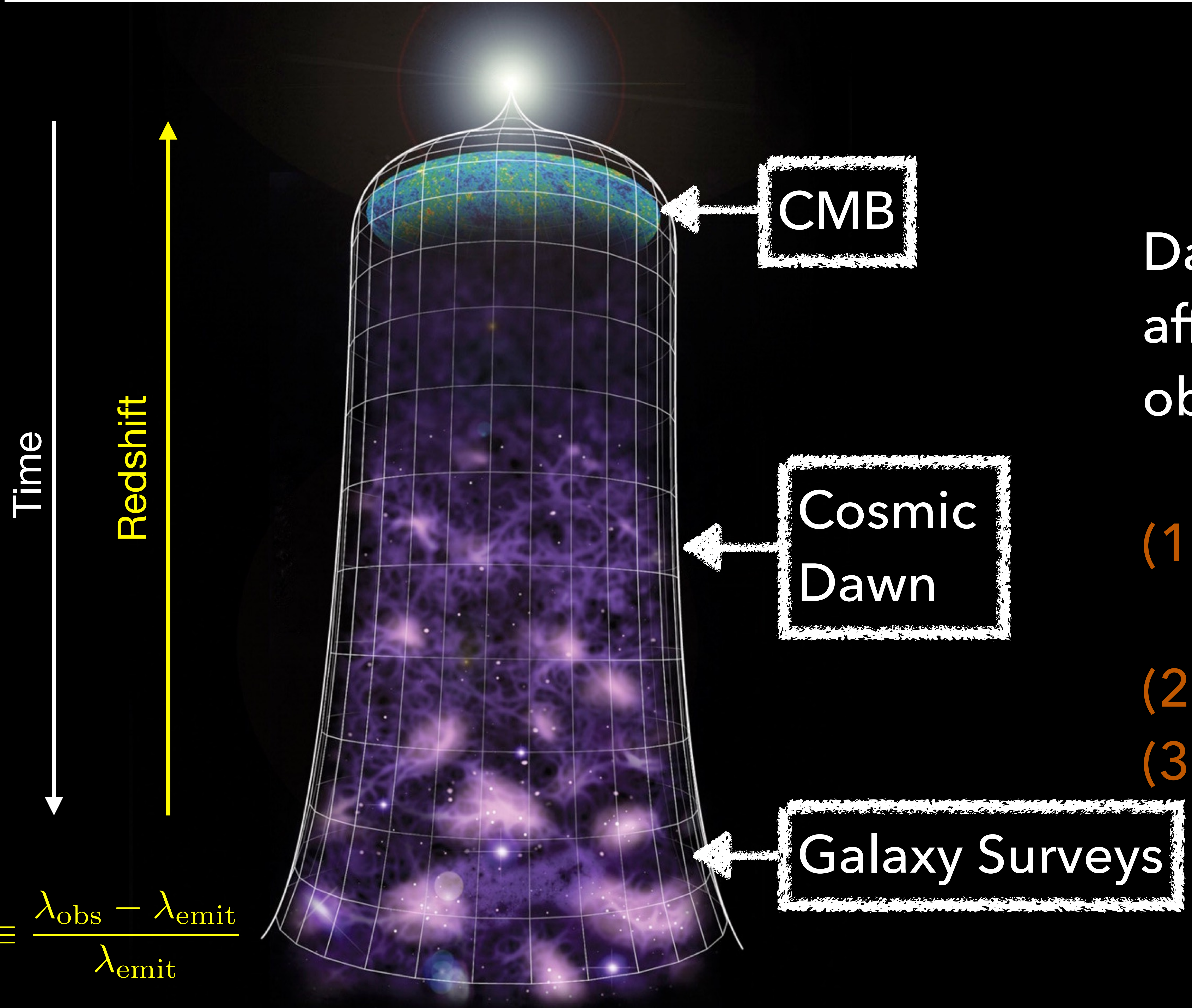
Understanding Cosmological Observations
Centro de Ciencias de Benasque, 23 July - 5 August 2023

COSMOLOGICAL PROBES OF DARK MATTER INTERACTIONS

Kimberly Boddy
University of Texas at Austin

Cosmic History

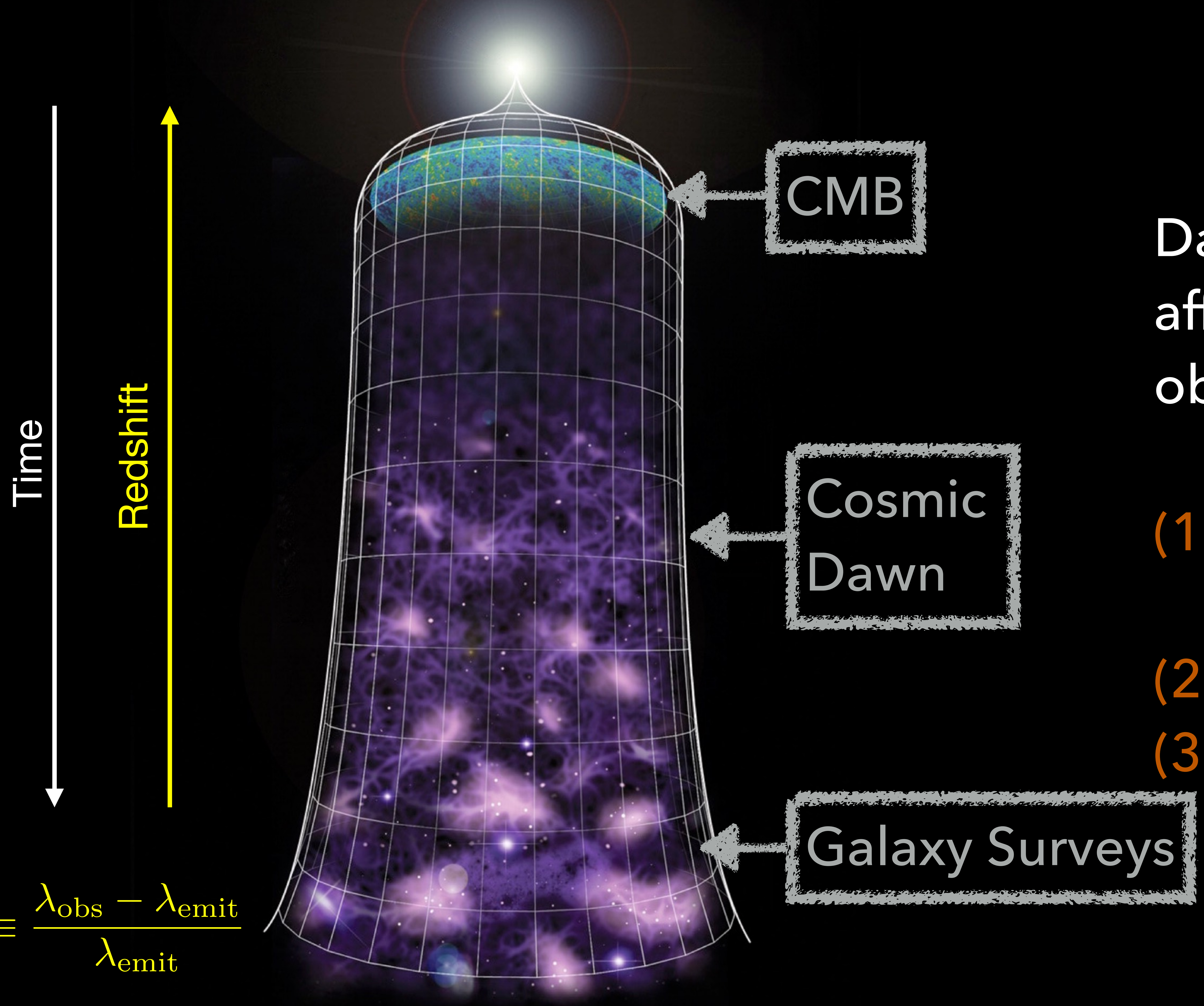


$$z \equiv \frac{\lambda_{\rm obs} - \lambda_{\rm emit}}{\lambda_{\rm emit}}$$

Dark matter microphysics can affect structure formation (or observations of structure)

(1) Particle physics motivations & dark matter-baryon scattering
(2) Small-scale power suppression
(3) 21cm signal from cosmic dawn

Cosmic History



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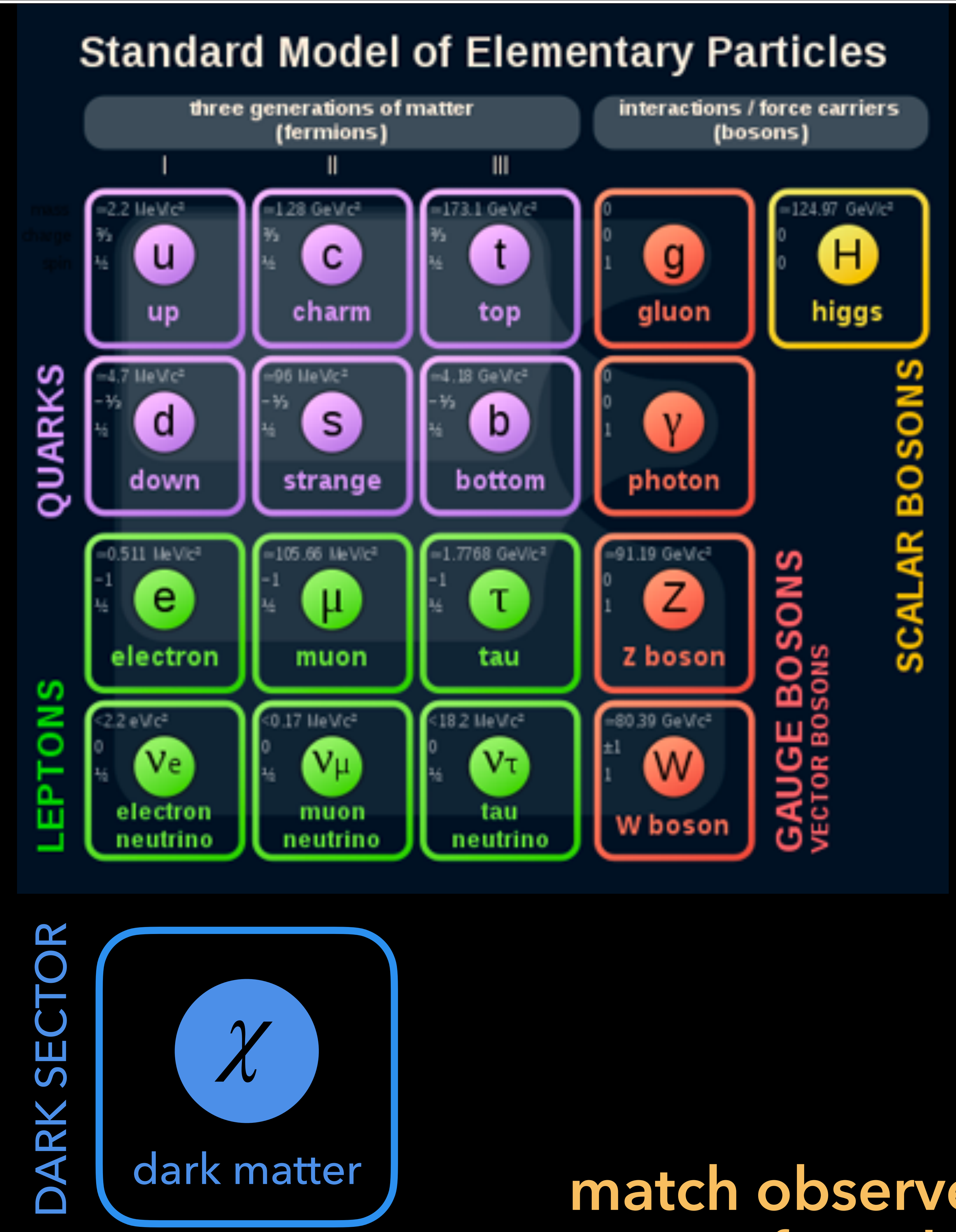
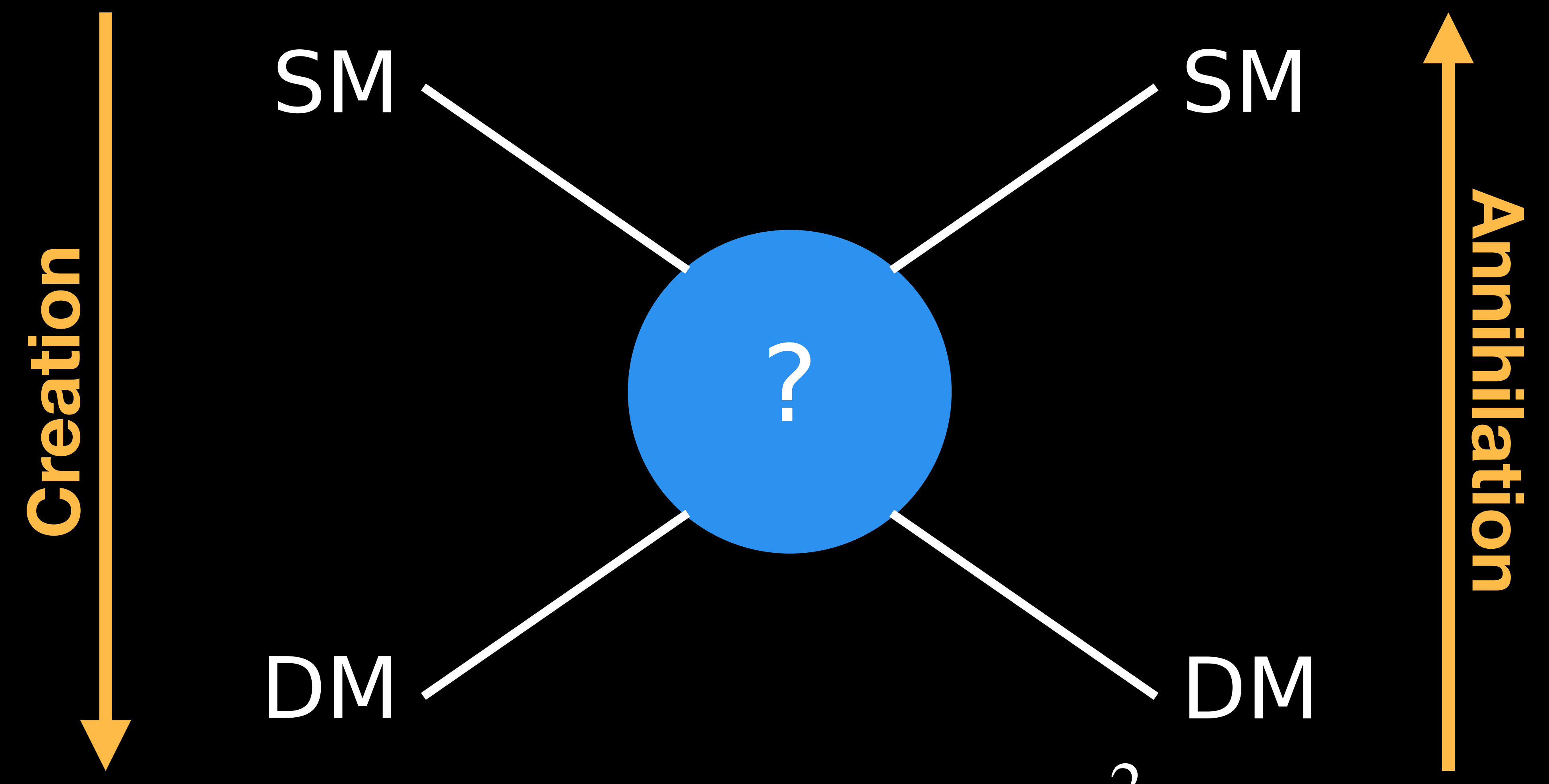
What does this symbol mean to you?

$$\mathscr{L}$$

Other ideas? Talk to José Bernal!

What is the particle nature of dark matter?

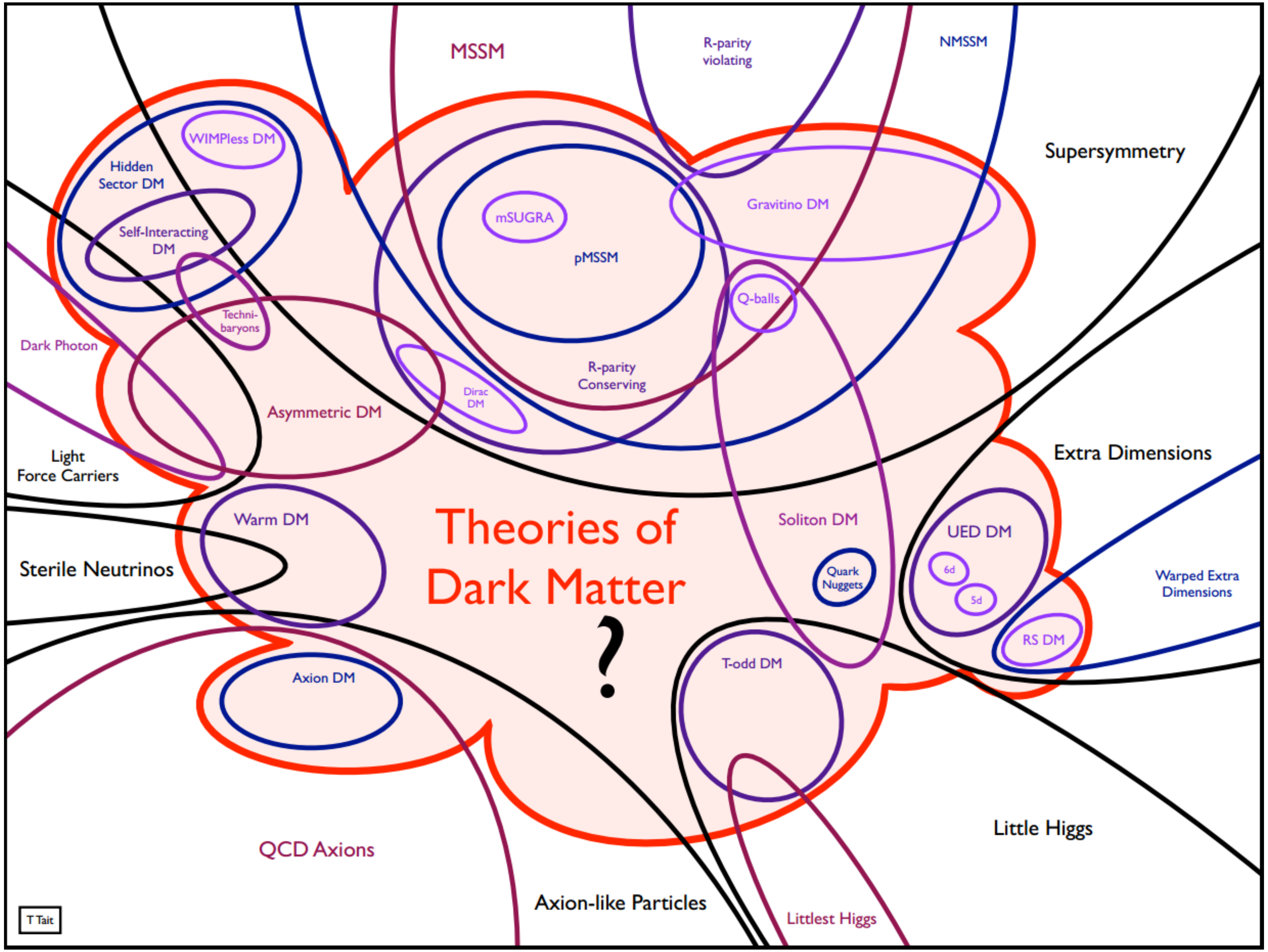




assume $\langle \sigma v \rangle \sim \dfrac{\pi \alpha^2}{m^2}$

match observed abundance for thermal freeze-out of weak-scale particles (WIMP miracle)

