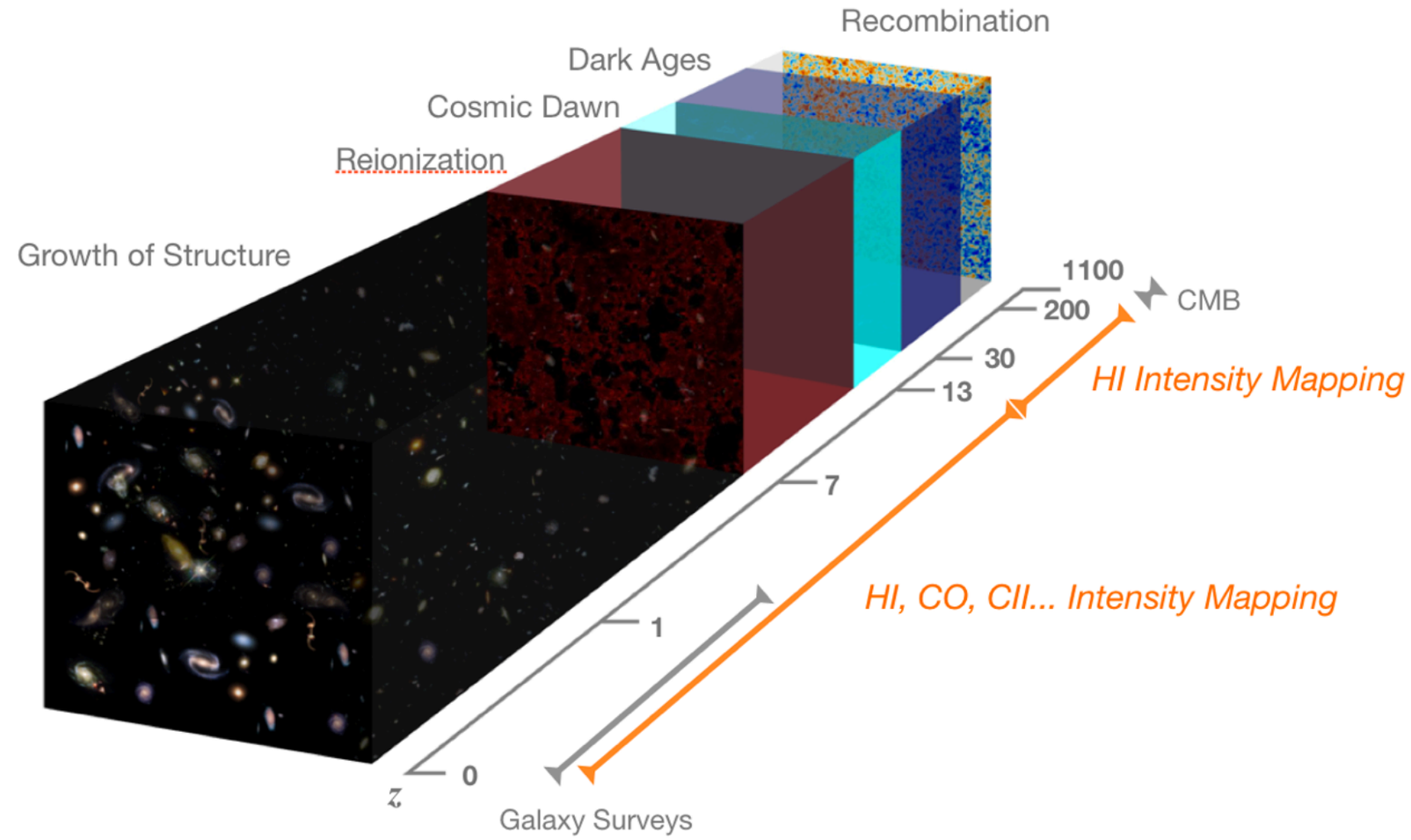
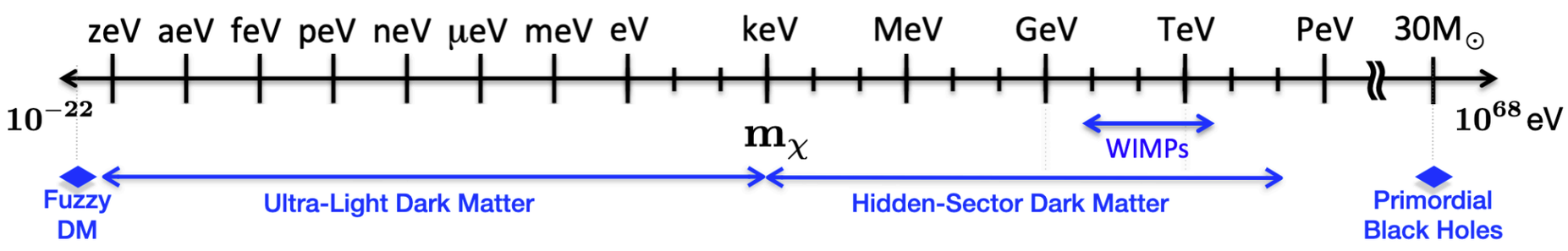
The 21cm signal from cosmic dawn as a unique probe of dark matter

Ely D. Kovetz
Ben-Gurion University



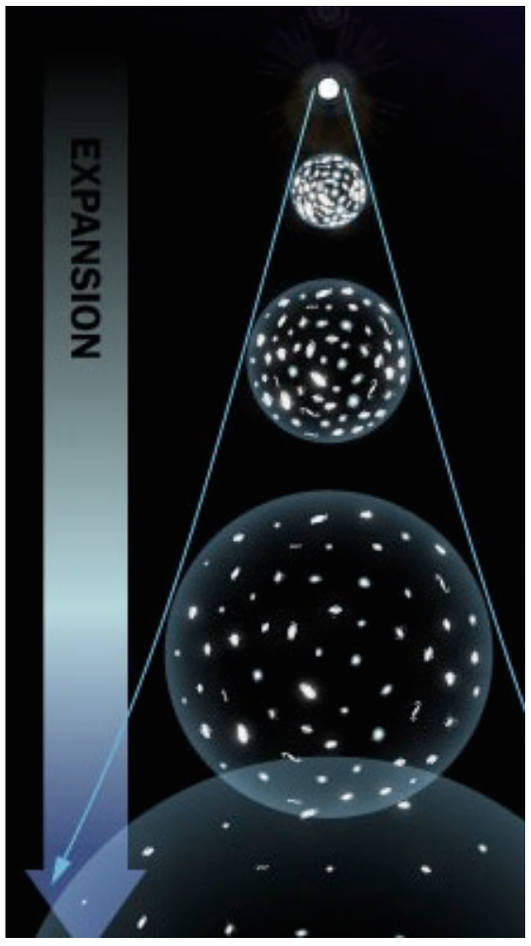
MPIK Colloquium
Feb 23rd, 2022



The Standard Cosmological Model

The Standard Cosmological Model

Hot big bang



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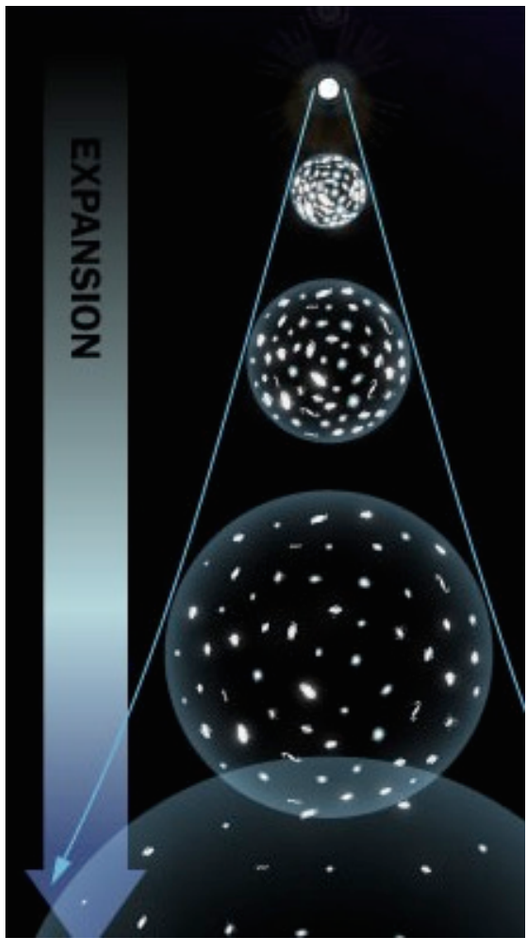

Gravitational instability

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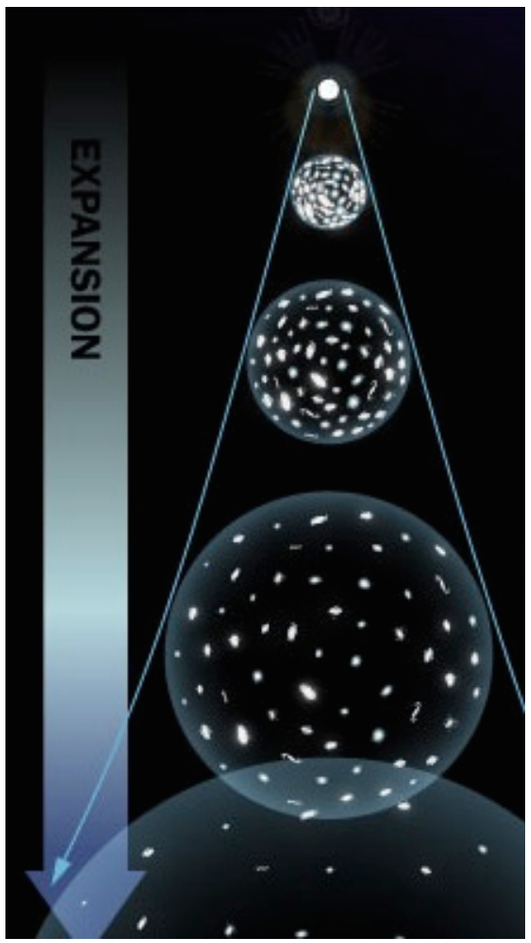

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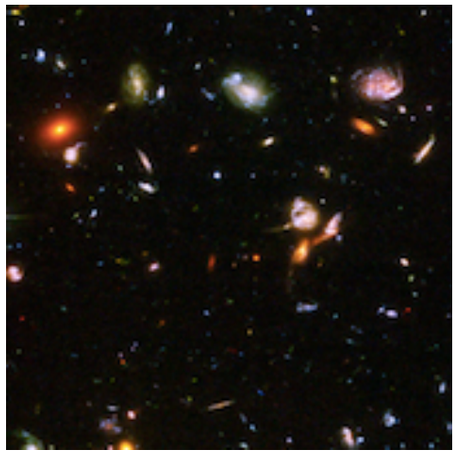

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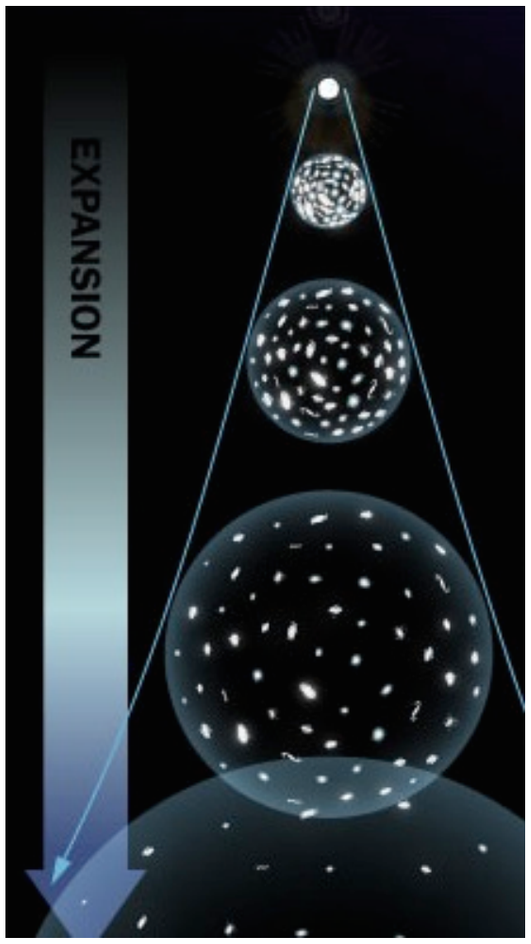

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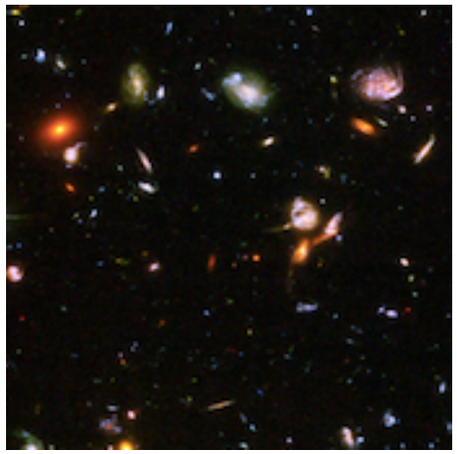

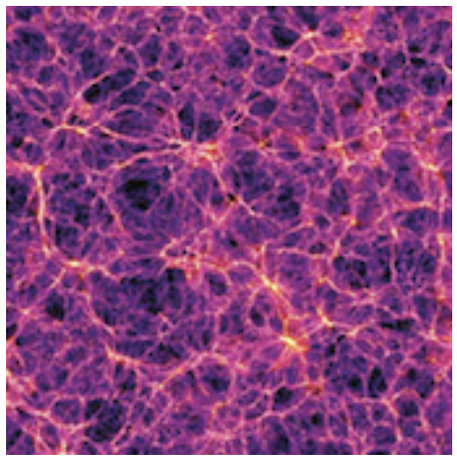

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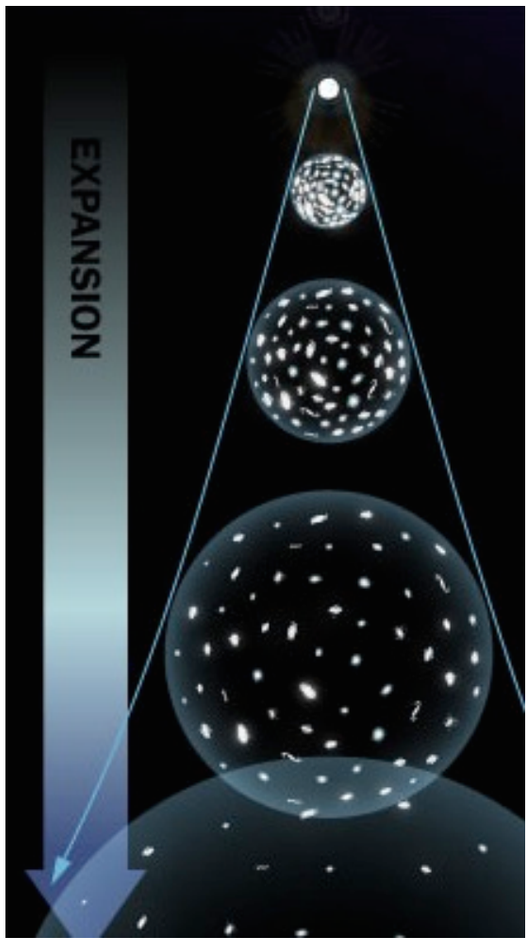

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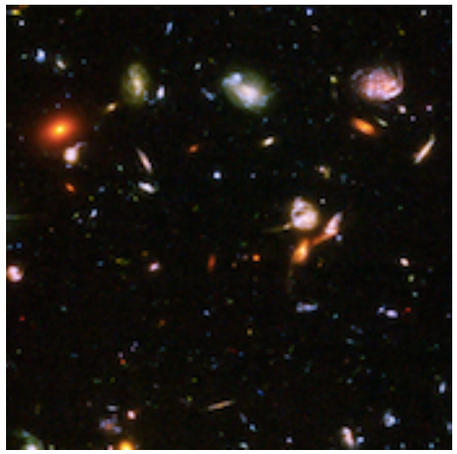

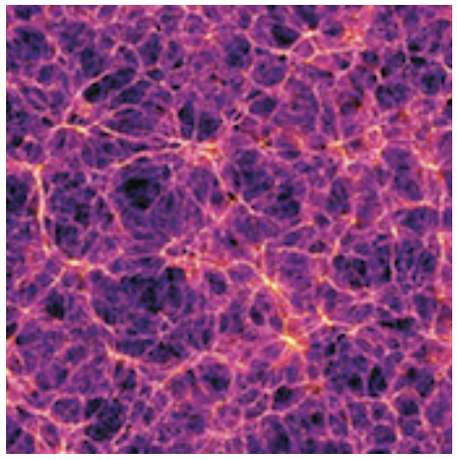

Inflation

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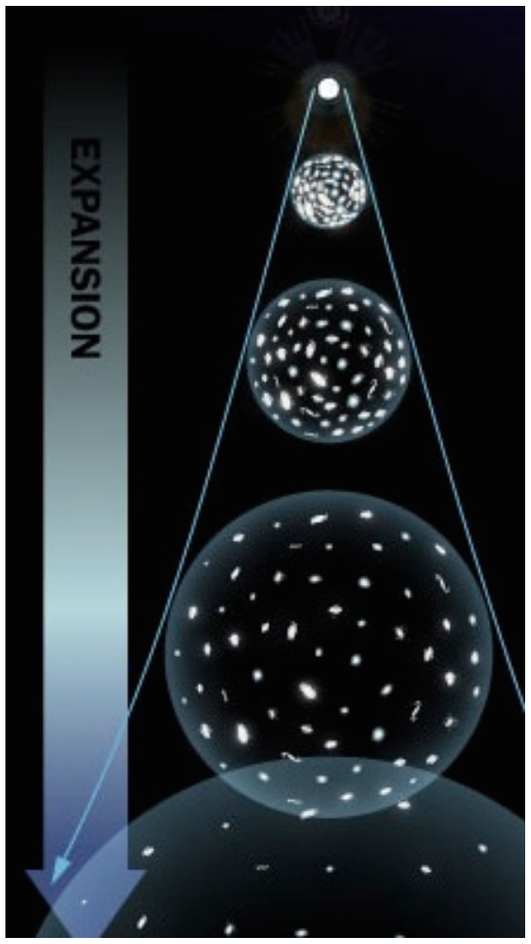

