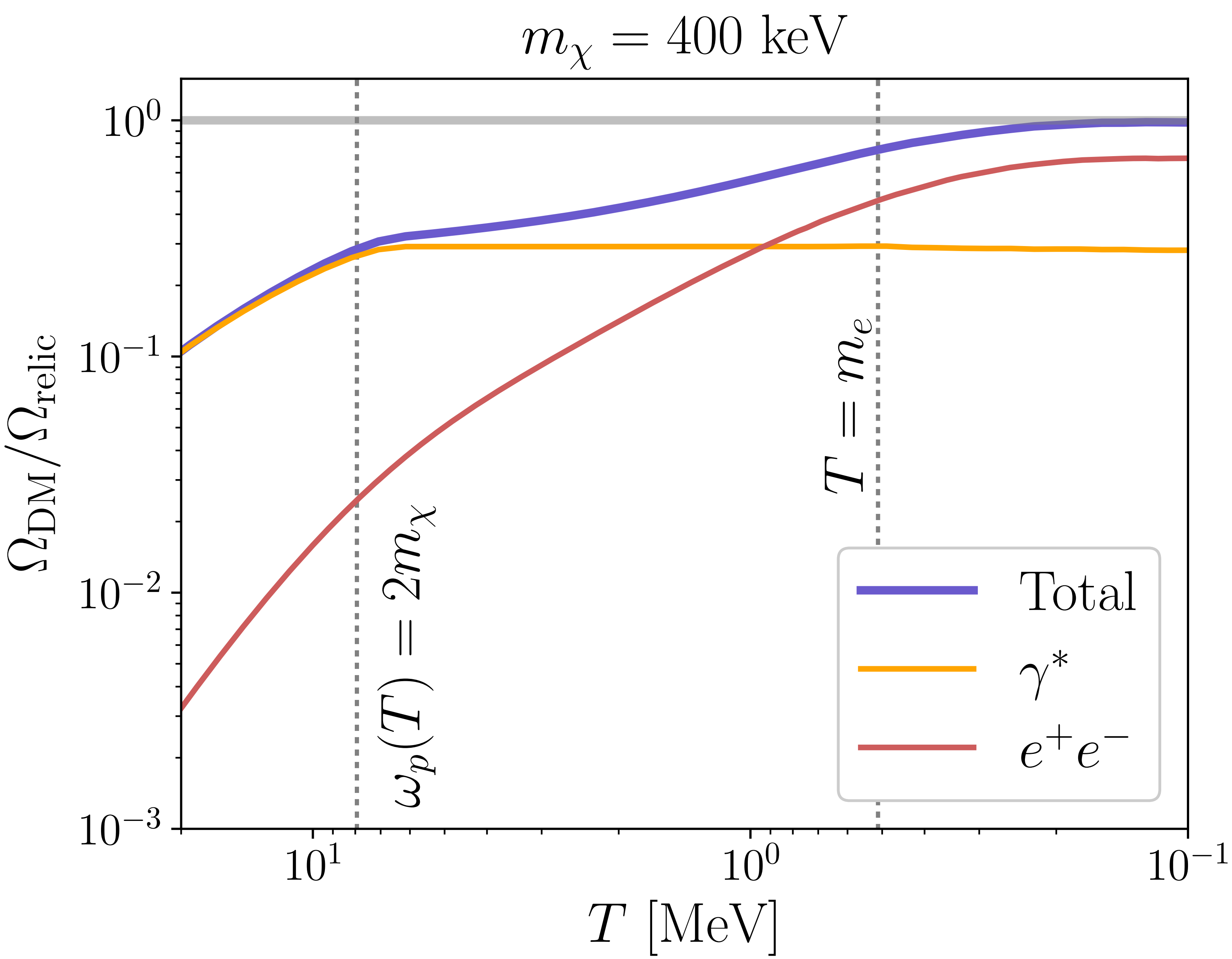
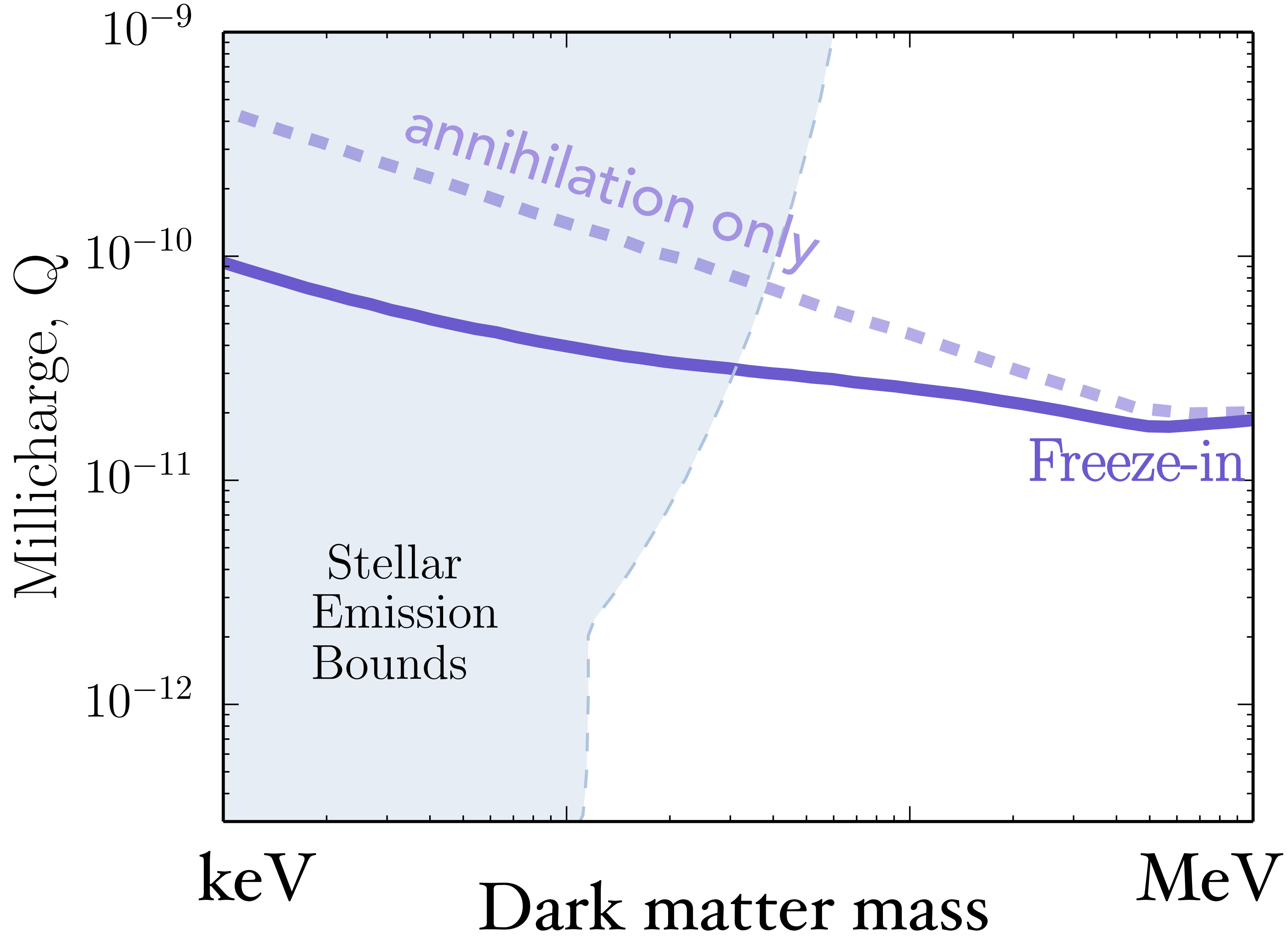
Freeze-in



Plasma effects most important for lower DM masses since $\omega_p \approx 0.1 k_B T$

