

*New Physics from Galaxy Clustering*  
*CERN, 21 November 2022*

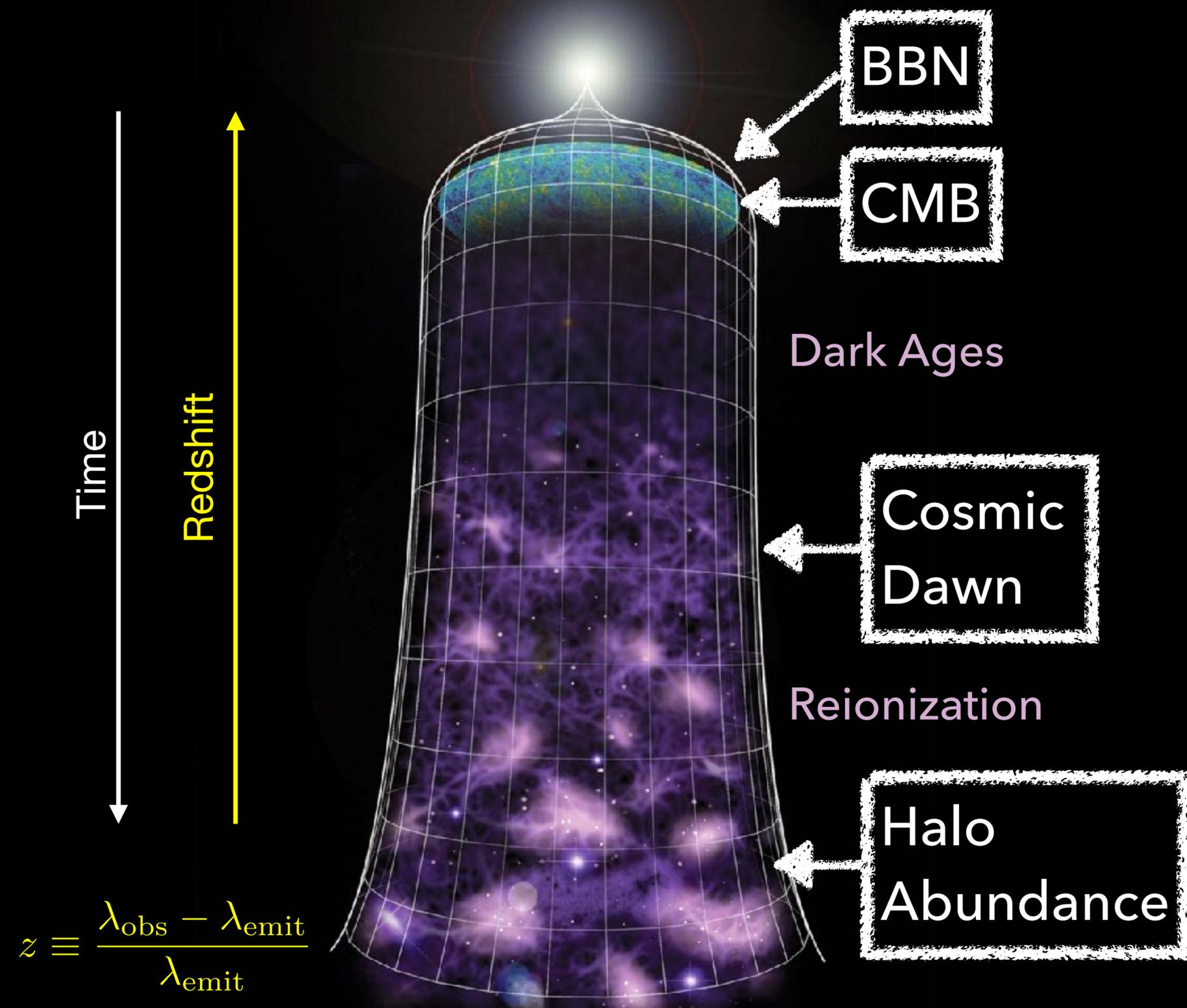
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# **CMB CONSTRAINTS ON DARK MATTER INTERACTIONS**

Kimberly Boddy  
University of Texas at Austin

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# Cosmic History



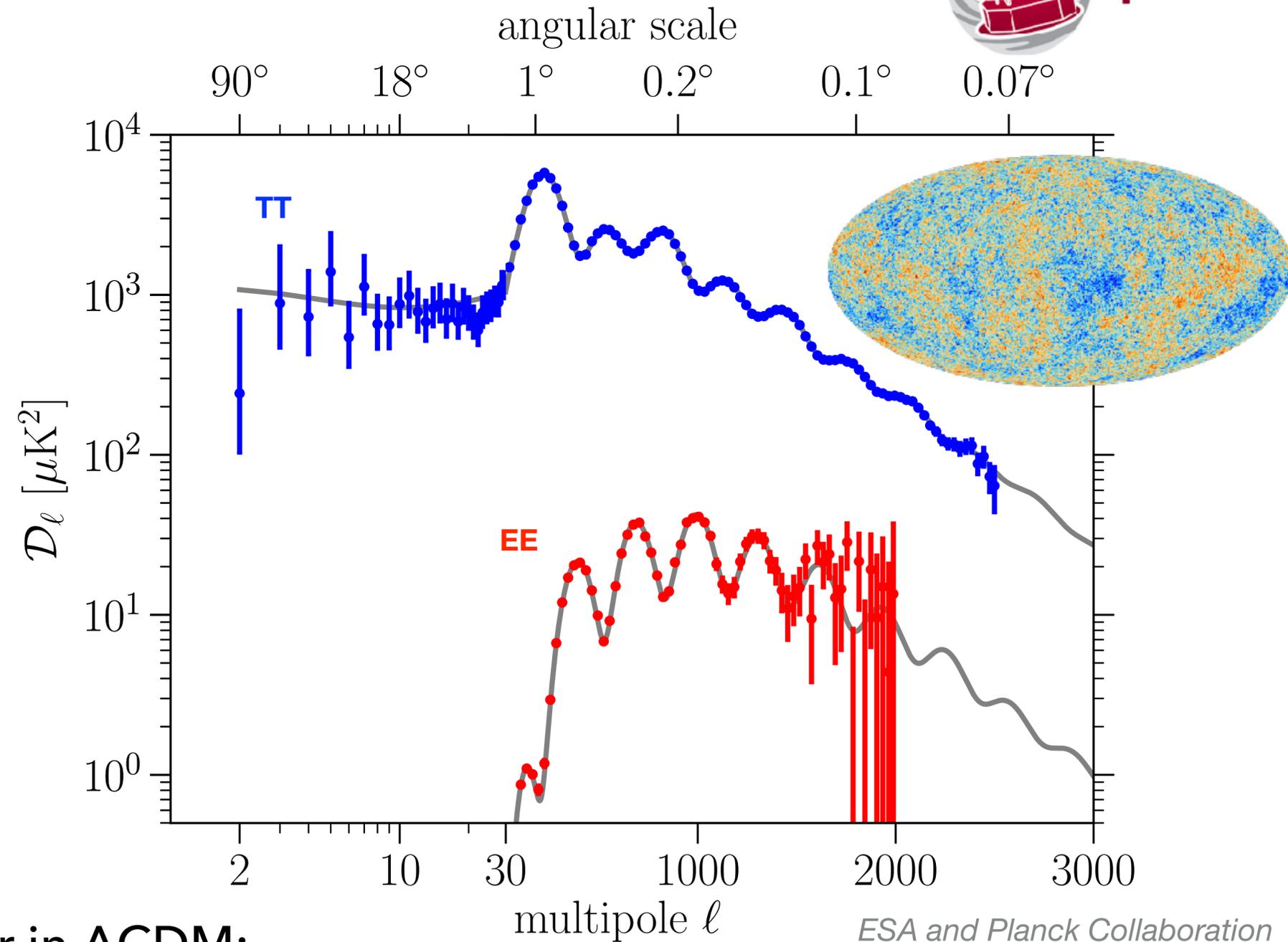
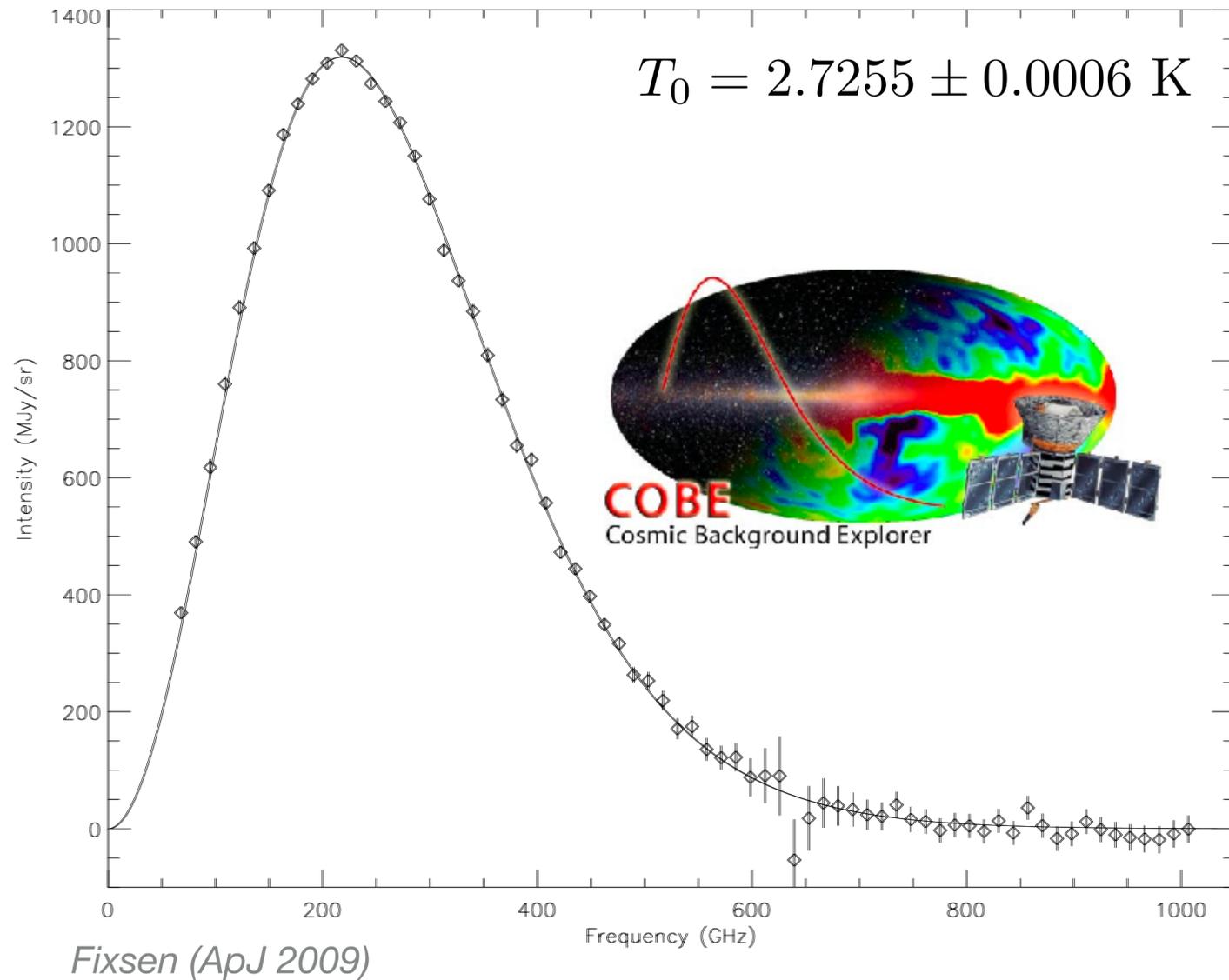
Dark matter interactions in 3 parts

- (1) Small-scale suppression
- (2) Energy injection
- (3) IGM cooling

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Dark matter scattering  
suppresses small-scale structure formation

# Cosmic Microwave Background



Dark matter in  $\Lambda$ CDM:

- ◆ cold, collisionless

- ◆ ~6x more abundant than baryons

“baryons” = protons + helium + electrons

# Dark Matter Scattering

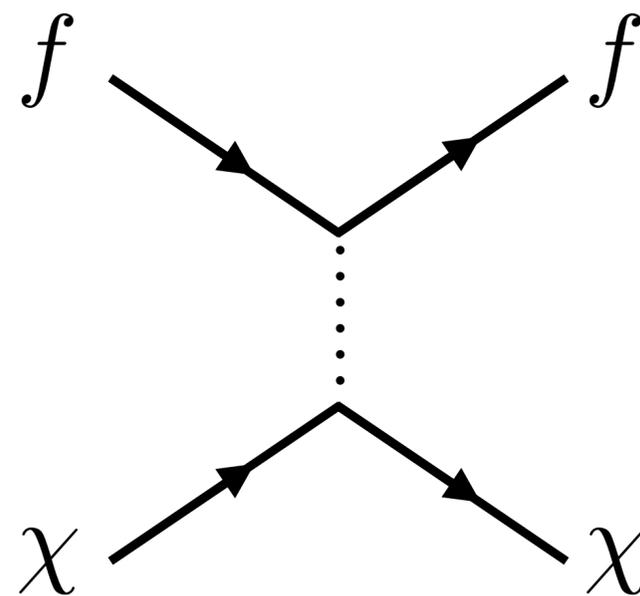
$$\sigma_{MT}(v) = \int (1 - \cos \theta) \frac{d\sigma}{d\Omega} d\Omega = \sigma_0 v^n$$

## Heavy mediator

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

## Light mediator

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



To be as model-independent as possible,  
decouple effects of annihilation and scattering

$f$  in early Universe:  $e^-, p, \text{He}$

see Boddy and Gluscevic (PRD 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

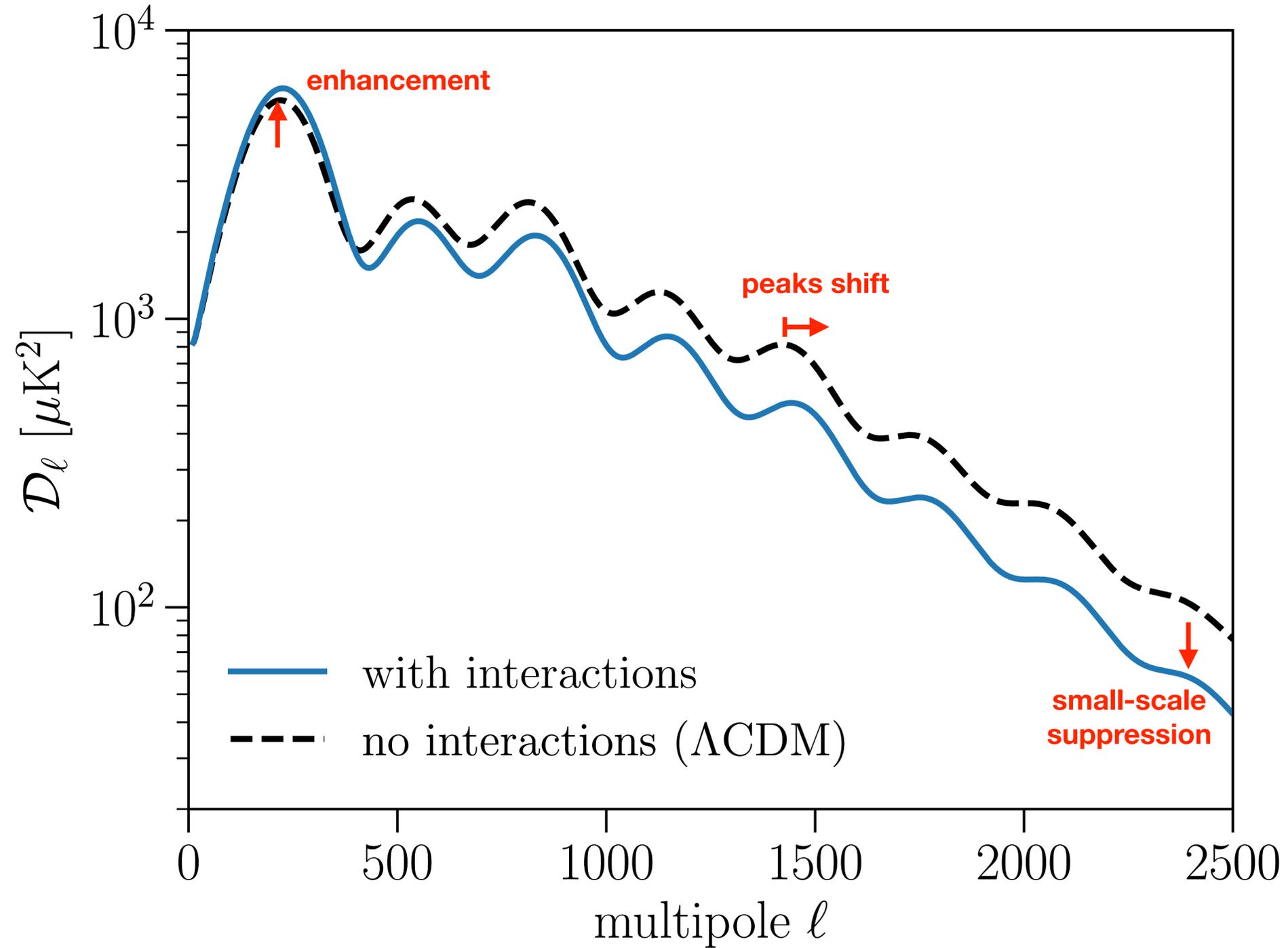
*see Ali-Haïmoud (PRD 2019); Gandhi, Ali-Haïmoud (PRD 2022) for Fokker-Planck analysis*

