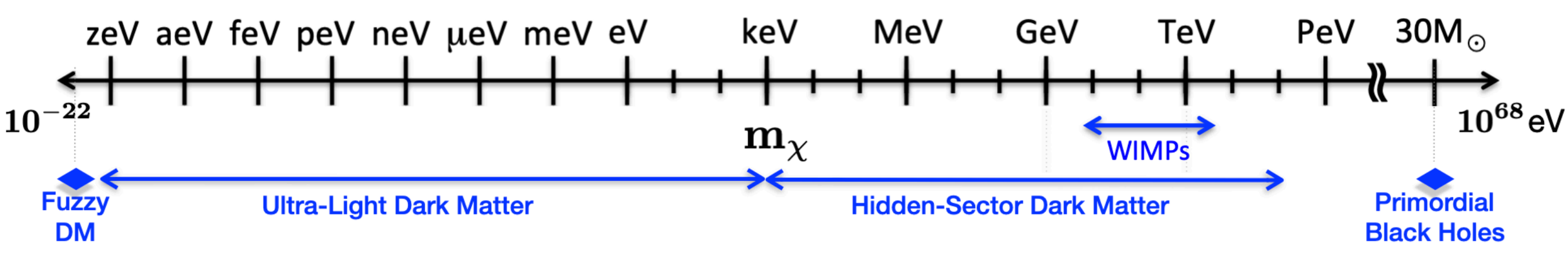
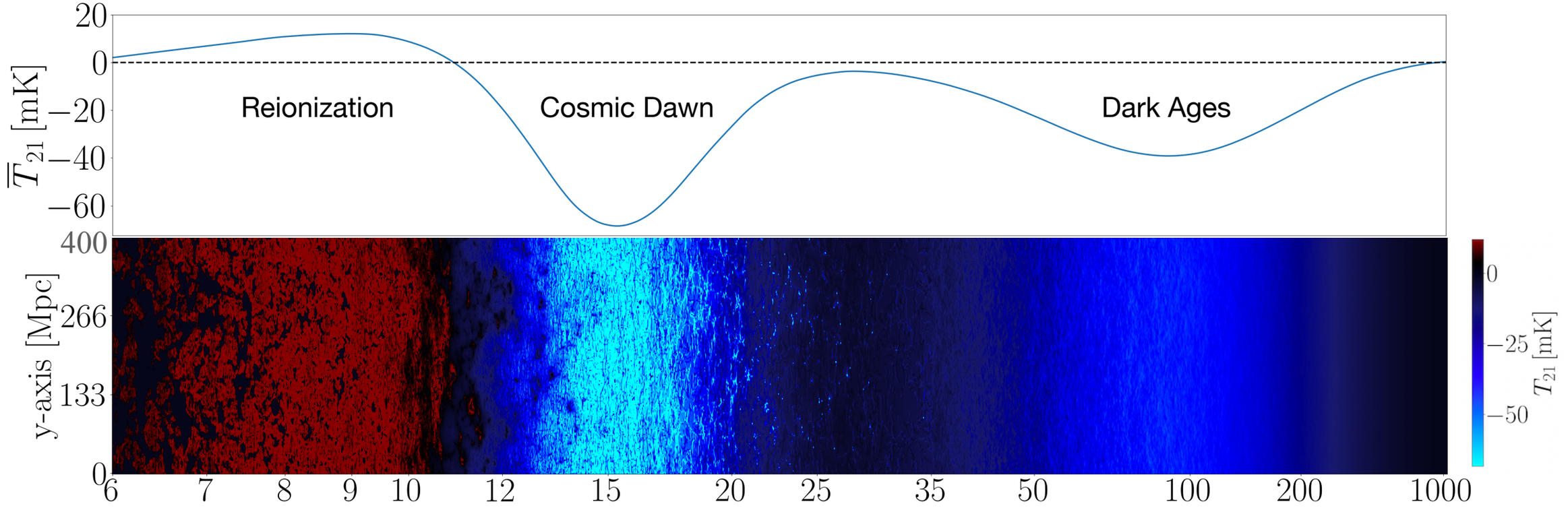
21cmFirstCLASS©: Probing DM at Cosmic Dawn

Ely Kovetz, Ben-Gurion University





ALPS2024 Dark Matter Workshop, Obergurgl, Apr. 2024

Goals of this talk:

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1

21cm LIM uniquely sensitive to dark matter physics

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First-class new tool to simulate 21cm power spectrum

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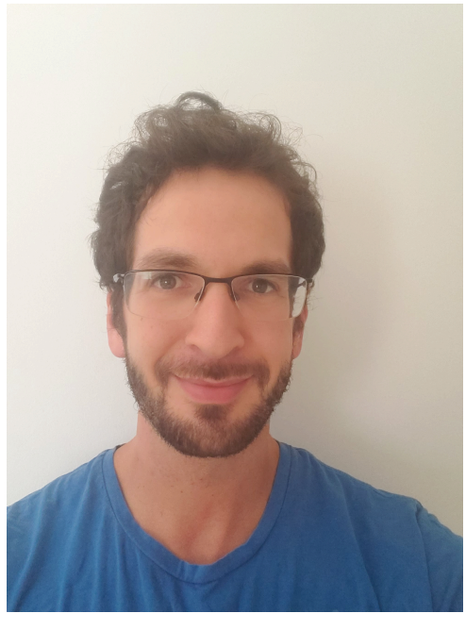

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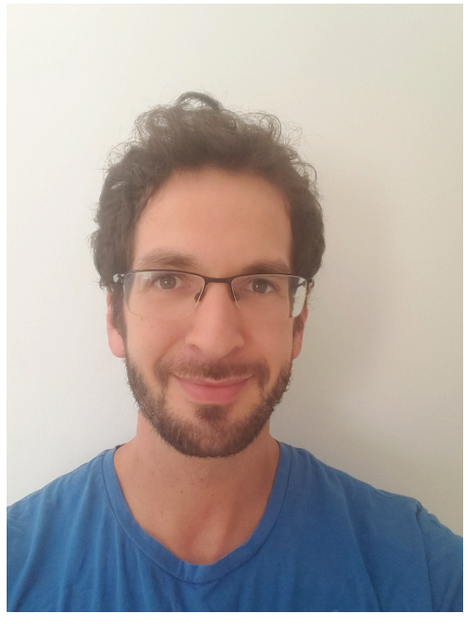

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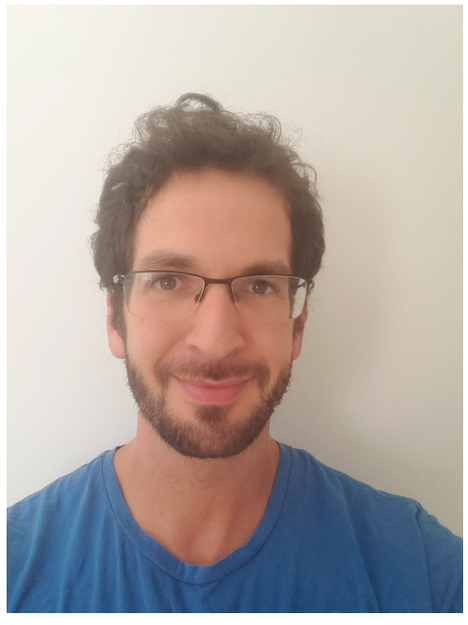

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Debanjan Sarkar

The Observable Universe: Key Historical Epochs

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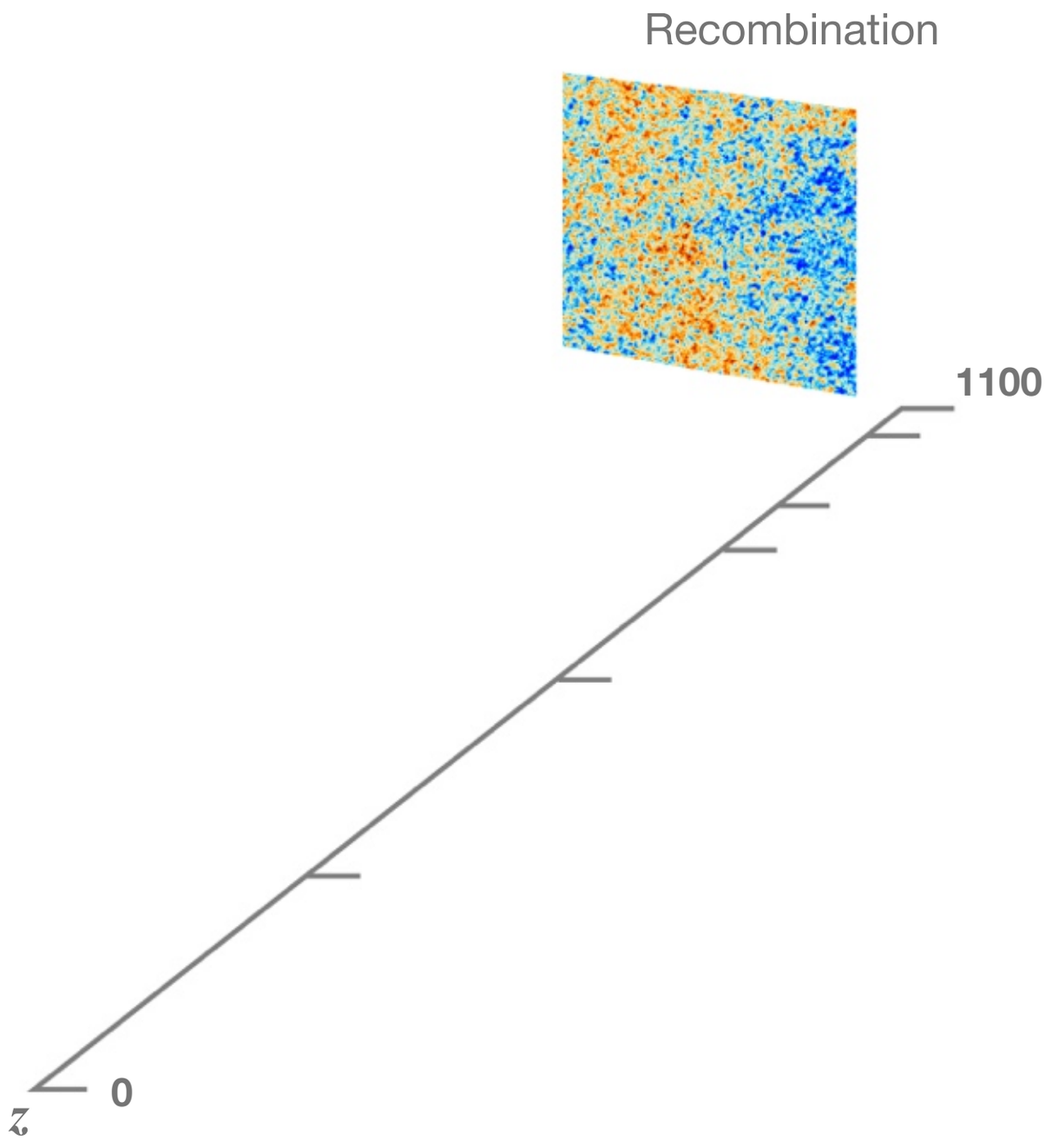

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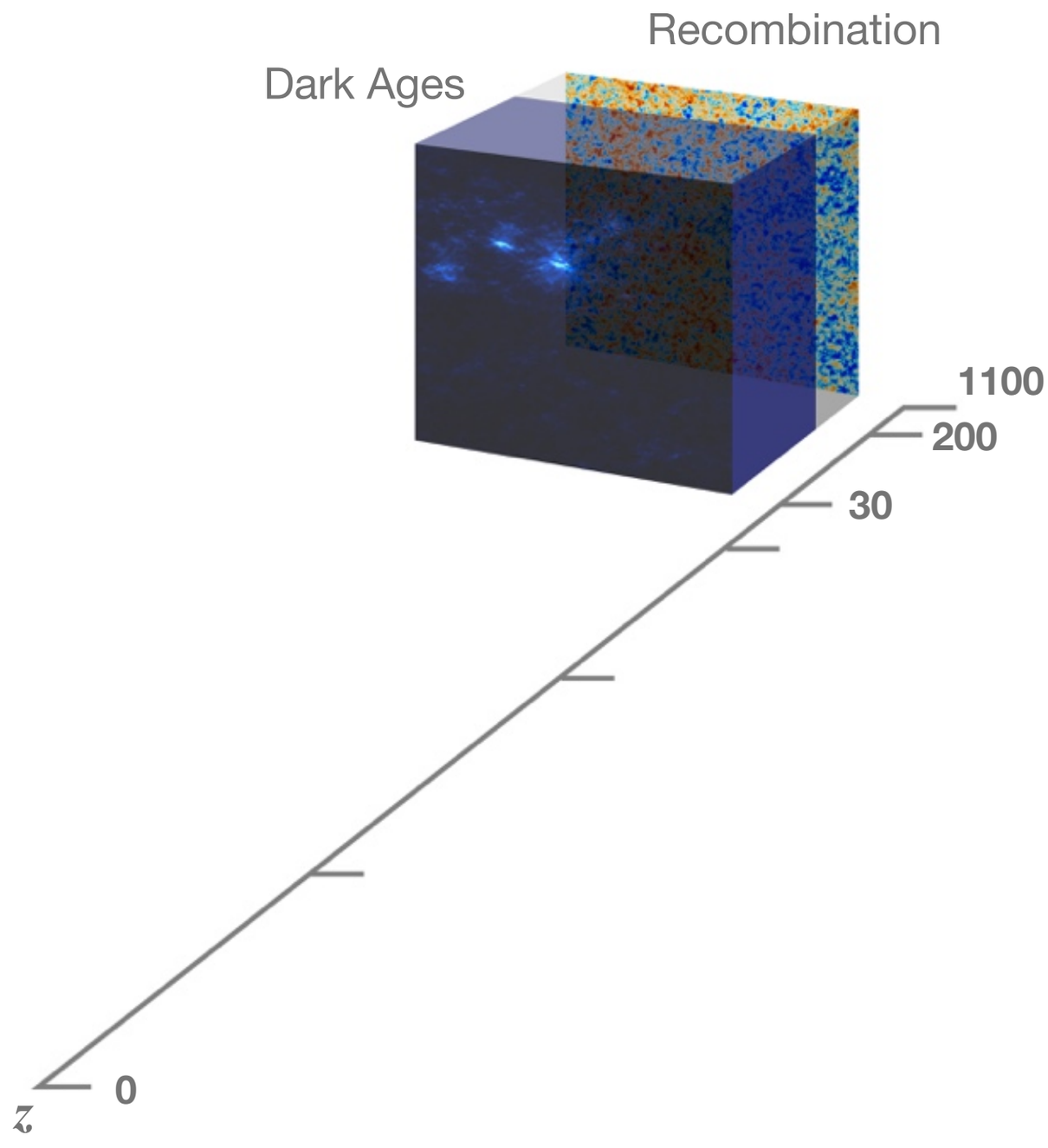

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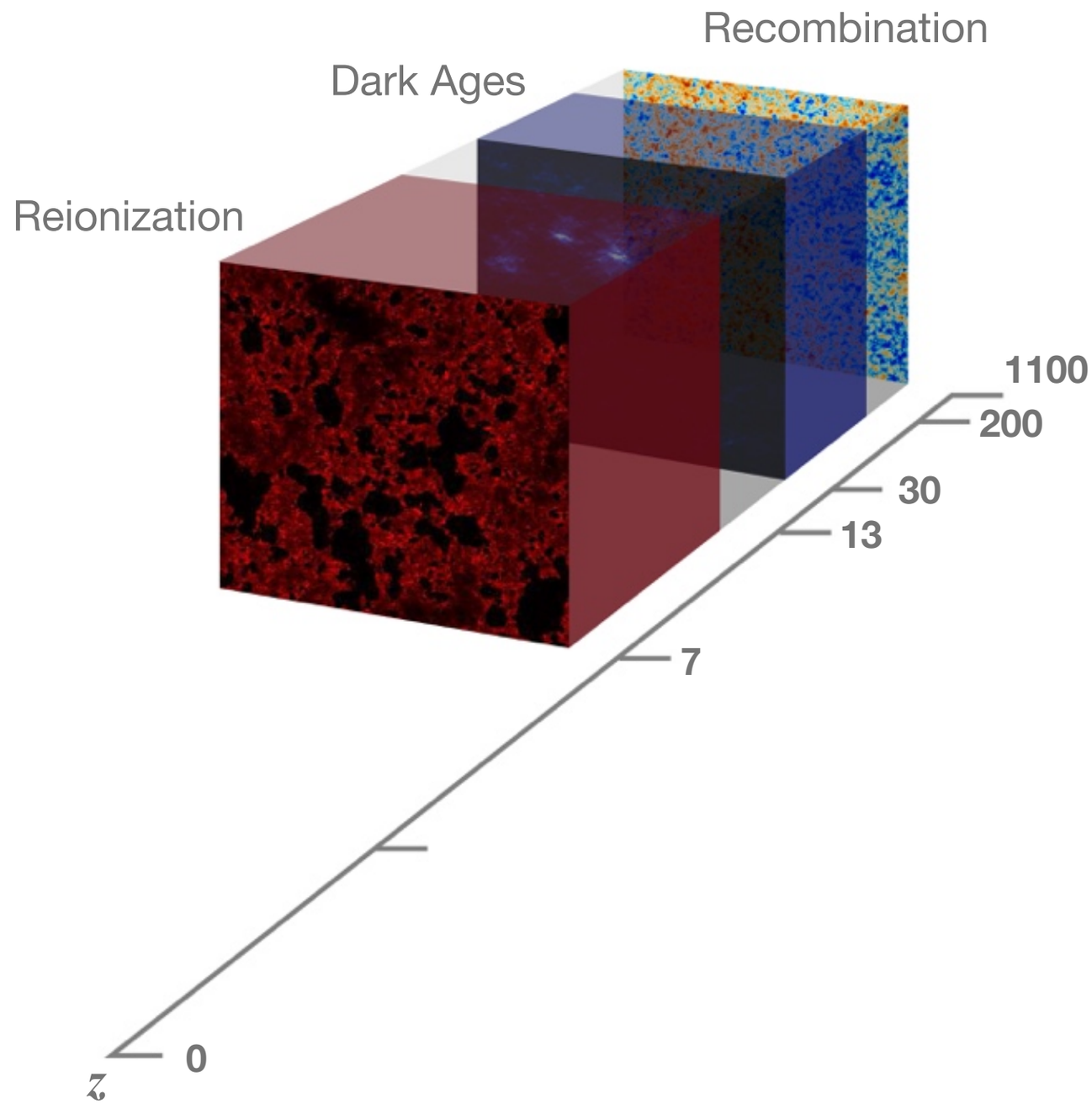

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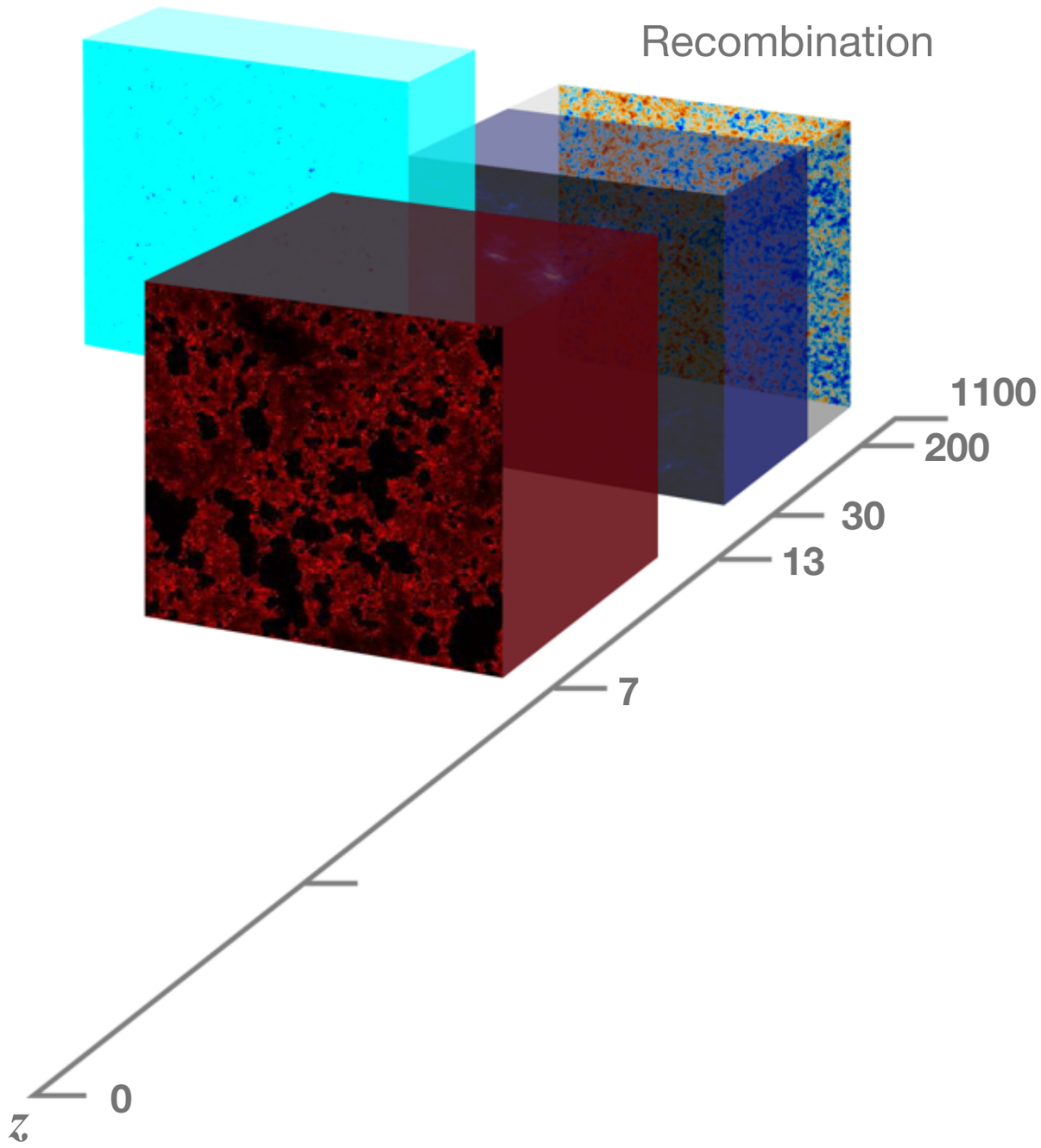

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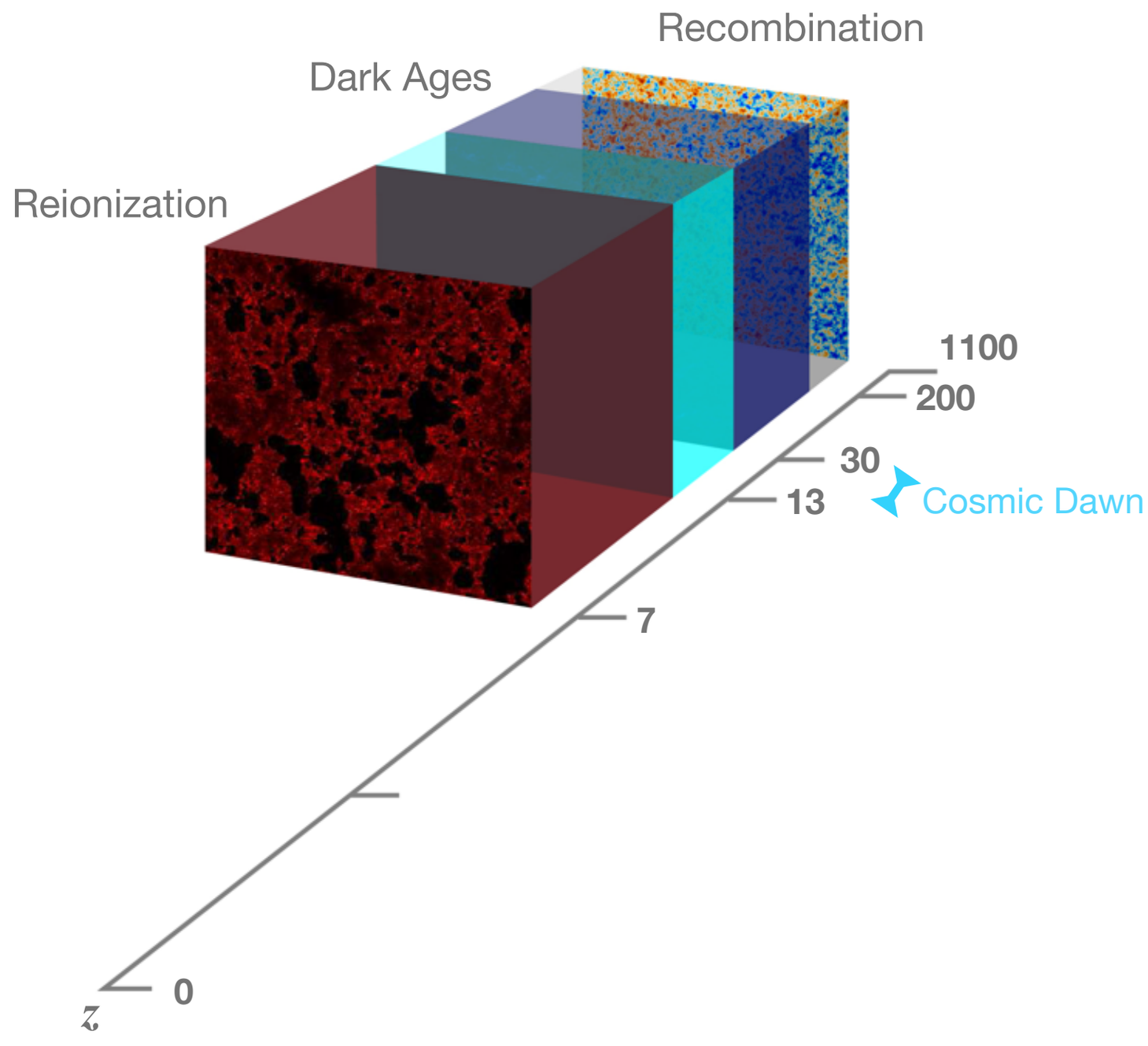

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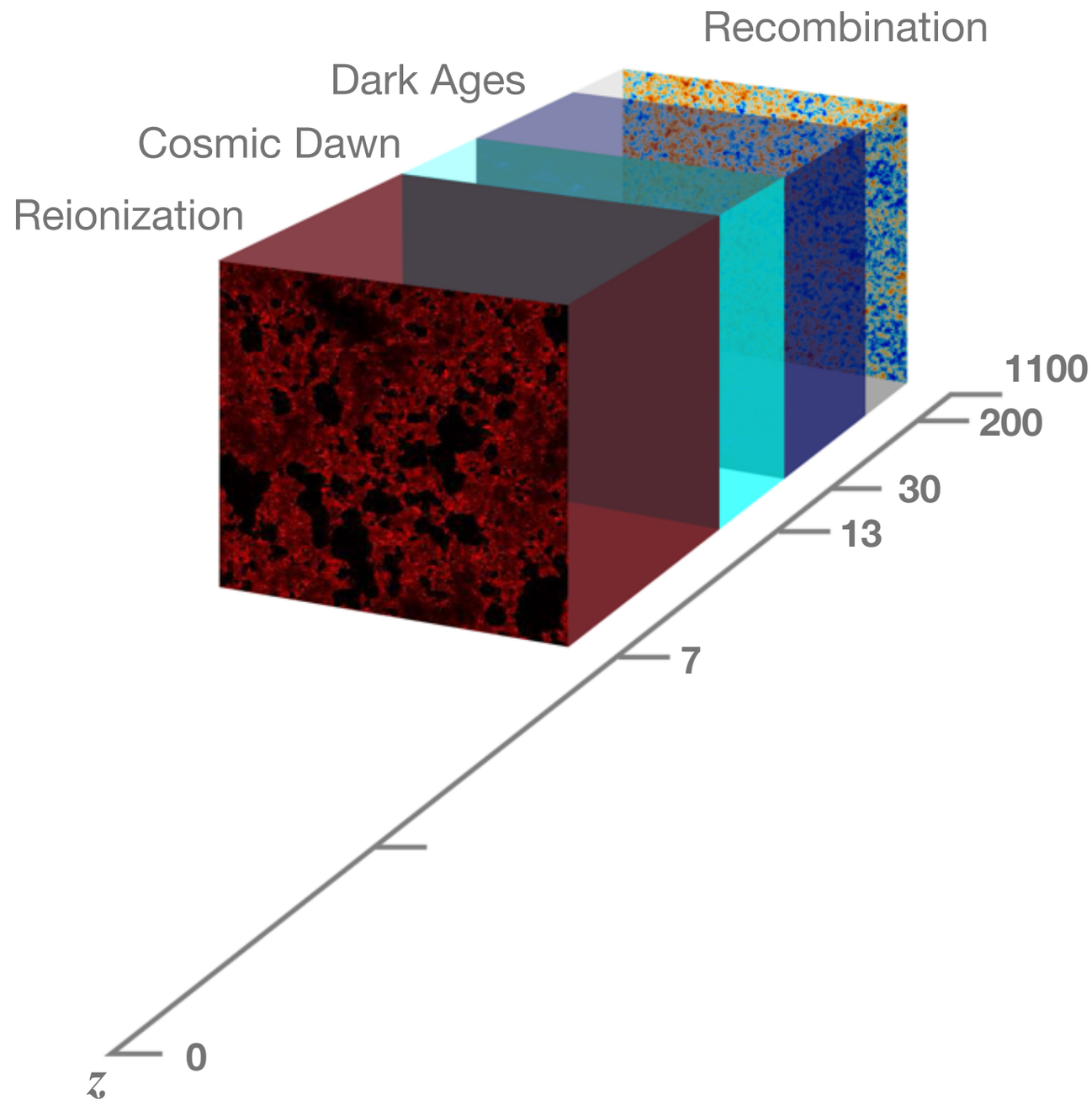

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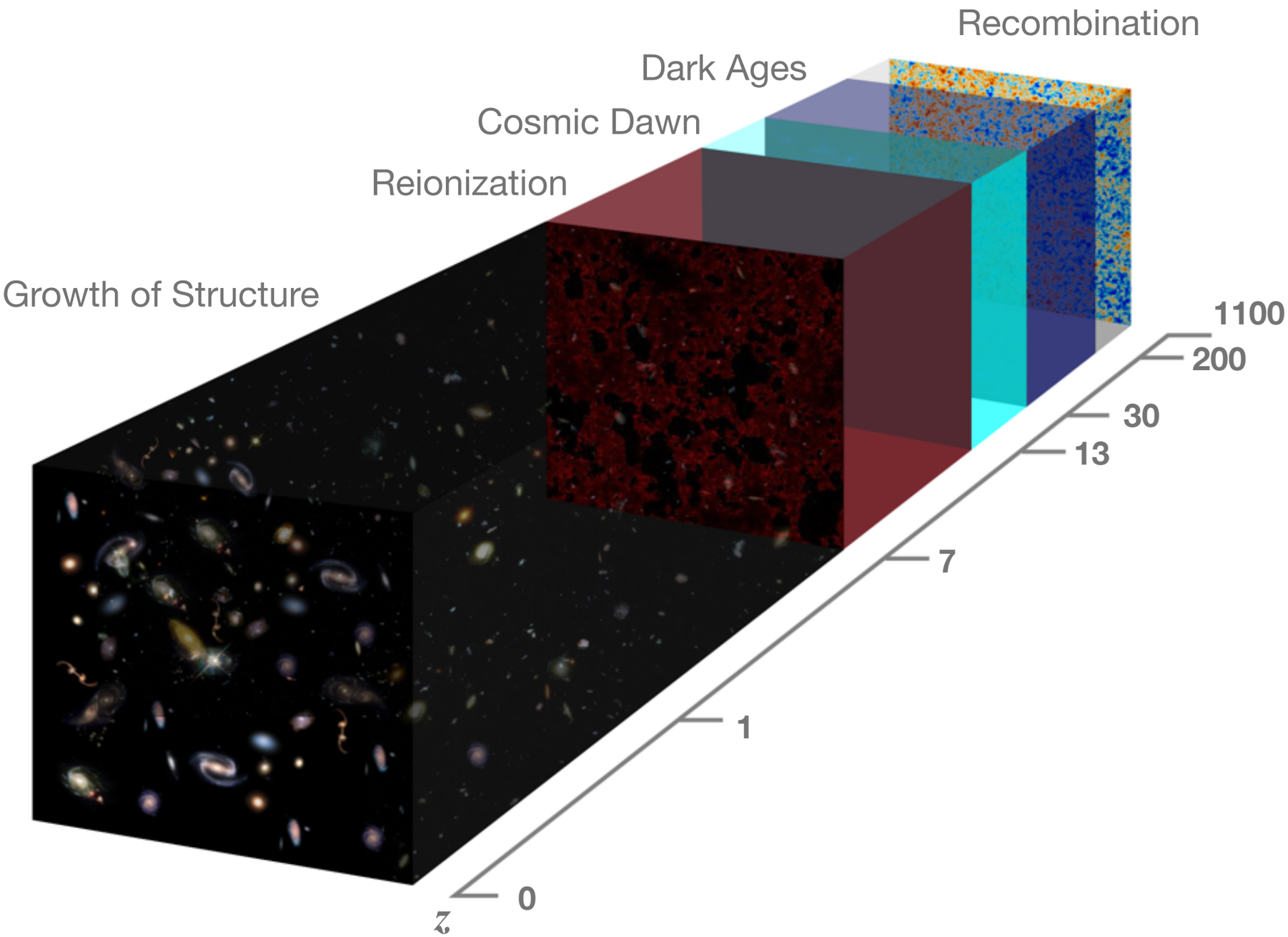

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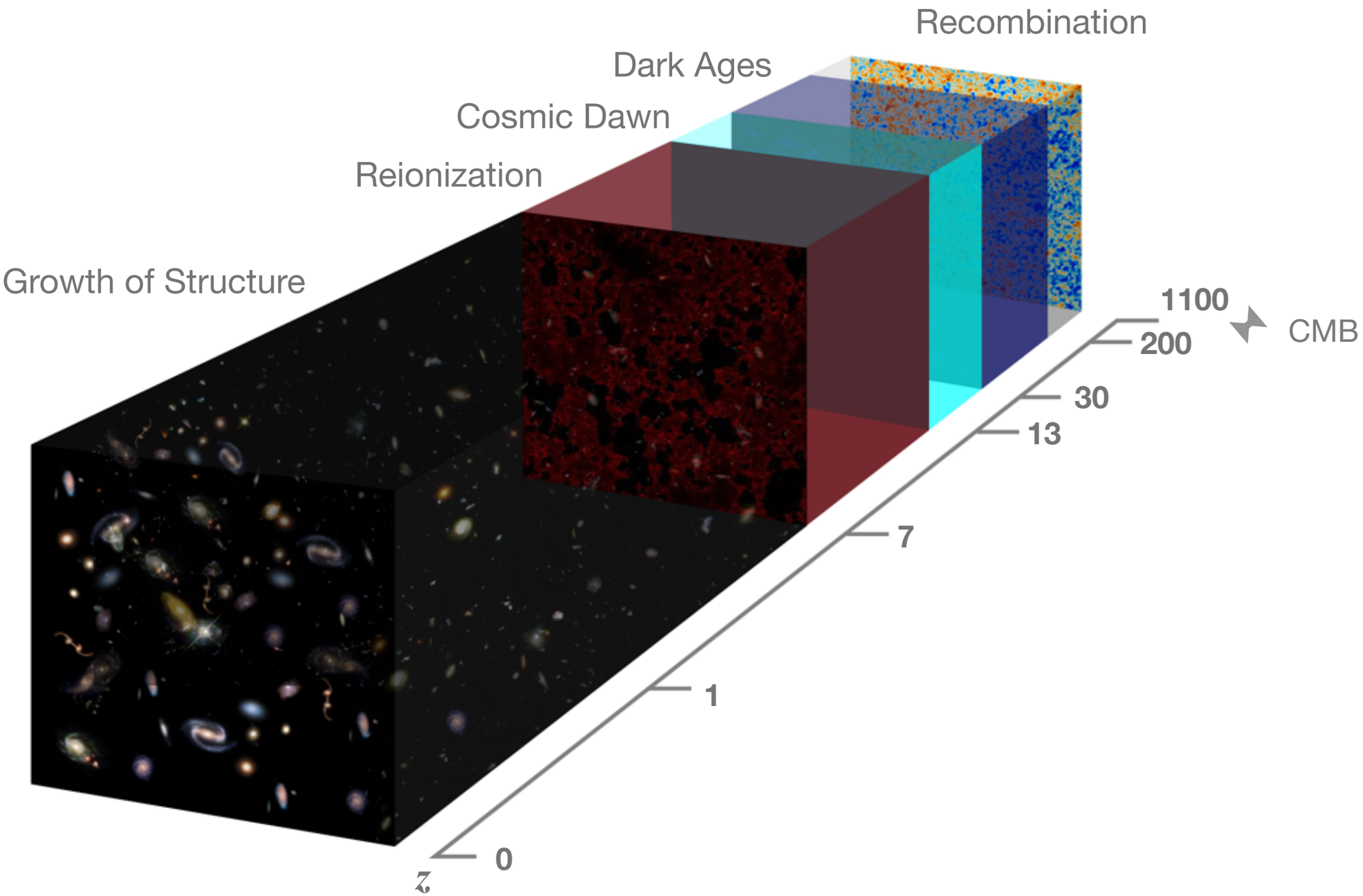

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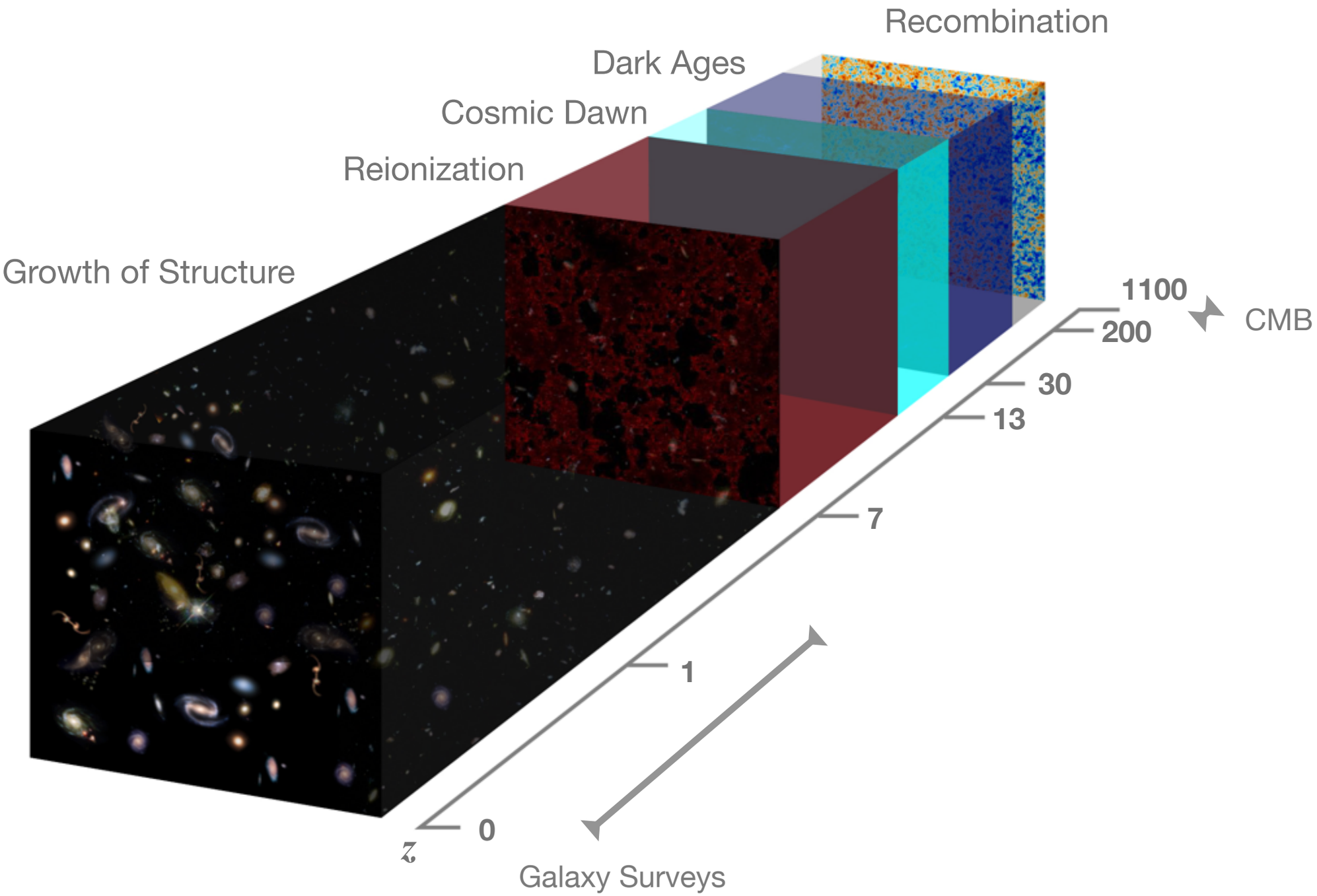

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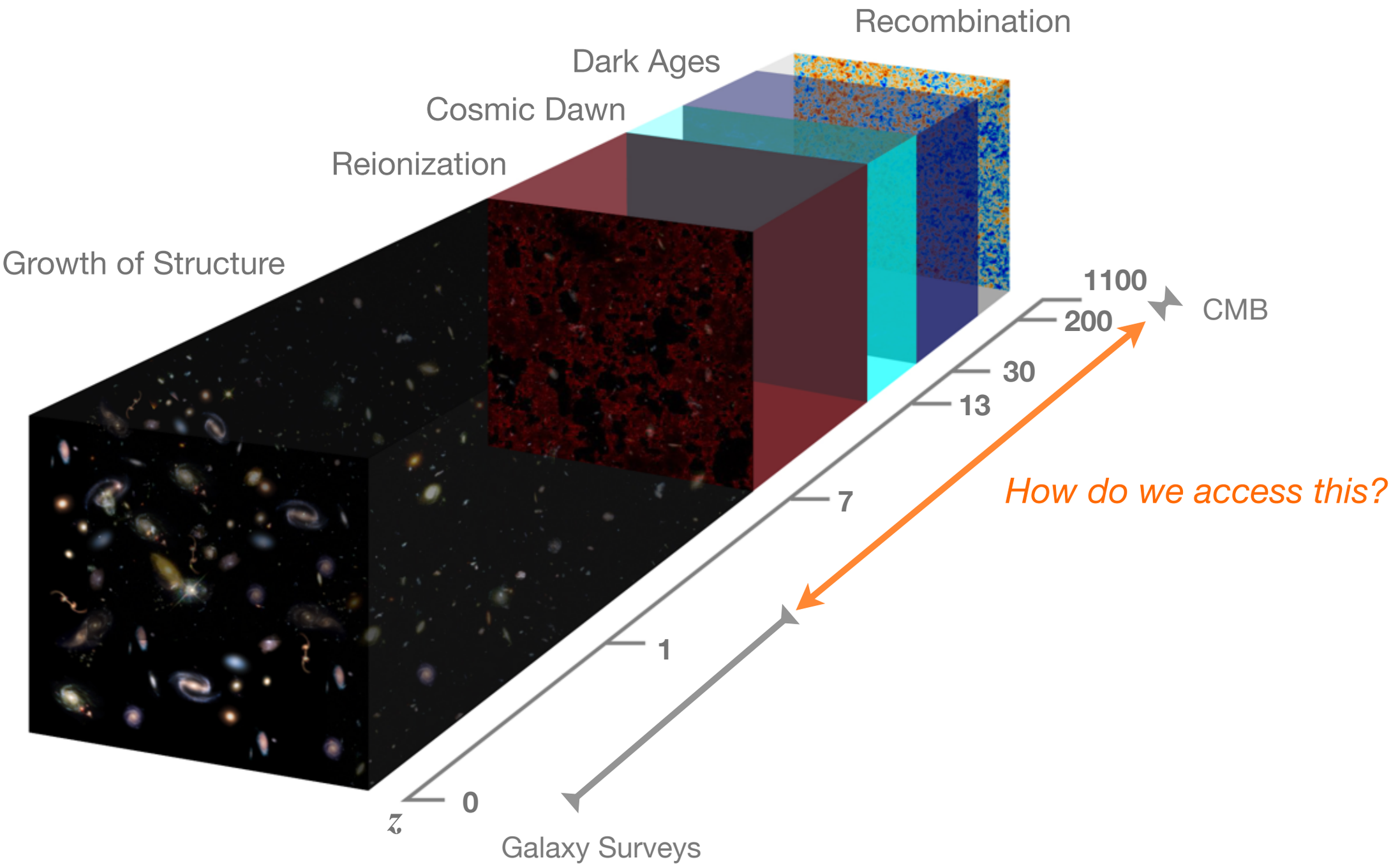

21cm: Early-Universe Signal

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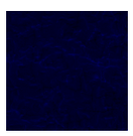
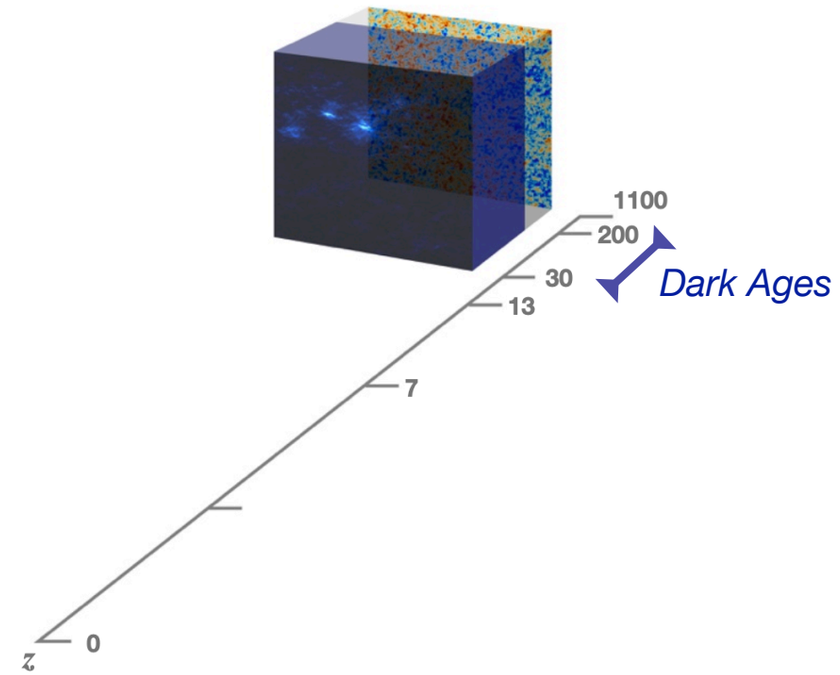
Dark Ages: $T_{\rm spin} < T_{\rm CMB}$ (absorption)





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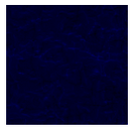
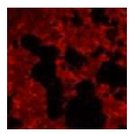
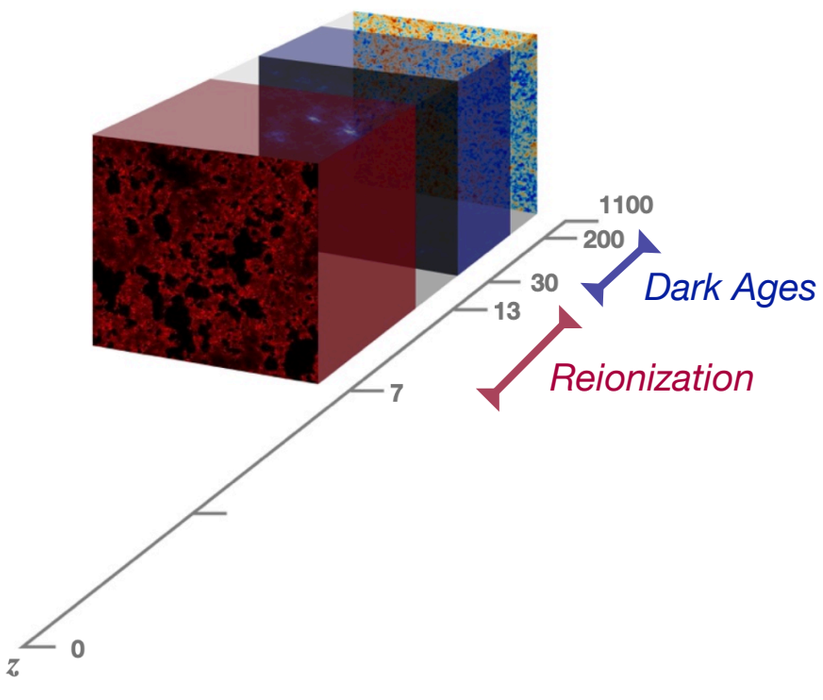


Reionization: $T_{\rm spin} > T_{\rm CMB}$ (emission)





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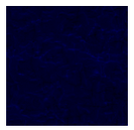

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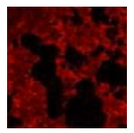
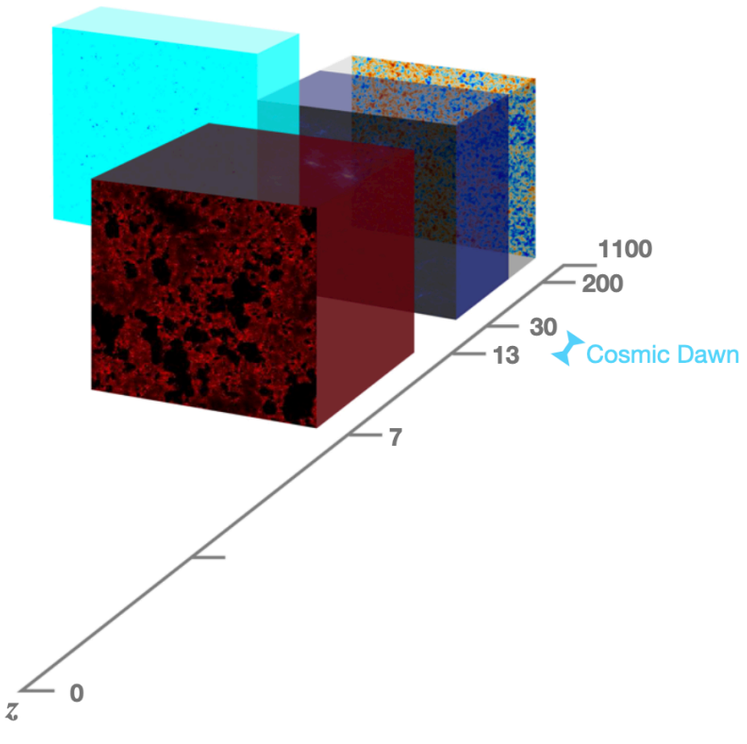


Cosmic dawn: $T_{\rm spin} < T_{\rm CMB}$ (absorption)

(signal turns on via Lyα from first stars)



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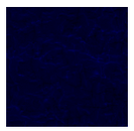

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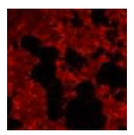

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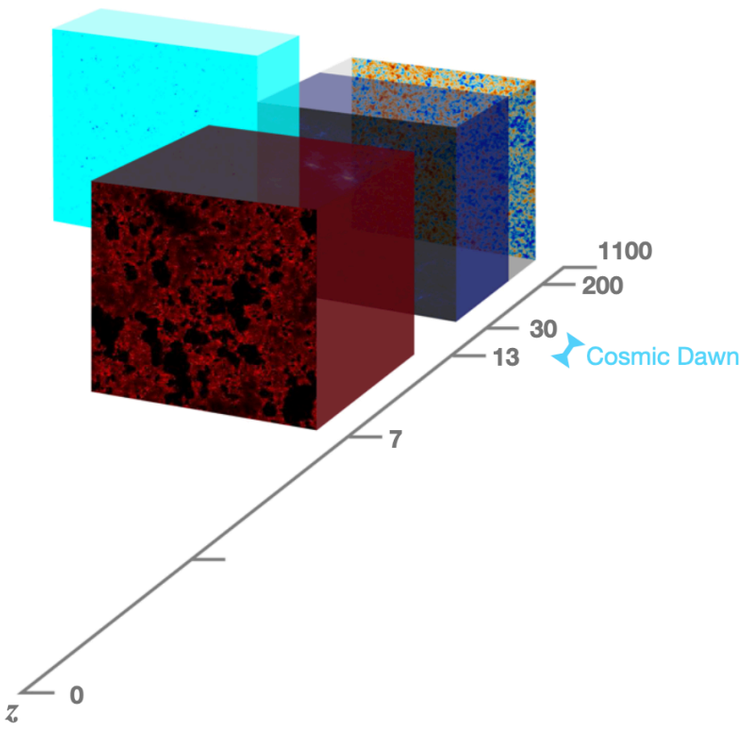

