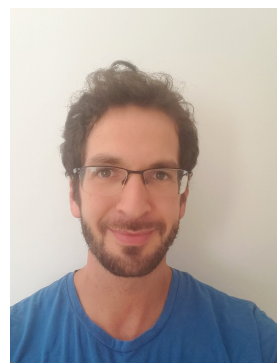
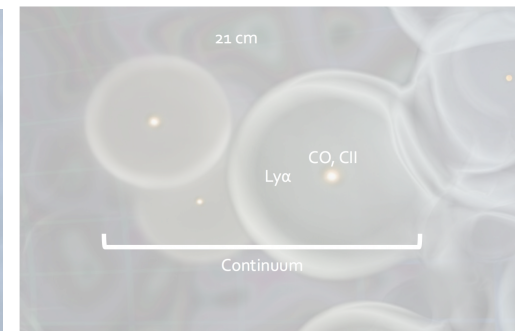
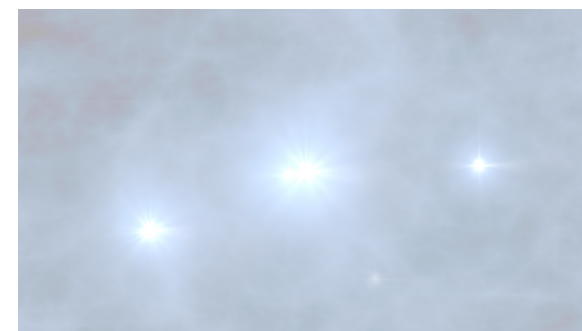
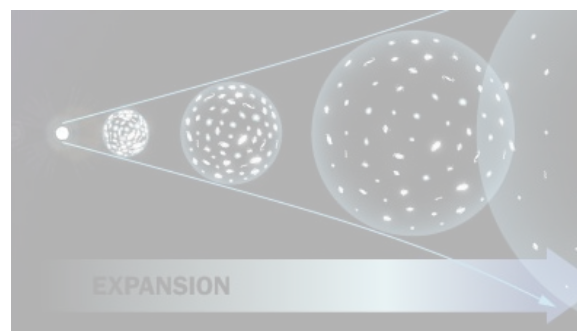
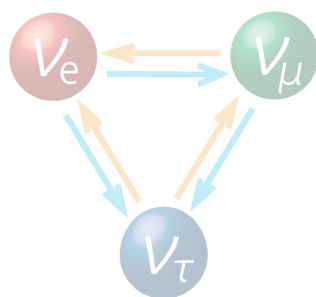
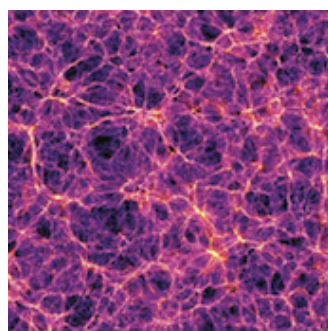
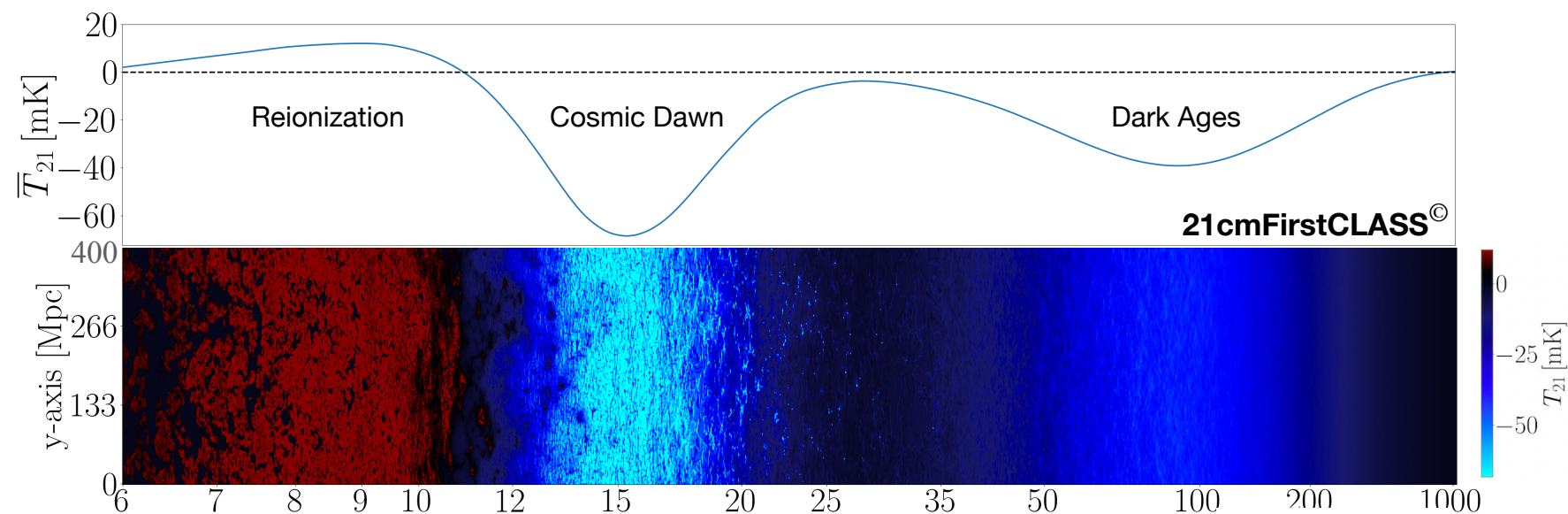
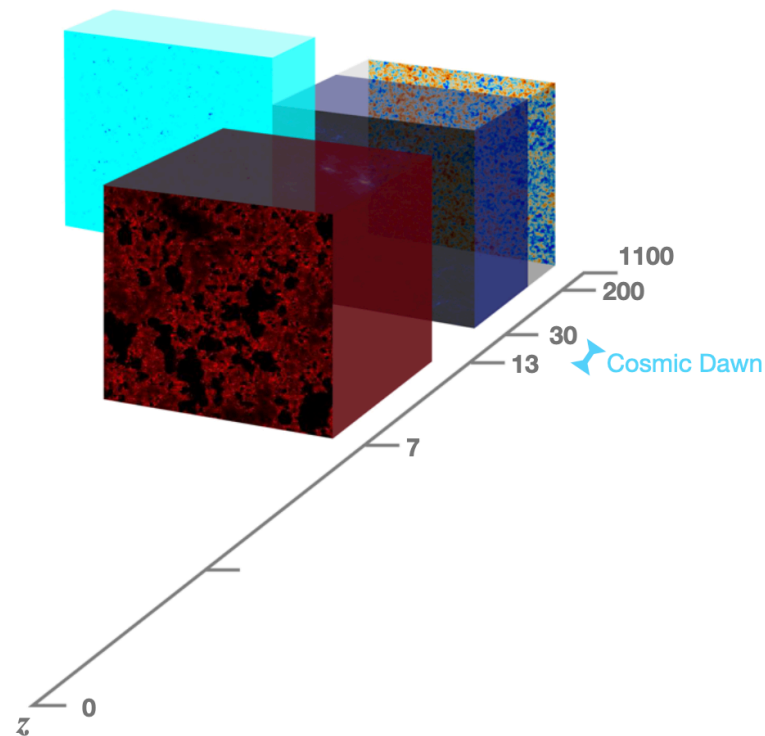


The Dawn of Cosmic Dawn Cosmology

Ely Kovetz

Ben-Gurion University & UT Austin (Sabbatical)



Jordan Flitter



Tal Adi



Hovav Lazare



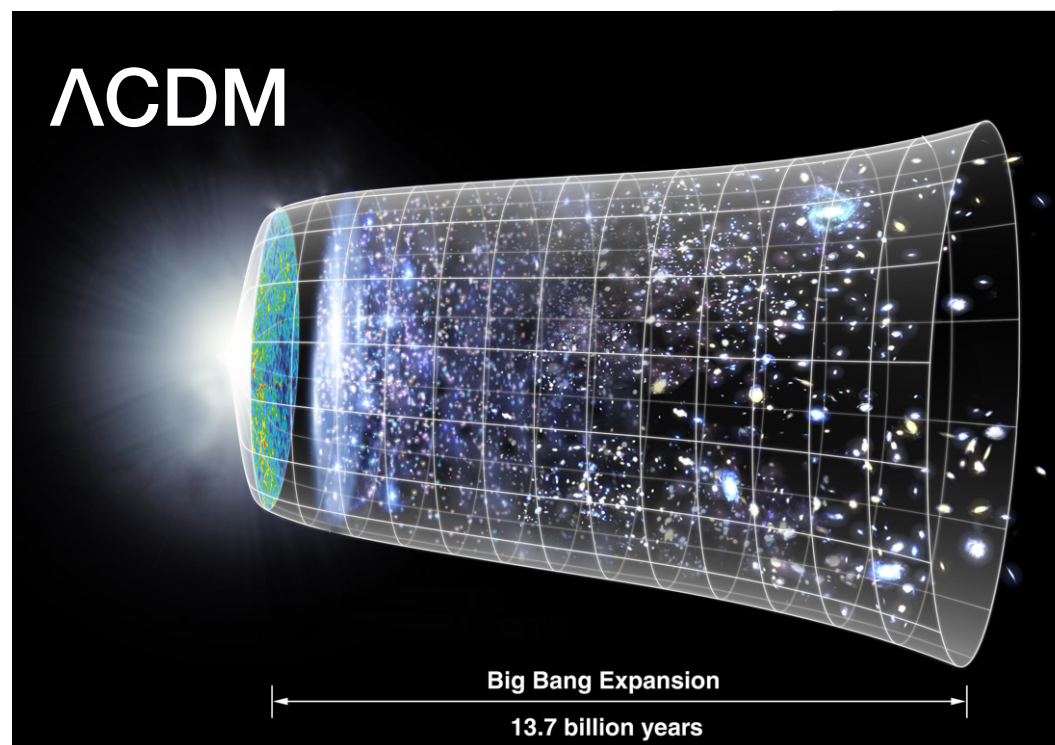
Sarah Libanore



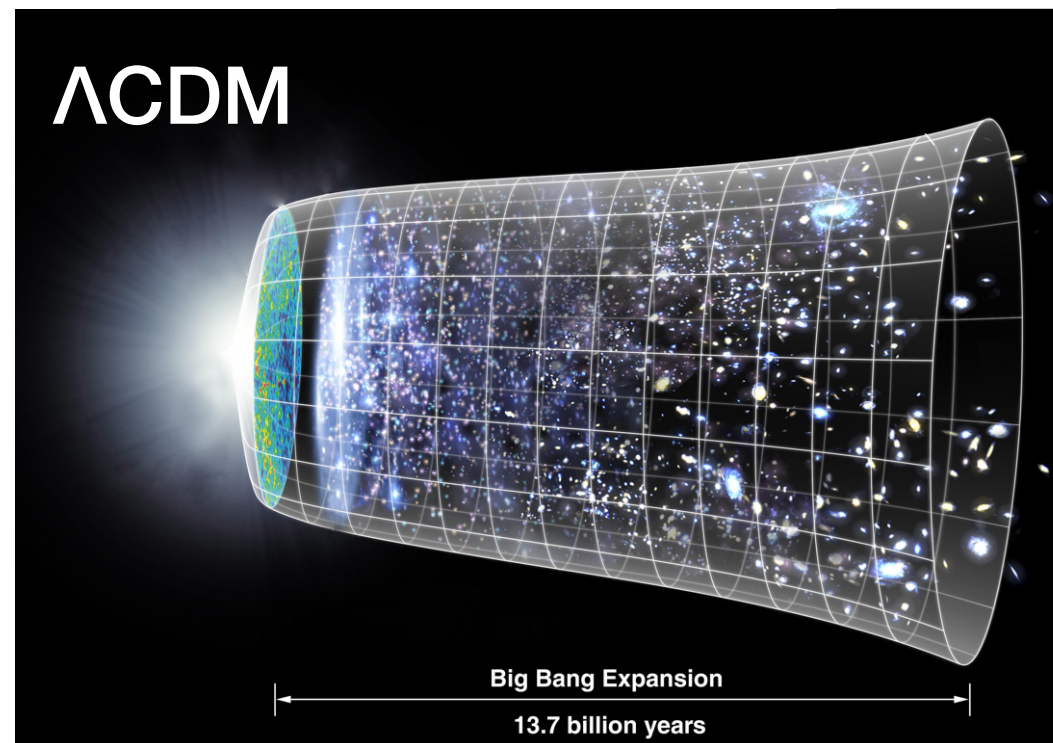
Debanjan Sarkar

LIM Probes all *Standard* Questions in Cosmology

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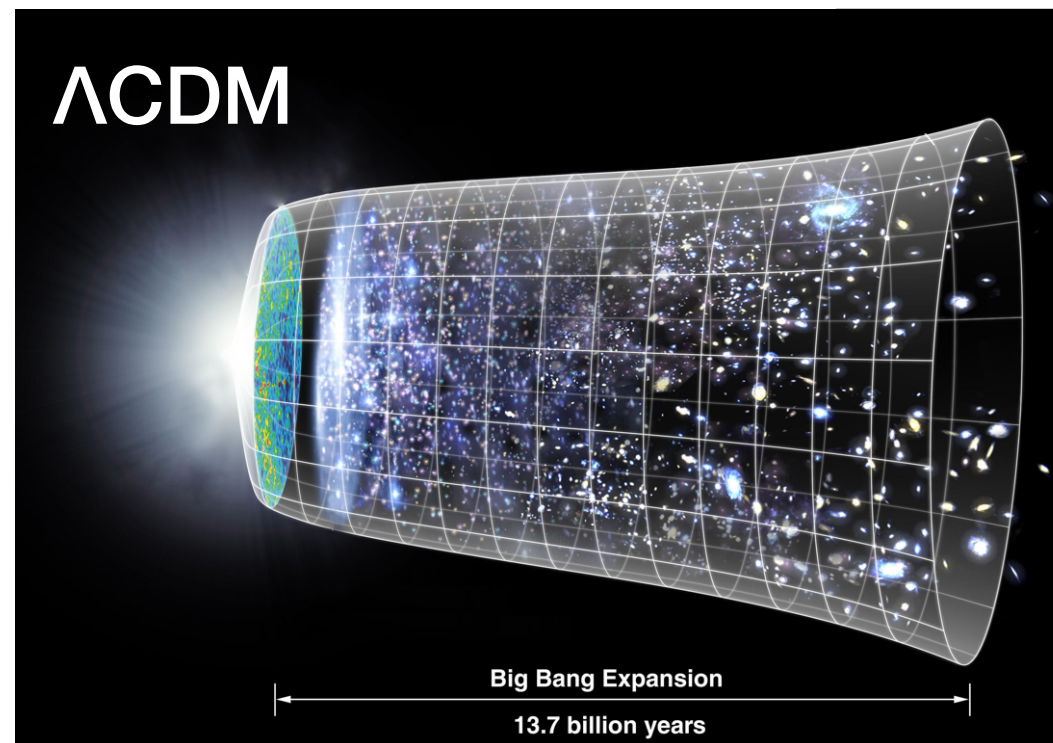


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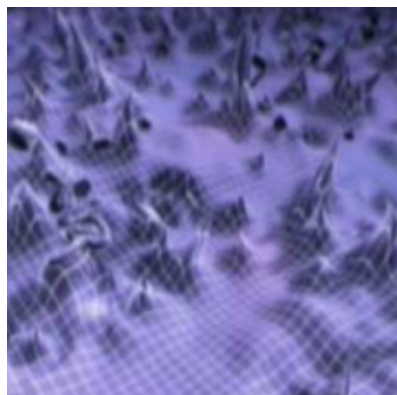


Core questions in cosmology?

LIM Probes all *Standard* Questions in Cosmology

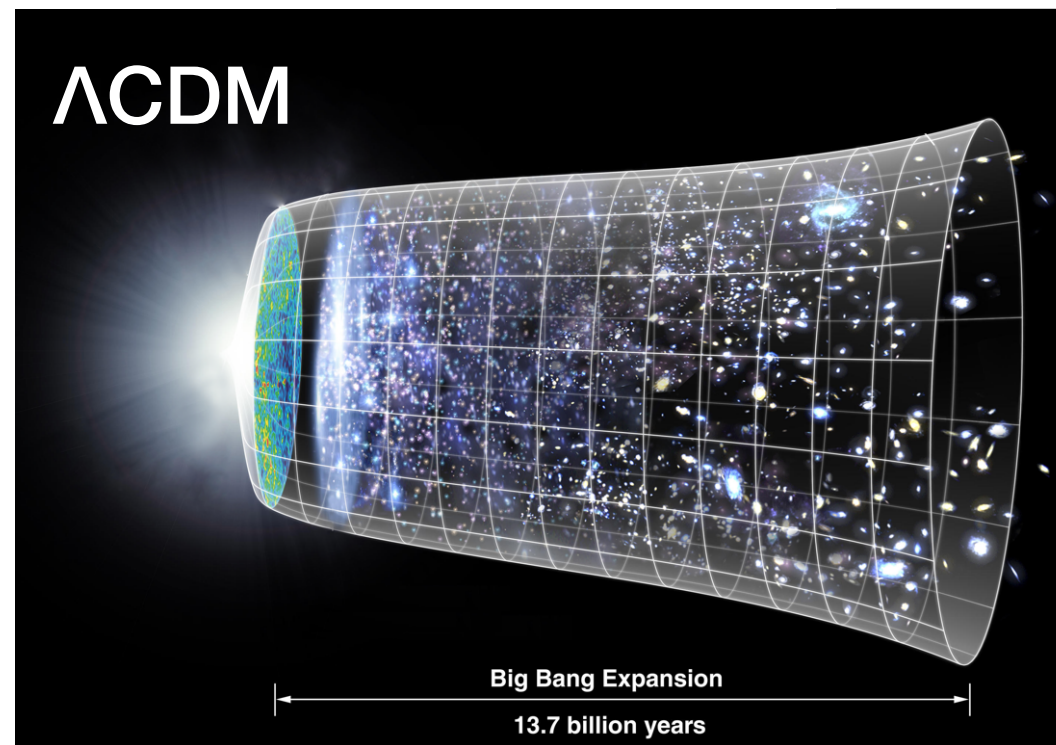


Core questions in cosmology?

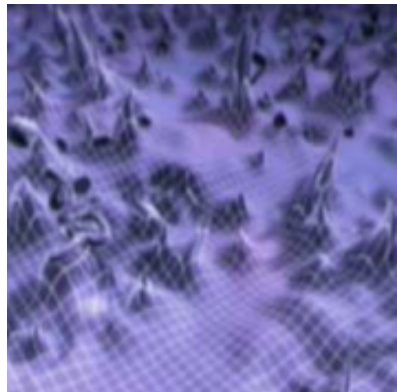


Inflation

LIM Probes all *Standard* Questions in Cosmology



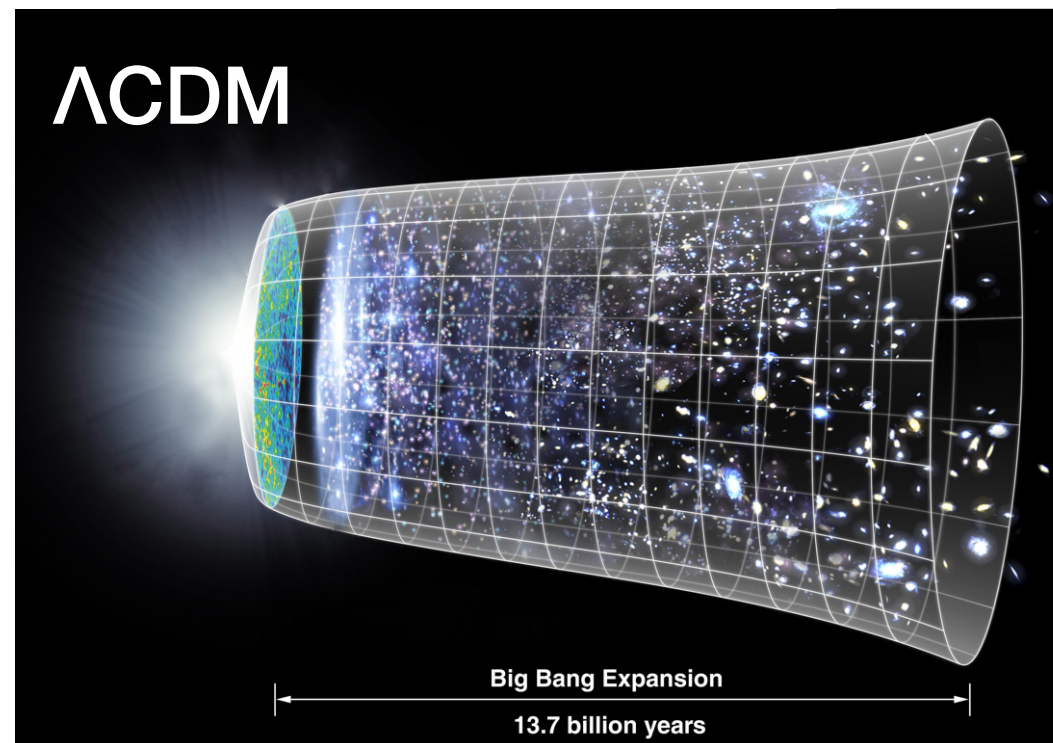
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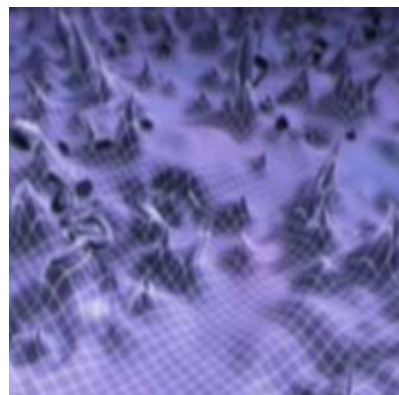
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$$\phi: m_\phi, V(\phi)$$

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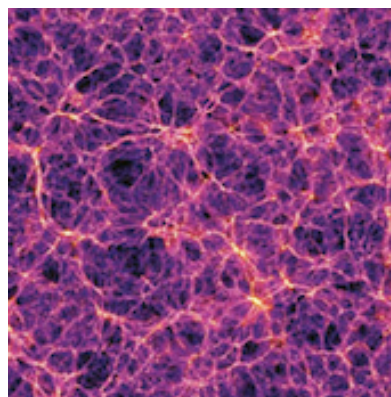


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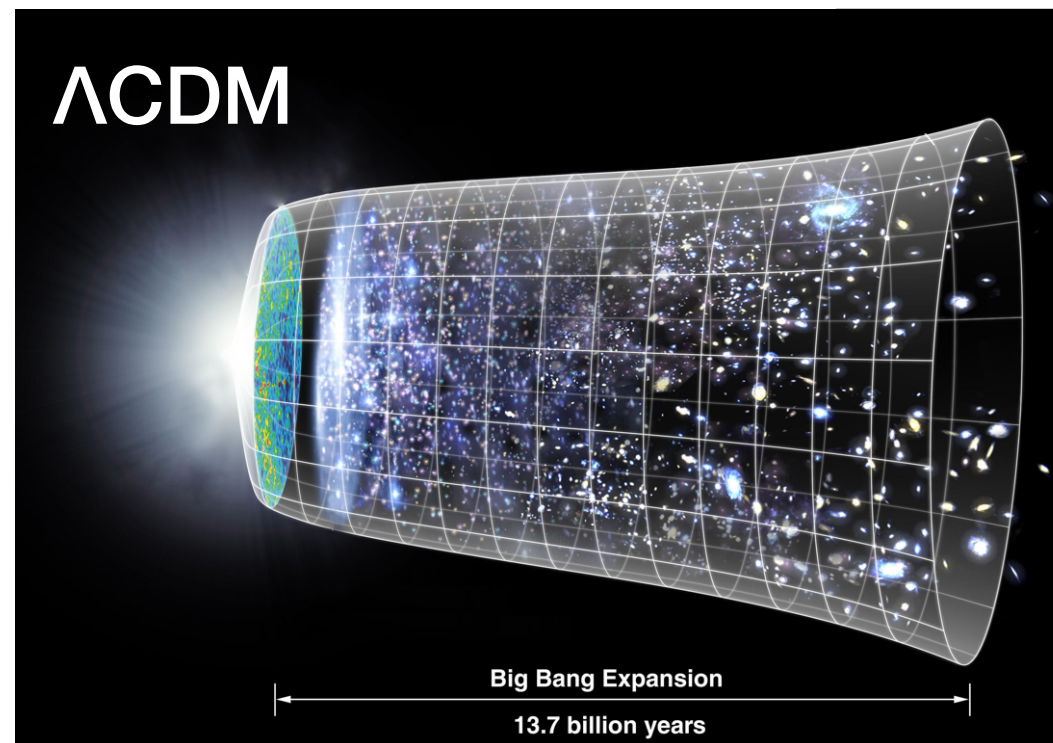
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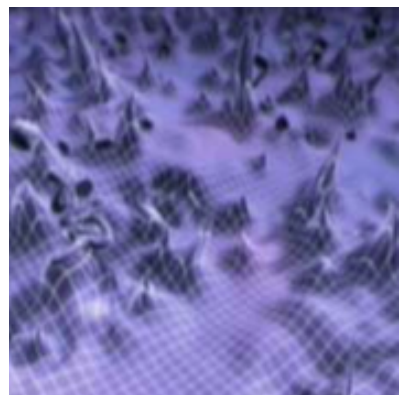


Dark Matter

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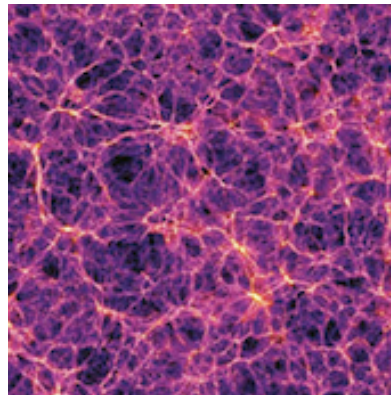


Core questions in cosmology?



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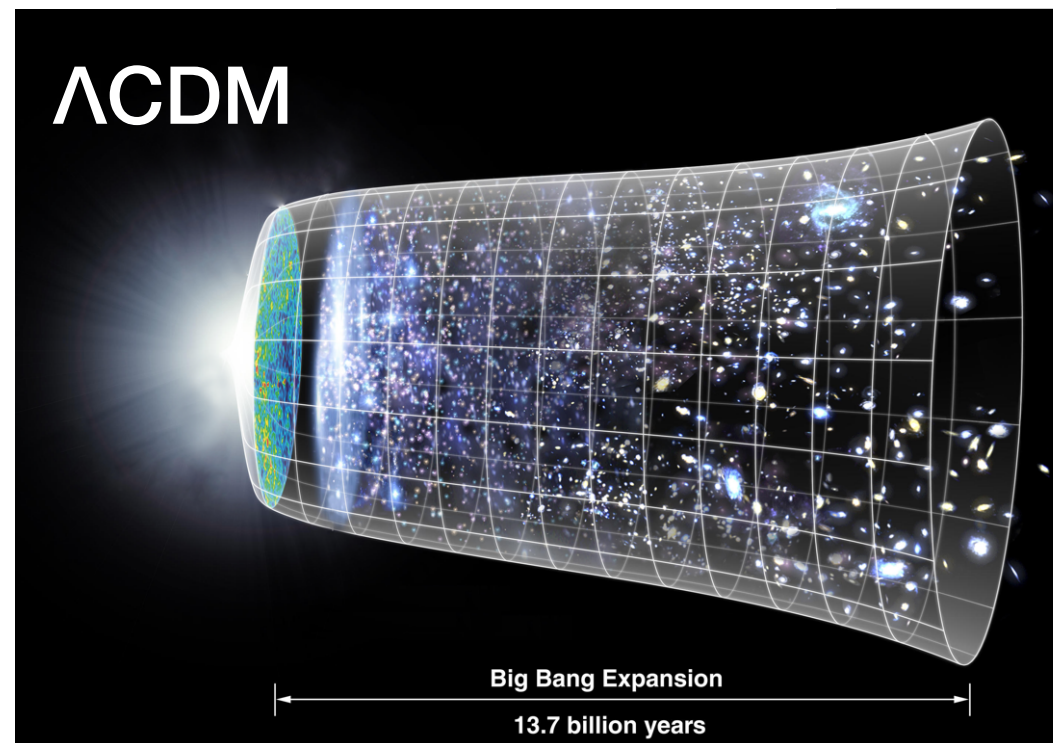
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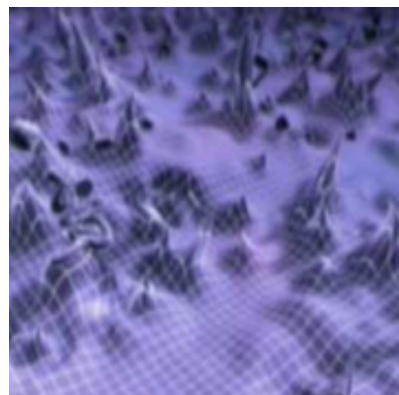
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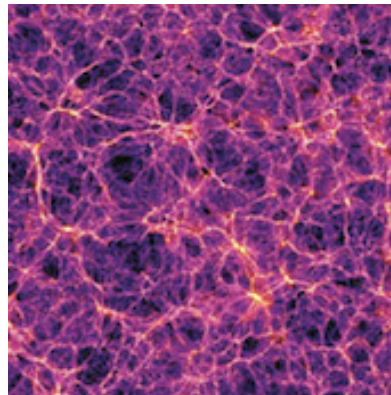


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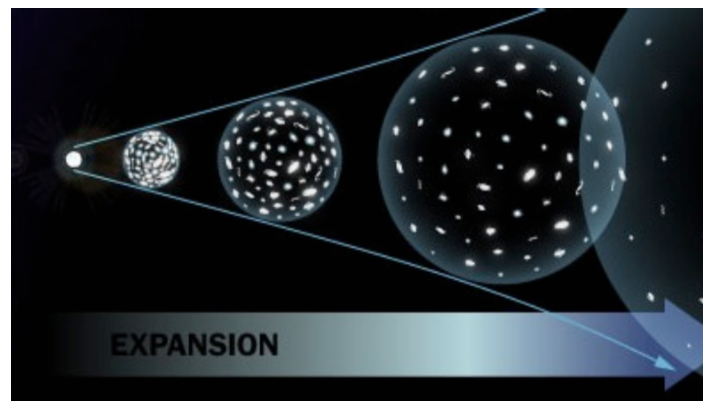
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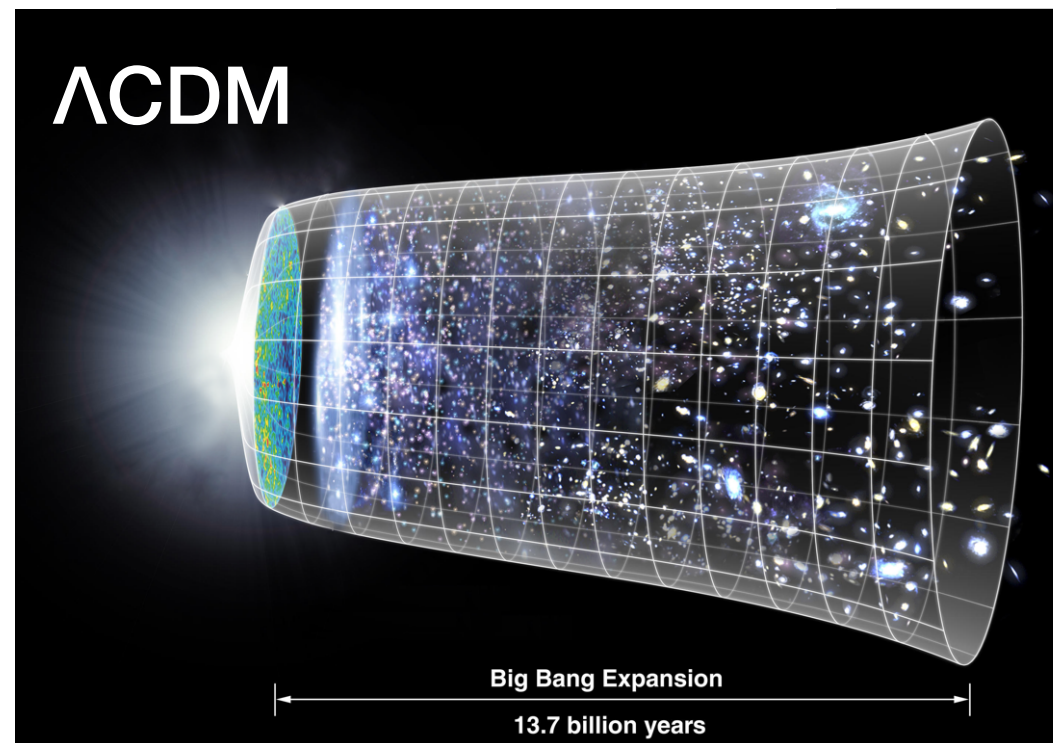
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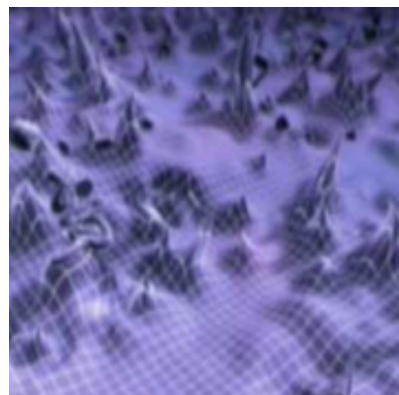


Dark Energy

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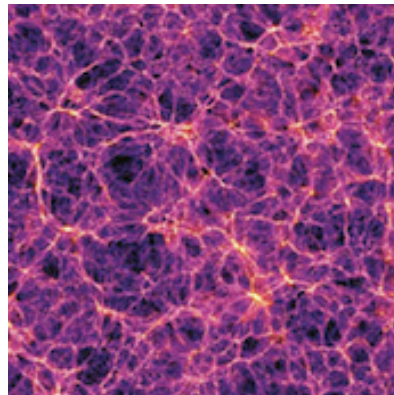


Core questions in cosmology?



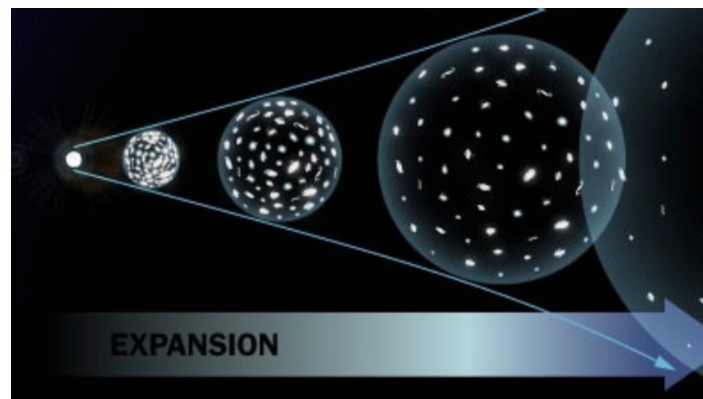
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Dark Matter

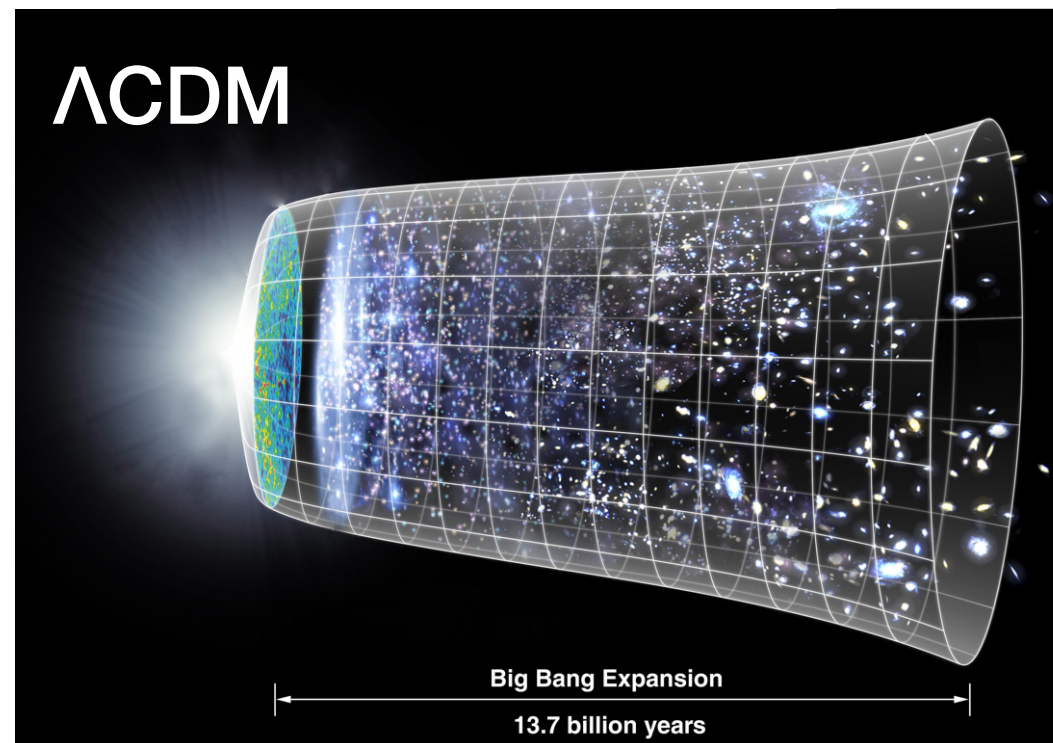
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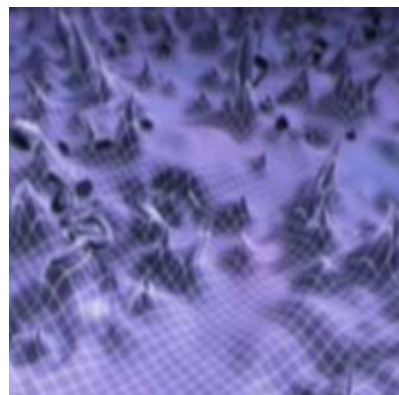
Dark Energy

$$\Lambda ?$$

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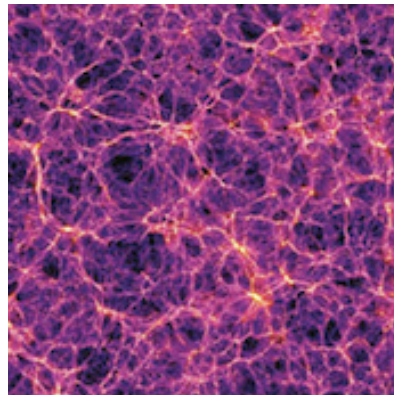


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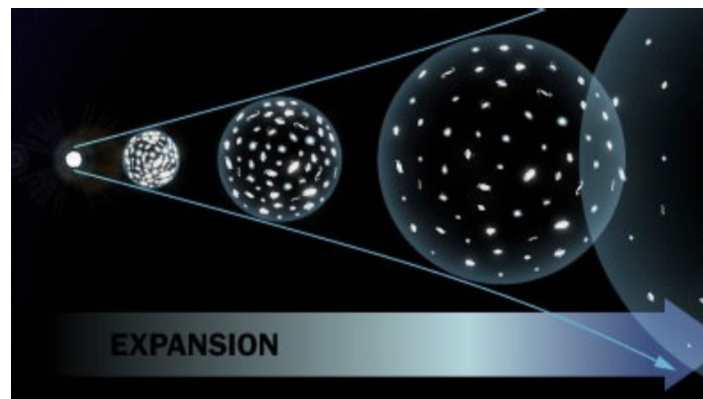
Inflation

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Dark Matter

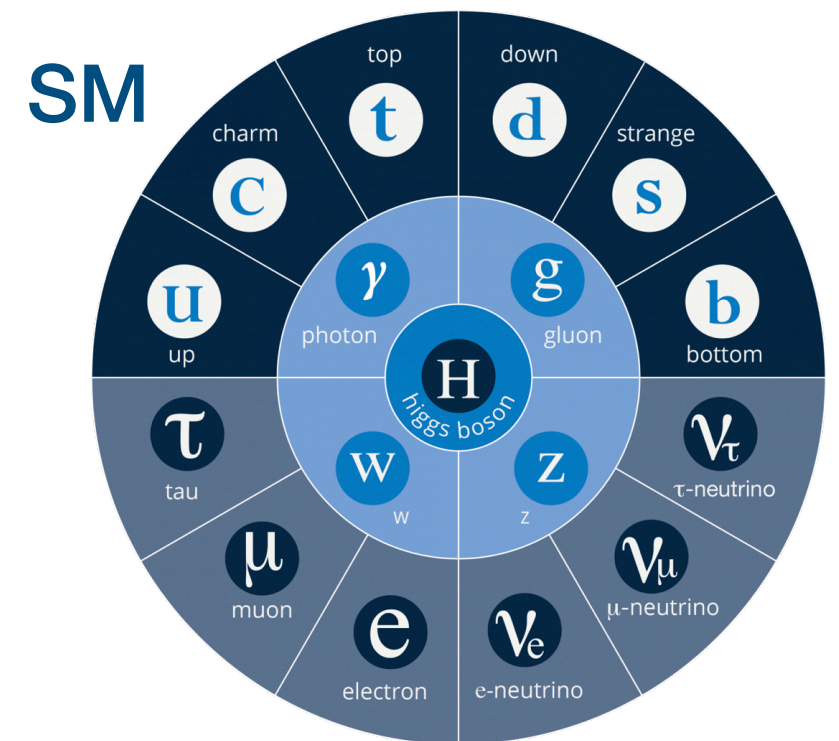
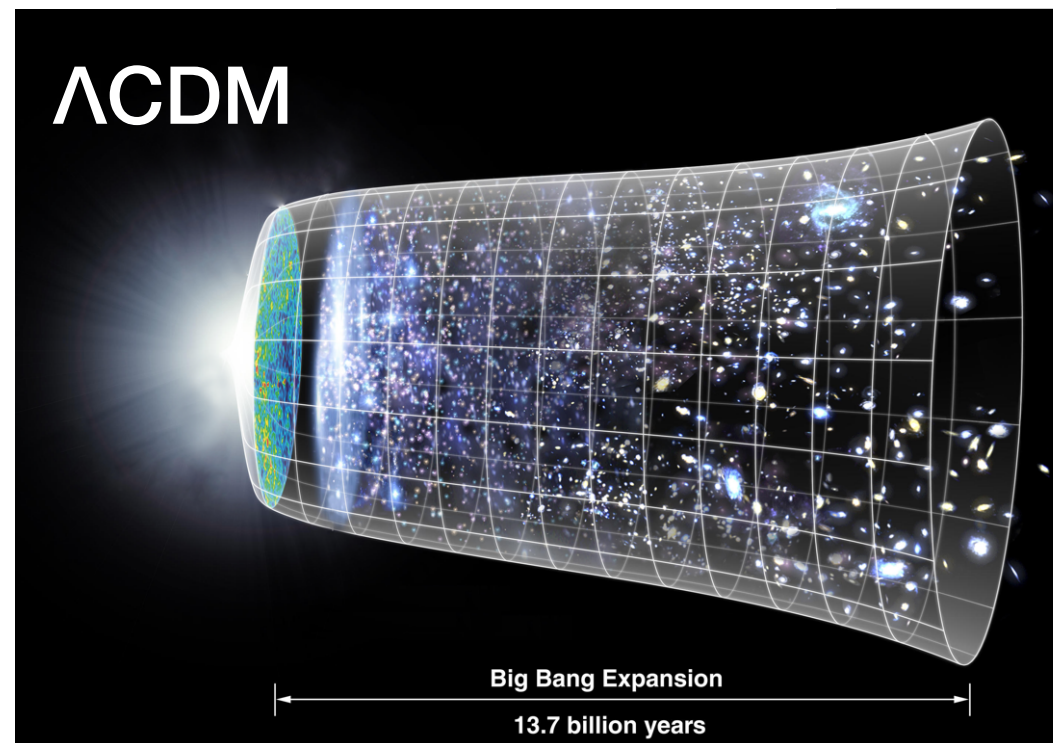
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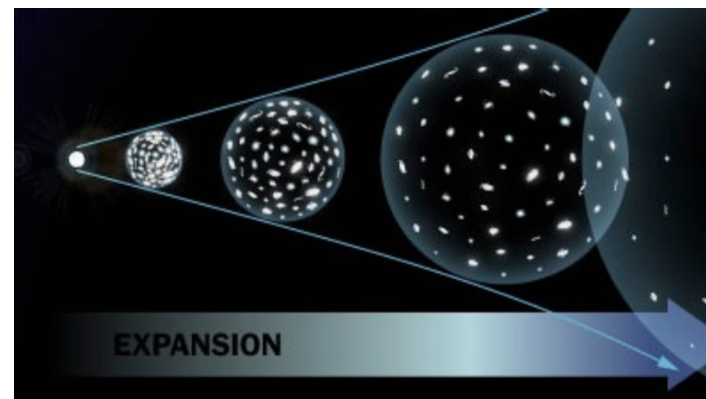
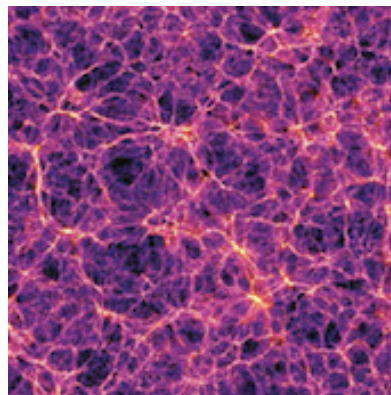
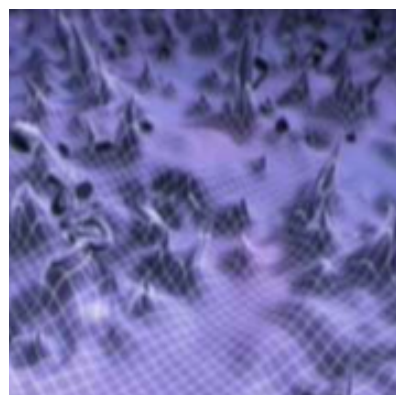
Dark Energy

$$\Lambda? \quad w(a) = w_0 + (1 - a)w_a?$$

LIM Probes all *Standard* Questions in Cosmology



Core questions in cosmology?



Inflation

Dark Matter

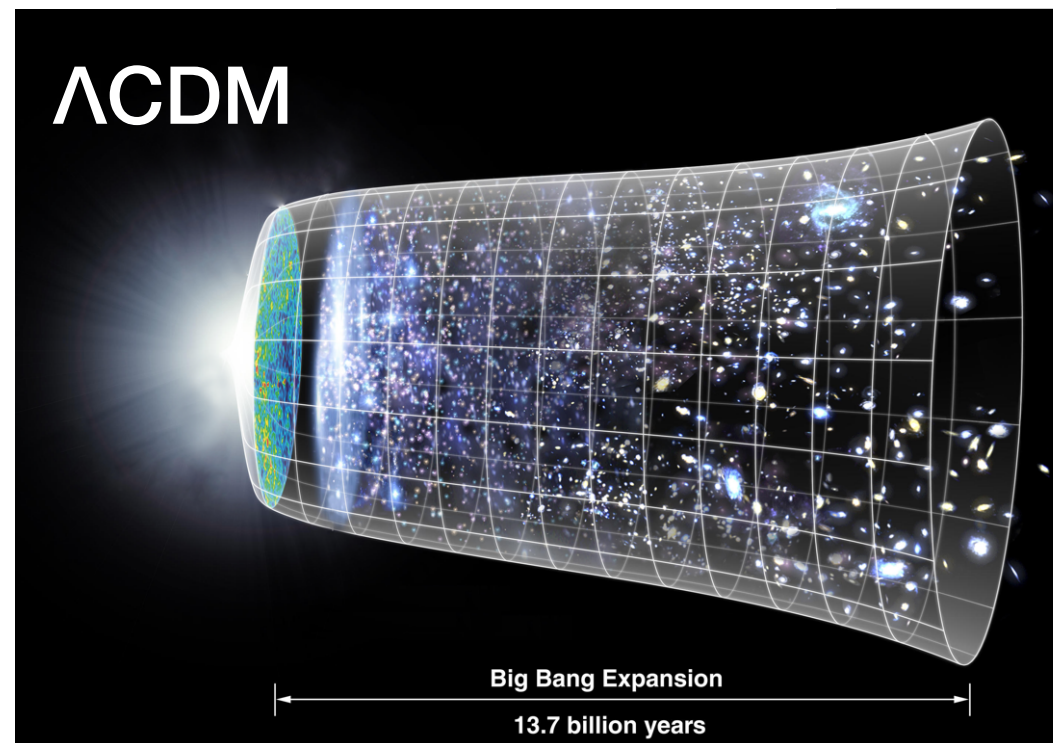
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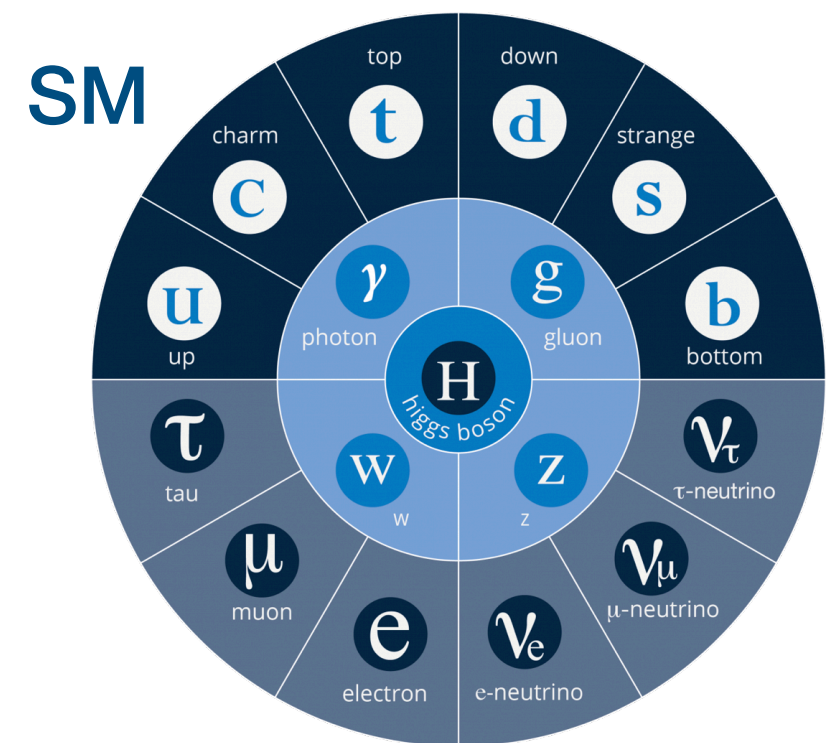
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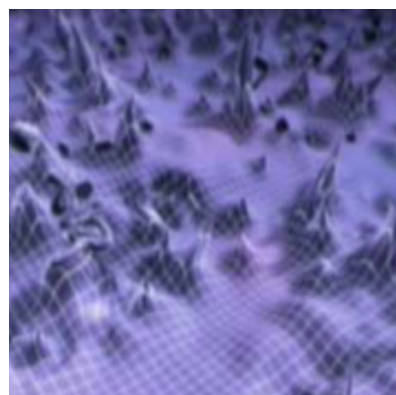
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Core questions in cosmology?

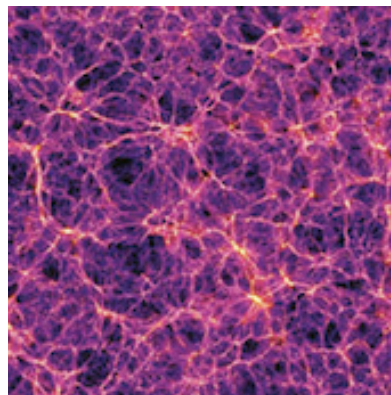


Can *cosmology* weigh in?



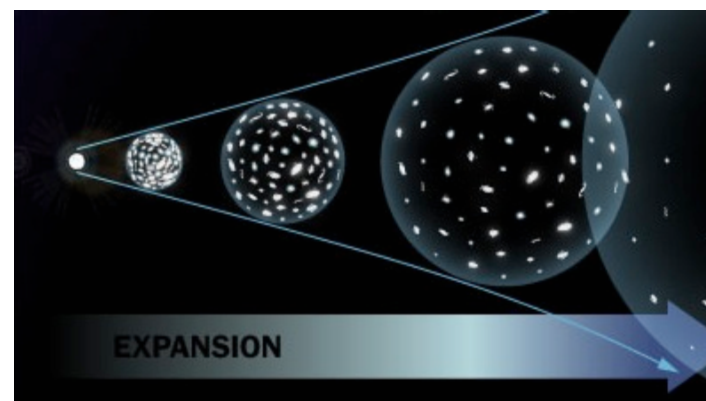
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Dark Matter

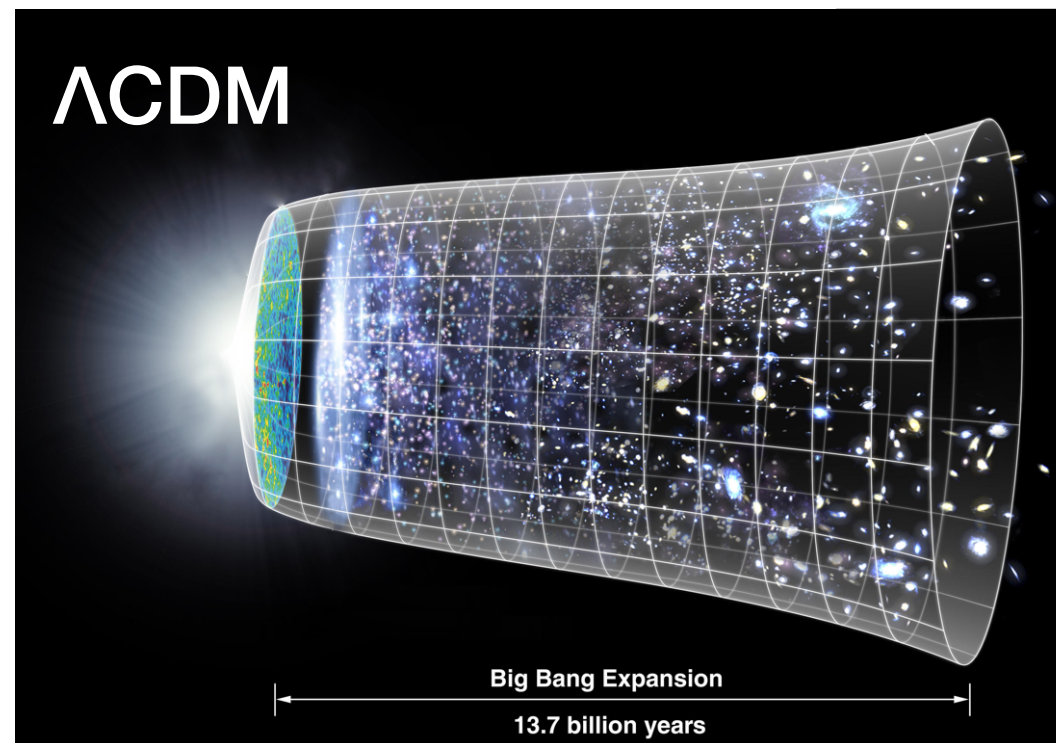
$$\chi: m_\chi, \mathcal{L}(\chi)$$



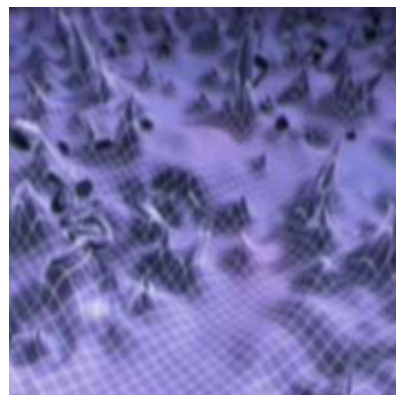
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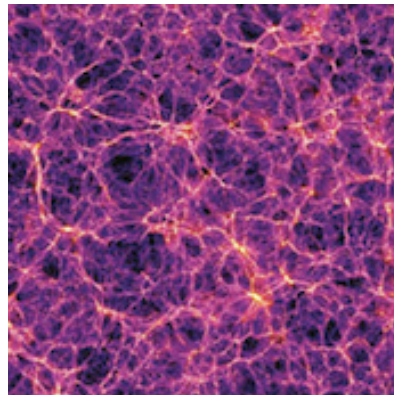


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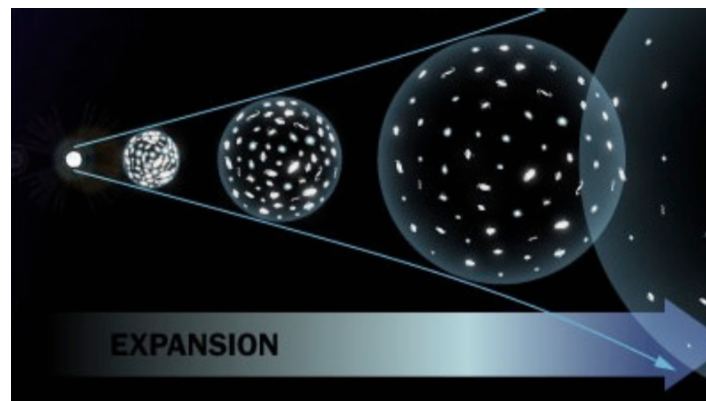
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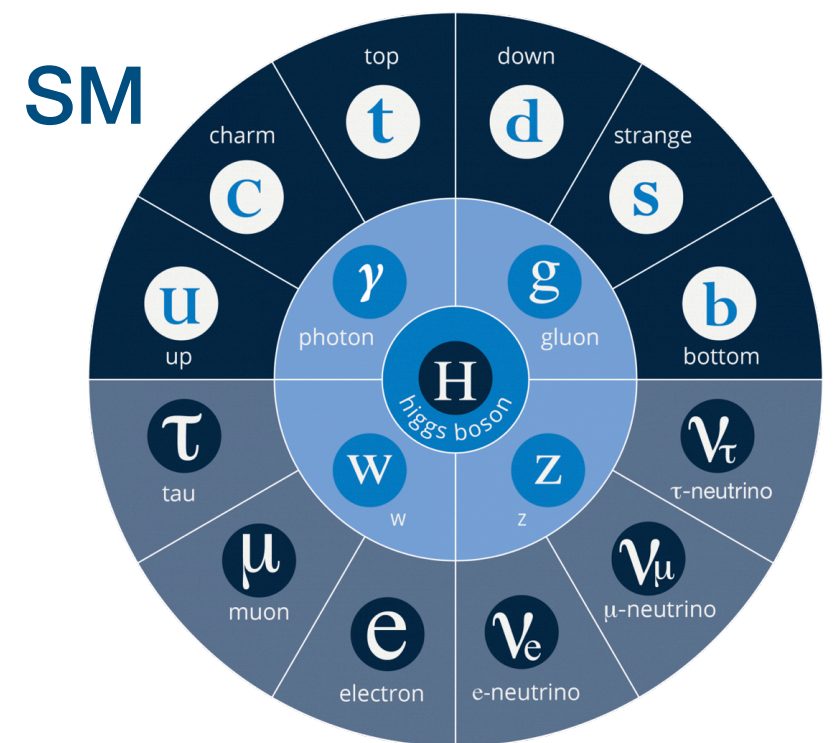
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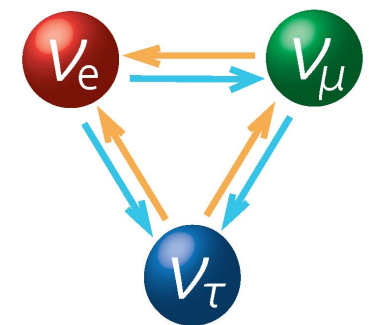


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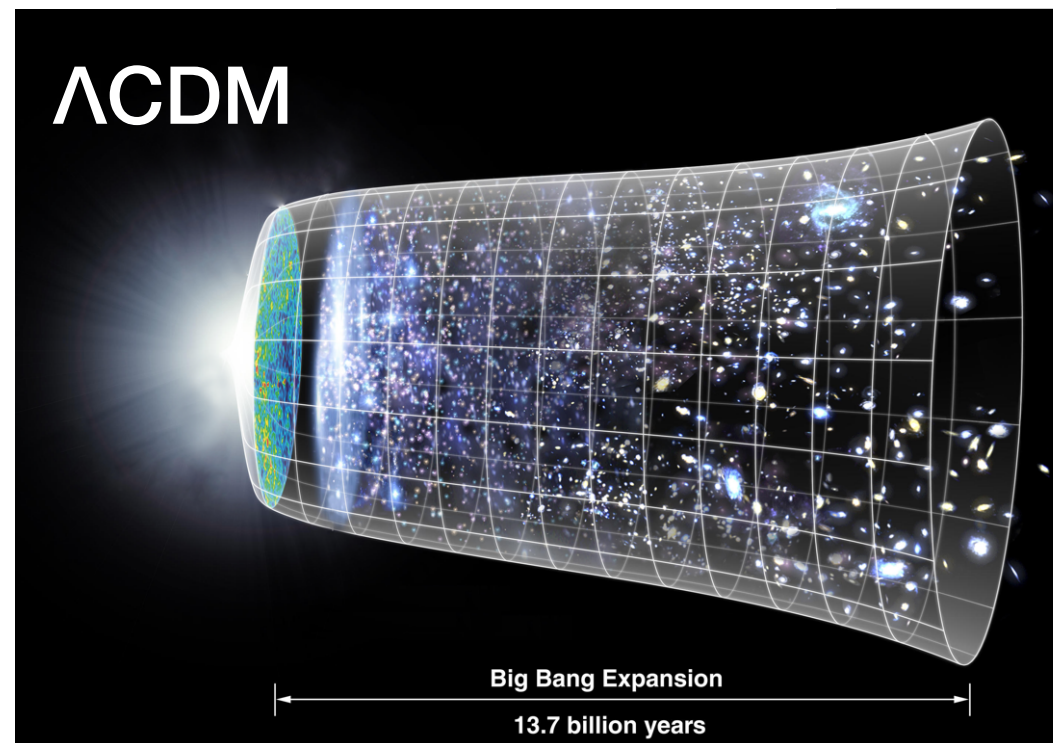


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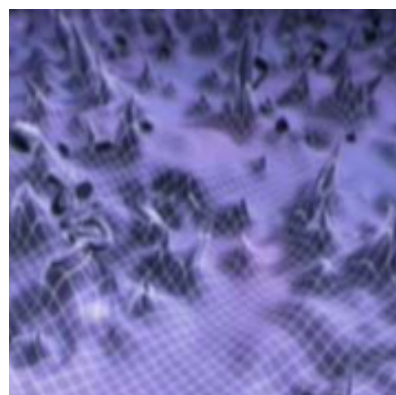


Neutrino masses

LIM Probes all *Standard* Questions in Cosmology

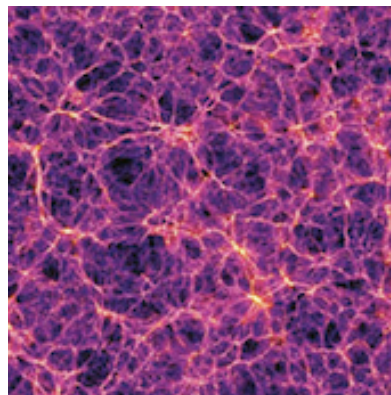


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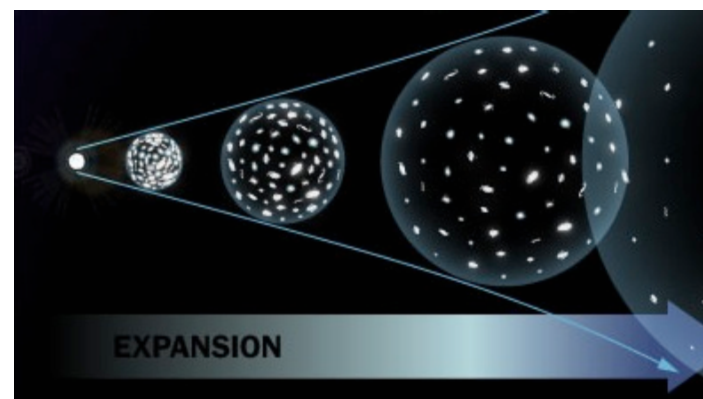
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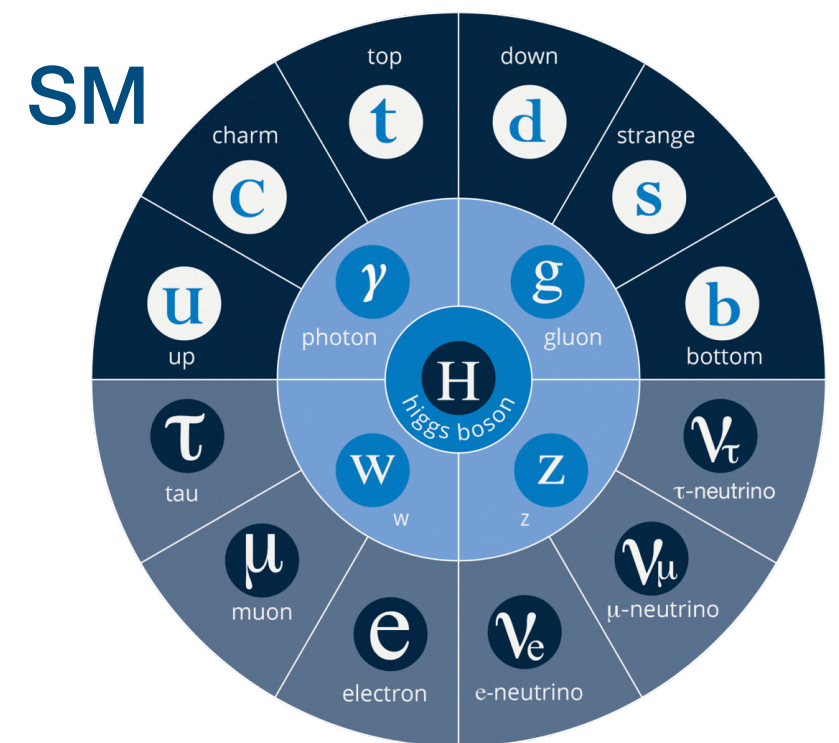
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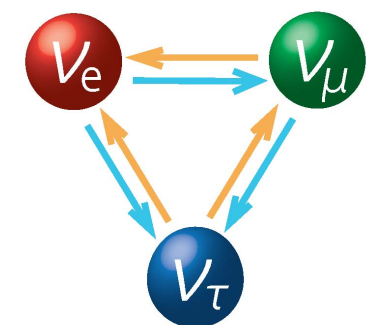


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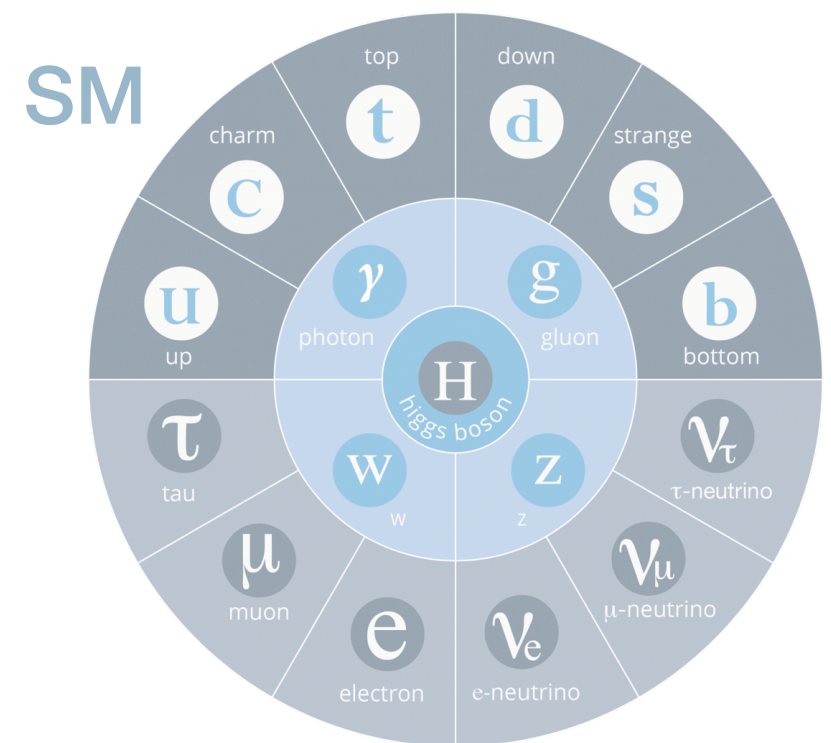
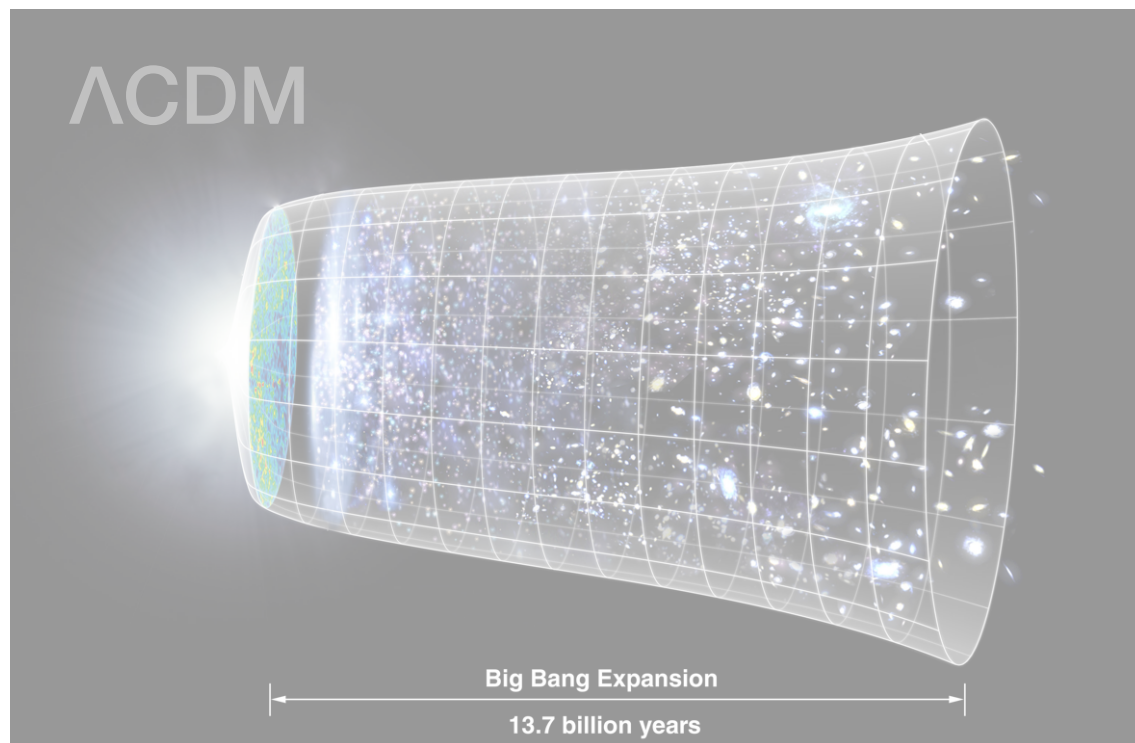
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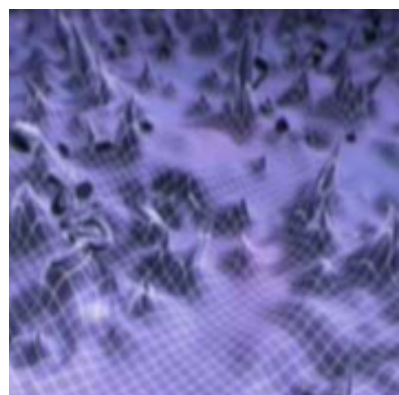
$$\sum_{e,\mu,\tau} m_\nu \gtrsim 60 \text{ meV? } 100 \text{ meV?}$$

Bold(?) claim: LIM can *uniquely* probe all of these!