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

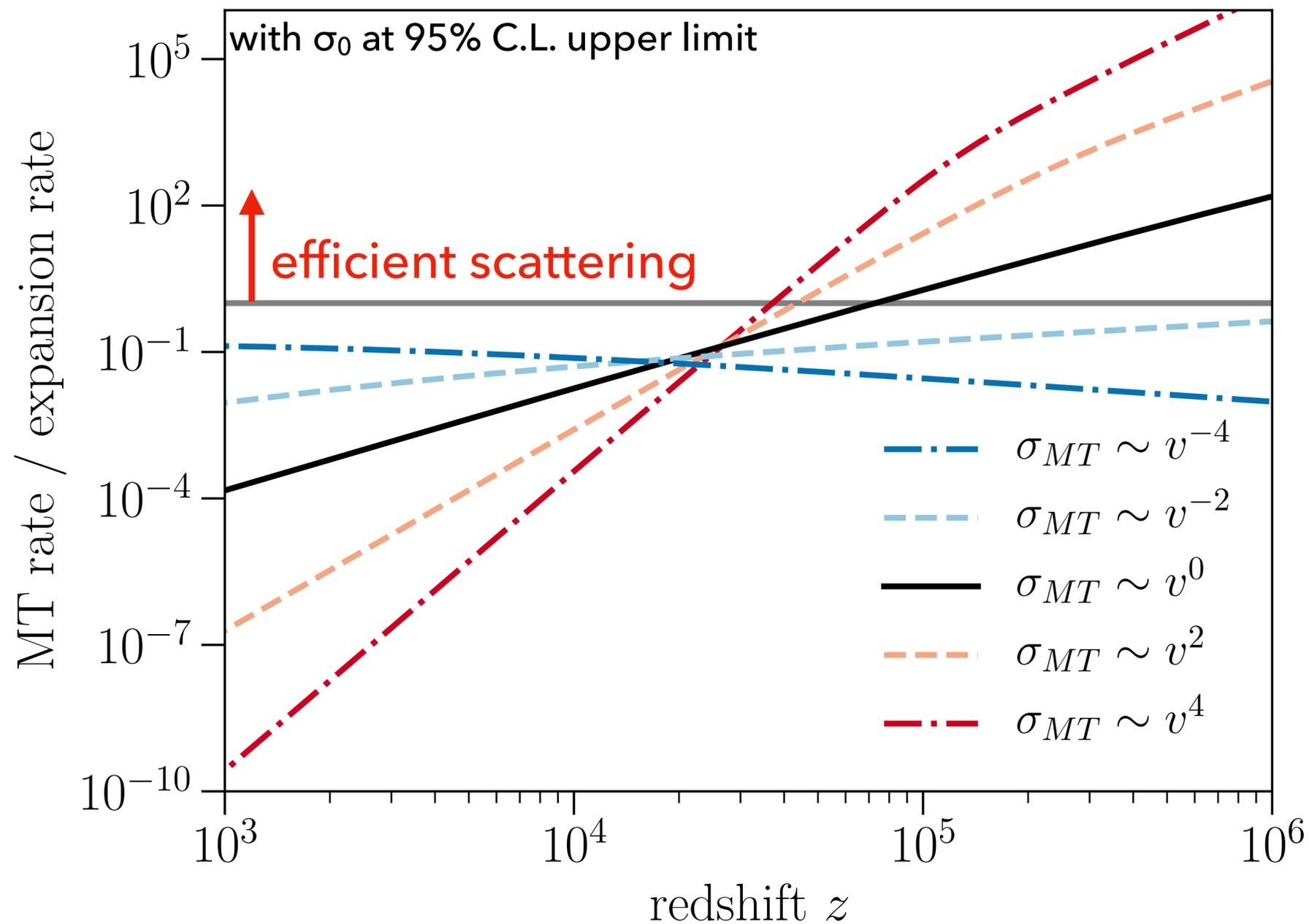
# Effects of Dark Matter Scattering



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

# Momentum Transfer

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

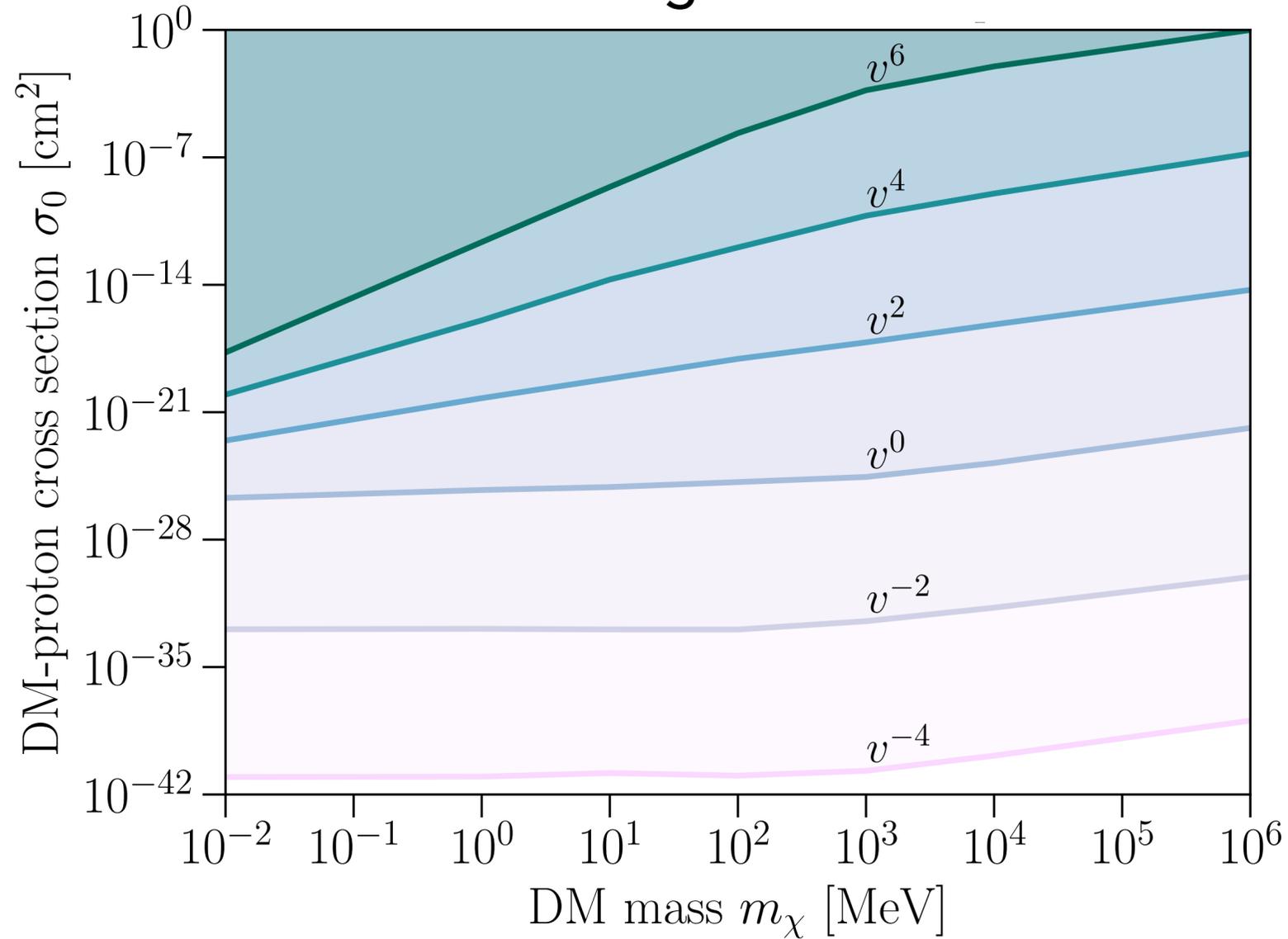


for  $n \geq 0$ : KB, Gluscevic (PRD 2018); Gluscevic, KB (PRL 2018)

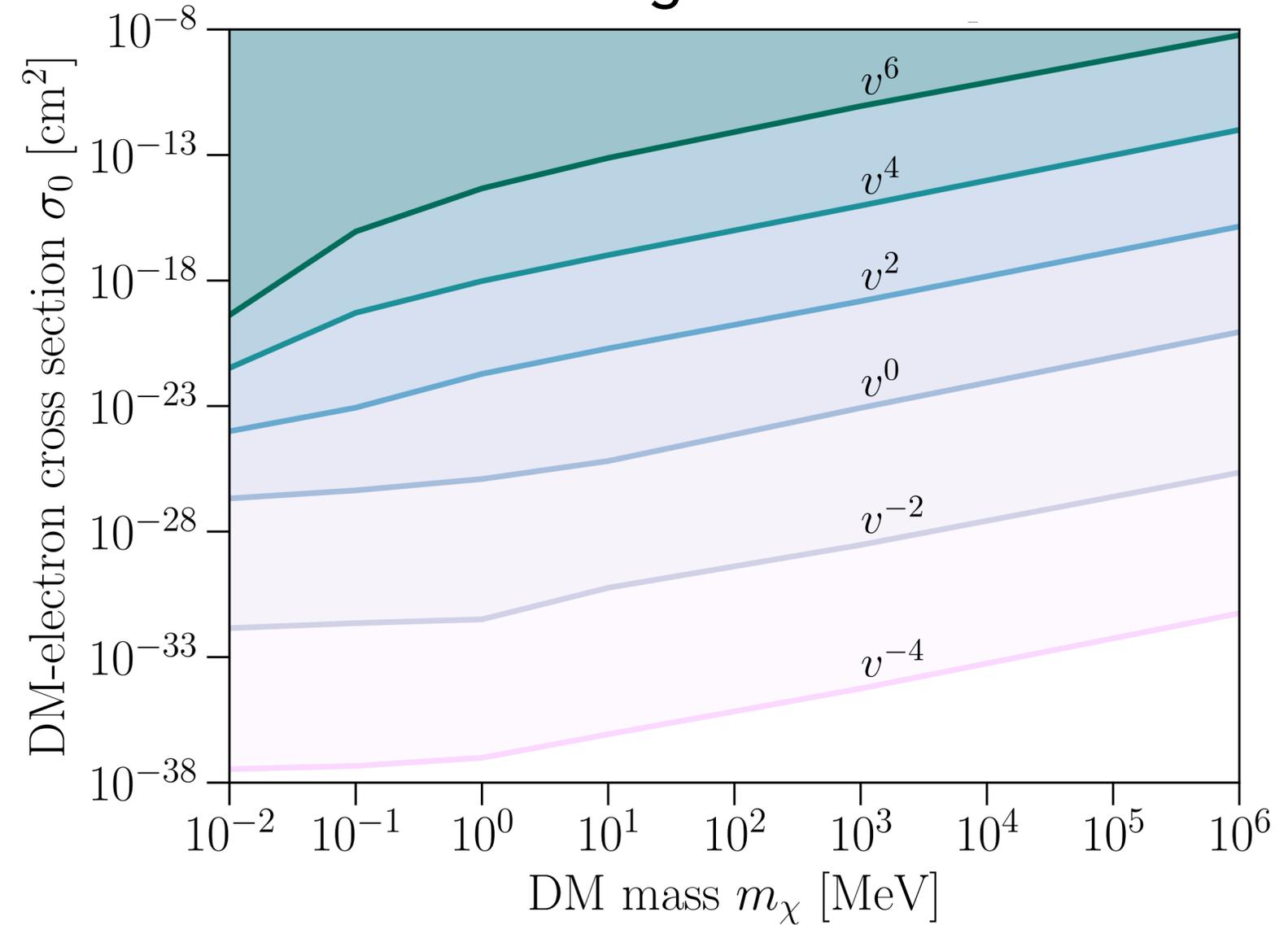
for  $n < 0$ : KB, Gluscevic, Poulin, Kovetz, Kamionkowski, Barkana (PRD 2018)

# CMB Constraints

## Scattering with Protons

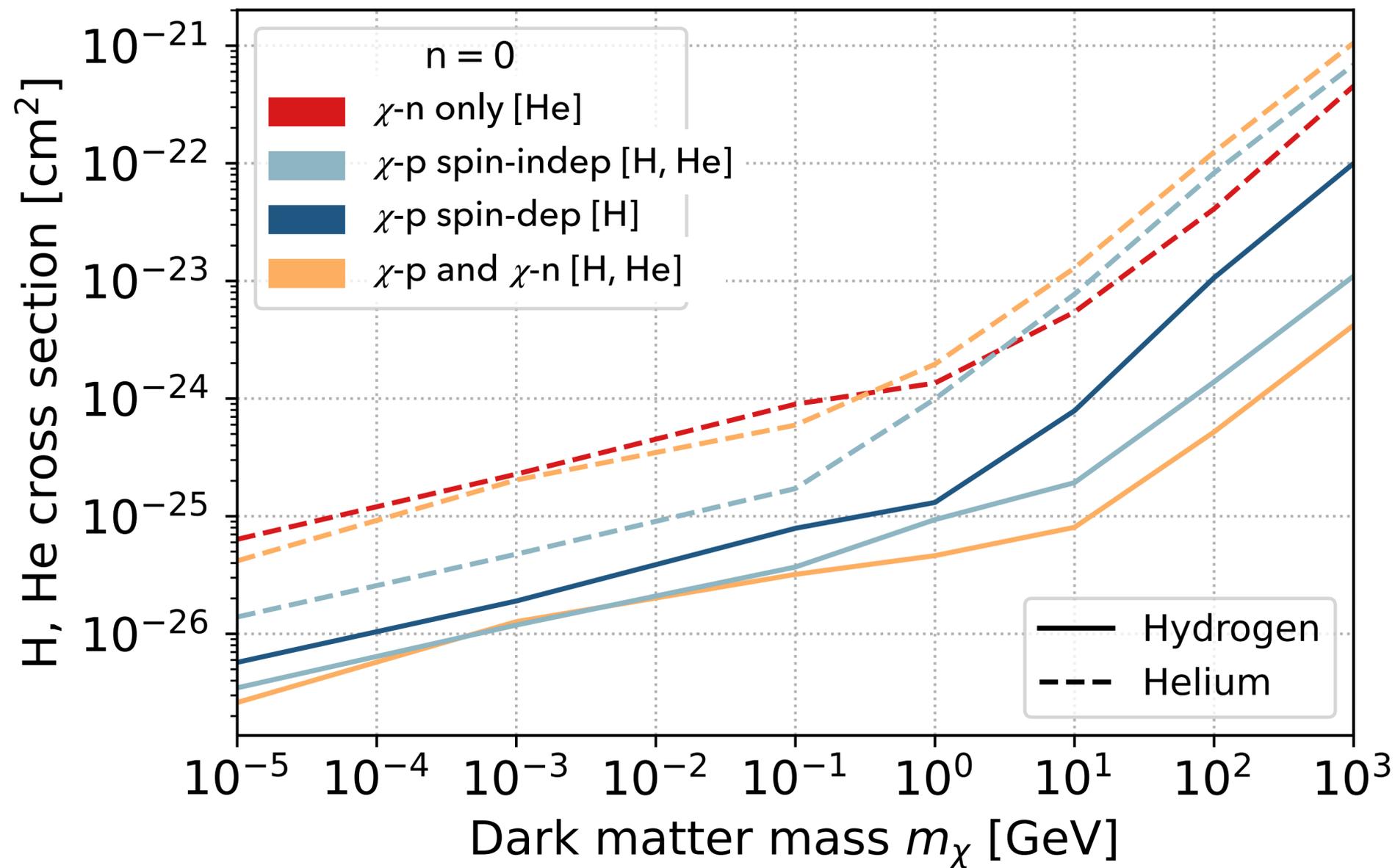


## Scattering with Electrons



using *Planck* 2018 temperature, polarization, lensing  
varying 6 standard  $\Lambda$ CDM parameters +  $\sigma_0$  @ fixed  $m_\chi$

