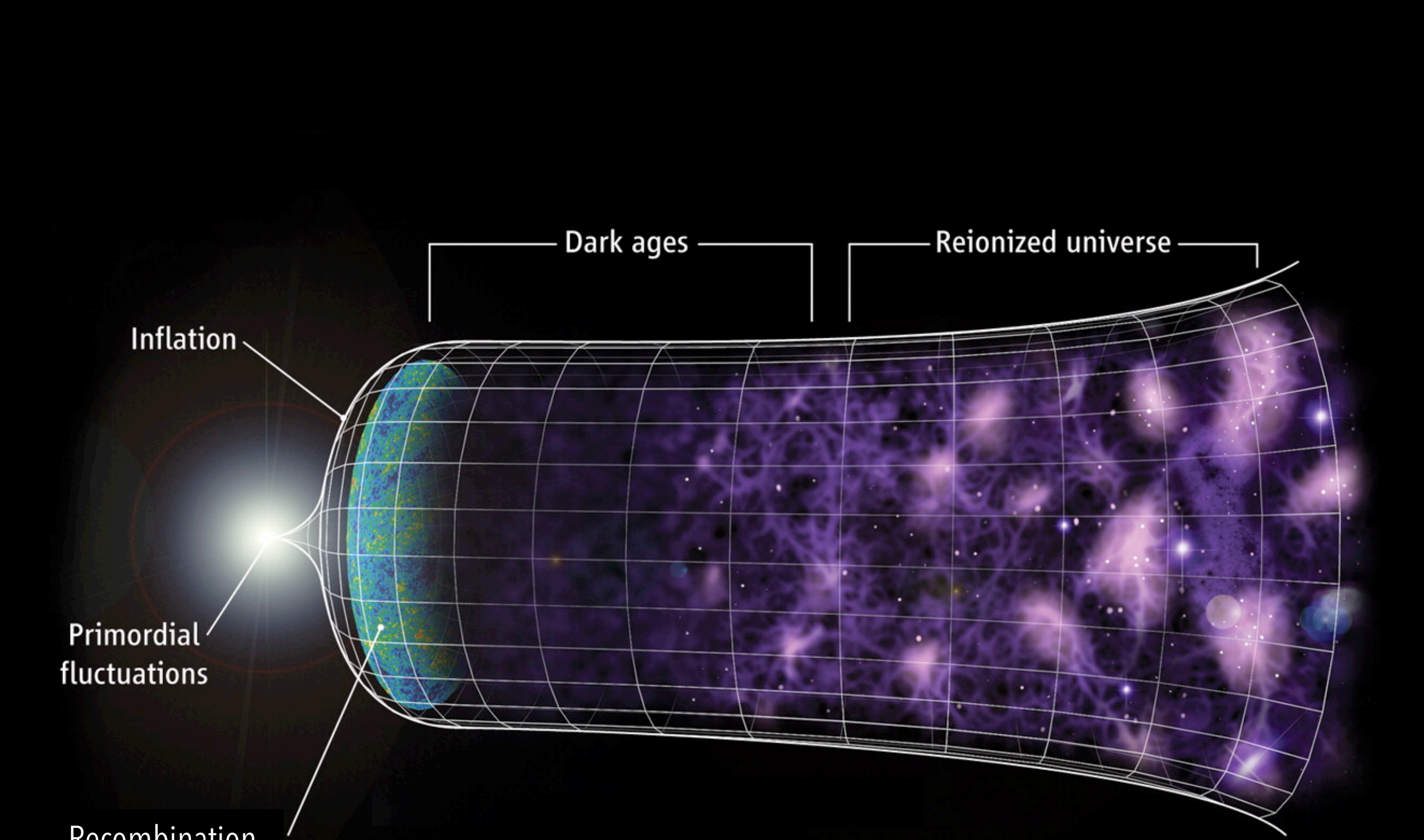
# Cosmological Probes of Dark Matter Physics

Kimberly Boddy
Johns Hopkins University

Light Dark World, KAIST

17 December 2018


Dark ages
Reionized universe
Inflation
Primordial fluctuations
Recombination

Big Bang Nucleosynthesis
(deuterium abundances)

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Cosmic microwave background radiation
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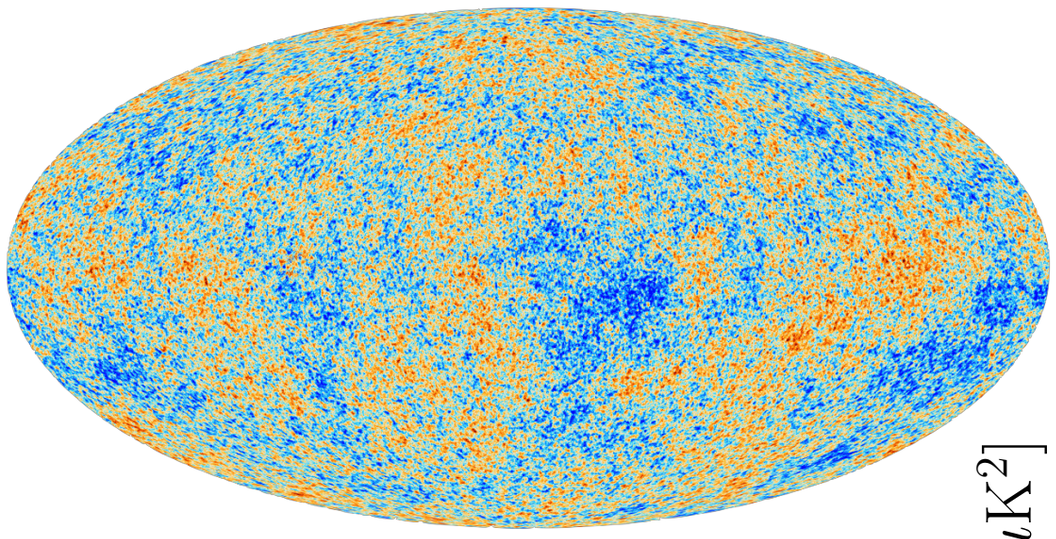
Cosmic microwave background radiation
(satellite and ground-based telescopes)

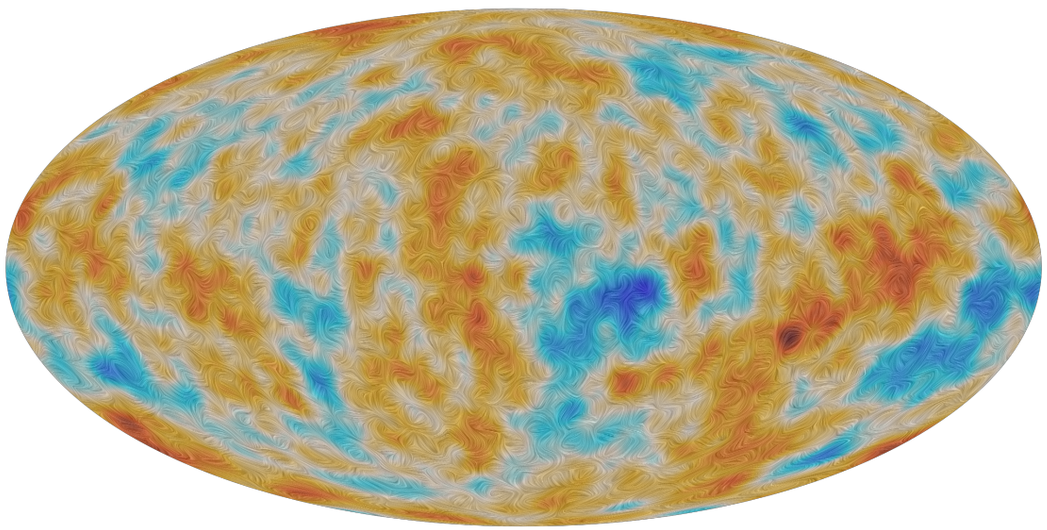
Large Scale Structure
(galaxy surveys)

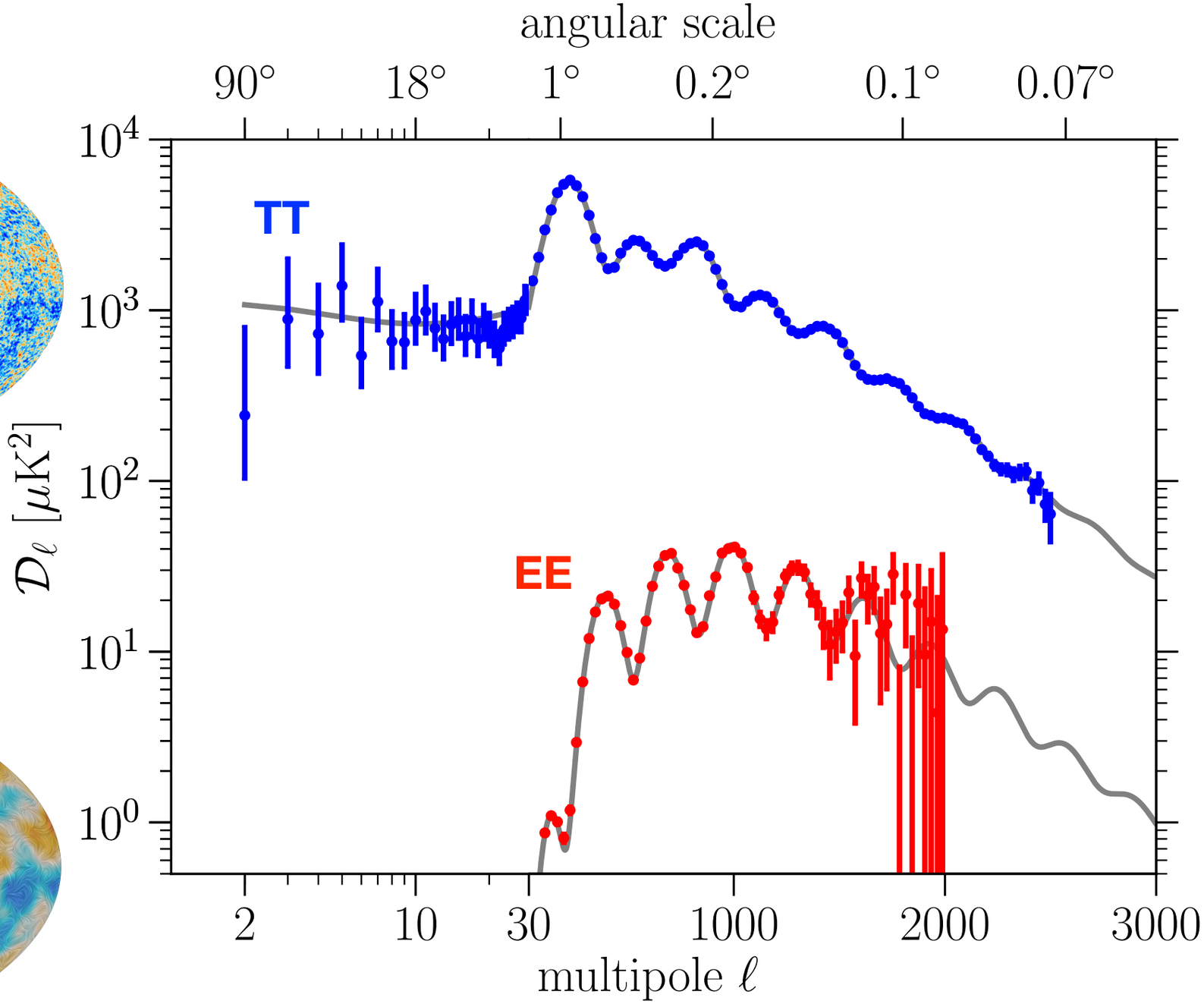
# Planck 2015

**Temperature anisotropy**



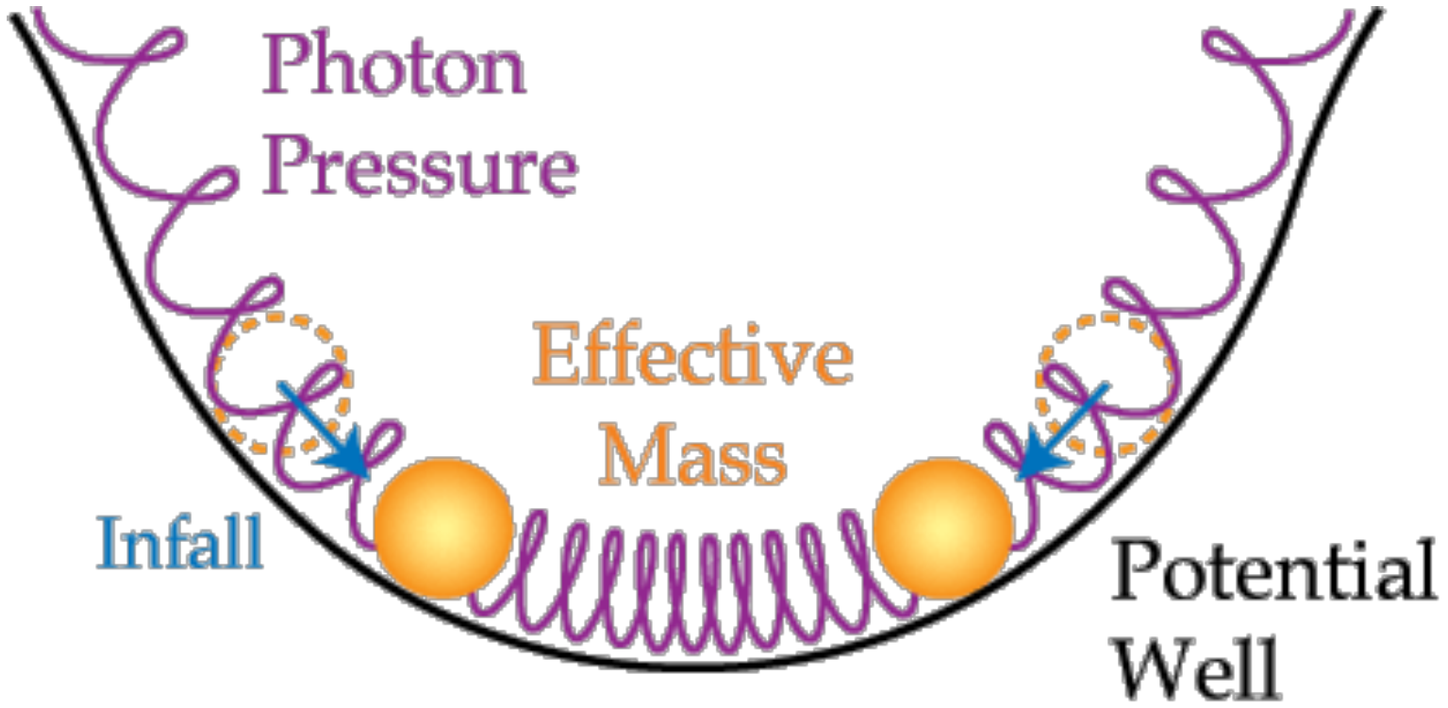
**Polarization anisotropy**






ESA and Planck Collaboration

# Baryon Acoustic Oscillations




W. Hu, http://background.uchicago.edu/~whu/index.html

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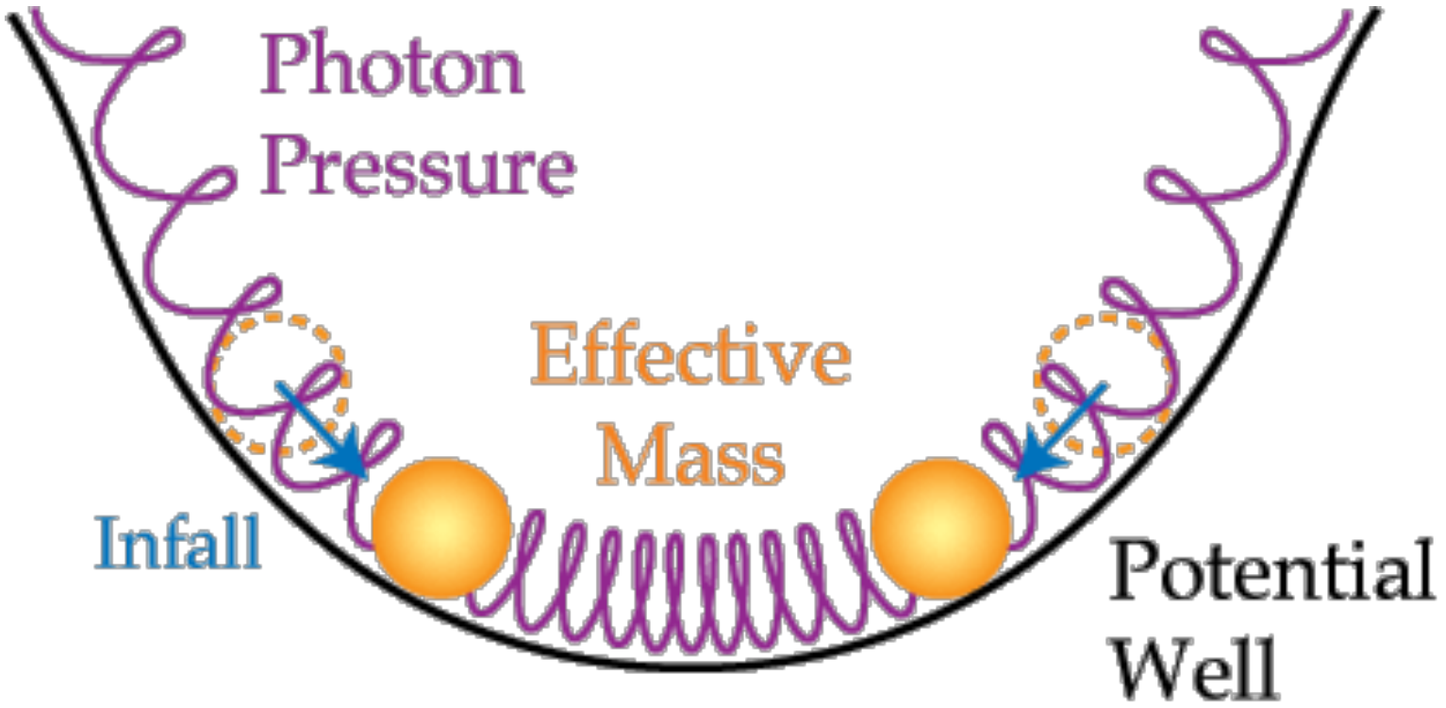
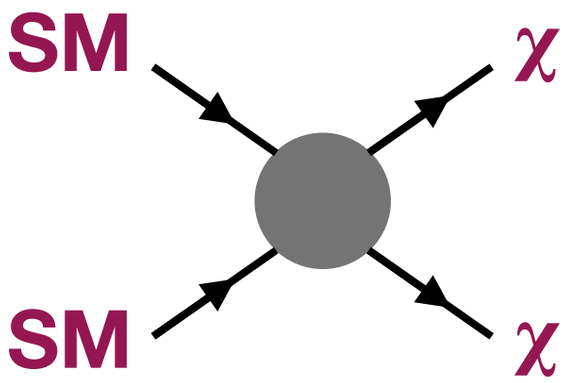



**How does this picture change with non-gravitational dark matter interactions?**

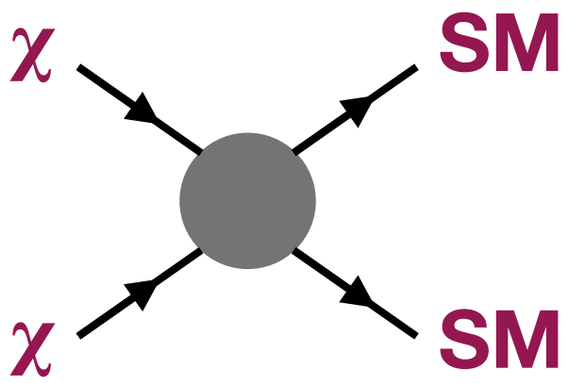
W. Hu, http://background.uchicago.edu/~whu/index.html

# Search Channels

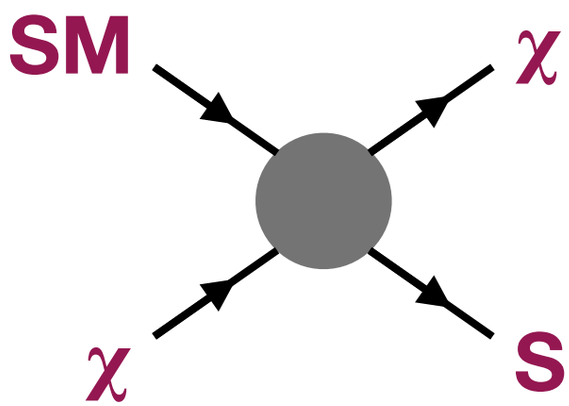
**Production**




**Annihilation**




**Scattering**




**in particle physics**

**Collider** **Indirect detection** **Direct detection**

**in cosmology**

**Relic abundance** **Energy injection** **Momentum transfer**

# Search Channels

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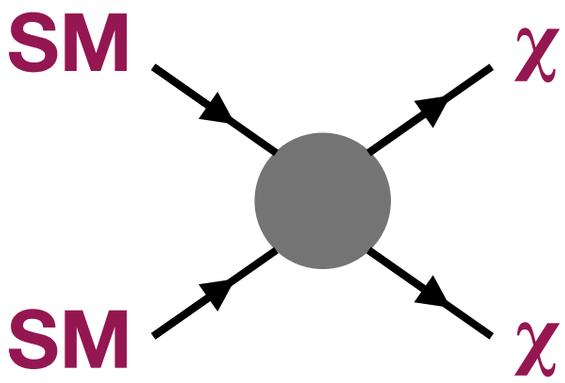


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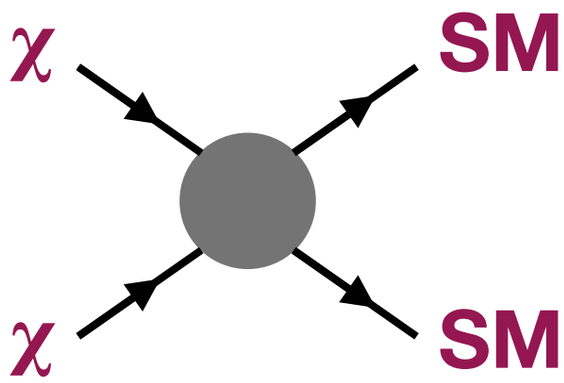


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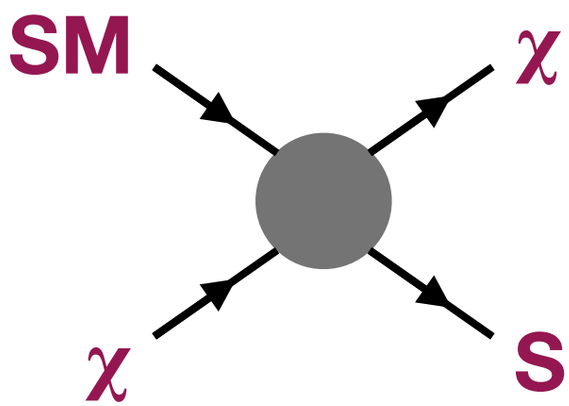


in particle physics

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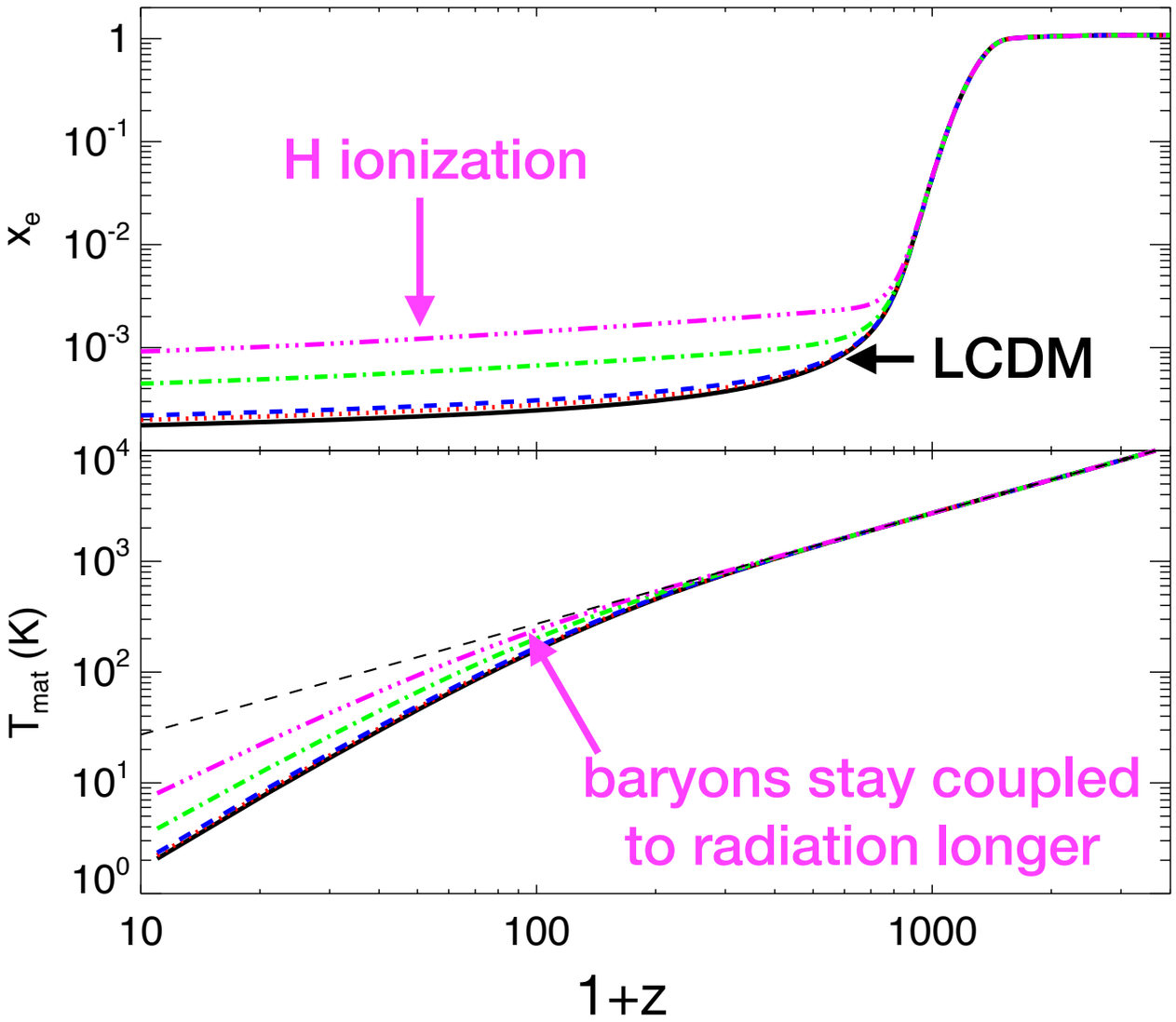
# Energy Injection

$$\left(\frac{dE}{dt\,dV}\right)_{\rm dep} = f(z)\left(\frac{dE}{dt\,dV}\right)_{\rm inj} = f(z)(1+z)^6\Omega_{\rm DM}^2 c^2 \rho_c^2 \frac{\langle\sigma v\rangle}{m_{\rm DM}}$$

