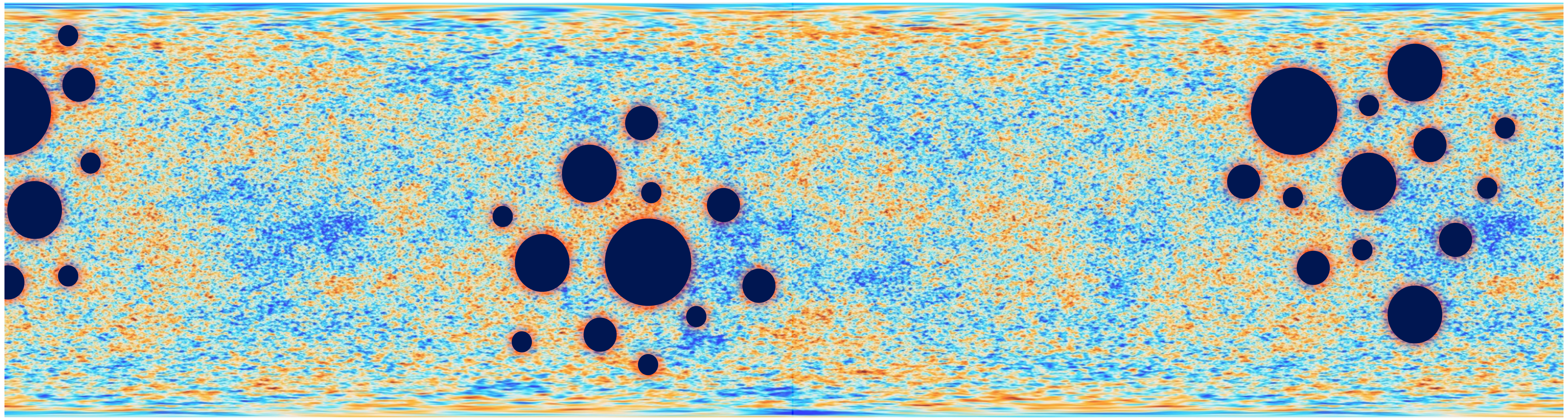
Small-scale probes of the early universe and late universe



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GRAPPA
GRavitation AstroParticle Physics Amsterdam

Université Libre de Bruxelles - 08/06/2023

1. EARLY UNIVERSE

Constraints on the **primordial power spectrum** using dark matter **minihalos** and the **CMB**

2. LATE UNIVERSE

Constraints on **neutrino masses** using dark matter **subhalos** and **Milky-Way satellites**

1. EARLY UNIVERSE

Constraints on the **primordial power spectrum** using dark matter **minihalos** and the **CMB**

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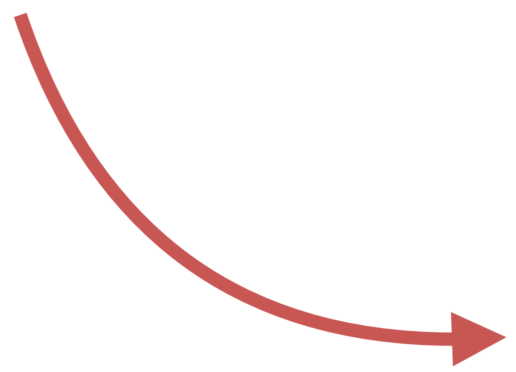
Constraints on the **primordial power spectrum** using dark matter **minihalos** and the **CMB**

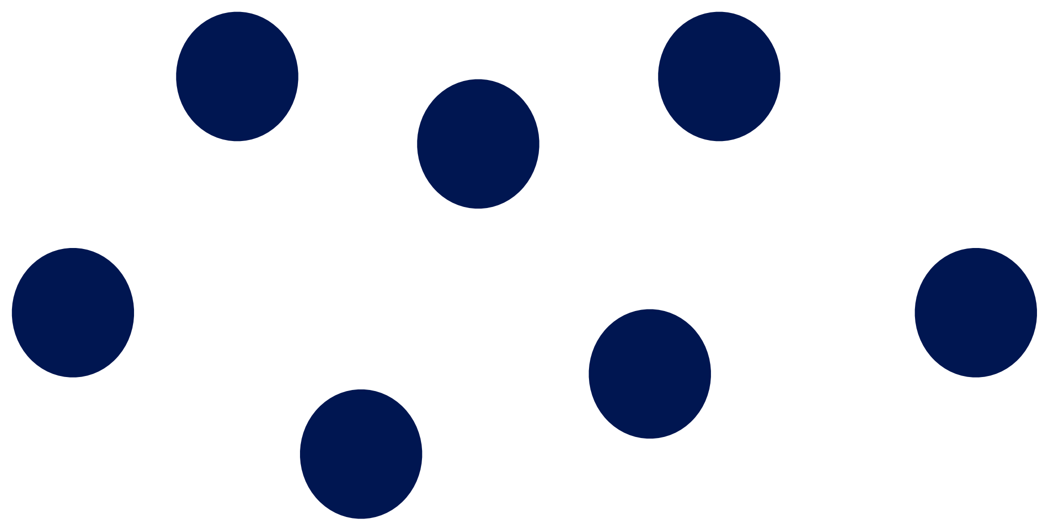
Based on: arXiv:2304.02996
with Gaétan Facchinetti

Primordial fluctuations

Primordial fluctuations



Halo collapse ($z \sim 30 - 100$)



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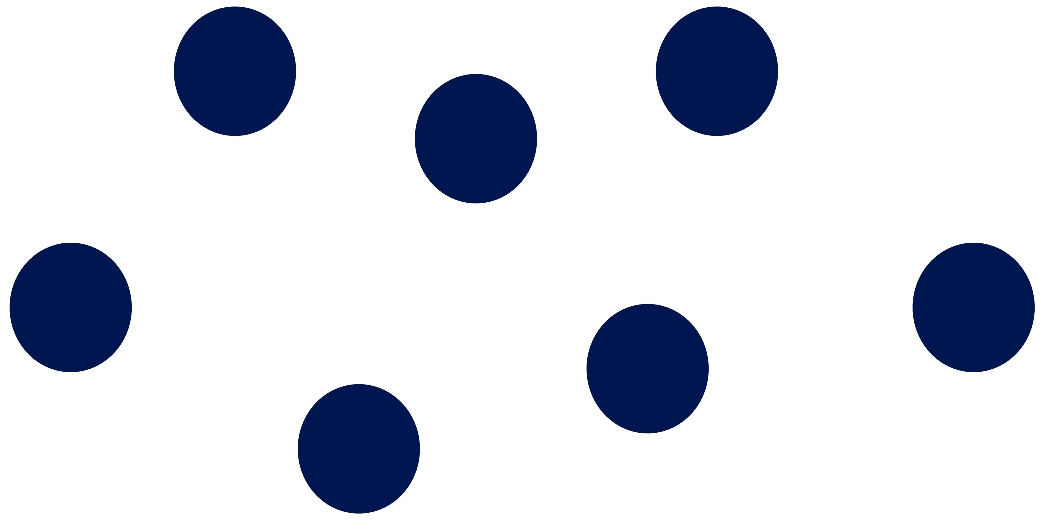
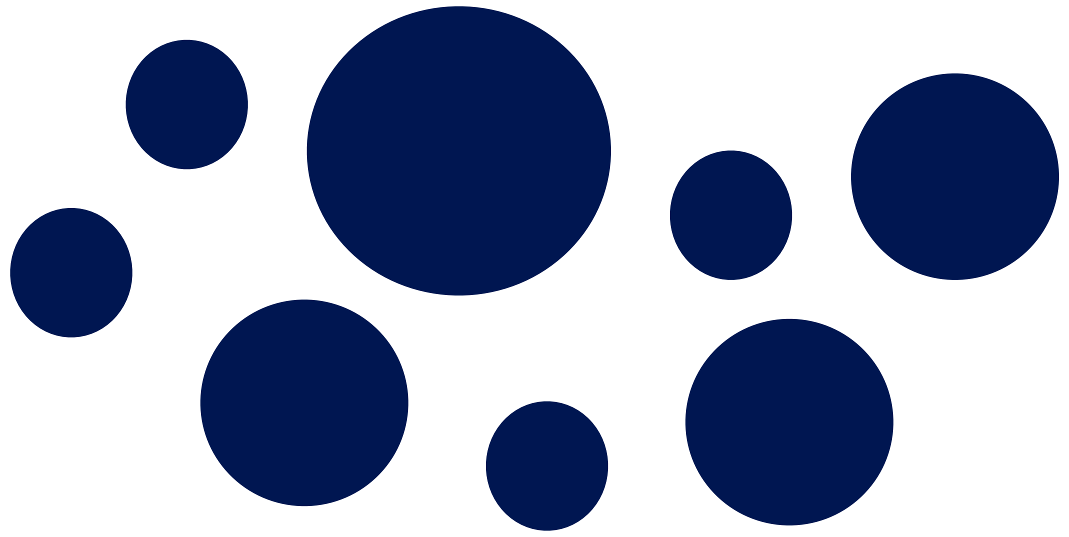


Hierarchical growth

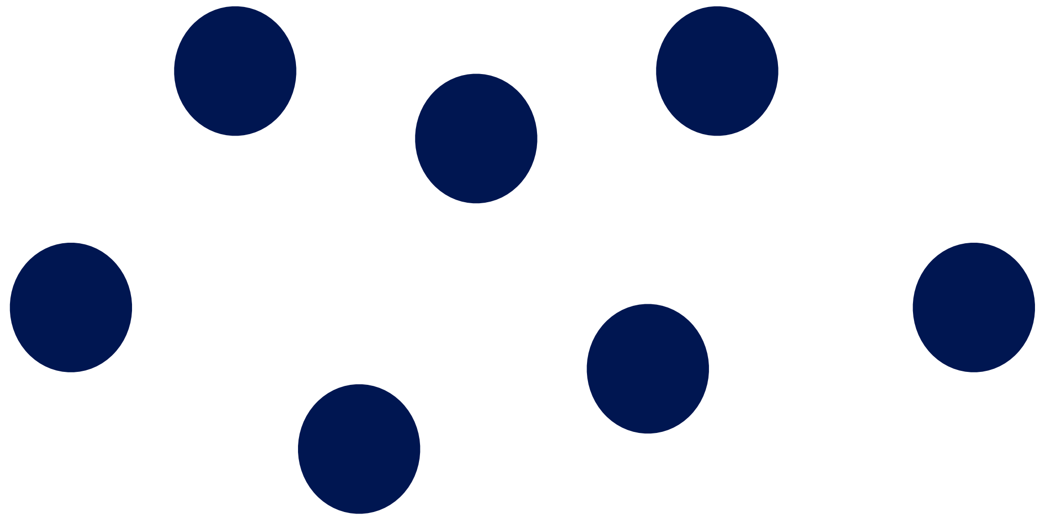


Primordial fluctuations

Primordial power spectrum

$$\mathcal{P}_{\mathcal{R}}(k)$$

Halo collapse ($z \sim 30 - 100$)



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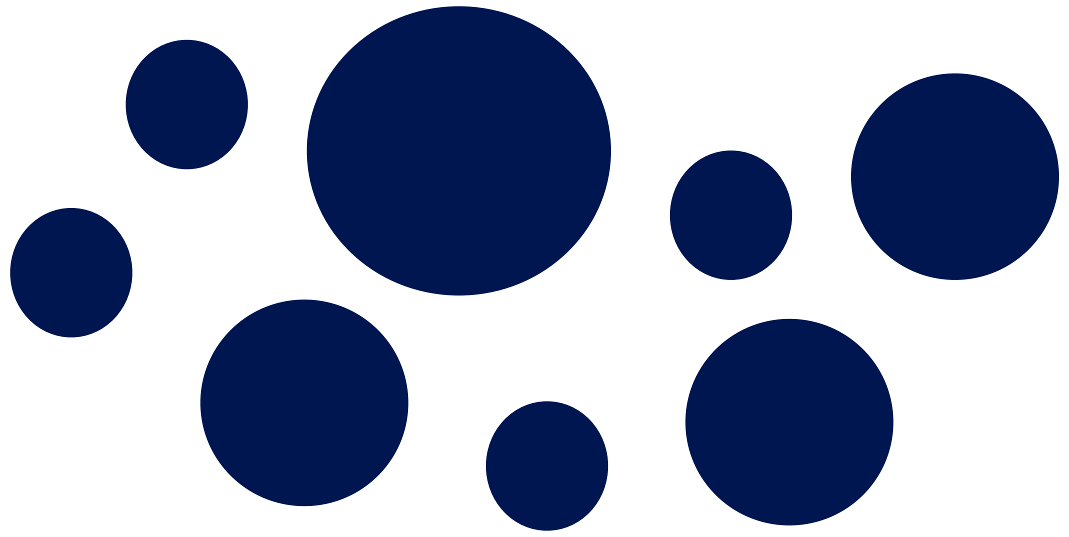
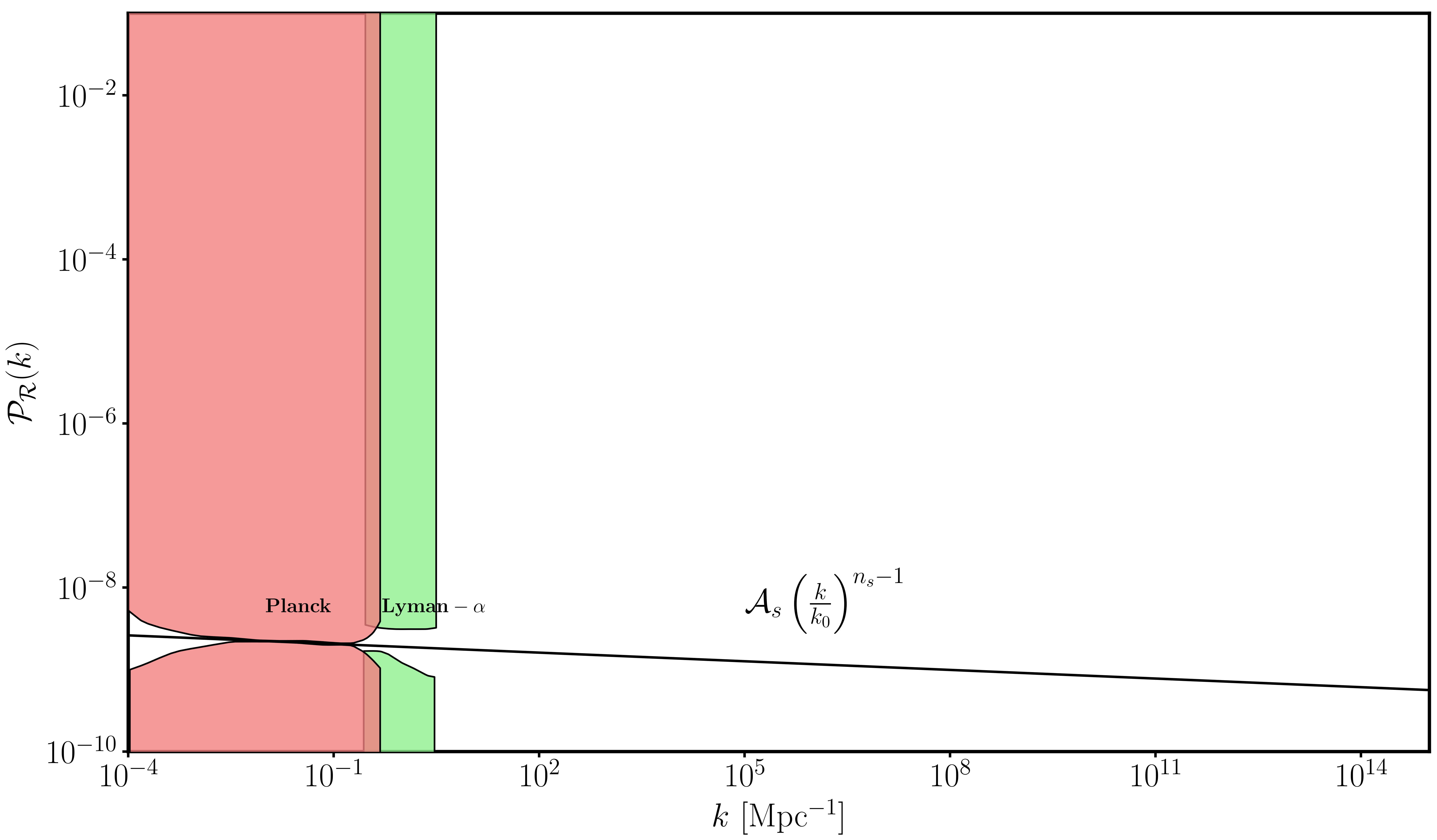
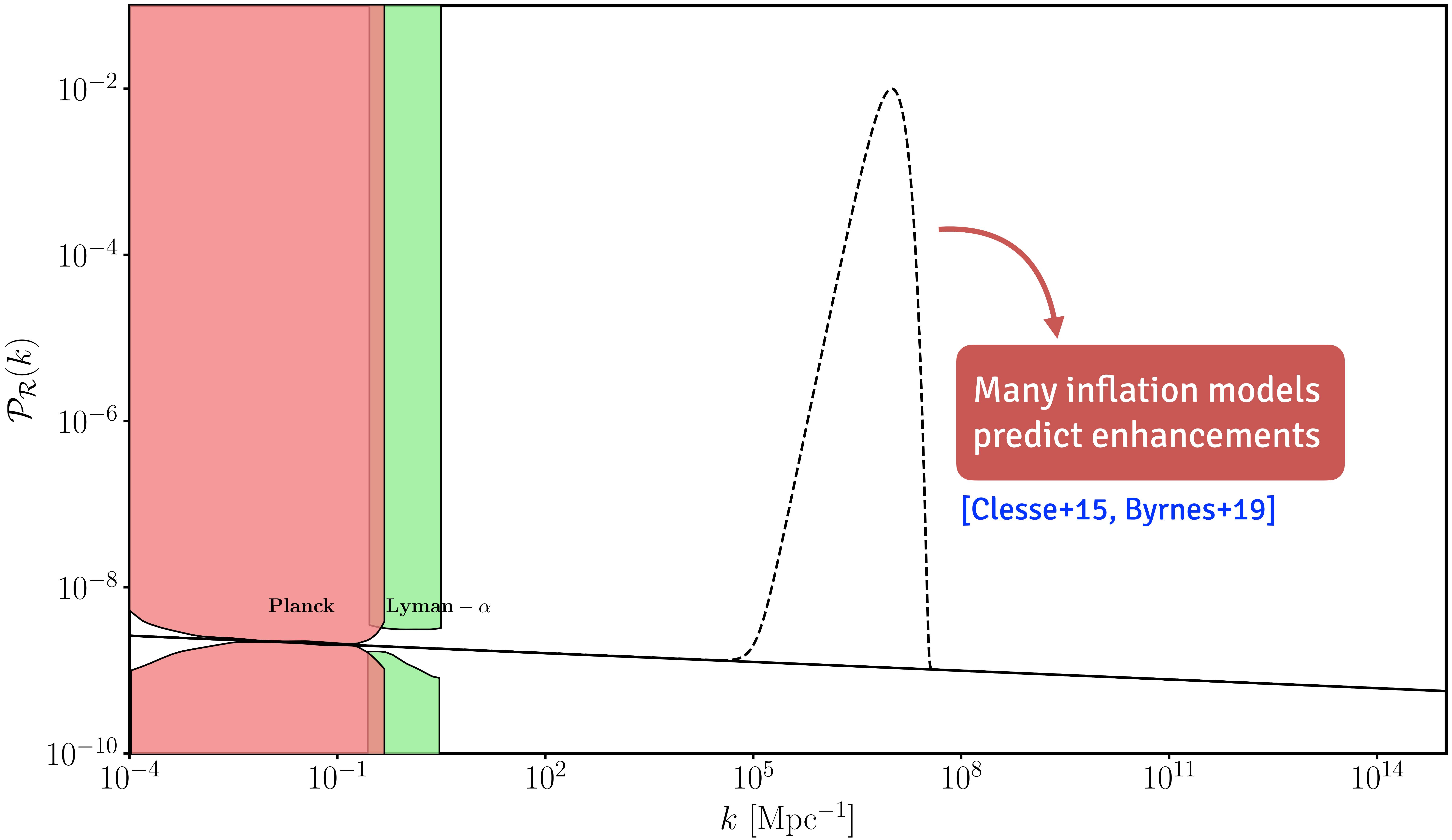
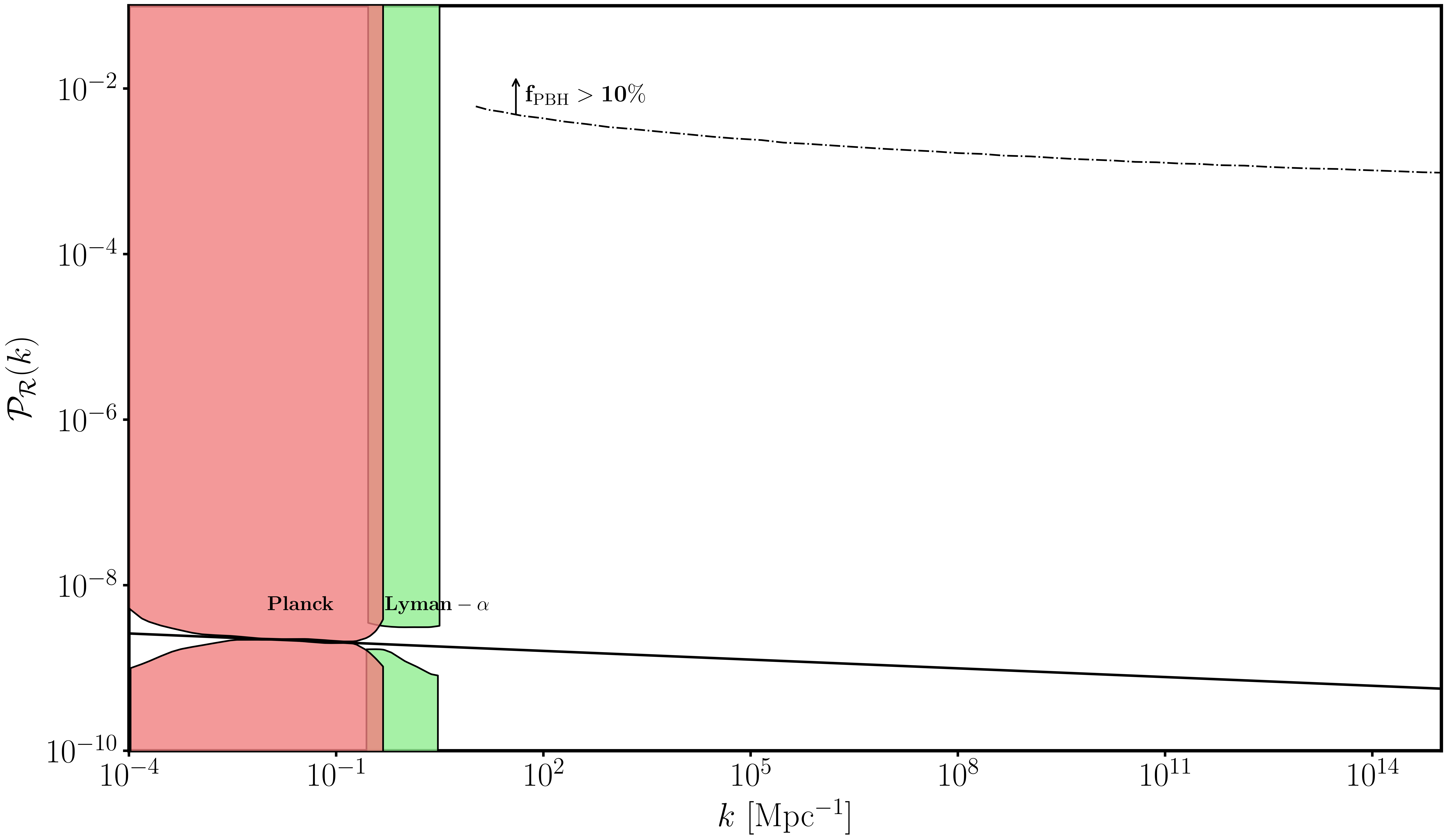


