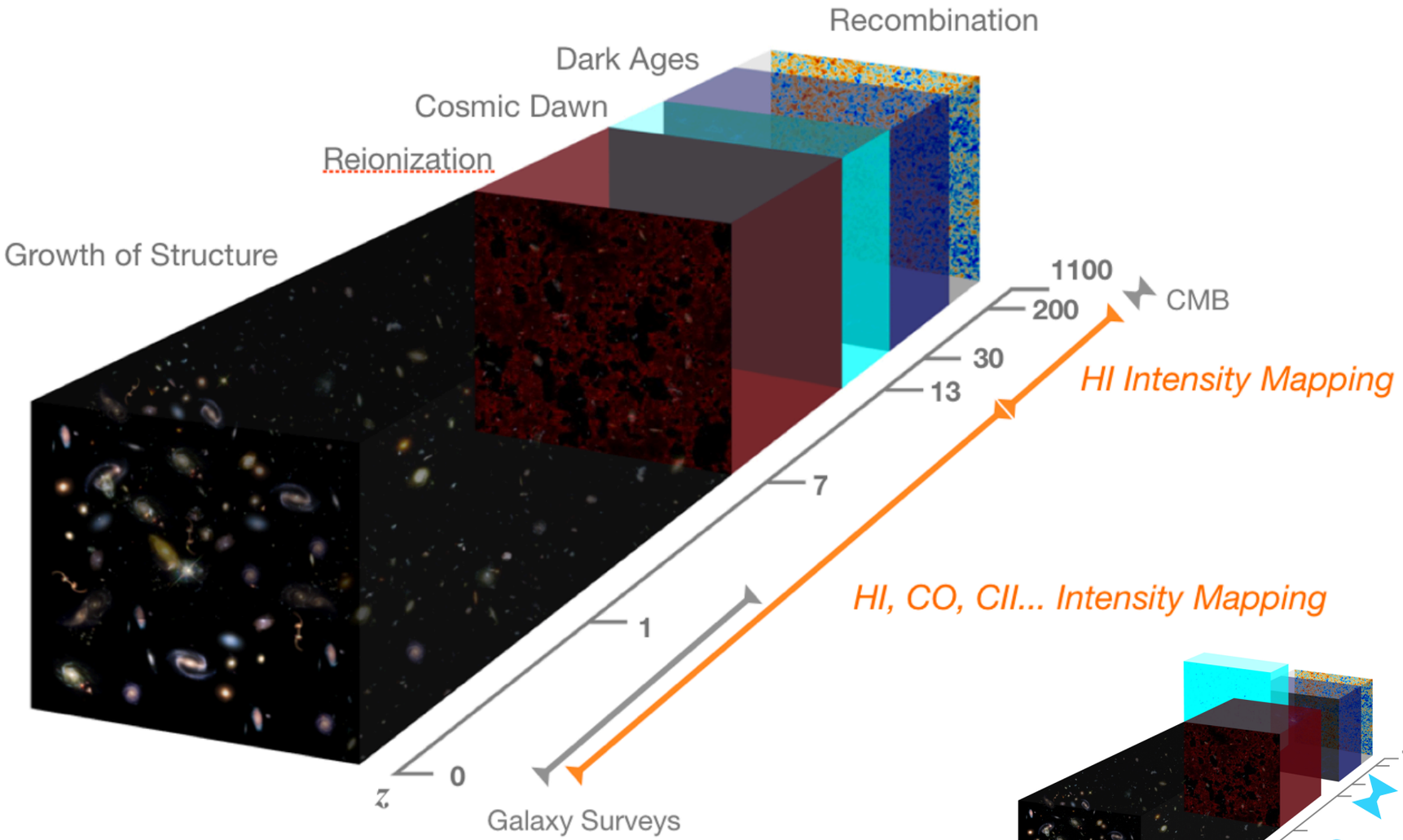
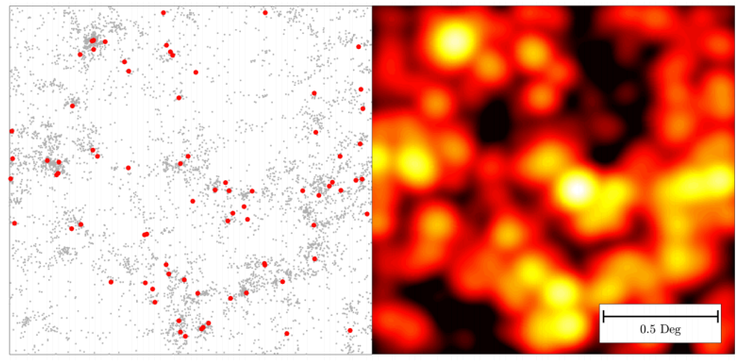
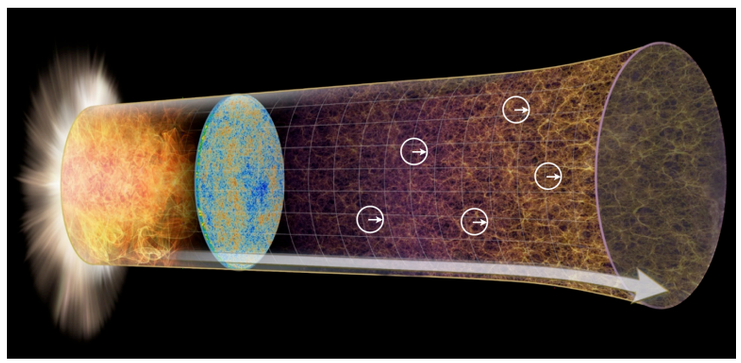
Beyond ΛCDM with Line-Intensity Mapping

Ely D. Kovetz
Ben-Gurion University



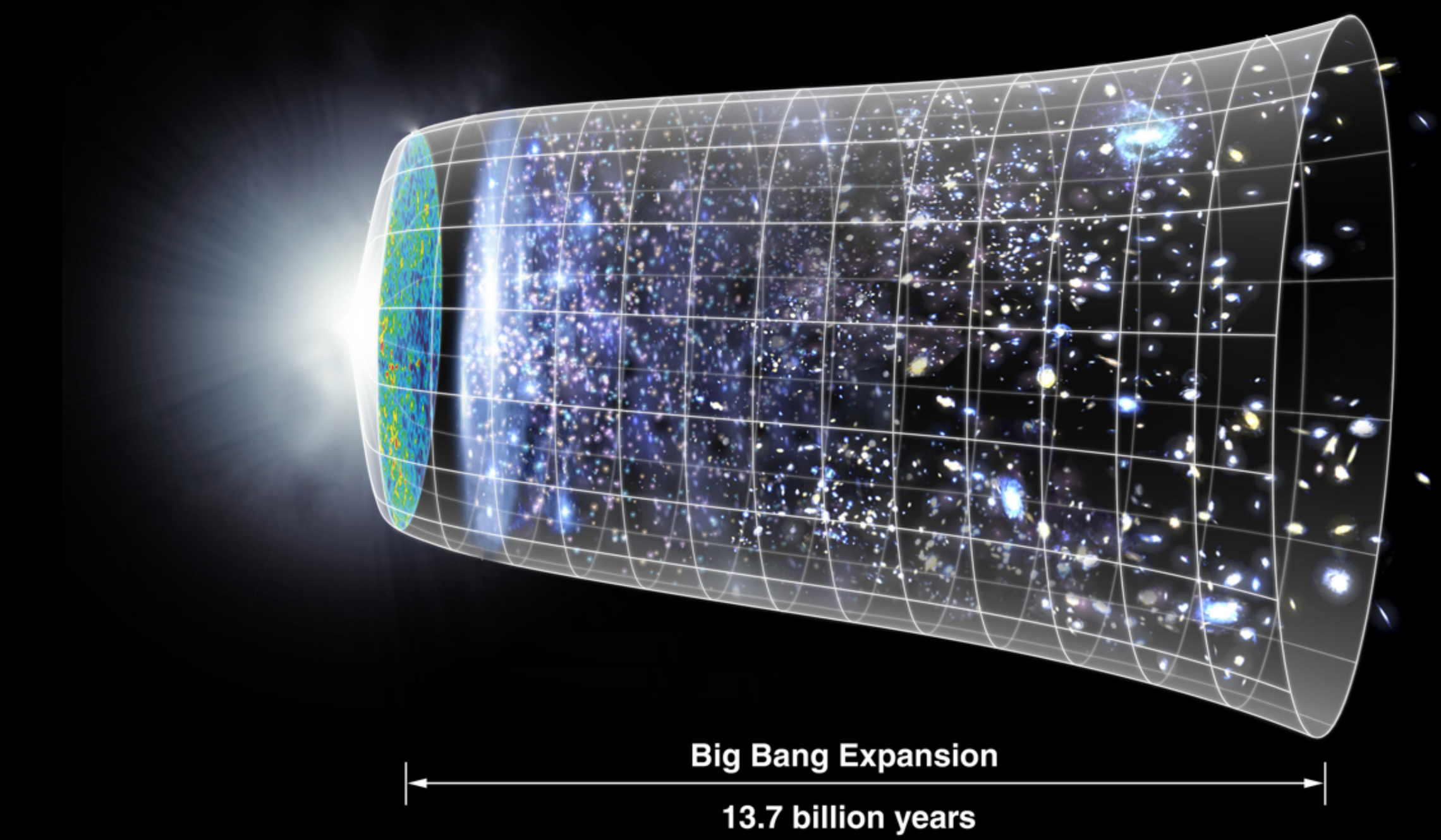
King's College Seminar
June 23th, 2021





Collaborators: Y. Ali-Haïmoud, R. Barkana, J. L. Bernal, K. Boddy, P. Breysse, I. Cholis, C. Creque-Sarbinowski, H. Gil-Marin, V. Gluscevic, Lingyuan Ji, D. Kaplan, M. Kamionkowski, J. Muñoz, V. Poulin & D. Sarkar

History of the ΛCDM Universe



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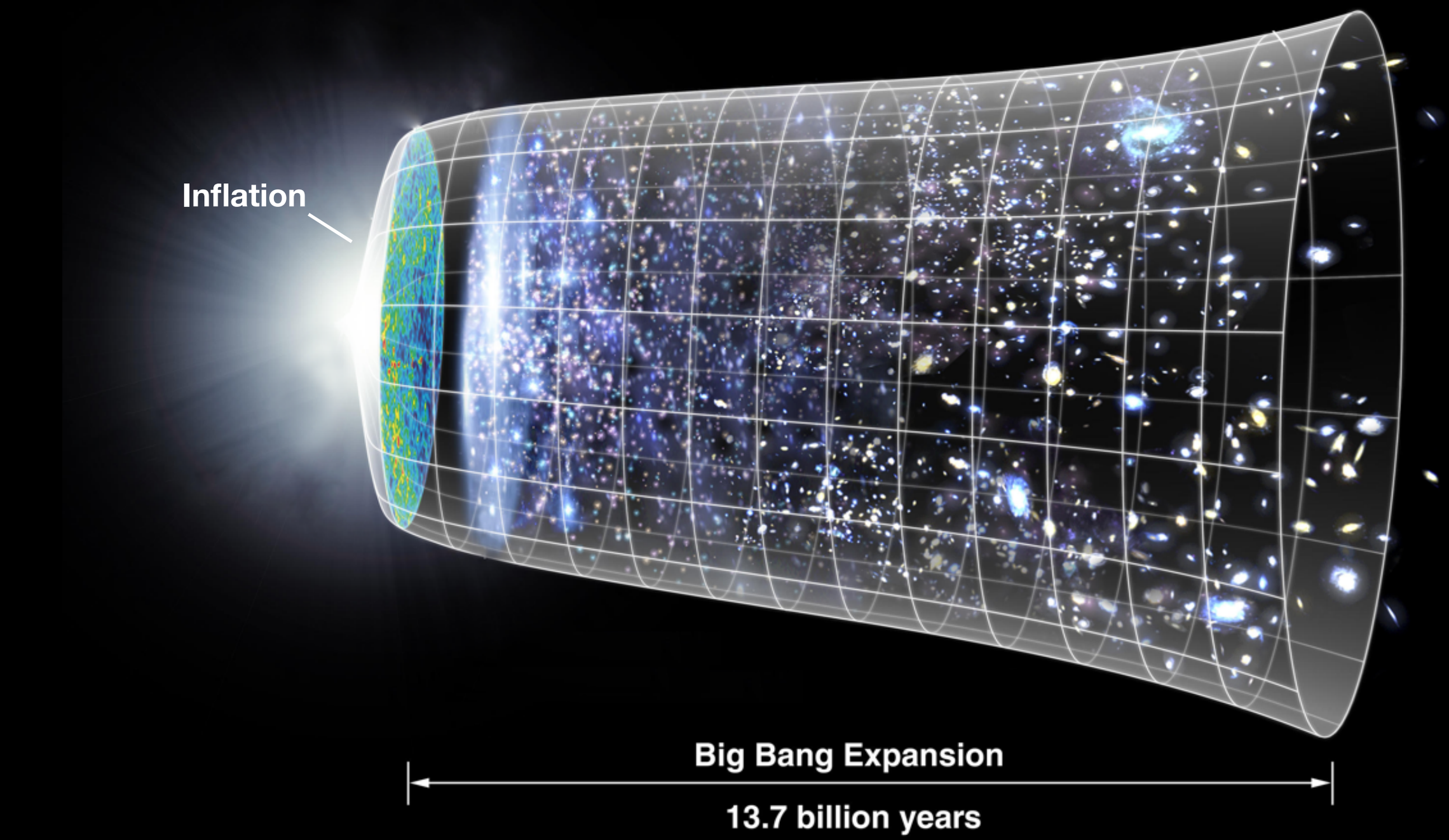

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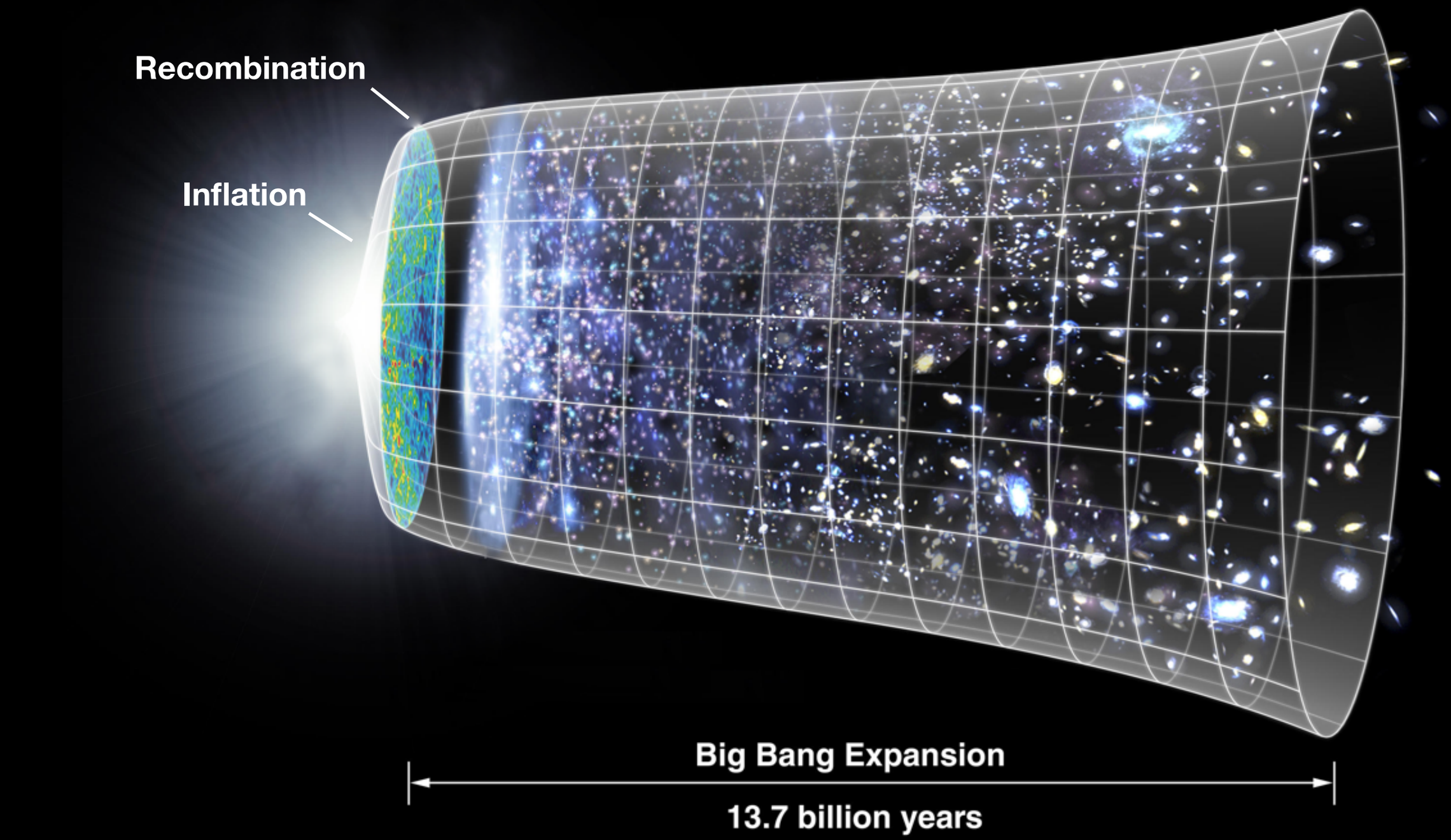

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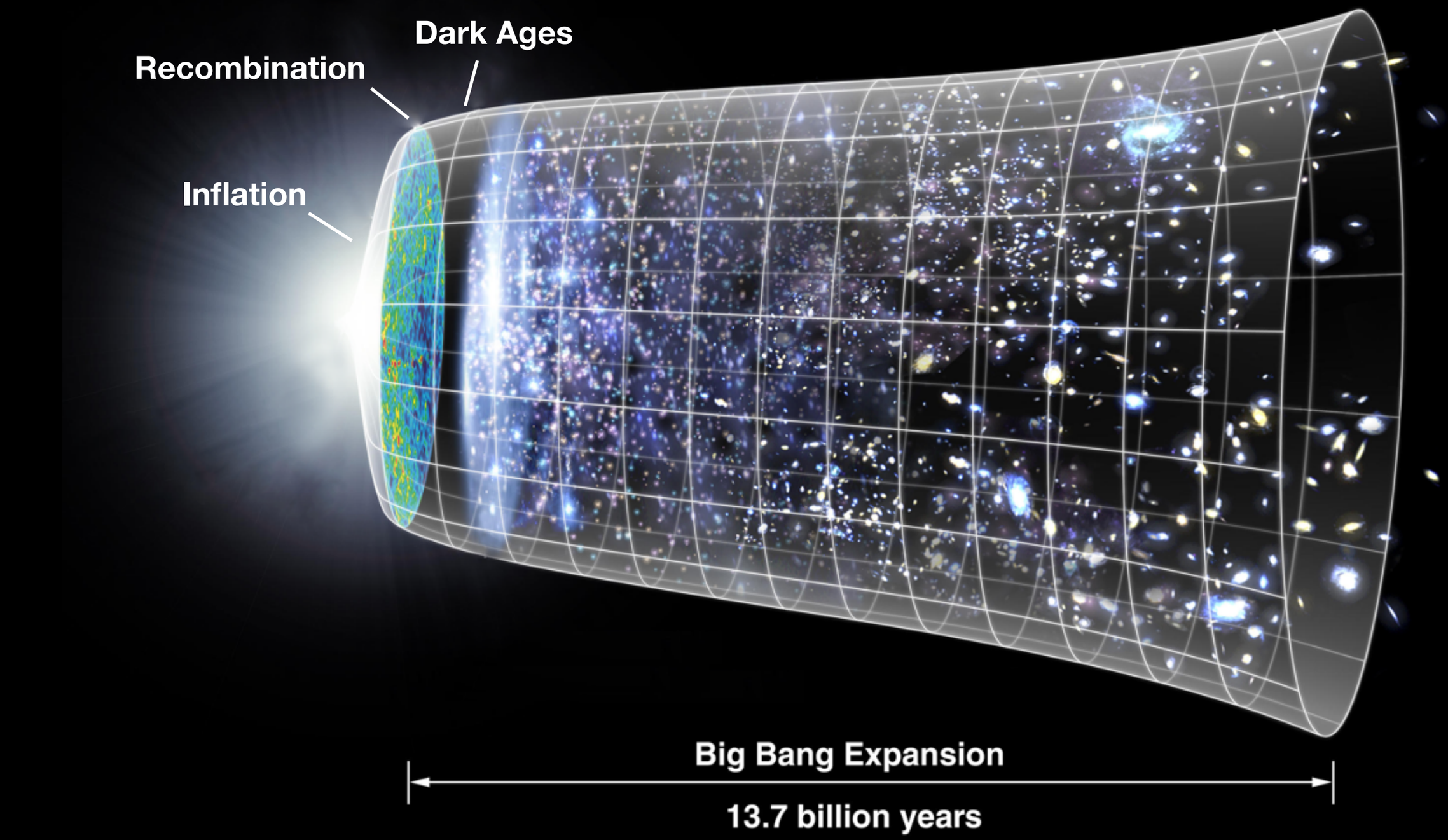

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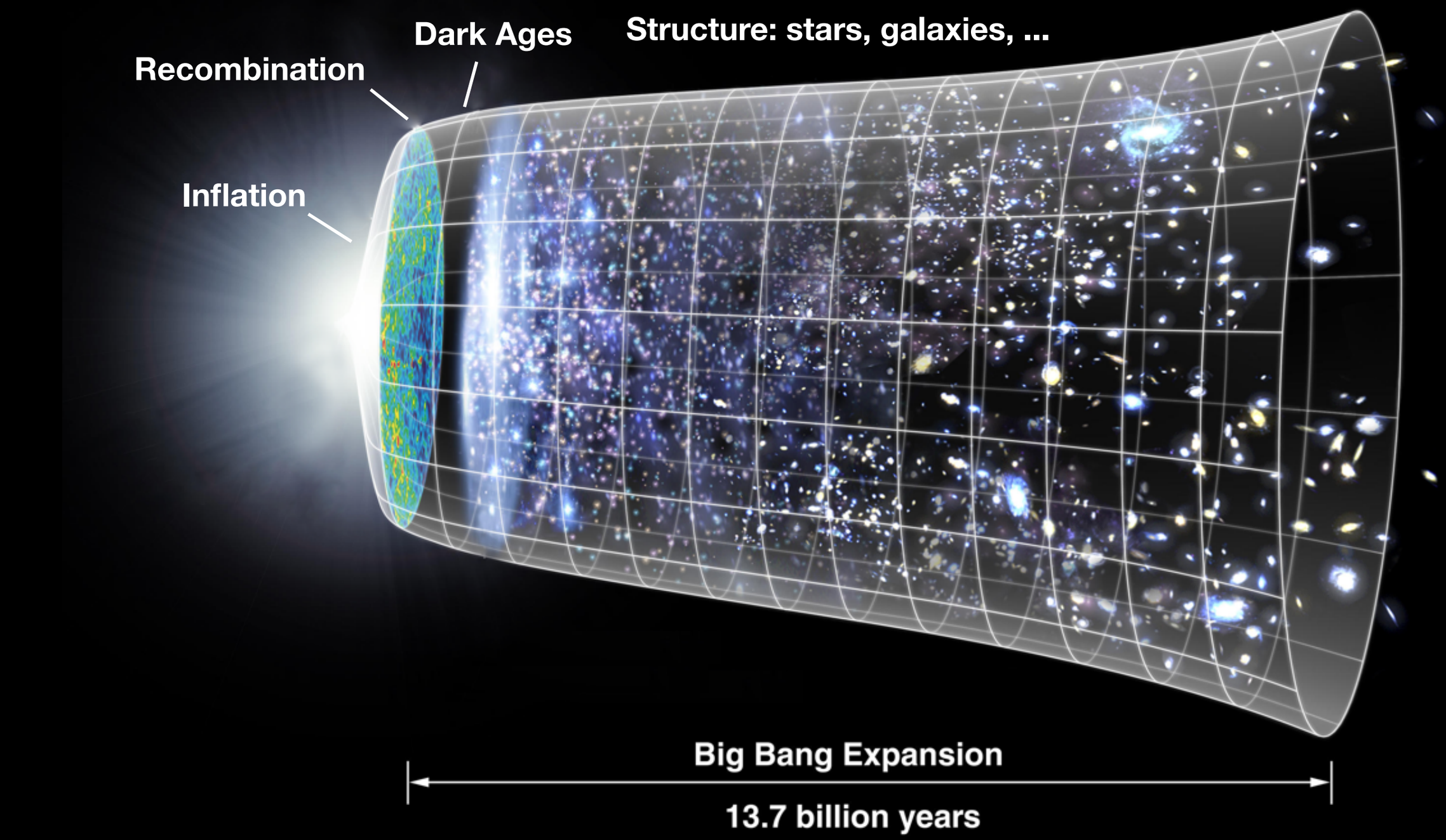

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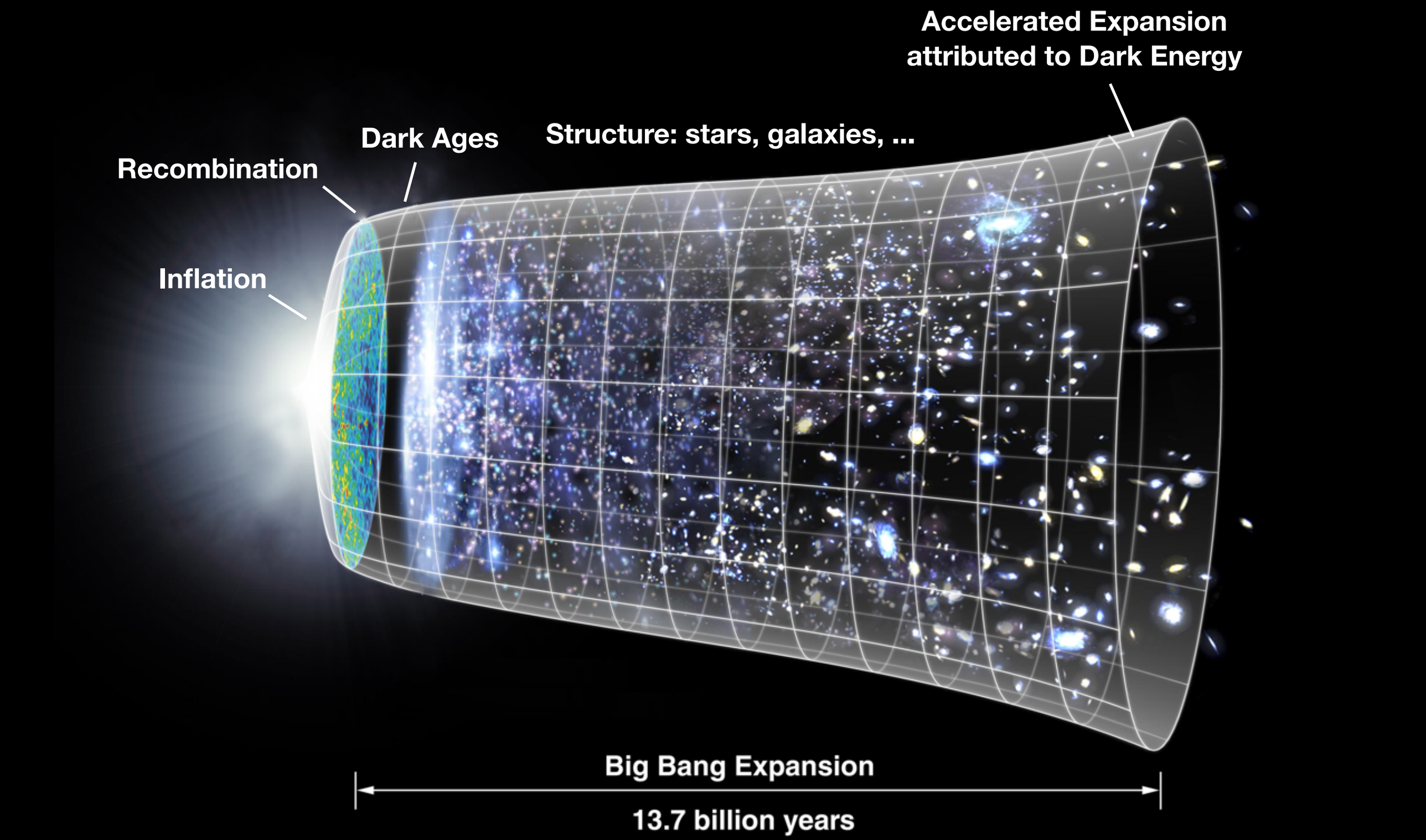

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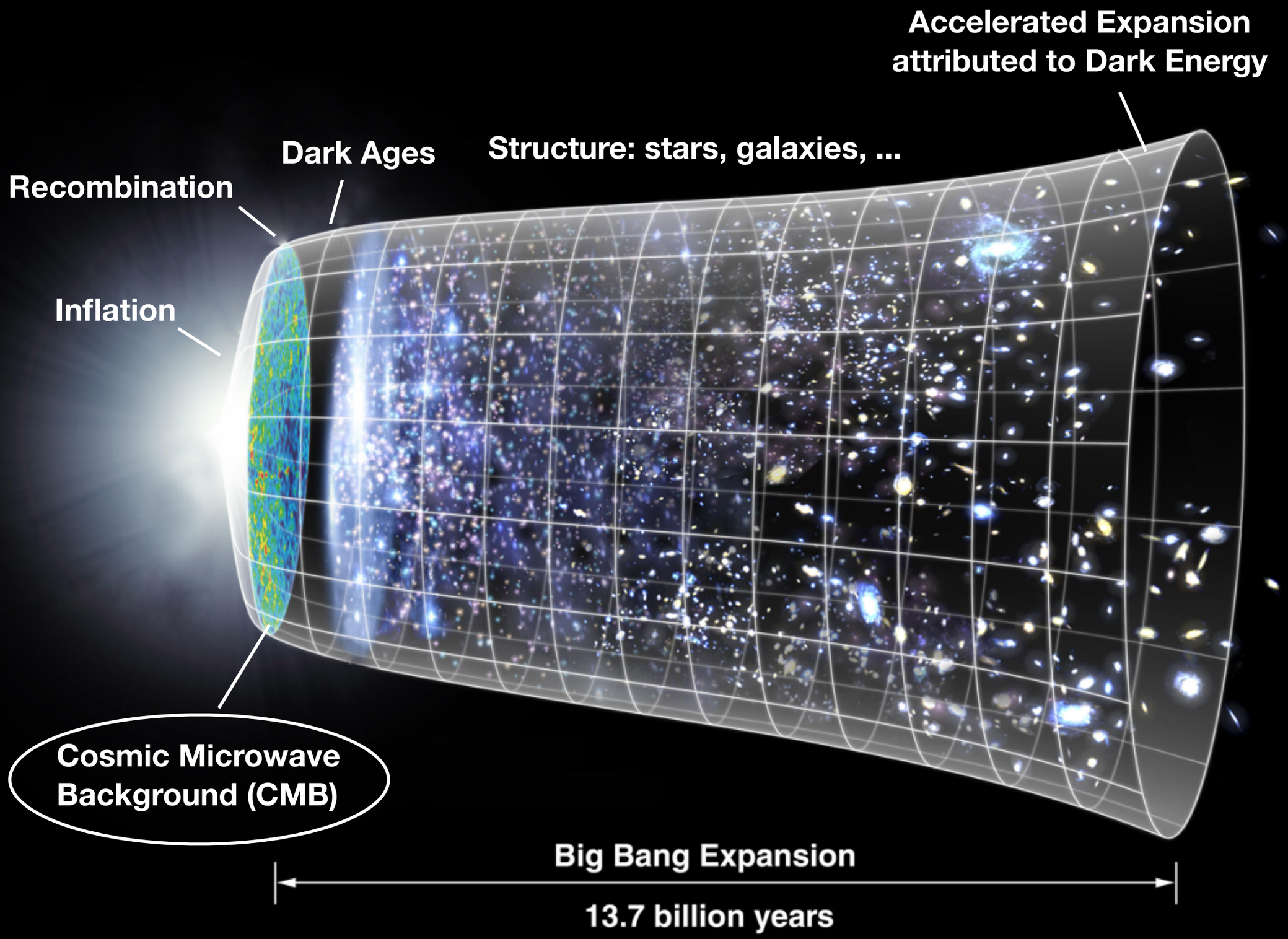

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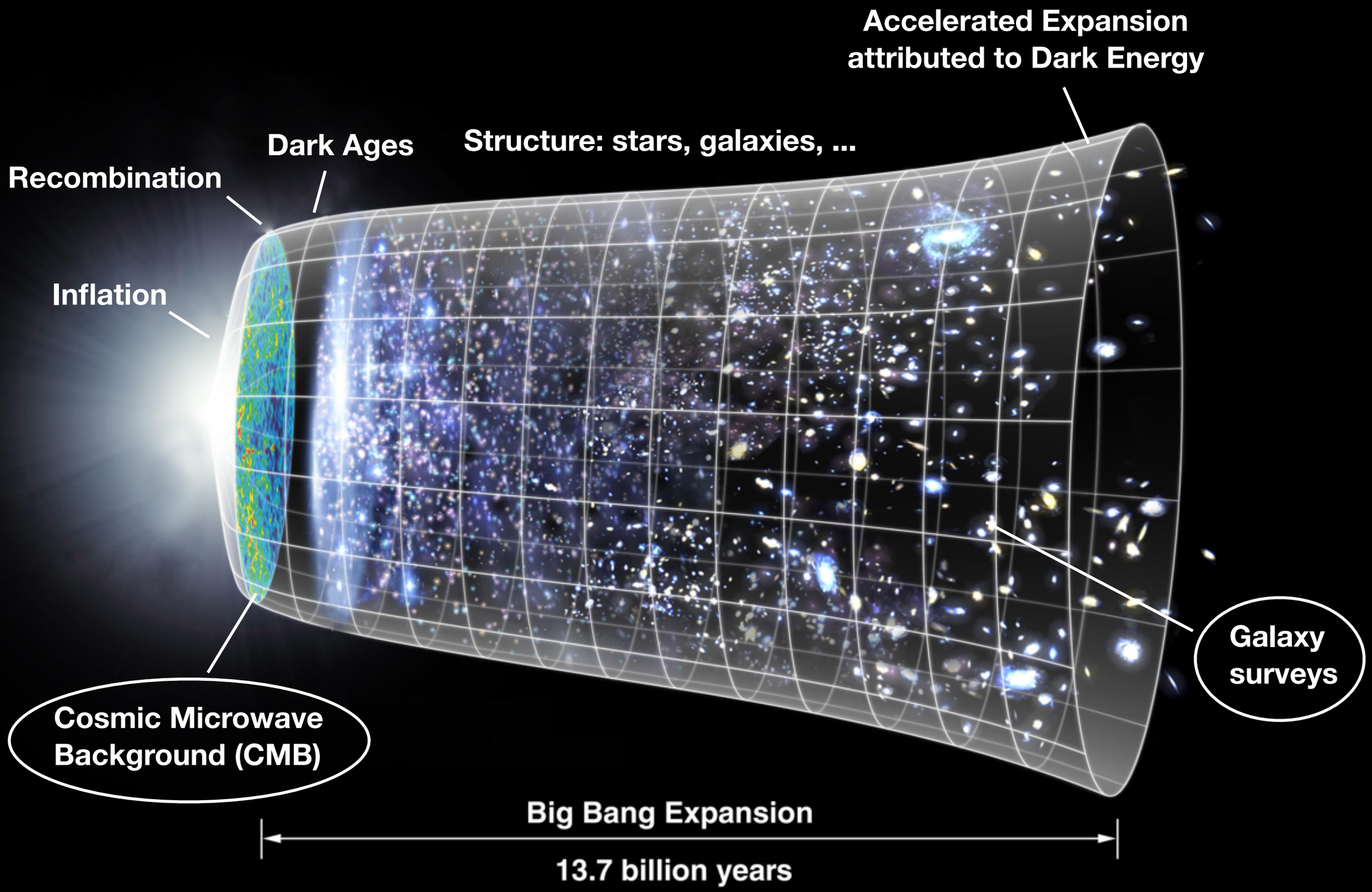

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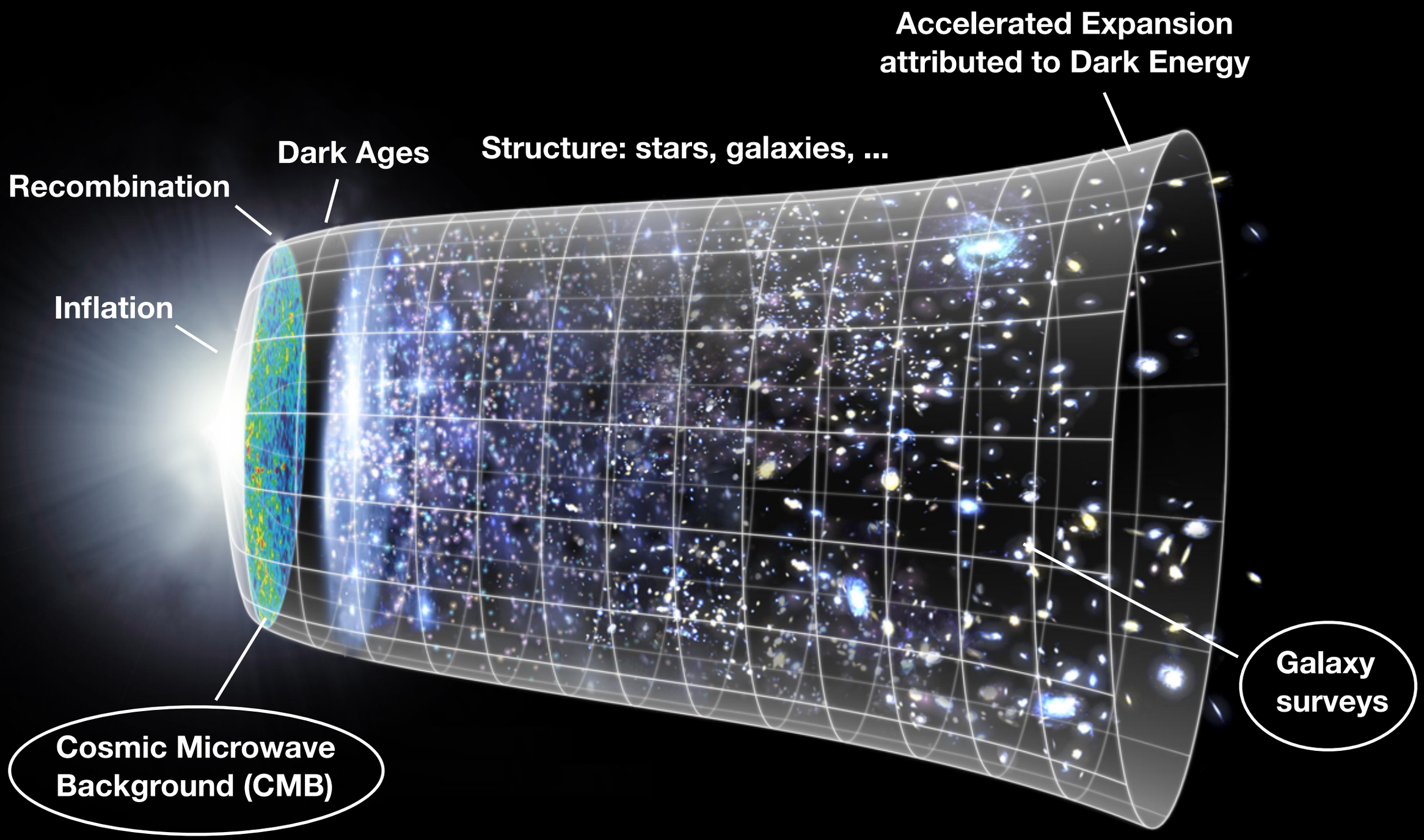


Parameters (H_0 n_s A_s $\Omega_{\rm M}$ $\Omega_{\rm b}$): measured to few percent uncertainty!

Core Questions in Cosmology

Core Questions in Cosmology

1

What is the nature of ***dark matter***?

Core Questions in Cosmology

1	2
What is the nature of ***dark matter***?	What makes up ***dark energy***?

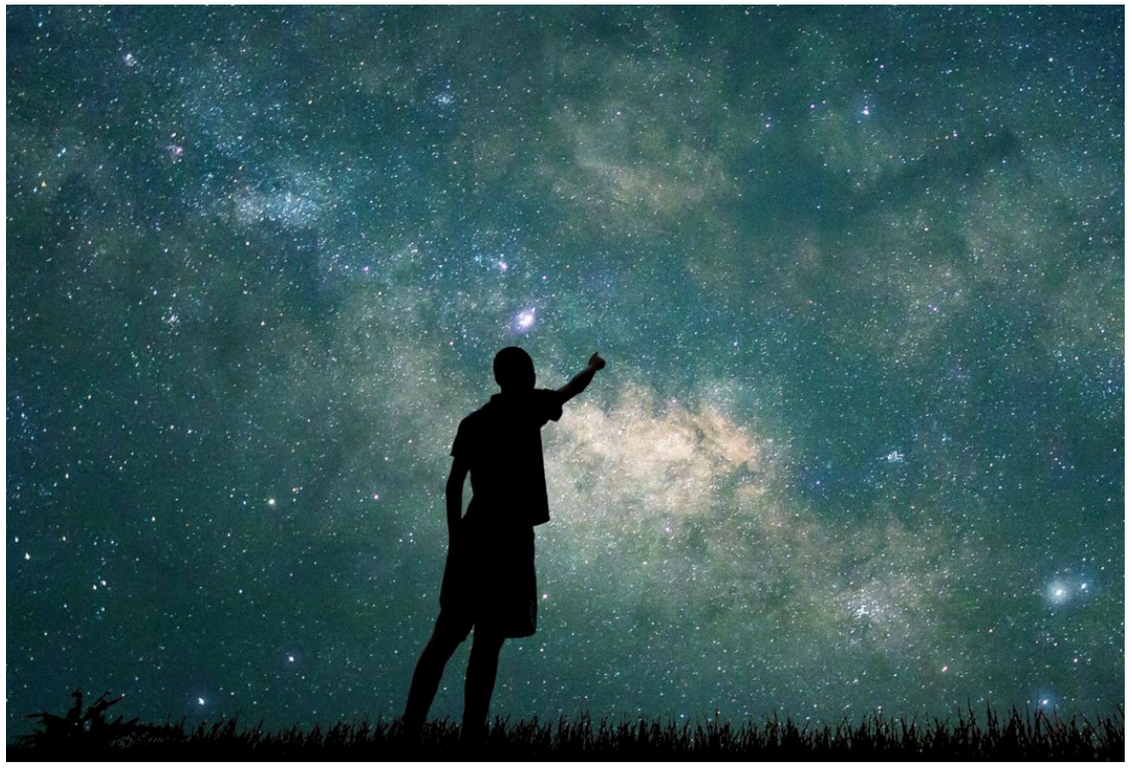
Core Questions in Cosmology

1	2	3
What is the nature of ***dark matter***?	What makes up ***dark energy***?	What are the properties of ***inflation***?

Core Questions in Cosmology

1	2	3
What is the nature of ***dark matter***?	What makes up ***dark energy***?	What are the properties of ***inflation***?

Where will new information come from?



The Observable Universe: Key Historical Epochs

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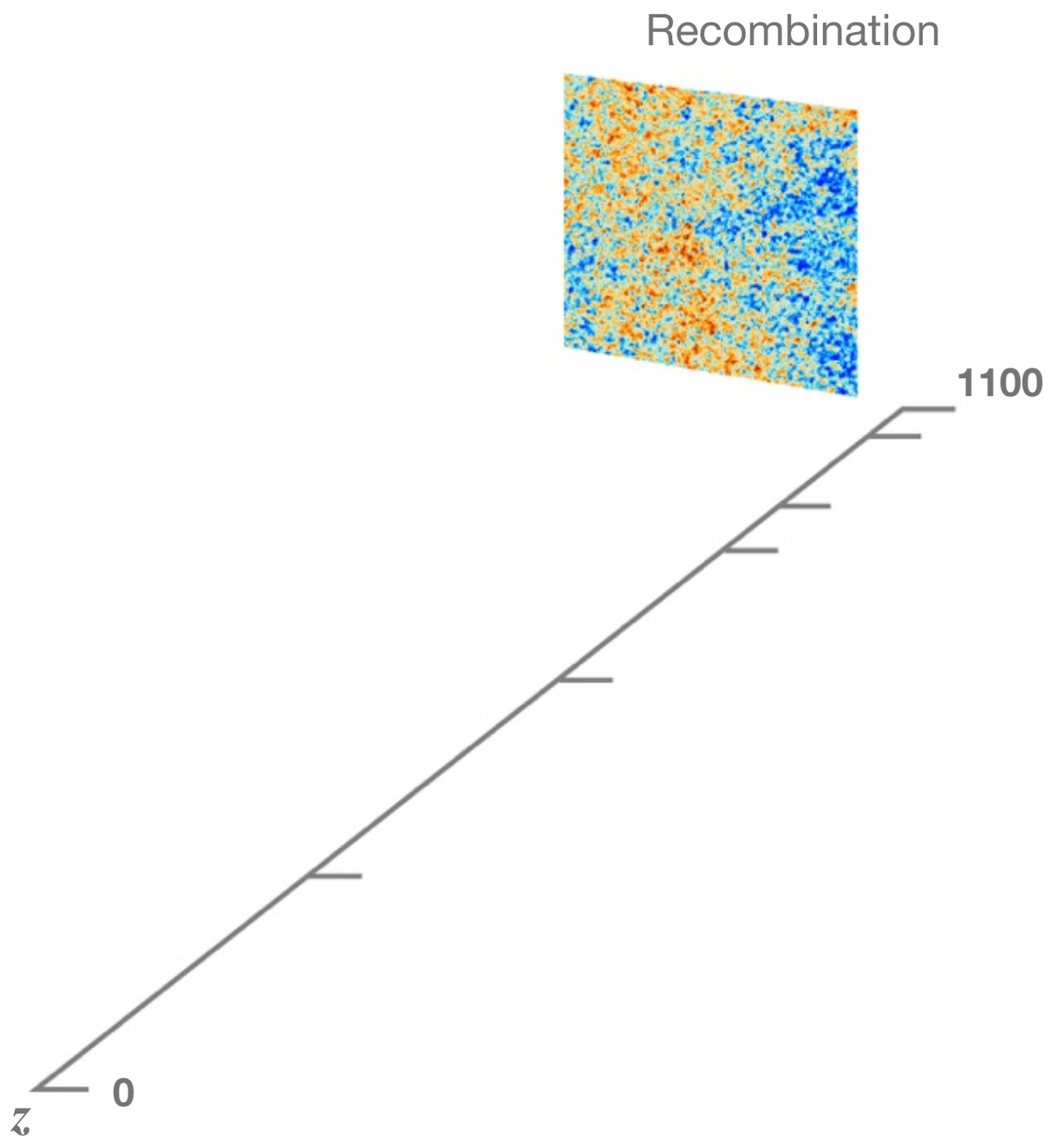

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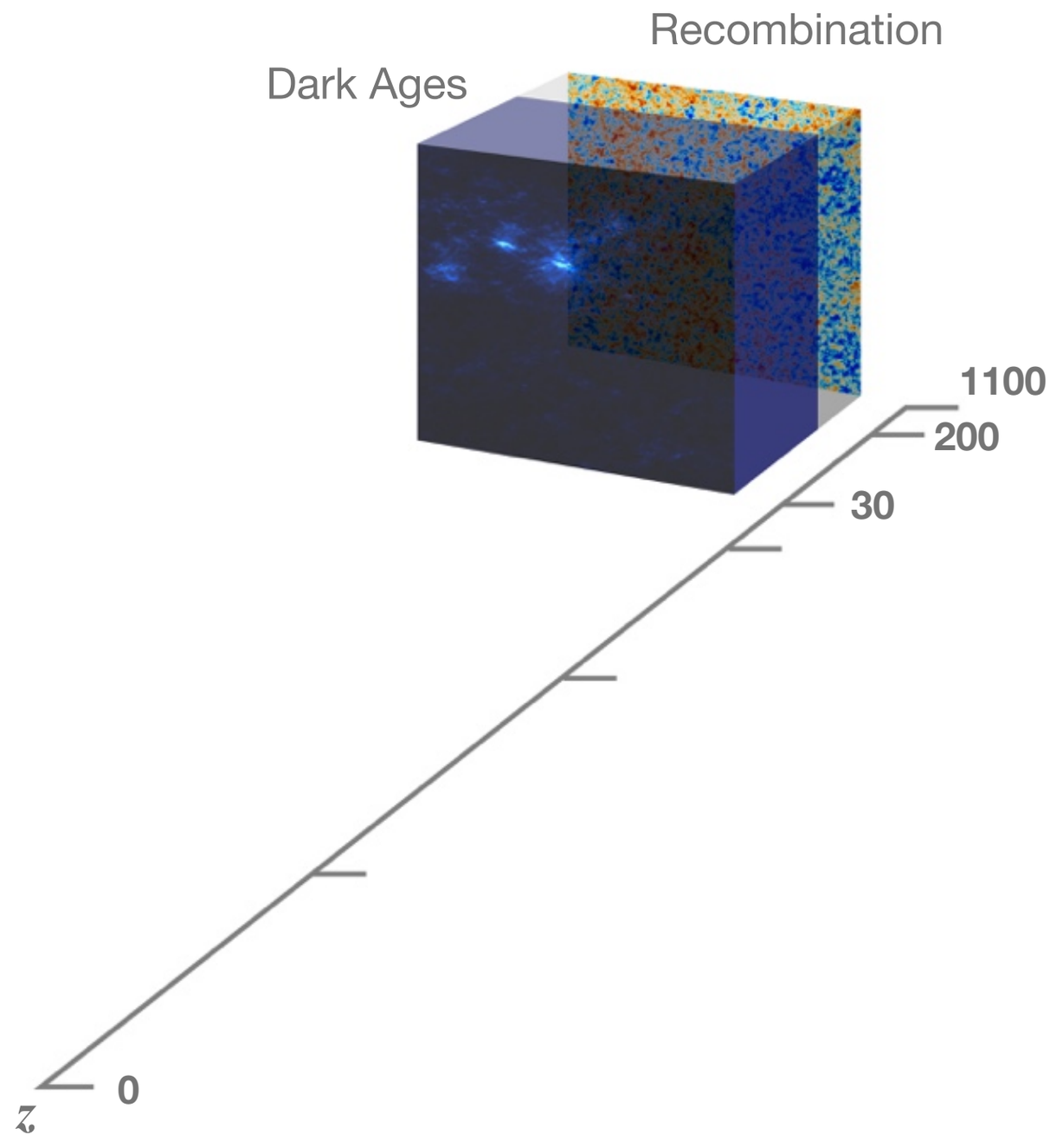

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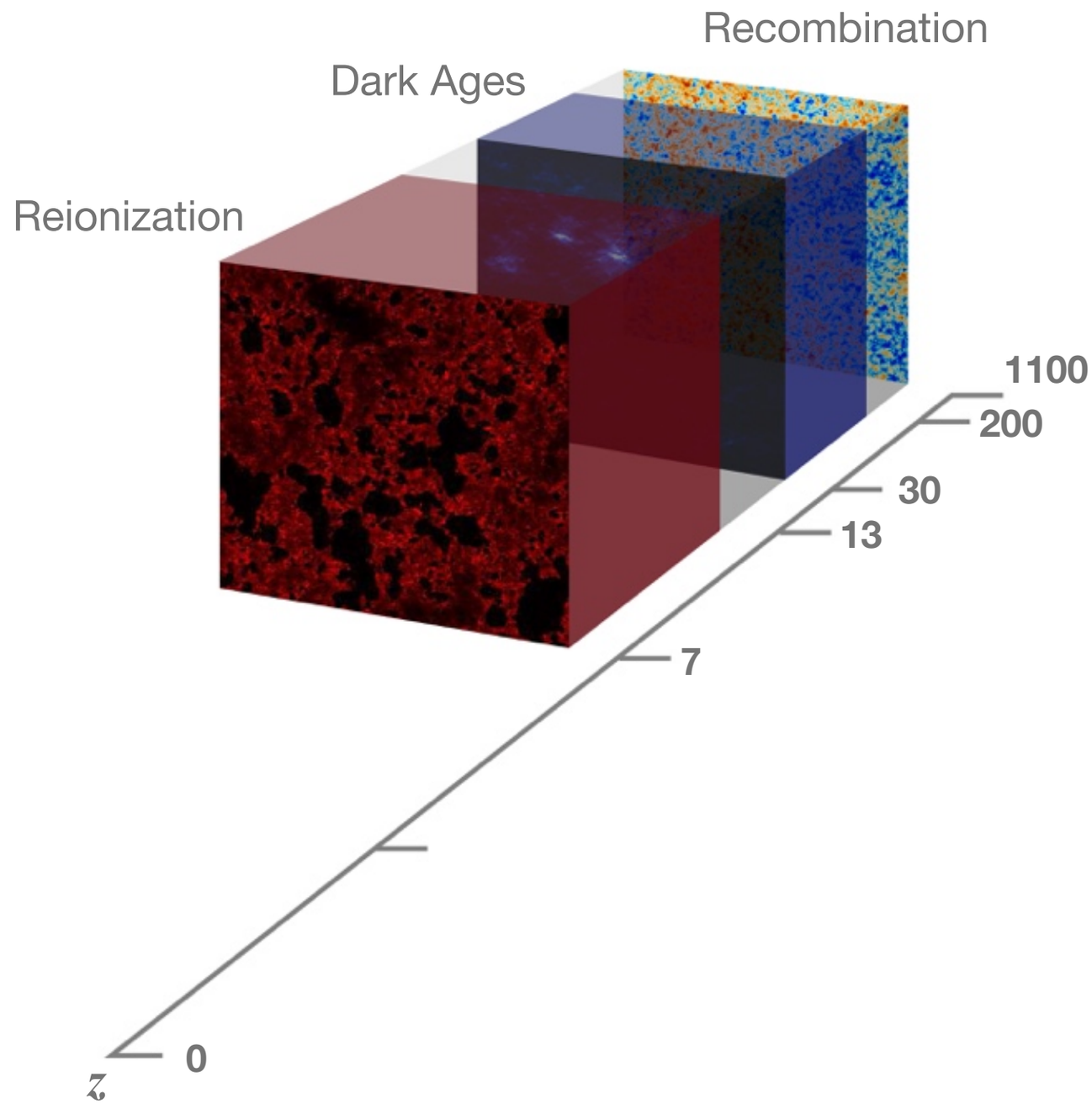

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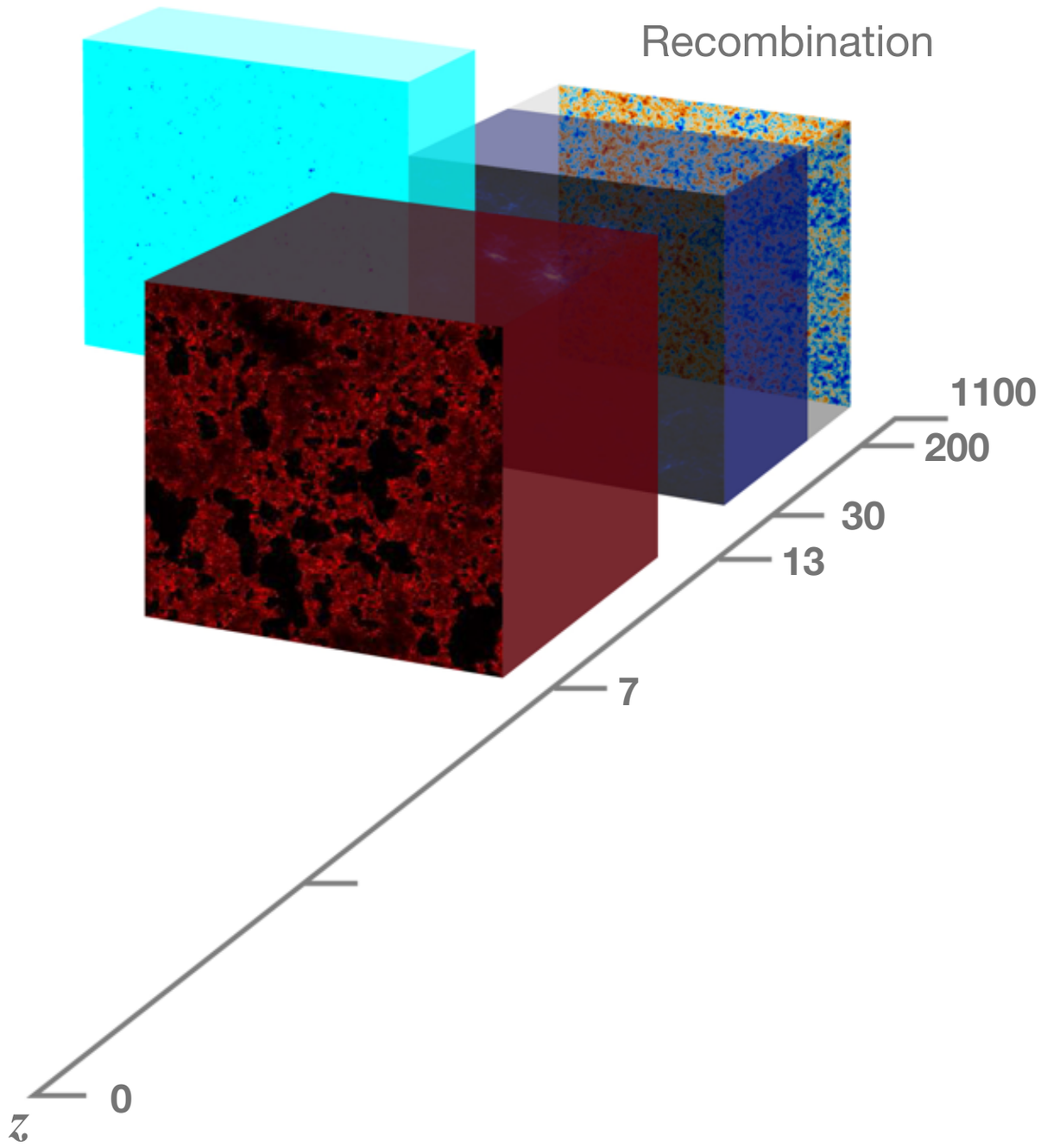

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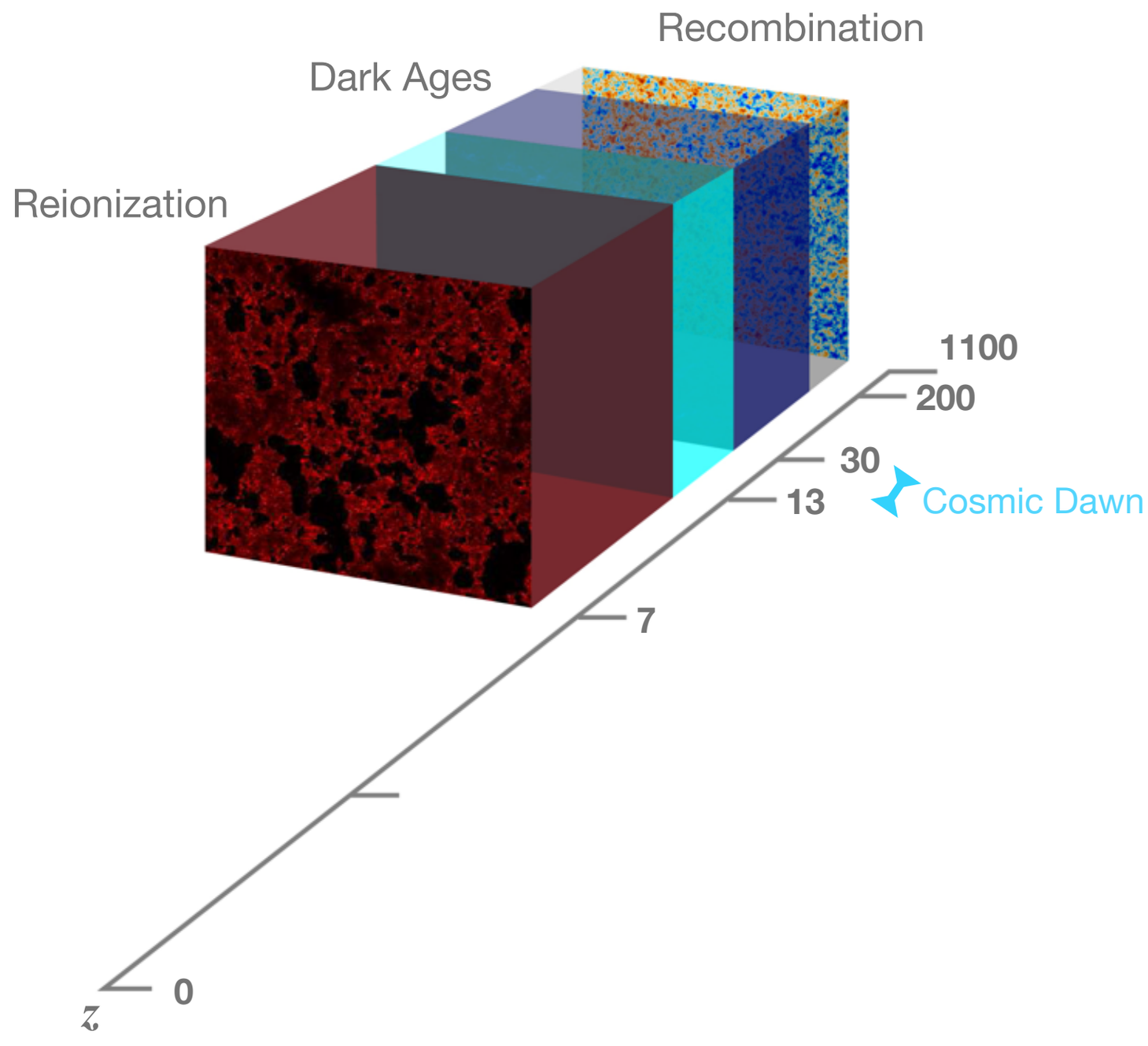

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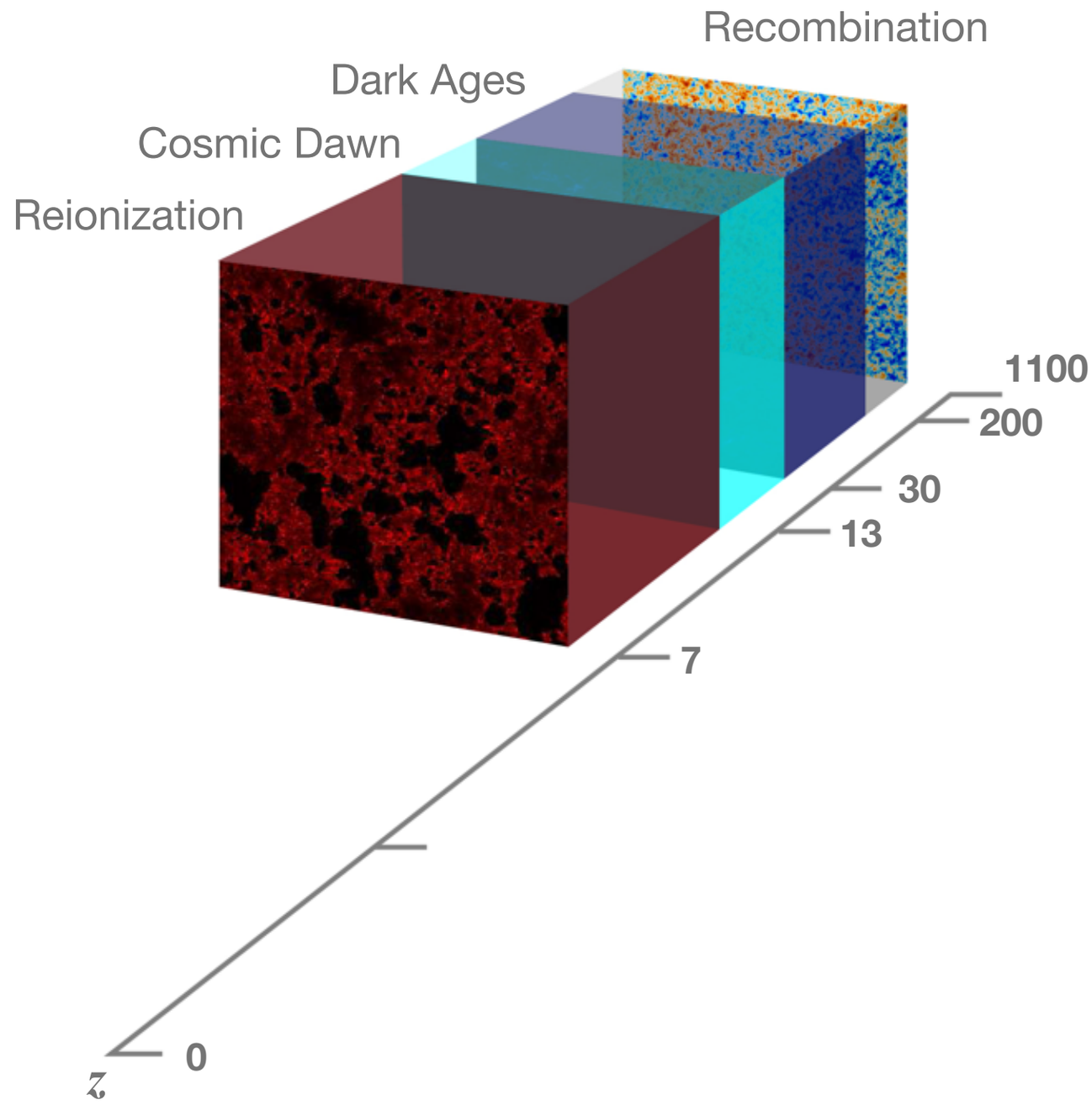

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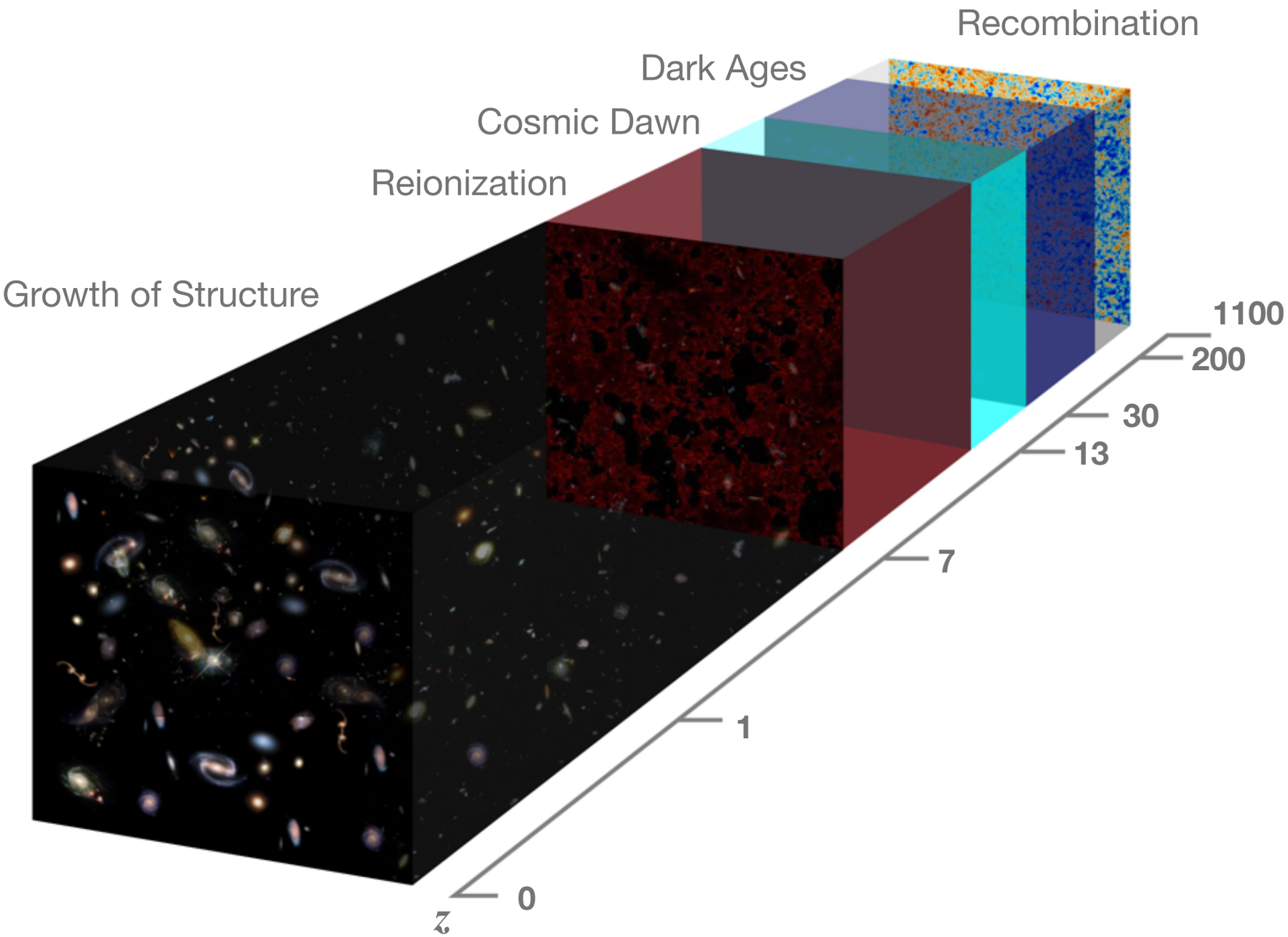

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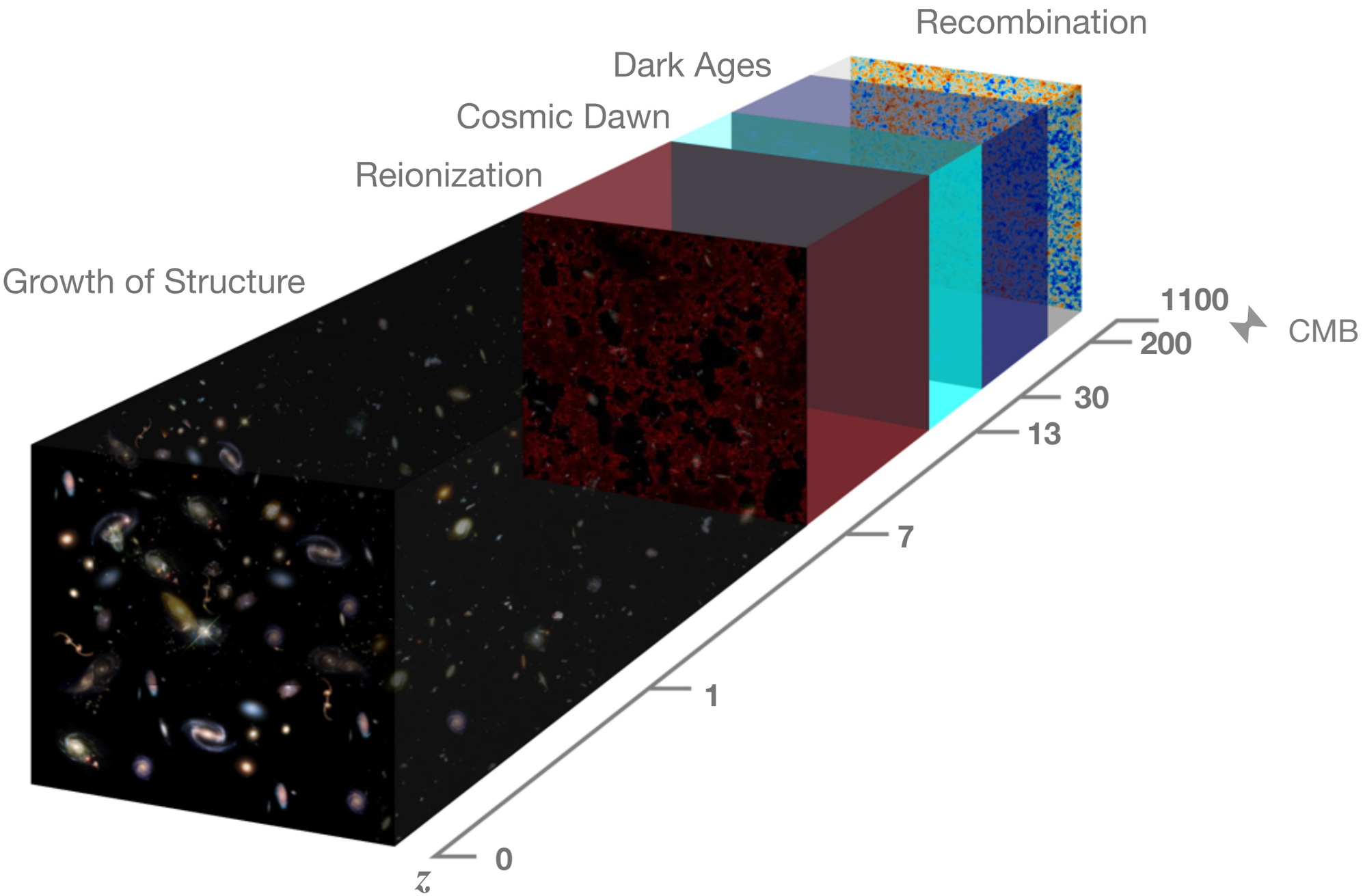

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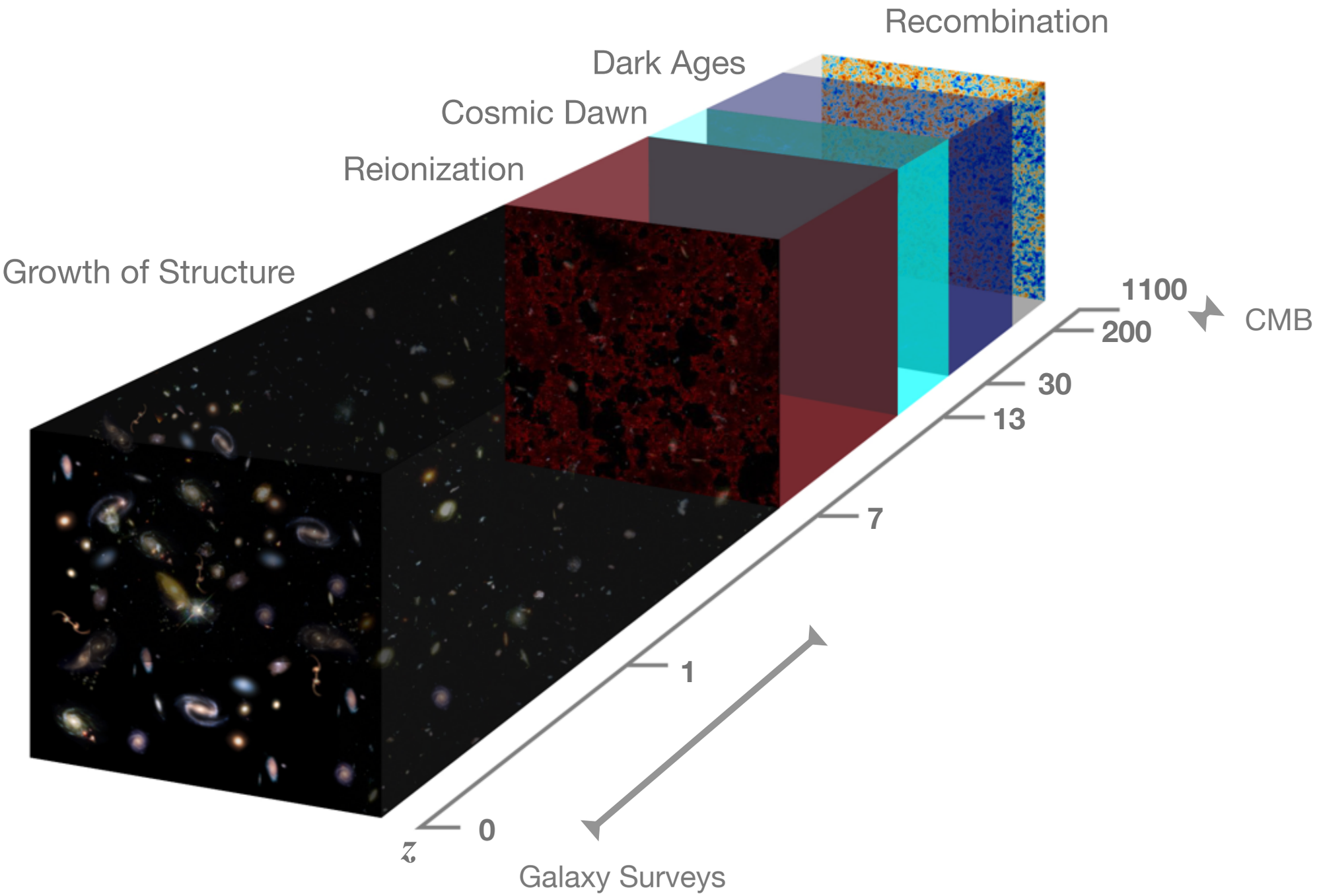

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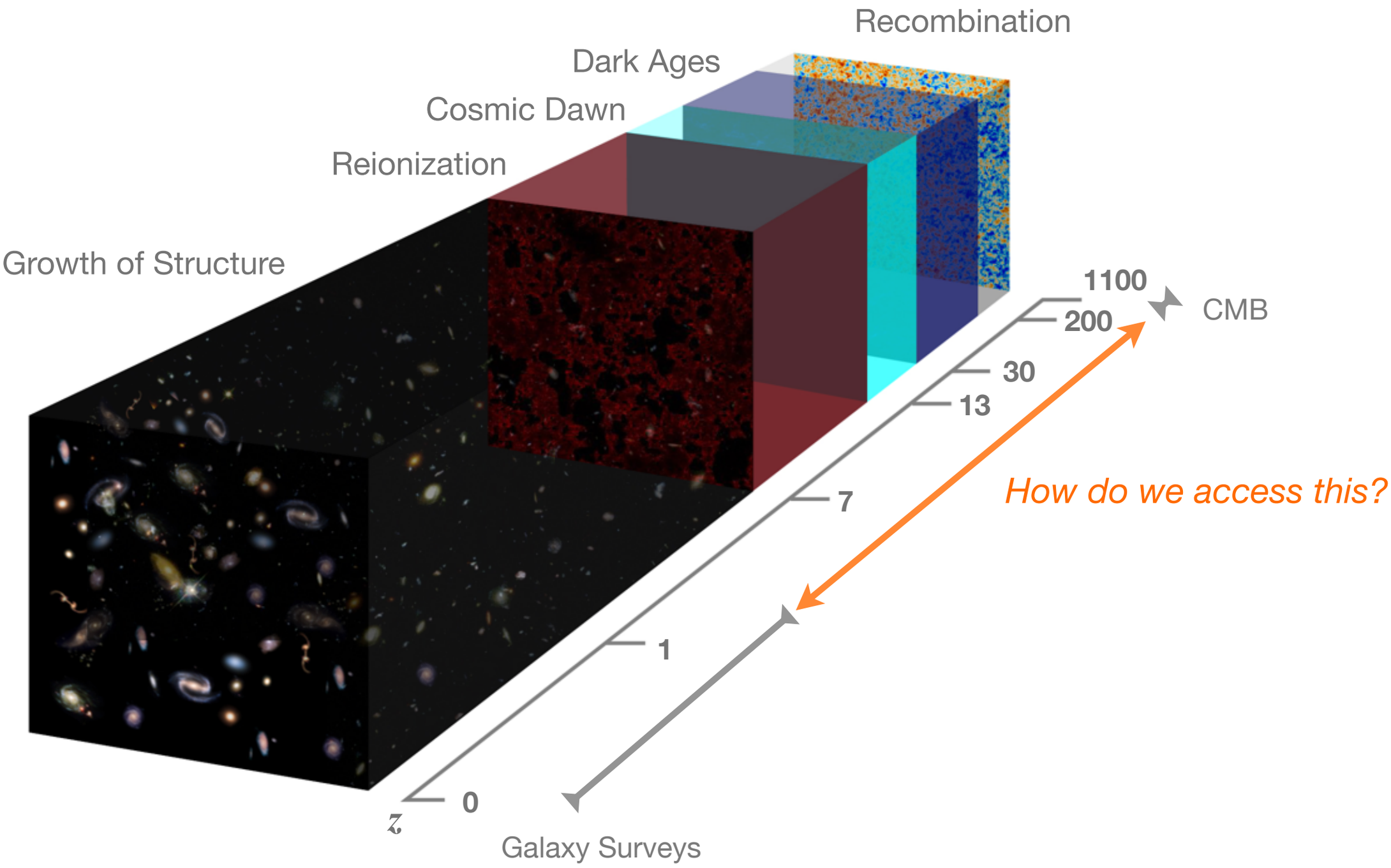

What is Line-Intensity Mapping?

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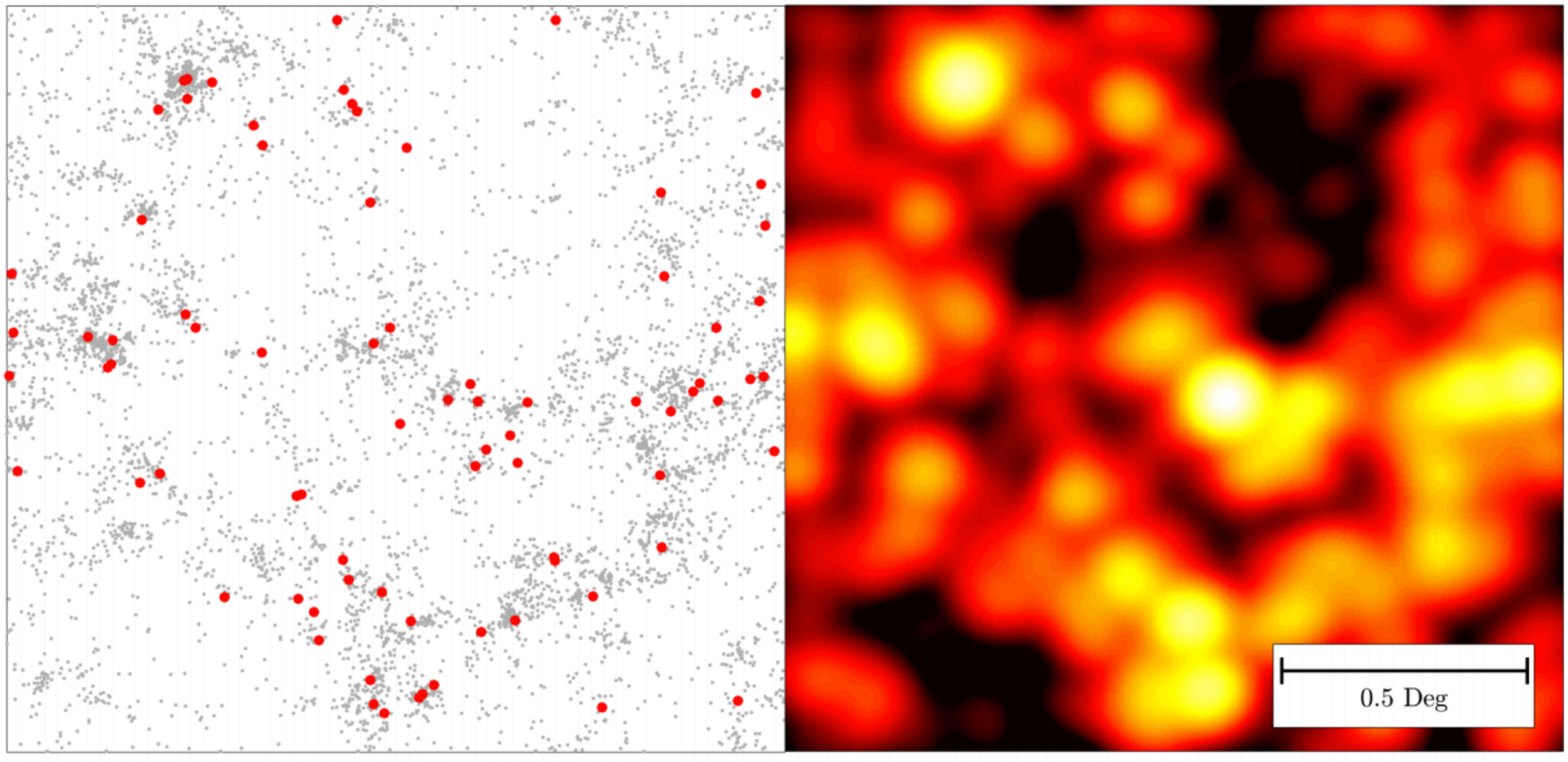
Intensity mapping: 3D mapping of the specific intensity due to line emission.



LIMFAST© Simulation

(Kovetz et al., arXiv:1709.09066)

- Left: in ~4500 hours, VLA can detect ~1% of the total number of CO-emitting galaxies.
- Right: in ~1500 hours, COMAP will map CO intensity fluctuations throughout the field.

The Promise of Line-Intensity Mapping

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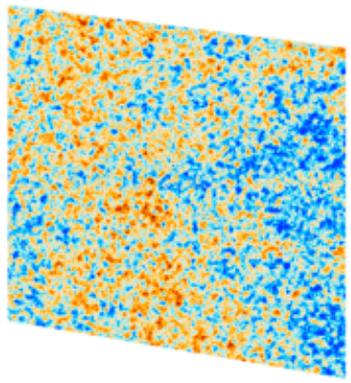
CMB



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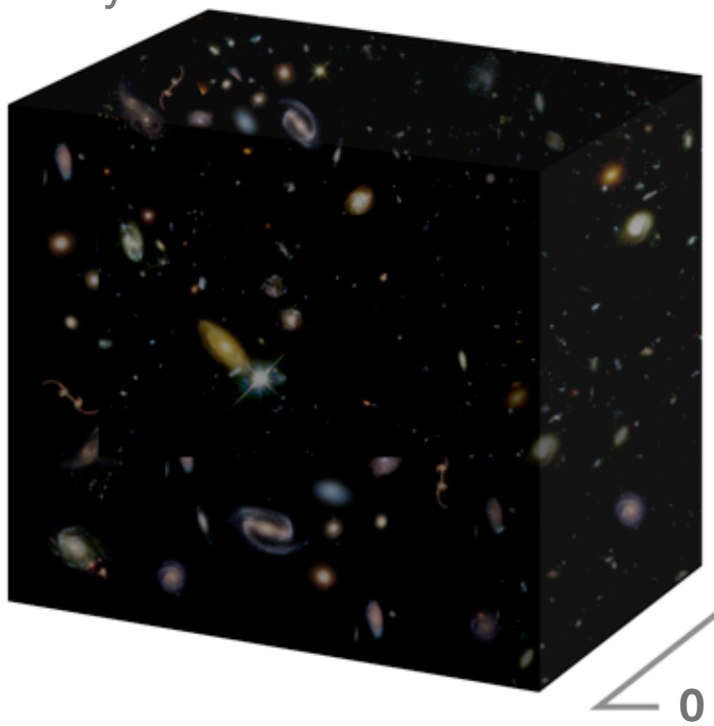
Galaxy Surveys



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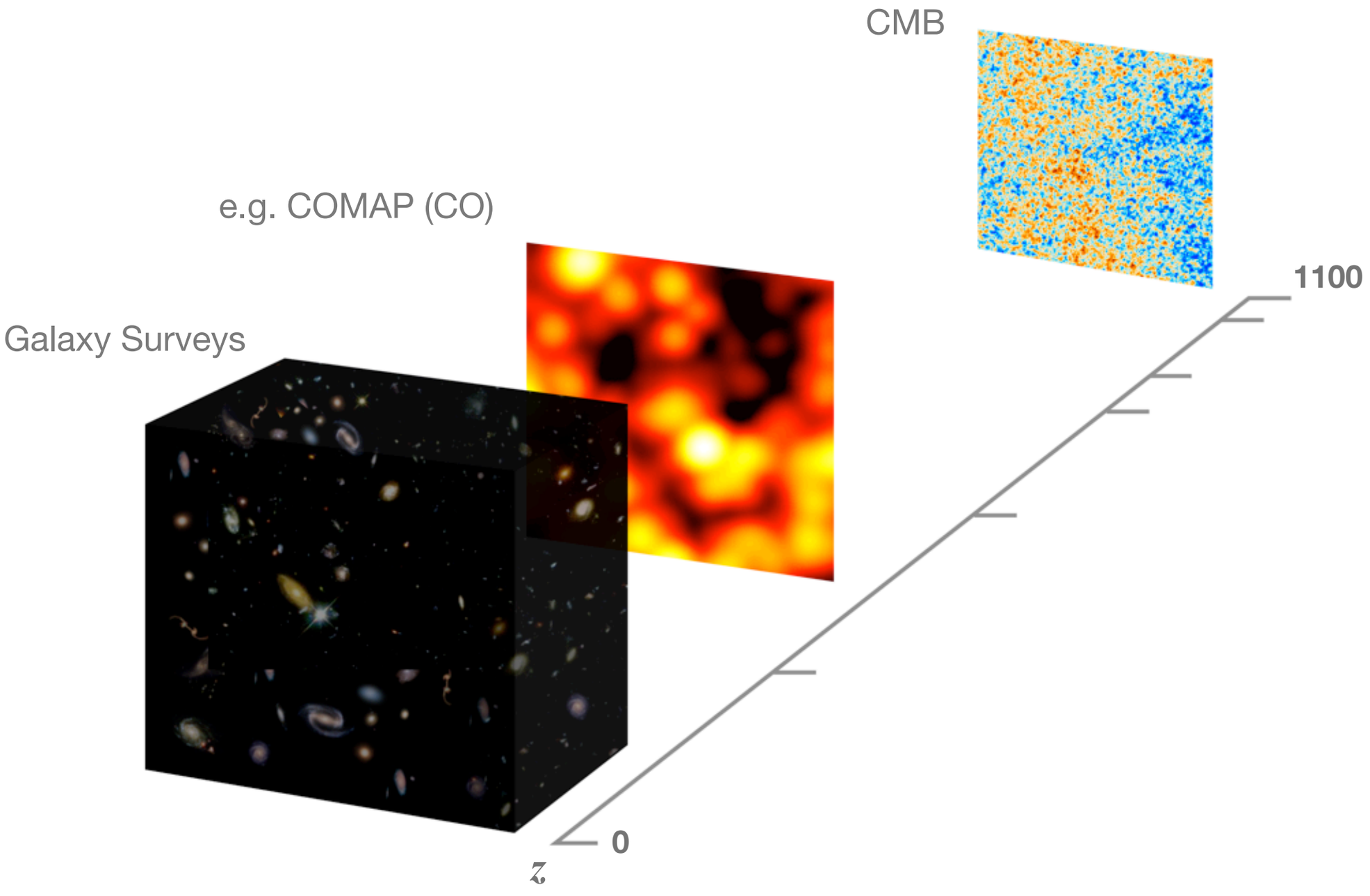

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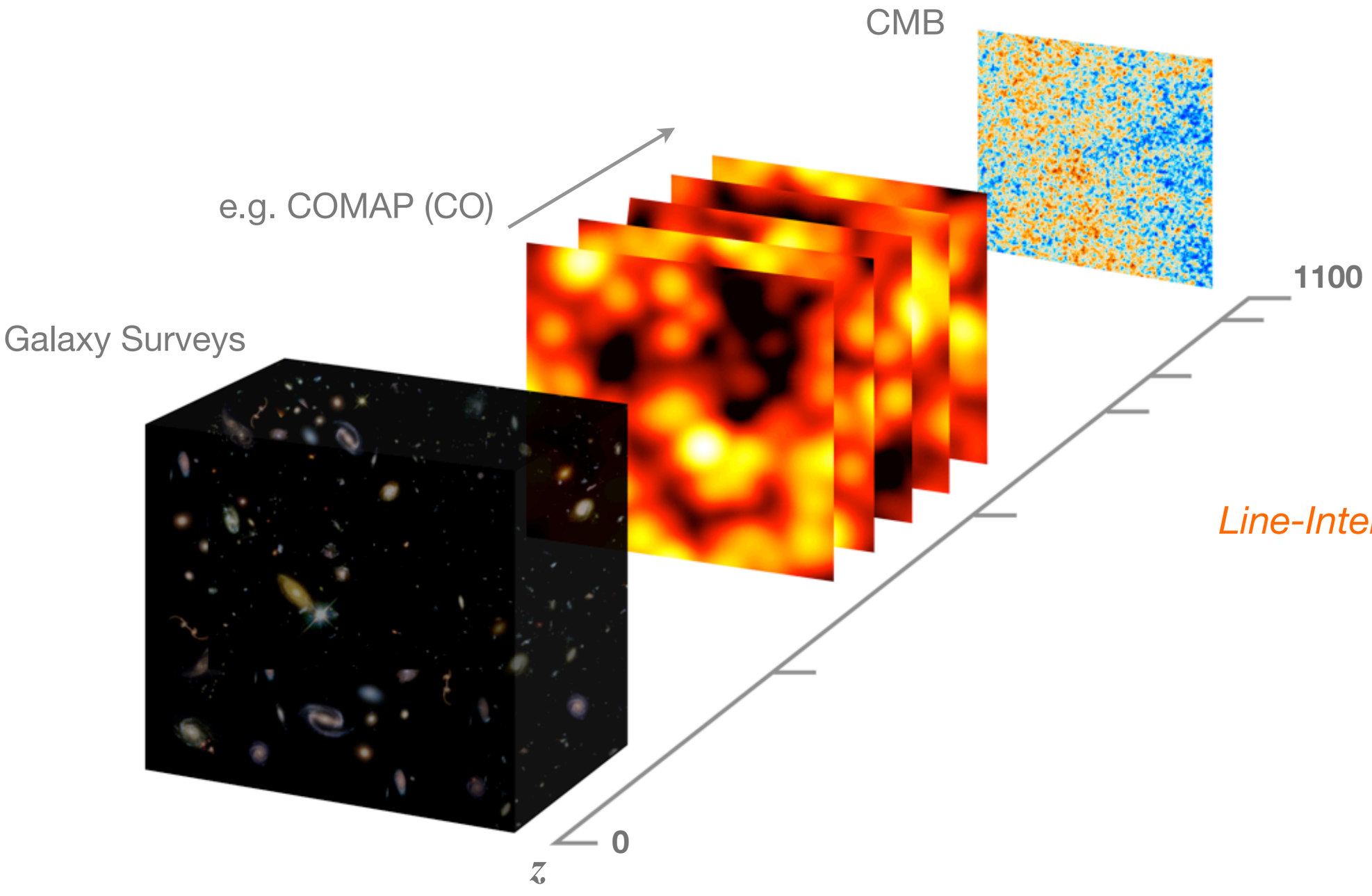

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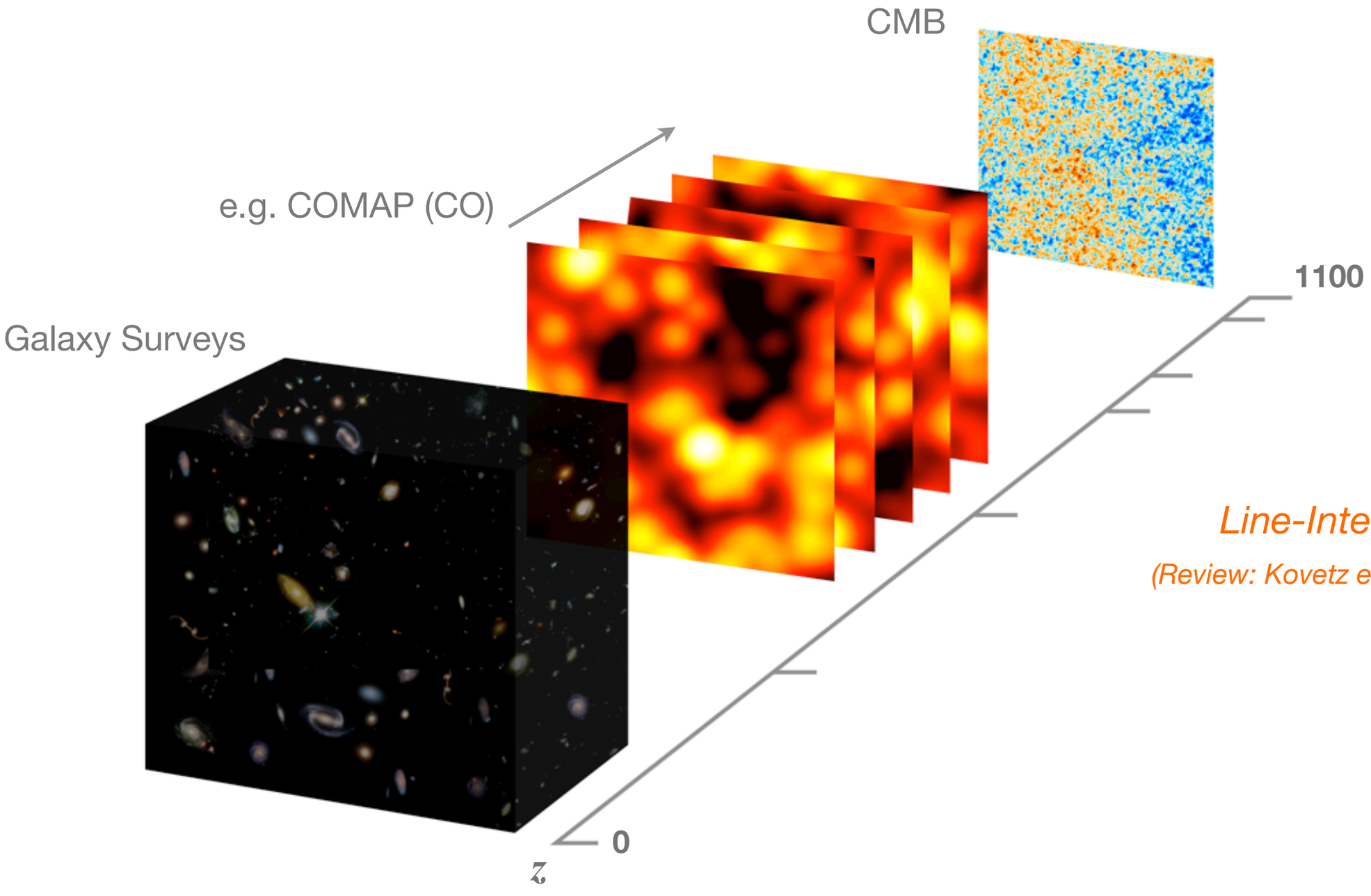

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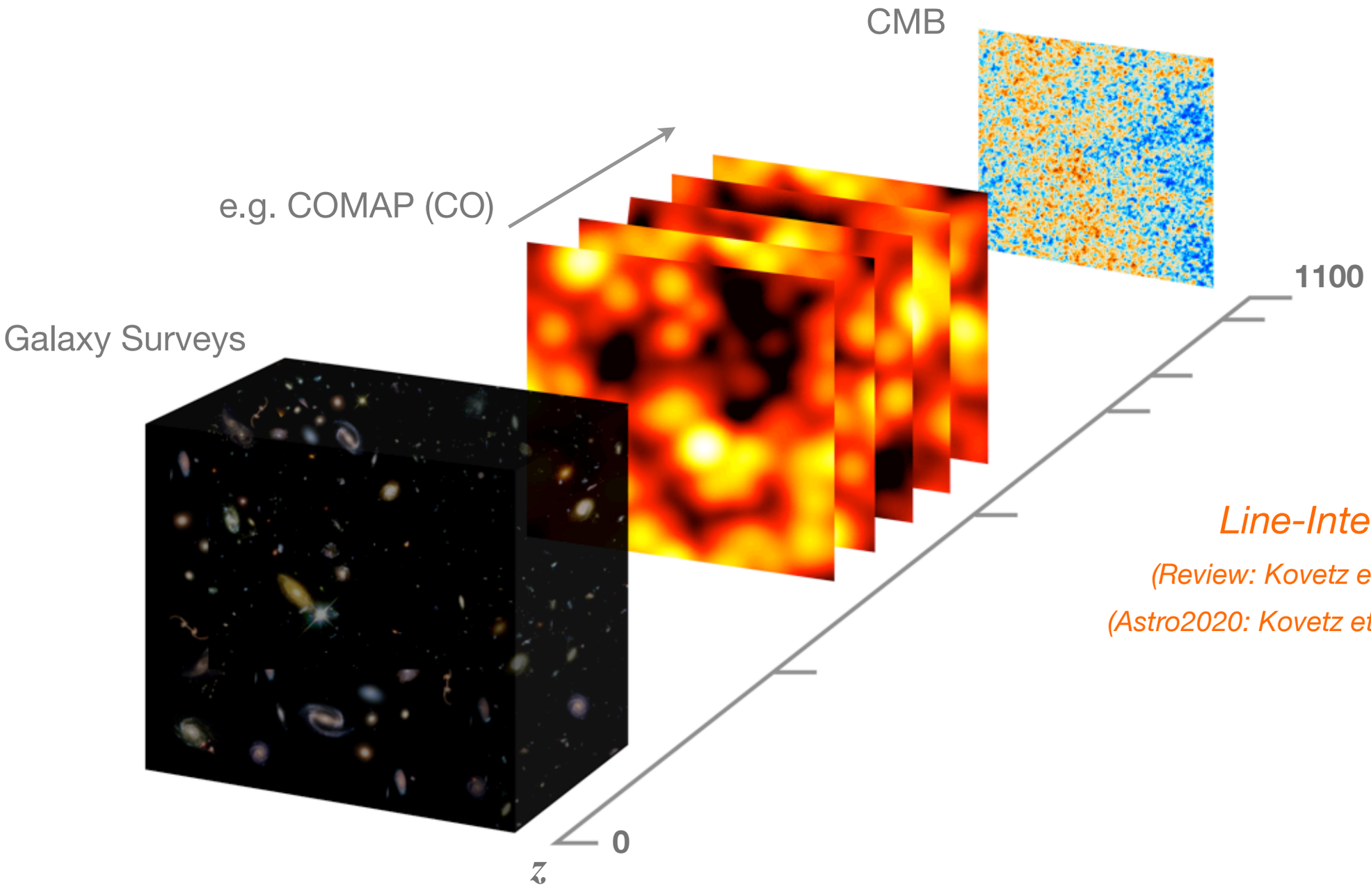

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(Astro2020: Kovetz et al., arXiv:1903.04496)

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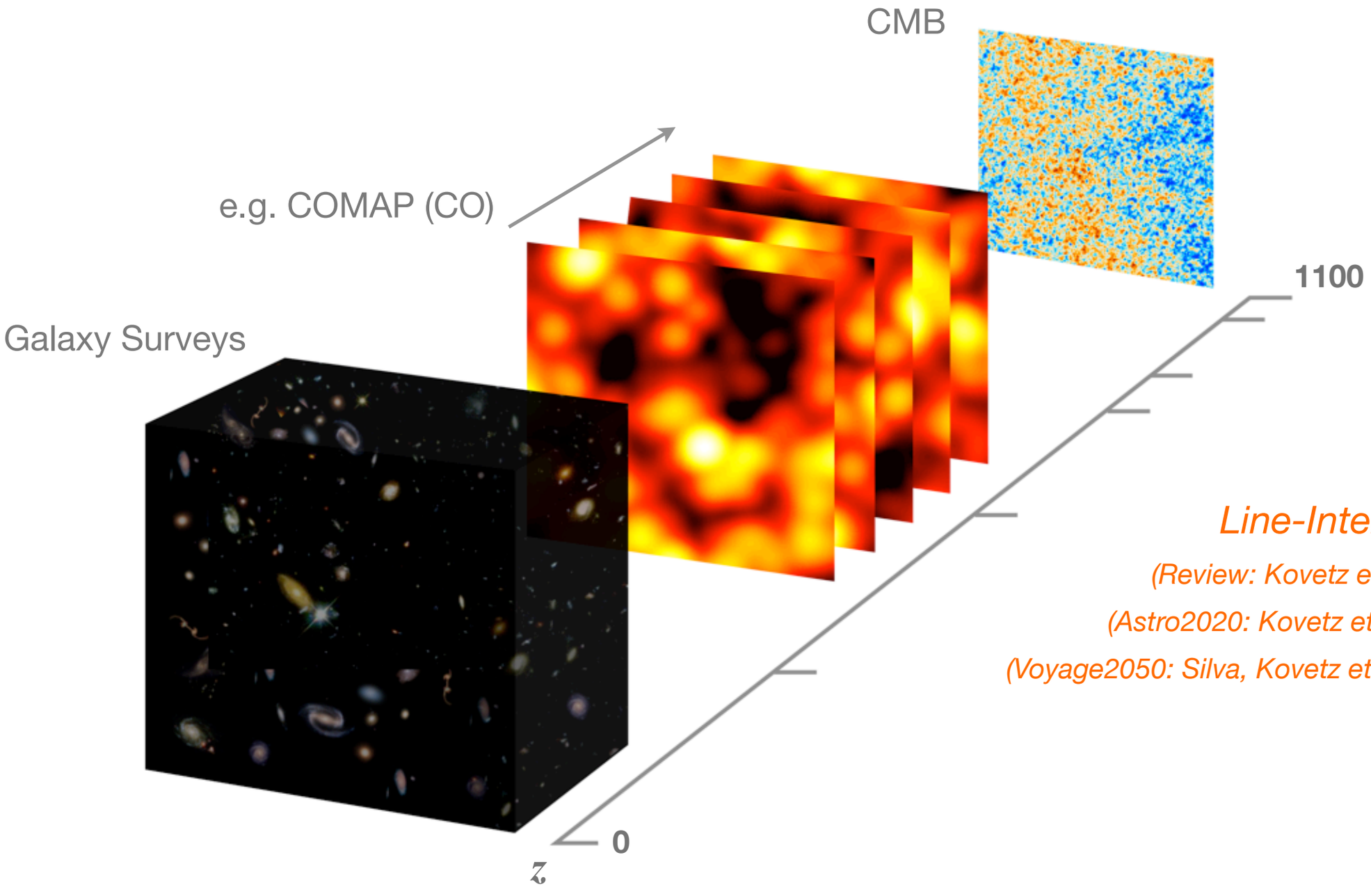

Line-Intensity Mapping!

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

(Voyage2050: Silva, Kovetz et al., arXiv:1908.07533)

The Reach of Line-Intensity Mapping

Different epochs can be probed with multiple lines at different frequencies.