**Example: s-wave annihilation**




Padmanabhan and Finkbeiner (2005)

see also Galli+ (2009, 2013), Finkbeiner (2011), Slatyer (2016)

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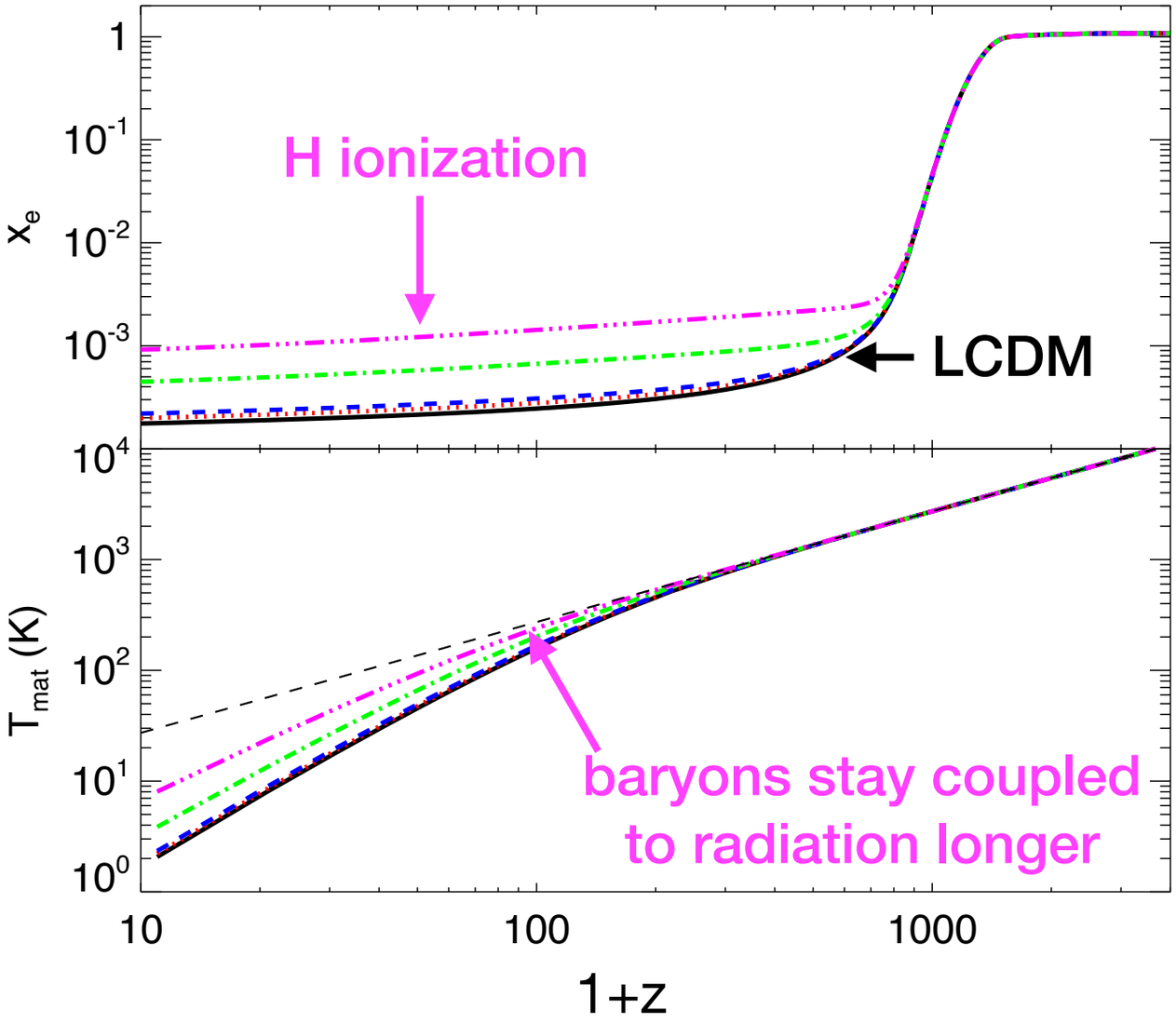


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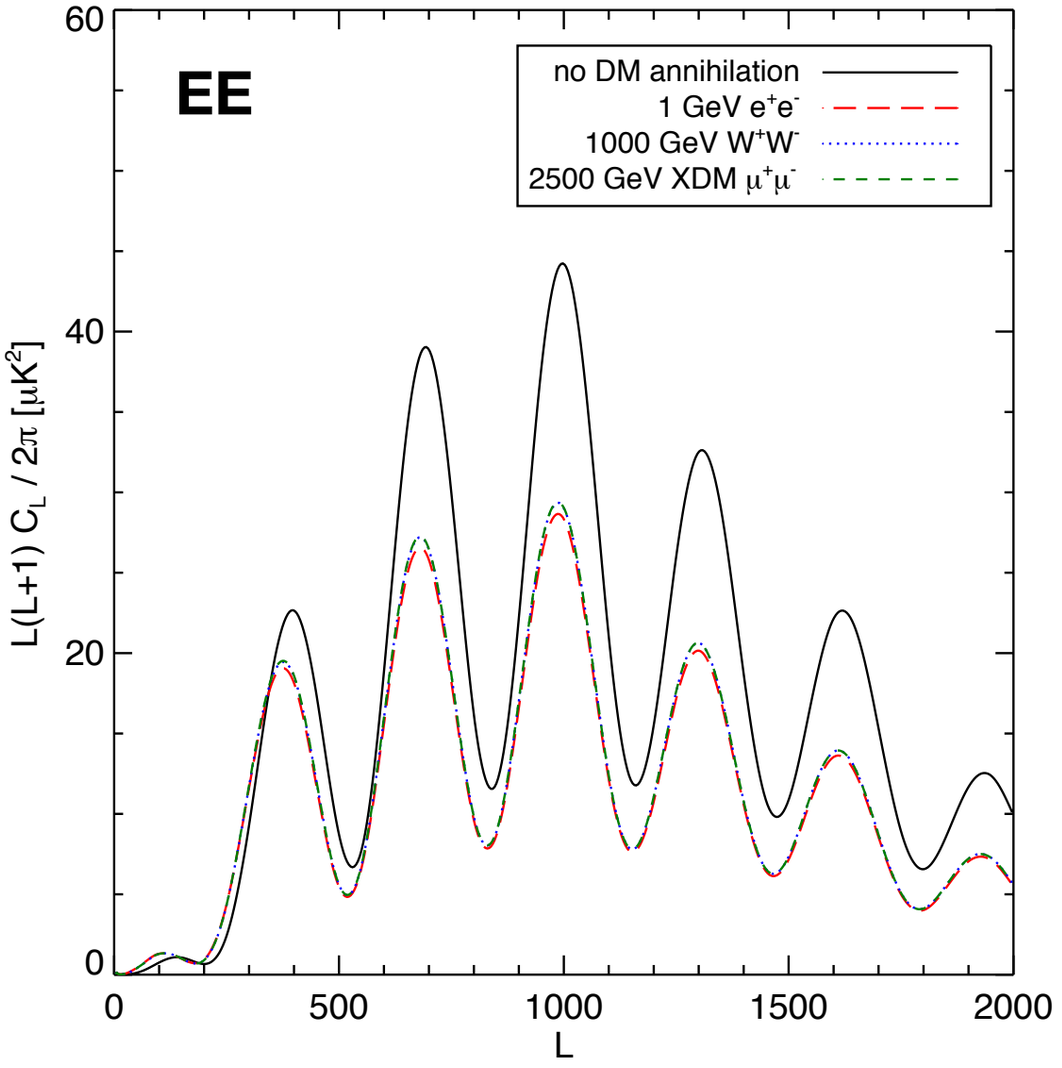
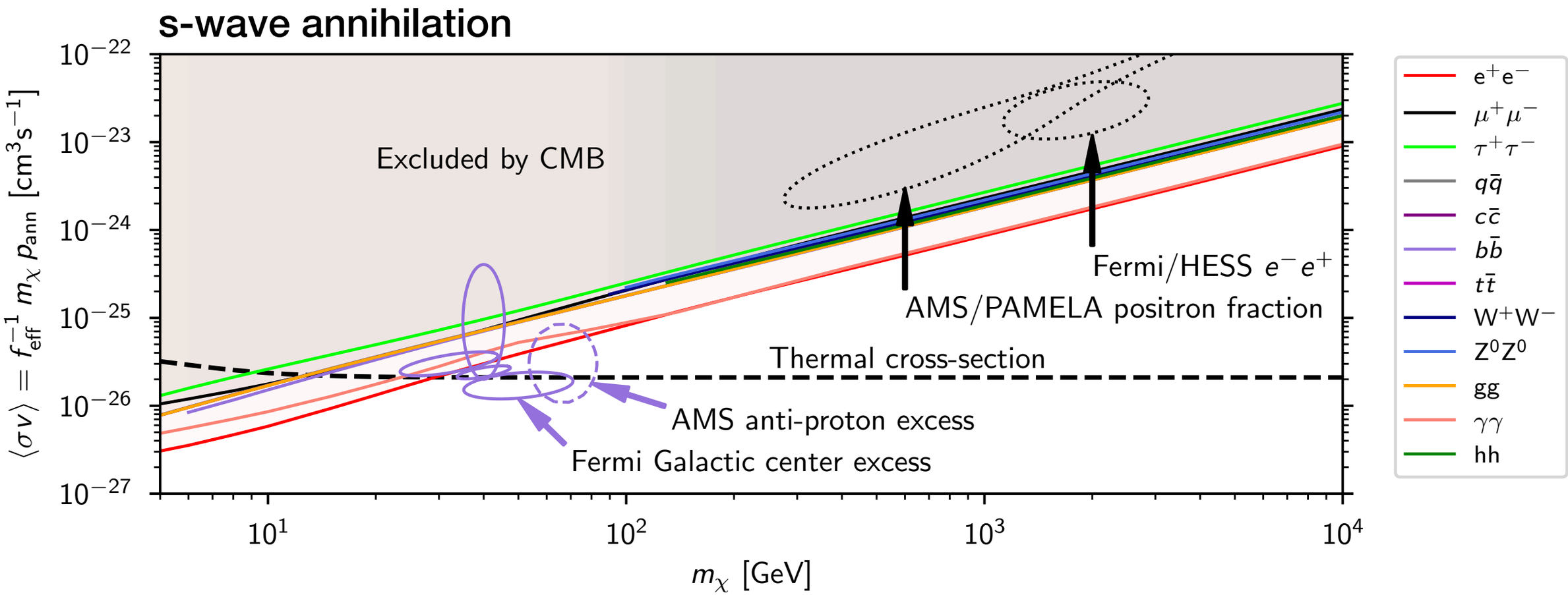



Slatyer+ (2009)

see also Galli+ (2009, 2013), Finkbeiner (2011), Slatyer (2016)

# CMB Annihilation Limits




~20% improvement over Planck 2015

Planck Collaboration (2018)

**For decay, see Poulin+ (2017), Slatyer and Wu (2017)**

# Search Channels

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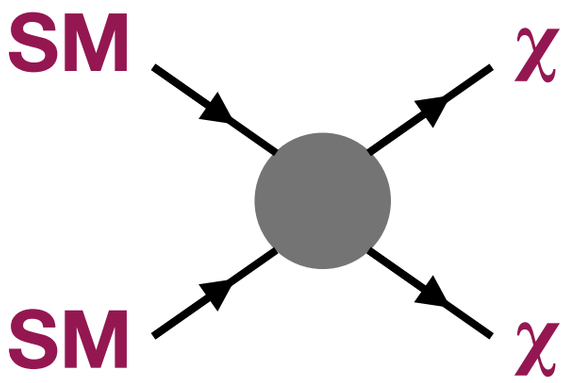


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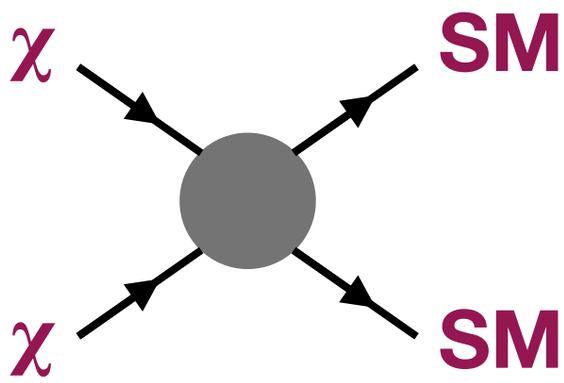
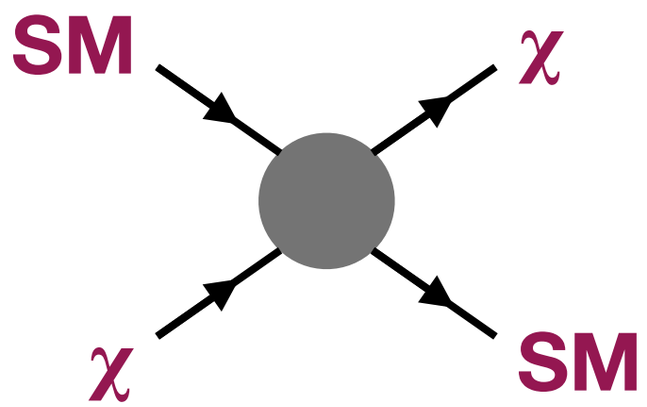



**Scattering**




**in particle physics**

**Collider** | **Indirect detection** | **Direct detection**

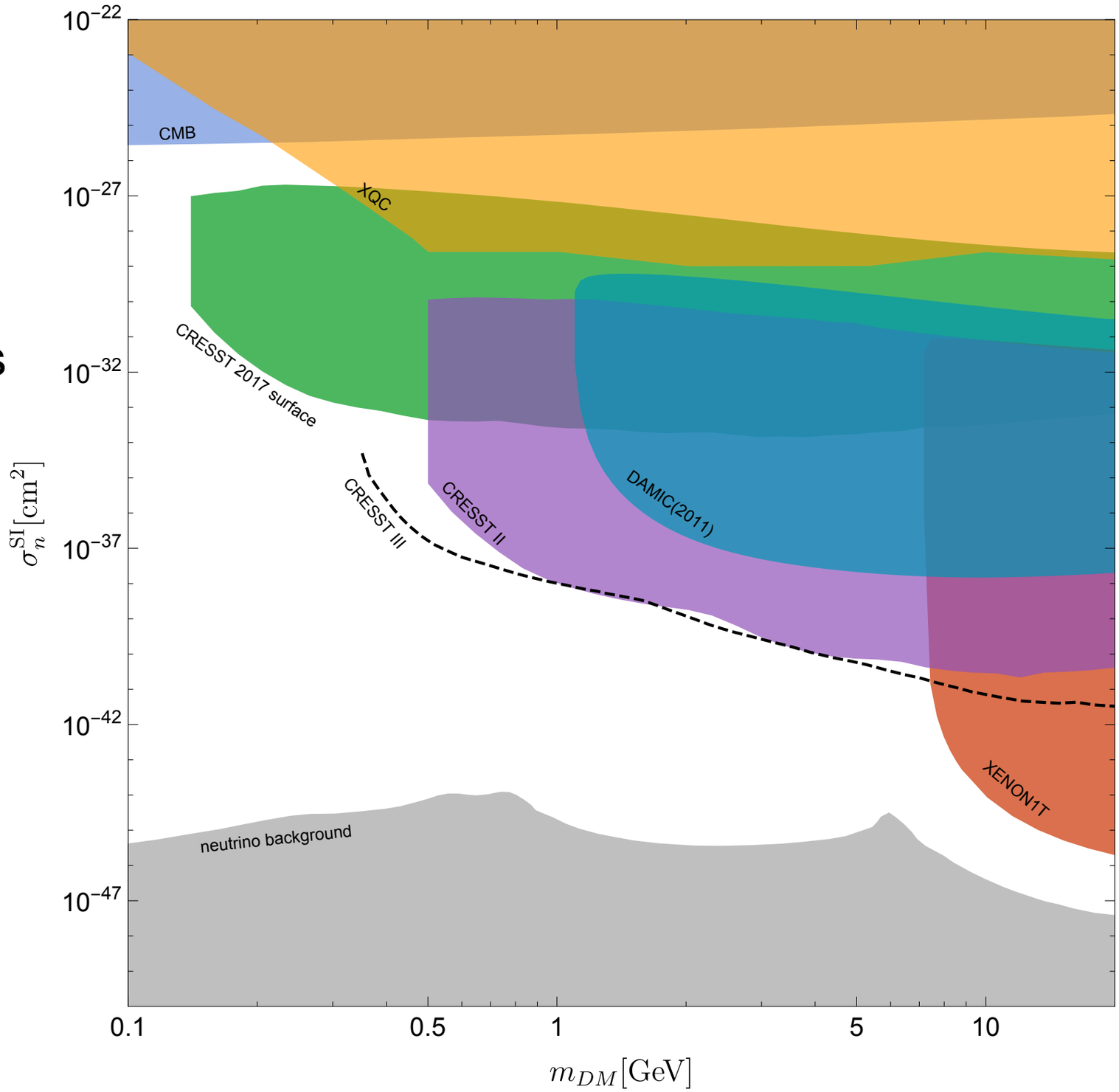
**in cosmology**

**Relic abundance** | **Energy injection** | **Momentum transfer**

# Direct Detection

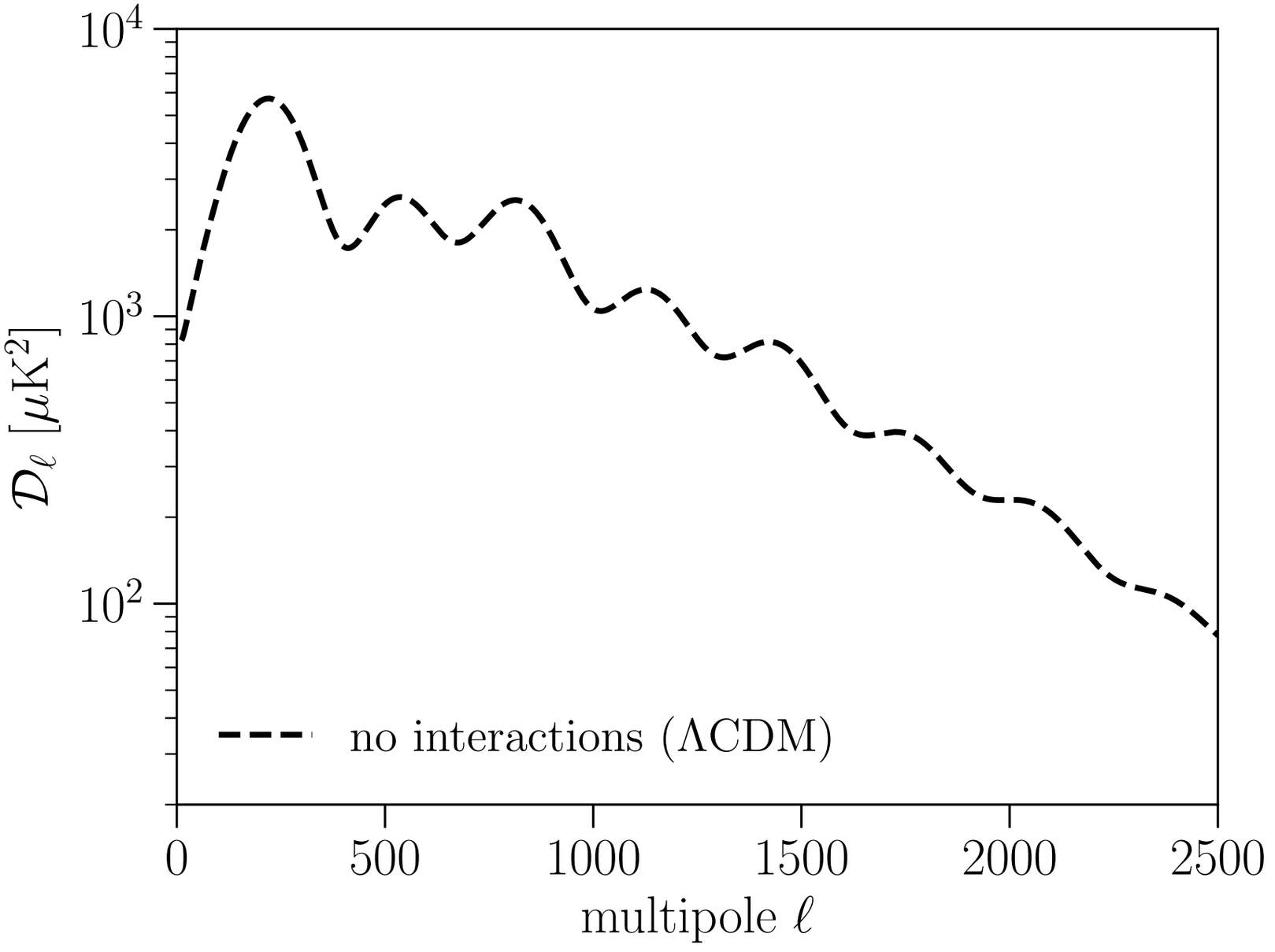
CMB complementarity:

- access high cross sections above direct detection ceilings
- access wide range of dark matter masses (down to keV range)
- independent of local halo properties
- search avenue beyond standard WIMP scenario




Emken and Kouvaris (2018)

# Elastic Scattering




Chen+ (2002), Sigurdson+ (2004), Dvorkin+ (2014),
Gluscevic and **KB** (2018), **KB** and Gluscevic (2018),
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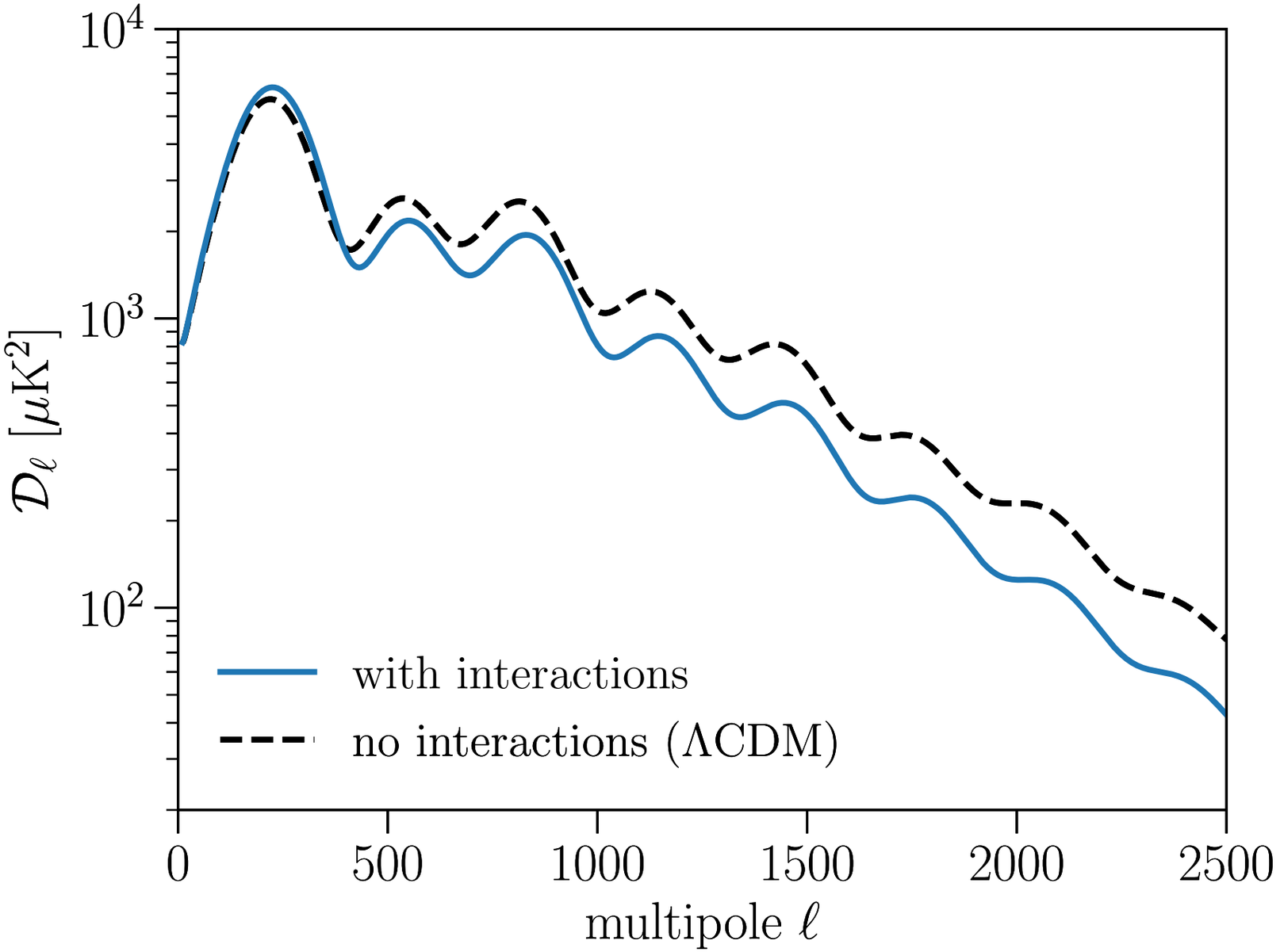
# Elastic Scattering