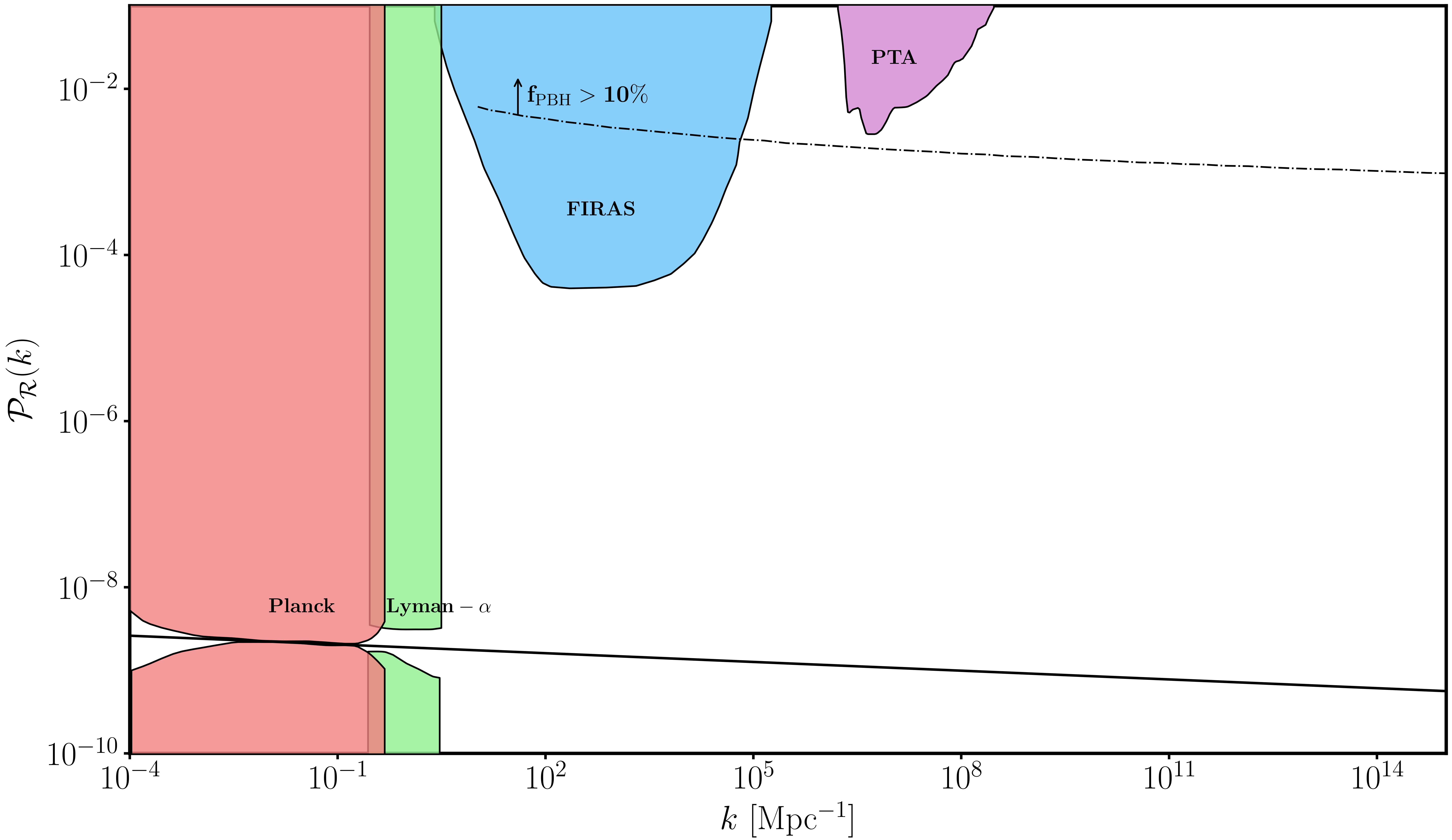


10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$\mathcal{P}_{\mathcal{R}}(k)$
Planck
Lyman $-\ \alpha$
$\mathcal{A}_s \left(\frac{k}{k_0}\right)^{n_s-1}$
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
10^{14}
k [Mpc^{-1}]

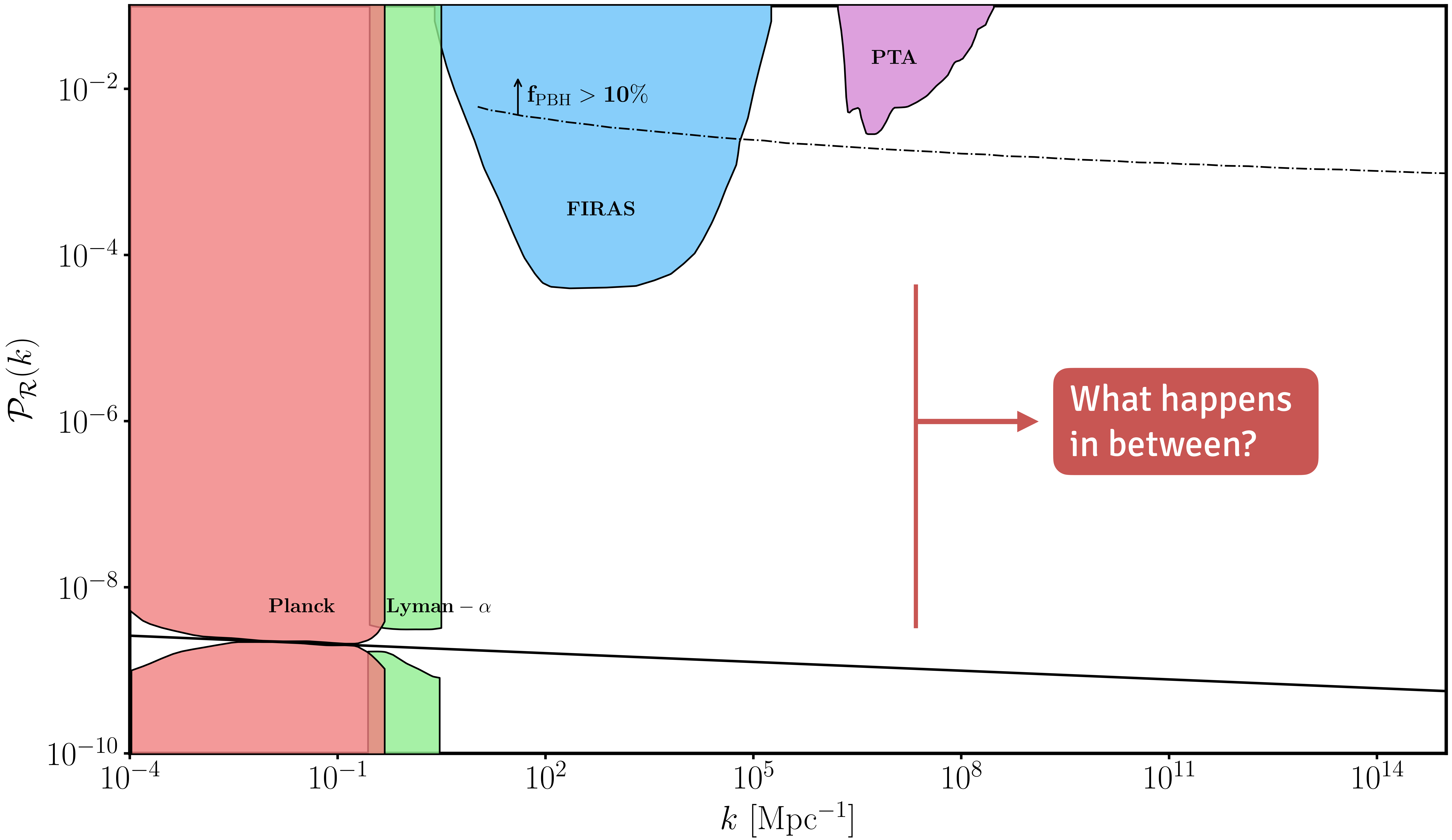

$\mathcal{P}_{\mathcal{R}}(k)$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
Planck
Lyman $-\alpha$
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
10^{14}
k [Mpc^{-1}]
Many inflation models predict enhancements
[Clesse+15, Byrnes+19]



Primordial Black Hole (PBH) formation

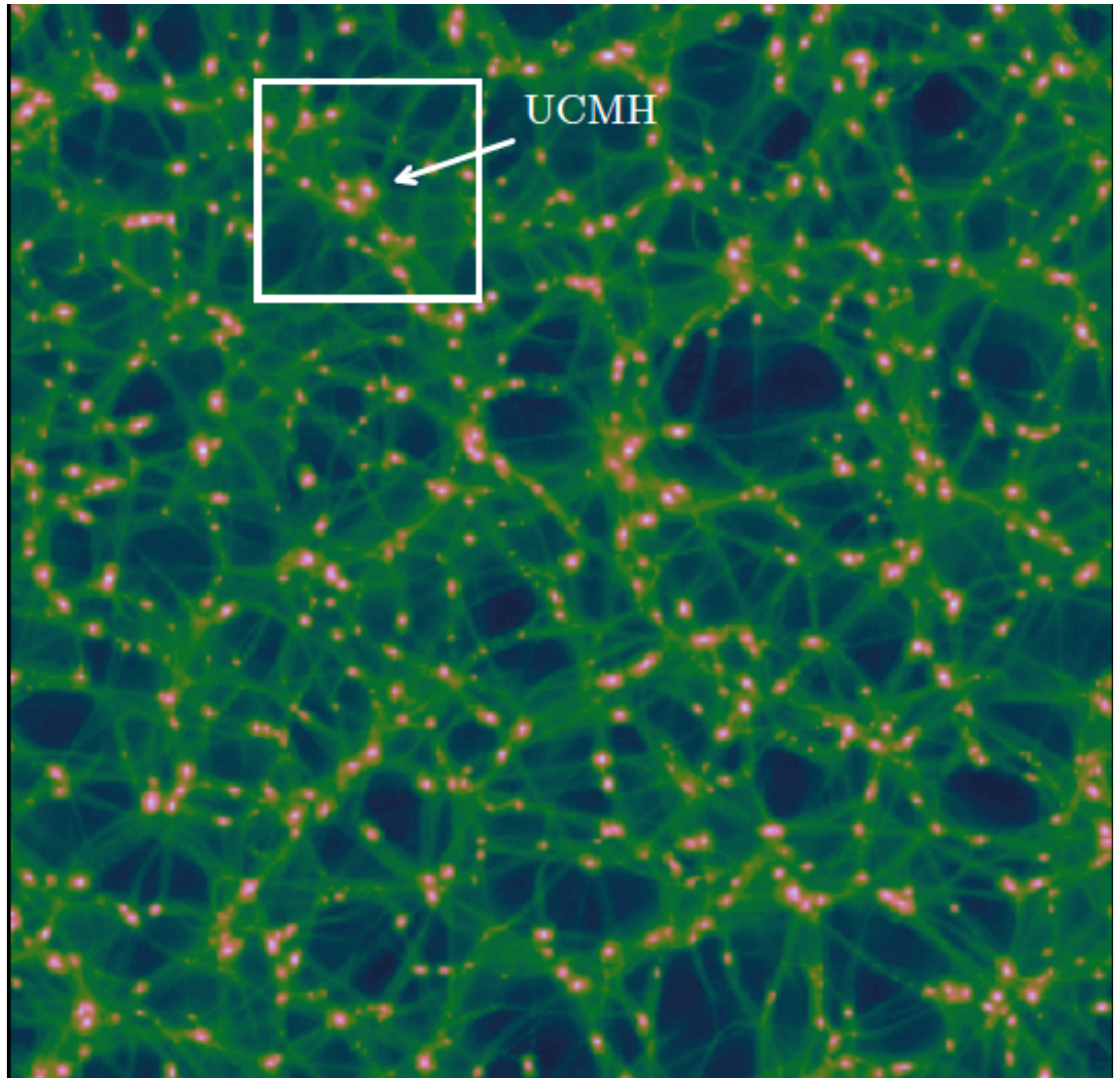


PTA
$\uparrow \mathbf{f}_{\mathrm{PBH}} > \mathbf{10\%}$
FIRAS
Planck
Lyman $-\,\alpha$
$\mathcal{P}_{\mathcal{R}}(k)$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
10^{14}
k [Mpc^{-1}]


PTA
f_PBH > 10%
FIRAS
What happens
in between?
Planck
Lyman − α
10^−2
10^−4
10^−6
10^−8
10^−10
P_R(k)
10^−4
10^−1
10^2
10^5
10^8
10^11
10^14
k [Mpc^−1]

Moderate enhancements can produce

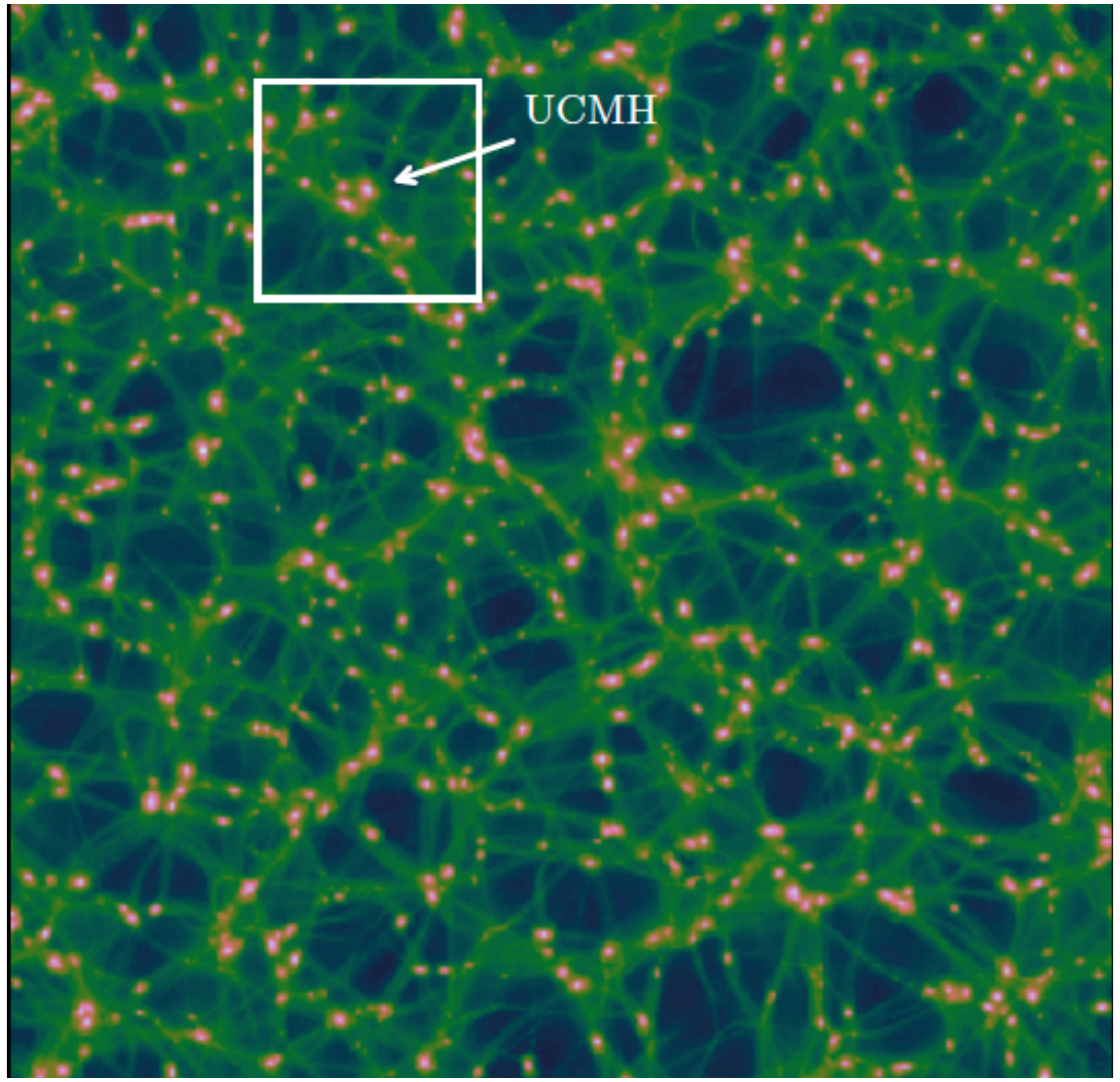
Ultra Compact Mini Halos (UCMHs)



[Delos+18]

Moderate enhancements can produce

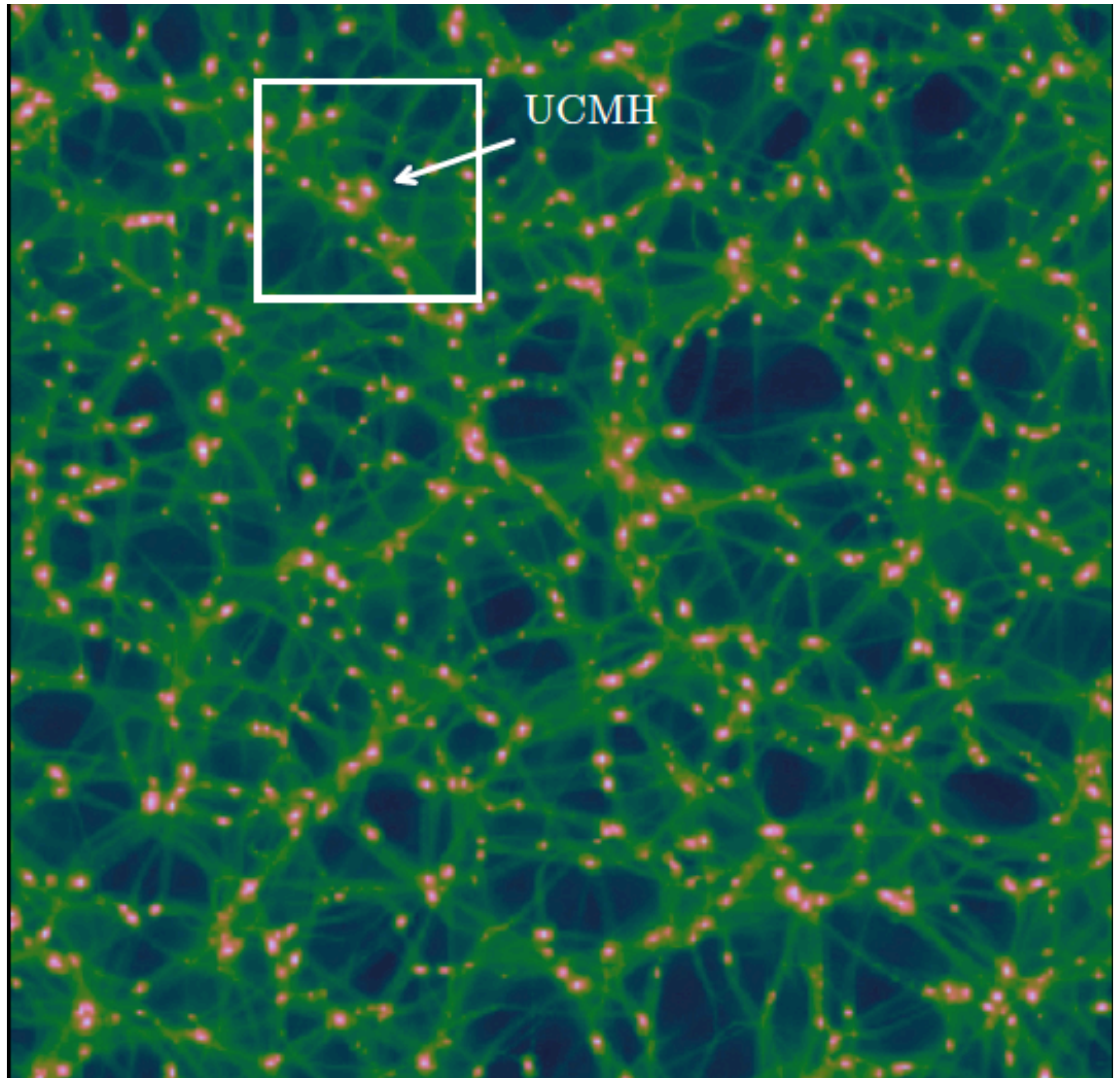
Ultra Compact Mini Halos (UCMHs)



[Delos+18]

Much earlier collapse ($z \sim 10^2 - 10^3$)

Moderate enhancements can produce
Ultra Compact Mini Halos (UCMHs)



[Delos+18]

- Much earlier collapse ($z \sim 10^2 - 10^3$)
- Potentially much stronger constraints on the small-scale $\mathcal{P}_{\mathcal{R}}(k)$ than PBHs

The presence of minihalos has been probed by various methods

- γ-ray fluxes [Bringmann+11, Delos+18]
- CMB anisotropies [Kawasaki+21]
- 21cm signal [Yang+16, Furugori+20]
- Microlensing [Erickcek+12]
- Free-free emission [Abe+21]

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If dark matter (DM) self-annihilates, minihalos can significantly **boost the DM annihilation signal**, leaving an imprint on the CMB

Deposited energy into the plasma per volume and time (**no halos**)

$$\left.\frac{dE}{dVdt}\right|_{\rm DM}(z) = \langle \rho_{\rm DM}^0 \rangle^2 (1+z)^6 p_{\rm ann}$$

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$$\left.\frac{dE}{dVdt}\right|_{\mathrm{DM}}(z) = \langle \rho^0_{\mathrm{DM}} \rangle^2 (1+z)^6 p_{\mathrm{ann}} \quad \text{with} \quad p_{\mathrm{ann}} = f(z) \frac{\langle \sigma v \rangle}{m_{\mathrm{DM}}}$$

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← Particle physics

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← Particle physics

↑ Deposition function (depends on annihilation channel)

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← Particle physics

↑ Deposition function (depends on annihilation channel)

$\left.\frac{dE}{dVdt}\right|_{\rm DM}$ → Modify ionization and thermal history $X_e(z), T_b(z)$ → Alter CMB spectra $C_\ell^{\rm TT,TE,EE}$

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Particle physics

Deposition function
(depends on annihilation channel)

