Searching for light dark matter, from the early universe to direct detection

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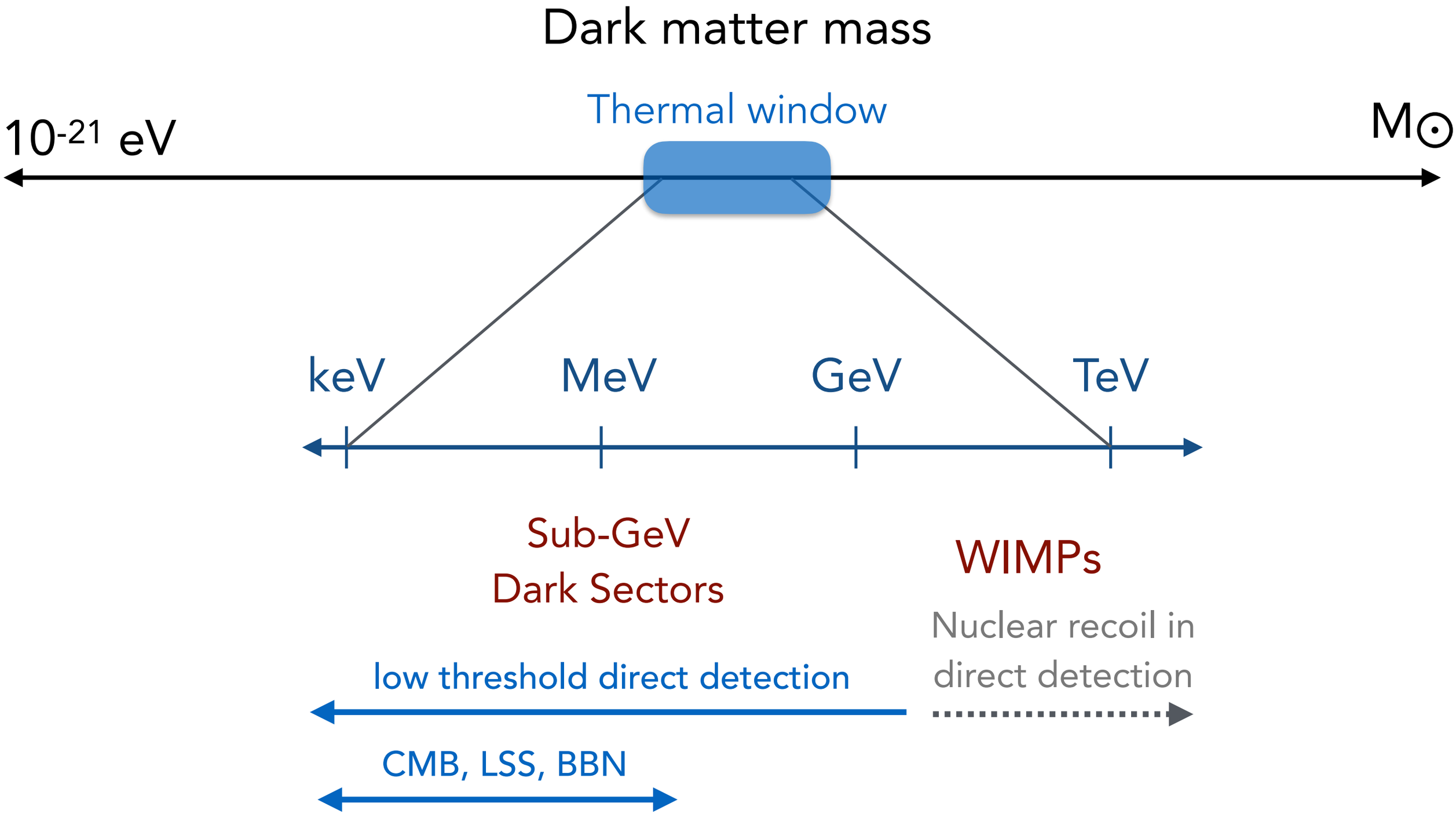
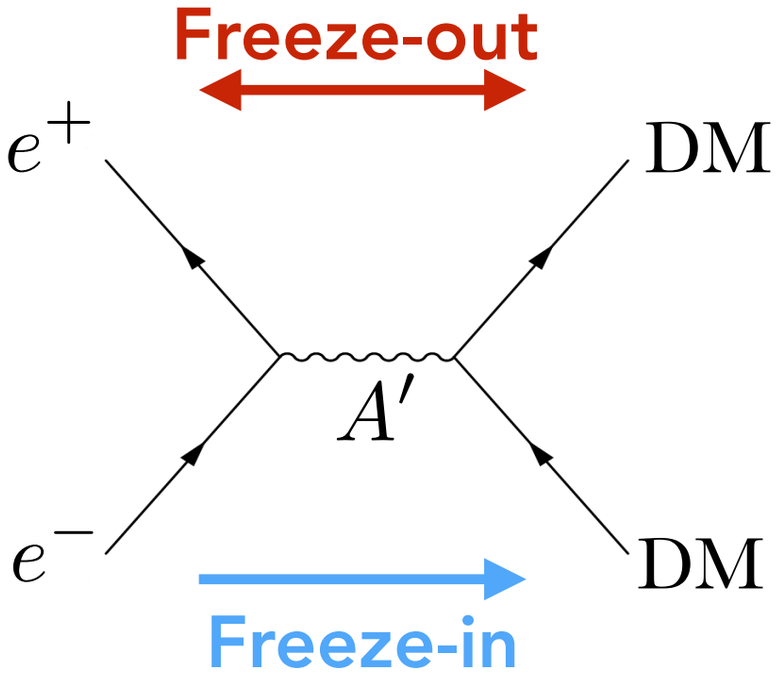
N3AS Seminar, September 8, 2020

Dark matter landscape



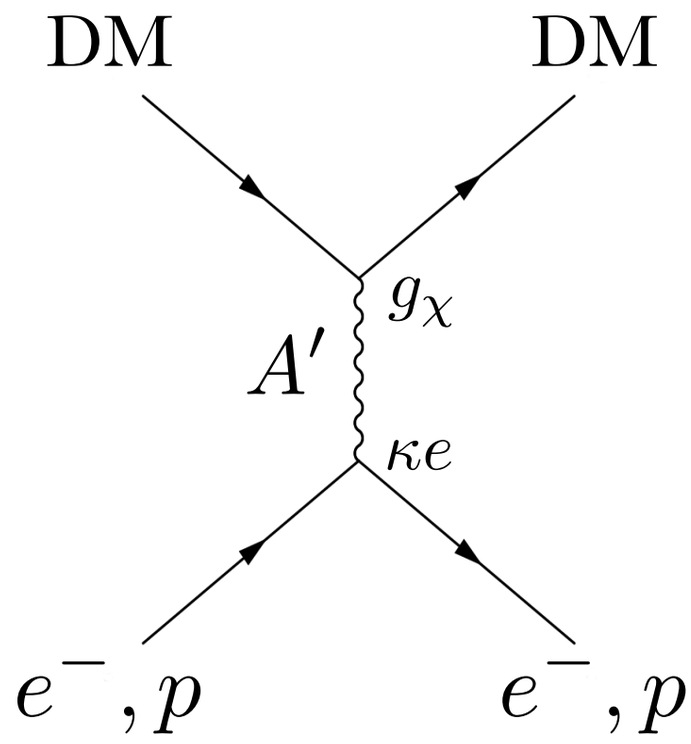
Benchmark models

Annihilation



A': Dark photon mediator

Scattering



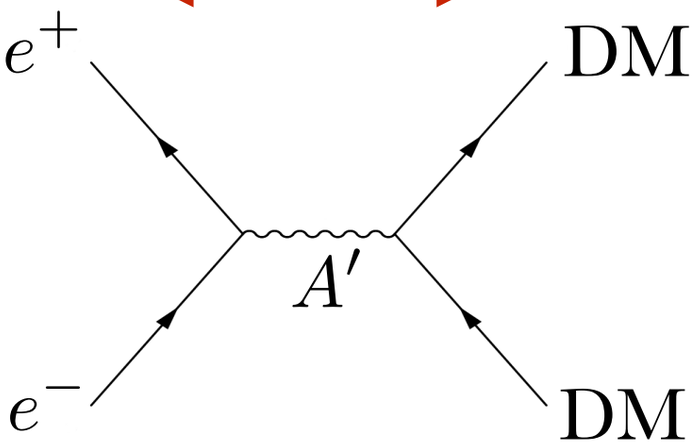
Relic abundance predicts scattering in these scenarios

(Warning: many others not considered here)

Benchmark models

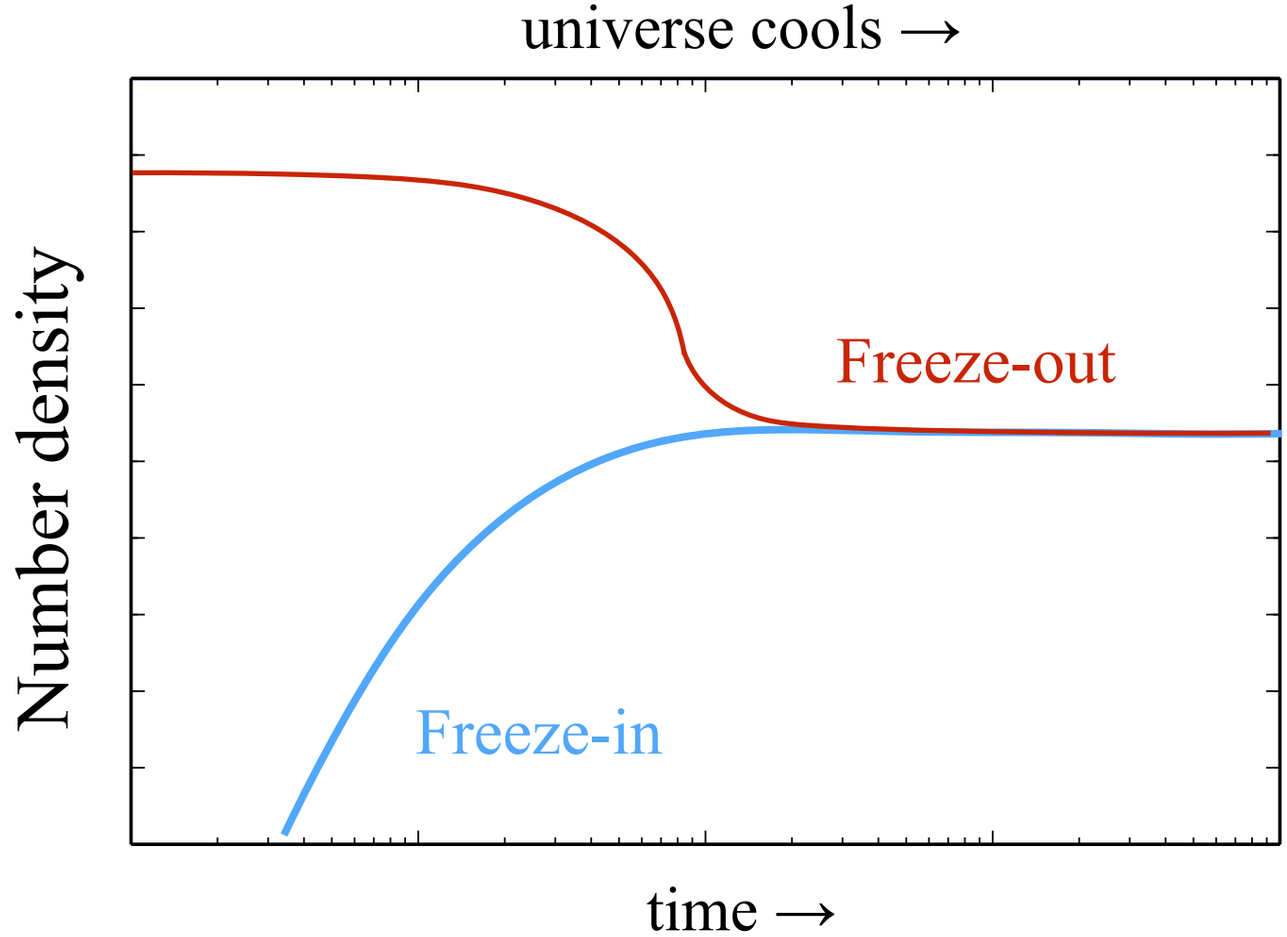
DM in thermal equilibrium with SM plasma