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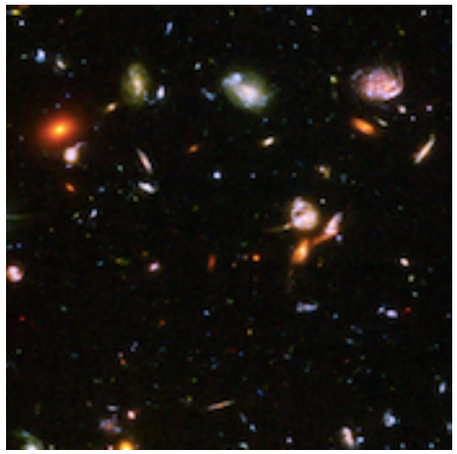

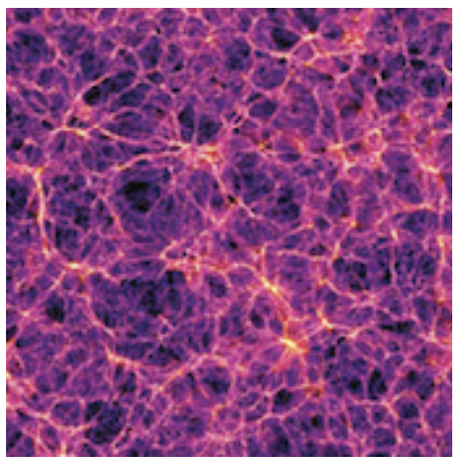

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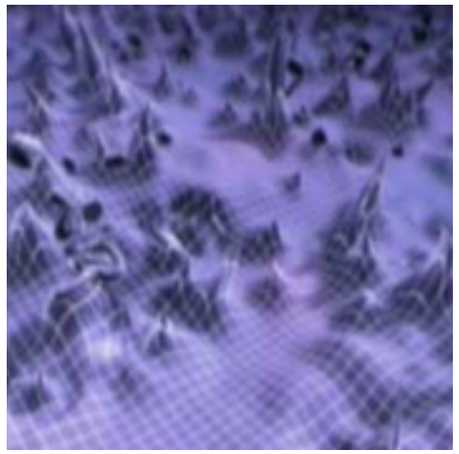

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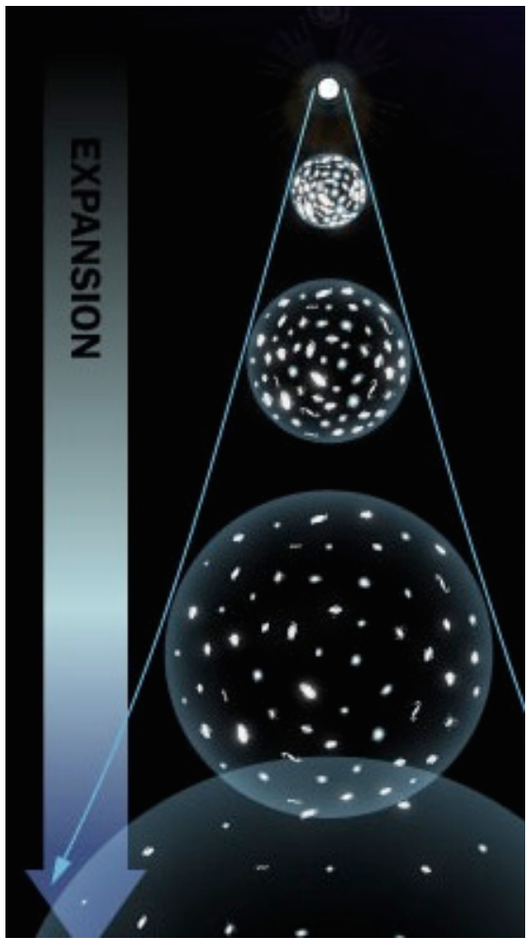

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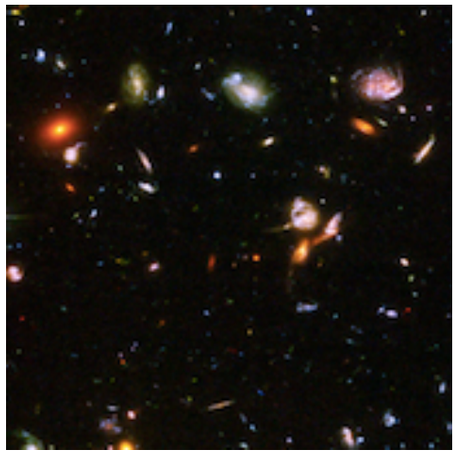

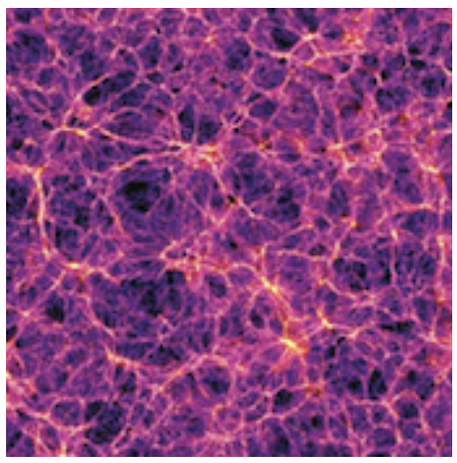

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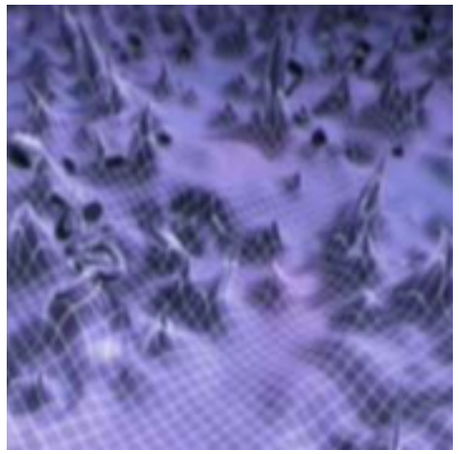

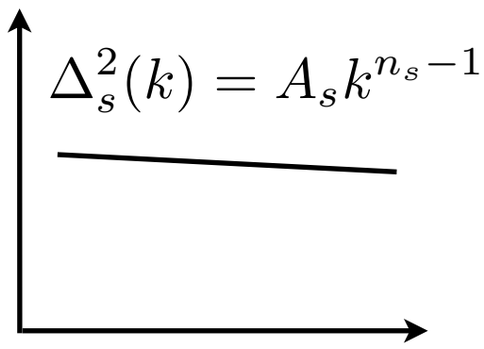

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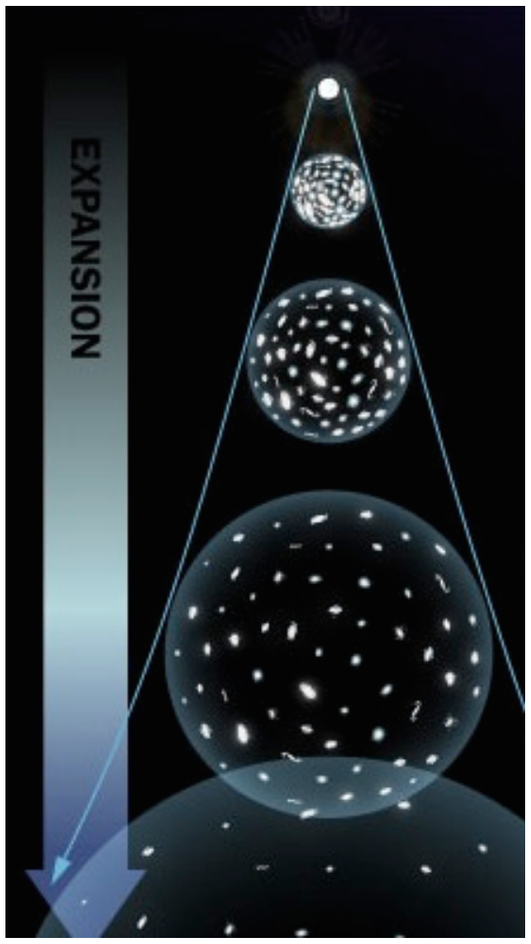

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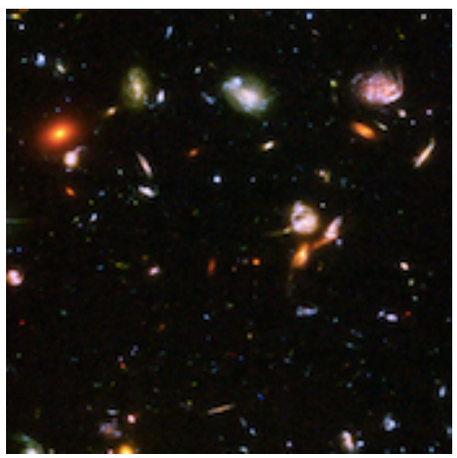

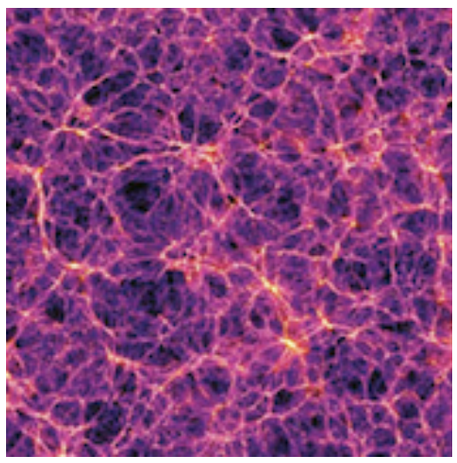

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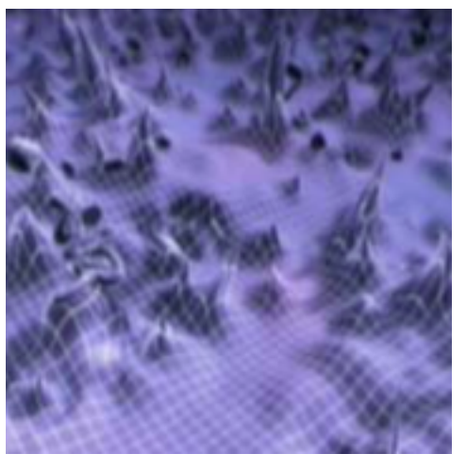
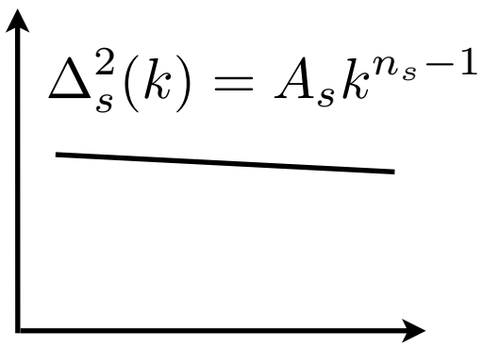
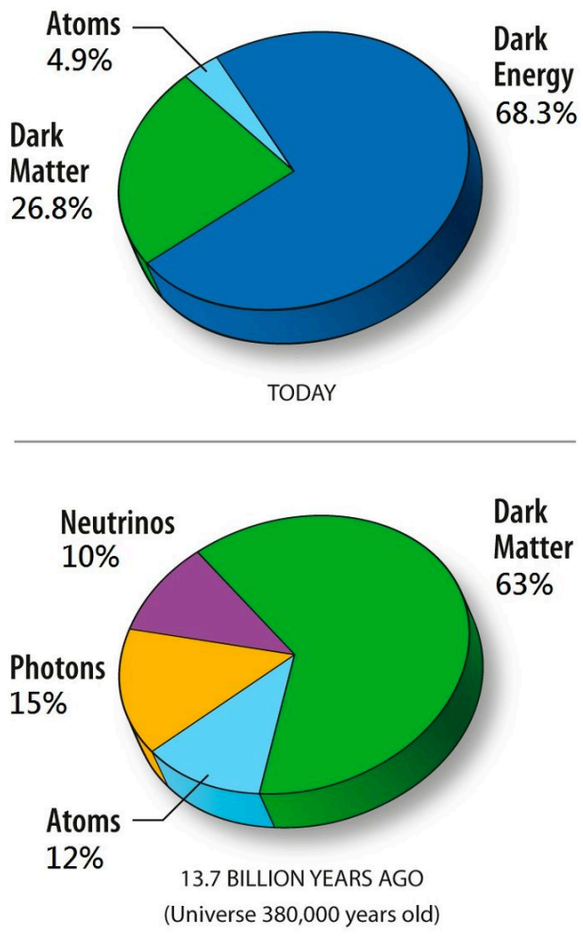




ΛCDM



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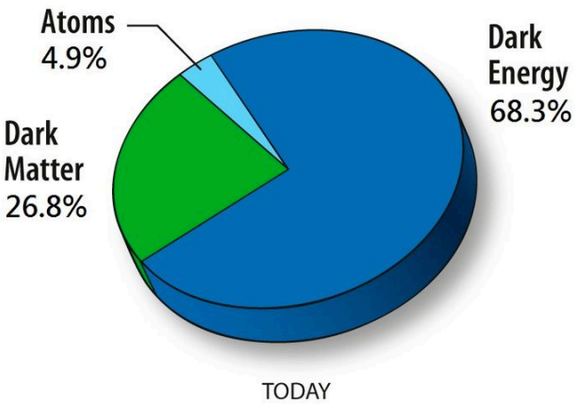

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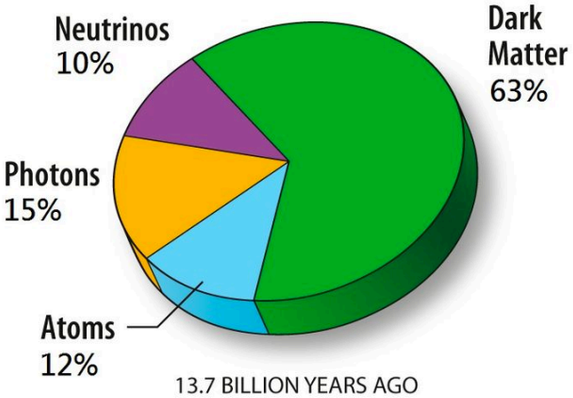

13.7 BILLION YEARS AGO
(Universe 380,000 years old)

The Standard Cosmological Model

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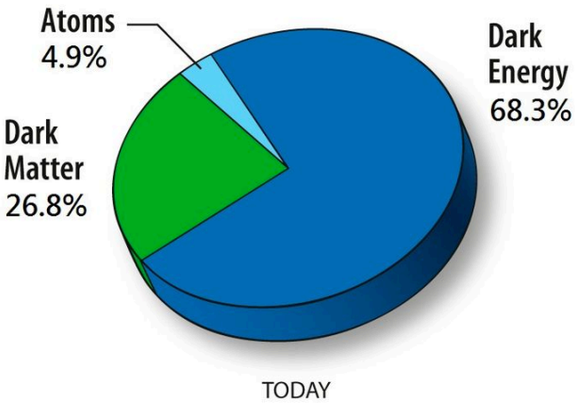

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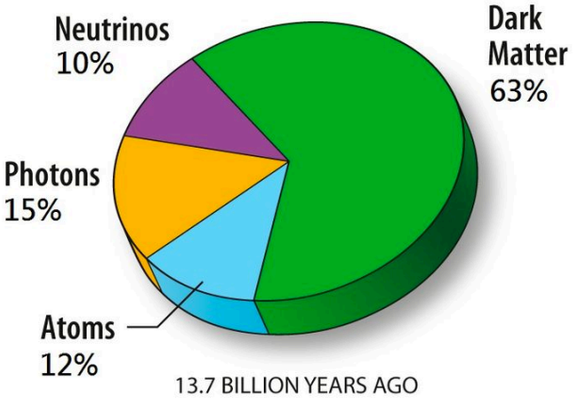

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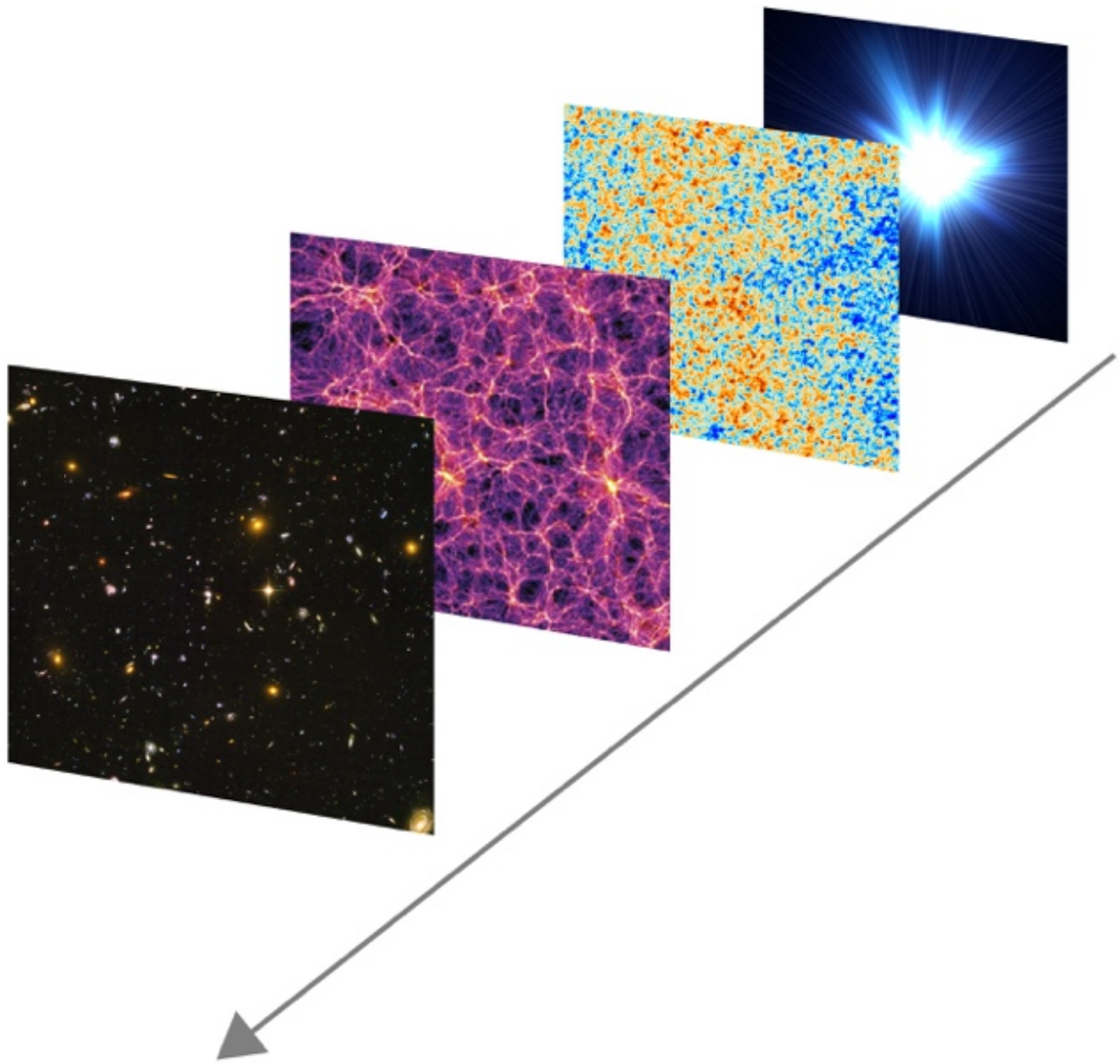