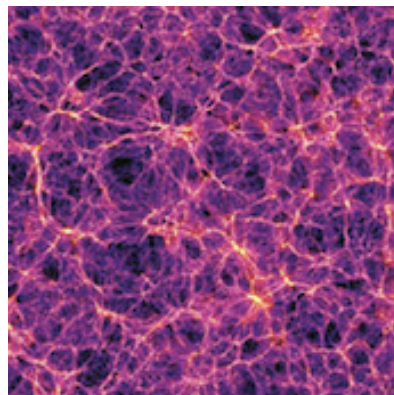


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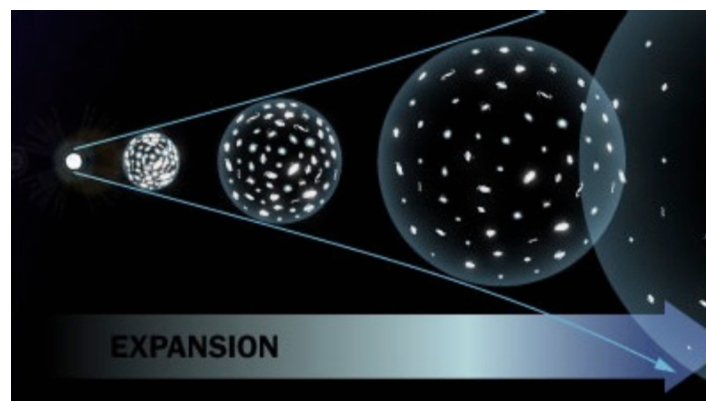
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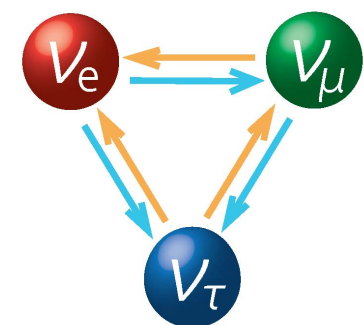
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Dark Matter



Dark Energy



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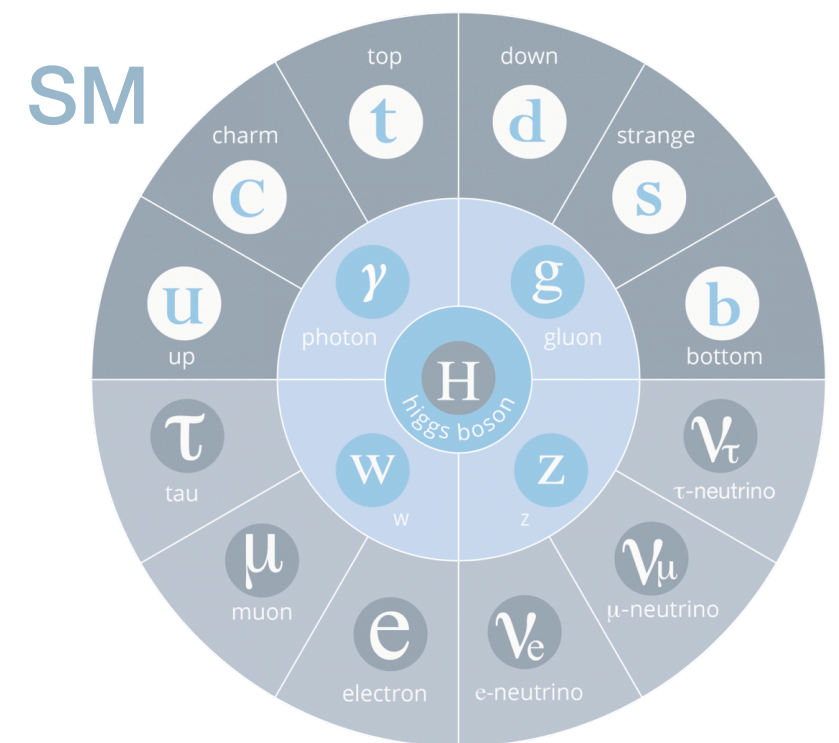
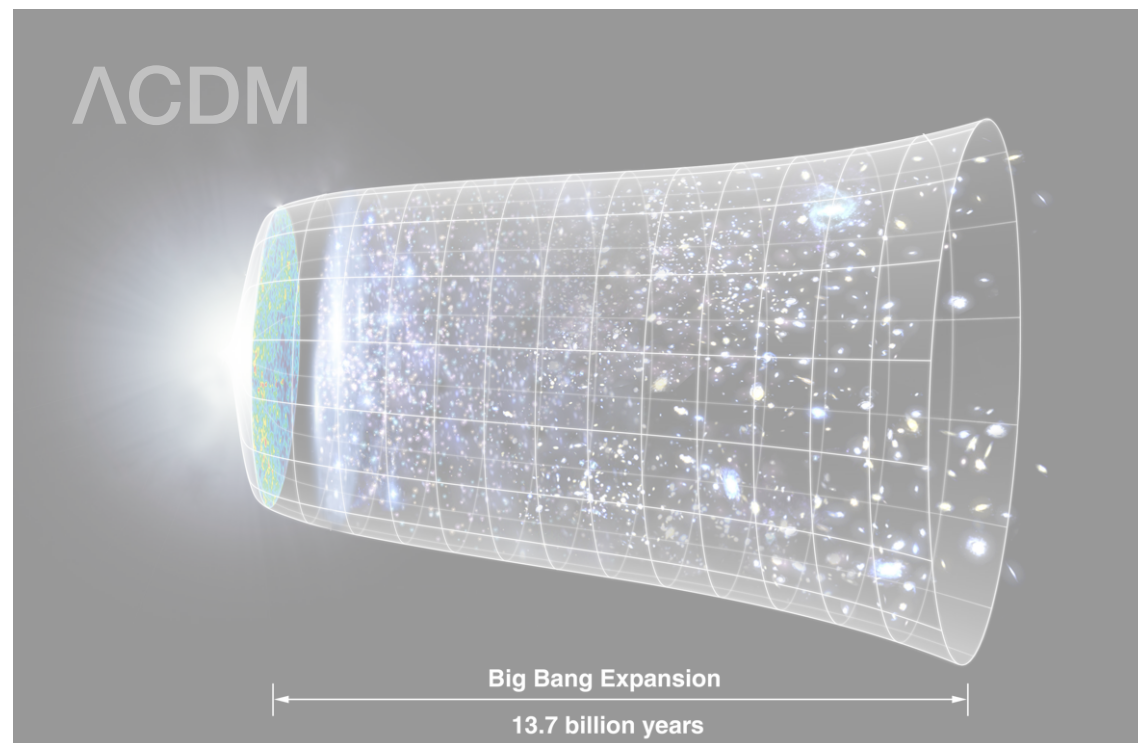
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Takeaway: LIM can *uniquely* probe Small Scales

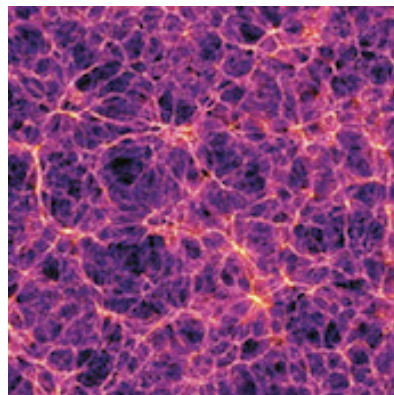


Core questions in cosmology?

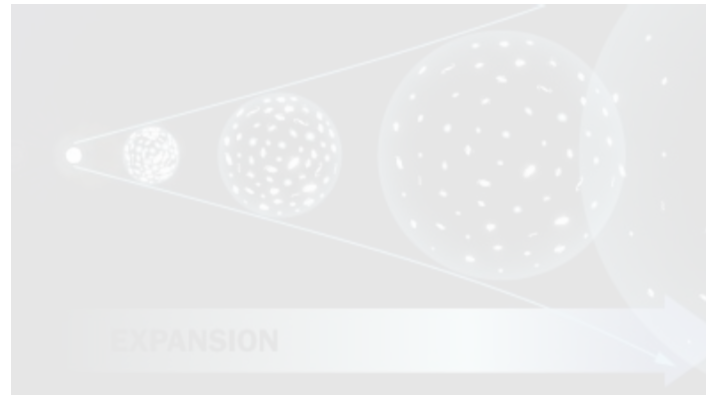
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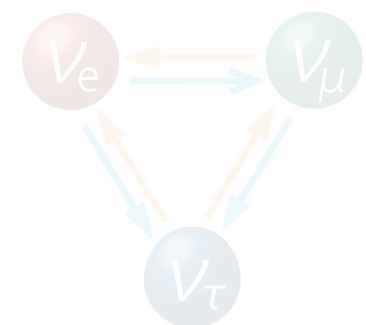
Inflation



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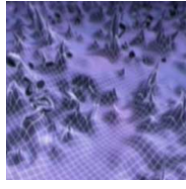
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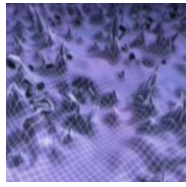
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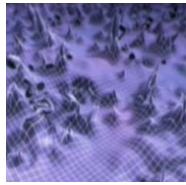


LIM Cosmology: Inflationary Fluctuations



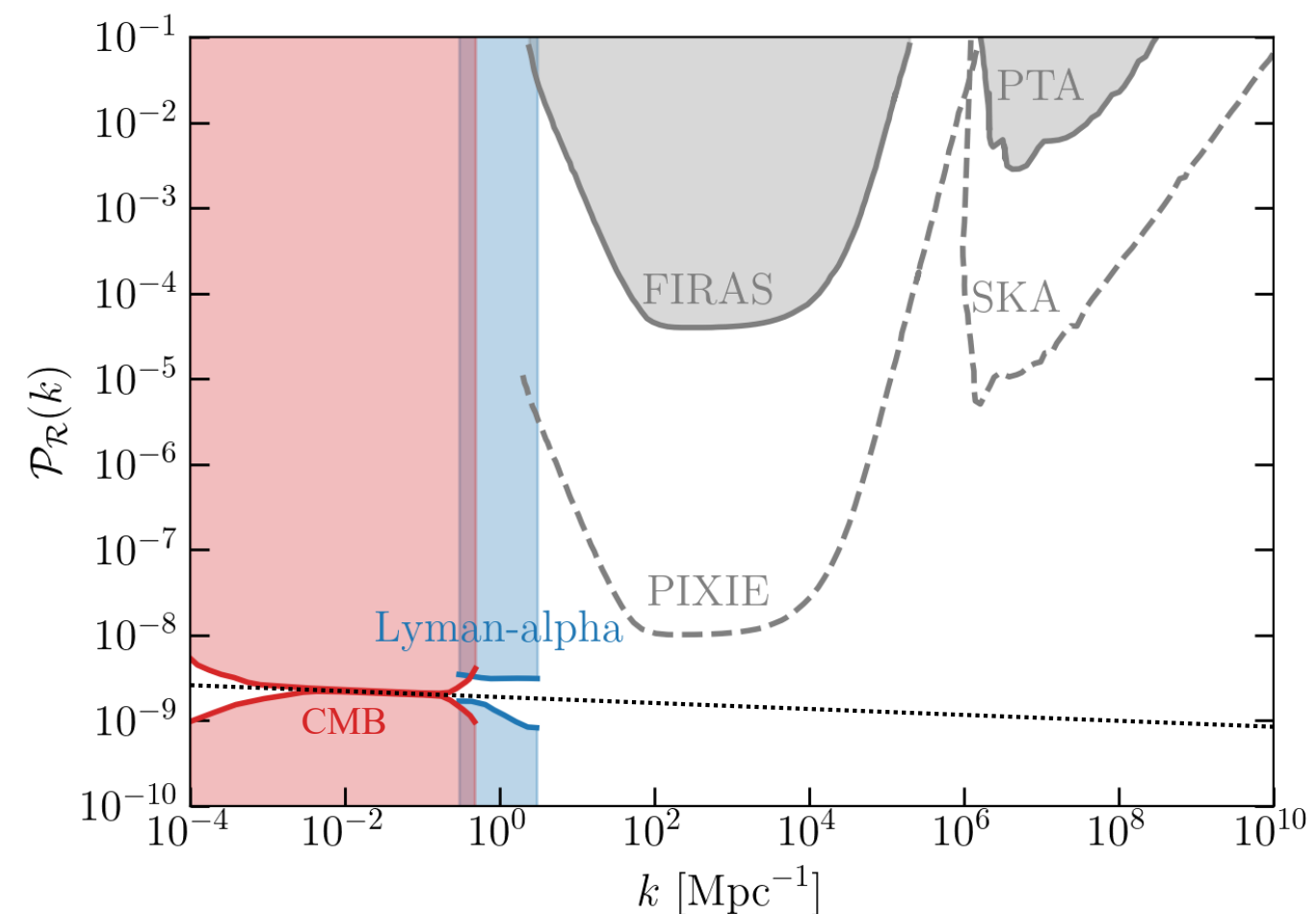
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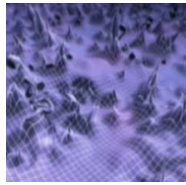
Inflation predicts scale-invariance over >20 orders of magnitude. We've probed only ~ 4 .



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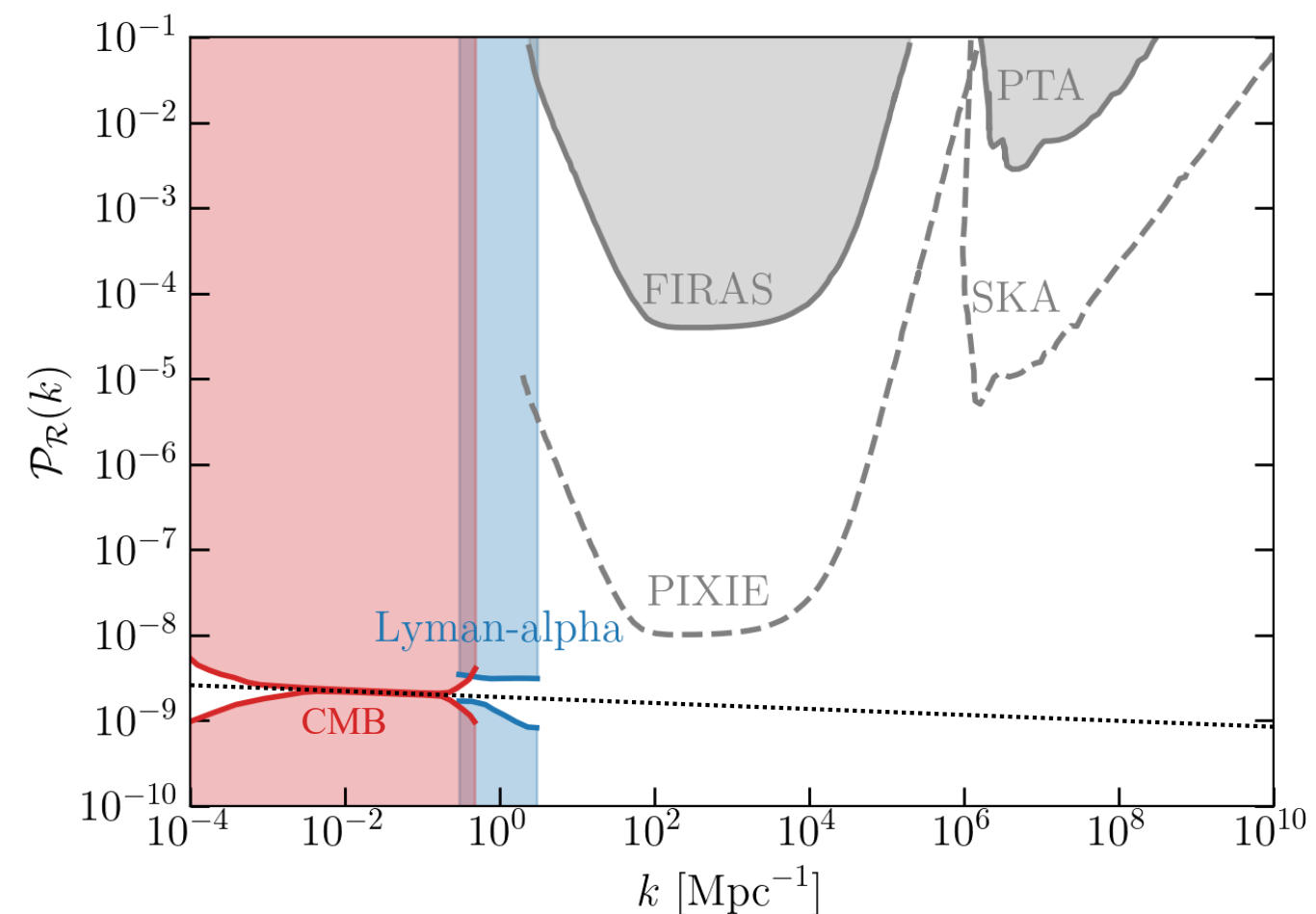


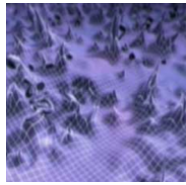


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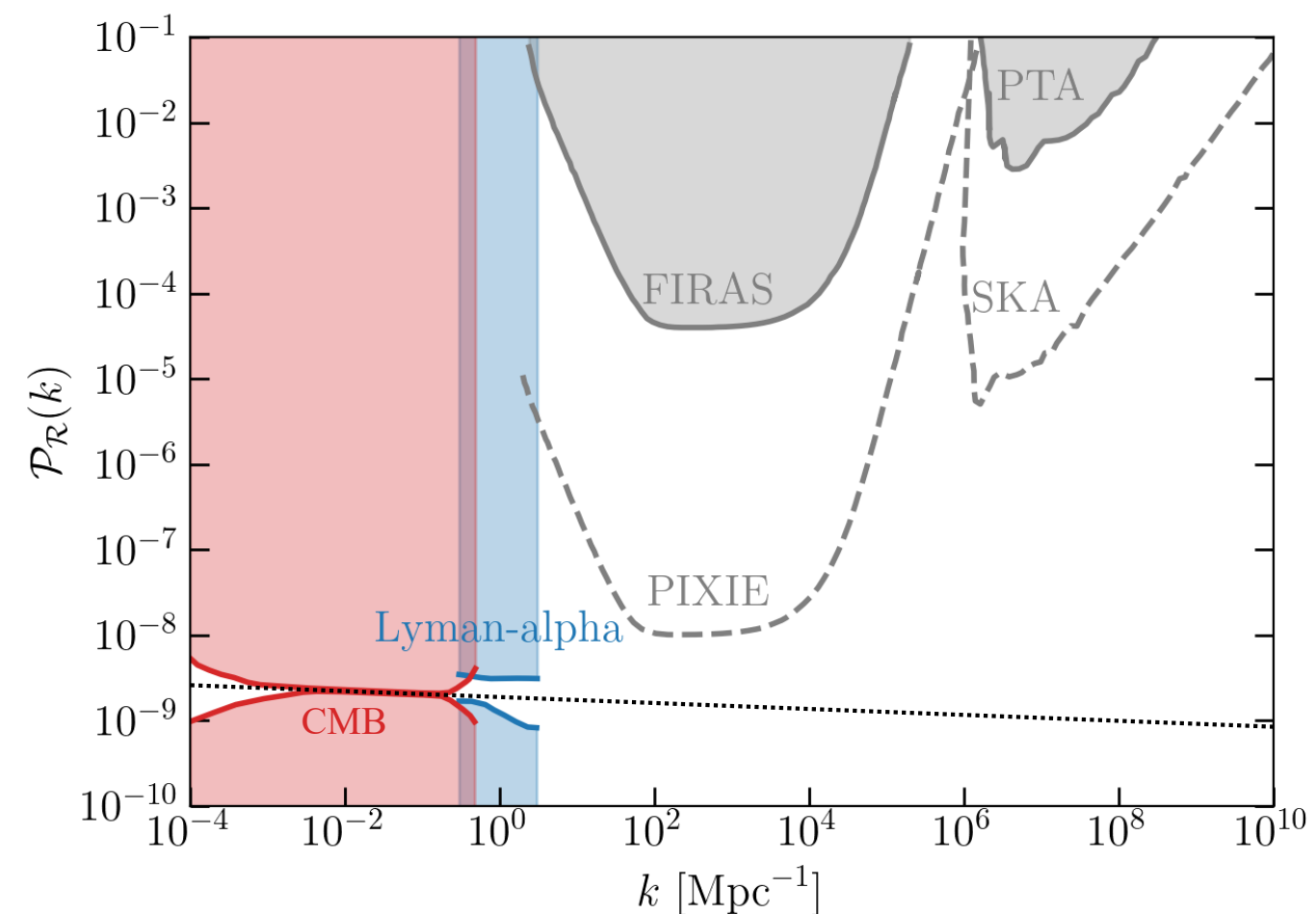


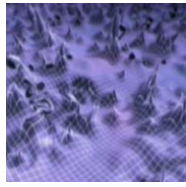


LIM Cosmology: Inflationary Fluctuations

Inflation predicts scale-invariance over >20 orders of magnitude. We've probed only ~ 4 .

(i) CMB: limited by Silk damping. (ii) LSS: theoretical control limited to linear scales.

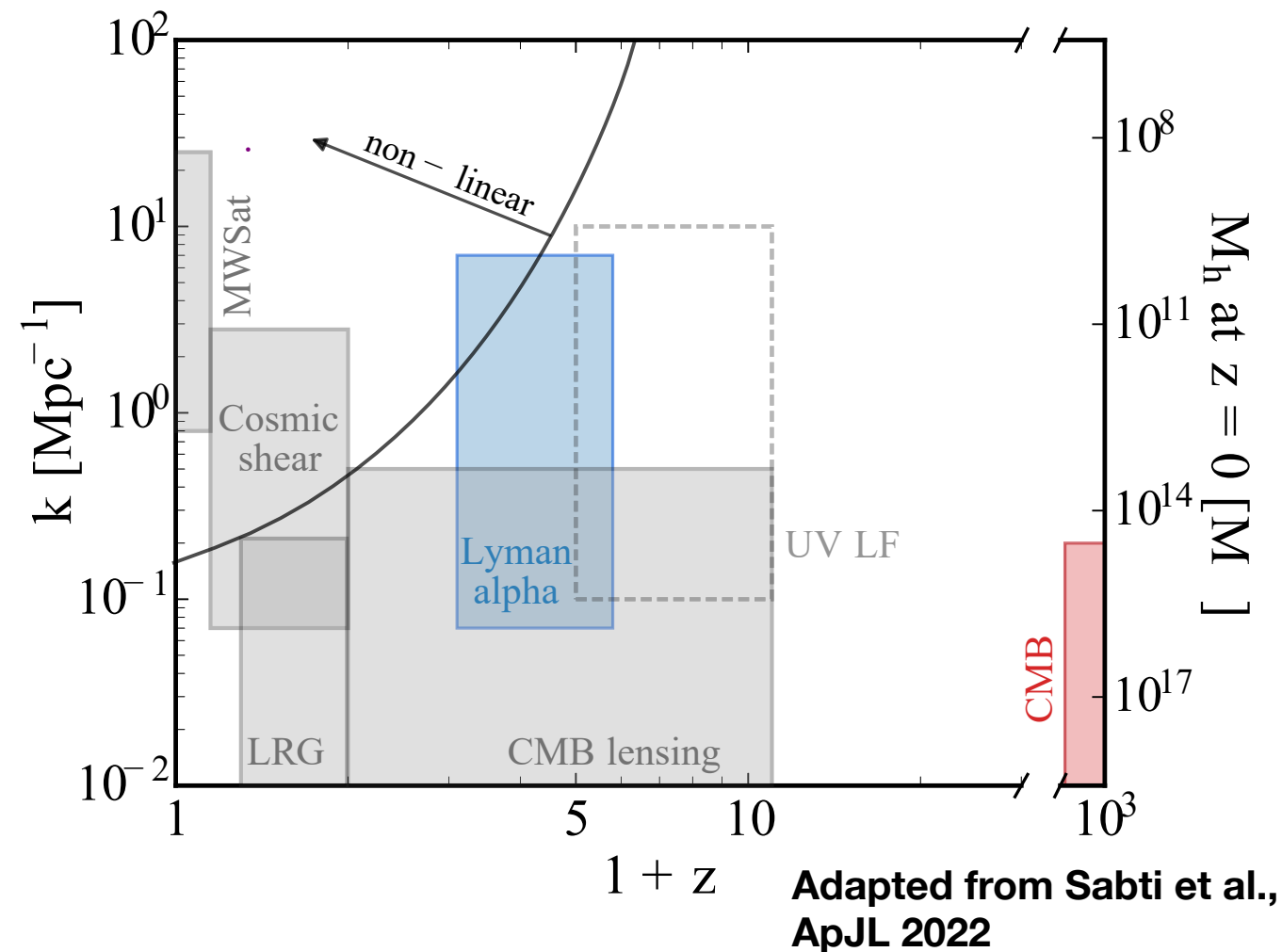
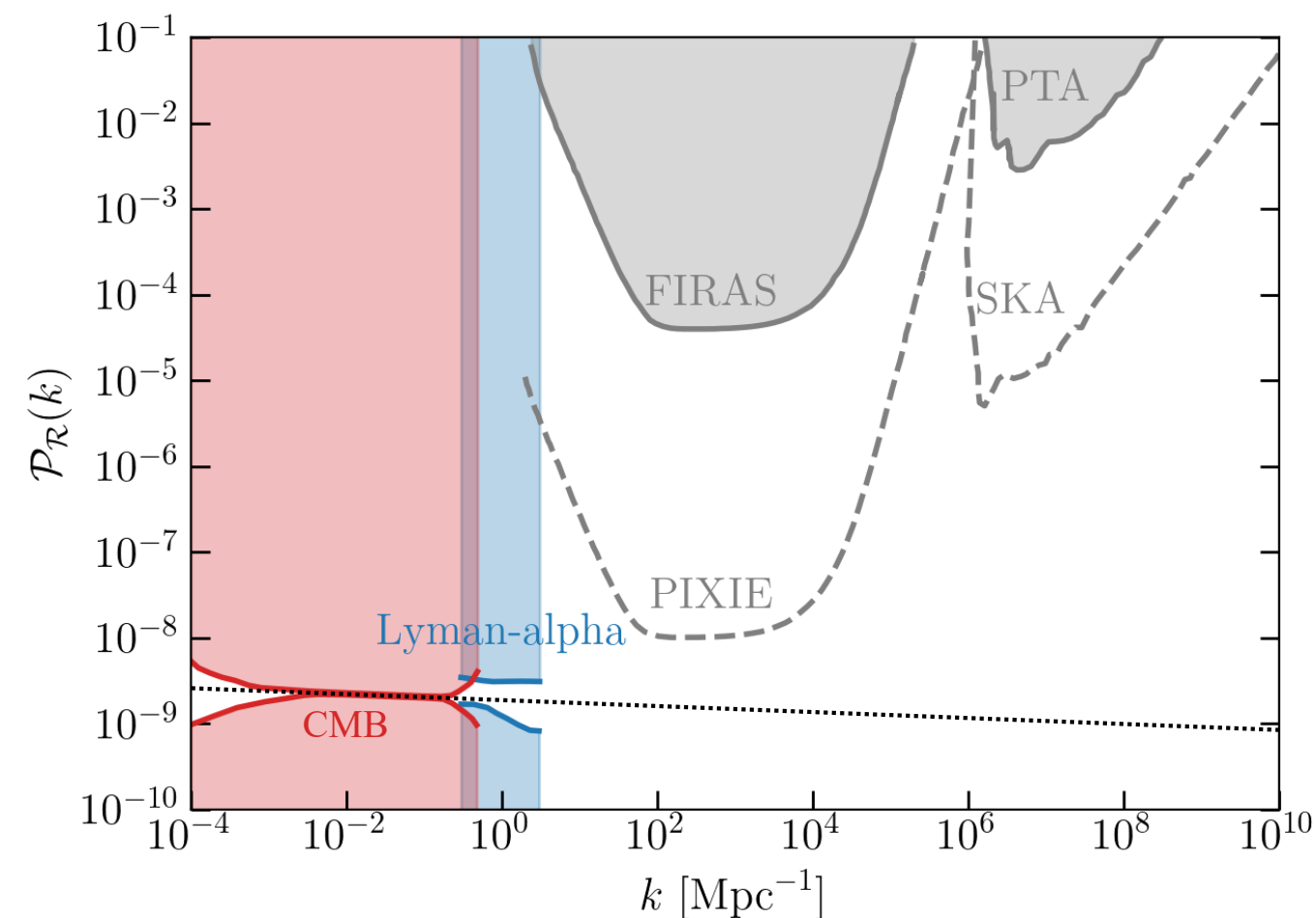




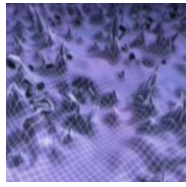
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Adapted from Sabti et al.,
ApJL 2022

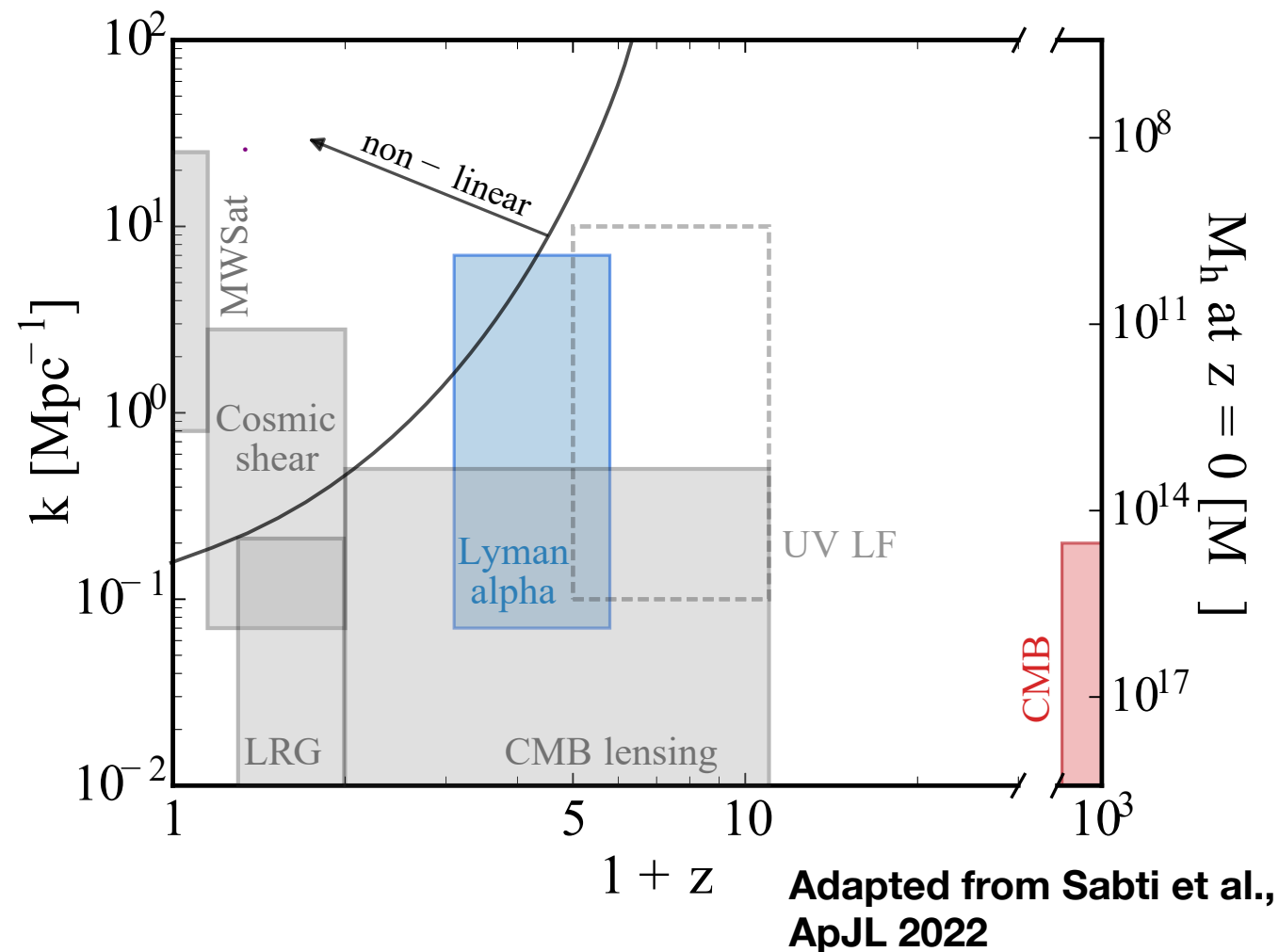
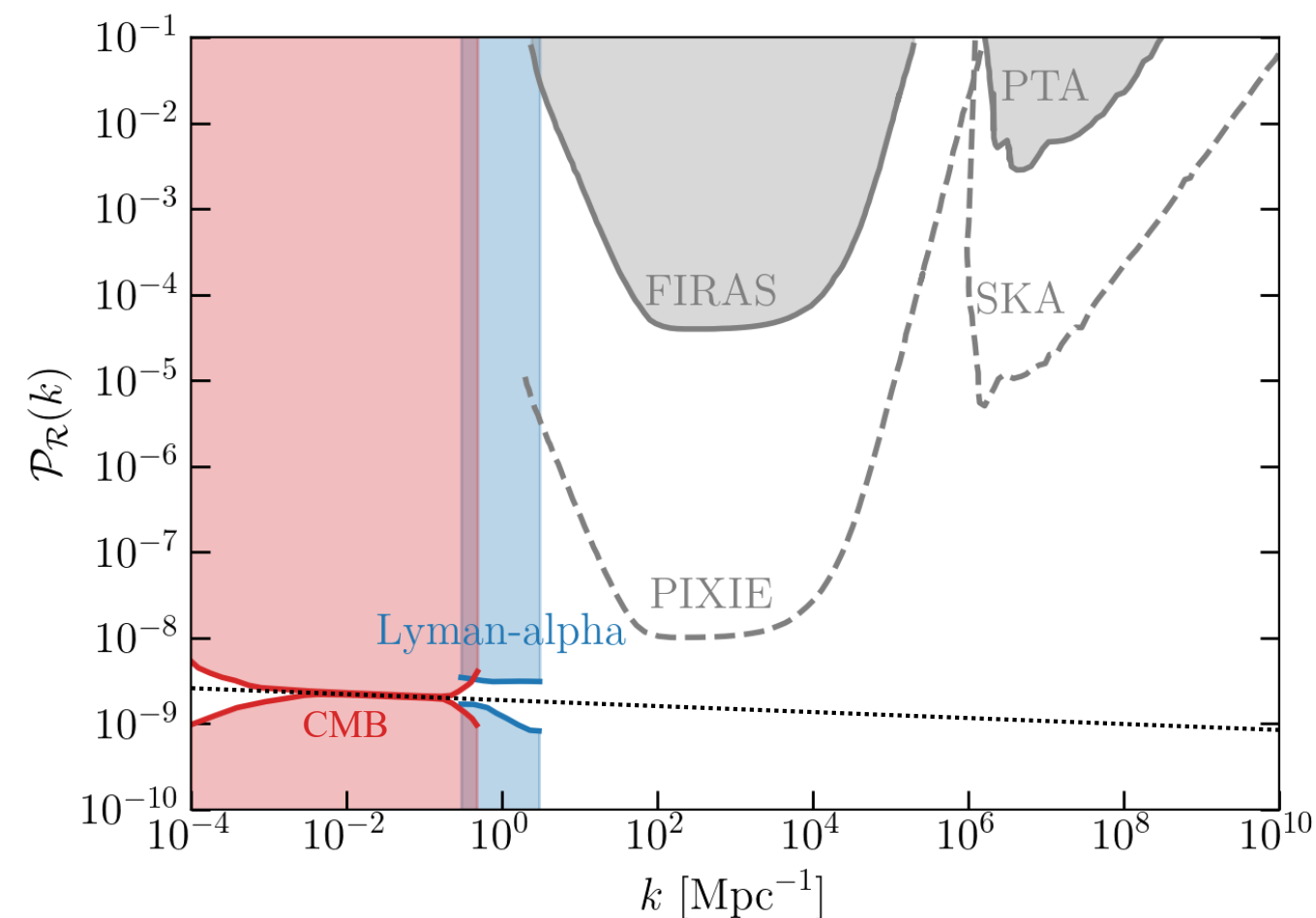


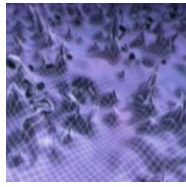
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LIM can access far smaller scales via galaxies residing in the smallest dark matter halos:





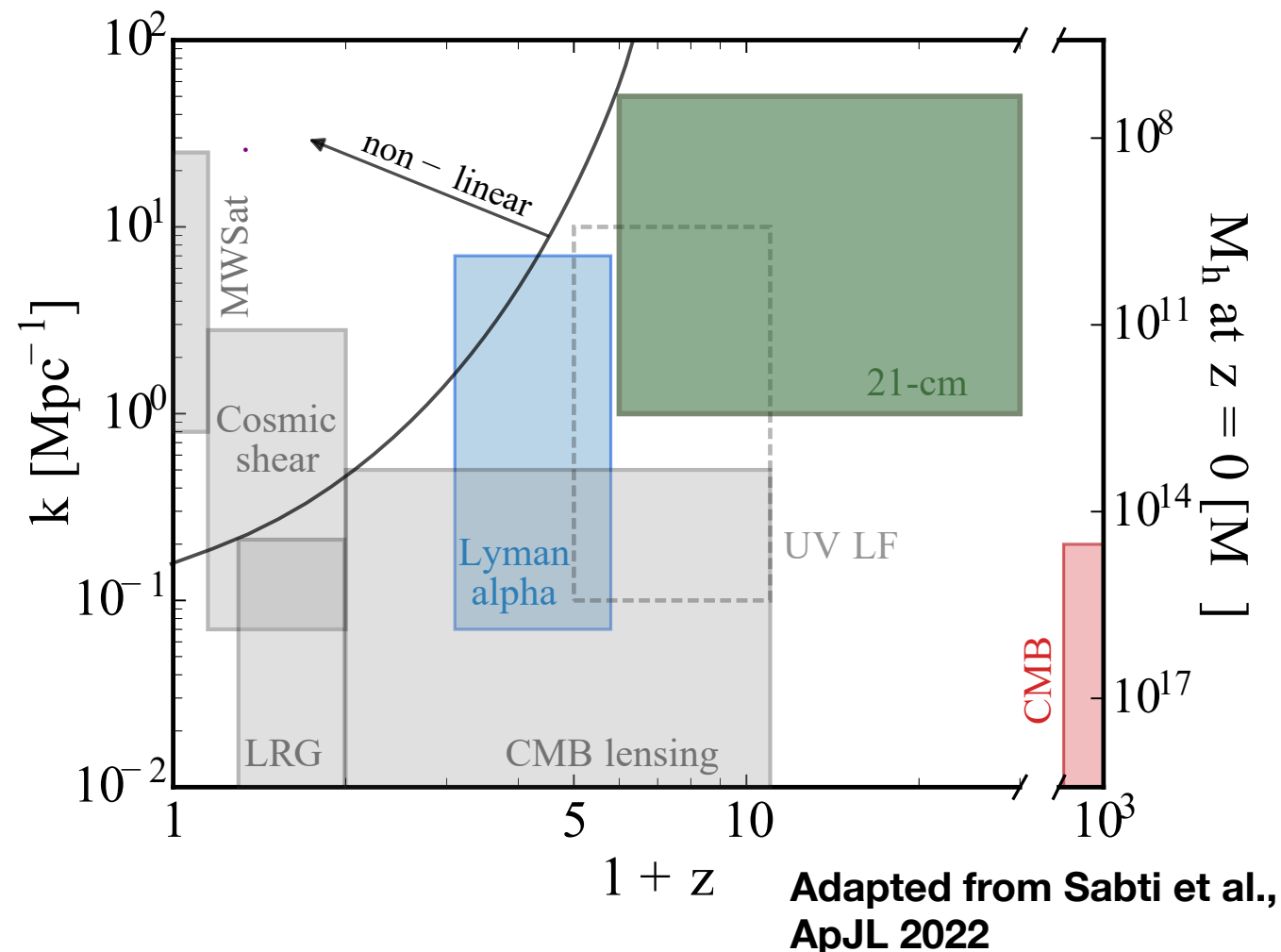
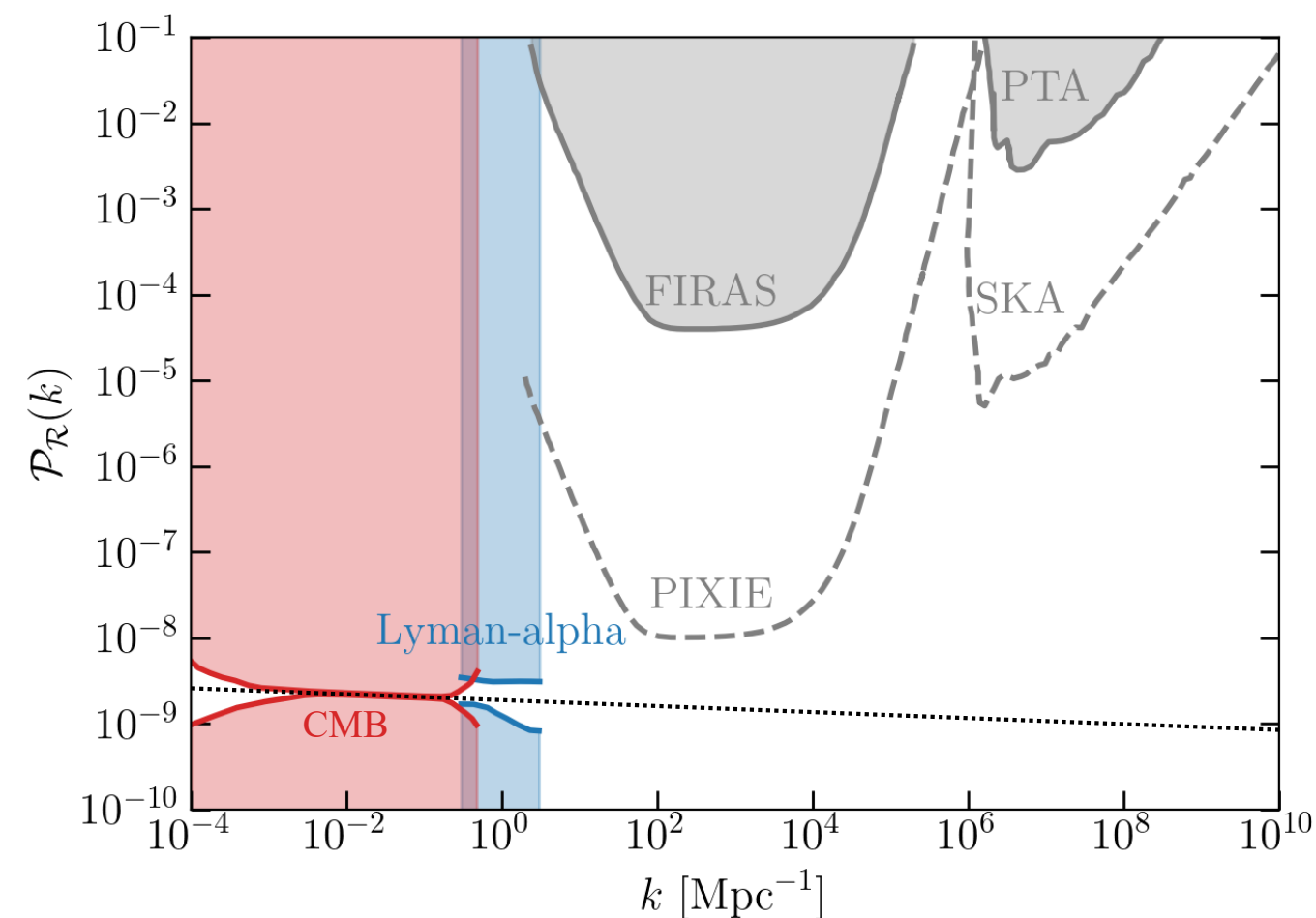
LIM Cosmology: Inflationary Fluctuations

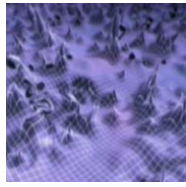
Inflation predicts scale-invariance over >20 orders of magnitude. We've probed only ~ 4 .

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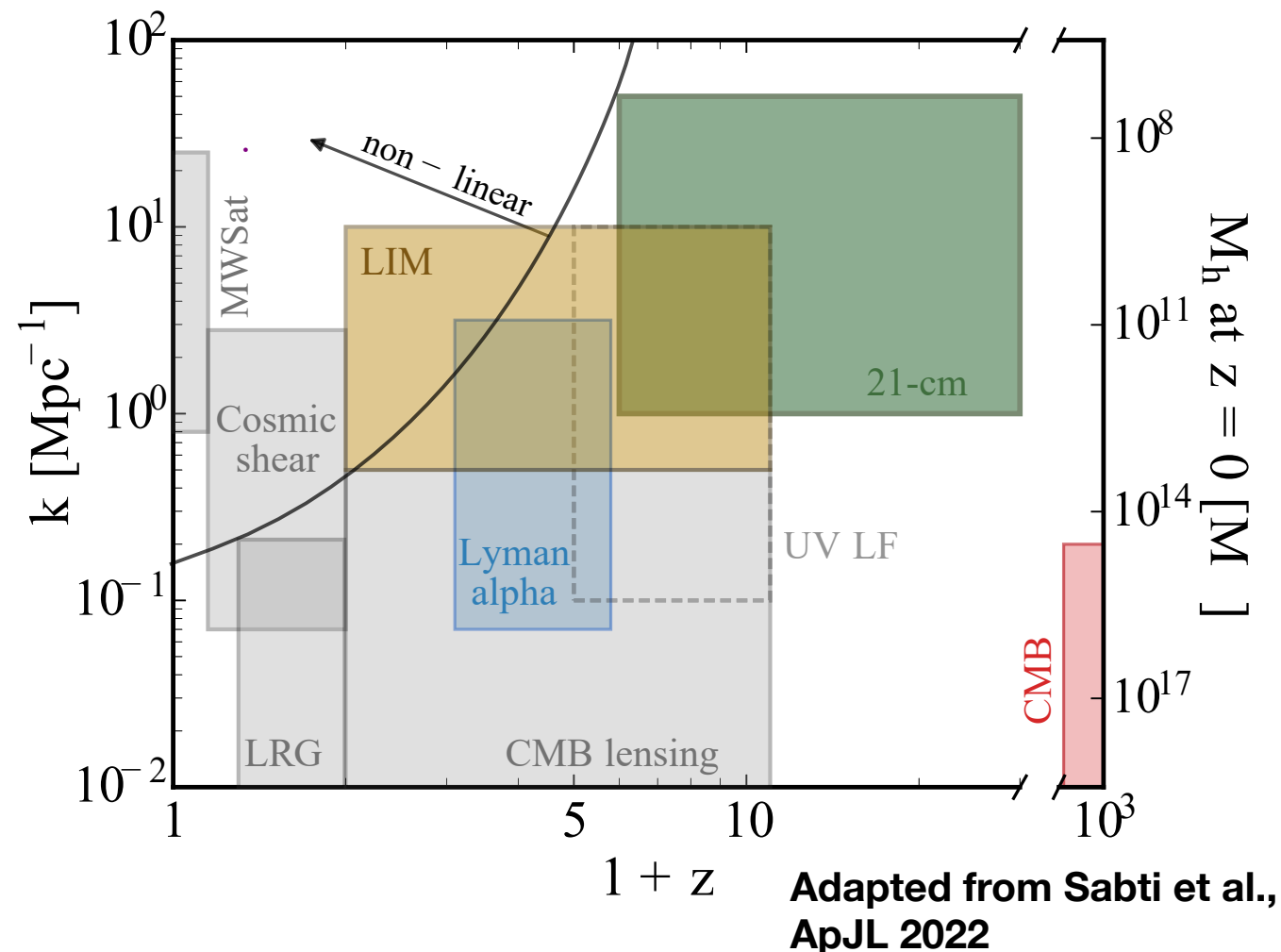
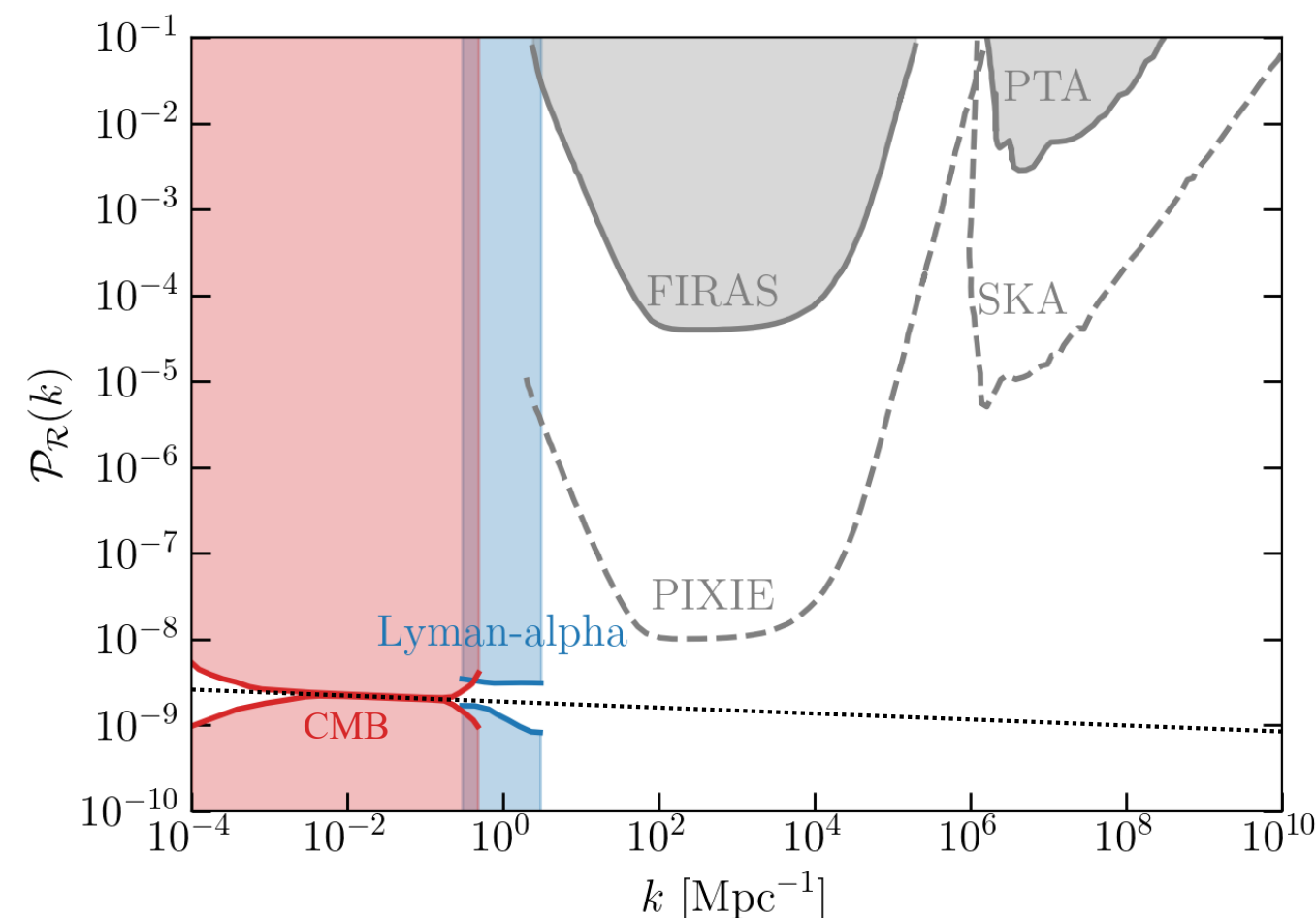
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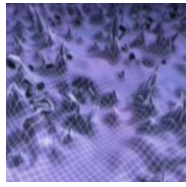
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Adapted from Sabti et al.,
ApJL 2022



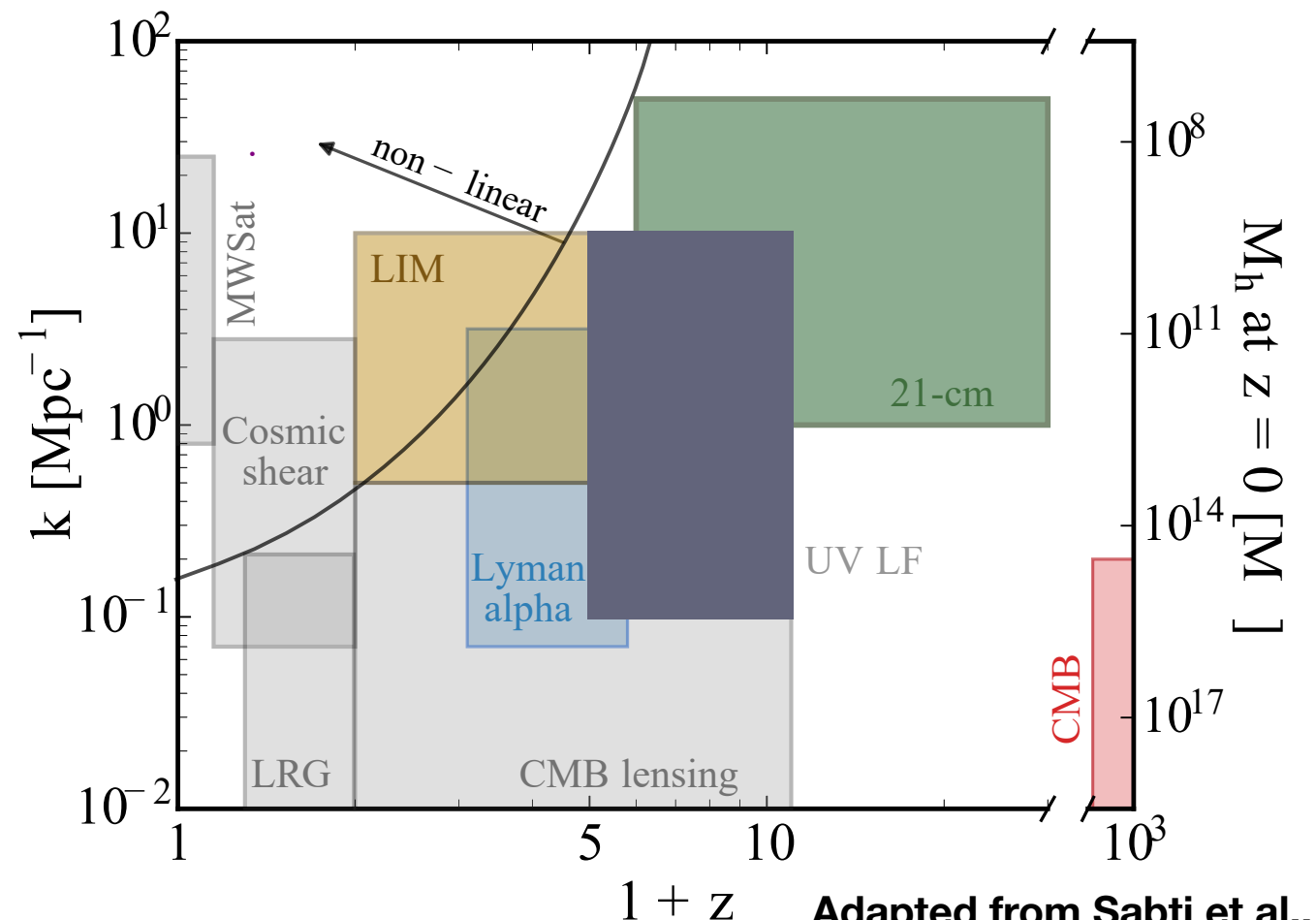
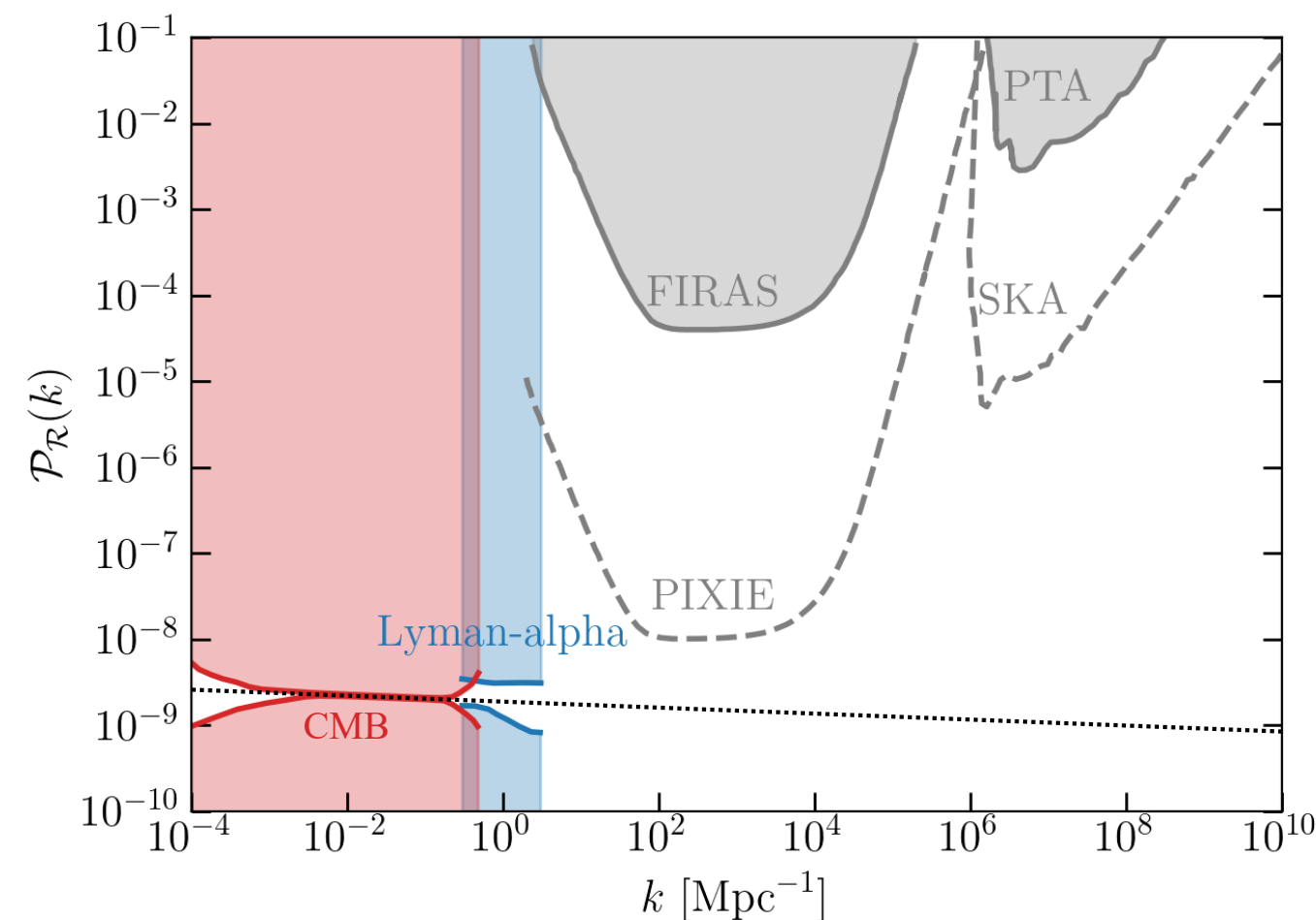
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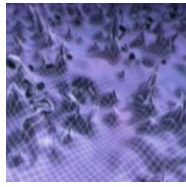
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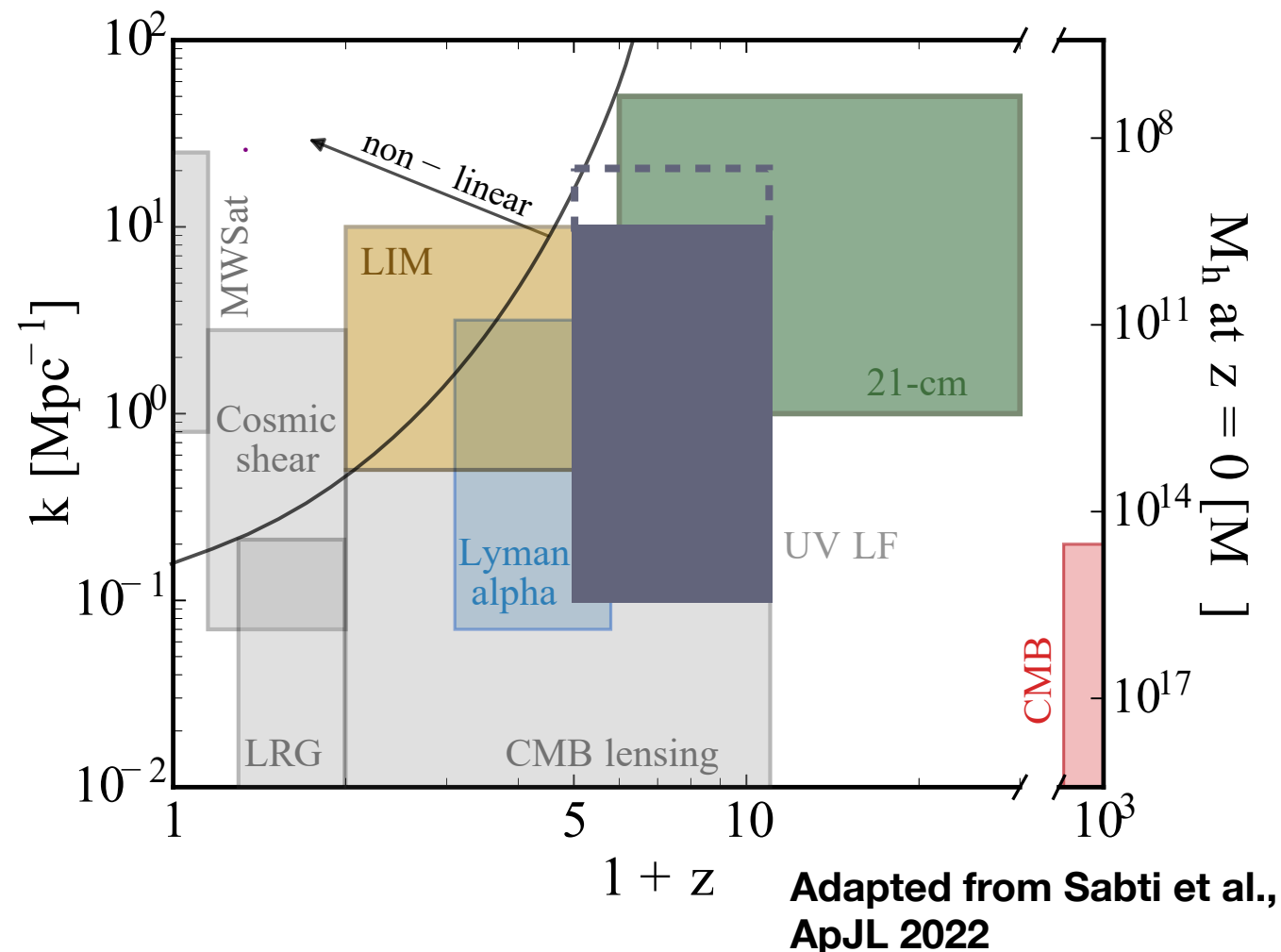
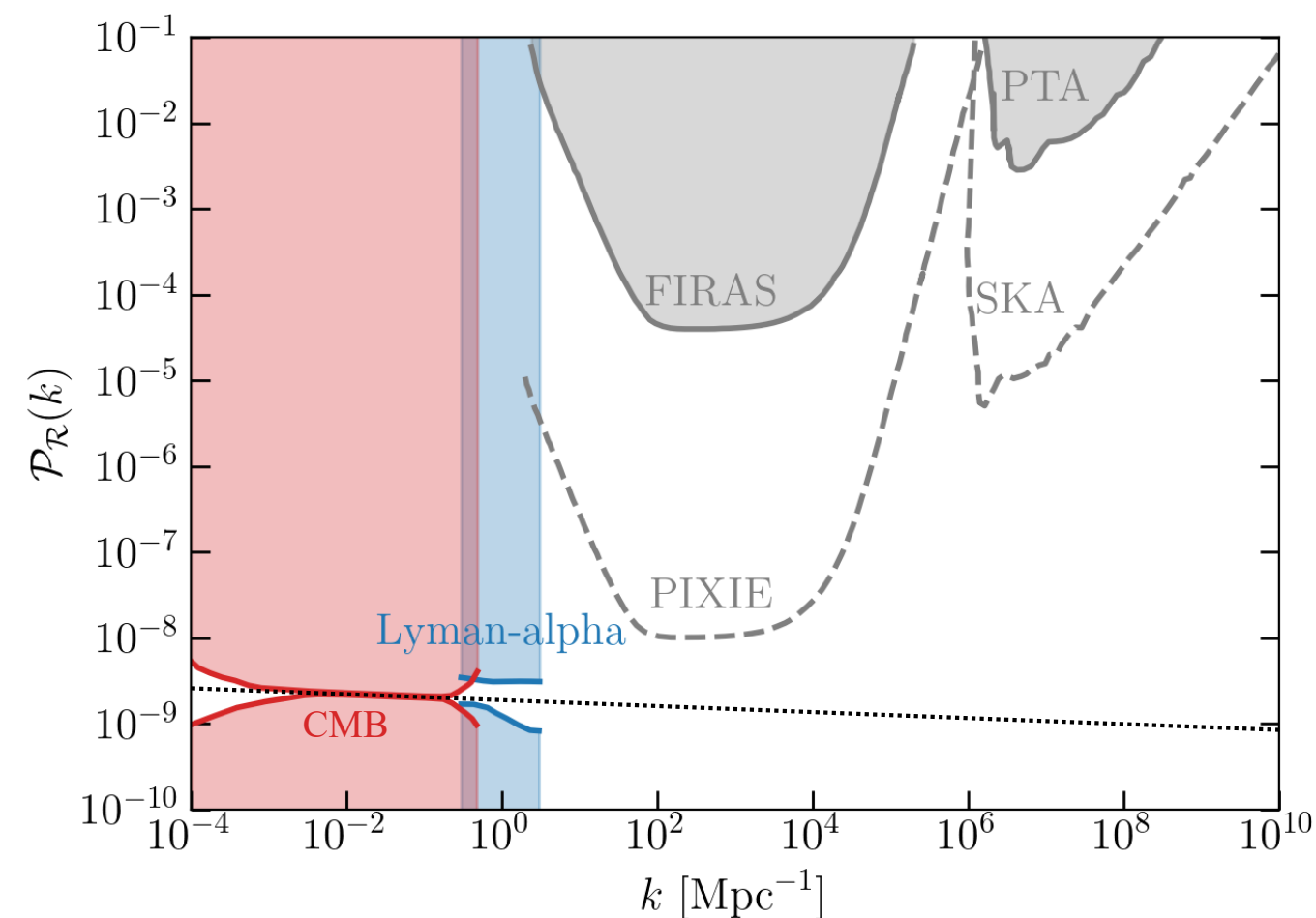
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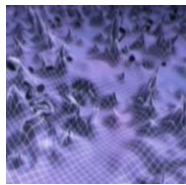
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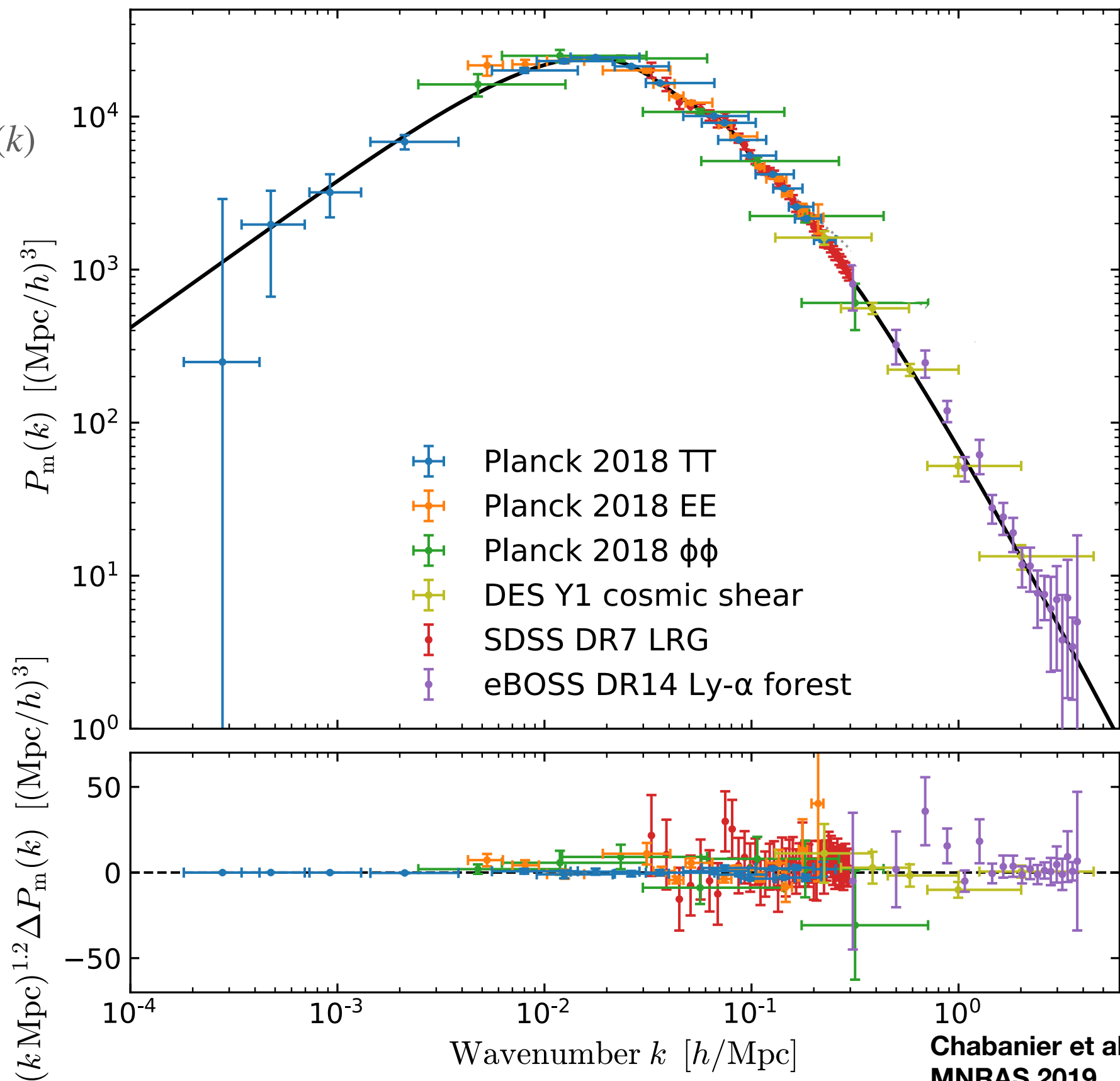
Adapted from Sabti et al.,
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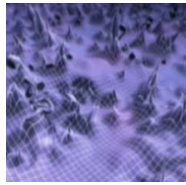


Cosmic Dawn Cosmology: Small-Scales

Matter power spectrum:

$$\langle \delta_{\mathbf{m}}(\vec{k}) \delta_{\mathbf{m}}(\vec{k}') \rangle = (2\pi)^3 \delta_D^3(\vec{k} - \vec{k}') P_m(k)$$





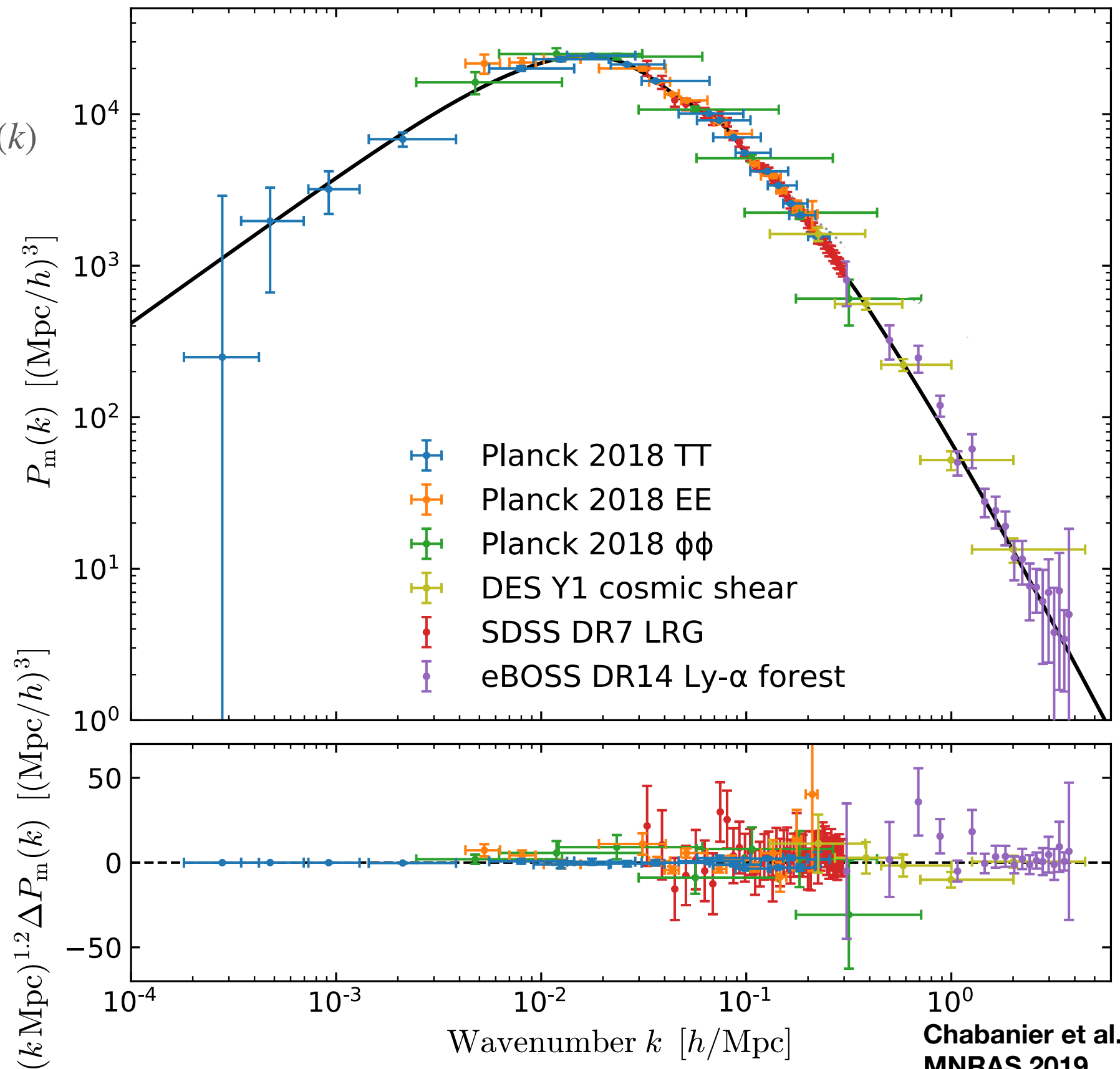
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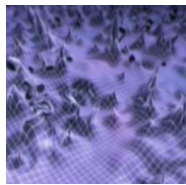
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Current bounds:

- CMB
- Galaxies
- Ly- α Forest





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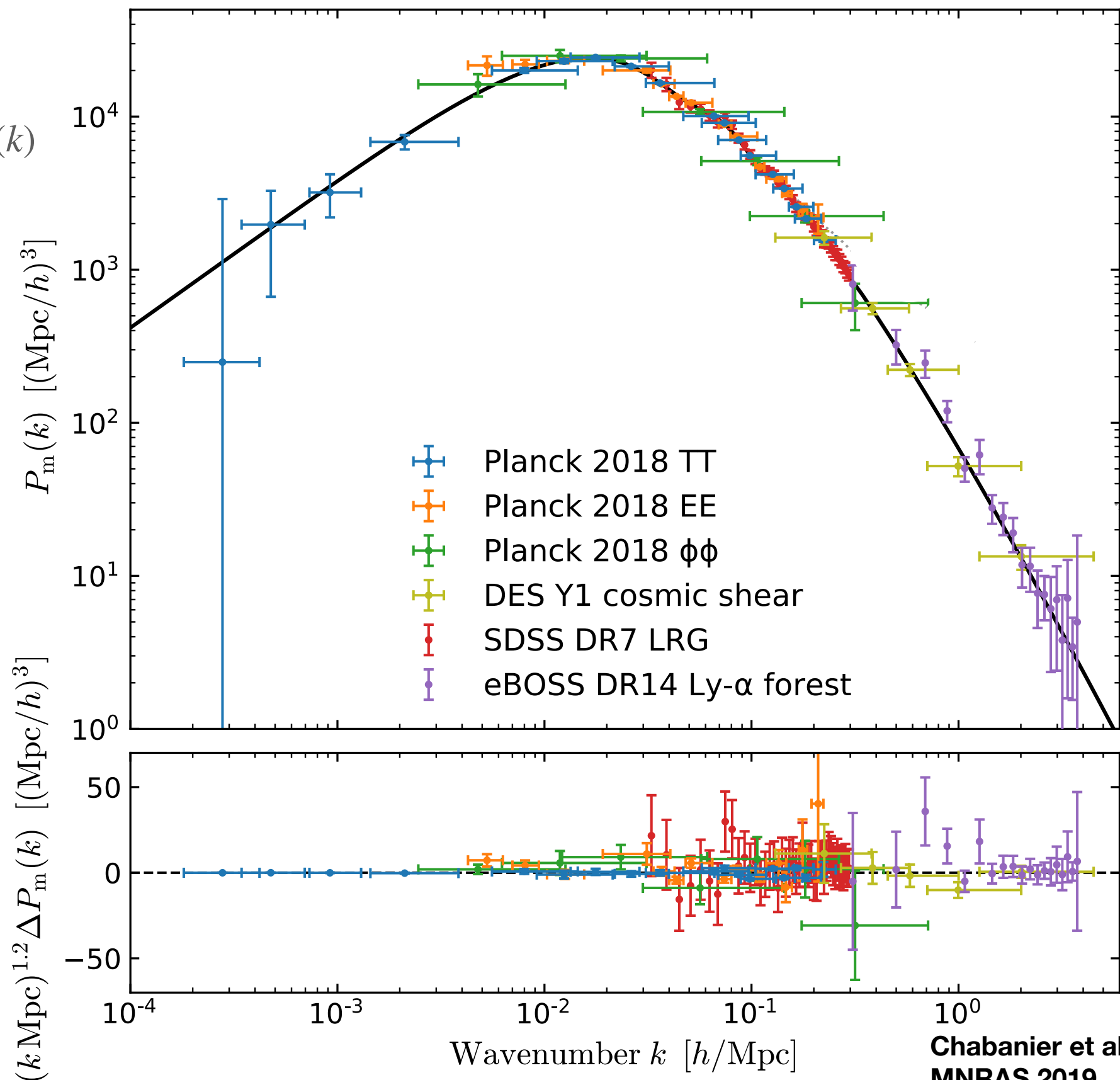
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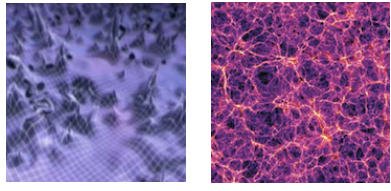
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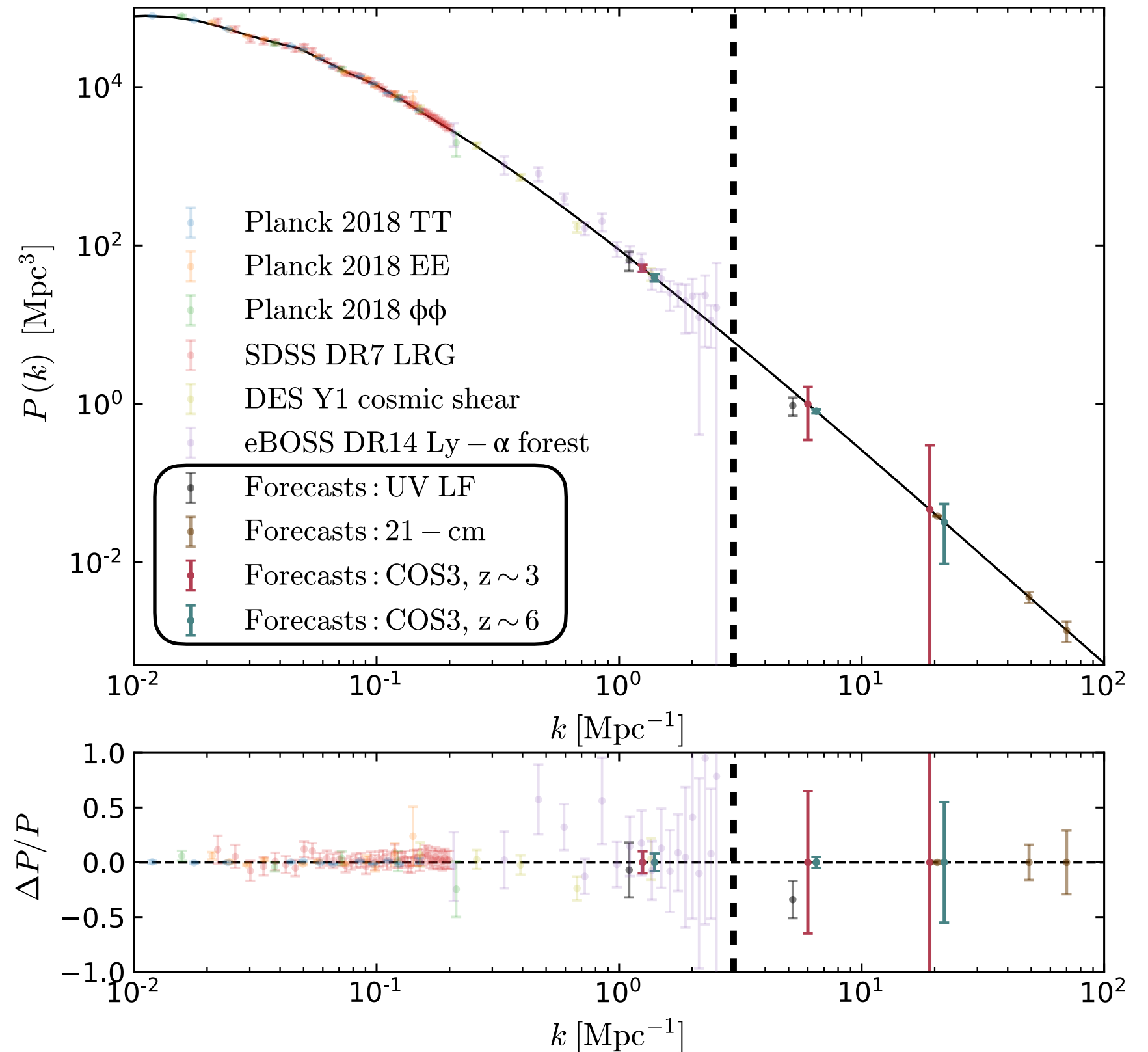
What about Cosmic Dawn?