Freeze-out



Freeze-in

DM produced from SM plasma but not in equilibrium



Benchmark models

DM in thermal equilibrium with SM plasma

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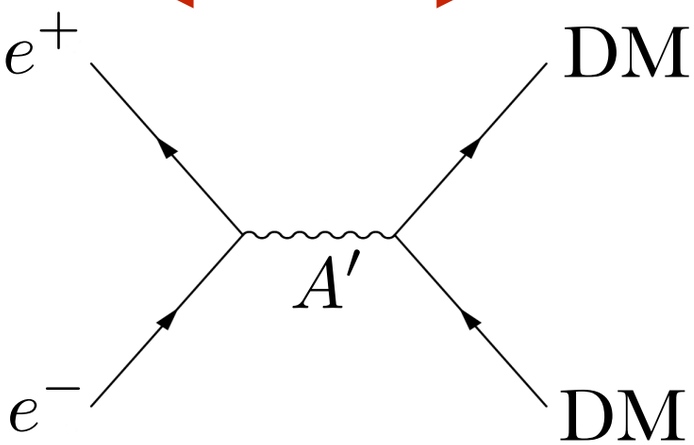

Freeze-in

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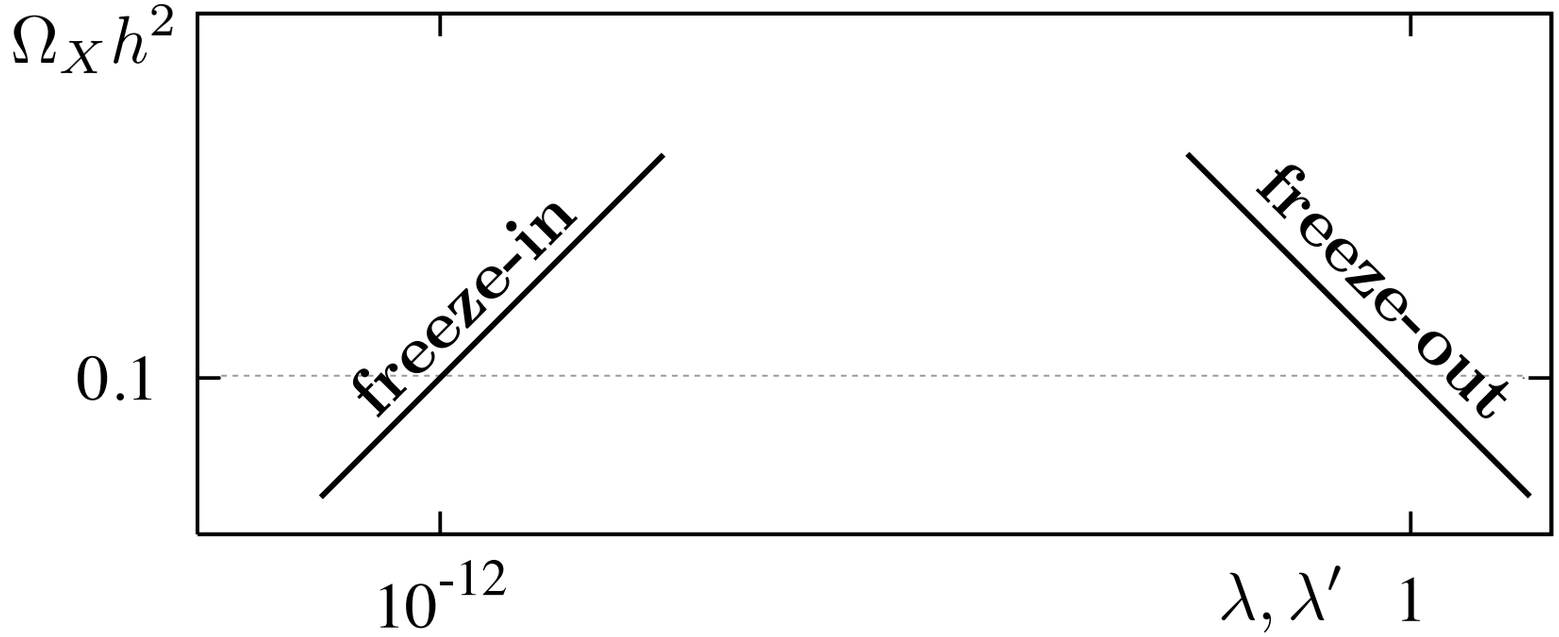
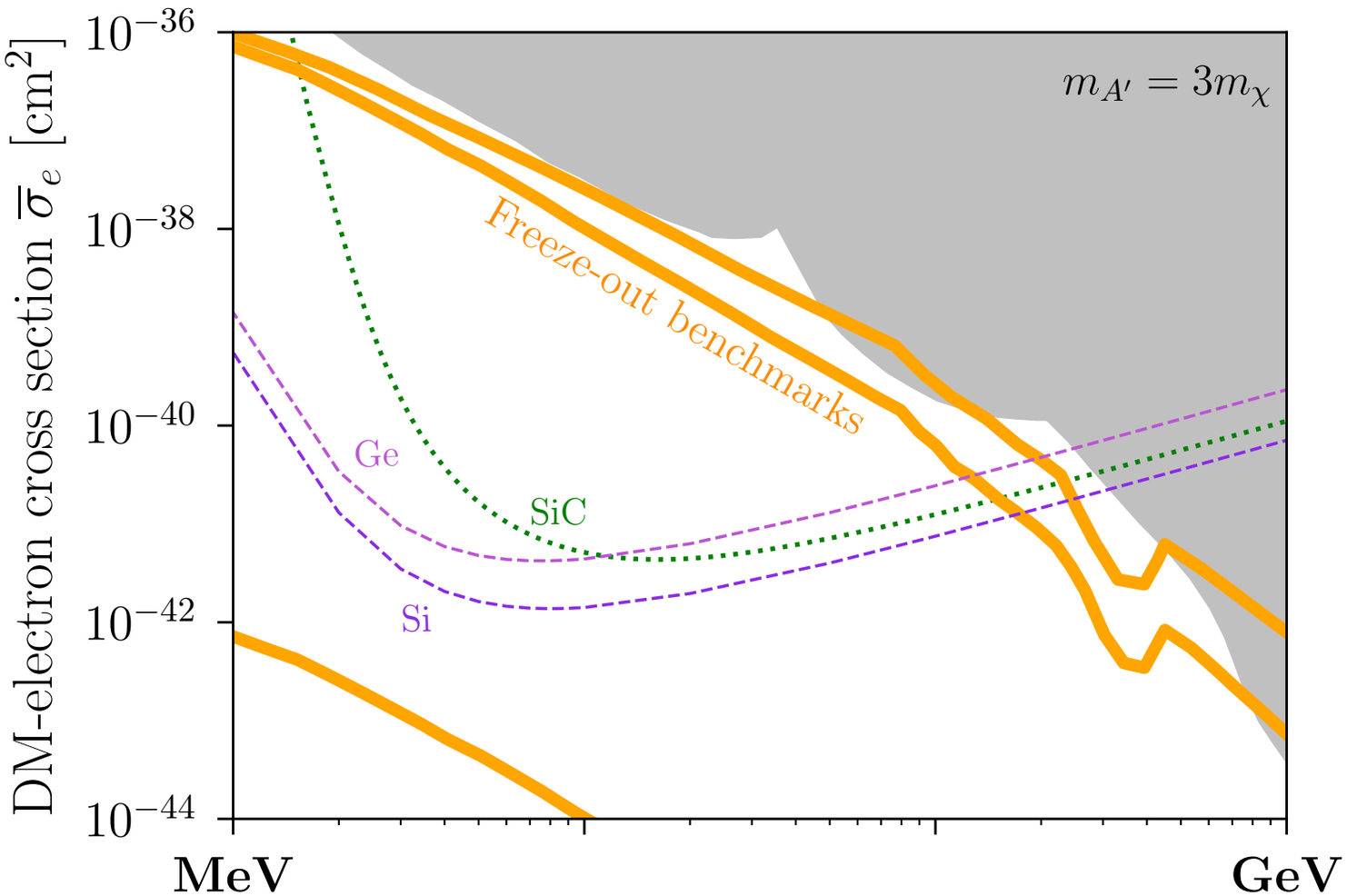


From Hall, Jedamzik, March-Russell, West 2009

Freeze-out

Can be tested with small (< kg) semiconductor experiments and accelerator experiments like LDMX

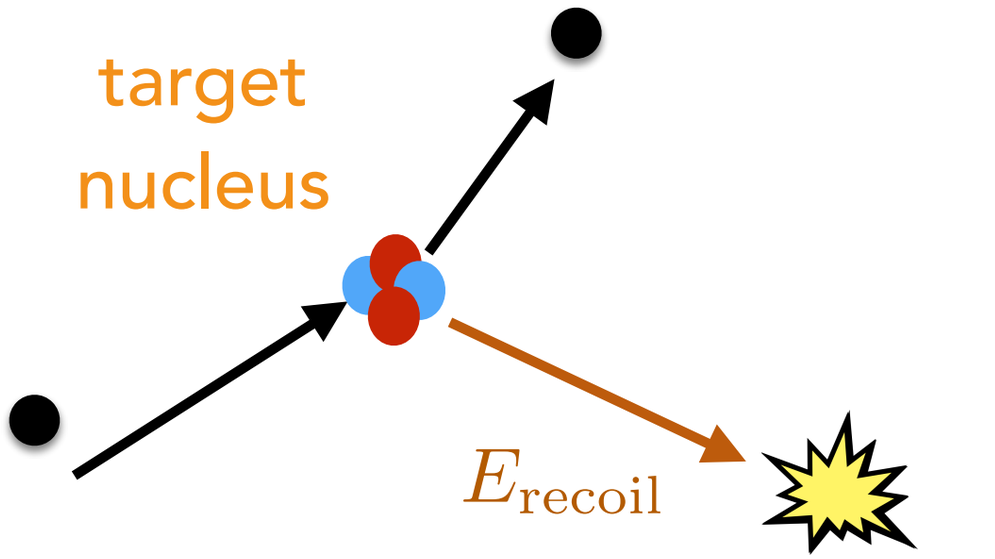


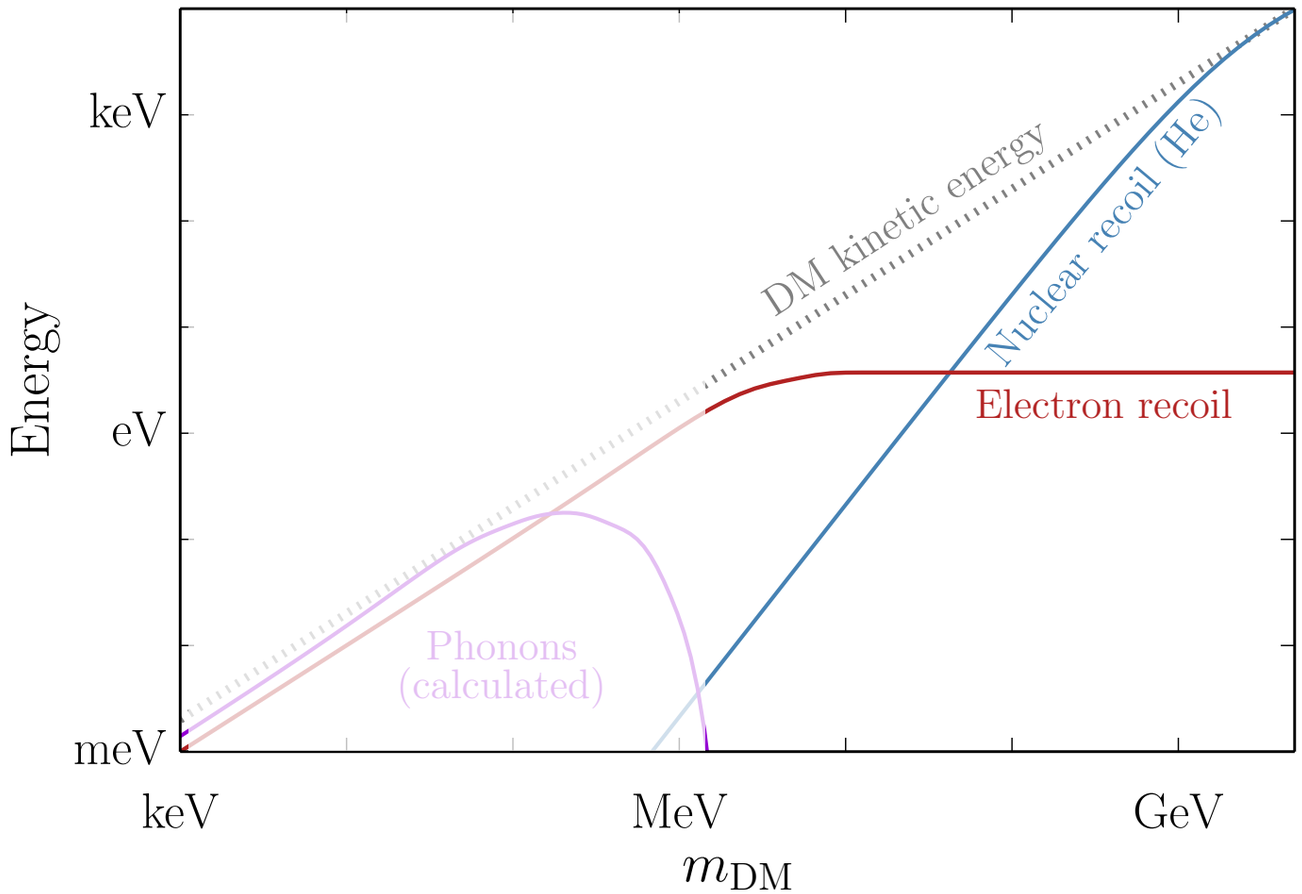
Warning: there exists viable param space away from benchmarks