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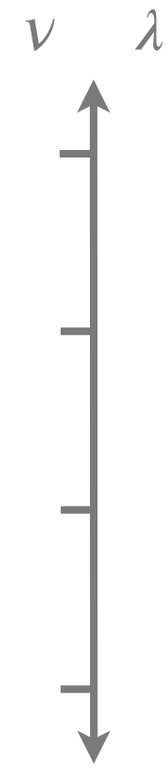

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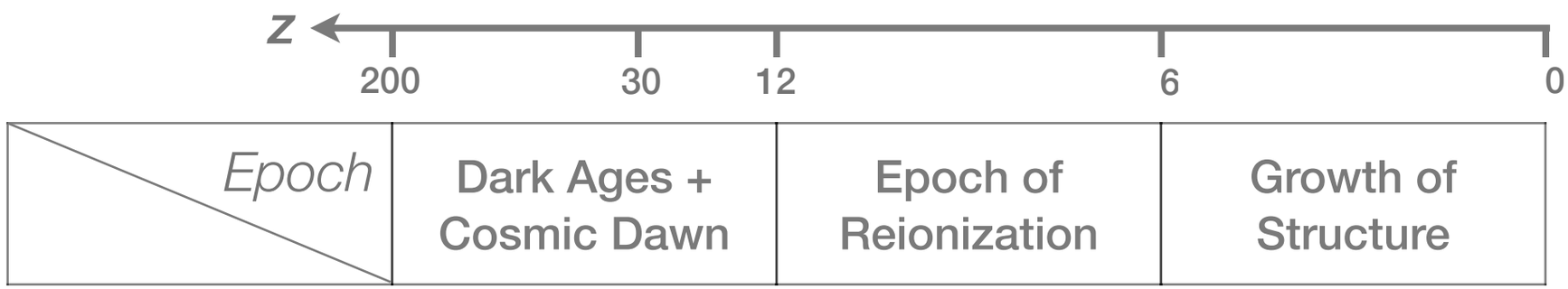

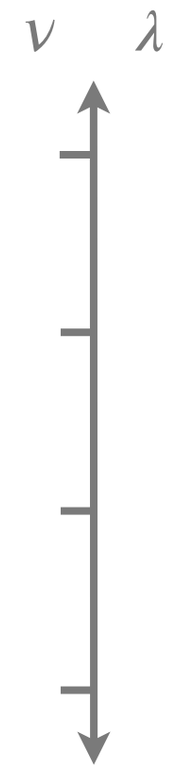

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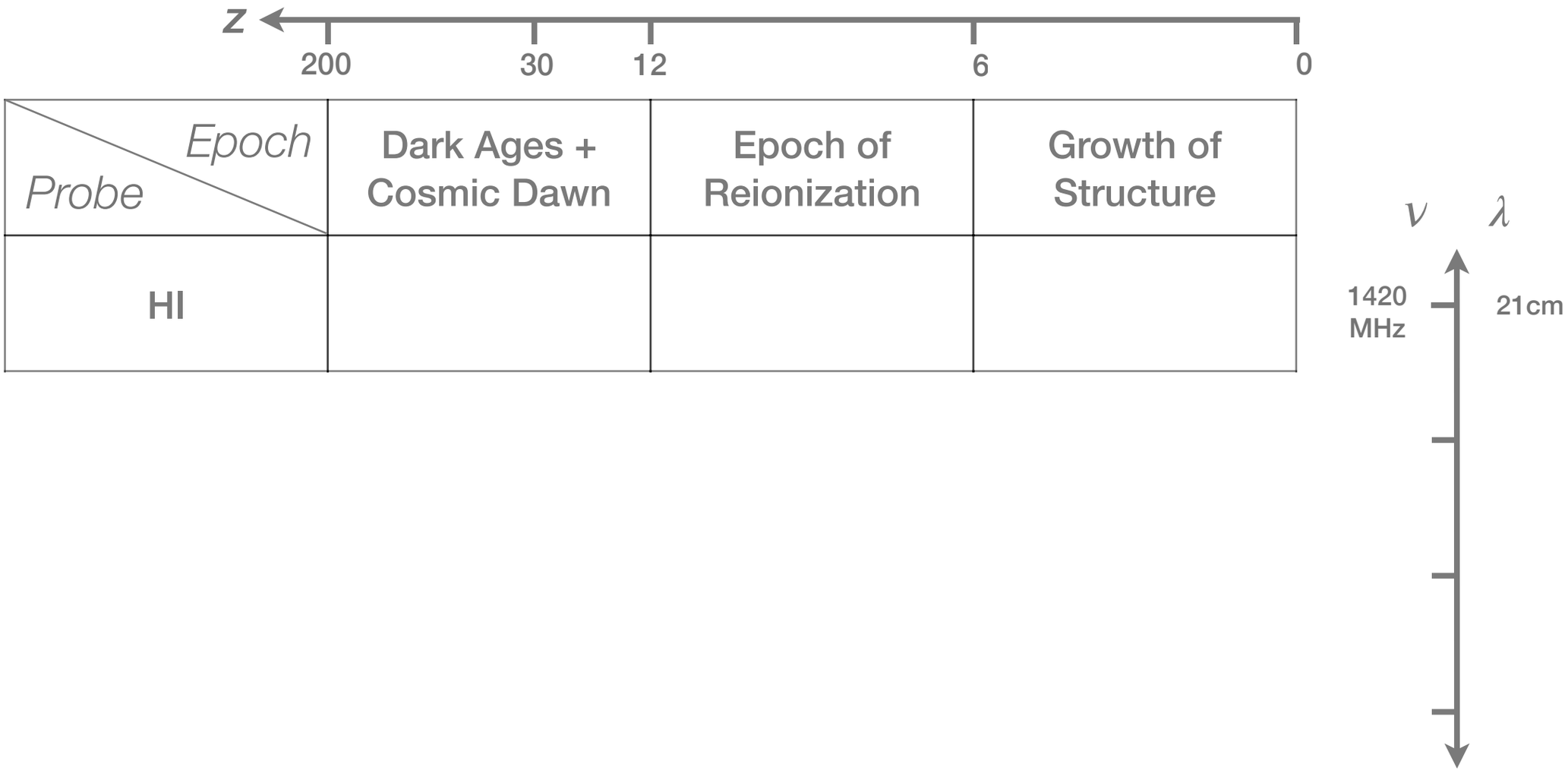

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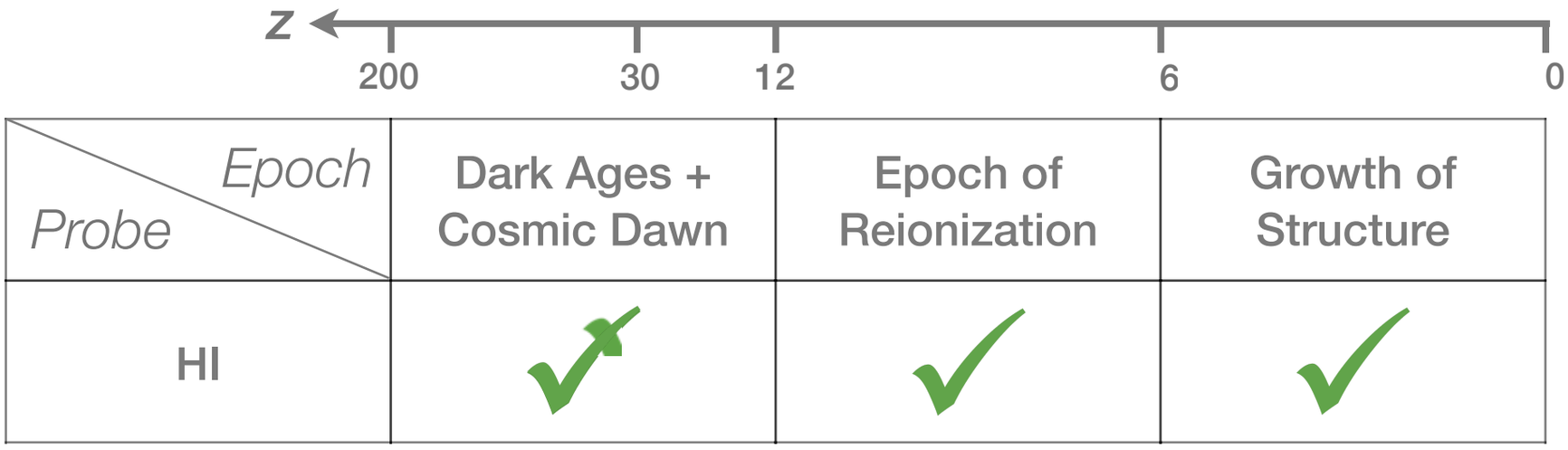
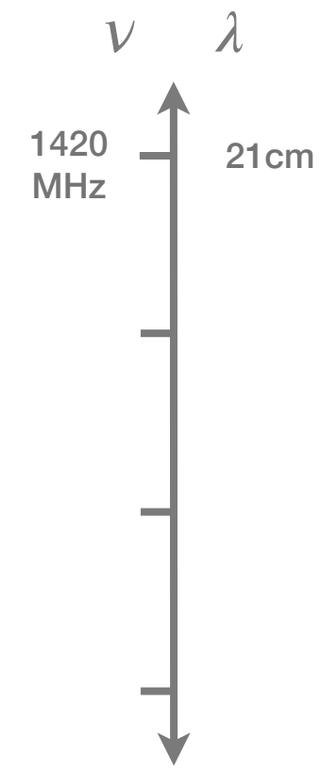


Probe \ Epoch	Dark Ages + Cosmic Dawn	Epoch of Reionization	Growth of Structure
HI	✓	✓	✓



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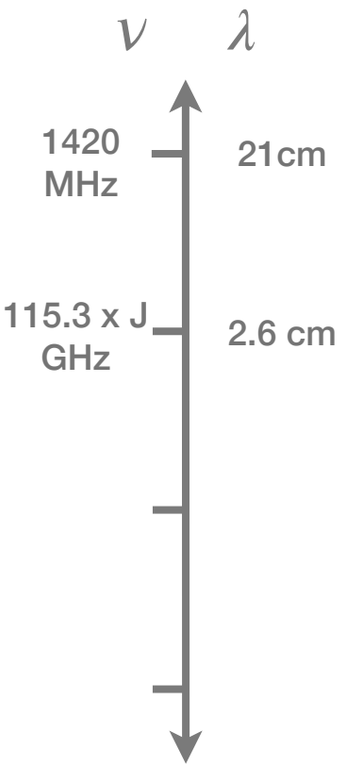
HI	✓	✓	✓
CO			



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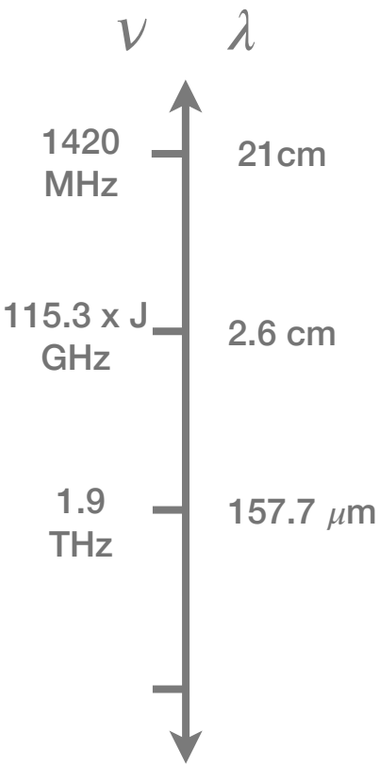
HI	✓	✓	✓
CO		✓	✓
[CII]			



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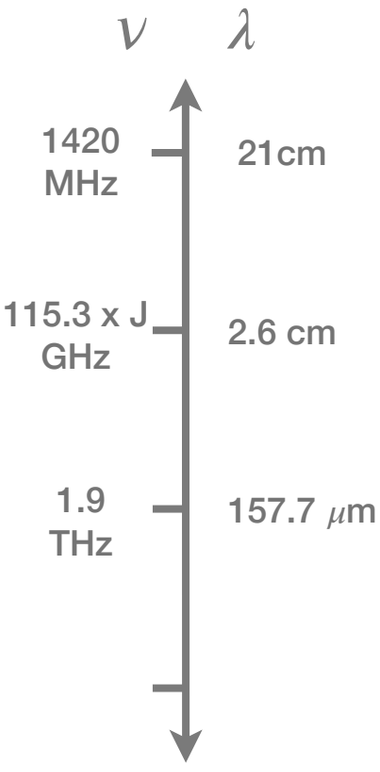
CO		✓	✓
[CII]		✓	✓



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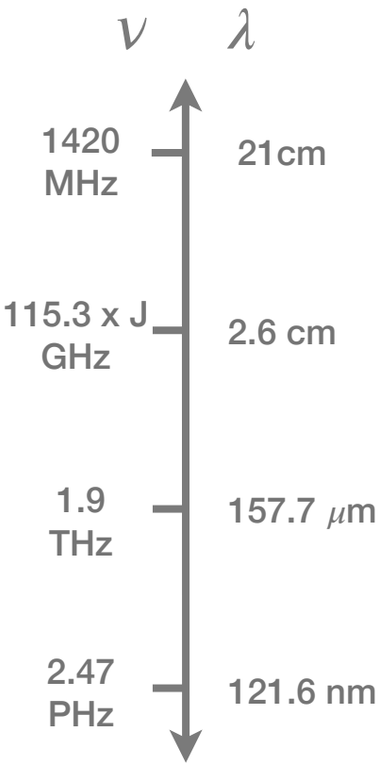
CO		✓	✓
[CII]		✓	✓
Lyα			



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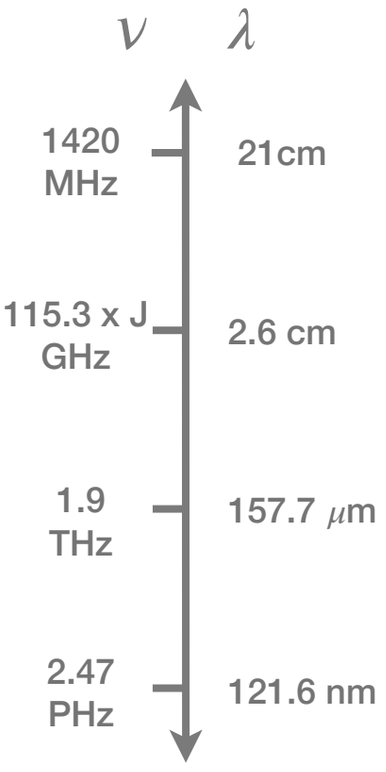
CO		✓	✓
[CII]		✓	✓
Lyα		✓	✓



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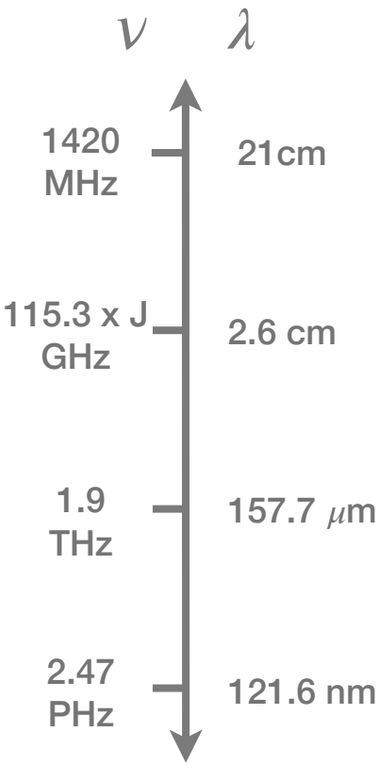
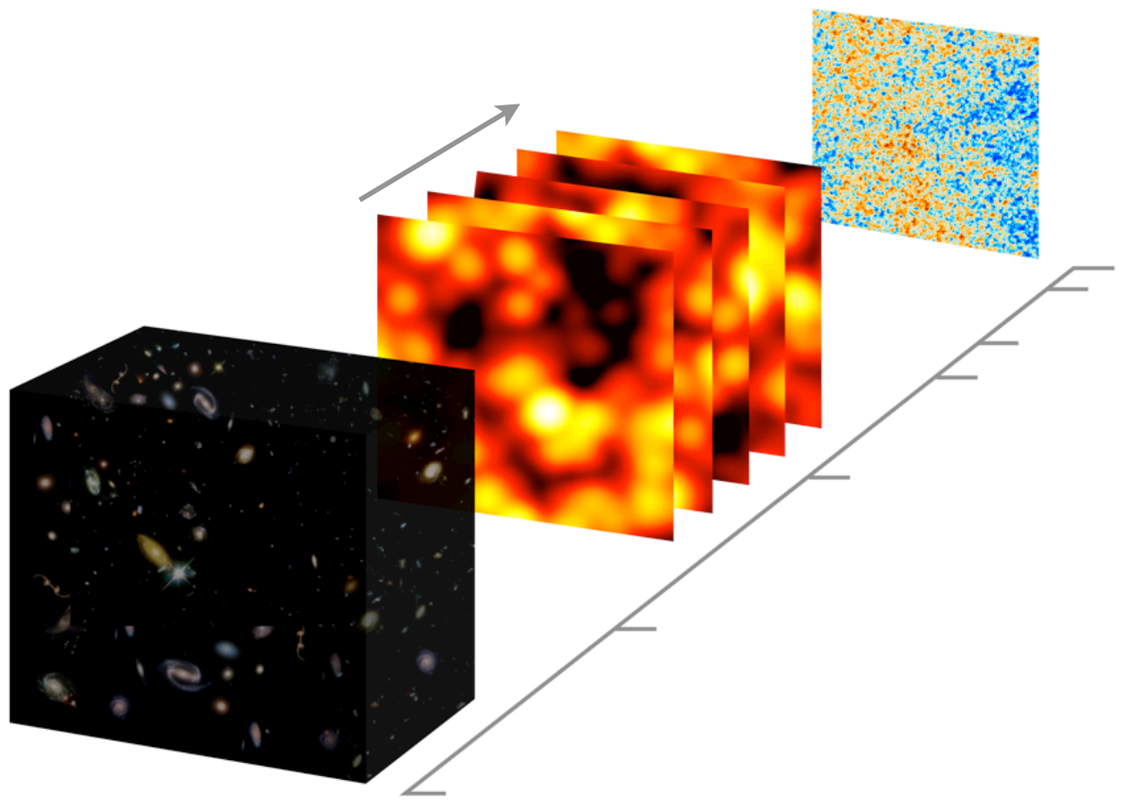
HI	✓	✓	✓
CO		✓	✓
[CII]		✓	✓
Lyα		✓	✓
Hα ⋮			



Science Goals of Line-Intensity Mapping

Tests of ΛCDM Cosmology (and beyond):



Science Goals of Line-Intensity Mapping

Tests of ΛCDM Cosmology (and beyond):

- Baryon acoustic oscillations (up to high redshift)
- Optical depth to reionization (improve CMB estimate)
- Neutrino masses (in synergy with galaxies, CMB)
- Inflation (running, primordial non-gaussianity, power spectrum oscillations)
- Dark energy (constrain equation of state)
- Dark matter (decaying, annihilating, interacting)
- Modified Gravity (Chameleon, Hordenski)

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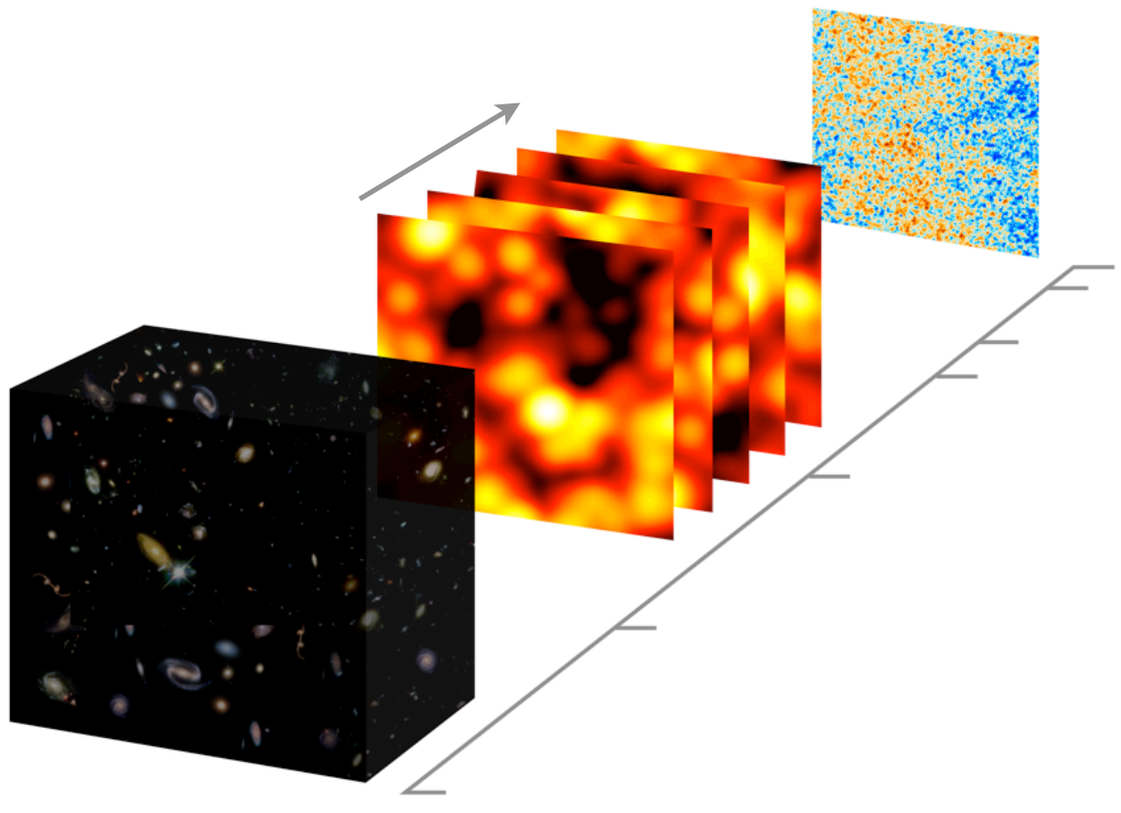

Line-Intensity Mapping: Experimental Landscape

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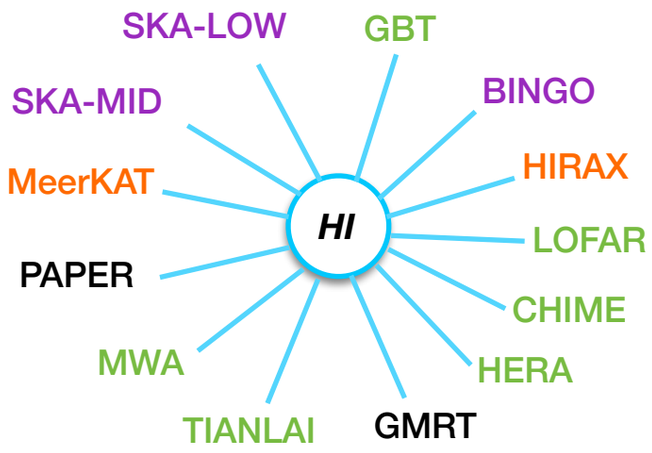

(Astro2020: Kovetz et al. arXiv:1903.04496)

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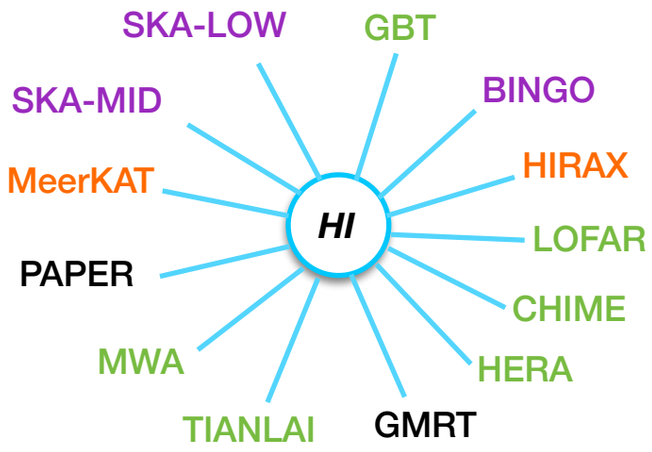

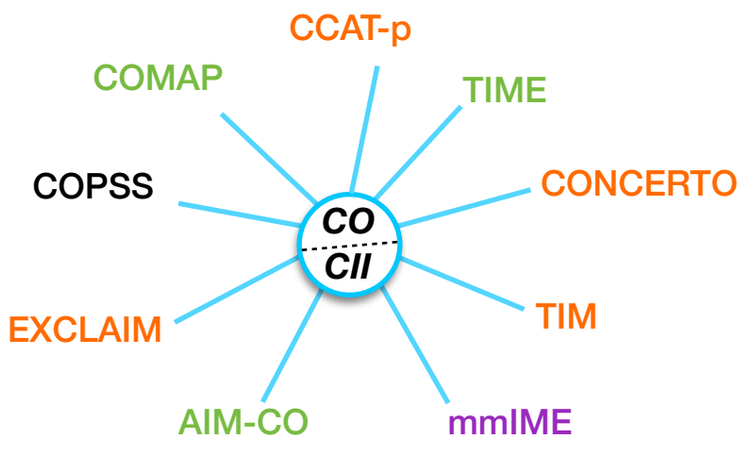

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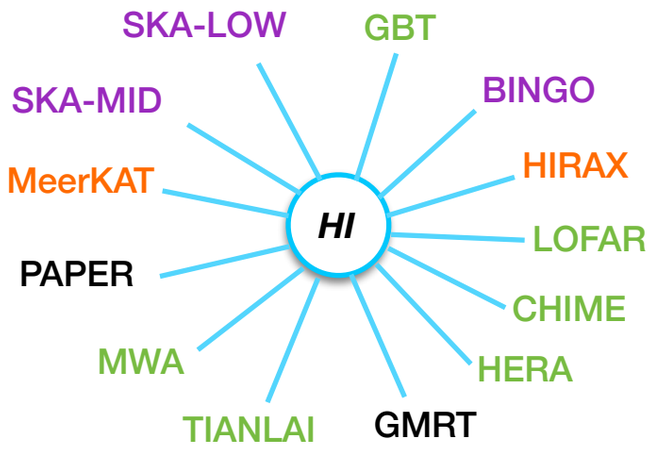
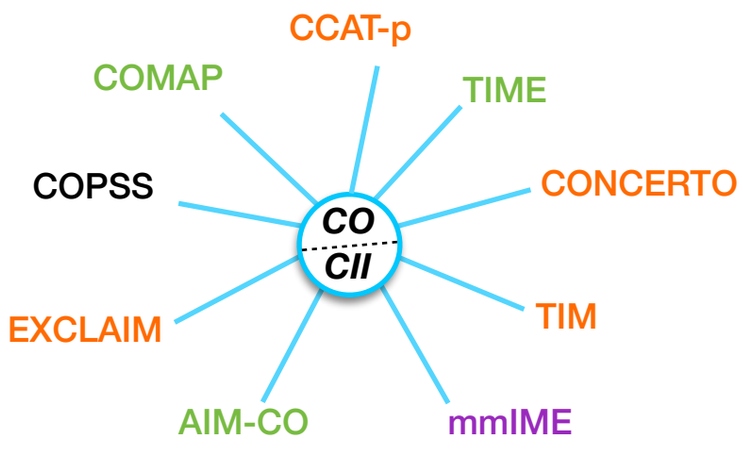
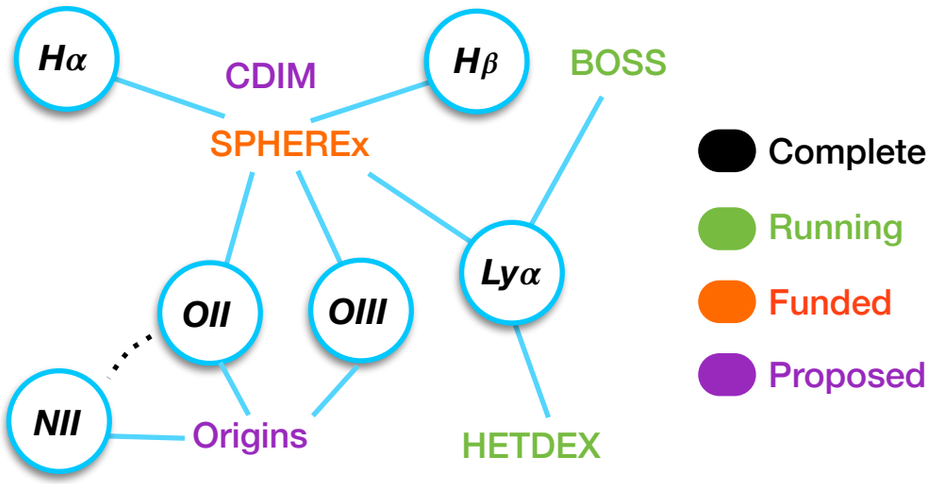
Line-Intensity Mapping: Experimental Landscape







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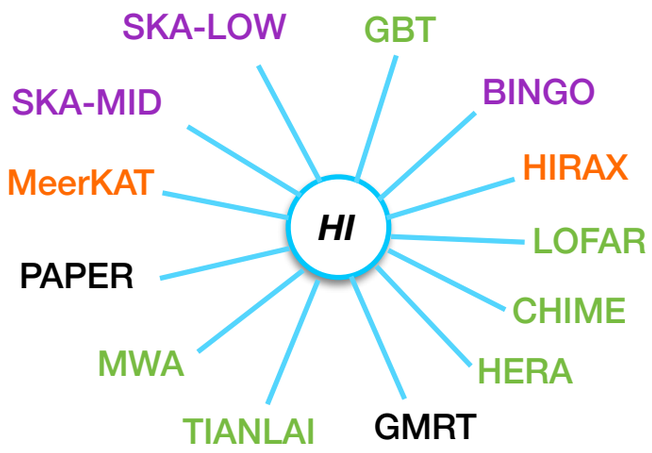

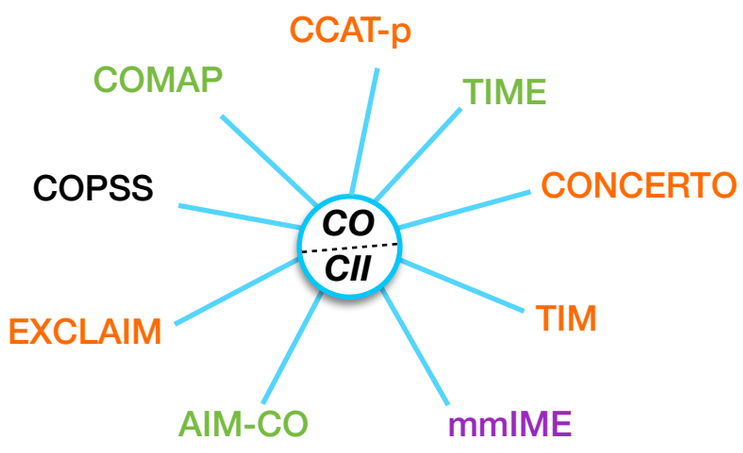

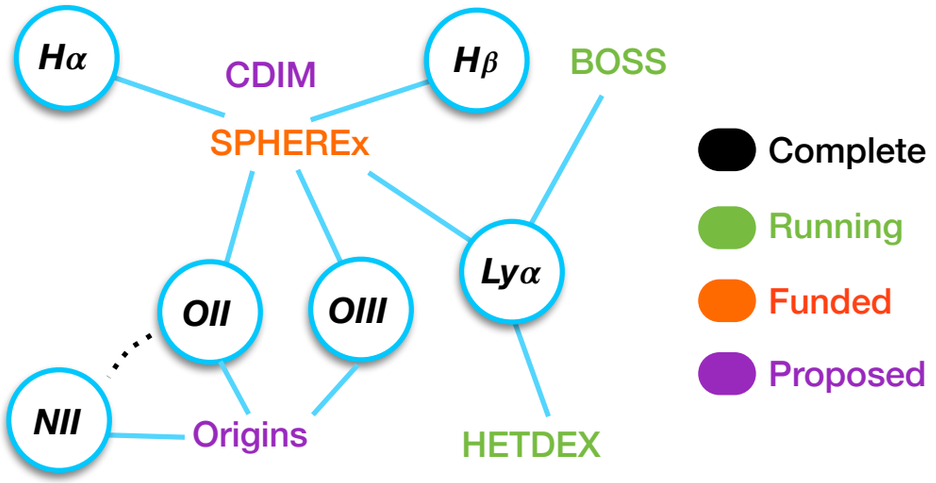

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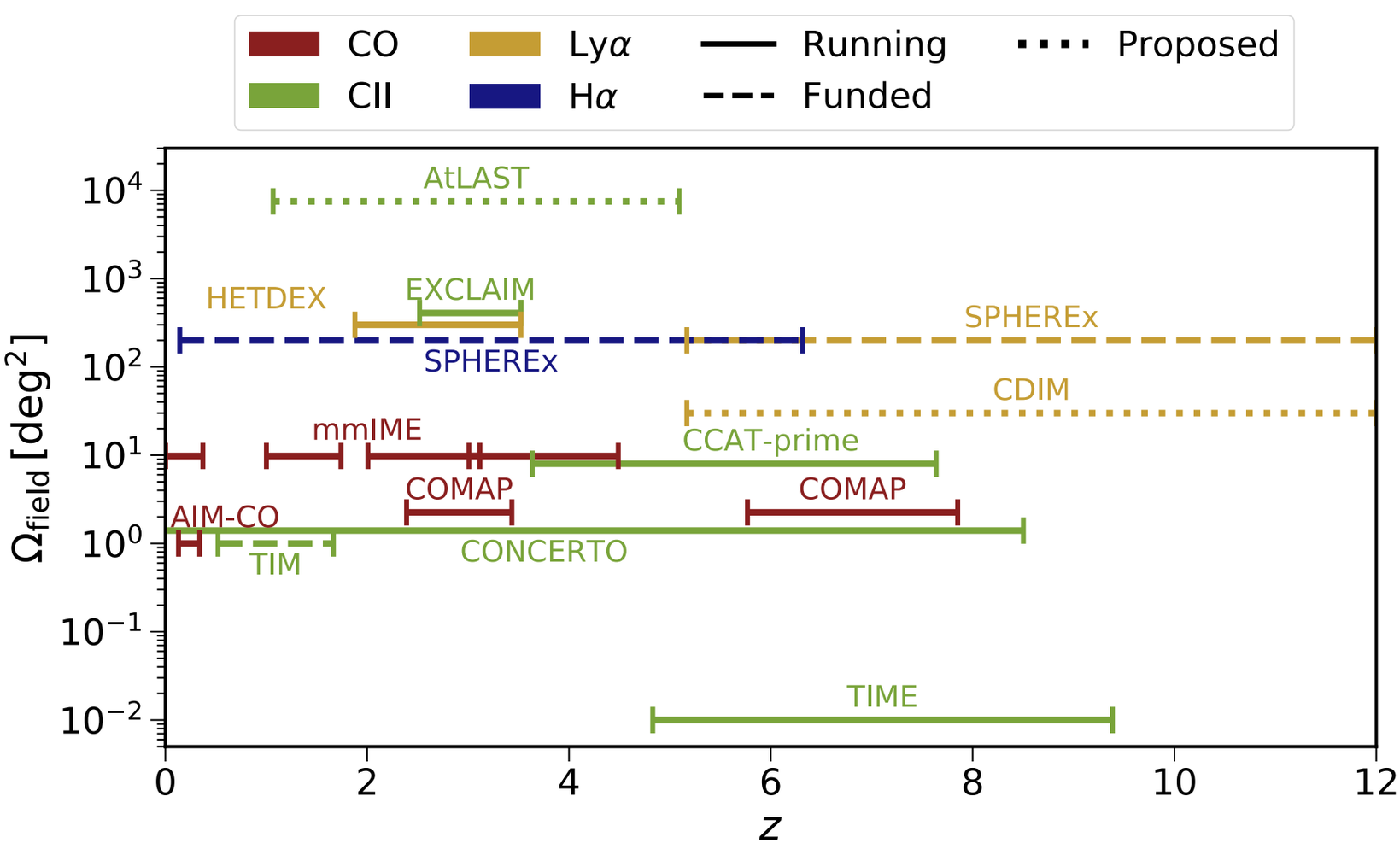
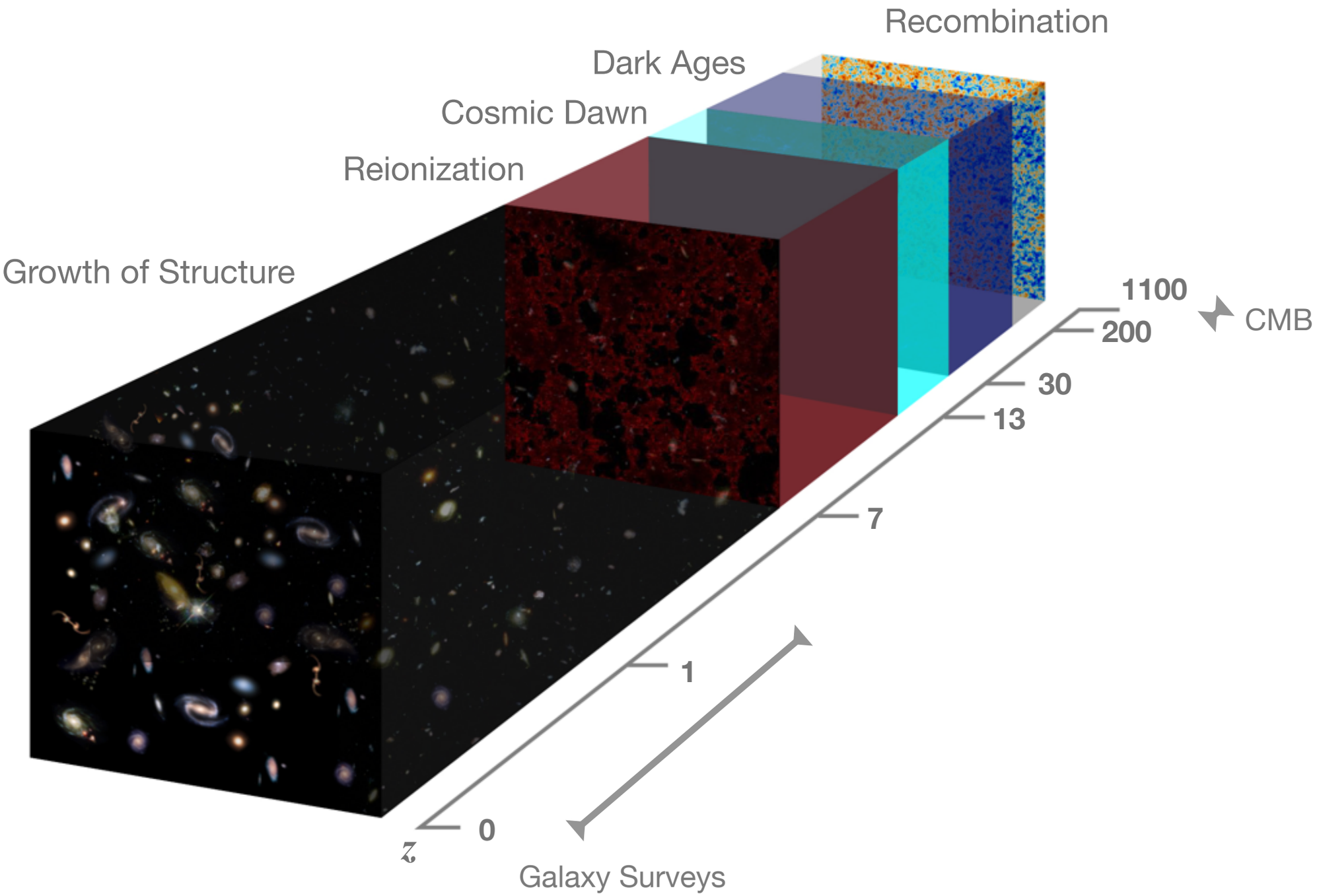


(Kovetz & Bernal, 2021:XXXXX)

The Observable Universe: A Multi-Layer Detector!



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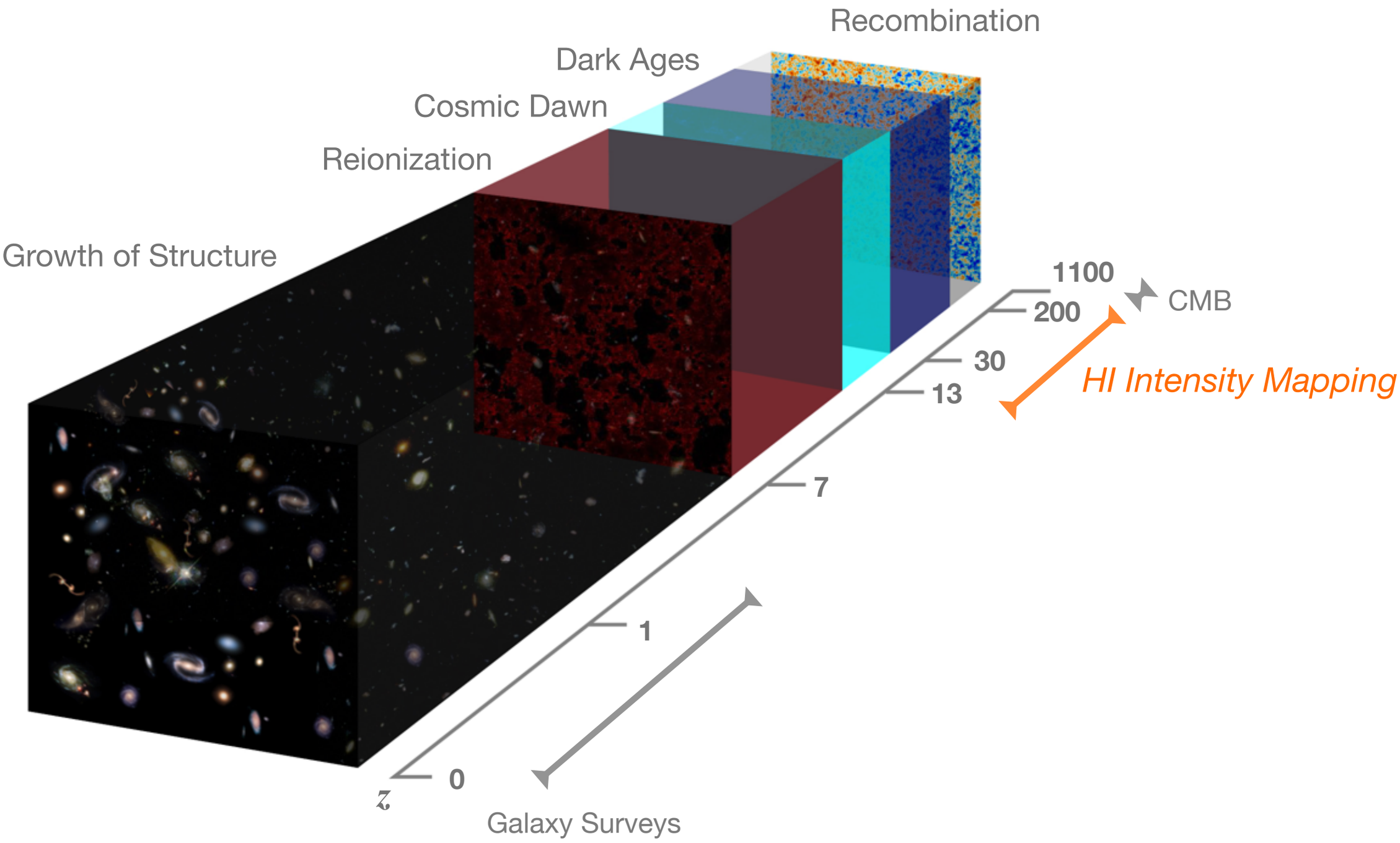

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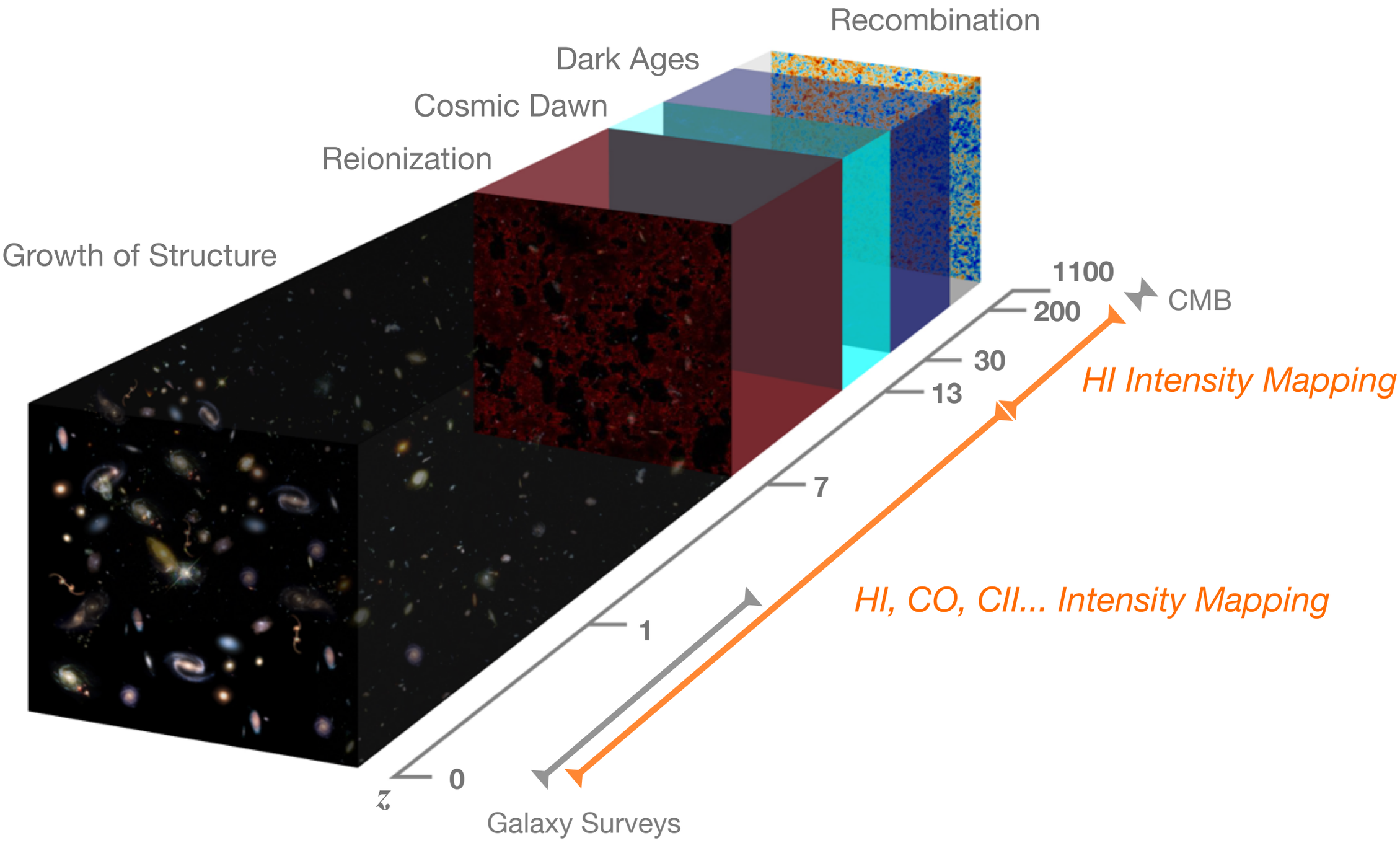

Case Study 1: The EDGES 21cm detection

1

What is the nature of ***dark matter***?

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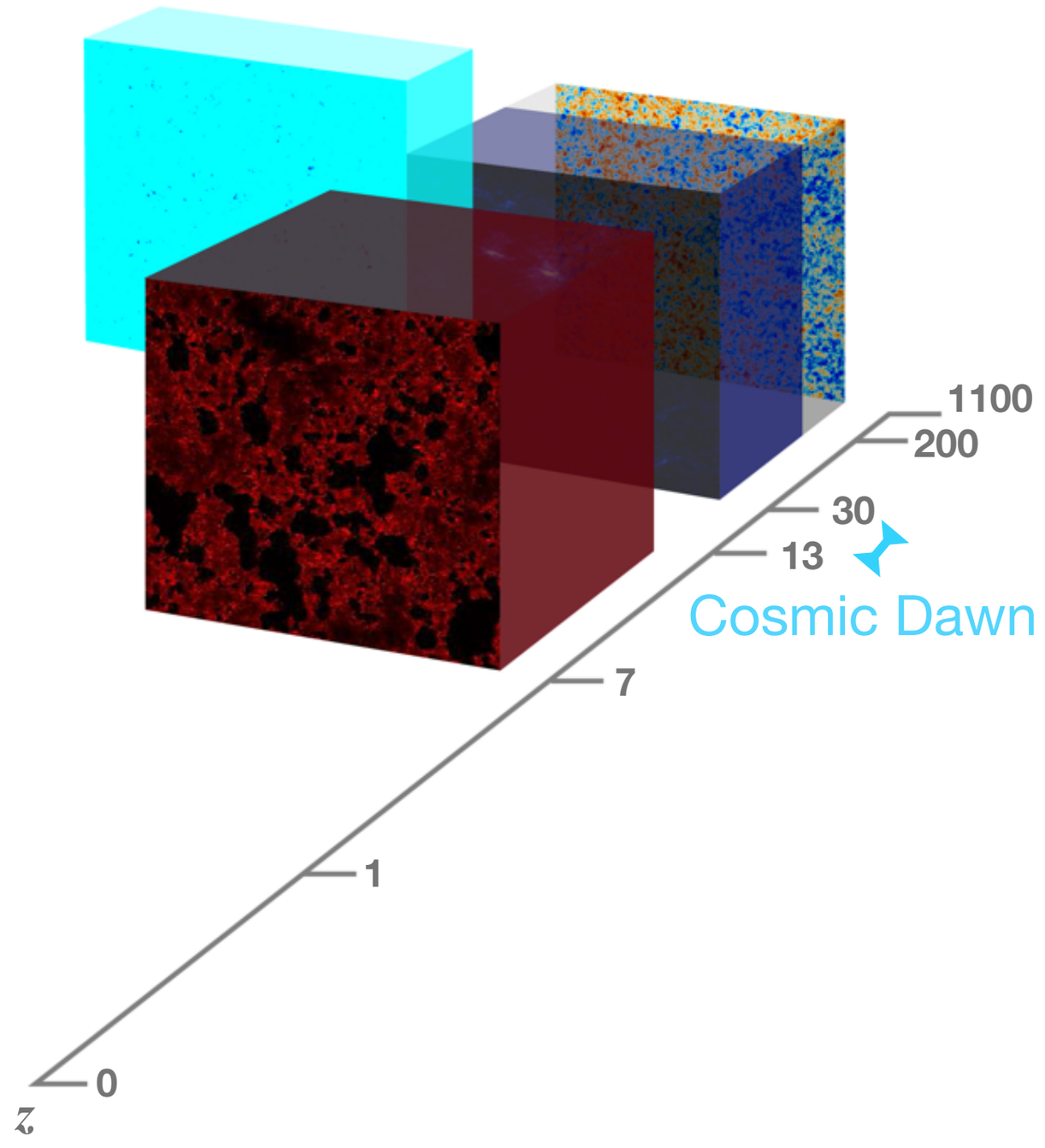

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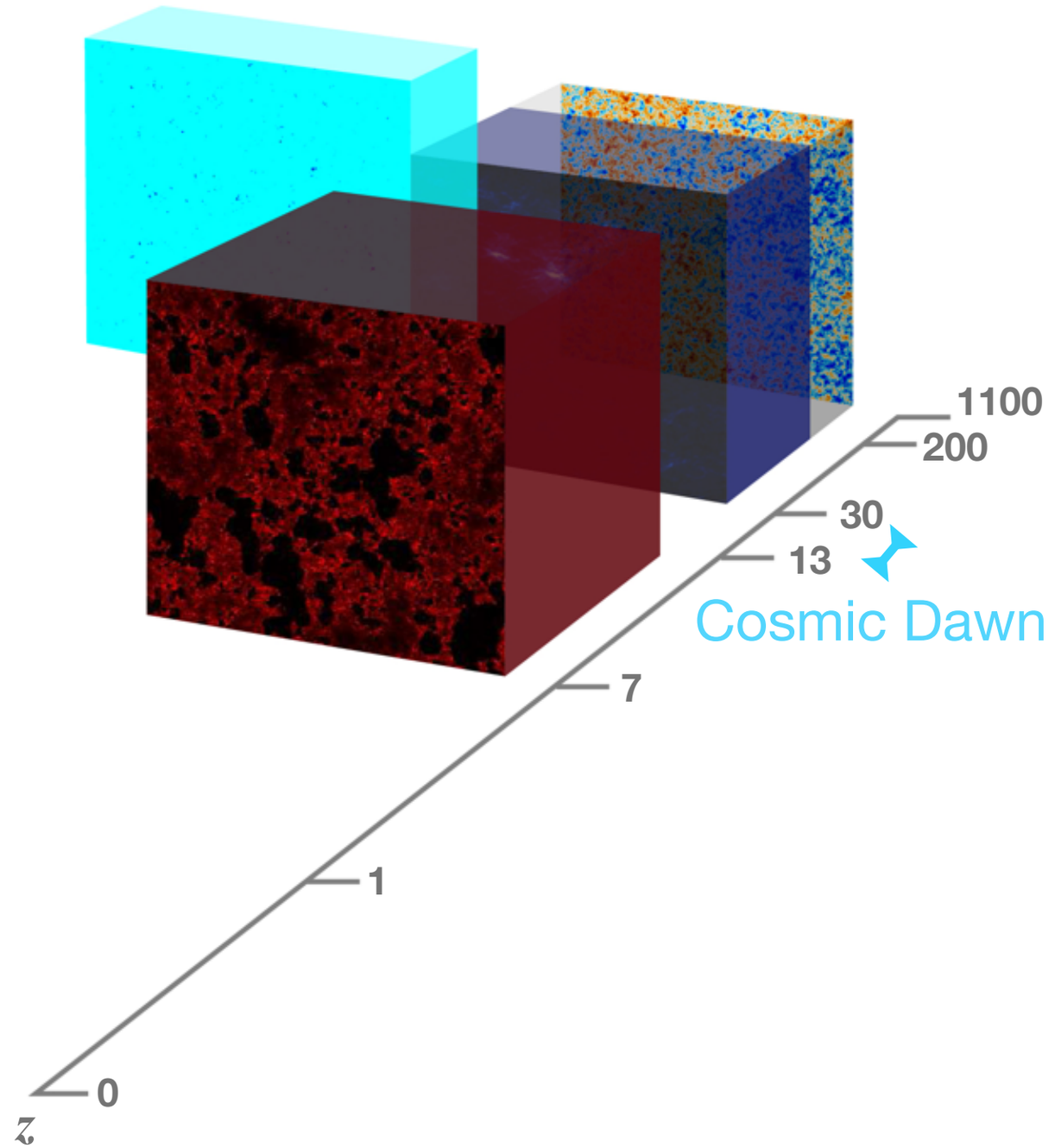


nature

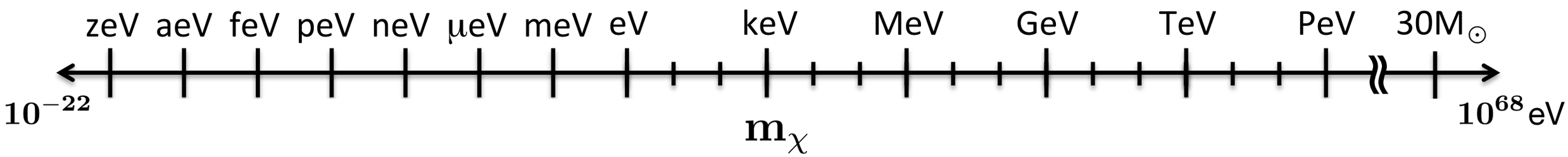
Letter | Published: 01 March 2018

Possible interaction between baryons and dark-matter particles revealed by the first stars

The Dark Matter Landscape

The Dark Matter Landscape

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



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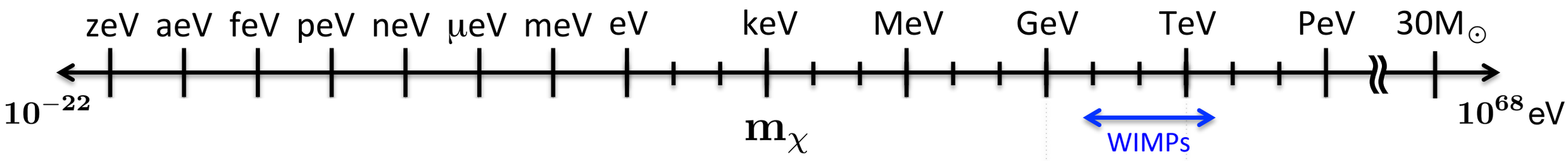

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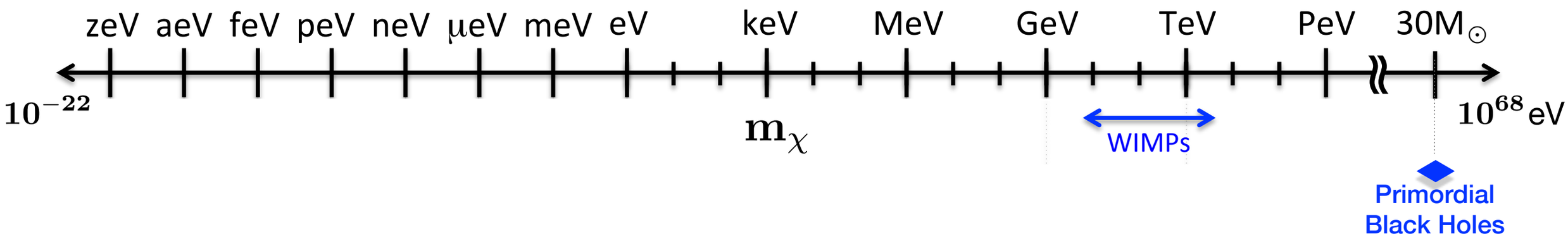

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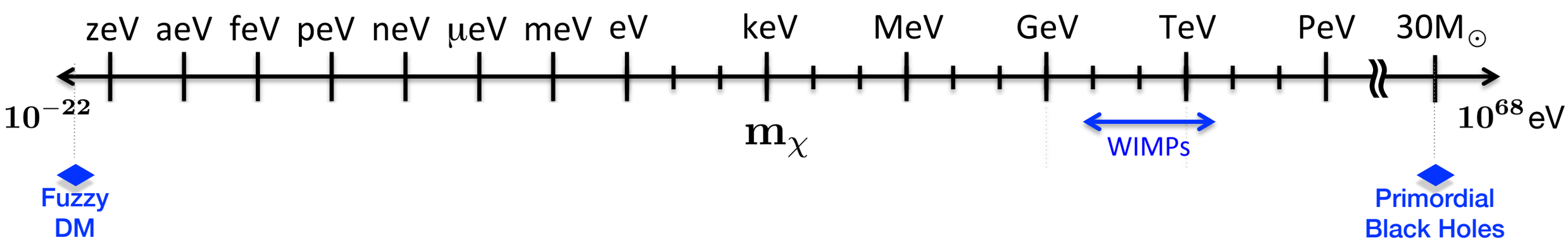

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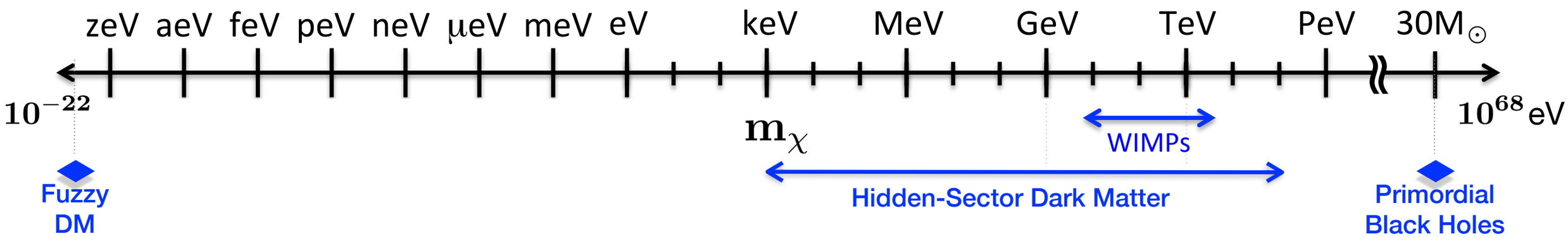

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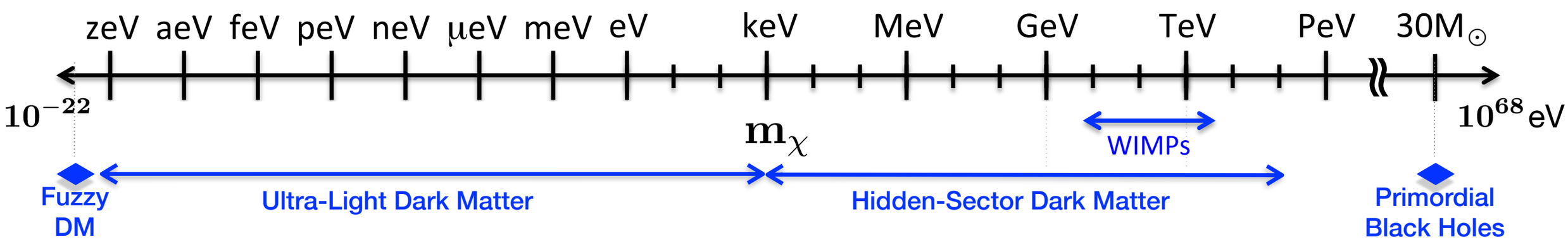

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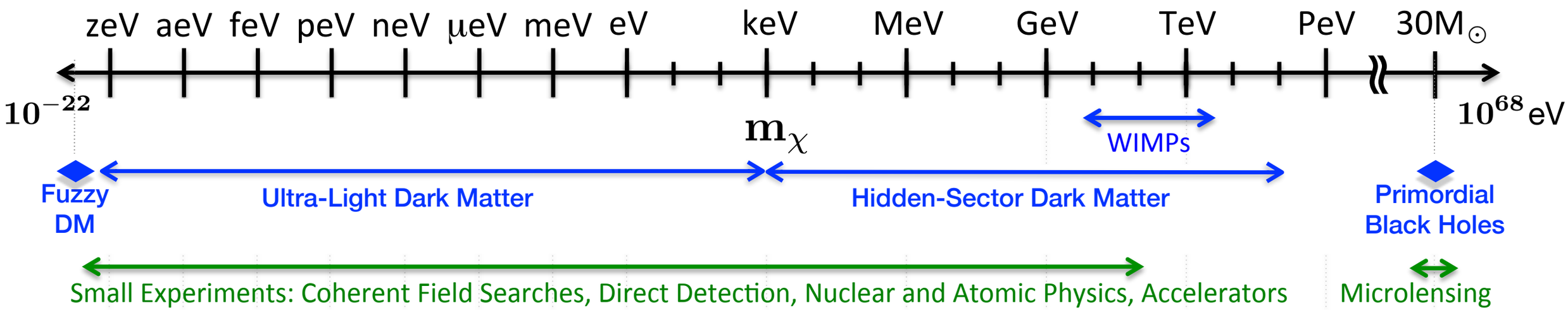

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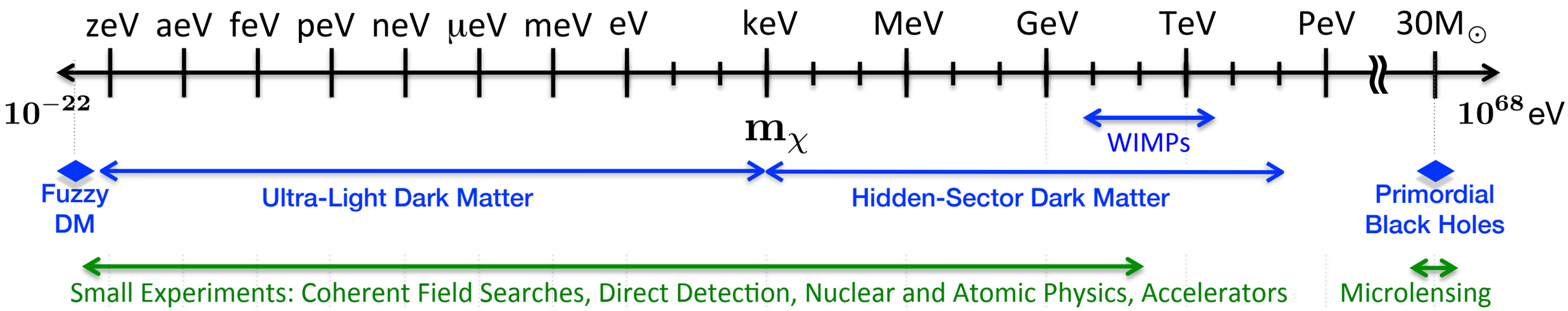
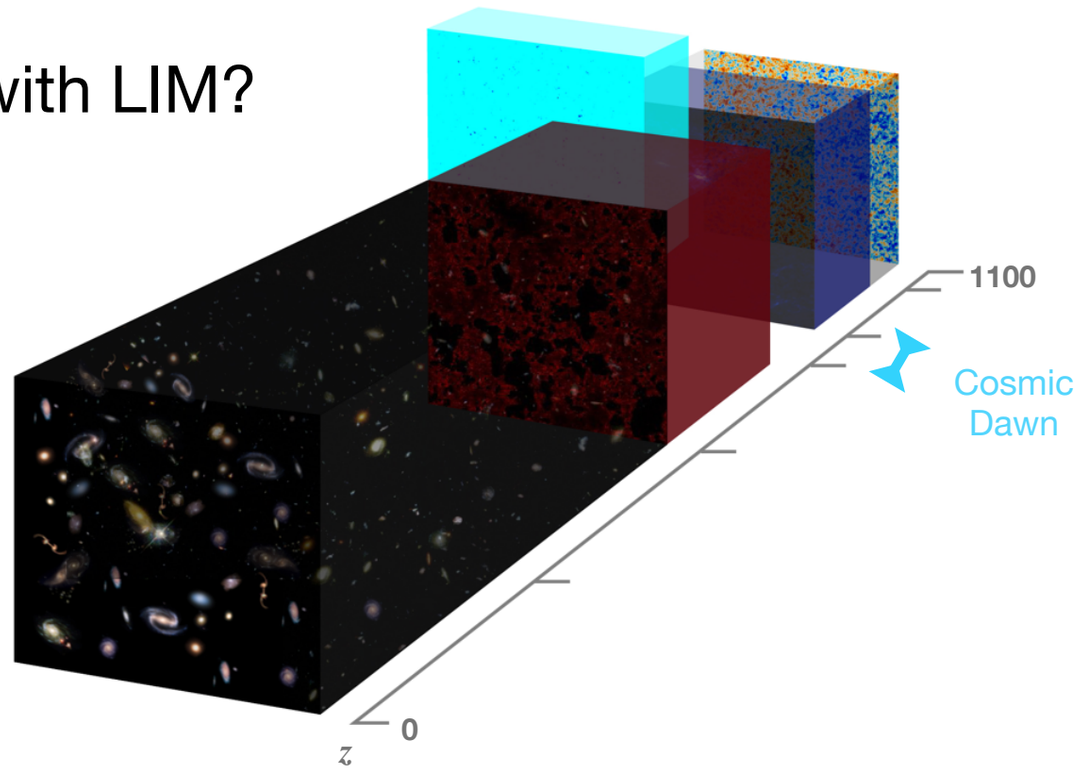


What can we do with LIM?



The Cosmological 21cm Signal: Lightning Review

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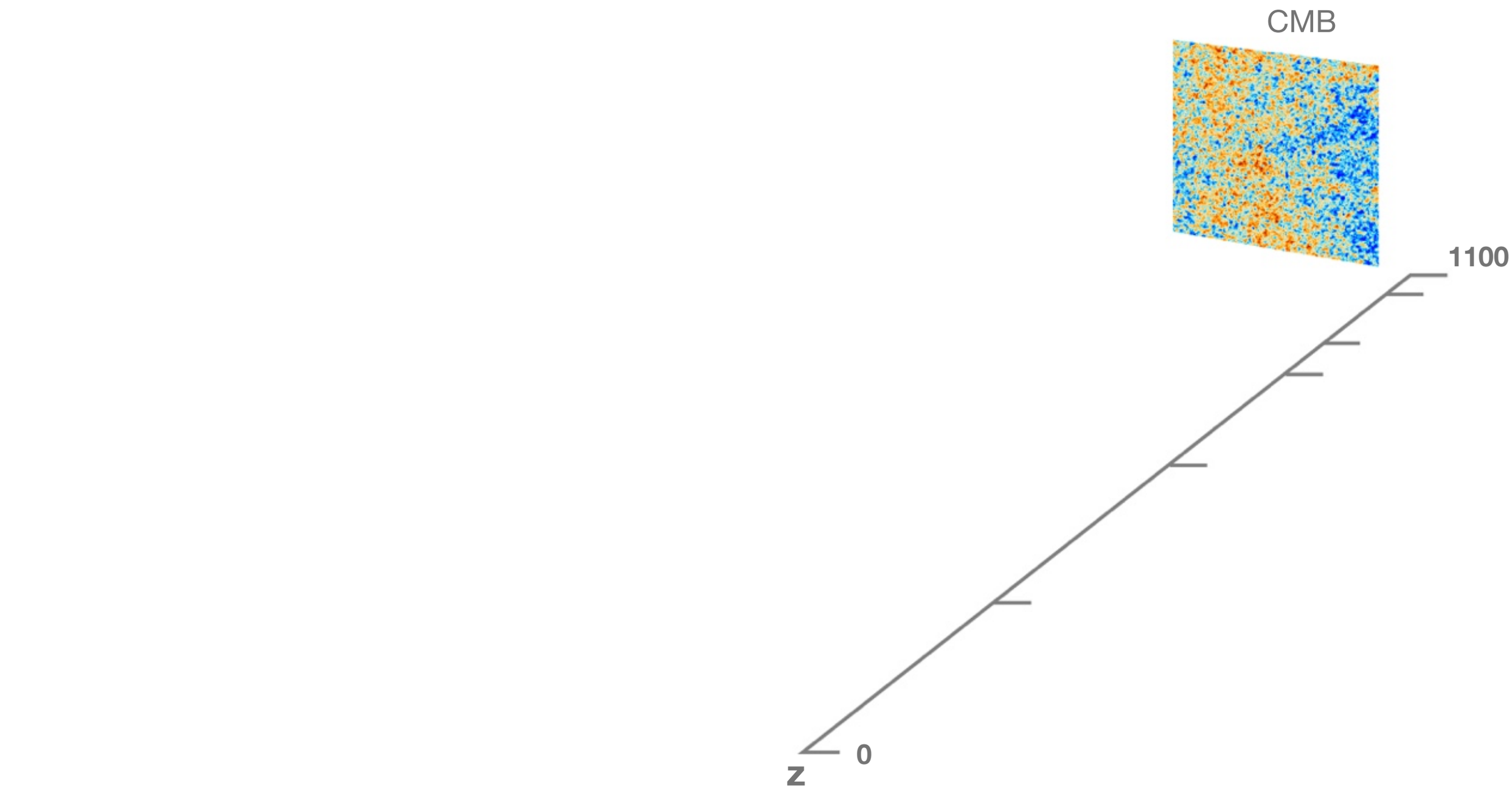

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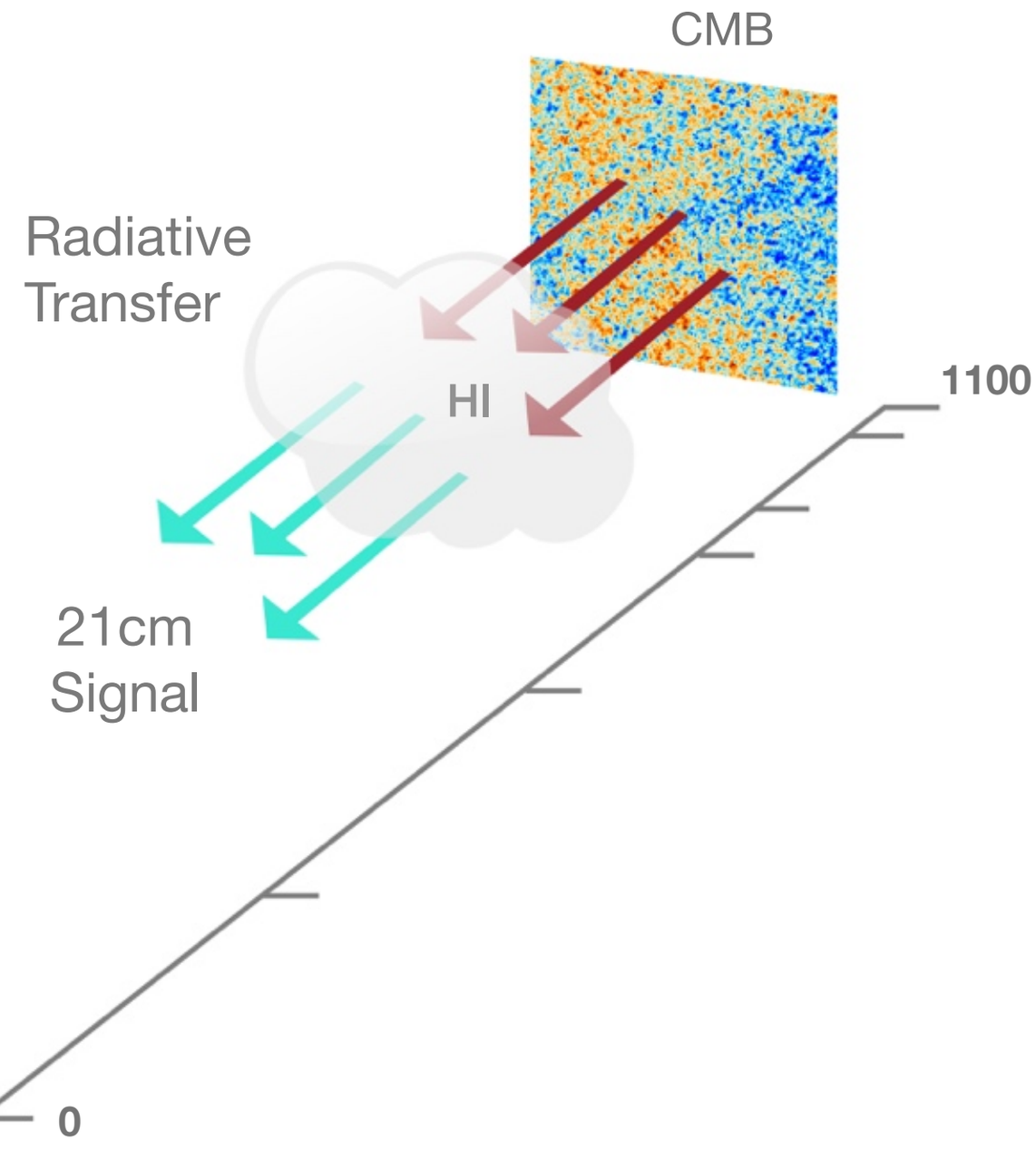

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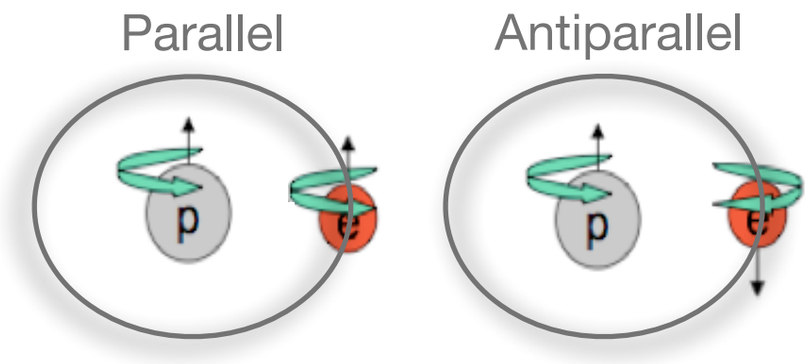

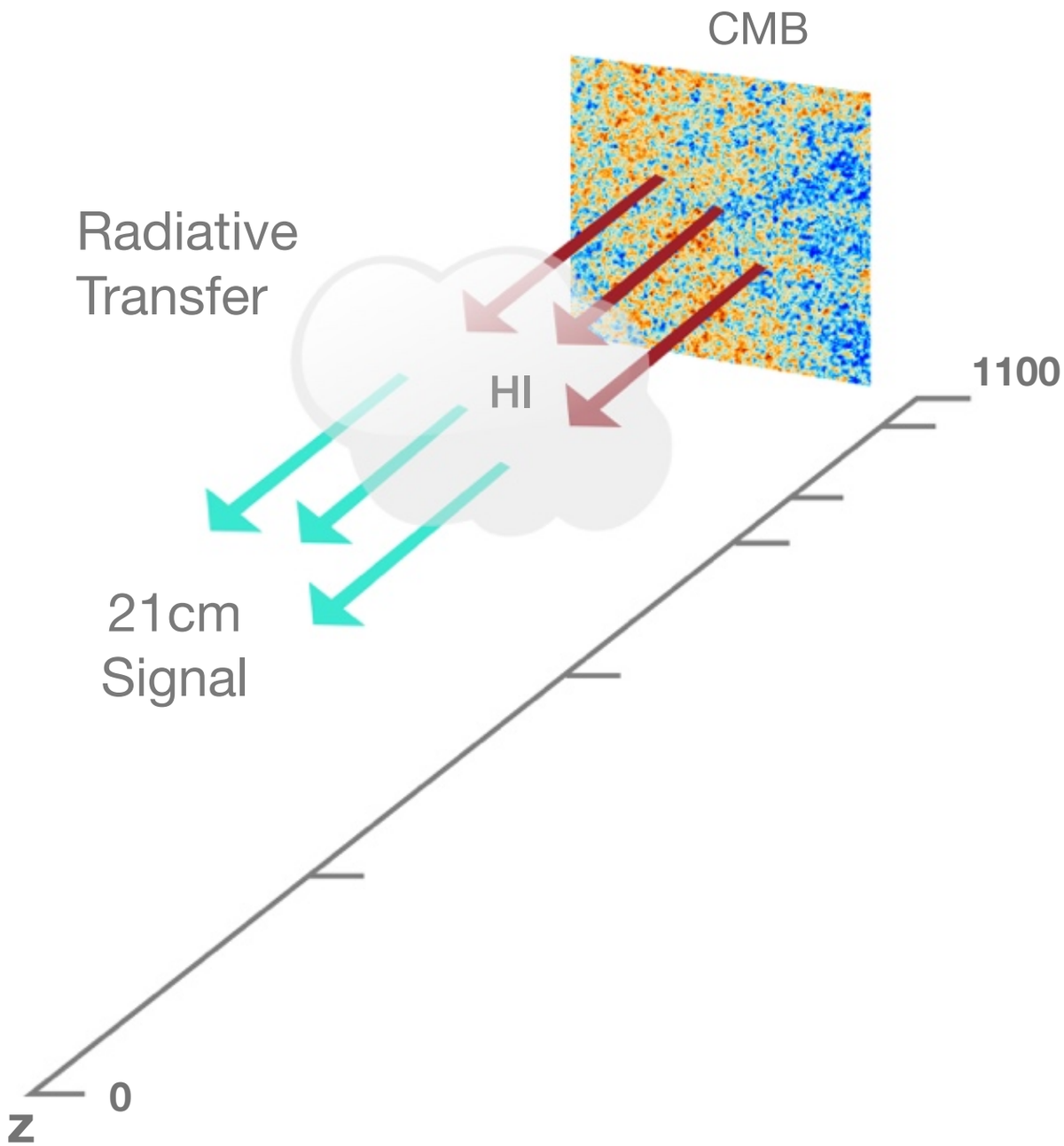

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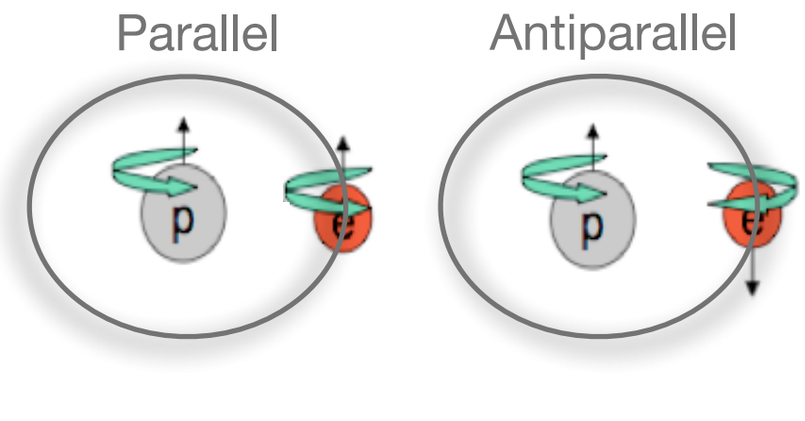

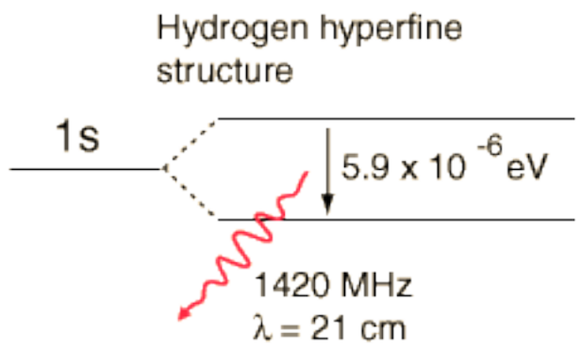

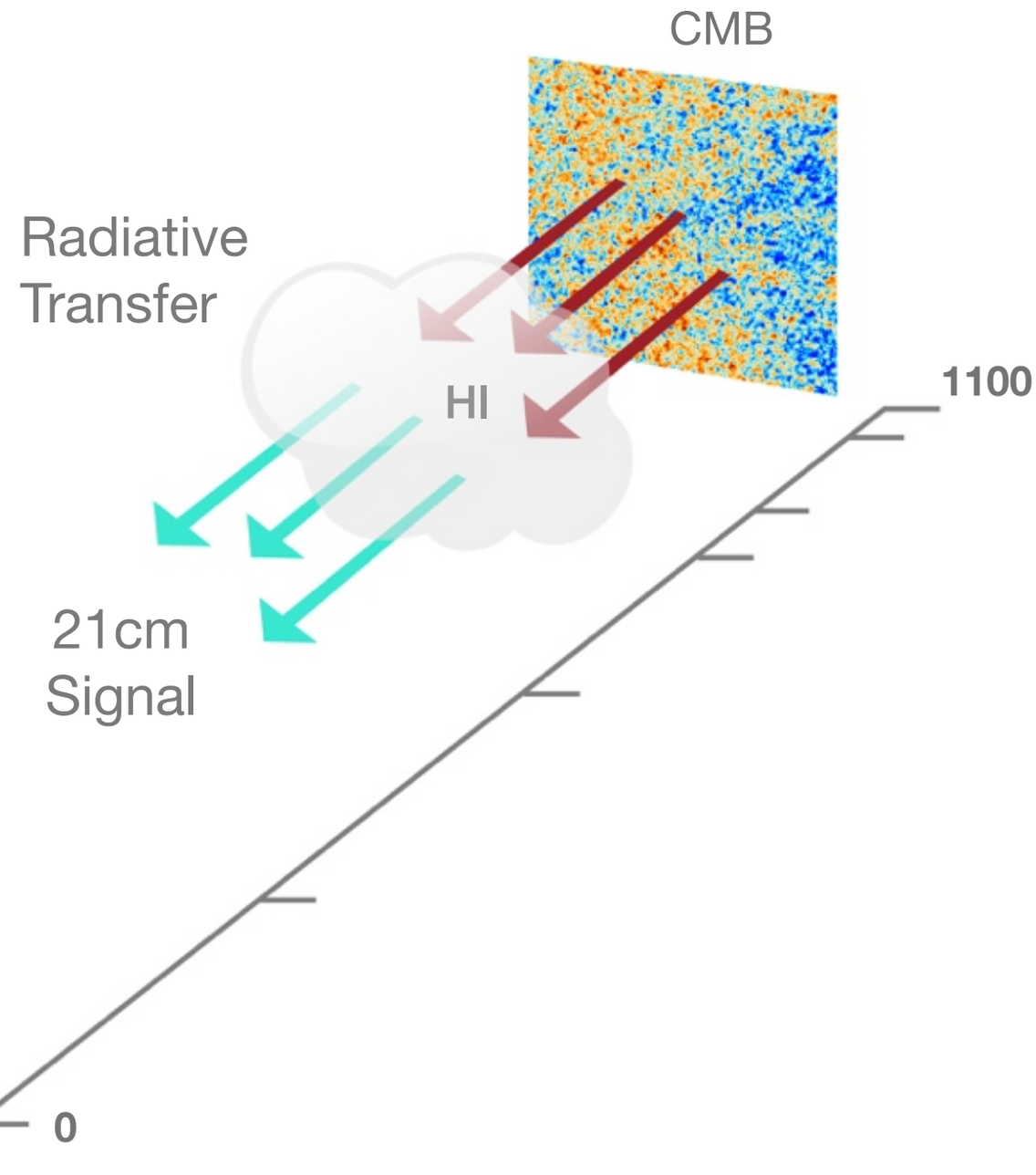

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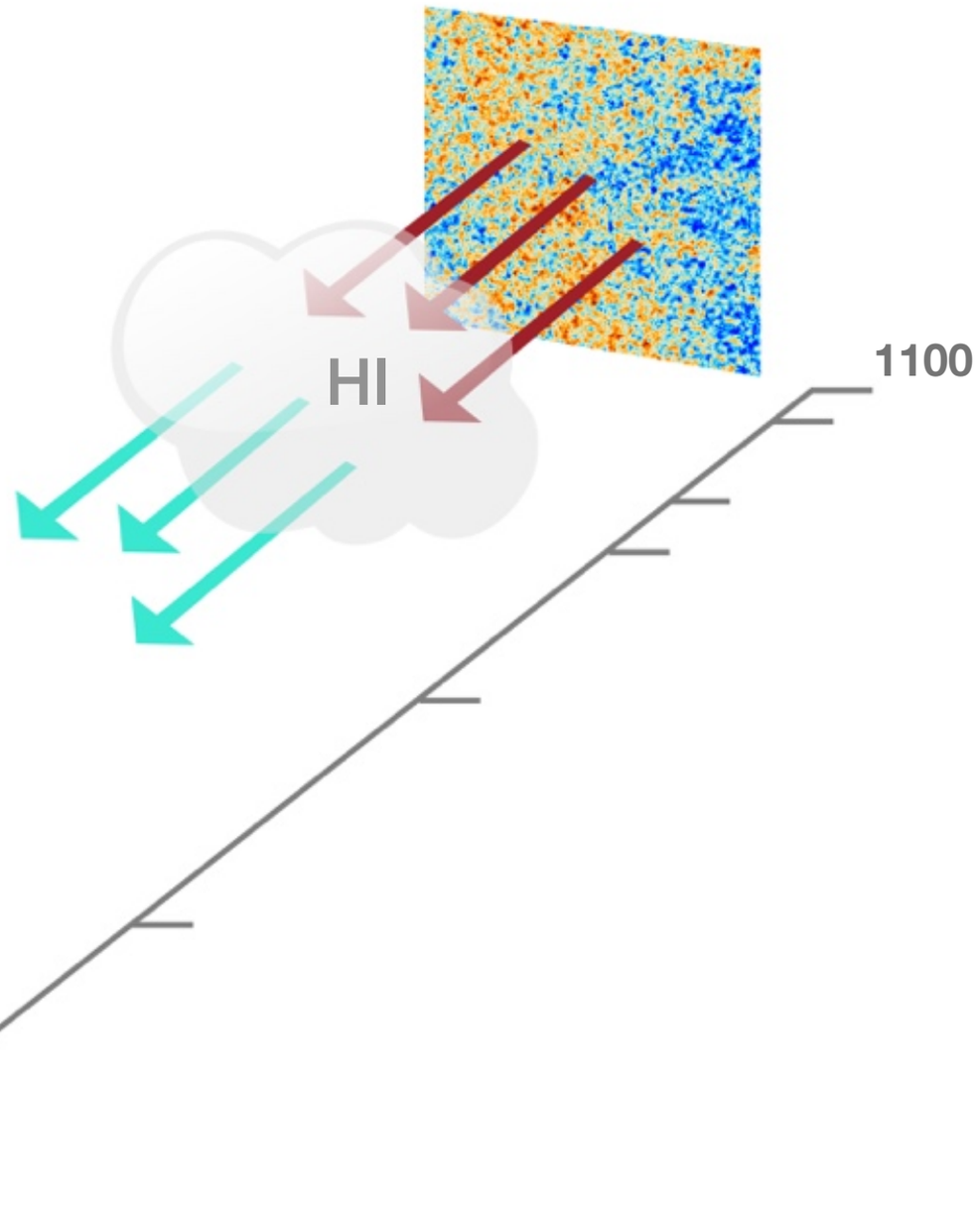

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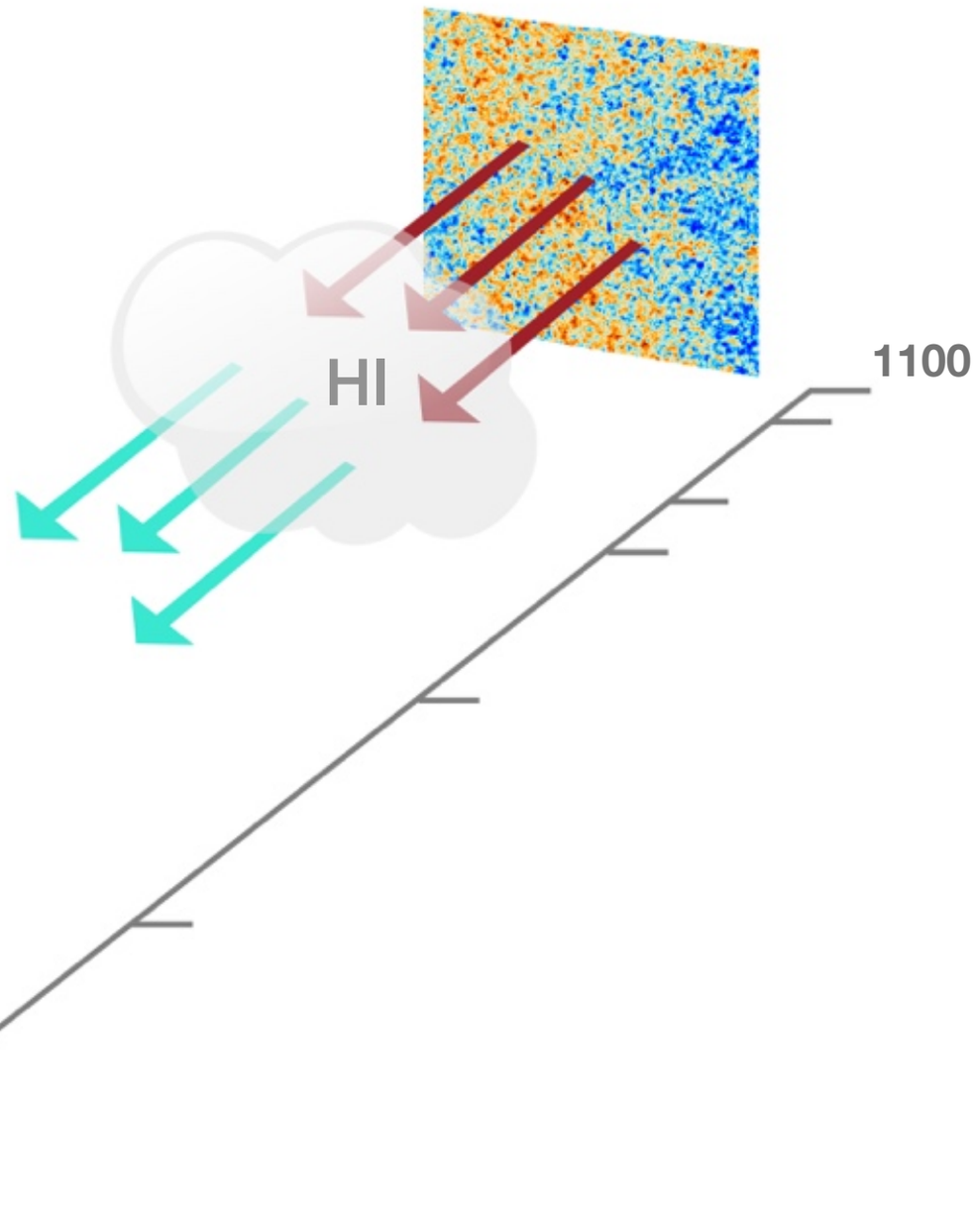
Game of *Temperatures*:



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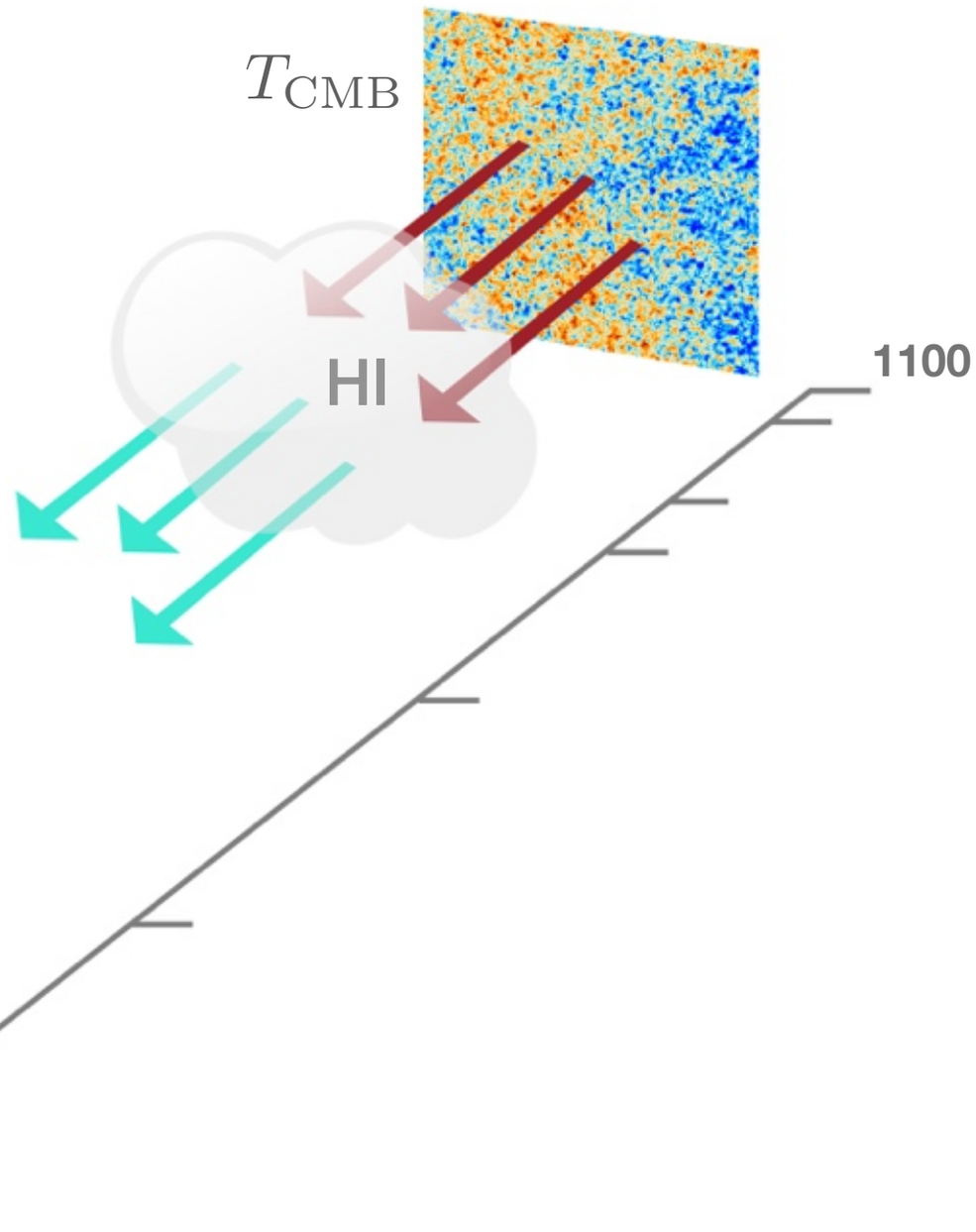

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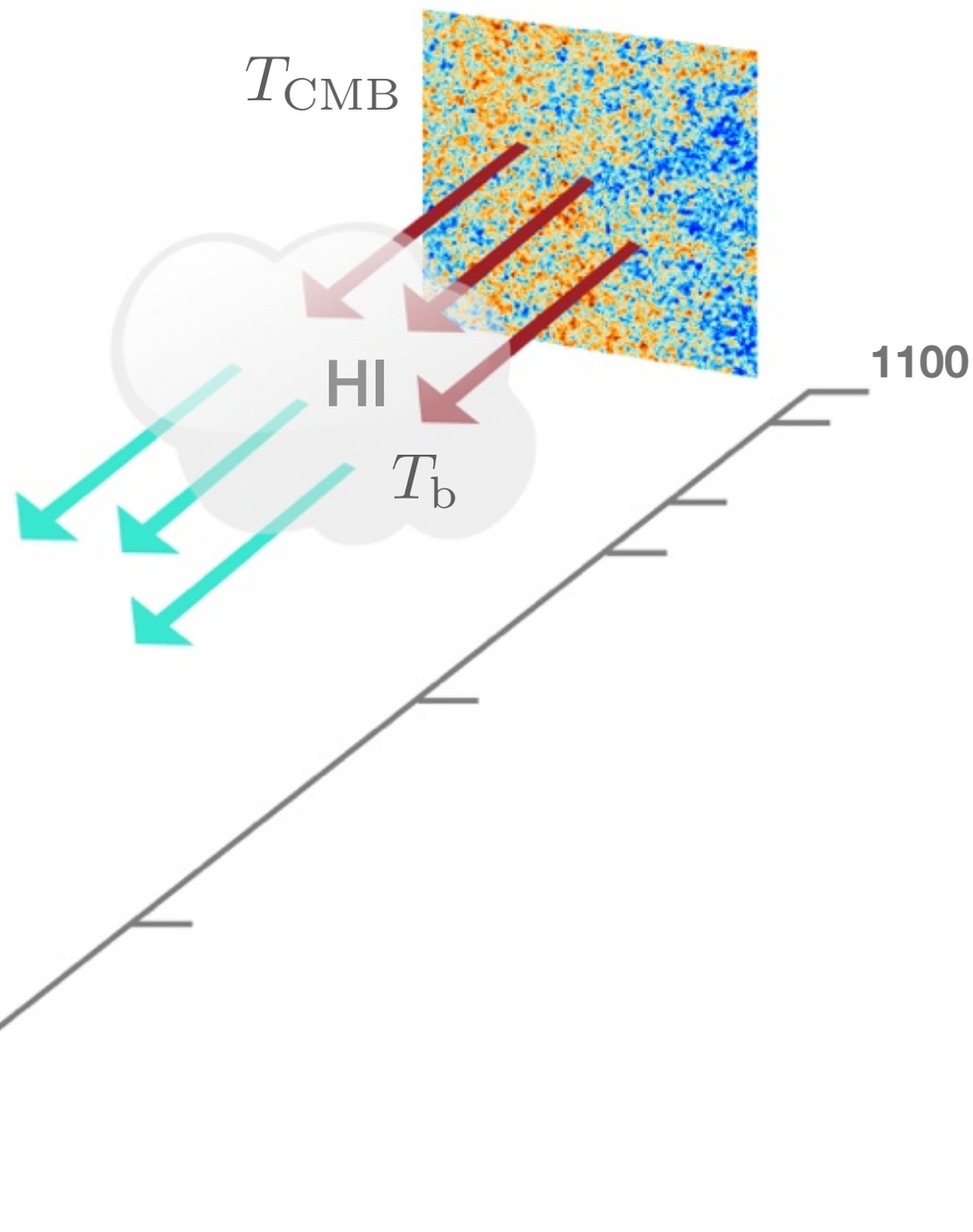

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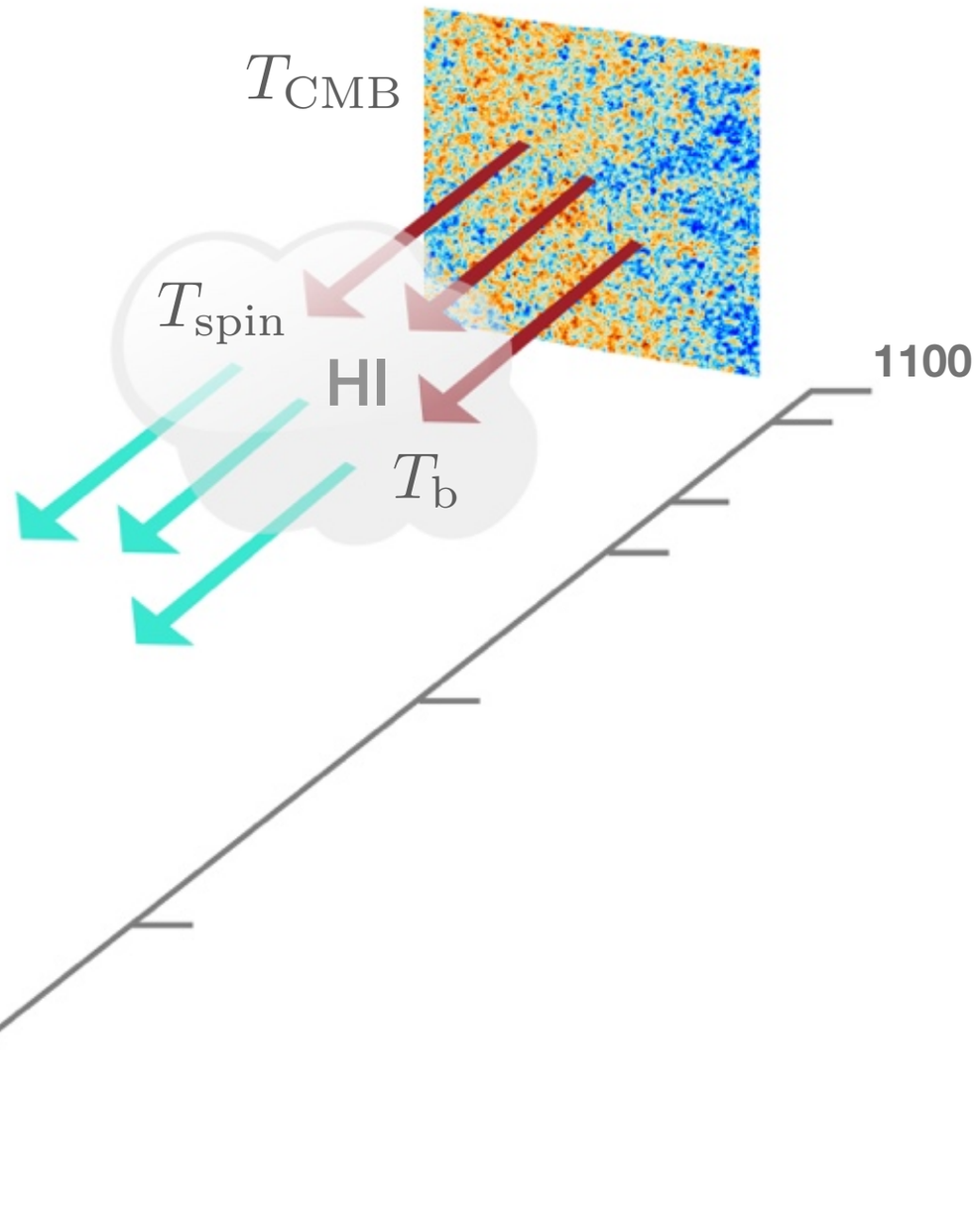

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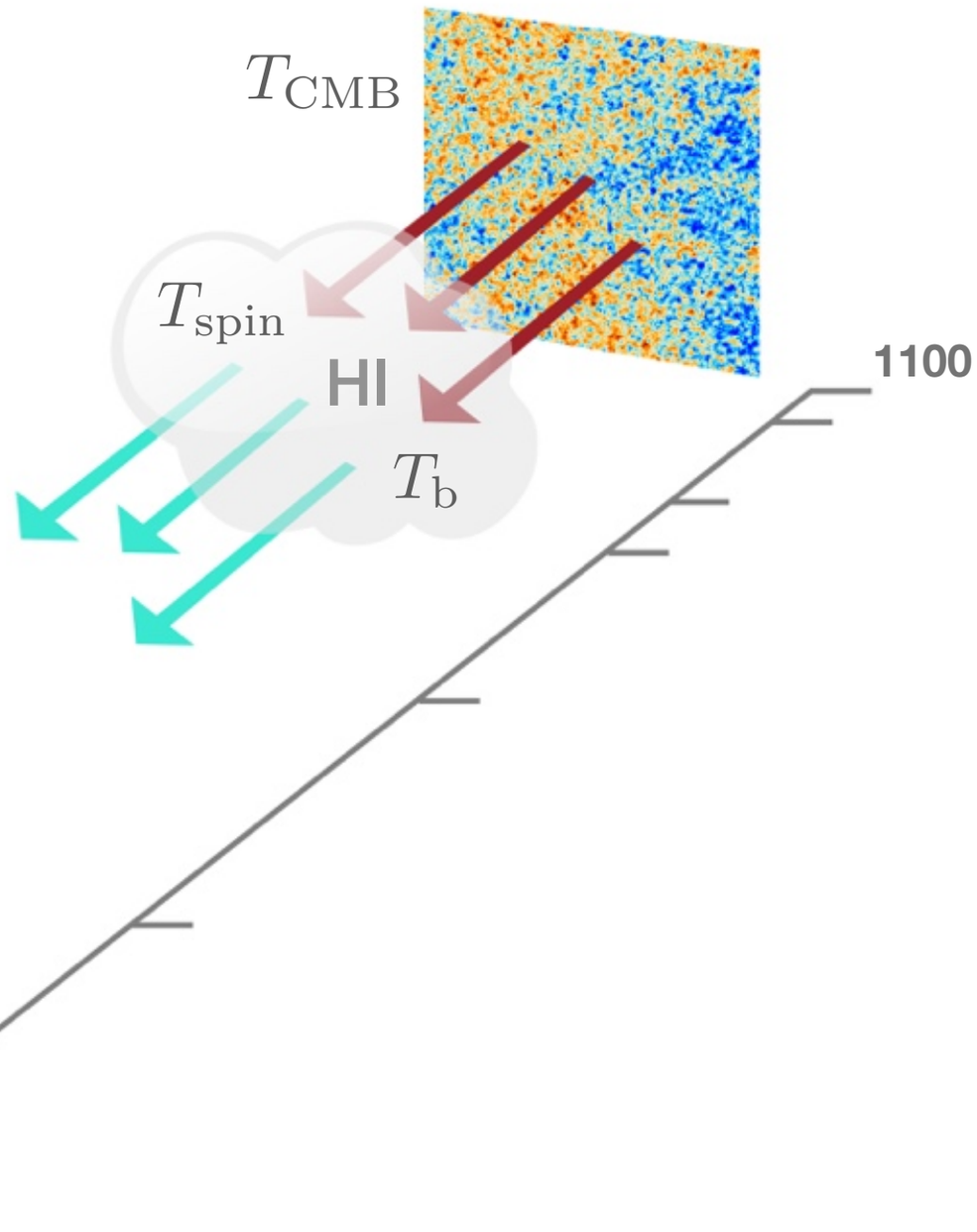

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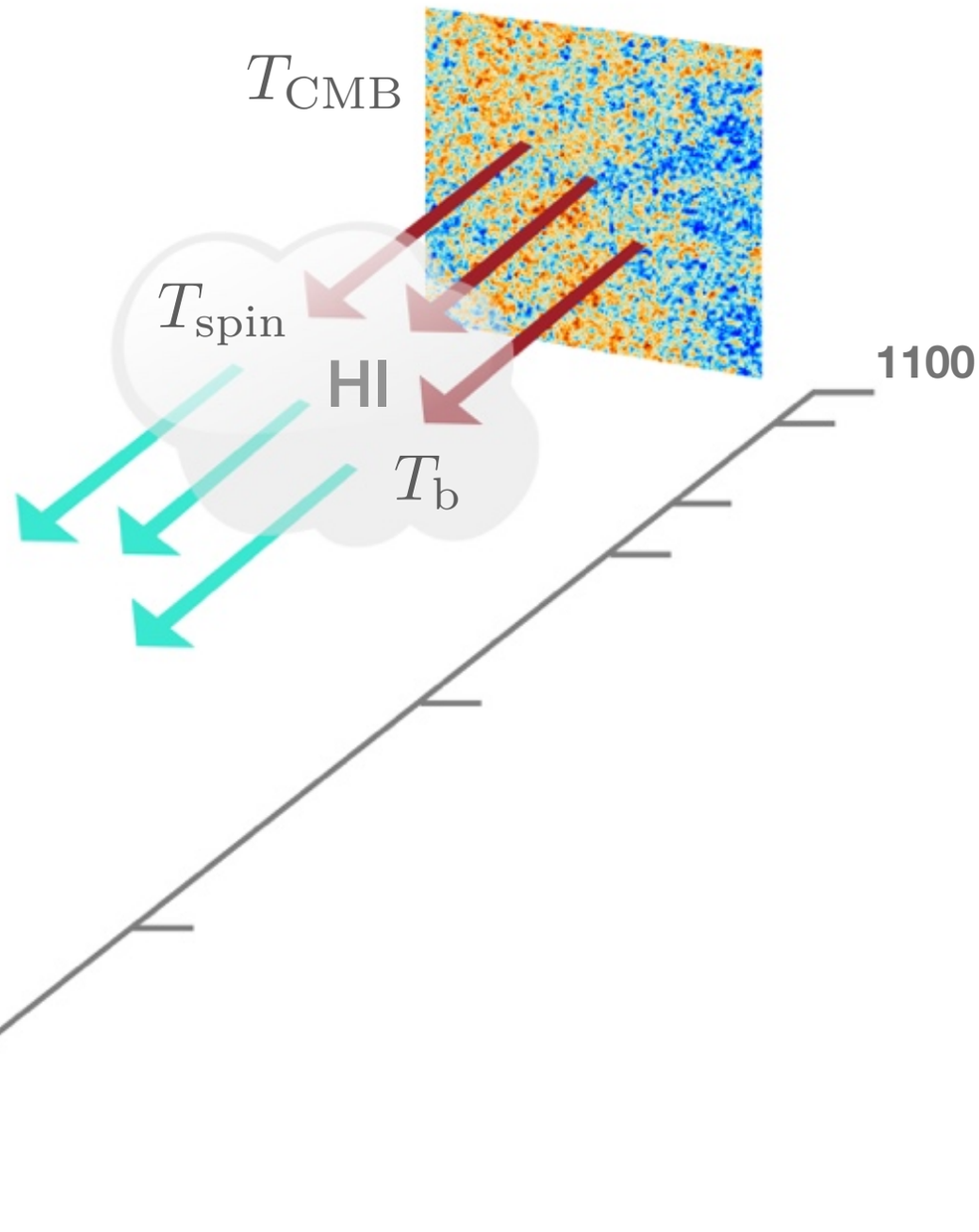