**DM-baryon scattering:**

- **heat exchange**
- **momentum exchange (drag force)**

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# Elastic Scattering

H, He nuclei

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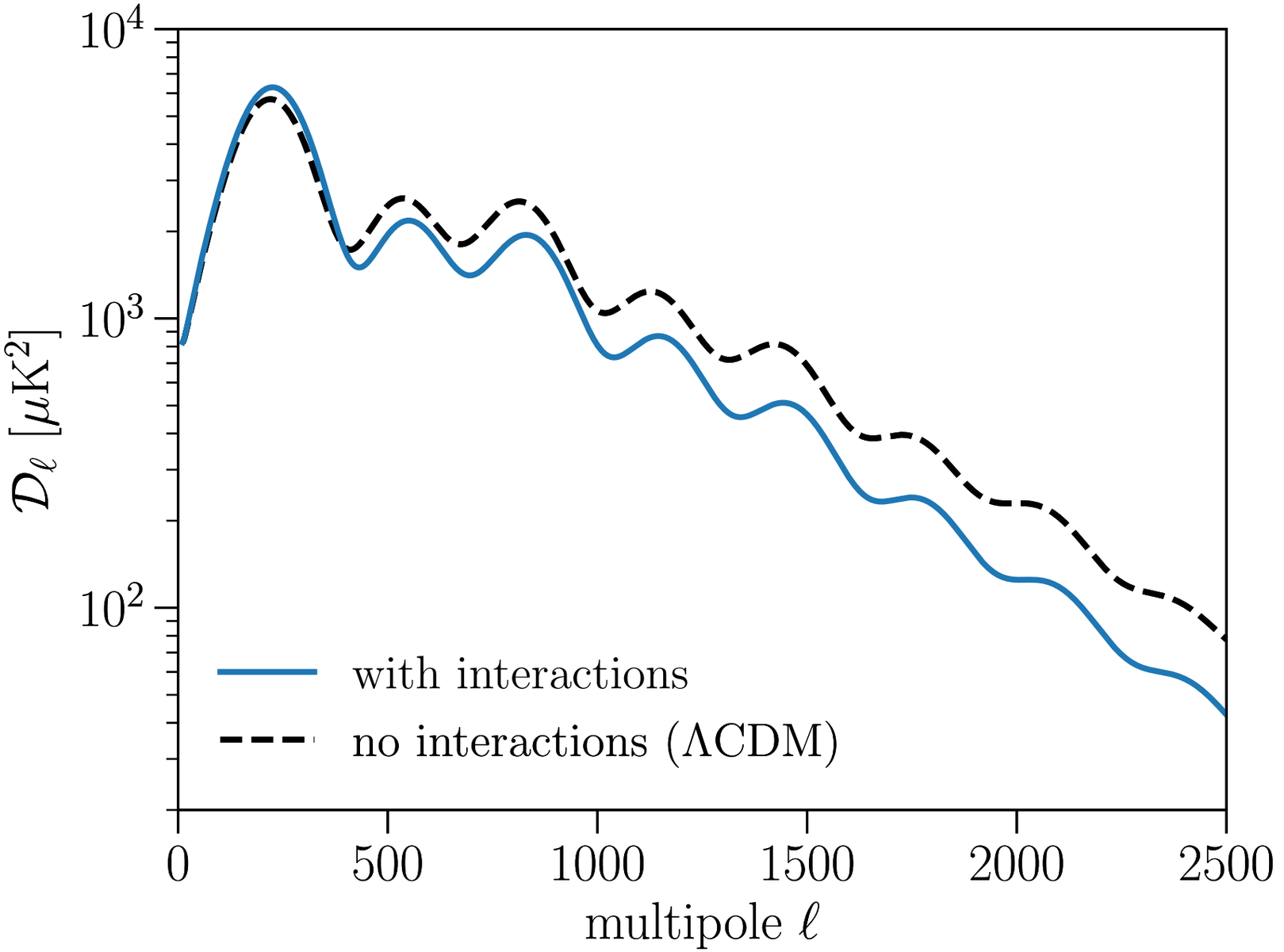


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H, He nuclei

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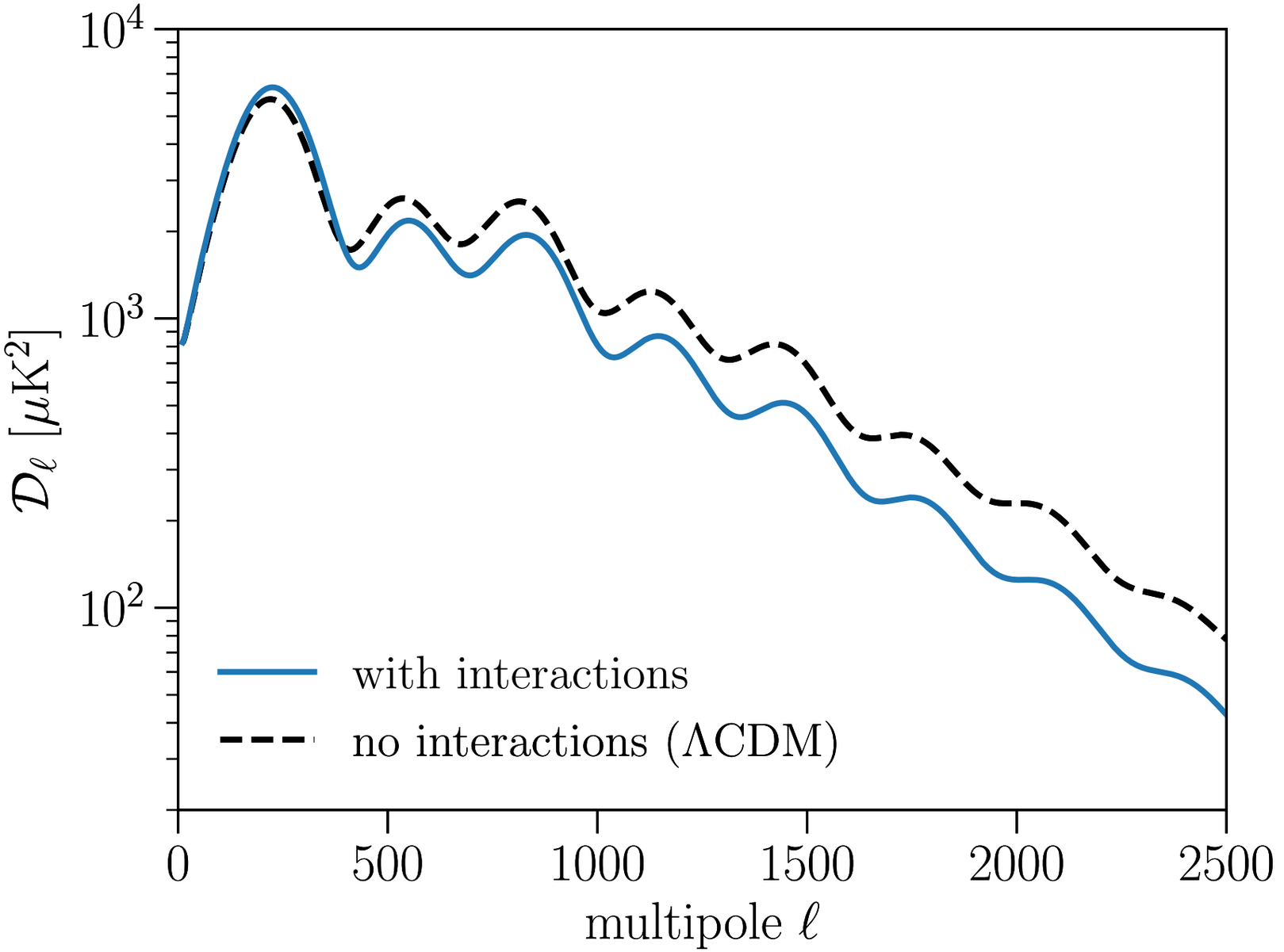
**Particle physics input?**

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# Non-Relativistic EFT

Fan et al. (2010), Fitzpatrick et al. (2013), Anand et al. (2014), Dent et al. (2015)

Observables

$$\mathcal{O} \sim \left|\vec{v}^{\perp}\right|^{\alpha} \left|\vec{q}\right|^{\beta}$$

- DM and nucleon spins
- Momentum transfer (MT) $\quad |\vec{q}| \sim |\vec{v}|(1-\cos\theta)^{1/2}$
- Perpendicular velocity $\qquad \vec{v}^{\perp}(\vec{v},\vec{q}) \;\rightarrow\; \vec{v}^{\perp}\cdot\vec{q} = 0$

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**DM response** **nuclear response**

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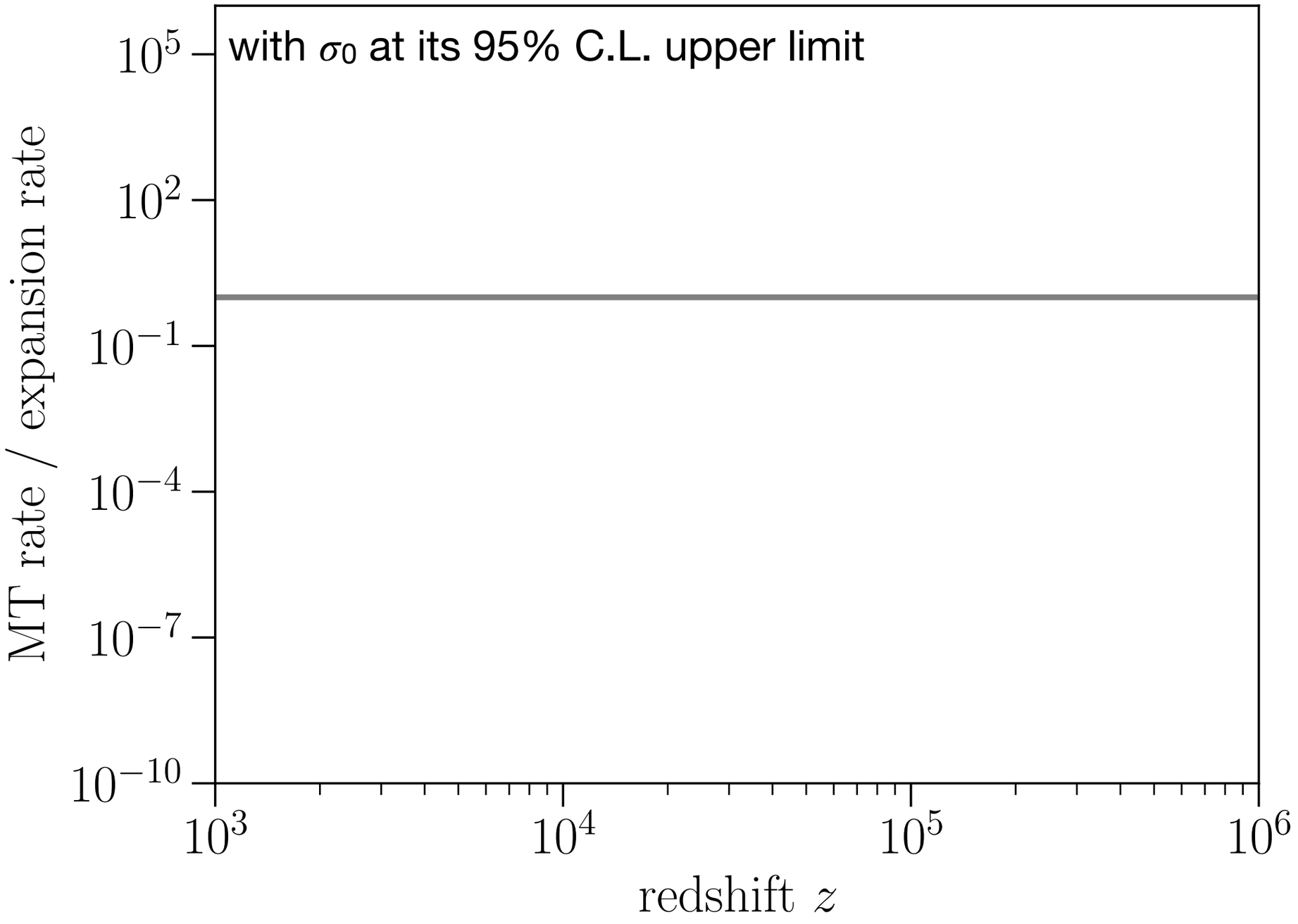
**DM response** **nuclear response**

**CMB is sensitive to rate of momentum transfer (and rate of heat transfer).**

**rate ~ (cross section)/mass x (number density of target) x (reduced mass)**

# Rate of Momentum Transfer

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




**KB** and Gluscevic (PRD 2018)

**KB**+ (PRD 2018)

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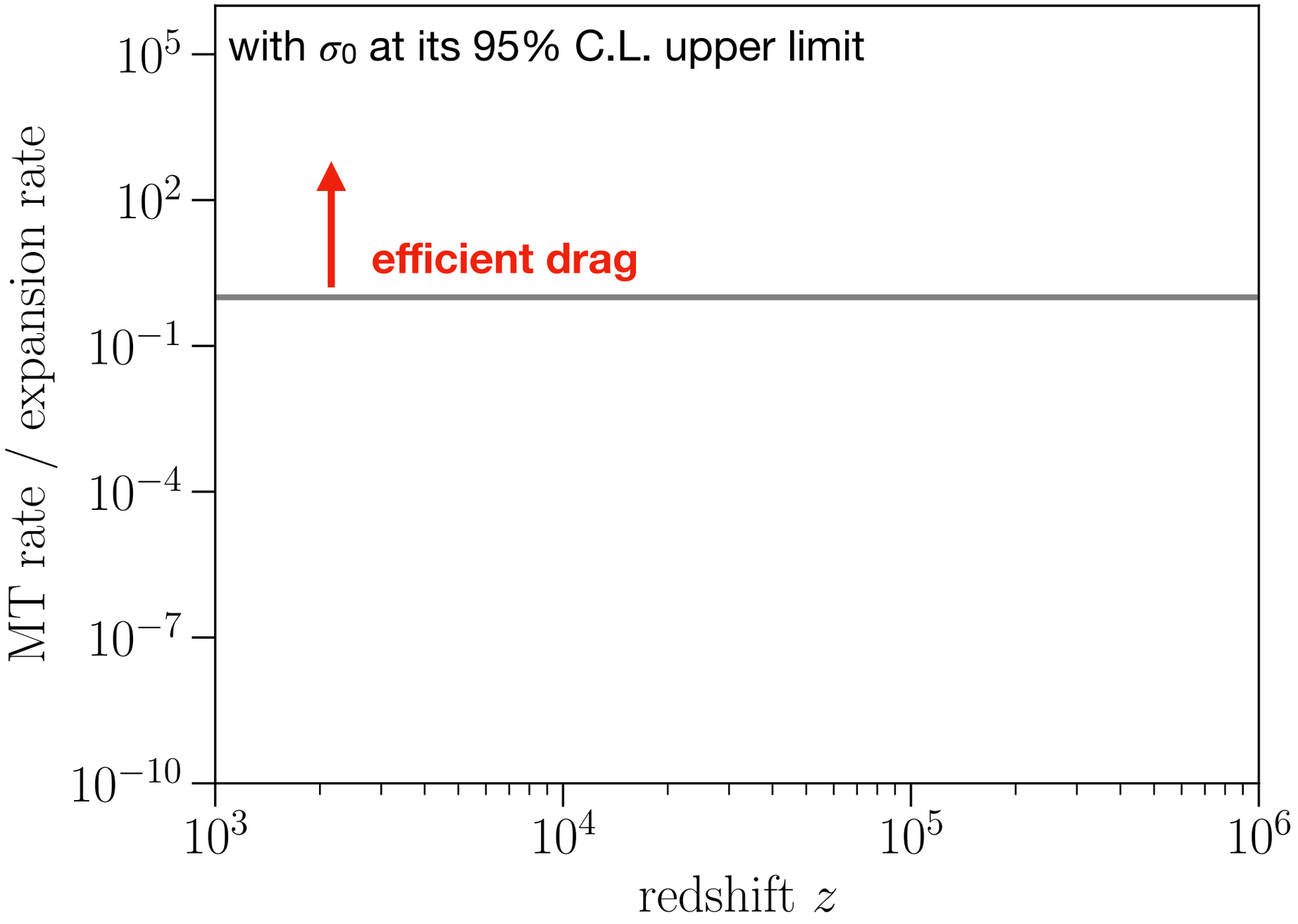


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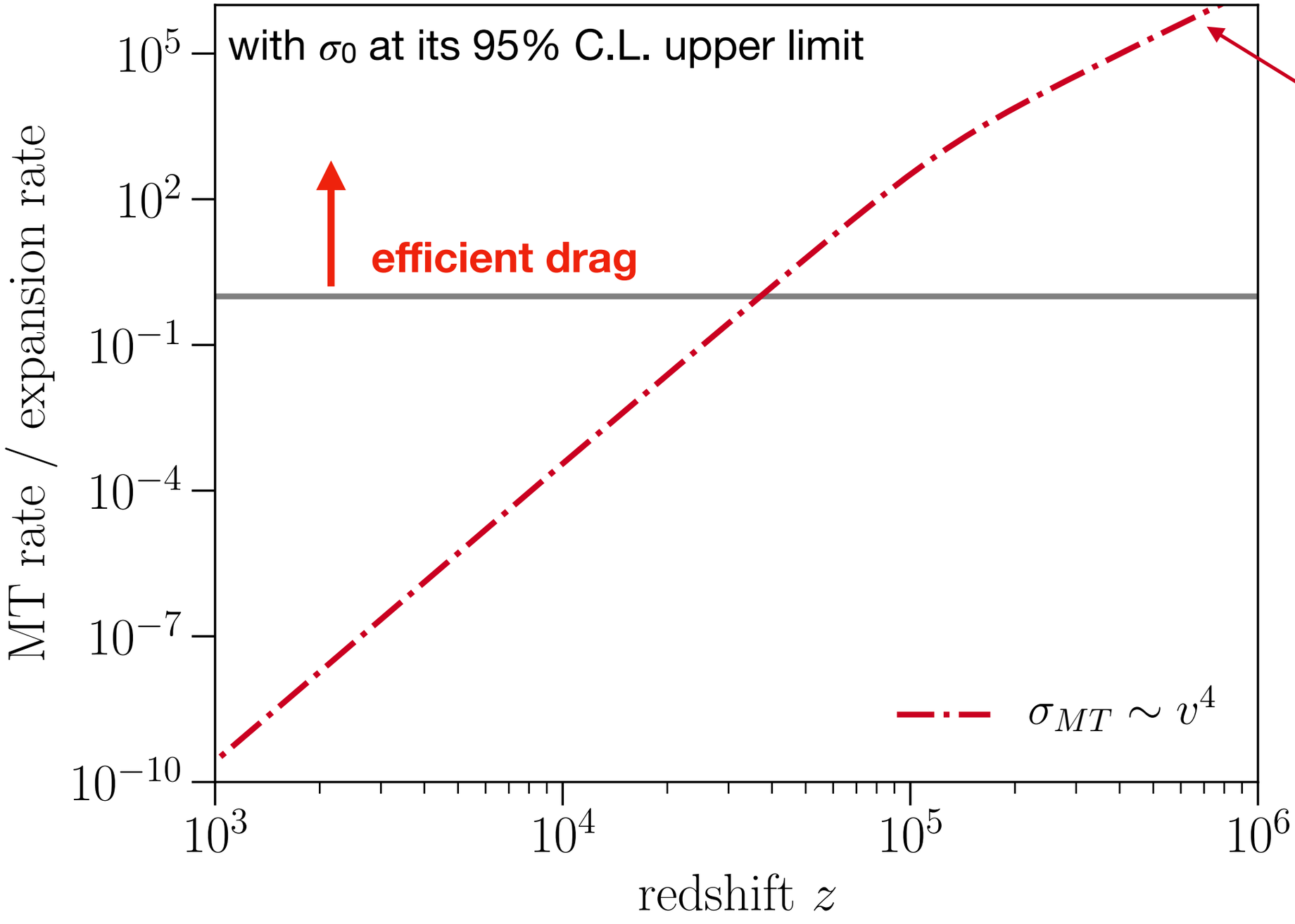


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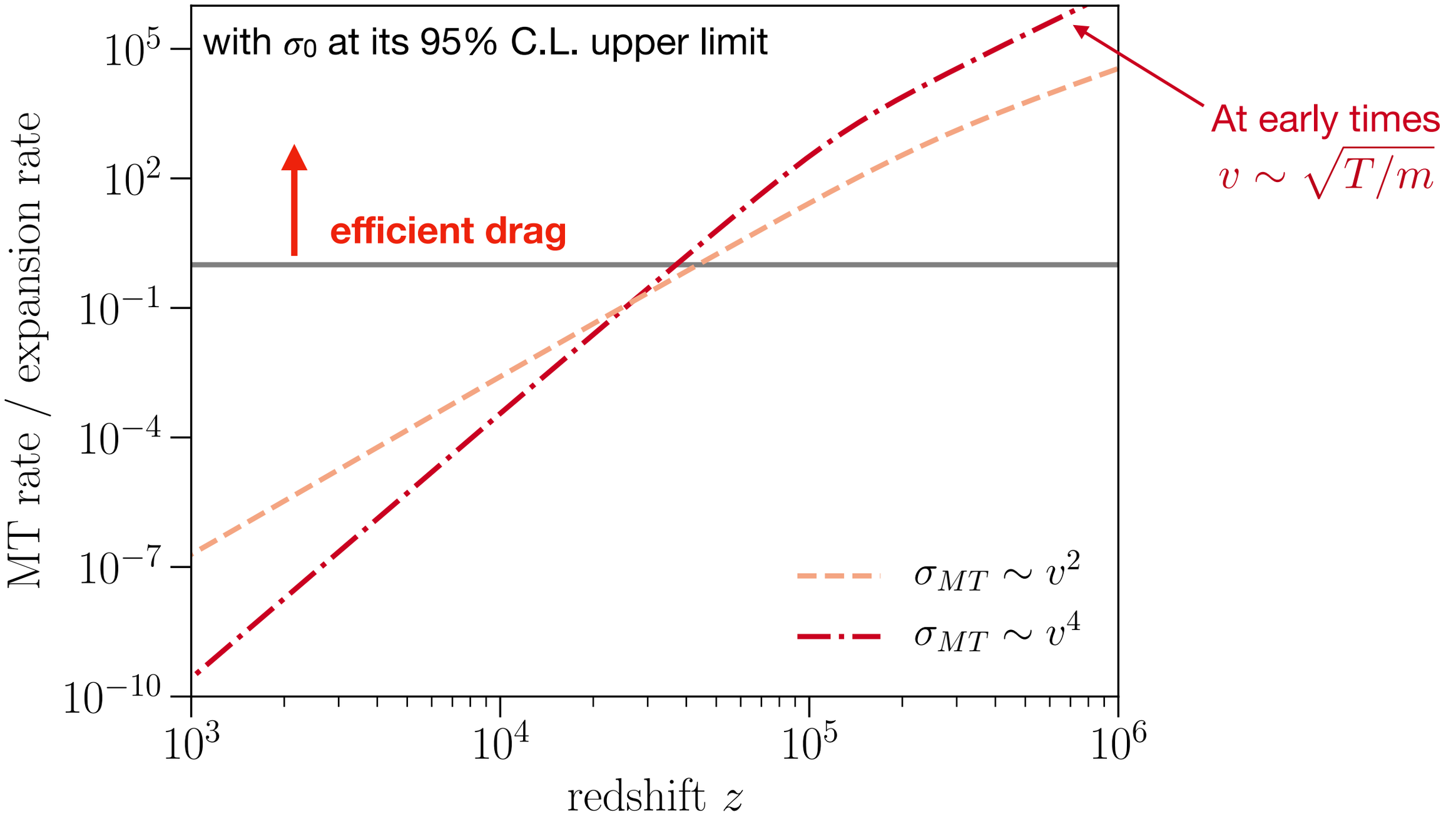