Electron excitations (theory): Essig, Fernandez-Serra, Mardon, Soto, Volansky Yu 2016; Griffin, Inzani, Trickle, Zhang, Zurek 2020; Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020; Knapen, Kozaczuk, TL in prep

Direct detection of sub-GeV DM

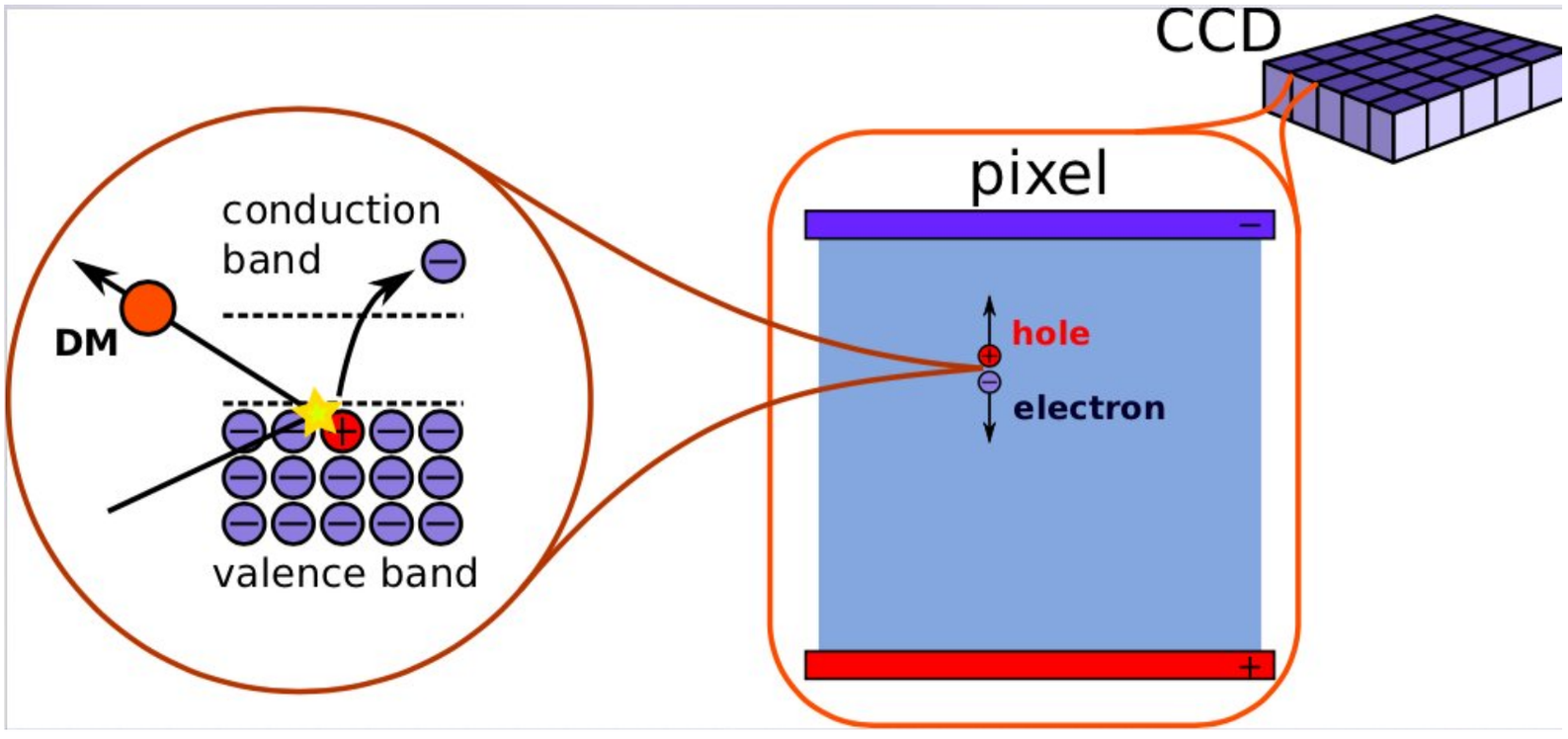
Low mass dark matter doesn't deposit much energy on heavy (free) nuclei





Electron recoil experiments

SENSEI: Skipper CCDs



2004.11378

SuperCDMS: athermal phonon readout

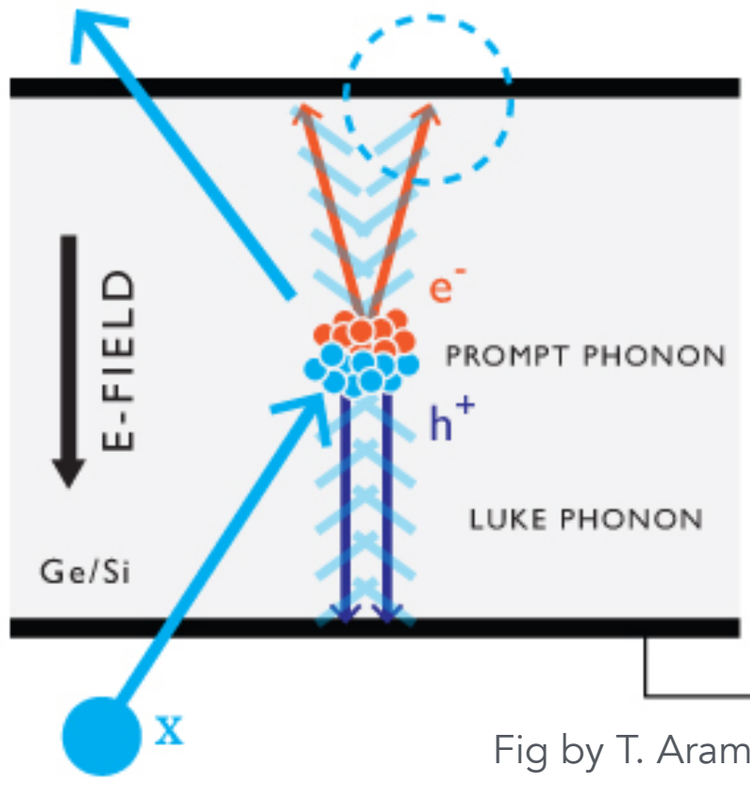


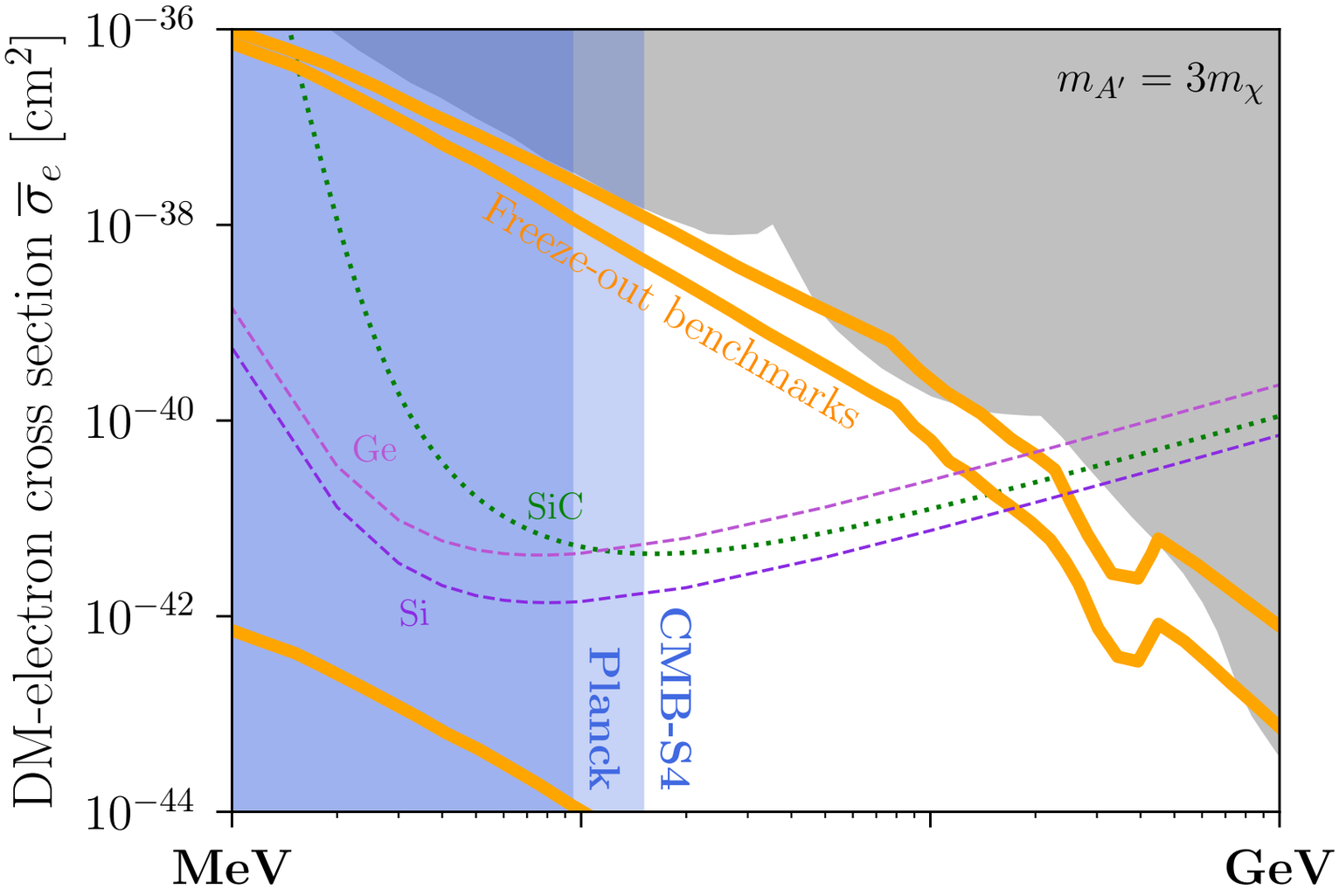
Fig by T. Aramaki

2005.14067

Recent surface runs from SuperCDMS and SENSEI have demonstrated single e- (~1 eV threshold) sensitivity

Freeze-out

MeV-scale DM in thermal equilibrium constrained by CMB, BBN



CMB bounds can be weakened somewhat by introducing additional dark radiation

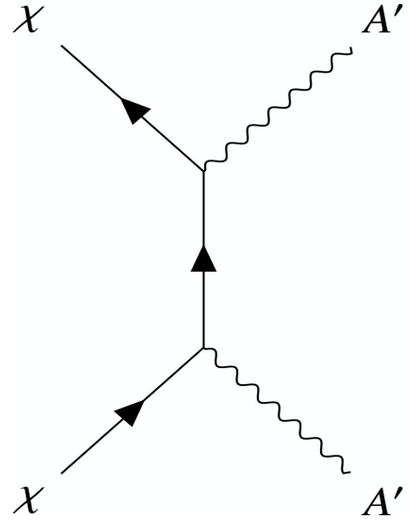
Sabti et al. 2019
See also: Knapen, TL, Zurek 2017
and Green, Rajendran 2017

Dark sectors below ~MeV

BBN and CMB bounds strongly constrain sub-MeV dark sectors in equilibrium with the standard model.

