Fundamental Physics from Future Spectroscopic Surveys
Lawrence Berkeley National Laboratory, 6 May 2024

OPPORTUNITIES FOR DARK MATTER SEARCHES IN COSMOLOGY

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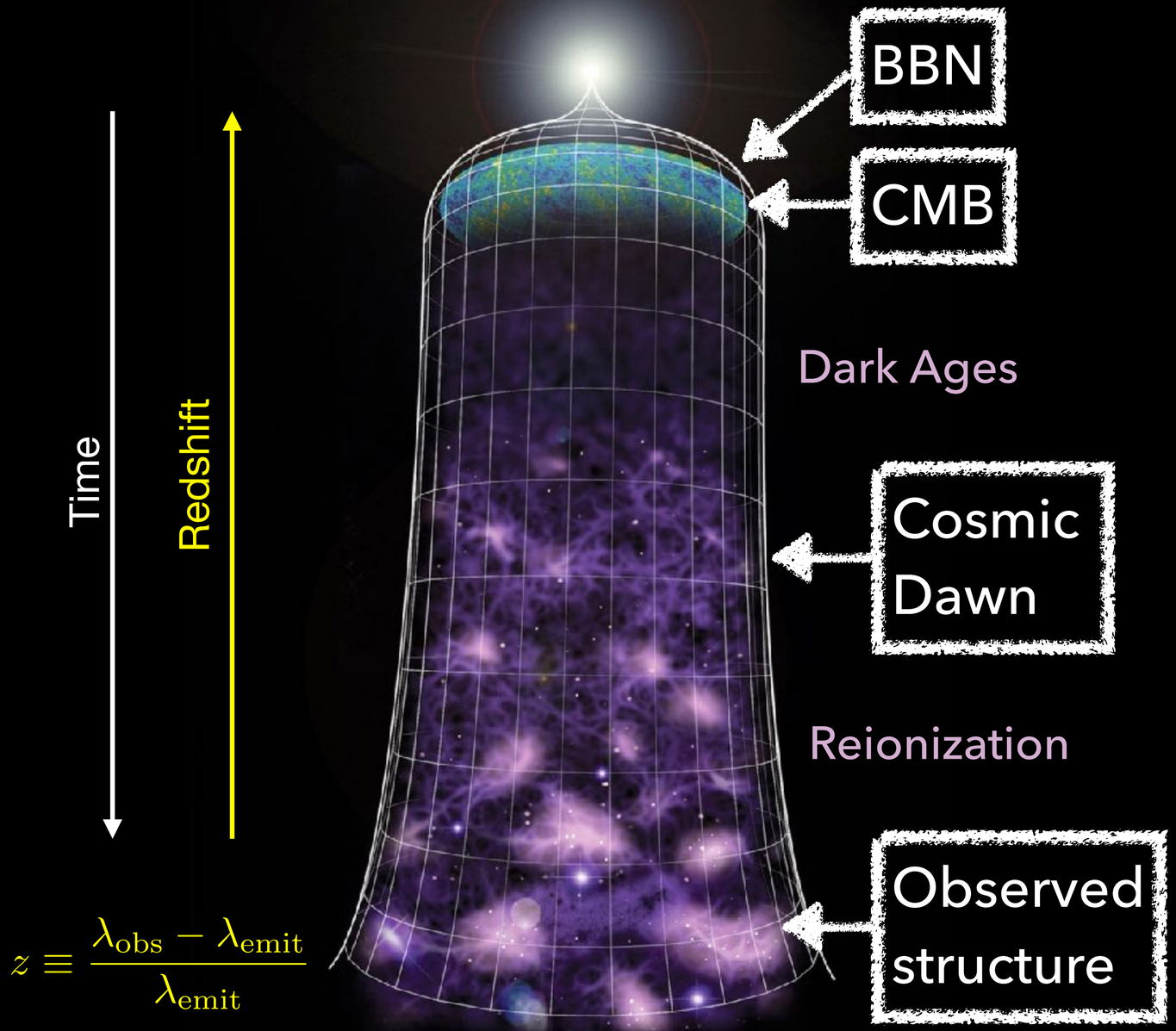
Cosmic History



Deviations from CDM due to DM properties/interactions:

(1) Early Universe:
impact initial conditions for structure formation

(2) Late Universe:
impact halo formation and evolution

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Early Universe:
impact initial conditions for structure formation

Dark Matter Scattering

$$\sigma_{MT}(v) = \int (1 - \cos\theta) \frac{d\sigma}{d\Omega}\, d\Omega = \sigma_0 v^n$$

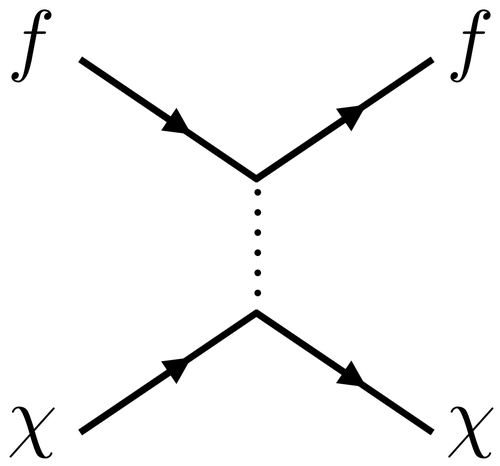
Heavy mediator

- $n = 0 \quad \mathscr{L} \sim \bar{\chi}\chi\bar{f}f$
- $n = 2 \quad \mathscr{L} \sim i\bar{\chi}\chi\bar{f}\gamma^5 f,\ i\bar{\chi}\gamma^5\chi\bar{f}f$
- $n = 4 \quad \mathscr{L} \sim \bar{\chi}\gamma^5\chi\bar{f}\gamma^5 f$

Light mediator

- $n = -2$ (electric dipole)
- $n = -4$ (Coulomb)

f in early Universe: e^-, p, He



see KB, Gluscevic (PRD 2018) and Gluscevic, KB (PRL 2018) for application of nonrelativistic EFT operator formalism

Modify Boltzmann Equations

$\sigma_{MT}(v) = \sigma_0 v^n$

$$\dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2}, \quad \dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}$$

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

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

$$\dot{T}_b + 2\frac{\dot{a}}{a}T_b = 2\frac{\mu_b}{m_e} R_\gamma(T_\gamma - T_b) + 2\frac{\mu_b}{m_\chi} R'_\chi(T_\chi - T_b)$$

$$\dot{T}_\chi + 2\frac{\dot{a}}{a}T_\chi = 2R'_\chi(T_b - T_\chi)$$

- Momentum-transfer rate

$$R_{\chi,f} \sim a n_f \left(\frac{\sigma_0}{m_\chi + m_f}\right)\left(\frac{T_b}{m_f} + \frac{T_\chi}{m_\chi}\right)^{(n+1)/2}$$

- Heat-transfer rate

$$R'_{\chi,f} = \frac{m_\chi}{m_\chi + m_f} R_{\chi,f}$$

- Assume Maxwell-Boltzmann distribution for dark matter

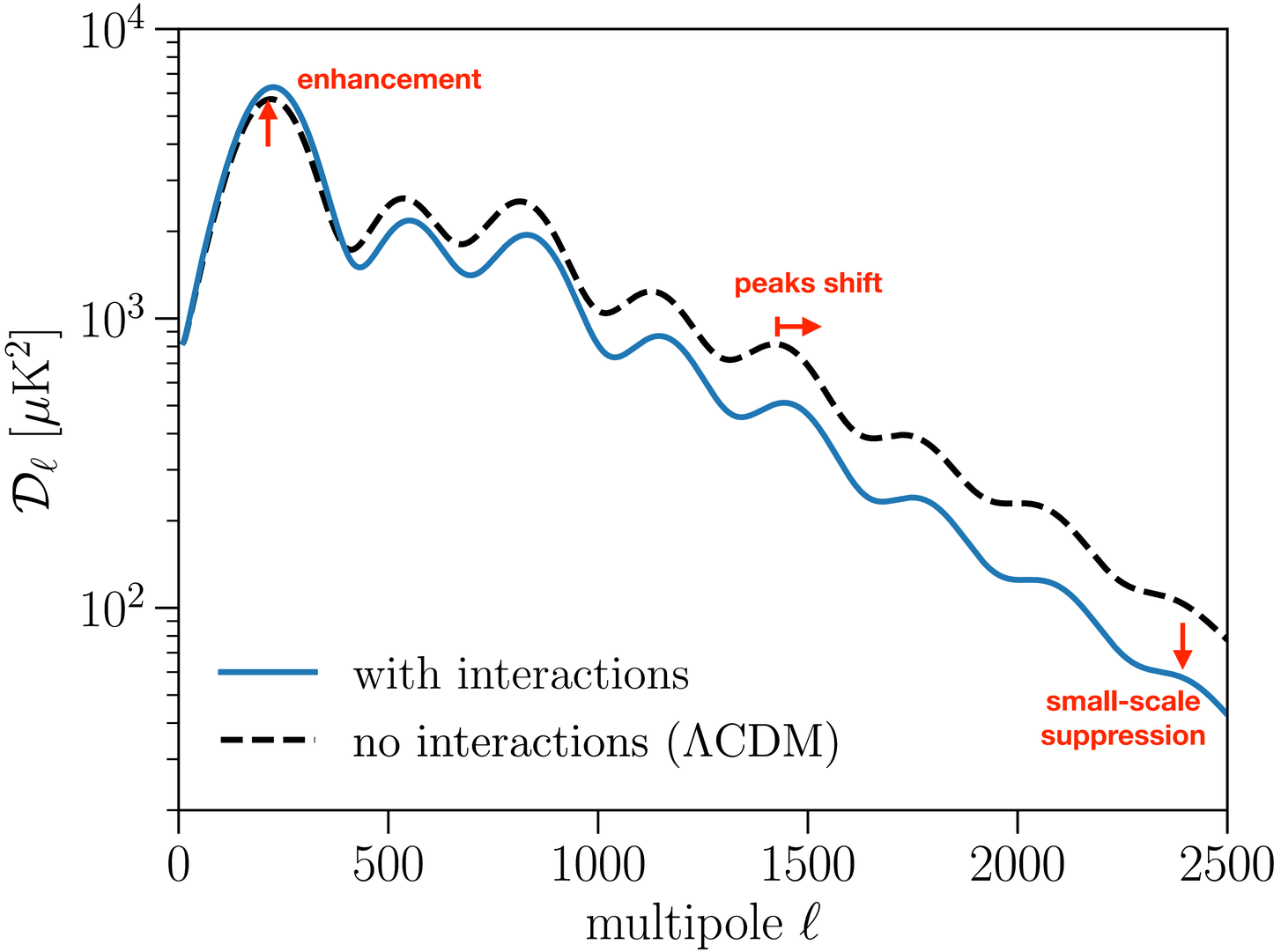
  see Ali-Haïmoud (PRD 2019); Gandhi, Ali-Haïmoud (PRD 2022) for Fokker-Planck analysis

- Nonlinearities arise for $n = -2, -4$

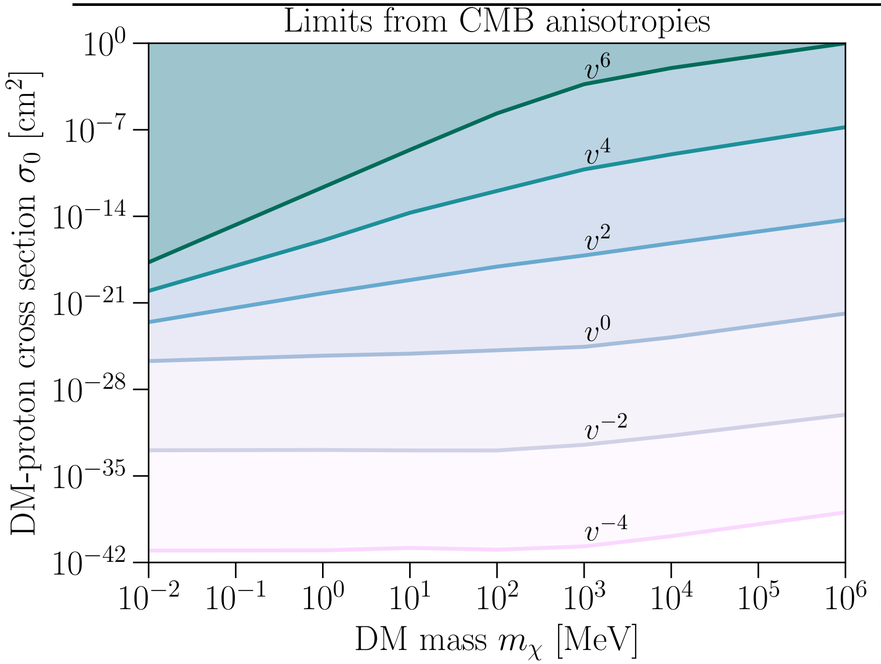
  Dvorkin+ (PRD 2014), KB+ (PRD 2018)