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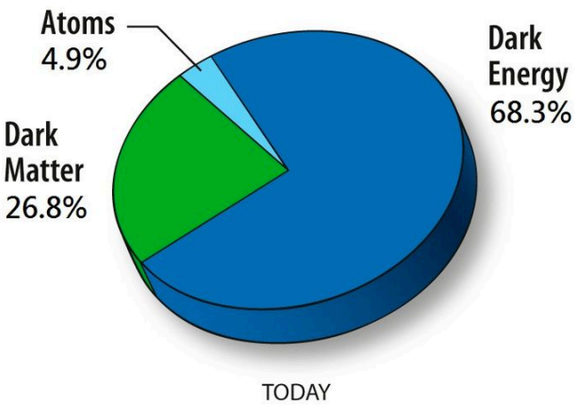

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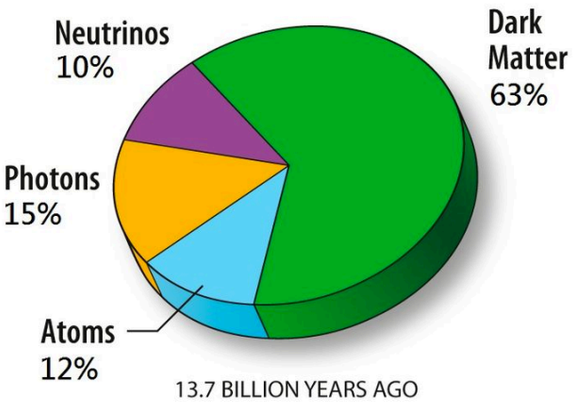

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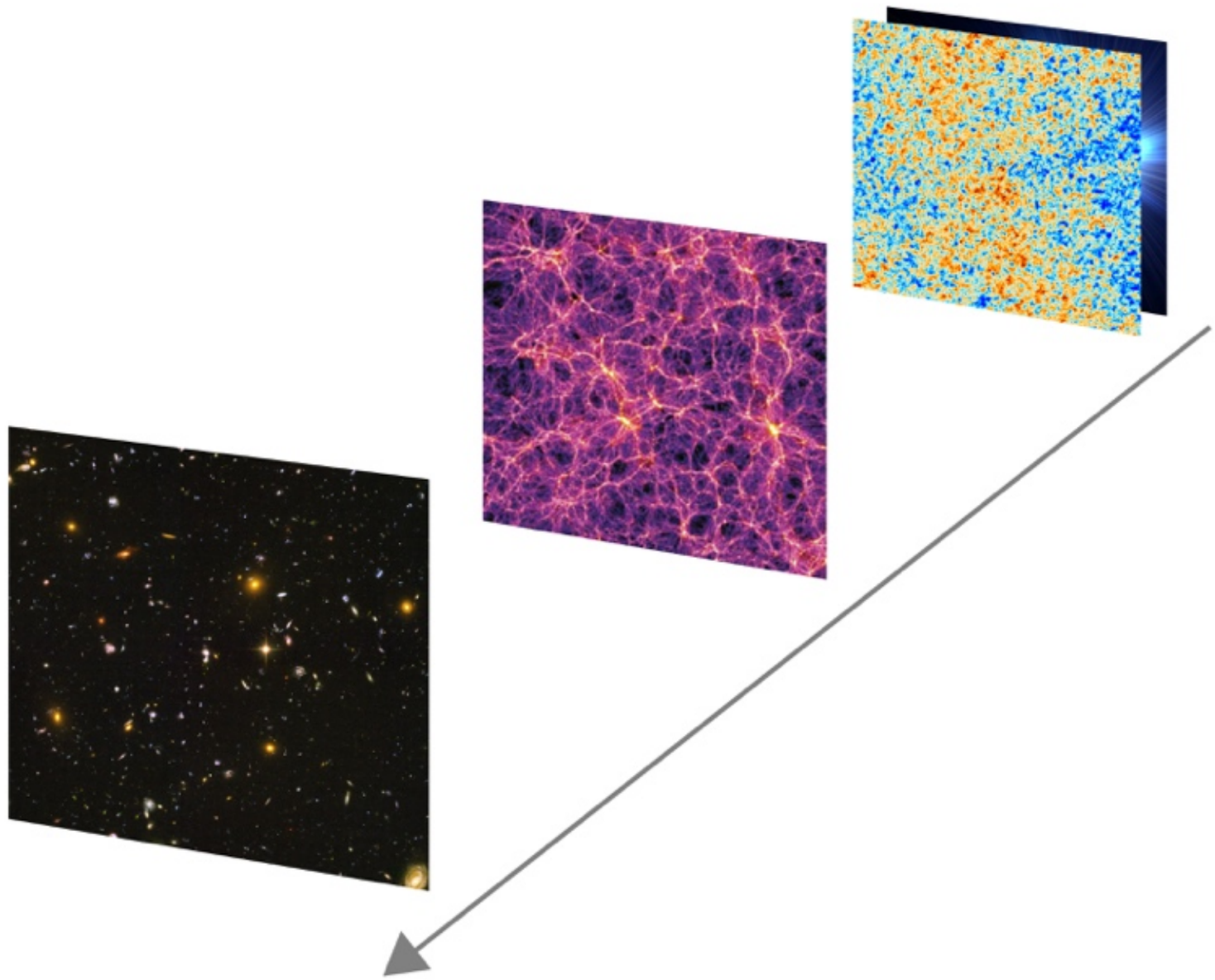

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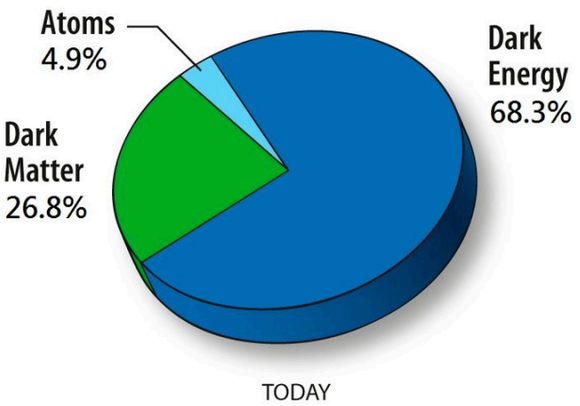

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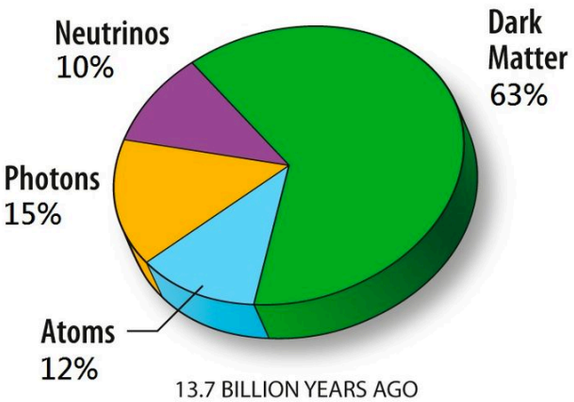

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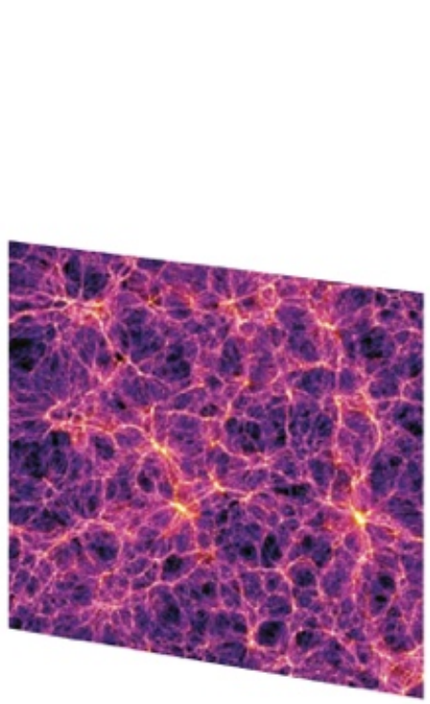

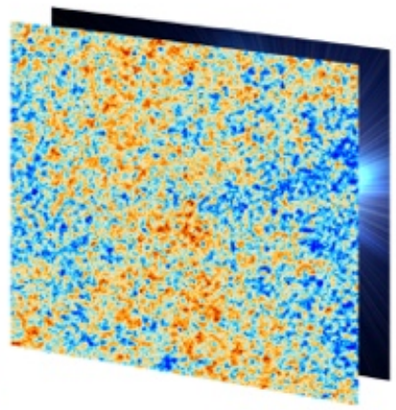

CMB

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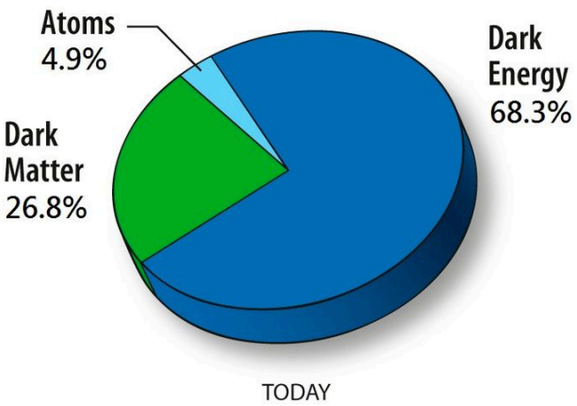
ΛCDM



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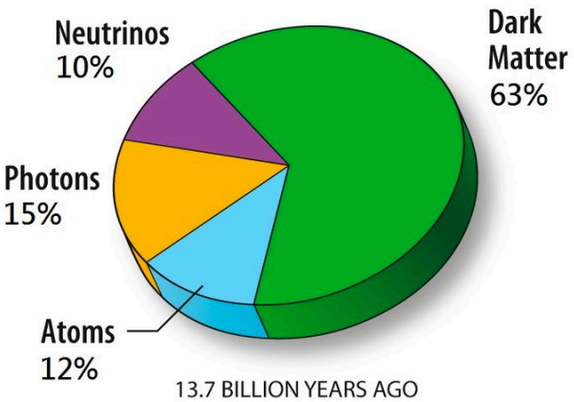

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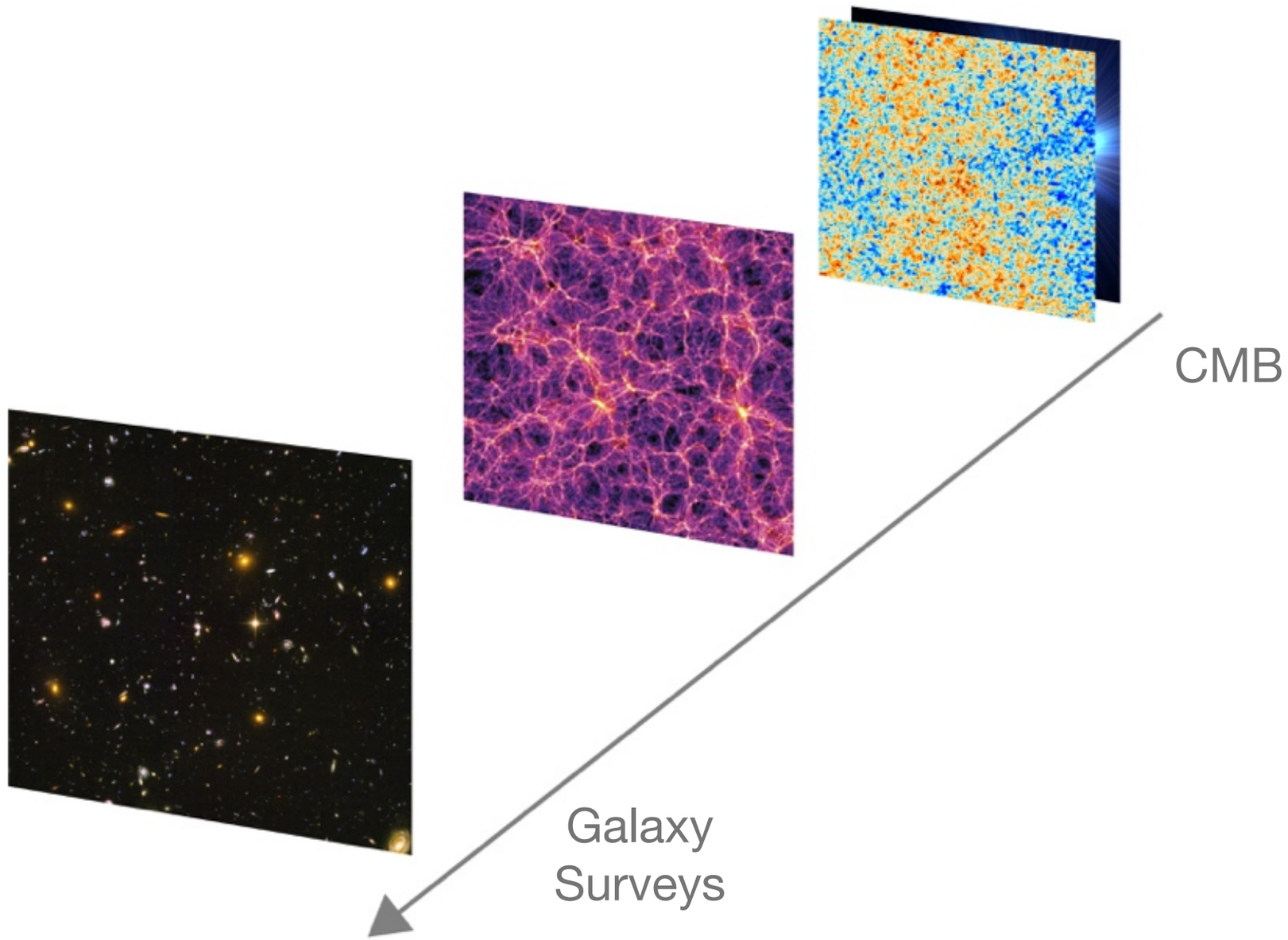

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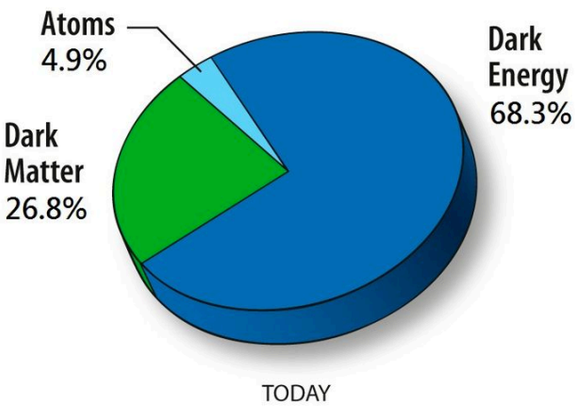