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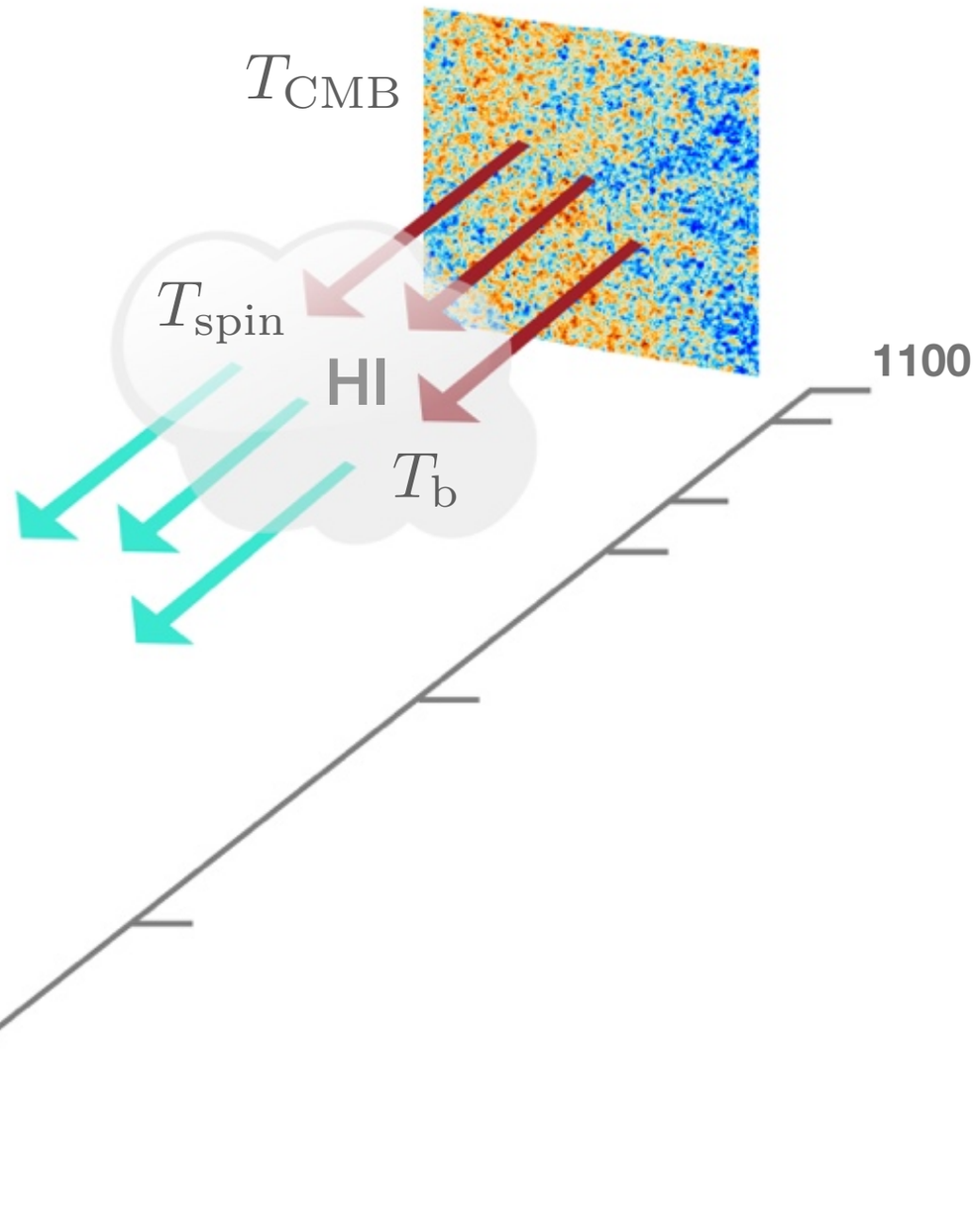

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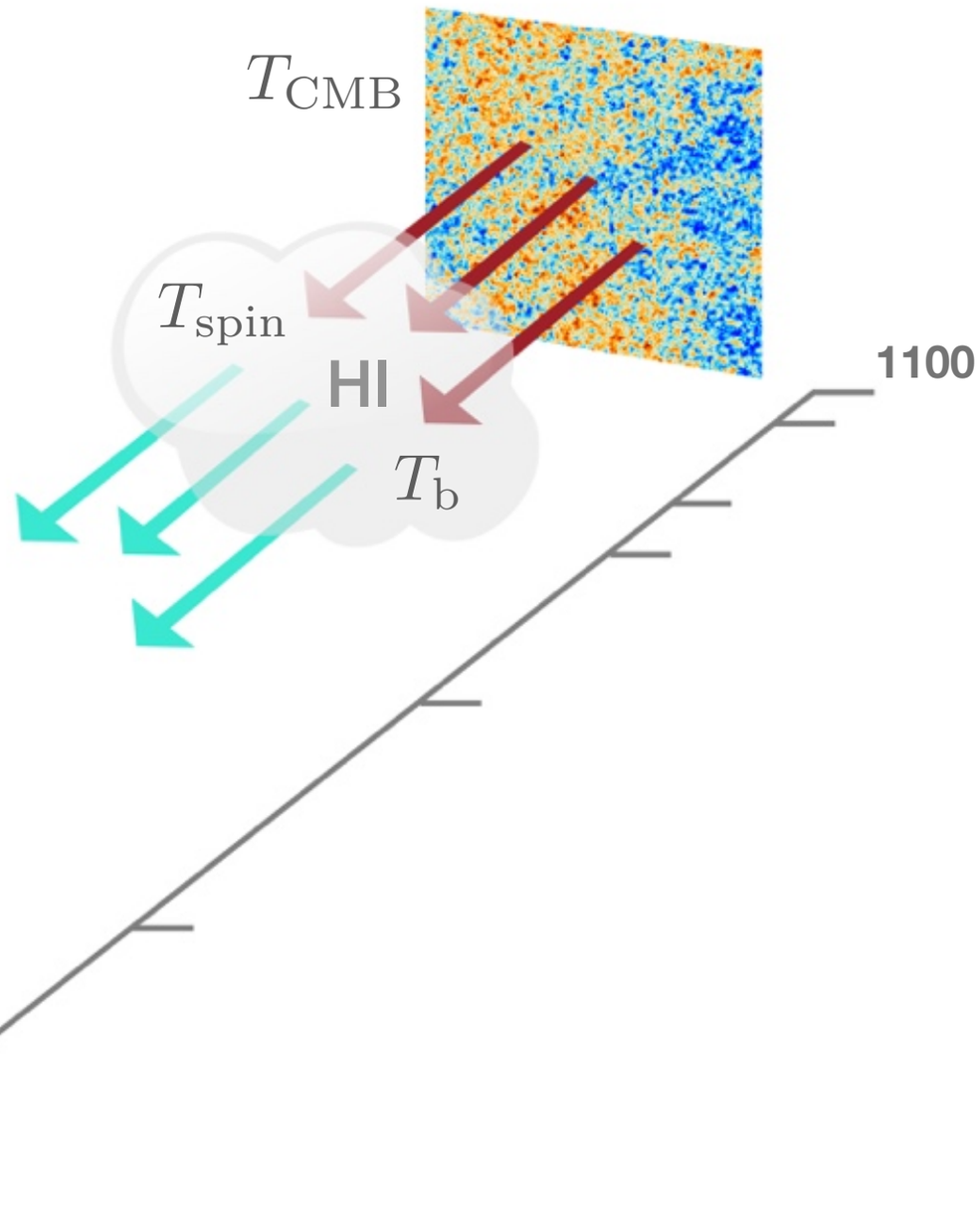
Detailed balance: $T_{\rm spin}^{-1} \simeq \frac{T_{\rm CMB}^{-1} + \sum_i x_i T_{\rm b}^{-1}}{1 + \sum_i x_i}$



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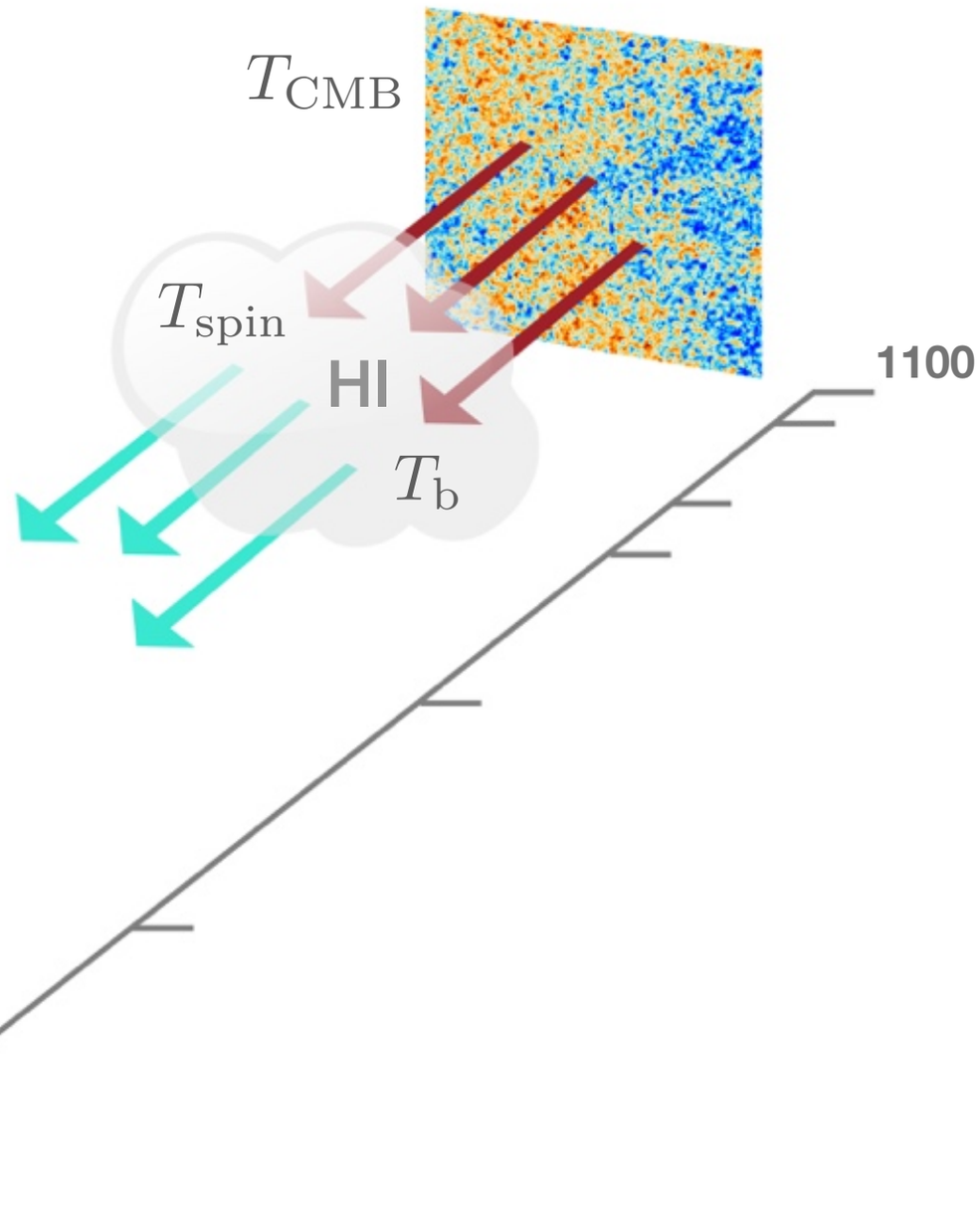

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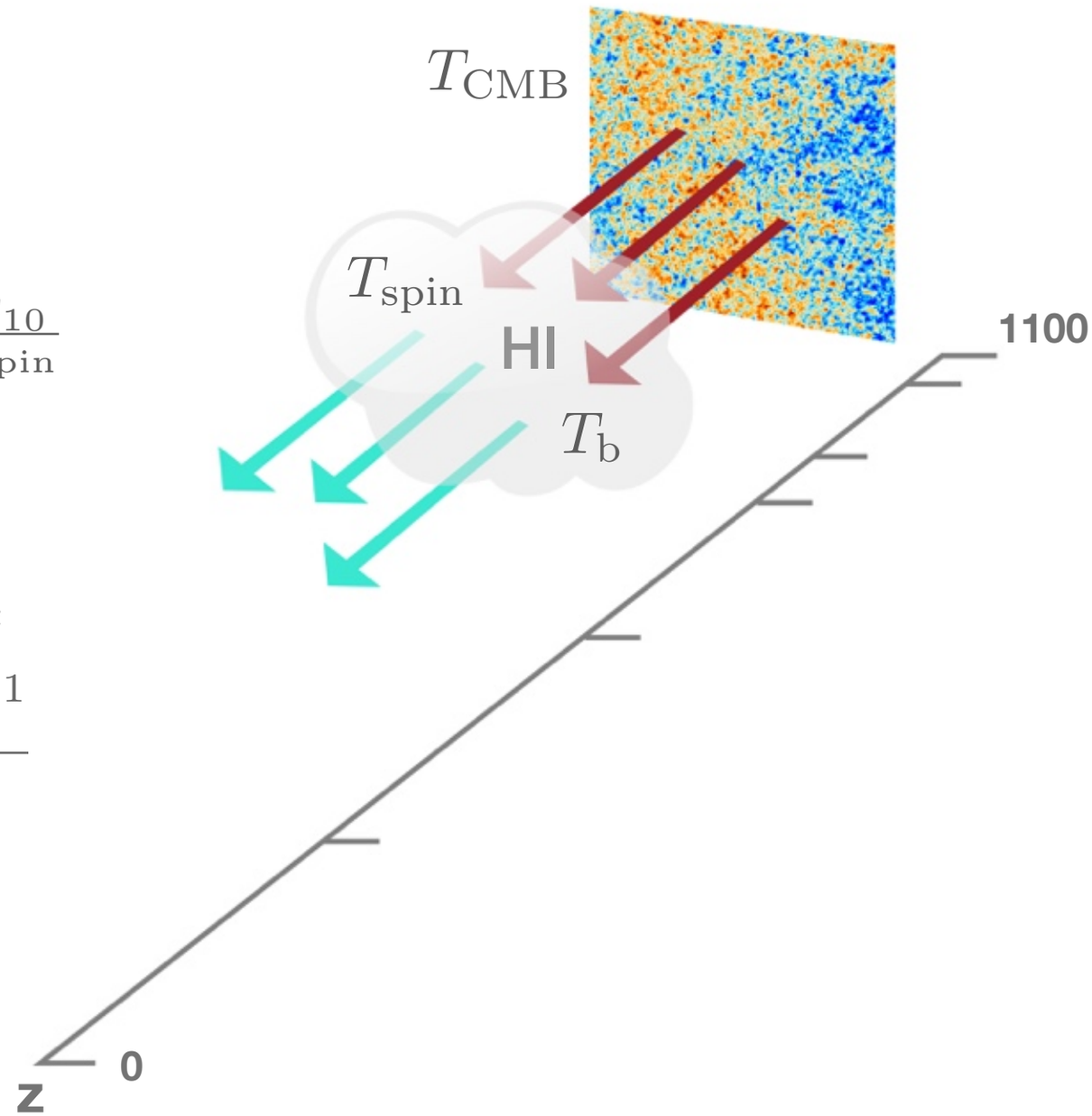

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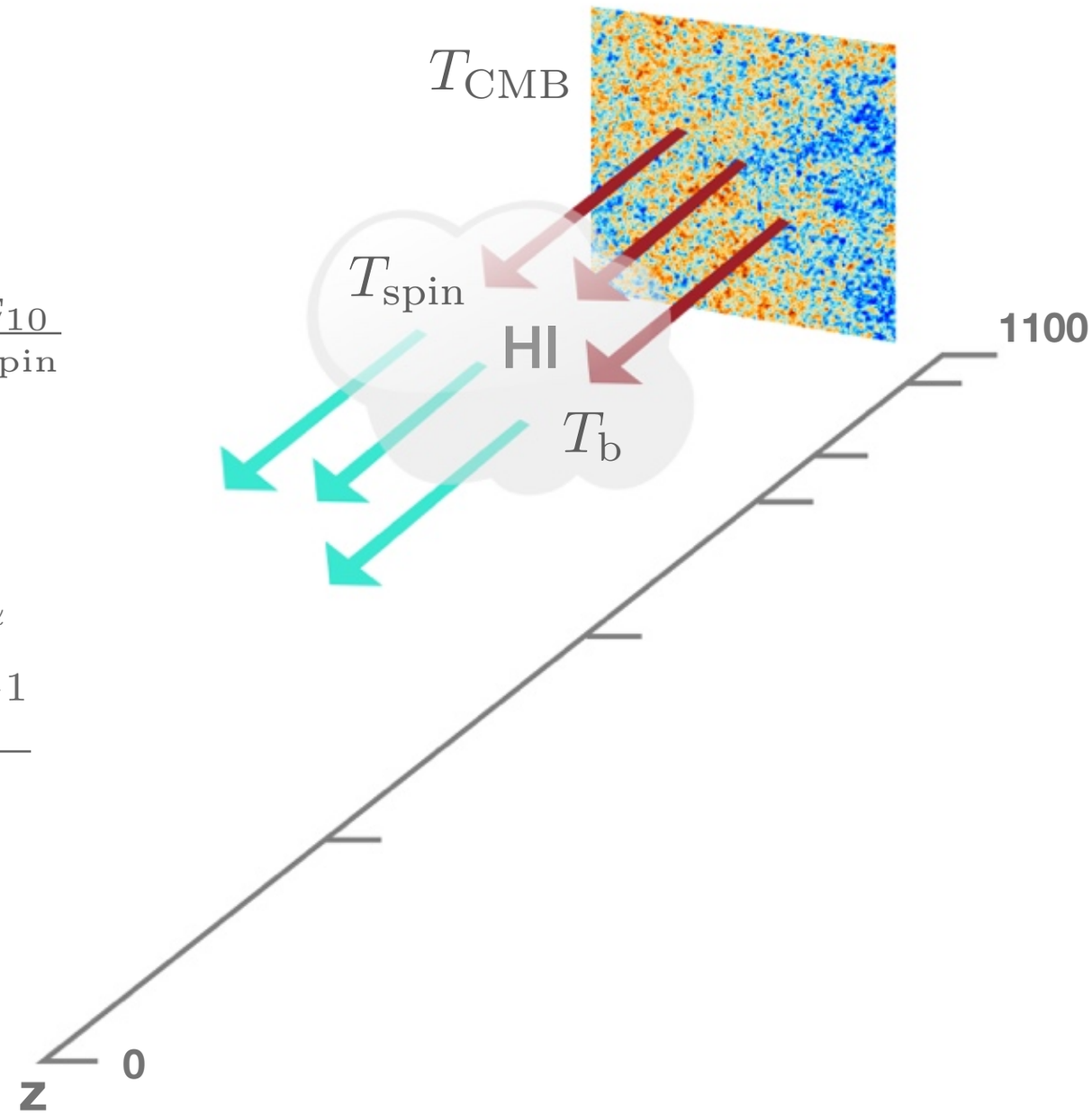
- Brightness temperature (radiative transfer):

$$T_{\rm bright} = T_{\rm spin}\left(1 - e^{-\tau}\right) + T_{\rm CMB} e^{-\tau}$$



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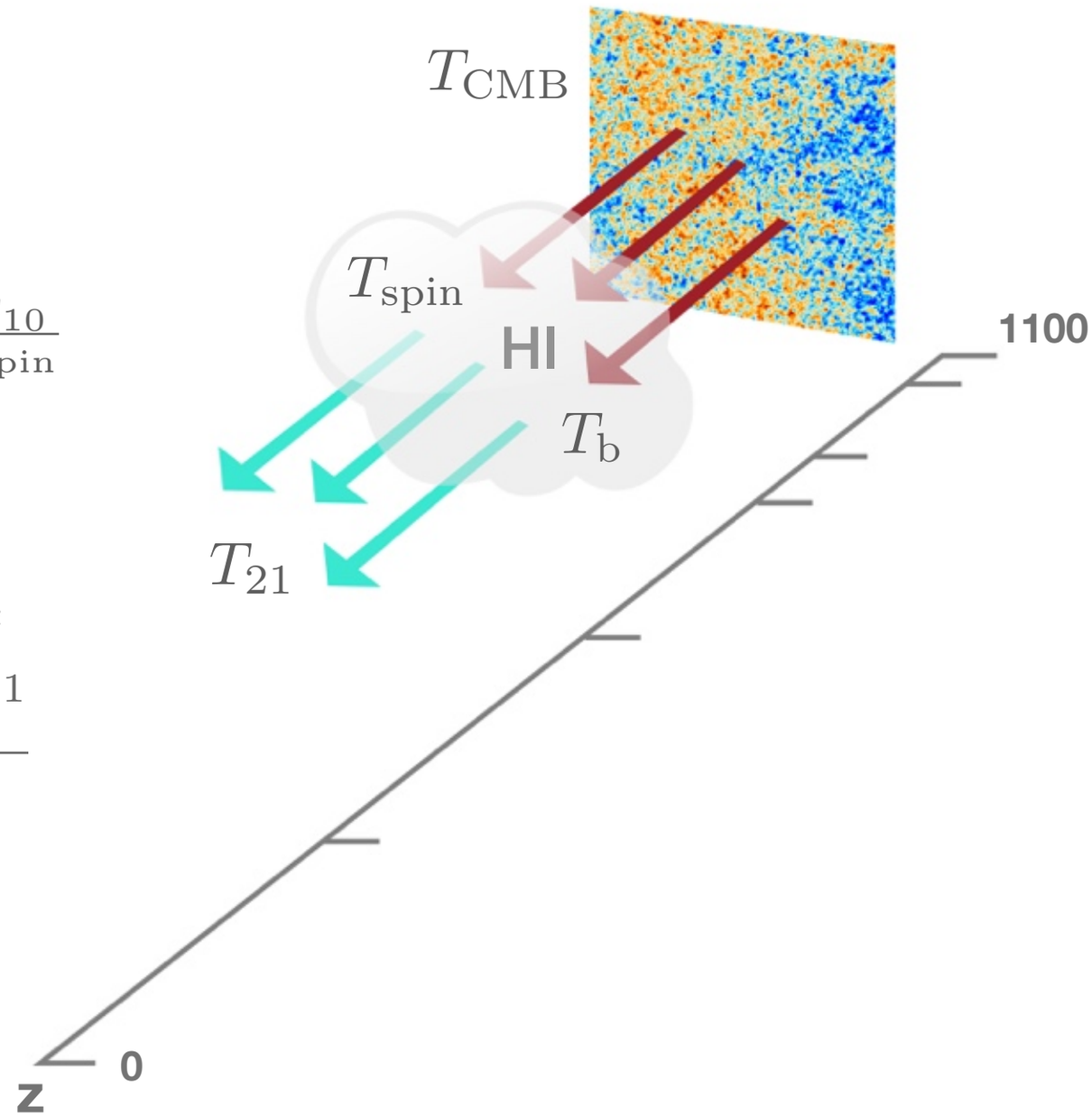

- Brightness temperature (radiative transfer):

$$T_{\rm bright} = T_{\rm spin}\left(1 - e^{-\tau}\right) + T_{\rm CMB} e^{-\tau}$$

- Brightness temperature contrast:

$$T_{21} \equiv \delta T_{\rm bright} = \frac{T_{\rm spin} - T_{\rm CMB}}{1+z}(1 - e^{-\tau}) \approx \frac{T_{\rm spin} - T_{\rm CMB}}{1+z}\tau$$

The Cosmological 21cm Signal: Lightning Review

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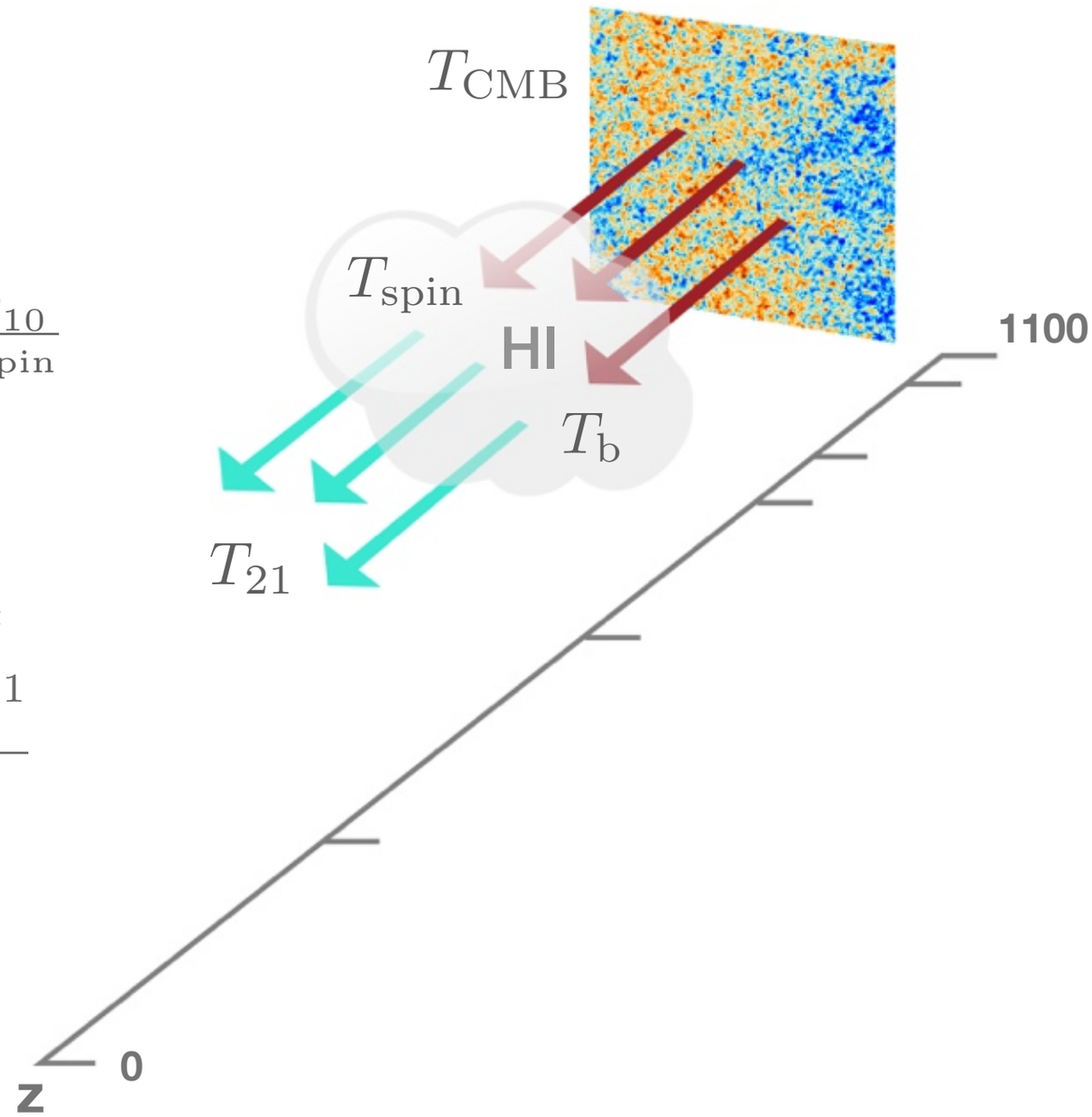

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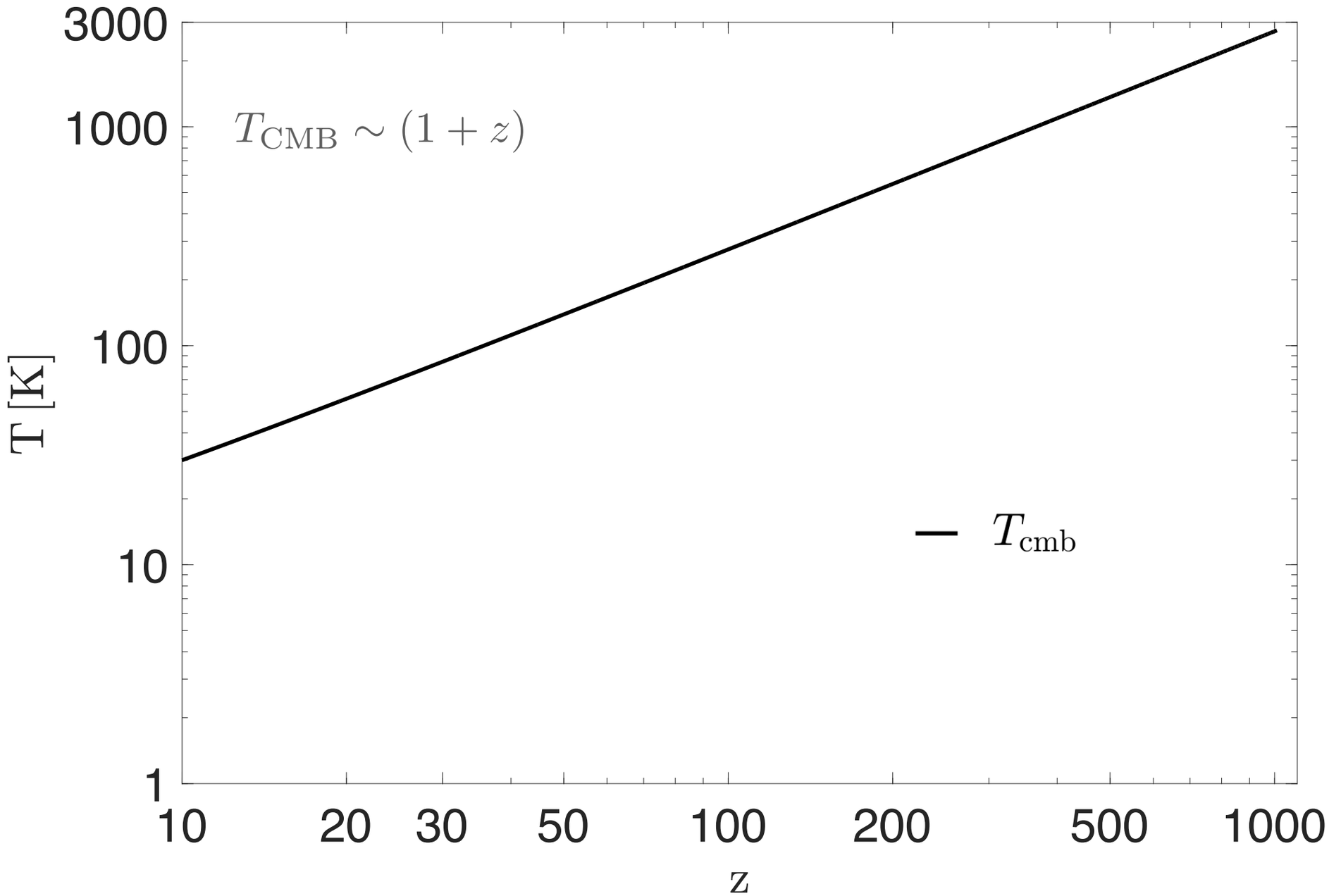

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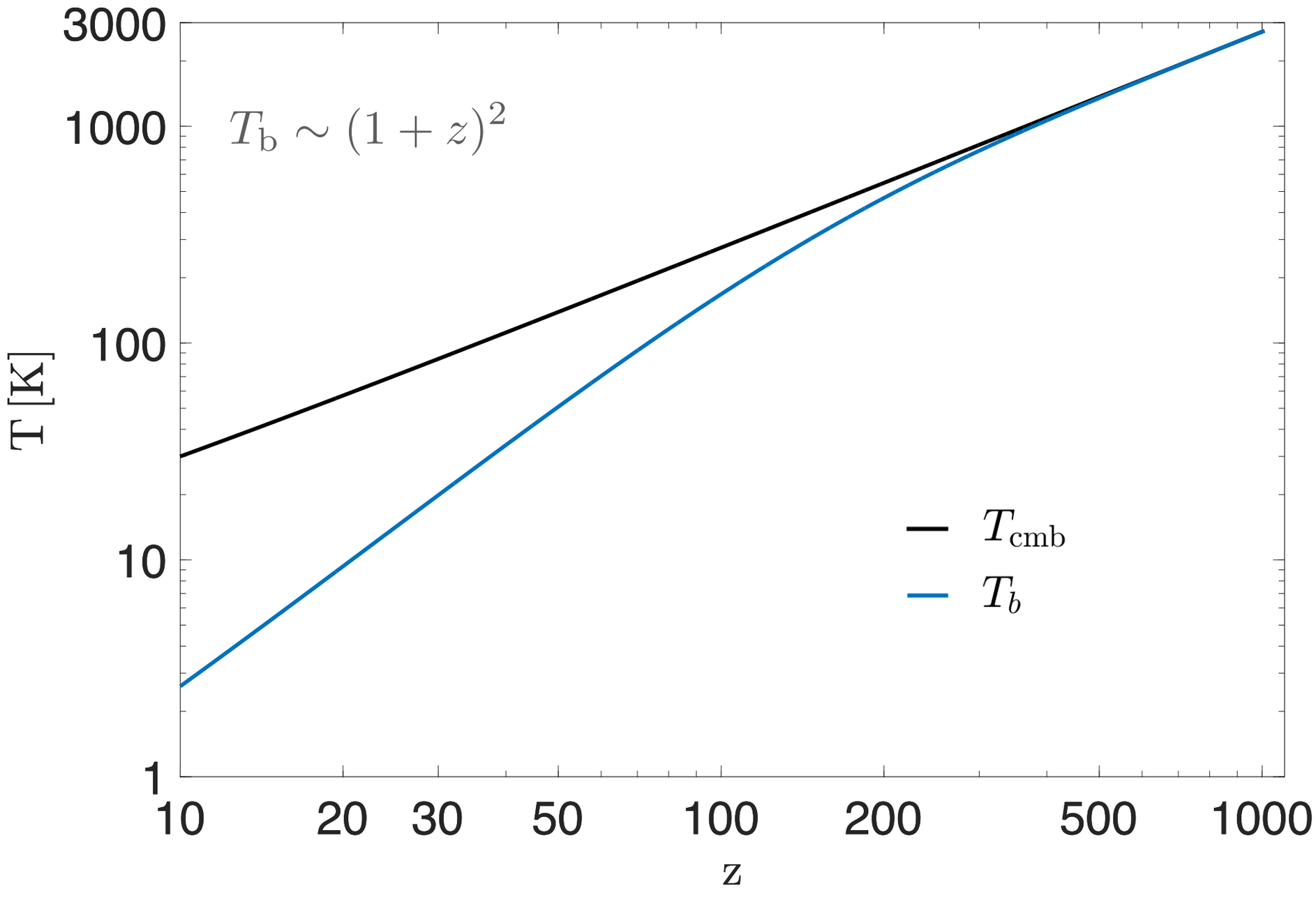

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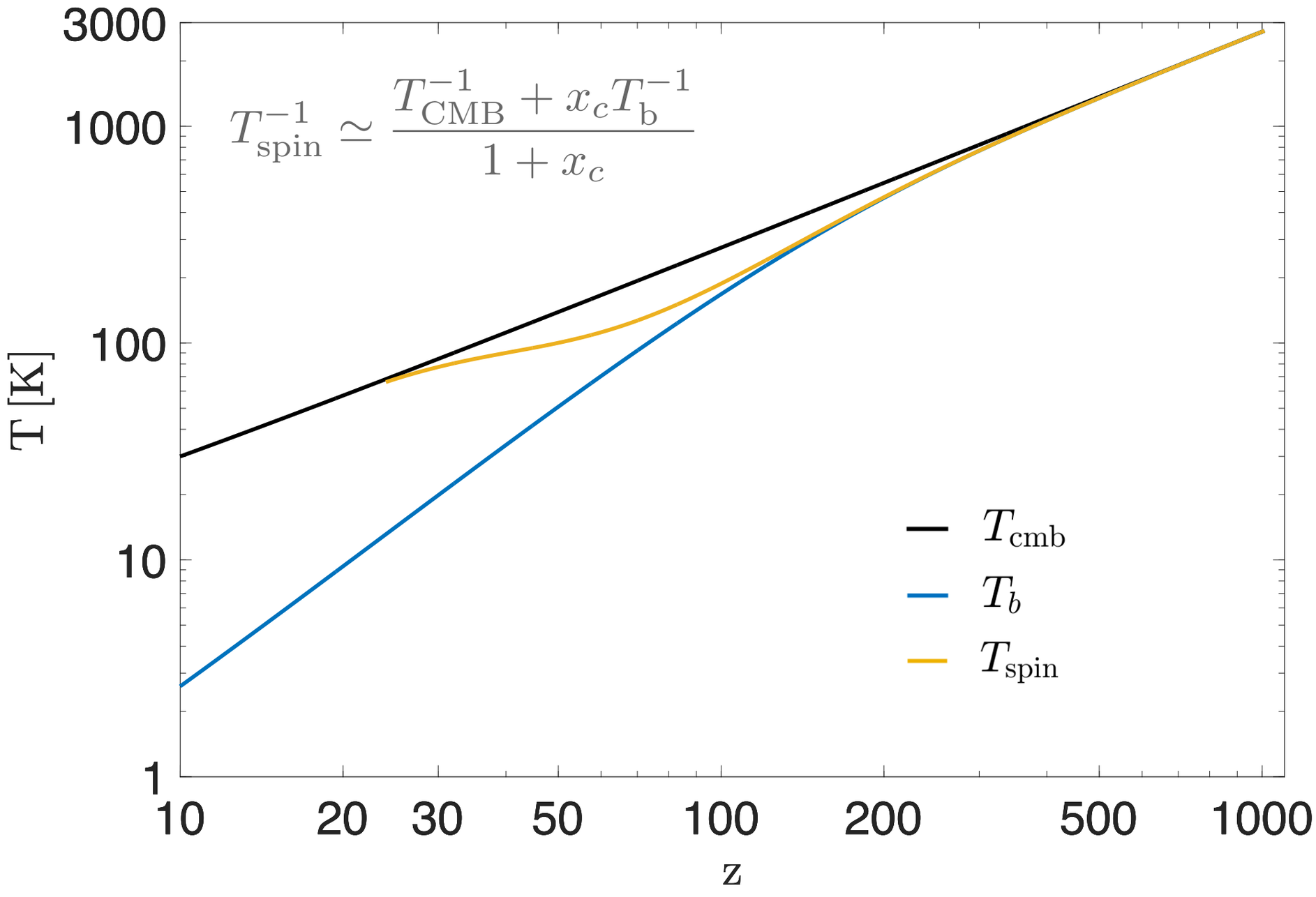

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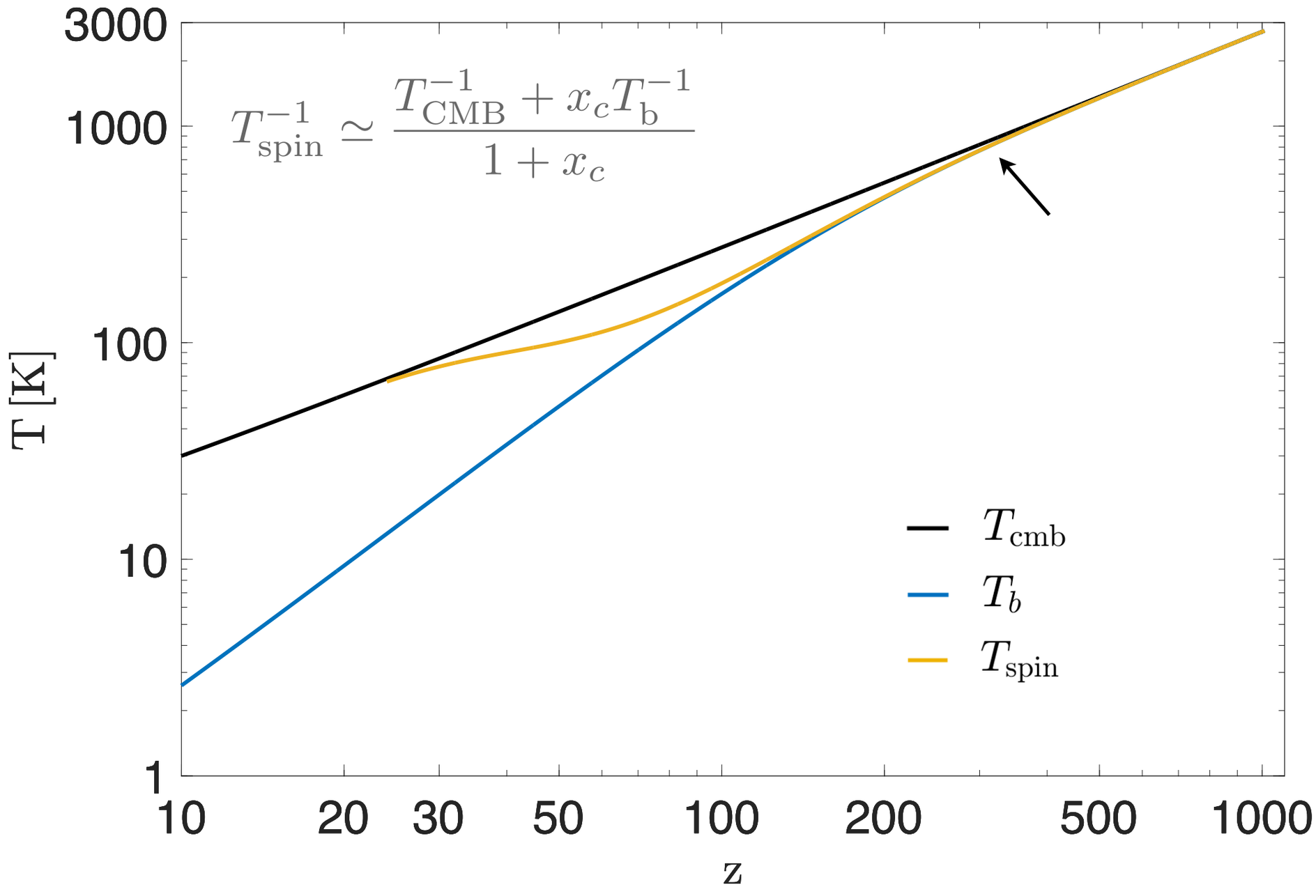

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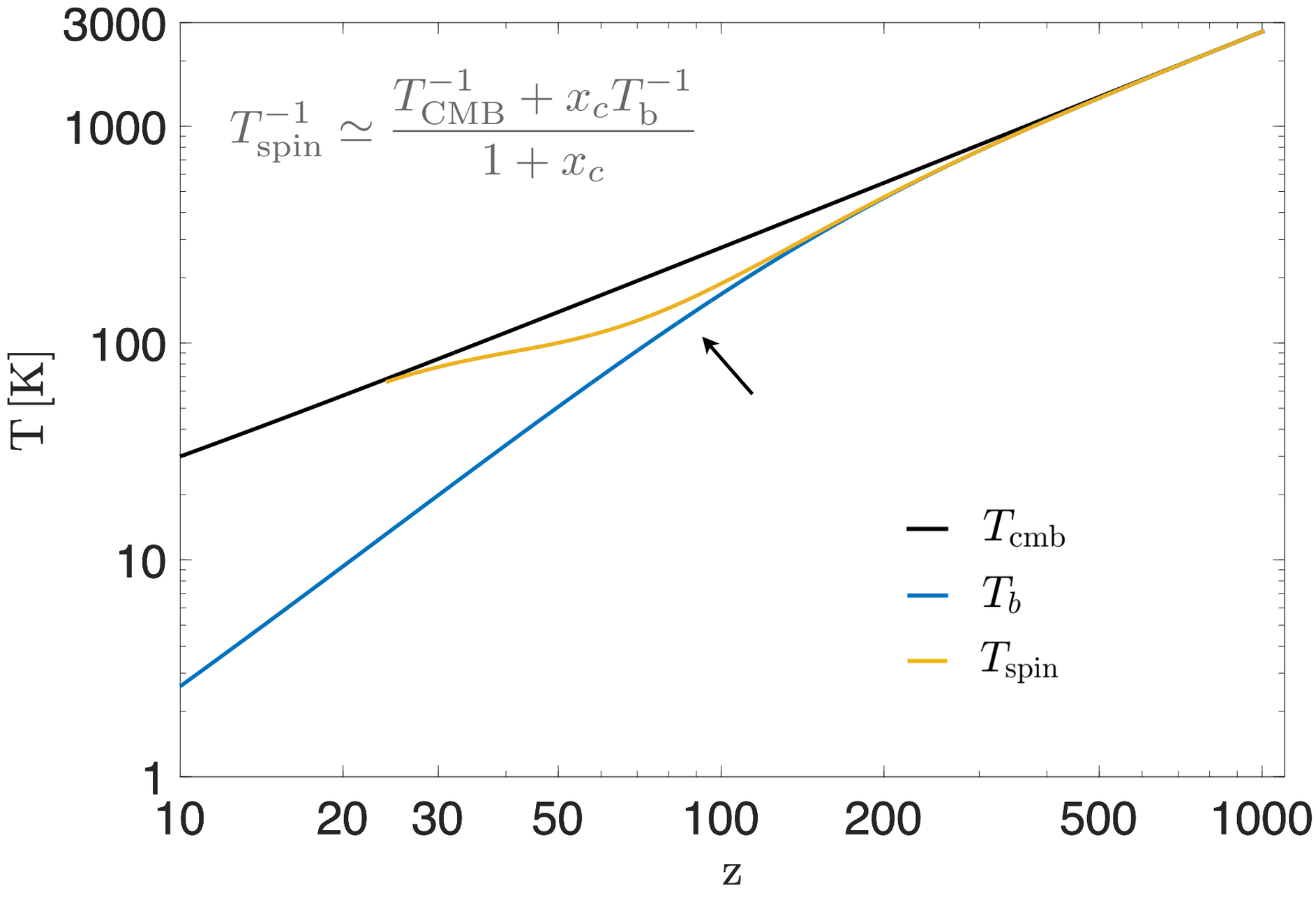

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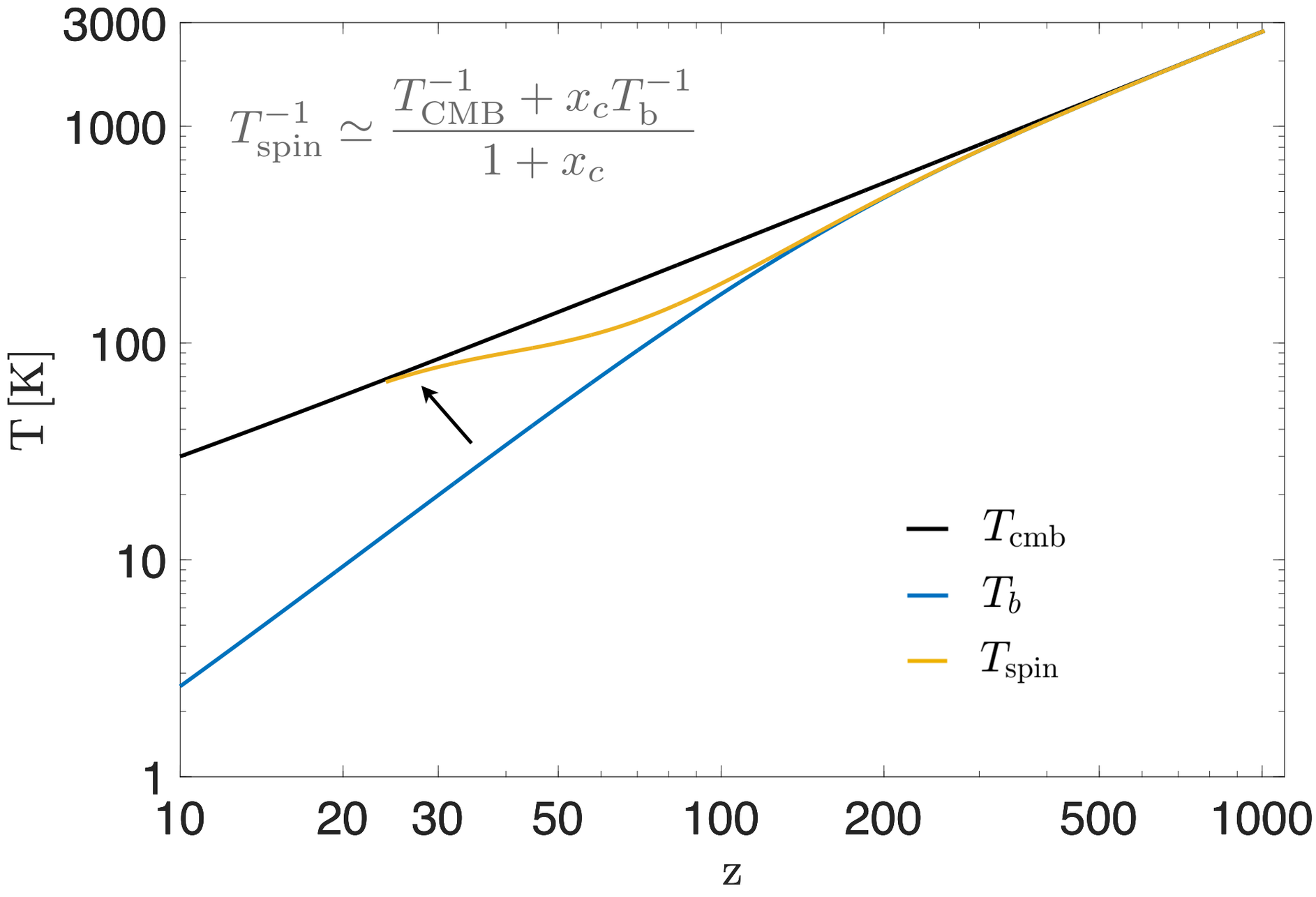

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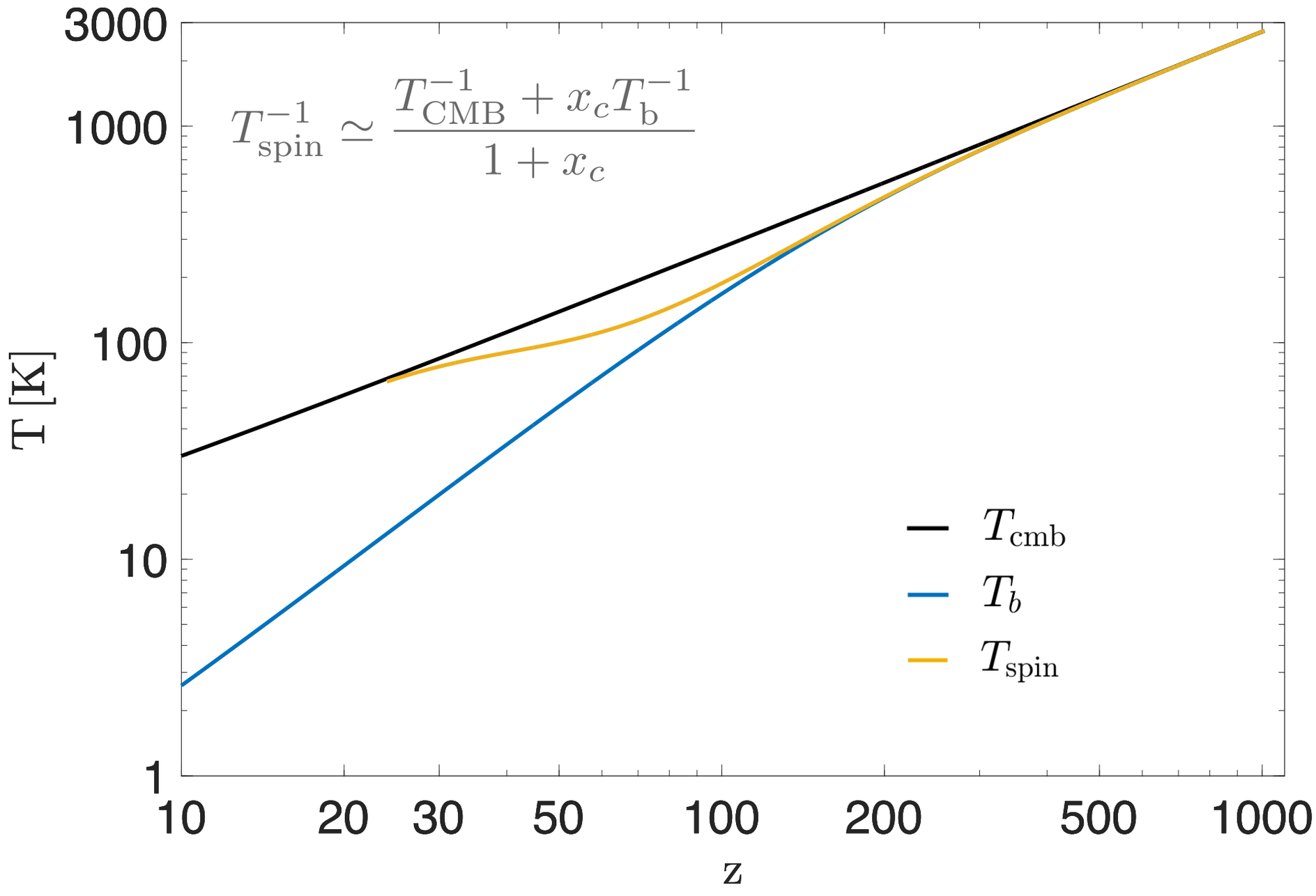

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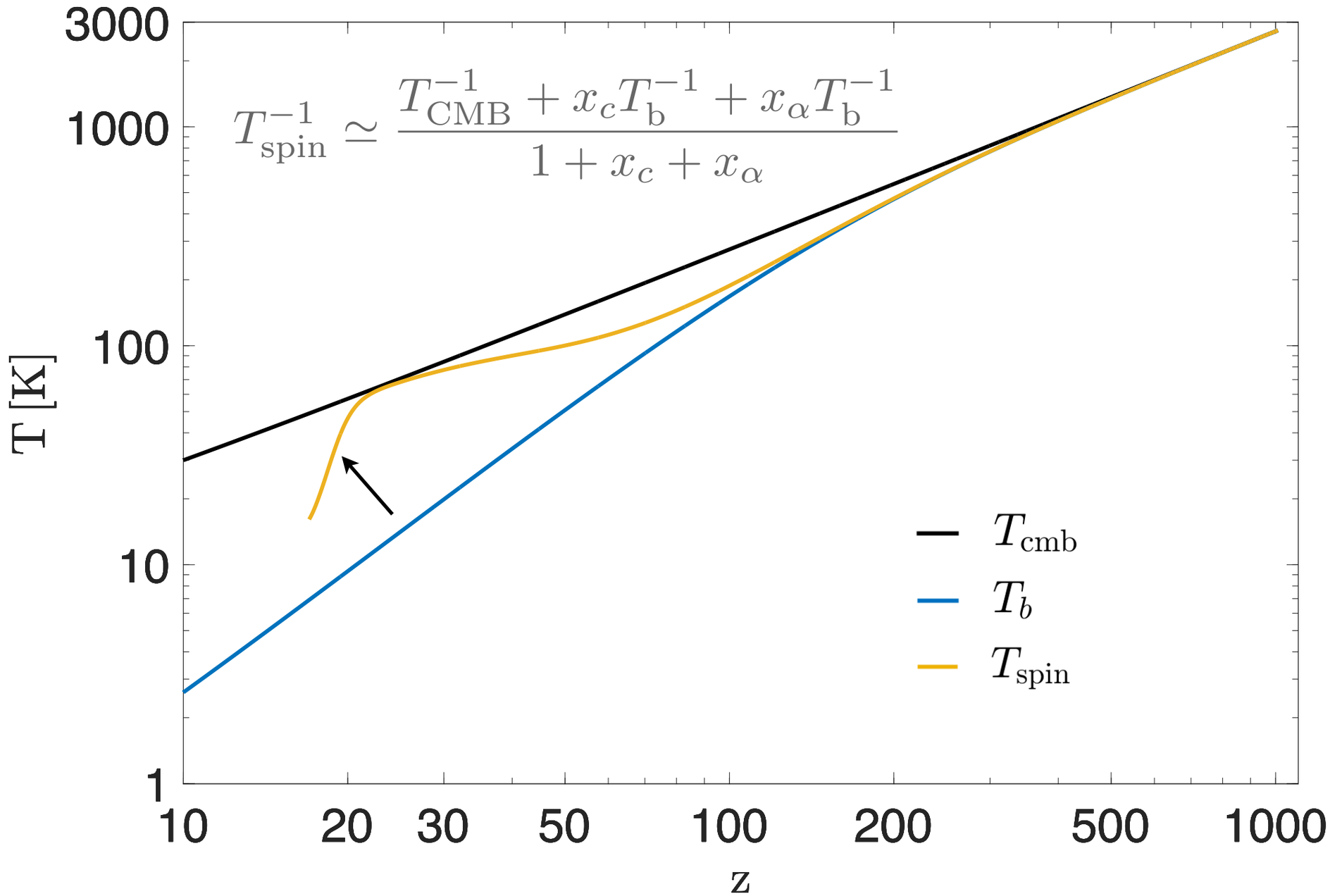

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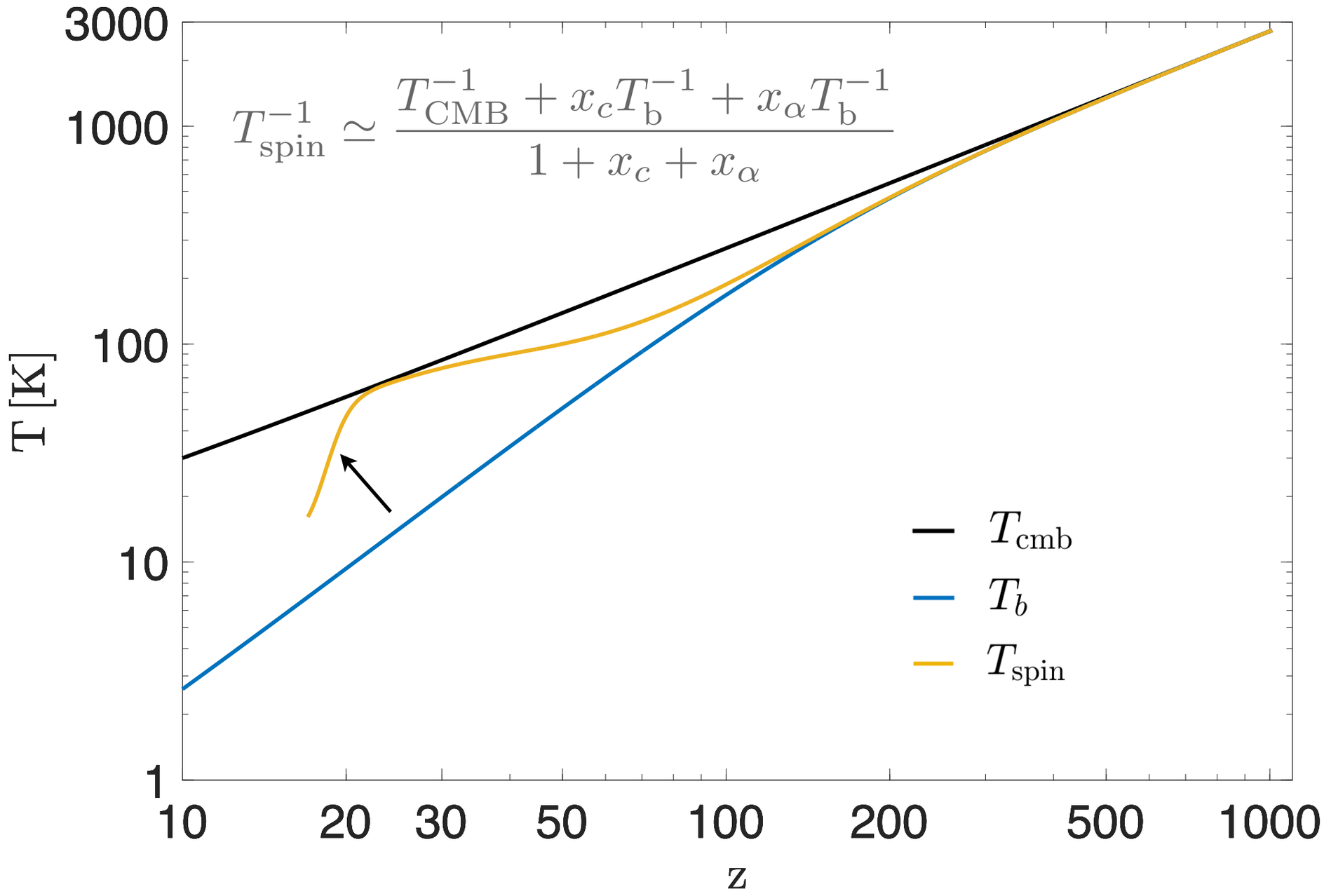

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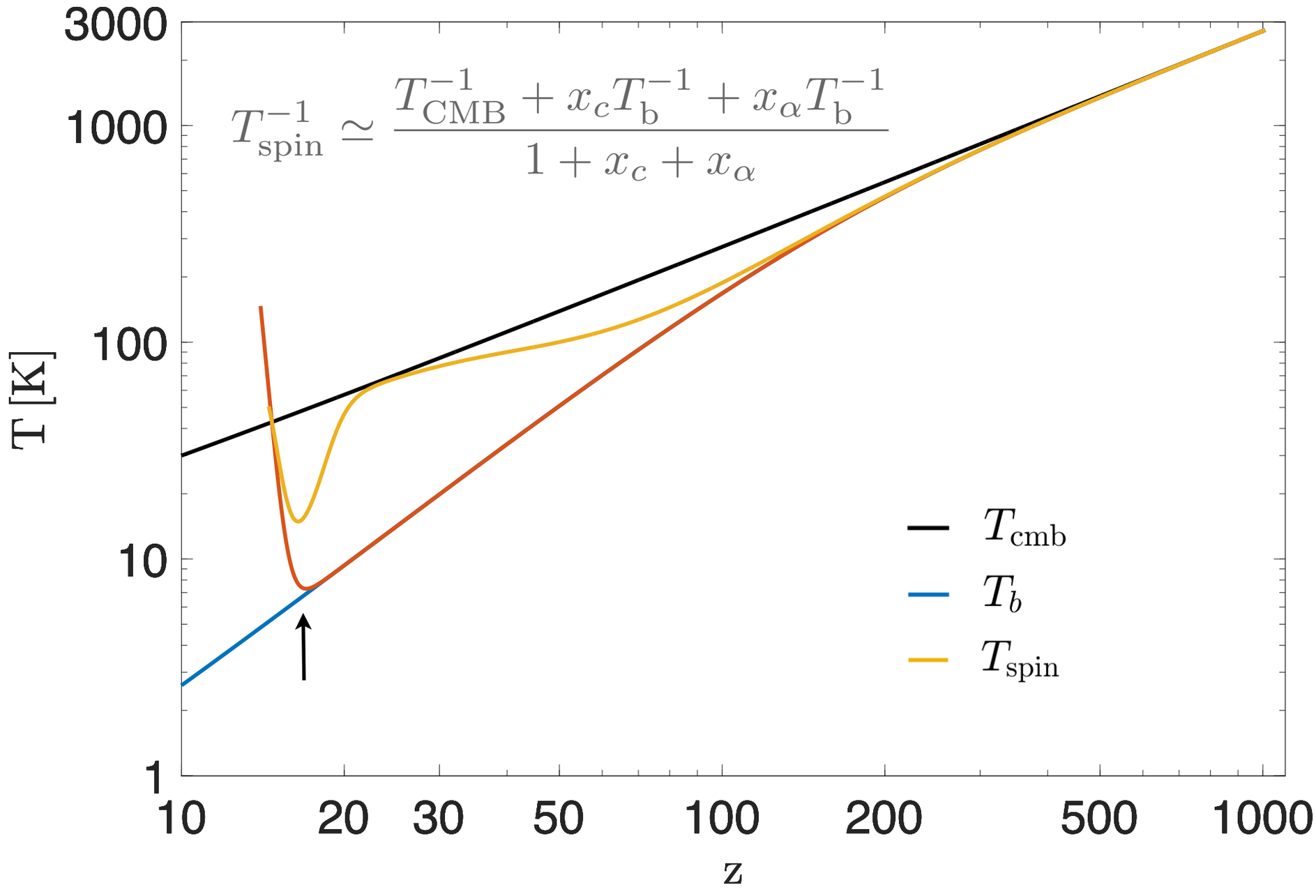

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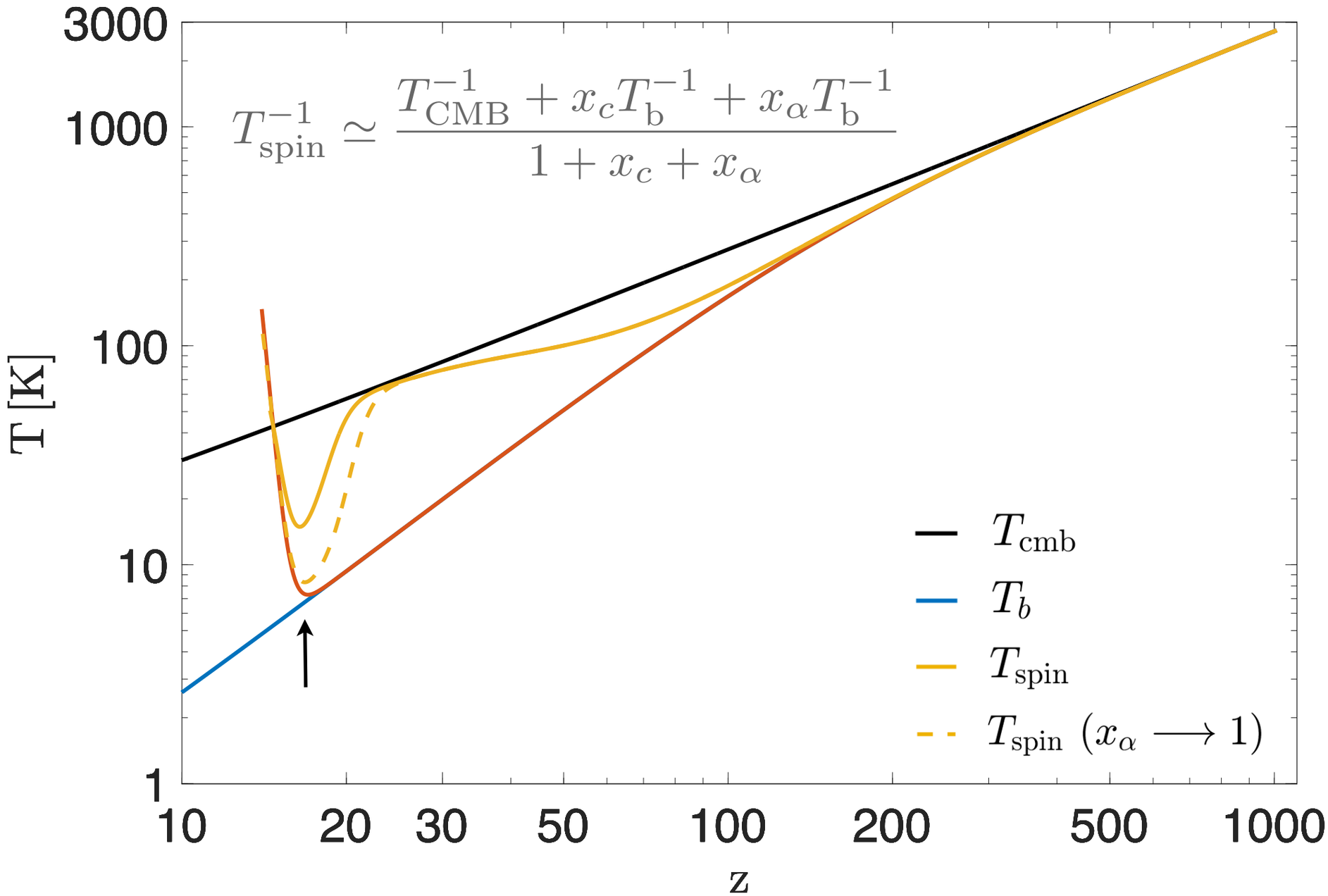

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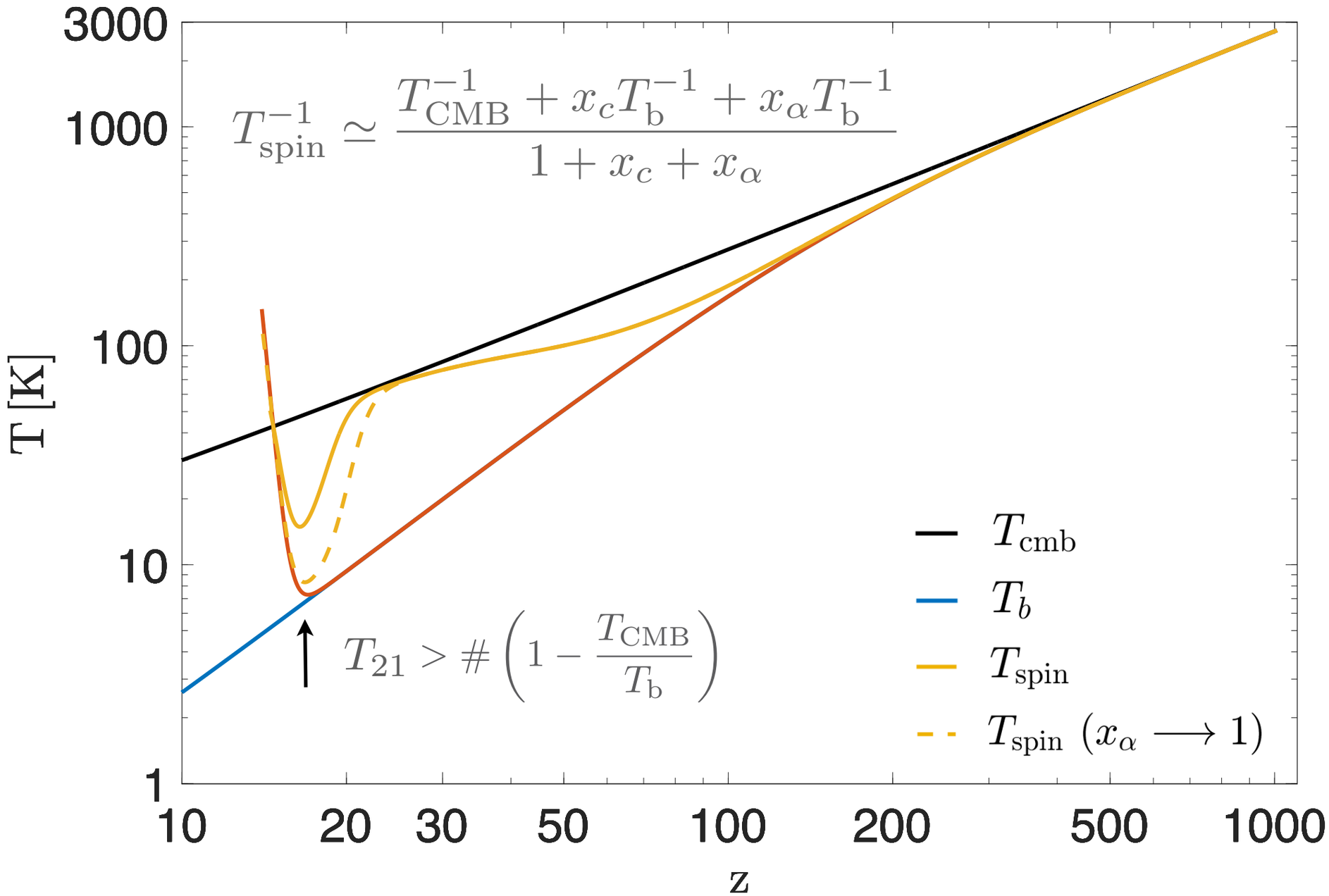

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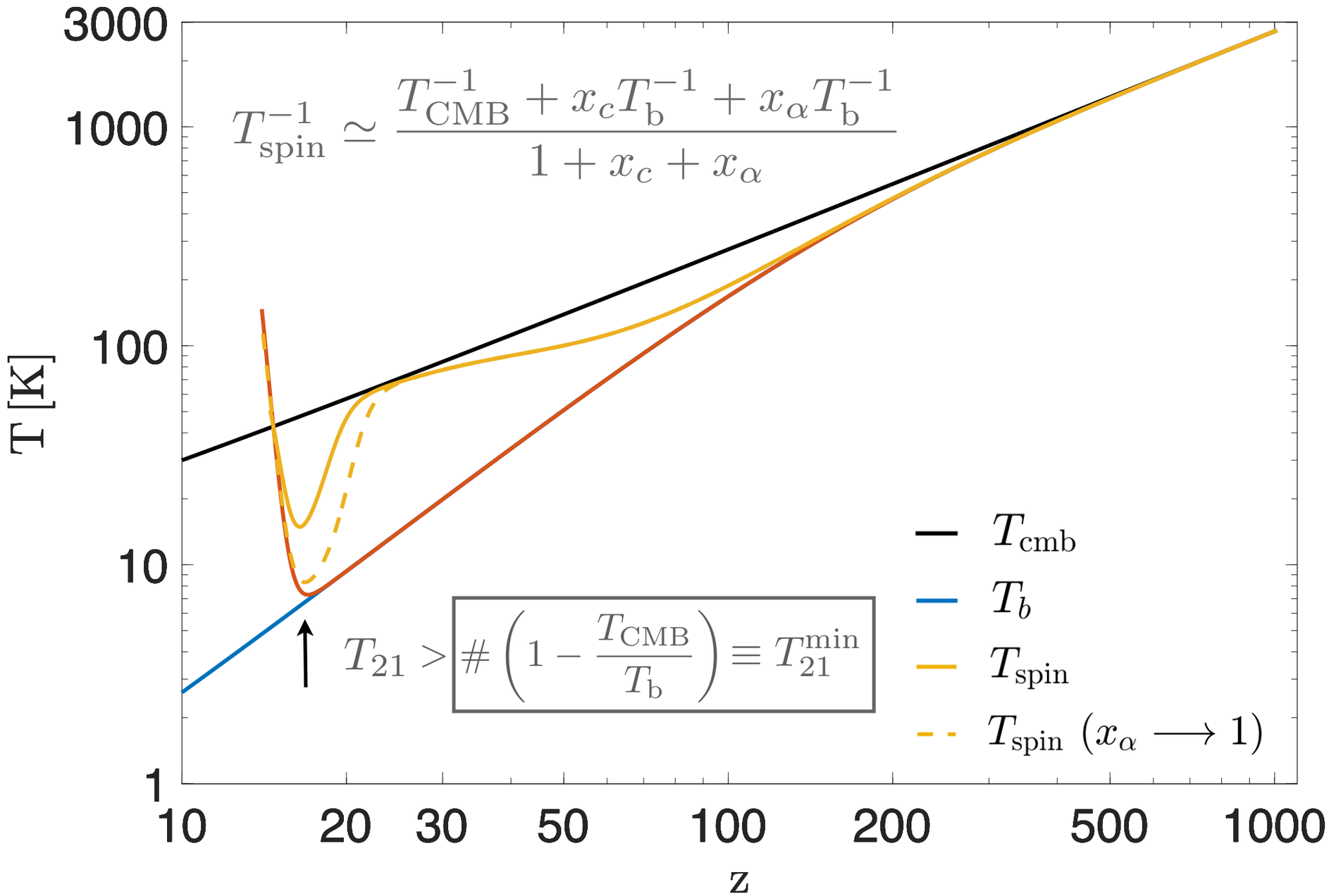

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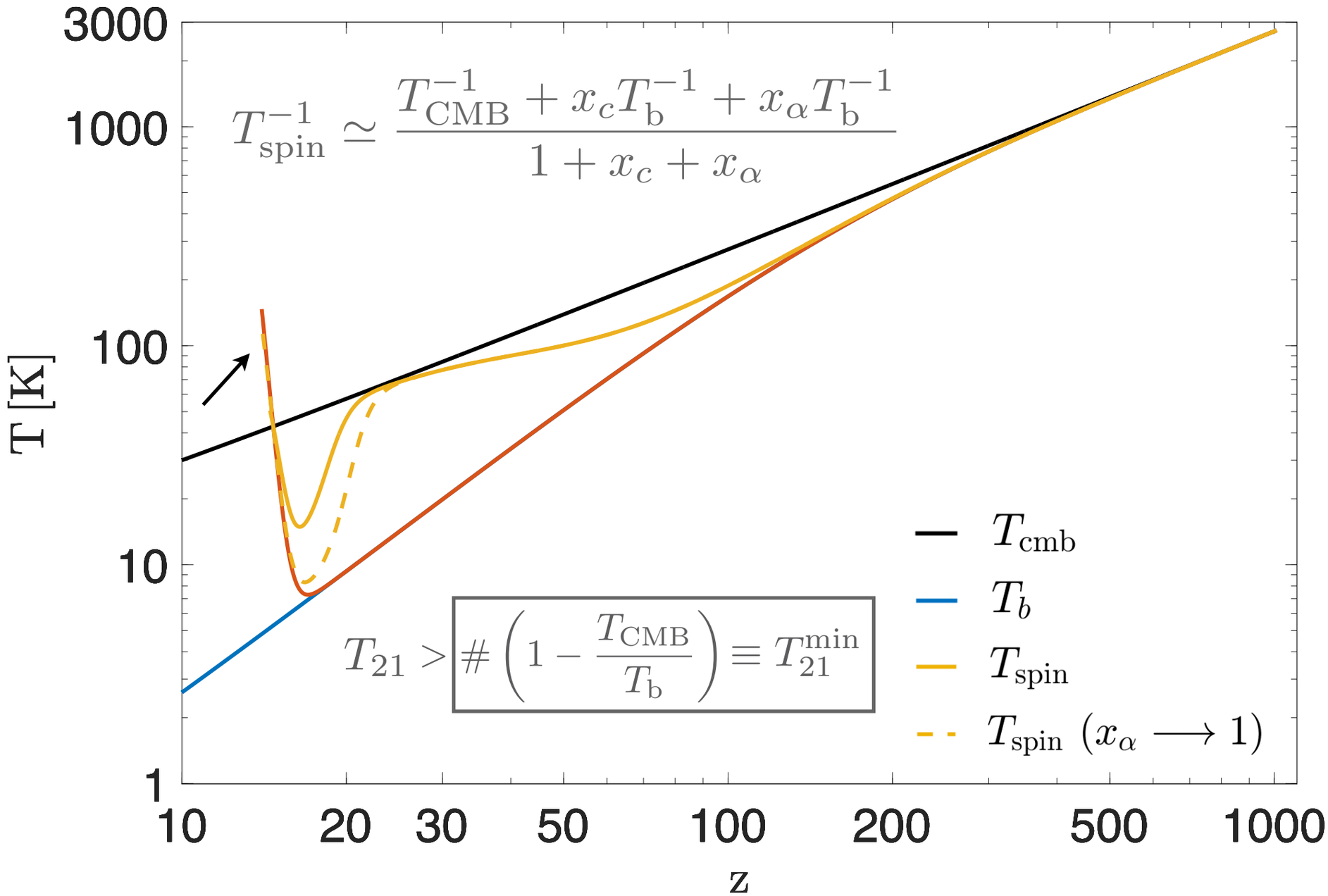
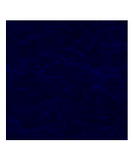
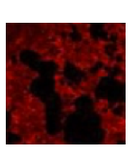


Absorption: (1) $T_{\rm spin} < T_{\rm CMB}$ (Dark Ages)  (2) $T_{\rm spin} < T_{\rm CMB}$ (Cosmic Dawn) 

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

Measuring the Cosmic Dawn Global 21cm Signal

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The observable:

$$T_{21}(z) \approx \frac{T_{\rm Spin} - T_{\rm CMB}}{1+z}\tau \sim 23\,{\rm mK} \times x_{\rm HI}(z) \left[\left(\frac{0.15}{\Omega_m}\right)\left(\frac{1+z}{10}\right)\right]^{1/2} \left(\frac{\Omega_b h}{0.02}\right)\left(1 - \frac{T_{\rm CMB}(z)}{T_{\rm Spin}(z)}\right)$$

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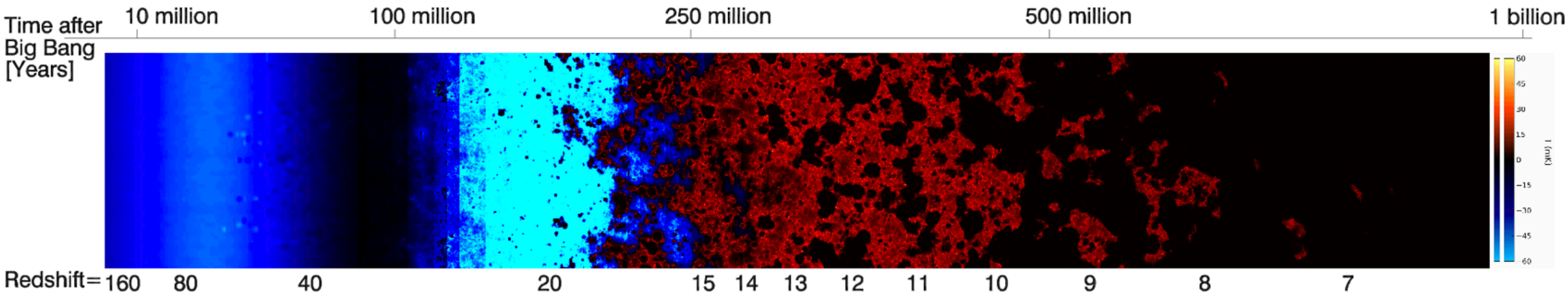

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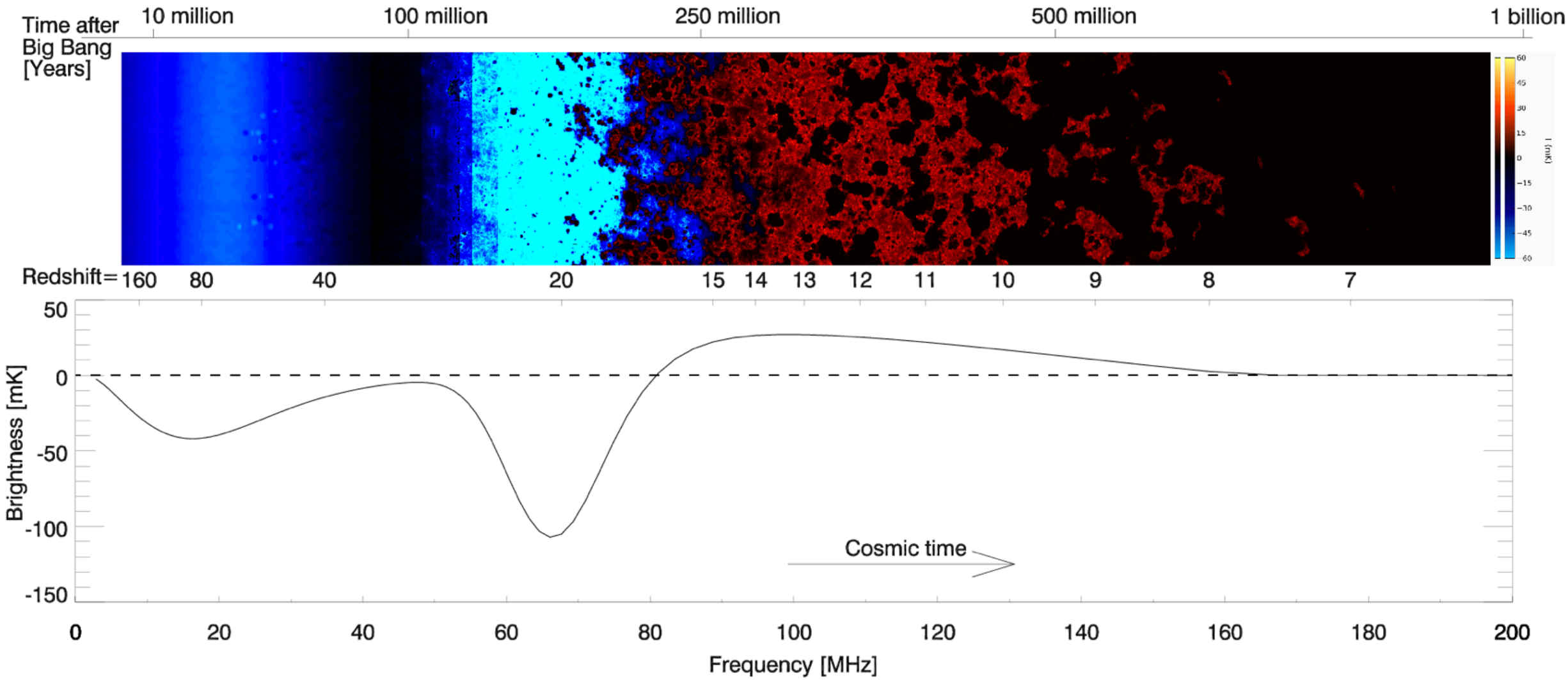

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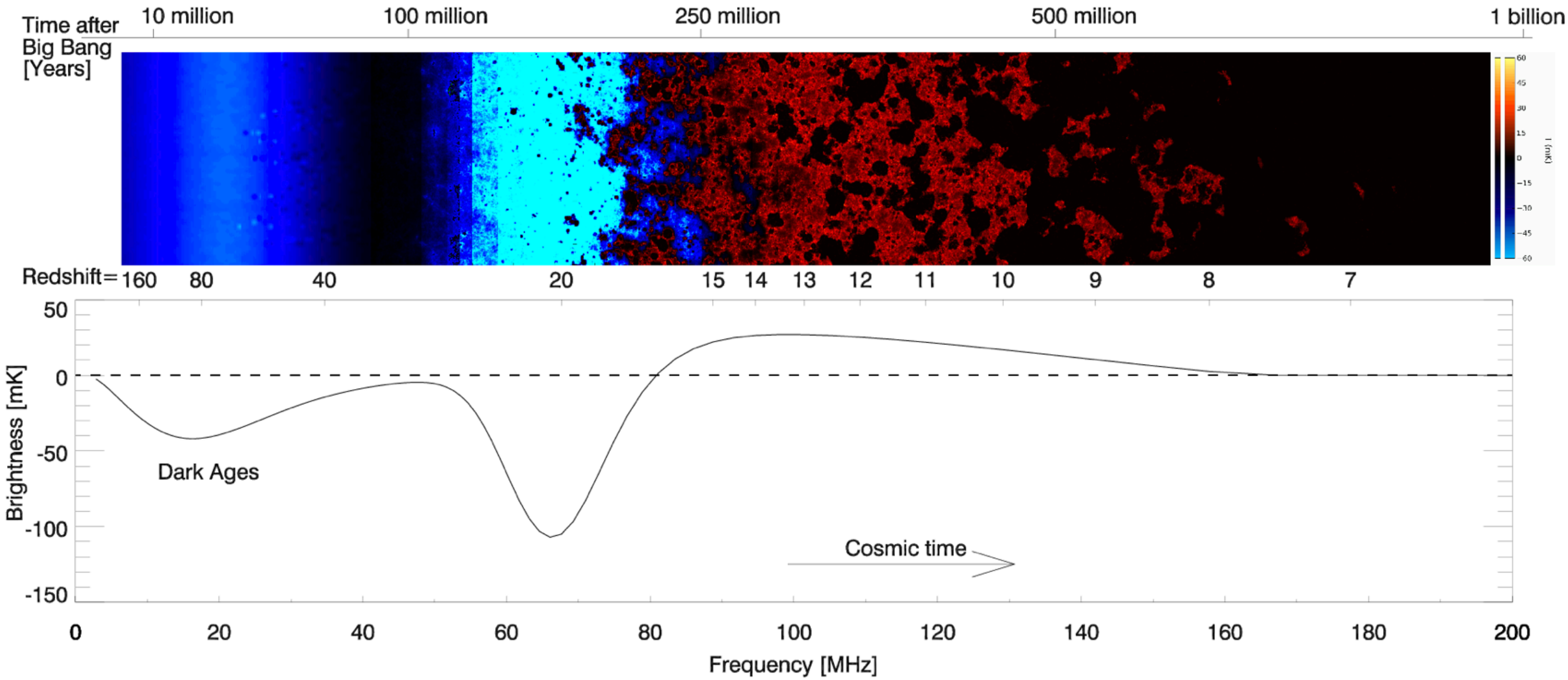

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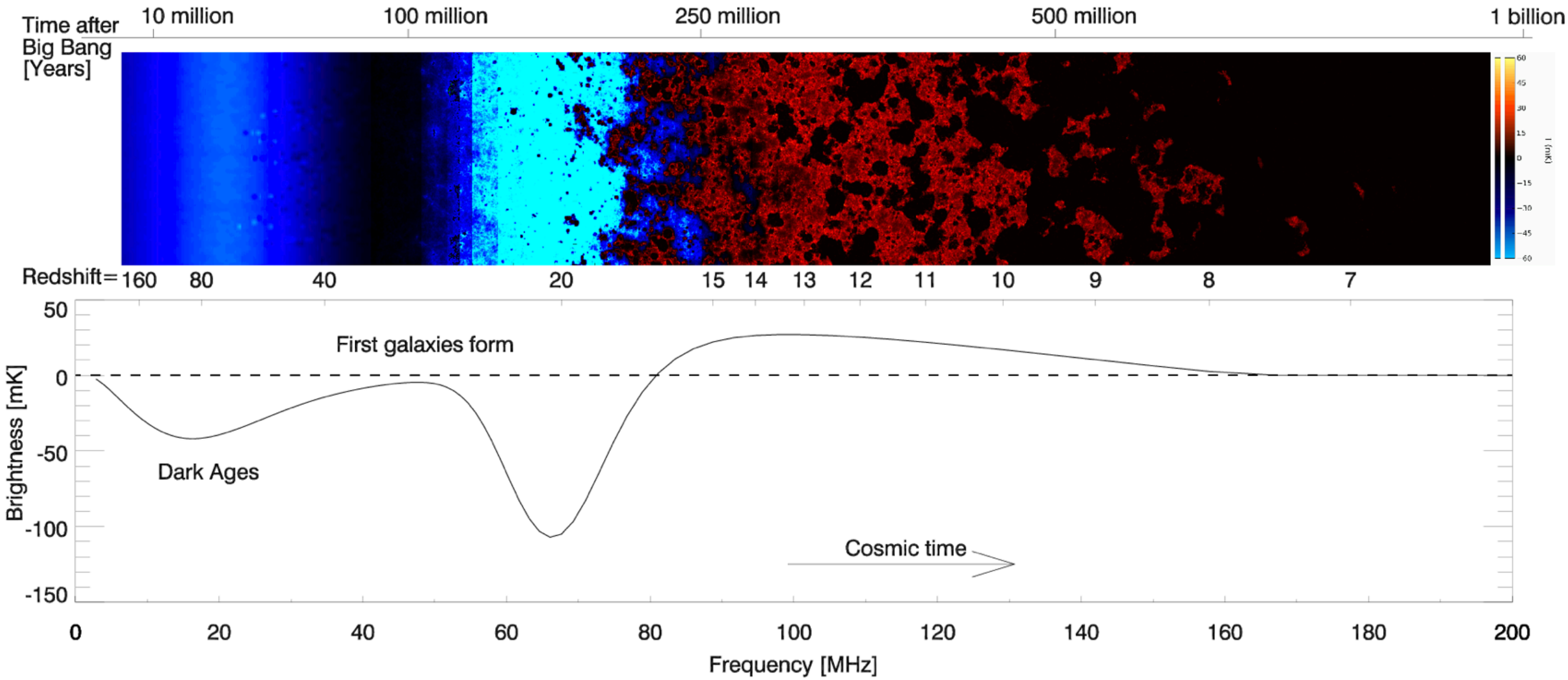

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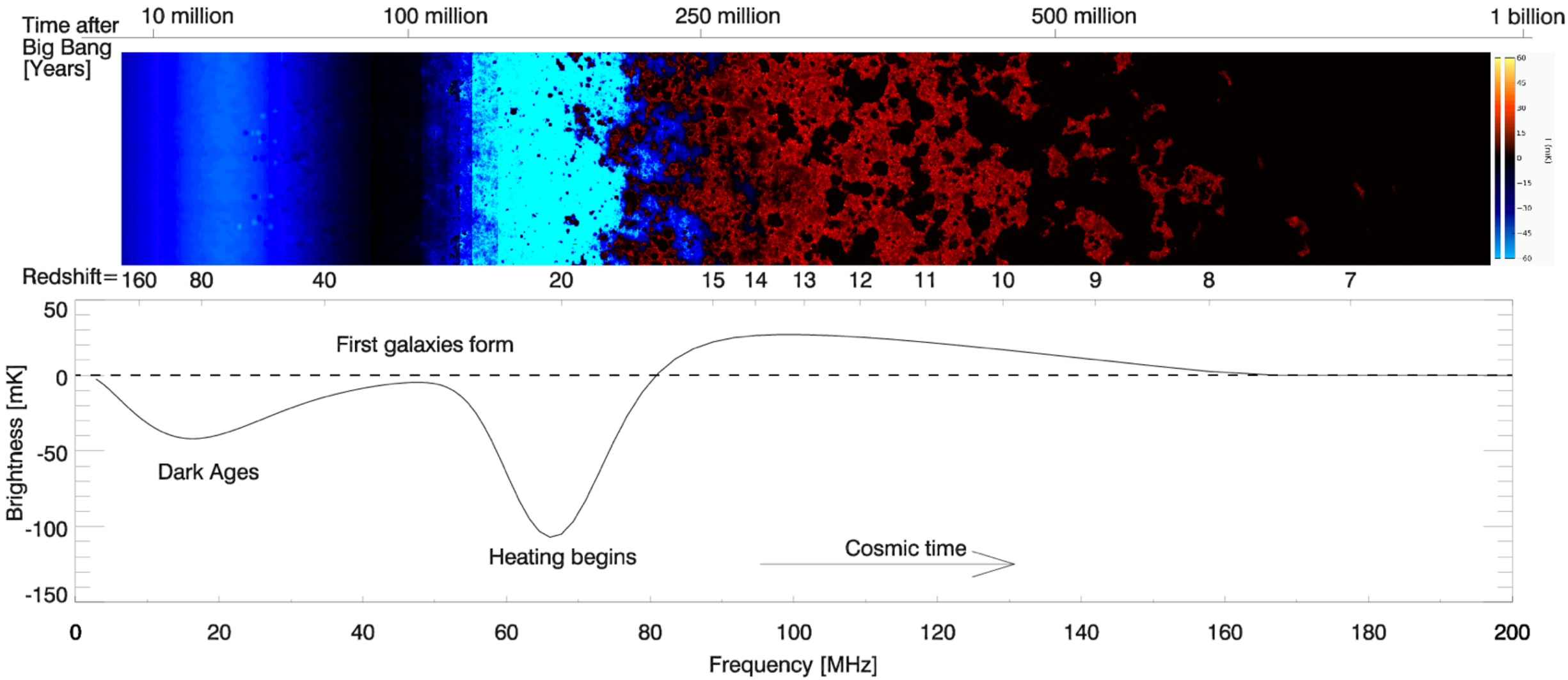

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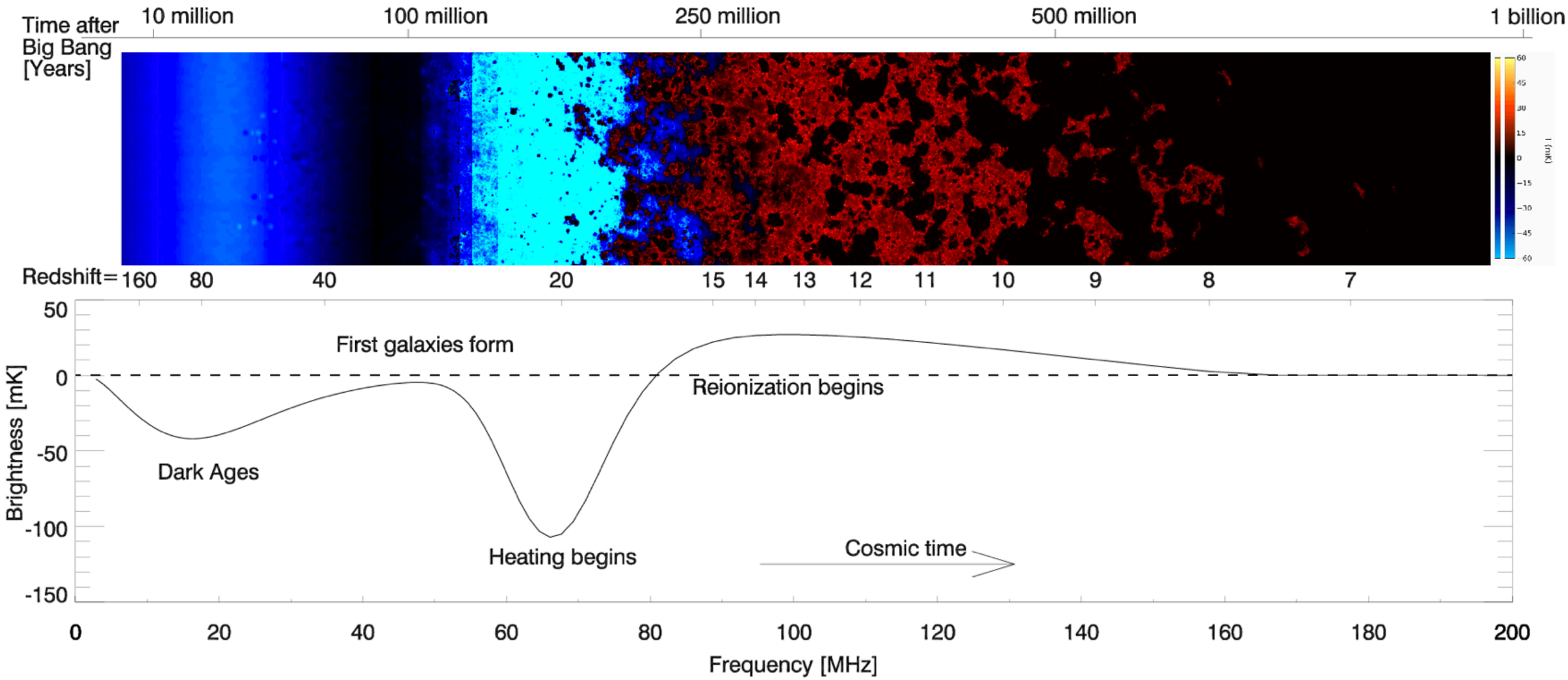

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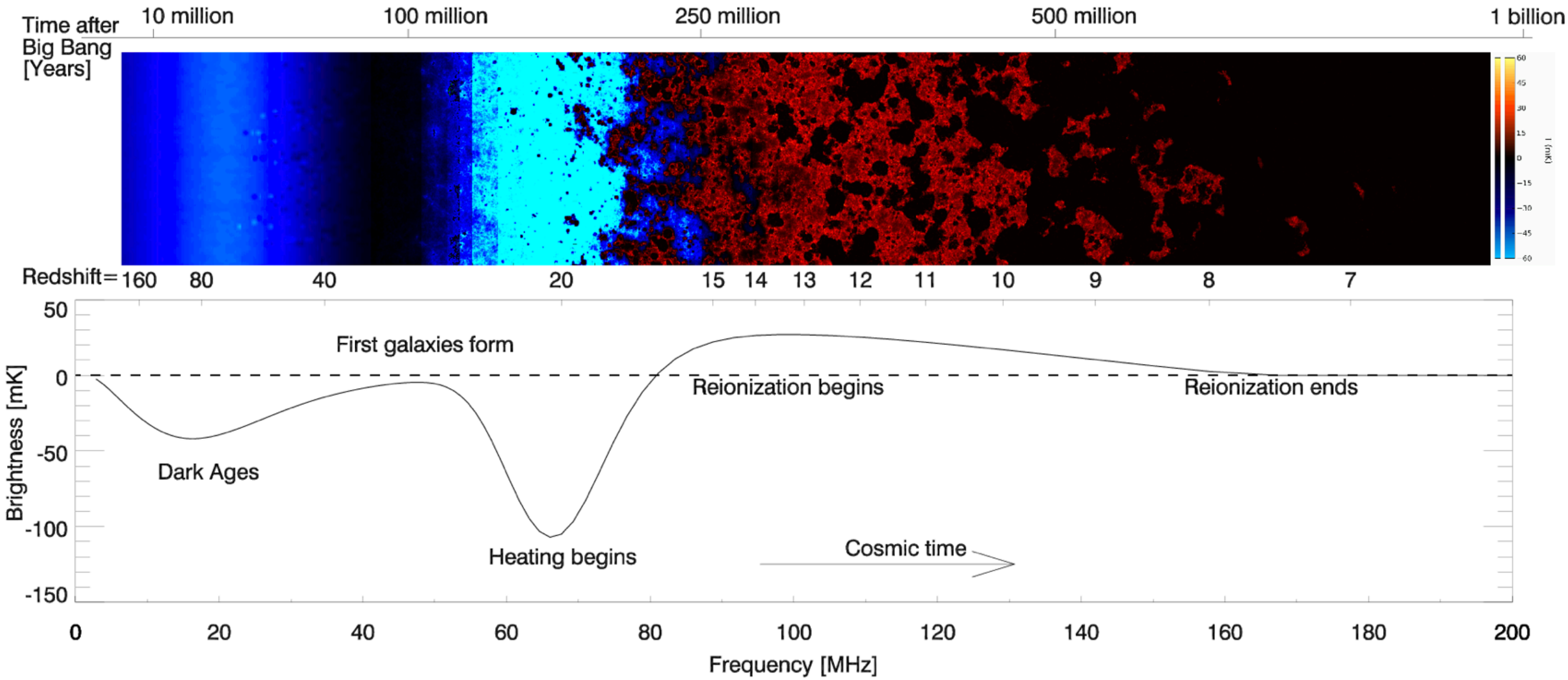

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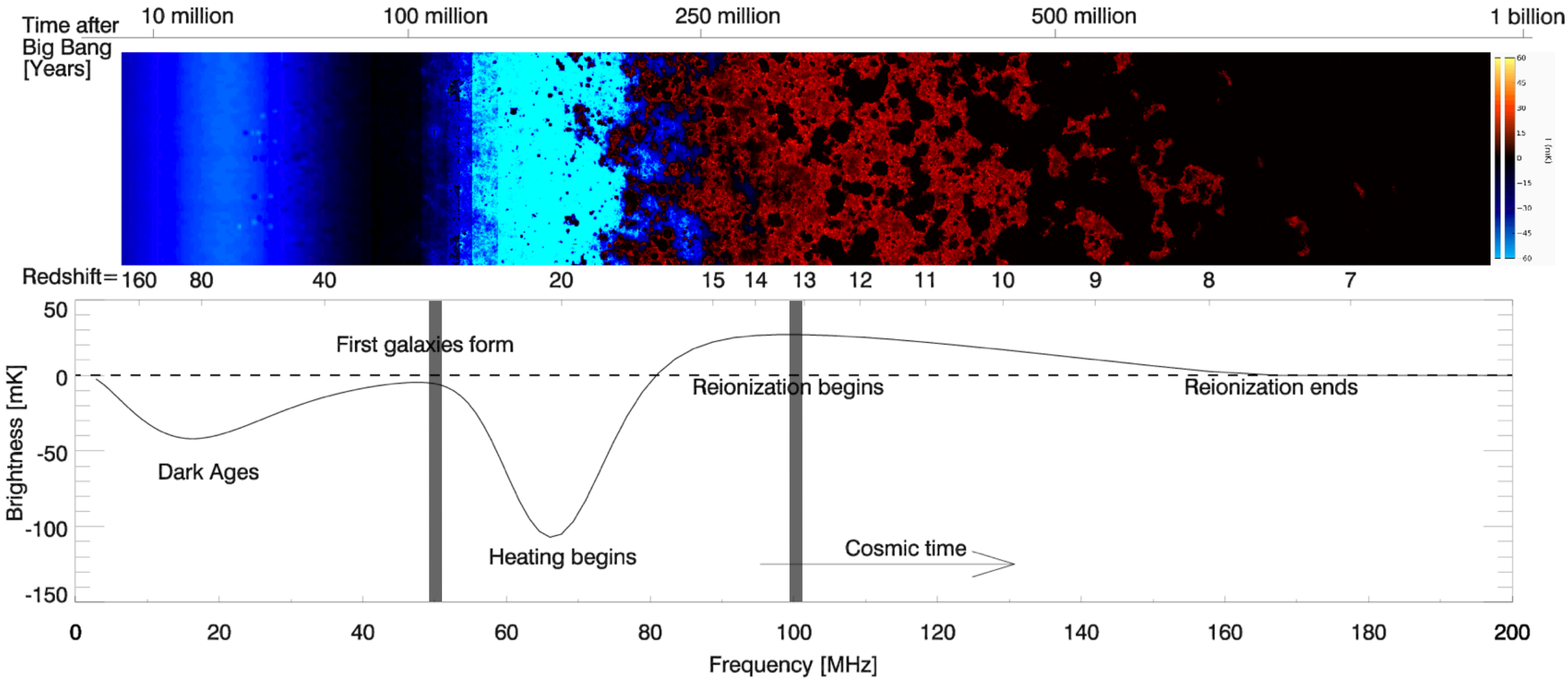

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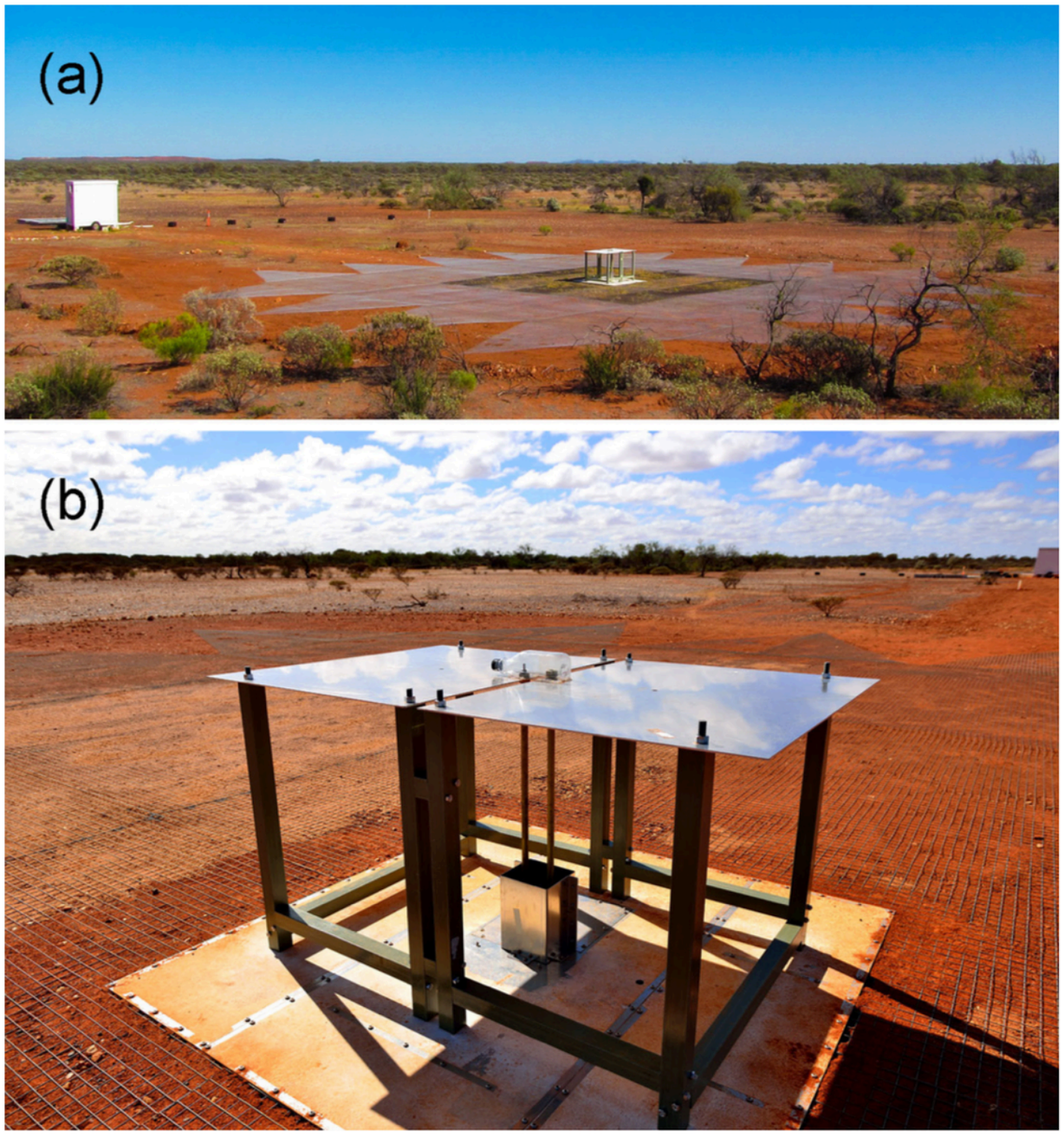
EDGES Low-Band