What kinds of sub-MeV thermal relic DM are possible?

Secluded sectors can evade this:



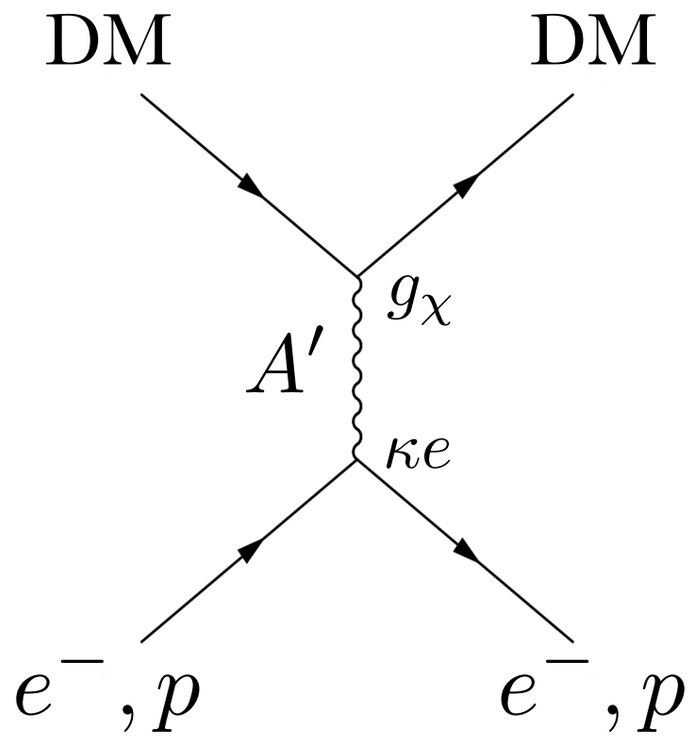
but loss in predictivity, observability

Freeze-in is also not subject to the same bounds.

Mass should be $\gtrsim 10$ keV due to stellar emission bounds

Freeze-in

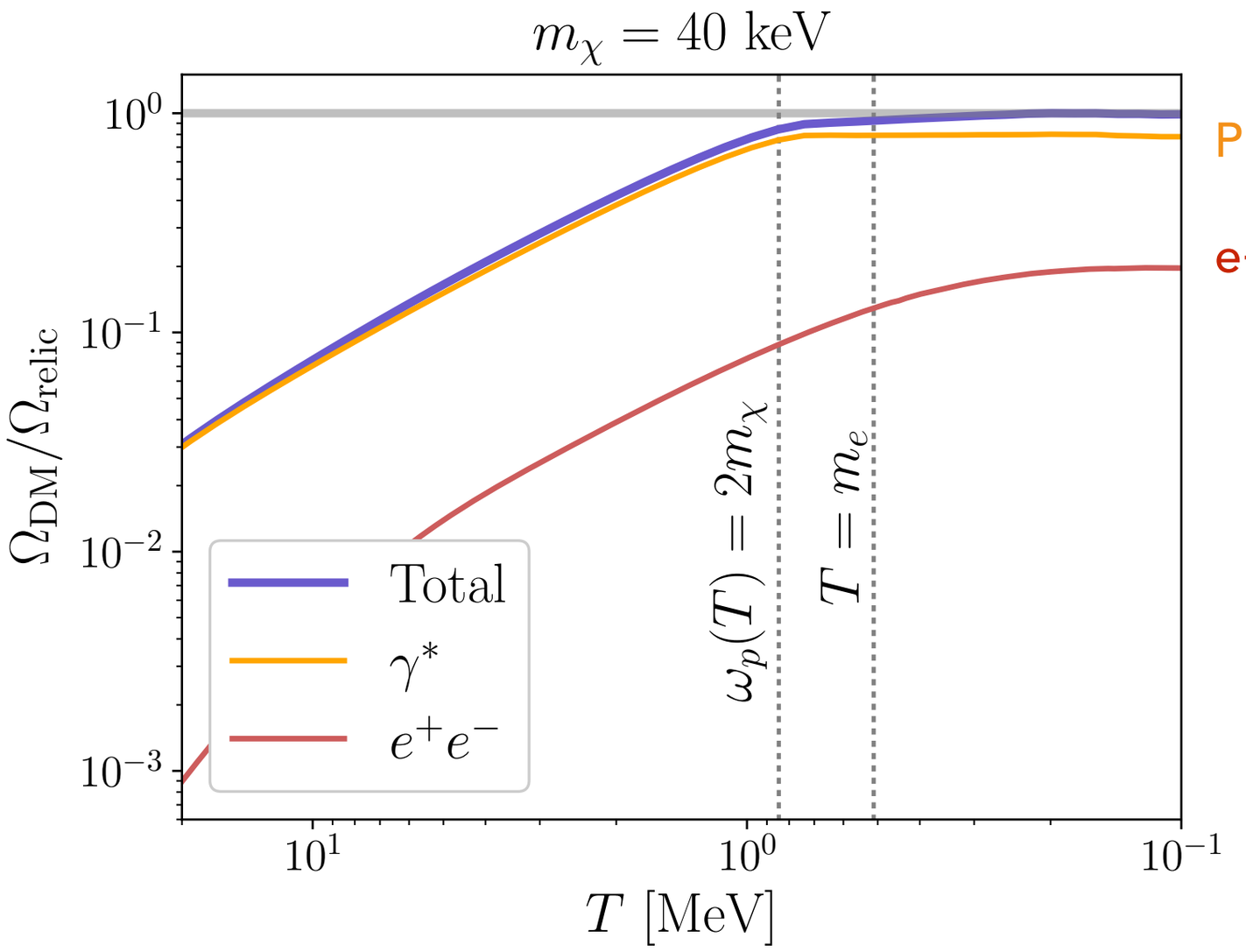
Tiny couplings $\kappa g_\chi \sim 10^{-11}$ for freeze-in — N_{eff} bounds don't apply



$$\sigma_{\mathrm{DM-target}} \propto \frac{1}{v^4}$$

Predictive and detectable benchmark for direct detection in the light mediator limit $m_{A'} \ll m_{\mathrm{DM}}$

Cosmology of freeze-in



Plasmon decay

e+e- annihilation

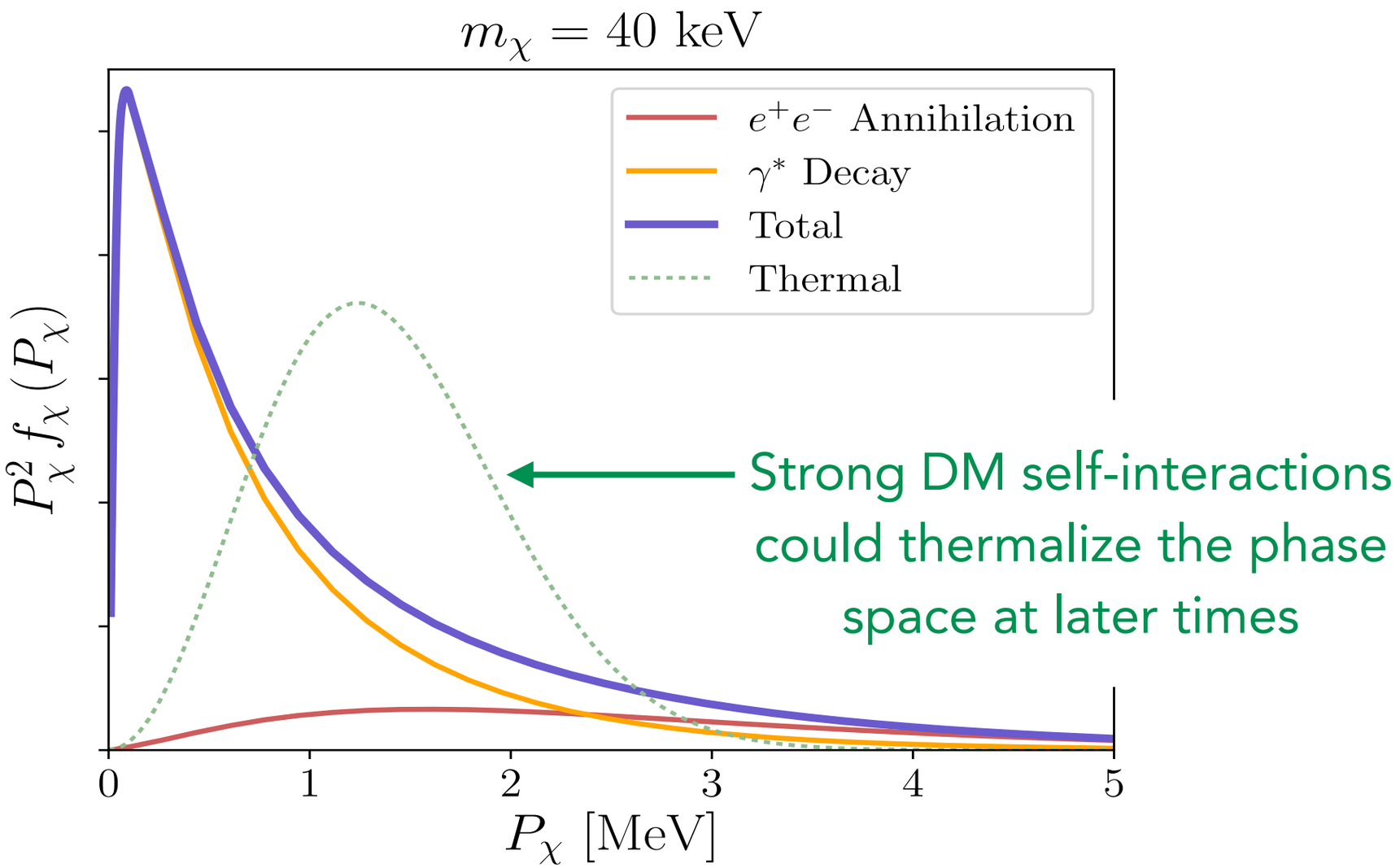
Plasmon decay to DM most important for lower DM masses since $\omega_p \approx 0.1 k_B T$