Modified CLASS: https://github.com/kboddy/class_public/tree/dmeff
see also CLASS v3.2 and Becker, Hooper, Kahlhoefer, Lesgourgues, Schöneberg (JCAP 2021)

Effects of Dark Matter Scattering

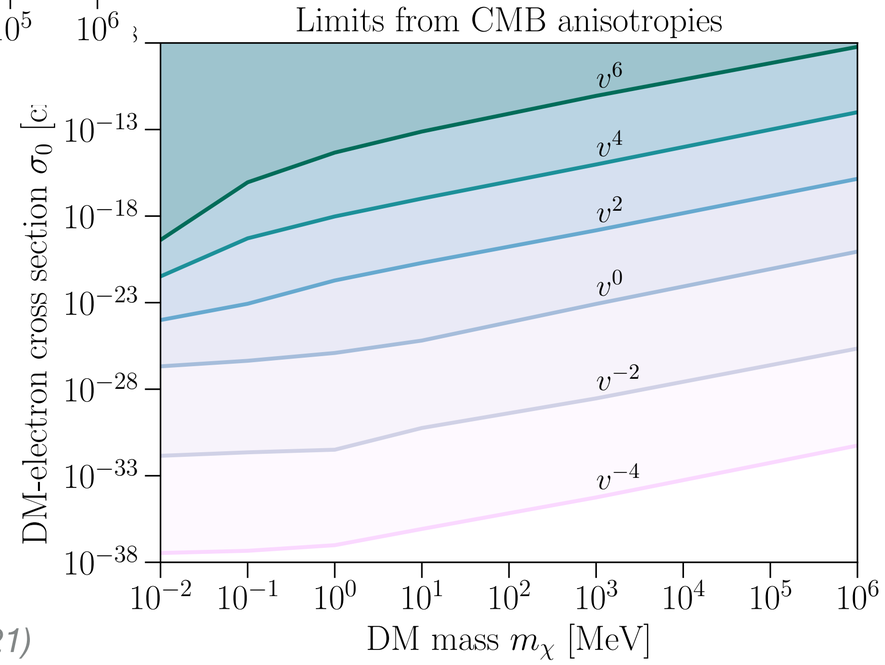


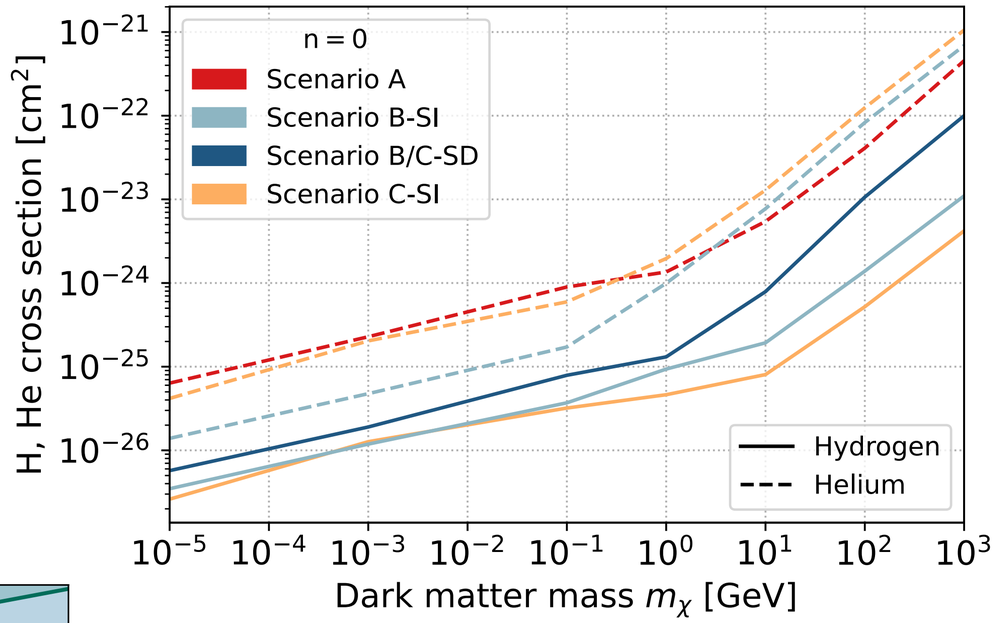
CMB Constraints from *Planck* 2018



Scattering with Protons

Scattering with Electrons





Scattering with Helium

Nguyen, Sarnaaik, KB, Nadler, Gluscevic (PRD 2021)

KB, Krnjaic, Moltner (PRD 2022)

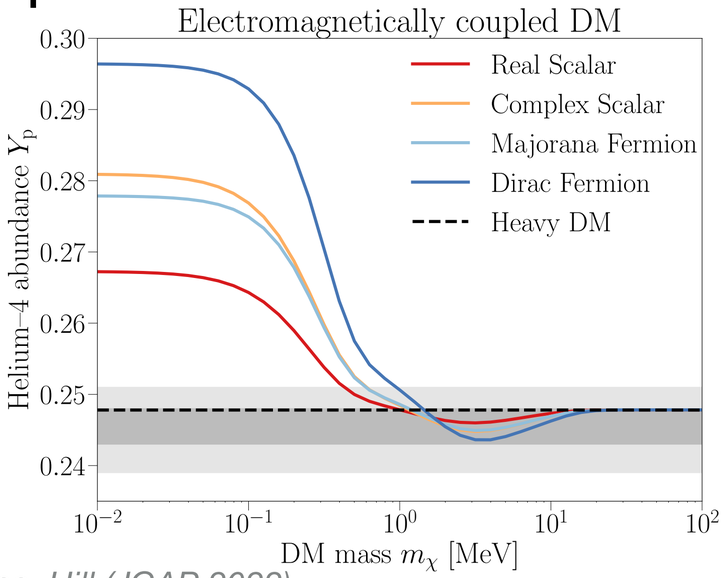
Including Effects from BBN

If DM mass ~ MeV, freeze-out occurs during BBN

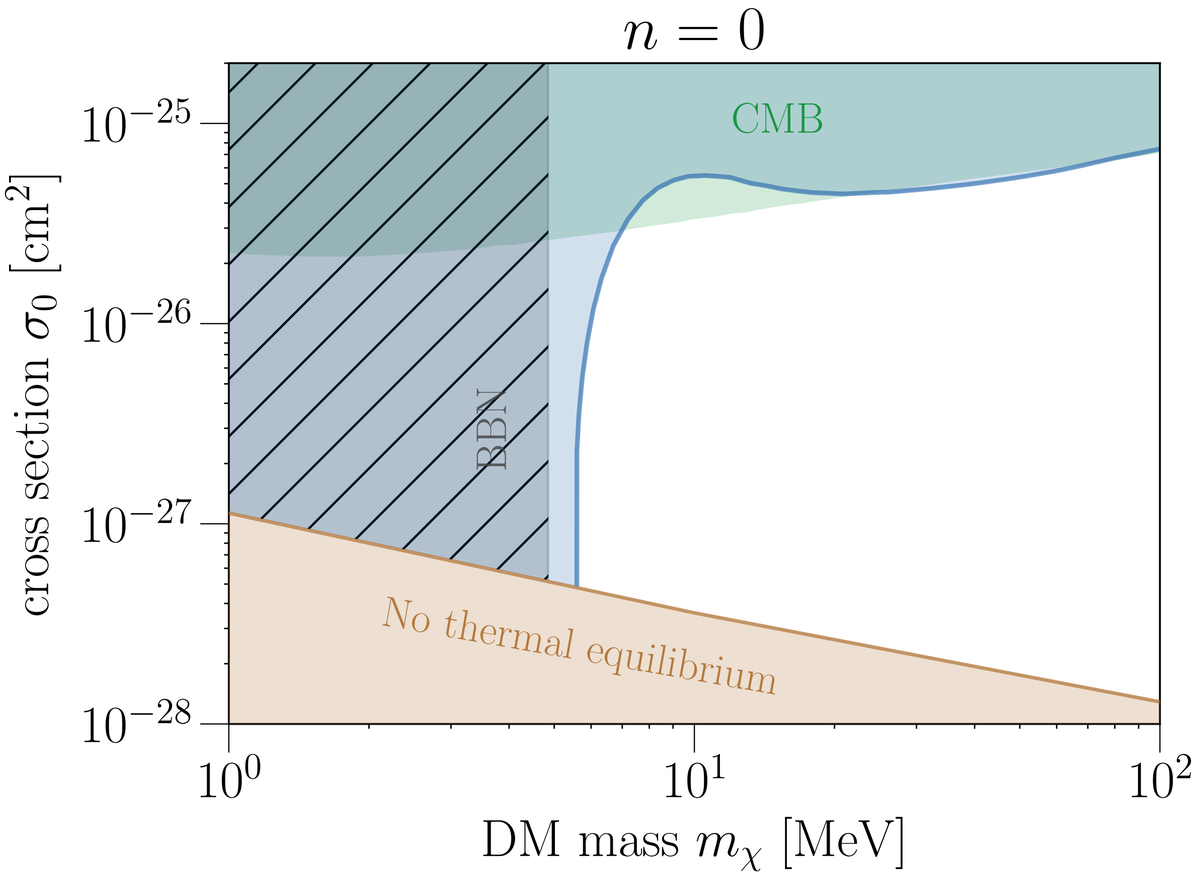
- DM annihilation transfers energy and entropy into visible sector

$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]$$

- Light DM modifies $p \leftrightarrow n$ conversion freeze-out via impact on Hubble