Cosmic Dawn Cosmology: Small-Scales

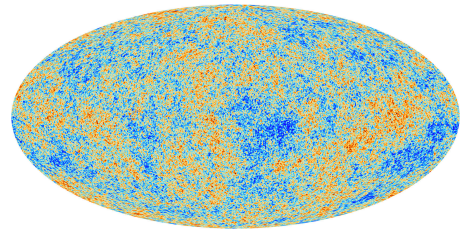
Cosmic Dawn bounds:



Starting Point: Combining CMB and 21cm-LIM

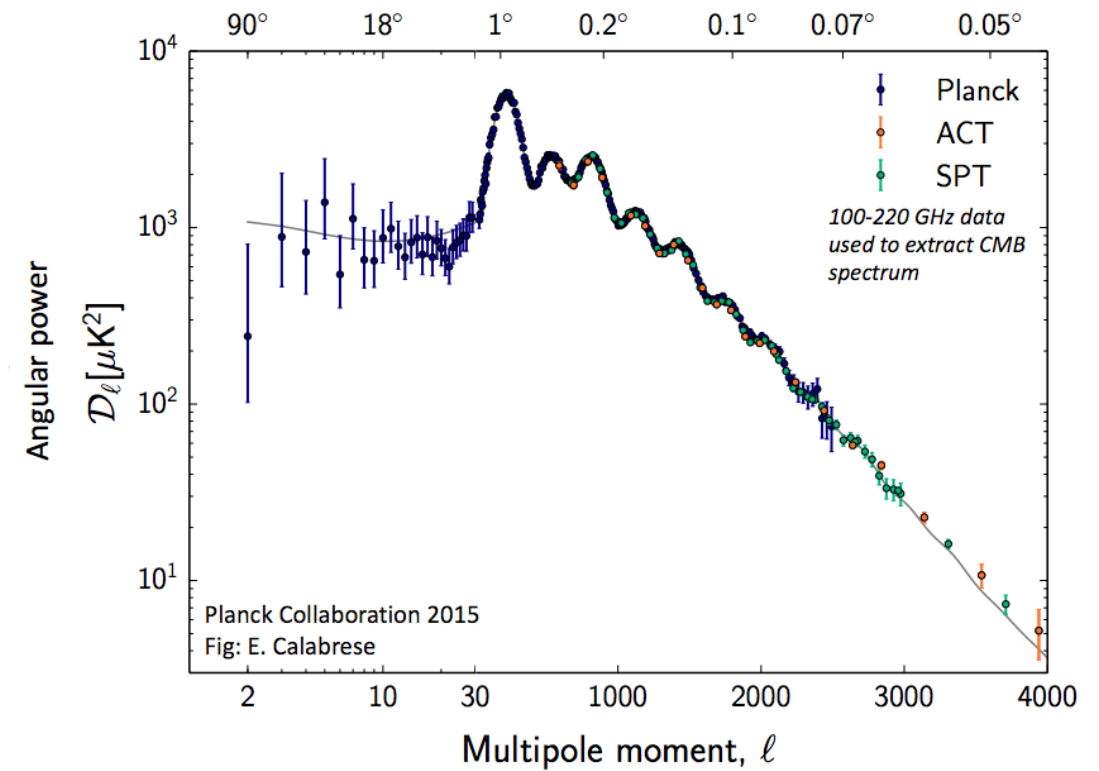
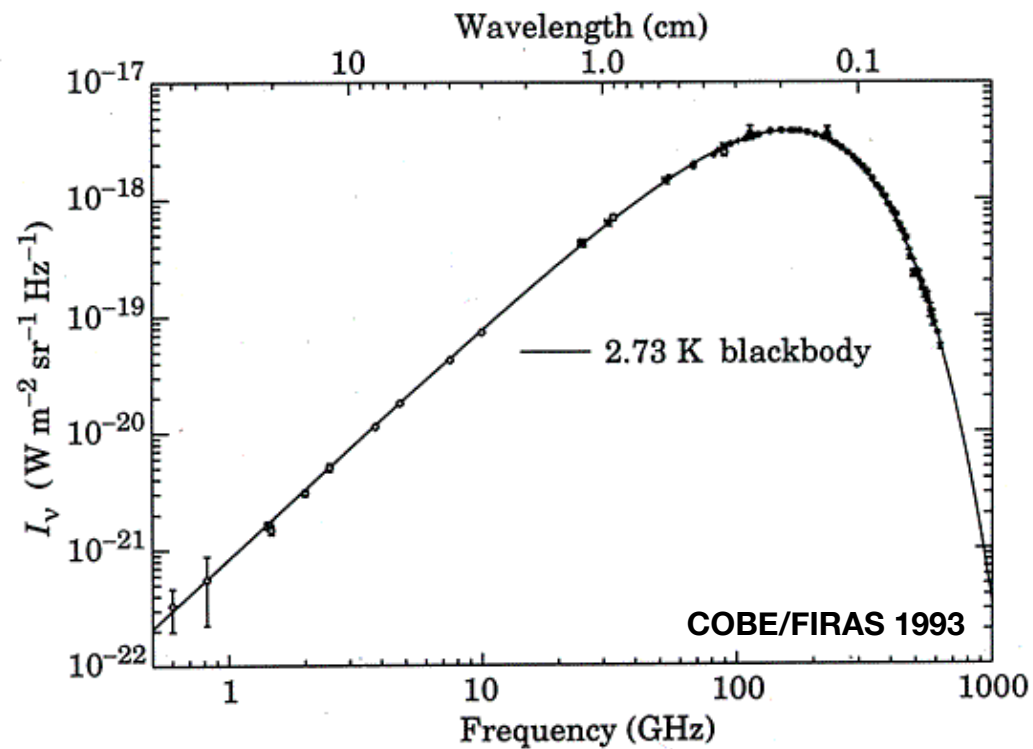
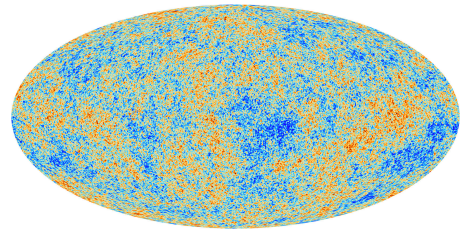
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CMB



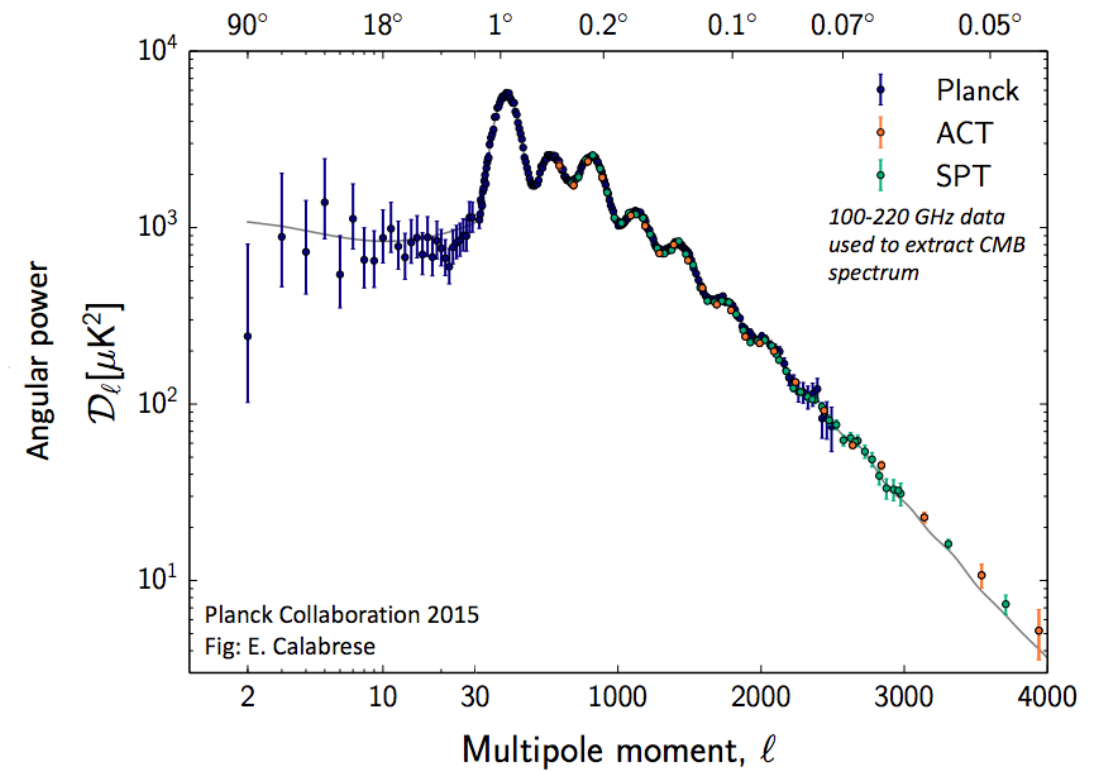
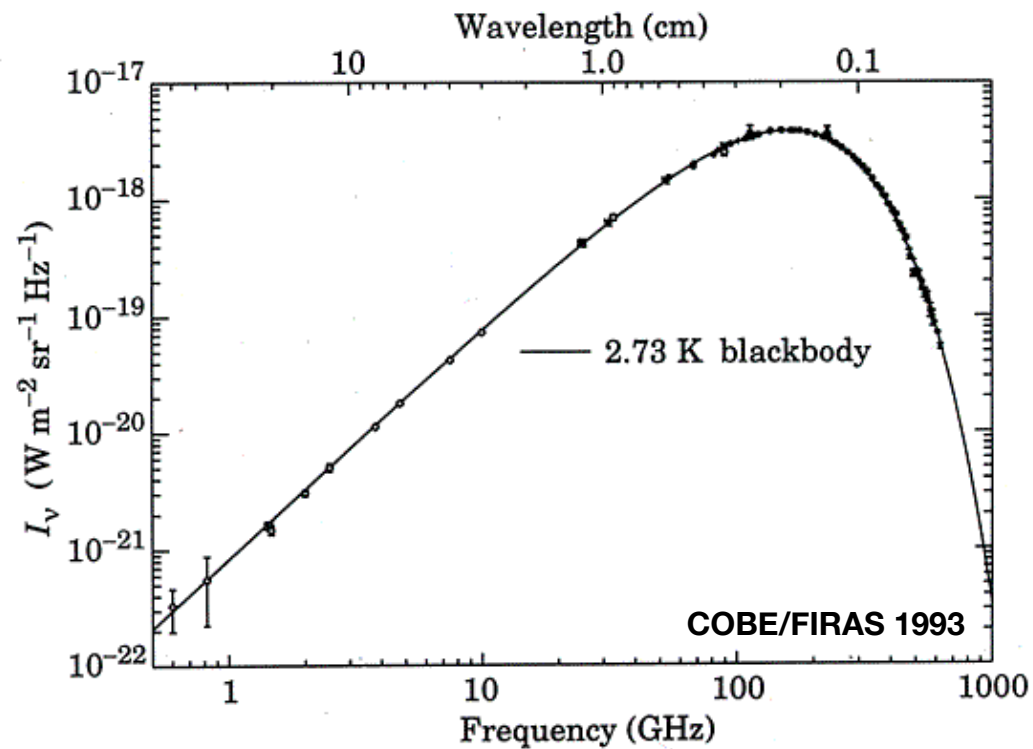
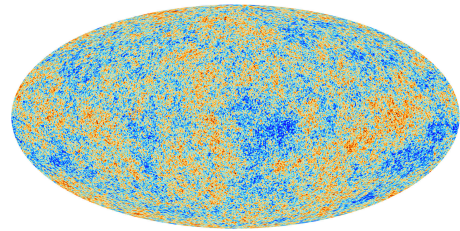
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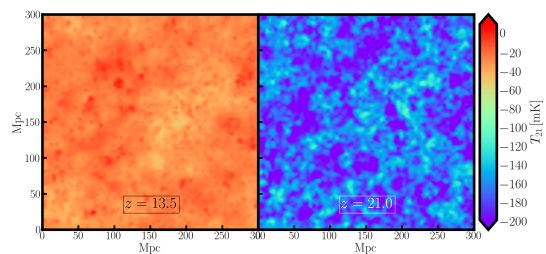


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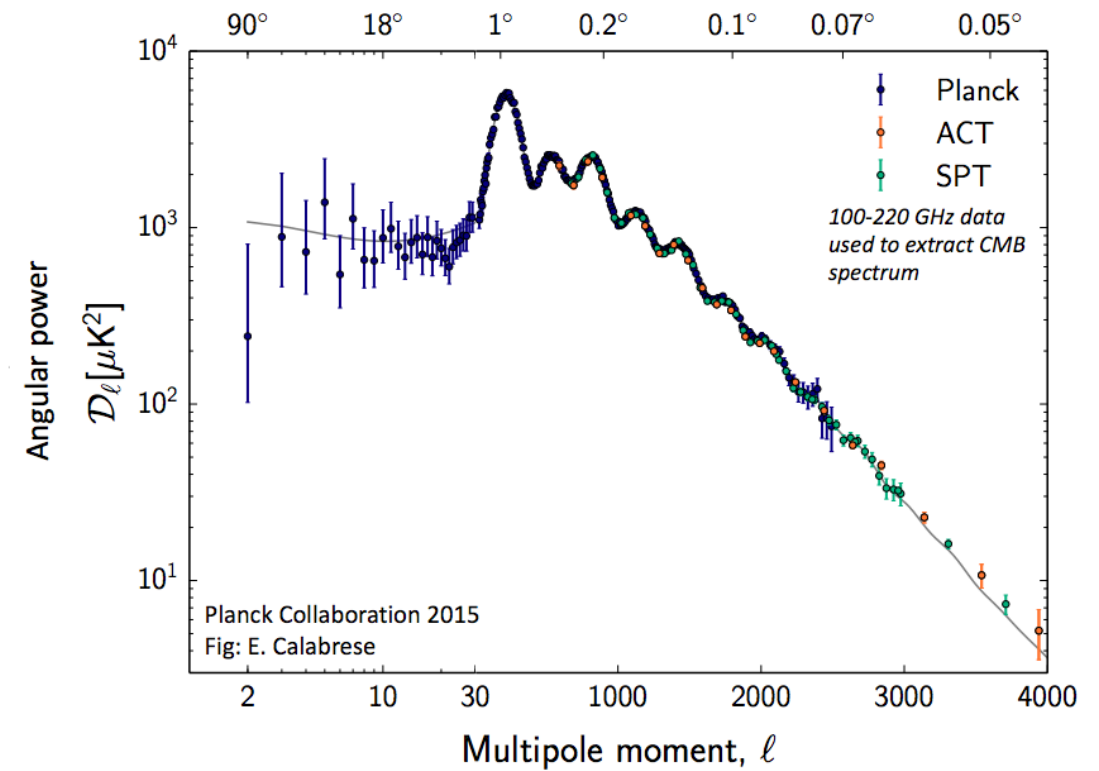
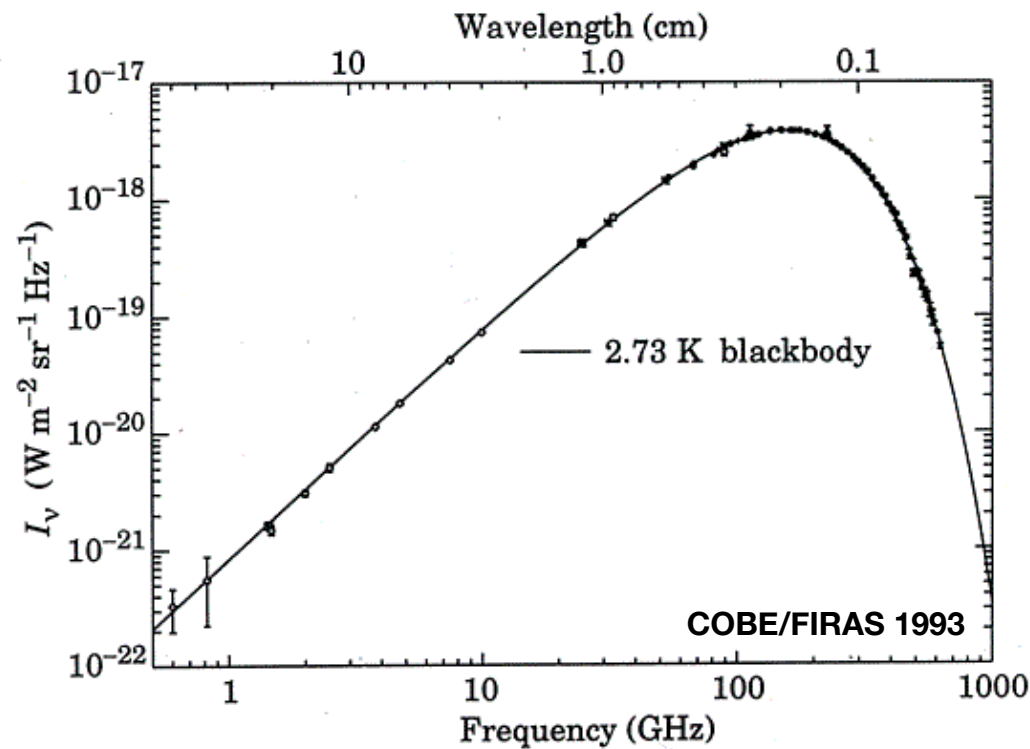
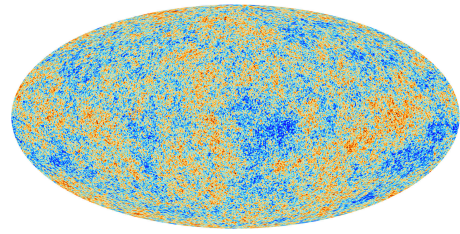


21cm

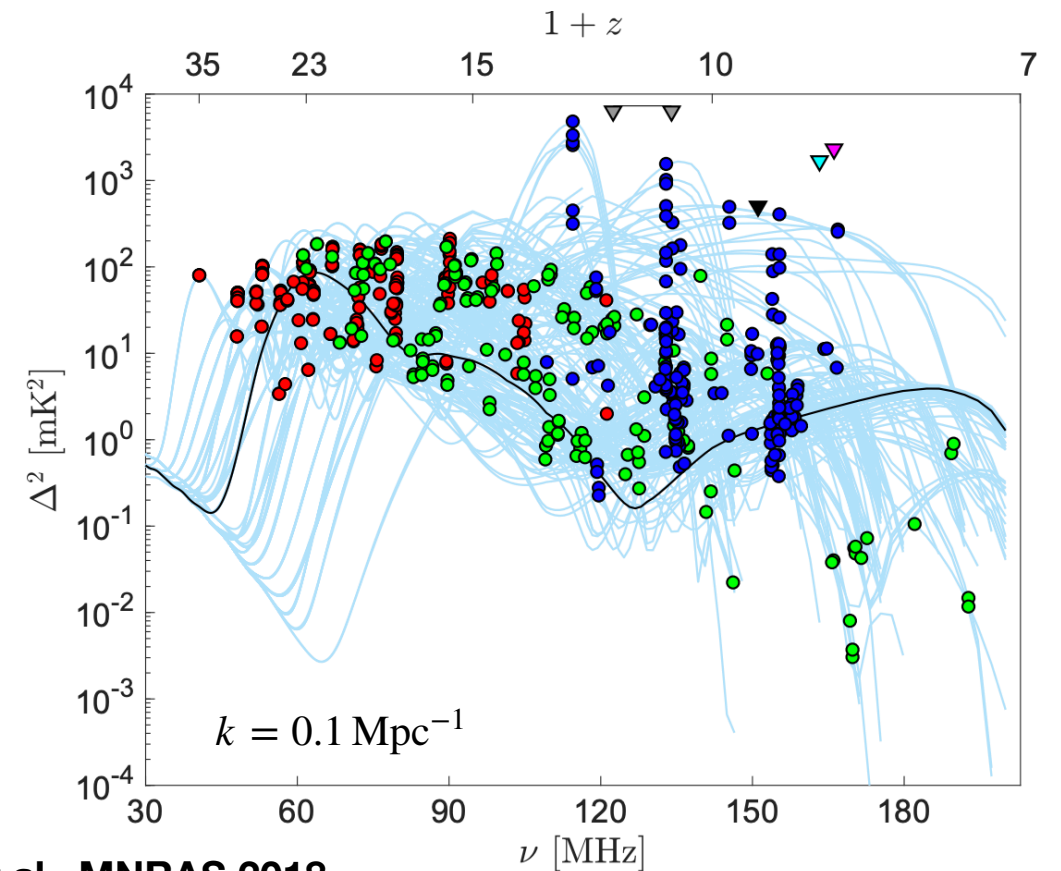
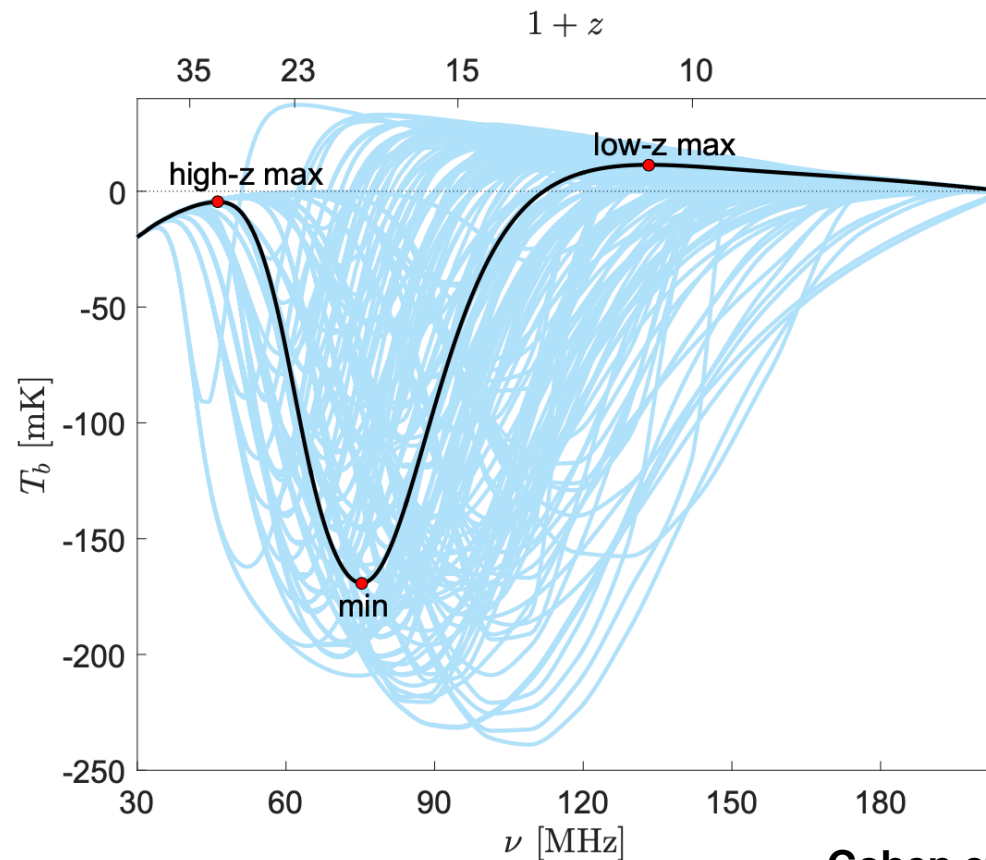
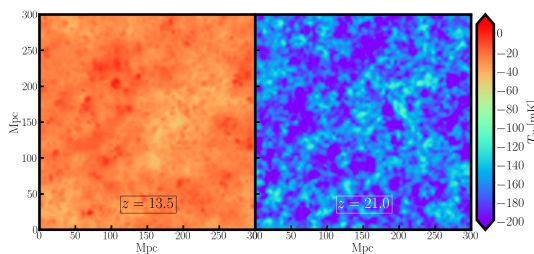


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CMB



21cm



Cohen et al., MNRAS 2018

21 cm Line-Intensity Mapping: 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):

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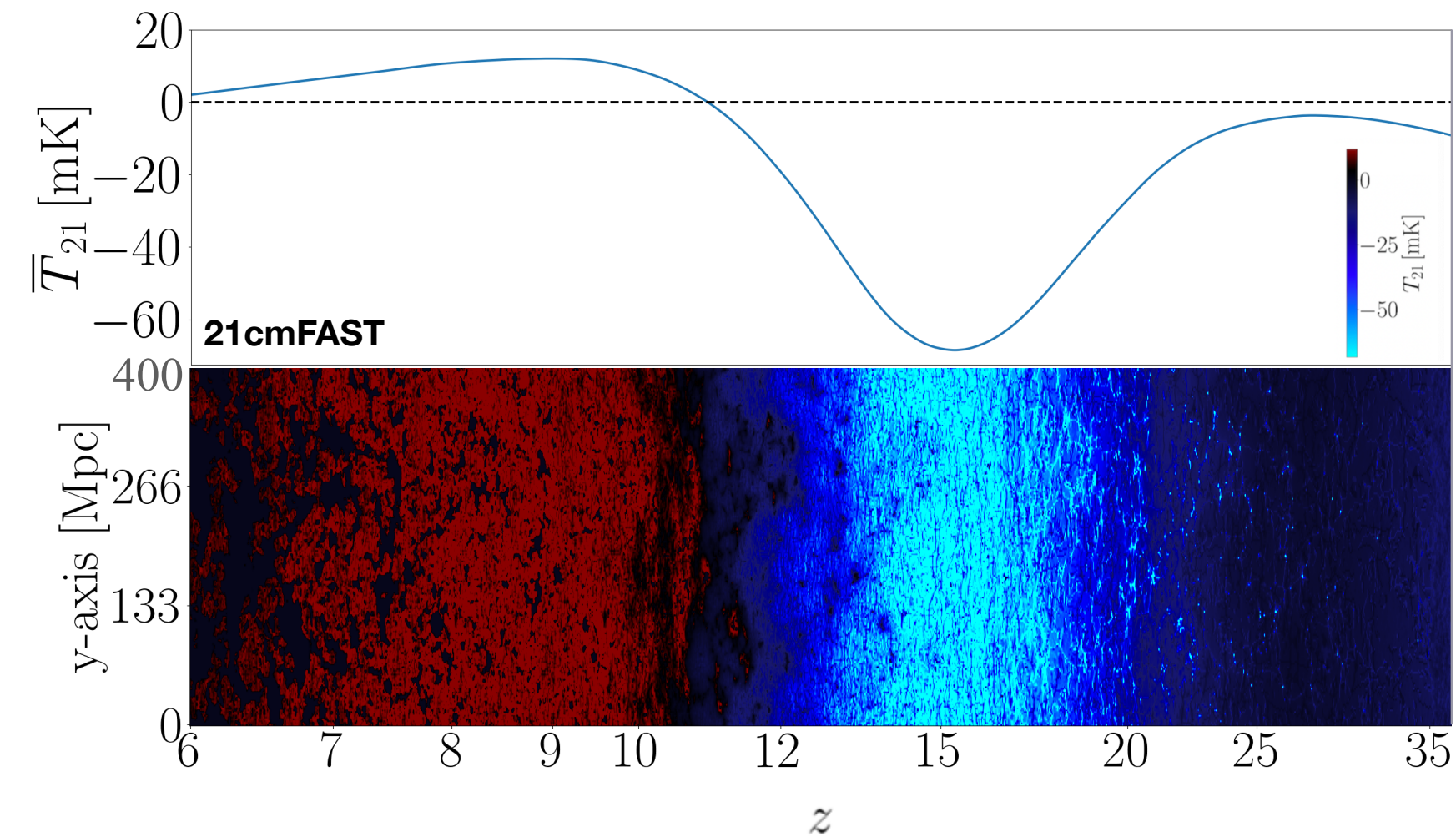
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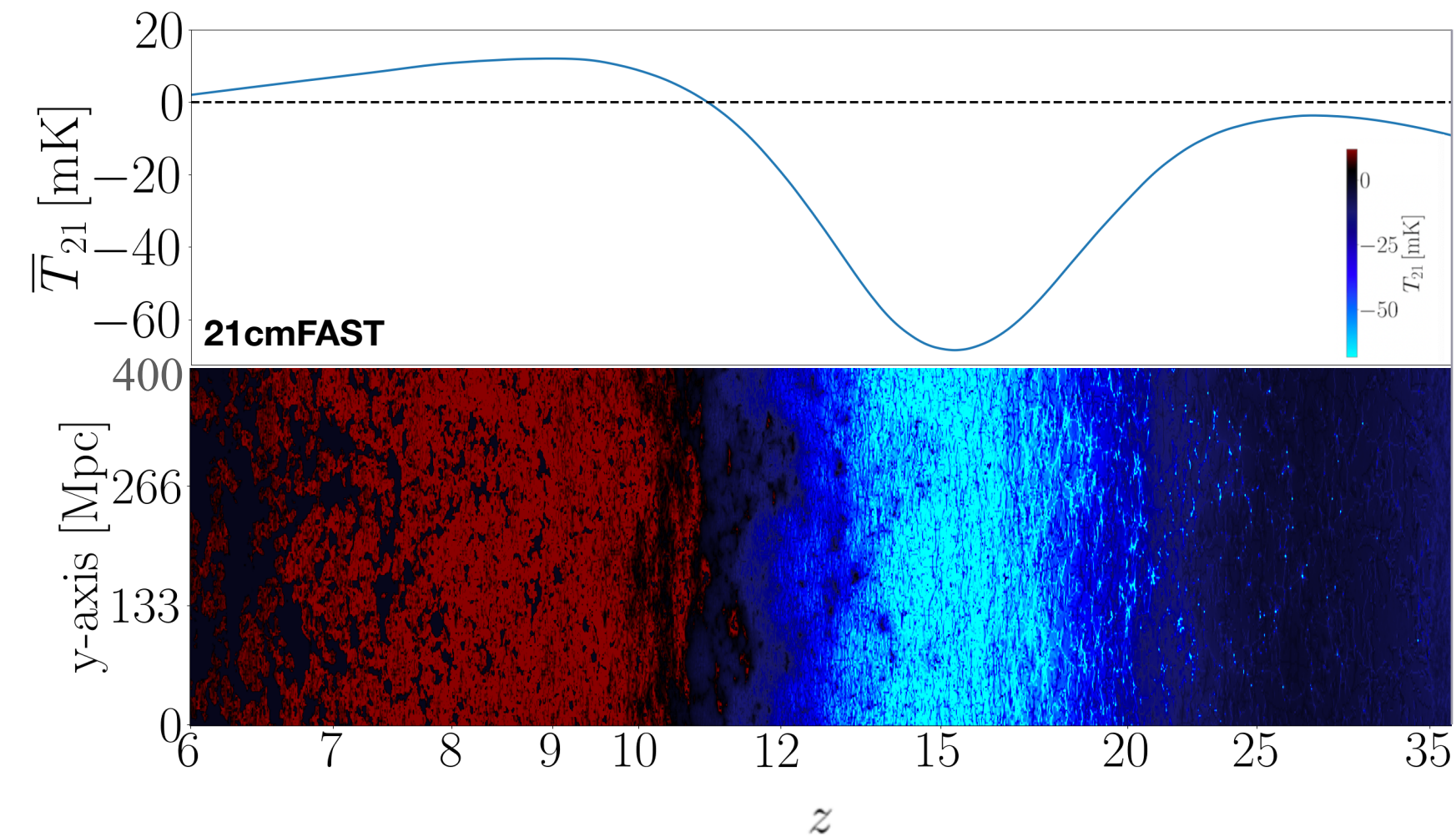
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New: First-Class Code for Cosmology with 21cm

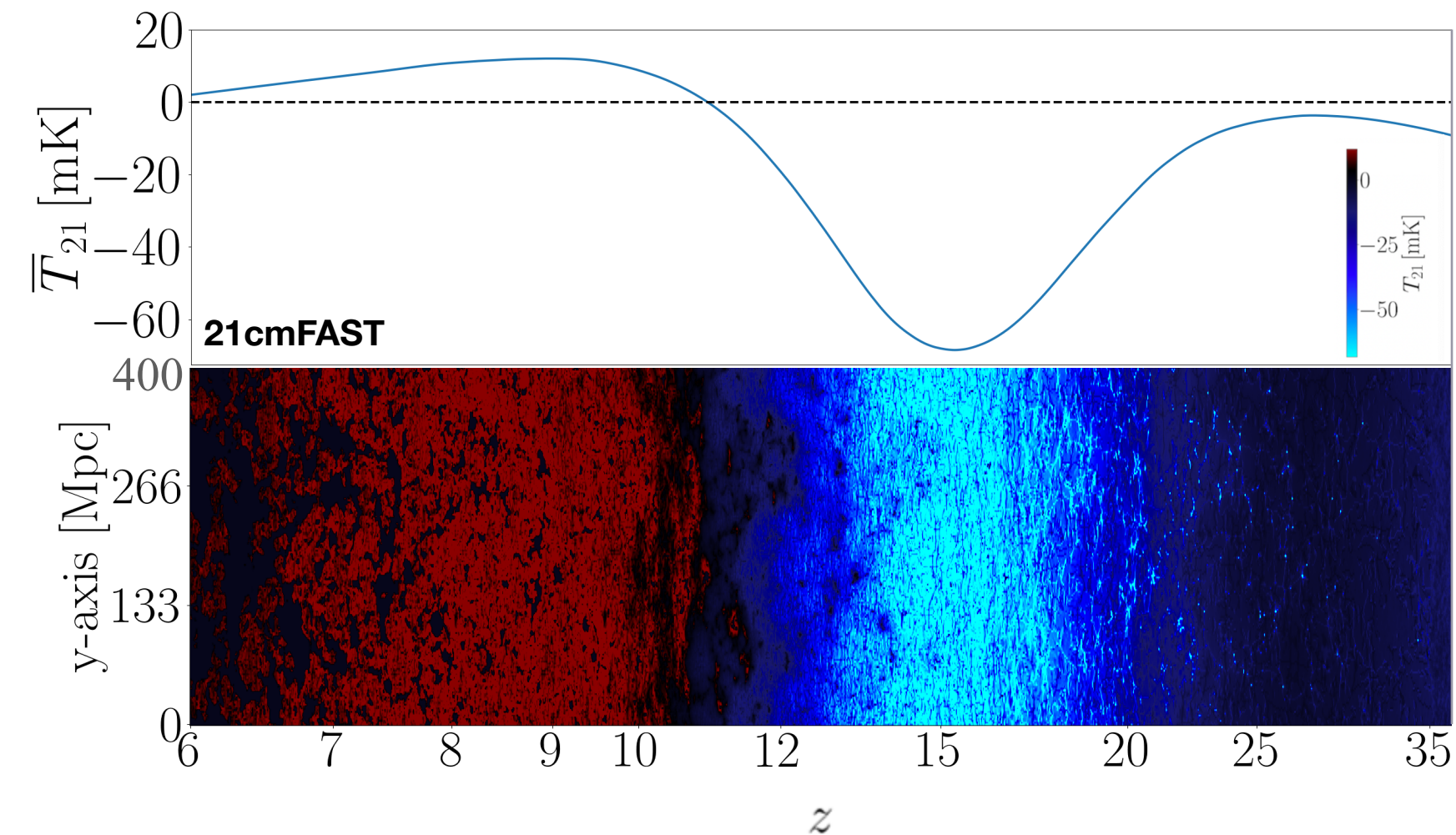


New: First-Class Code for Cosmology with 21cm

Limitations for new physics:



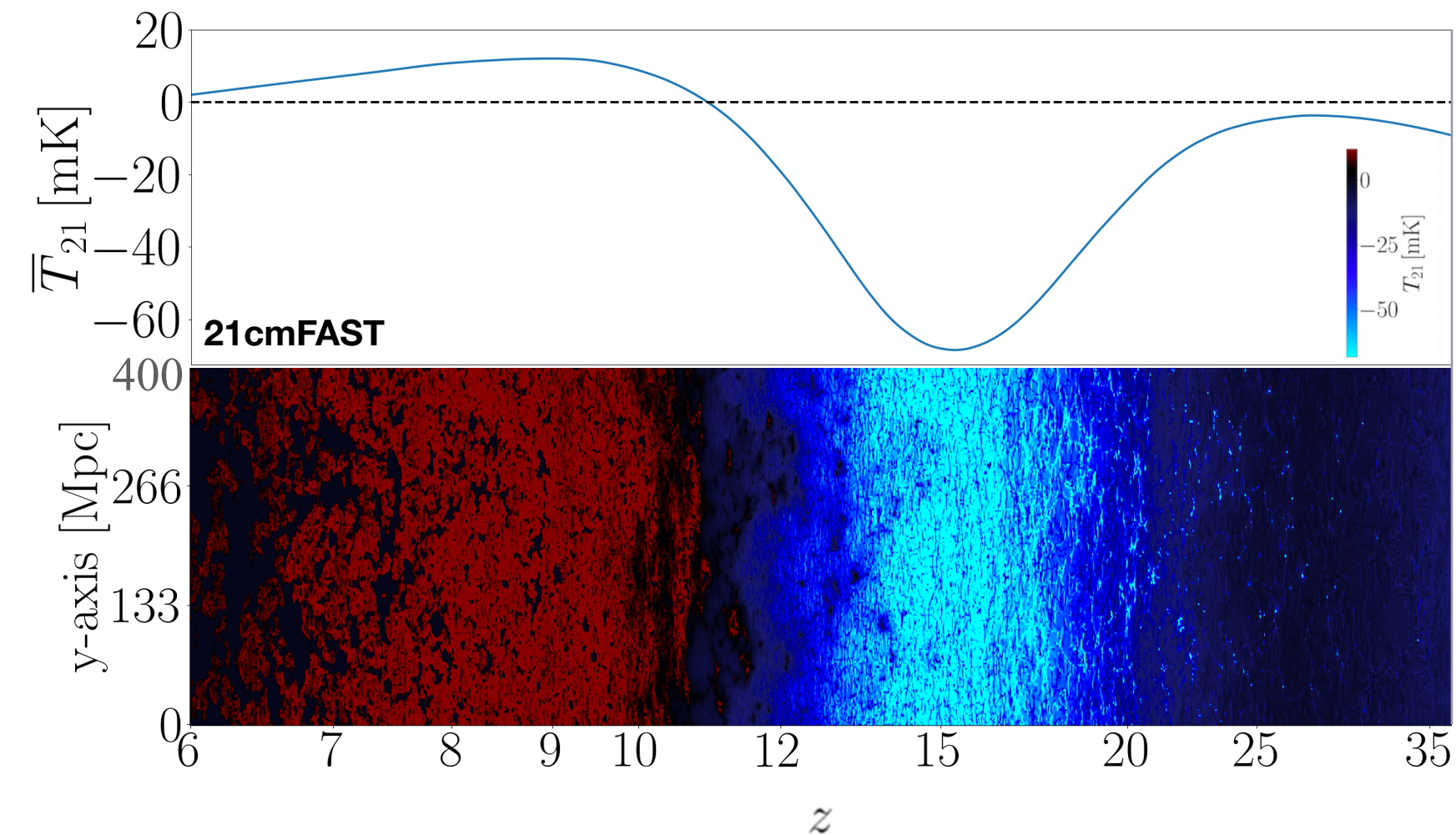
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Limitations for new physics:

- Initialized at $z = 35$

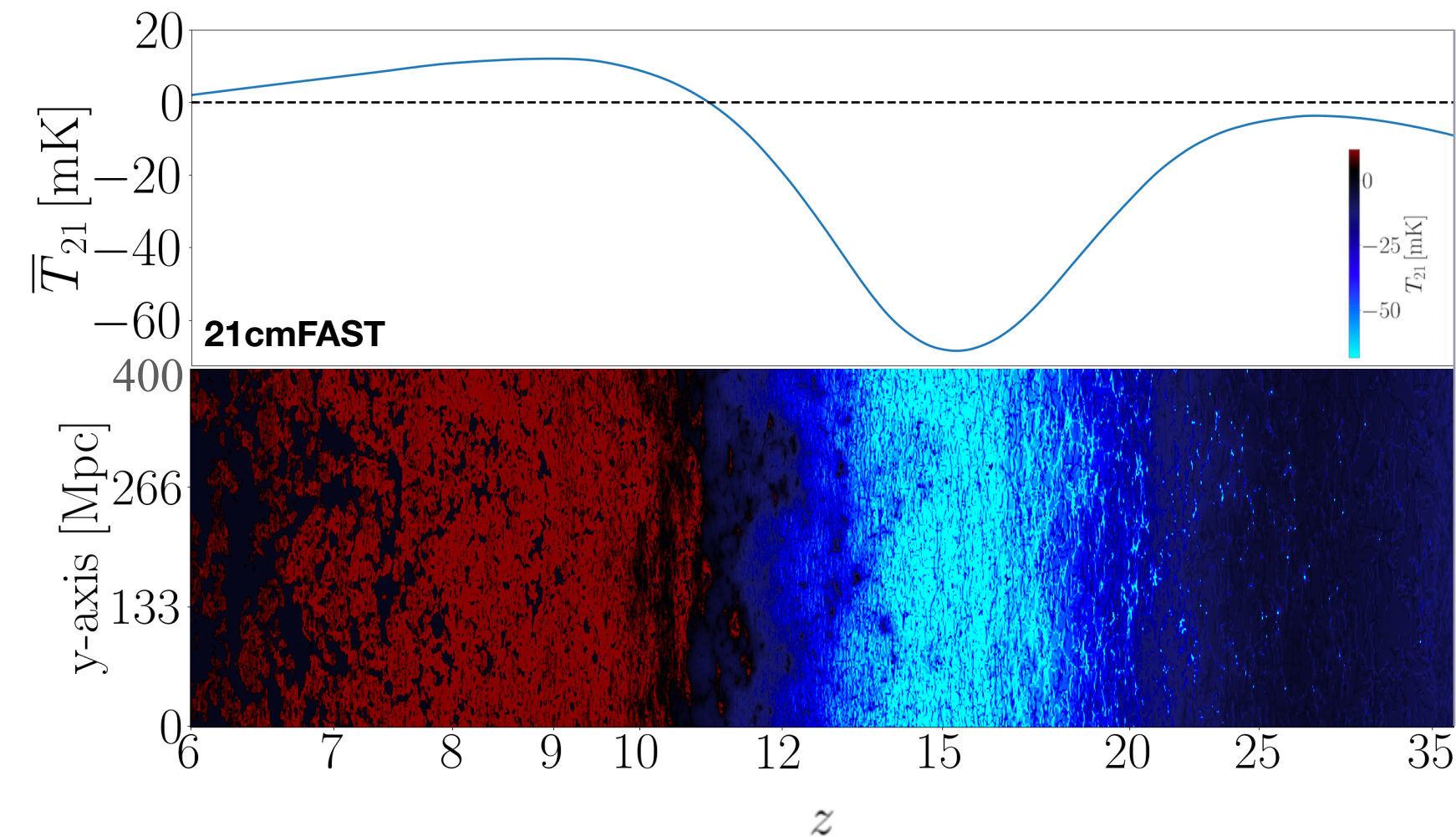
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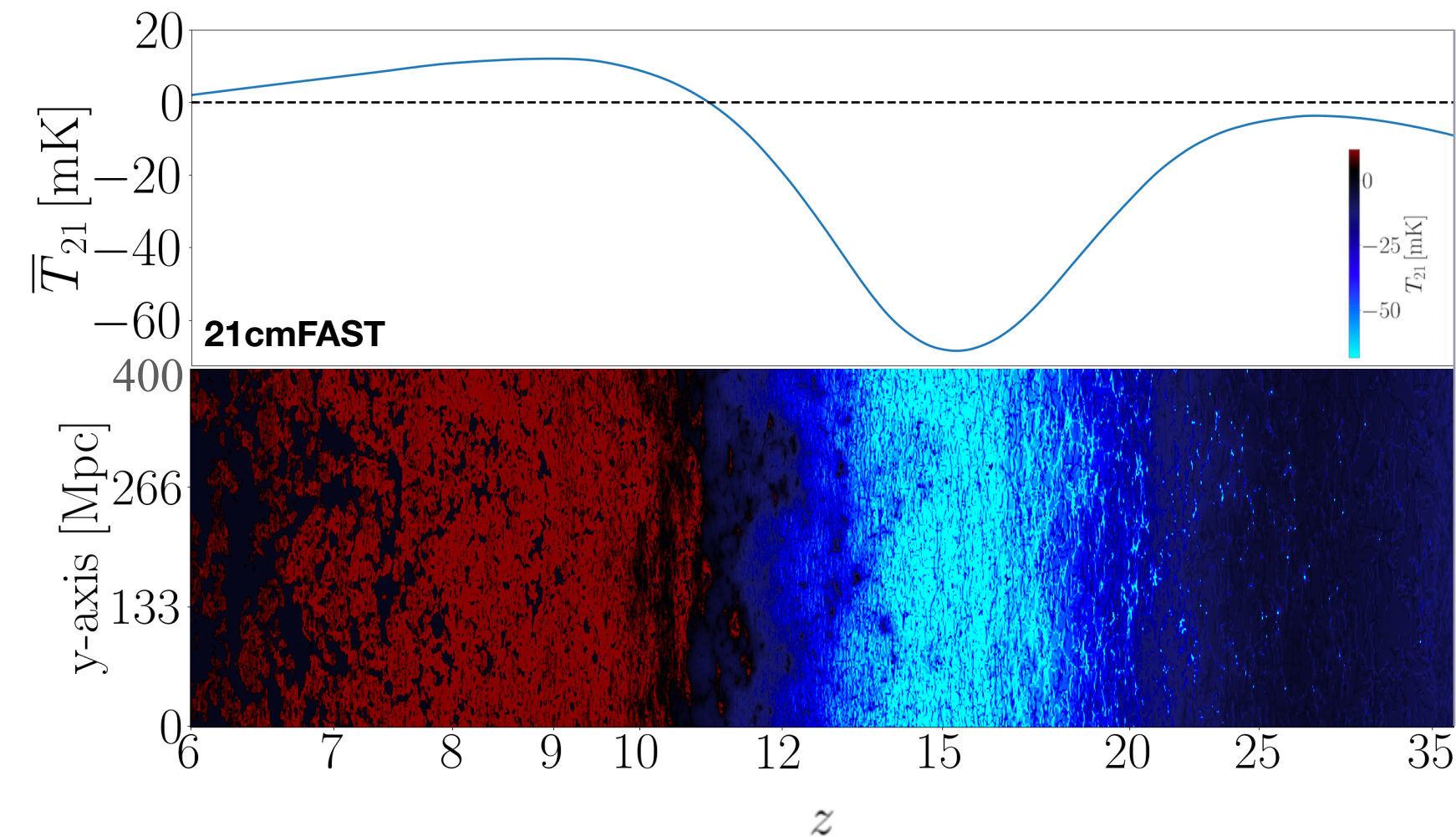
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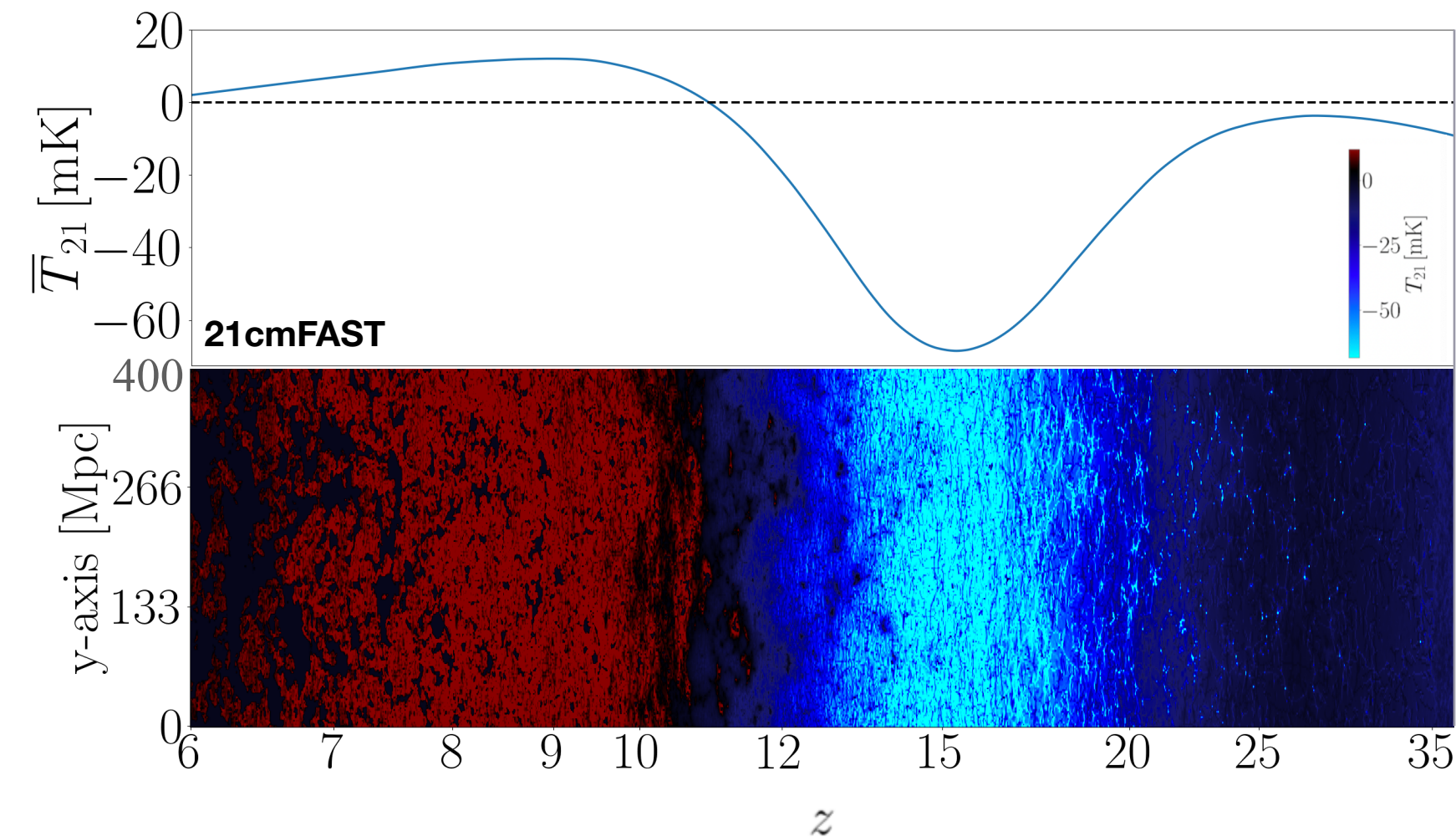
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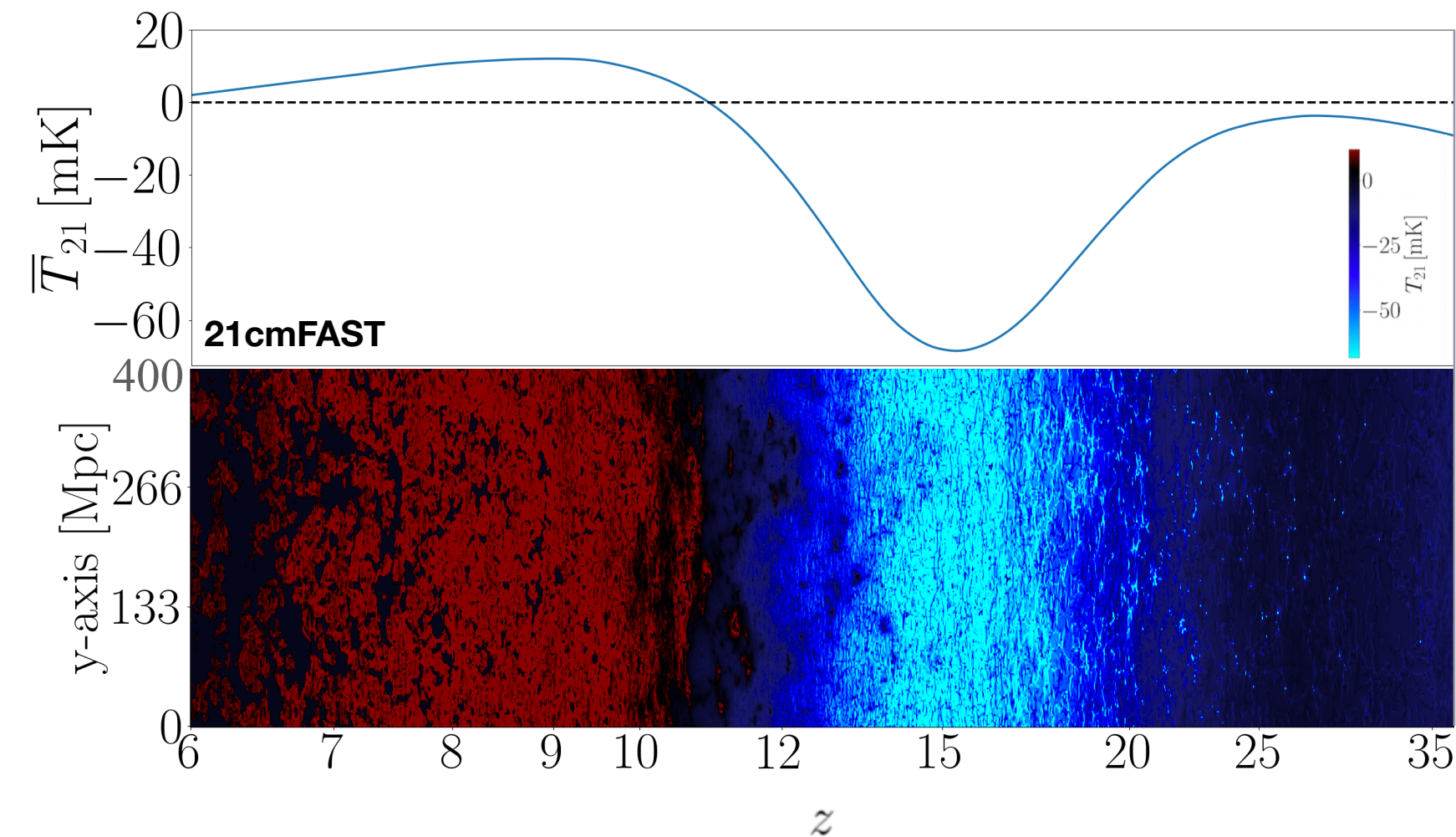
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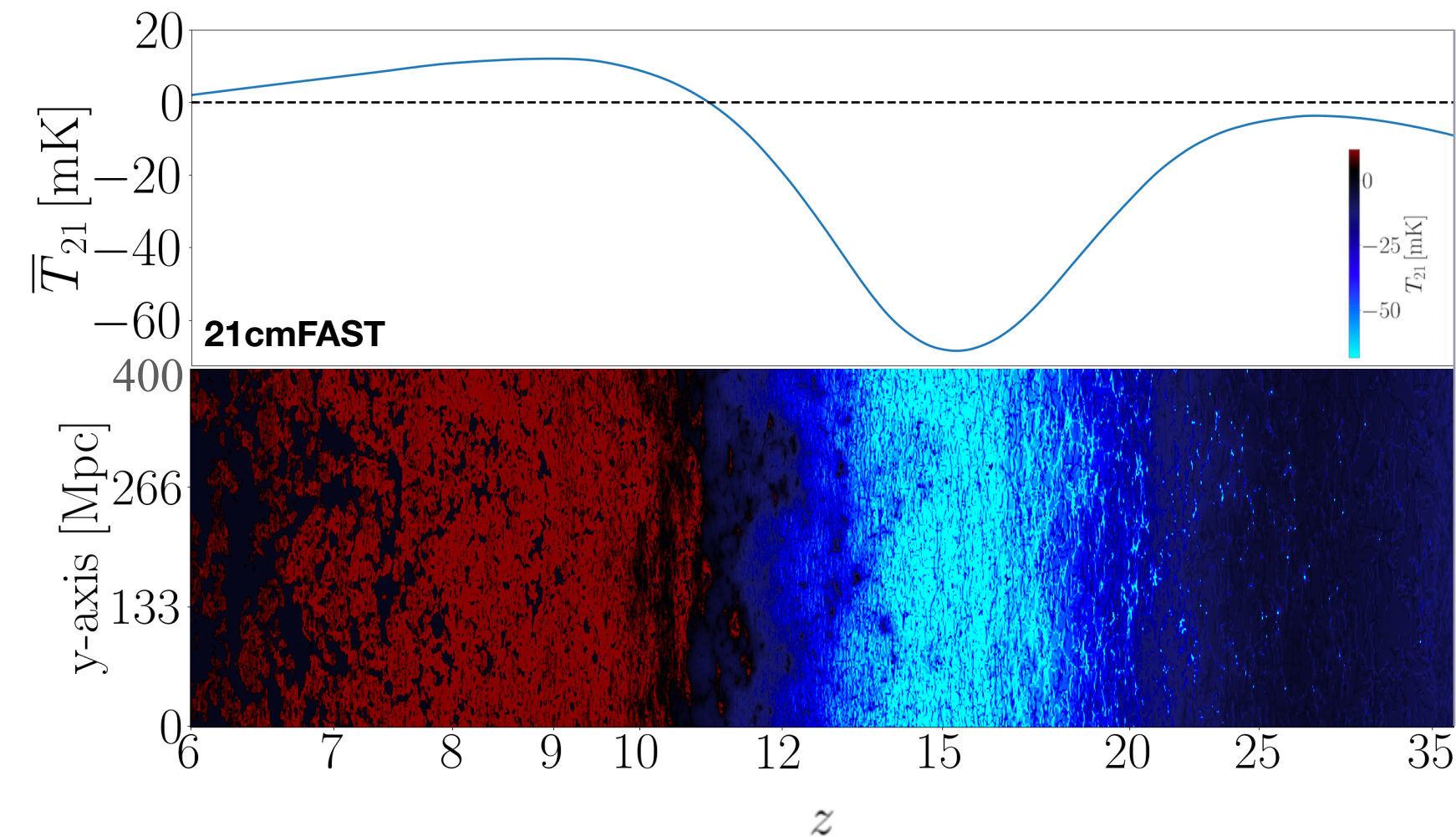
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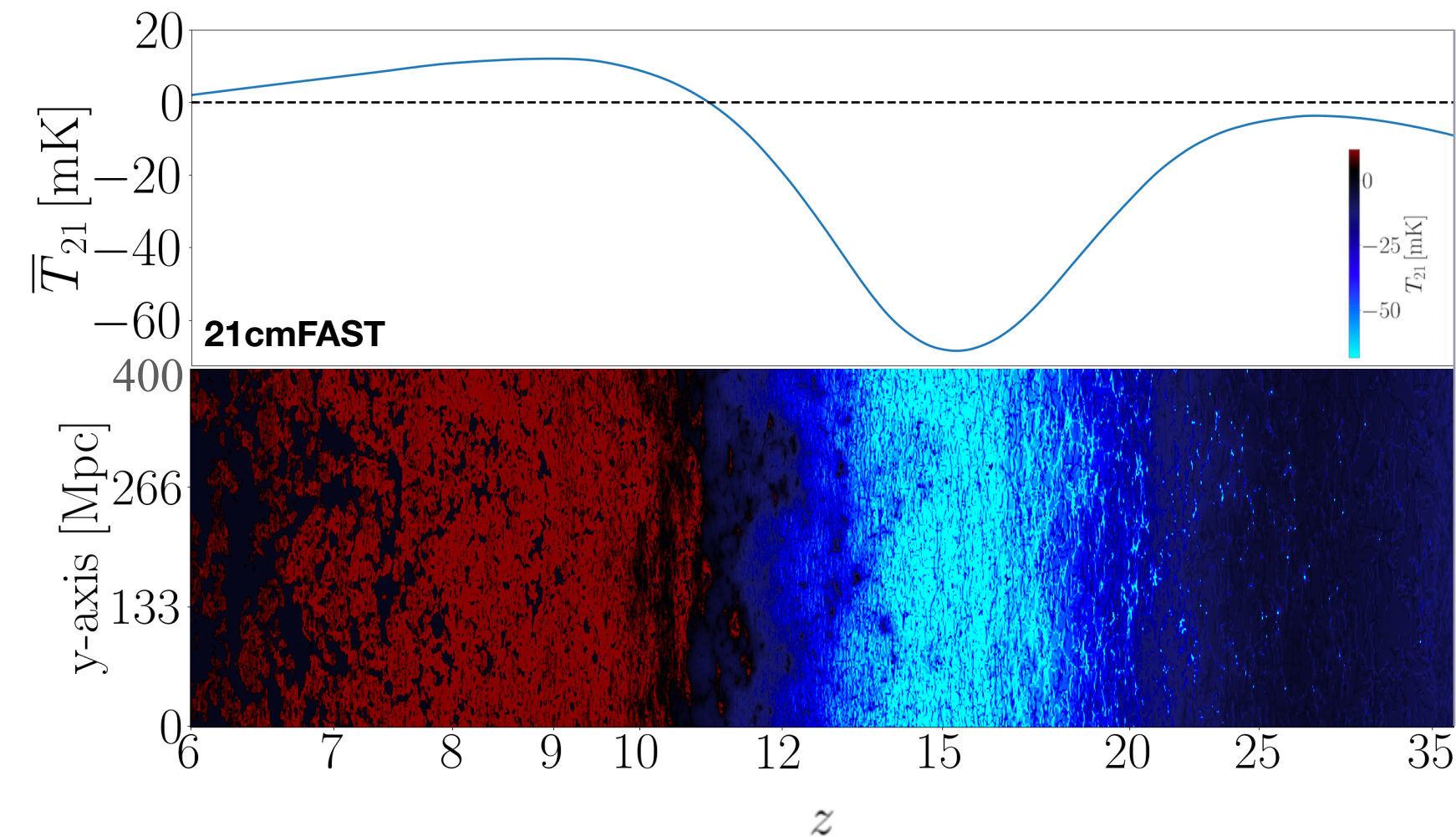


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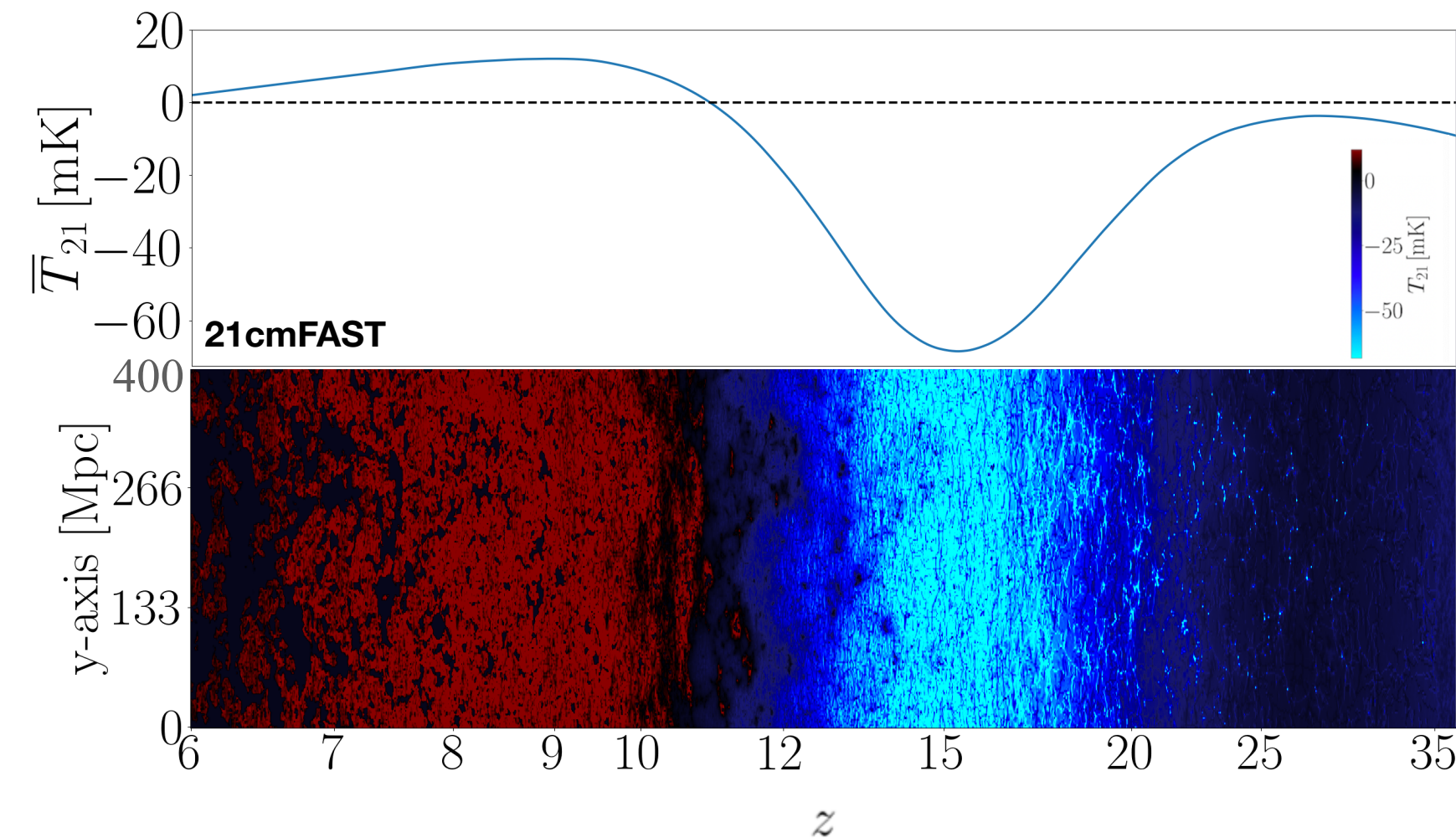