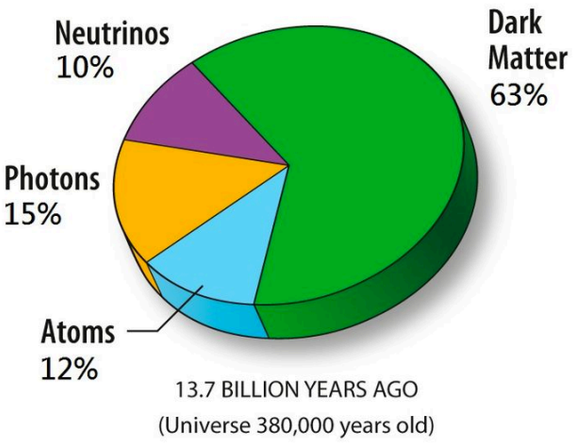

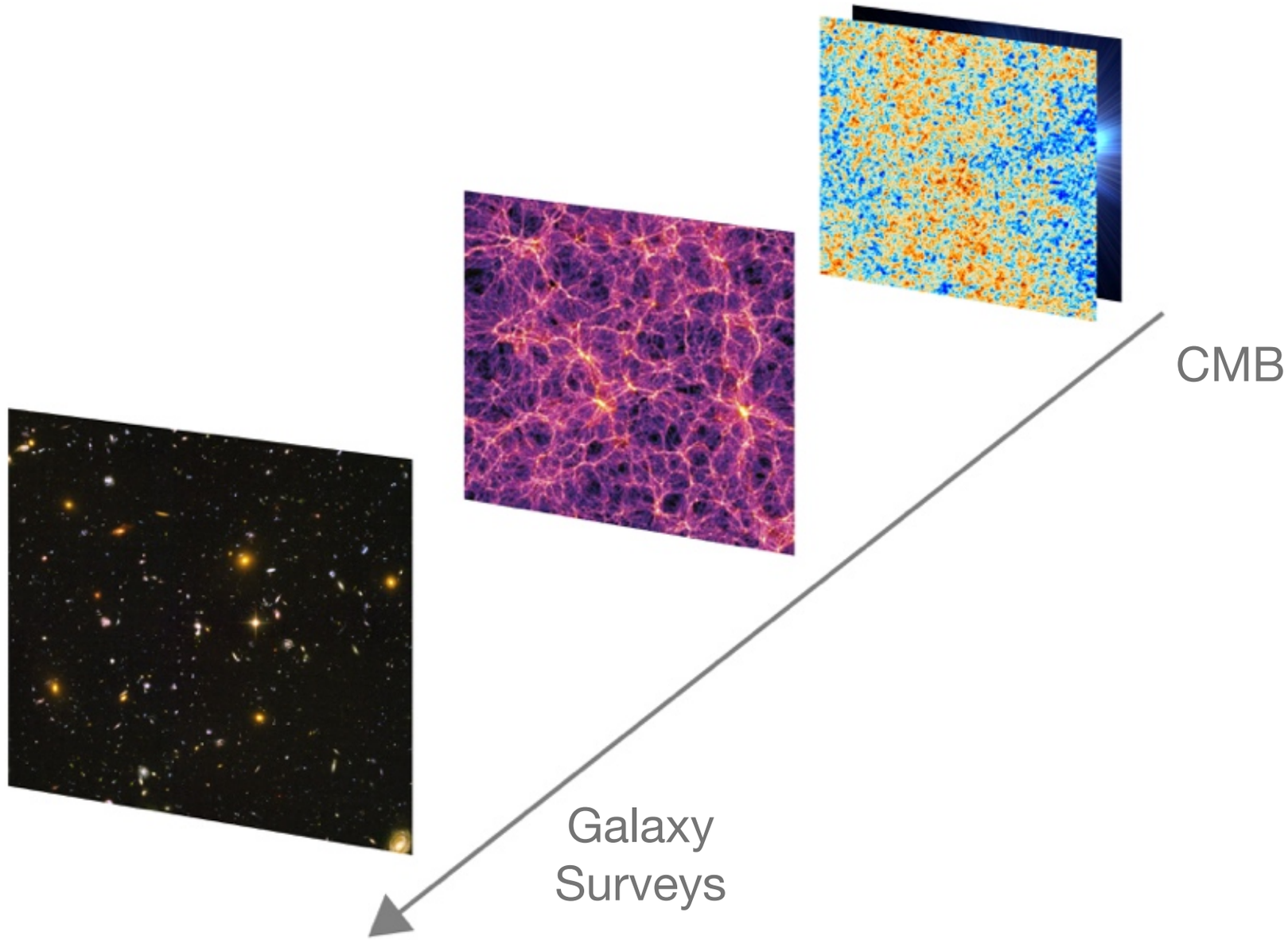

Amazingly: just six parameters are enough to fit all existing data.

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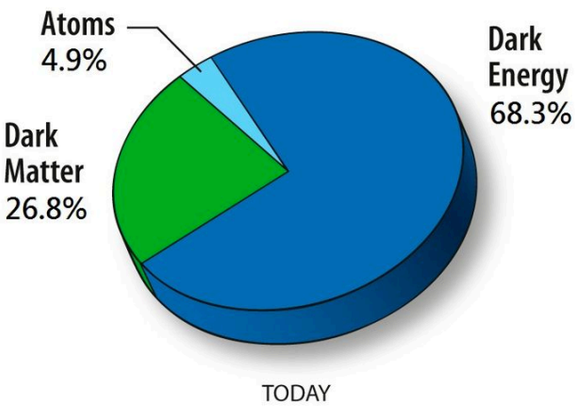

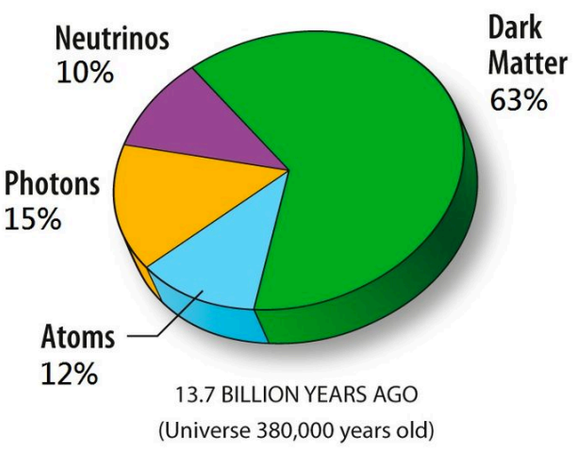

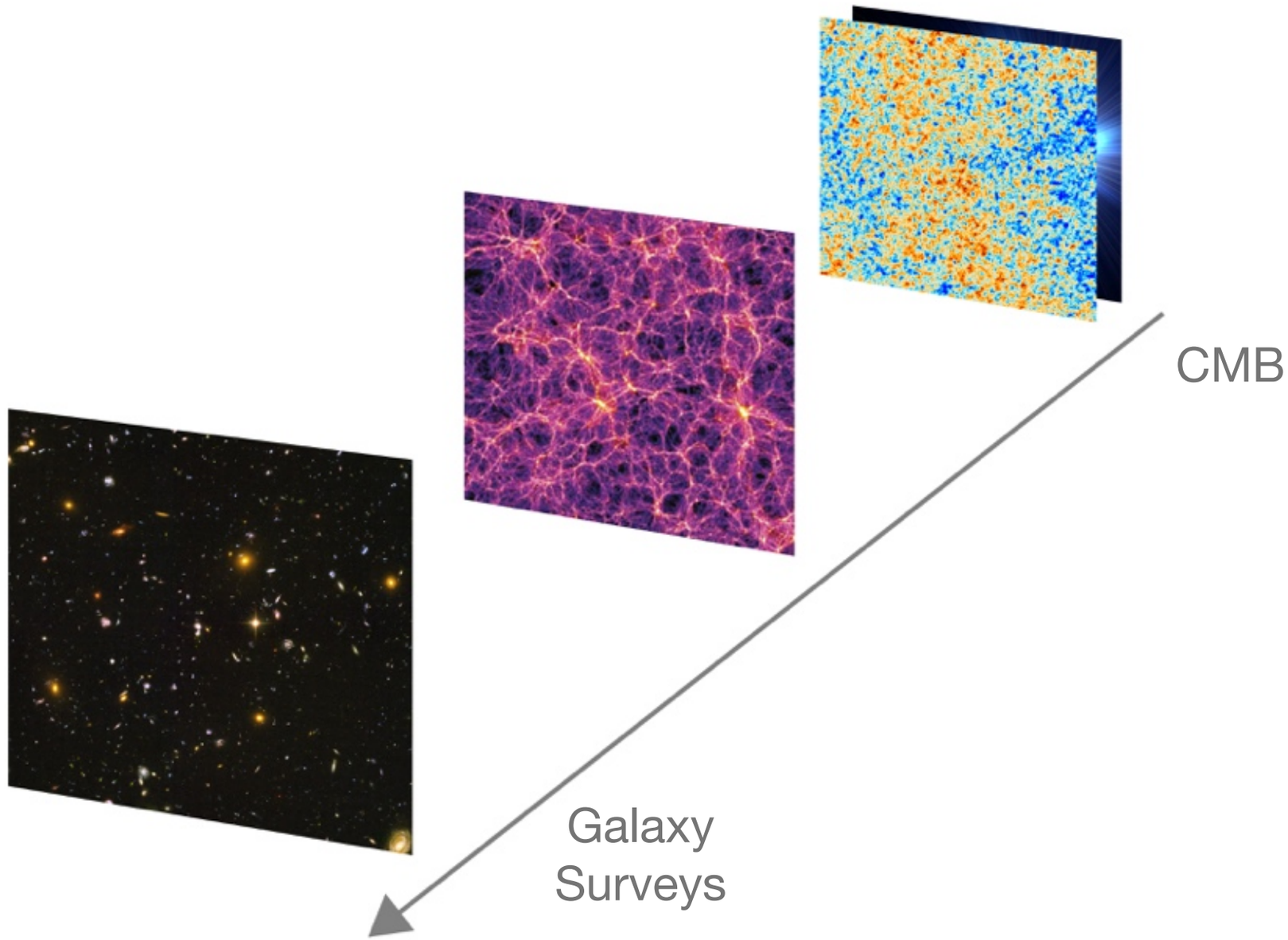

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H_0	τ	A_s	n_s	$\Omega_{\rm b}$	$\Omega_{\rm CDM}$

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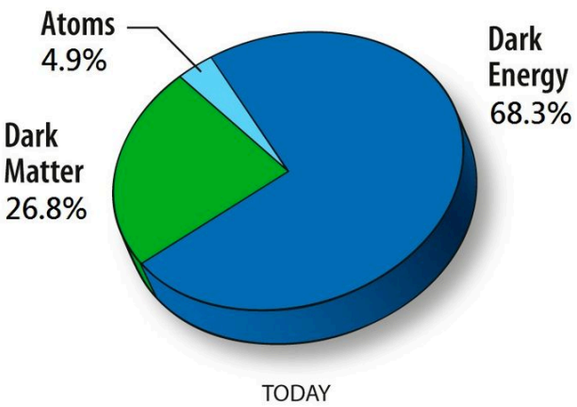
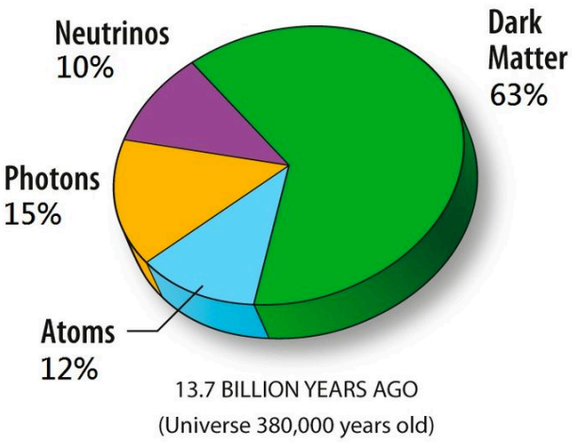
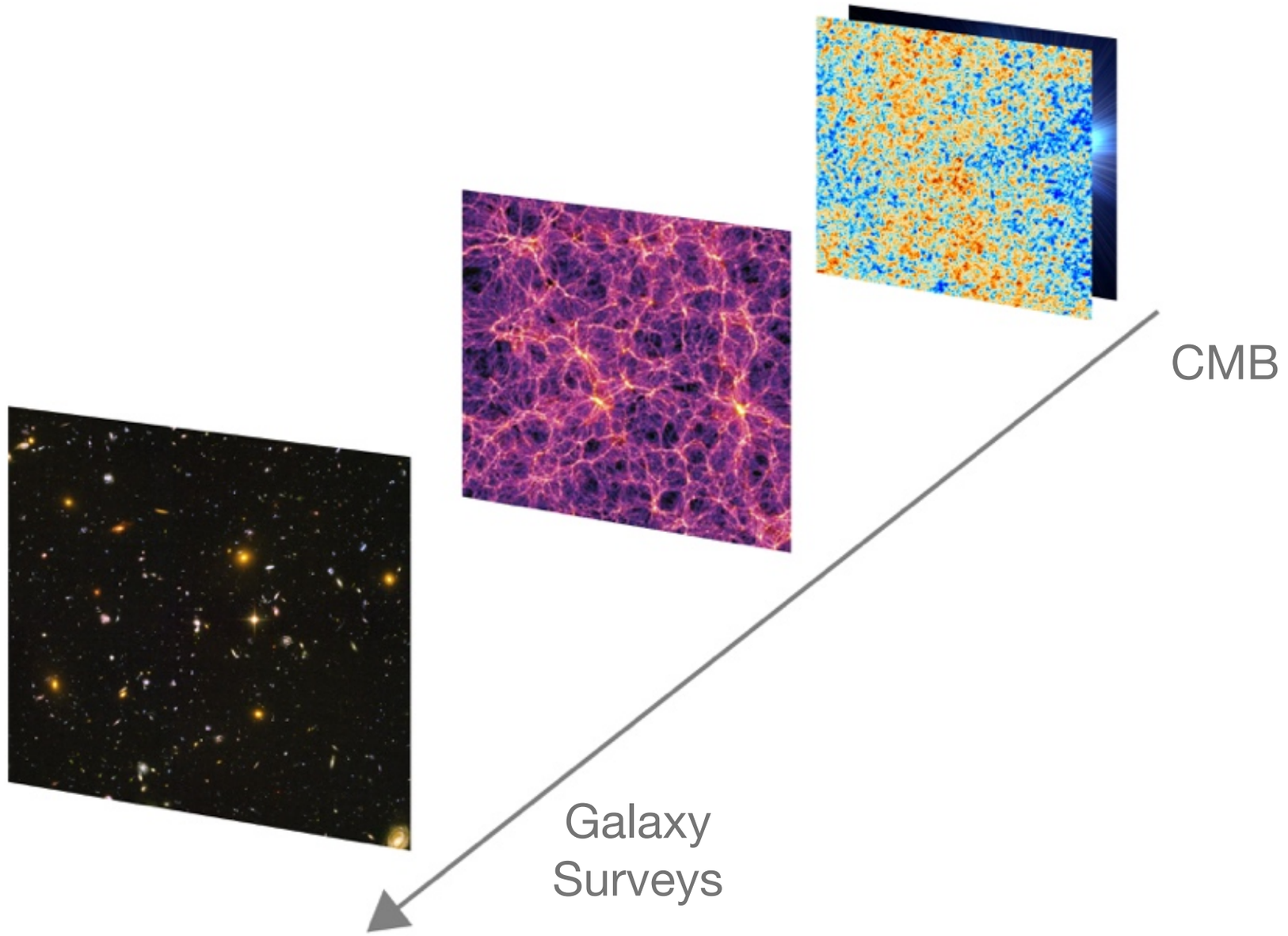
ΛCDM







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H_0	τ	A_s	n_s	$\Omega_{\rm b}$	$\Omega_{\rm CDM}$

measured to a few percent uncertainty

Core Questions in Cosmology

Core Questions in Cosmology

ΛCDM

Core Questions in Cosmology

$$\Lambda CDM = \Lambda + CDM$$

Core Questions in Cosmology

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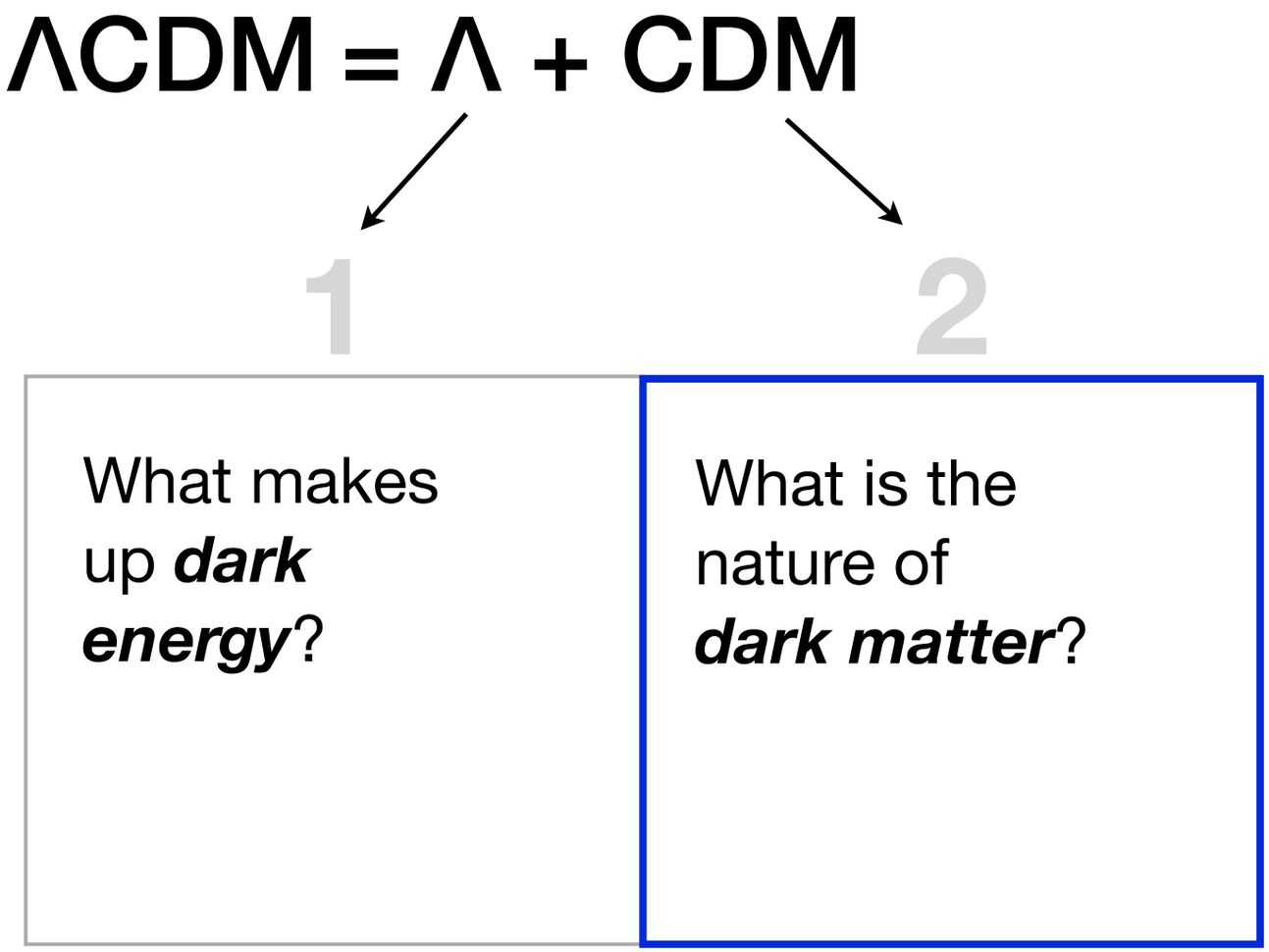
1

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

Core Questions in Cosmology



Core Questions in Cosmology

$\Lambda CDM = \Lambda + CDM$

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

Core Questions in Cosmology

ΛCDM = Λ + CDM

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Core Questions in Cosmology

ΛCDM = Λ + CDM

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

Where will new information come from?

