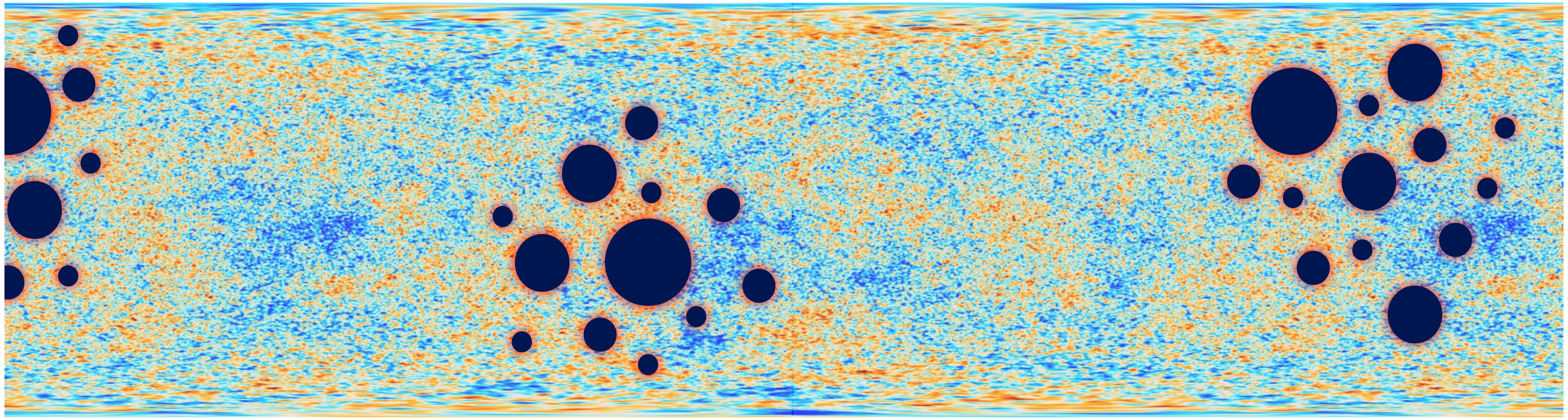
Probing the primordial power spectrum with dark matter minihalos and the CMB



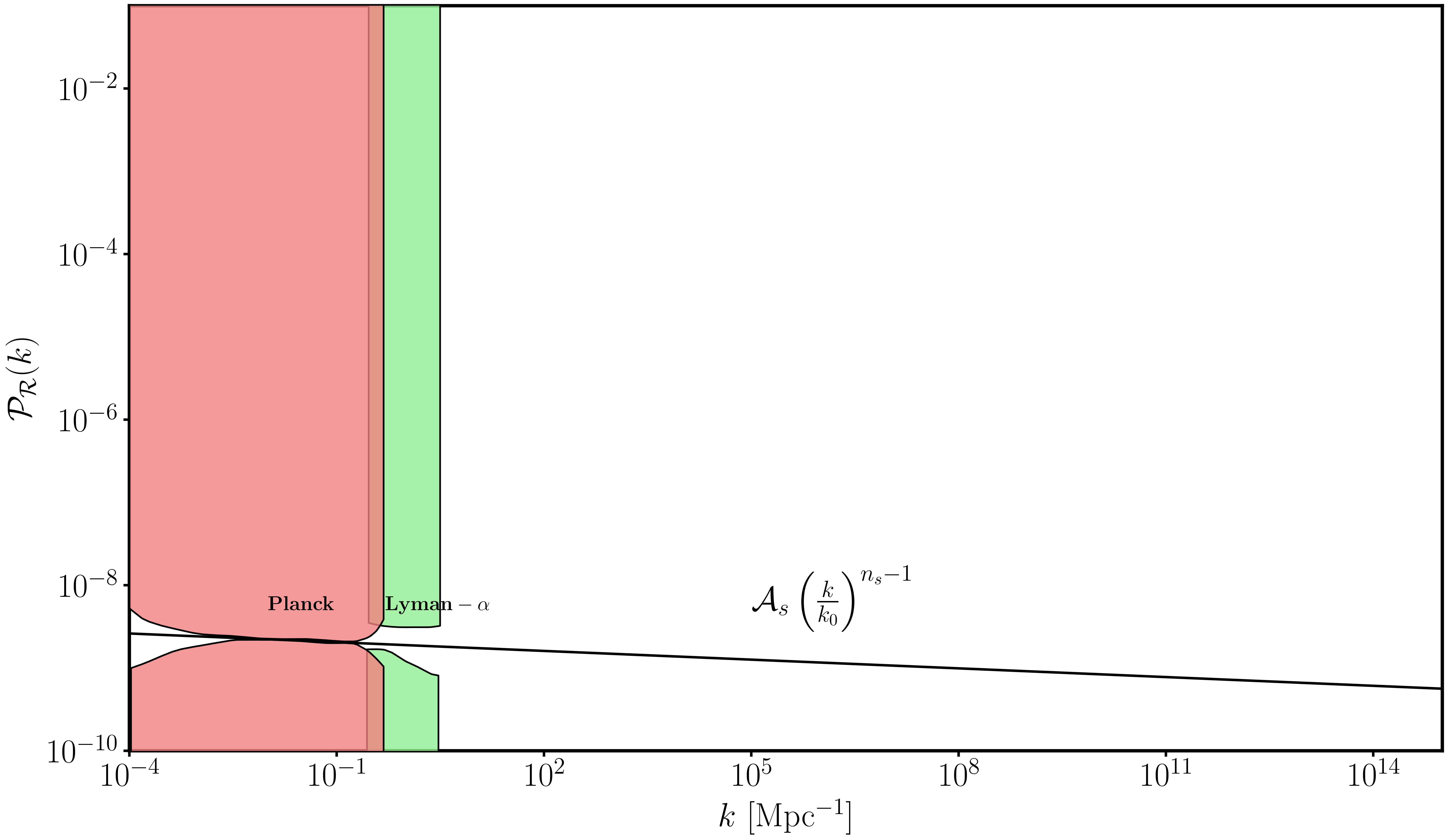
Guillermo Franco Abellán

GRAPPA
GRavitation AstroParticle Physics Amsterdam

Based on: arXiv:2304.02996
with Gaétan Facchinetti (ULB)