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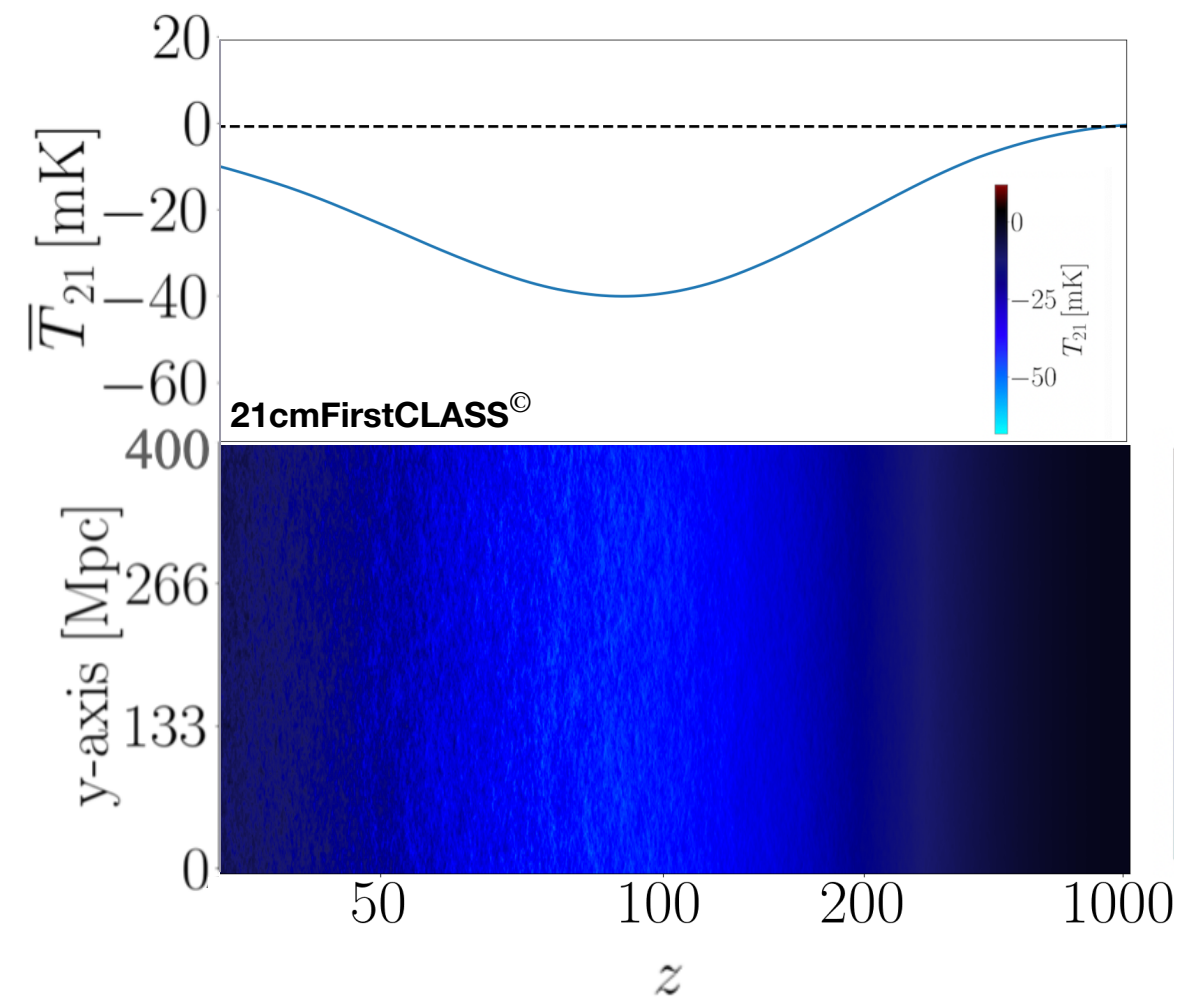
$$dT_k/dz \propto (\Gamma_C/H) \begin{pmatrix} T_\gamma - T_k \\ \gg 1 & \ll 1 \end{pmatrix}$$

→ requires $\Delta z \ll 1$ to solve

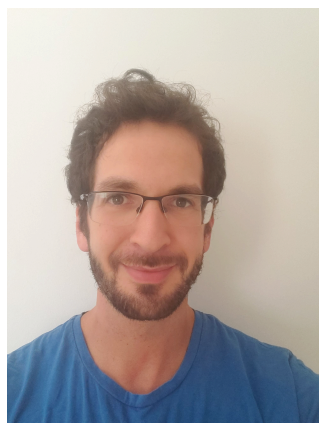
New: First-Class Code for Cosmology with 21cm

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 $\delta_b, \delta_m, \nu_{cb}, T_{\{i\}}$ 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 $\epsilon_{\gamma b} = H/\Gamma_C$, and solve for $\epsilon_{\gamma b}, \Delta T_{\gamma b}, \bar{T}_{\gamma b}$



New: First-Class Code for Cosmology with 21cm



J. Flitter

21cmFirstCLASS I. Cosmological tool for Λ CDM and beyond

Jordan Flitter^{1,*} and Ely D. Kovetz¹

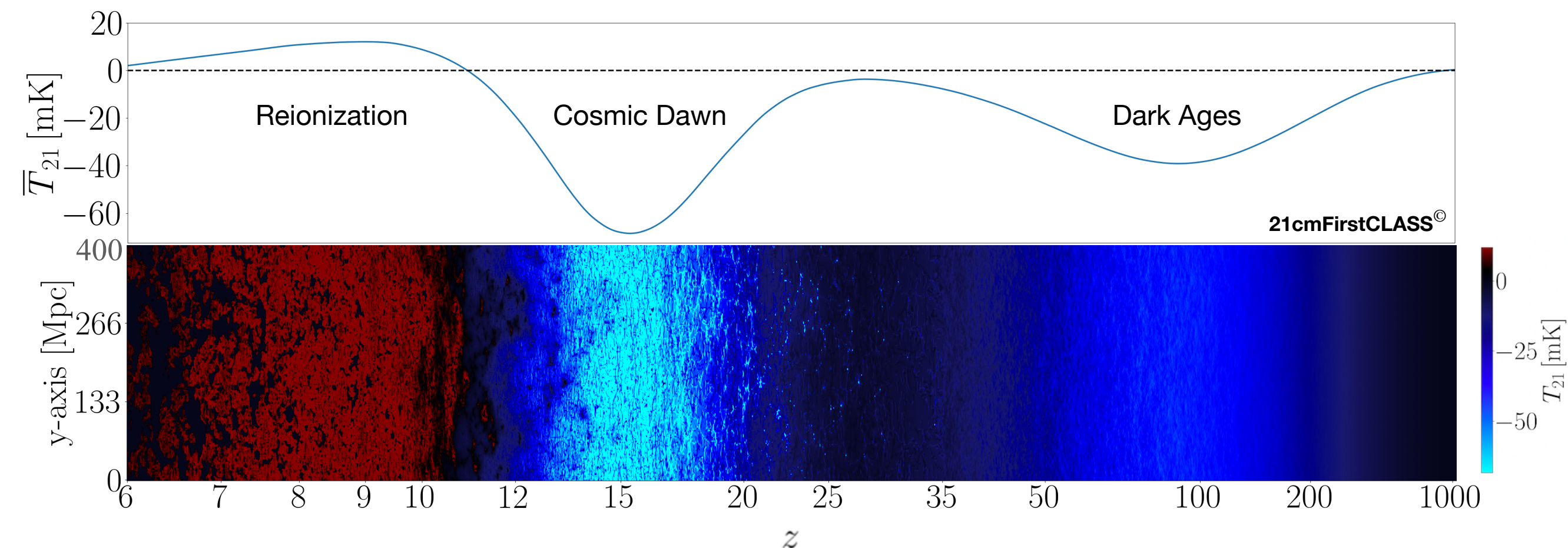
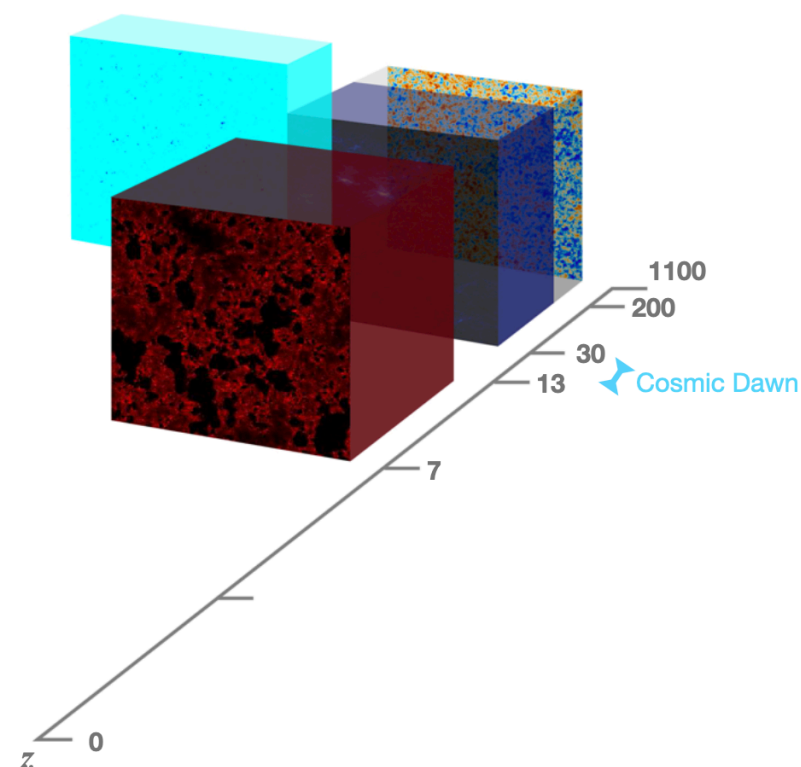
¹*Physics Department, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel*

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

Jordan Flitter^{1,*} and Ely D. Kovetz¹

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

Find it on Github: <https://github.com/jordanflitter/21cmFirstCLASS>



New: First-Class Code for Cosmology with 21cm

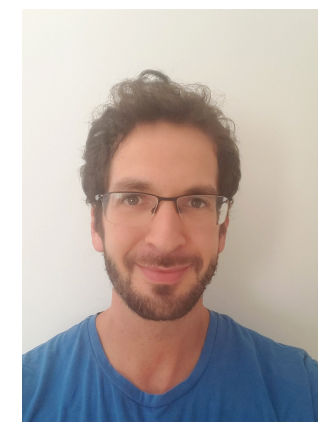
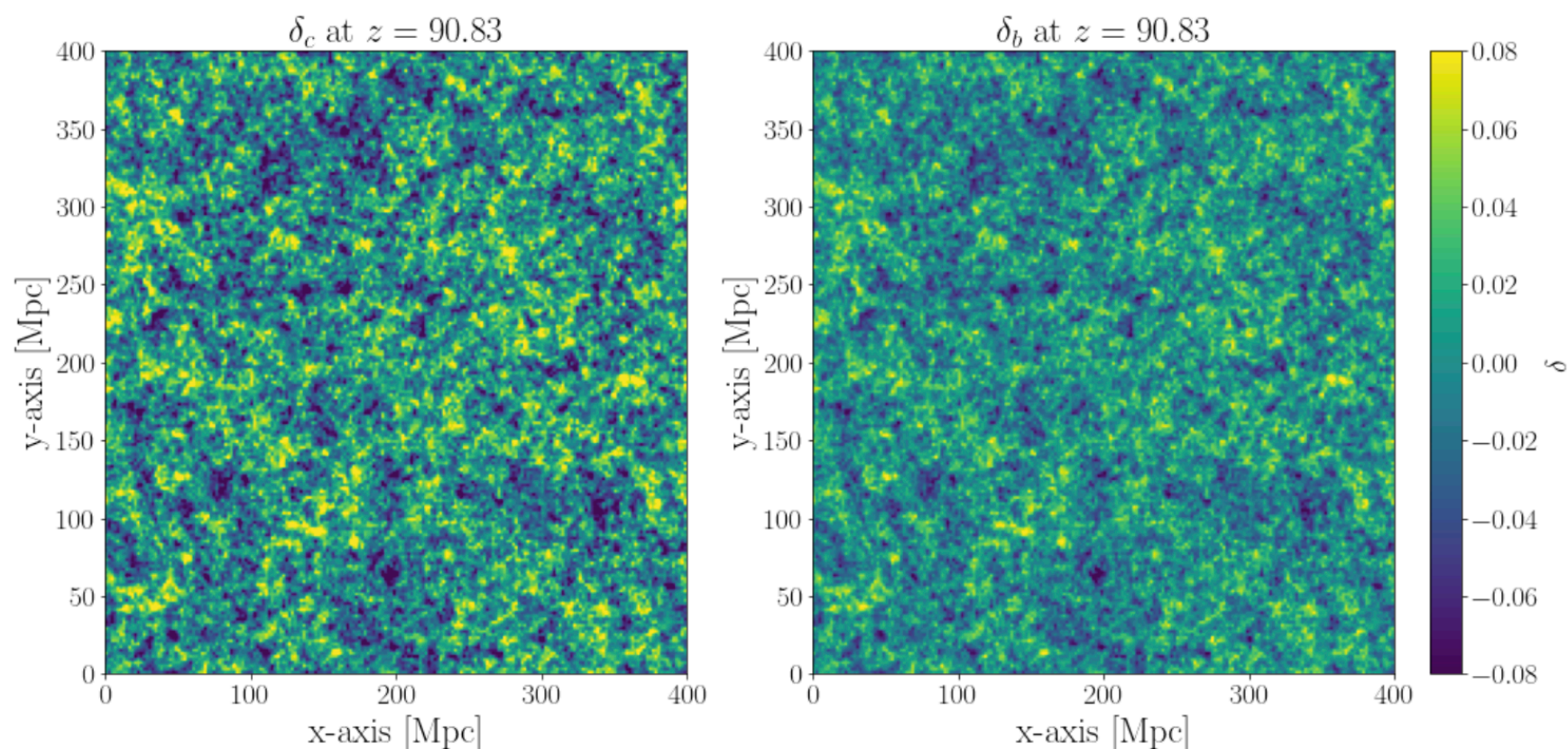
README MIT license

21cmFirstCLASS

This is an extension of the popular `21cmFAST` code that interfaces with `CLASS` to generate initial conditions at recombination that are consistent with the input cosmological model. These initial conditions can be set during the time of recombination, allowing one to compute the 21cm signal (and its spatial fluctuations) throughout the dark ages, as well as in the proceeding cosmic dawn and reionization epochs, just like in the standard `21cmFAST`.

A small taste of what can be done with the code

`21cmFirstCLASS` tracks both the CDM density field δ_c as well as the baryons density field δ_b .



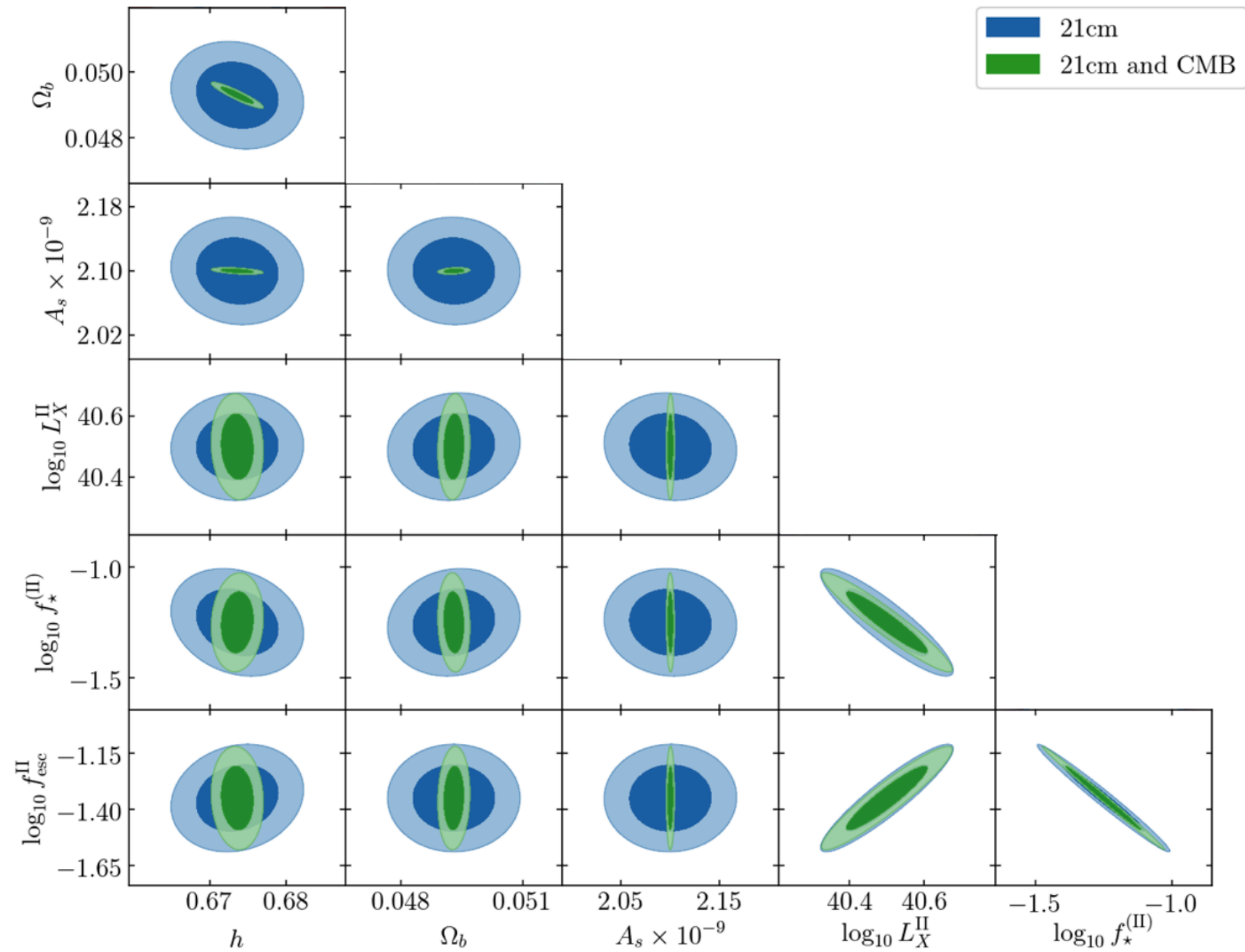
J. Flitter



S. Libanore

Find it on Github: <https://github.com/jordanflitter/21cmFirstCLASS>

New: 21cm+CMB Forecasts with 21cmFirstCLASS

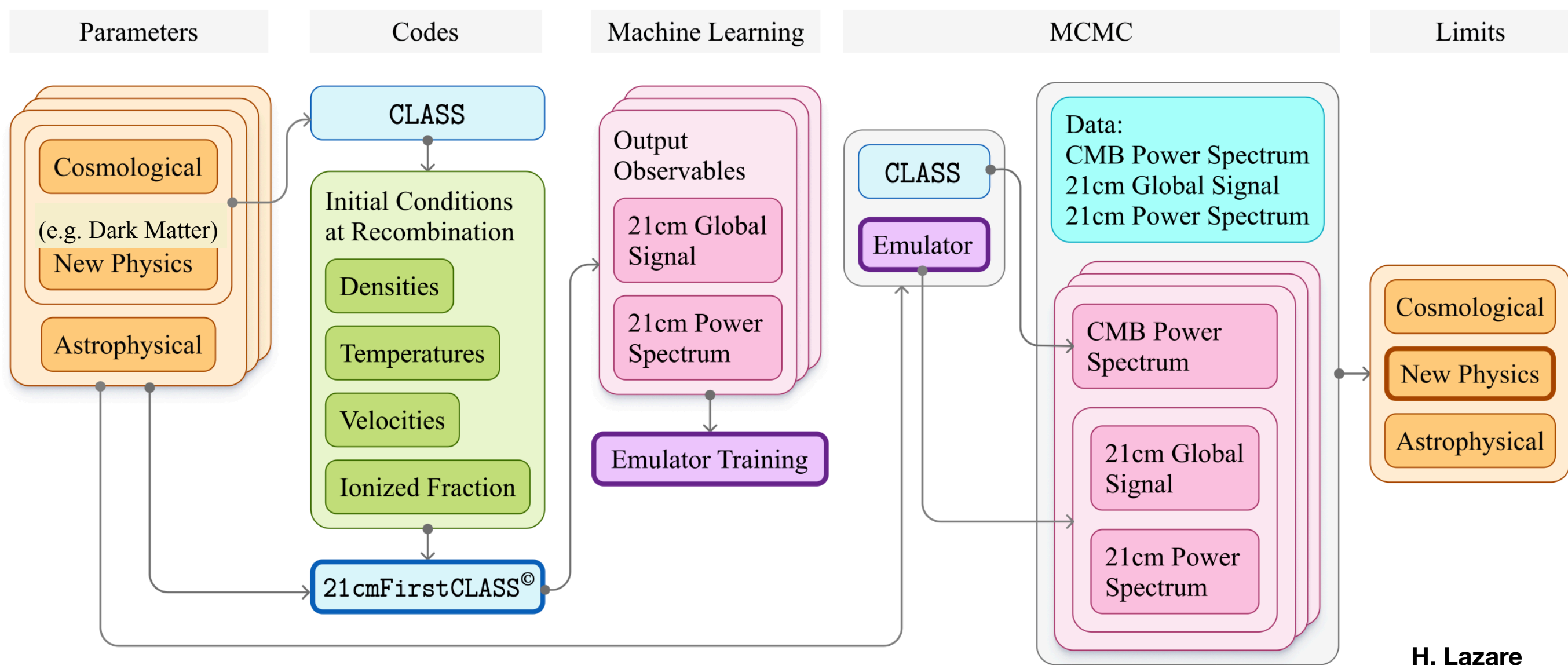


New: End-to-End ML Pipeline for 21cm Analysis

H. Lazare



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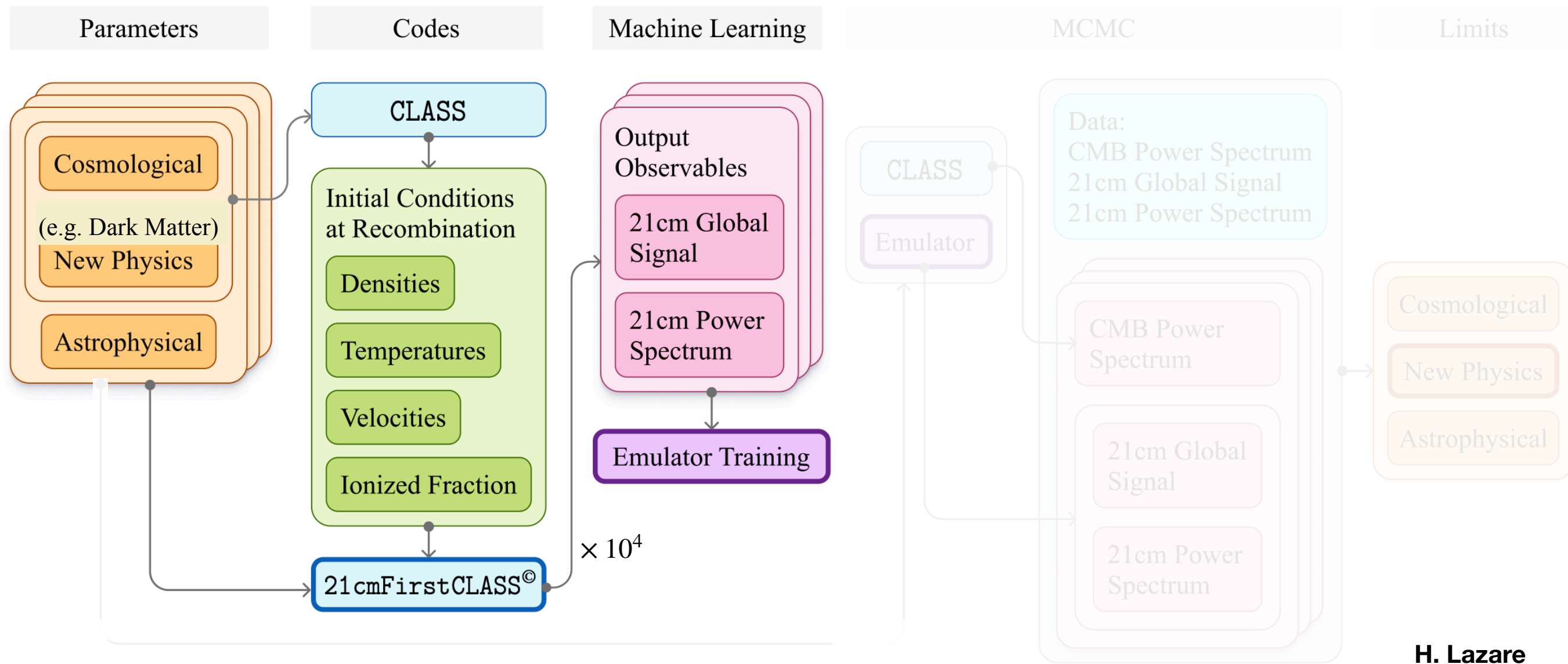


Lazare, Sarkar and Kovetz, PRD 2023; Lazare, Flitter and Kovetz, PRD 2024

H. Lazare



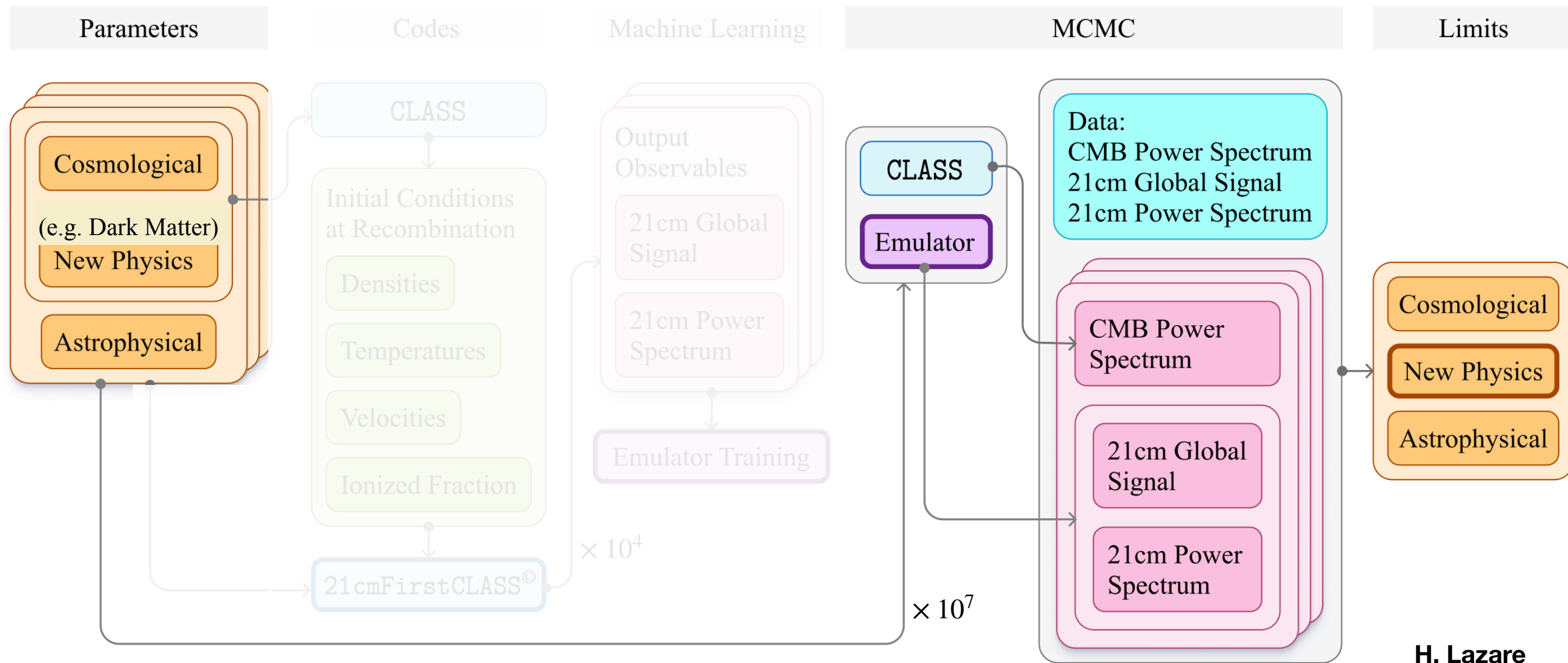
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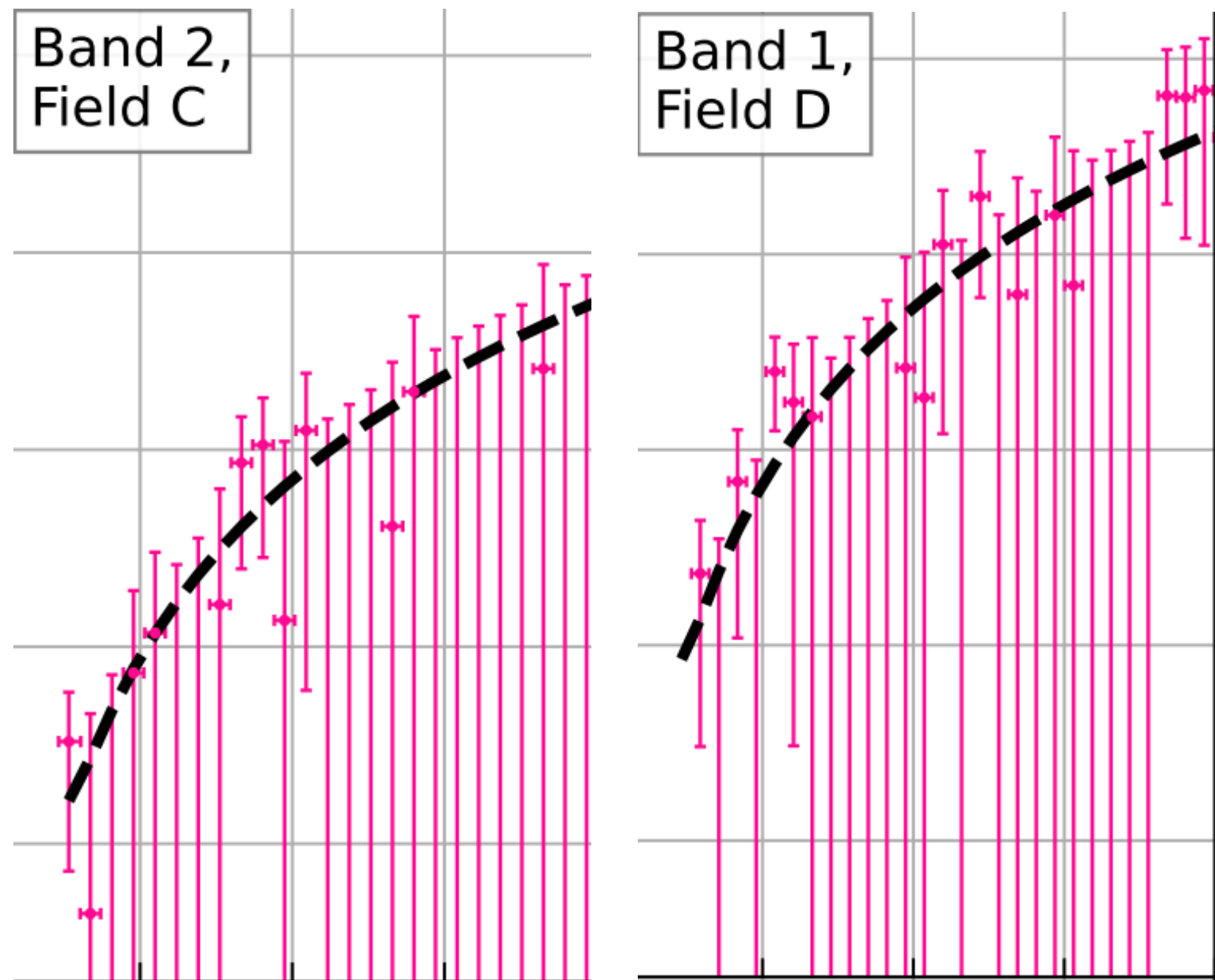
H. Lazare



Pipeline Verification: Reproducing HERA Results

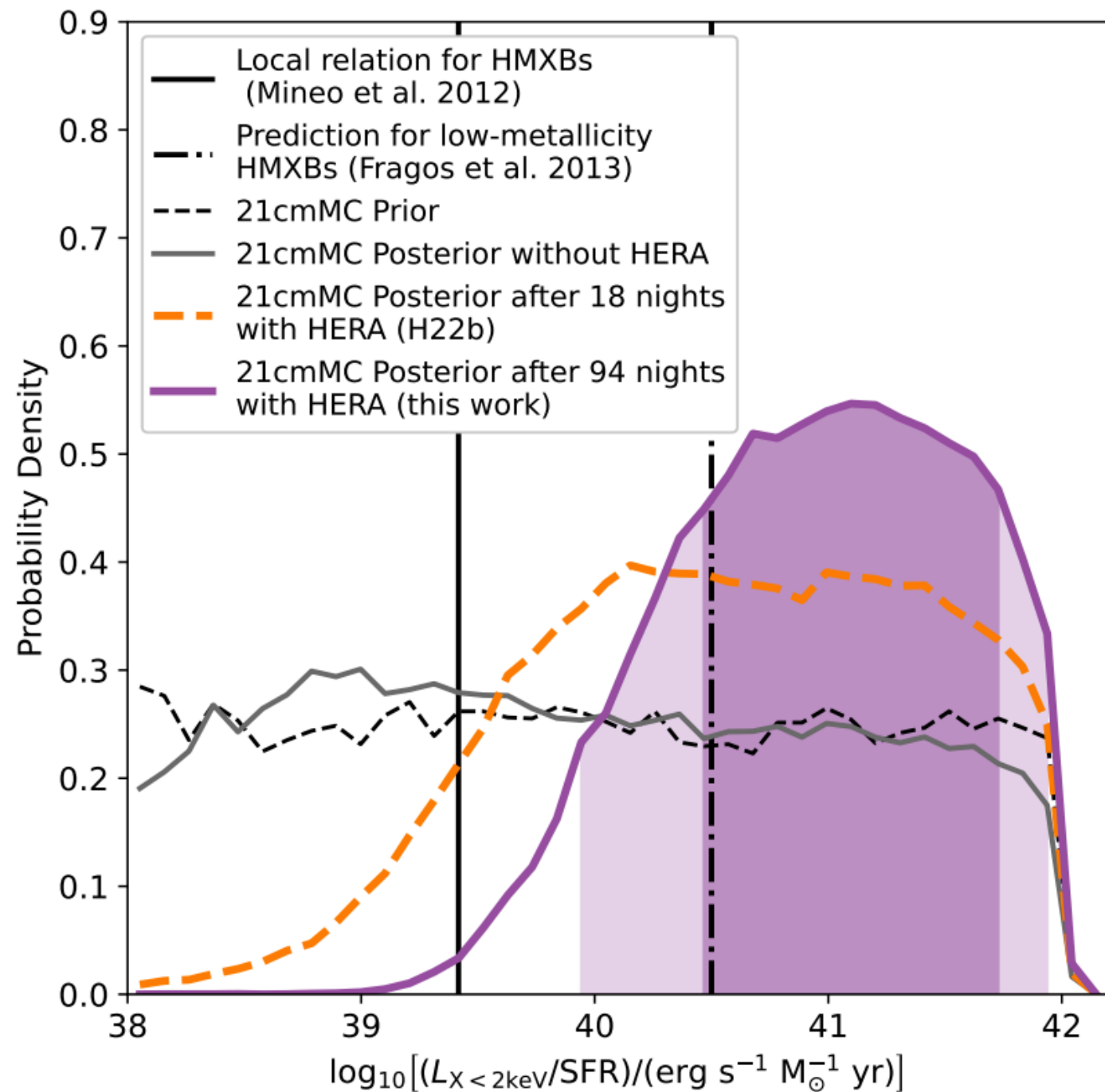
The HERA Collaboration (2022)

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



Pipeline Verification: Reproducing HERA Results

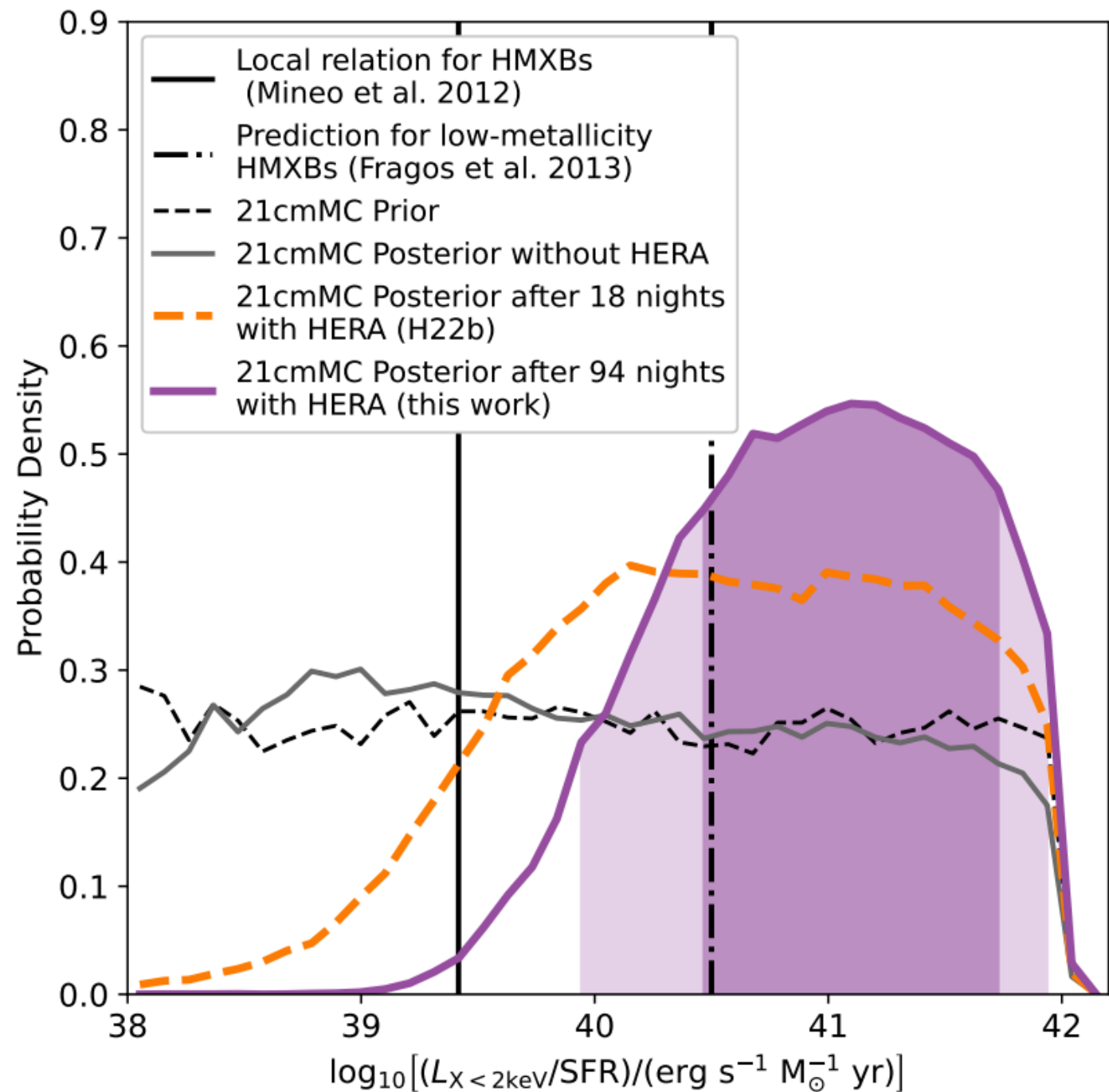
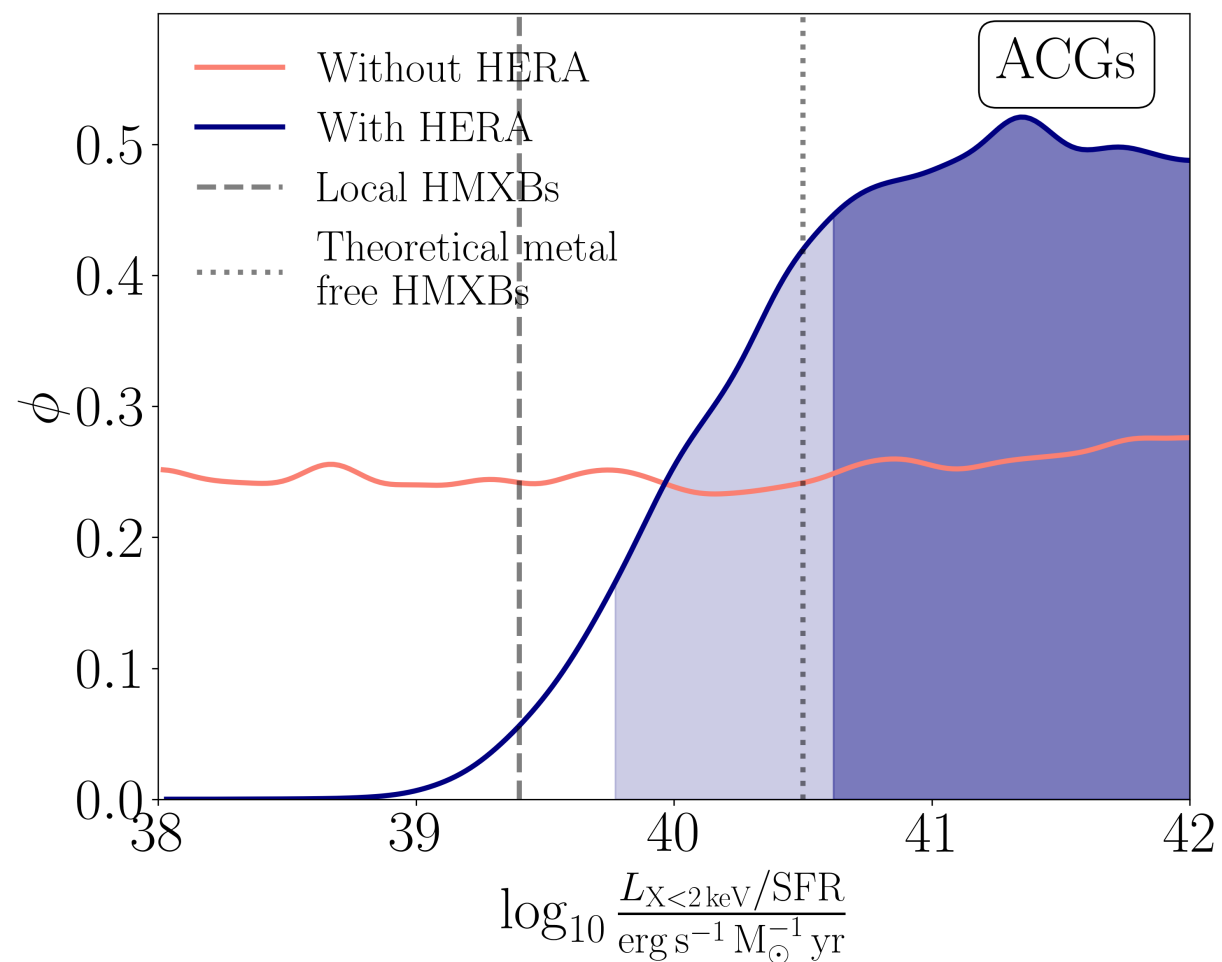
Assuming only atomic-cooling halos
(hosting popII stars):



HERA Phase-I results

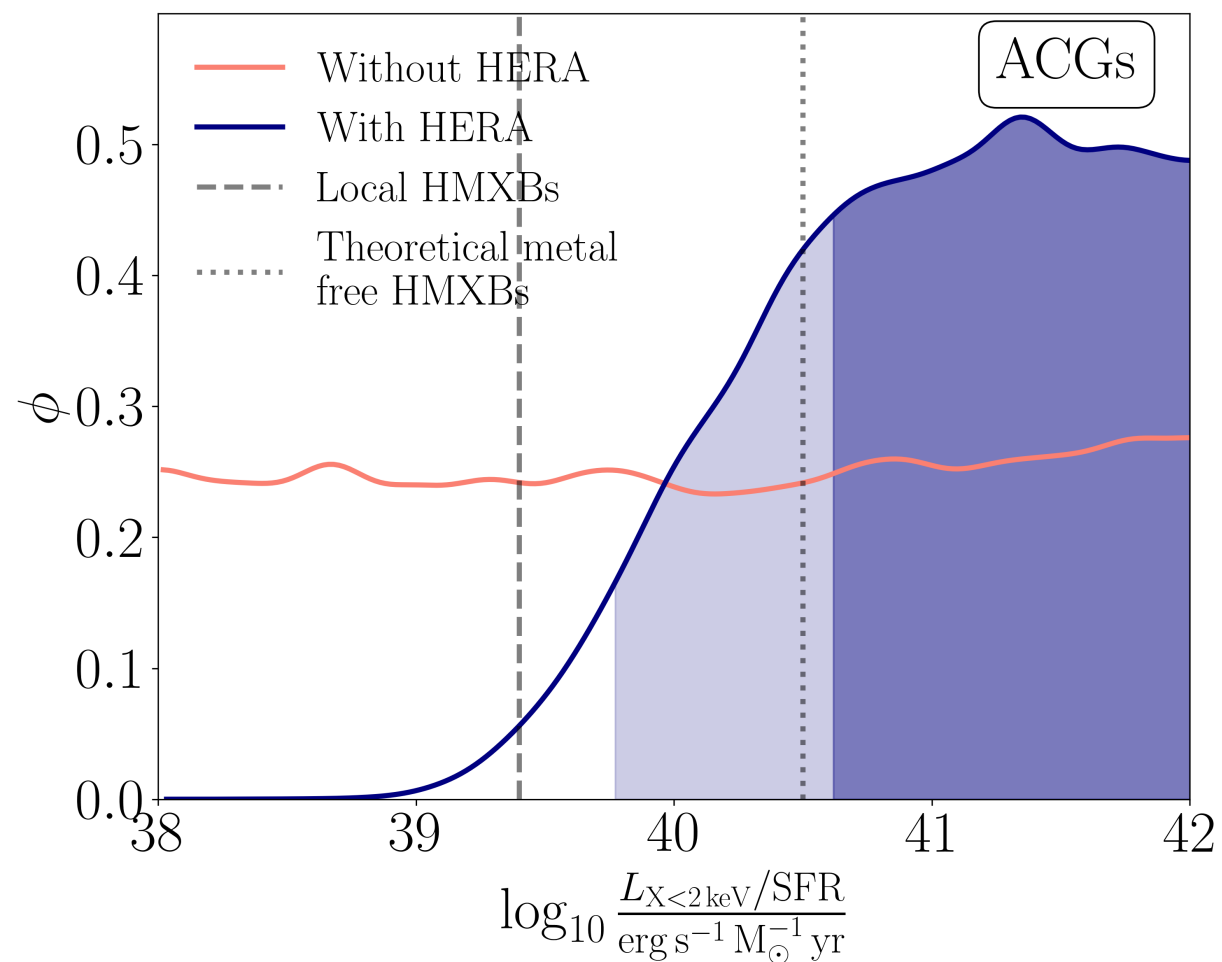
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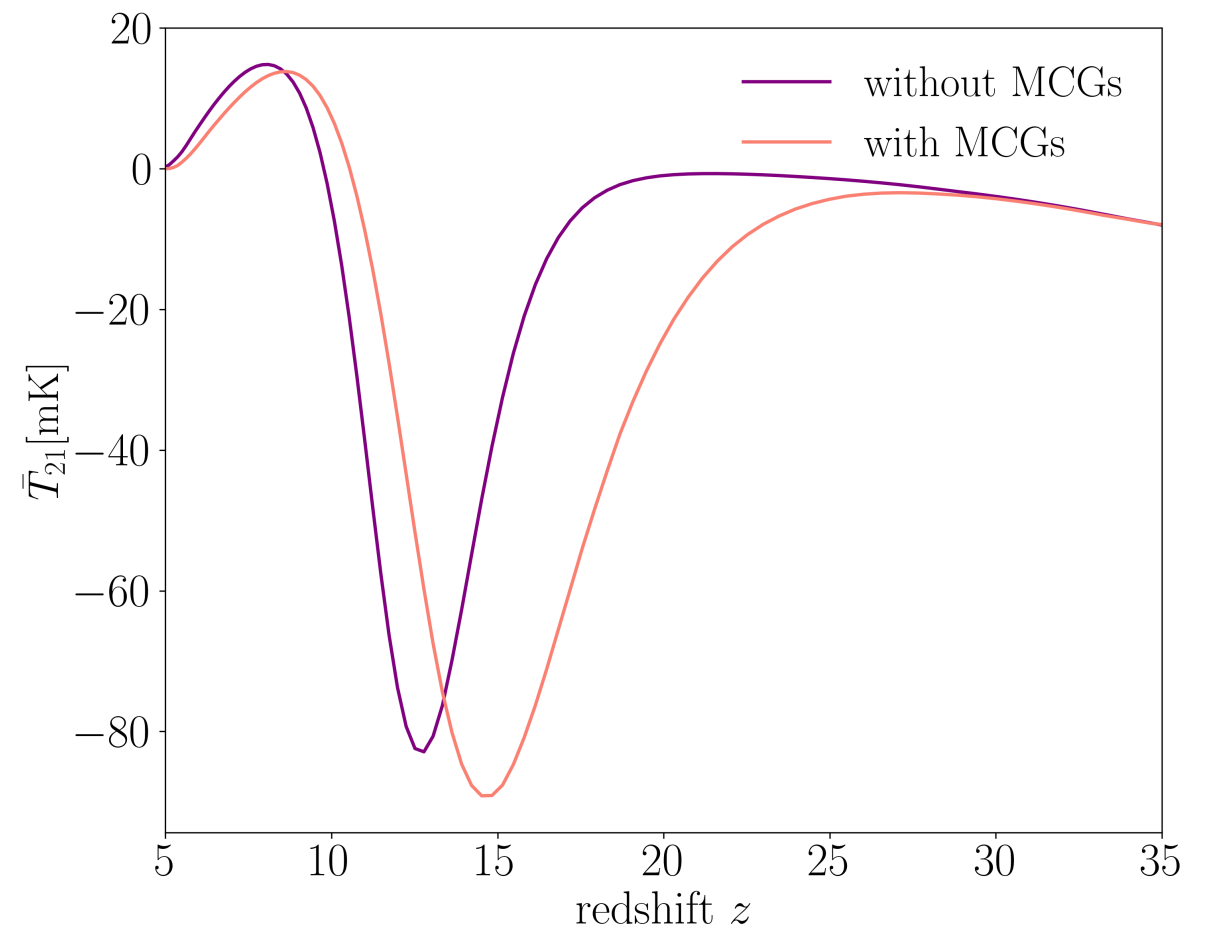
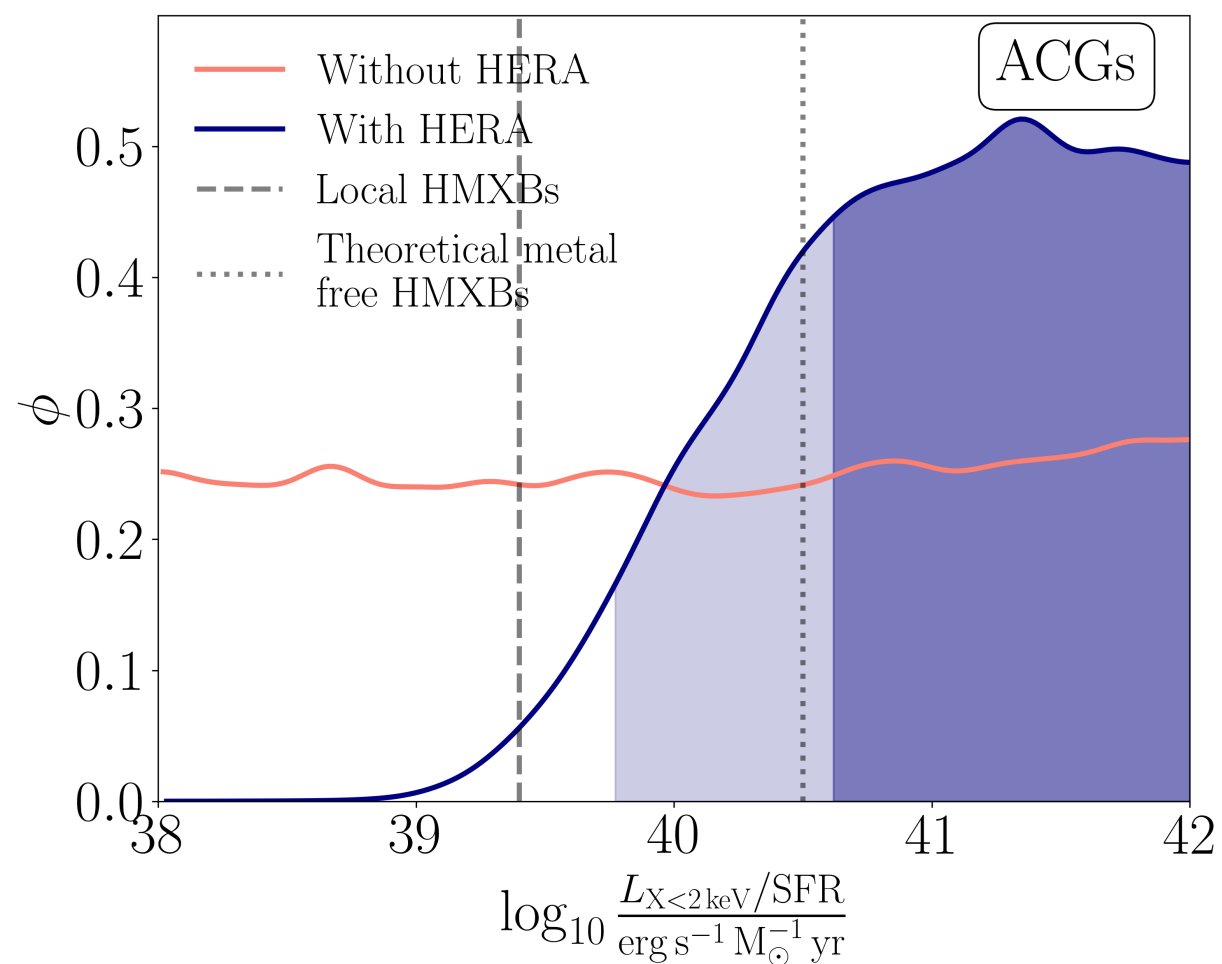
New: 21cm Data Analysis beyond HERA Results

What if we include popIII stars (residing in molecular cooling galaxies)?



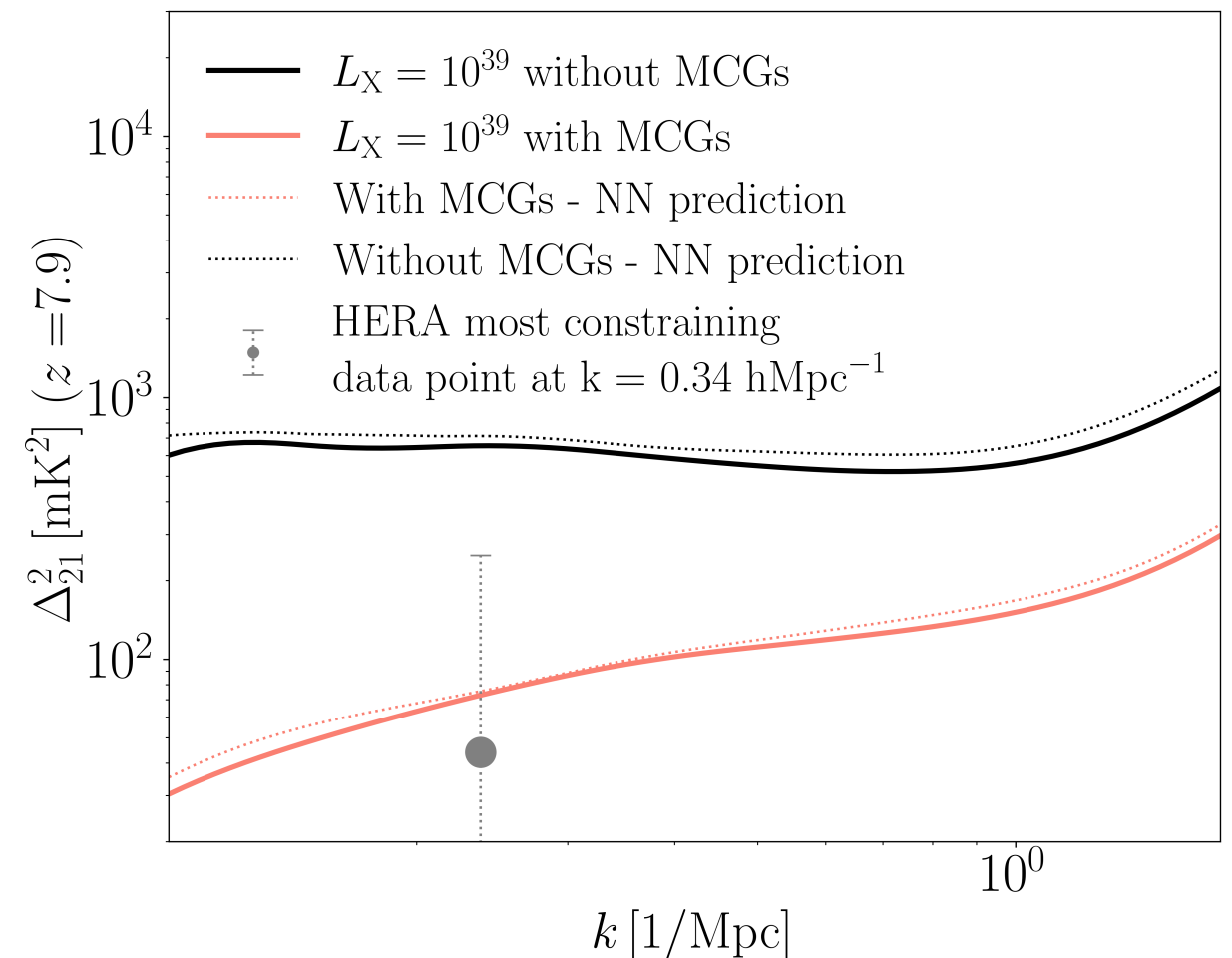
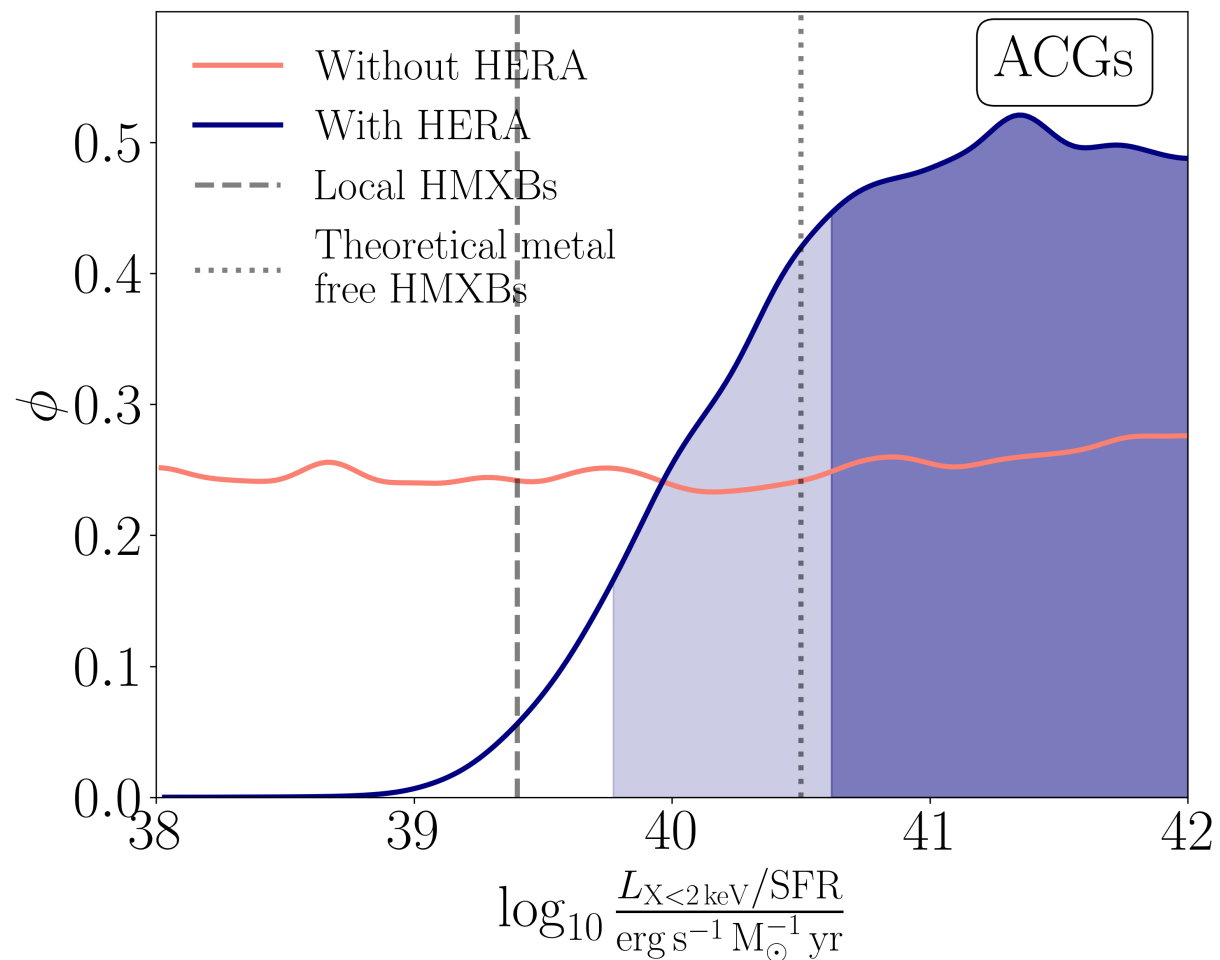
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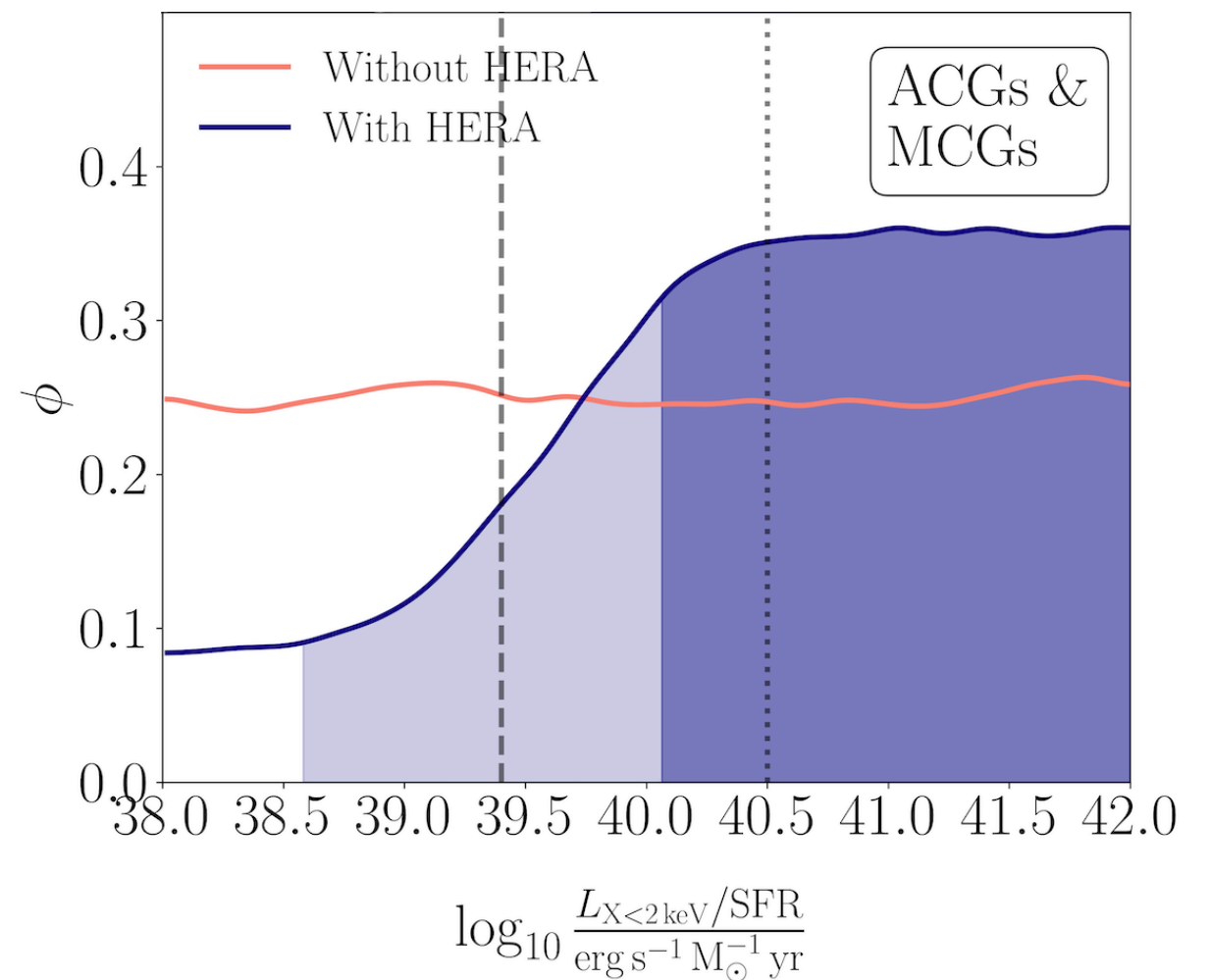
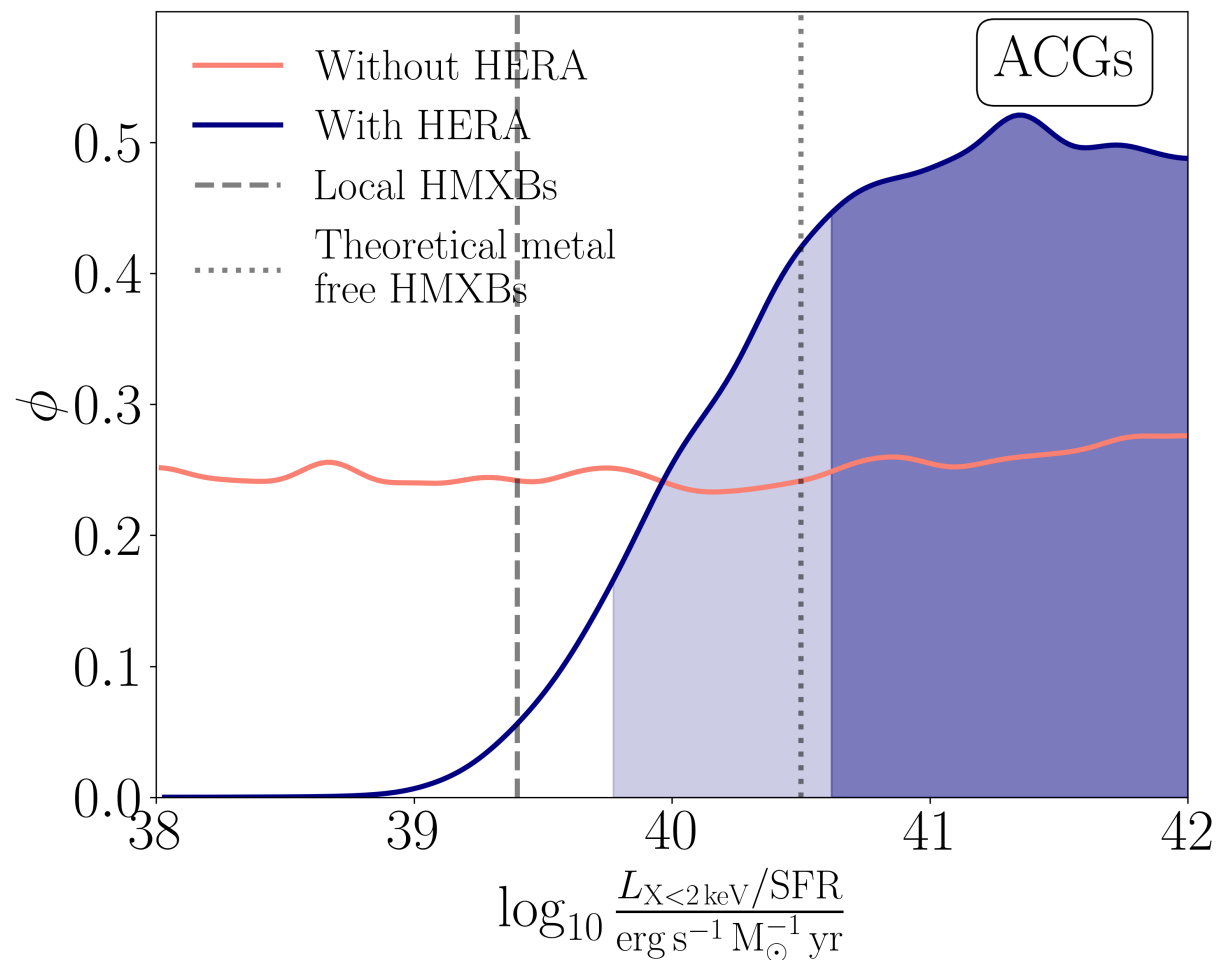
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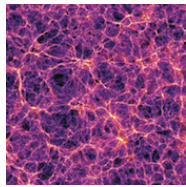
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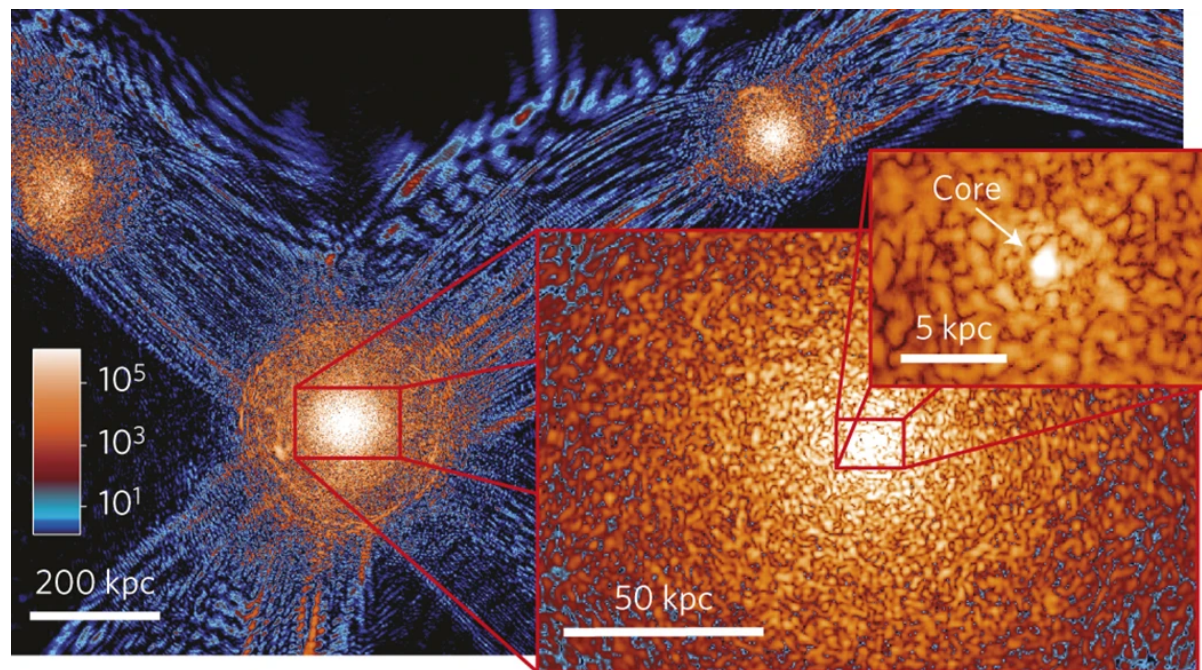
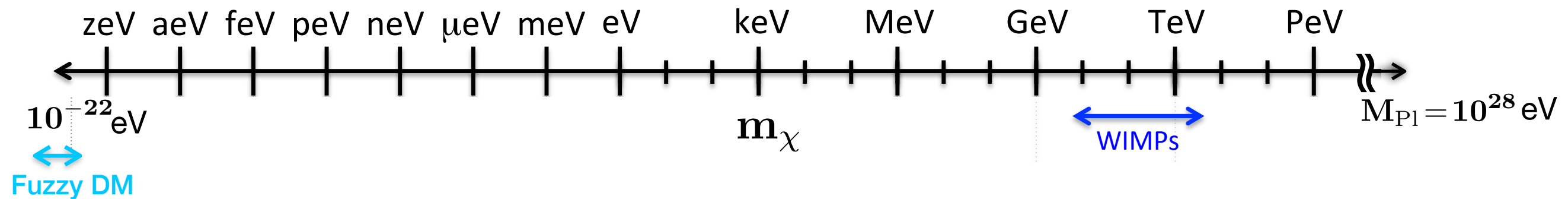
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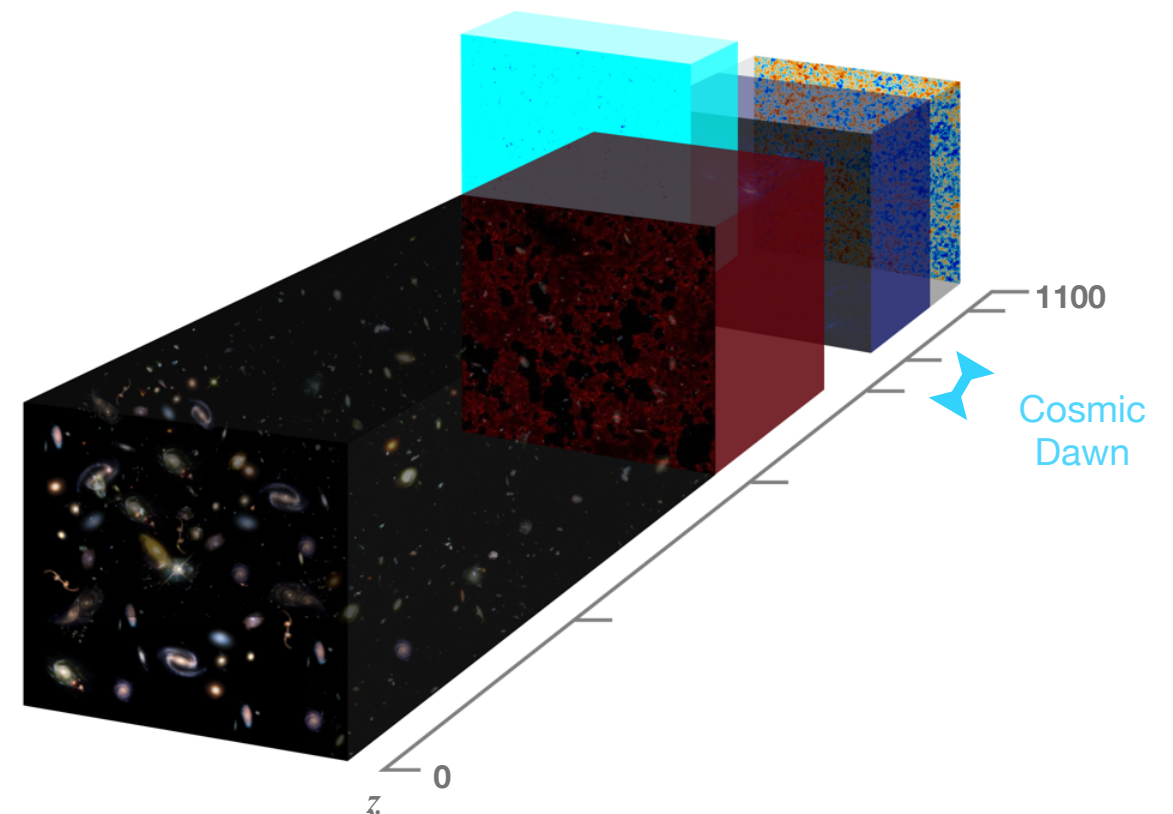