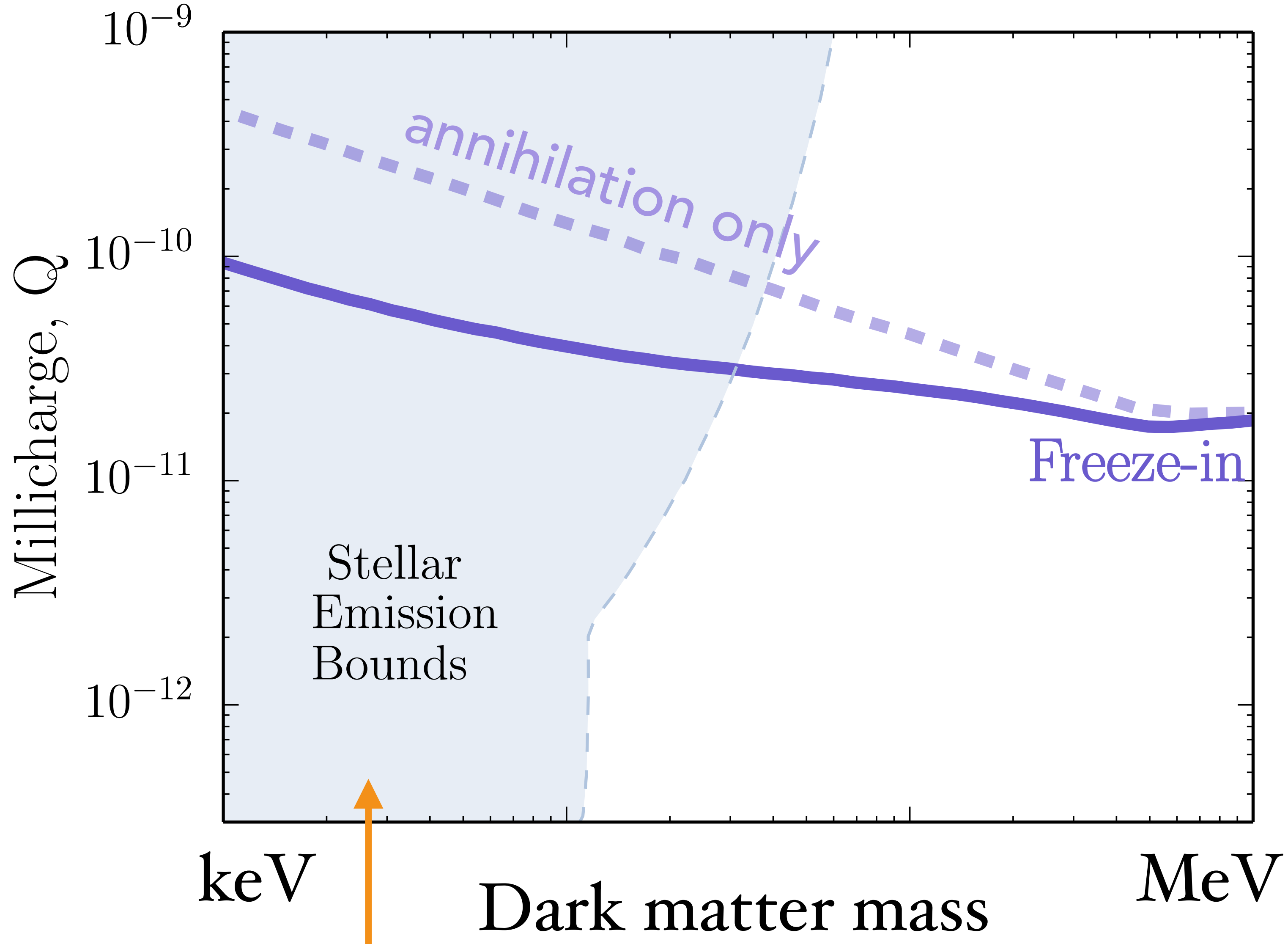
Dvorkin, TL, Schutz 2019

Sub-MeV freeze-in DM



Dvorkin, TL, Schutz 2019

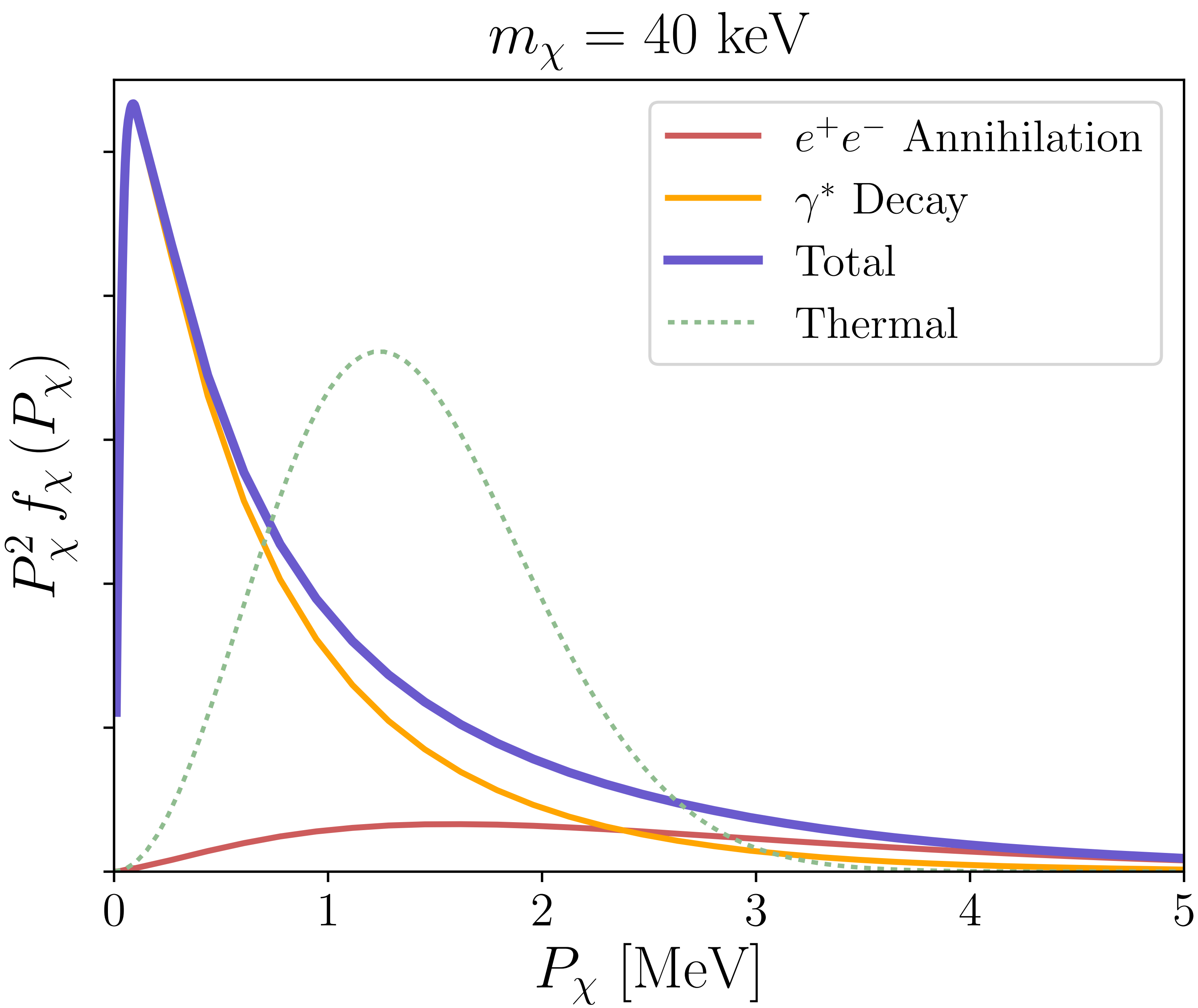
Sub-MeV freeze-in DM



Stellar bounds from Vogel and Redondo 2013; High mass part sensitive to temps, models

