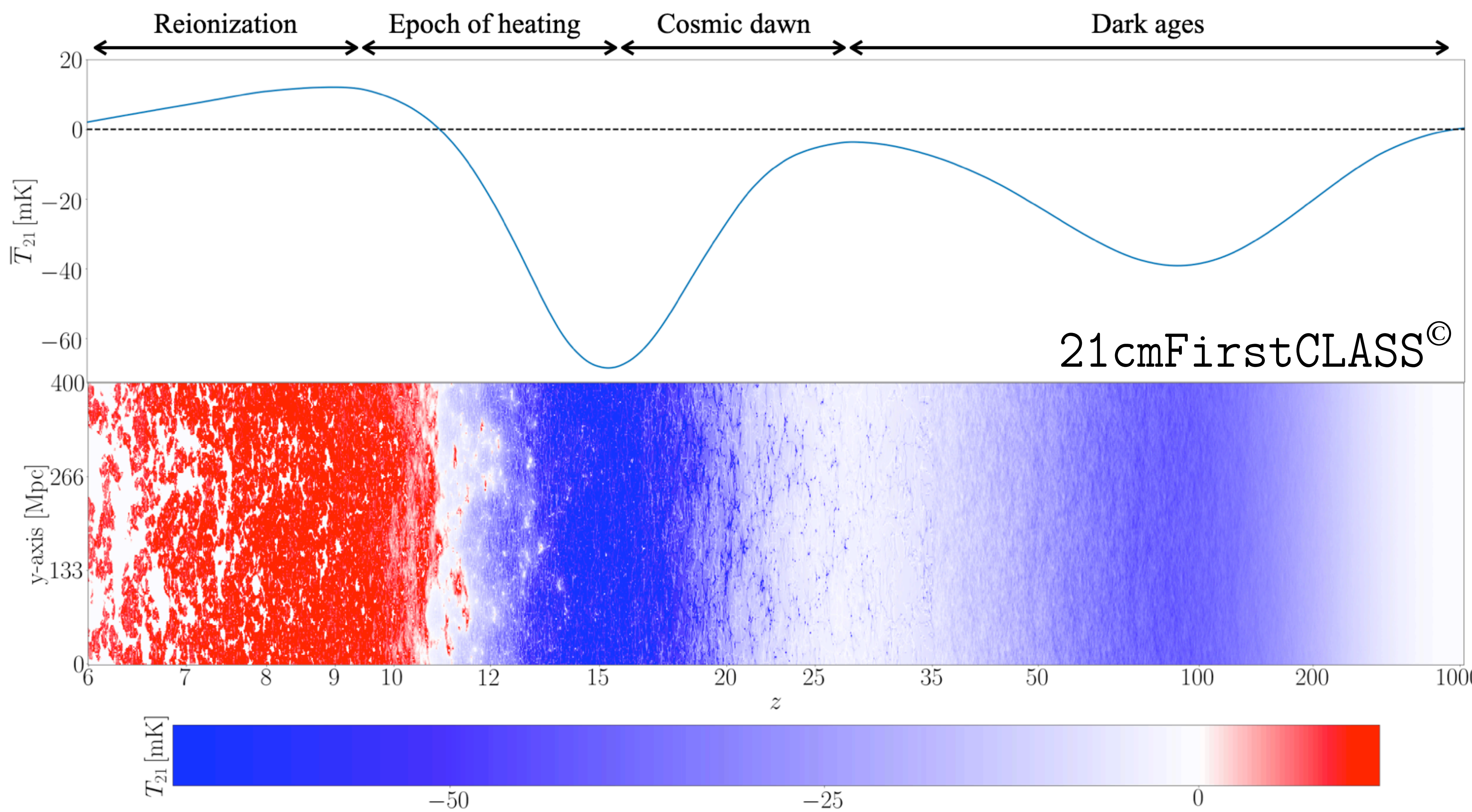
LIM*: a first-class probe of physics beyond ΛCDM

*21cm as well as other atomic/molecular lines



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Line*-intensity mapping (LIM*) is a unique probe of cosmology

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Specific examples:
- Inflation
- Dark Matter
- Dark Energy

Goals of this talk:

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There are lines *beyond* 21-cm that will(!) also be measured	Line*-intensity mapping (LIM*) is a unique probe of cosmology	Specific examples: - Inflation - Dark Matter - Dark Energy	Need to improve our simulation (public) codes with cosmology in mind

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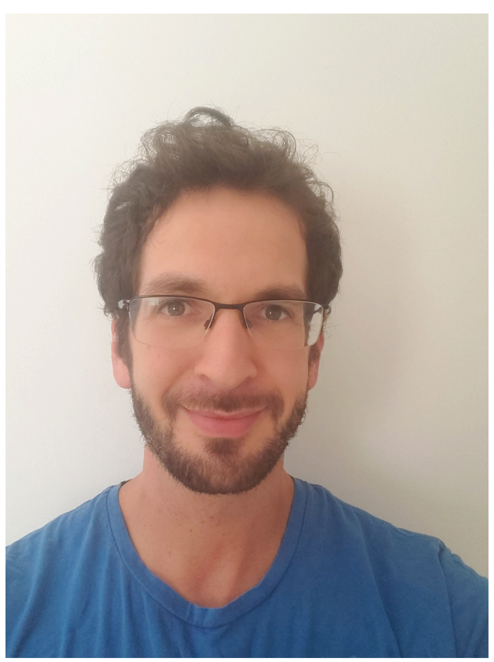

Jordan Flitter

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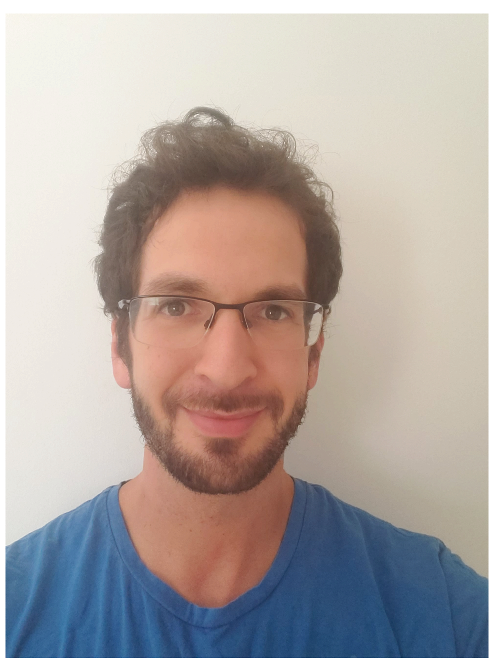
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Debanjan Sarkar


Sarah Libanore


Caner Unal

Line*-Intensity Mapping: Introduction

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Intensity mapping: 3D mapping of the specific intensity due to line emission.

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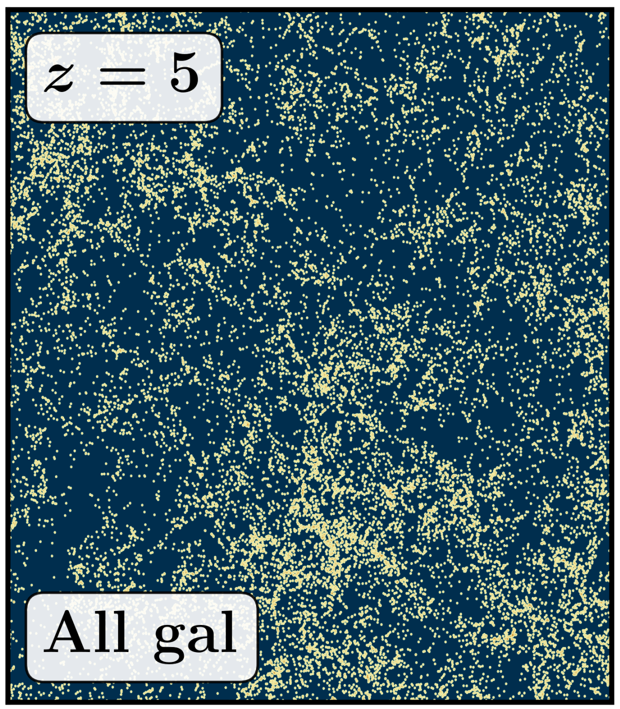

Bernal and Kovetz, arXiv:2206.15377, Astronomy and Astrophysics Review

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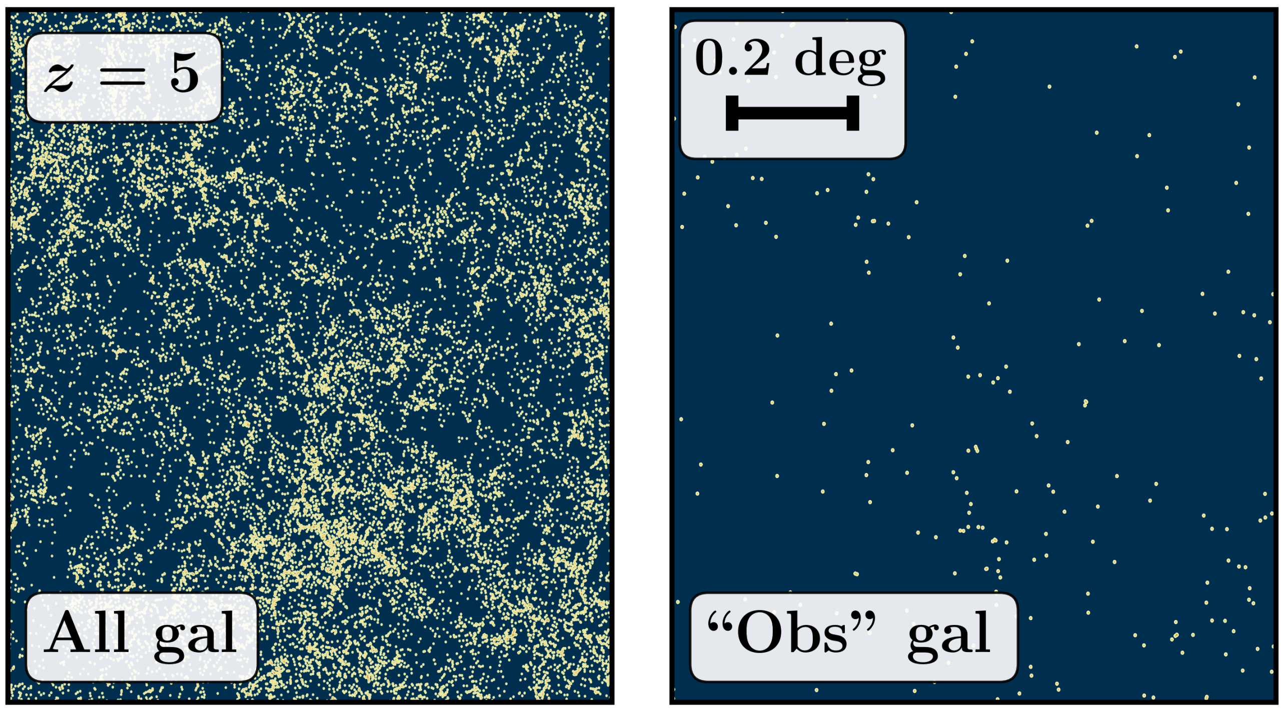

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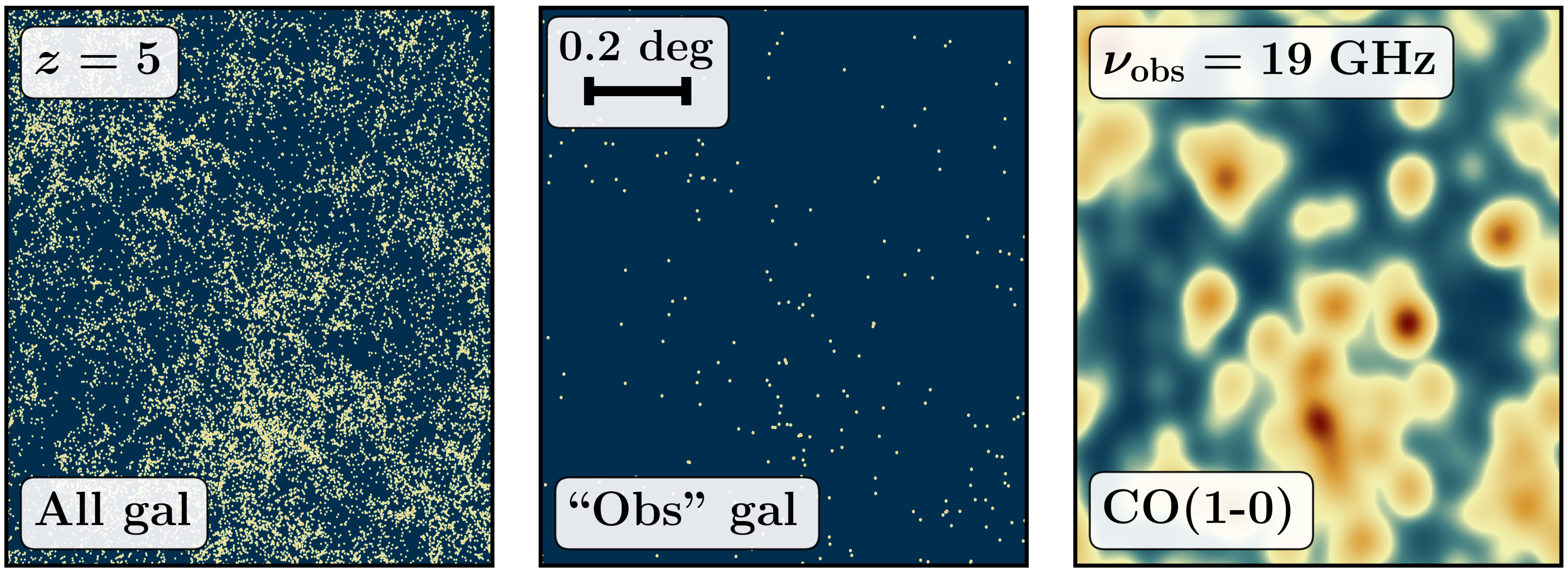

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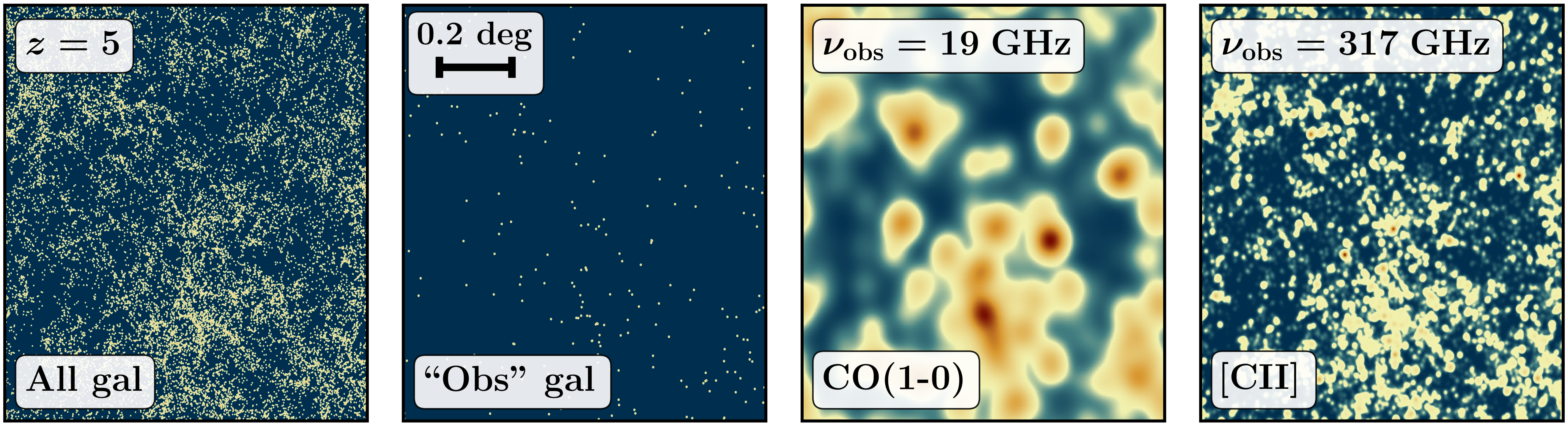

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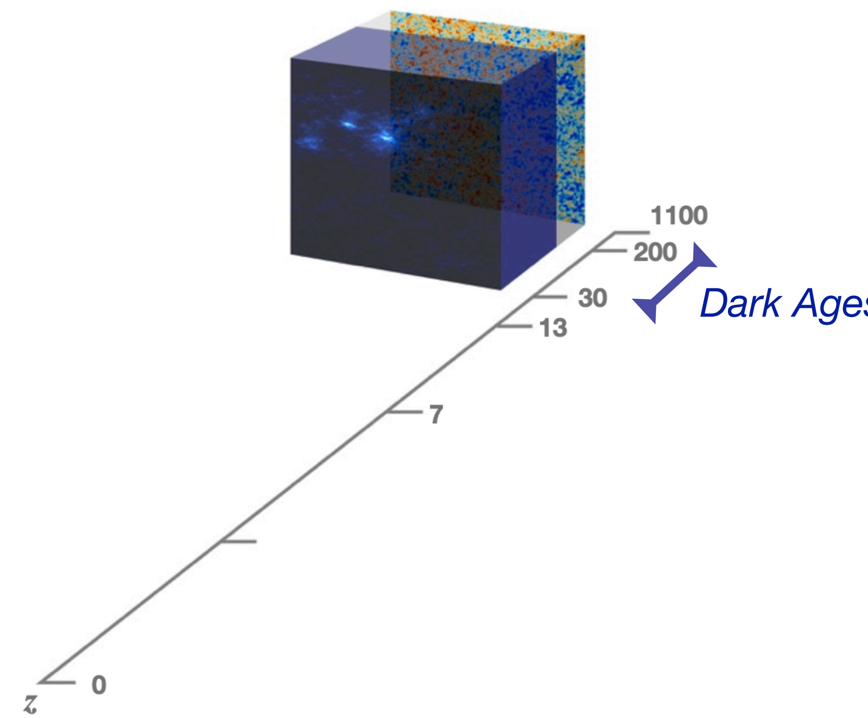
Earliest signal: CMB absorption in HI



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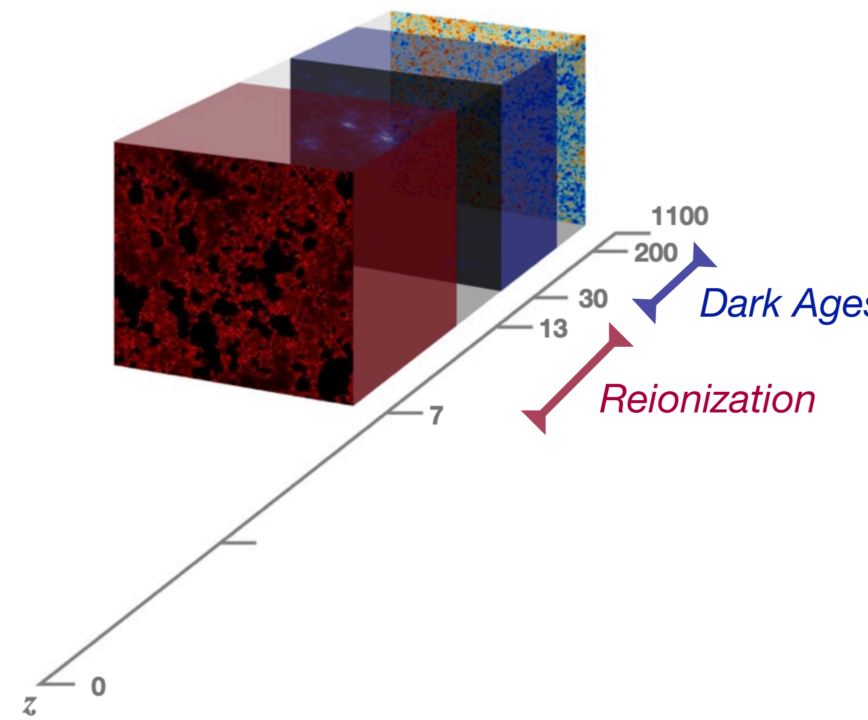

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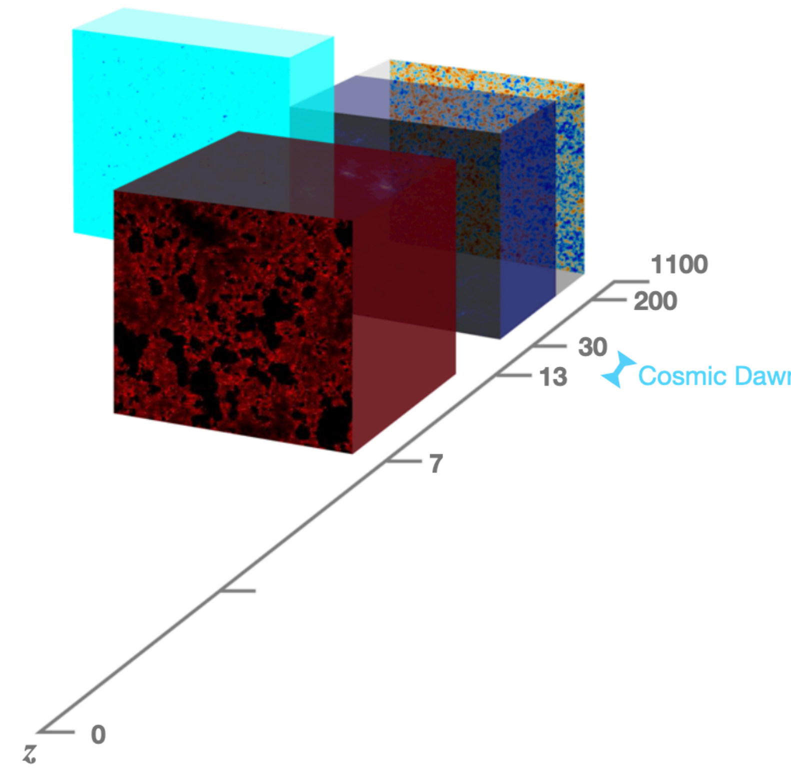
Cosmic dawn: signal turns on via Lyα from first stars



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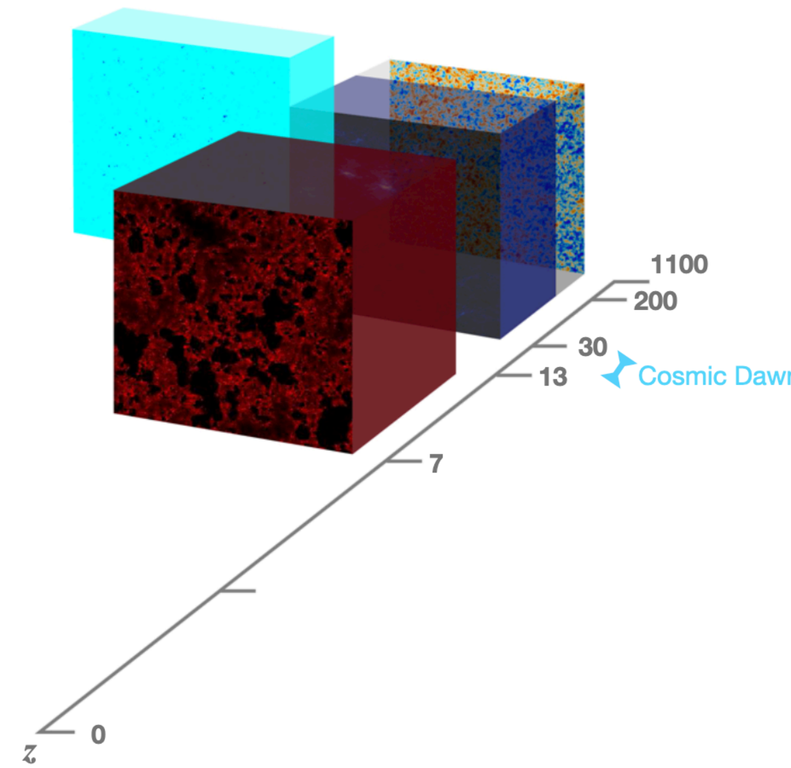
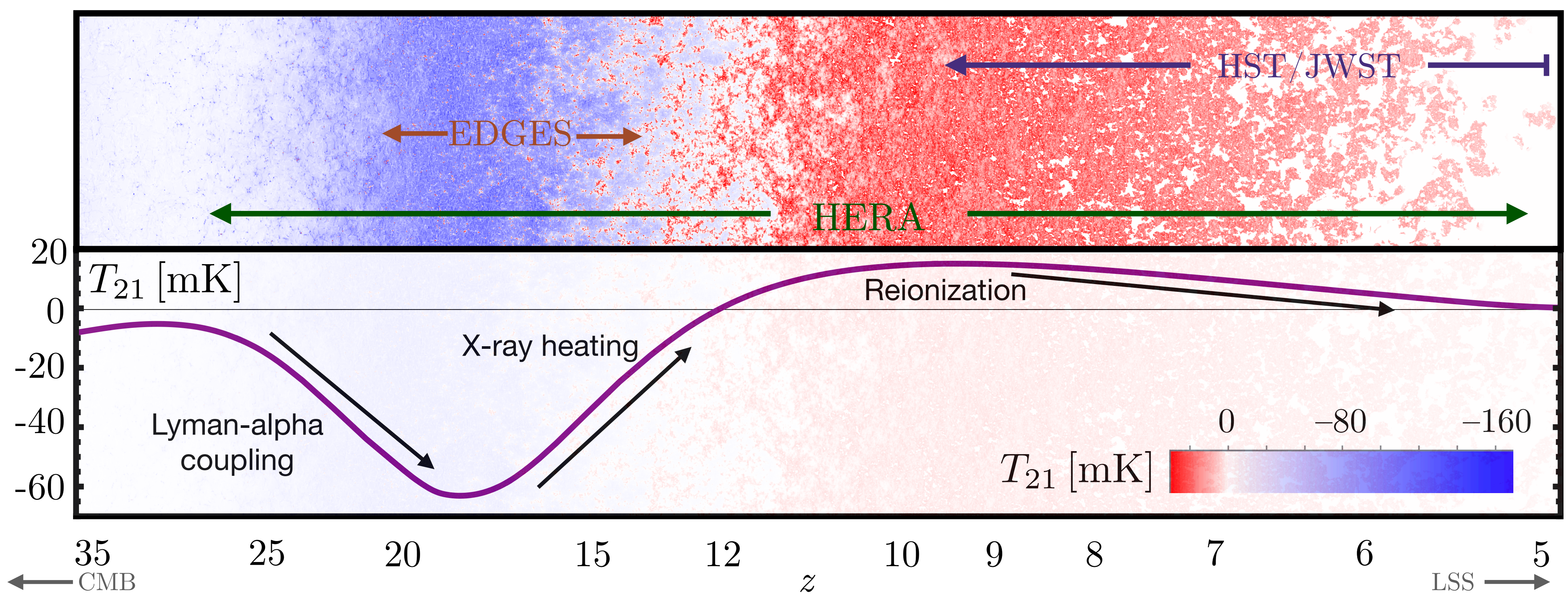


The 21cm brightness temperature contrast:



Credit: J. Munoz

Line*-Intensity Mapping: Introduction

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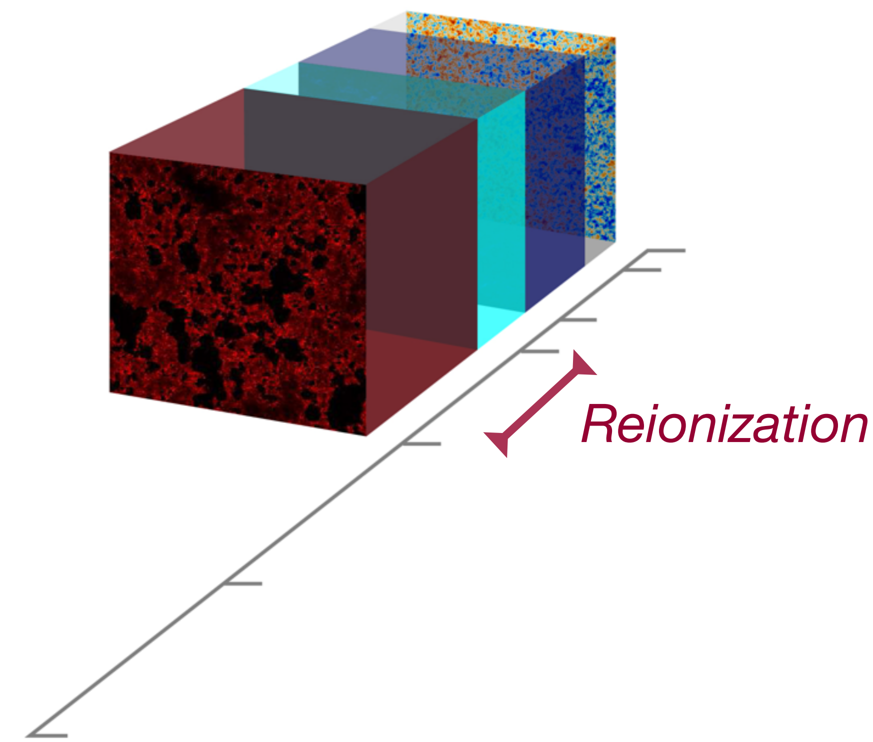
Reionization: Multi-line emission



Line*-Intensity Mapping: Introduction

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- HI (21cm): maps the neutral IGM, outside of the ionized bubbles.
- CO/[CII]: trace star-forming galaxies that source the ionizing photons.
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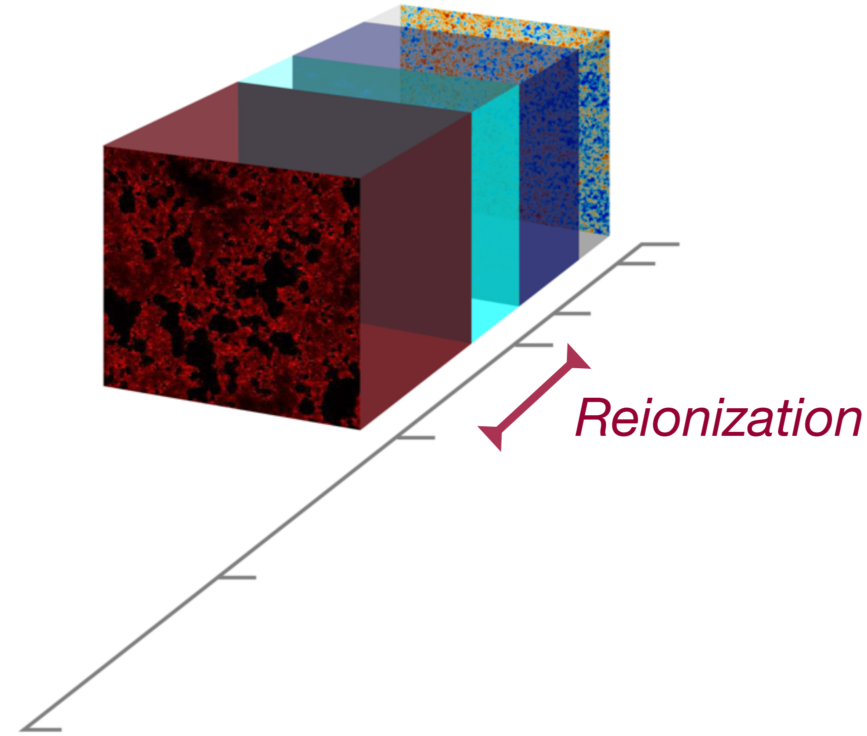

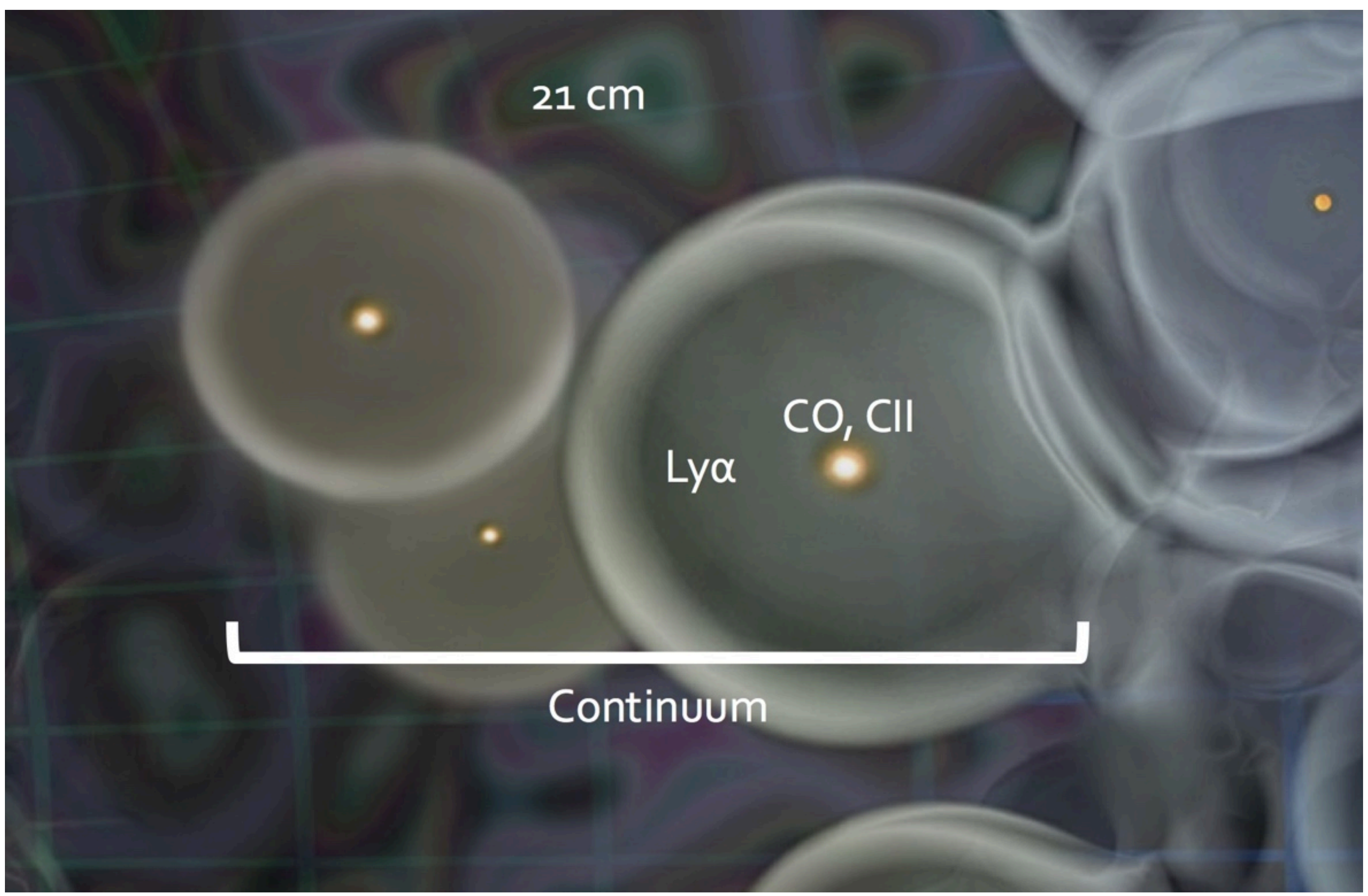

Kovetz et al., LIM: Status Report, arXiv:1709.09066

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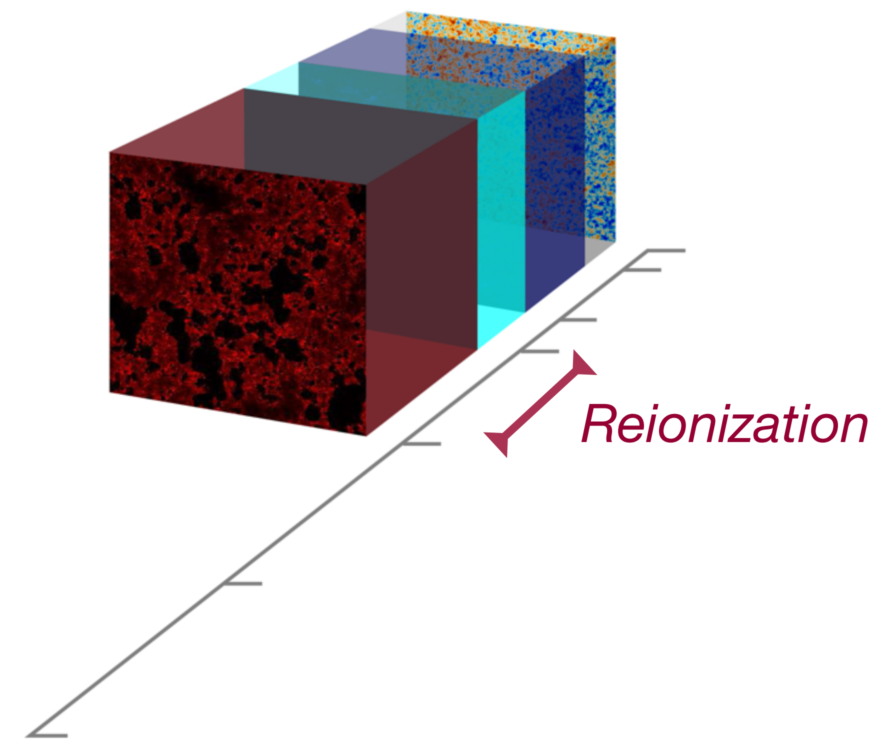

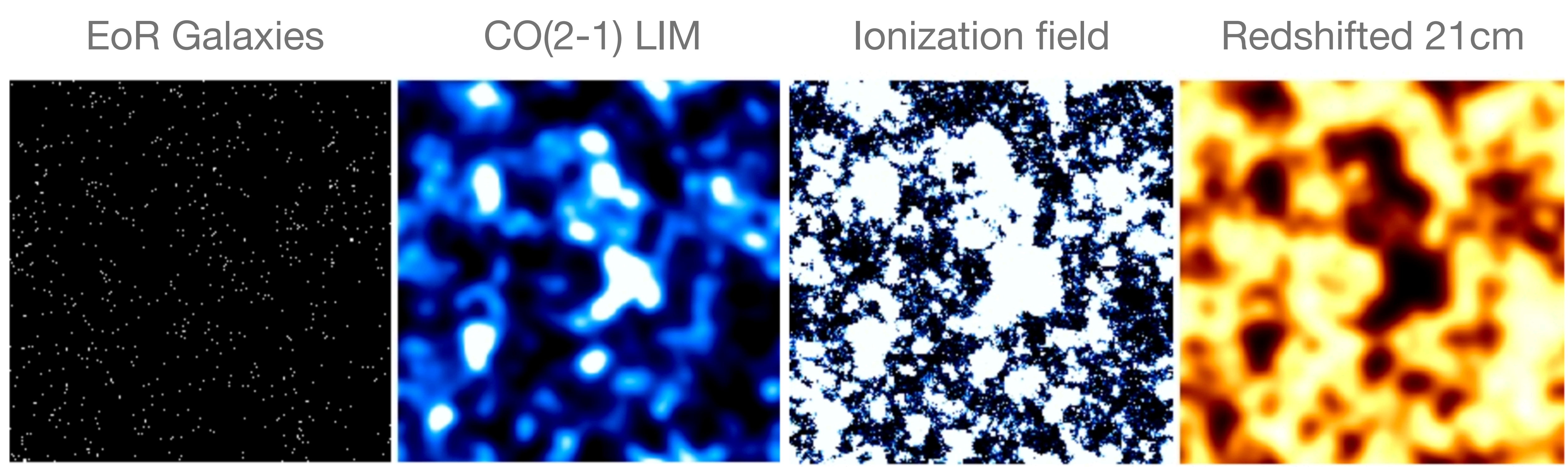

(Courtesy of A. Lidz)

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Disclaimer: This will take time…

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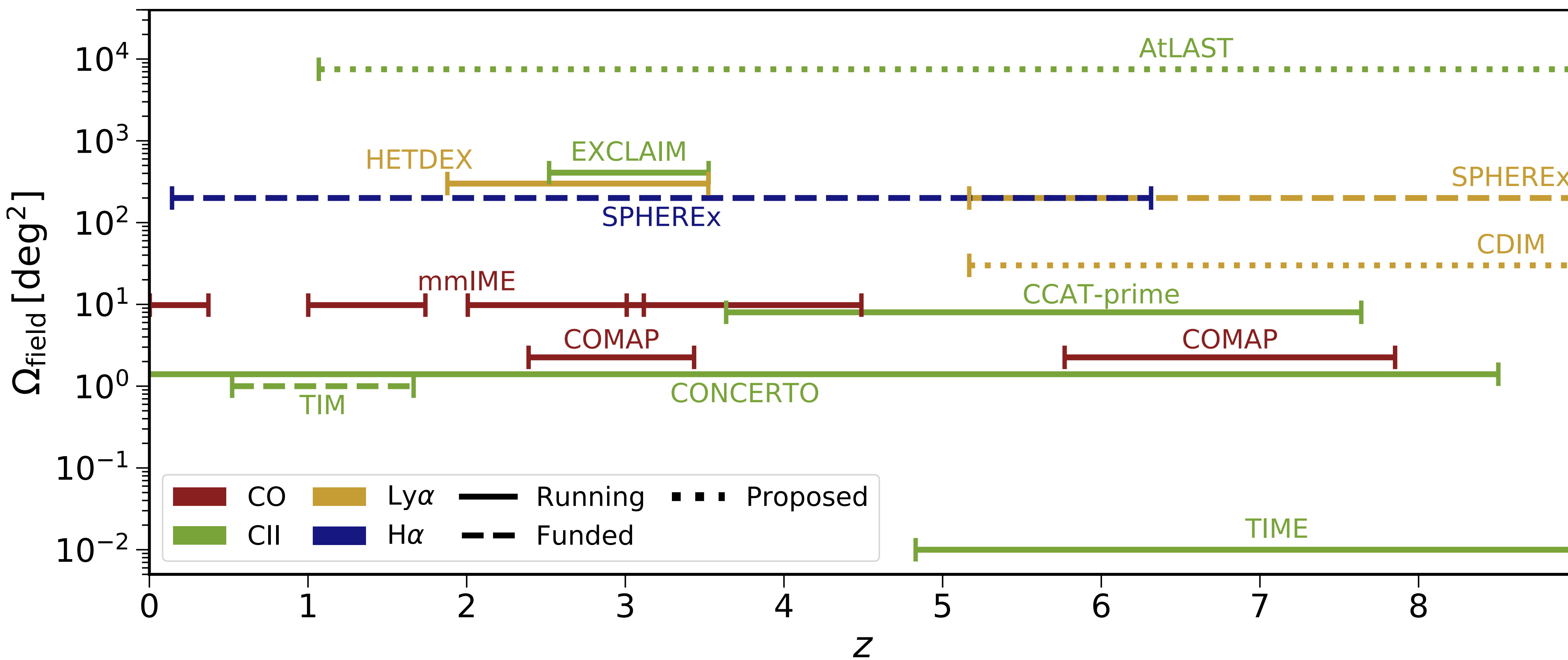

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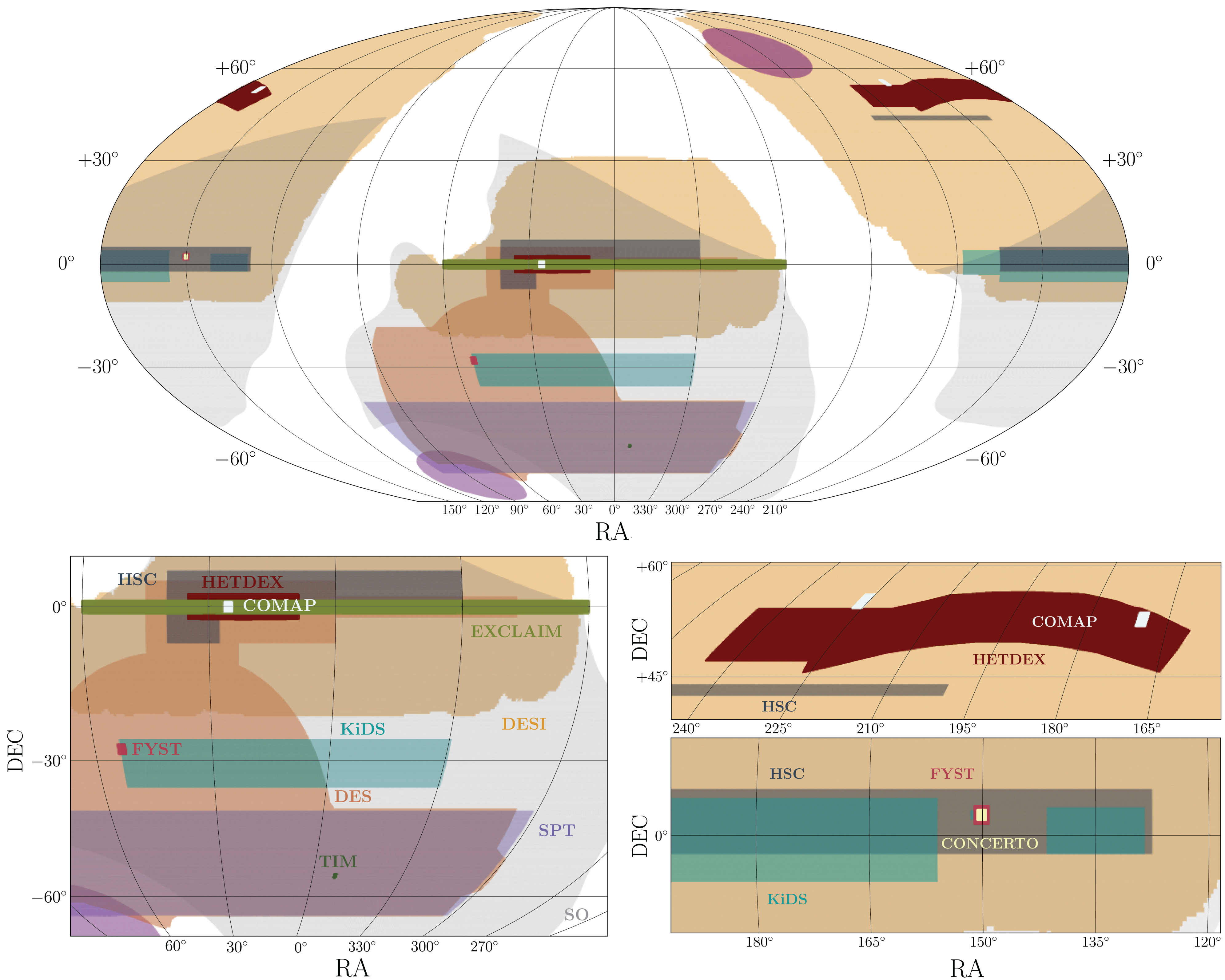

Line*-Intensity Mapping: Introduction

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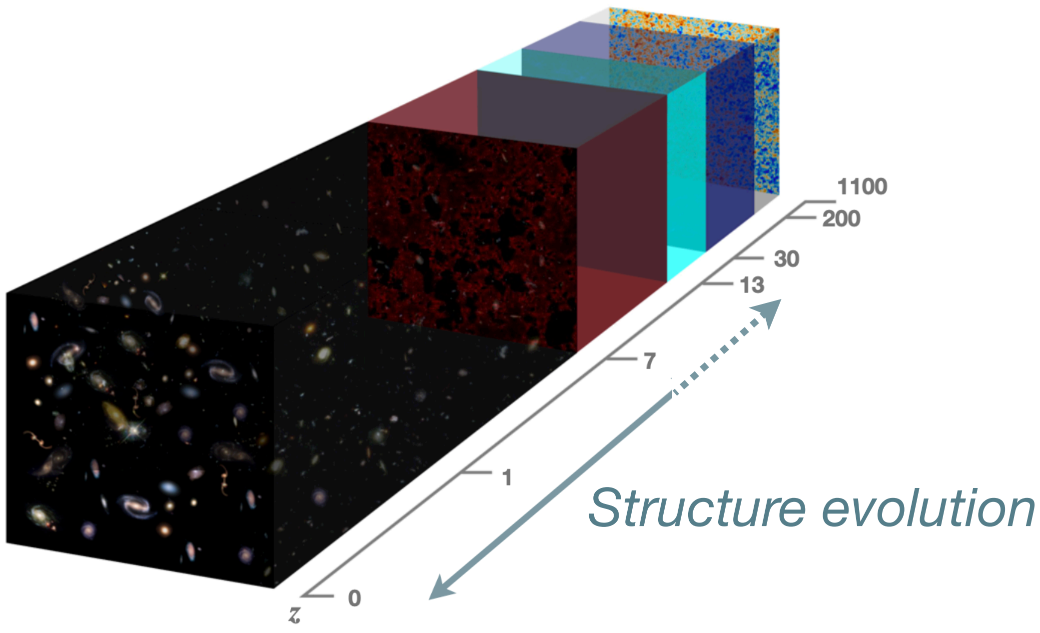
Growth of Structure: Star-formation lines



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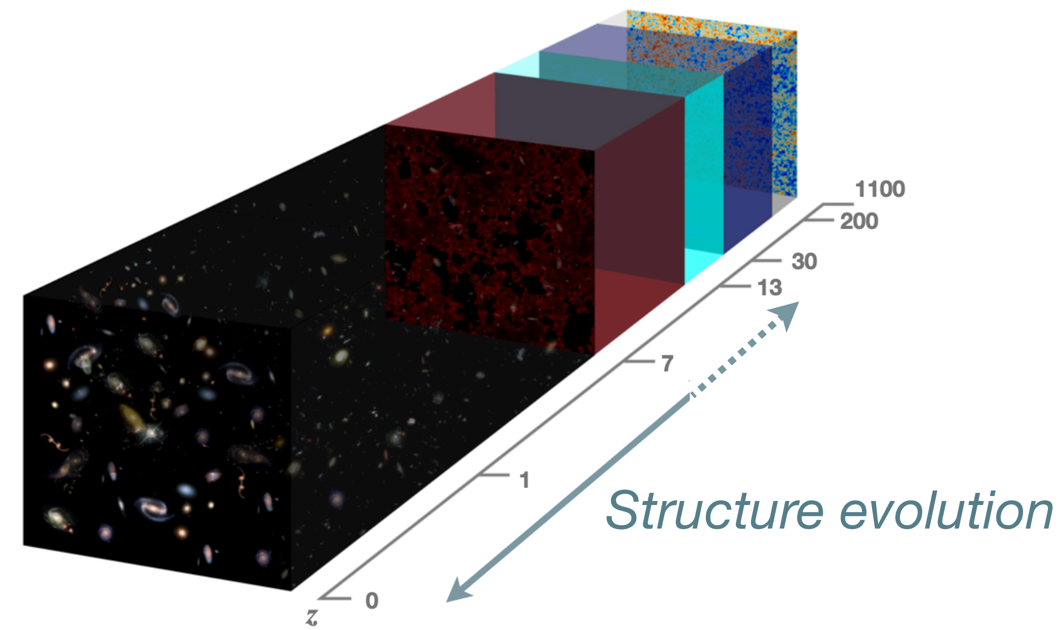
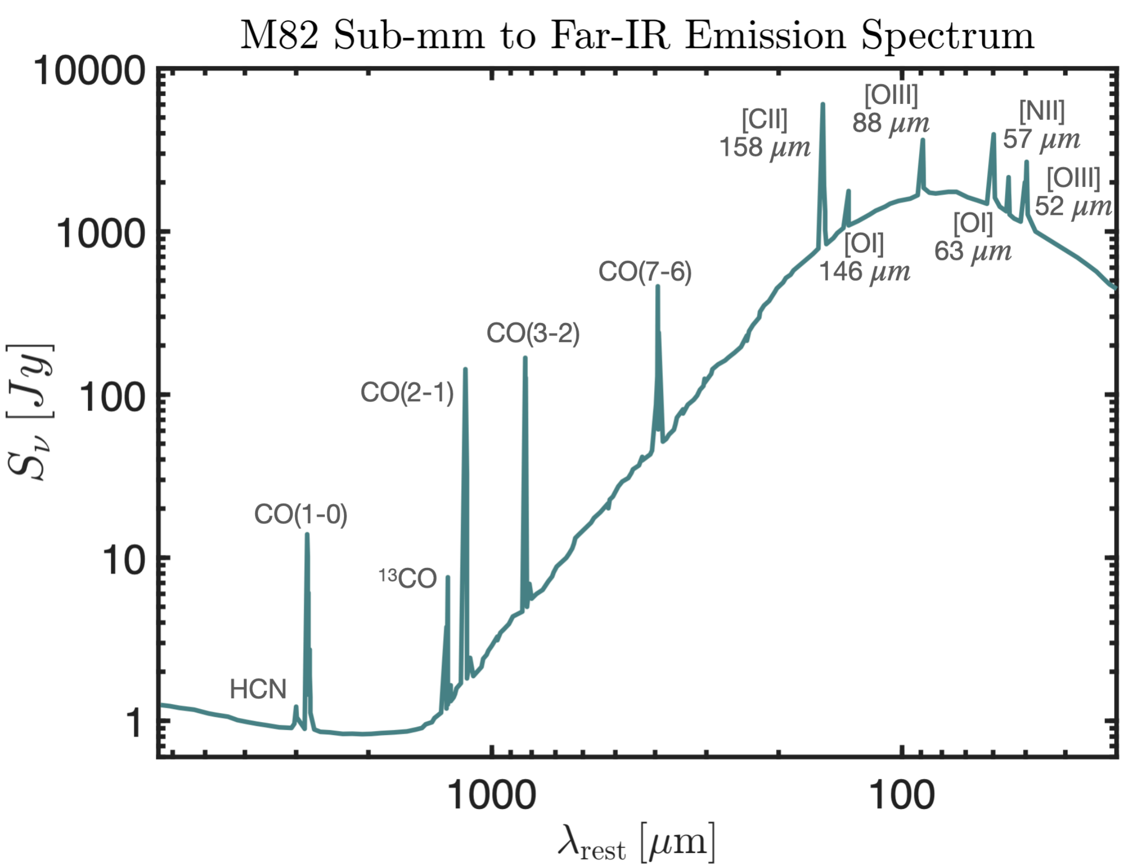
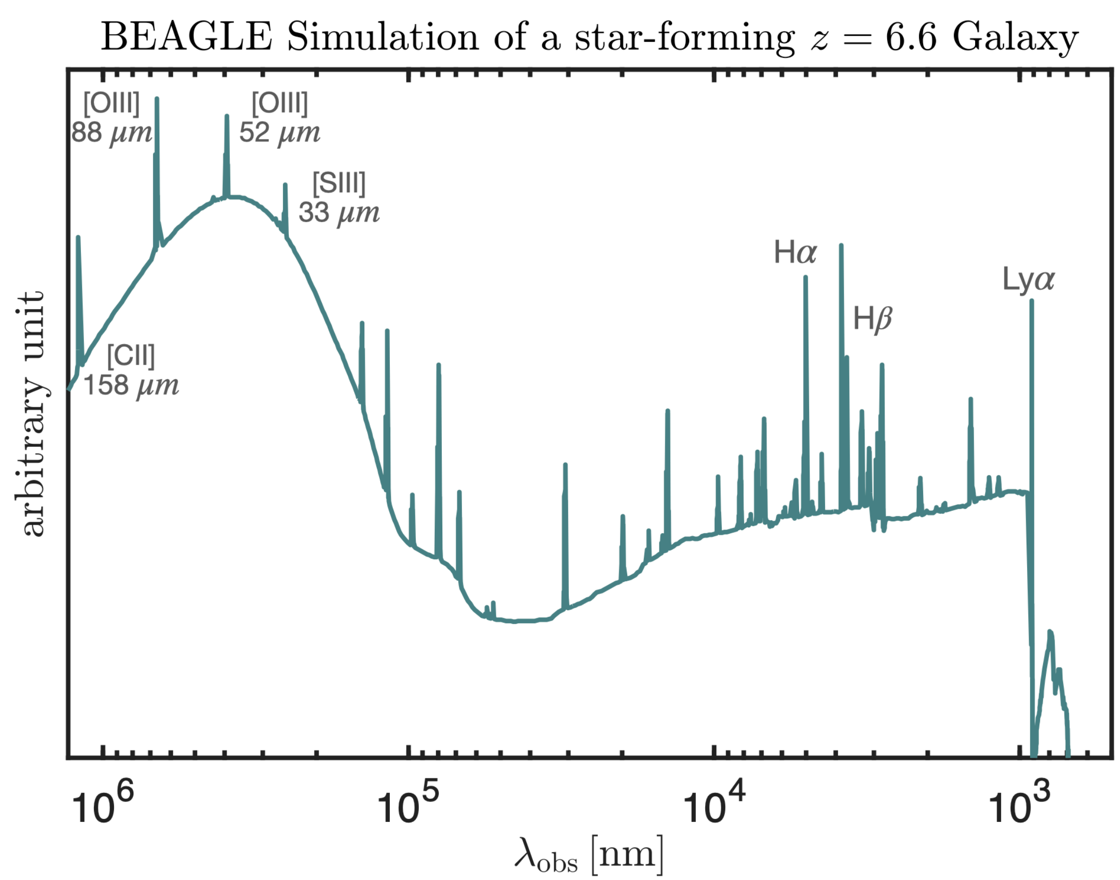


Spectrum of a typical galaxy:





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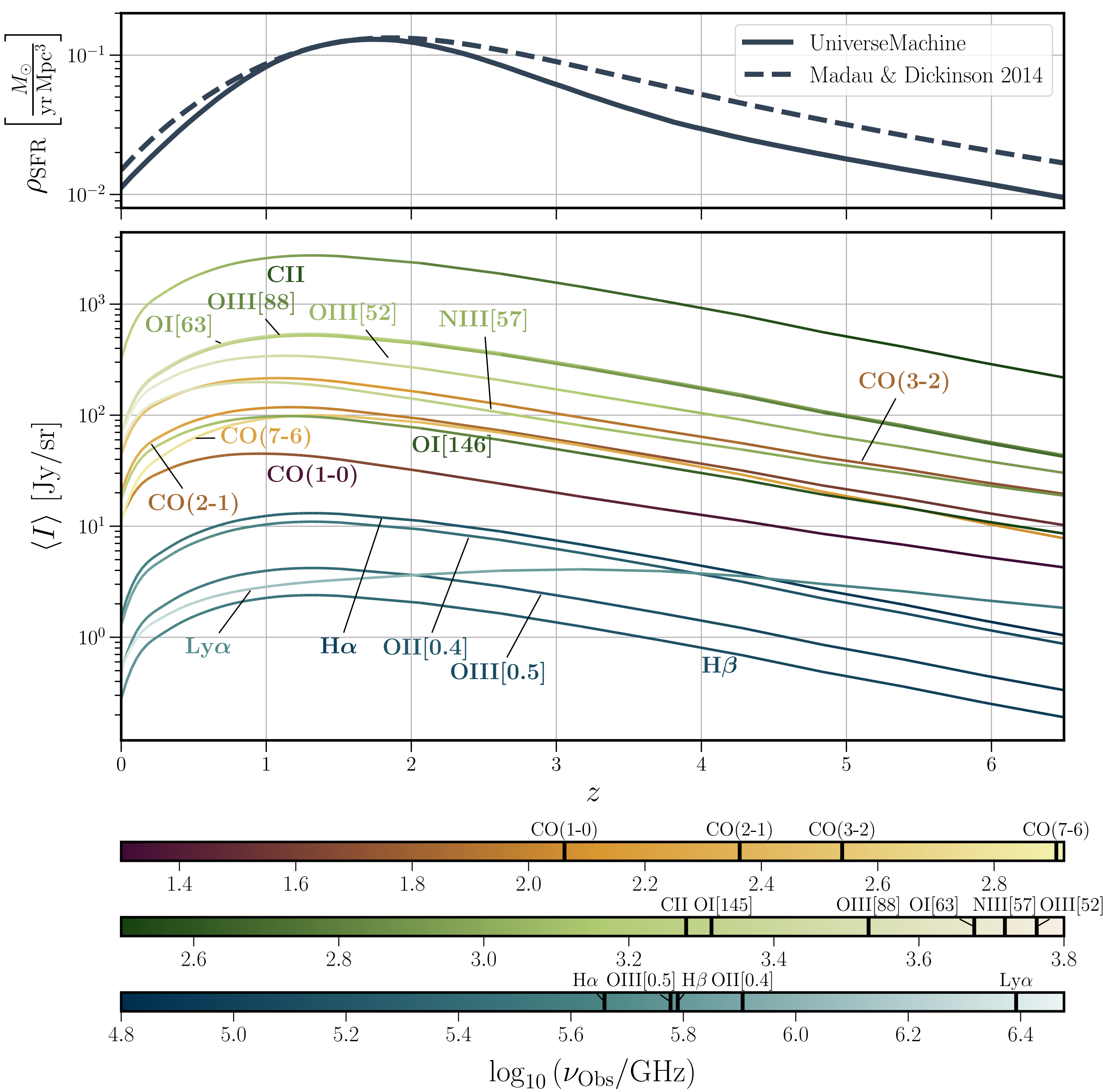

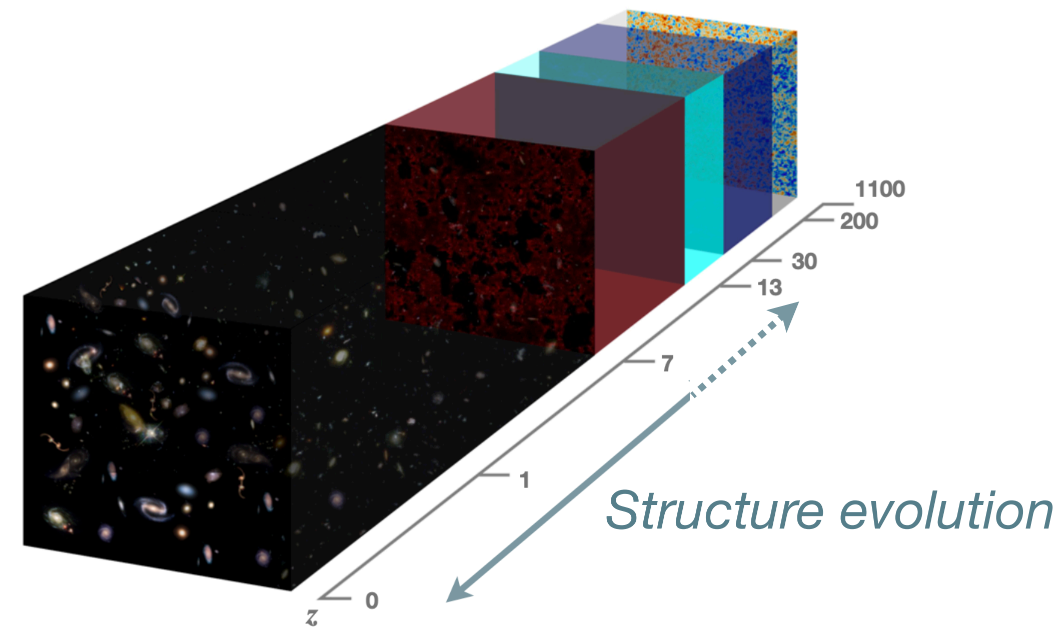

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Line*-Intensity Mapping: Experimental Landscape

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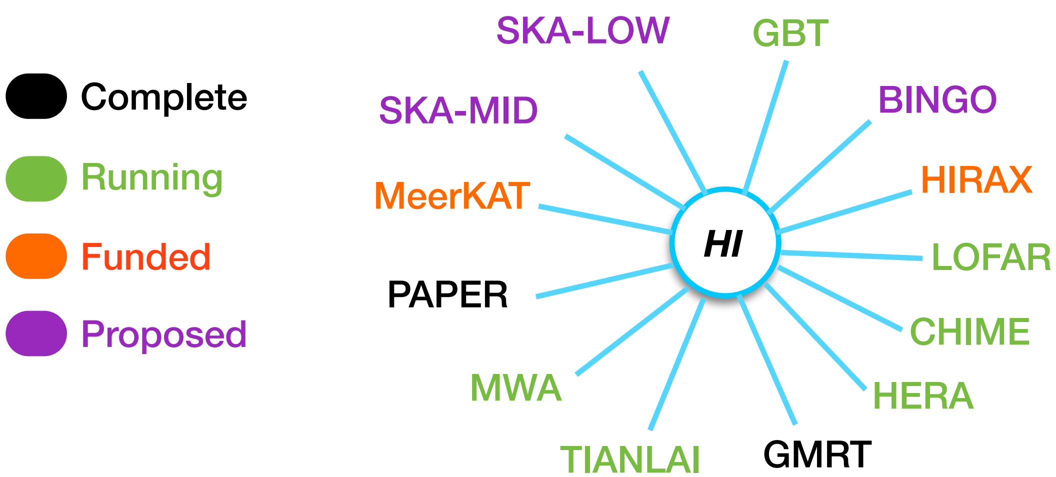

(Astro2020: Kovetz et al., arXiv:1903.04496)

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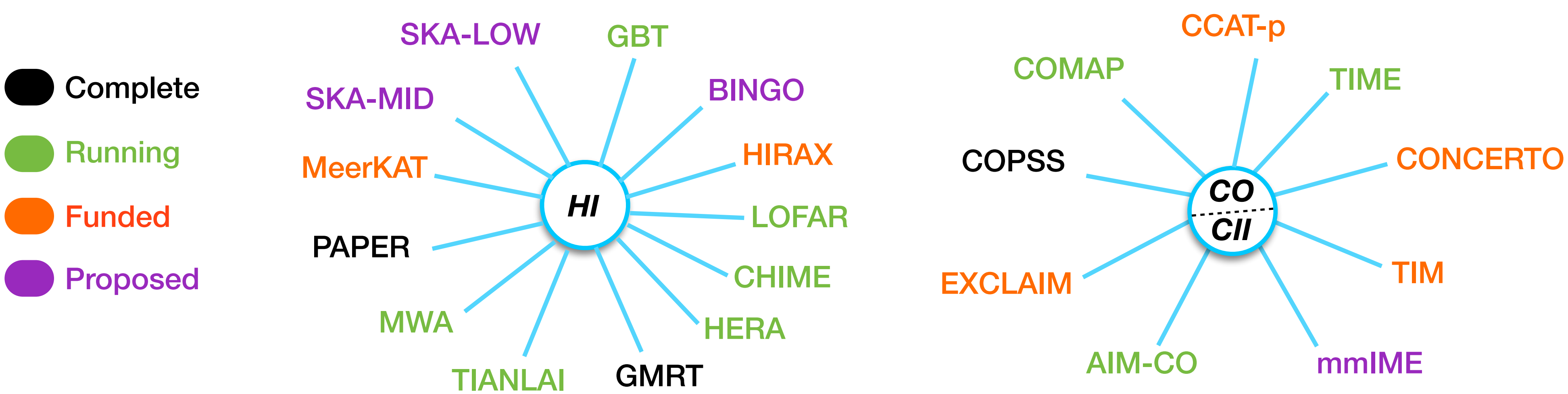

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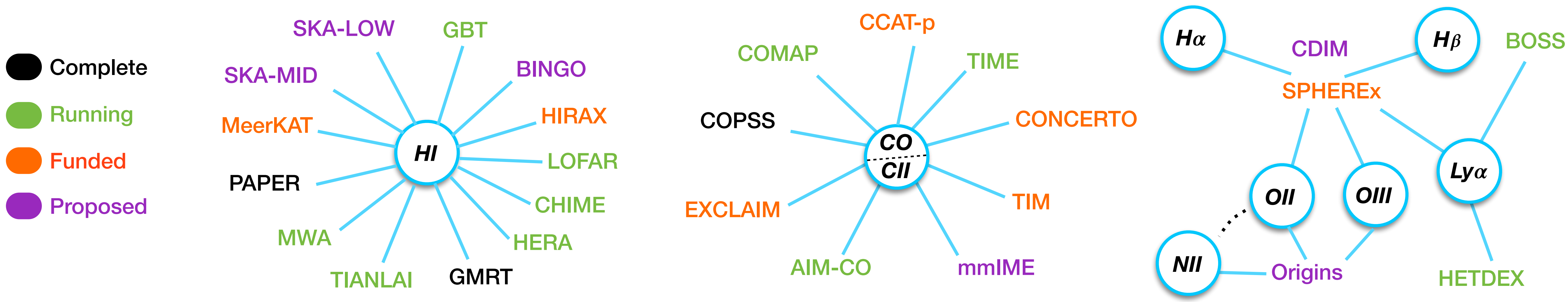

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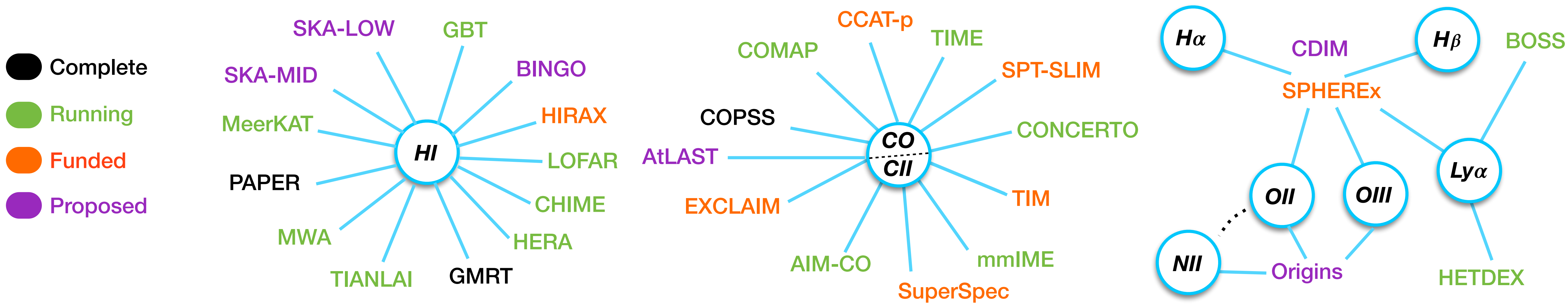

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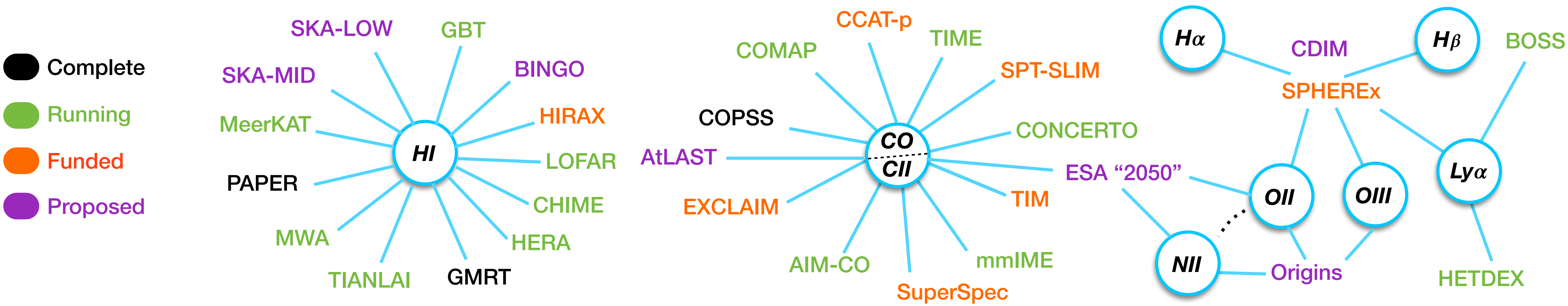

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(ESA2050: Silva, Kovetz et al., arXiv:1908.07533)

Voyage 2050 sets sail: ESA chooses future science mission t...