Impacts predicted direct detection cross sections

Cora Dvorkin, TL, Katelin Schutz 2019

Dark matter phase space

Dark matter is produced hot, with non thermal phase space

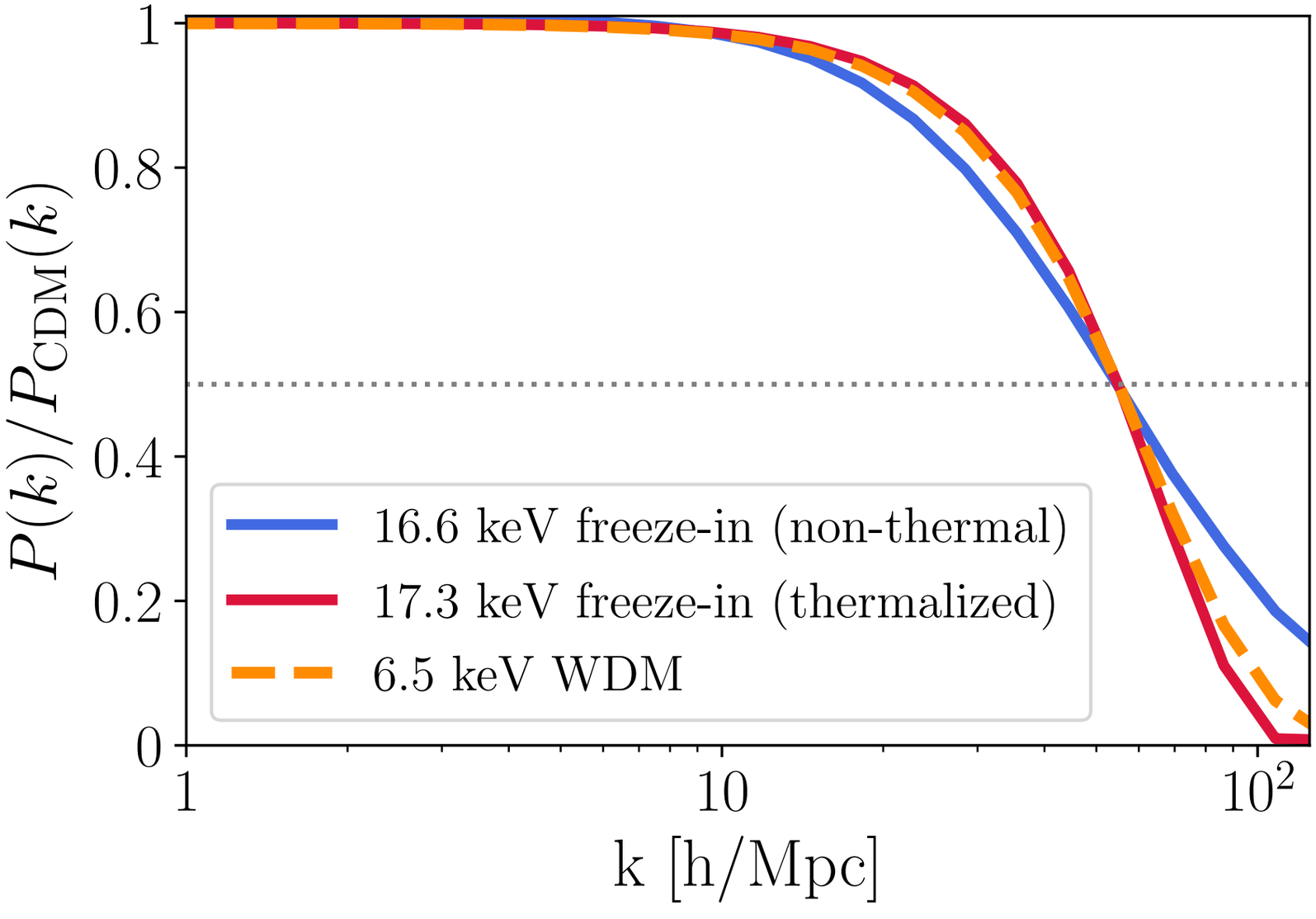


Strong DM self-interactions could thermalize the phase space at later times

Dvorkin, TL, Schutz 2019

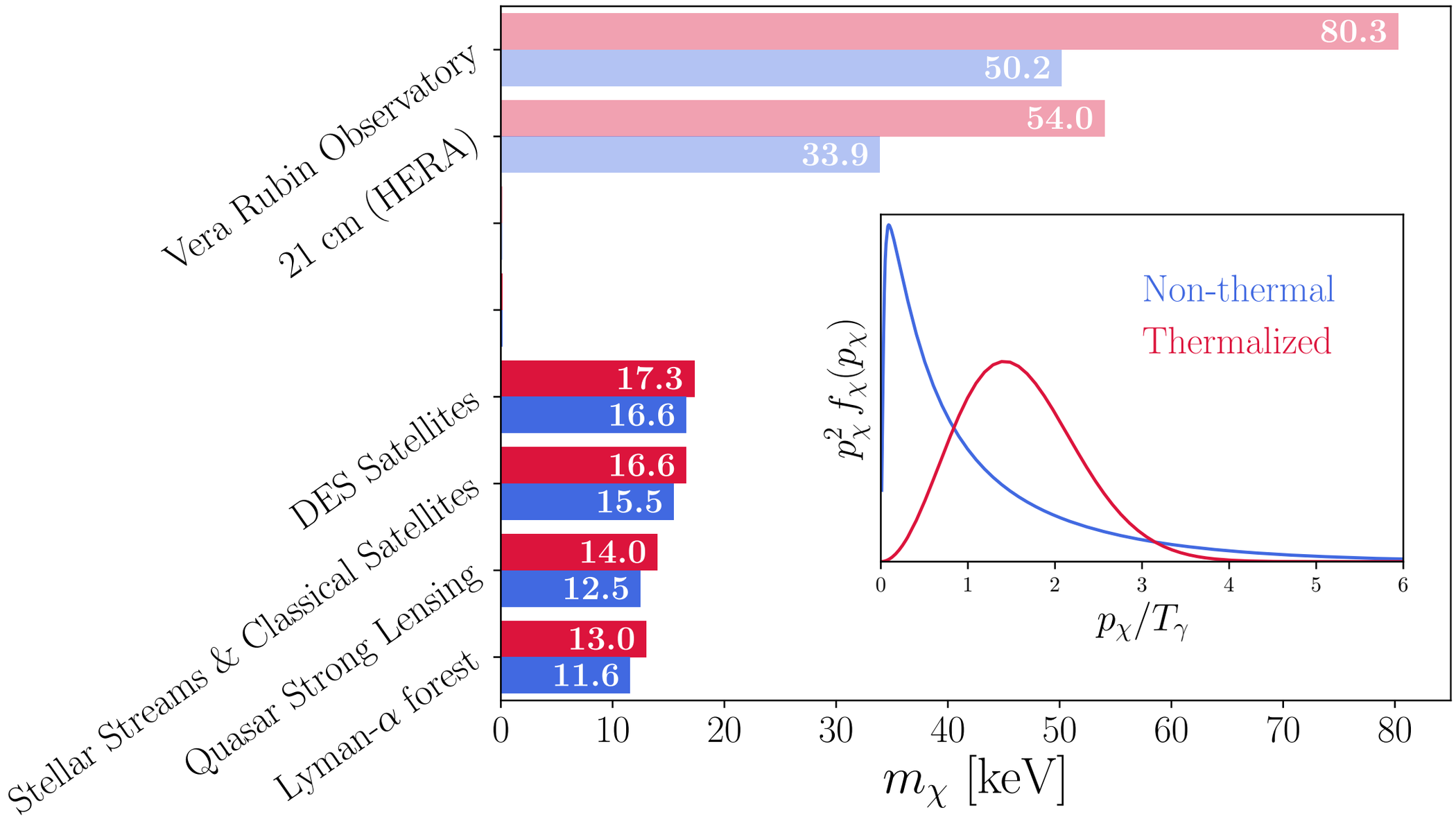
Suppression of small-scale structure

Comparison with best WDM limits (> 6.5 keV, Nadler+ 2020)



Dvorkin, TL, Schutz, to appear

Bounds from structure formation



Dvorkin, TL, Schutz, to appear

DM-baryon scattering

$1/v^4$ scattering cross section implies possible momentum-transfer between DM and baryon fluids during recombination

Drag in DM, baryon velocity perturbations:

$$c_\chi^2 = \frac{5T_\chi^{\rm eff}}{3m_\chi} \qquad R_\chi \sim a\, n_p \frac{\sigma_0}{v^4} v$$

$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi),$$

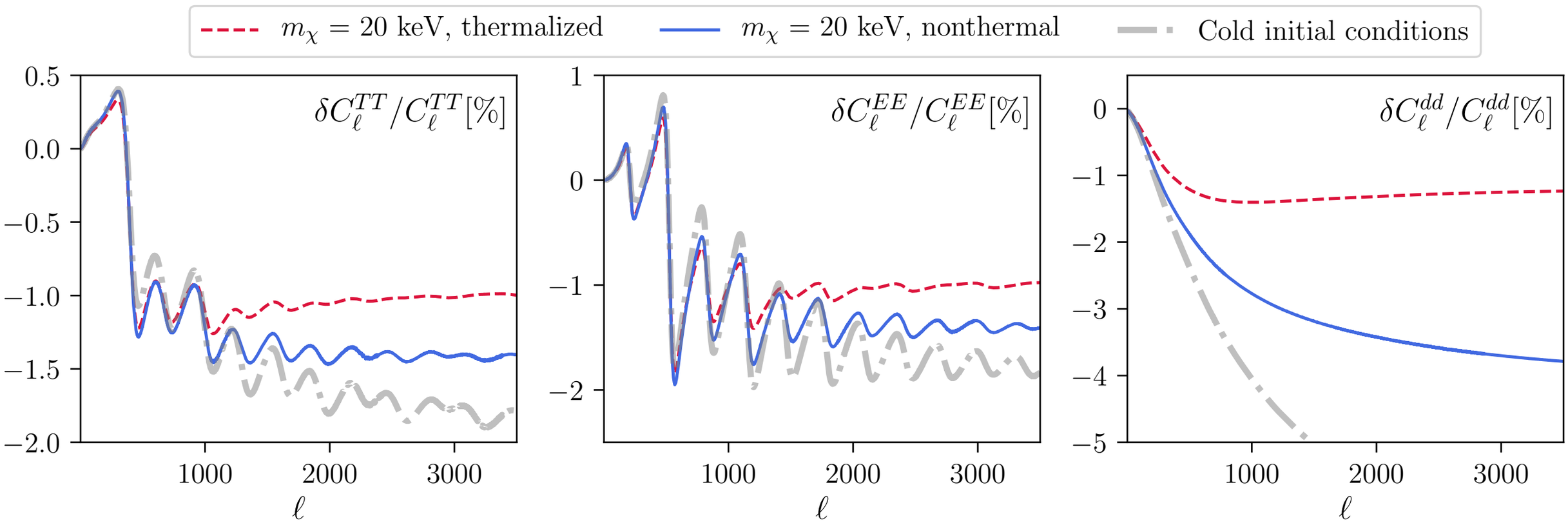
$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b} R_\chi(\theta_\chi - \theta_b)$$

Effect is sensitive to DM phase space and thermal history

Dvorkin, TL, Schutz, to appear

DM-baryon scattering

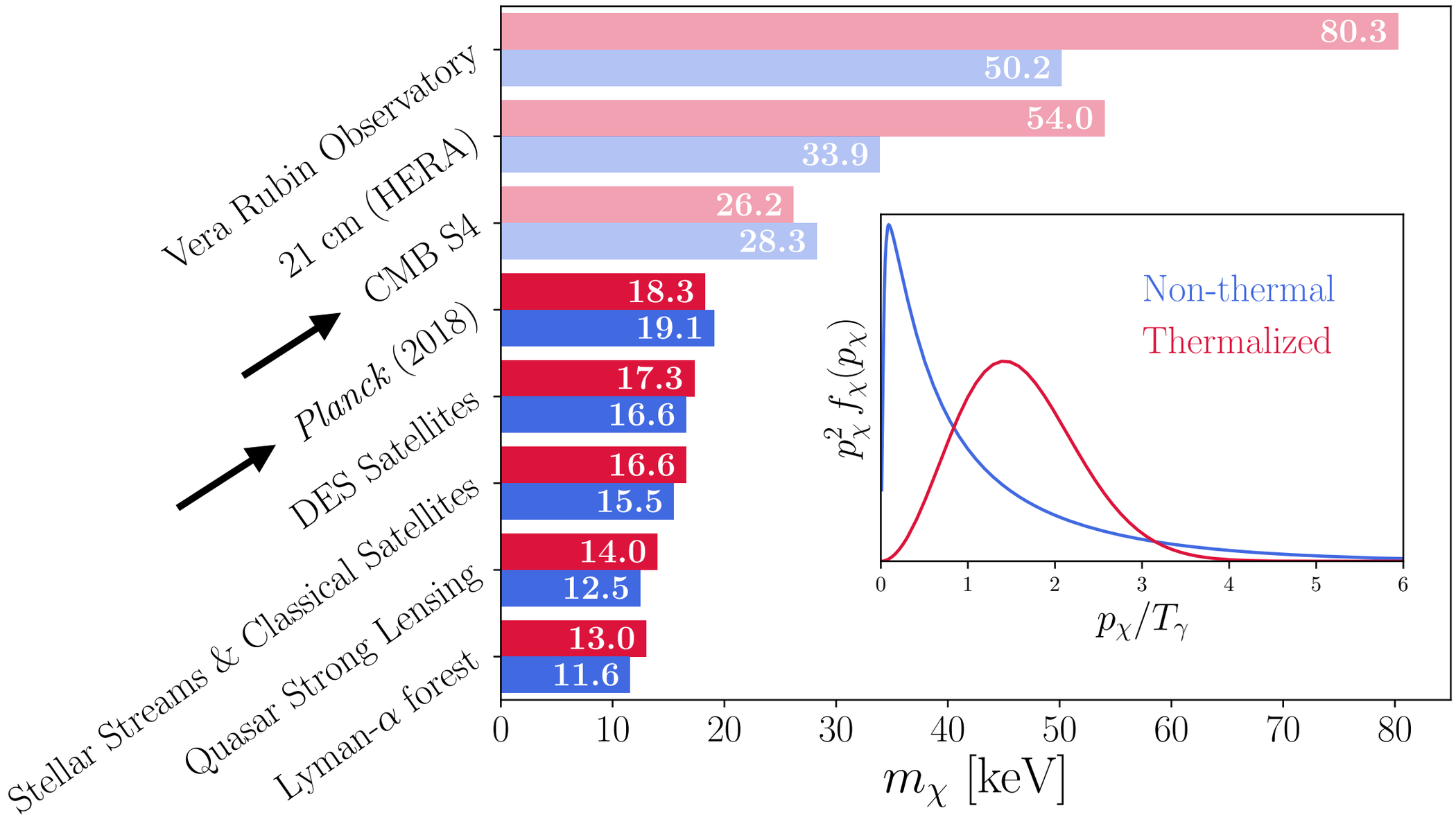
Suppression in power at small scales, shift in peaks due to drag



Effect differs from CDM limit for DM-baryon scattering, and depends on size of DM self-scattering.