The Observable Universe: Key Historical Epochs

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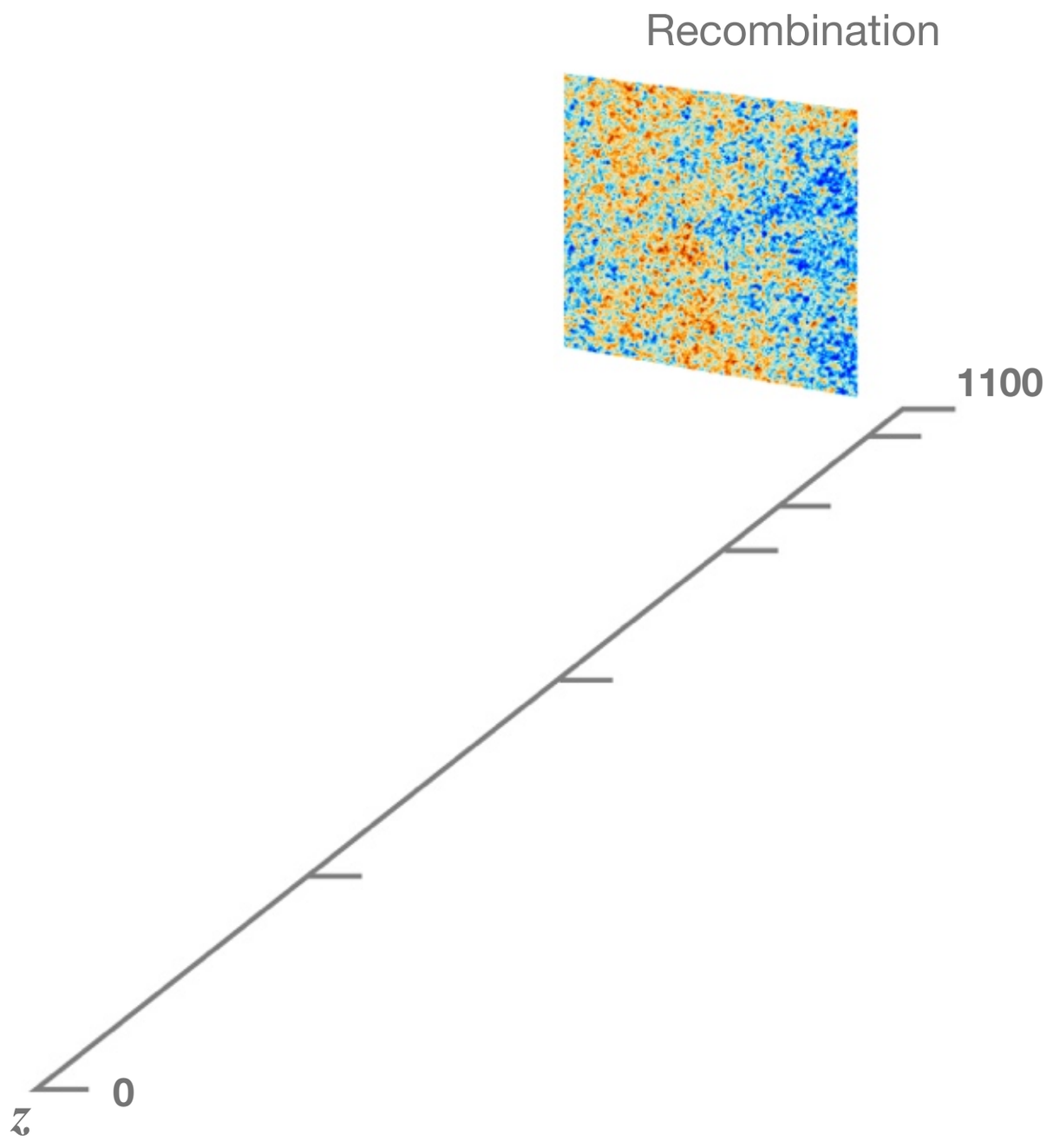
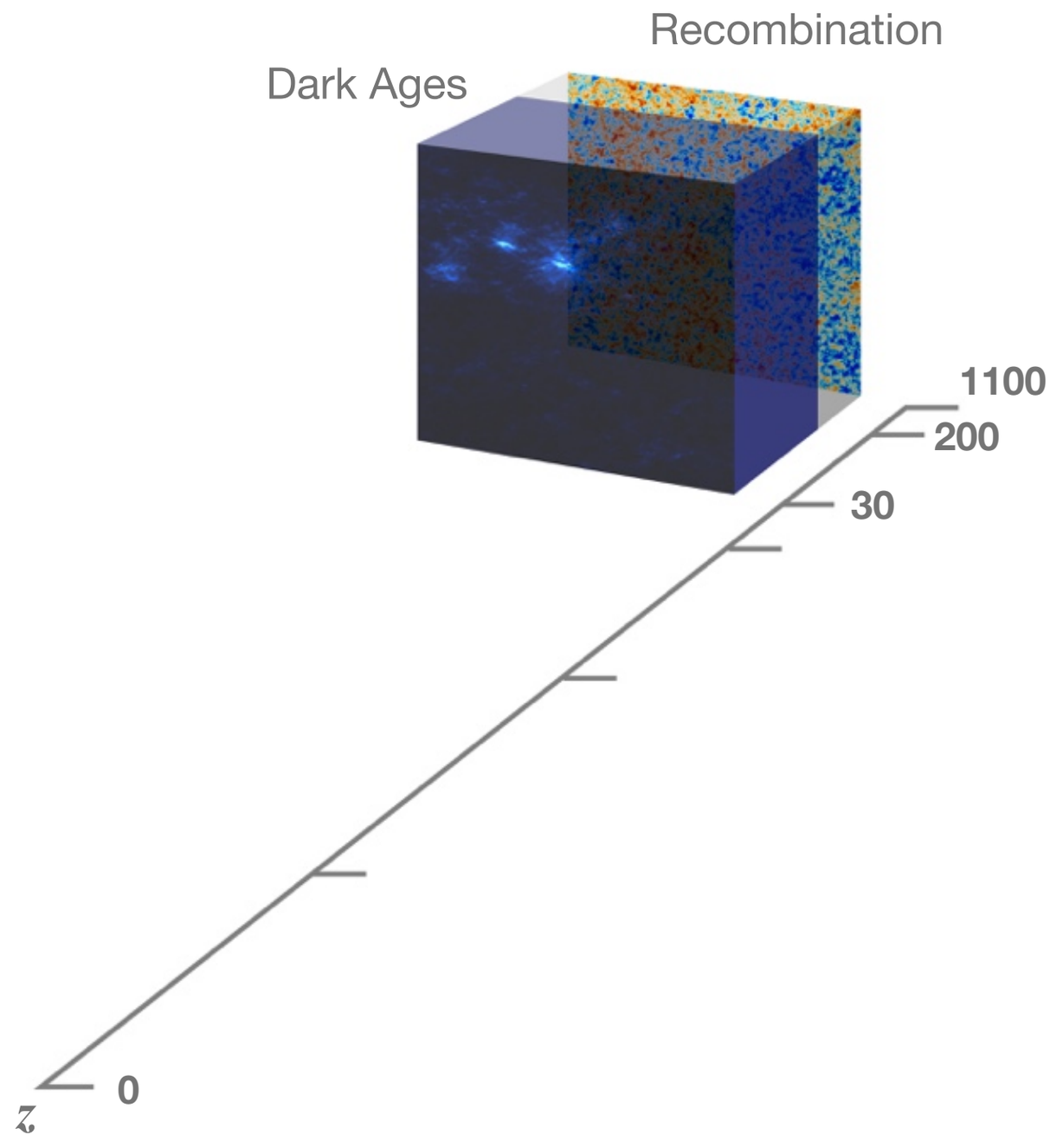


The Observable Universe: Key Historical Epochs



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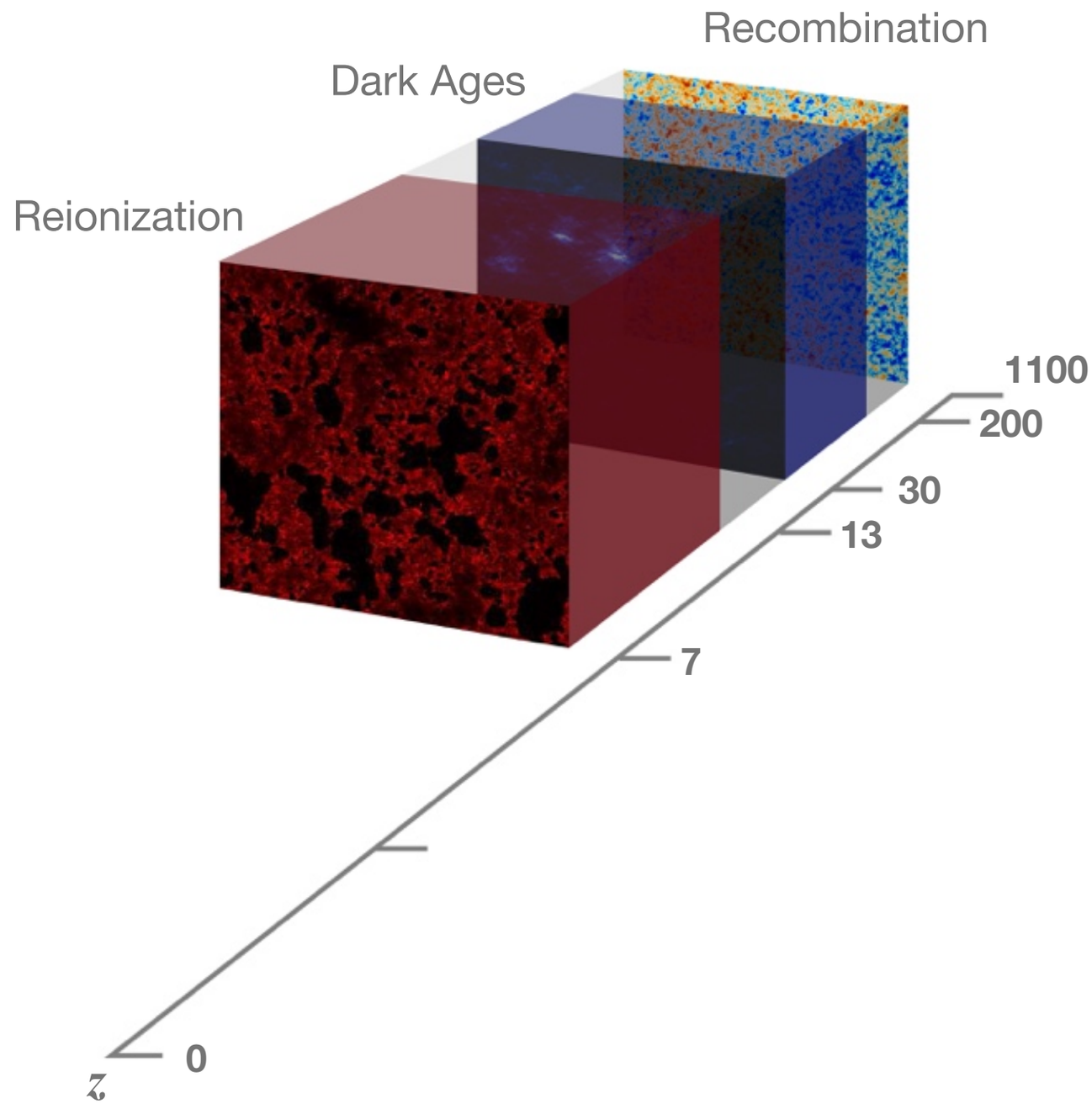

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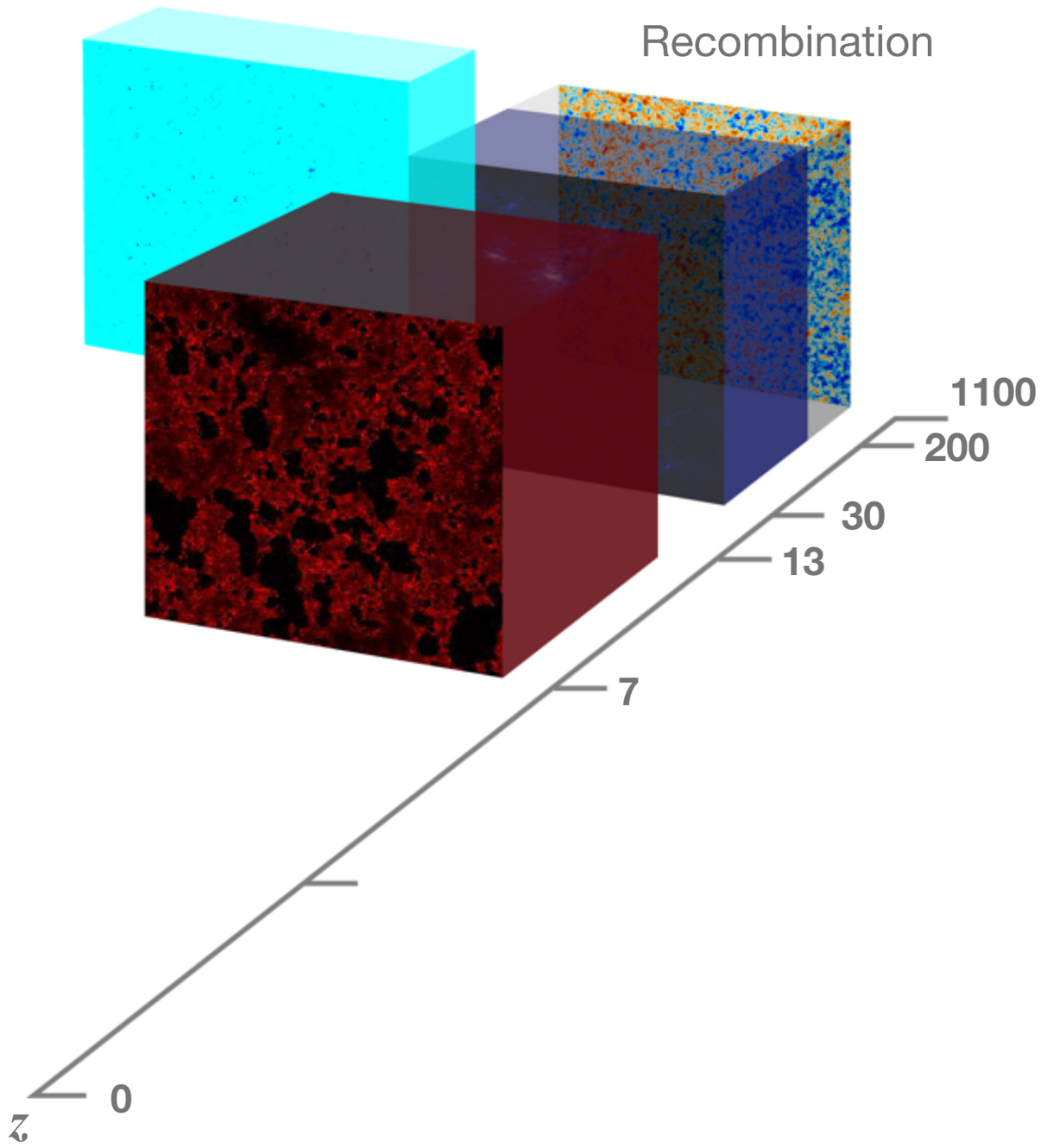
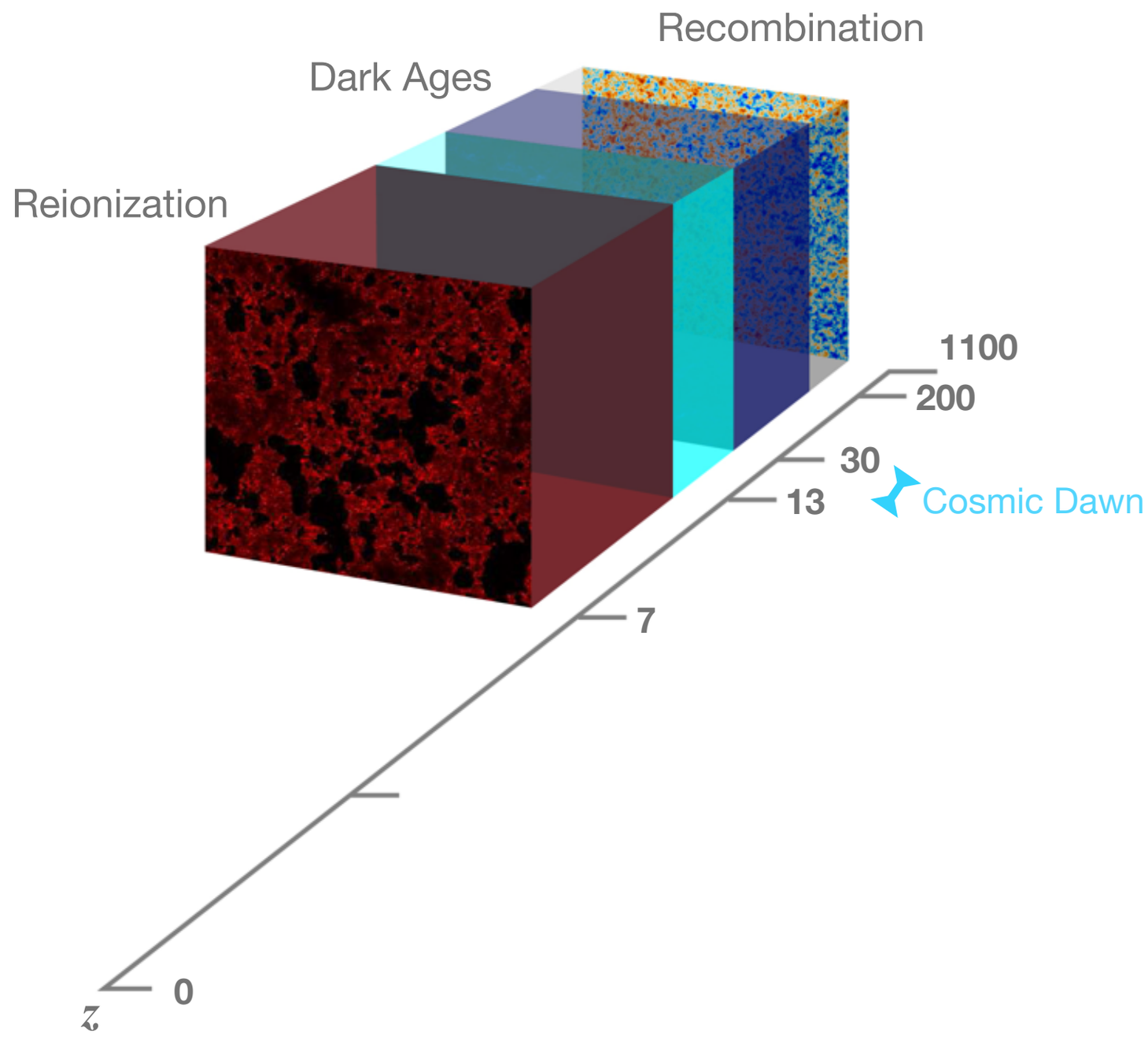