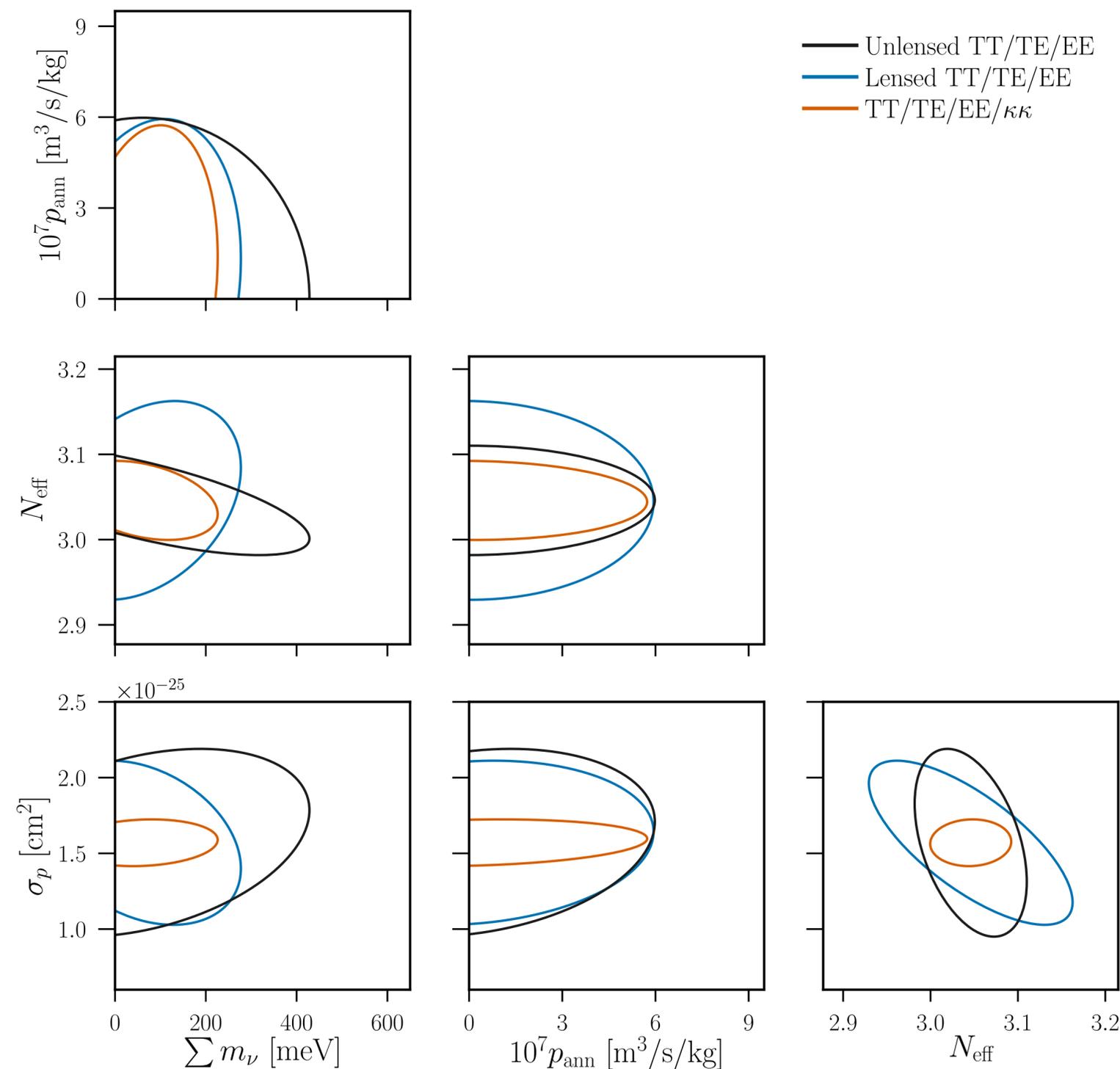
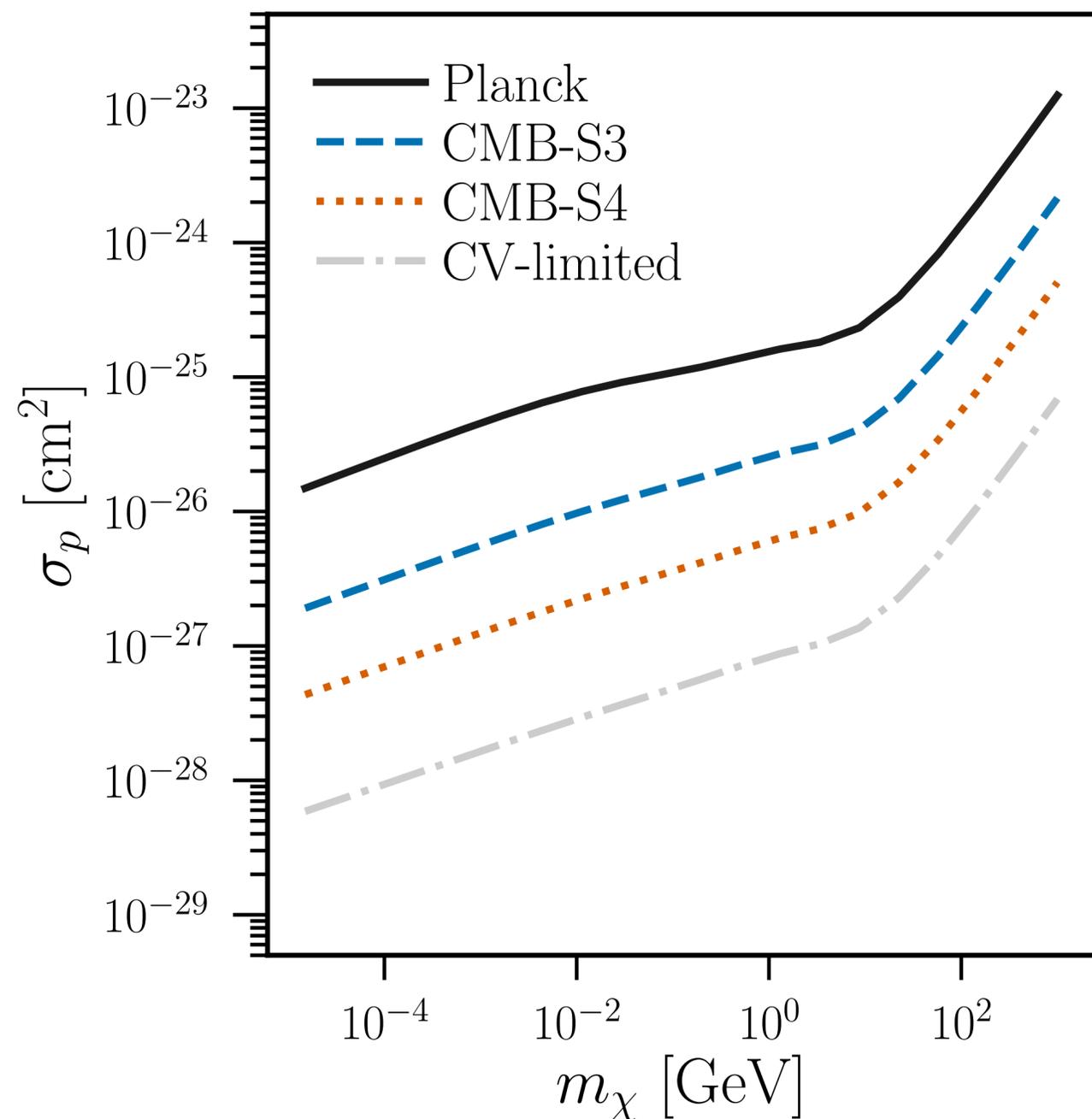
# CMB Constraints: Scattering with Helium



Incorporating helium scattering is model-dependent, but important for large DM mass and  $n \geq 0$

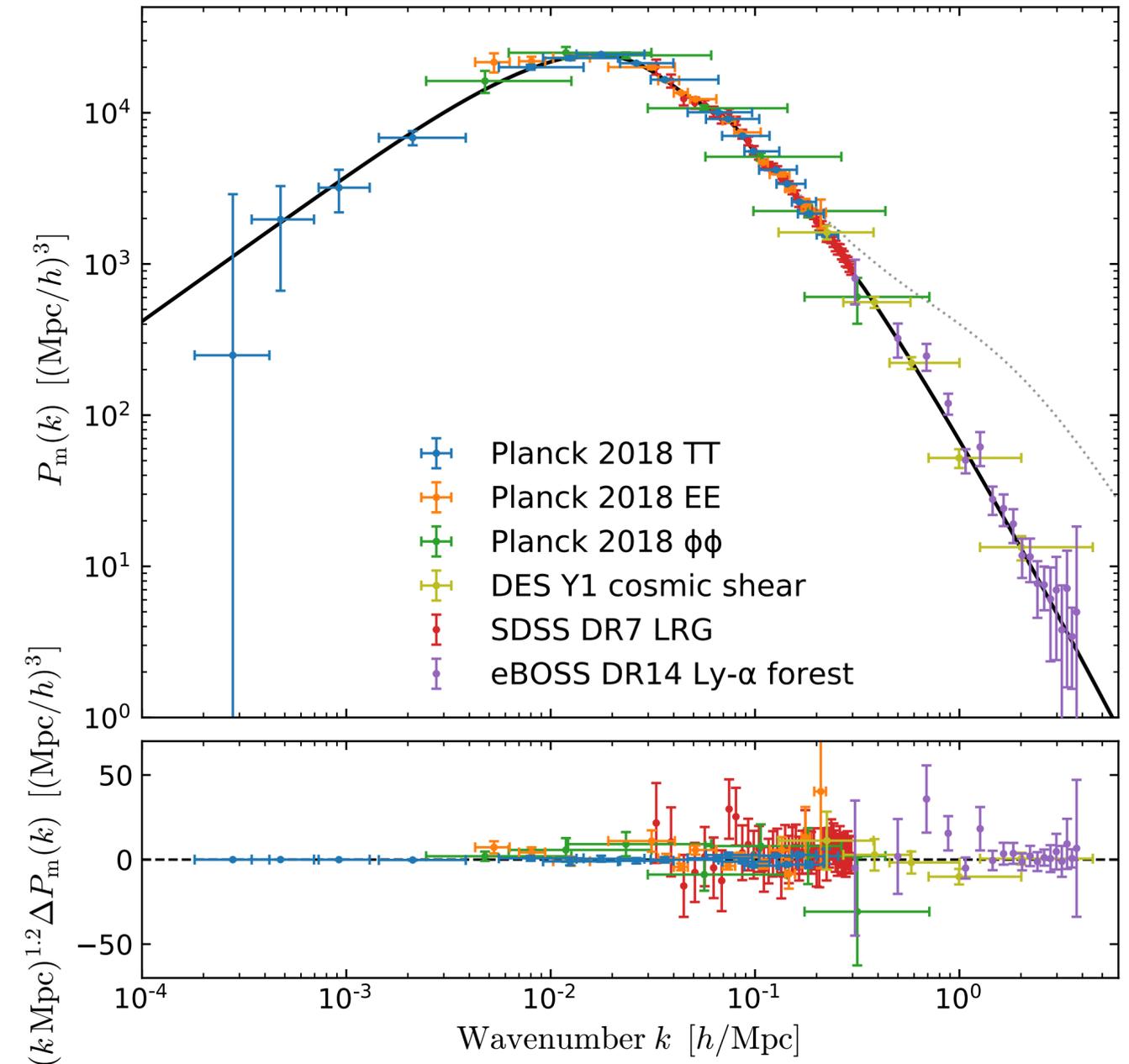
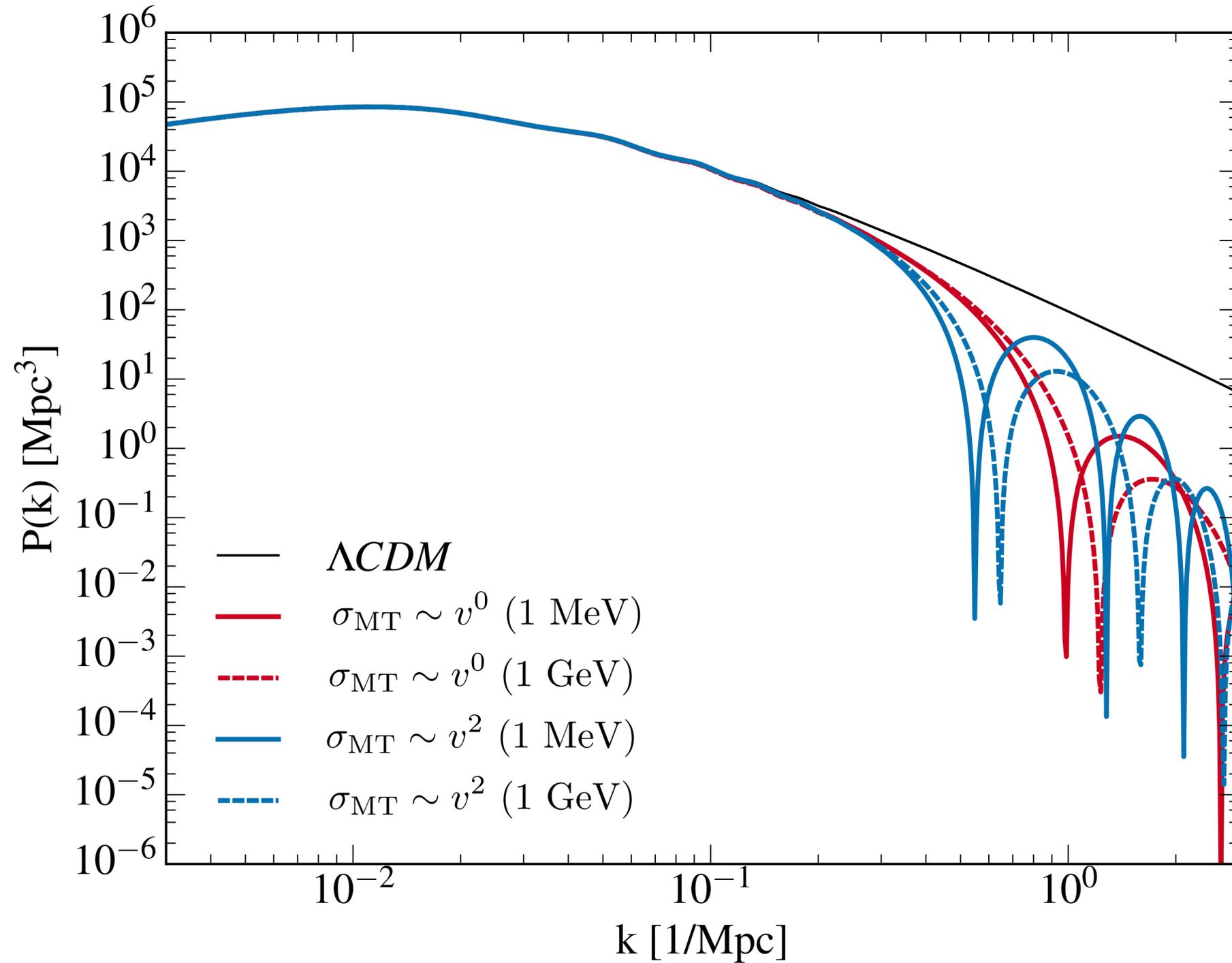
DM may preferentially interact with neutrons, rather than protons  
 $\Rightarrow$  scattering with He, not H