Experiment to Detect the Global Epoch of Reionization Signature



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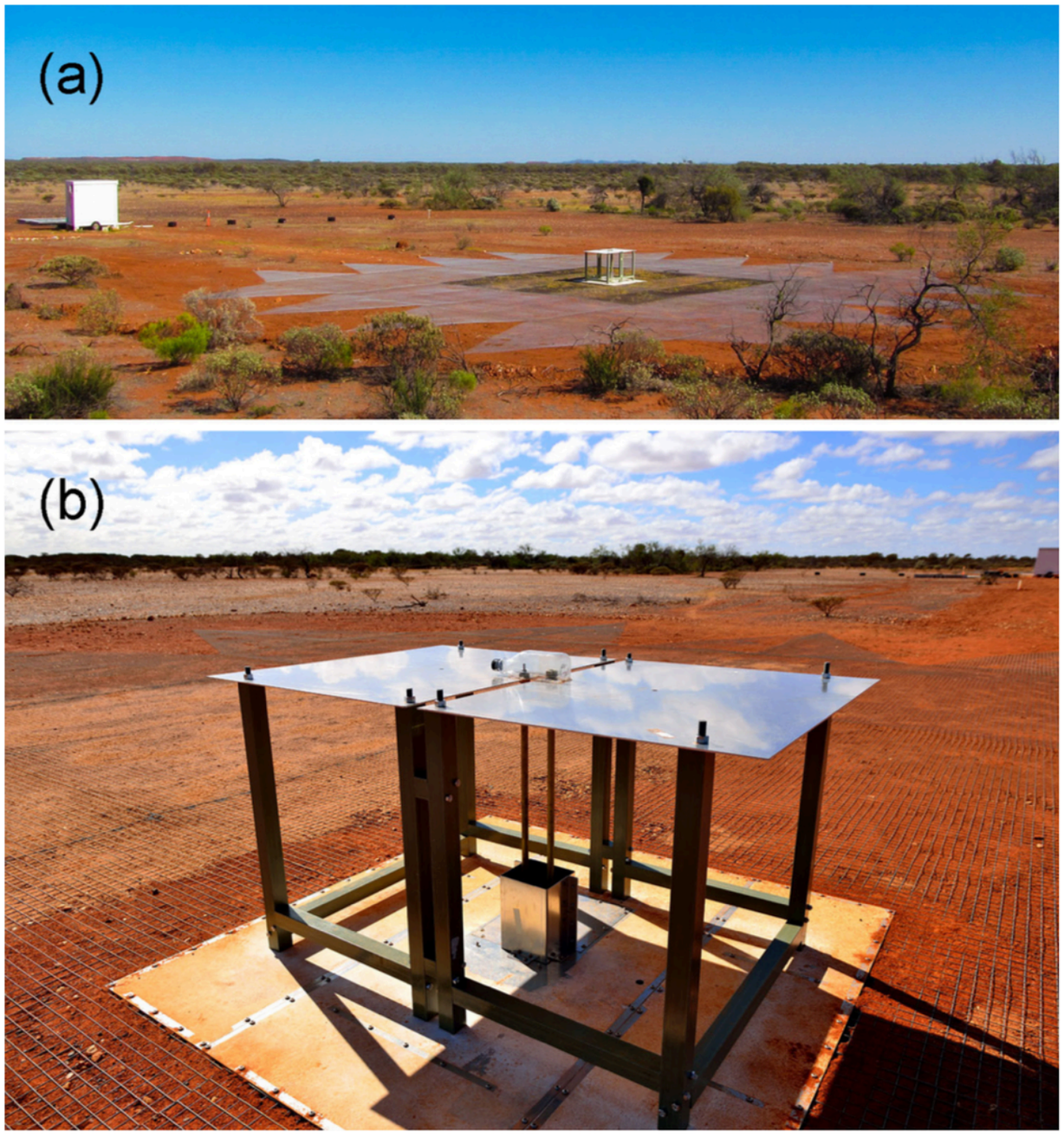

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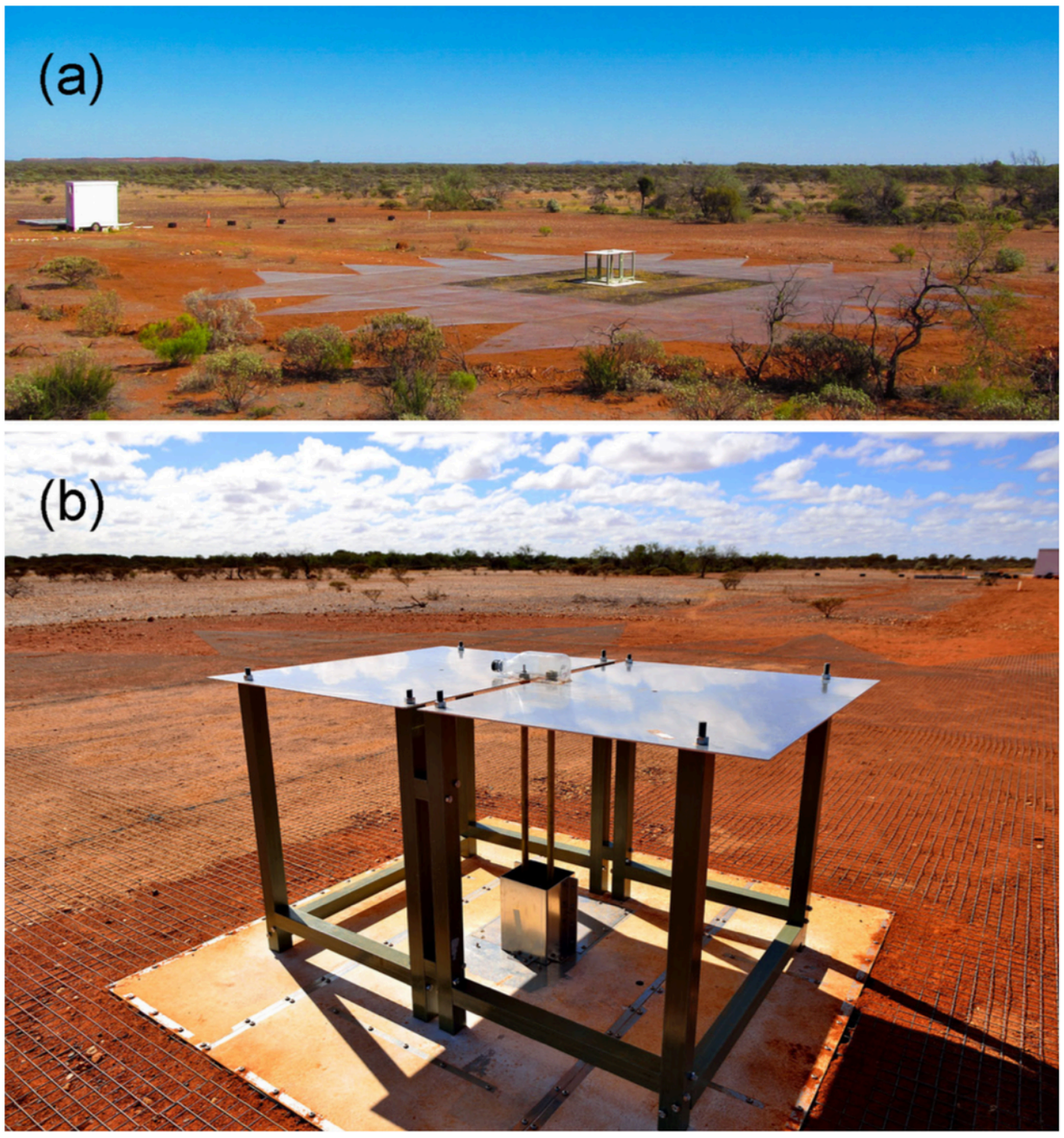

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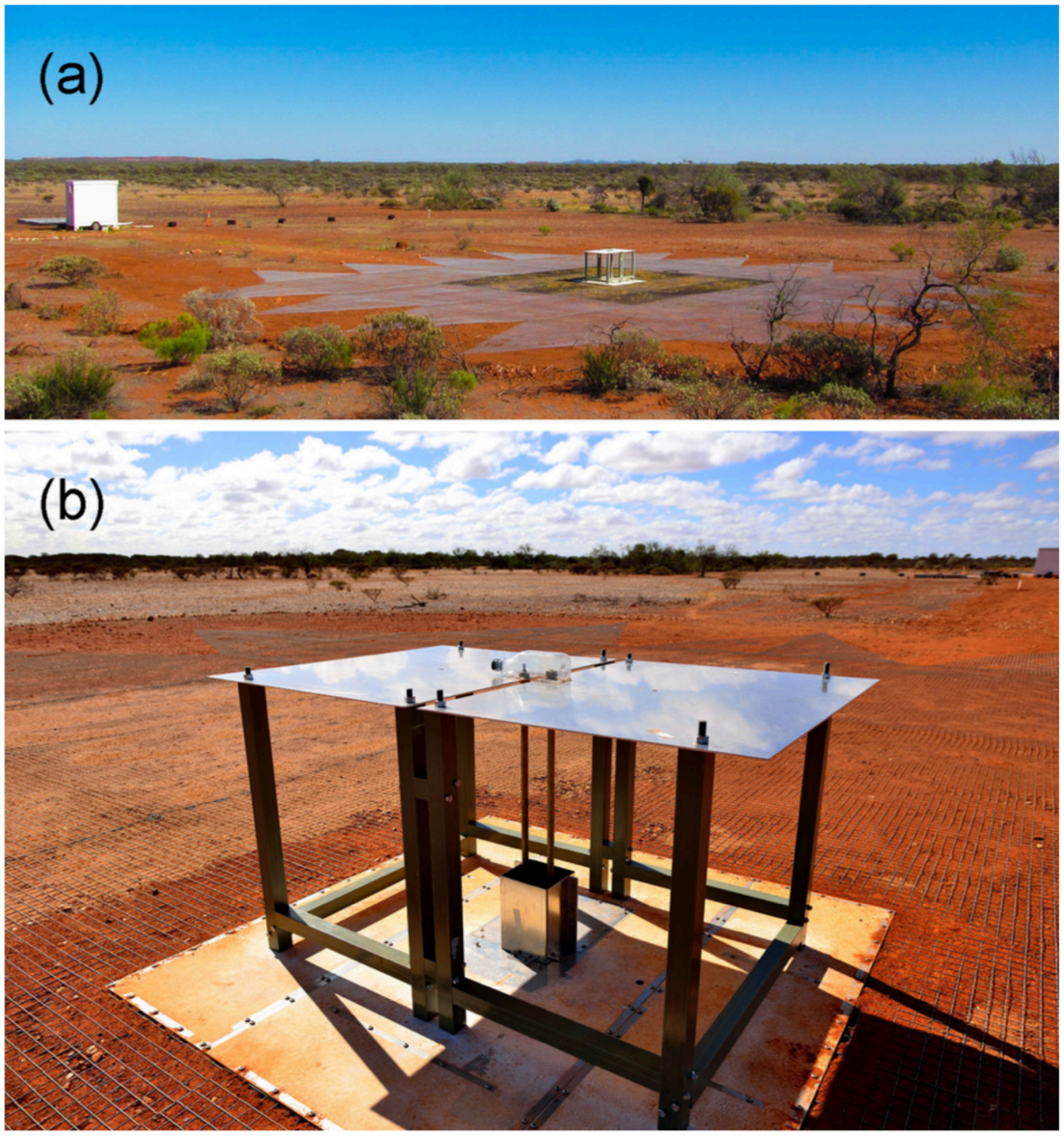

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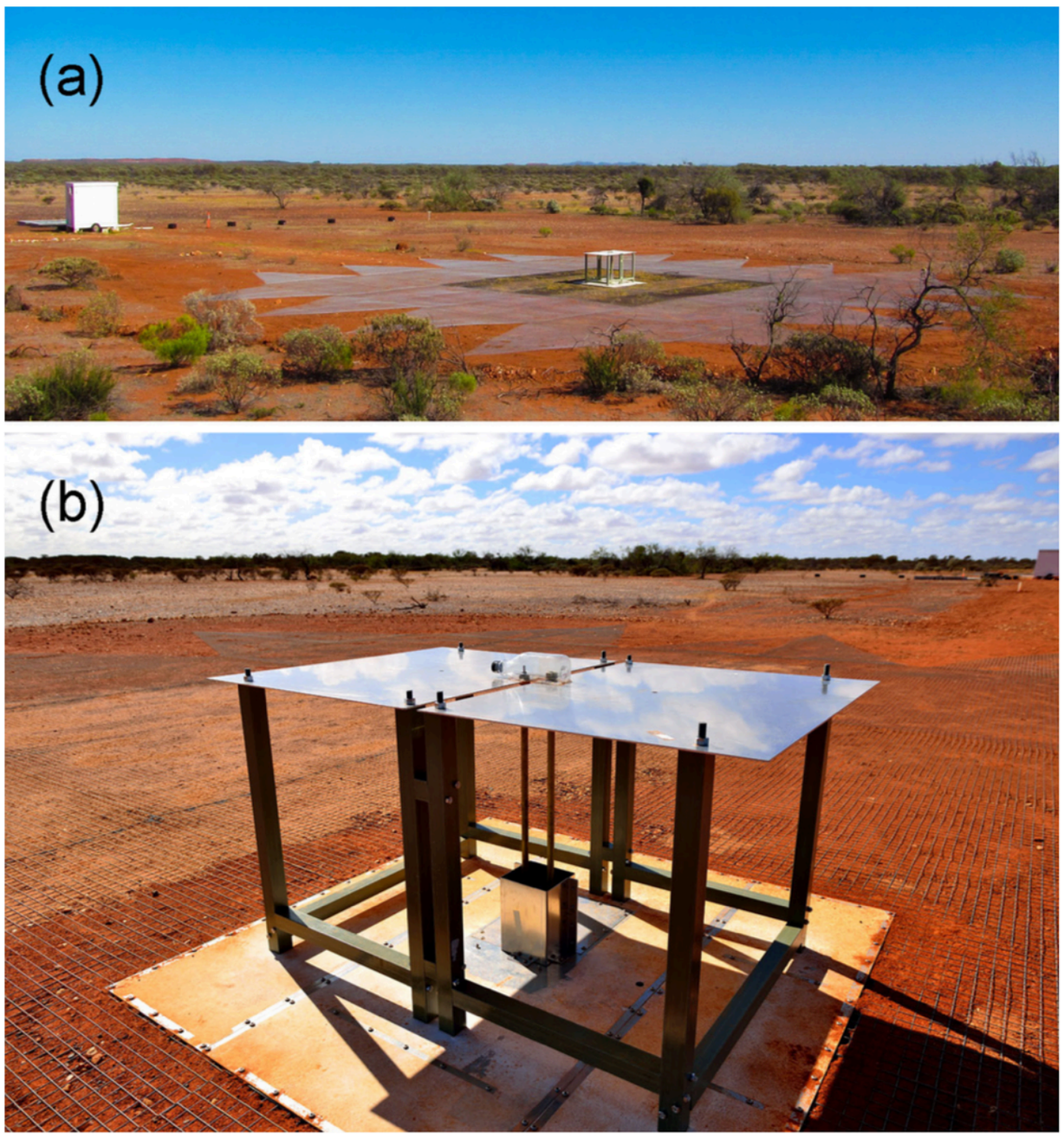

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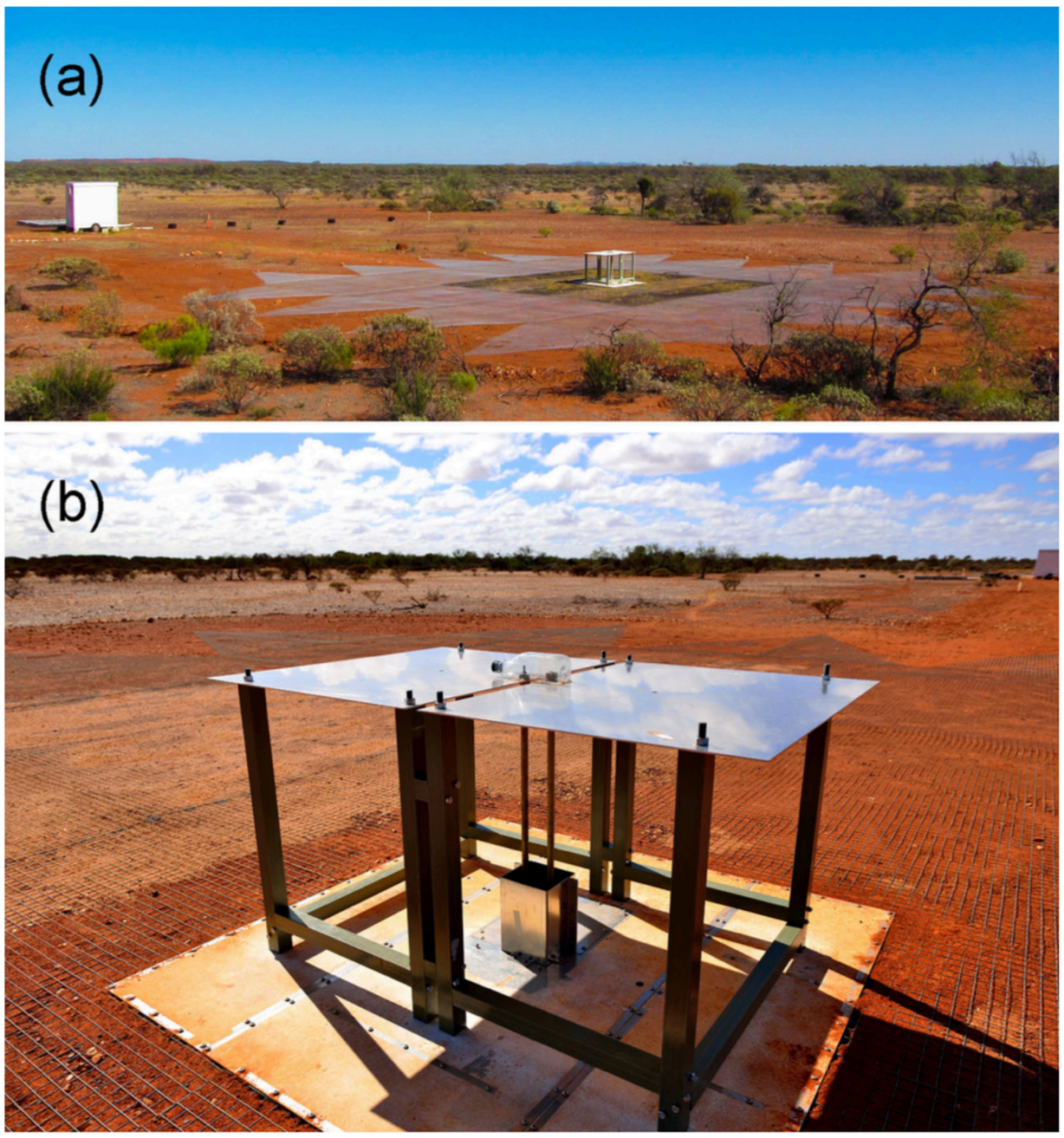

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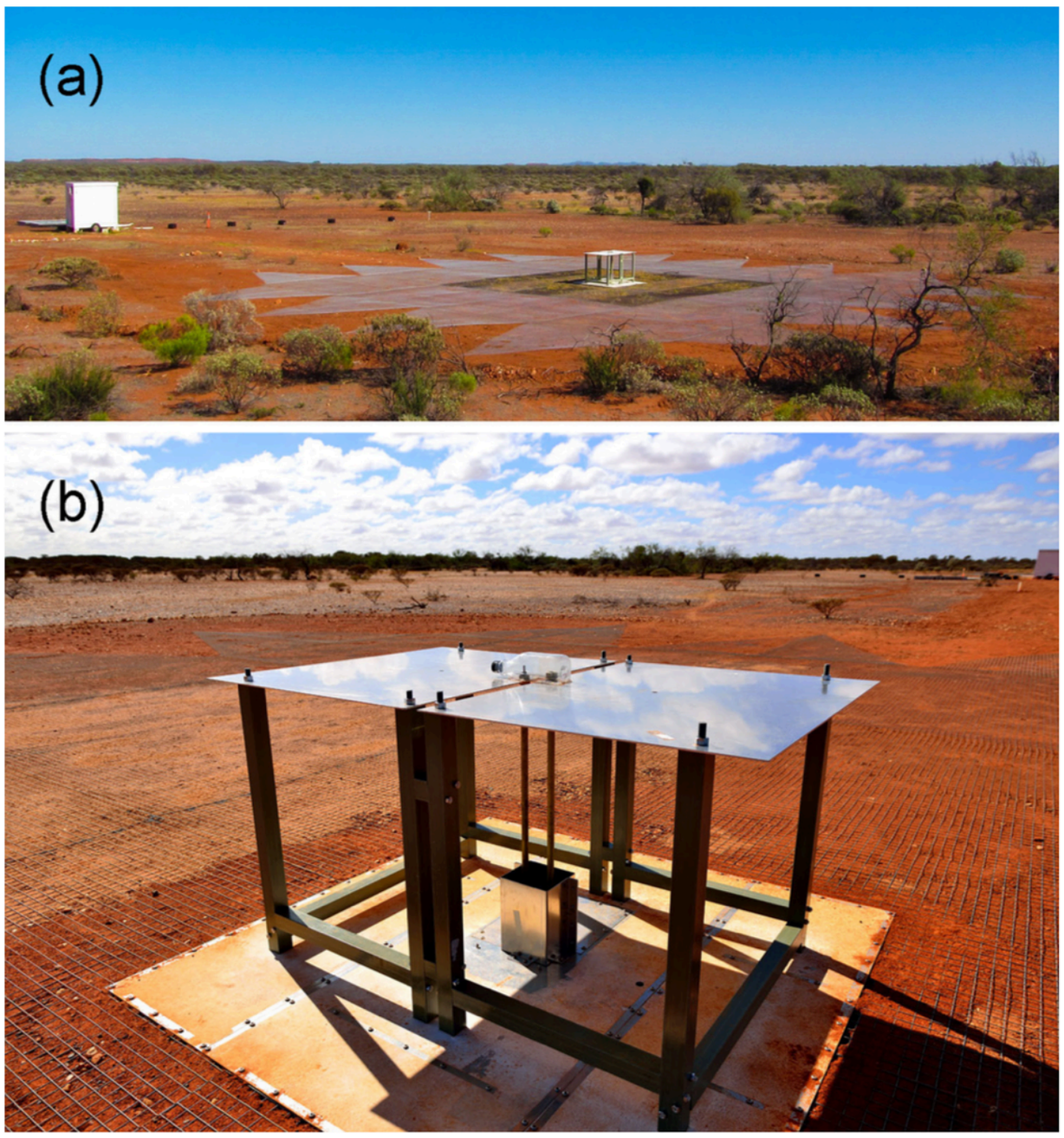

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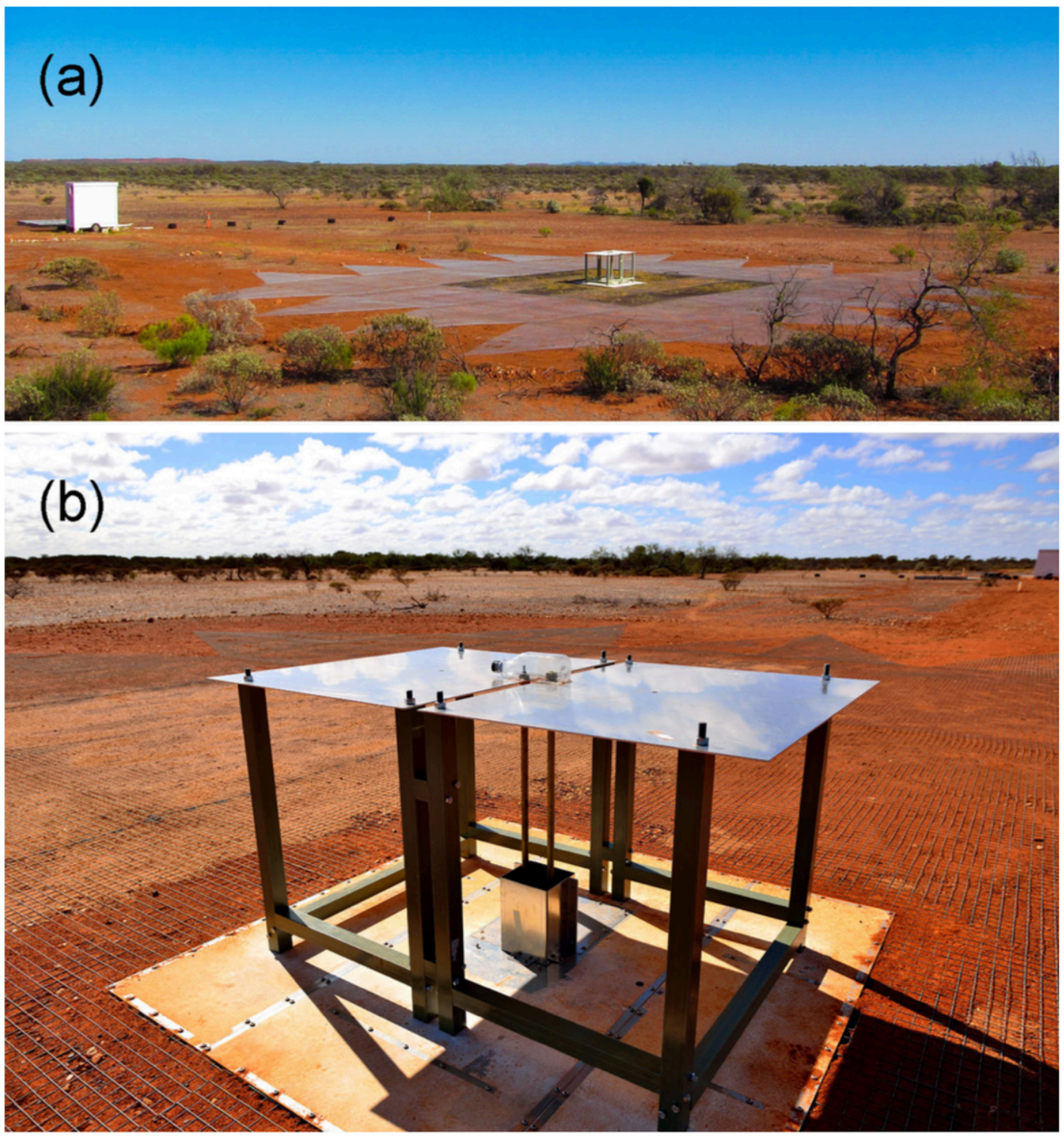

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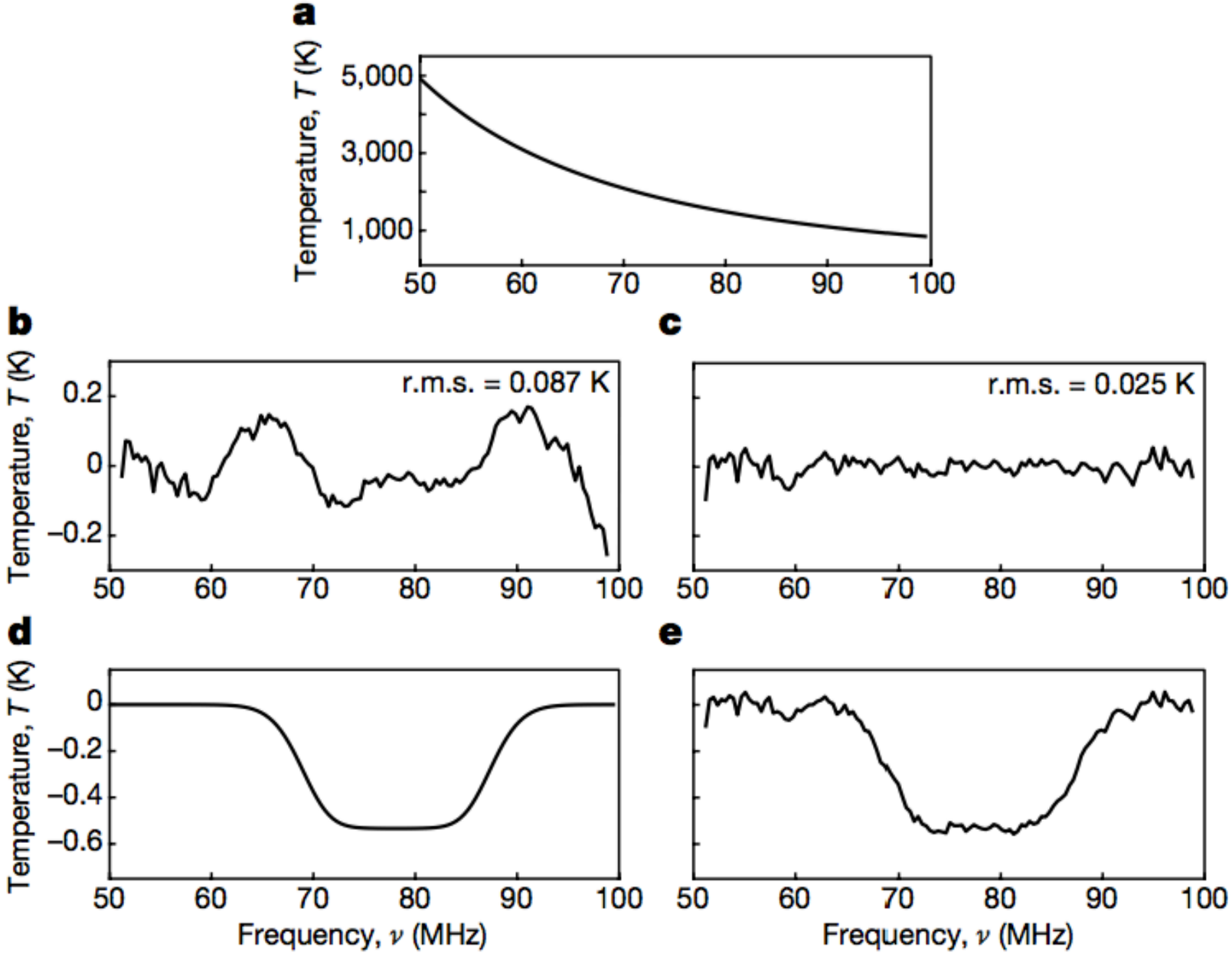

Bowman et al., Nature (2018)

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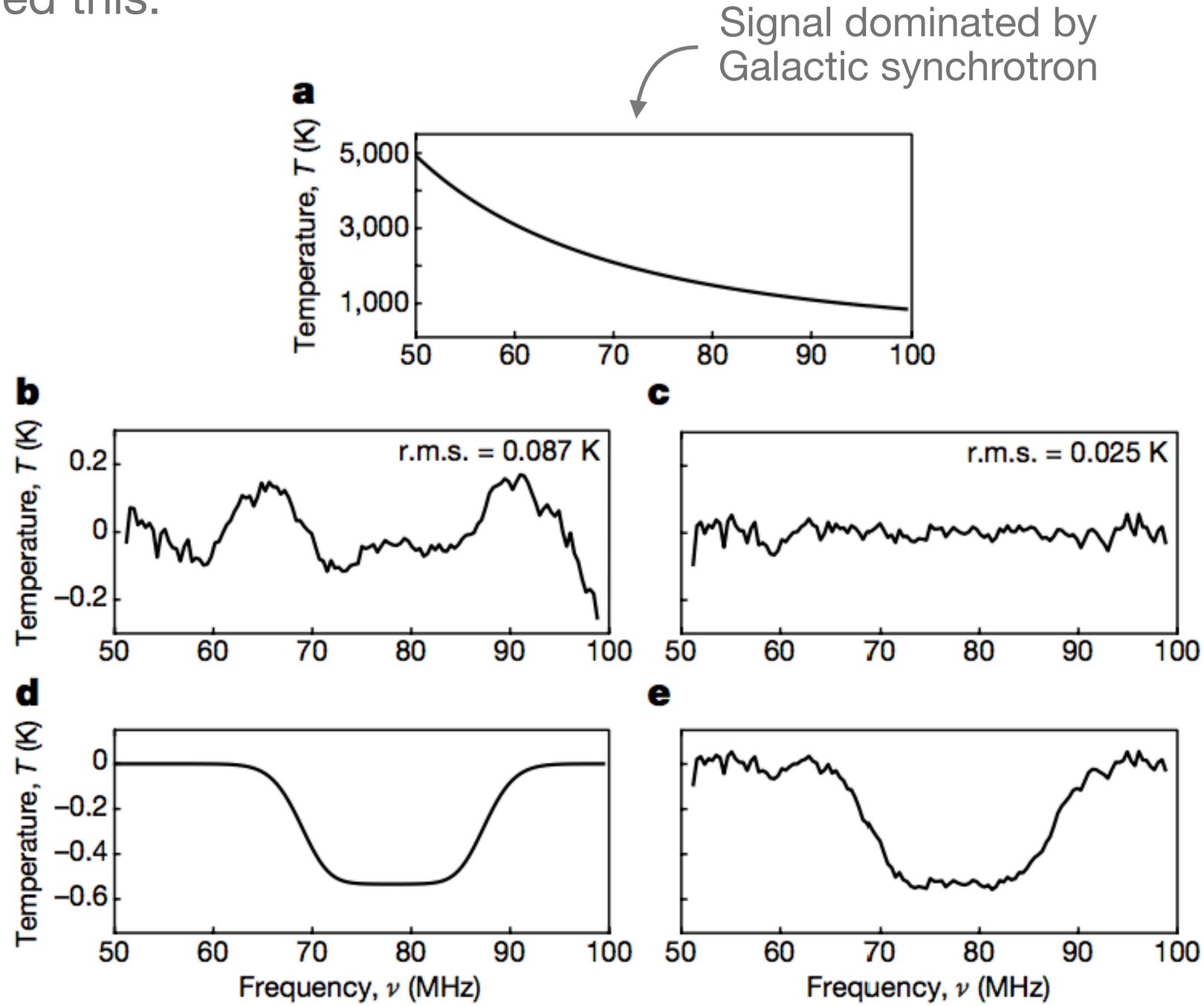

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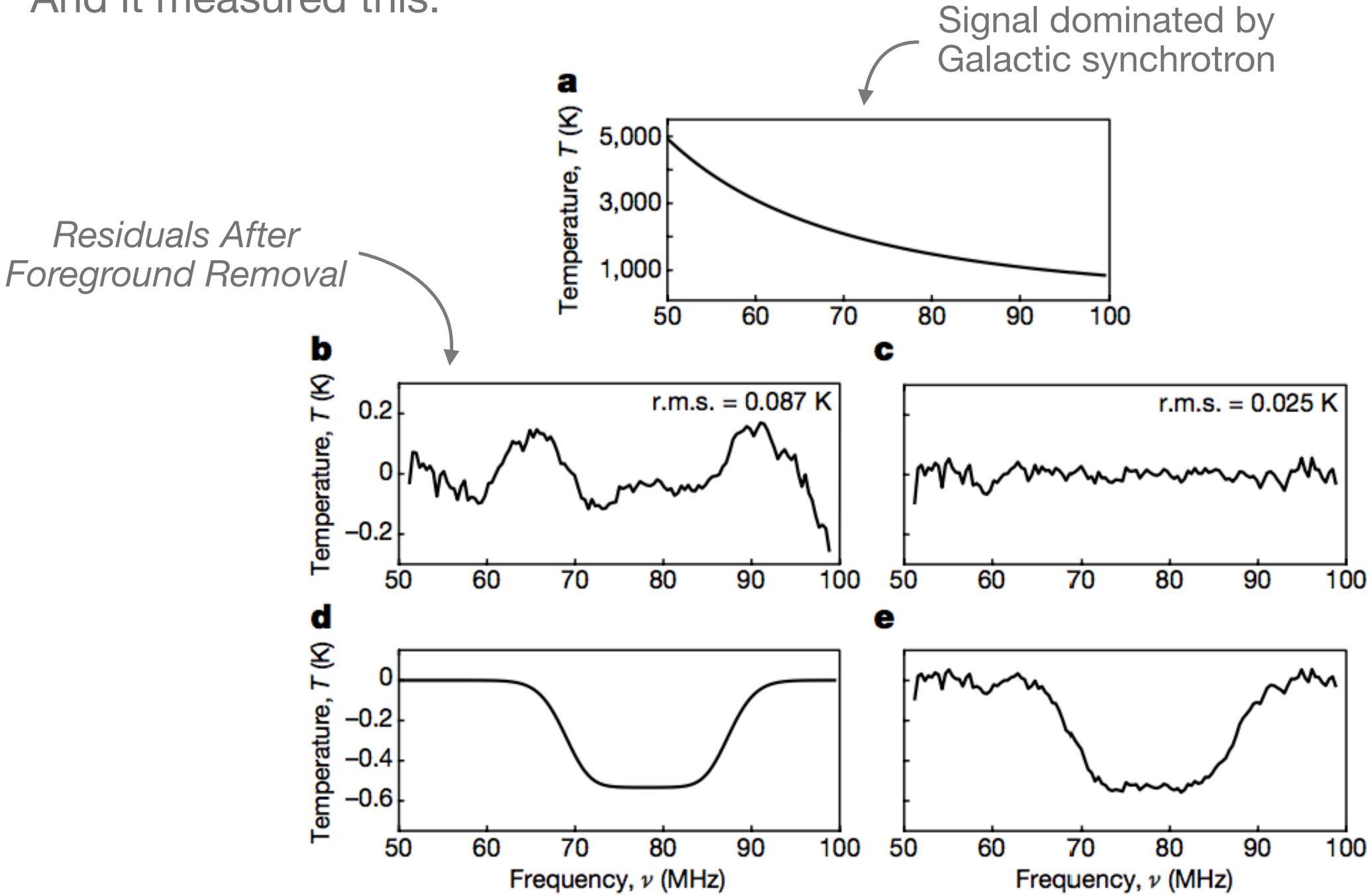

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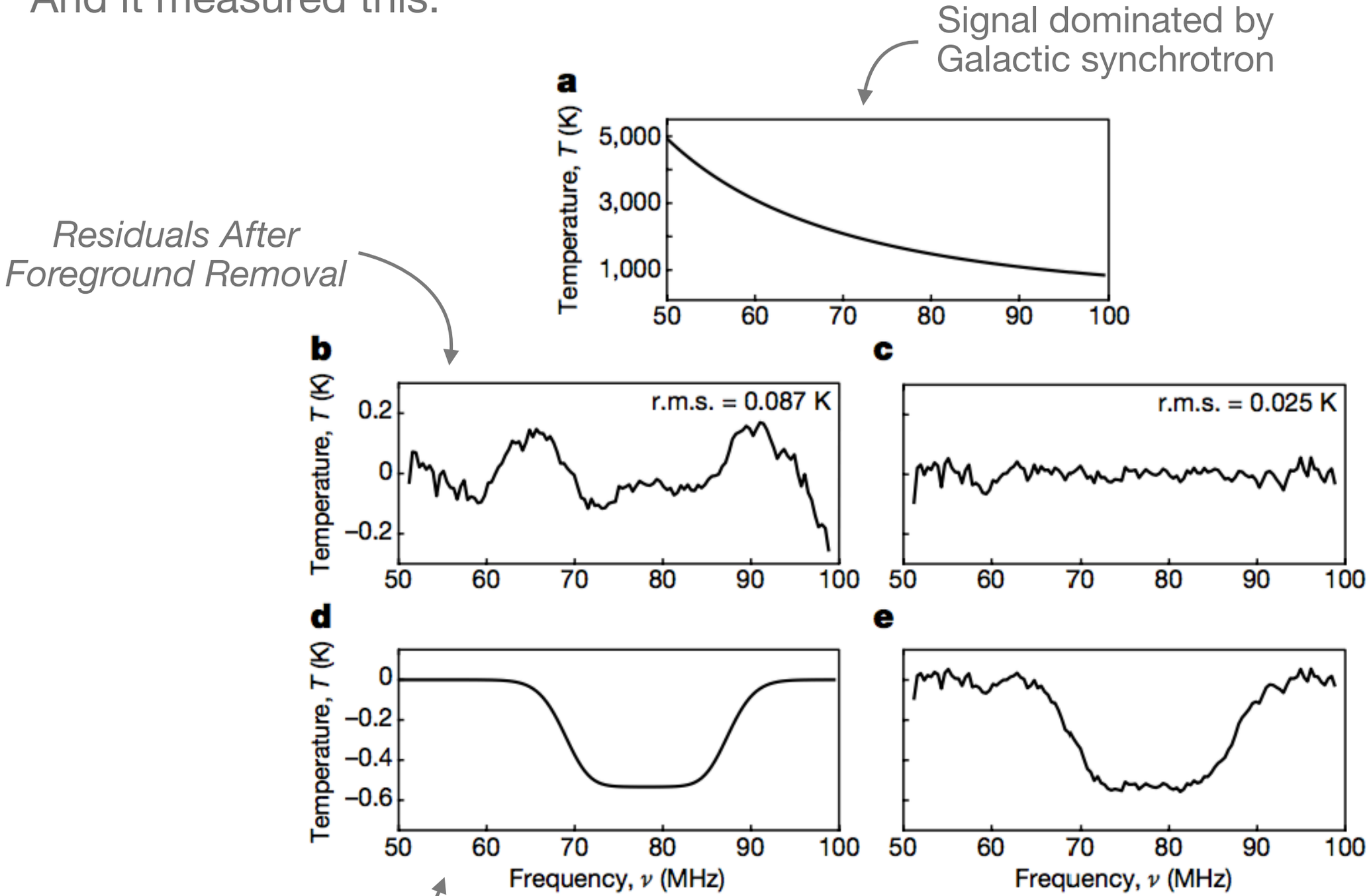

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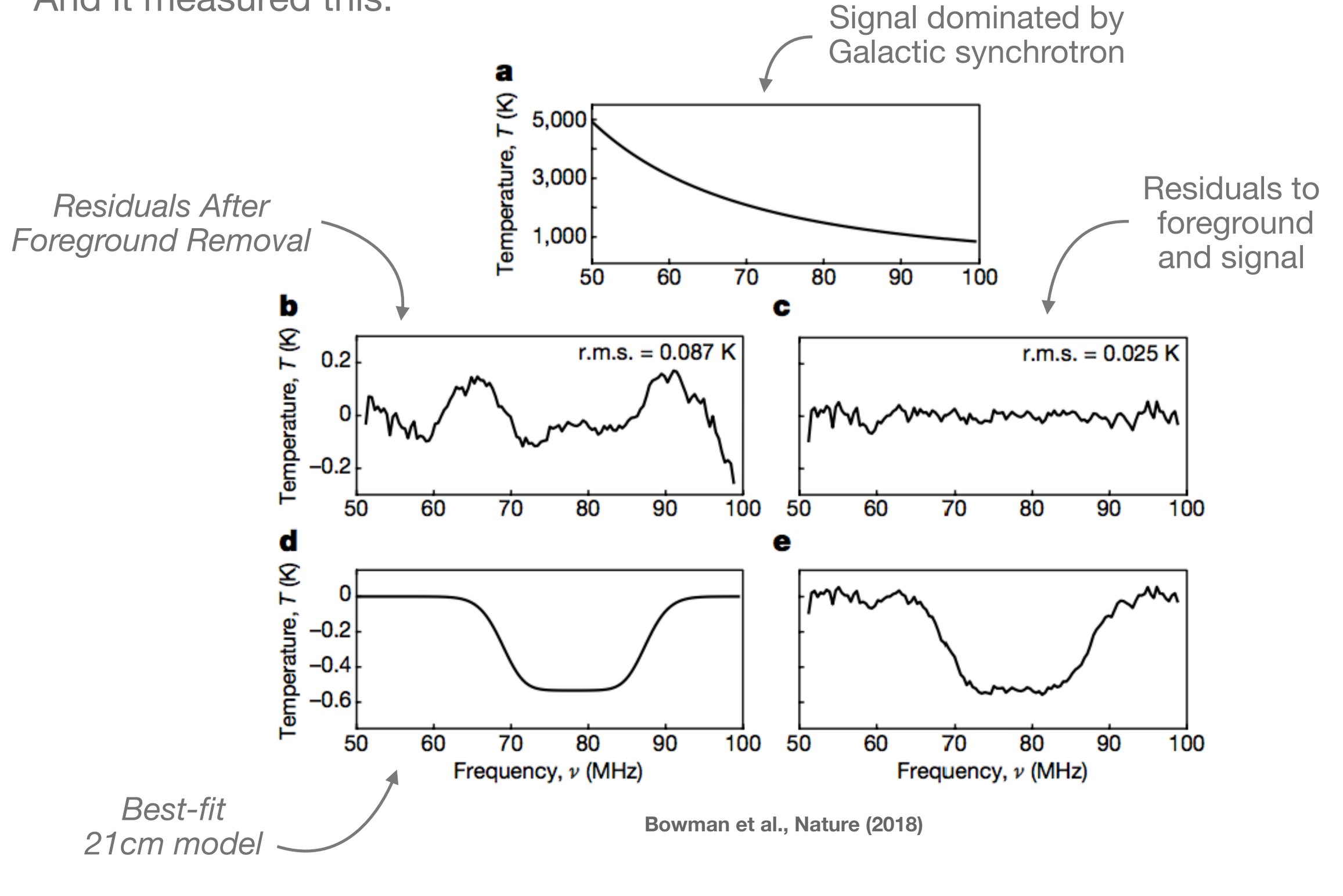

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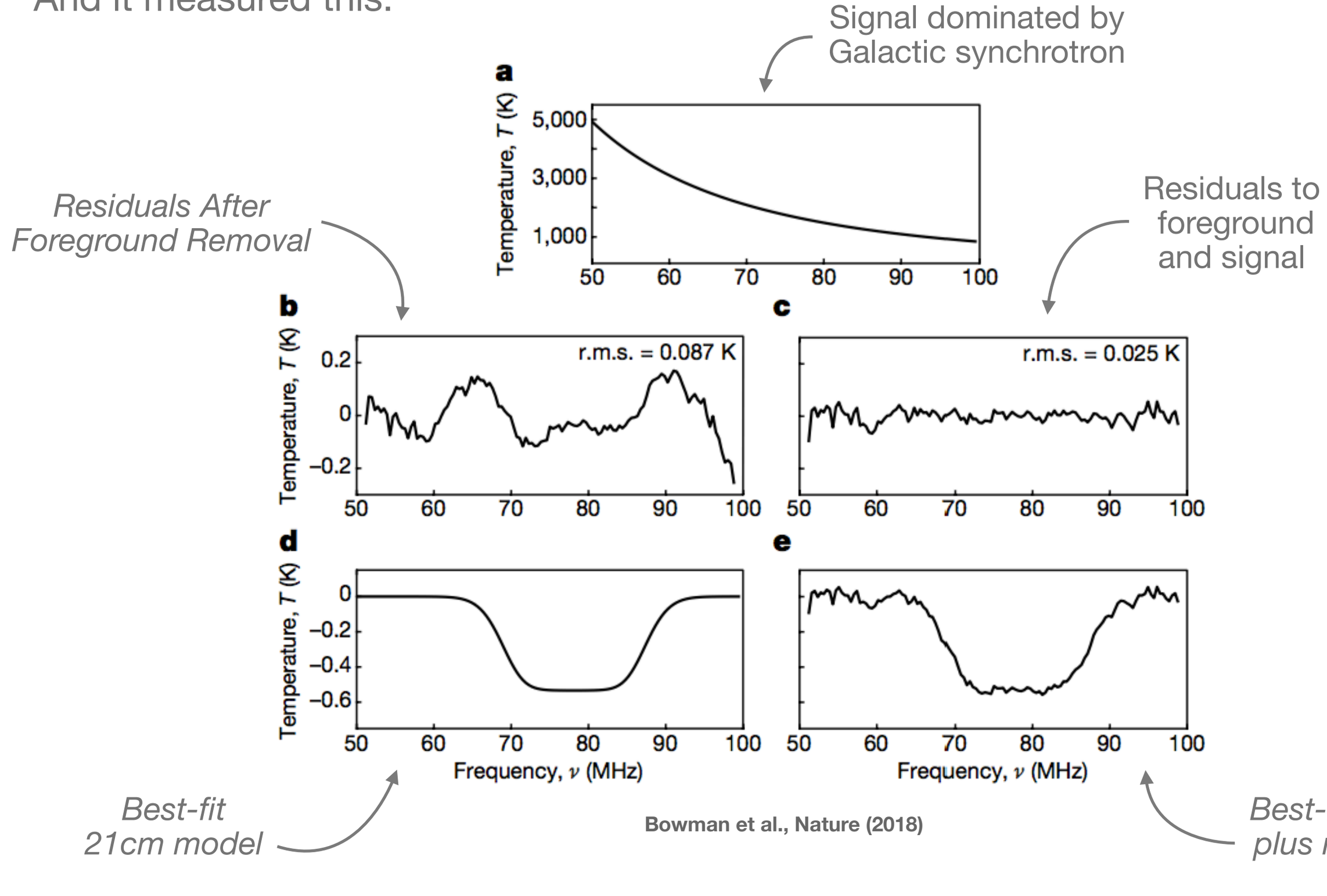

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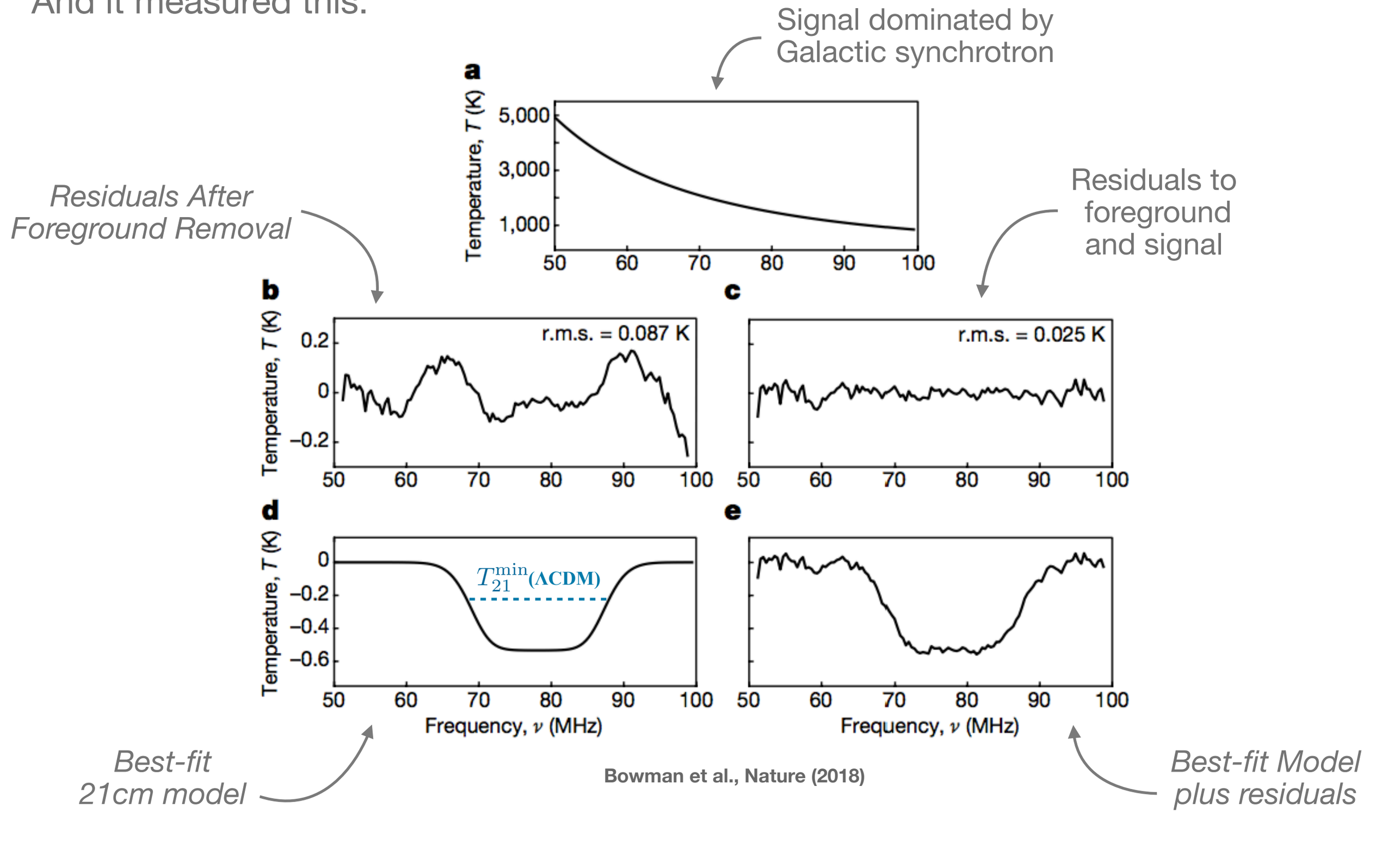

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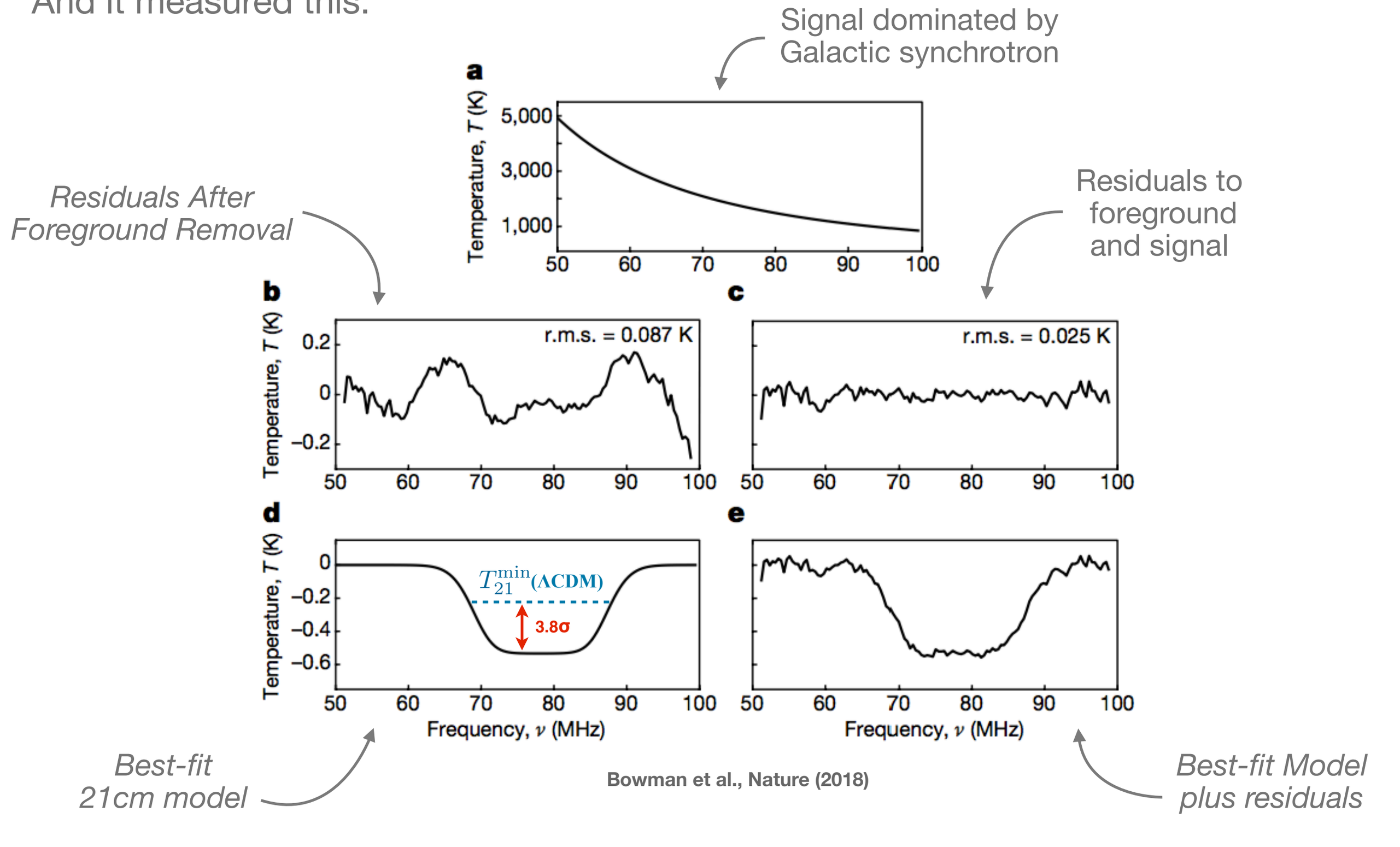

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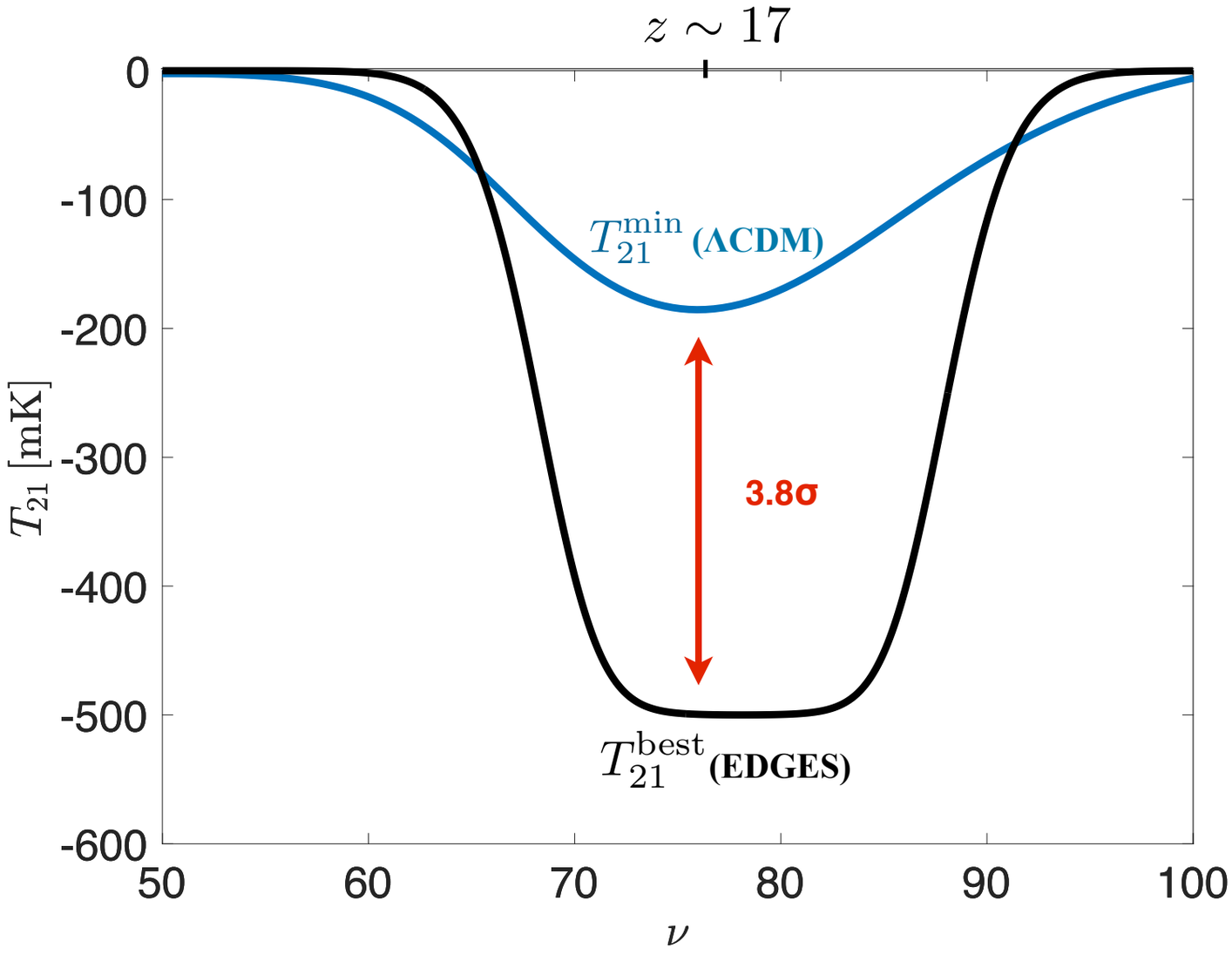
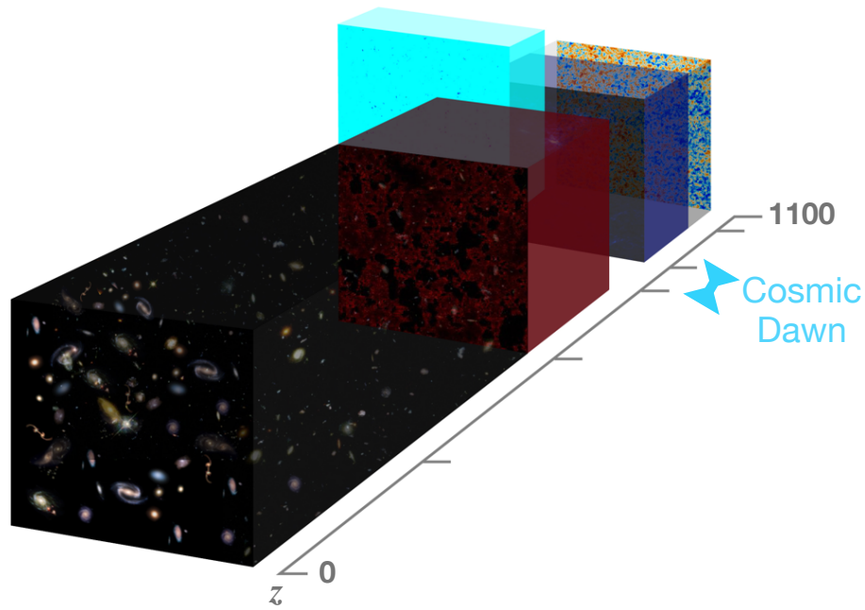
Q: Can Dark Matter Explain the EDGES Signal?





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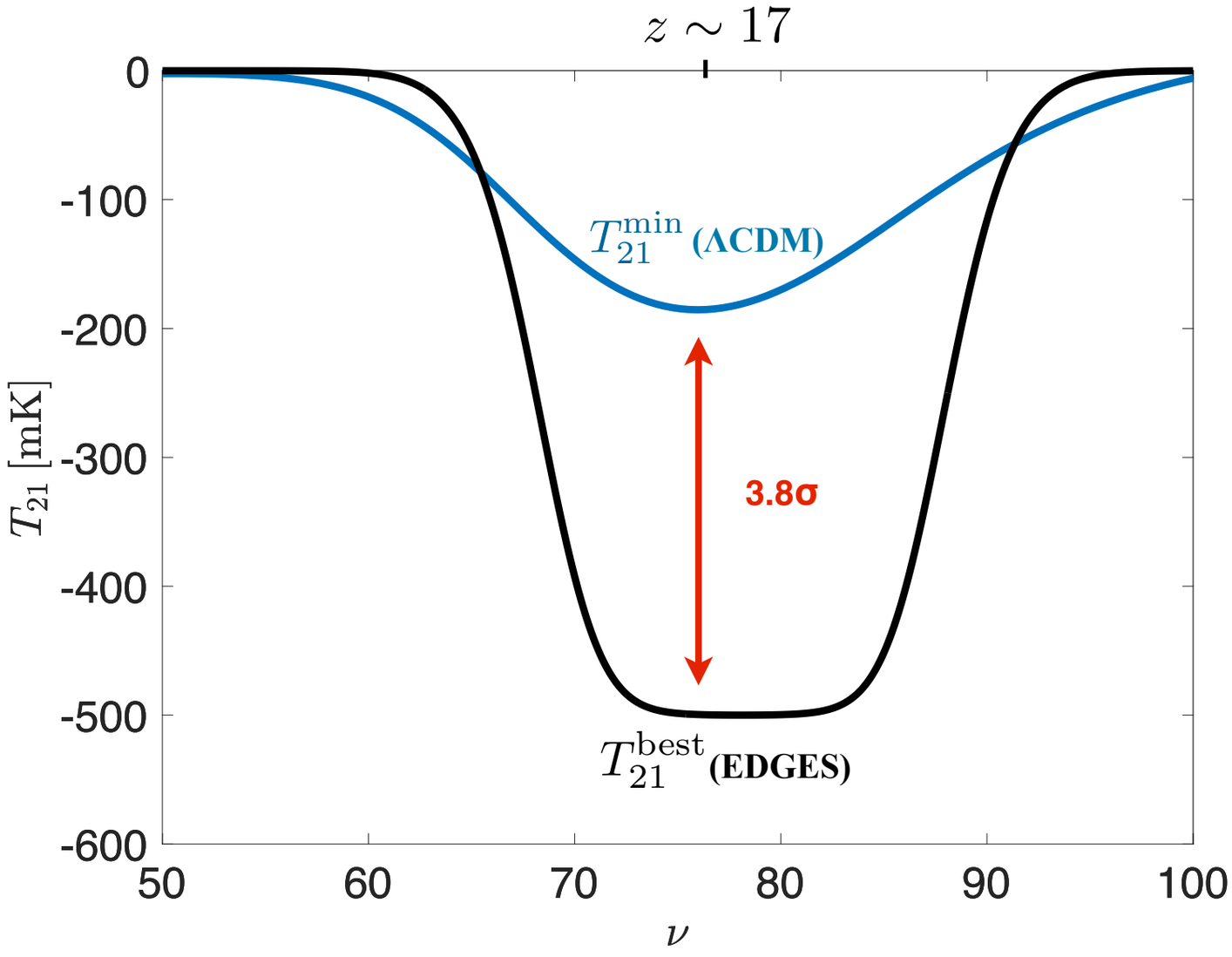
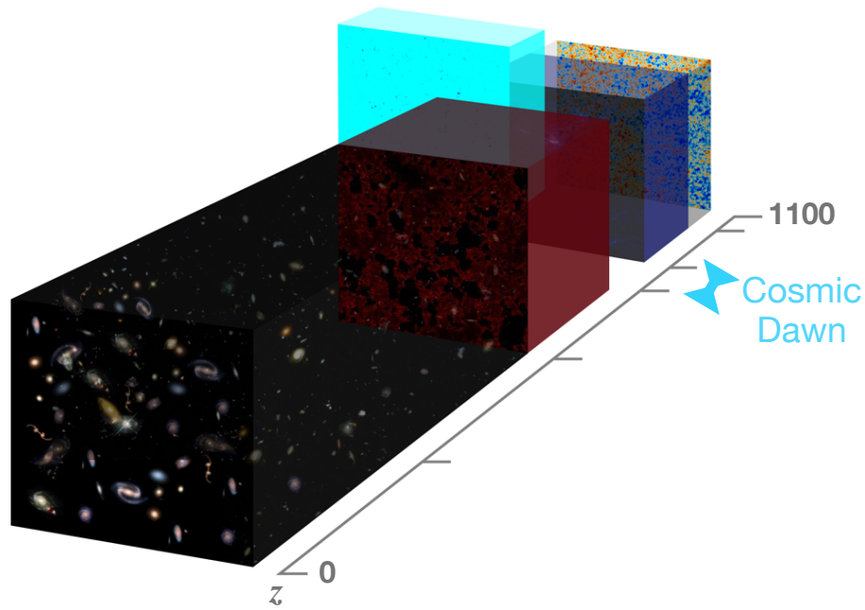
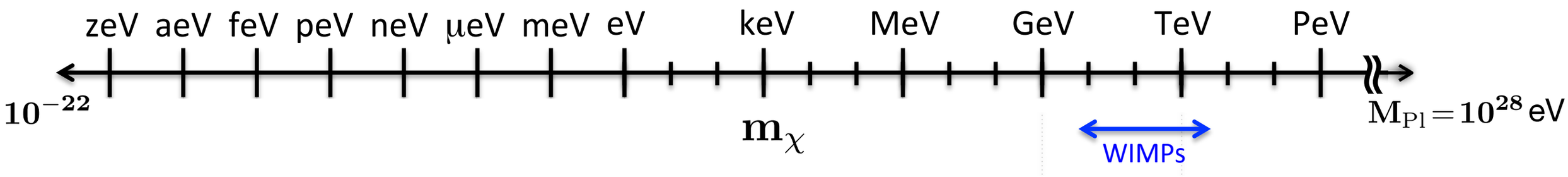




Signatures of Dark Matter-Baryon Scattering



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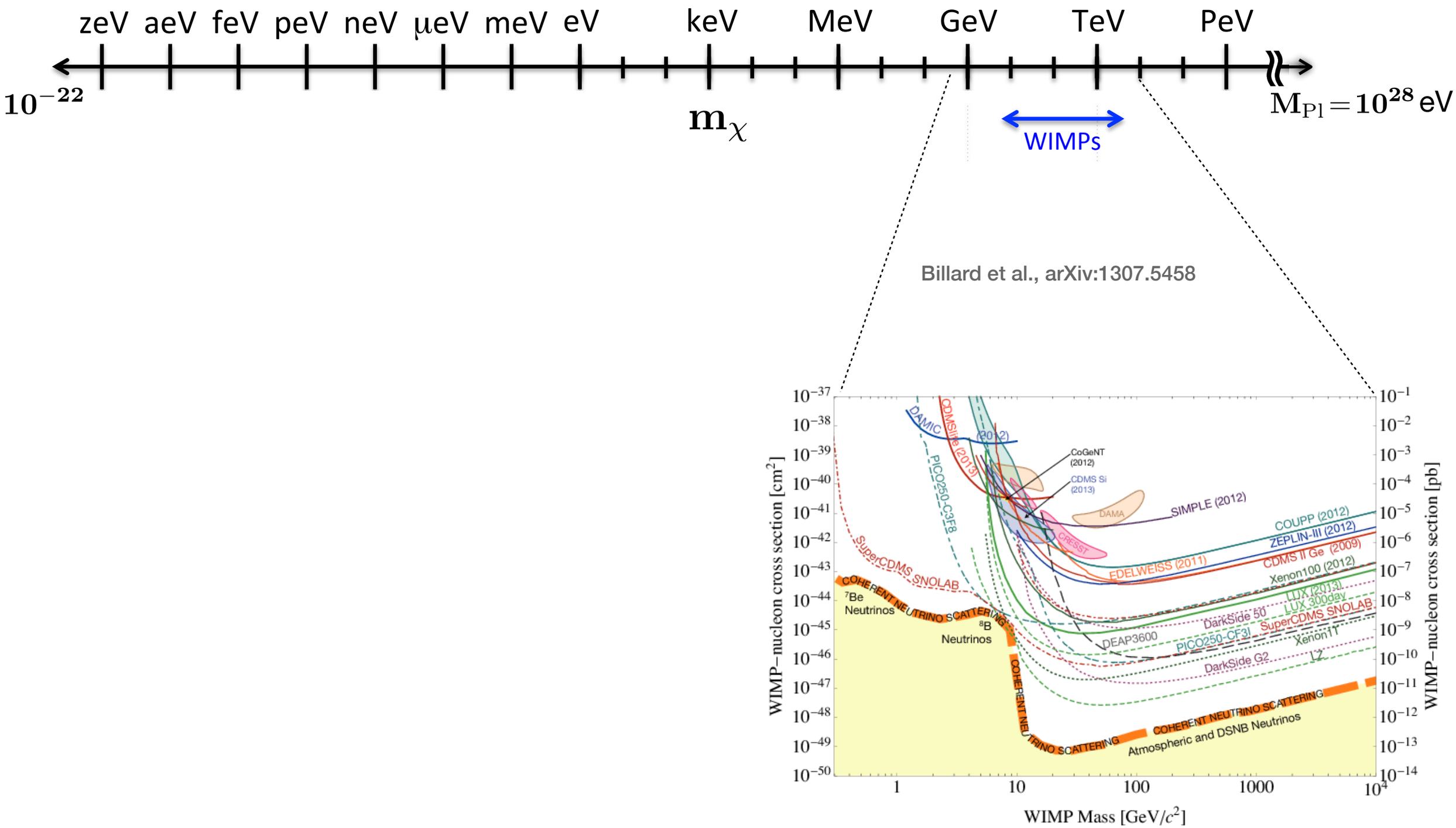

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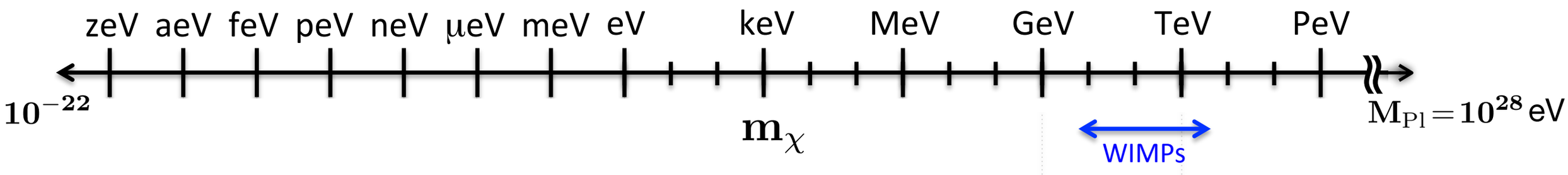

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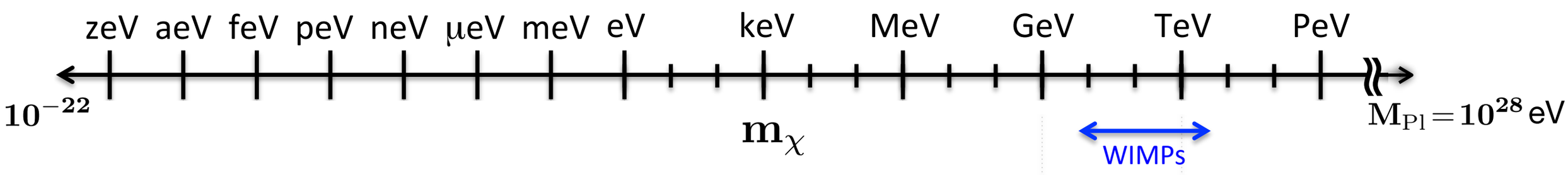

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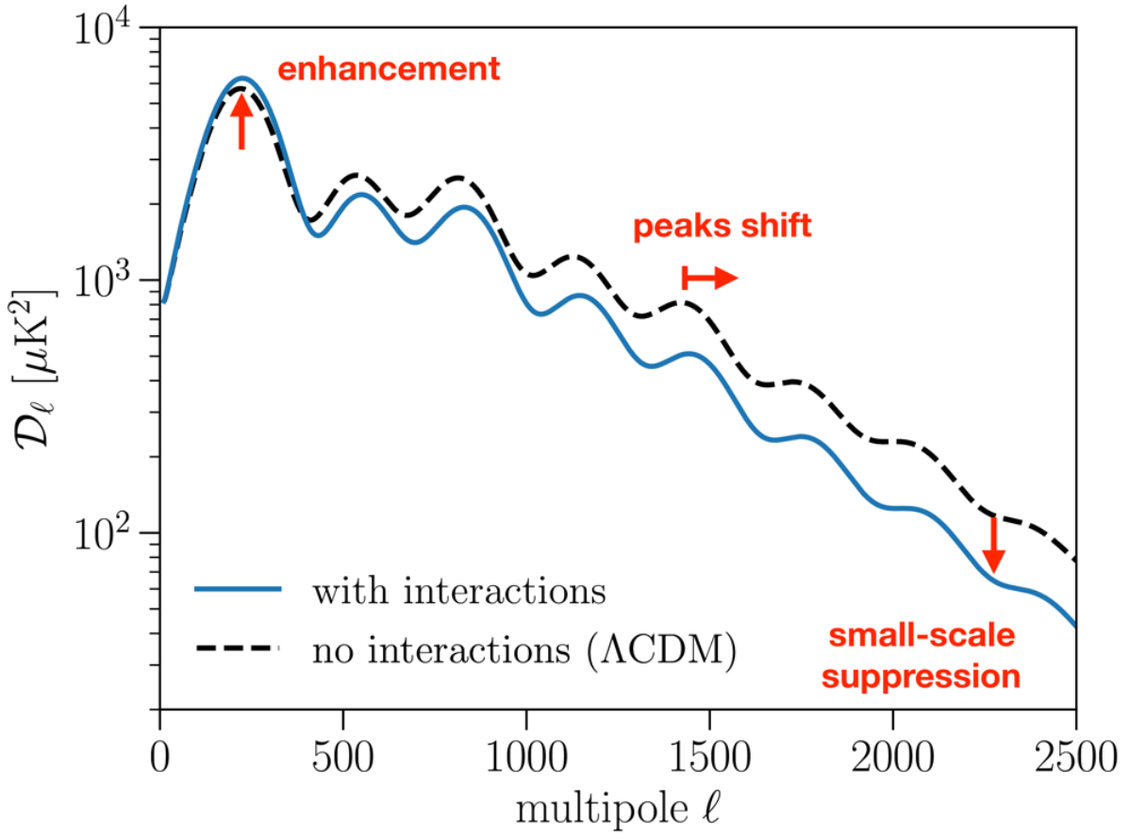

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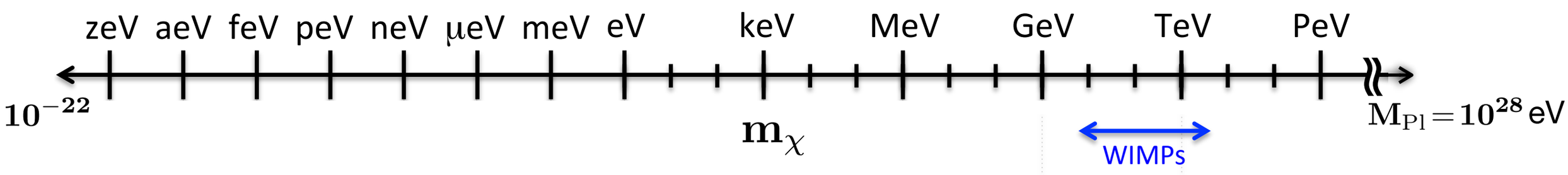

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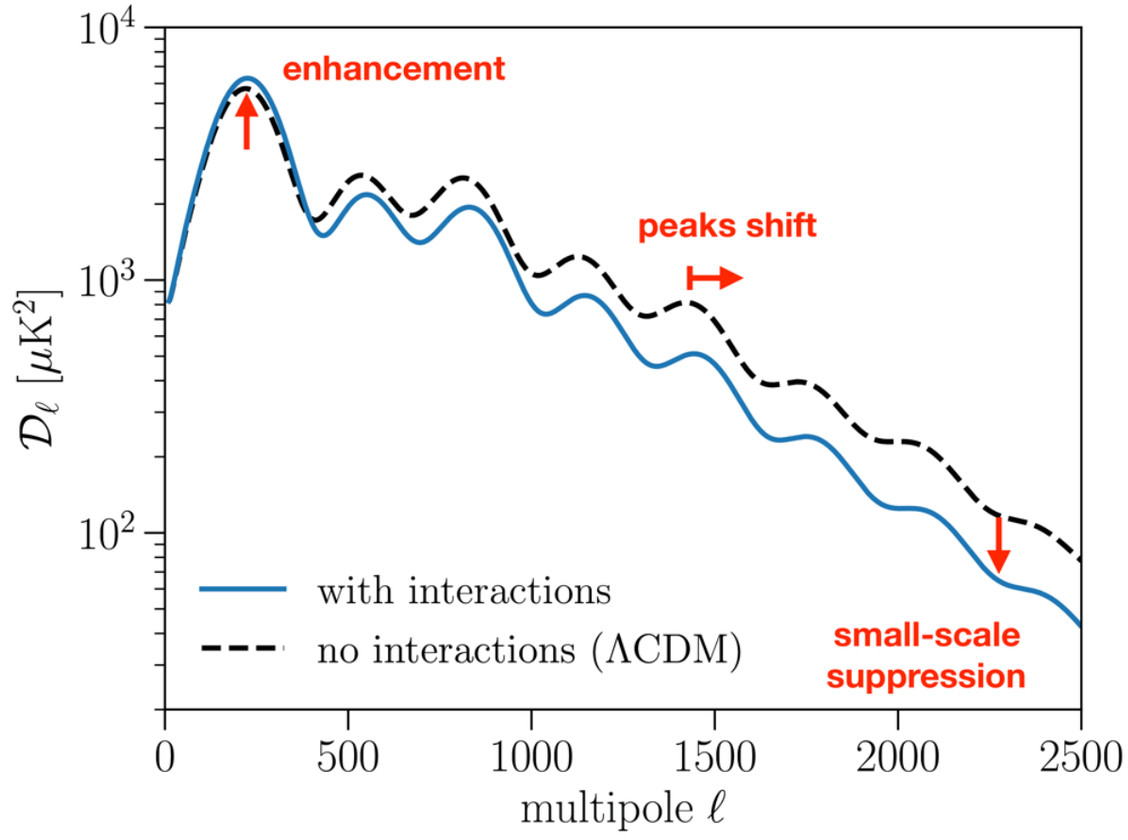

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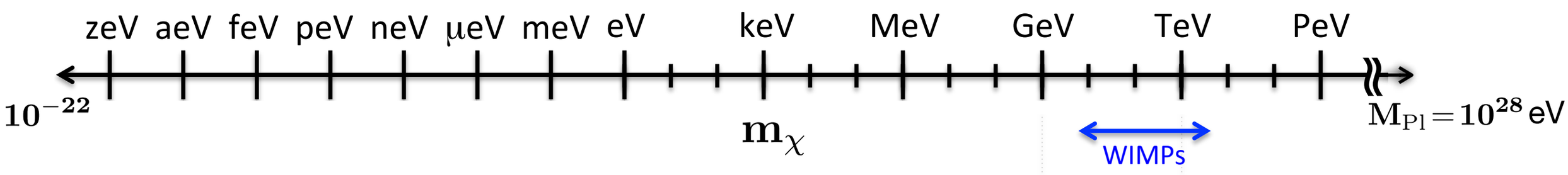

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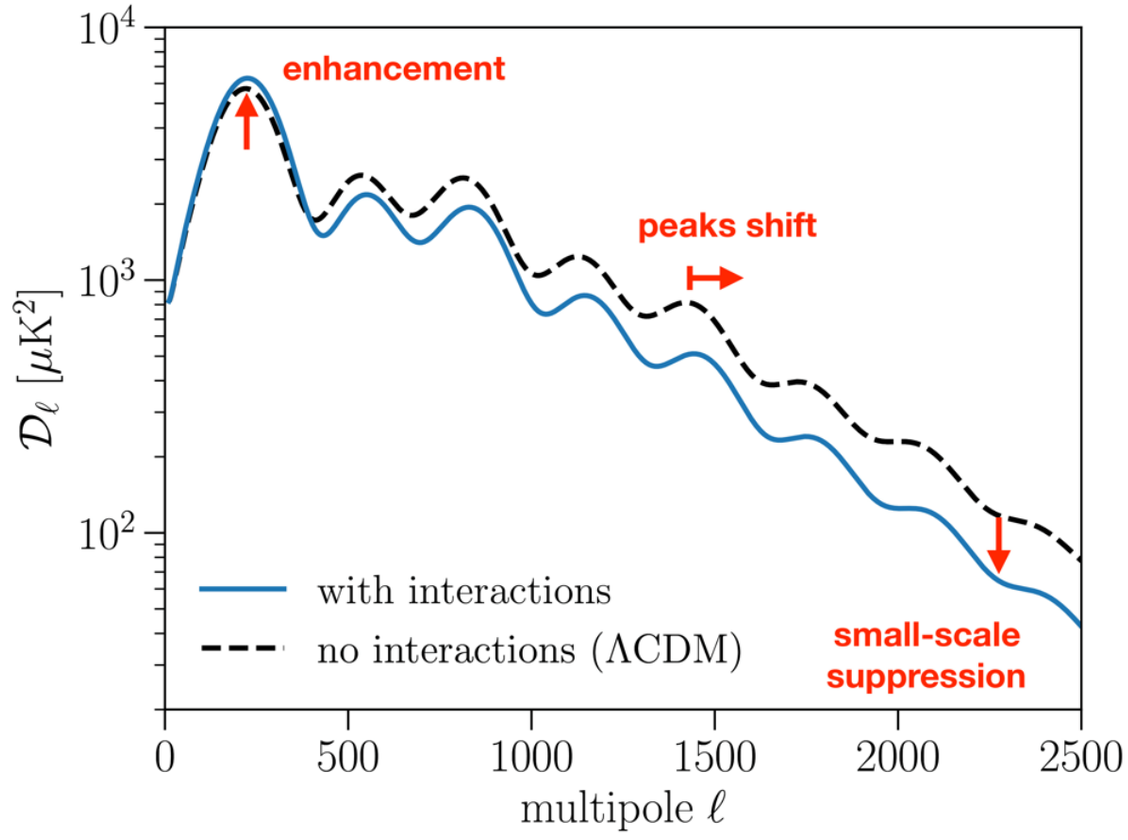

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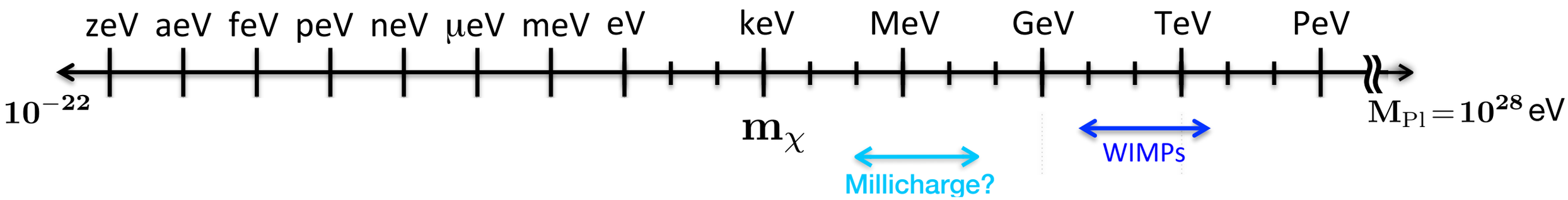

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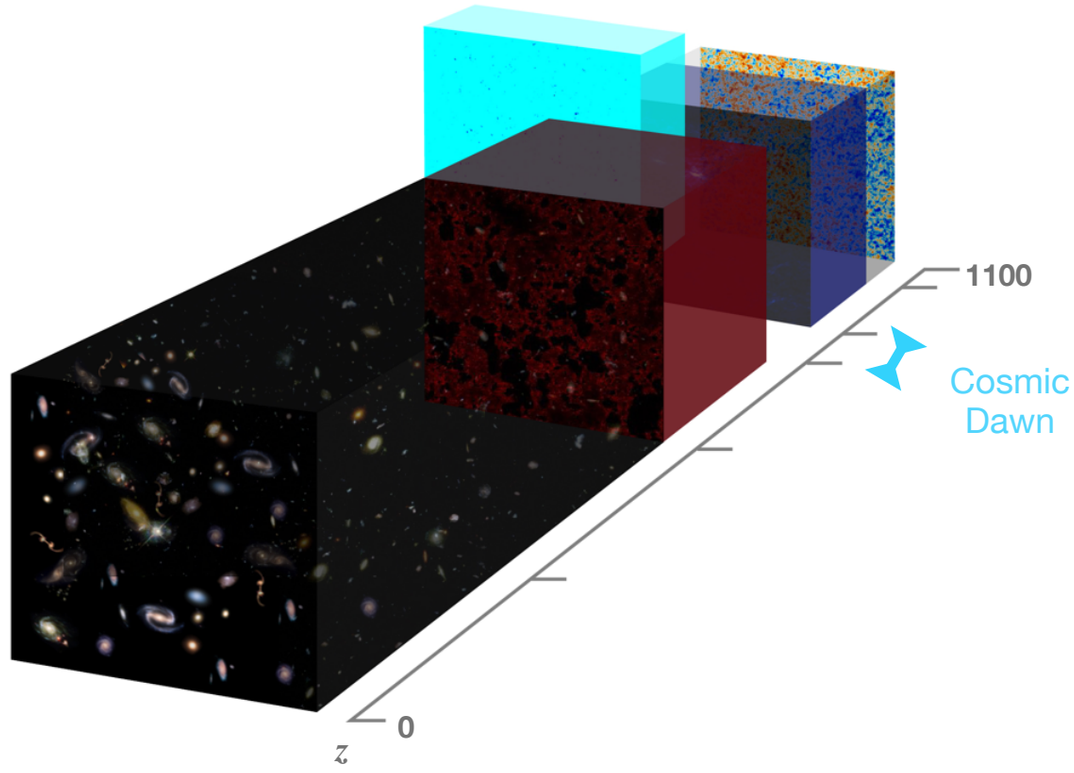

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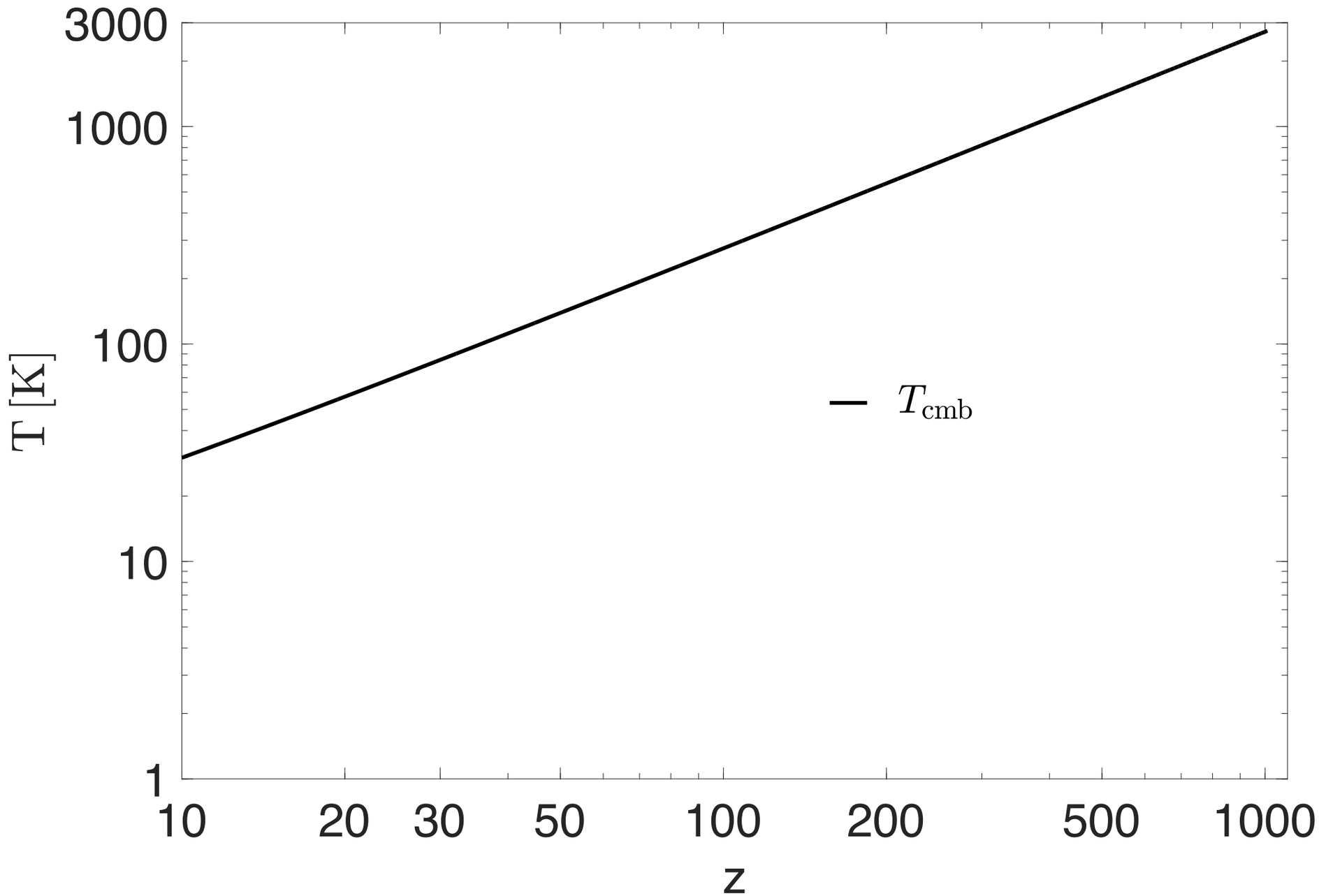

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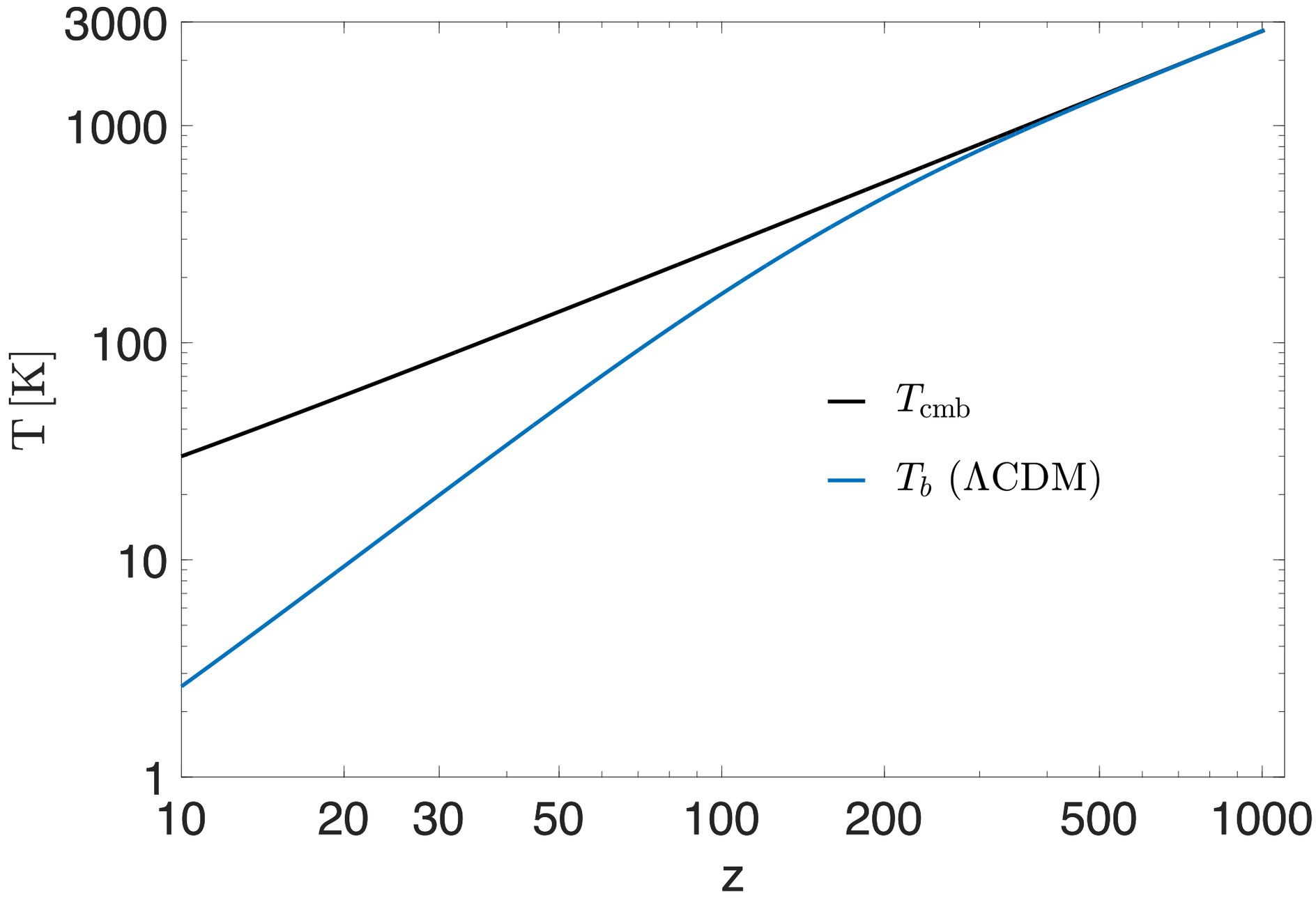

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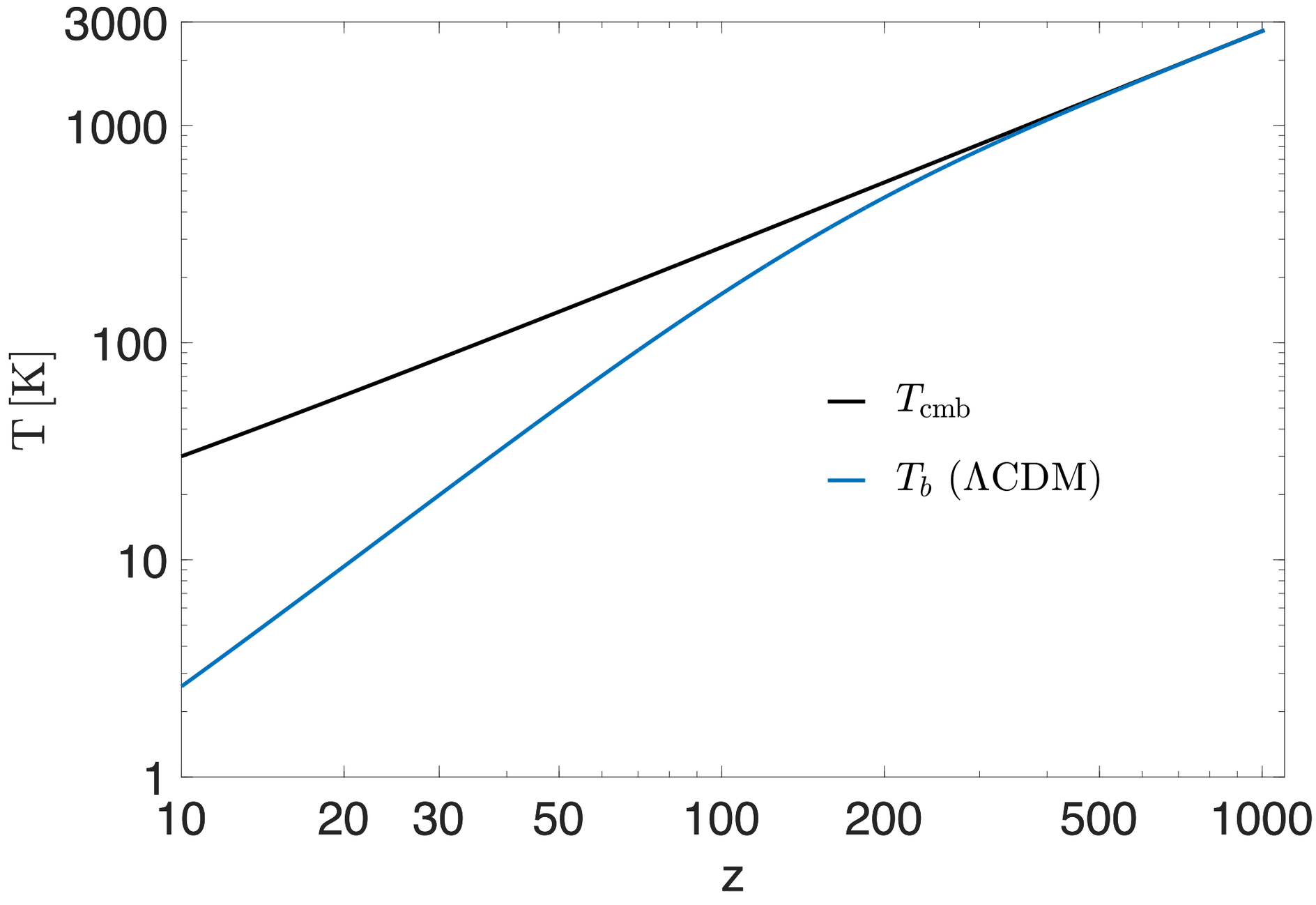

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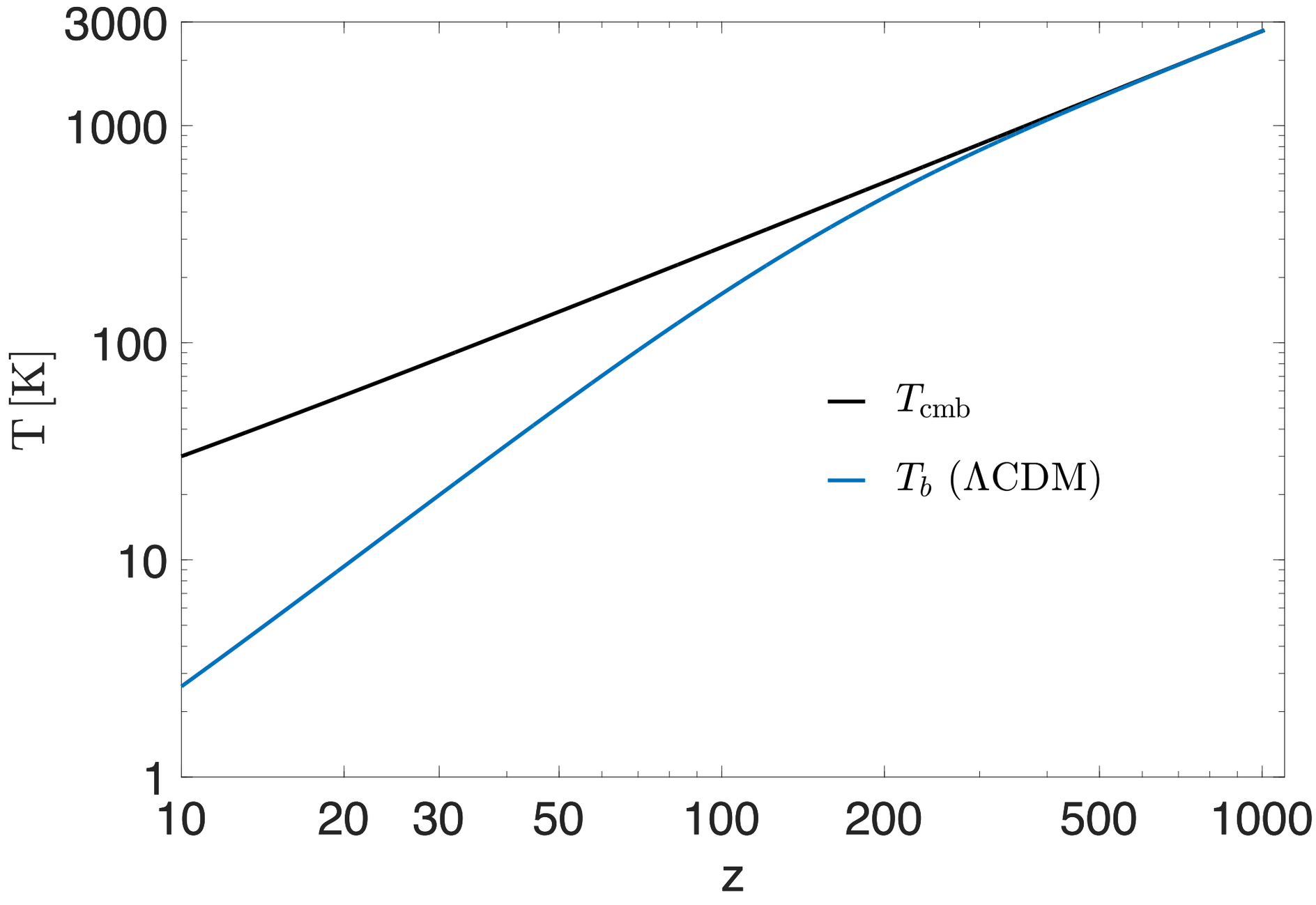

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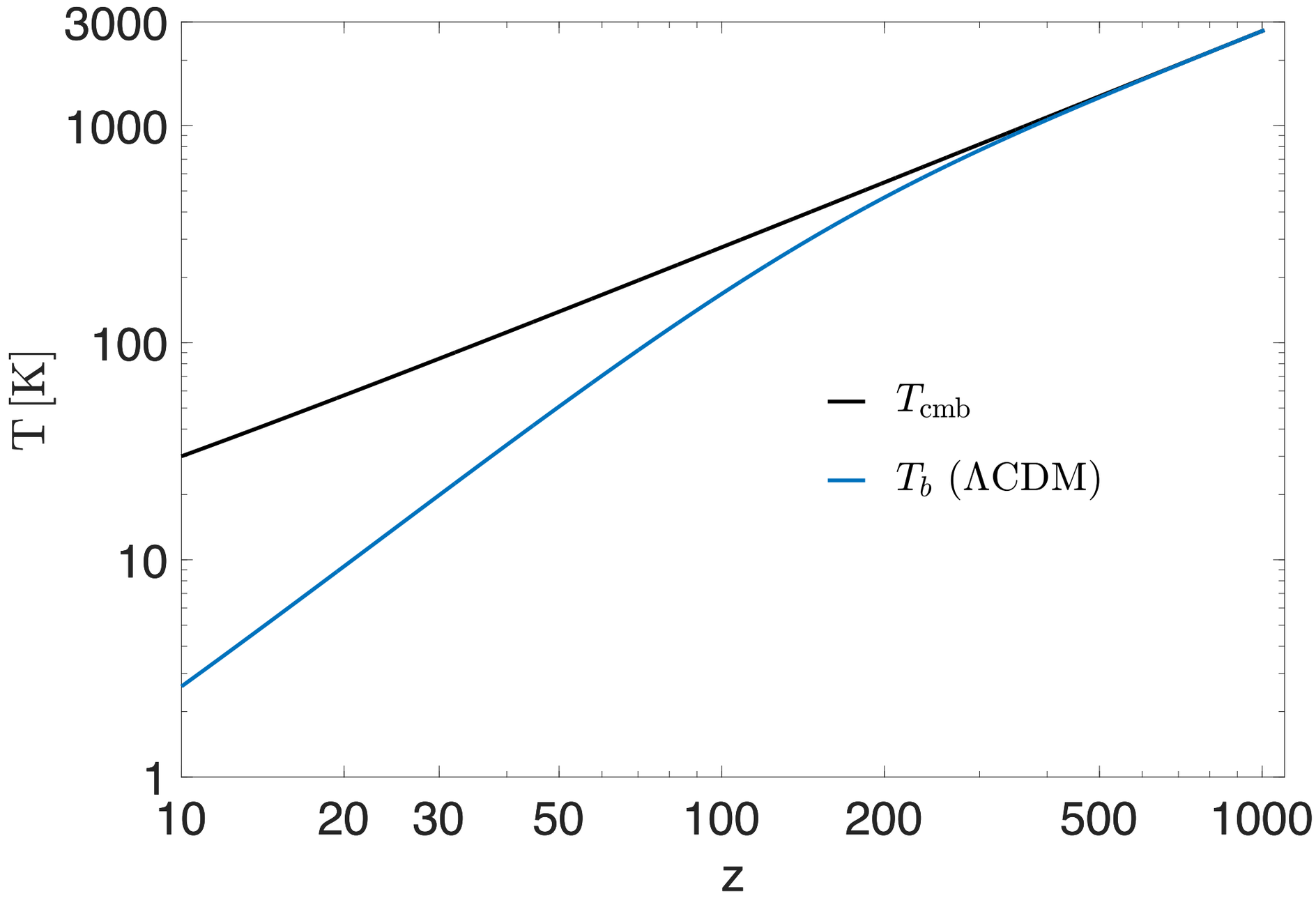