Dvorkin, TL, Schutz 2019

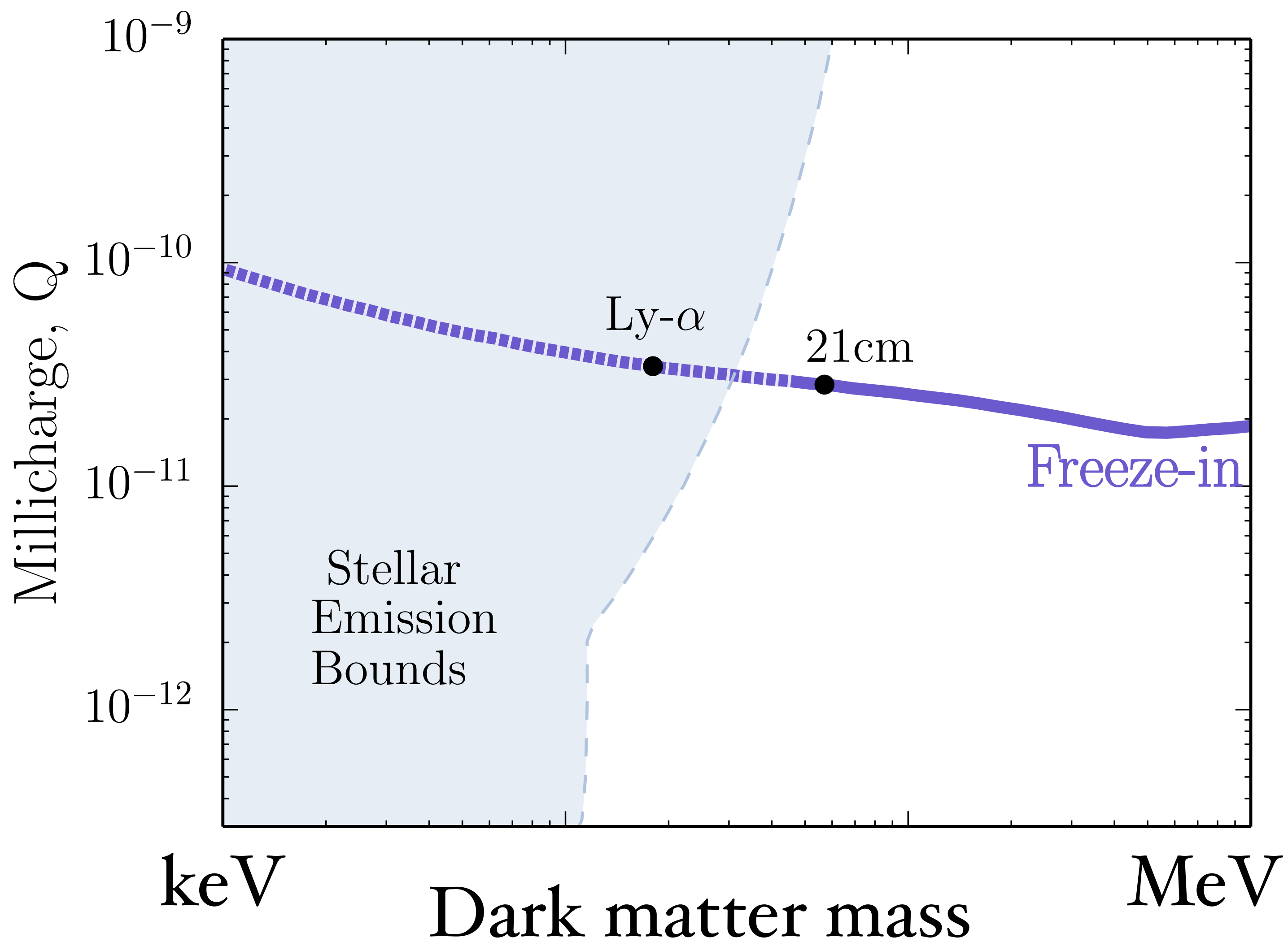
Dark matter phase space



Dark matter is produced hot, but with highly non thermal phase space

Dvorkin, TL, Schutz (in progress)

Free-streaming of freeze-in DM

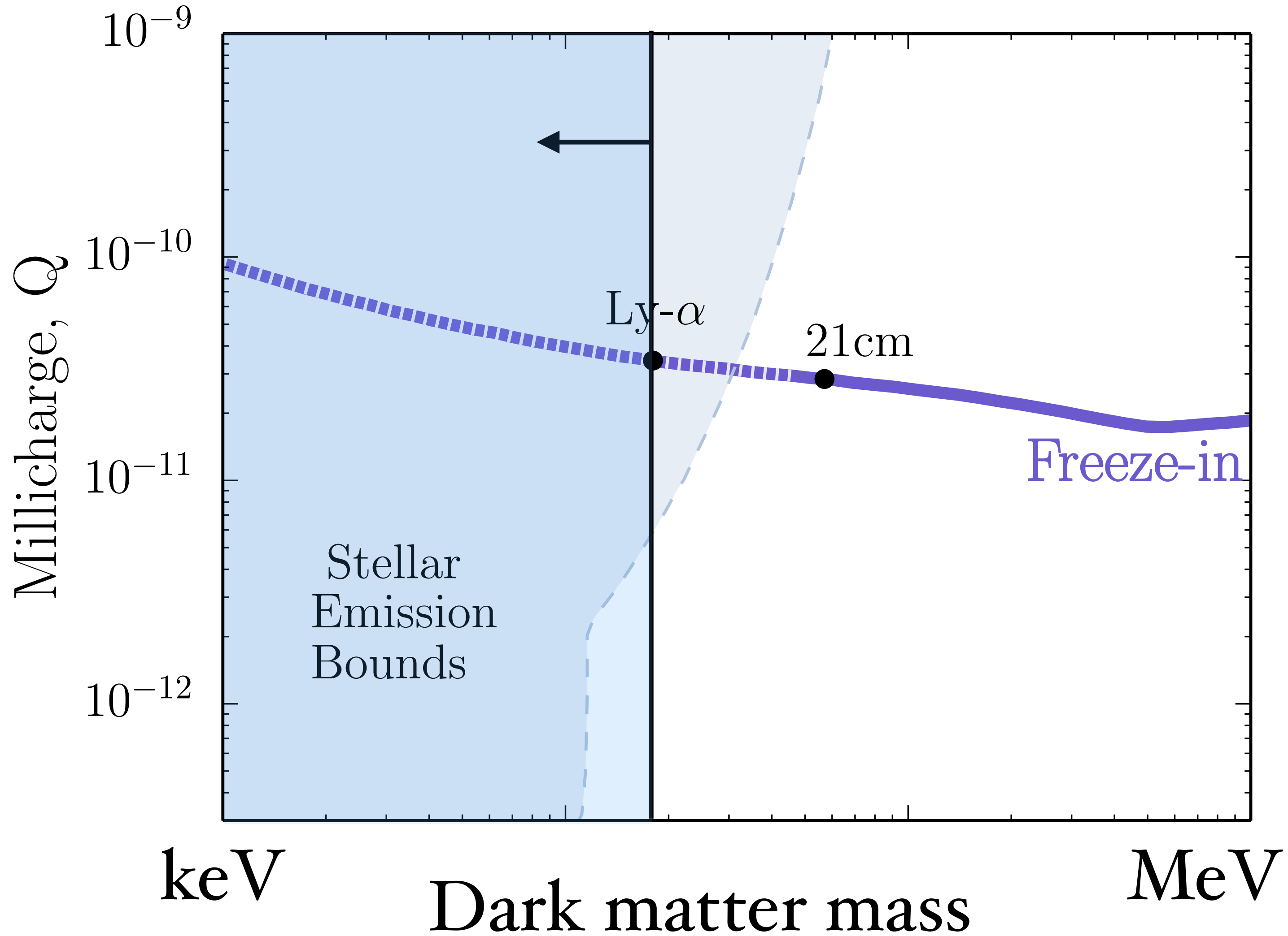


Lyman-α bound: Yeche et al. 2017
21cm projection: Sitwell et al. 2013

Bounds for non thermal DM distribution.
Sensitivity improves by O(30%) for DM with dark photon self-interactions

Dvorkin, TL, Schutz 2019

Free-streaming of freeze-in DM



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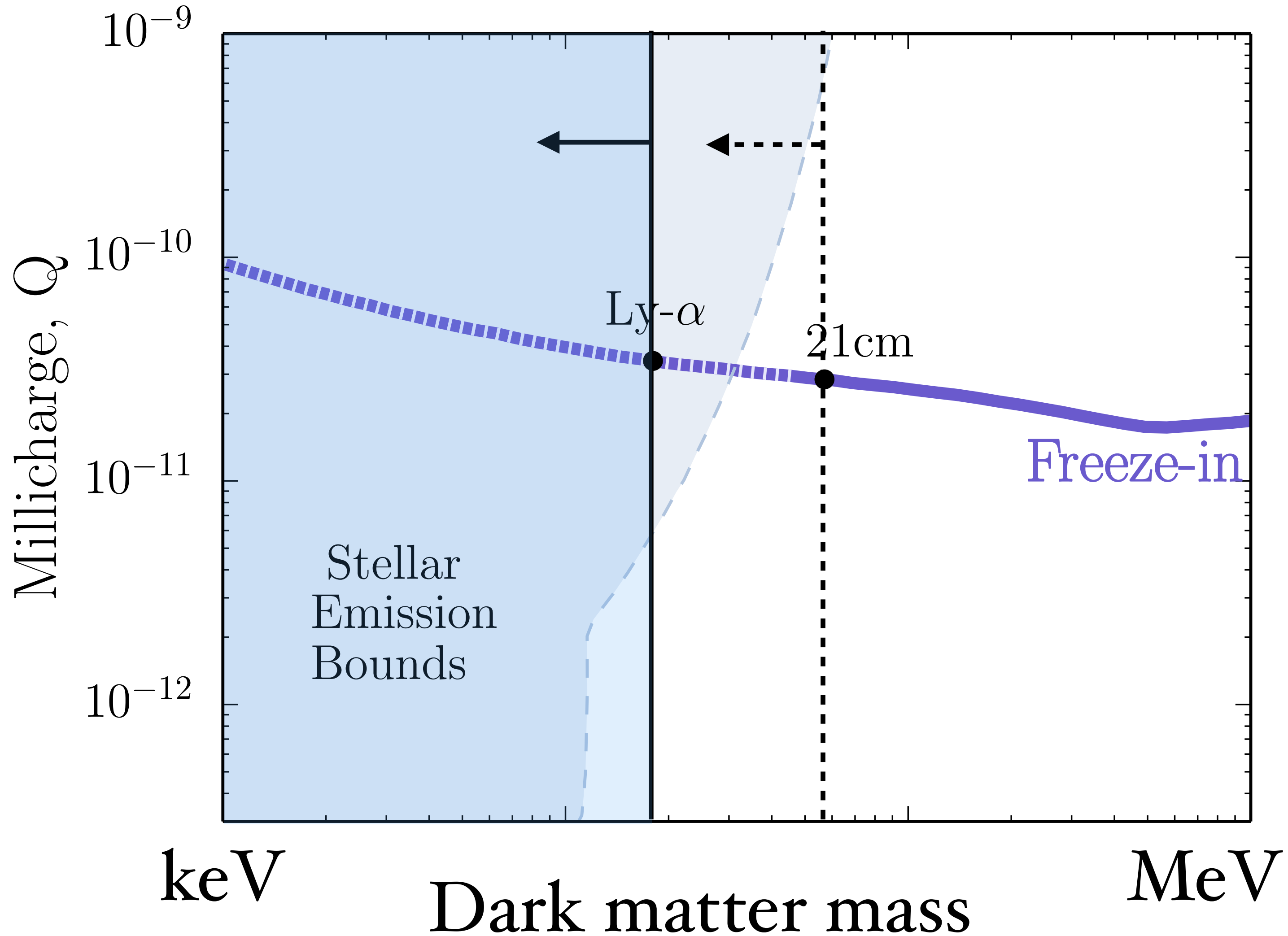