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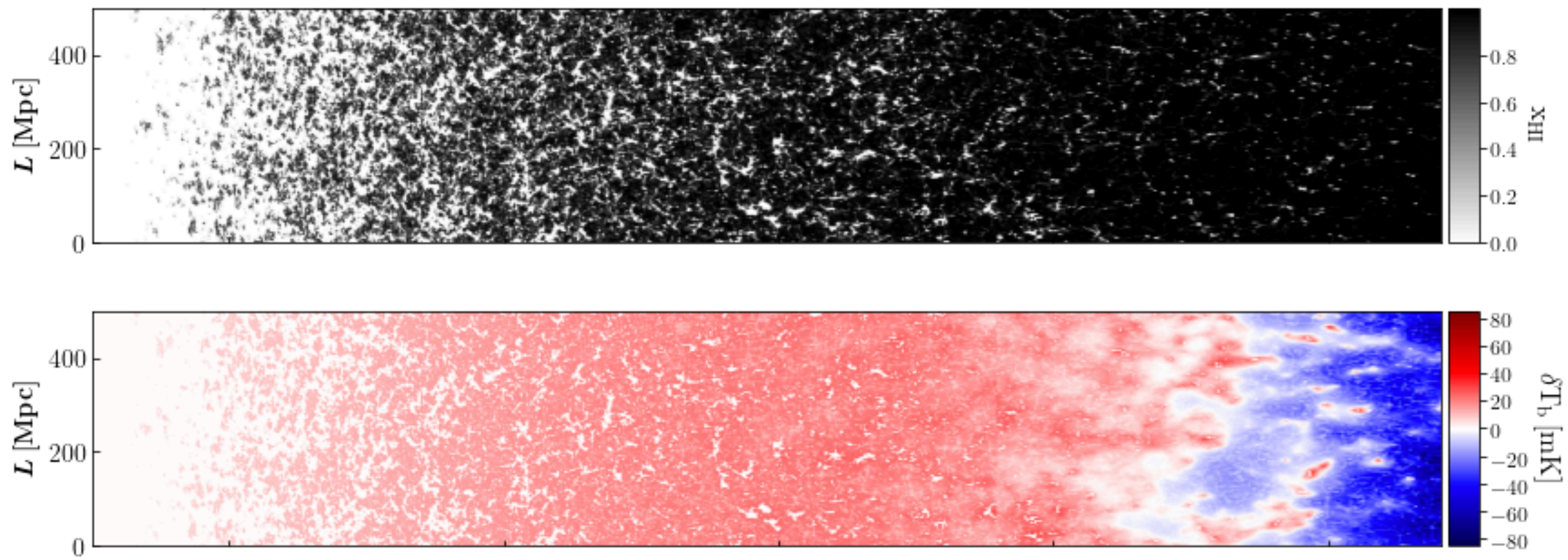
Line*-Intensity Mapping: Simulations

Reionization:

Multi-line emission



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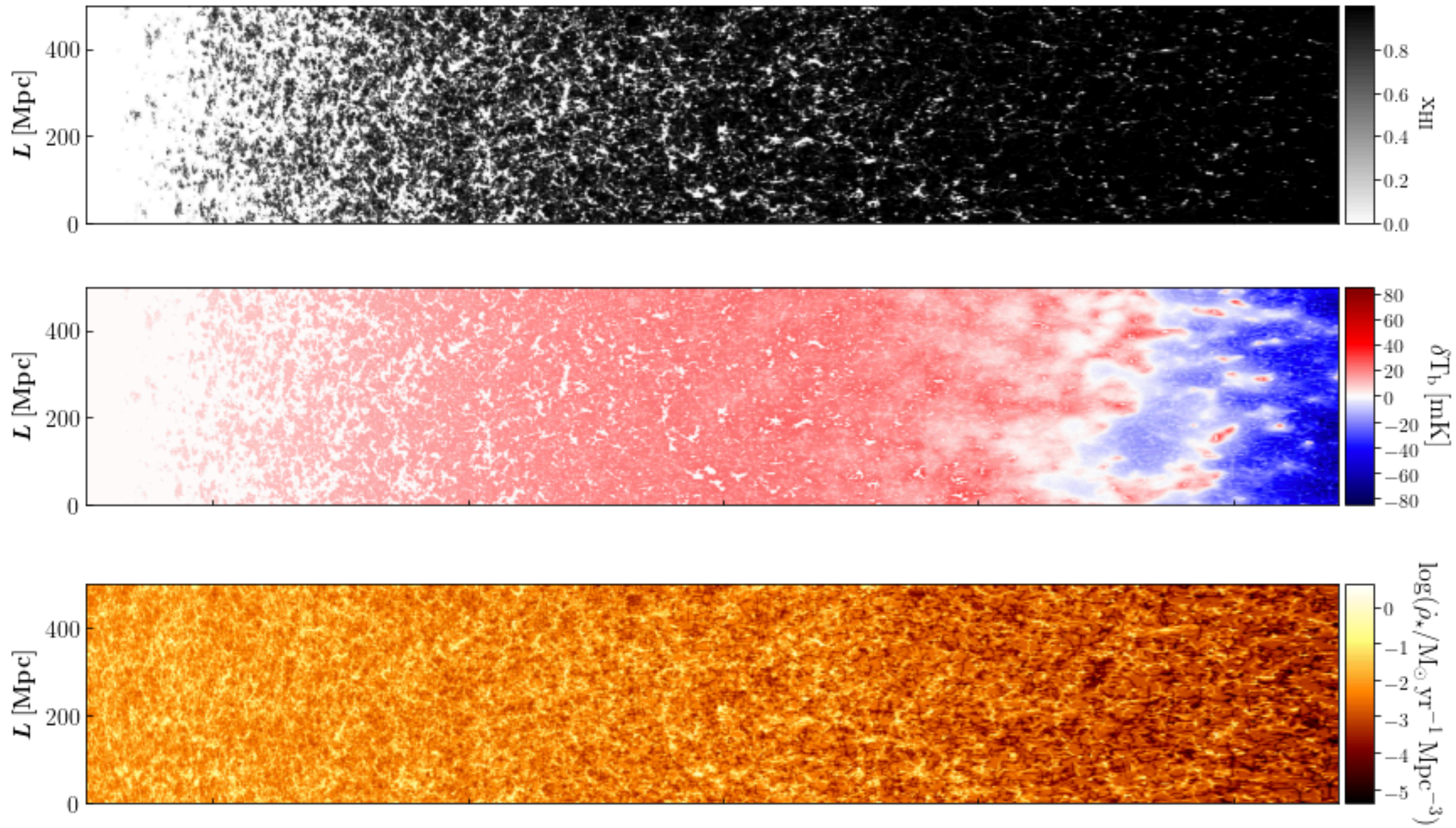

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LIMFAST
Mas-Ribas et al.,
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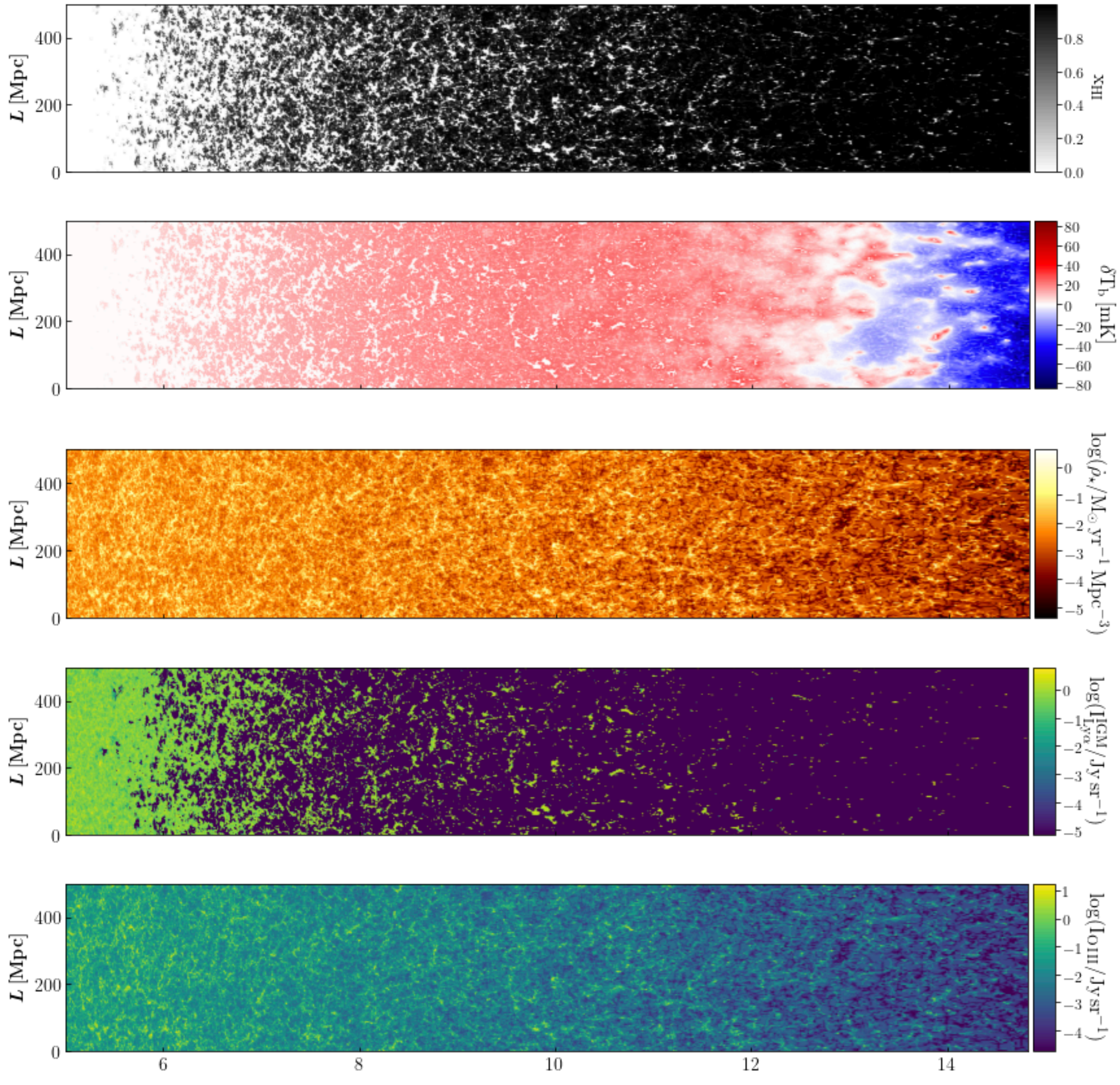
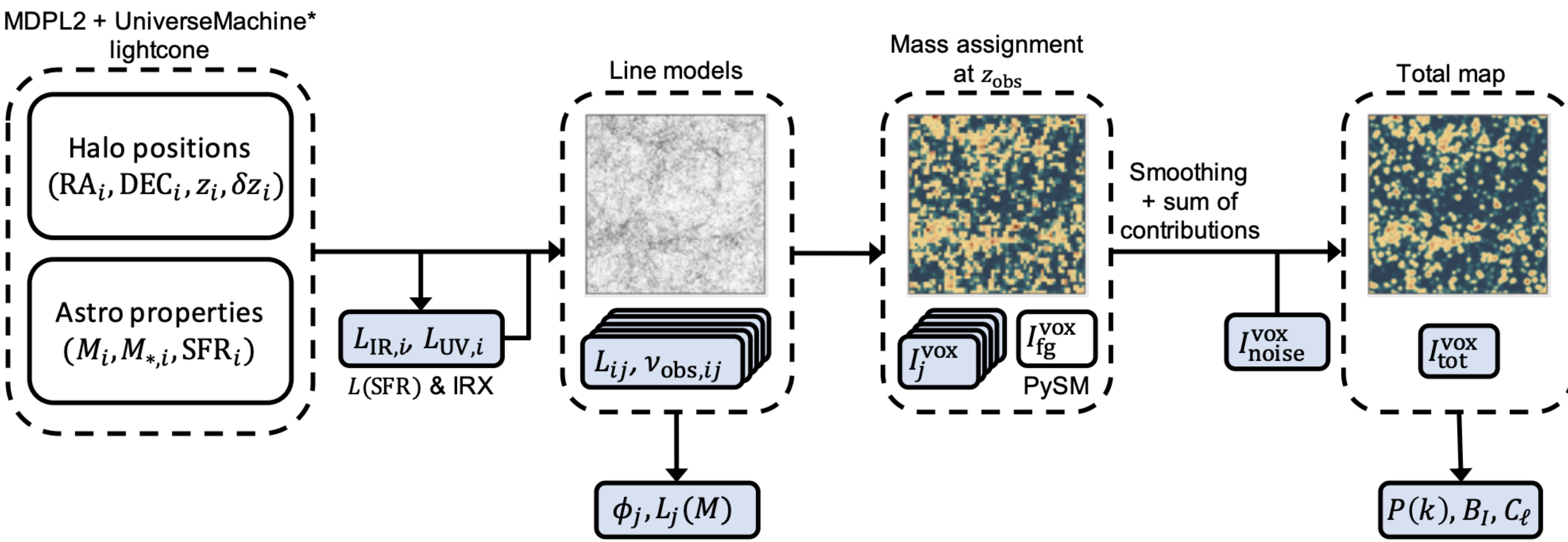
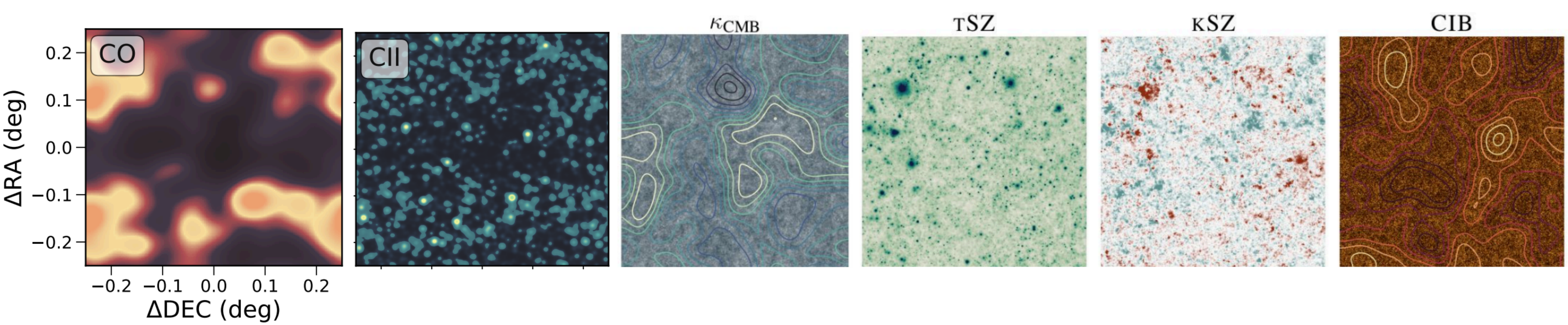


Line*-Intensity Mapping: Simulations

Multi-tracer light cones:

Skyline, Sato-Polito et al., arXiv:2212.08056





Line*-Intensity Mapping: Science Goals

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Astrophysics:

- Reionization: bubble sizes, ionized fraction, duration
- Star formation rate (history, peak rise/fall, Pop III stars)
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- AGN feedback
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LIM* as the Ultimate Cosmological Probe

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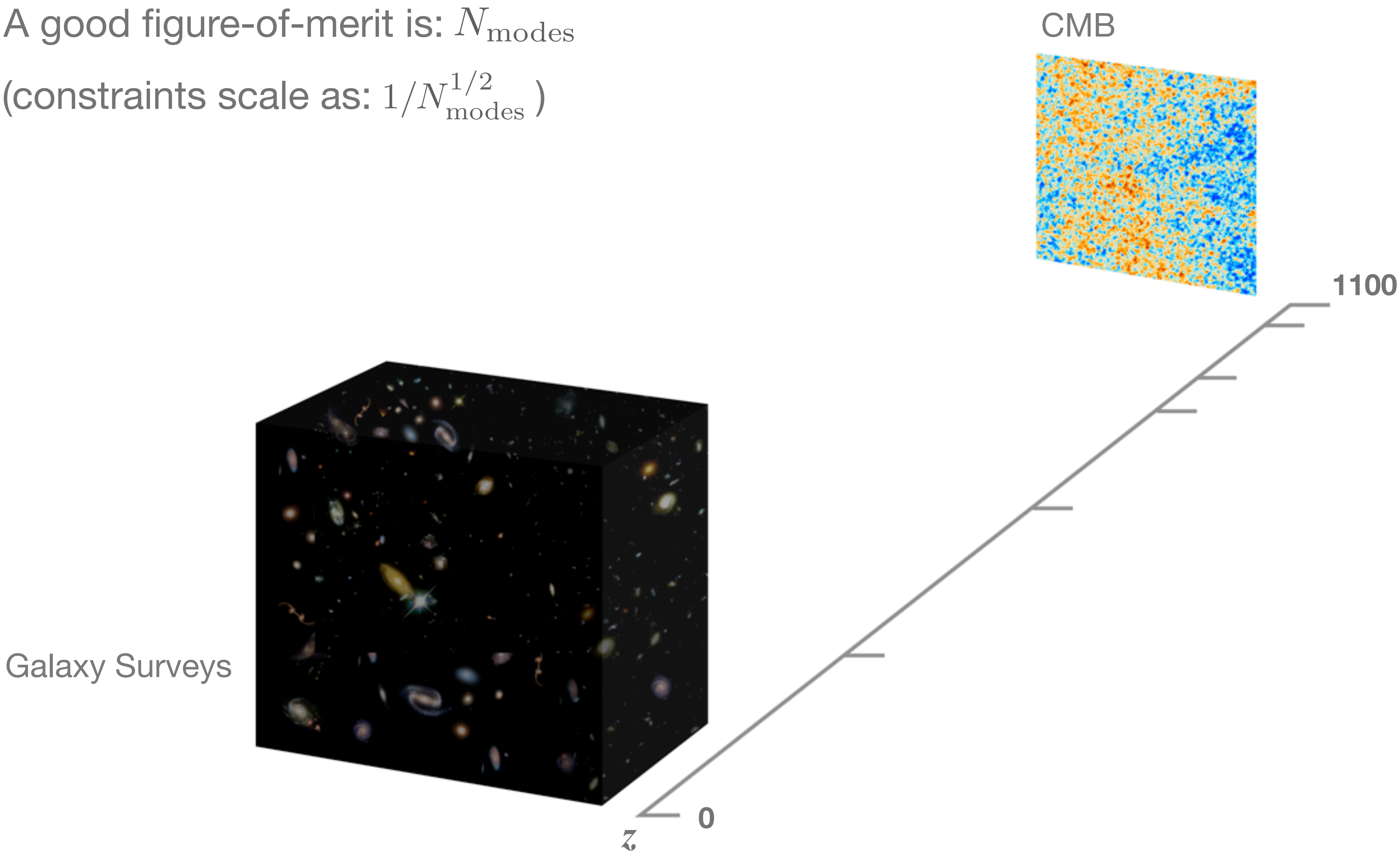

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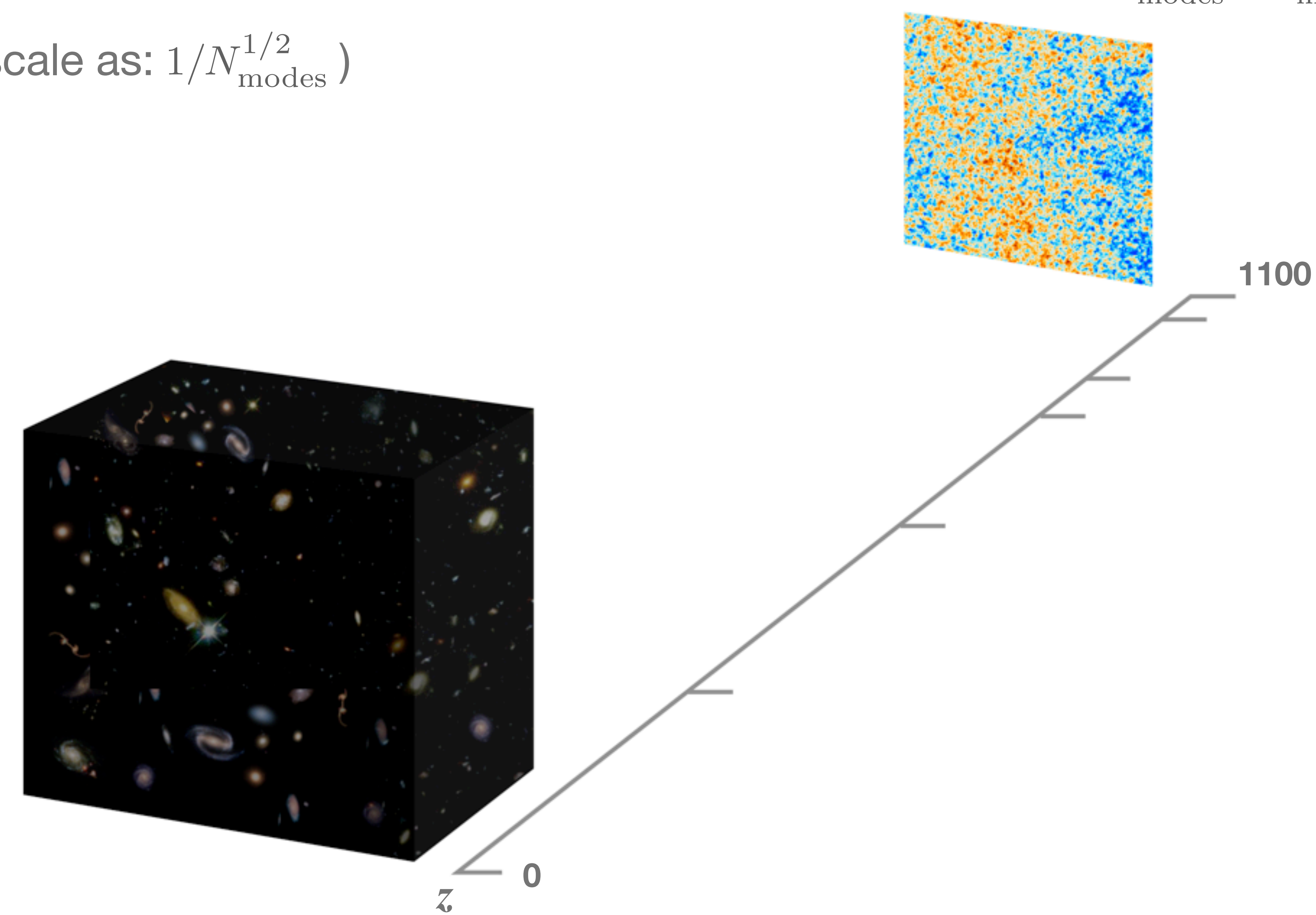

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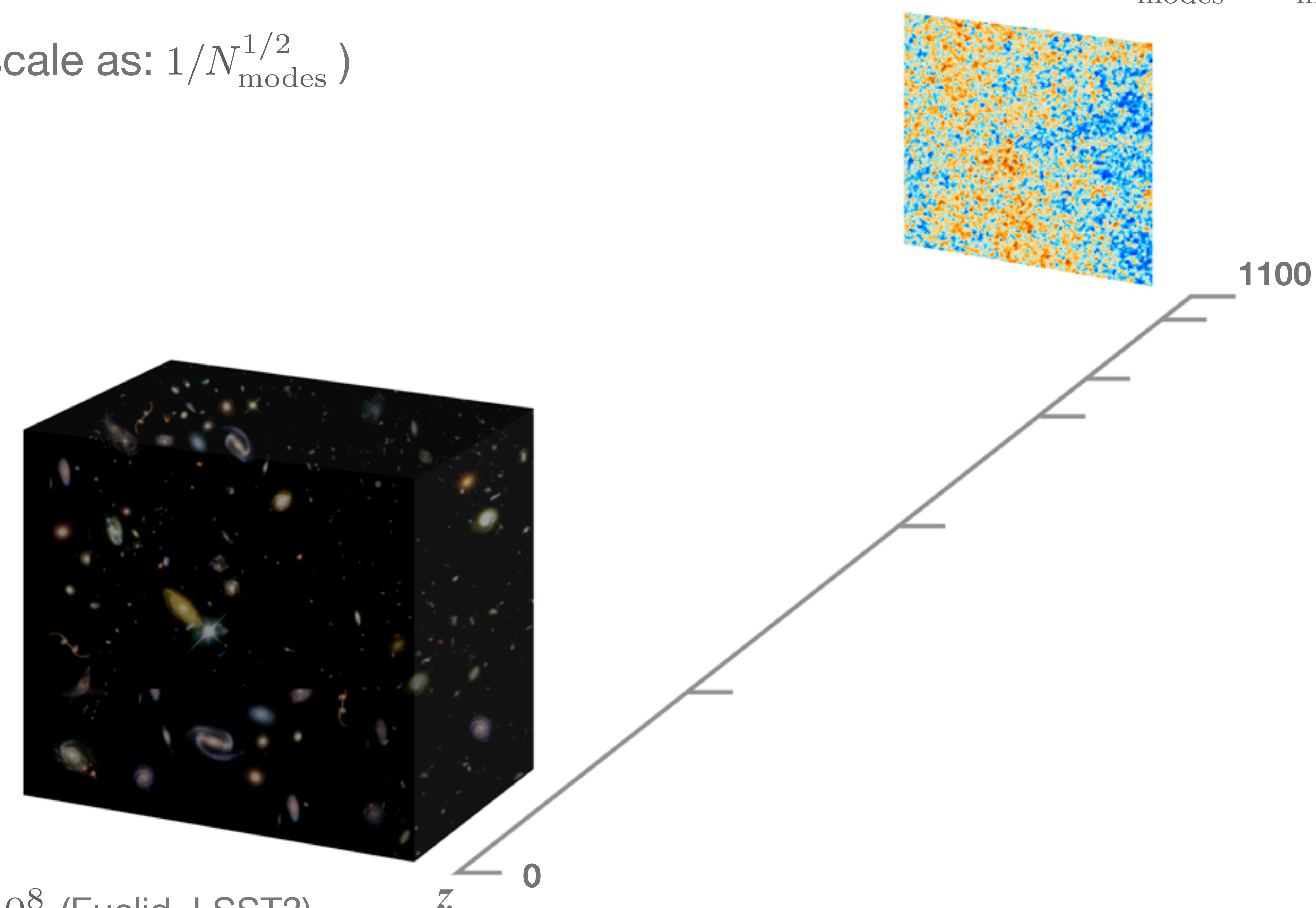

Galaxy Surveys

$N_{\rm modes}^{\rm Gal} > N_{\rm modes}^{\rm CMB}$

$\longrightarrow N_{\rm sources} > 10^8$ (Euclid, LSST?)

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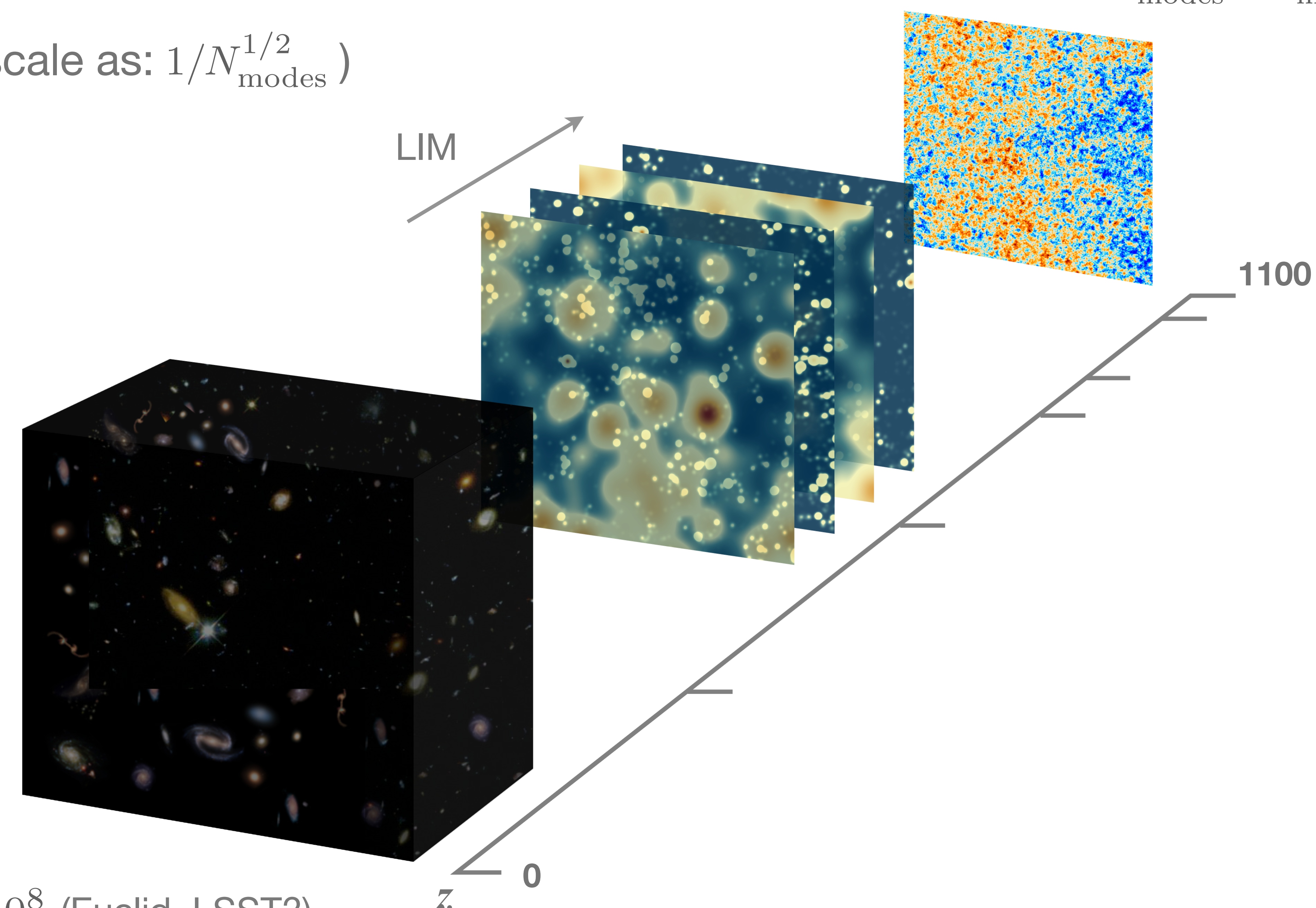

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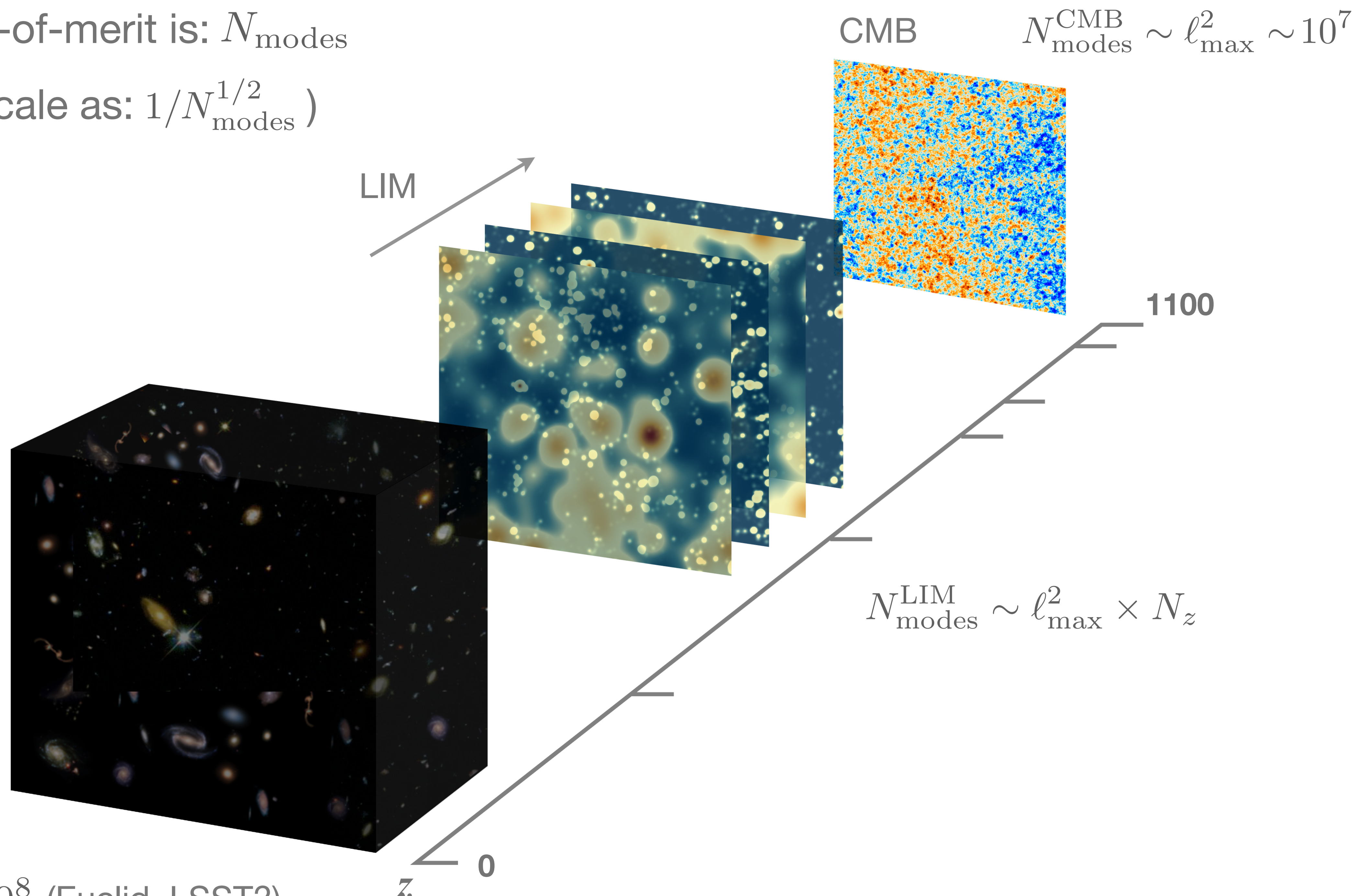

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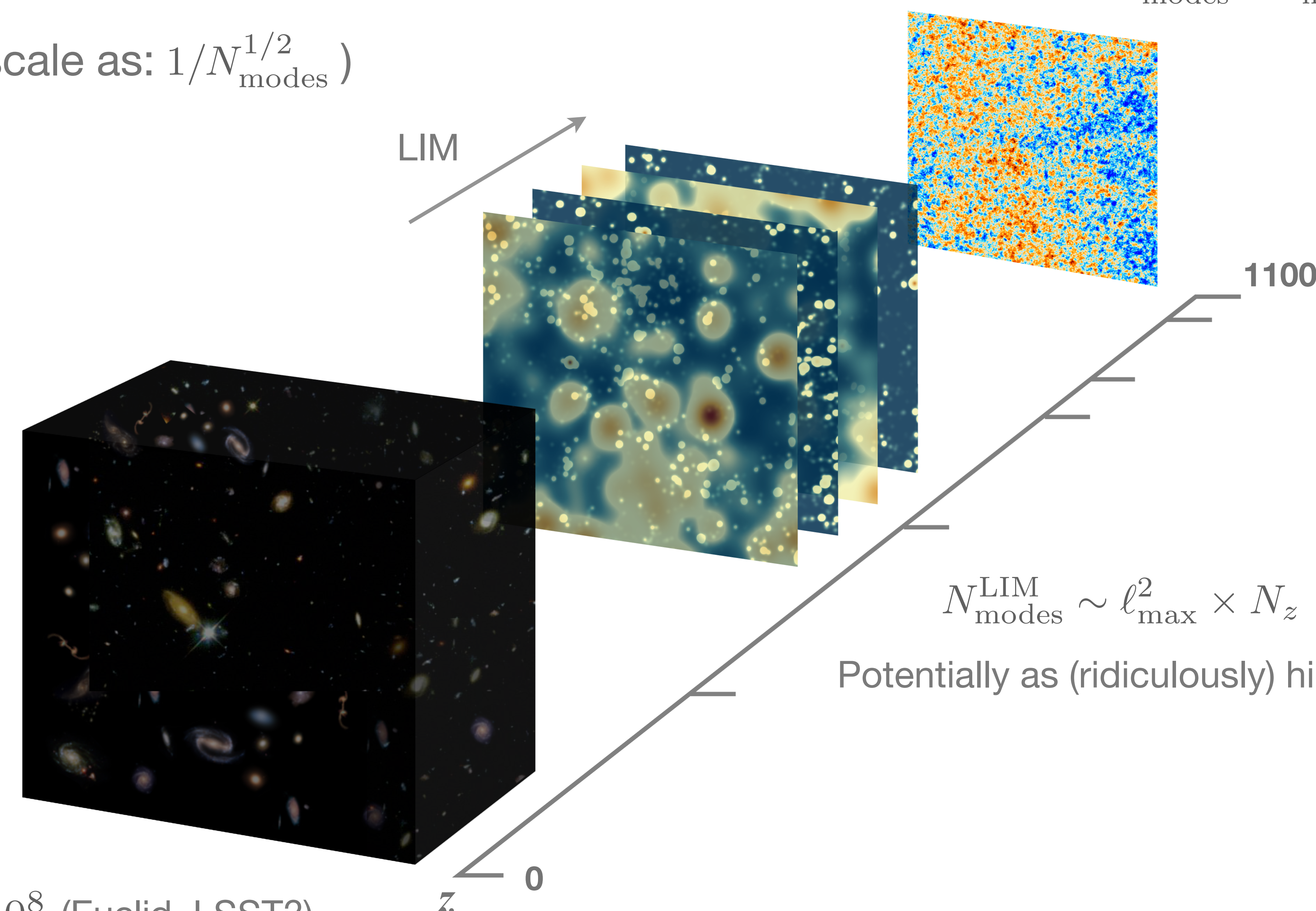

$N_{\rm modes}^{\rm LIM} \sim \ell_{\rm max}^2 \times N_z$

Potentially as (ridiculously) high as 10^{16}...

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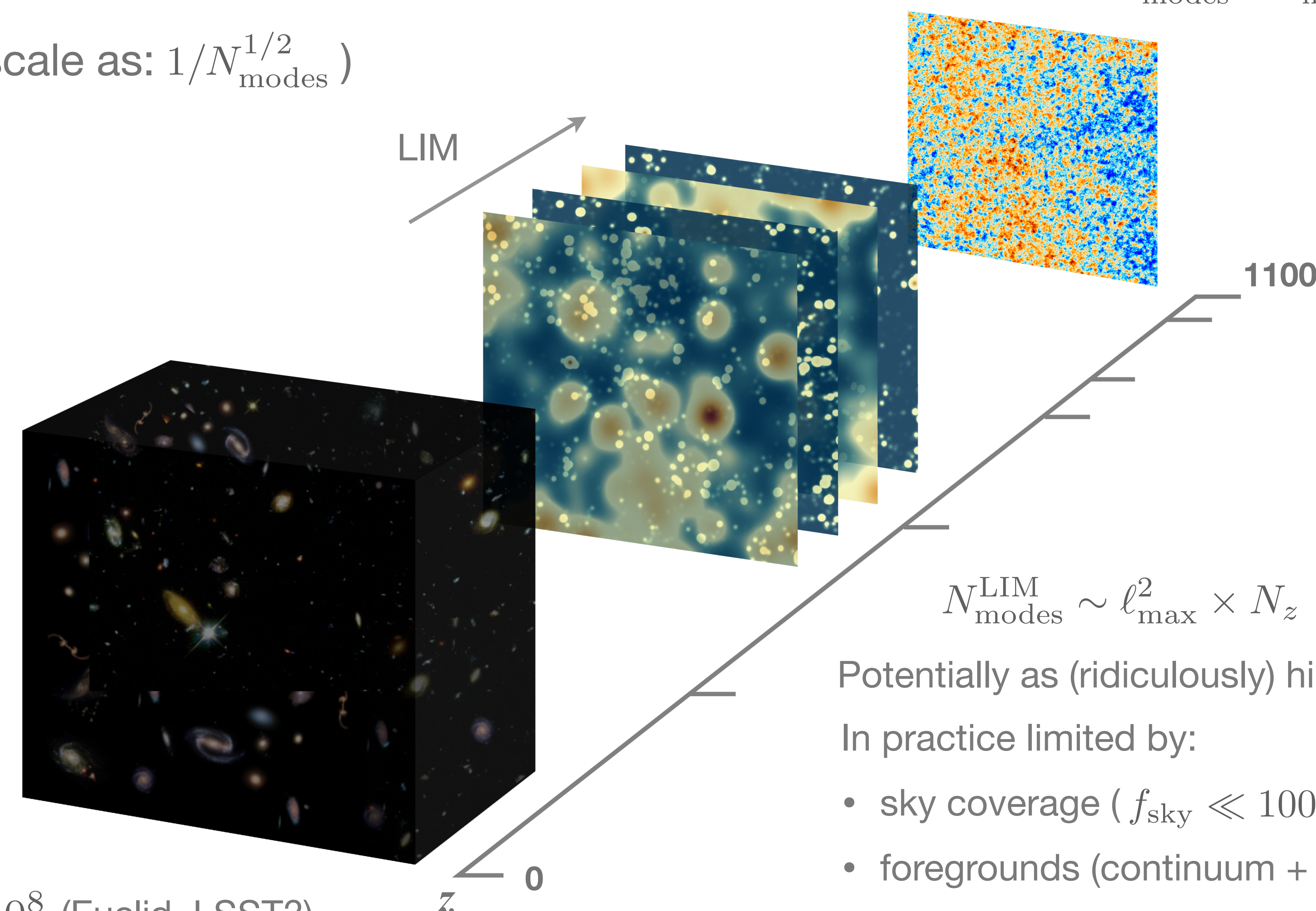

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Potentially as (ridiculously) high as 10^{16}...

In practice limited by:

- sky coverage ($f_{\rm sky} \ll 100\%$)
- foregrounds (continuum + interlopers)
- astrophysics/cosmology degeneracy

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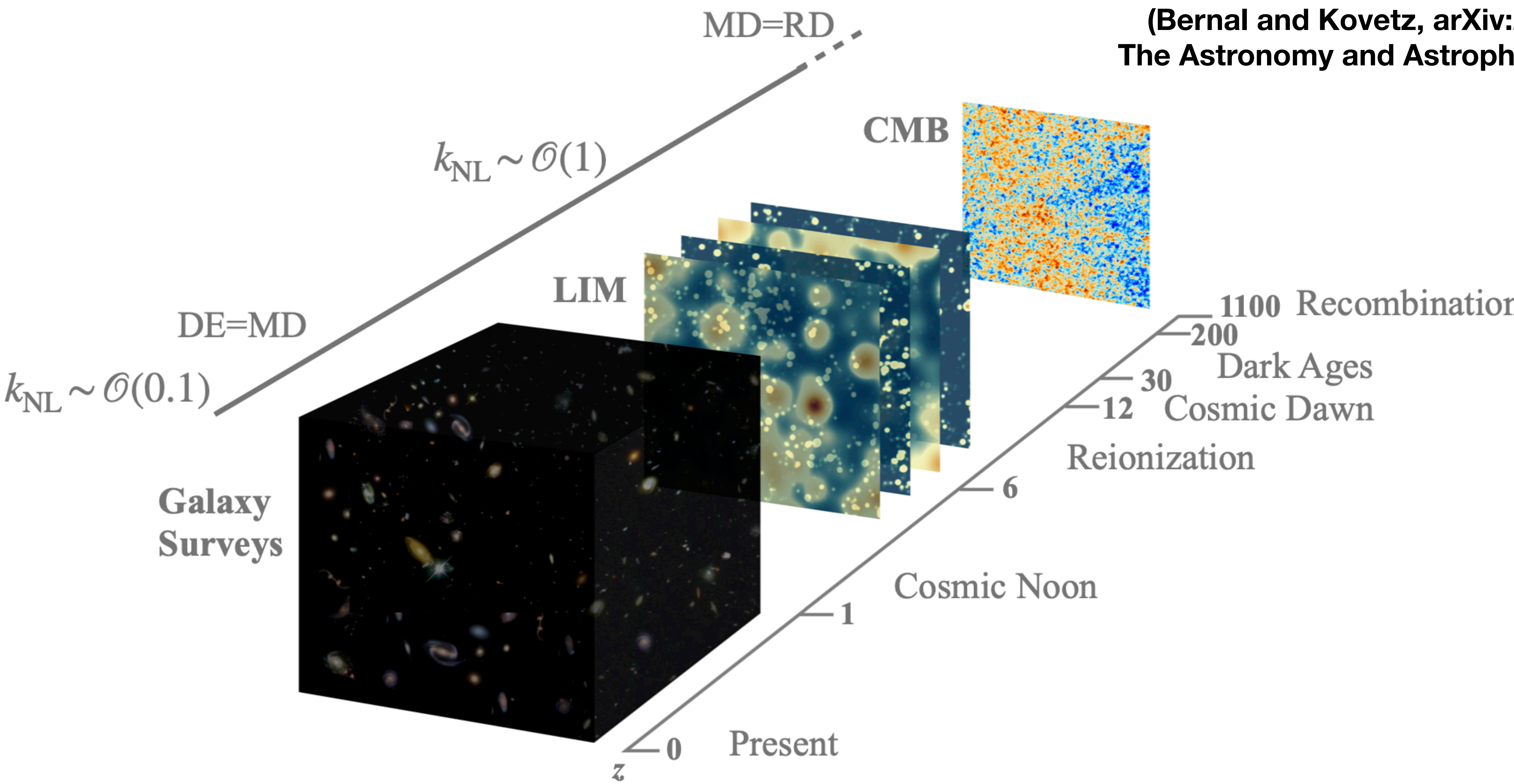

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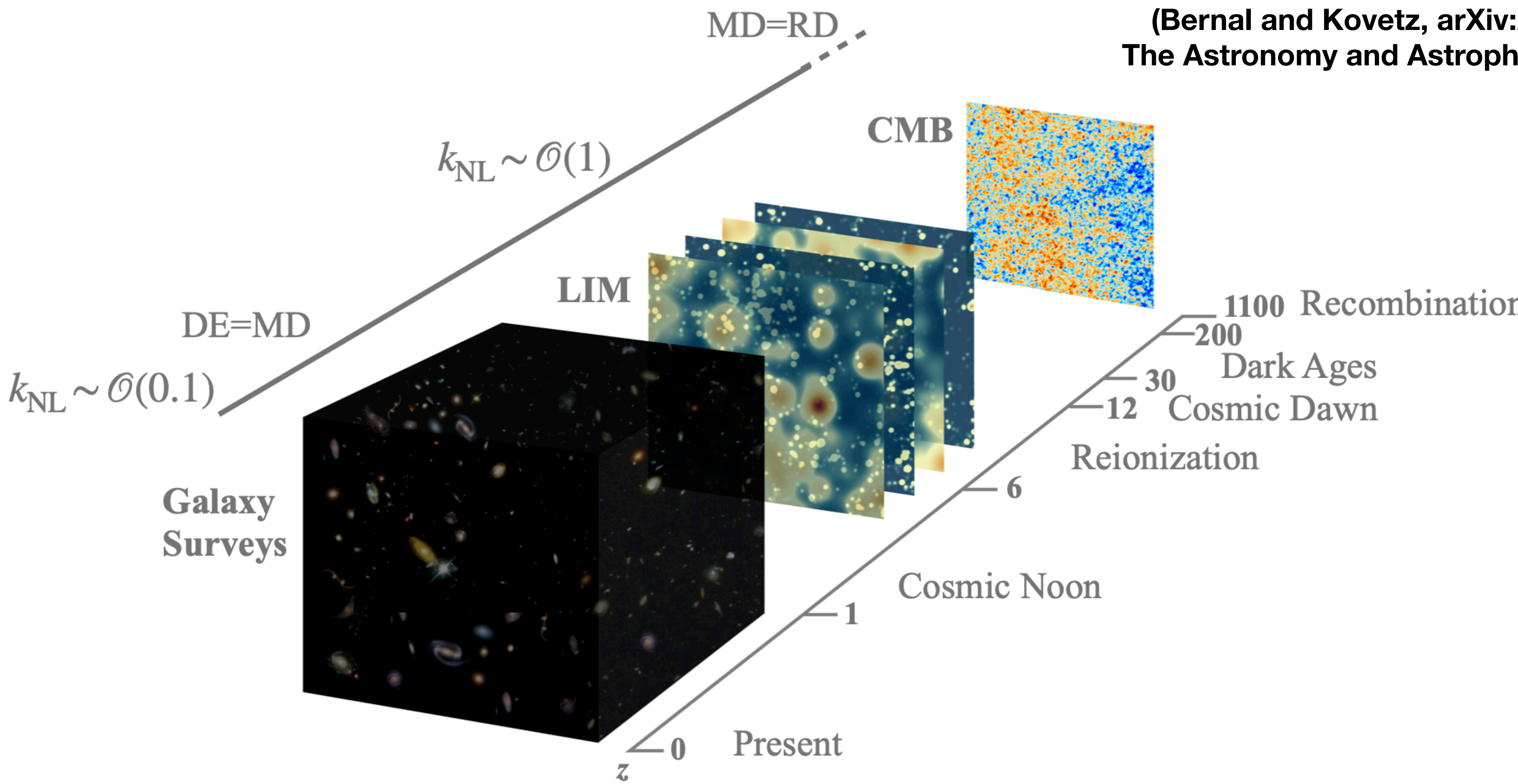

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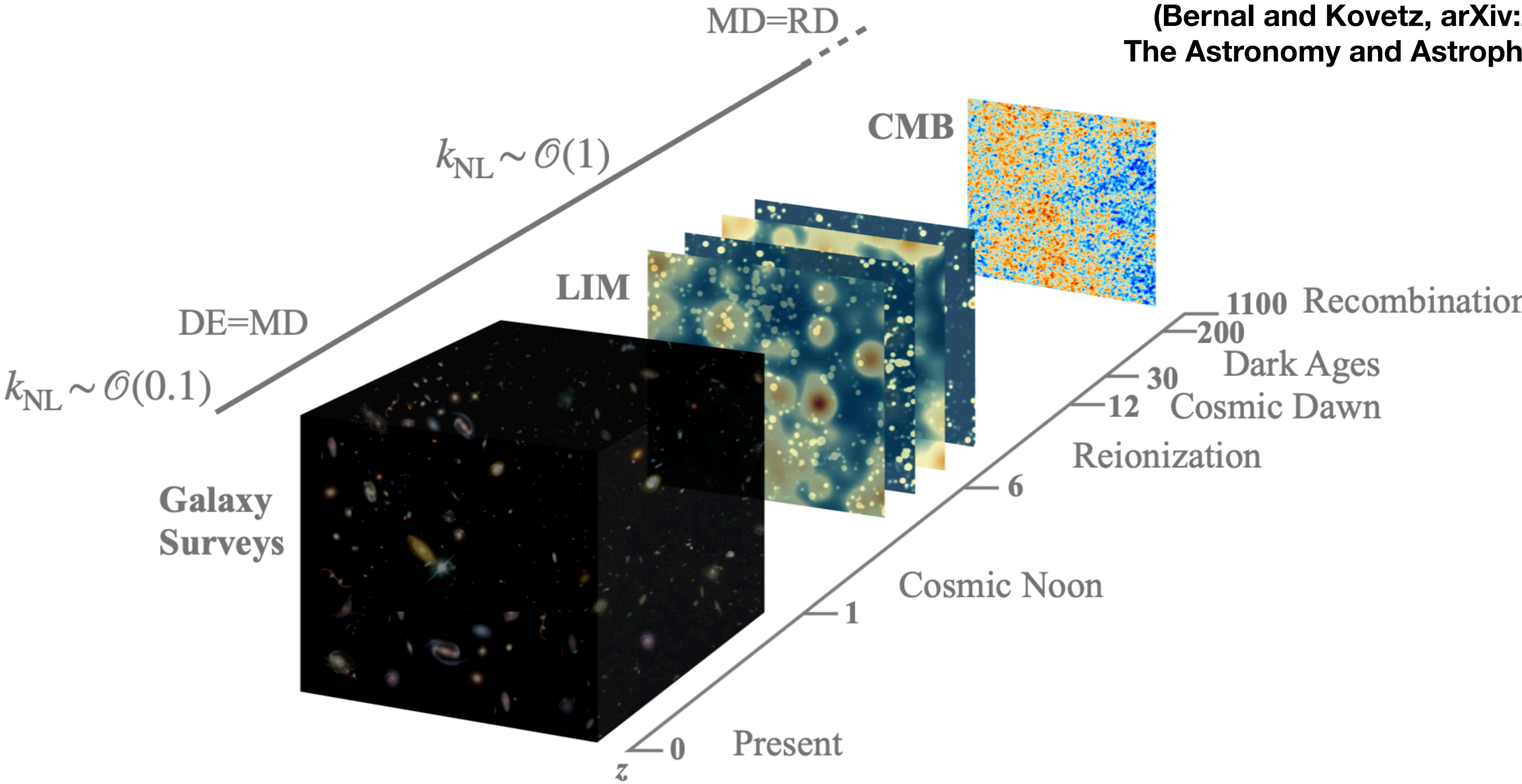

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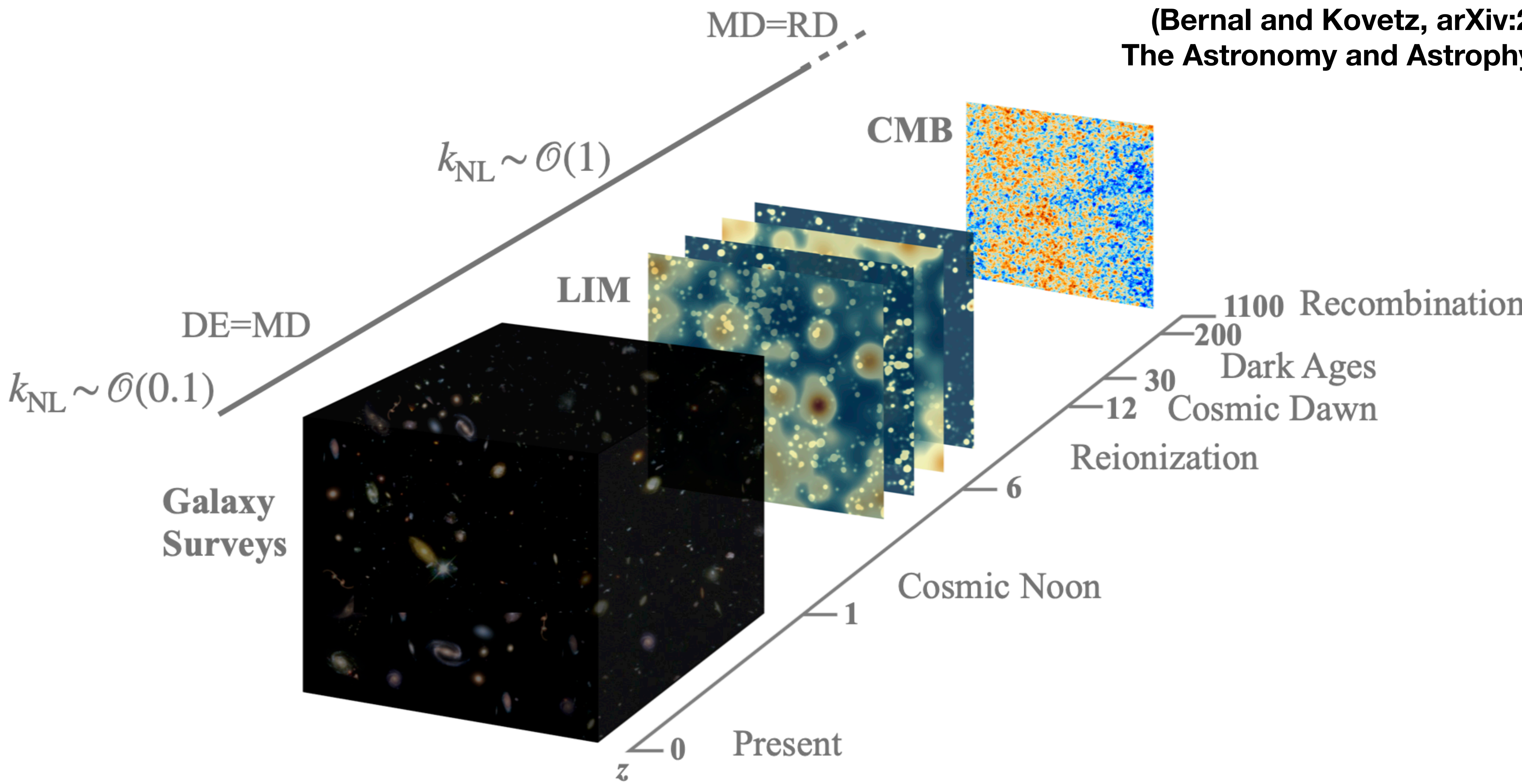

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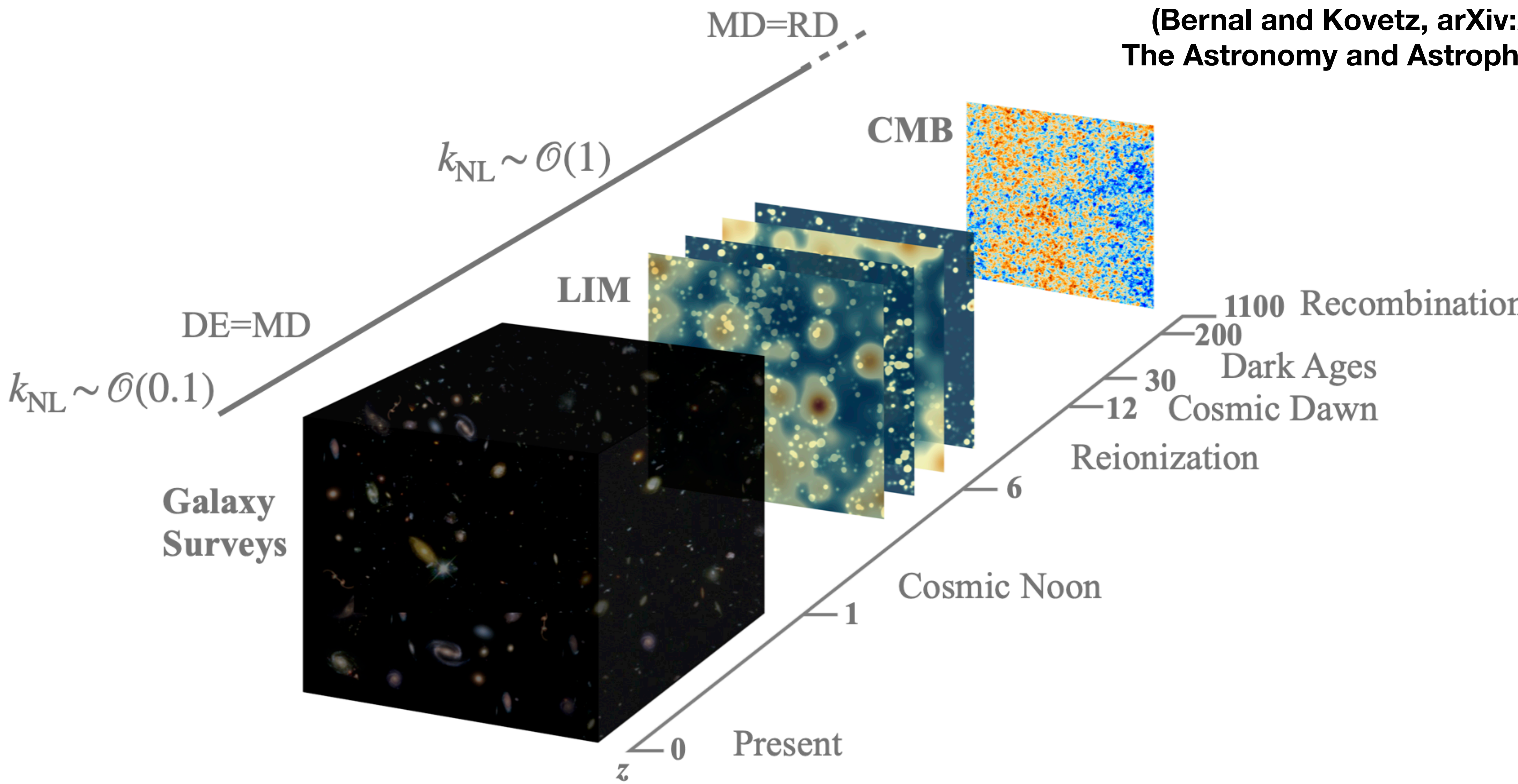

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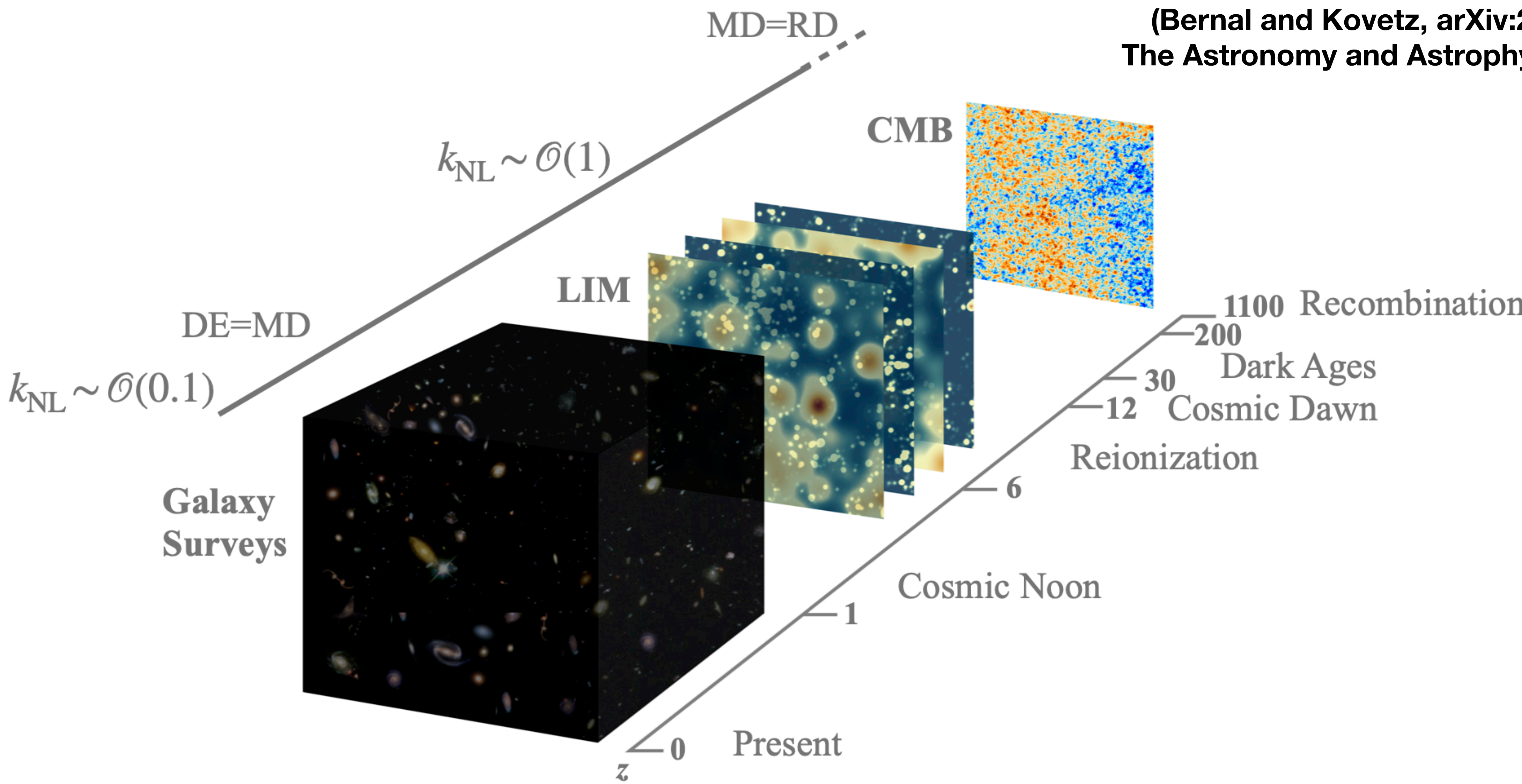

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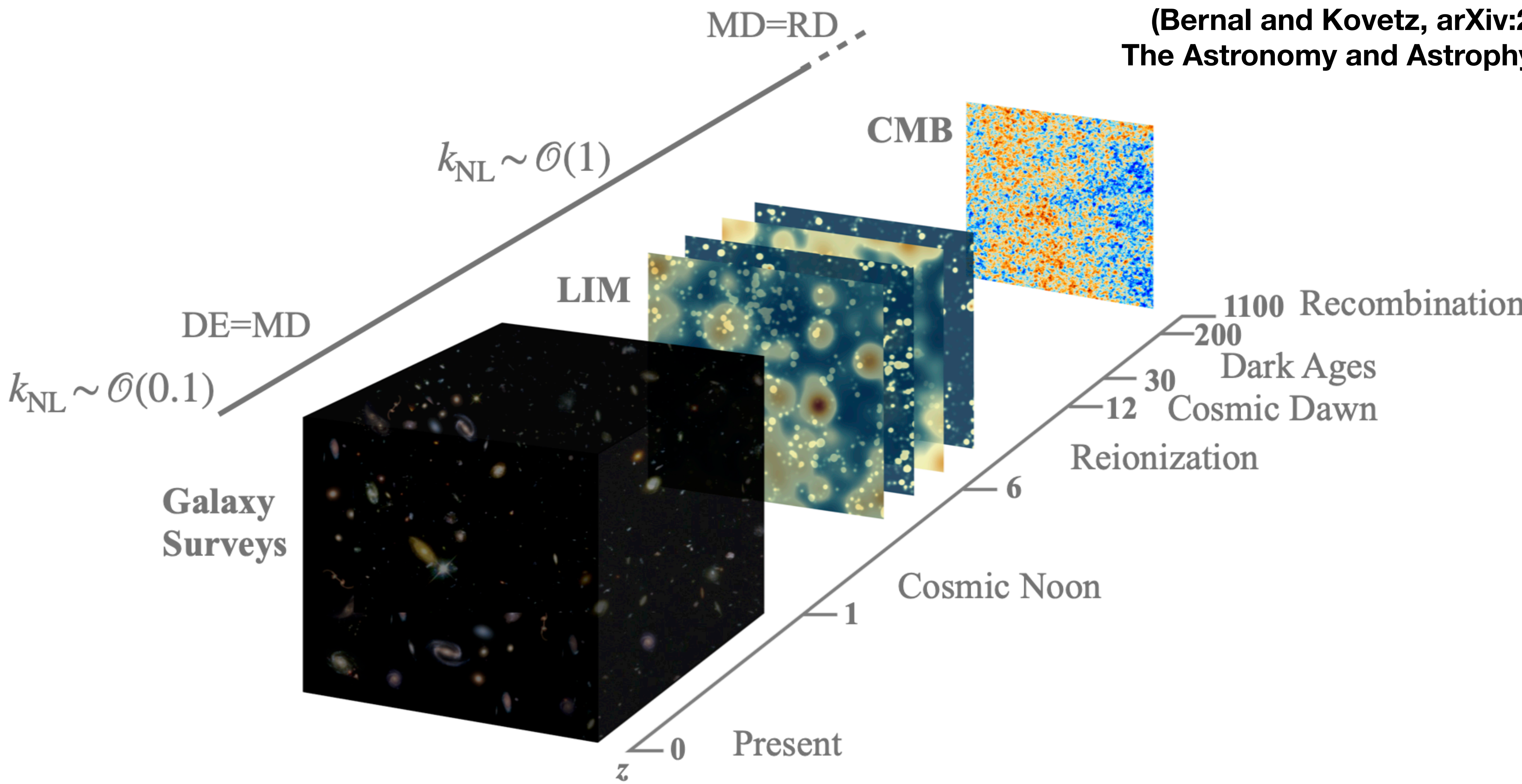

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21cm Cosmology: Sensitivity to New Physics

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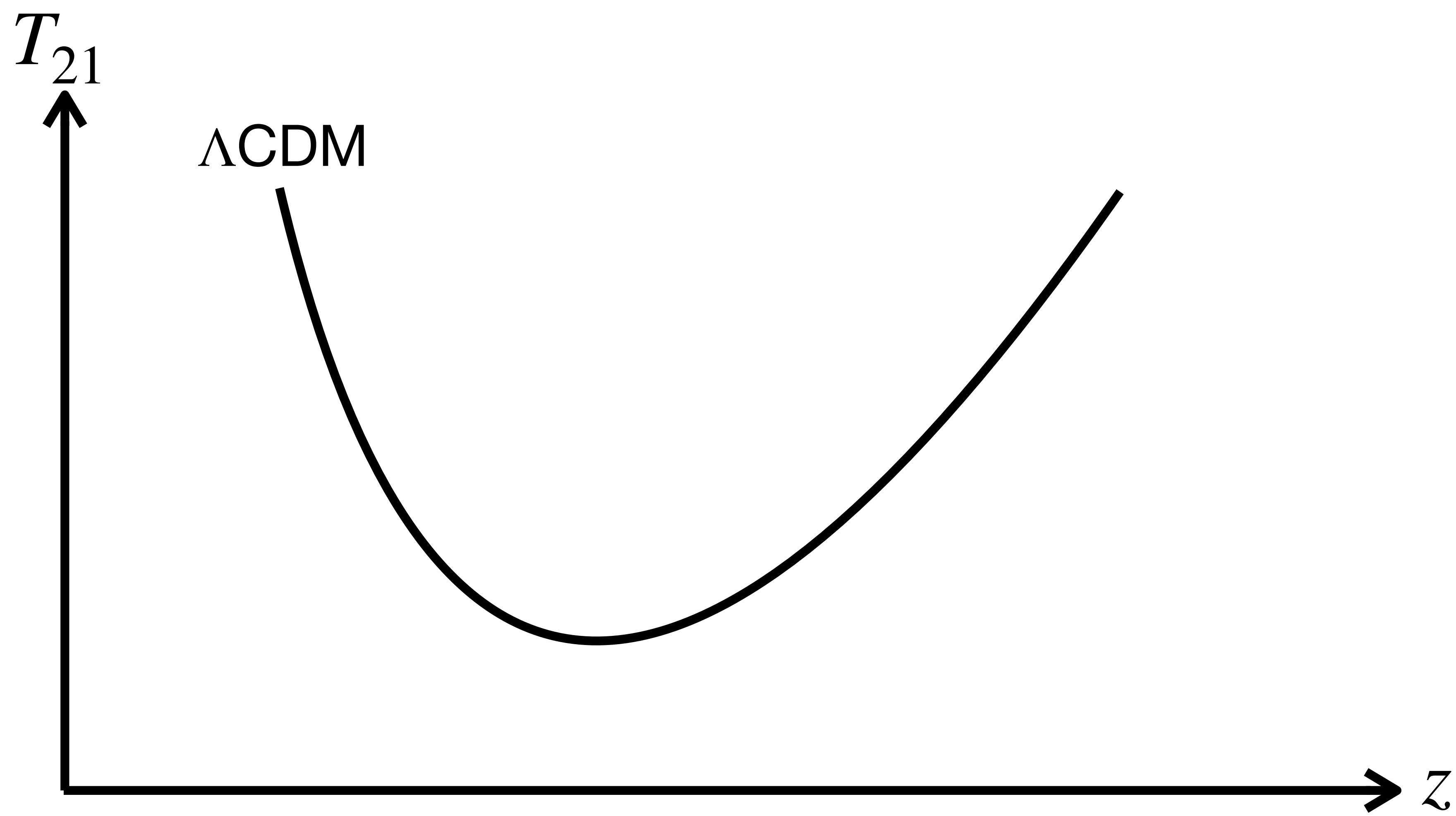
Q: For global signal hunters, how does new physics affect the signal?