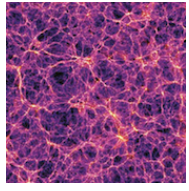
Cosmic Dawn Cosmology: Fuzzy Dark Matter

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



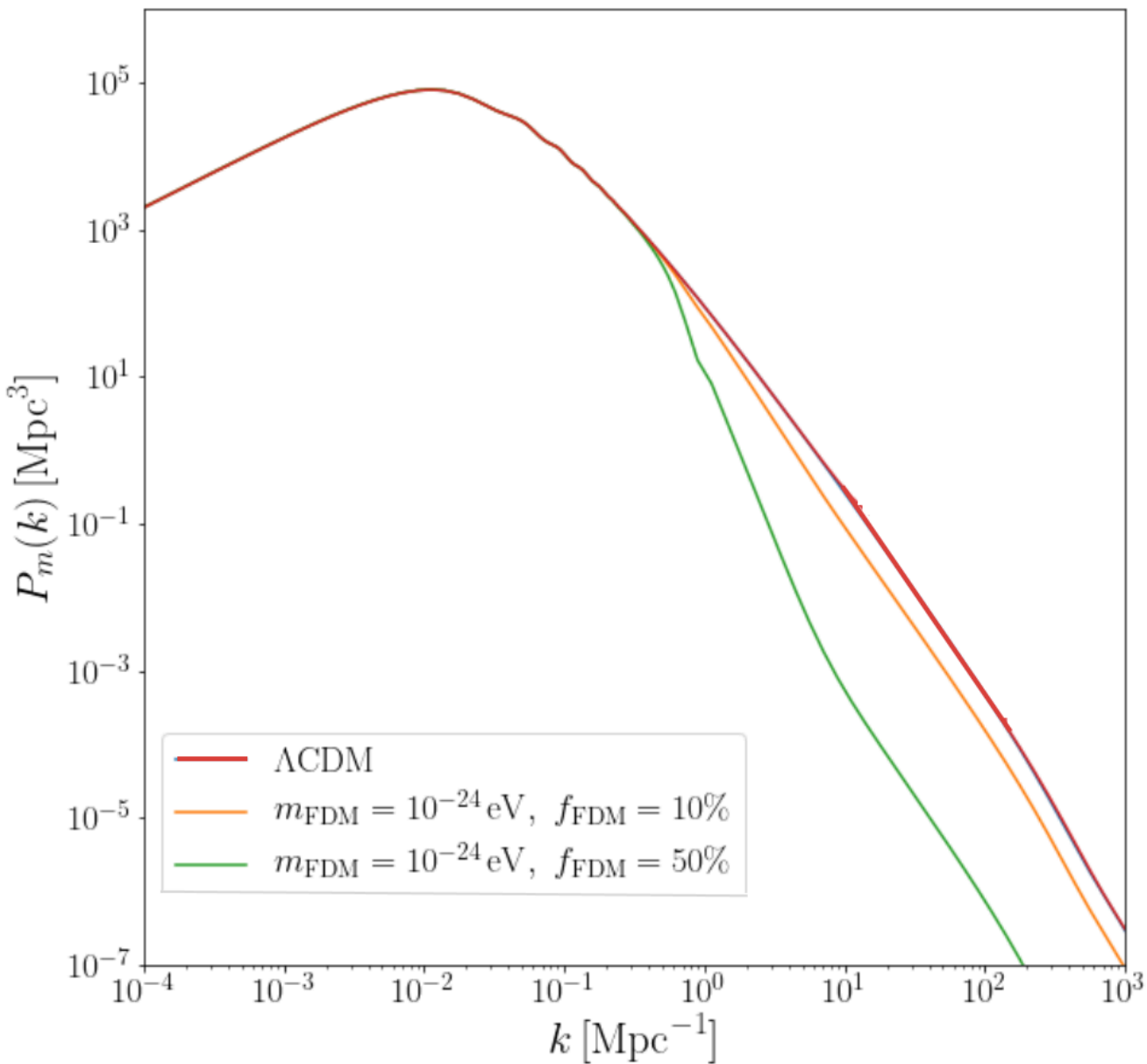
Schive et al, Nature 2014



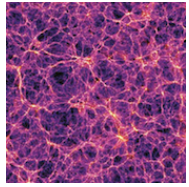


Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ delays the 21cm signal

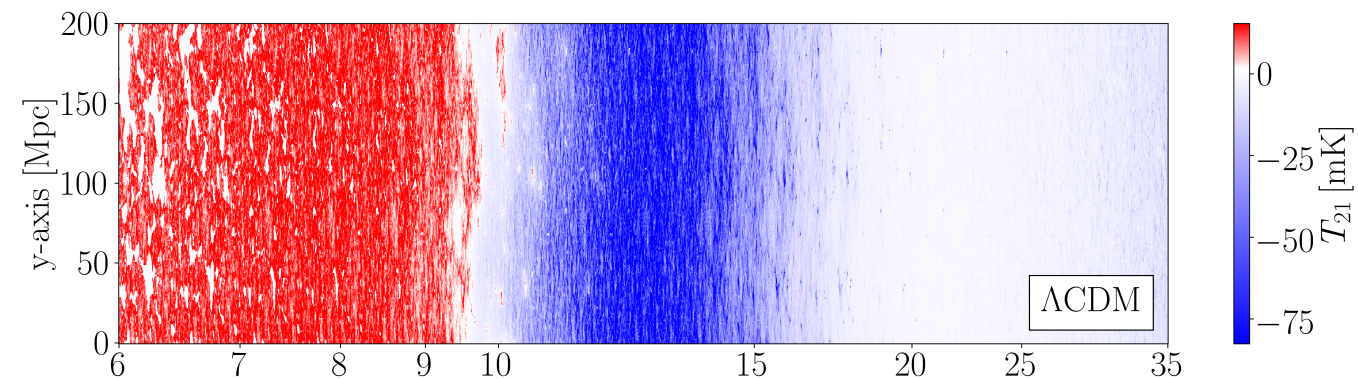
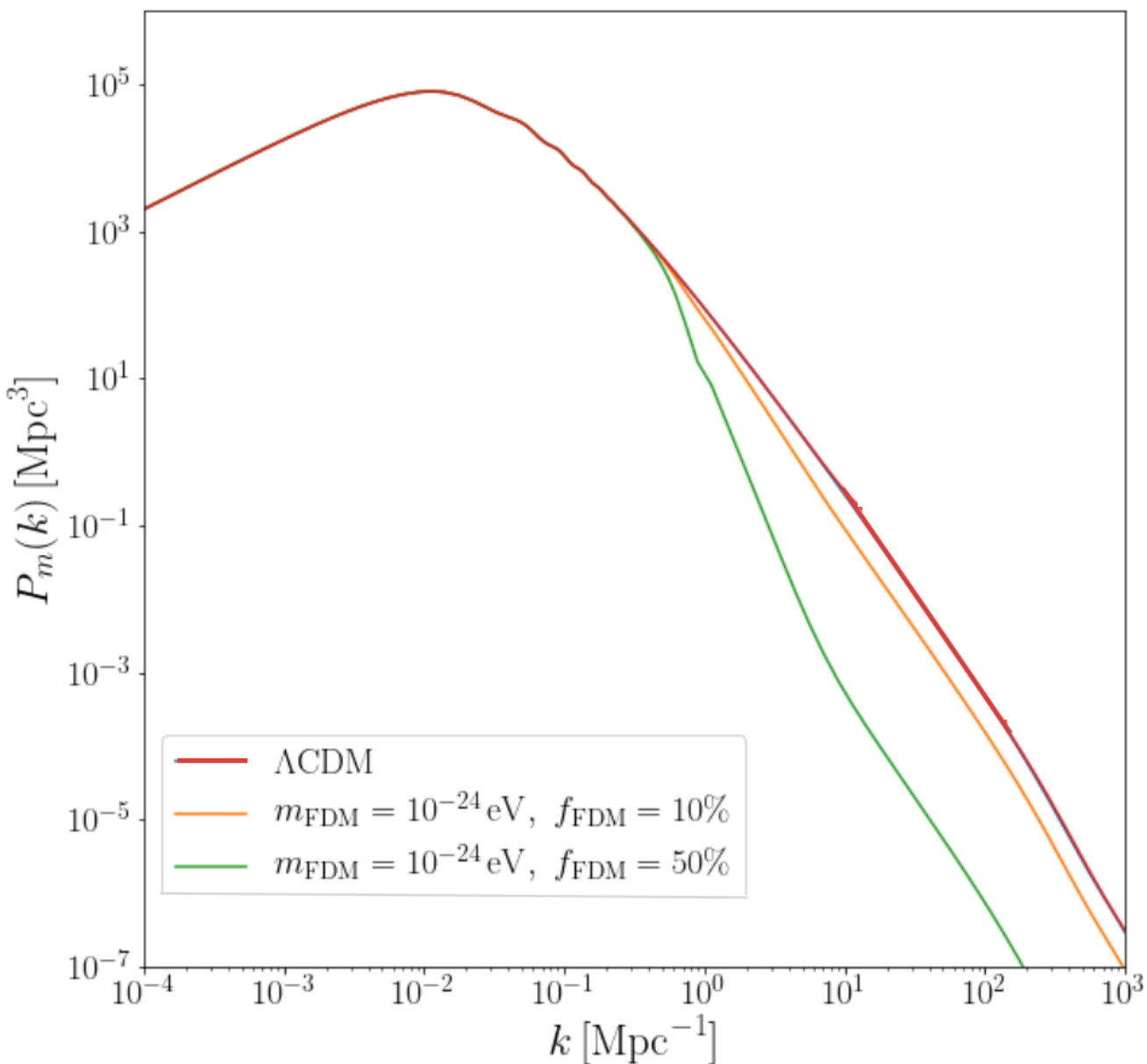


Flitter and Kovetz, PRD 2022

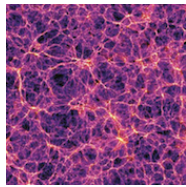


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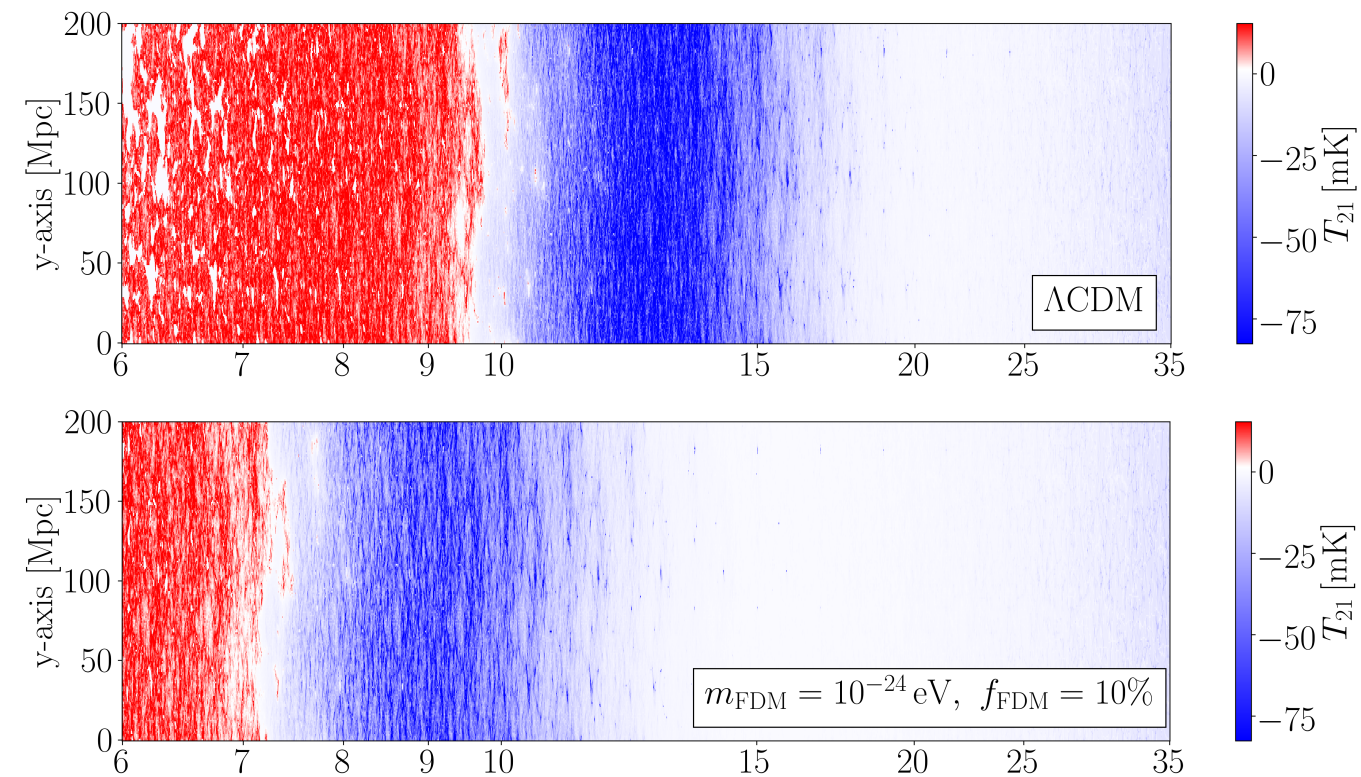
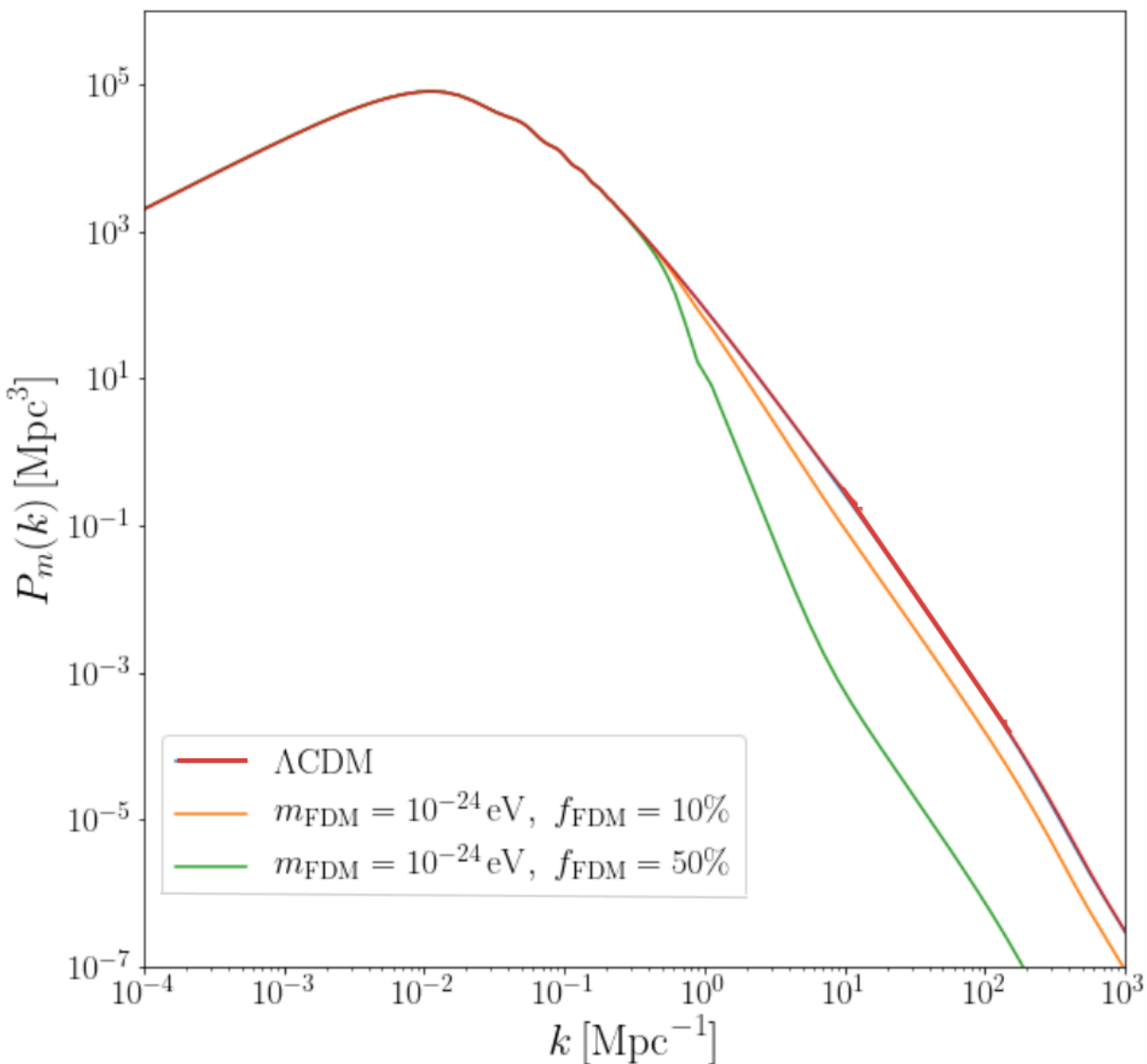


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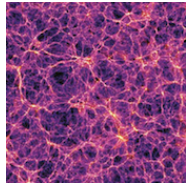


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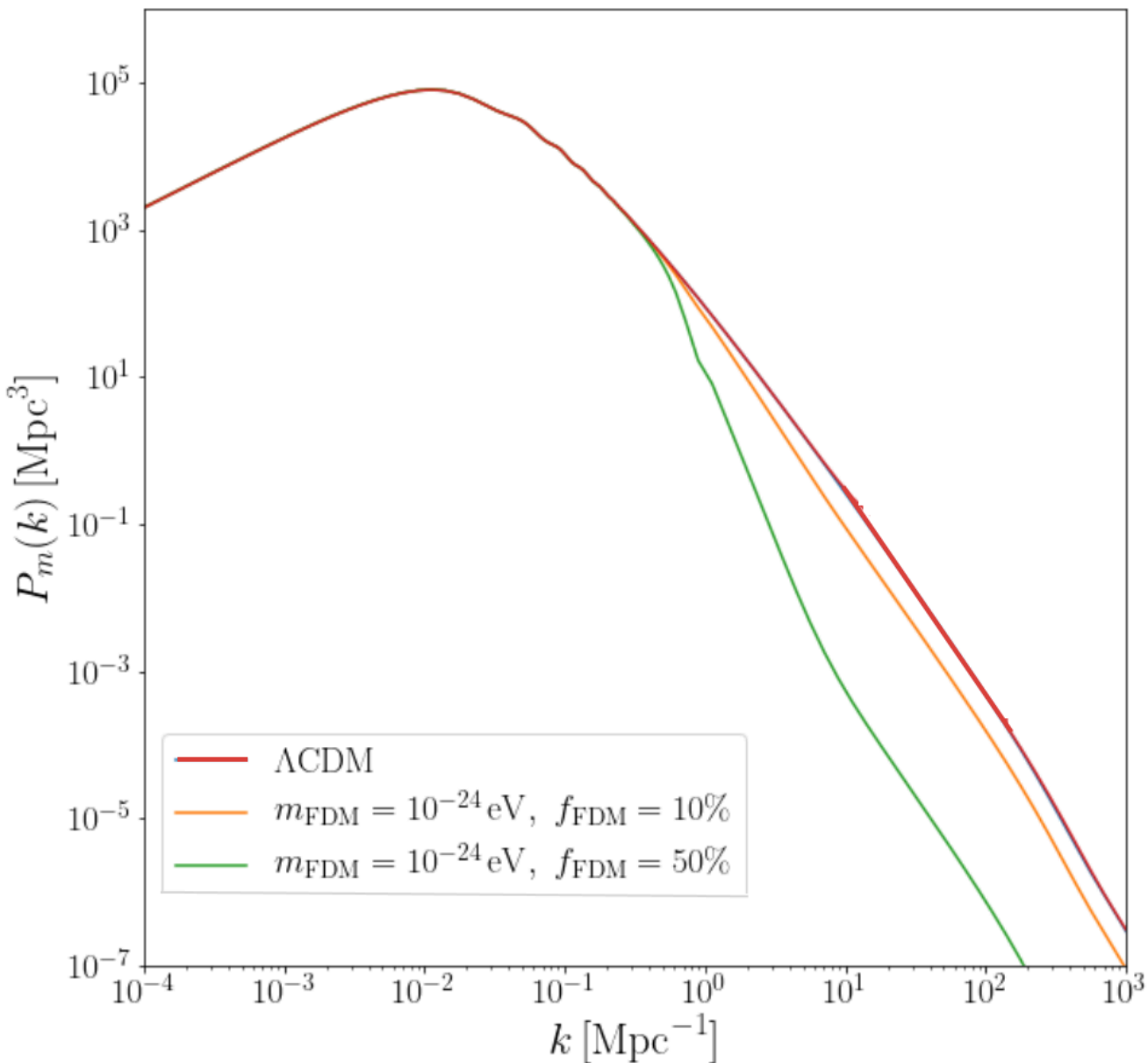


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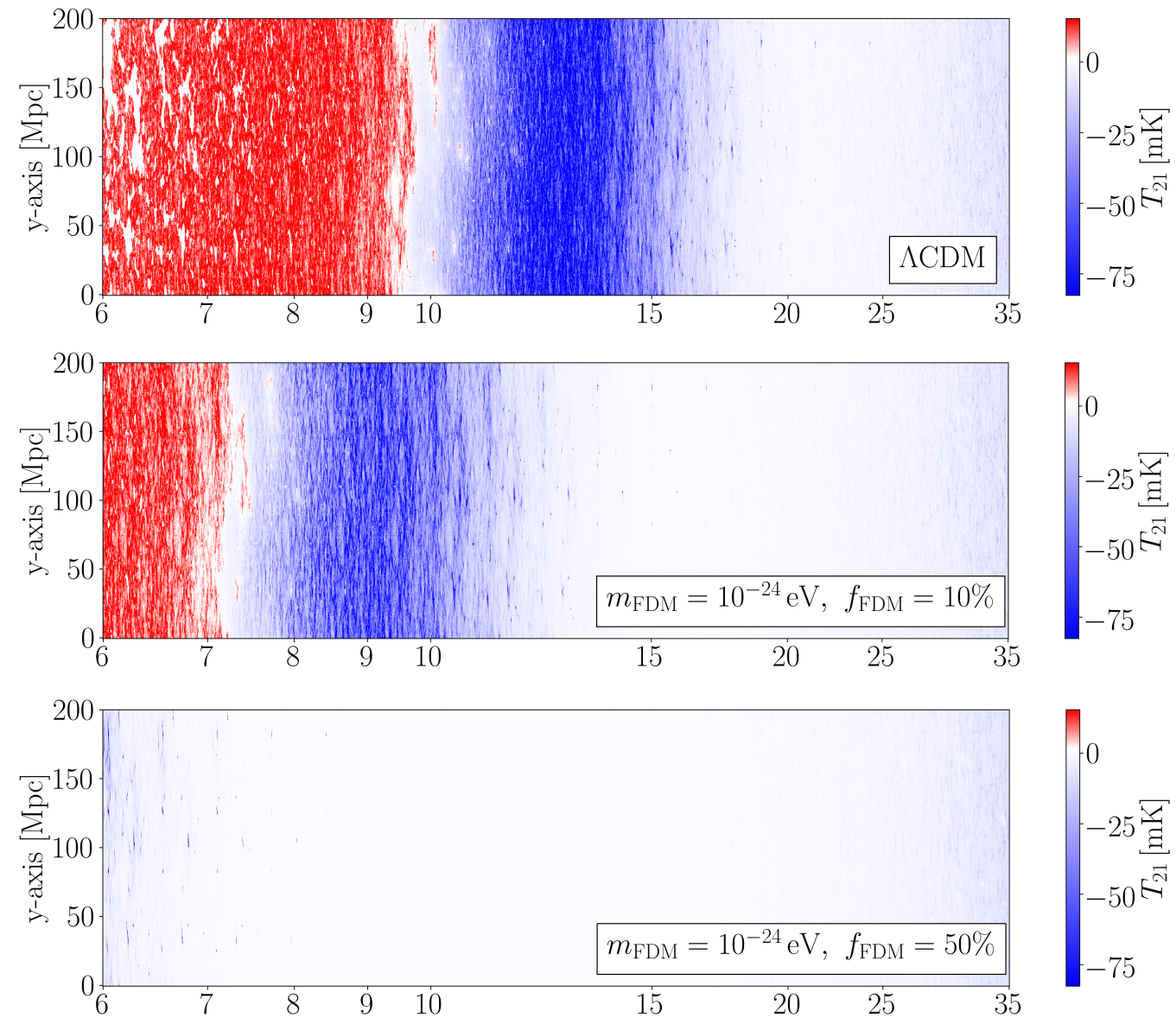


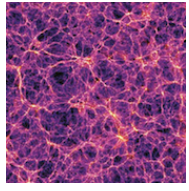
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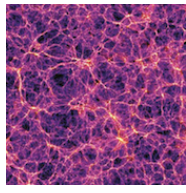
Flitter and Kovetz, PRD 2022





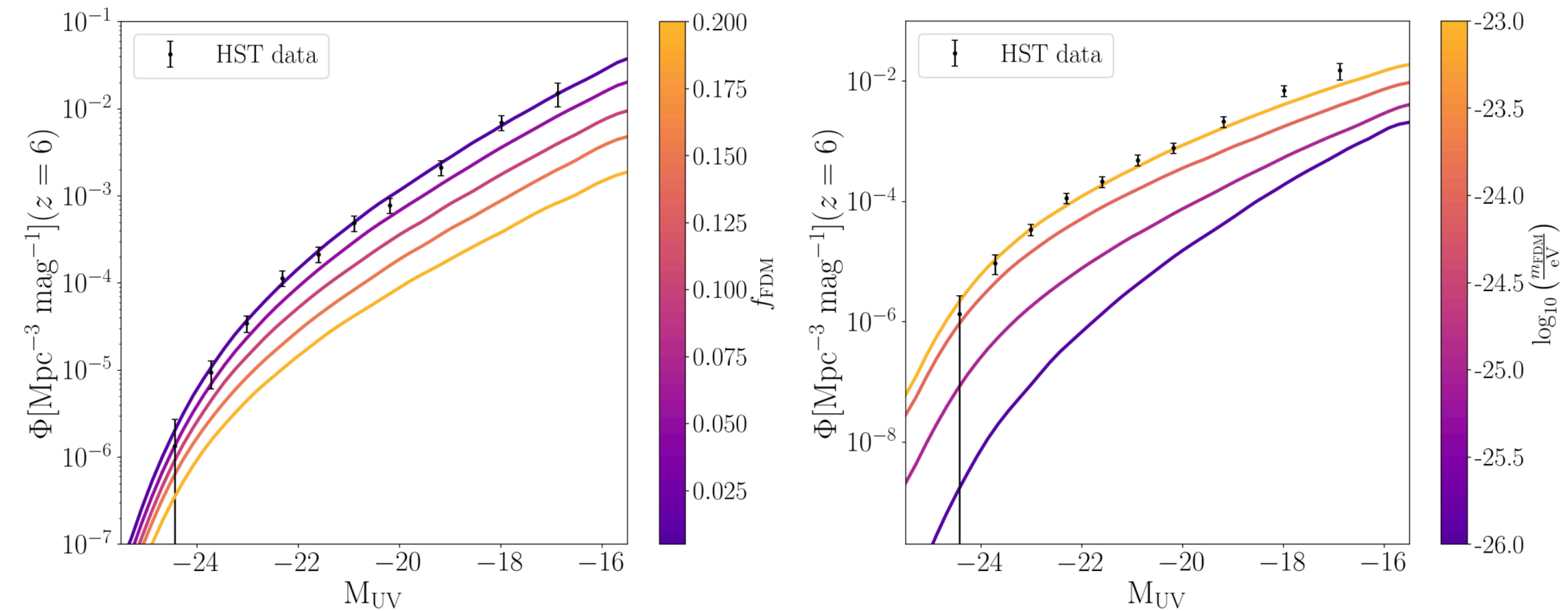
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Fuzzy DM suppresses small scale clustering $\rightarrow$ what about high- z UVLF?

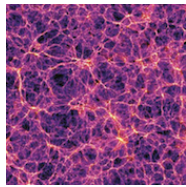


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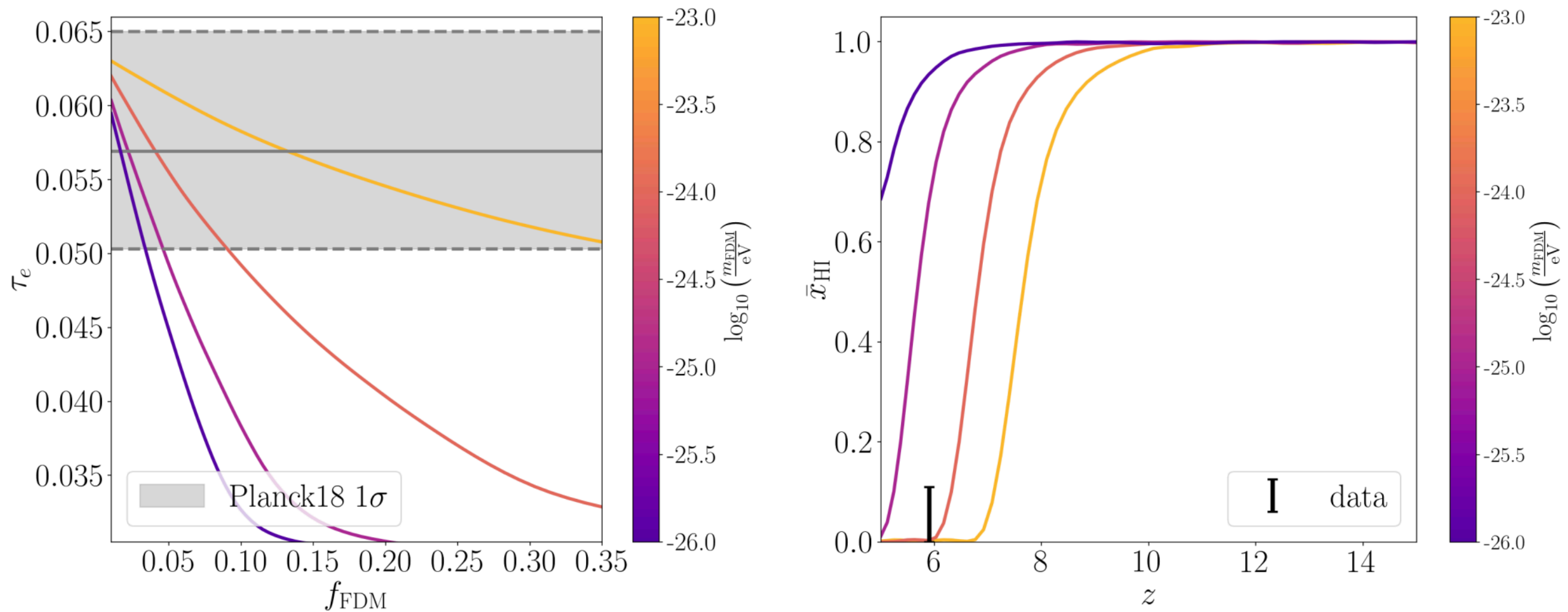


Lazare, Flitter and Kovetz, PRD 2024

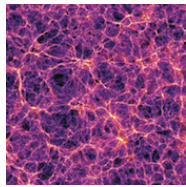


Cosmic Dawn Cosmology: Fuzzy Dark Matter

Fuzzy DM suppresses small scale clustering $\rightarrow$ what about reionization?

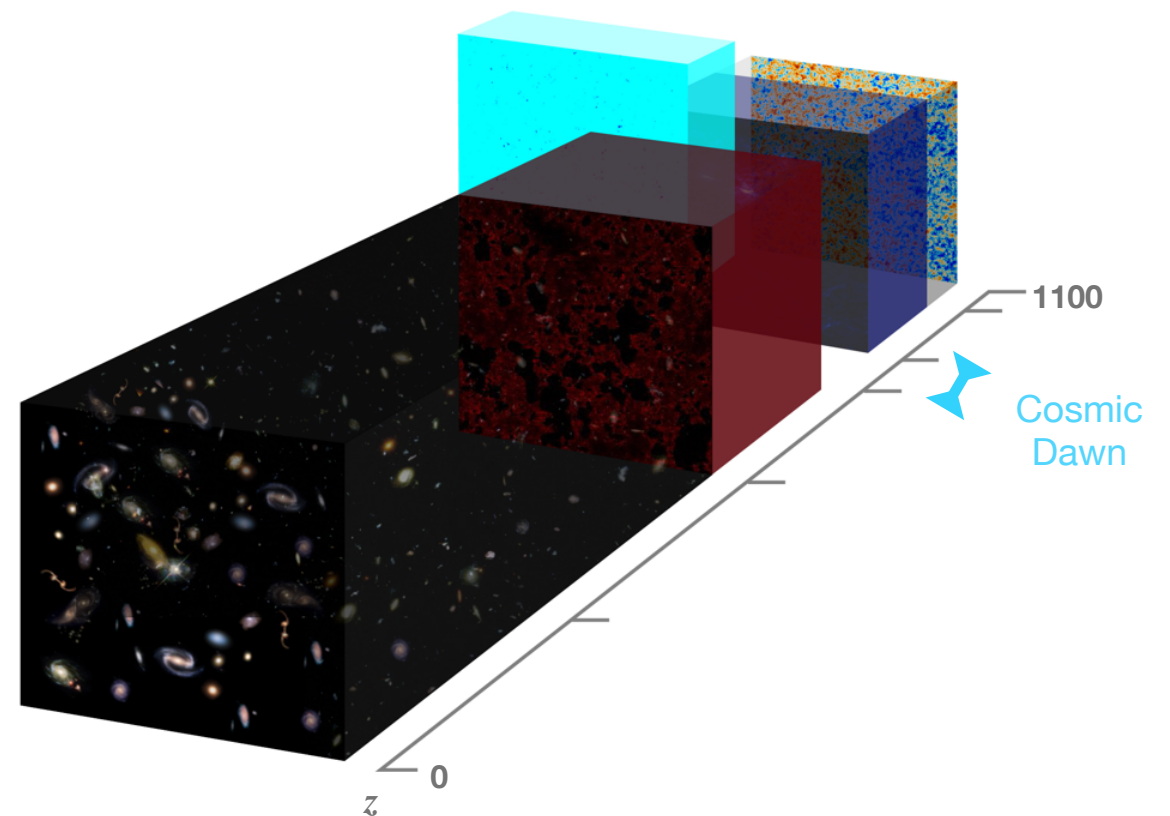
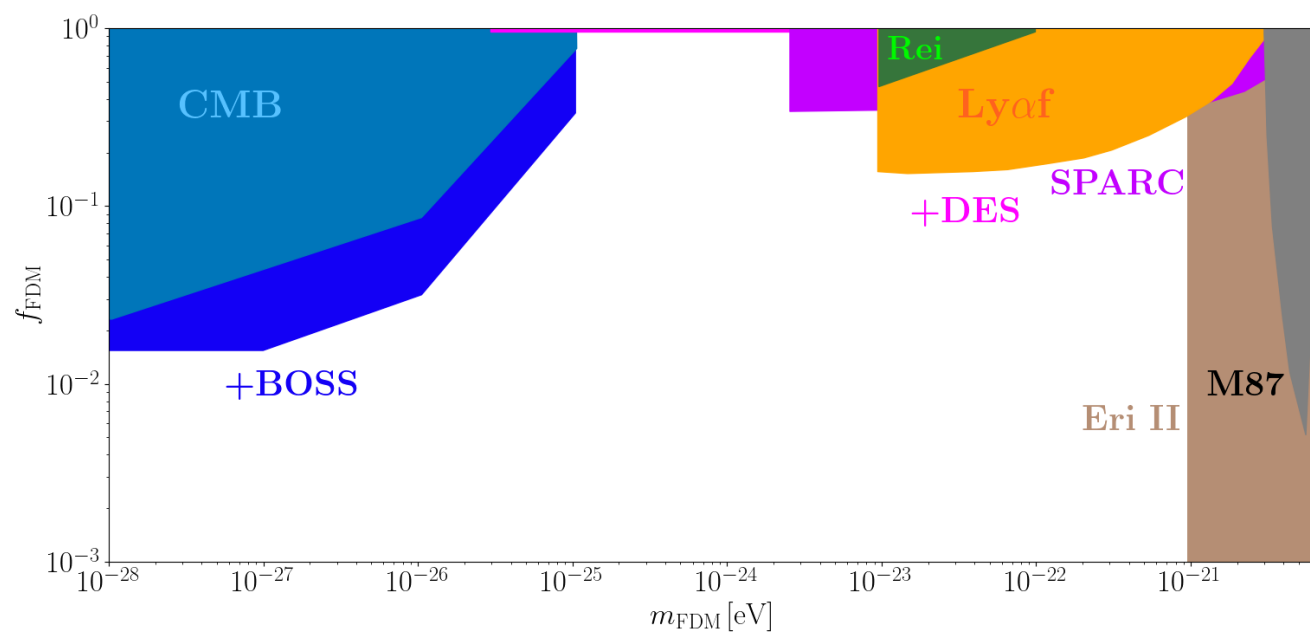
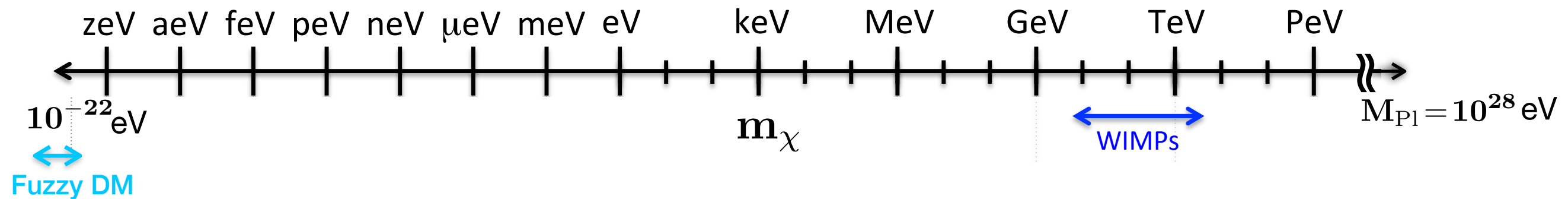


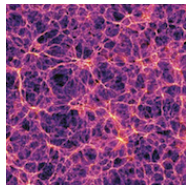
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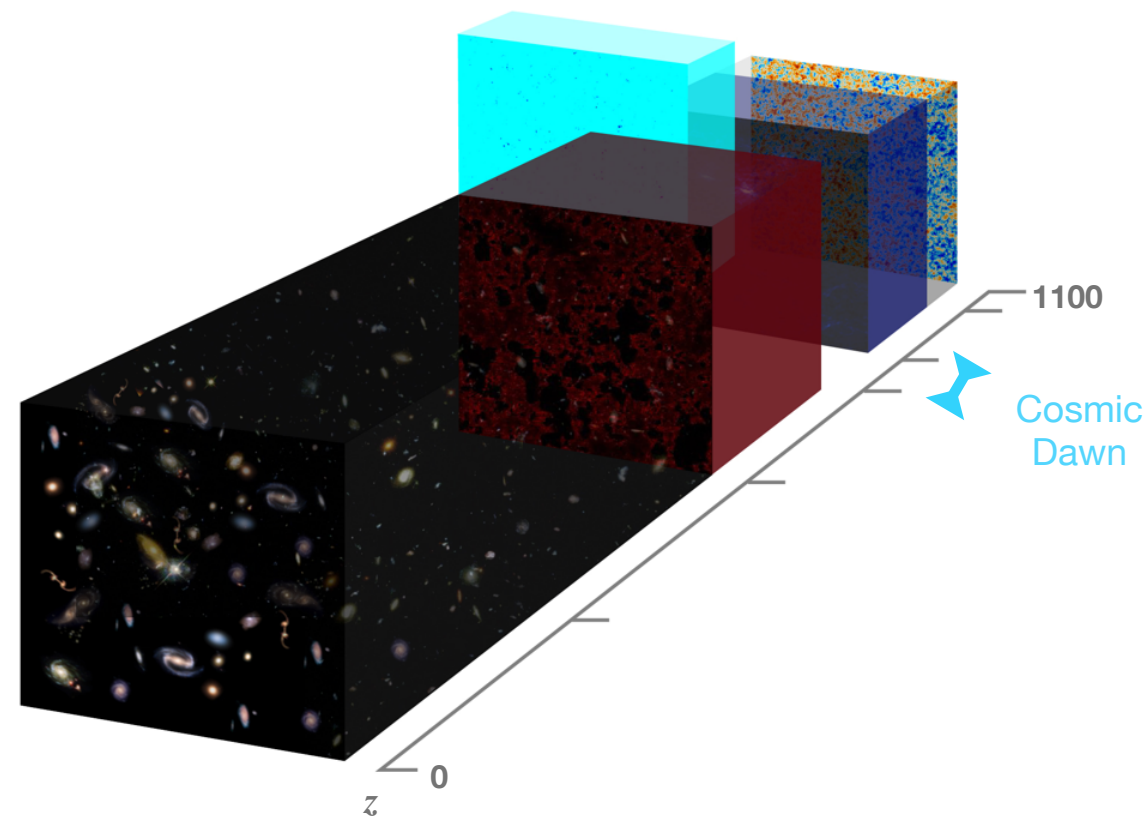
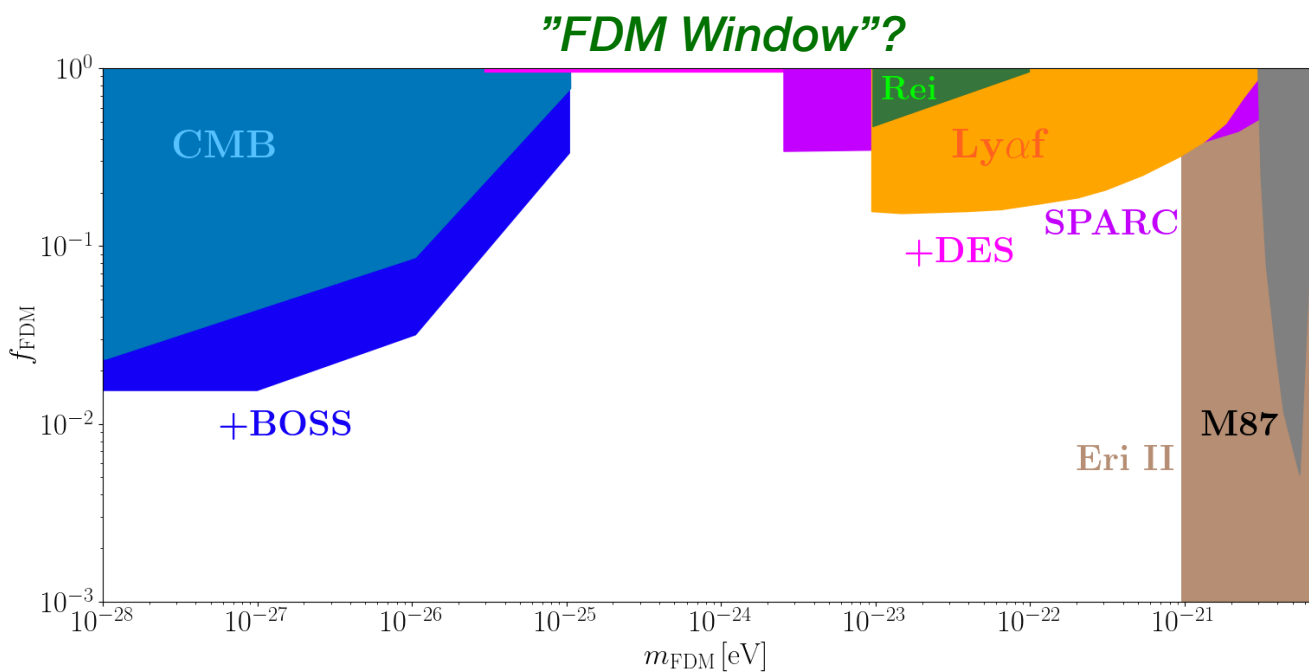
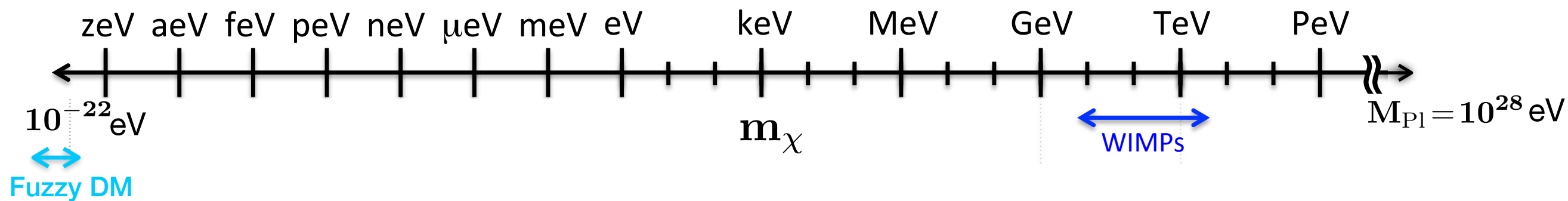
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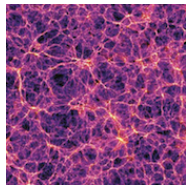




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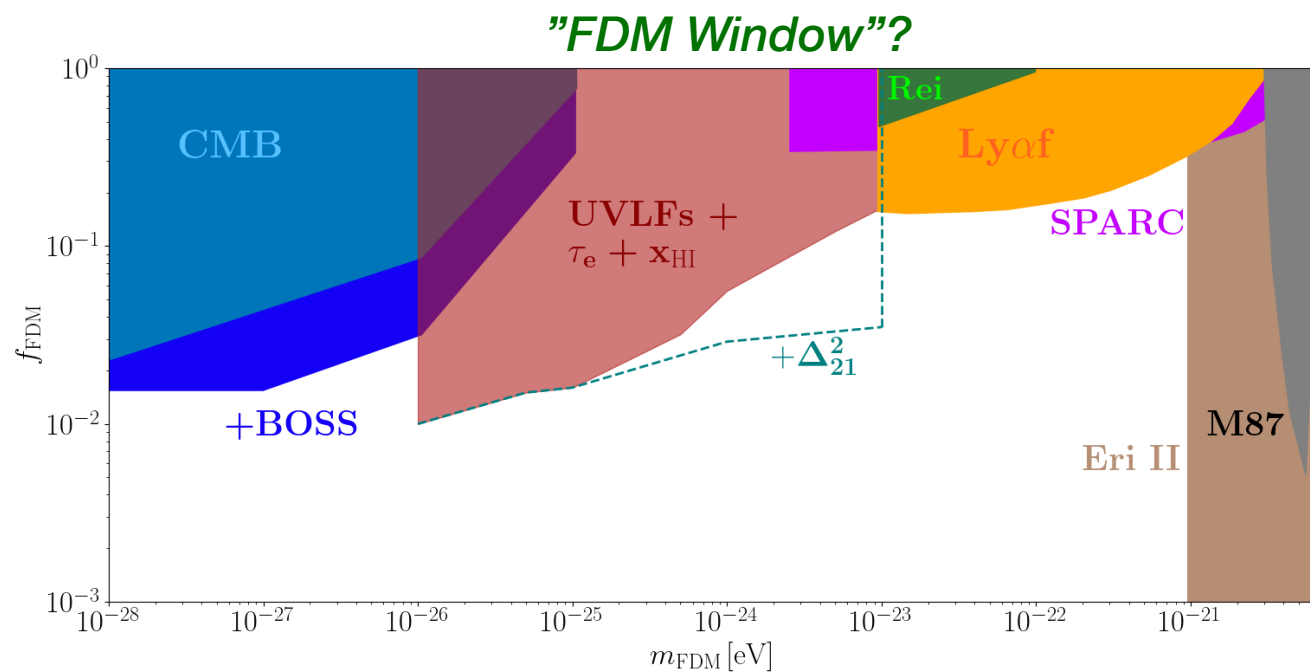
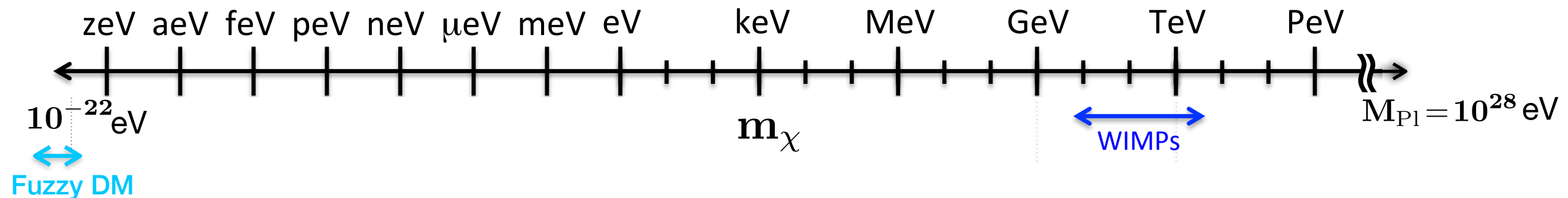
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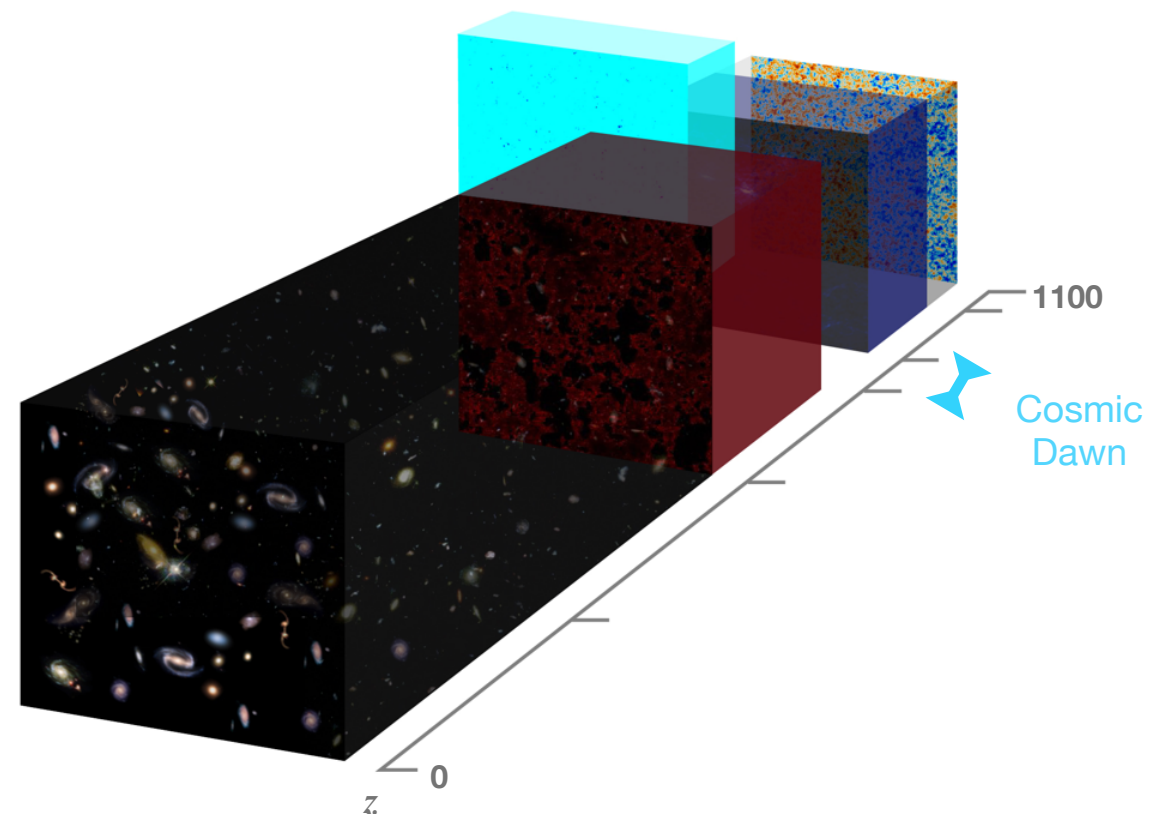


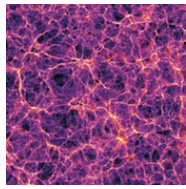
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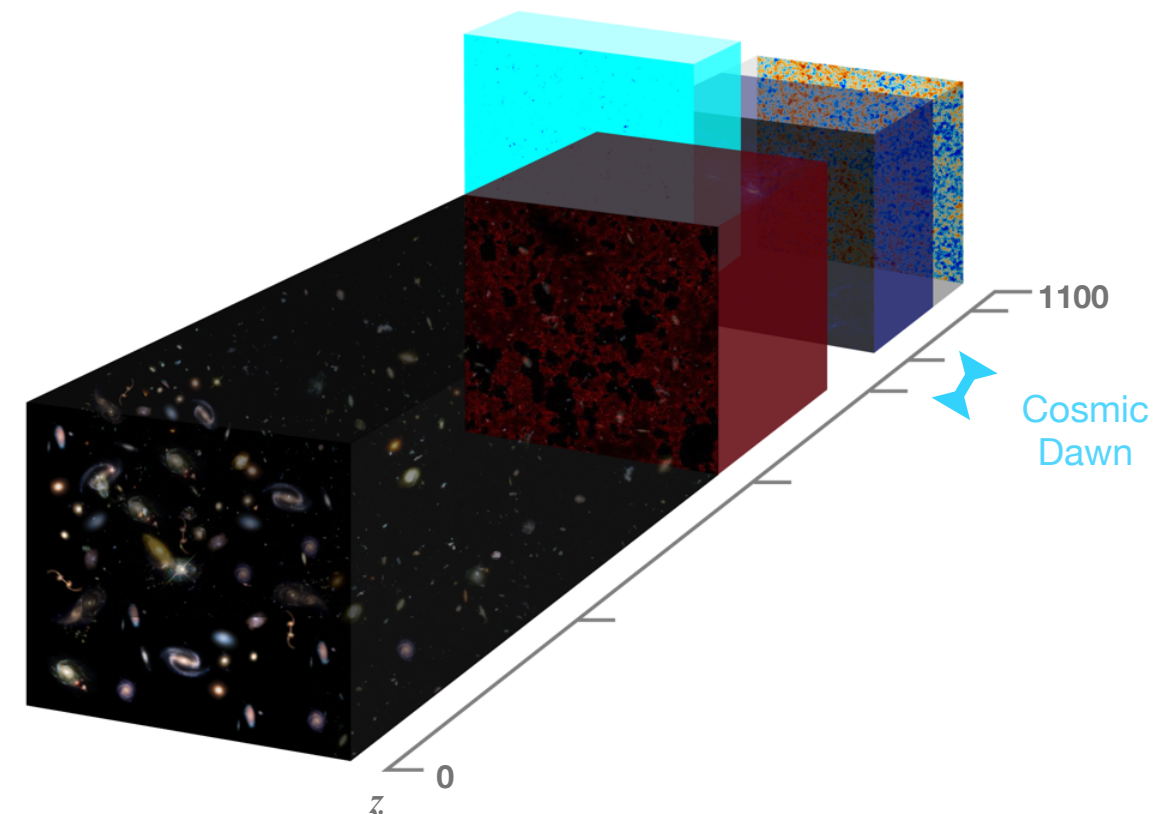
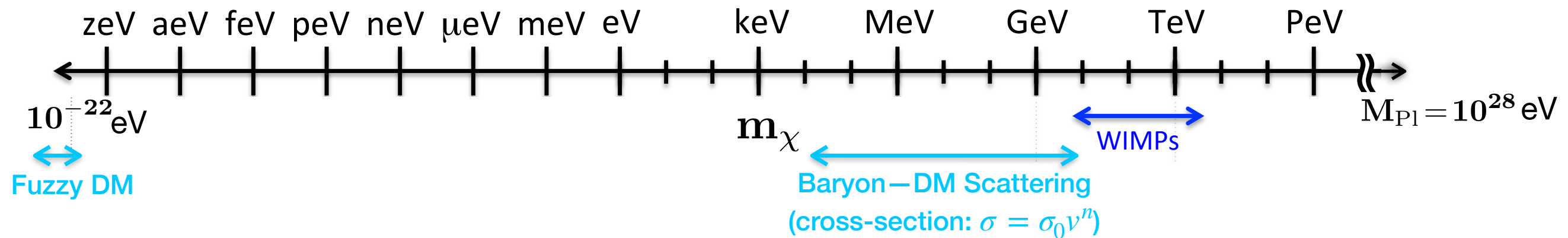
Lazare, Flitter and Kovetz, PRD 2024
(See also: Winch et al., ApJ 2024)

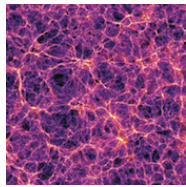




Cosmic Dawn Cosmology: Scattering DM

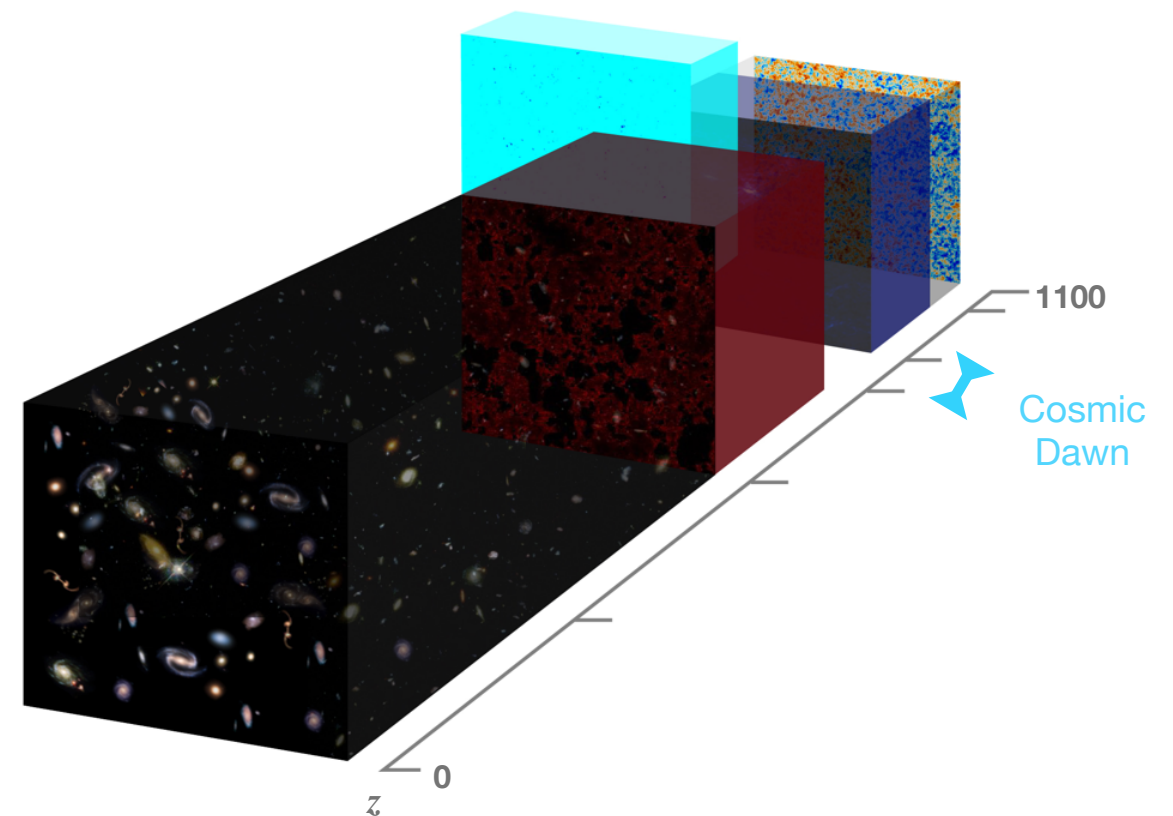
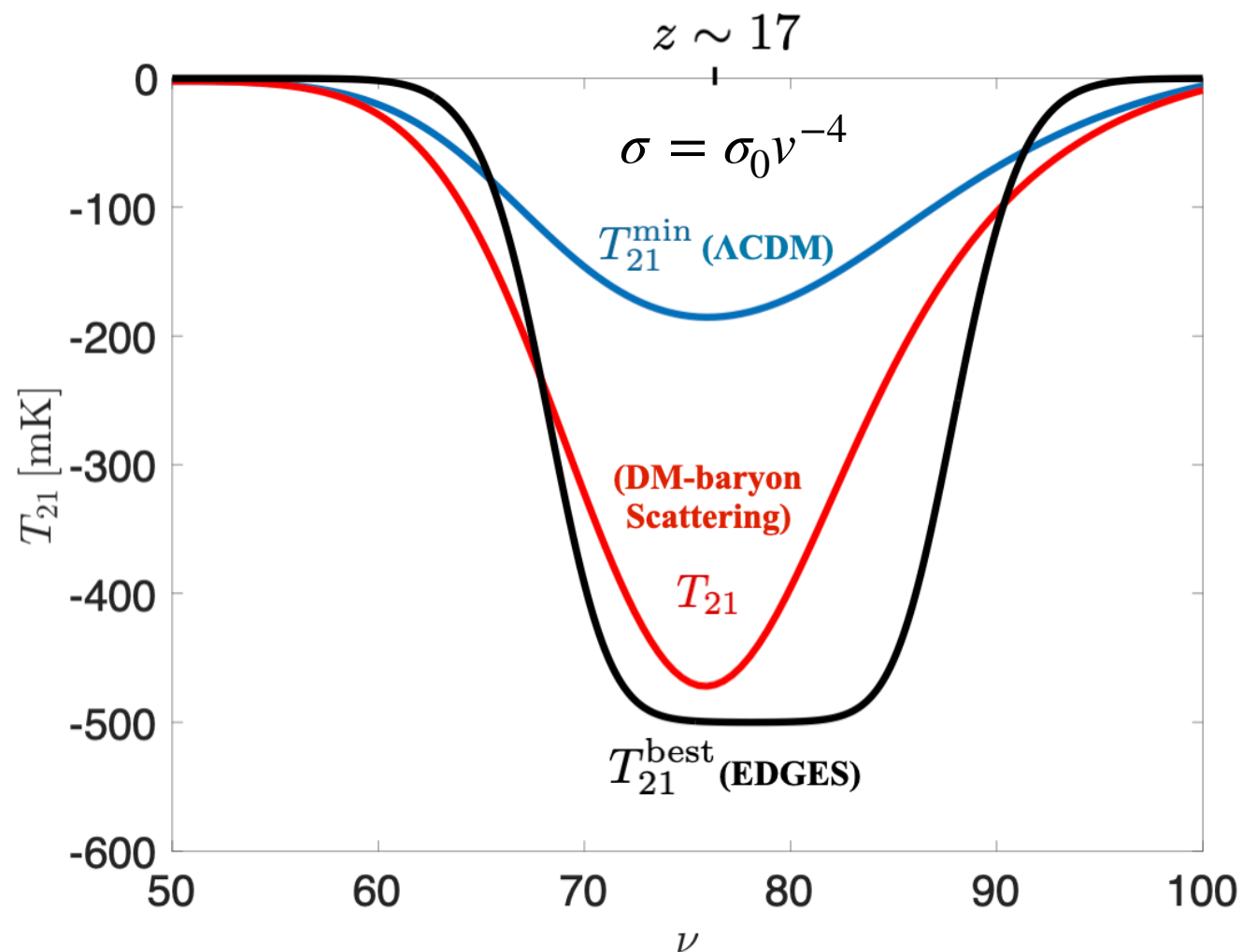
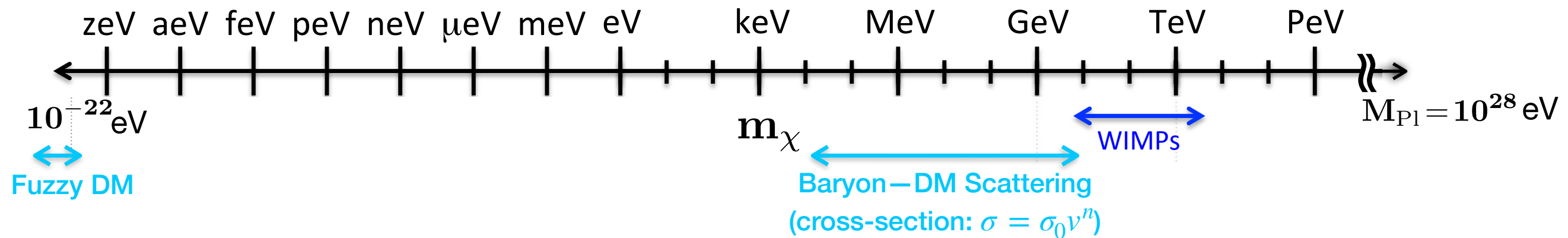
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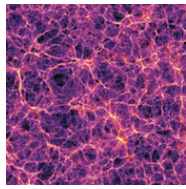




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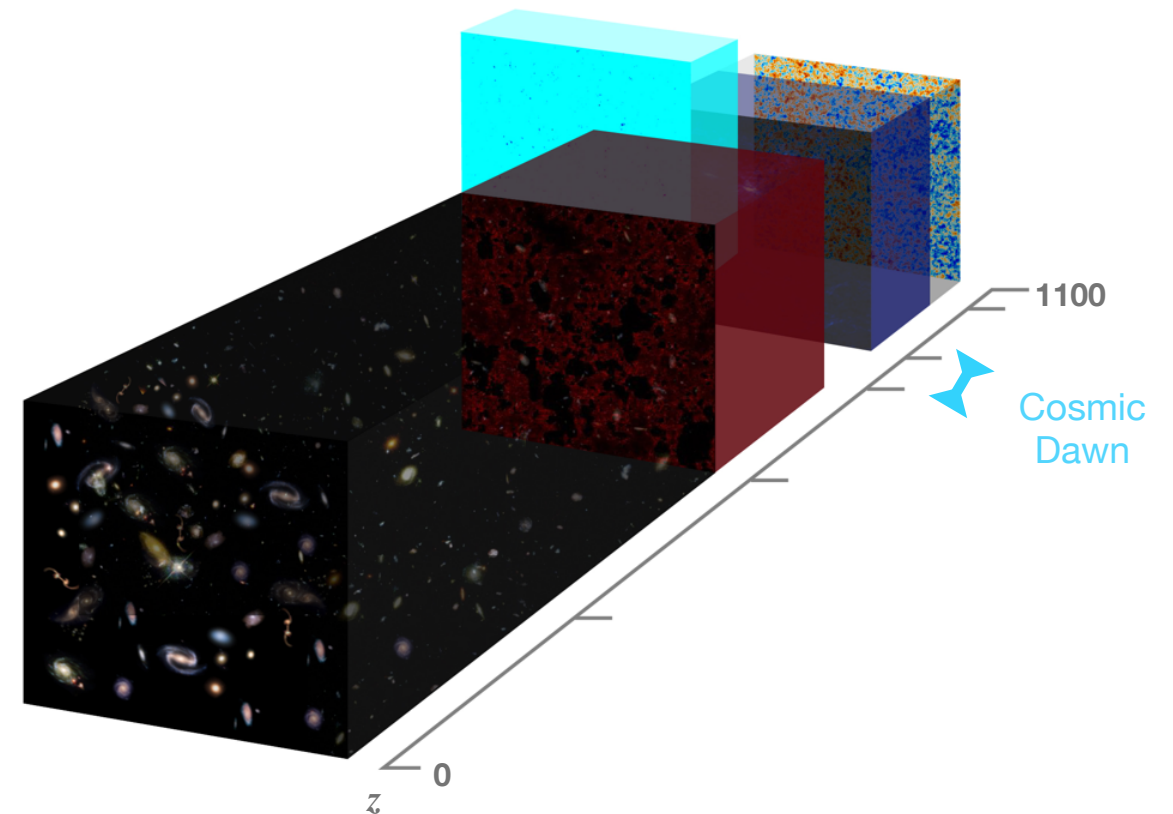
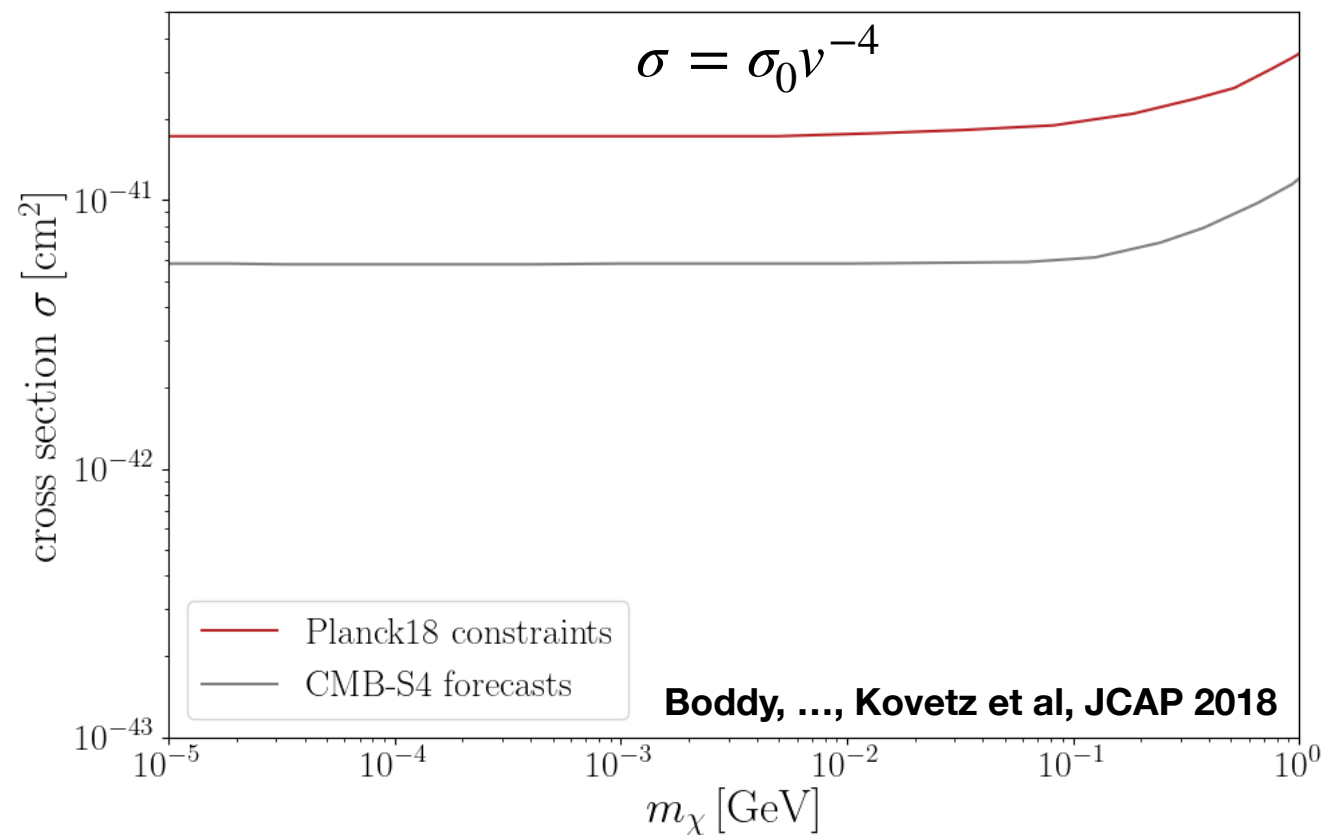
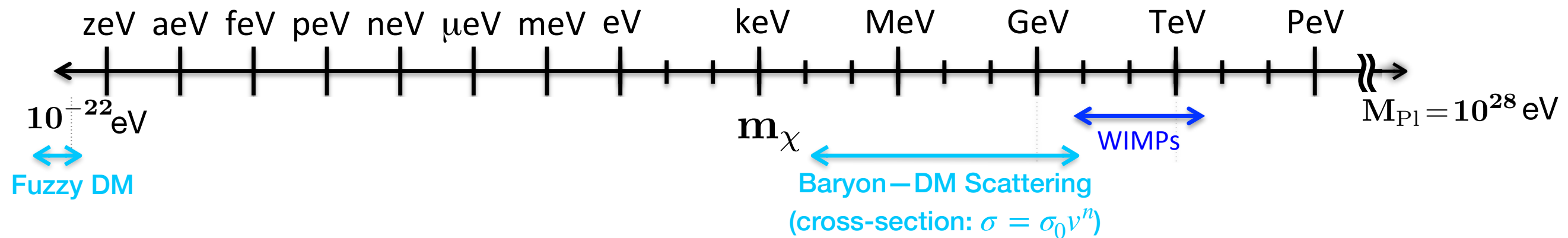
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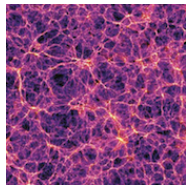