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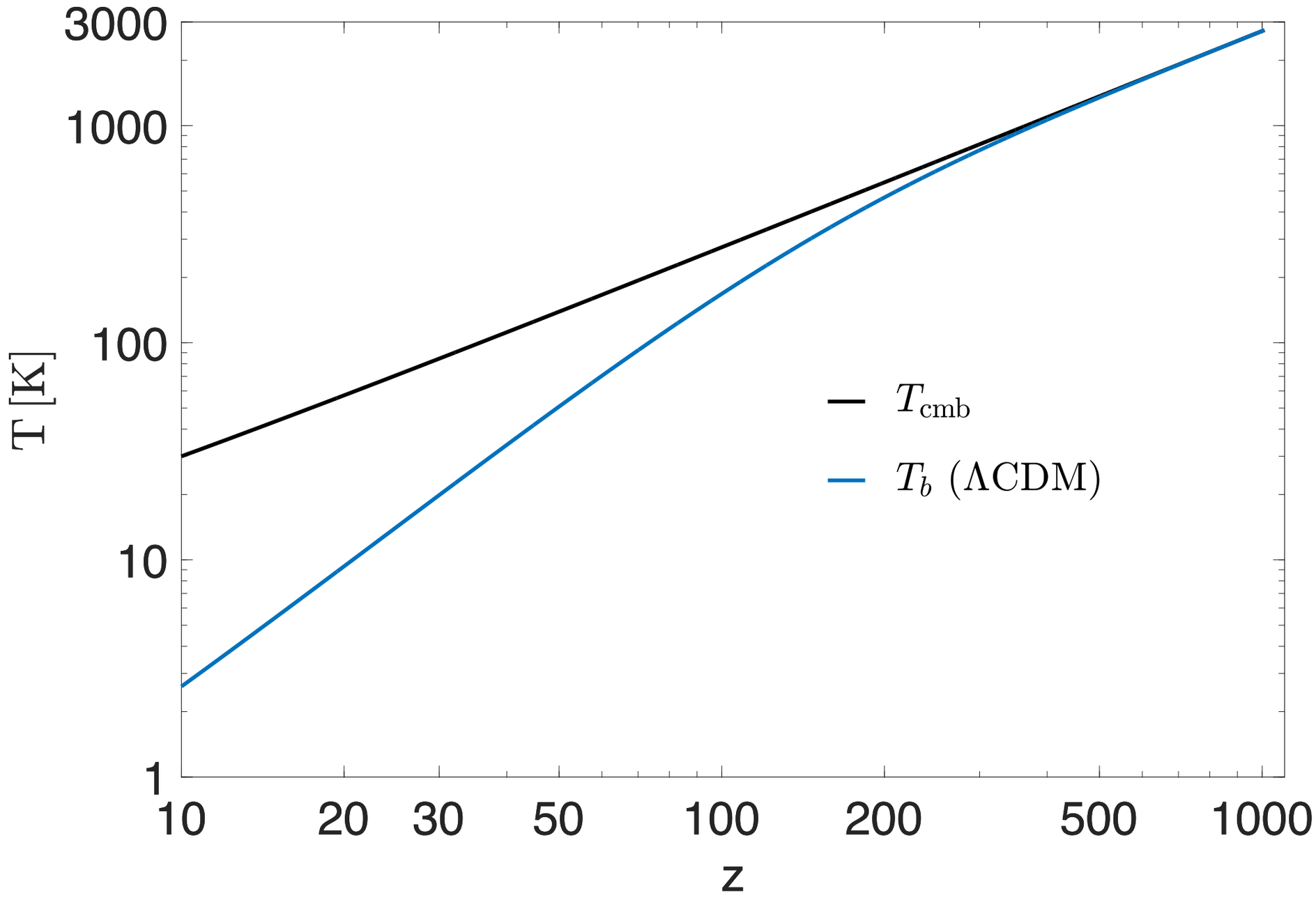

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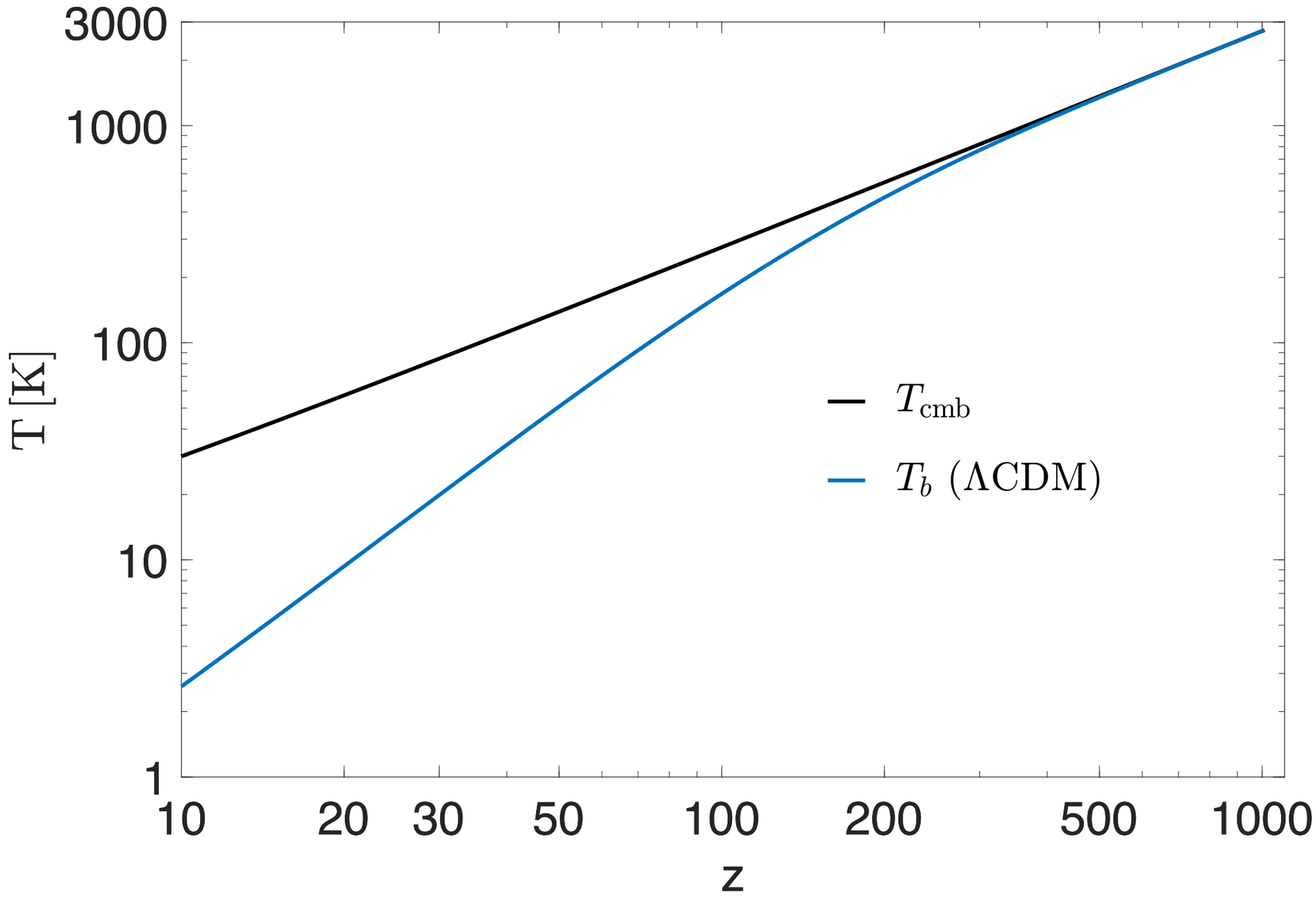

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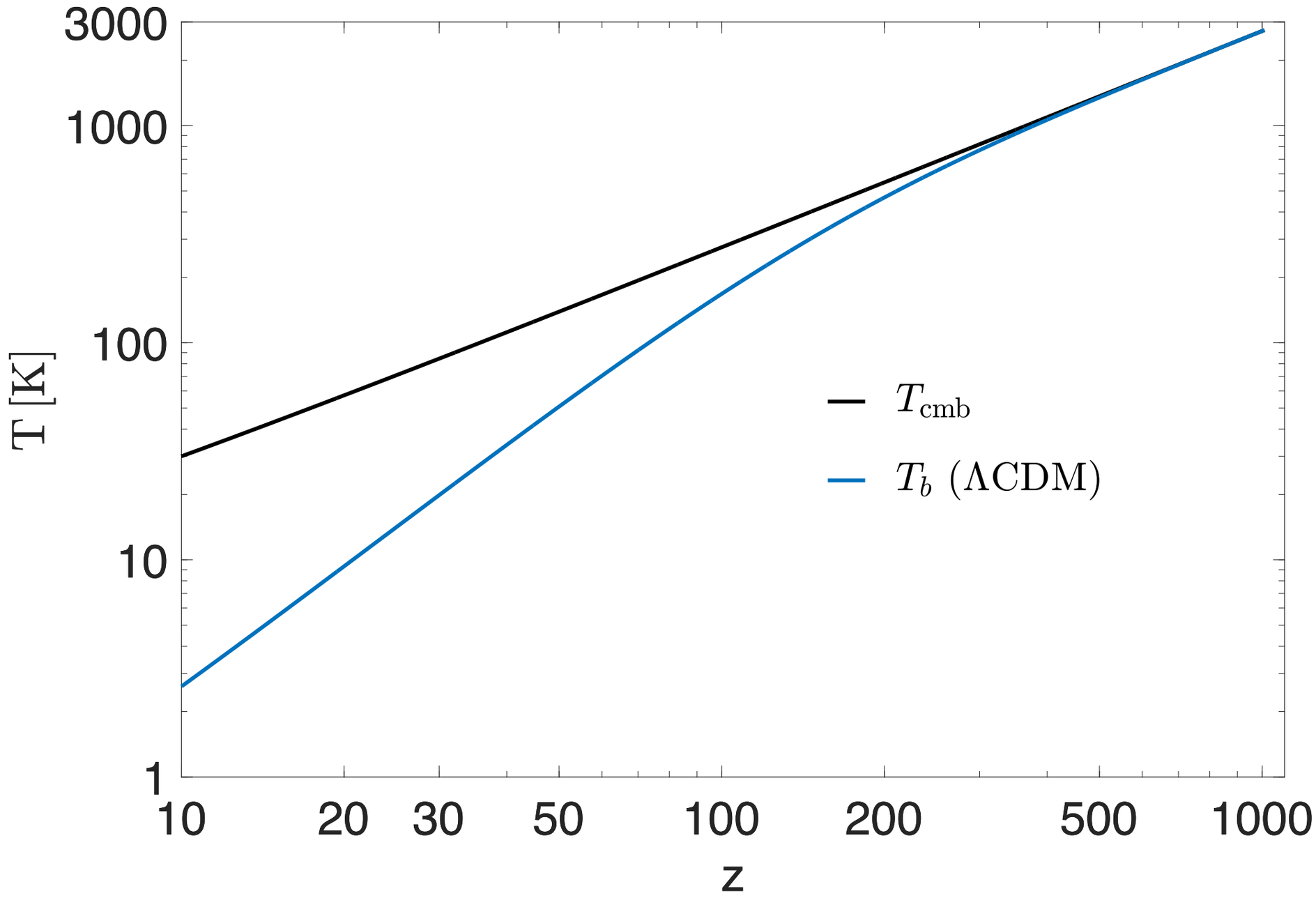

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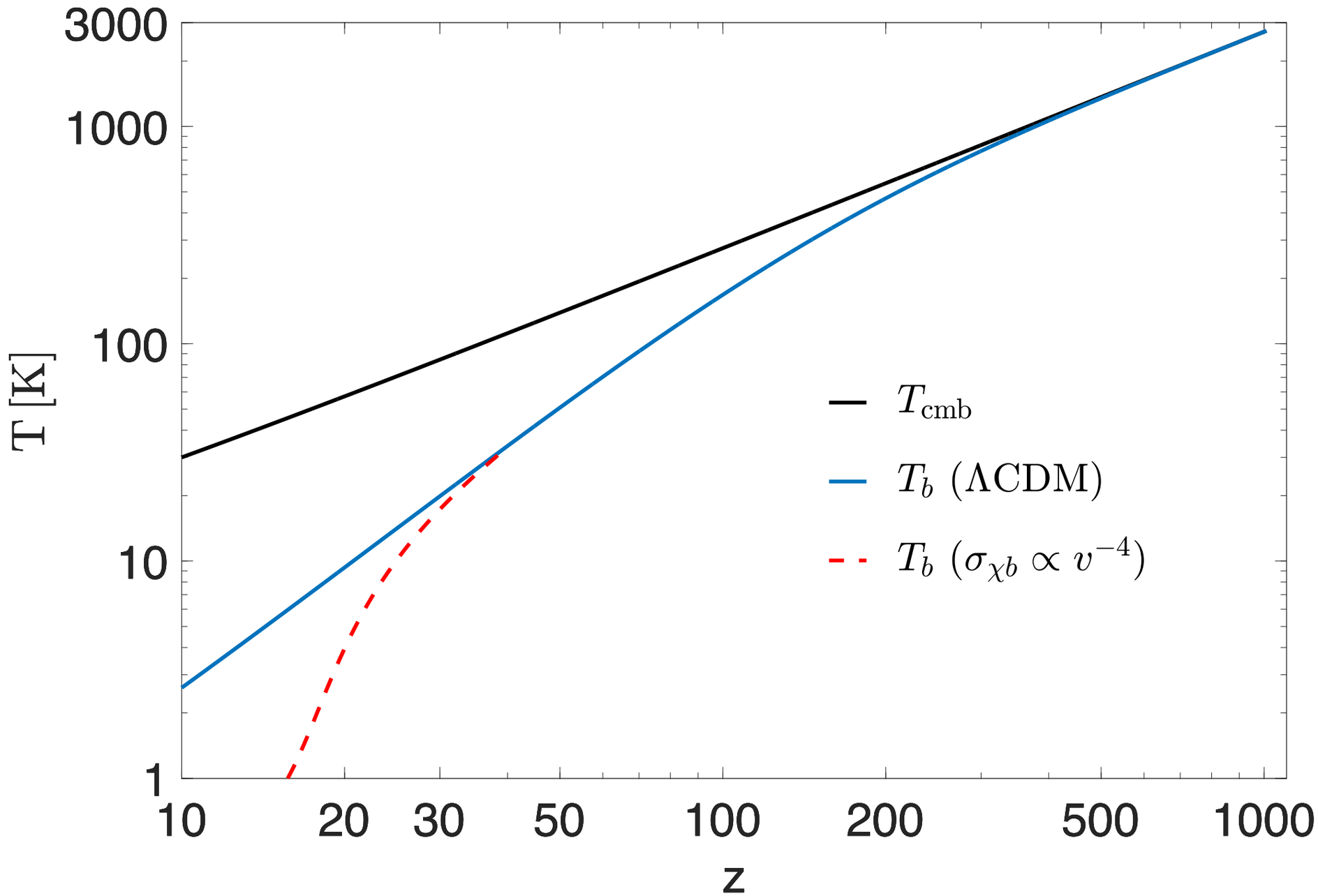

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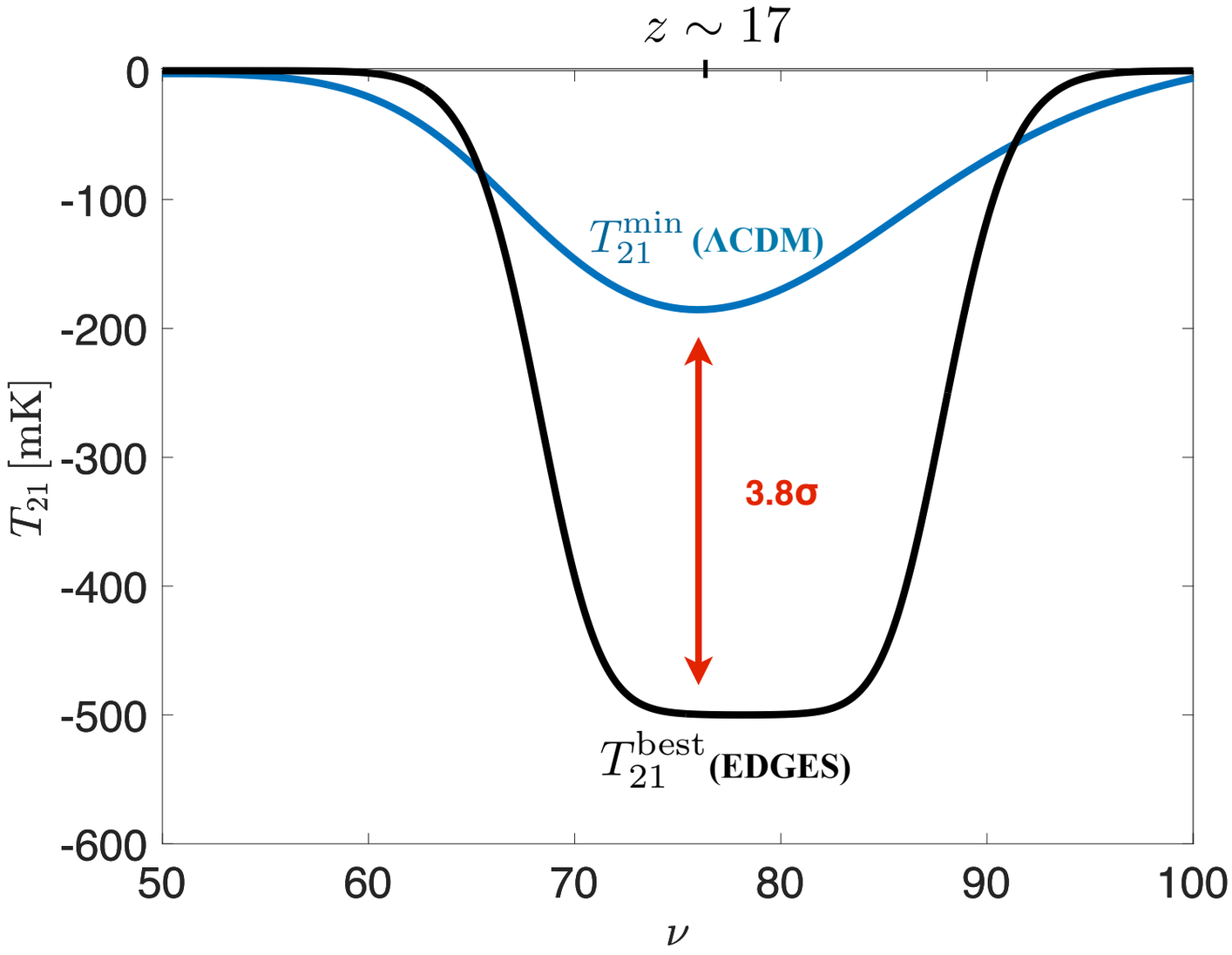

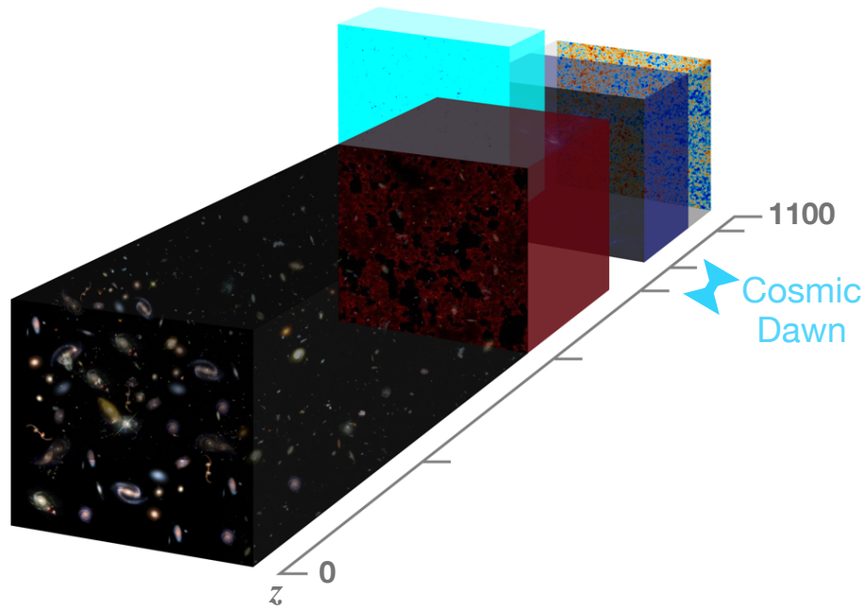

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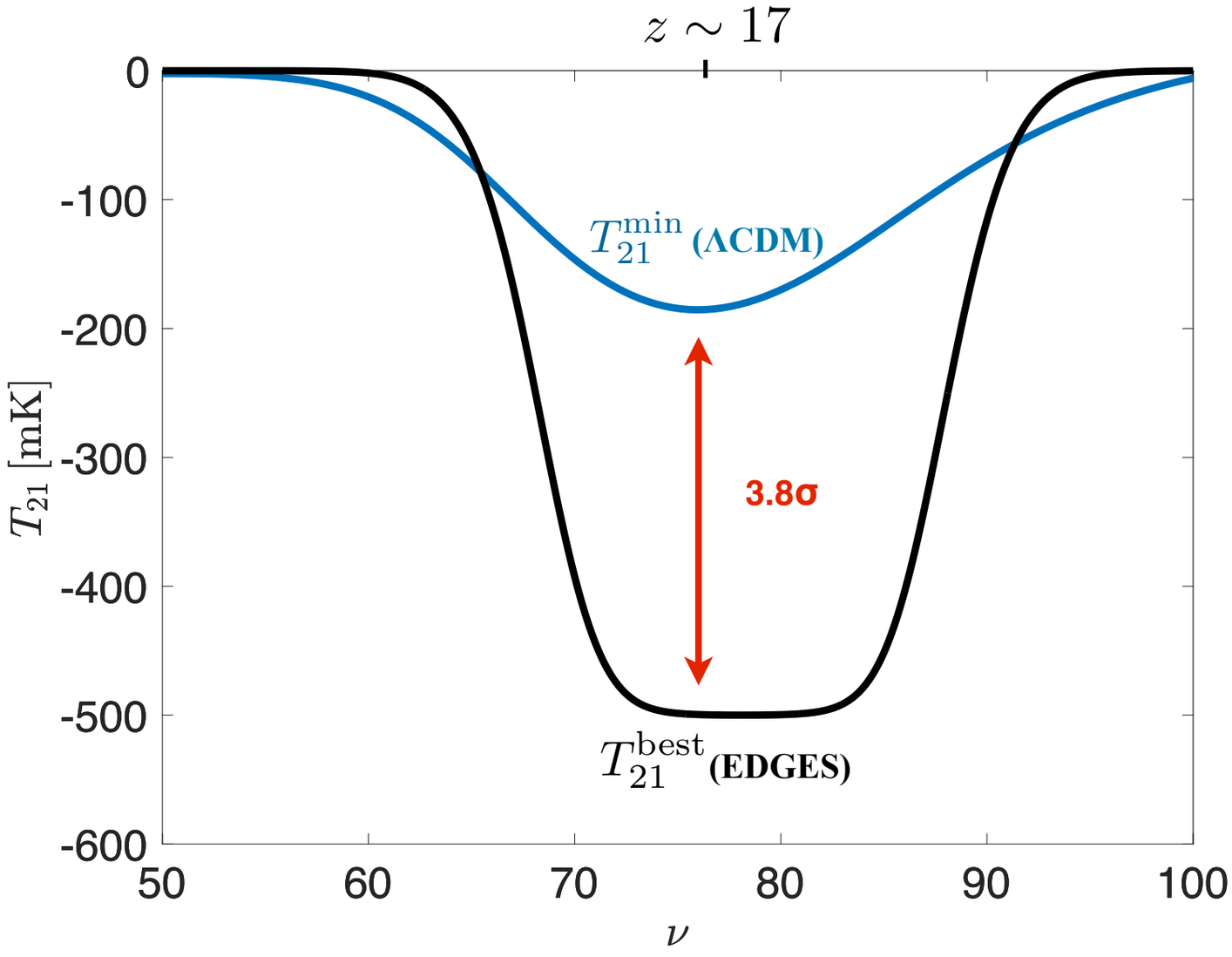

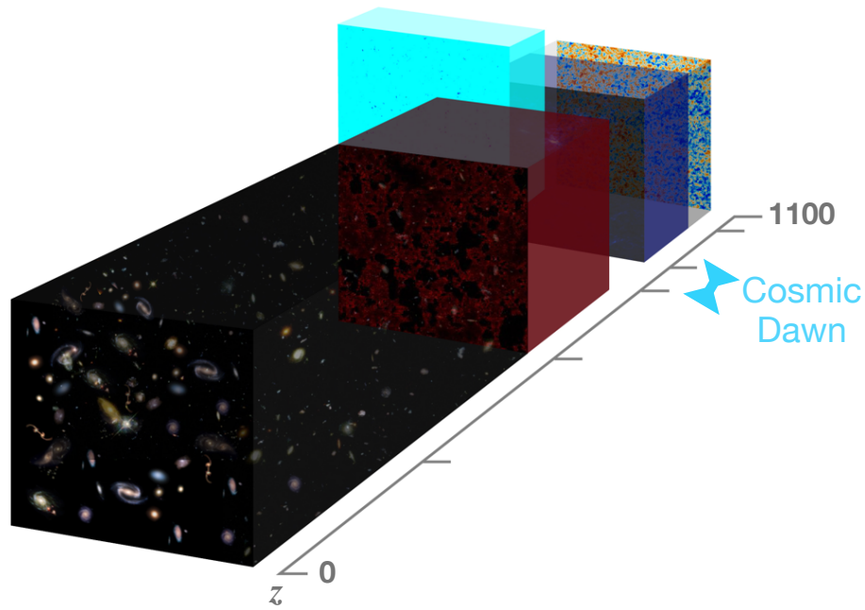

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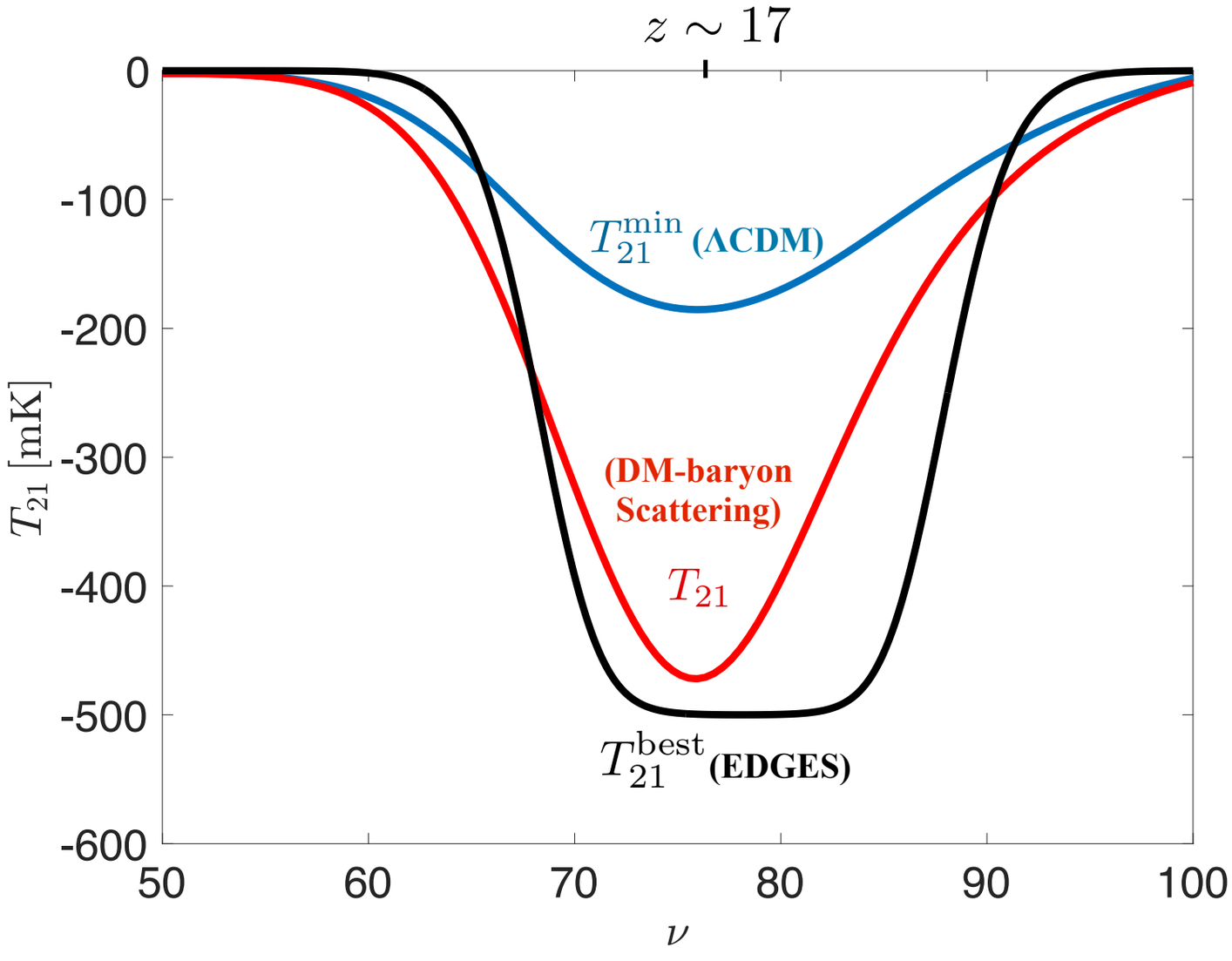

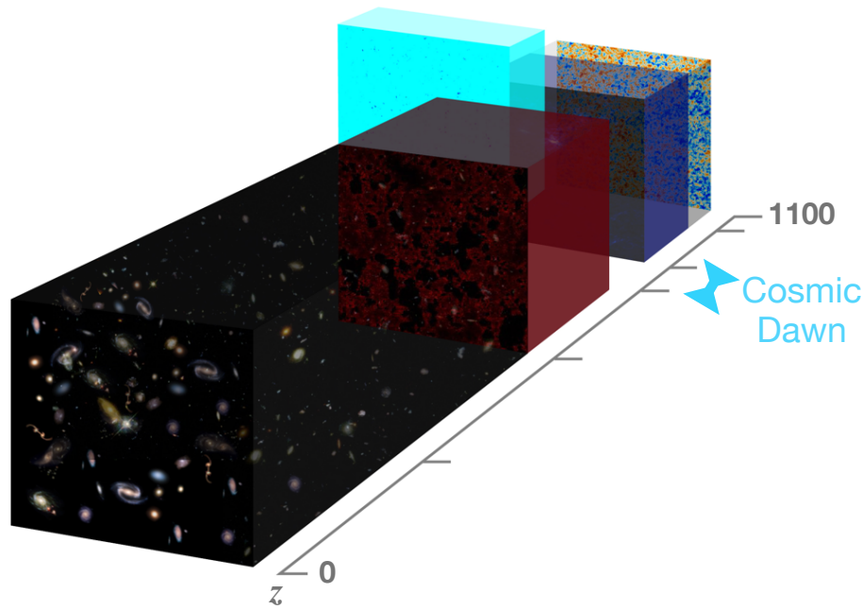

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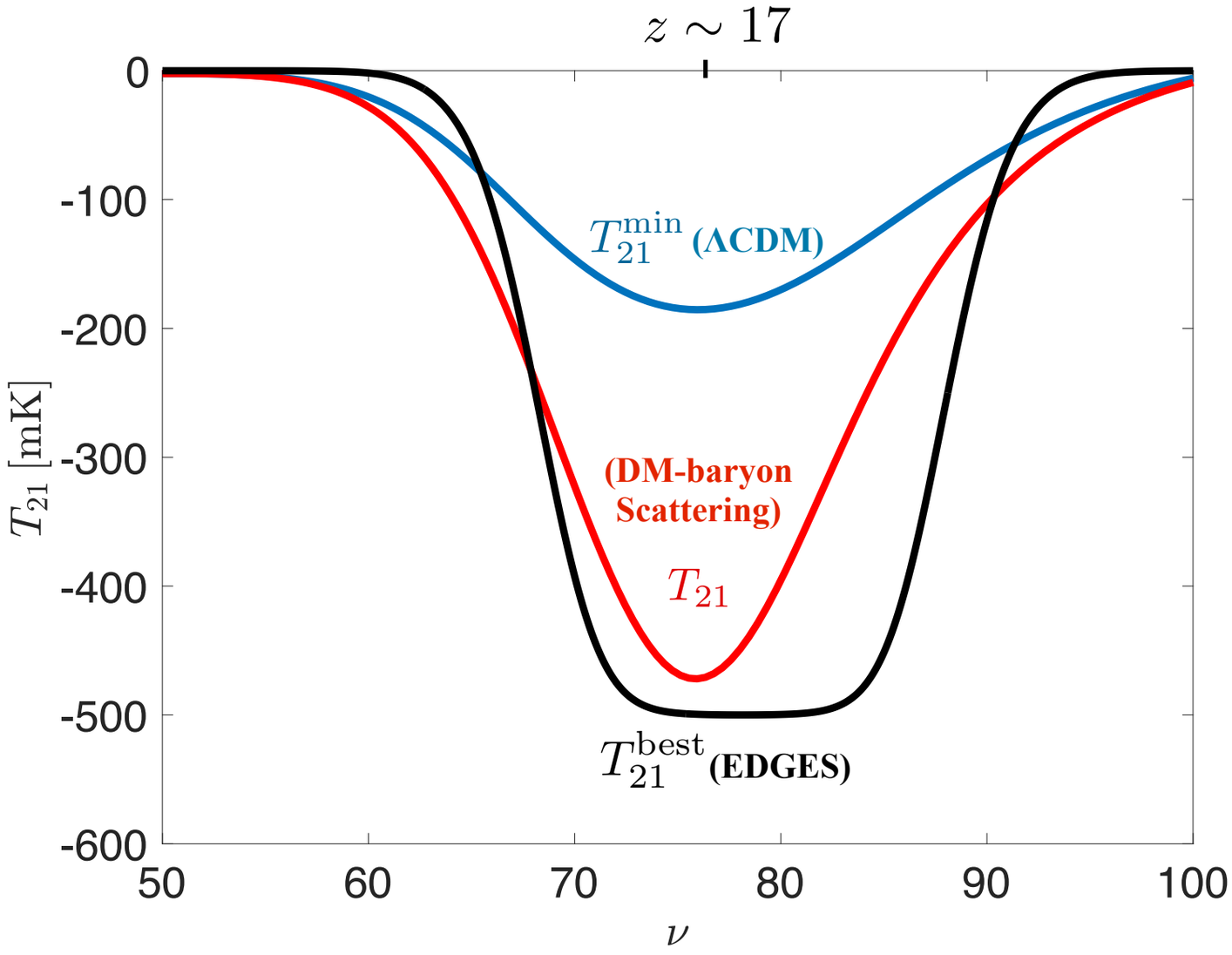

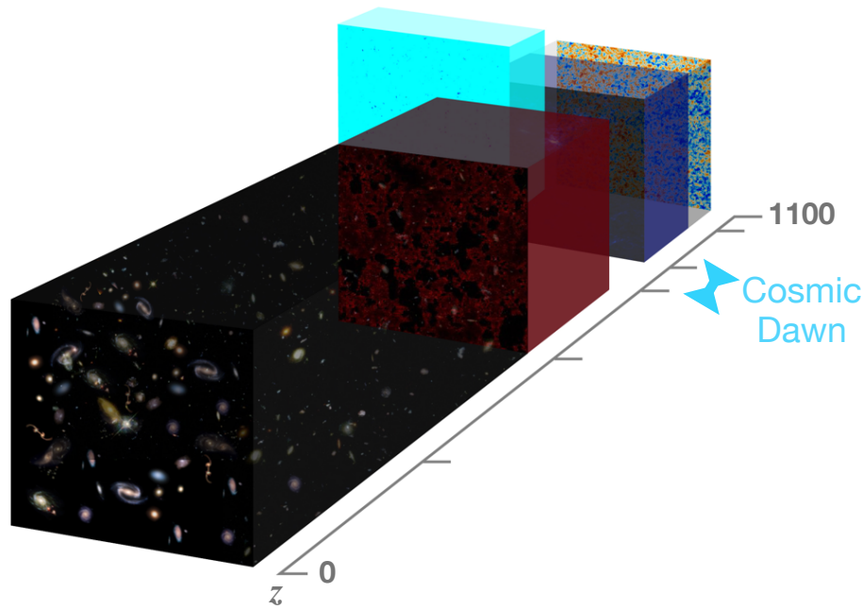

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Maybe...
- Muñoz and Loeb, Nature (2018)
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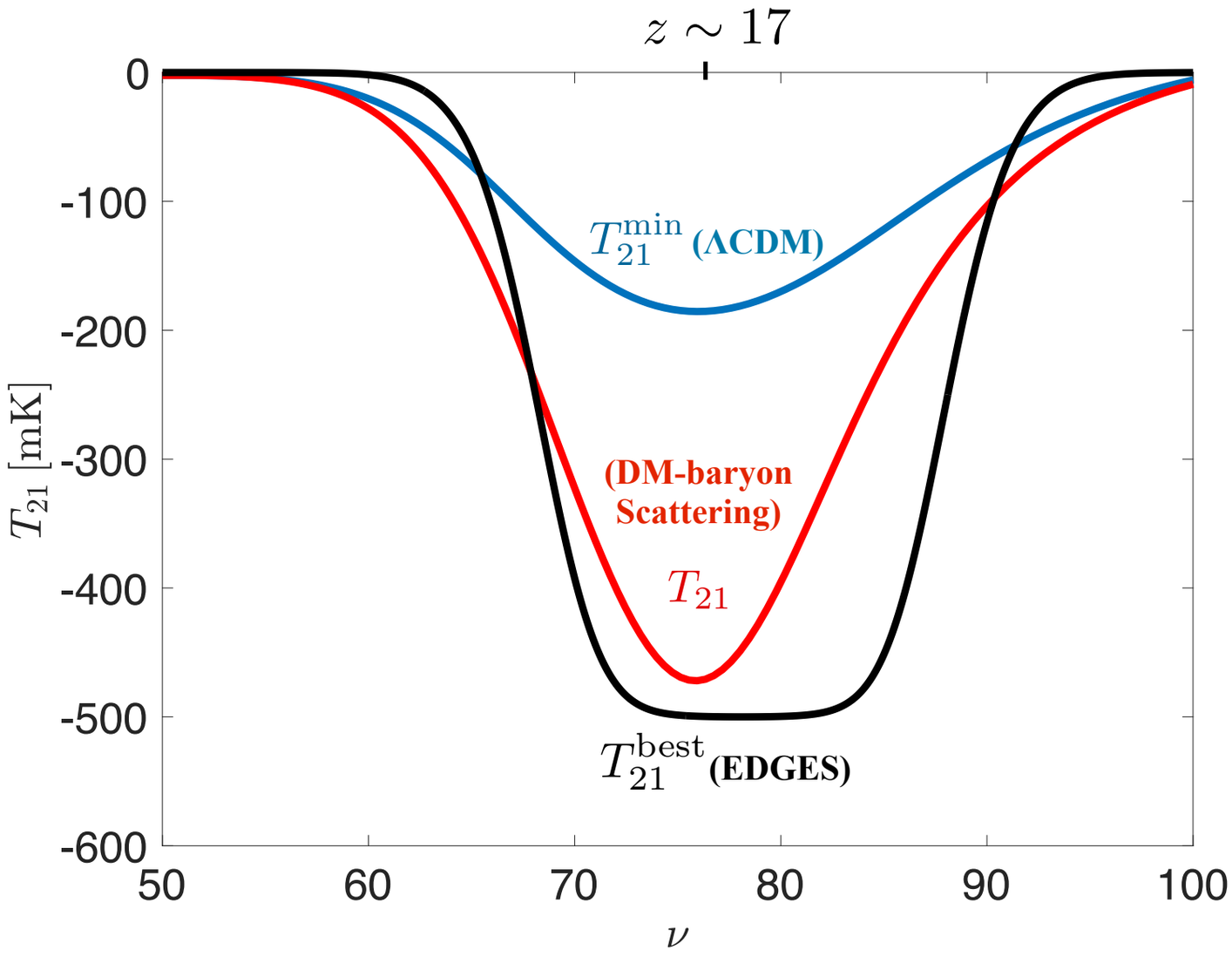

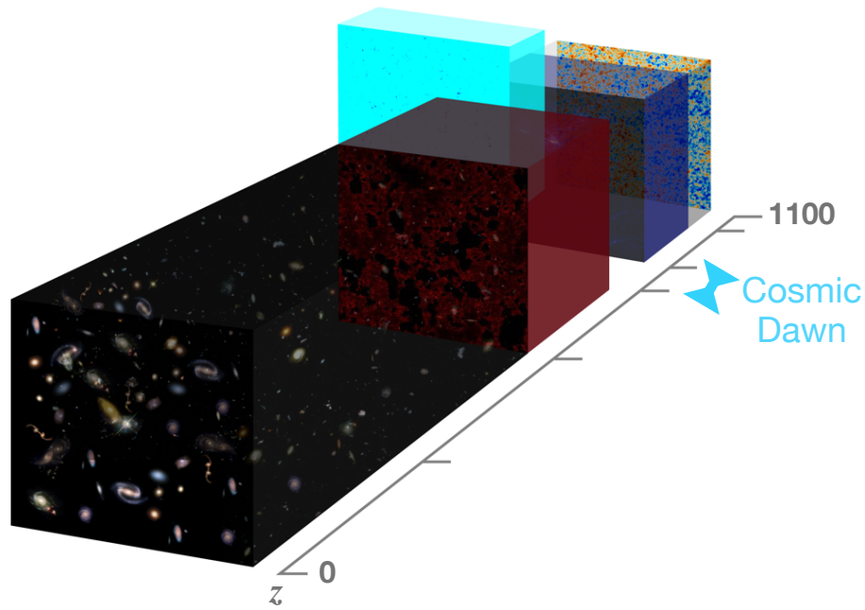

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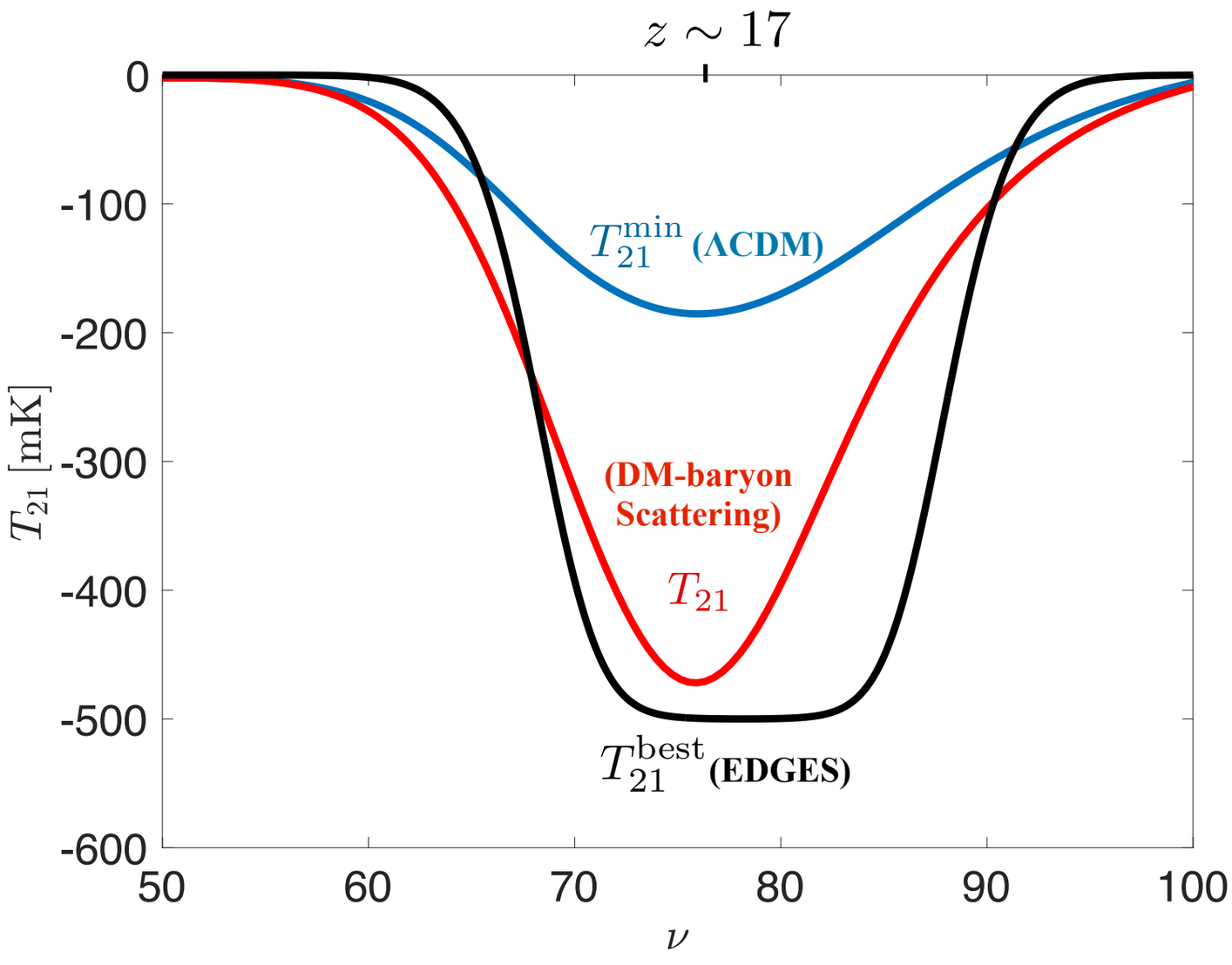

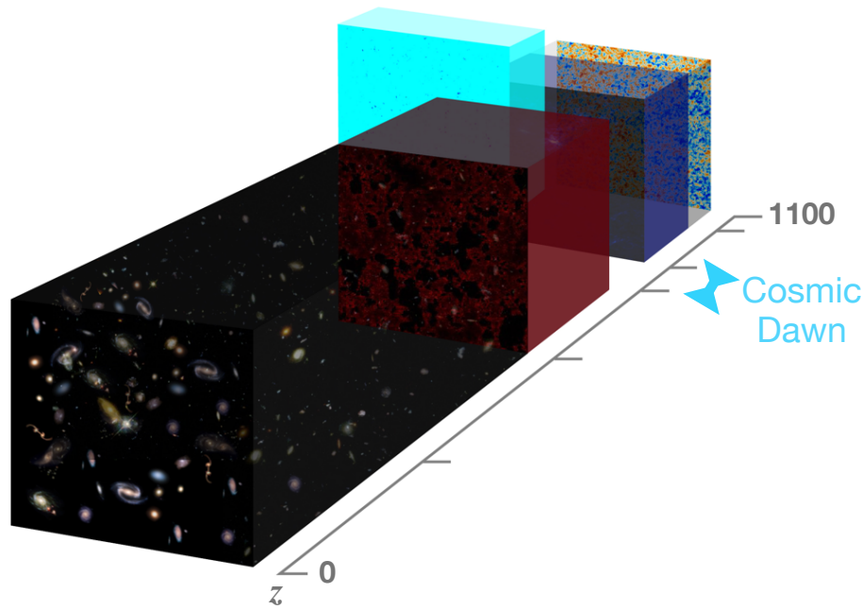

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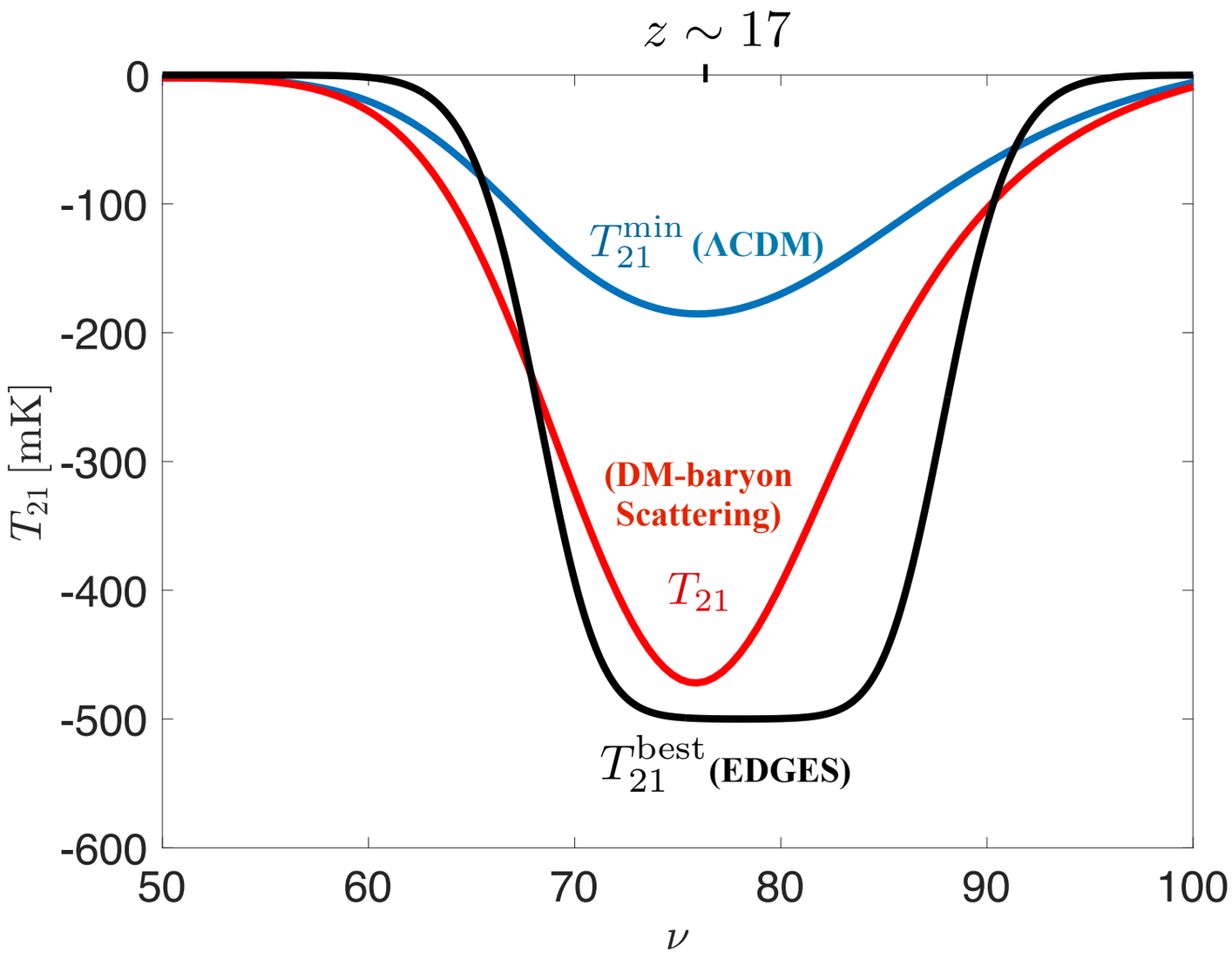
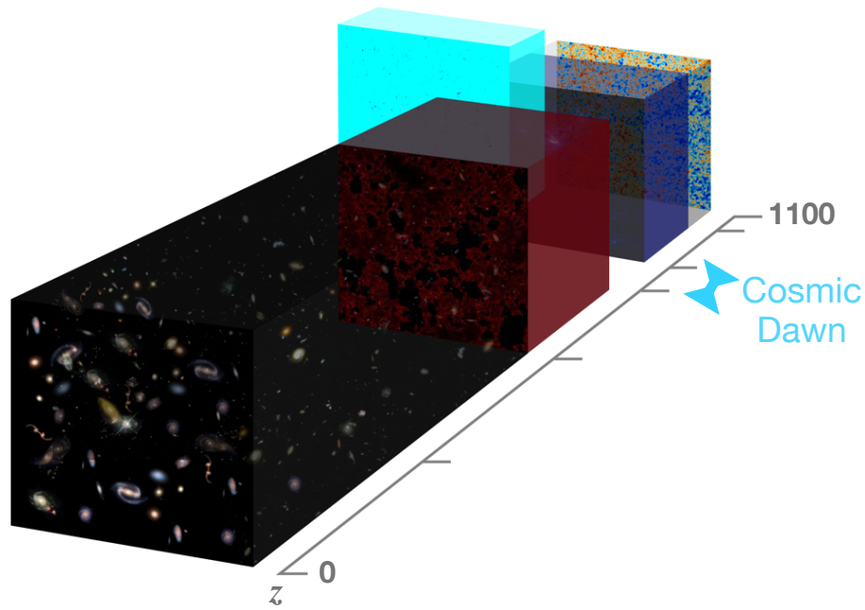
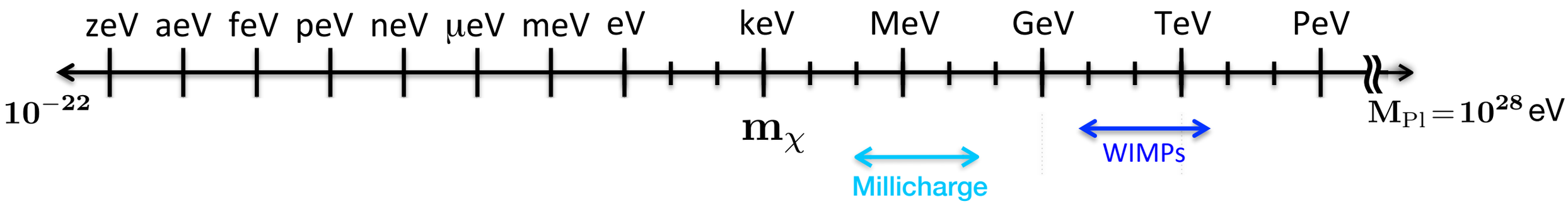
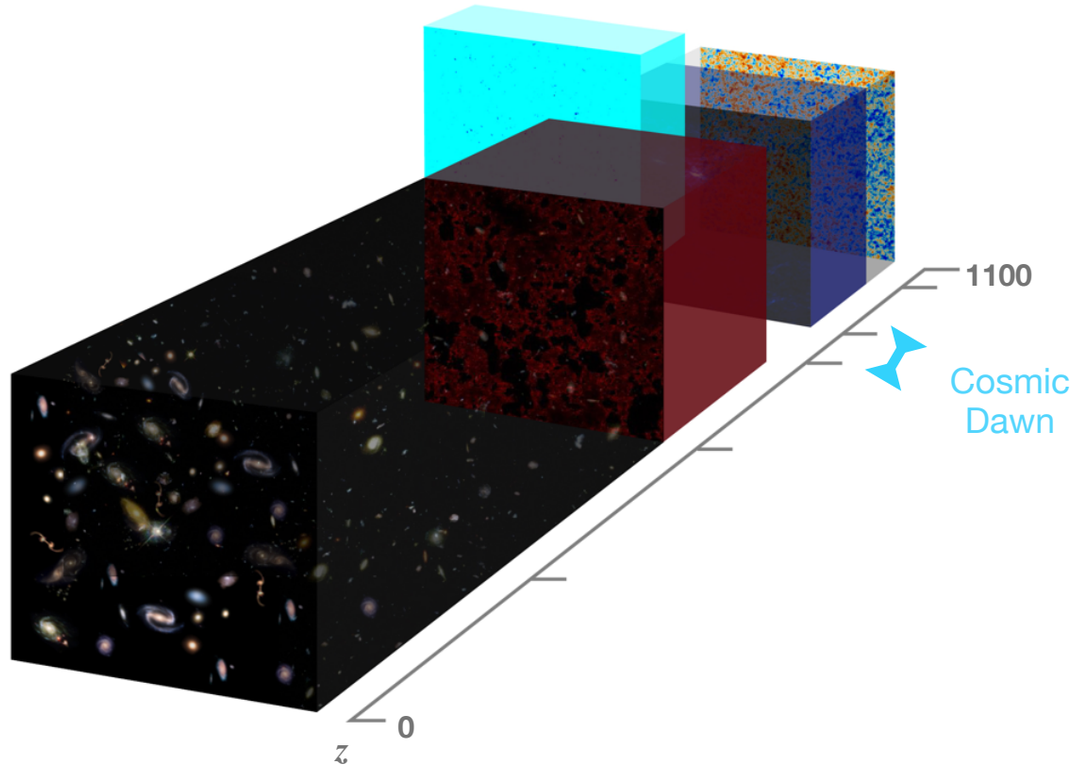




Probing Dark Matter with 21cm at Cosmic Dawn





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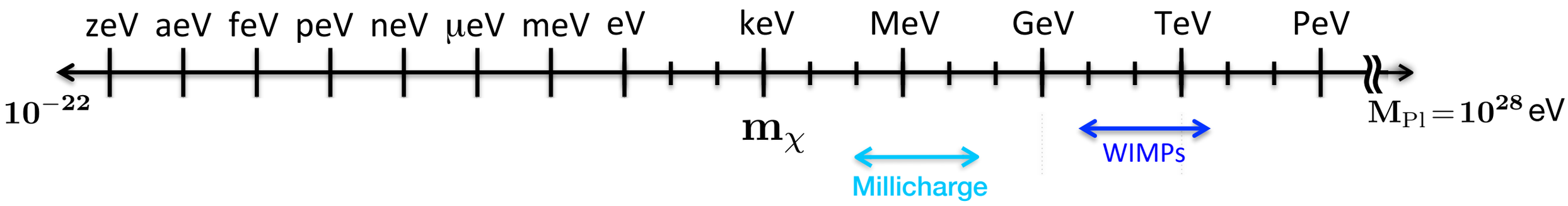

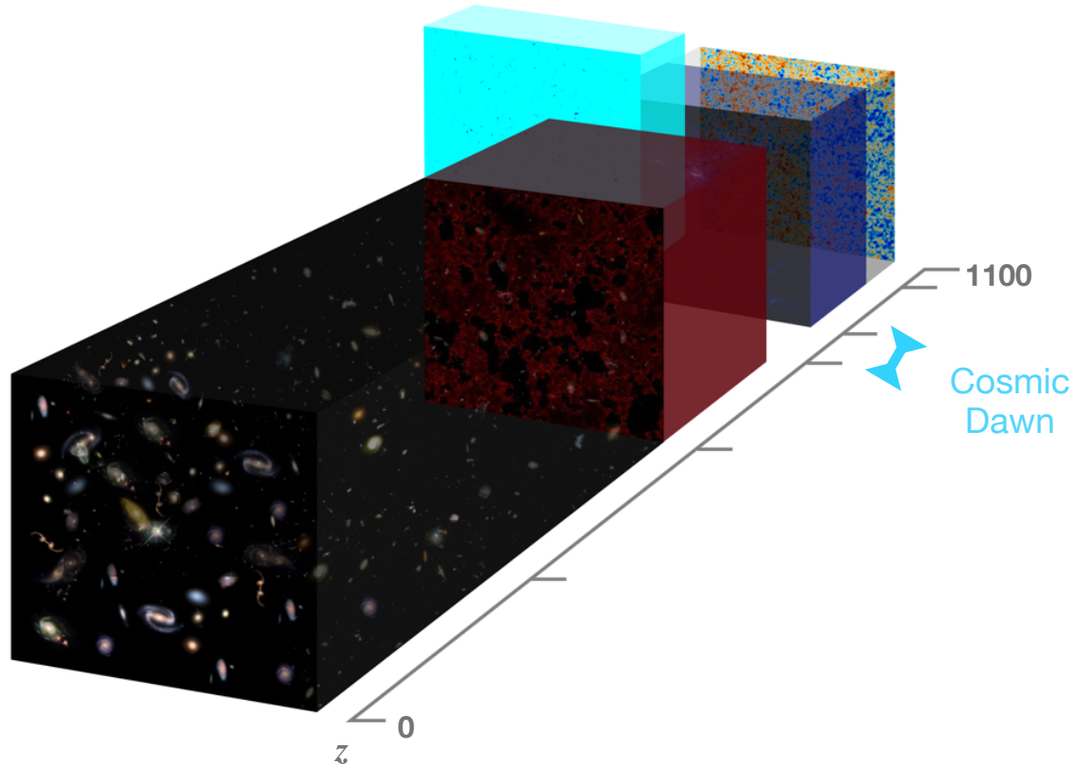

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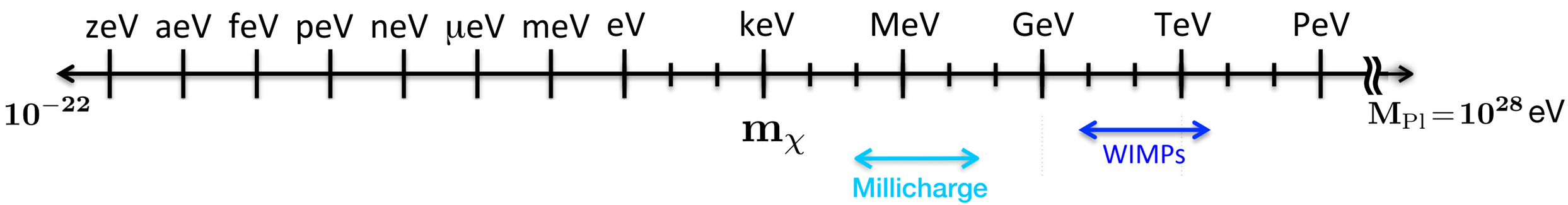

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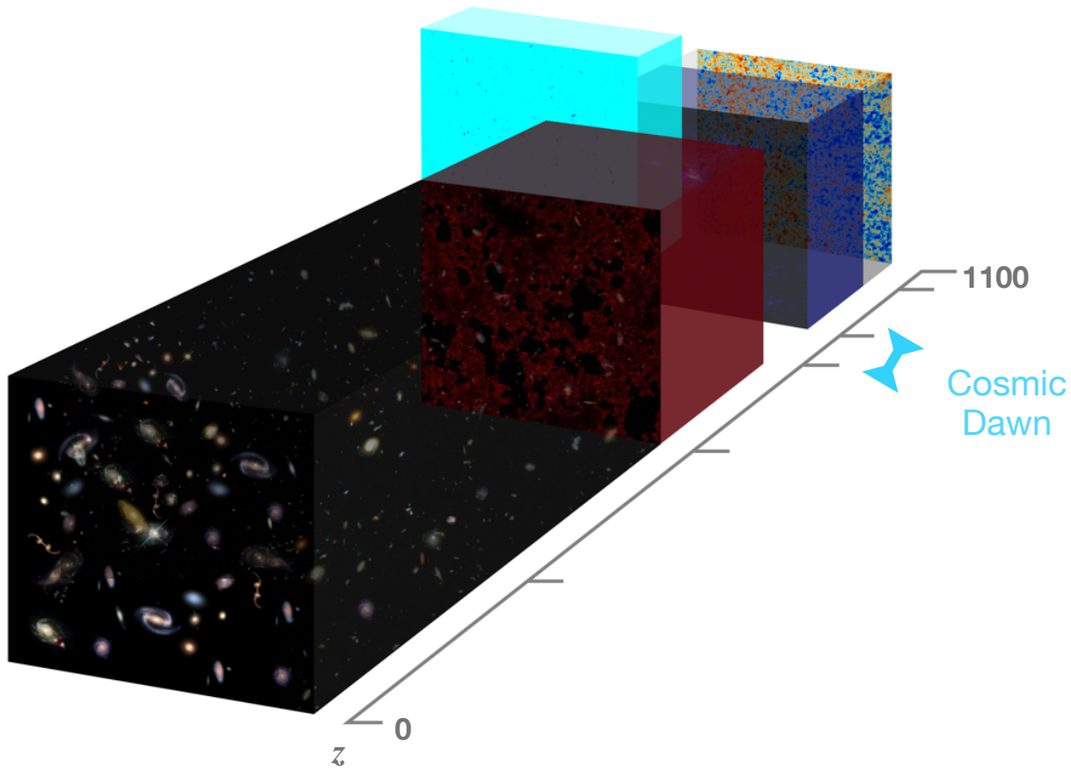

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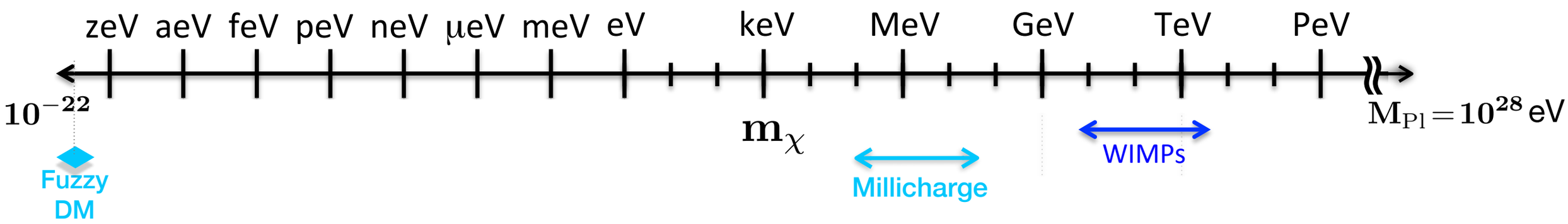

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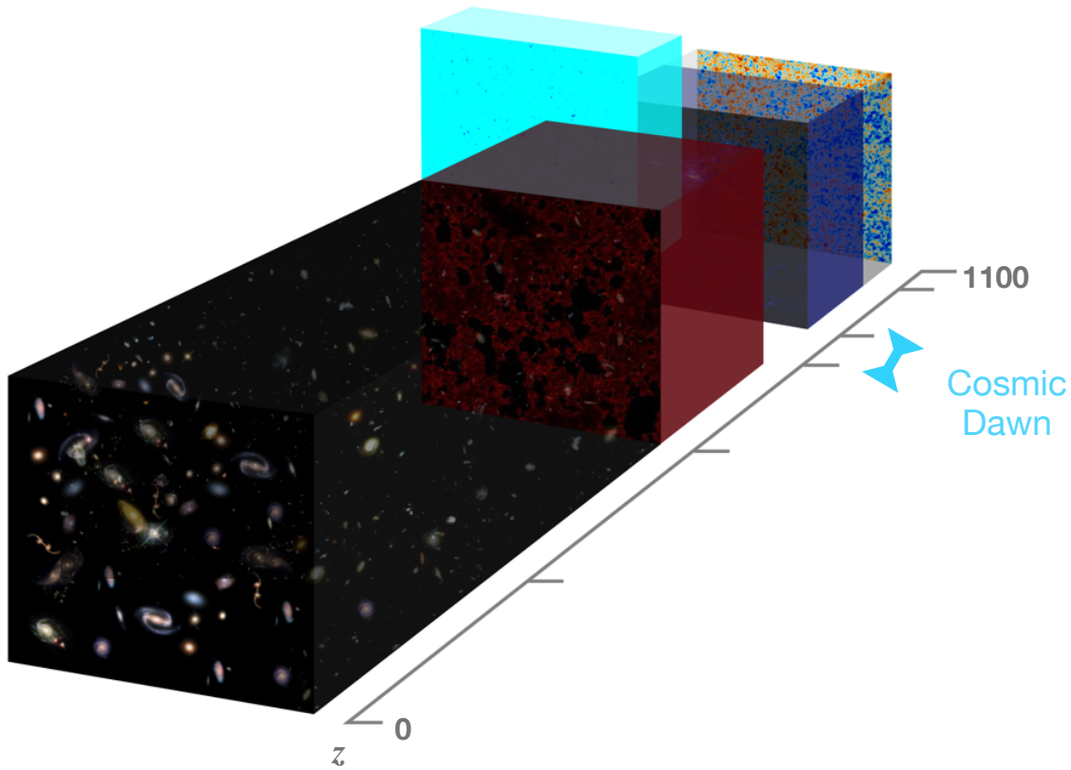

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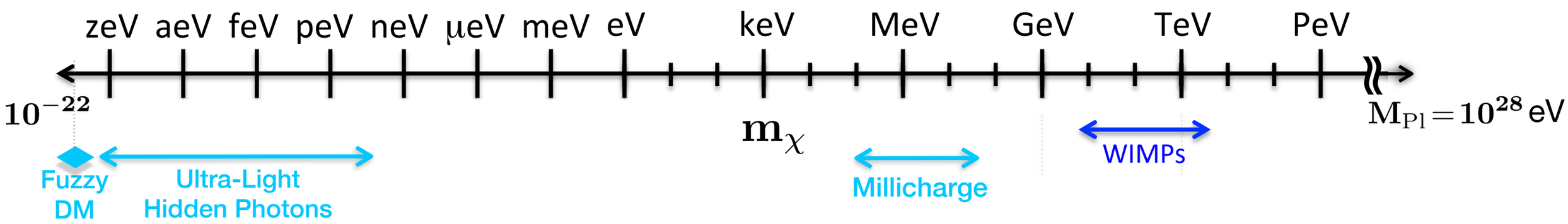

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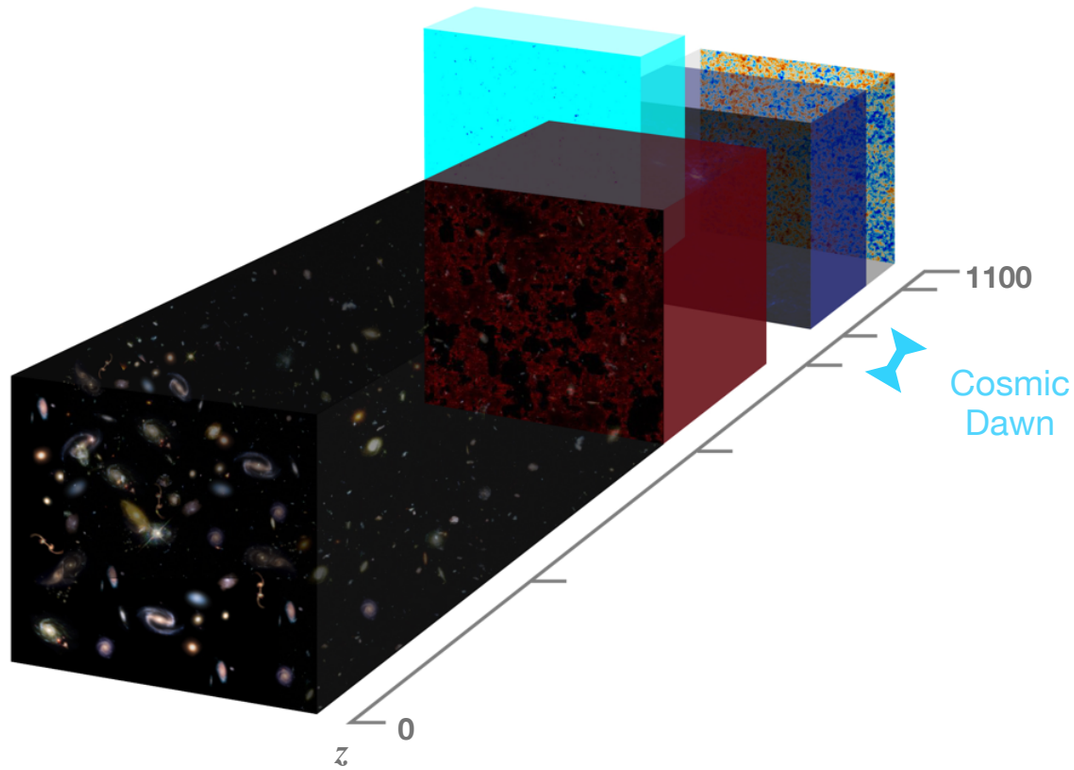

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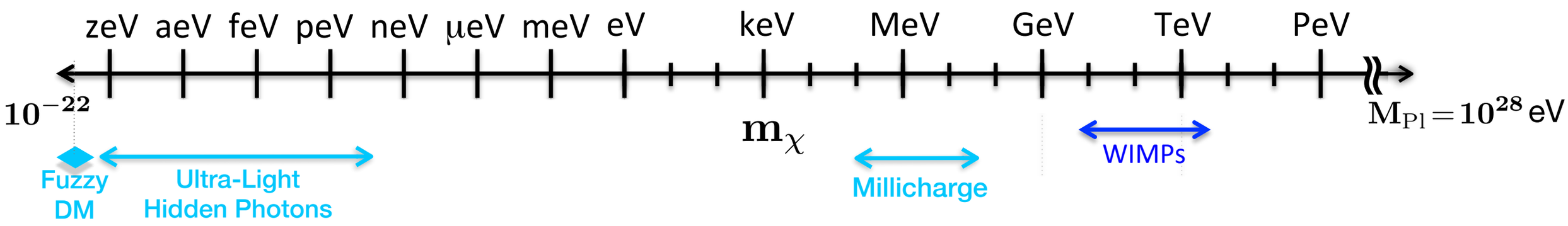

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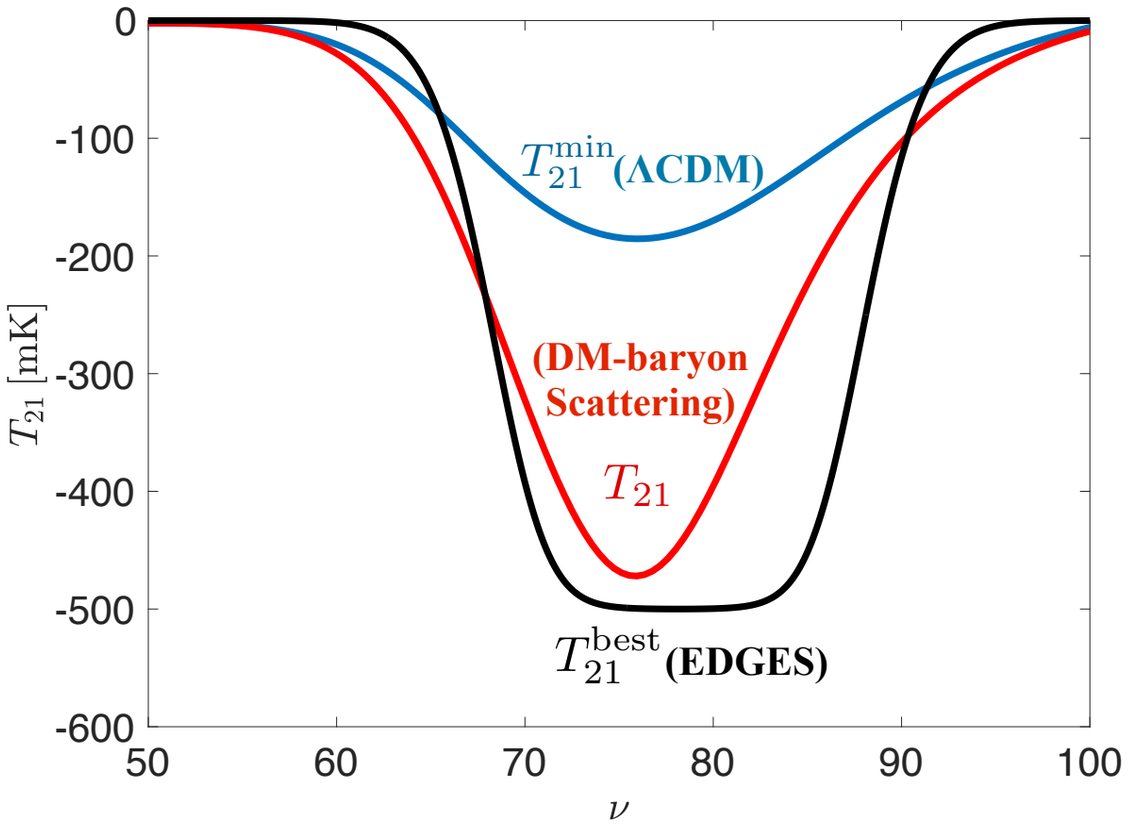

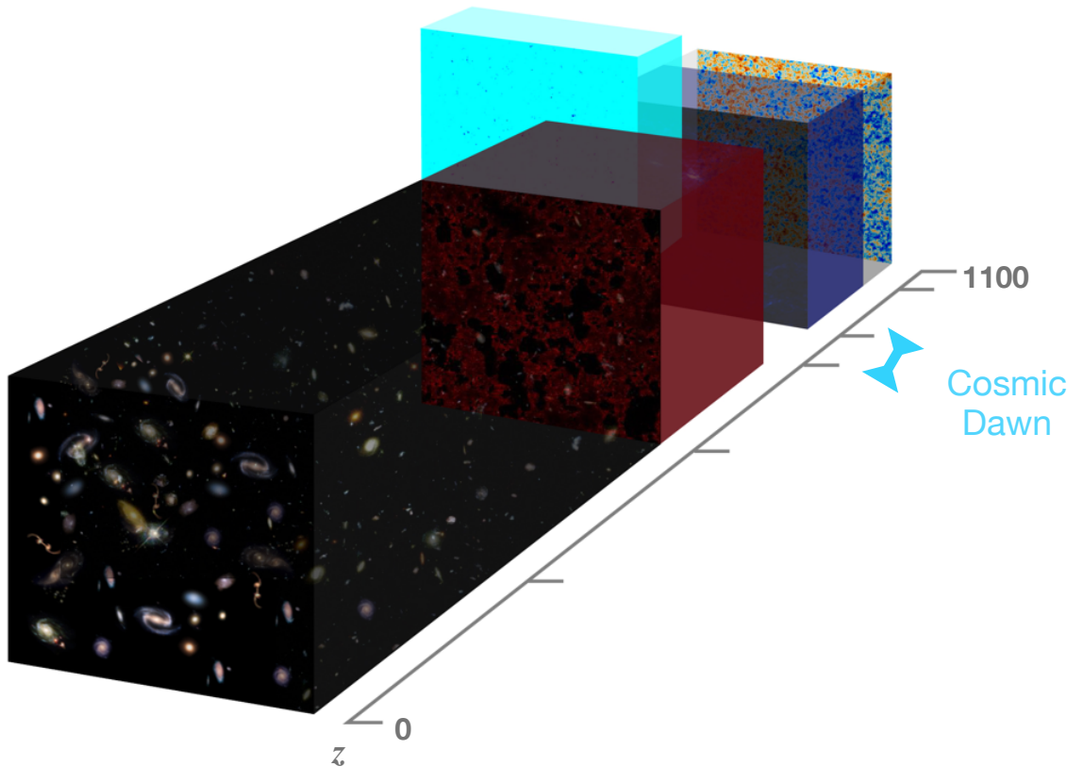

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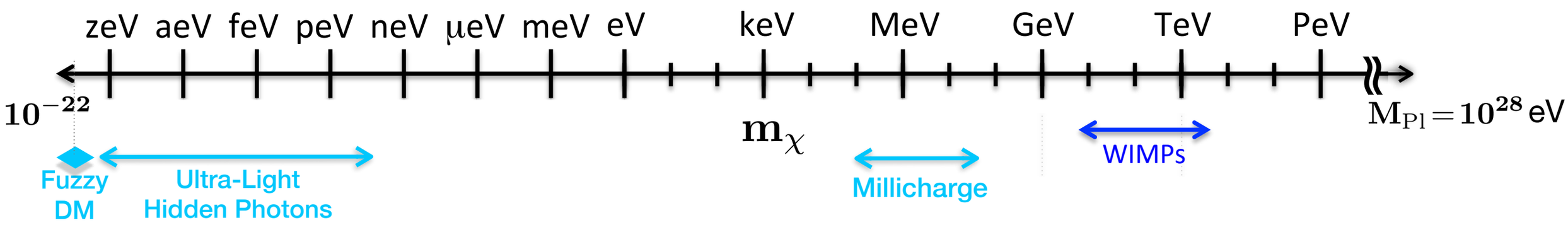

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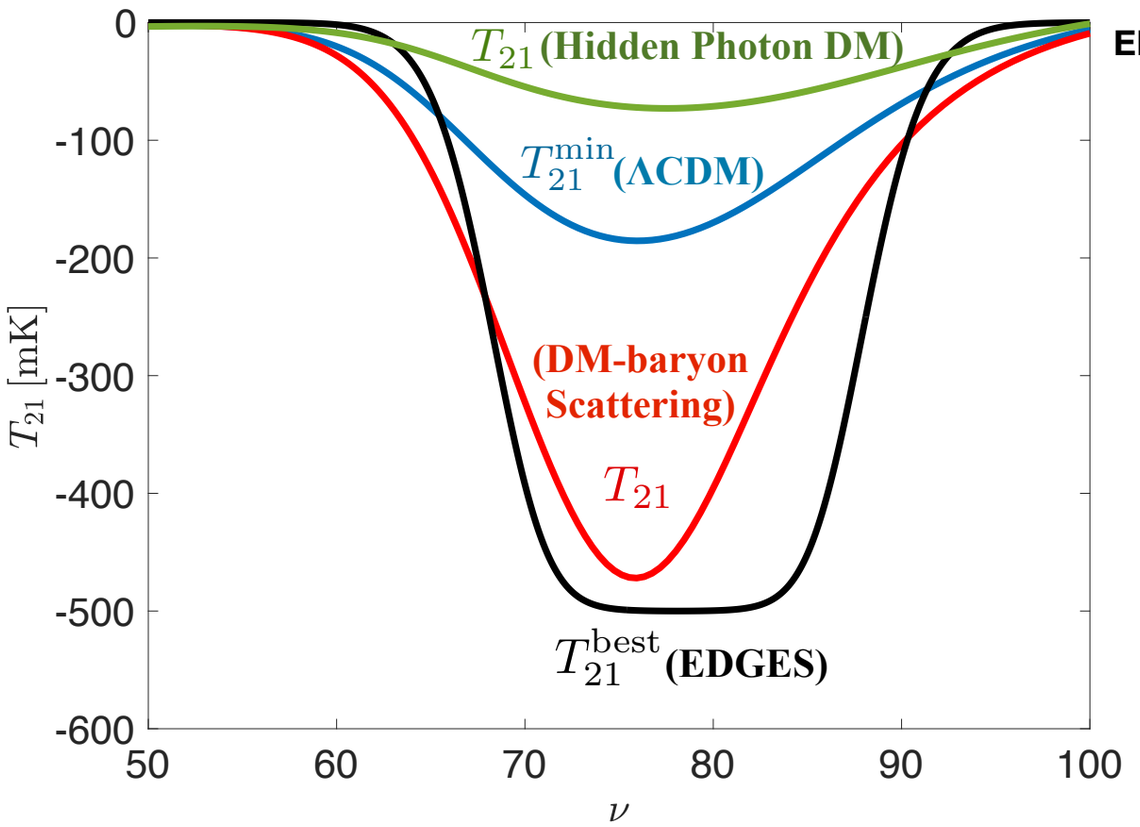

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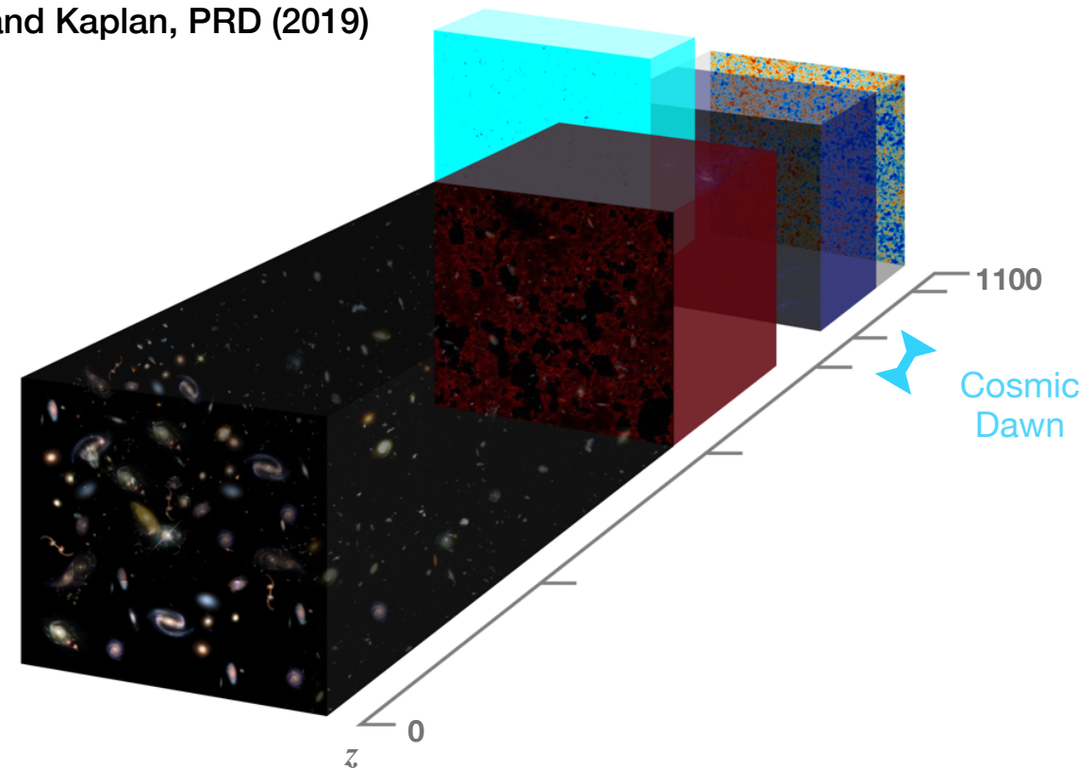

Ultra-Light Hidden-Photon Dark Matter

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- Hidden photons couple to the standard model electric current:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{m^2}{2}\tilde{A}_\mu\tilde{A}^\mu - \frac{e}{(1+\varepsilon^2)^{1/2}}J^\mu\left(A_\mu + \varepsilon\tilde{A}_\mu\right)$$

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$$\text{At } z = 17: \qquad \omega_p = \left(\frac{4\pi n_e \alpha}{m_e}\right) = 1.7\times10^{-14}\left(\frac{n_e}{2\times10^{-7}\,\text{cm}^{-3}}\right)^{1/2}\ \text{eV}$$

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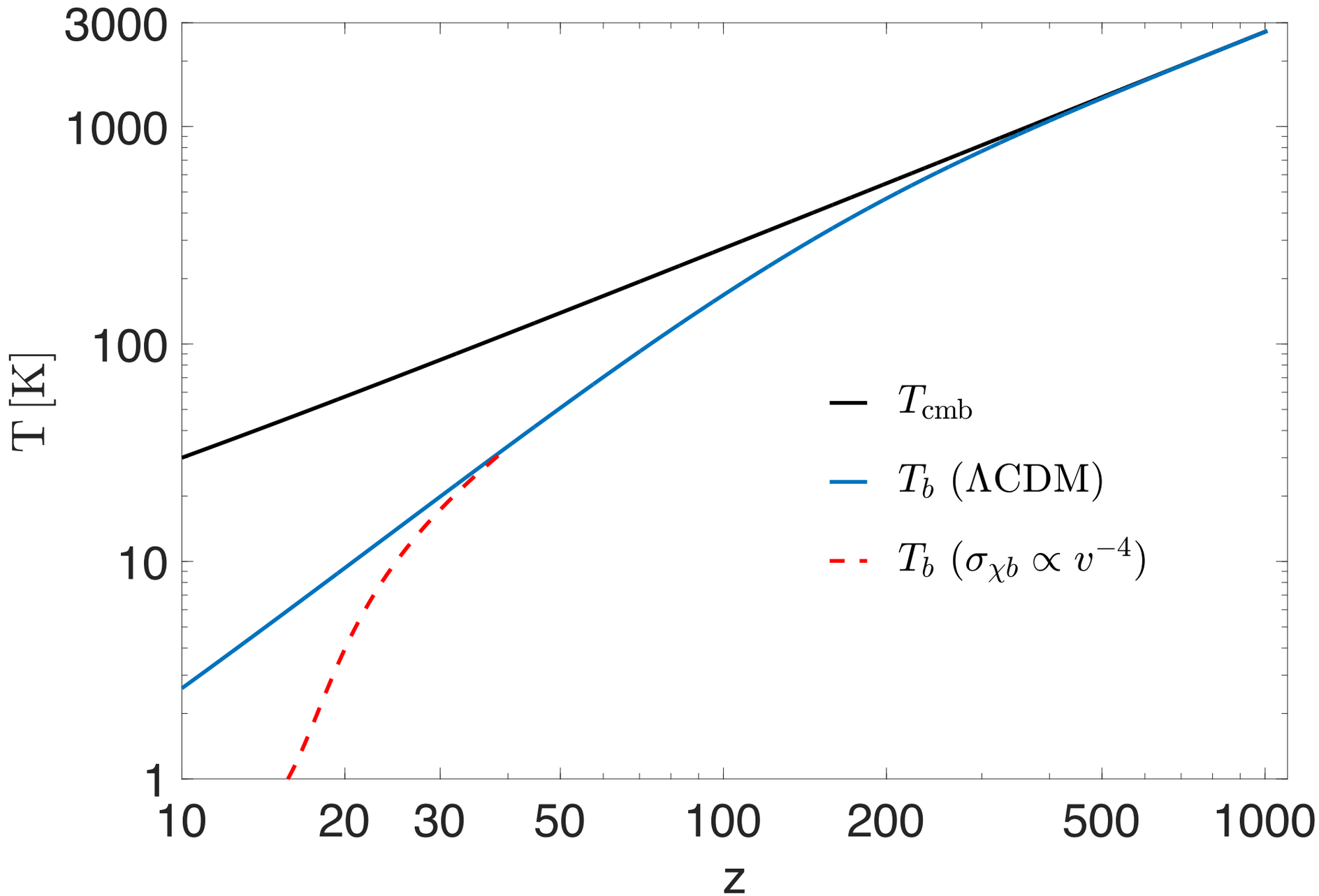

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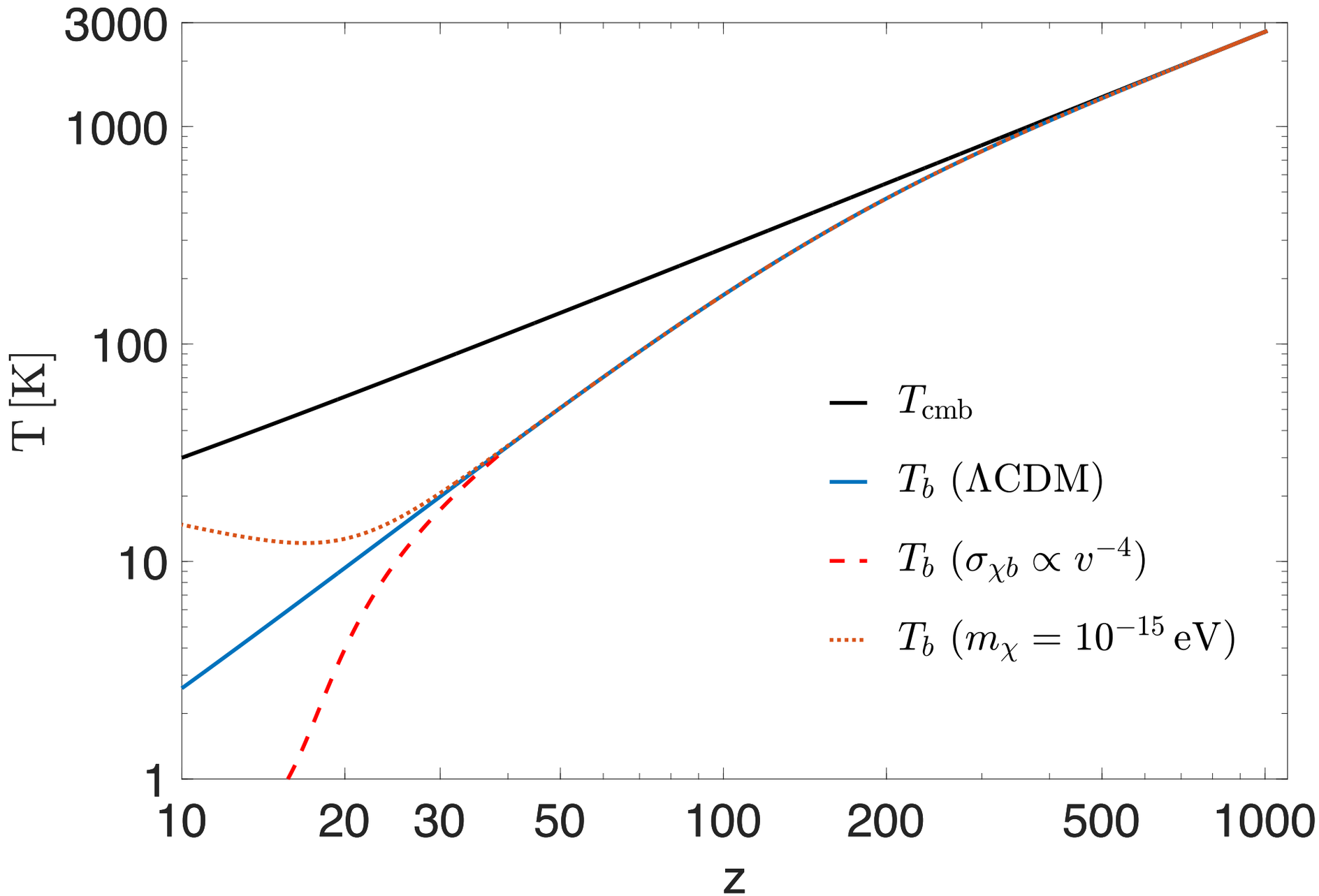

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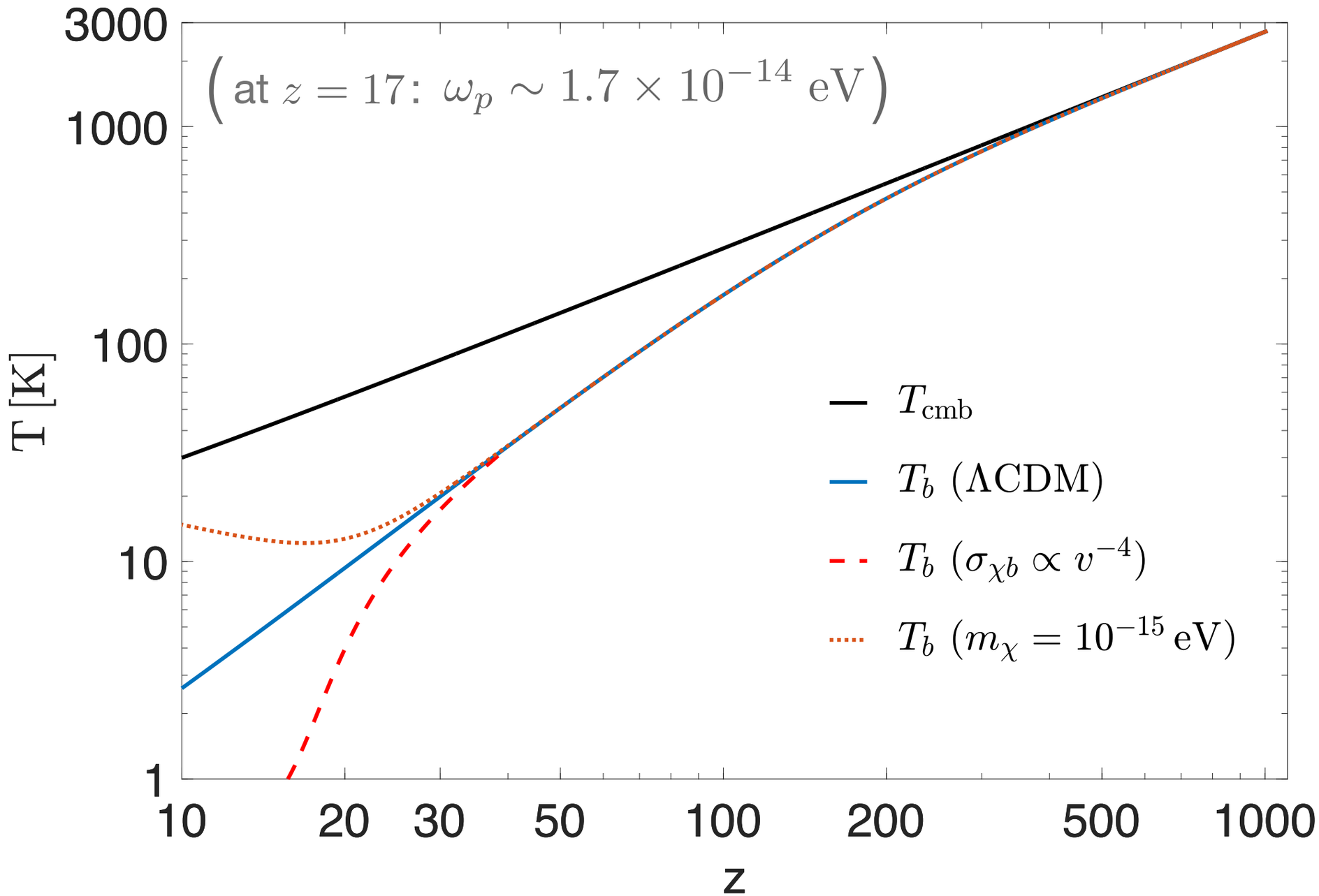

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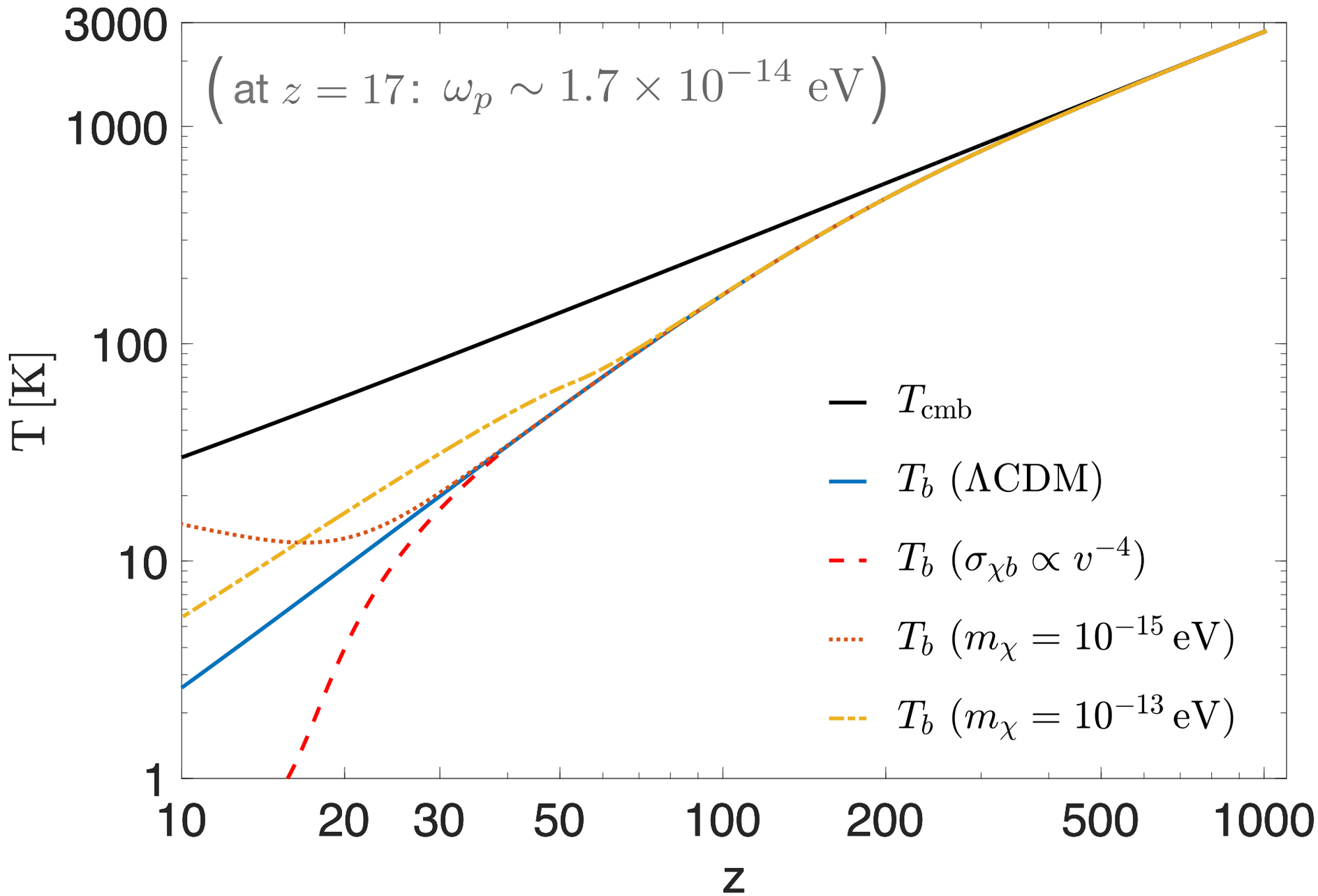

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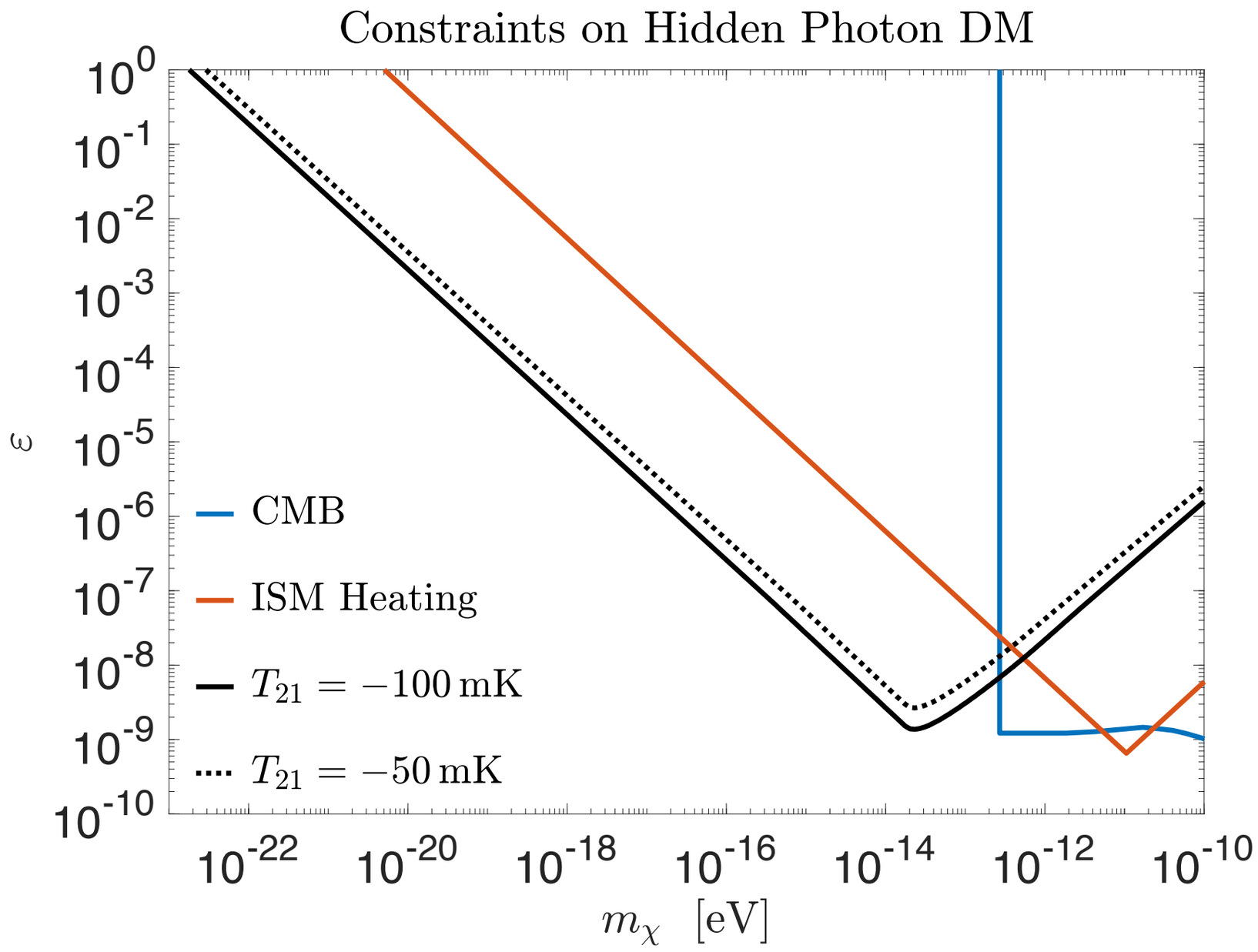

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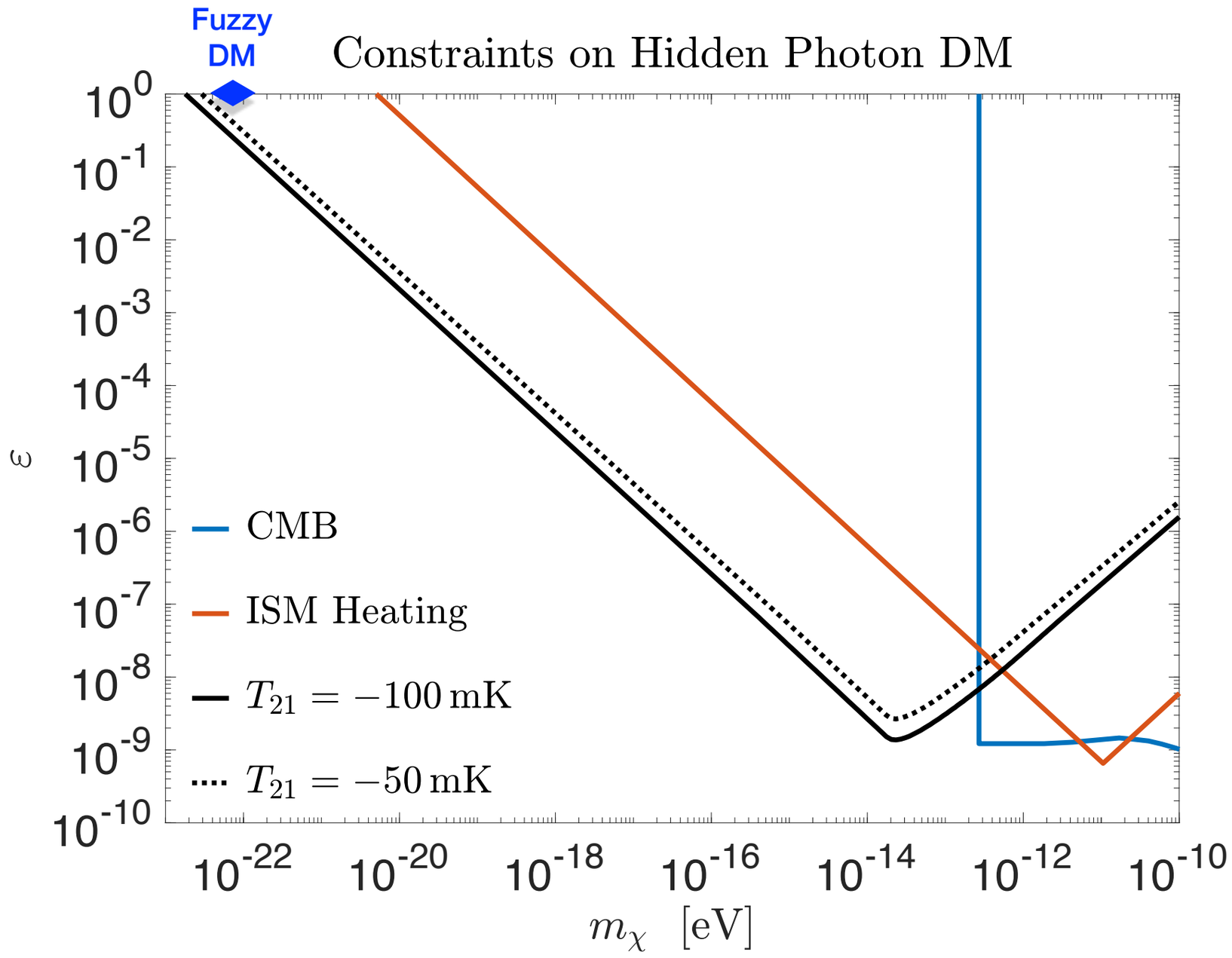