EuCAPT - 01/06/2023

The primordial power spectrum



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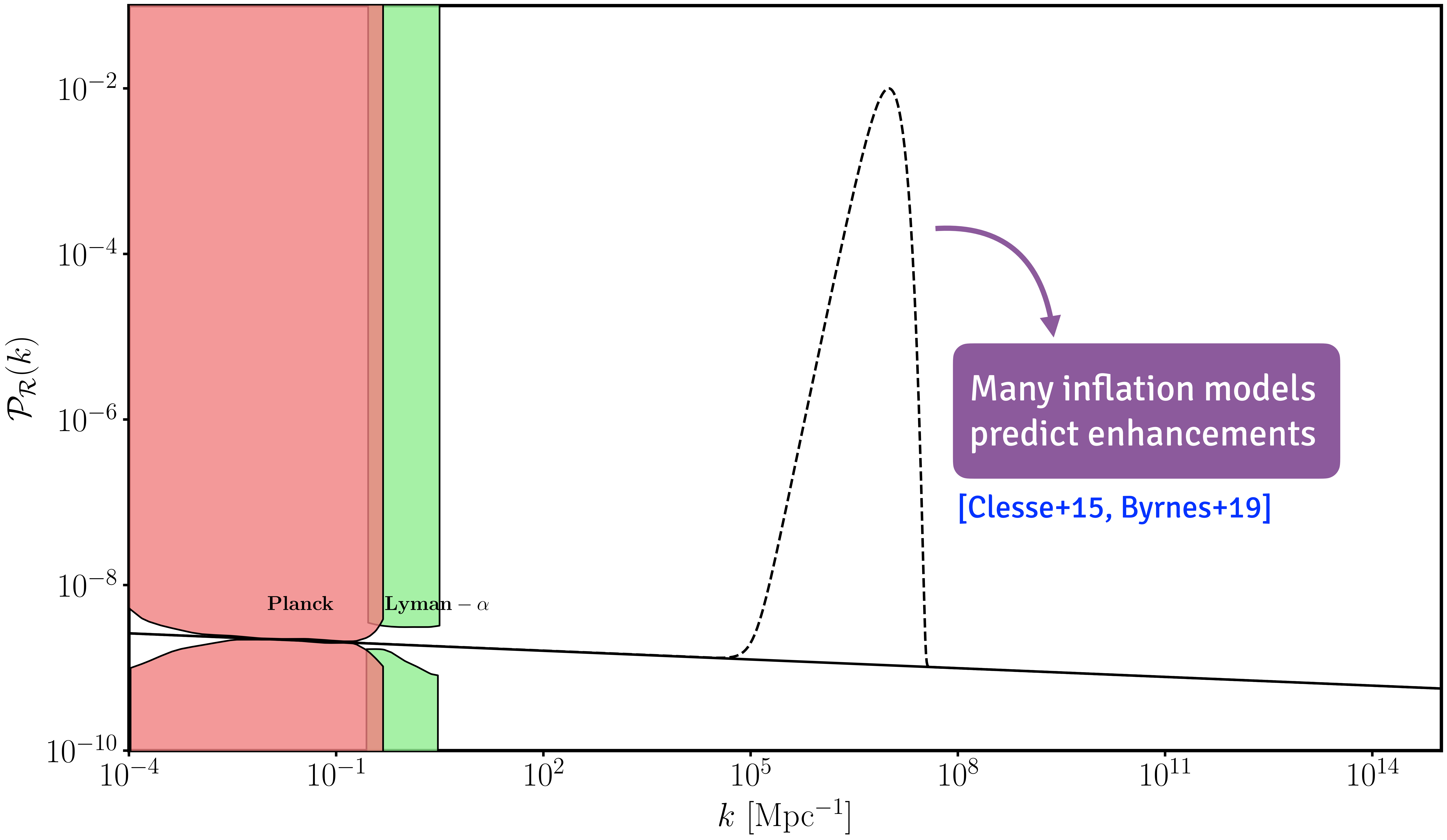