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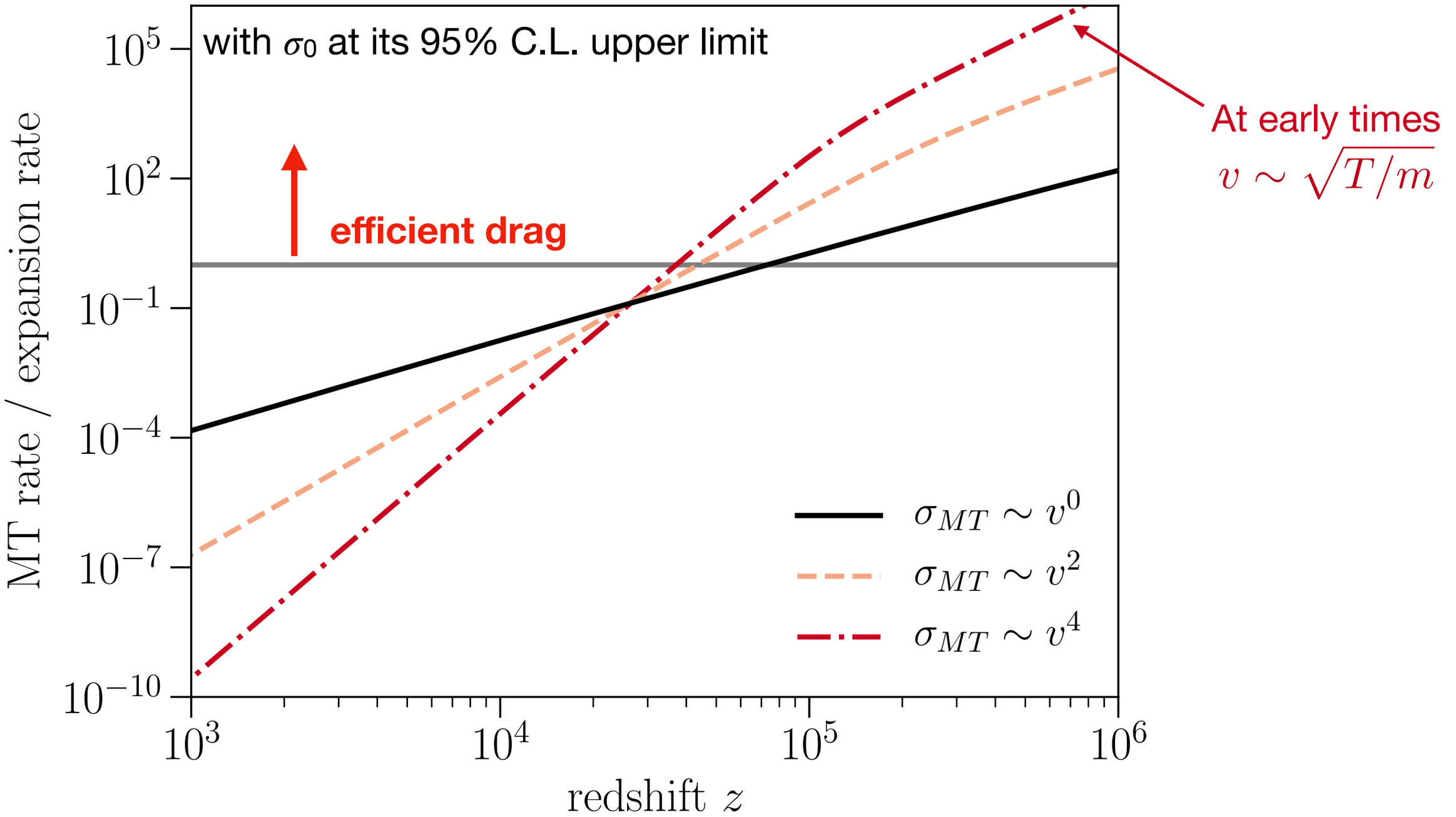


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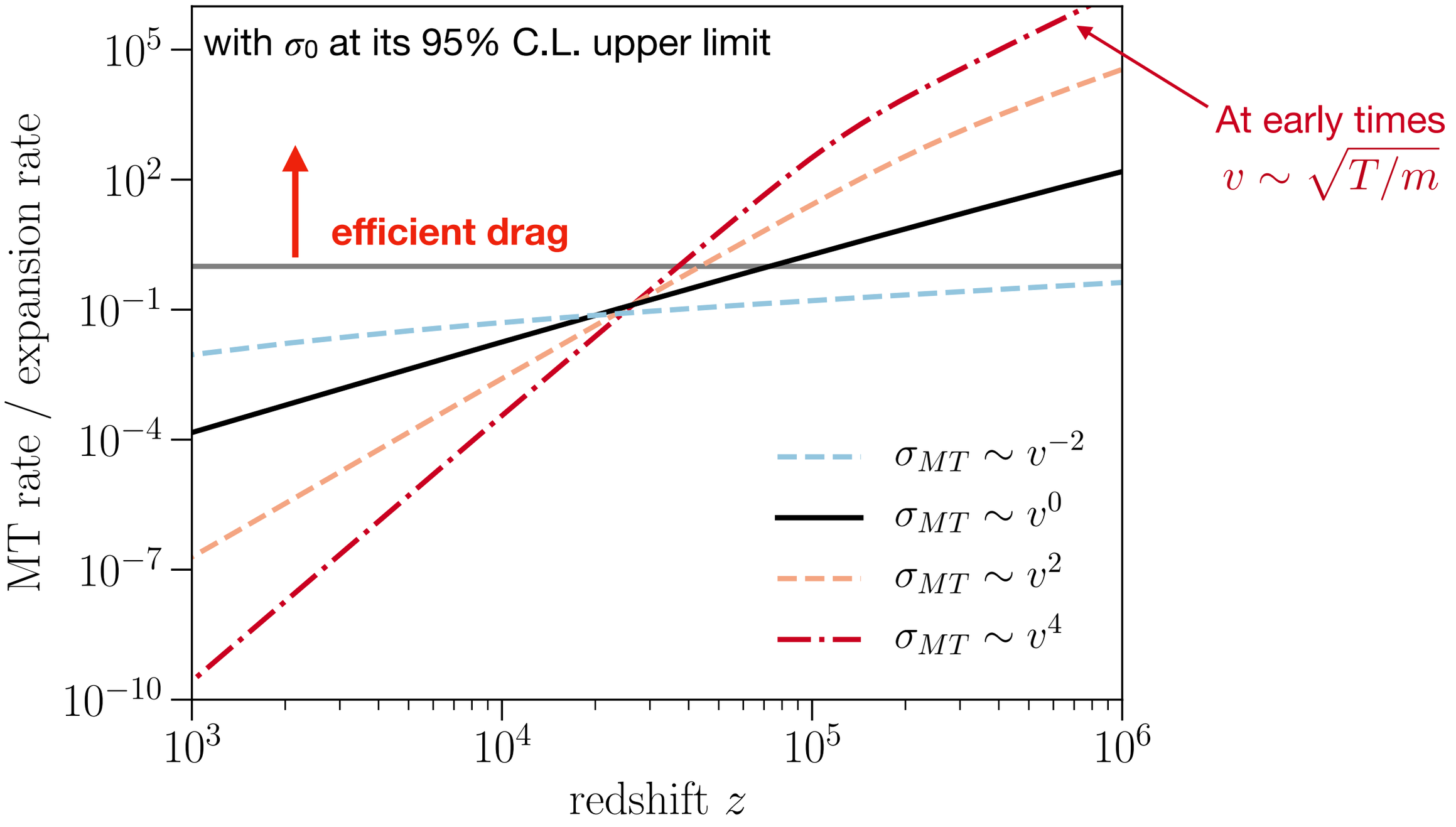


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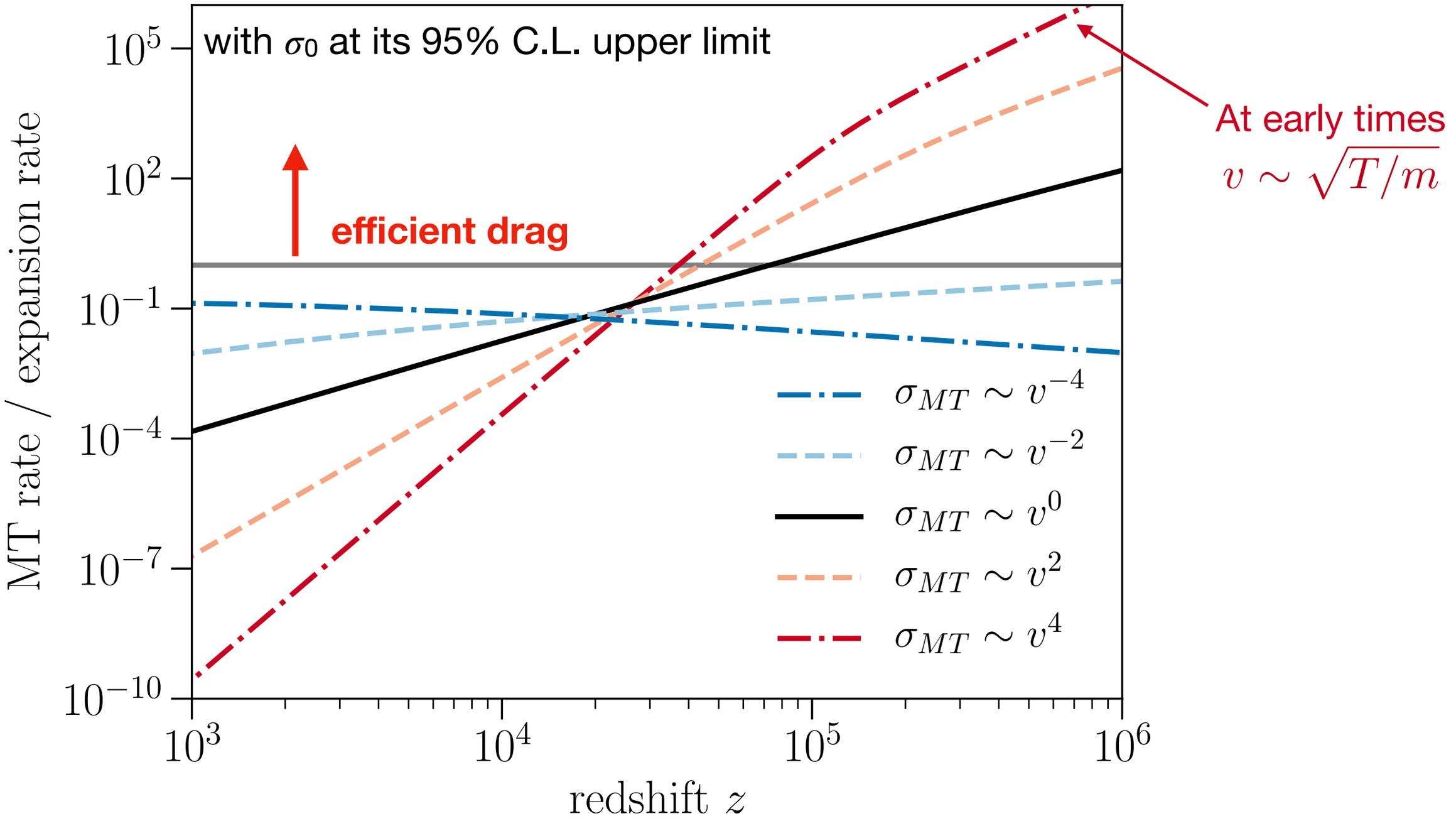


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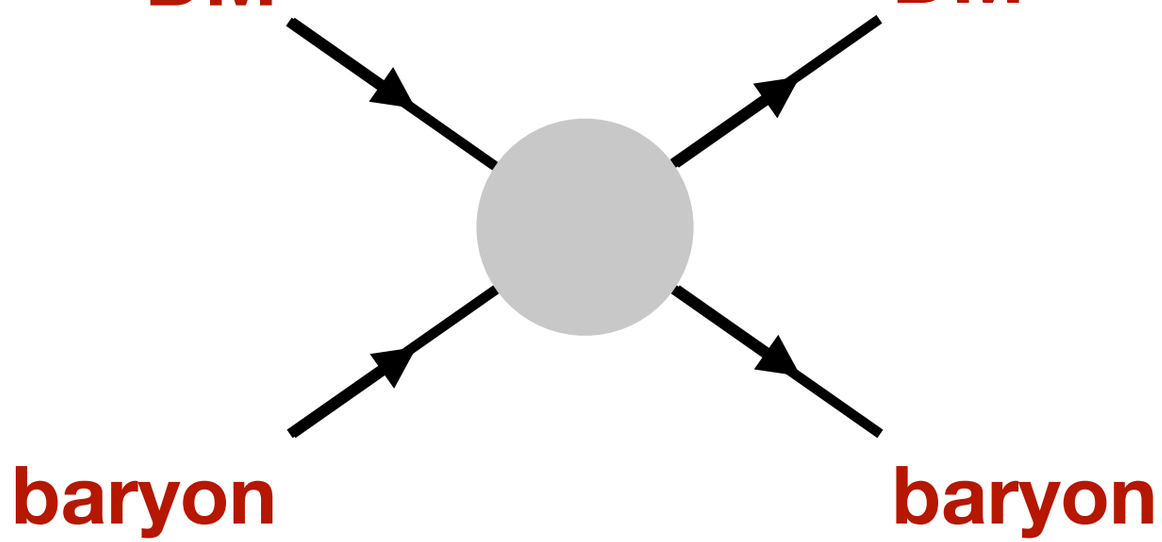
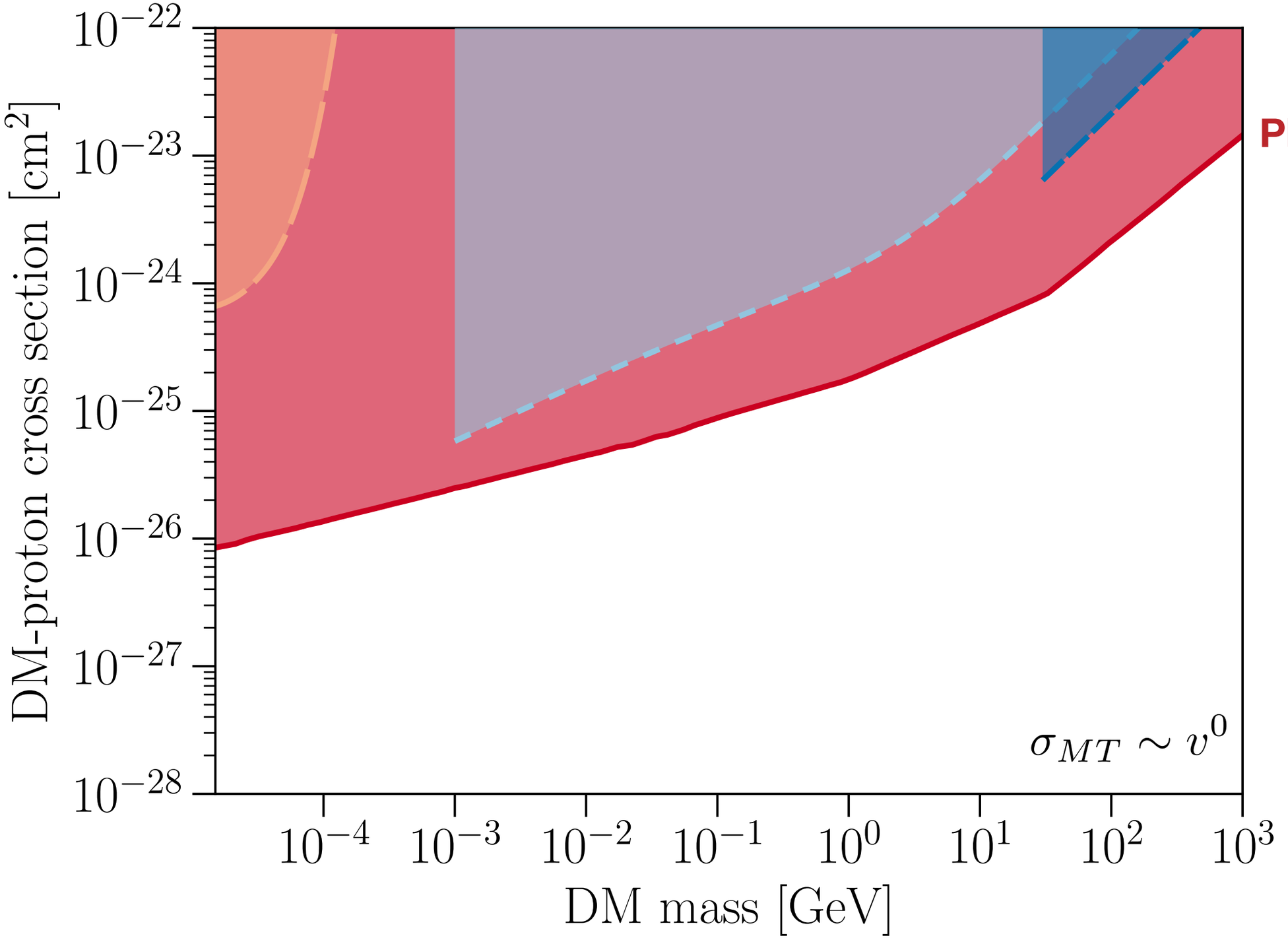
# Interactions via heavy mediators (early-time scattering)



**SI scattering**




**Planck 2015**

Spectral distortions (Ali-Haïmoud et al, 2015)
COBE+2dF (Chen et al., 2002)
Planck 2013 (Dvorkin et al., 2014)

**KB** and Gluscevic (PRL 2017, PRD 2018)

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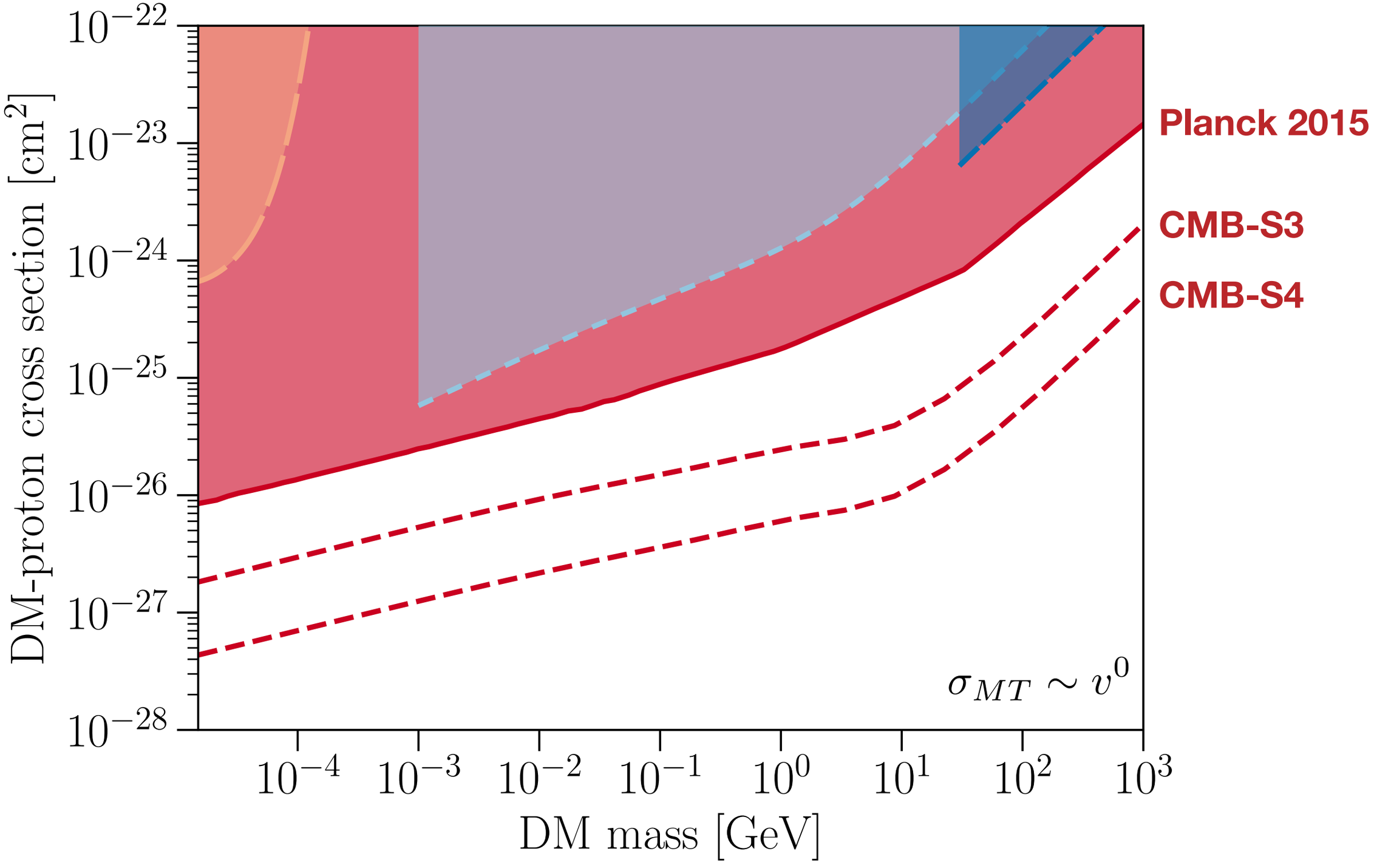


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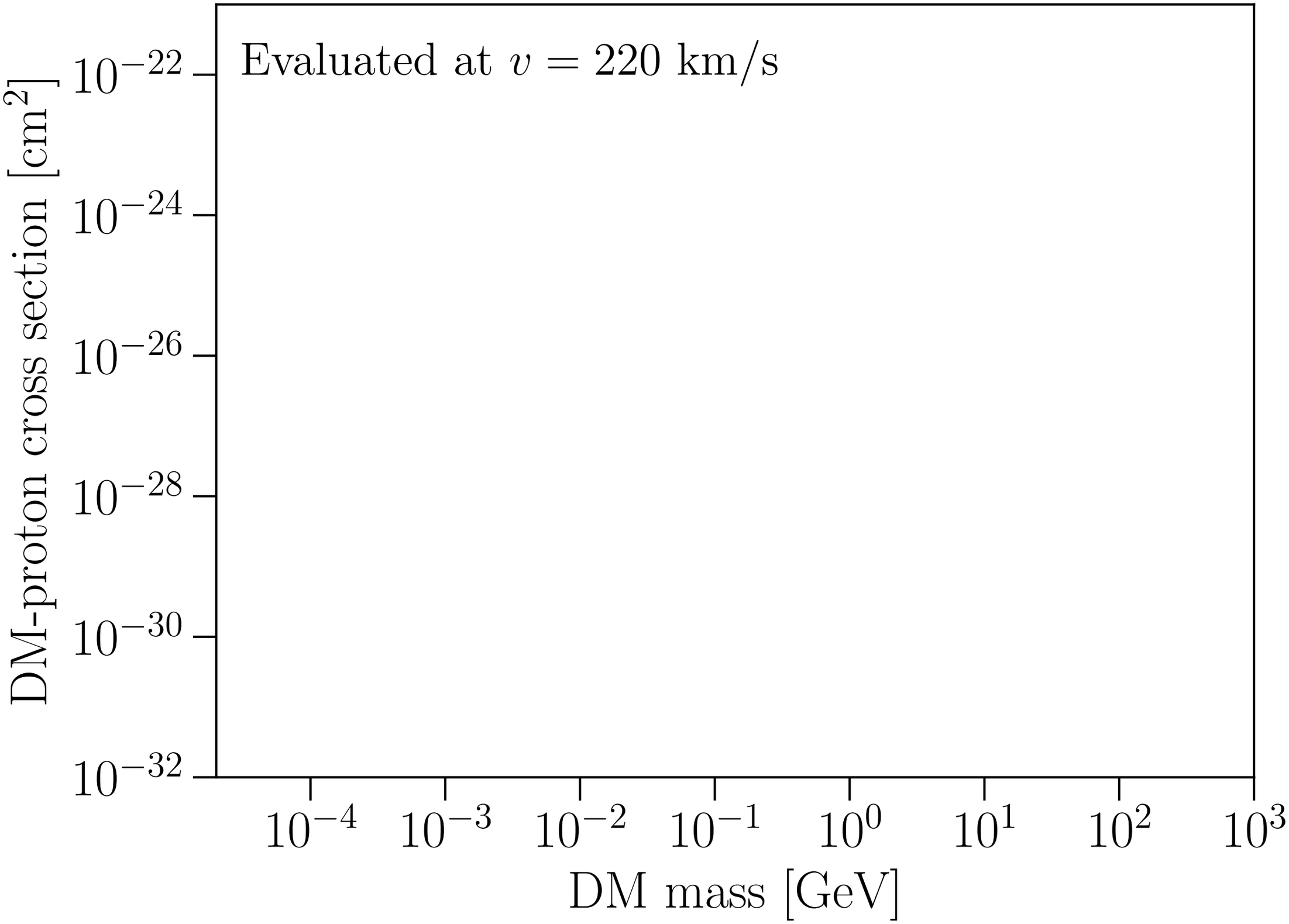
Li, Gluscevic, **KB**, Madhavacheril (2018)