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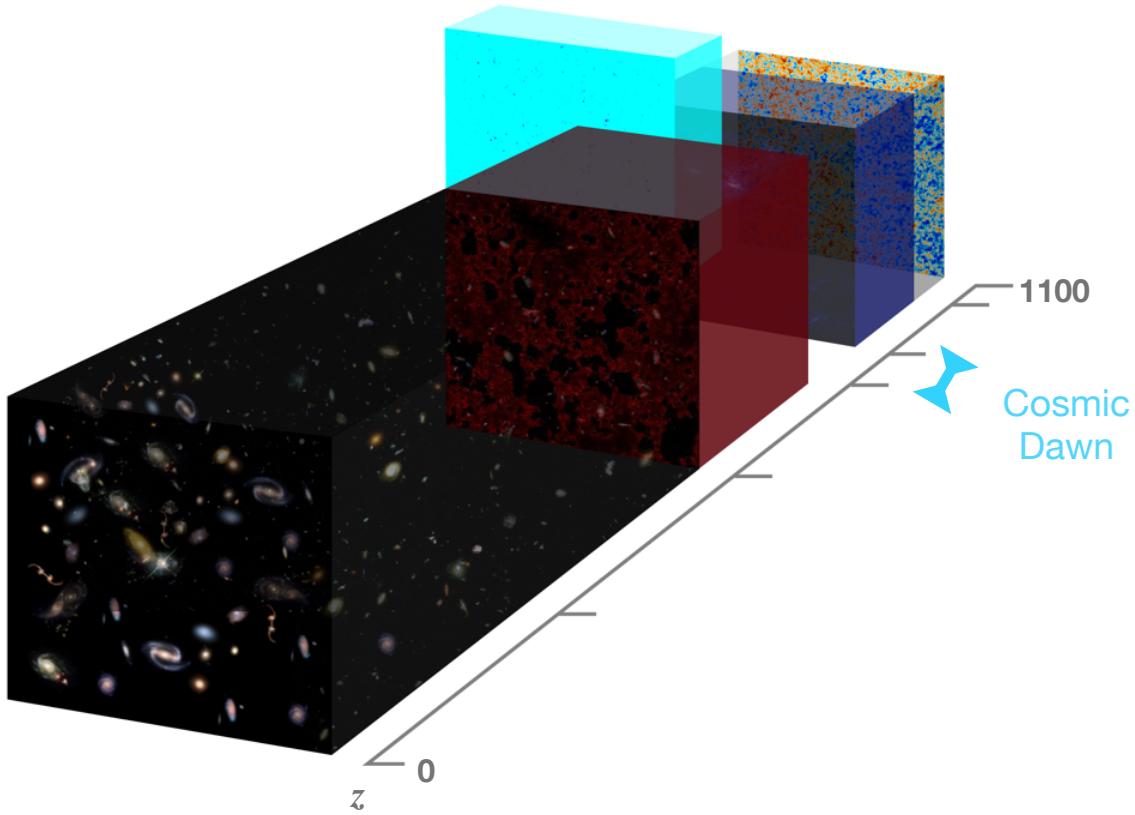
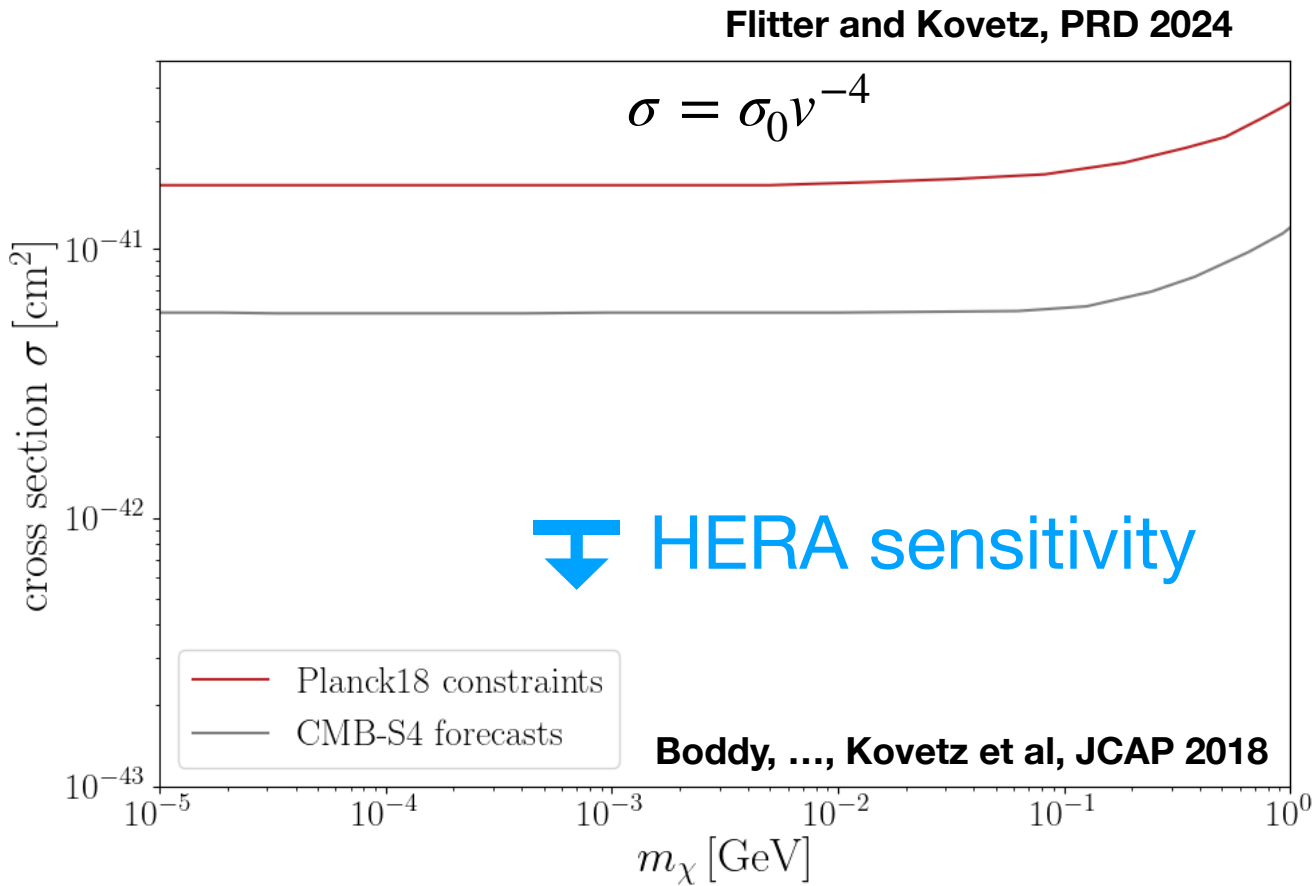
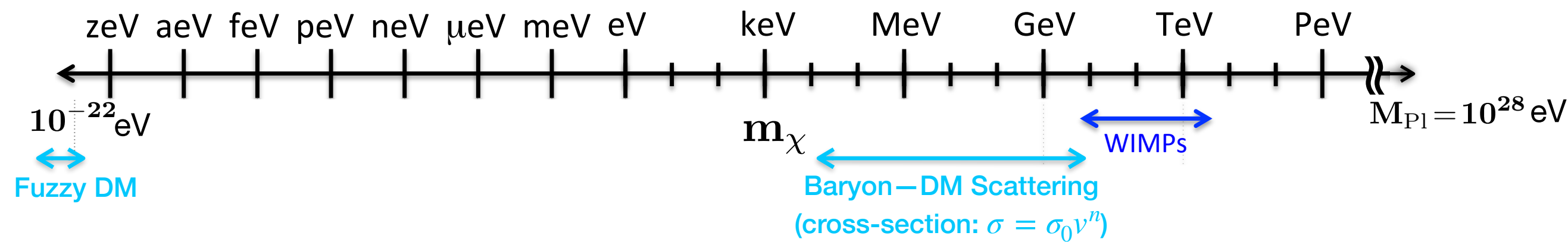
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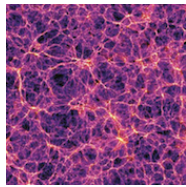




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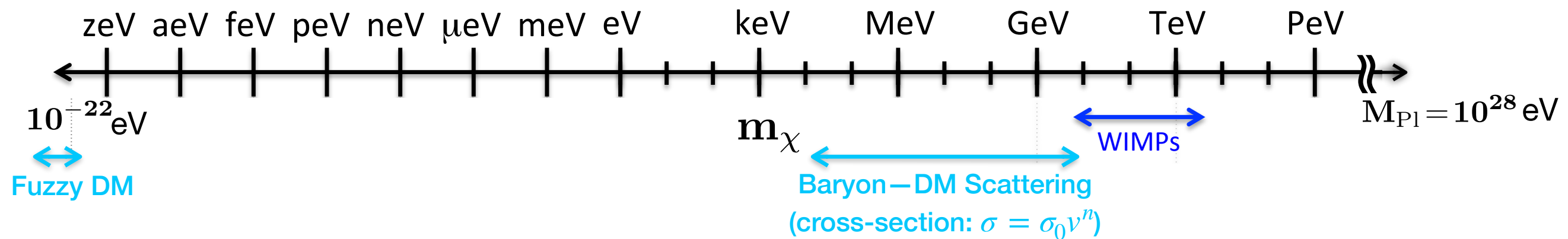
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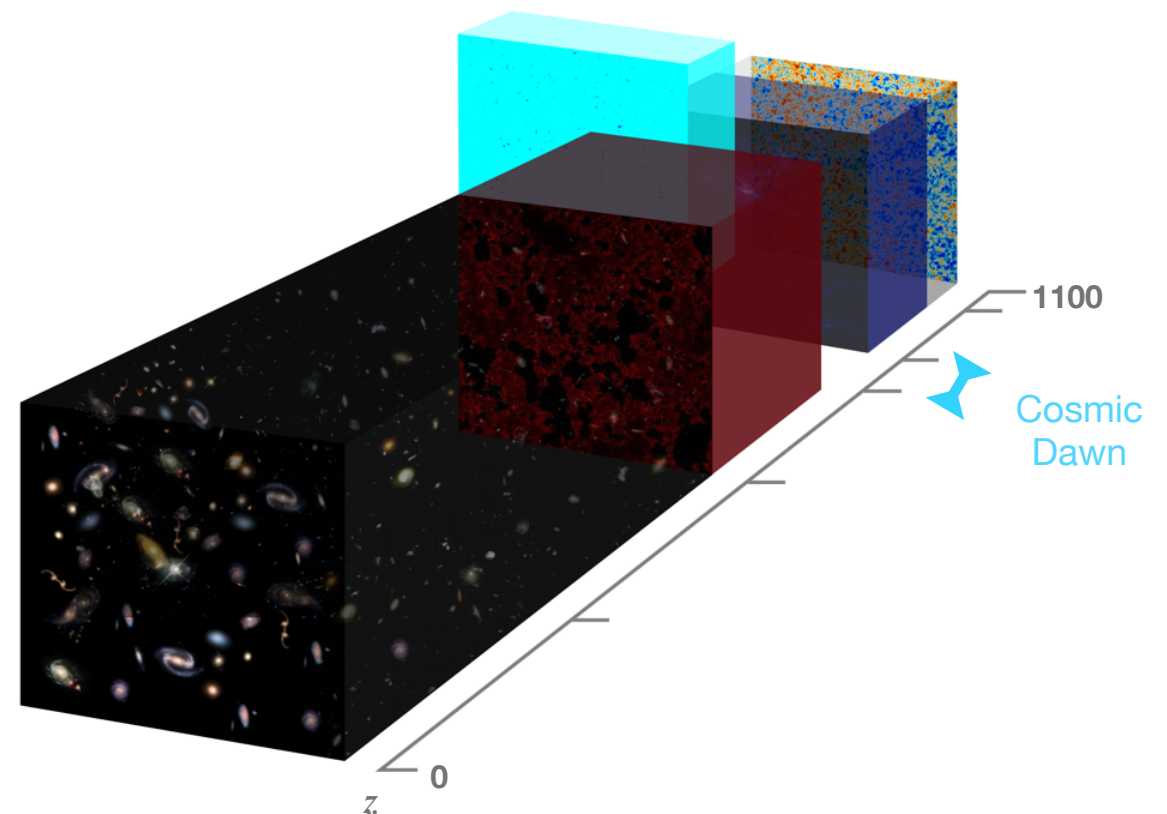
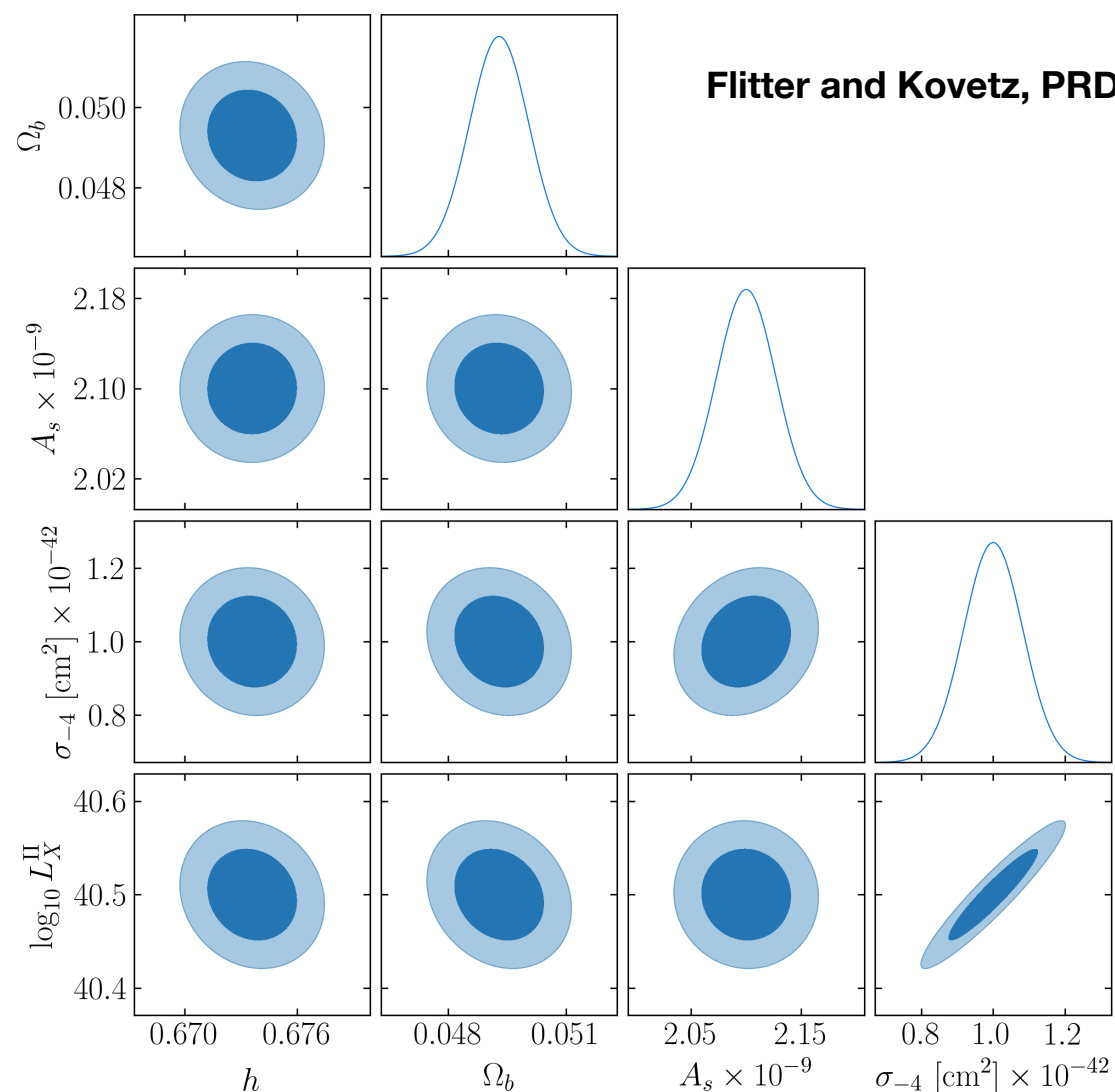


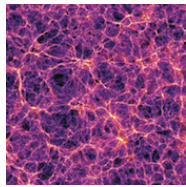
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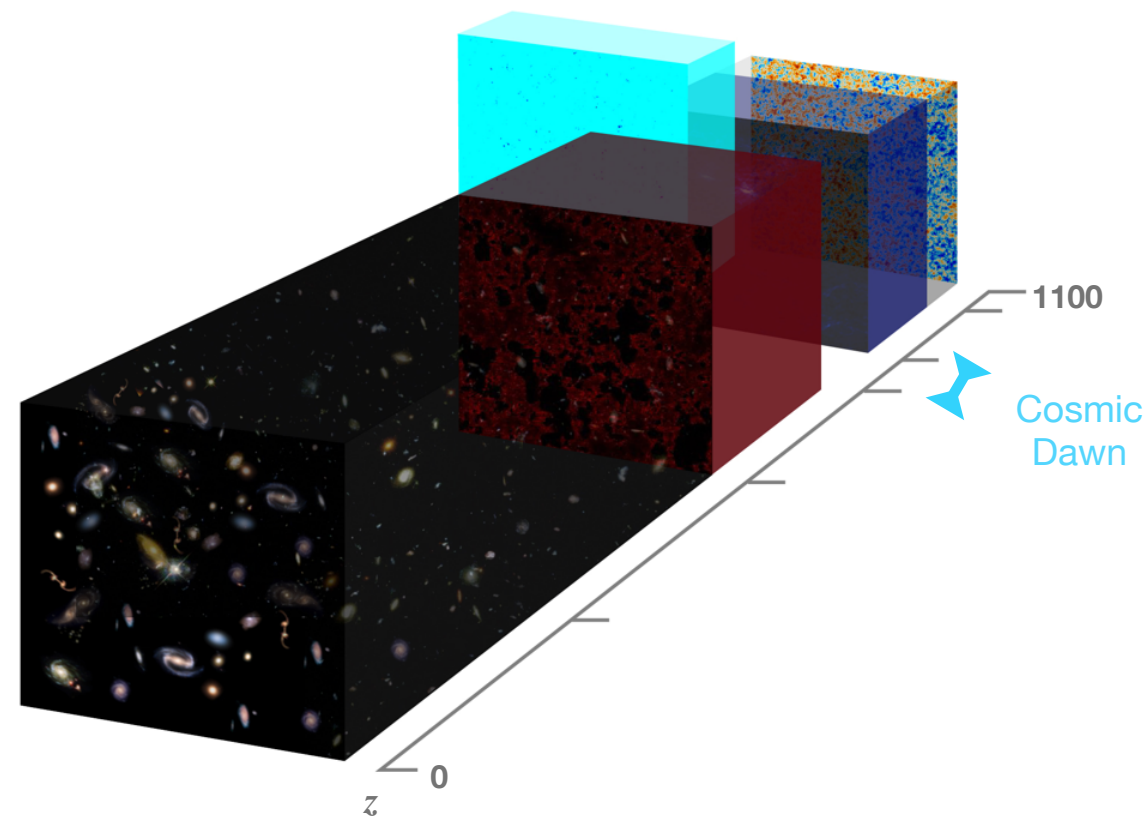
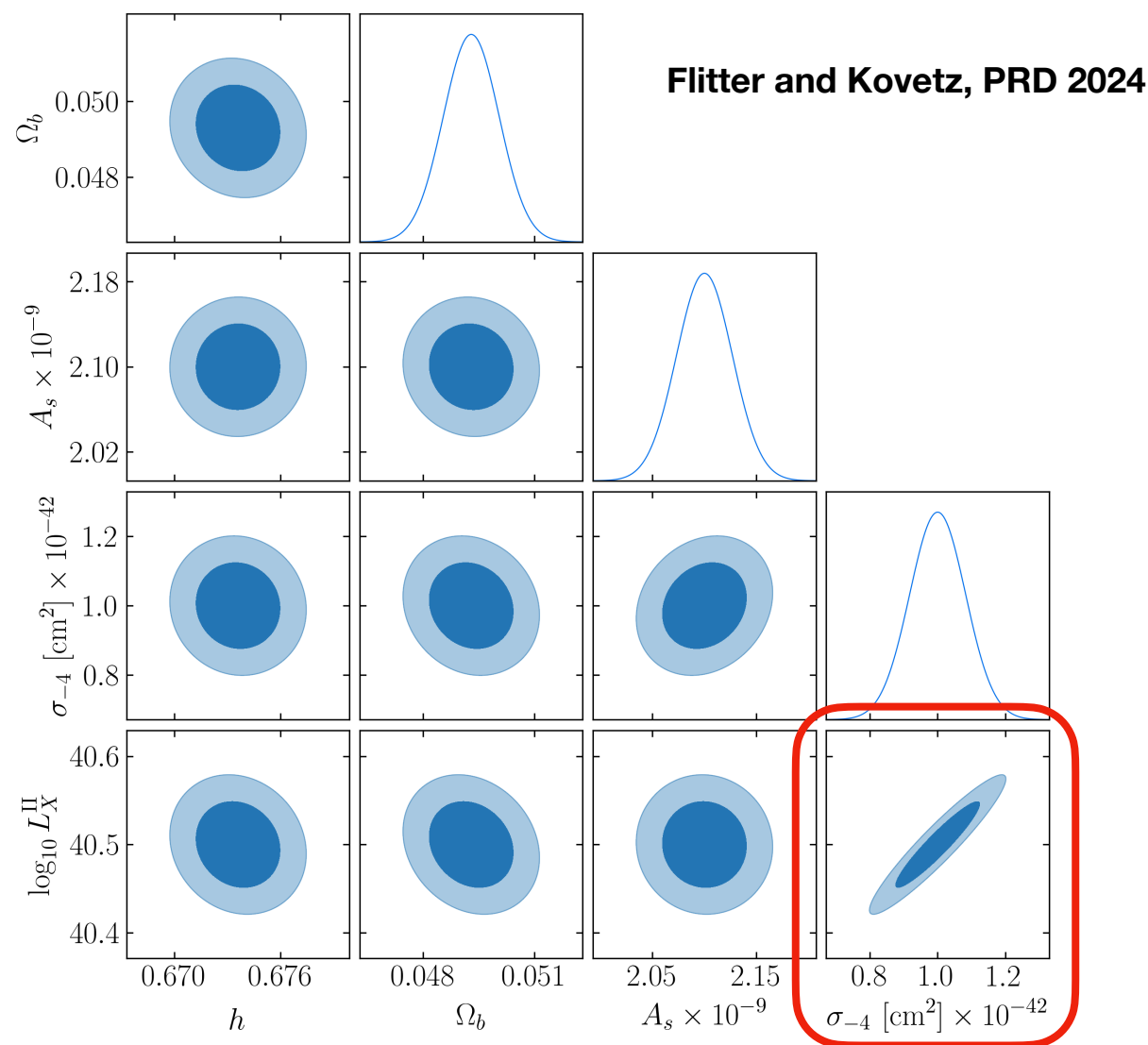
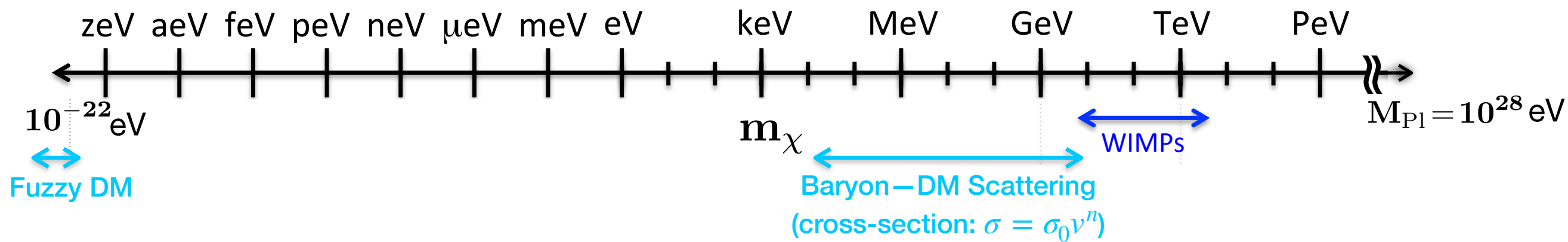
Flitter and Kovetz, PRD 2024

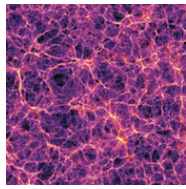




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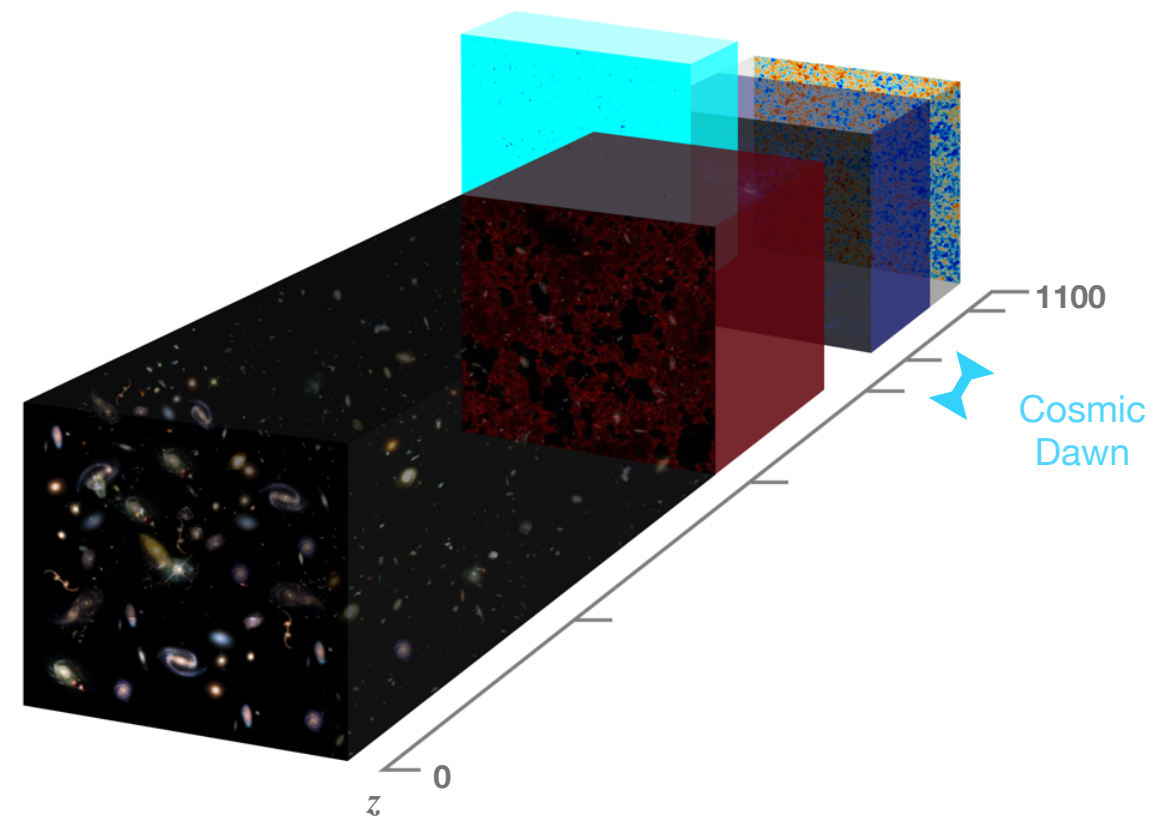
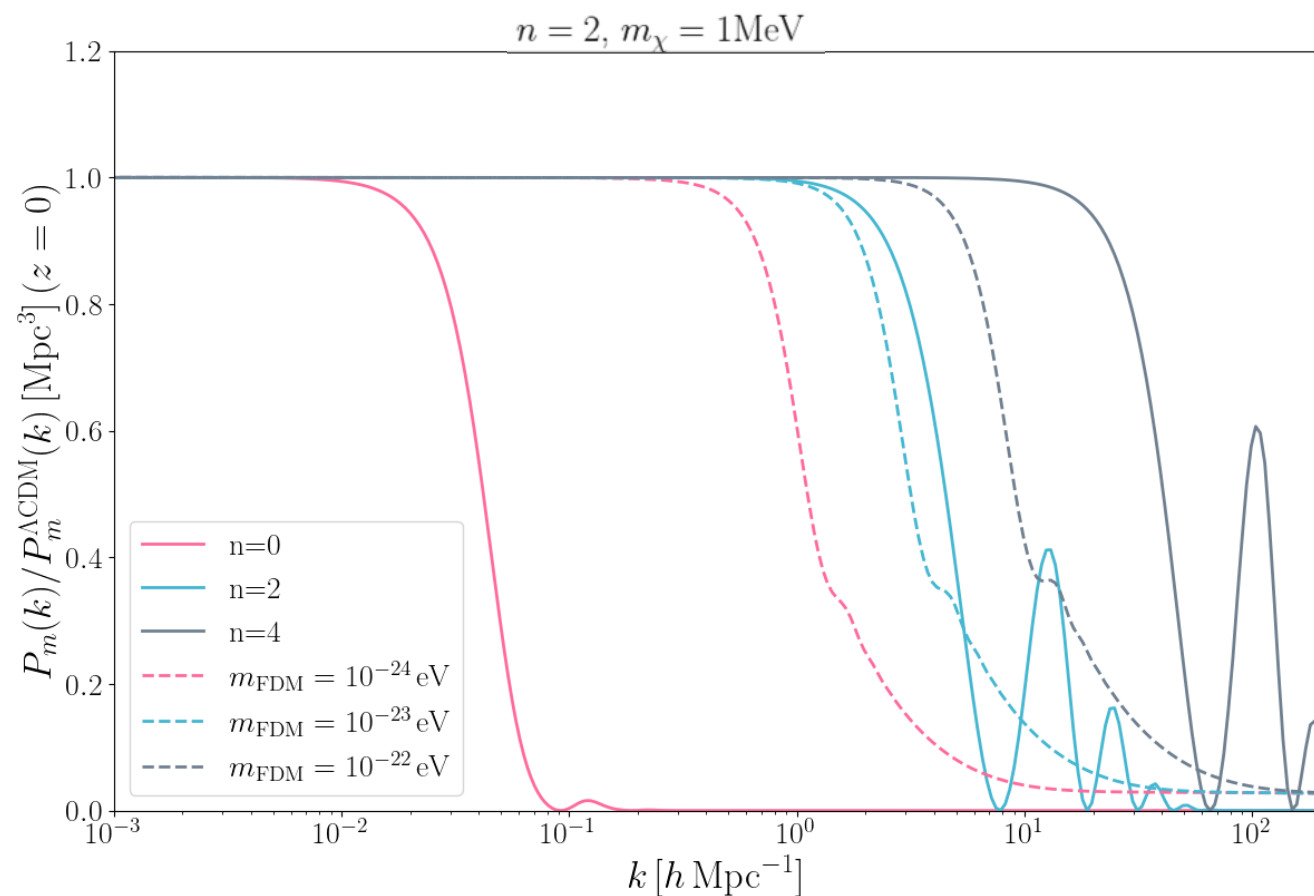
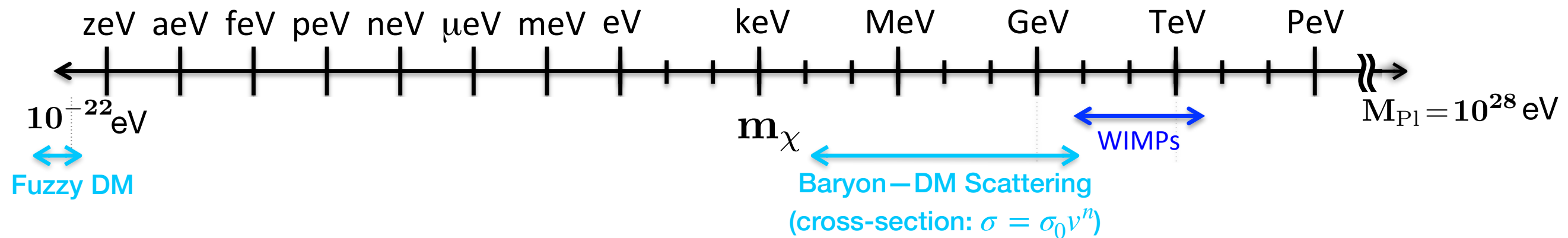
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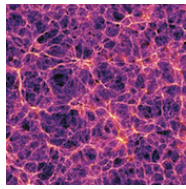


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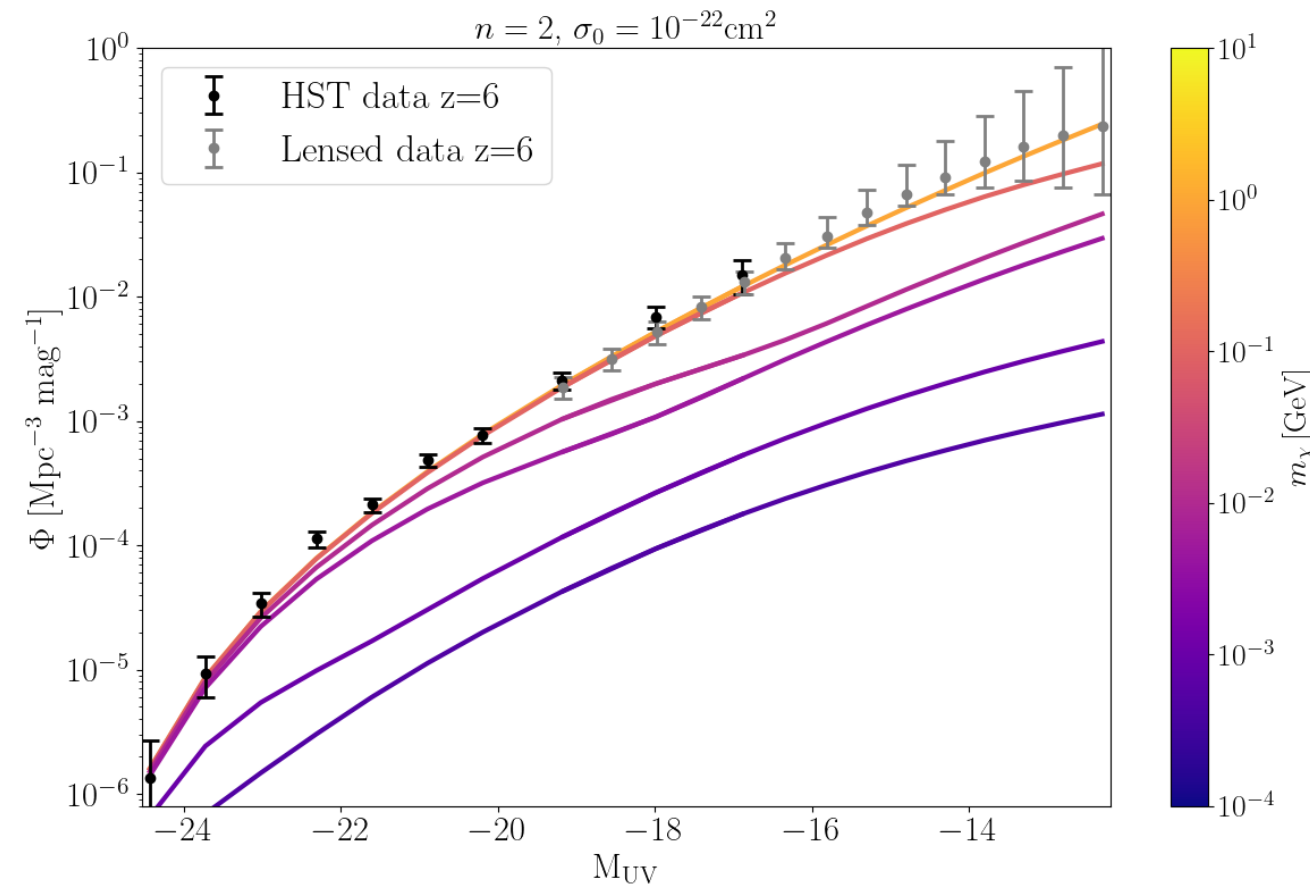
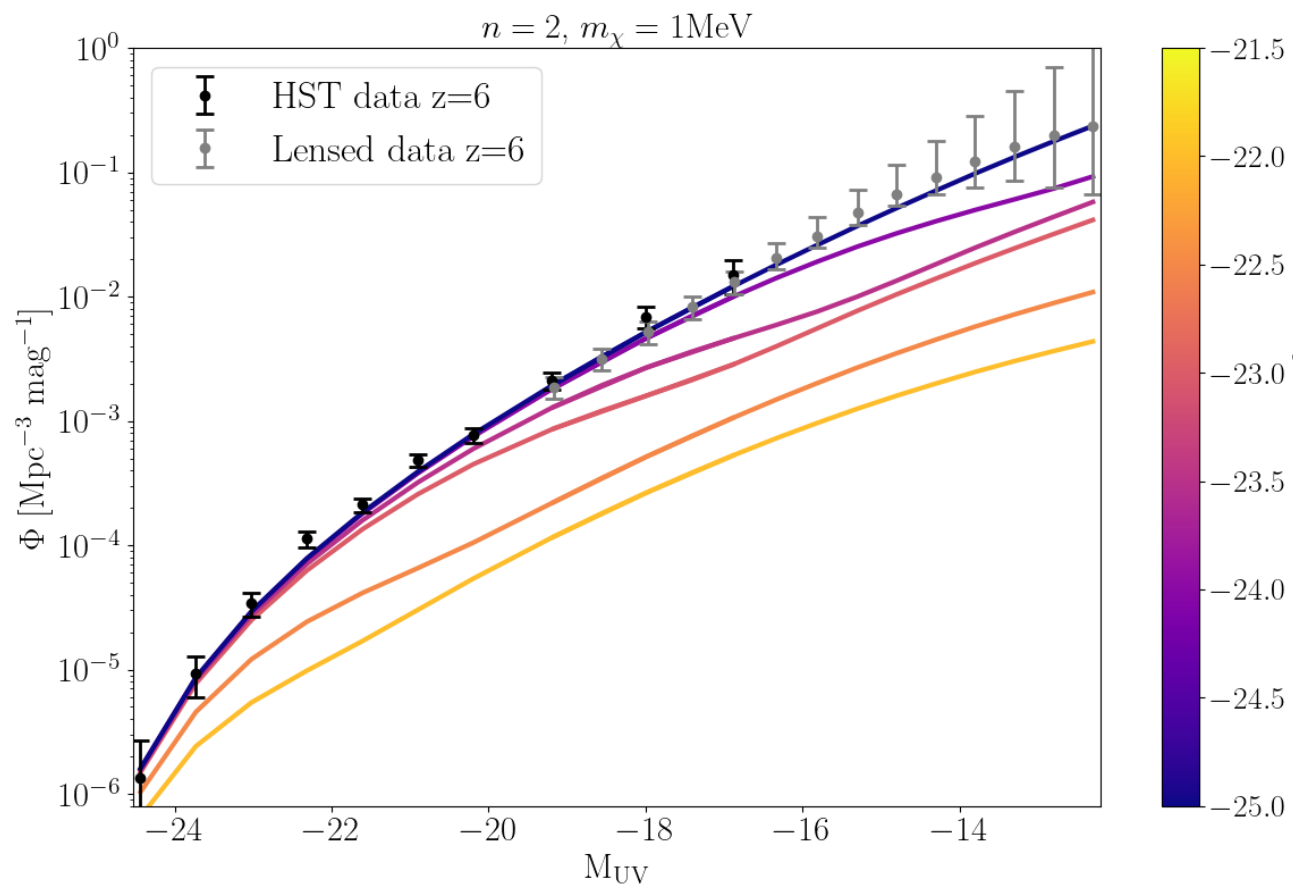
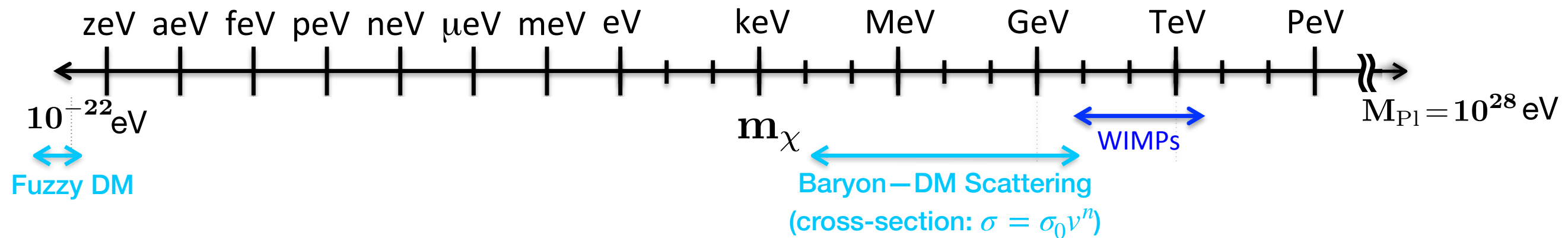


Lazare, Munoz, Boddy and Kovetz, to appear

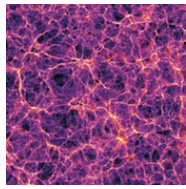


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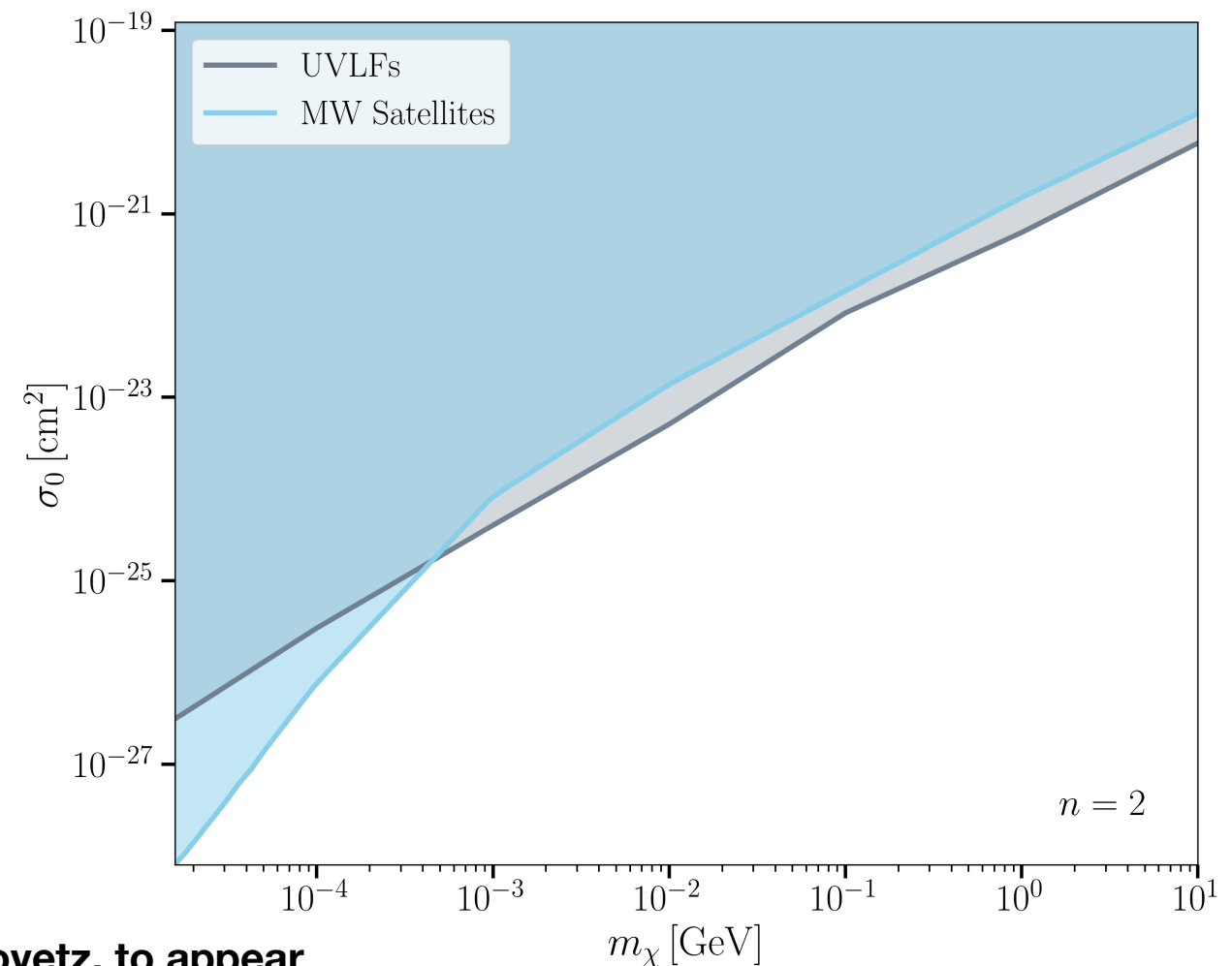
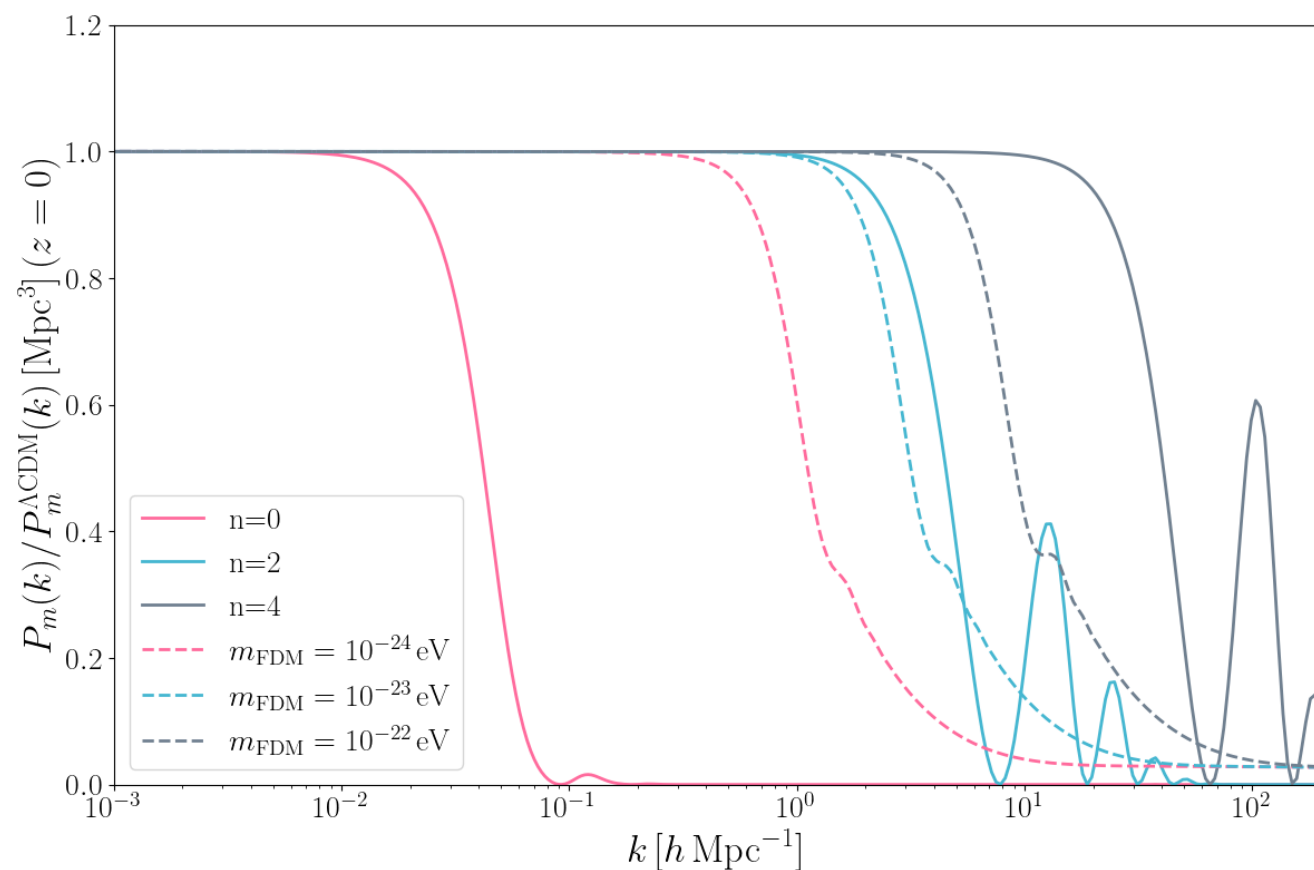
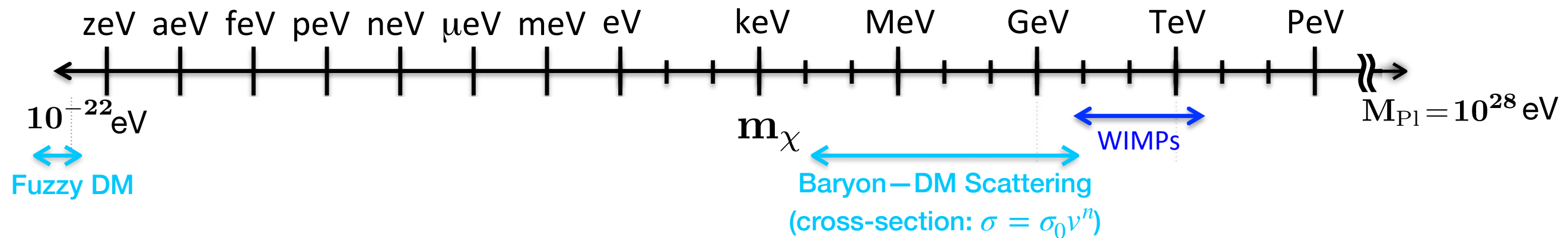


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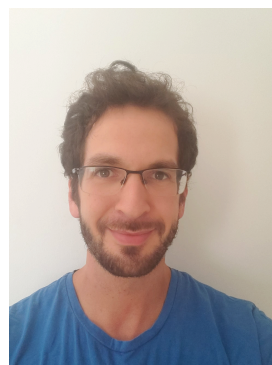
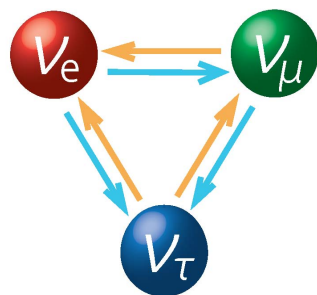
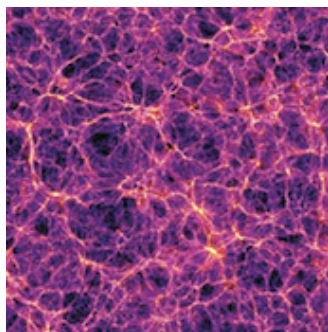
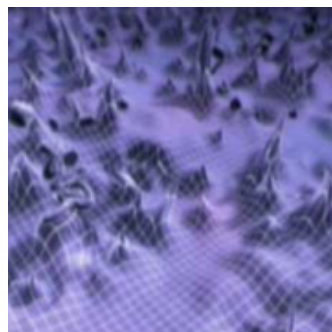
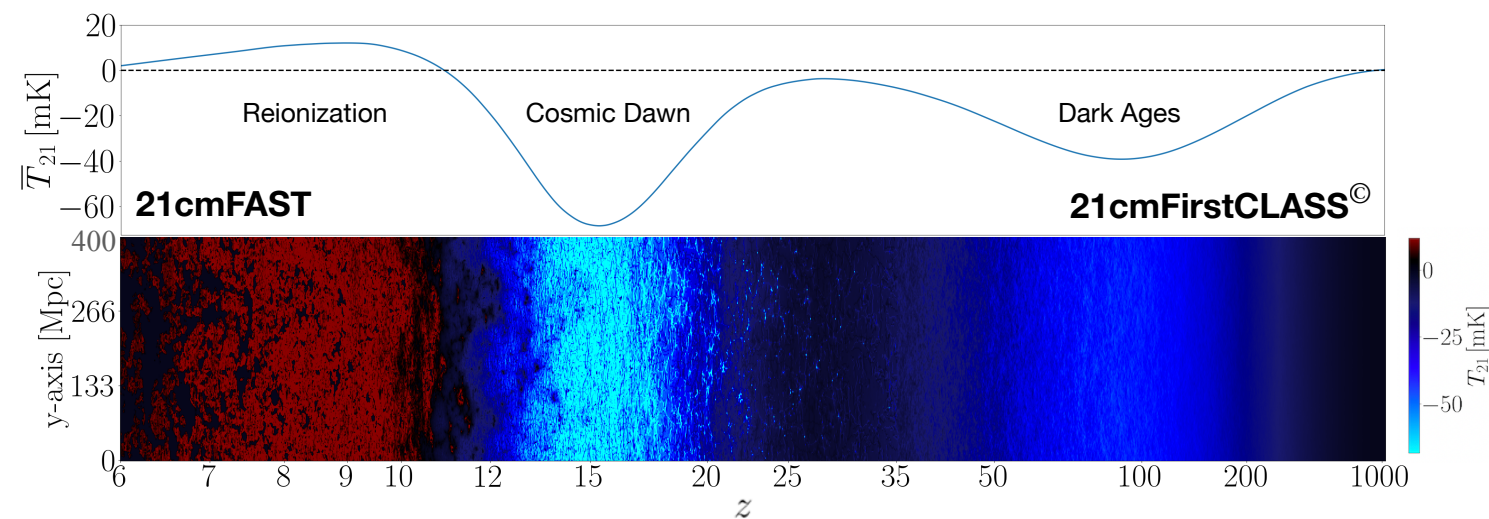
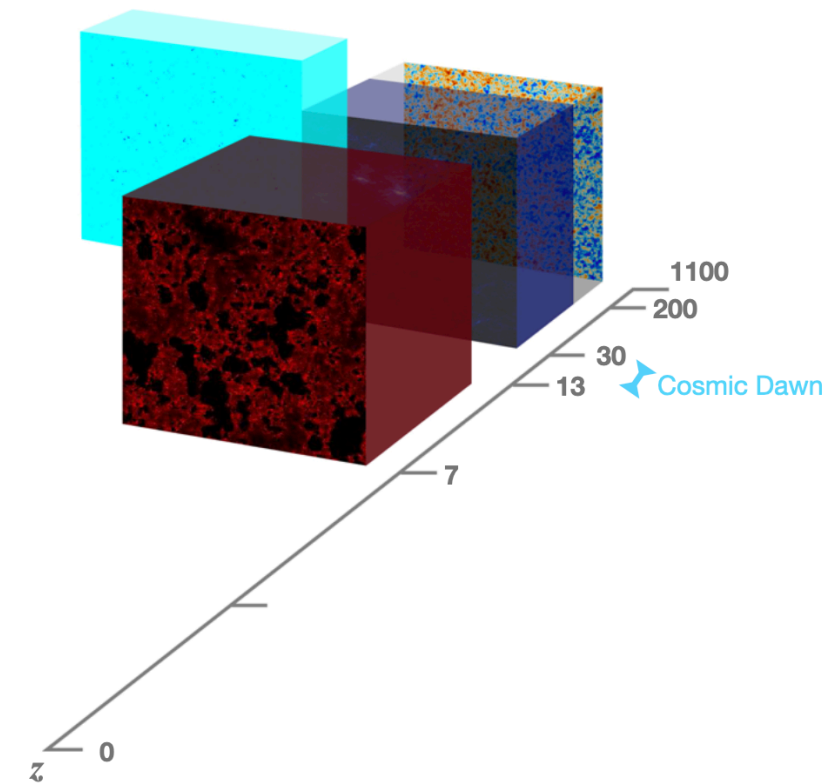
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Lazare, Munoz, Boddy and Kovetz, to appear

The Dawn of Cosmic Dawn Cosmology



Jordan Flitter



Tal Adi



Hovav Lazare



Sarah Libanore

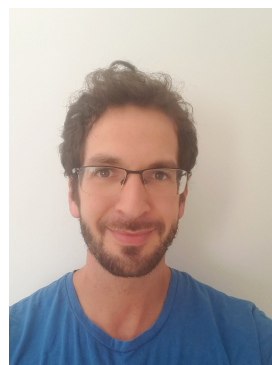
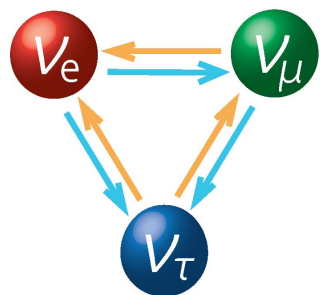
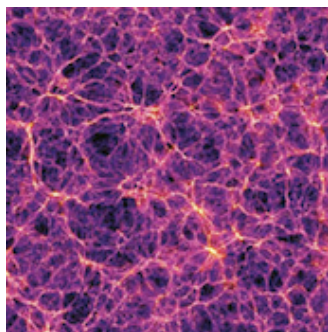
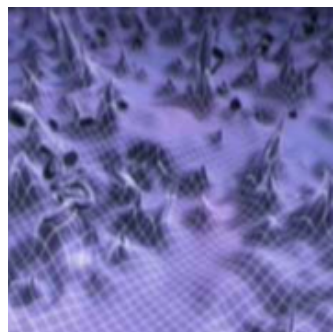
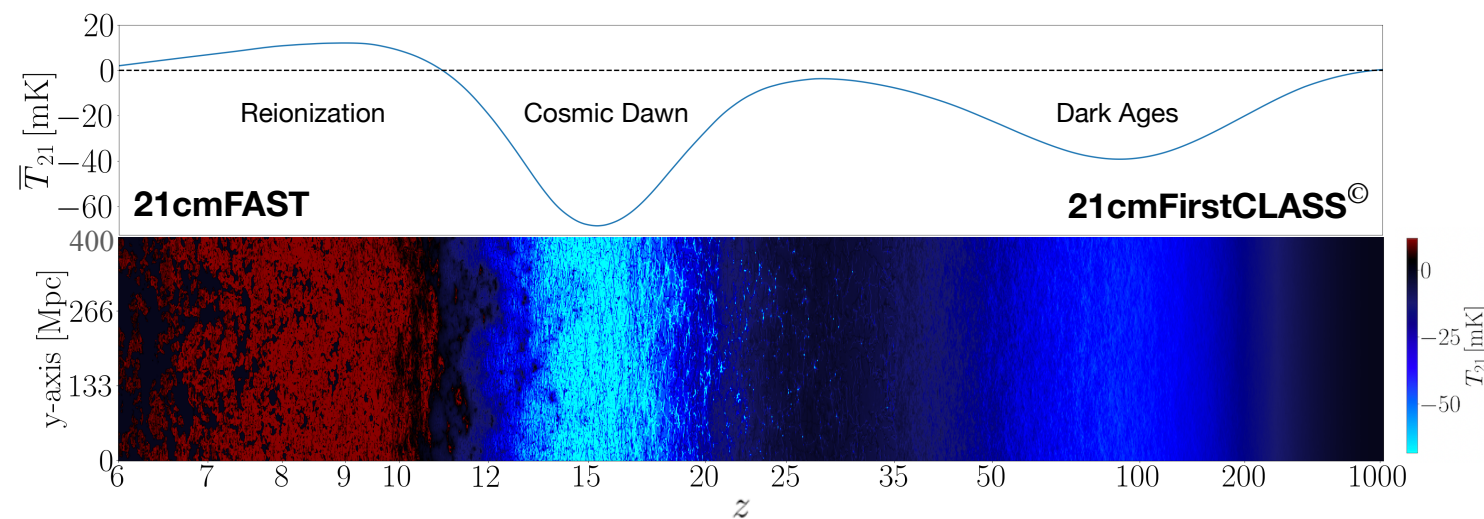
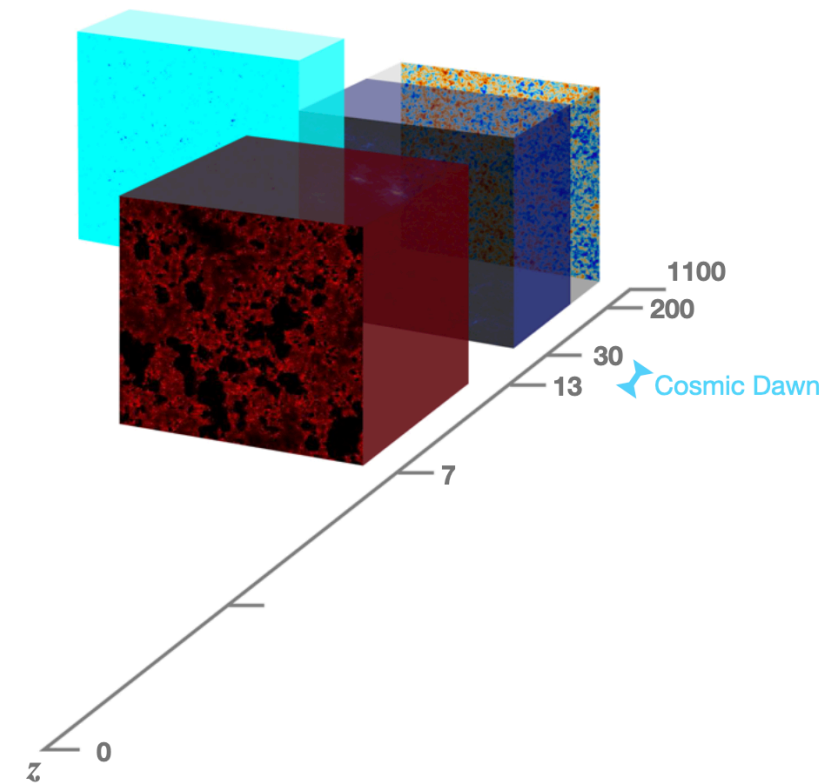


Debanjan Sarkar

The Dawn of Cosmic Dawn Cosmology

Some conclusions:

- We need robust, consistent and fast simulations.
- LIM is *unique* in many cases.
- At small scales, cosmic dawn can constrain:
 - Ultralight (fuzzy) dark matter
 - Interacting dark matter
 - Primordial magnetic fields
 - Early dark energy
 - Self-interacting neutrinos
 - Neutrino masses
 - ...