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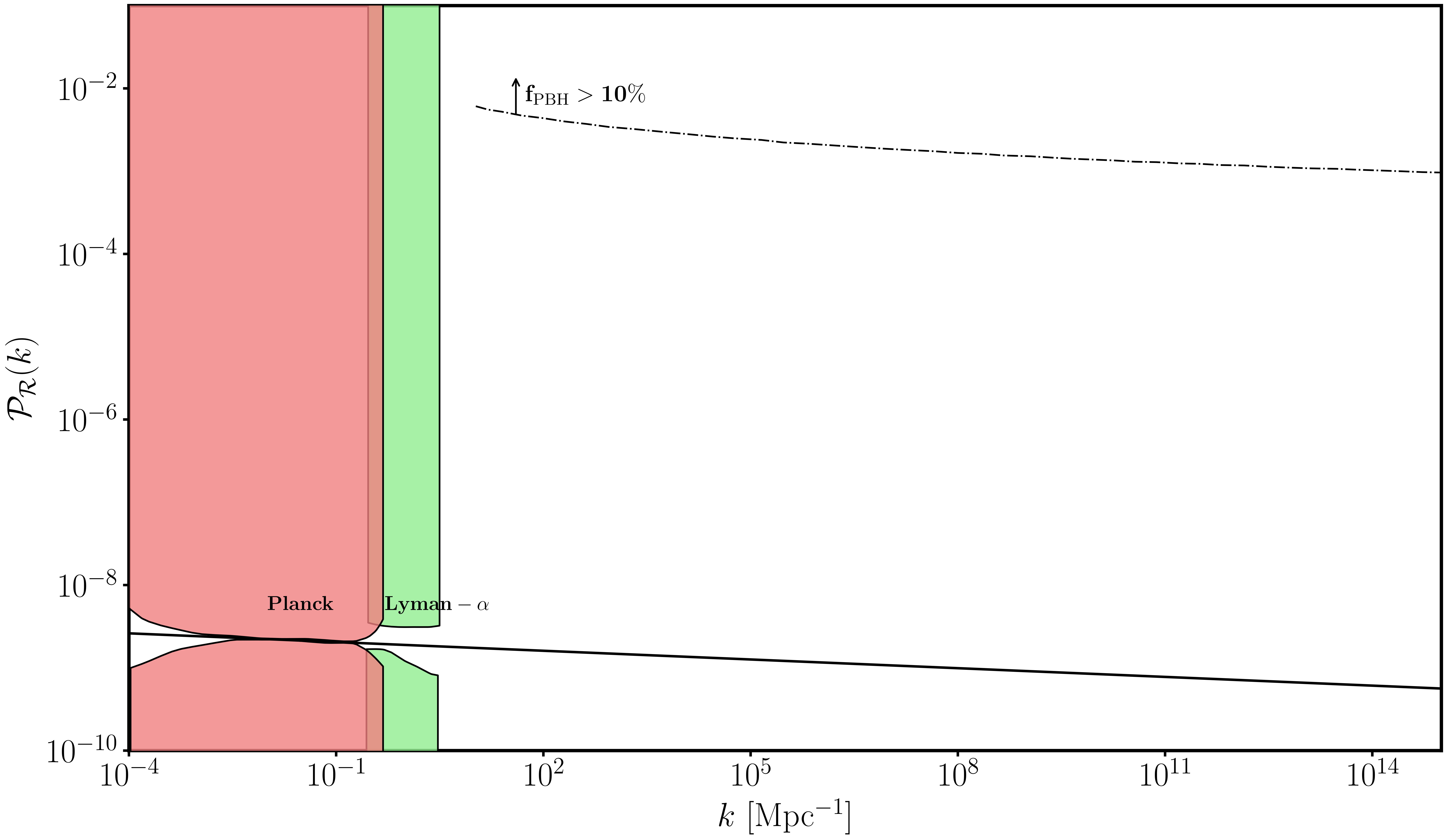
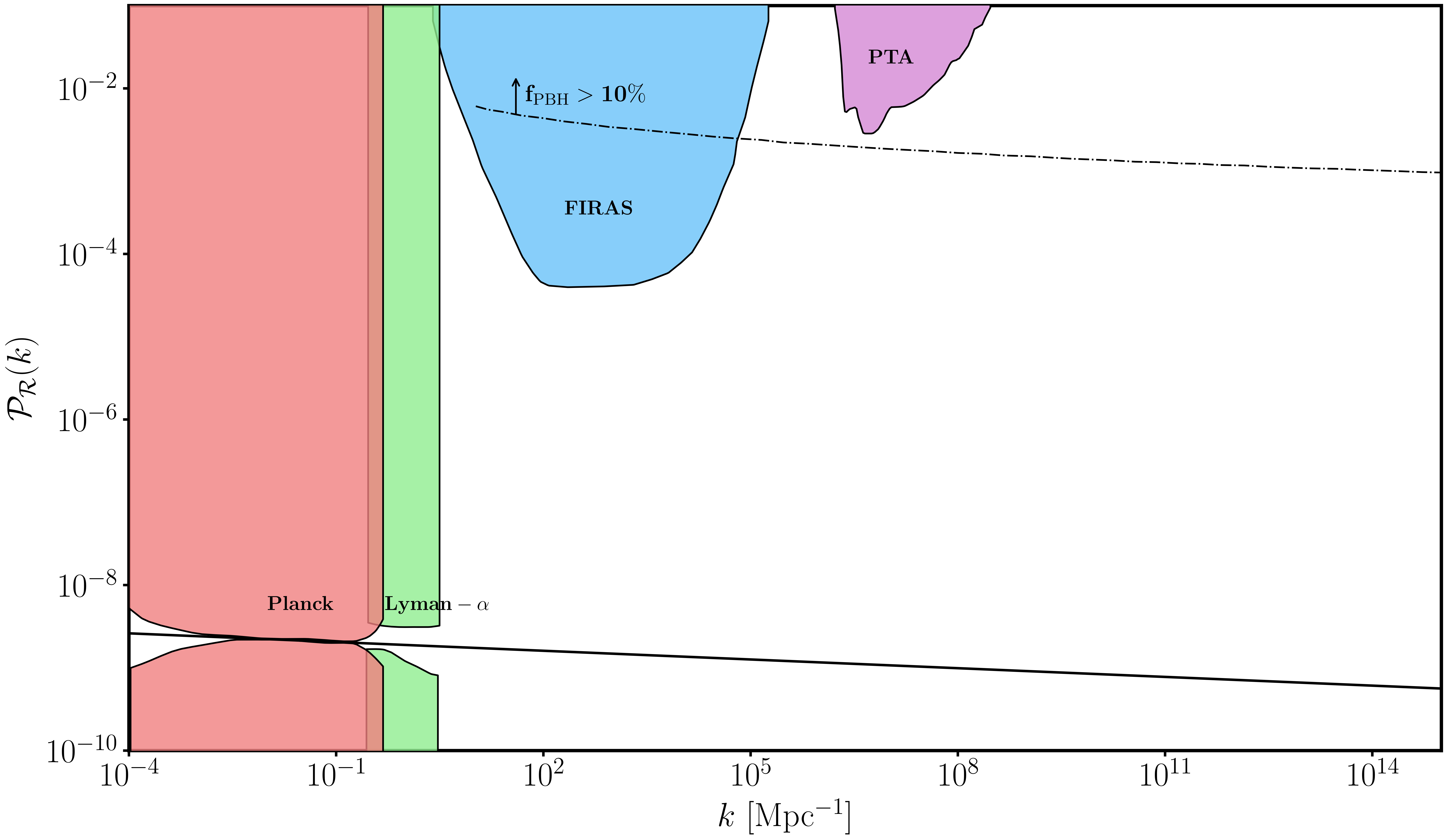
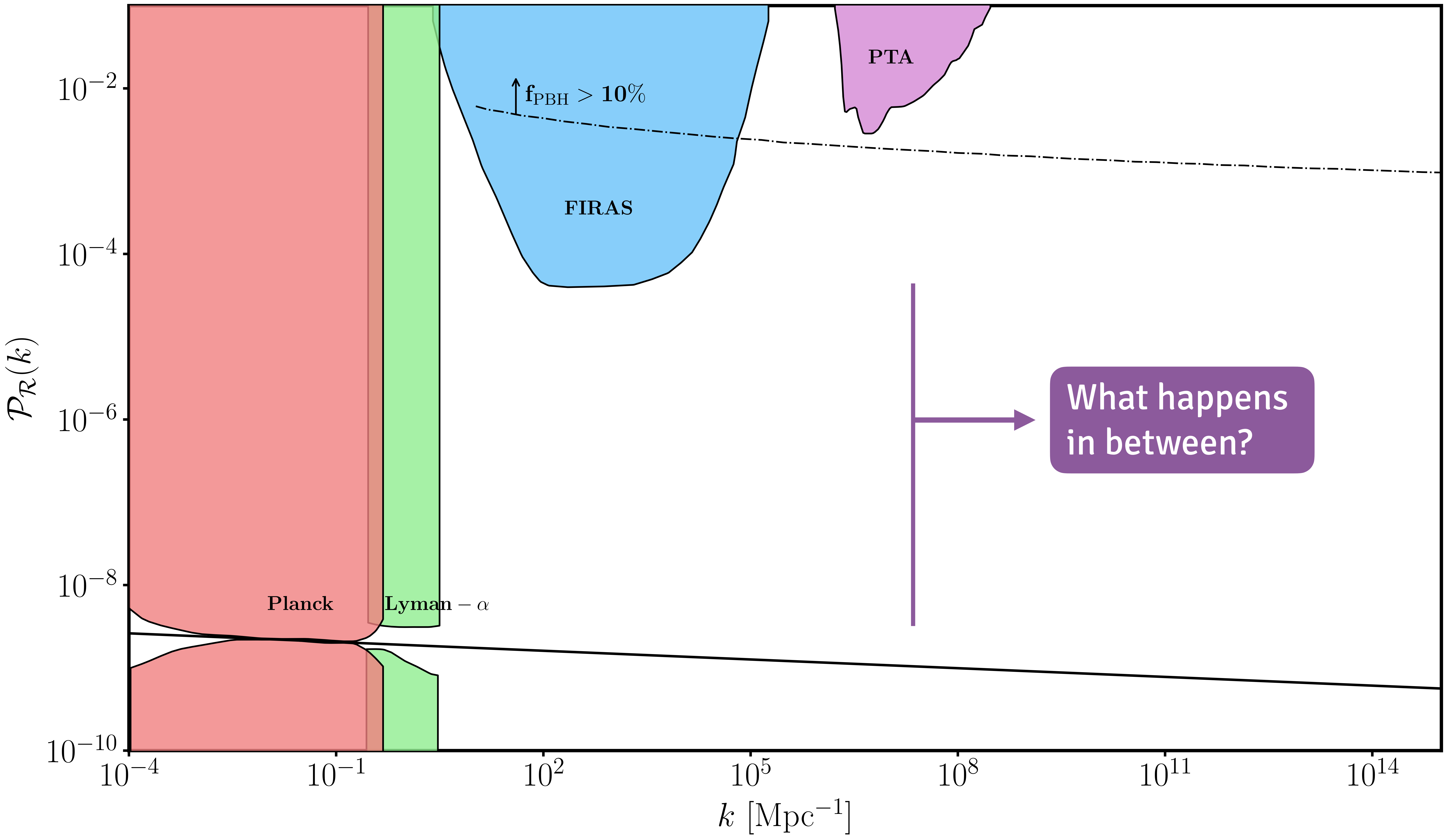