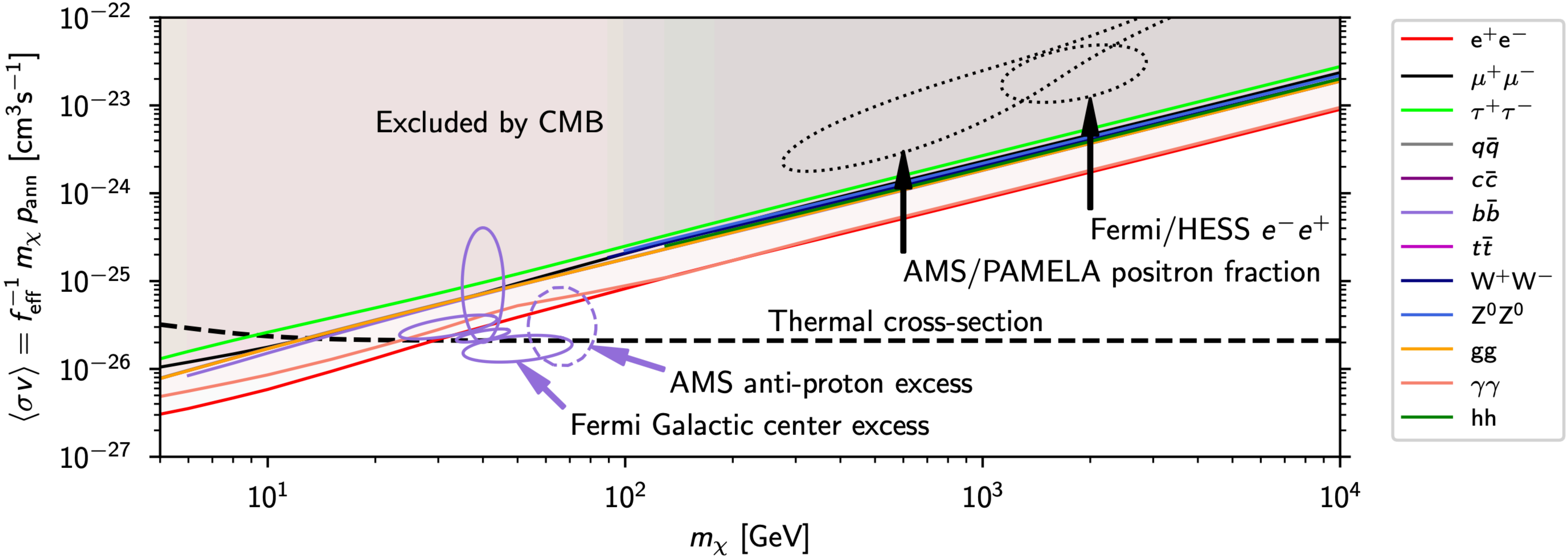
$\left.\frac{dE}{dVdt}\right|_{\rm DM}$ → Modify ionization and thermal history $X_e(z), T_b(z)$ → Alter CMB spectra $C_\ell^{\rm TT,TE,EE}$

ExoCLASS = DarkAges + HyRec/Recfast + CLASS
[Stocker+18]

Most recent constraints from PlanckTTTEEE+lensing+BAO

$$p_{\text{ann}} < 3.2 \times 10^{-28}\ \text{cm}^3\text{s}^{-1}\text{GeV}^{-1} \quad (95\,\%\,\text{C.L.})$$

[Planck 18]

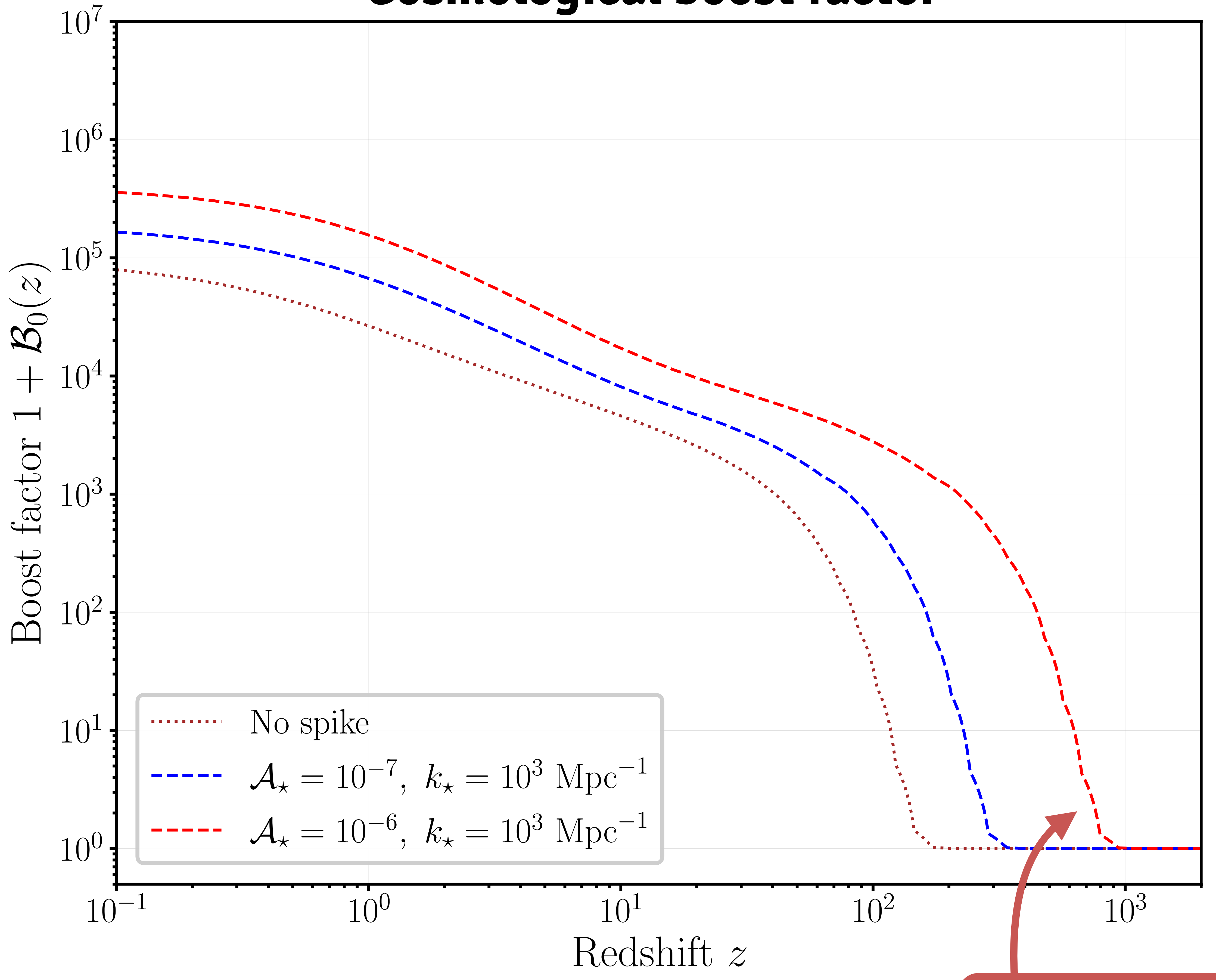


In presence of halos, deposited energy is modified as

$$\left.\frac{dE}{dVdt}\right|_{\mathrm{DM}}(z) = (1 + B(z))\langle\rho^0_{\mathrm{DM}}\rangle^2(1+z)^6 p_{\mathrm{ann}}$$

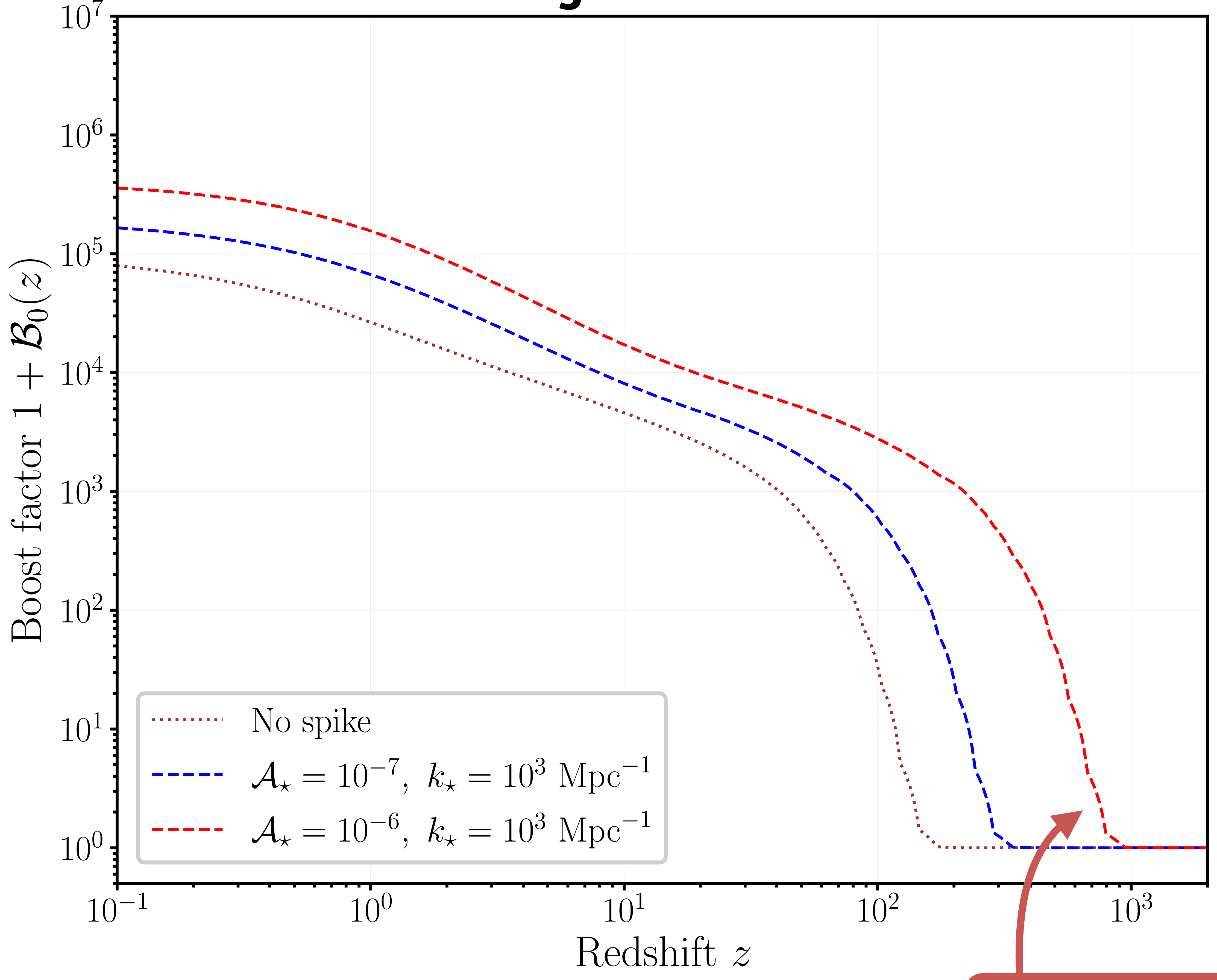
where $B(z) \equiv \frac{\langle\rho^2_{\mathrm{DM}}\rangle}{\langle\rho_{\mathrm{DM}}\rangle^2} - 1$ is the **cosmological boost factor**

Cosmological boost factor



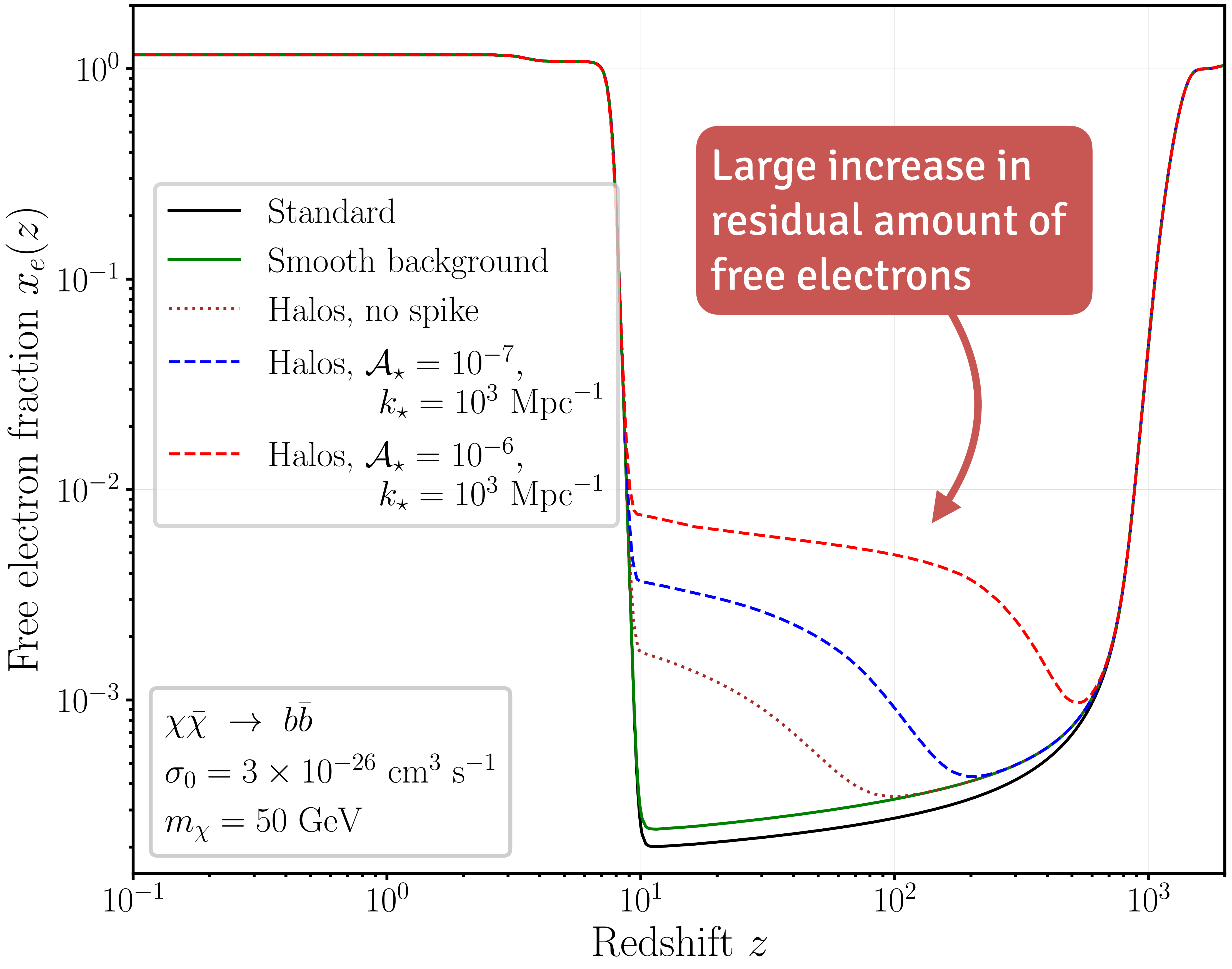
UCMH boost starts to rise at z >> 100

Cosmological boost factor



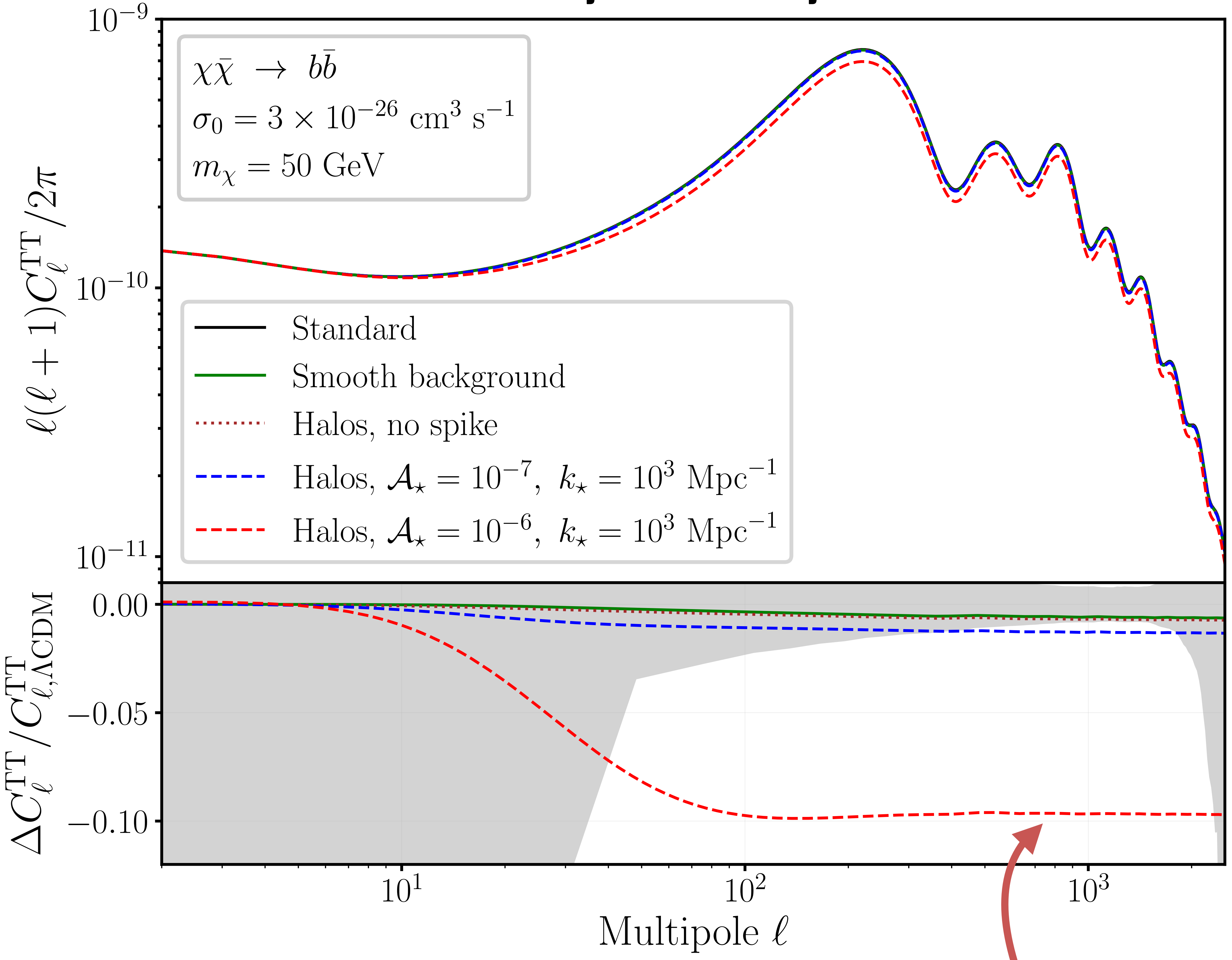
UCMH boost starts to rise at z >> 100

Free electron fraction

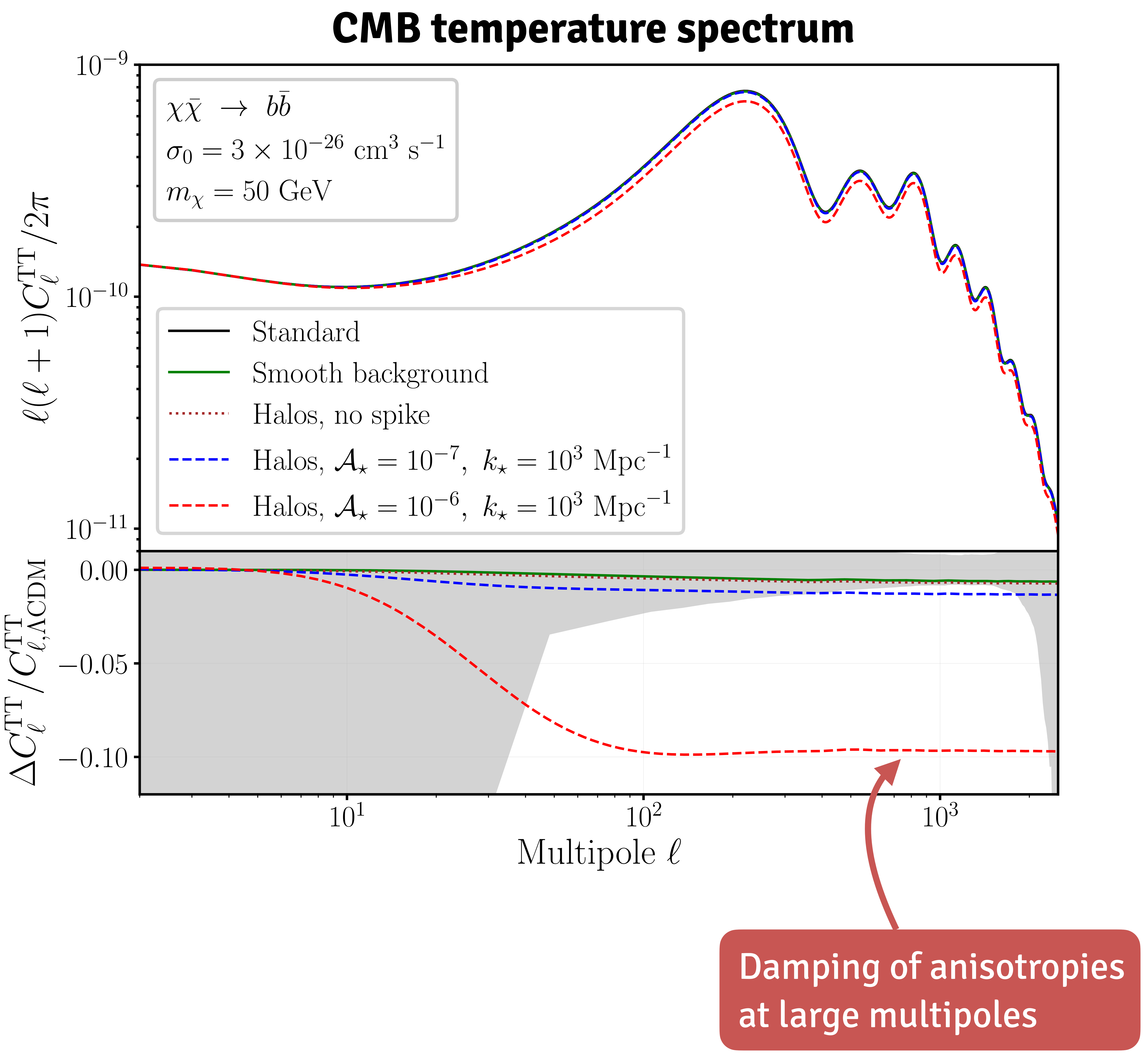
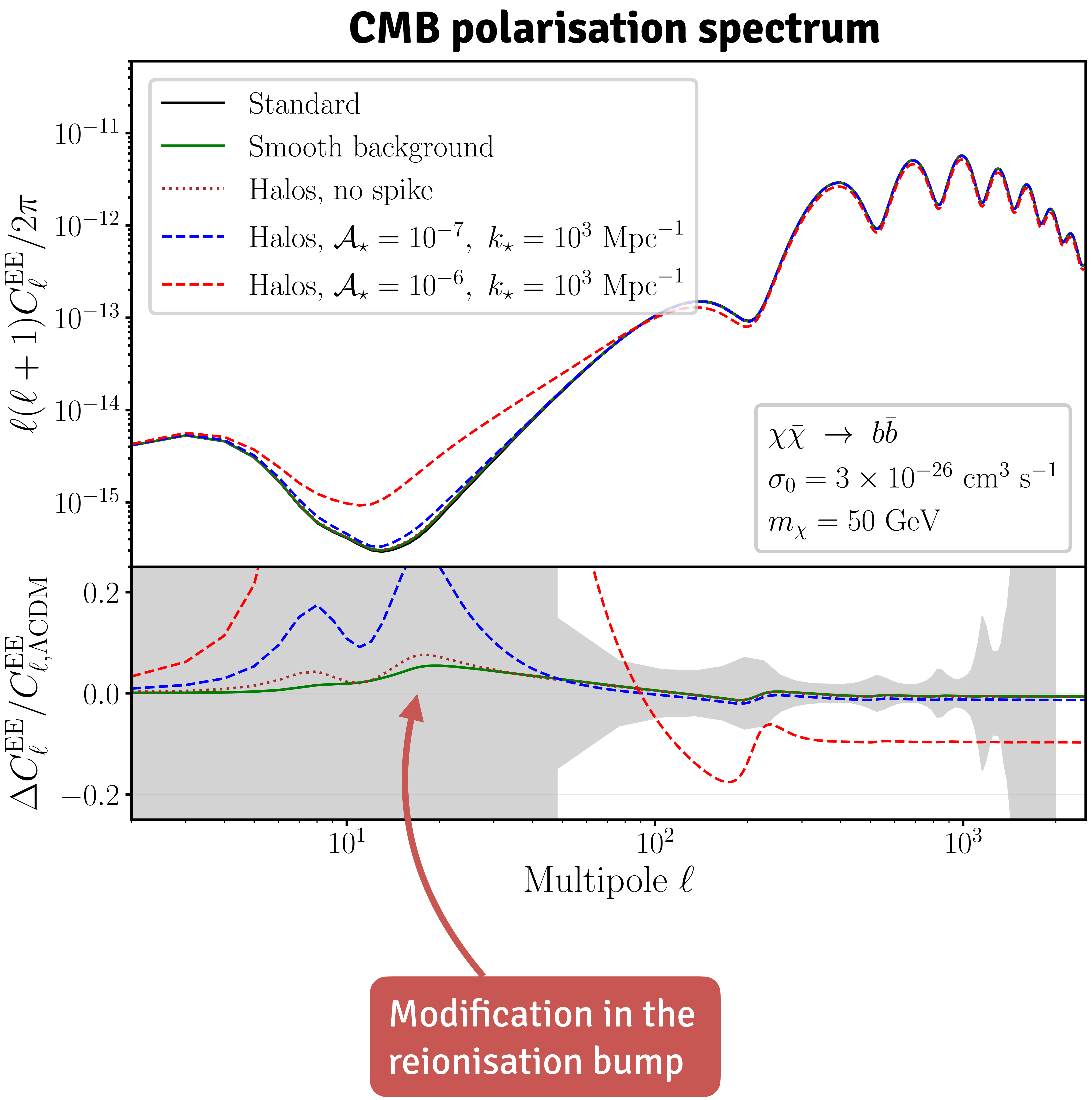


Large increase in residual amount of free electrons

CMB temperature spectrum



Damping of anisotropies at large multipoles


CMB temperature spectrum
$\chi\bar{\chi} \to b\bar{b}$
$\sigma_0 = 3 \times 10^{-26}$ cm^3 s^{-1}
$m_\chi = 50$ GeV
Standard
Smooth background
Halos, no spike
Halos, $\mathcal{A}_\star = 10^{-7}$, $k_\star = 10^3$ Mpc^{-1}
Halos, $\mathcal{A}_\star = 10^{-6}$, $k_\star = 10^3$ Mpc^{-1}
$\ell(\ell+1)C_\ell^{\rm TT}/2\pi$
$\Delta C_\ell^{\rm TT}/C_{\ell,\Lambda\rm CDM}^{\rm TT}$
Multipole ℓ
Damping of anisotropies at large multipoles

CMB polarisation spectrum
Standard
Smooth background
Halos, no spike
Halos, $\mathcal{A}_\star = 10^{-7}$, $k_\star = 10^3$ Mpc^{-1}
Halos, $\mathcal{A}_\star = 10^{-6}$, $k_\star = 10^3$ Mpc^{-1}
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$m_\chi = 50$ GeV
$\ell(\ell+1)C_\ell^{\rm EE}/2\pi$
$\Delta C_\ell^{\rm EE}/C_{\ell,\Lambda\rm CDM}^{\rm EE}$
Multipole ℓ
Modification in the reionisation bump

But how do we compute the **boost factor** B(z)?