Web of Dark Matter Theories

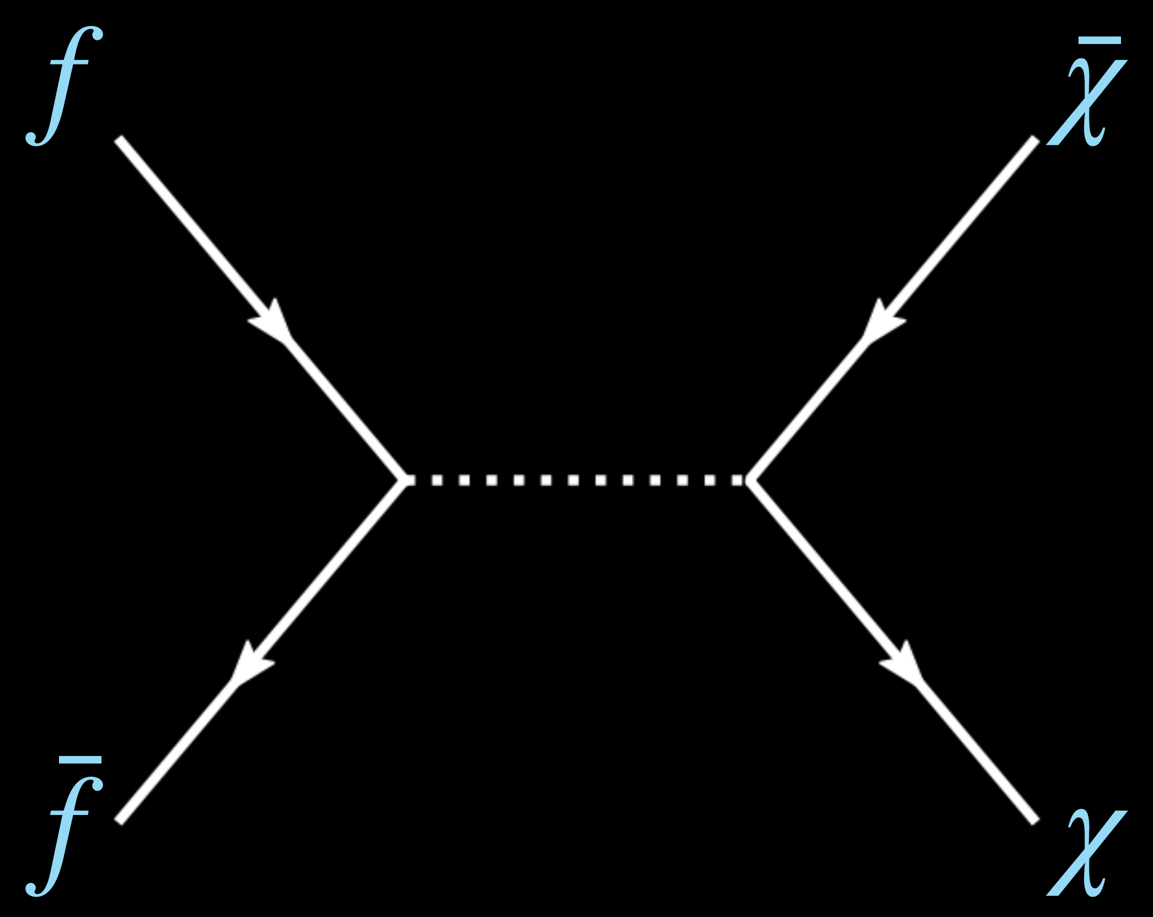


Standard WIMP Assumptions (and Examples of How to Break Them)

- cold (non-relativistic) thermal relic
  warm dark matter; non-thermal dark matter
- abundance set through freeze-out of 2-to-2 annihilations
  different freeze-out scenario; freeze-in; asymmetric dark matter
- weak-scale mass and coupling
  WIMPless miracle
- exhibits particle properties
  wave-like (e.g., axion, ALP, ultra-light boson); MACHO/PBH
- single point-like or fundamental particle
  composite particle; complex dark sector with multiple new particles/forces
- interacts with Standard Model
  "nightmare scenario": dark sector may be secluded

Dark Matter Searches

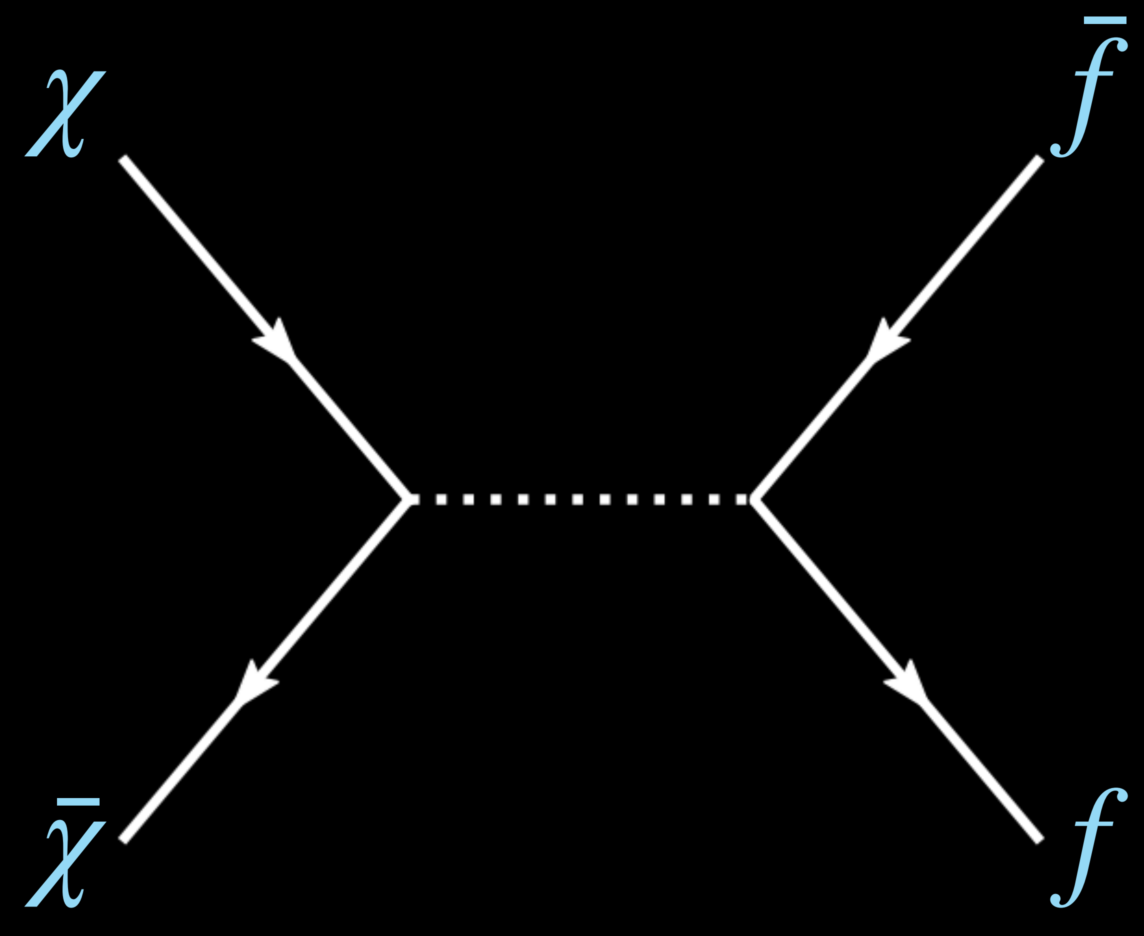
- Significant effort dedicated to searching for WIMPs through interactions with Standard Model



Production

collider searches

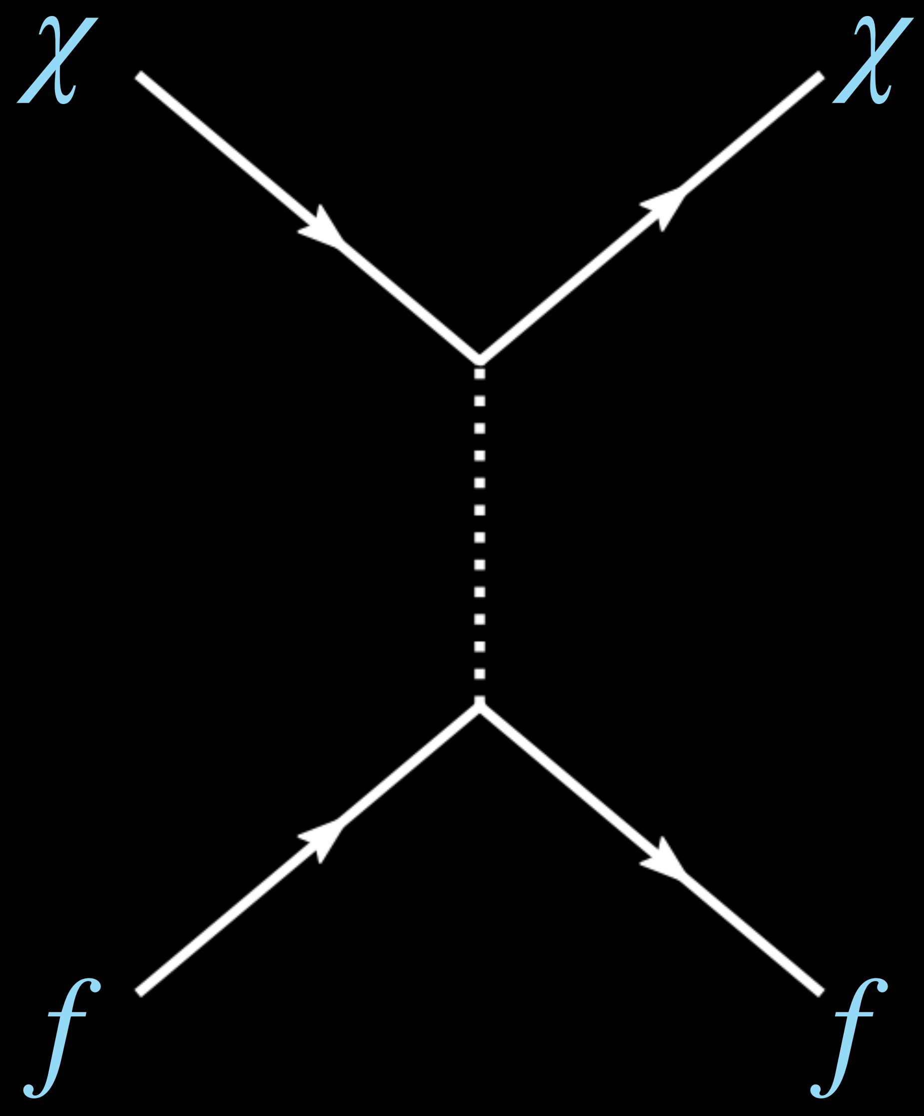
abundance



Annihilation

indirect detection

energy injection

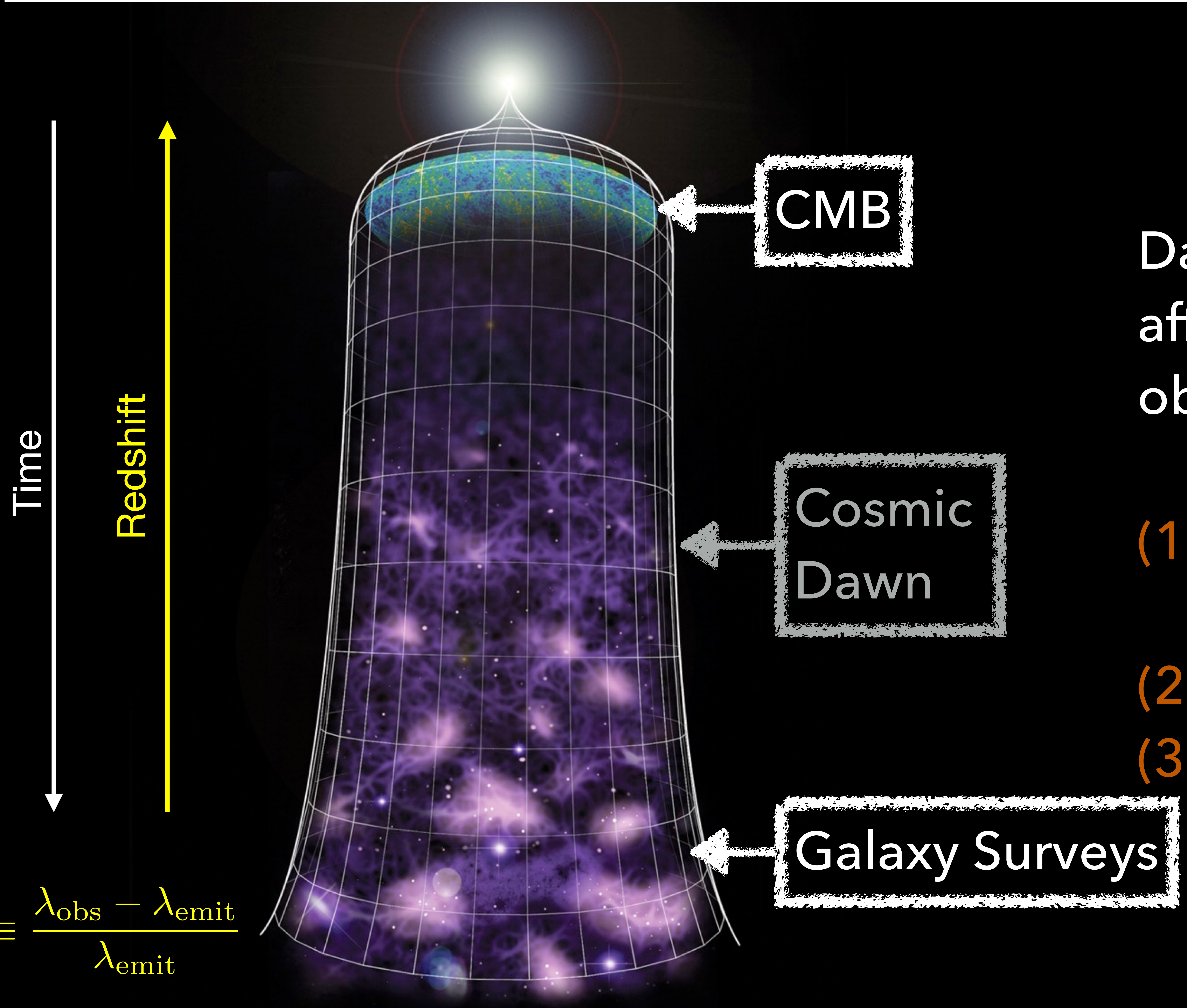


Scattering

direct detection

momentum transfer

Cosmic History



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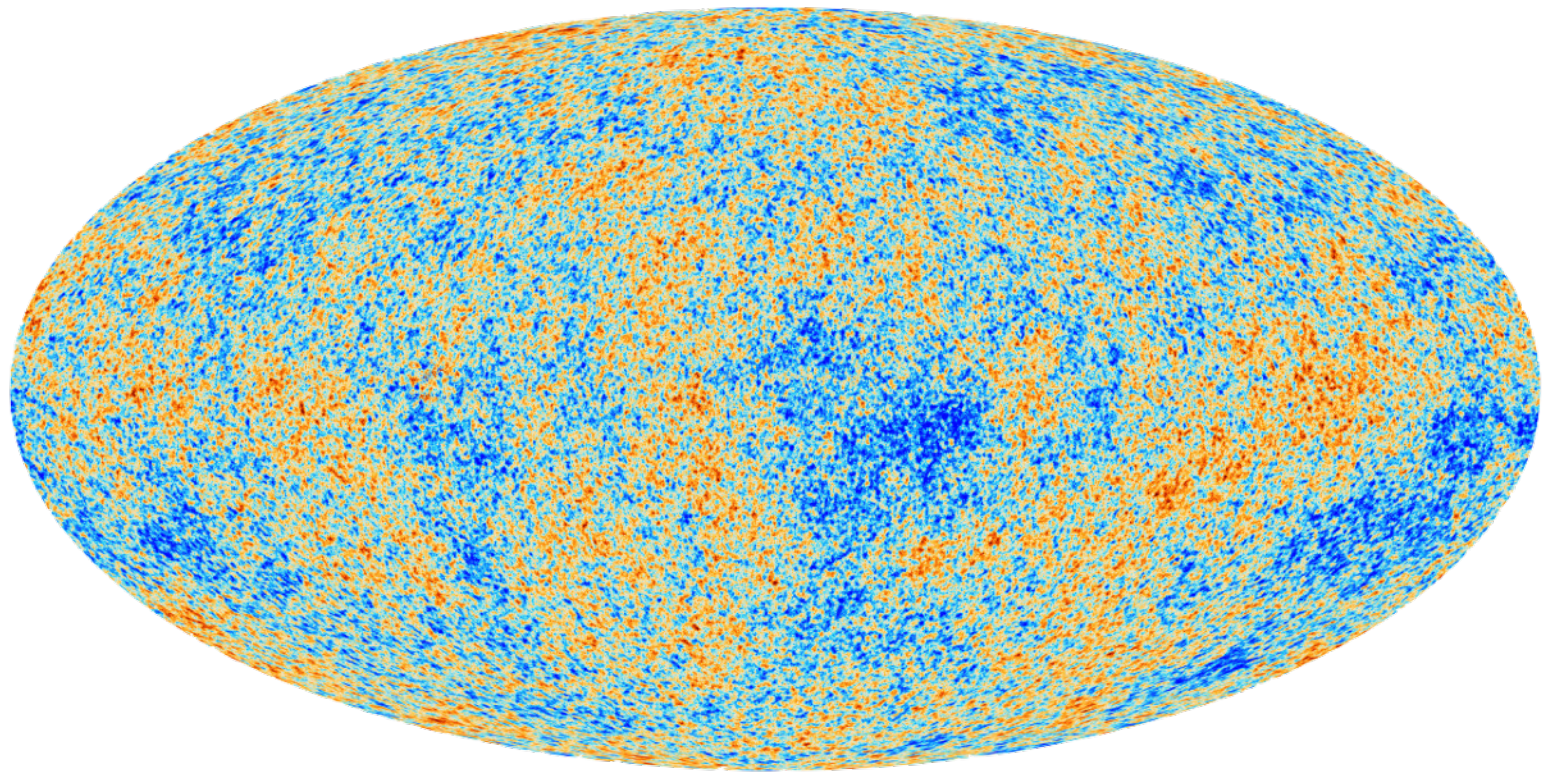
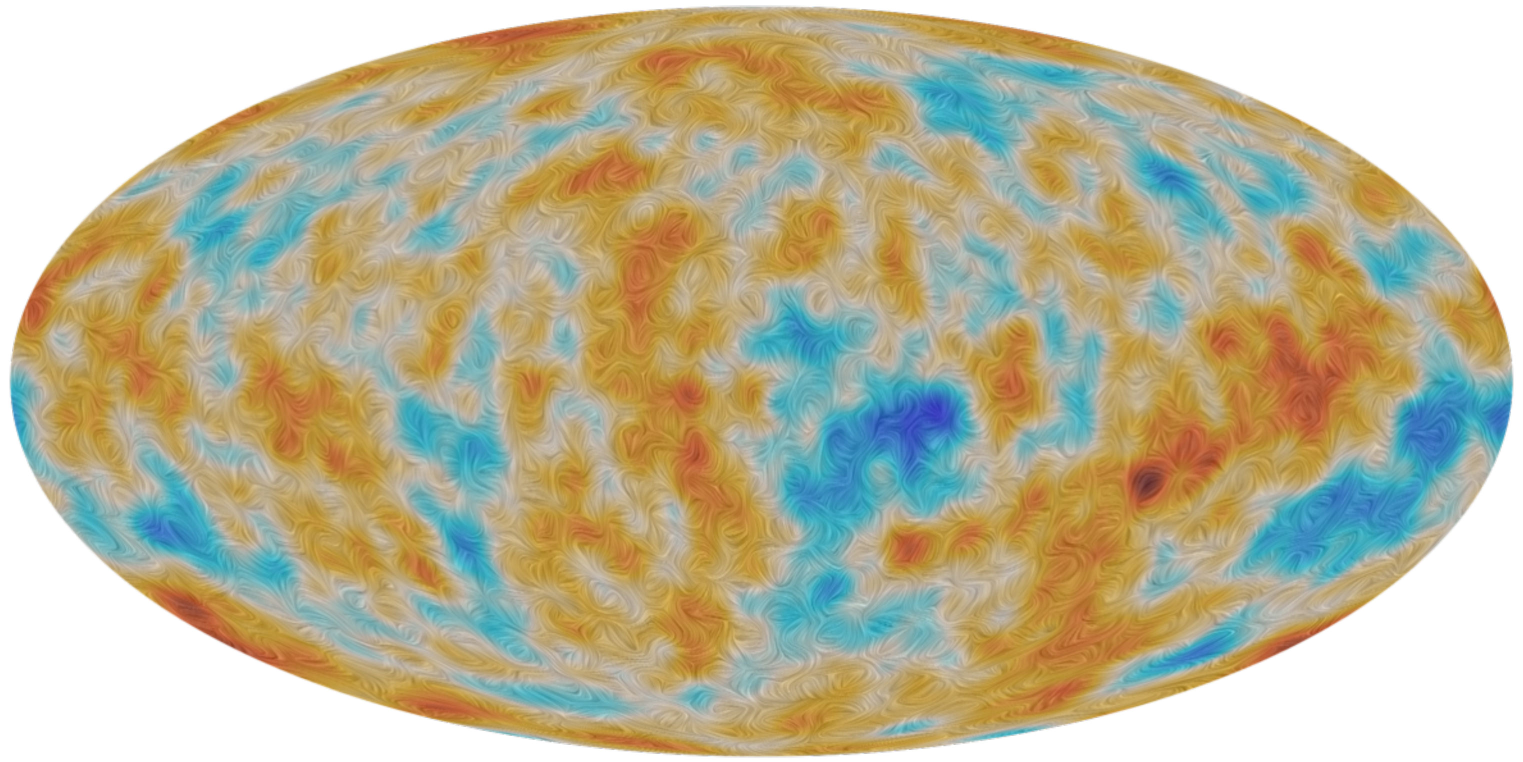
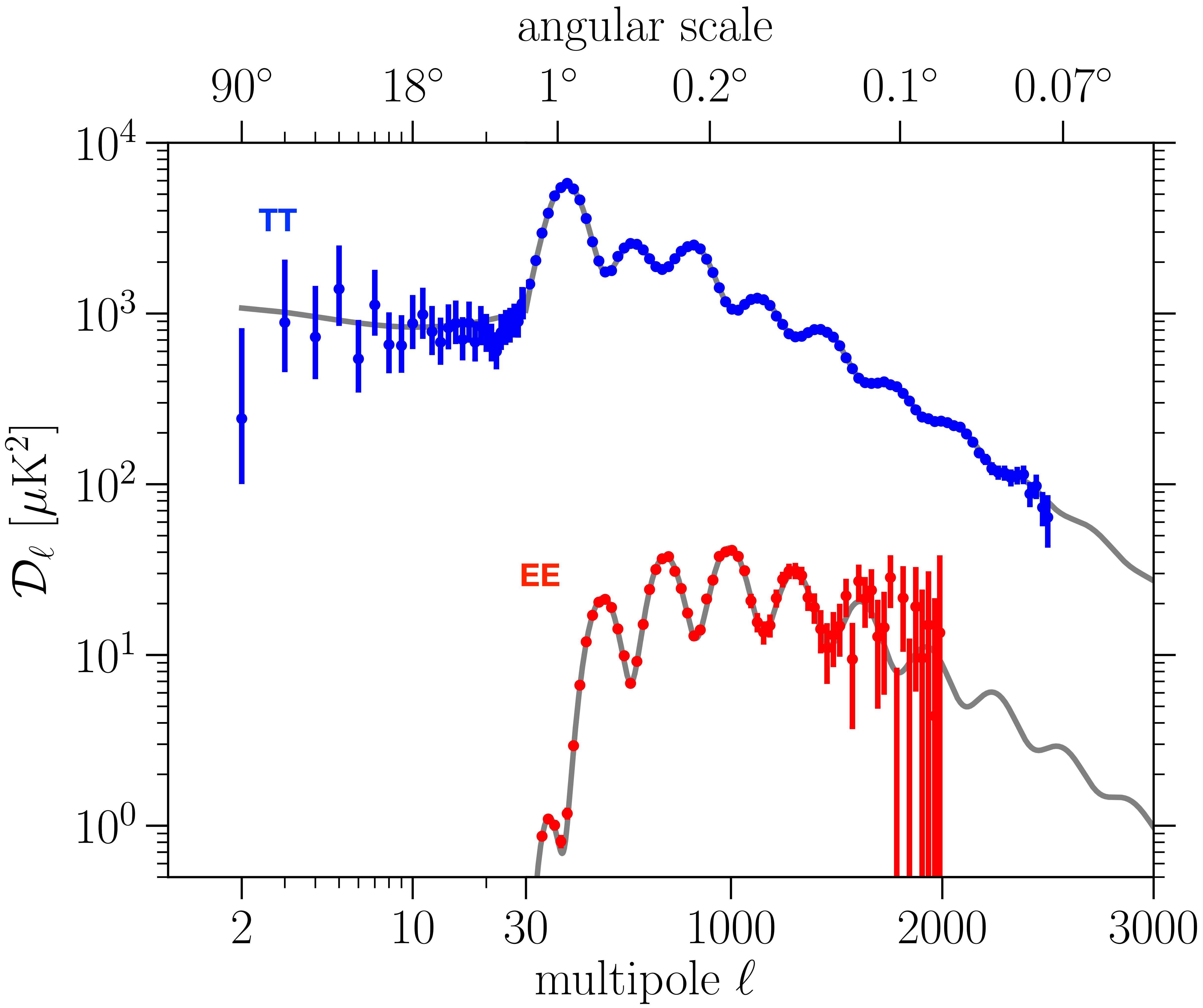
CMB Anisotropies