Primordial Black Hole (PBH) formation

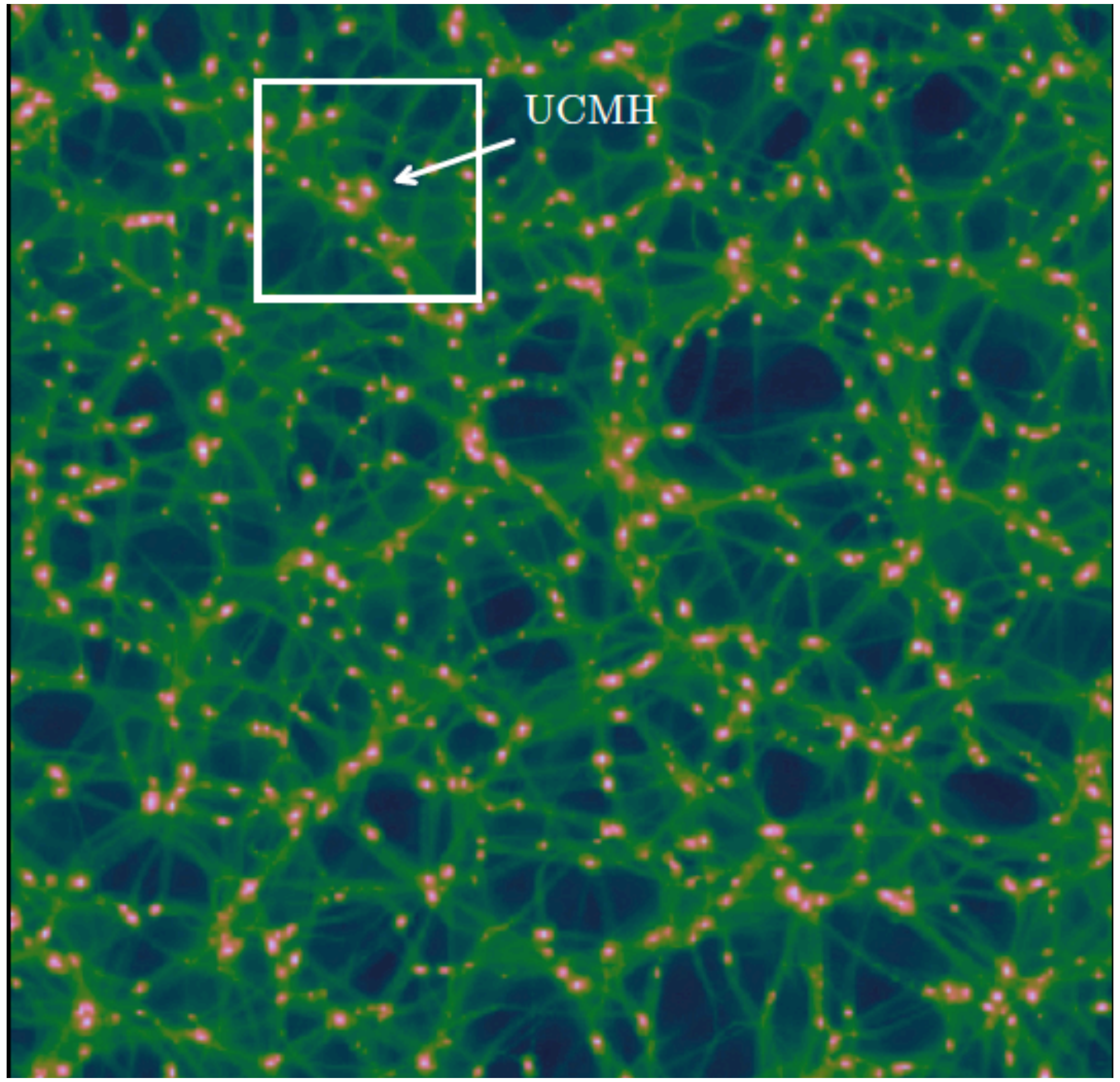
The primordial power spectrum



The primordial power spectrum



Moderate enhancements can produce
Ultra Compact Mini Halos (UCMHs)



[Delos+18]