Dvorkin, TL, Schutz, to appear

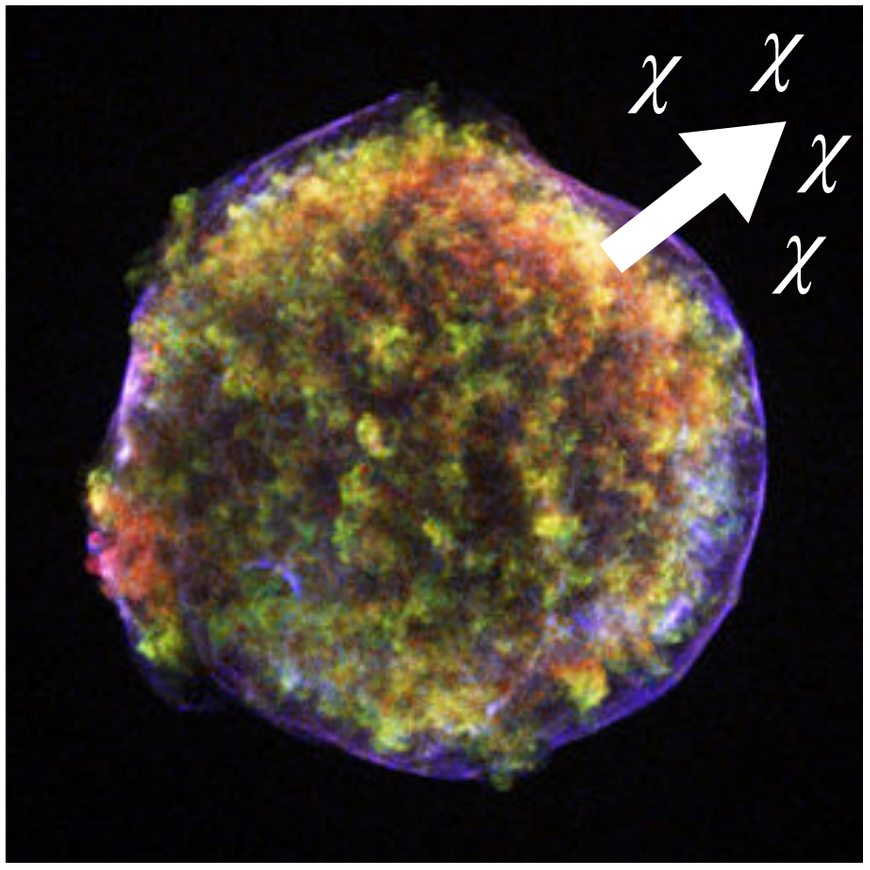
Cosmological probes of freeze-in

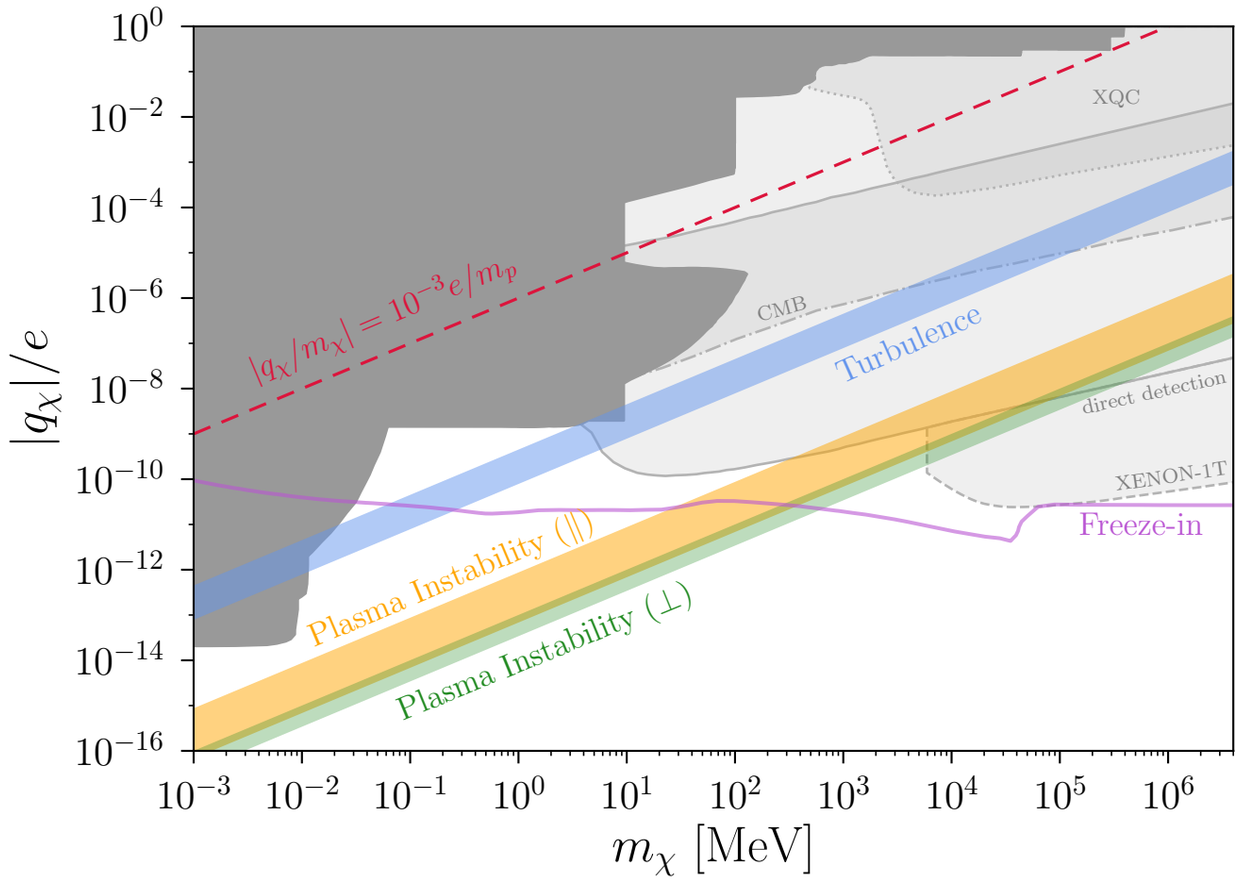


Dvorkin, TL, Schutz, to appear

Freeze-in as millicharged DM

In the limit $m_{A'}$ is very small, this DM candidate behaves as millicharged (nano-charged) particle.





DM could be swept up (and maybe accelerated) in supernova remnants.

Jung-Tsung Li, TL 2020
See also: Lasenby 2020

Freeze-in as millicharged DM

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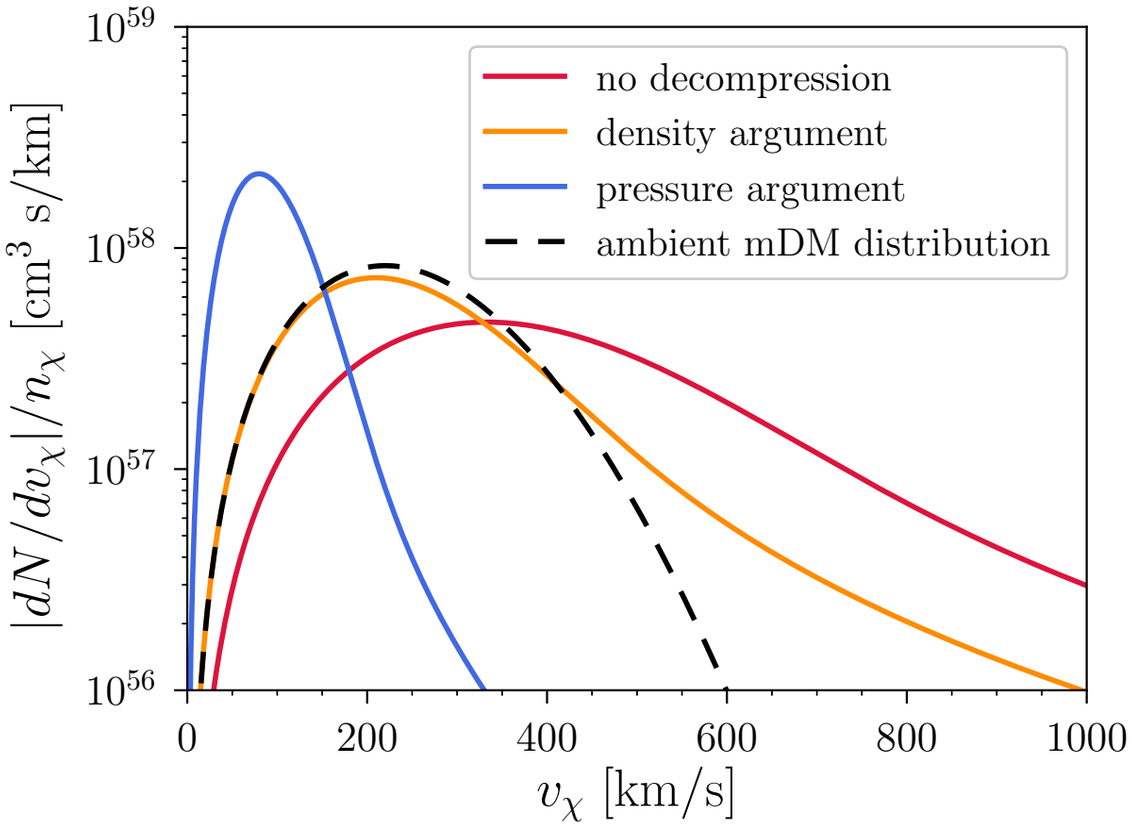


How does this affect viability of candidate and direct detection?

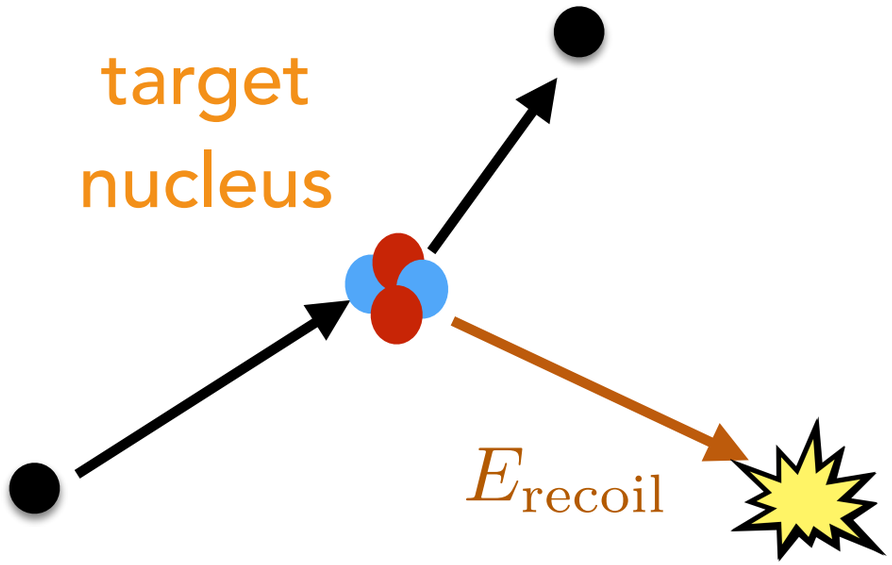
We find most of the DM will return to having roughly the original/ ambient DM velocity.