# CMB Projections: Scattering with Protons ( $n=0$ )

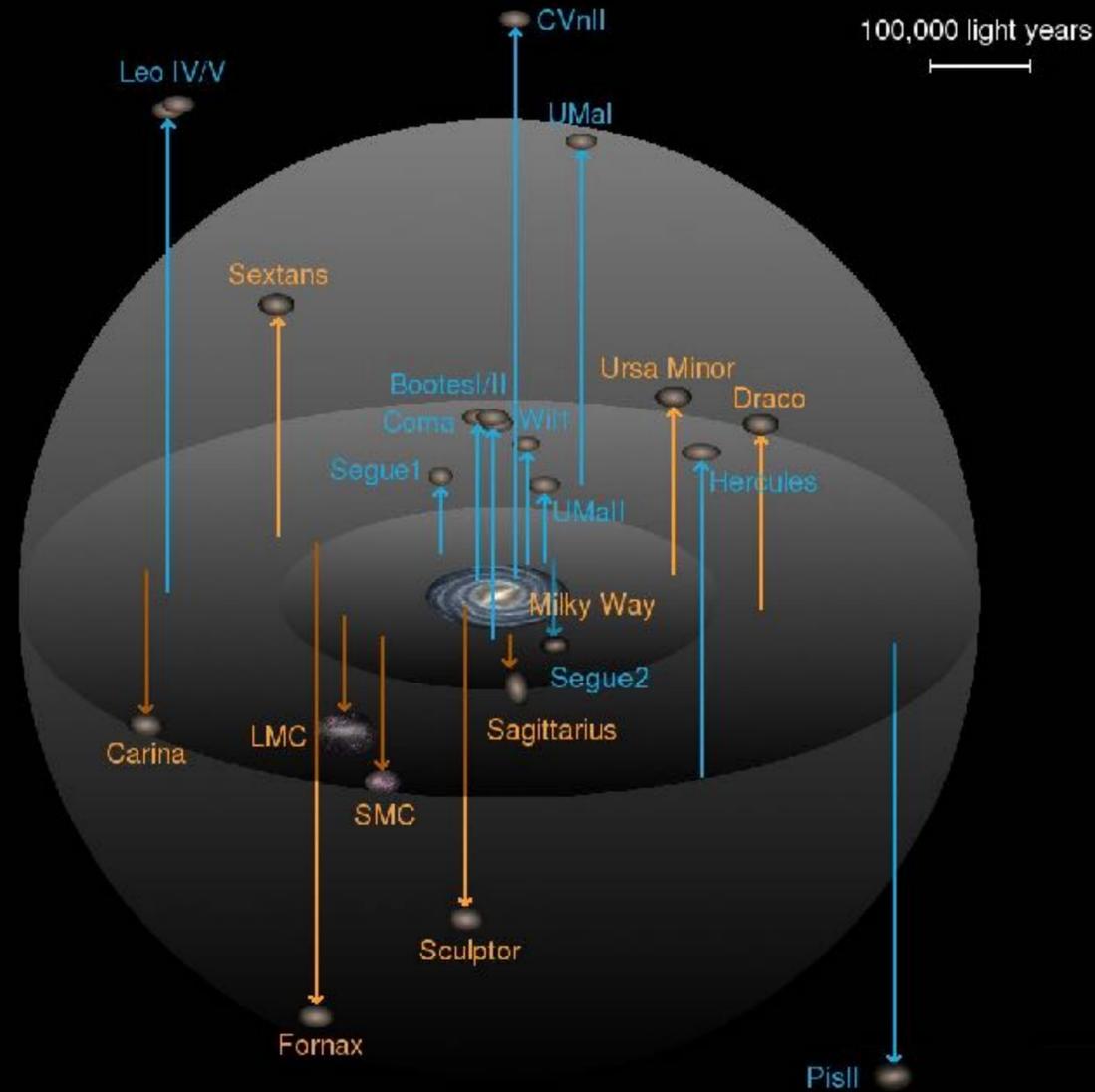


Li, Gluscevic, KB, Madhavacheril (PRD 2018)  
 WIP with Gluscevic to make projections for other values of  $n$

# Matter Power Spectrum



# Milky Way Satellites

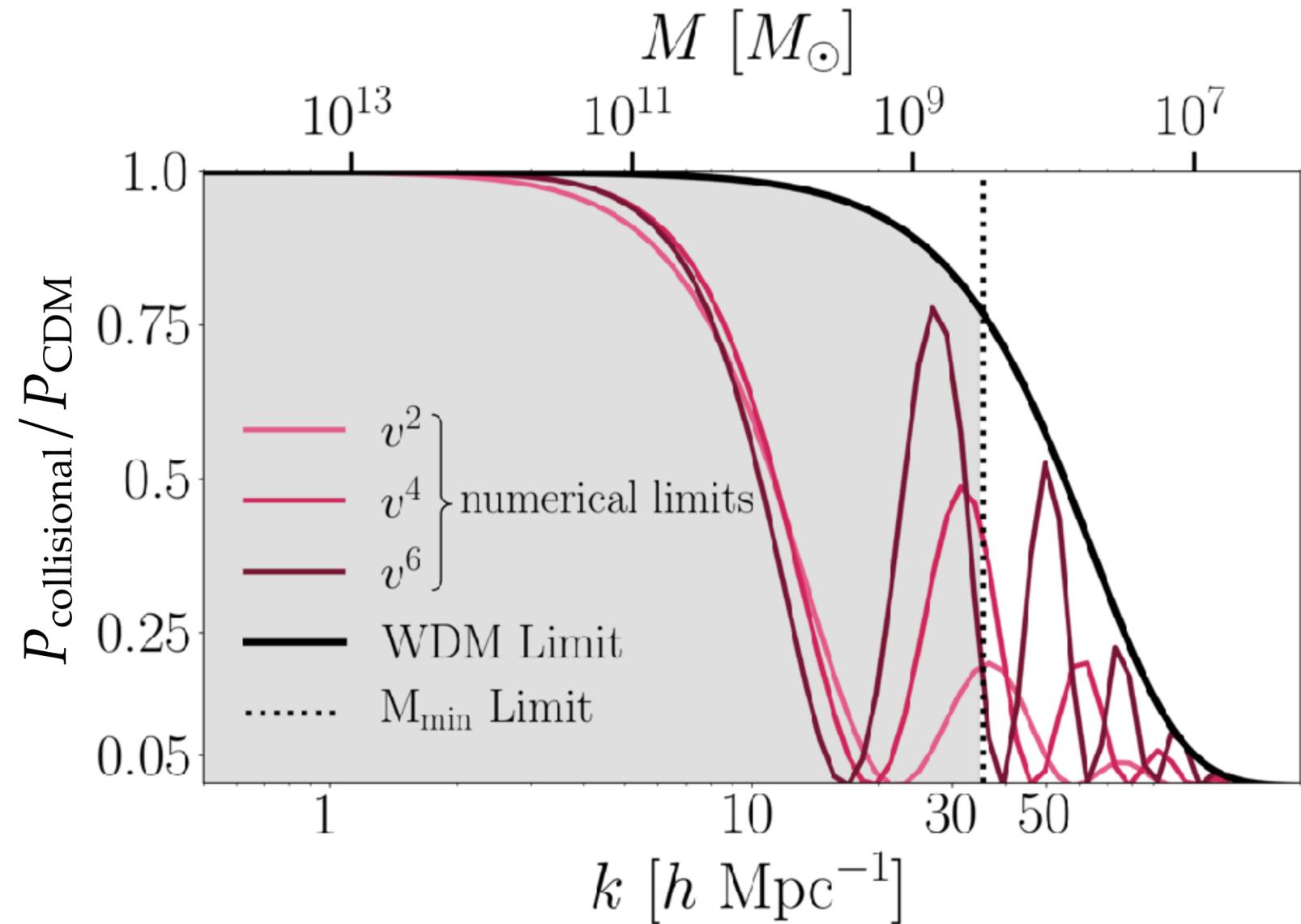
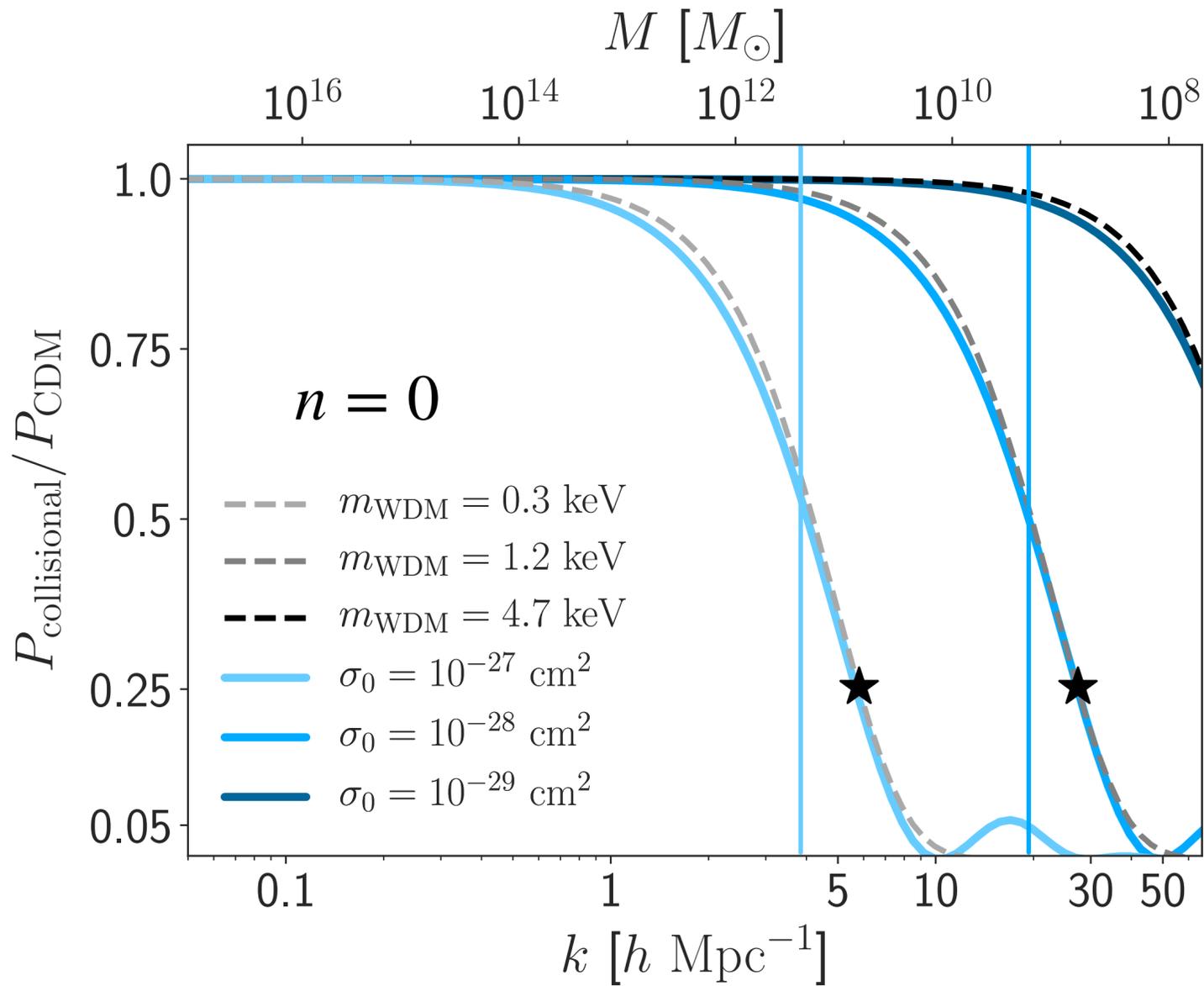