Temperature



Polarization





ESA and Planck Collaboration

Modify Boltzmann Equations

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

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

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

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

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

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

- 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

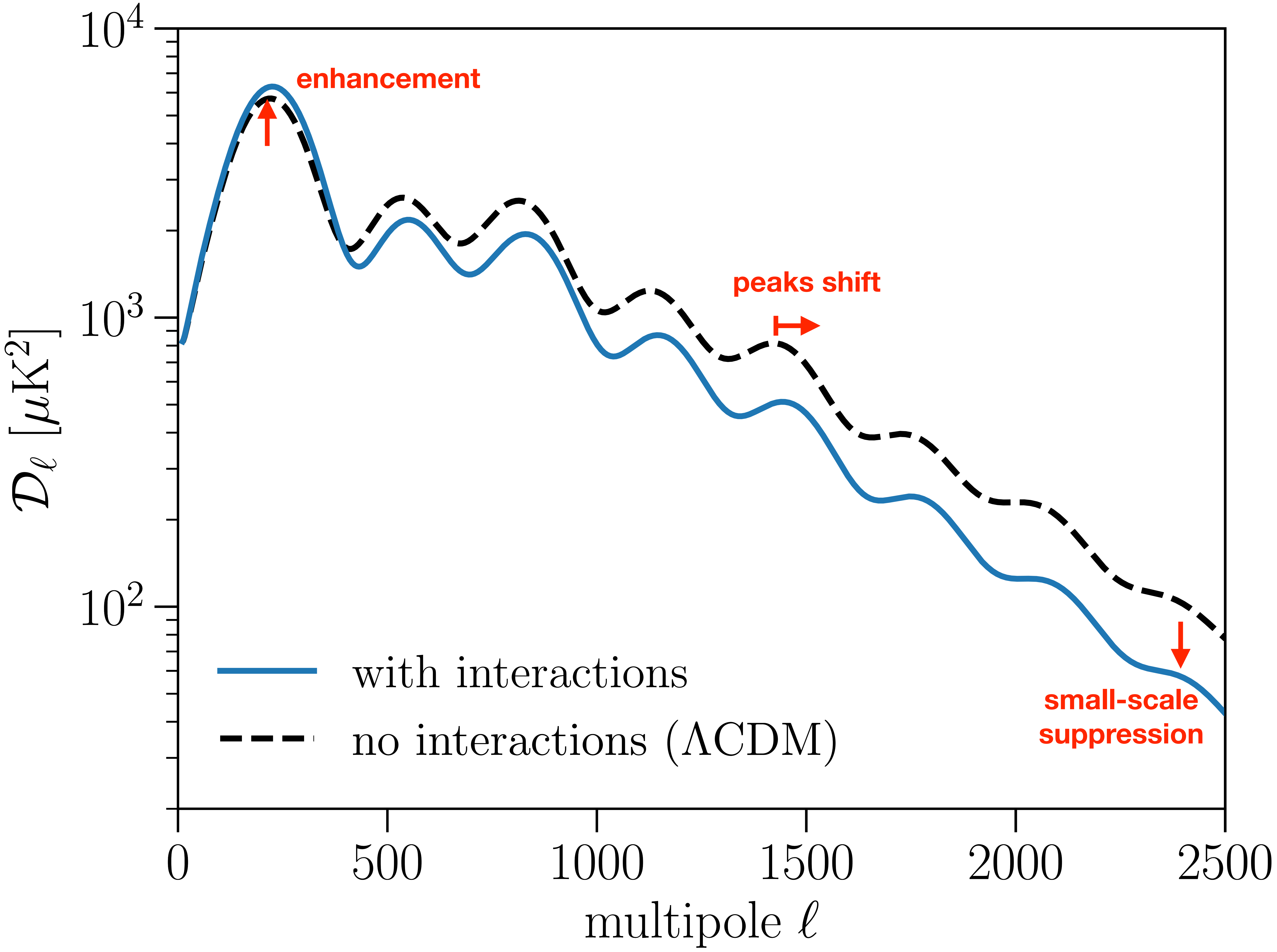
- Nonlinearities arise if relative bulk velocity > thermal velocity (relevant for $n = -2, -4$)

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

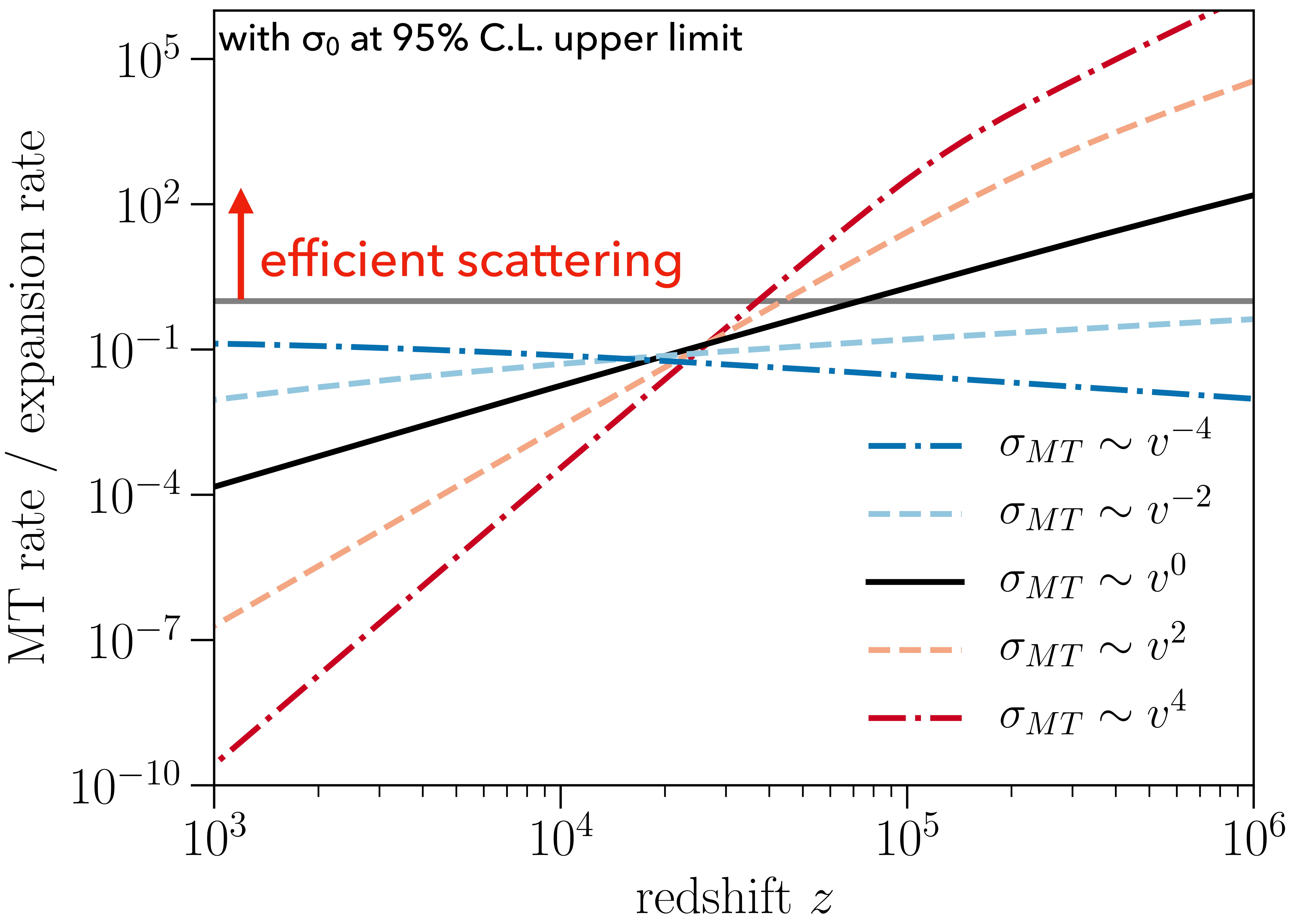
for $n = 0$



Chen+ (2002); Sigurdson+ (2004); Dvorkin+ (2014); Gluscevic and KB (2018); KB and Gluscevic (2018); Xu+ (2018); Slatyer+ (2018); KB+ (2018)

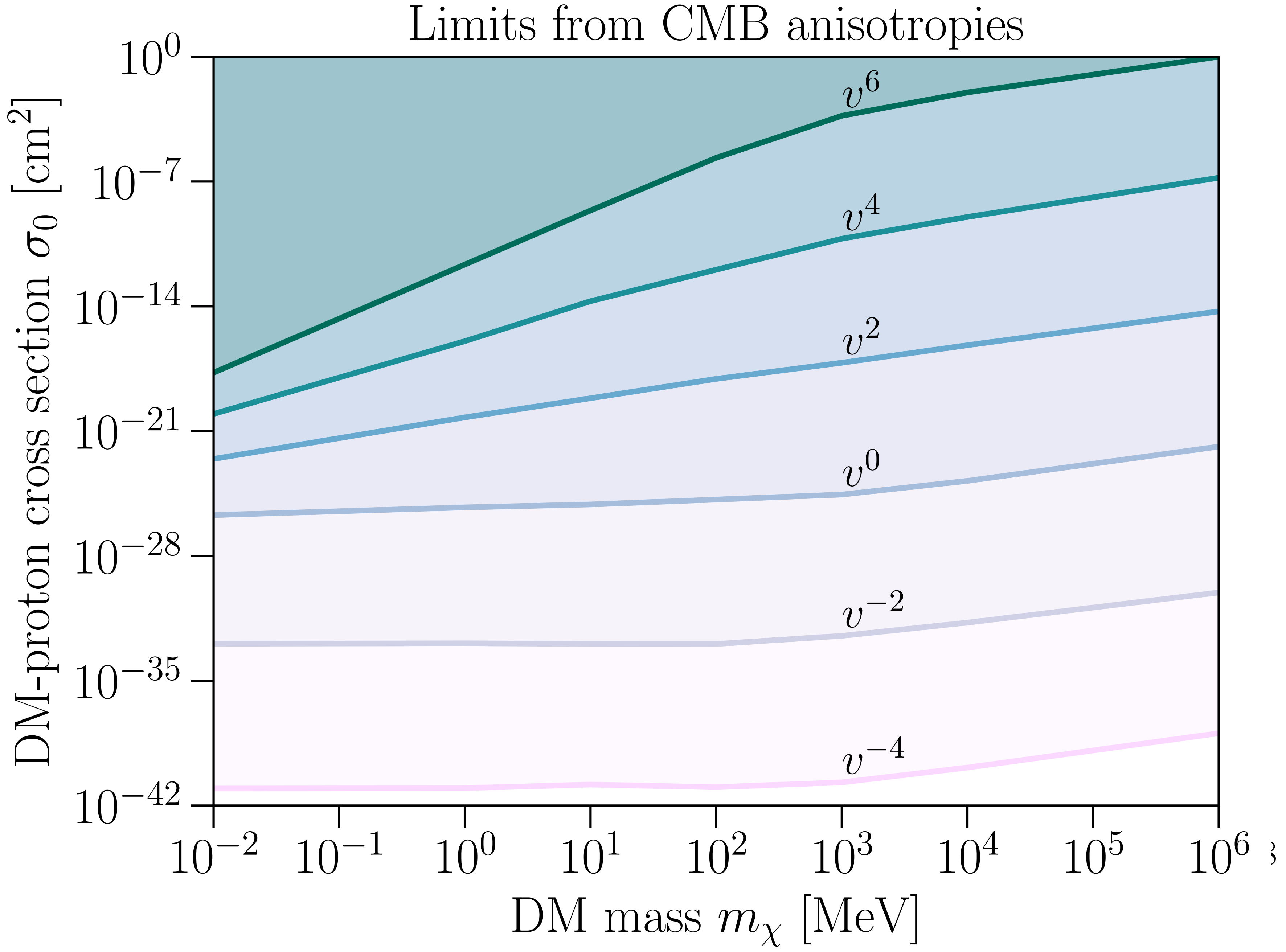
Momentum Transfer

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

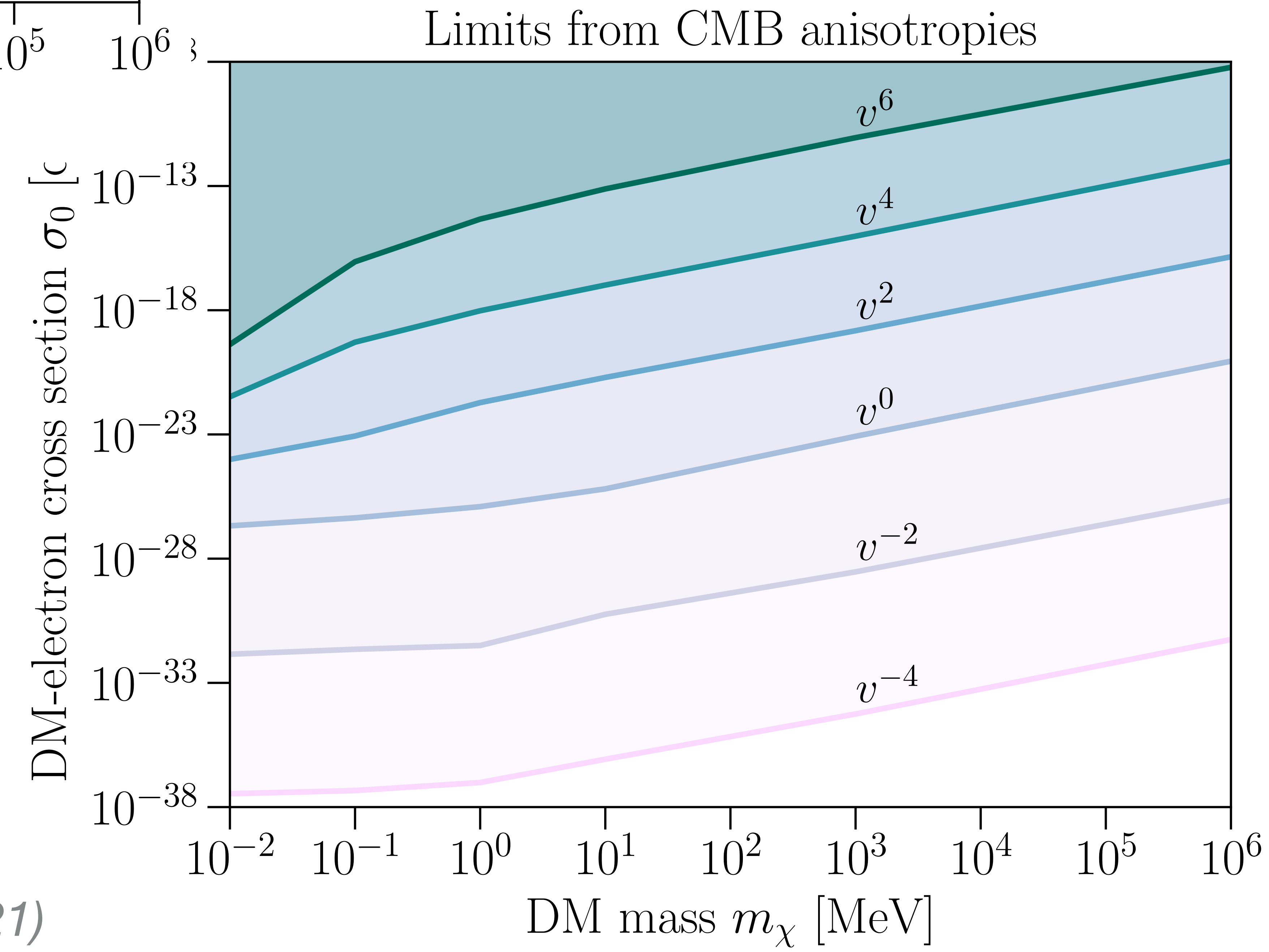


for n≥0: KB, Gluscevic (PRD 2018); Gluscevic, KB (PRL 2018)
for n<0: KB, Gluscevic, Poulin, Kovetz, Kamionkowski, Barkana (PRD 2018)