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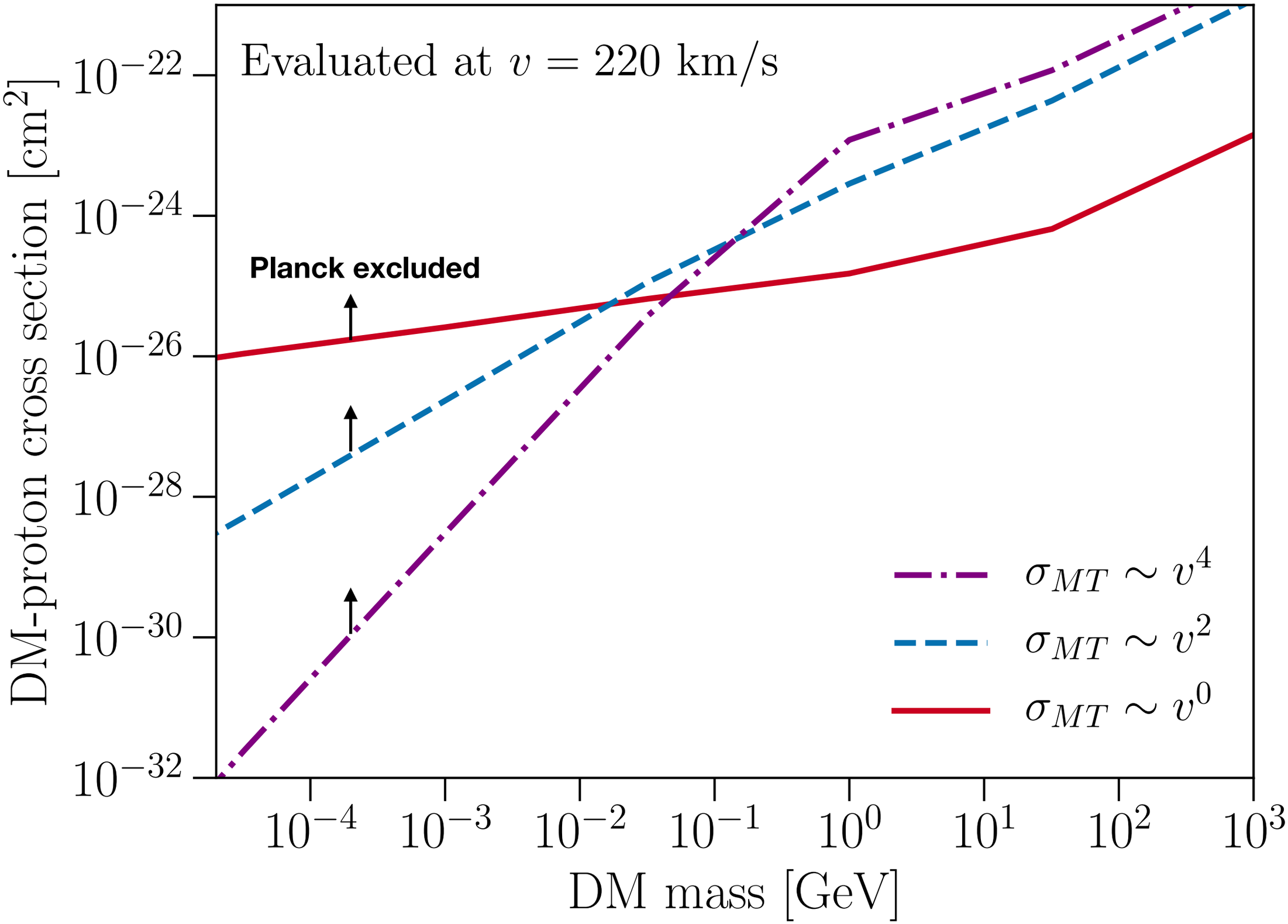
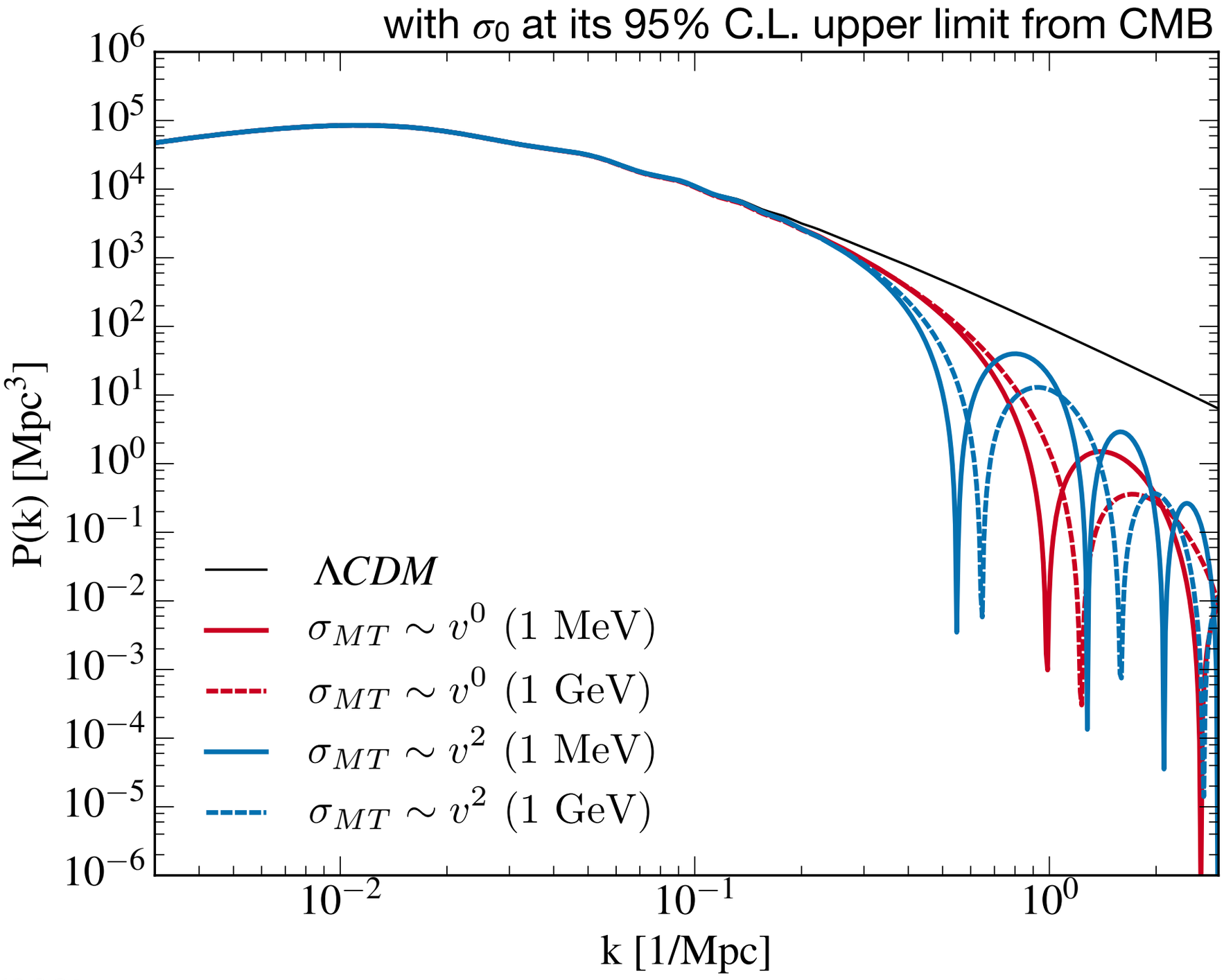



**KB** and Gluscevic (PRD 2018)

# Large Scale Structure

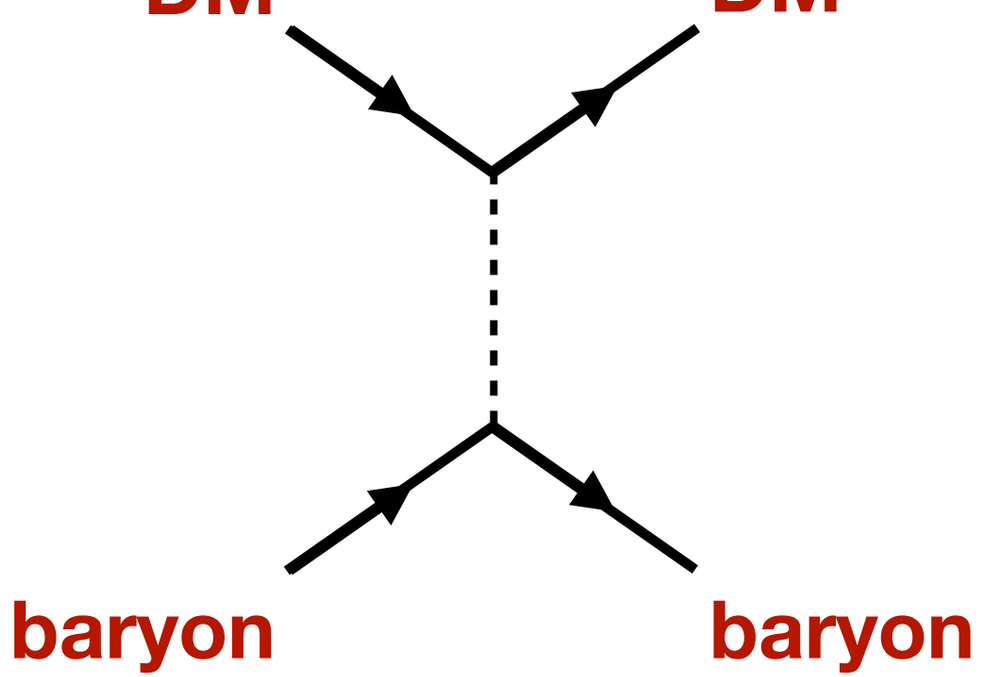



Work in progress:

- Ly-$\alpha$ forest
- Galaxy counts

**KB** and Gluscevic (PRD 2018)

# Interactions via light mediators (late-time scattering)



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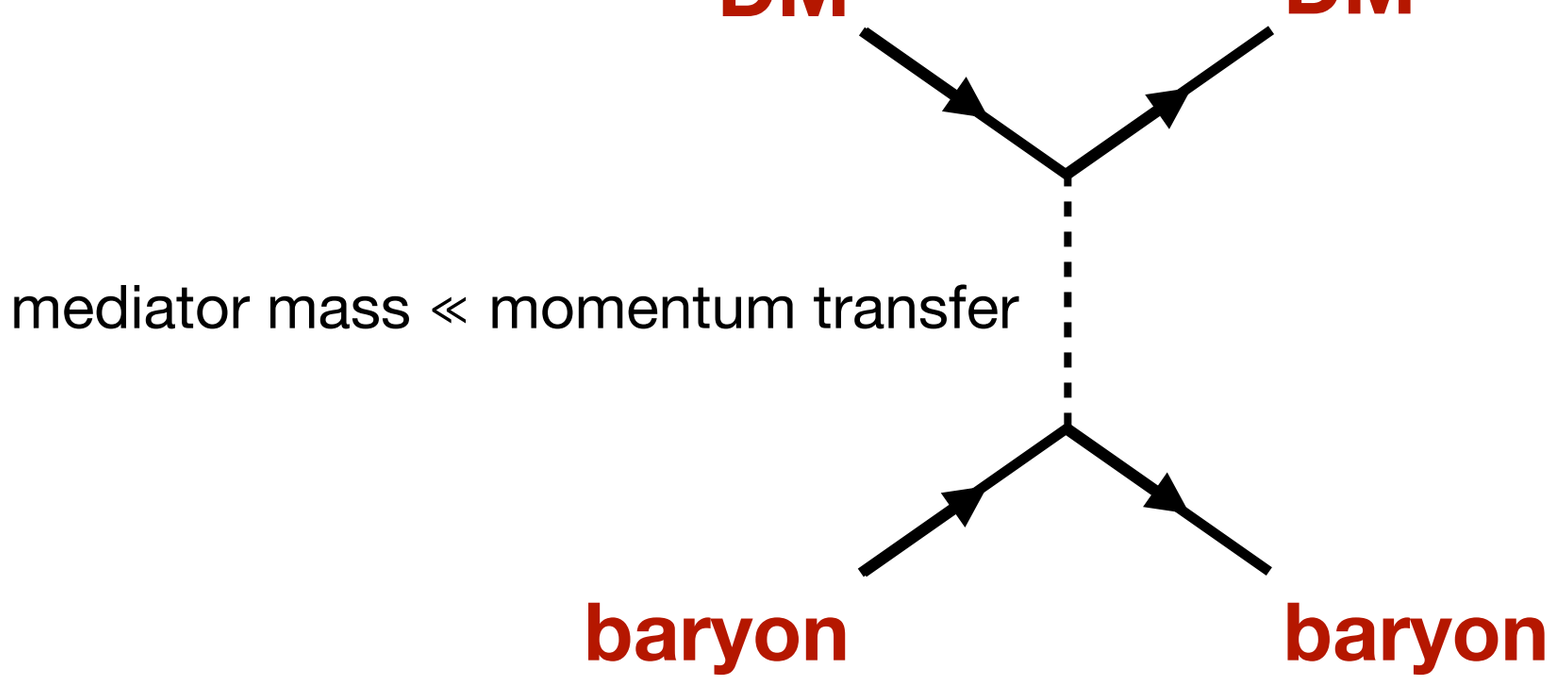

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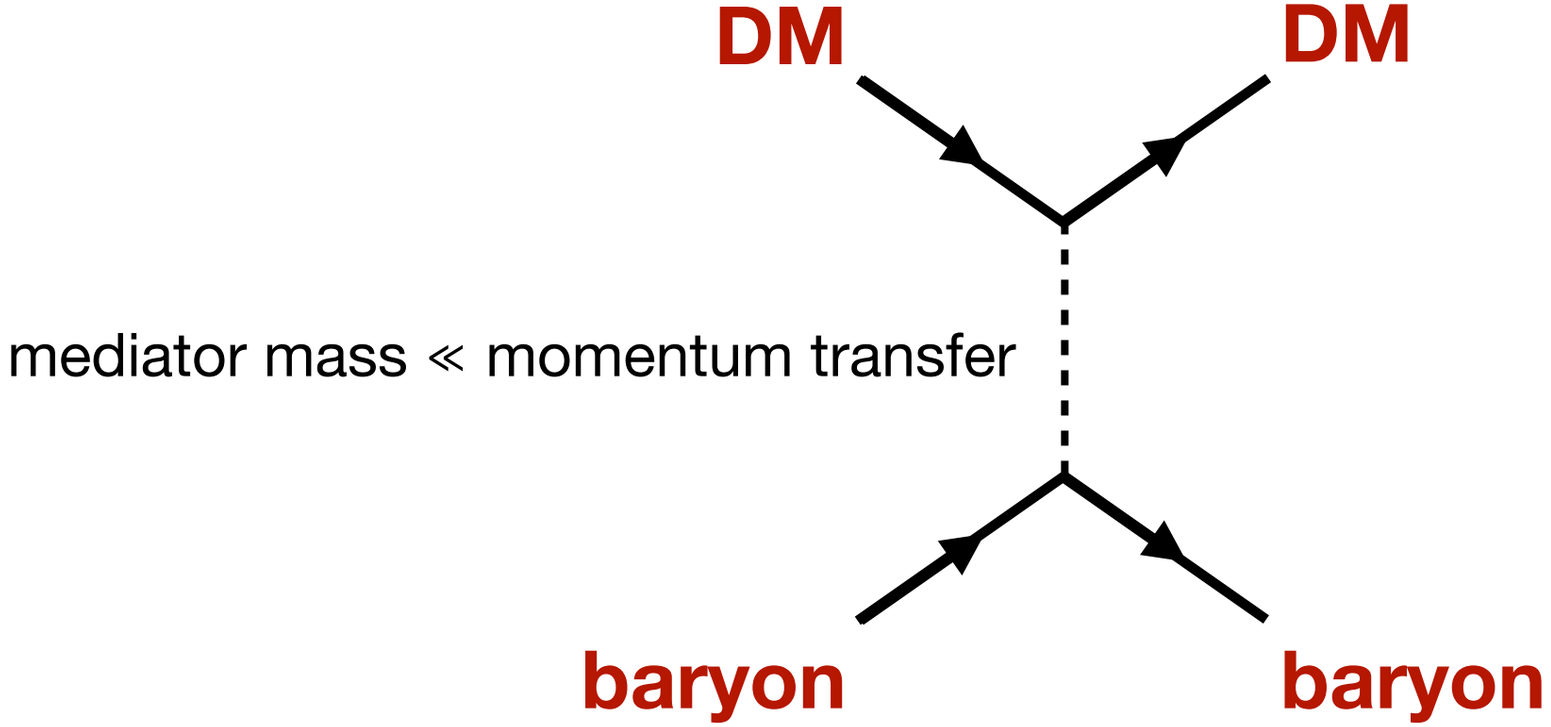
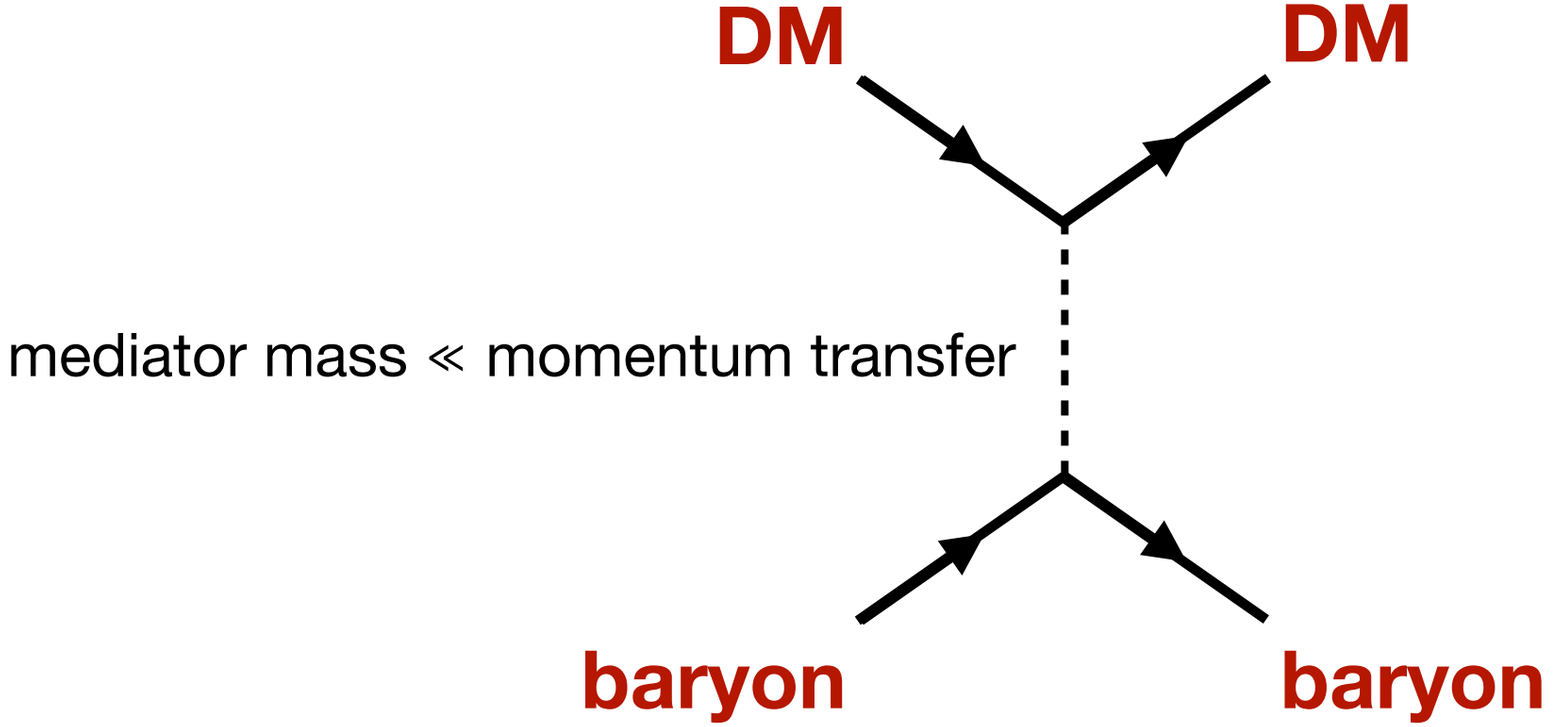



DM with electric/magnetic dipole moment

$$\sigma_{MT} \sim v^{-2}$$

# Interactions via light mediators (late-time scattering)




DM with electric/magnetic dipole moment

$$\sigma_{MT} \sim v^{-2}$$

DM with Coulomb-like interaction

$$\sigma_{MT} \sim v^{-4}$$

# Bulk Velocity

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

**KB**+ (PRD 2018)

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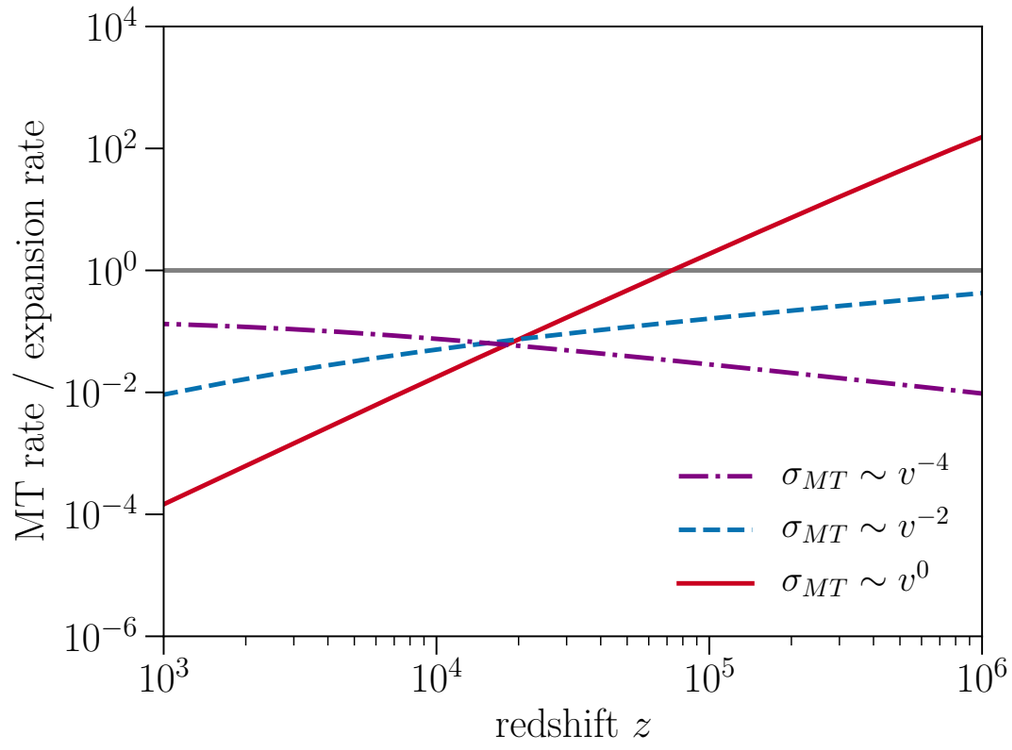
- Expect small (large) cross sections at early (late) times, but reconsider relative velocity




**KB**+ (PRD 2018)

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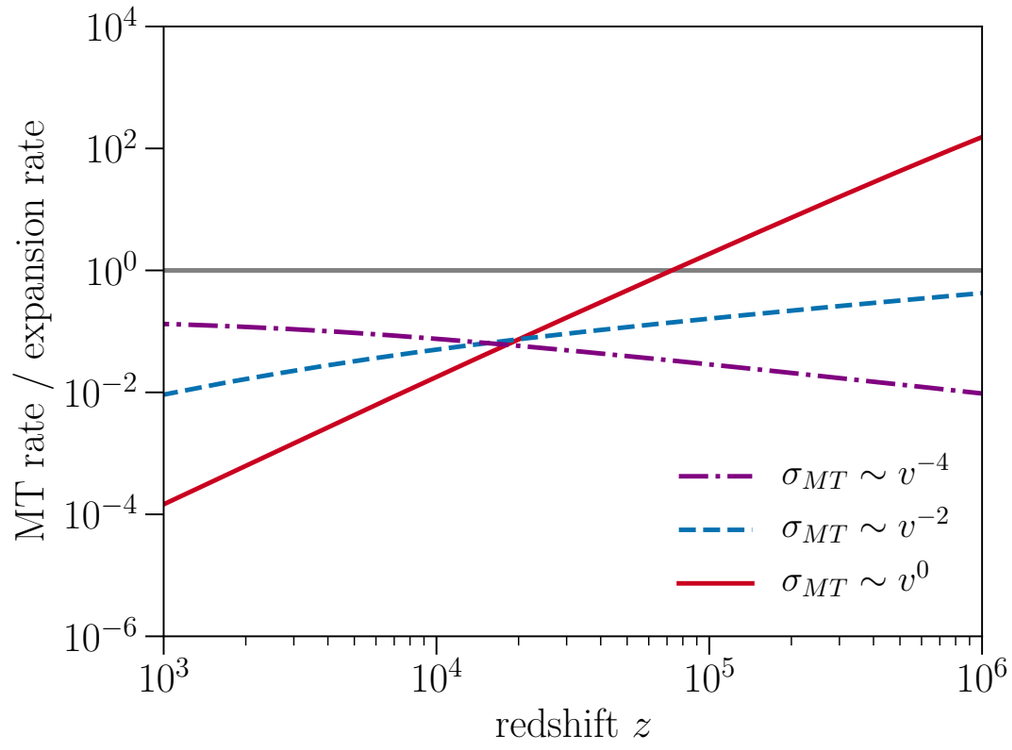
$$|\vec{V}_{\rm DM} - \vec{V}_b|^2 \ll \bar{v}_{\rm th}^2$$