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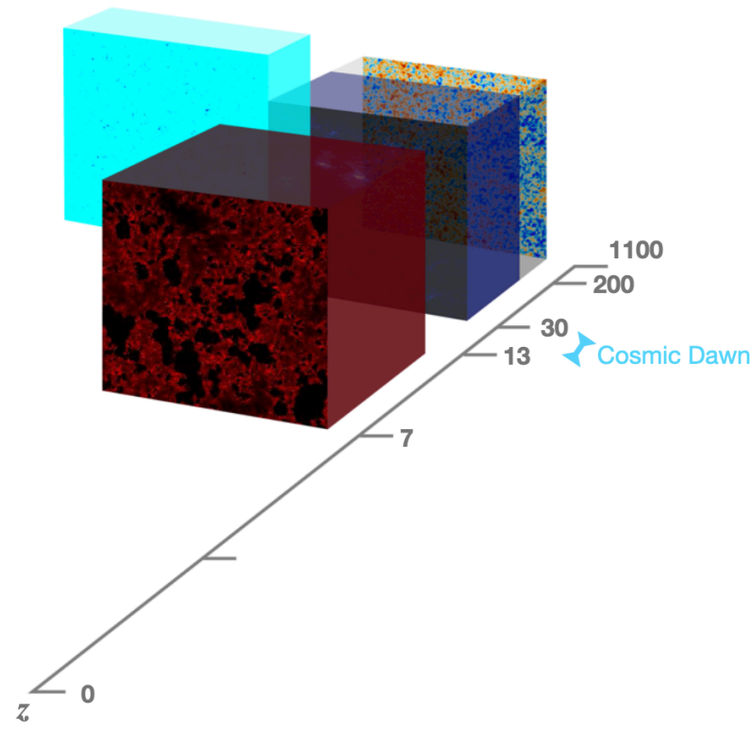

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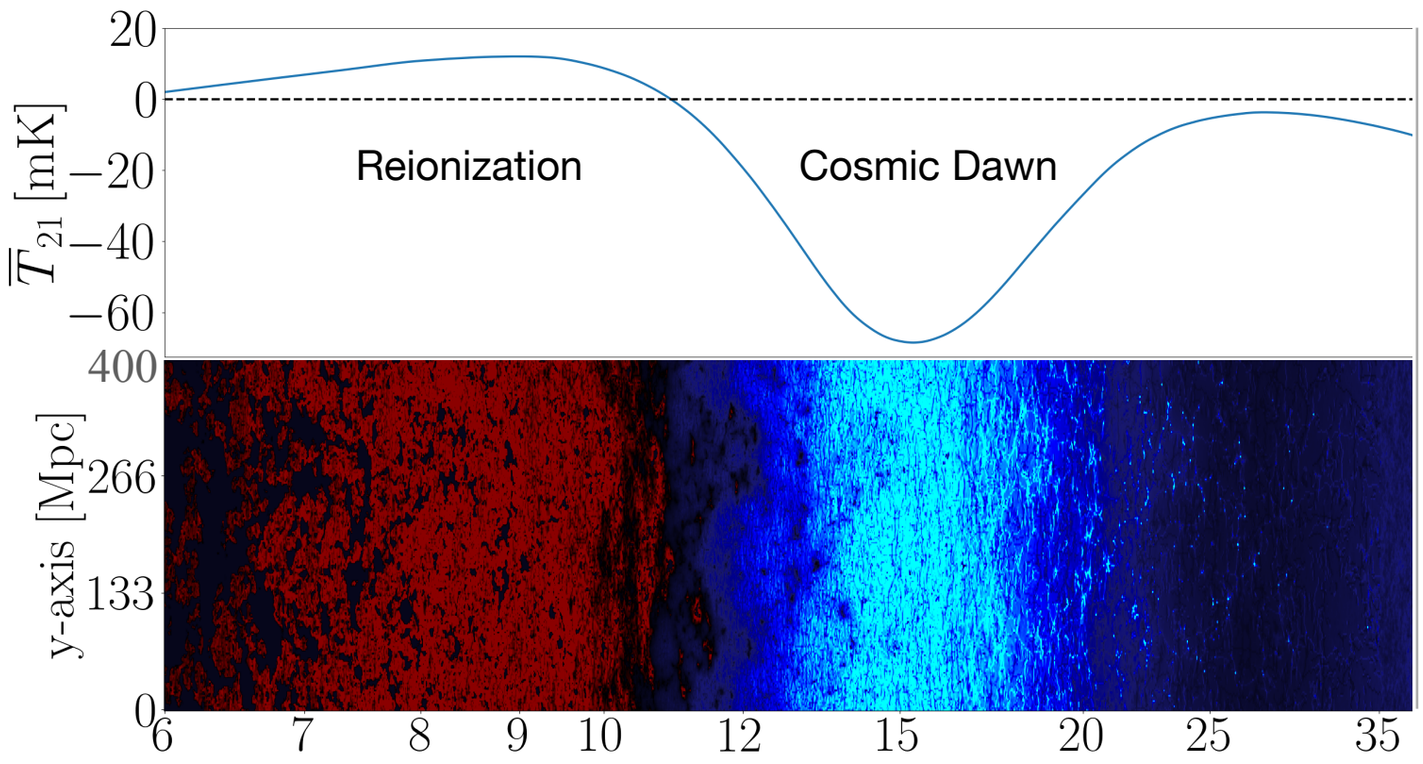

21cmFAST Simulation

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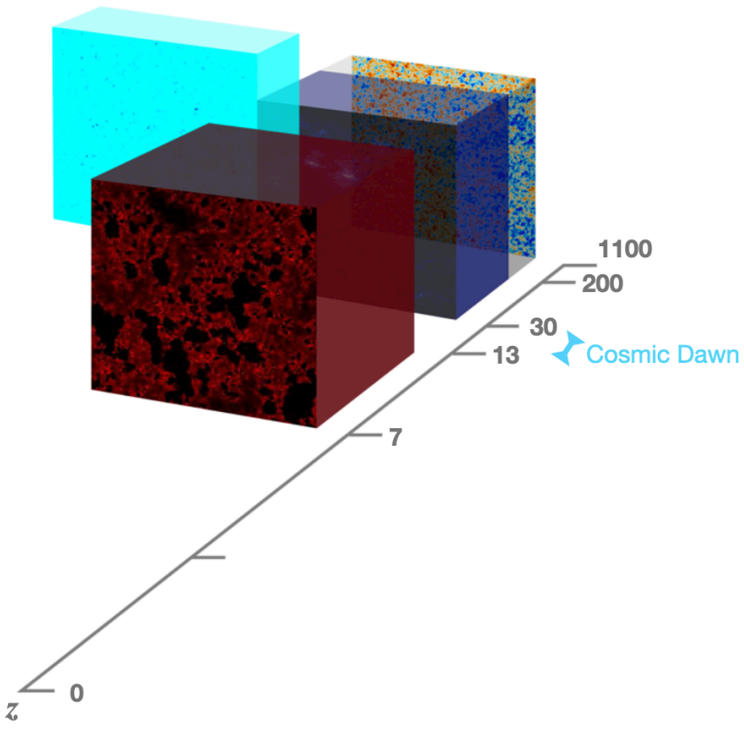

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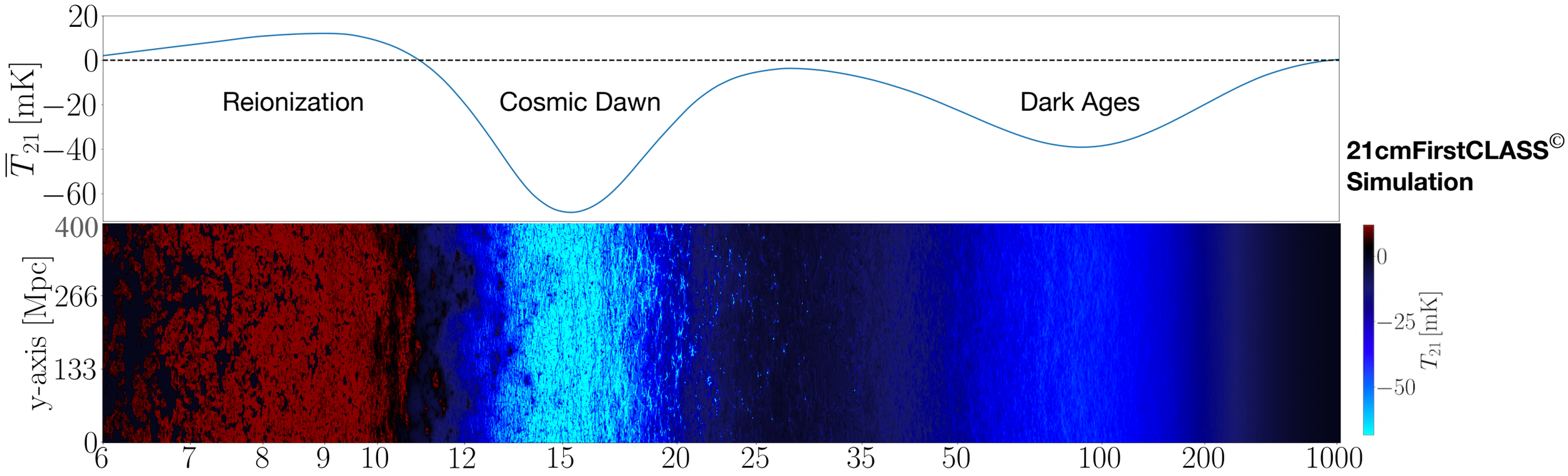

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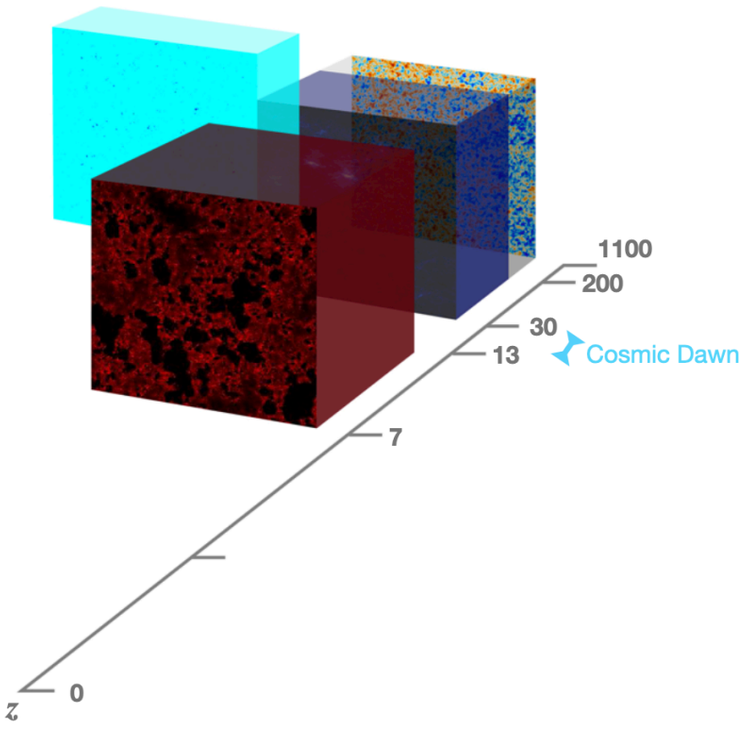

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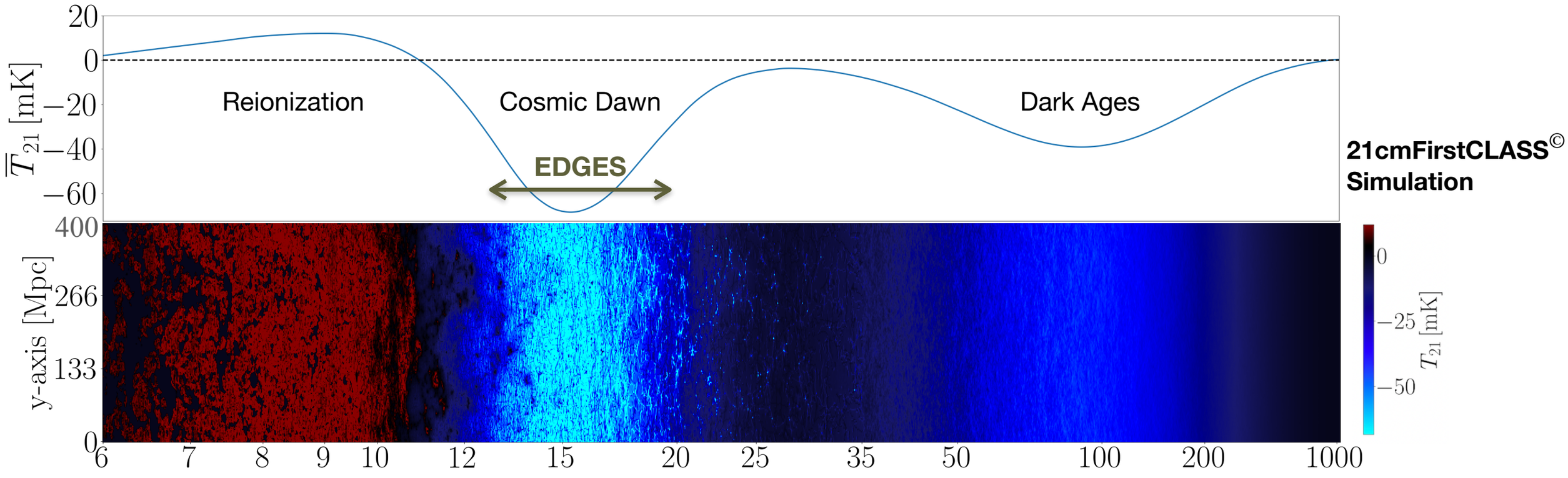

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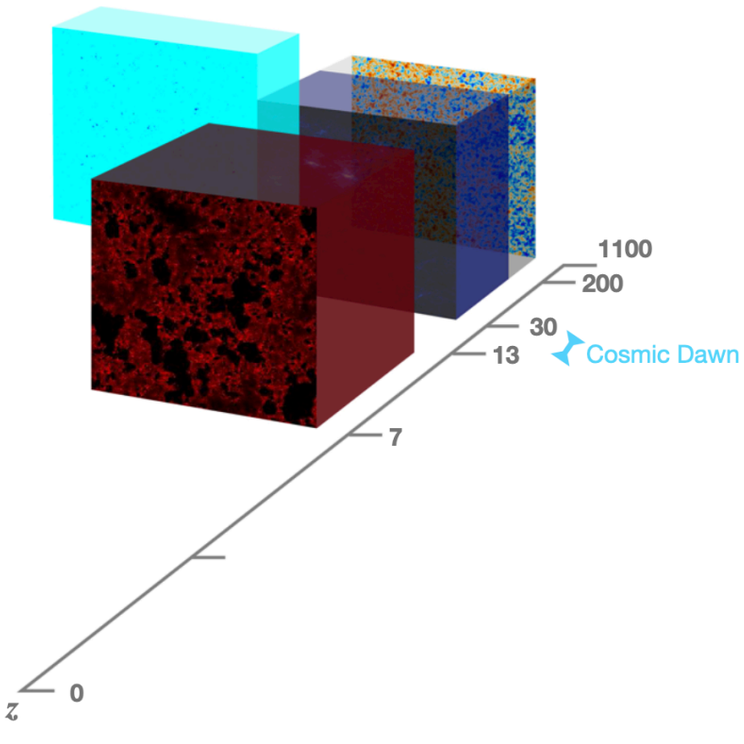

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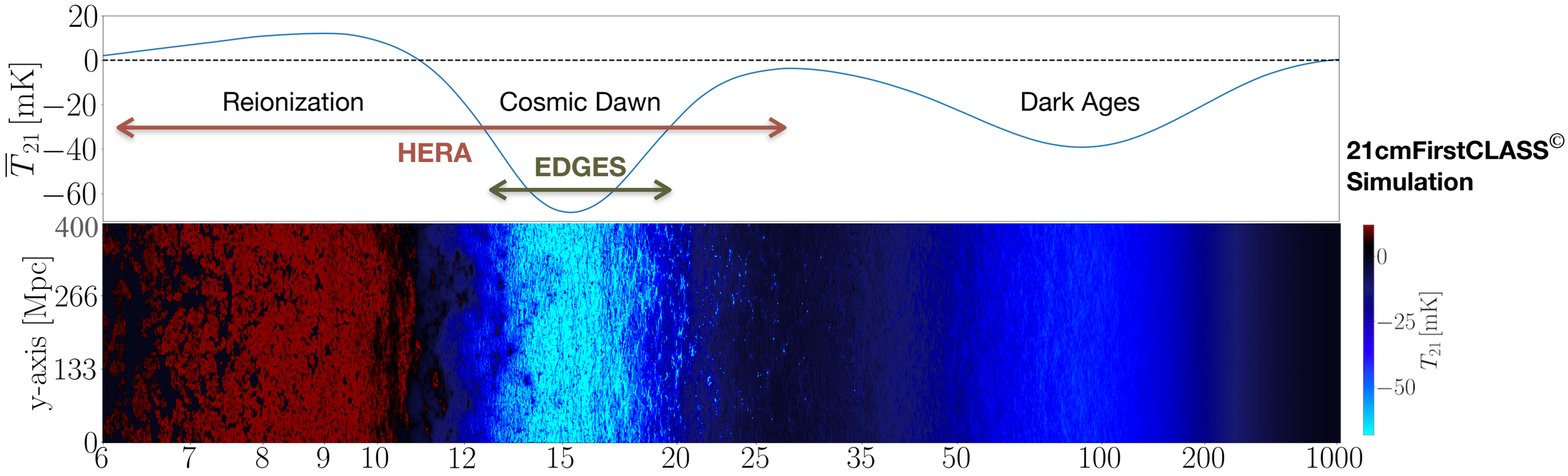

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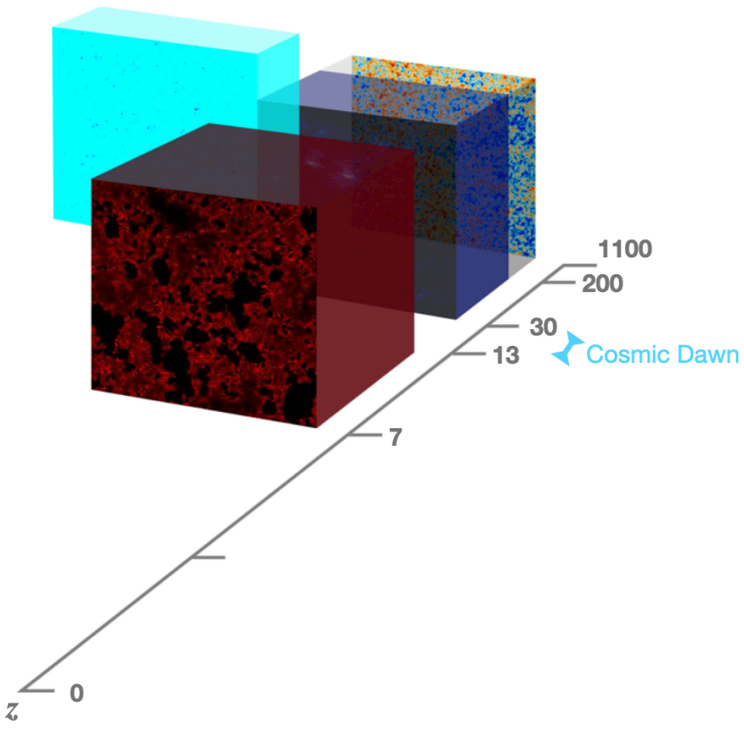

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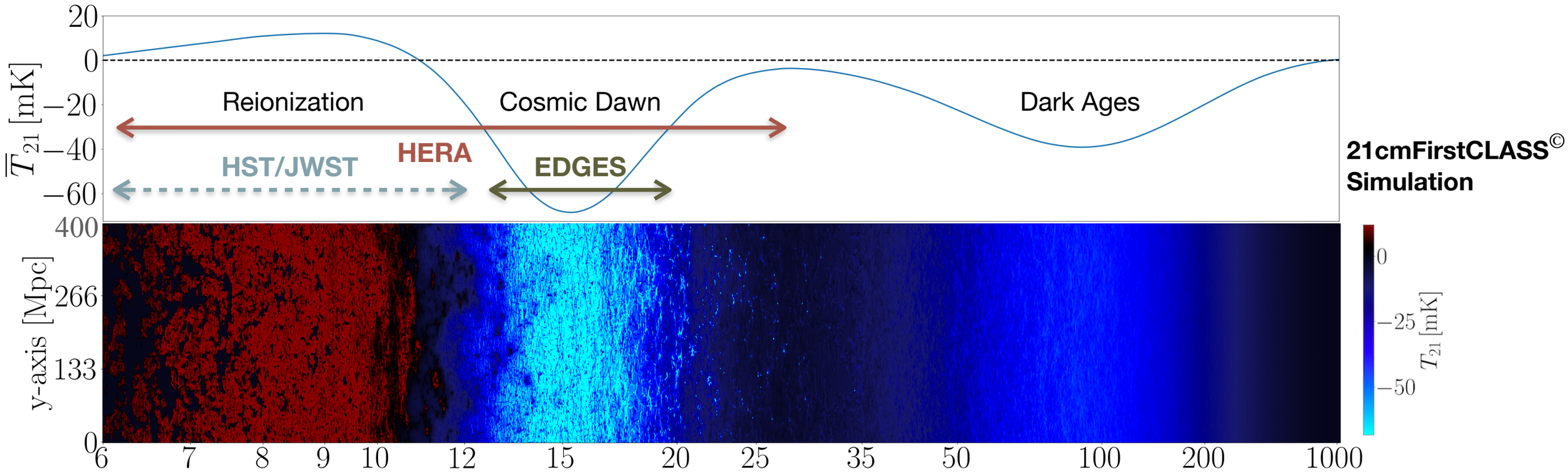

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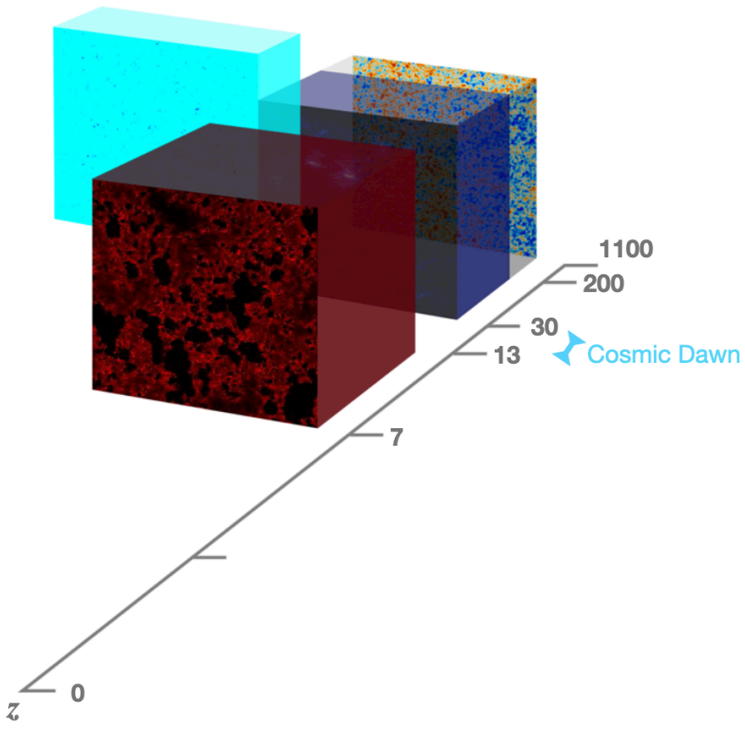

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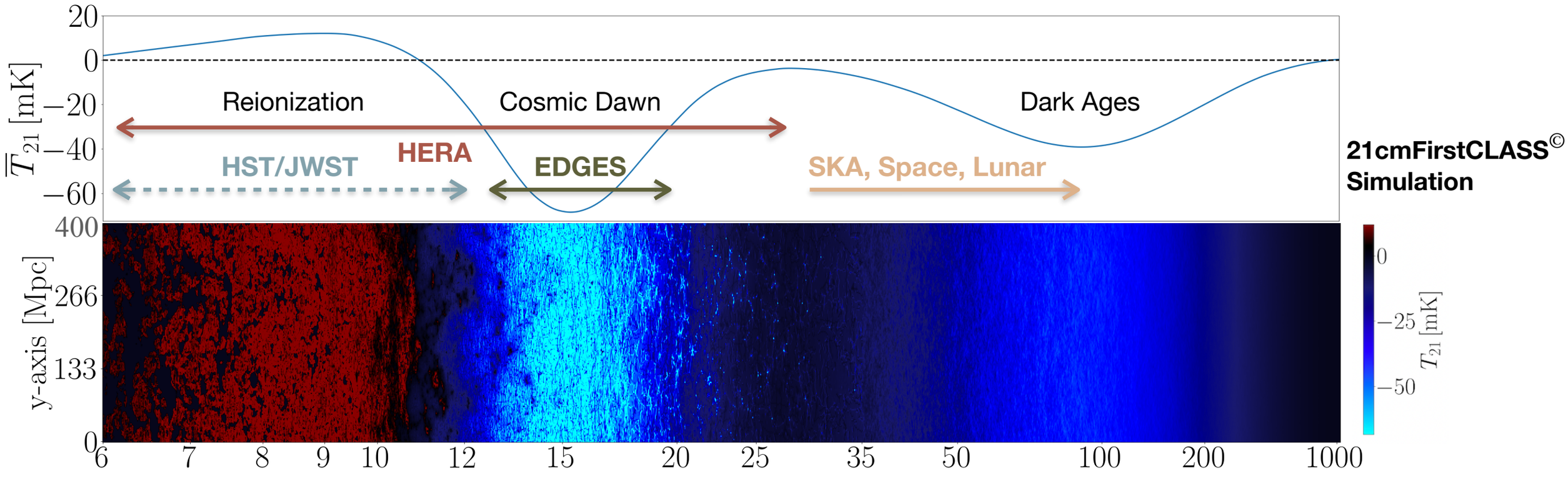

21cm Cosmology: Sensitivity to New Physics

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Q: Focusing on the global signal, What is the effect of new physics?

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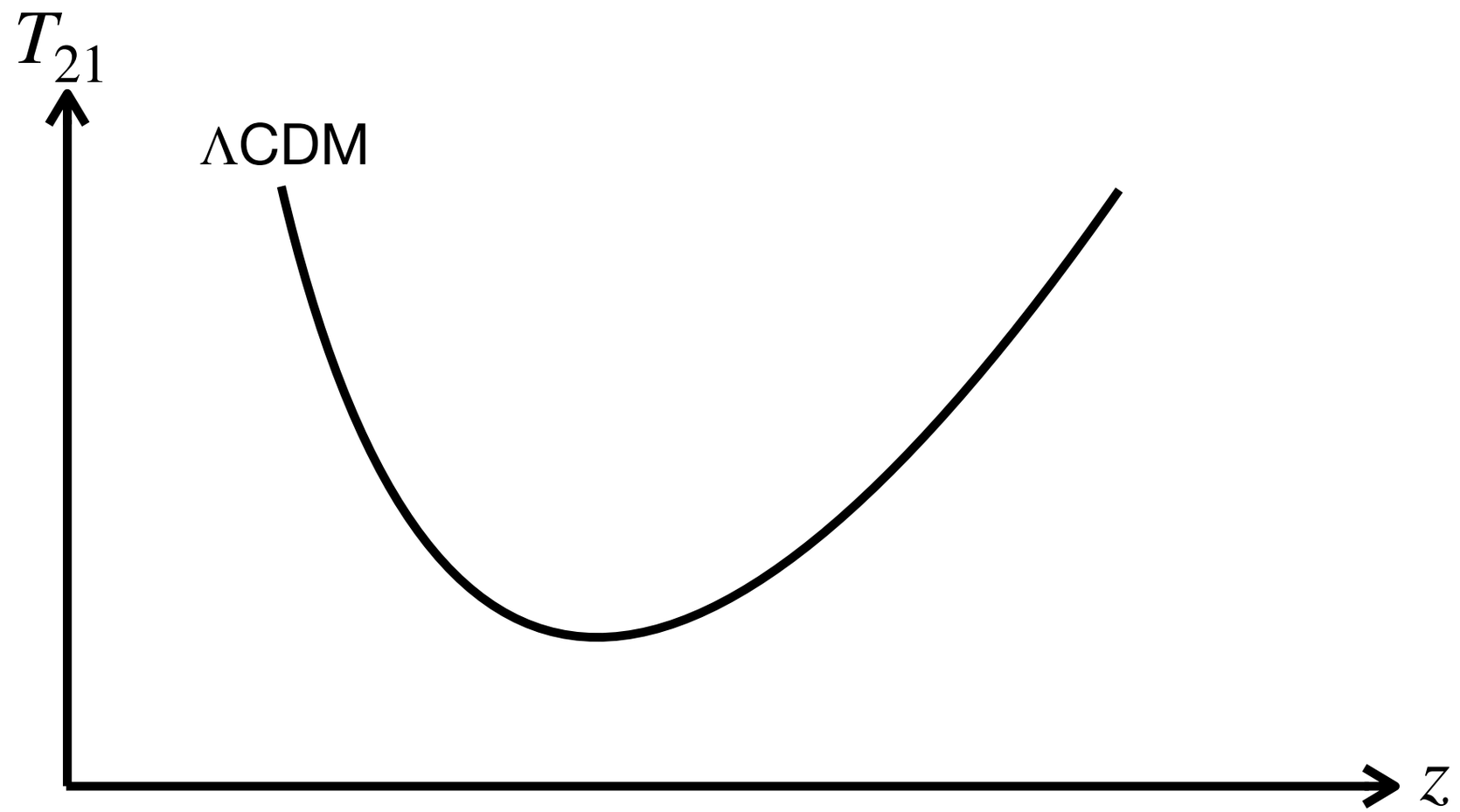

Credit: J. Flitter

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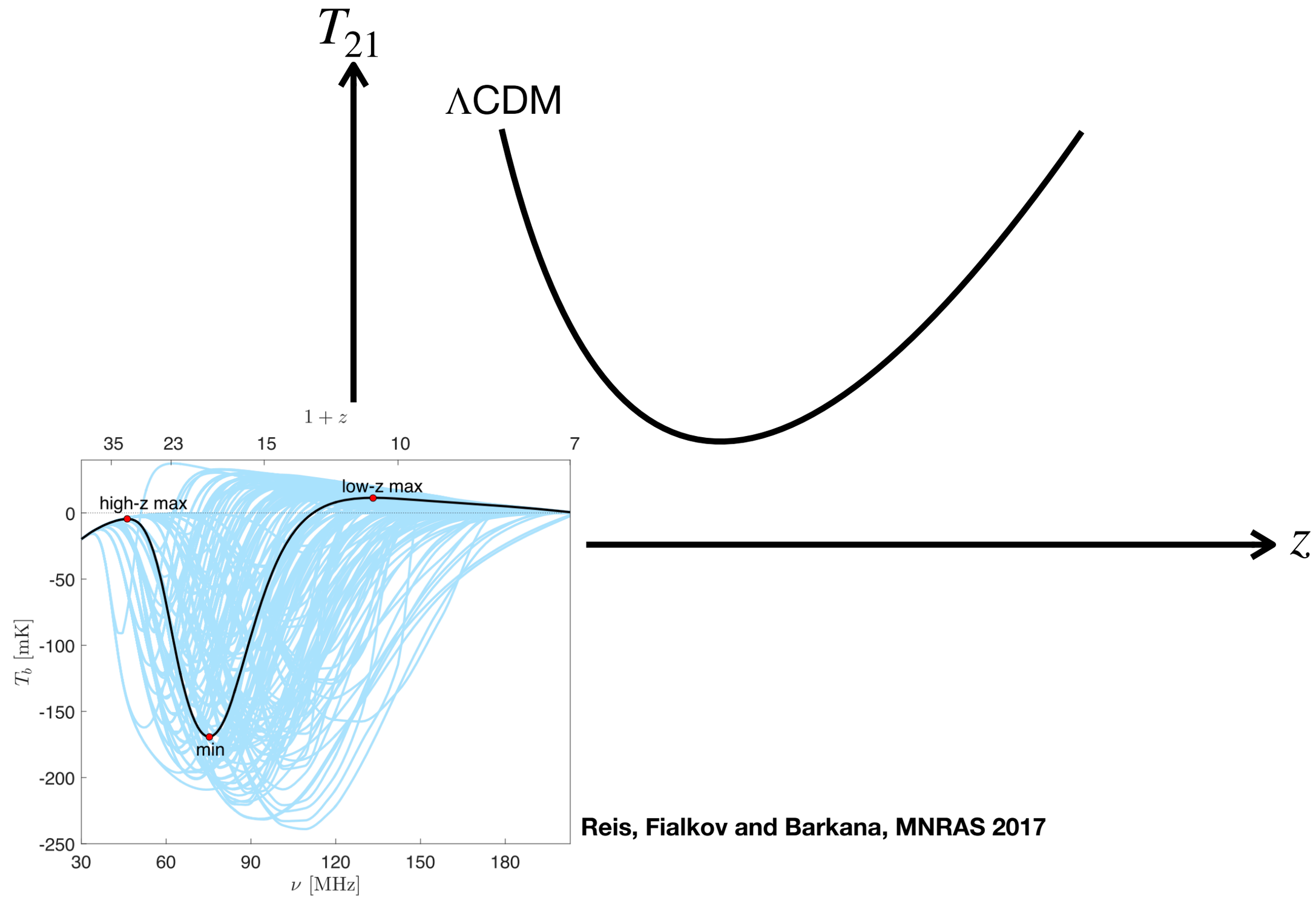

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Reis, Fialkov and Barkana, MNRAS 2017

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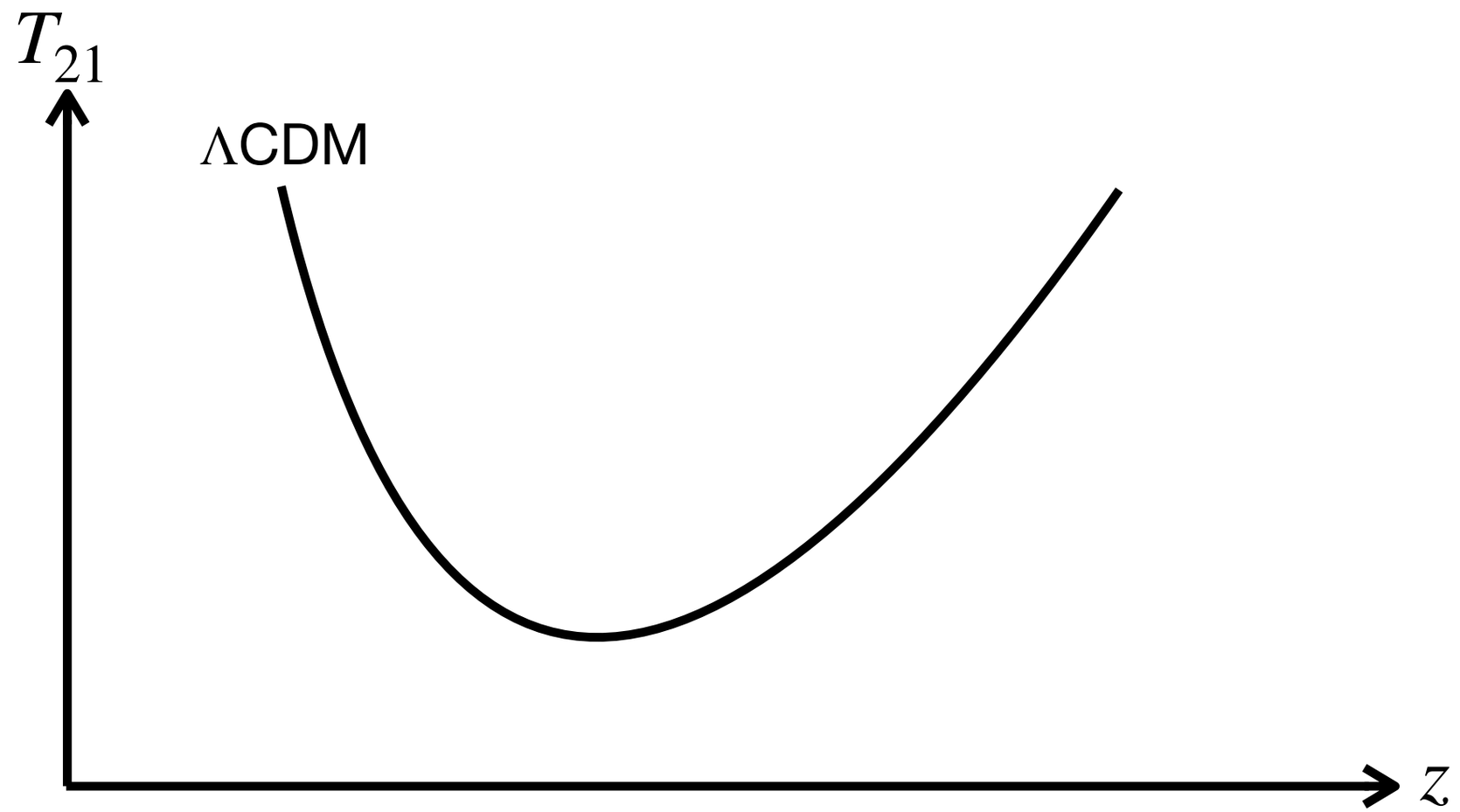

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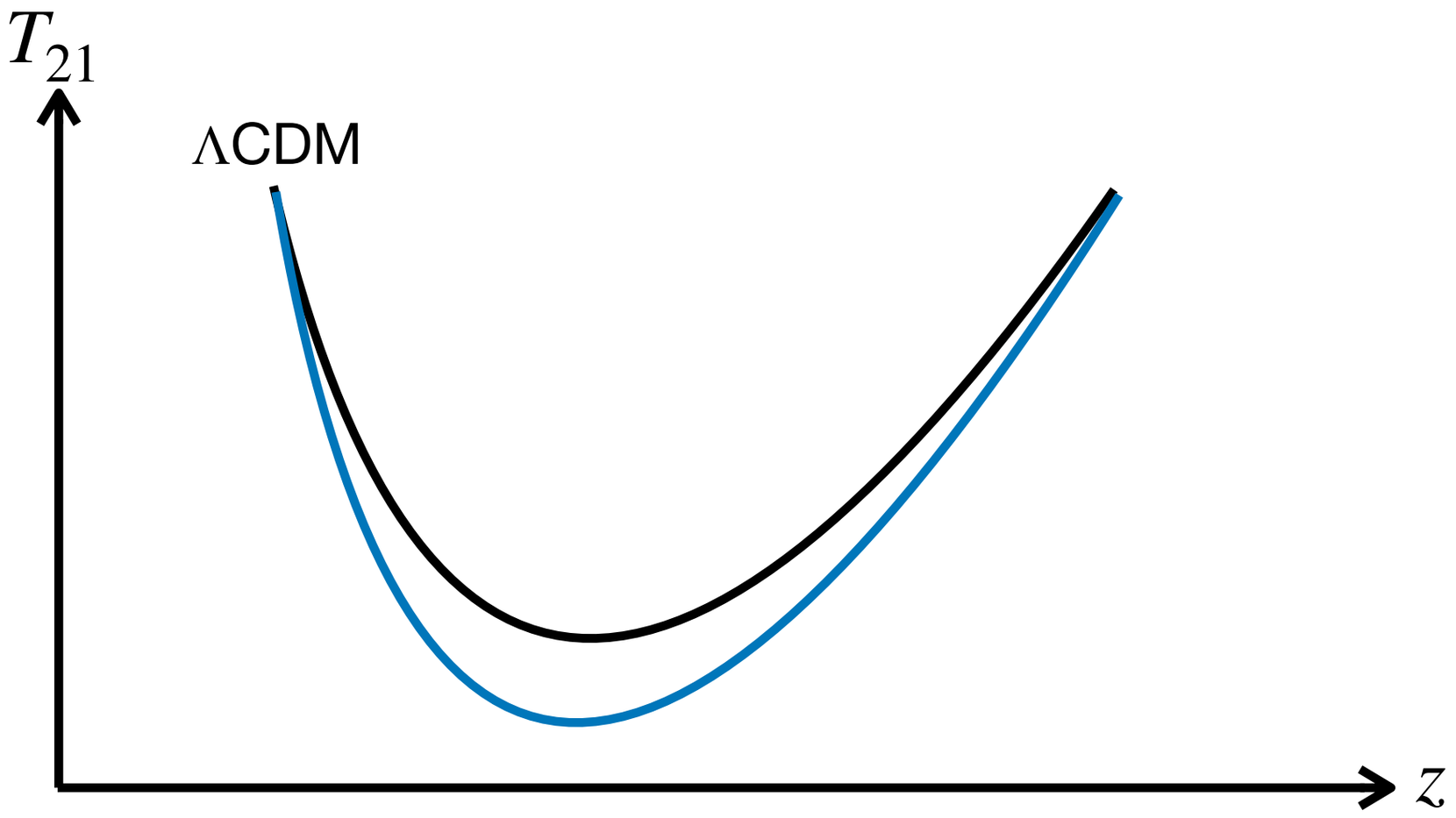

Credit: J. Flitter

"Something" cools down the IGM!
e.g.: DM scatters with baryons

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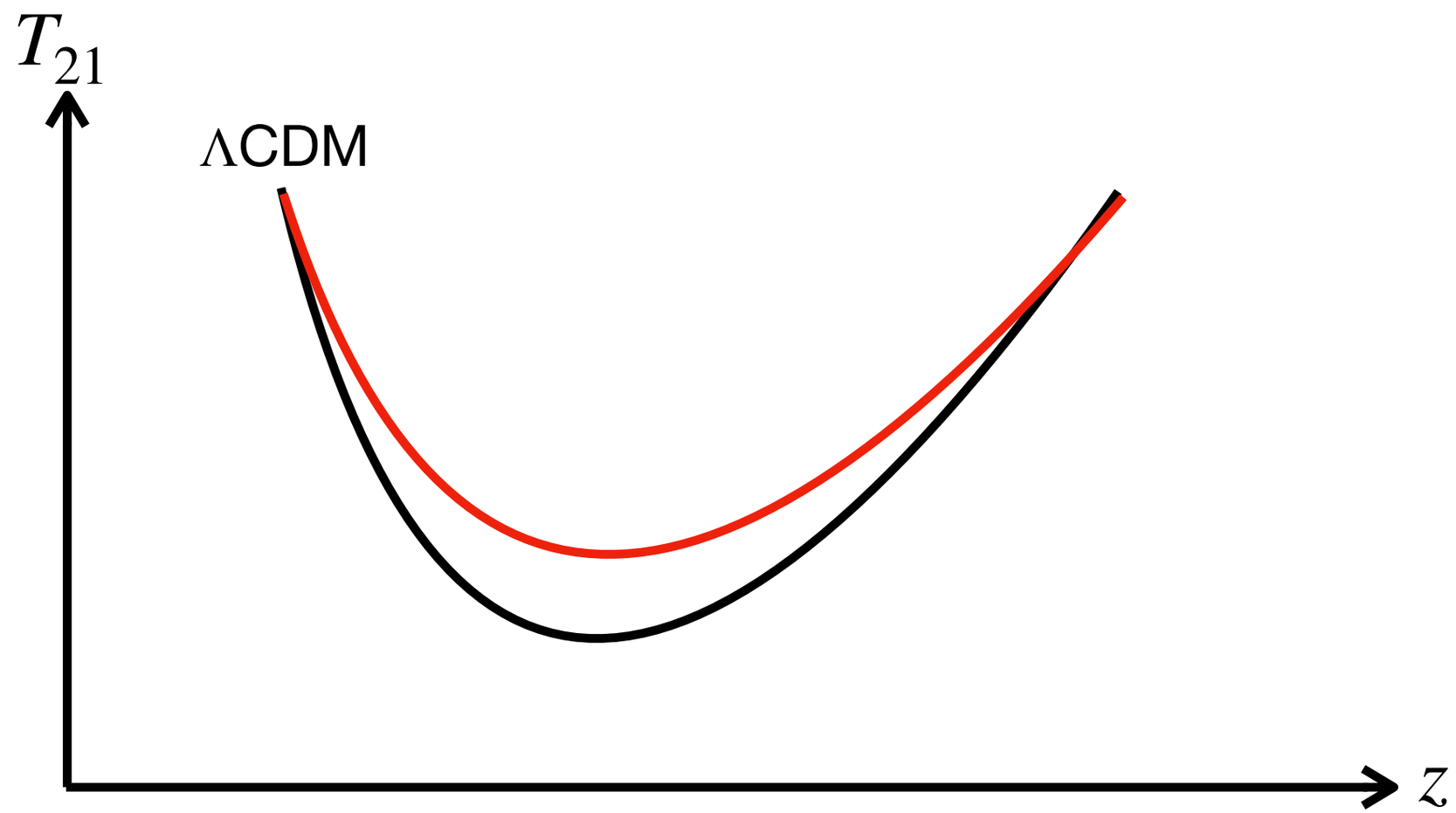

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"Something" heats up the IGM!

e.g.: annihilating/decaying DM, hidden photon DM, PBHs

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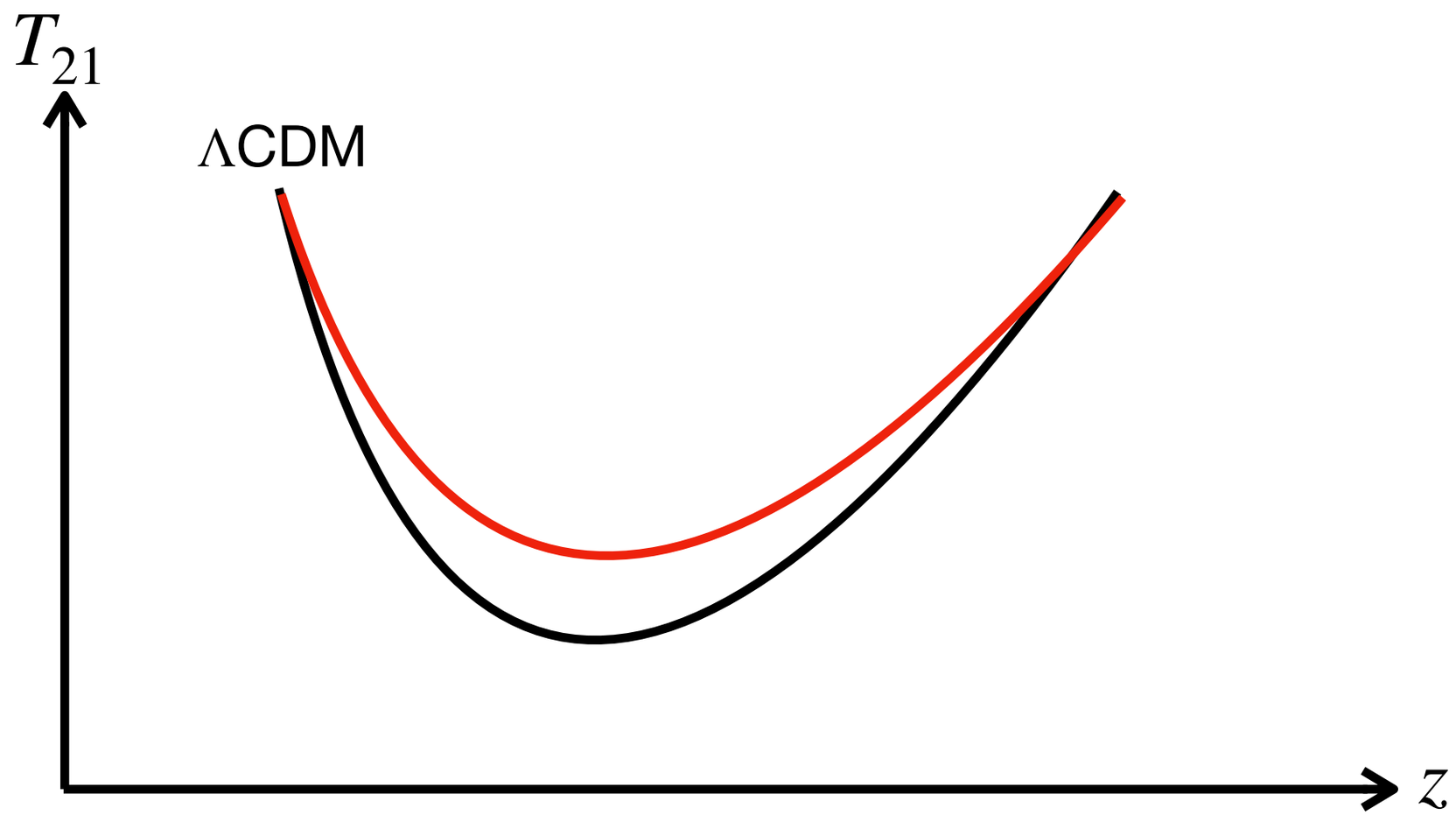

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→ see Tracy's talk

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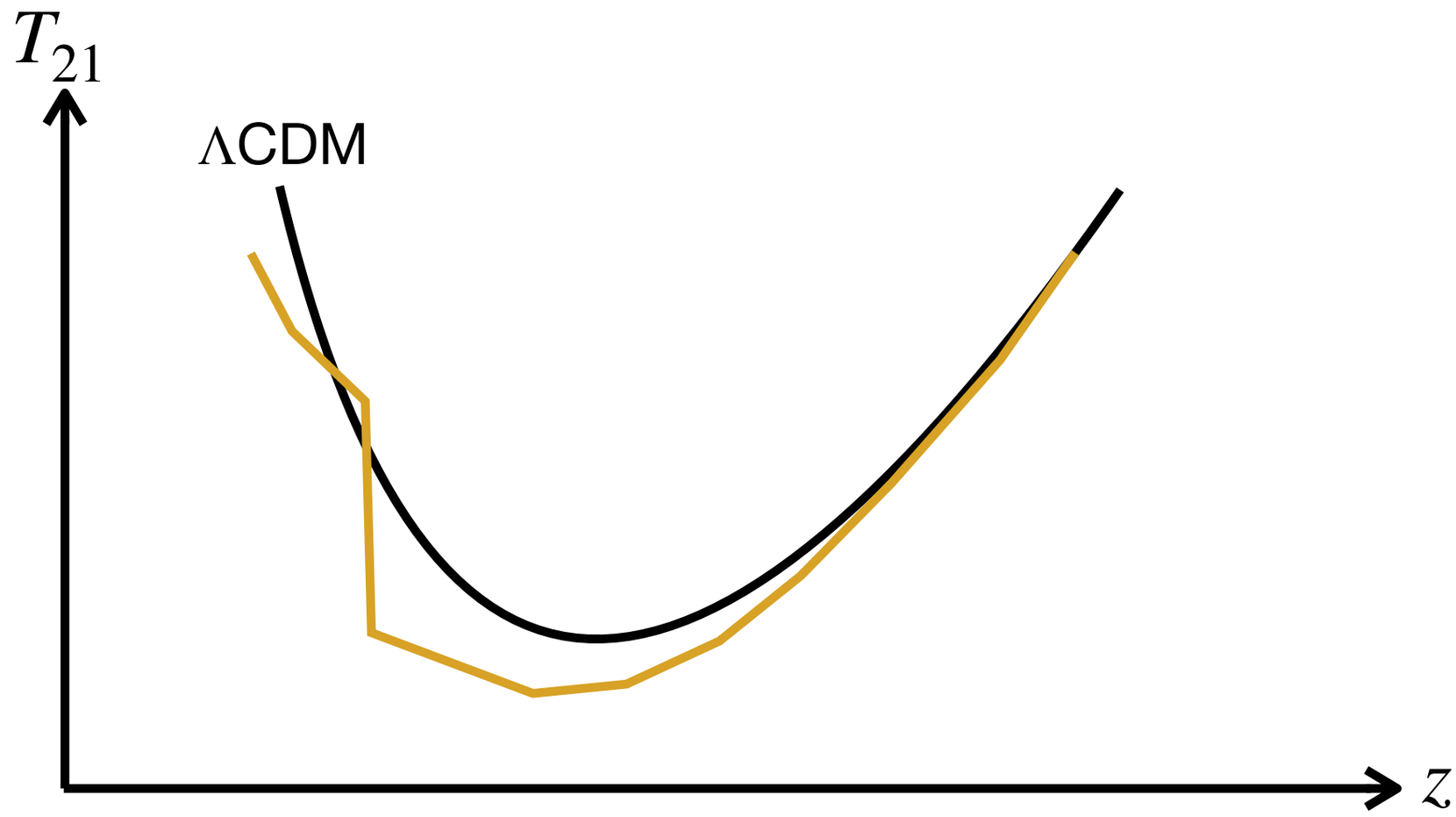