CMB Constraints from *Planck* 2018

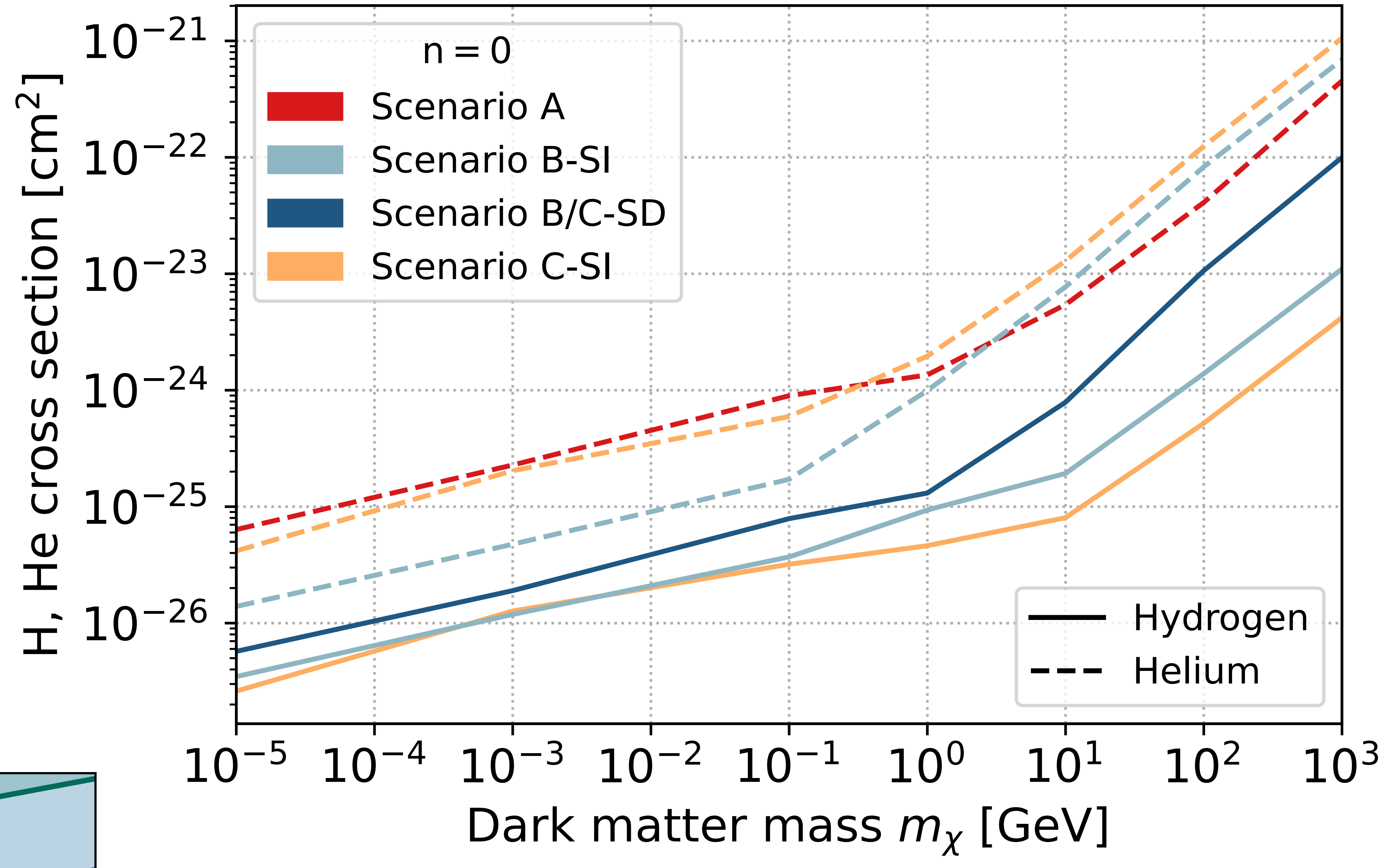


Scattering with Protons



Scattering with Electrons

KB, Krnjaic, Moltner (PRD 2022)

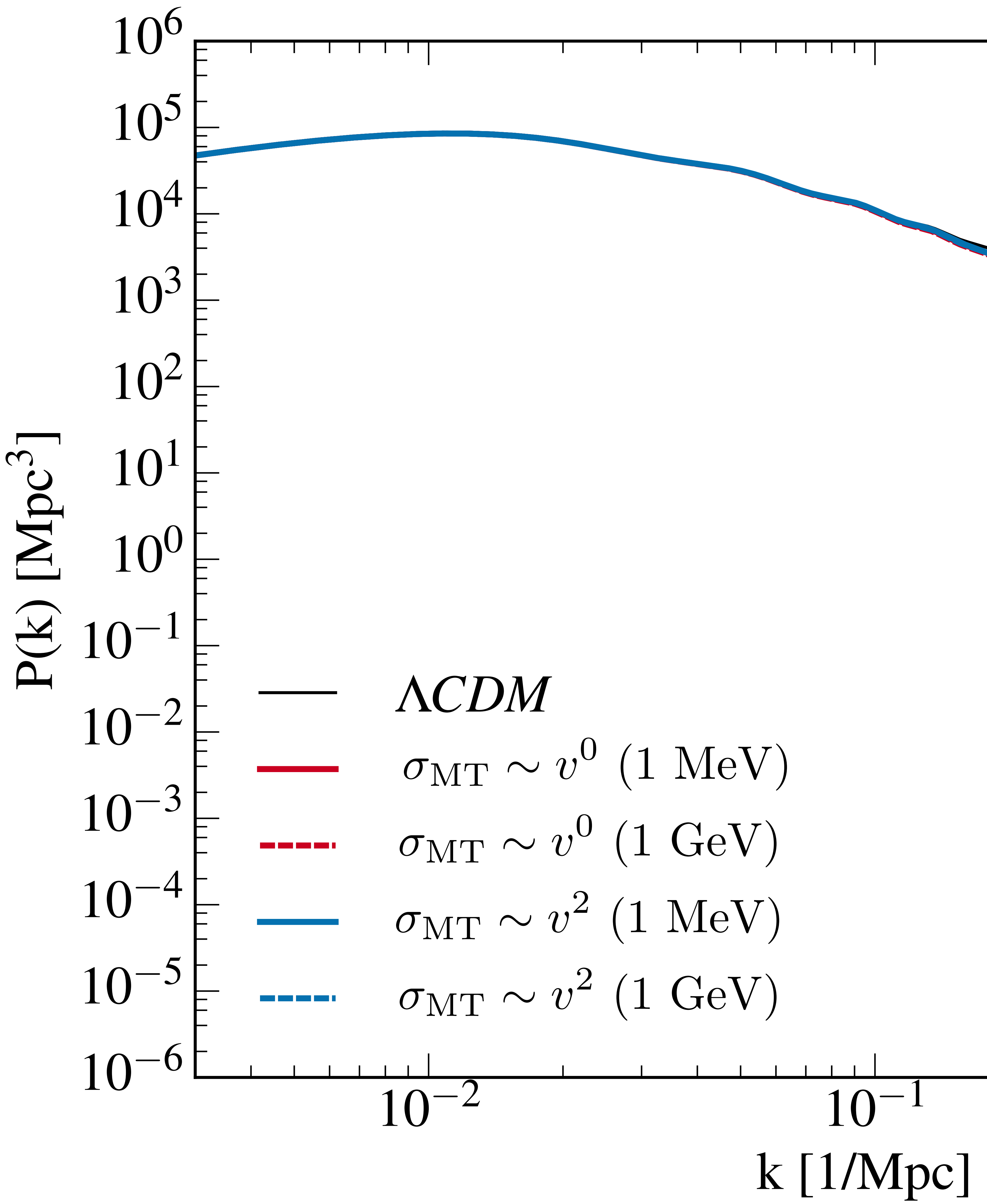


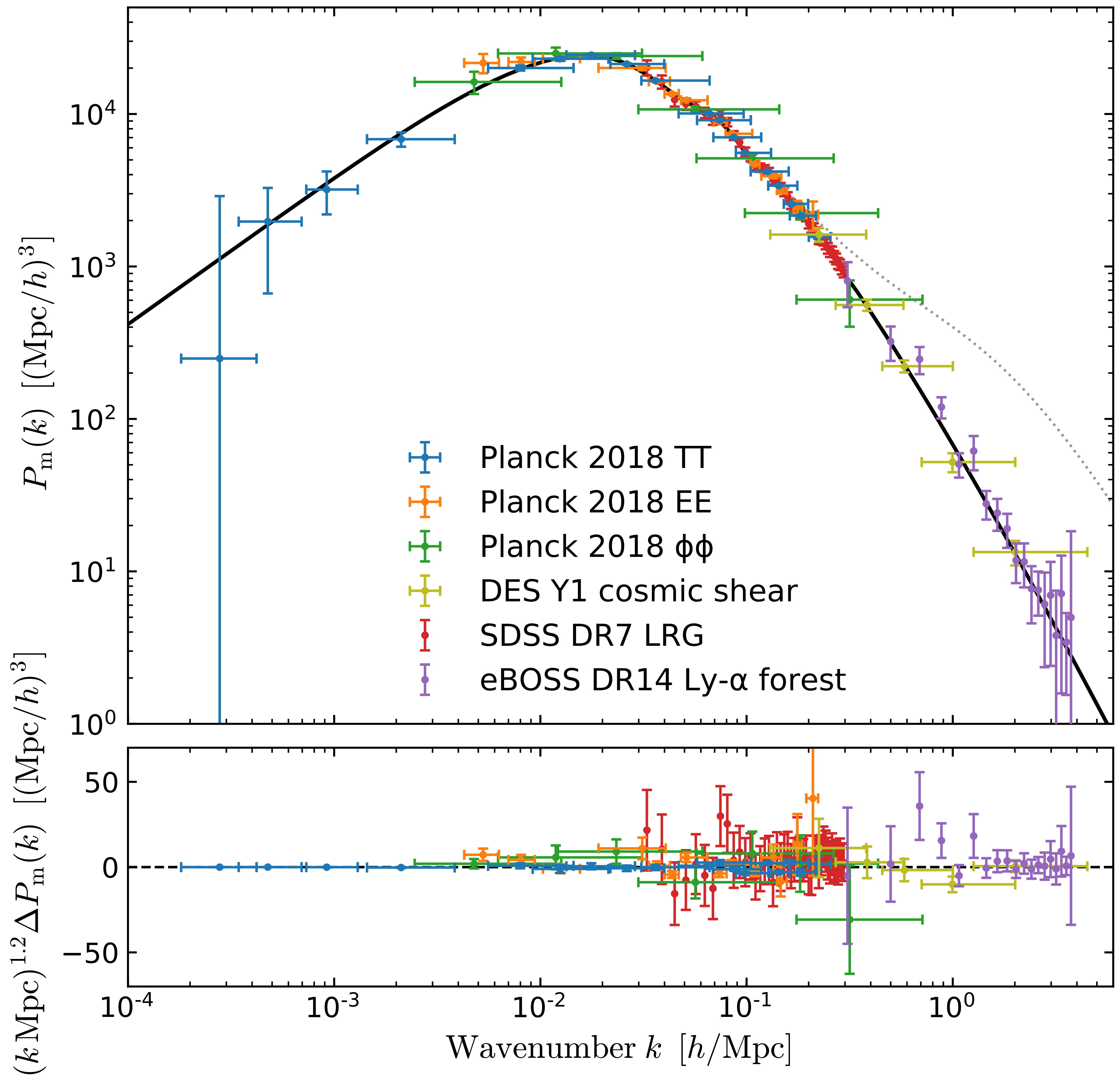
Scattering with Helium

using *Planck* 2018 temperature, polarization, lensing
varying 6 standard ΛCDM parameters + σ_0 @ fixed m_χ

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

Matter Power Spectrum

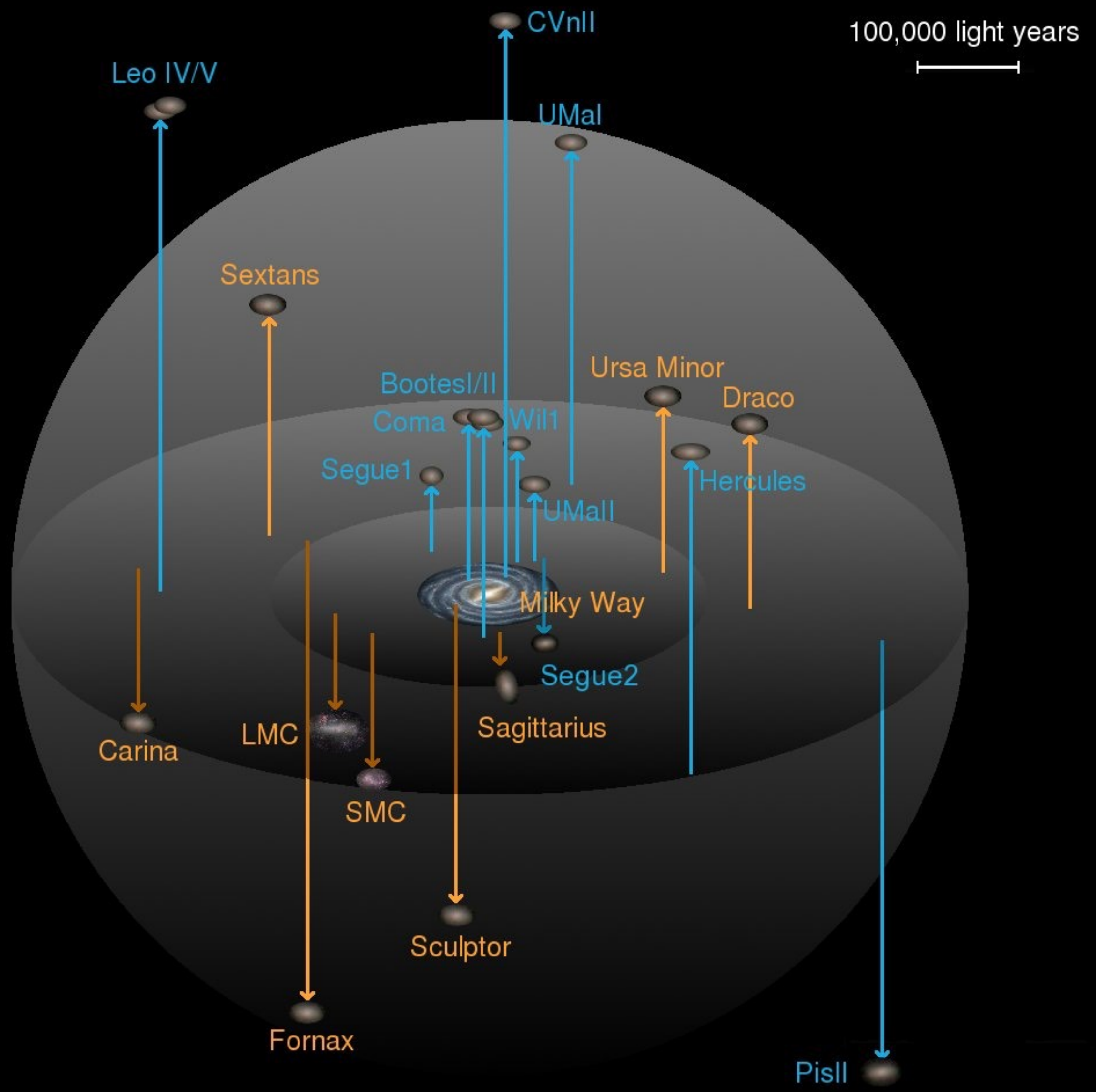




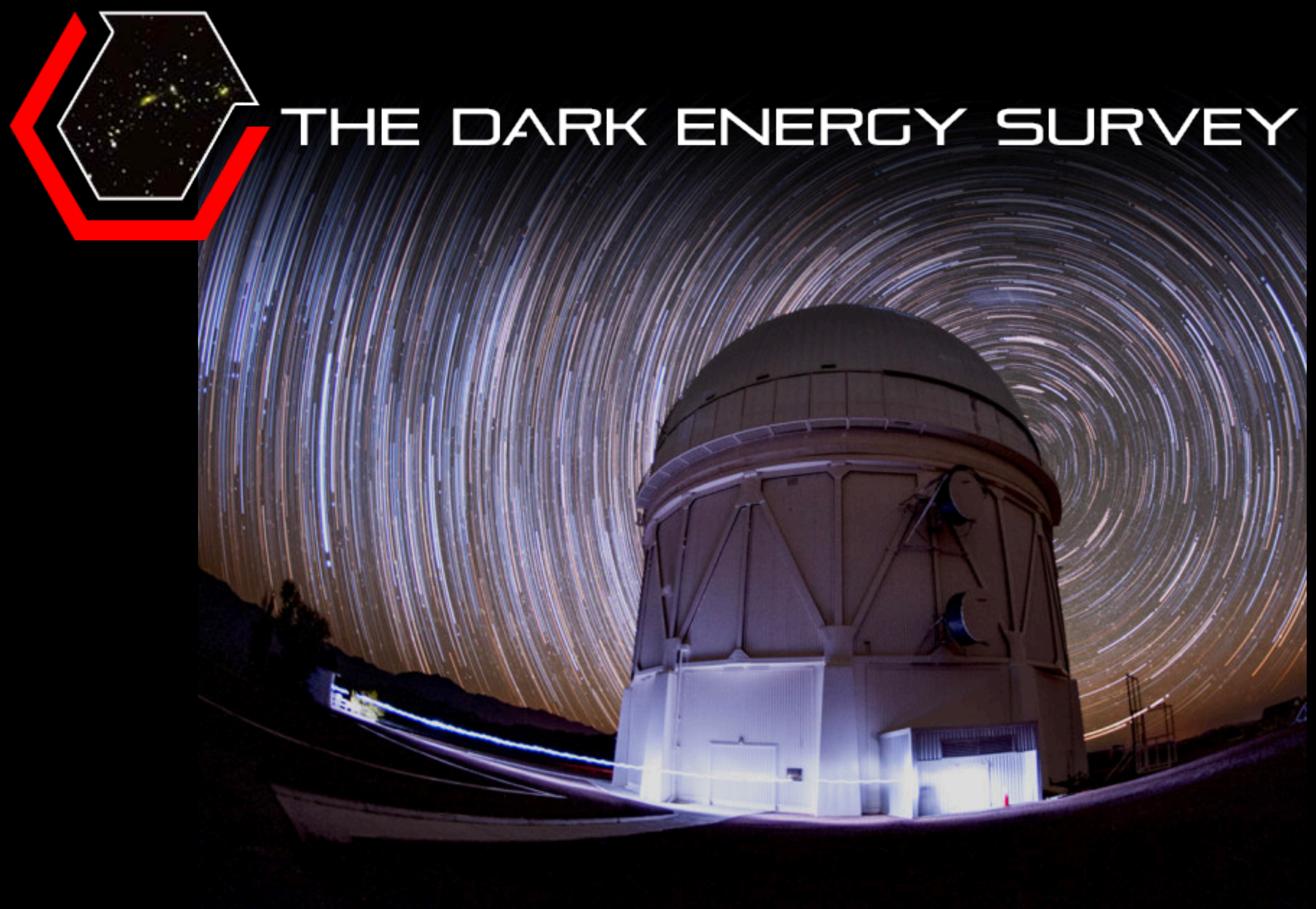
KB and Gluscevic (PRD 2018)

Chabanier+ (MNRAS 2019)