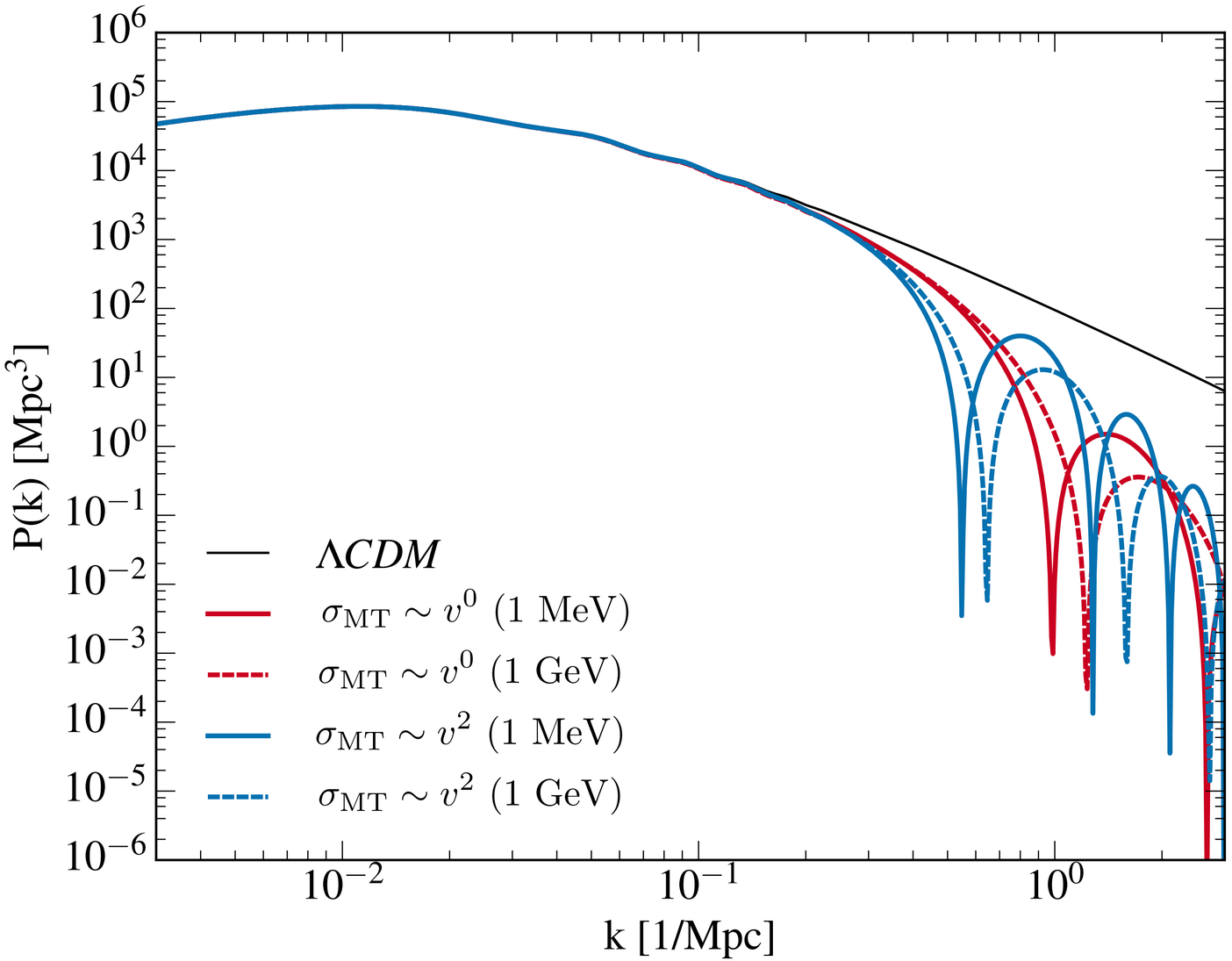


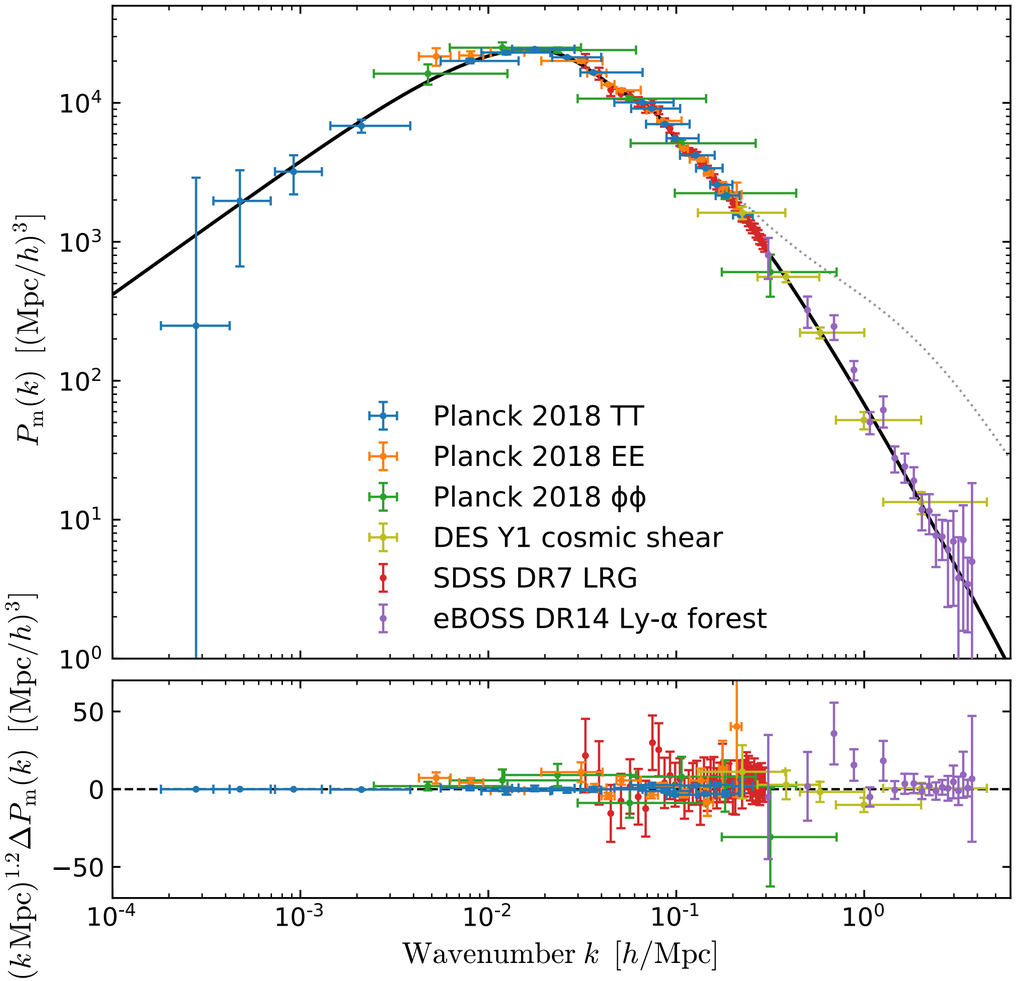
An, Gluscevic, Calabrese, Hill (JCAP 2022)



An, KB, Gluscevic (2402.14223)

Matter Power Spectrum

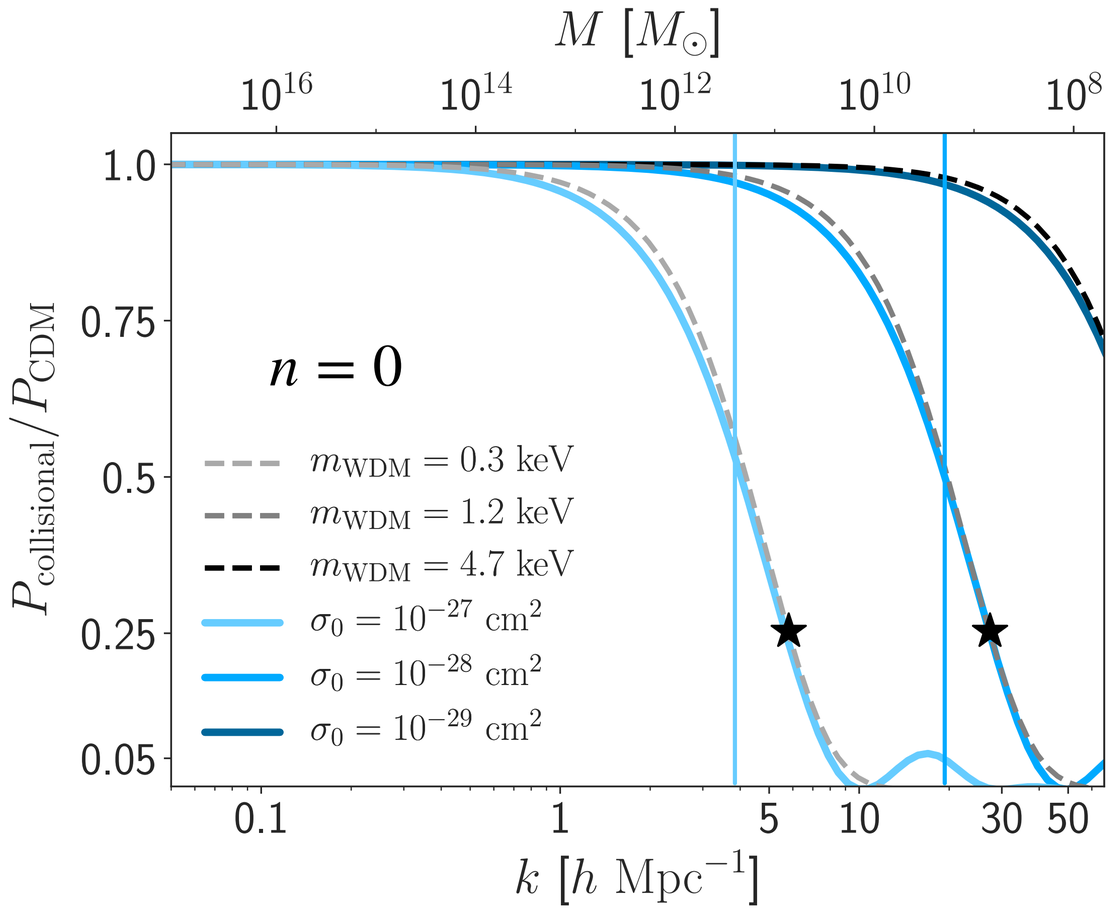


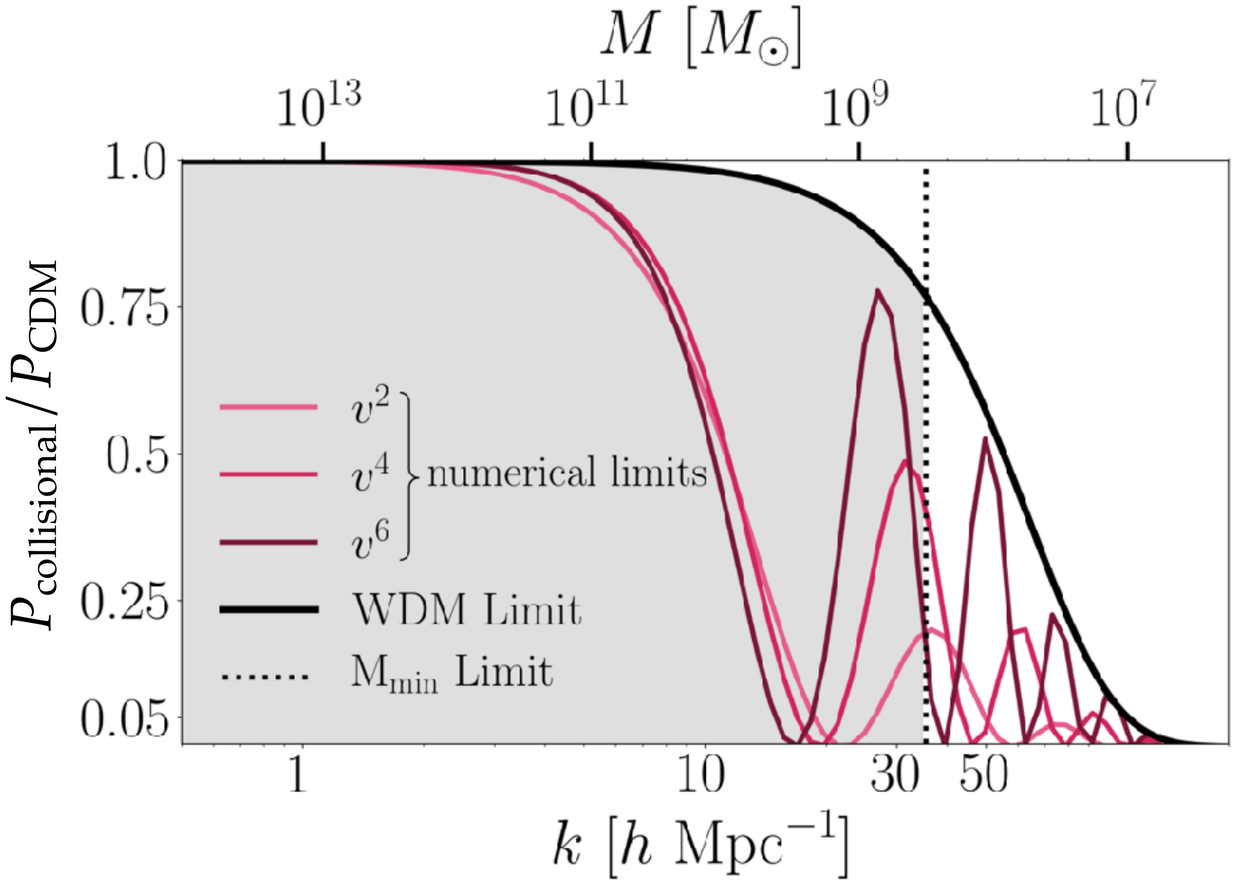


KB and Gluscevic (PRD 2018)

Chabanier+ (MNRAS 2019)