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Dvorkin, TL, Schutz 2019

Acoustic oscillations

Dark matter is a cold and clumpy fluid, while the baryon-photon fluid oscillates in and out of the gravitational potential.

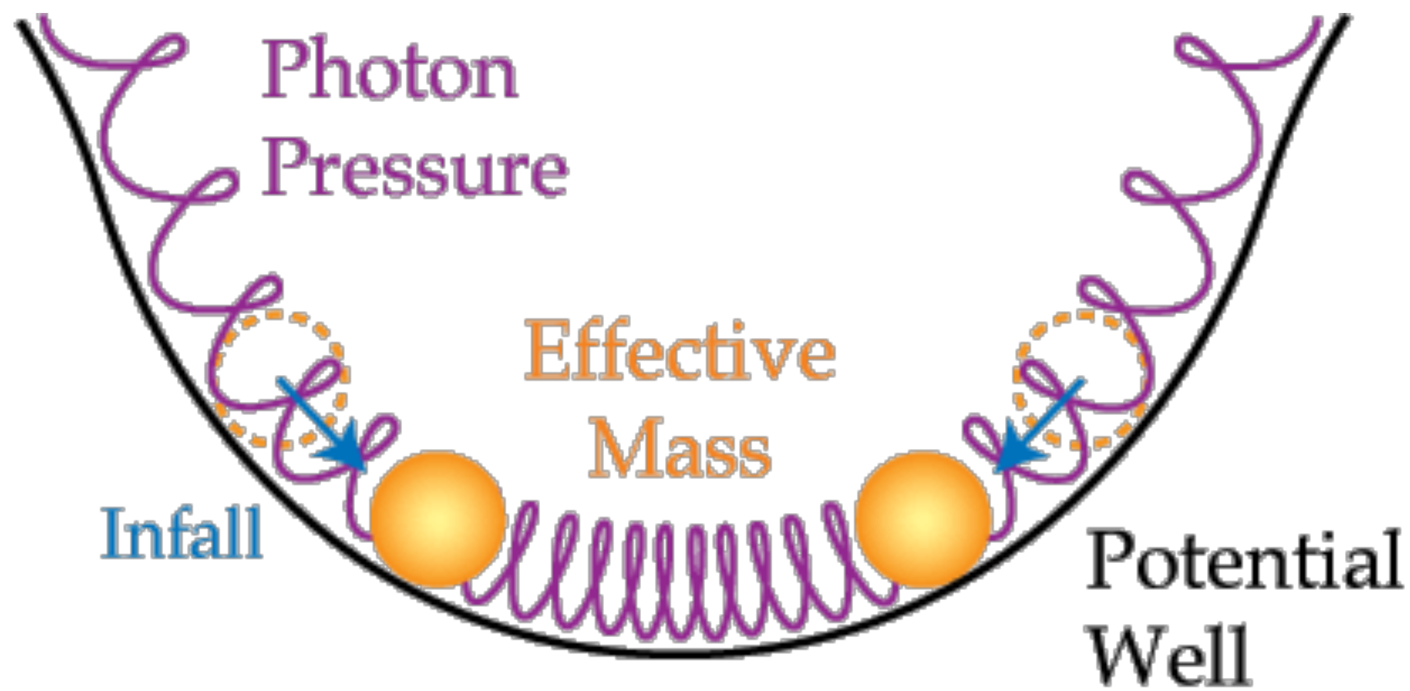

Figure from Wayne Hu's CMB tutorial

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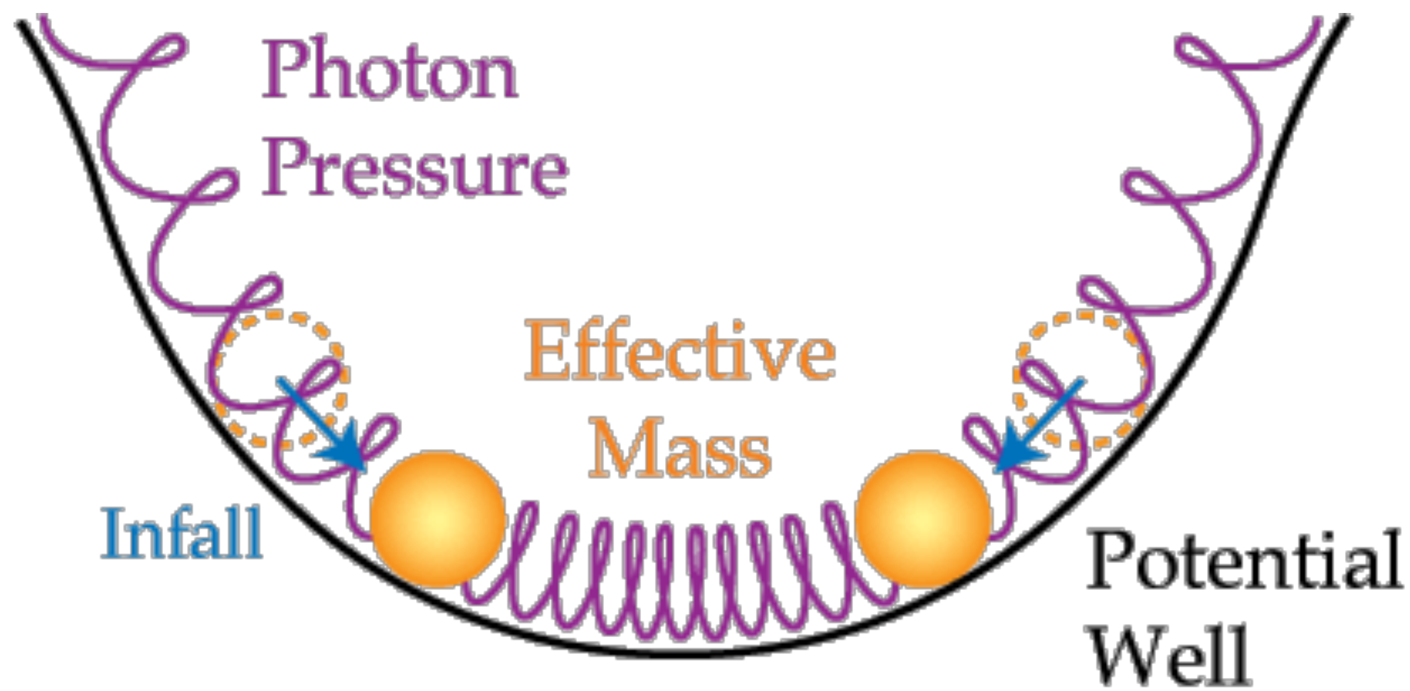