Milky Way Satellites



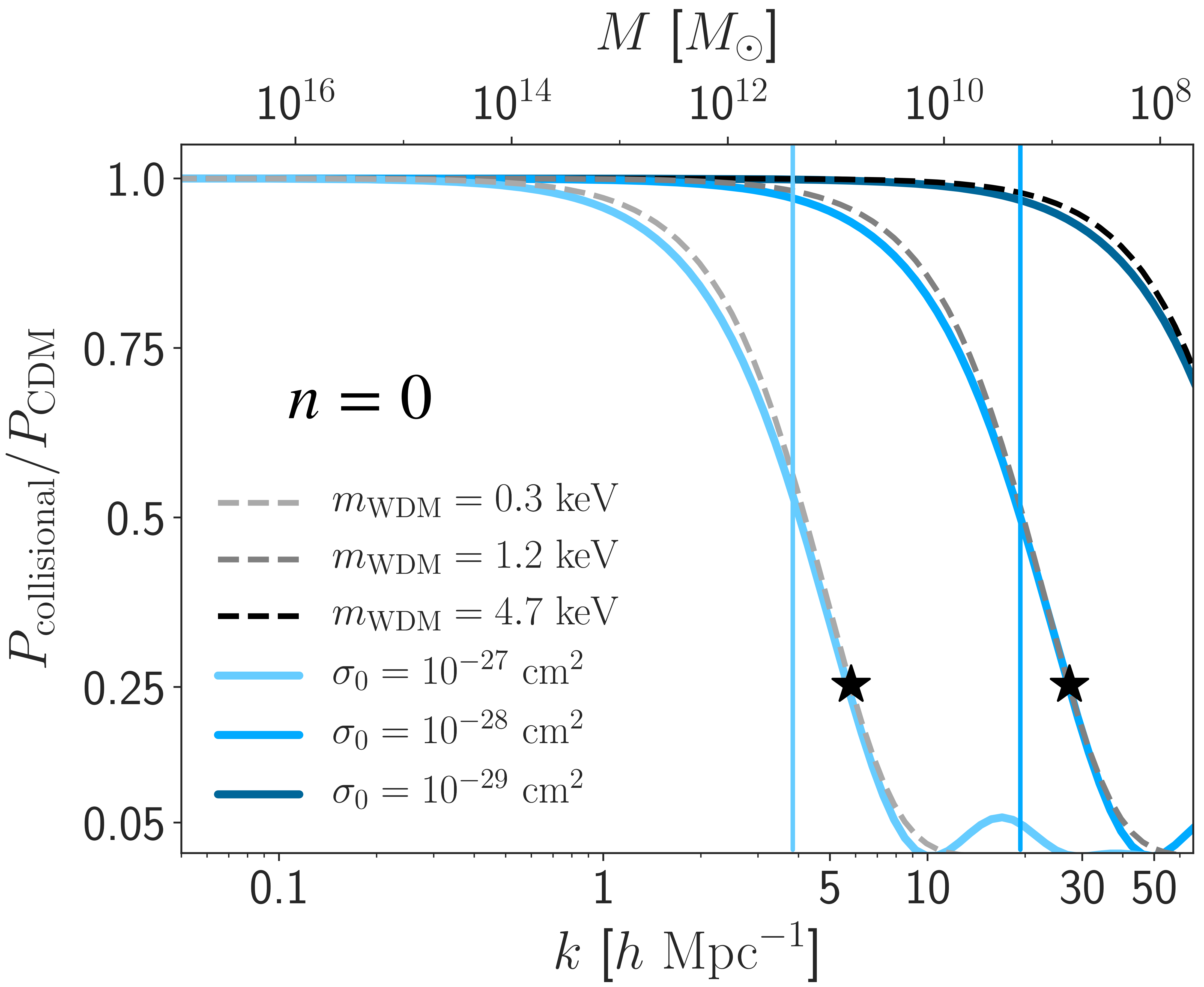
DES and Pan-STARRS1 identified dwarfs

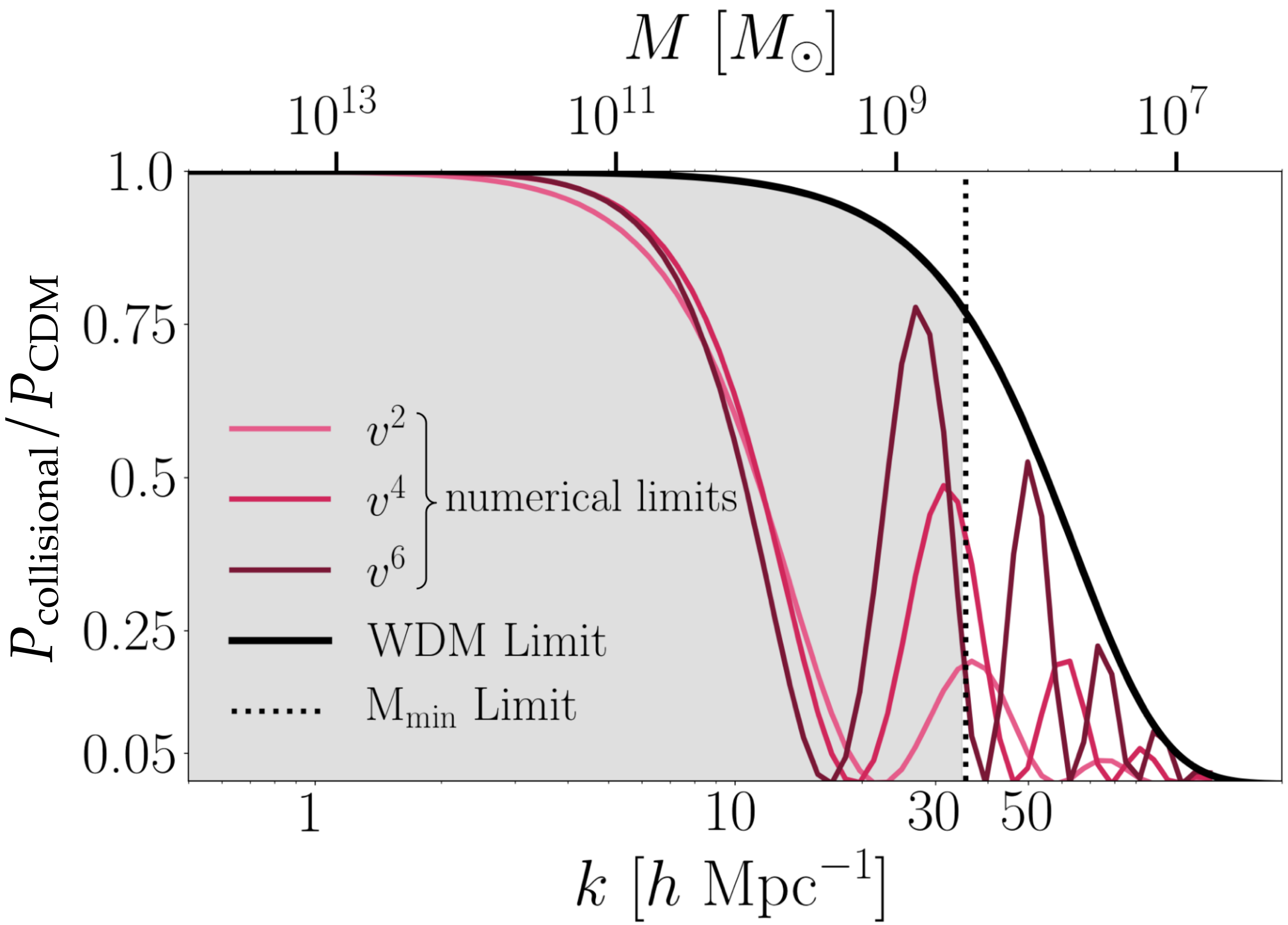


Classic dwarfs

SDSS-identified dwarfs

Suppression of (Linear) Matter Power Spectrum

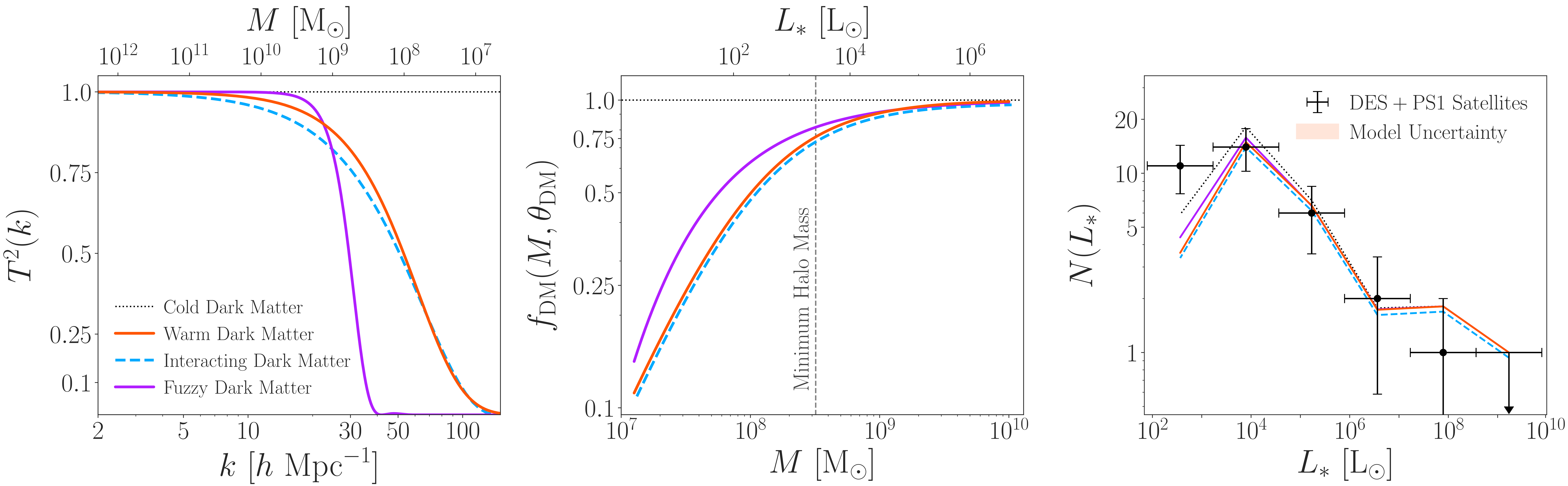




Nadler, Gluscevic, KB, Wechsler (ApJL 2019)

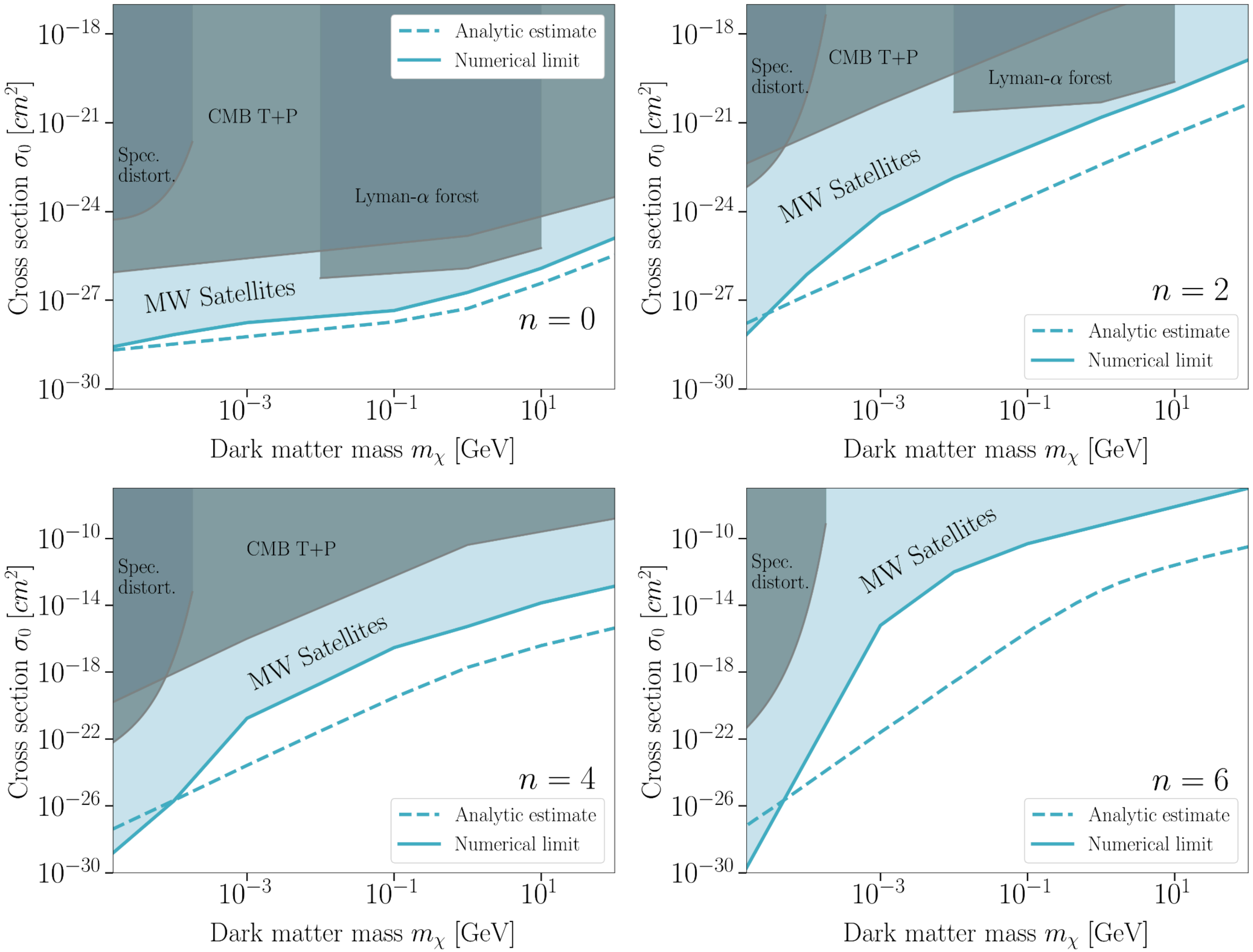
Maamari, Gluscevic, KB, Nadler, Wechsler (ApJL 2021)

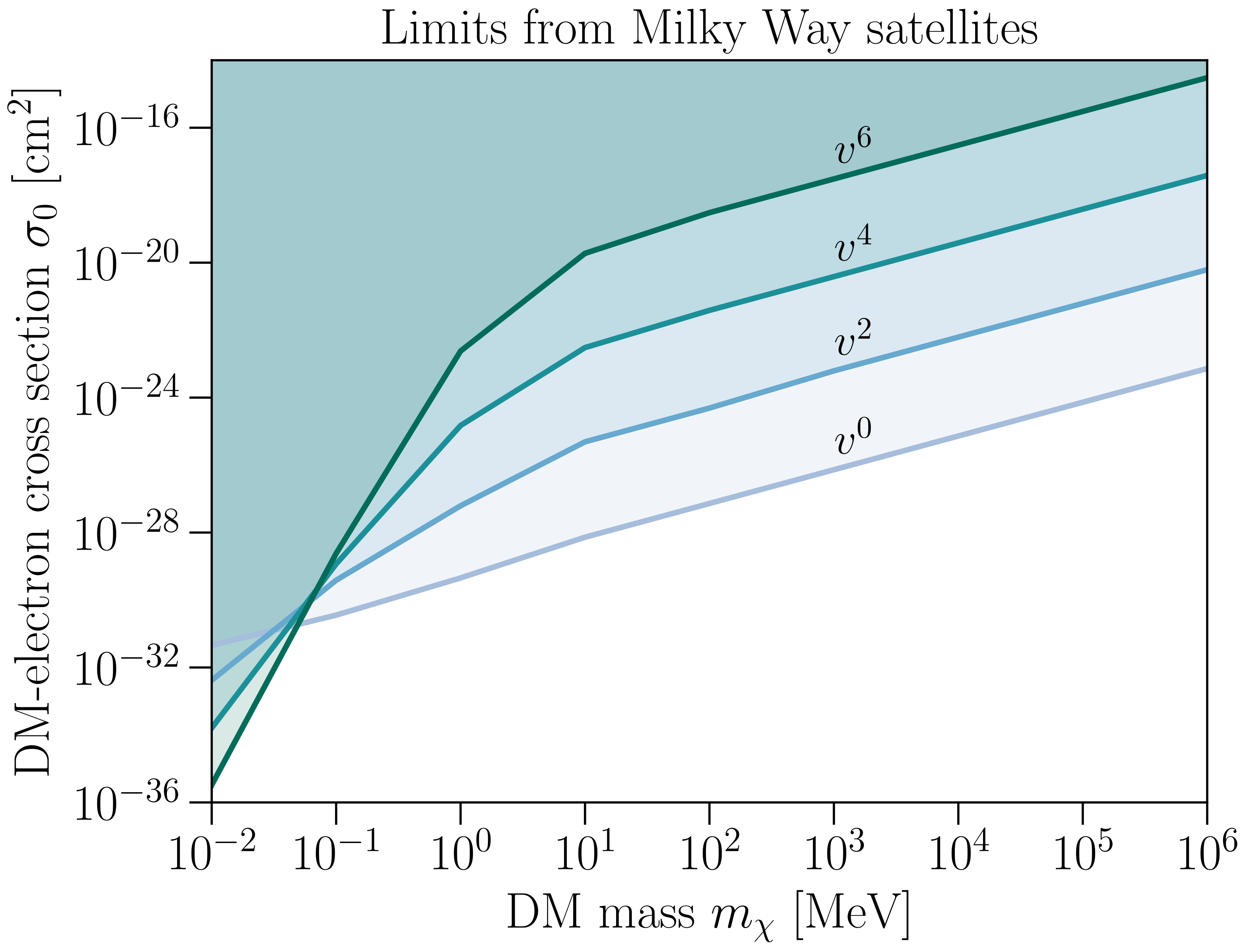
Suppression for Various Models



DES Collaboration, Nadler (PRL 2021)