Suppression of (Linear) Matter Power Spectrum

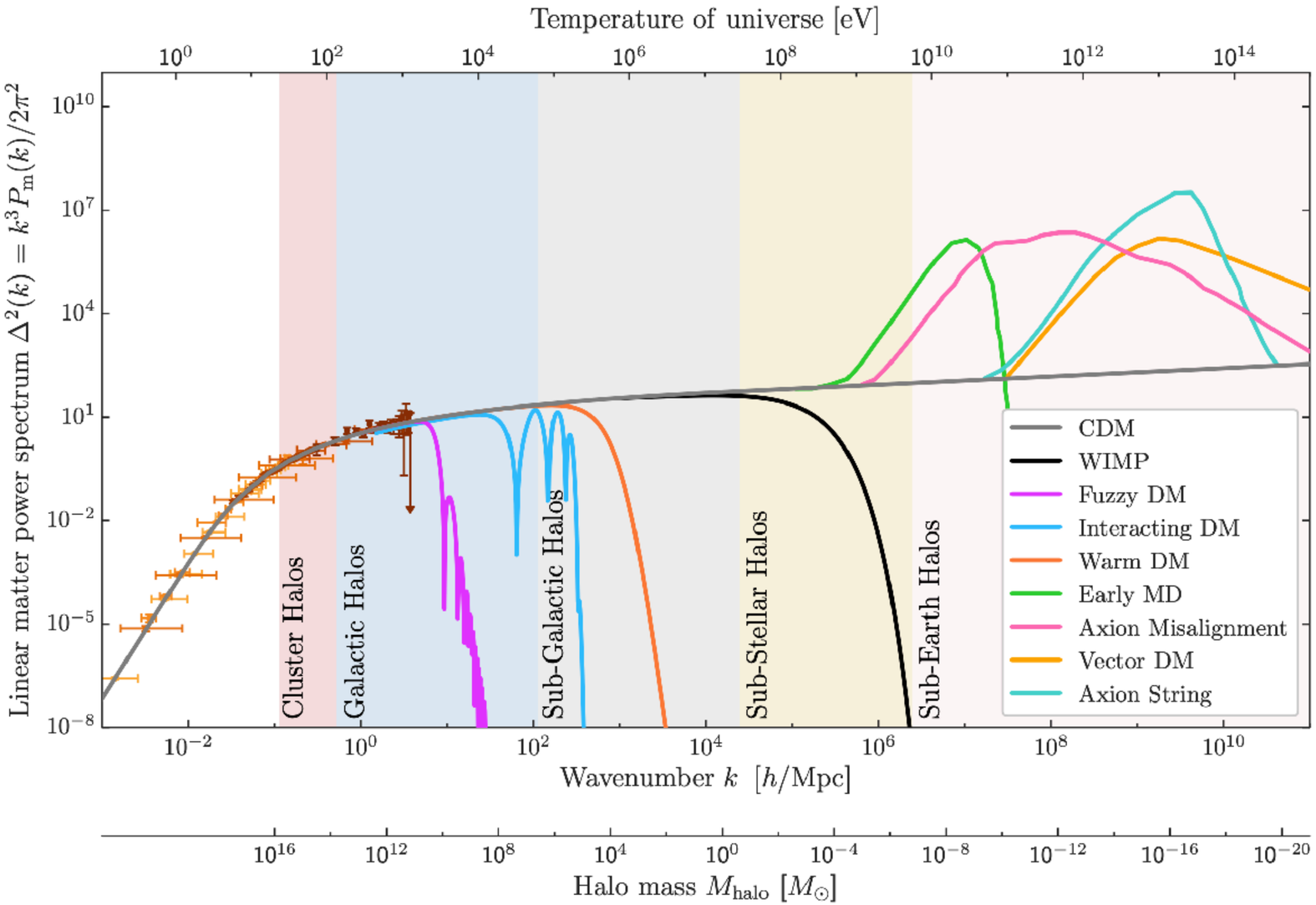




Nadler, Gluscevic, KB, Wechsler (ApJL 2019)

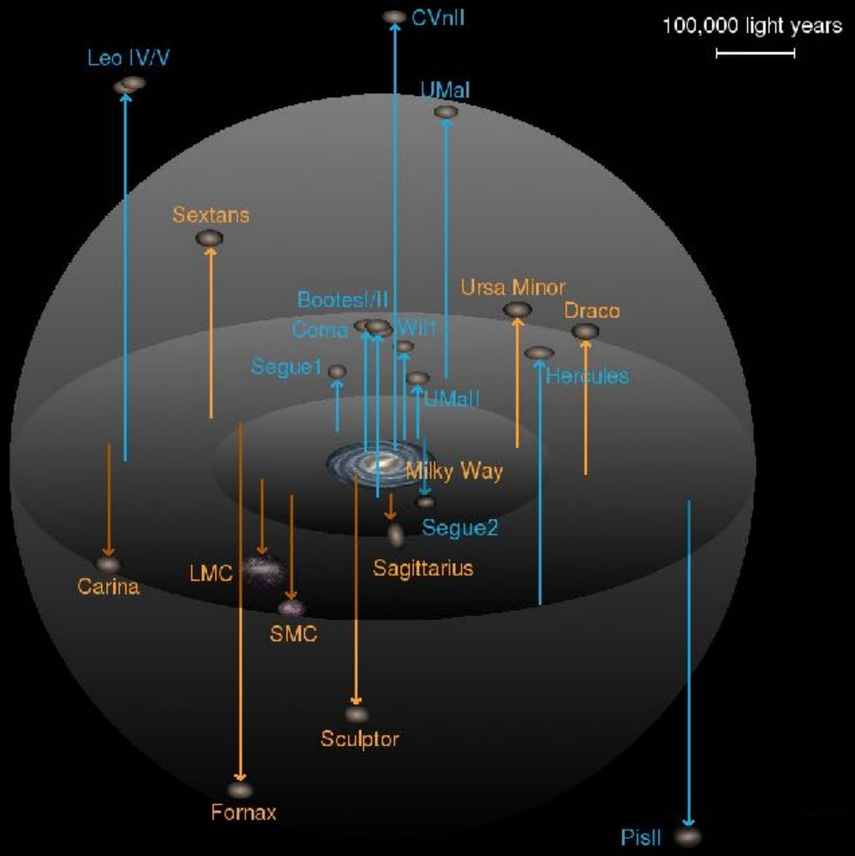
Maamari, Gluscevic, KB, Nadler, Wechsler (ApJL 2021)

Small-Scale Modifications



Snowmass 2021 Cosmic Frontier: Dark Matter Physics from Halo Measurements
Bechtol, Birrer, Cyr-Racine, Schutz+ (2203.07354)