21cm Cosmology: Sensitivity to New Physics



Credit: J. Flitter

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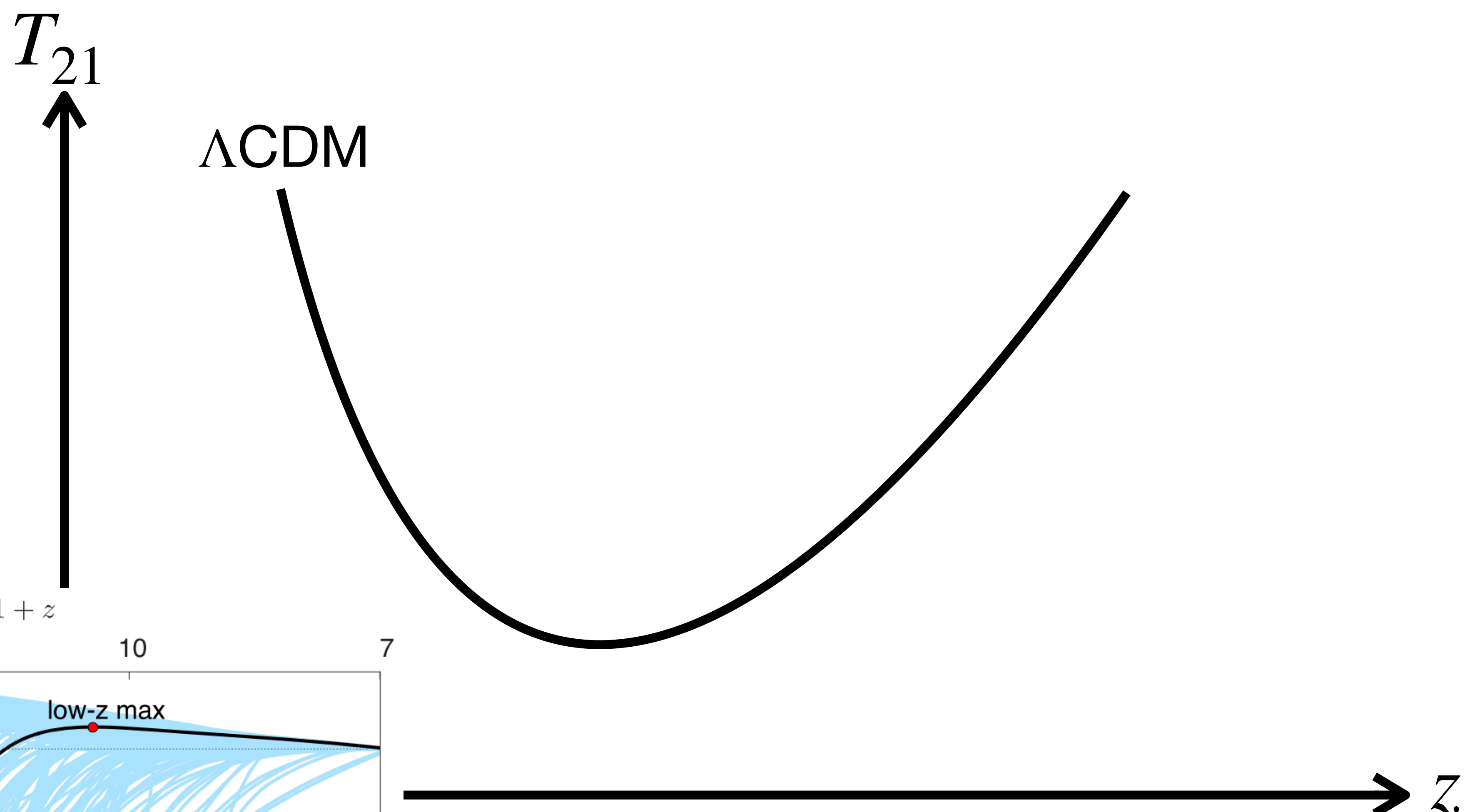

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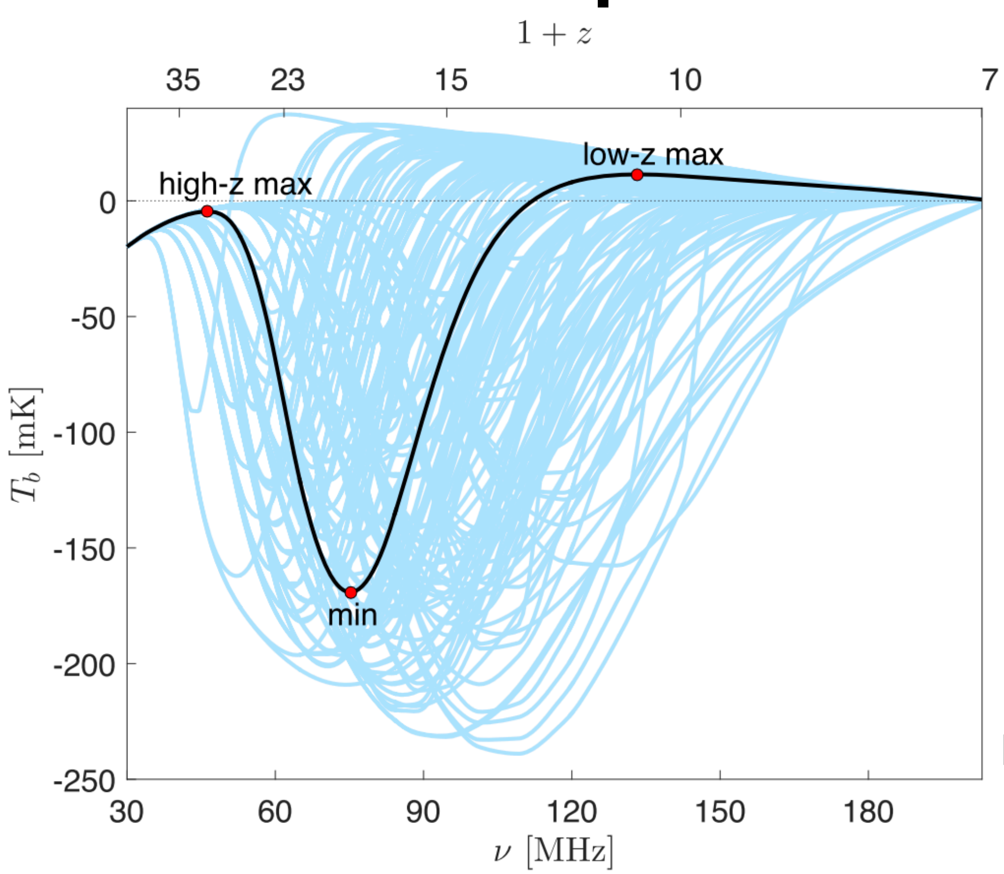

Reis, Fialkov and Barkana, MNRAS 2017

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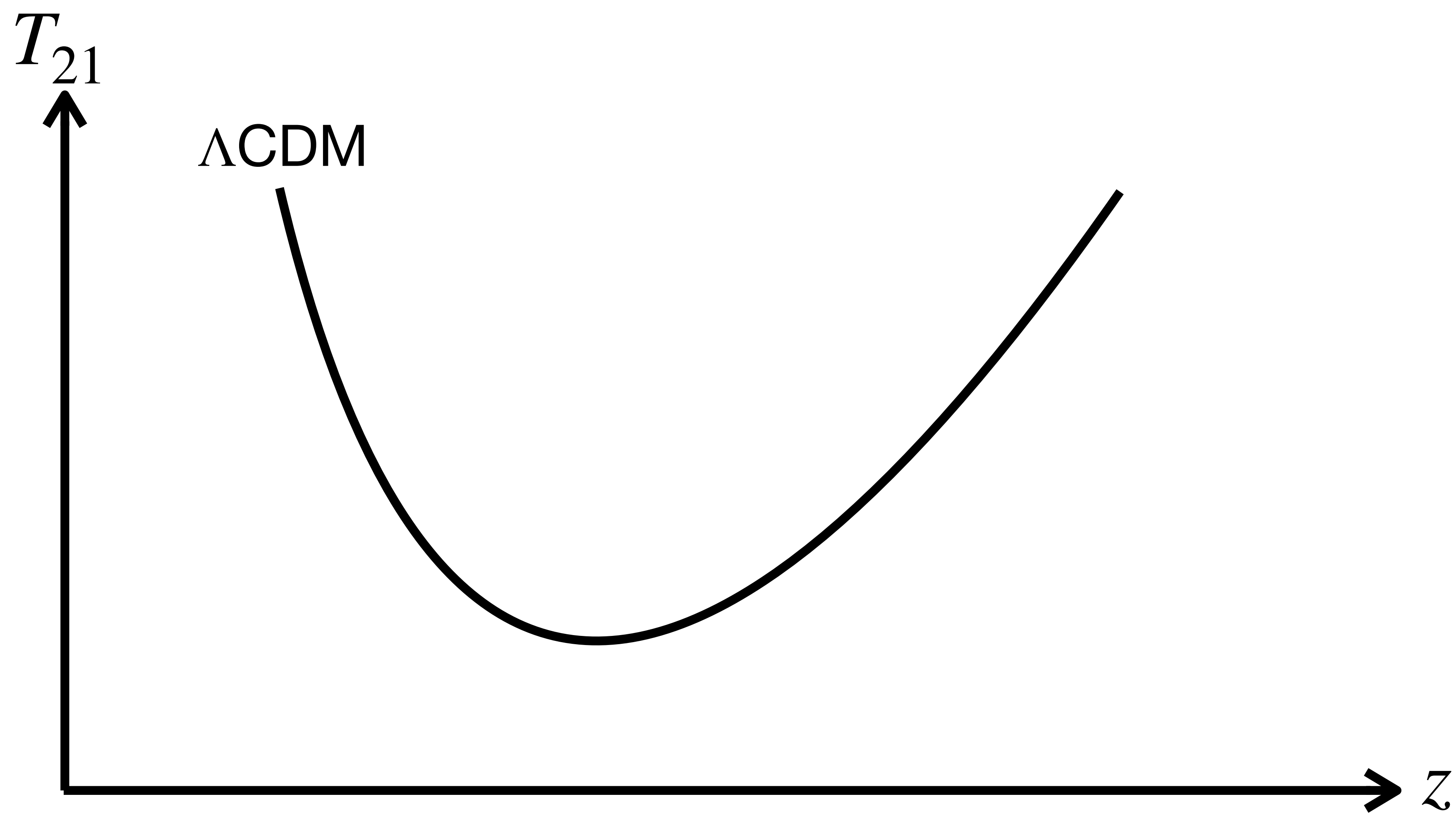

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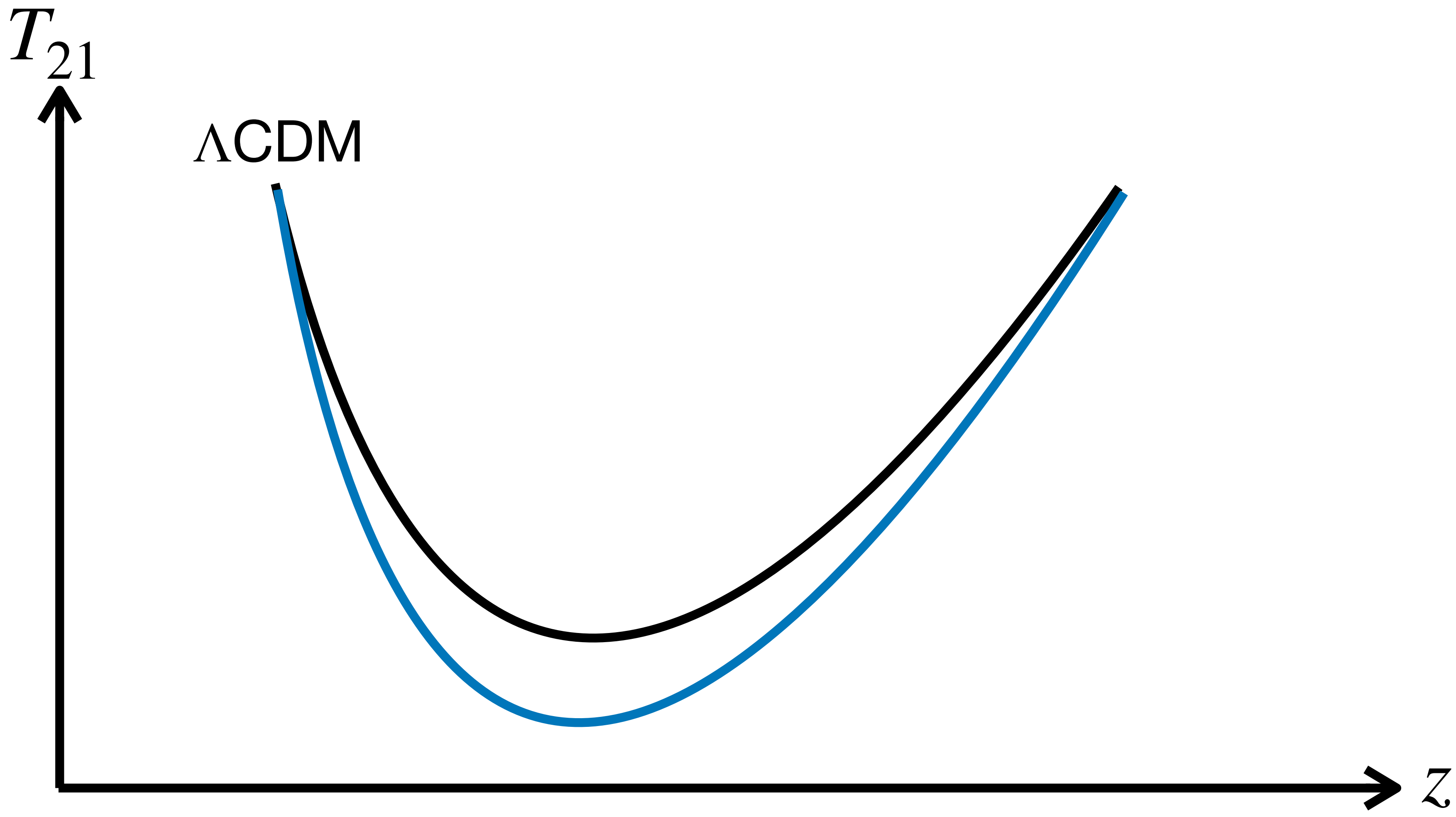

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“Something” cools down the IGM!

e.g.: DM scatters with baryons

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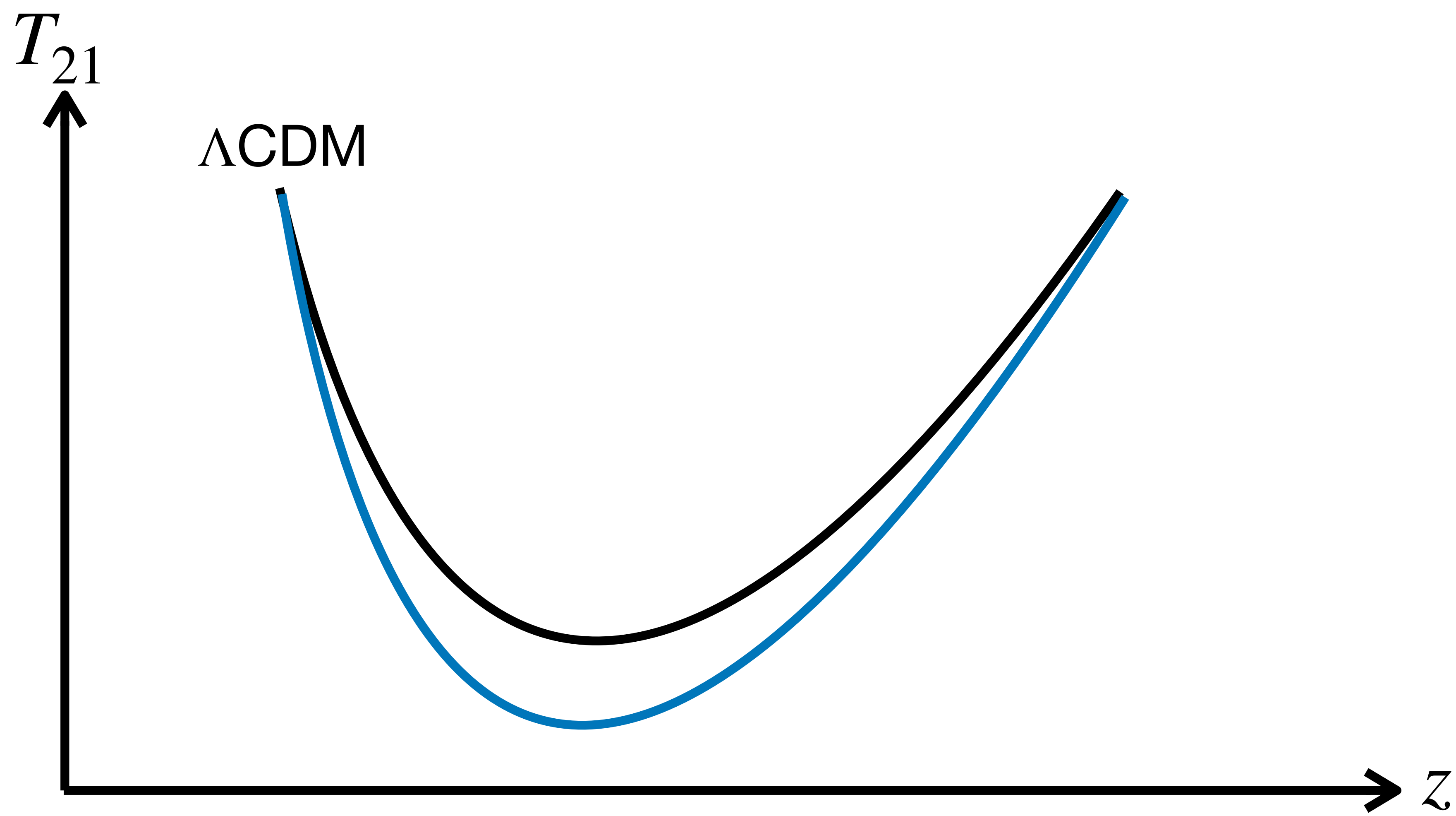

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→ see Rennan's and Omer's talks, also later here

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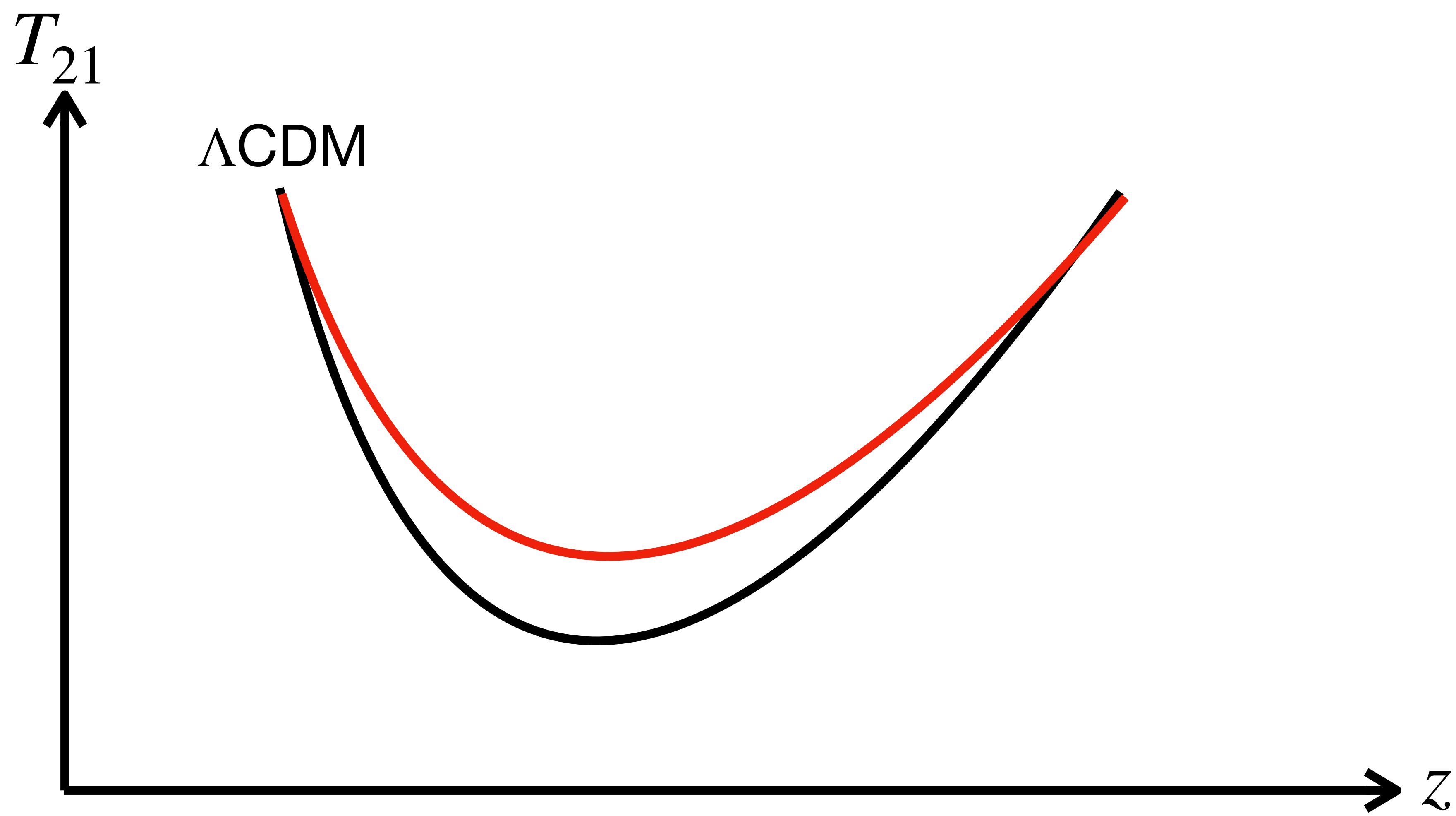

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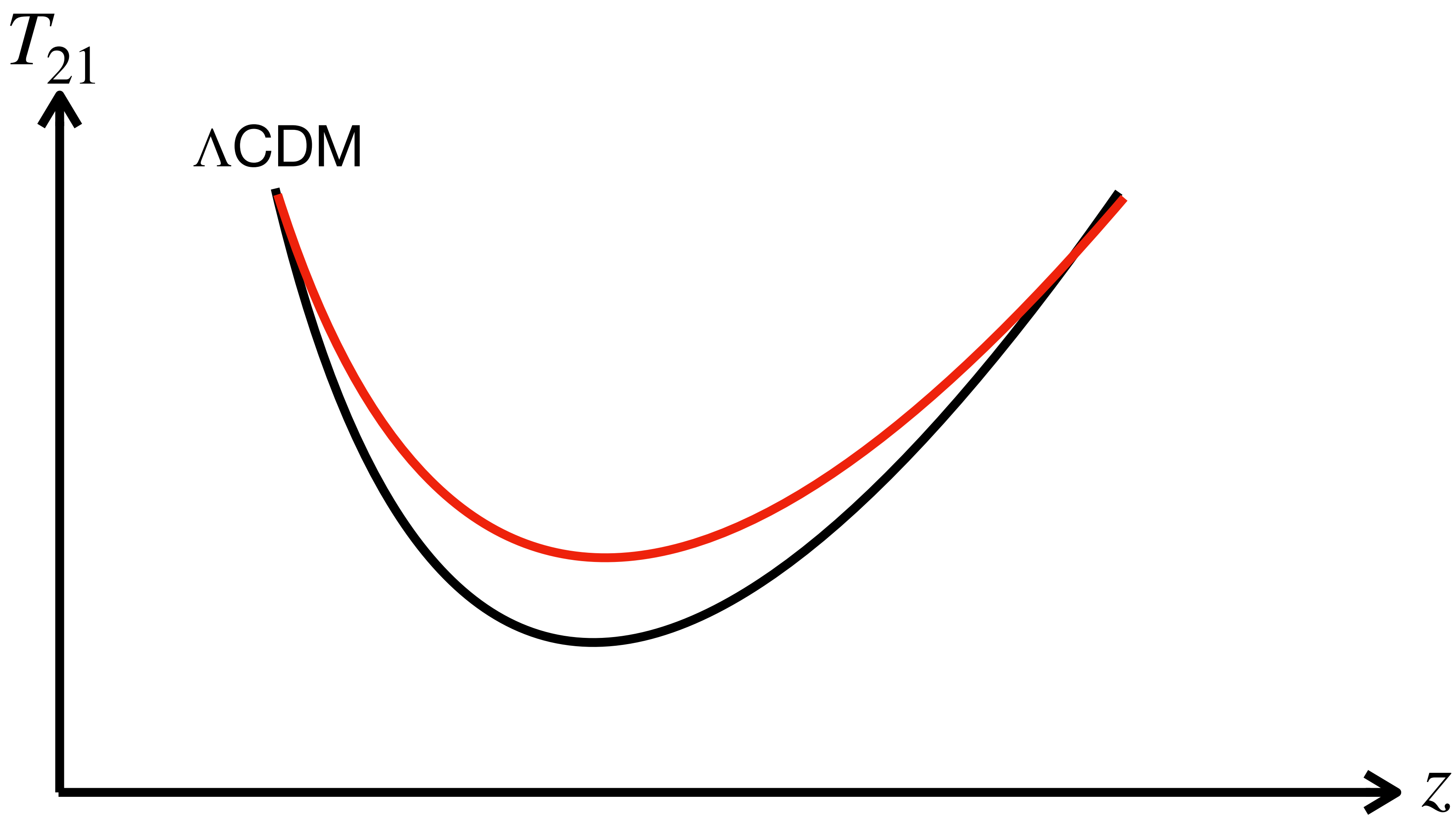

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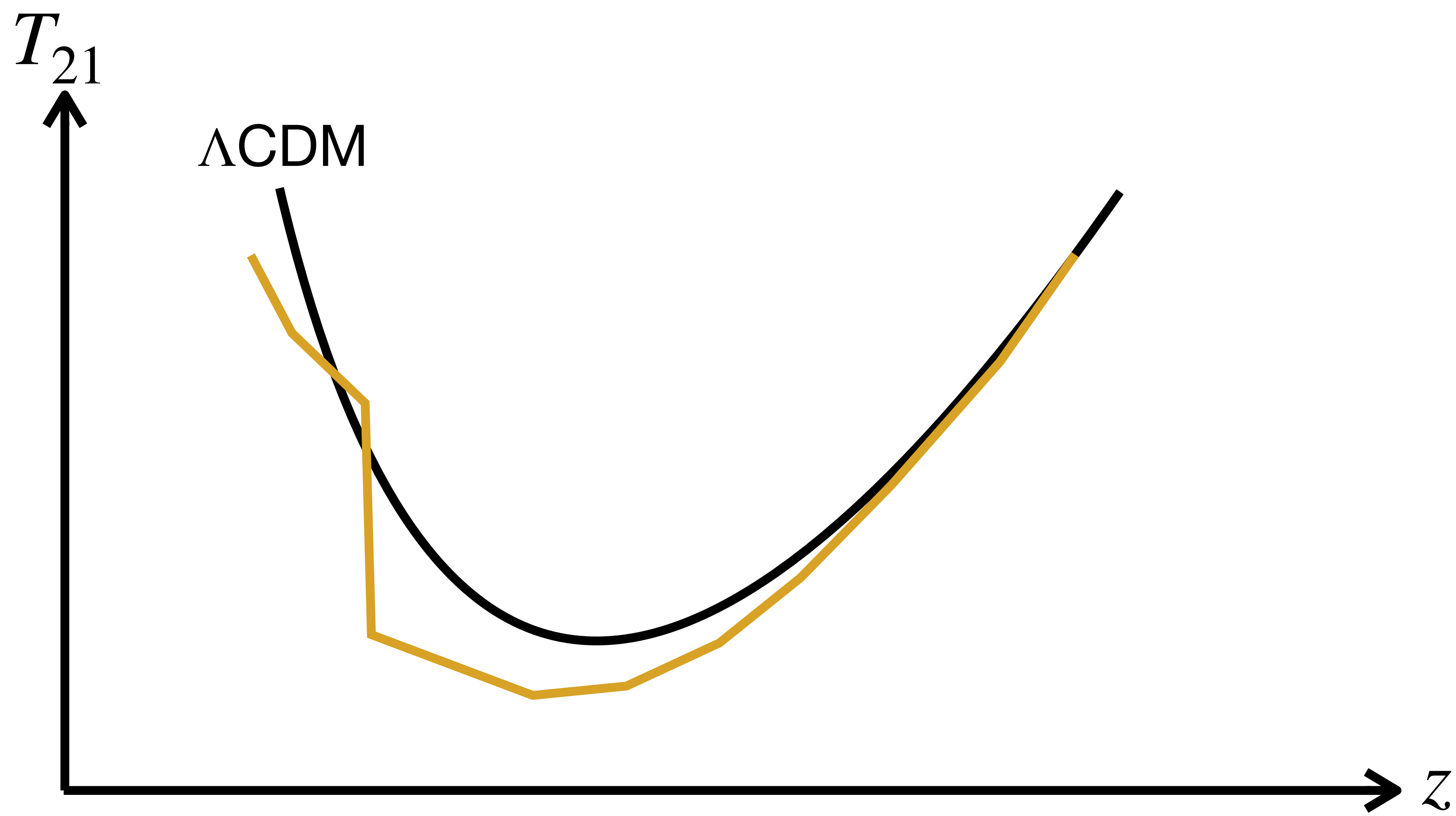

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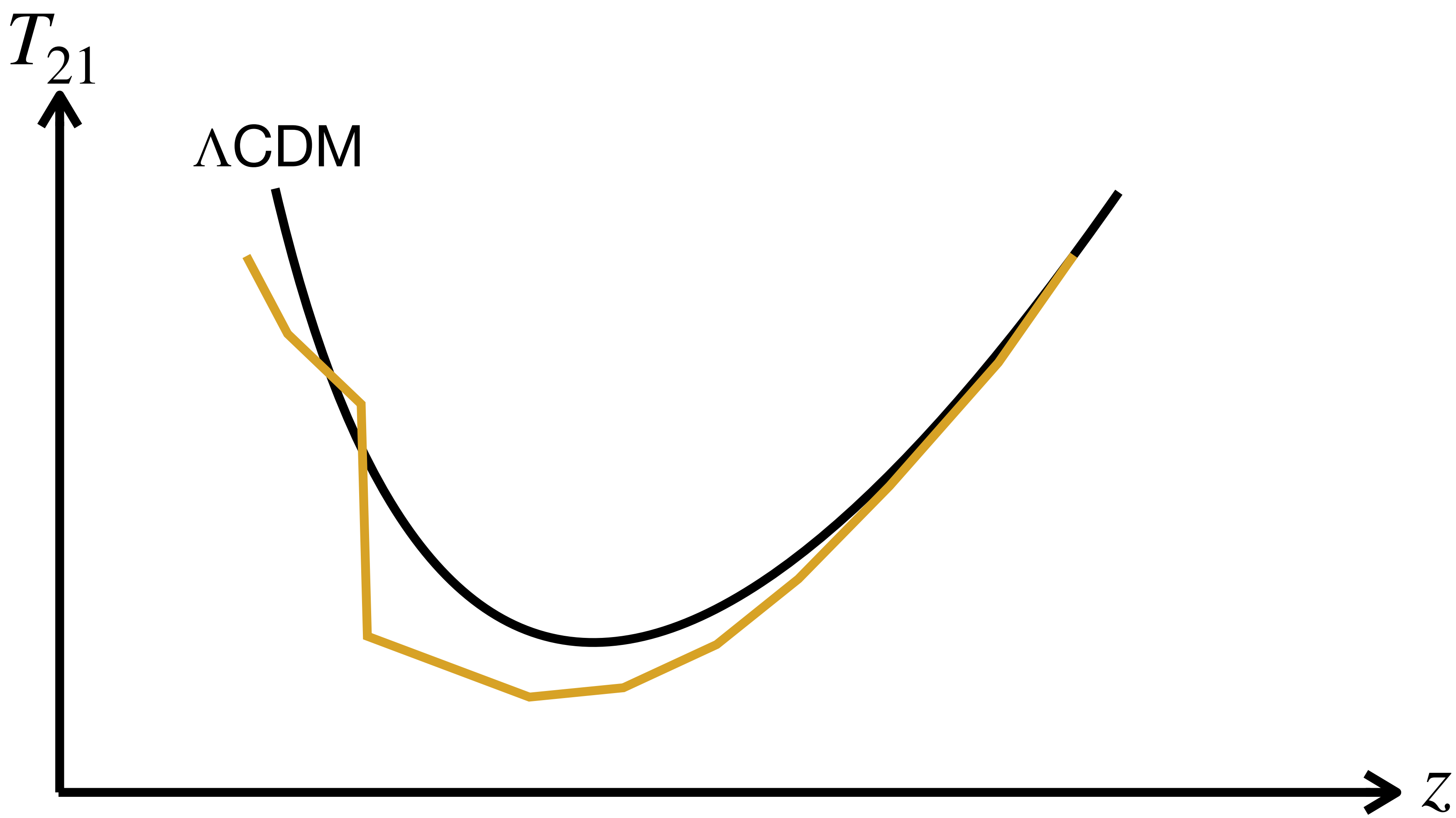

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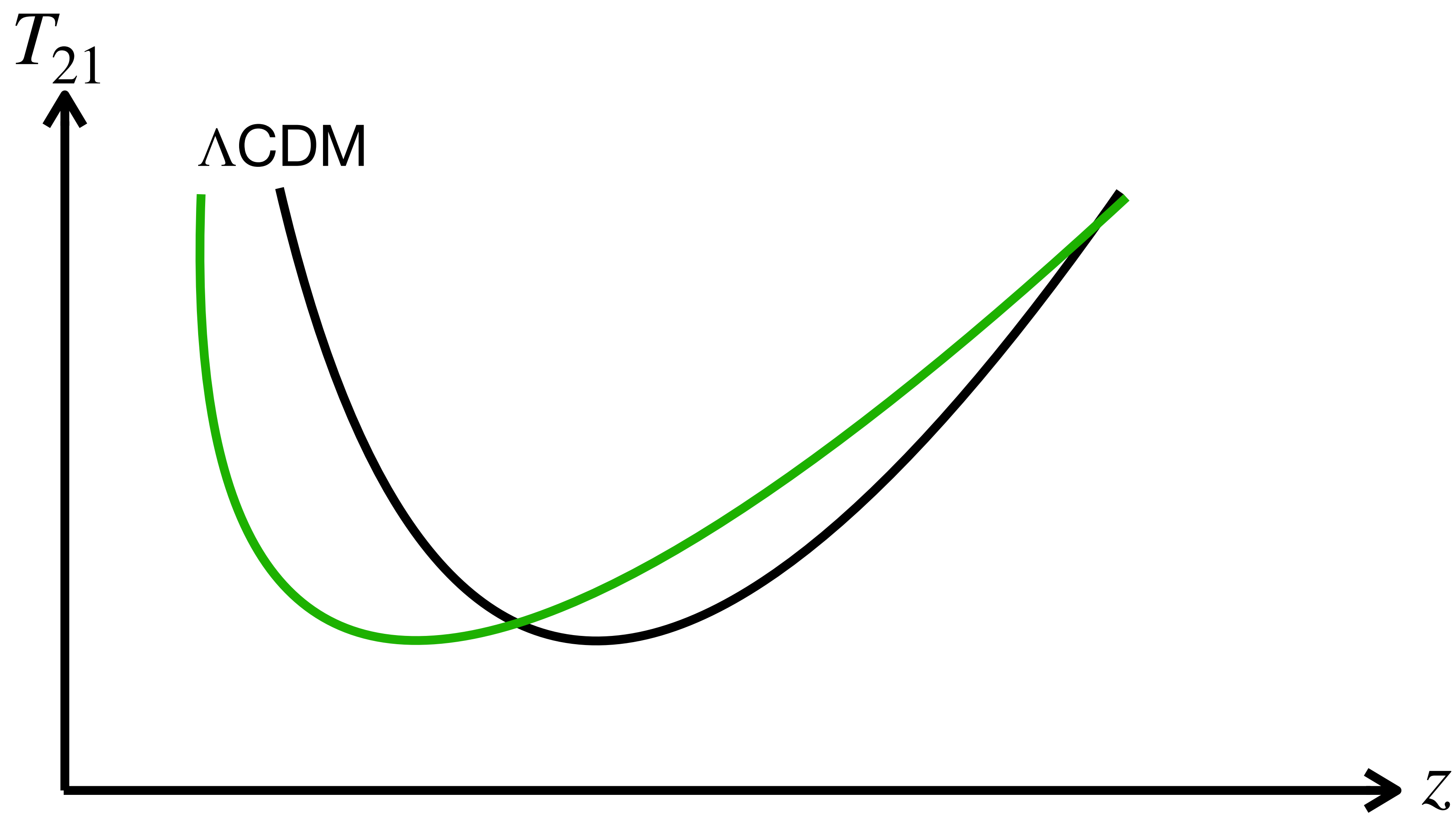

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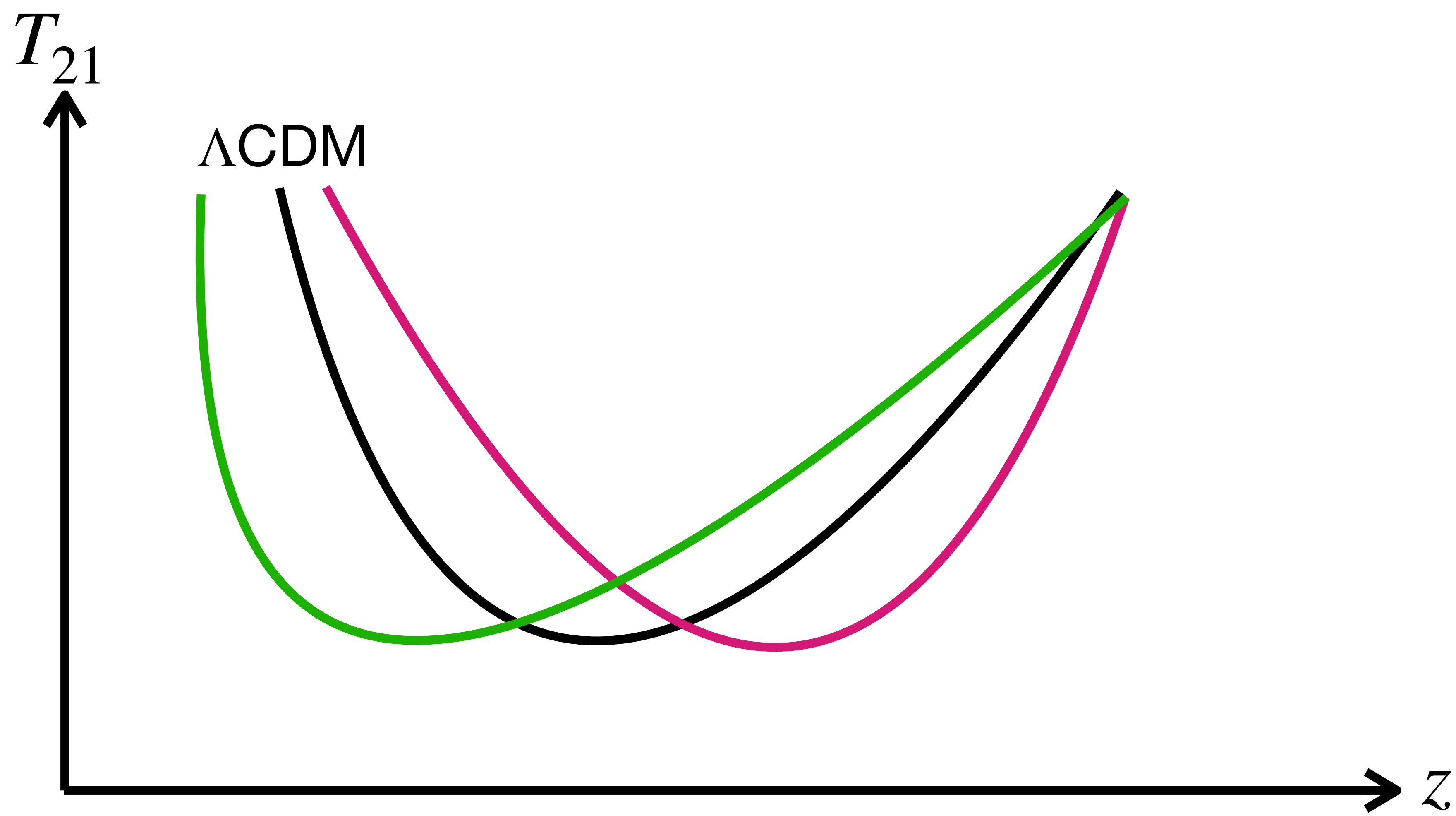

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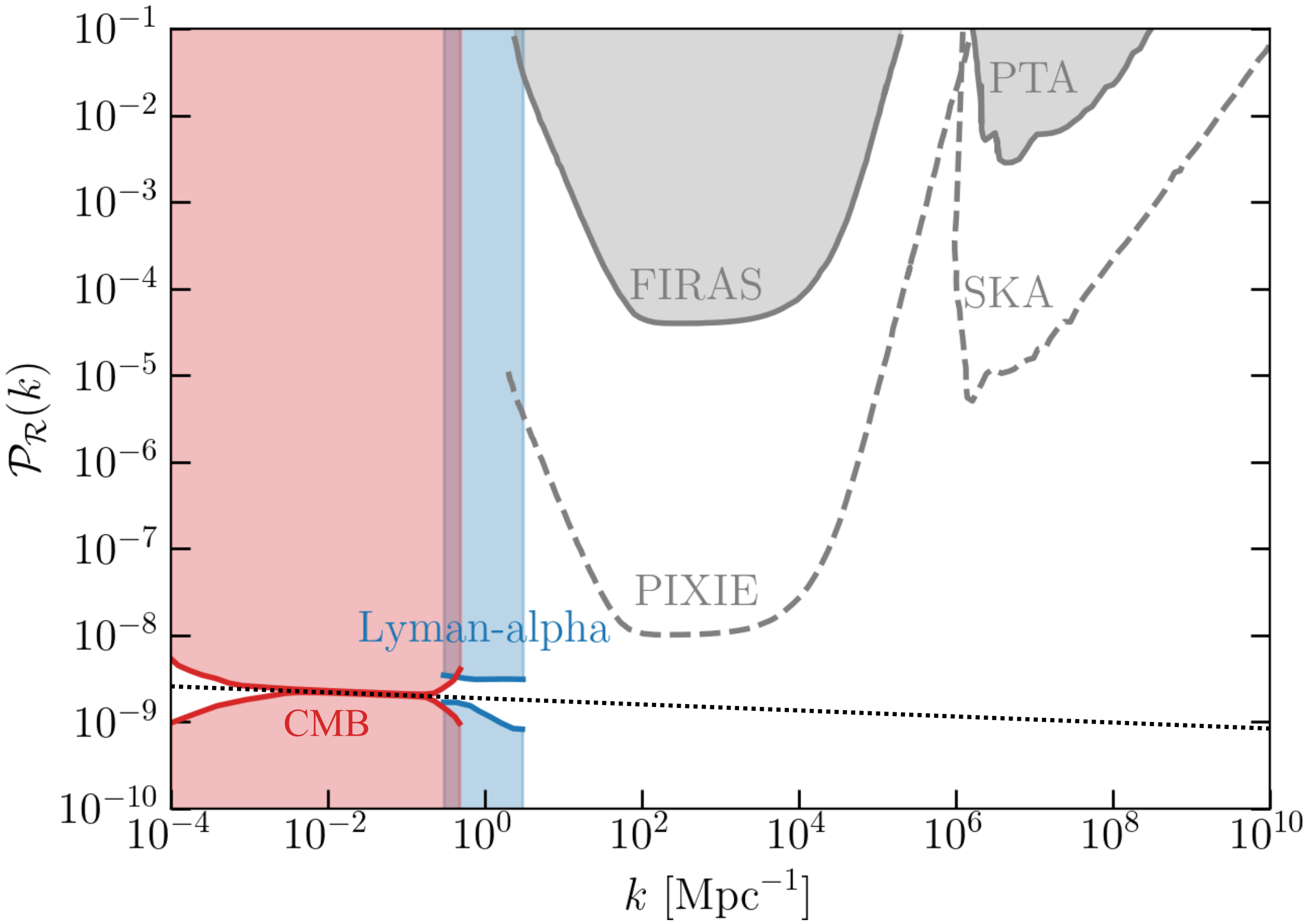

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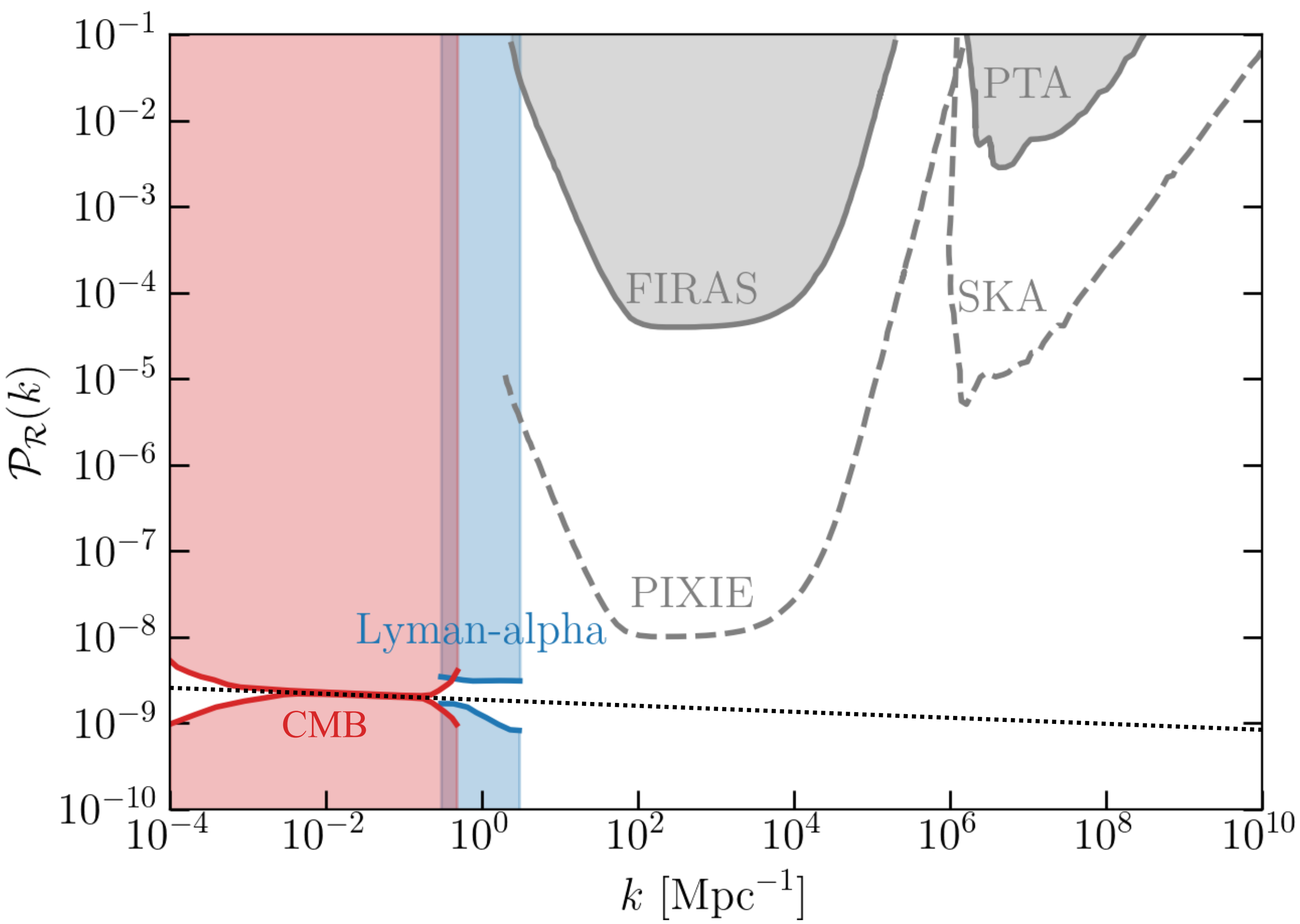

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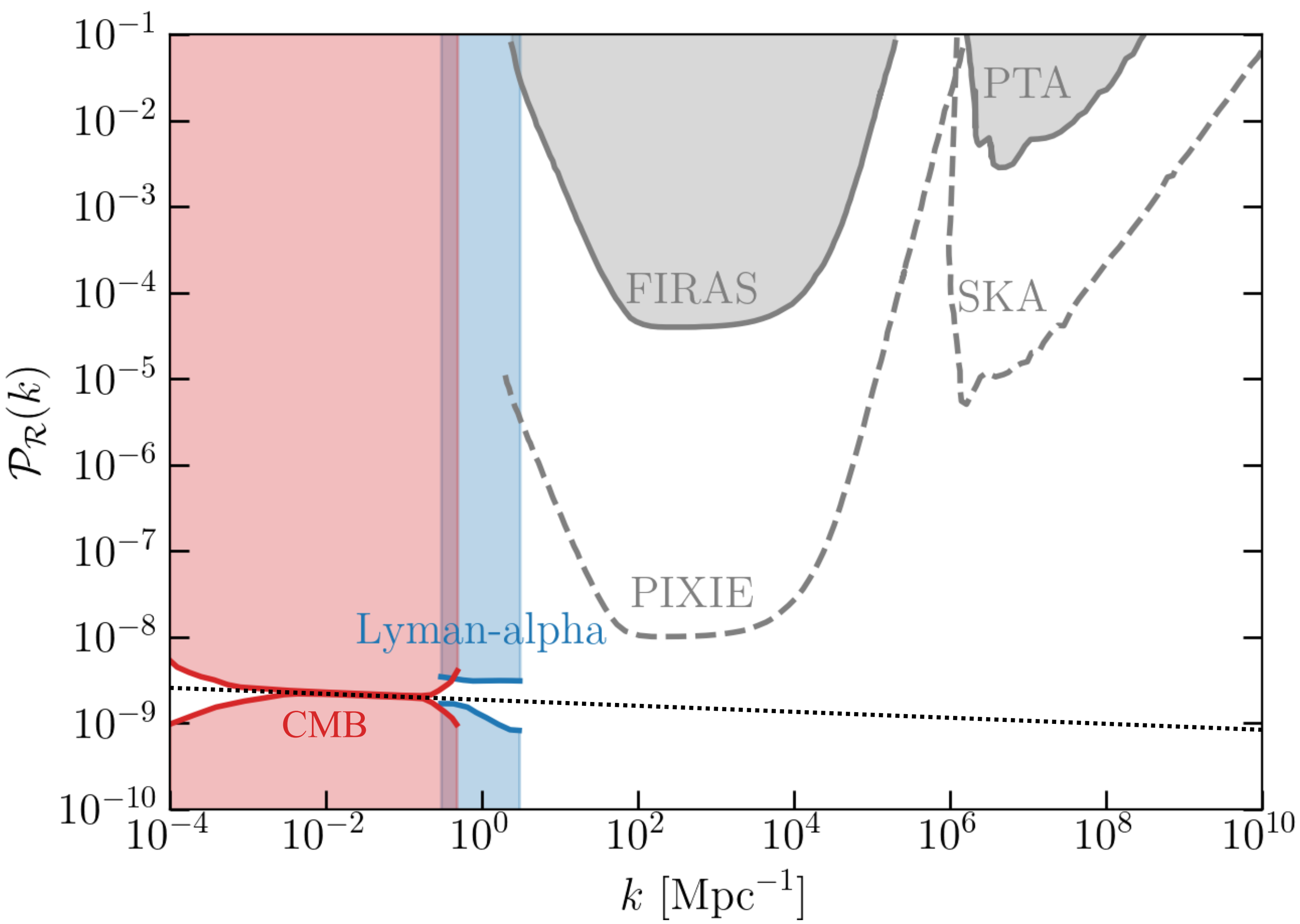

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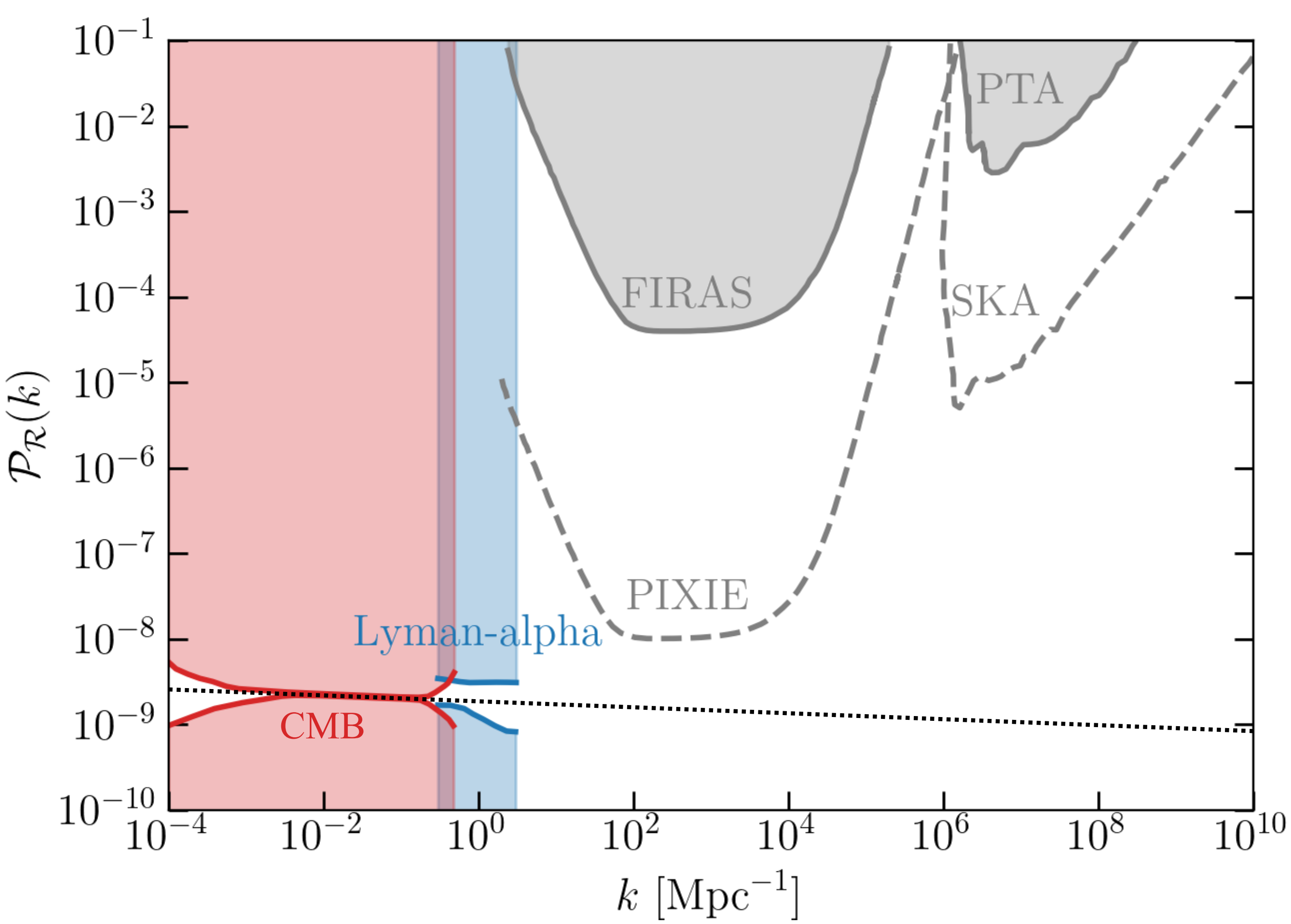

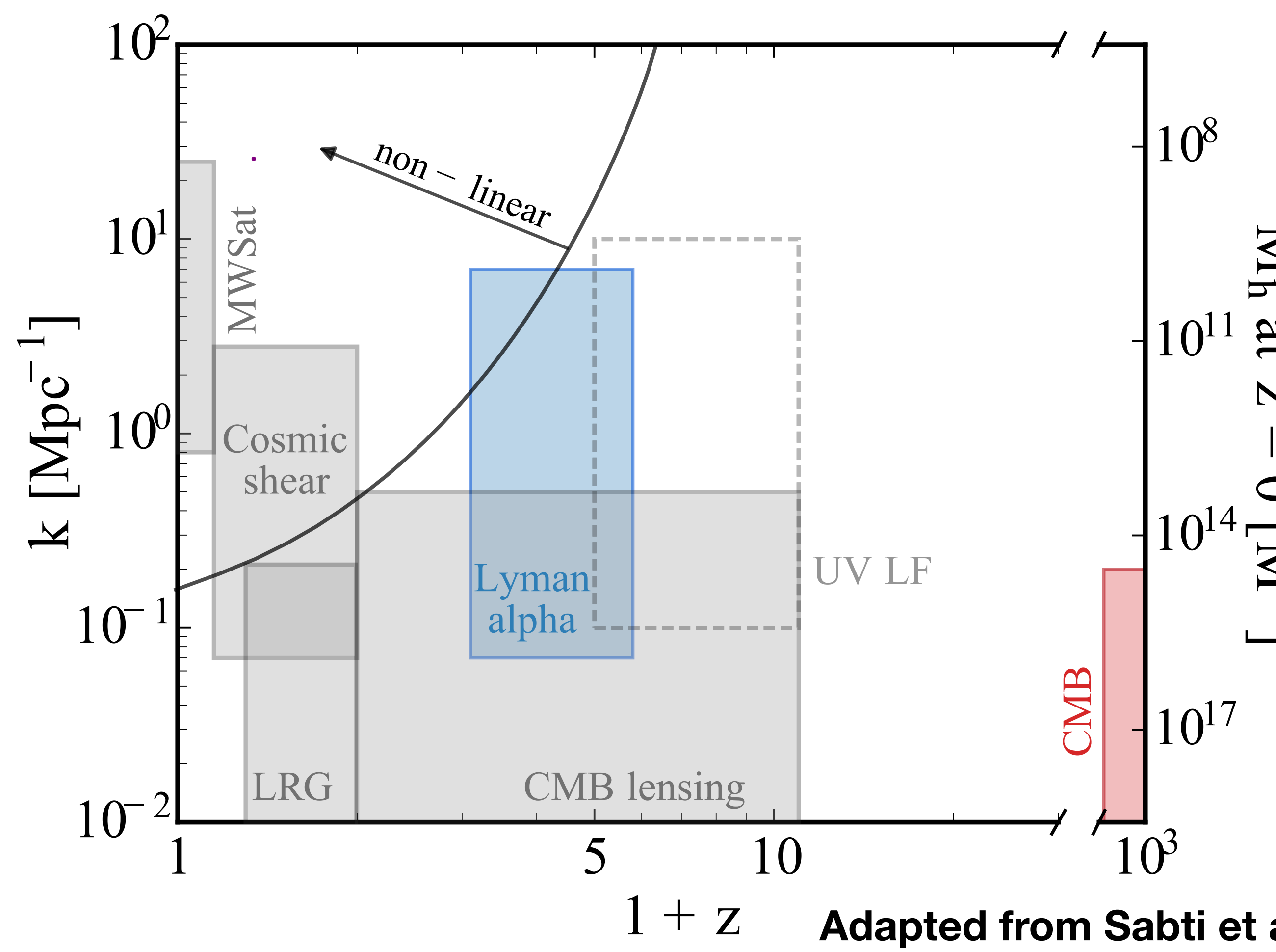

Adapted from Sabti et al., ApJL 2022

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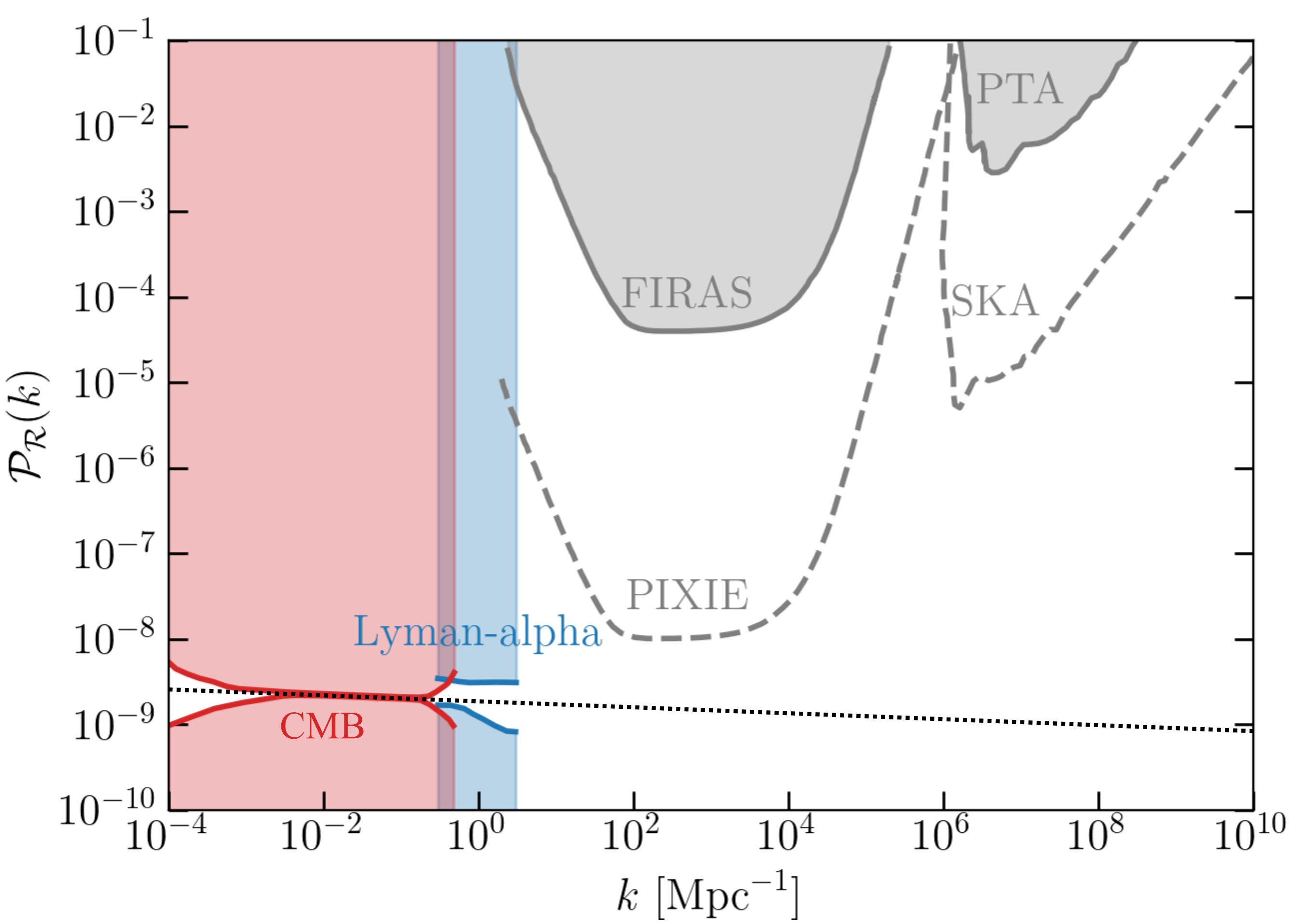

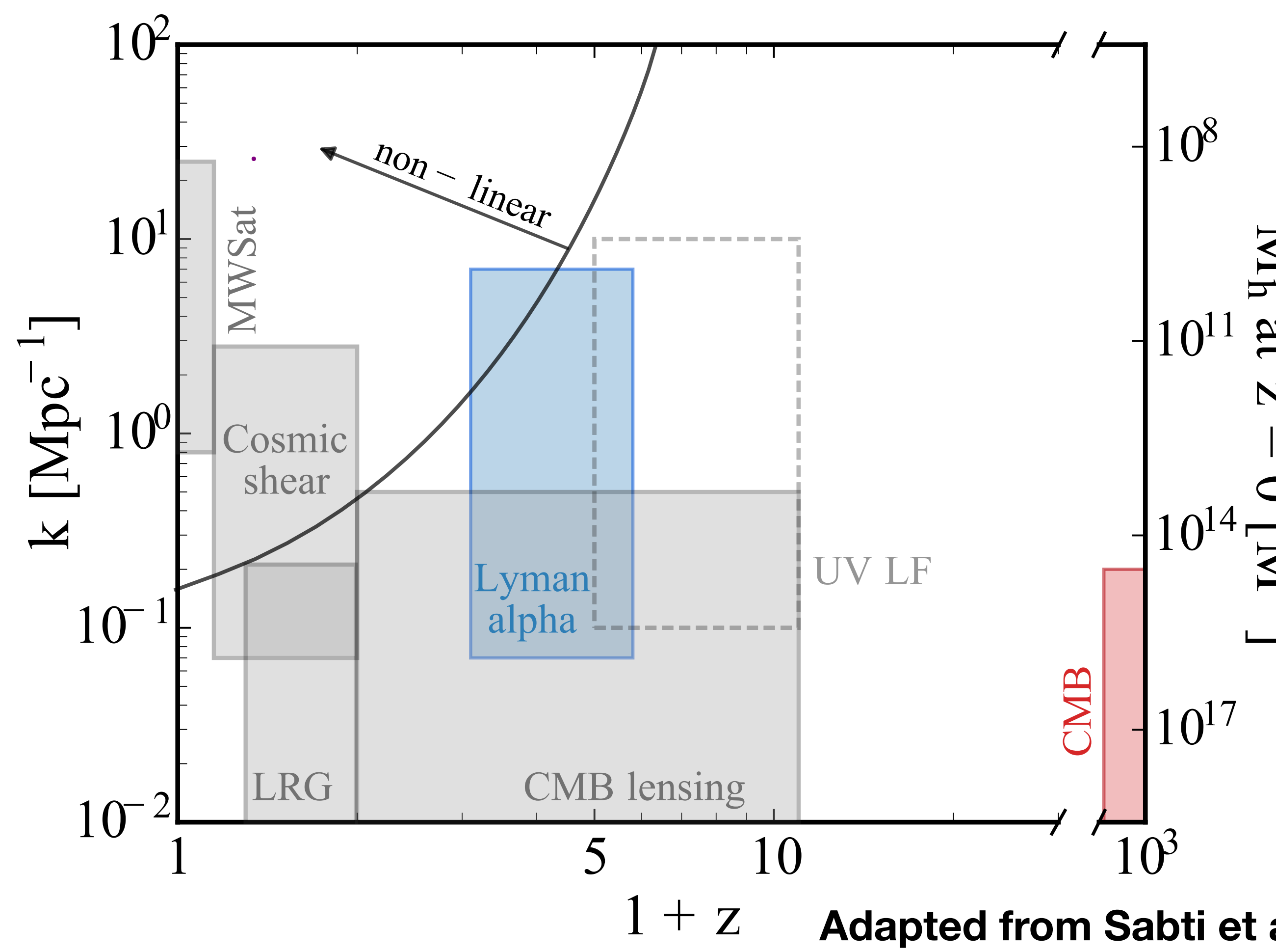

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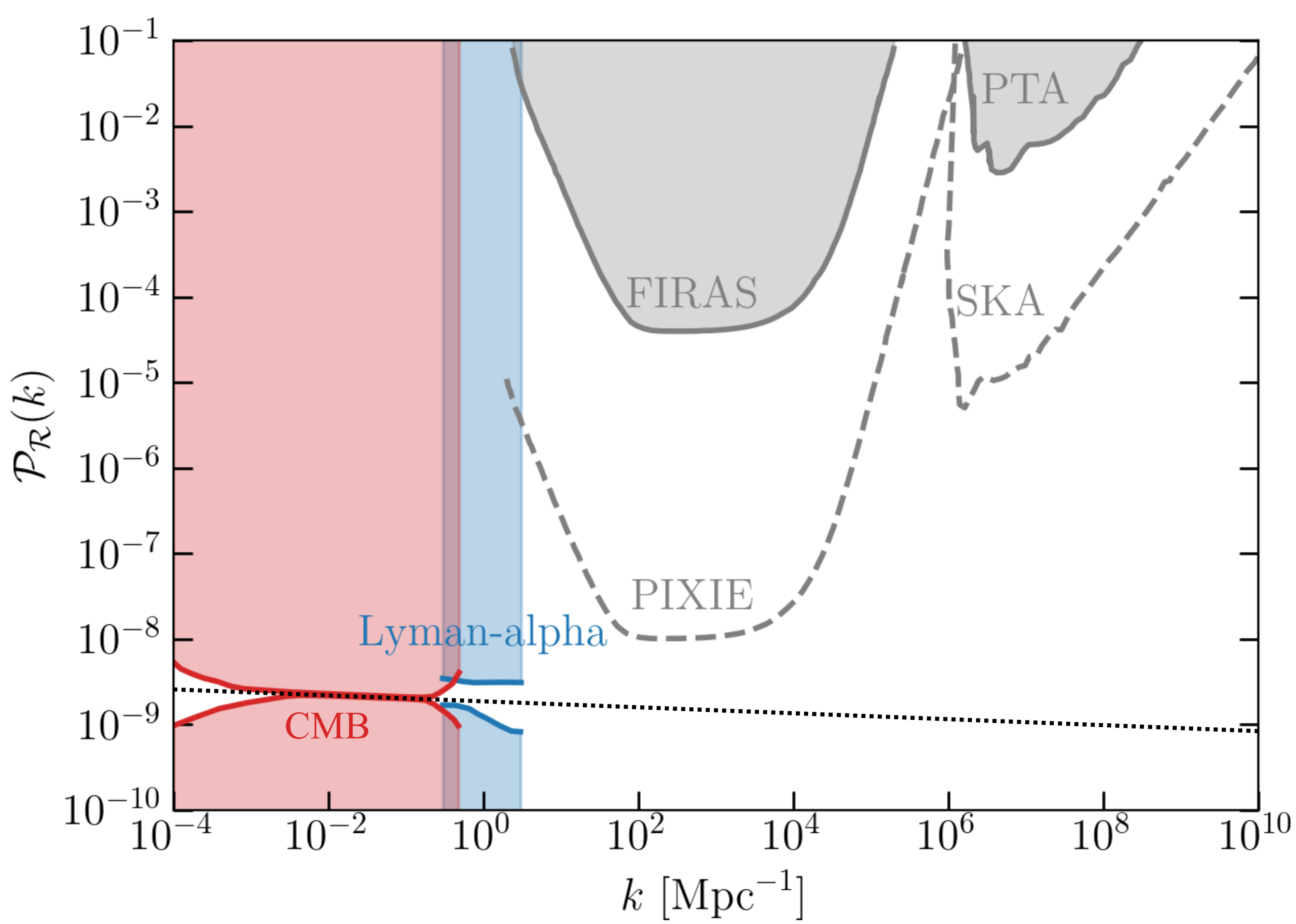

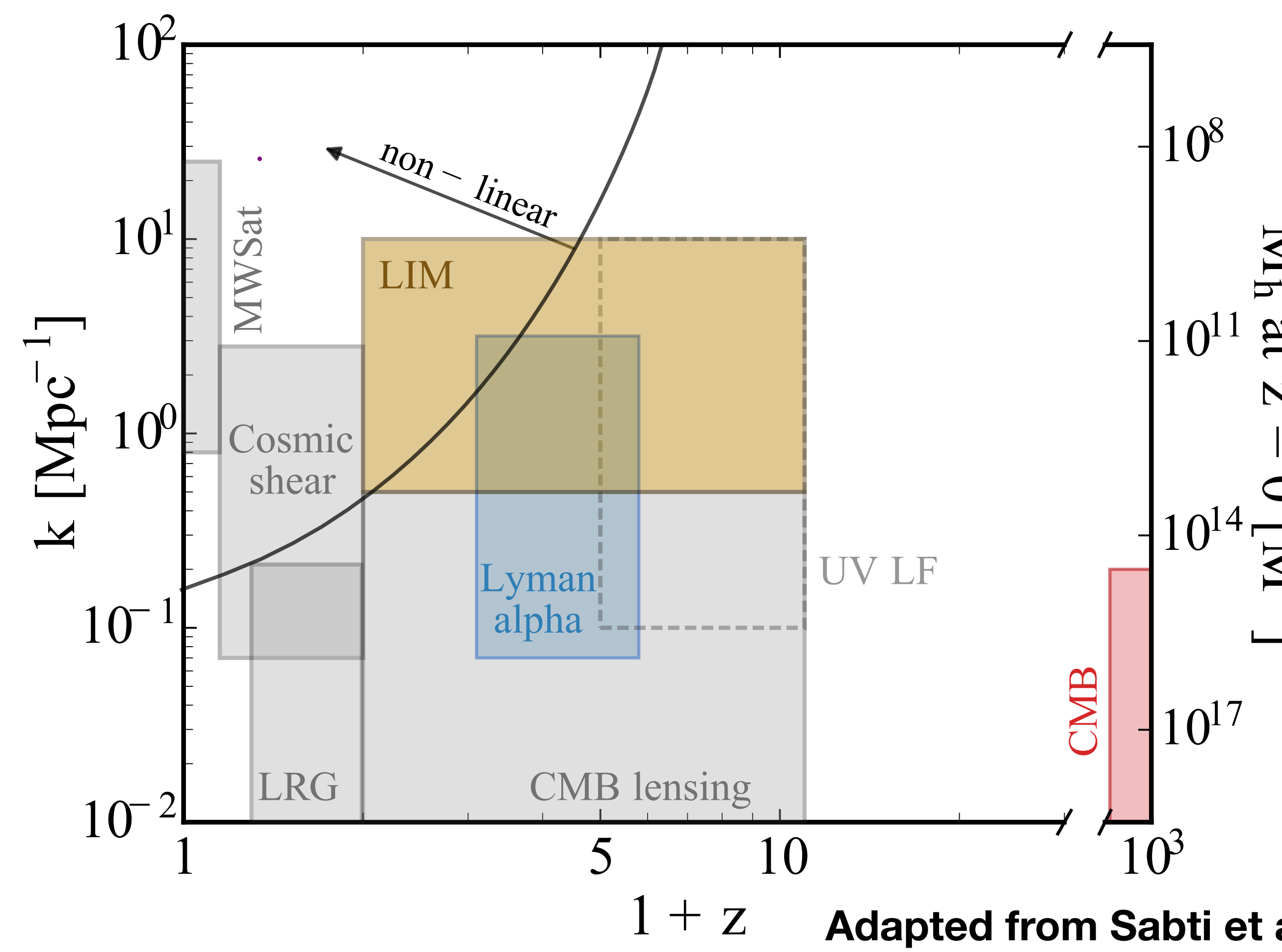

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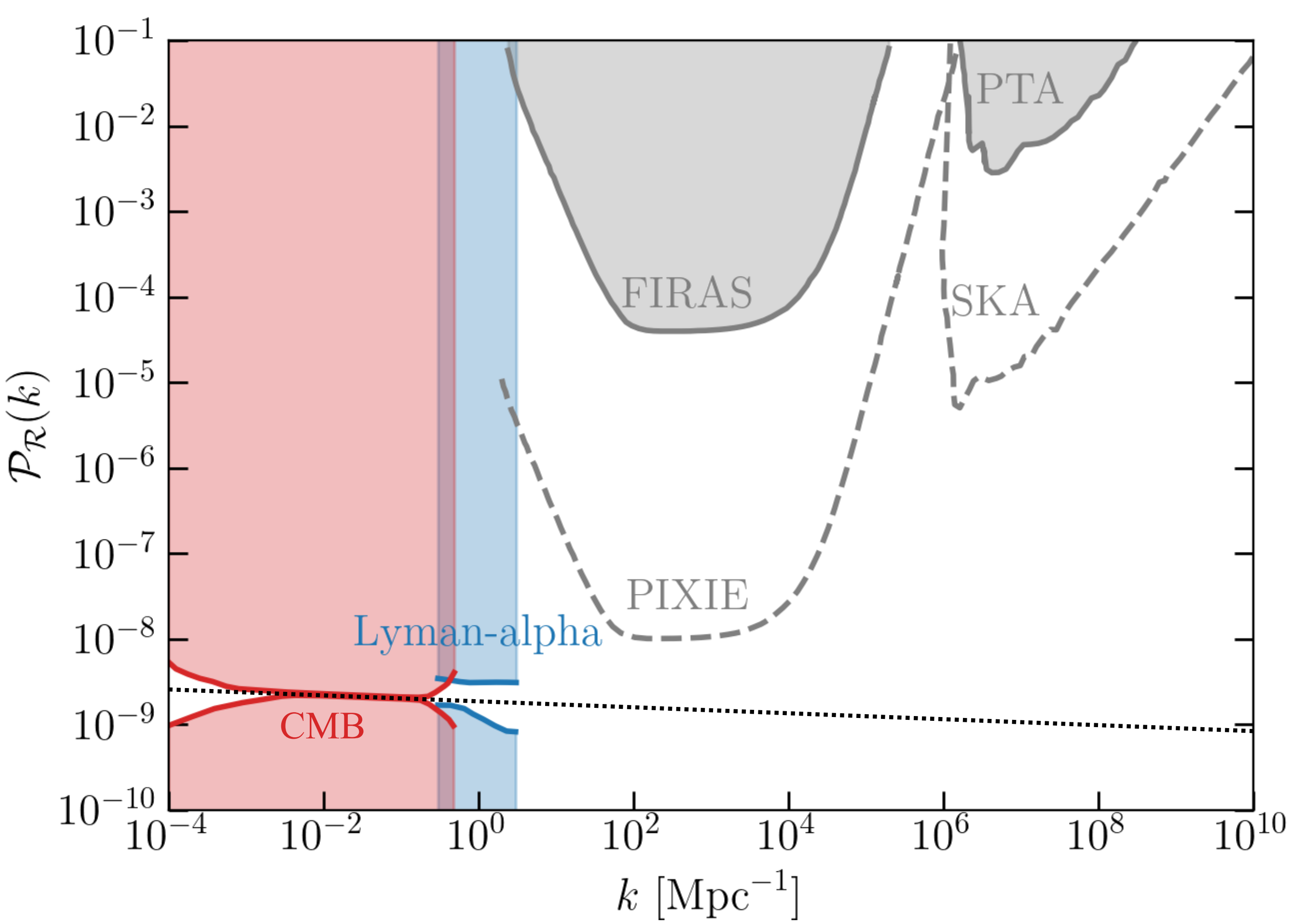
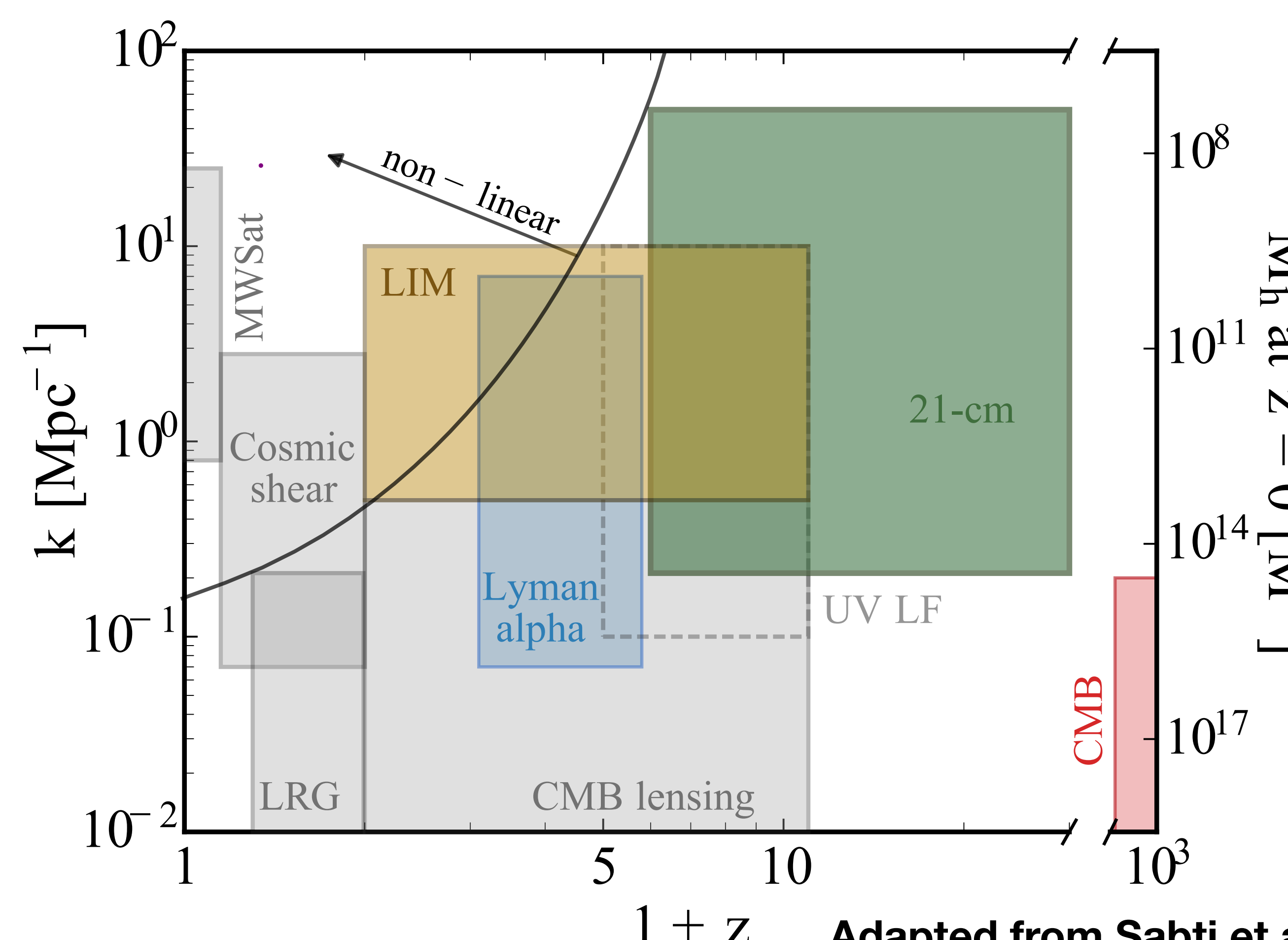
- 21-cm: Sensitive to the first (and smallest) galaxies in the Universe