**DES and Pan-STARRS1  
identified dwarfs**

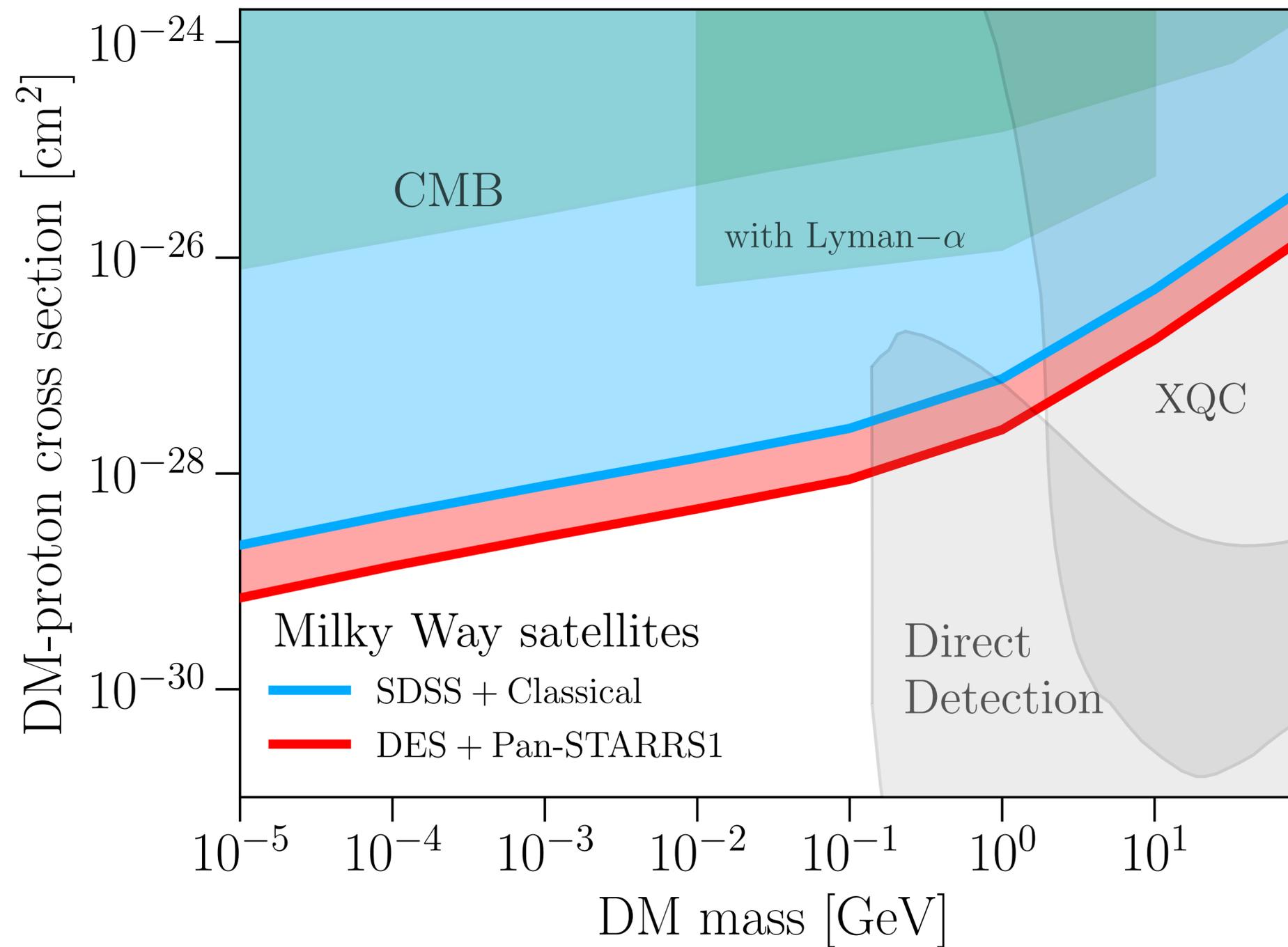


**Classic dwarfs**  
**SDSS-identified dwarfs**

# Suppression of (Linear) Matter Power Spectrum

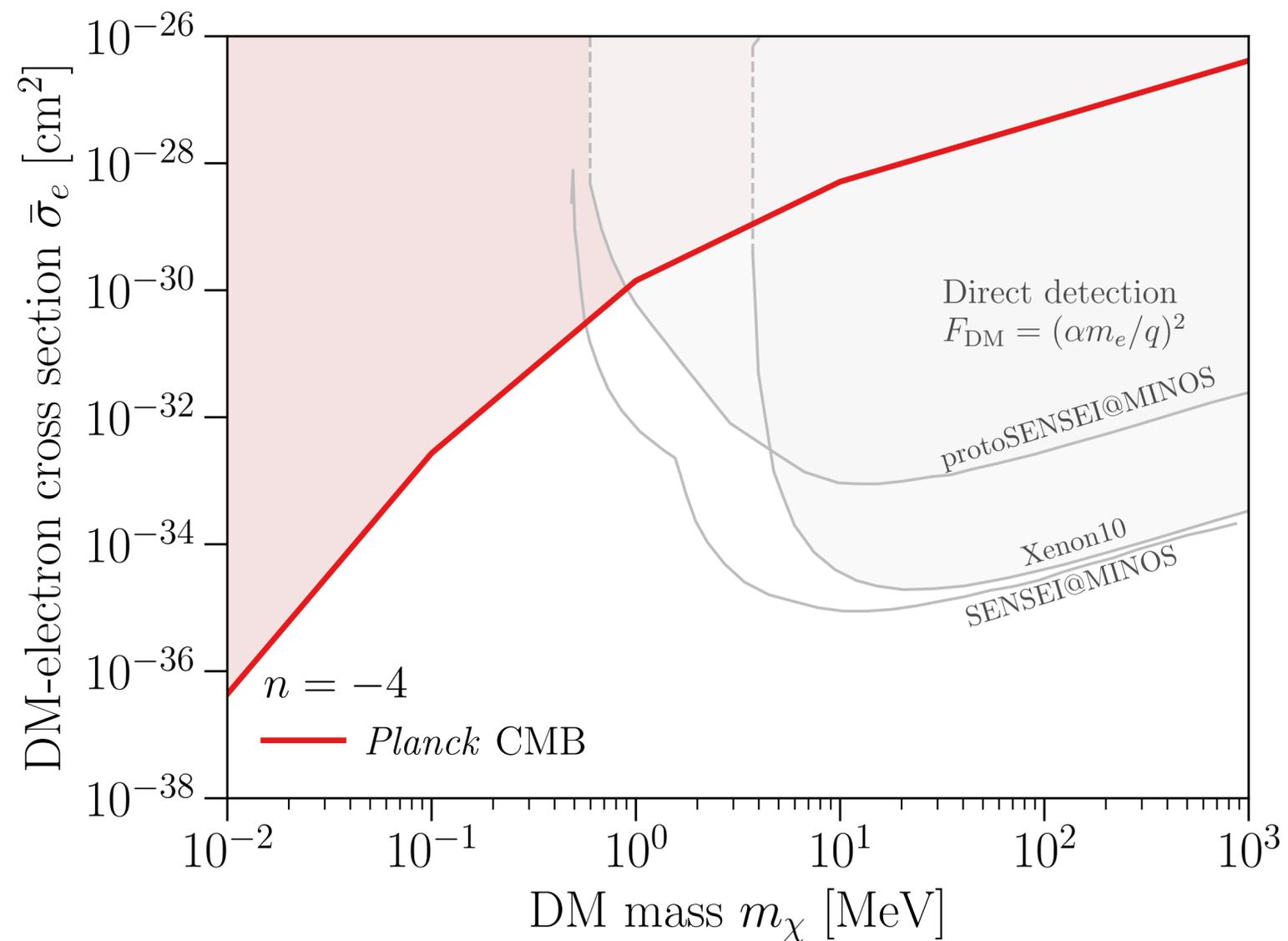
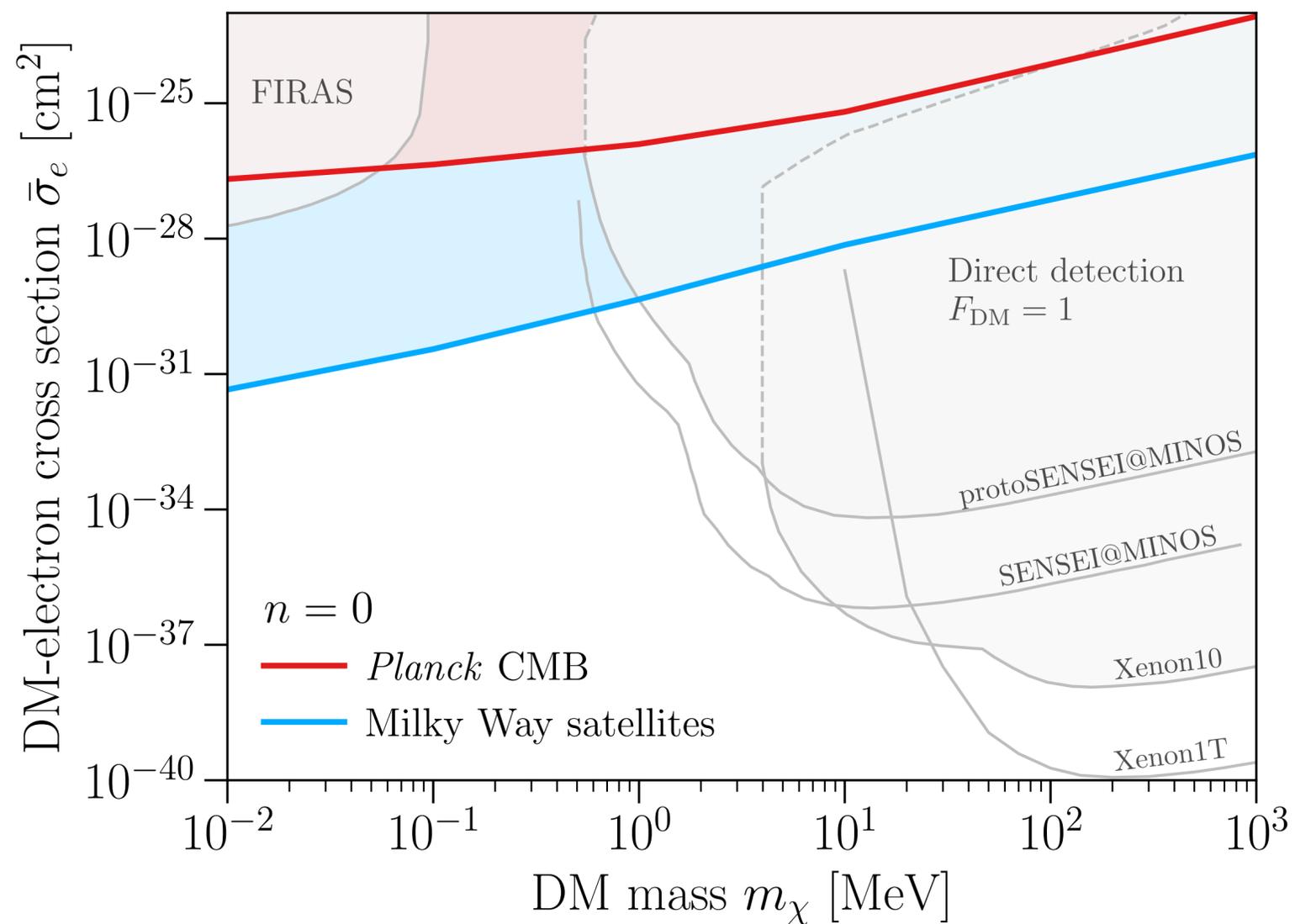


# Constraints: Scattering with Protons (n=0)



see also Rogers+ (PRL 2021) and Hooper+ (JCAP 2022) using Ly-alpha forest  
and Ali-Haimoud (PRD 2021) using spectral distortions

# Constraints: Scattering with Electrons



Nguyen, Sarnaik, KB, Nadler, Gluscevic (PRD 2021)  
see also Buen-Abad+ (2021)

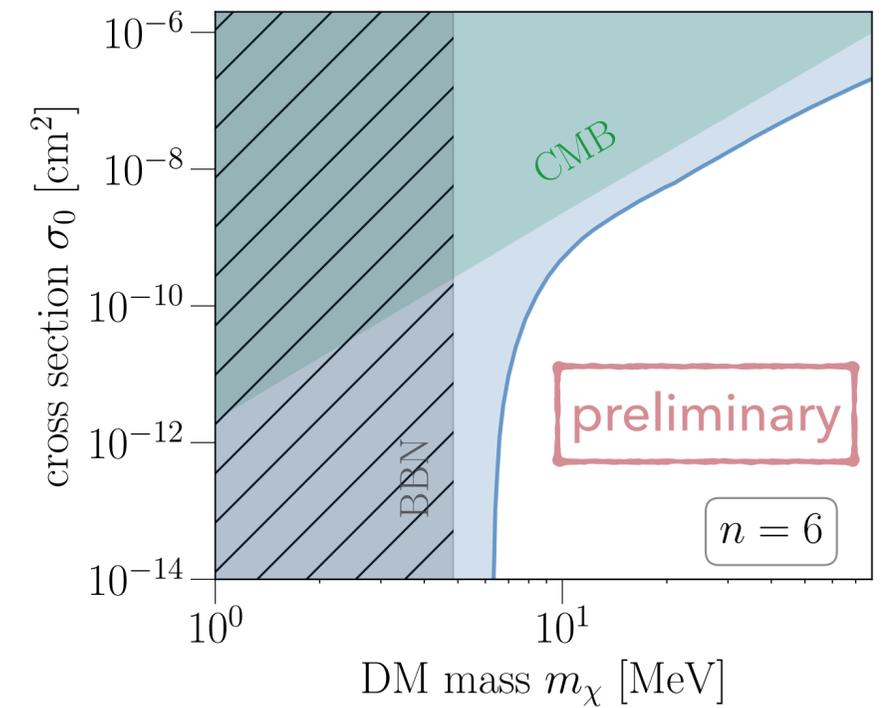
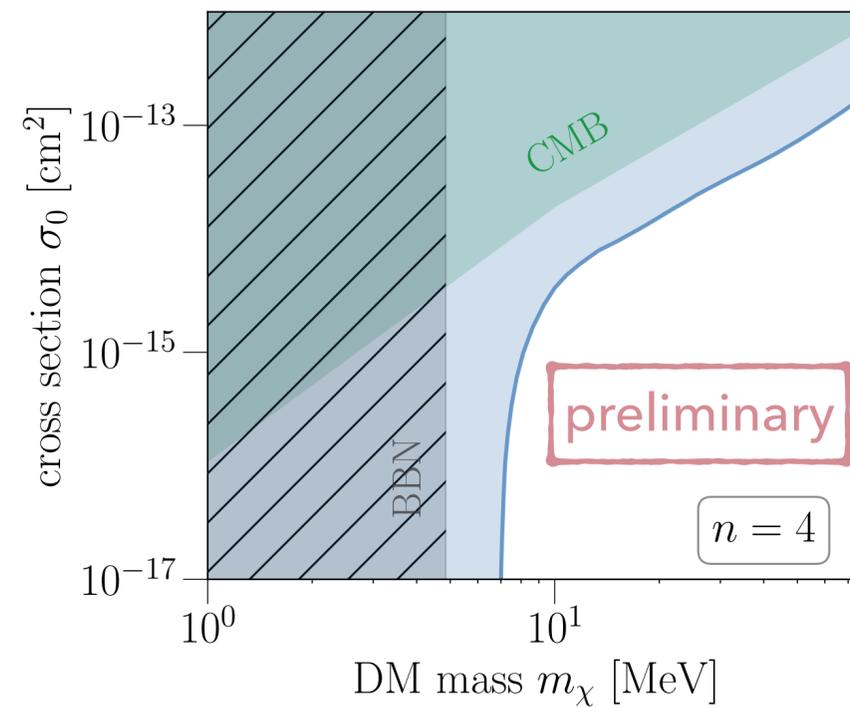
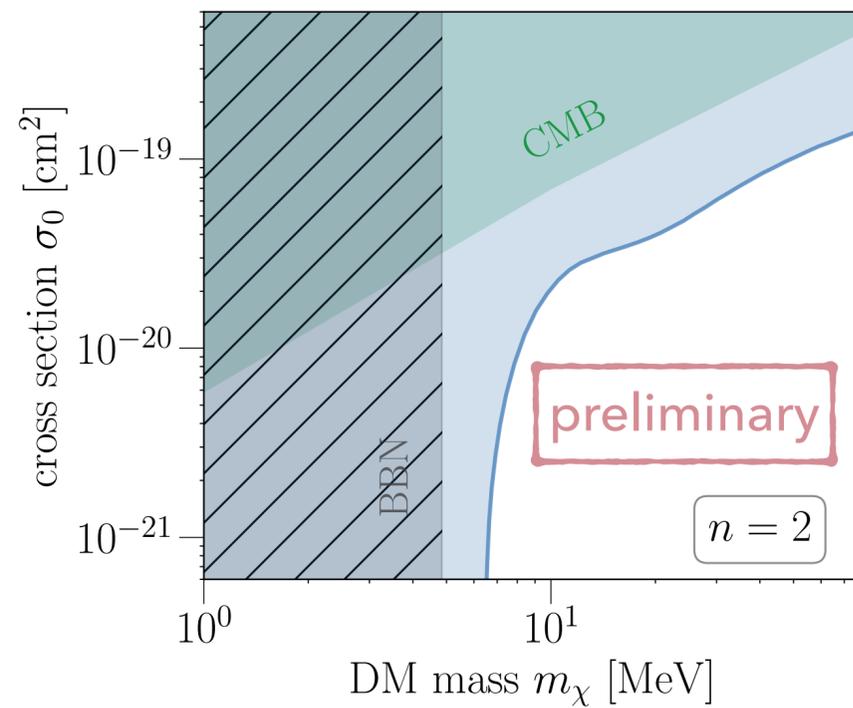
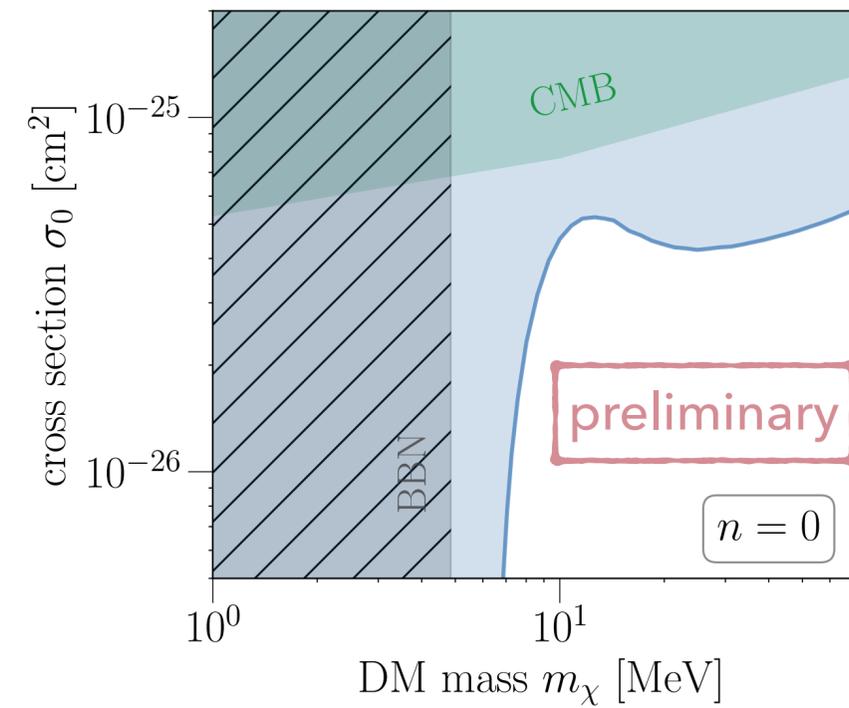
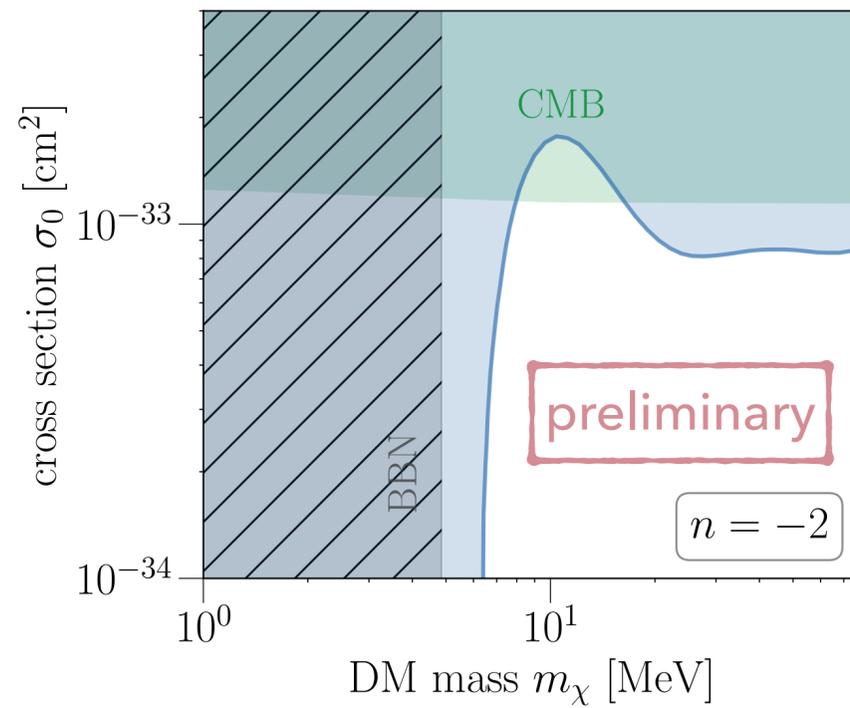
② Dark matter annihilation  
injects energy