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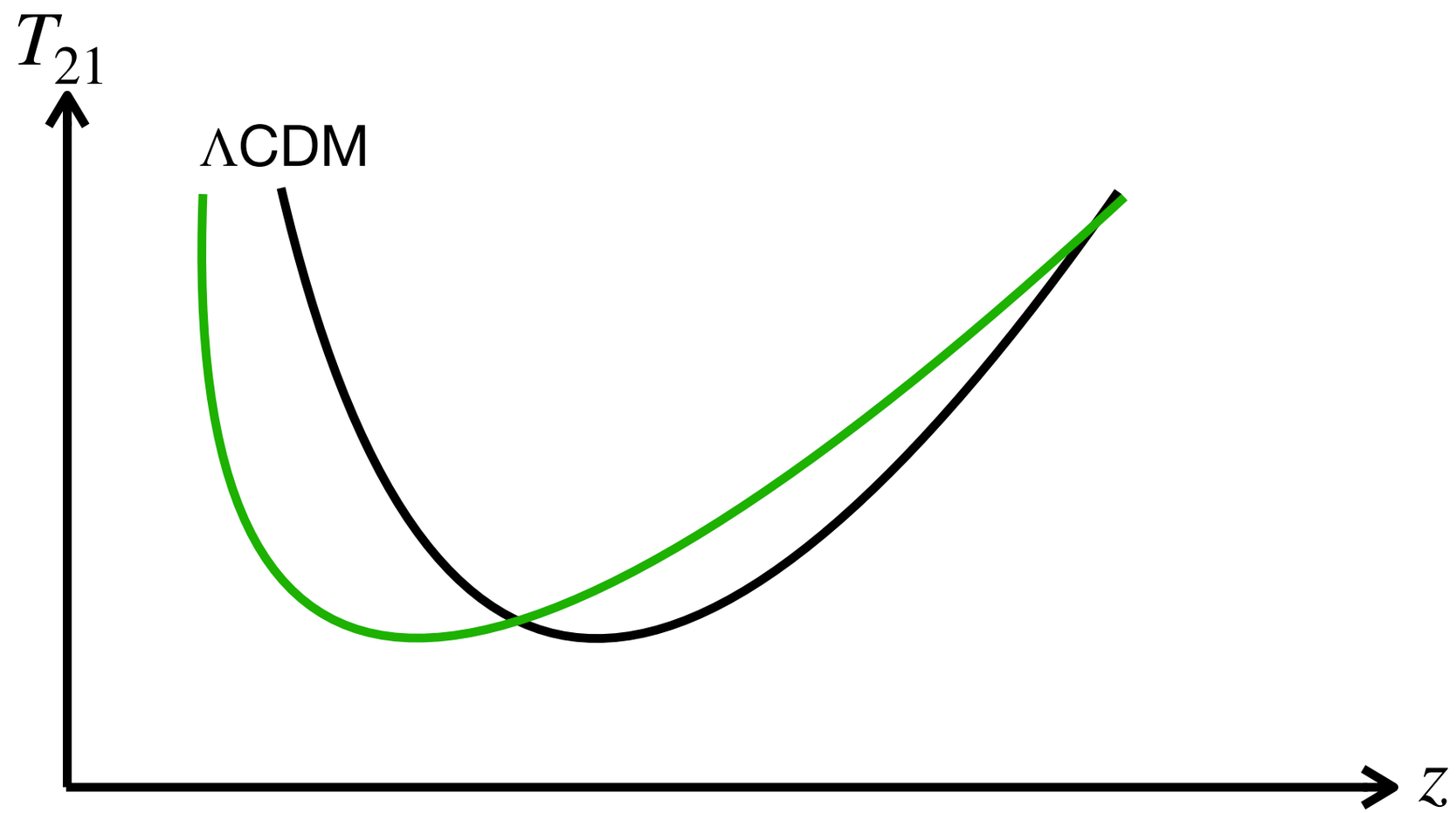
"Something" generates edges and endpoints!

e.g.: resonant photon injection (dark photon ⟶ photon)

21cm Cosmology: Sensitivity to New Physics



Credit: J. Flitter

"Something" delays structure formation!

e.g.: fuzzy DM, ultra light axions, ALPs

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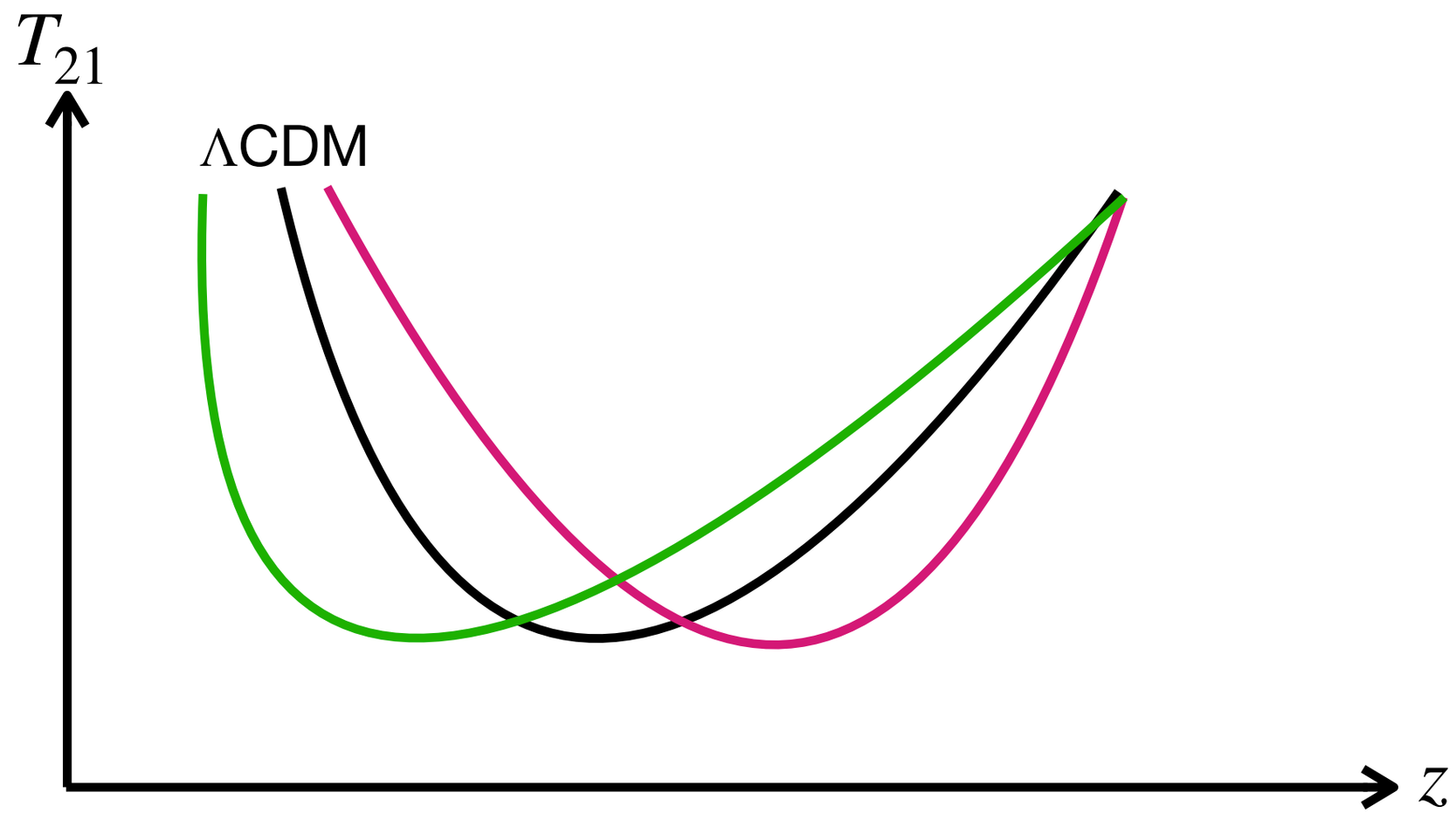

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"Something" delays structure formation!

e.g.: fuzzy DM, ultra light axions, ALPs

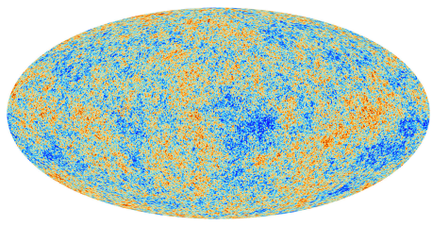
"Something" speeds up structure formation!

e.g.: primordial magnetic fields

21cm: from Global Signal to the Power Spectrum

21cm: from Global Signal to the Power Spectrum

CMB



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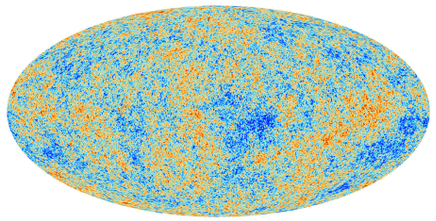

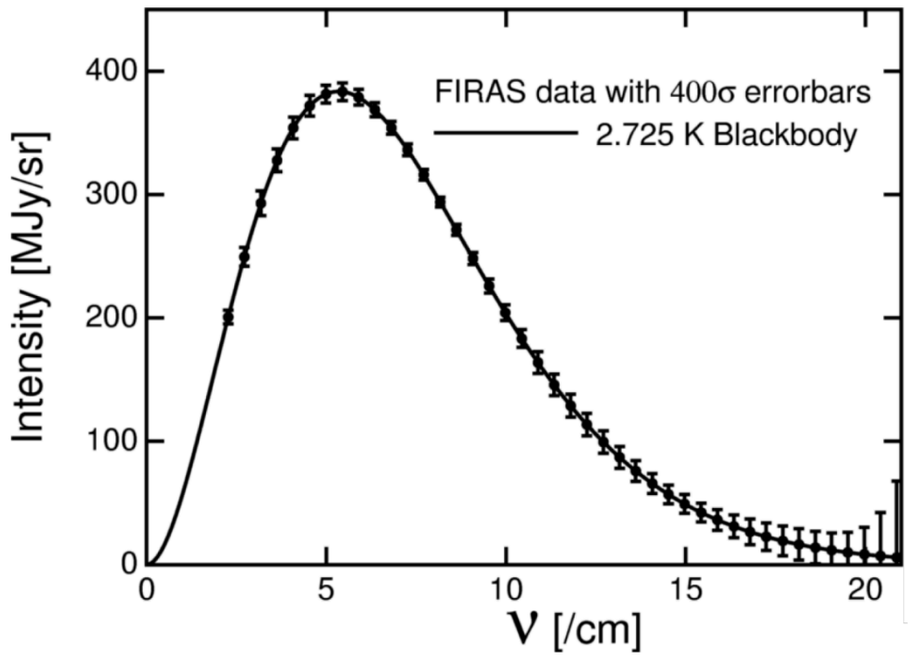

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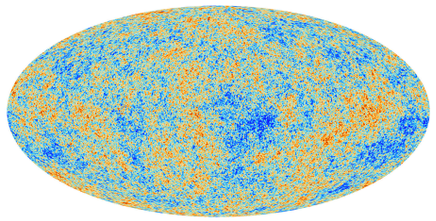

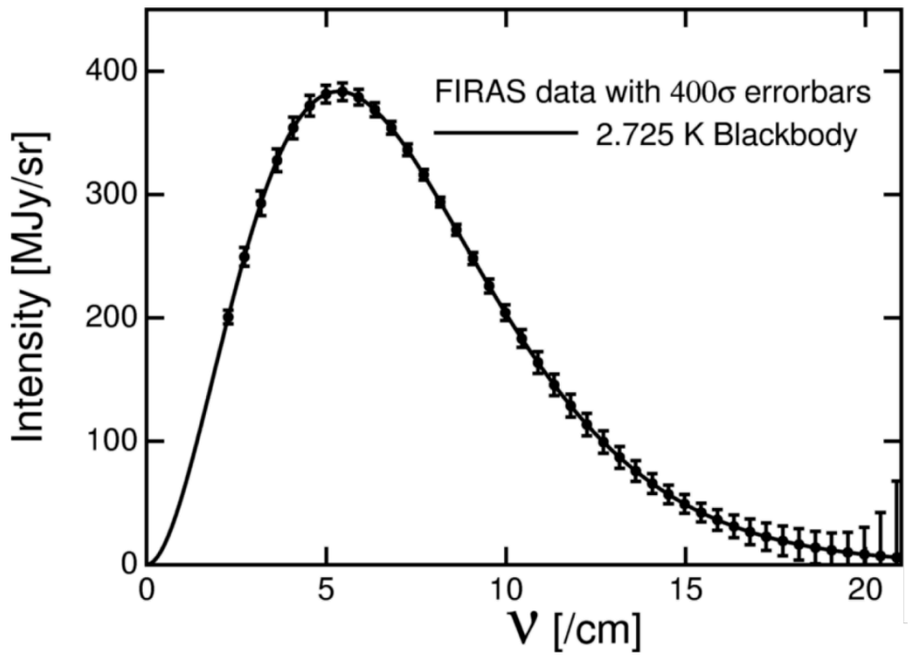

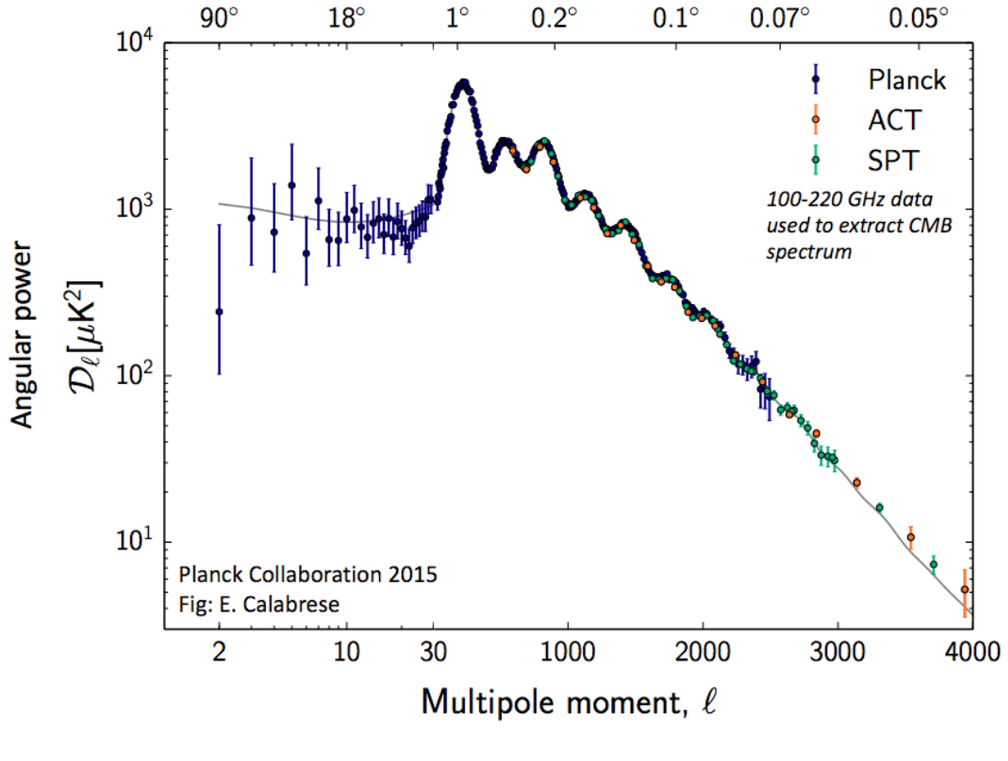

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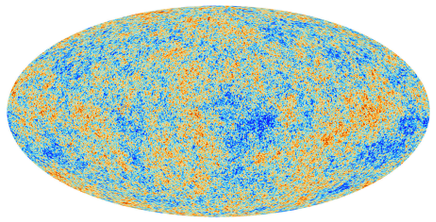

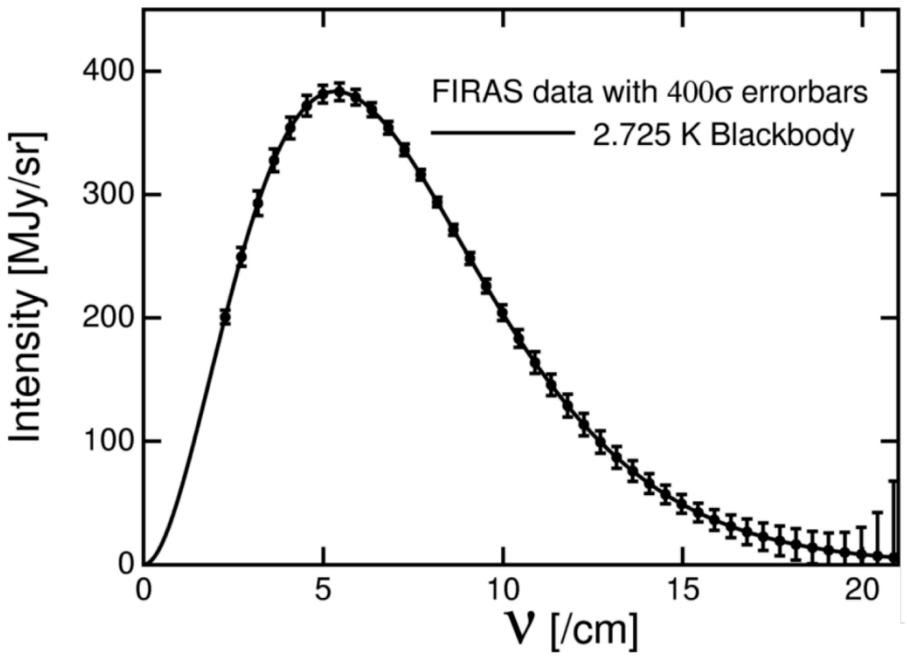

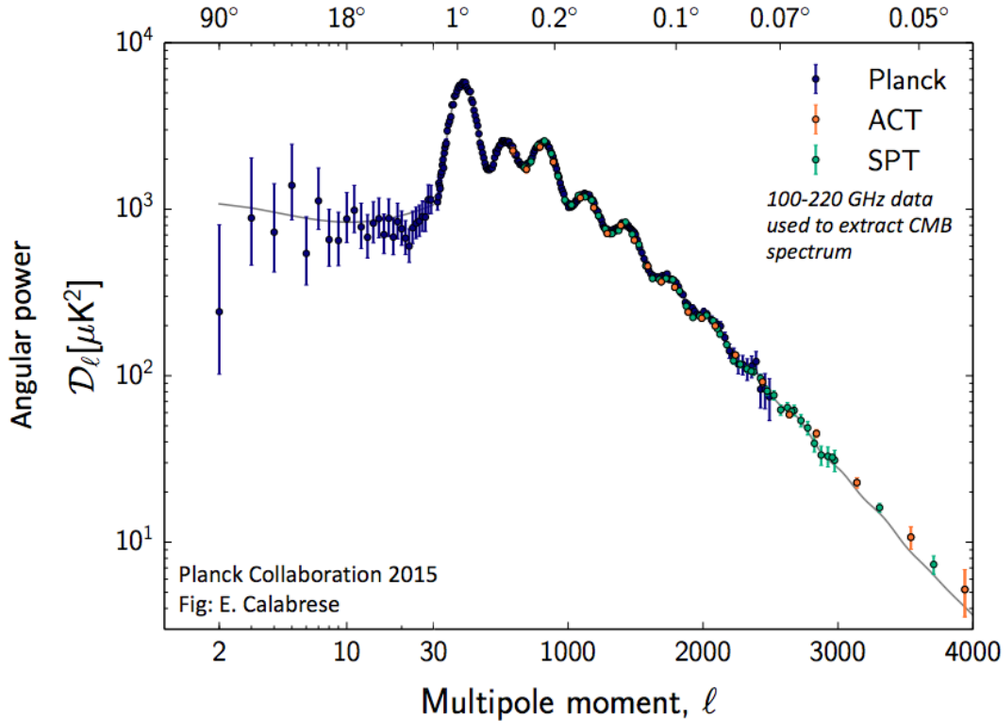

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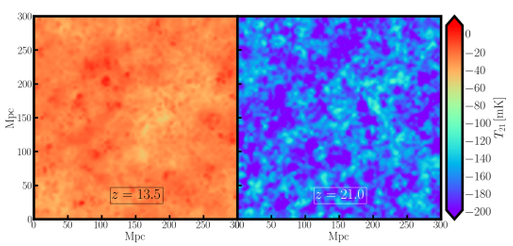

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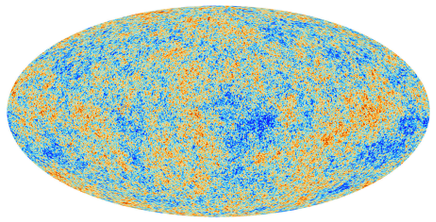

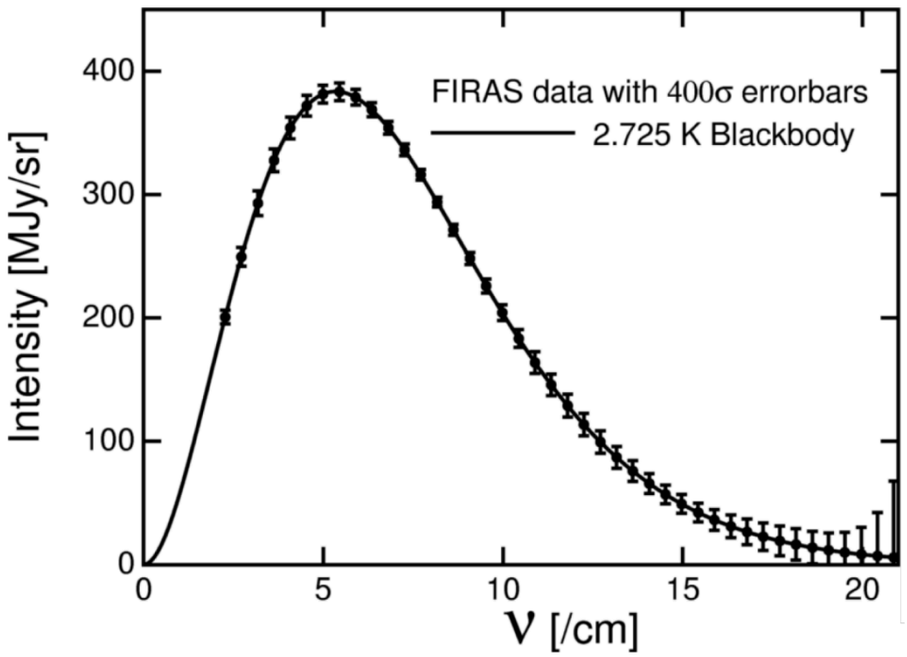

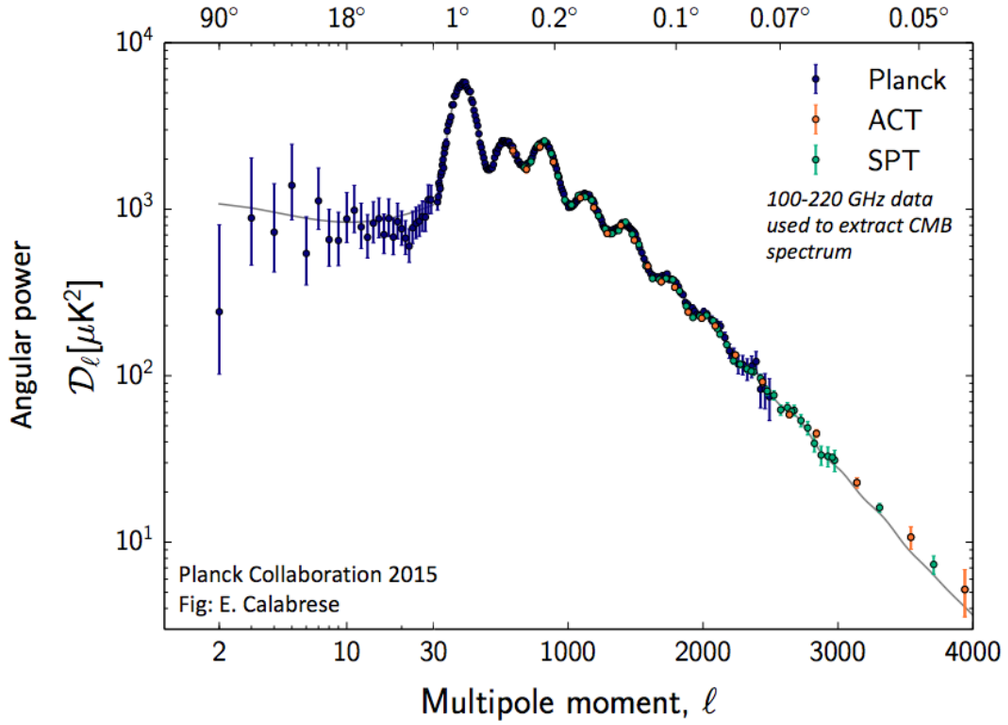

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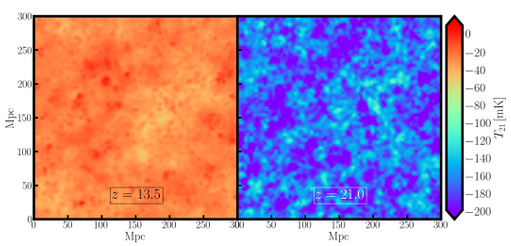

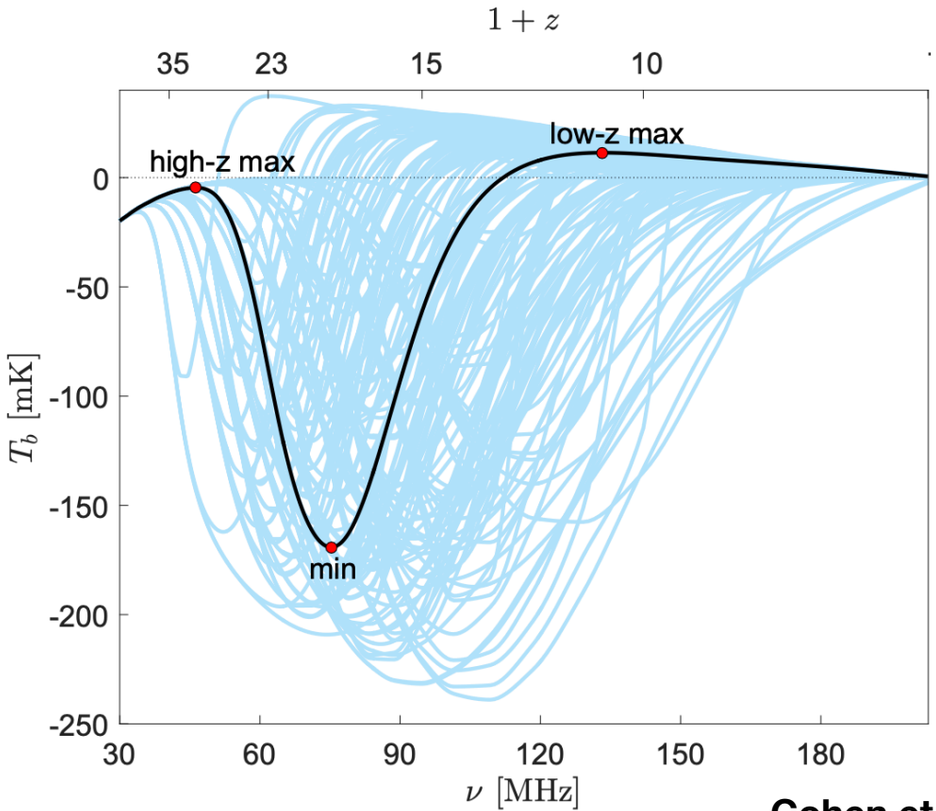

Cohen et al., MNRAS 2018

21cm: from Global Signal to the Power Spectrum

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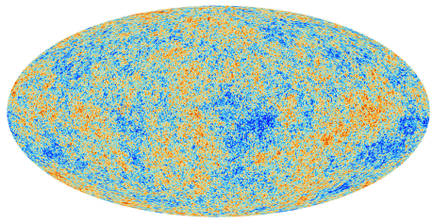

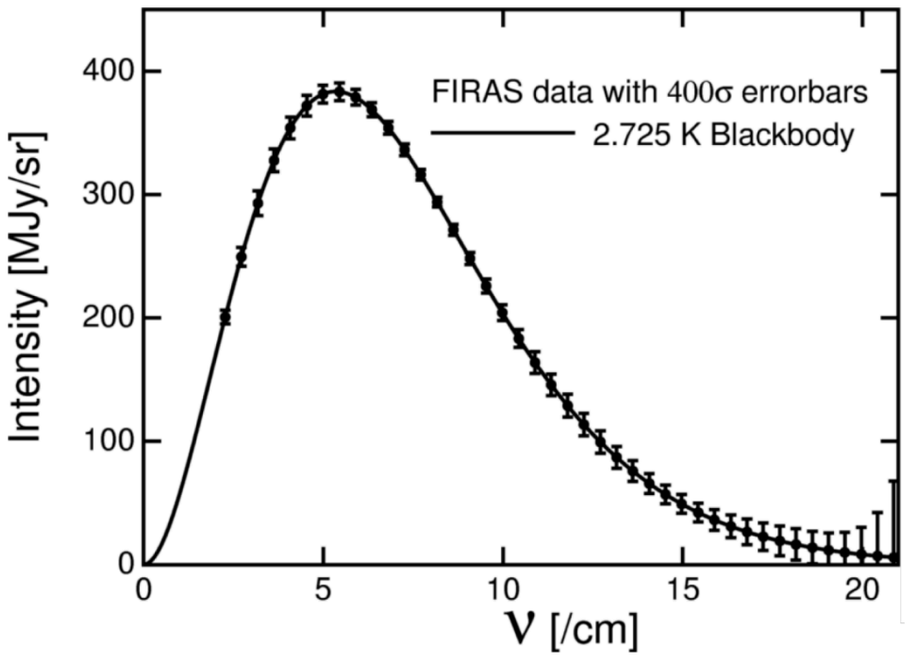

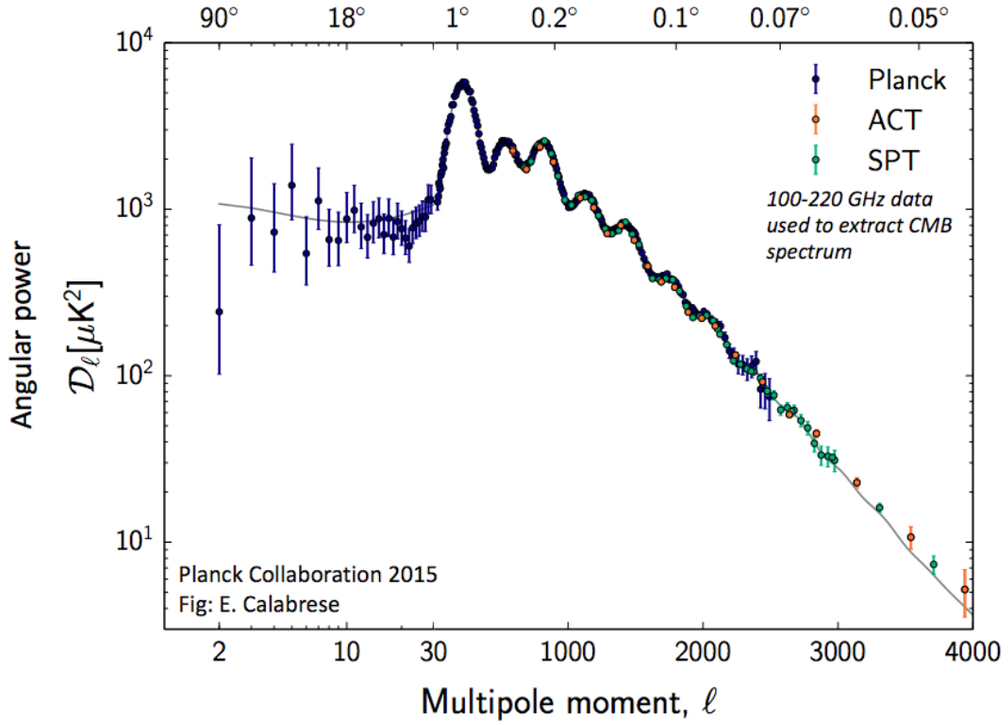

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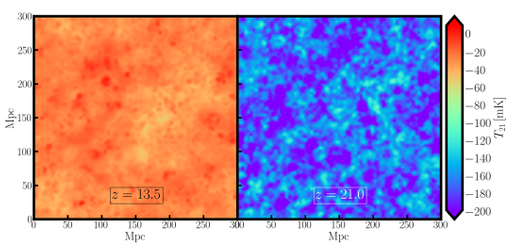
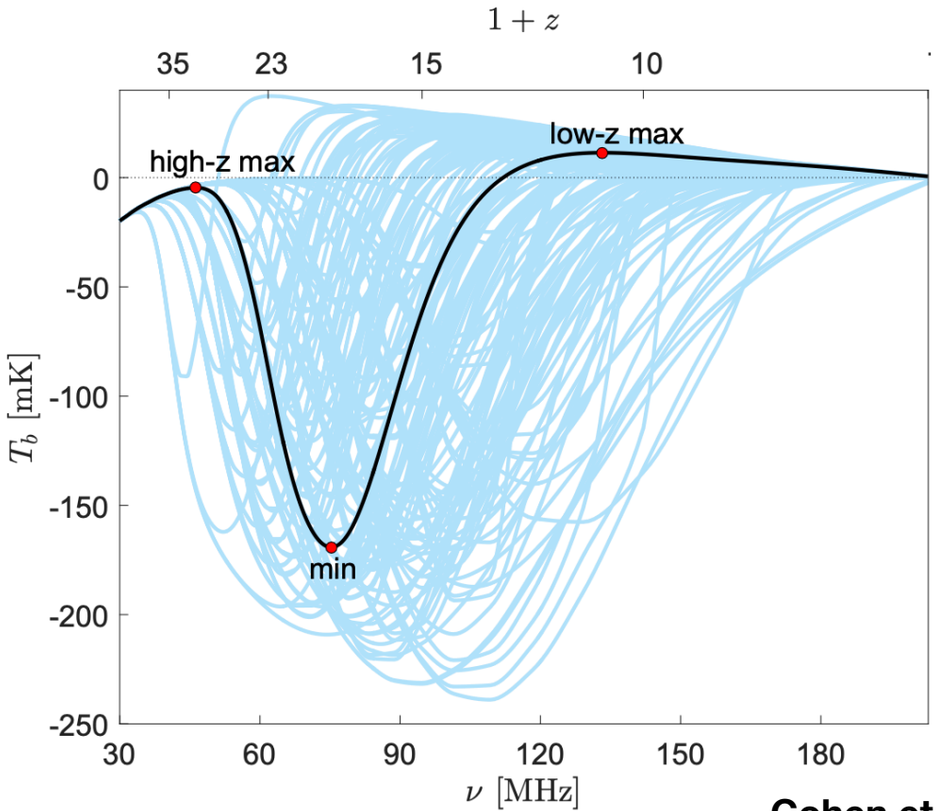
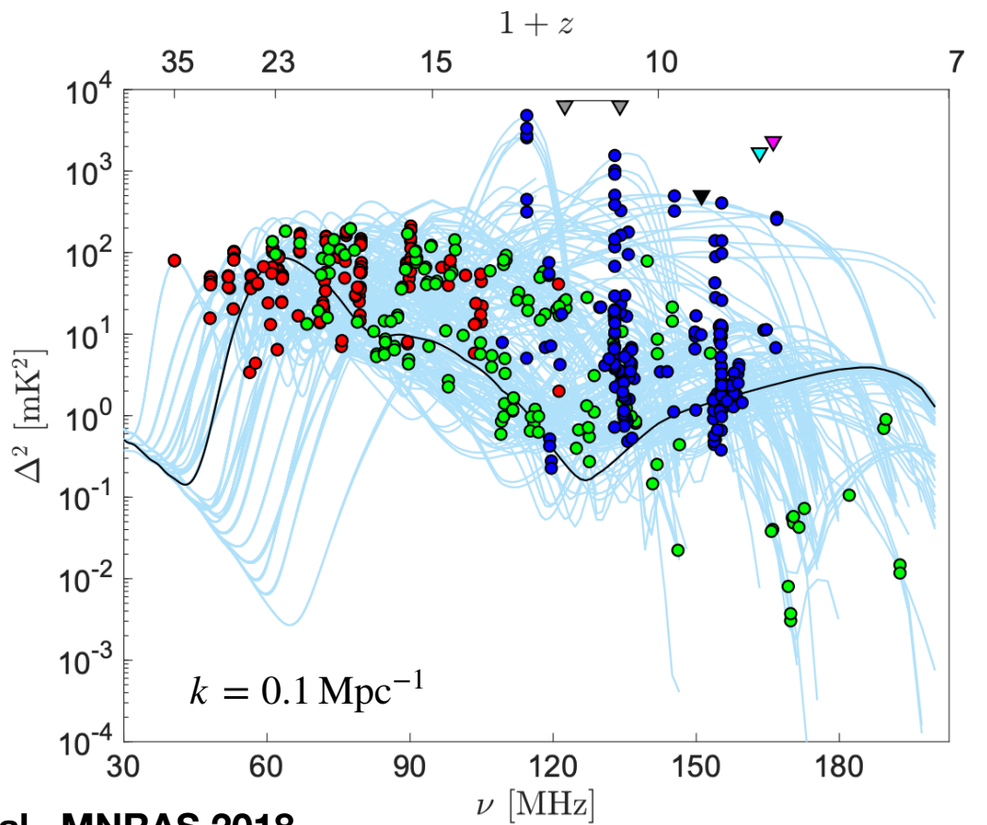






Cohen et al., MNRAS 2018

21cm Simulations: Public Codes

Full radiative-transfer hydrodynamical simulation (extremely computationally expensive):

CoDa **(Ocvirk et al., MNRAS 2016)** 21SSD **(Semelin, MNRAS 2017)** THESAN **(Kannan et al., MNRAS 2011)**

Ray-tracing algorithms (applied to N-body simulations; also very expensive):

C^2 – Ray **(Mellema et al., New Astron. 2006)** CRASH **(Maselli et al., MNRAS 2003)**

One-dimensional radiative transfer (much faster, approximated):

BEARS **(Thomas et al., MNRAS 2009)** GRIZZLY **(Ghara et al., MNRAS 2018)** BEoRN **(Schaeffer et al., arXiv:2305.15466)**

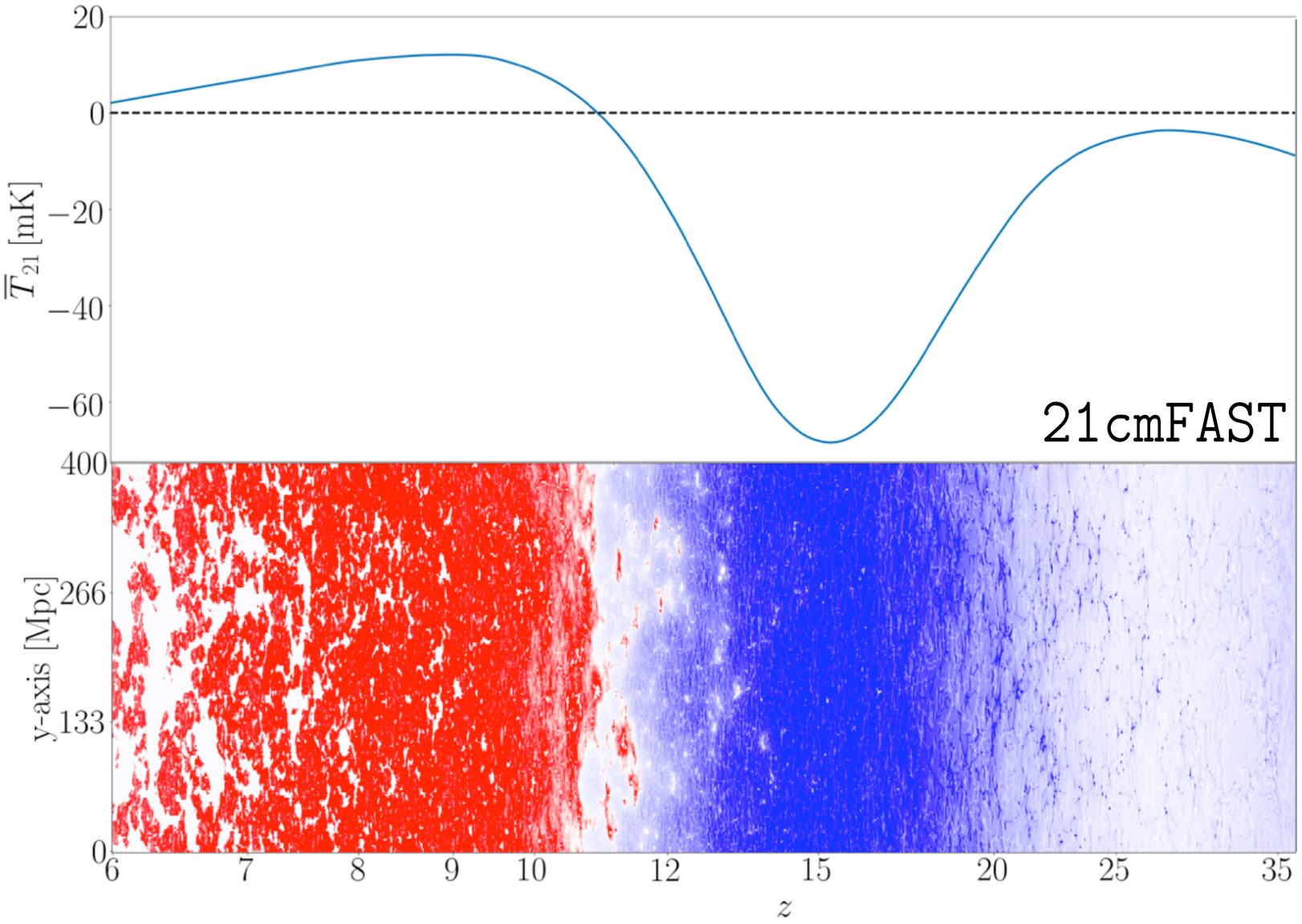
Purely analytic codes (fastest):

CAMB **(Lewis and Challinor, PRD 2007)** Zeus21 **(Munoz, arXiv:2302.08506)** X21 **(Katz et al., arXiv:2309.XXXXX)**

Semi-numerical codes (excursion-set formalism):

SimFAST21 **(Santos et. al, MNRAS 2010)** 21cmFAST **(Mesinger et al., MNRAS 2011)**

21cm Simulations: a Code for Cosmology



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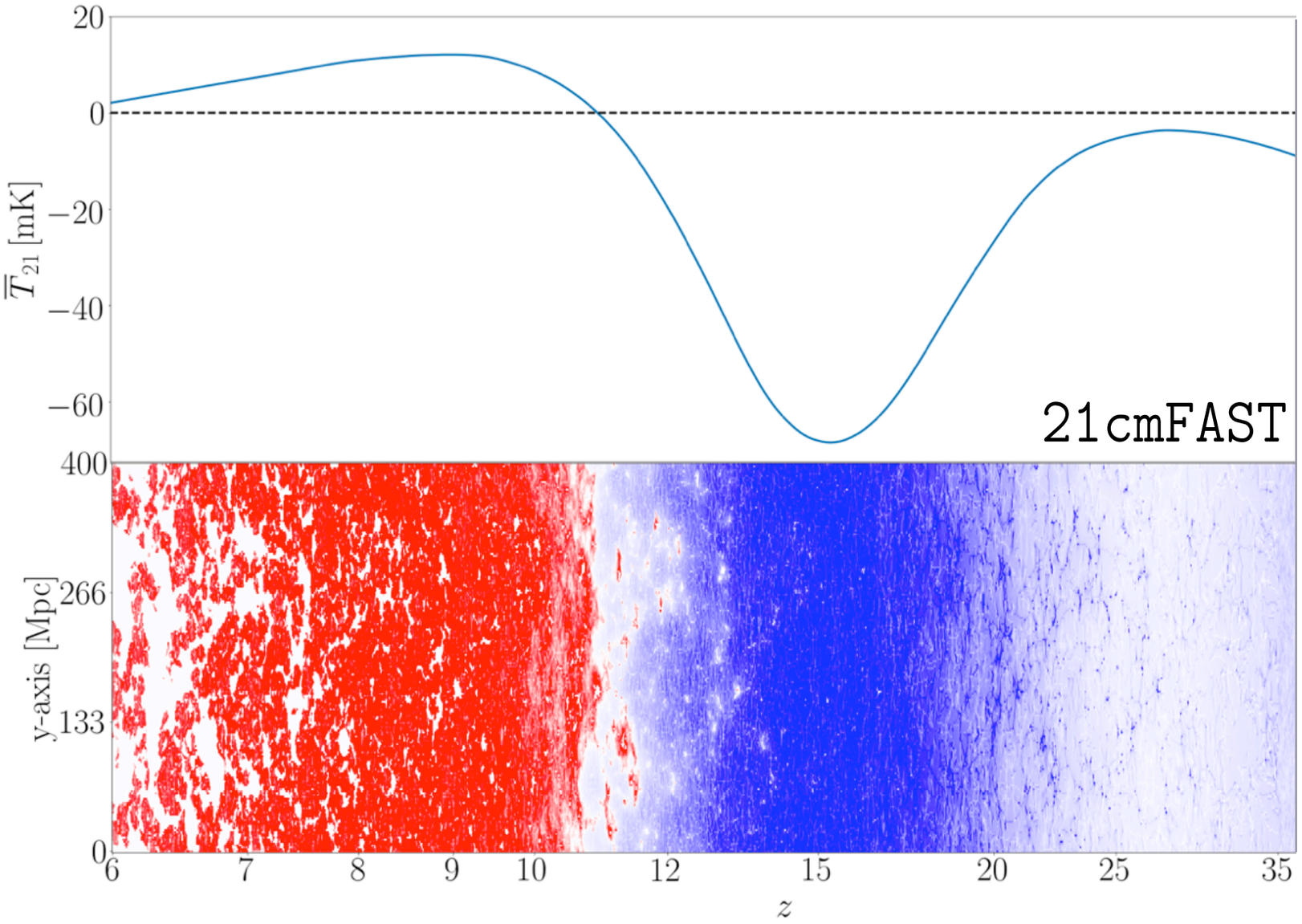
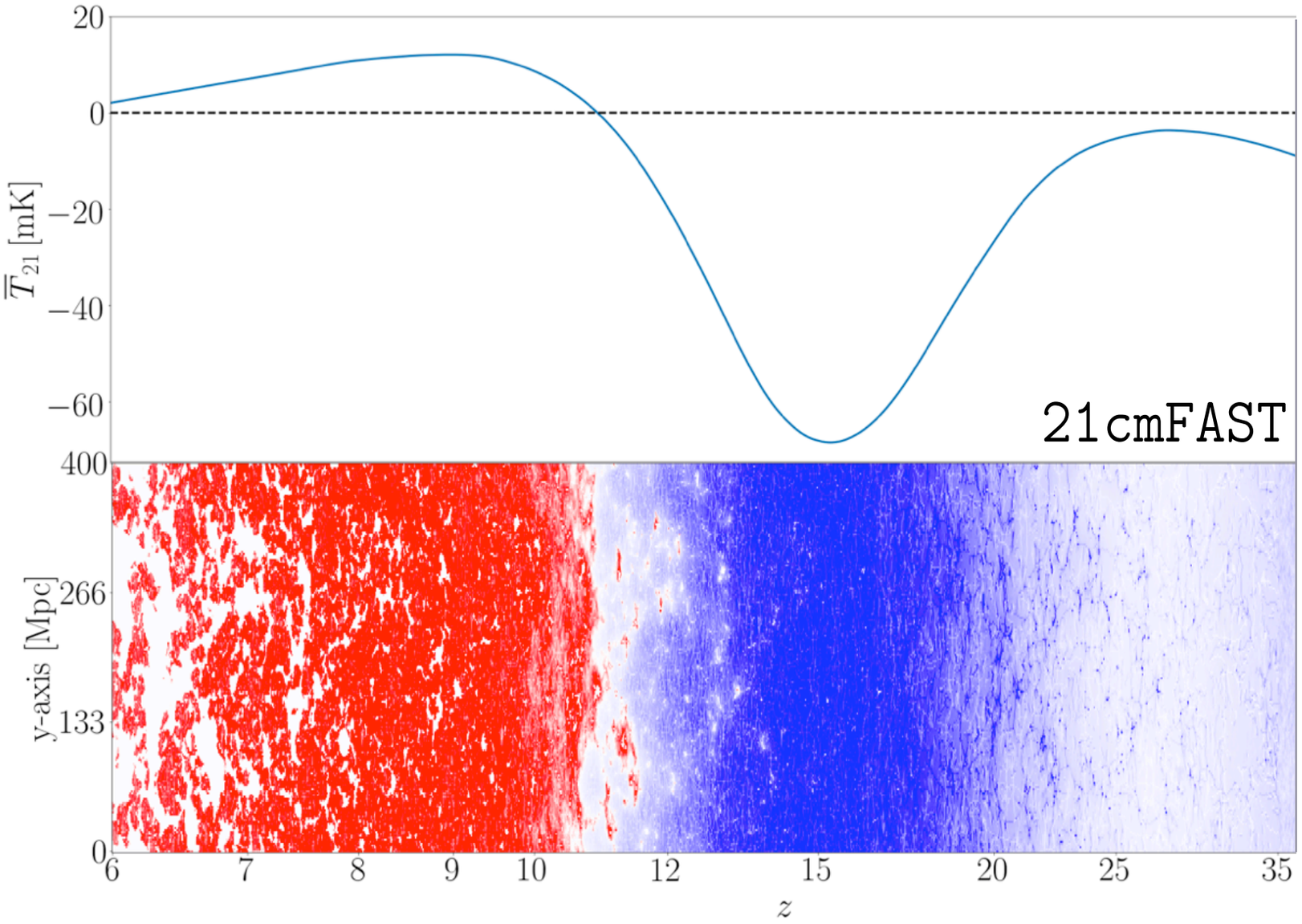


Limitations for new physics:

21cm Simulations: a Code for Cosmology



Limitations for new physics:

- Initialized at $z = 35$

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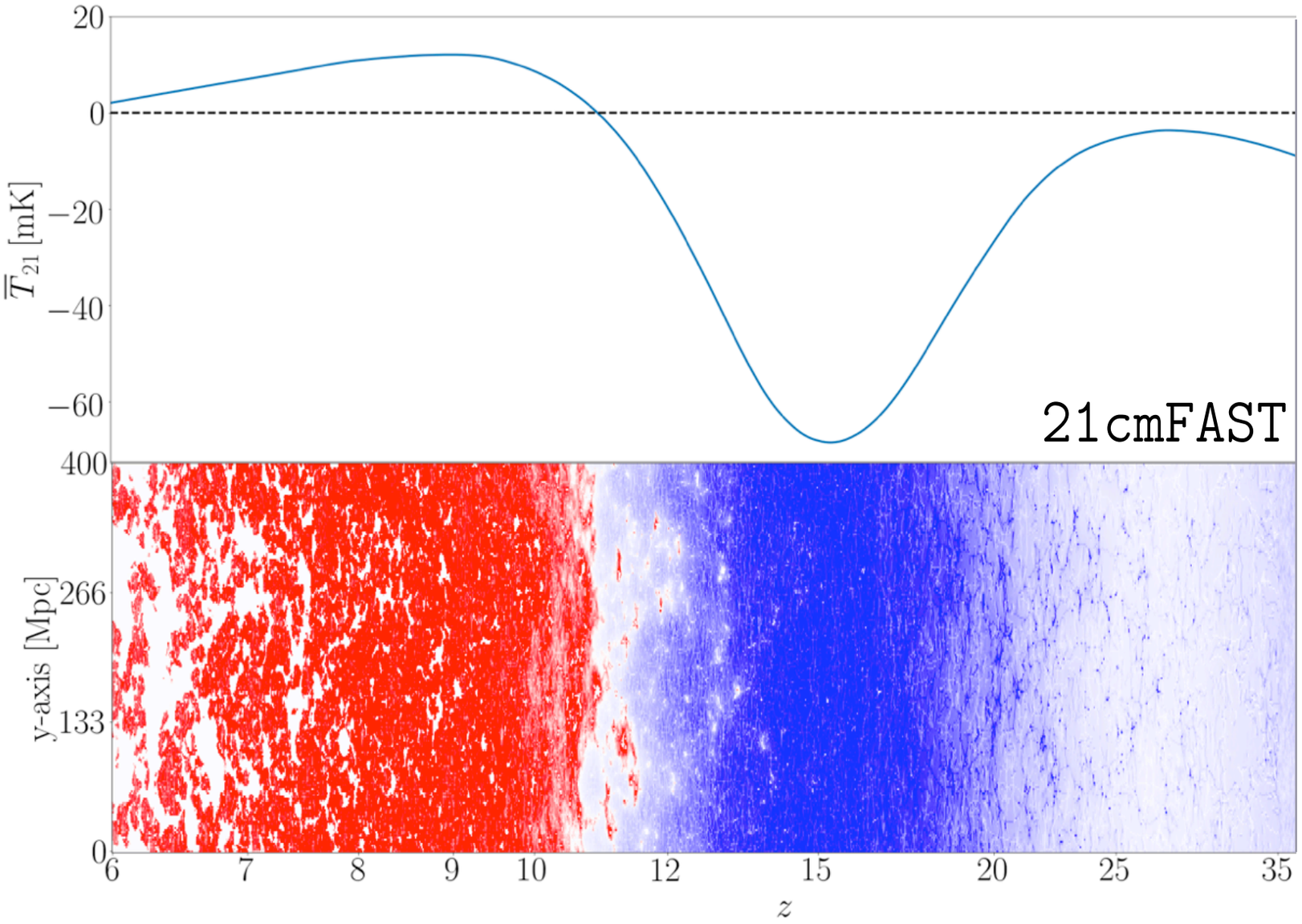

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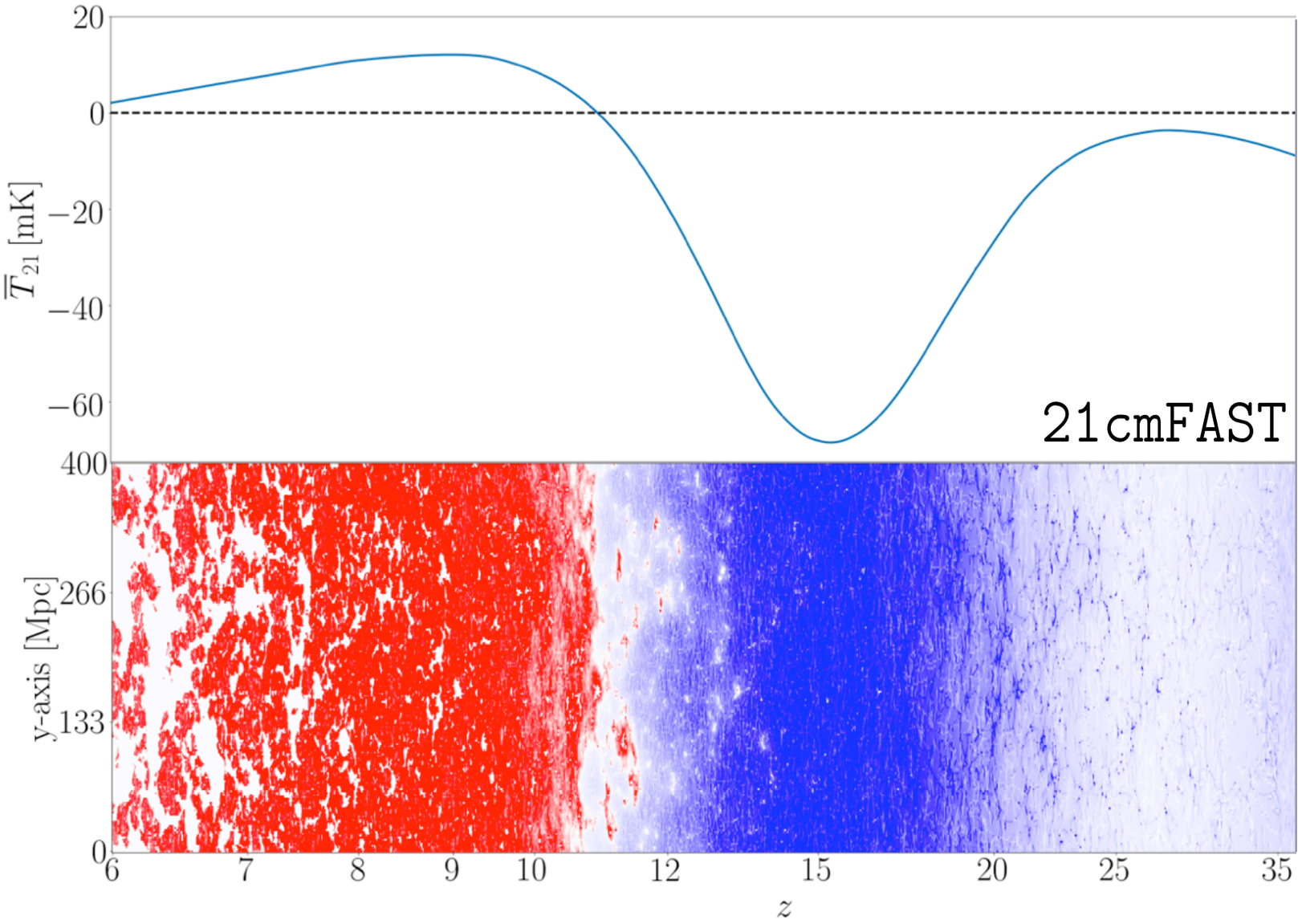

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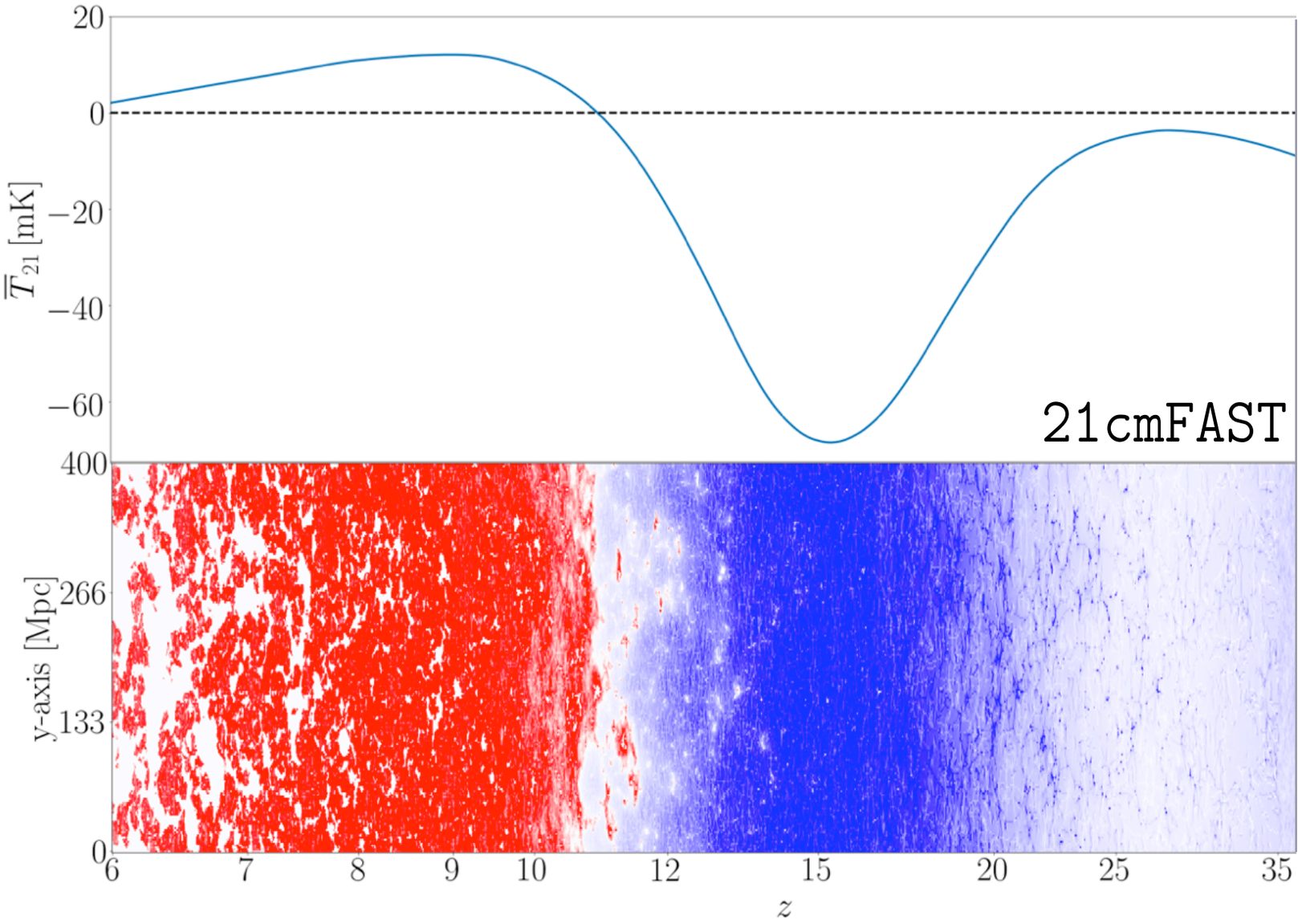

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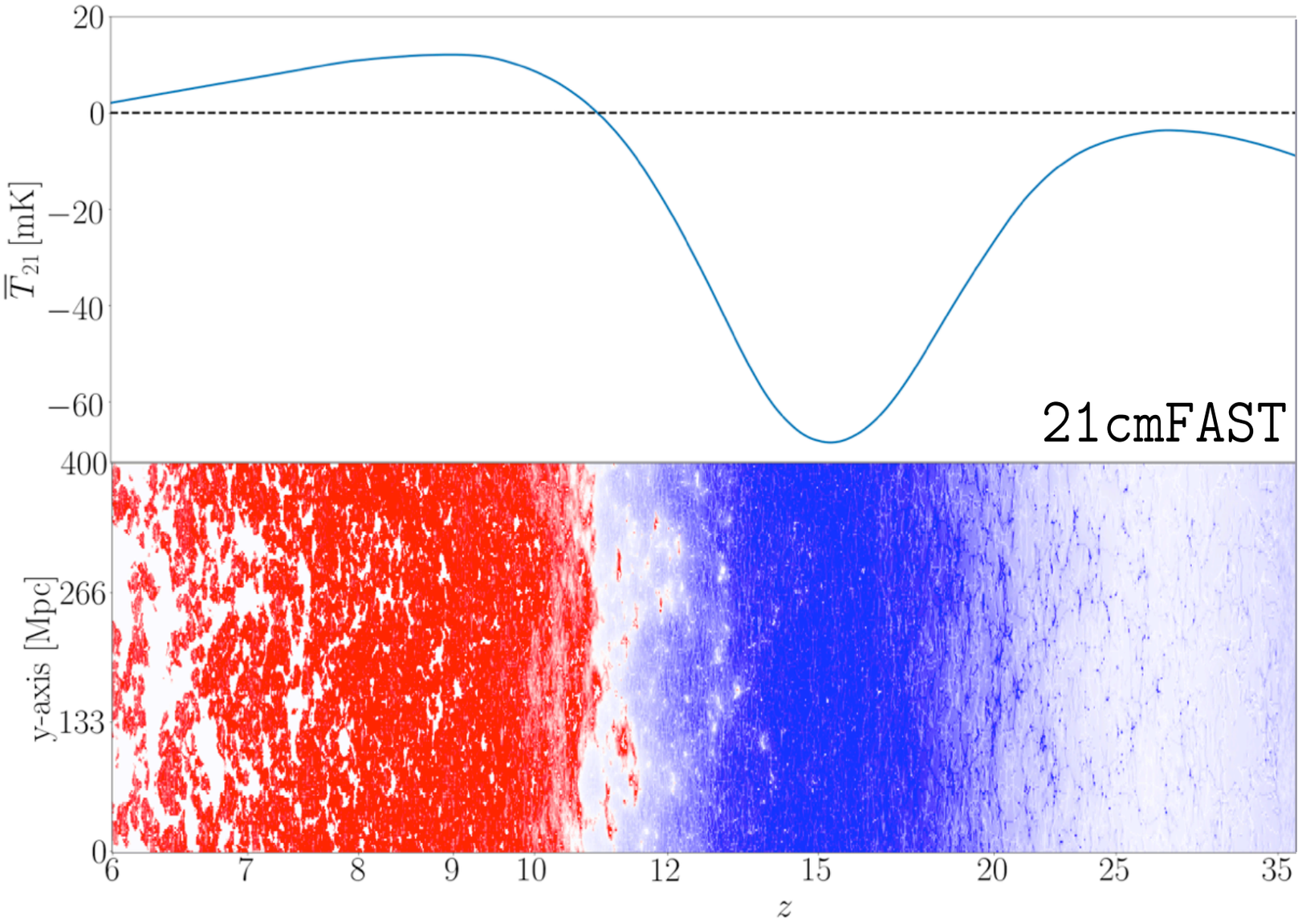

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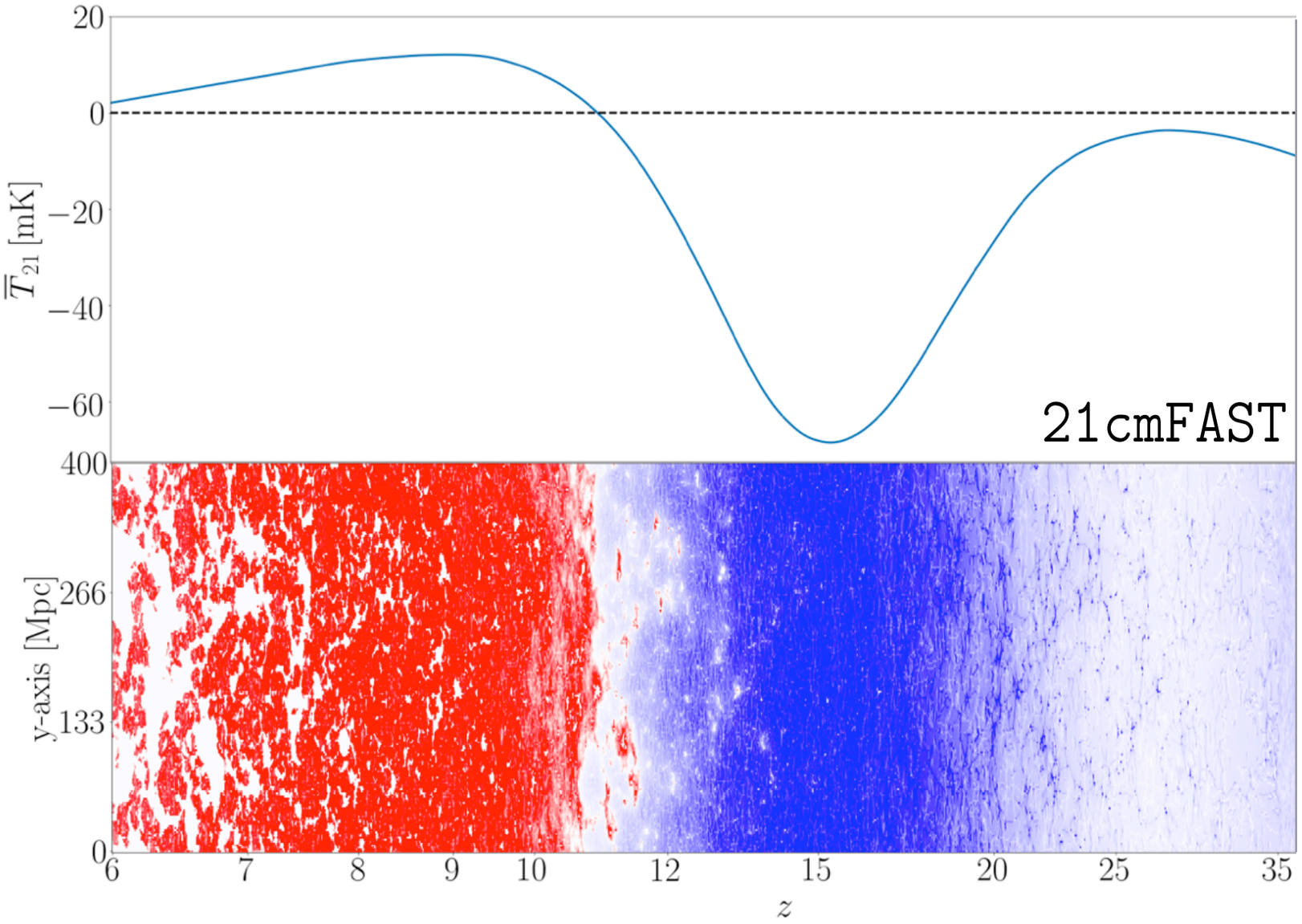

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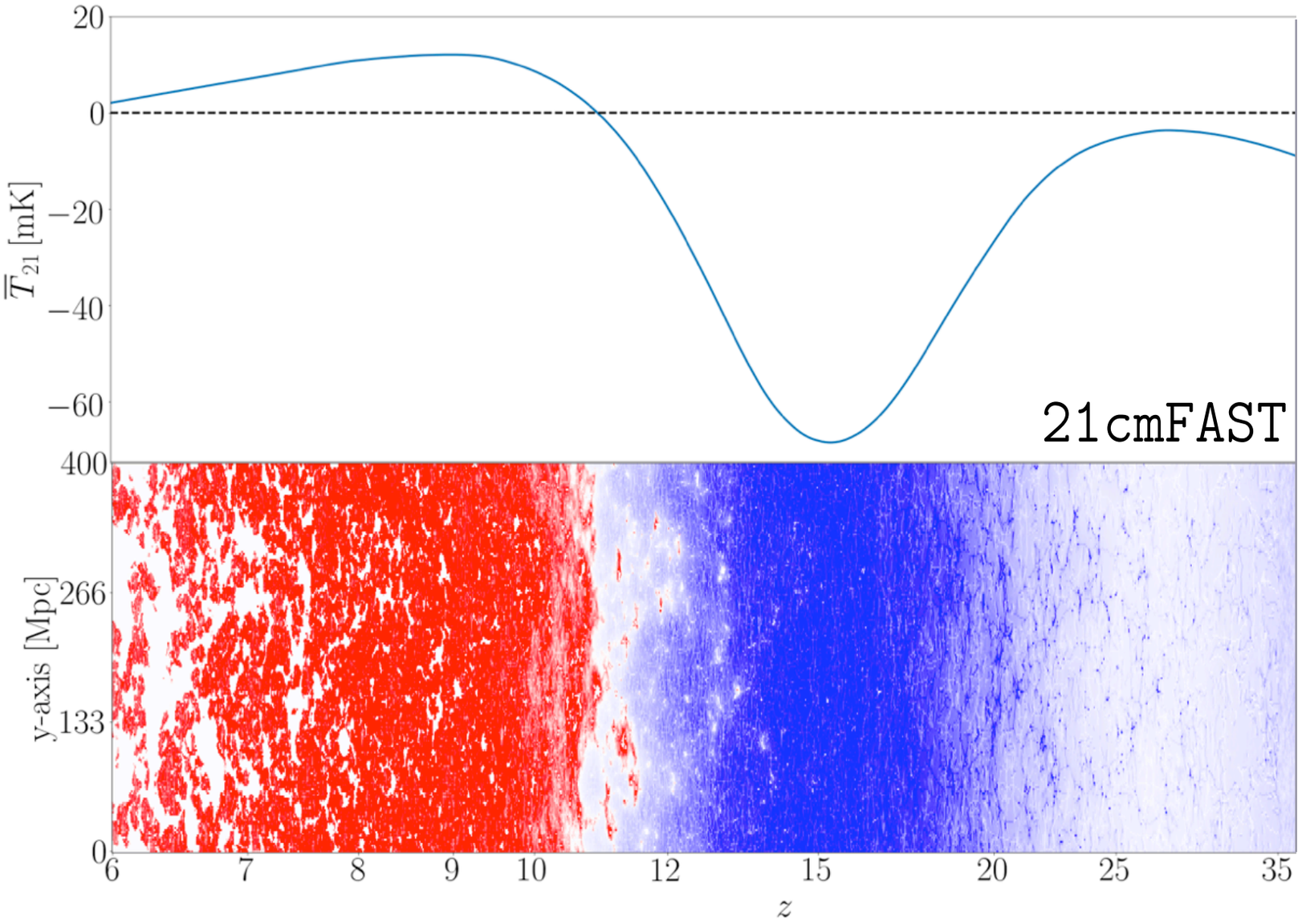

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$$dT_k/dz \propto \left(\Gamma_C/H\right)\left(T_\gamma - T_k\right)$$

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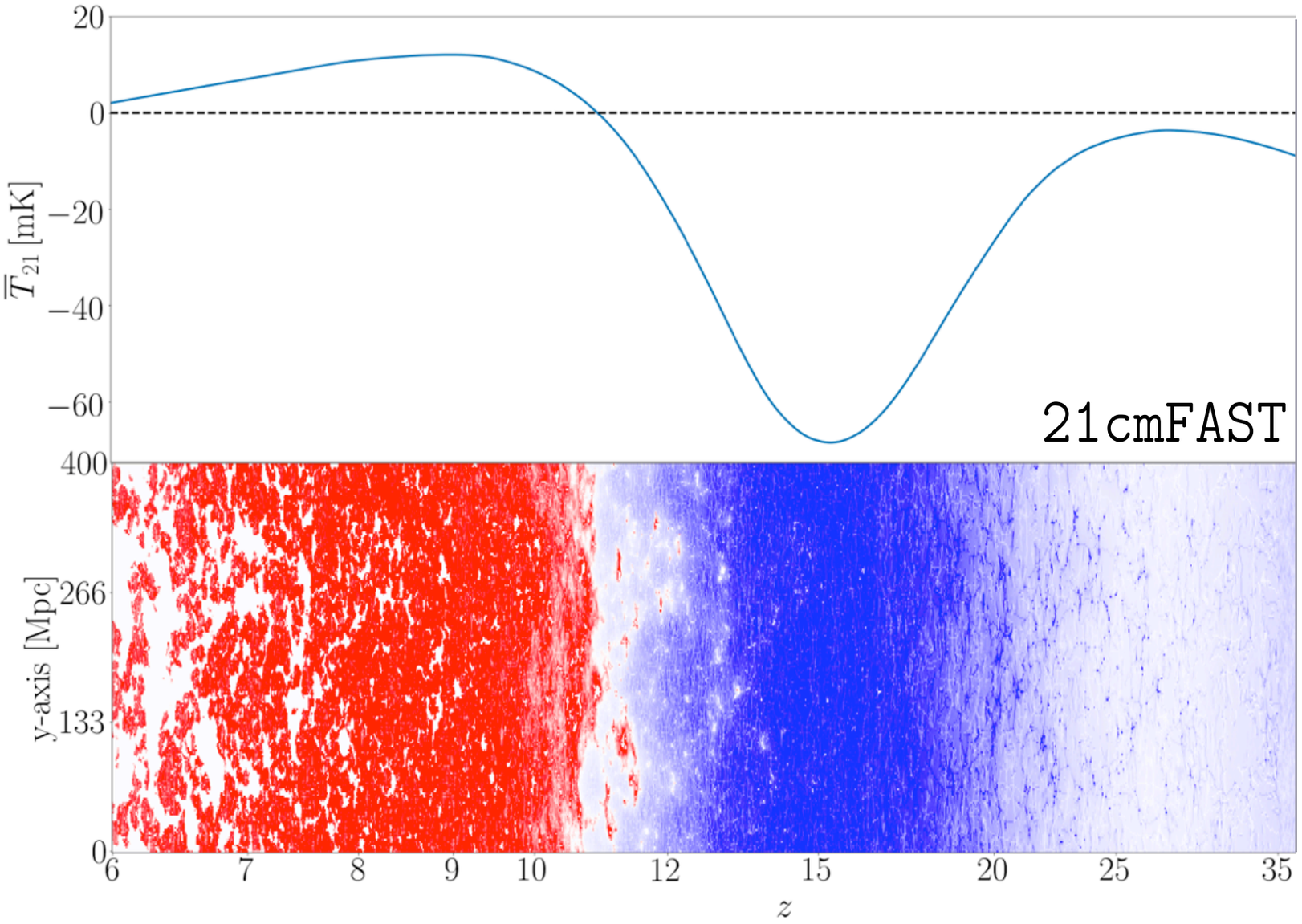

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$$dT_k/dz \propto \underset{\gg 1}{\left(\Gamma_C/H\right)} \underset{\ll 1}{\left(T_\gamma - T_k\right)}$$

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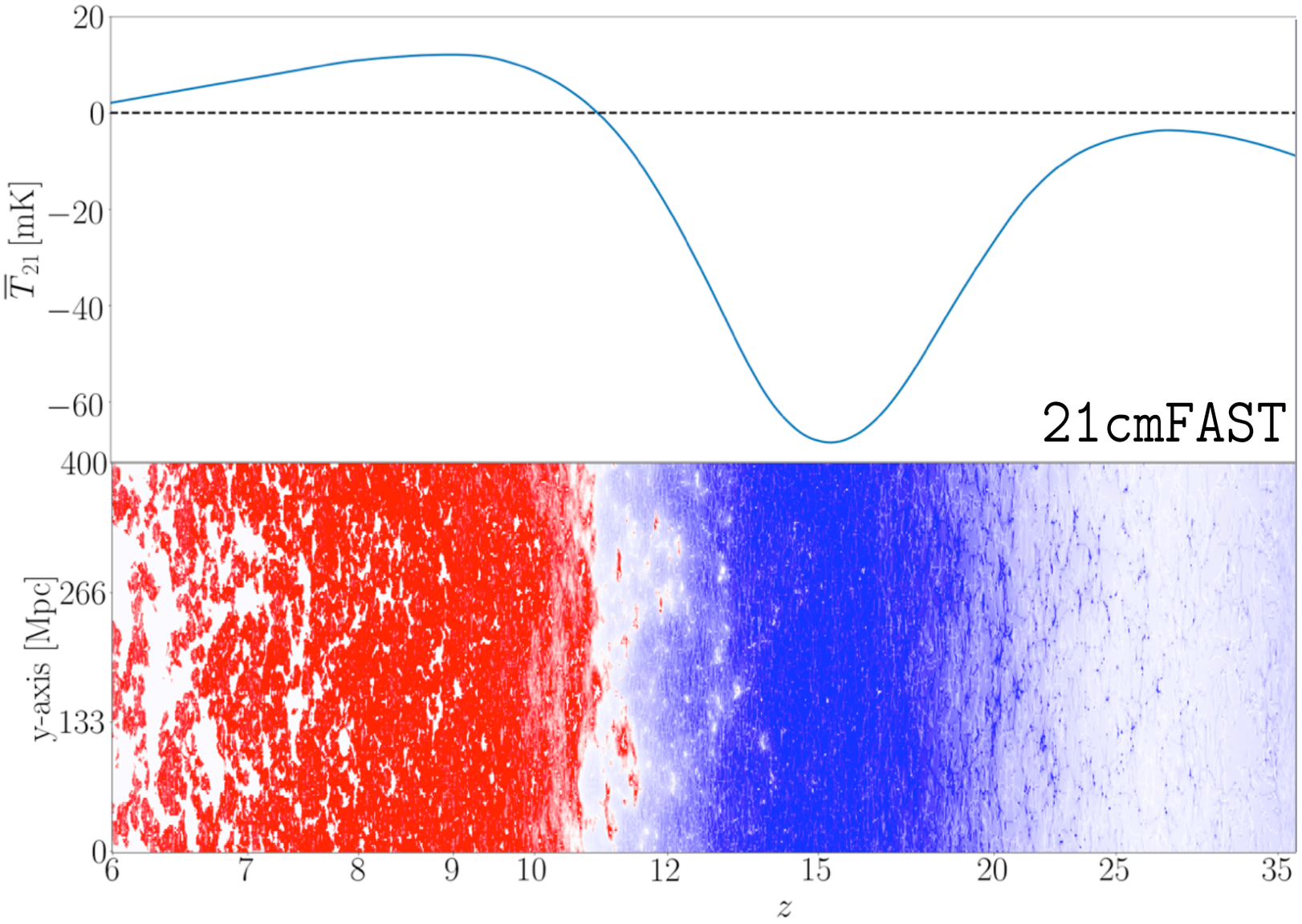

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$\longrightarrow$ requires $\Delta z \ll 1$ to solve

21cm Simulations: a Code for Cosmology

Solution:

- Use initial conditions from a Boltzmann solver

  → Initialize with `CLASS` at $z = 1100$

- Calculate accurate recombination history

  → Incorporate `Hyrec` into the code

- Consistently track $\delta_b\,, \delta_c\,, v_{cb}\,, T_i$ evolution

  → Inhomogeneous boxes at $z = 35$

- Fold-in cosmic microwave background

  → Combined CMB+21cm constraints

- Astrophysical vs. cosmological effects

  → Explore parameter degeneracies

- Slow? (need $\Delta z \ll 1$ at Compton tight coupling)

  → Perturb in $\epsilon_{\chi b} = H/\Gamma_C$, and solve for $\epsilon_{\gamma b}, \Delta T_{\gamma b}, \bar{T}_{\gamma b}$

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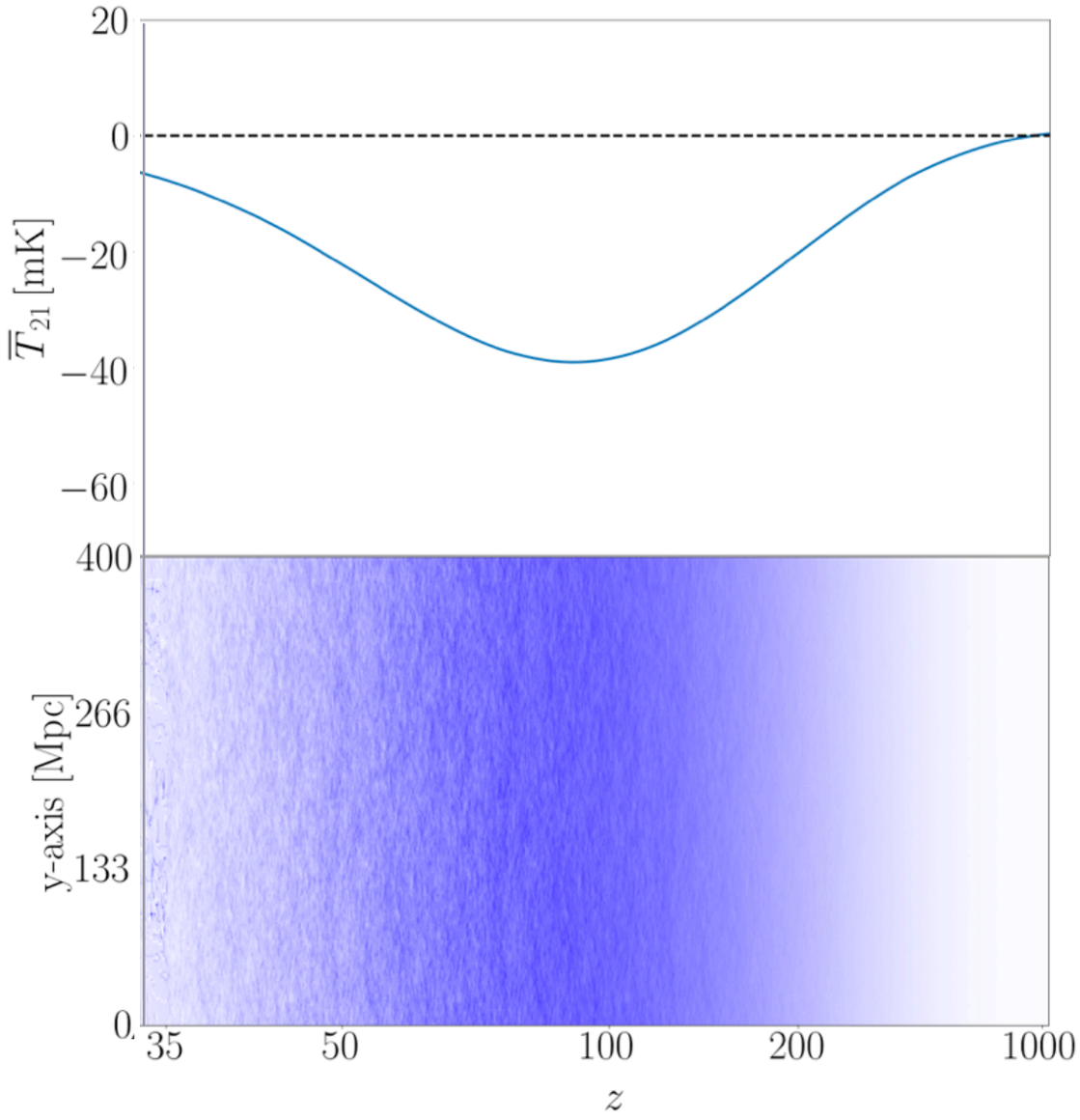

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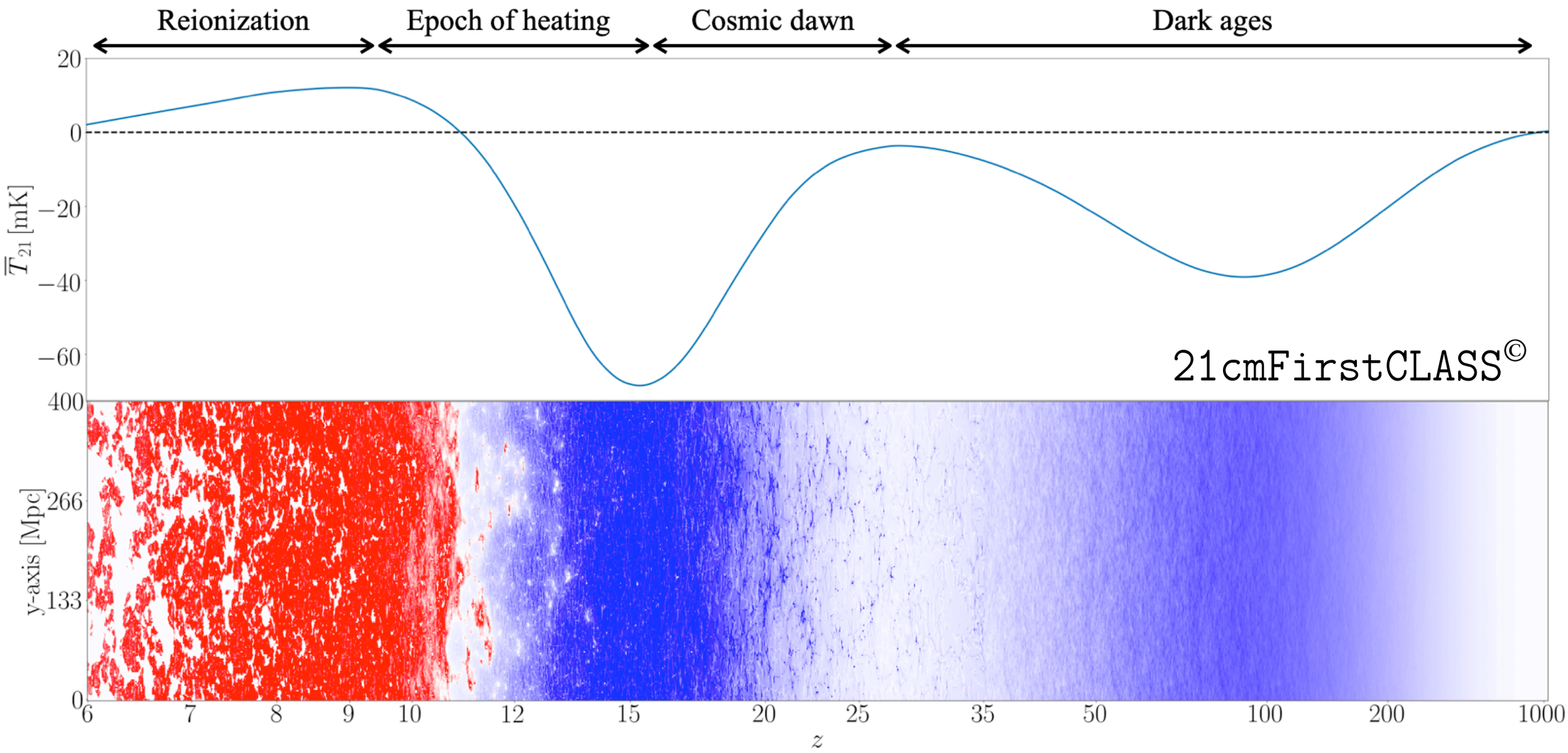

21cmFirstCLASS I. Cosmological tool for ΛCDM and beyond

Jordan Flitter[1,*] and Ely D. Kovetz[1]

[1] *Physics Department, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel*

21cmFirstCLASS II. Early linear fluctuations of the 21cm signal

Jordan Flitter[1,*] and Ely D. Kovetz[1]

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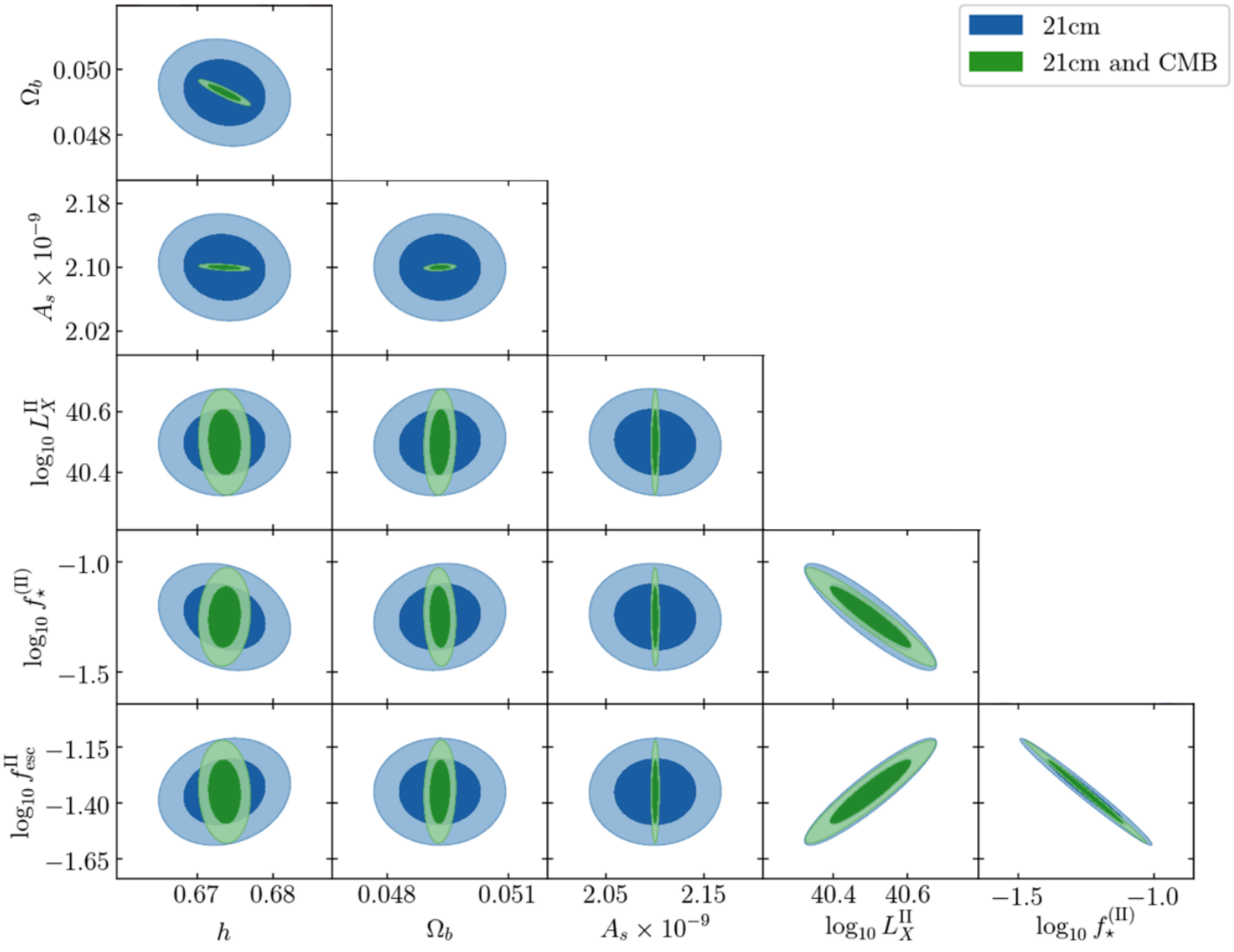
Coming to a GitHub near you…!

21cm Simulations: Using `21cmFirstCLASS`



Flitter and Kovetz, arXiv:2309.03942

21cm Data Analysis: New End-to-End ML Pipeline

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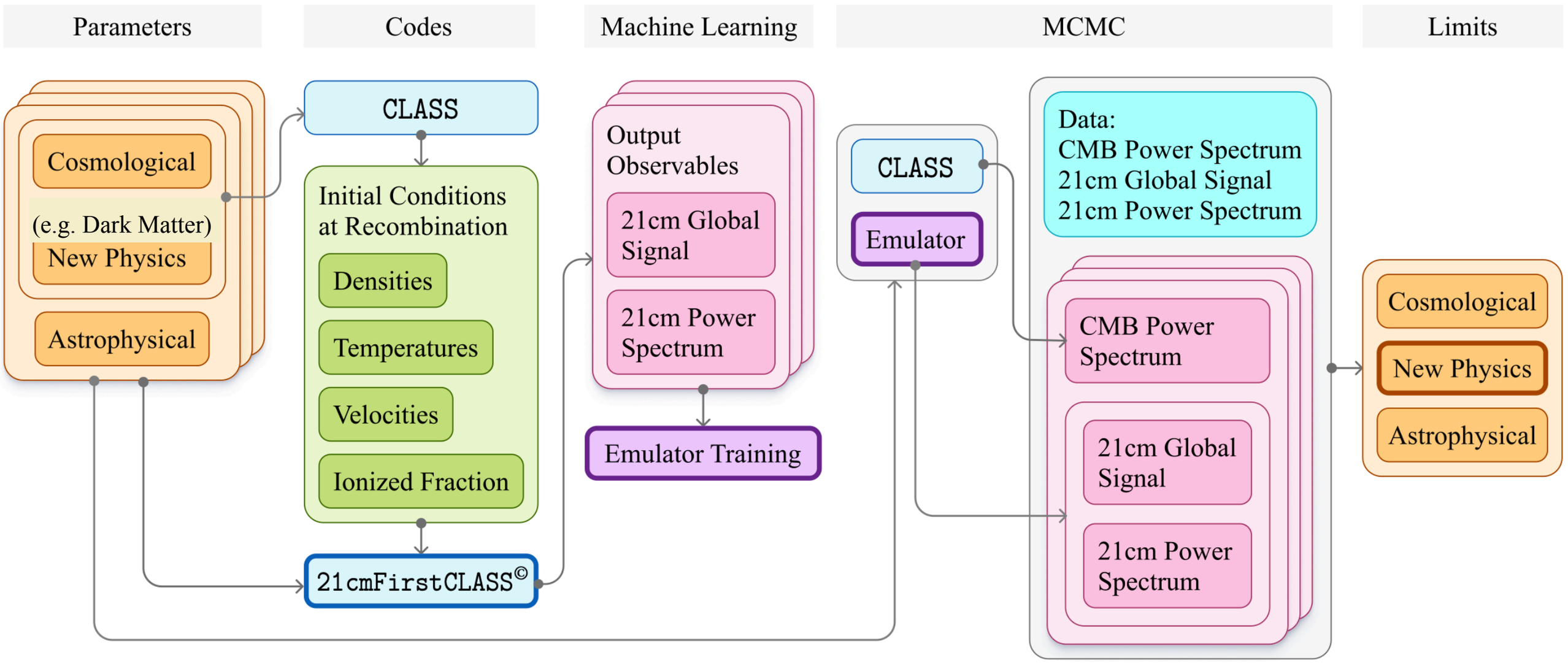

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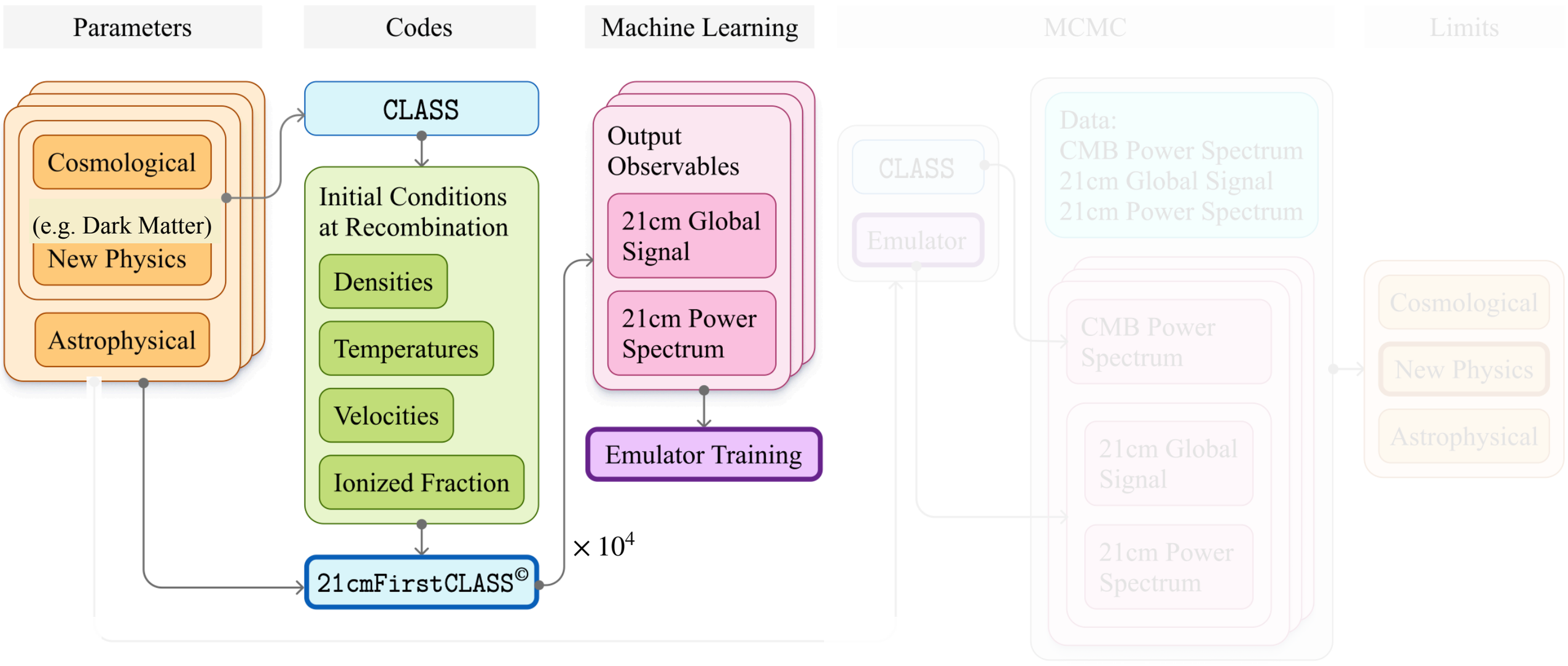