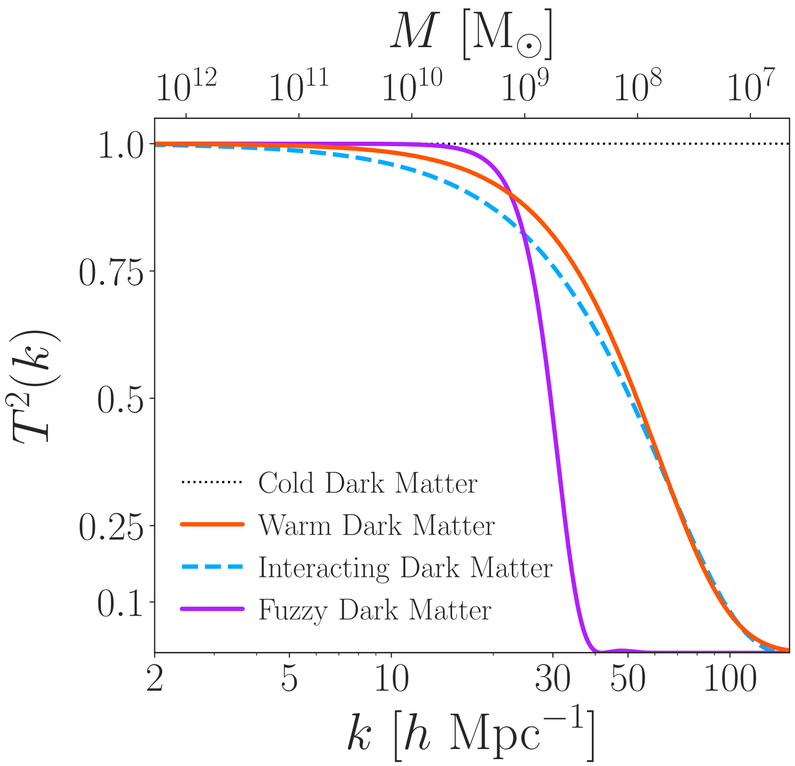
Milky Way Satellites

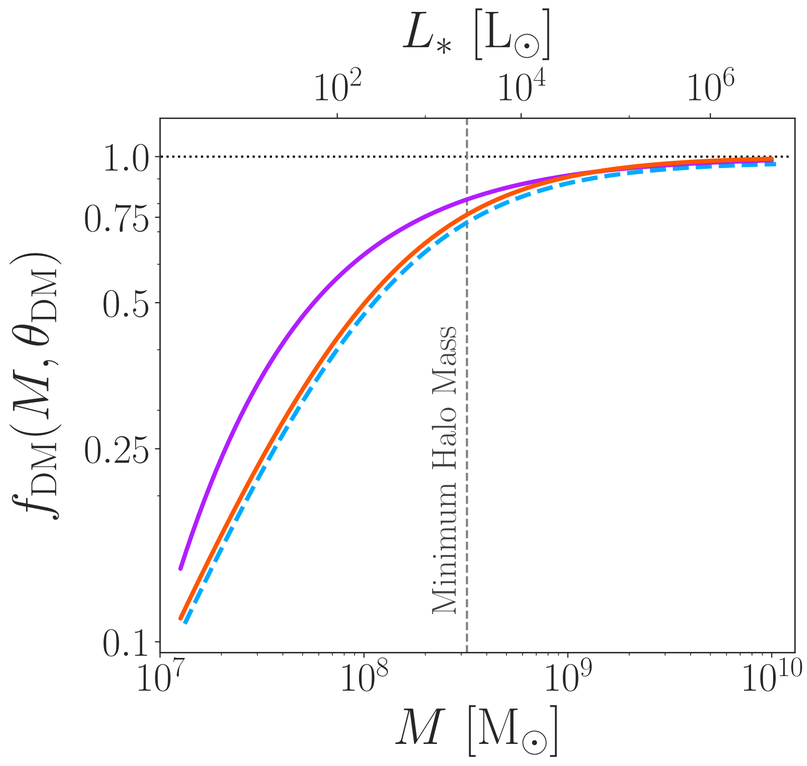


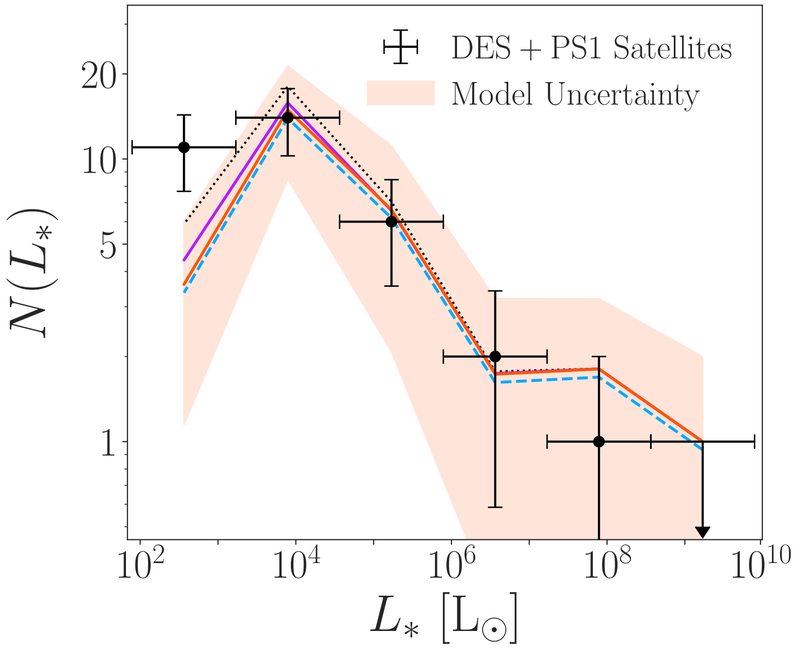
DES and Pan-STARRS1 identified dwarfs

Classic dwarfs
SDSS-identified dwarfs

Suppression for Various Models

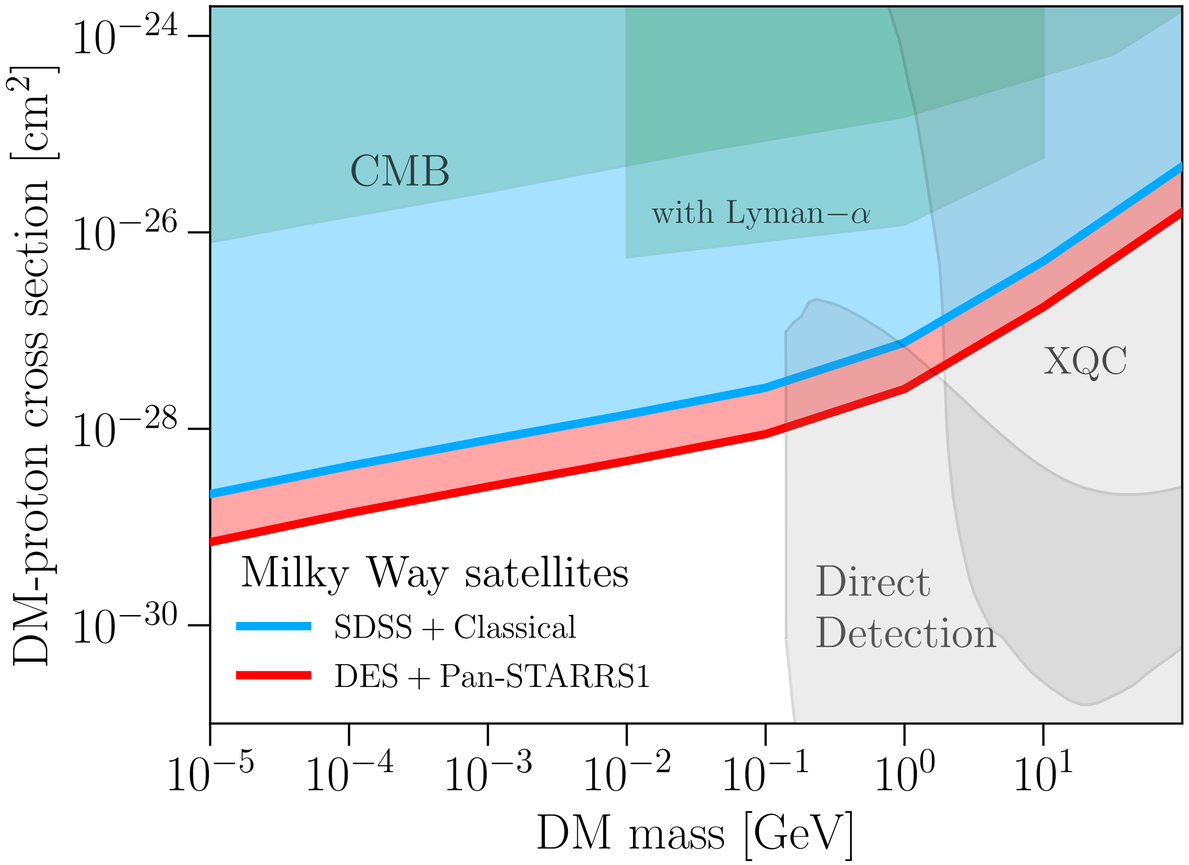


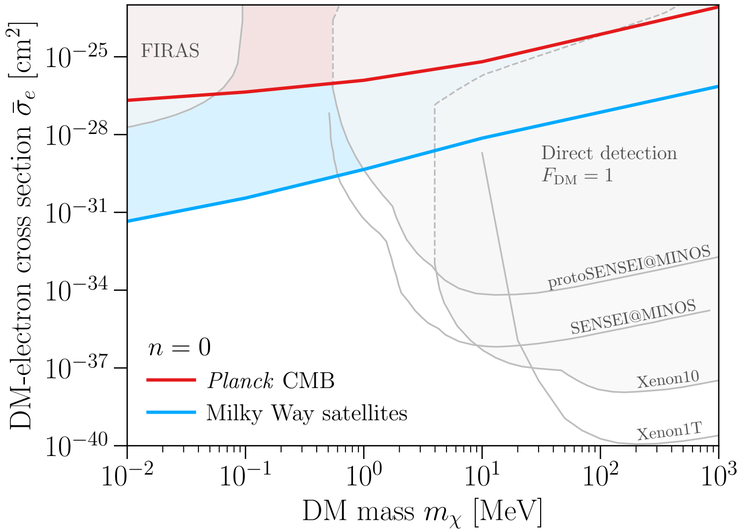


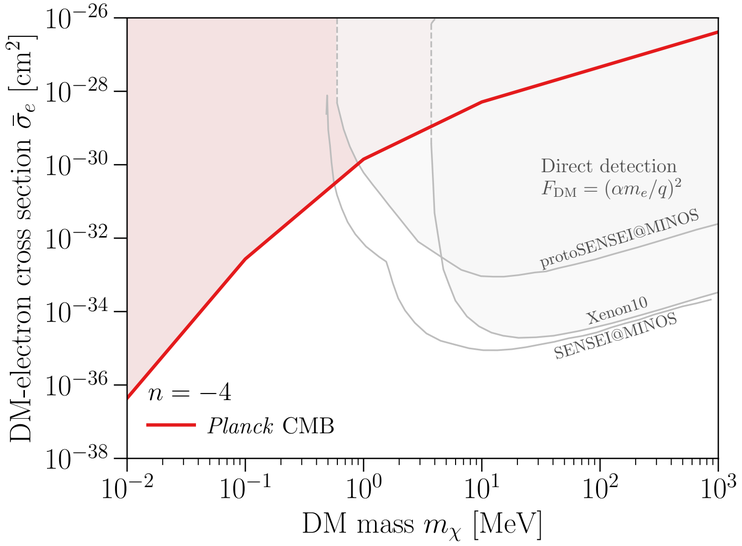


DES Collaboration, Nadler, incl. KB (PRL 2021)

Constraints: Scattering with Protons and Electrons



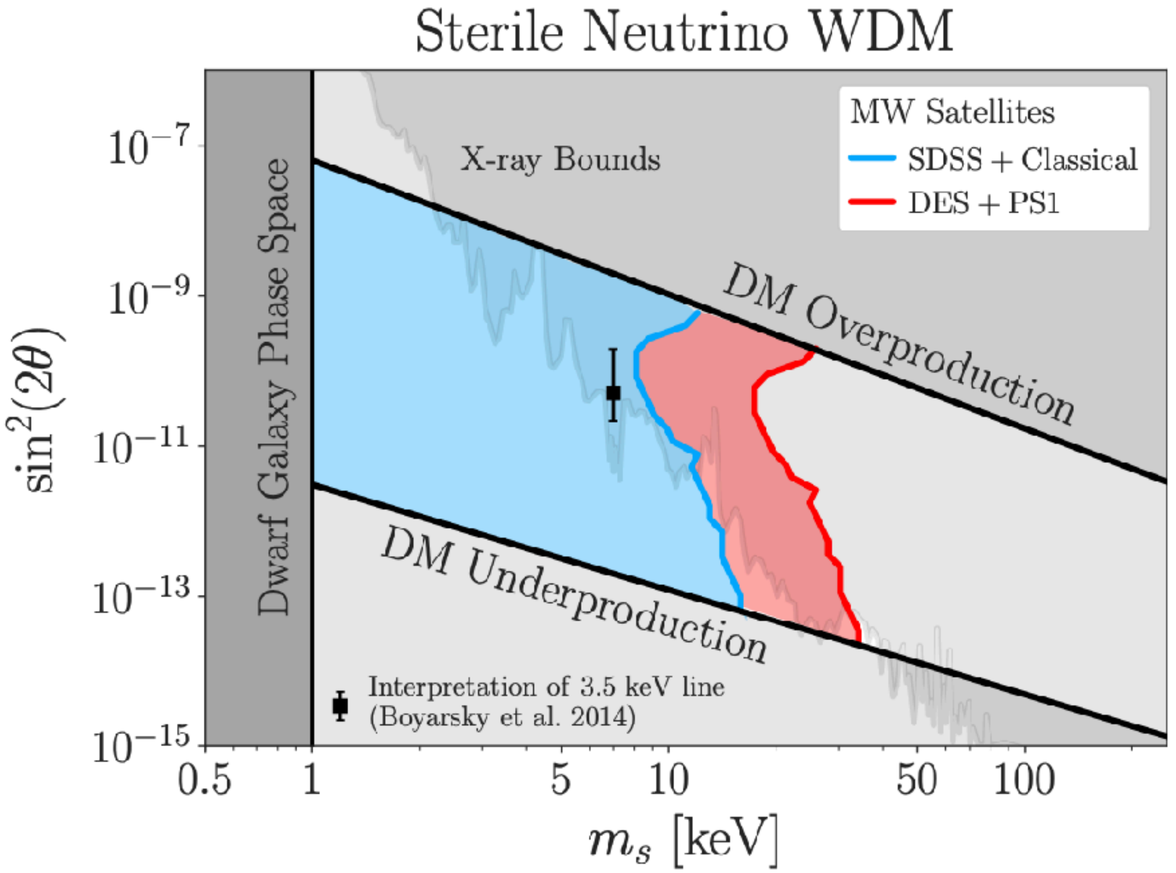


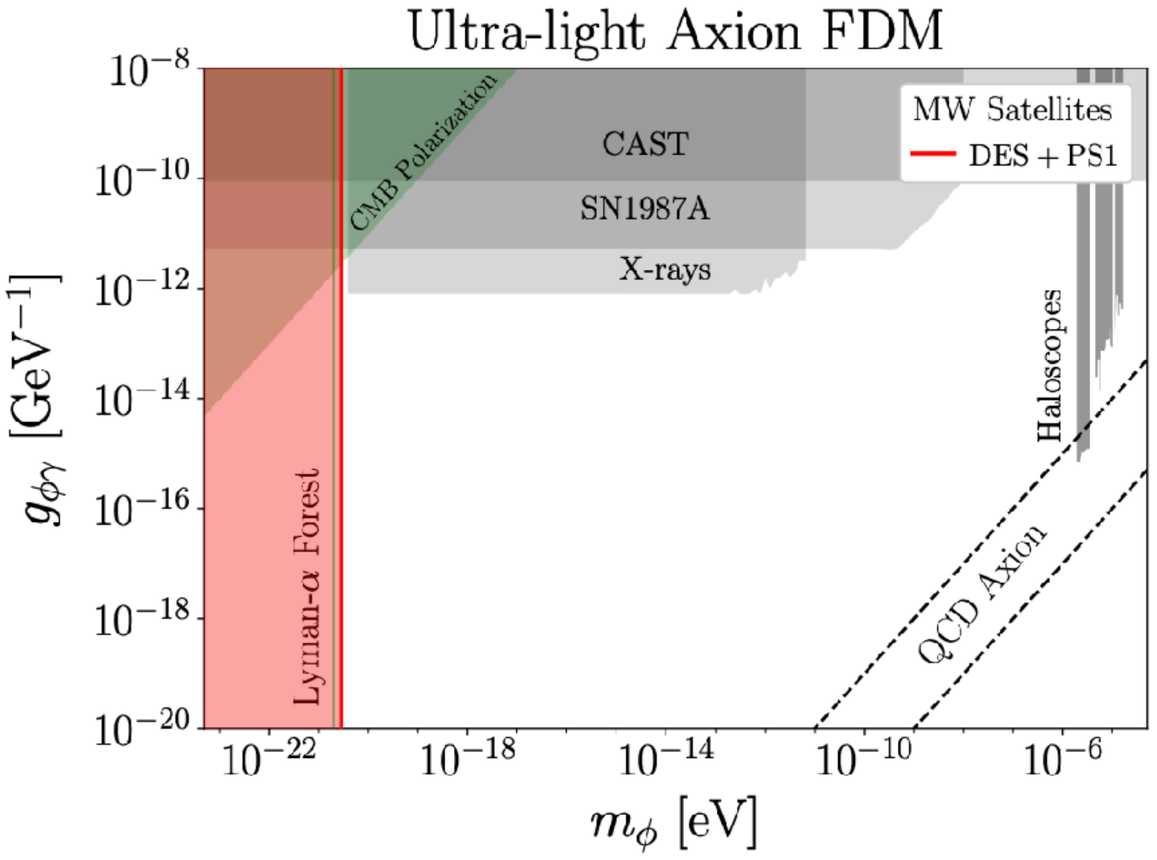


DES Collaboration, Nadler, incl. KB (PRL 2021)