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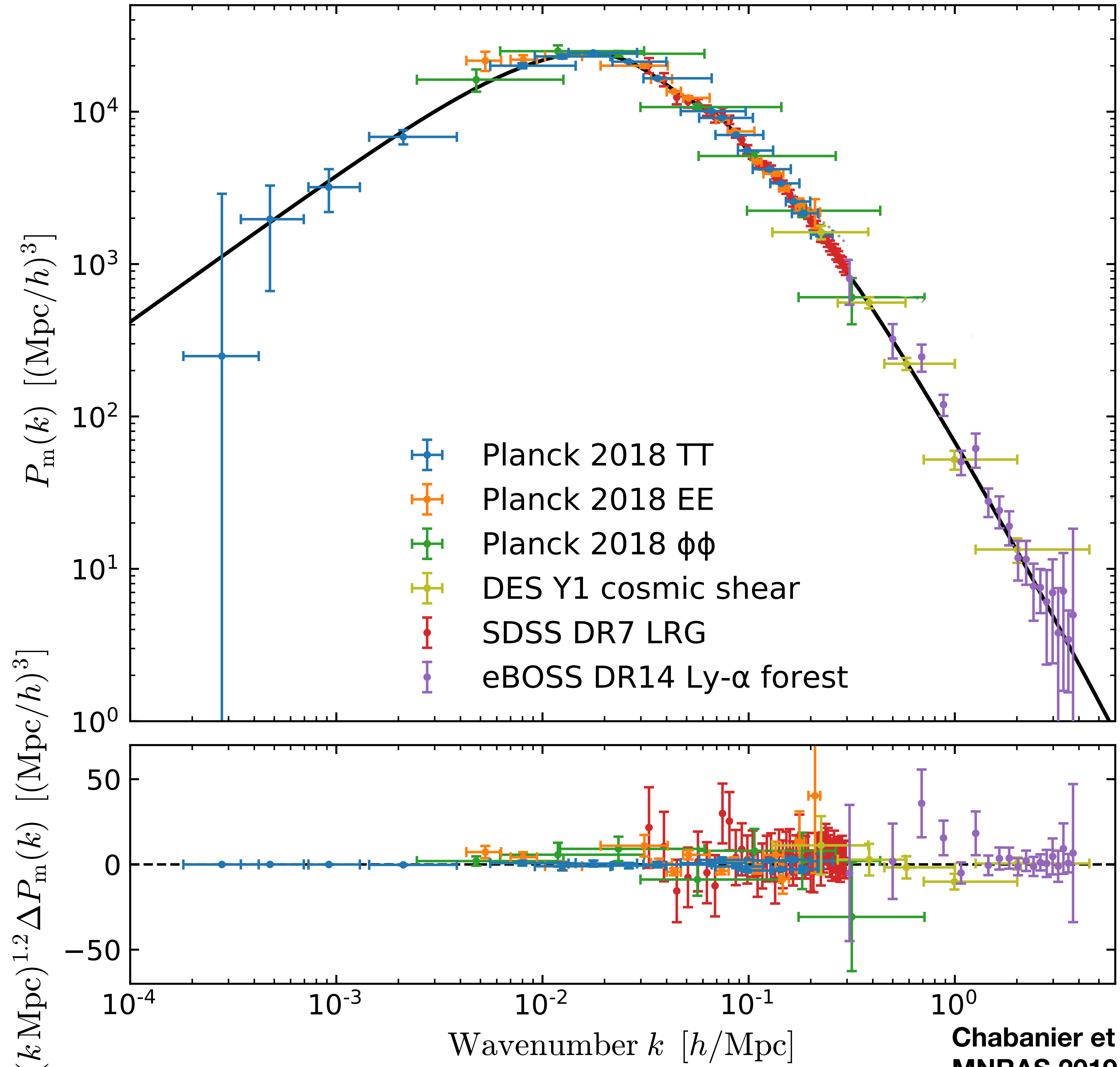
The Matter Power Spectrum on Small Scales

Current bounds:

CMB+Ly-α (+…)



Chabanier et al., MNRAS 2019

21cm-Intensity Mapping: Small Scale Sensitivity

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Changes in the power spectrum propagate to the global 21cm signal:

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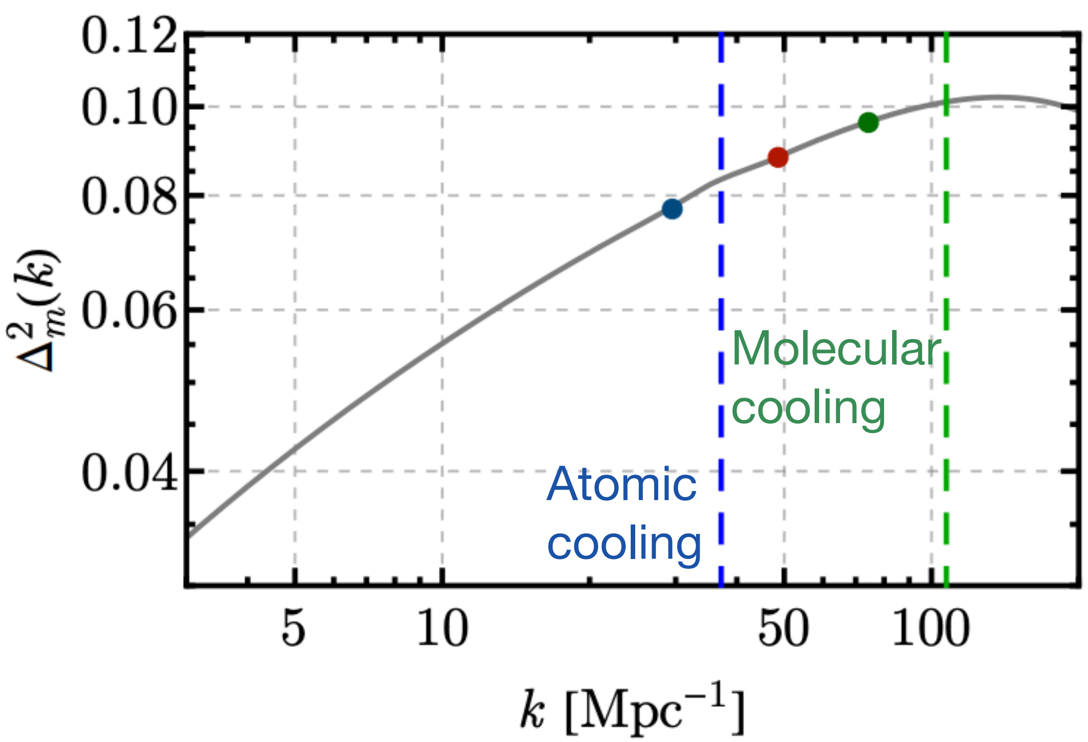
Munoz, Dvorkin and Cyr-Racine, PRD 2020



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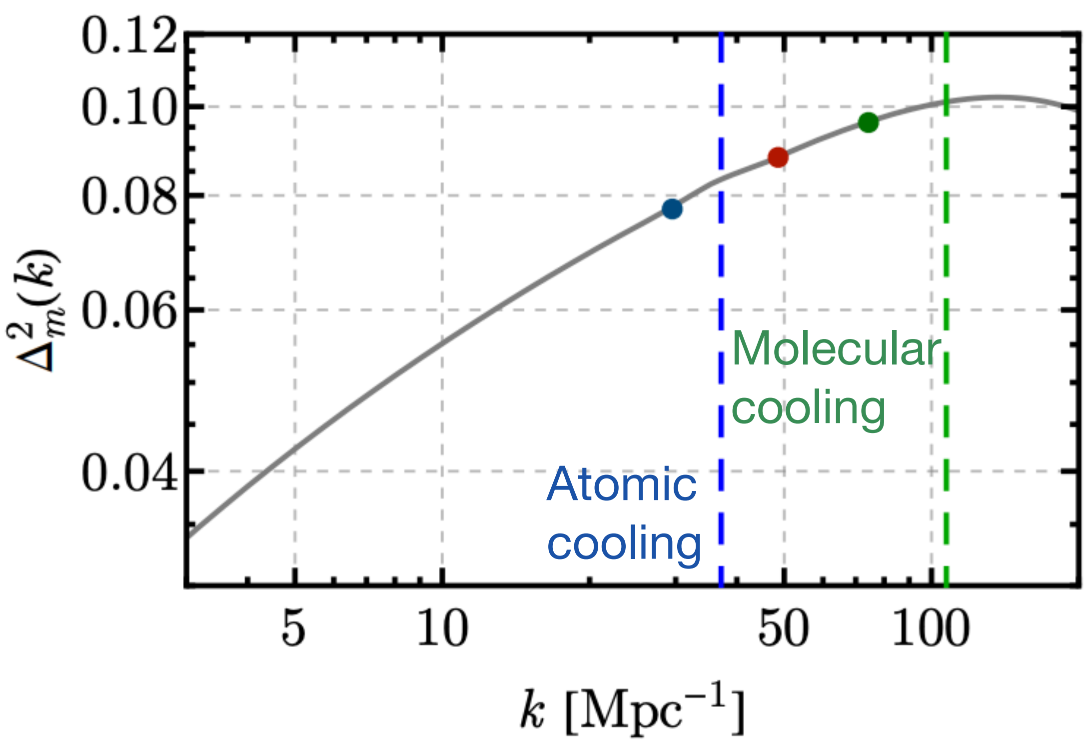

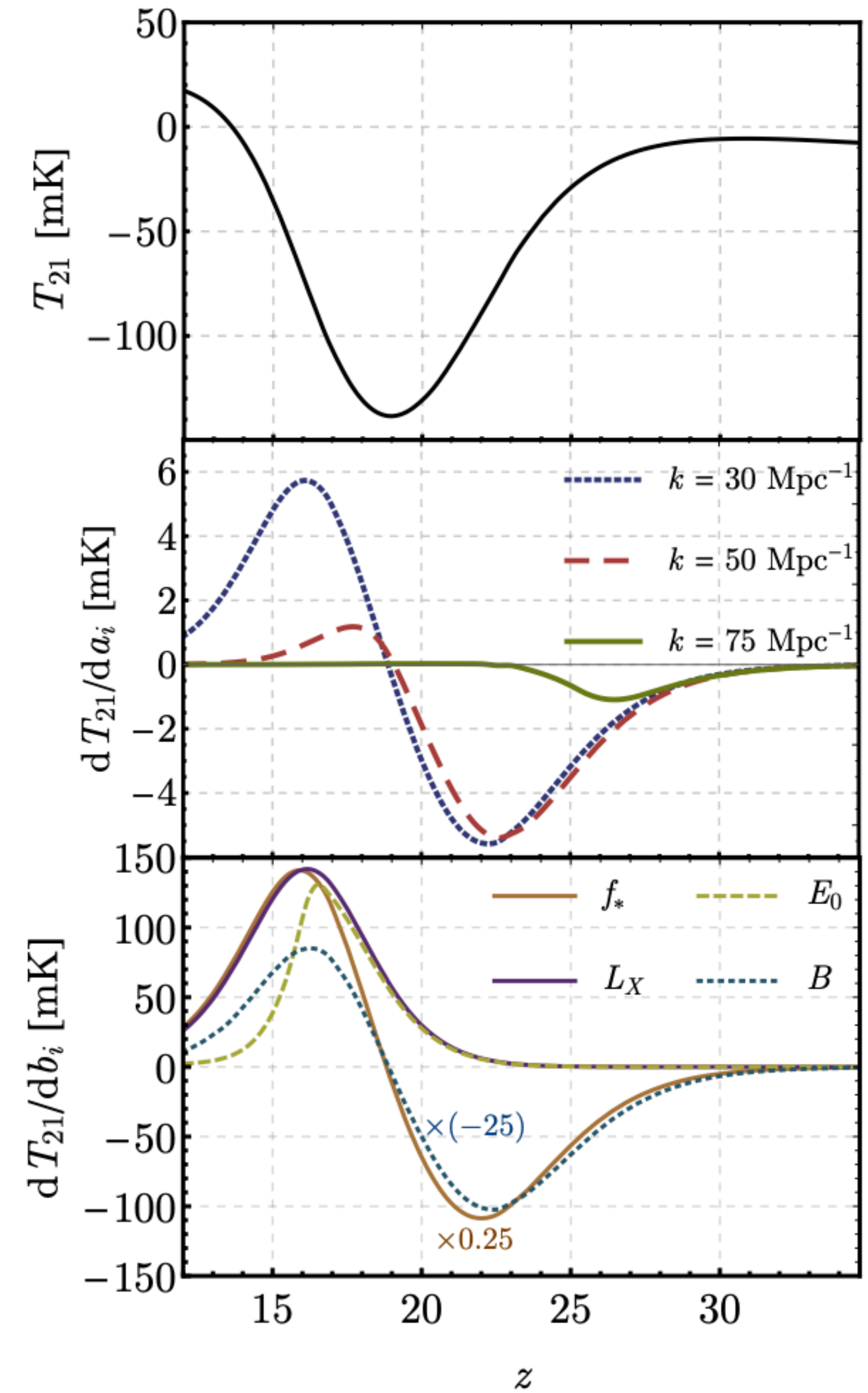

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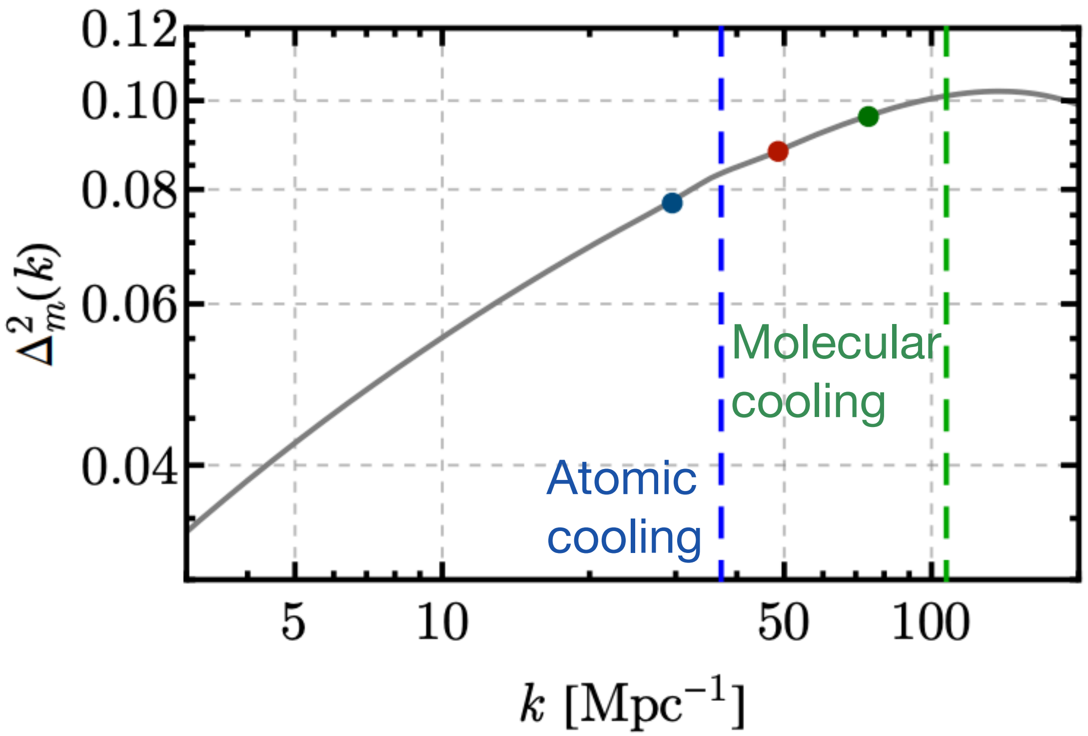

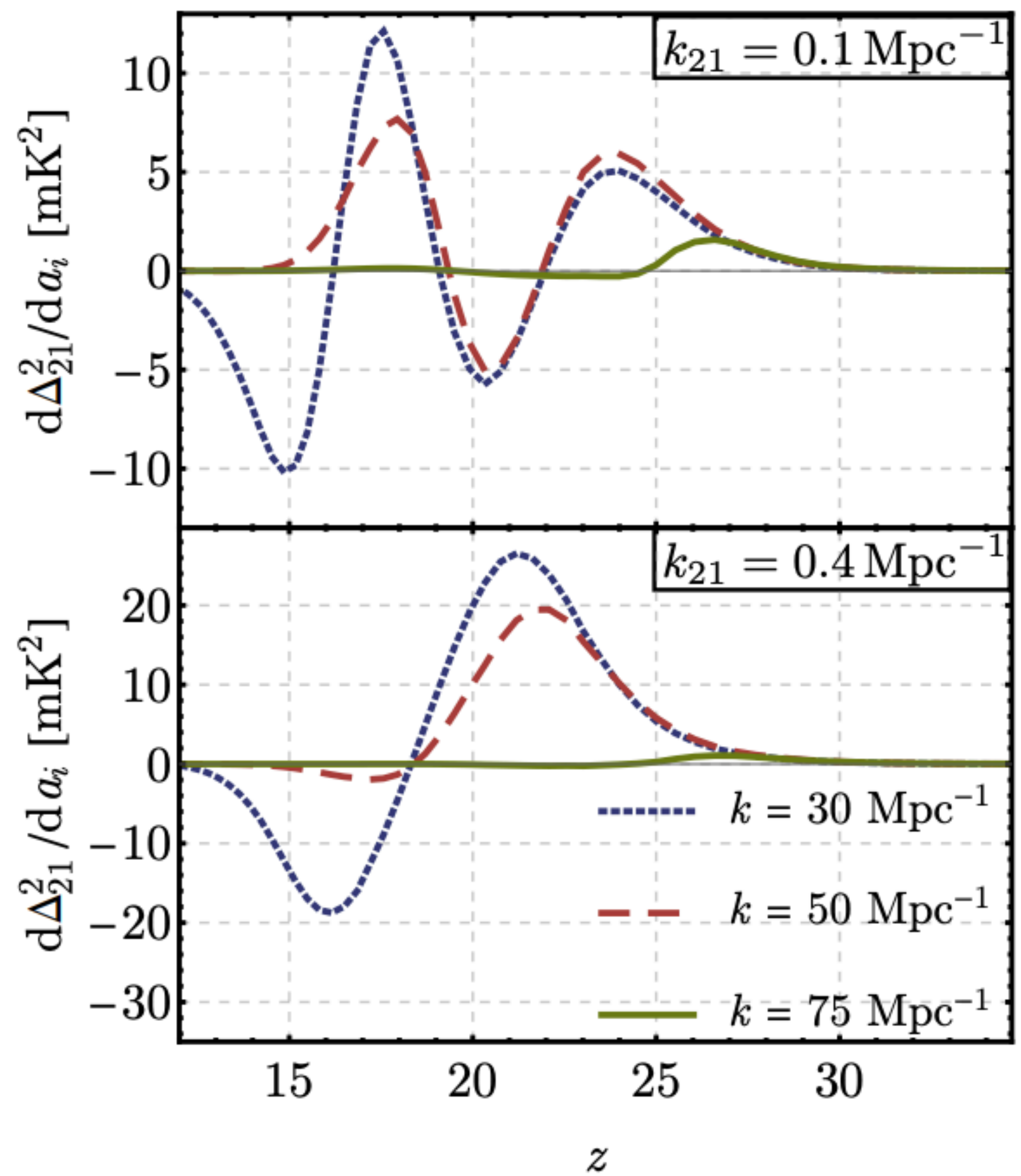

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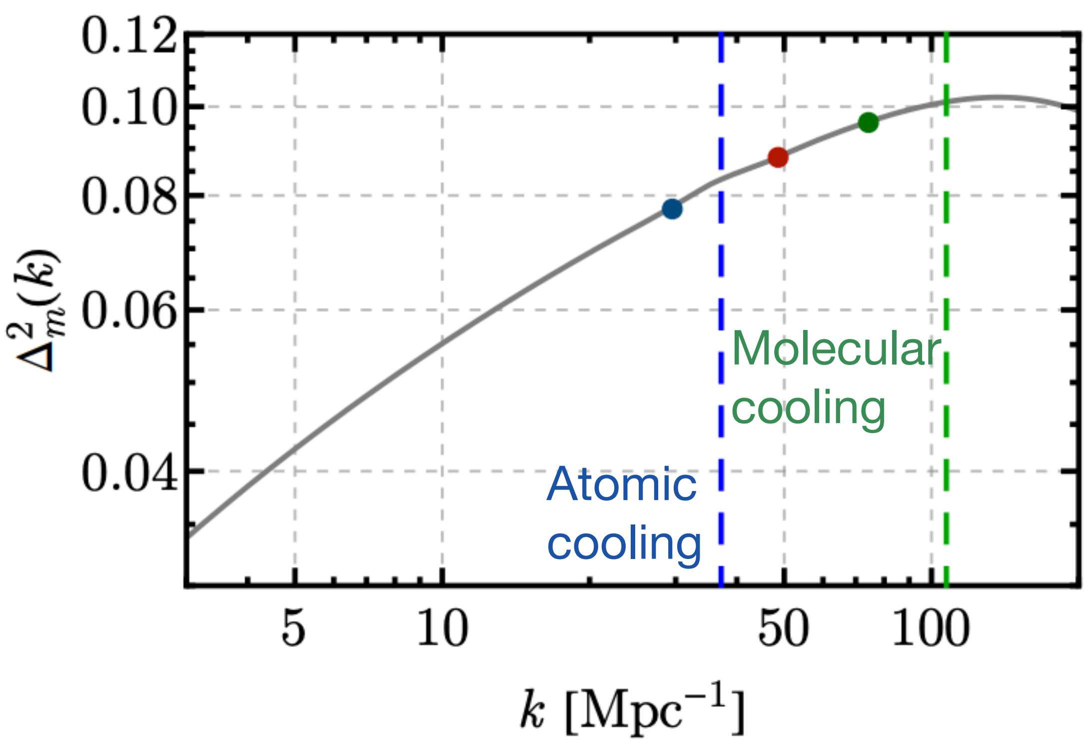

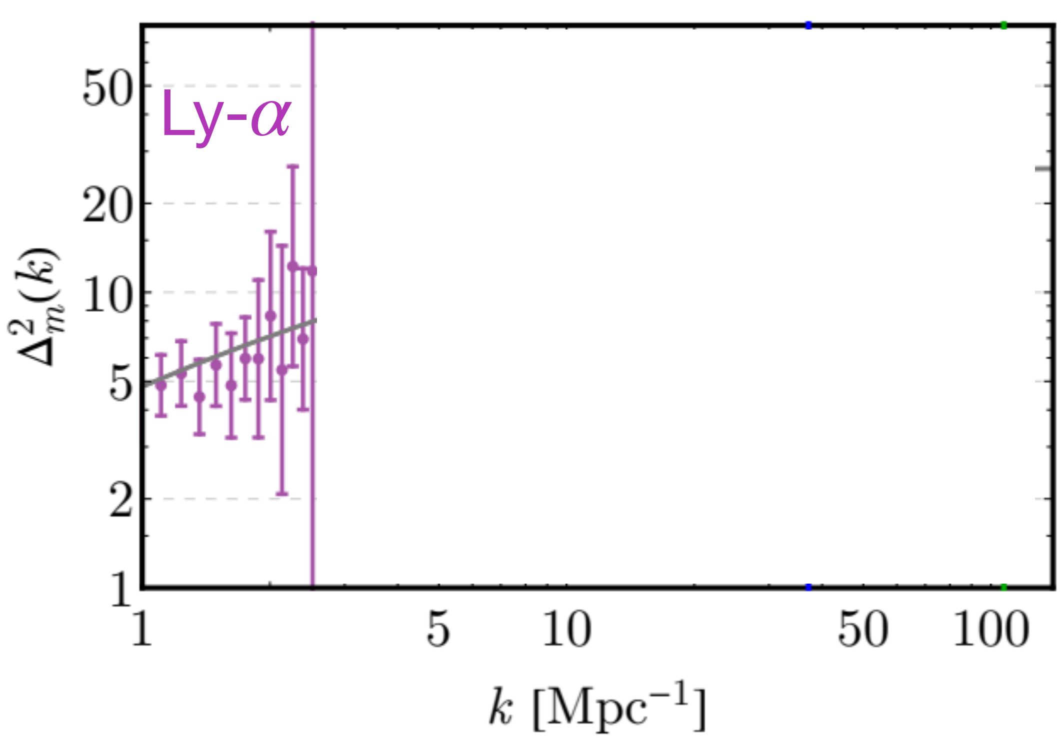

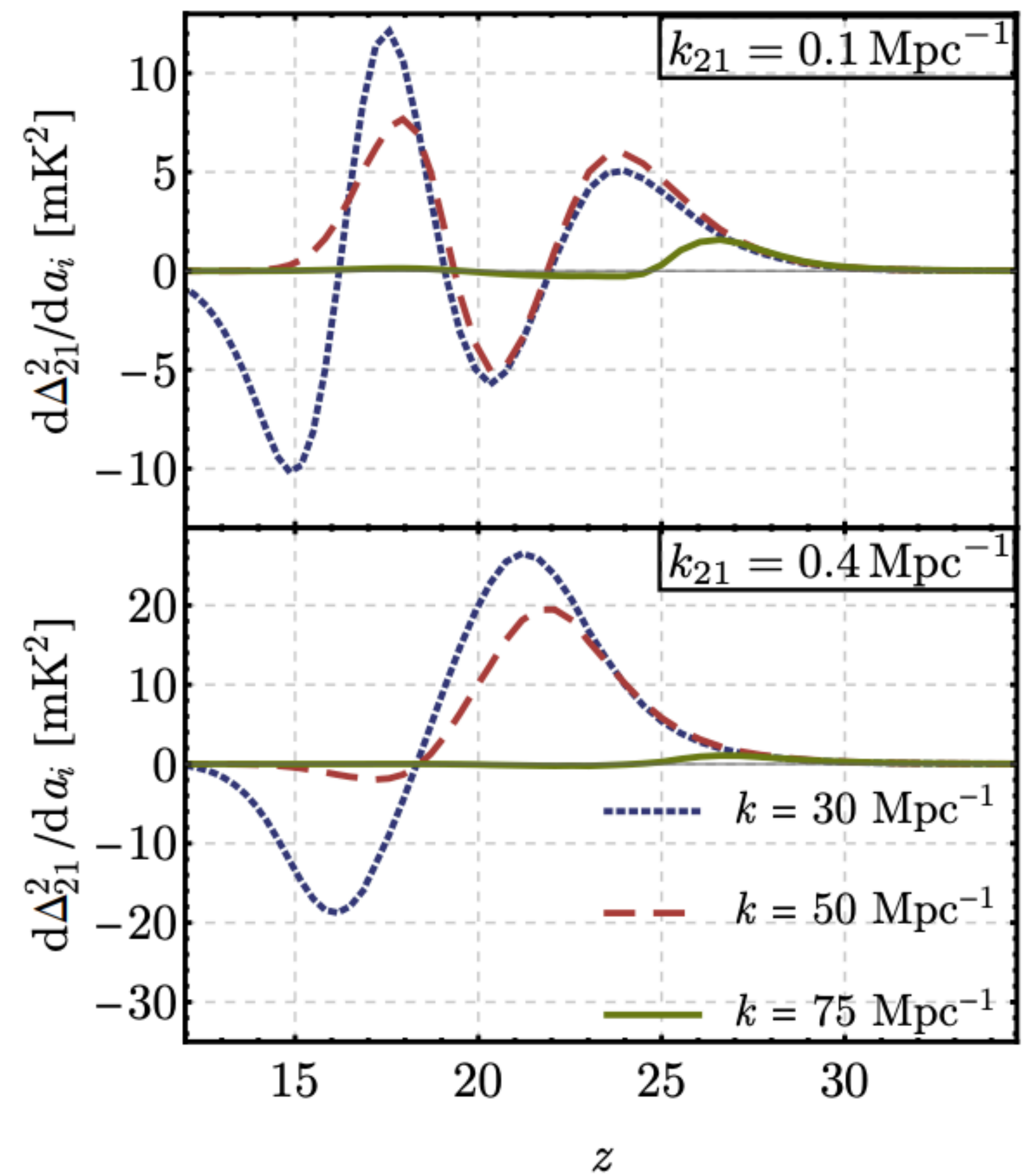

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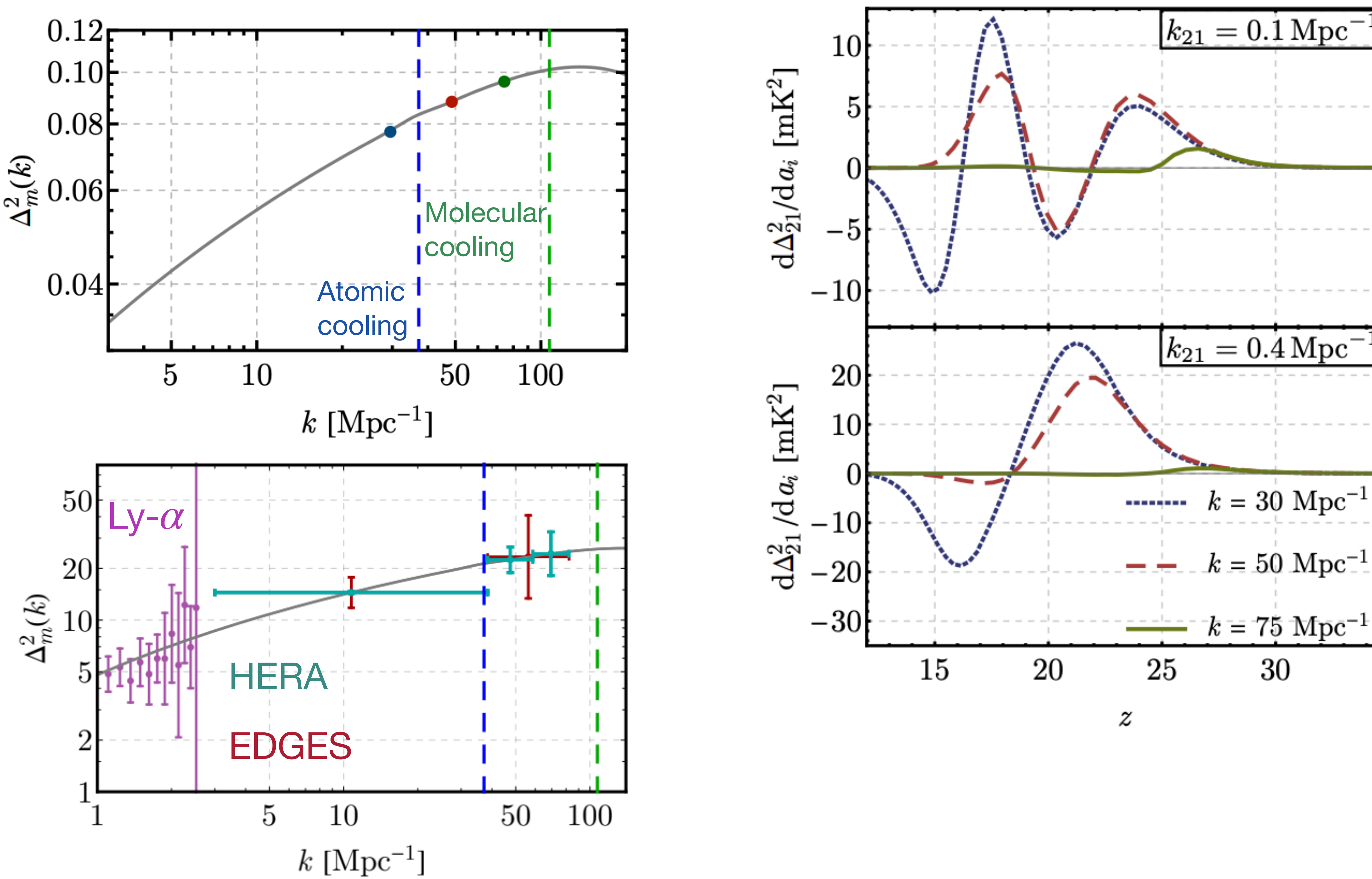

Line-Intensity Mapping: Small Scale Sensitivity

Changes in the power spectrum propagate all the way to the *VID* (map histogram):

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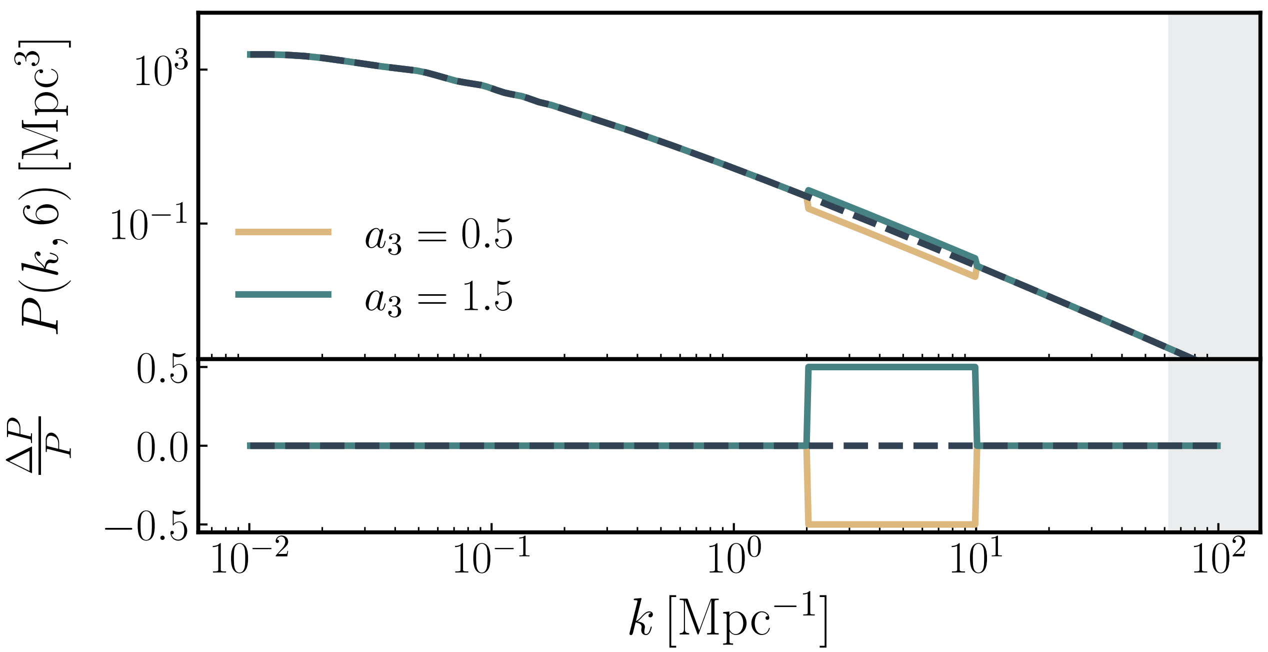
Libanore, Unal, Sarkar and Kovetz, PRD 2022



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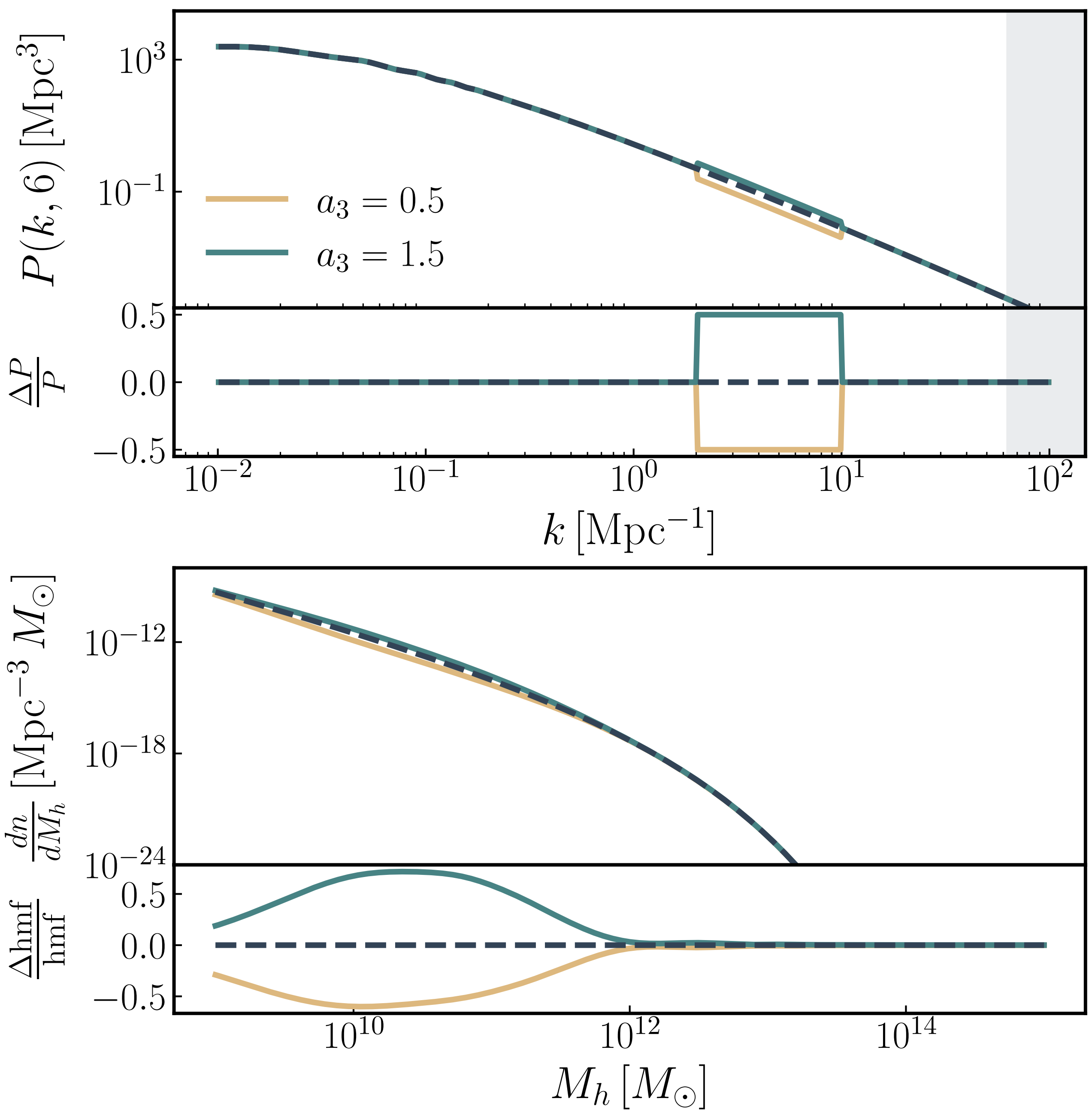

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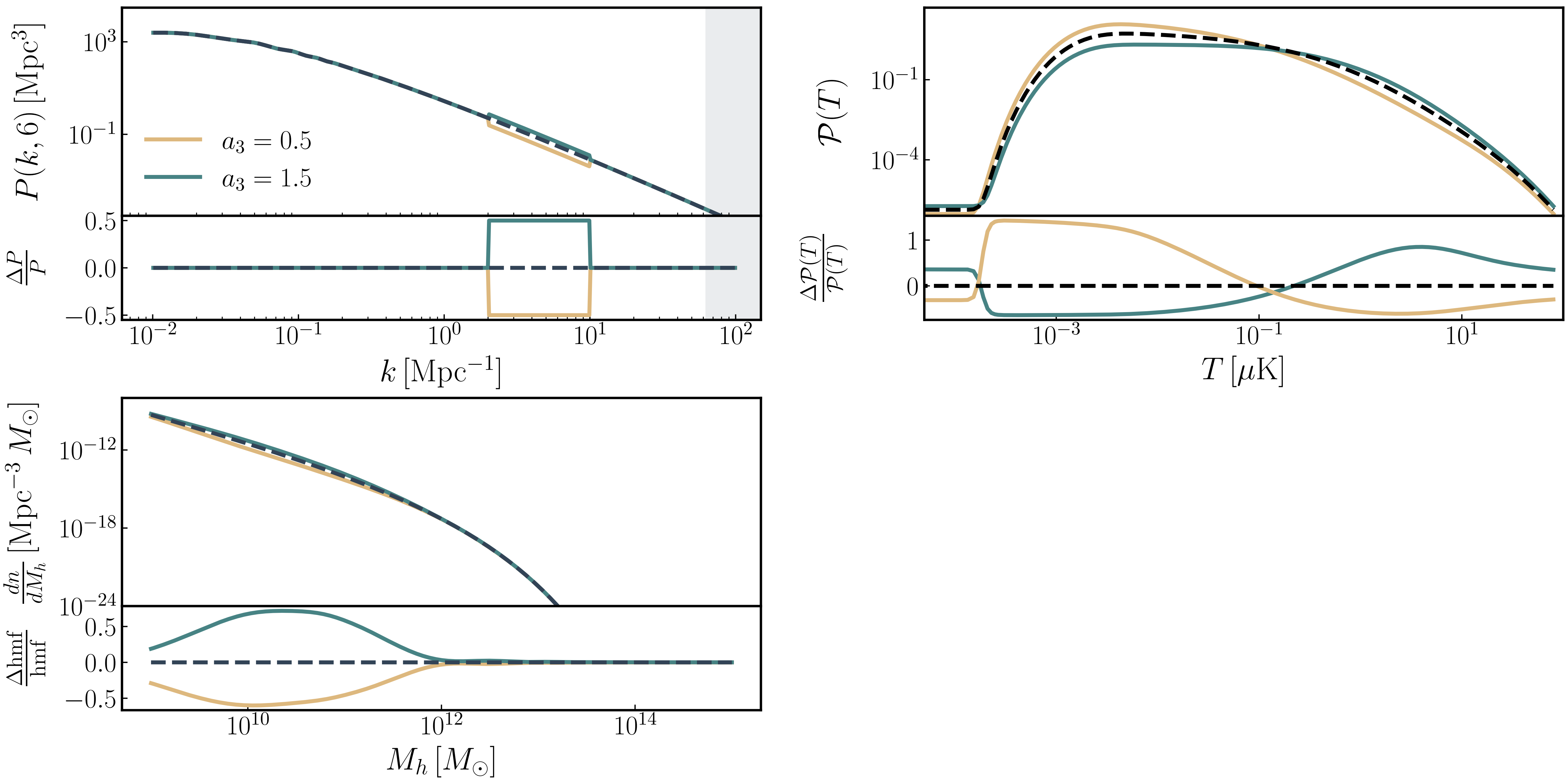

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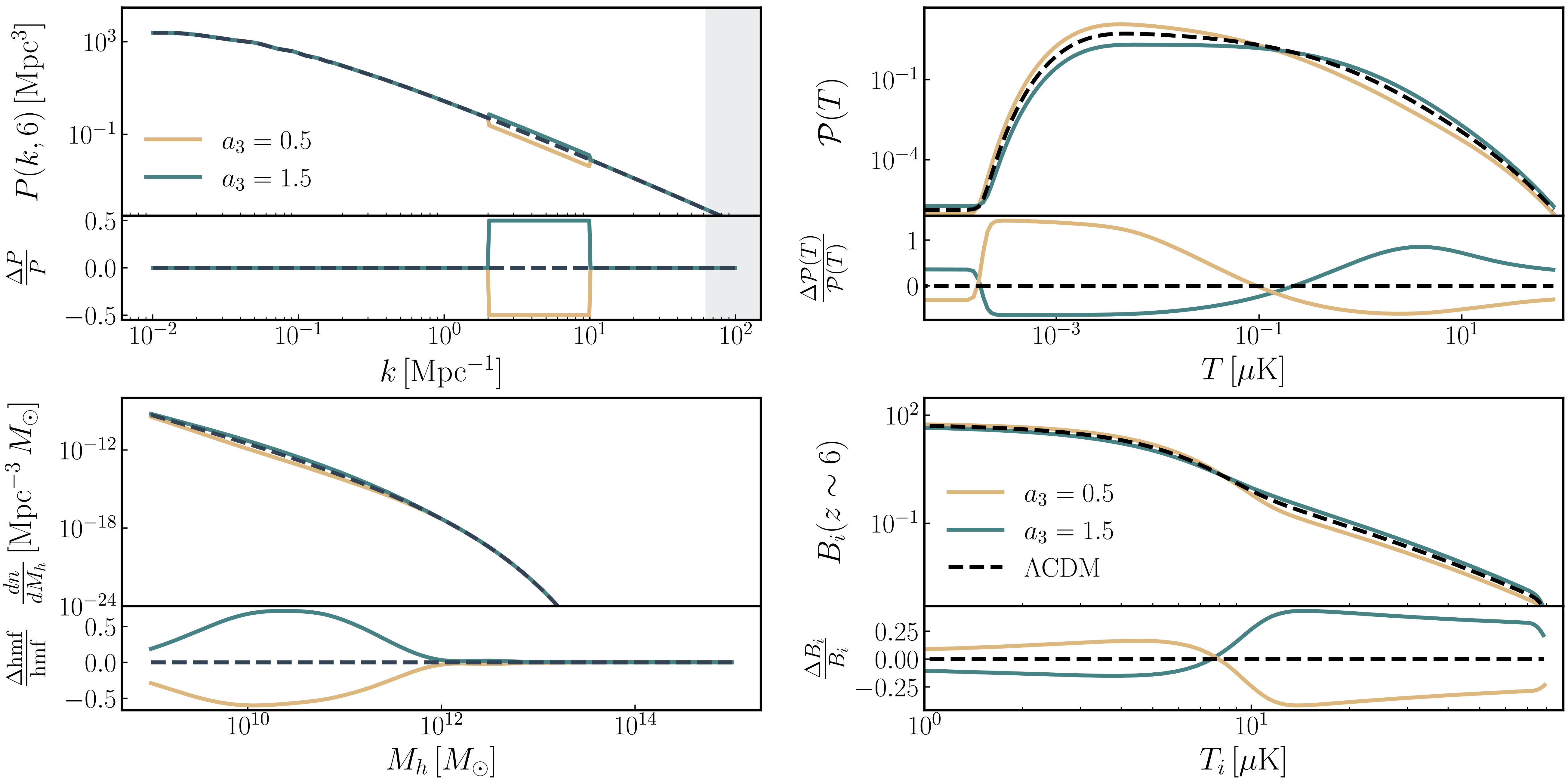
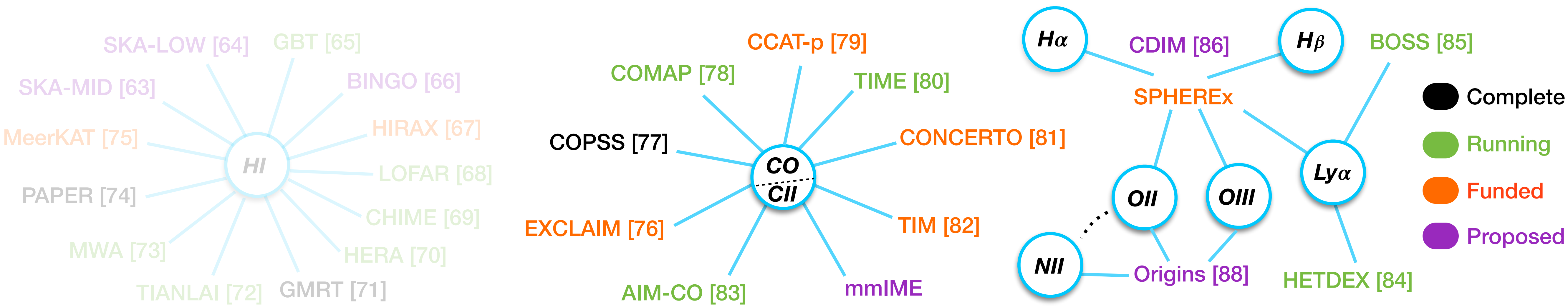


Line-Intensity Mapping: Small Scales with VID



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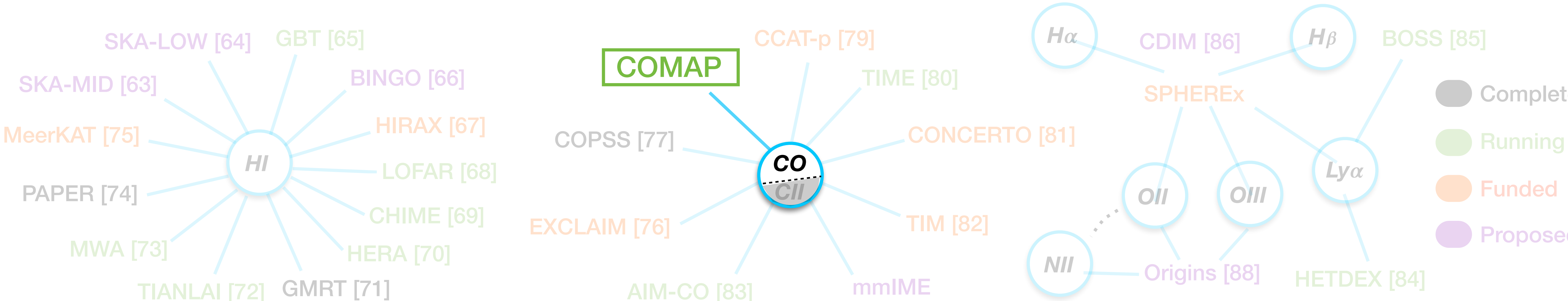

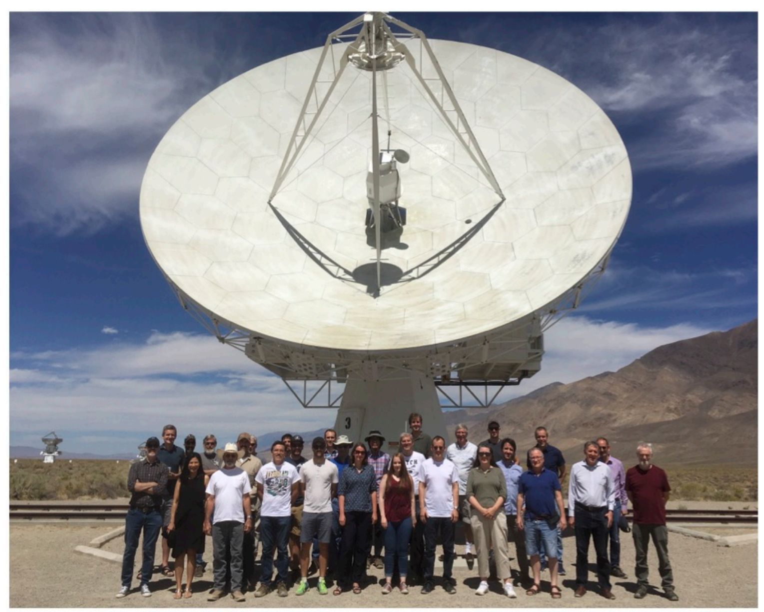

Instrumental Paramater	COMAP 1	COMAP 2	COS3 (CO)
$T_{\rm sys}$ [K]	40	40	max(20,$\nu_{\rm obs}$)
Total # of independent detectors	19	95	1000
Ang. resolution (FWHM) [arcmin]	4	4	4
Frequency band [GHz]	26-34	26-34	12-36
$\delta\nu$ [MHz]	15.6	8.0	2.0
$t_{\rm obs}$ [h]	6000	10000	10000
$\Omega_{\rm field}$ [deg^2]	2.25	60	1000

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LIM* Small Scale Bounds:

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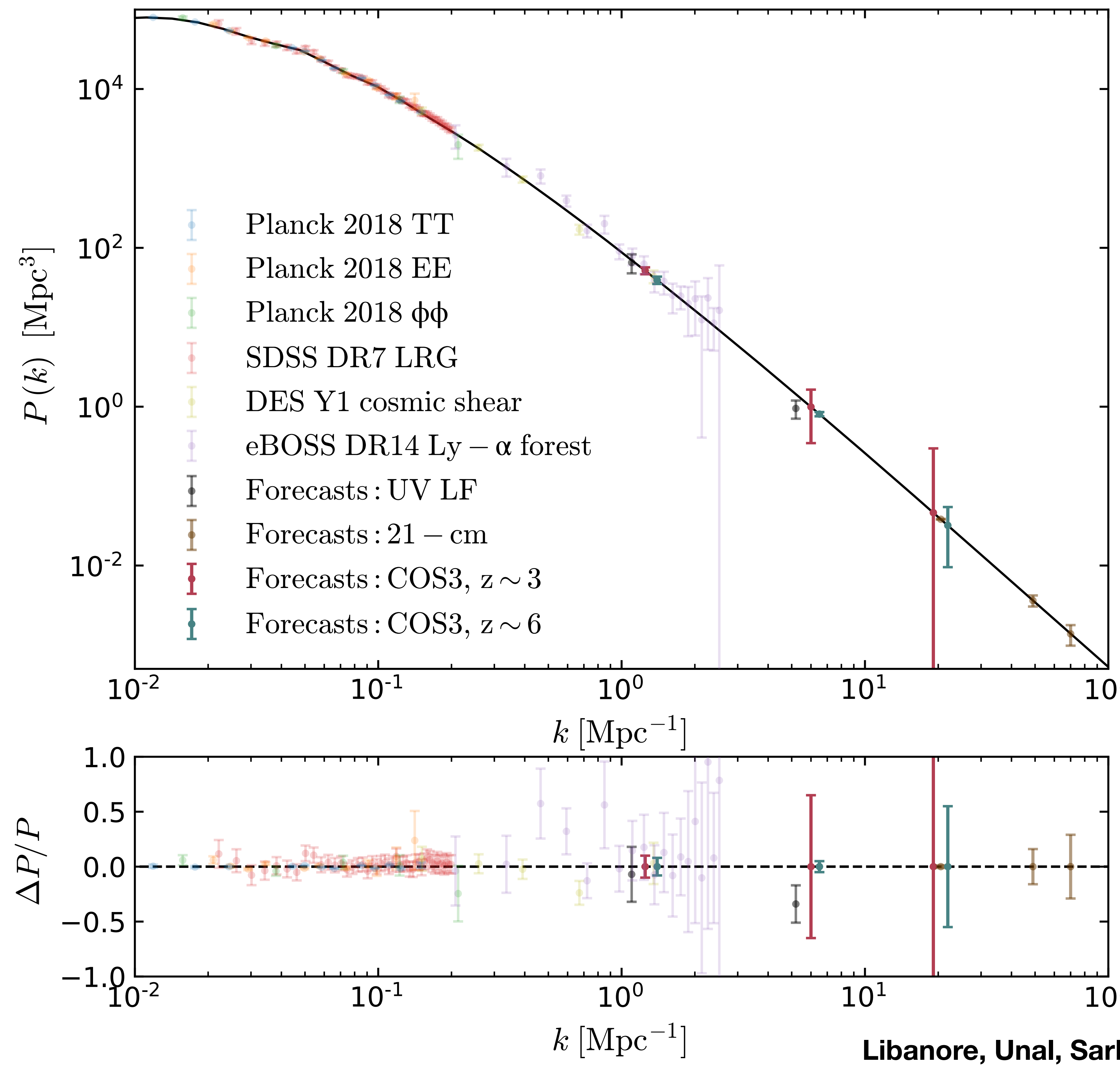

Libanore, Unal, Sarkar and Kovetz, PRD 2022

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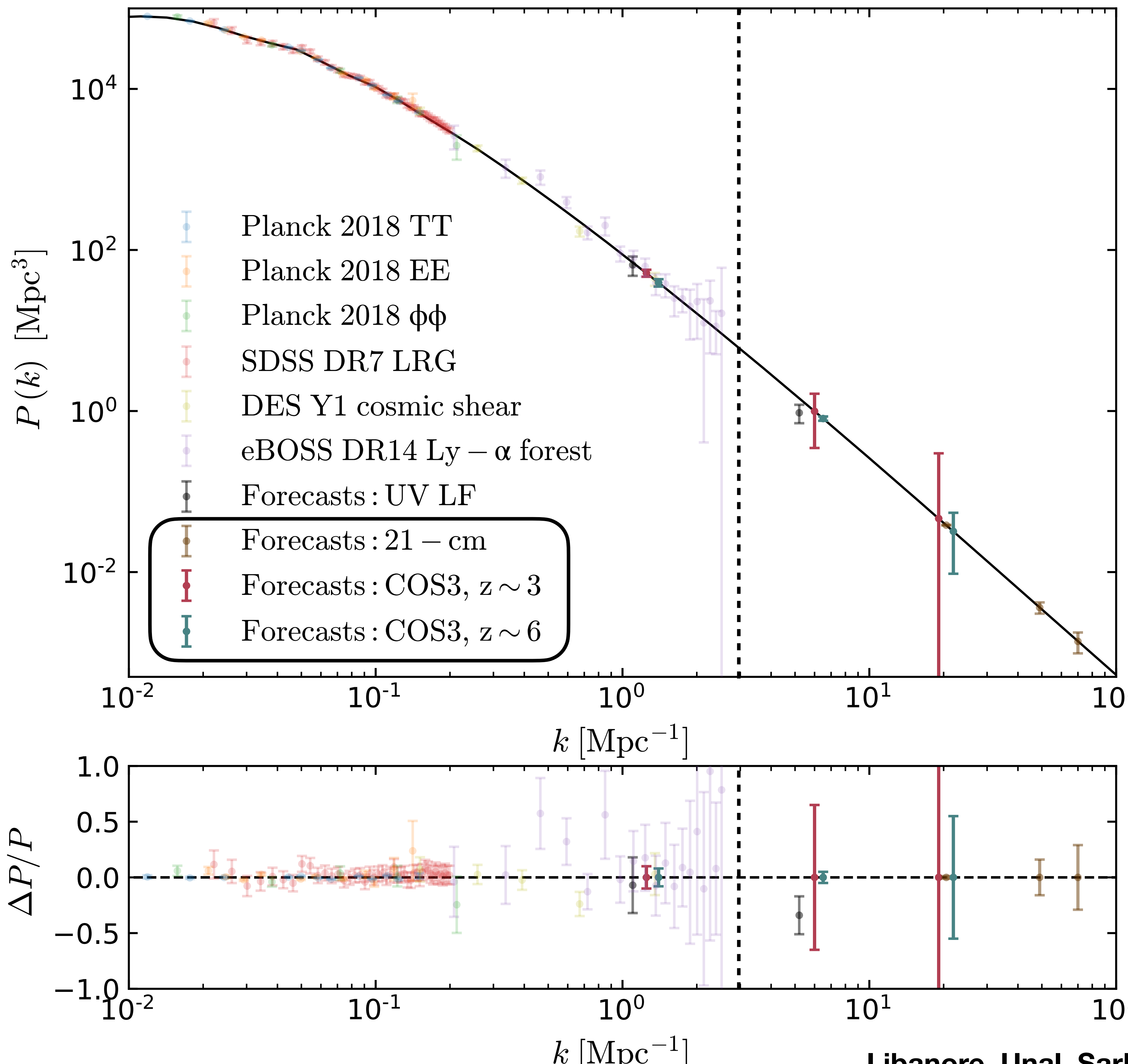

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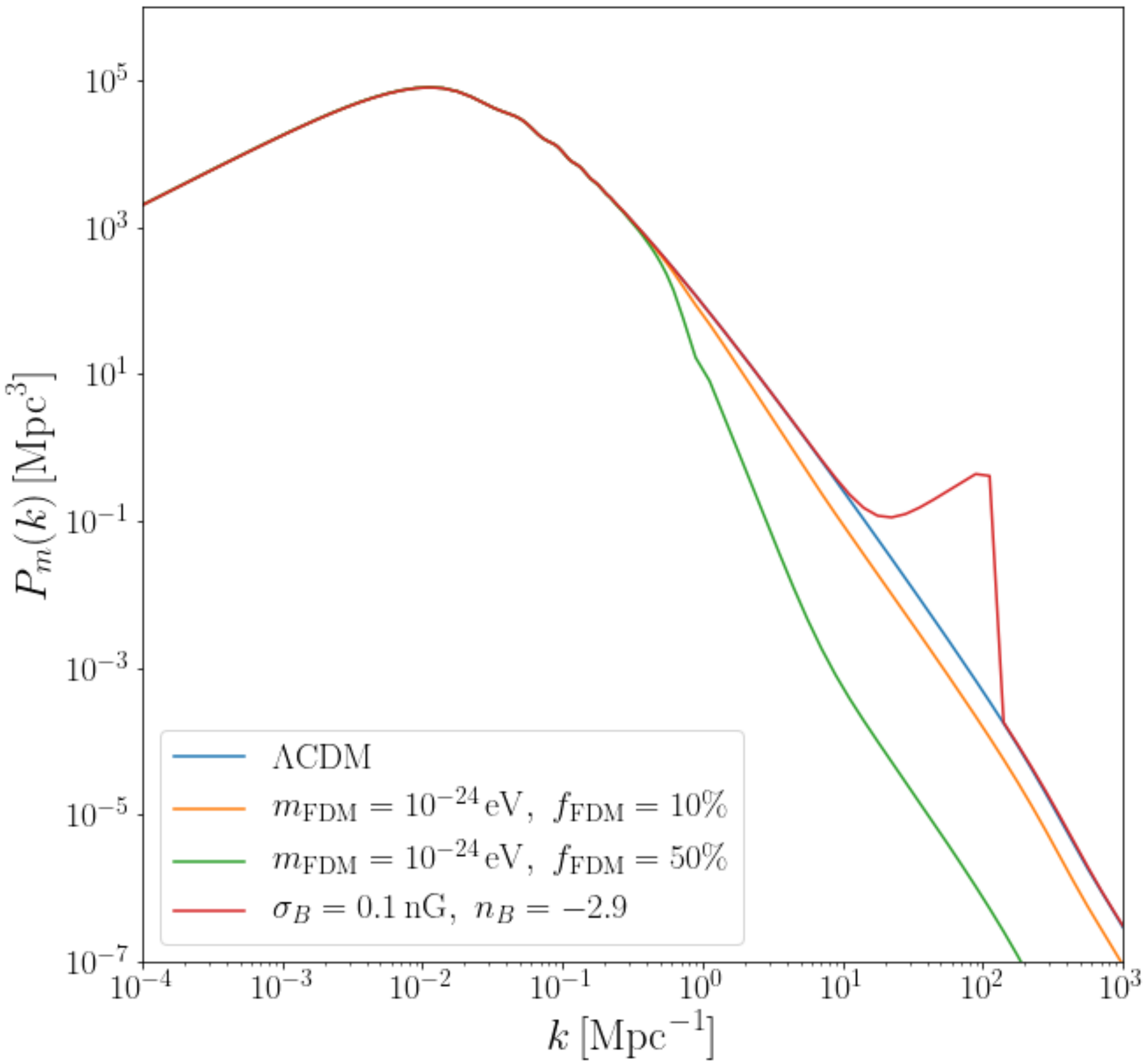

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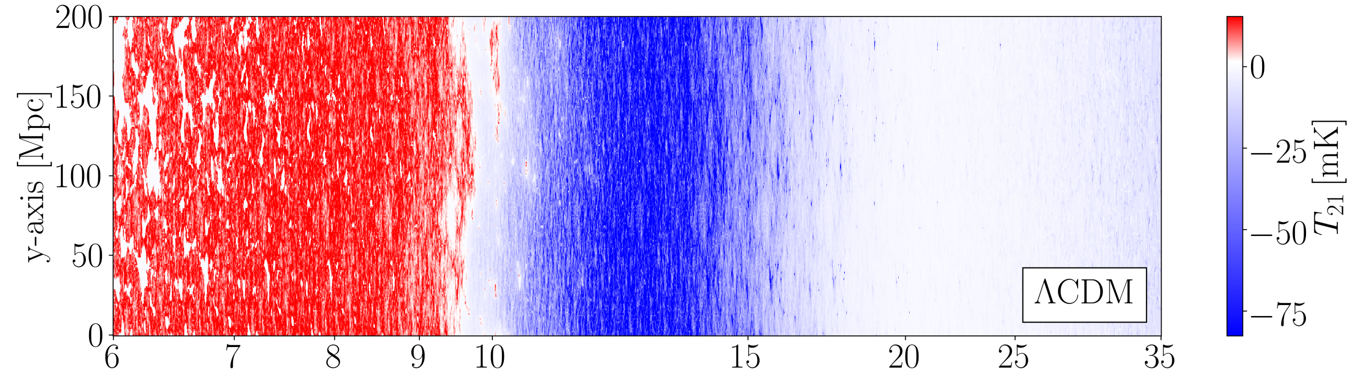

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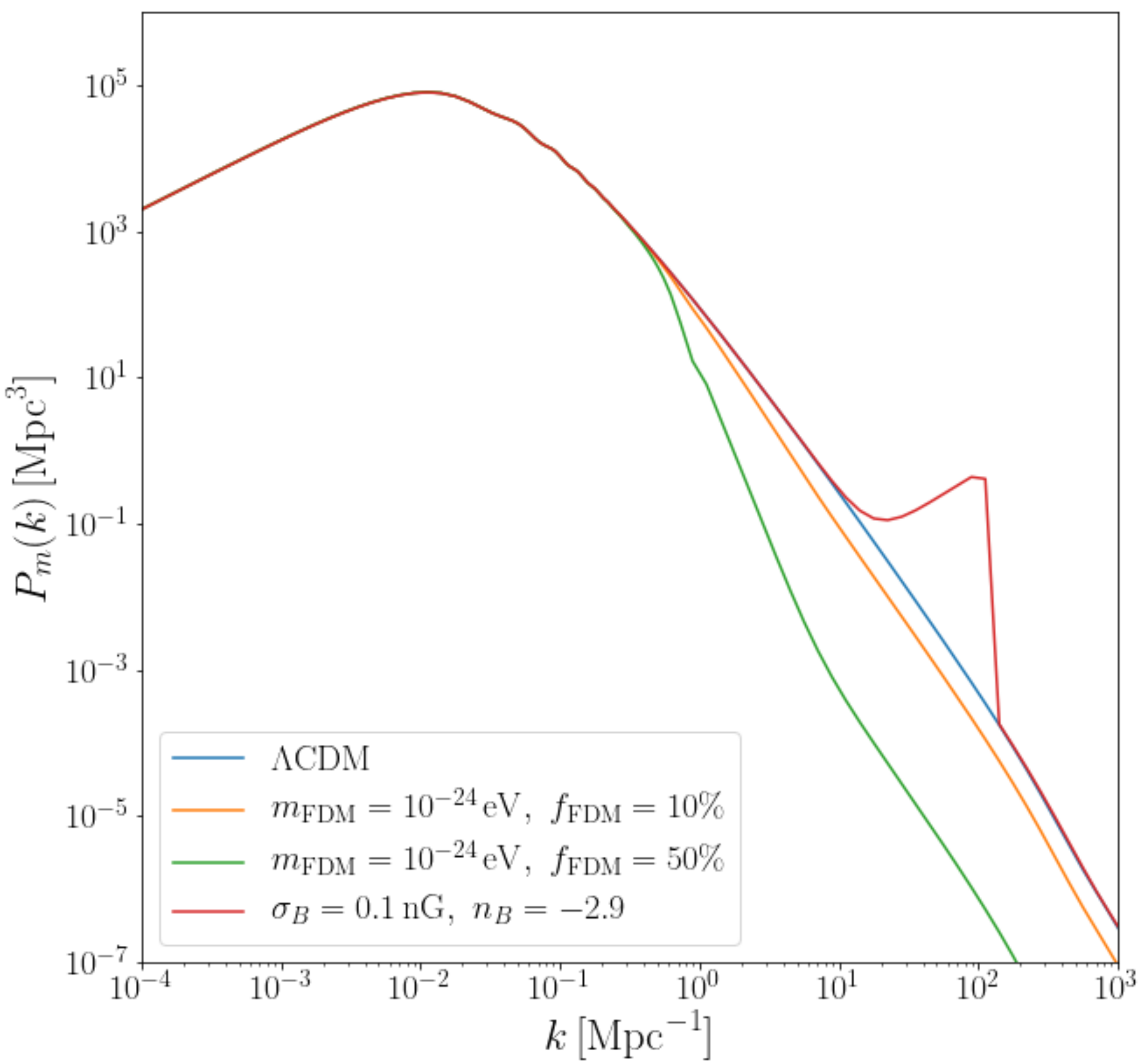