Still many open questions as to the astrophysics of millicharged DM

Jung-Tsung Li, TL 2020
See also: Lasenby 2020

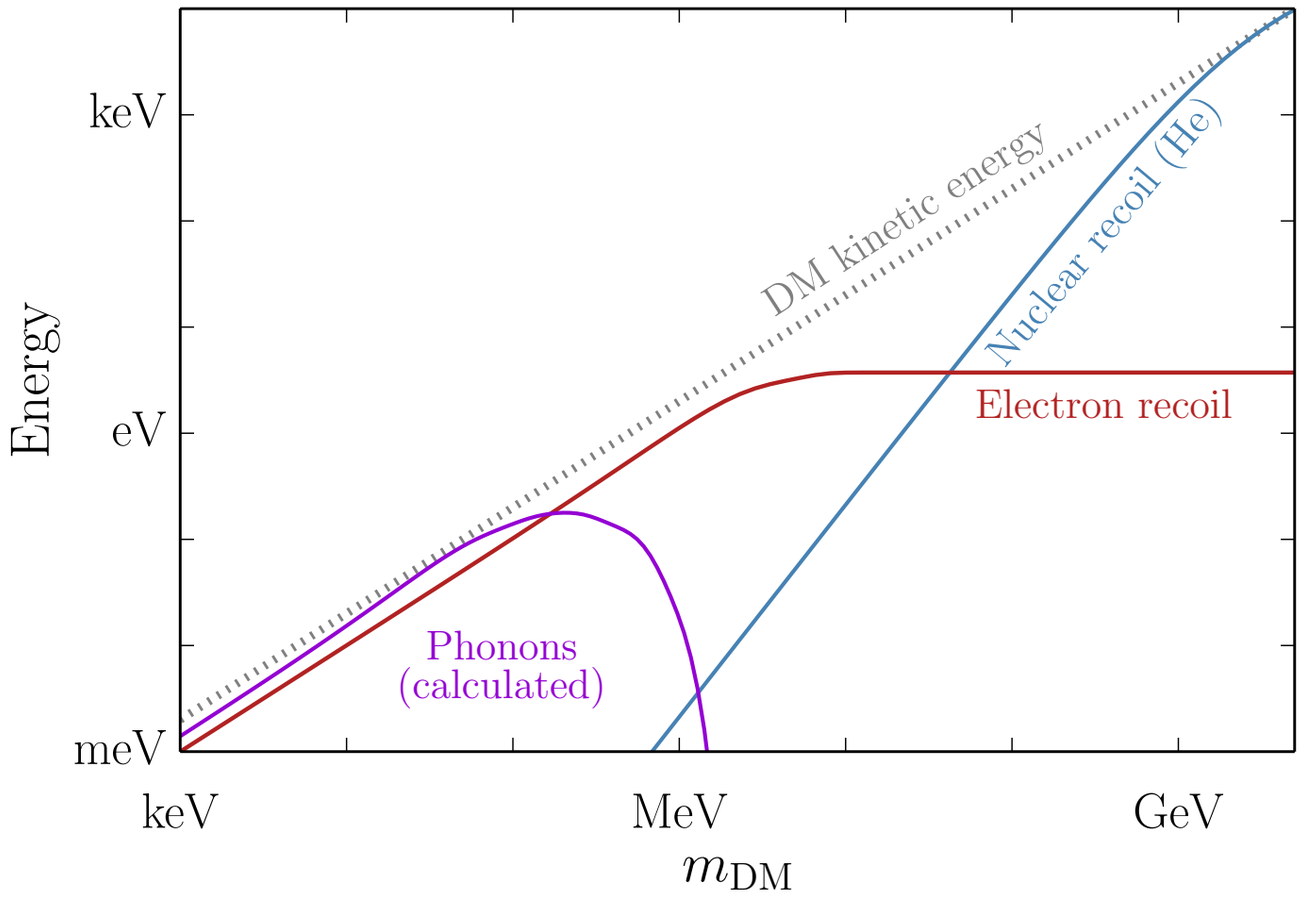
Direct detection of freeze-in

Low mass dark matter doesn't deposit much energy on heavy (free) nuclei

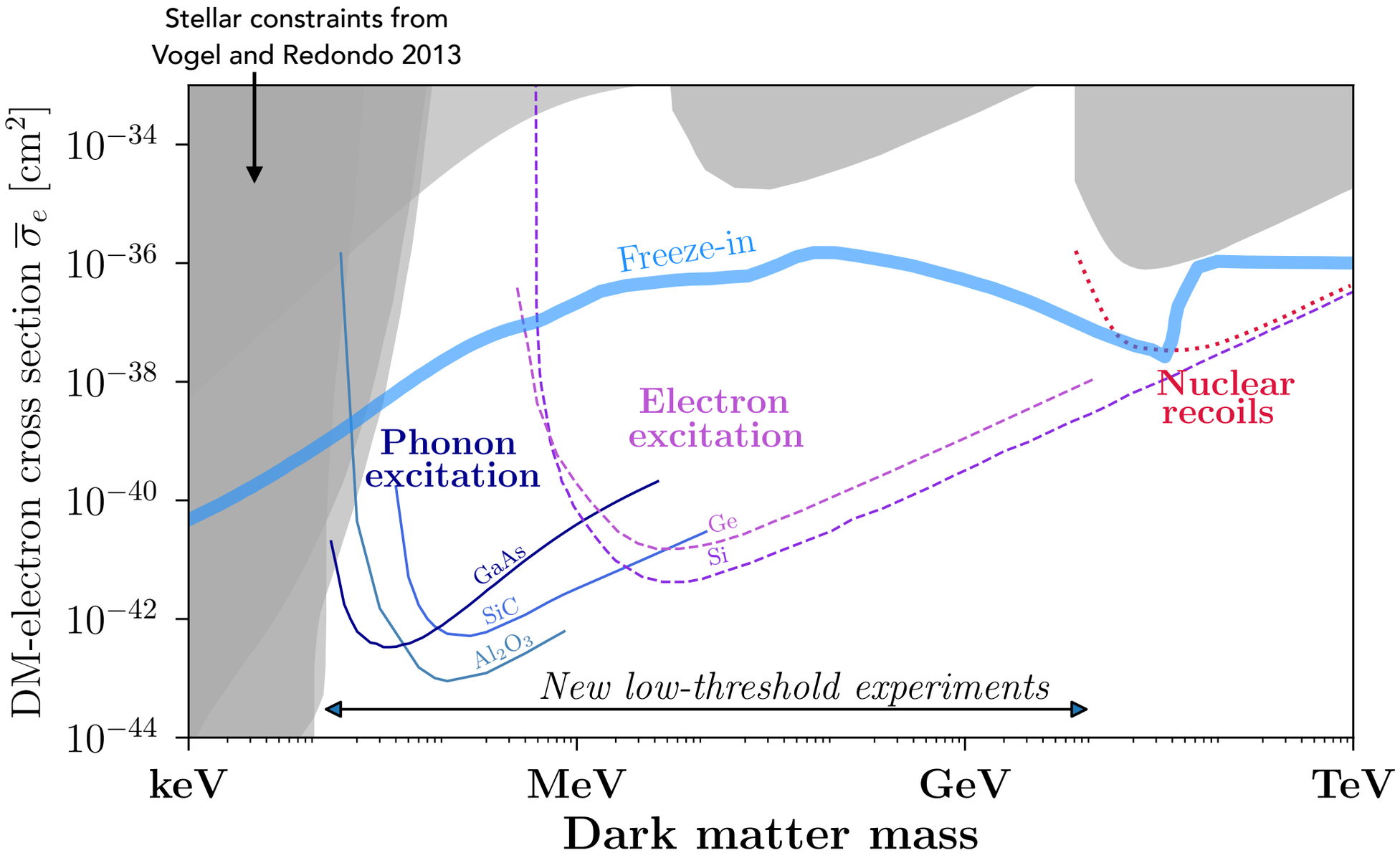


Detect recoiling nucleus

Free-particle kinematics: inefficient, and doesn't accurately describe target response



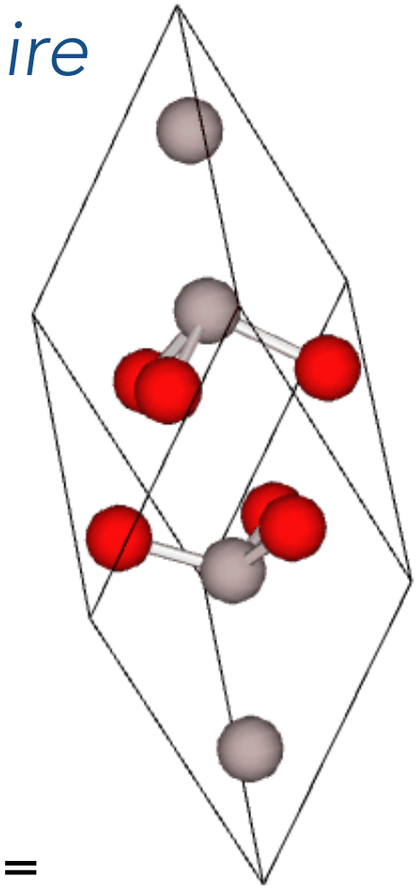
Direct detection of freeze-in



Phonon excitations (theory): Pyle, Knapen, TL, Zurek 2018; Griffin, Knapen, TL, Zurek 2018; Griffin, Inzani, Trickle, Zhang, Zurek 2020; Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020; …