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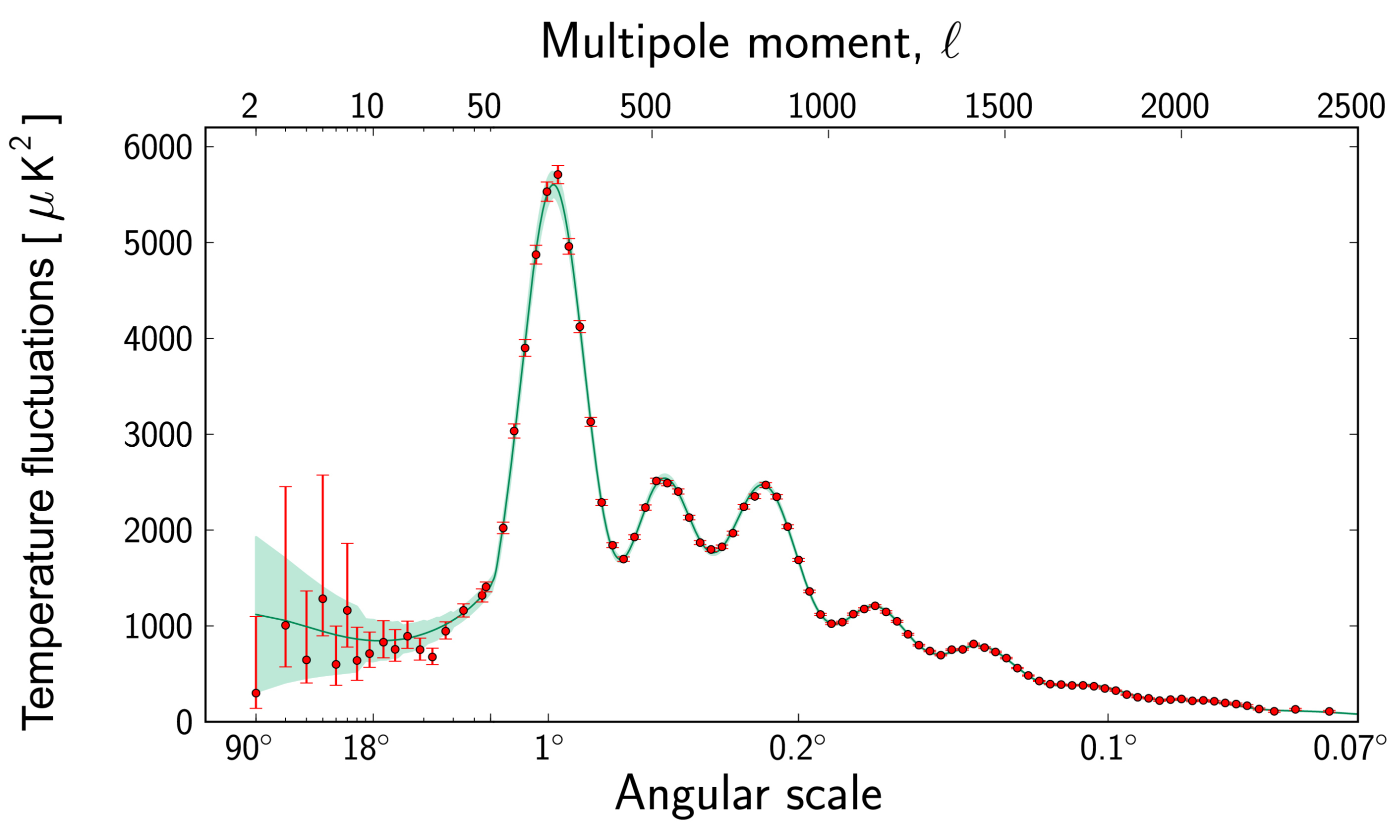

Figure from Wayne Hu's CMB tutorial

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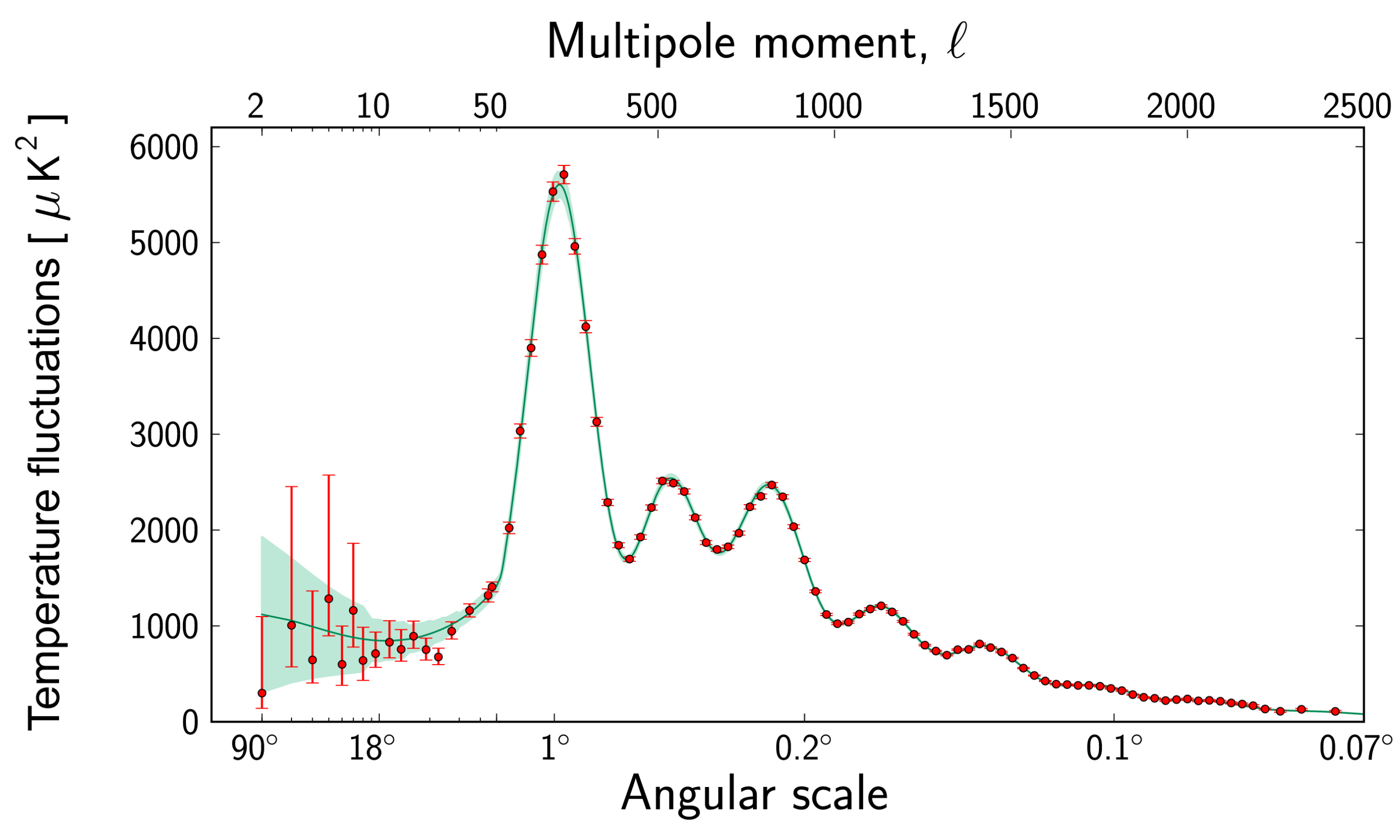

Momentum transfer cross section $\sigma_T \propto \frac{\pi Q_\chi^2 \alpha^2}{m_{\rm DM}^2 v^4}$