# Effect of Energy Injection during BBN

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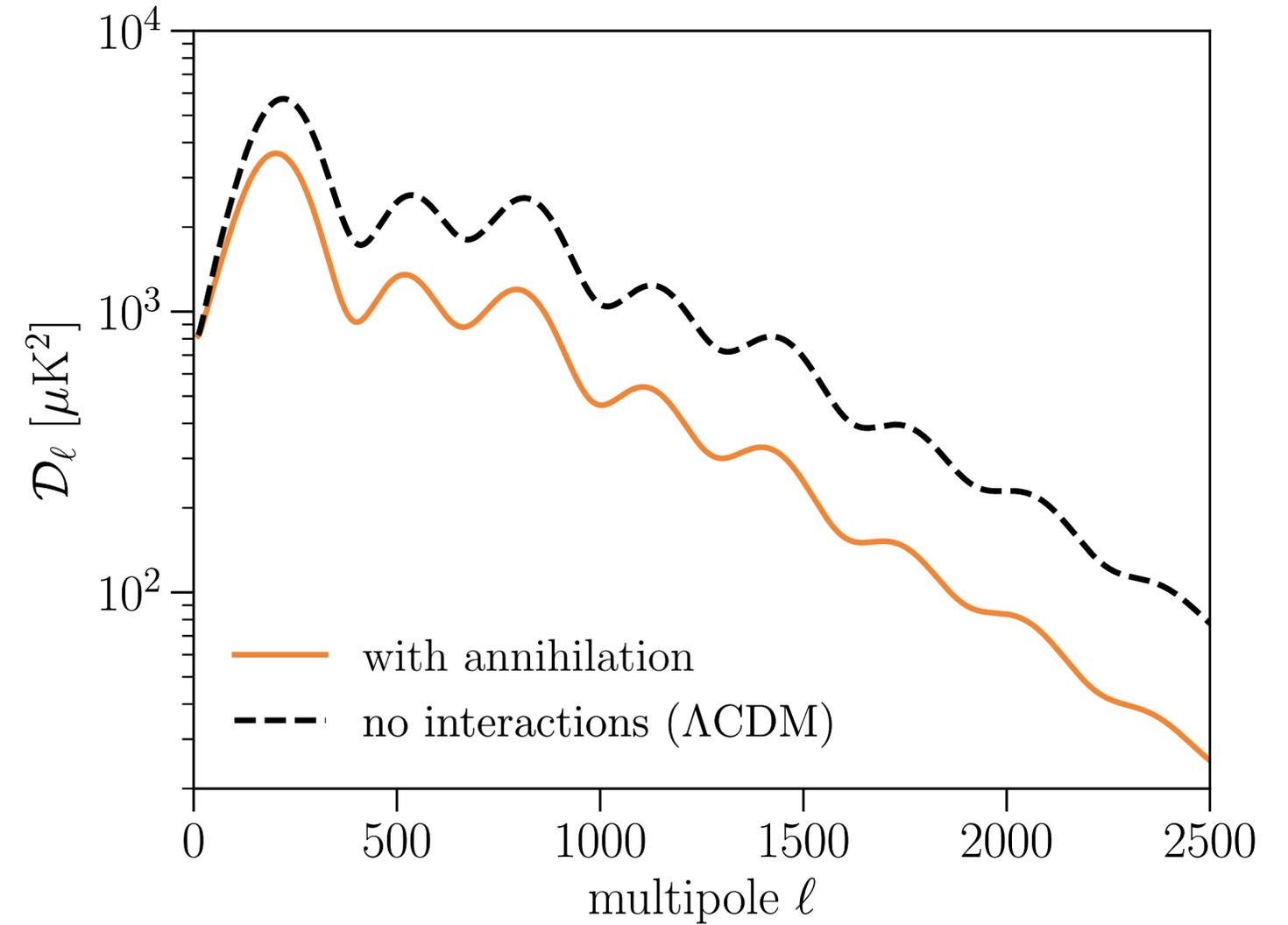
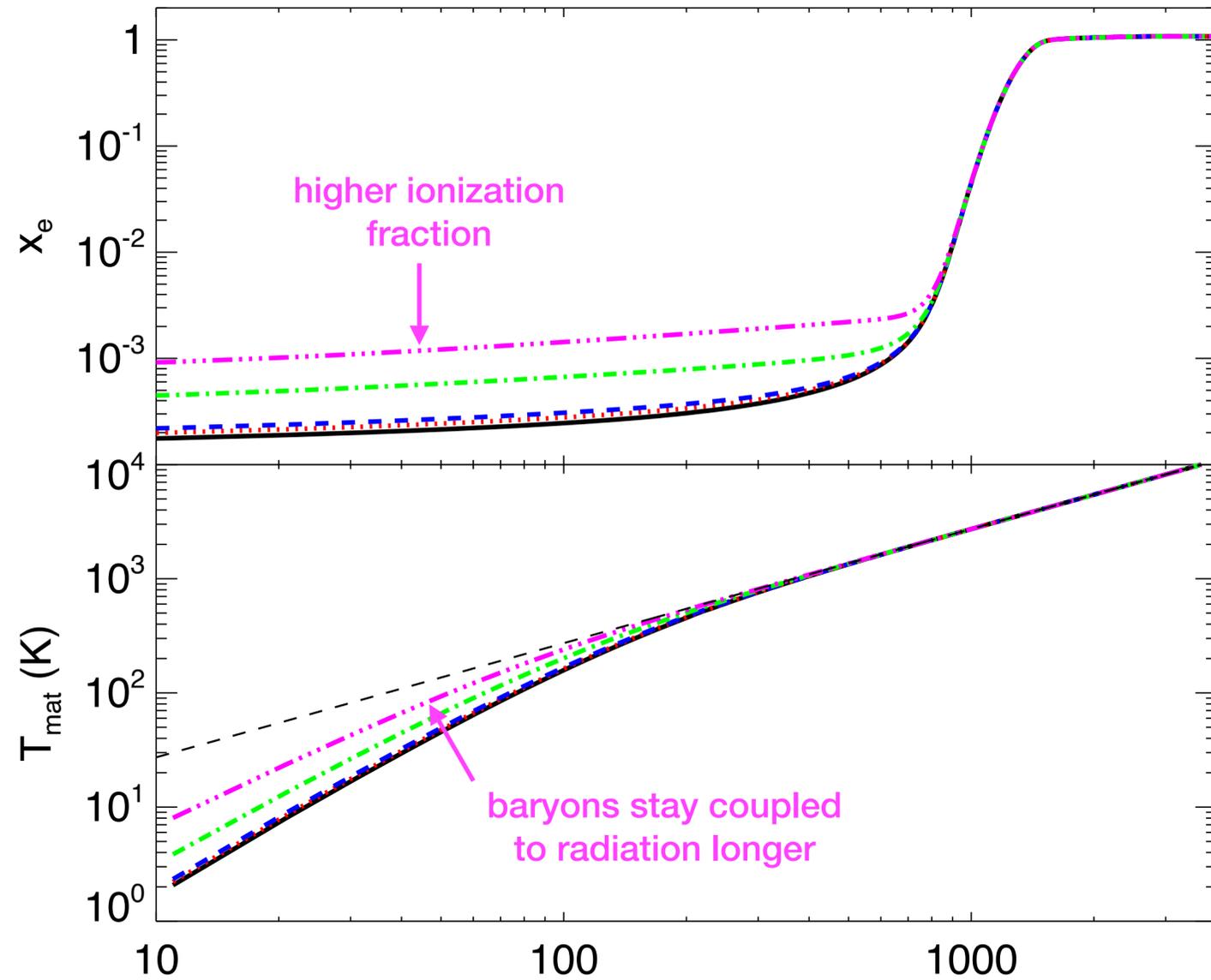
- ◆ Assume thermal relic, freeze-out DM
- ◆ DM annihilation (or decay) transfers energy and entropy into SM sector, which affects radiation content of Universe (parameterized by  $N_{\text{eff}}$ )
- ◆ Light DM itself affects expansion rate, modifying proton-neutron conversion freeze out (affects primordial element abundances)
- ◆ Consider joint constraint for DM scattering and thermal relic DM by adjusting  $Y_p$ ,  $\Delta N_{\nu}$ , and DM mass  $m_\chi$

# Combined Constraints from CMB and BBN



An, KB, Gluscevic (to appear)

# Effect of Energy Injection on CMB

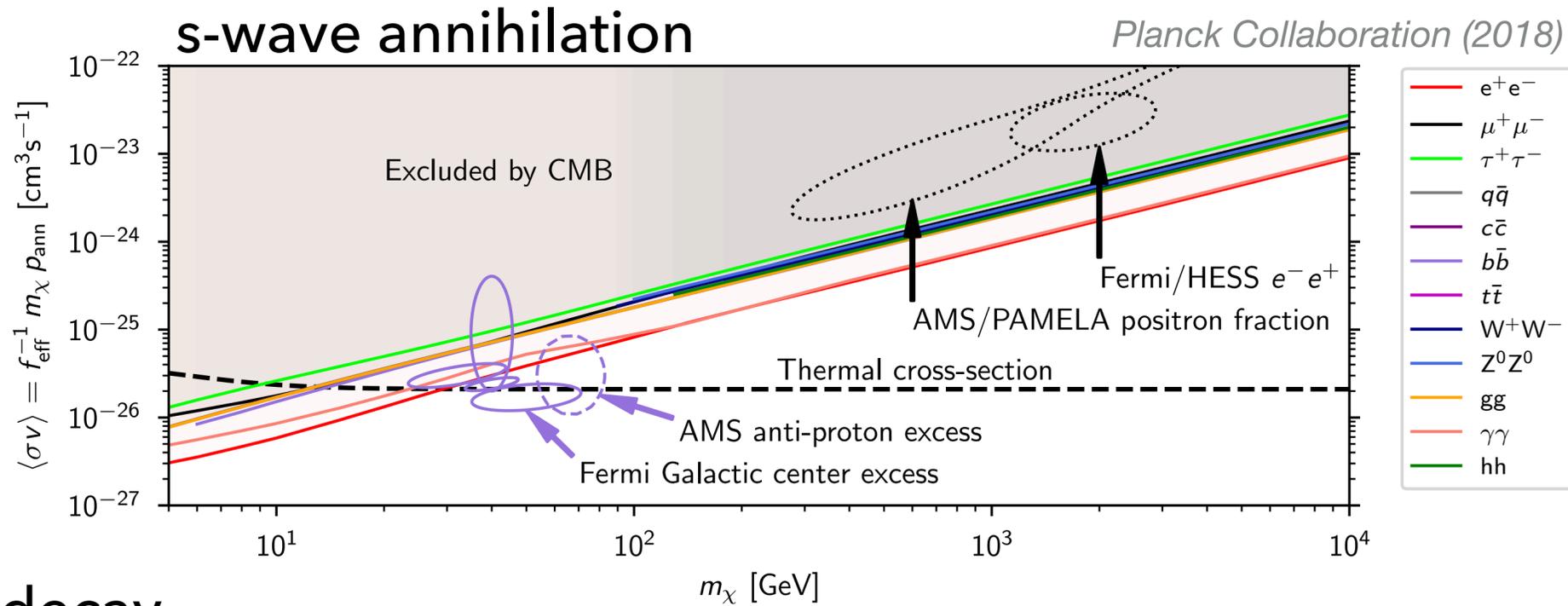


**DM annihilation**

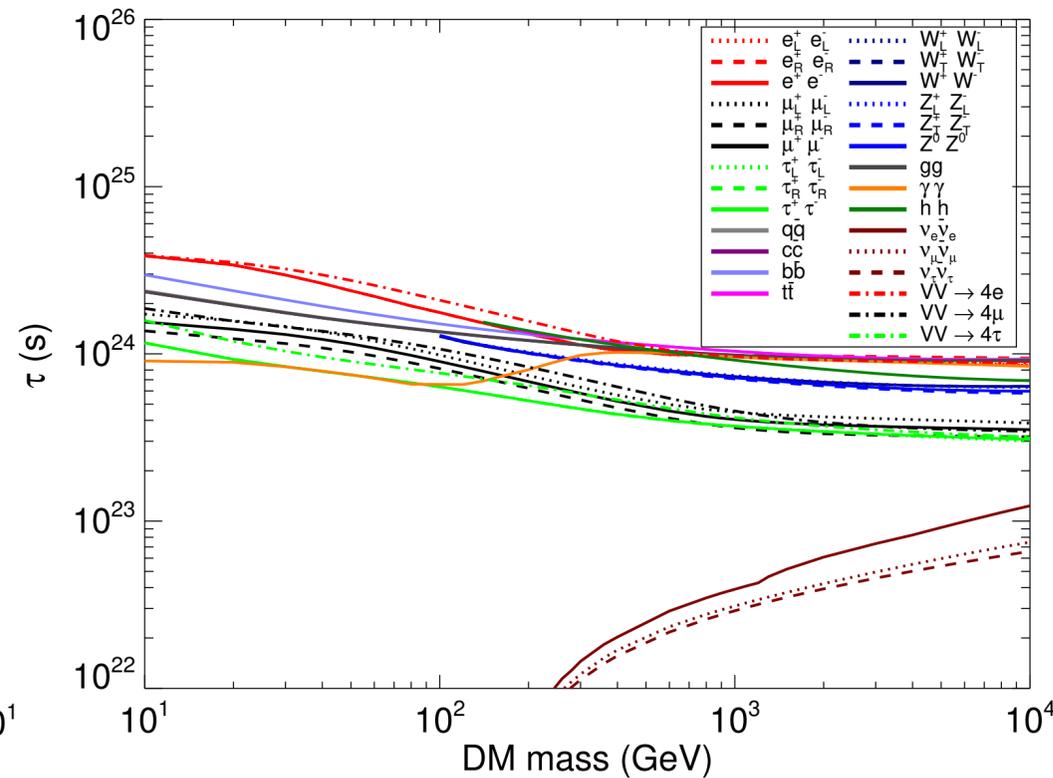
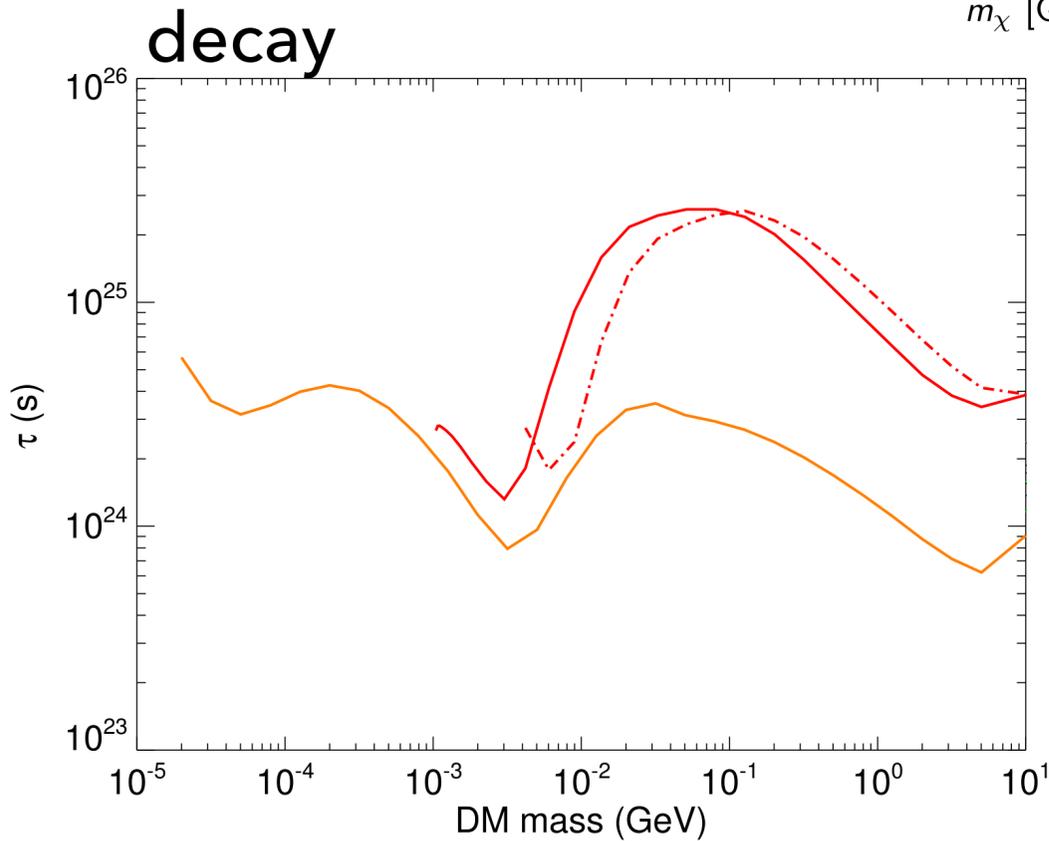
▸ suppression across (mostly) all scales

Example: *s*-wave annihilation from Padmanabhan and Finkbeiner (2005)  
 see also Slatyer+ (2009); Galli+ (2009,2013); Finkbeiner (2011); Slatyer (2016)