The Observable Universe: Key Historical Epochs



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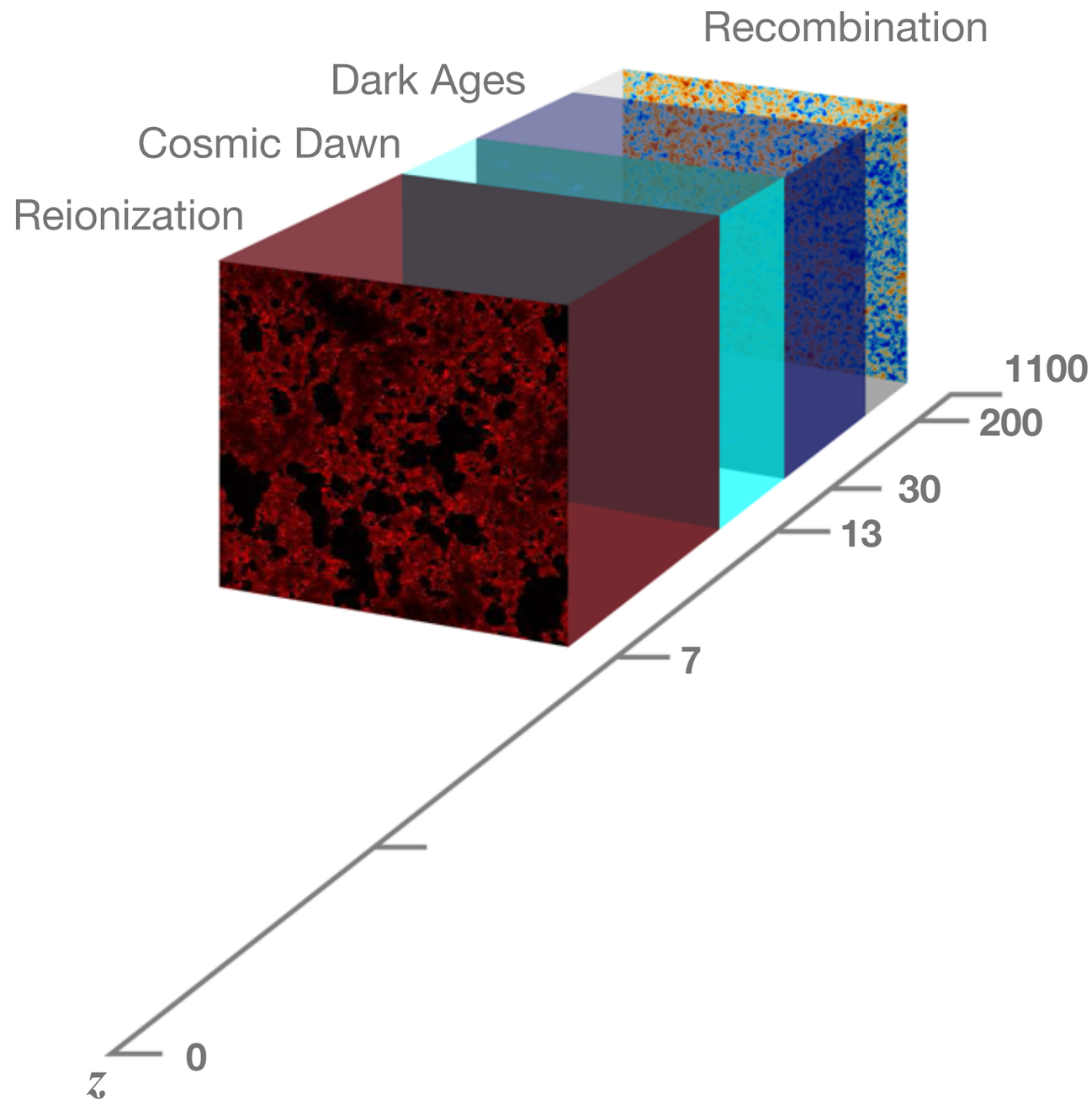

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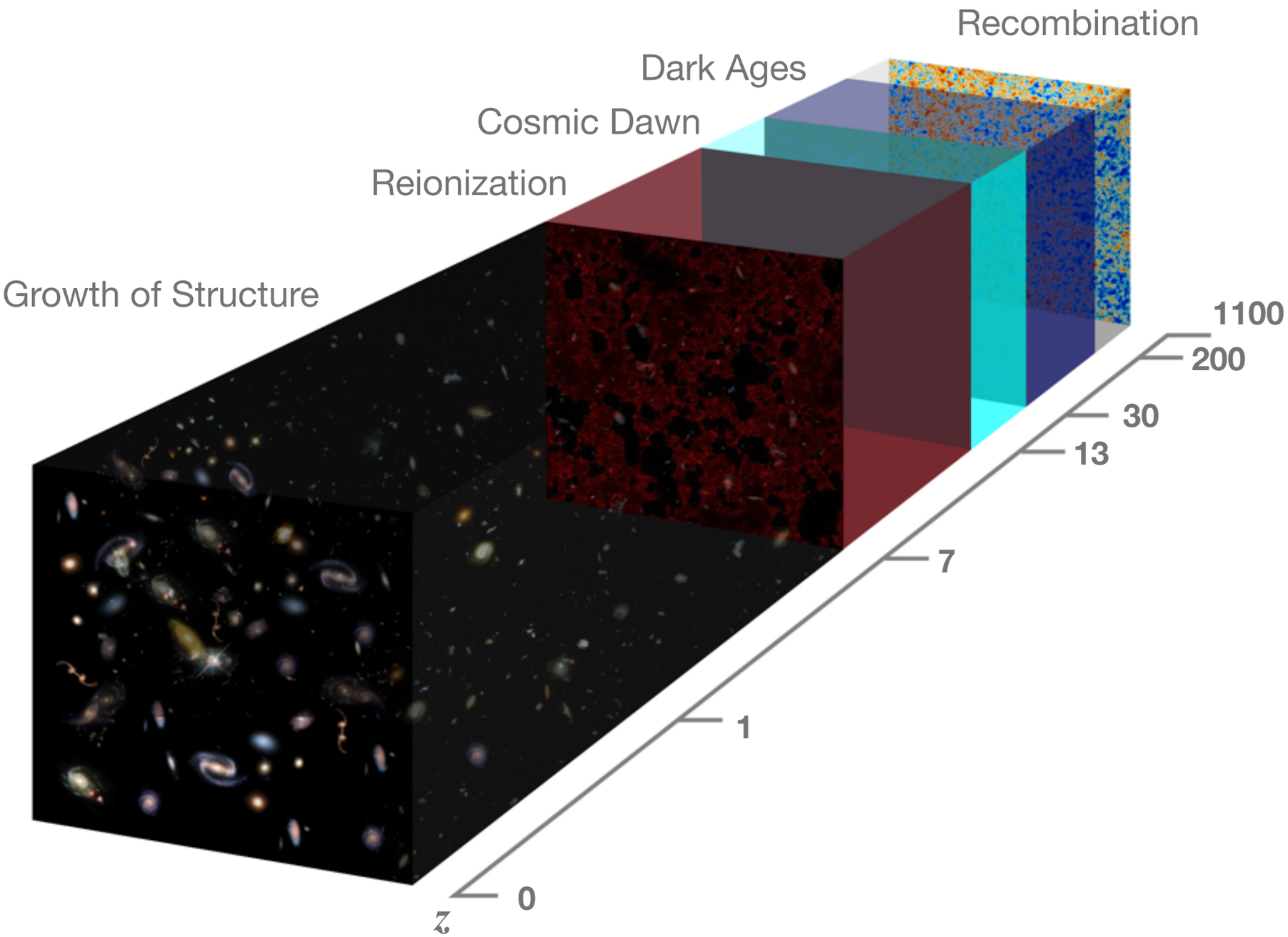

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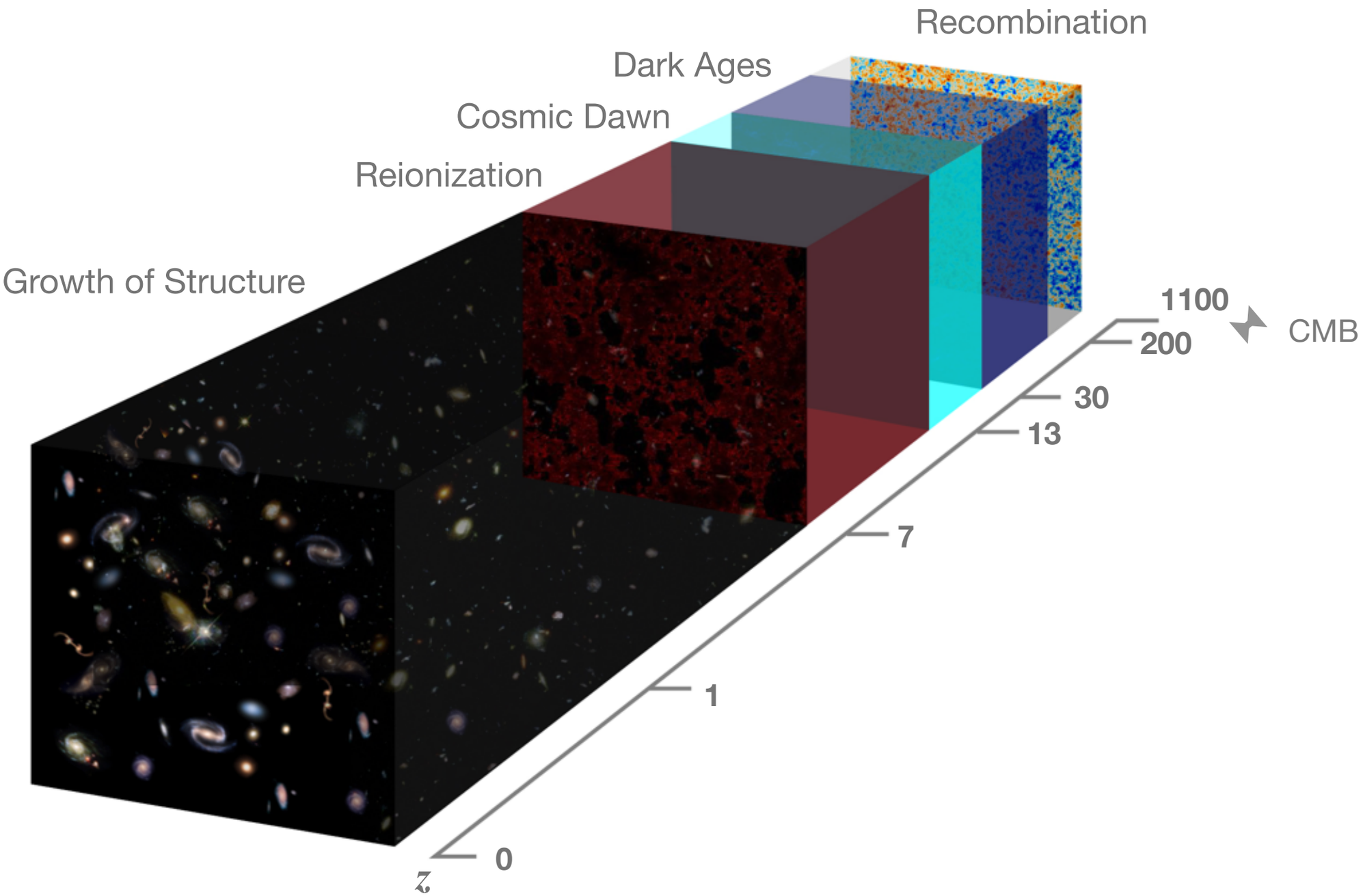

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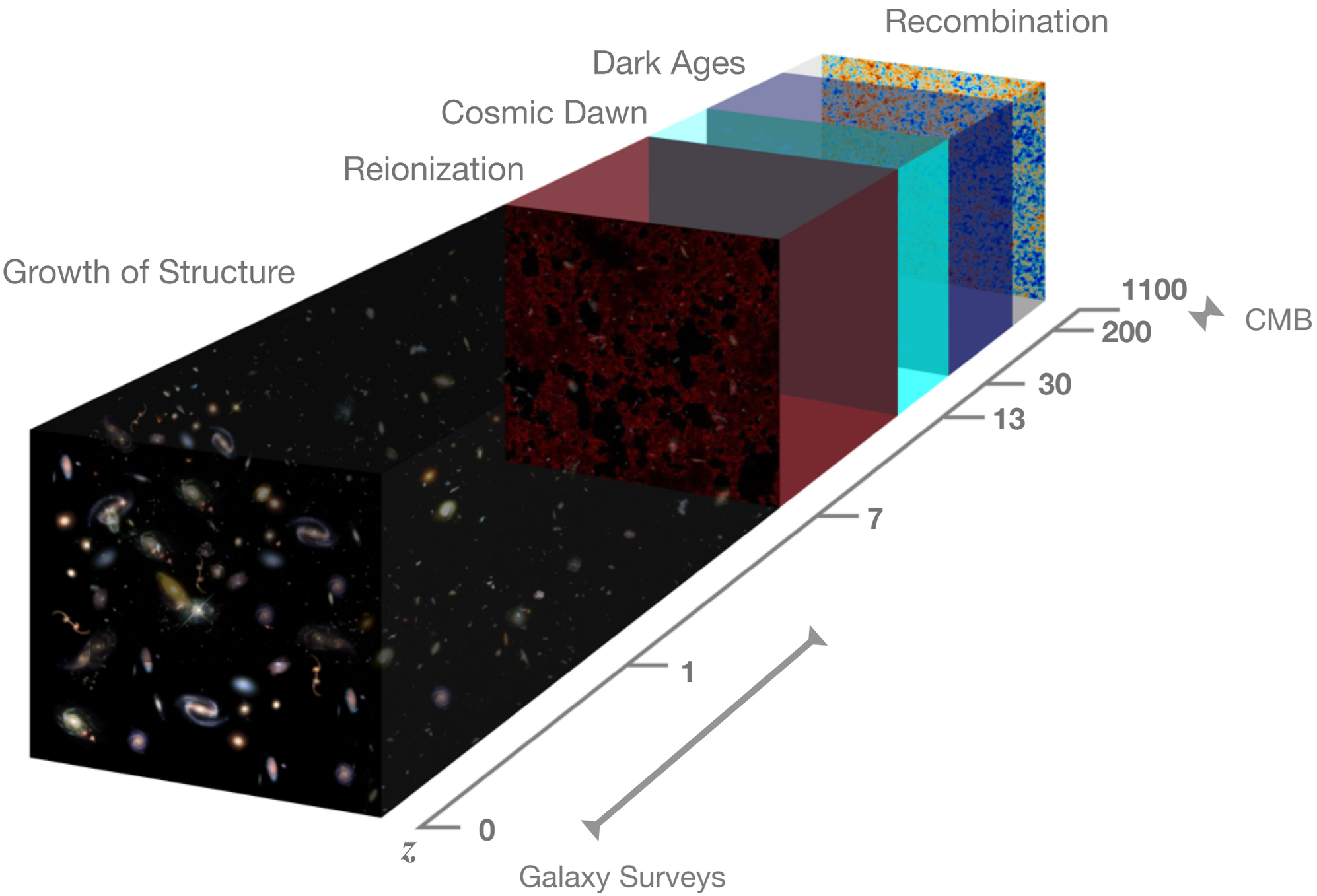