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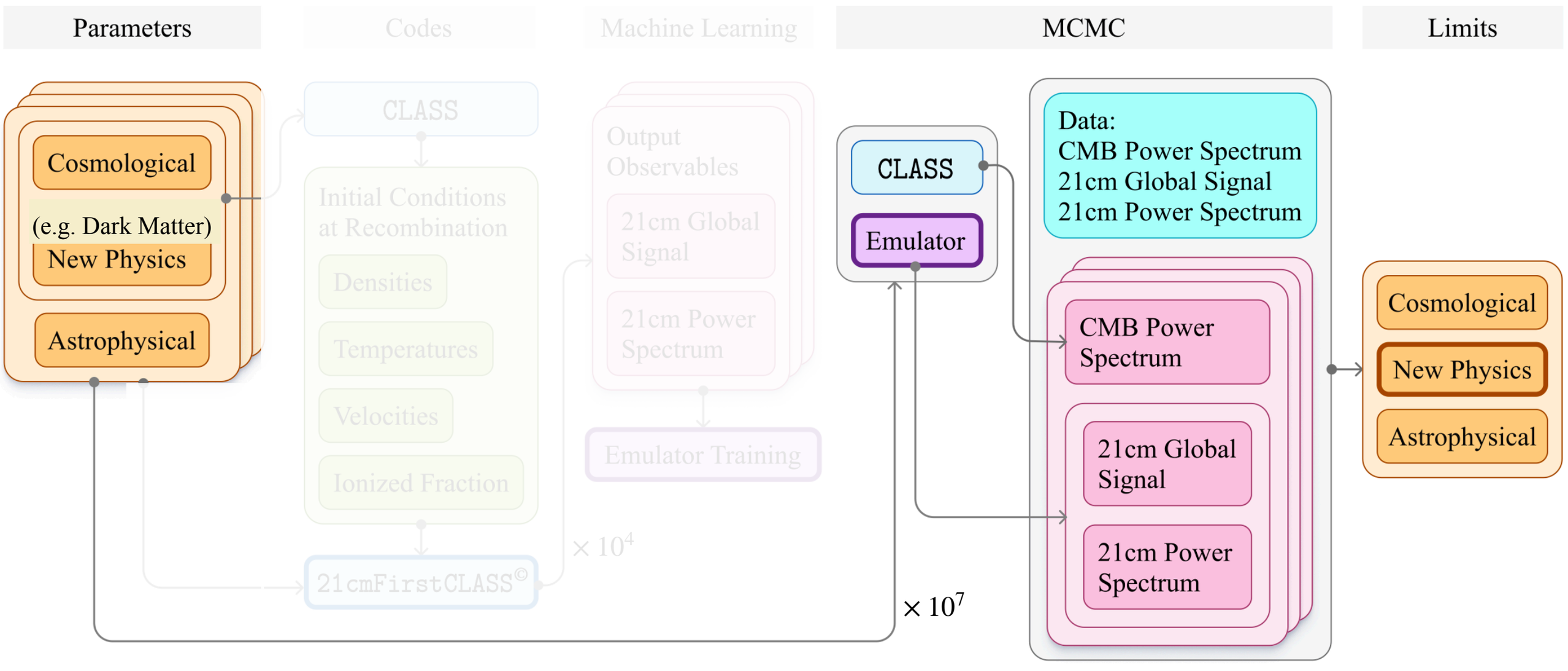
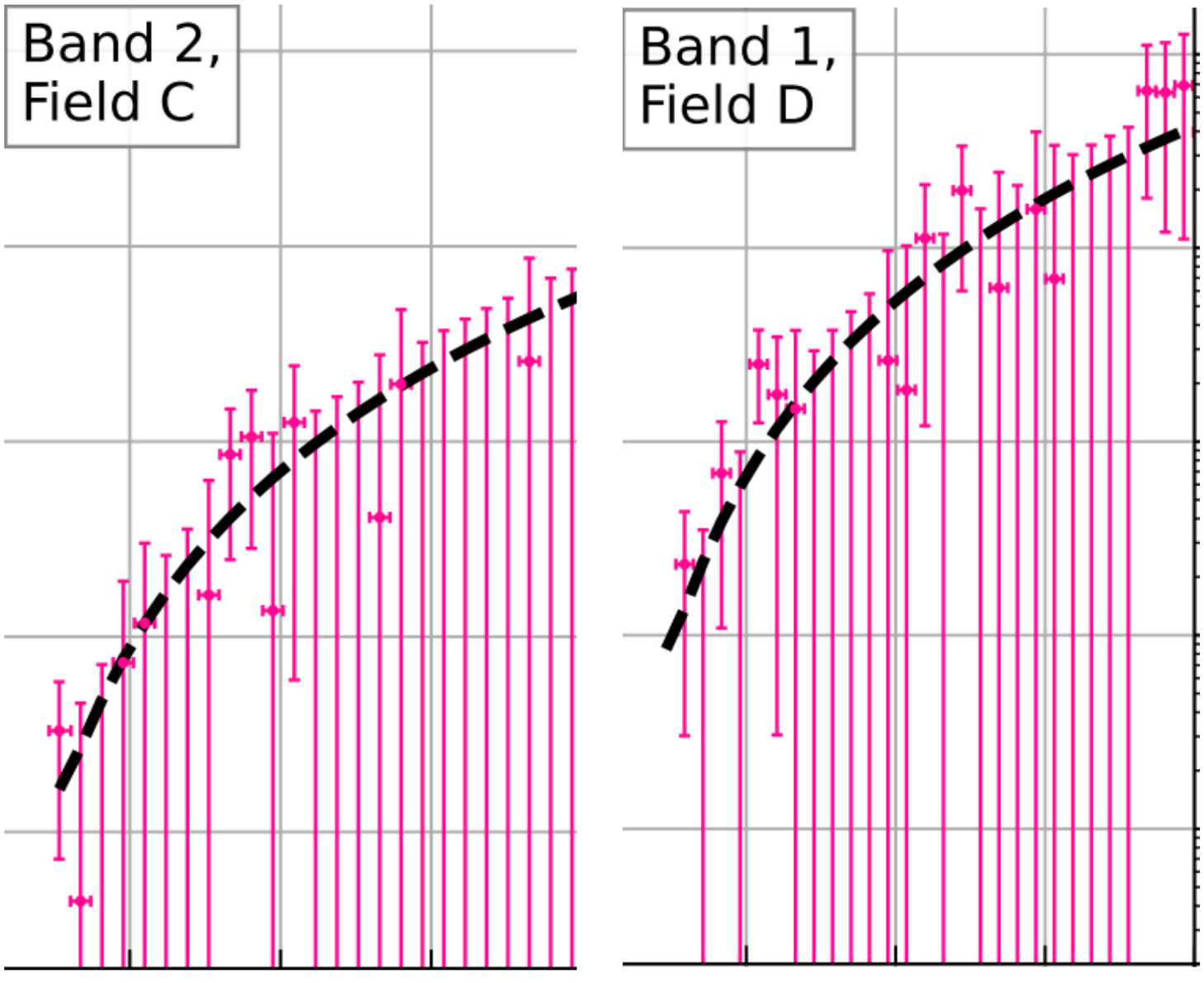


21cm Data Analysis: Five Sets of Likelihoods

- $\Delta^2_{21}(\mathbf{k})$ at $z = 7.9$
- $\Delta^2_{21}(\mathbf{k})$ at $z = 10.4$
- $\tau_e = 0.0569^{+0.0081}_{-0.0066}$
- $x_{HI} < 0.06 + 0.05(1\sigma)$
- HST UV LFs: $z = 6,7,8,10$

The HERA Collaboration (2022)



21cm Data Analysis: Emulator Architecture

Four separate emulators:

- $\Delta^2_{21}(\mathbf{k})$ at $z = 7.9$
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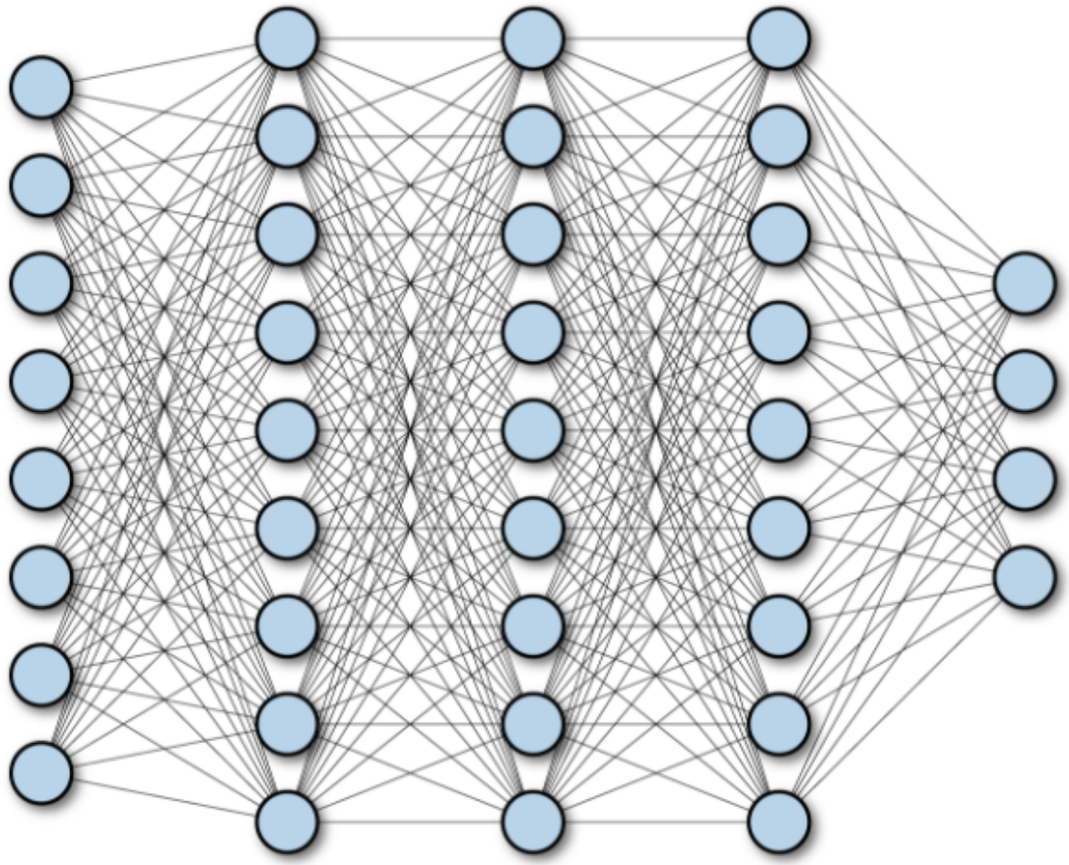
- CMB optical depth τ_e
- x_{HI} at $z = 5.9$



All NNs have fully connected layers

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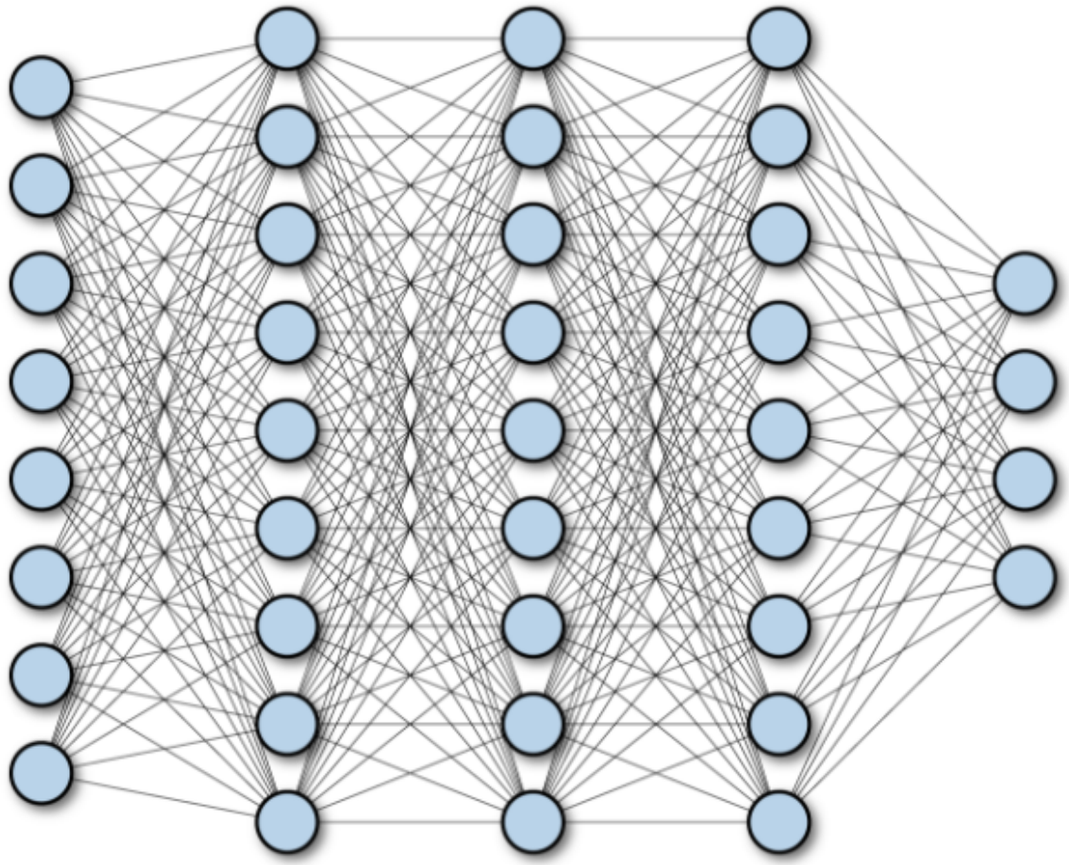

All NNs have fully connected layers

Input parameters:

21cm Data Analysis: Emulator Architecture

Four separate emulators:

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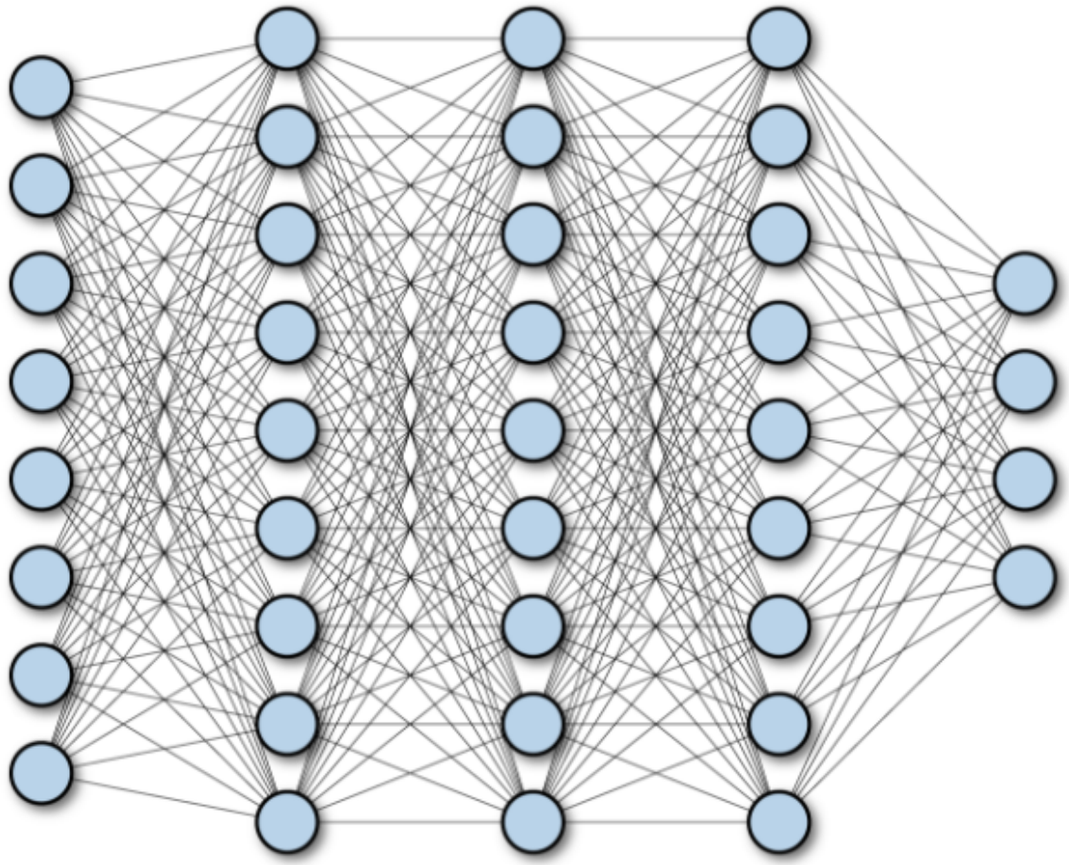

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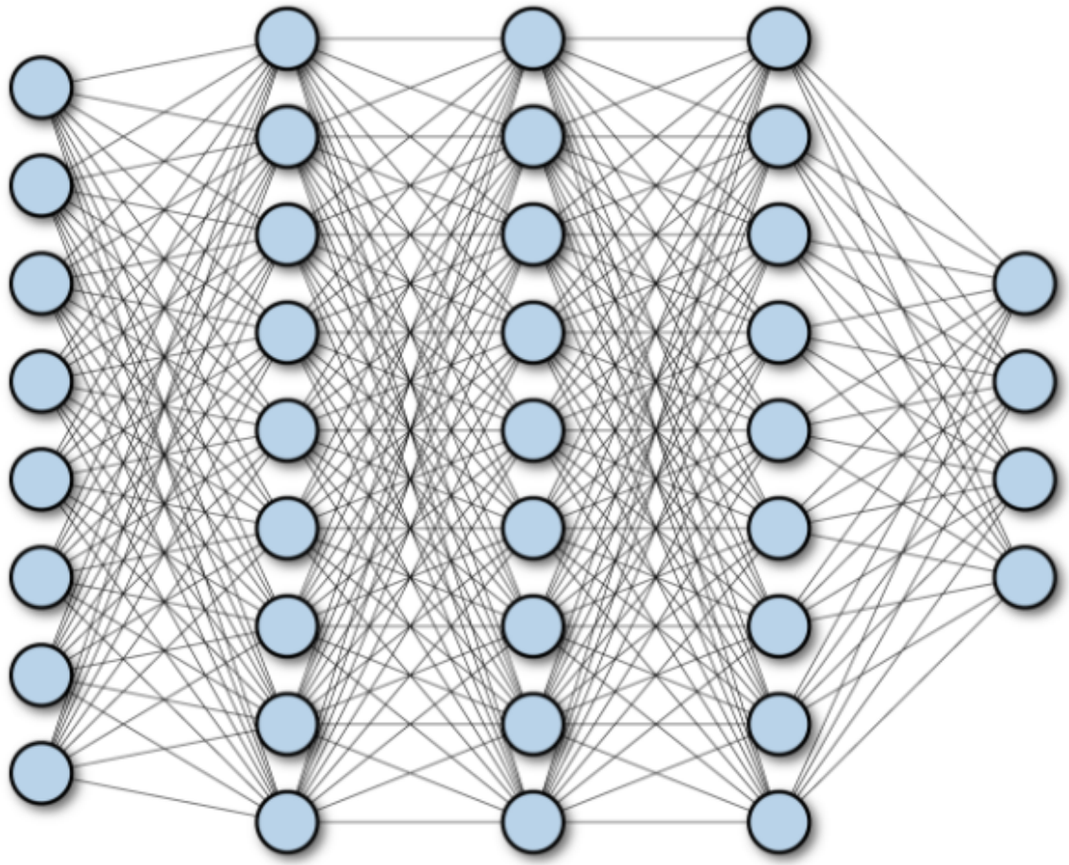

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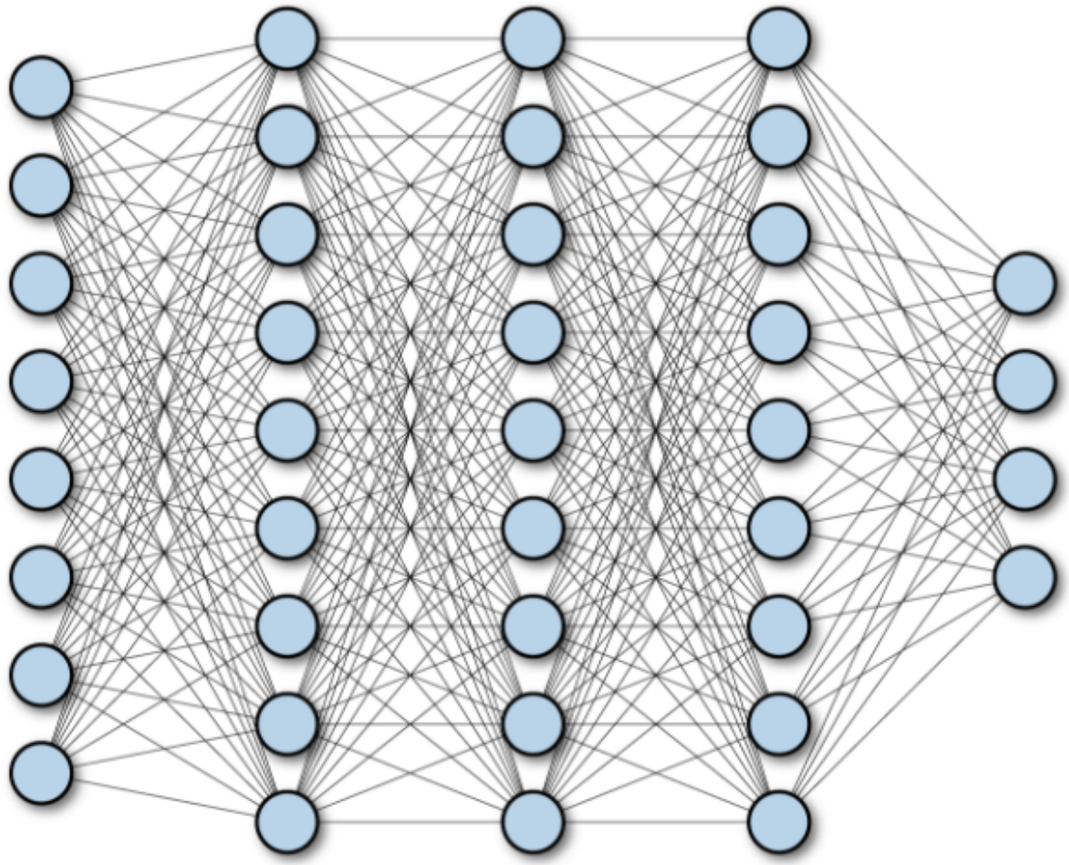

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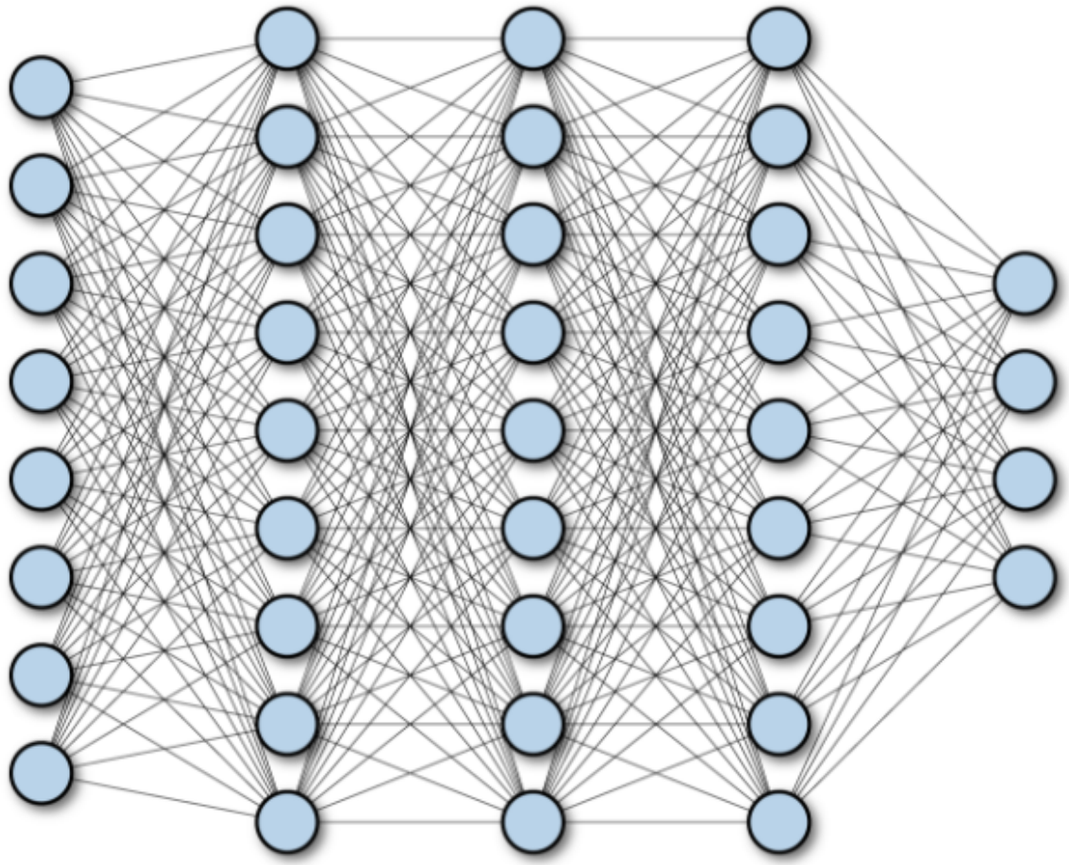

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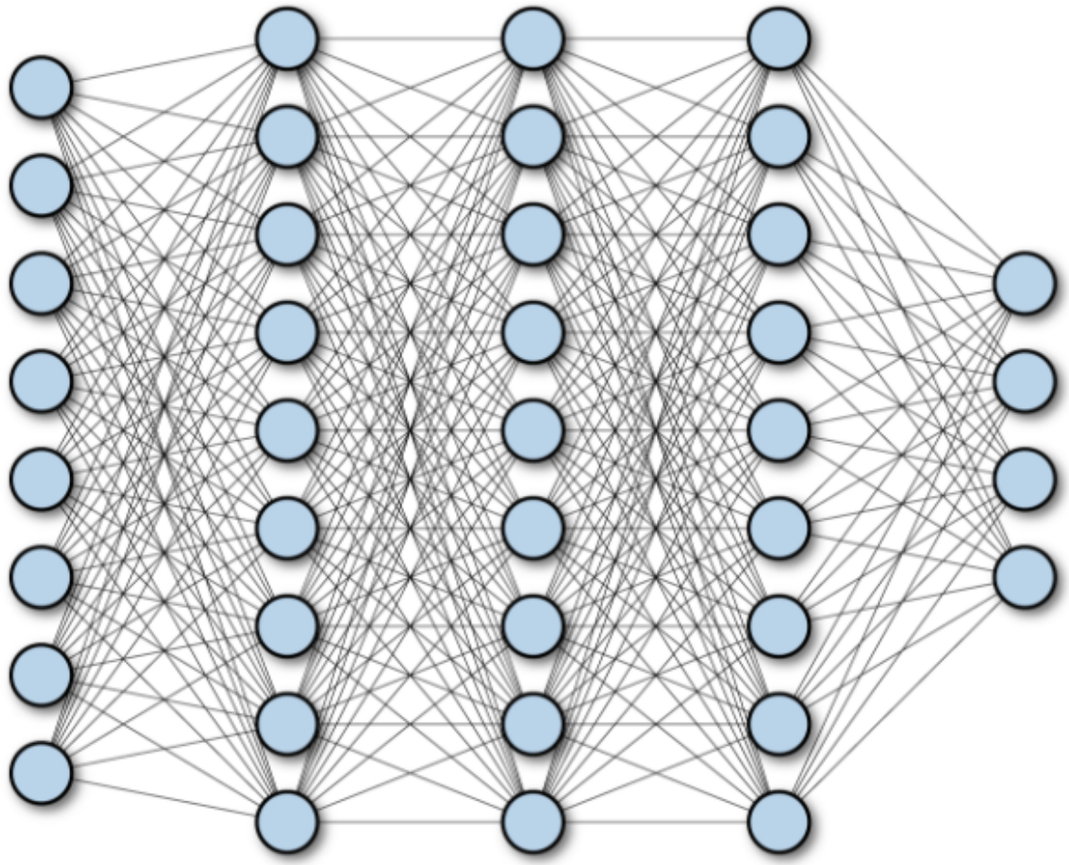

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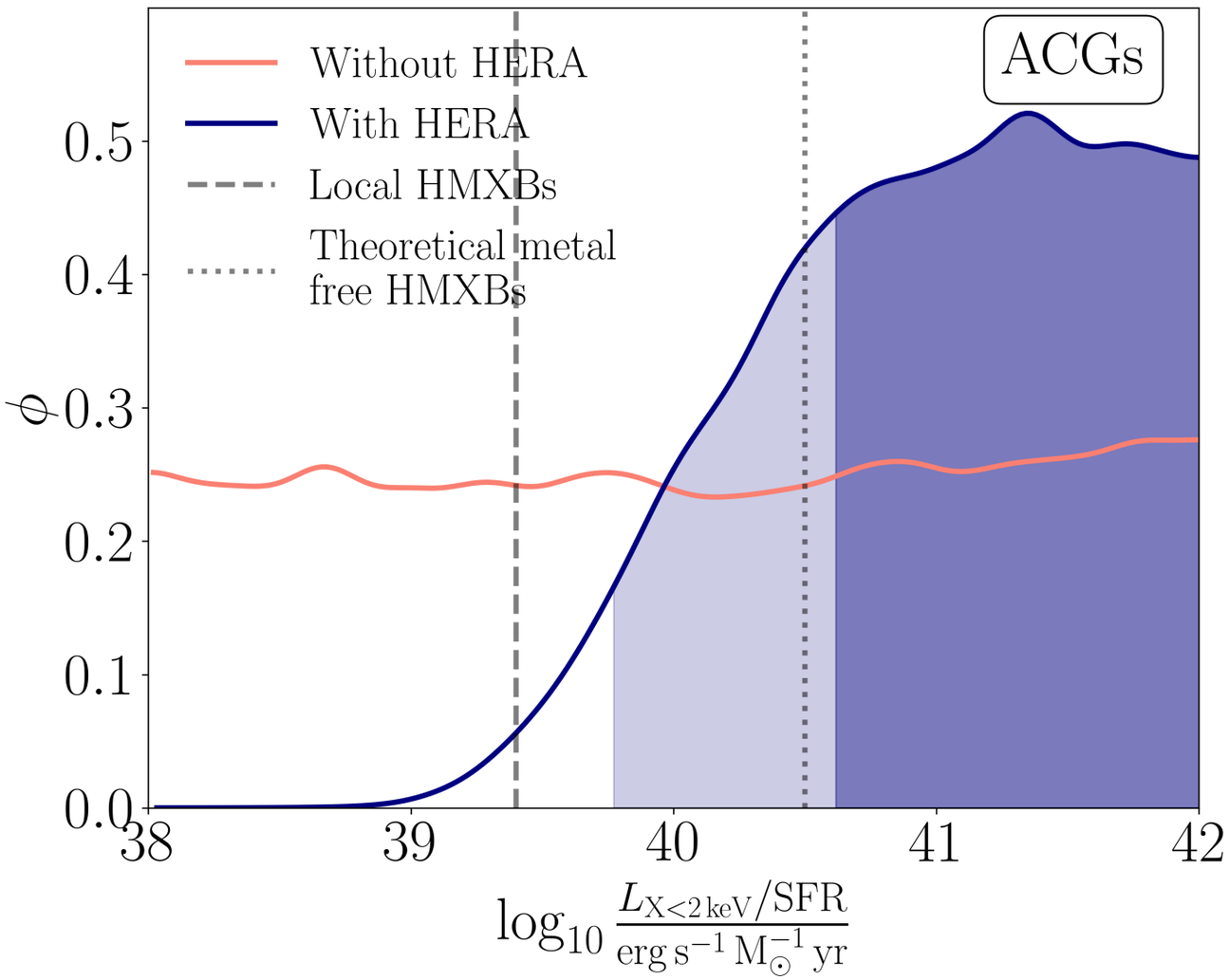
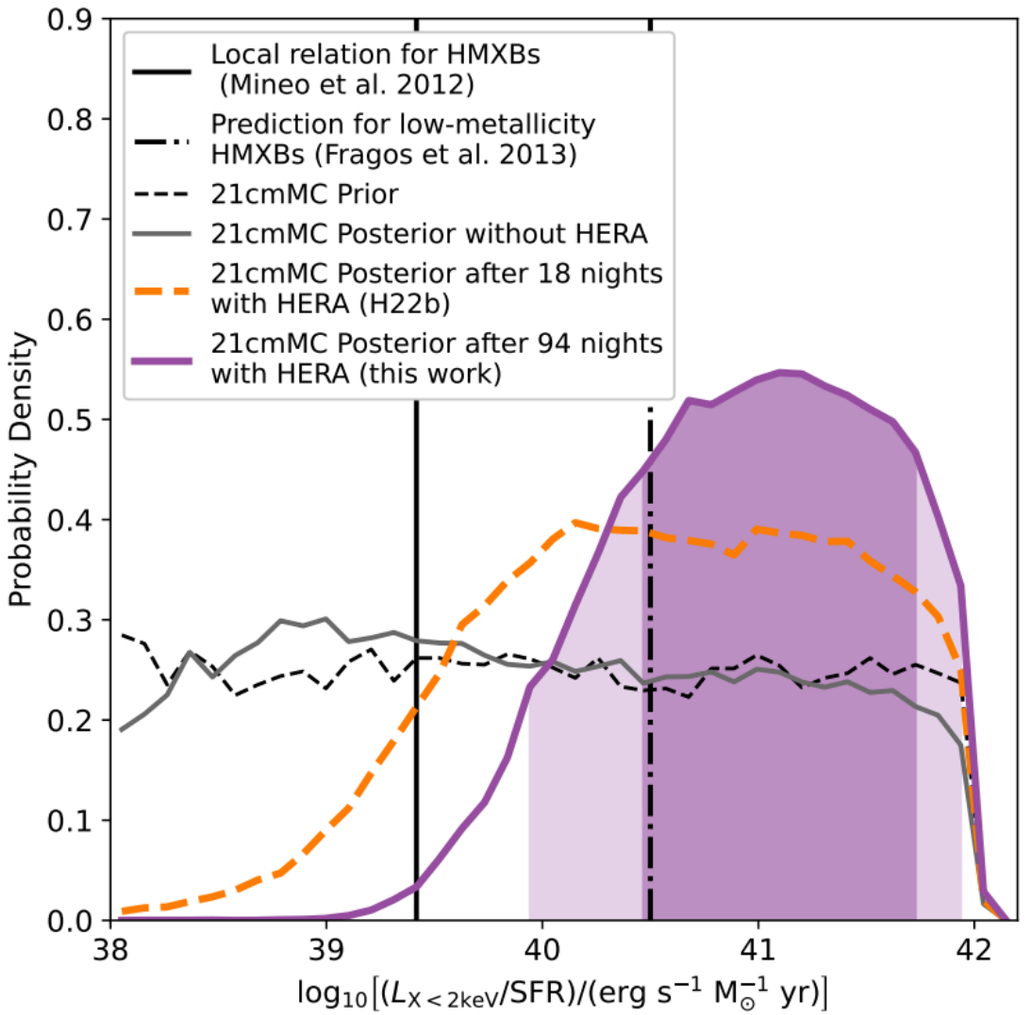
21cm Data Analysis: Reproducing HERA Results

Assuming only atomic-cooling halos (hosting popII stars):





HERA Phase-I results

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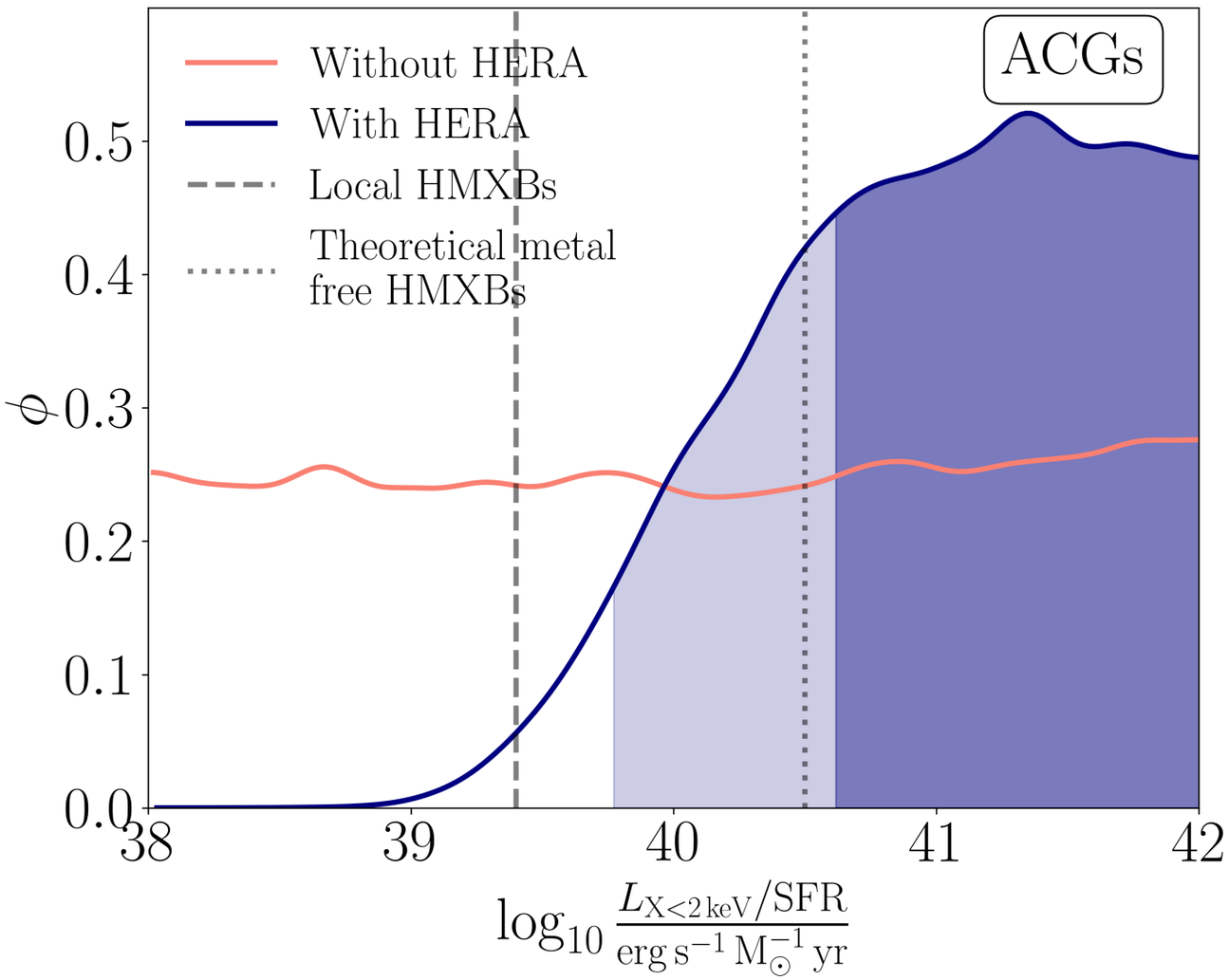
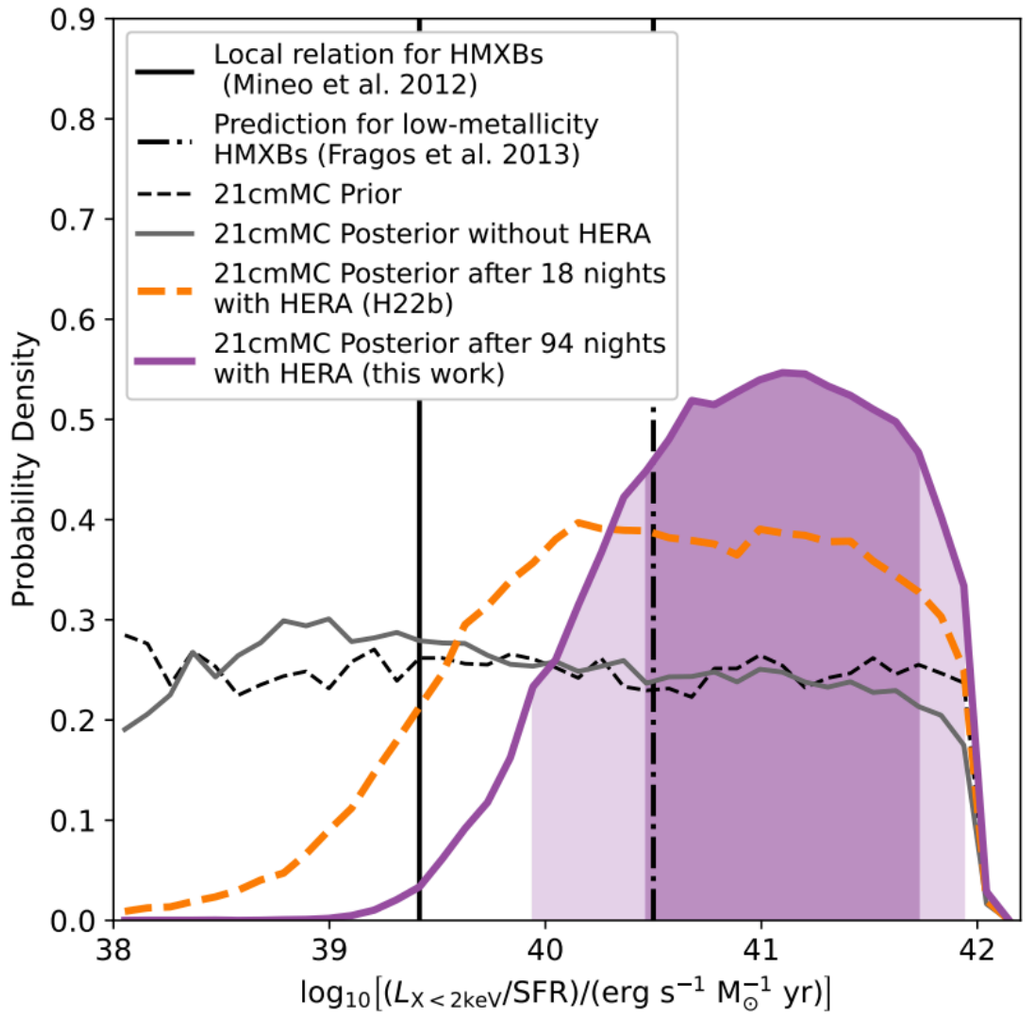


Lazare, Sarkar and Kovetz, PRD 2024



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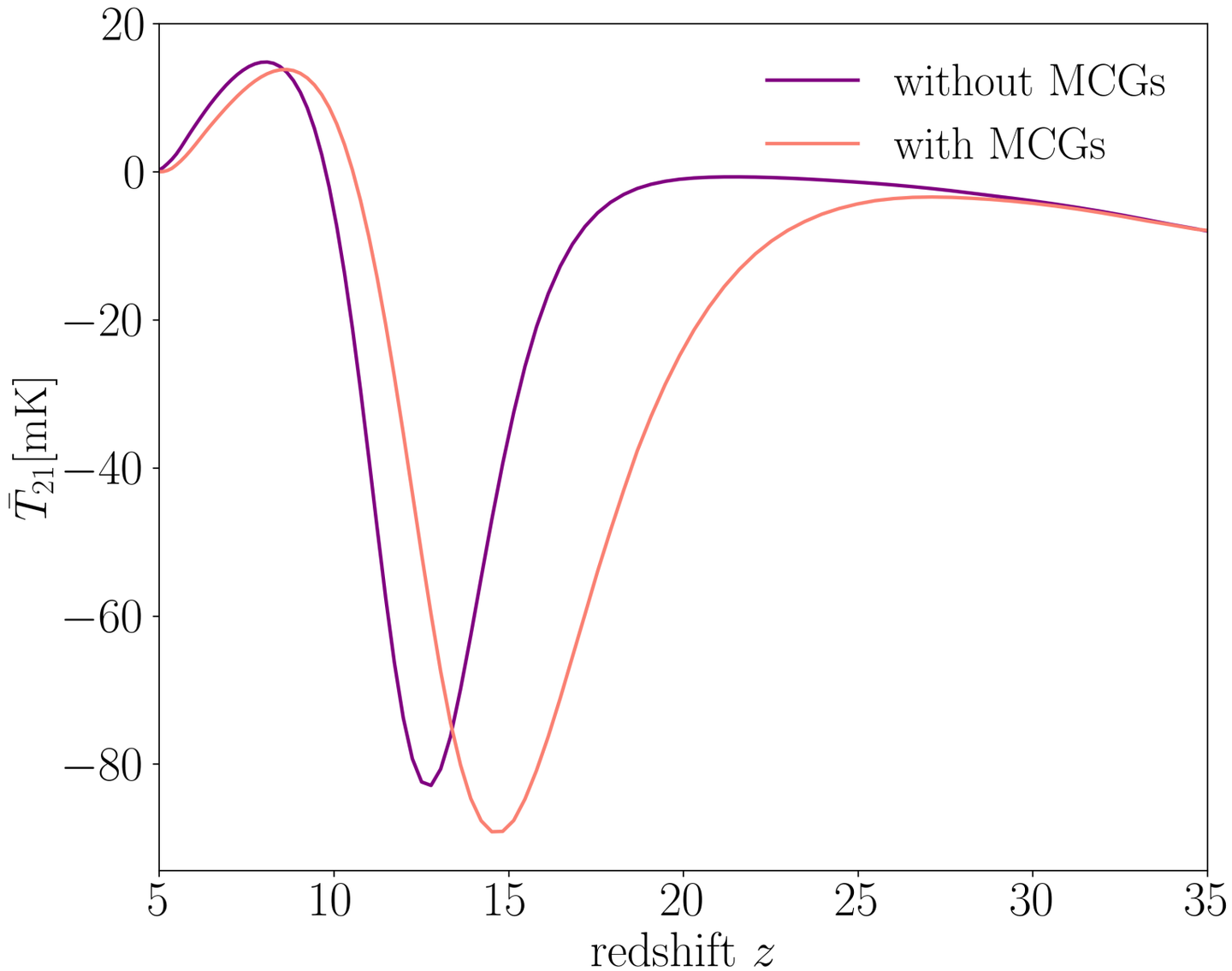

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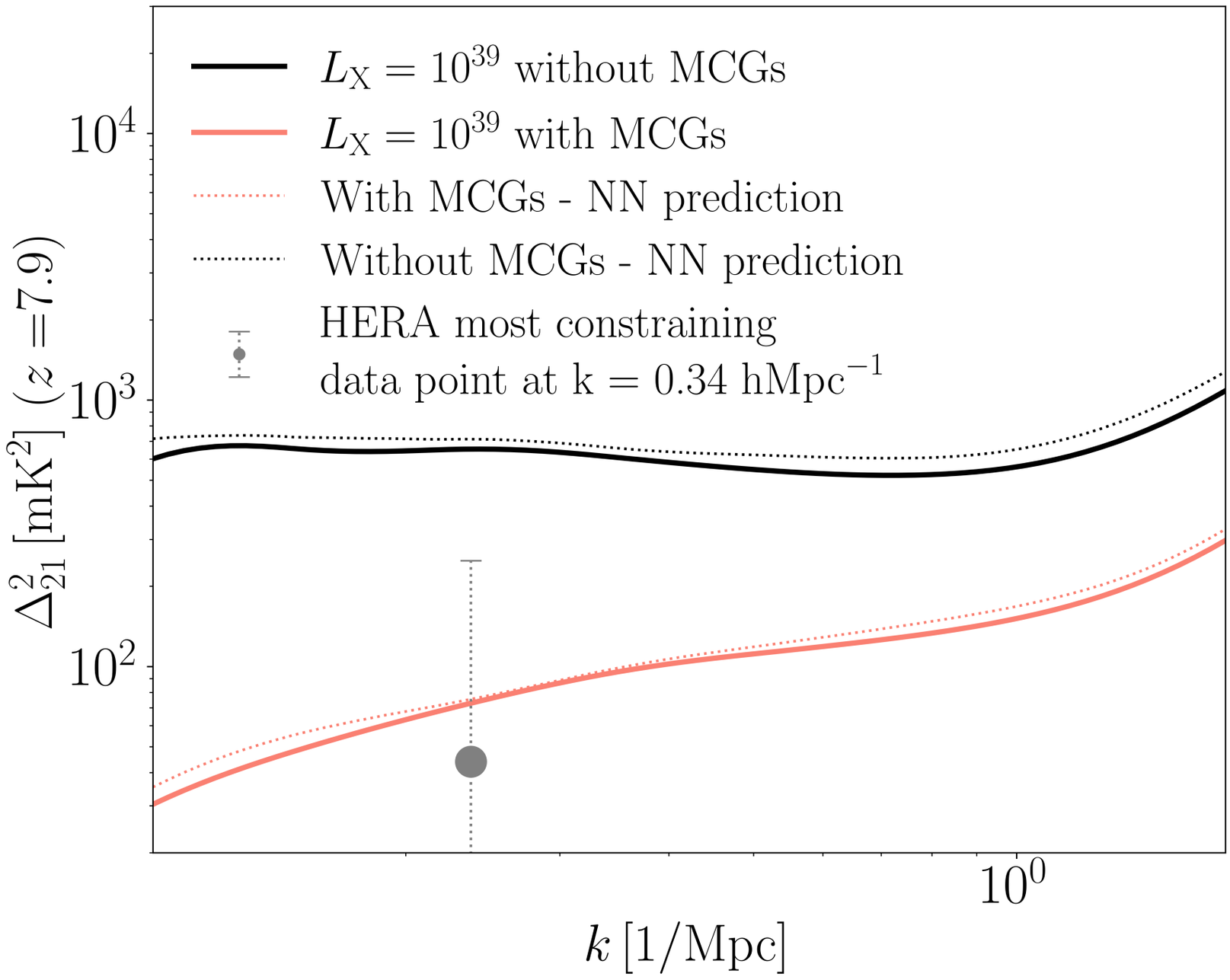

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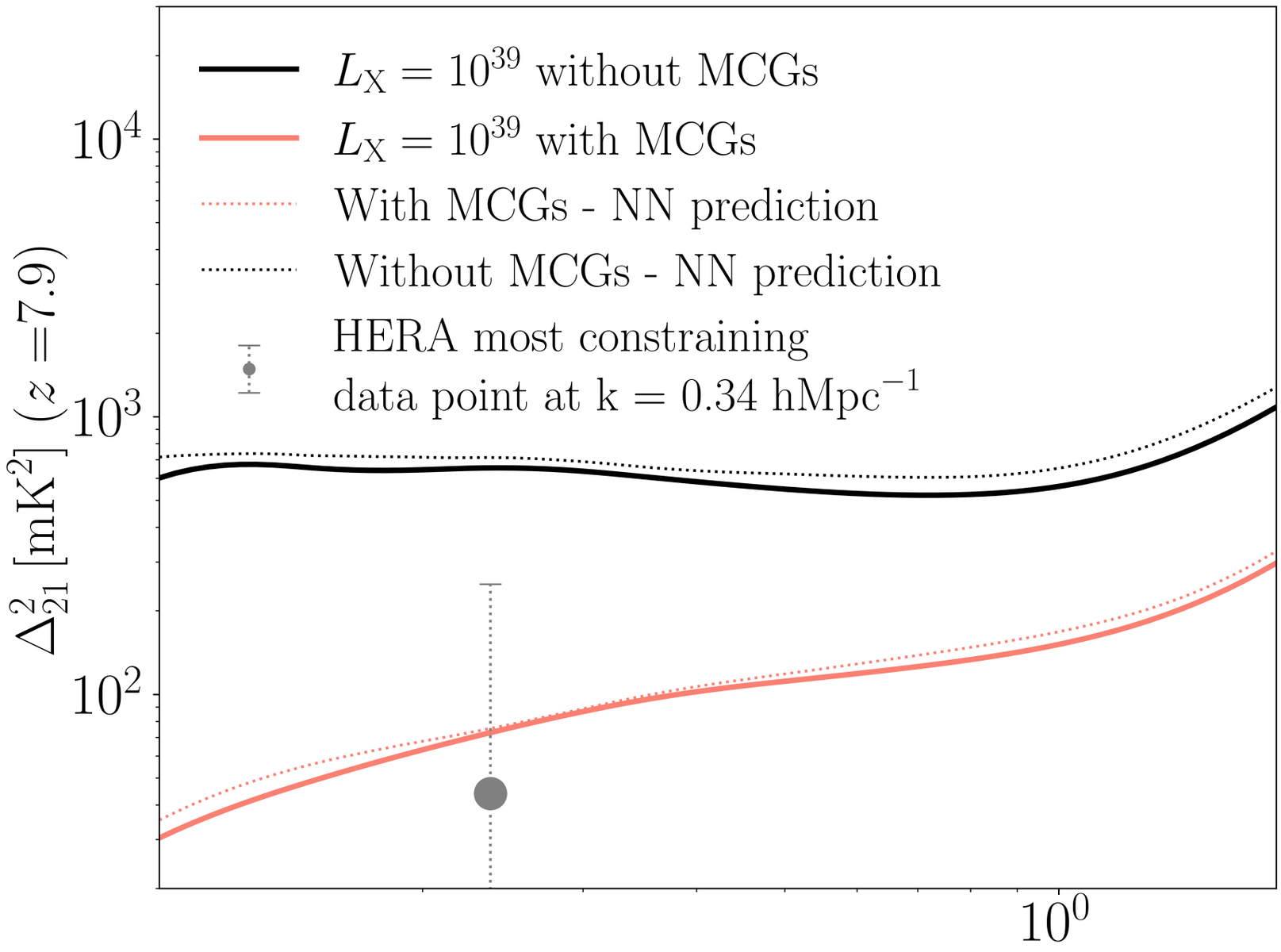