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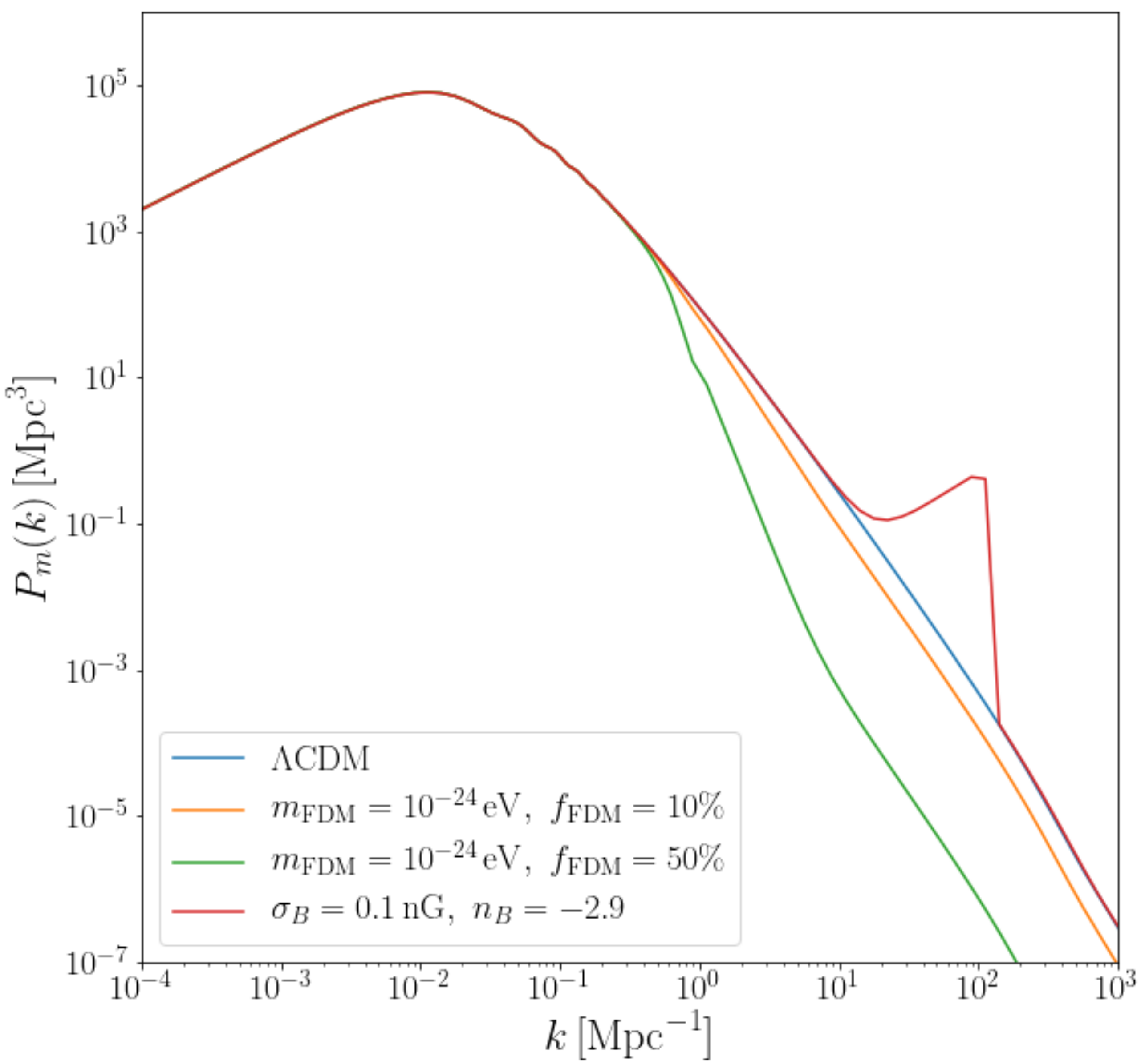

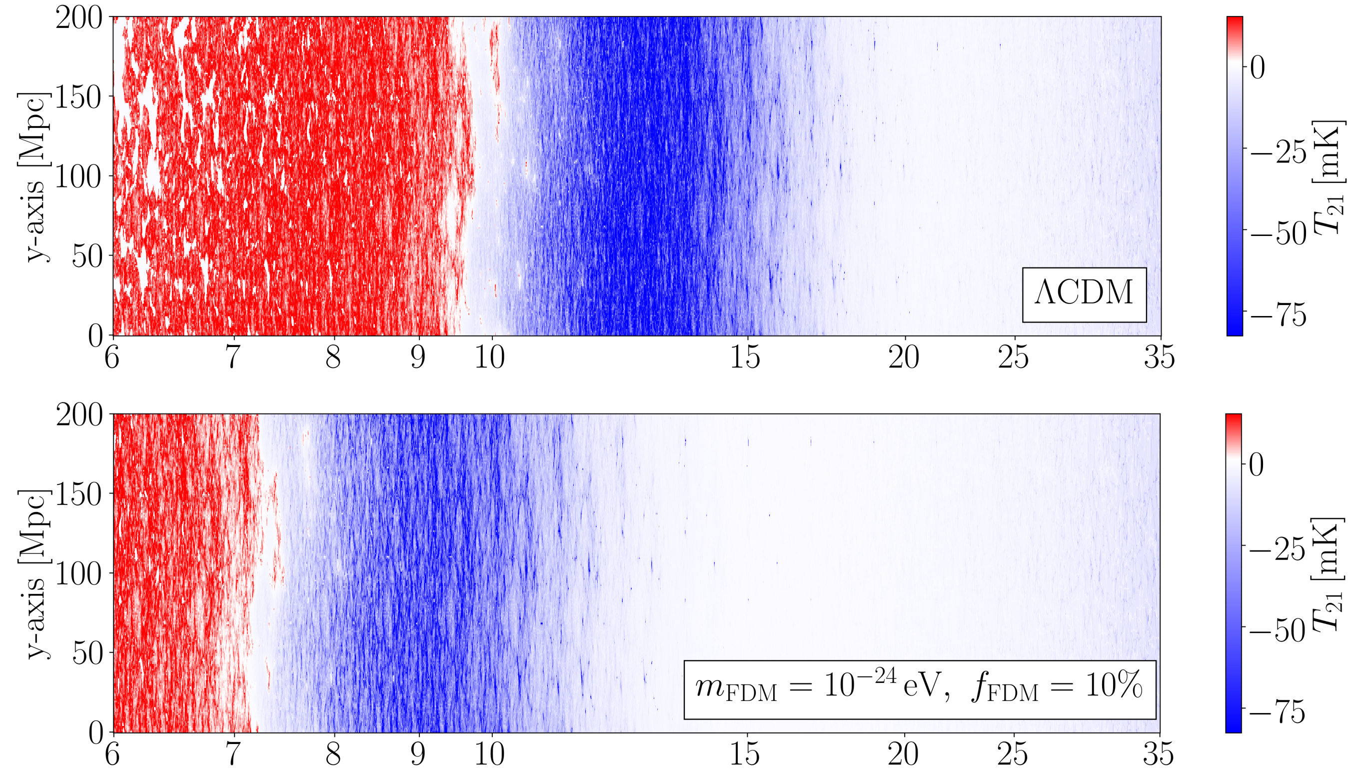

Credit: J. Flitter

21cm LIM: Small Scale Fluctuations

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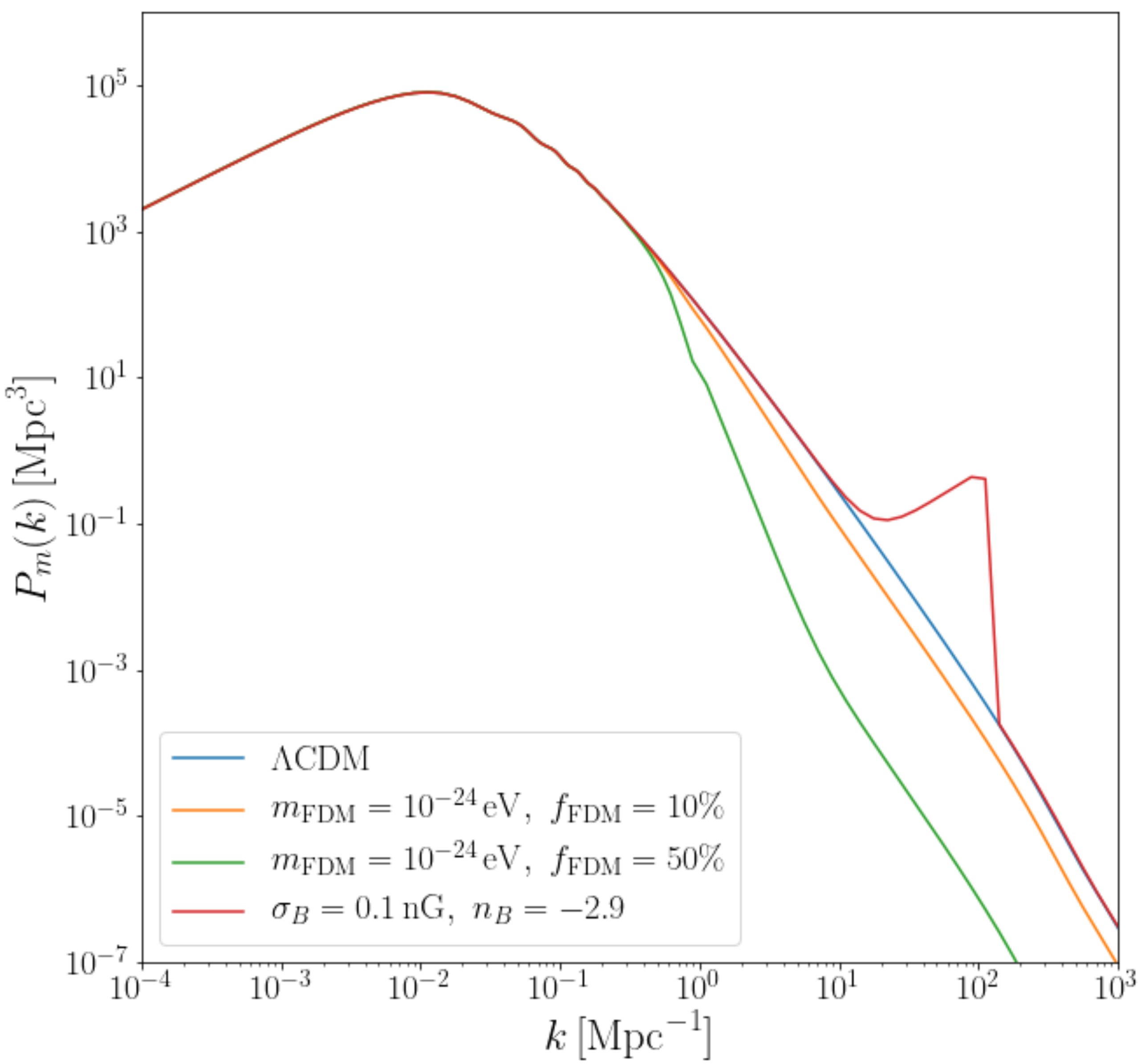

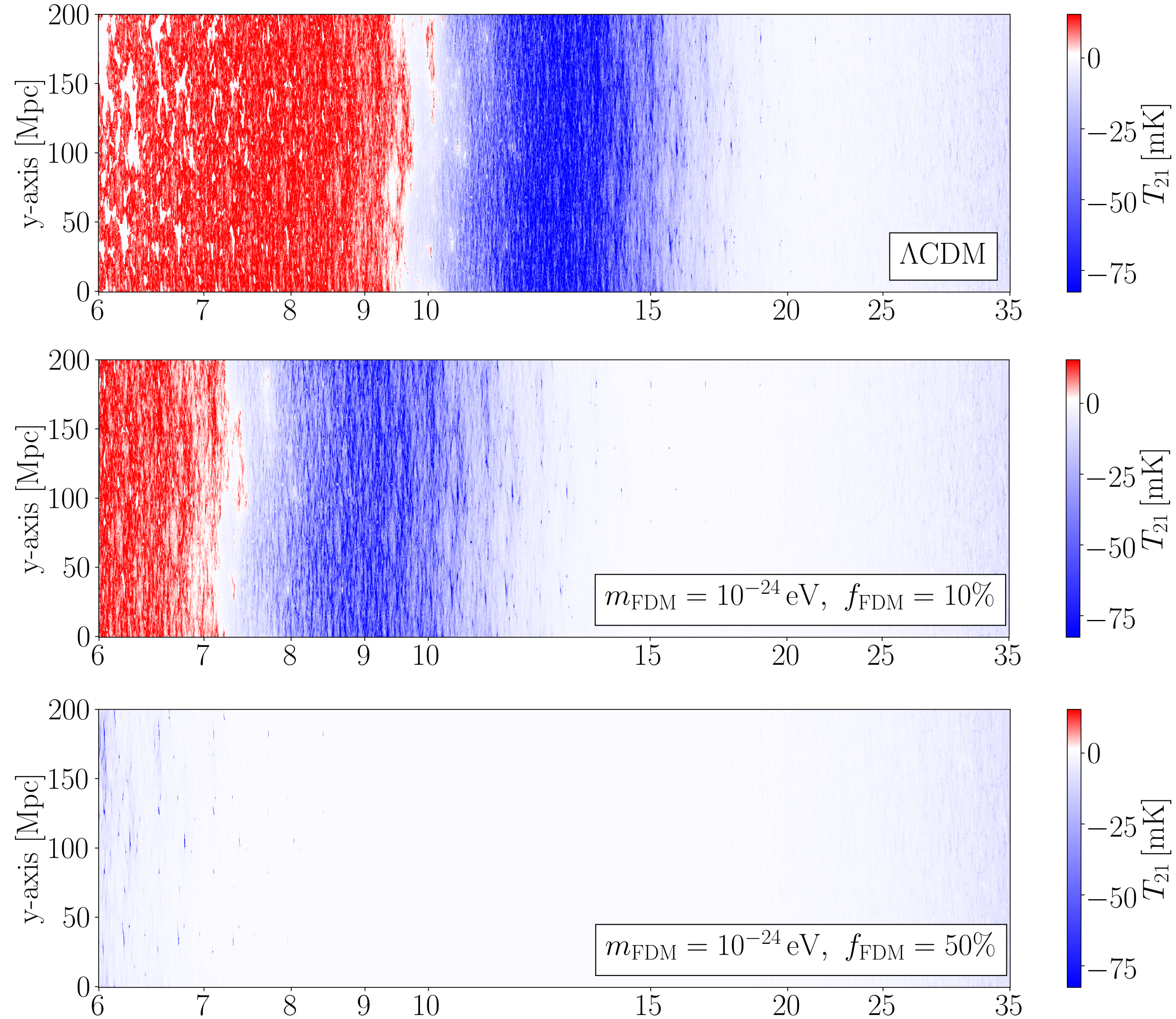

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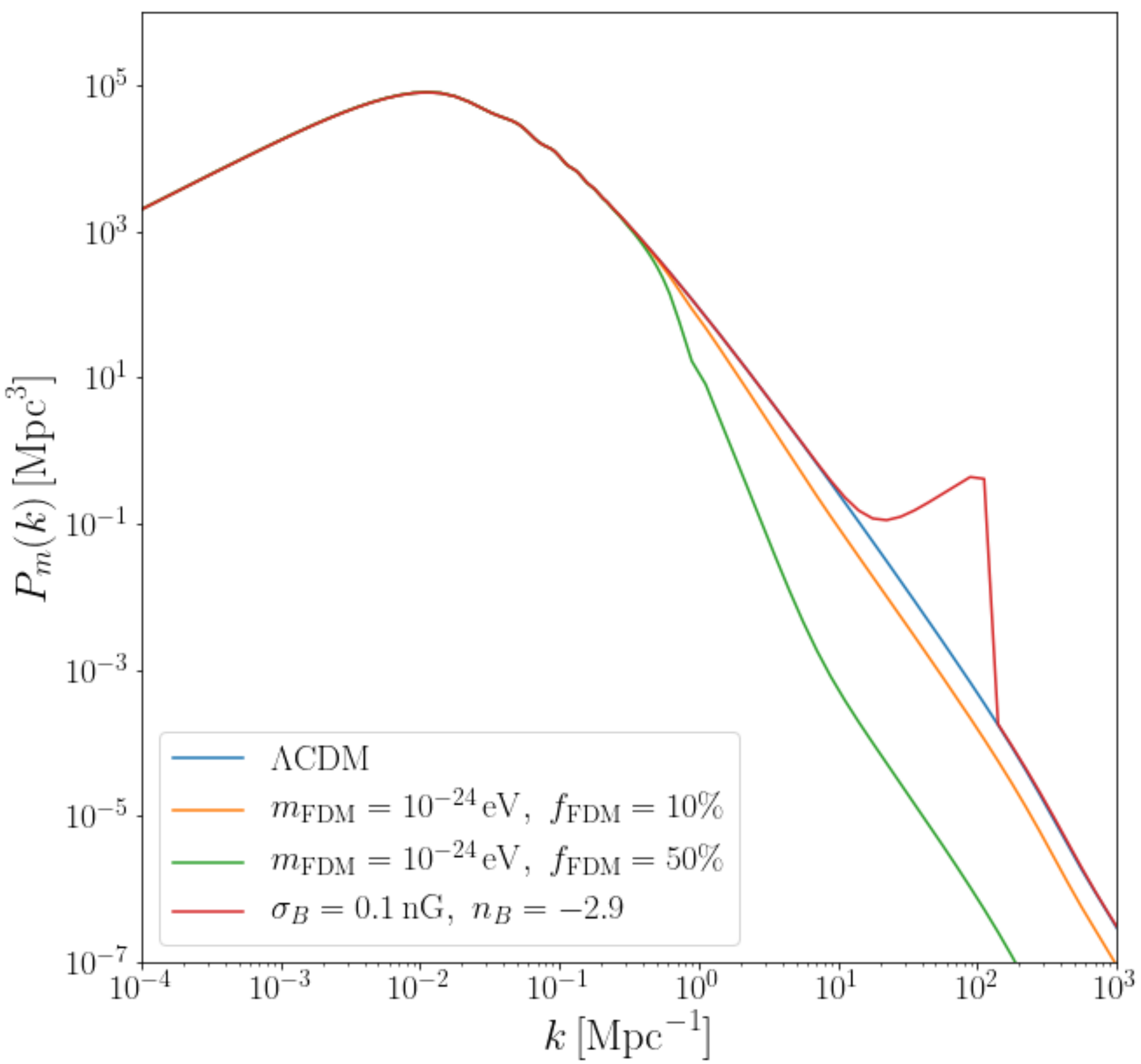

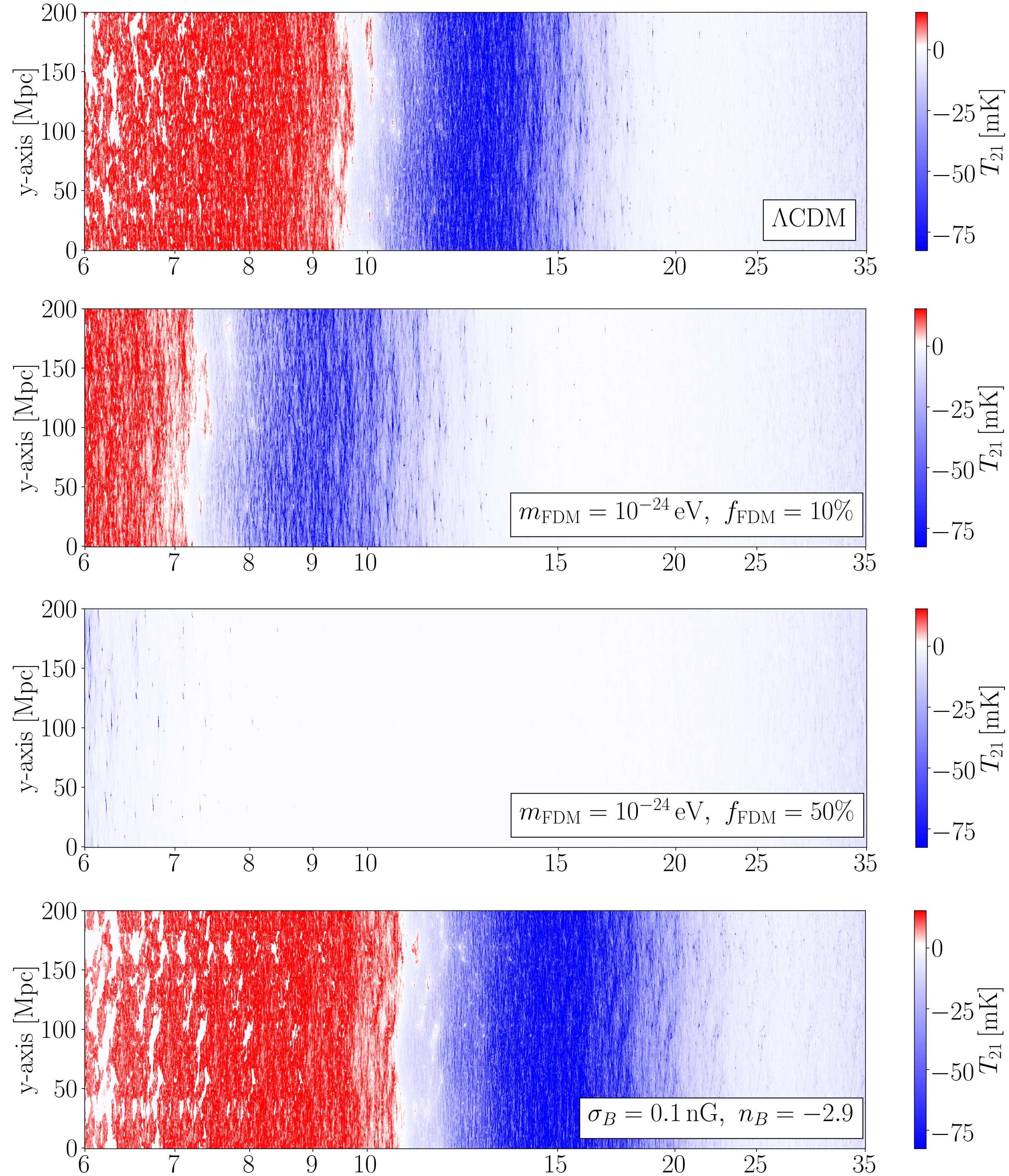

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Fuzzy Dark Matter: 21cm IM can close the weakly constrained mass window

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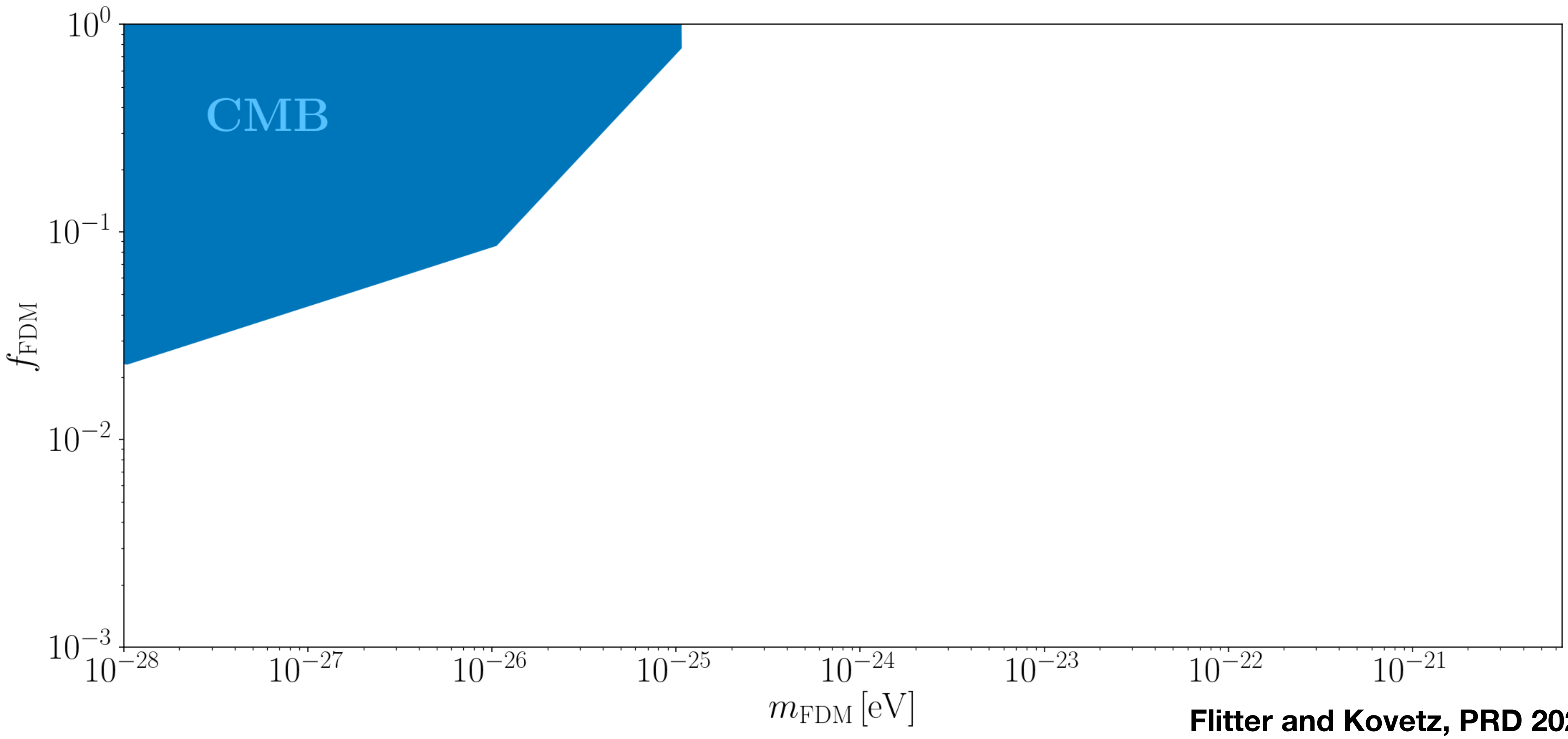

Flitter and Kovetz, PRD 2022

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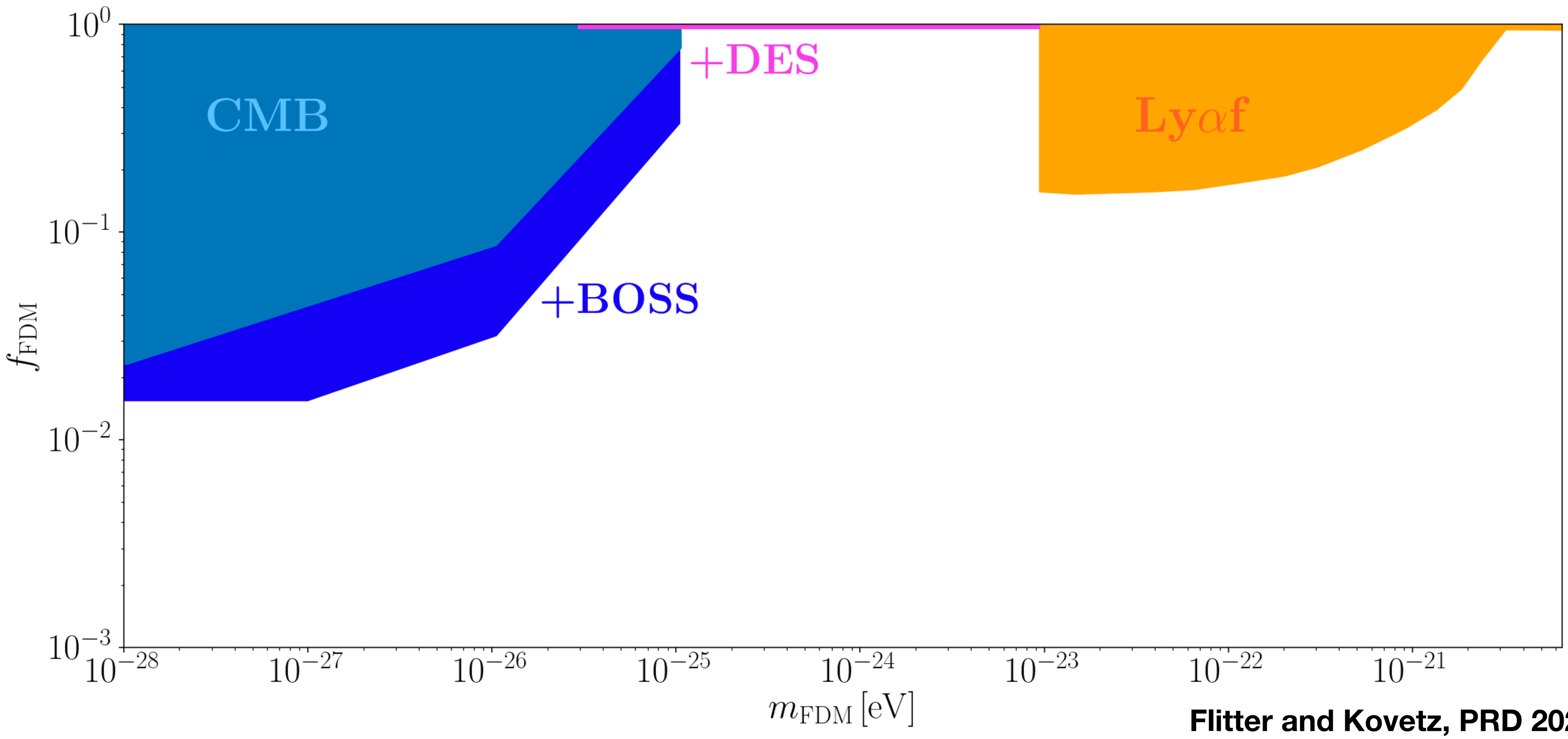

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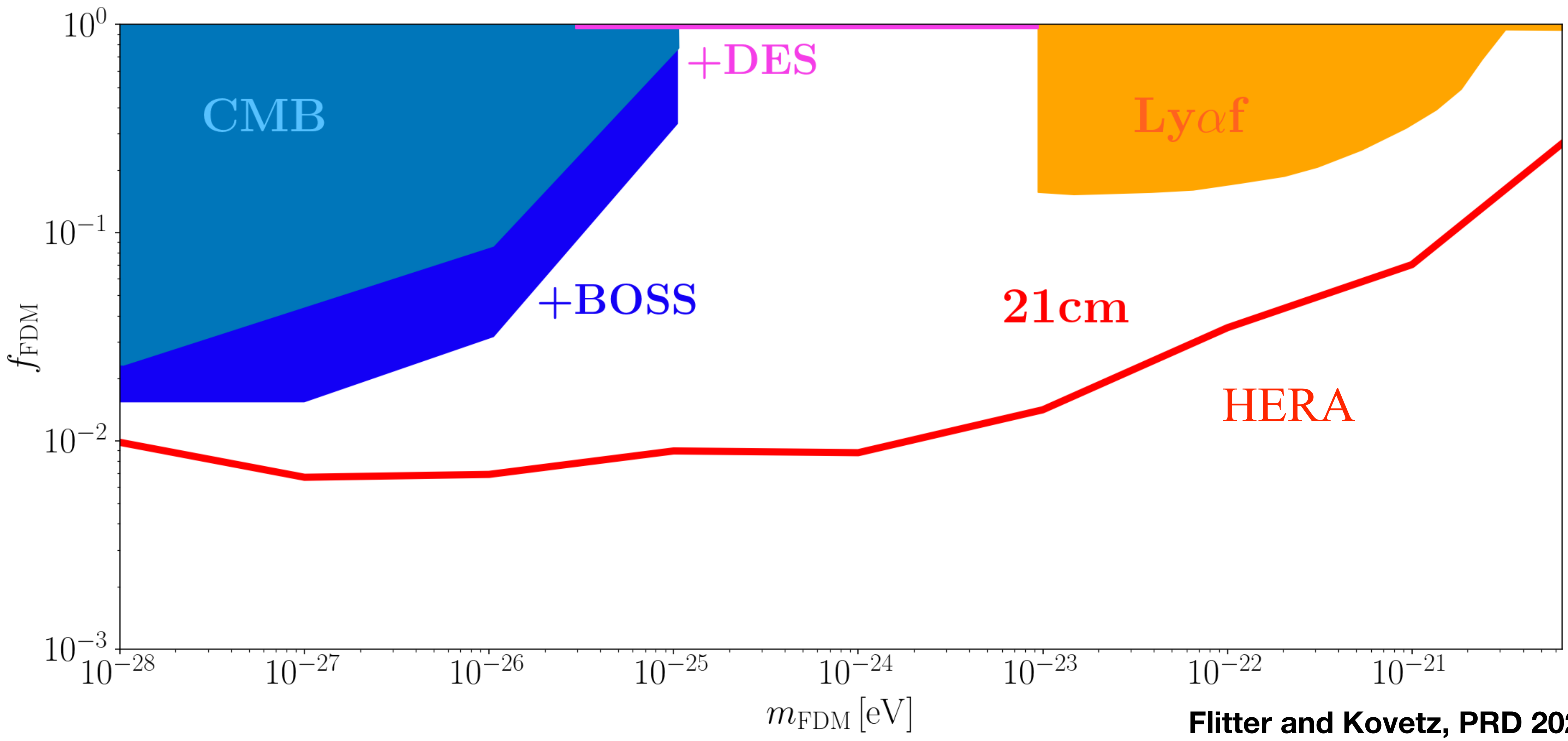

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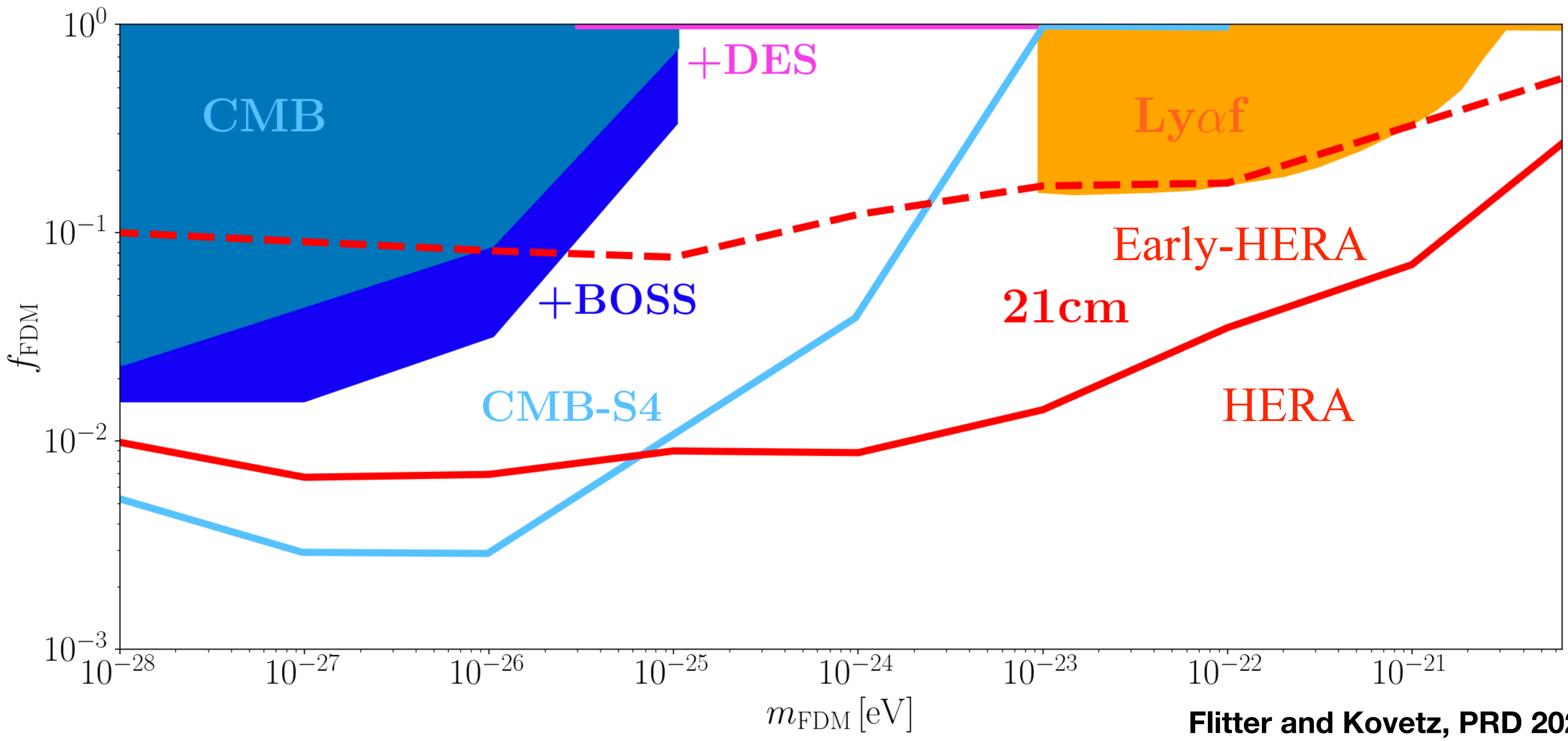

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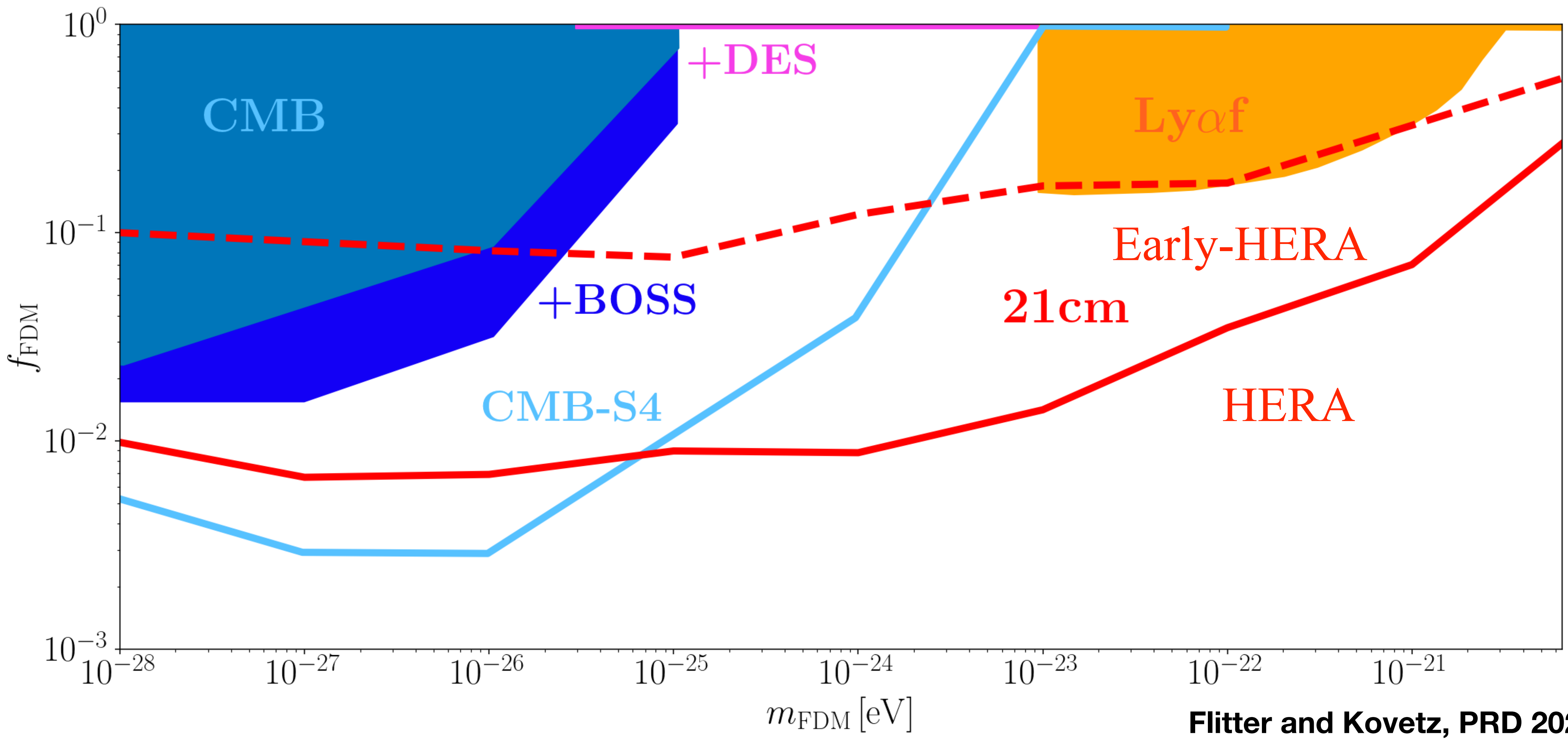

Flitter and Kovetz, PRD 2022

Primordial Magnetic Fields:

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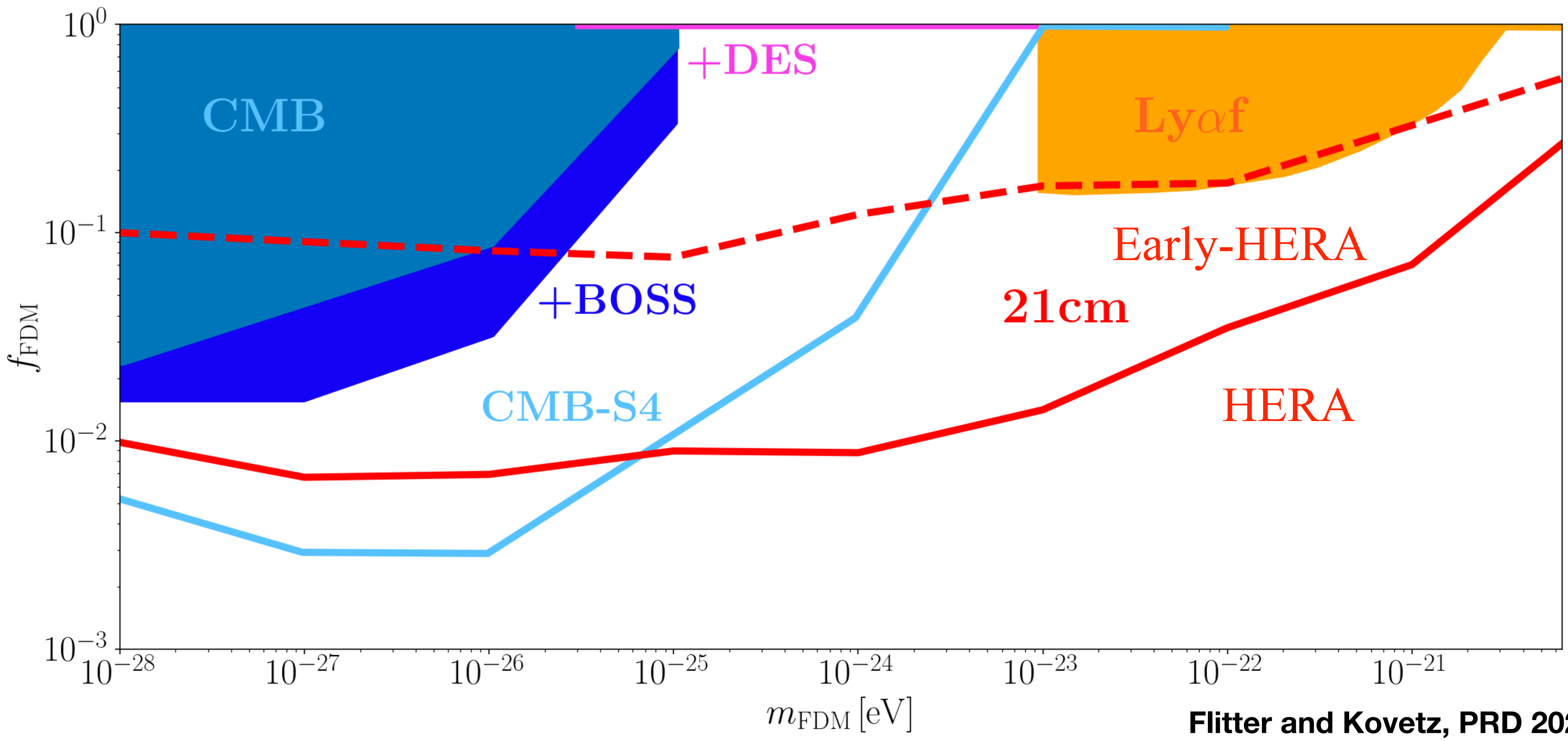

Flitter and Kovetz, PRD 2022

Primordial Magnetic Fields:

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

Adi, Libanore and Kovetz, JCAP 2023

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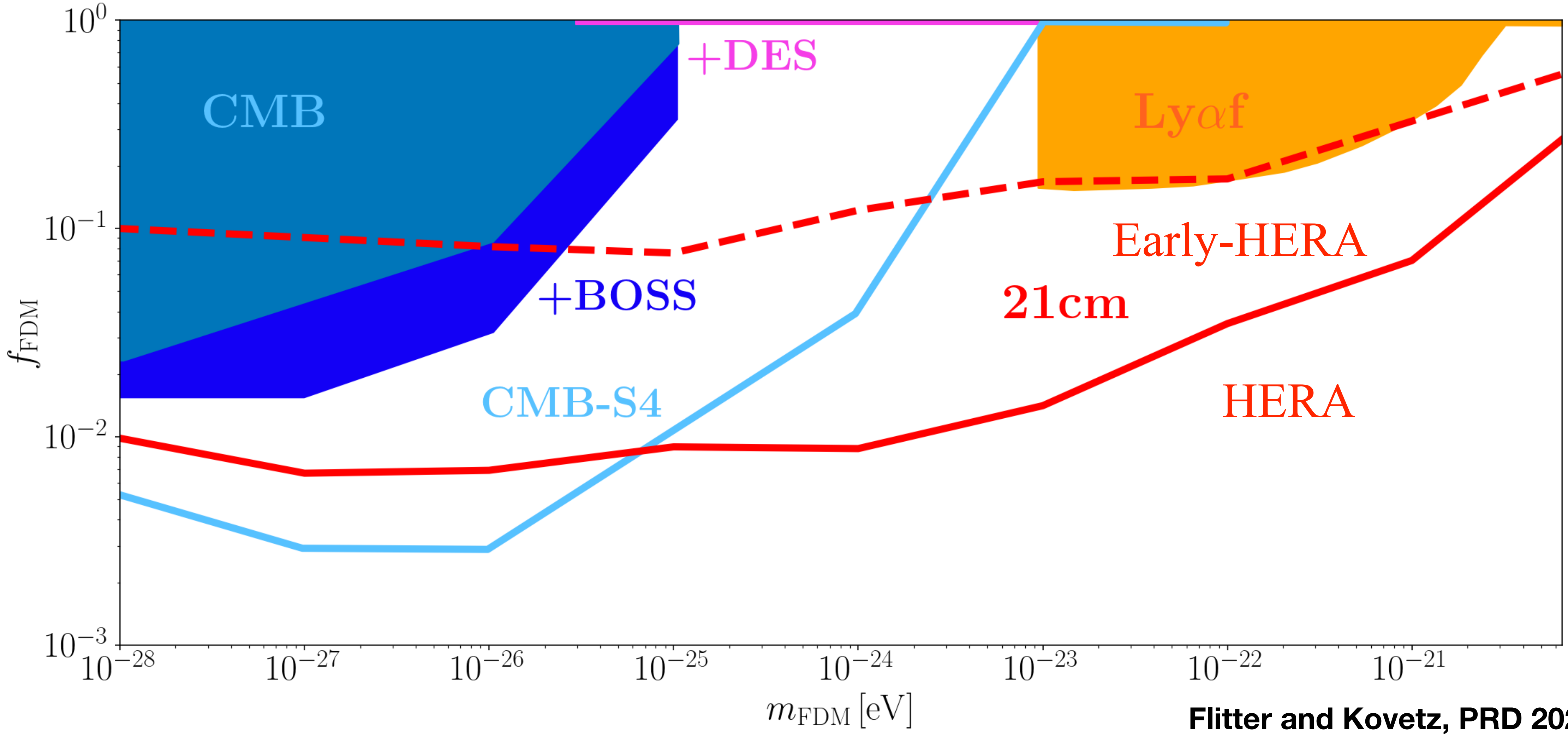

Flitter and Kovetz, PRD 2022

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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, arXiv:2308.04483

LIM Cosmology: Baryon Acoustic Oscillations

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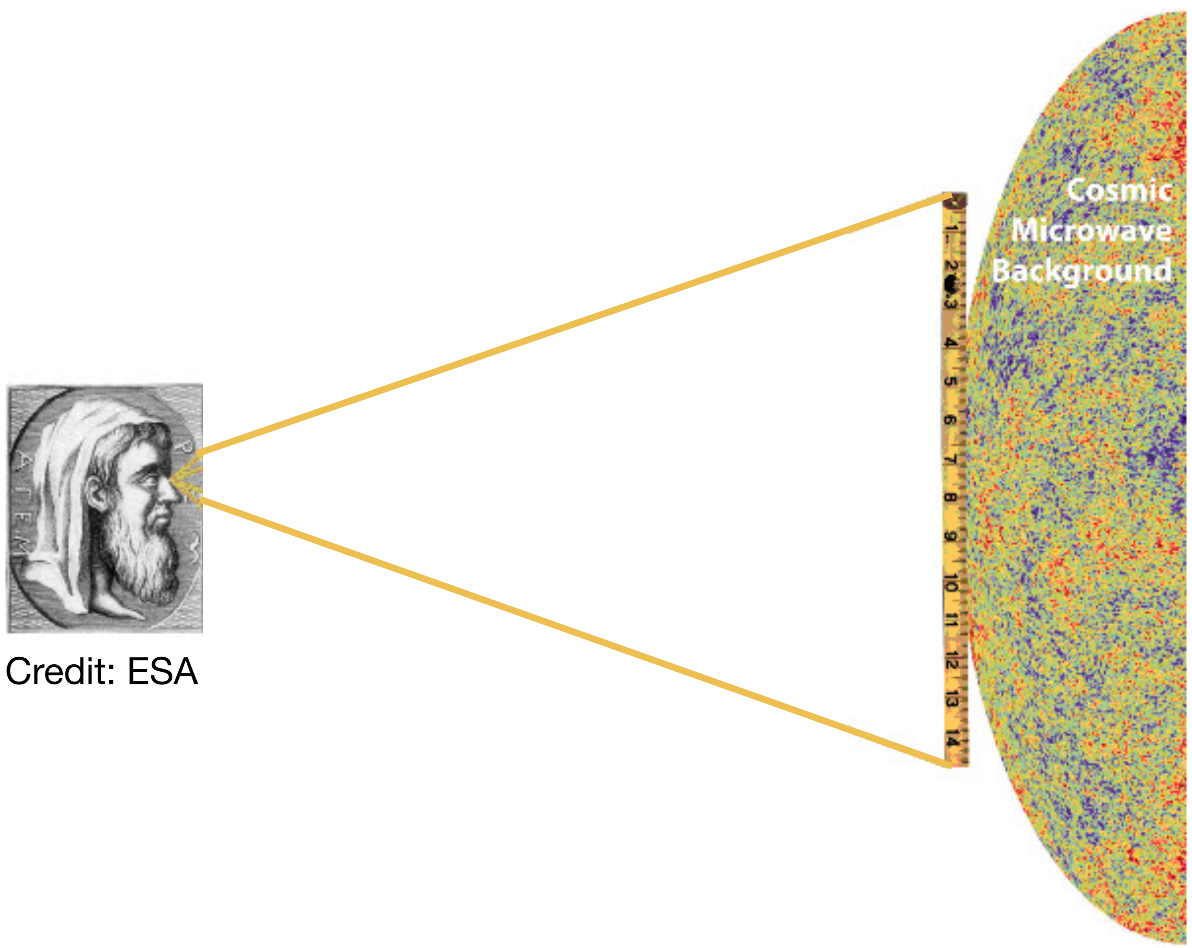
The comoving sound horizon at recombination: $r_s^* = \int_{z^*}^{\infty} \frac{c_s(z)}{H(z)} dz$



Credit: ESA

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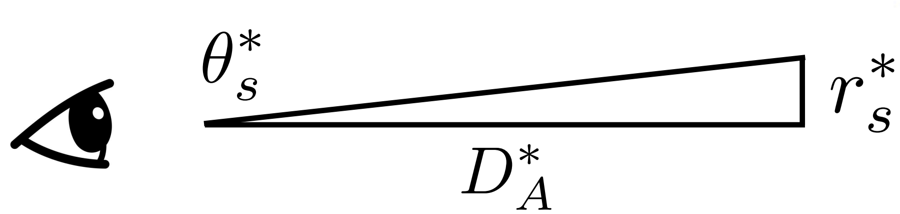

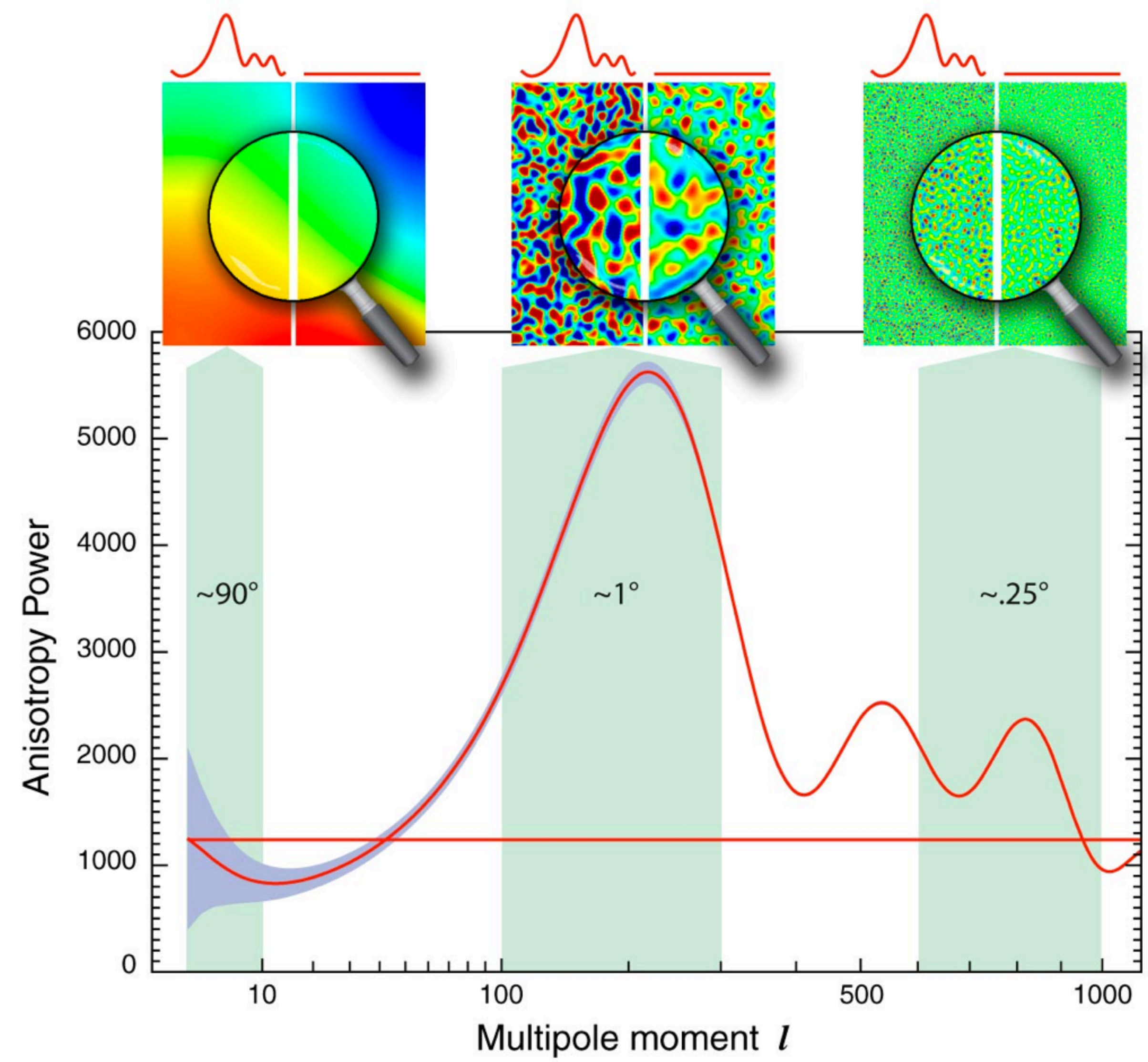

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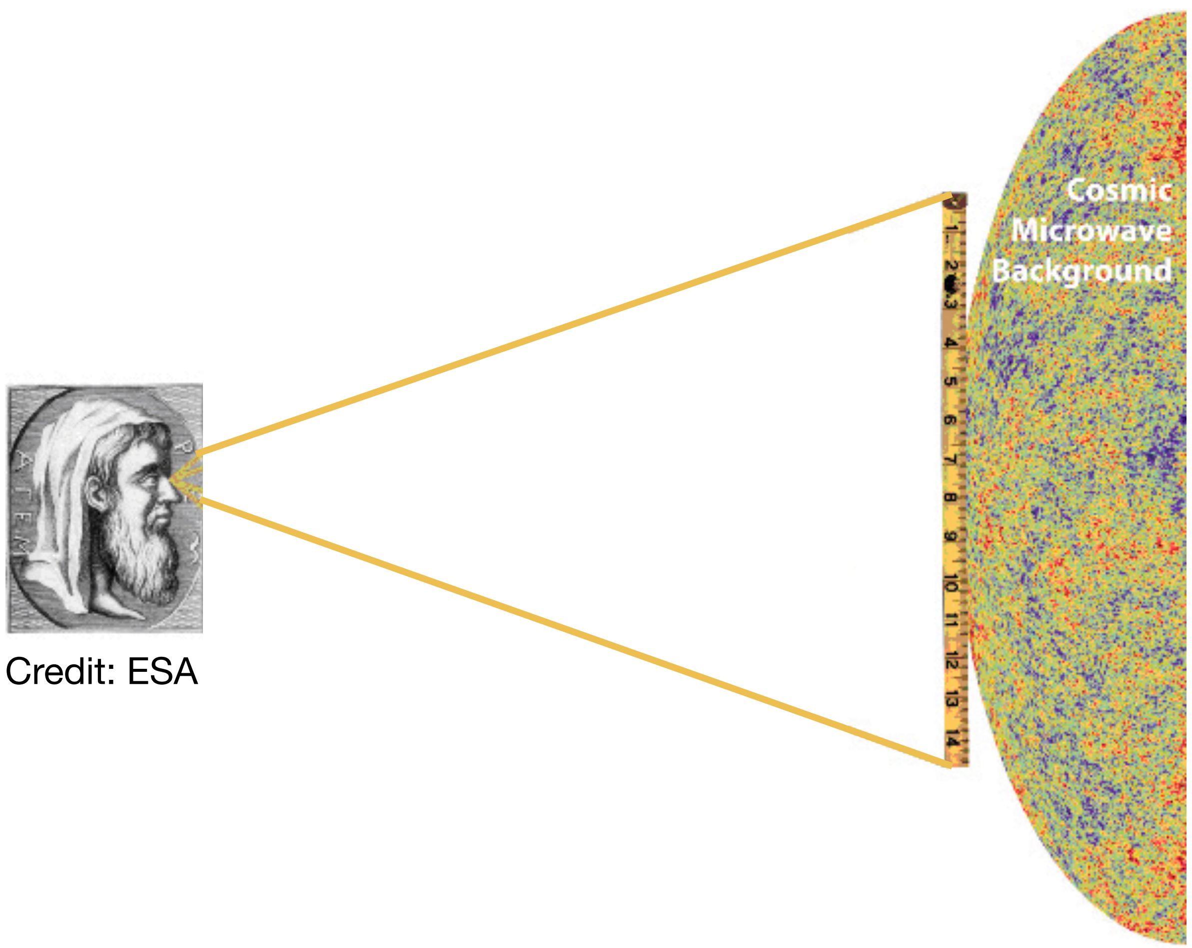

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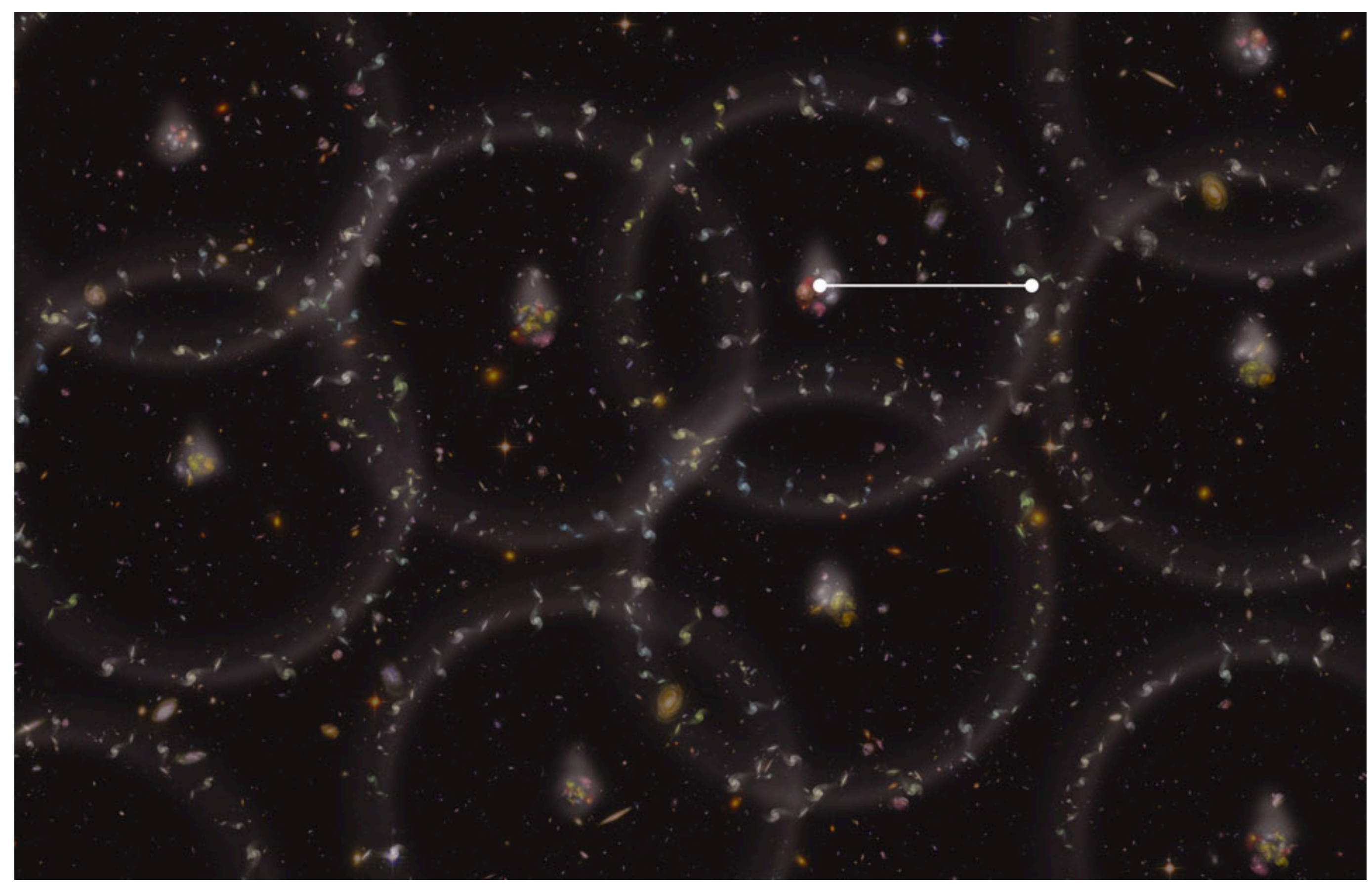

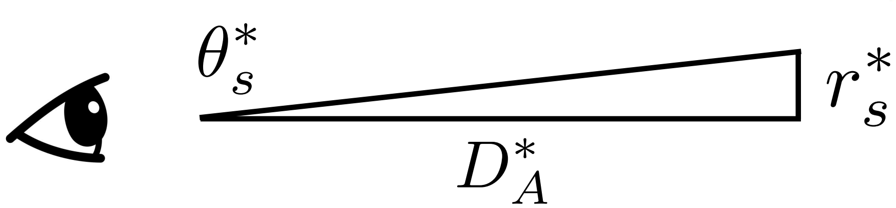

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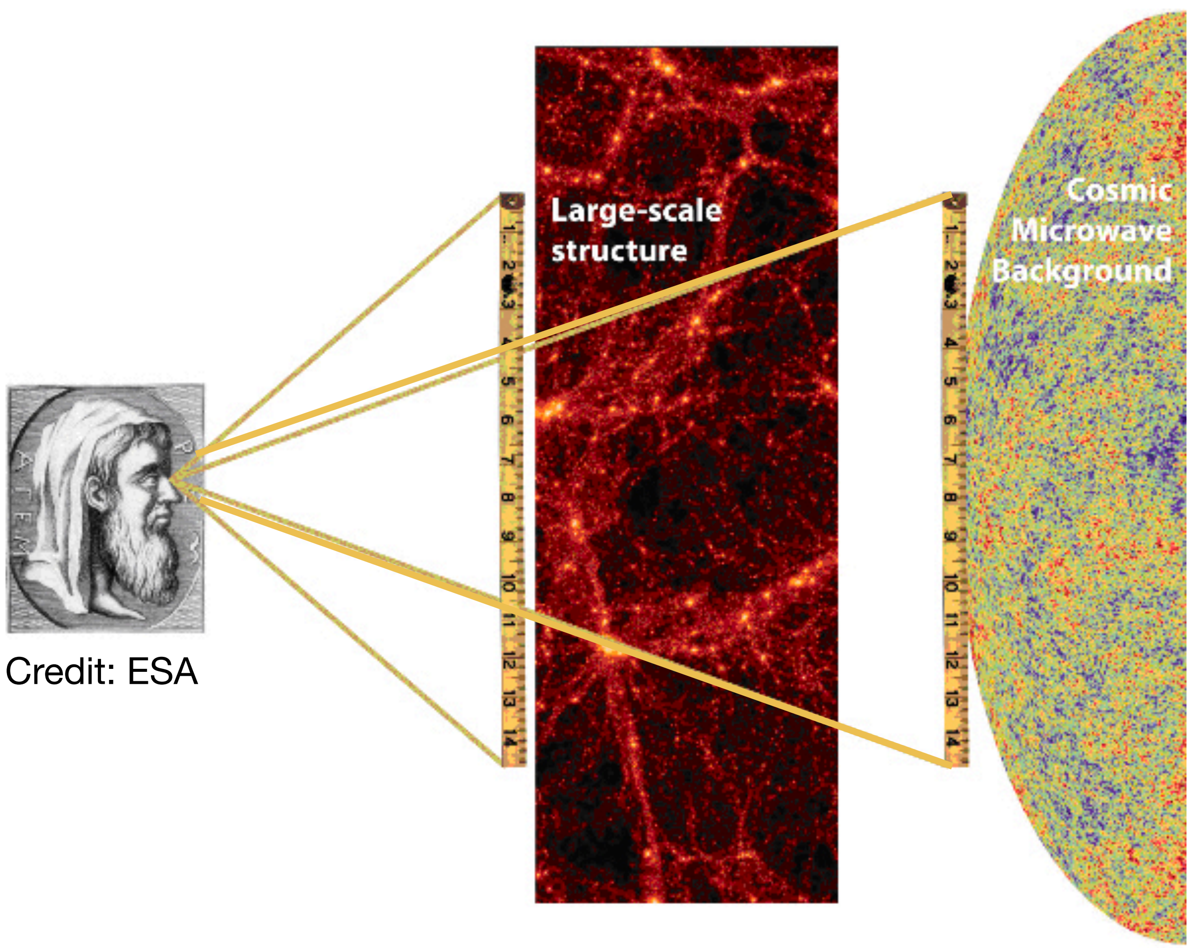

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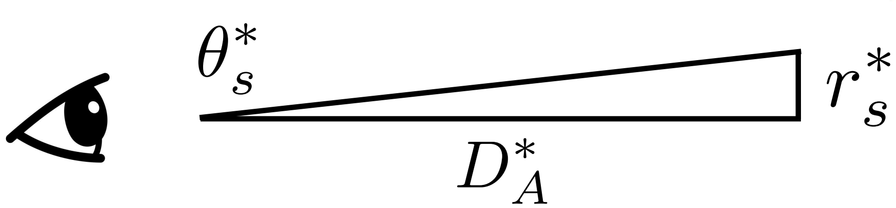
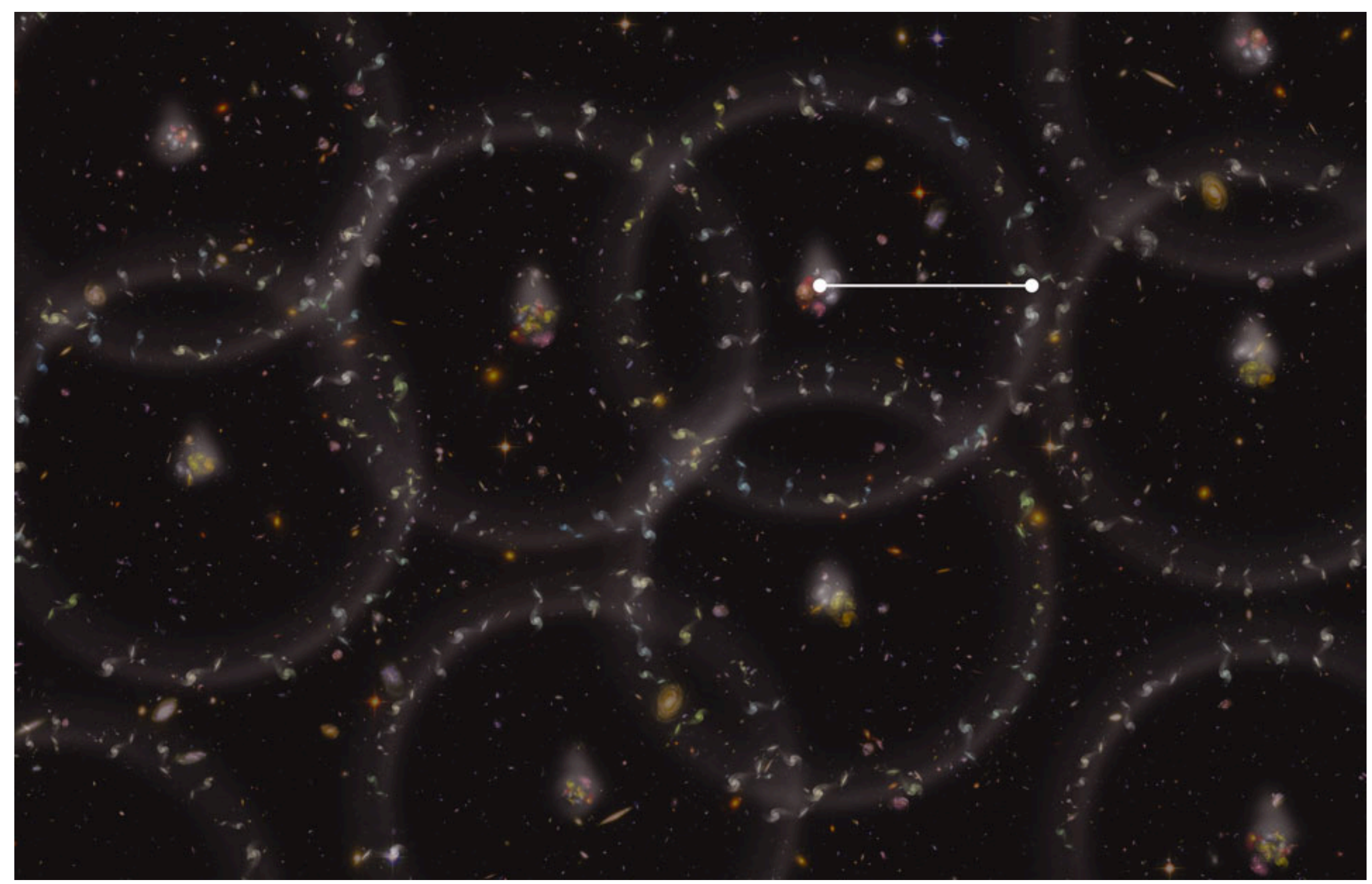
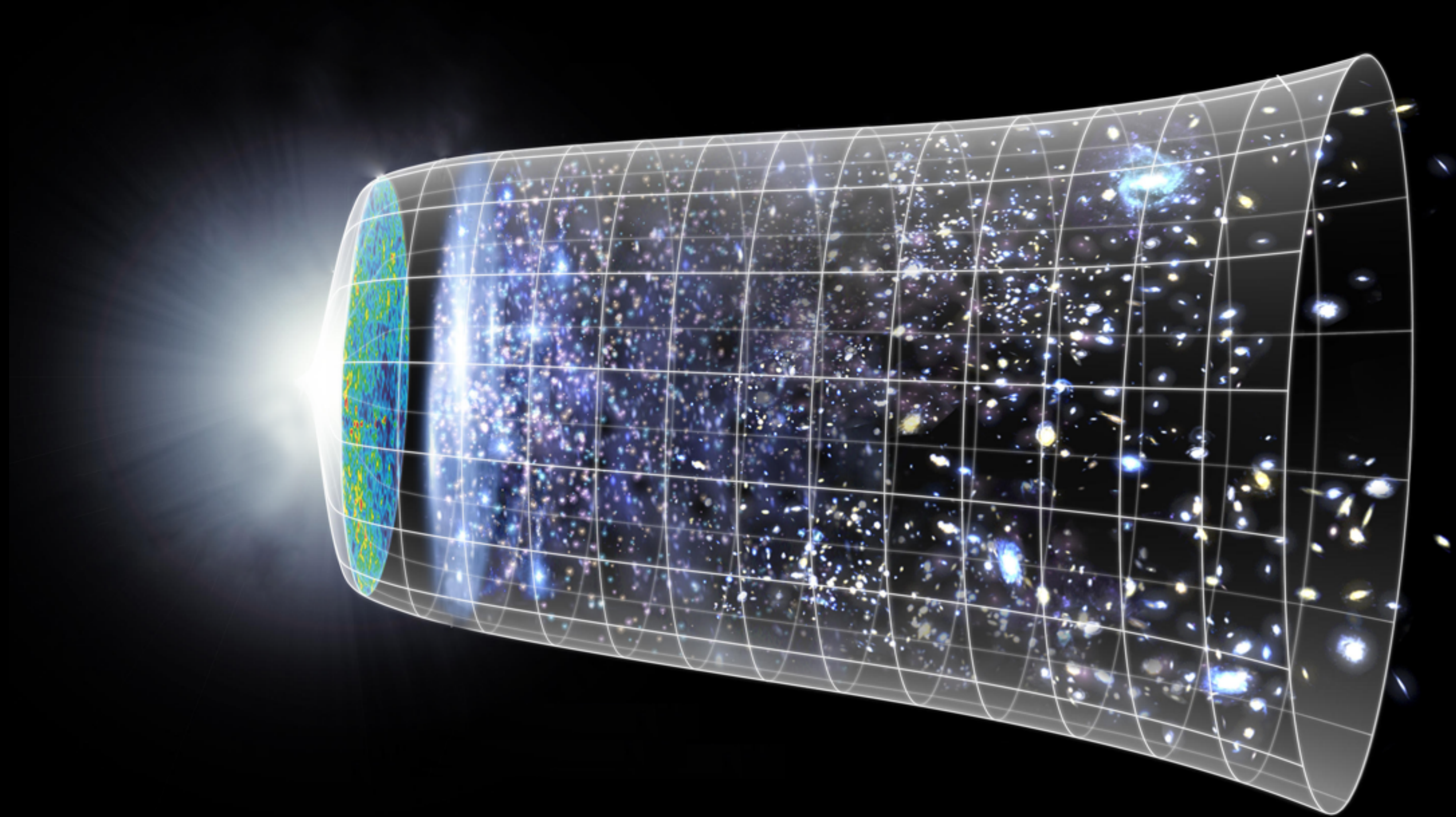