Scattering Constraints with MW Satellites

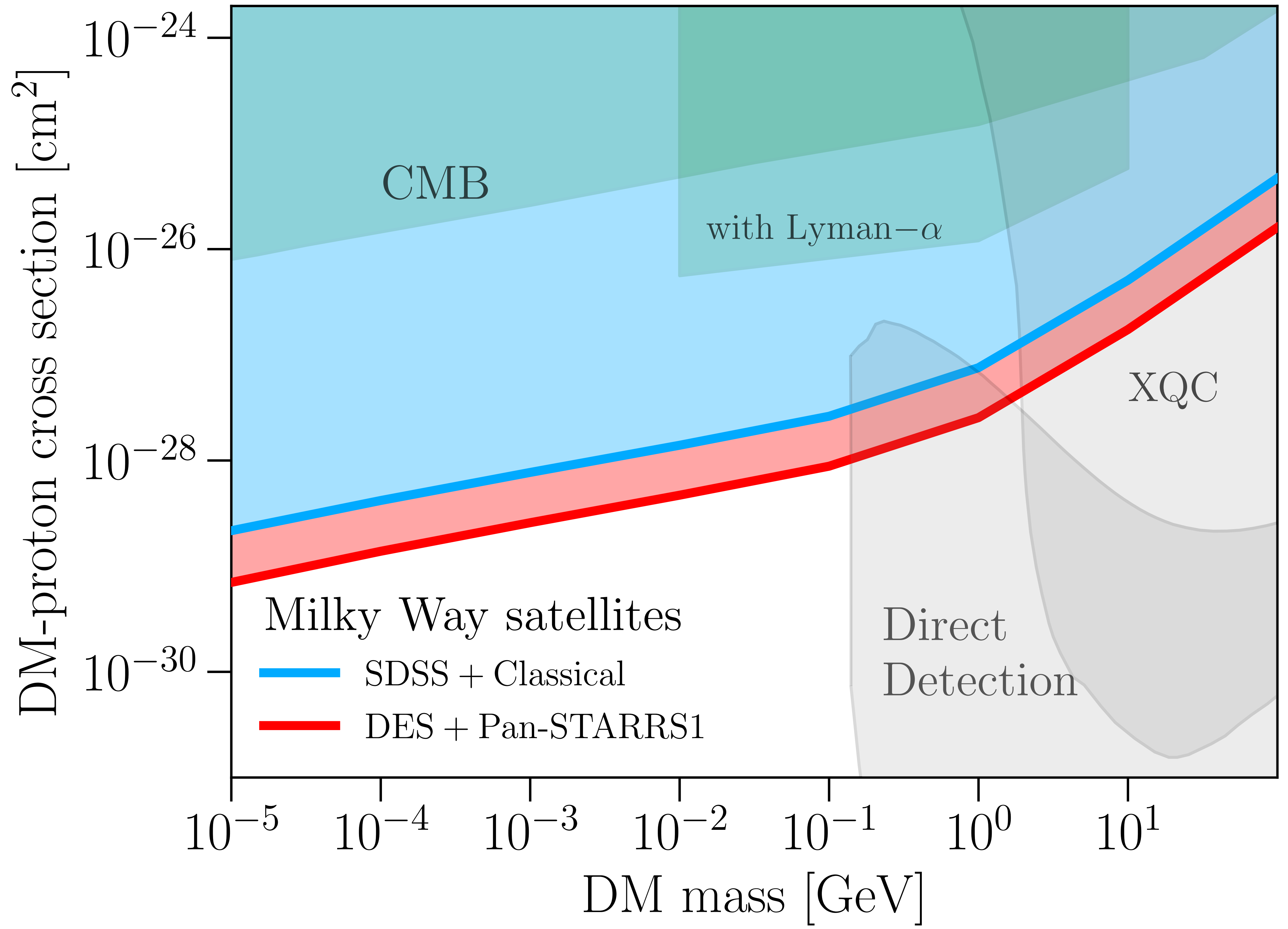


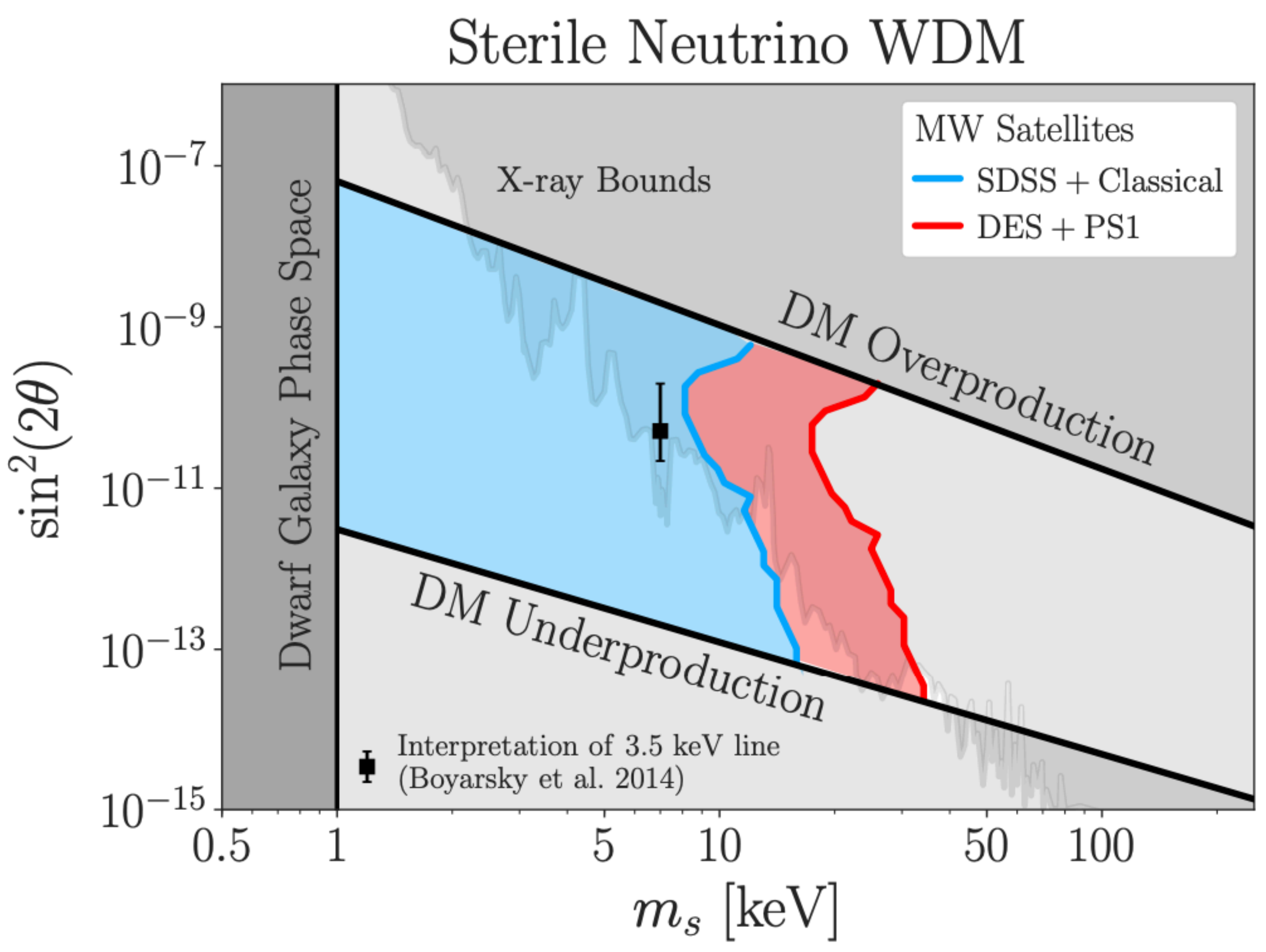


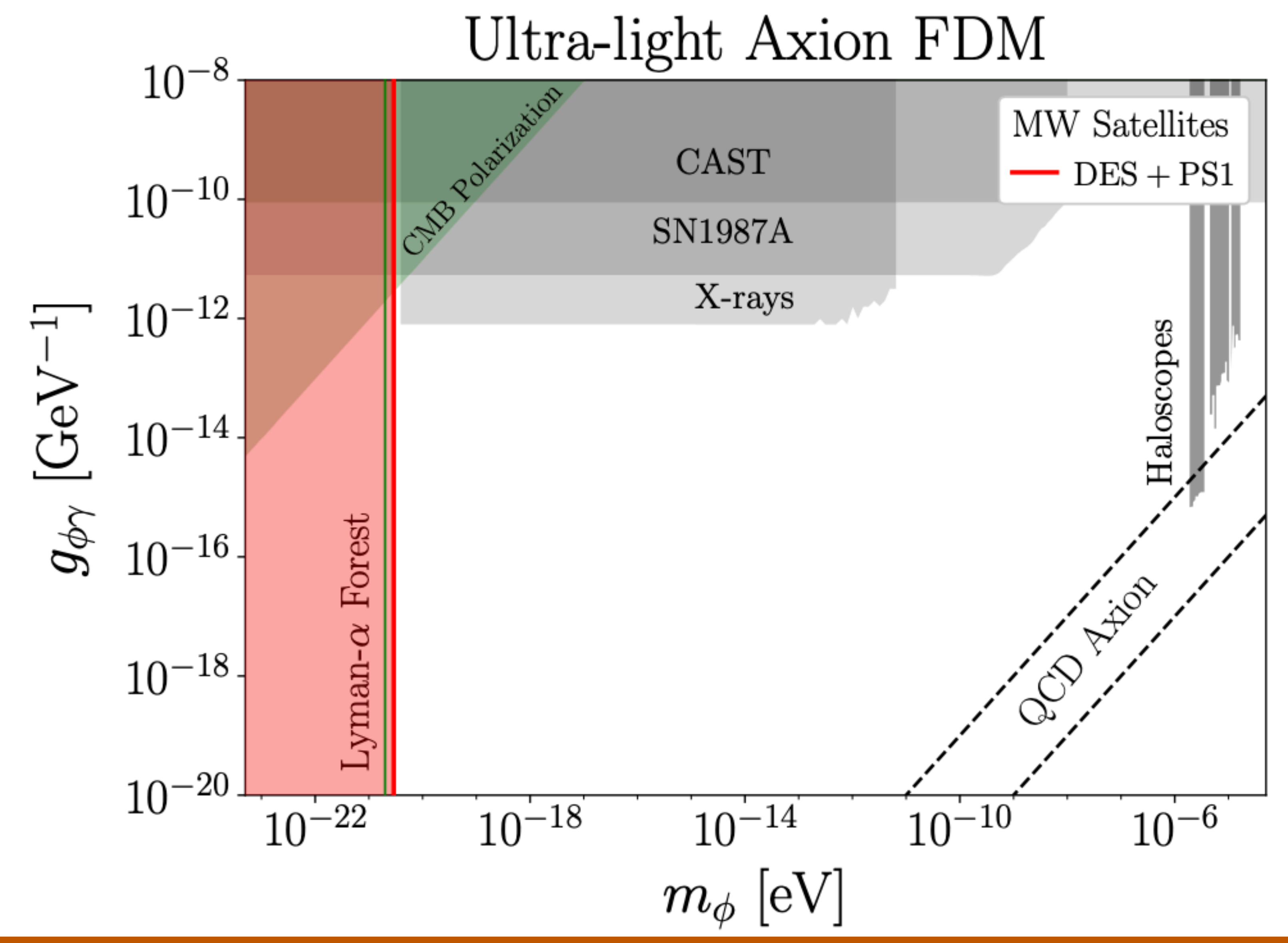
Maamari, Gluscevic, KB, Nadler, Wechsler (ApJL 2021)

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

Constraints from MW Satellites

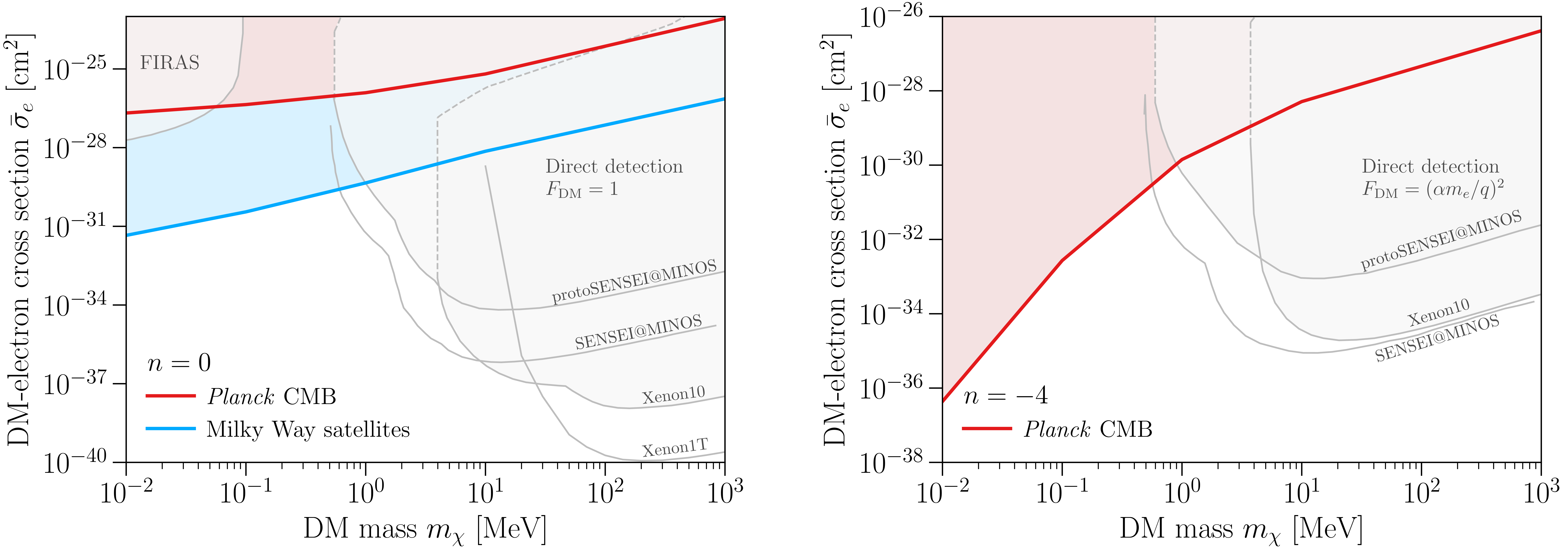






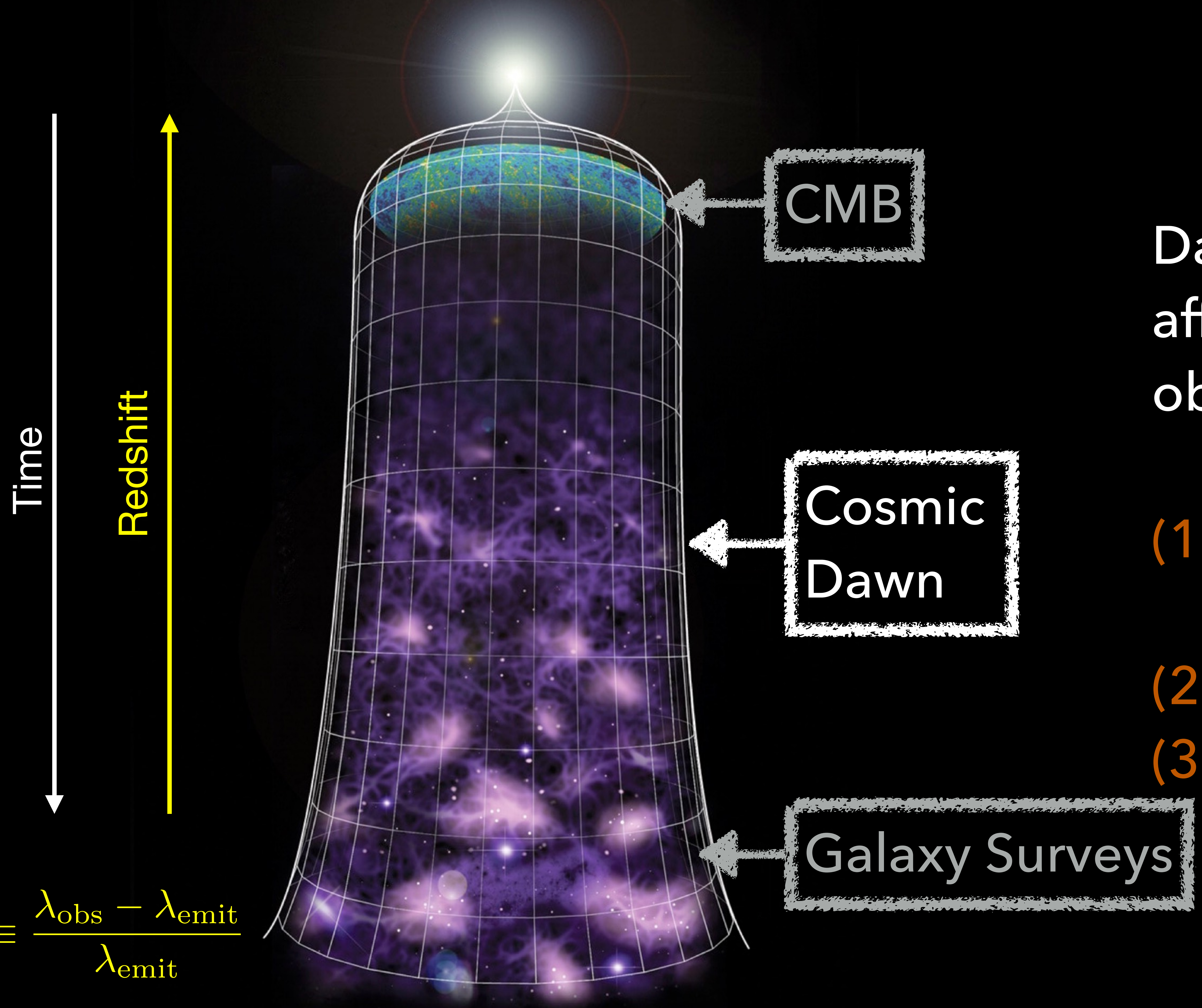
DES Collaboration (PRL 2021)

Constraints: Scattering with Electrons



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

Cosmic History



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21cm Cosmology

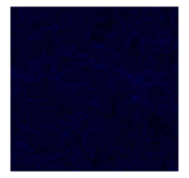
Time dependence of different temperatures:

At $z > 200$: $T_{\rm CMB} \sim T_{\rm gas} \sim T_{\rm spin}$ (Compton scattering off remaining electrons)

At $z < 200$: $T_{\rm CMB} \sim (1+z)$; $T_{\rm gas} \sim (1+z)^2$ (Gas decouples from CMB, cools adiabatically)

$30 < z < 200$: First, $T_{\rm spin} \sim T_{\rm gas}$ (Collisions in the IGM). After $z \sim 80$: $T_{\rm spin} \to T_{\rm CMB}$

Absorption: $T_{\rm spin} < T_{\rm CMB}$ (dark ages)



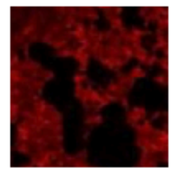
At $z \lesssim 30$: First stars form!

Stars emit Lyα photons: $T_{\rm spin} \to T_{\rm gas}$

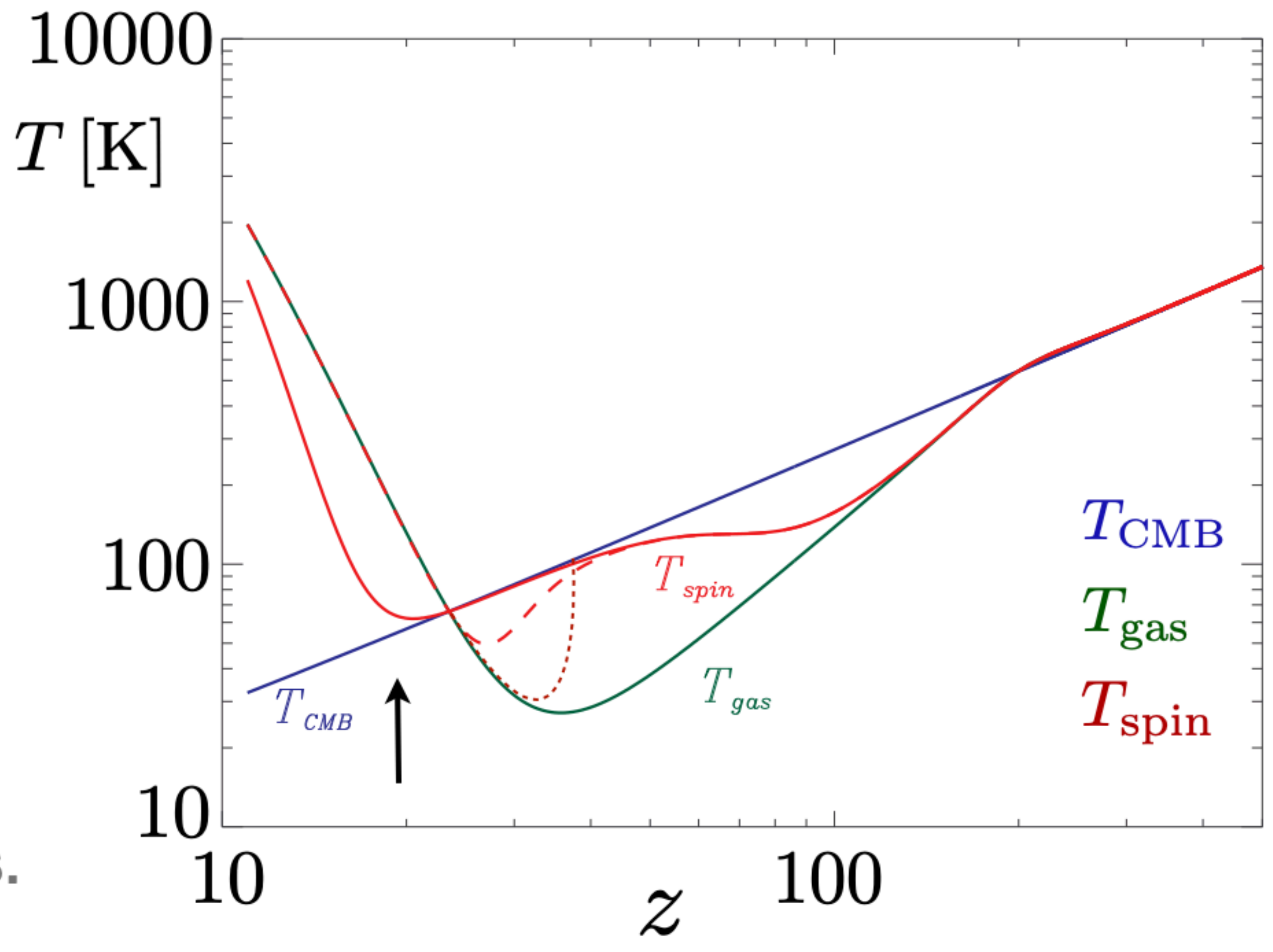
Absorption: $T_{\rm spin} < T_{\rm CMB}$ (cosmic dawn)

By $z \sim 13$: remnants heat gas above CMB.

Emission: $T_{\rm spin} > T_{\rm CMB}$ (reionization)



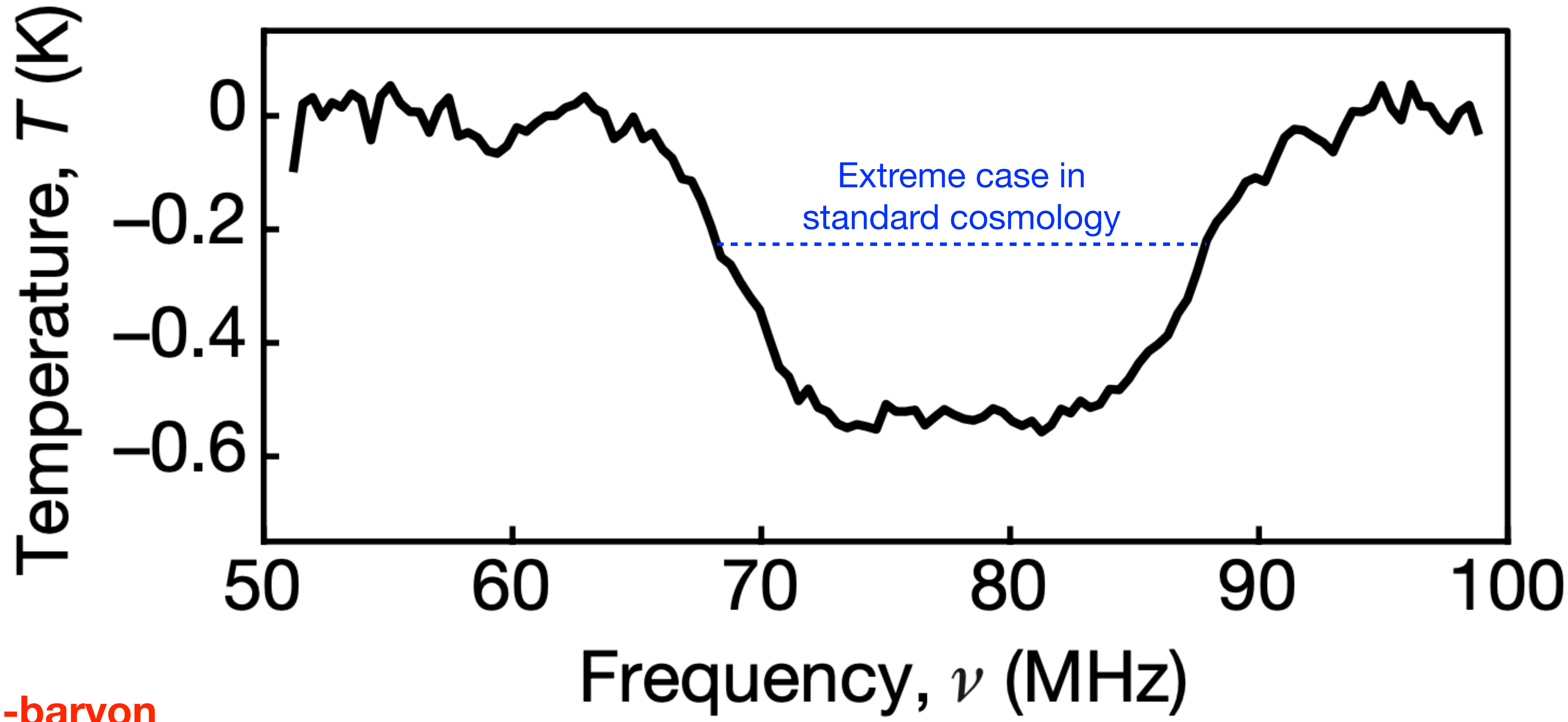
The 21cm signal cuts off when reionization ends.