Drag rate between bulk fluid motions $\approx n_b \sigma_T v_{\rm rel}$

Figure from Wayne Hu's CMB tutorial

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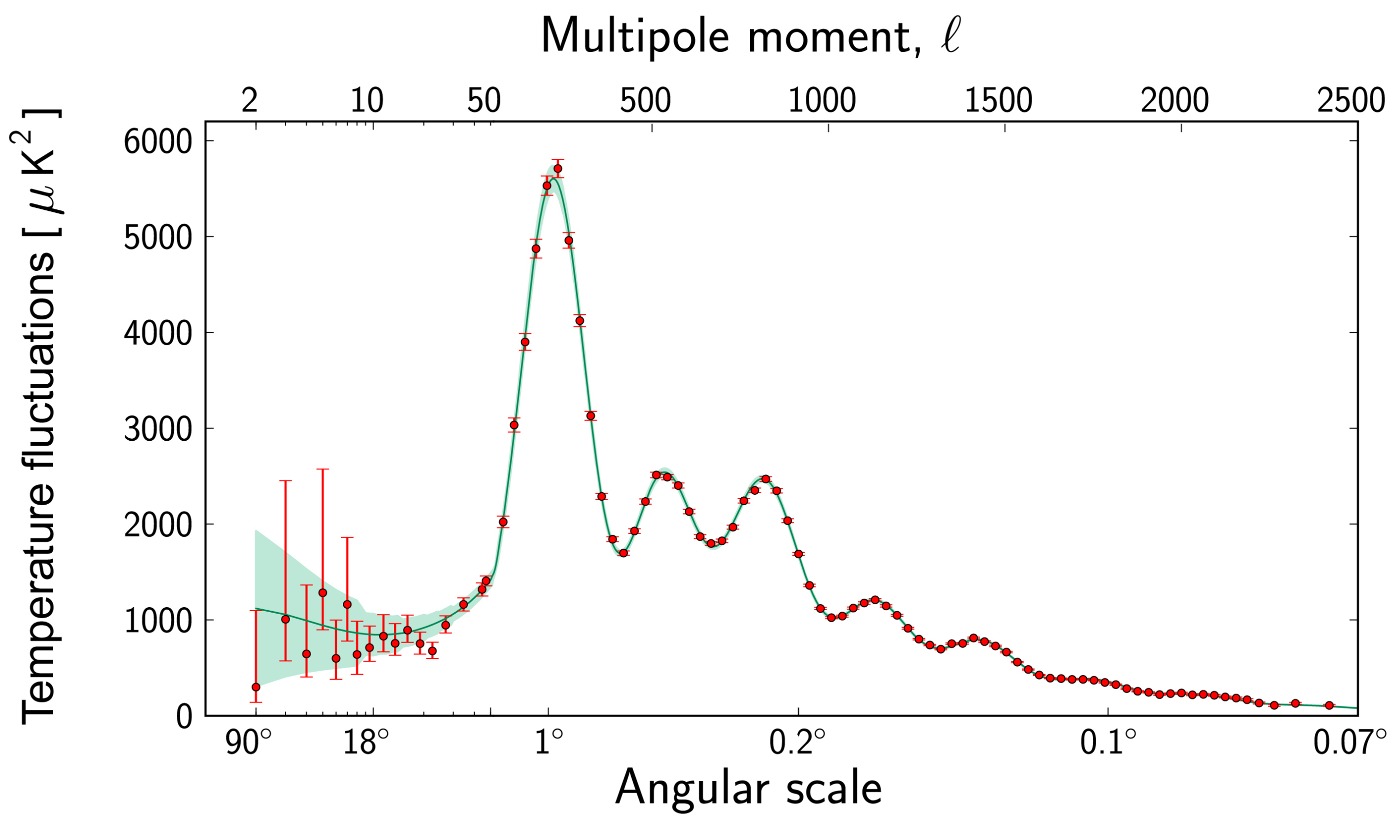

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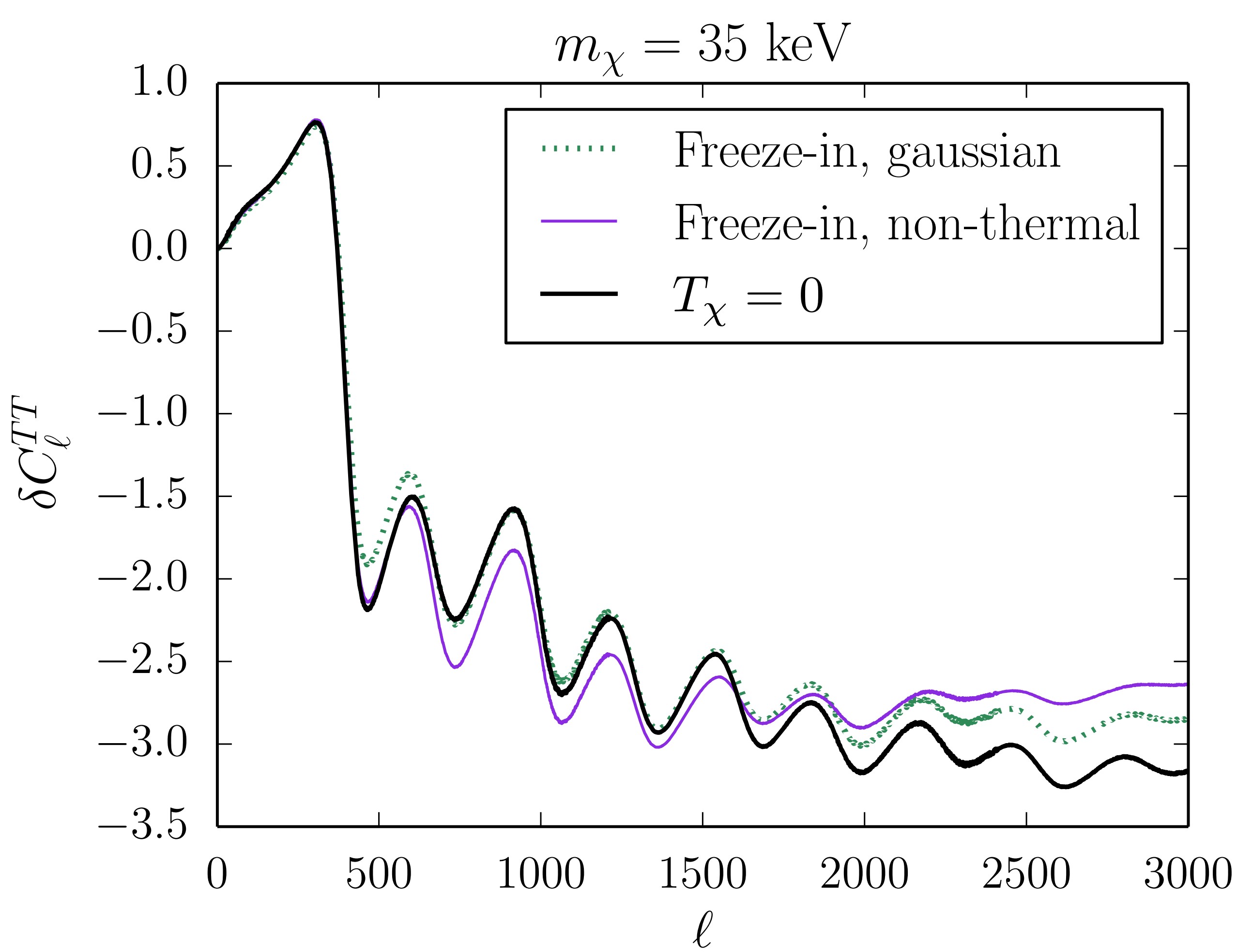
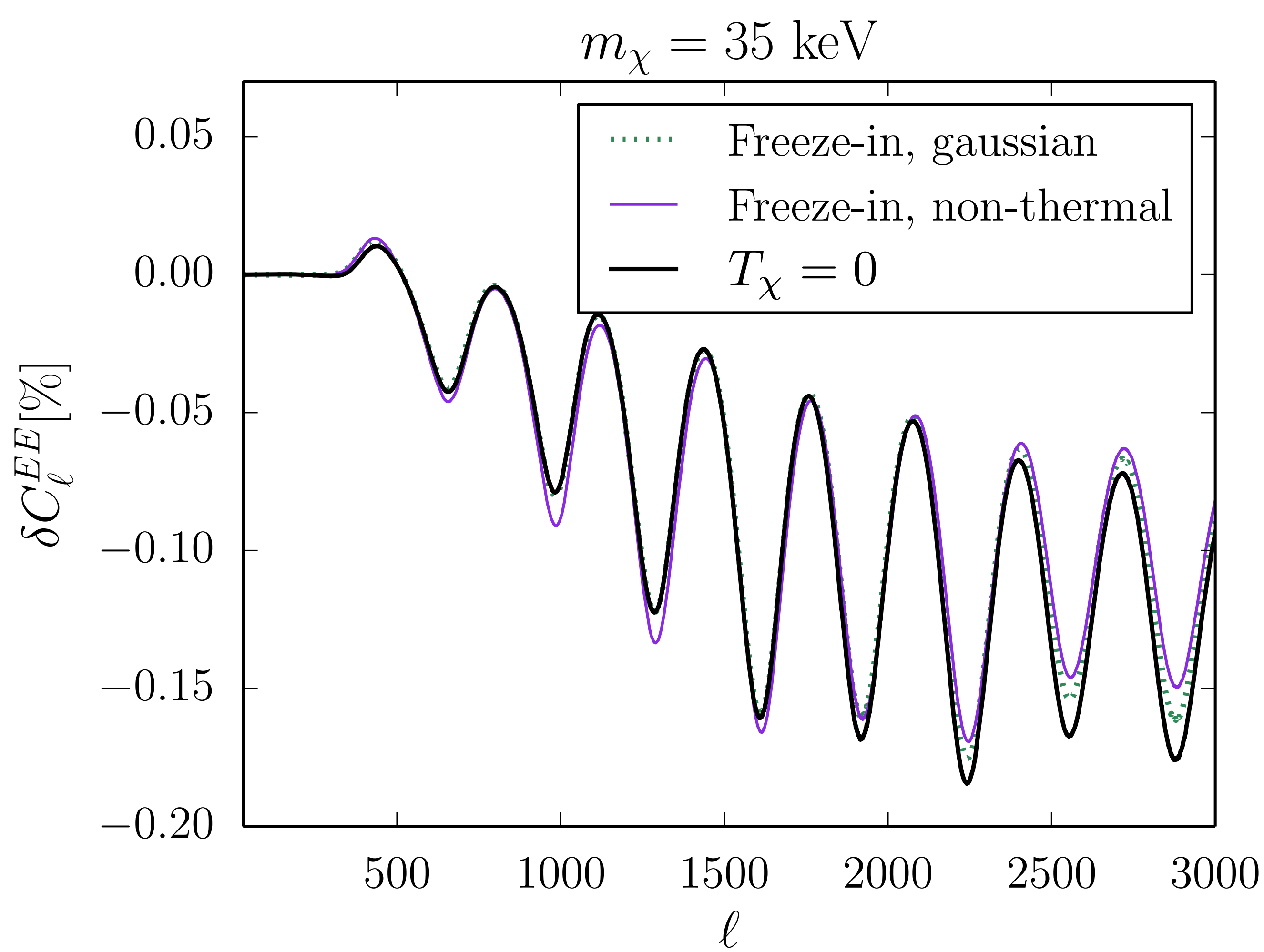
Drag rate between bulk fluid motions $\approx n_b \sigma_T v_{\rm rel}$