LIM Cosmology: Extracting the BAOs

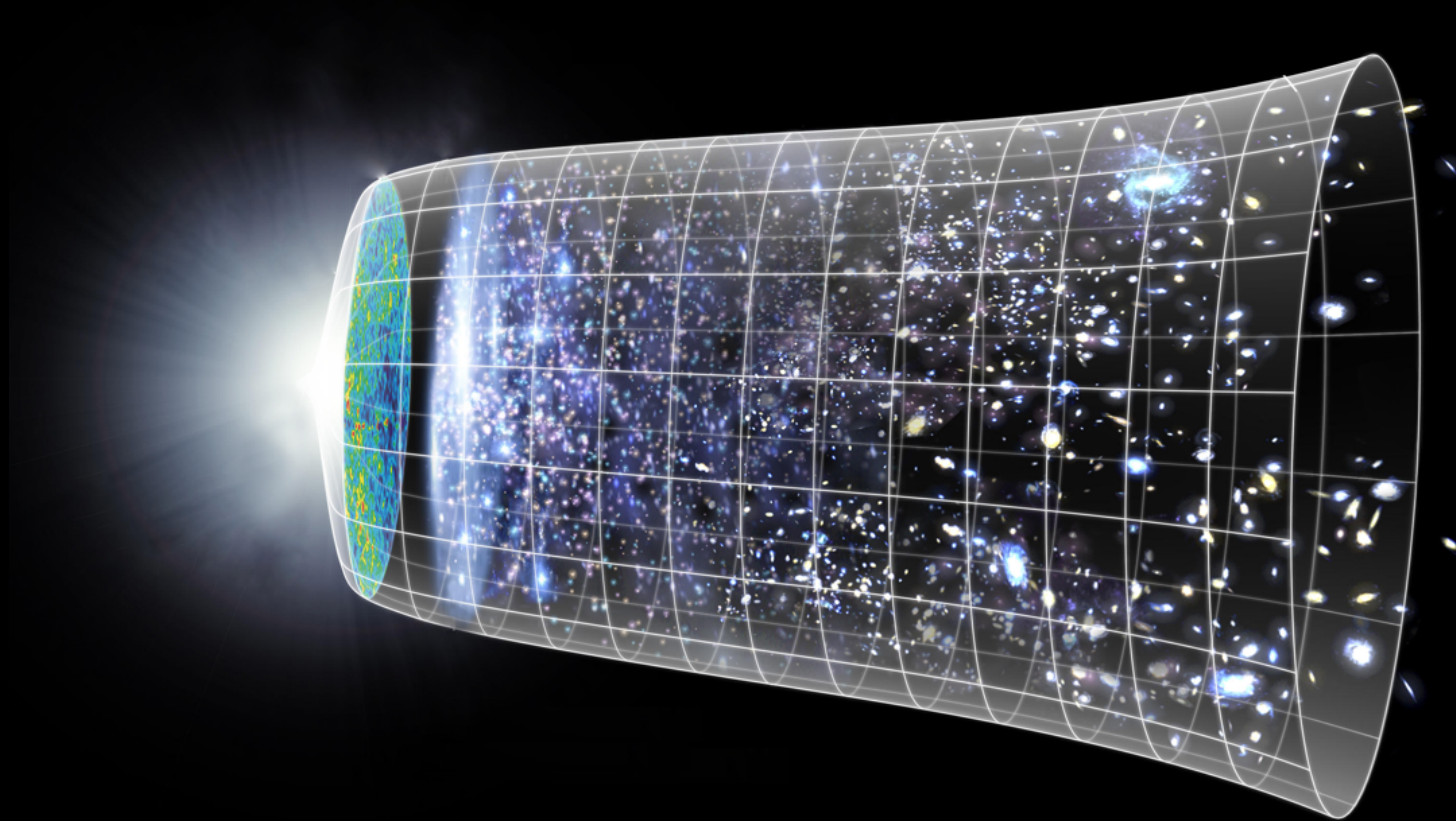
Credit: NASA/WMAP Science Team



LIM Cosmology: Extracting the BAOs

Credit: NASA/WMAP Science Team

Structure: stars, ISM, galaxies, IGM, clusters



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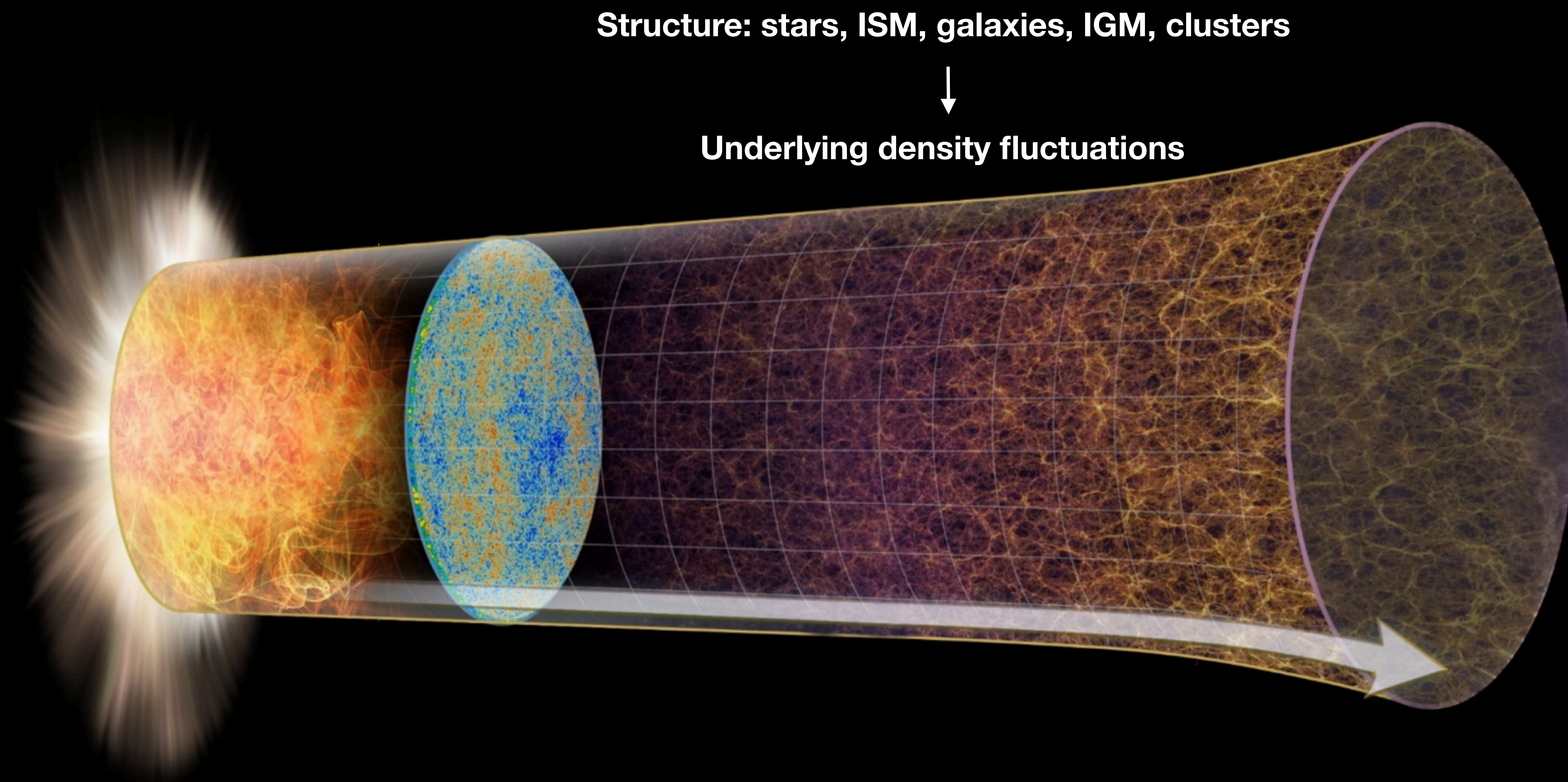

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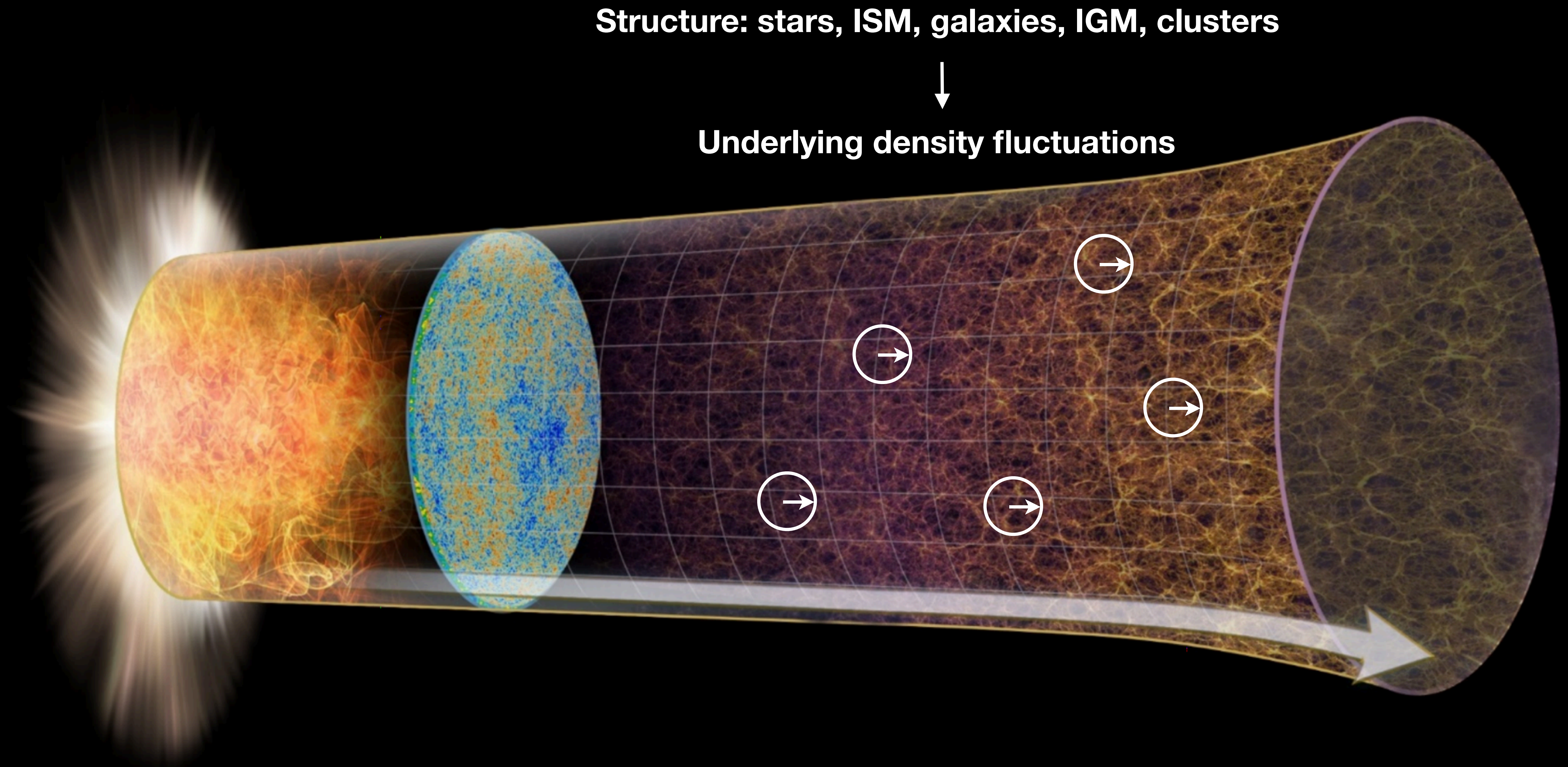

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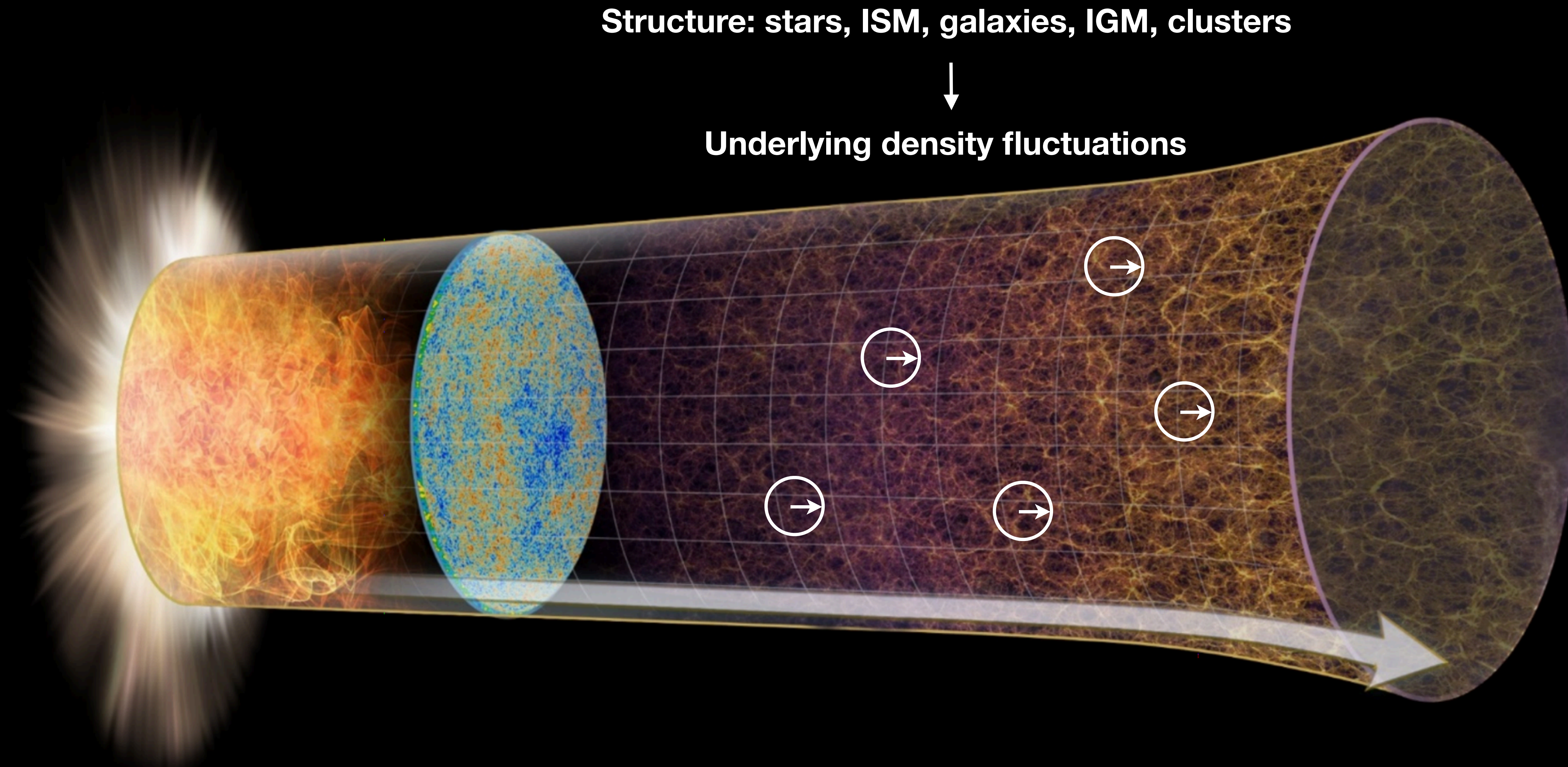

Solution: Use Power Spectrum Anisotropy (AP effect)

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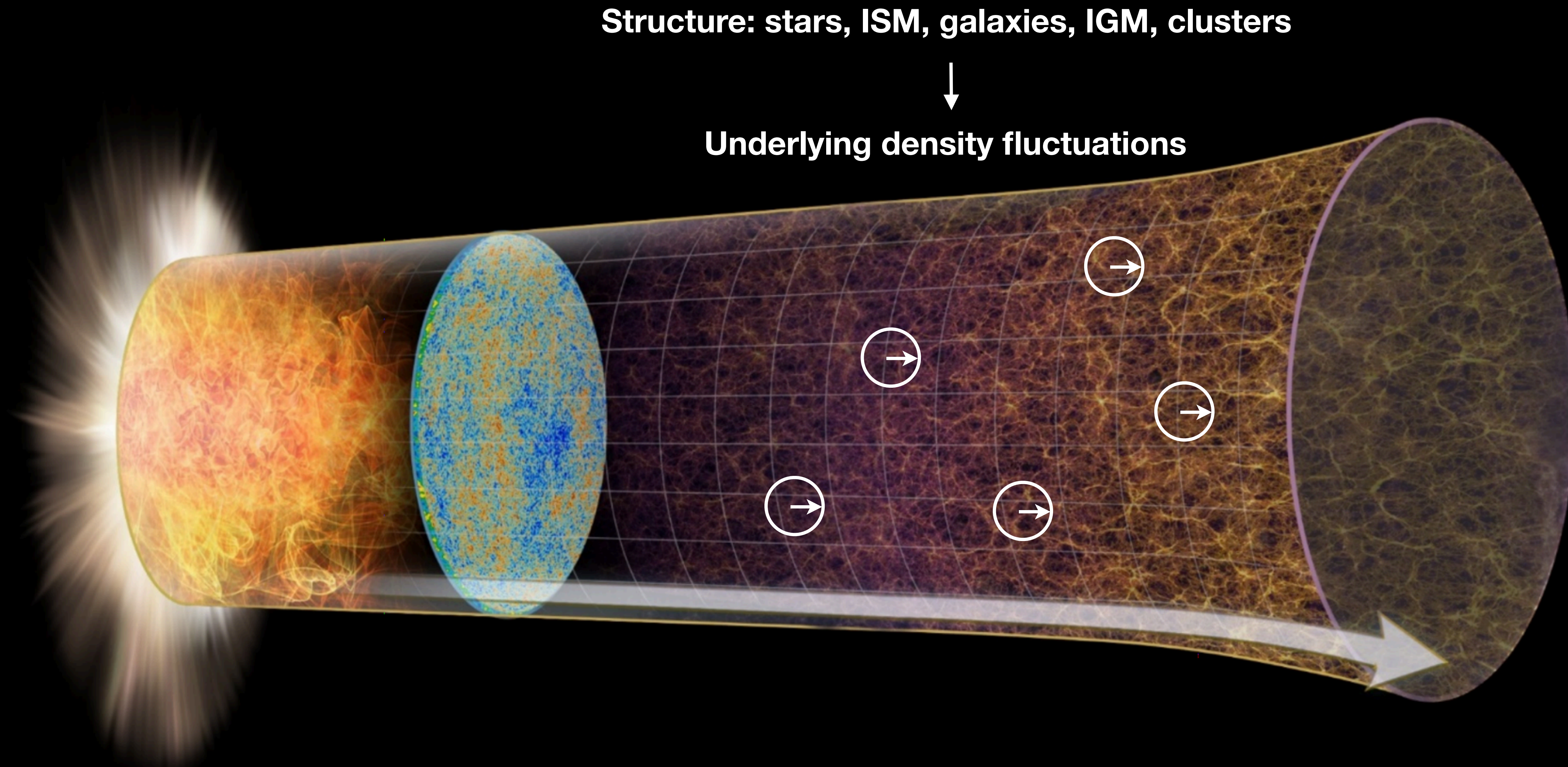

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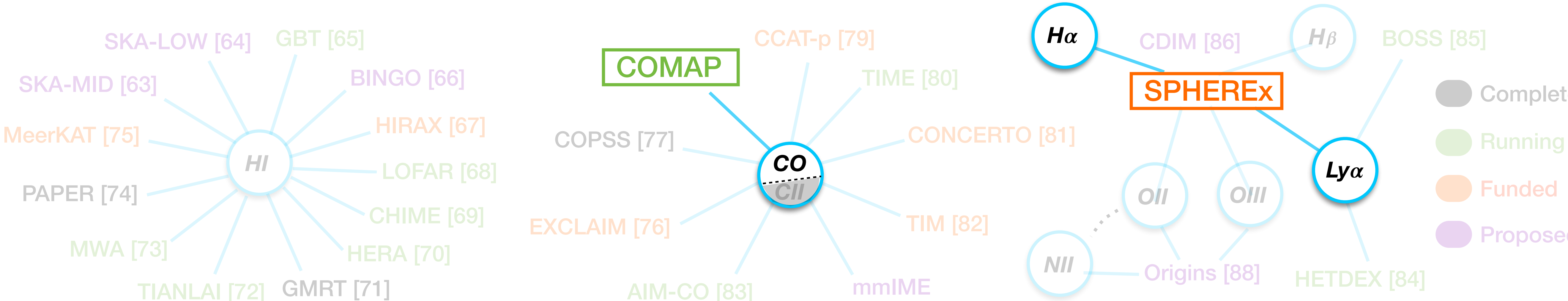
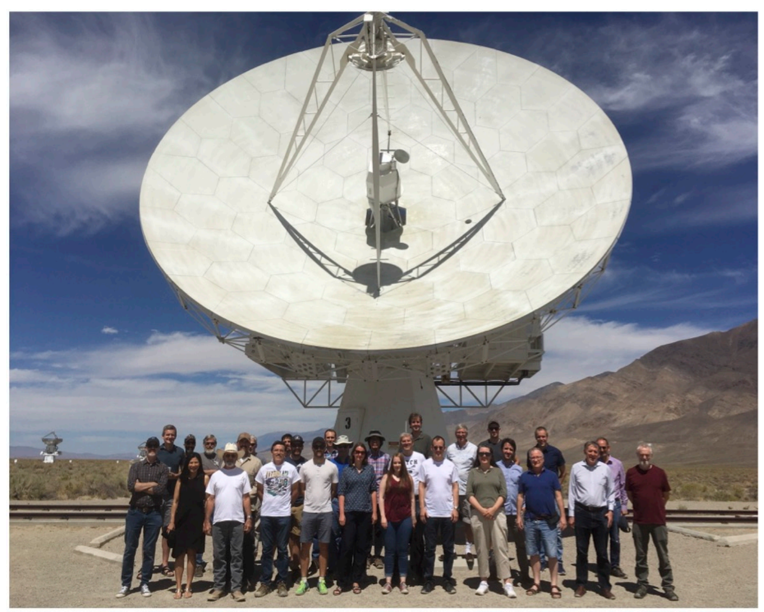
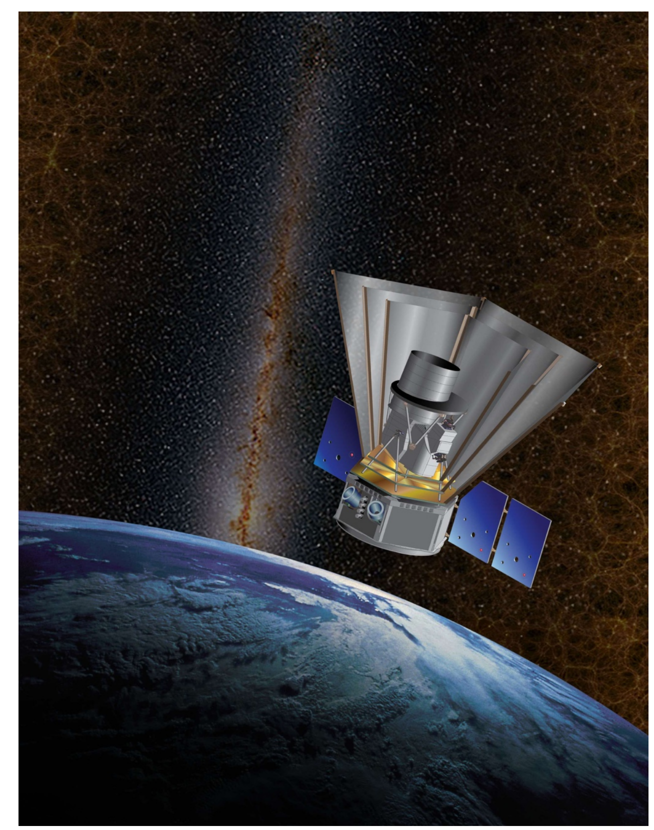
Addressed in: Bernal, Breysse and Kovetz, PRL 2019
Bernal, Breysse, Gil-Marin and Kovetz, PRD 2019

LIM Cosmology: Expansion History from BAOs







Instrumental Paramater	COMAP 1	COMAP 2	IMS3 (CO)
$T_{\rm sys}$ [K]	40	40	max(20,$\nu_{\rm obs}$)
Total # of independent detectors	19	95	1000
Ang. resolution (FWHM) [arcmin]	4	4	4
Frequency band [GHz]	26-34	26-34	12-36
$\delta\nu$ [MHz]	15.6	8.0	2.0
$t_{\rm obs}$ [h]	6000	10000	10000
$\Omega_{\rm field}$ [deg^2]	2.25	60	1000

Hα	*Lyα*
80-300 THz	250-360 THz
200 deg^2	200 deg^2

LIM Cosmology: Expansion History from BAOs

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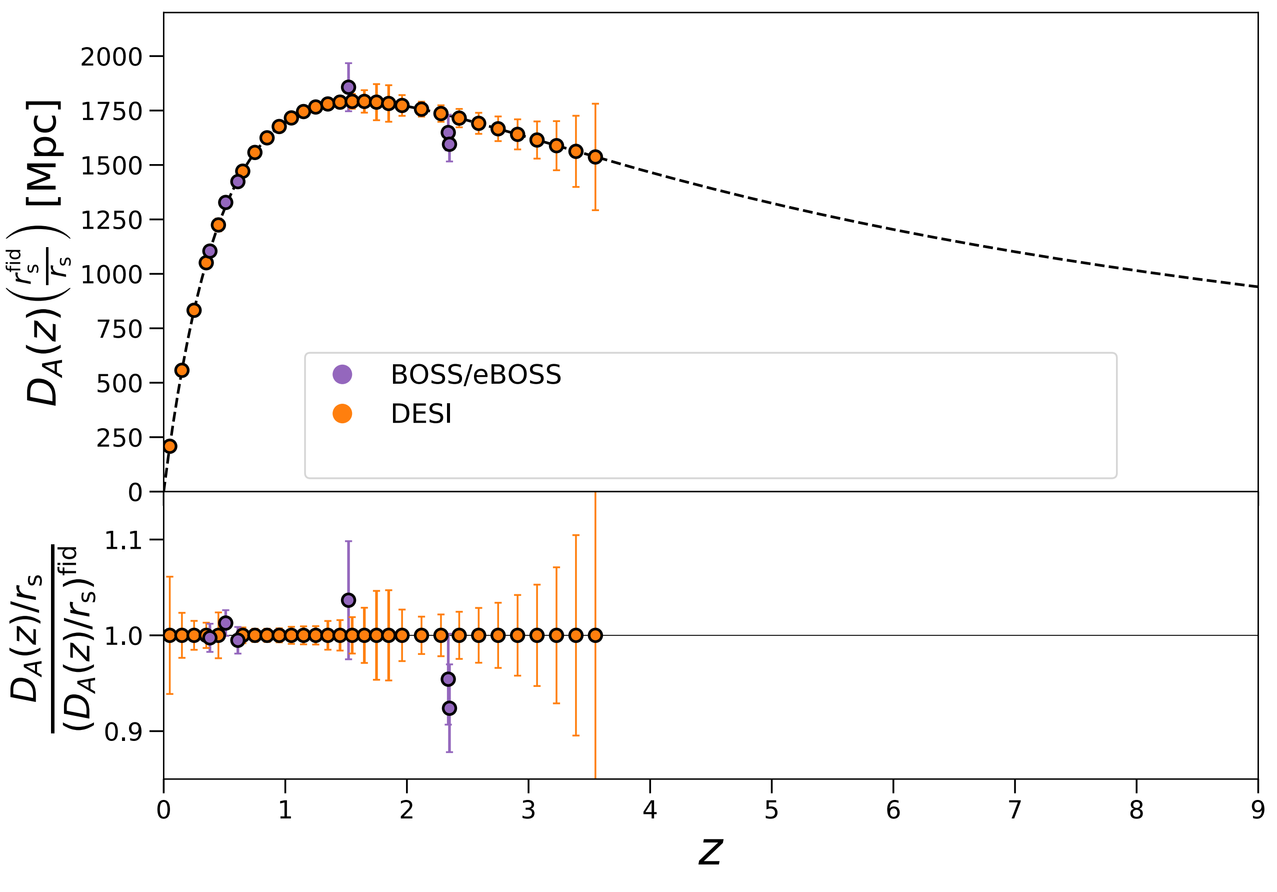
Angular diameter distance



Bernal, Breysse and Kovetz, PRL 2019

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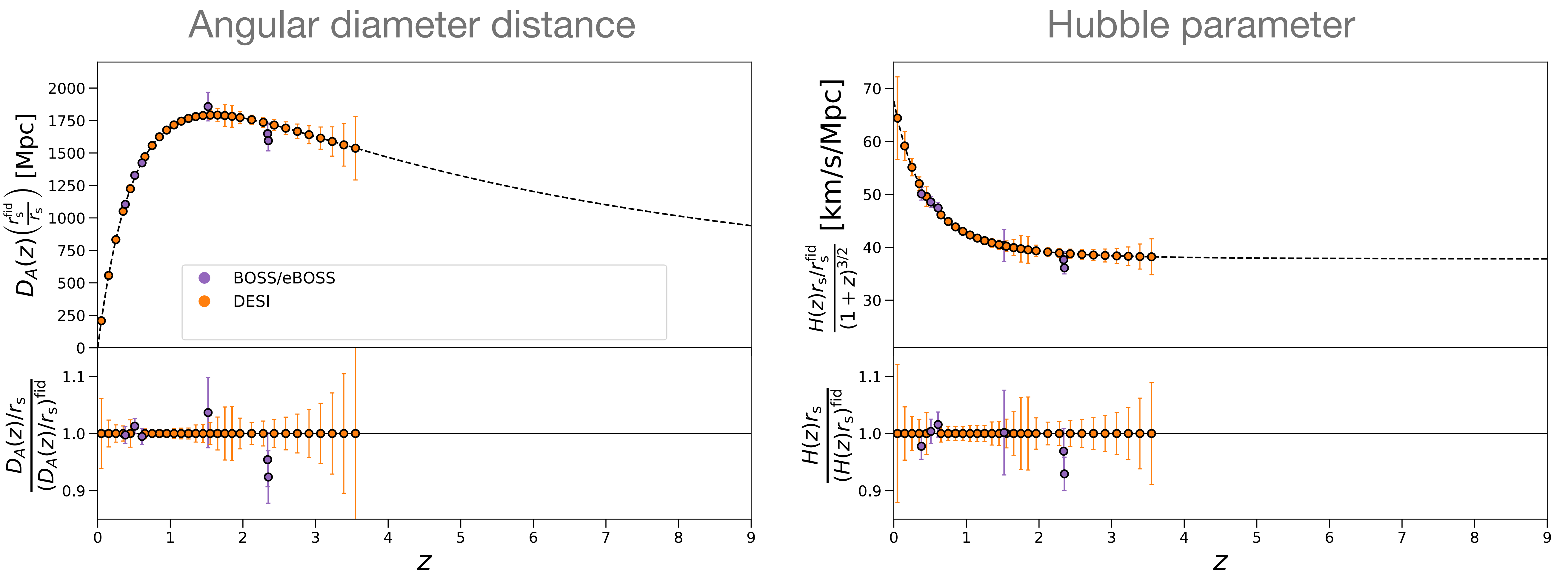

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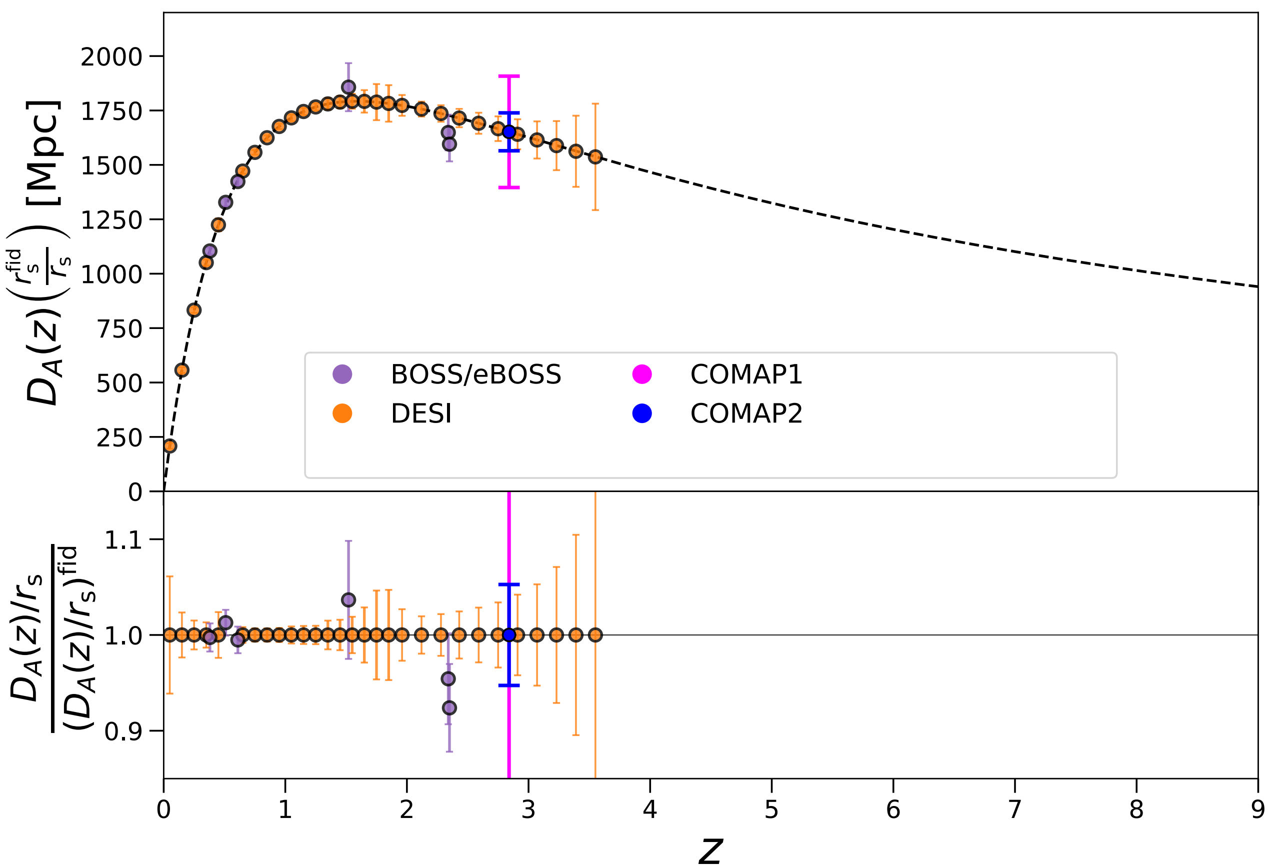
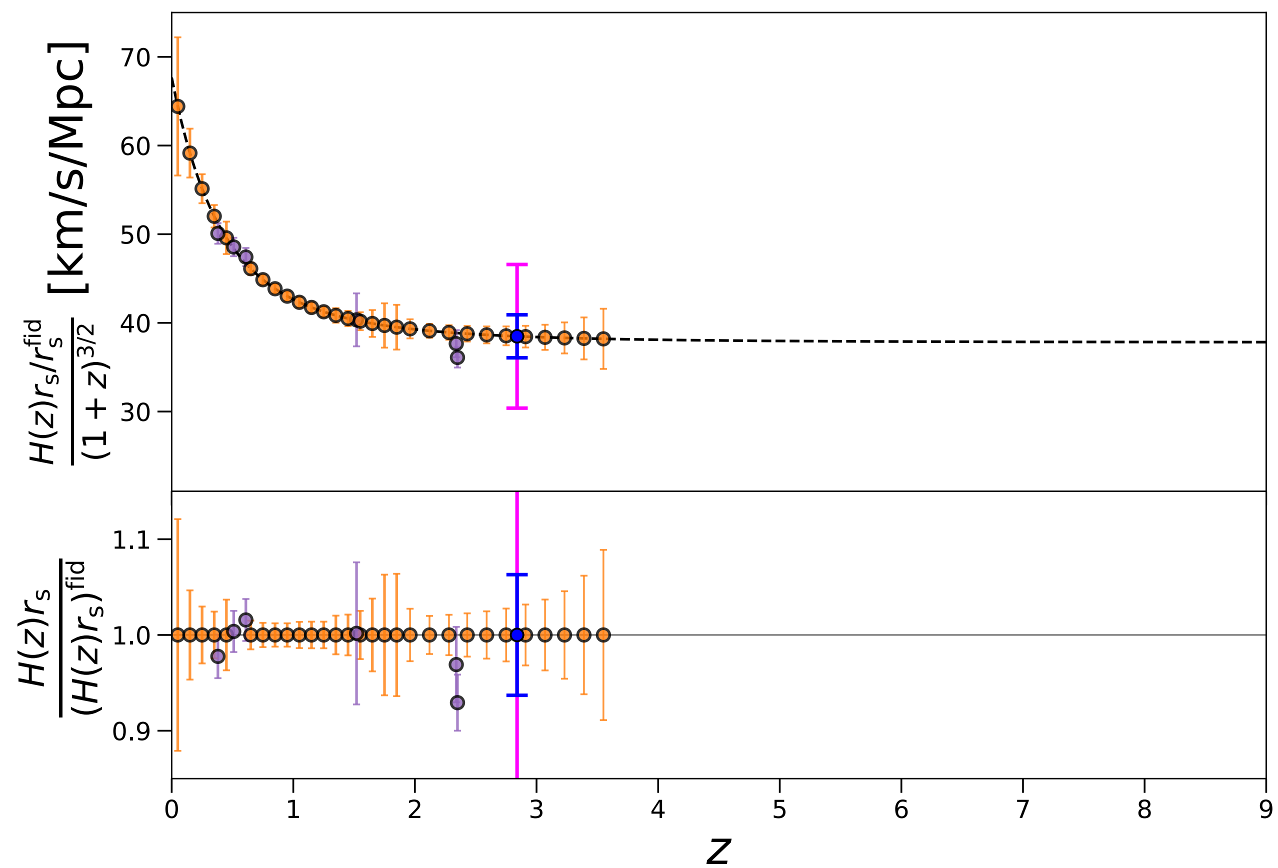


Hubble parameter



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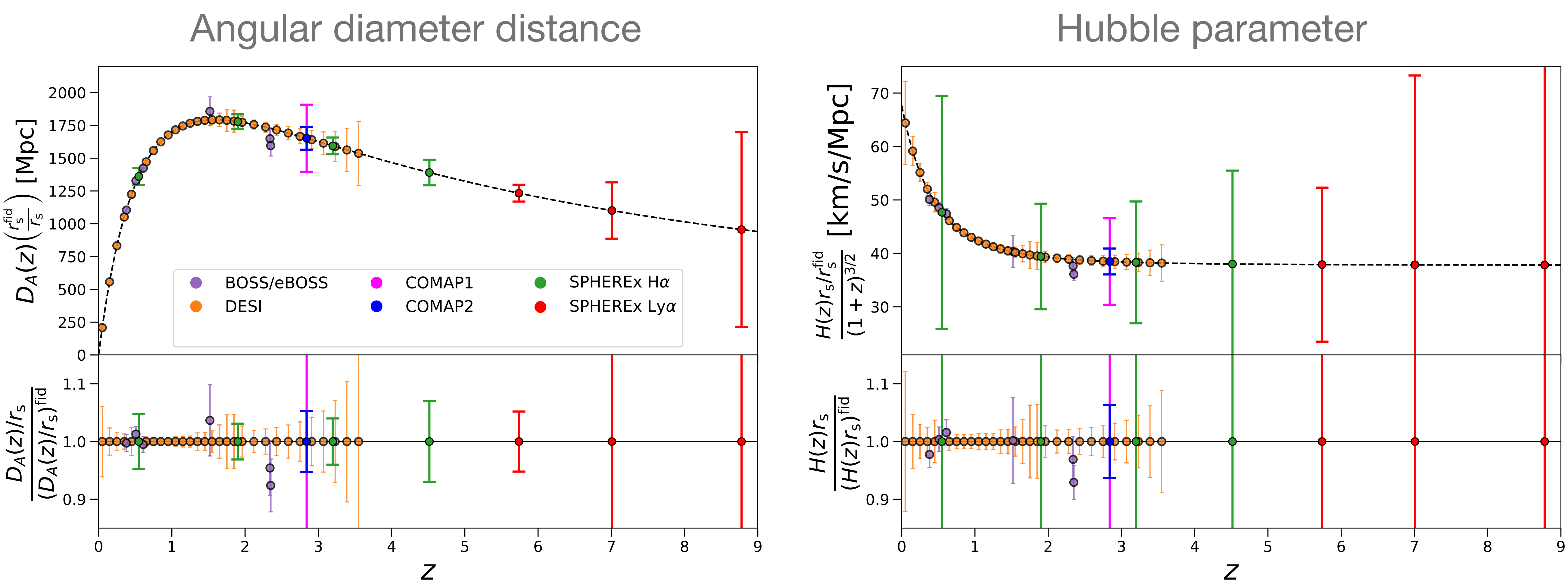

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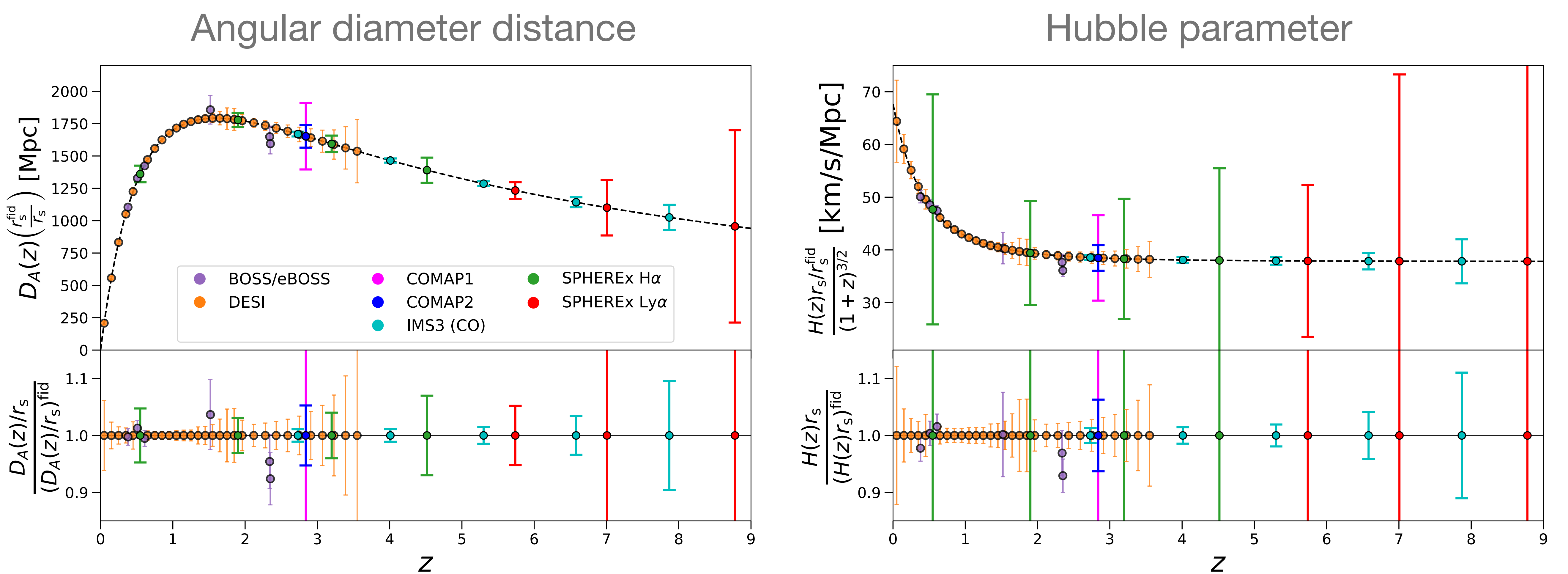

Bernal, Breysse and Kovetz, PRL 2019

21cm-IM: Velocity Acoustic Oscillations

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

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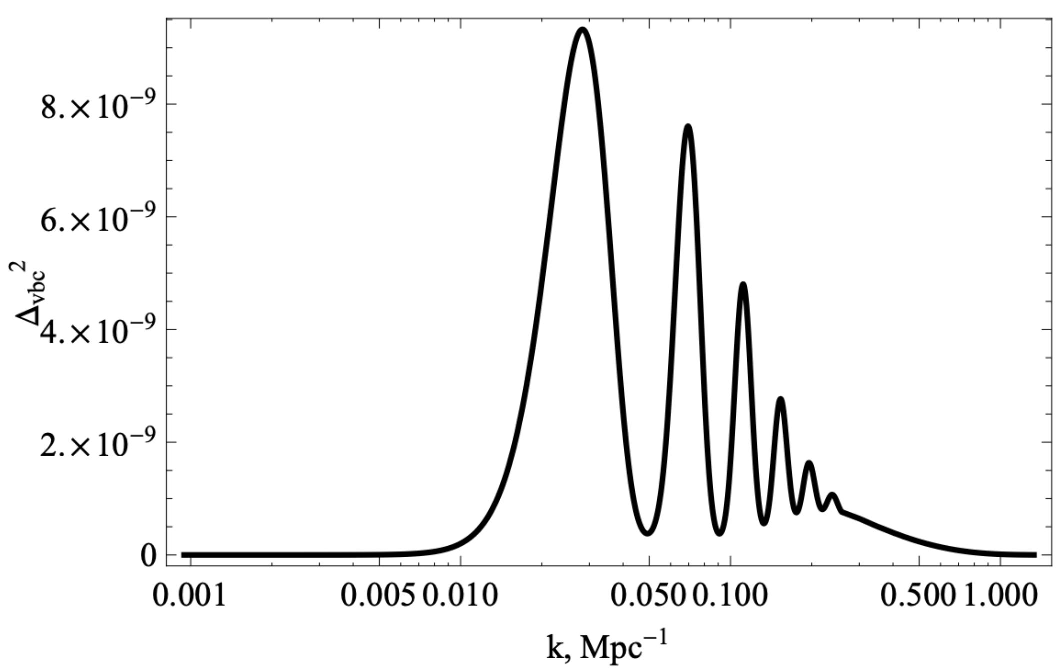
Tseliakovich and Hirata, PRD 2010



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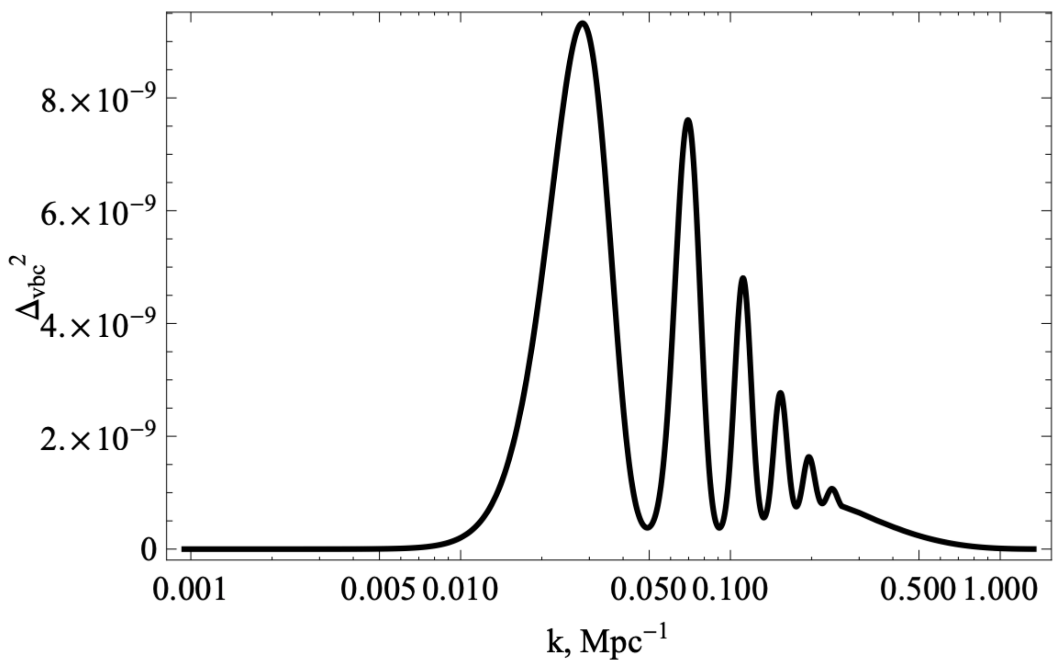
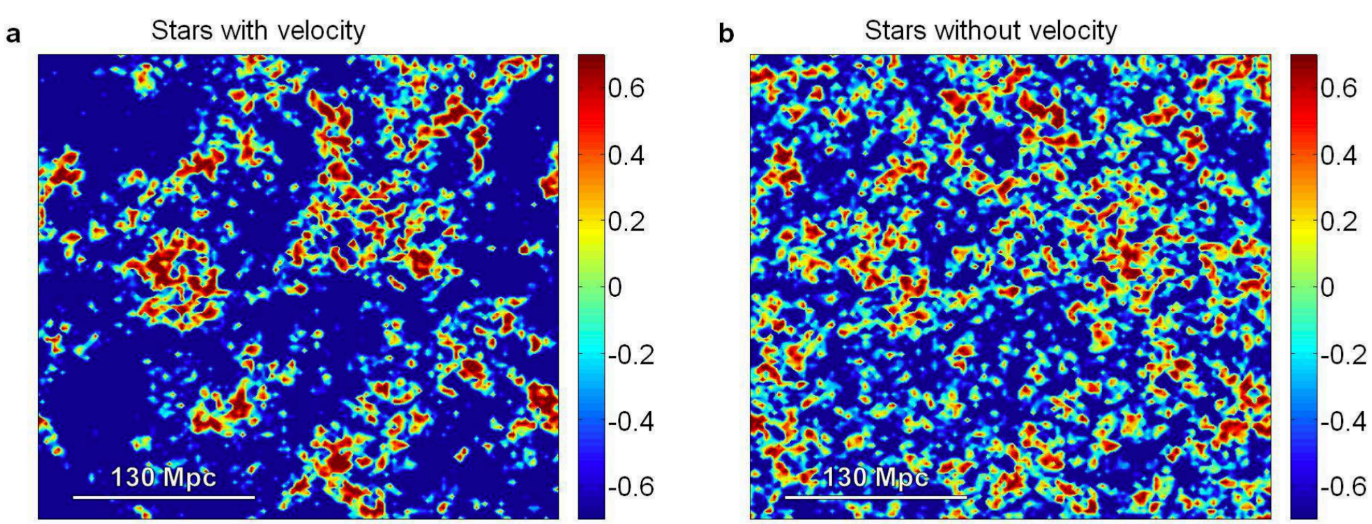


Visbal, Barkana, Fialkov, Tseliakovich and Hirata, Nature 2012



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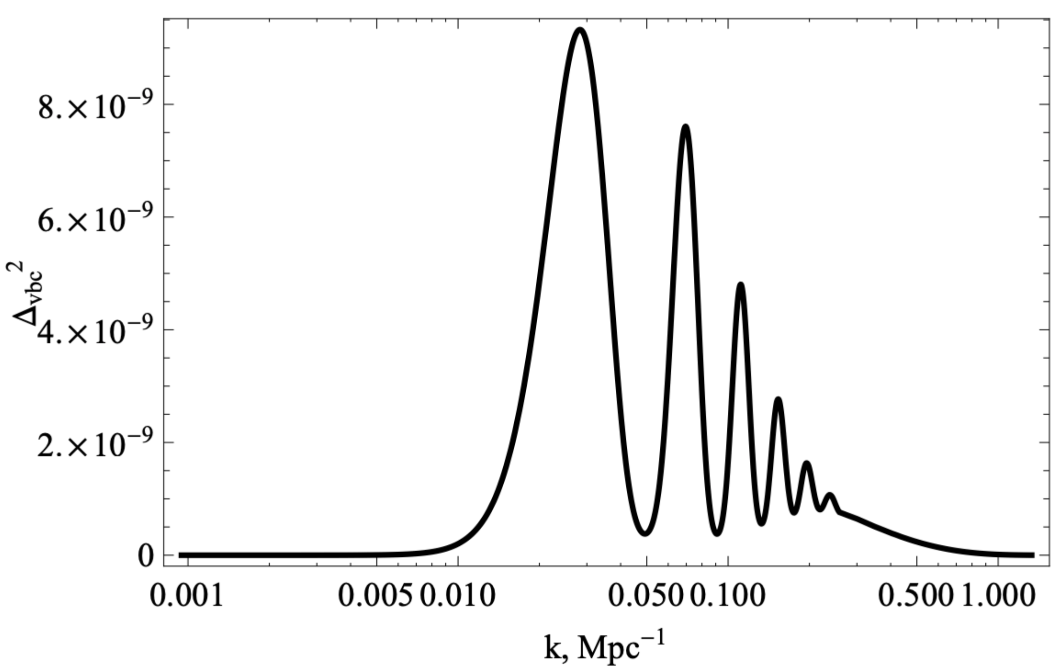
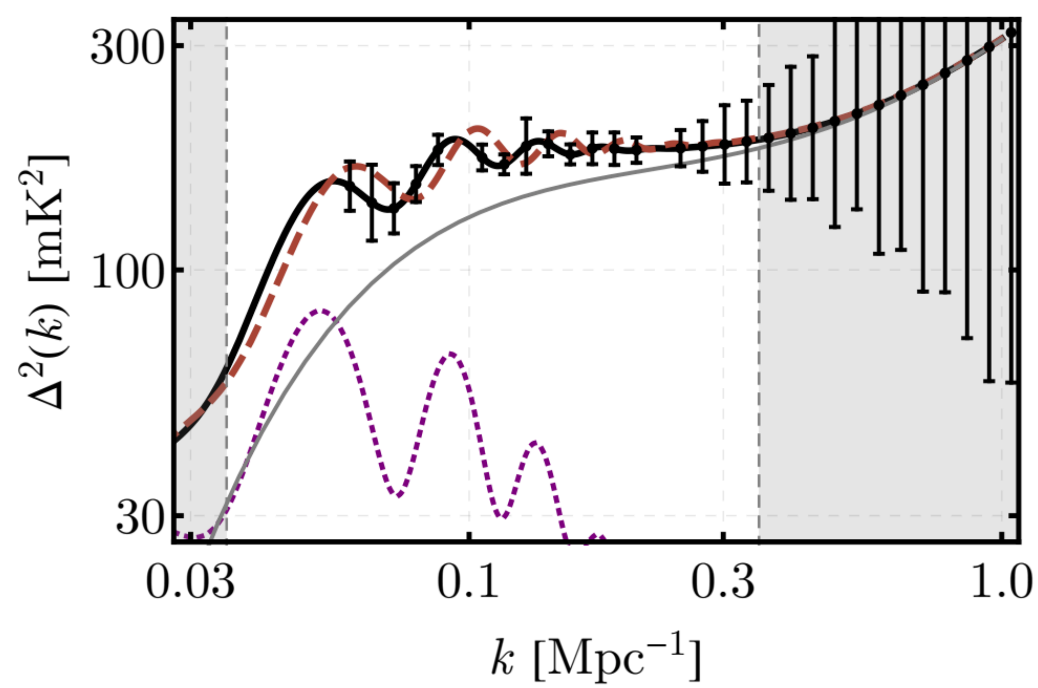


Muñoz, PRL 2019



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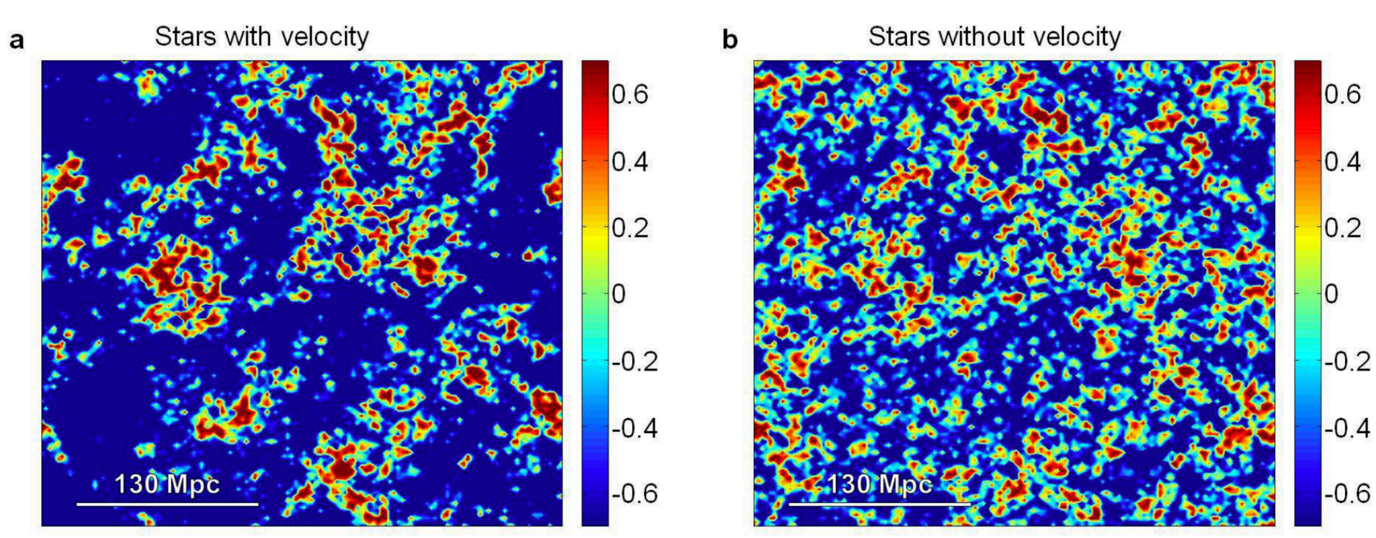

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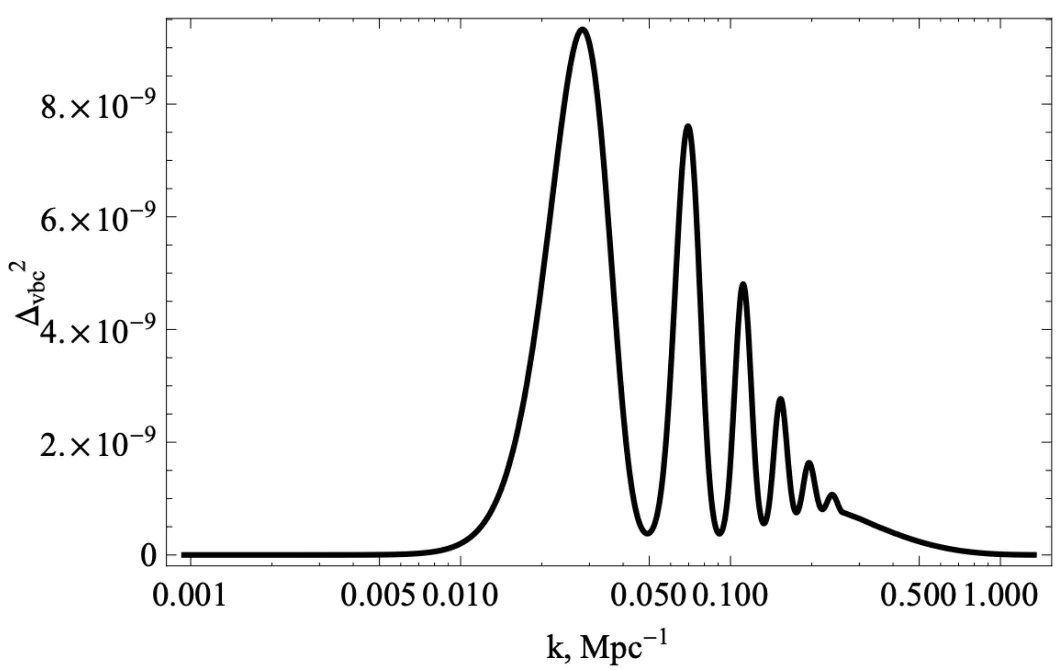
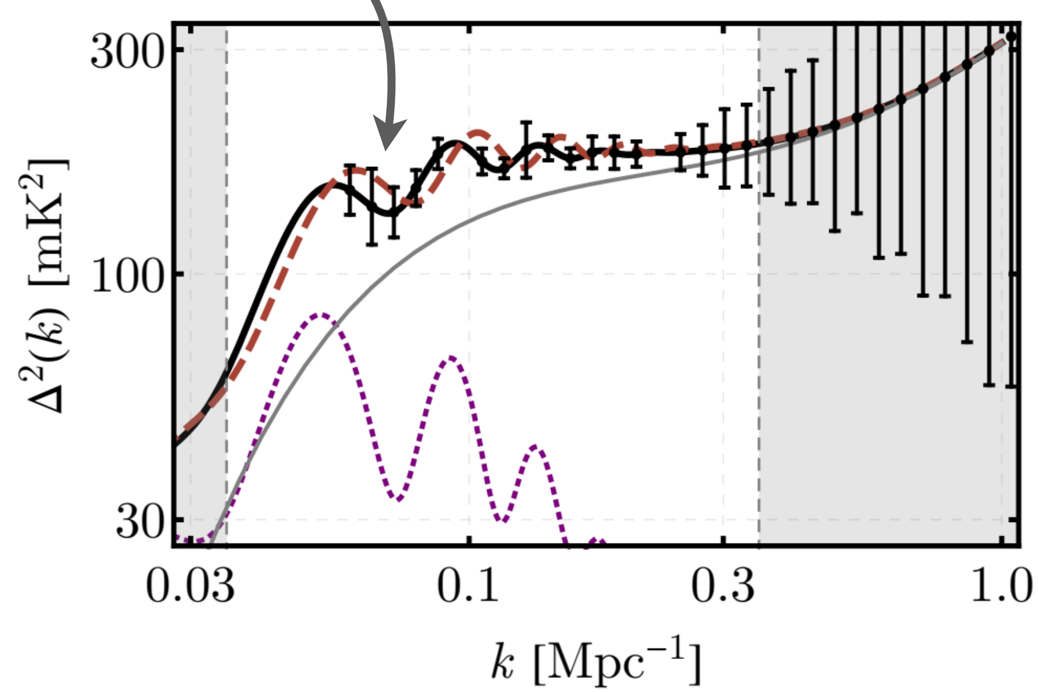


AP effect!