In the framework of the halo model

$$B(z) = \frac{1}{\langle \rho_{\rm m}^0 \rangle} \int M \frac{dn(M\,|\,z)}{dM} \; B_h(z_{\rm f}(M), z) \; dM$$

In the framework of the halo model

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Halo mass function

Depends on $\mathcal{P}_{\mathcal{R}}(k)$

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Halo mass function
Depends on $\mathcal{P}_{\mathcal{R}}(k)$

1-halo boost
Depends on density profile $\rho_h(r)$

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Halo mass function
Depends on $\mathcal{P}_{\mathcal{R}}(k)$

1-halo boost
Depends on density profile $\rho_h(r)$

Which halo mass function?
Which density profile?

Past studies often considered peak theory (**mergers neglected**) and Moore density profiles:

$$\rho_h(r) \propto r^{-3/2}$$

[Delos+17]

Past studies often considered peak theory (**mergers neglected**) and Moore density profiles:

$$\rho_h(r) \propto r^{-3/2}$$ [Delos+17]

Based on excursion set theory, we propose a mixed population of halos with different density profiles

Low-mass halos (UCMH): $\rho_h(r) \propto r^{-3/2}$

High-mass halos (NFW): $\rho_h(r) \propto r^{-1}$

RECIPE

to get the constraints

Ingredients

- Modified version of `ExoCLASS`
- Data from `PlanckTTTEEE+lensing+BAO+SNIa`

Instructions

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Instructions

1. Consider a **spike** at large k

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{A}_s \left(\frac{k}{k_0}\right)^{n_s - 1} + \mathcal{A}_\star k_\star \delta(k - k_\star)$$

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3. Compare prediction against `Planck` data

RECIPE

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2. Compute **boost factor** and the **DM annihil. signal** in the CMB (ExoCLASS)

3. Compare prediction against Planck data

4. Obtain constraints on $\mathcal{A}_\star$ vs. $k_\star$ (for a fiducial param. $p_{\rm ann} \propto \langle \sigma v \rangle / m_{\rm DM}$)

A note on priors

$$0 \leq \mathrm{Log}_{10}(k_\star/\mathrm{Mpc}^{-1}) \leq 7$$

$$-8 \leq \mathrm{Log}_{10}\mathcal{A}_\star \leq -4$$

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Typical value for the **free-streaming** scale of WIMPs

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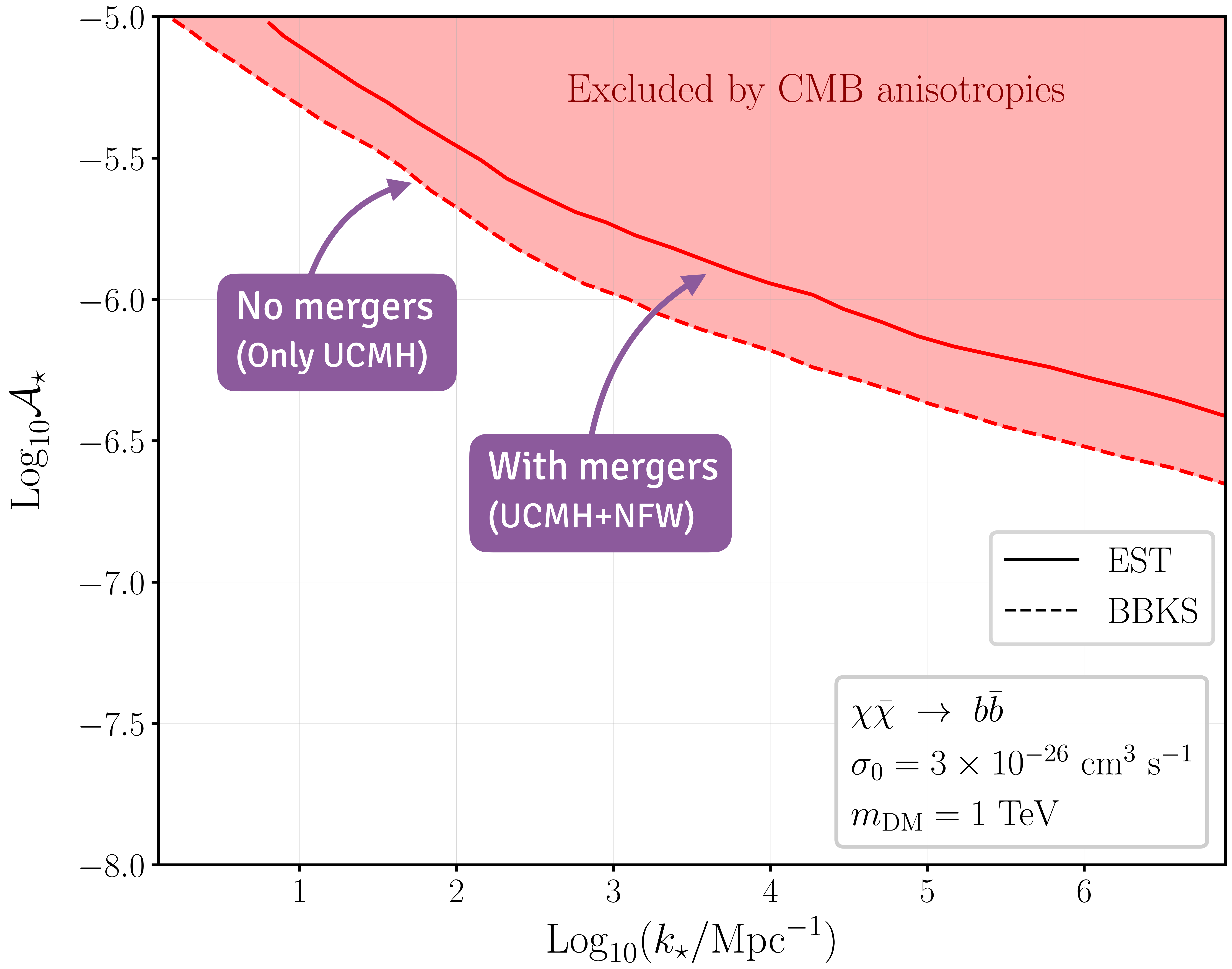
$$-8 \leq \mathrm{Log}_{10}\mathcal{A}_\star \leq -4$$

Typical value for the **free-streaming** scale of WIMPs

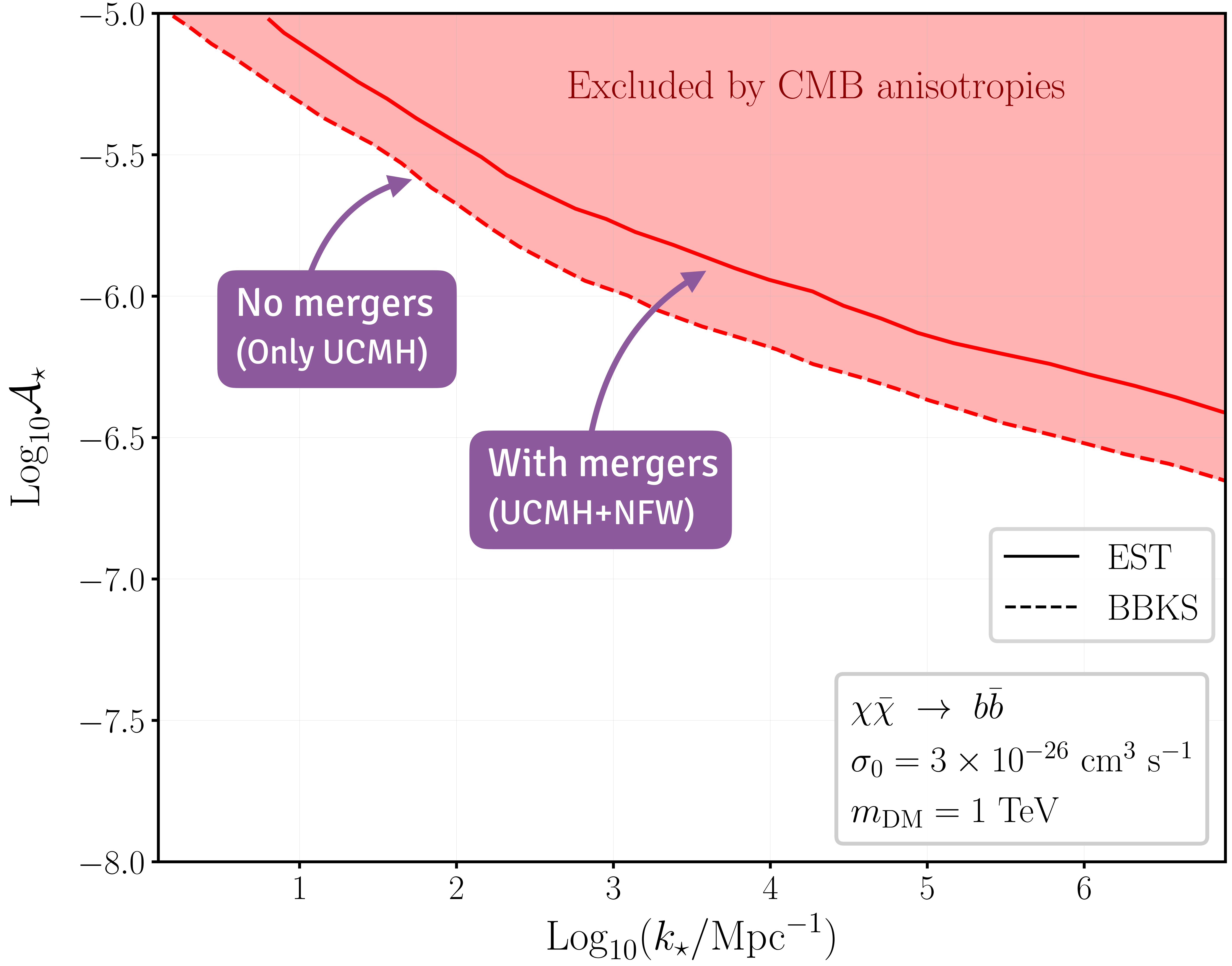
Larger amplitudes may lead to **PBH formation** or minihalo formation during the radiation era

RESULTS



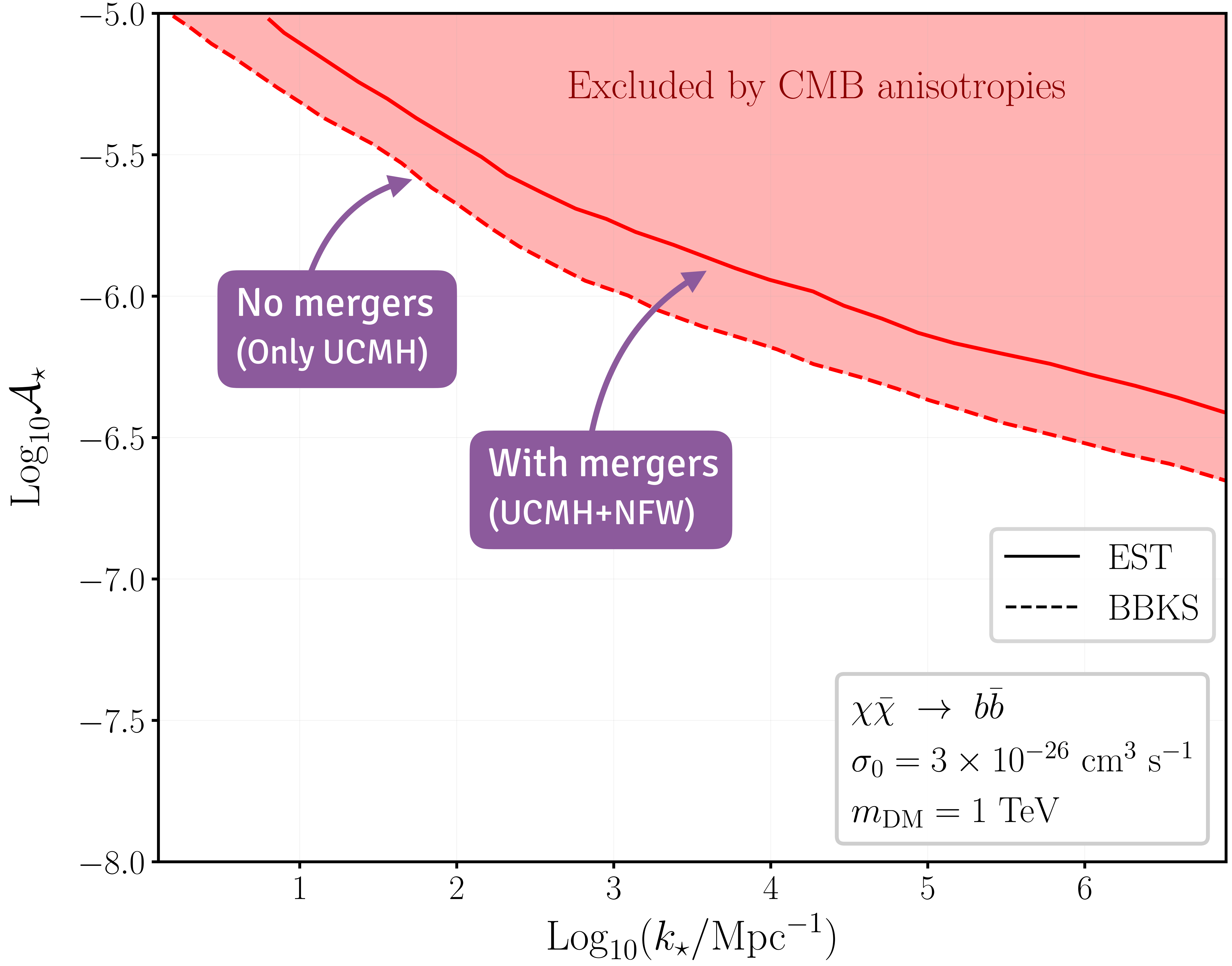
Excluded by CMB anisotropies
No mergers
(Only UCMH)
With mergers
(UCMH+NFW)
EST
BBKS
$\chi\bar{\chi} \to b\bar{b}$
$\sigma_0 = 3 \times 10^{-26}$ cm^3 s^{-1}
$m_{\rm DM} = 1$ TeV
$\mathrm{Log}_{10}\mathcal{A}_\star$
$\mathrm{Log}_{10}(k_\star/\mathrm{Mpc}^{-1})$
−5.0
−5.5
−6.0
−6.5
−7.0
−7.5
−8.0
1
2
3
4
5
6

RESULTS



Accounting for mergers leads to slightly weaker bounds

RESULTS



- Accounting for mergers leads to slightly weaker bounds
- Expected to be much more relevant for lower-z probes (e.g. 21 cm signal)

RESULTS

- So far, we only looked at s-wave DM annihilations

$$\langle \sigma v \rangle = \underbrace{\sigma_0}_{\text{s-wave}} + \underbrace{\sigma_1 v^2}_{\text{p-wave}} + \dots$$

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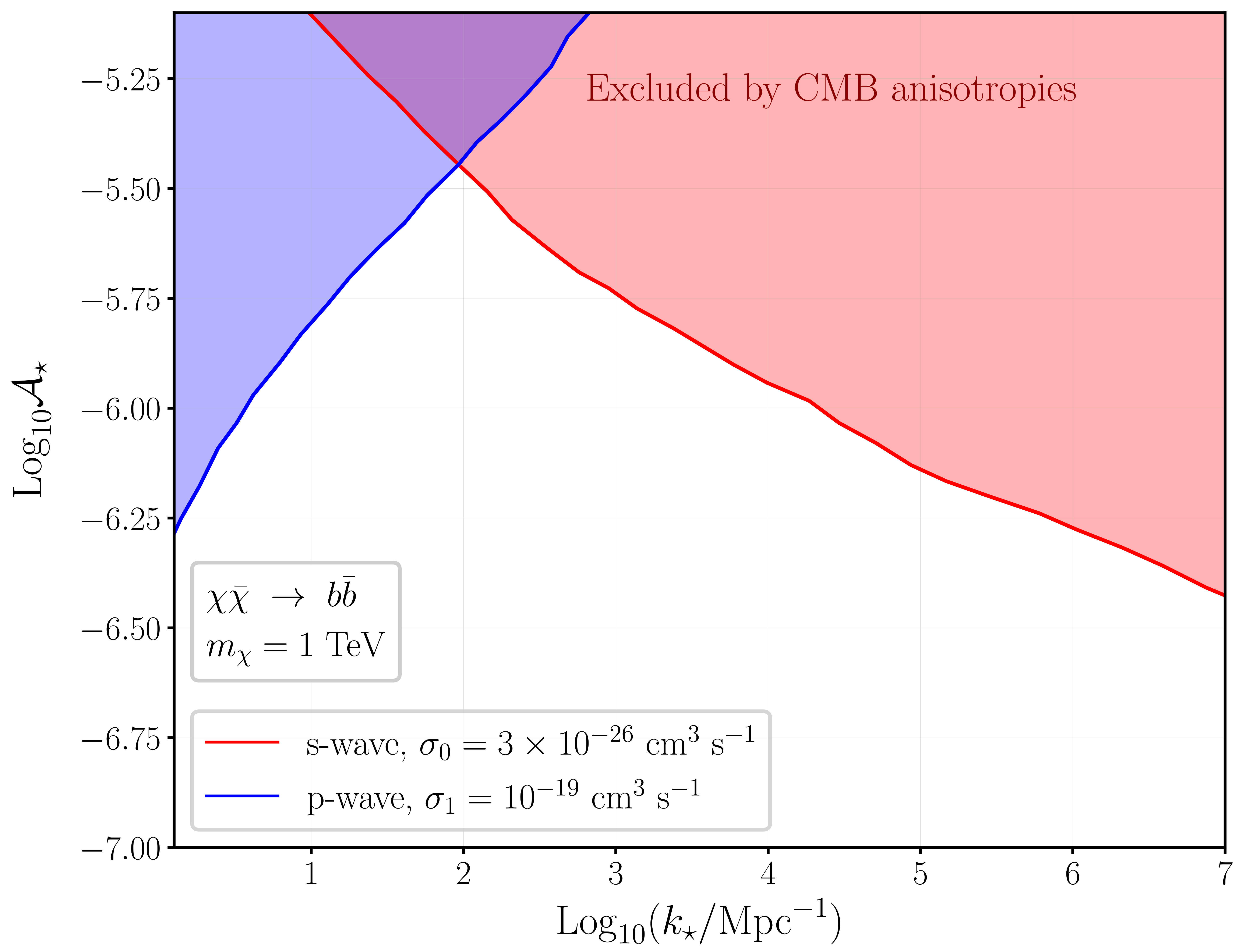
- First calculation of p-wave boost factor in presence of UCMHs

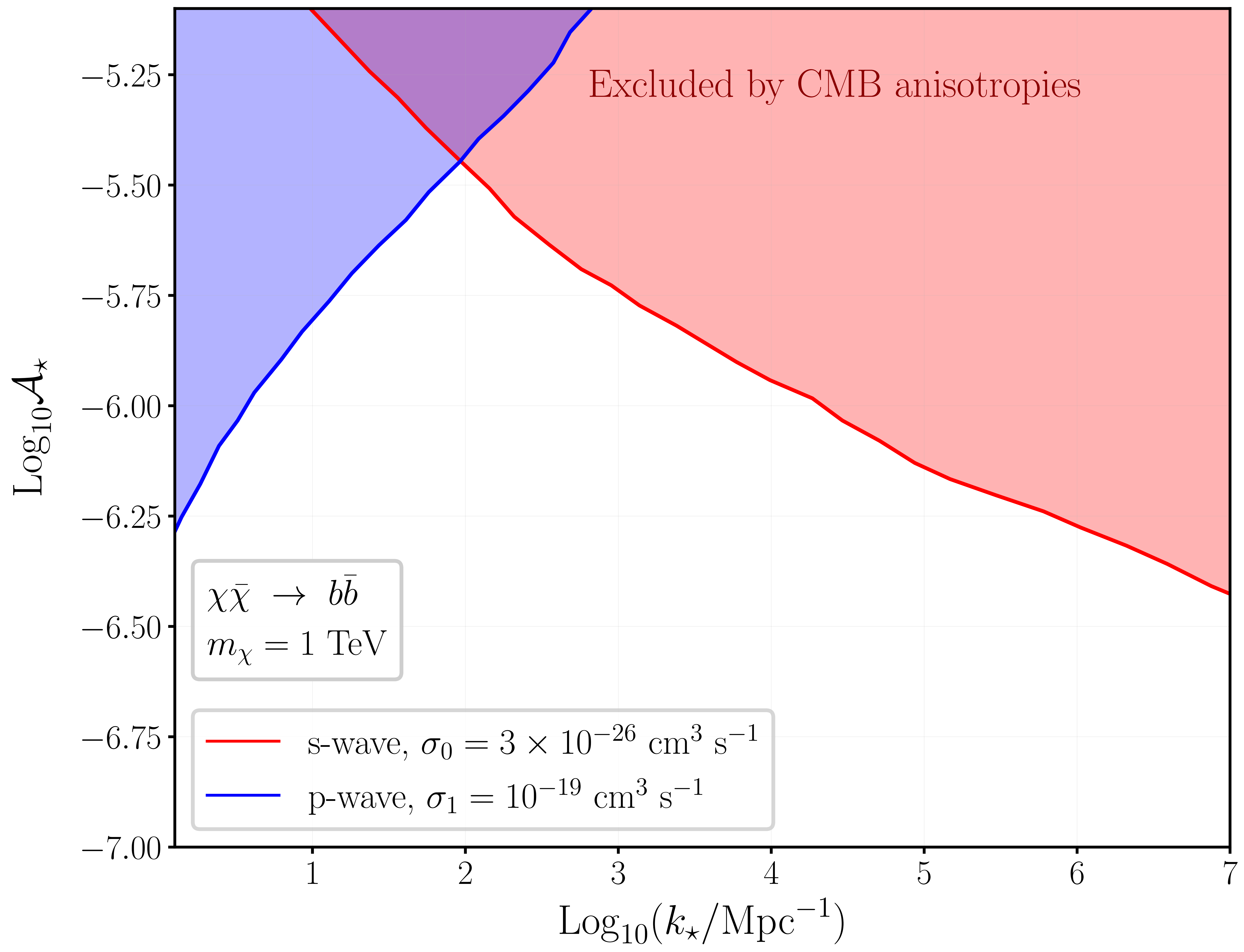
  (we use Jeans eq. to relate velocity dispersion with density profile)