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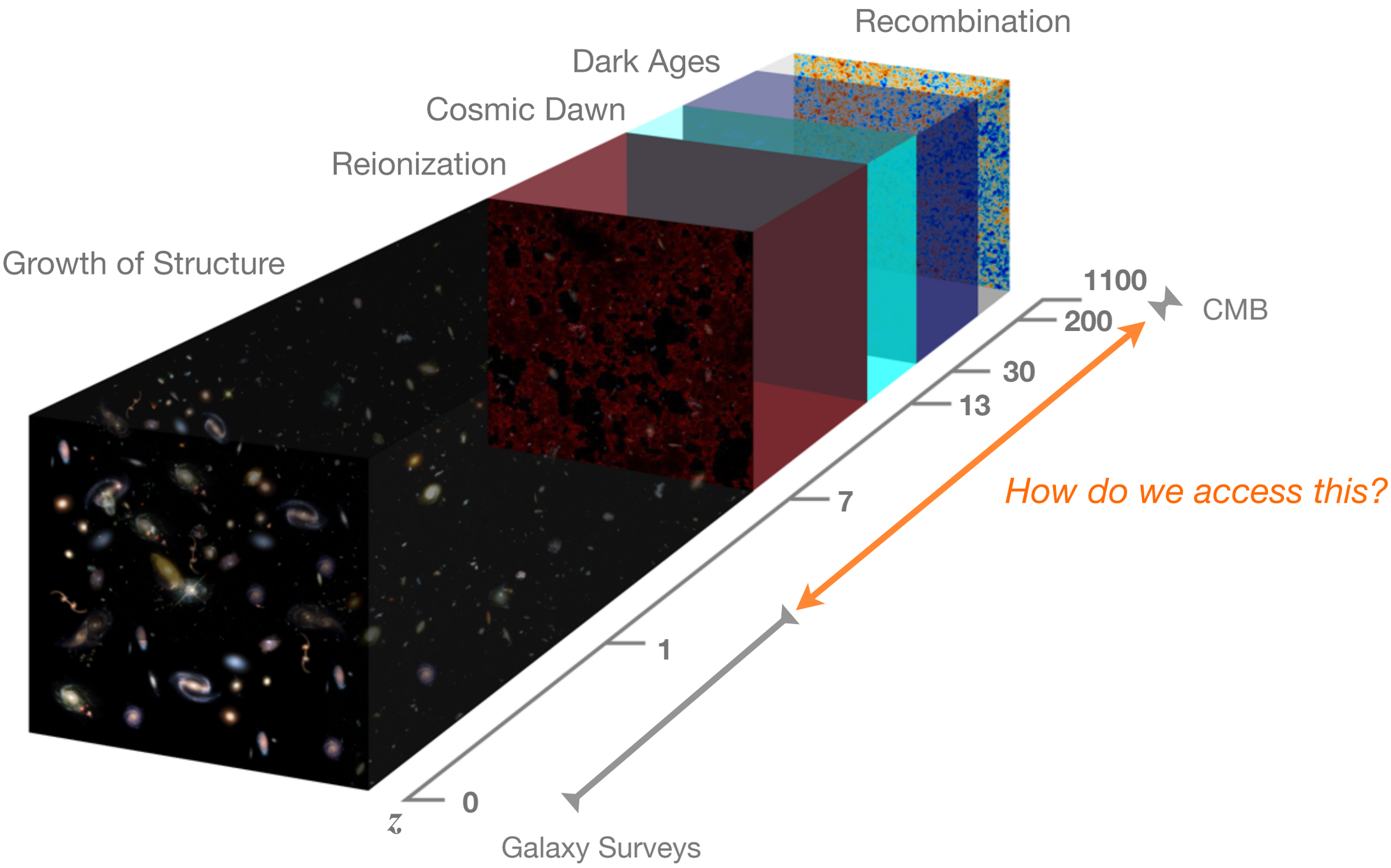
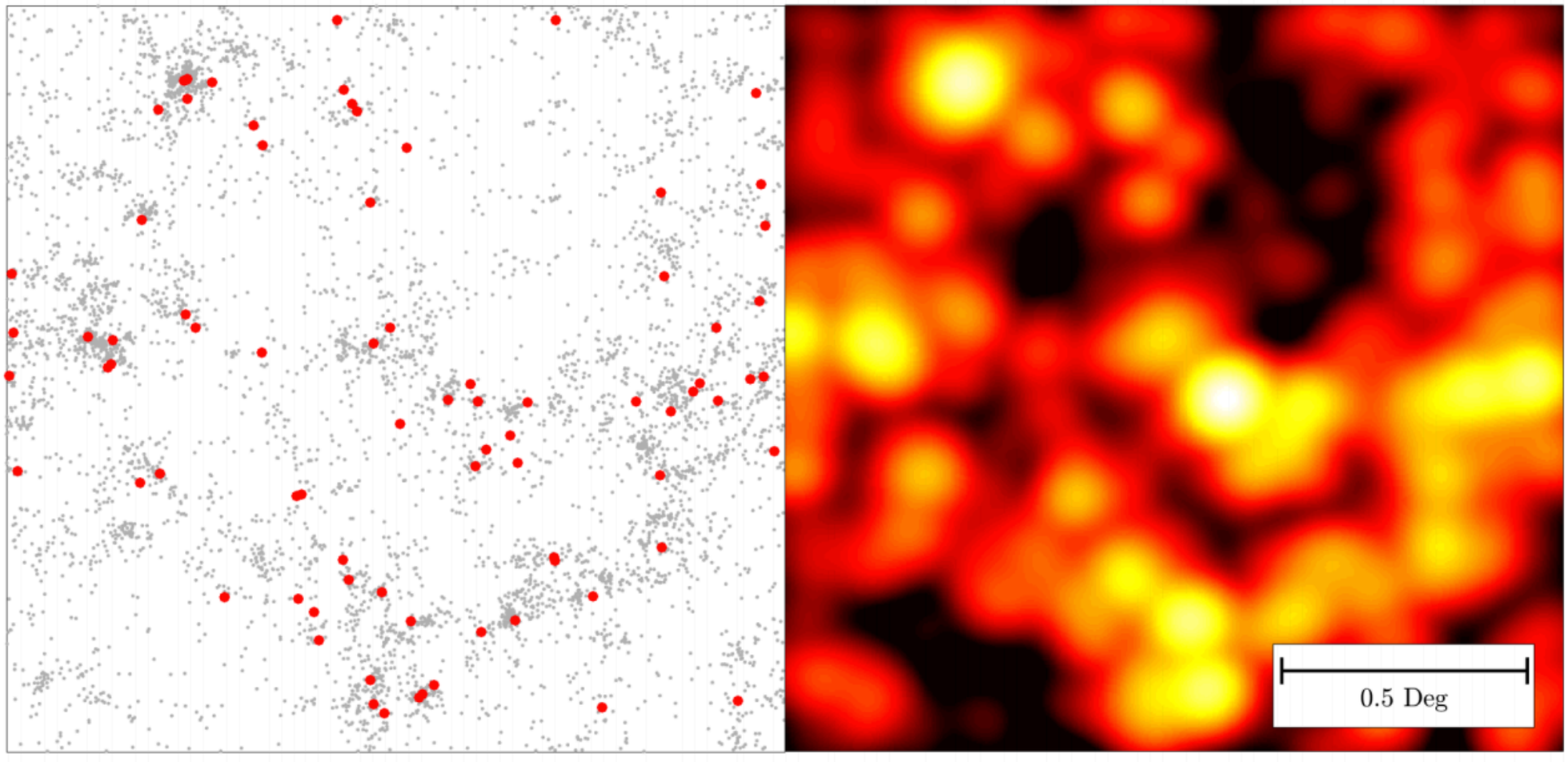


Line-Intensity Mapping

Line-Intensity Mapping

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.

Line-Intensity Mapping as the Ultimate Probe

Tests of ΛCDM Cosmology (and beyond):

- A good figure-of-merit is: $N_{\rm modes}$

  (constraints scale as: $1/N_{\rm modes}^{1/2}$)

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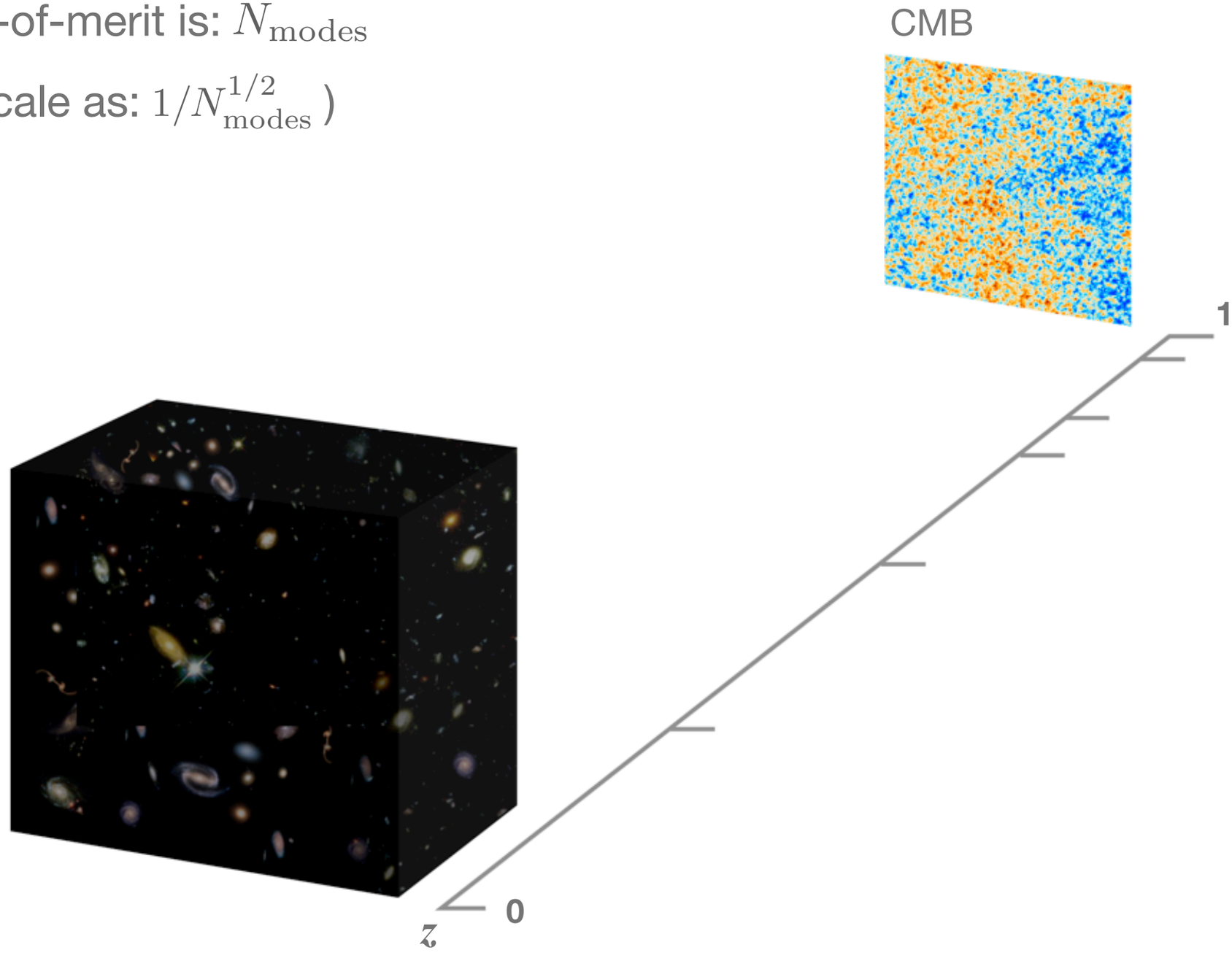

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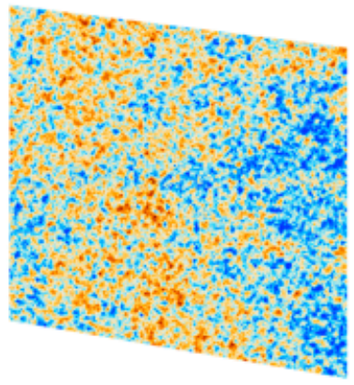
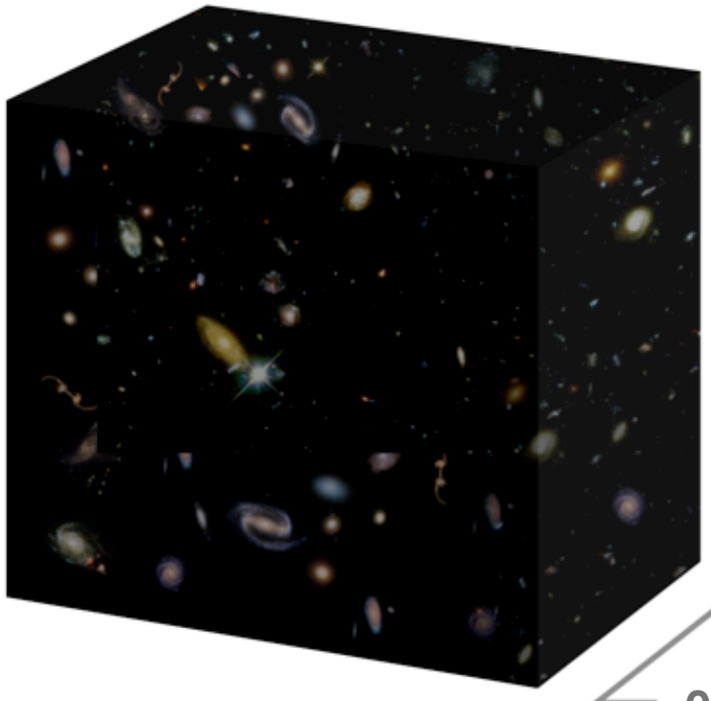
CMB $N_{\rm modes}^{\rm CMB} \sim \ell_{\rm max}^2 \sim 10^7$



1100



Galaxy Surveys

0

z

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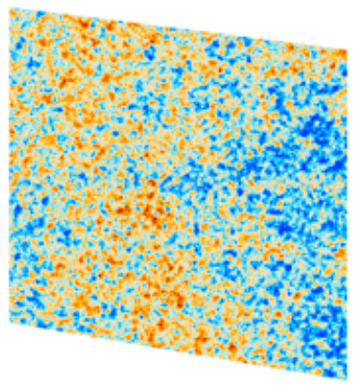

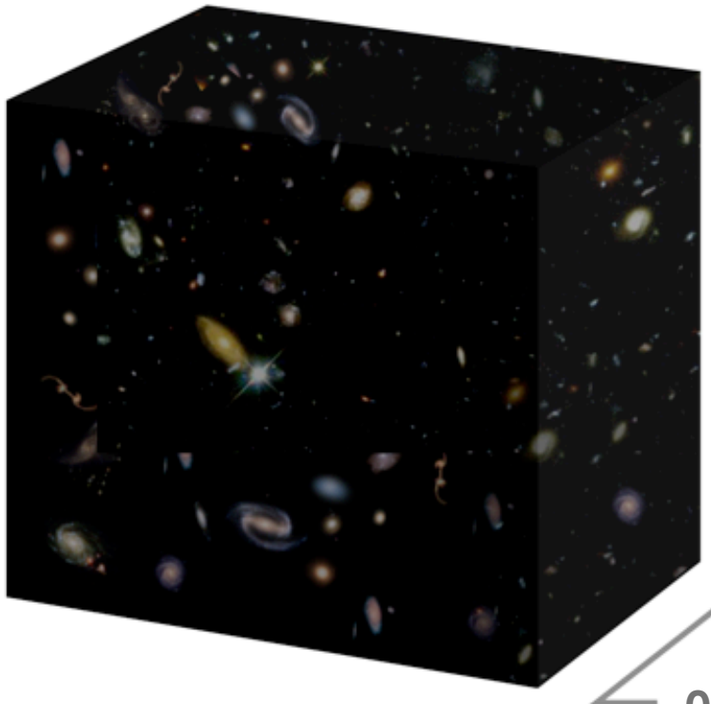

Galaxy Surveys

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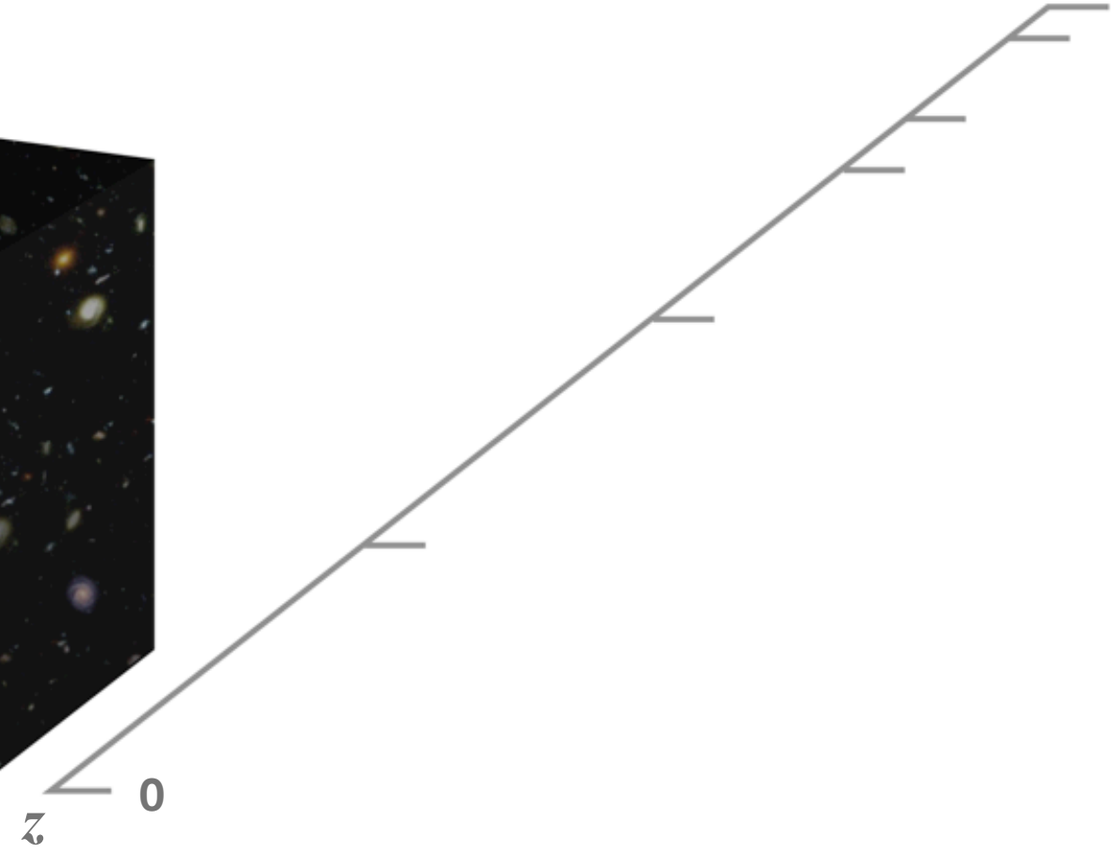