Muñoz, PRL 2019



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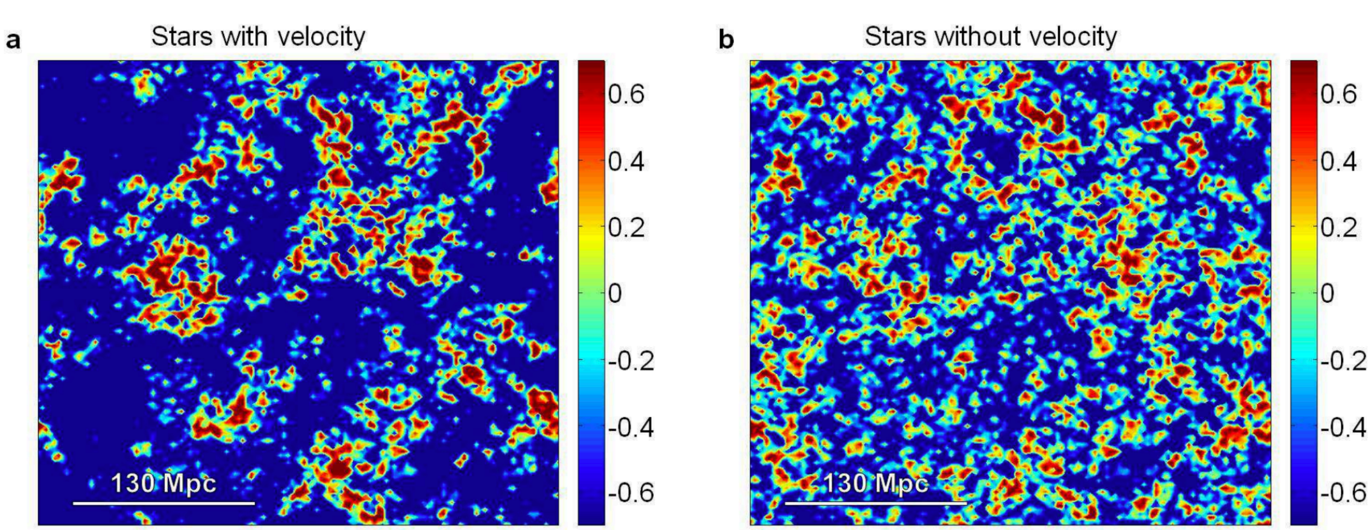

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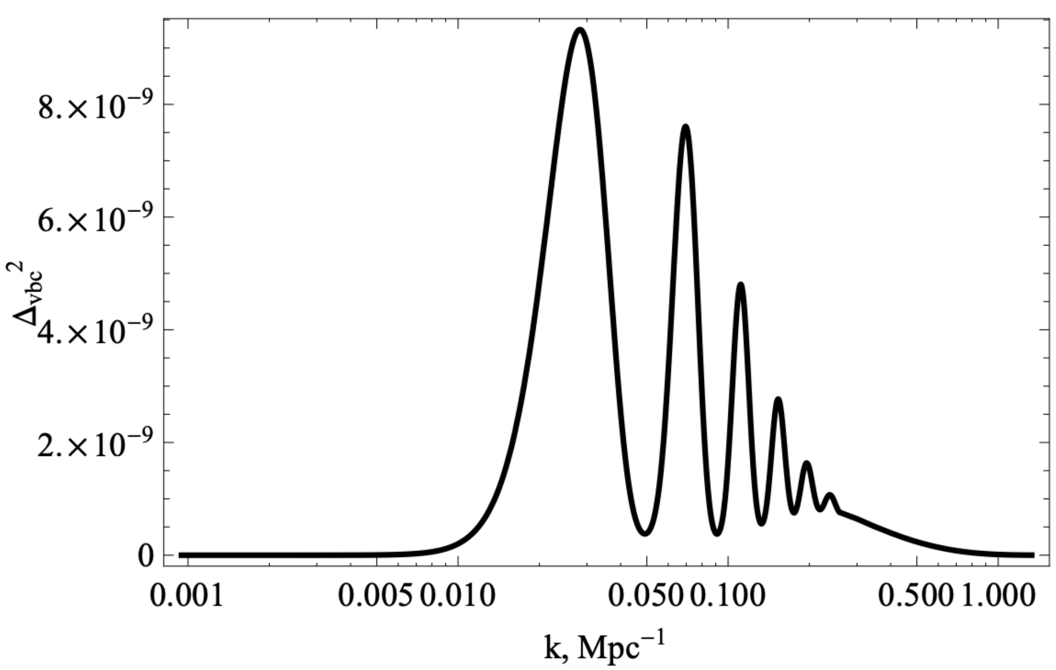

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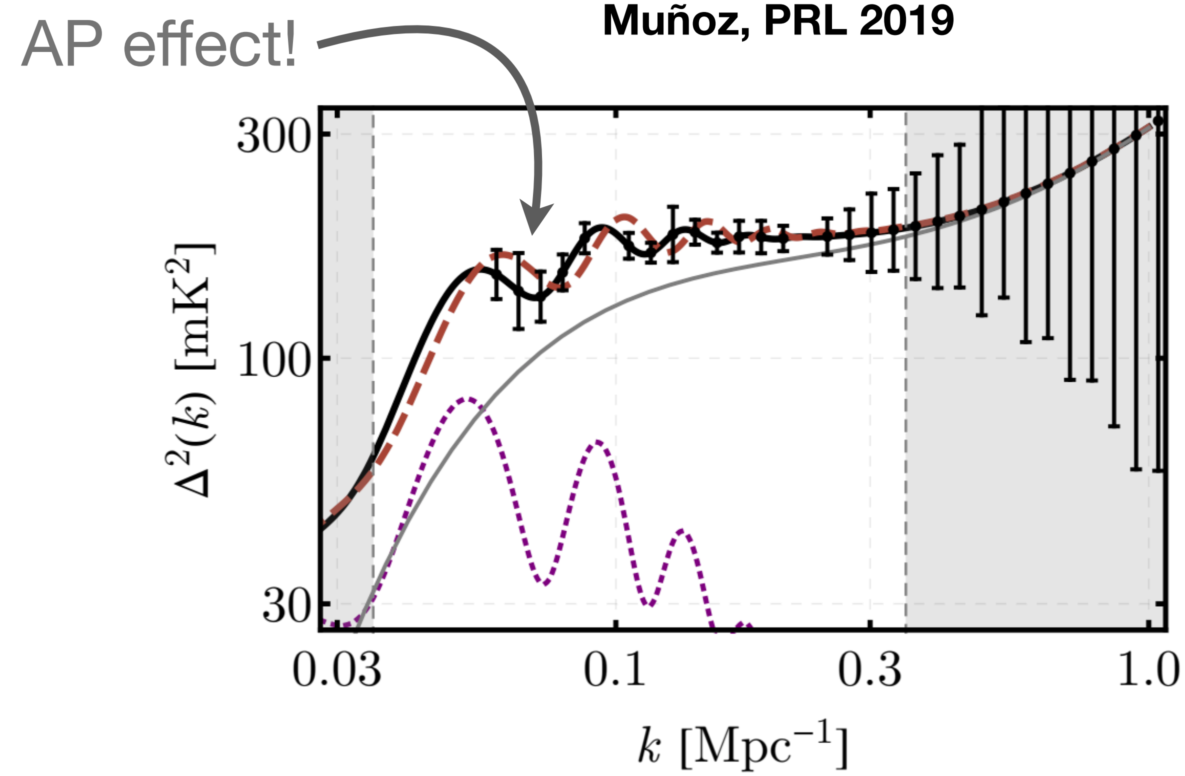

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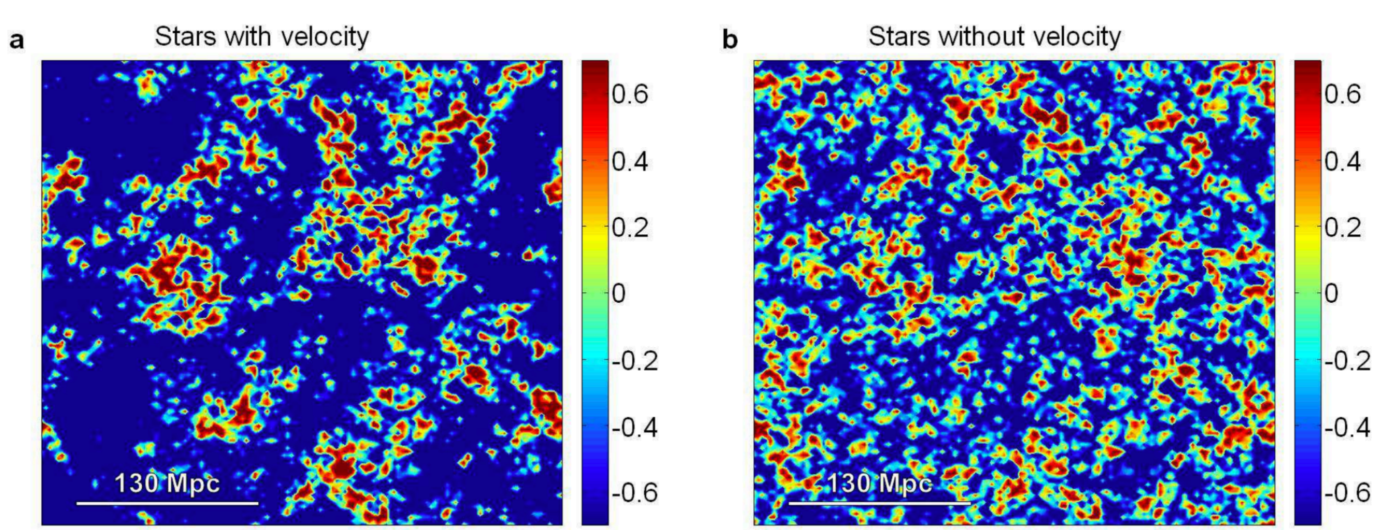

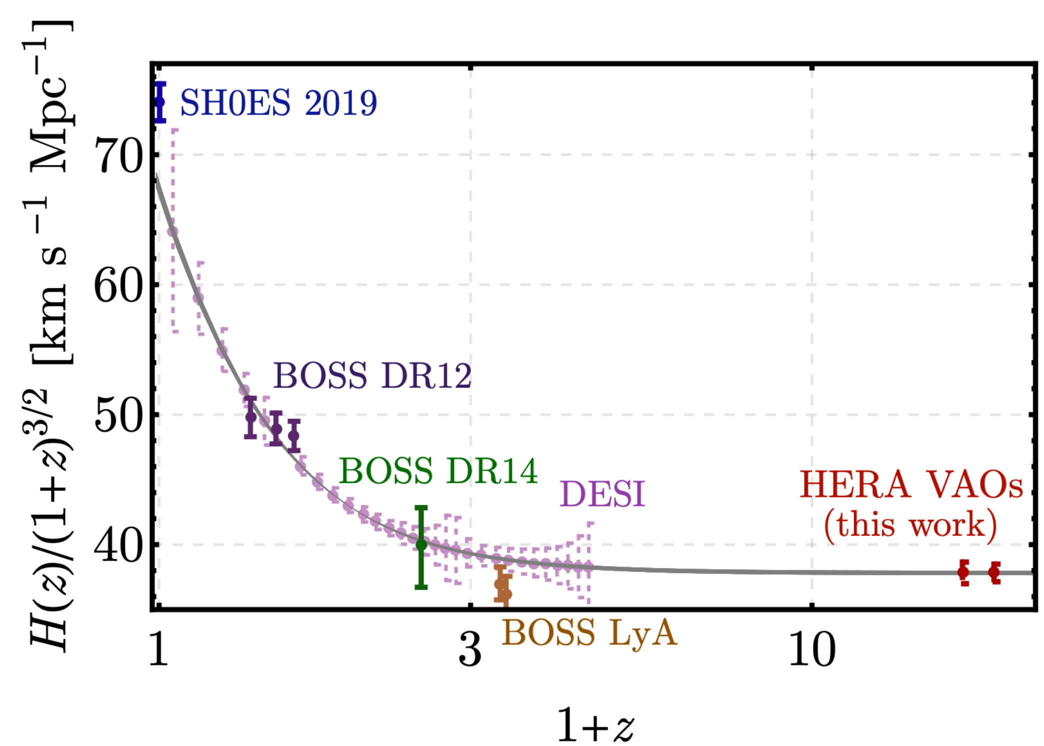

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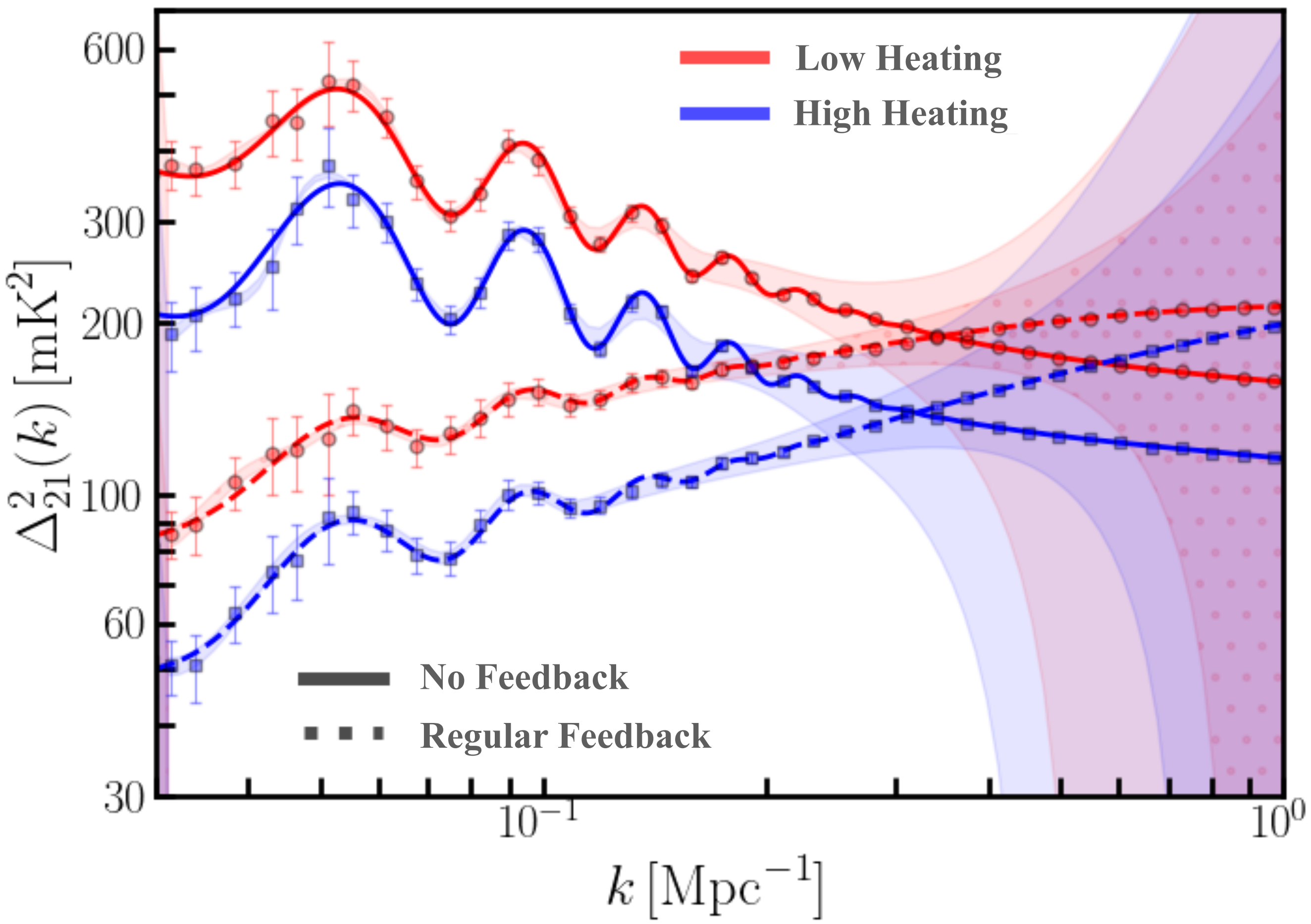

Sarkar and Kovetz, PRD 2022

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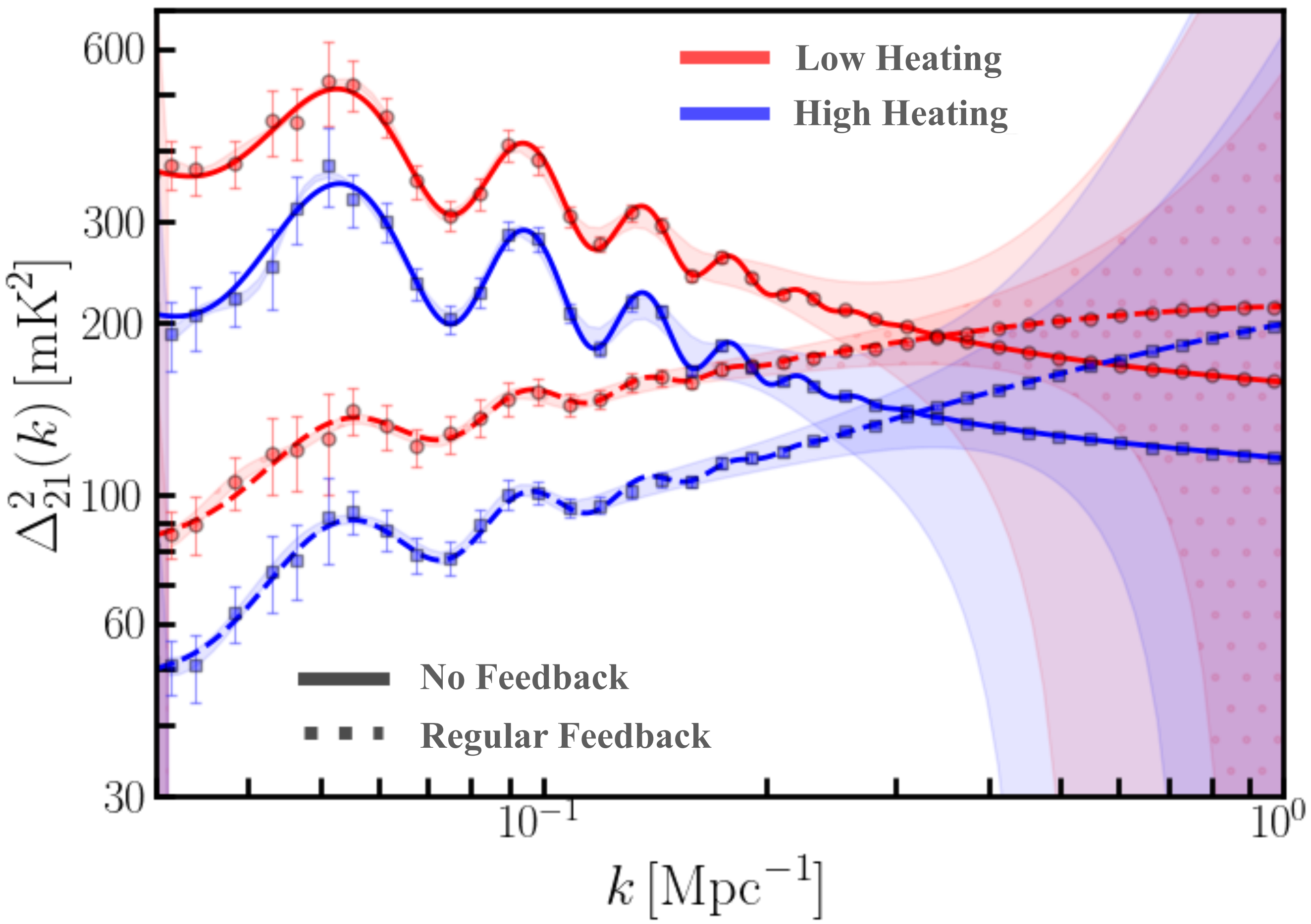

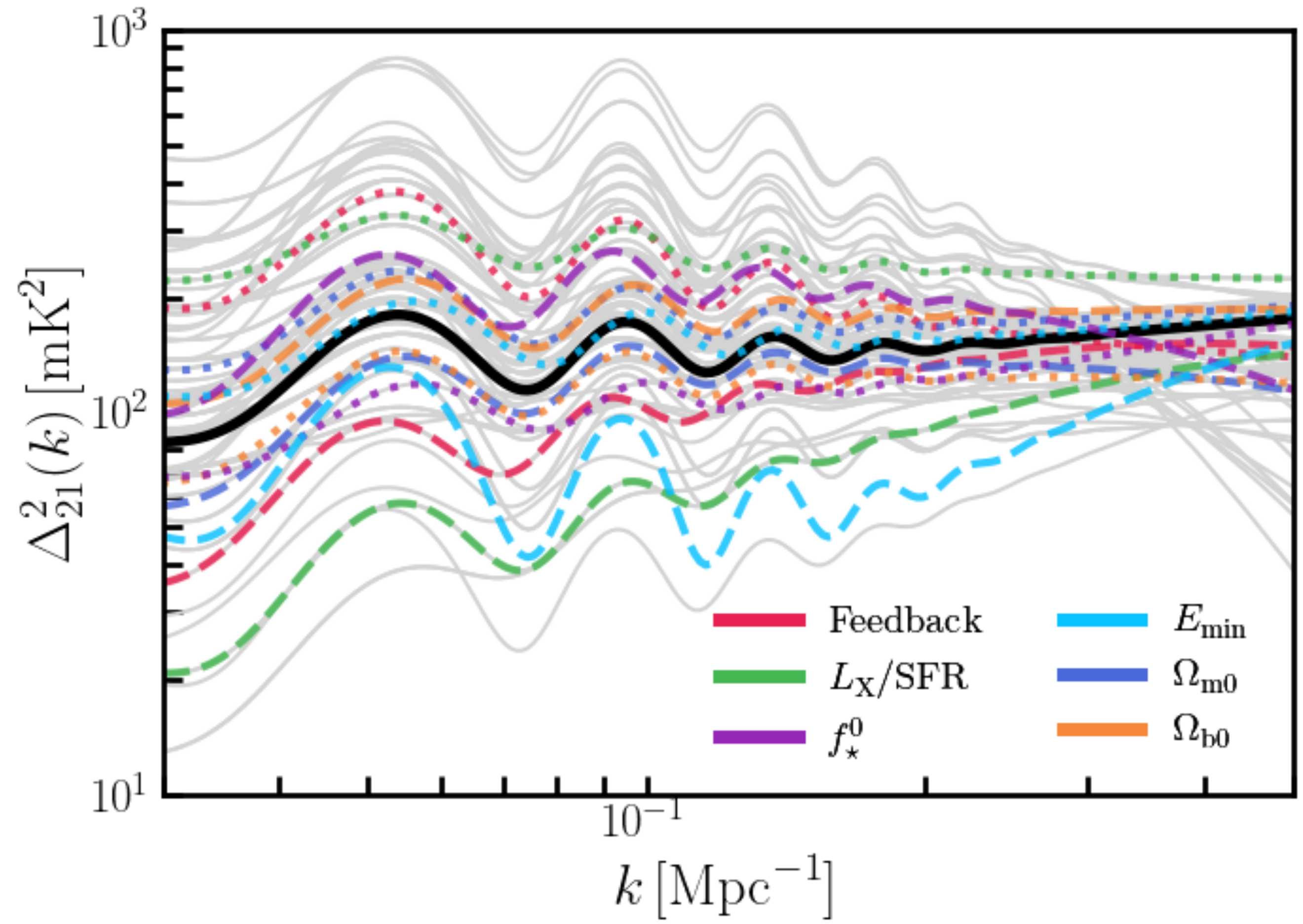

Sarkar and Kovetz, PRD 2022

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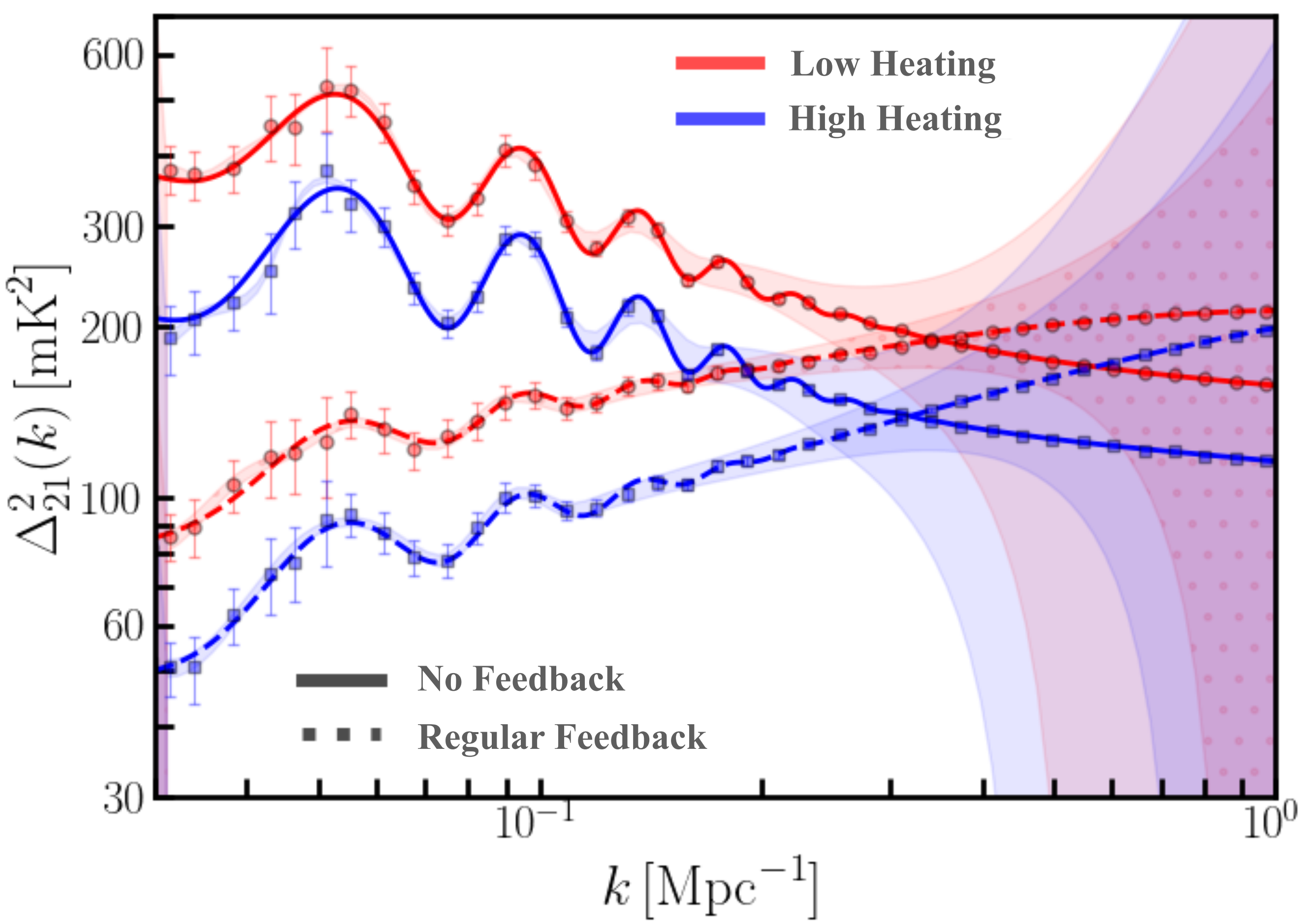
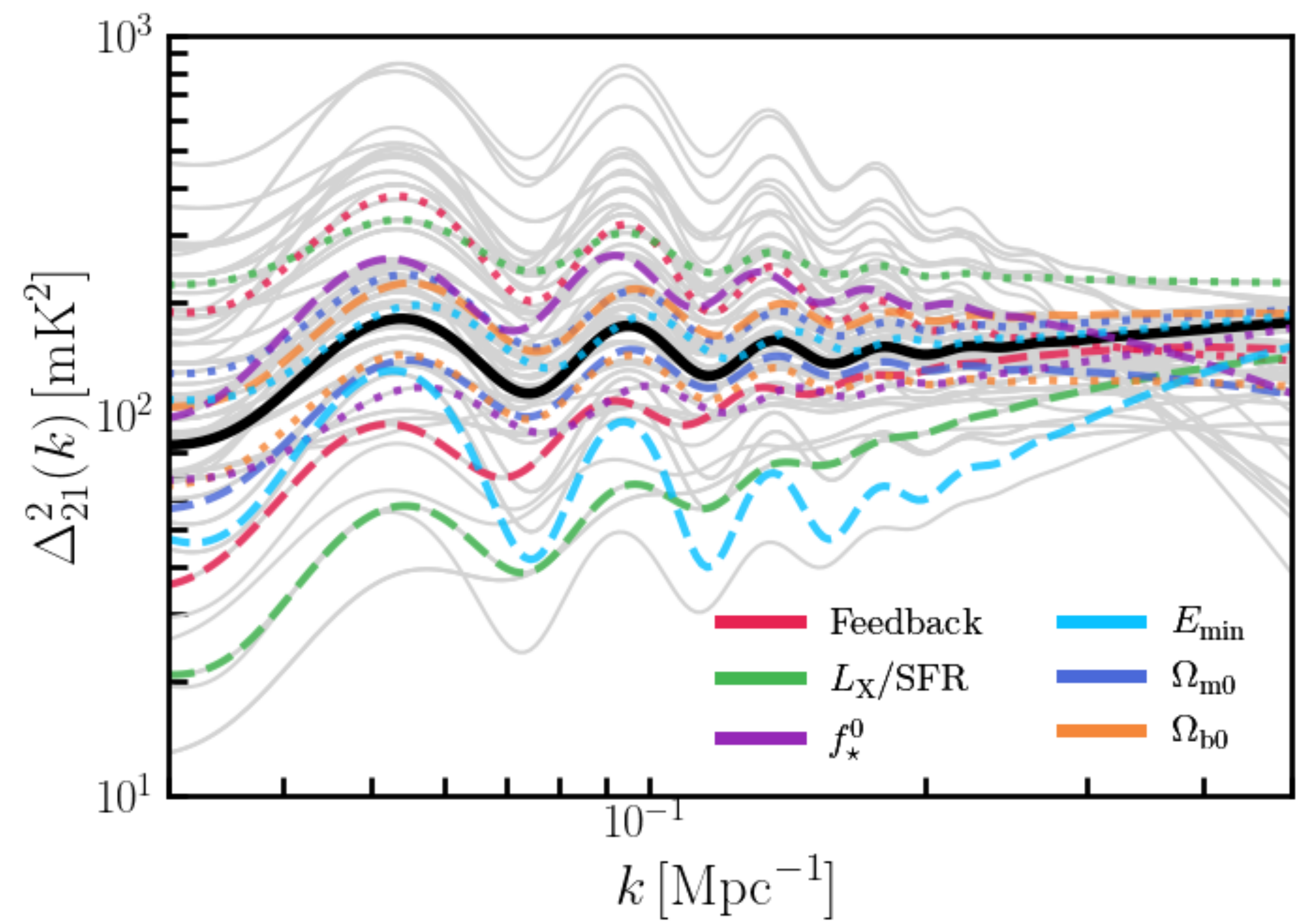




Sarkar and Kovetz, PRD 2022

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

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):

$\mathtt{C}^2-\mathtt{Ray}$ (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)

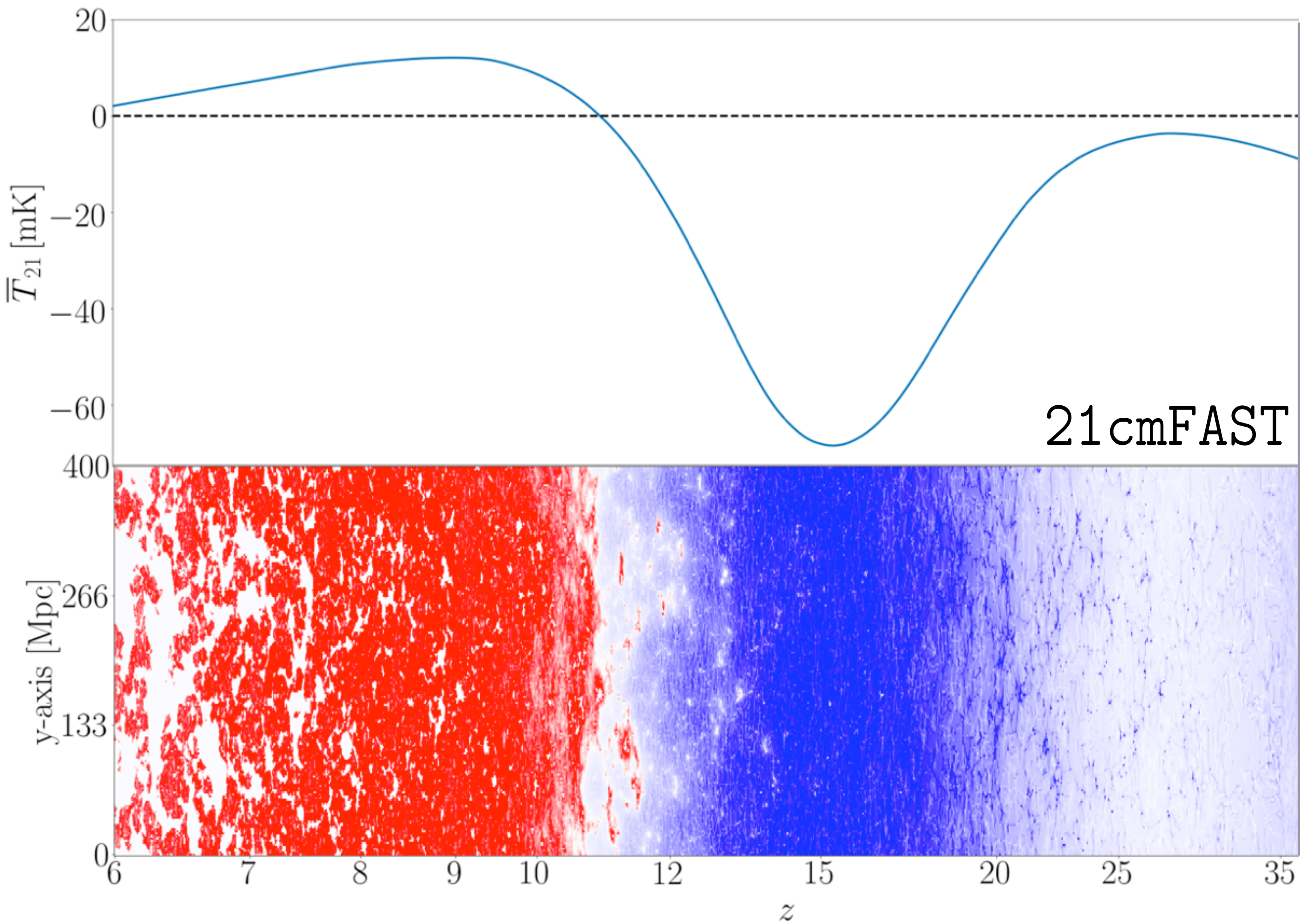
Purely analytic codes (fastest):

`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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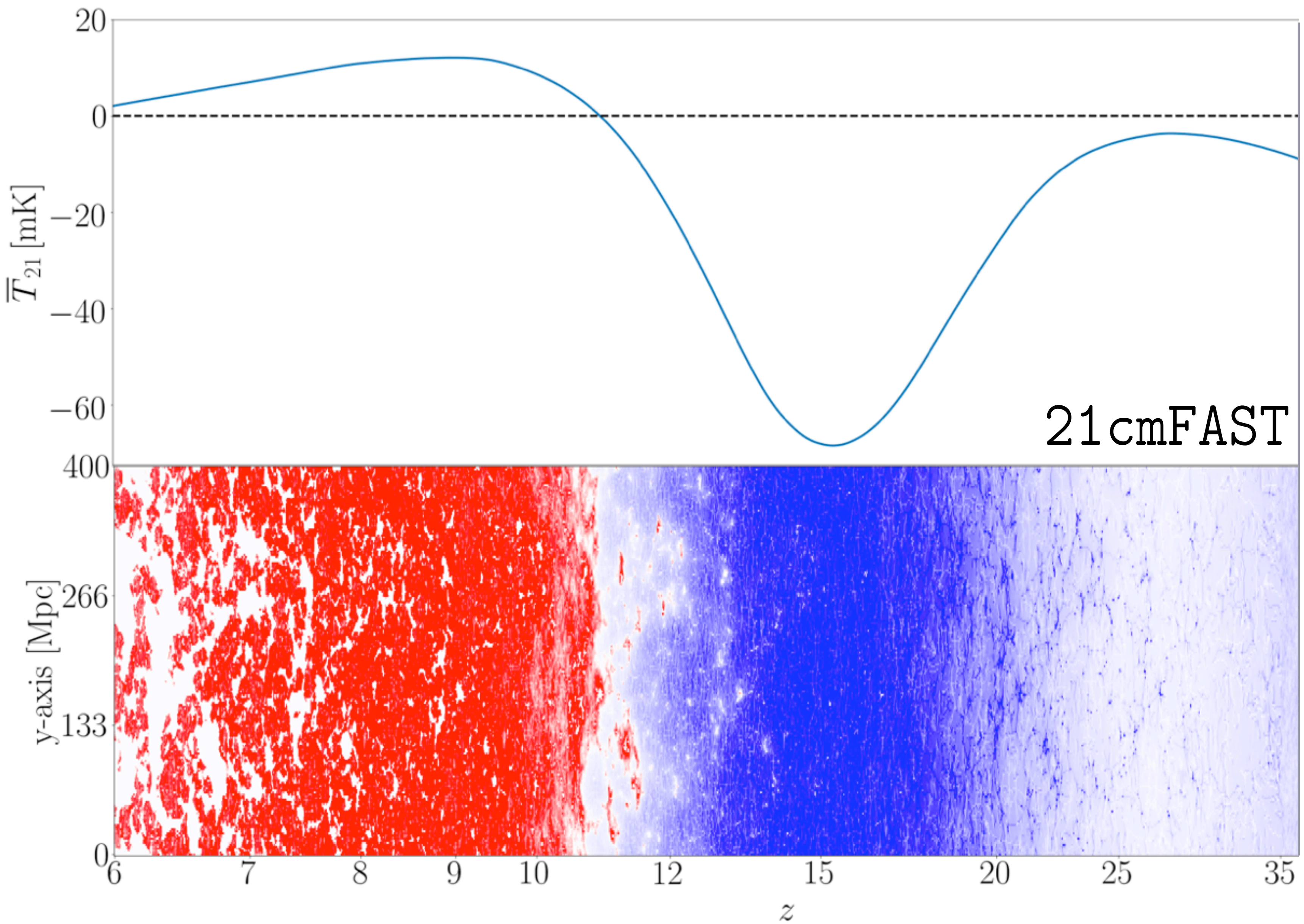
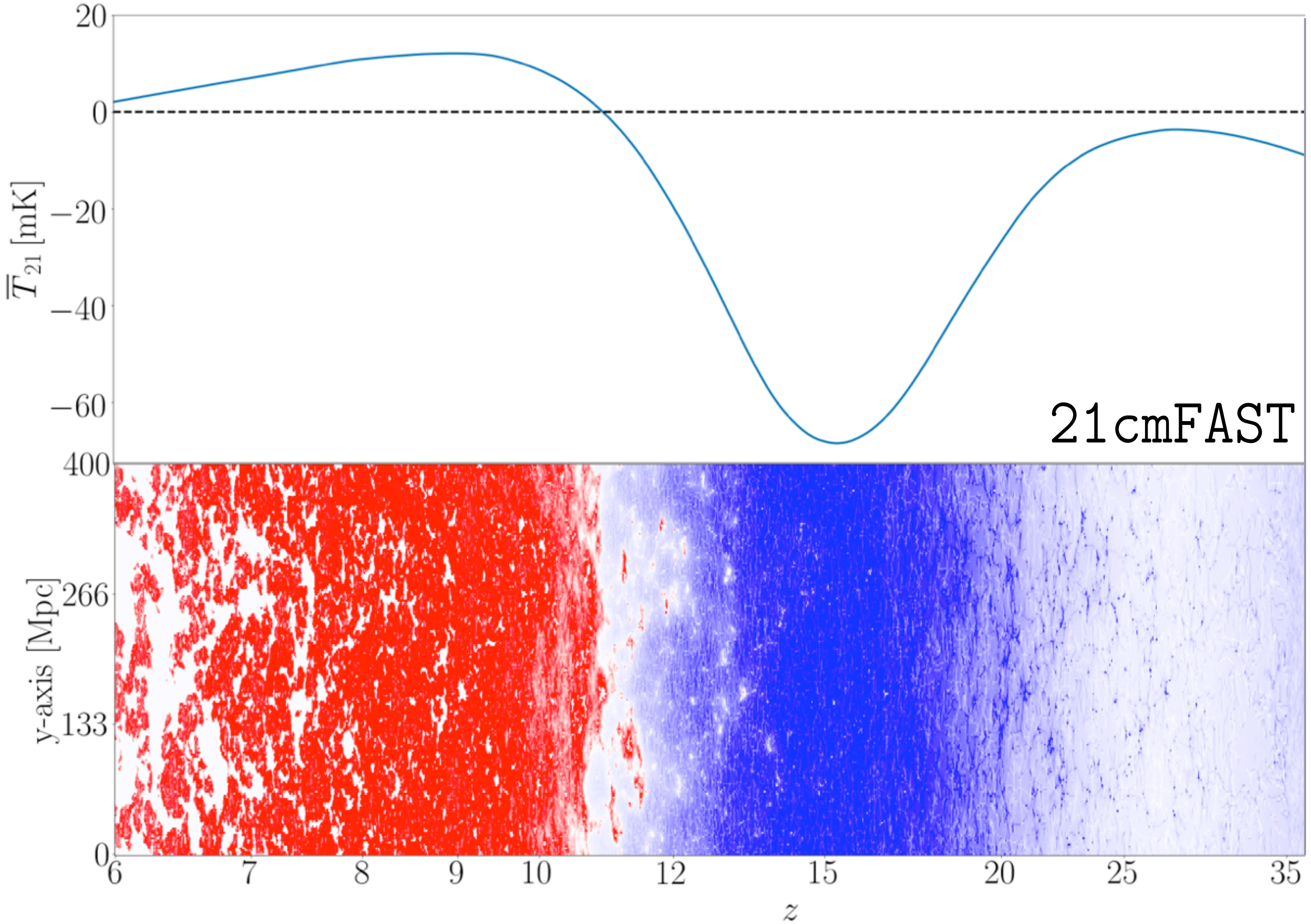


Limitations for new physics:

21cm Simulations: a Code for Cosmology



Limitations for new physics:

- Initialized at $z = 35$

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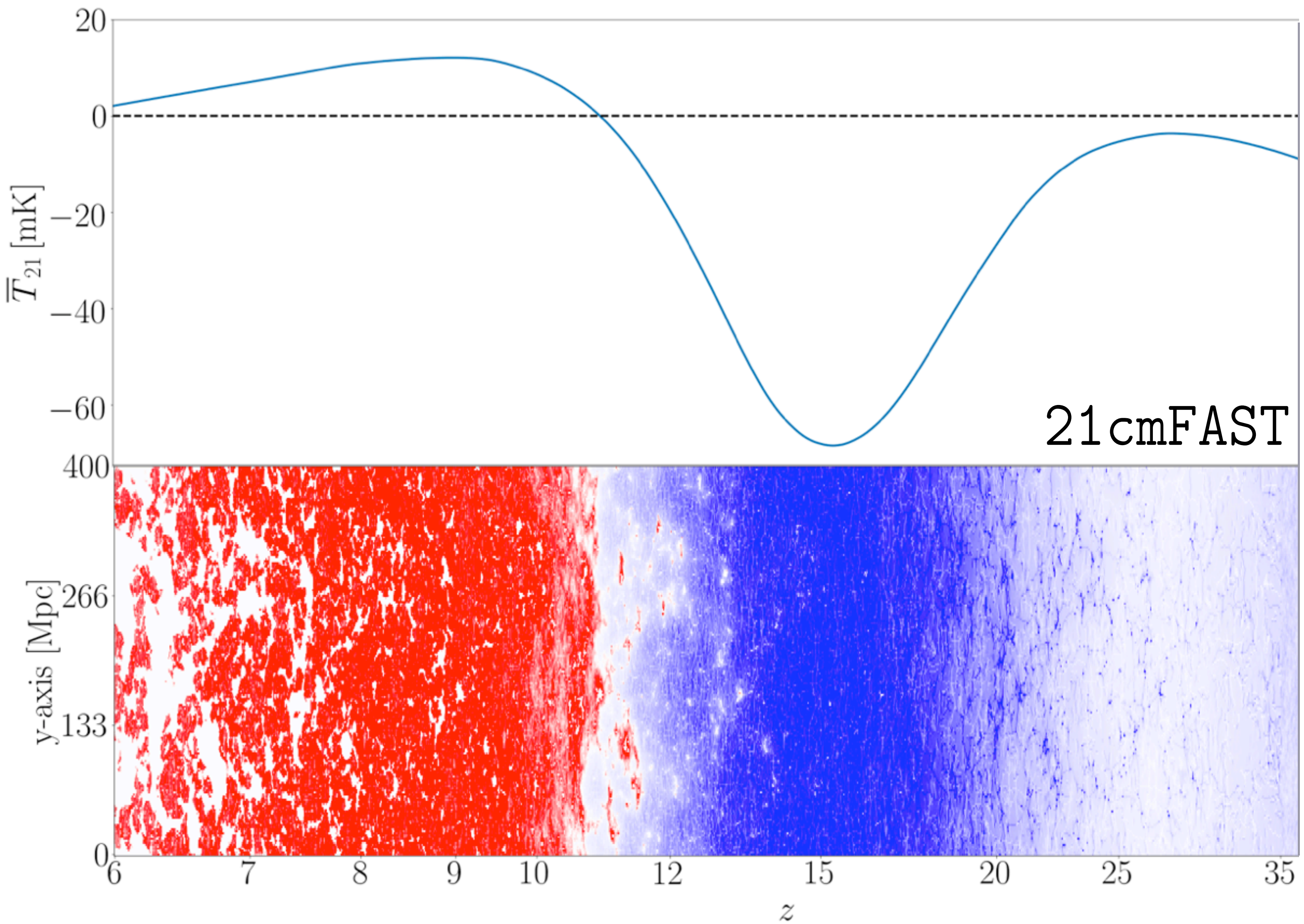

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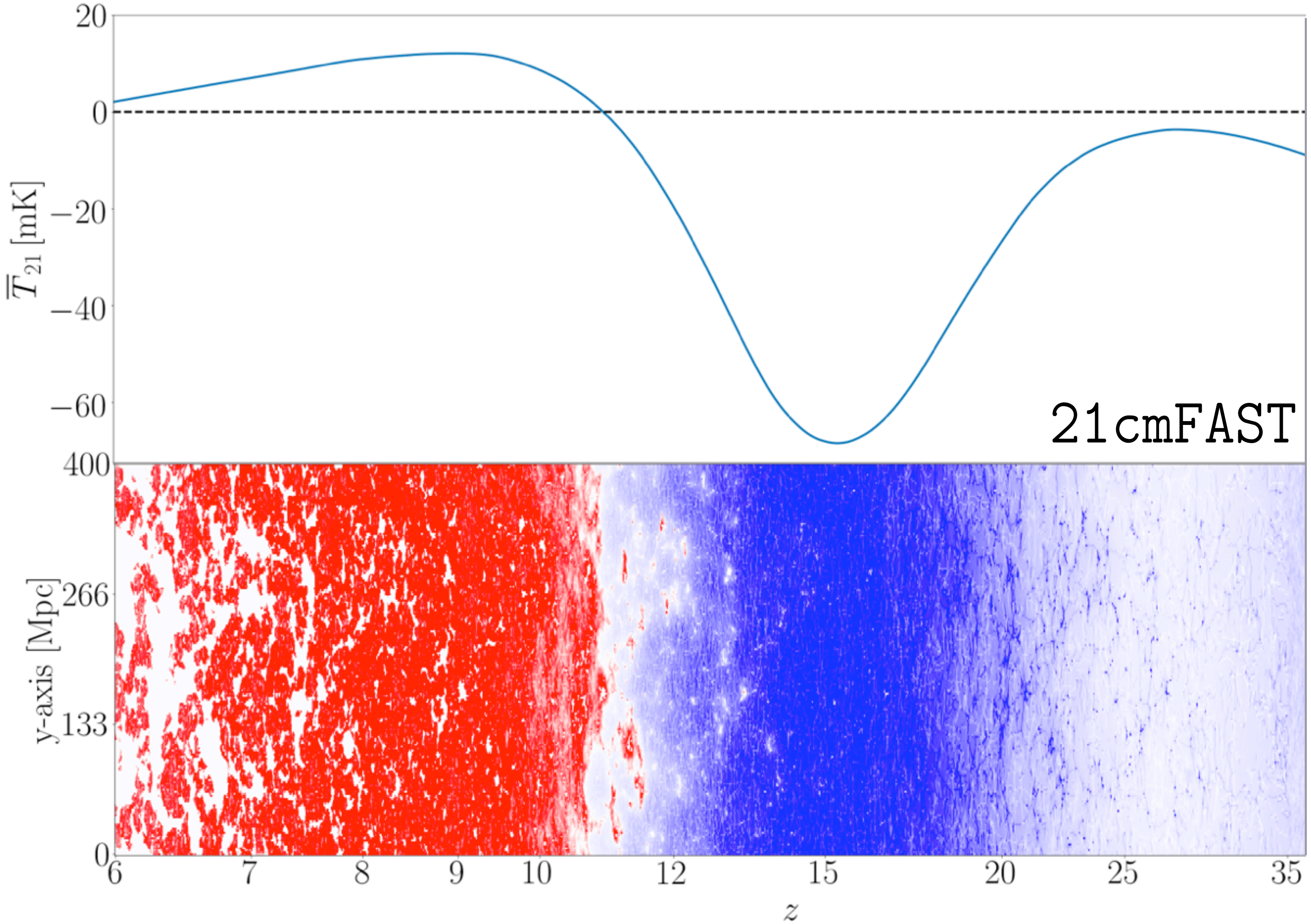

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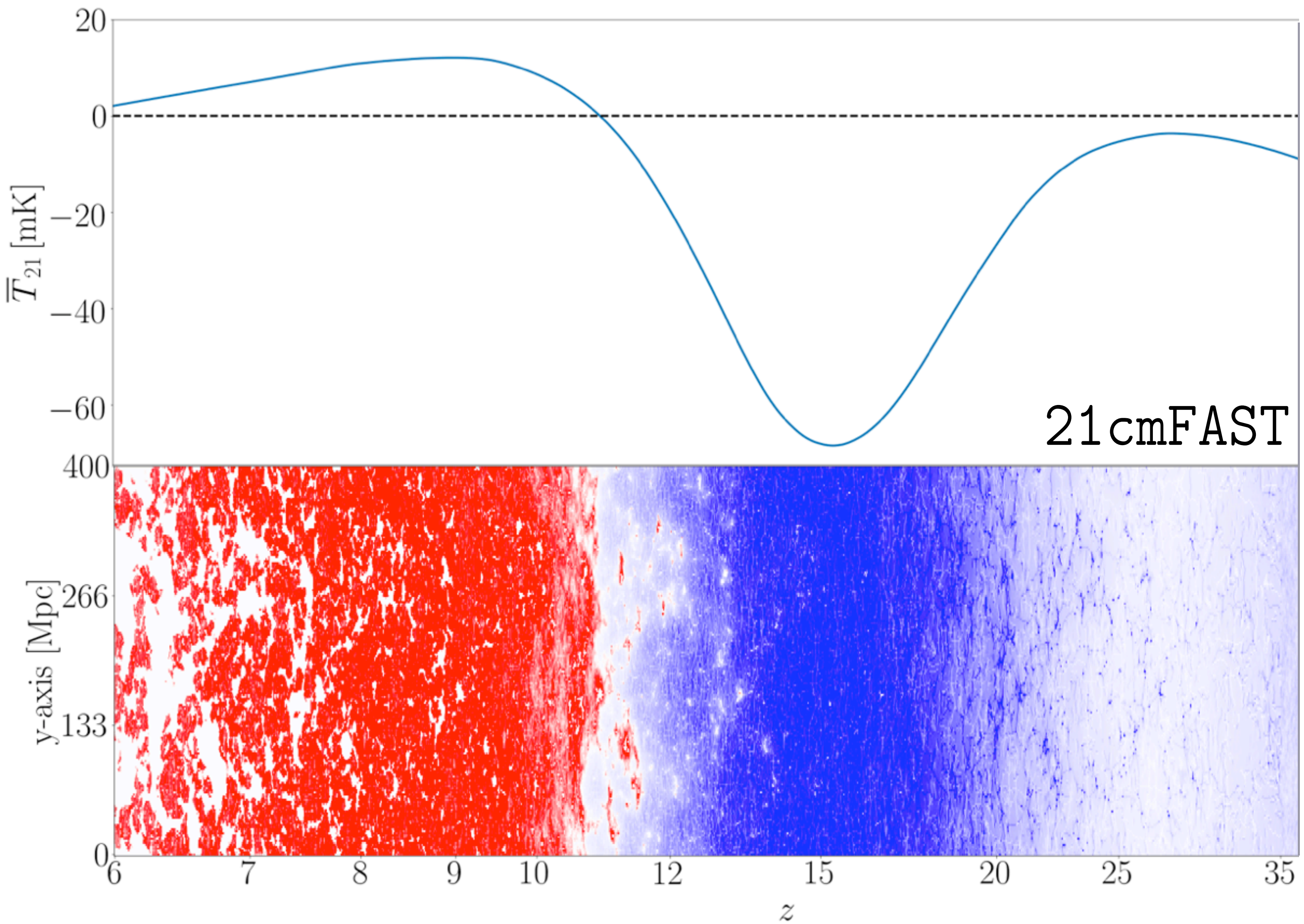

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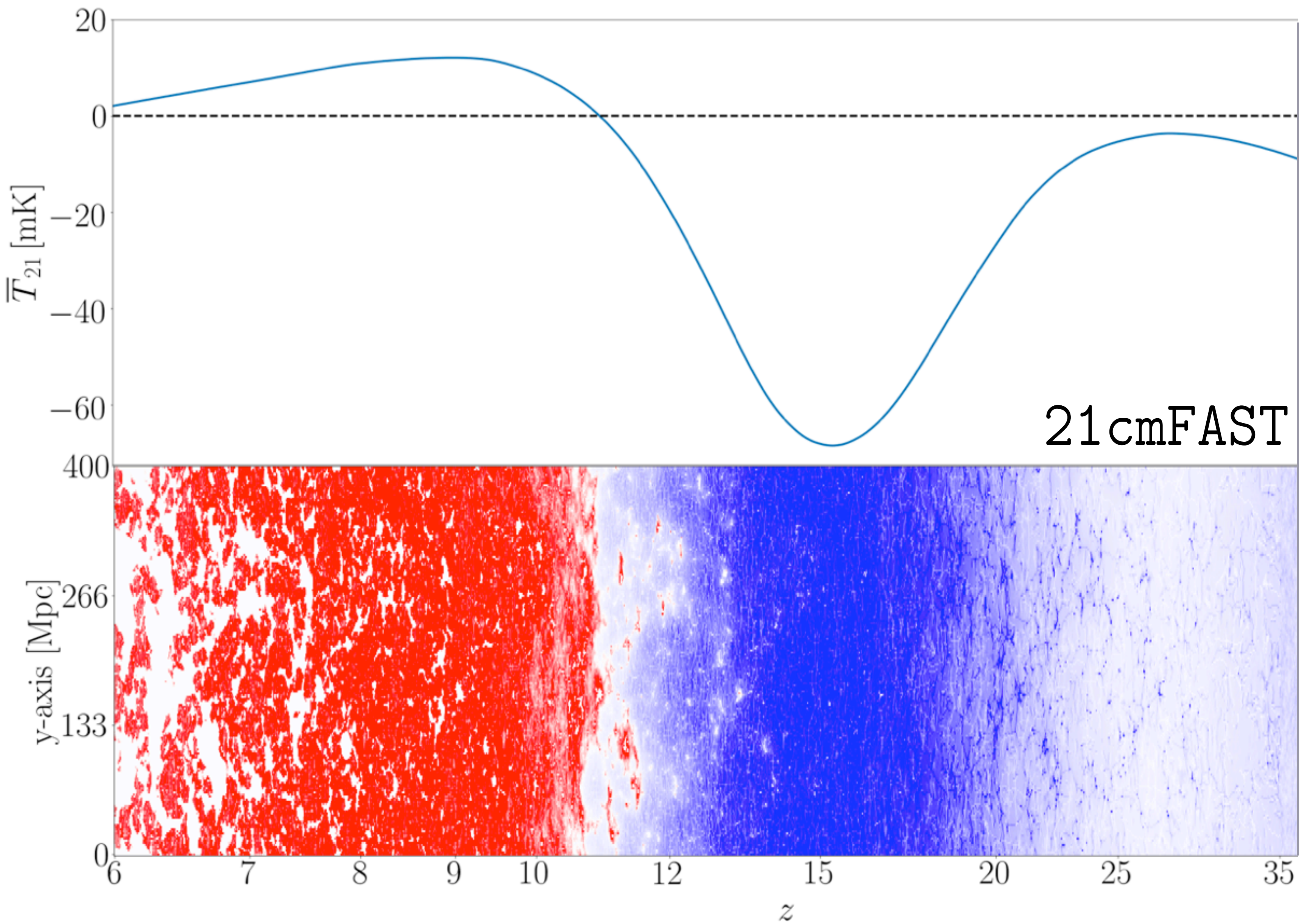

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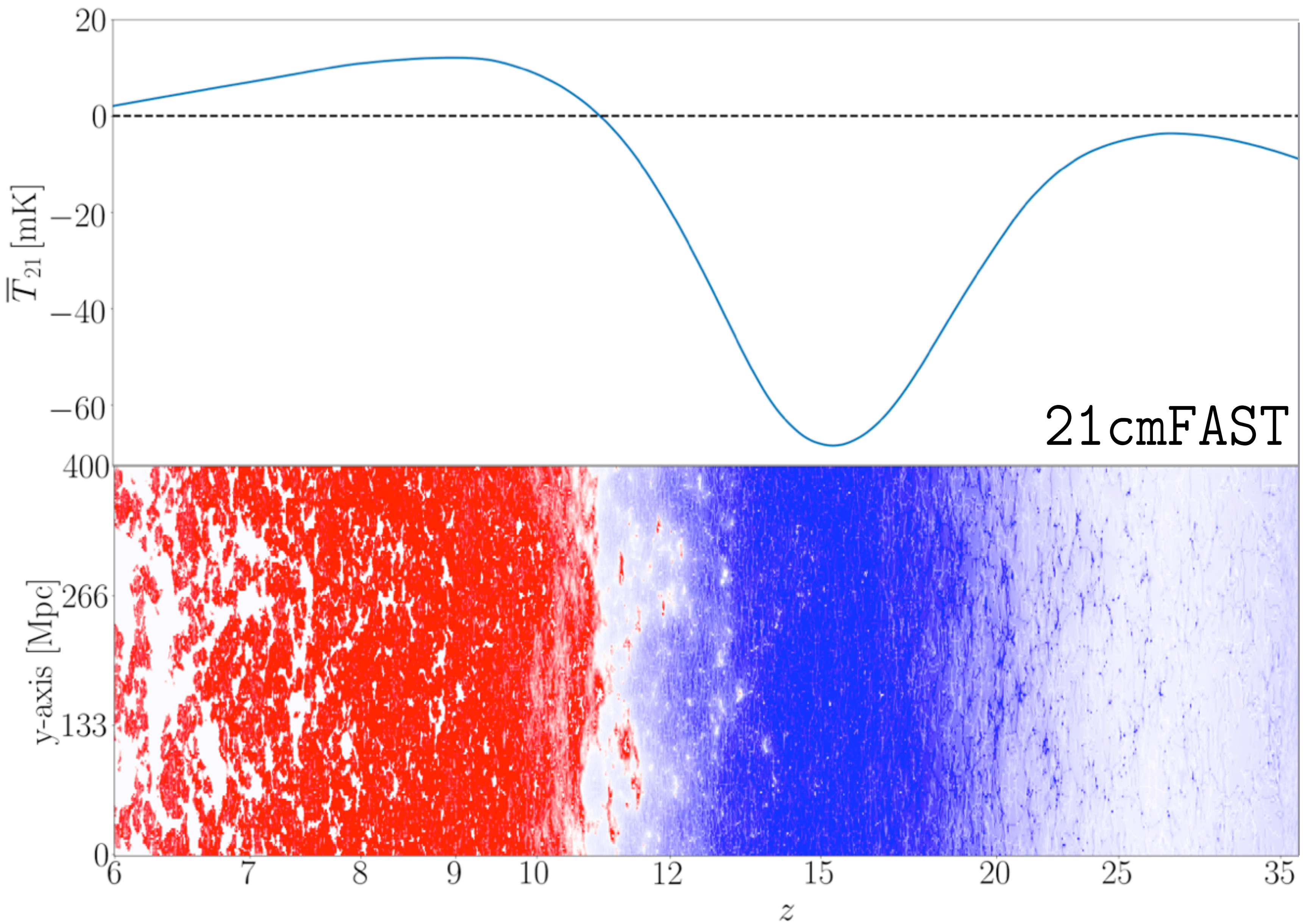

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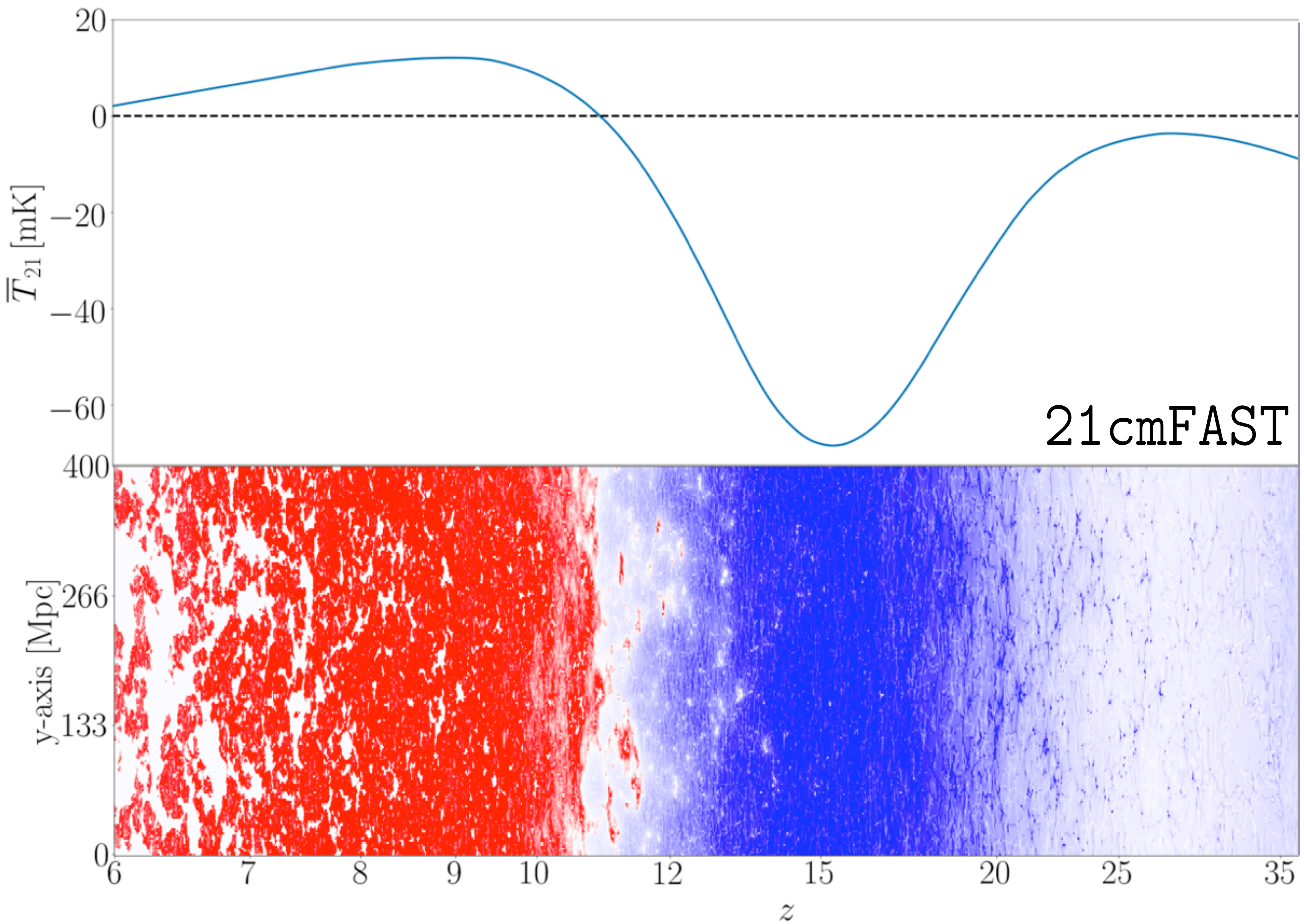

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$$dT_k/dz \propto \left(\Gamma_C/H\right)\left(T_\gamma - T_k\right)$$

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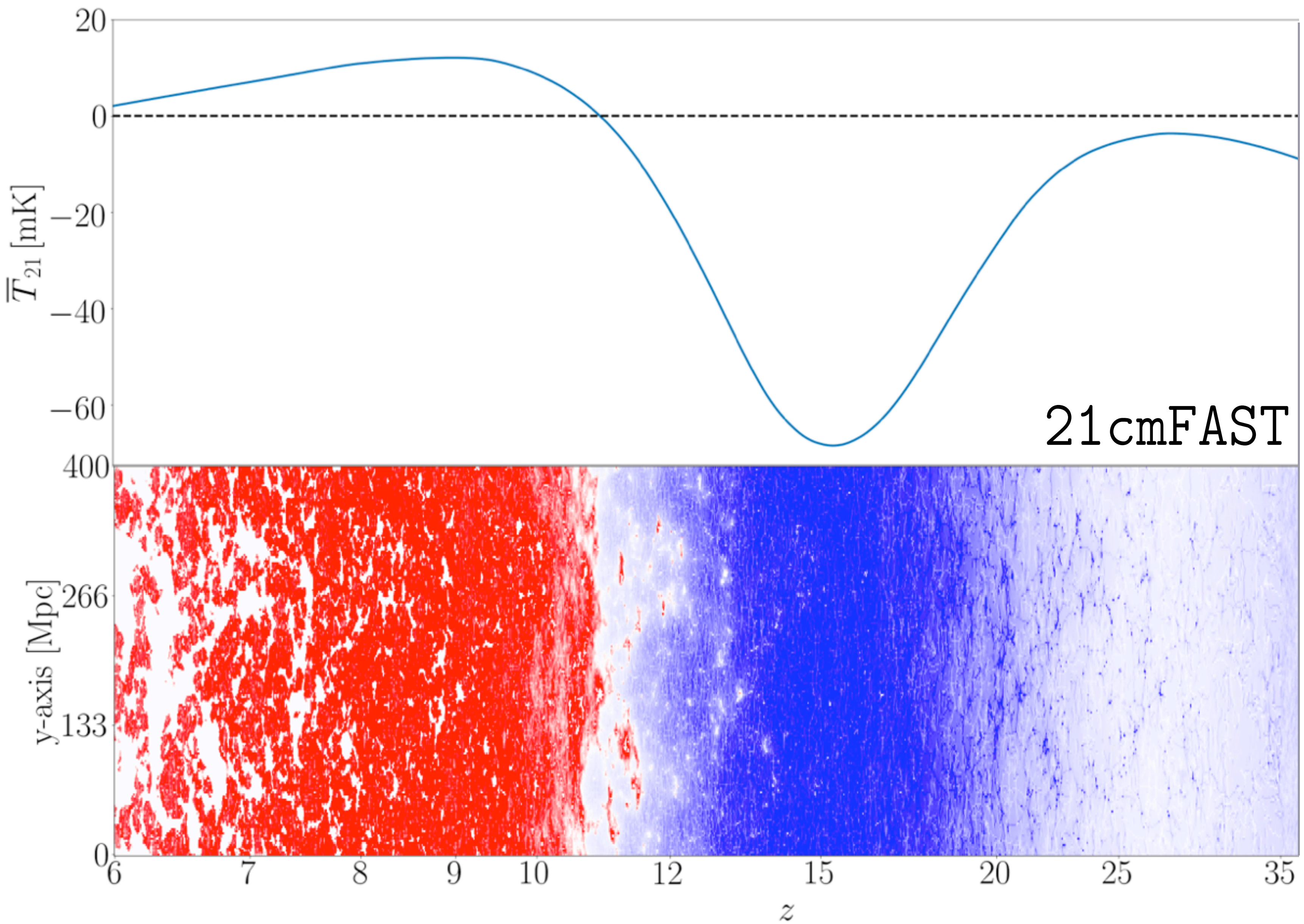

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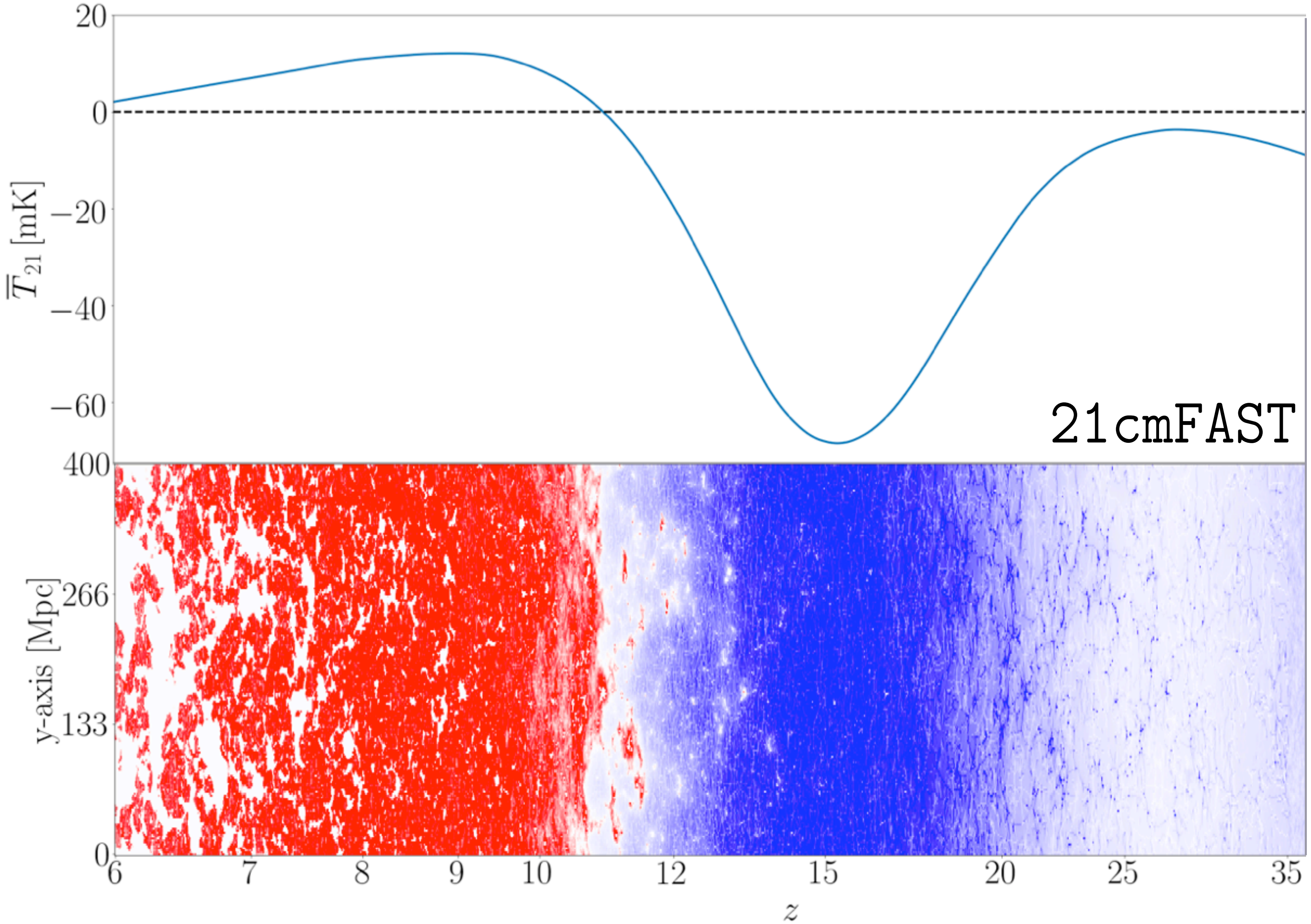

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⟶ requires $\Delta z \ll 1$ to solve

21cm Cosmology: a Code for Cosmology

Solution:

- Use initial conditions from a Boltzmann solver

  → Initialize with $\texttt{CLASS}$ at $z = 1100$

- Calculate accurate recombination history

  → Incorporate $\texttt{Hyrec}$ into the code

- Consistently track (non-linear?) evolution

  → Inhomogeneous box 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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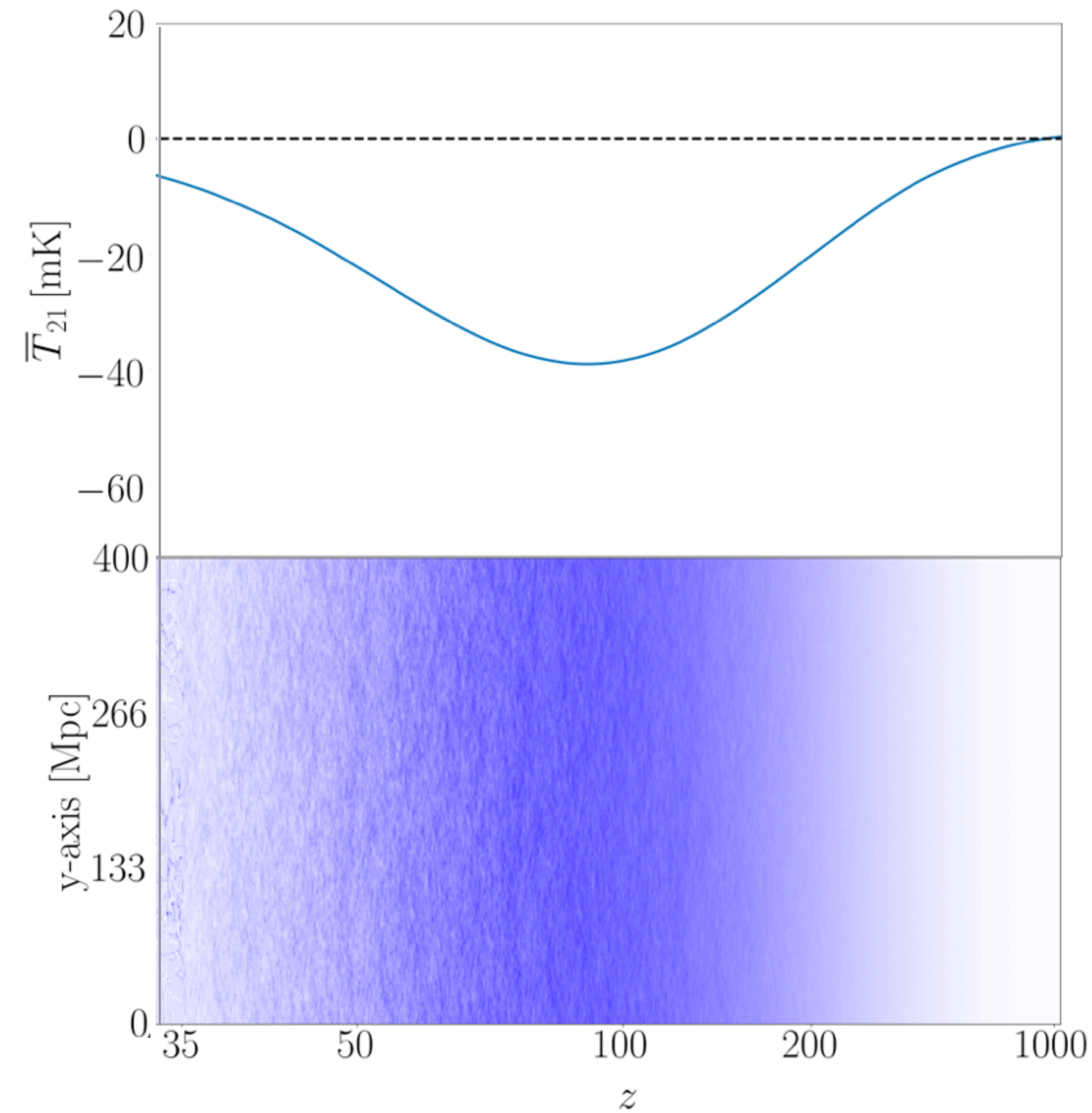
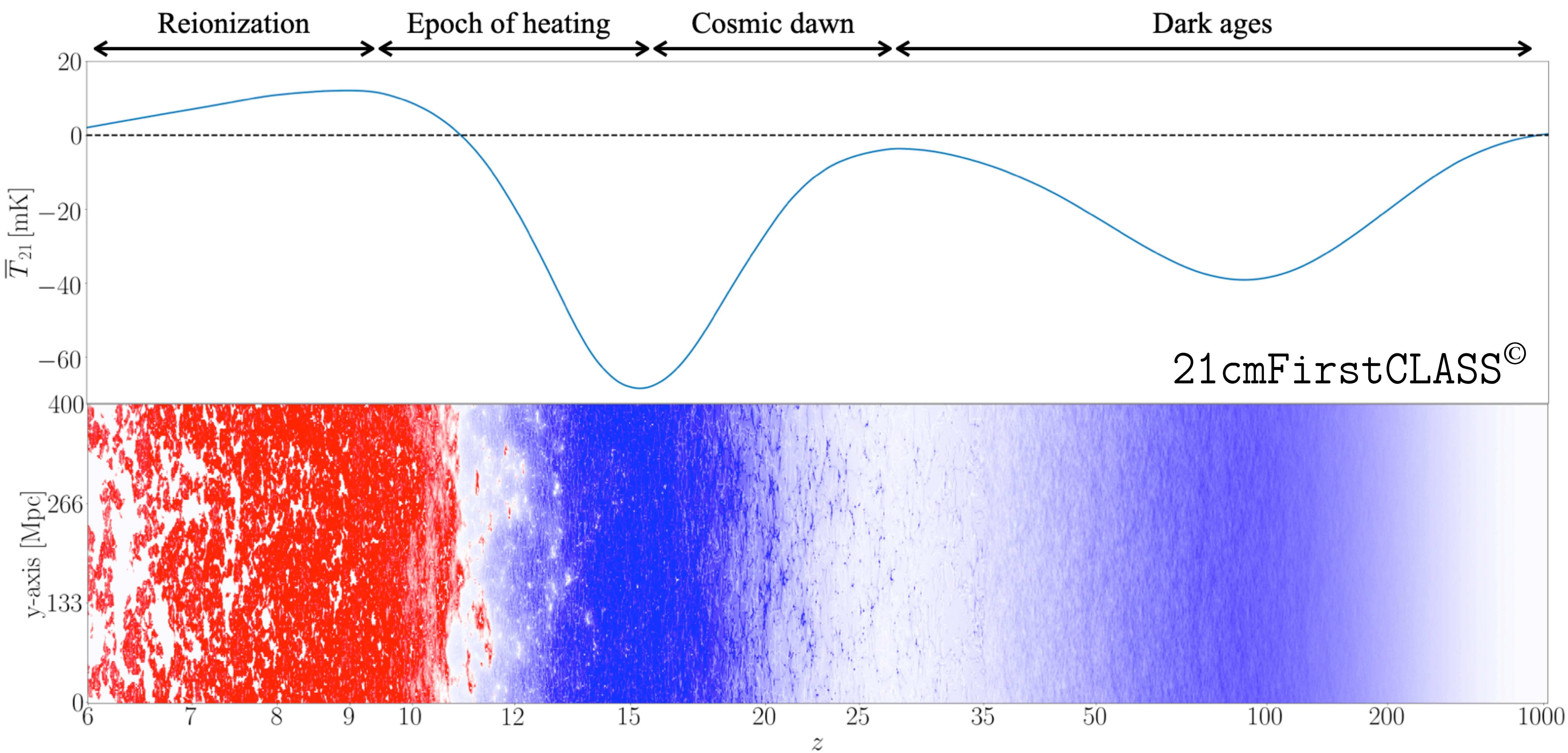


21cm Cosmology: a Code for Cosmology



21cmFirstCLASS I. Cosmological tool for ΛCDM and beyond

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

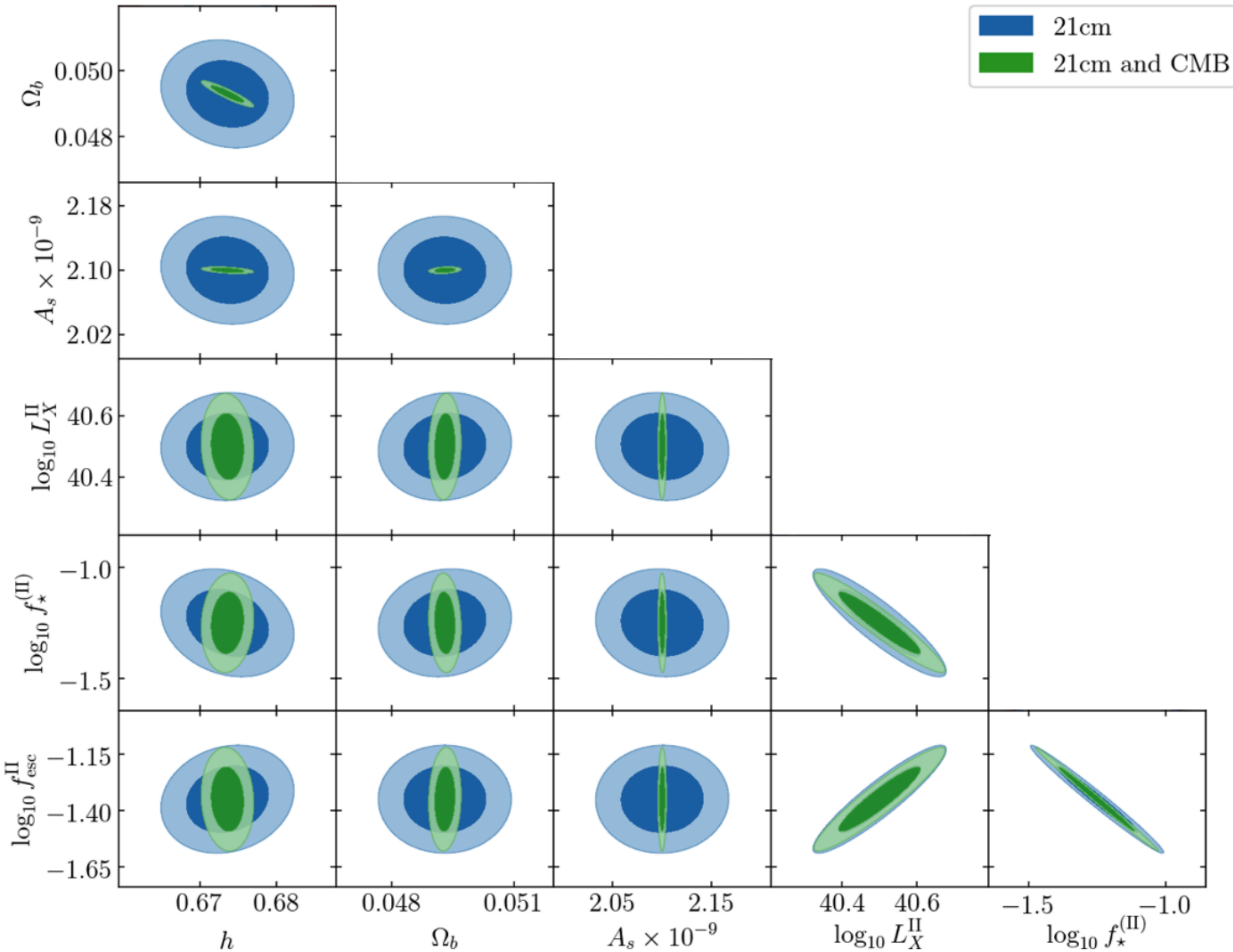
[1] *Physics Department, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel*