RESULTS



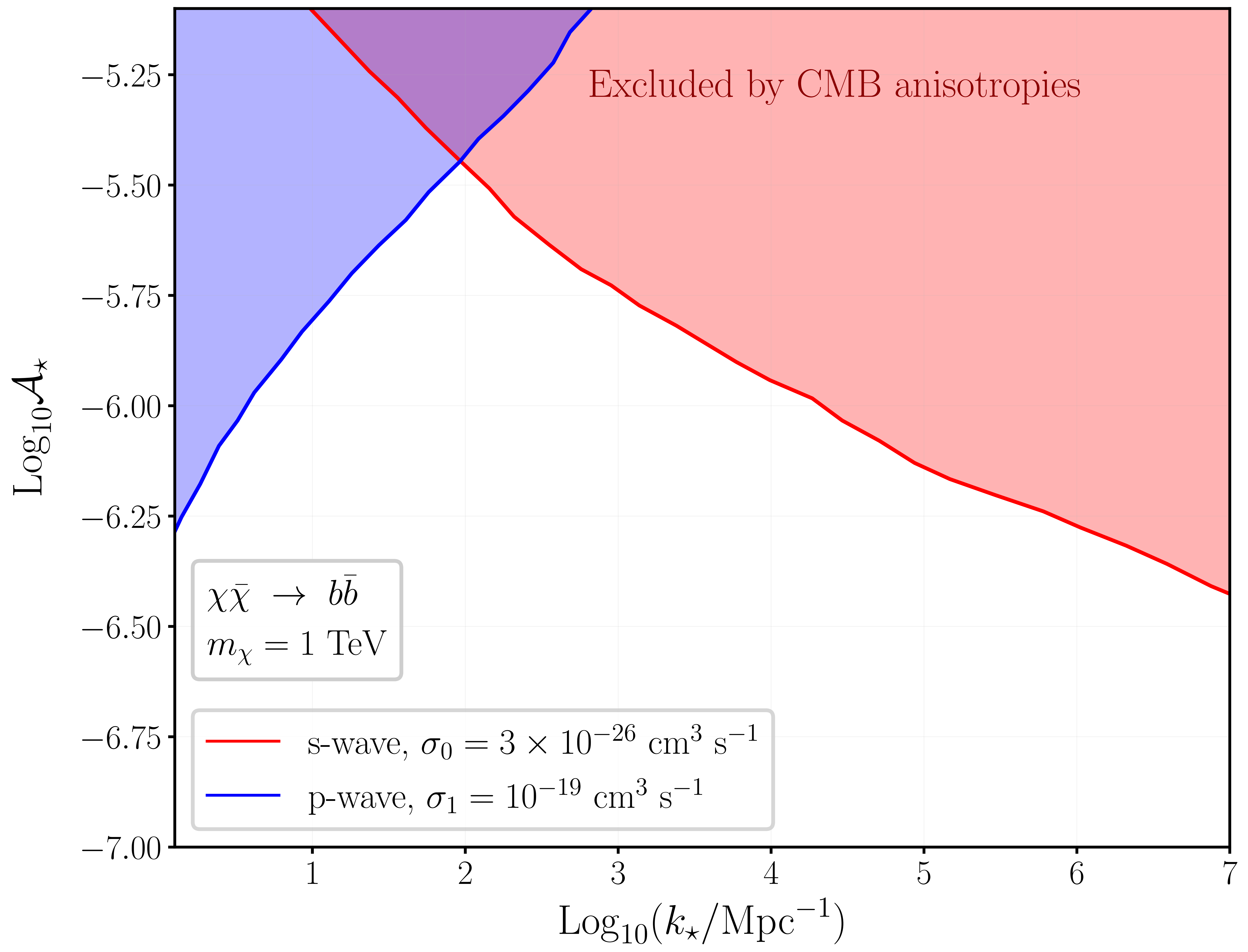
Excluded by CMB anisotropies
$\chi\bar{\chi} \rightarrow b\bar{b}$
$m_\chi = 1$ TeV
s-wave, $\sigma_0 = 3 \times 10^{-26}$ cm^3 s^{-1}
p-wave, $\sigma_1 = 10^{-19}$ cm^3 s^{-1}
$\mathrm{Log}_{10}\mathcal{A}_\star$
$\mathrm{Log}_{10}(k_\star/\mathrm{Mpc}^{-1})$
−5.25
−5.50
−5.75
−6.00
−6.25
−6.50
−6.75
−7.00
1
2
3
4
5
6
7

RESULTS



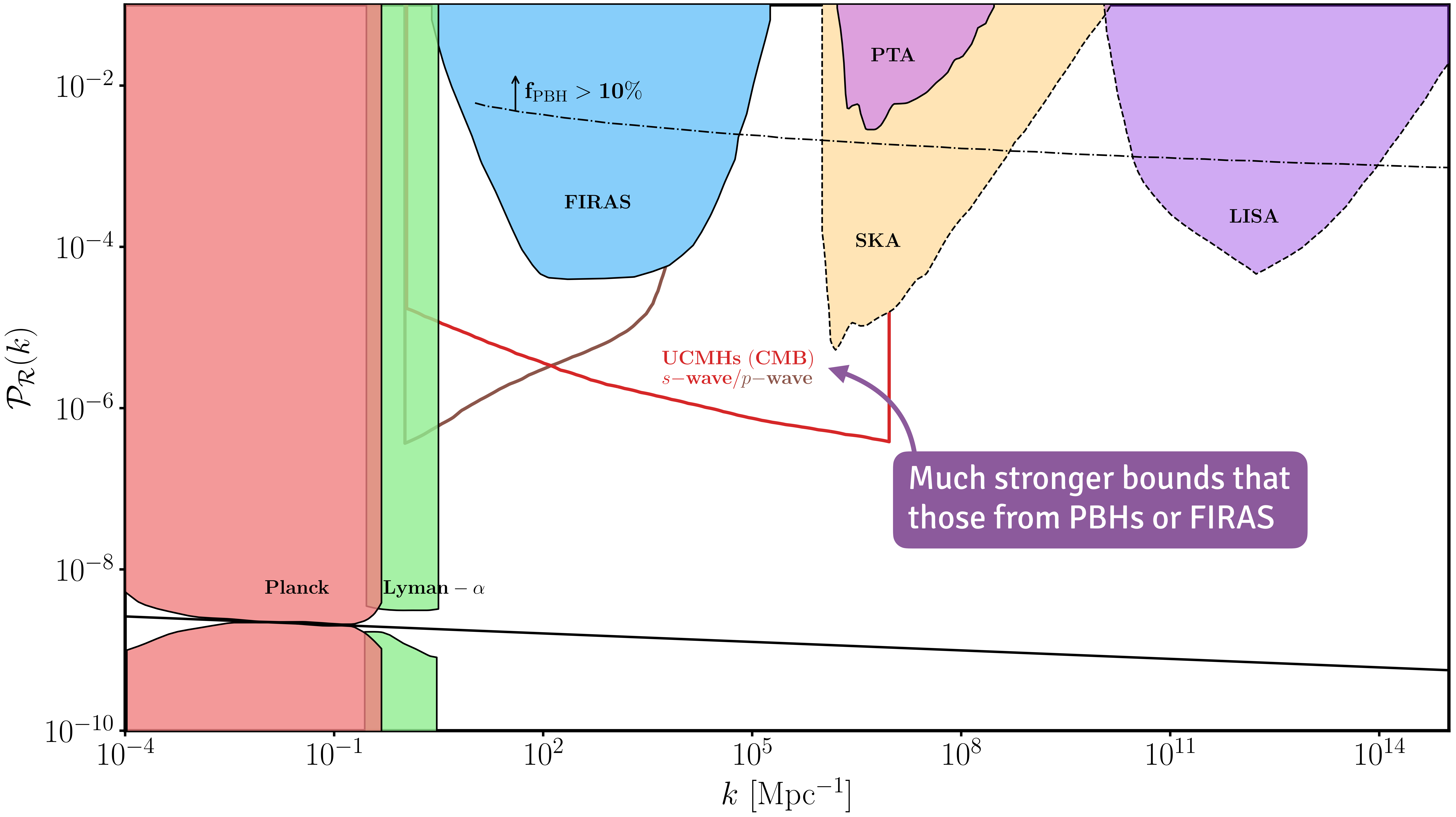
- p-wave constraints are competitive at small k

RESULTS



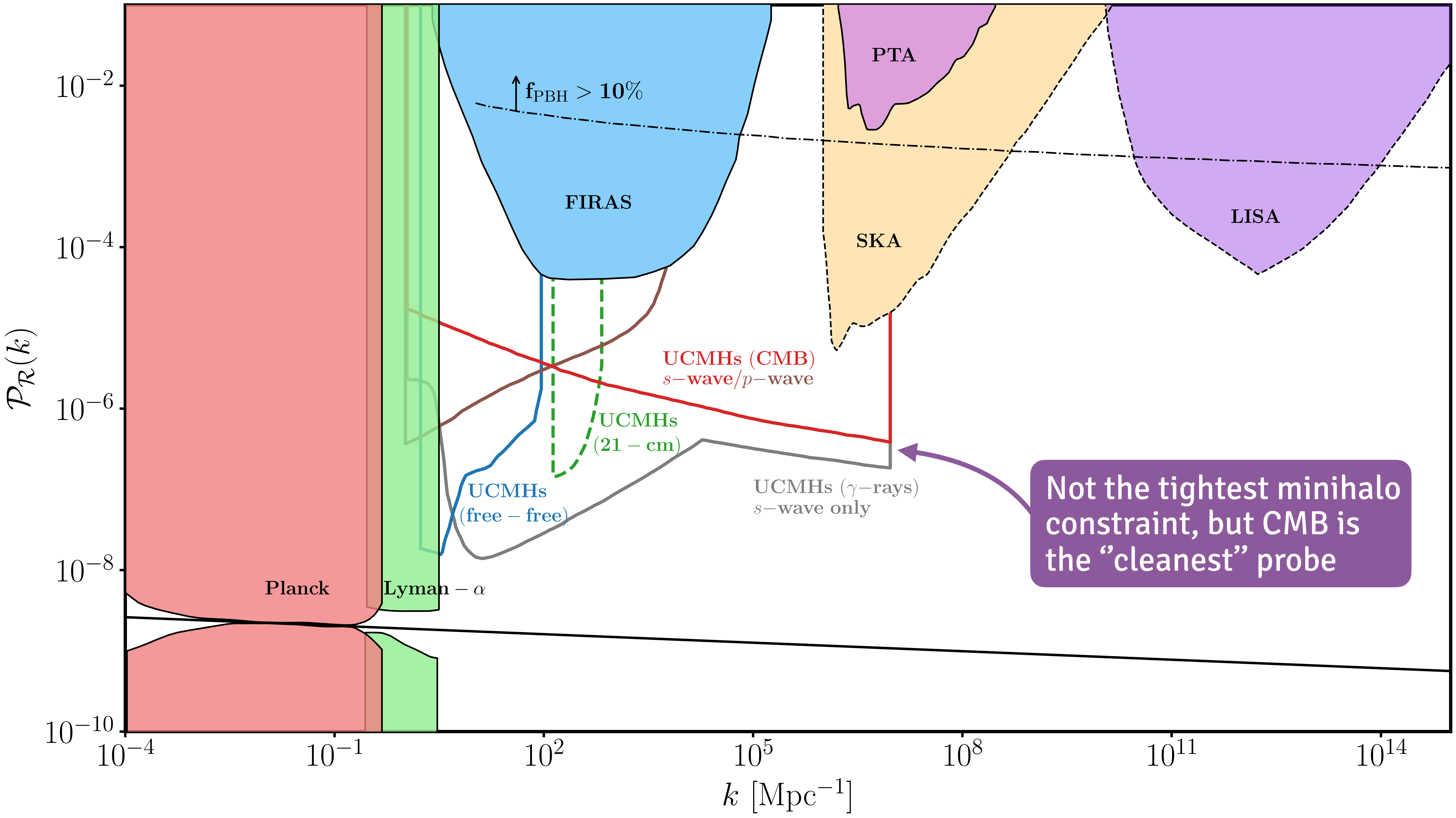
- p-wave constraints are competitive at small k
- Relevant for models that predict vanishing s-wave terms

RESULTS



$f_{\rm PBH} > 10\%$
FIRAS
PTA
SKA
LISA
UCMHs (CMB)
$s-$wave/$p-$wave
Planck
Lyman $-\ \alpha$
Much stronger bounds that those from PBHs or FIRAS
$\mathcal{P}_{\mathcal{R}}(k)$
k [Mpc^{-1}]
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-4}
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
10^{14}

RESULTS



Not the tightest minihalo constraint, but CMB is the "cleanest" probe

2. LATE UNIVERSE

Constraints on neutrino masses using dark matter subhalos and Milky-Way satellites

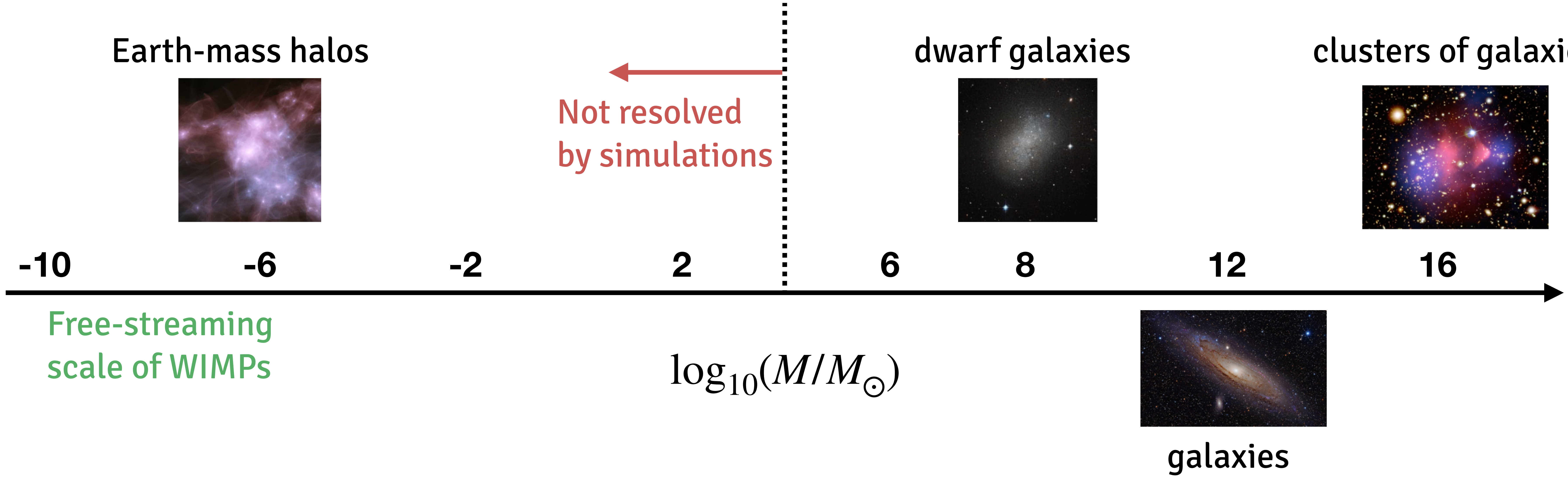
Ongoing work with
Shin'ichiro Ando (GRAPPA)
Youyou Li (GRAPPA)
David Krejcik
Yonnes Lourens
Antoine Marechal
Tiernan O'Neill
Scott Visser
Kjartan van Driel
Maxim Zewe

→ Master students at UVA

2. LATE UNIVERSE

Constraints on **neutrino masses** using dark matter **subhalos** and **Milky-Way satellites**

ΛCDM predicts structure formation across a wide range of scales



ΛCDM predicts structure formation across a wide range of scales

Earth-mass halos

Not resolved
by simulations

dwarf galaxies

clusters of galaxies

-10 -6 -2 2 6 8 12 16

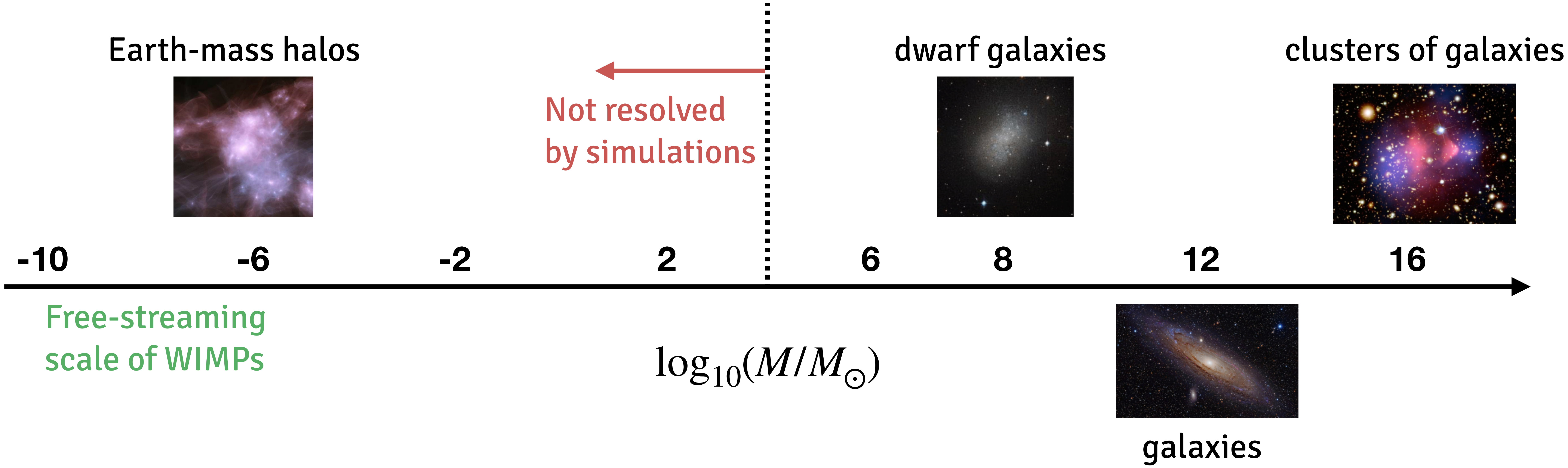
Free-streaming
scale of WIMPs

$\log_{10}(M/M_{\odot})$

galaxies

Subhalos: smaller halos that accreted onto a larger host

ΛCDM predicts structure formation across a wide range of scales



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Important to model them **analytically**

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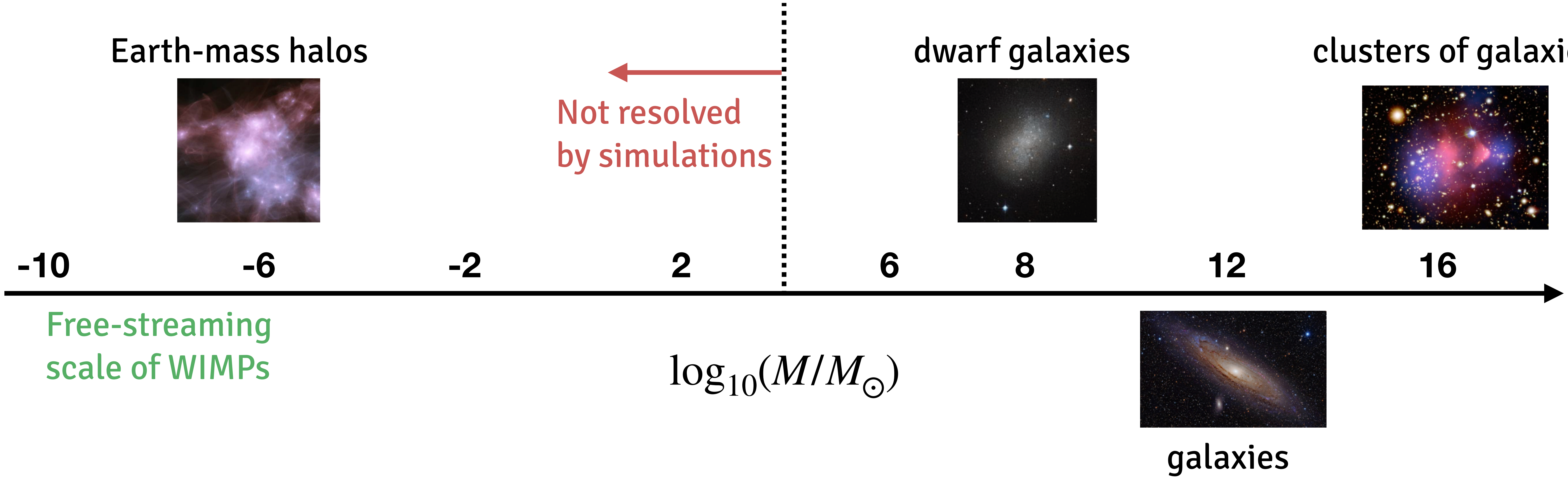
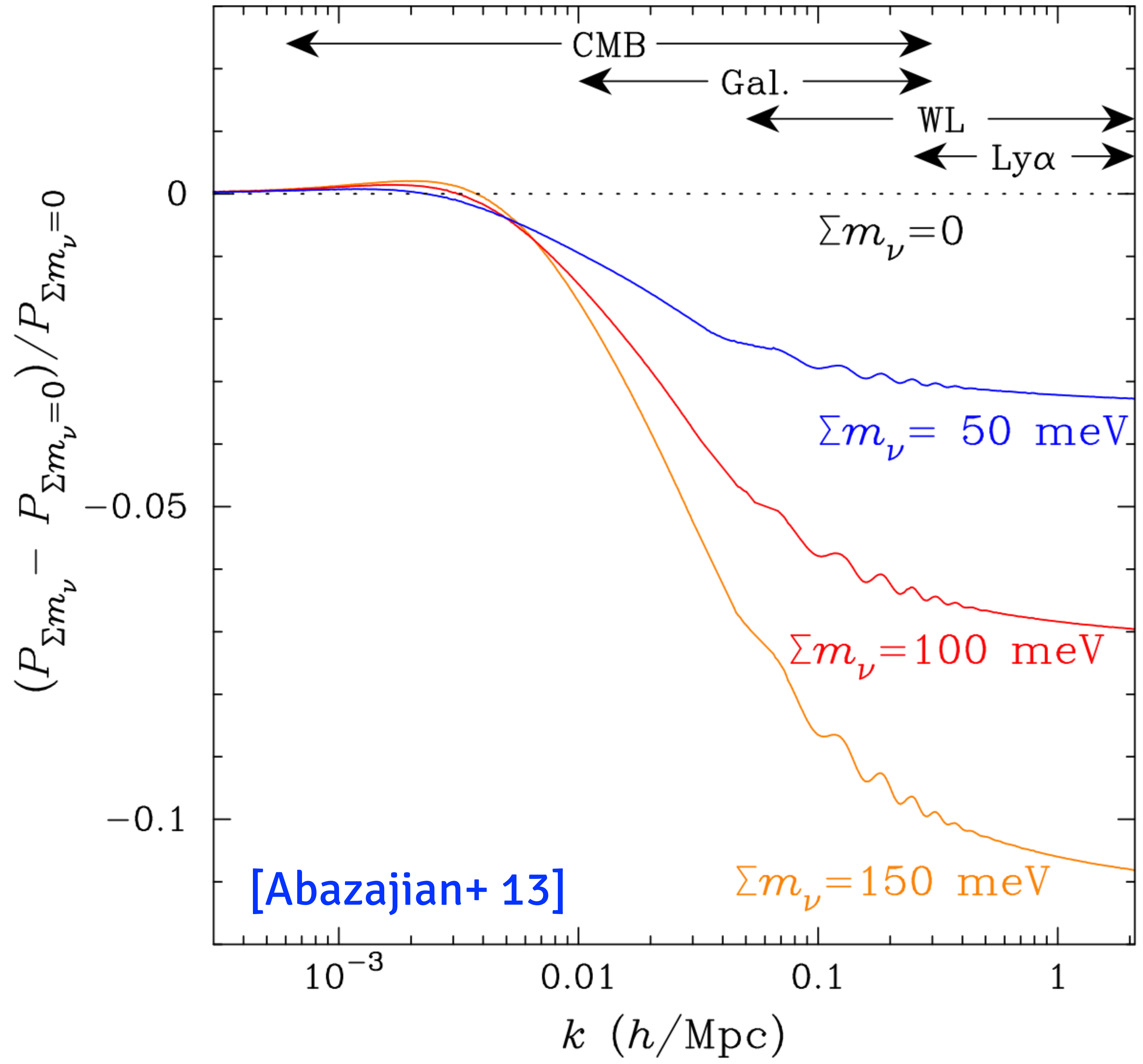