Jordan Flitter



Tal Adi



Hovav Lazare



Sarah Libanore



Debanjan Sarkar

Cosmic Dawn Cosmology: Other Models

Primordial Magnetic Fields:

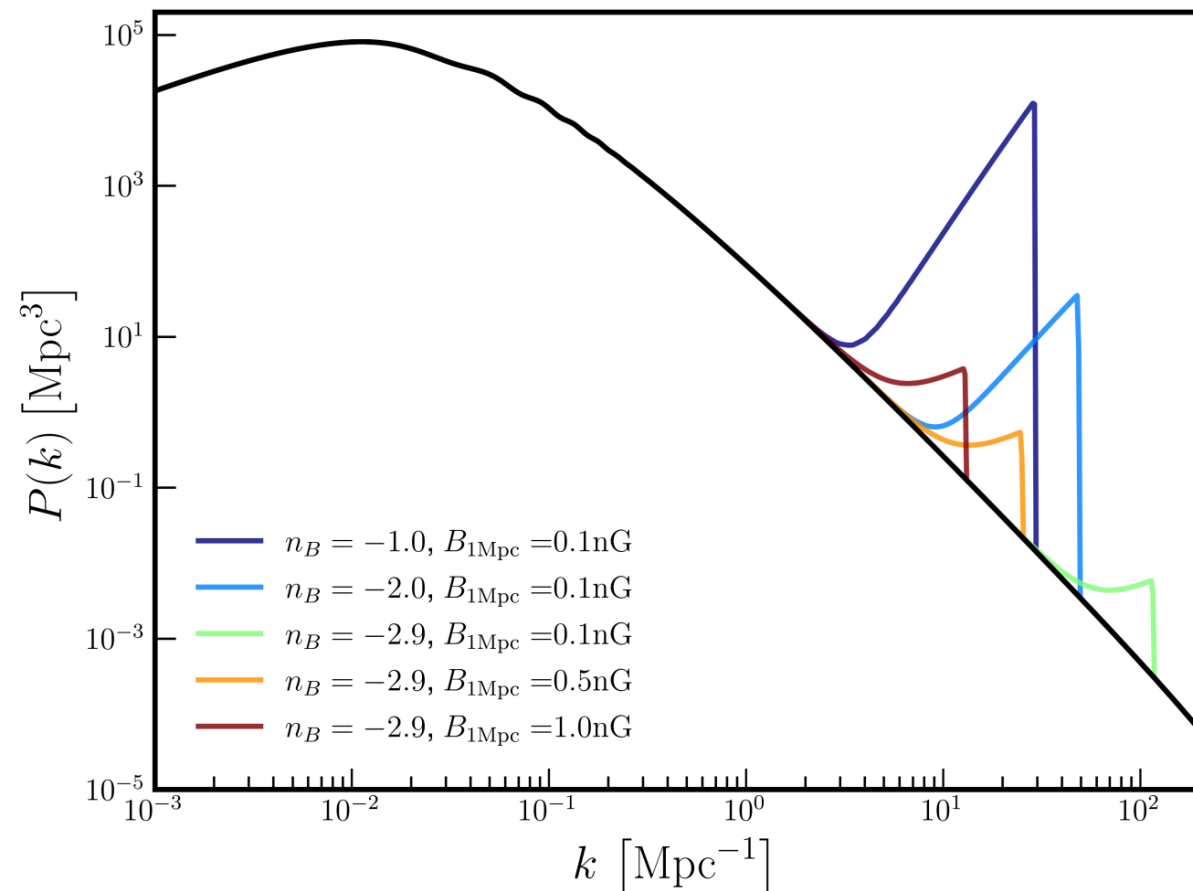
$$(P_B(k) \propto B_{1\text{Mpc}}^2 k_B^n)$$

Cosmic Dawn Cosmology: Other Models

Primordial Magnetic Fields:

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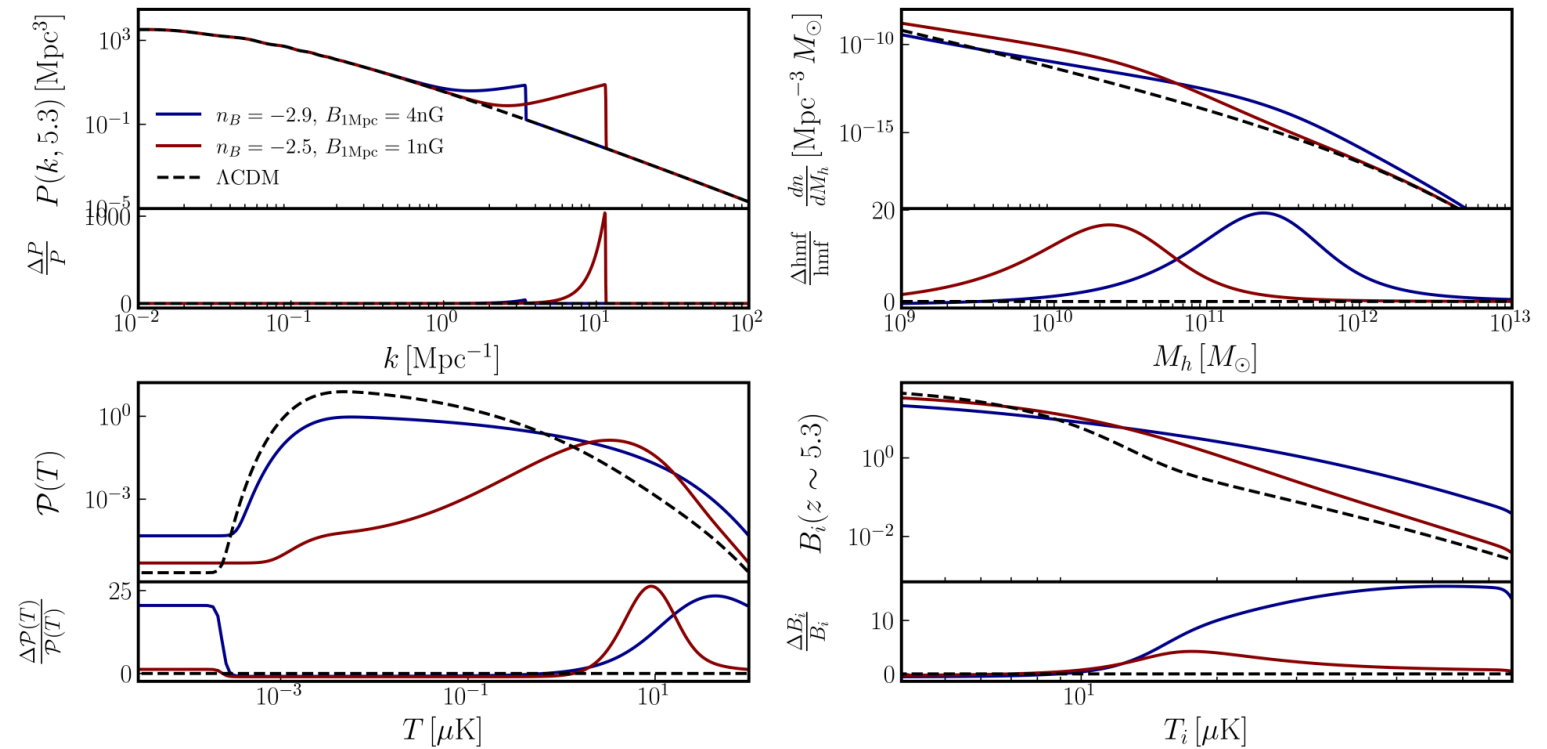
Adi, Libanore, Cruz and Kovetz, JCAP 2023



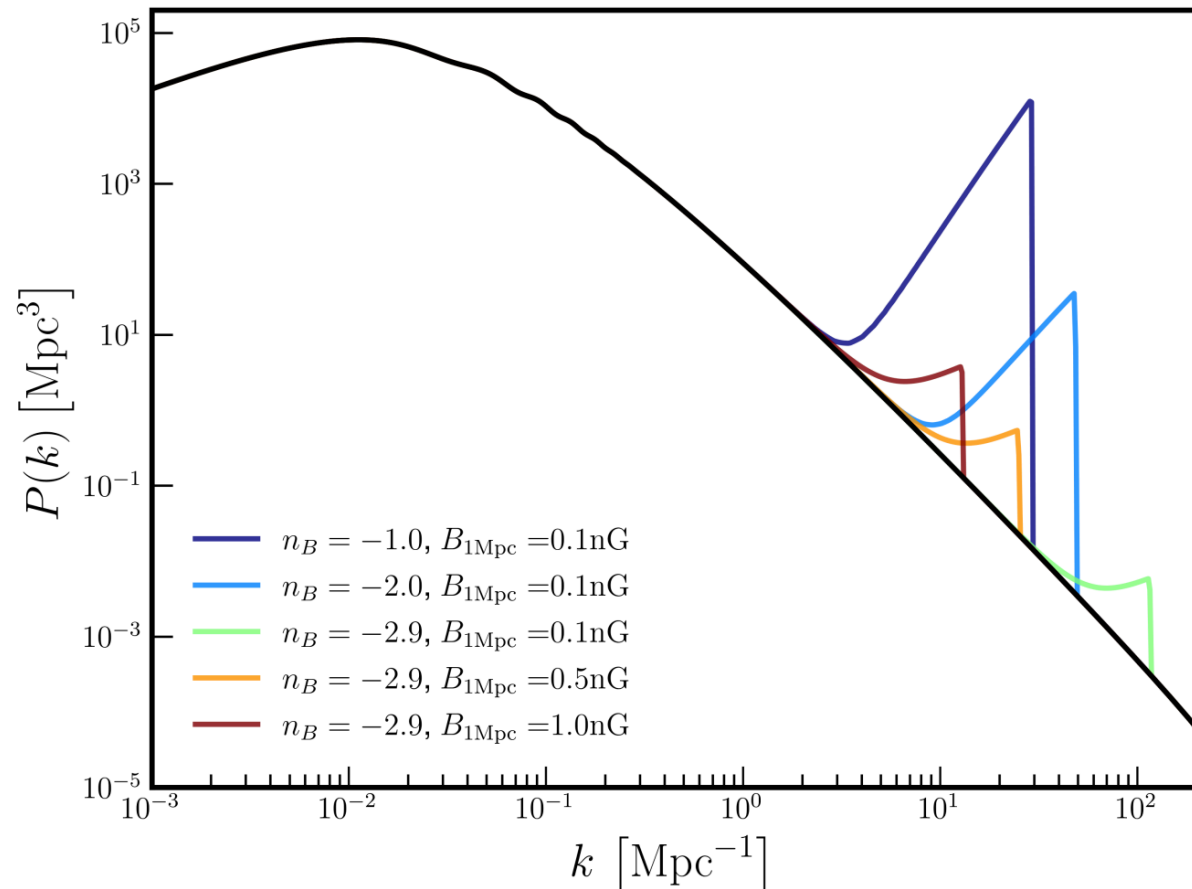
Cosmic Dawn Cosmology: Other Models

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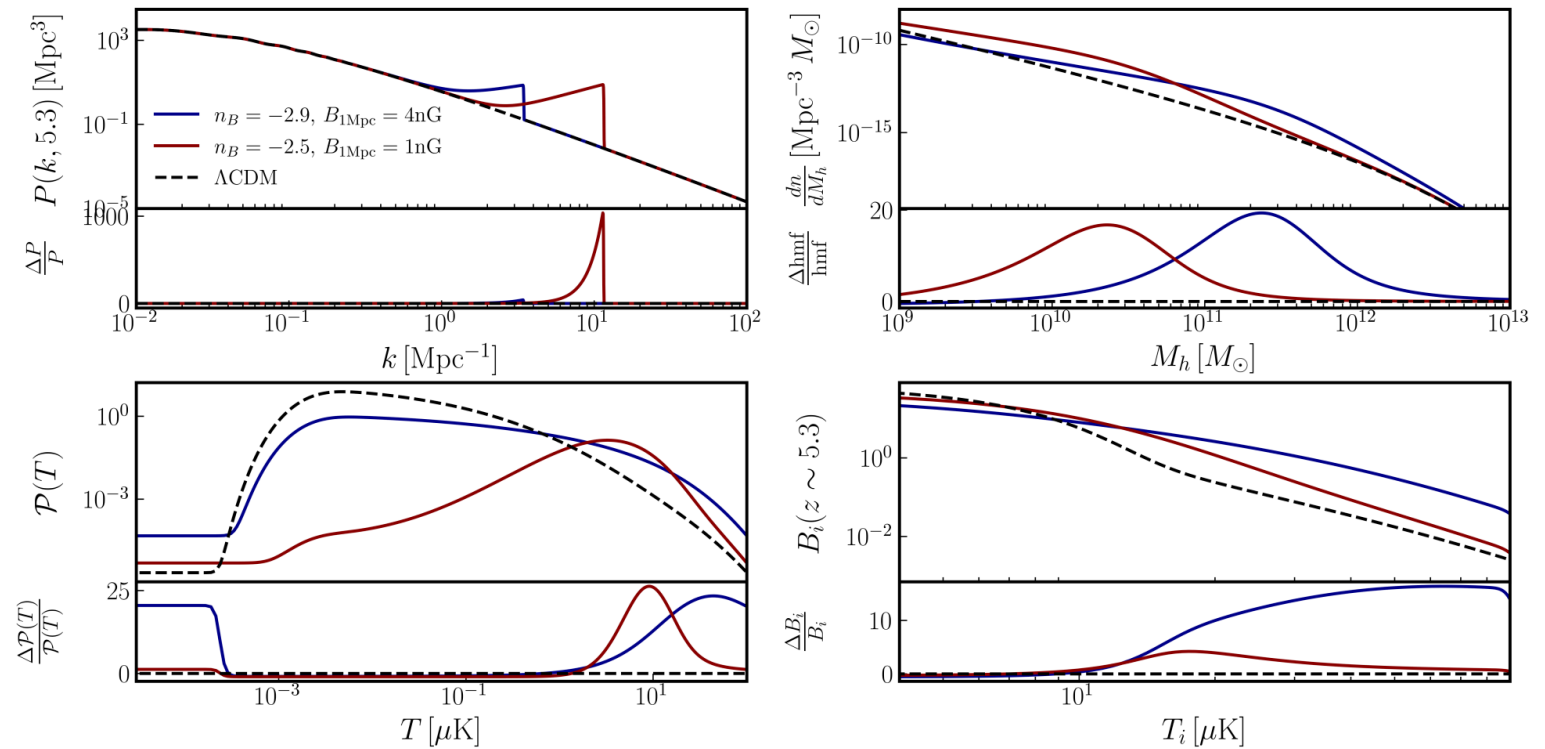
Adi, Libanore, Cruz and Kovetz, JCAP 2023



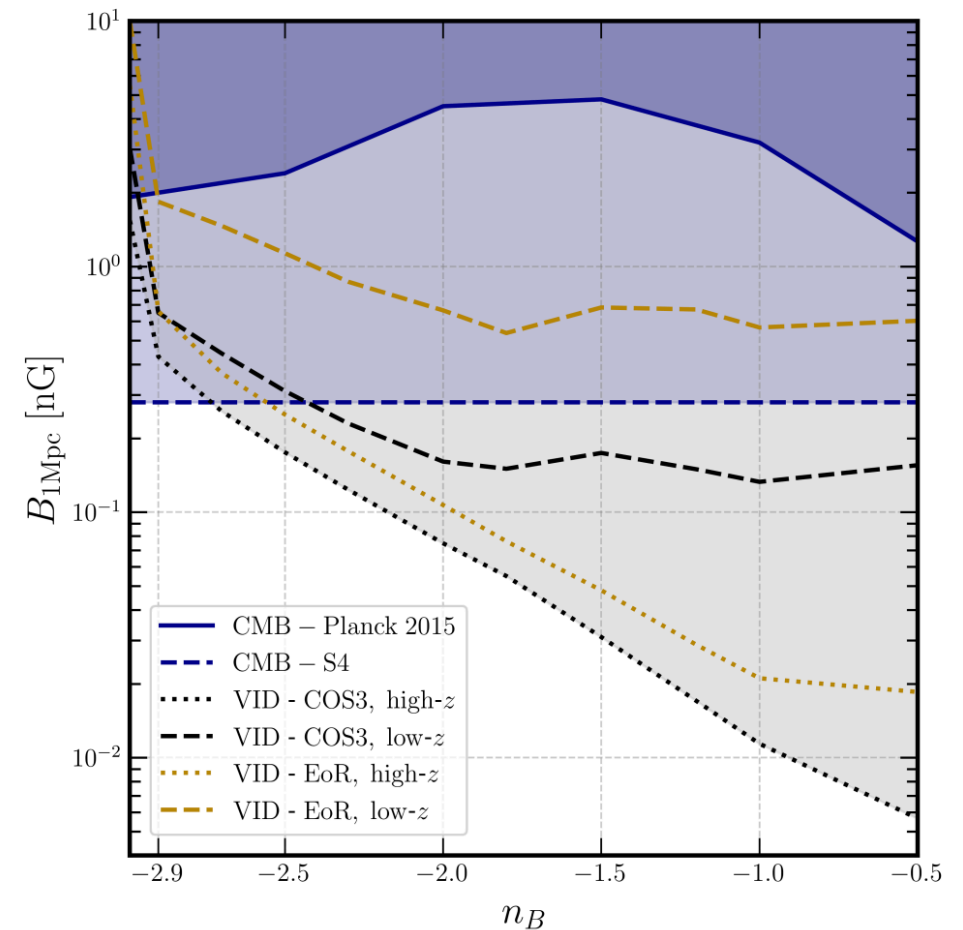
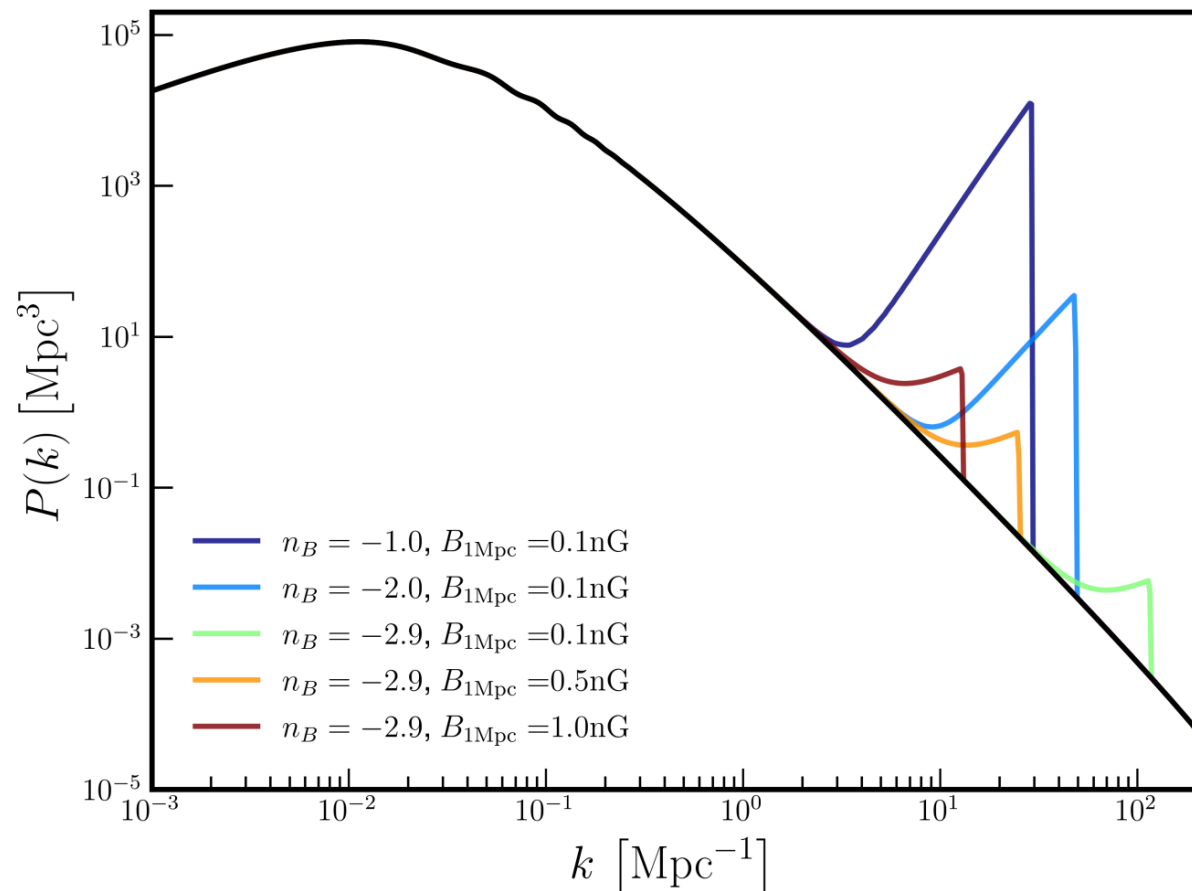
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Cosmic Dawn Cosmology: Other Models

Early Dark Energy:

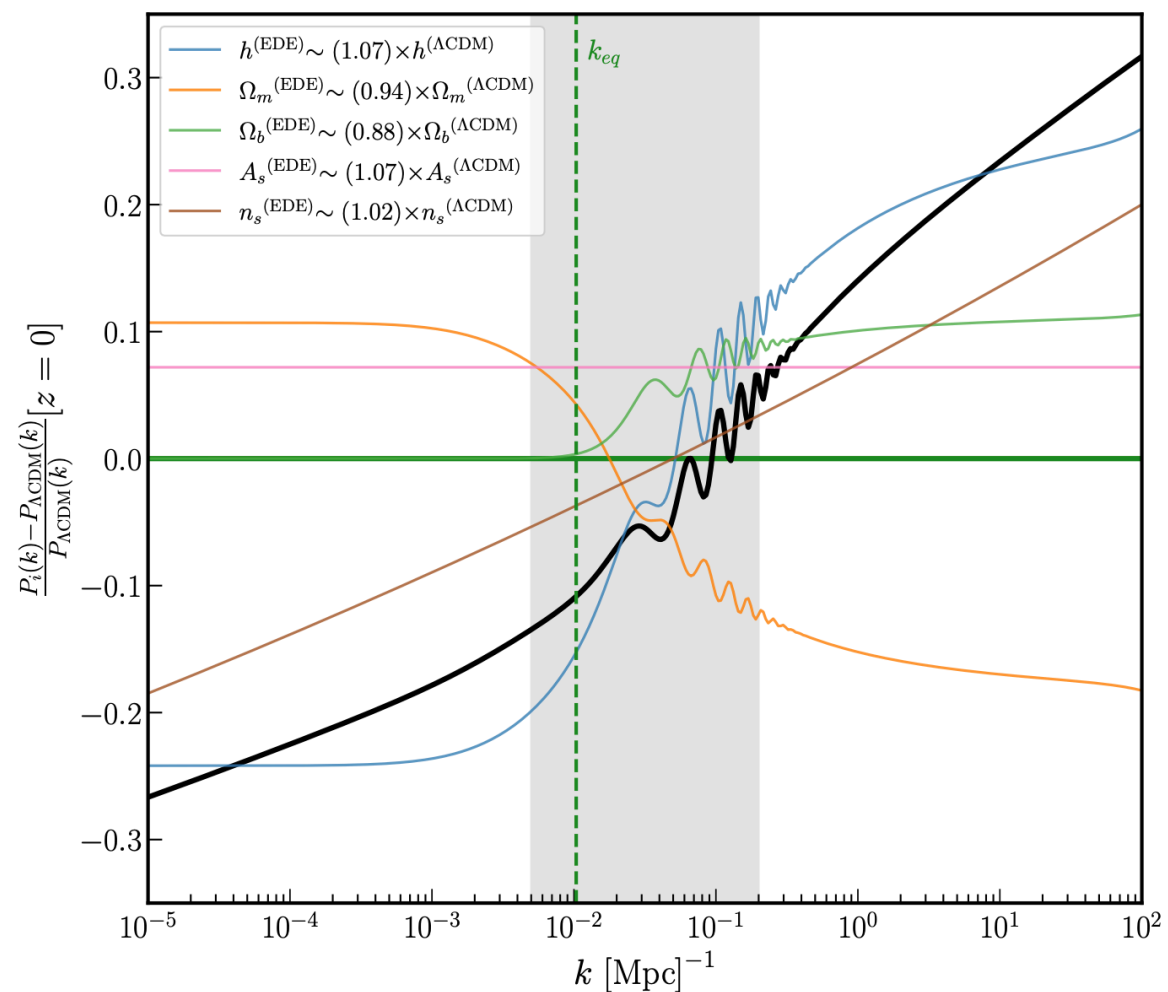
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Cosmic Dawn Cosmology: Other Models

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Adi, Flitter and Kovetz, PRD 2025

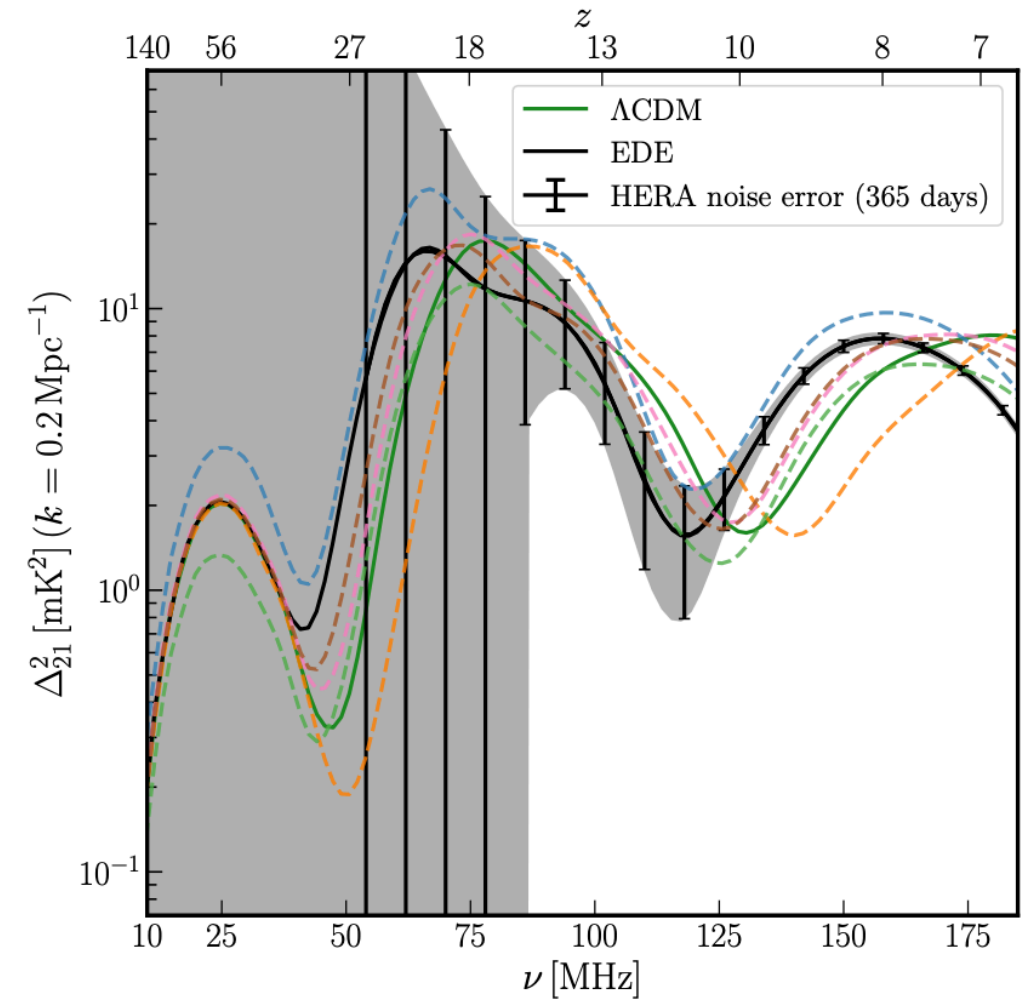
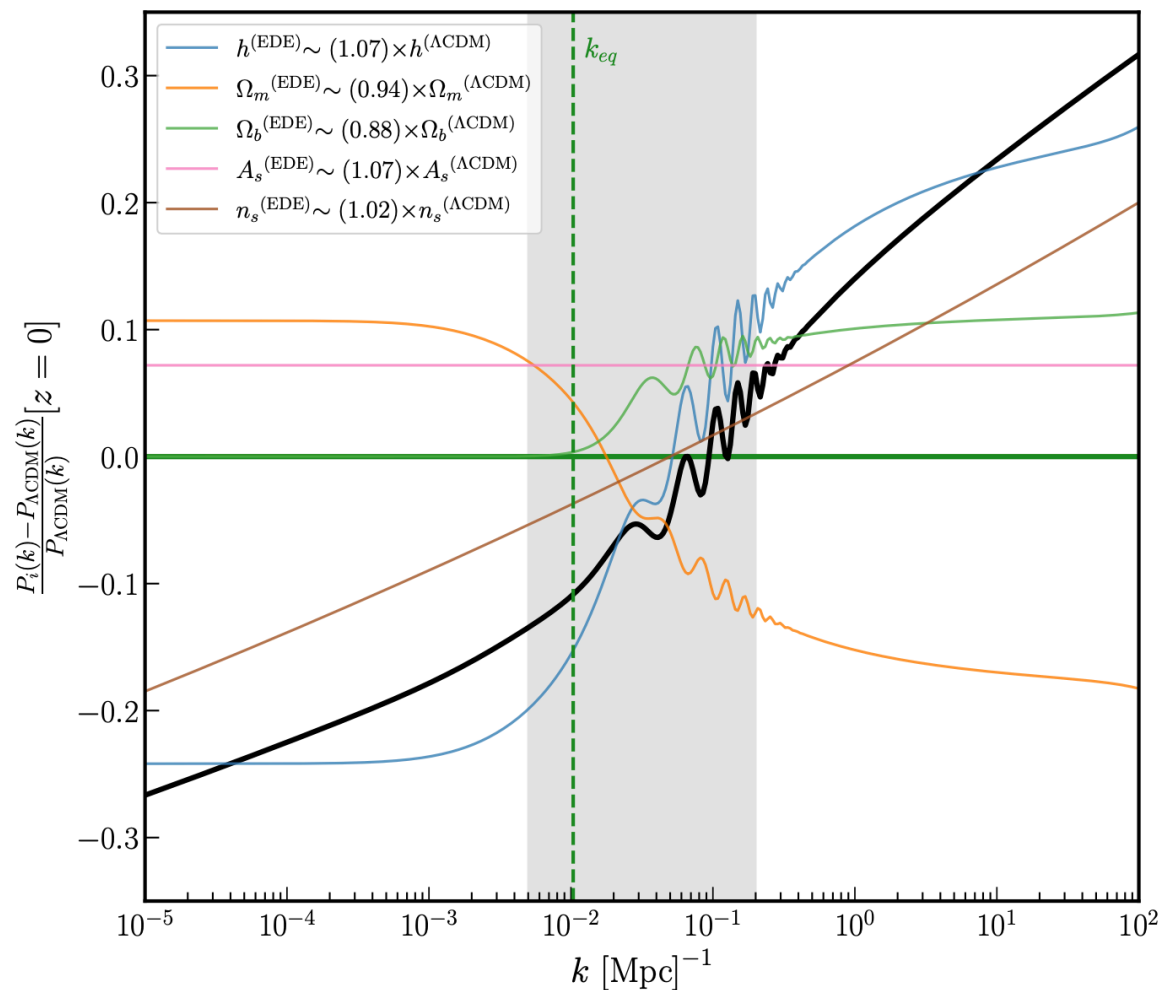


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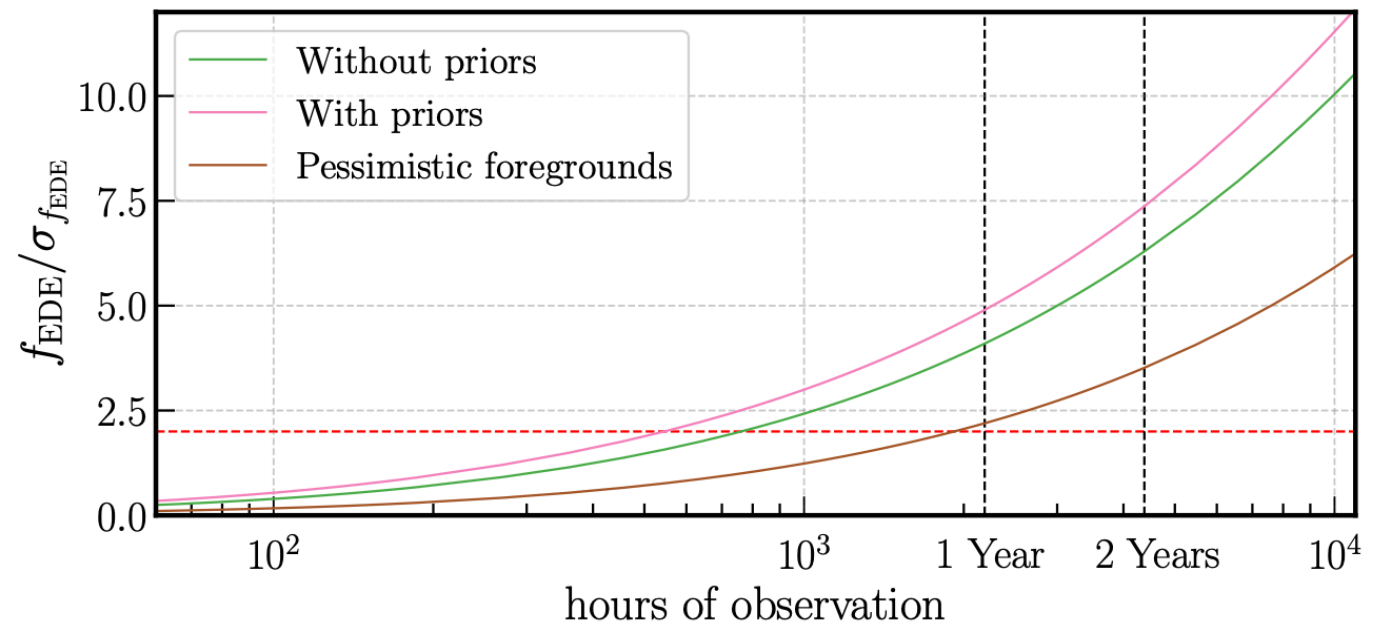
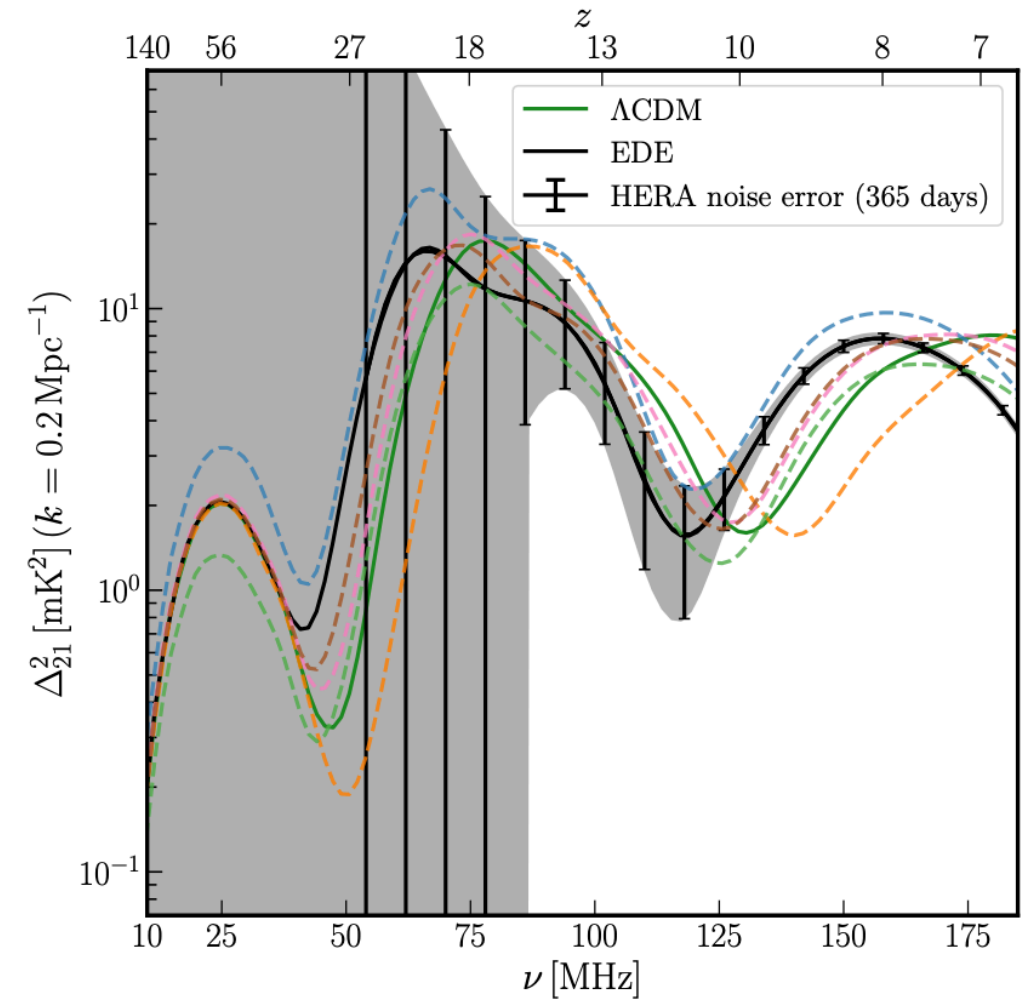
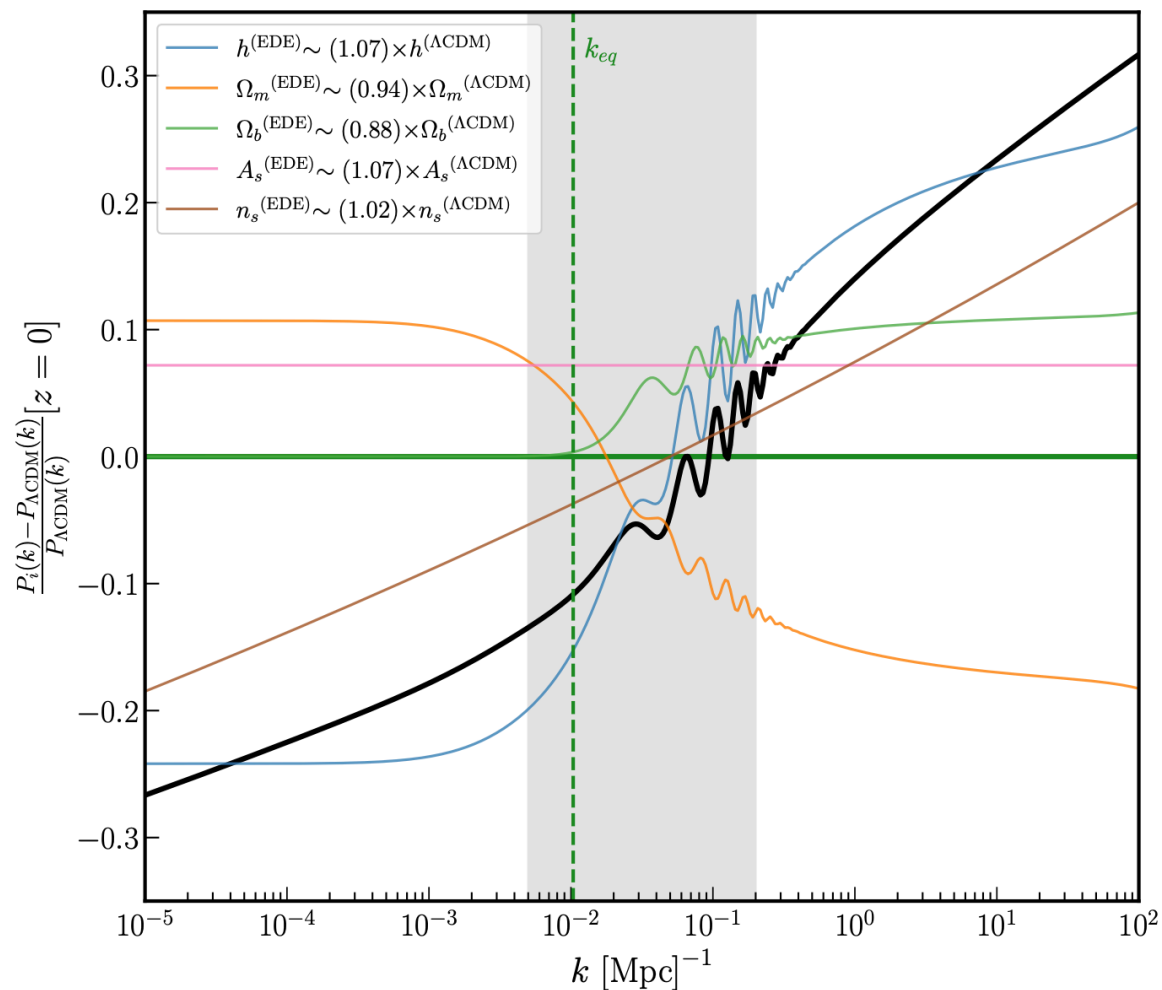


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Cosmic Dawn Cosmology: Other Models

Self-Interacting Neutrinos:

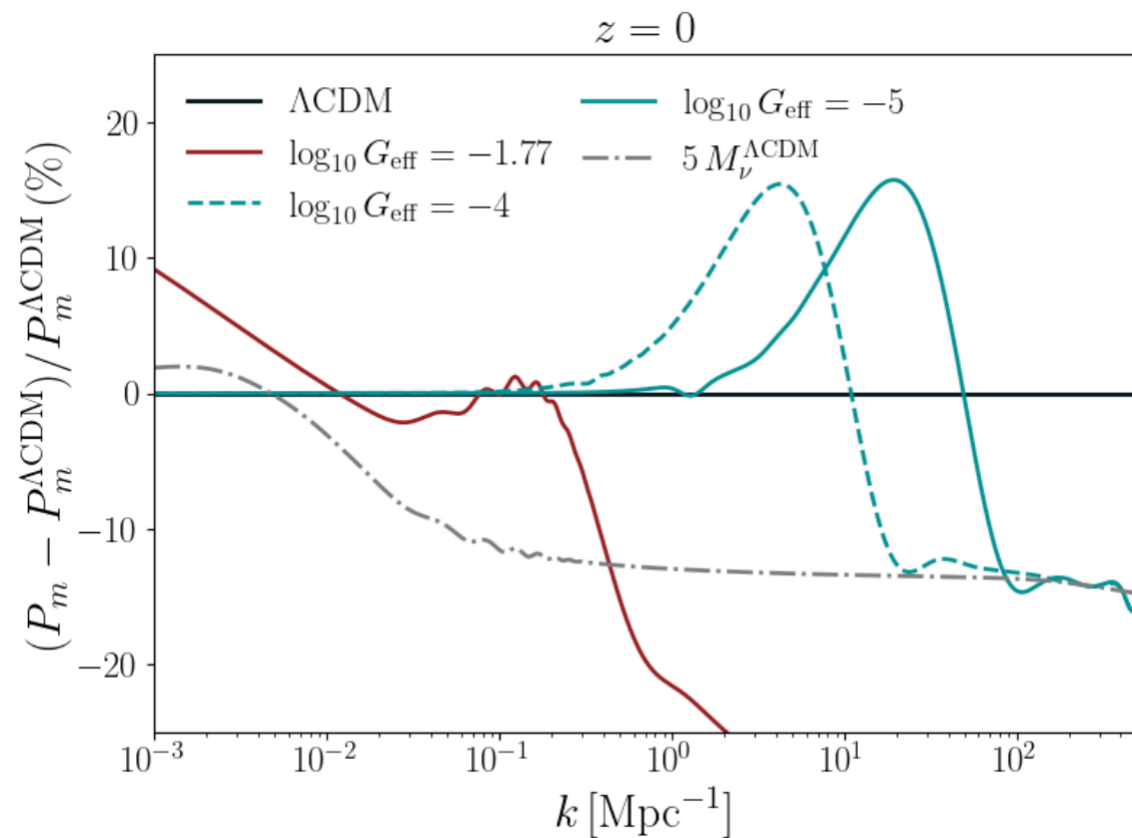
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Cosmic Dawn Cosmology: Other Models

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Libanore, Gosh, Kovetz, Boddy and Raccañelli, arXiv:2504.15348

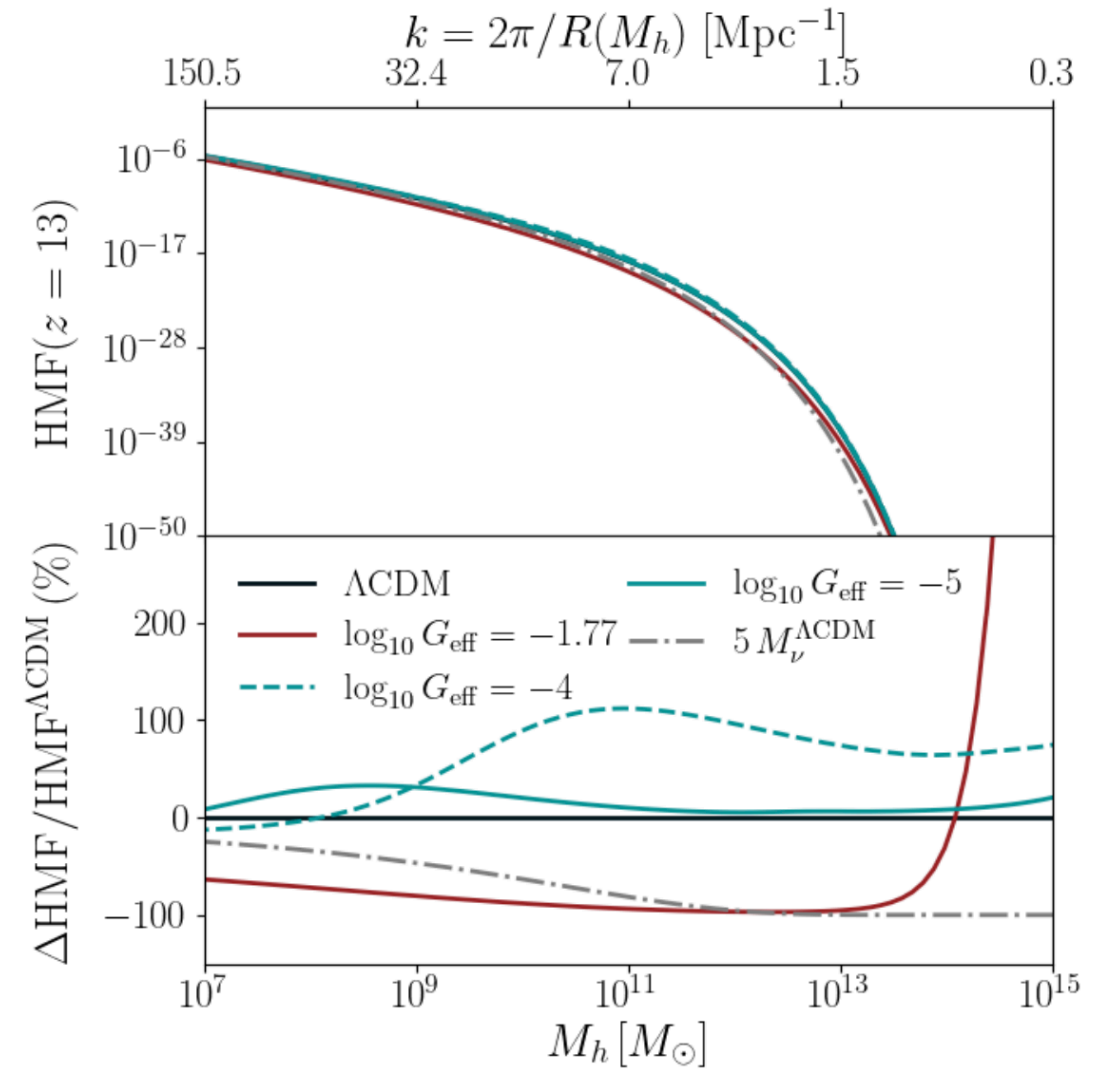
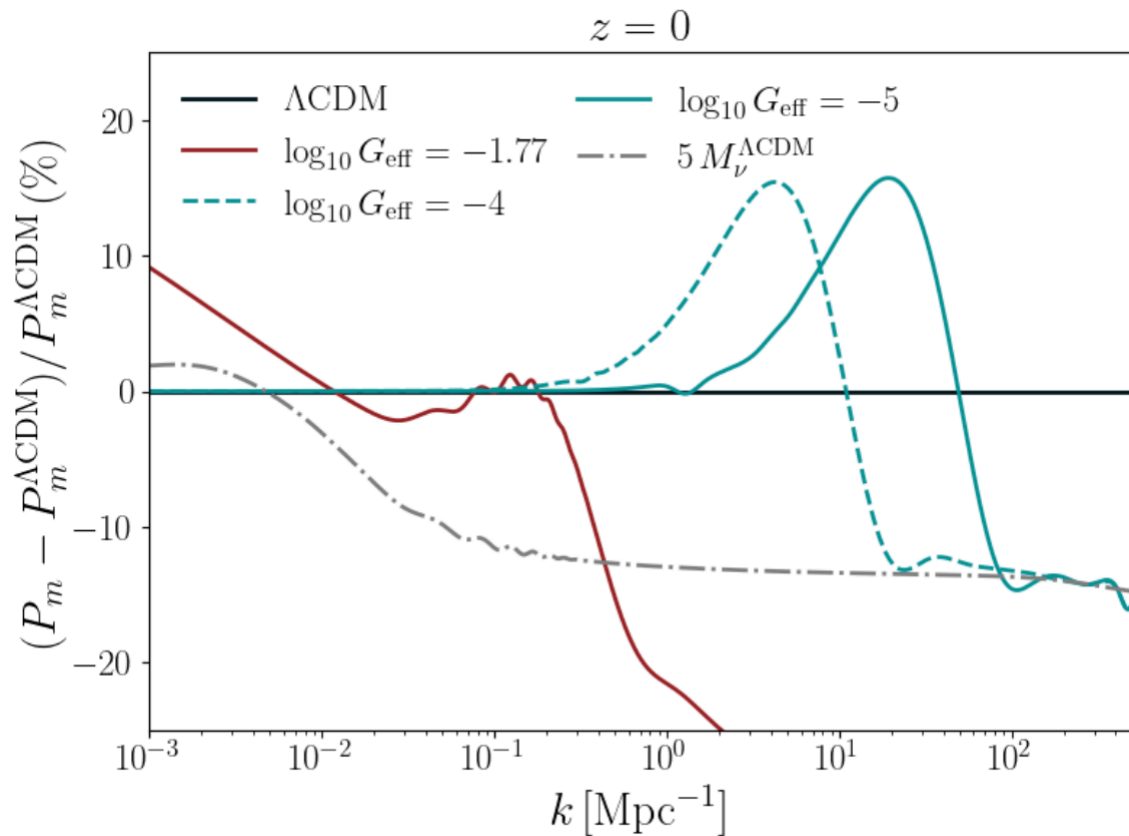


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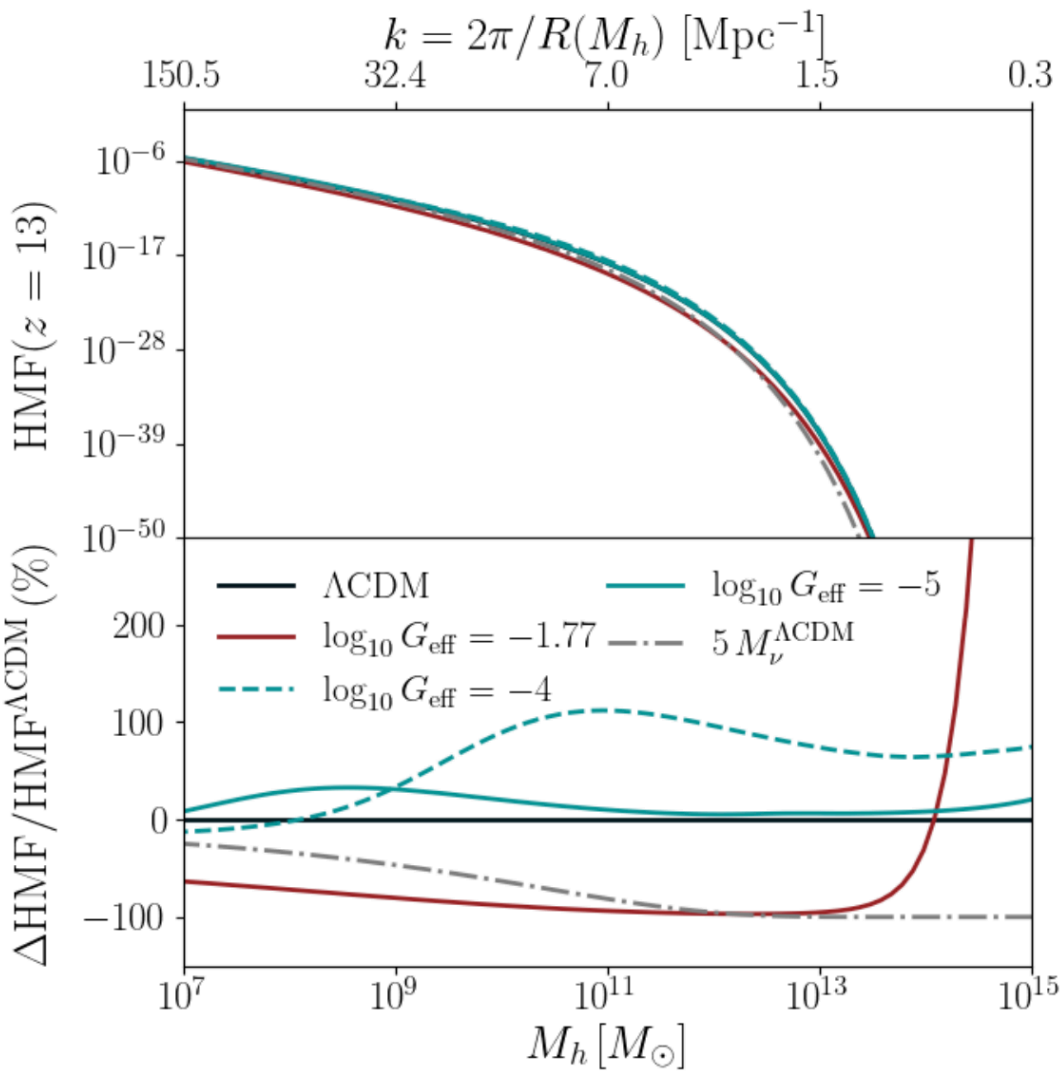
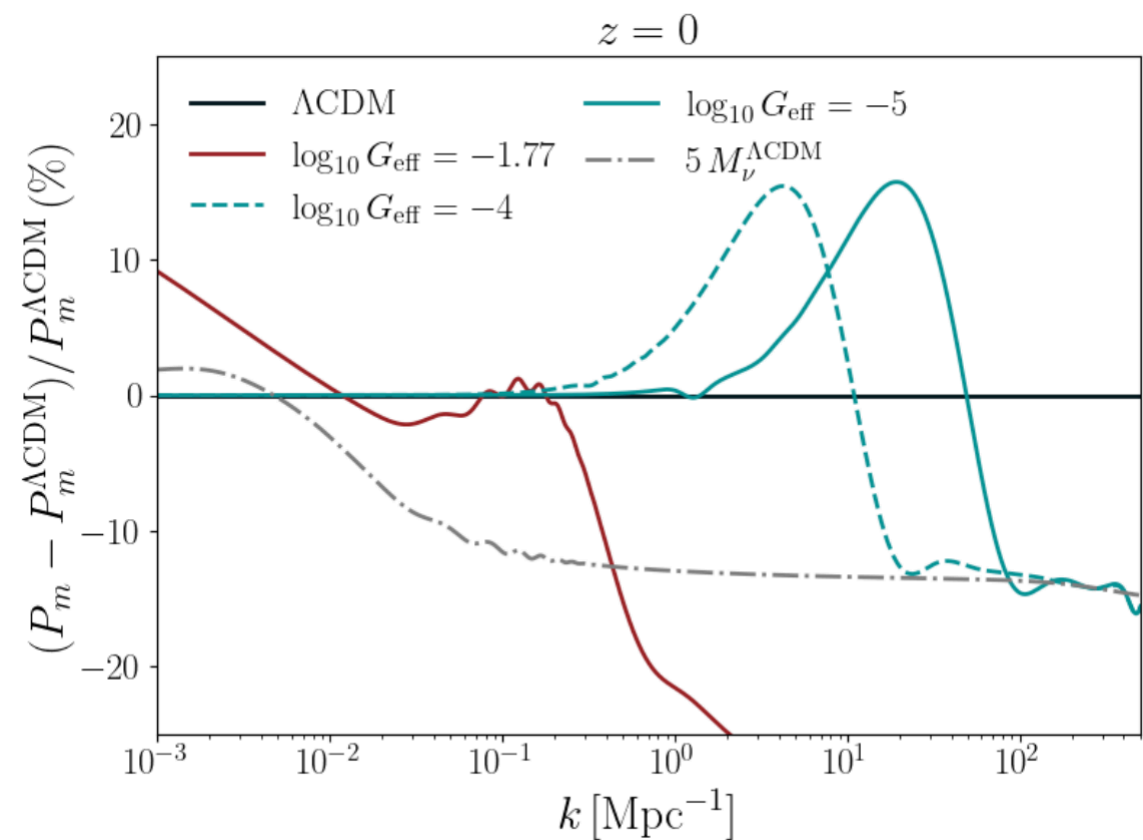


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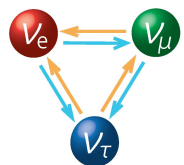
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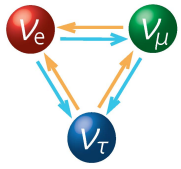
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	SI_{ν}	MI_{ν}	mI_{ν}
$\log_{10} G_{\text{eff}}$ fiducial value	-1.77	-4	-5
CMB-S4	14%	66%	534%
HERA (cosmic dawn)	32%	16%	112%
HERA + CMB-S4	8%	11%	12%



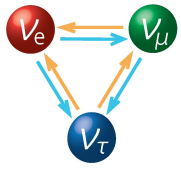
Cosmic Dawn Cosmology: Neutrino Masses



Cosmic Dawn Cosmology: Neutrino Masses

Using 21cm to mitigate CMB optical depth uncertainty (τ is degenerate with Σm_ν)

$$\tau_{\text{reio}} \propto \int \overline{n_e(z)} \frac{dl}{dz} dz \propto \int_0^{z_{\text{CMB}}} \frac{dz(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}} \overline{x_{\text{HII}}(1+\delta_b)}$$

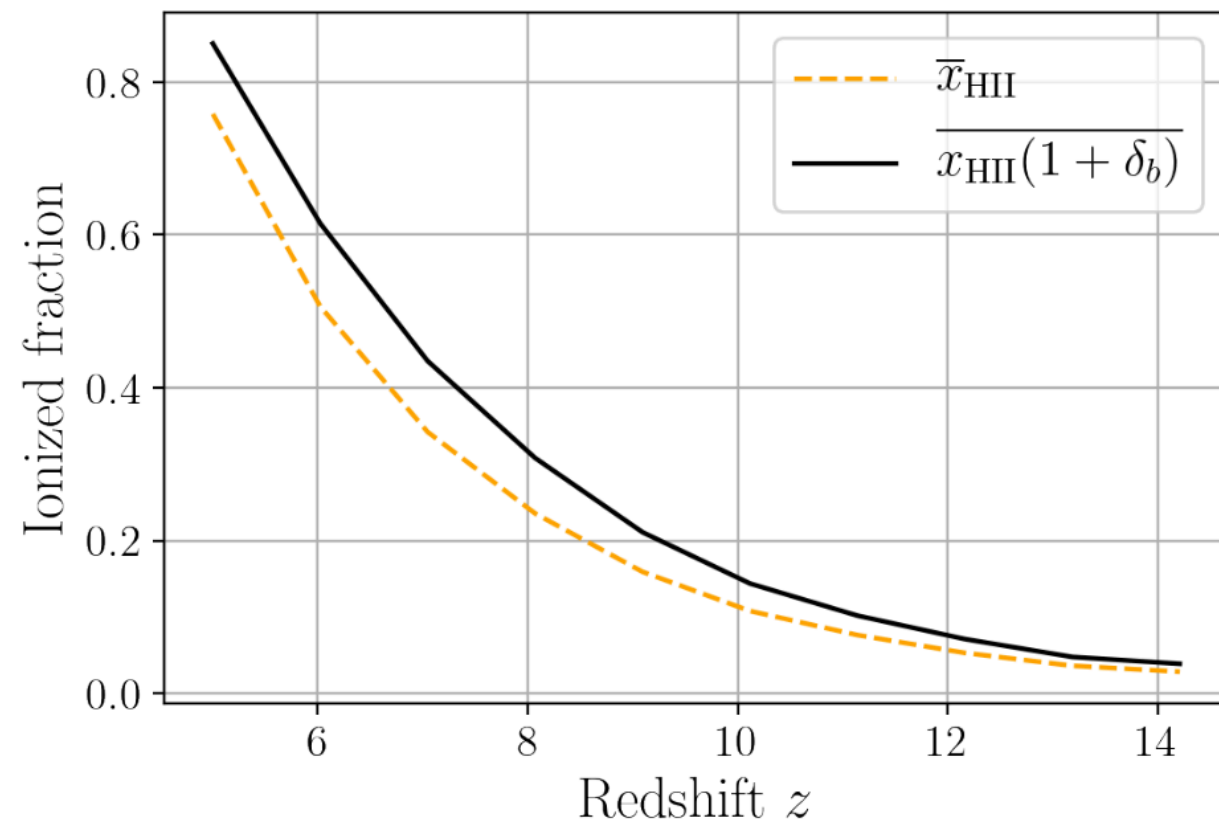


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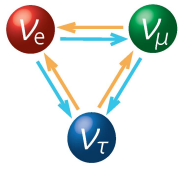
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We can *predict* the reionization contribution:



Shmueli, Sarkar and Kovetz, PRD 2023
(See also: Liu et al., PRD 2016)

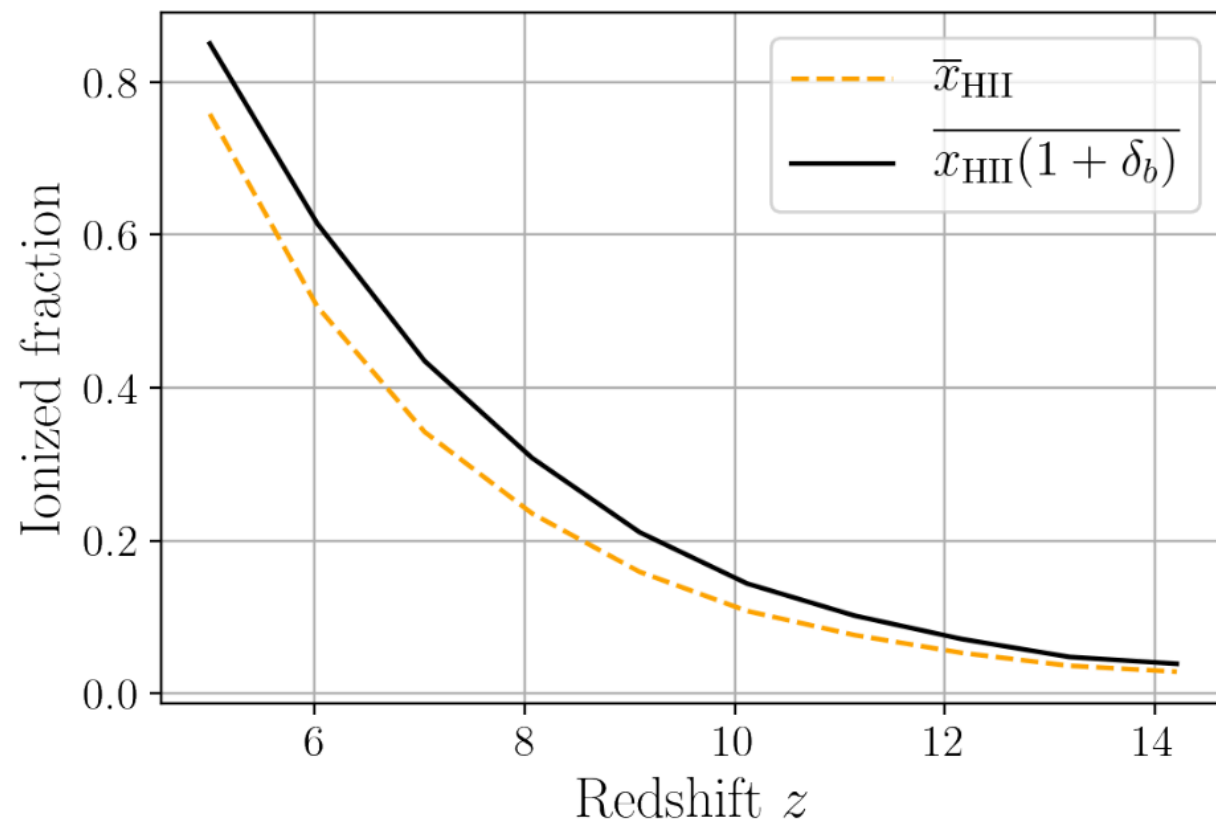


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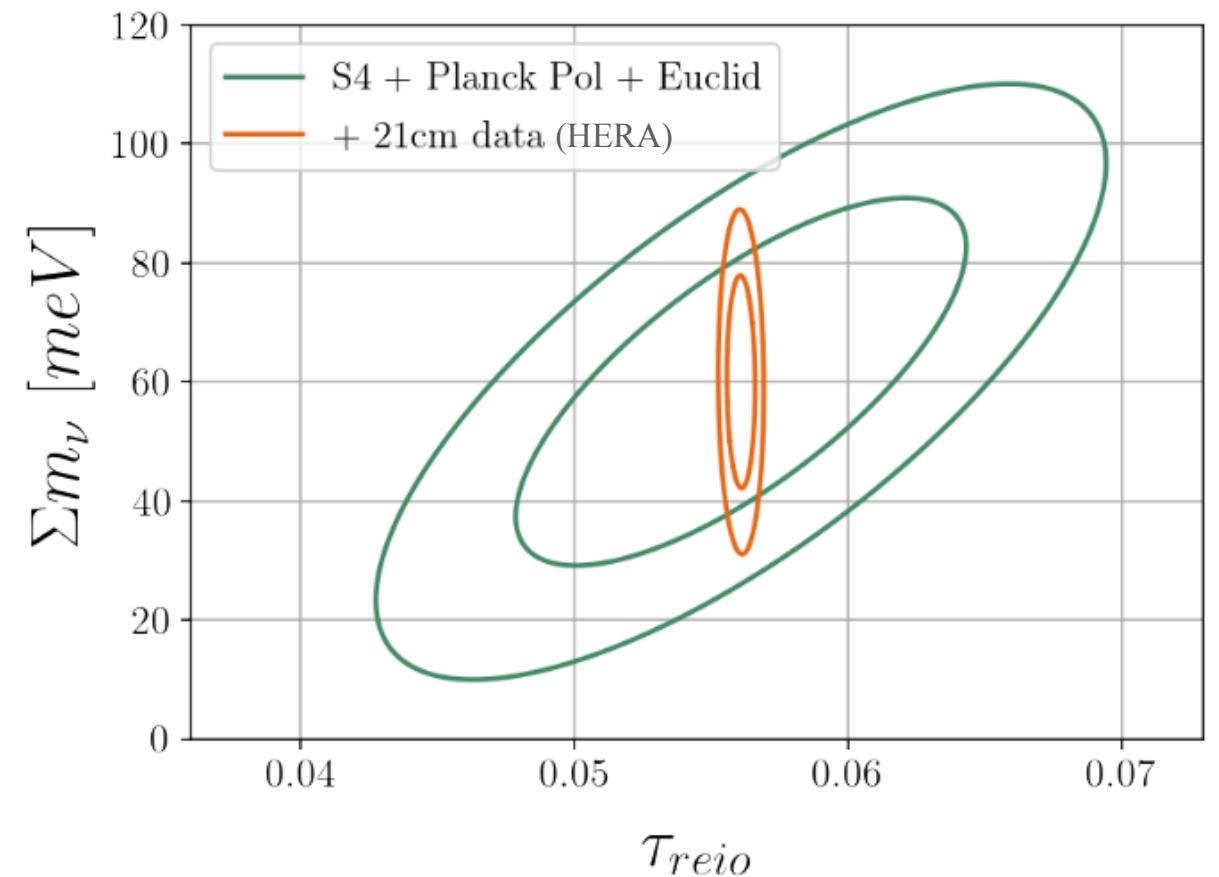
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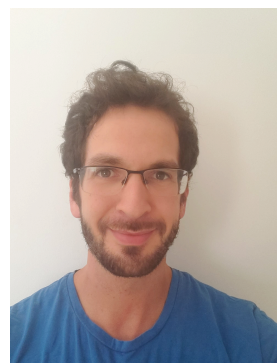
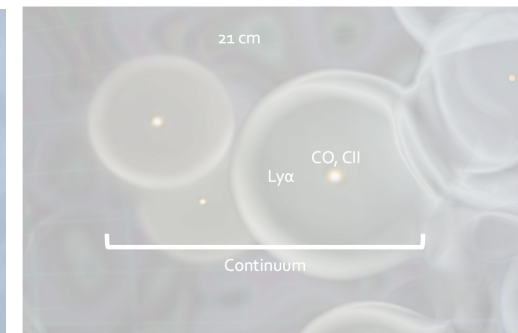
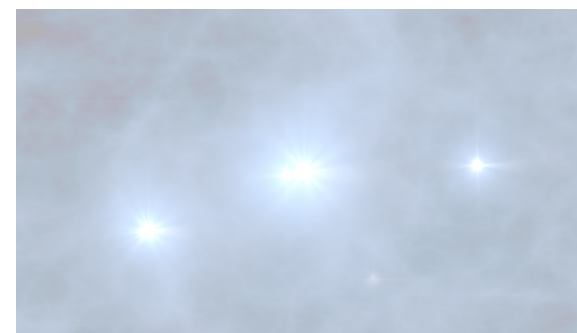
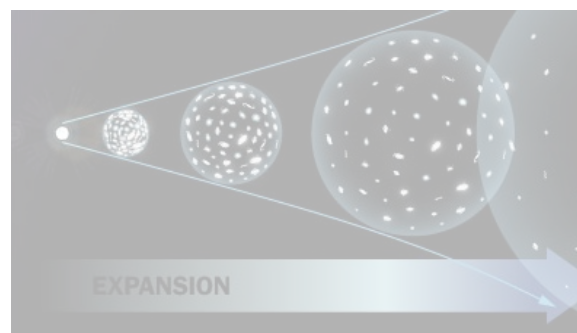
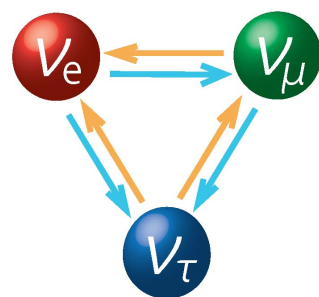
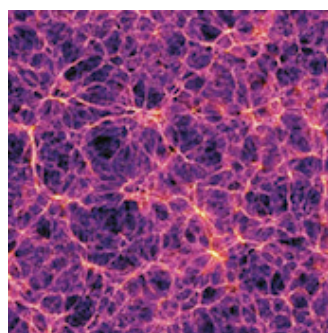
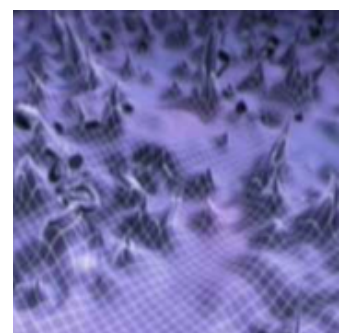
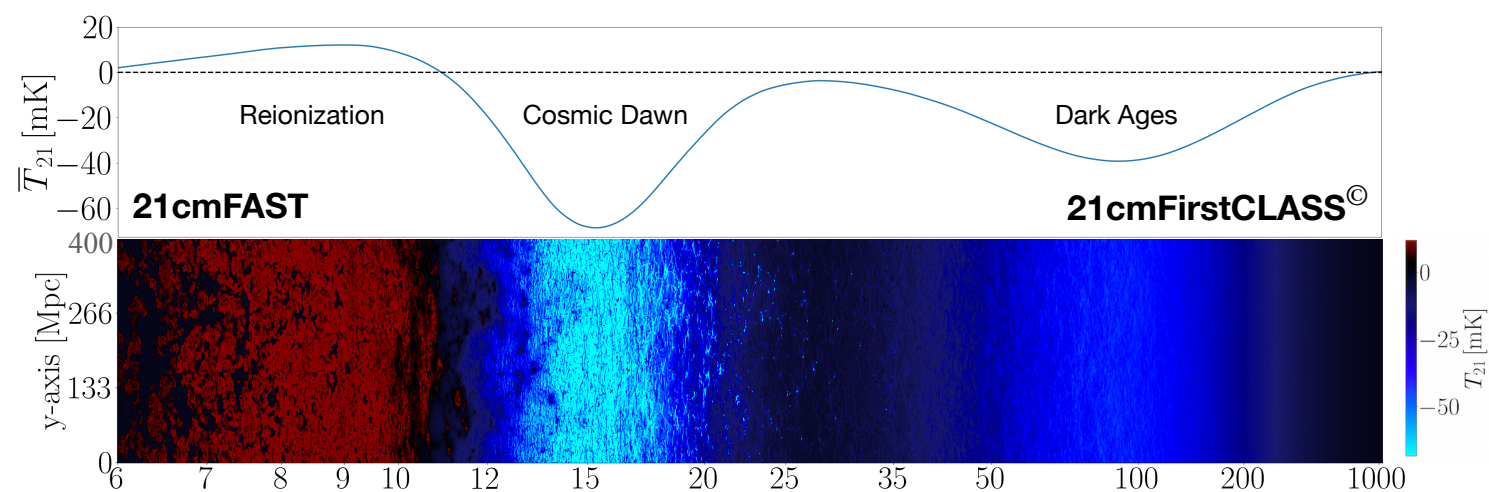
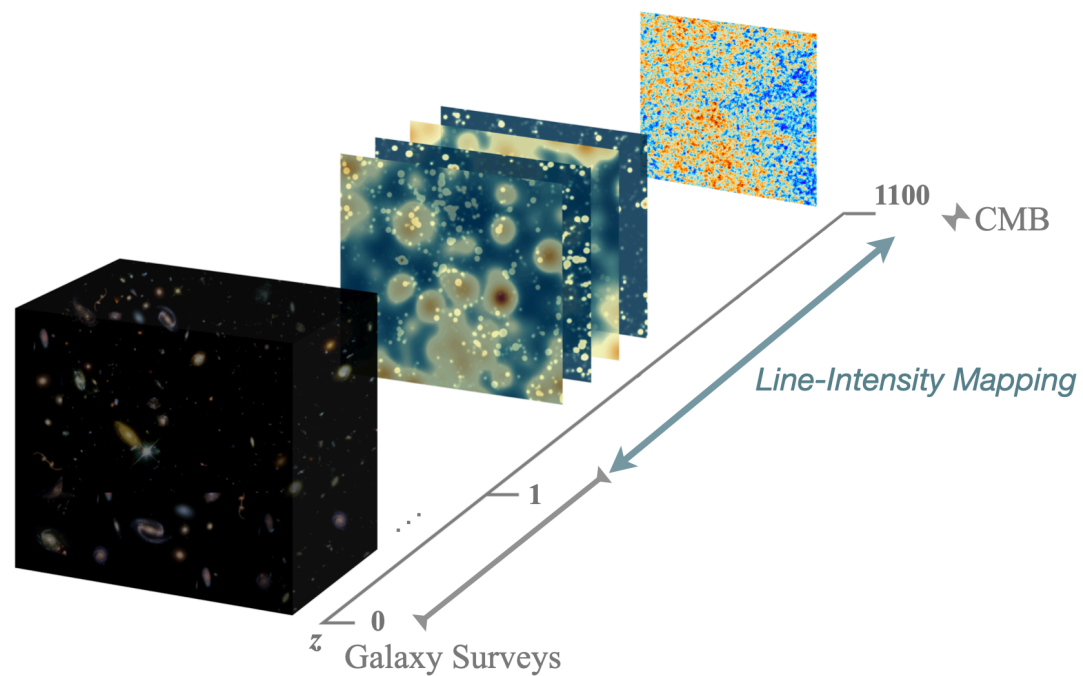
Parameter	Fiducial Value	S4 _{ℓ>50} +Euclid + <i>Planck</i> Pol	+ <i>P</i> ₂₁ (<i>k</i>) +21 cm τ
H_0	67.66	± 0.18	± 0.09
$\Omega_b h^2$	0.02242	± 0.000031	± 0.000030
$\Omega_c h^2$	0.11933	± 0.00032	± 0.00011
$\ln(10^{10} A_s)$	3.047	± 0.0078	± 0.0009
n_s	0.9665	± 0.0015	± 0.0013
τ	0.056	± 0.0043	$\pm \mathbf{0.00035}$
Σm_ν [meV] ...	60	± 16.2	$\pm \mathbf{11.8}$



A lot to look forward to!

Ely Kovetz

Ben-Gurion University & UT Austin (Sabbatical)



Jordan Flitter



Tal Adi



Hovav Lazare

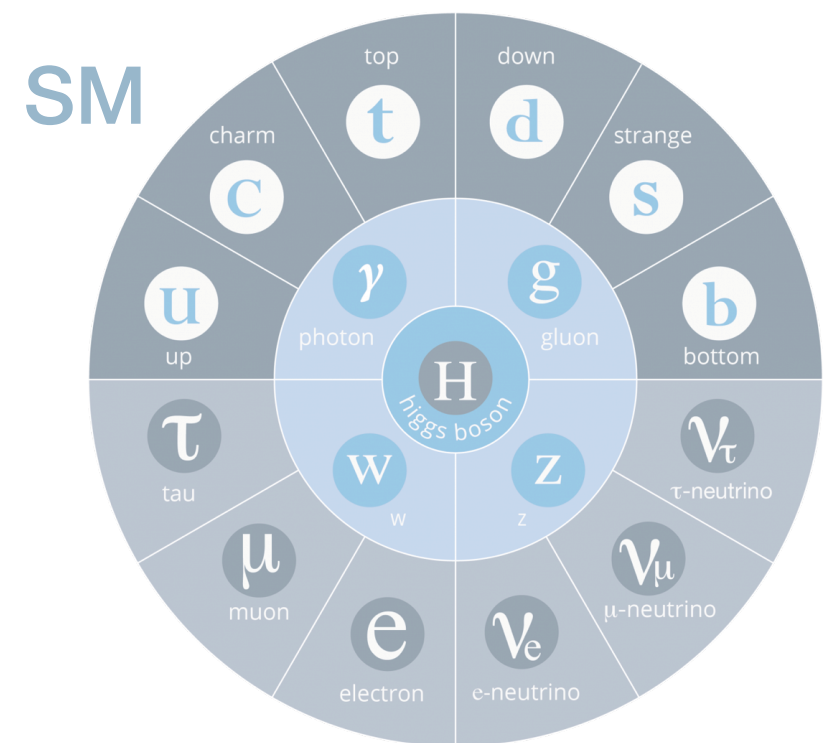
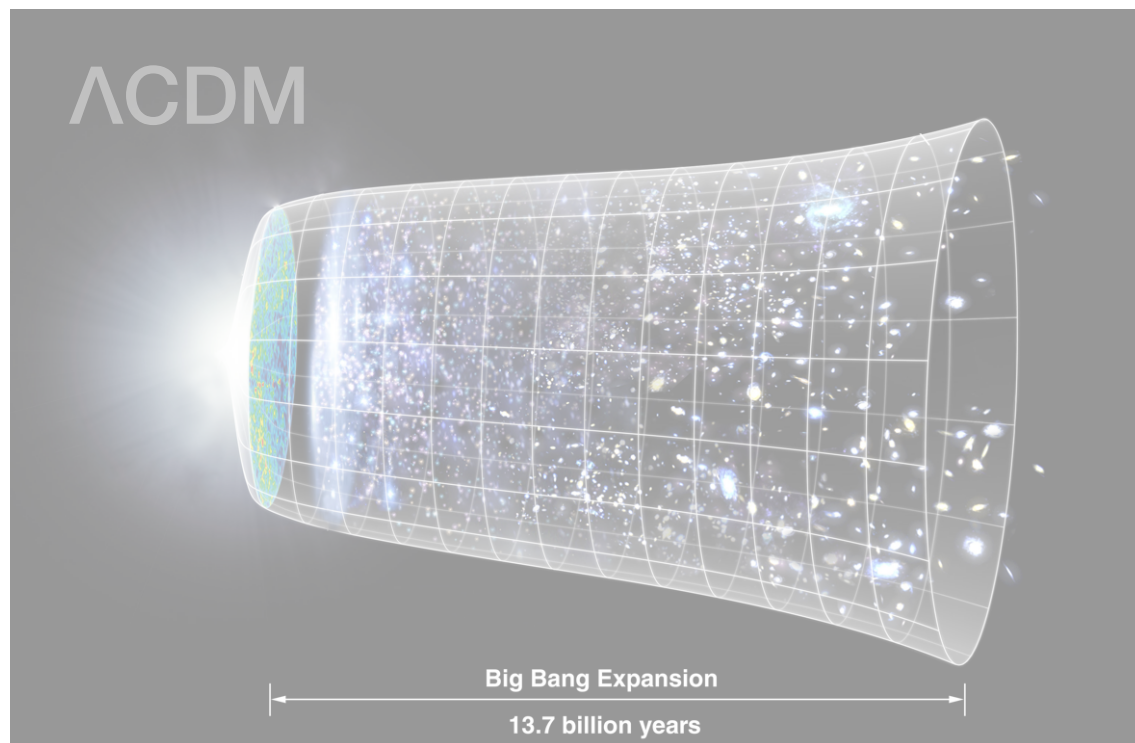


Sarah Libanore



Debanjan Sarkar

Bonus: LIM can *uniquely* probe Dark Energy



Core questions in cosmology?