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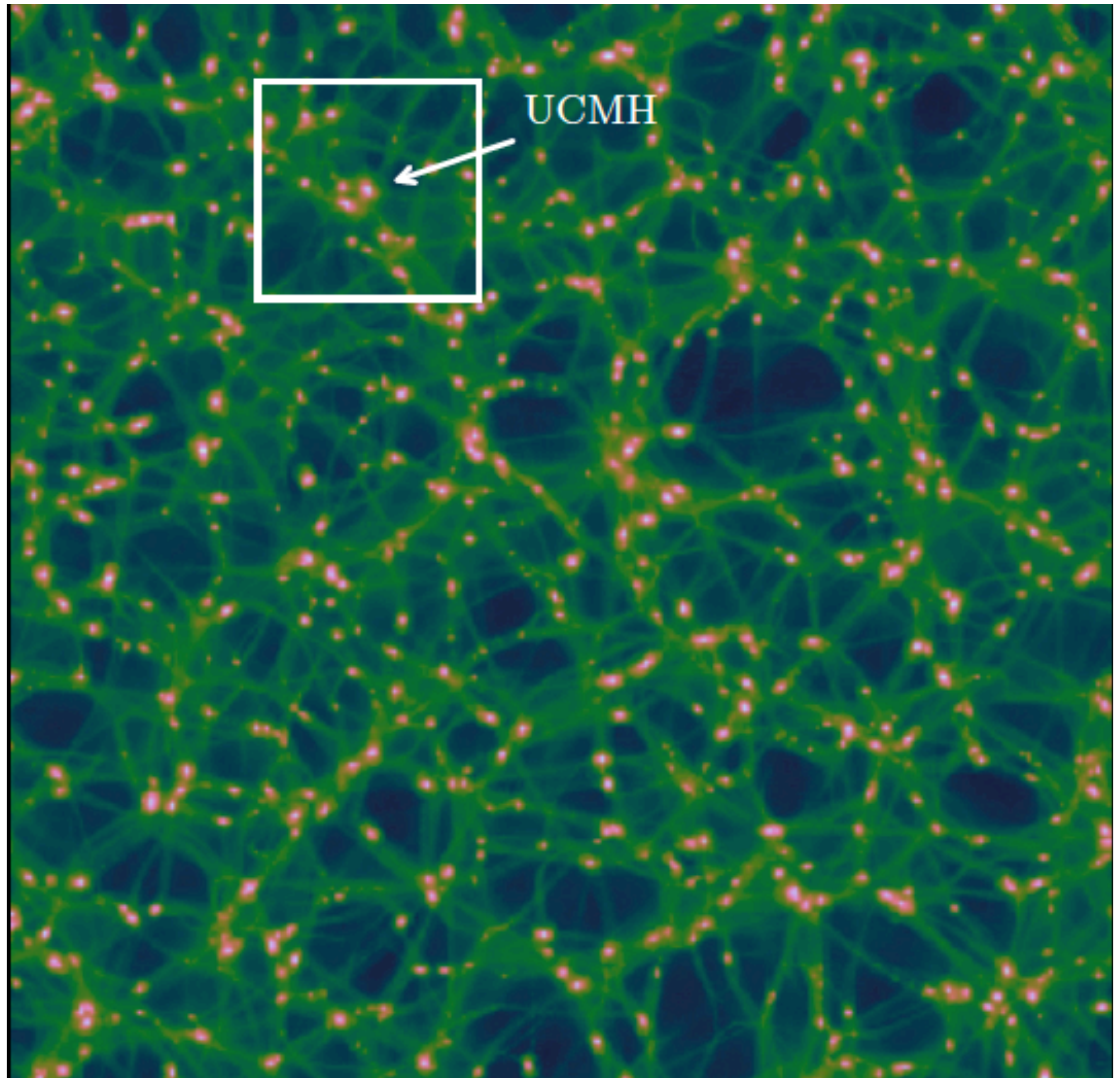

[Delos+18]

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

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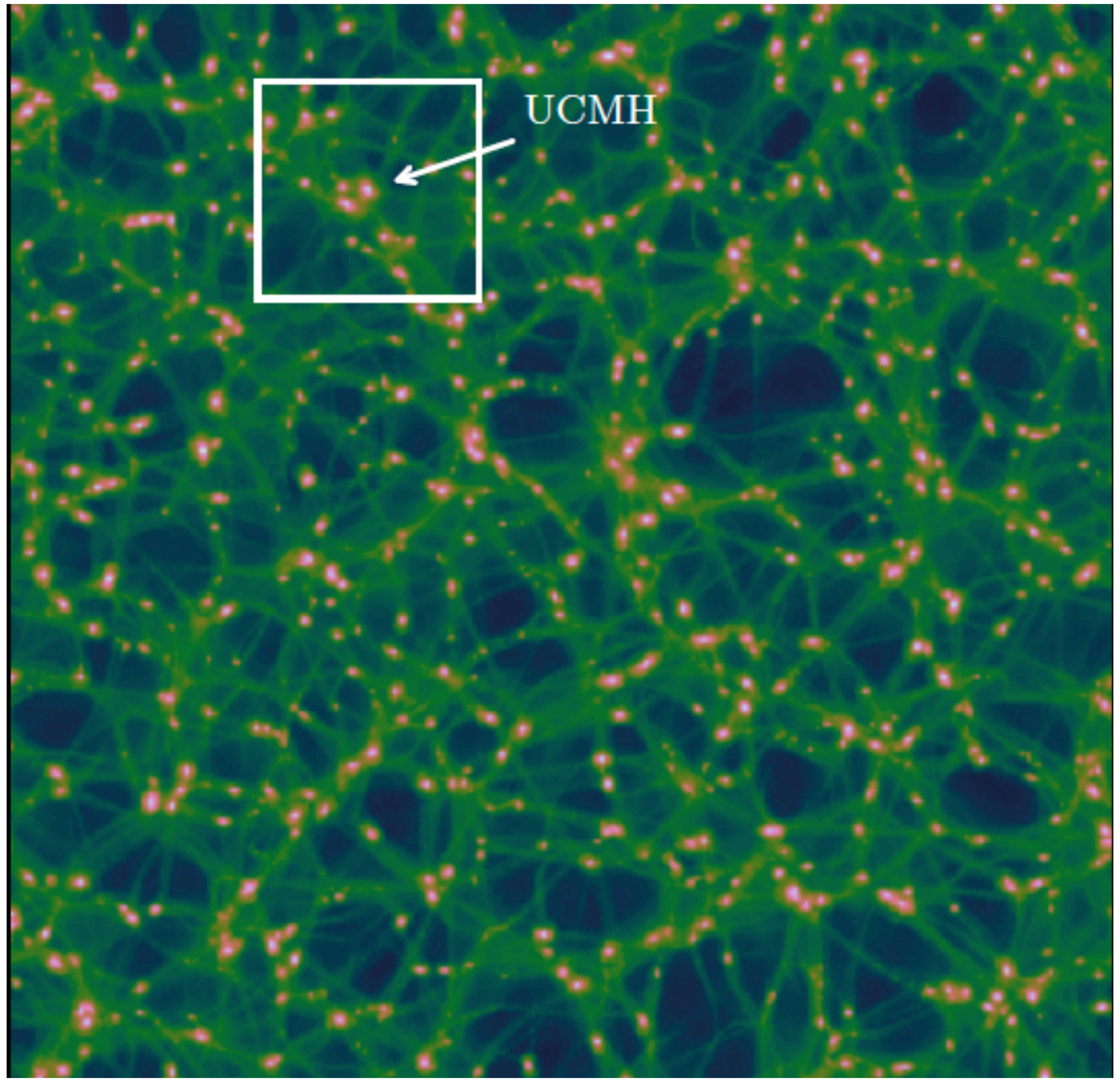

[Delos+18]

- 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

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

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Cosmological boost factor

$$B(z) \equiv \frac{\langle\rho^2_{\mathrm{DM}}\rangle}{\langle\rho_{\mathrm{DM}}\rangle^2} - 1$$

Annihilation parameter

$$p_{\mathrm{ann}} \equiv \frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}}$$

In the framework of the halo model

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

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Halo mass function

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

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Depends on density profile $\rho_h(r)$

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

- New formalism (based on ext. Press-Schechter) to account for **effects of halo mergers**