Subhalos: smaller halos that accreted onto a larger host

- Important to model them **analytically**
- Provide a valuable way to **test** models that change **the growth of structures**

Massive neutrinos suppress the matter power spectrum at scales smaller than their **free-streaming length:** $k_{fs}(z_{nr}) \simeq 0.01 \left(m_\nu/\text{eV}\right)^{1/2} h\ \text{Mpc}^{-1}$



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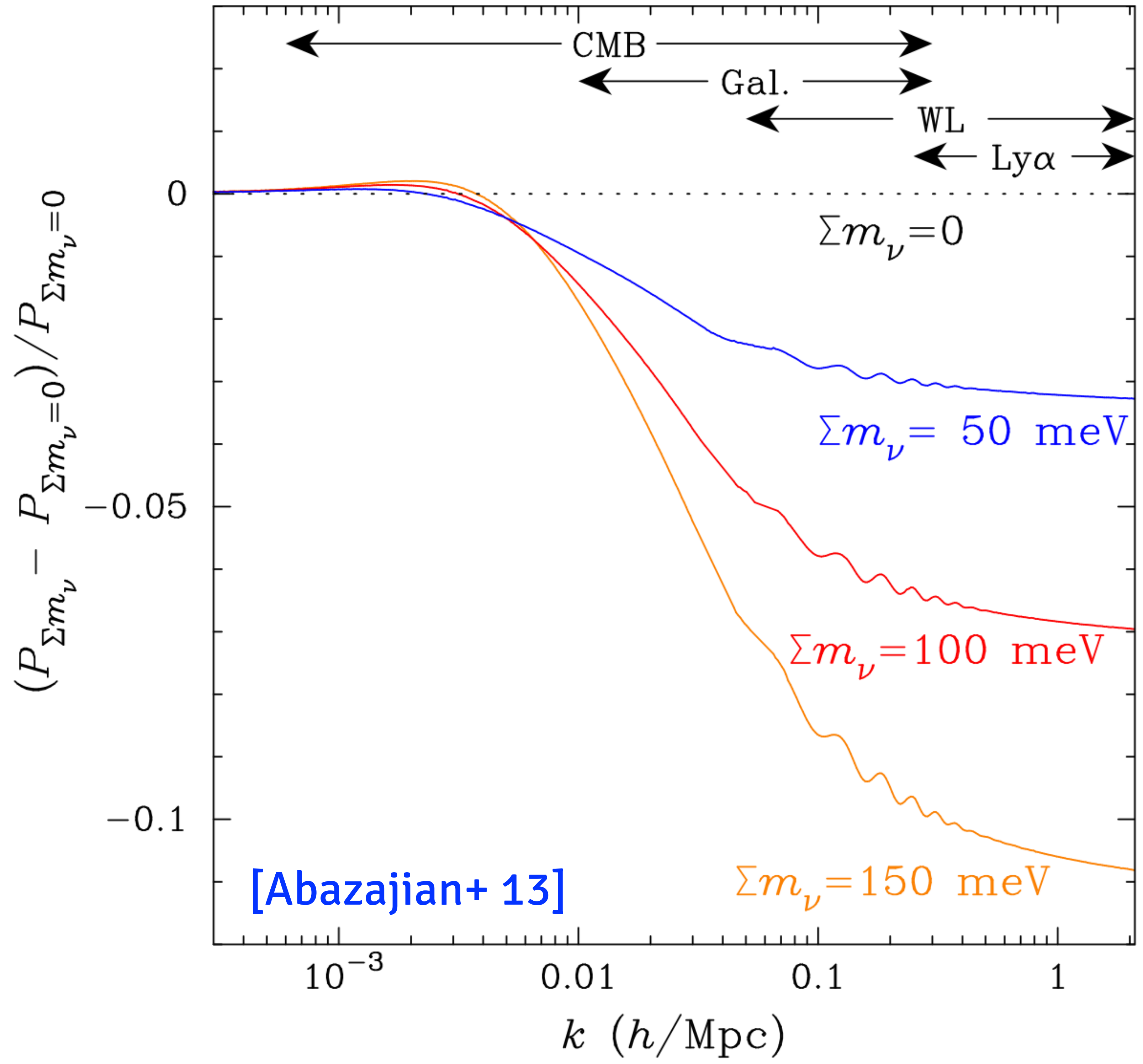
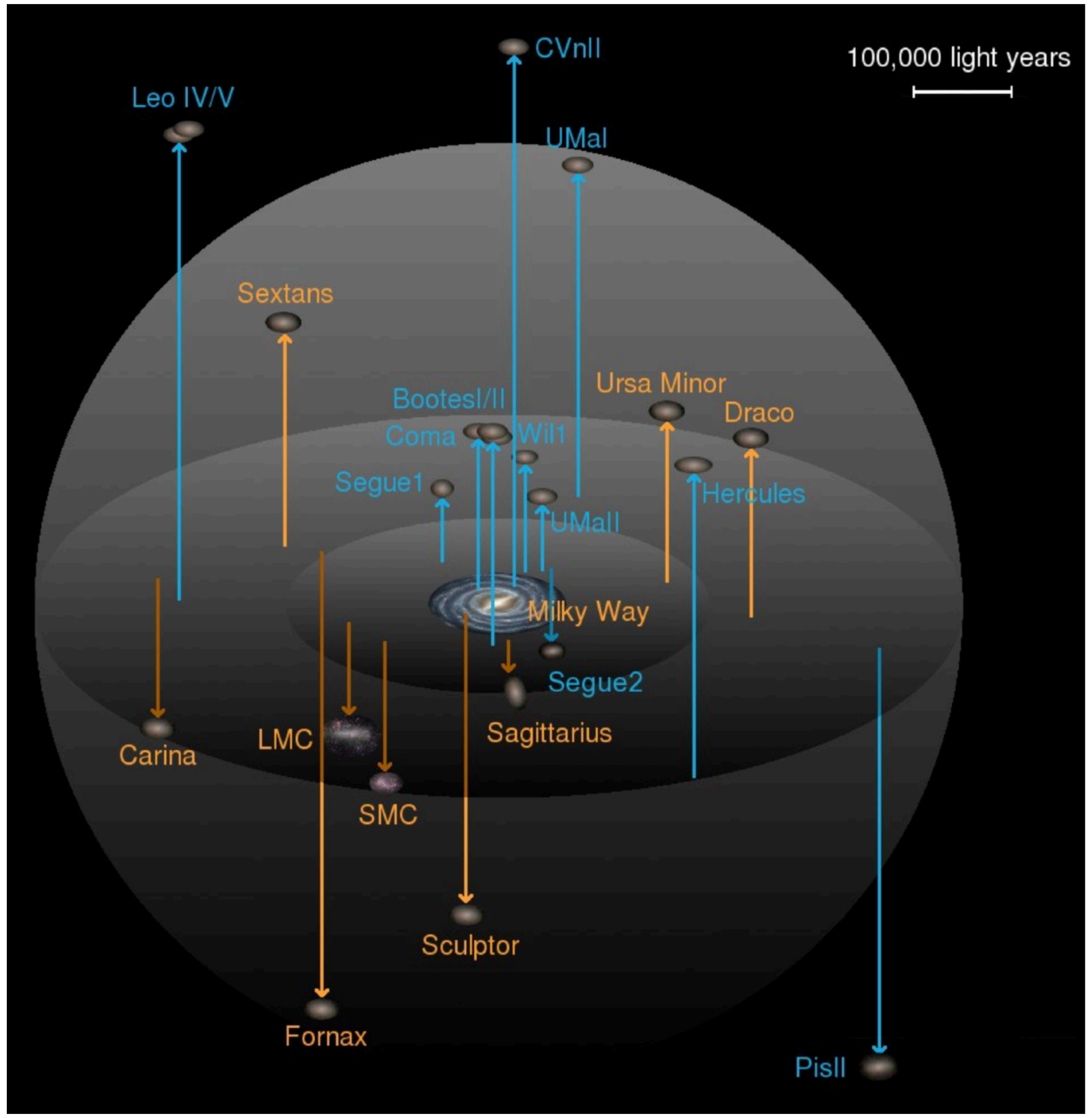
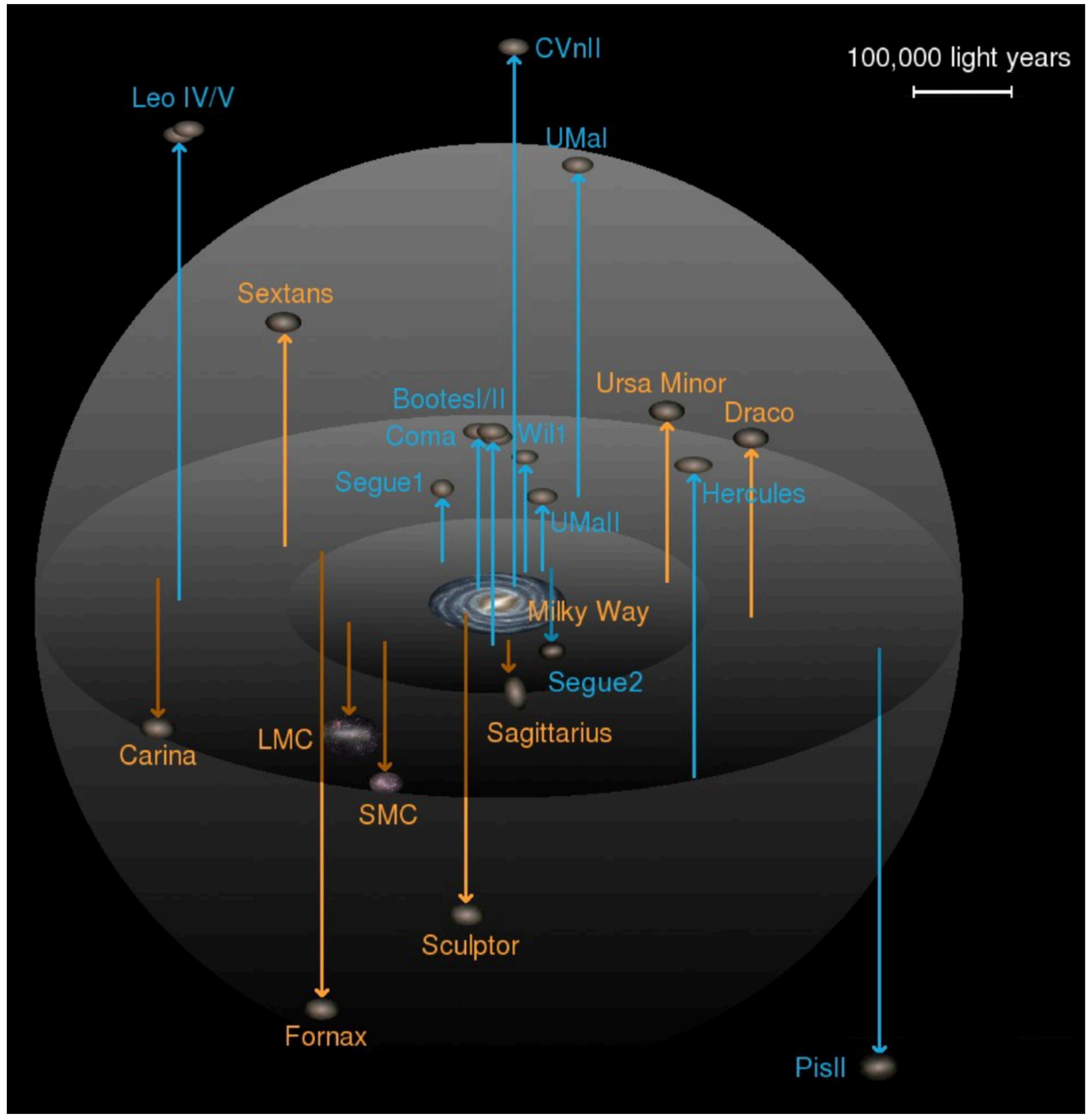


Very stringent limits from PlanckTTTEEE+lensing+BAO:

$$\sum m_\nu < 0.12\ {\rm eV} \quad (95\,\%\,{\rm C.L.})$$



Dark Energy Survey and Pan-STARRS1 have reported **270 ultrafaint Milky-Way satellite** galaxies after completeness correction



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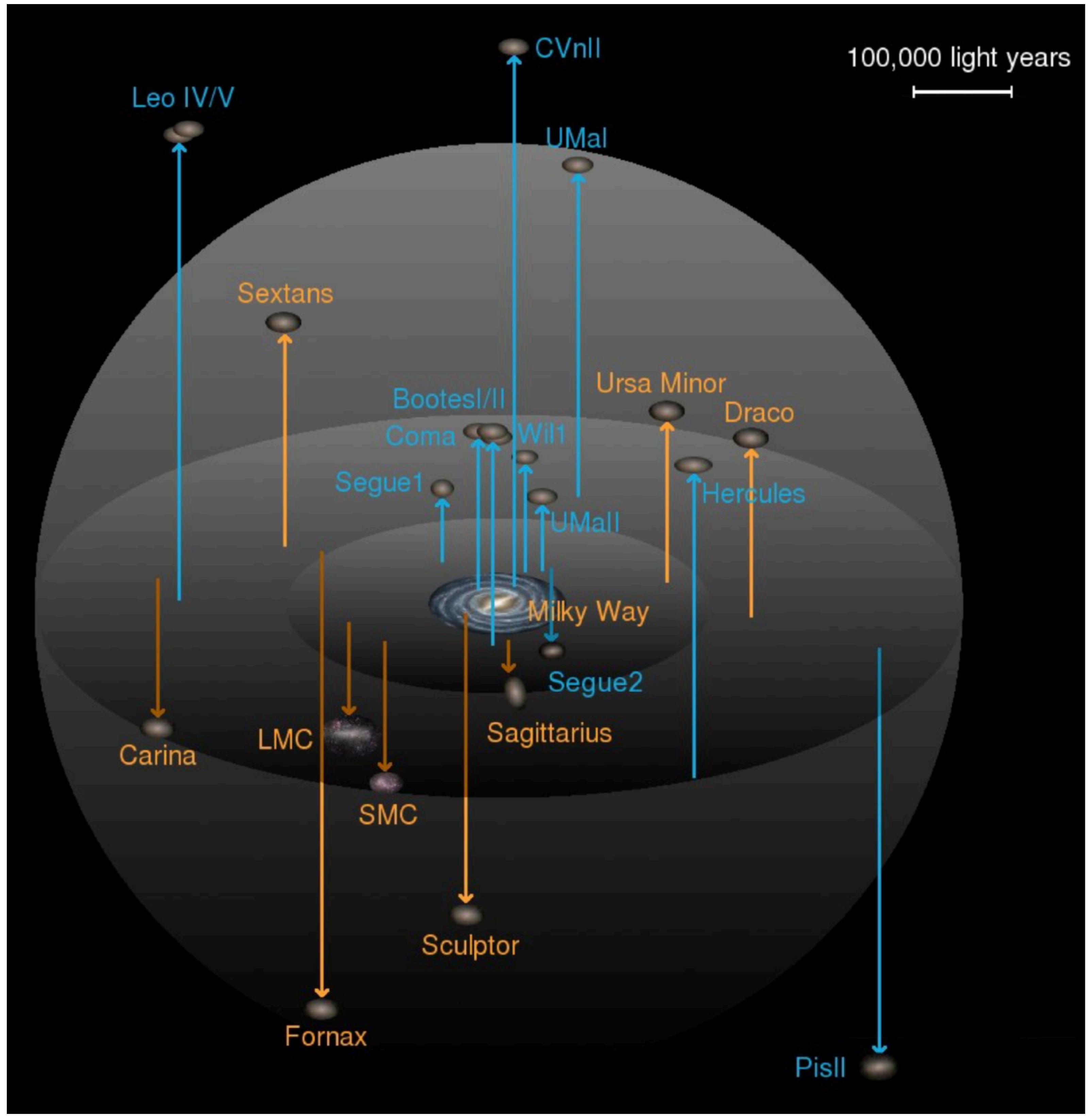

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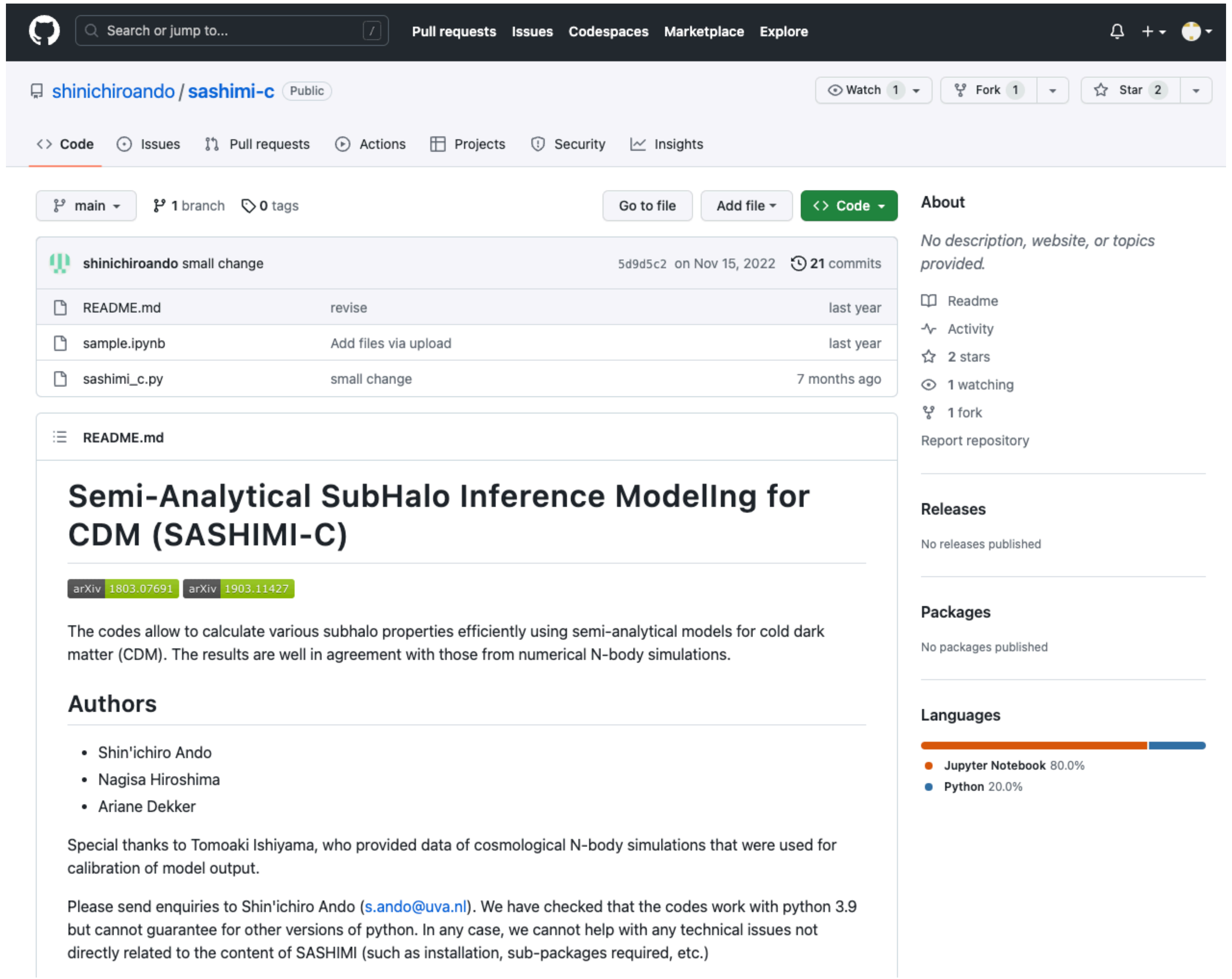
Use this to constrain neutrino masses

SASHIMI: Semi-Analytical SubHalo Inference ModelIng

Publicly available at https://github.com/shinichiroando/sashimi-c



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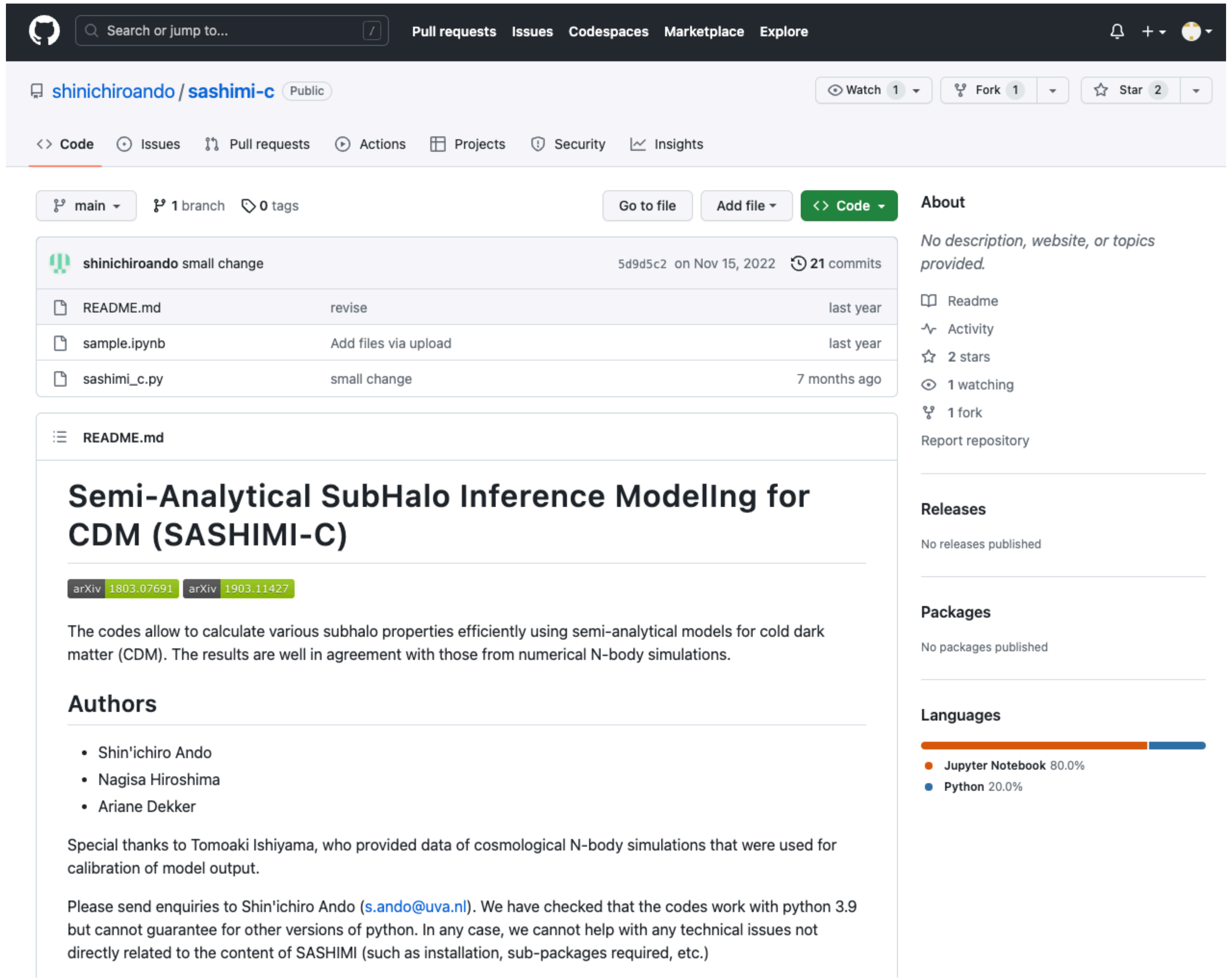