Nguyen, Sarnaaik, KB, Nadler, Gluscevic (PRD 2021)

Constraints: Warm and Fuzzy Dark Matter





DES Collaboration, Nadler, incl. KB (PRL 2021)

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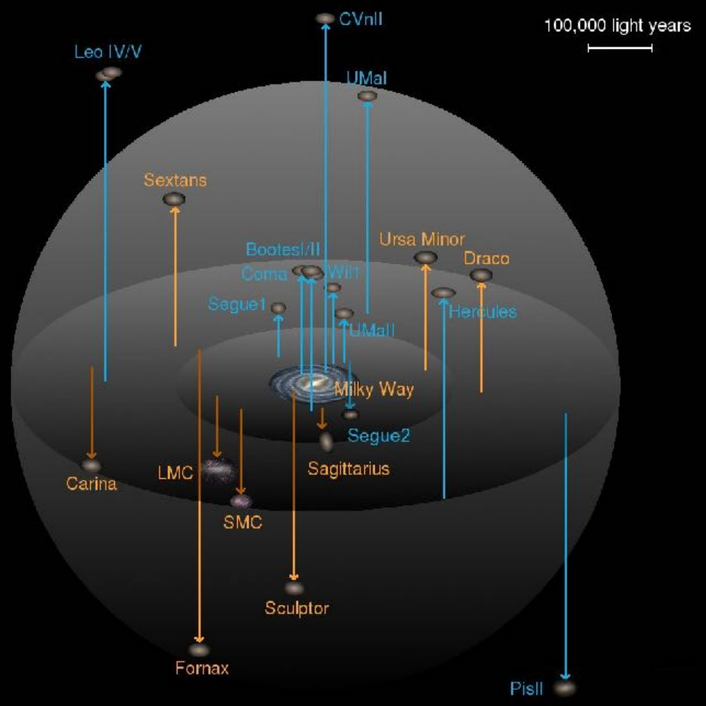
Late Universe:
impact halo formation and evolution

Small-Scale Structure Puzzles

Dwarf Spheroidals

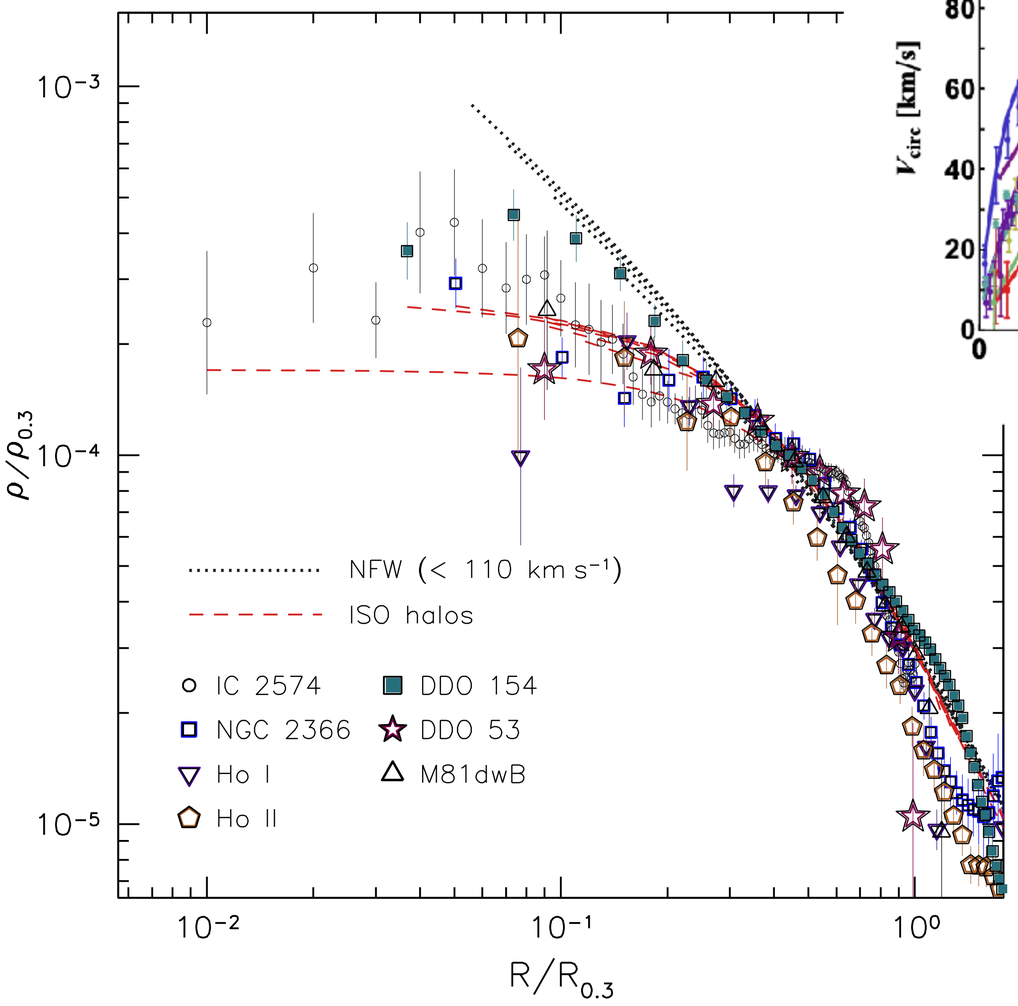


Low-Surface Brightness (LSB)

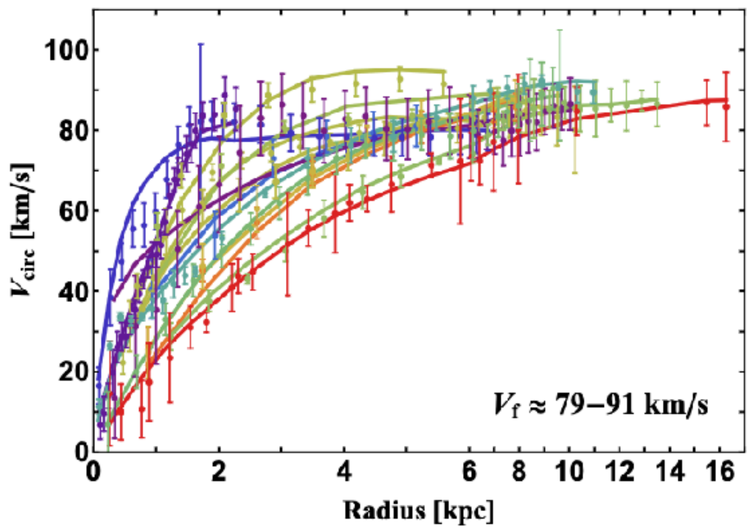
Clusters

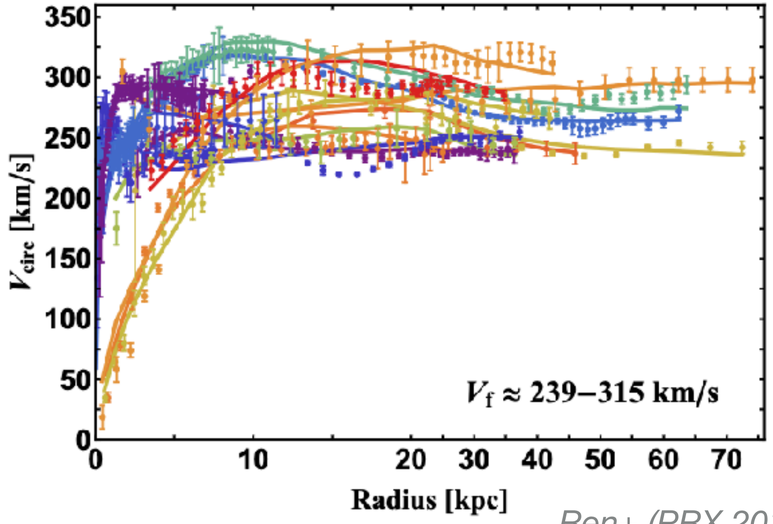
Small-scale structure puzzles arise in various systems:
~~missing satellites~~, core-cusp, too-big-to-fail, diversity

Small-Scale Structure Puzzles



Oh+ (ApJ 2010)





Ren+ (PRX 2019)

Attempt to address these issues with SIDM with self-interaction cross sections per mass ~ few cm^2/g

Spergel, Steinhardt (PRL 2000)
for recent review, see Adhikari, Banerjee, KB, Cyr-Racine+ (2207.10638)