- For the first time, considered **both s-wave and p-wave** annihilations

RECIPE

to get the constraints

Ingredients

- Modified version of ExoCLASS [Stocker+18]
- Planck legacy data

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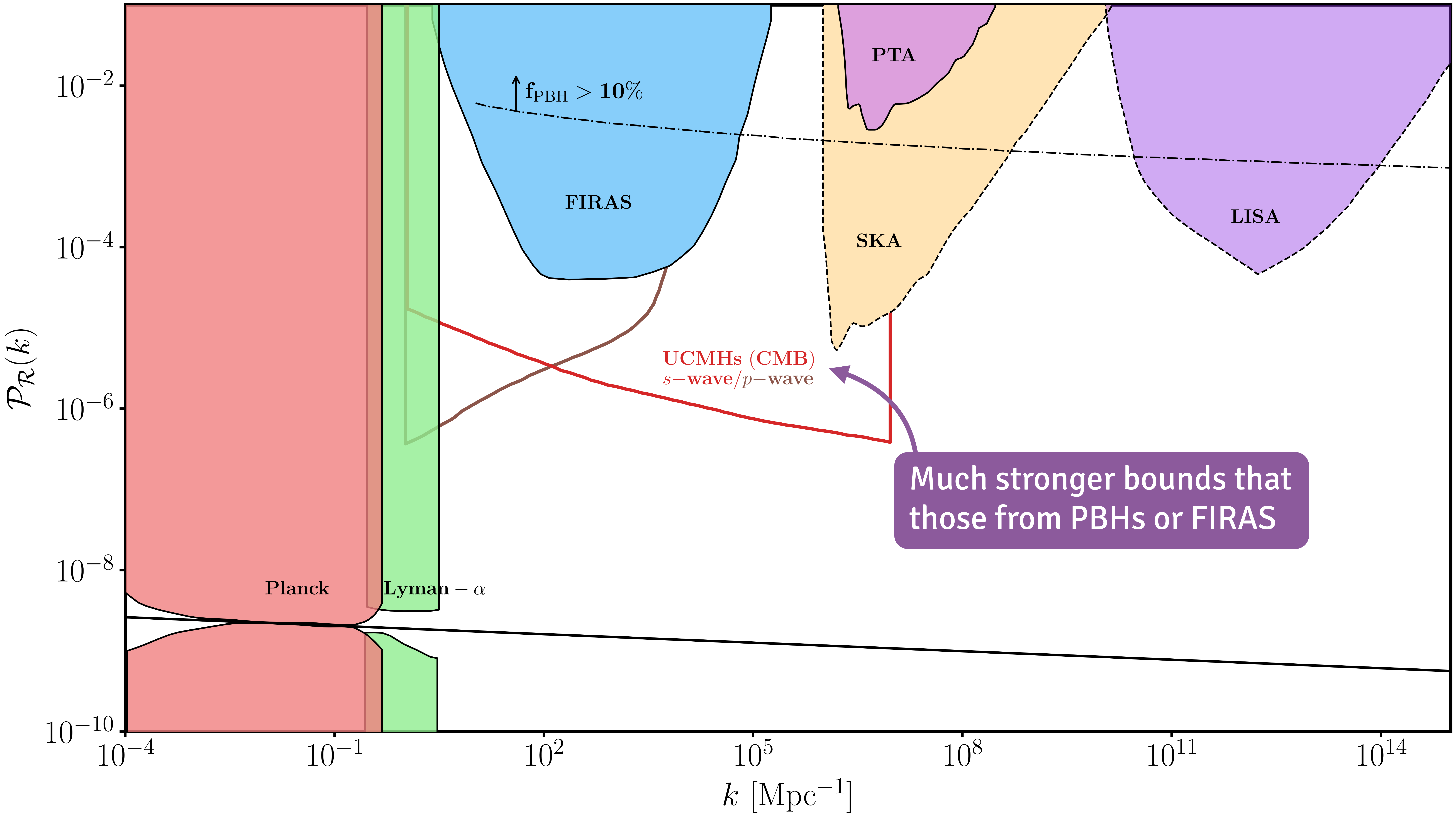
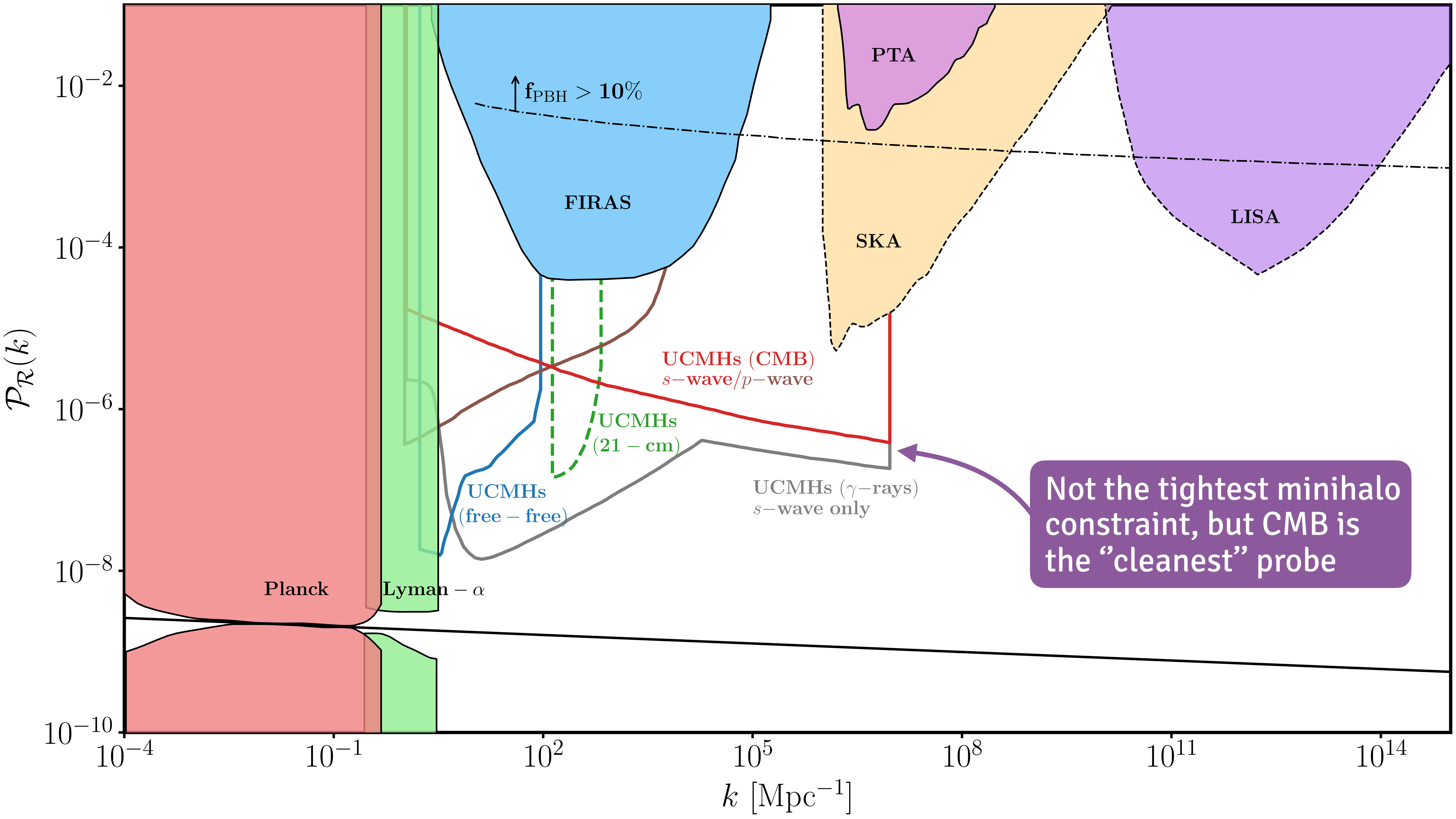
4. Obtain constraints on $\mathcal{A}_\star$ vs. $k_\star$ (for a fiducial param. $p_{\rm ann} \propto \langle \sigma v \rangle / m_{\rm DM}$)