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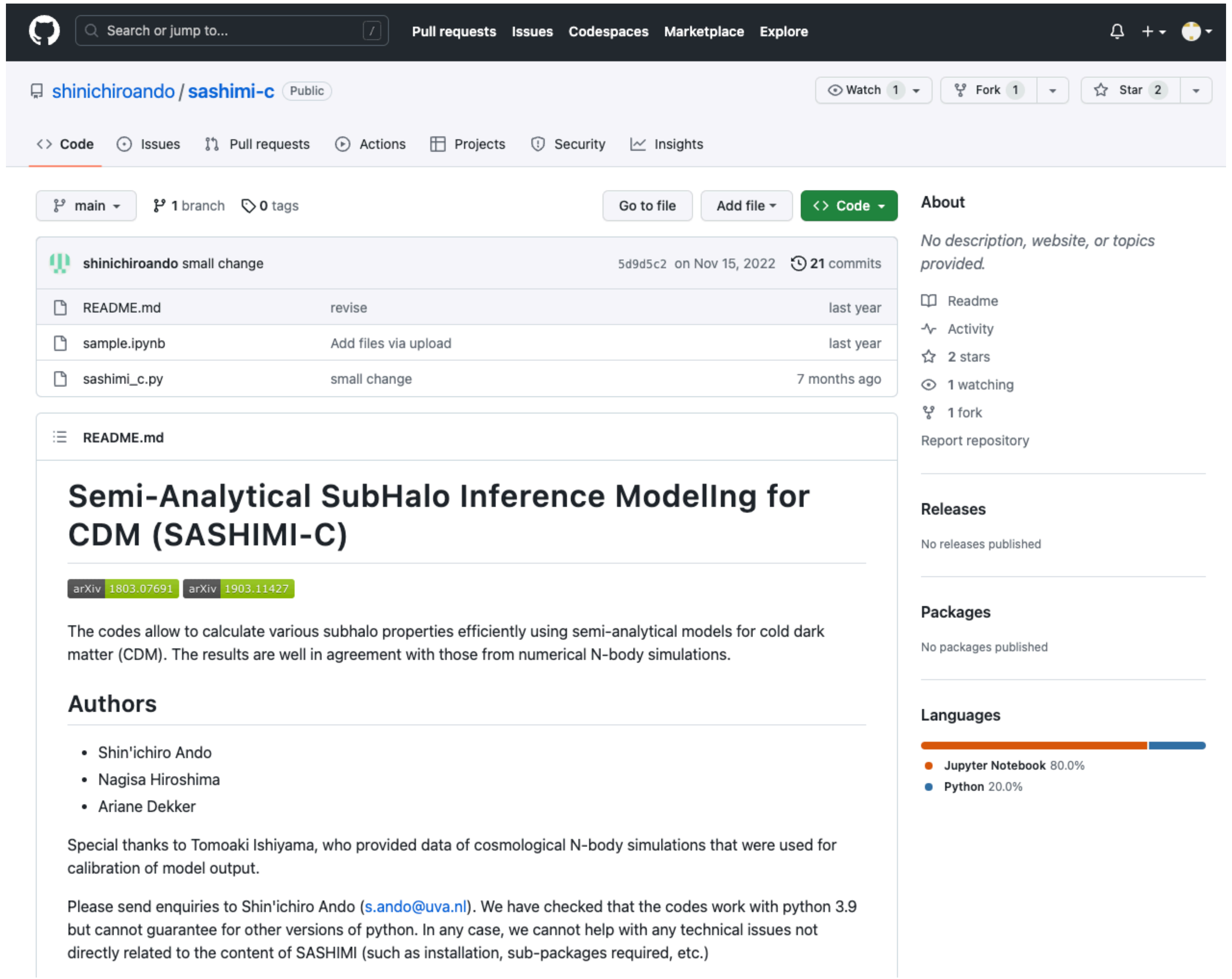

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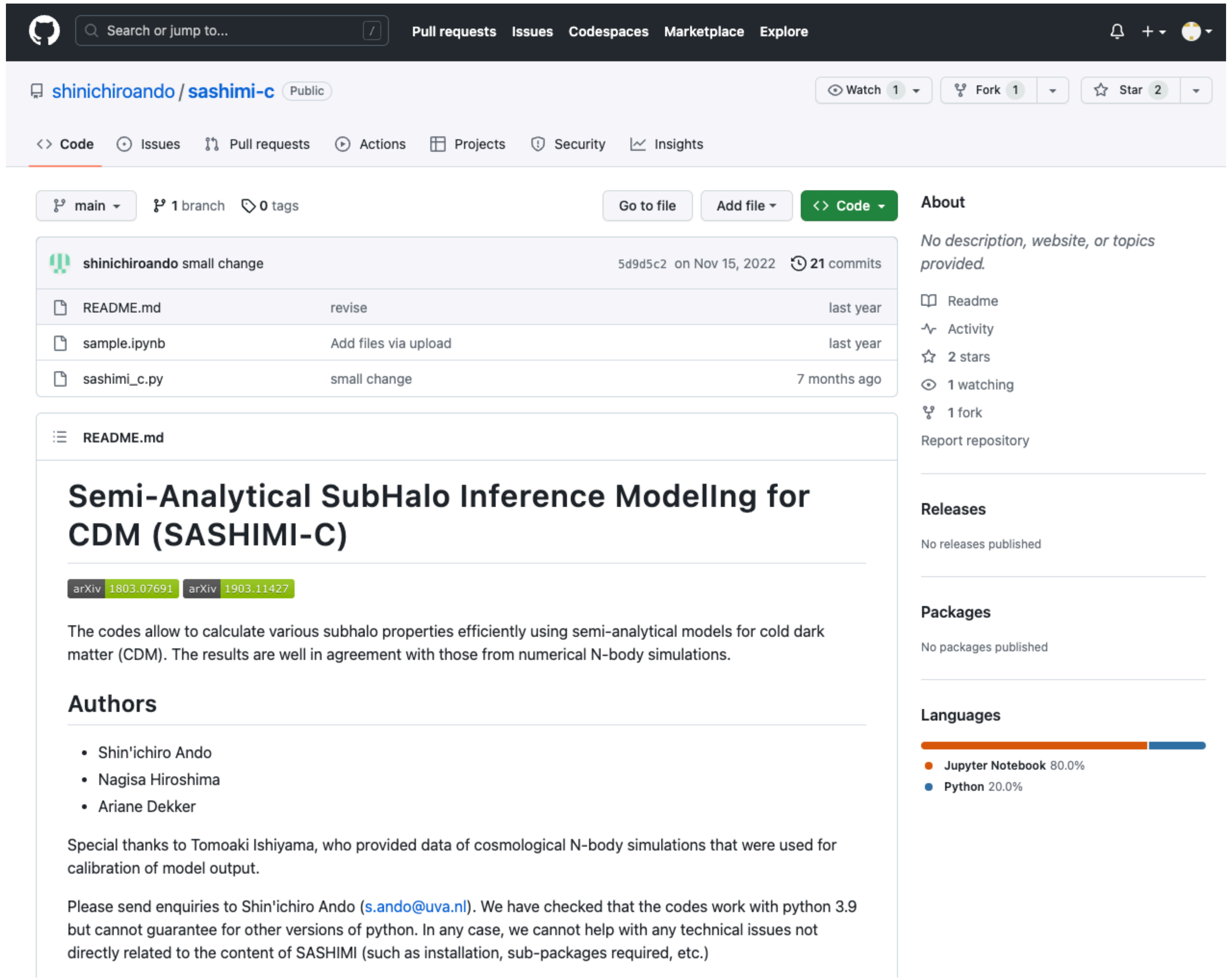
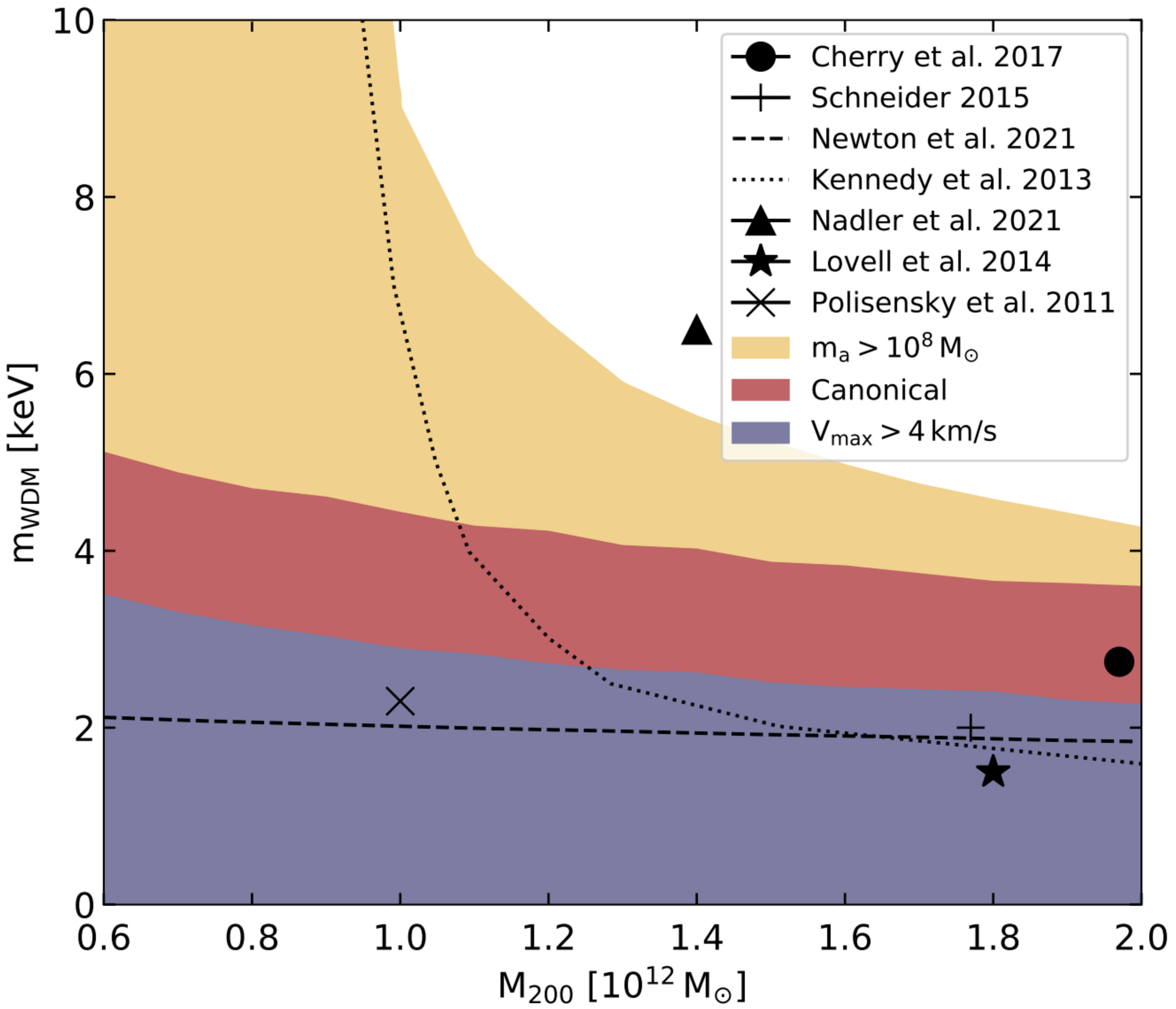


- Based on excursion set theory and subhalos' tidal evolution prescription
- Allows to calculate efficiently subhalo boost factor, subhalo mass function, etc
- Results agree well with those from N-body simulations

SASHIMI has already been used to set **stringent bounds on Warm Dark Matter** mass with MW satellite data

[Dekker+ 21]



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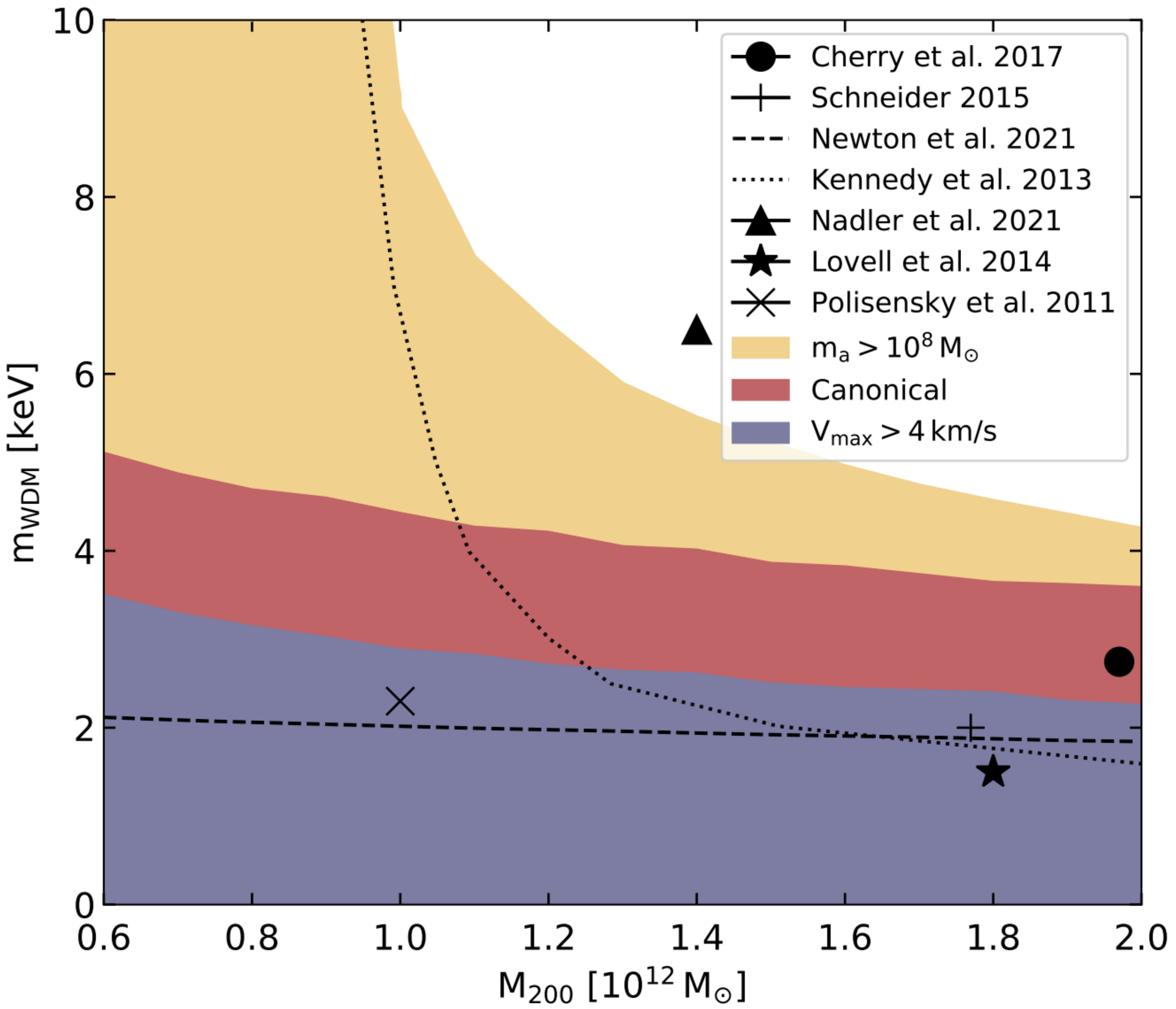
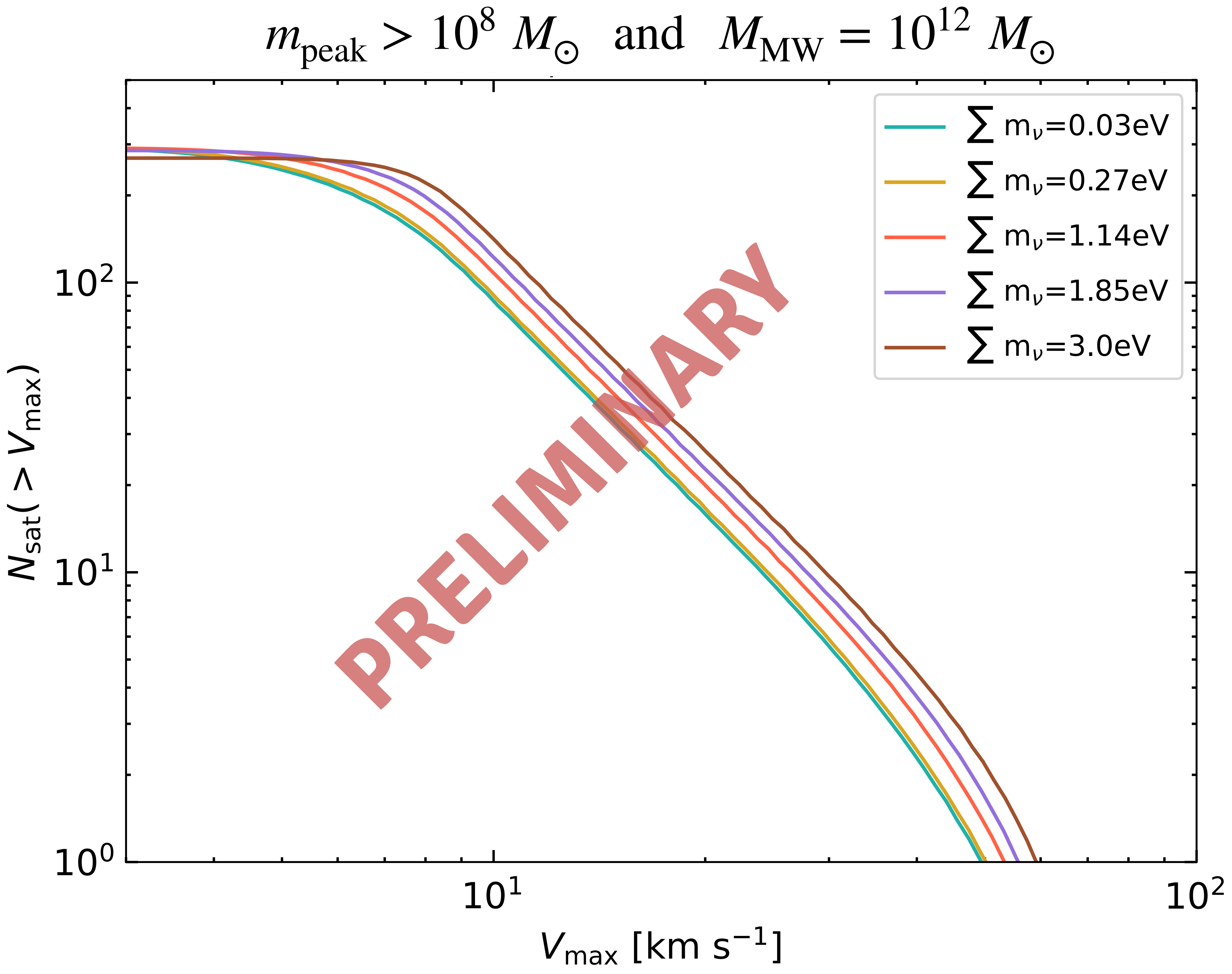


In a similar way, we can derive bounds on neutrino masses by modifying SASHIMI code accordingly

RESULTS



Surprisingly, we find an **increase** in the number of satellites for large neutrino masses!

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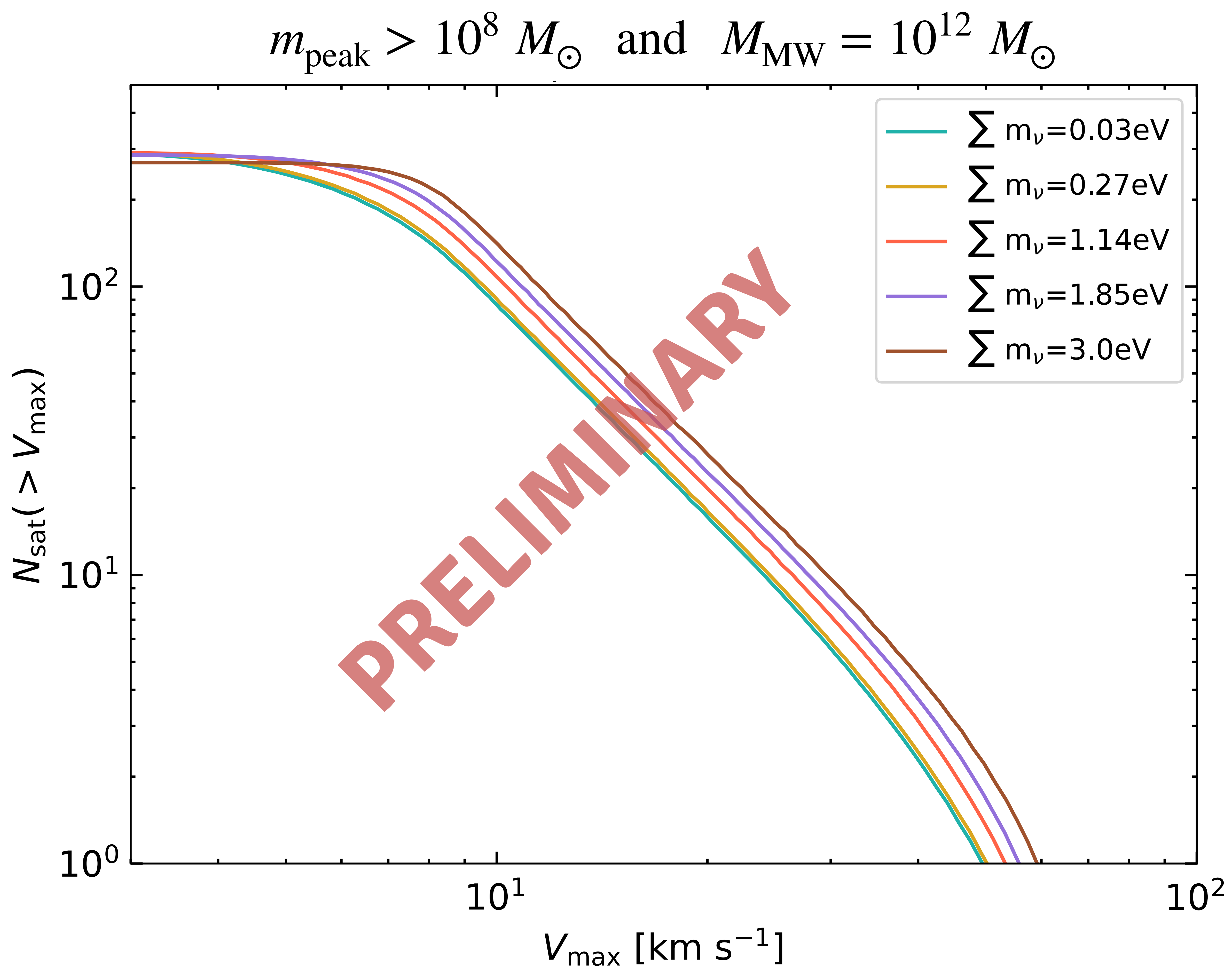

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Is this result robust?