Need simulations, especially to disentangle baryonic effects and SIDM

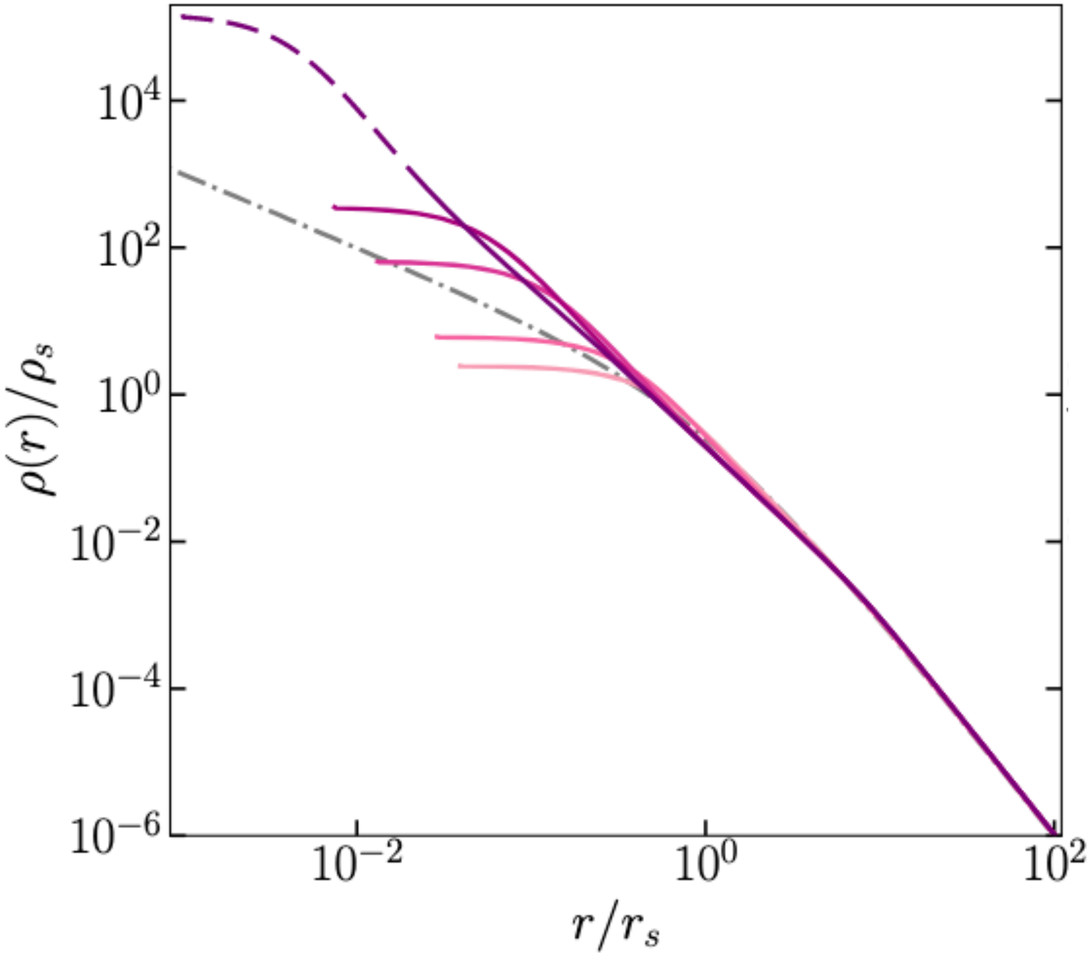
Gravothermal Evolution

Model halo as

- self-gravitating fluid
- with spherical symmetry
- in hydrostatic equilibrium

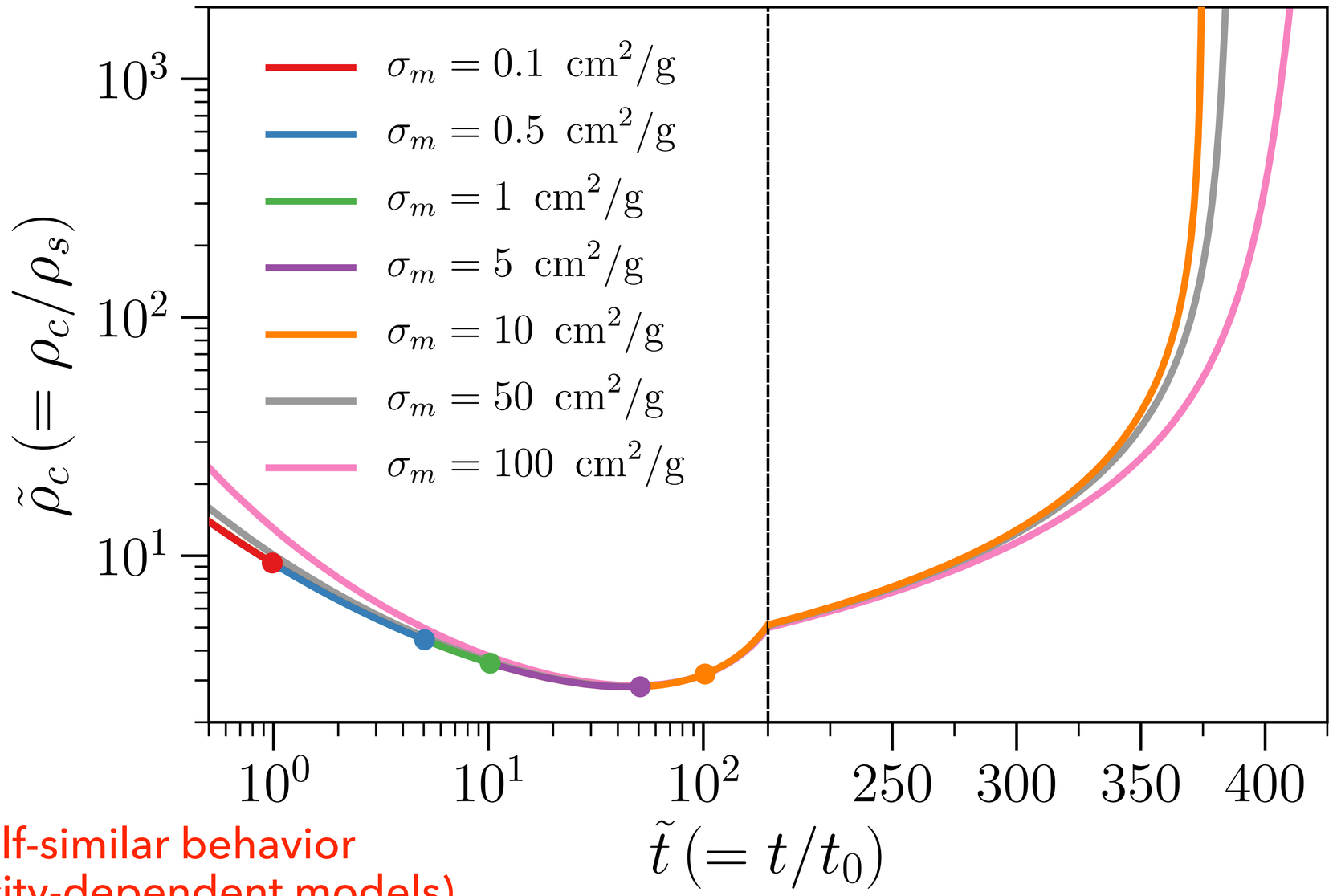
Self-interactions create low-density cores, but…

Negative specific heat causes runaway collapse of halo core



Outmezguine, KB, Gad-Nasr, Kaplinghat, Sagunski (MNRAS 2023)

Central Density Evolution



Obtain self-similar behavior
(even for velocity-dependent models)

Outmezguine, KB, Gad-Nasr, Kaplinghat, Sagunski (MNRAS 2023)
Gad-Nasr, KB, Kaplinghat, Outmezguine, Sagunski (2312.09296)

$$t_0^{-1} \sim (\sigma/m) r_s \rho_s^{3/2}$$

Nishikawa, KB, Kaplinghat (PRD 2020)

Accelerate Core Collapse

- Collapsed cores produce high central densities: bug or feature?
- Observe some systems with larger central densities than expected from CDM
- Various ways of accelerating collapse:
  - Tidal stripping of subhalos

    Nishikawa, KB, Kaplinghat (PRD 2020)

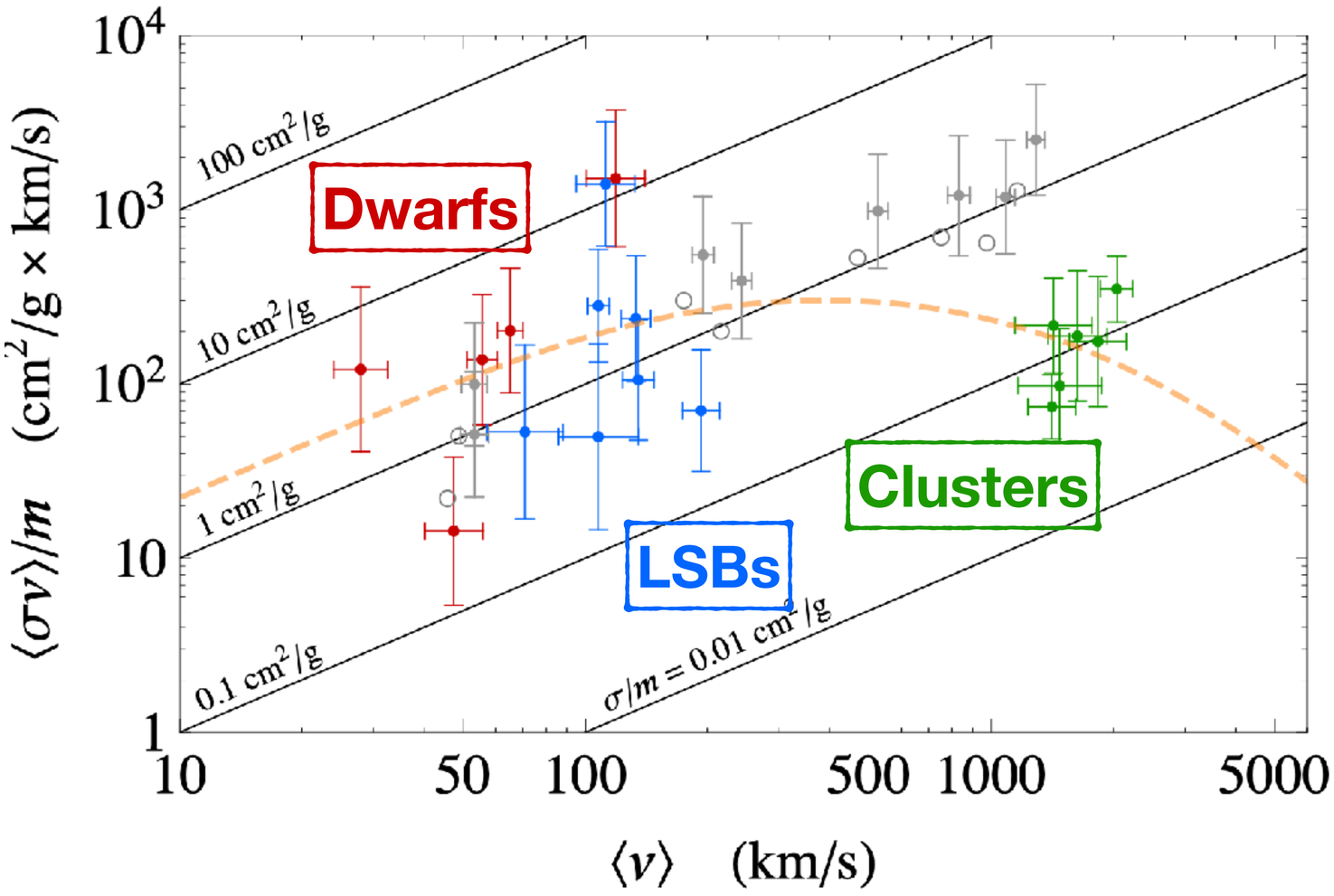
  - Dark matter dissipation

    Essig, Yu, Zhong, McDermott (PRL 2019)

  - Baryonic potential

    e.g., Sameie, Yu, Sales, Vogelsberger, Zavala (PRL 2020)

Particle Physics of SIDM



Need to model halo formation and evolution with velocity-dependent SIDM

Kaplinghat, Tulin, Yu (PRL 2016)

Impact on Halo Morphology

Snowmass 2021 Cosmic Frontier: Dark Matter Physics from Halo Measurements
Bechtol, Birrer, Cyr-Racine, Schutz+ (2203.07354)

3 Early and late Universe!

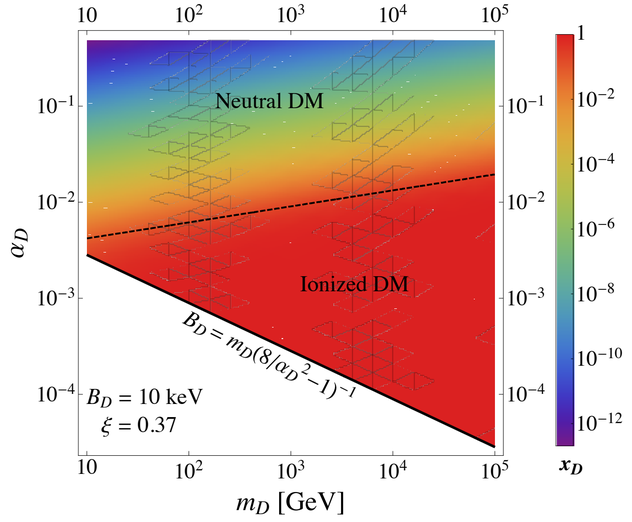
Composite Dark Matter: Impact Structure at Early and Late Times

- Light mediators contribute to $N_{\rm eff}$

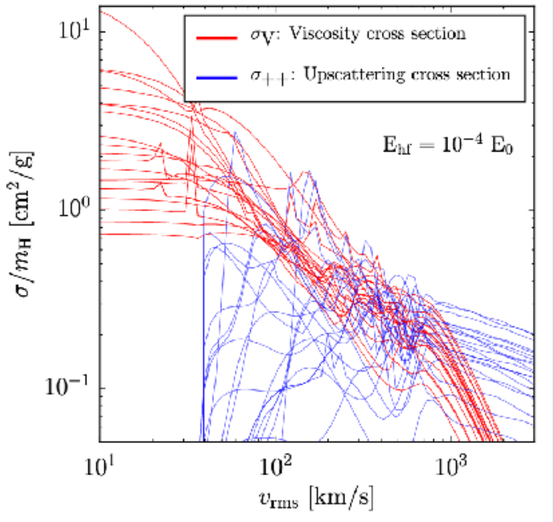
$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\rm eff} \right]$$

- Dark radiation induces dark acoustic oscillations

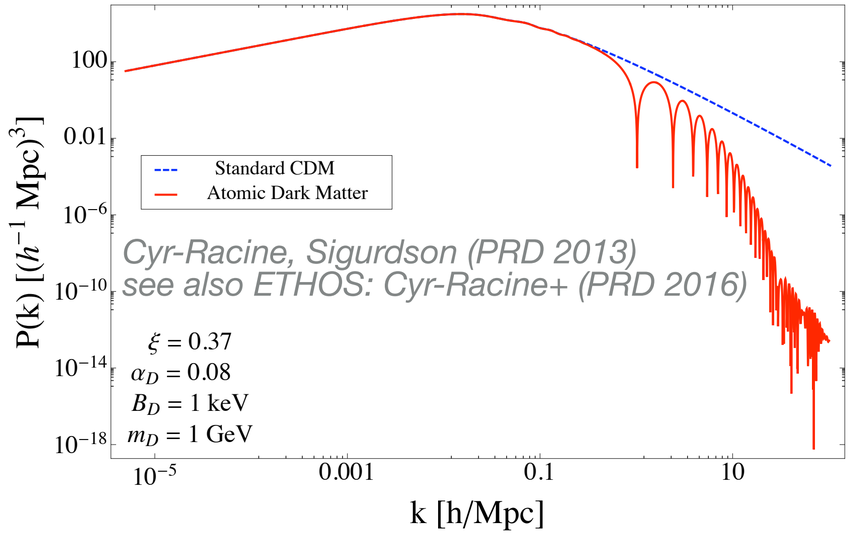
- Composite dark matter (e.g. atomic, nuclear) permits different pheno in early & late Universe