Phonon excitations

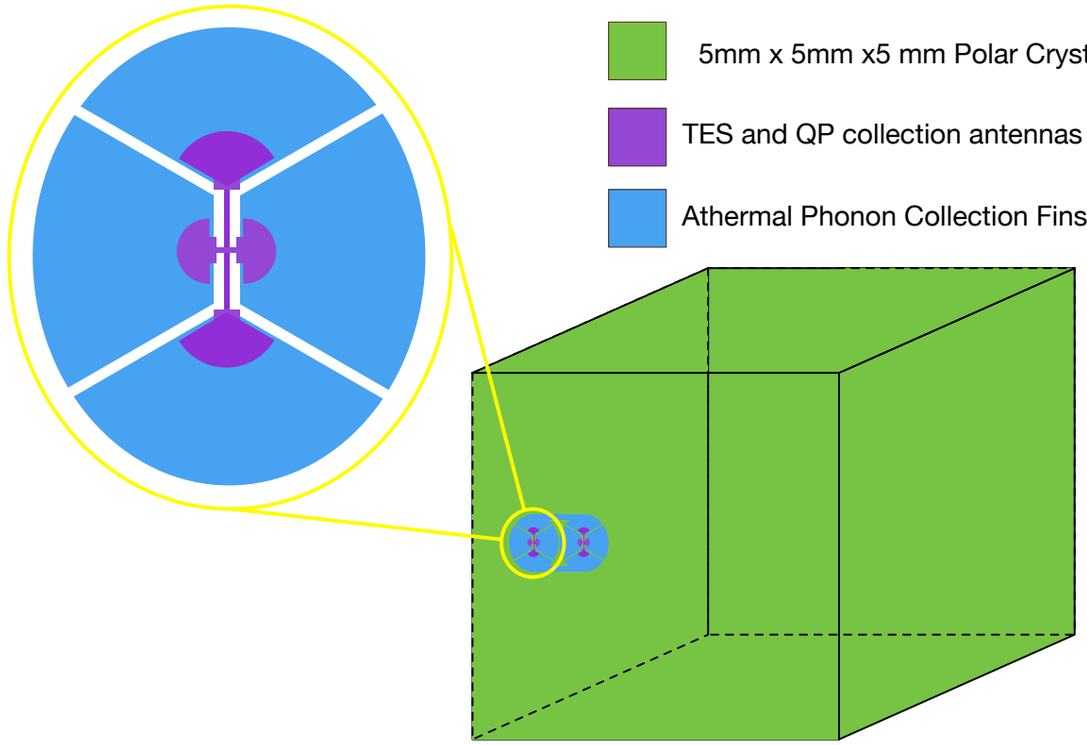
Sapphire



DM scatters and excites dipole moment = optical phonon

+

Athermal phonon readout



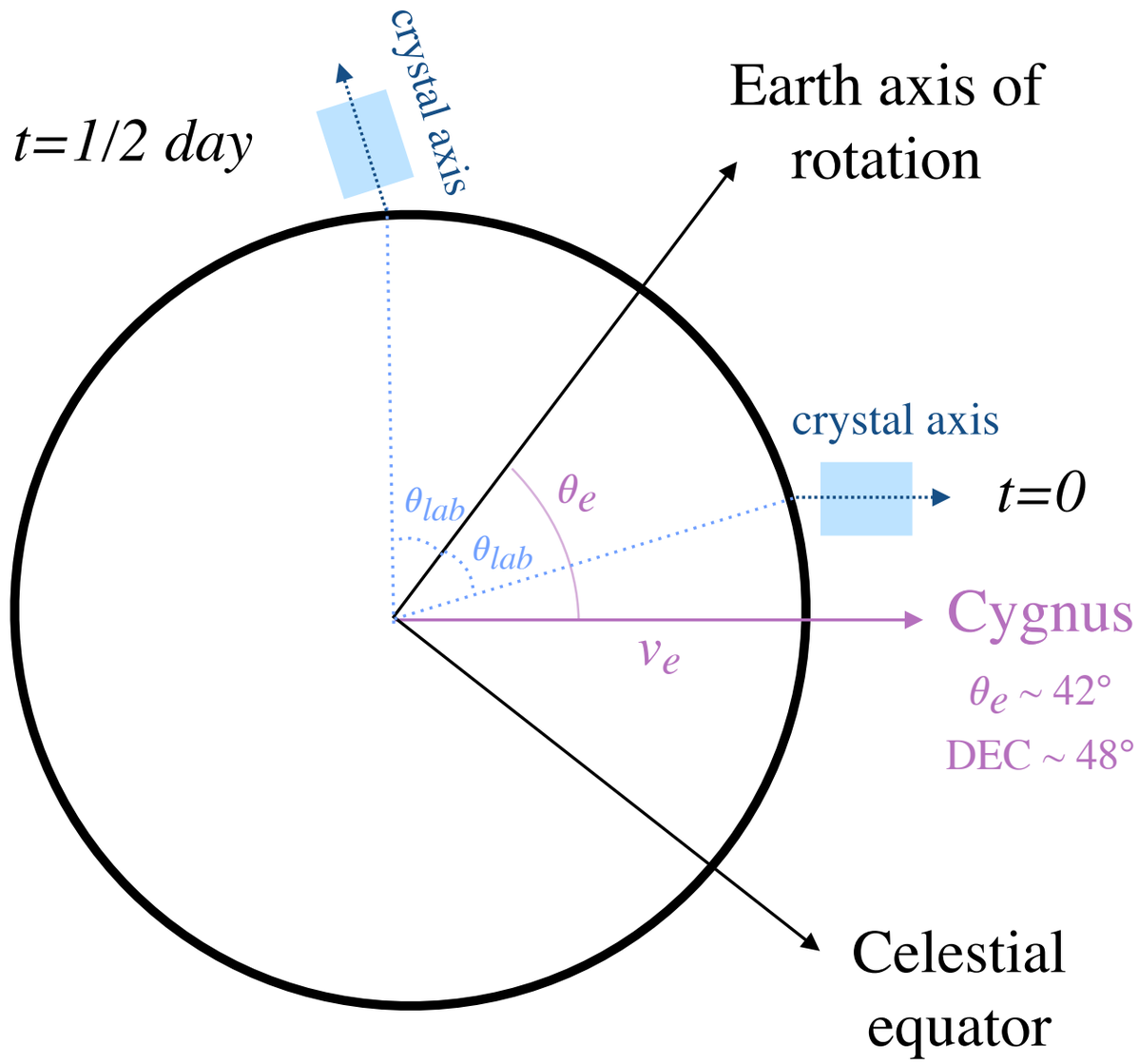
~gram size detector

Phonon excitations (theory): Pyle, Knapen, TL, Zurek 2018; Griffin, Knapen, TL, Zurek 2018; Griffin, Inzani, Trickle, Zhang, Zurek 2020; Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020; …

Directional detection

Direction-dependent phonon modes in sapphire (Al_2O_3) lead to daily modulation as the Earth rotates

In phase with sidereal day, not solar day — could be distinguished from terrestrial backgrounds.

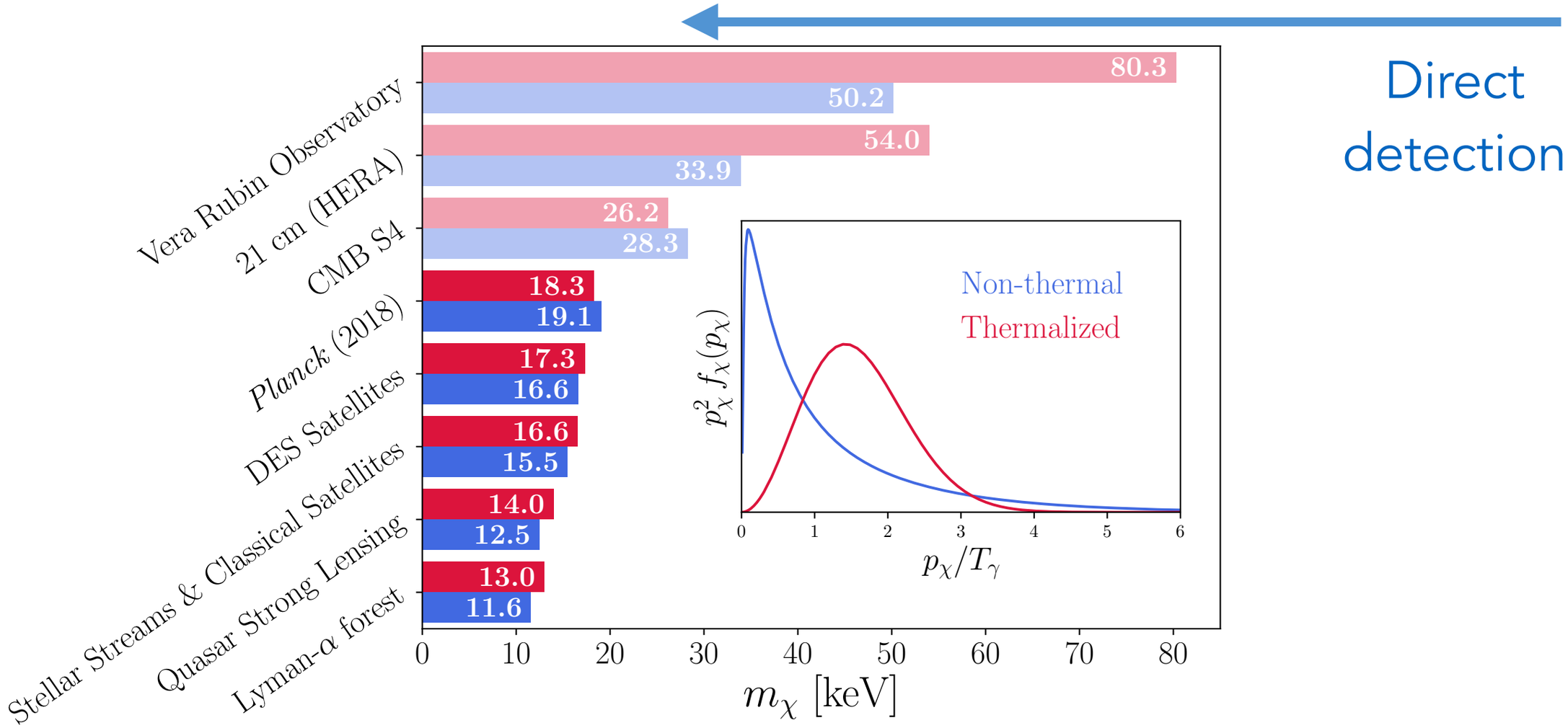


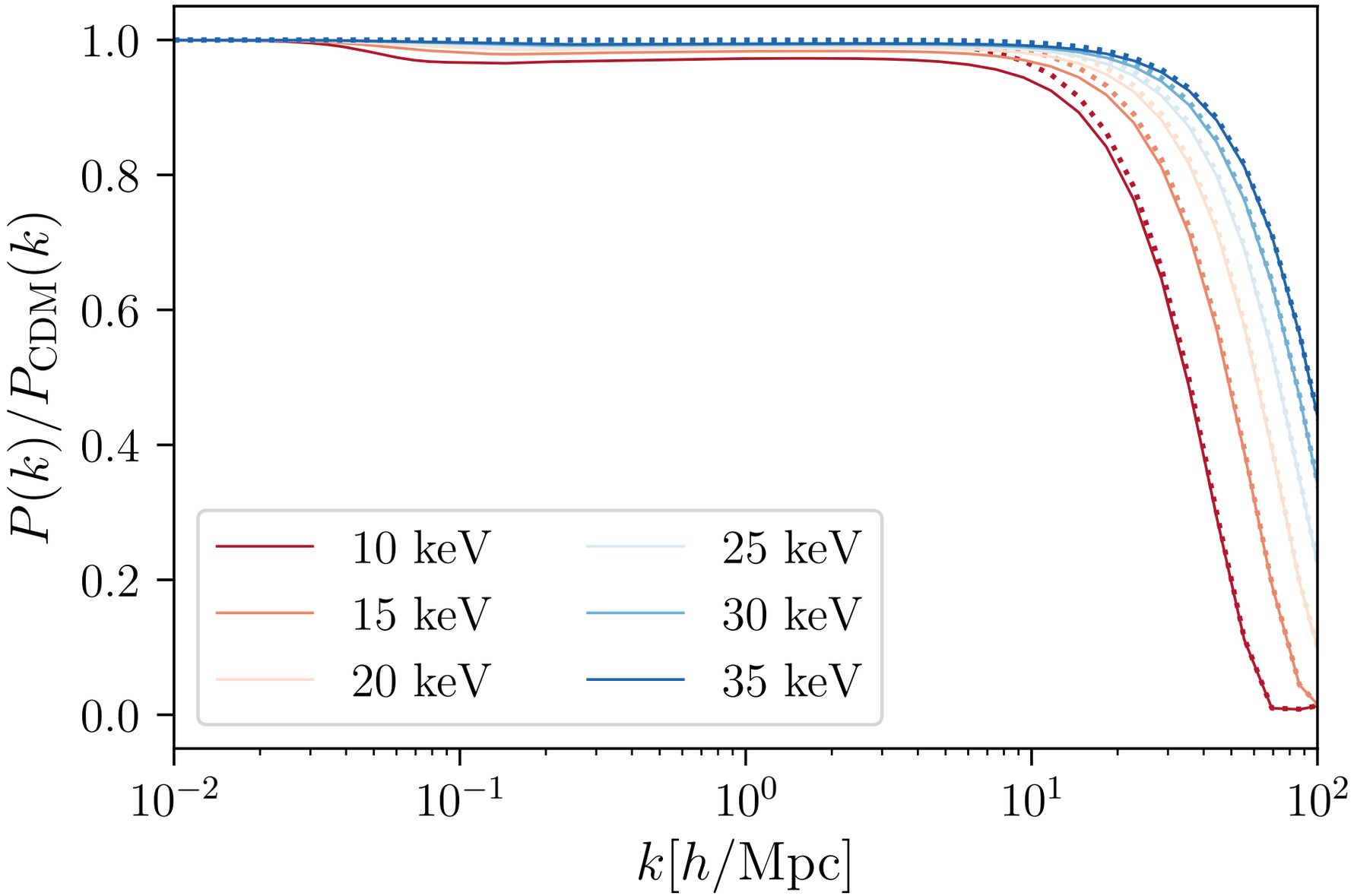
Griffin, Knapen, TL, Zurek 2018;
Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020

Conclusions

Thermal relic dark sectors are a motivated class of dark matter models, with mass as low as ~10 keV.

Freeze-in is one of the leading benchmarks below ~ MeV in mass. Complementary approaches from cosmology, astrophysics, and direct detection.




1.0
0.8
0.6
0.4
0.2
0.0
$P(k)/P_{\rm CDM}(k)$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
$k[h/{\rm Mpc}]$
10 keV
15 keV
20 keV
25 keV
30 keV
35 keV