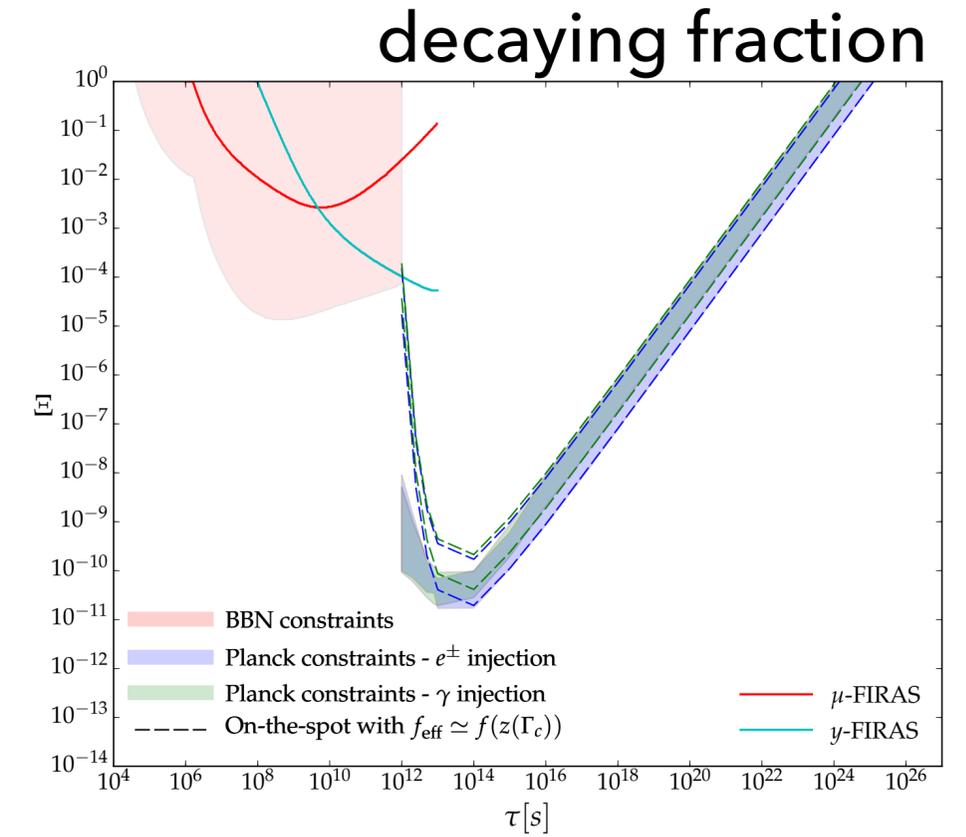
# CMB Annihilation and Decay Constraints



Anisotropies most sensitive at  
 $z \sim 600$  (annihilation)  
 $z \sim 300$  (decay)

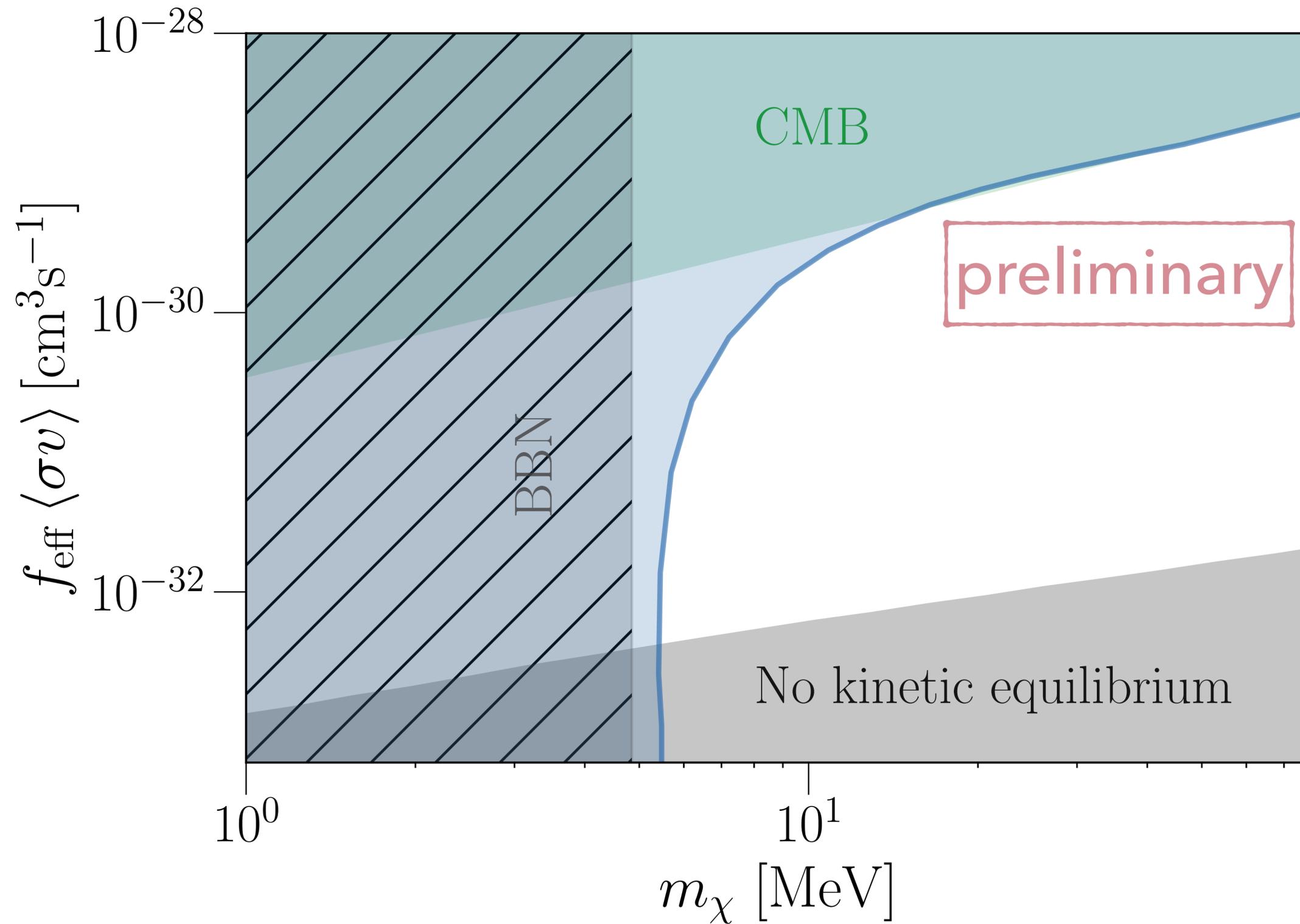


*Slatyer and Wu (PRD 2017)*



*Poulin, Lesgourgues, Serpico (JCAP 2017)*

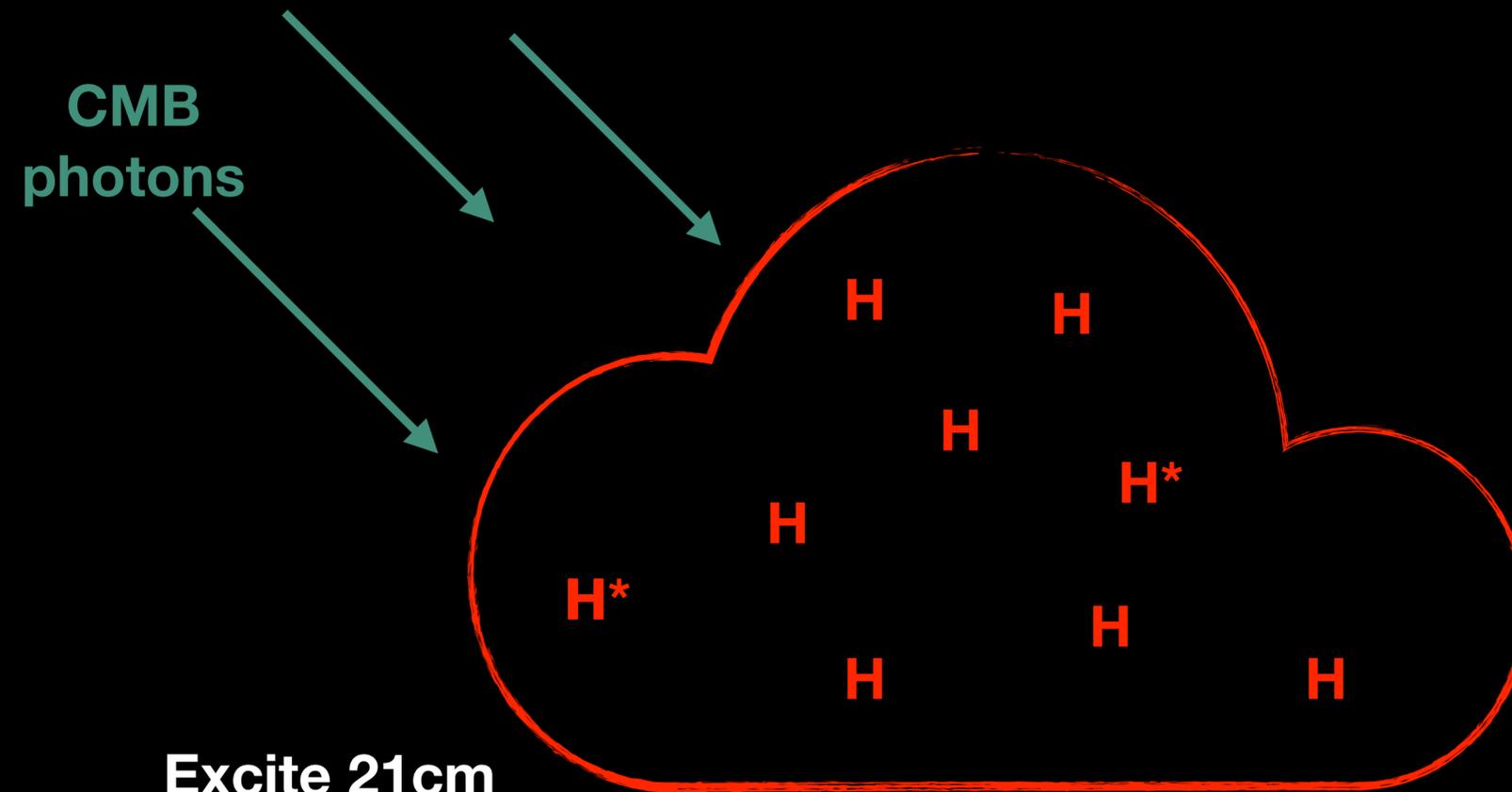
# Annihilation Constraints from BBN and CMB



An, KB, Gluscevic (to appear)

3 Dark matter scattering  
can cool intergalactic medium during  
cosmic dawn (and dark ages)

# 21-cm Global Signal: Schematic Overview



CMB serves as backlight

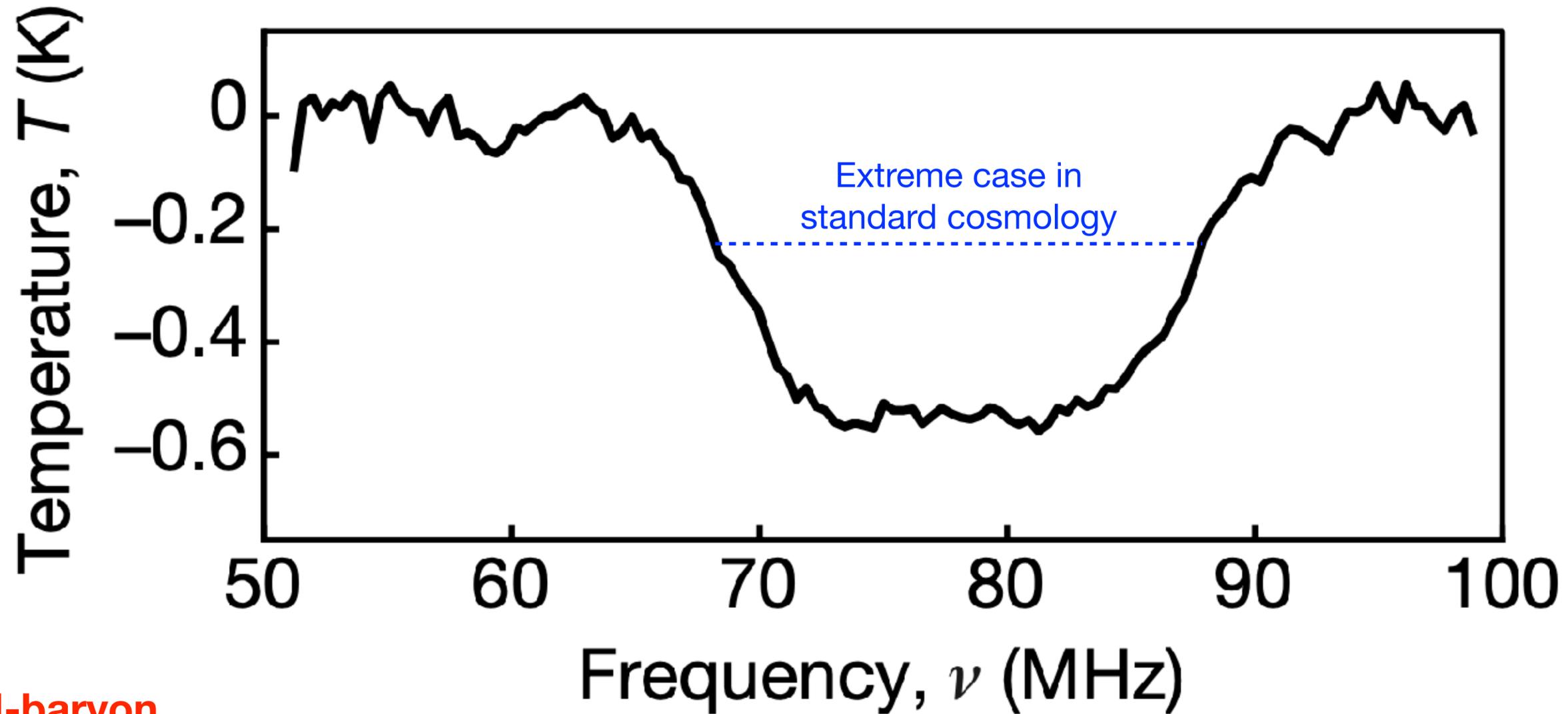
Observe brightness temperature contrast



*Bowman+ (Nature 2018)*

# EDGES Absorption Signal

Experiment to Detect the Global Epoch of Reionization Signature

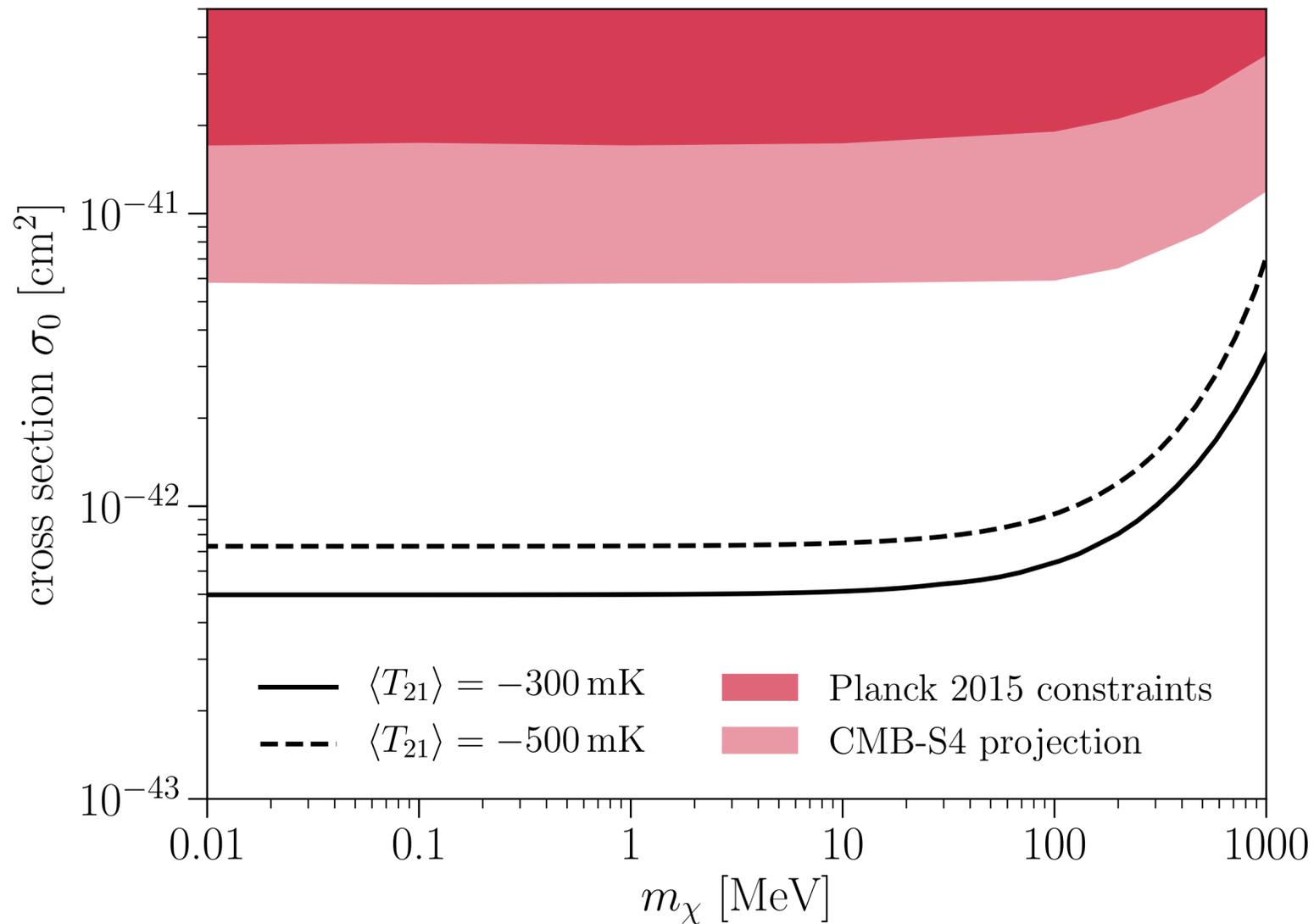


$\sigma \sim \nu^{-4}$  **DM-baryon scattering cools gas**

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

*Bowman+ (Nature 2018)*

# CMB constraints



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

*Driskell, Mirocha, Morton, Gluscevic, KB, Benson, Nadler (2209.04499)*

- ◆ DM-H vs DM-ion scattering?
  - ◆ DM-H scattering highly constrained
  - ◆ DM-ion scattering suffers from low  $x_e$ , so need larger  $\sigma_0$  than allowed by CMB
- ◆ Allow only fraction of DM to interact