Overview slide from E. Kovetz

EDGES Absorption Signal

Experiment to Detect the Global Epoch of Reionization Signature



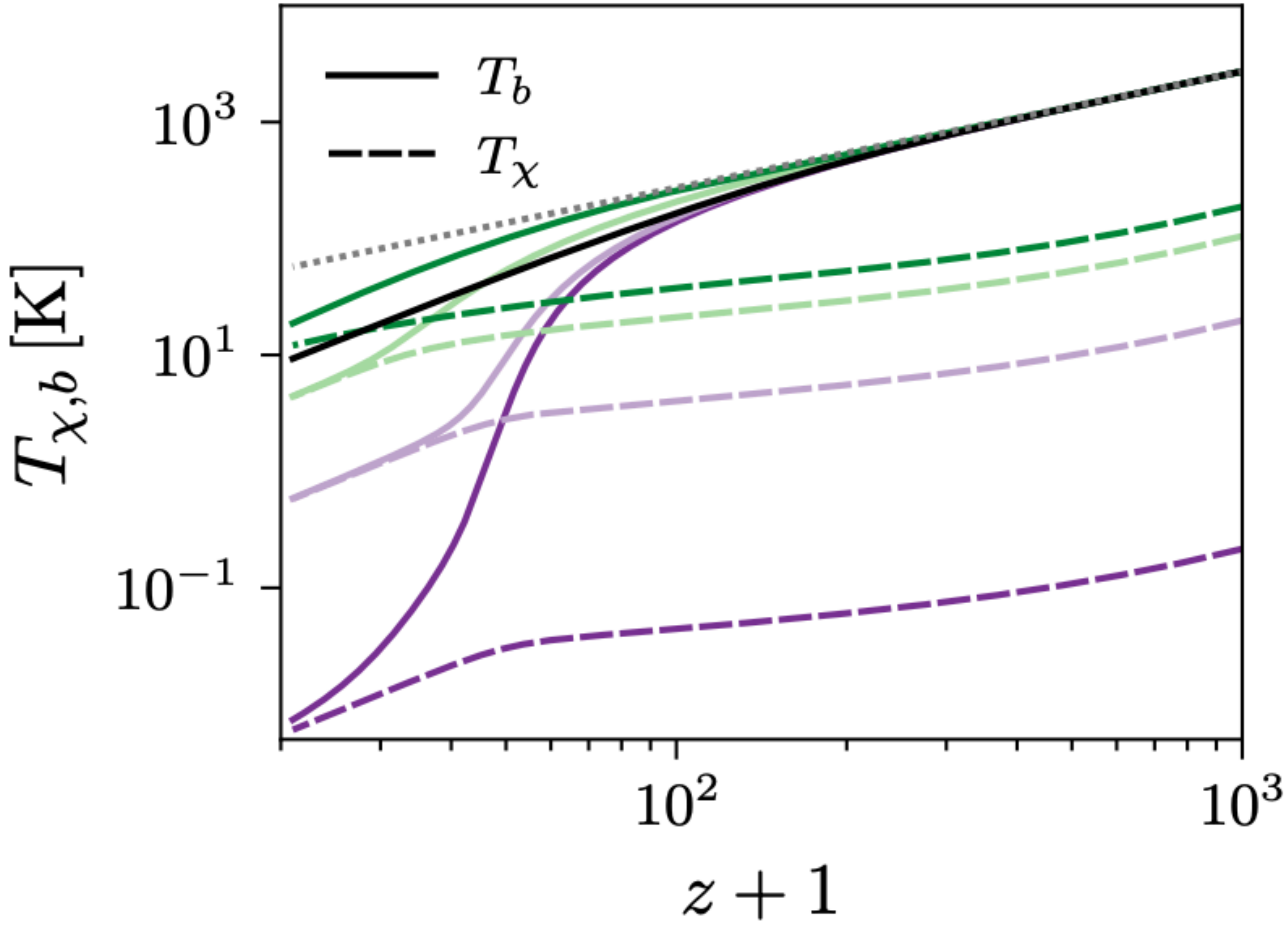
$\sigma \sim v^{-4}$ DM-baryon scattering cools gas

Barkana (Nature 2018)
see also Tashiro, Kadota, Silk (PRD 2014); Muñoz, Kovetz, Ali-Haïmoud (PRD 2015)

Bowman+ (Nature 2018)

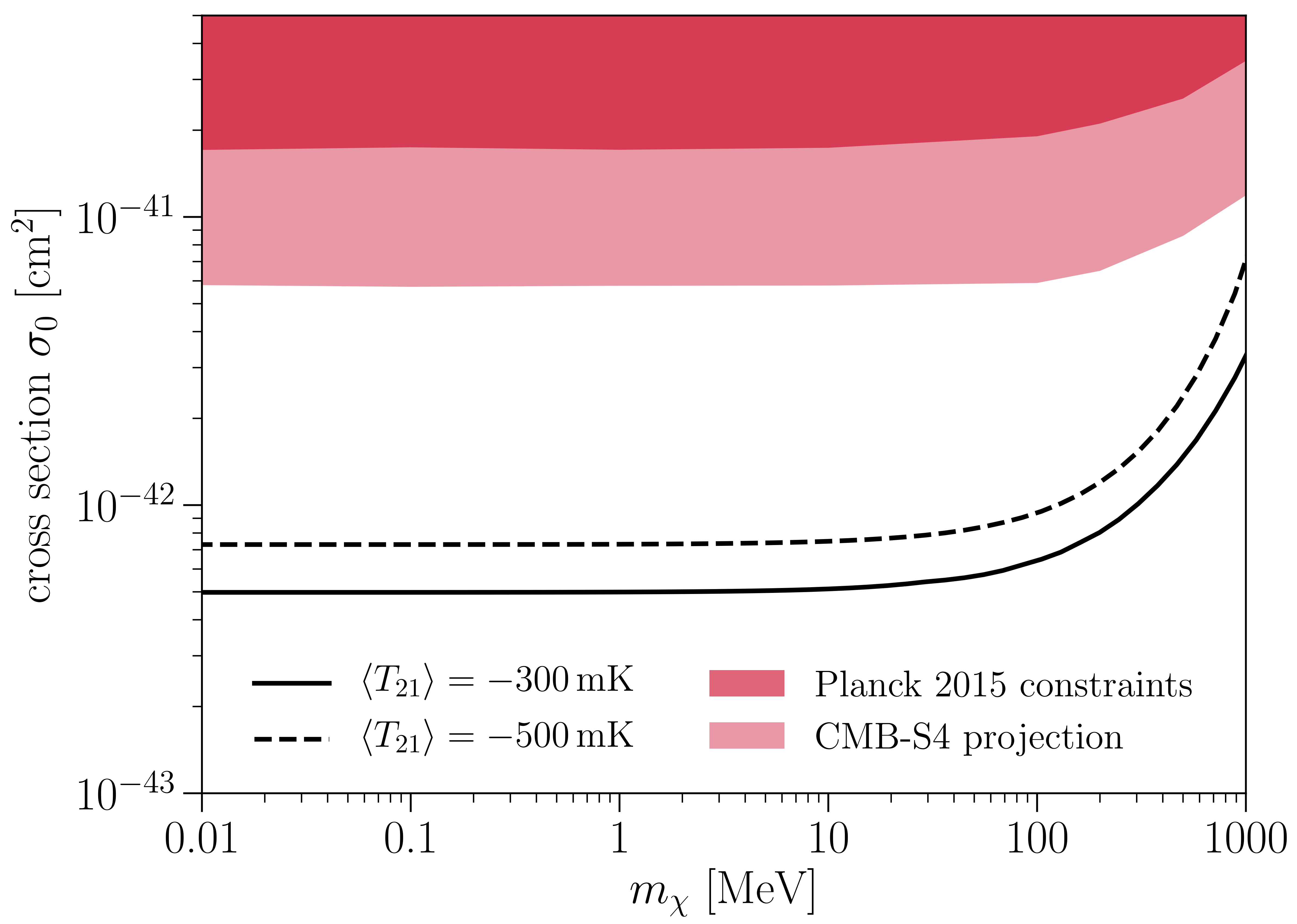
21cm and Late-Time Scattering

$\sigma \sim v^{-4}$ 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)

CMB Constraints

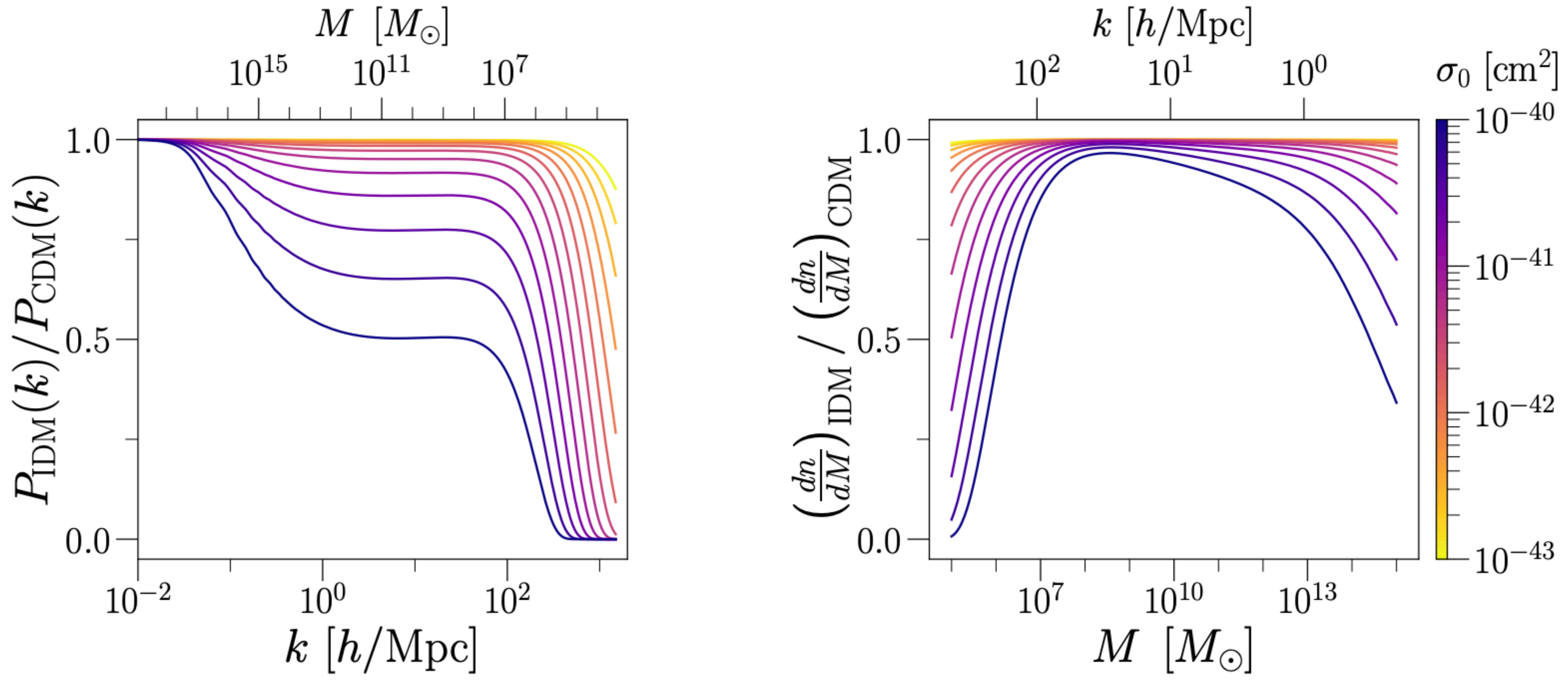


- T_{21} lines assume all DM interacts, but neglects suppression of matter power spectrum

Driskell, Mirocha, Morton, Gluscevic, KB, Benson, Nadler (PRD 2022)

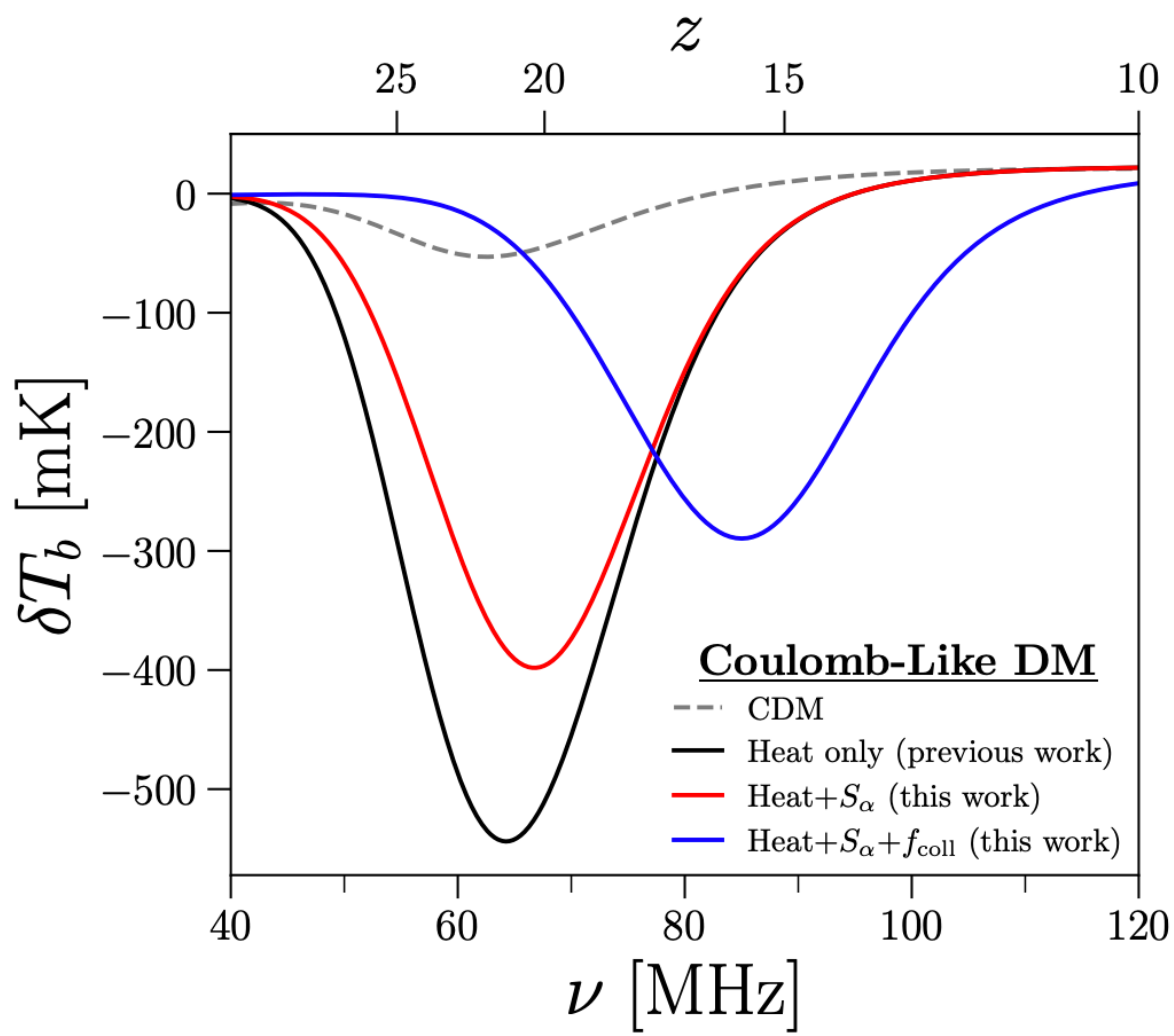
KB, Gluscevic, Poulin, Kovetz, Kamionkowski, Barkana (PRD 2018)
Kovetz, Poulin, Gluscevic, KB, Barkana, Kamionkowski (PRD 2018)

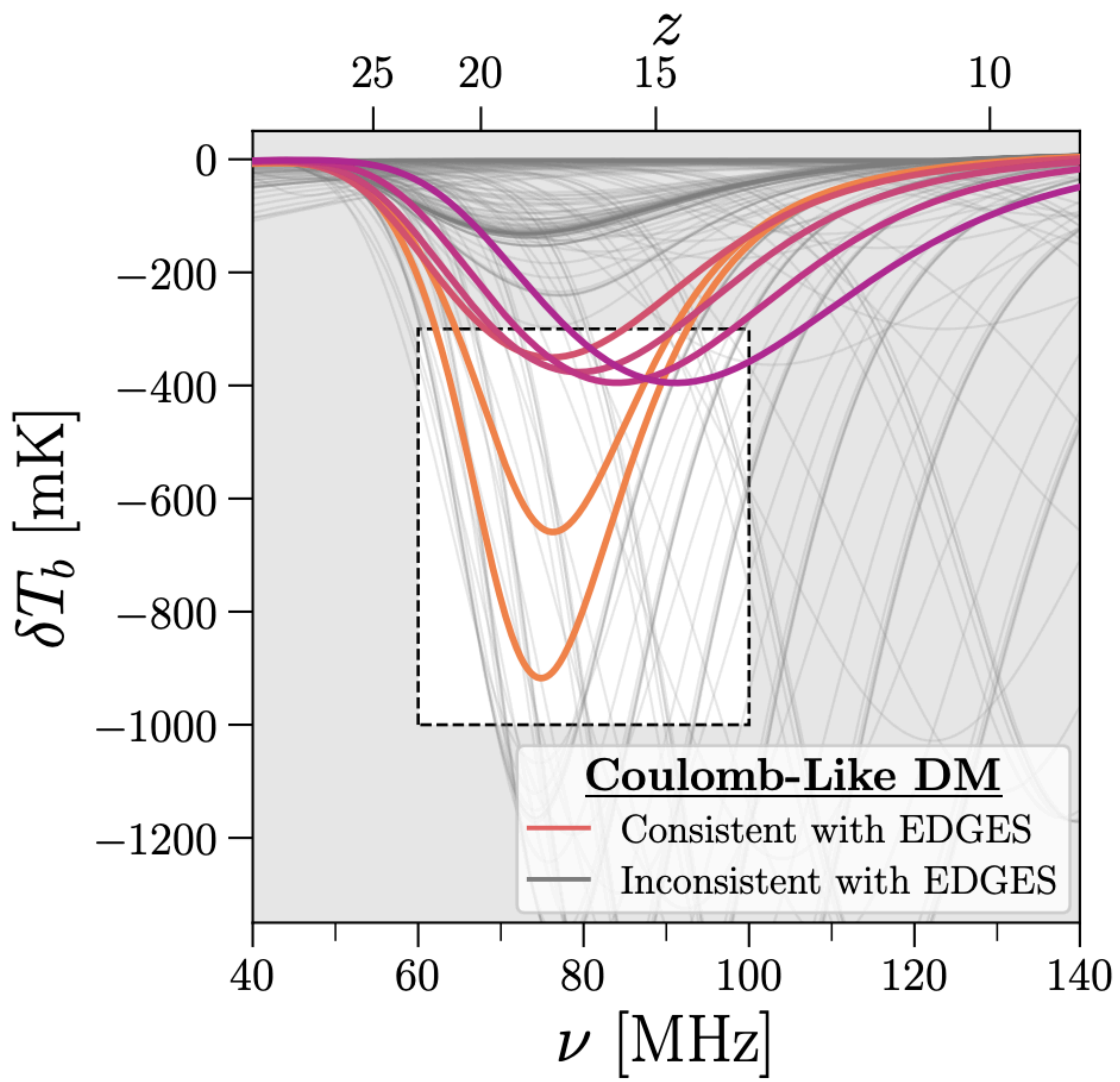
Matter Power Suppression



Driskell, Nadler, Mirocha, Benson, KB, Morton, Lashner, An, Gluscevic (PRD 2022)