More work to be done...

Summary

- Robust CMB bounds on small-scale $\mathcal{P}_{\mathcal{R}}(k)$ using both s-wave and p-wave DM annihil. in minihalos

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Summary

THANKS FOR YOUR ATTENTION

g.francoabellan@uva.nl

- Robust CMB bounds on small-scale $\mathcal{P}_{\mathcal{R}}(k)$ using both s-wave and p-wave DM annihil. in minihalos

- New formalism that allows to better take into account effects of halo mergers (relevant for 21cm studies)

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BACK-UP

The CMB in a nutshell

$$\mathscr{D}_\ell^{TT} \equiv \ell(\ell+1)C_\ell^{TT} \sim \int d\log k\ \Theta_\ell^2(\tau_0,k)\mathscr{P}_{\mathscr{R}}(k)$$

- Line-of-sight solution

$$\Theta_\ell(\tau_0,k) = \int_\tau^{\tau_0} d\tau\ S_T(\tau,k)\ j_\ell(k(\tau_0-\tau))$$

- Source function

$$S_T(\tau,k) \equiv \underbrace{g(\Theta_0+\Psi)}_{\text{SW}} + \underbrace{\partial_\tau(gv_b/k)}_{\text{Doppler}} + \underbrace{e^{-\kappa}(\dot\Phi+\dot\Psi)}_{\text{ISW}}$$

- Visibility function and optical depth

$$g(\tau) \equiv -\dot\kappa(\tau)e^{-\kappa(\tau)}, \qquad \kappa(\tau) = \int_\tau^{\tau_0} \mathrm{d}\tau\ a\sigma_\mathrm{T}\ \mathrm{n_e}$$

Energy injection from DM could affect n_e, which directly impacts CMB anisotropies

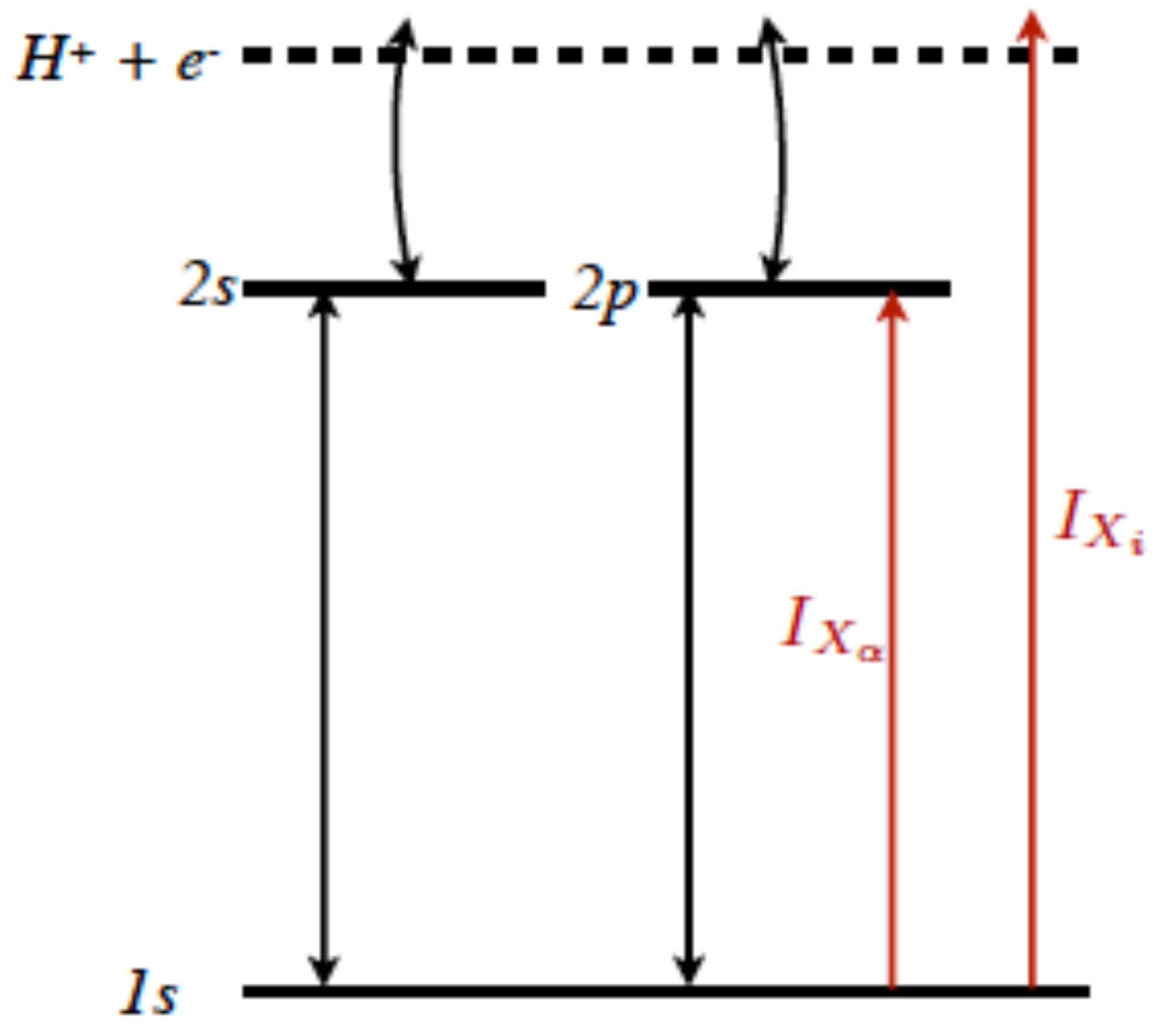
Exotic energy injection in the CMB

DM annihilations have three effects:
ionization, excitation and heating

$$\frac{dx_e}{dz} = \left.\frac{dx_e}{dz}\right|_{\rm st} + I_{X_\alpha} + I_{X_i}$$

$$\frac{dT_b}{dz} = \left.\frac{dT_b}{dz}\right|_{\rm st} + K_h$$

with $I_{X_\alpha}, I_{X_i}, K_h \propto \left.\frac{dE}{dVdt}\right|_{\rm DM} \propto p_{\rm ann}$



[Giesen+12]

Excursion set theory

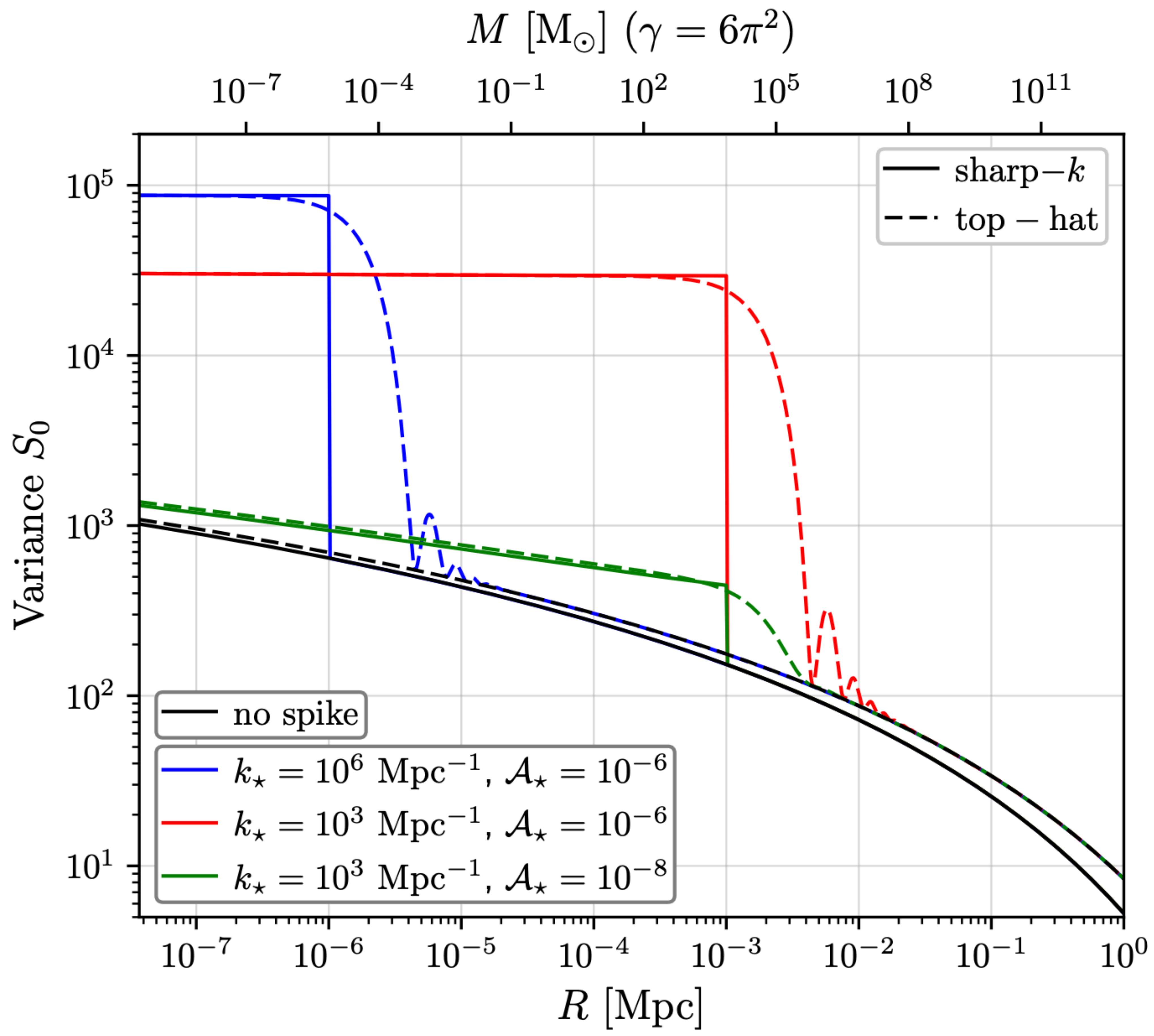
- Halo mass function:

$$\frac{\mathrm{d}n(M\,|\,z)}{\mathrm{d}M} = \frac{\langle\rho_\mathrm{m}^0\rangle}{M}\frac{\nu(M,z)}{2S(M)}\left|\frac{\mathrm{d}S}{\mathrm{d}M}\right|\sqrt{\frac{2}{\pi}}e^{-\nu^2(M,z)/2} \quad \text{with} \quad \nu(M,z) \equiv \frac{\omega(z)}{\sqrt{S(M)}} \quad \text{and} \quad \omega(z) \equiv \delta_\mathrm{c}\frac{D(0)}{D(z)}$$

- Smoothed variance:

$$\sigma_R^2 = S(R) \sim \int_0^\infty k^3 T^2(k)\mathcal{P}_\mathcal{R}(k)\,|\,\hat{W}_R(k)\,|^2\,\mathrm{d}k \quad \text{with} \quad M = \langle\rho_\mathrm{m}^0\rangle\gamma R^3$$

Variance in presence of spike



- With a sharp-k window function:

$$S_0(M) = \alpha(M) + \beta\Theta(M_s - M)$$

with $M_s = \langle \rho_m^0 \rangle \gamma k_\star^{-3}$

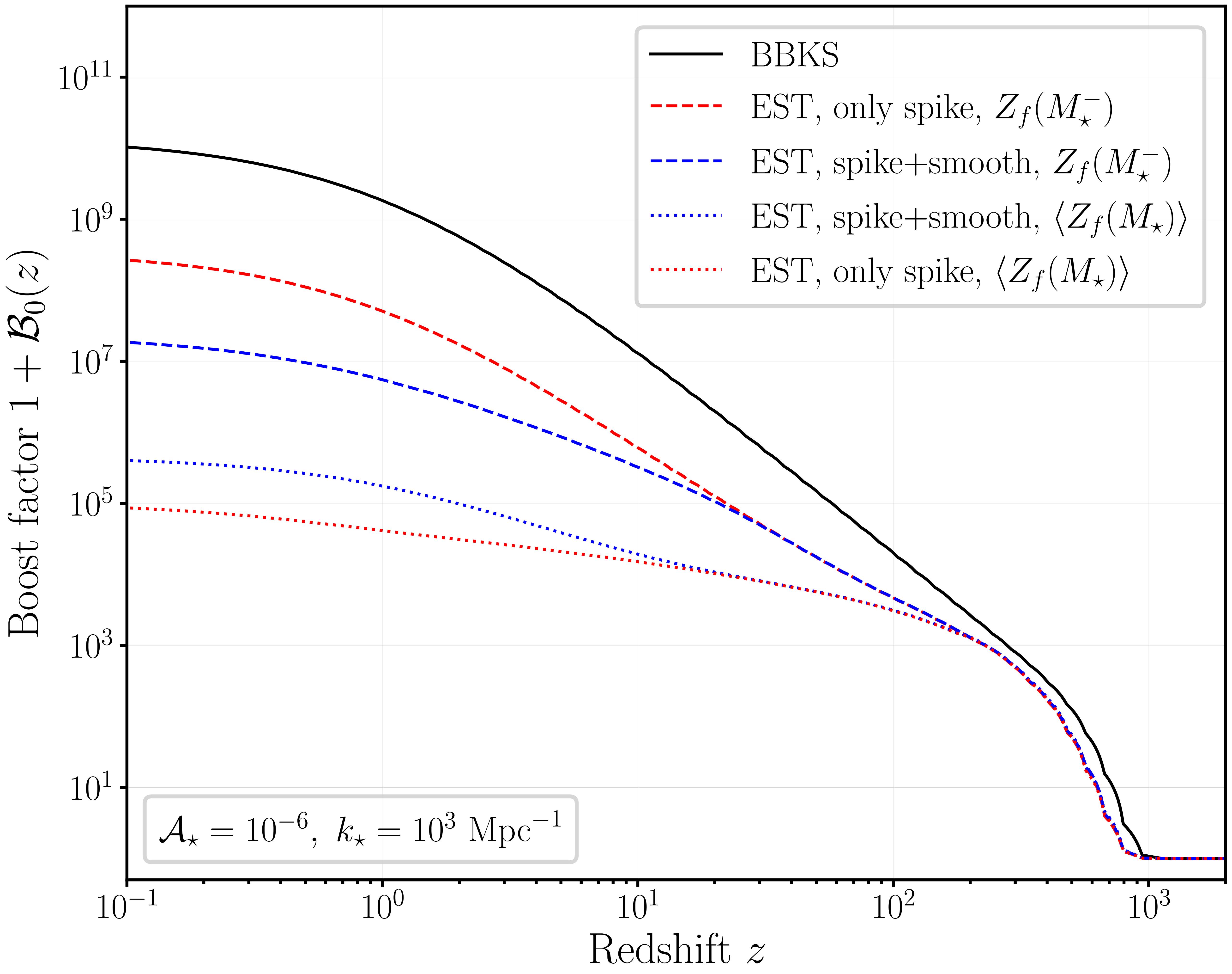
- Idea: split mass interval as

$$[M_{min}, M_s] \cup [M_s, \infty]$$

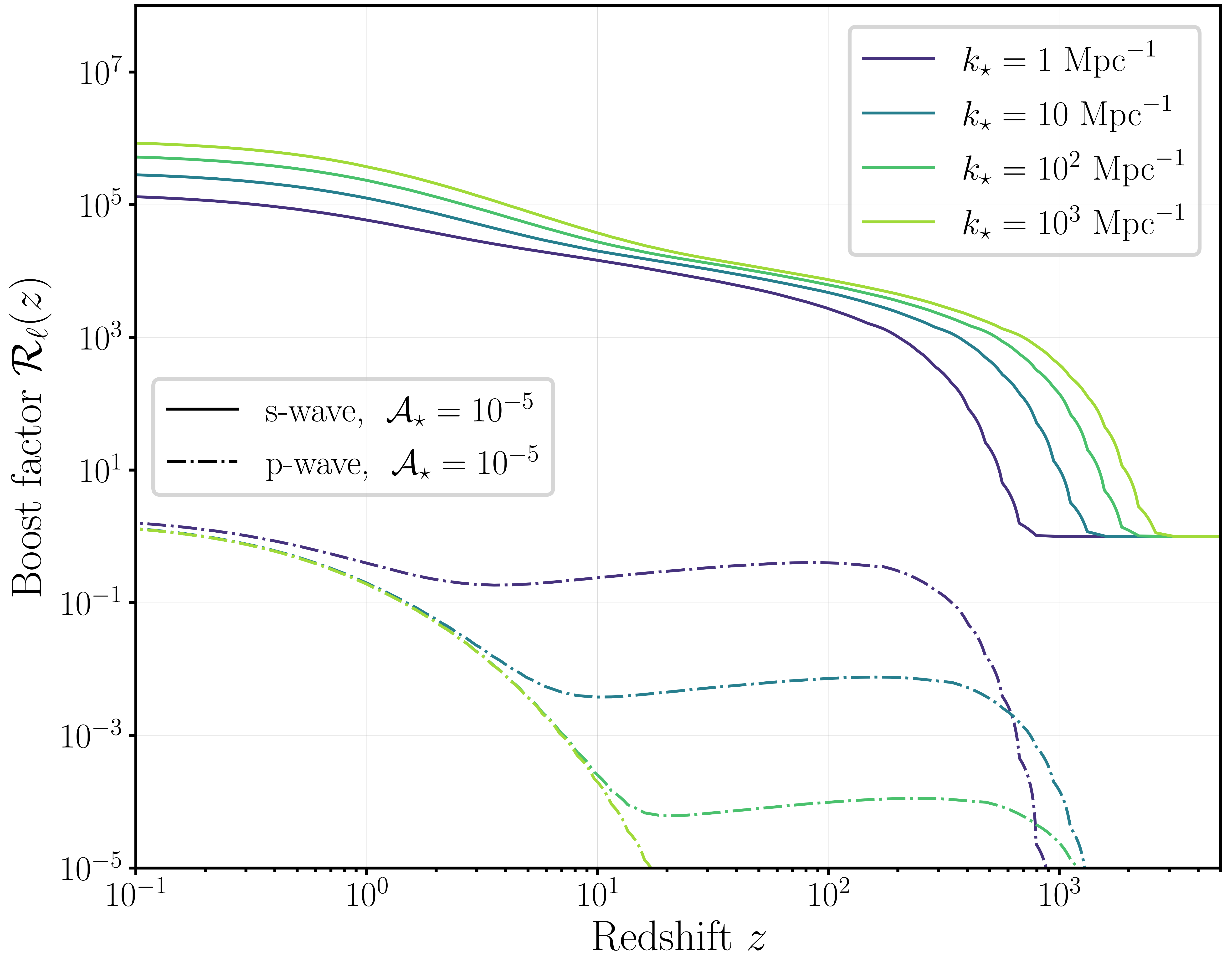
UCMH profile

NFW profile

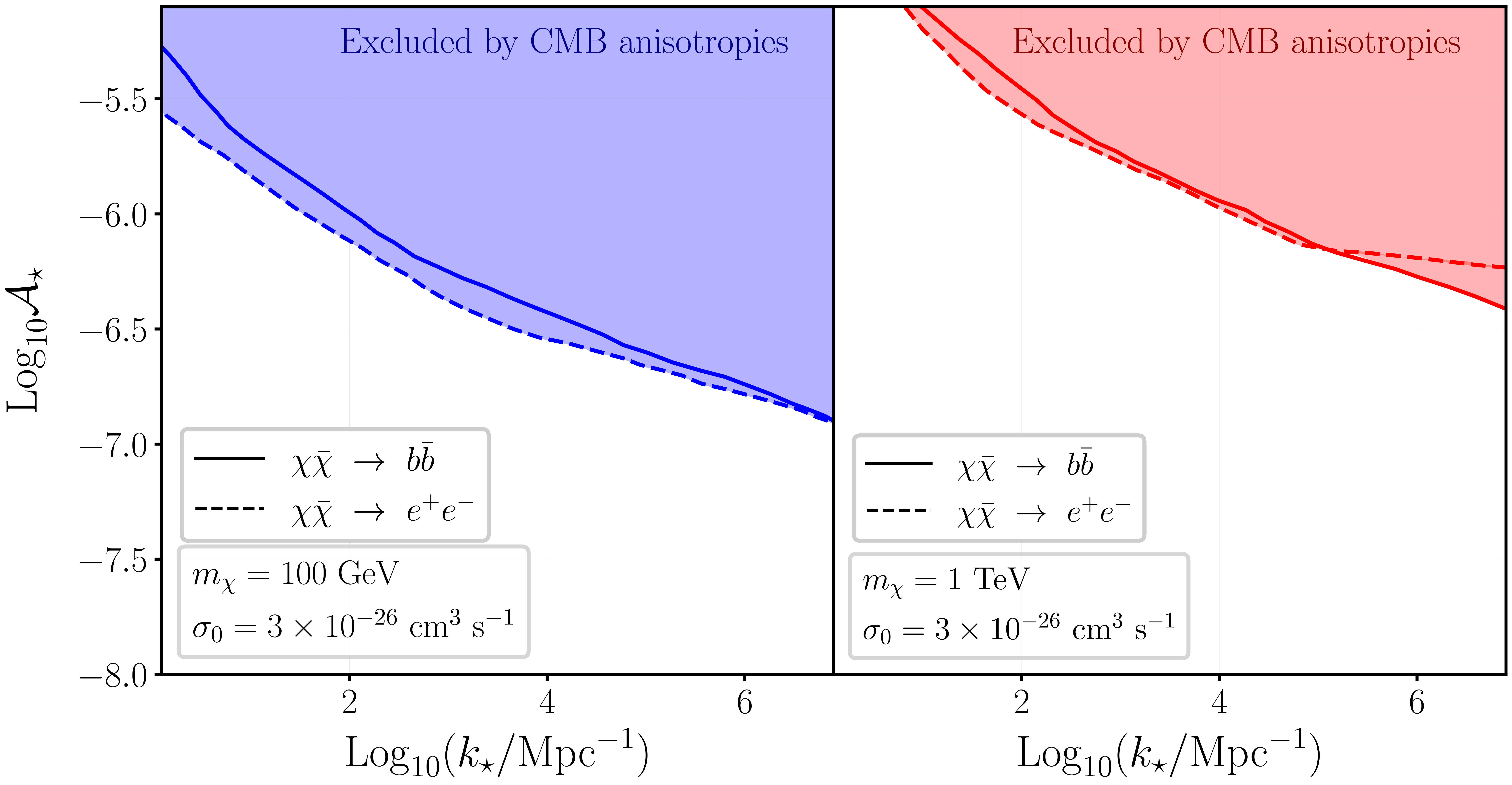
Boost factor: comparison between formalisms



Boost factor: s-wave vs. p-wave



Constraints for different DM masses and annihil. channels



Press-Schechter halo mass function for ΛCDM, νΛCDM and ΛWDM cosmologies