Lazare, Sarkar and Kovetz, PRD 2024

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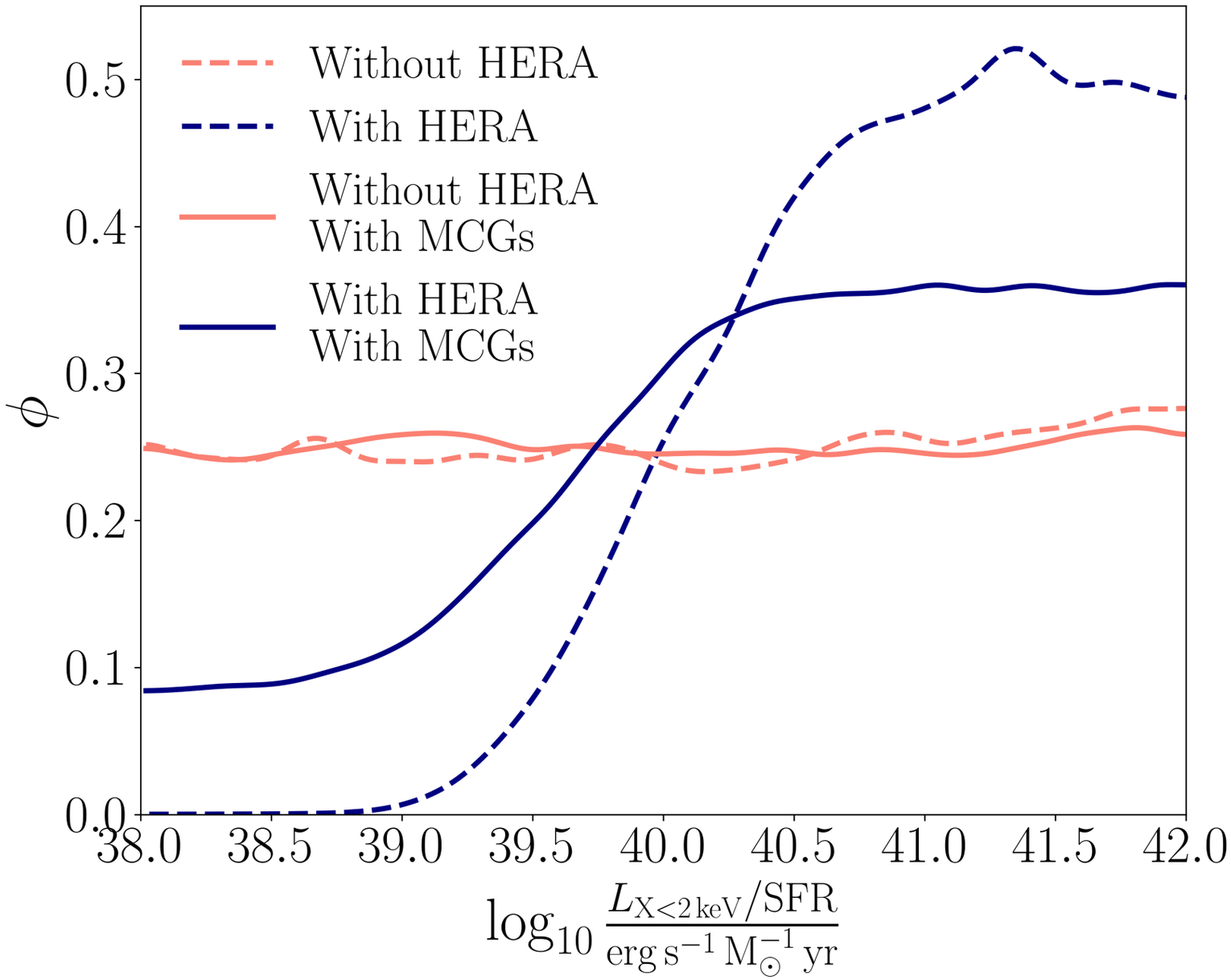

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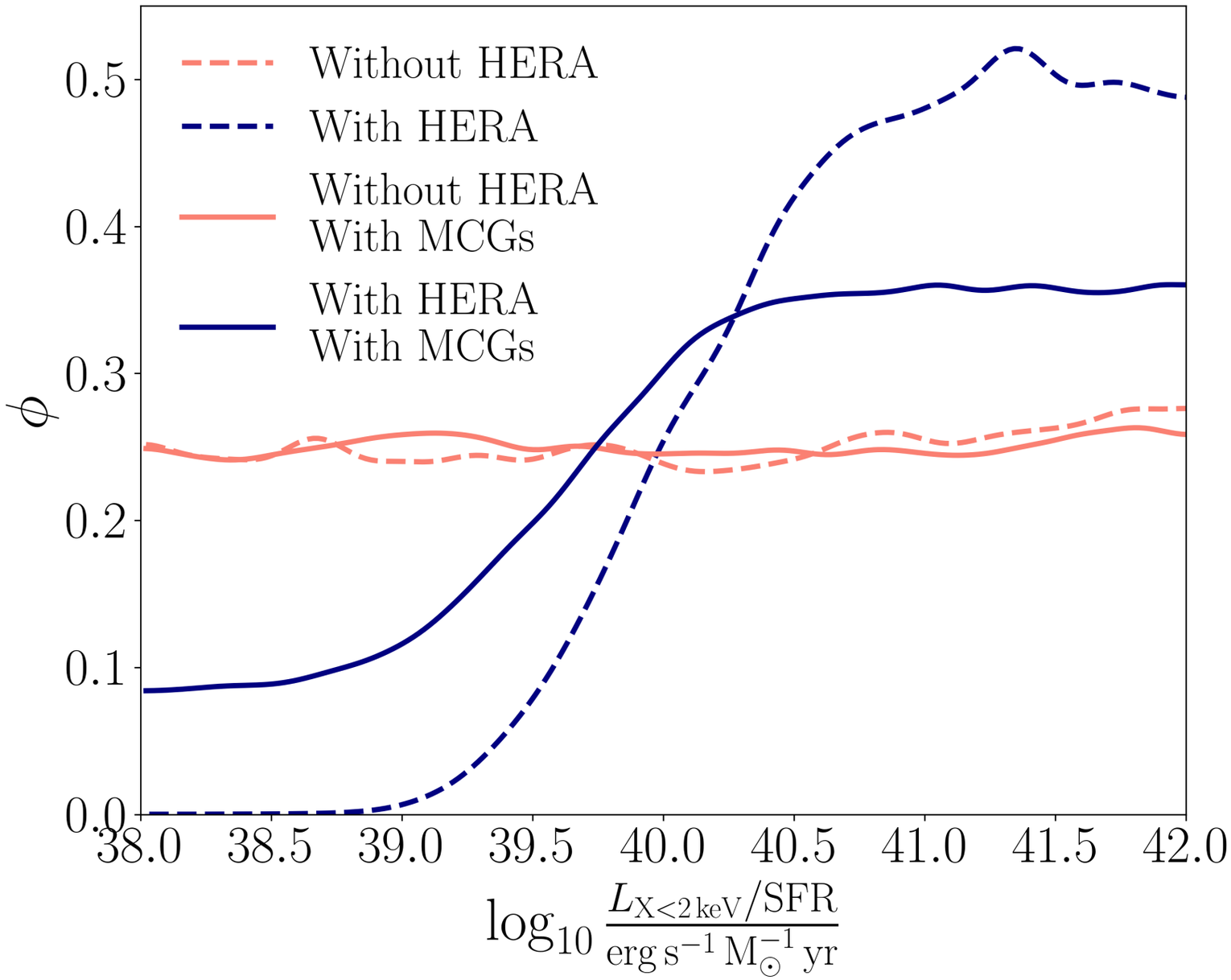

Lazare, Sarkar and Kovetz, PRD 2024

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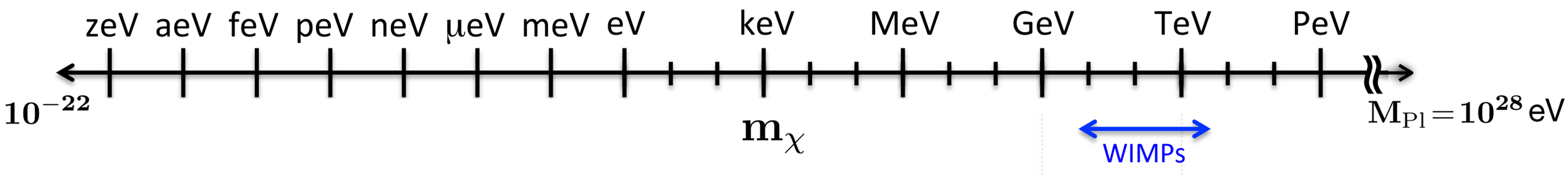
(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)



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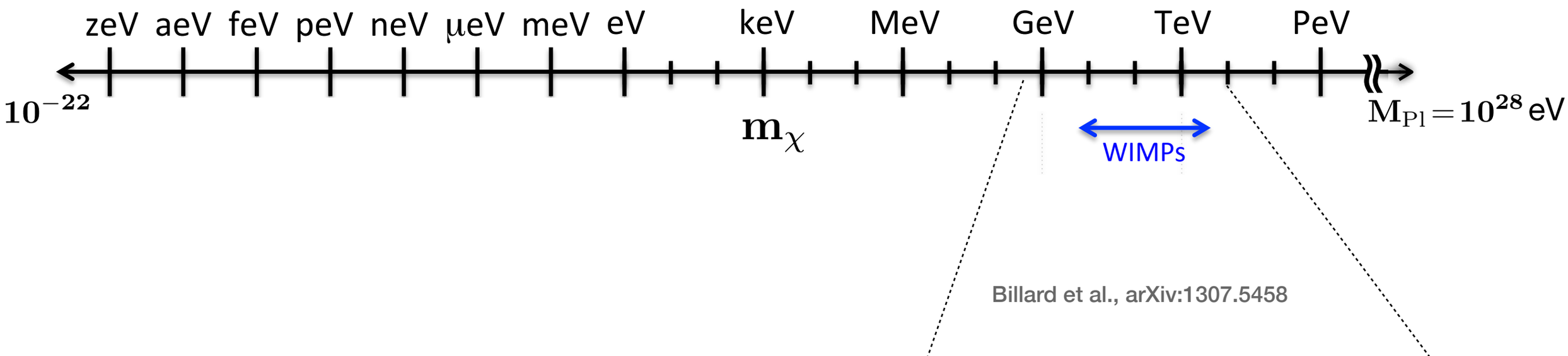
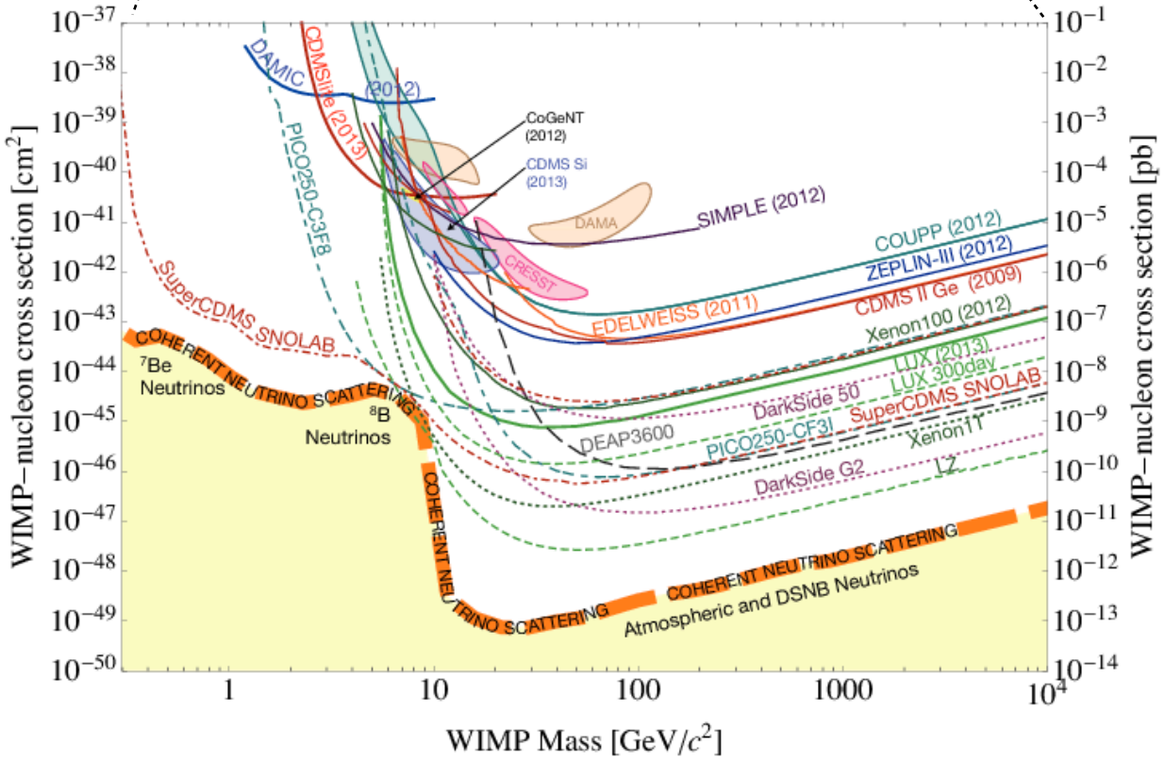


Billard et al., arXiv:1307.5458



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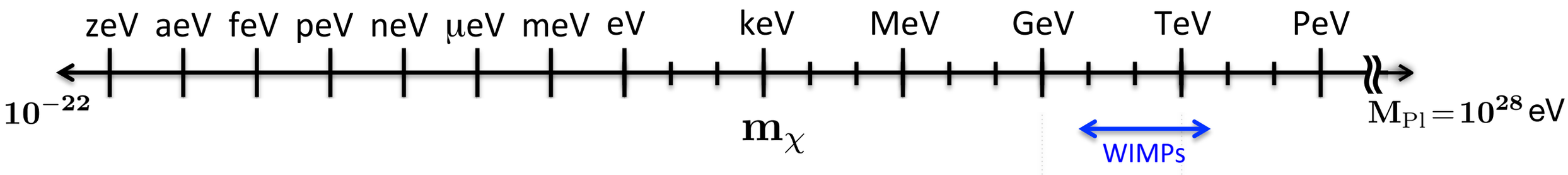

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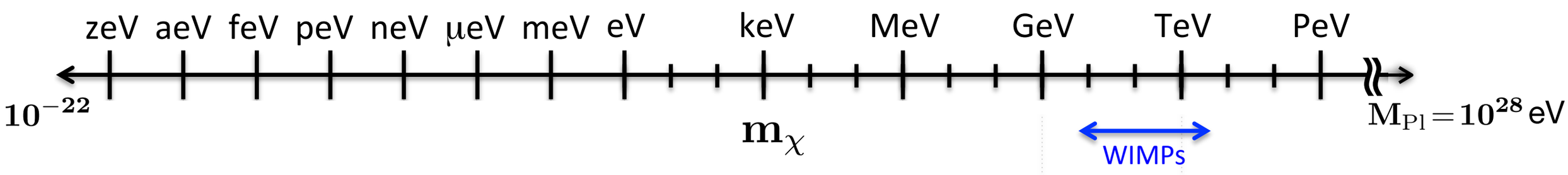

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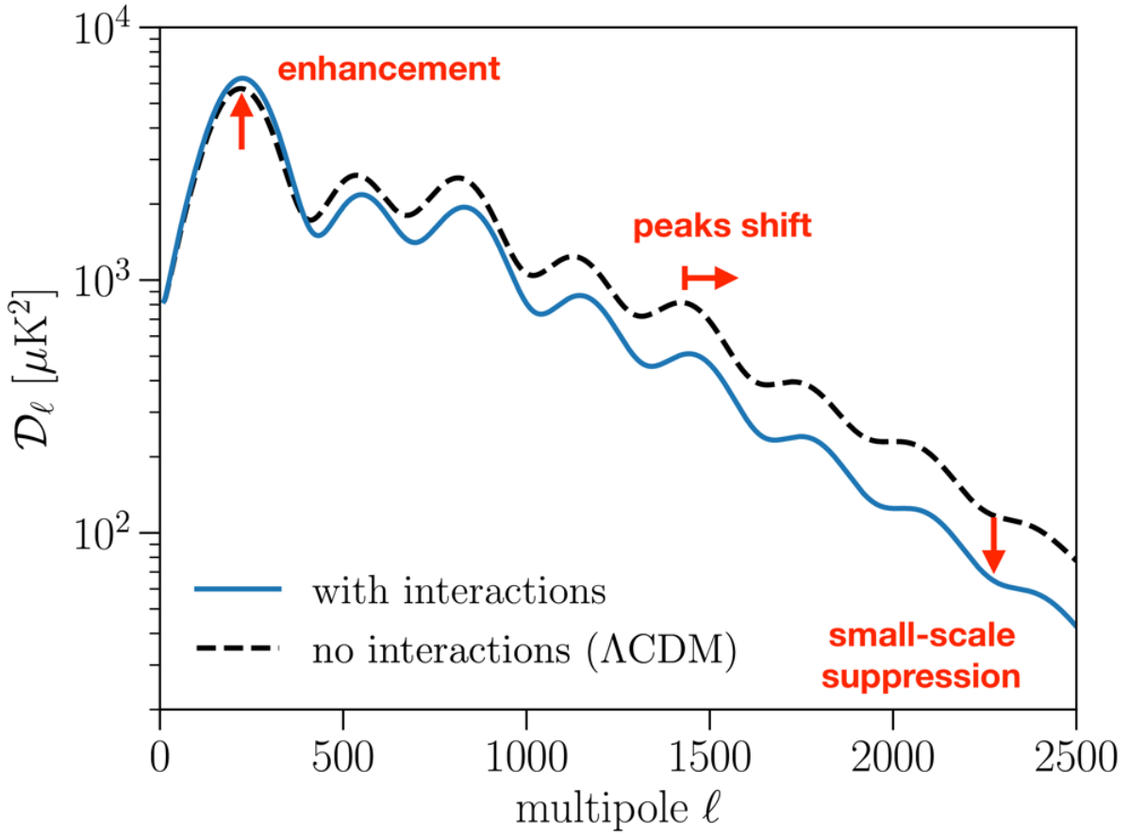
Cosmology remains sensitive at $m_\chi \ll \mathrm{GeV}$:



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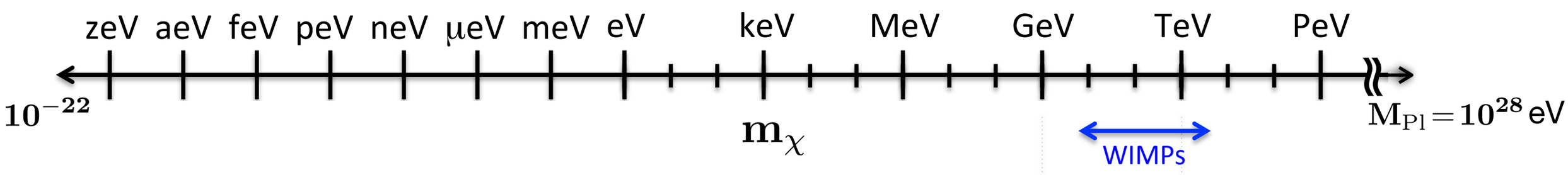

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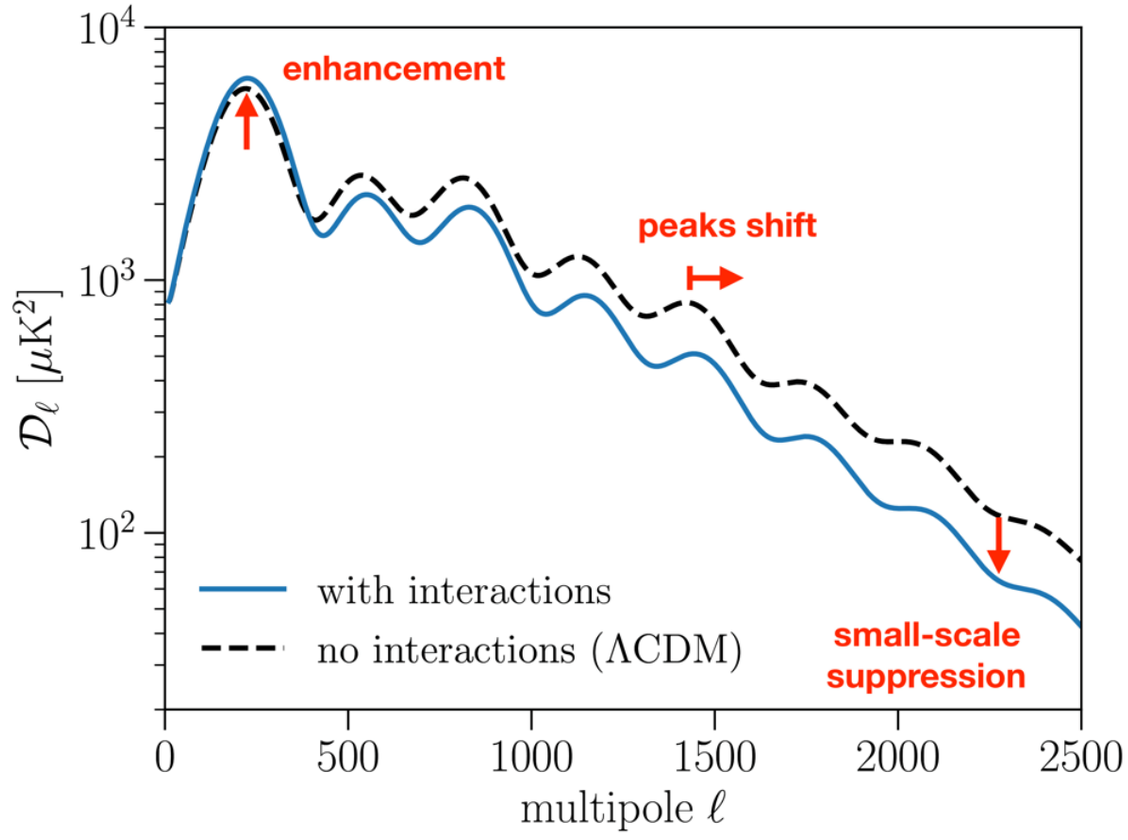

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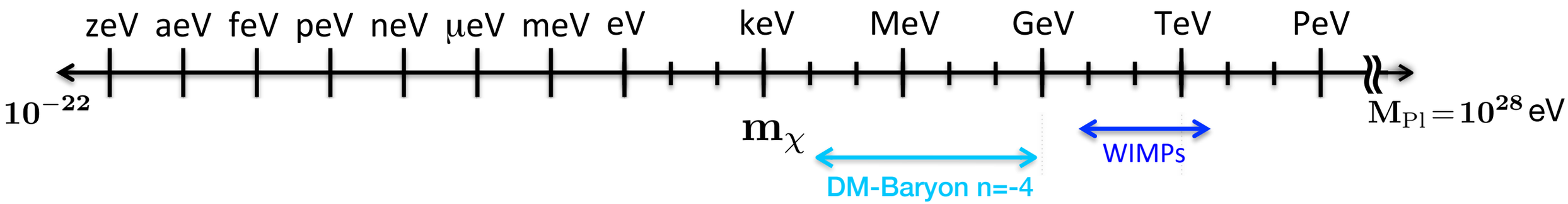

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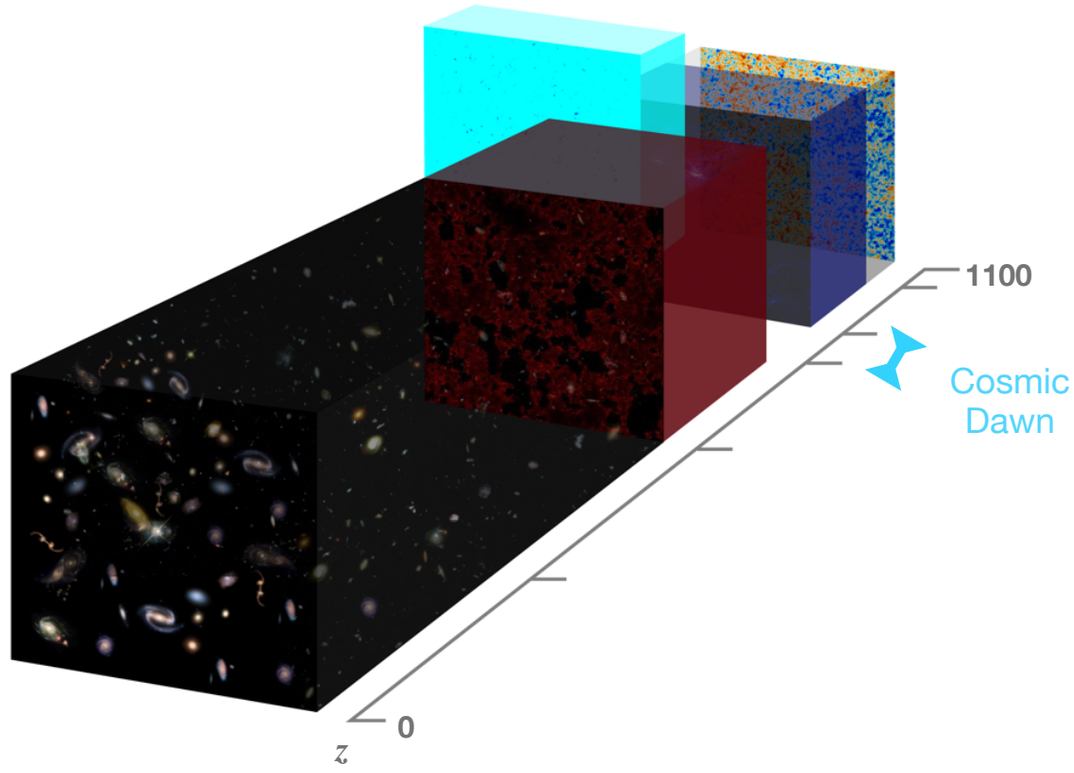
Let’s examine the case: $\sigma(v) = \sigma_c \left(\frac{v}{c}\right)^{-4}$



Example 1: (Rutherford) Scattering DM

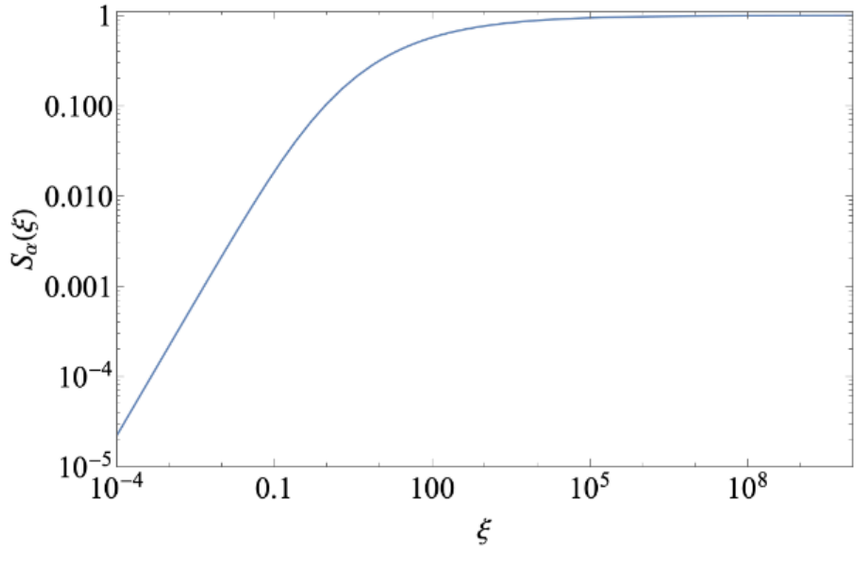
Curve	Dotted	Dashed	Solid
σ_{-4}	0 (ΛCDM)	$10^{-42}\,\mathrm{cm}^2$	$10^{-41}\,\mathrm{cm}^2$

$m_\chi = 1\,\mathrm{MeV}$

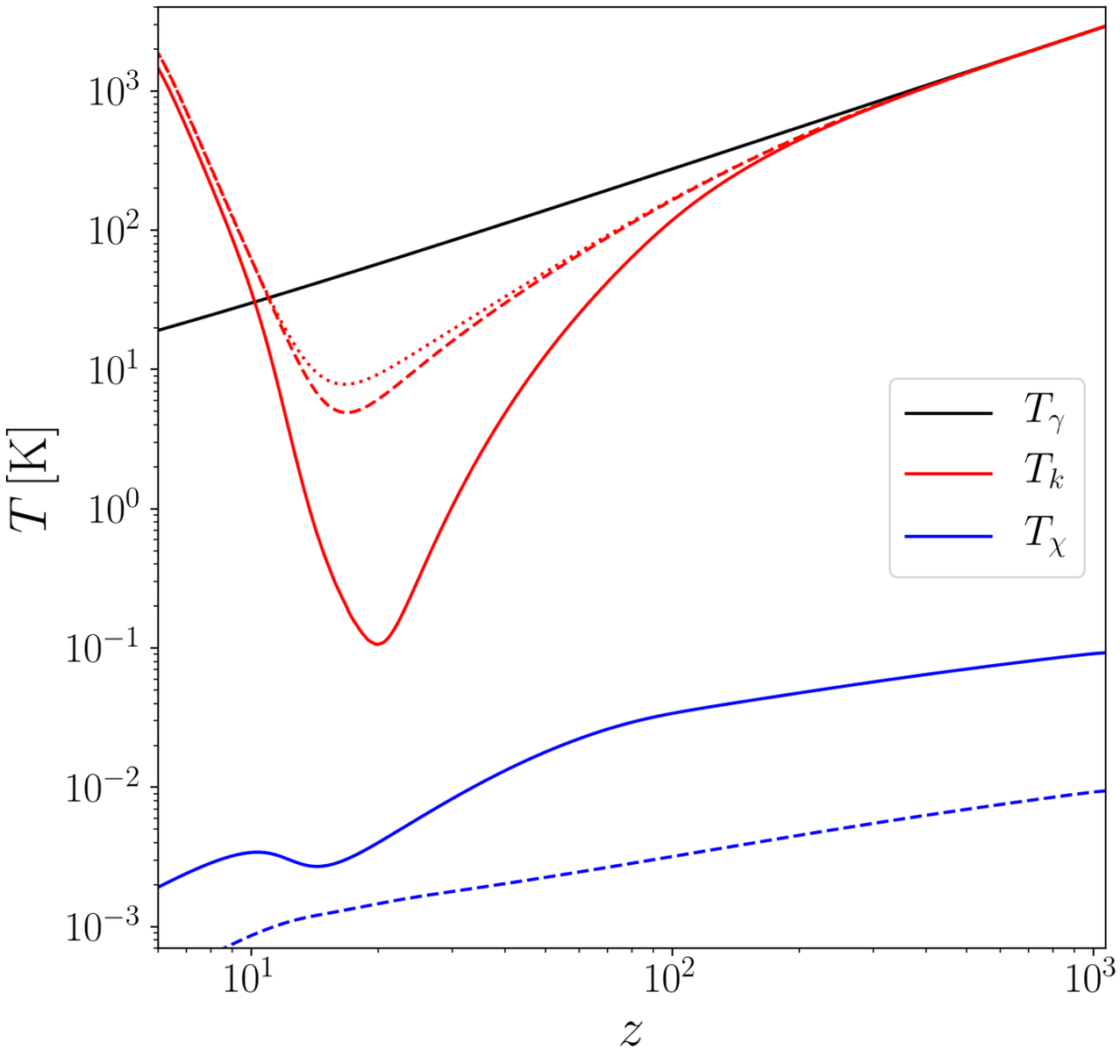
$f_\chi = 100\,\%$

+ χ, b tight coupling approximation

+ small temperature correction for S_α



Mittal and Kulkarni, MNRAS 2021



Flitter and Kovetz, arXiv:2309.03942

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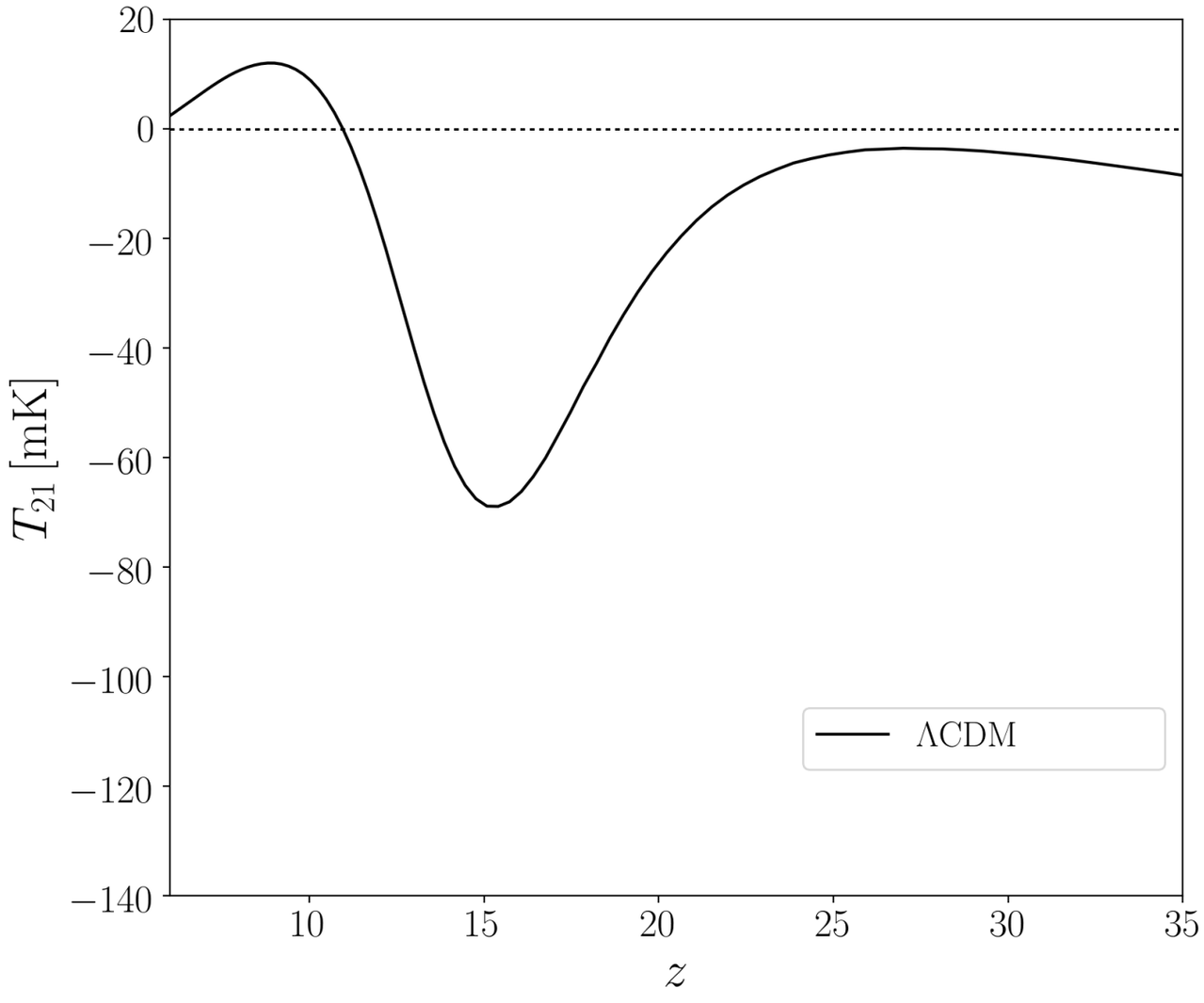

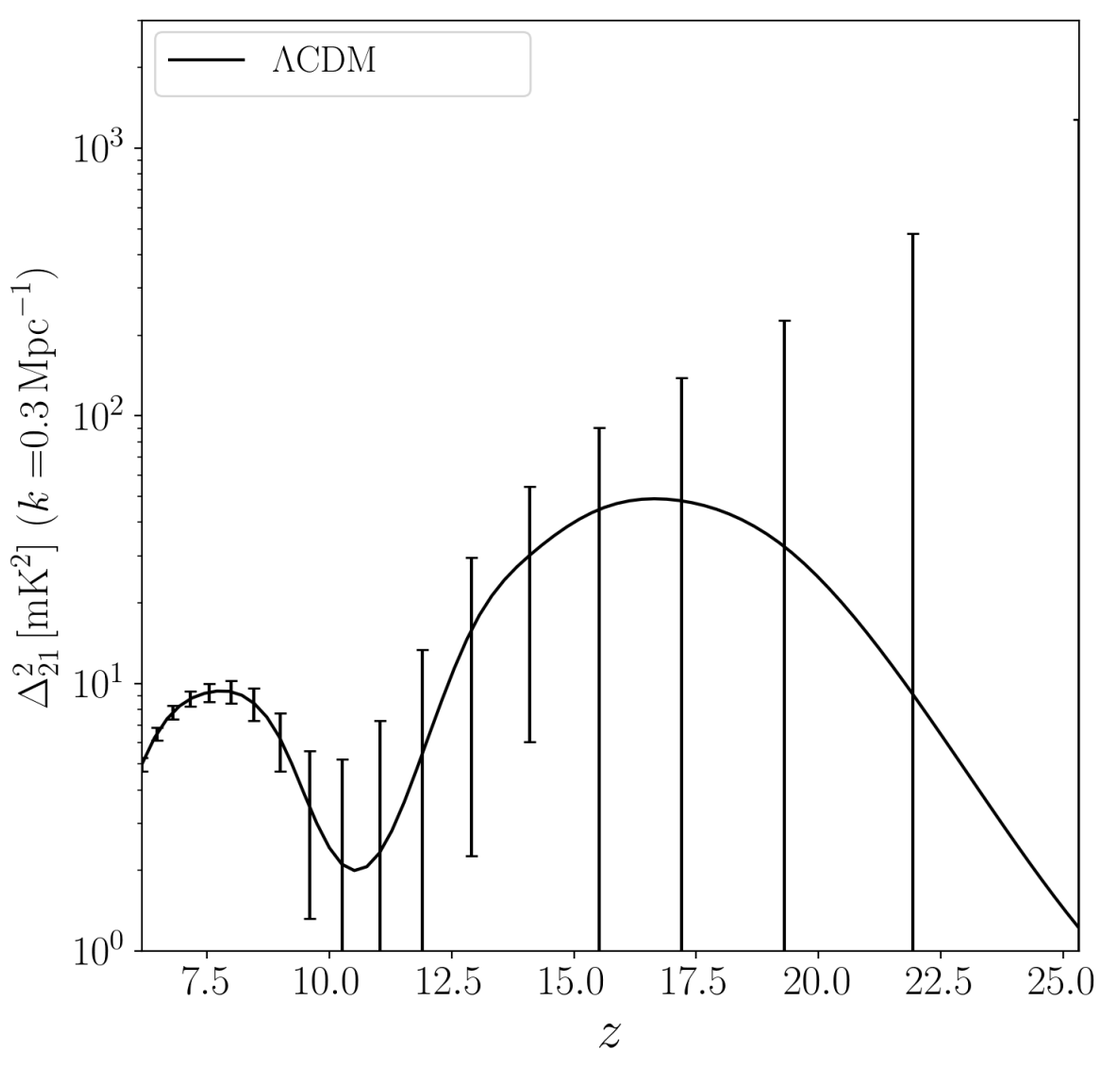

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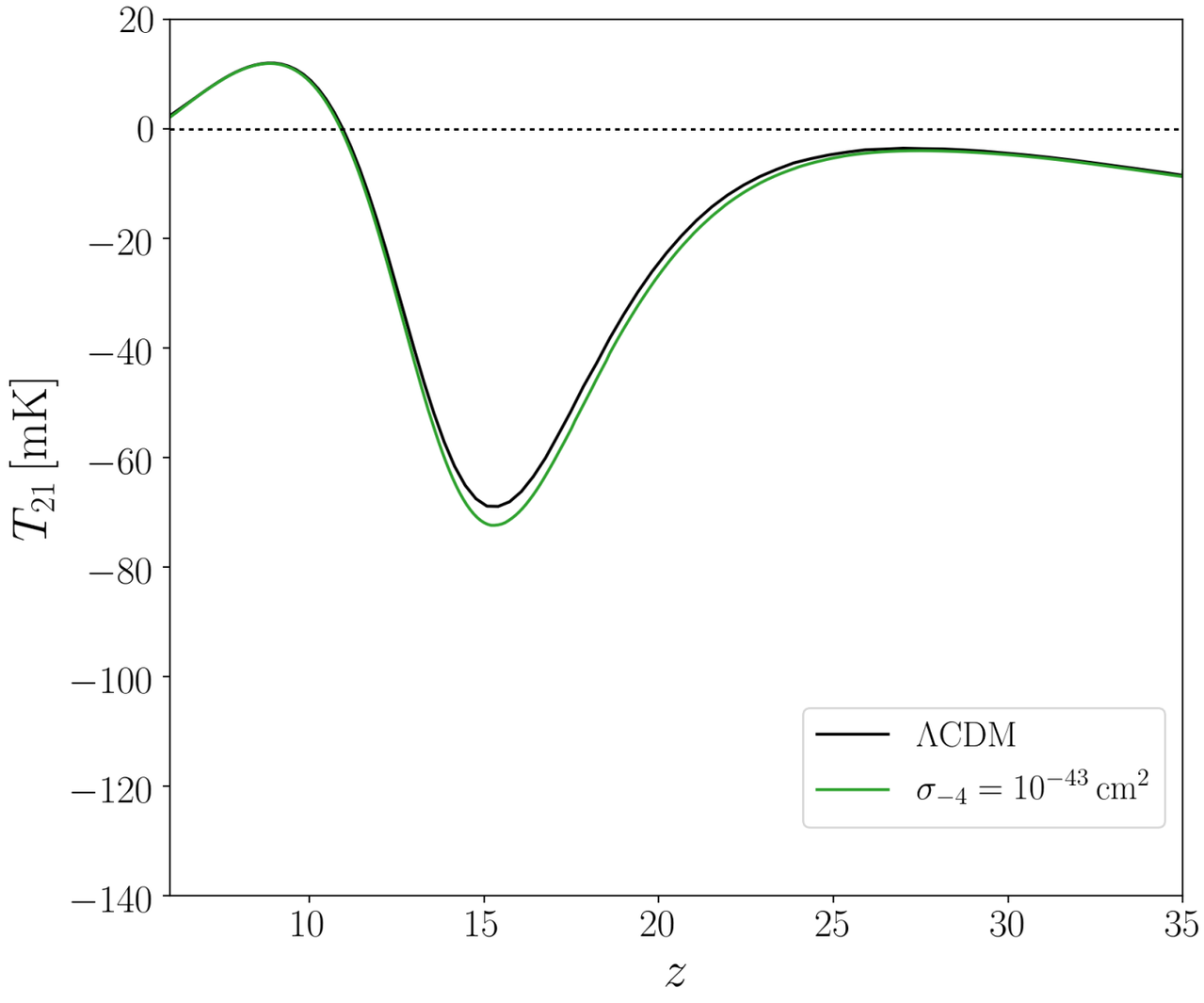

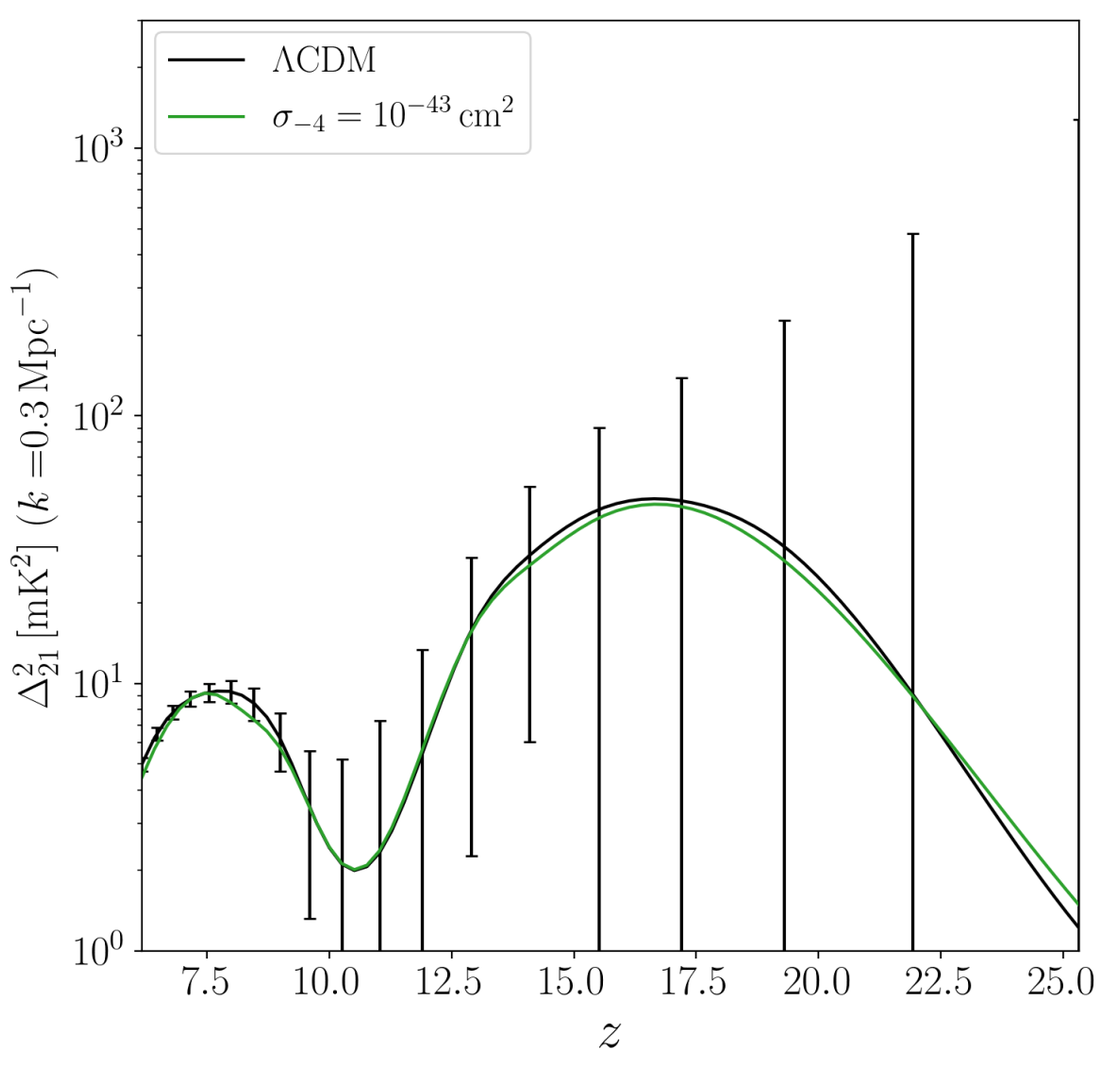

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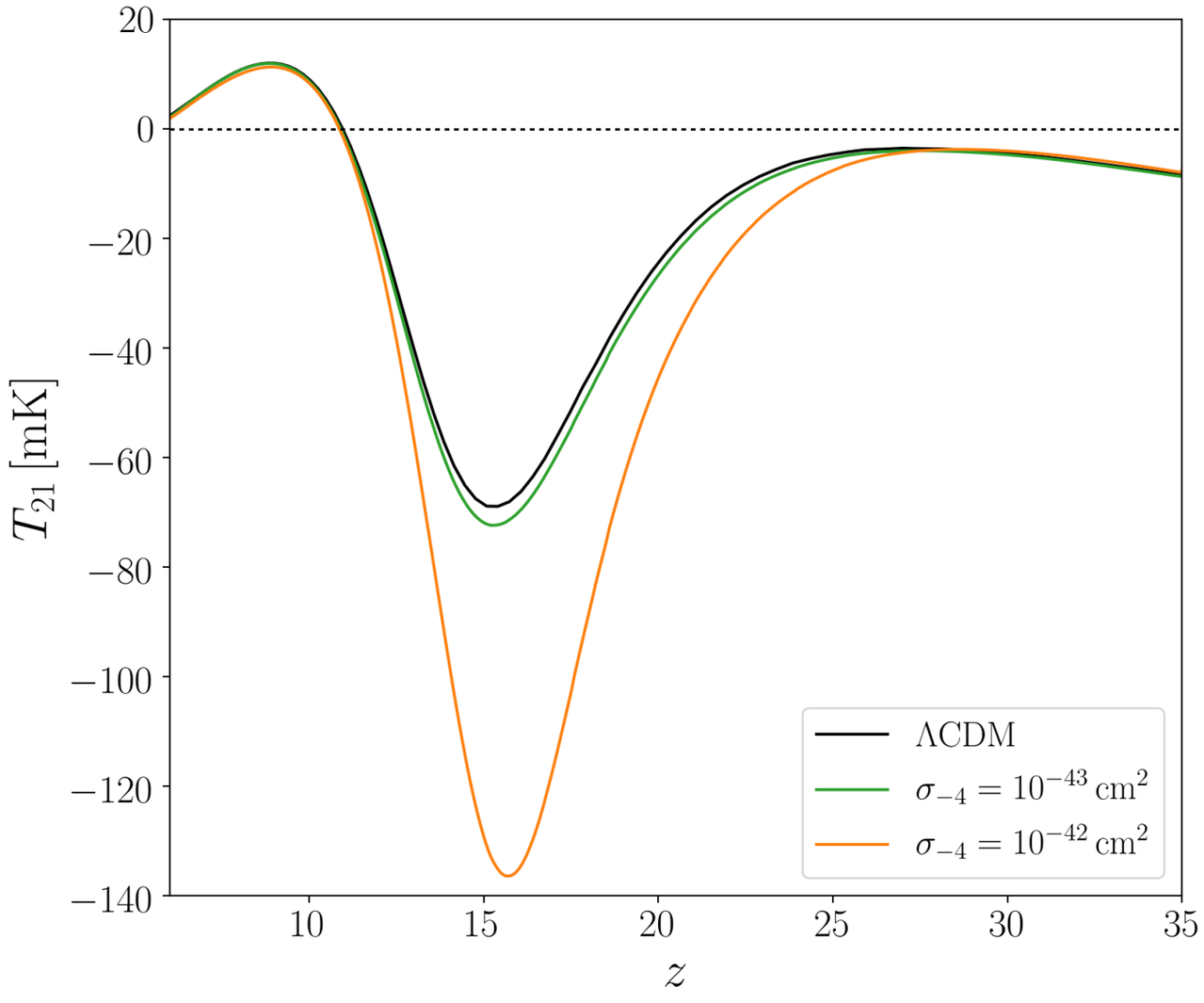