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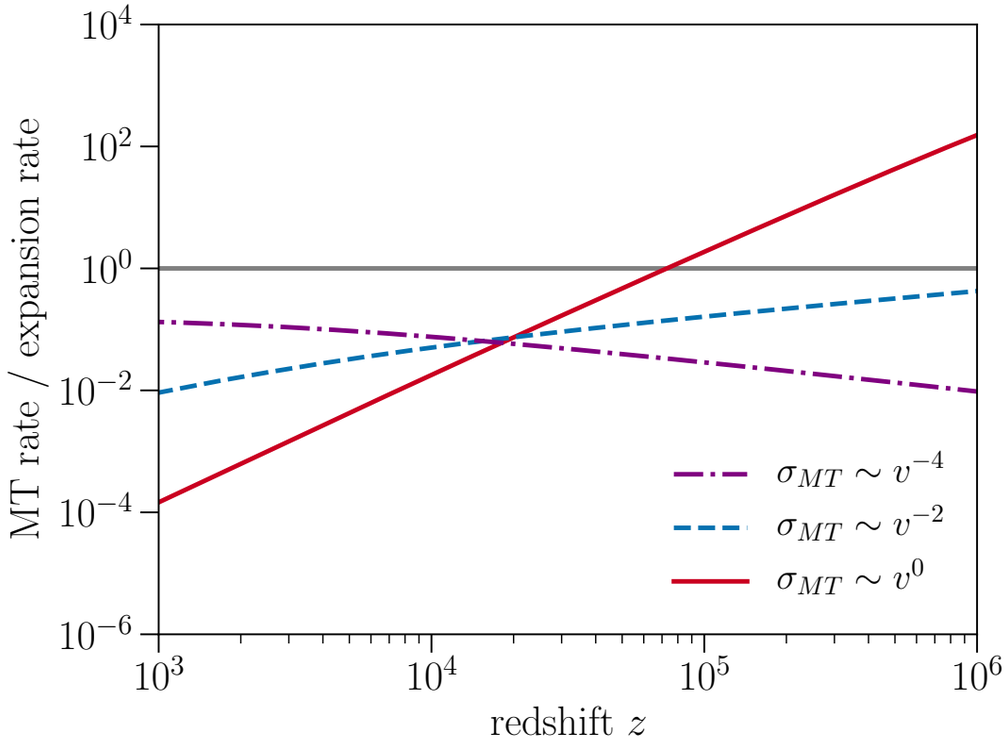


**KB**+ (PRD 2018)

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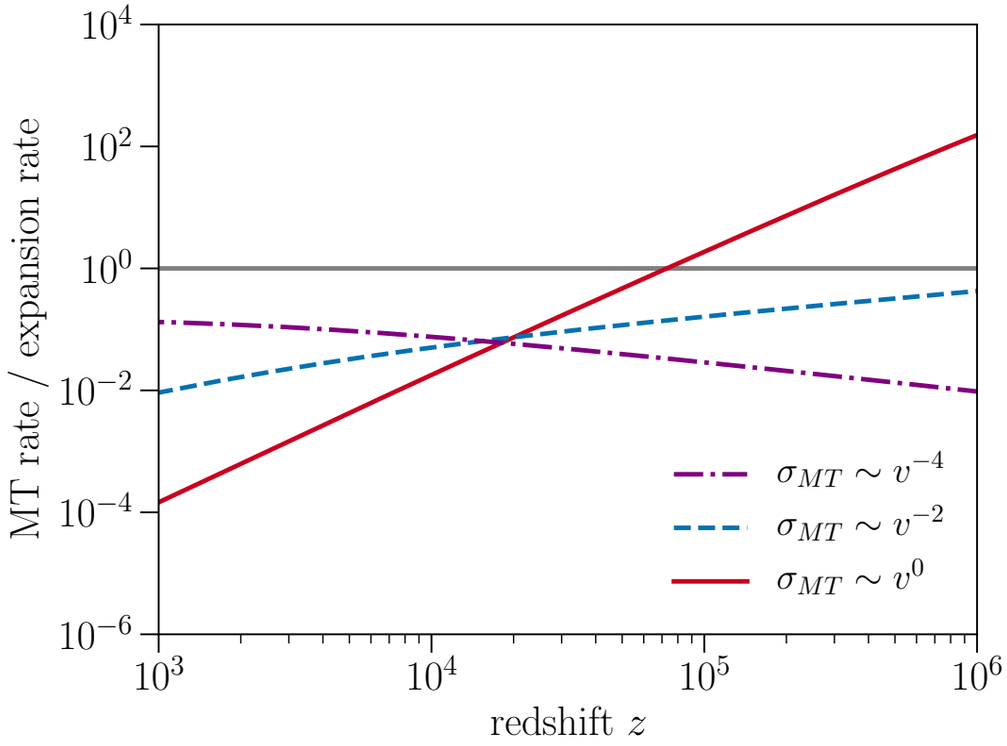
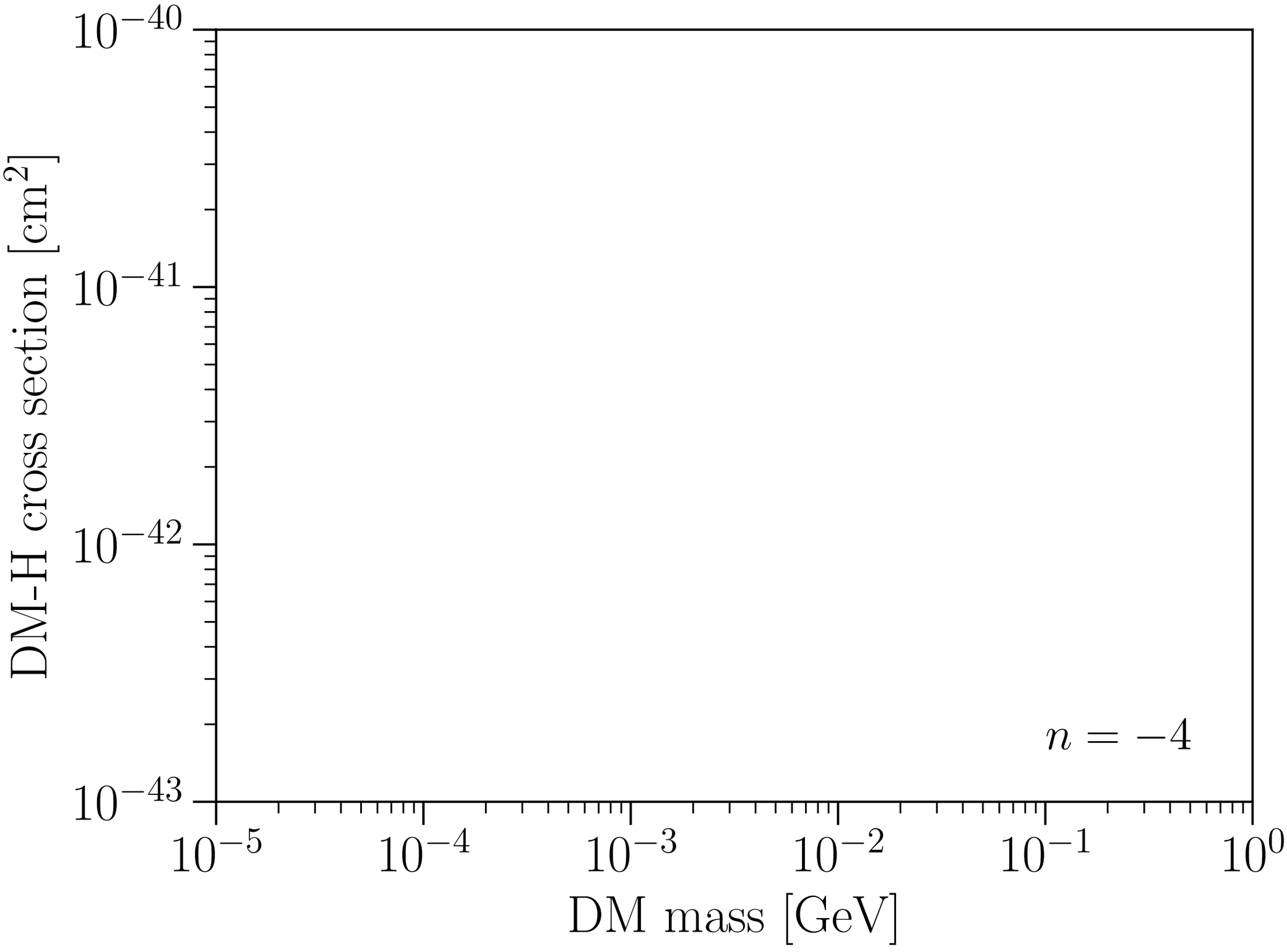
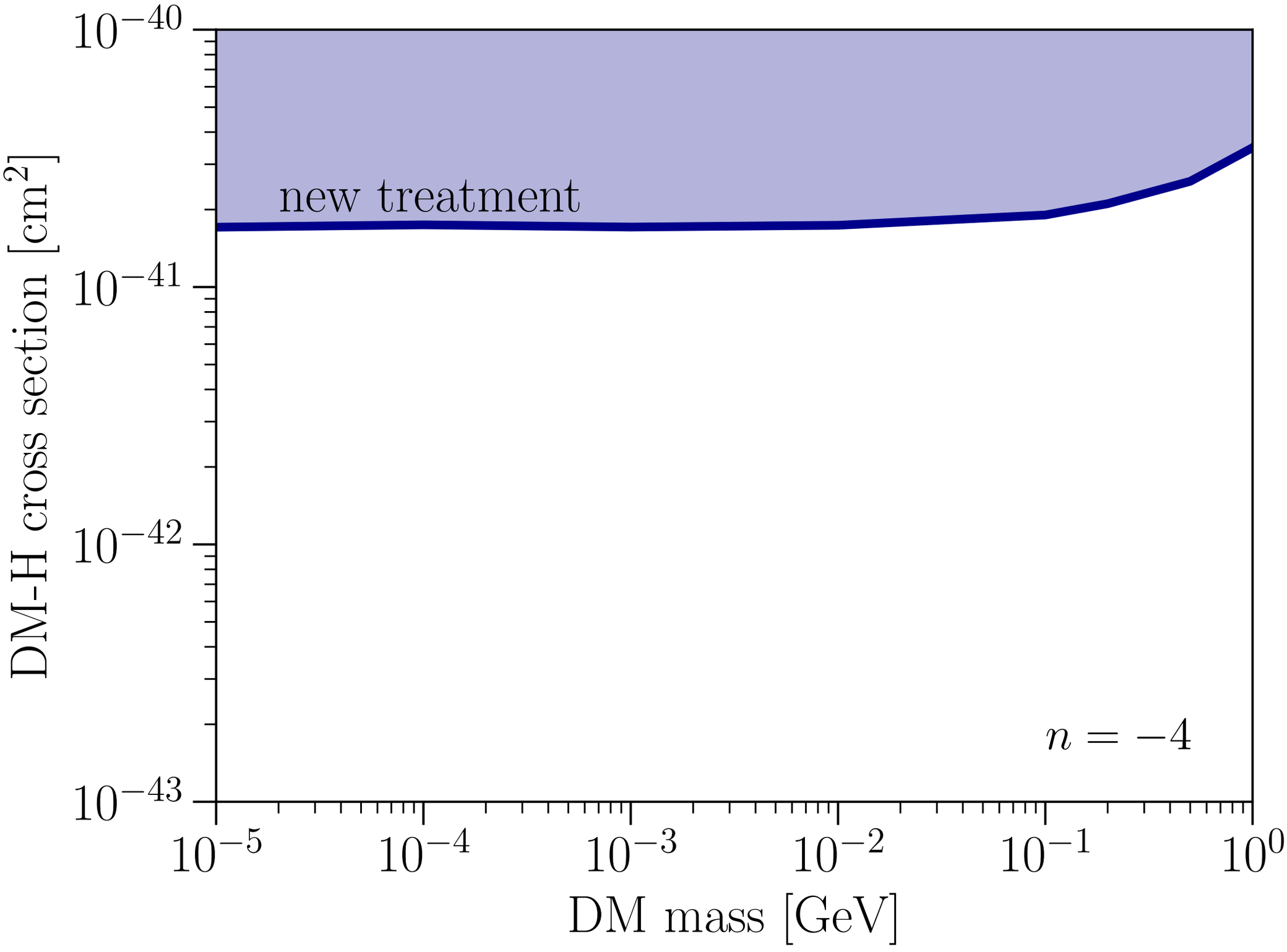
- Introduce new treatment of bulk velocities



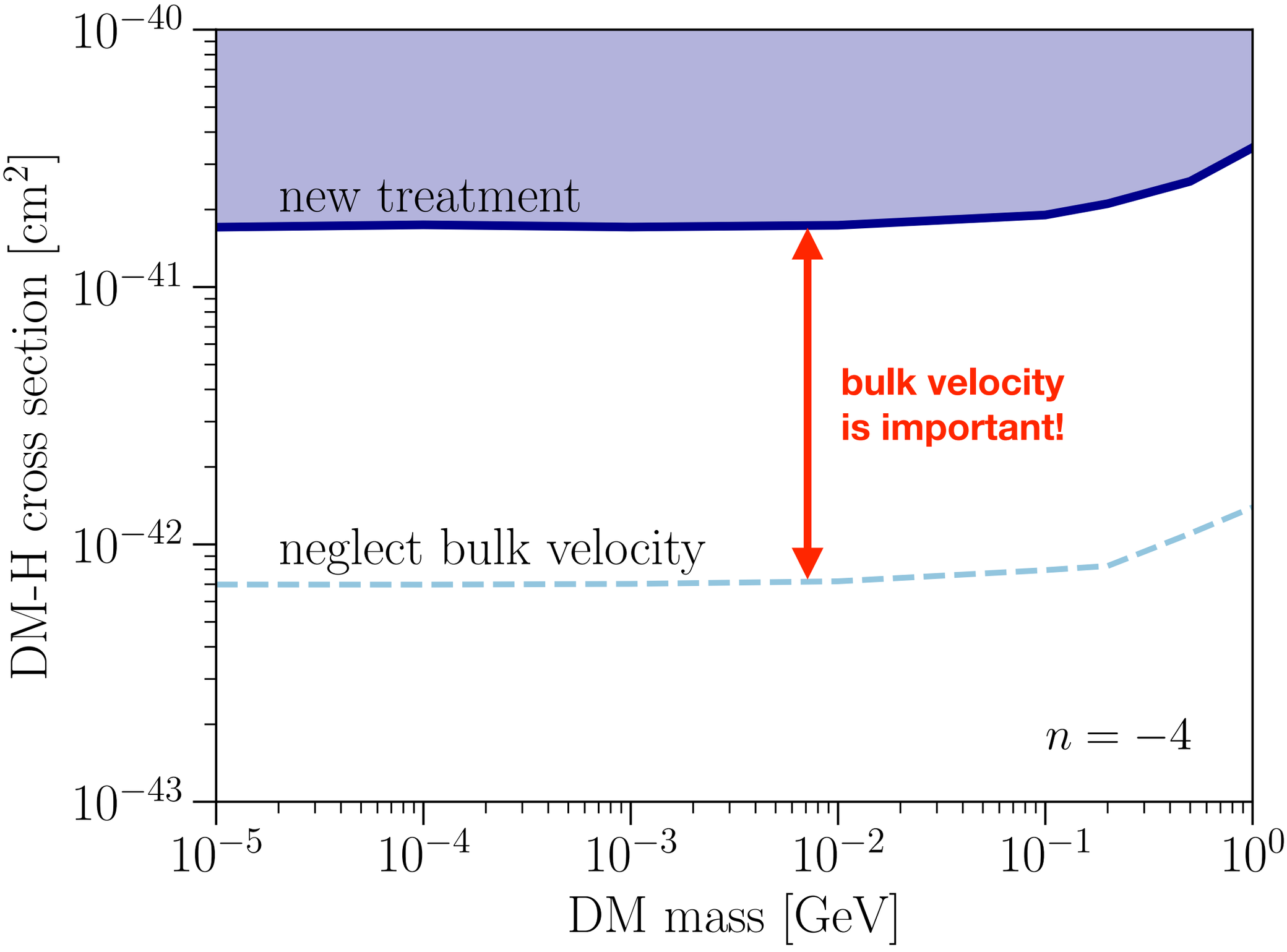

**KB**+ (PRD 2018)


$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
DM-H cross section [cm$^2$]
$n = -4$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
DM mass [GeV]

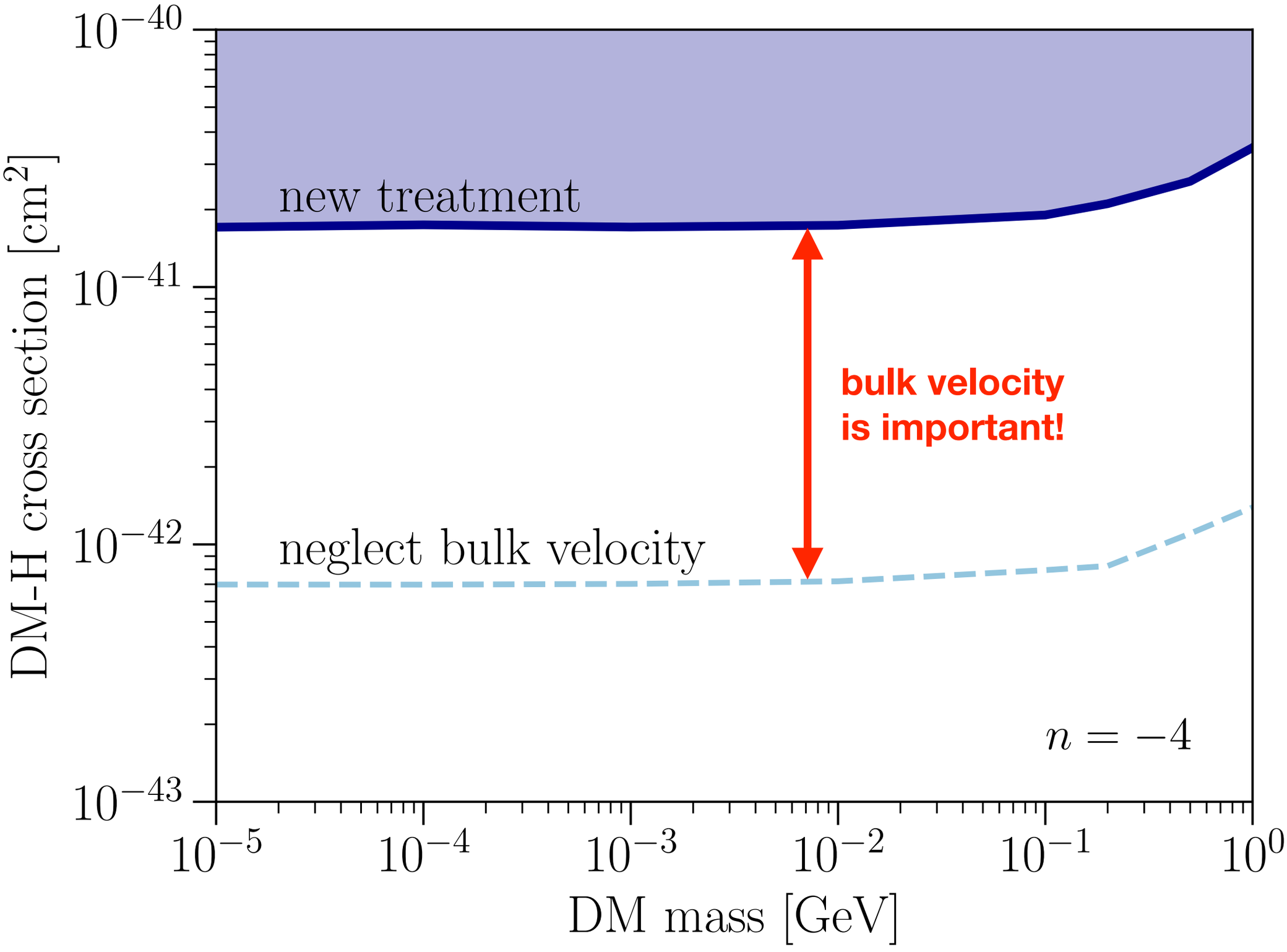
**KB**+ (PRD 2018)


new treatment
$n = -4$
DM-H cross section [cm$^2$]
DM mass [GeV]
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$

**KB**+ (PRD 2018)


$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
DM-H cross section [cm$^2$]
new treatment
neglect bulk velocity
bulk velocity
is important!
$n = -4$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
DM mass [GeV]

**KB**+ (PRD 2018)

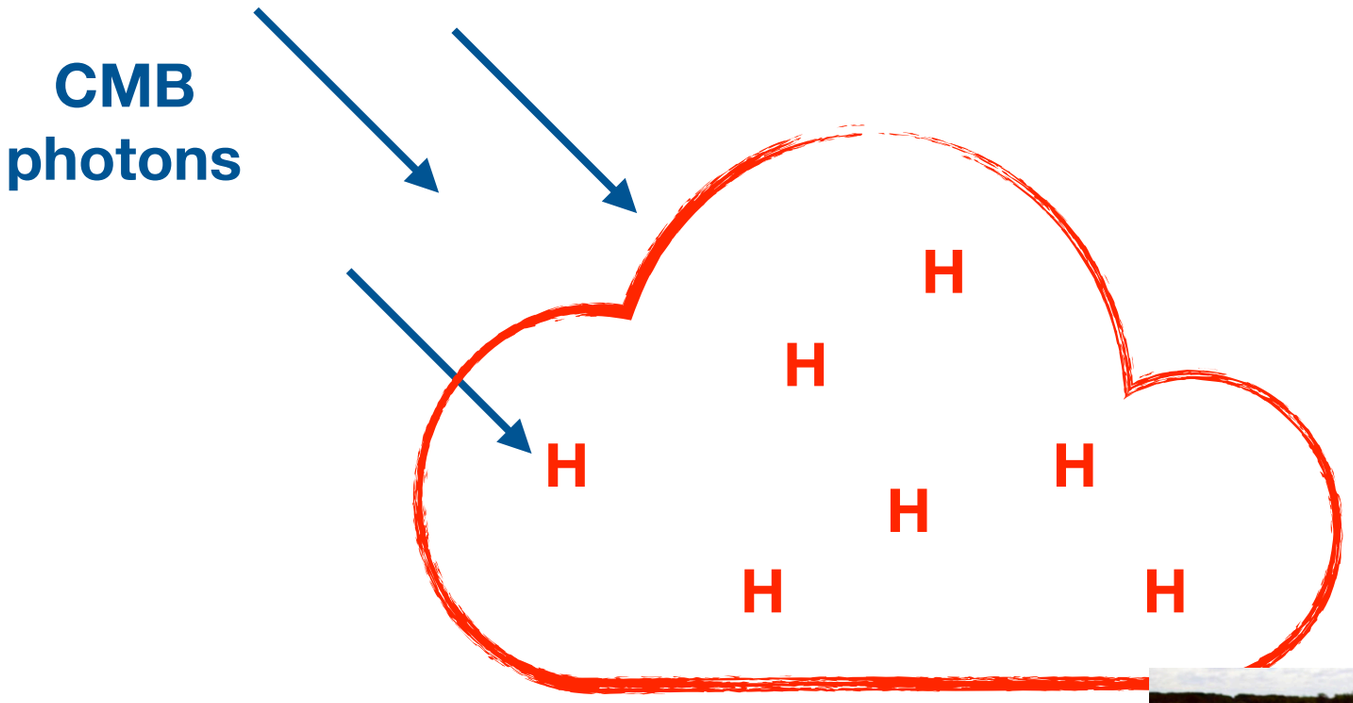



**How do late-time interactions affect other cosmological observables?**

**KB**+ (PRD 2018)

# EDGES Absorption Signal

**E**xperiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature




**Redshift z~17**

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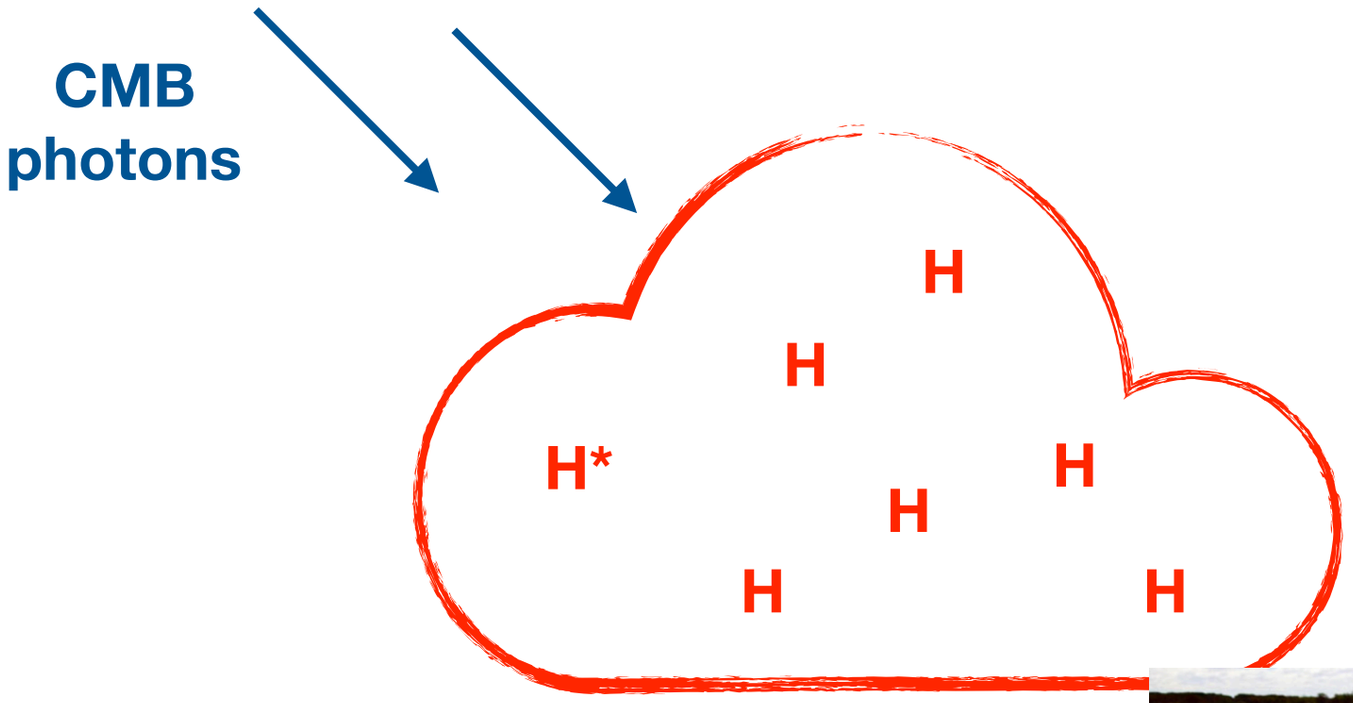