RESULTS



$\uparrow$ $\mathrm{f_{PBH}} > 10\%$
PTA
FIRAS
SKA
LISA
UCMHs (CMB)
$s-$wave/$p-$wave
Much stronger bounds that those from PBHs or 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}]

RESULTS



$\mathcal{P}_{\mathcal{R}}(k)$
10^{-2}
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$\mathrm{f_{PBH}} > 10\%$
FIRAS
PTA
SKA
LISA
Planck
Lyman $-\ \alpha$
UCMHs (CMB)
$s-$wave/$p-$wave
UCMHs
(21 − cm)
UCMHs
(free − free)
UCMHs ($\gamma-$rays)
$s-$wave only
Not the tightest minihalo constraint, but CMB is the "cleanest" probe

Conclusions

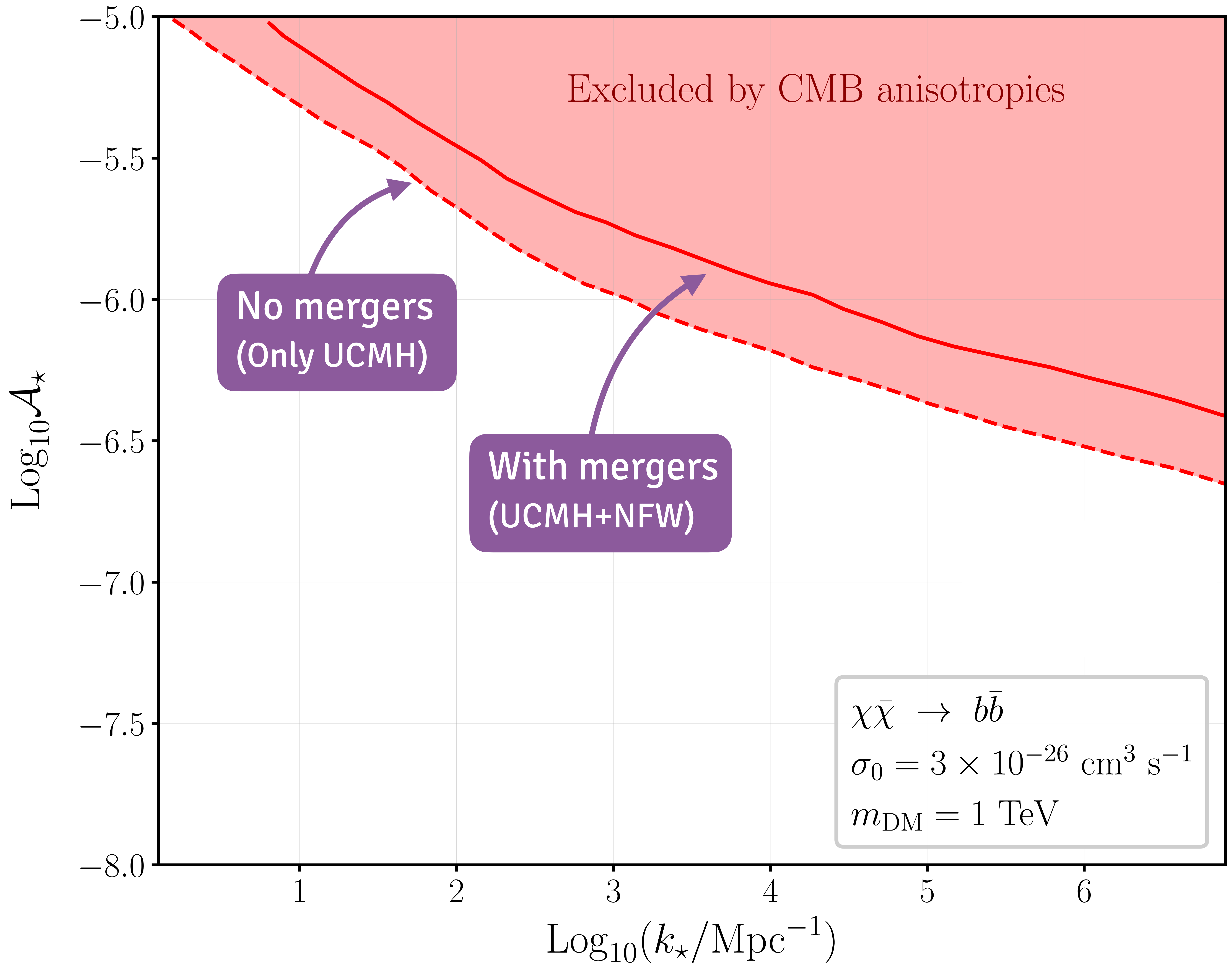
THANKS FOR YOUR ATTENTION

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
- Minihalos extend observable window of inflation in presence of CDM, coupling two key problems in cosmology