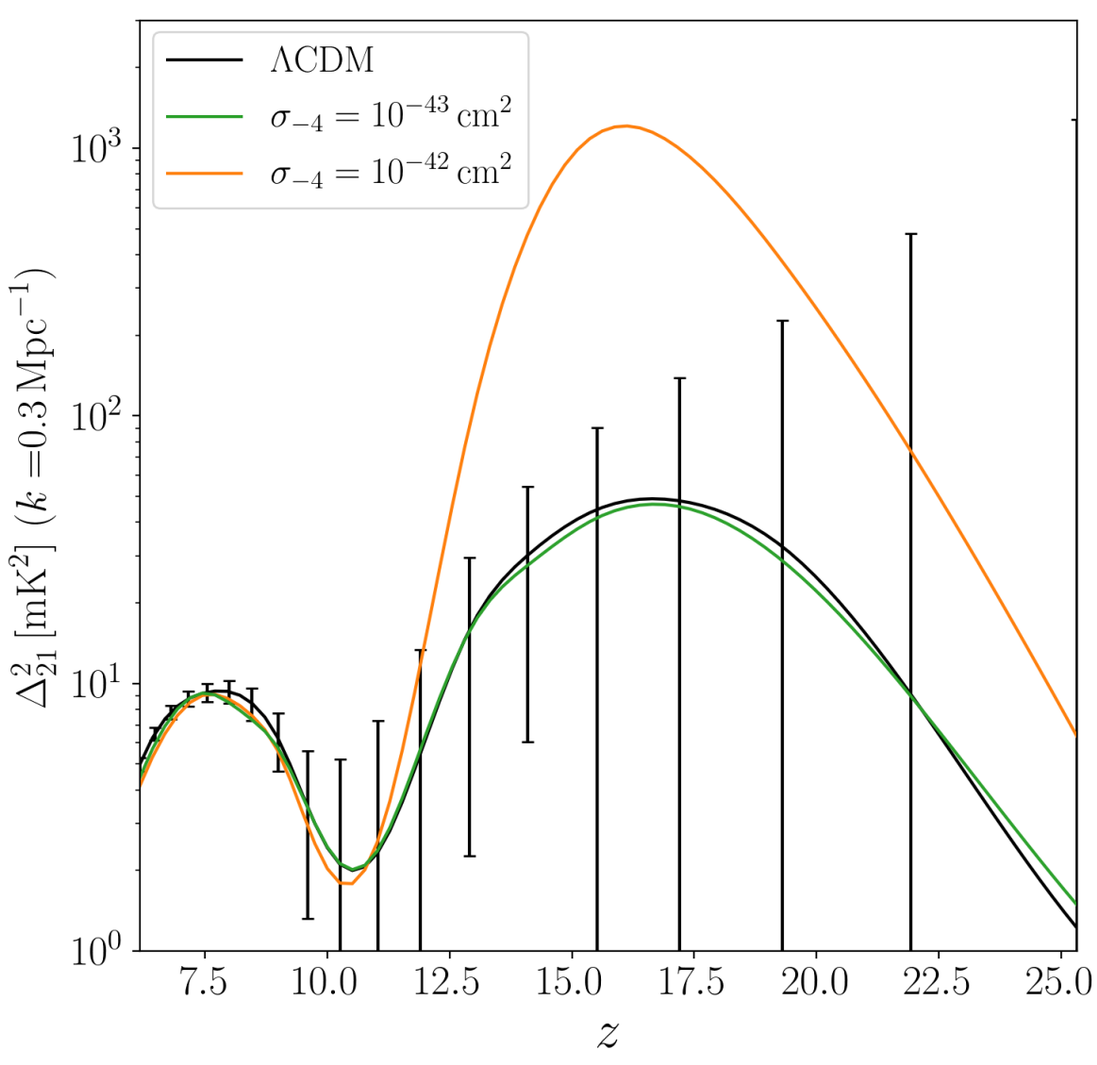

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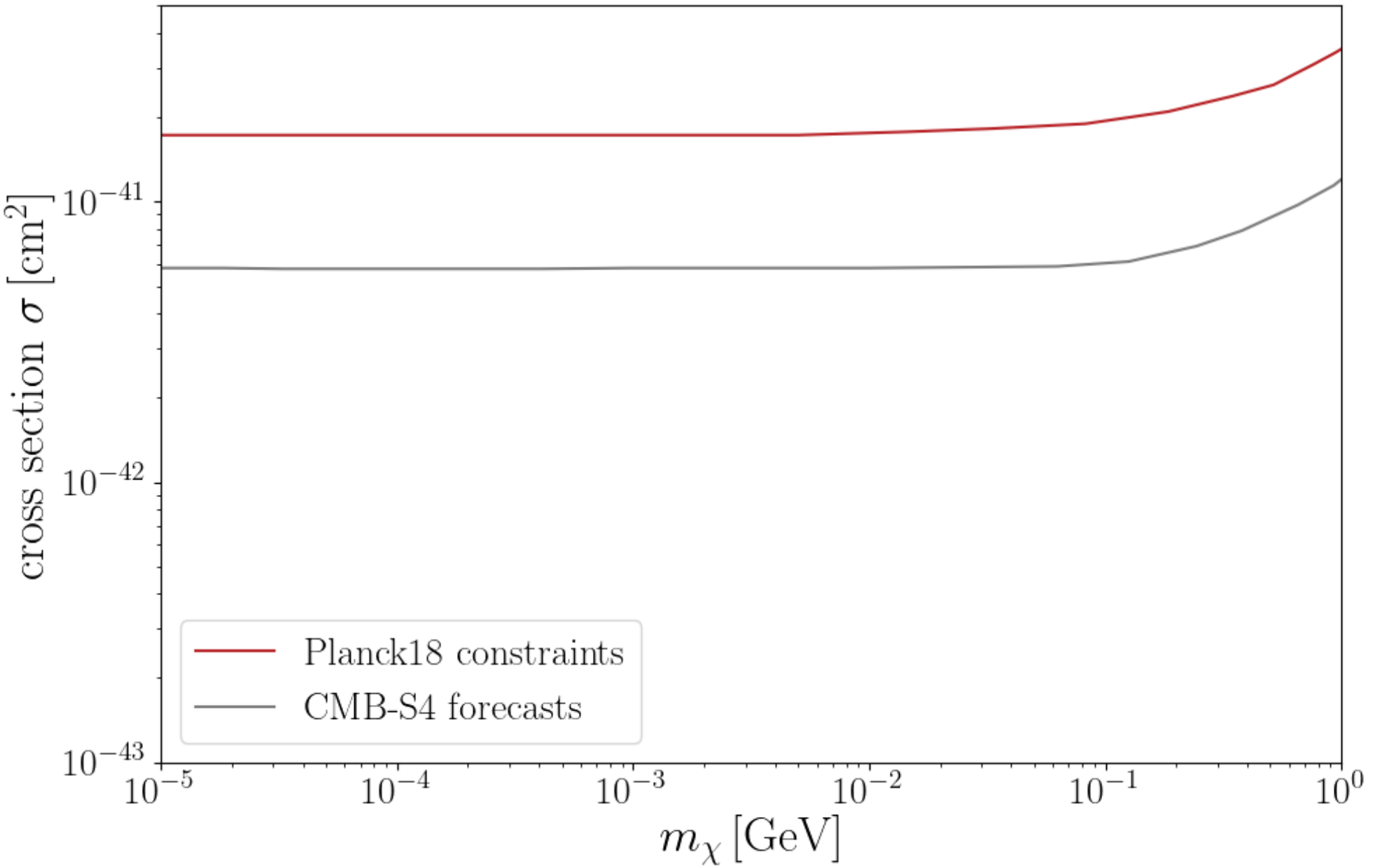
Boddy, Poulin, Gluscevic, Kovetz, Barkana and Kamionkowski, PRD 2018



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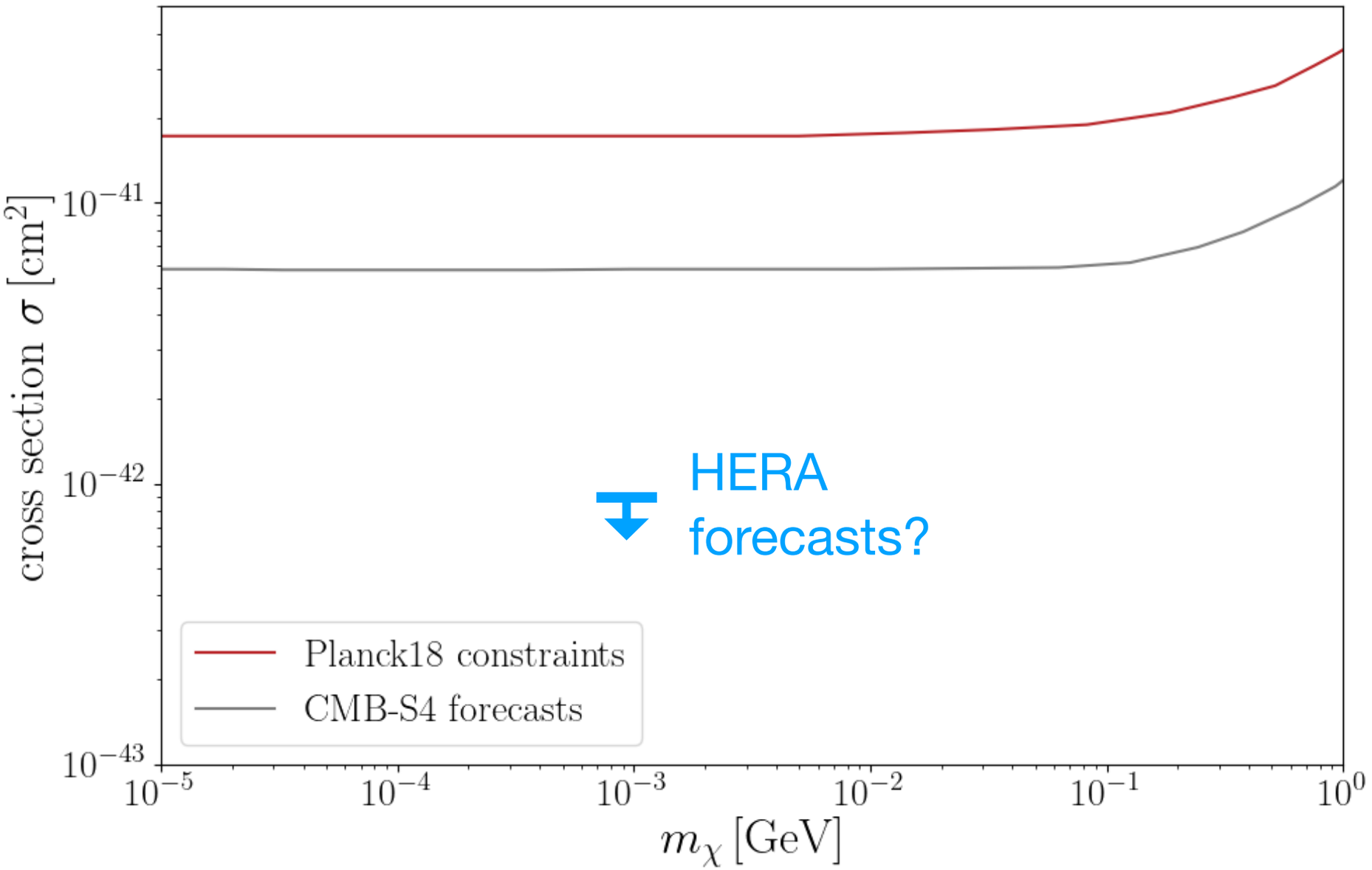

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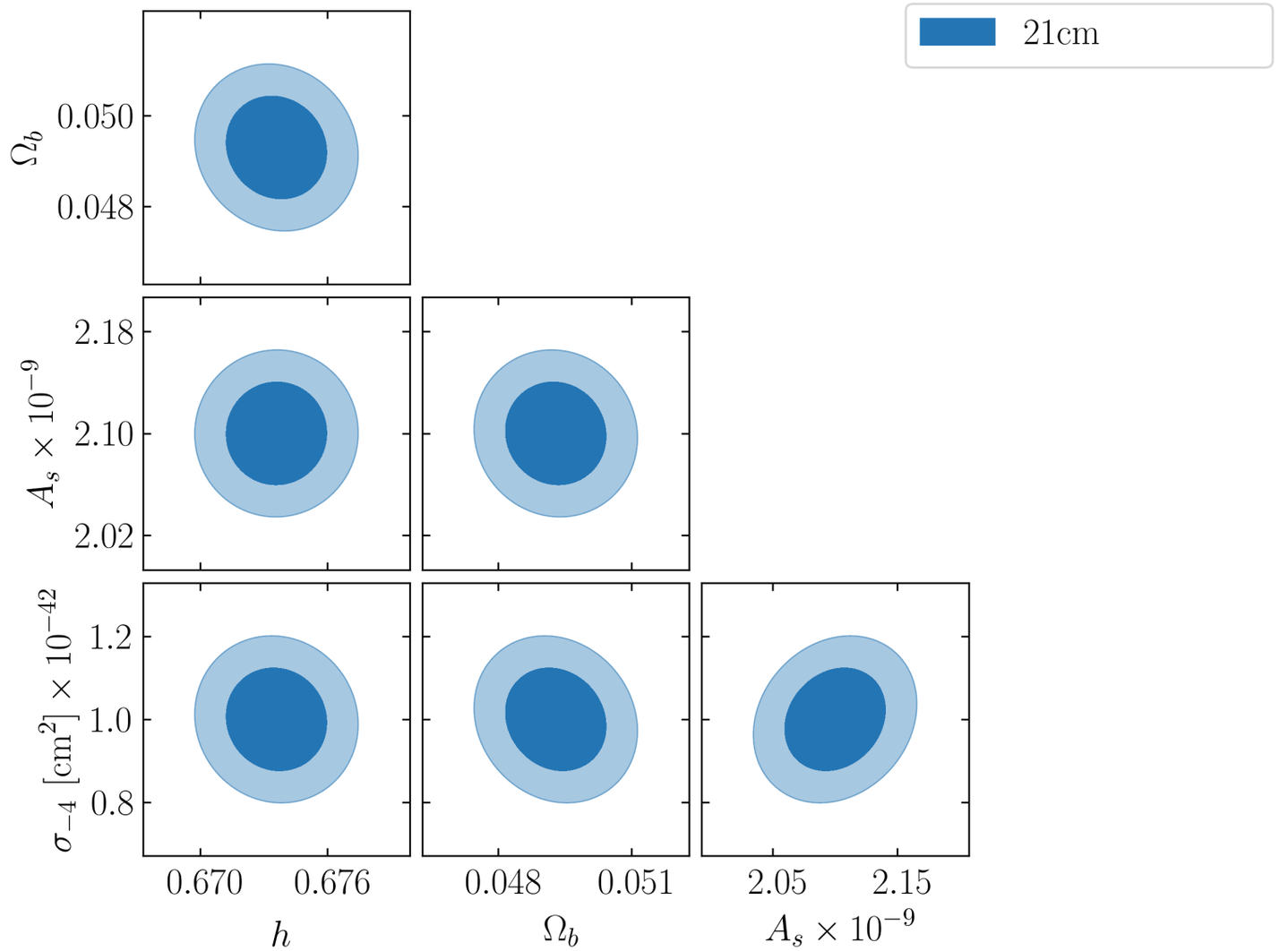

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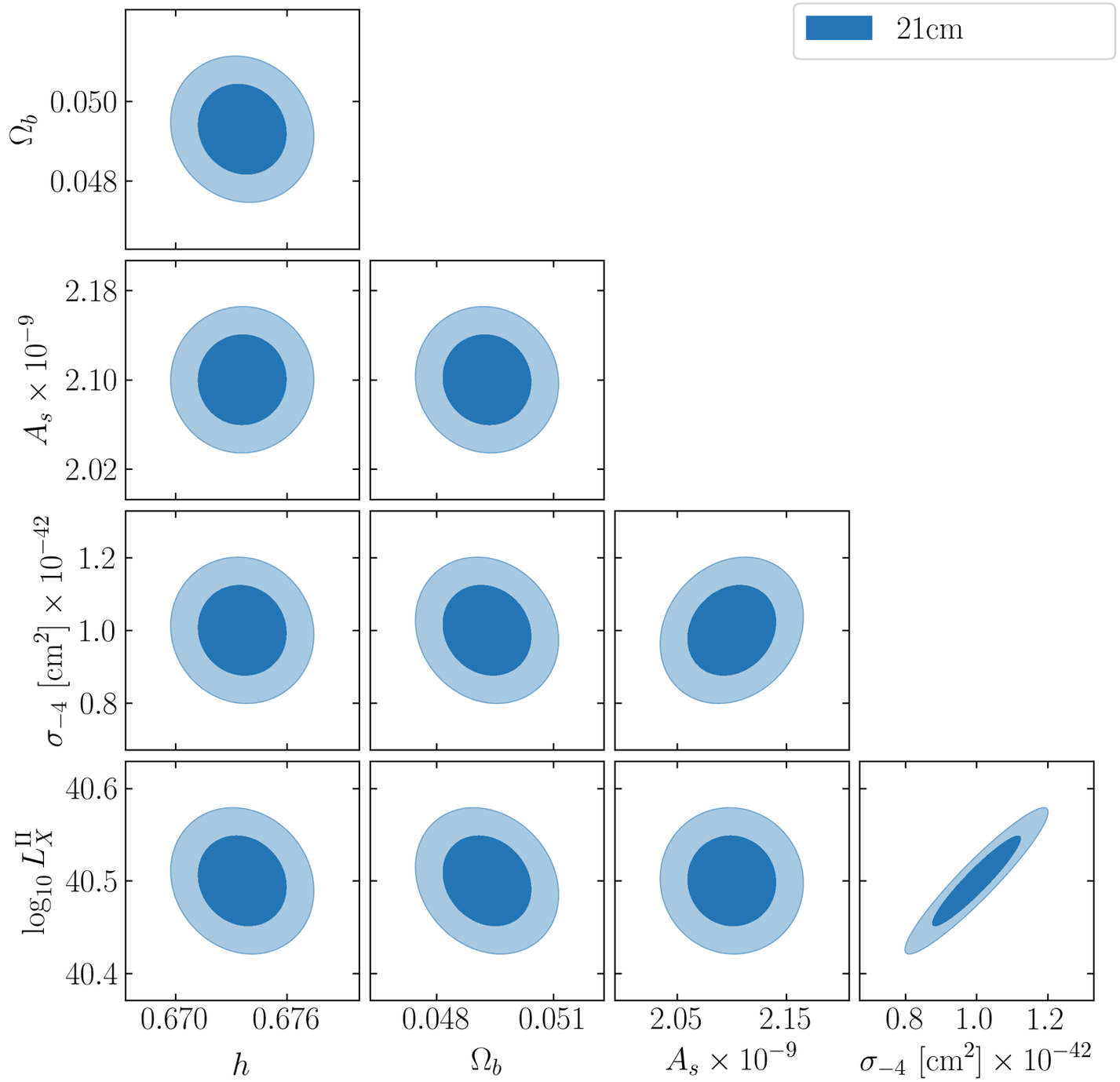

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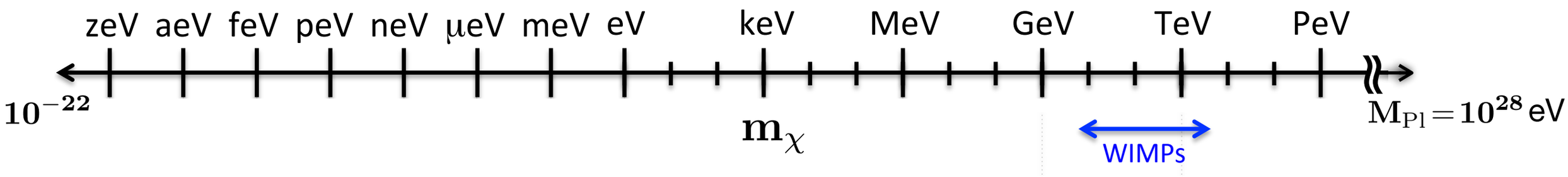
Example 2: Ultralight (Fuzzy) Dark Matter



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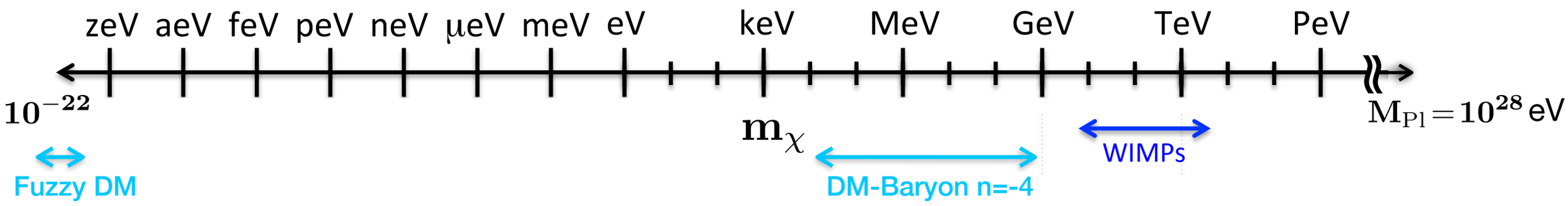

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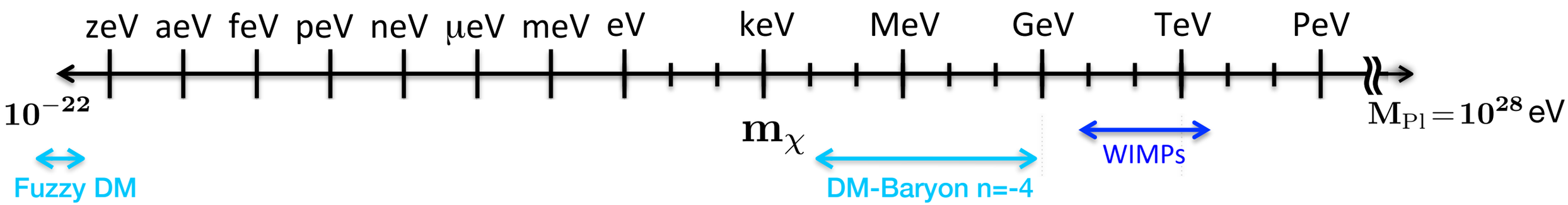

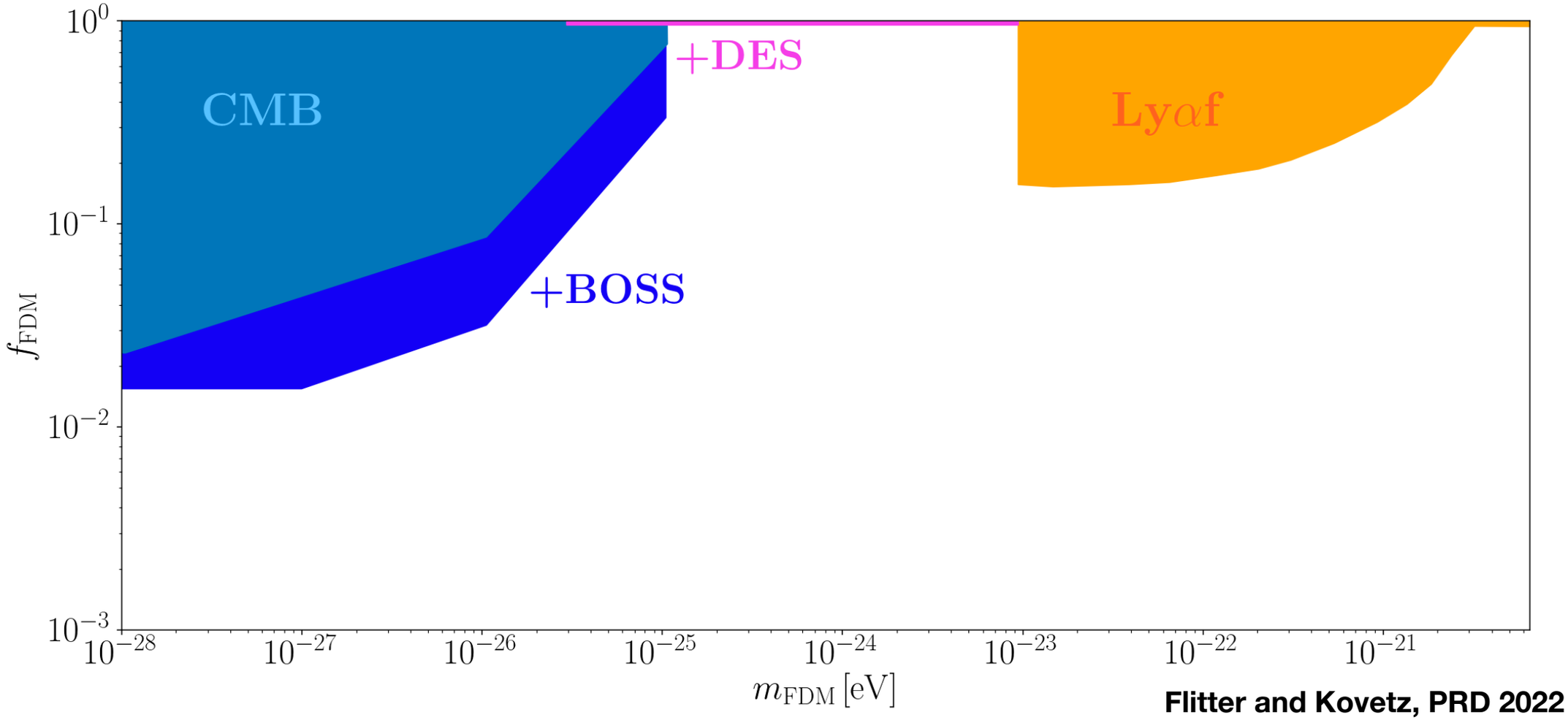

Flitter and Kovetz, PRD 2022

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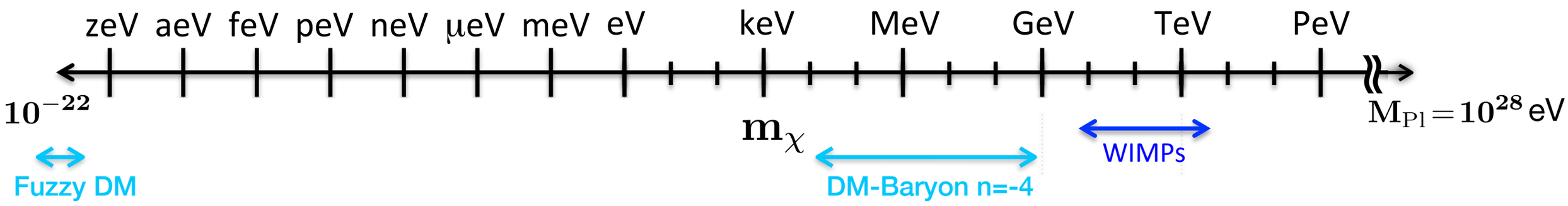

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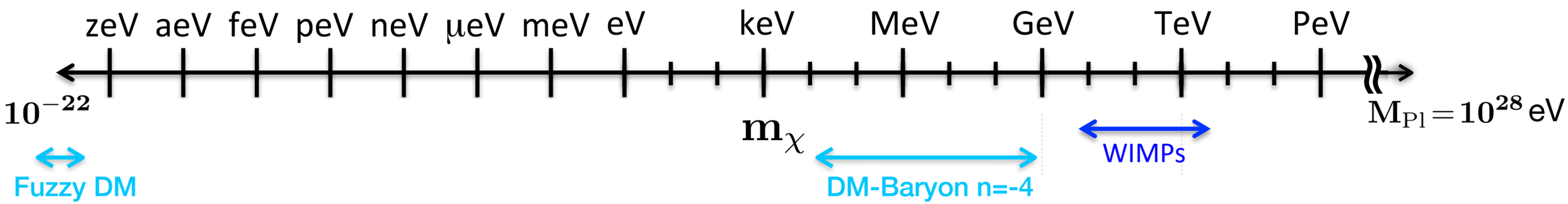

LIM can access far smaller scales via galaxies residing in the smallest dark matter halos:

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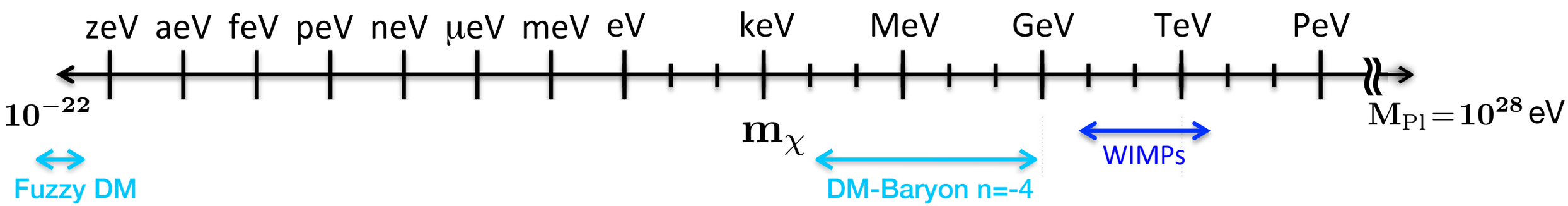

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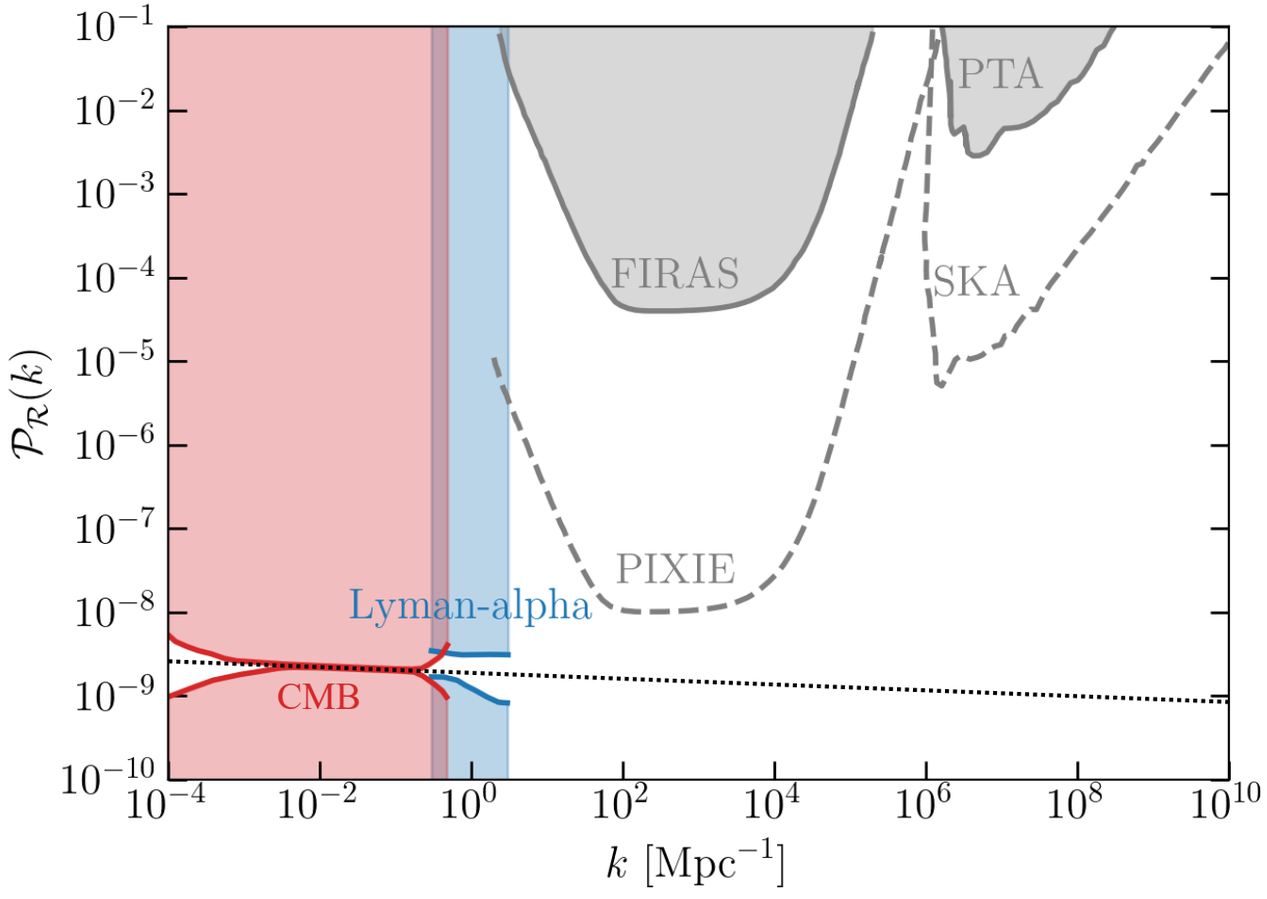

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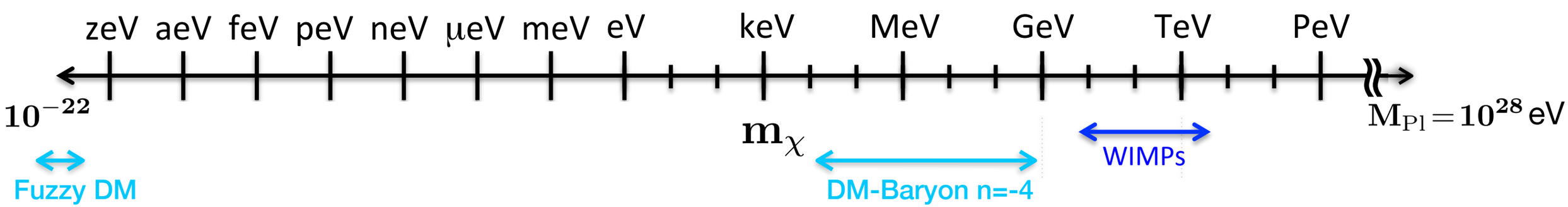

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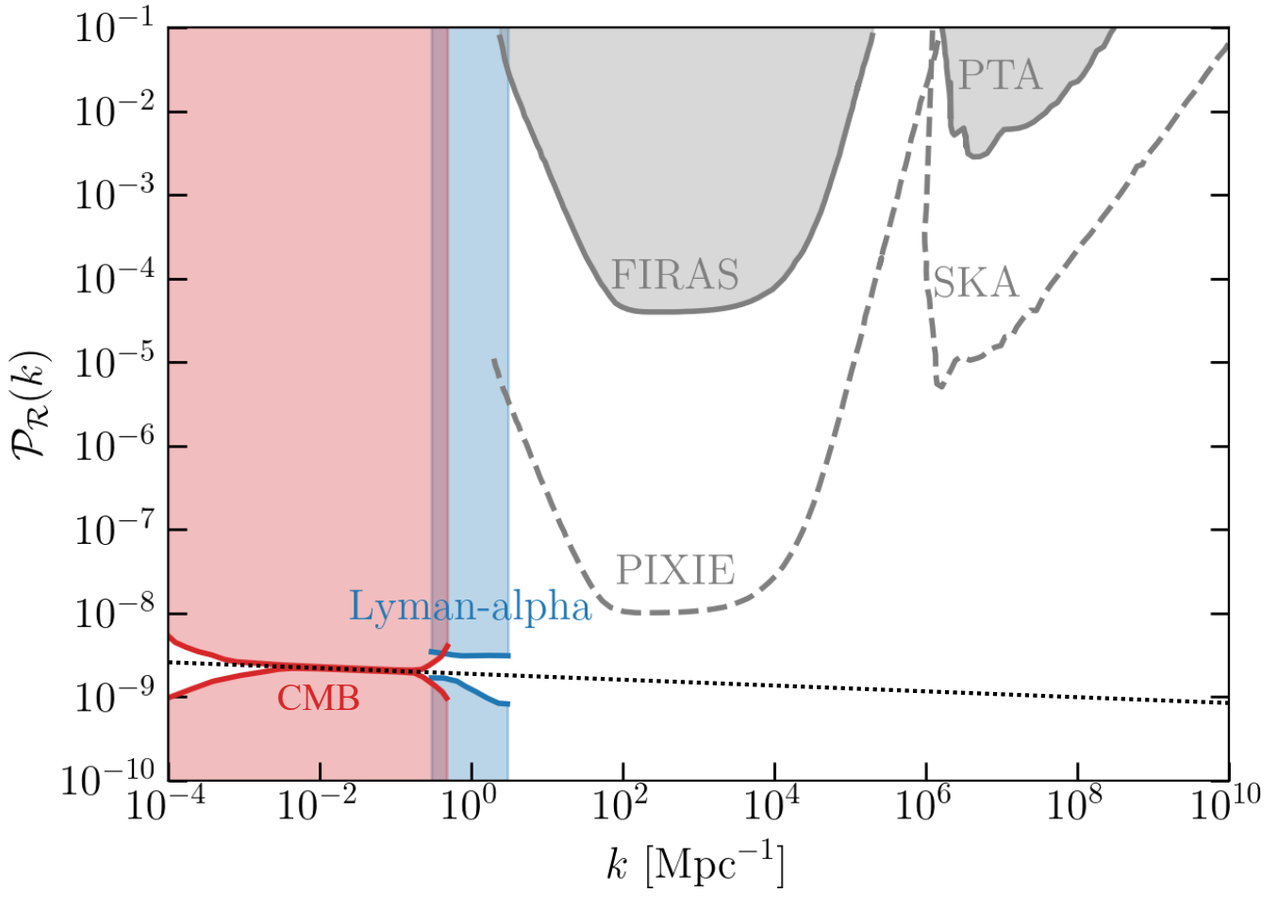

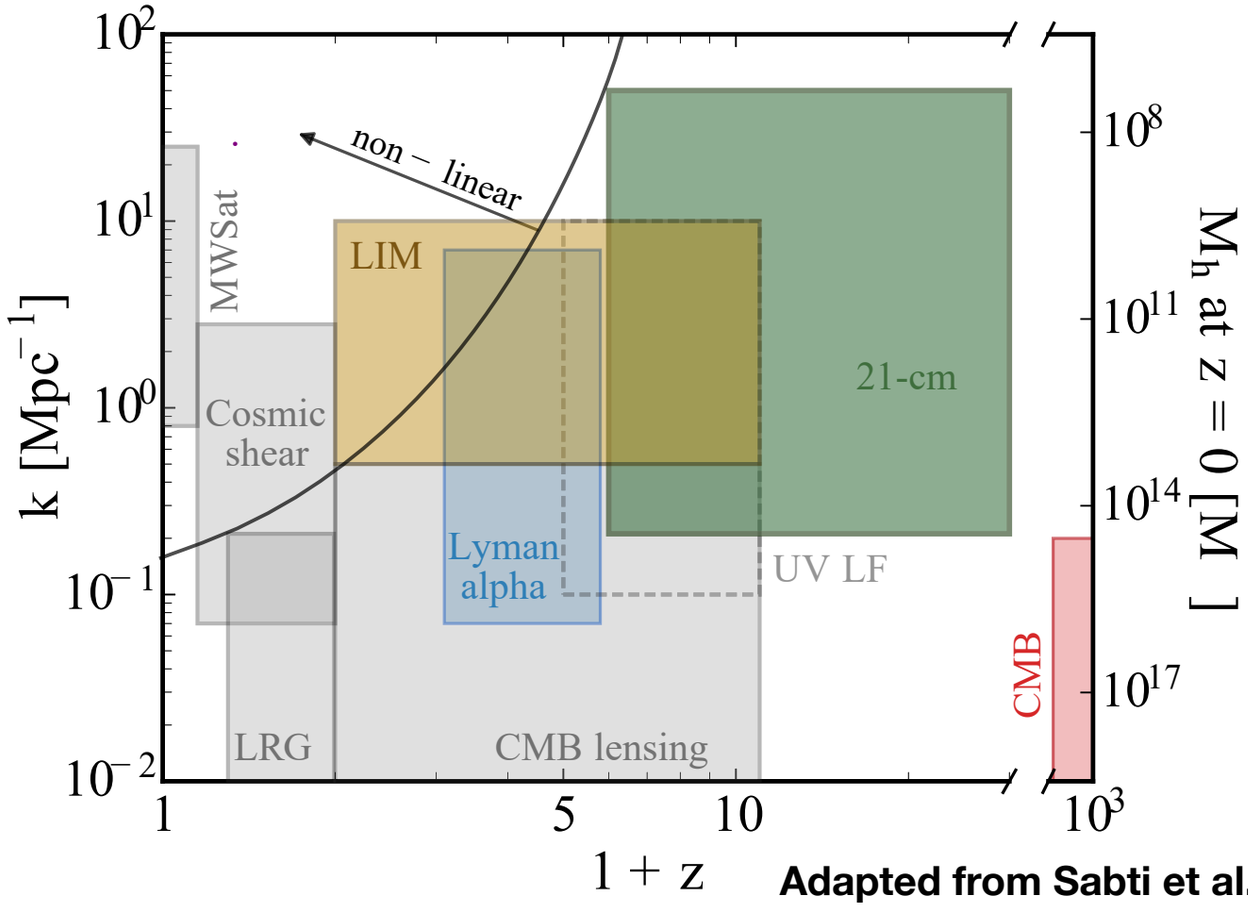

Adapted from Sabti et al., ApJL 2022

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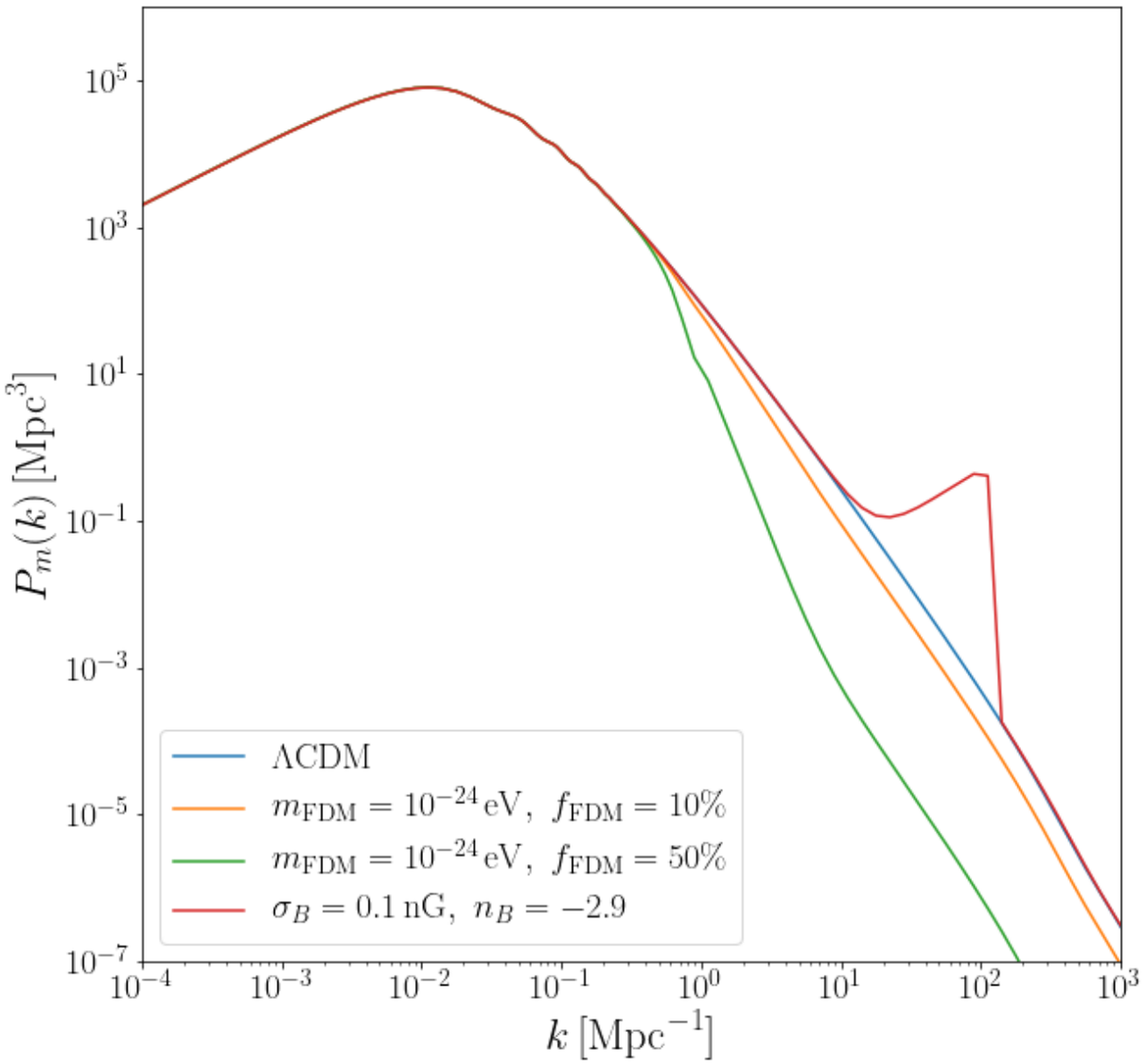

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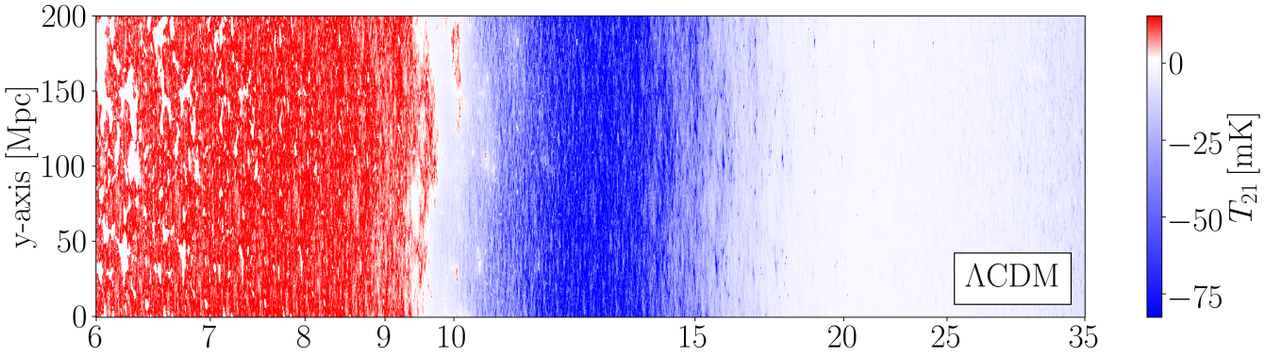

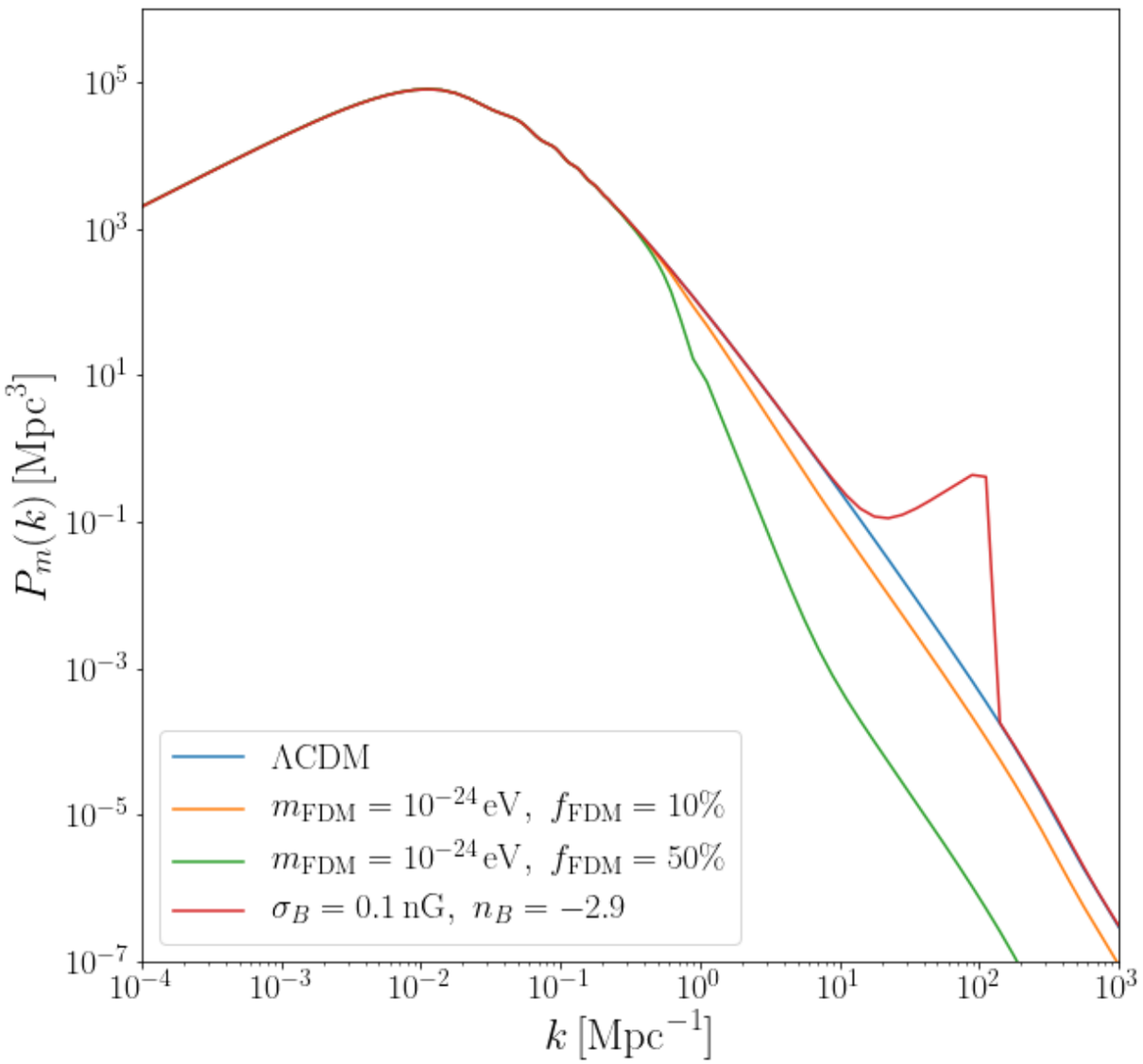

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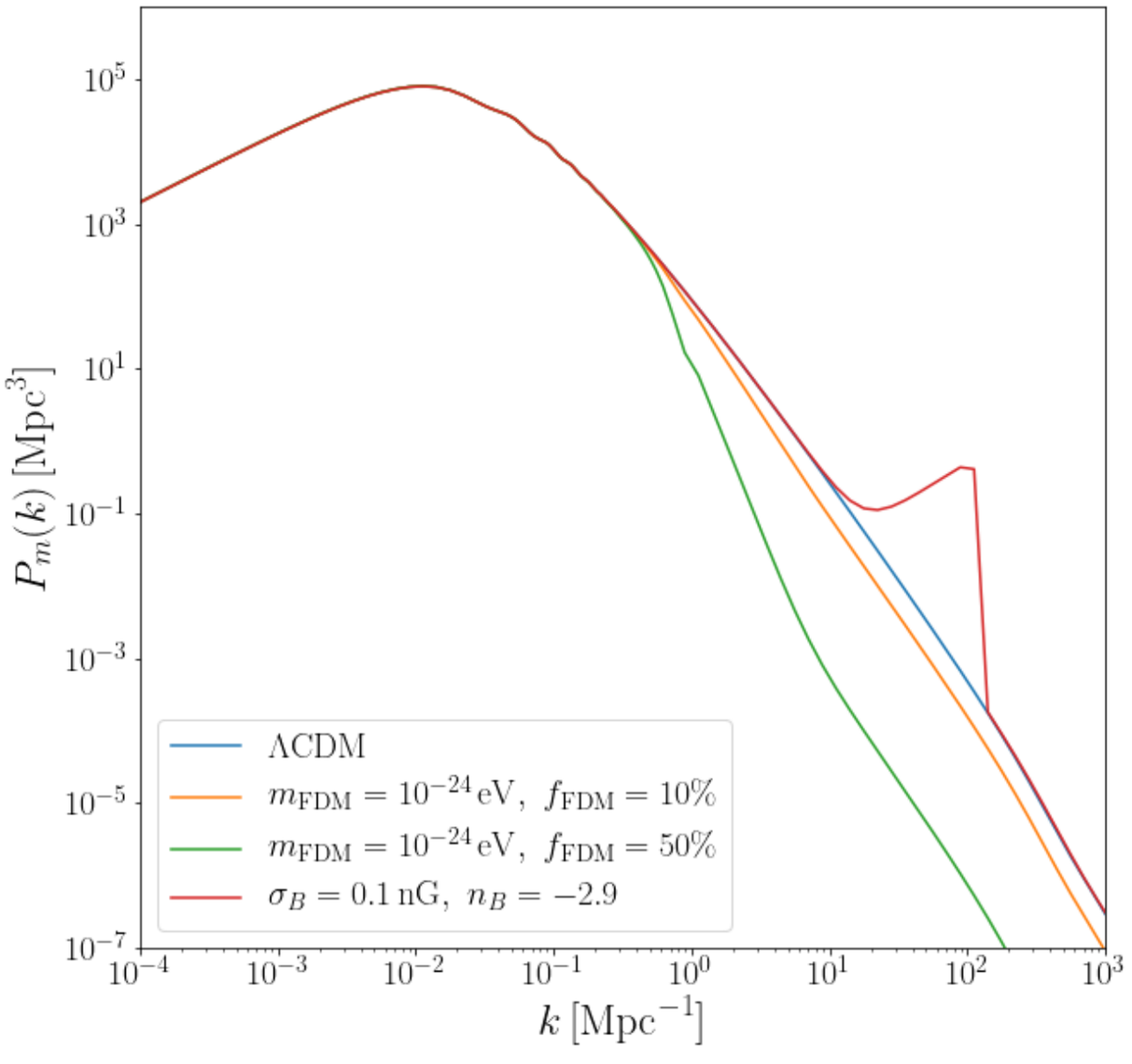