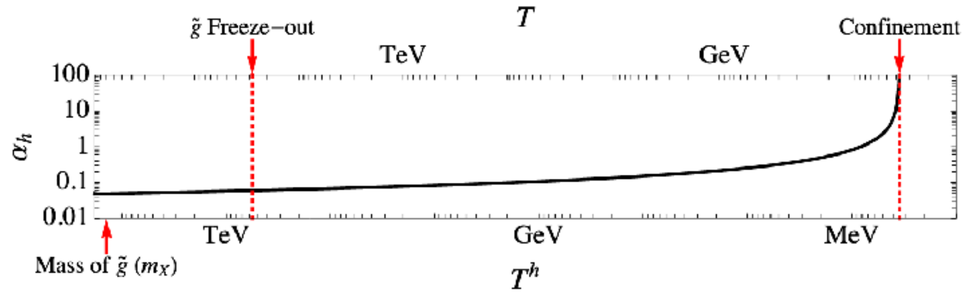
Cyr-Racine, Sigurdson (PRD 2013)



KB, Kaplinghat, Kwa, Peter (PRD 2016)

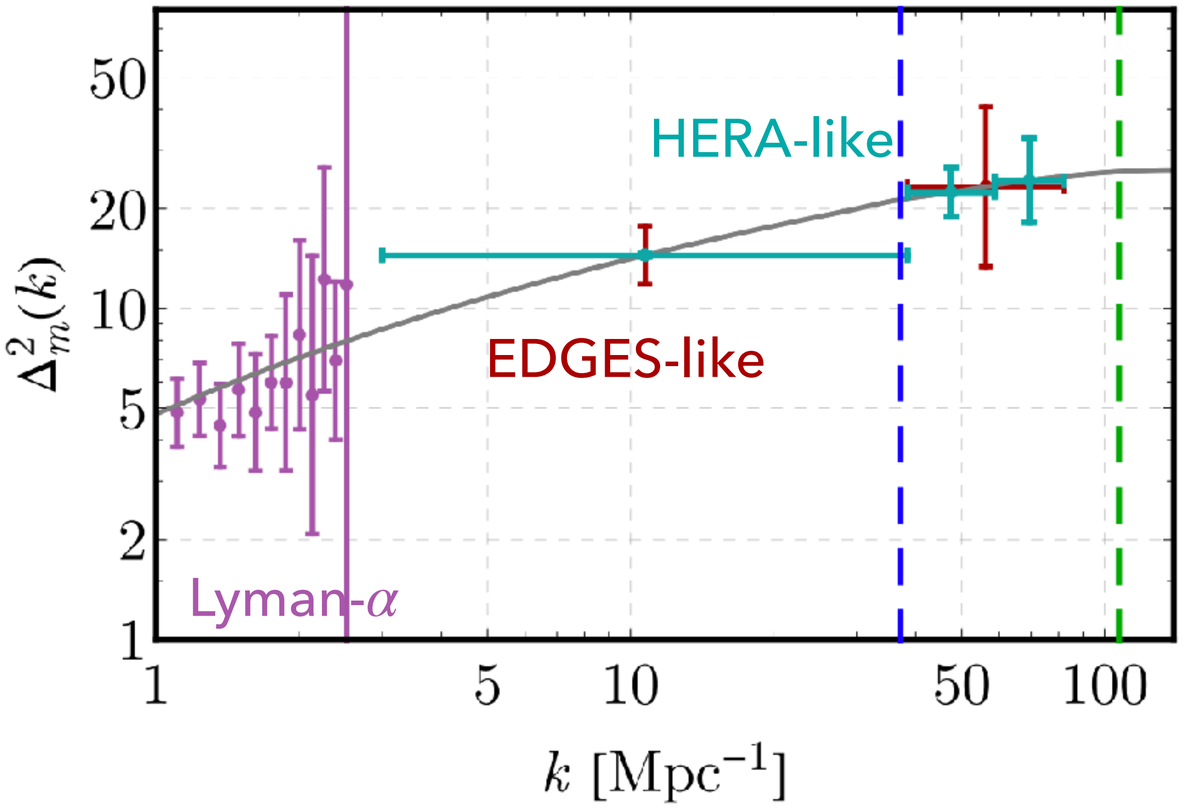


Cyr-Racine, Sigurdson (PRD 2013)
see also ETHOS: Cyr-Racine+ (PRD 2016)



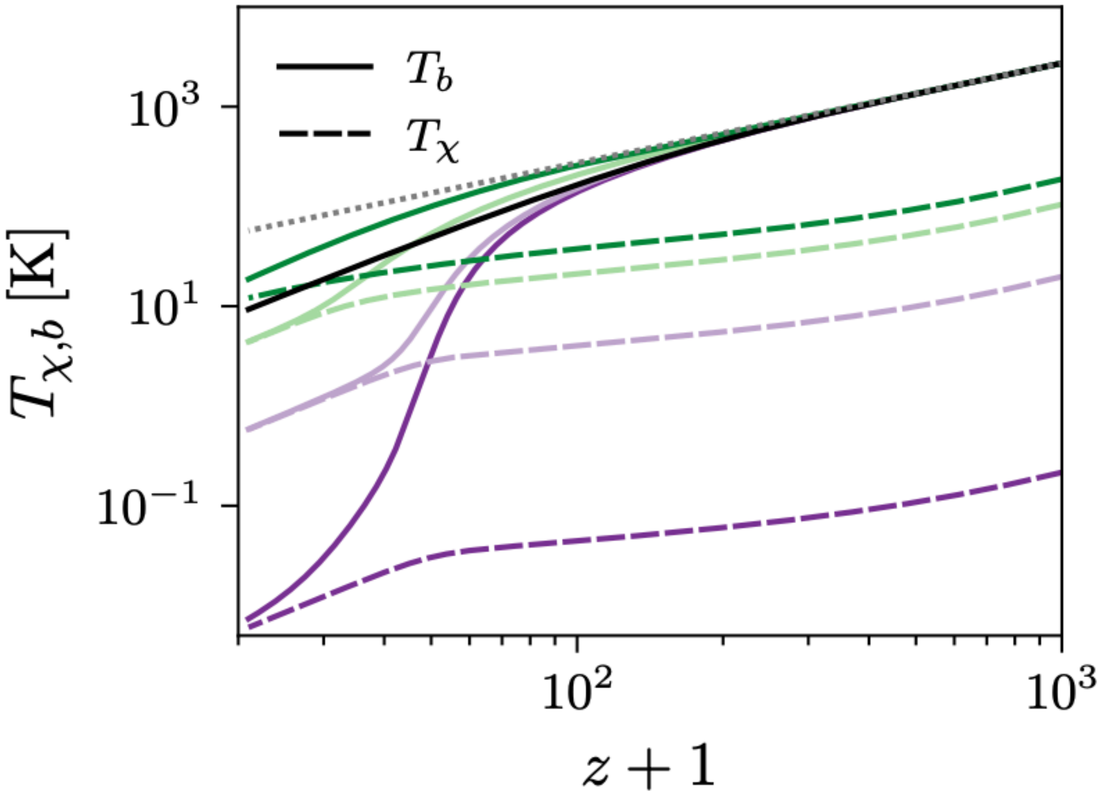
KB, Feng, Kaplinghat, Tait (PRD 2014)

Probing Small-Scale Structure with 21cm



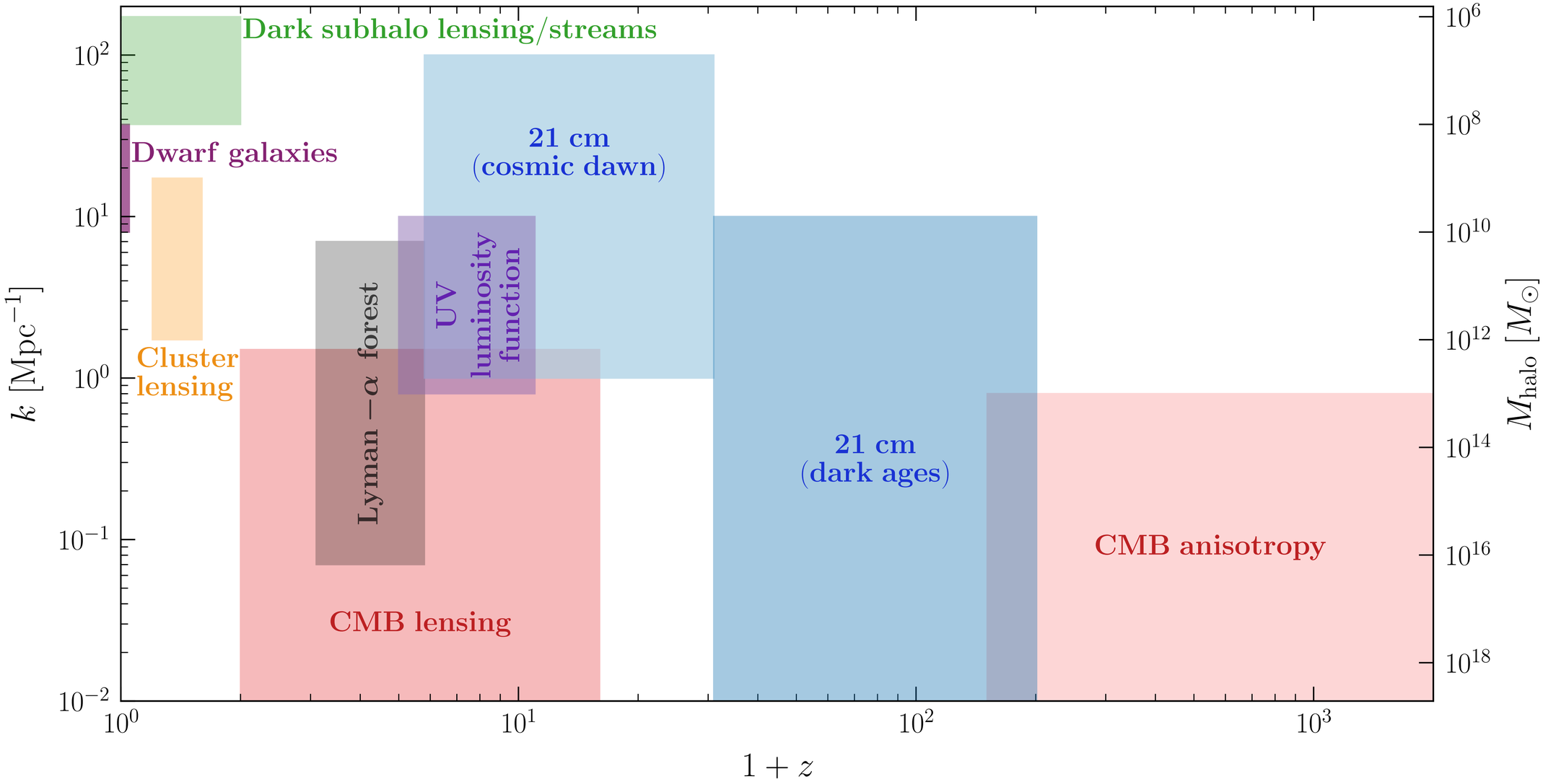
Muñoz, Dvorkin, Cyr-Racine (PRD 2020)

$\sigma \sim v^{-4}$ **DM-baryon scattering cools gas**



Short, Bernal, KB, Gluscevic, Verde (2203.16524)
see also Tashiro, Kadota, Silk (PRD 2014); Muñoz, Kovetz, Ali-Haïmoud (PRD 2015); Kovetz, Poulin, Gluscevic, KB, Barkana, Kamionkowski (PRD 2018); Driskell, Nadler, Mirocha, Benson, KB, Morton, Lashner, An, Gluscevic (PRD 2022)

Complementarity



Snowmass 2021 Theory Frontier: Astrophysical and Cosmological Probes of Dark Matter
KB, Lisanti, McDermott, Rodd, Weniger+ (2203.06380)