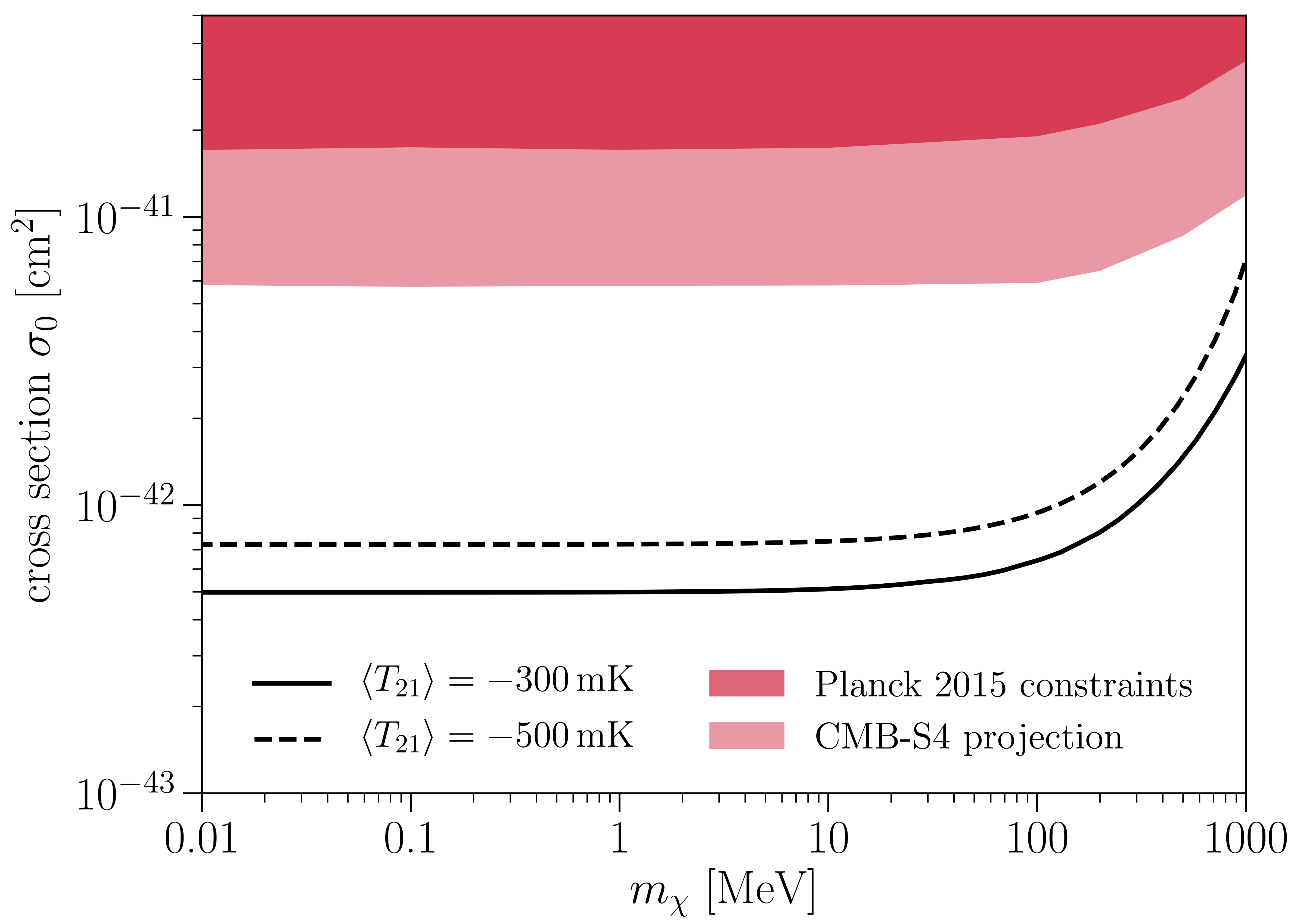
Impact on 21cm Signal





Driskell, Nadler, Mirocha, Benson, KB, Morton, Lashner, An, Gluscevic (PRD 2022)

CMB Constraints



- T_{21} lines assume all DM interacts, but neglects suppression of matter power spectrum

Driskell, Mirocha, Morton, Gluscevic, KB, Benson, Nadler (PRD 2022)

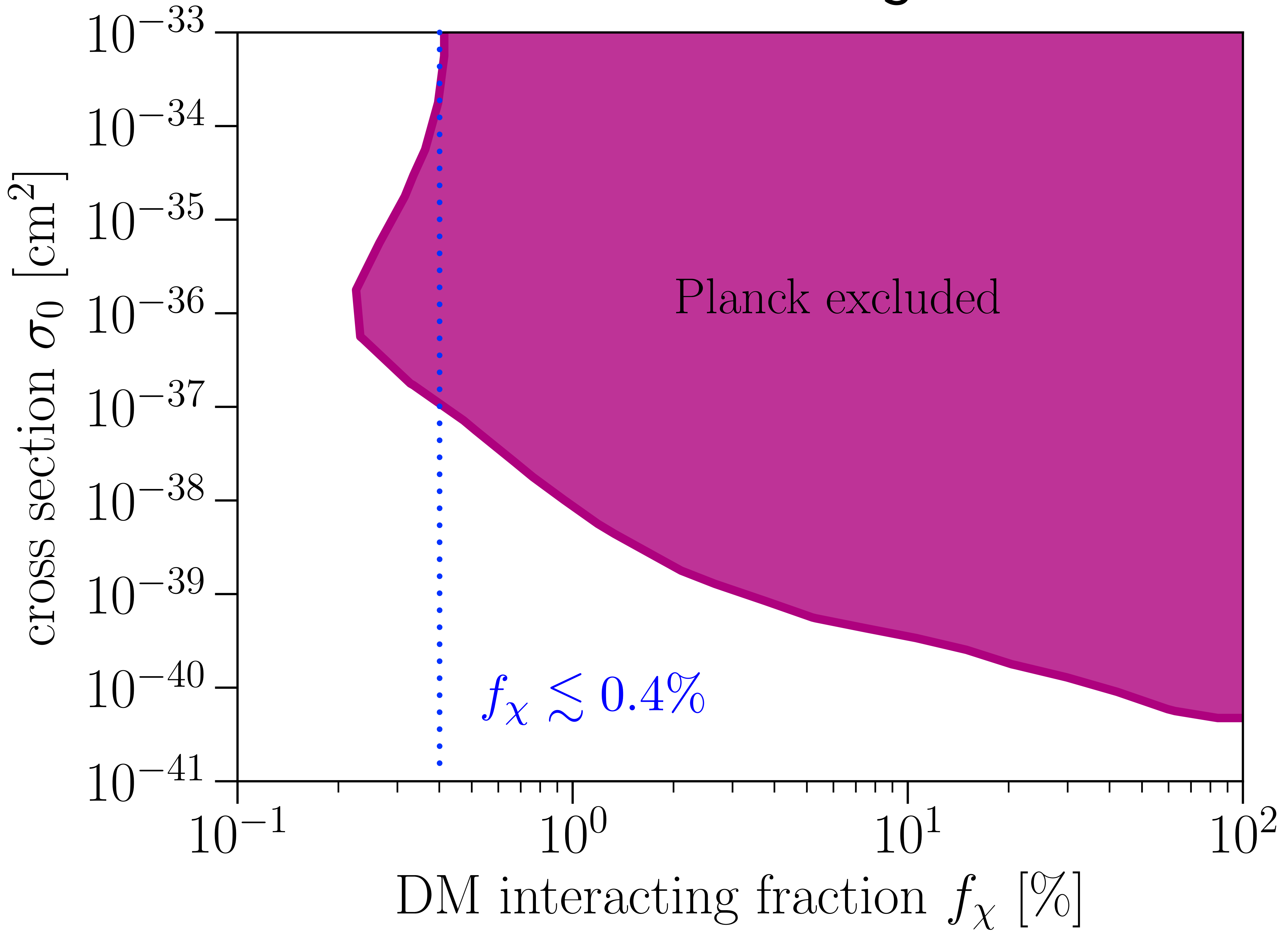
- DM-H vs DM-ion scattering?
  - DM-H scattering highly constrained
  - DM-ion scattering suffers from low x_e, so need larger σ_0 than allowed by CMB
- Allow only fraction of DM to interact

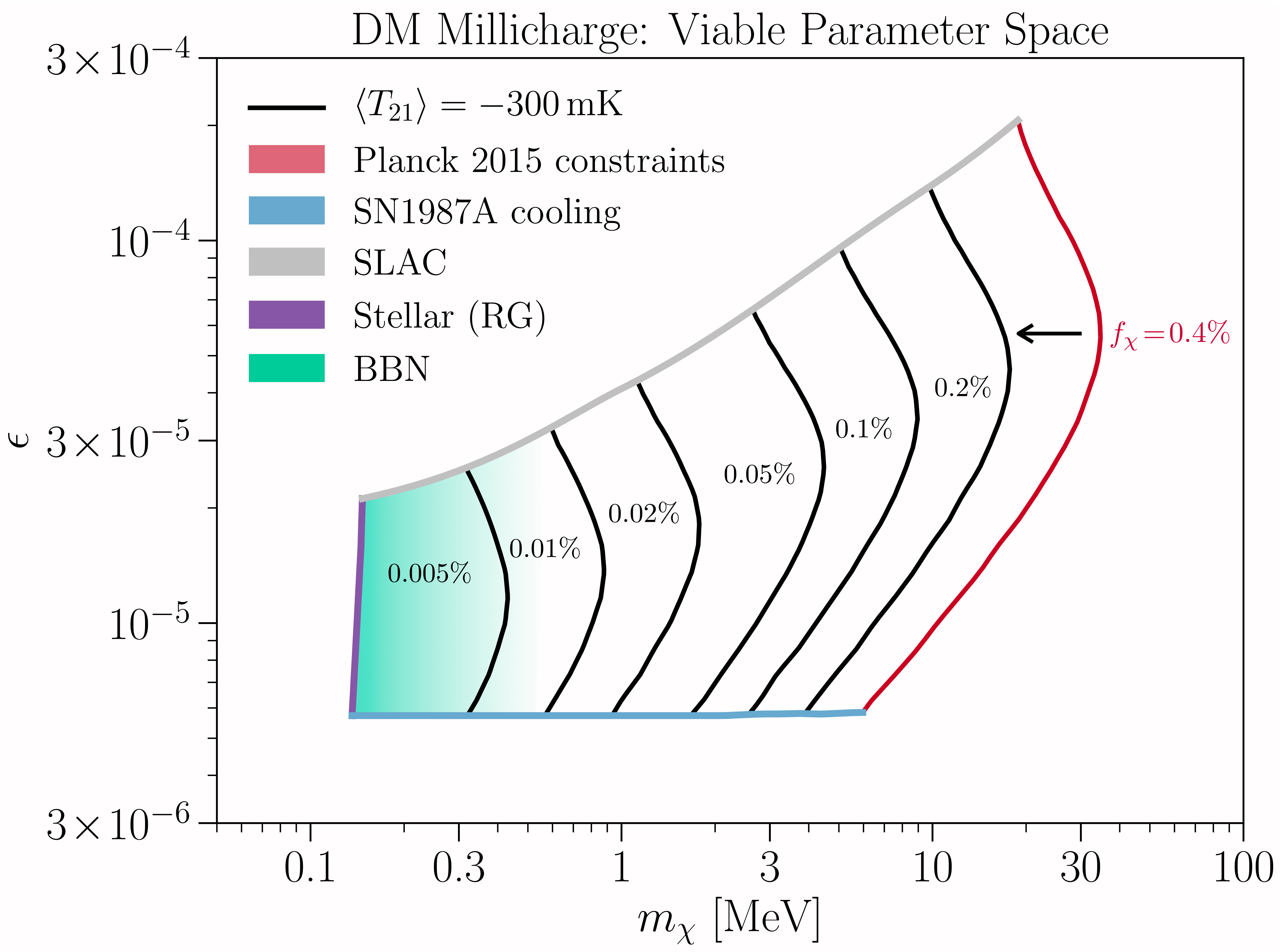
Muñoz, Loeb (2018)
Berlin, Hooper, Krnjaic, McDermott (2018)
Barkana, Outmezguine, Redigolo, Volansky (2018)

KB, Gluscevic, Poulin, Kovetz, Kamionkowski, Barkana (PRD 2018)
Kovetz, Poulin, Gluscevic, KB, Barkana, Kamionkowski (PRD 2018)

Millicharged Dark Matter

Planck loses sensitivity to small fractions of millicharged DM



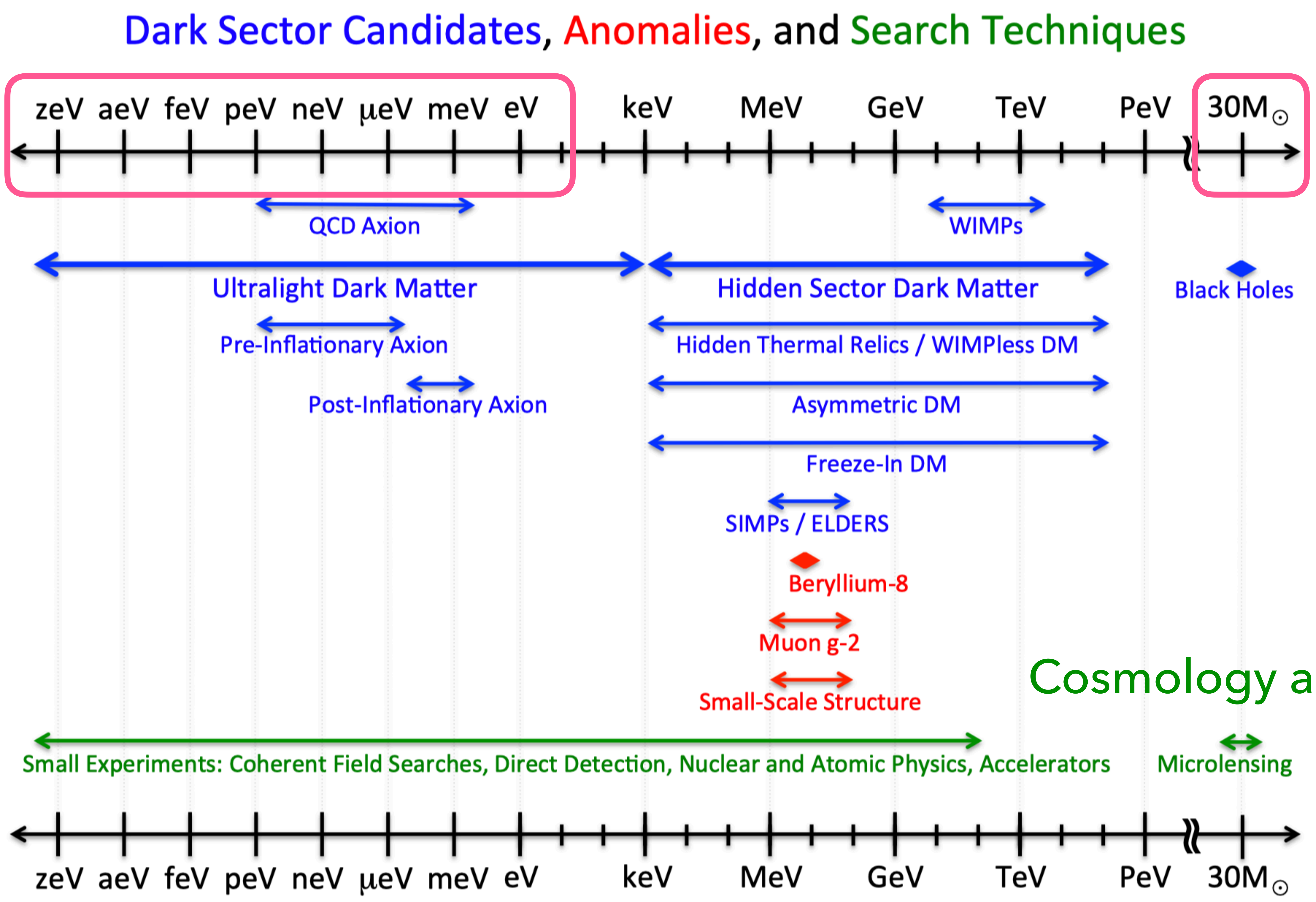


KB, Gluscevic, Poulin, Kovetz, Kamionkowski, Barkana (PRD 2018)
see also de Putter+ (PRL 2018)

Kovetz, Poulin, Gluscevic, KB, Barkana, Kamionkowski (PRD 2018)

Mass Range of Possibilities

"wave-like" ultralight boson, axion, ALP



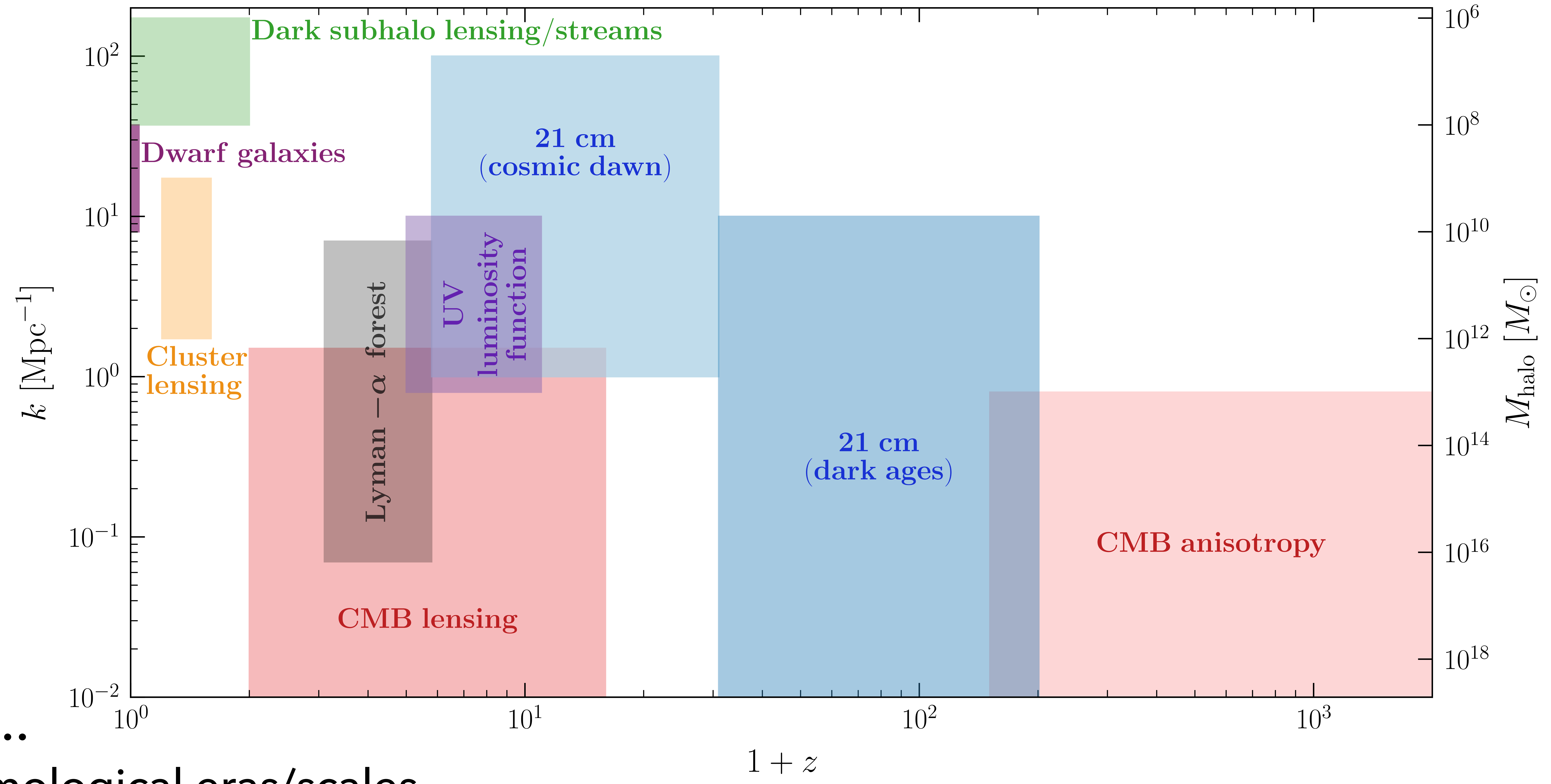
primordial black holes

Cosmology and Astrophysics

US Cosmic Visions: New Ideas in Dark Matter (1707.04591)

Outlook

Still plenty of work to do!



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

Different observables…

- probe different cosmological eras/scales
- have different systematics
- are sensitive to different types of dark matter models