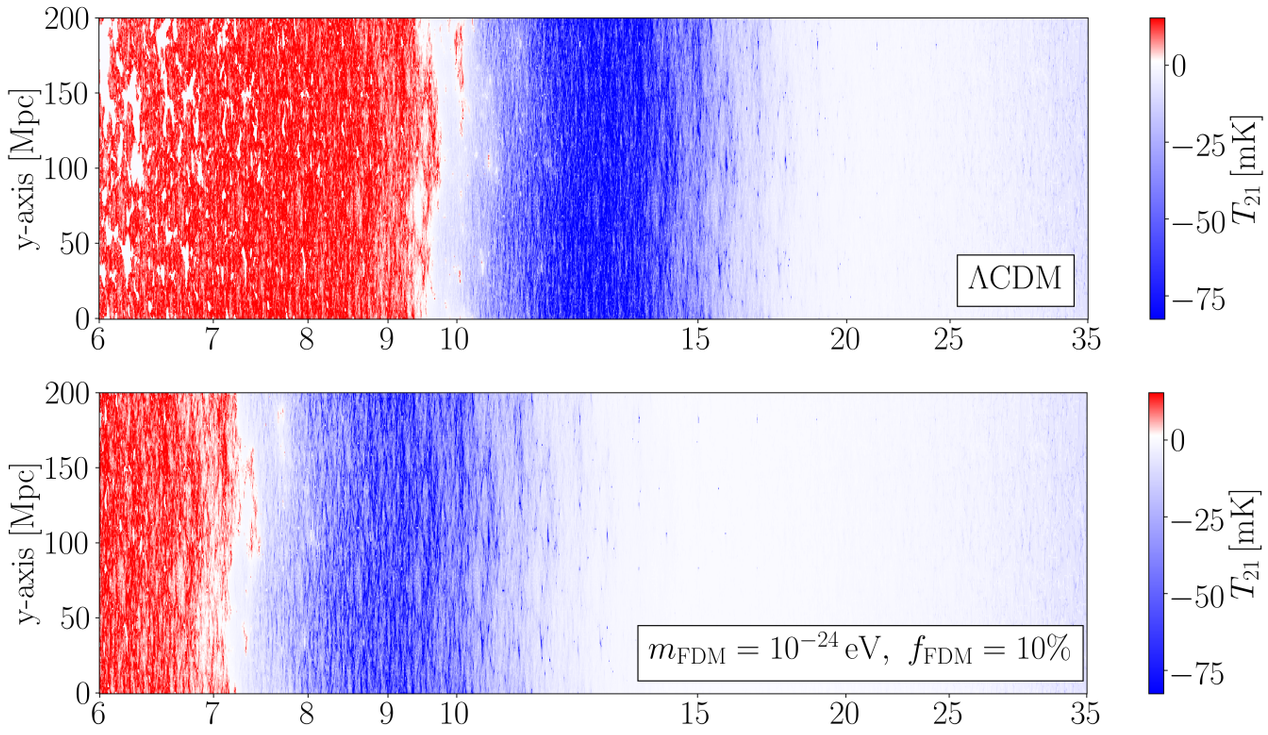

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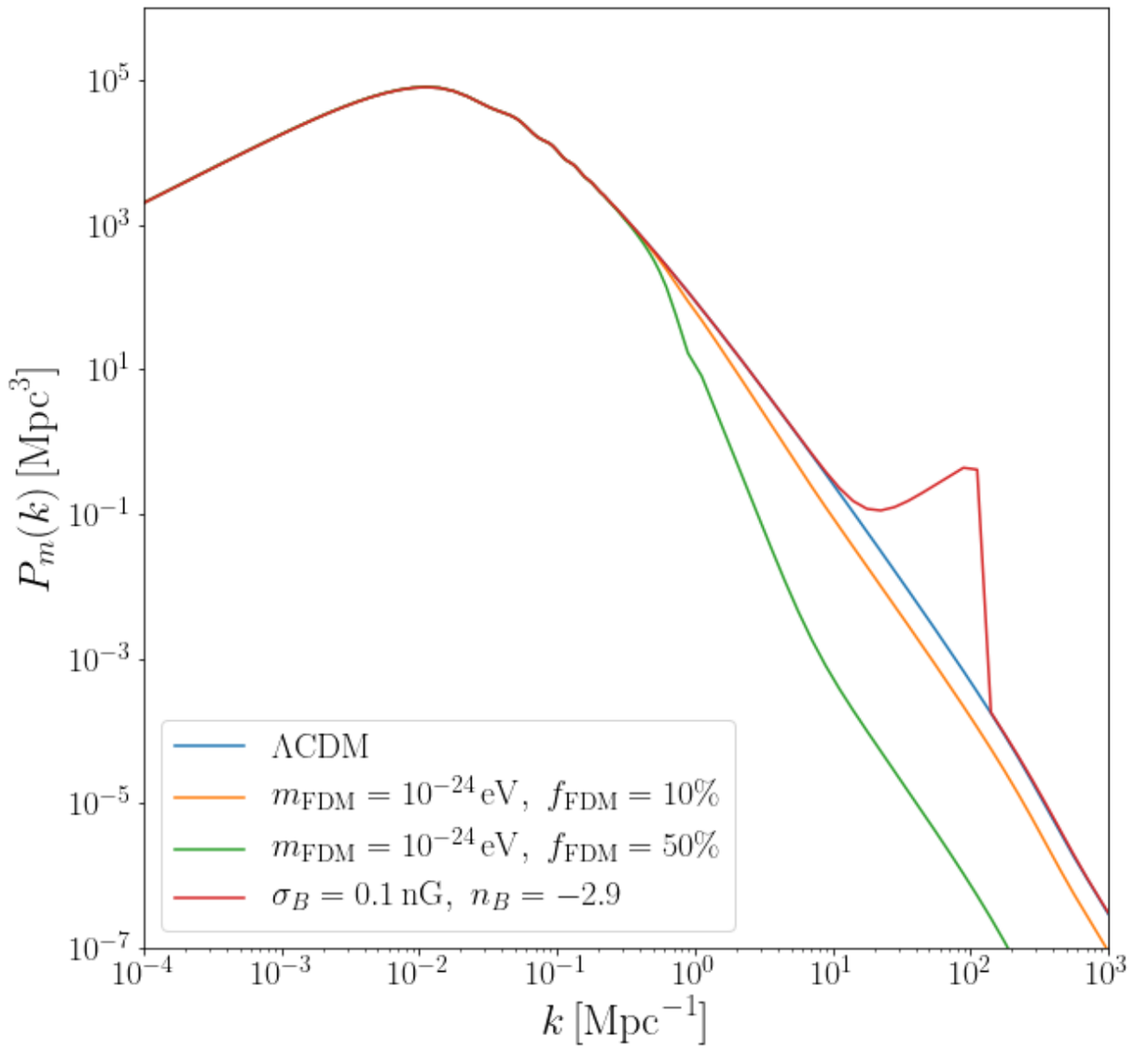

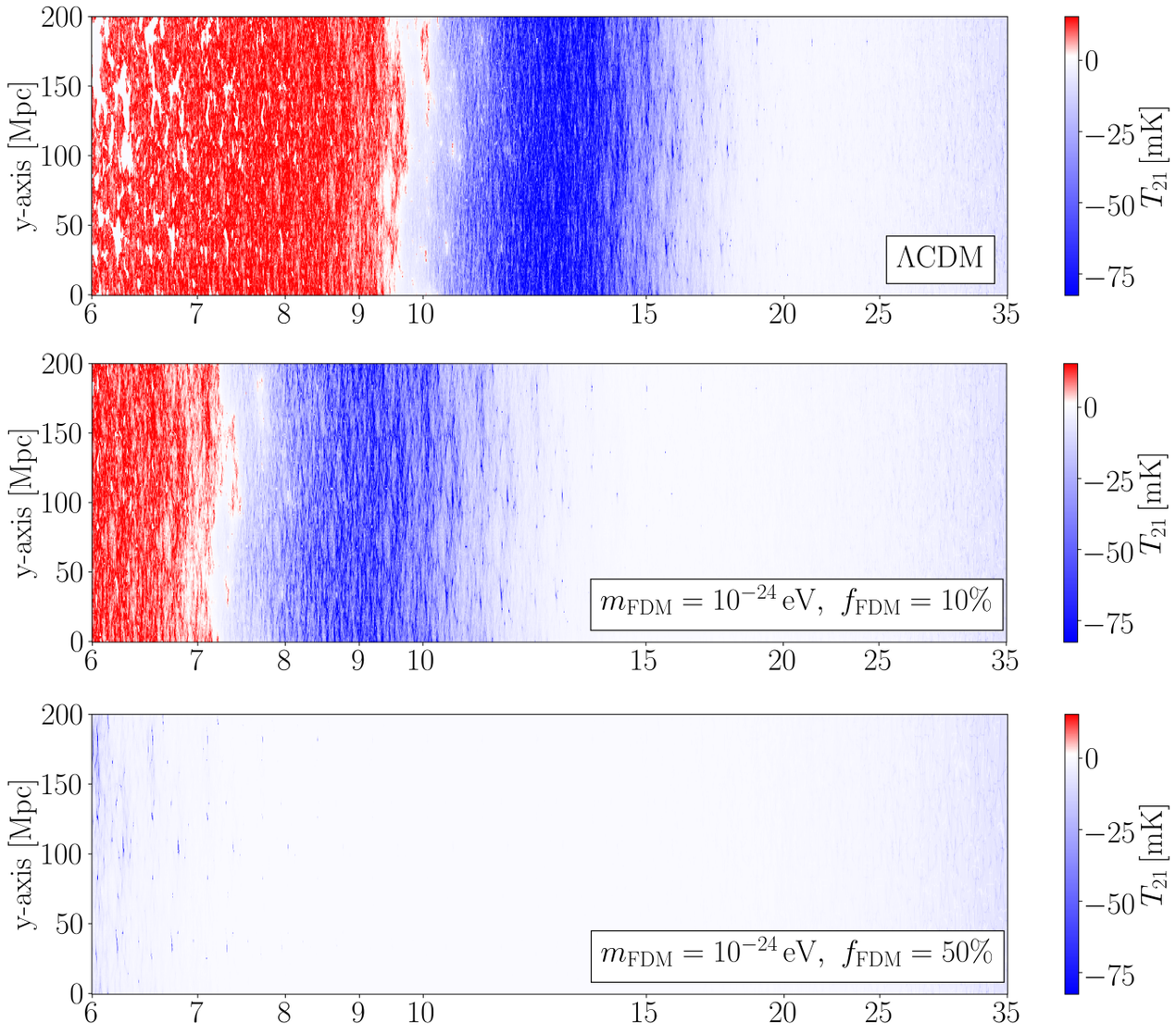

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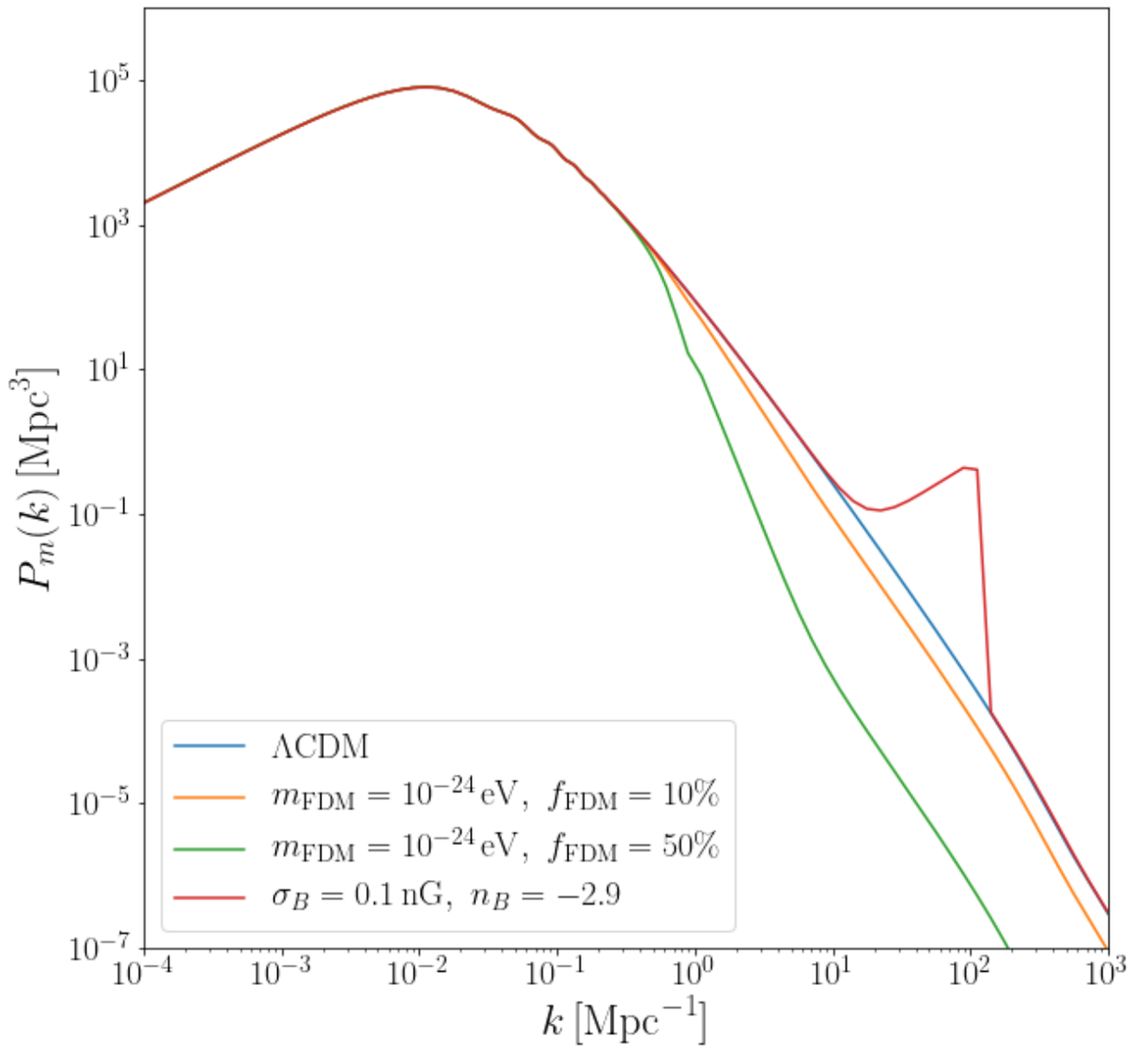

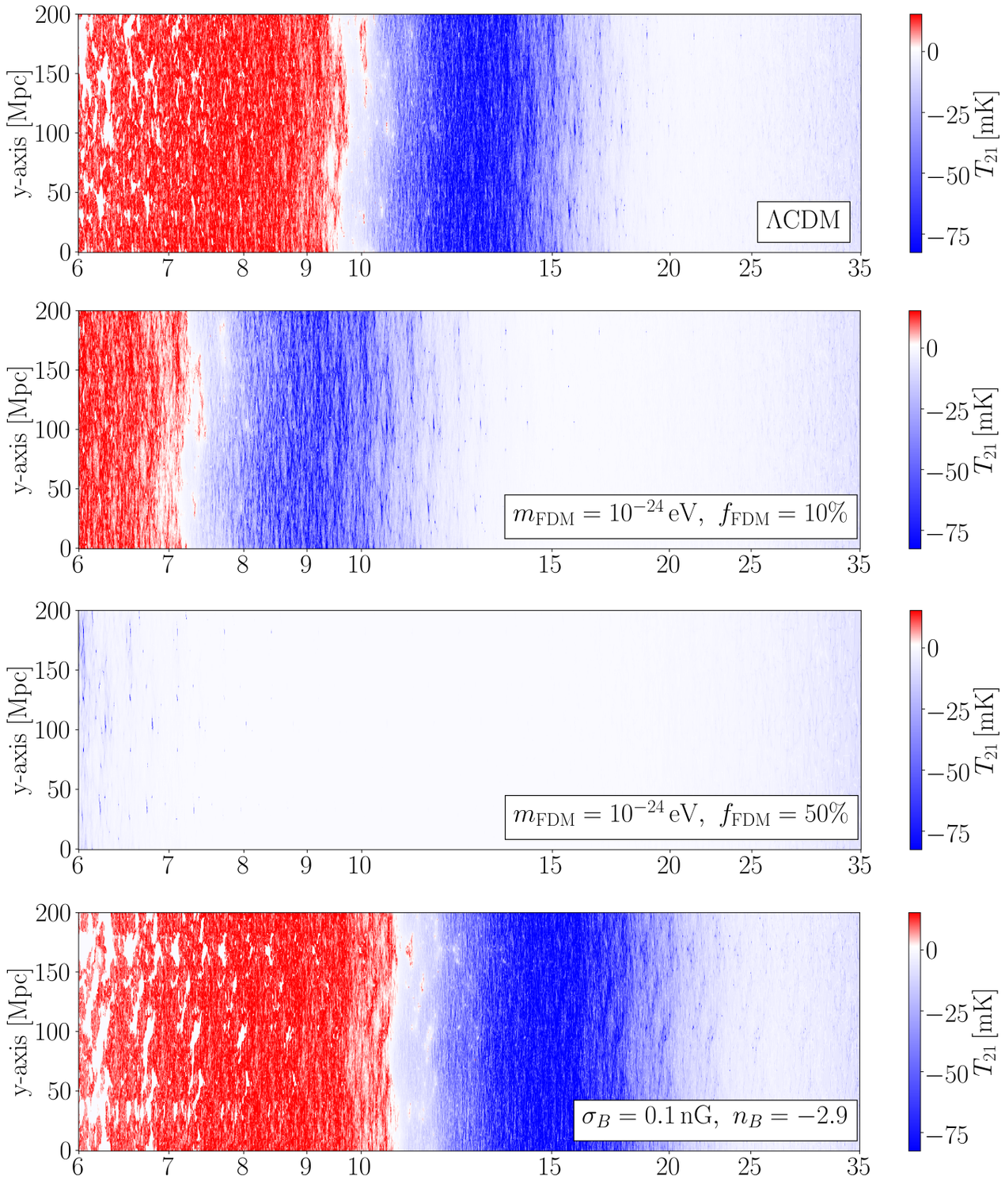

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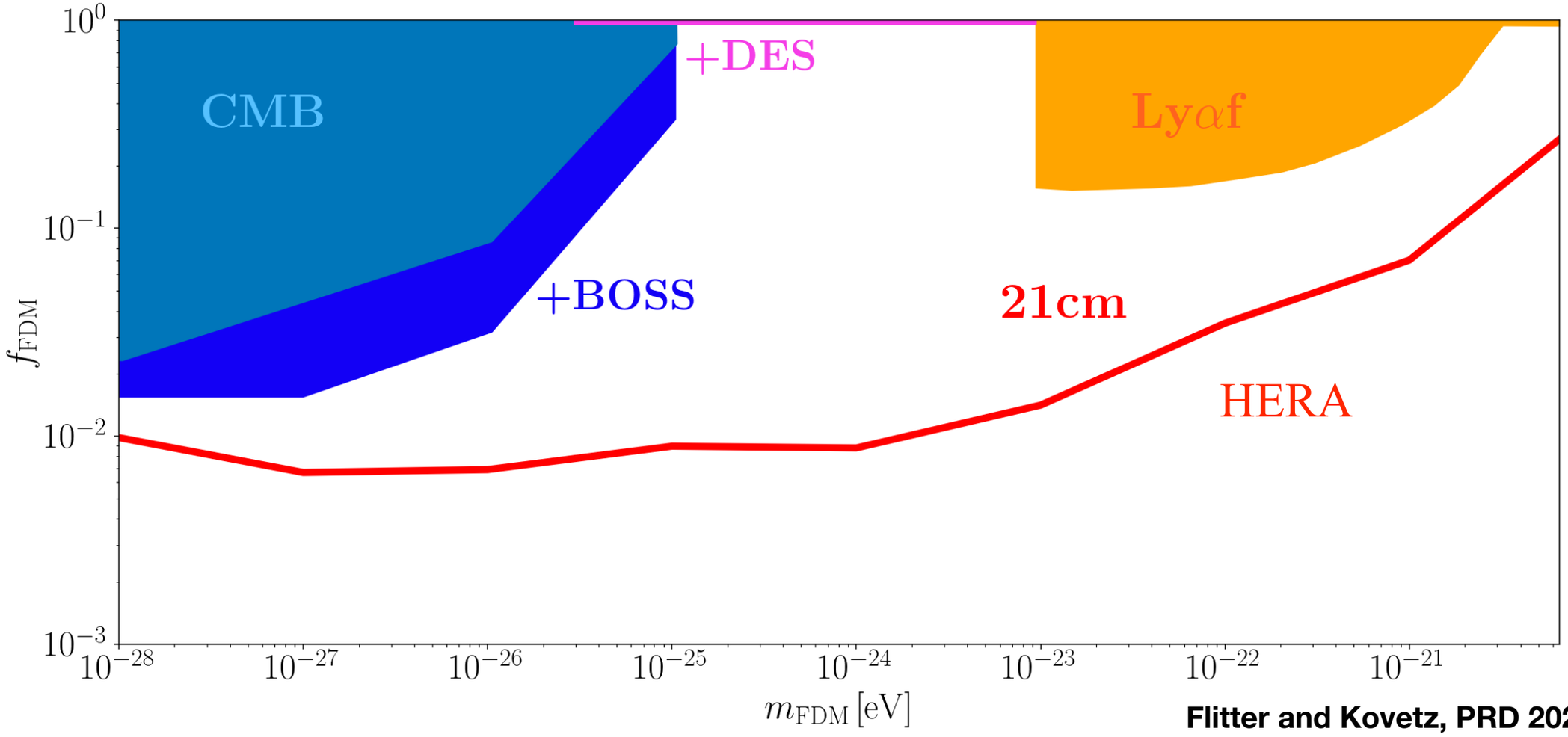

Flitter and Kovetz, PRD 2022

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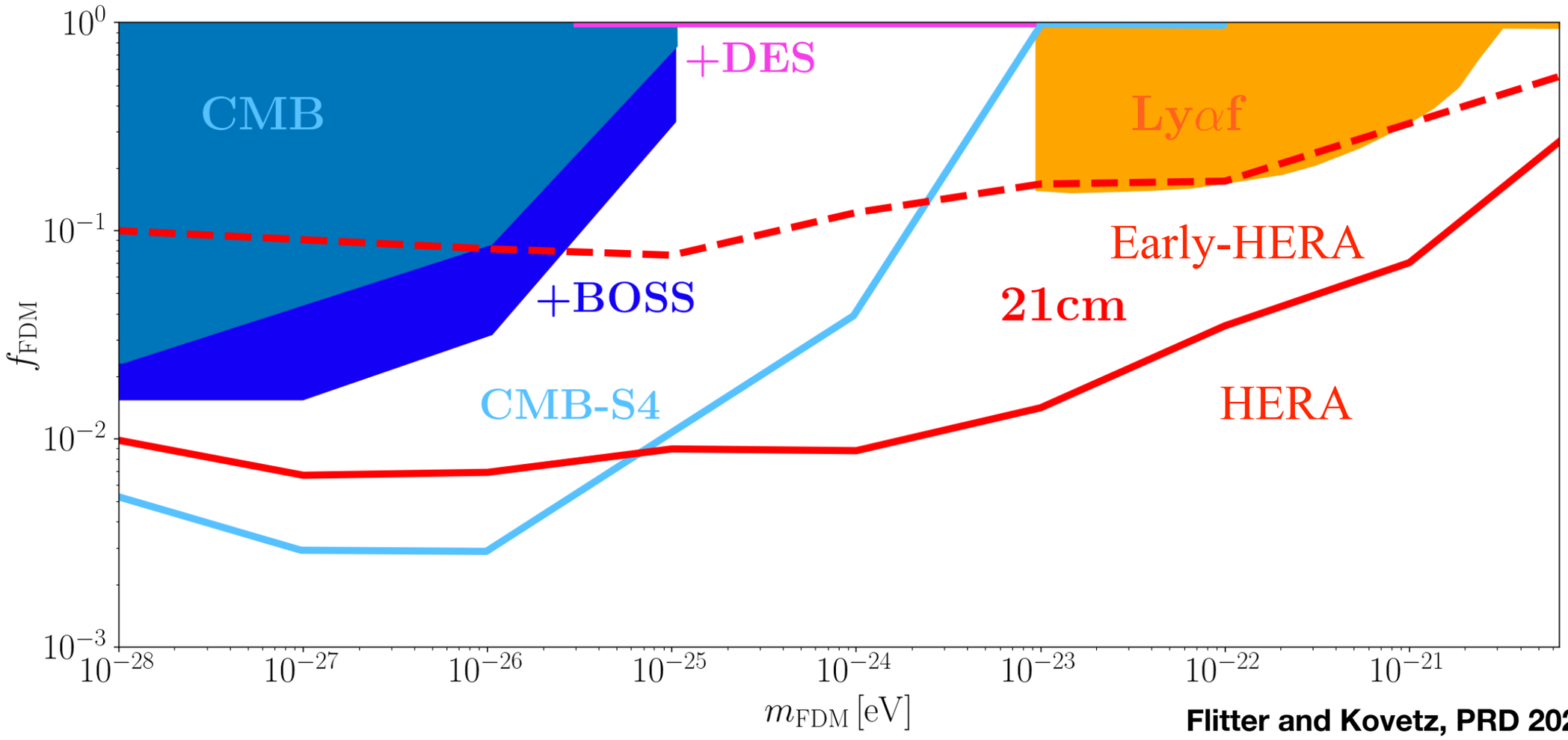

Flitter and Kovetz, PRD 2022

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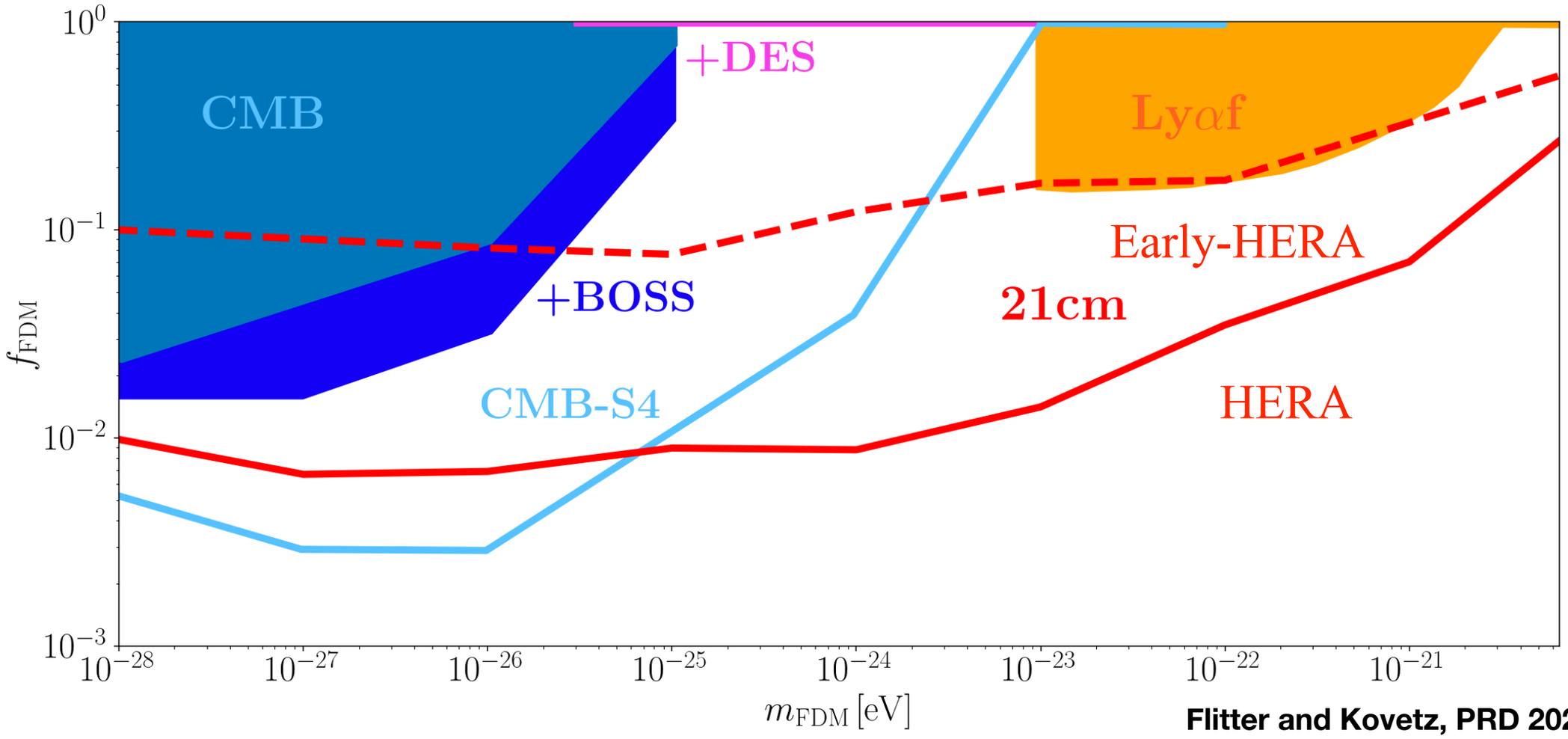

Flitter and Kovetz, PRD 2022

Primordial Magnetic Fields:

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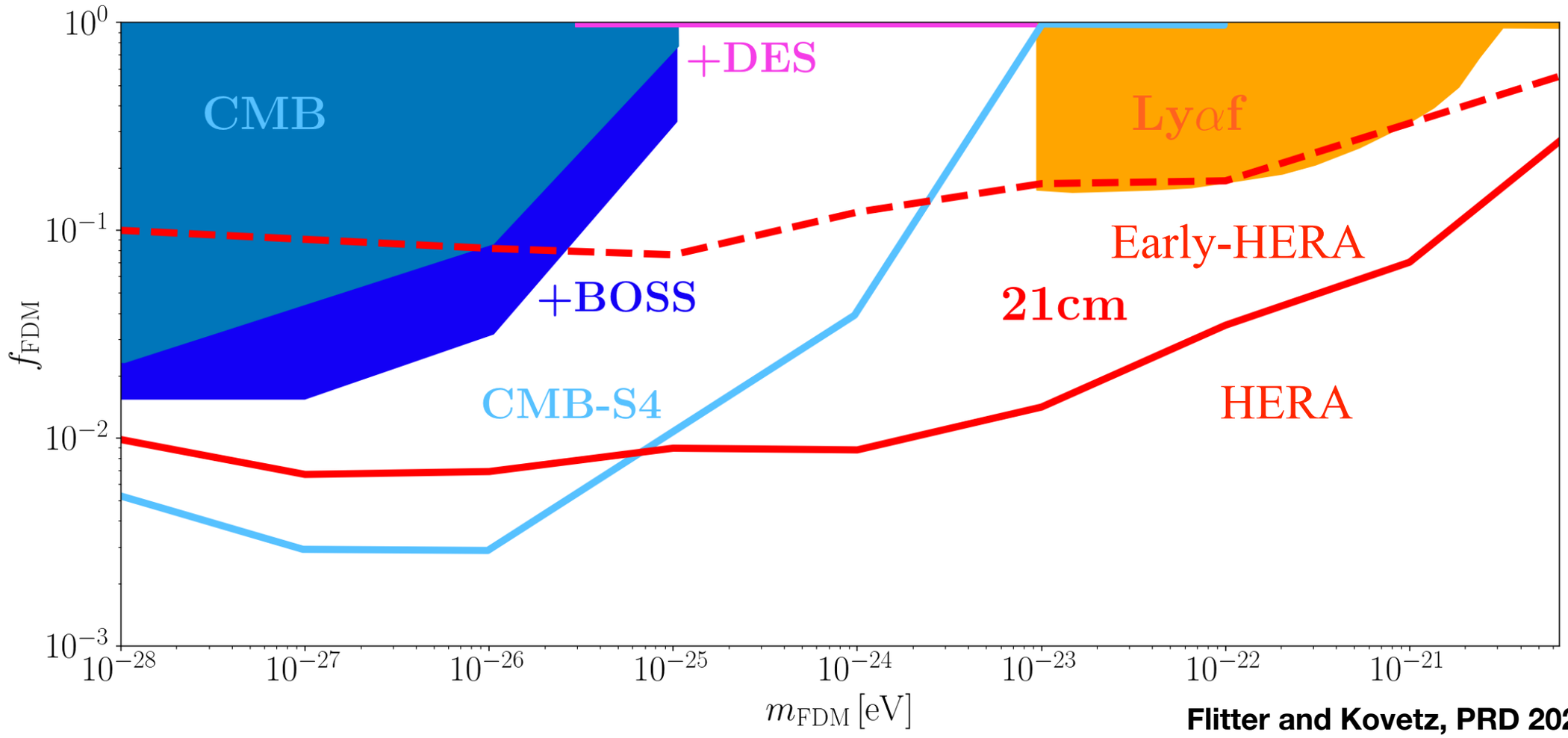

Flitter and Kovetz, PRD 2022

Primordial Magnetic Fields:

LIM (e.g. CO) will outdo future CMB experiments

Adi, Libanore and Kovetz, JCAP 2023

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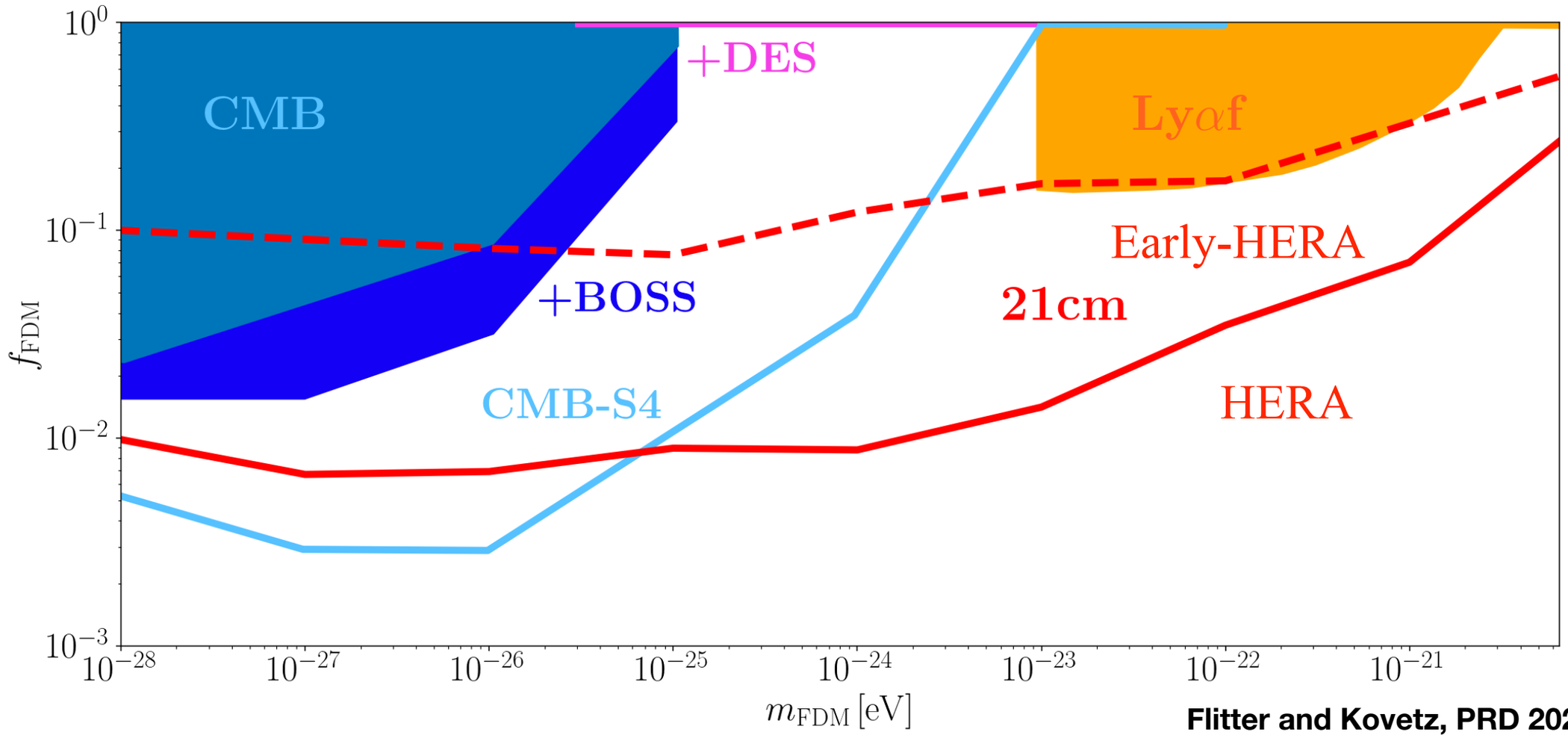

Flitter and Kovetz, PRD 2022

Primordial Magnetic Fields:

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Adi, Libanore and Kovetz, JCAP 2023

21cm will beat other probes by more than order of magnitude

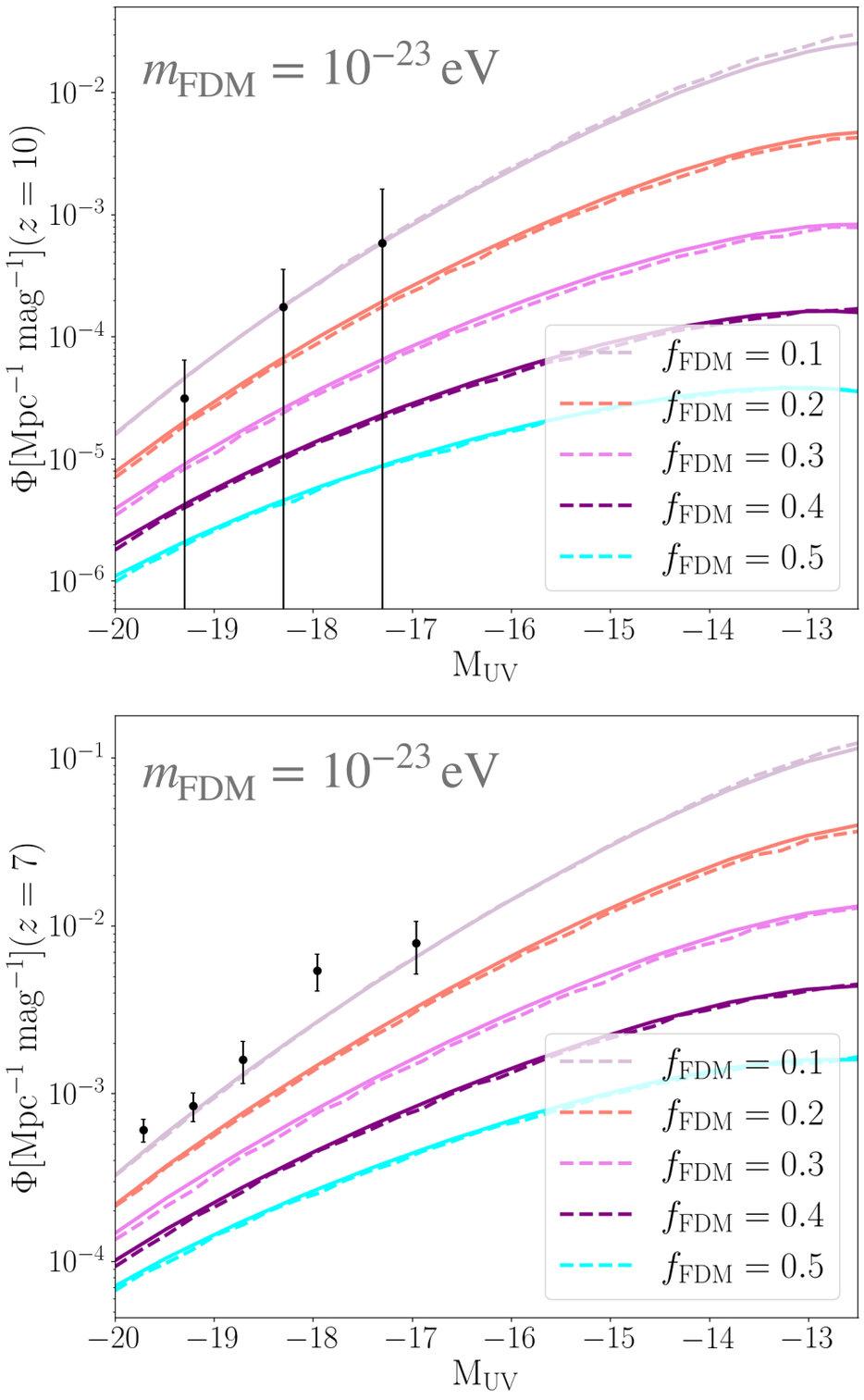
Cruz, Adi, Flitter, Kamionkowski and Kovetz, PRD 2024

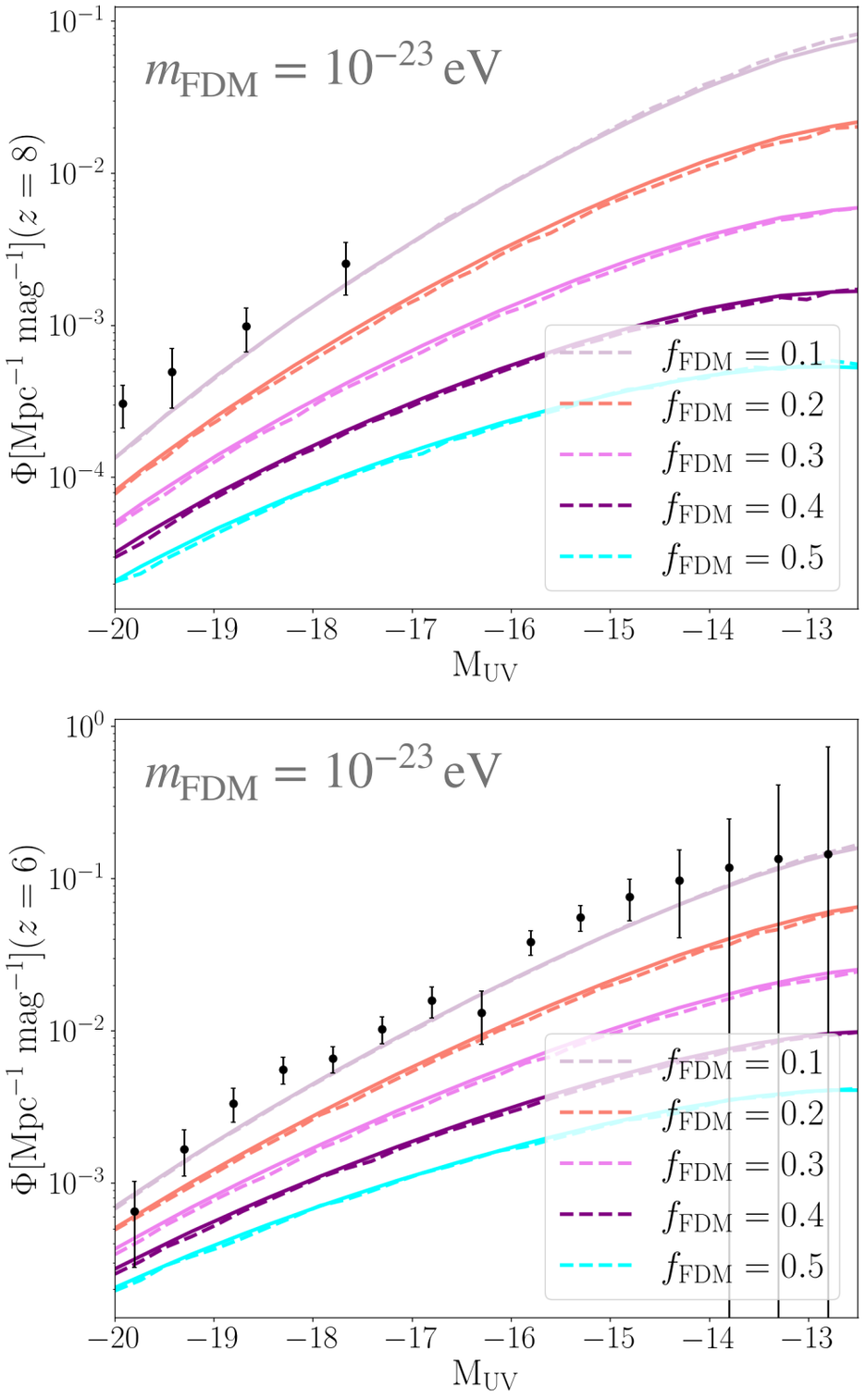
Example 2: Is the FDM Window Already Closed?

HST UV LFs:

$+\tau_e$

$+x_{HI}$





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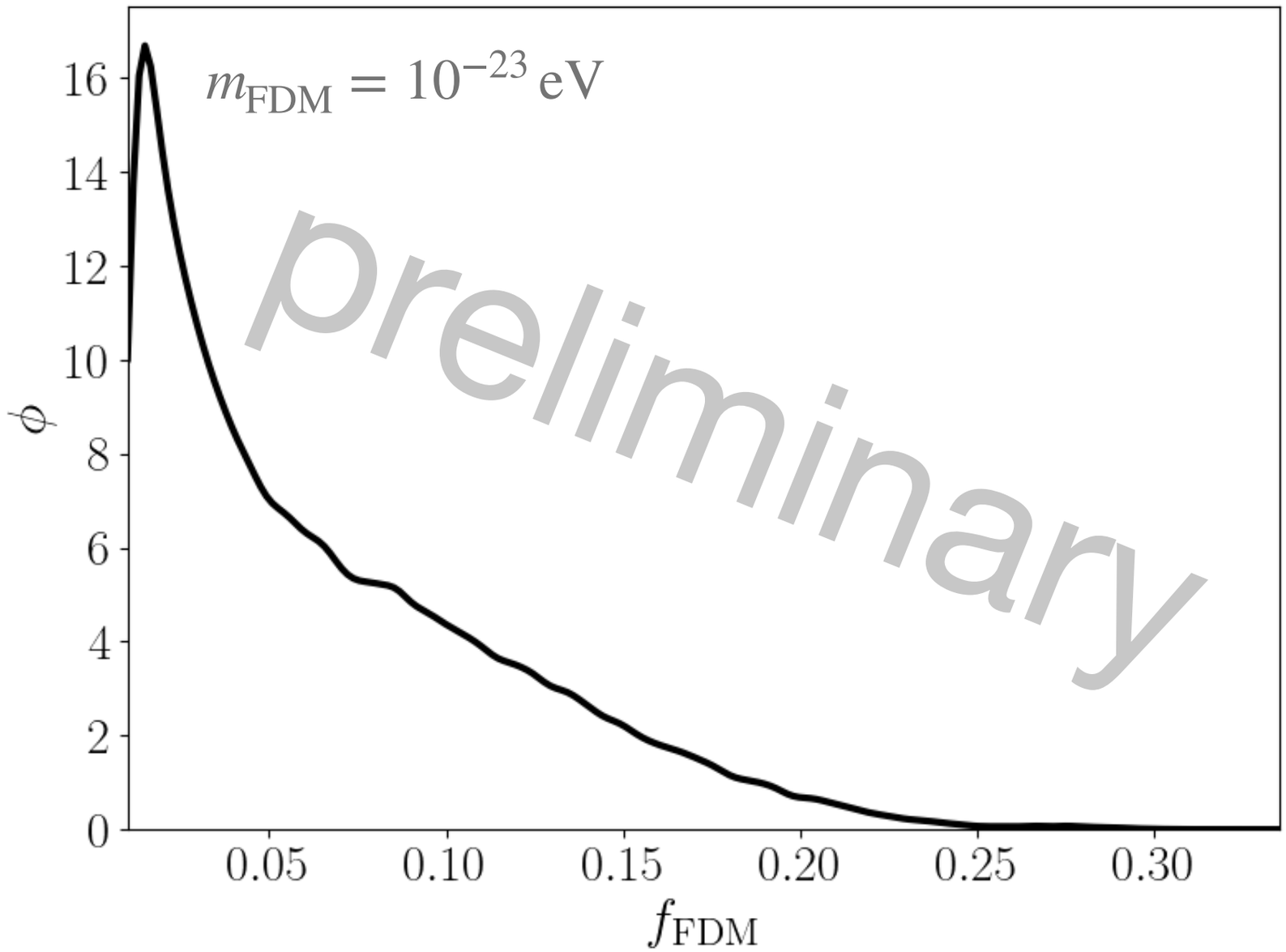
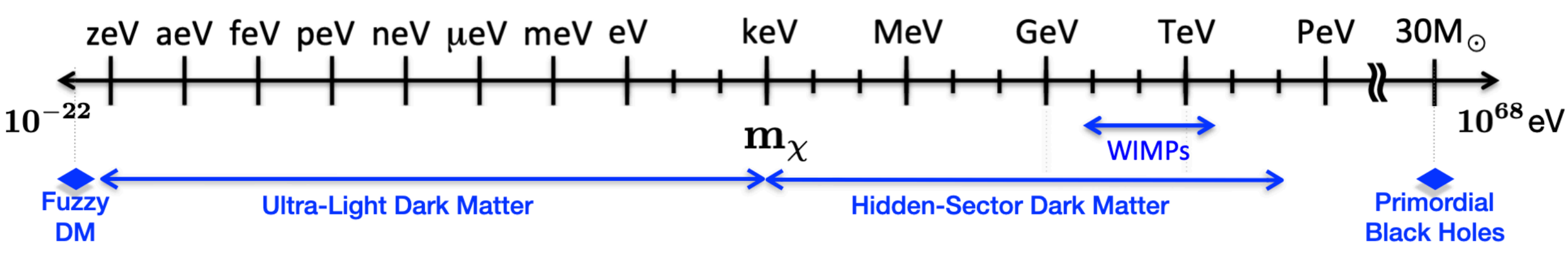
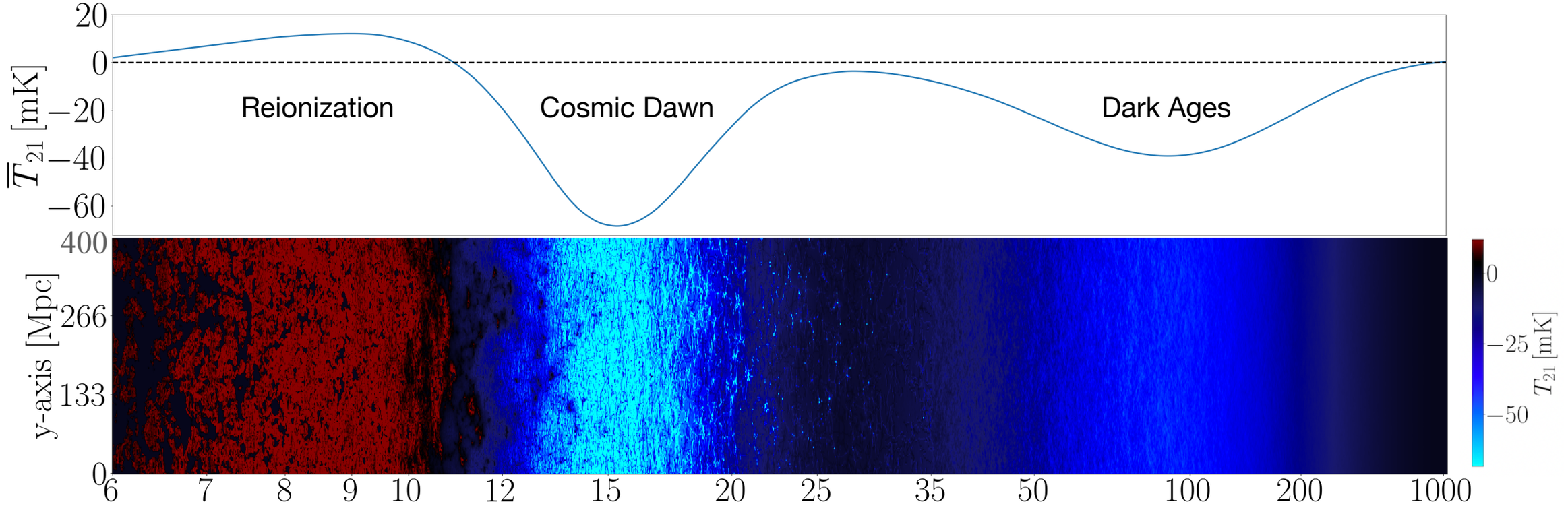
A preliminary analysis using Hubble UV luminosity functions



21cmFirstCLASS©: Probing DM at Cosmic Dawn

Ely Kovetz, Ben-Gurion University





ALPS2024 Dark Matter Workshop, Obergurgl, Apr. 2024