*Muñoz, Loeb (2018)*

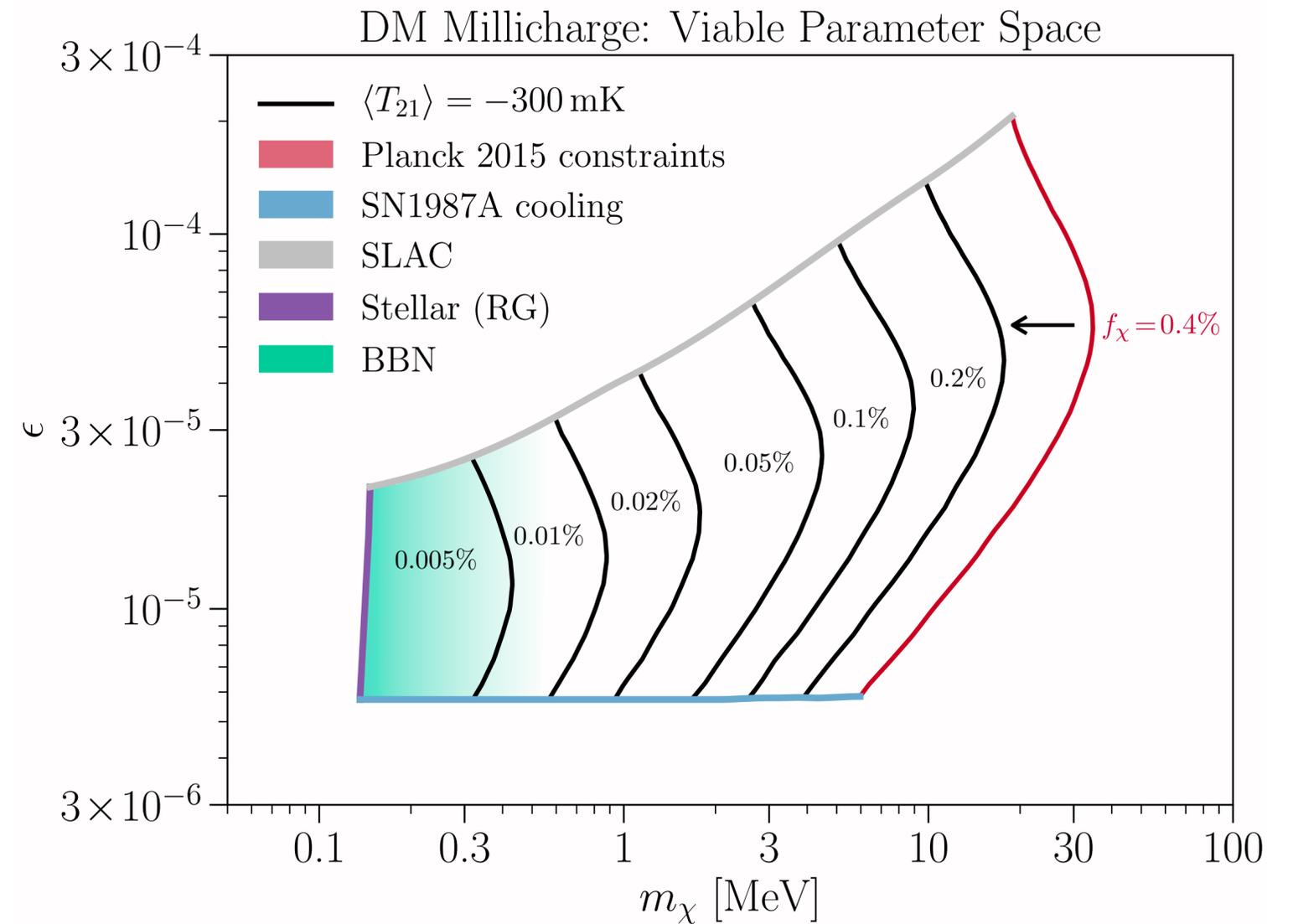
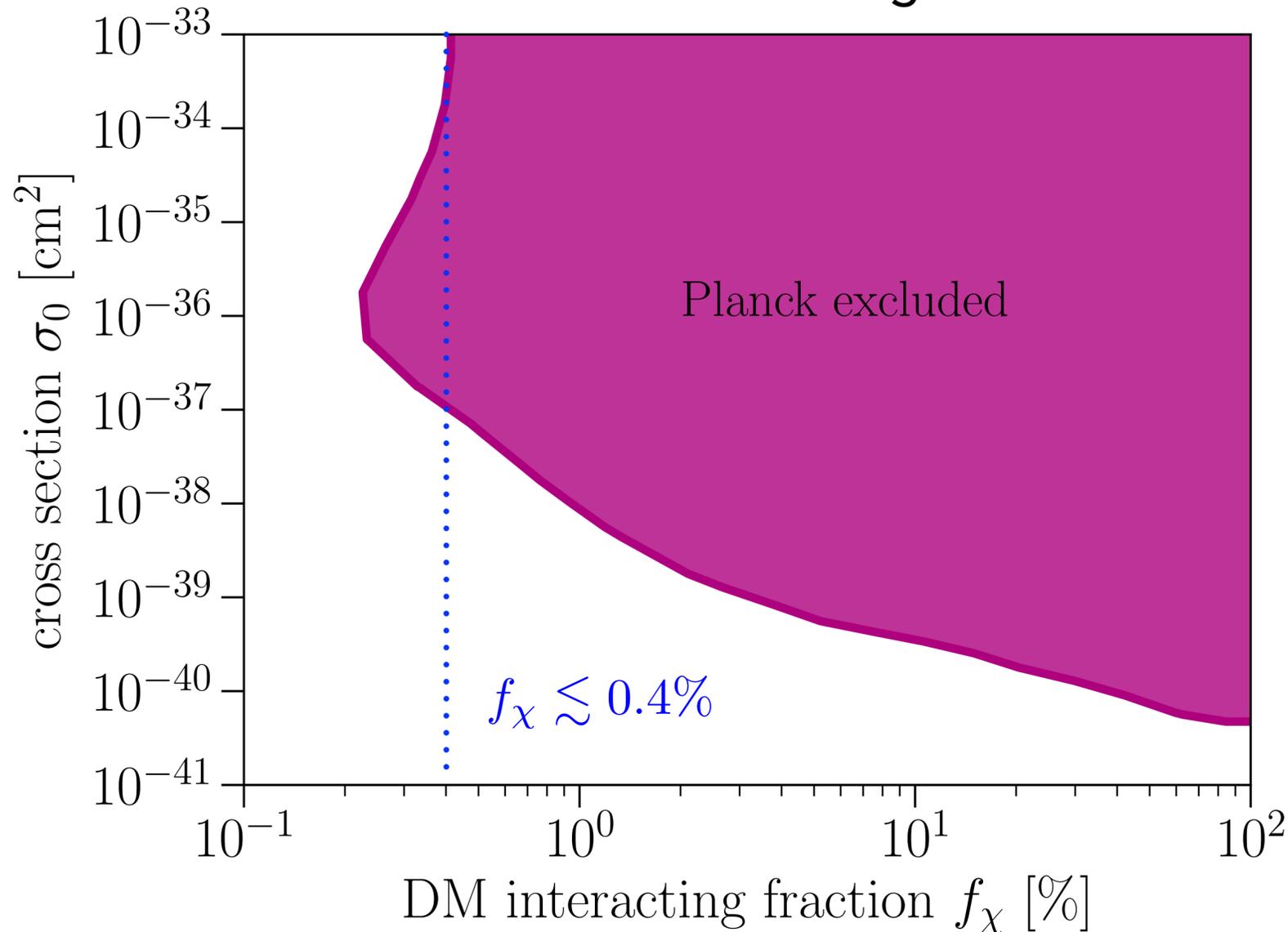
*Berlin, Hooper, Krnjaic, McDermott (2018)*

*Barkana, Outmezguine, Redigolo, Volansky (2018)*

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

# Millicharged Dark Matter

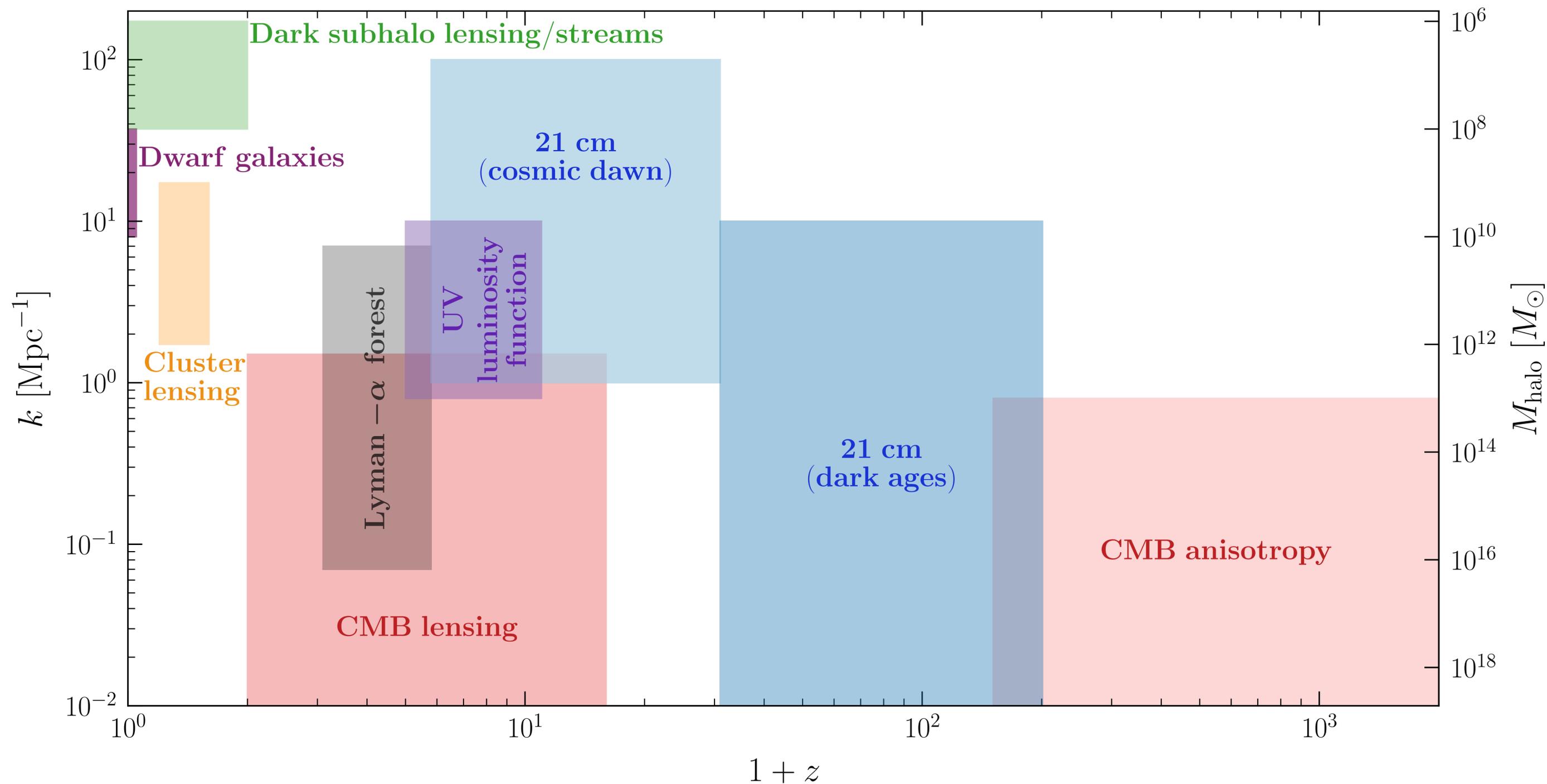
Planck loses sensitivity to small fractions of millicharged DM



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

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

# Complementarity

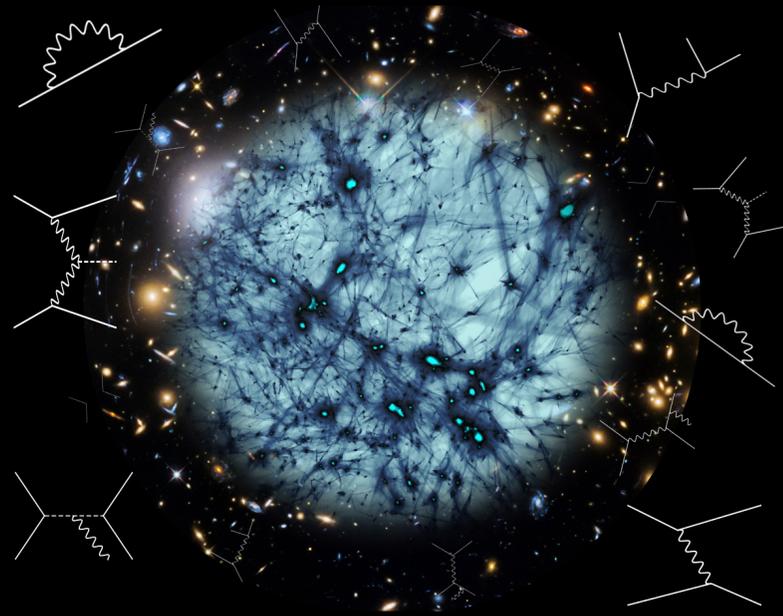


- ① Dark matter scattering suppresses small-scale structure formation
- ② Dark matter annihilation injects energy
- ③ Dark matter scattering can cool intergalactic medium during cosmic dawn (and dark ages)

Exciting times for cosmo/astro probes of dark matter!

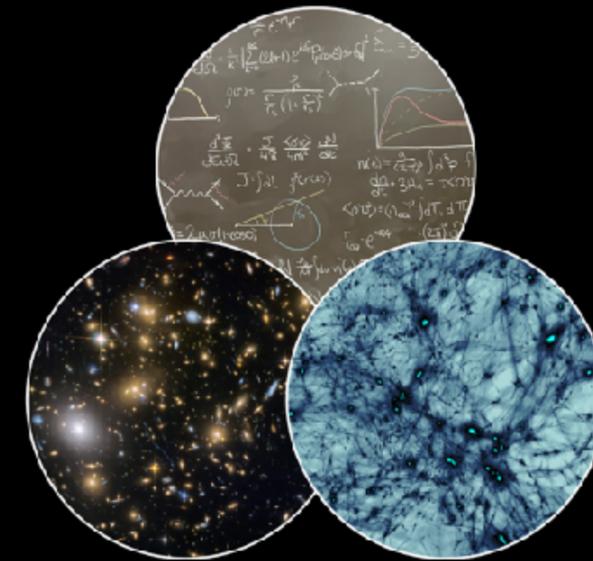
# KITP 2024 Program Plug

## Dark Matter Theory, Simulation, and Analysis in the Era of Large Surveys



- ◆ Coordinators:  
KB, Vera Gluscevic, Ferah Munshi, Annika Peter
- ◆ Scientific advisors:  
Jo Dunkley, Tim Tait, Risa Wechsler
- ◆ May 20 – July 12, 2024  
[Application deadline: February 12, 2023]

## Cosmic Signals of Dark Matter Physics: New Synergies



- ◆ Coordinators:  
KB, Ferah Munshi, Ethan Nadler, Annika Peter
- ◆ June 3 – 6, 2024  
[Registration deadline: May 5, 2024]