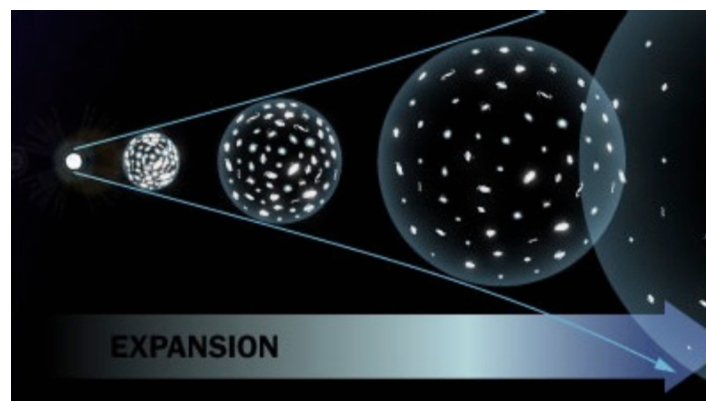
Can *cosmology* weigh in?



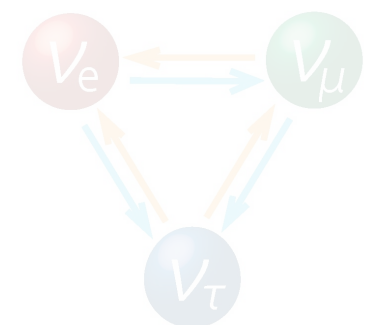
Inflation



Dark Matter



Dark Energy



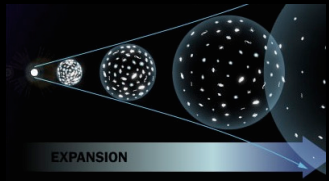
Neutrino masses

$$\phi : m_\phi, V(\phi)$$

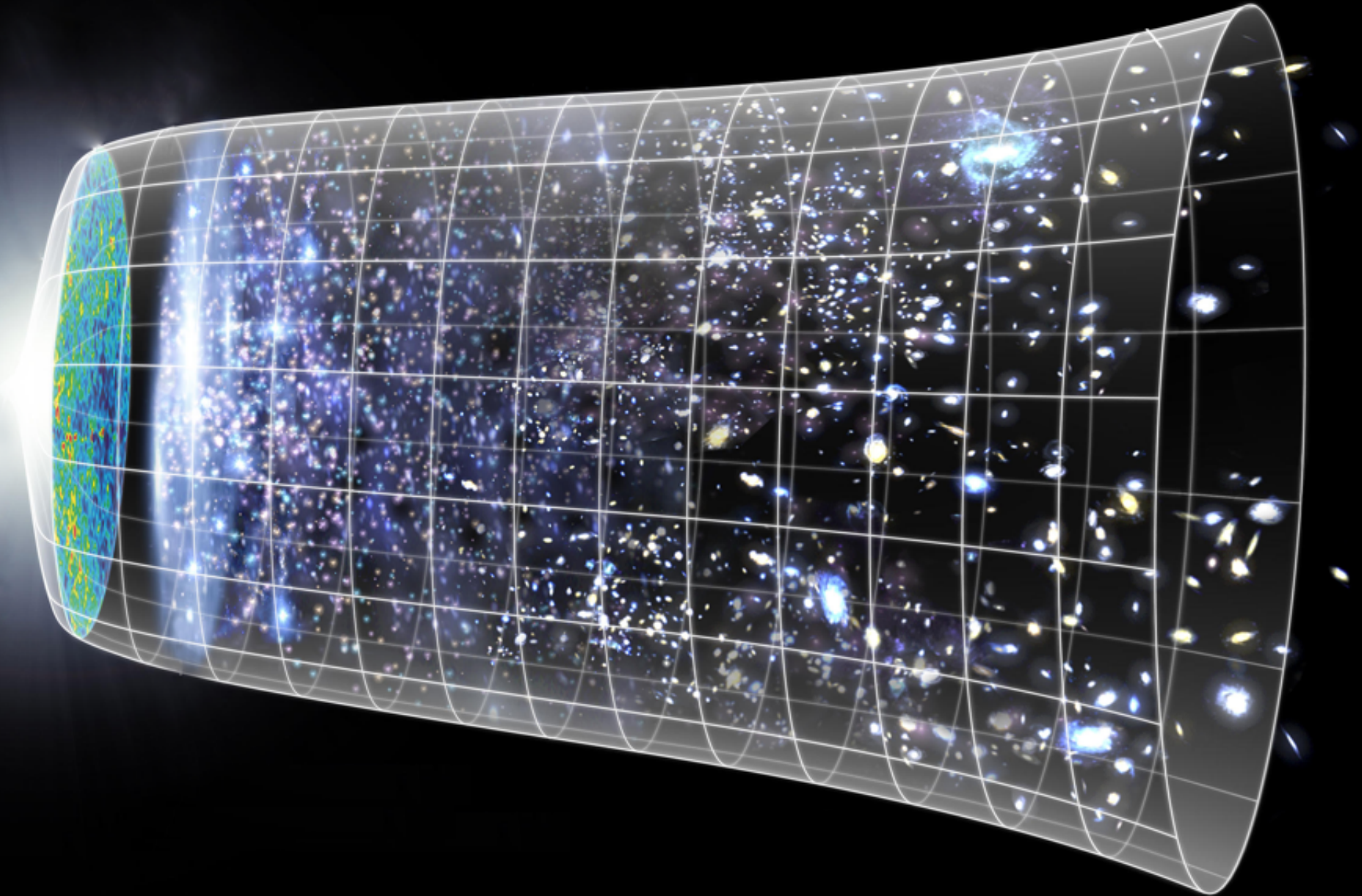
$$\chi : m_\chi, \mathcal{L}(\chi)$$

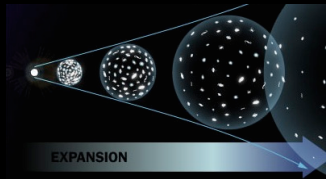
$$\Lambda ? w(a) = w_0 + (1 - a)w_a ?$$

$$\sum_{e,\mu,\tau} m_\nu \gtrsim 60 \text{ meV? } 100 \text{ meV?}$$



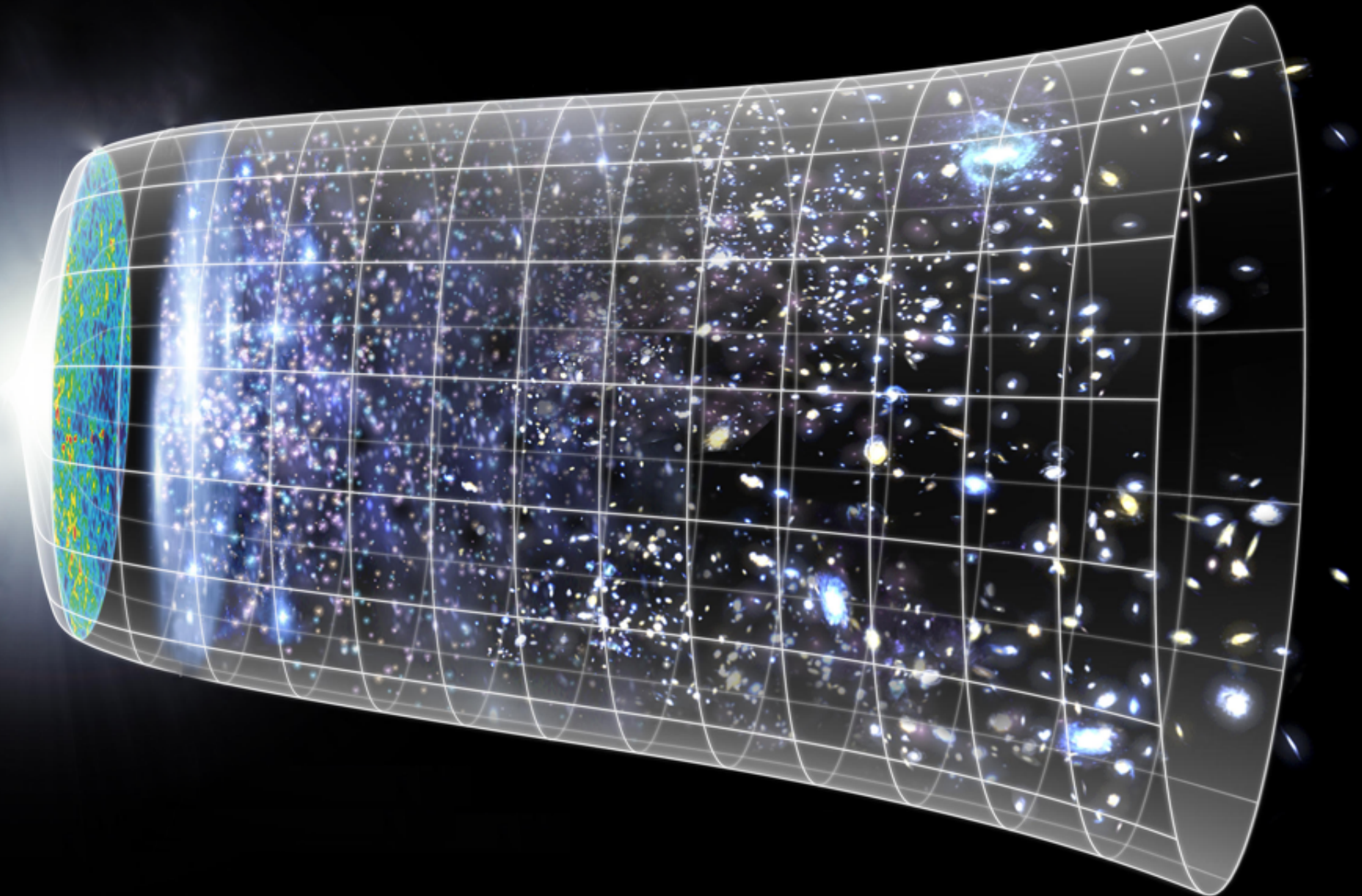
CDC Cosmology: High-z Expansion History

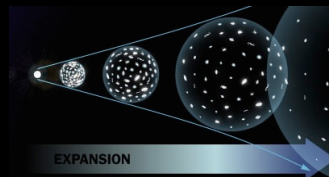




CDC Cosmology: High-z Expansion History

Structure: stars, ISM, galaxies, IGM, clusters





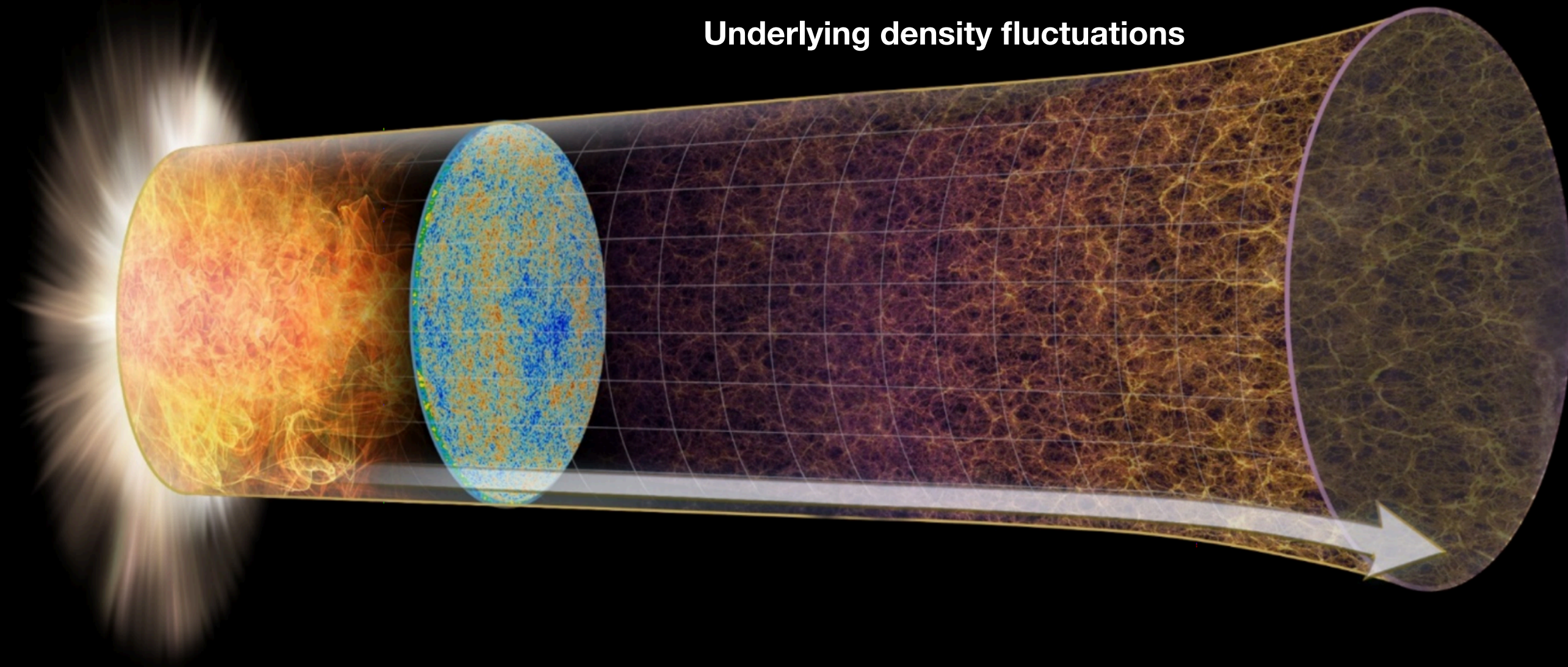
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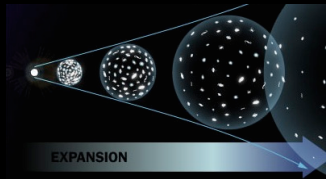
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Underlying density fluctuations

Image Credit: SPHEREx collaboration





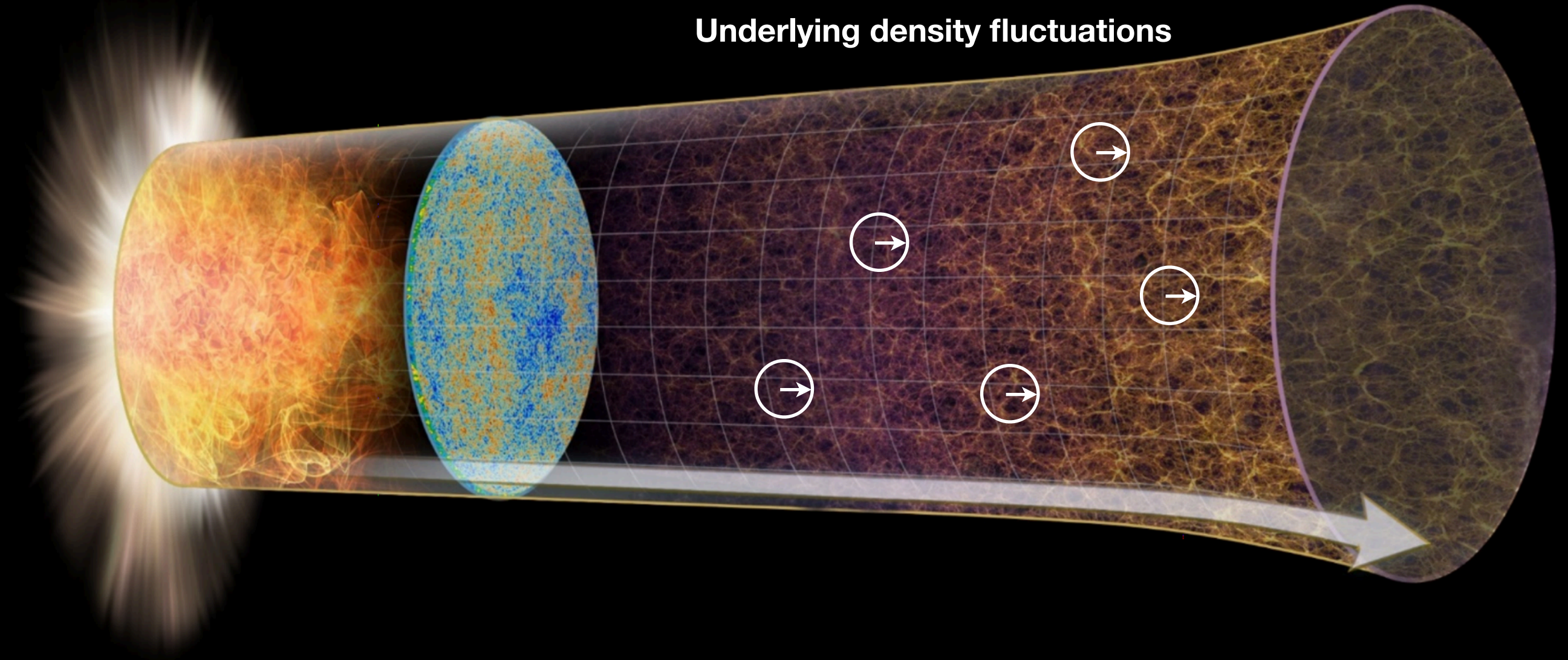
CDC Cosmology: High-z Expansion History

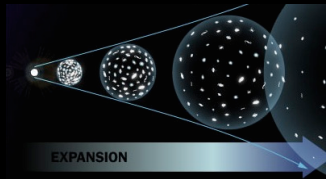
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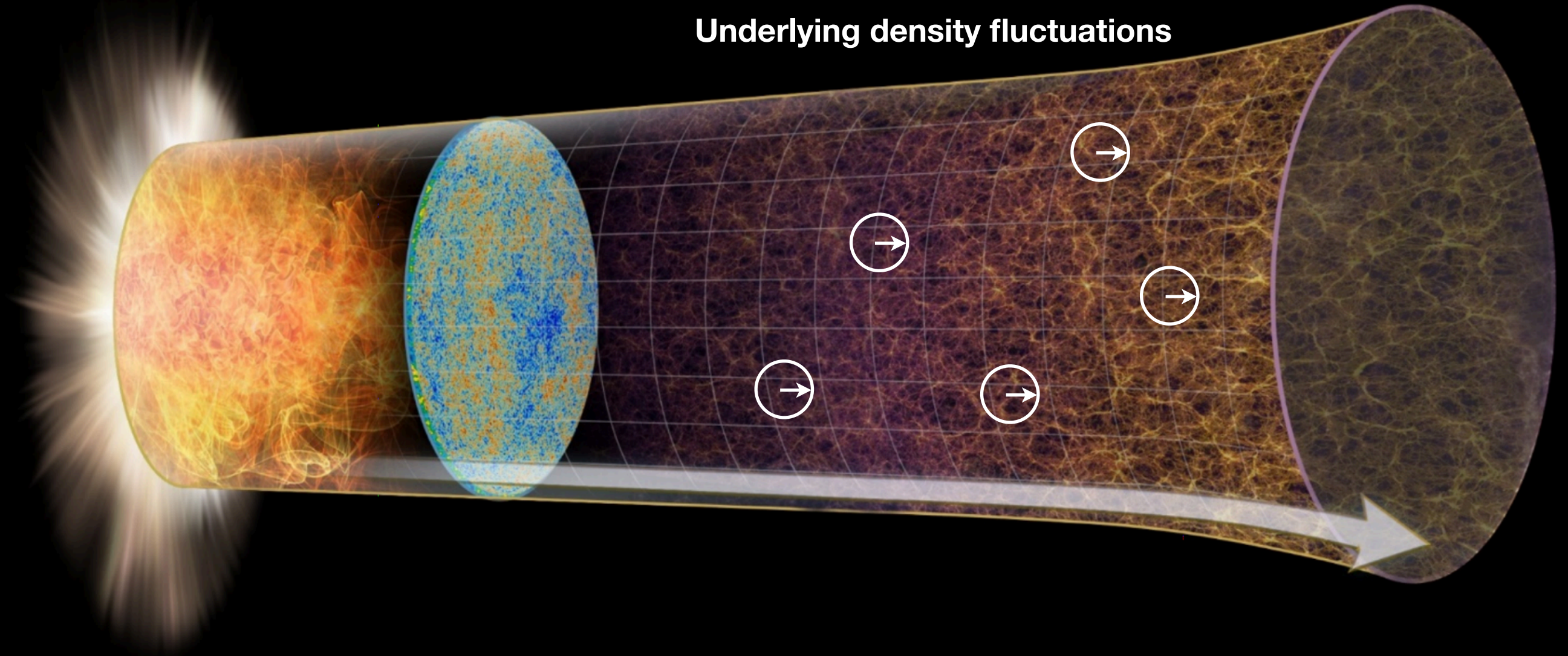
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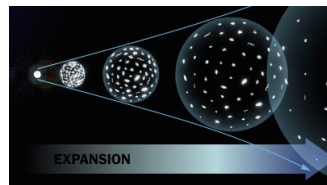
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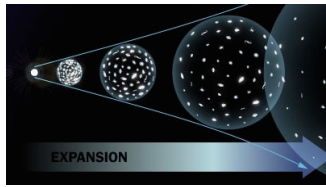


Prescription: “A User’s Guide to Extracting Cosmological Information from Line-Intensity Maps”

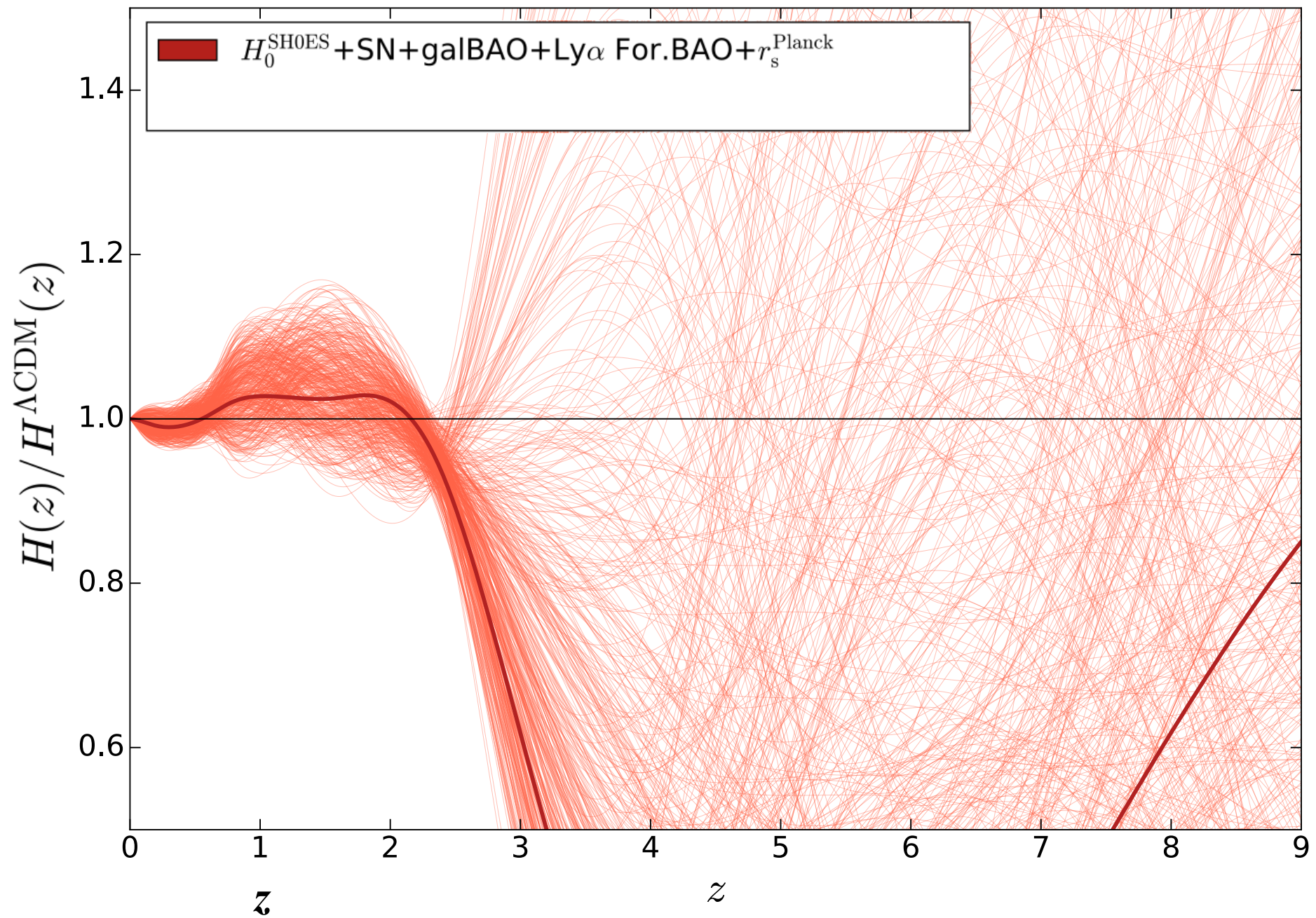
Bernal, Breysse, Gil-Marín and Kovetz, PRD 2019

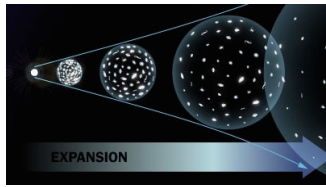


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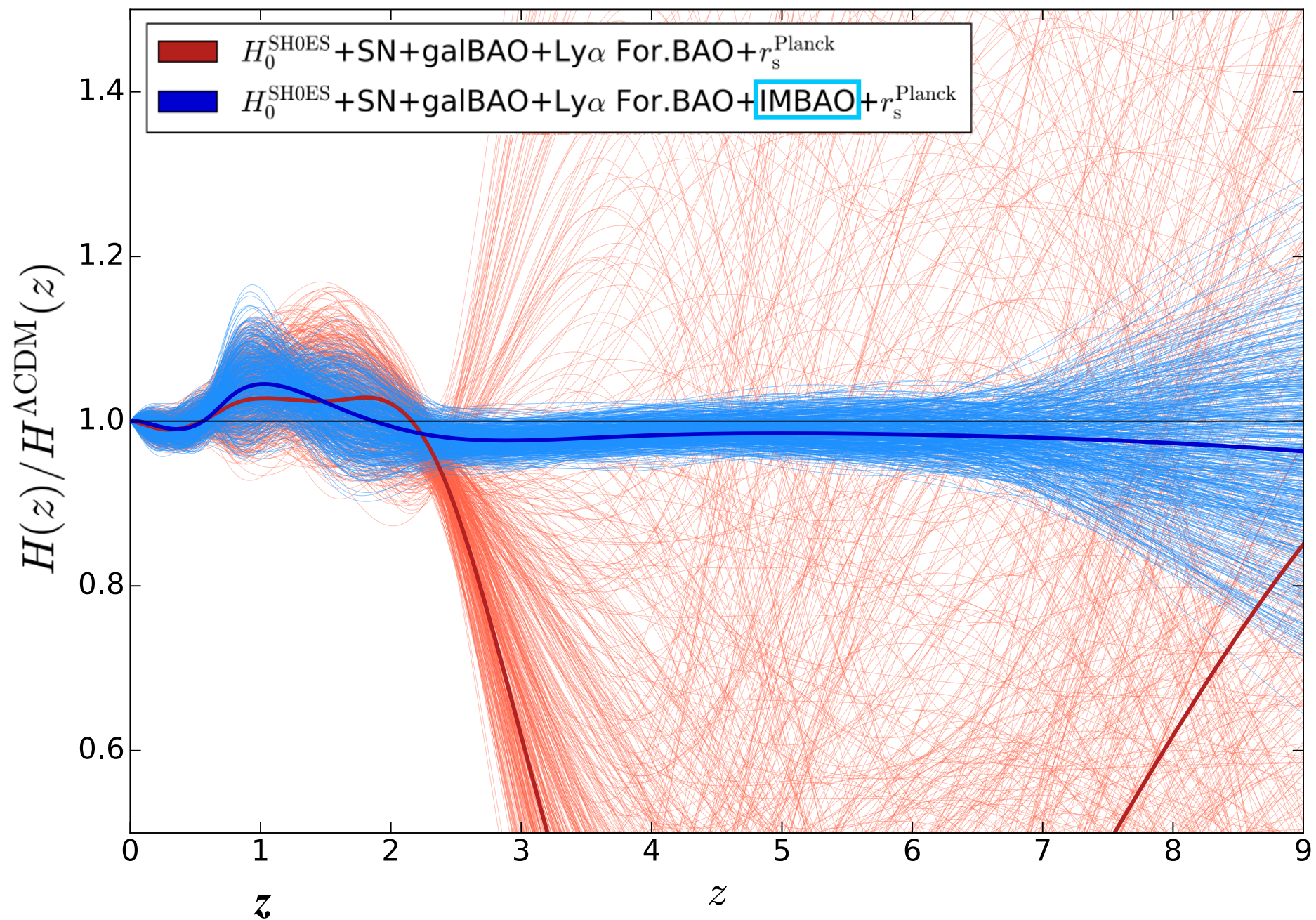


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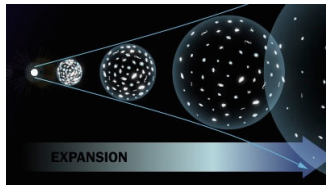




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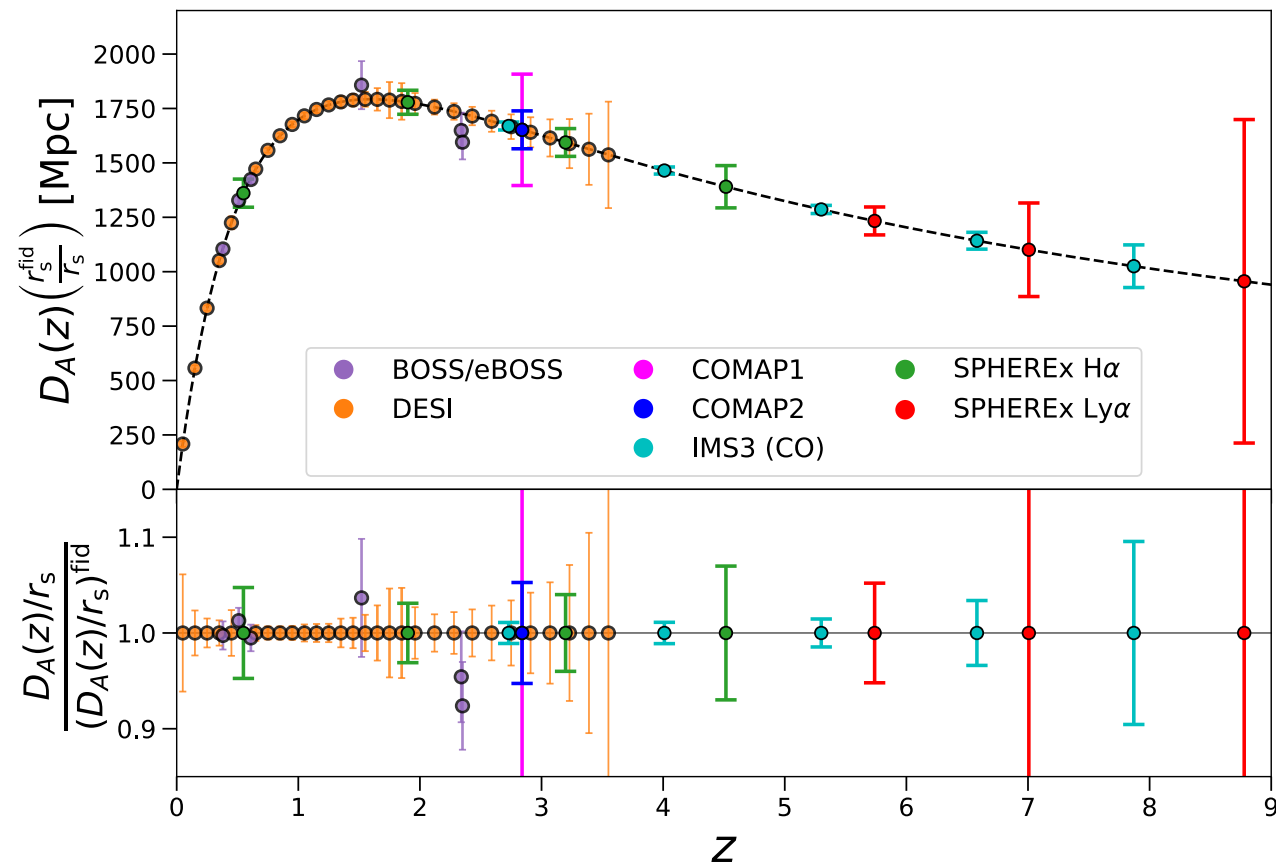


Bernal, Breysse and Kovetz, PRL 2019

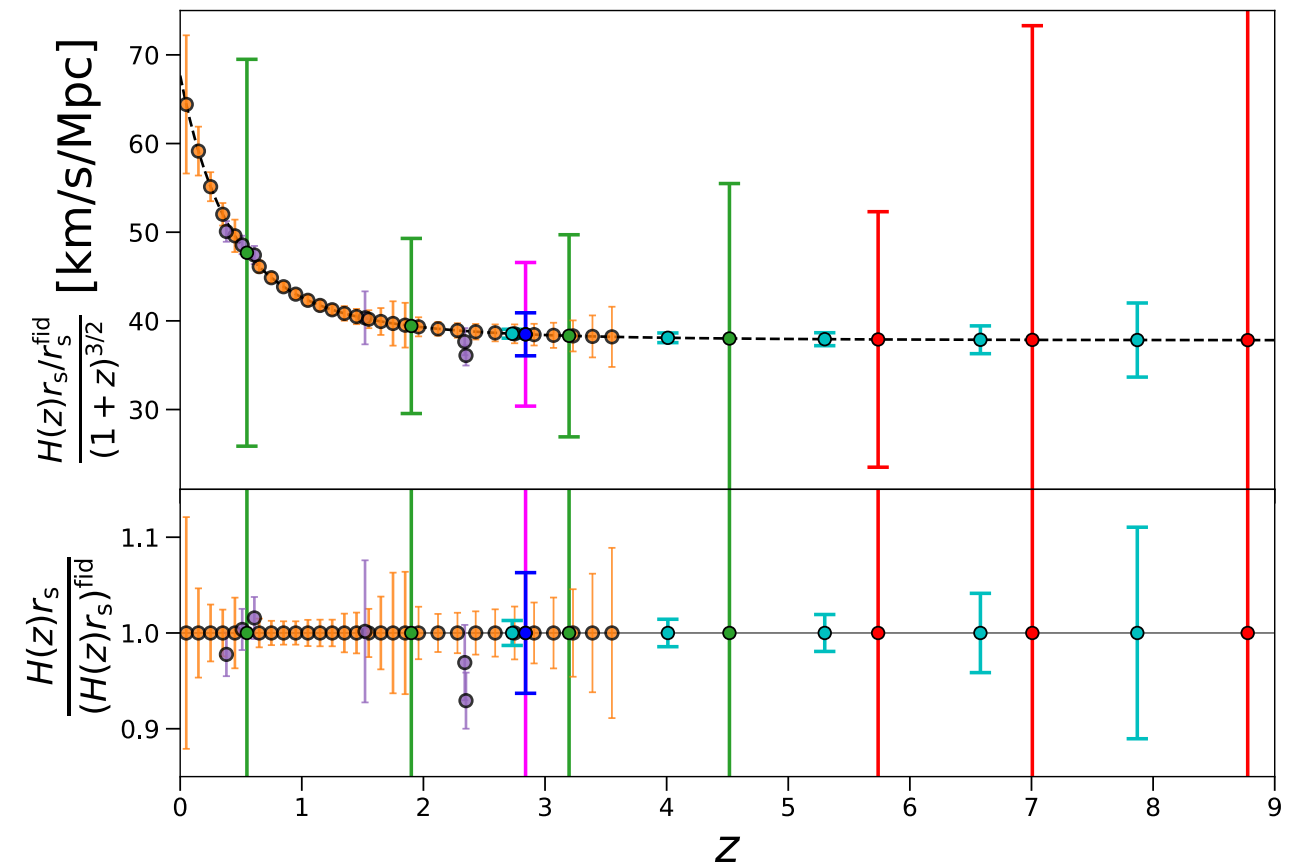


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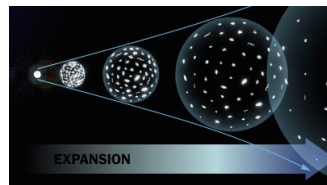
Angular diameter distance



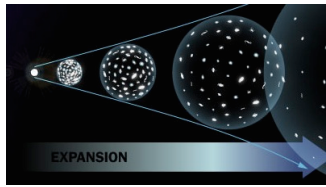
Hubble parameter



Bernal, Breysse and Kovetz, PRL 2019

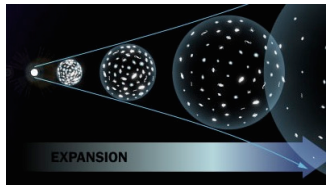


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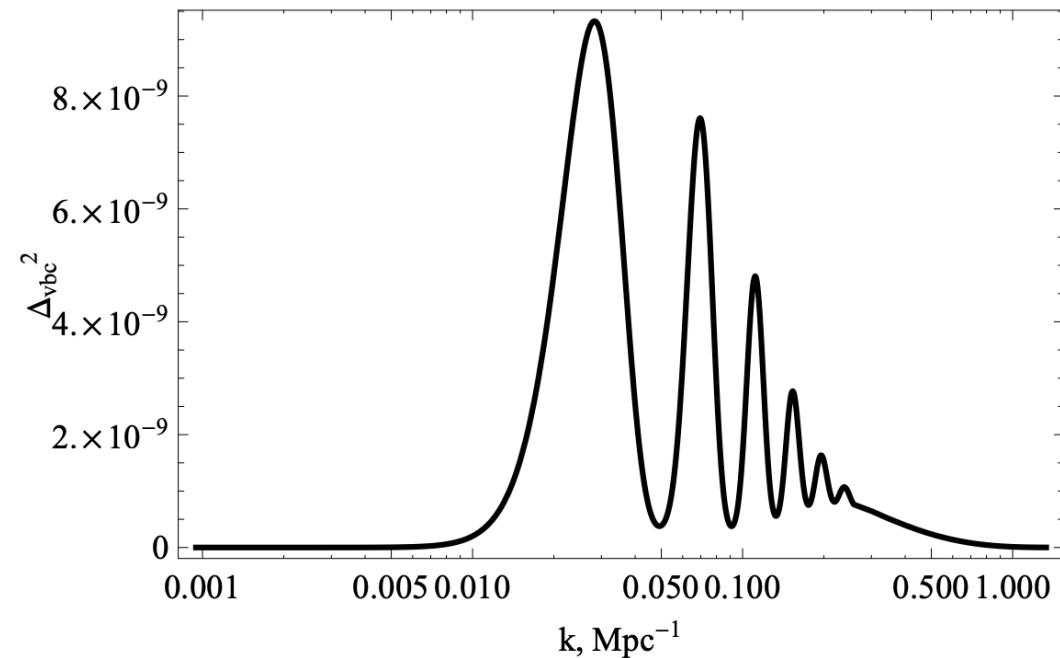
VAOs: relative velocity between DM and baryons modulates the star-formation rate.

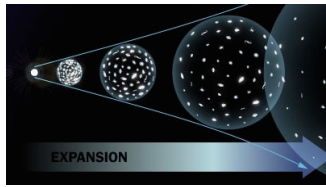


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Tseliakovich and Hirata, PRD 2010

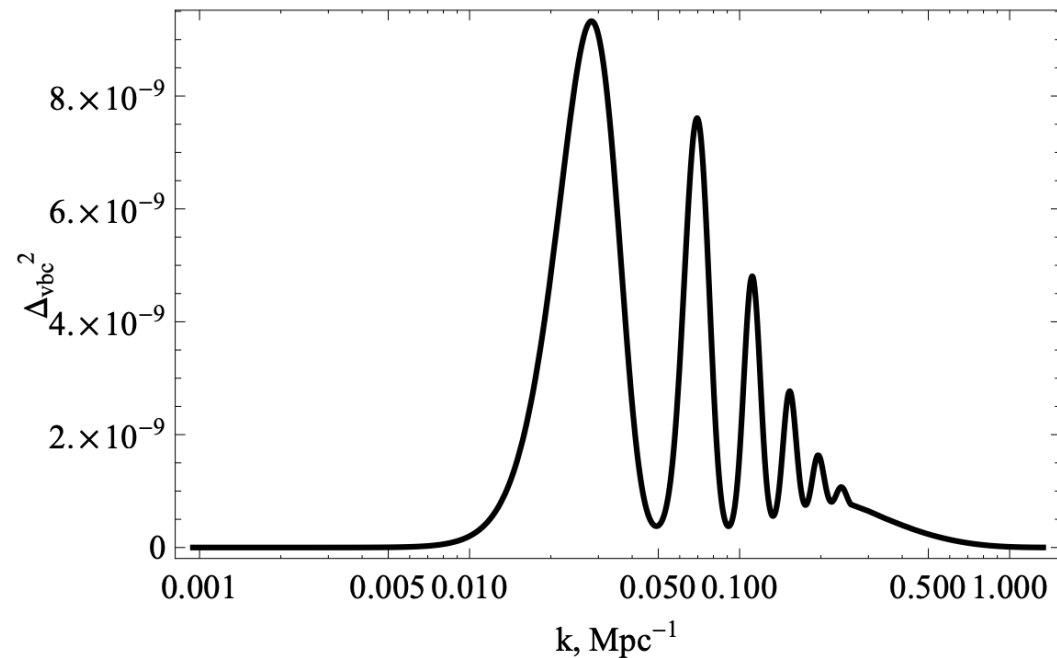




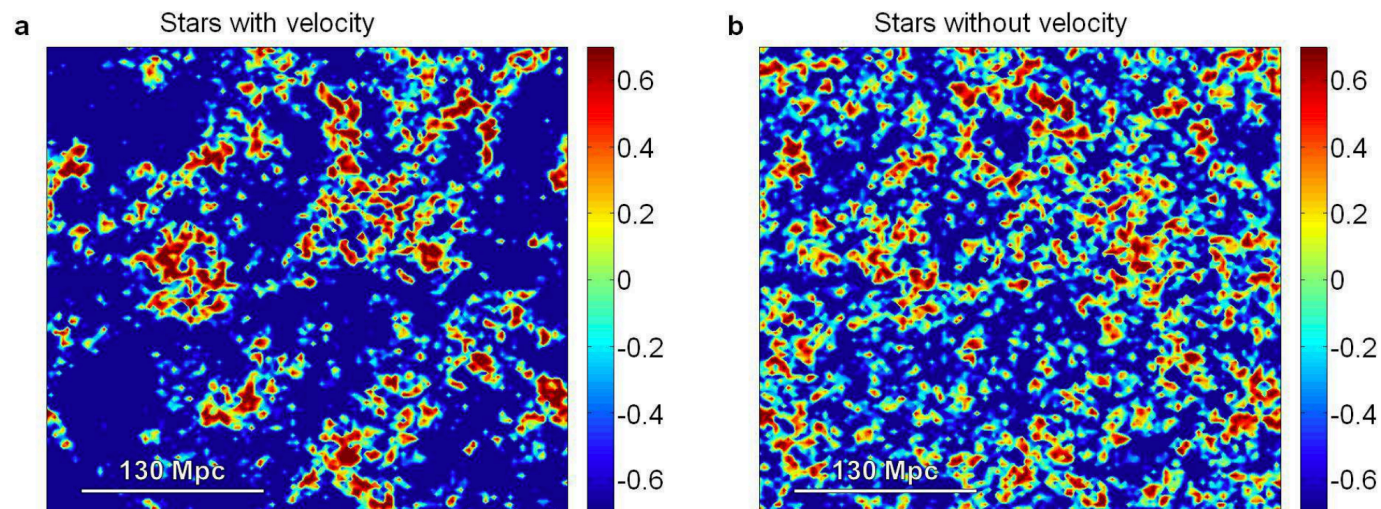
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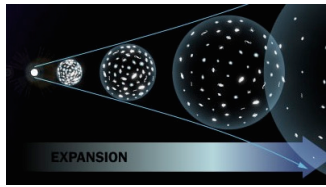
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Visbal, Barkana, Fialkov, Tseliakovich and Hirata, Nature 2012

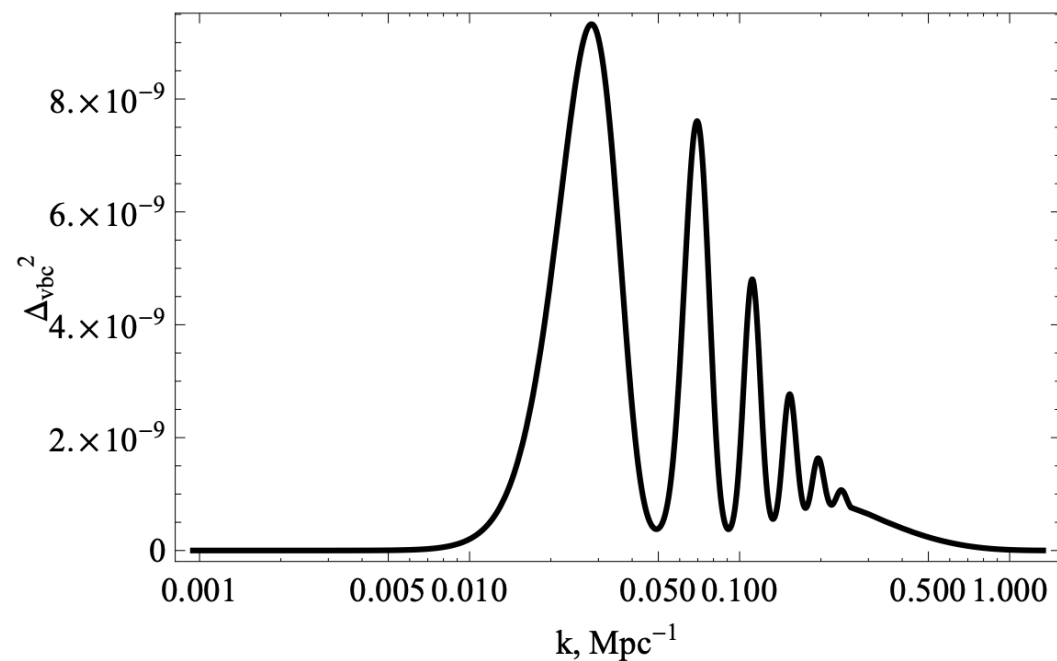




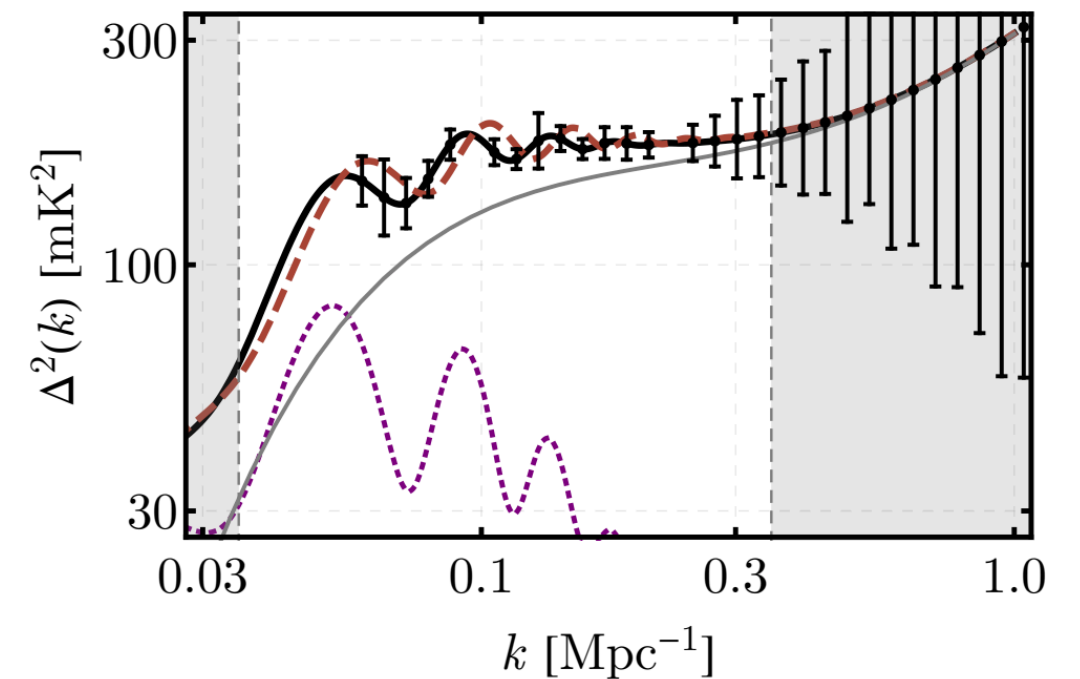
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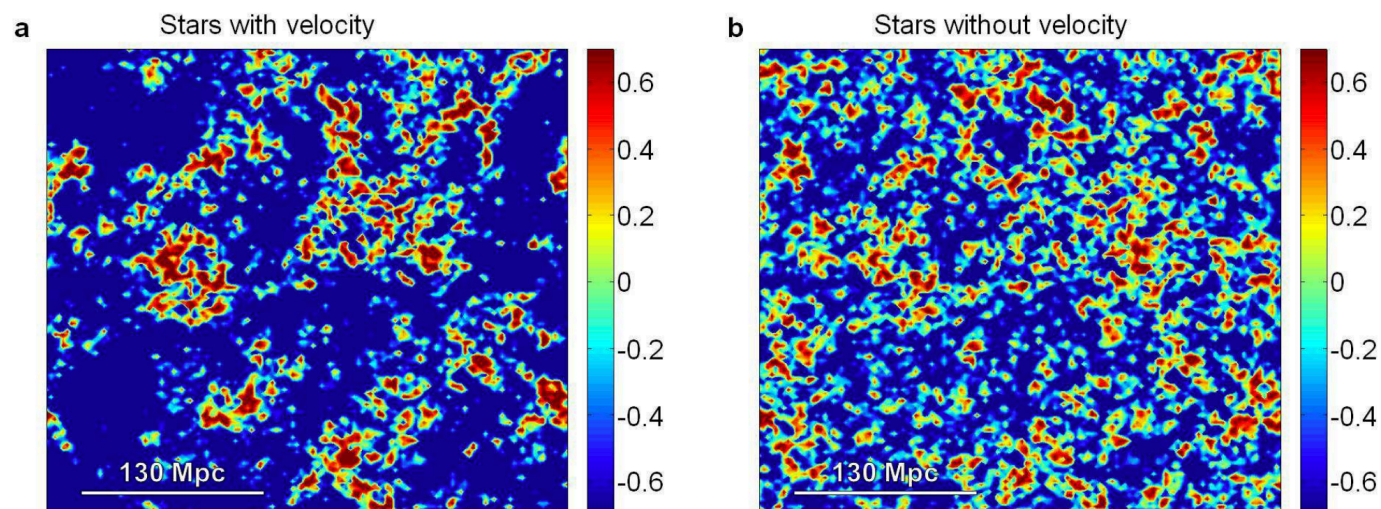
Tseliakovich and Hirata, PRD 2010

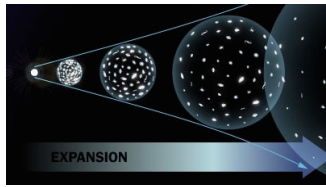


Muñoz, PRL 2019



Visbal, Barkana, Fialkov, Tseliakovich and Hirata, Nature 2012

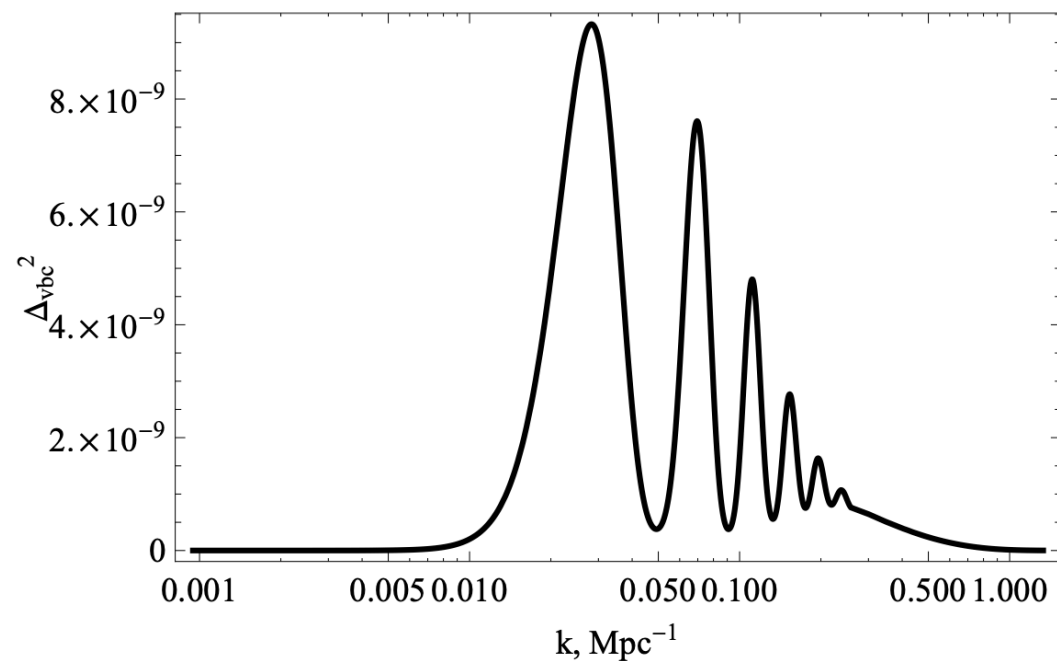




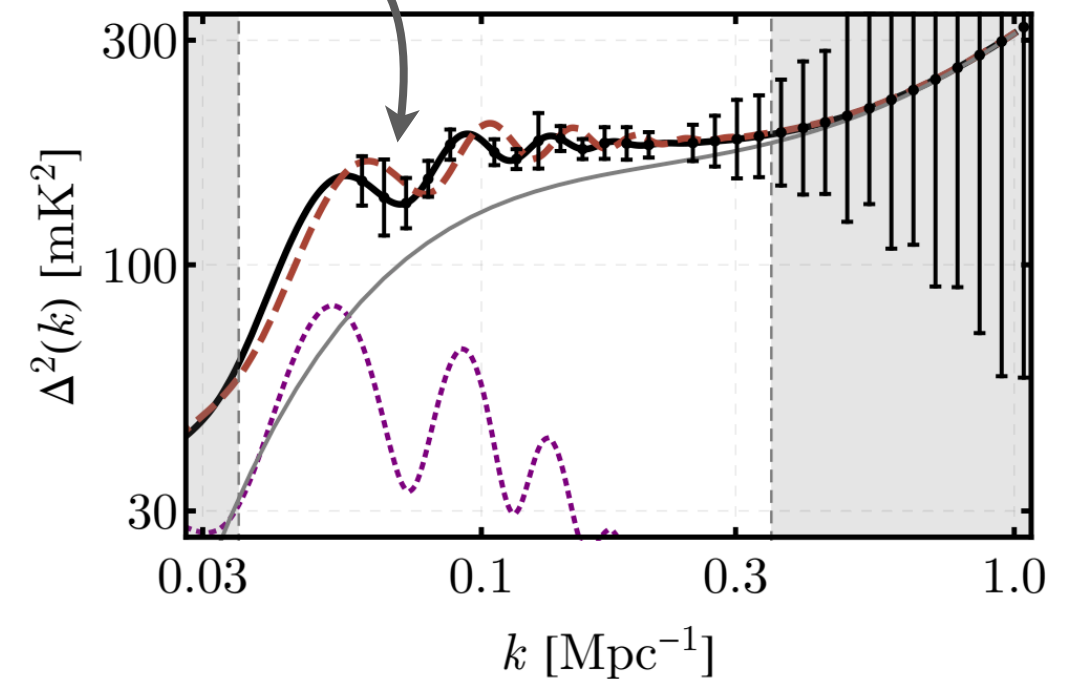
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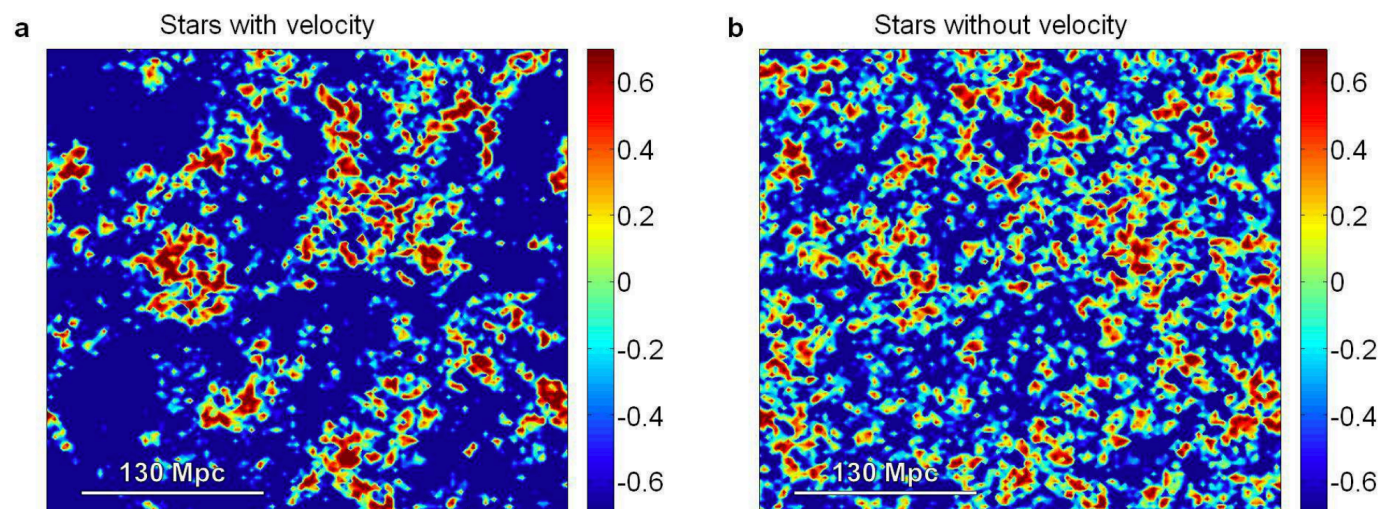
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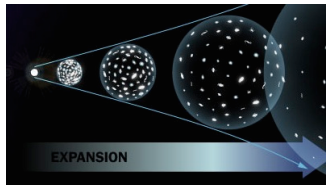


AP effect! Muñoz, PRL 2019



Visbal, Barkana, Fialkov, Tseliakovich and Hirata, Nature 2012

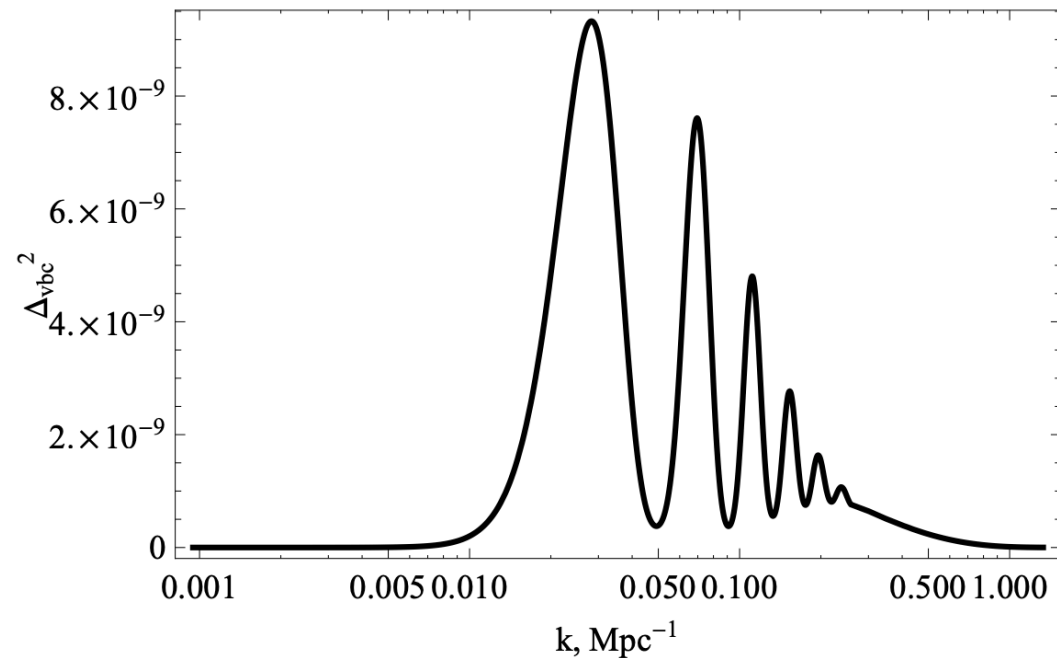




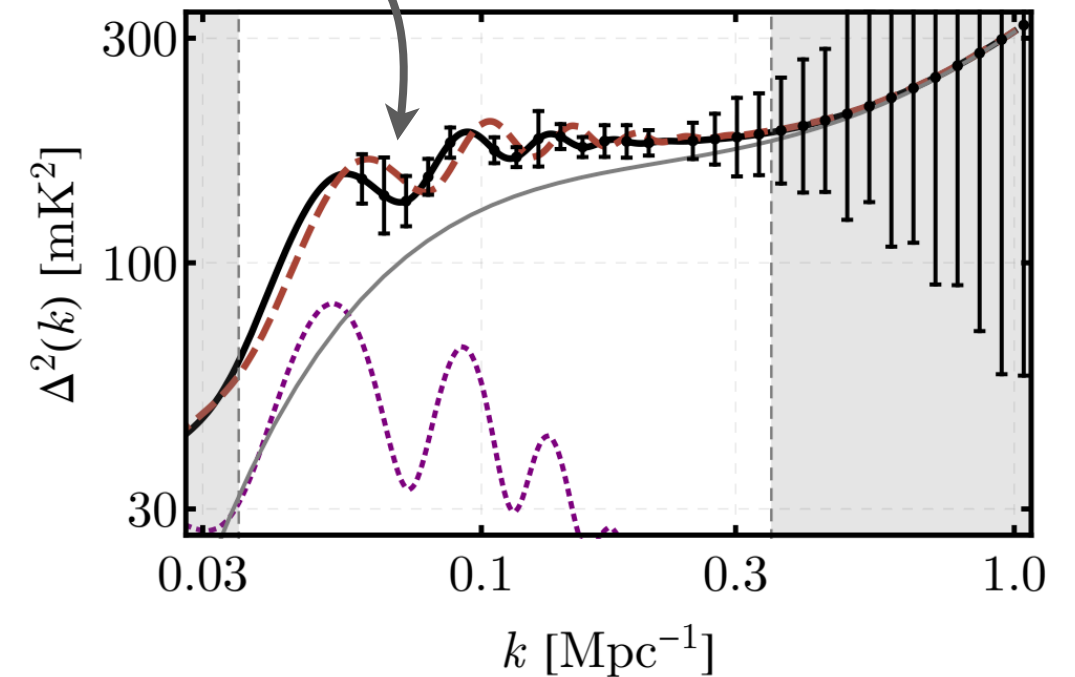
CDC Cosmology: High-z Expansion History

VAOs: relative velocity between DM and baryons modulates the star-formation rate.

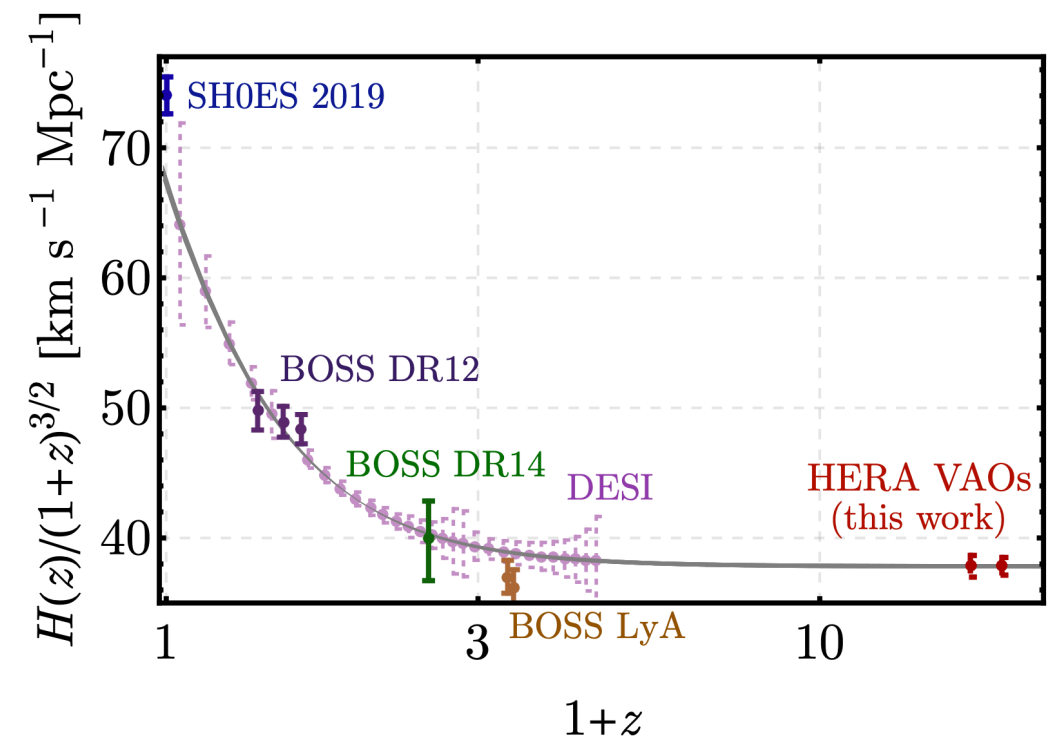
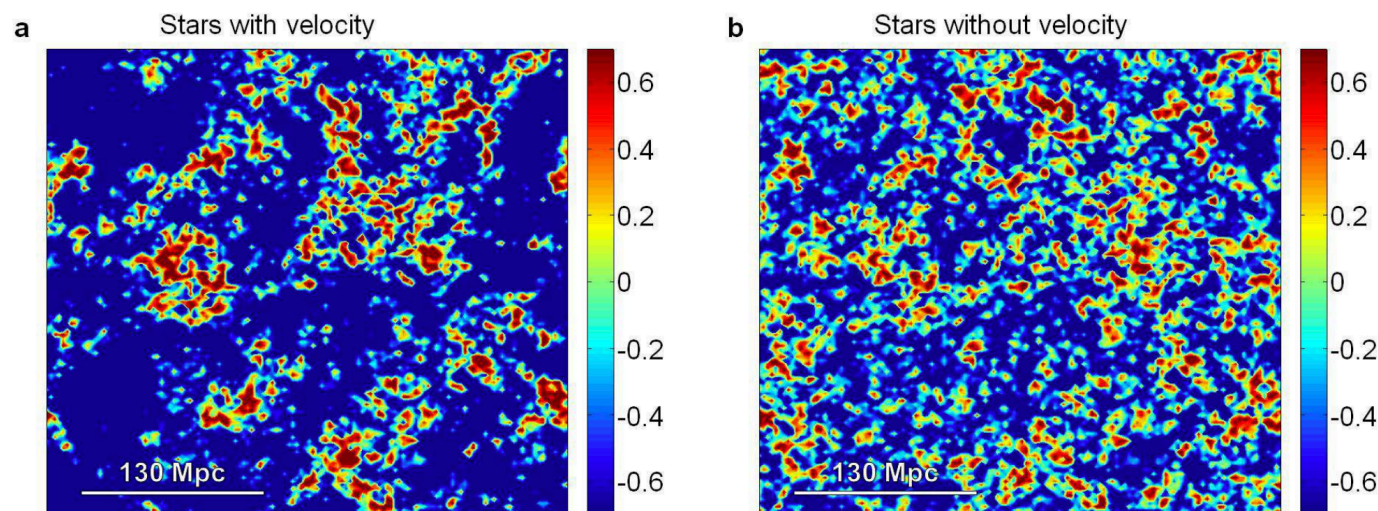
Tseliakovich and Hirata, PRD 2010

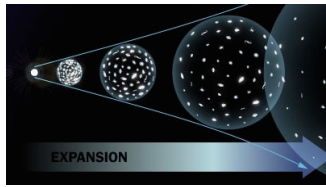


AP effect! Muñoz, PRL 2019



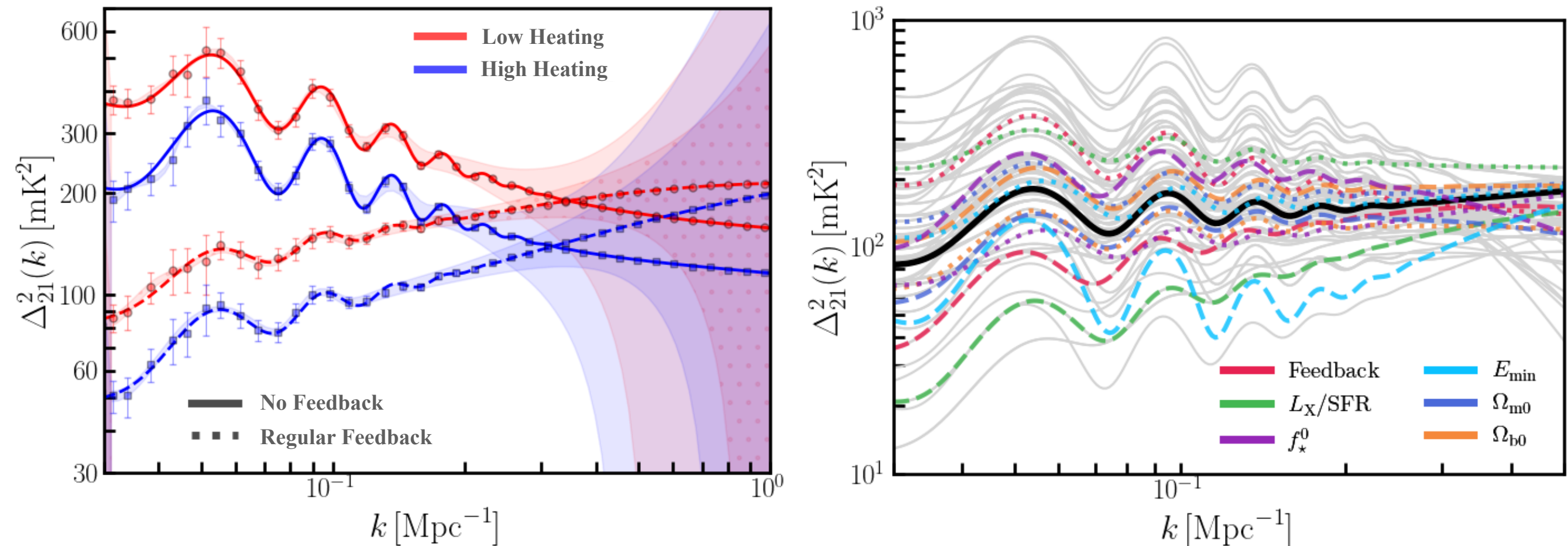
Visbal, Barkana, Fialkov, Tseliakovich and Hirata, Nature 2012





CDC Cosmology: High-z Expansion History

VAOs: relative velocity between DM and baryons modulates the star-formation rate.



Sarkar and Kovetz, PRD 2022

Expansion rate constraints:

Feedback	z_{half}	$\Delta(Hr_d)/(Hr_d)\%$		
		Optimistic	Moderate	Pessimistic
No	14.8	0.3	0.62	1.82
Low	12.7	0.51	1.14	3.51
Regular	12.2	0.73	1.51	4.62