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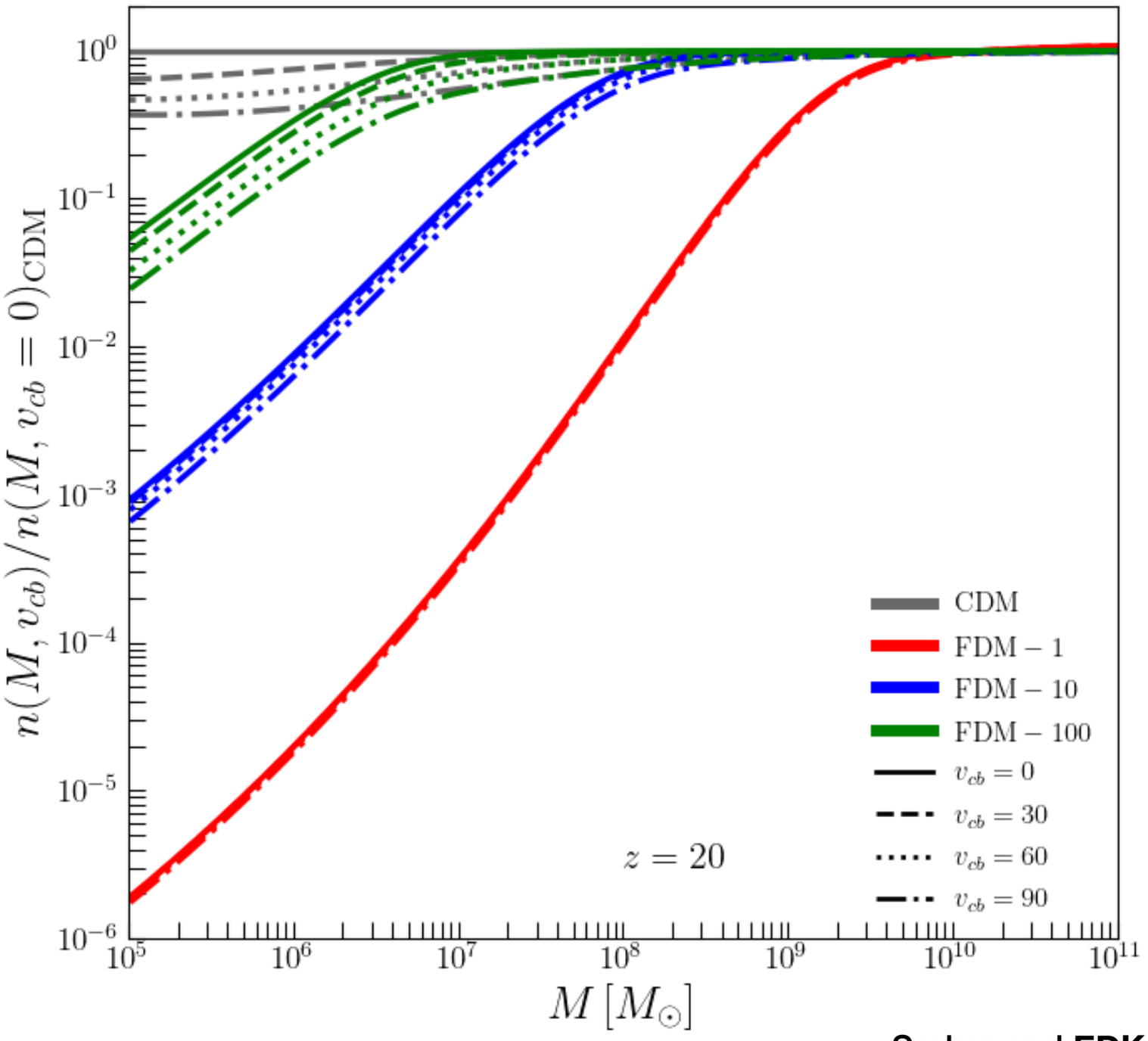

Sarkar and **EDK**, in progress

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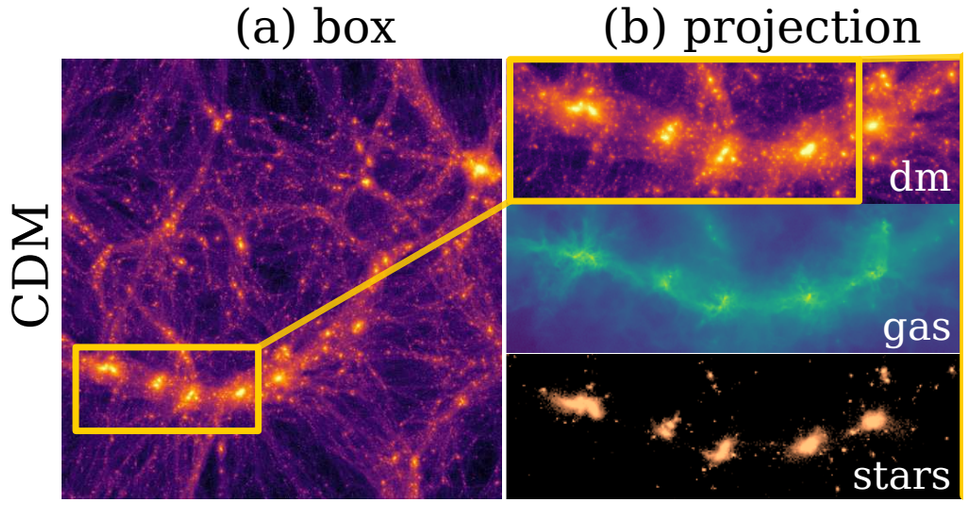

Mocz, Fialkov et al., PRL 2019

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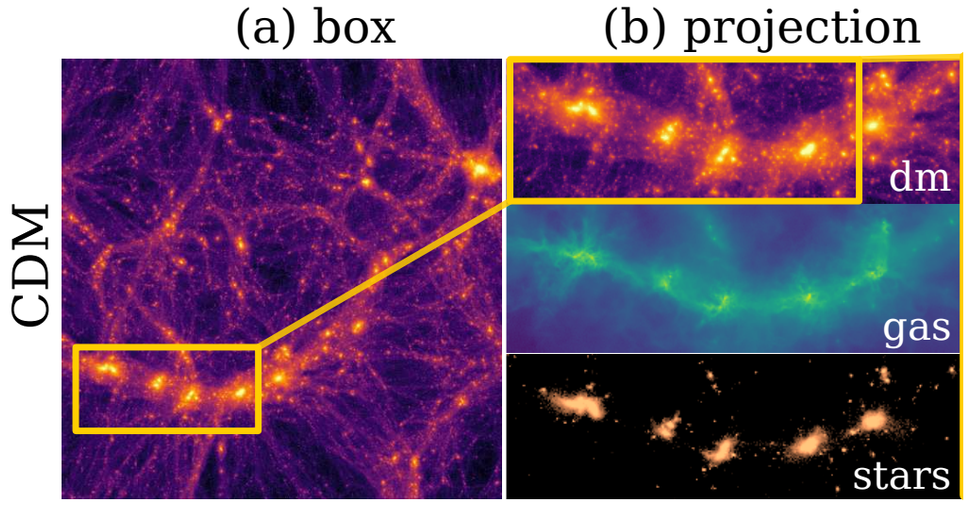

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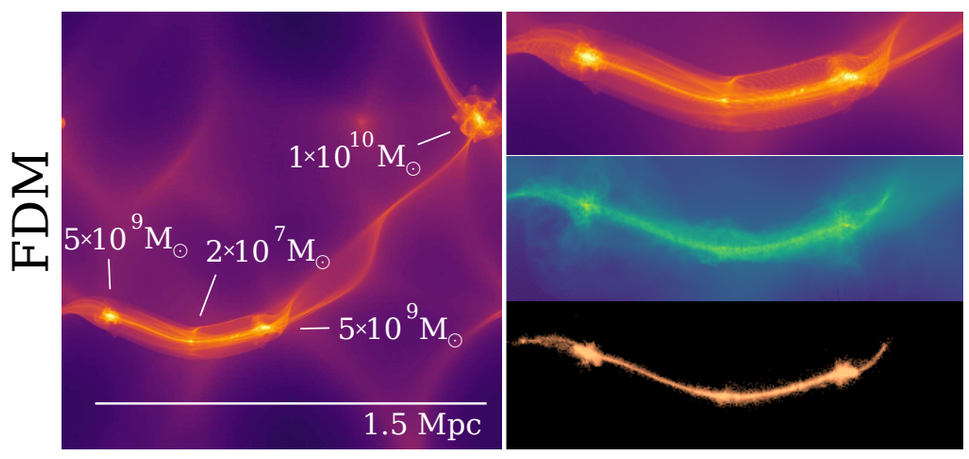

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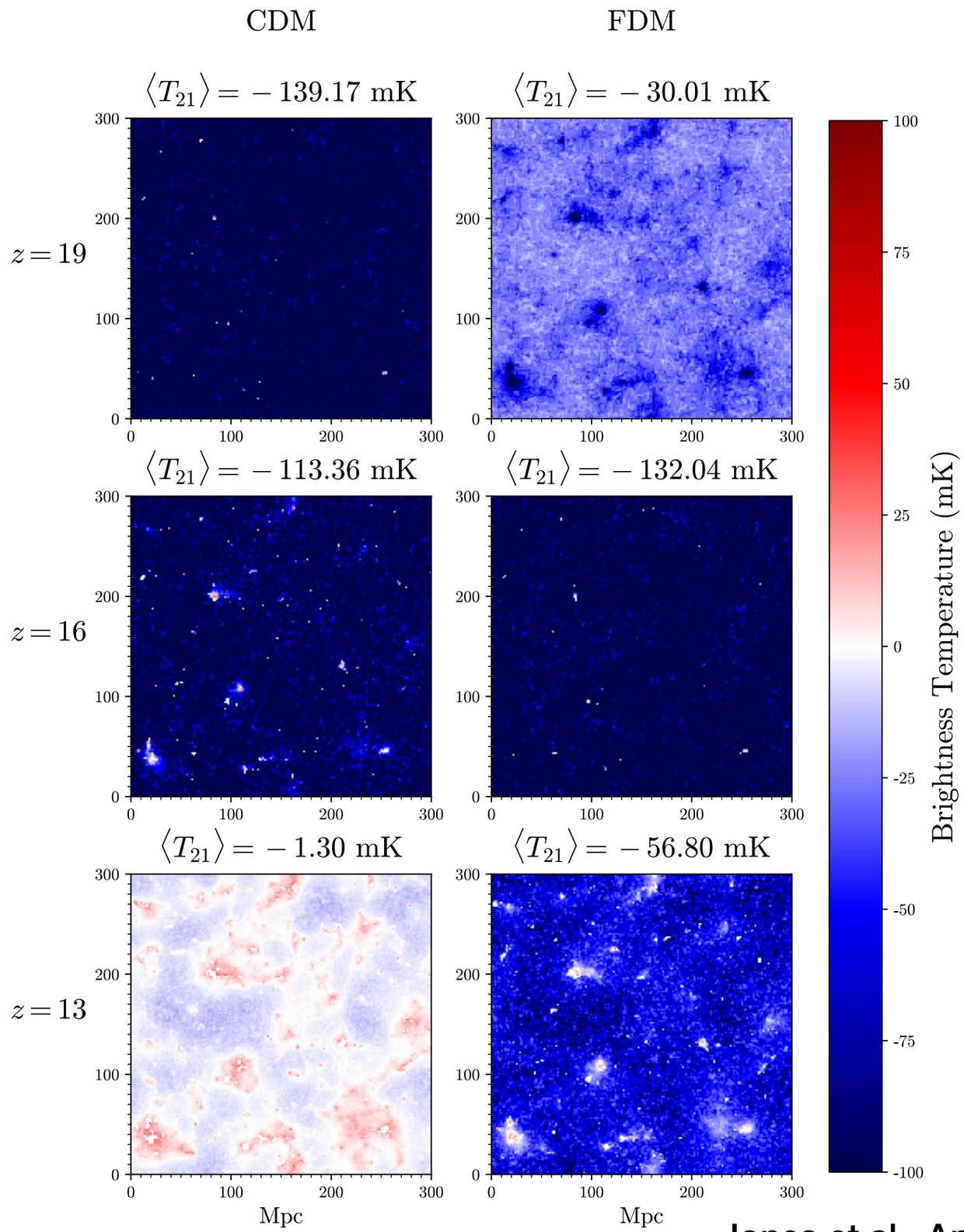

Jones et al., Apj 2021

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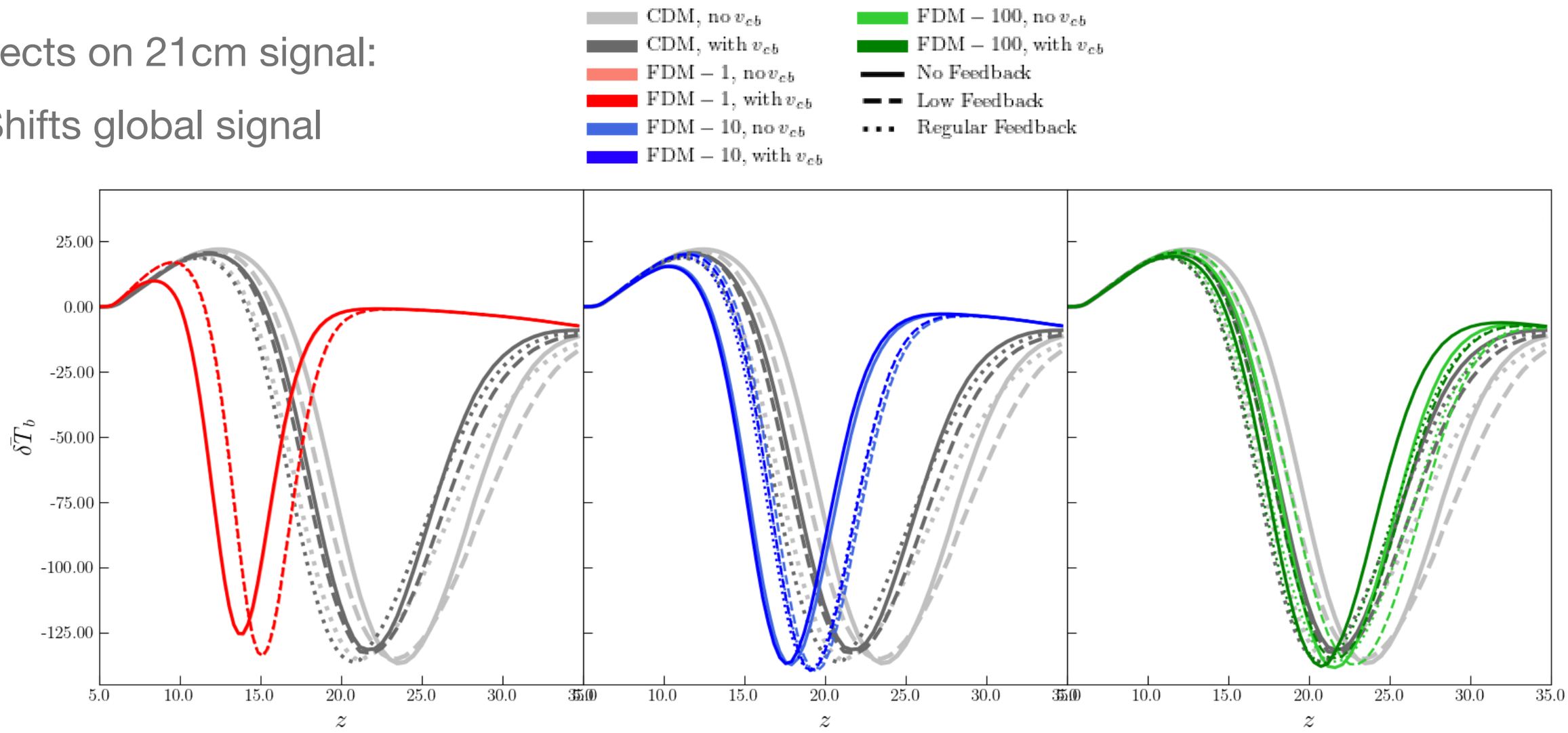

Sarkar and **EDK**, in progress

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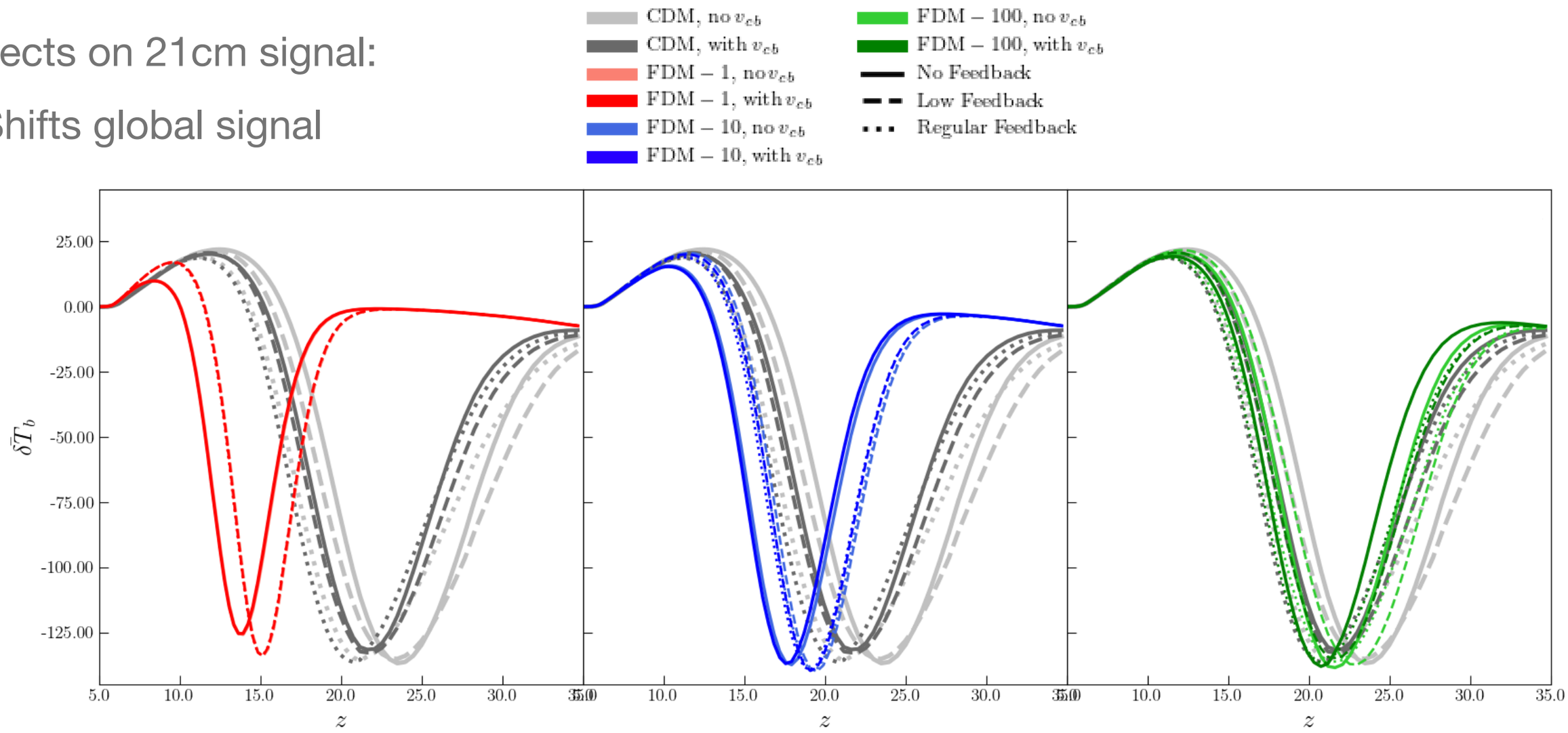

Sarkar and EDK, in progress

Important to take into account:

- DM-baryon relative velocities
- Lyα feedback on star formation
- Lyα- and CMB-induced heating
- Astro/Cosmo degeneracies

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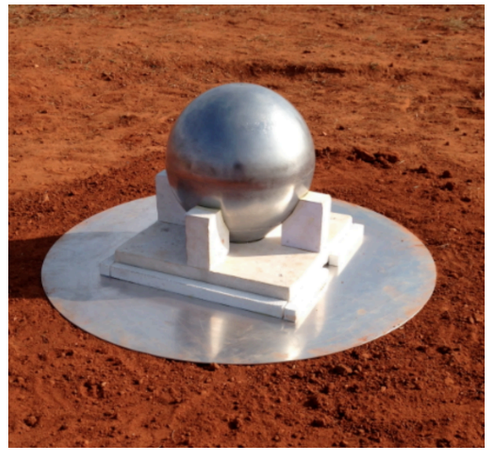

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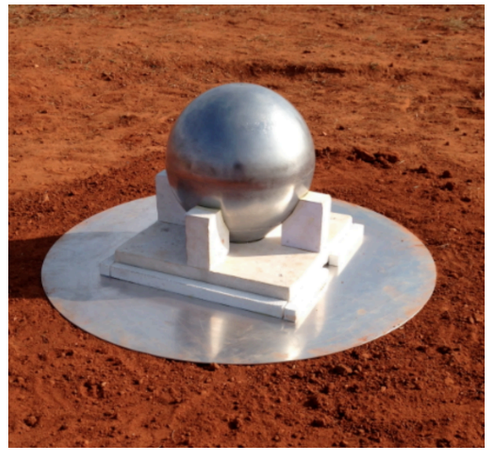

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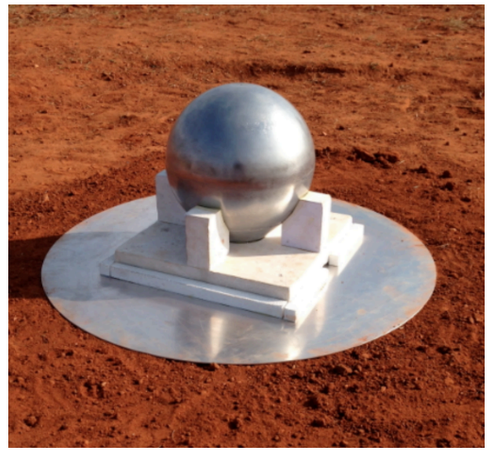

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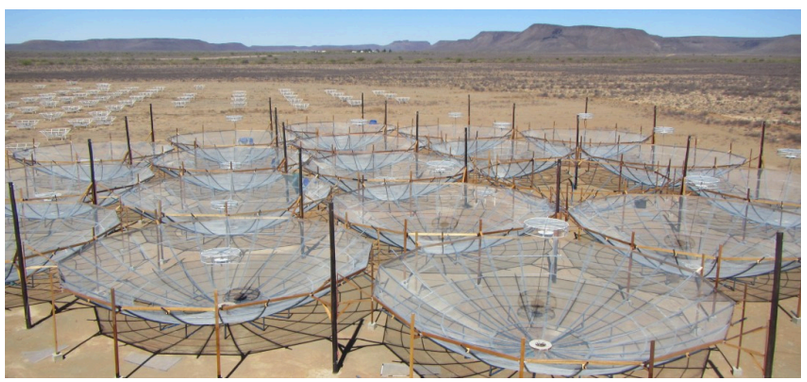
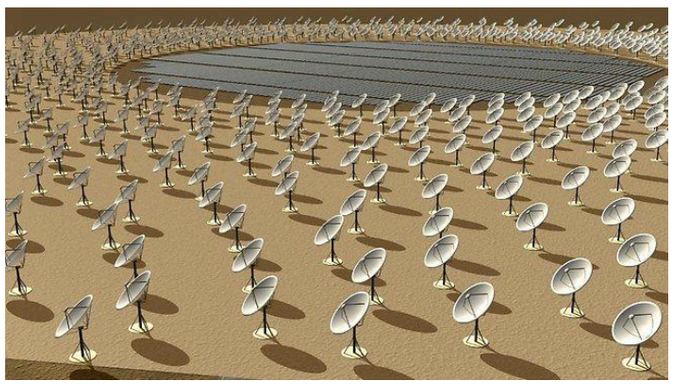
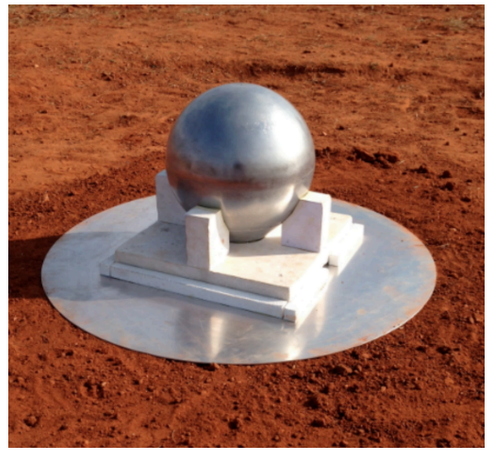




Cosmic Dawn 21cm: Observational Outlook

- 21cm global signal: LEDA, PRIZM, SARAS2...



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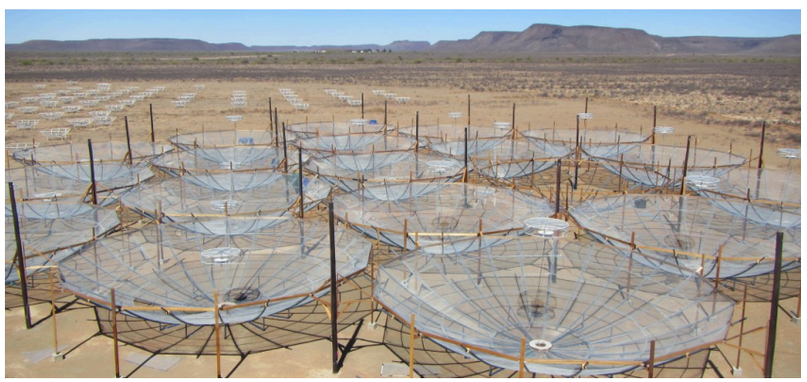

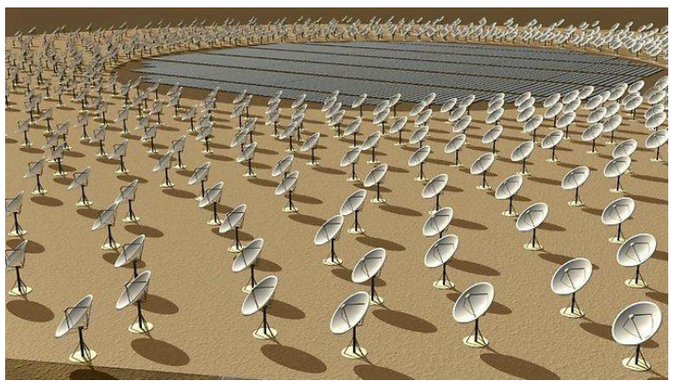

If EDGES is correct, power spectrum signal should be x10 higher than expected.

Case Study 2: The “Hubble Tension”

2

What makes up ***dark energy***?

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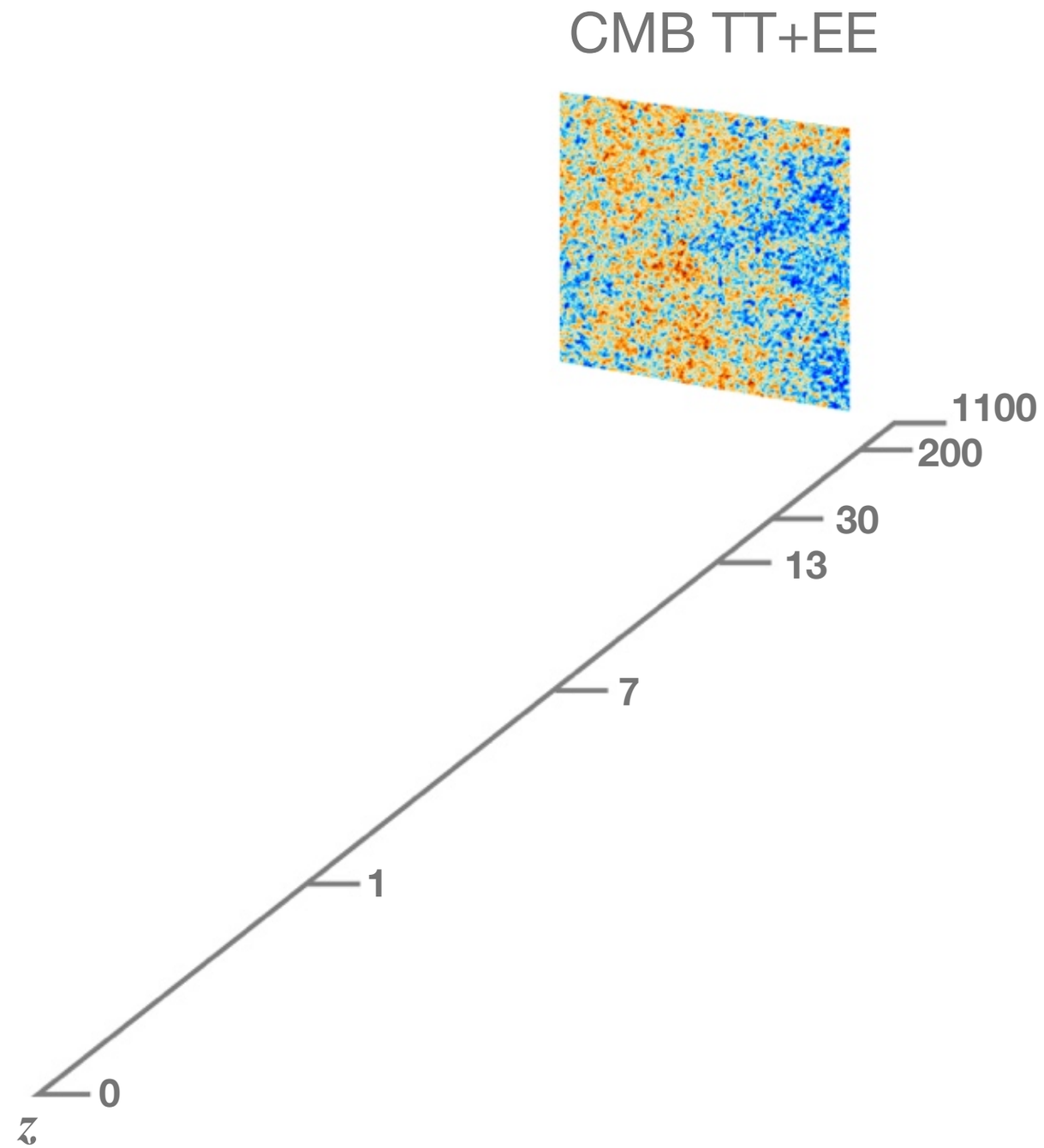

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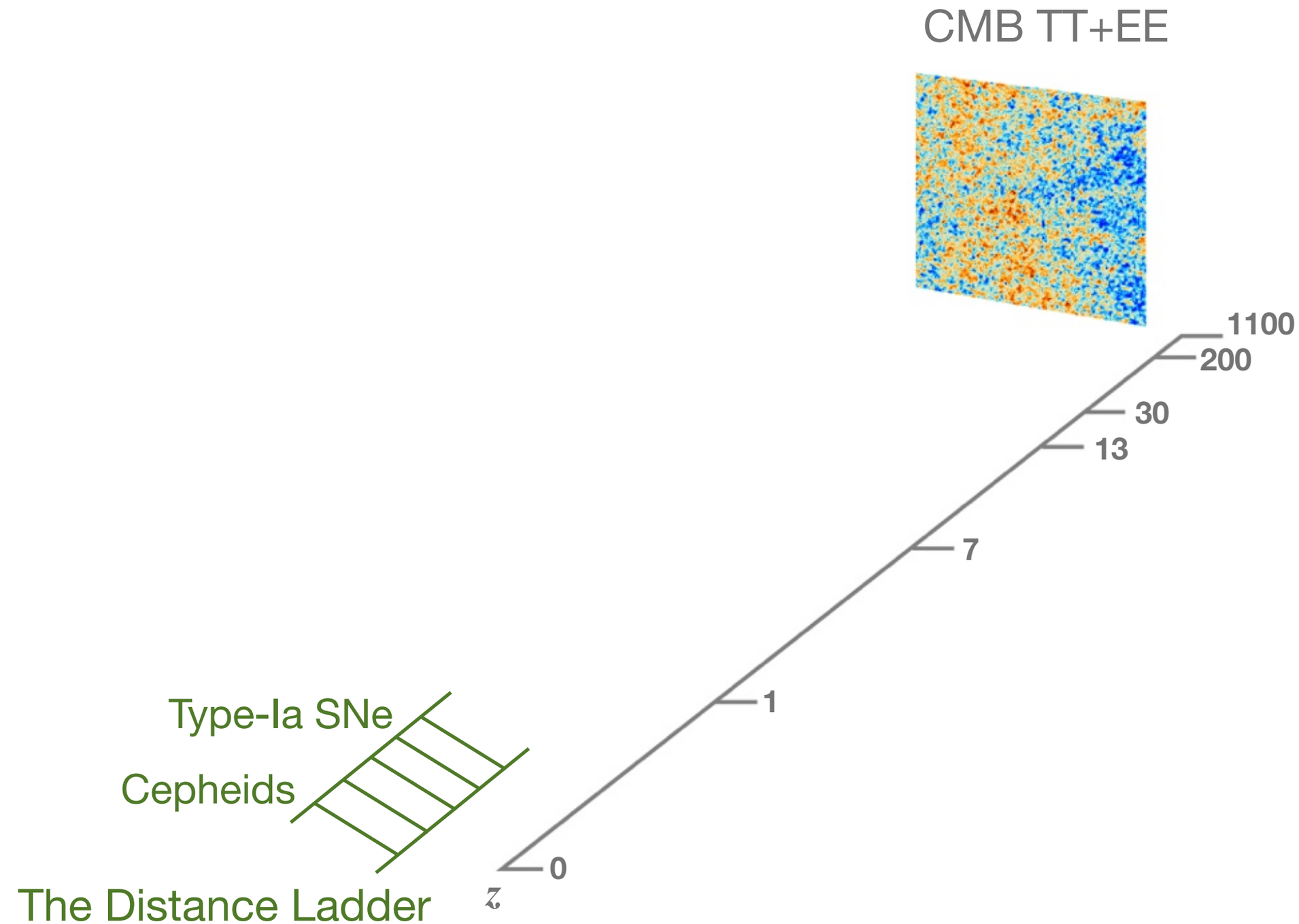

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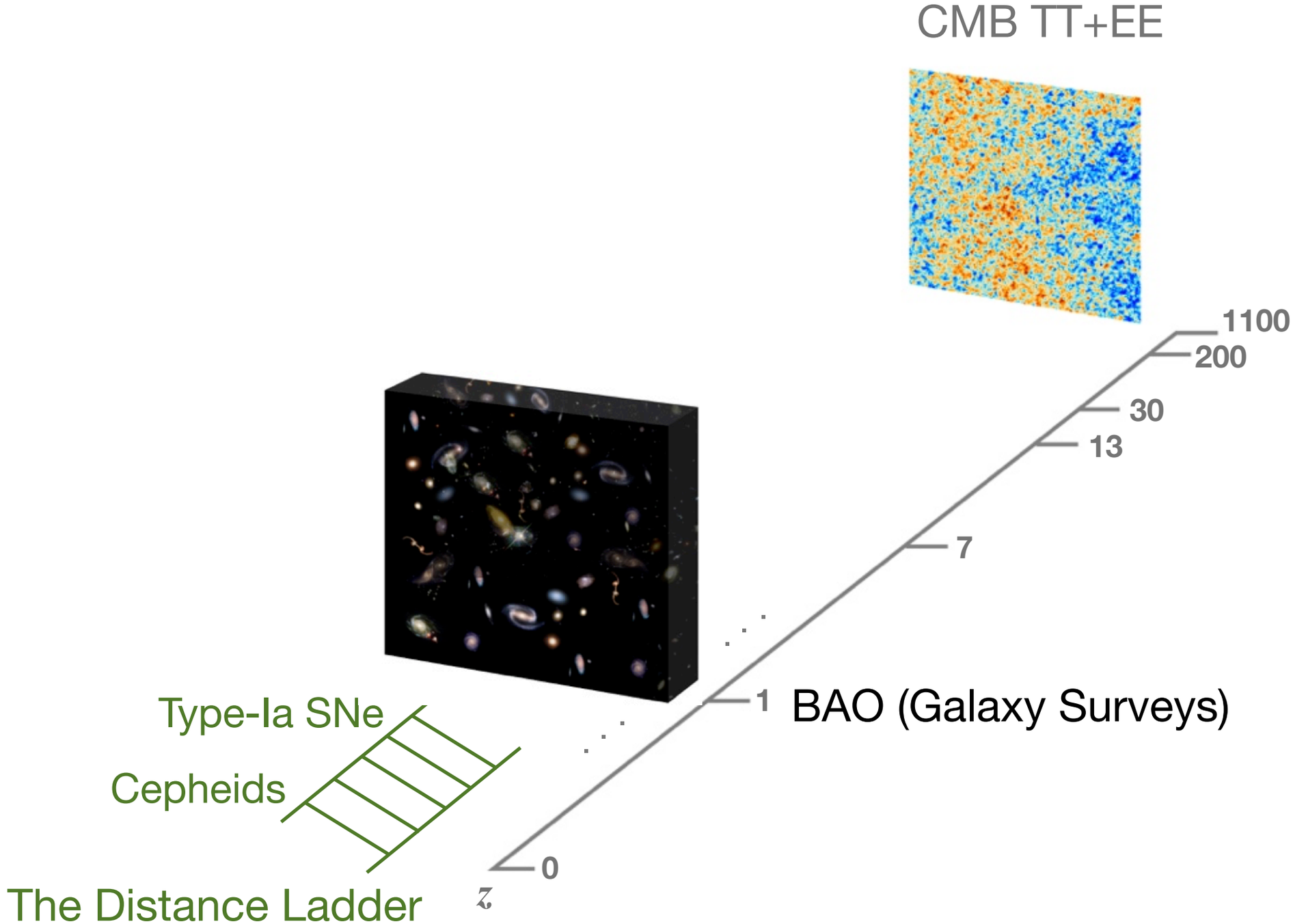


Case Study 2: The “Hubble Tension”

nature astronomy

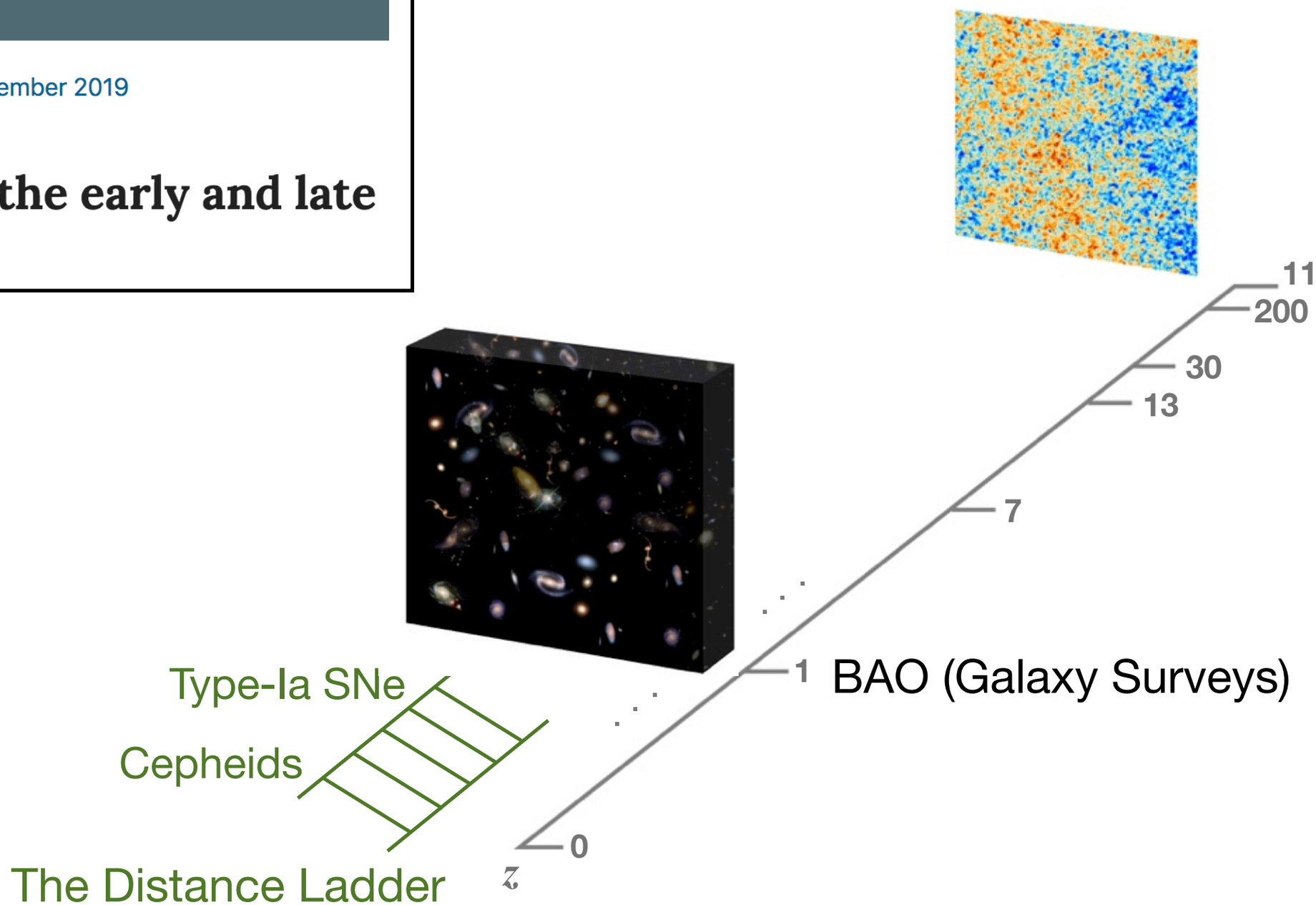
Meeting Report | Published: 27 September 2019

COSMOLOGY

Tensions between the early and late Universe

2

What makes up ***dark energy***?



Almost a Centennial for this Core Question:

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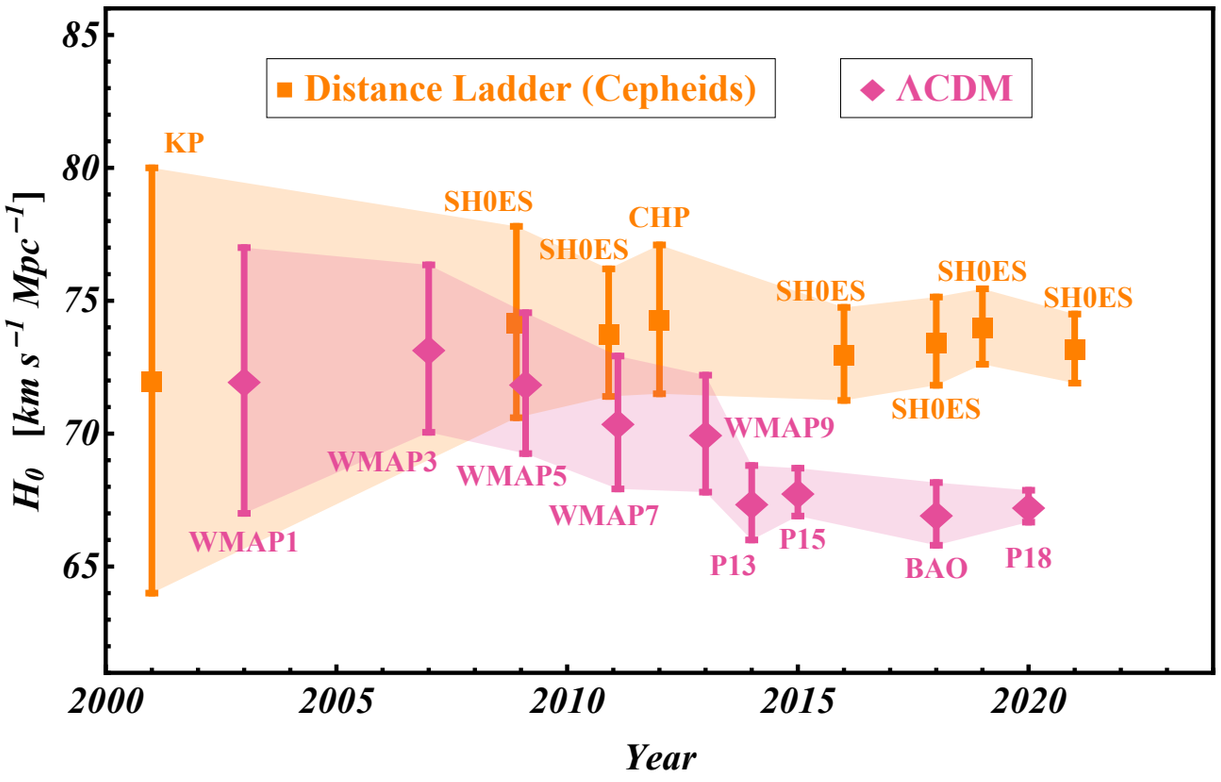
How fast is the *current* expansion of the Universe?

(what is H_0?)

A Growing H0 Tension

Credit: Perivolaropoulos and Skara, 2021



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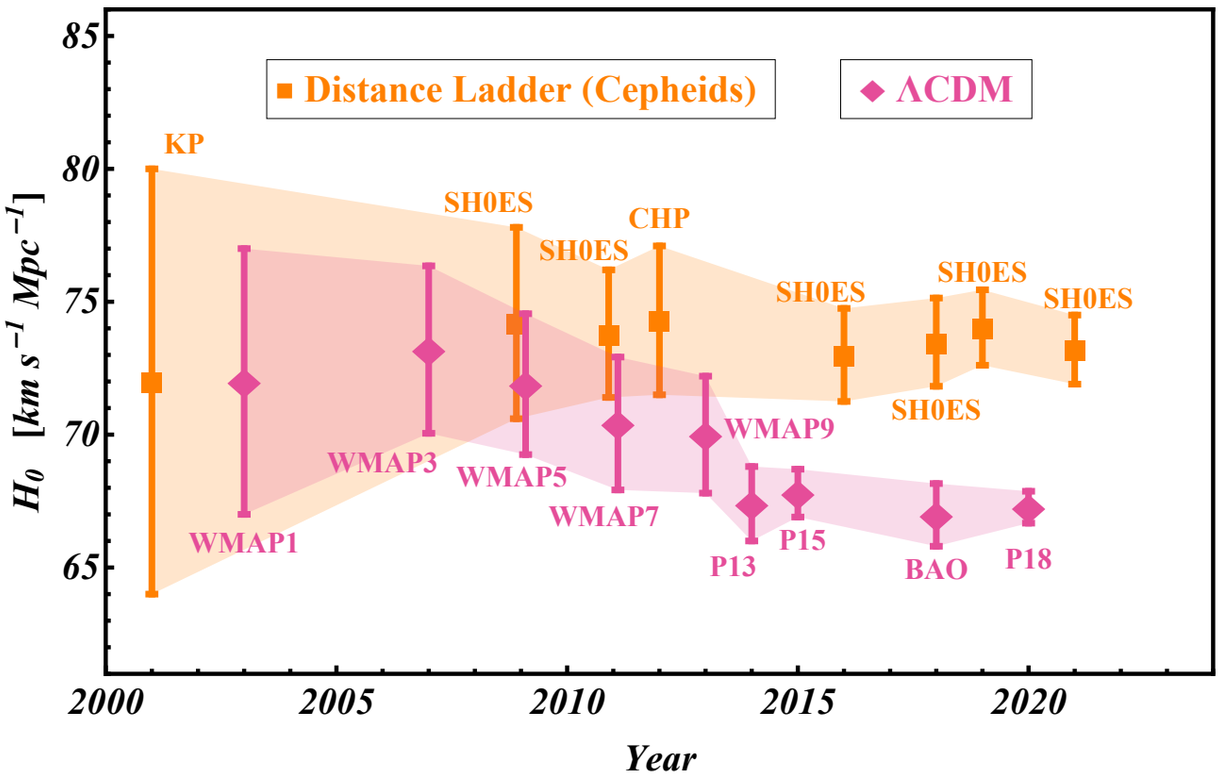

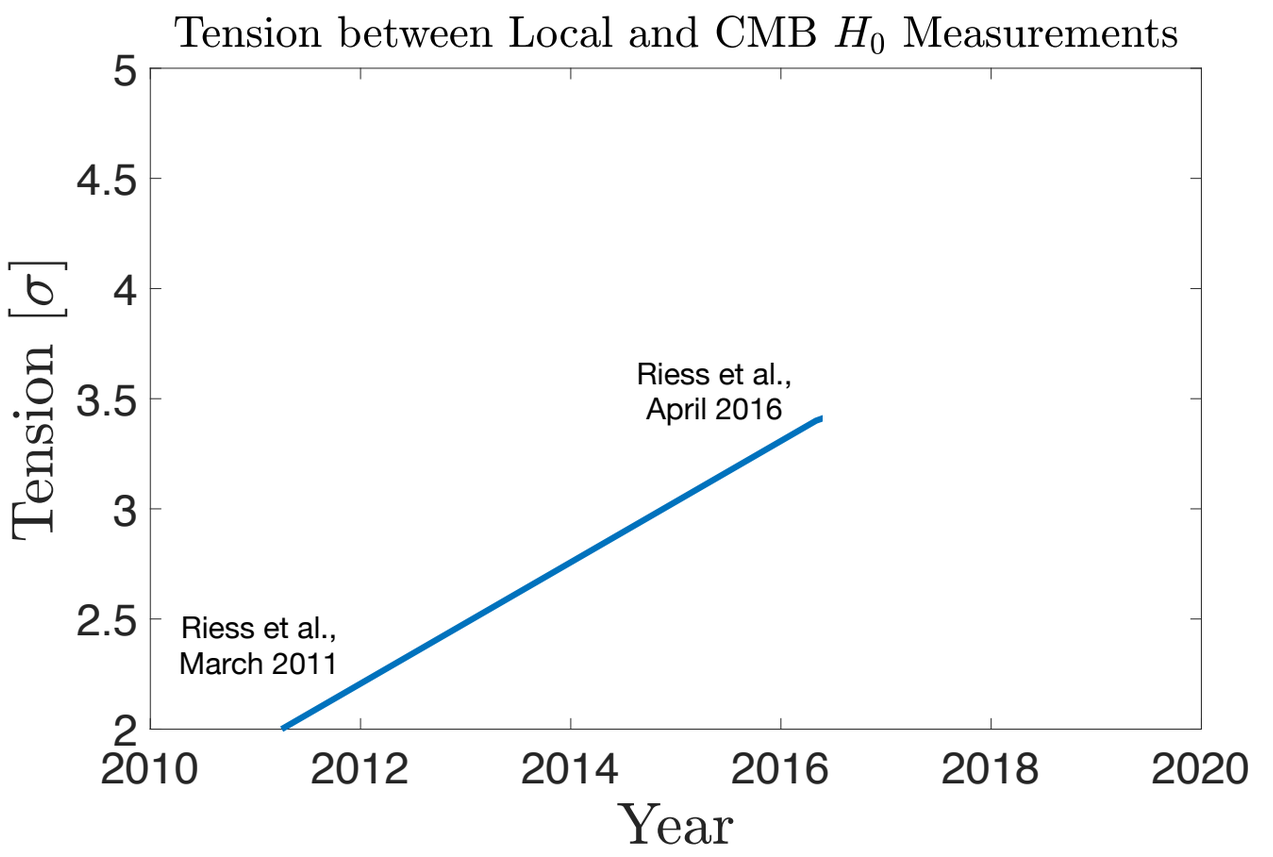

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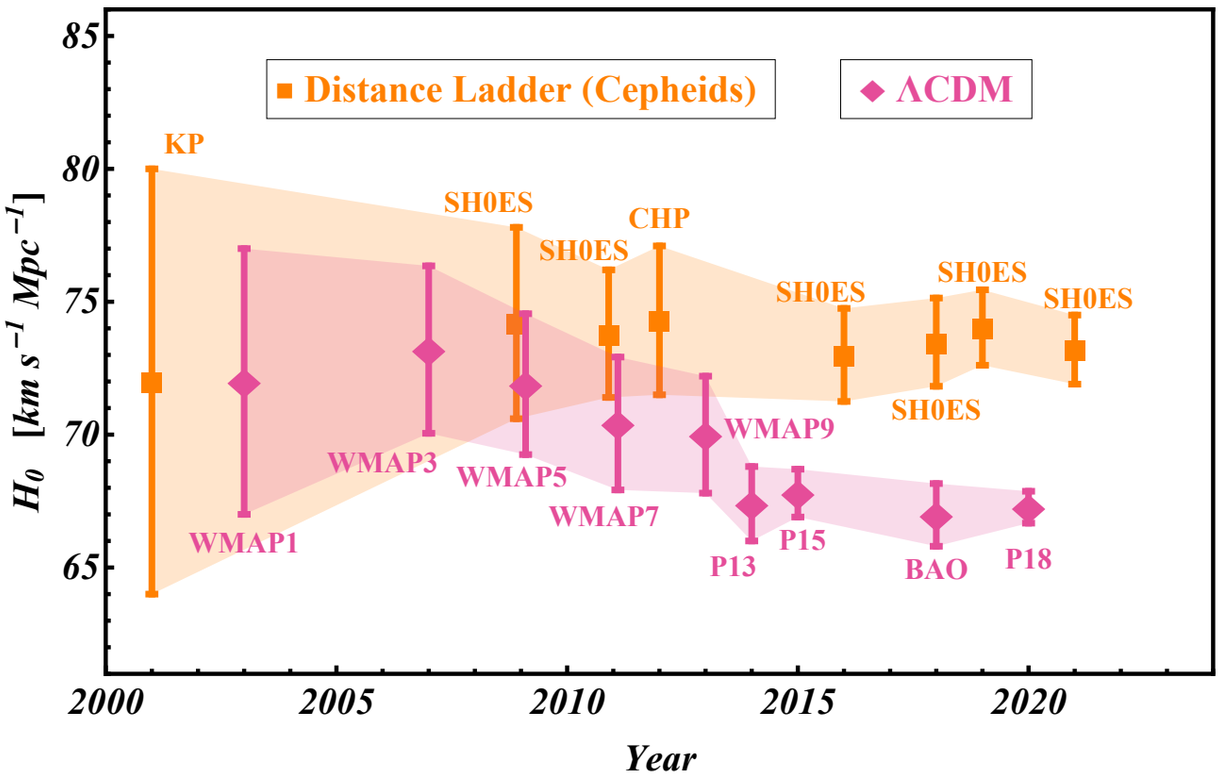

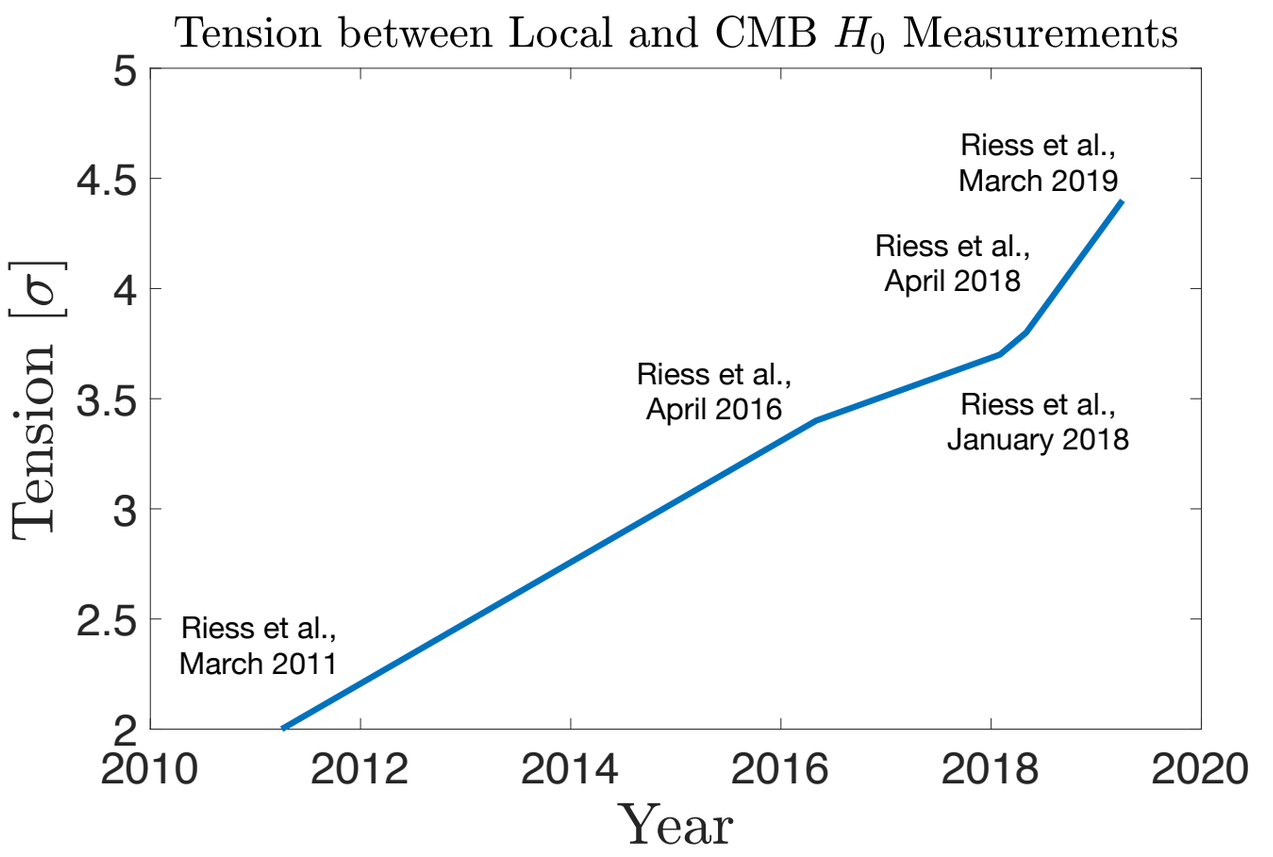

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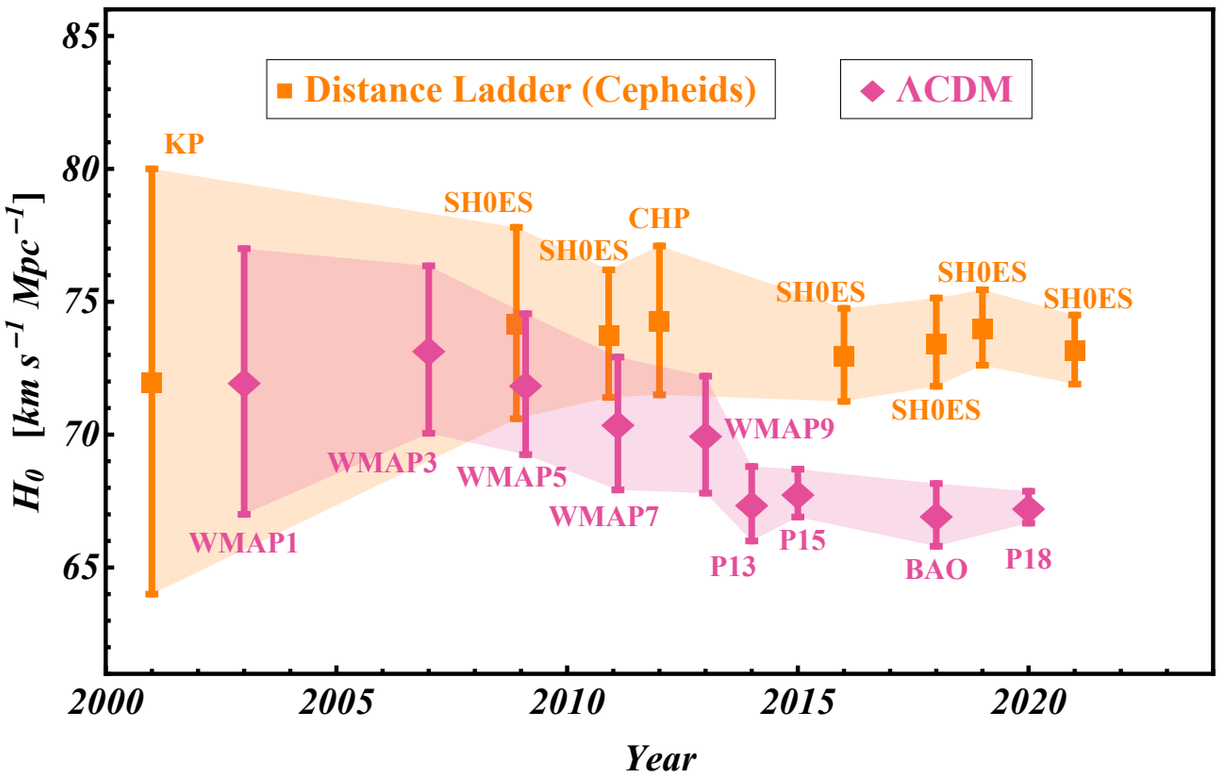

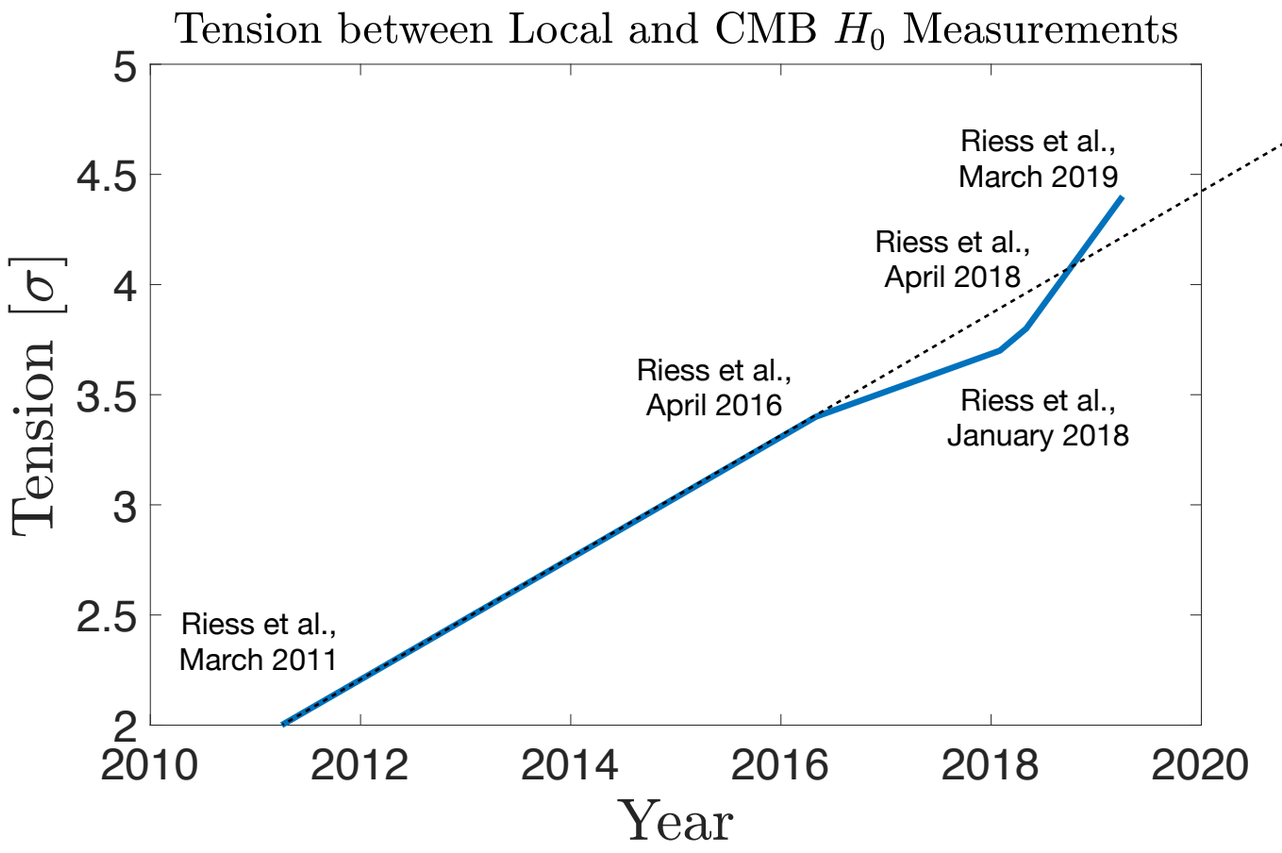

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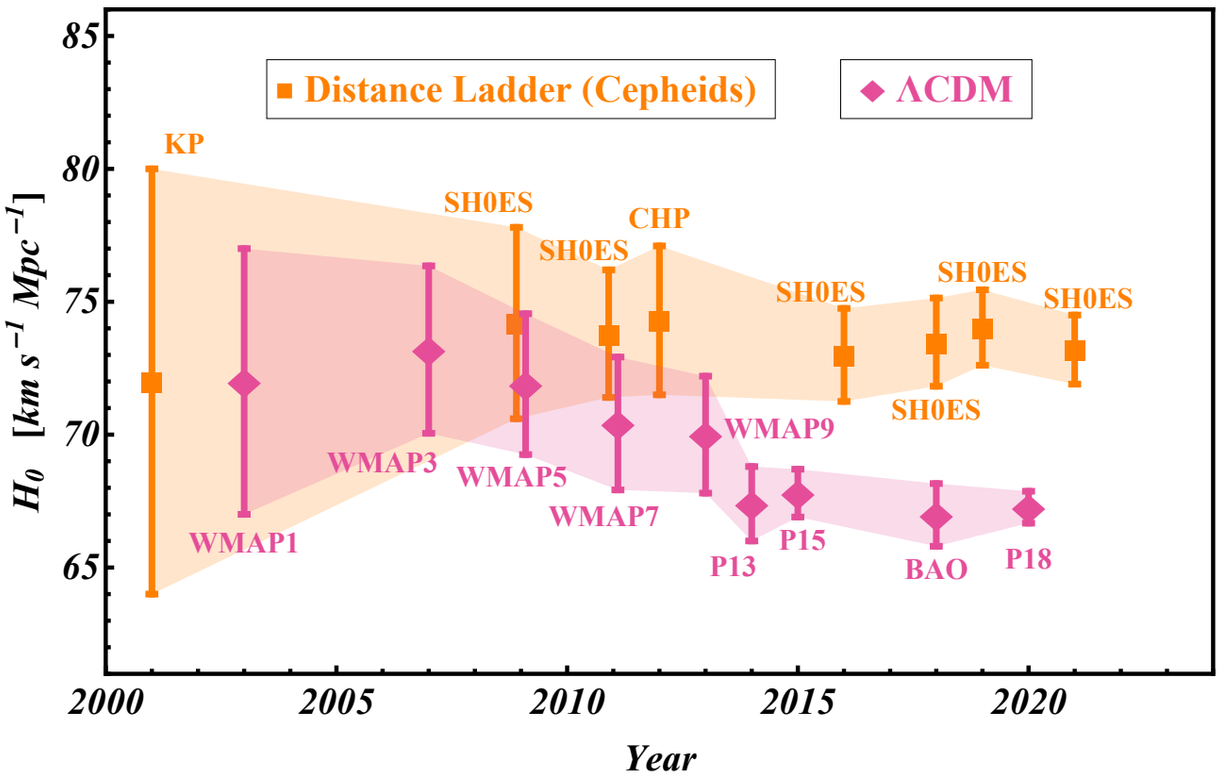
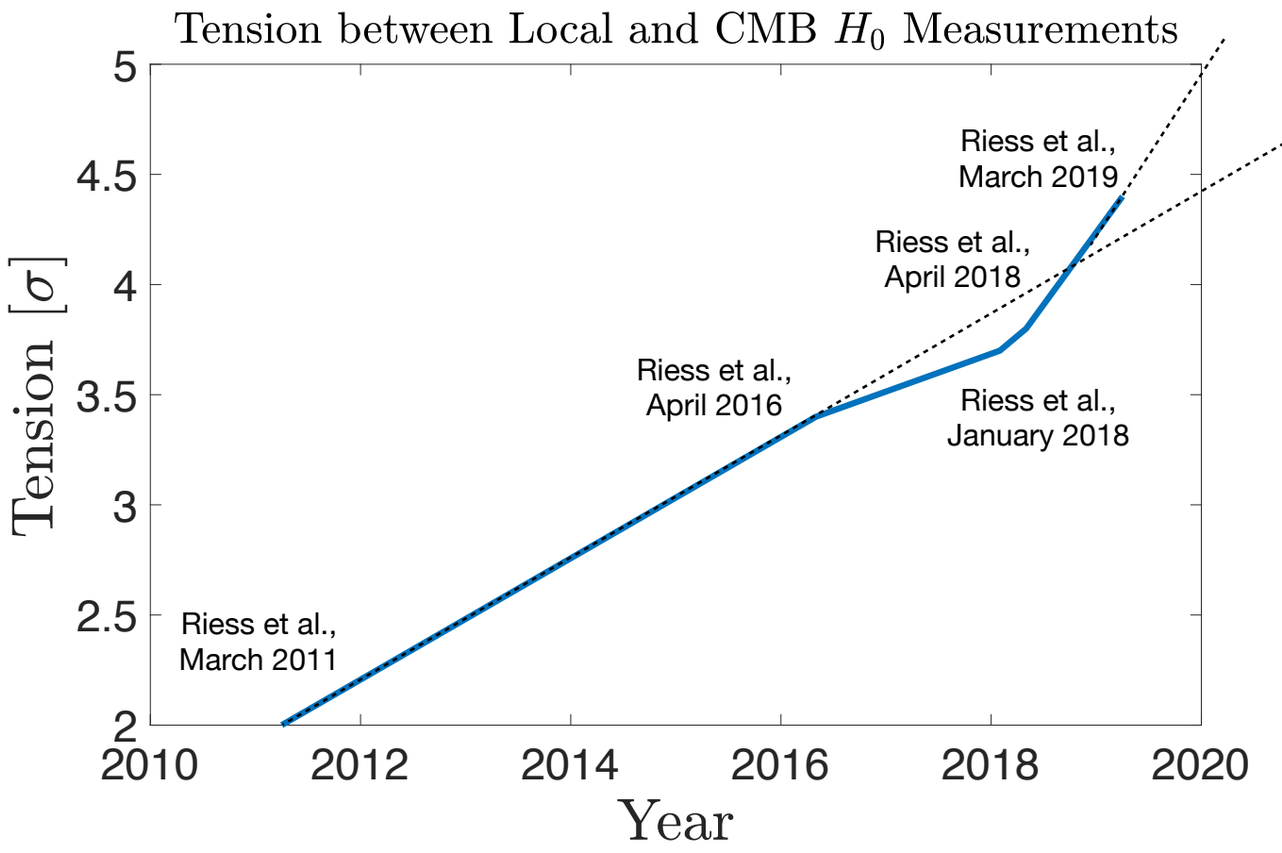
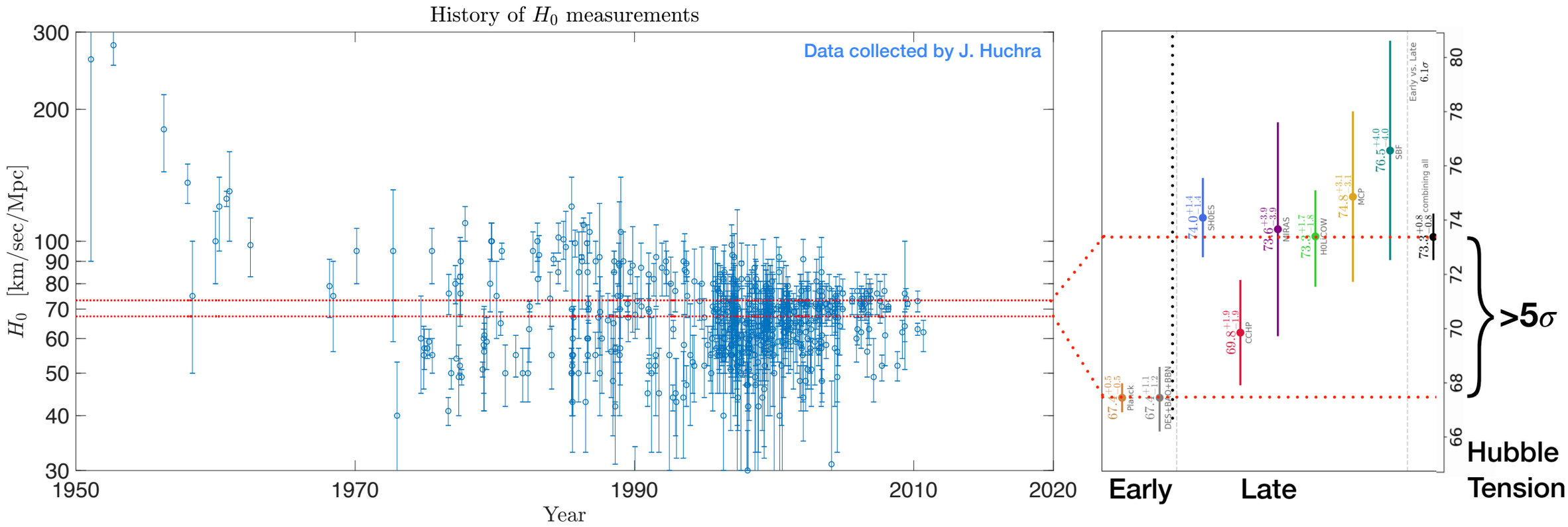
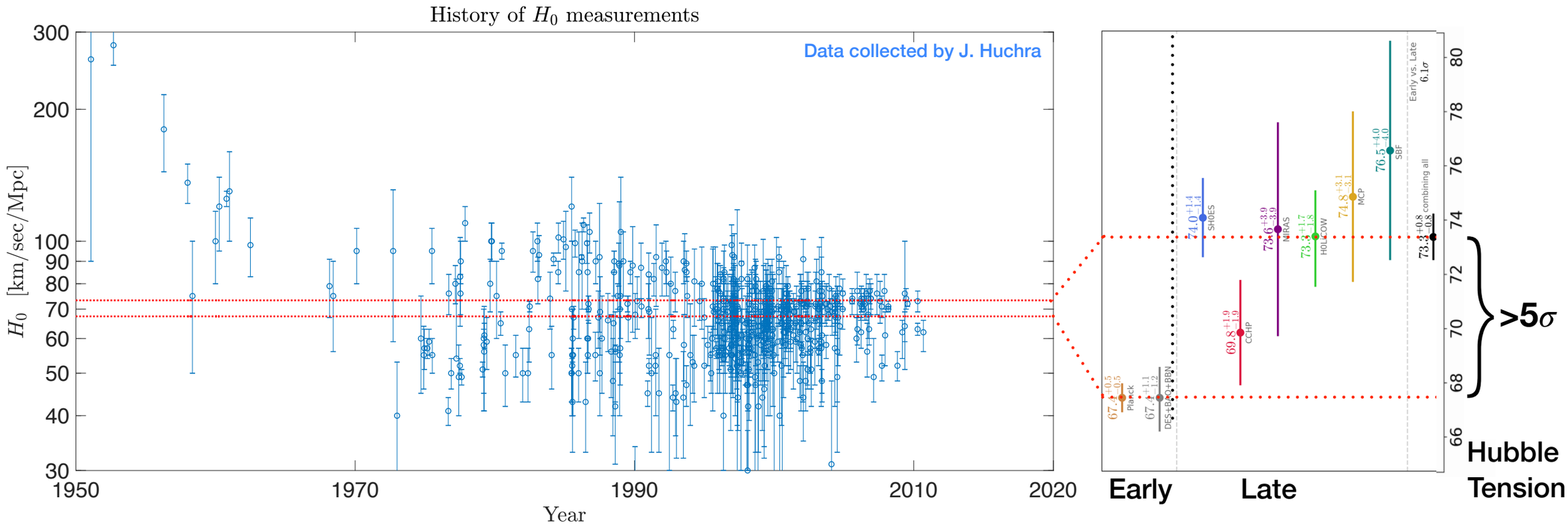




Prognosis


History of H_0 measurements
Data collected by J. Huchra
H_0 [km/sec/Mpc]
Year
Early vs. Late
6.1σ
Planck
DES+BAO+BBN
CCHP
SHOES
MIRAS
HOLiCOW
MCP
SBF
combining all
Early
Late
>5σ
Hubble
Tension

Prognosis



Need new ways to probe this....

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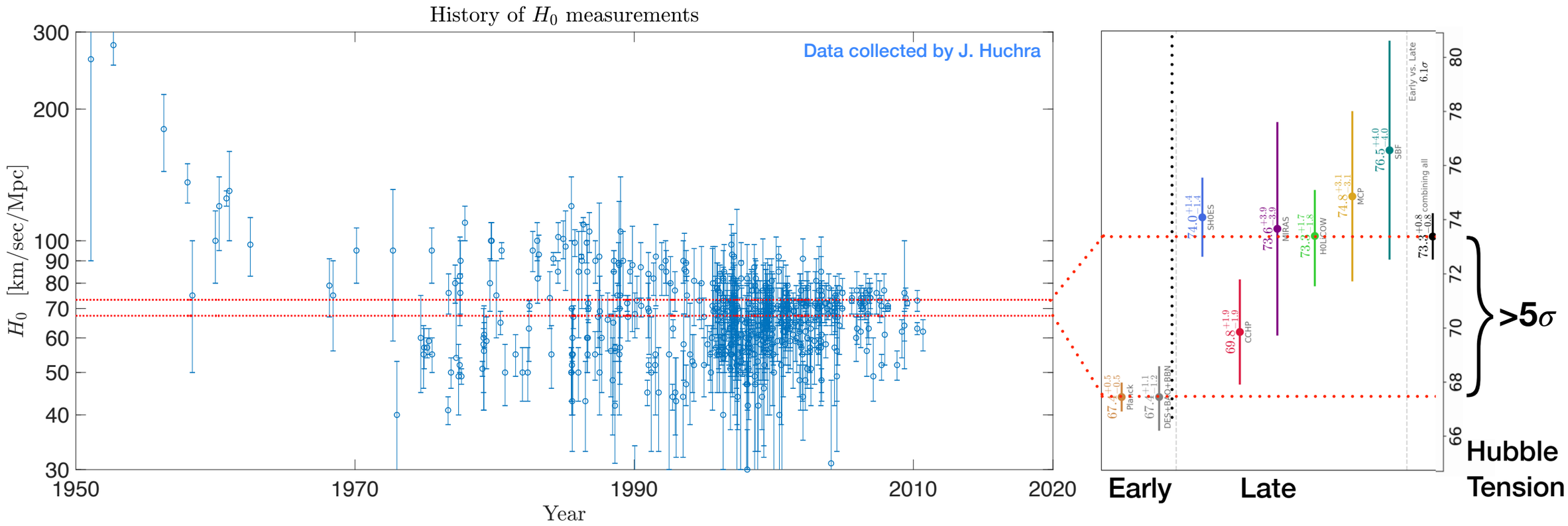

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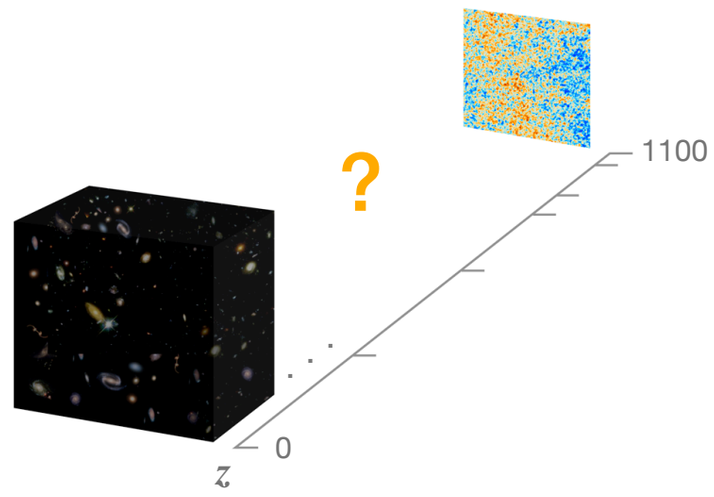

Baryon Acoustic Oscillations: A Standard Ruler

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Rely on a *Standard Ruler* which is imprinted onto CMB and large-scale structure:

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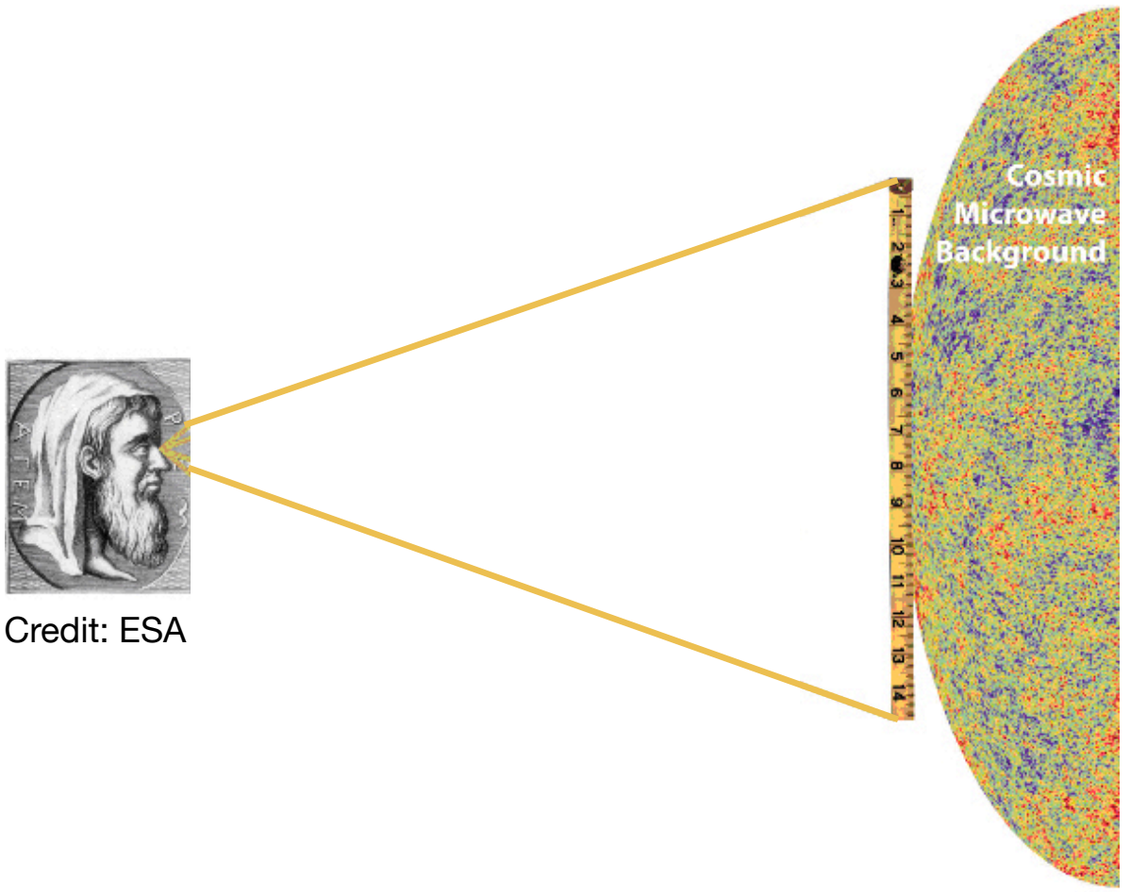

Credit: ESA

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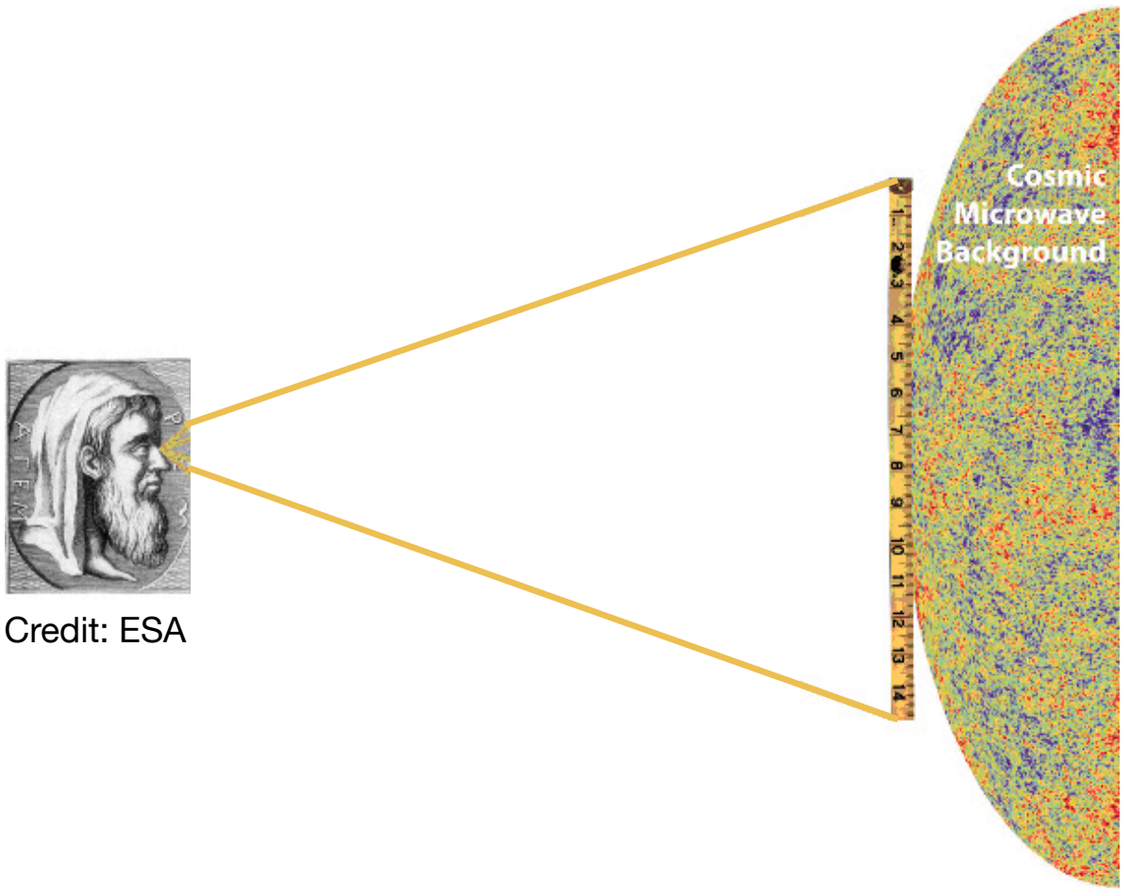
Rely on a *Standard Ruler* which is imprinted onto CMB and large-scale structure:

The distance a sound wave could have traveled in the time before recombination.



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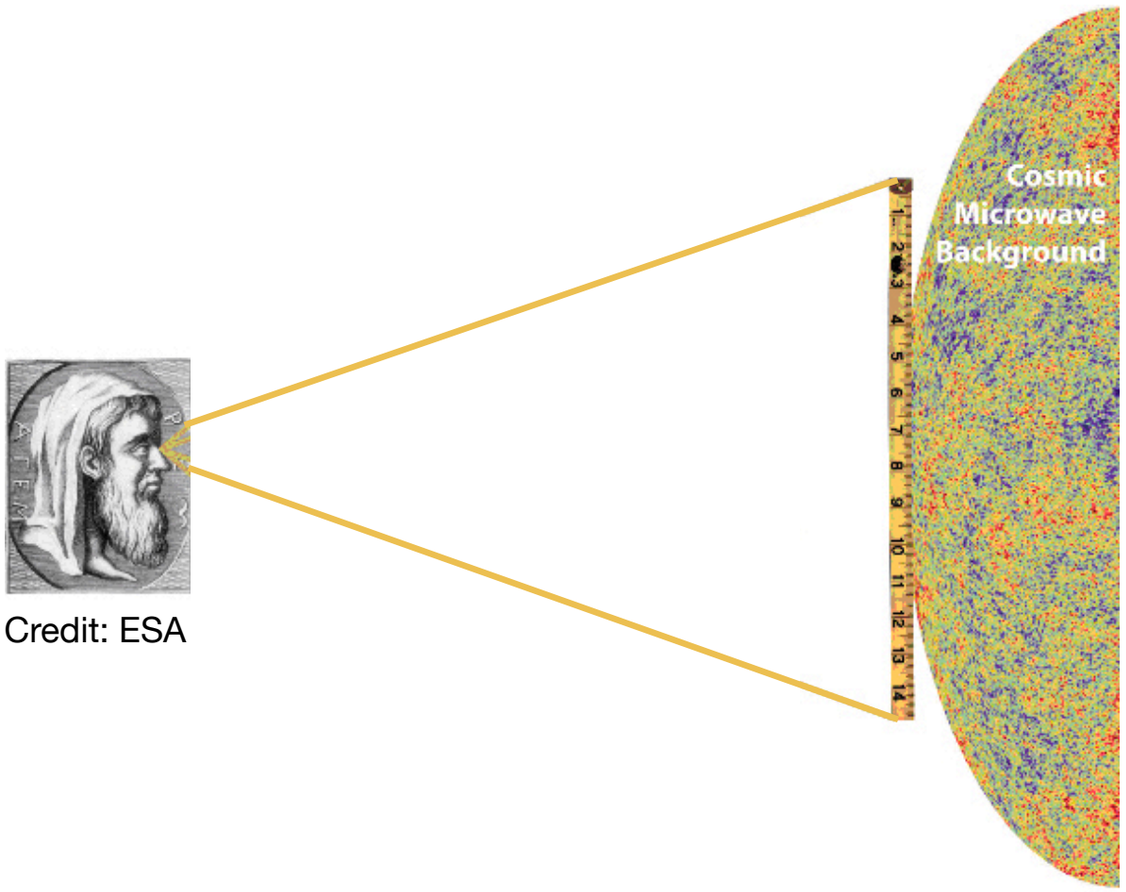

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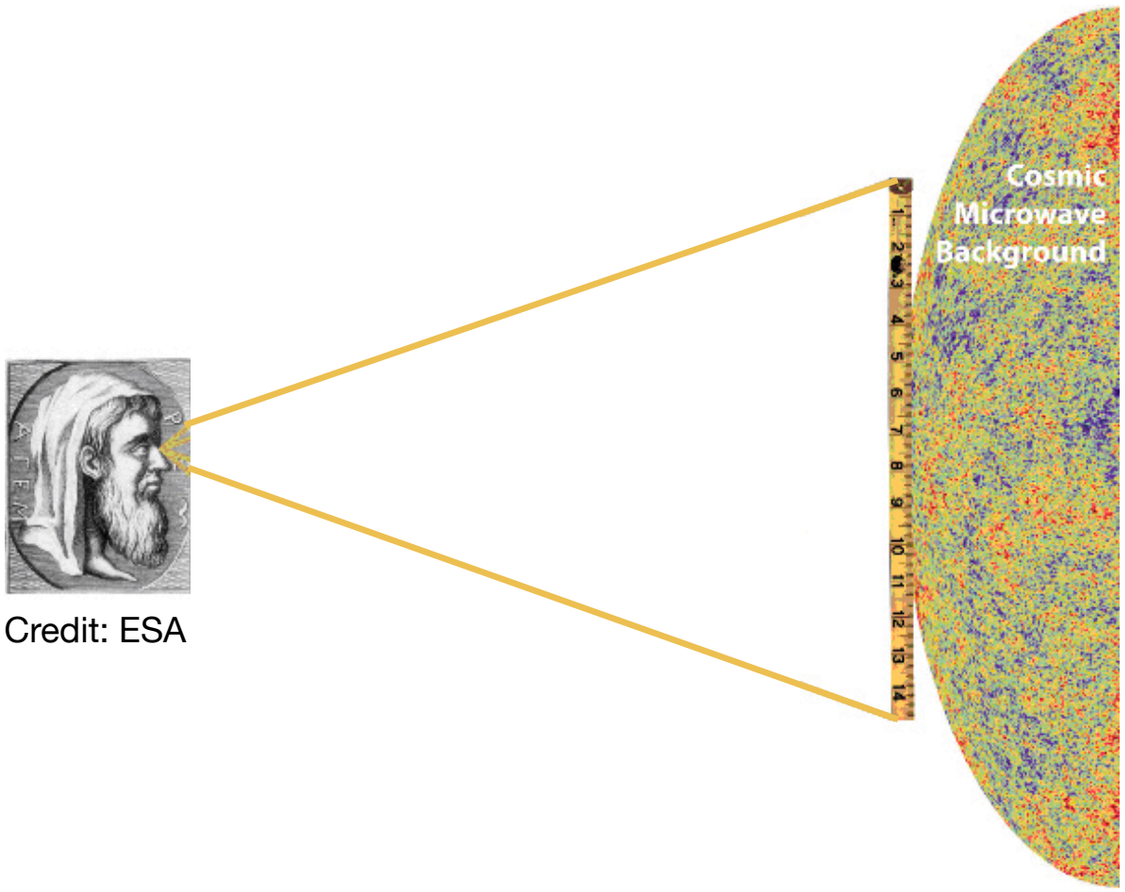

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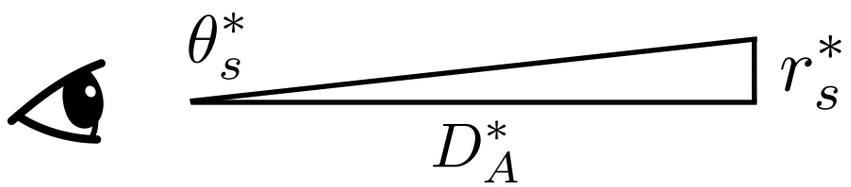

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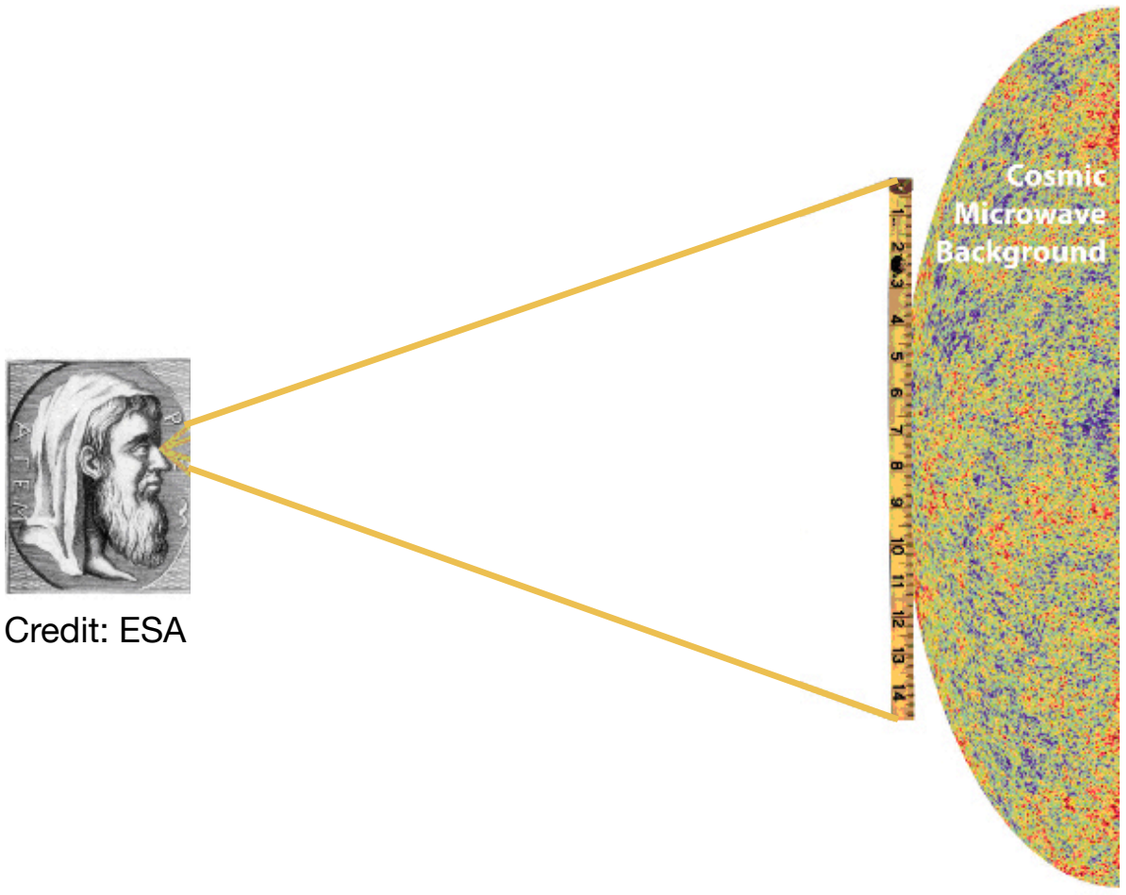

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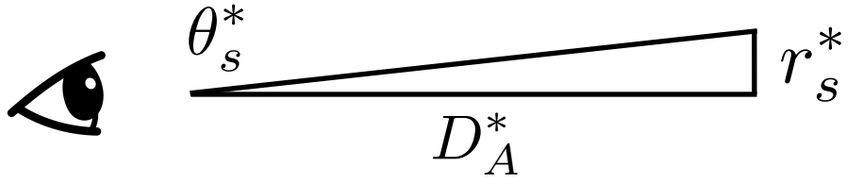

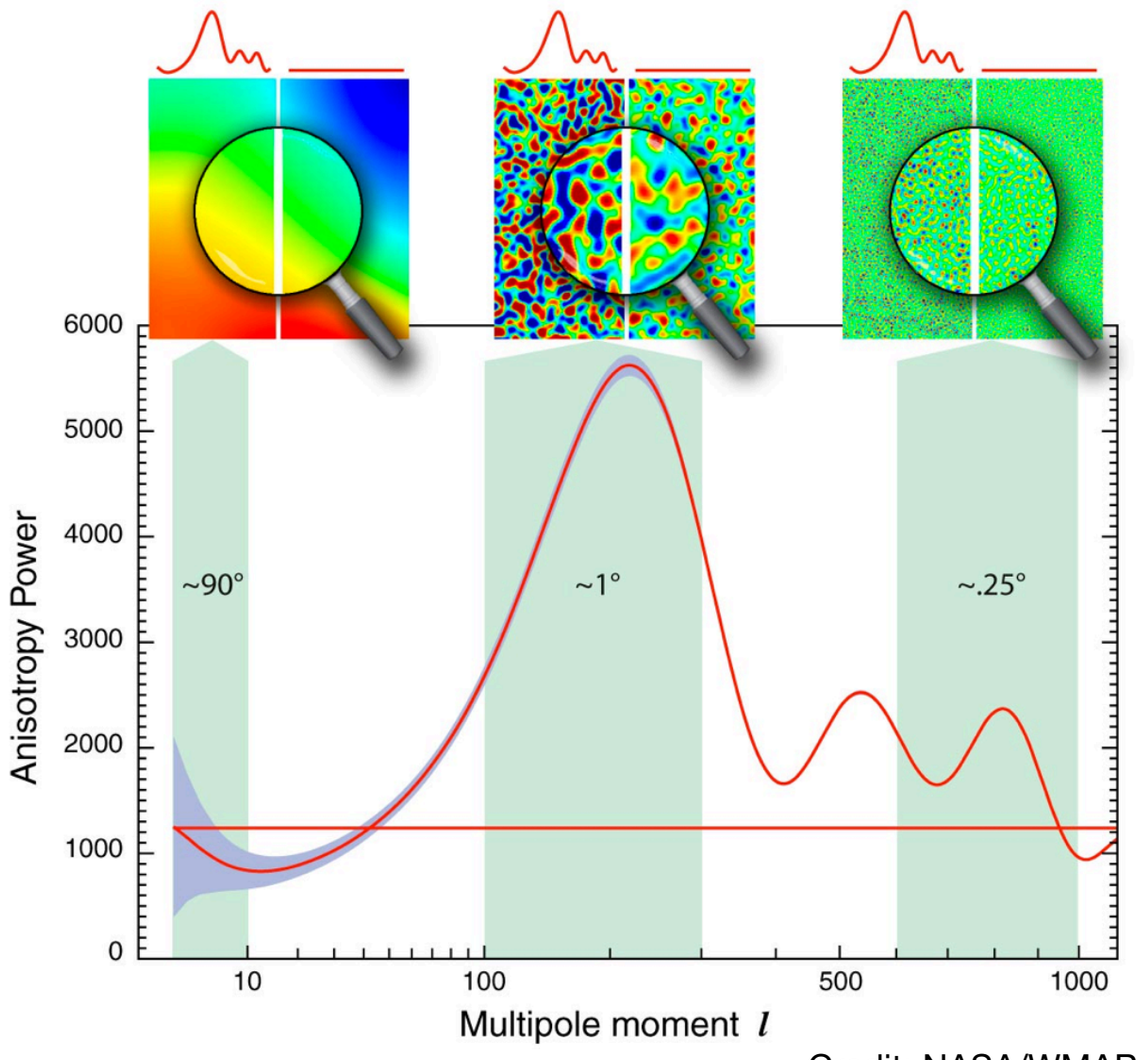

Credit: NASA/WMAP

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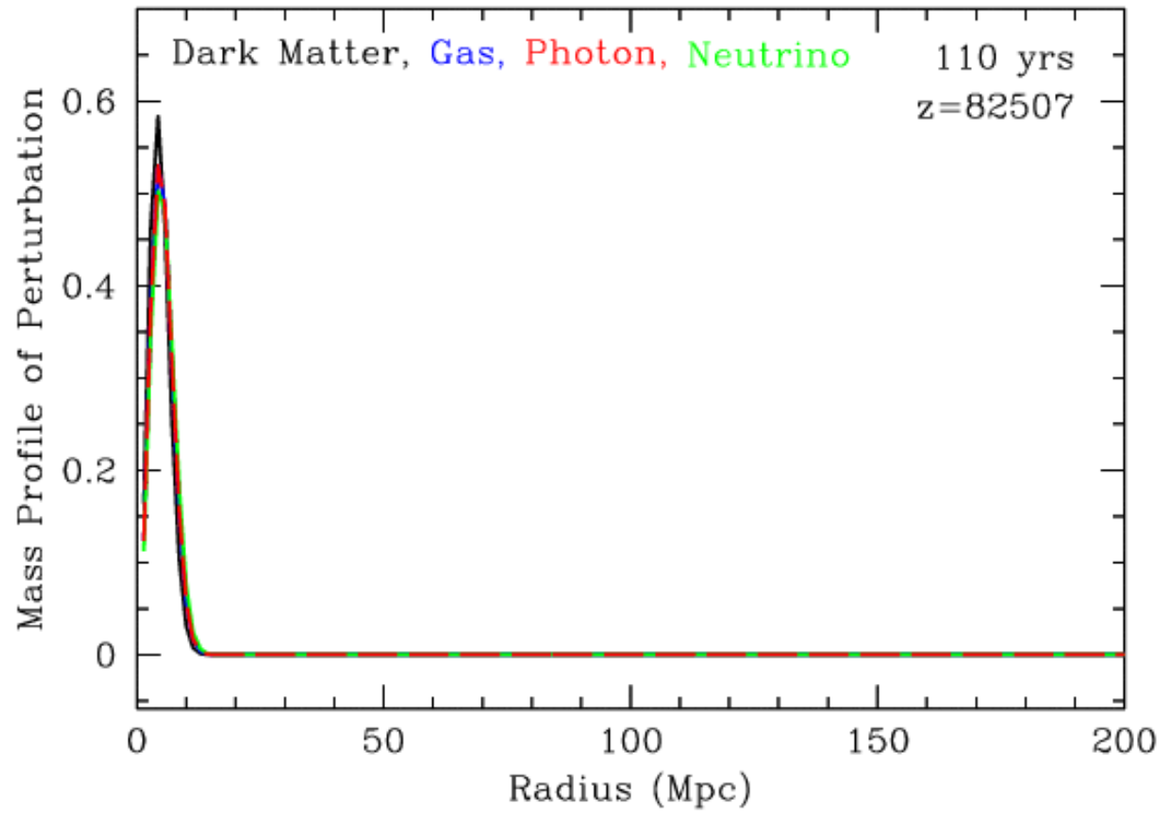
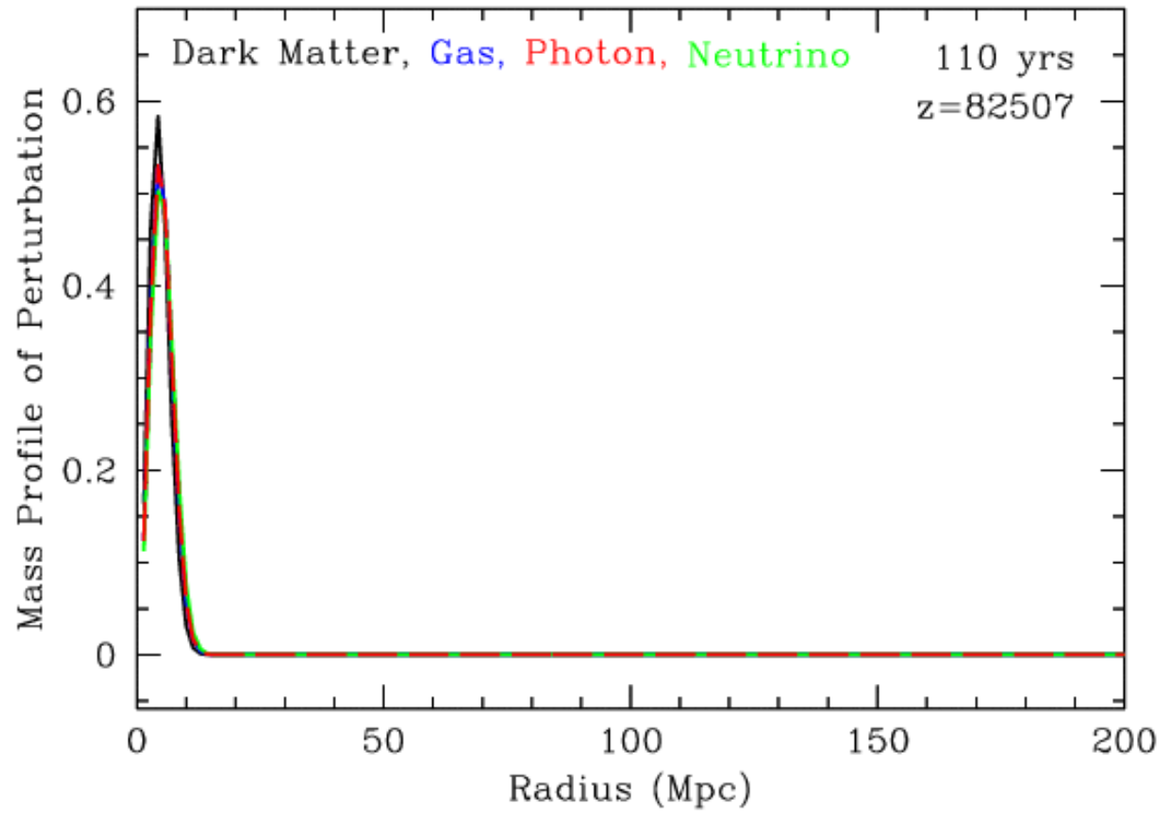


Baryon Acoustic Oscillations: A Standard Ruler

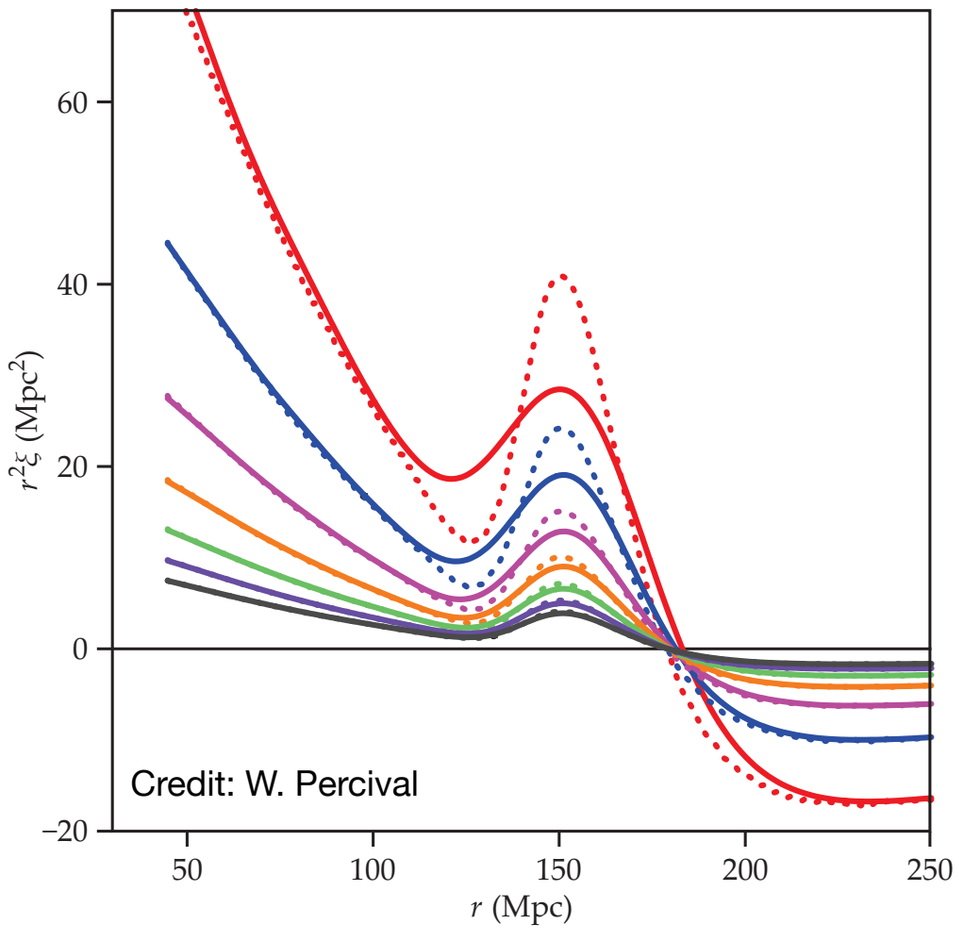
The sound horizon is *imprinted* in the statistics of galaxy locations:



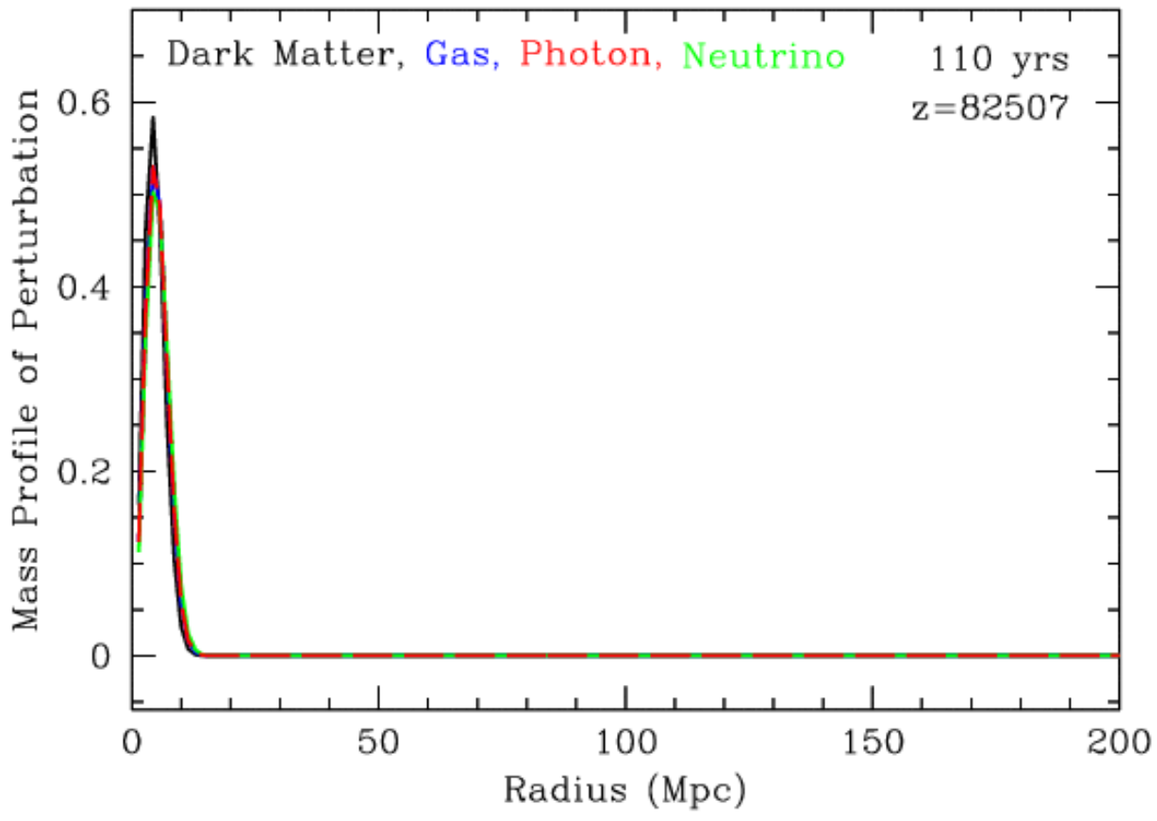
Baryon Acoustic Oscillations: A Standard Ruler

The sound horizon is *imprinted* in the statistics of galaxy locations:

Galaxy correlation function



Plot: Excess probability to find a pair of galaxies separated by a given comoving distance, relative to a Poisson distribution



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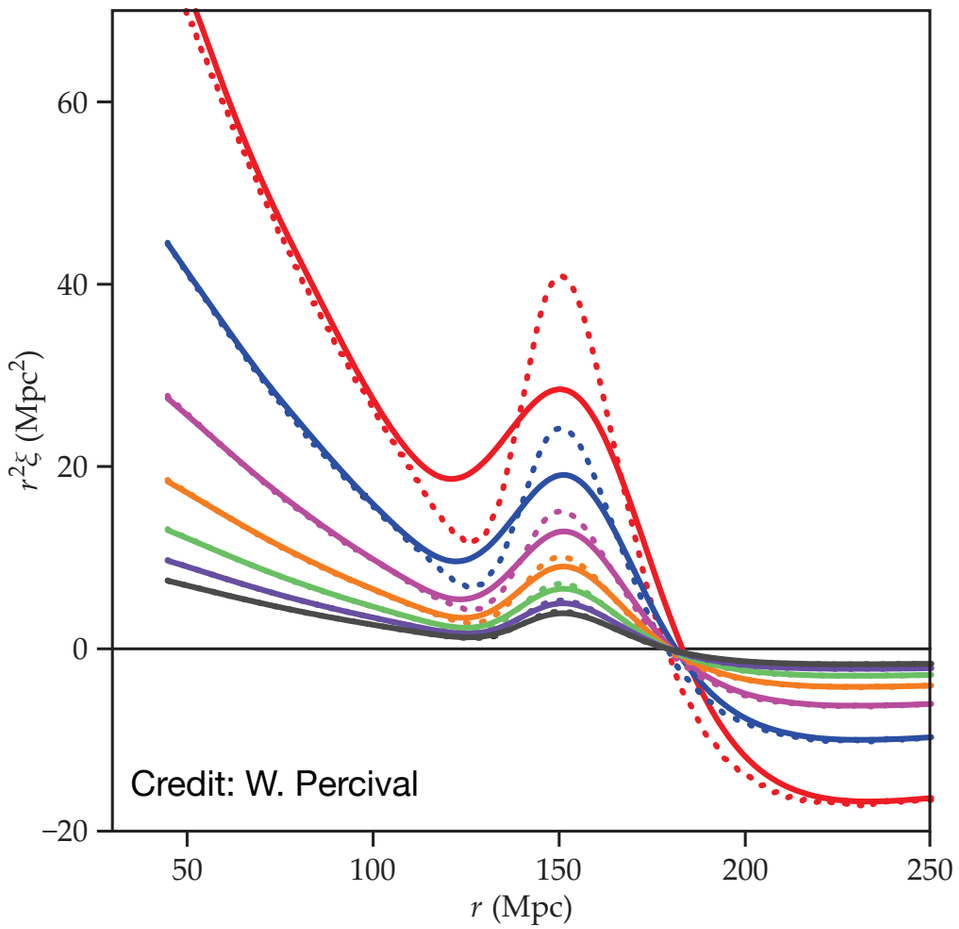

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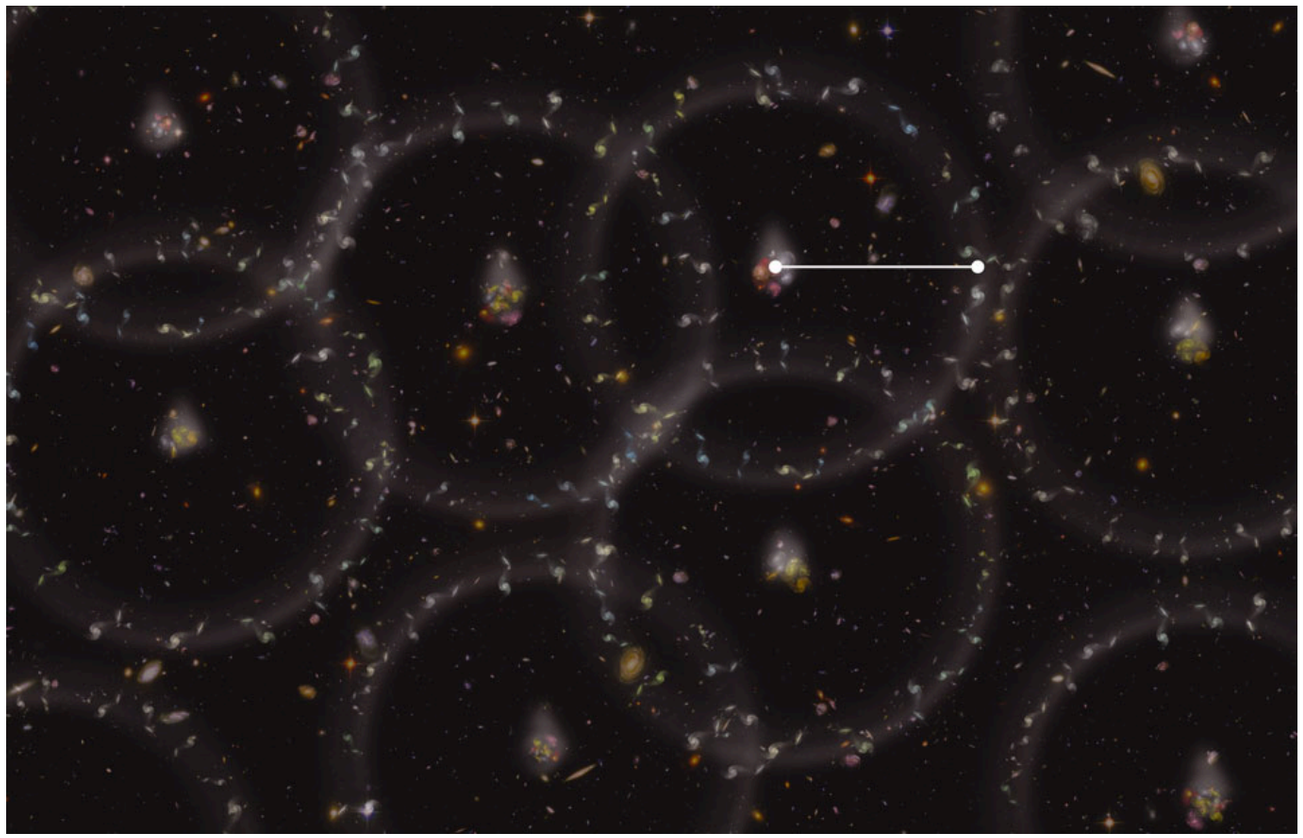
Galaxy spatial distribution (illustration)

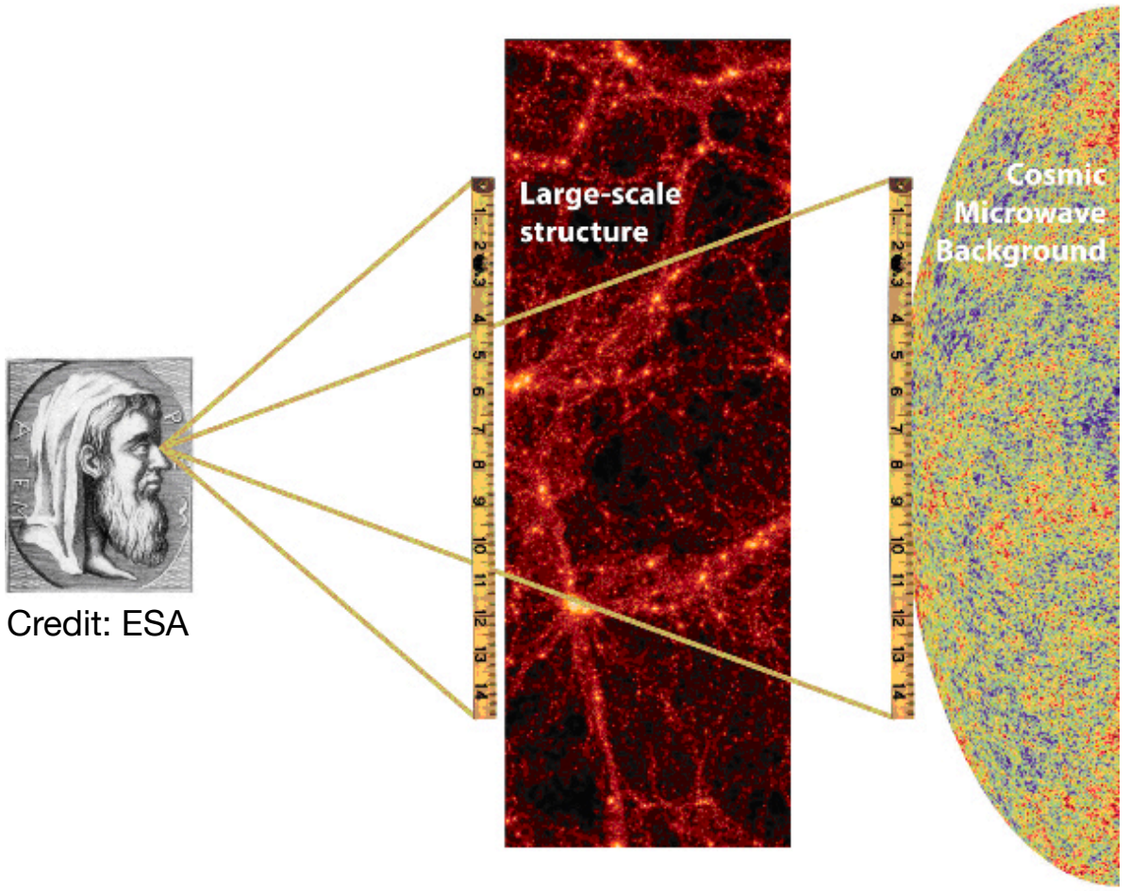


Credit: Z. Rostomian, LBNL

Baryon Acoustic Oscillations: A Standard Ruler

The sound horizon is *imprinted* in the statistics of galaxy locations:

LIM will also show this feature!