Extra DM-baryon drag force changes the characteristic size of sound waves in the baryon-photon fluid —> modify CMB peaks

Figure from Wayne Hu's CMB tutorial

Effect on CMB anisotropies

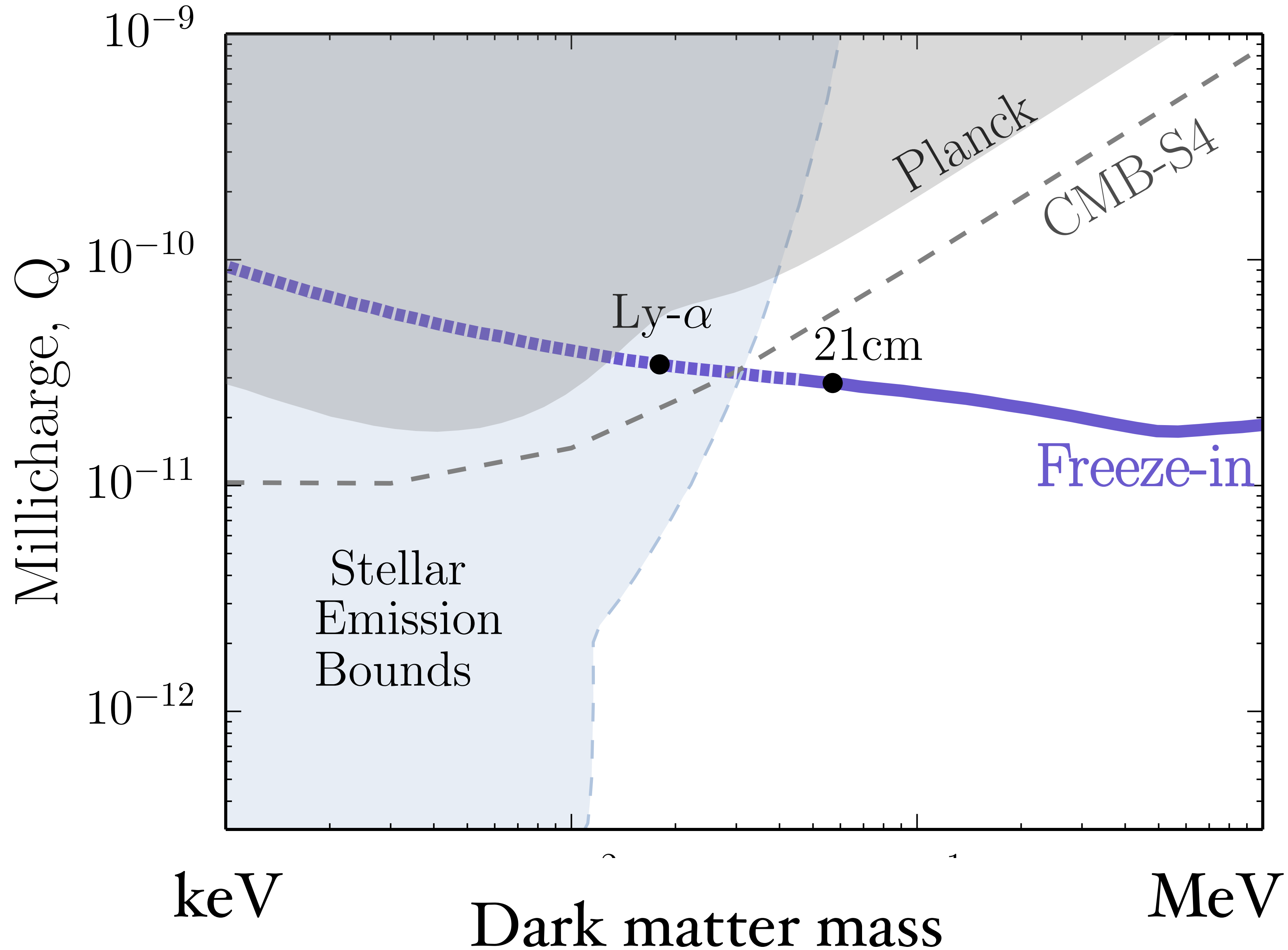




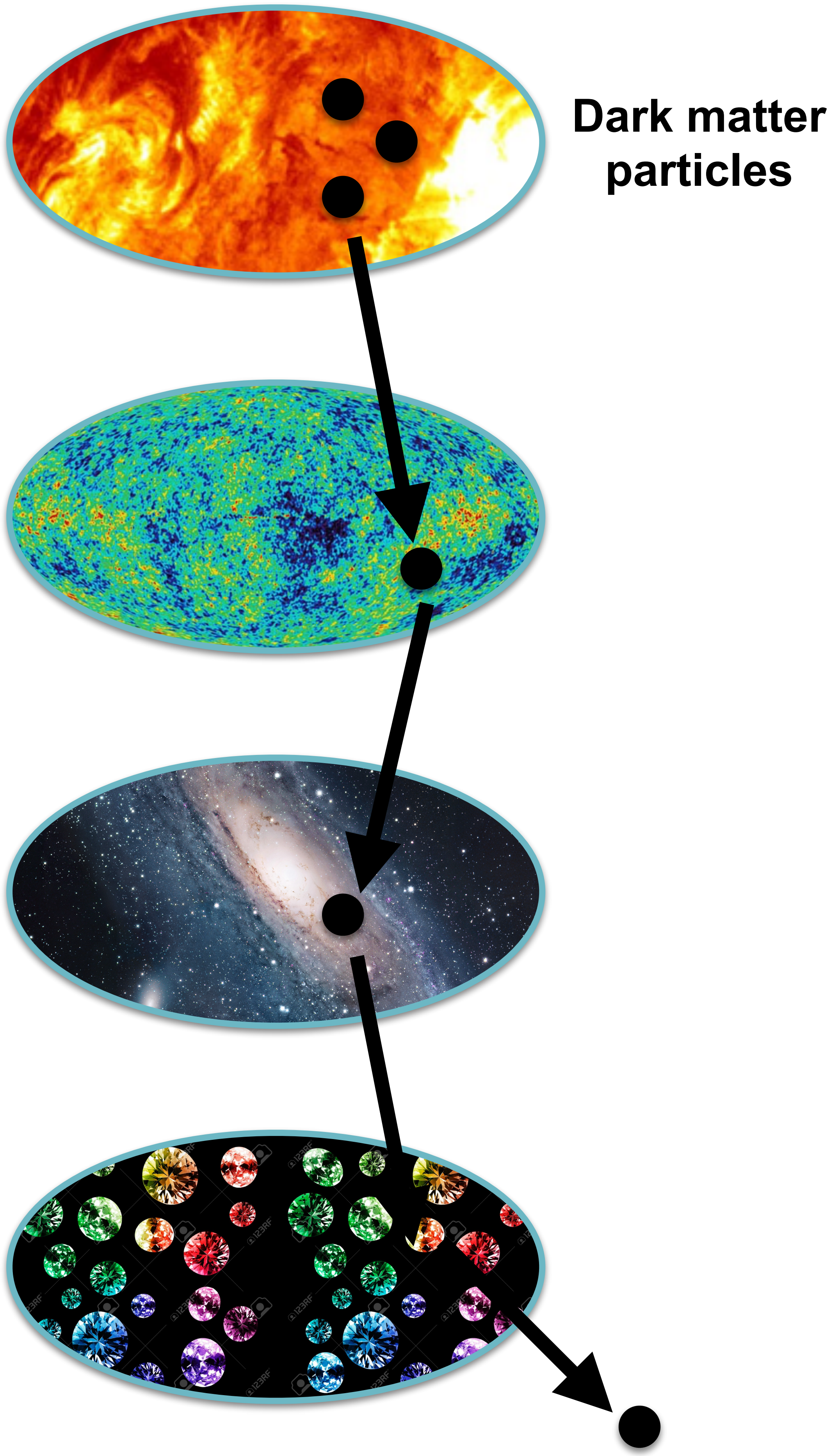
Drag force leads to
damped perturbations, shifted peaks