**Excite 21cm hyperfine transition**

**Redshift z~17**

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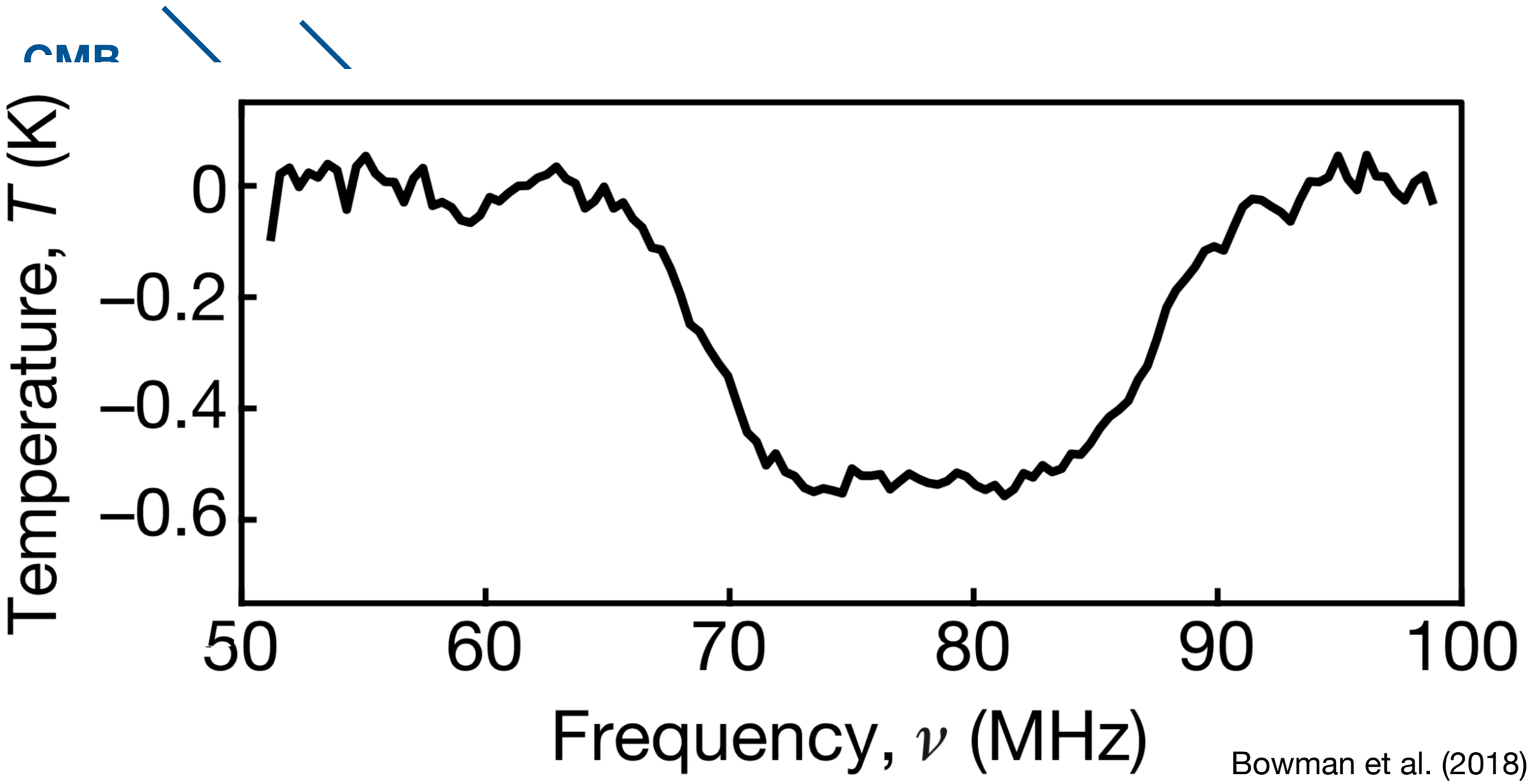
**E**xperiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature



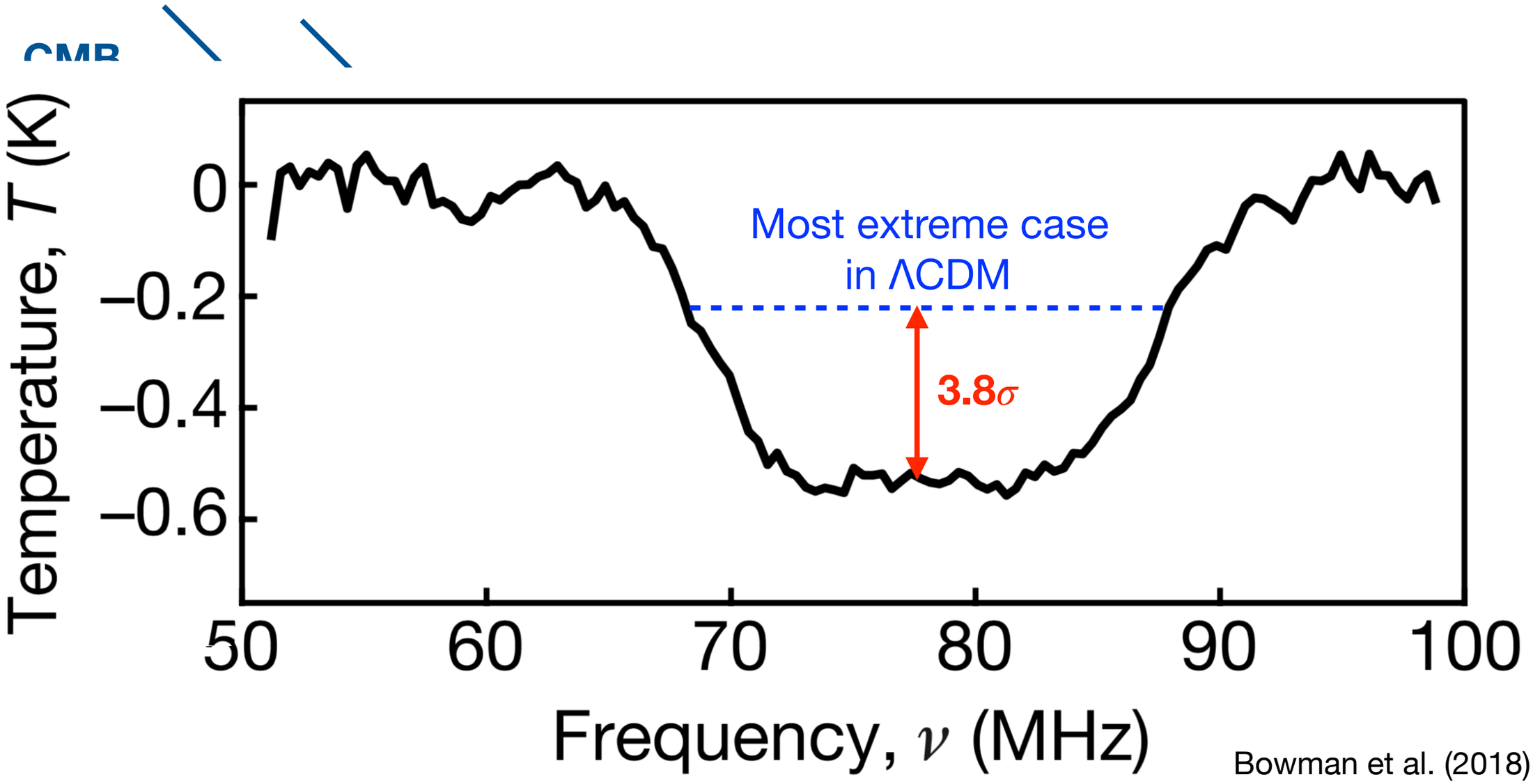

Bowman et al. (2018)

**Redshift z~17**

Bowman et al.

# EDGES Absorption Signal

**E**xperiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature




Bowman et al. (2018)

**Redshift z~17**

Bowman et al.

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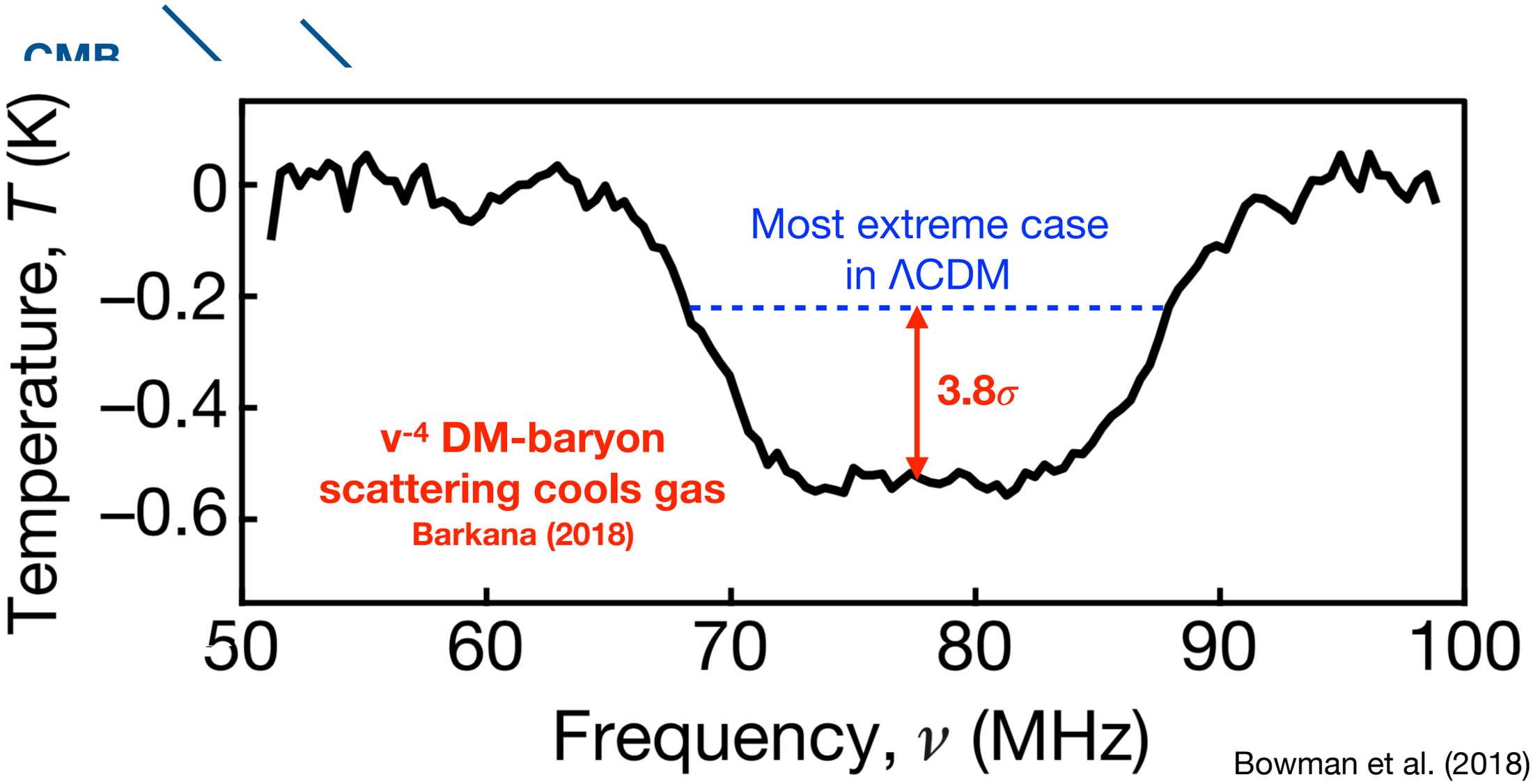
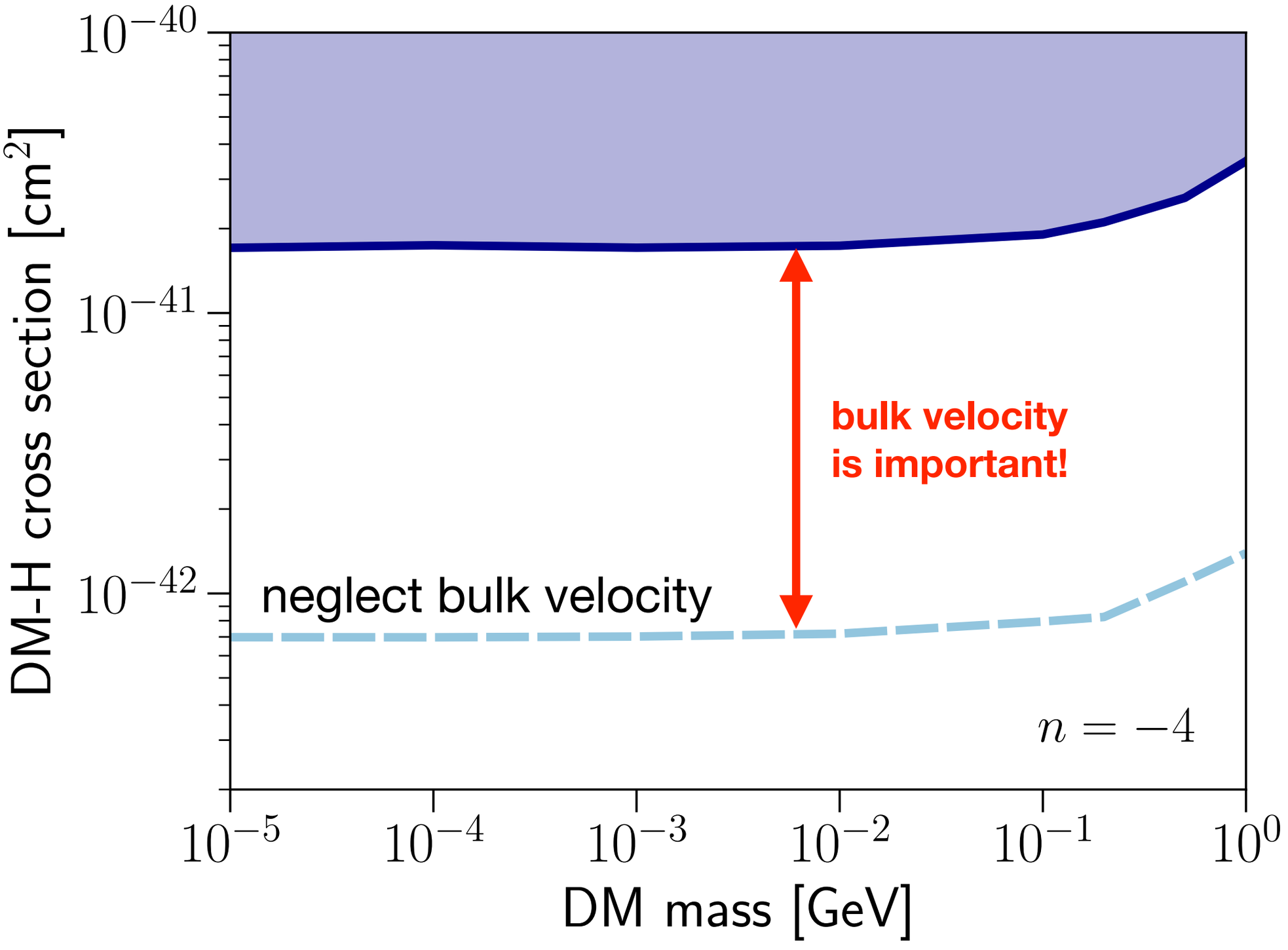



Bowman et al. (2018)

**Redshift z~17**

# Implication for EDGES




**KB**+ (PRD 2018)

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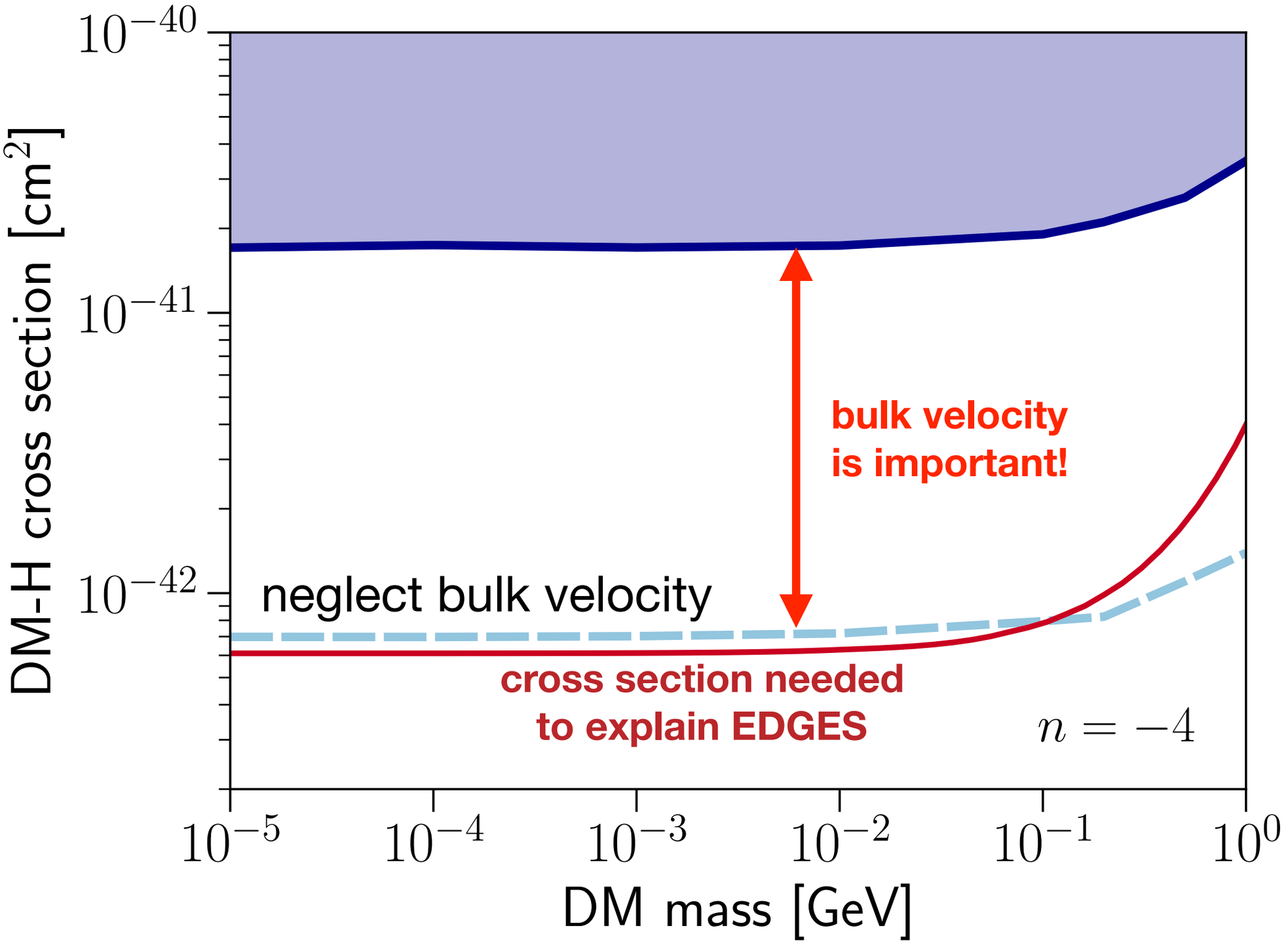


**KB**+ (PRD 2018)

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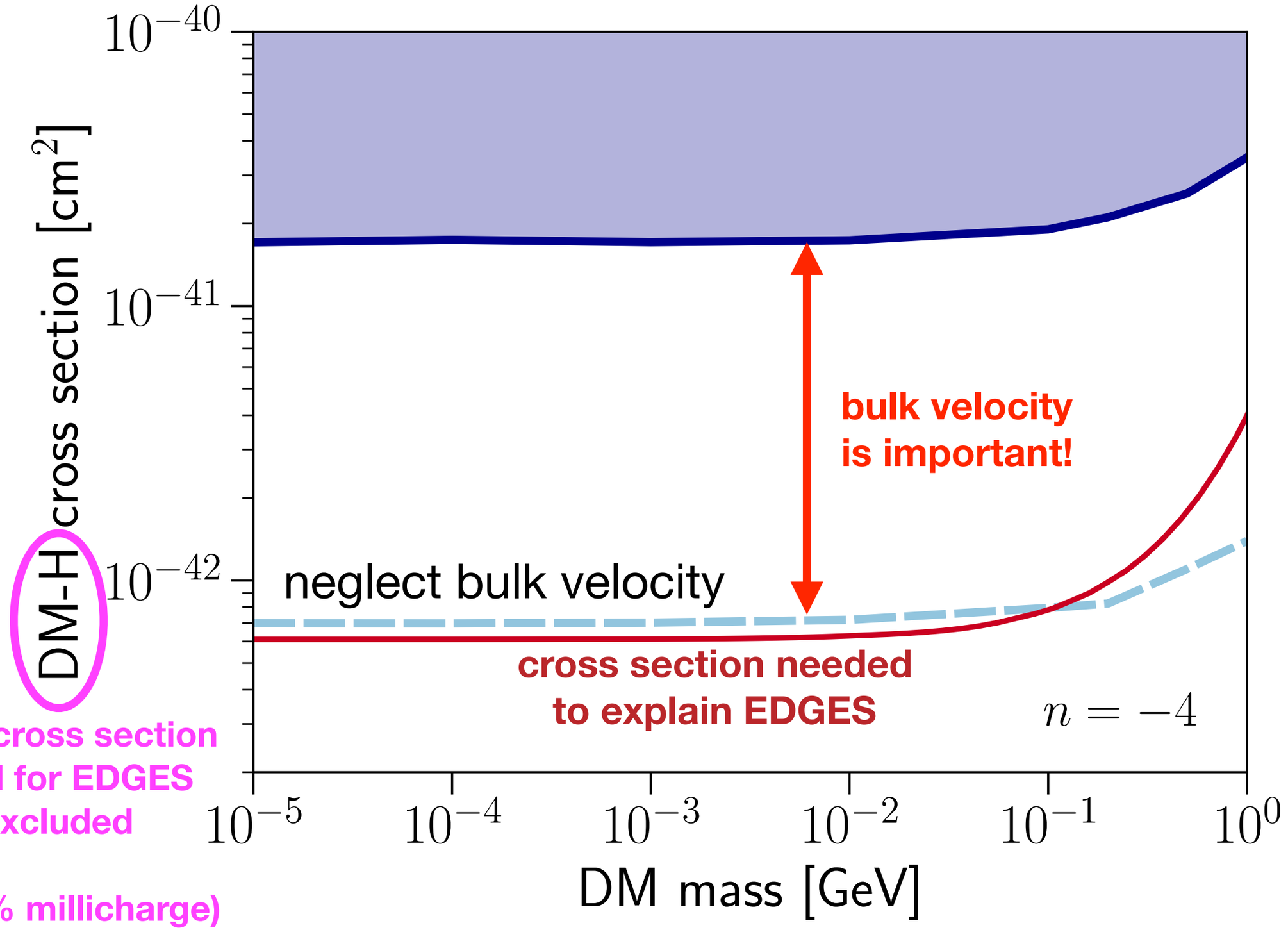