BACK-UP

RESULTS



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

RESULTS

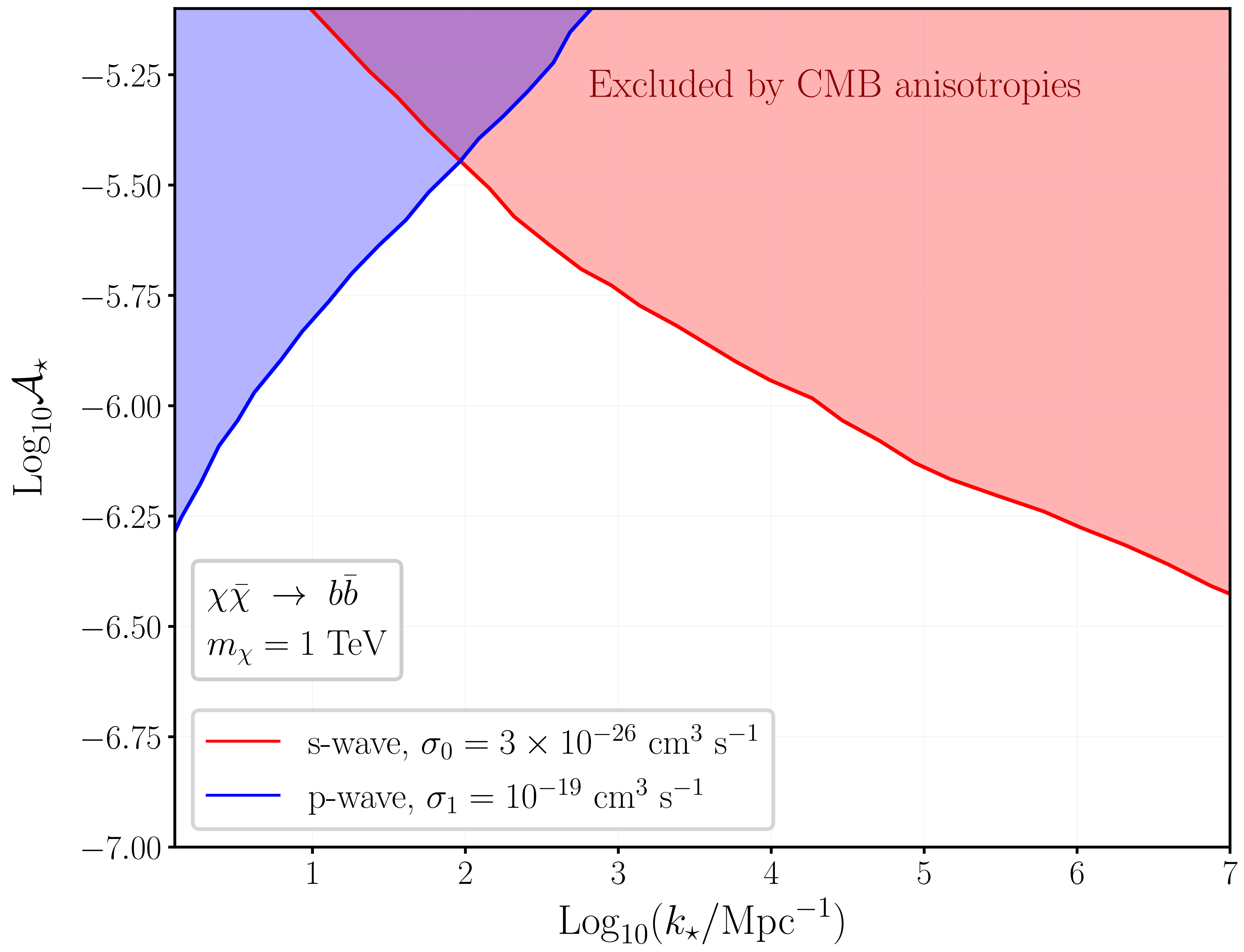
- So far, we only looked at s-wave DM annihilations

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

- **p-wave** terms might be non-negligible (velocity is enhanced in virialised structures). In addition, bounds on σ_1 are very weak

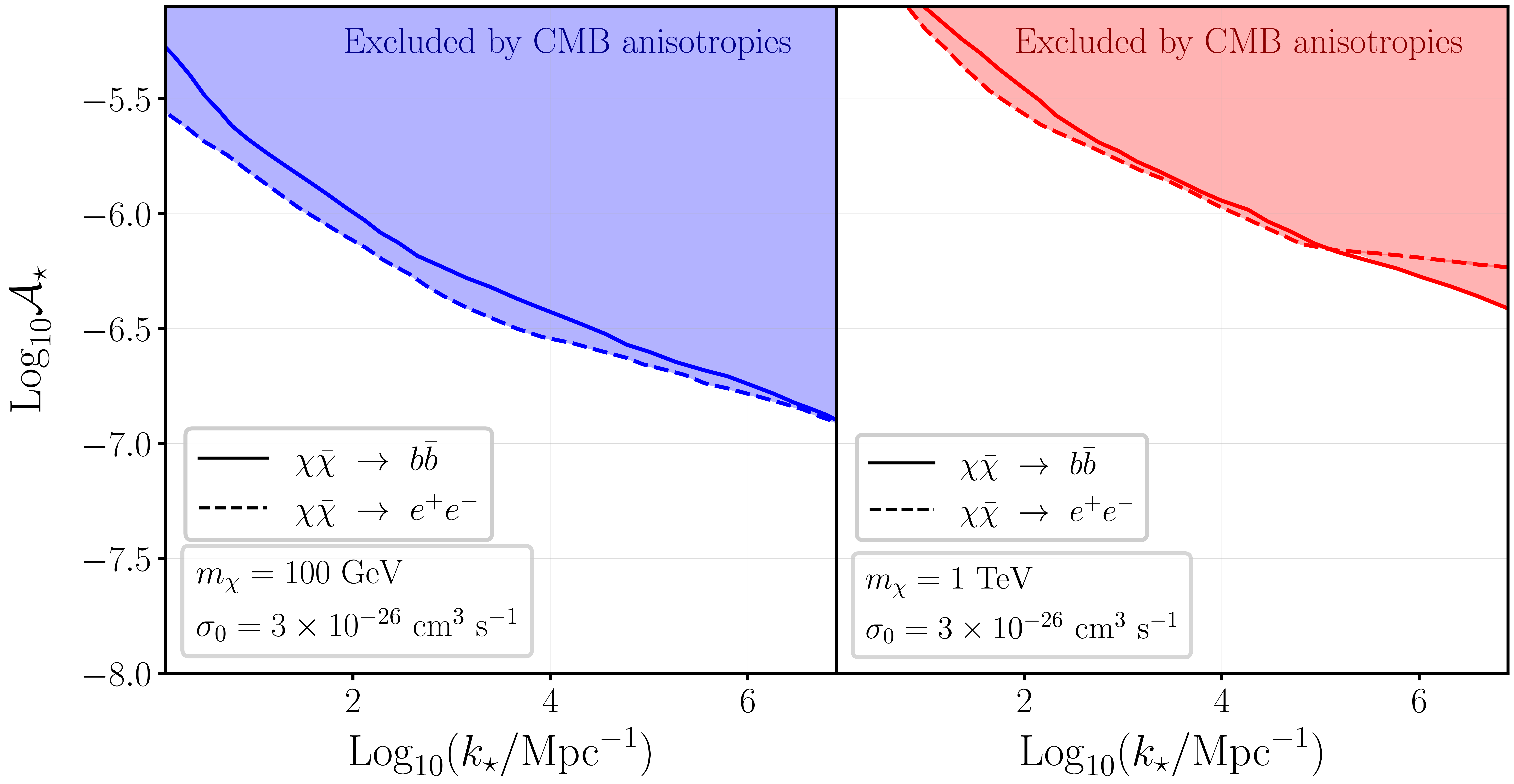
- First calculation of p-wave boost factor in presence of UCMHs

RESULTS



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

Constraints for different DM masses and annihil. channels



Prior range for the amplitude and location of the spike

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

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

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

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