See also Dvorkin et al 2013; Boddy et al. 2018; Slatyer & Wu 2018

Using the CMB as a cosmic detector for dark matter scattering



Dvorkin, TL, Schutz (in progress)



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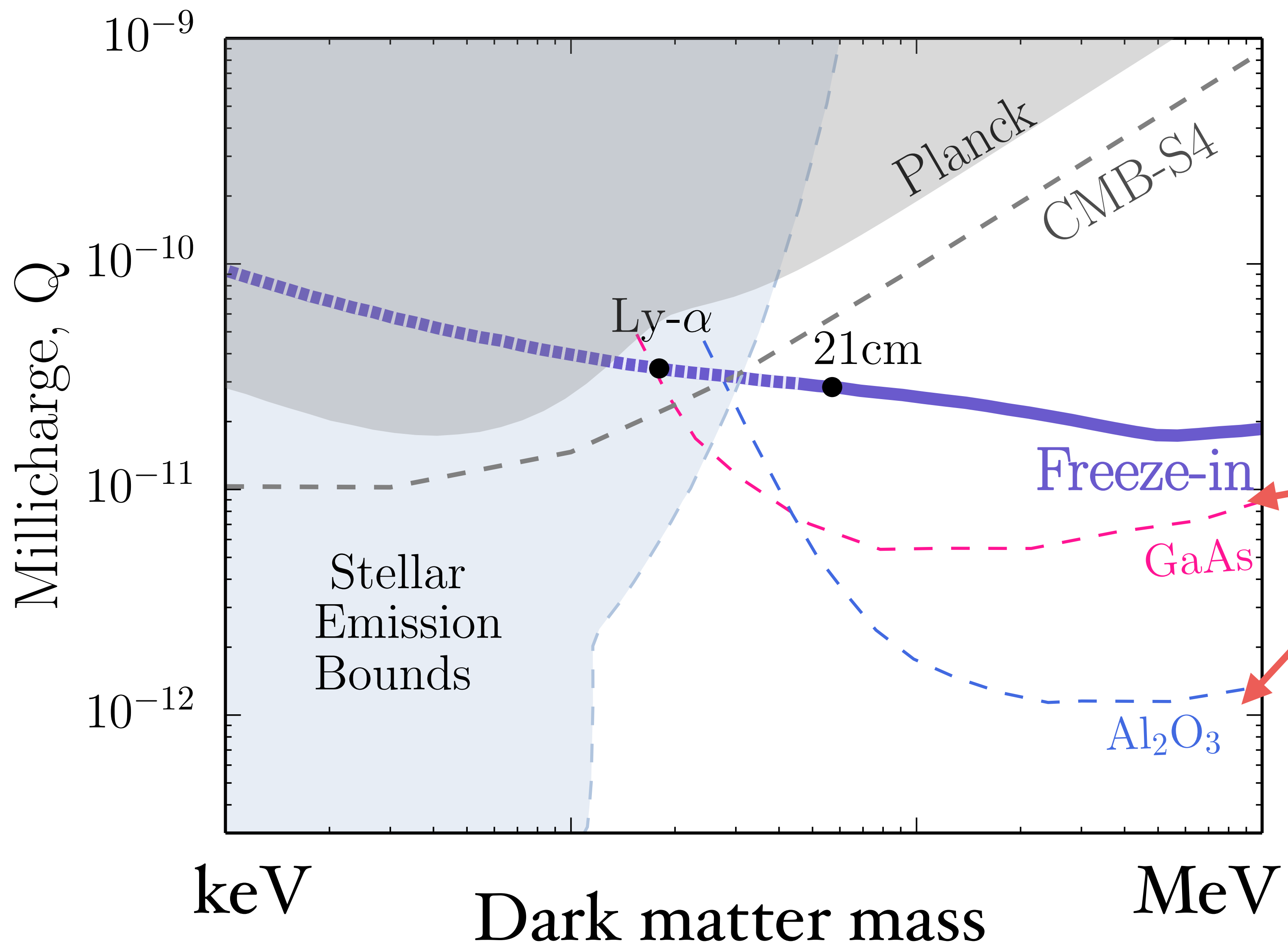
Direct detection of freeze-in DM

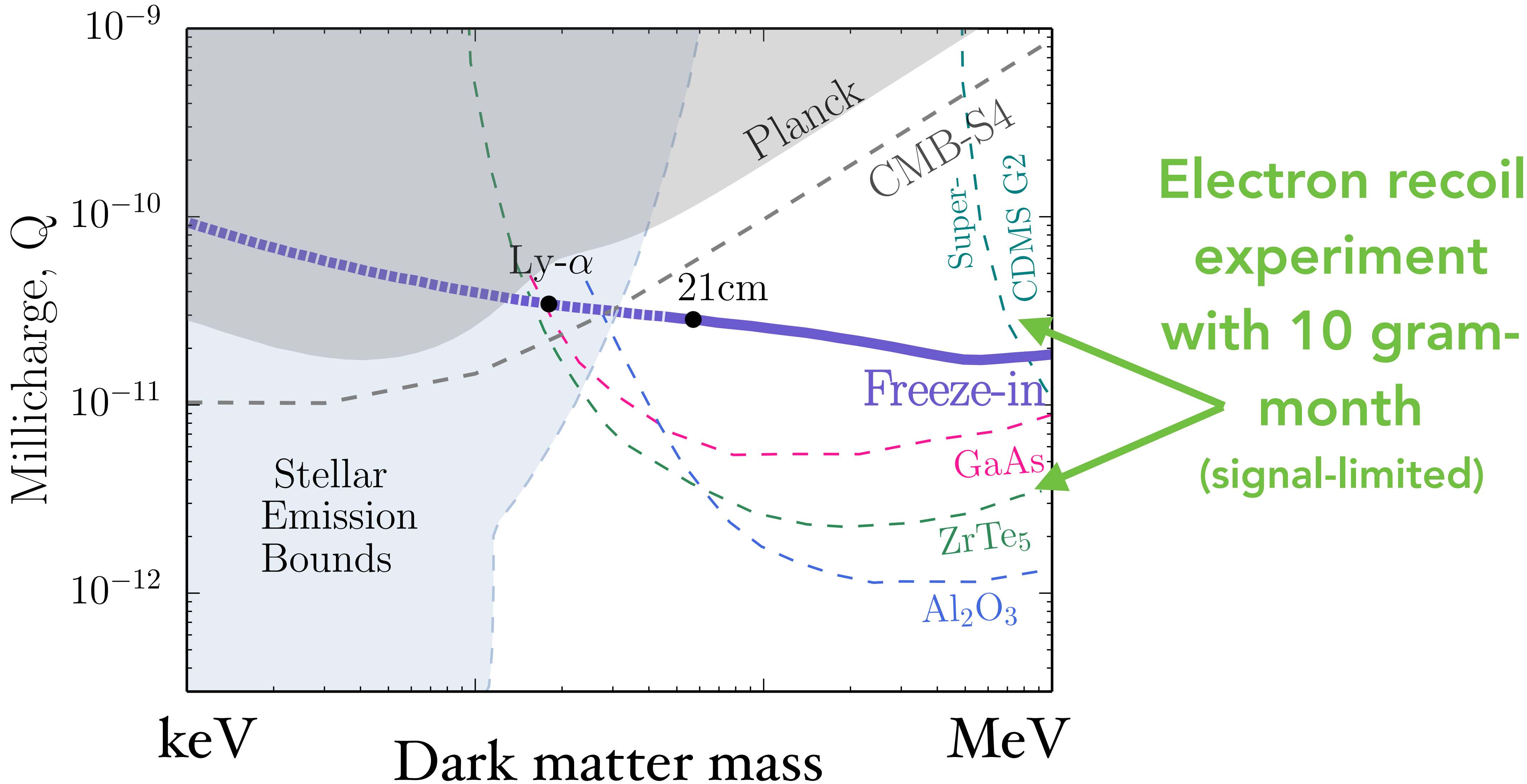


Phonon-based experiment with 10 grams running for 1 month
(signal-limited)

DM-induced optical phonon excitations in polar crystal targets

Knapen, TL, Pyle, Zurek 2018
Griffin, Knapen, TL, Zurek 2019

Direct detection of freeze-in DM



Electron scattering in materials with small electron band gap

SuperCDMS: Cosmic Visions Report 2017
Dirac Materials: Hochberg et al. 2017

Summary

Simplest scalar & vector dark sector portals give rise to direct detection signatures for mX > MeV.

We learned "The Standard Model is fragile" …
ΛCDM is also fragile! Sub-MeV dark matter faces cosmological constraints.

For mX < MeV, the most compelling scenario is freeze-in through an ultralight vector mediator. Fortunately, this can be tested with a combination of methods in cosmology and in the lab.