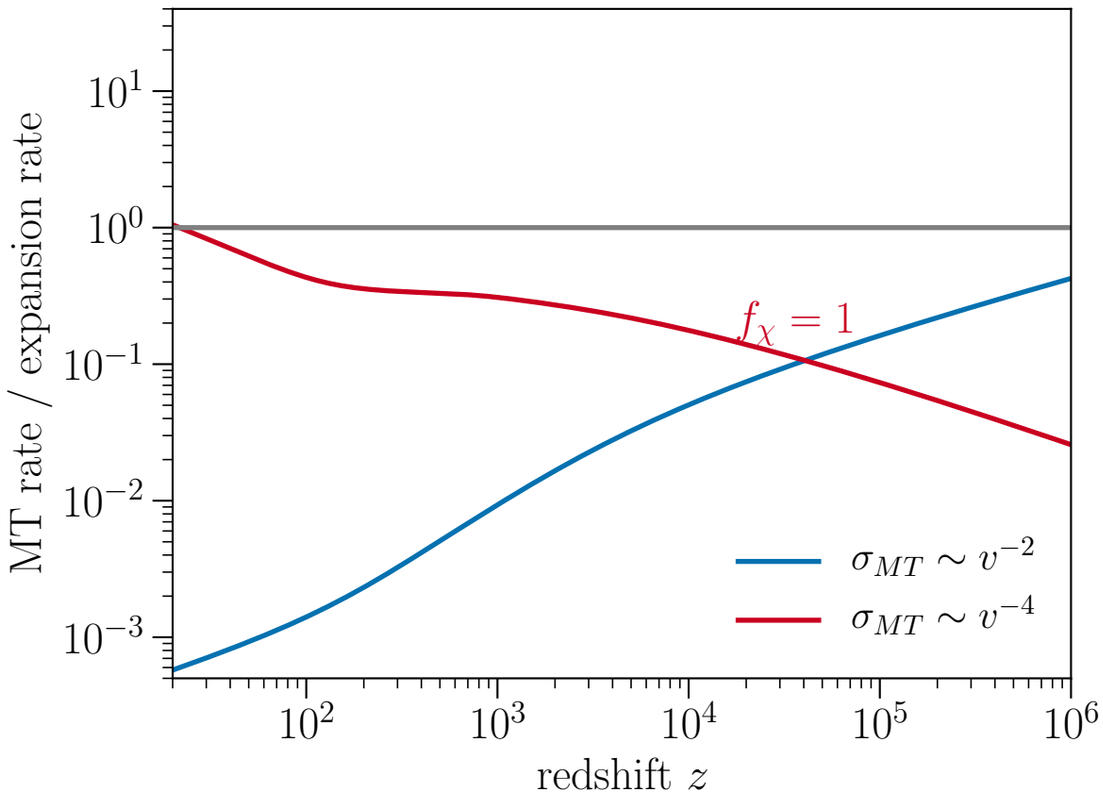

DM-ion cross section needed for EDGES is excluded

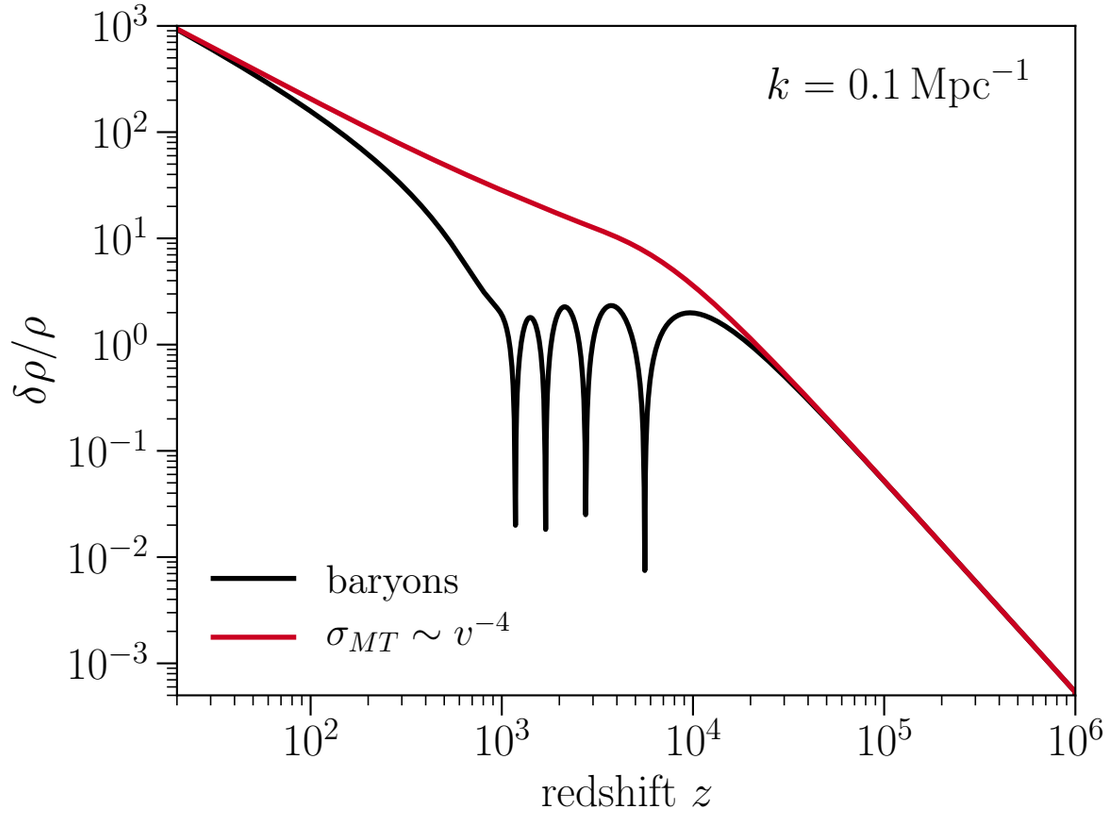
(for 100% millicharge)

see also: Munoz and Loeb (2018), Berlin+ (2018), Barkana+ (2018)

**KB**+ (PRD 2018)

# Fractional Case




**KB**+ (PRD 2018)

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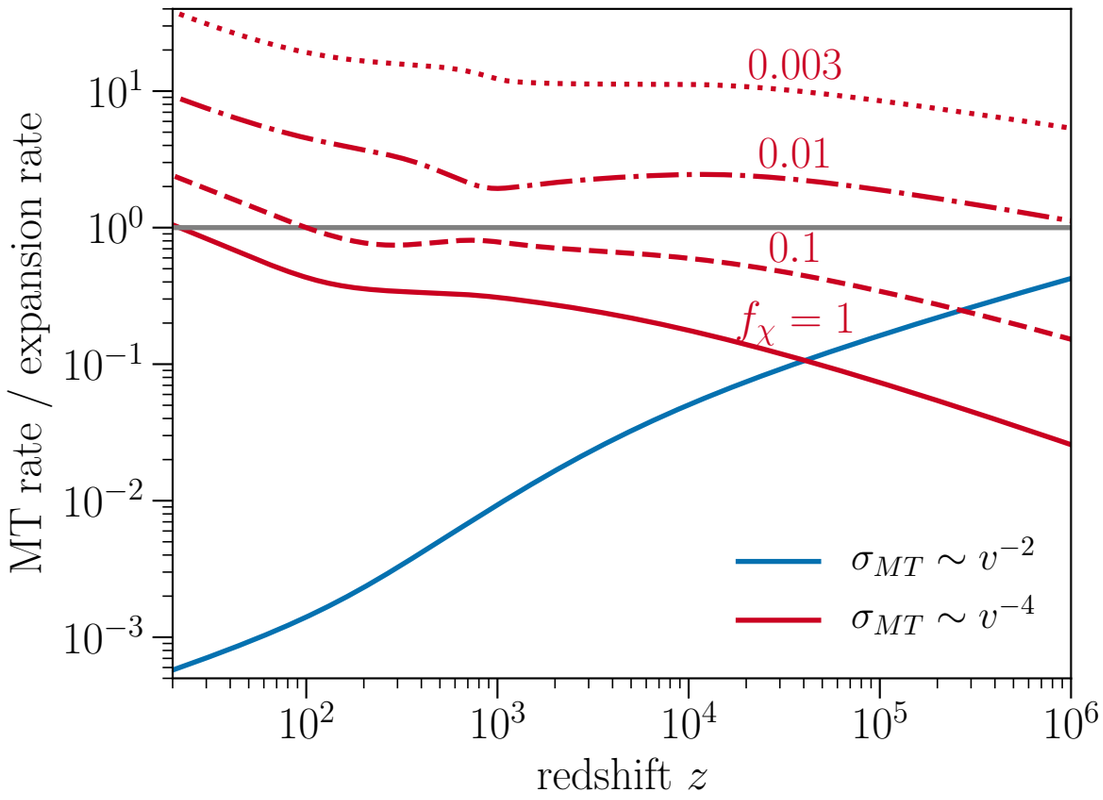


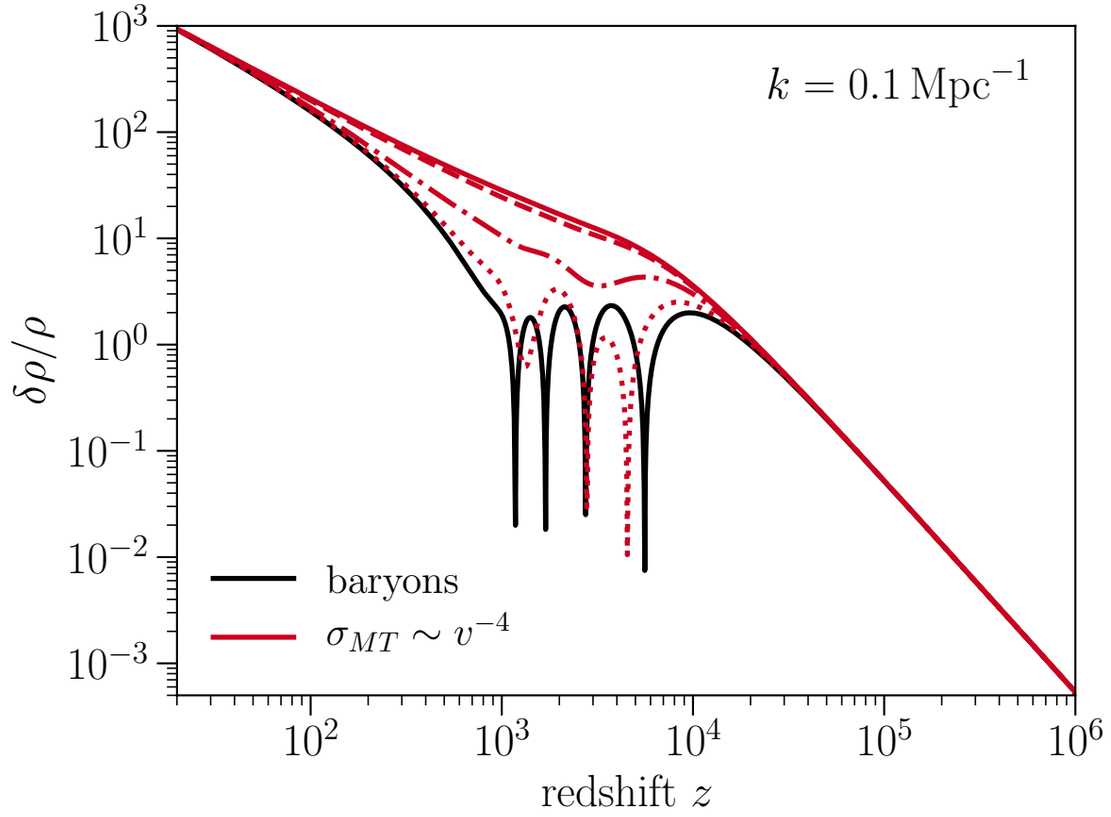


**KB**+ (PRD 2018)

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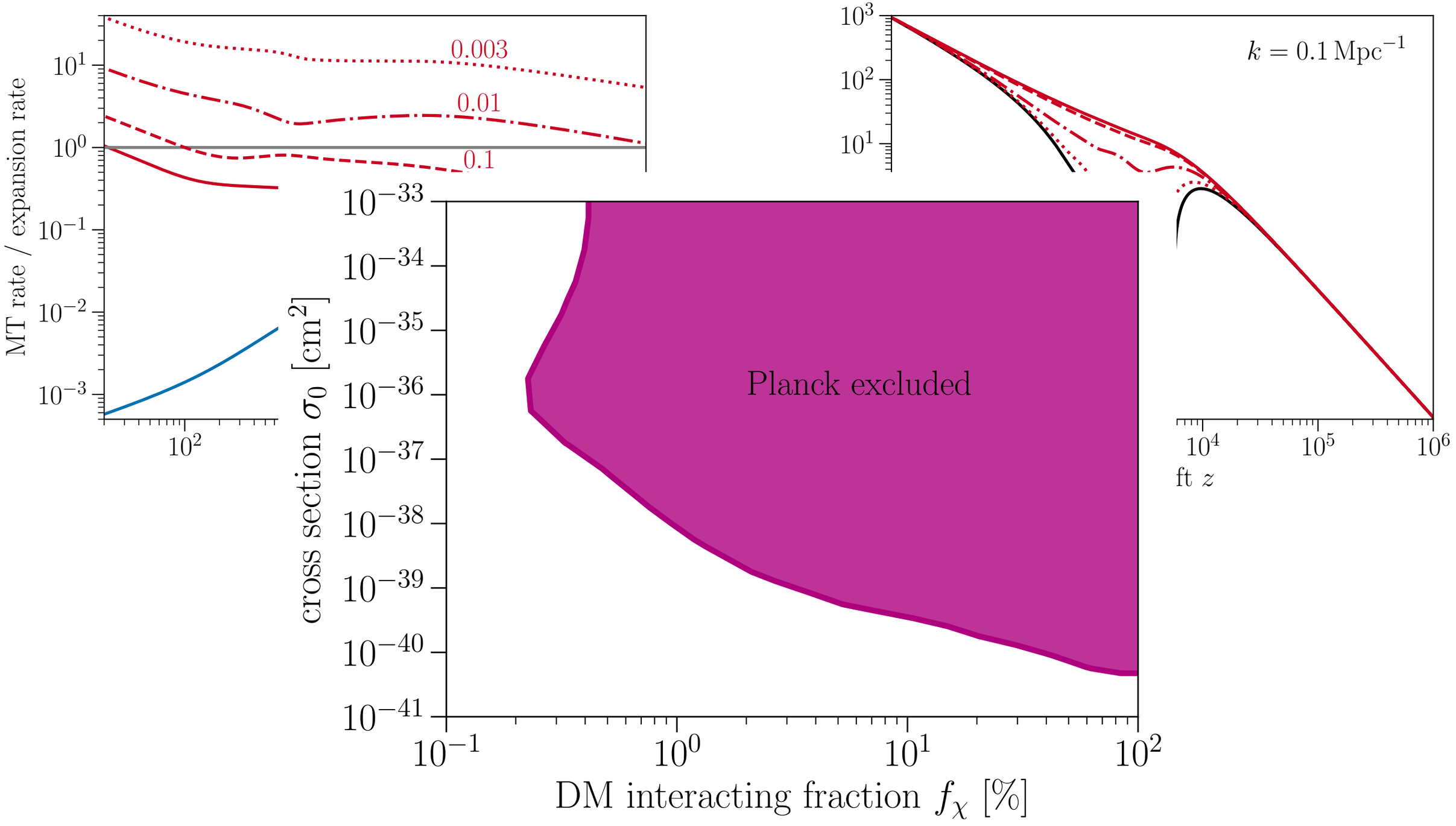


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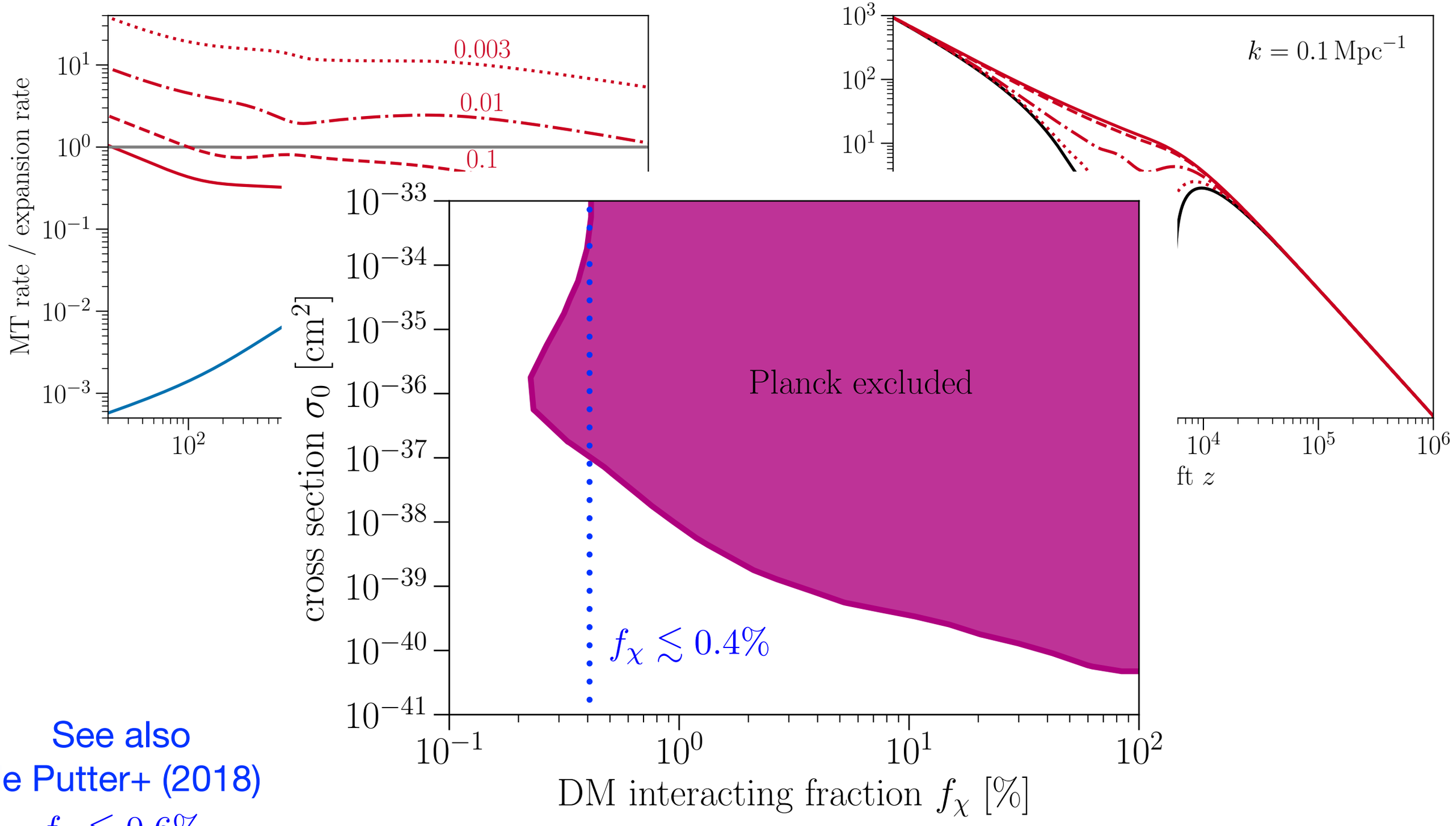
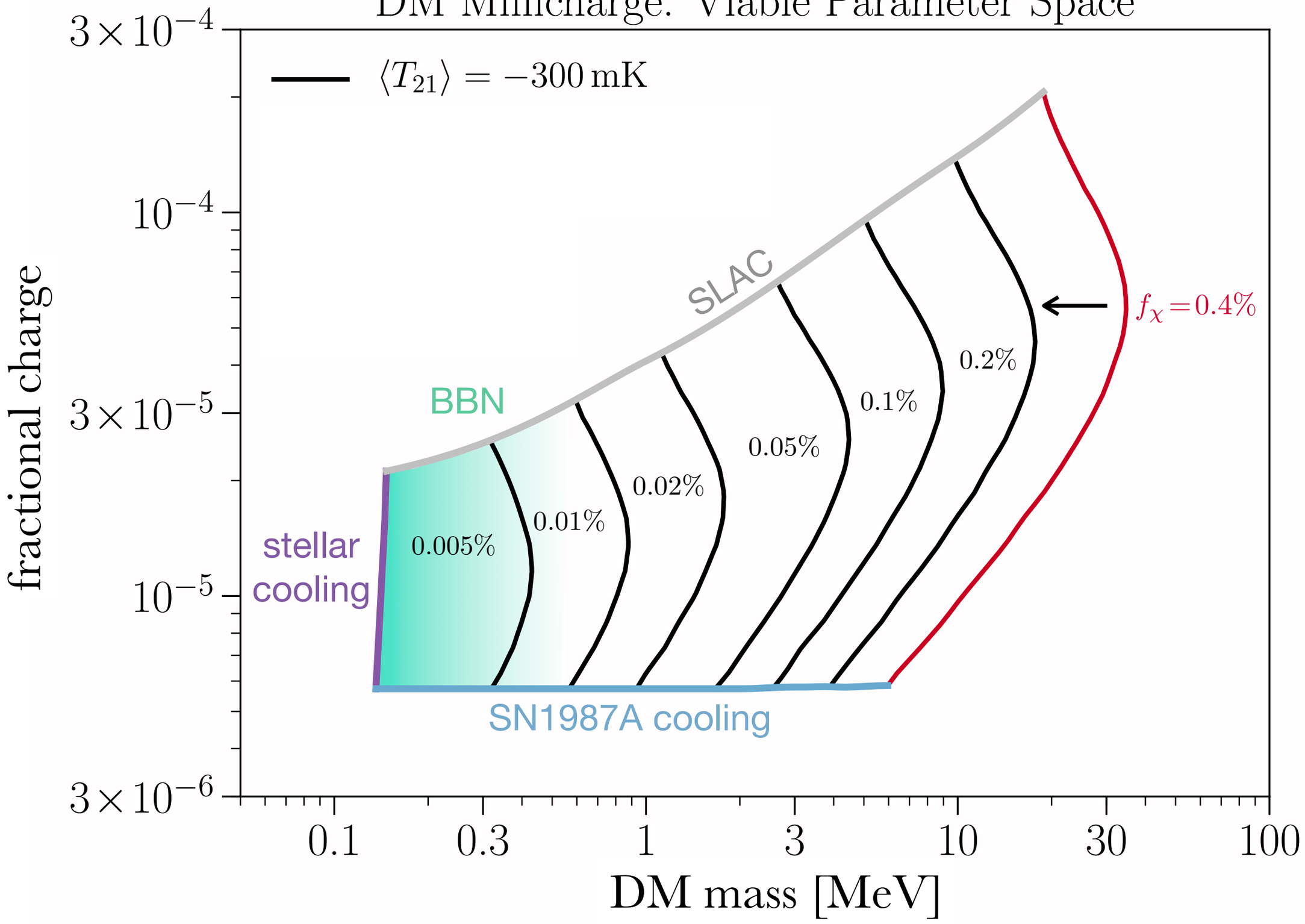


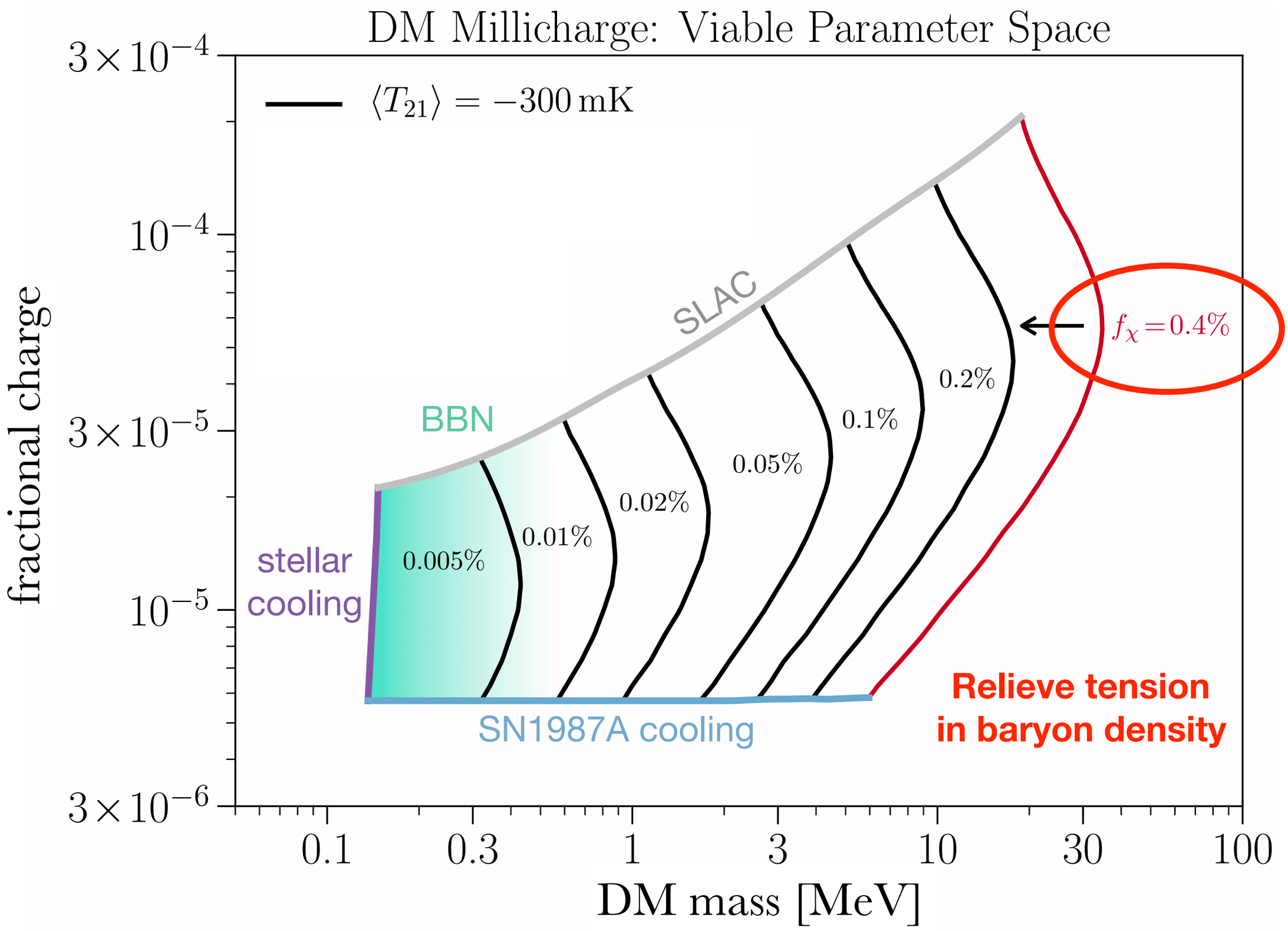

See also
de Putter+ (2018)
$f_\chi \lesssim 0.6\%$

**KB**+ (PRD 2018)




SN1987A: Chang, Essig, and McDermott (2018)
SLAC: Prinz et al. (1998)
Stellar: Vogel and Redondo (2014)

Kovetz, Poulin, Gluscevic, **KB**+ (PRD 2018)

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# Summary and Outlook

Cosmological observables provide a unique and rich foundation for complementary searches of particle dark matter interactions.