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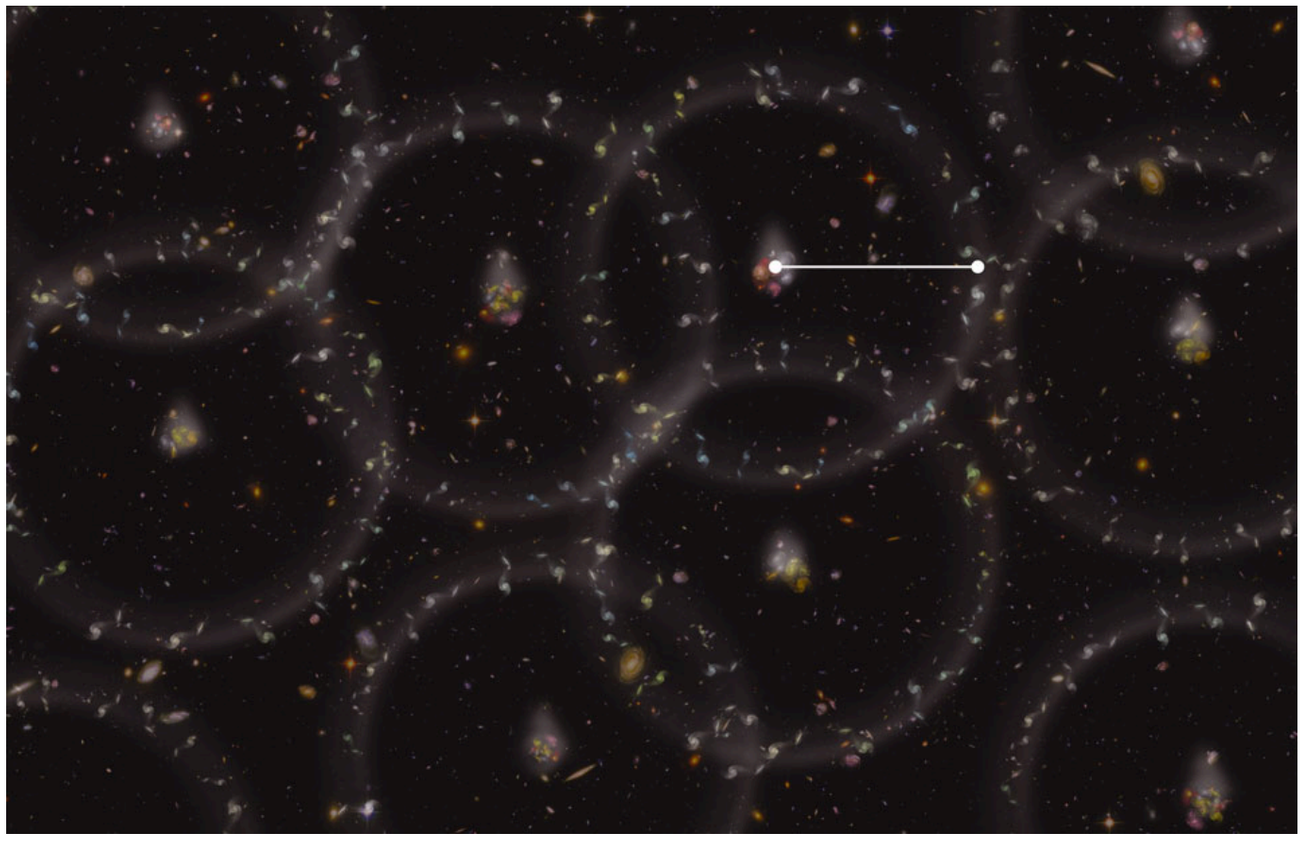

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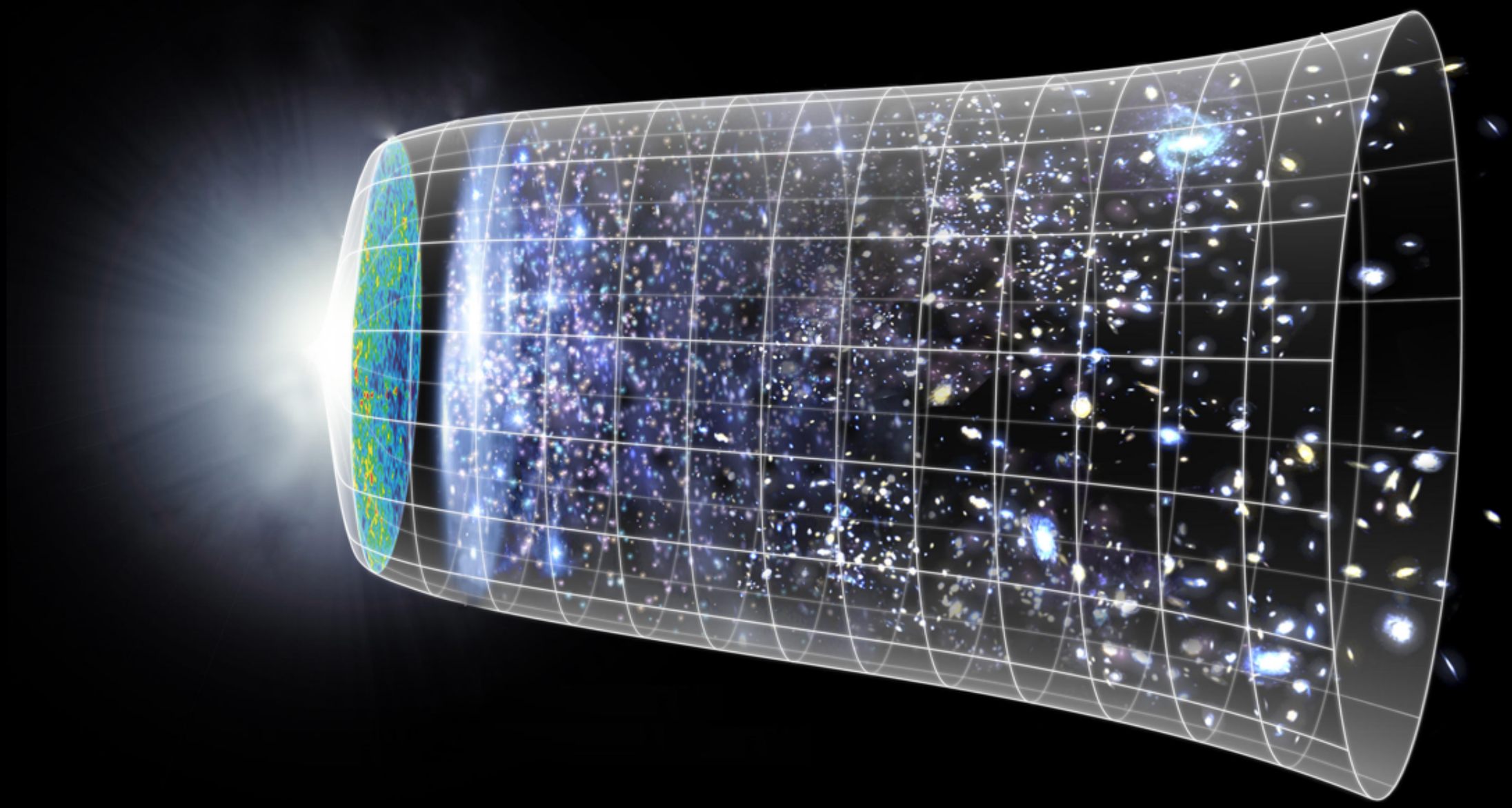
LIM Challenge: Extract Cosmological Information

Credit: NASA/WMAP Science Team



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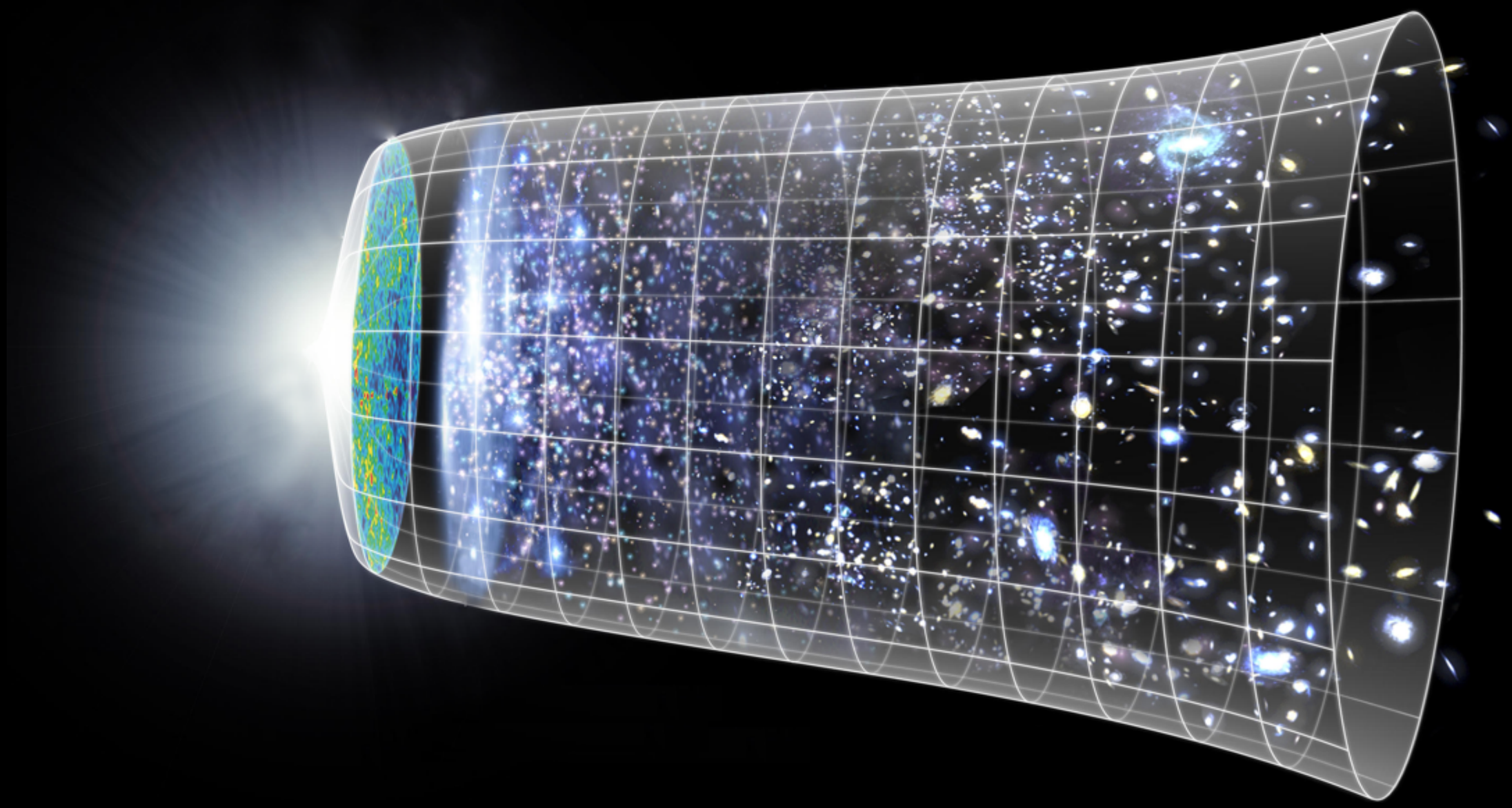
Structure: stars, ISM, galaxies, IGM, clusters



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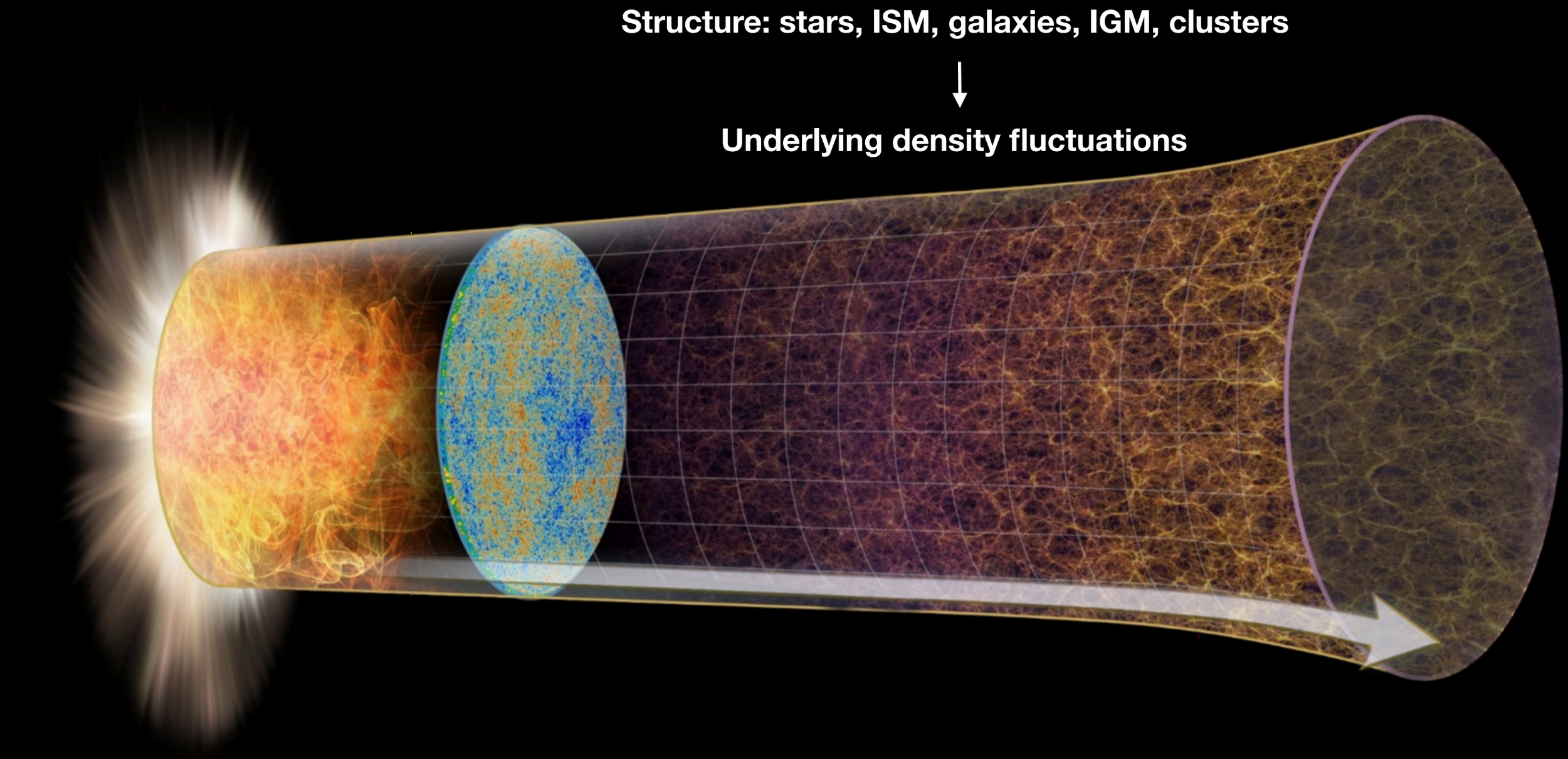

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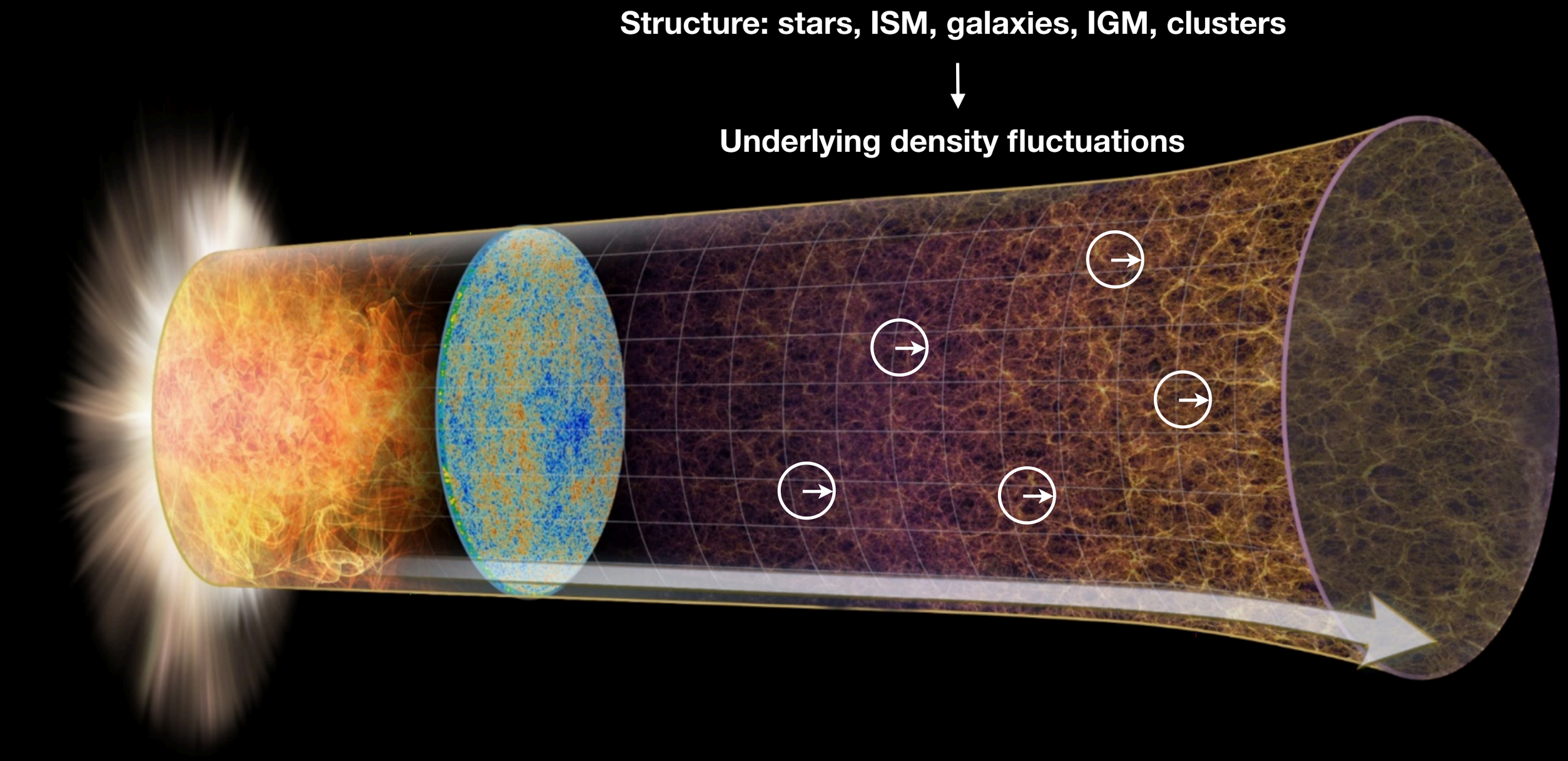

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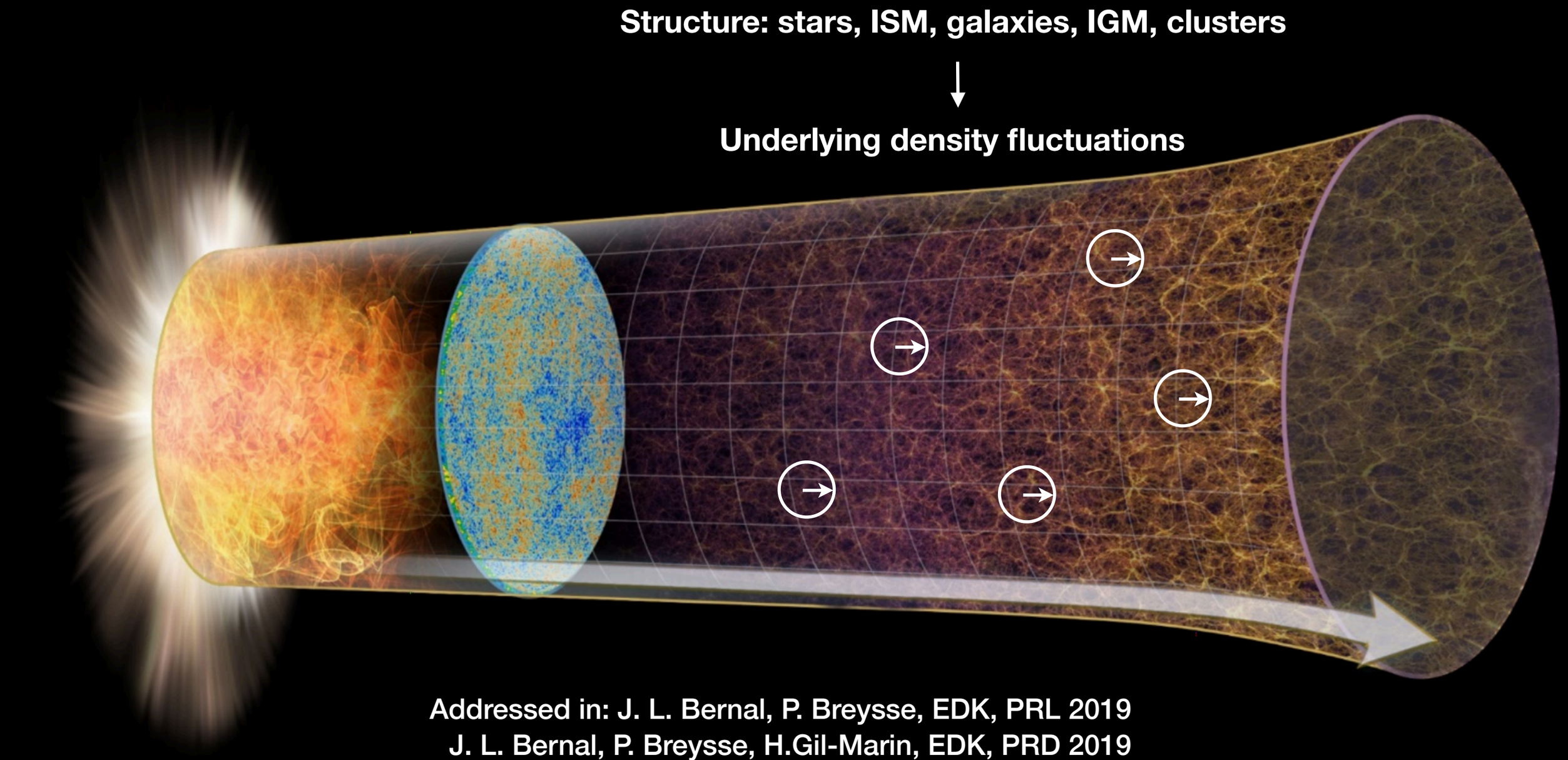

Addressed in: J. L. Bernal, P. Breysse, EDK, PRL 2019
J. L. Bernal, P. Breysse, H.Gil-Marin, EDK, PRD 2019

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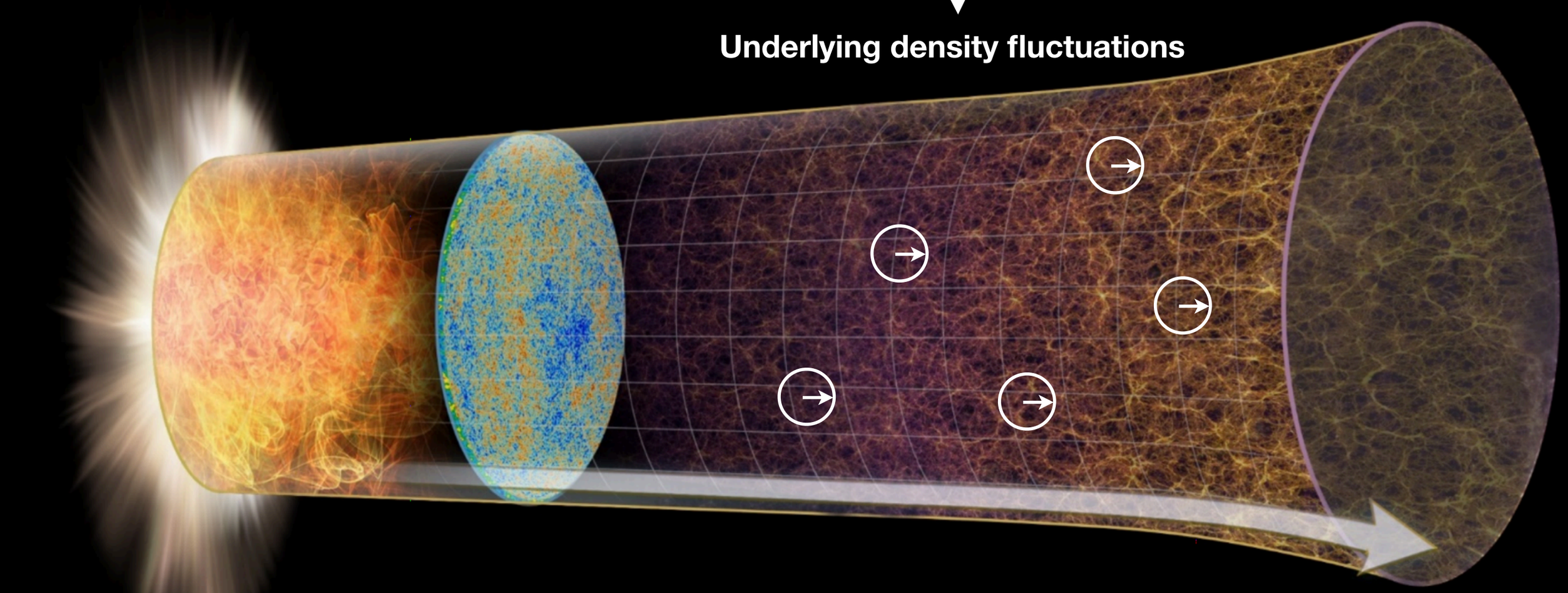
↓

Underlying density fluctuations



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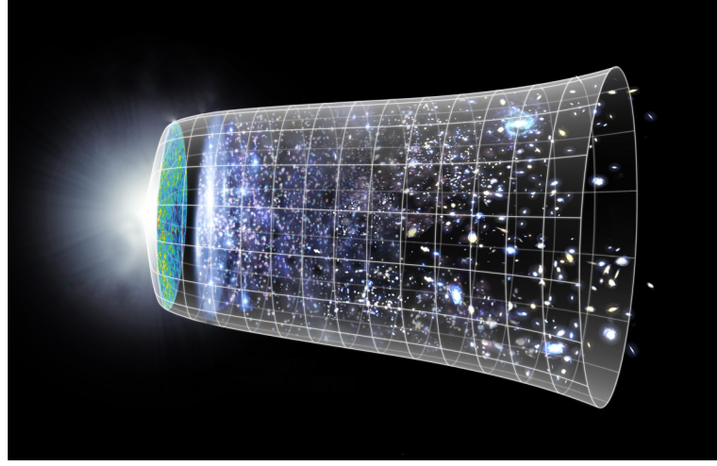
⟶ **How can LIM weigh in on Hubble Tension?**

Dependence on Astrophysics

(J. L. Bernal, P. Breysse, H. Gil-Marin, EDK, PRD 2019)



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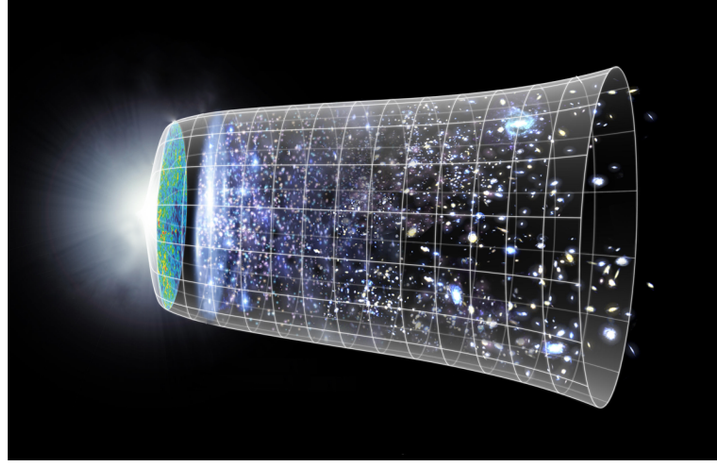

Focus on the power spectrum:

$$P(k,z) = \langle T(z) \rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}(z)$$

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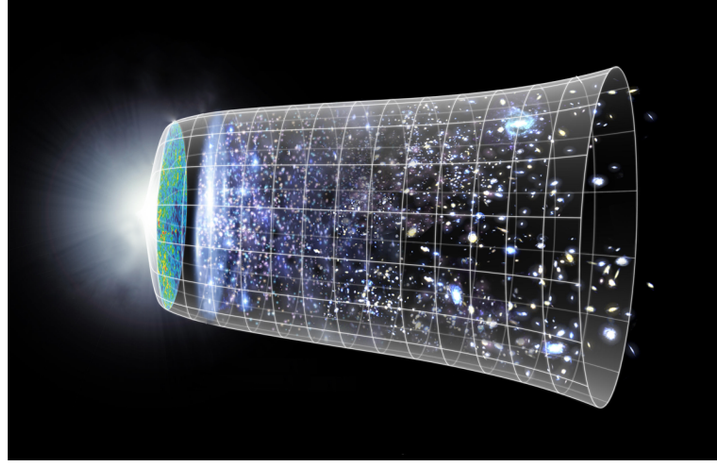

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$$\downarrow$$

$$\langle T(z) \rangle \propto \int L \frac{dn(z)}{dL} dL$$

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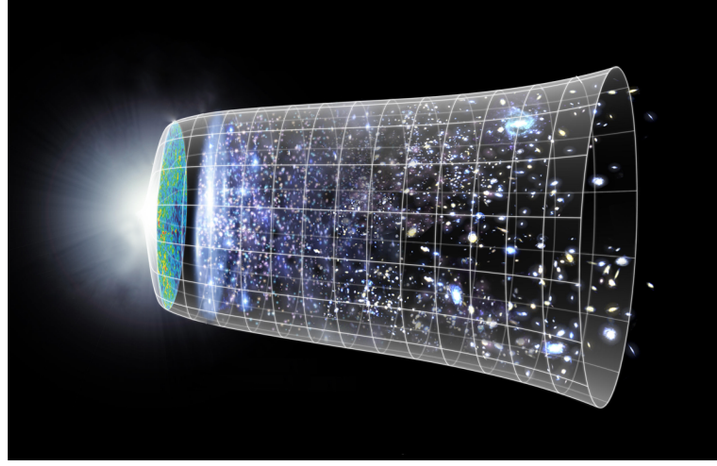

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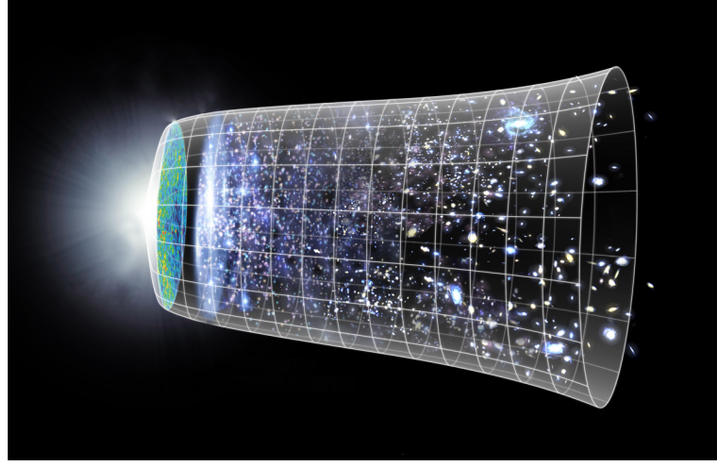
Dependence on Astrophysics

(J. L. Bernal, P. Breysse, H. Gil-Marin, EDK, PRD 2019)



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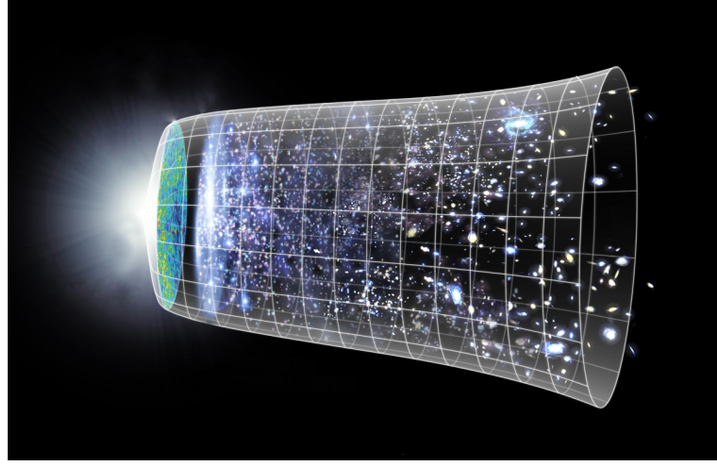

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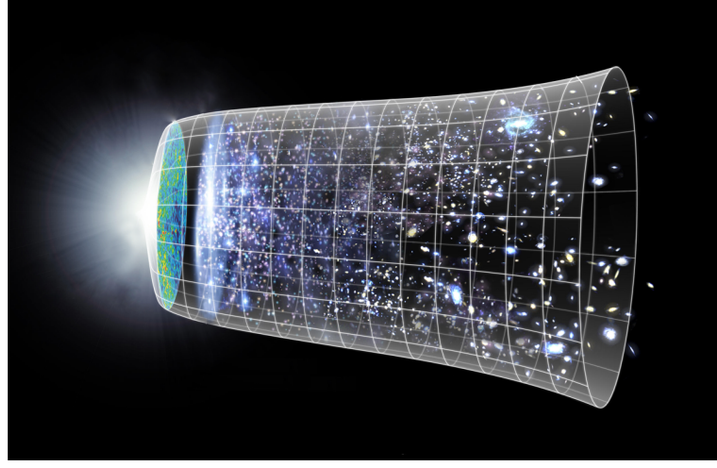

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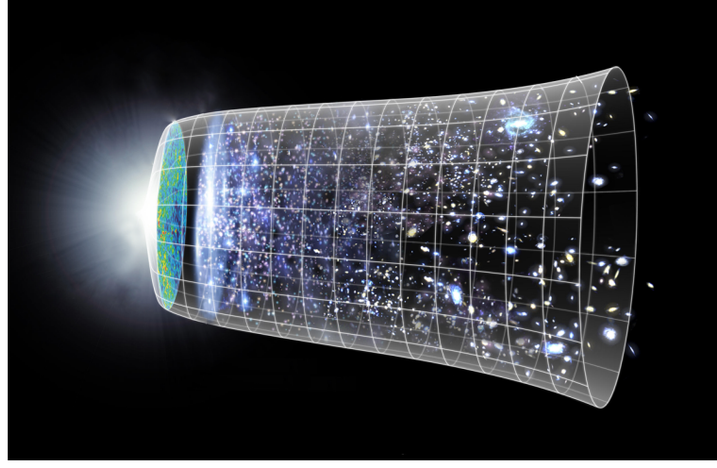

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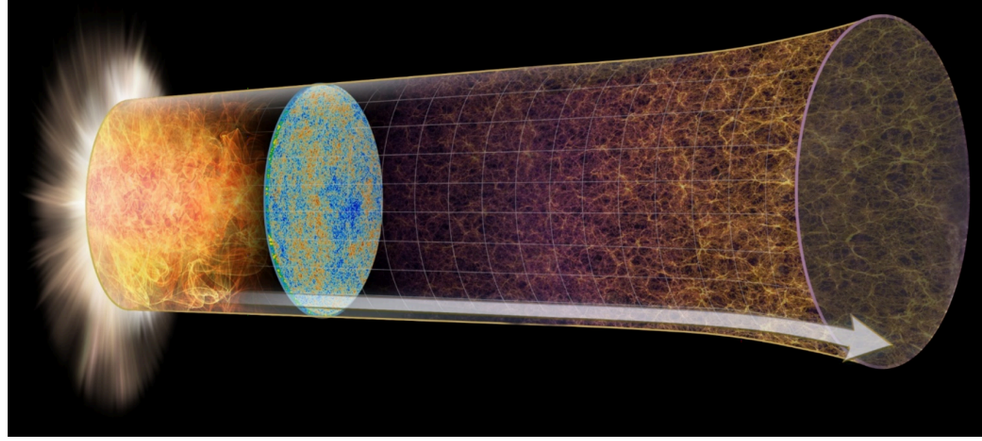
For cosmology, we do not care about all this. Or at least we do not *want* to care.

Dependence on Cosmology

(J. L. Bernal, P. Breysse, H. Gil-Marin, EDK, PRD 2019)



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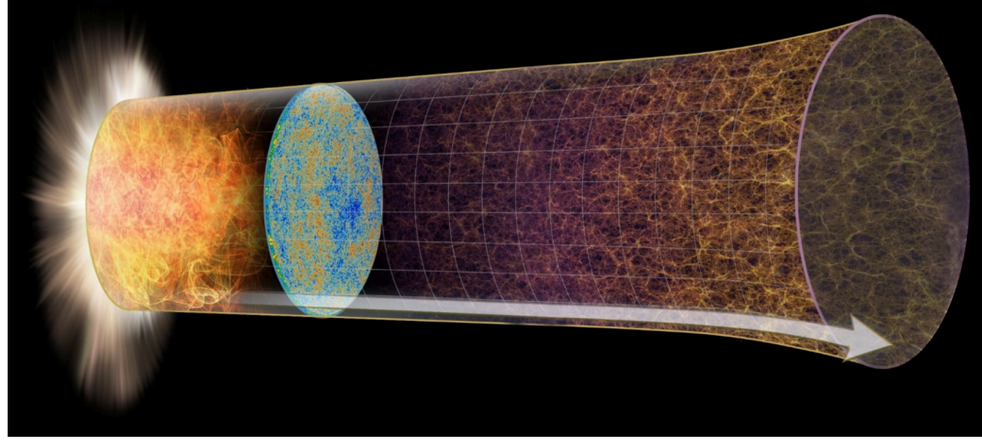

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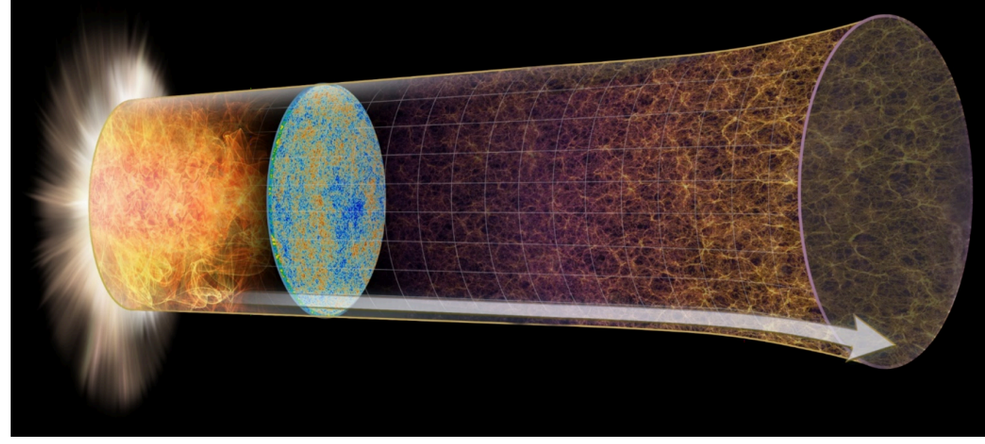

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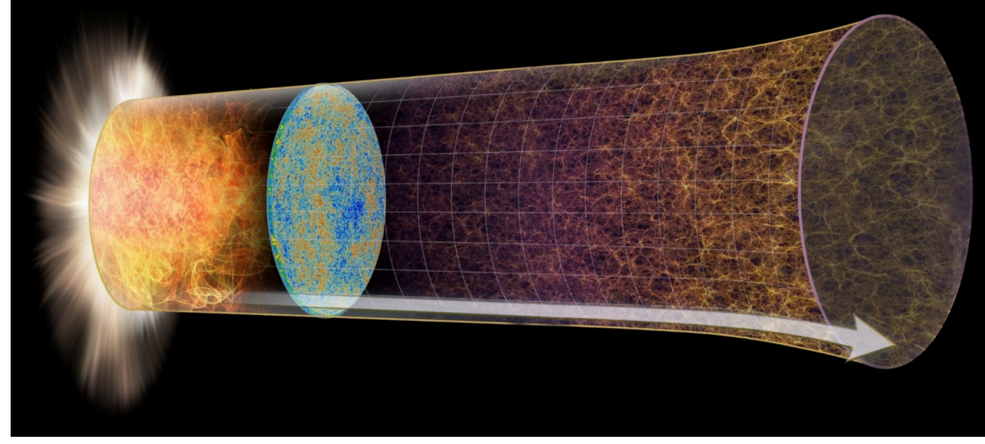

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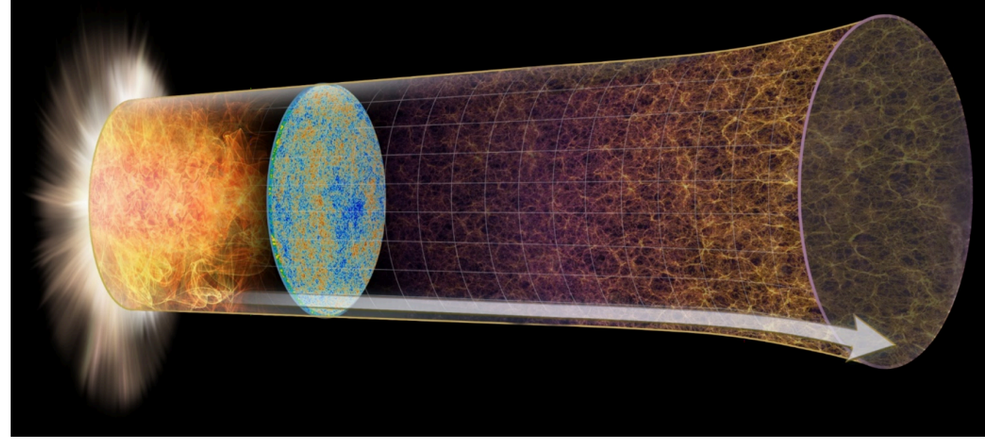

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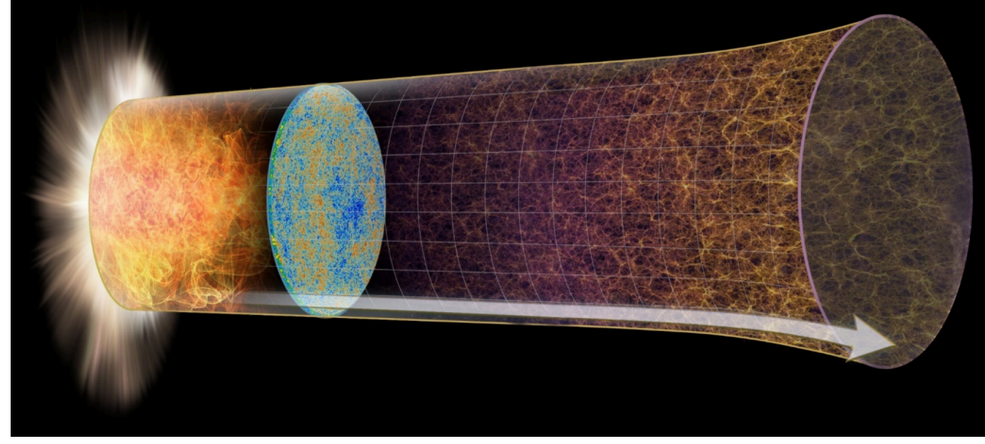

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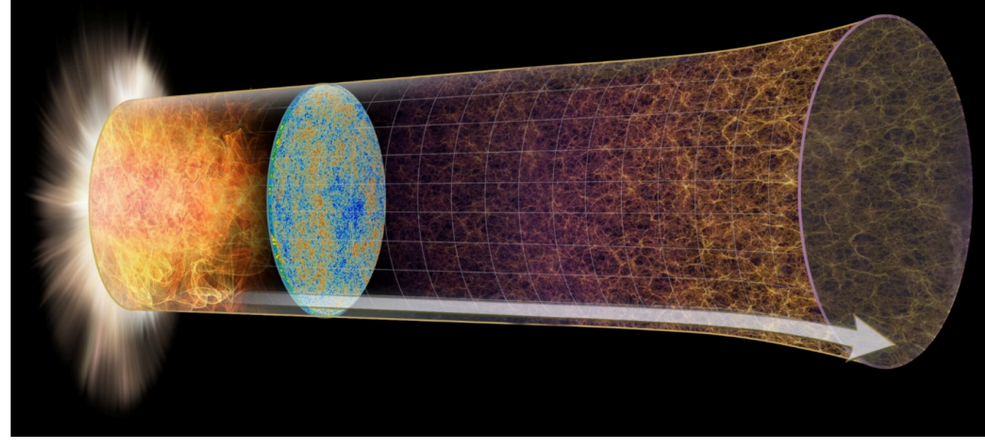

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Correction for volume modification:

(see Lidz and Taylor 2016)

$$P^{\rm meas}(k^{\rm meas},\mu^{\rm meas},z) = \left(\alpha_{||}\alpha^2_{\perp}\right)^{-1} P^{\rm true}(k^{\rm true},\mu^{\rm true},z)$$

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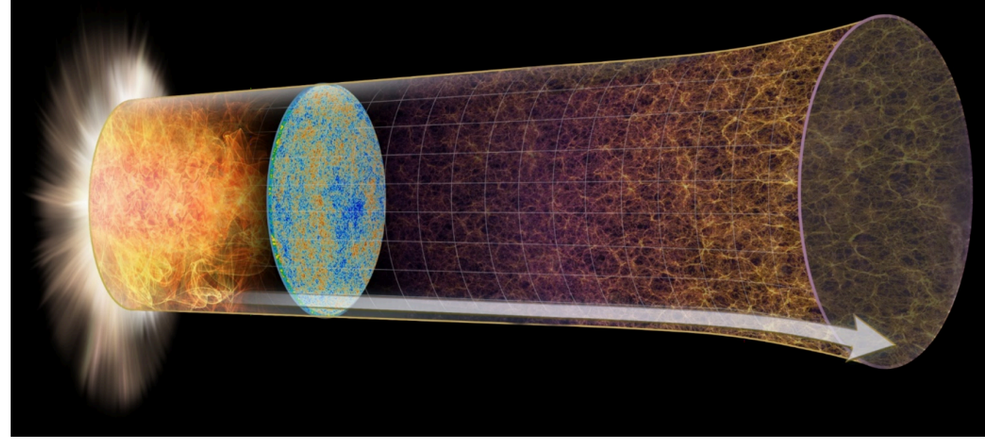

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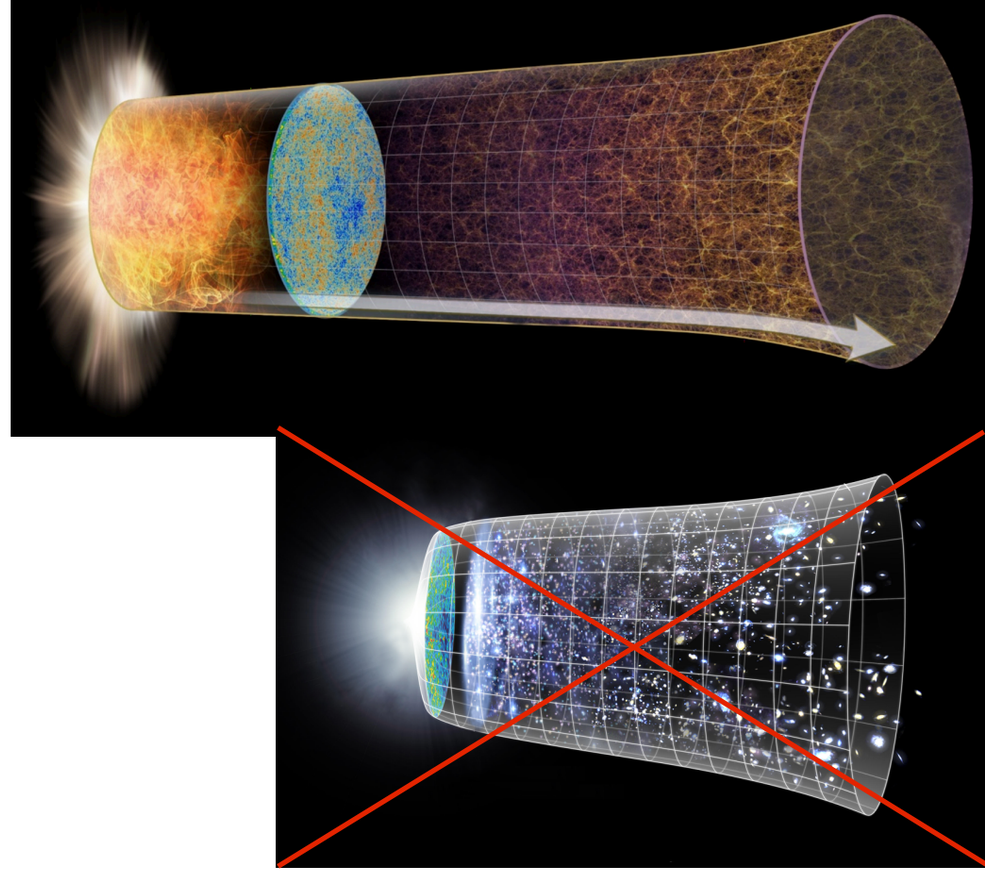
Breaking the Degeneracies

(J. L. Bernal, P. Breysse, H. Gil-Marin, EDK, PRD 2019)



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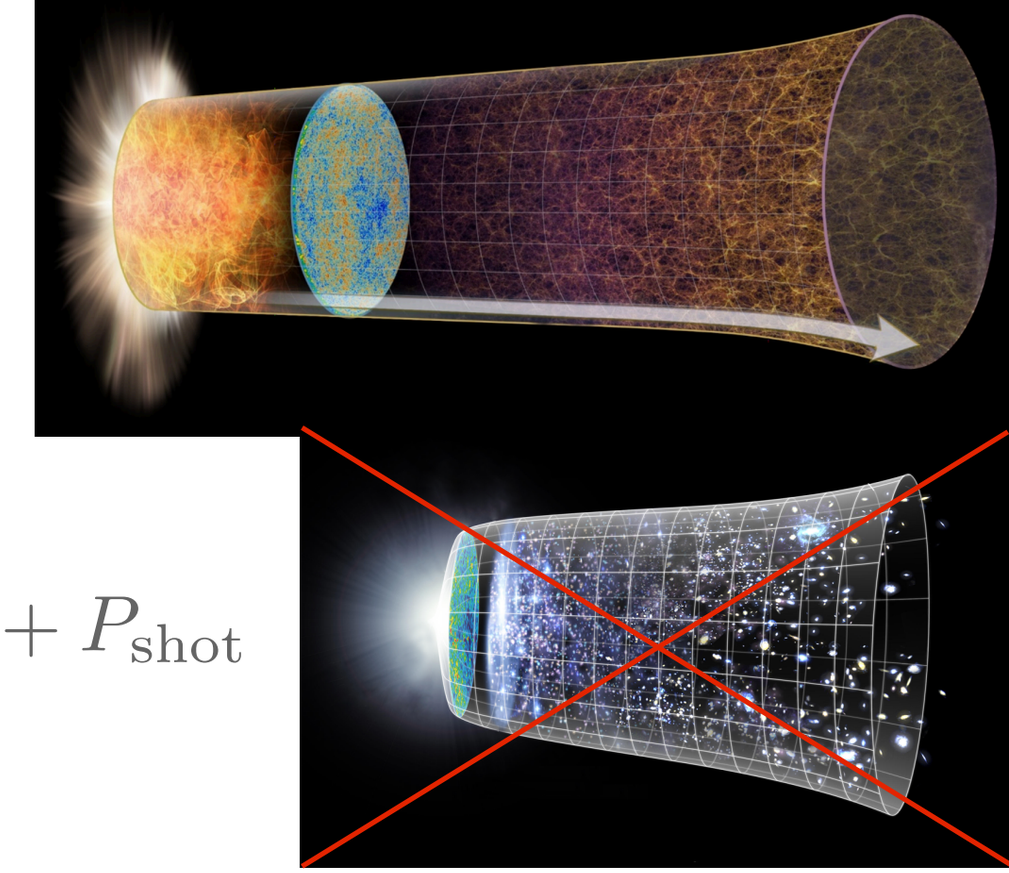
Reparameterize the power spectrum:

$$P(k,\mu) = \left(\frac{\langle T \rangle b \sigma_8 + \langle T \rangle f \sigma_8 \mu^2}{1 + 0.5 \left(k \mu \sigma_{\rm FoG} \right)^2} \right)^2 \frac{P_m(k)}{\sigma_8^2} + P_{\rm shot}$$



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Measurable parameters:

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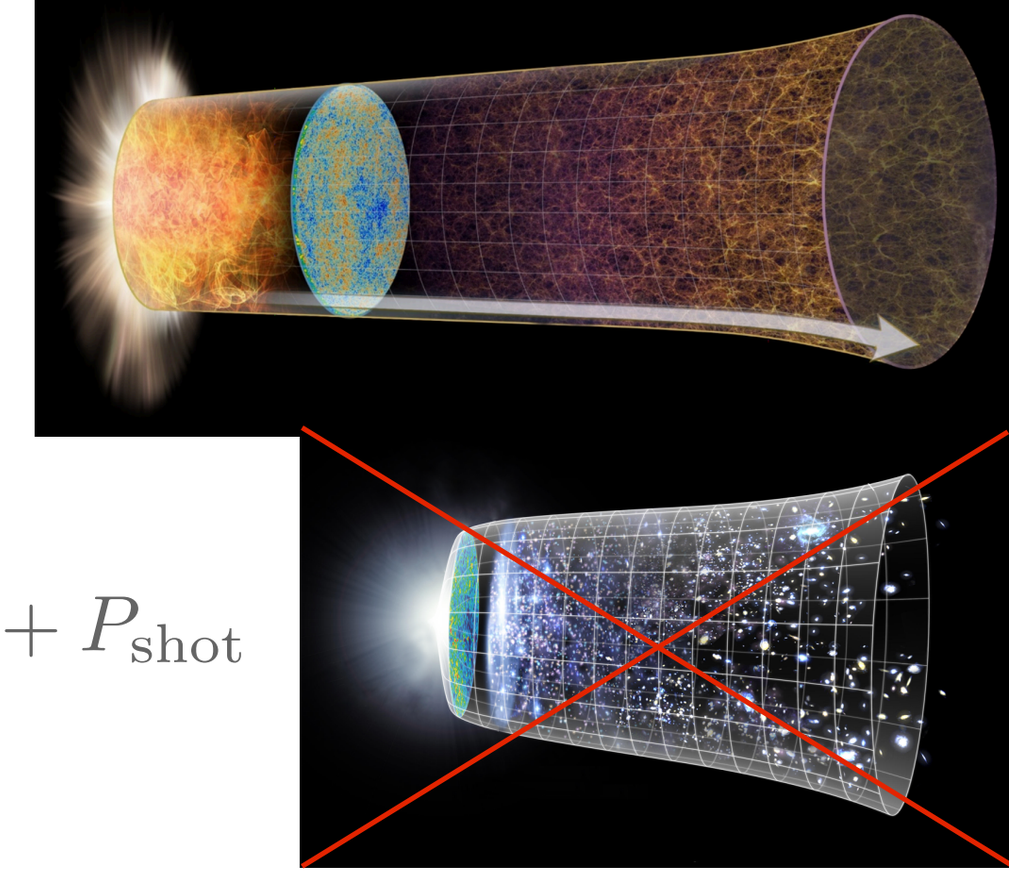

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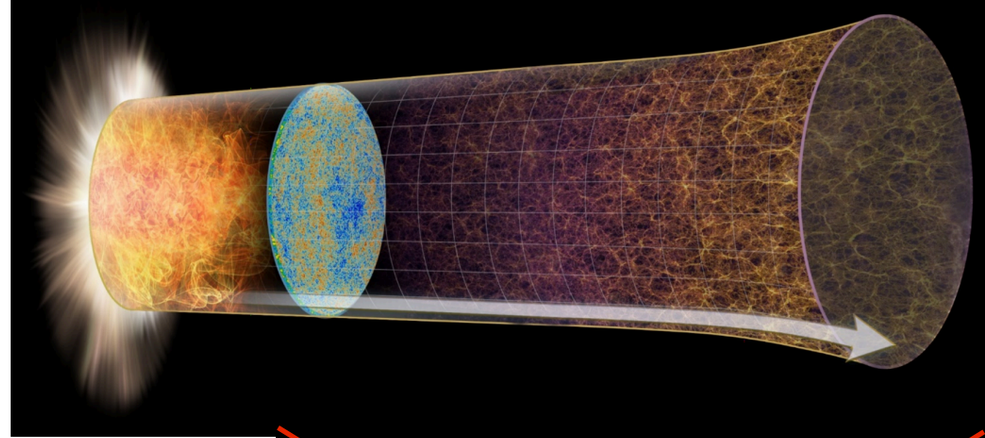

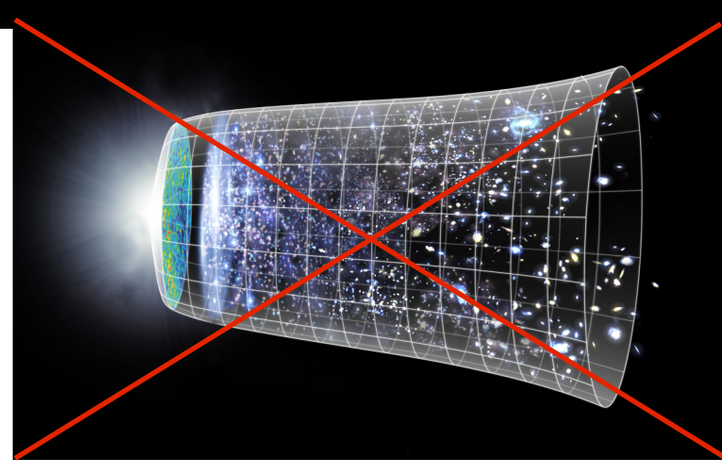

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Breaking the Degeneracies

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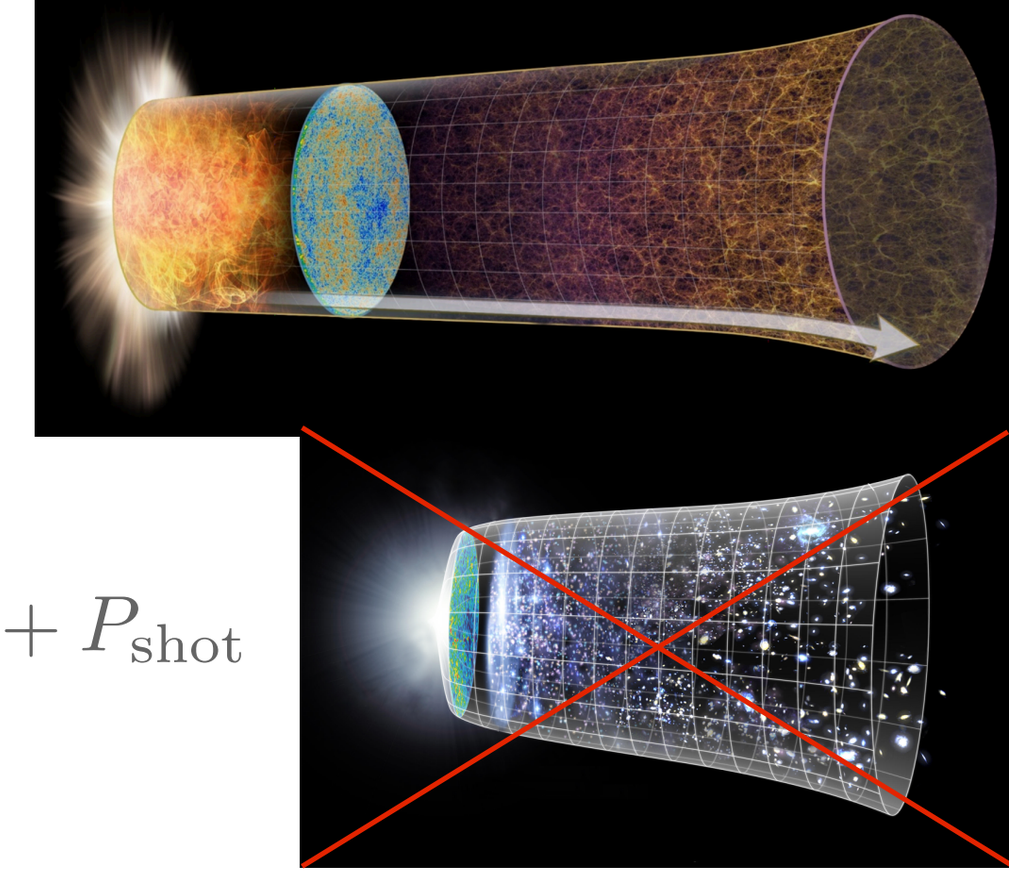

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Account for the experimental window function:

$$\tilde{P}(k,\mu,z) = W(k,\mu,z)P(k,\mu,z)$$

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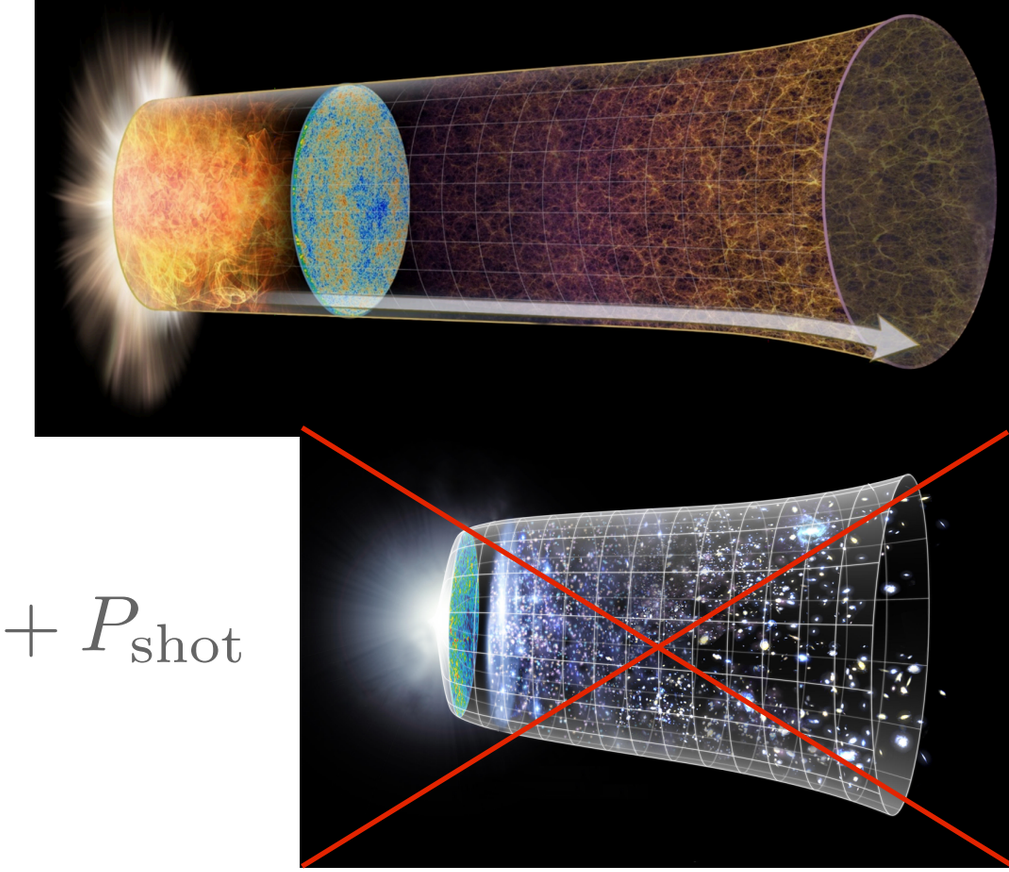

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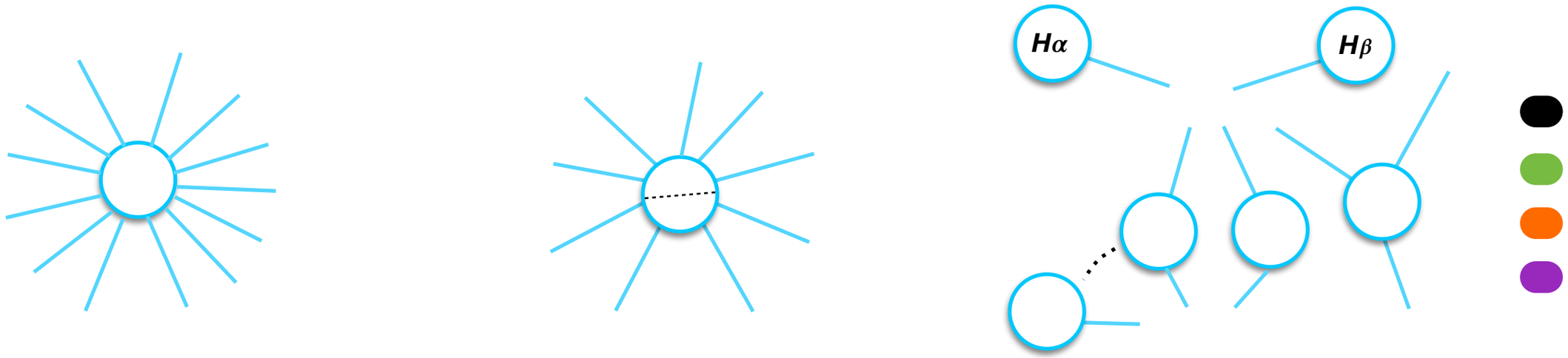
Use the Legendre multipole expansion:

$$\tilde{P}_\ell(k^{\rm meas}) = \frac{H(z)}{H^{\rm fid}(z)} \left(\frac{D_A^{\rm fid}(z)}{D_A(z)} \right)^2 \frac{2\ell+1}{2} \int_{-1}^{1} {\rm d}\mu^{\rm meas} \tilde{P}(k^{\rm true}, \mu^{\rm true}) \mathcal{L}_\ell(\mu^{\rm meas})$$

Line-Intensity Mapping: Experimental Landscape



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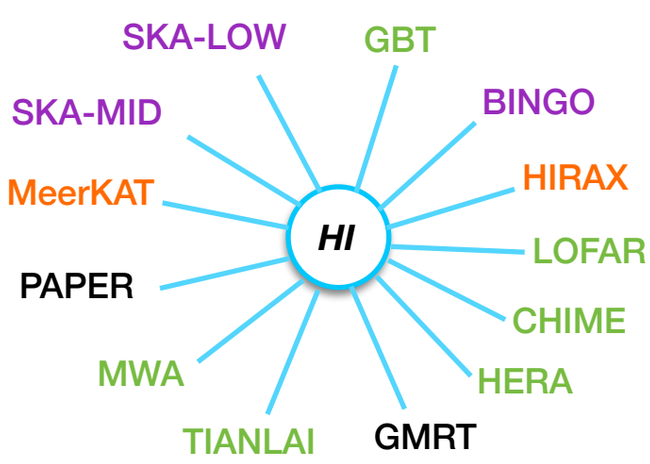

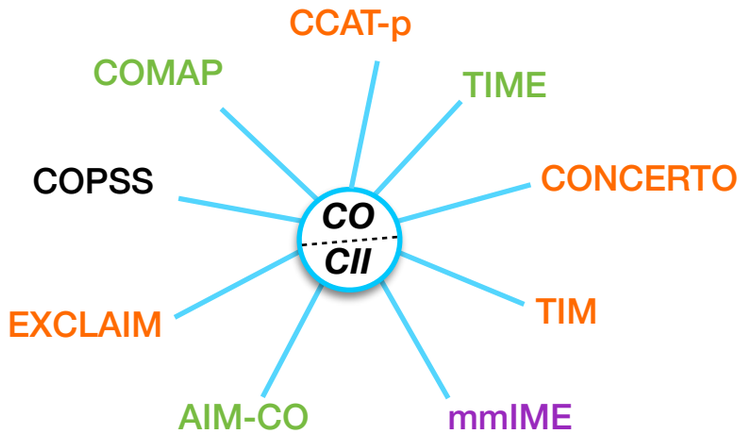

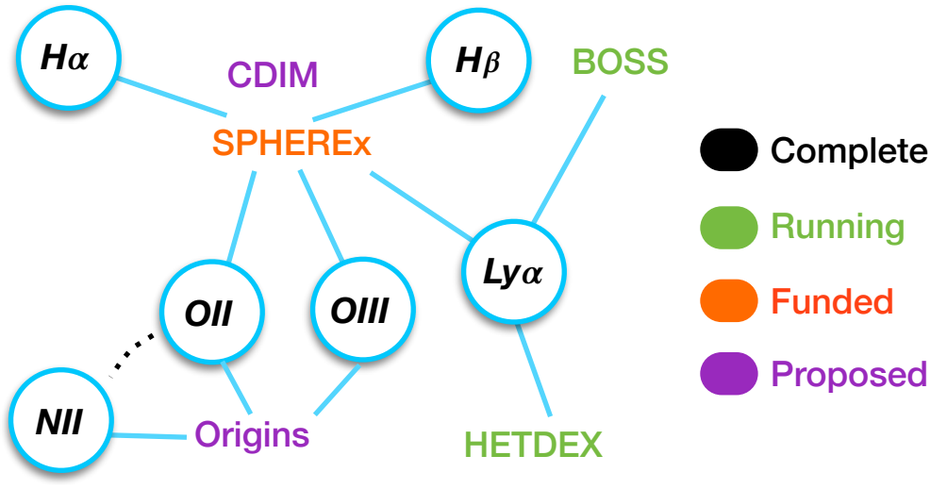

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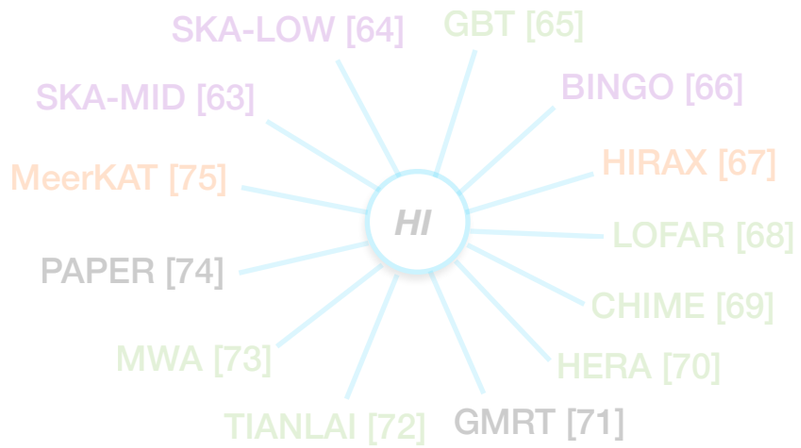

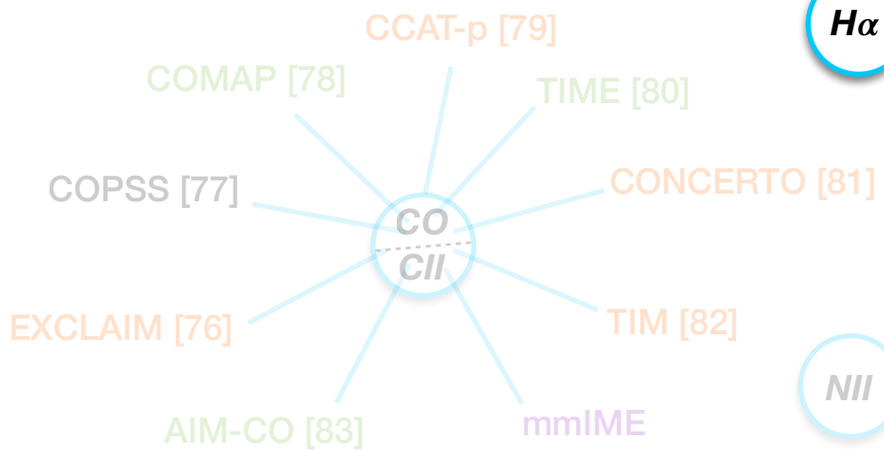

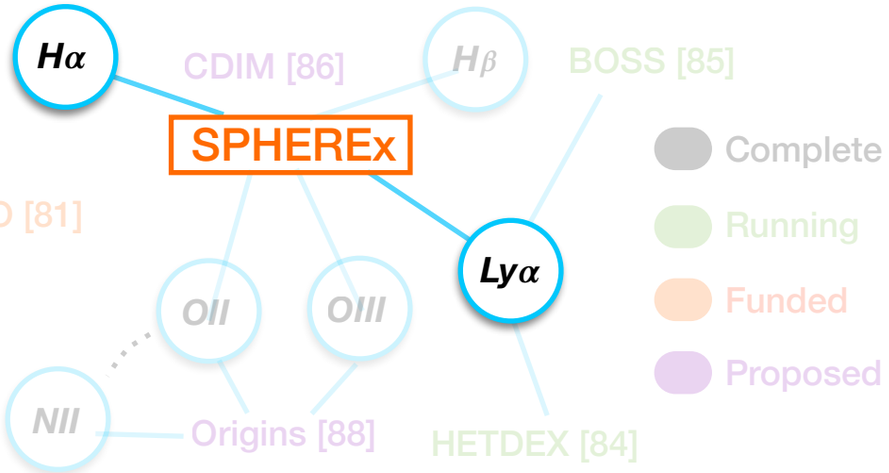

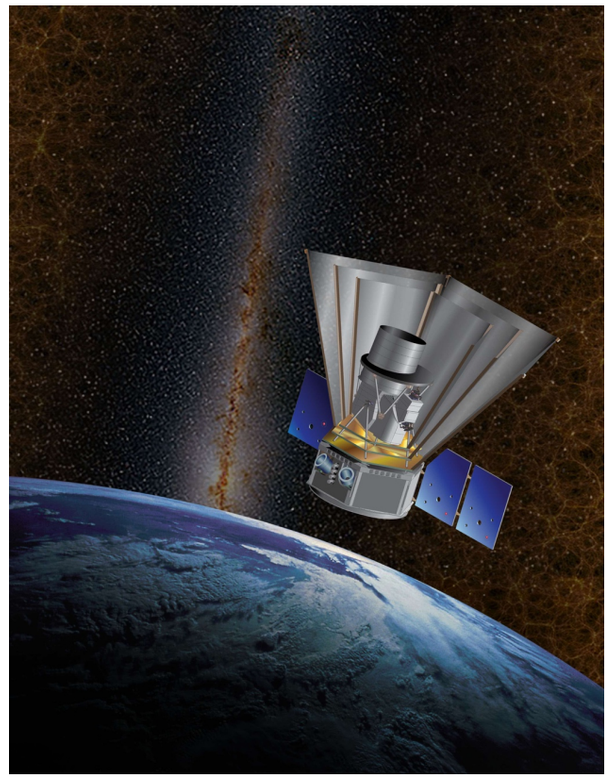

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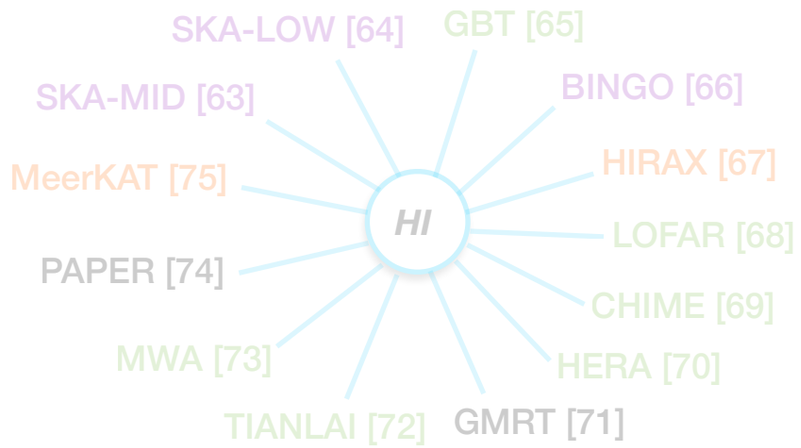

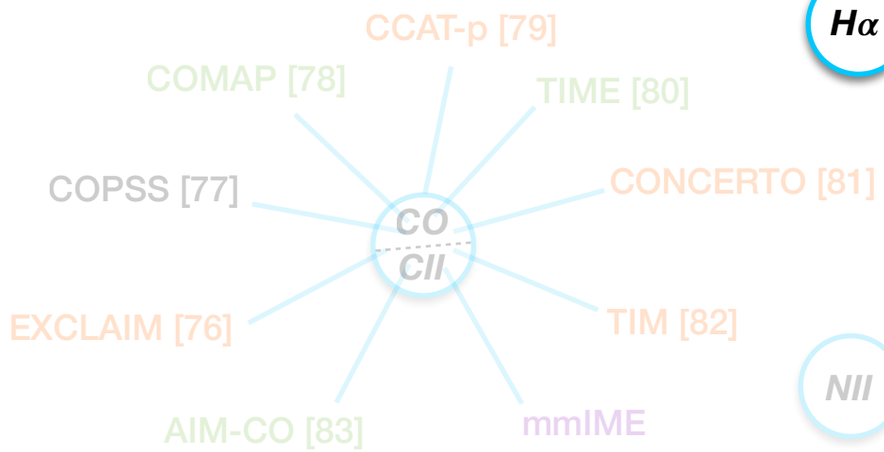

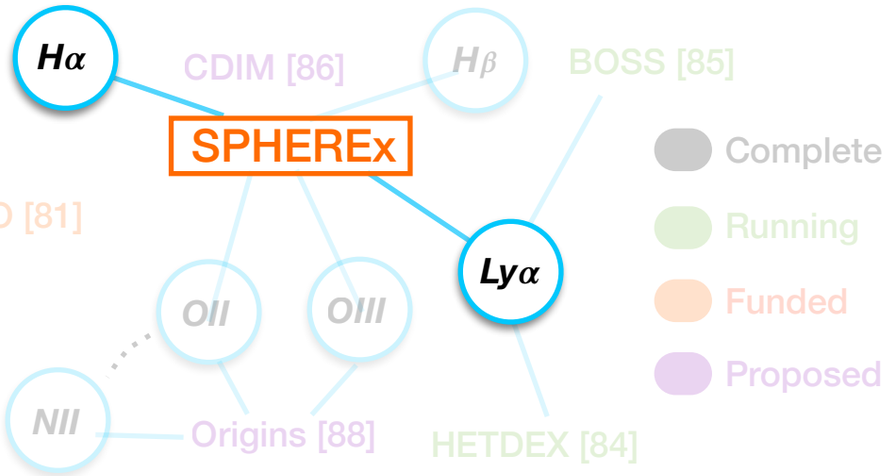

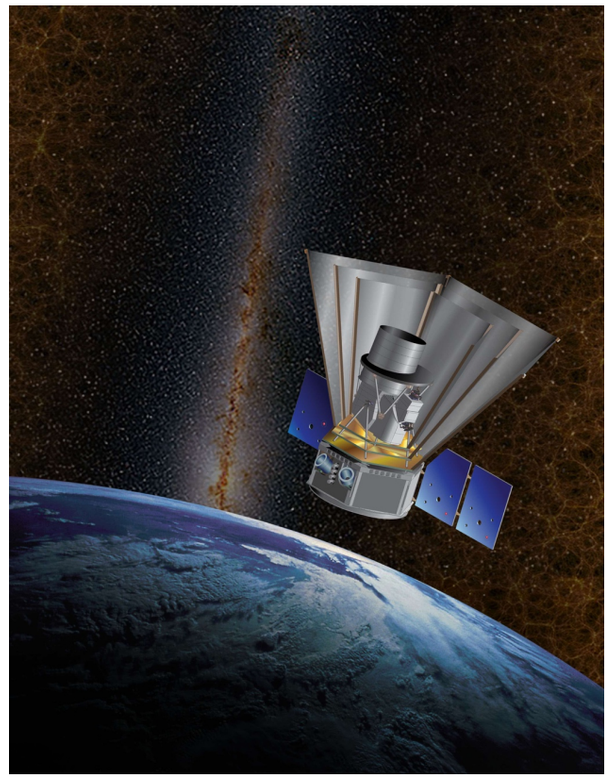

Hα	***Lyα***
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200 deg^2	200 deg^2

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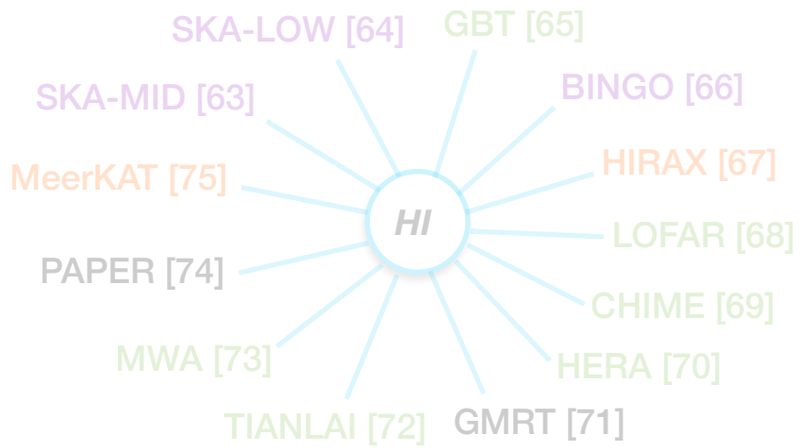

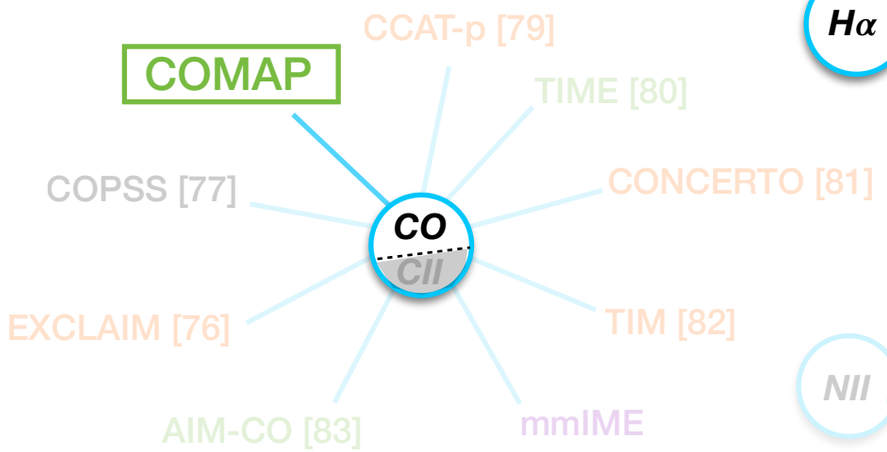

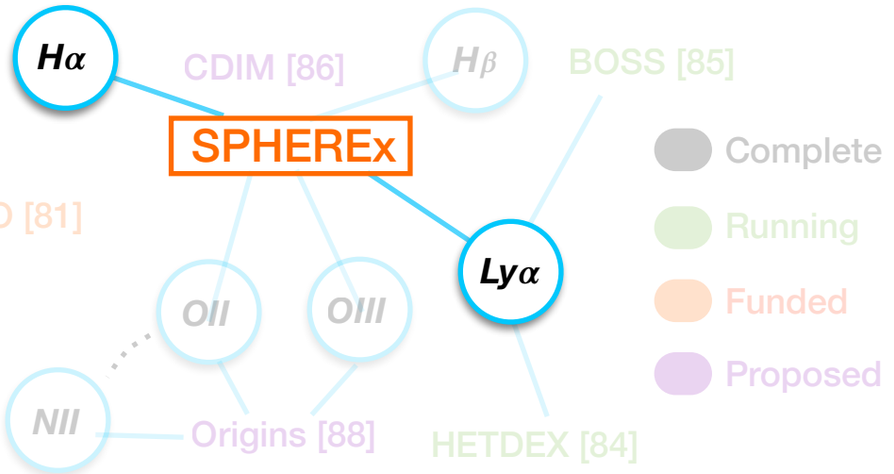

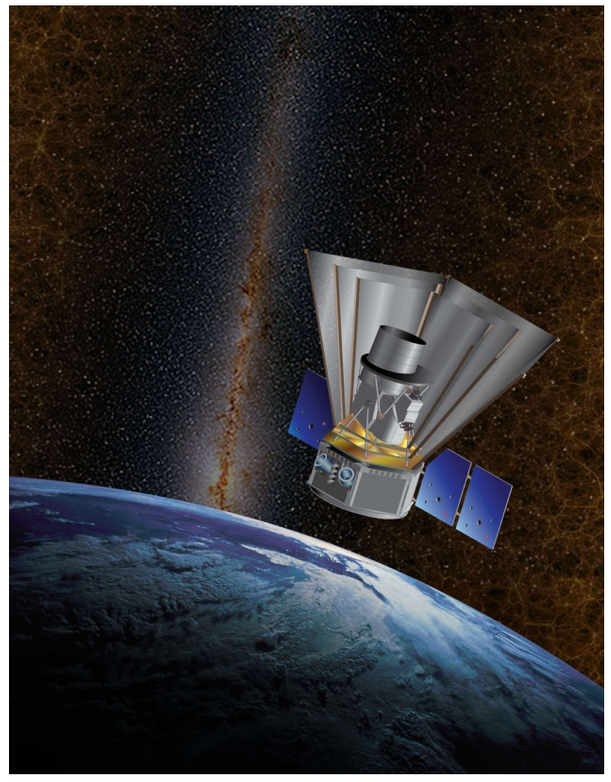

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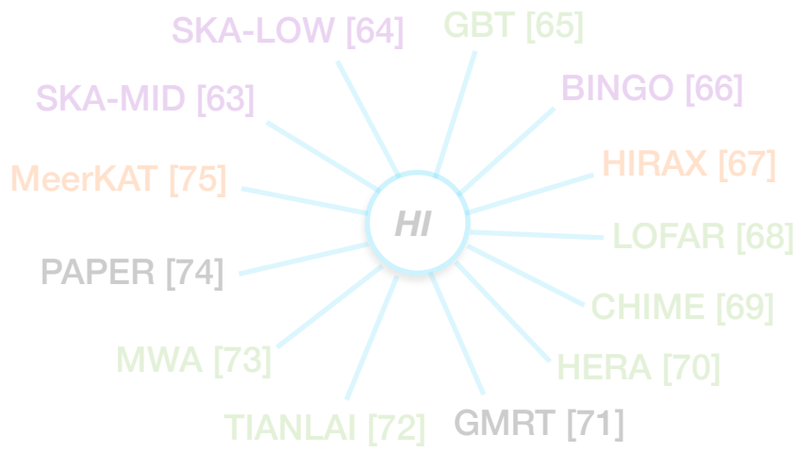

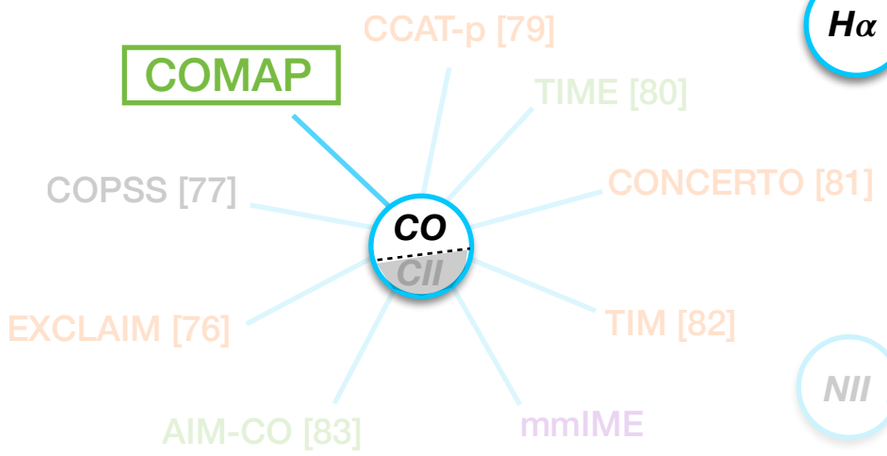

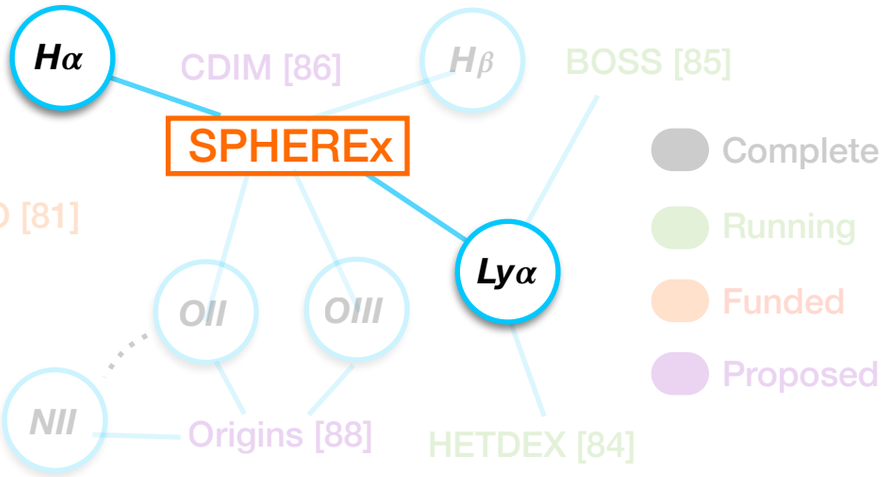

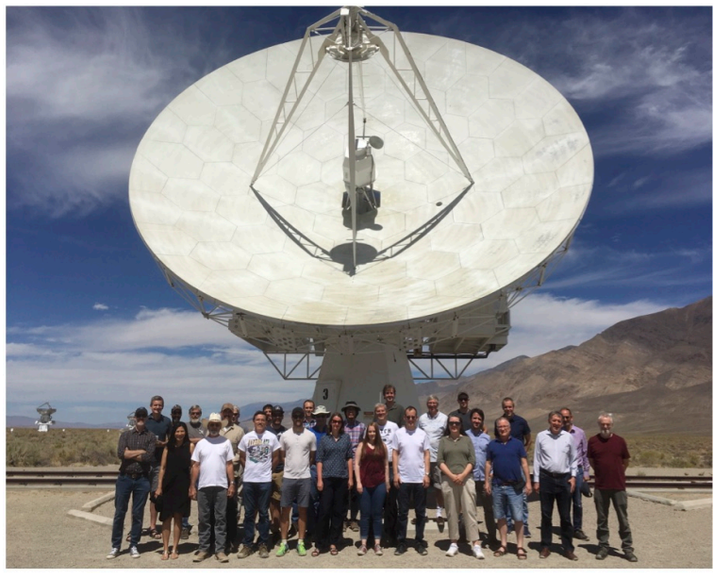

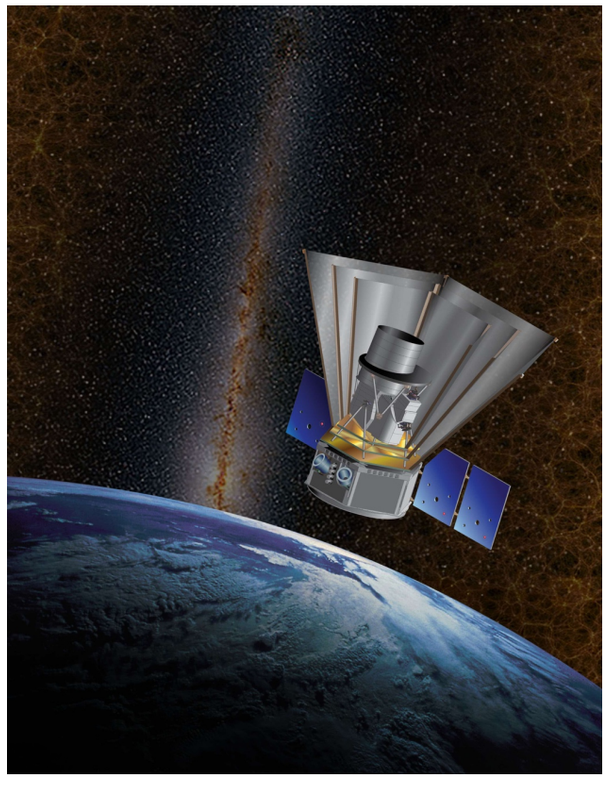

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$T_{\rm sys}$ [K]	40	40	max(20,$\nu_{\rm obs}$)
Total # of independent detectors	19	95	1000
Ang. resolution (FWHM) [arcmin]	4	4	4
Frequency band [GHz]	26-34	26-34	12-36
$\delta\nu$ [MHz]	15.6	8.0	2.0
$t_{\rm obs}$ [h]	6000	10000	10000
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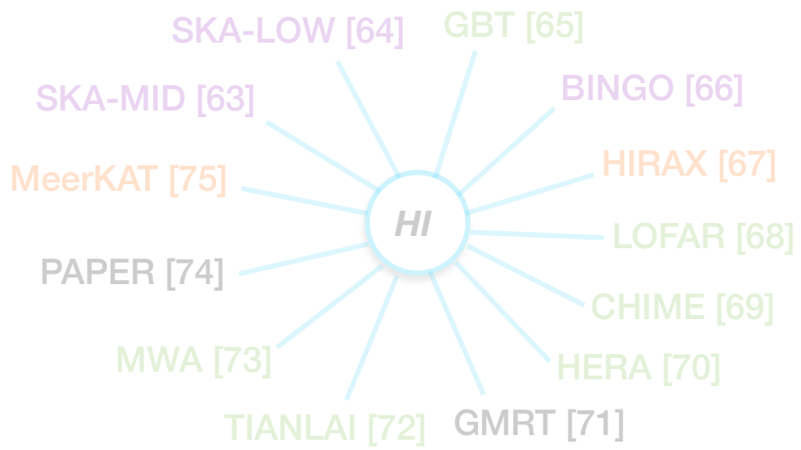