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

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

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

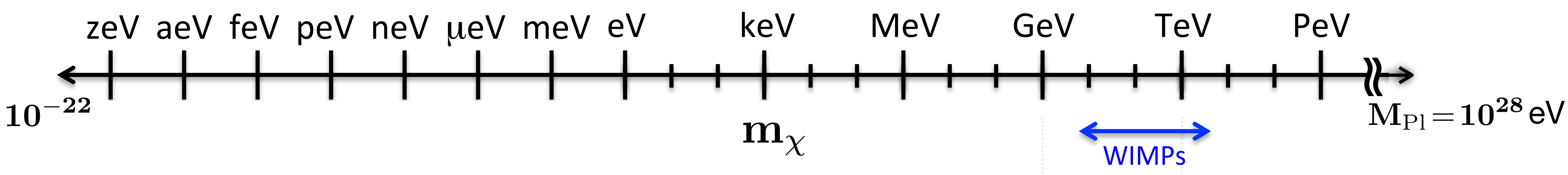
21cm Cosmology: Using 21cmFirstCLASS



Flitter and Kovetz, arXiv:2309.03942

21cm Cosmology: Using 21cmFirstCLASS

Example: Dark Matter-Baryon Scattering



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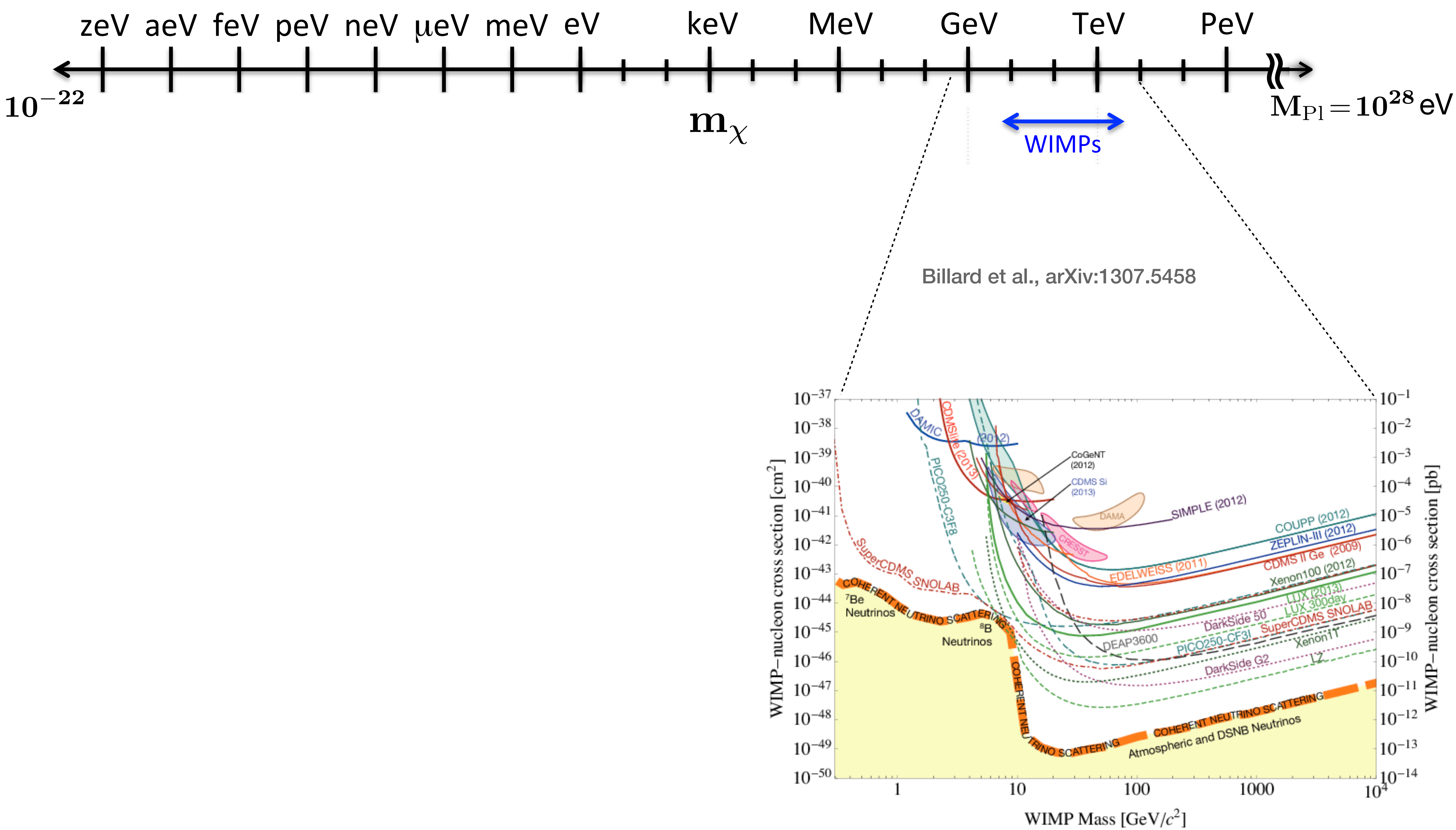

Billard et al., arXiv:1307.5458

21cm Cosmology: Using 21cmFirstCLASS

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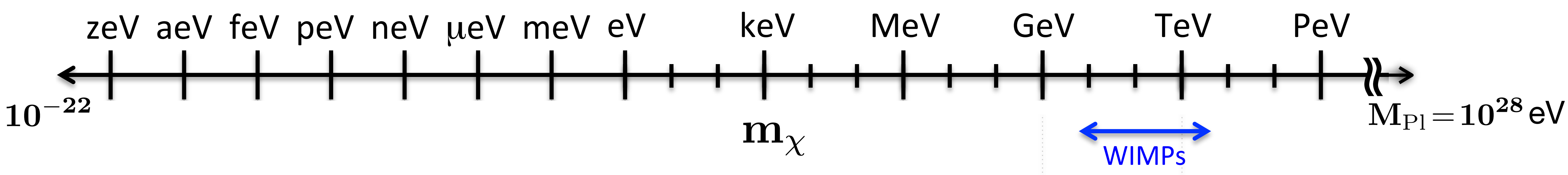

Consider a cross-section: $\sigma = \sigma_0 v^n$

21cm Cosmology: Using `21cmFirstCLASS`

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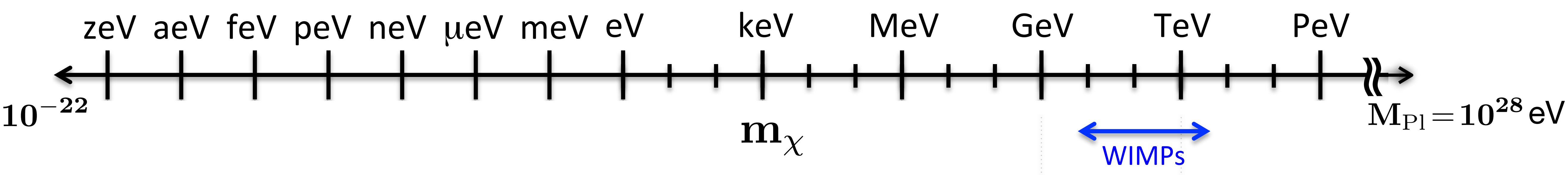
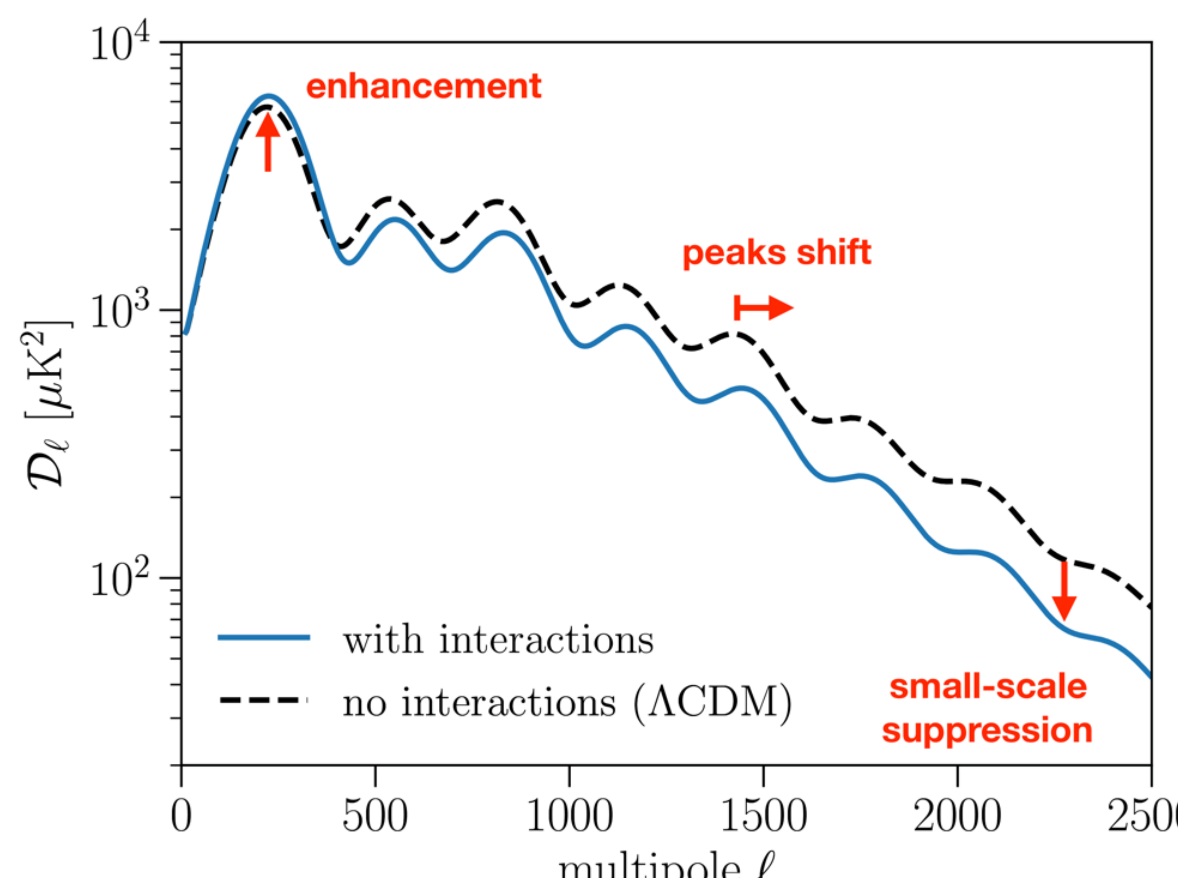


Consider a cross-section: $\sigma = \sigma_0 v^n$

(see: Chen et al. (2012), Sigurdson et. al (2004), Dvorkin et al. (2014), Gluscevic and Boddy (2018), Boddy and Gluscevic (2018), Boddy et al. (2018), Xu et al. (2018), Slatyer et al. (2018))

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



21cm Cosmology: Using 21cmFirstCLASS

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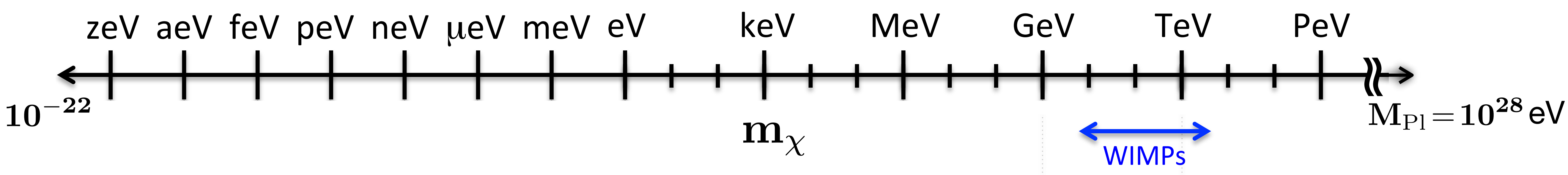

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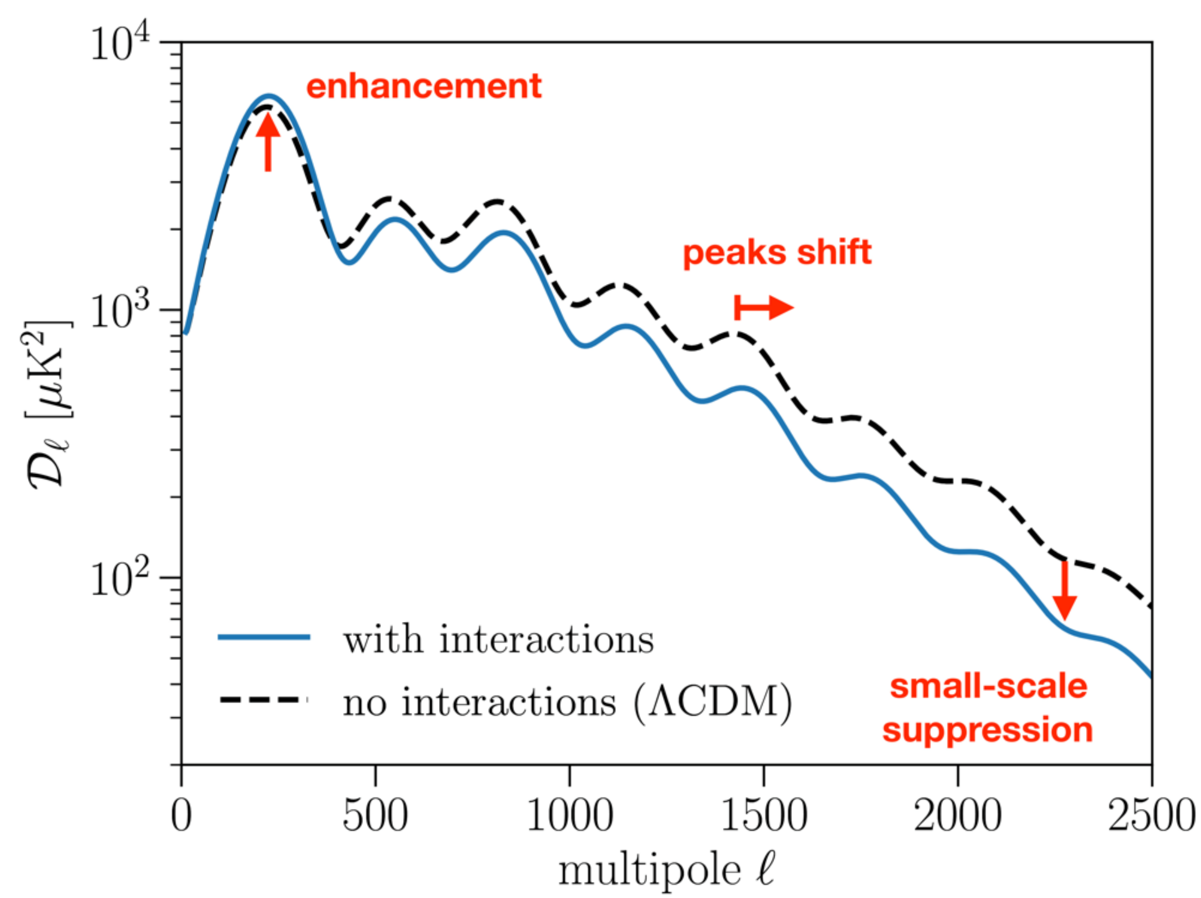
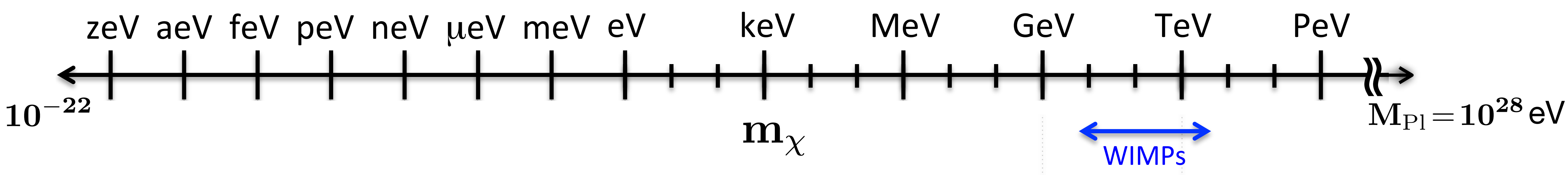


But CMB is less effective for $n < 0$.

21cm Cosmology: Using 21cmFirstCLASS

Example: Dark Matter-Baryon Scattering



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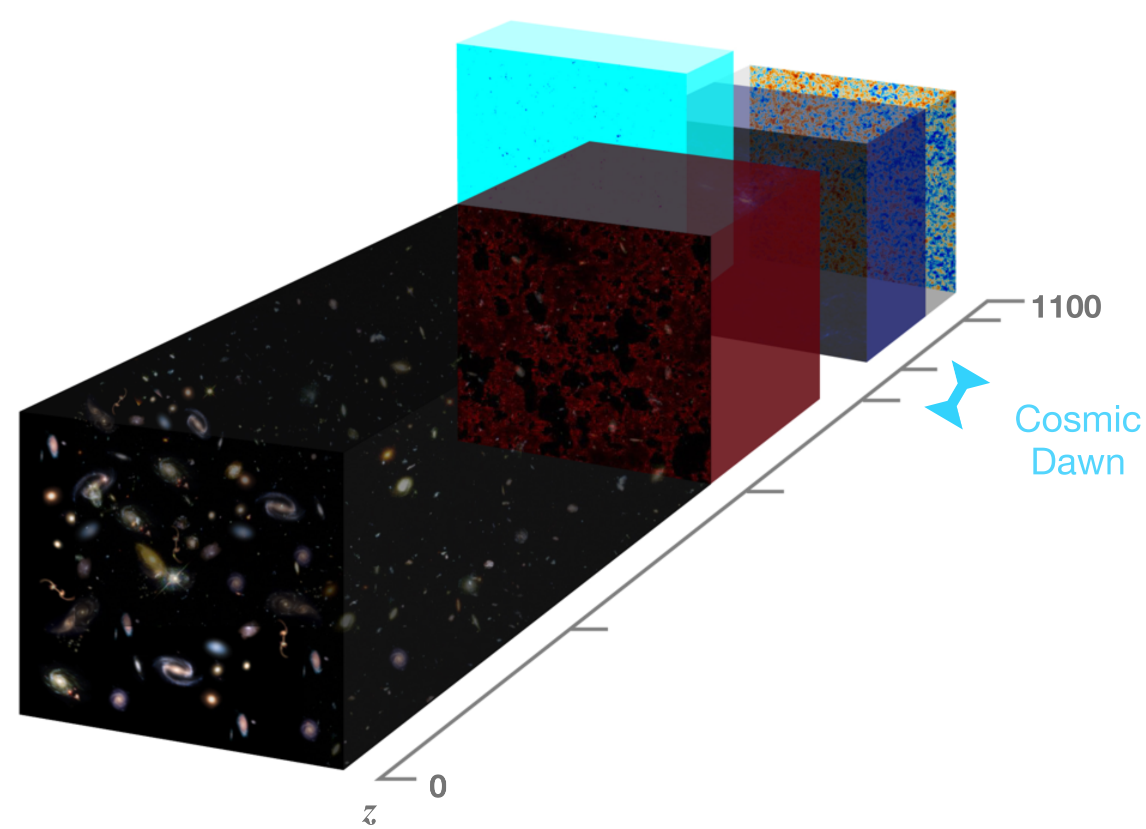
Let's examine the case: $\sigma(v) = \sigma_c \left(\frac{v}{c}\right)^{-4}$



21cm Cosmology: Using `21cmFirstCLASS`

Example: Dark Matter-Baryon Scattering

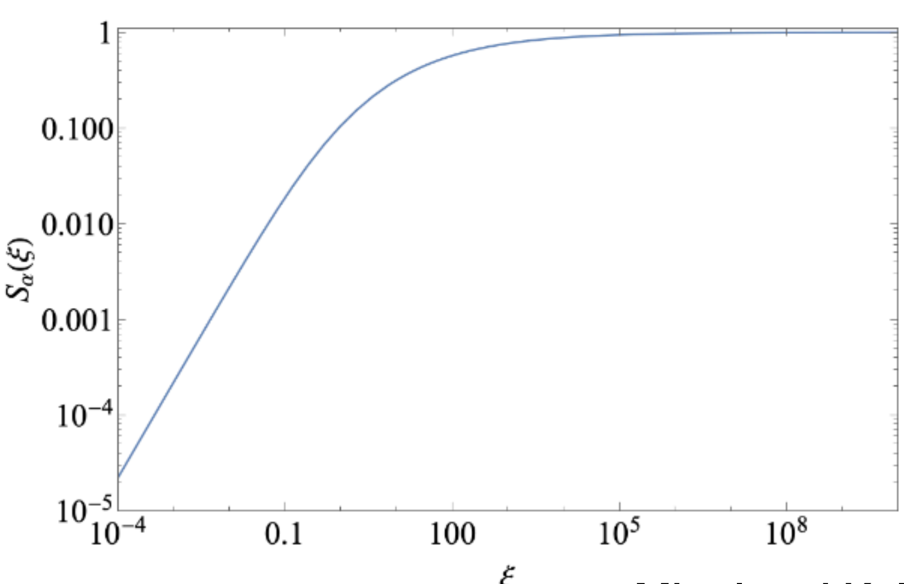
Curve	Dotted	Dashed	Solid
σ_{-4}	0 (ΛCDM)	$10^{-42}\,\mathrm{cm}^2$	$10^{-41}\,\mathrm{cm}^2$

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

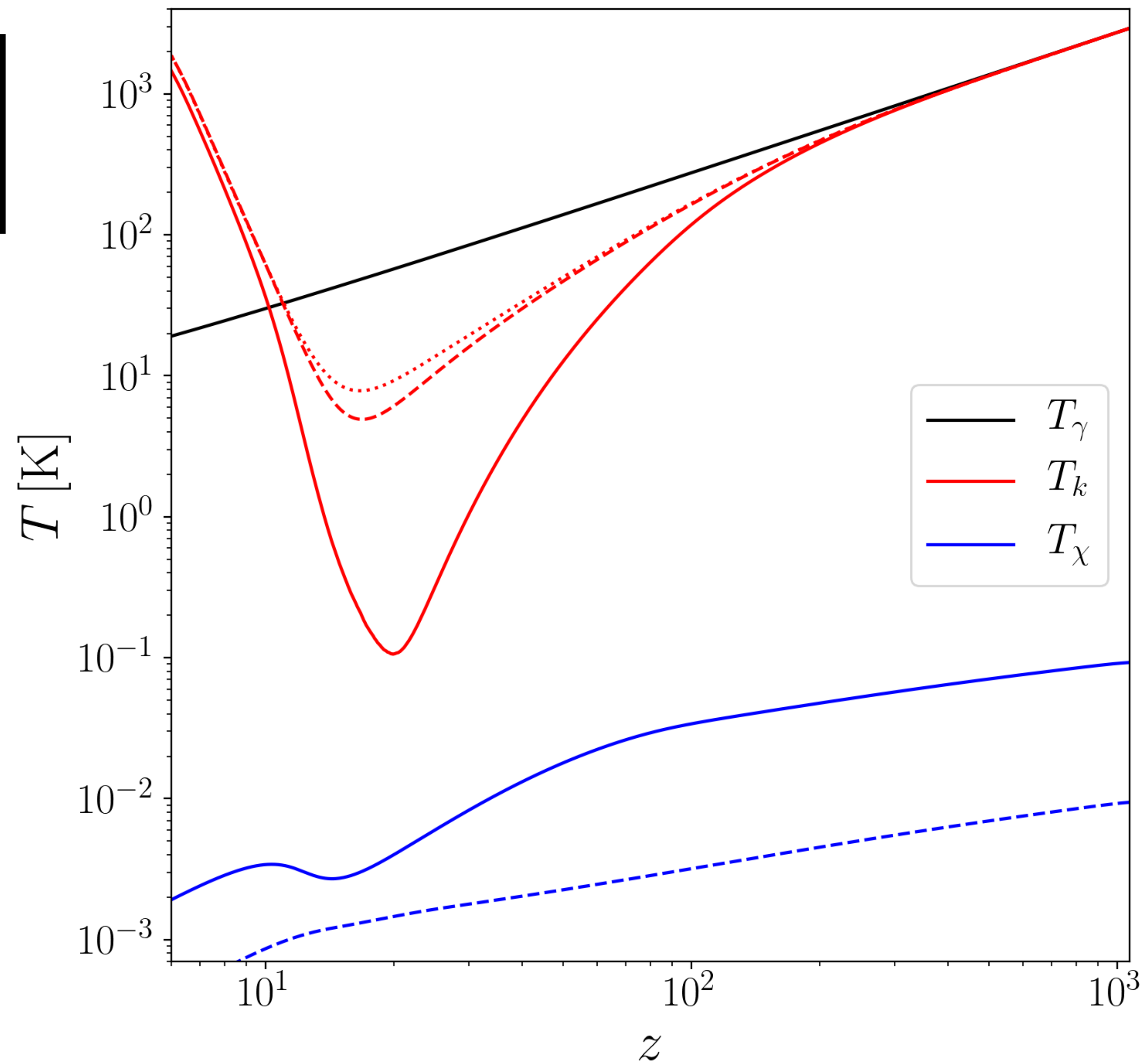
$f_\chi = 100\,\%$

+ 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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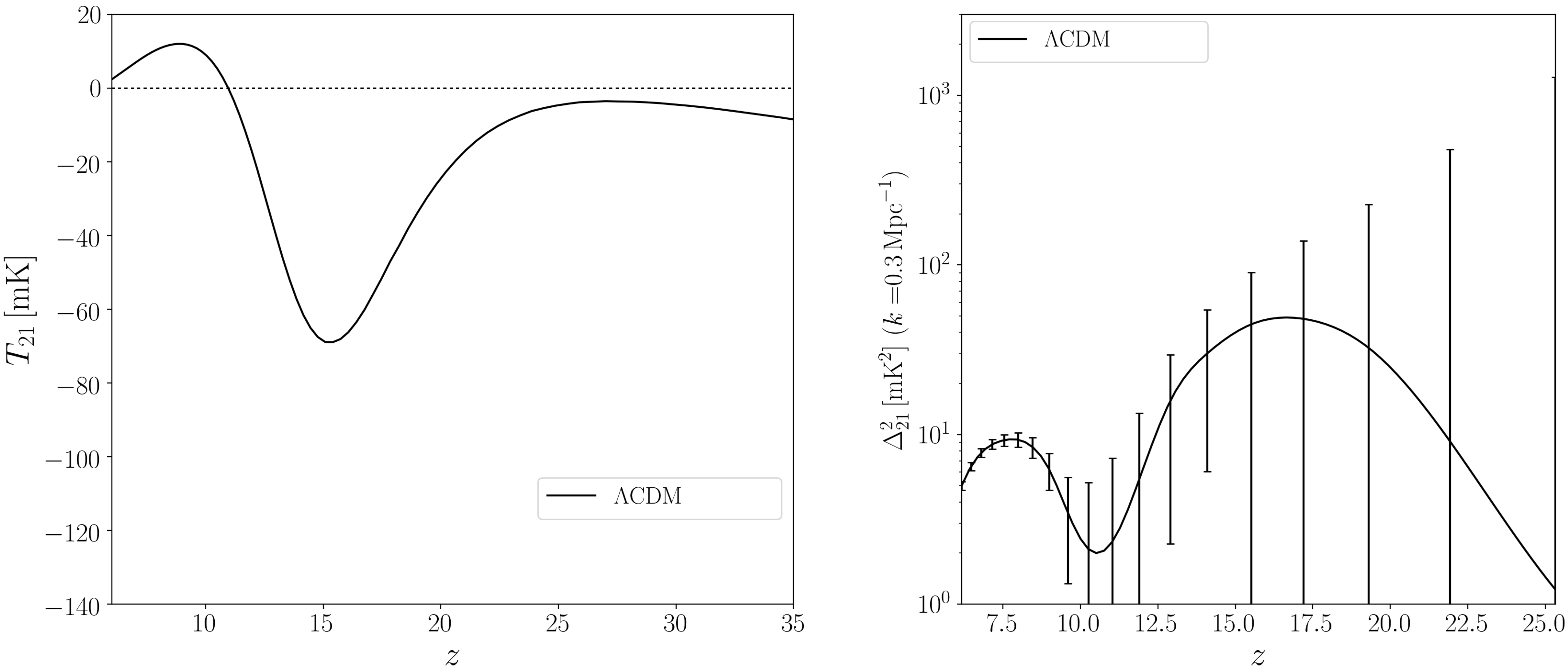

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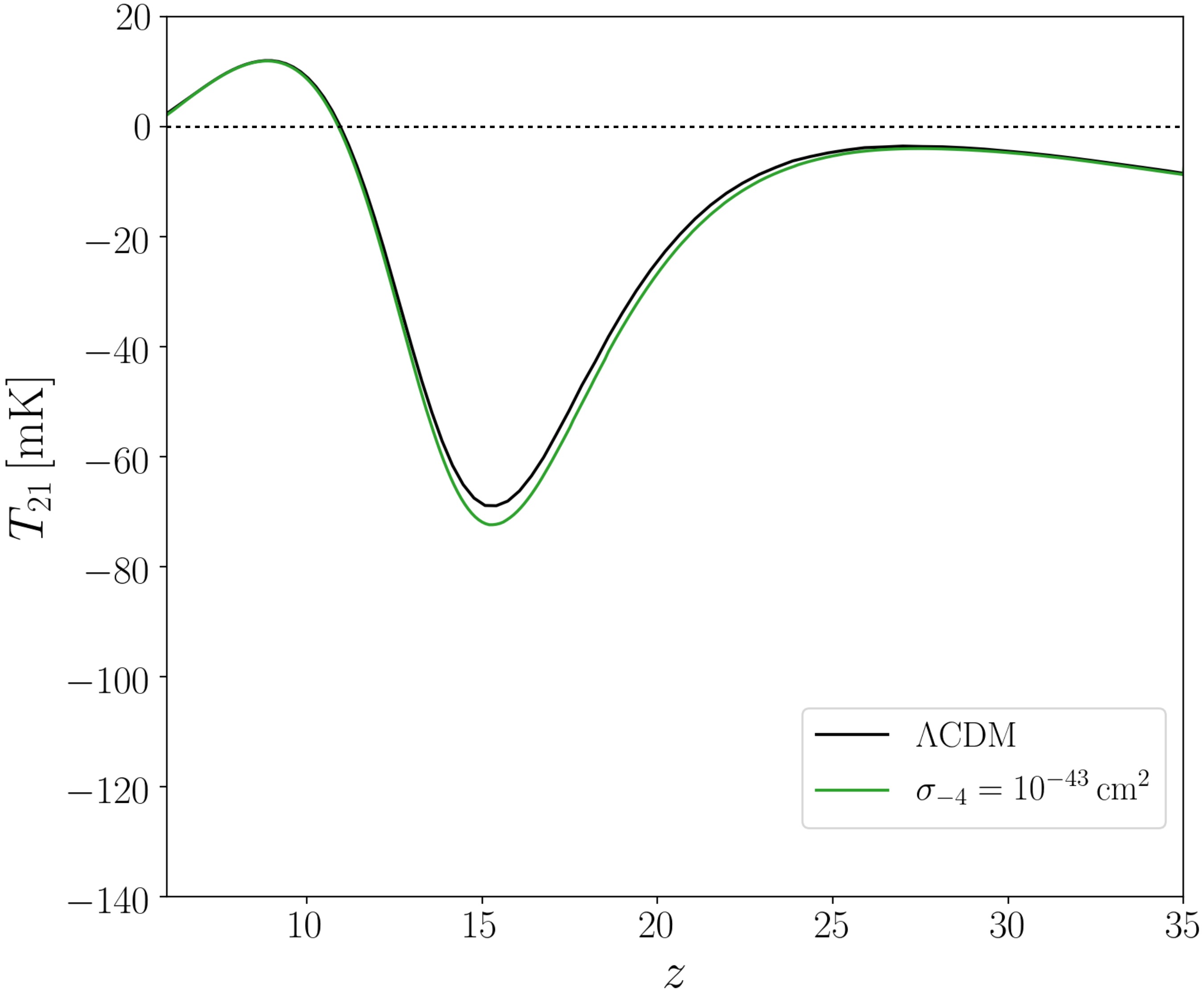

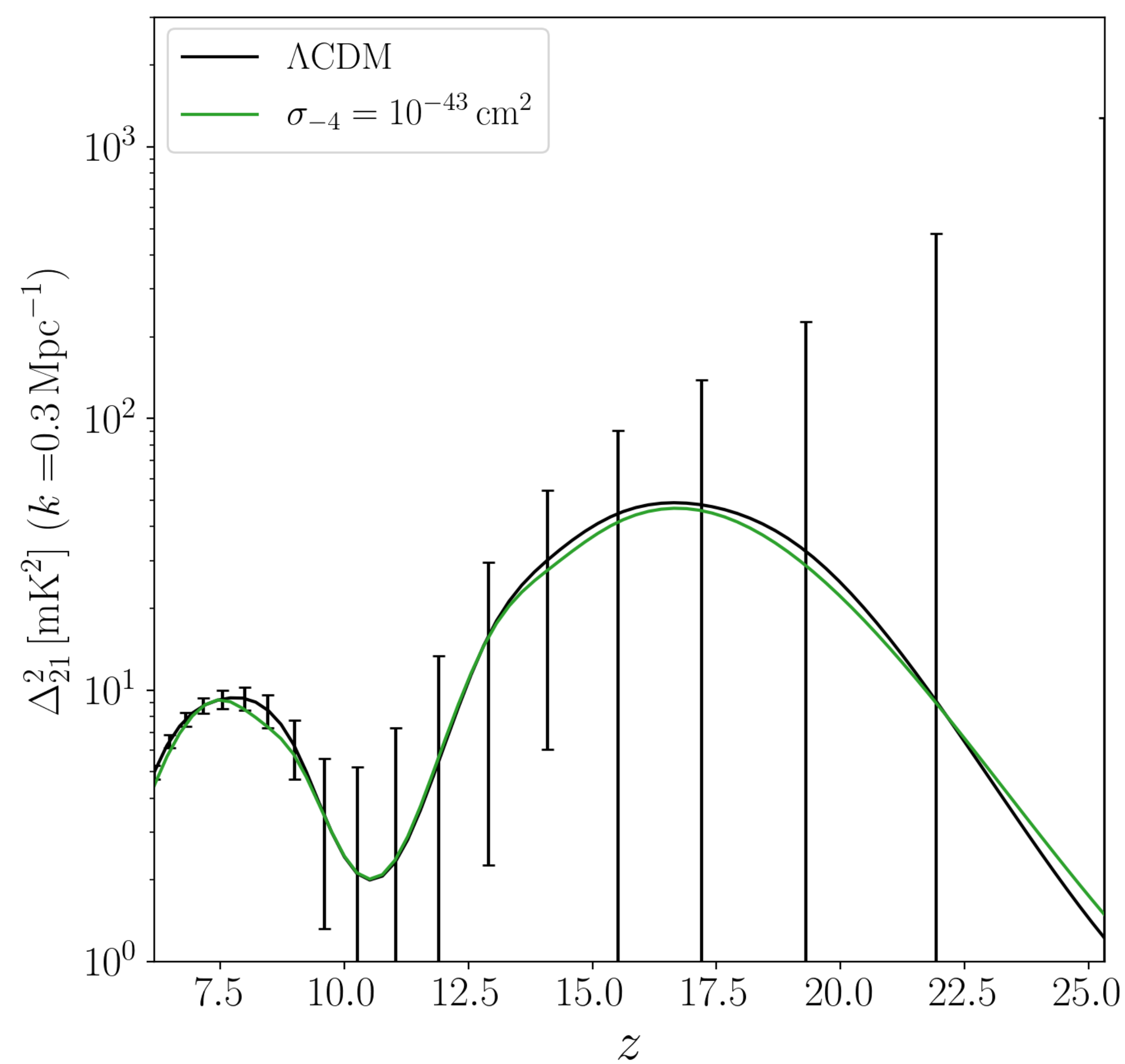

Flitter and Kovetz, arXiv:2309.03942

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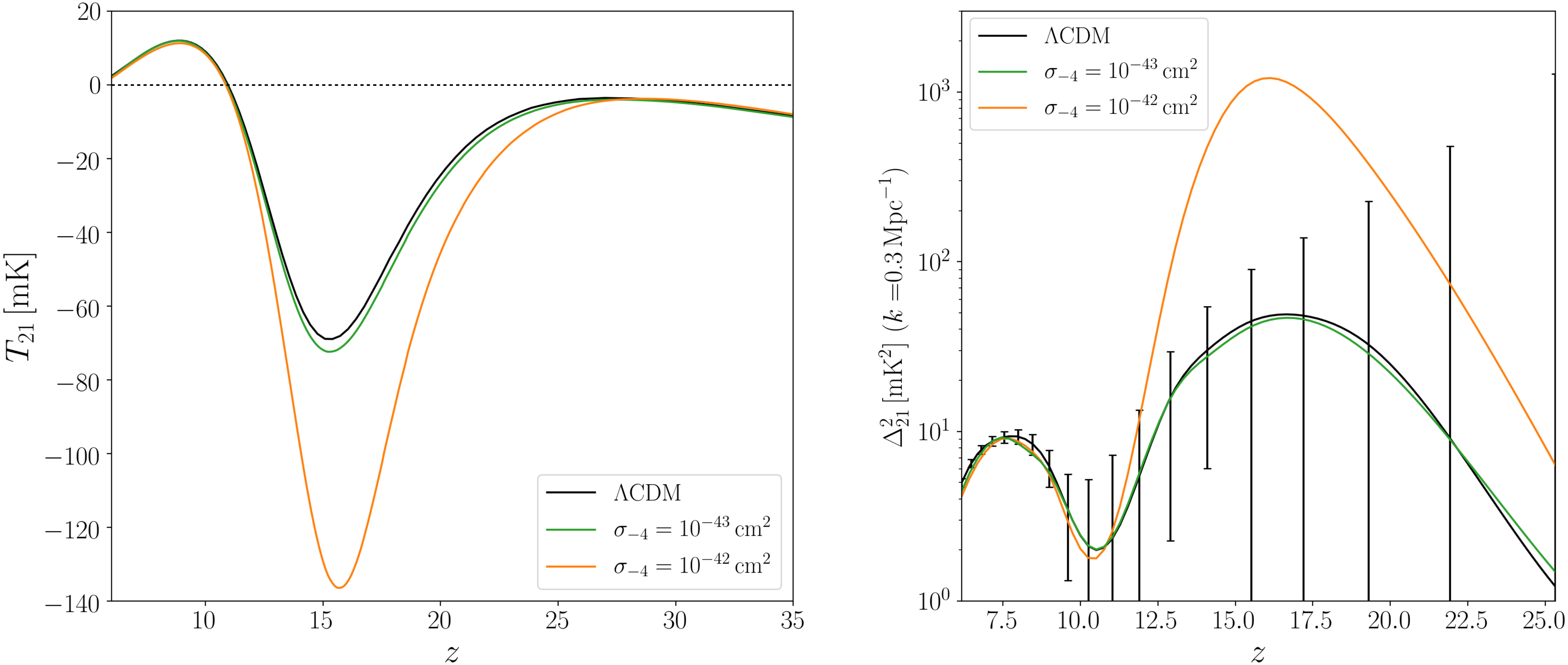
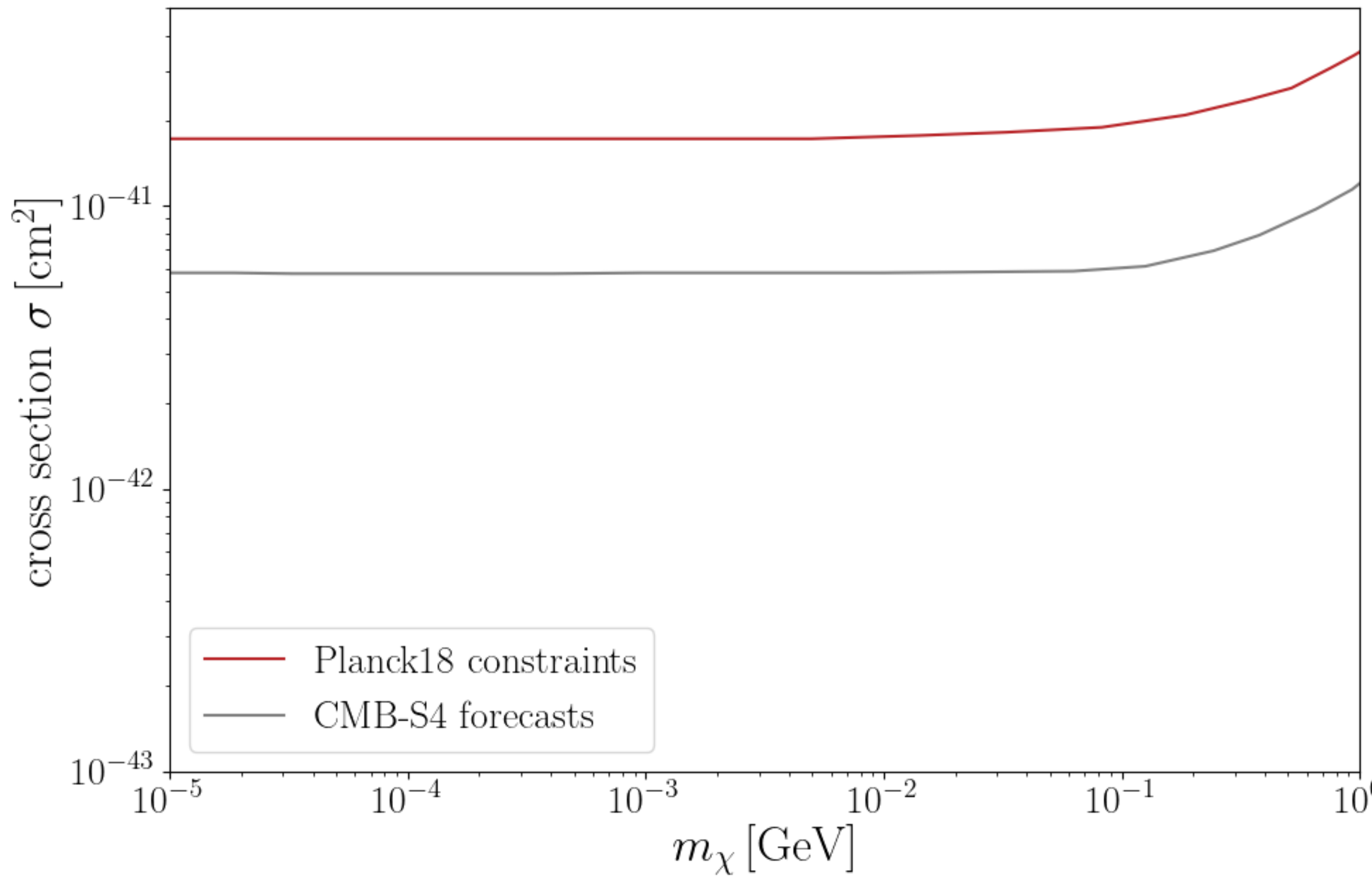


Flitter and Kovetz, arXiv:2309.03942

21cm Cosmology: Using 21cmFirstCLASS

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



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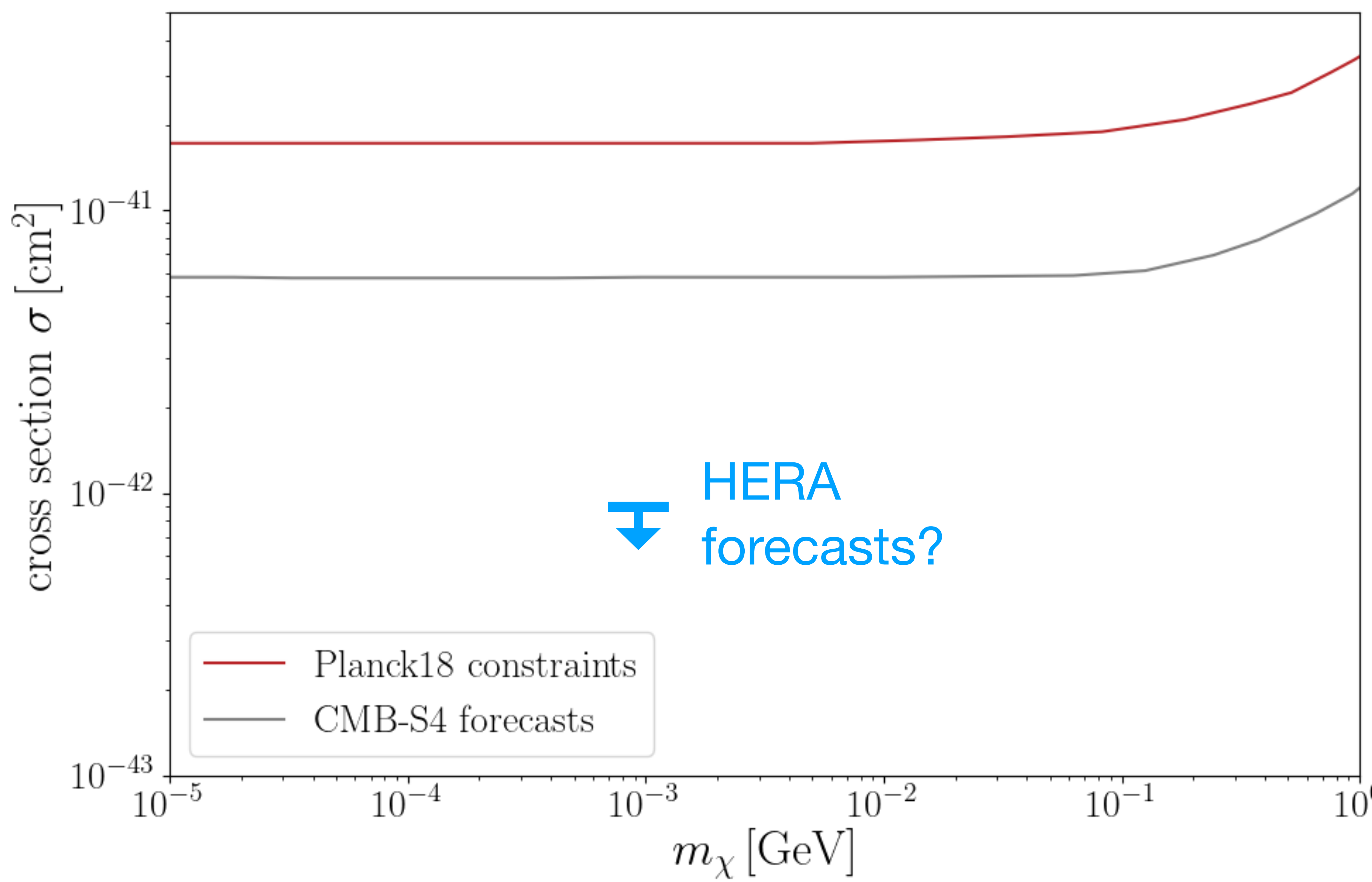

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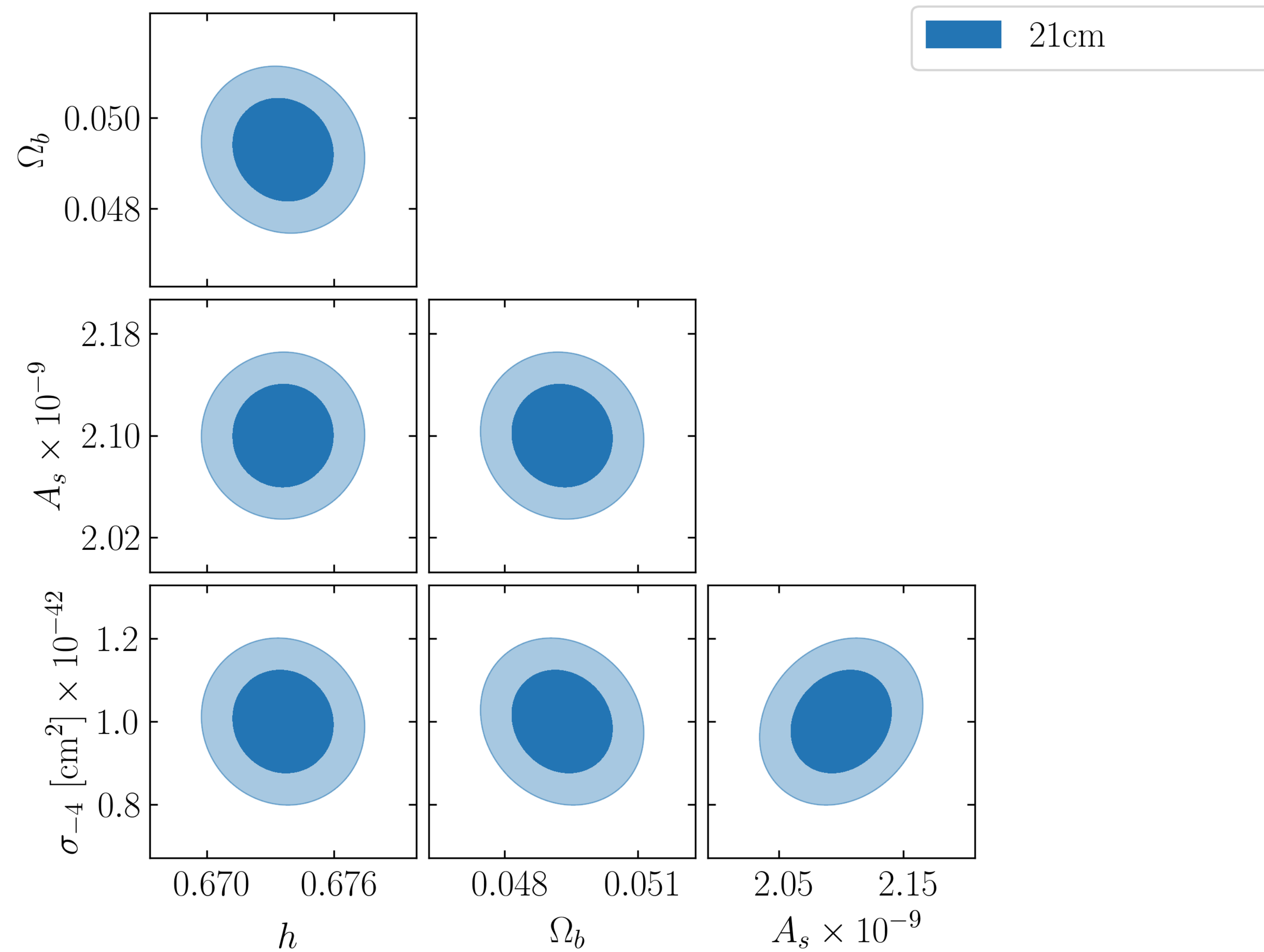

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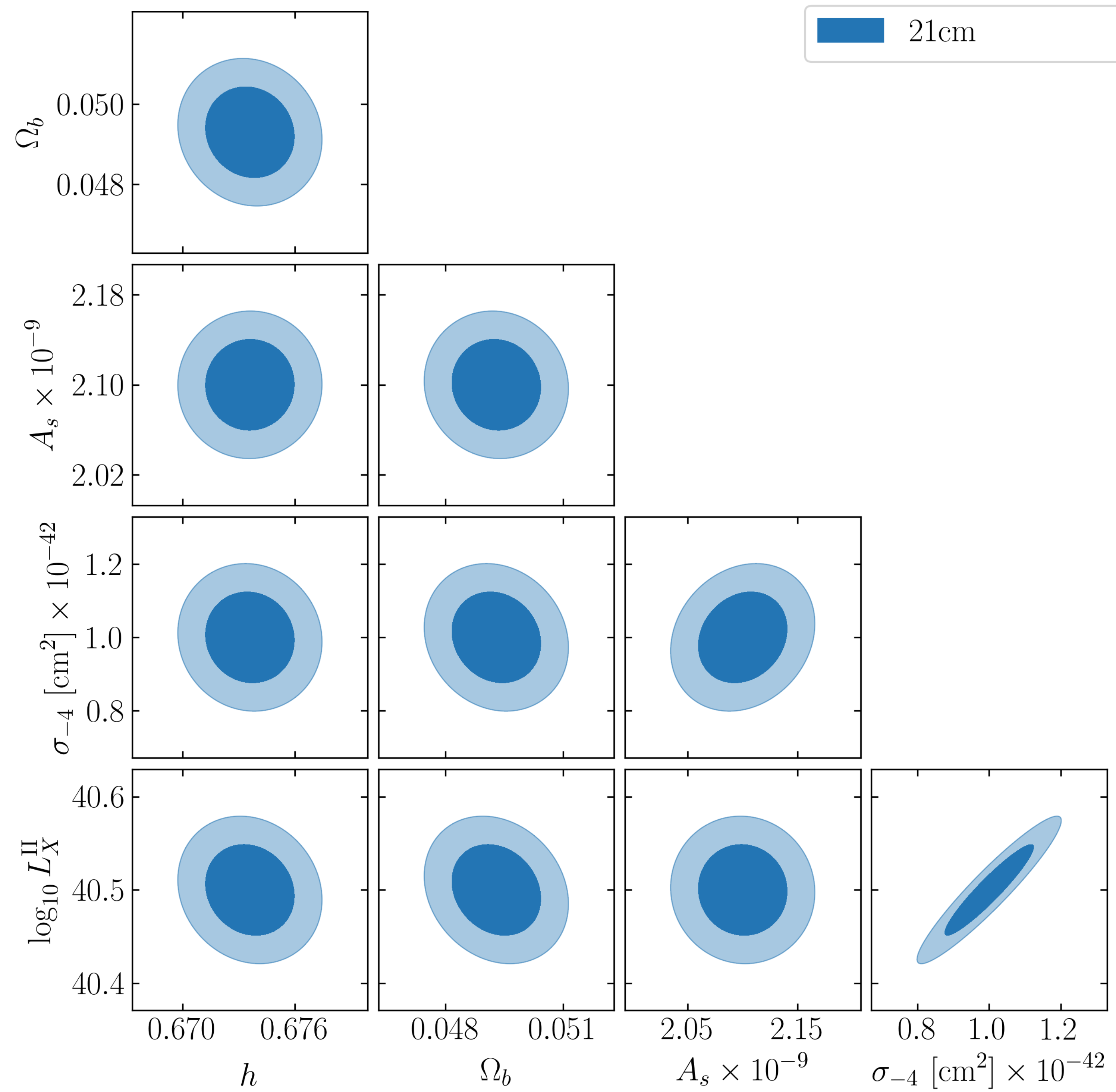

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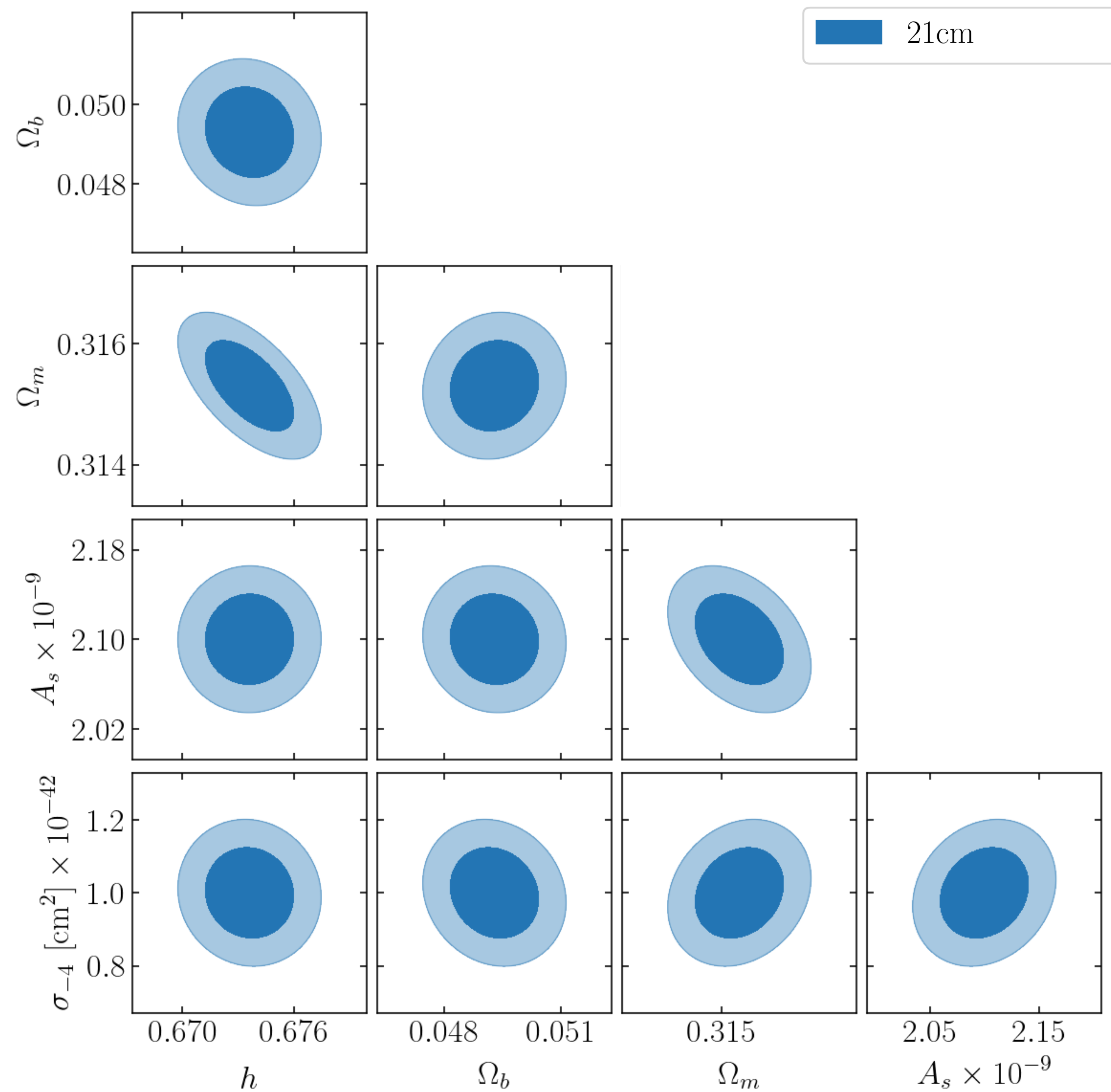

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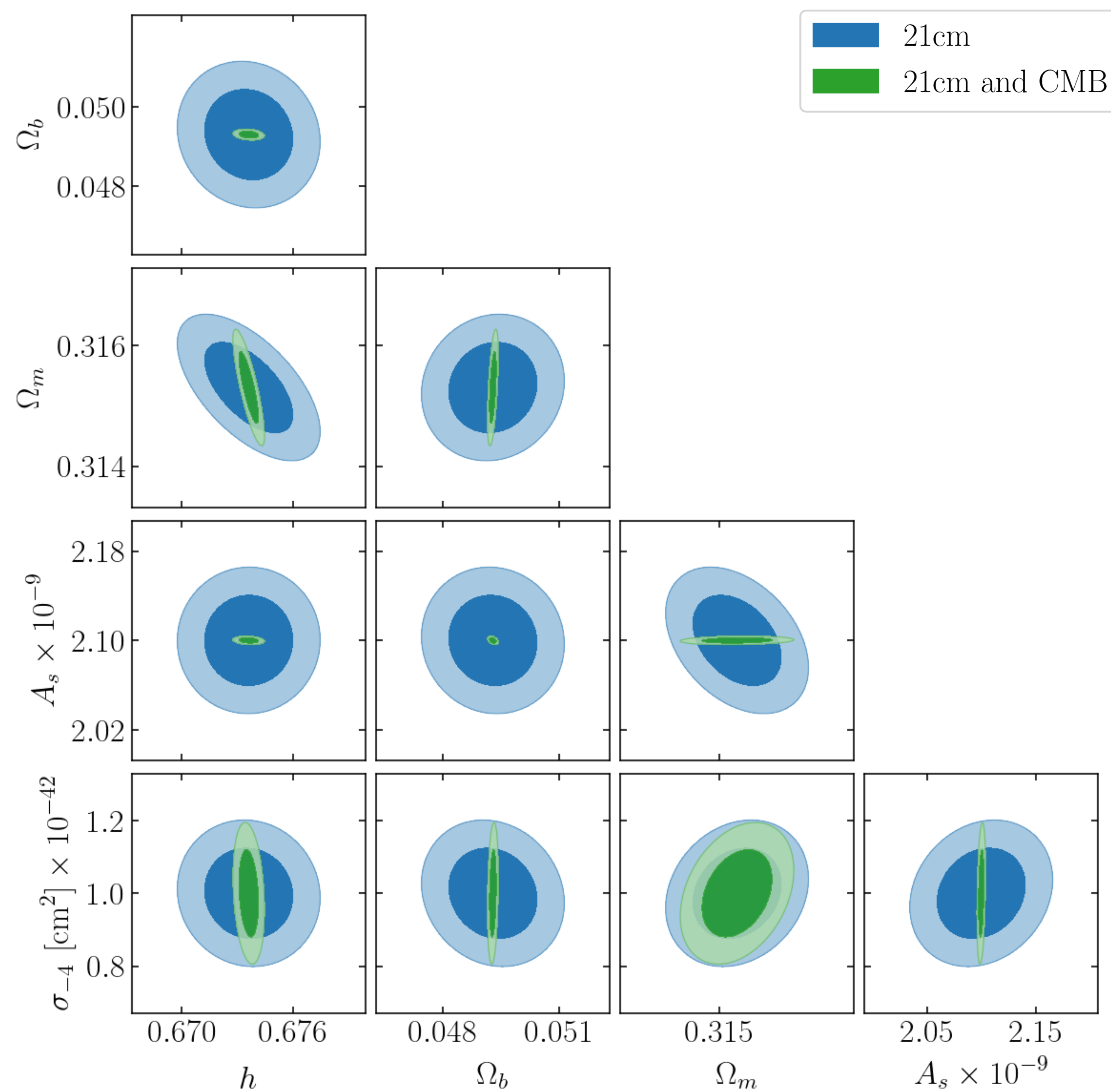

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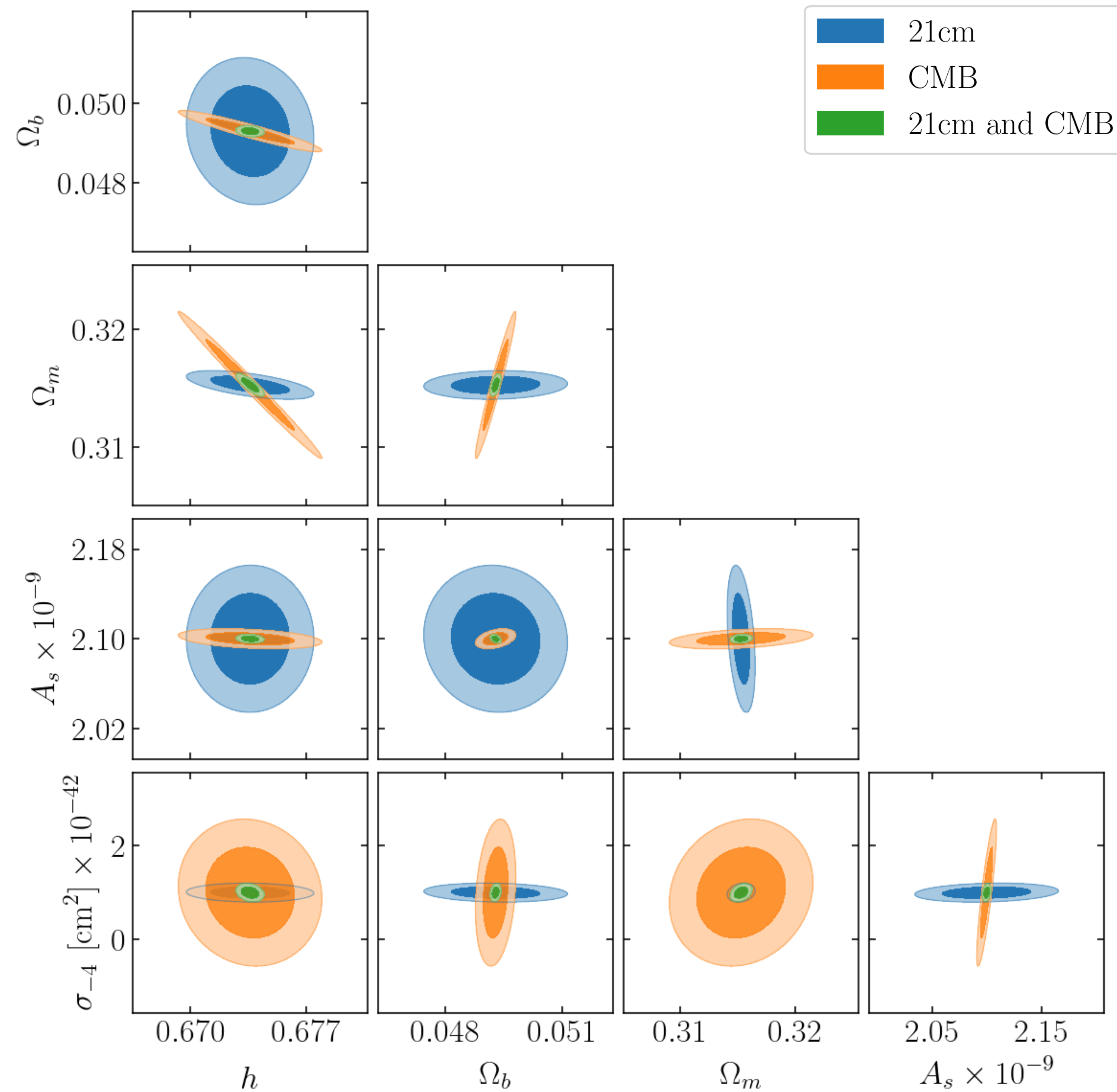


Flitter and Kovetz, arXiv:2309.03942

21cm Cosmology: `21cmFirstCLASS` vs. `CAMB`

Flitter and Kovetz, arXiv:2309.03948

Additional conclusions:

- $\mathcal{O}(20\%)$ error at $z < 35$ from homogeneous I.C.s

- $\mathcal{O}(20\%)$ error at $z < 35$ from $\delta_b = \delta_c$ assumption.

- Introducing a scale-dependent growth factor:

$$\mathscr{D}_b\left(k,z\right) \equiv \mathscr{T}_{b/c}\left(k,z\right) D\left(z\right)$$

yields percent agreement with CAMB at $z < 80$.

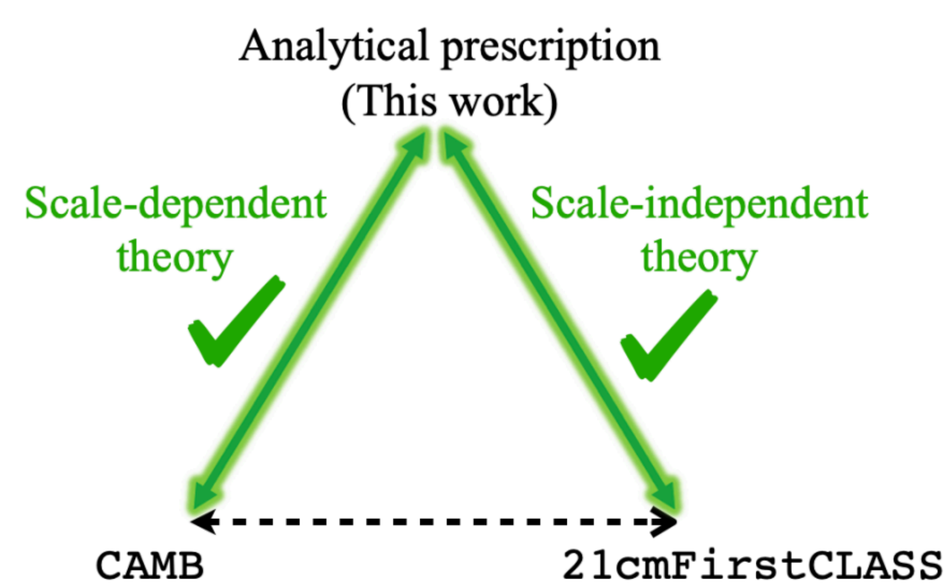
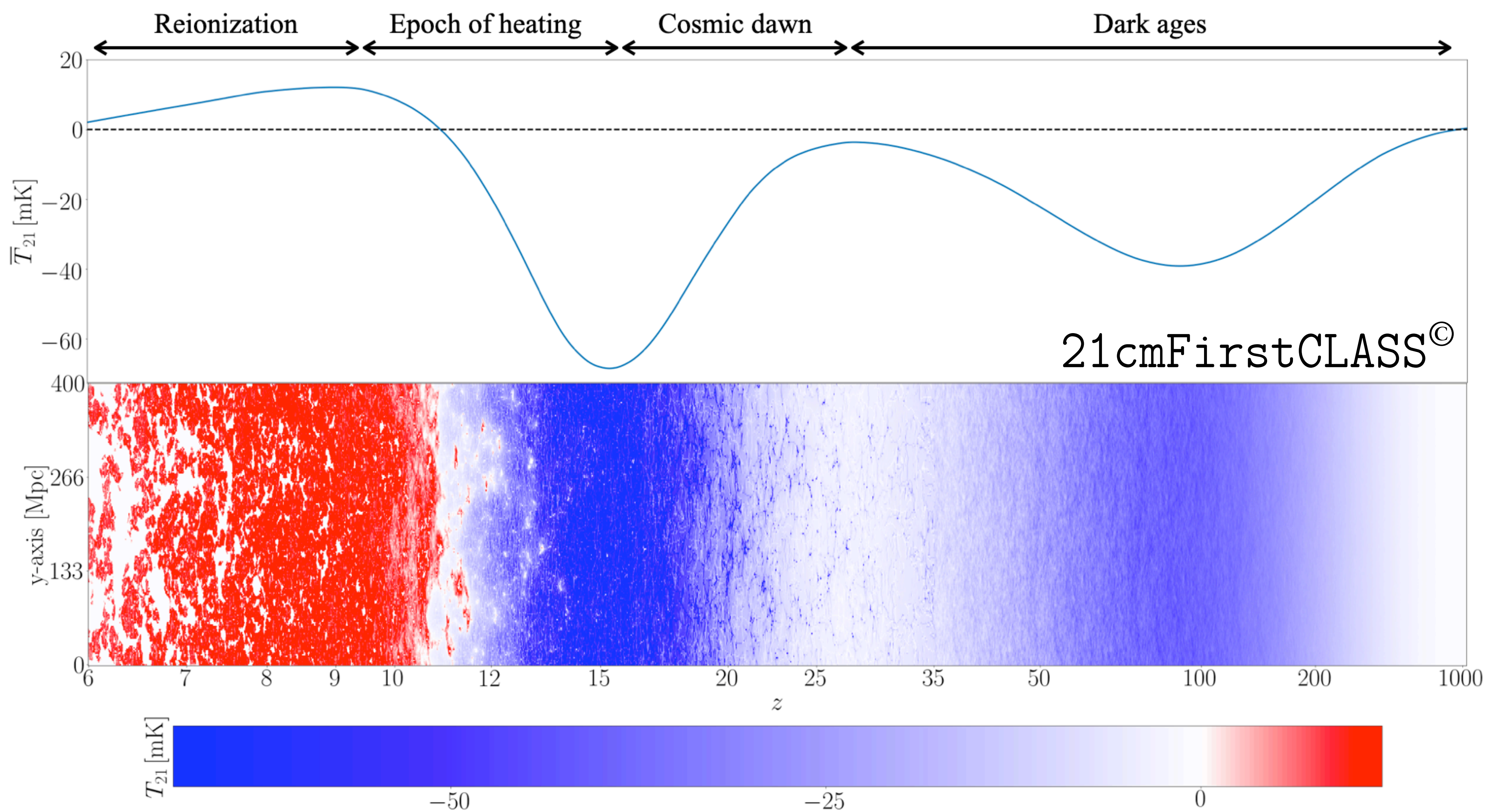


FIG. 1. Schematic representation of our comparison strategy.

LIM*: a first-class probe of physics beyond ΛCDM

*21cm as well as other atomic/molecular lines



Ely Kovetz, Trieste 21cm conference, Sep. 2023