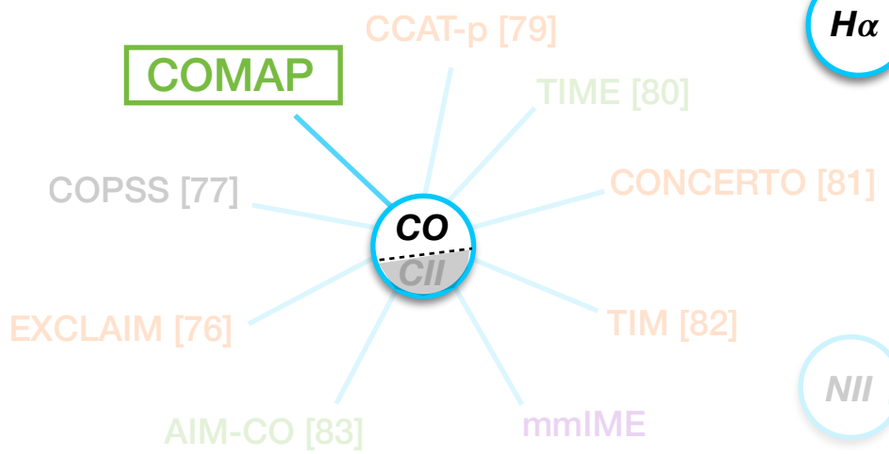

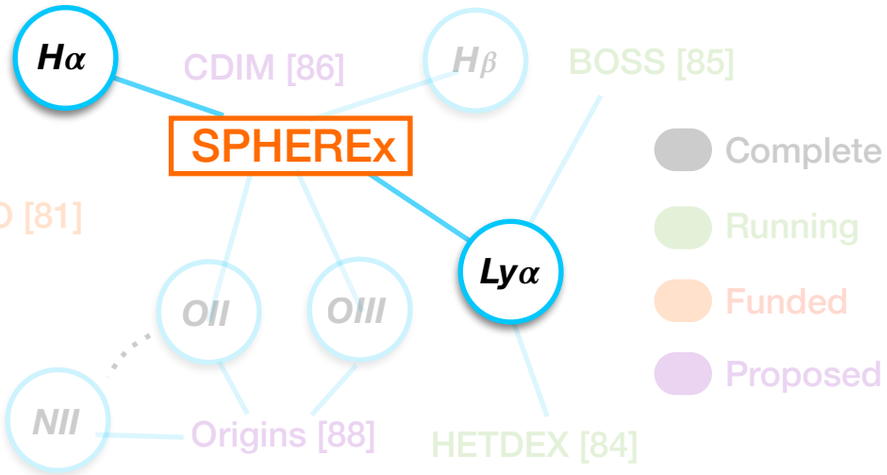

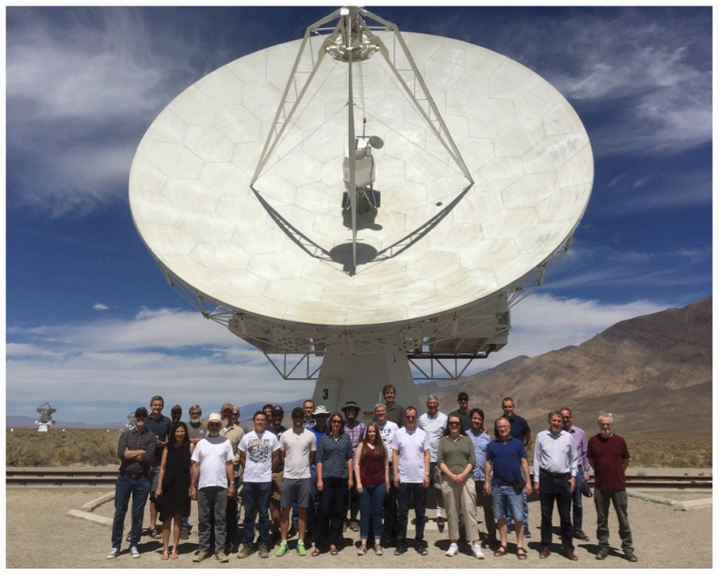

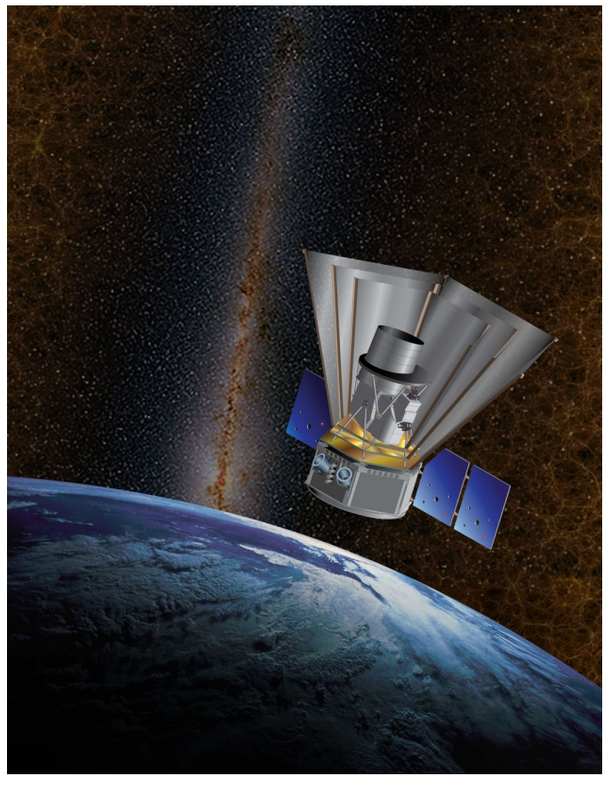

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(J. L. Bernal, P. Breysse, EDK, PRL 2019, J. L. Bernal, P. Breysse, H. Gil-Marin, EDK, PRD 2019)

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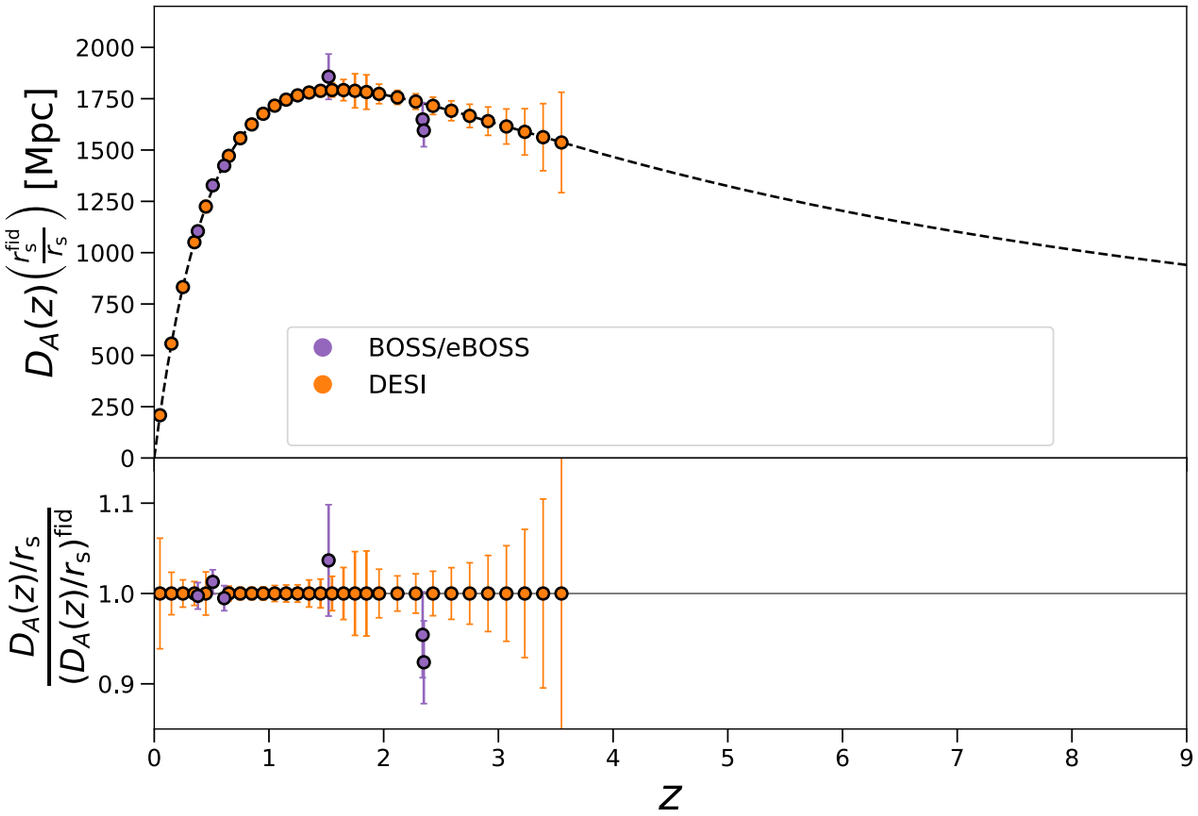
Angular diameter distance



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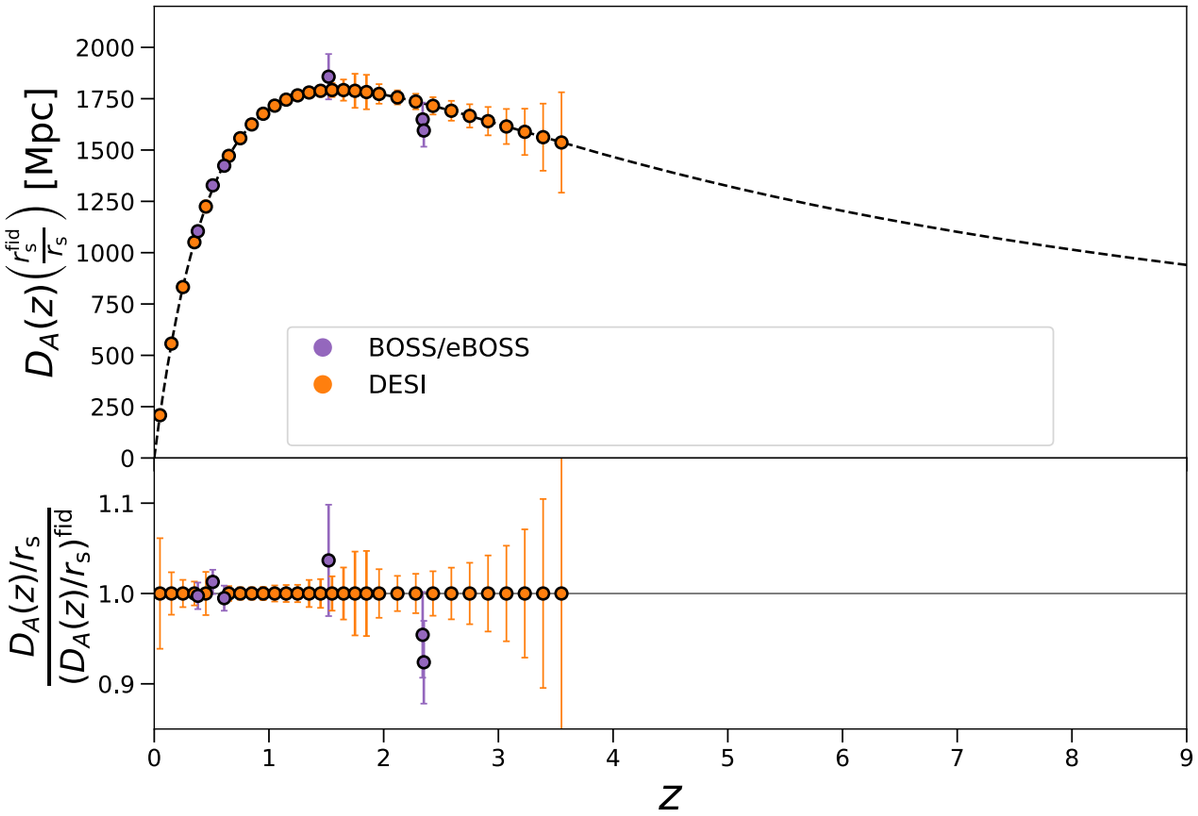
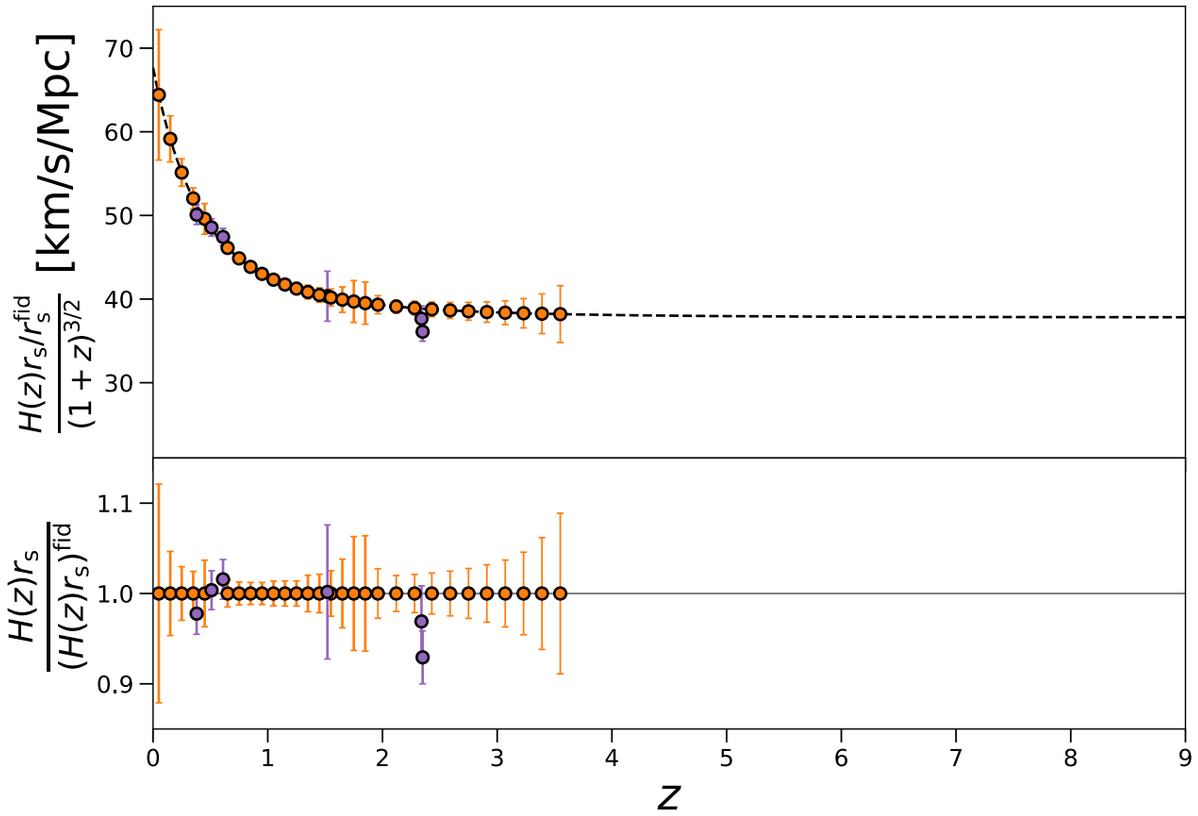


Hubble parameter



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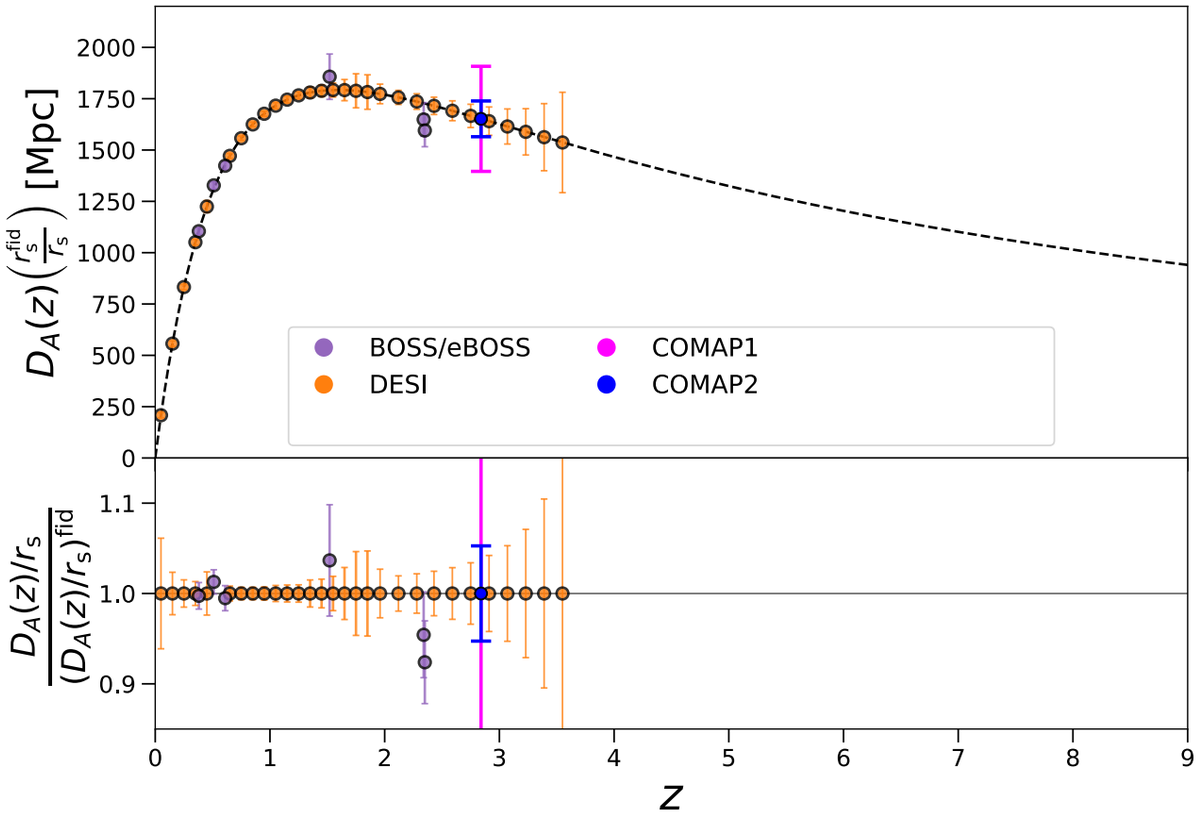

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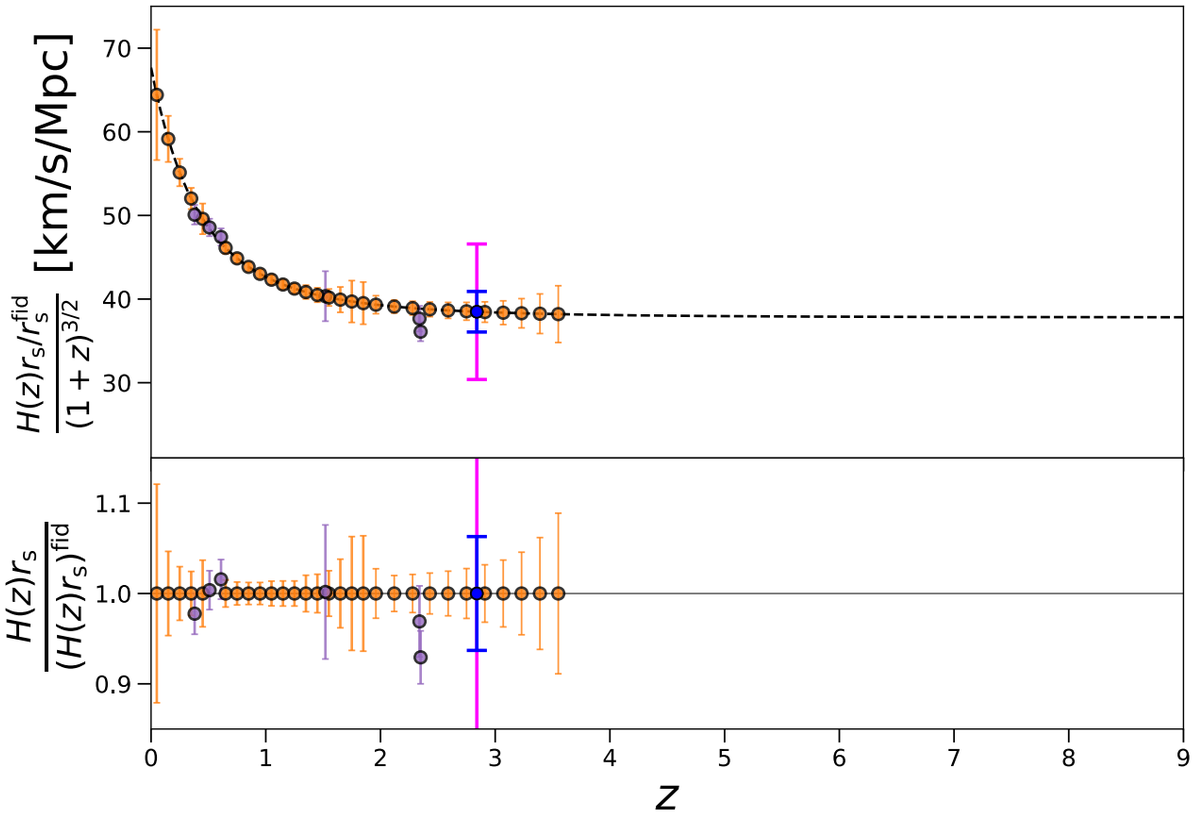

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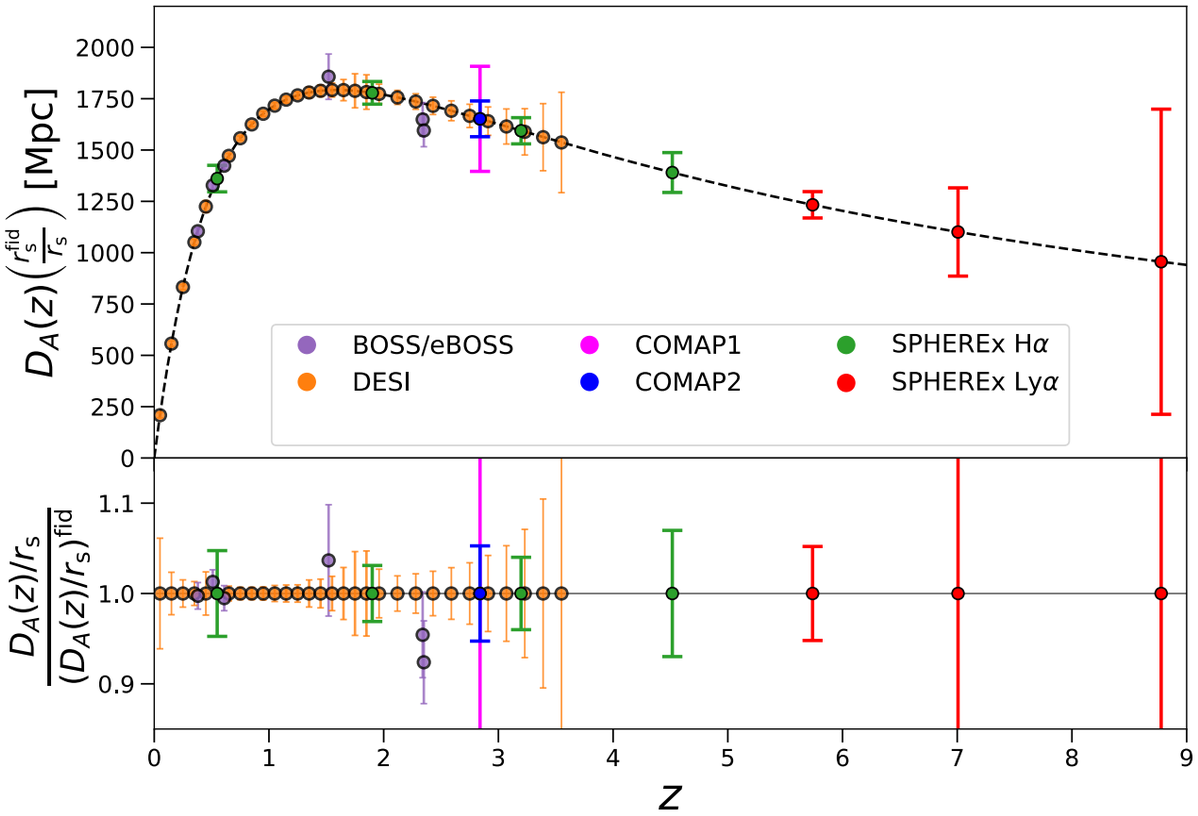

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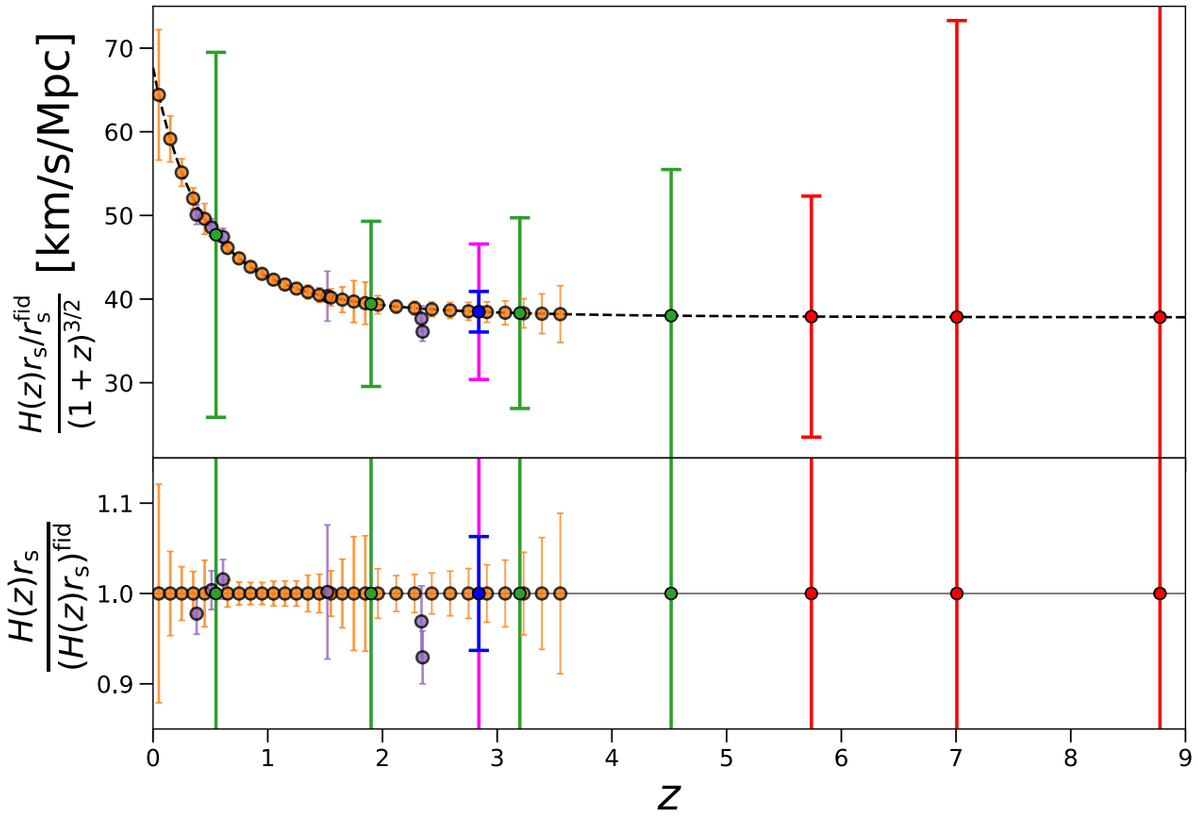

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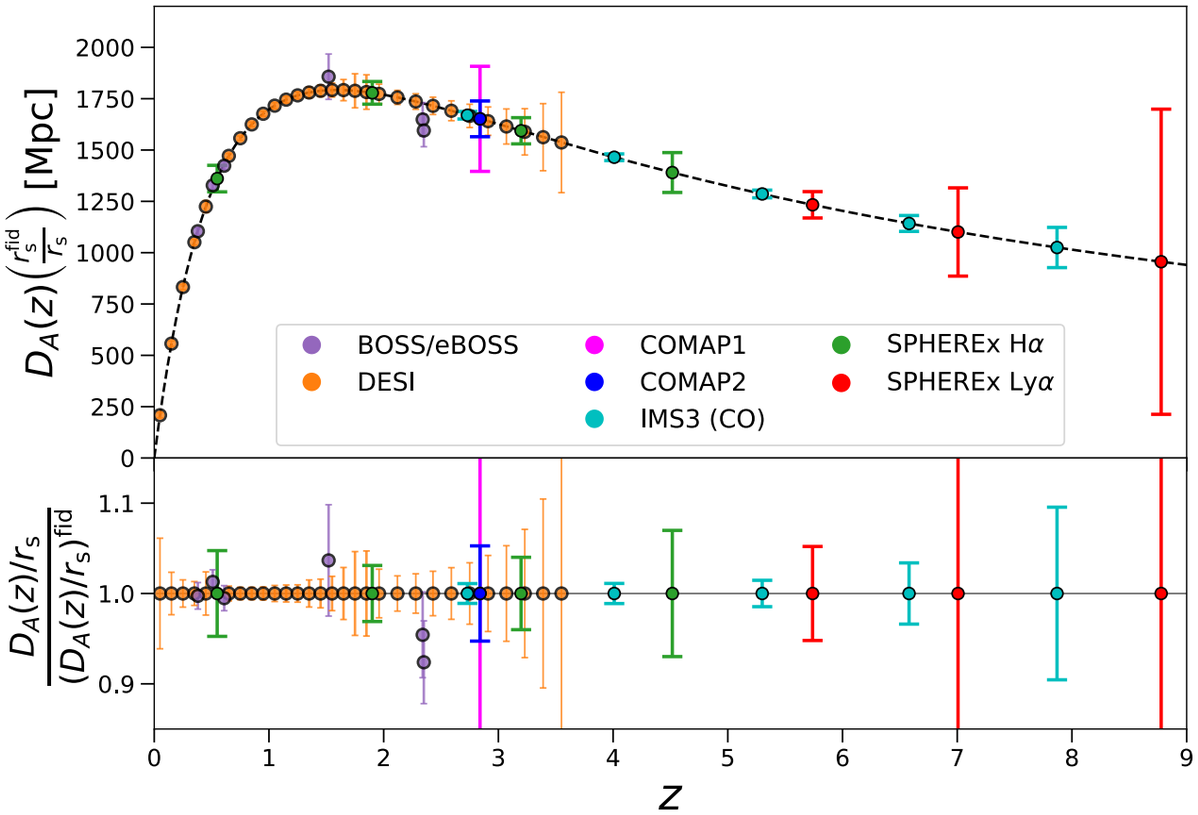

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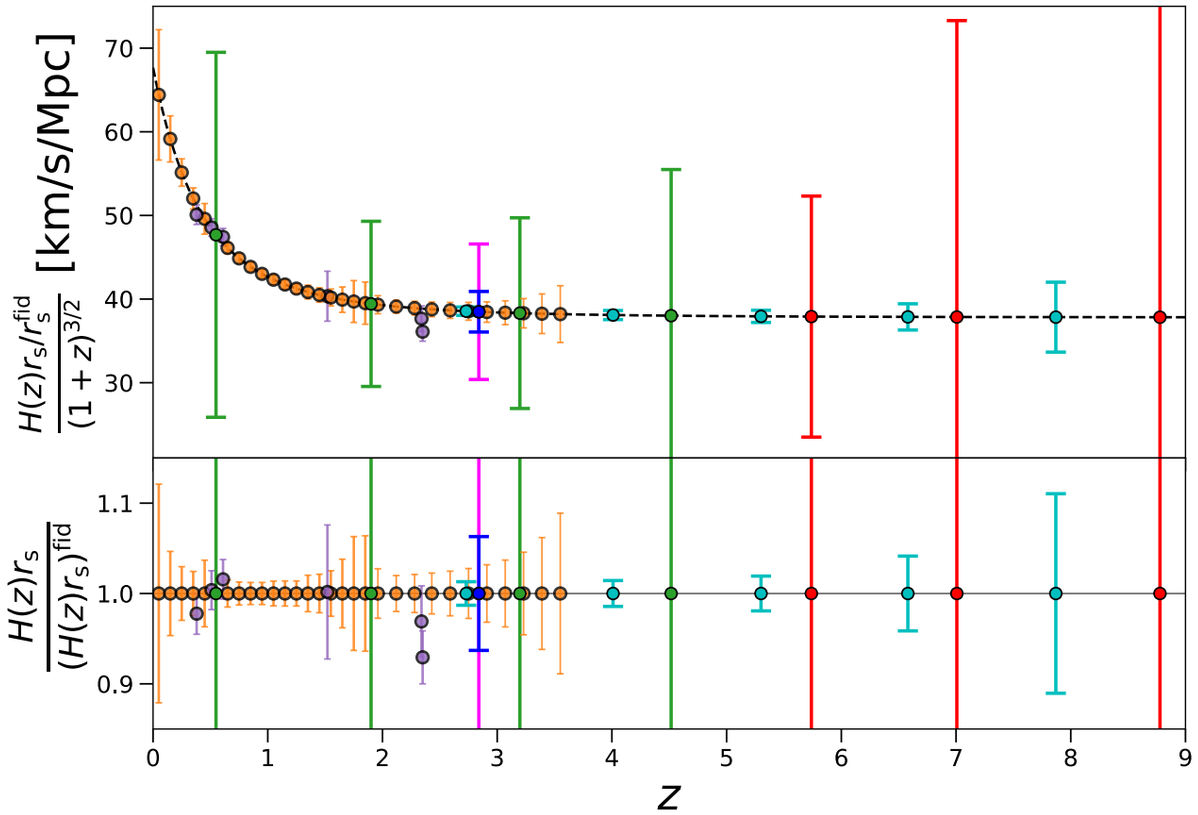

Reconstructing the Expansion History using LIM

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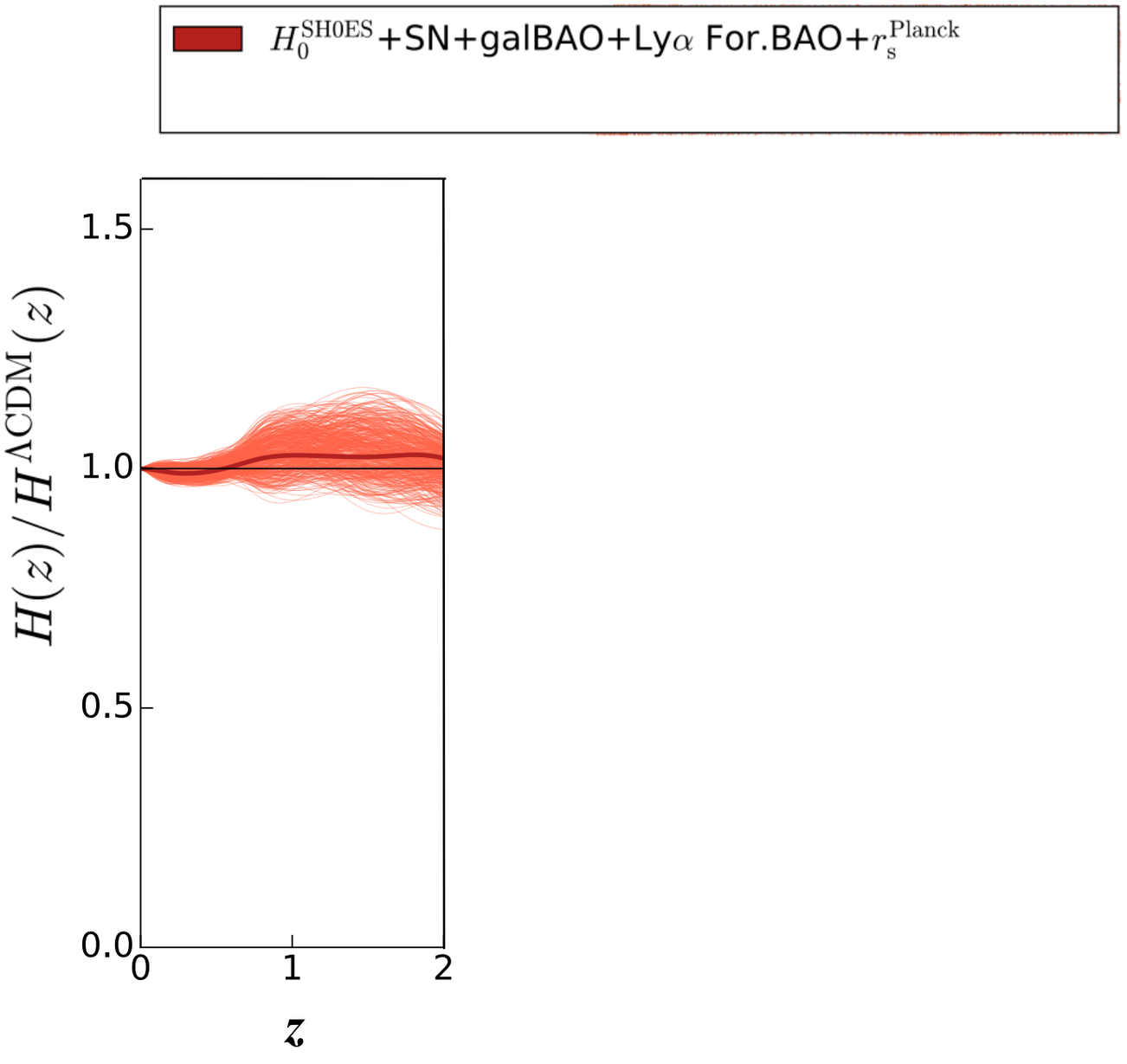

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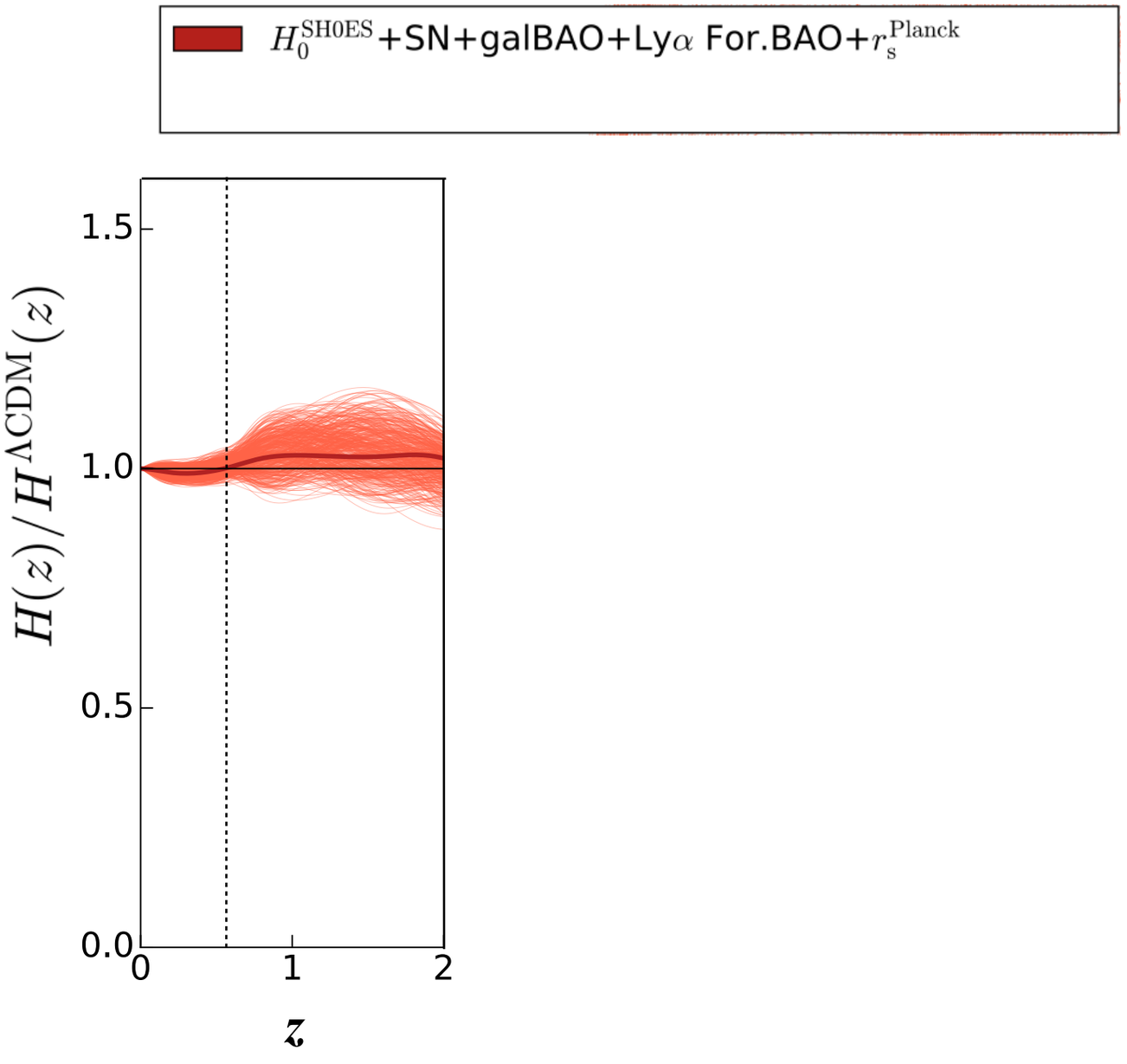

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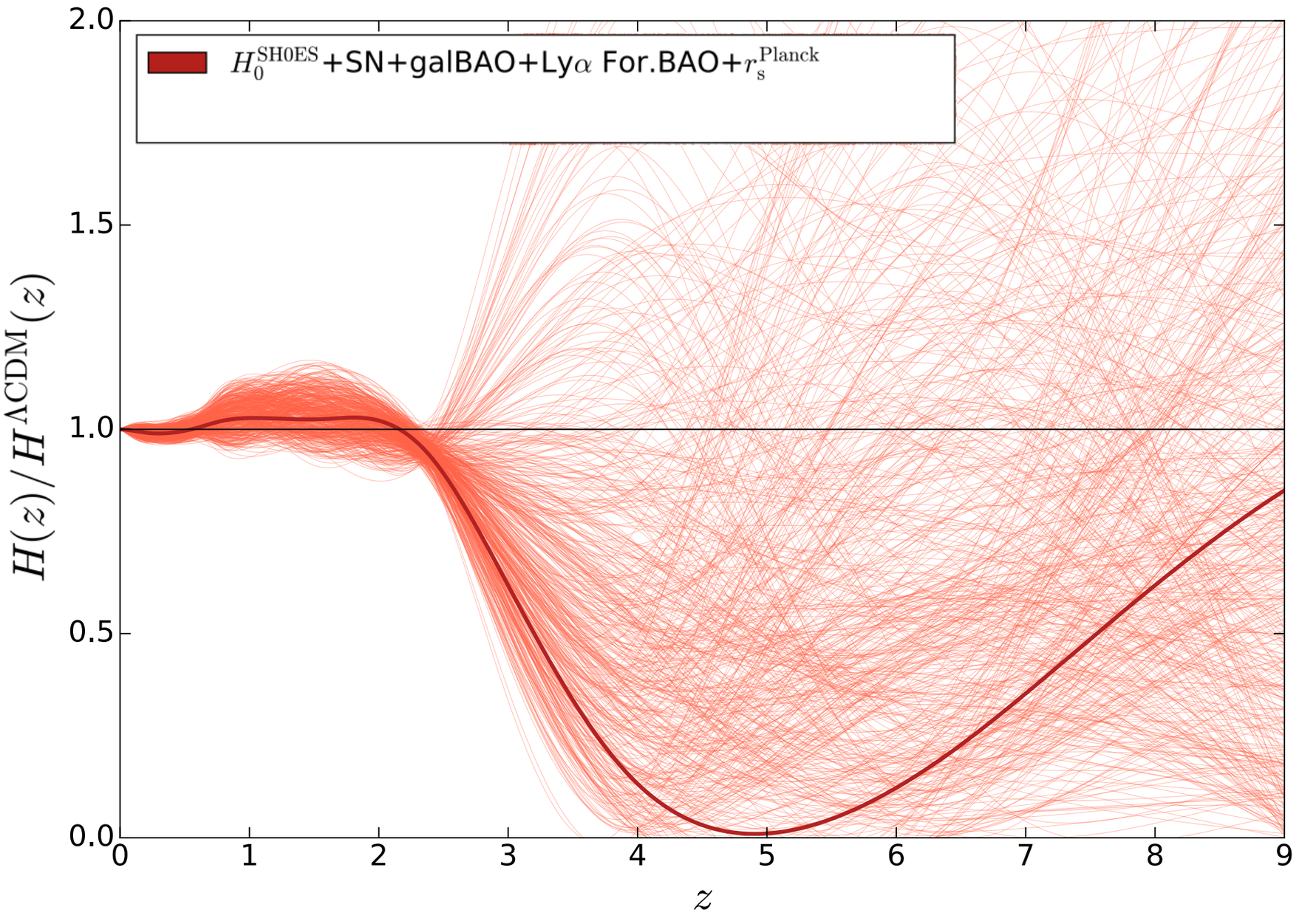

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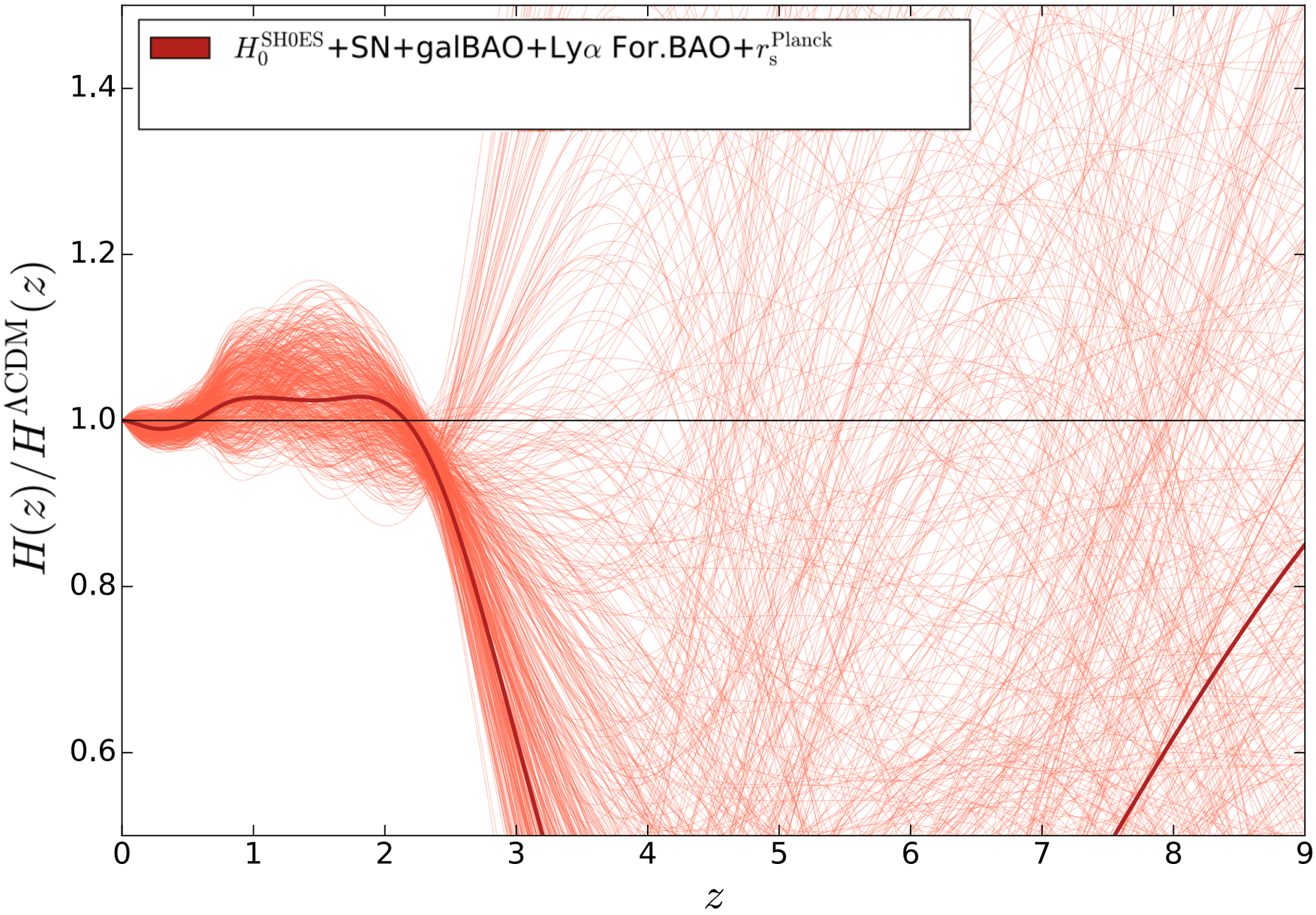

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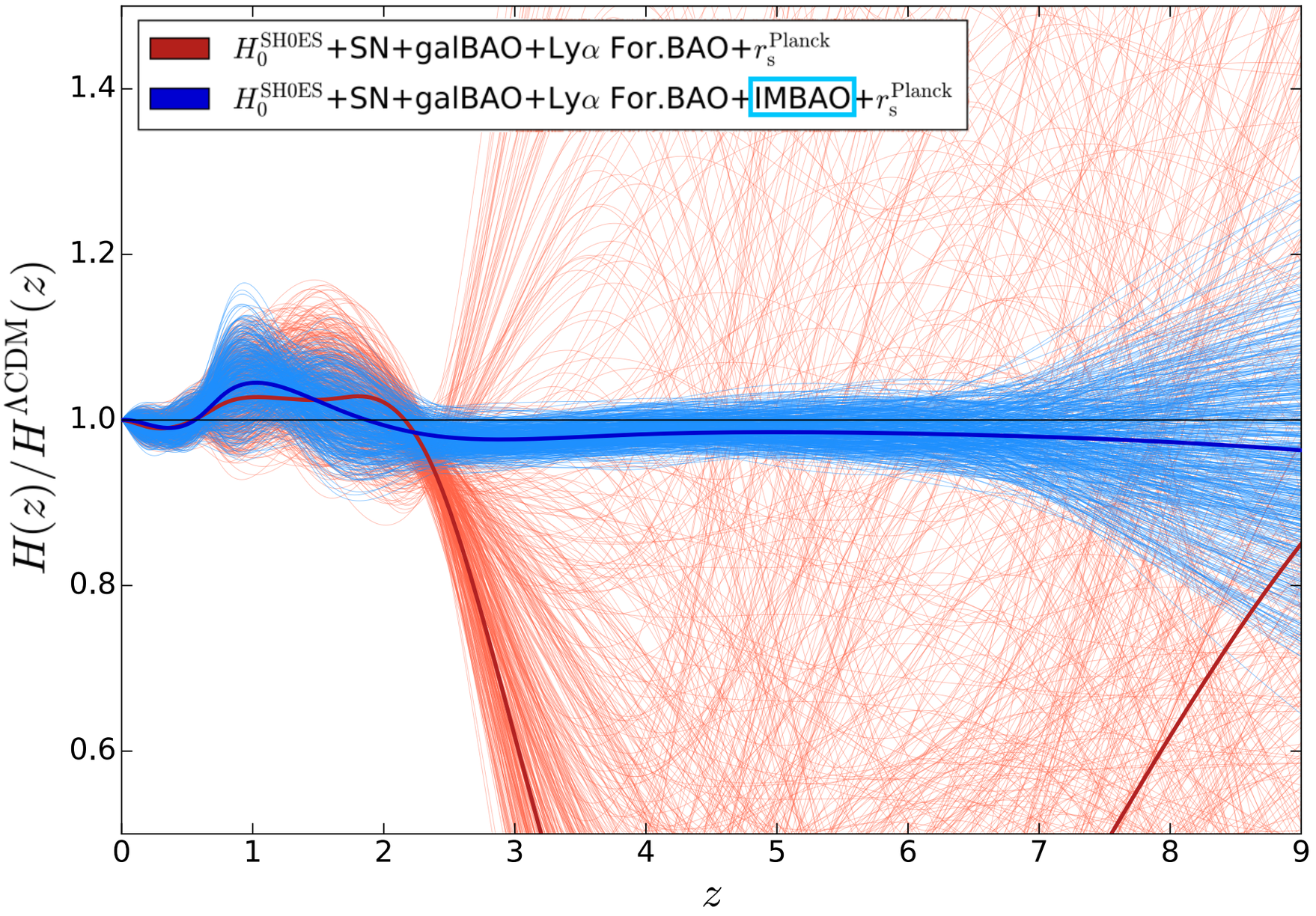
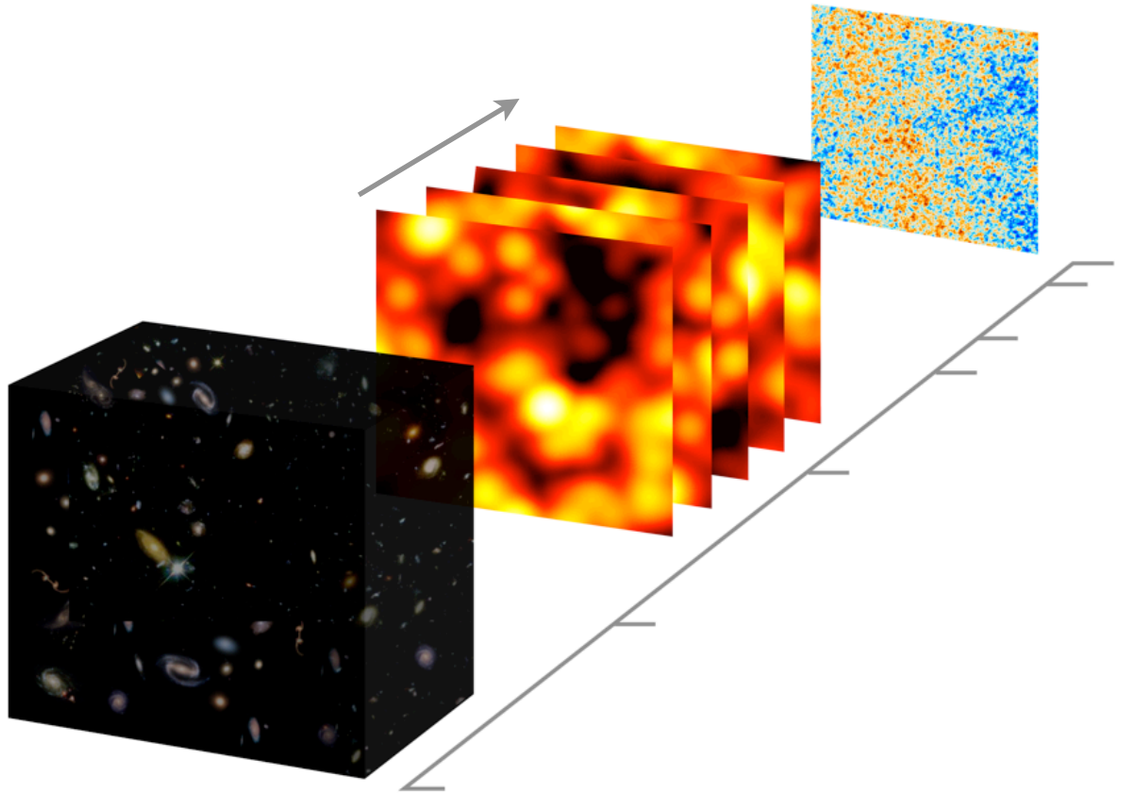


Conclusions and Outlook



Conclusions and Outlook

Opportunities:

- Cosmology: Inflation, dark matter, dark energy, modified gravity...
- Epoch of Reionization: bubble sizes, ionized fraction, duration,....
- Astrophysics: star-formation, galaxy assembly, metallicity history,....
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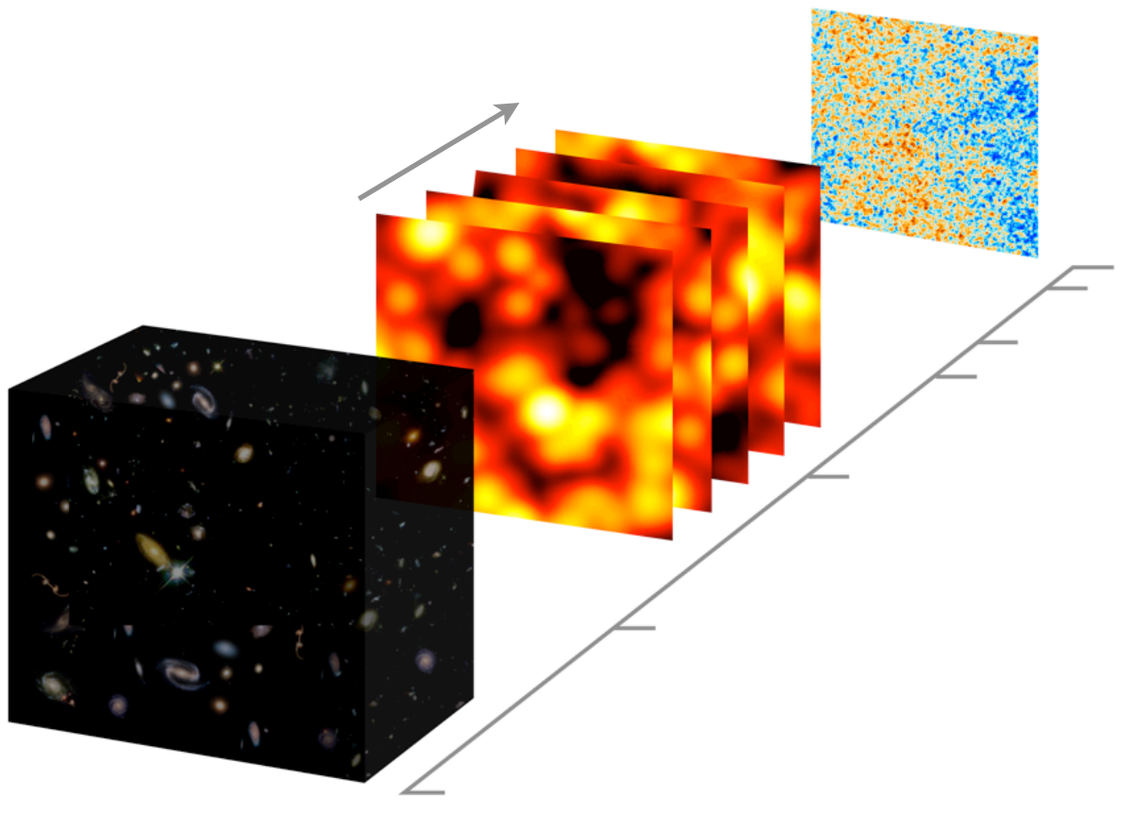

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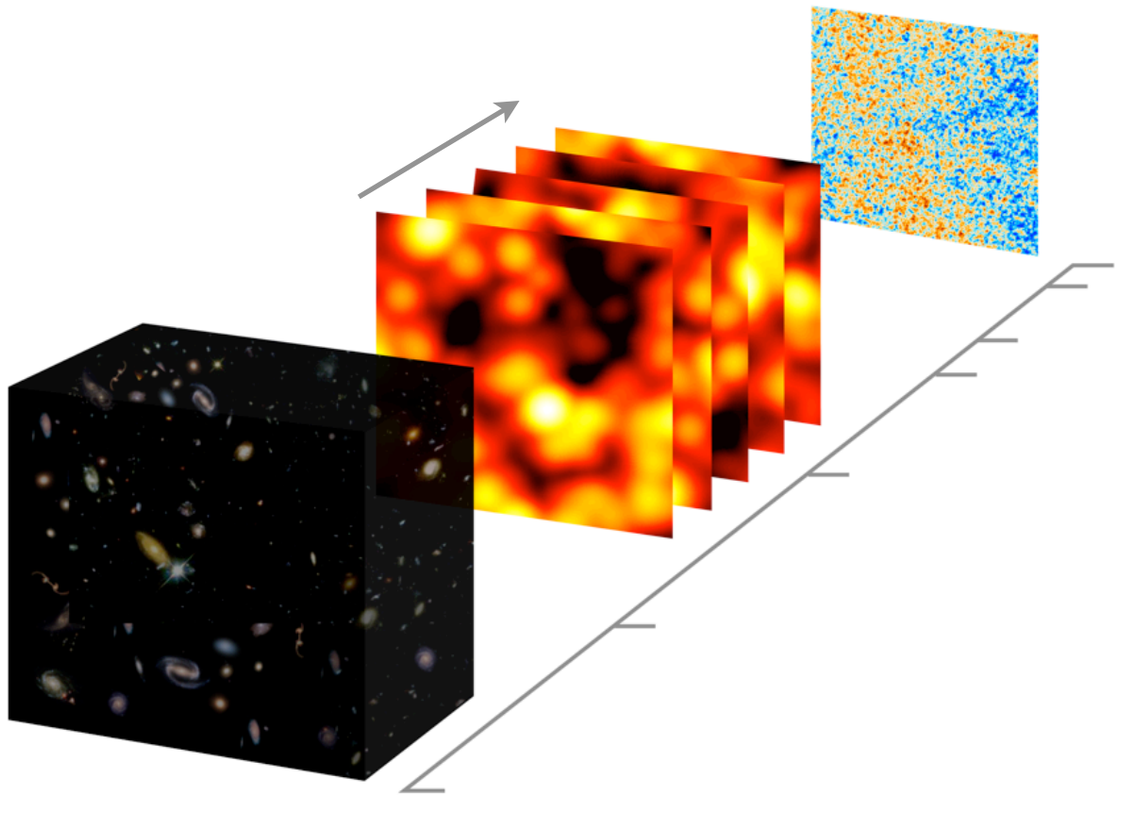
Challenges:

- Foregrounds?!
- Modeling: how to interpret a measurement?
- Optimal observables/estimators
- Simulations



The Next Decade(s): Multi-Messenger Cosmology!

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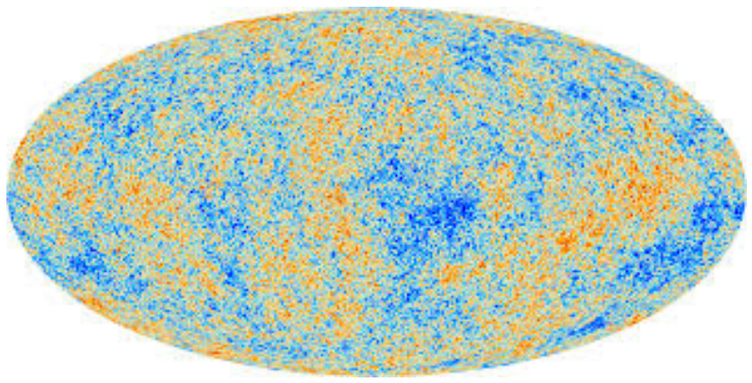

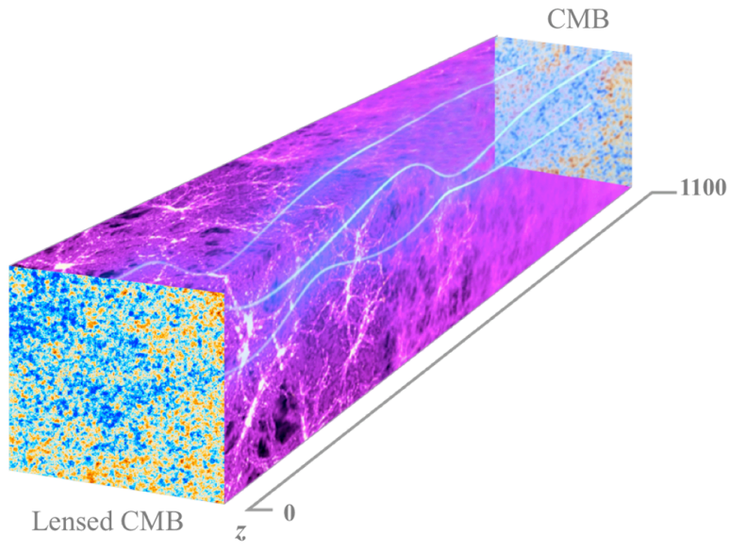

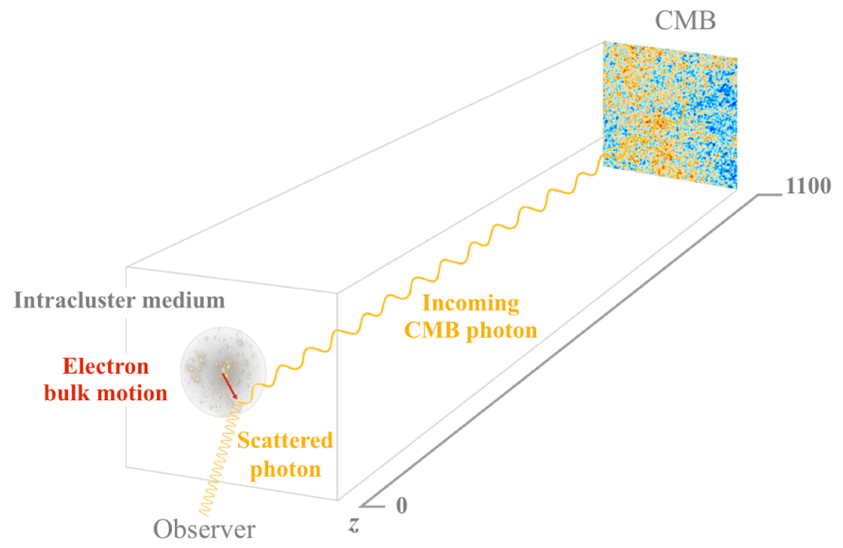

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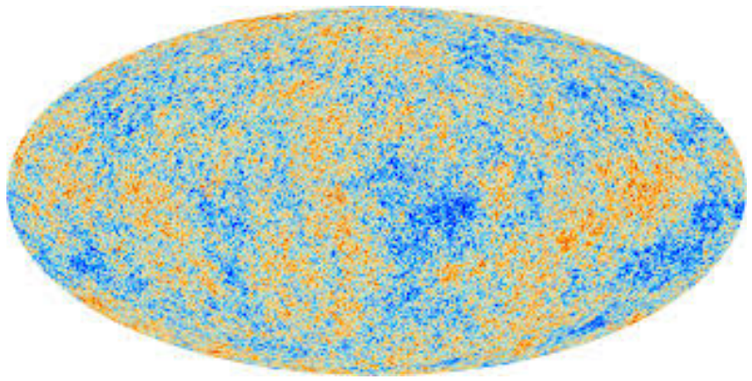

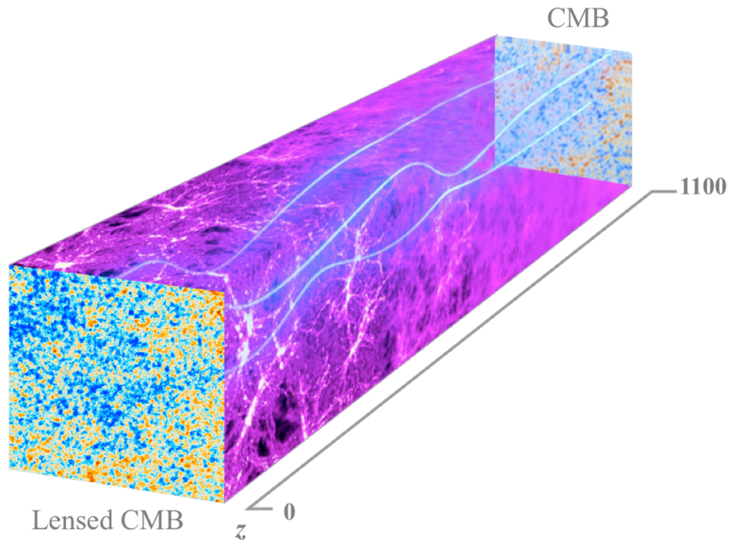

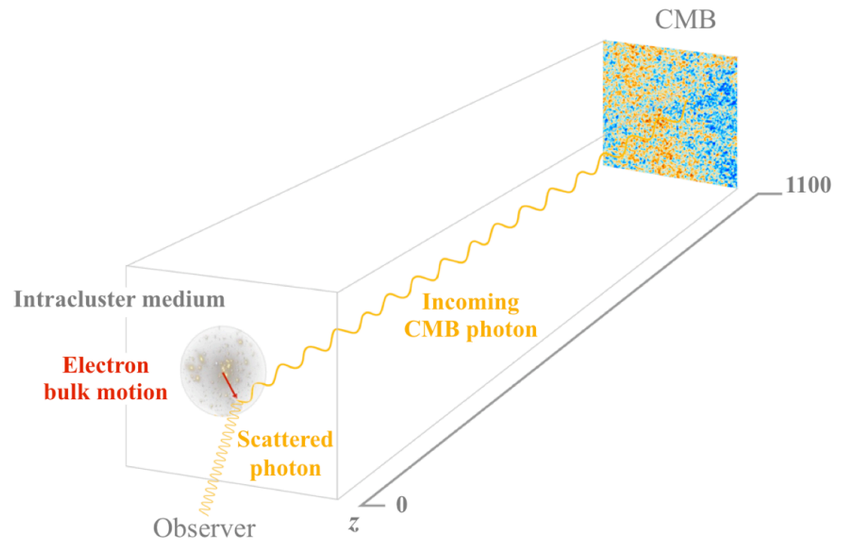

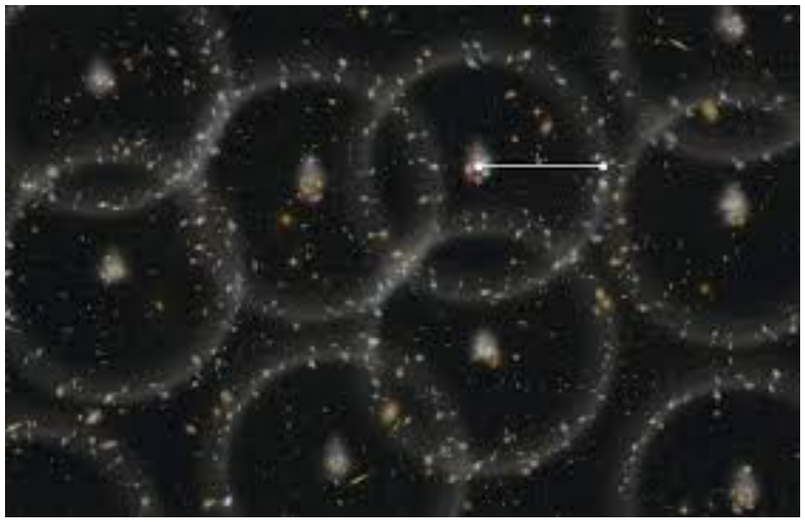

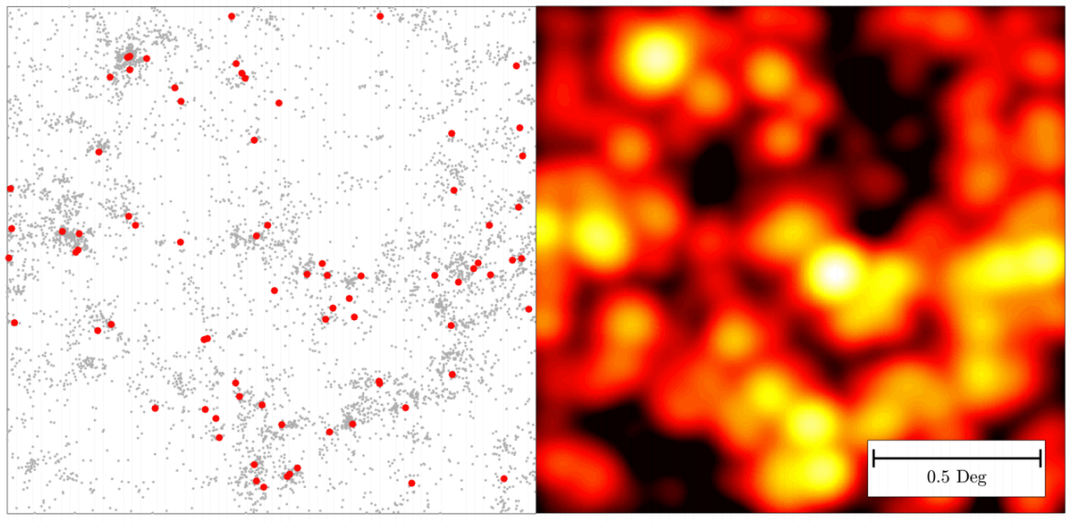

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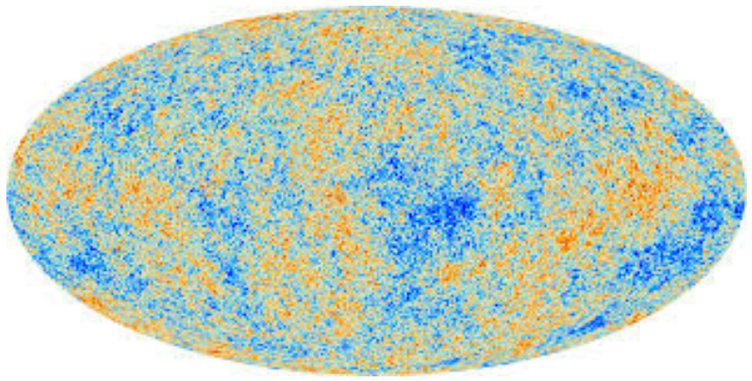

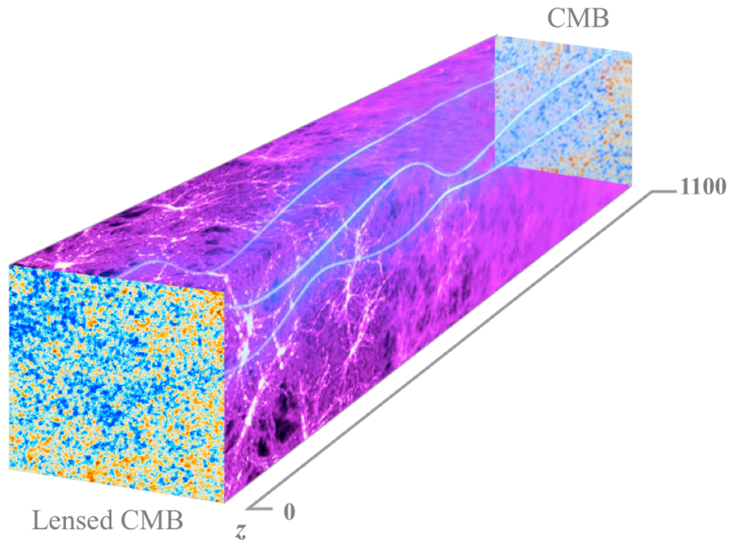

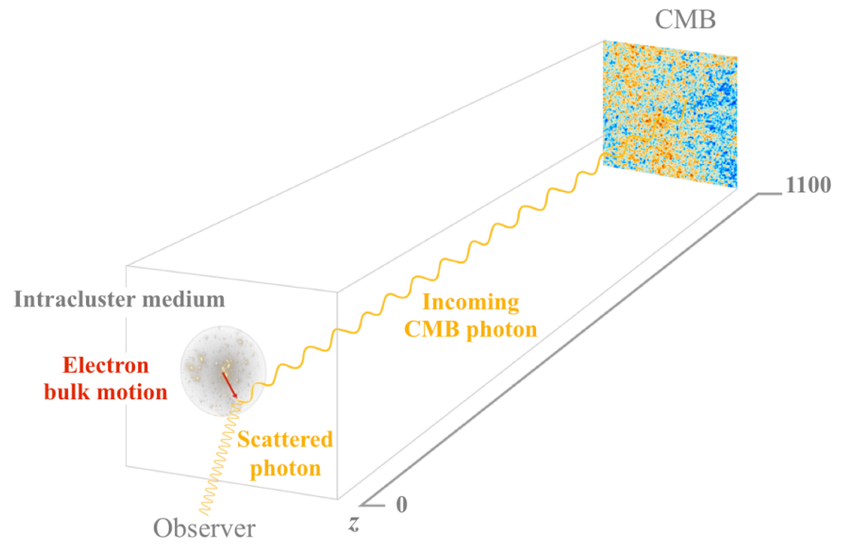

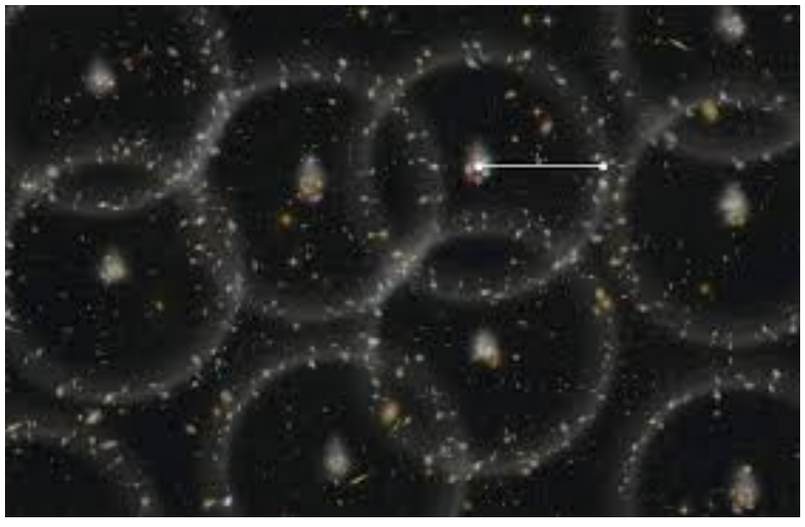

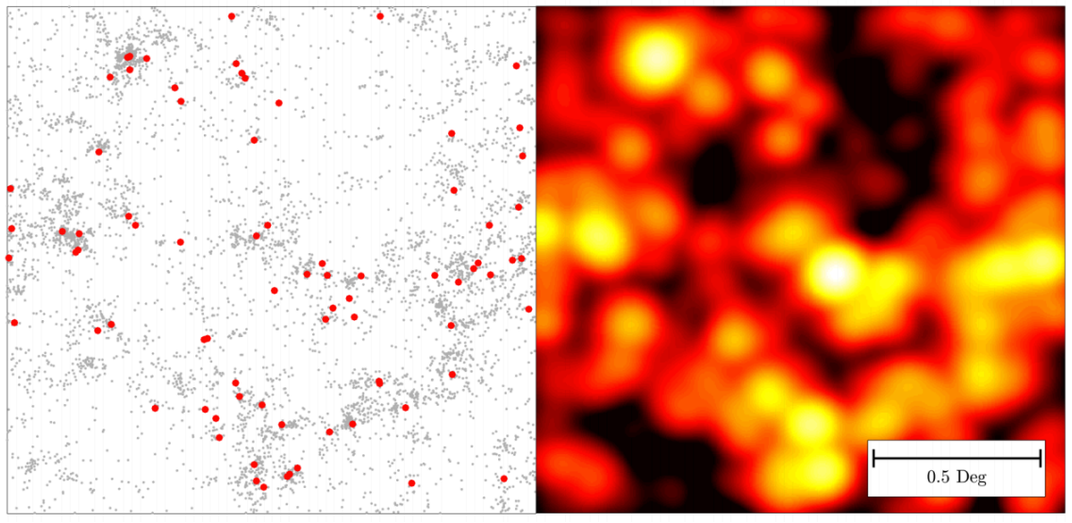

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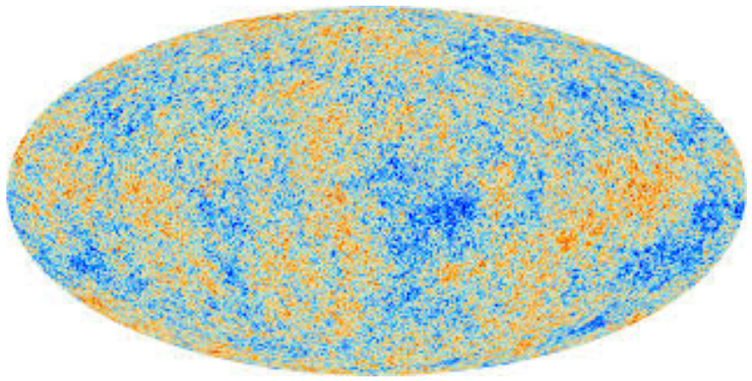
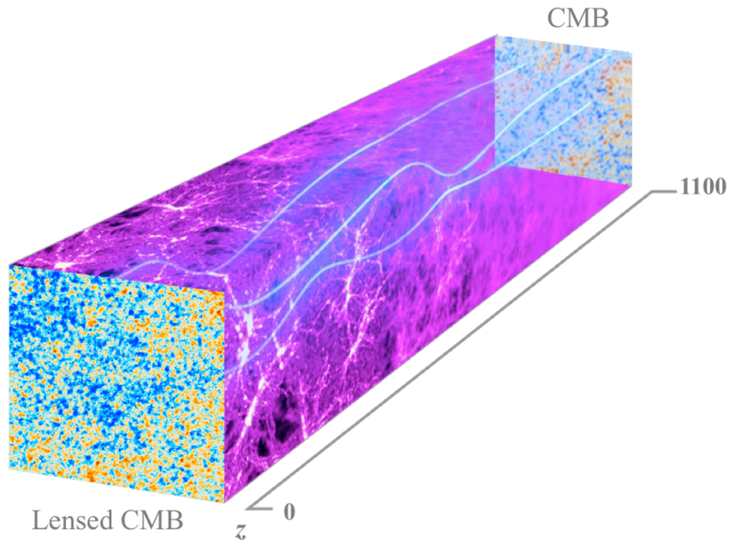
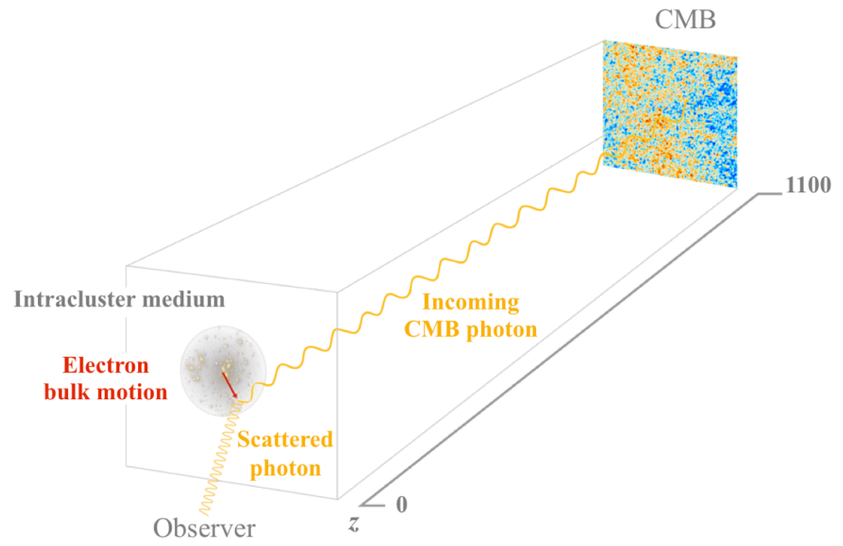
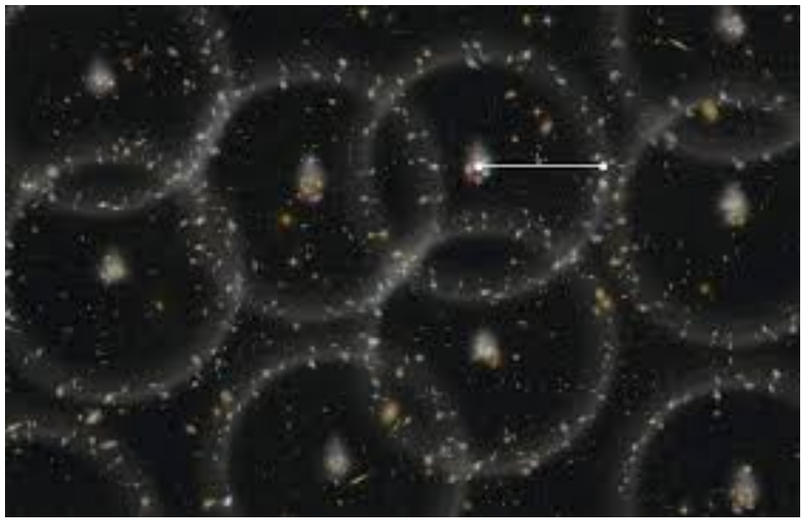
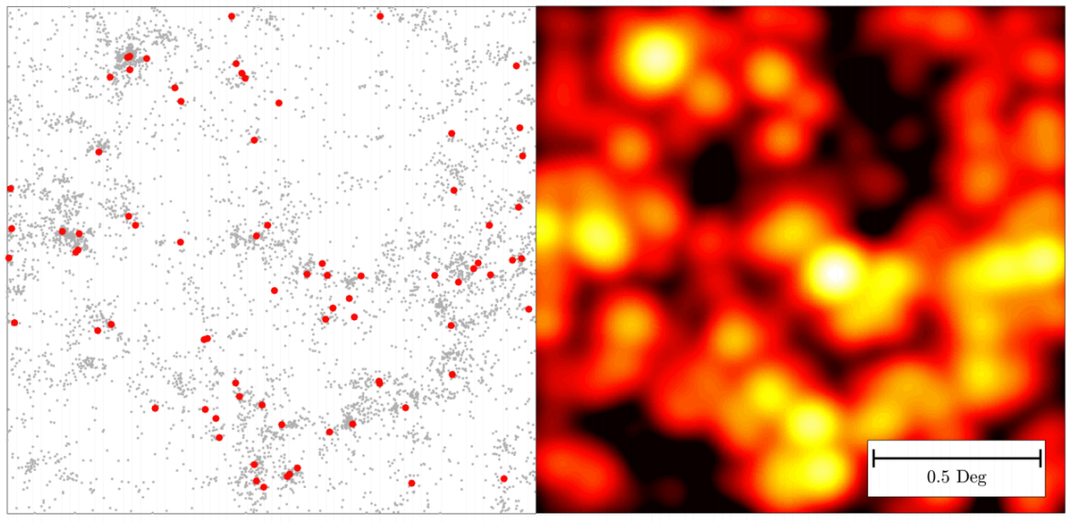


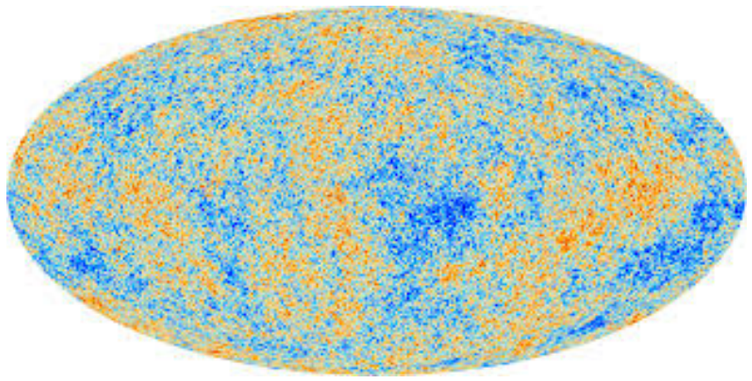


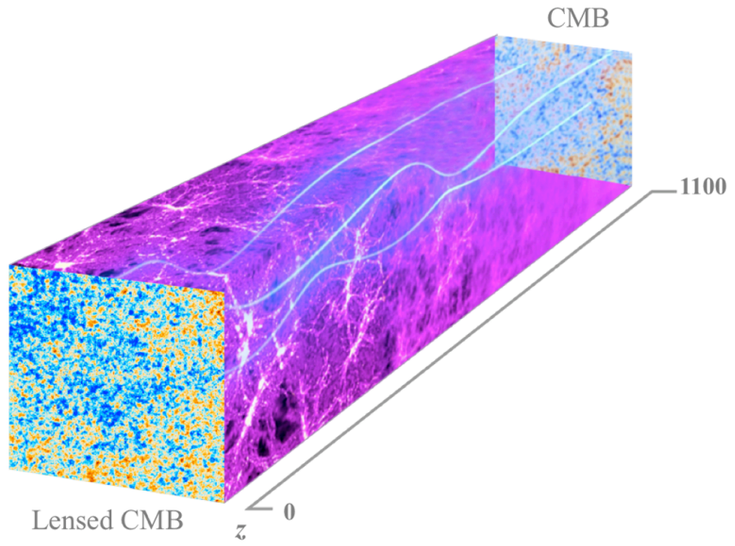


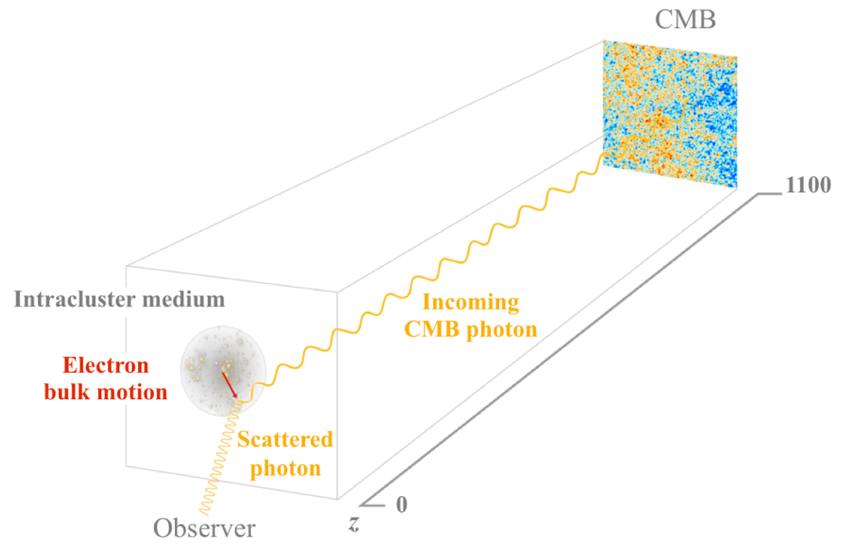


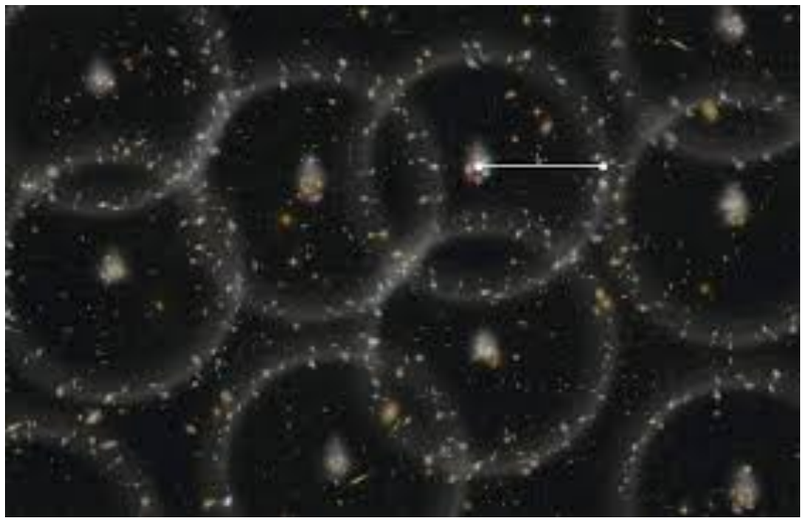


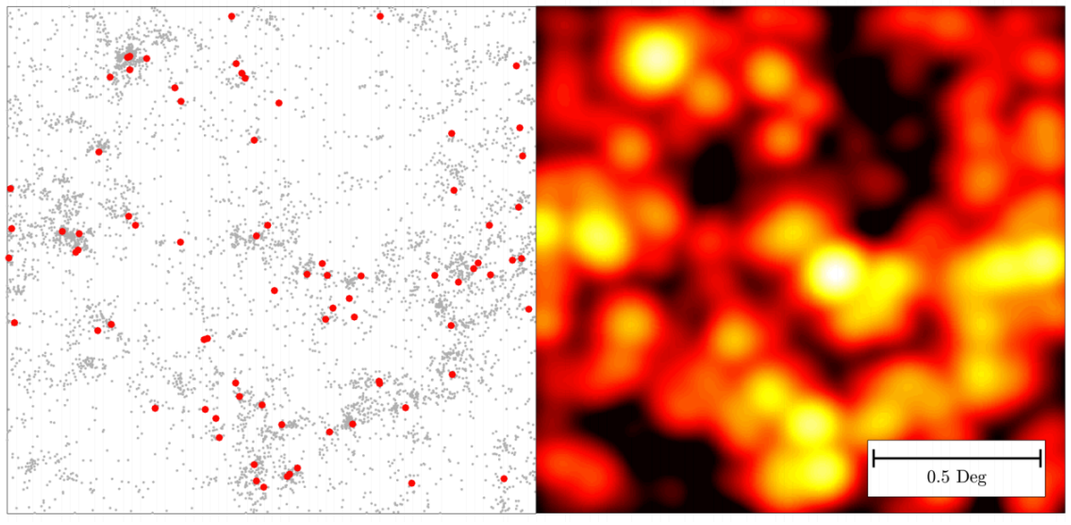
The Next Decade(s): Multi-Messenger Cosmology!

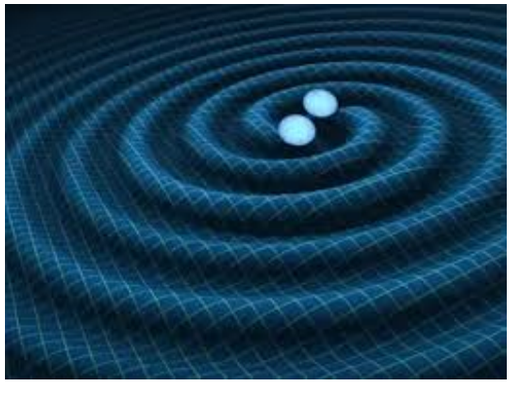




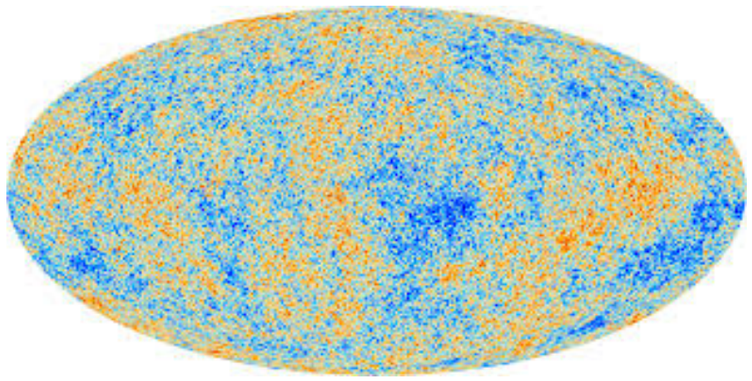


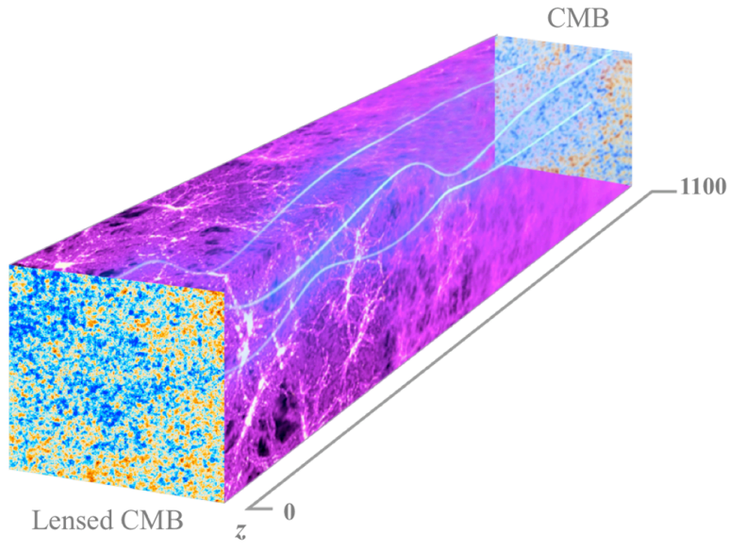


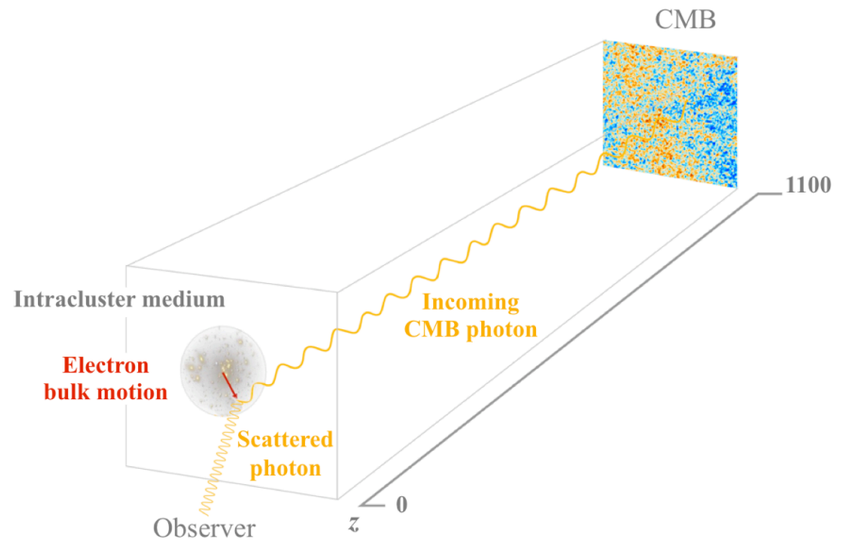


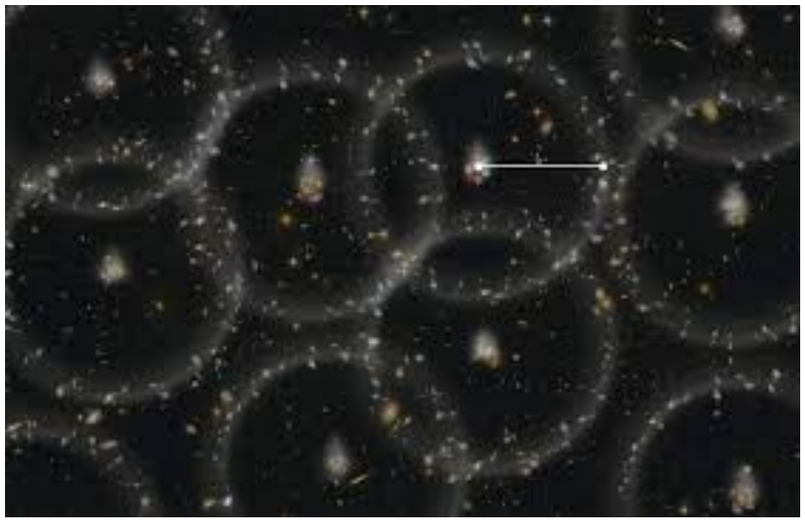


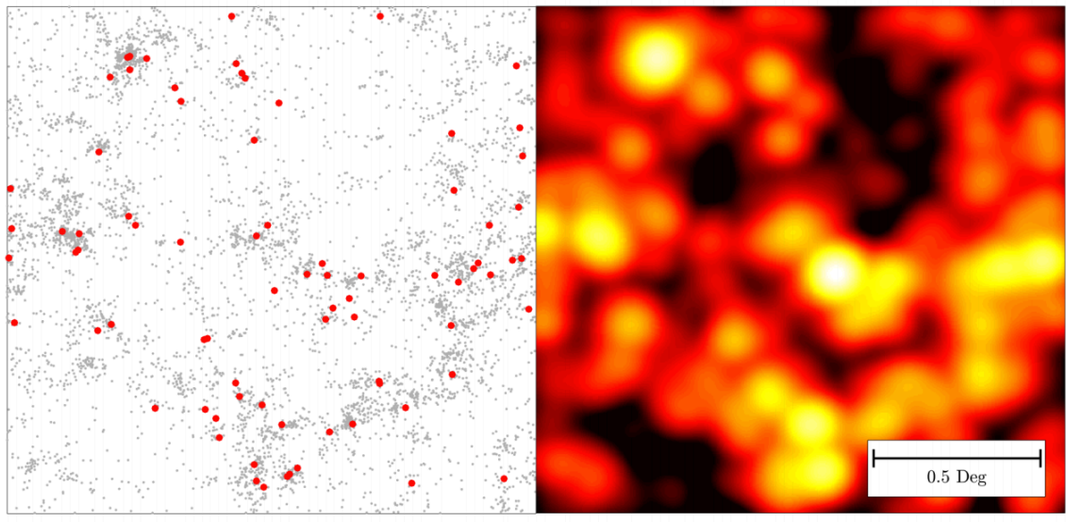
The Next Decade(s): Multi-Messenger Cosmology!

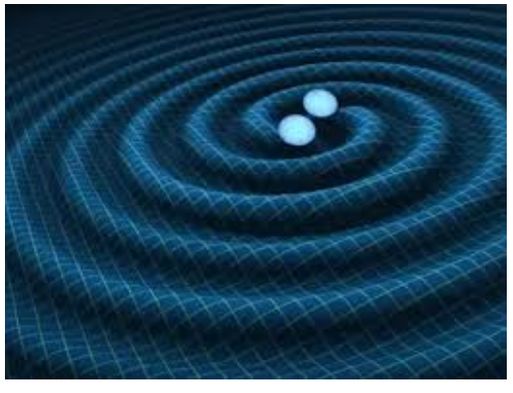


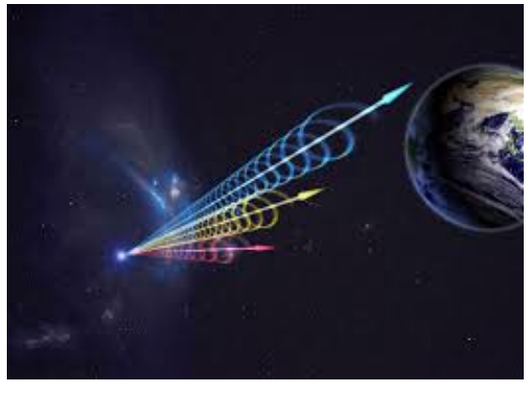












Thank You!

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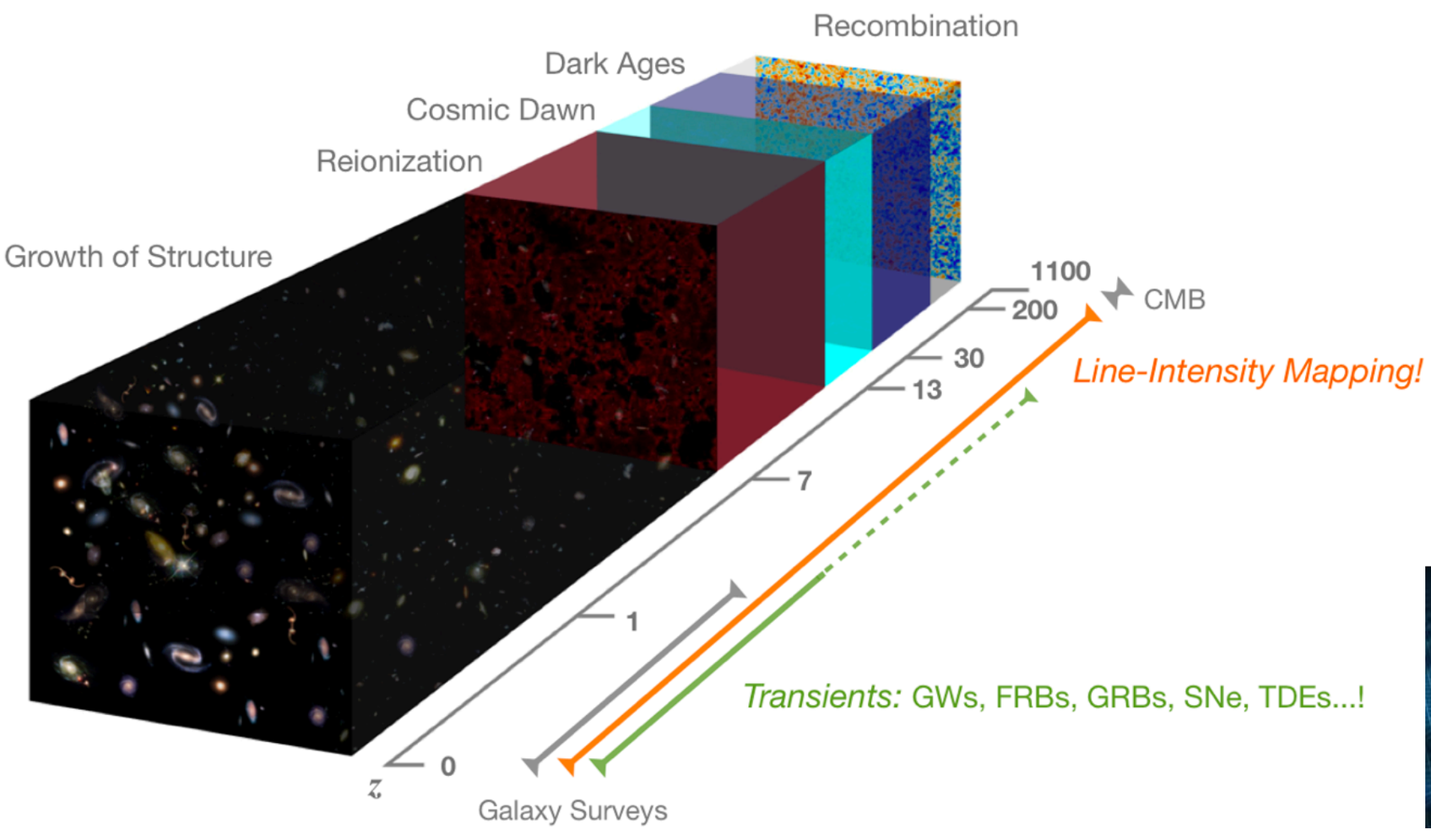
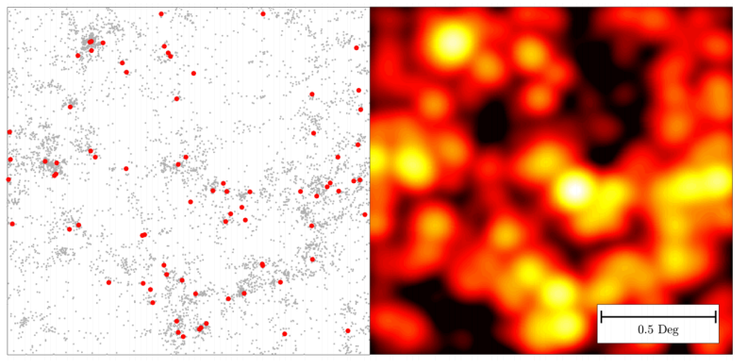
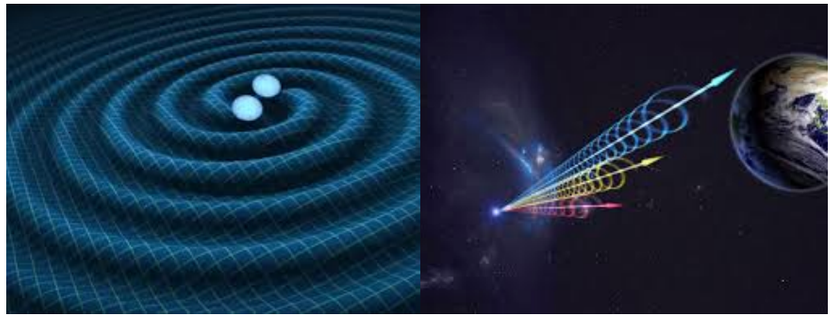
Ben-Gurion University







Collaborators: Y. Ali-Haïmoud, R. Barkana, J. L. Bernal, K. Boddy, P. Breysse, I. Cholis, C. Creque-Sarbinowski, H. Gil-Marin, V. Gluscevic, Lingyuan Ji, D. Kaplan, M. Kamionkowski, J. Muñoz, V. Poulin & D. Sarkar