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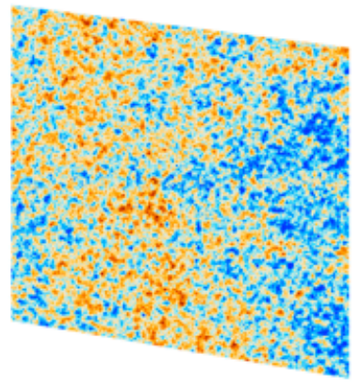
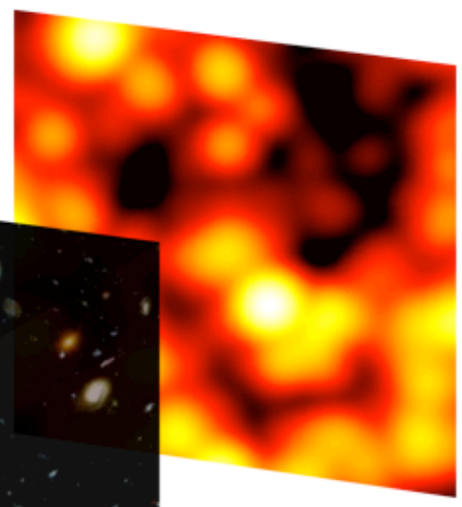
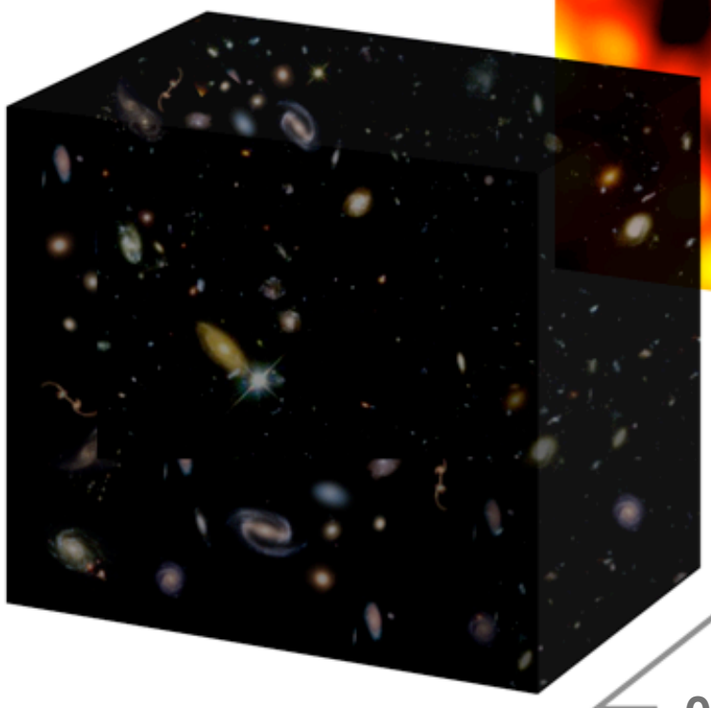


LIM





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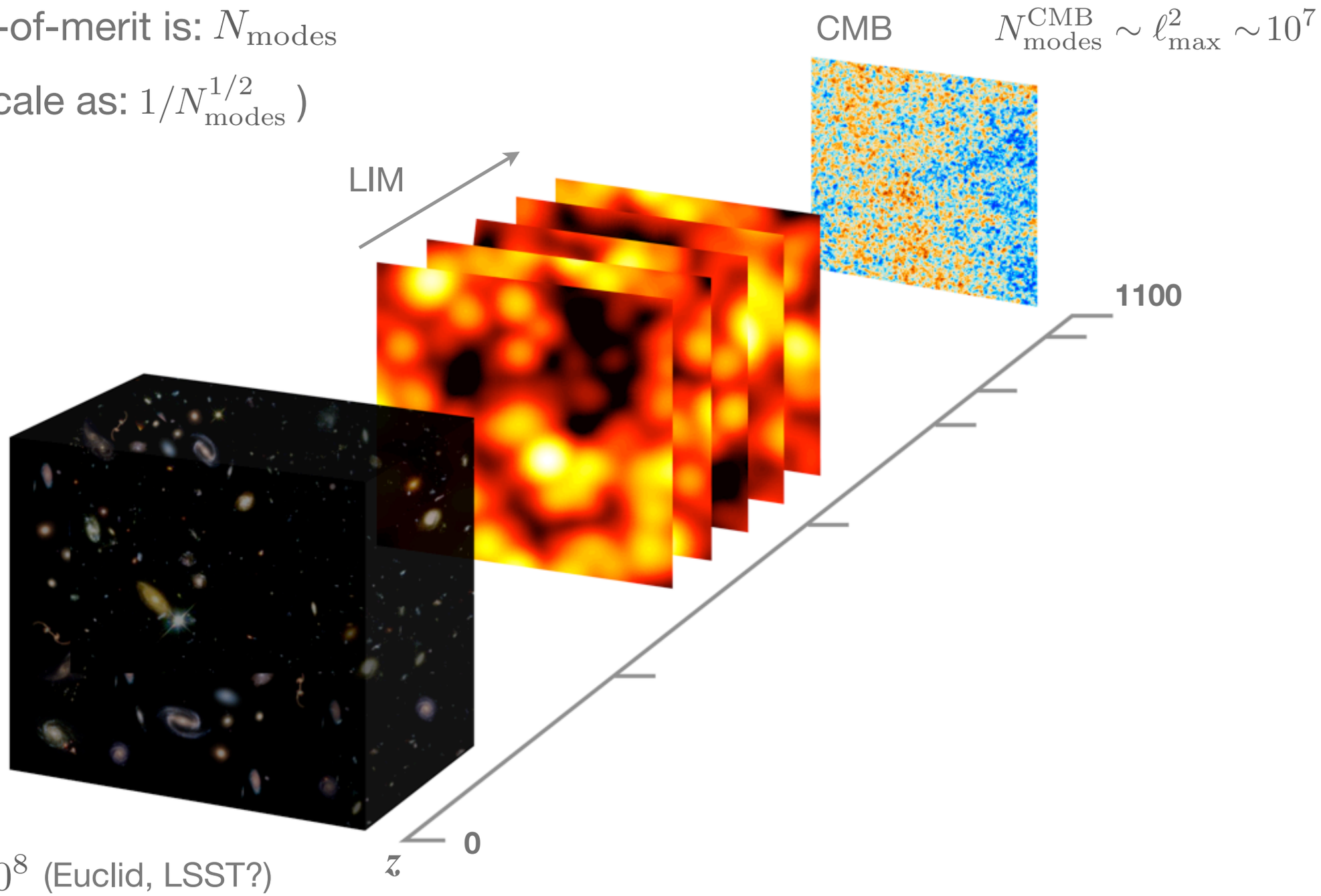

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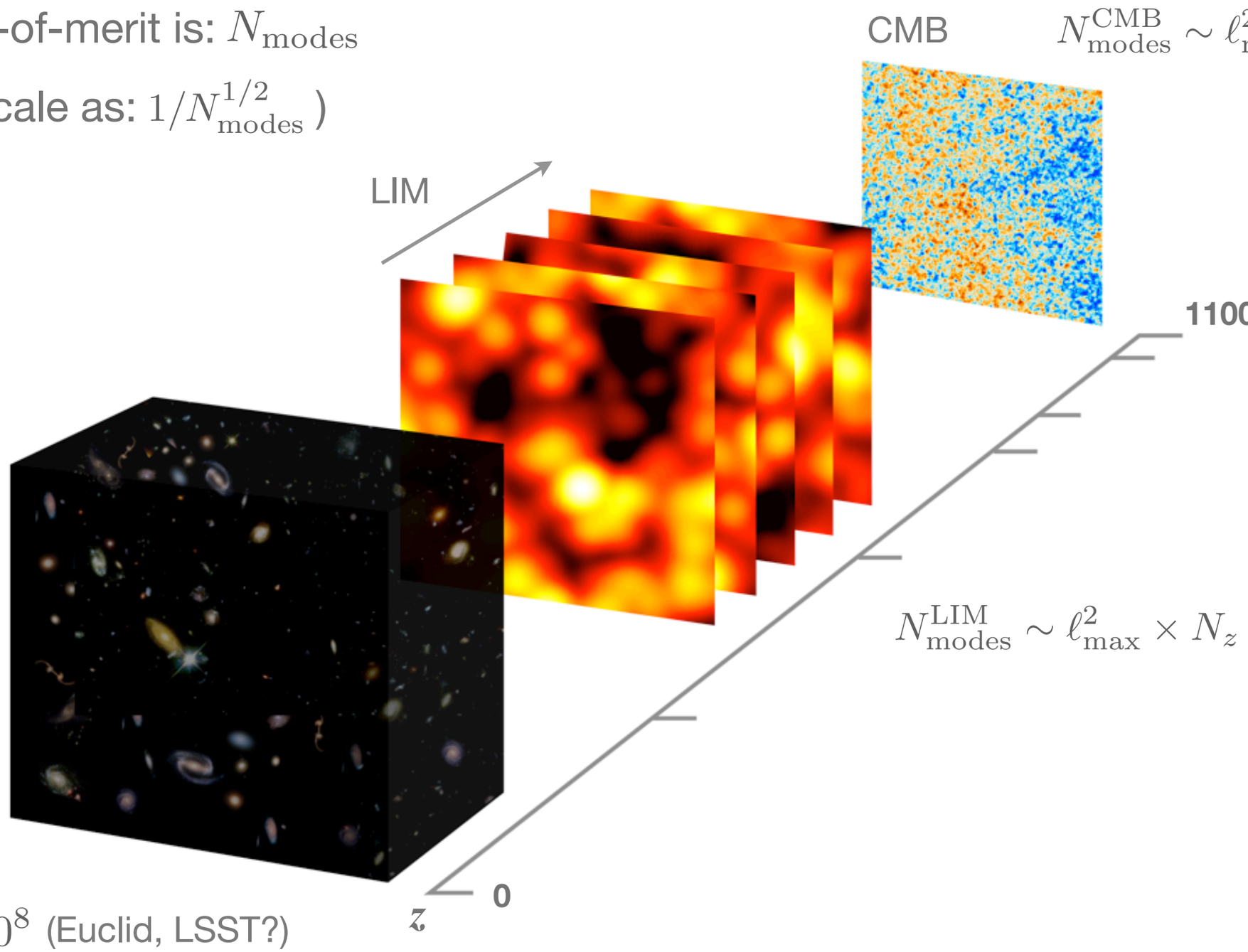

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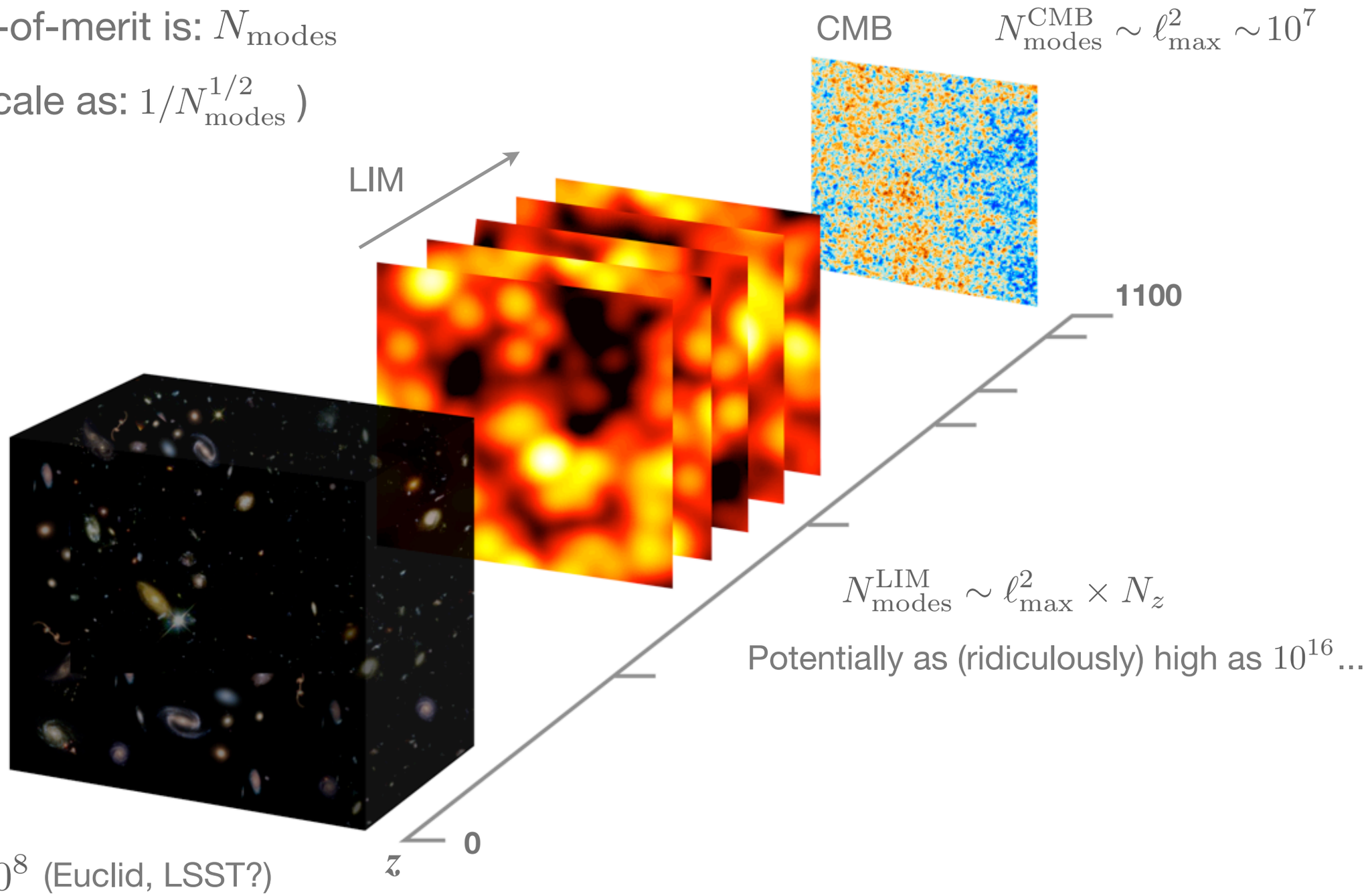

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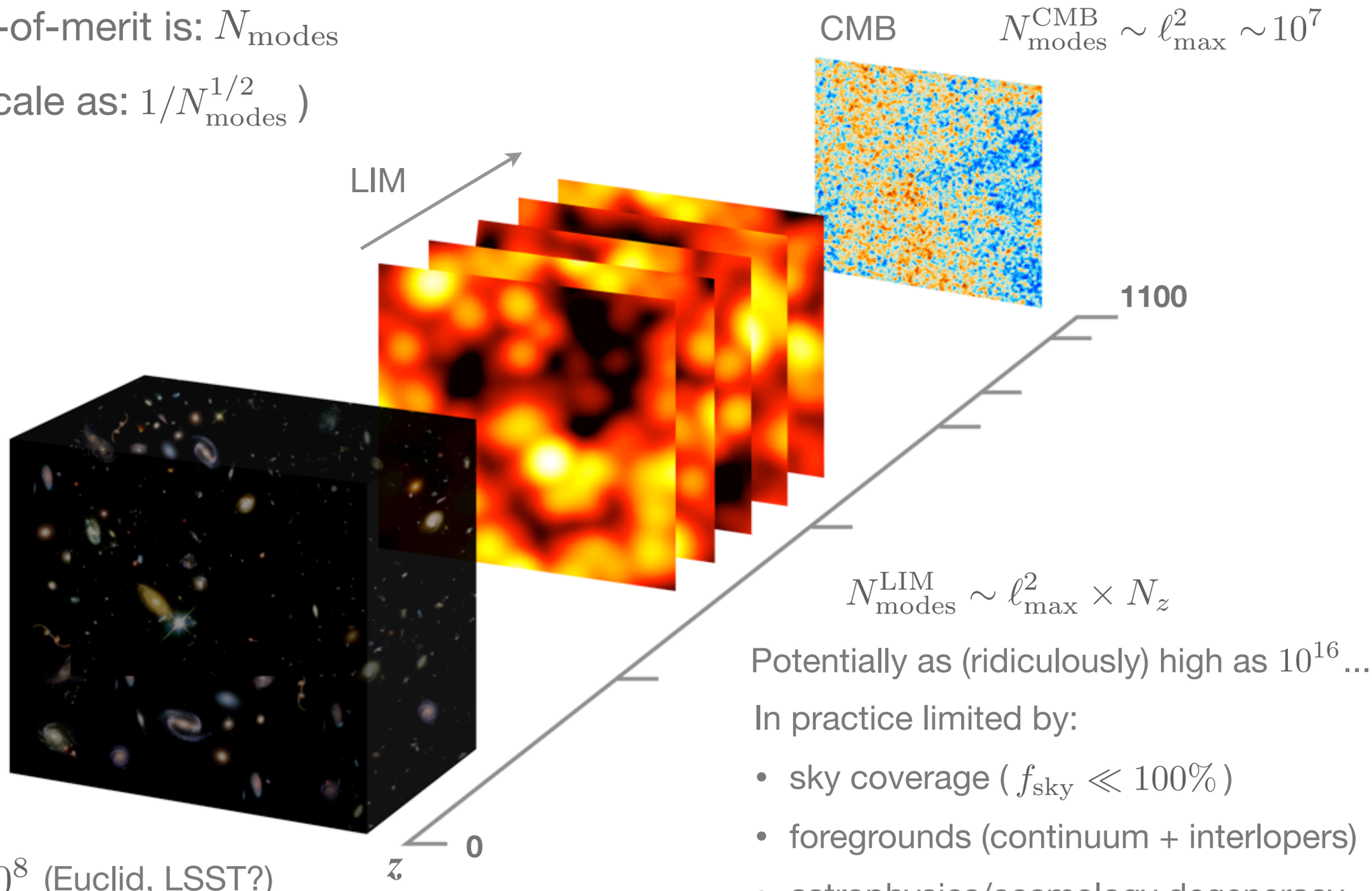

Galaxy Surveys

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

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

In practice limited by:

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

The Reach of Line-Intensity Mapping

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

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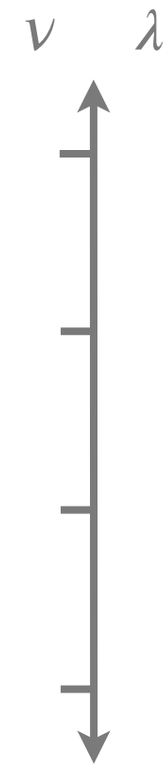

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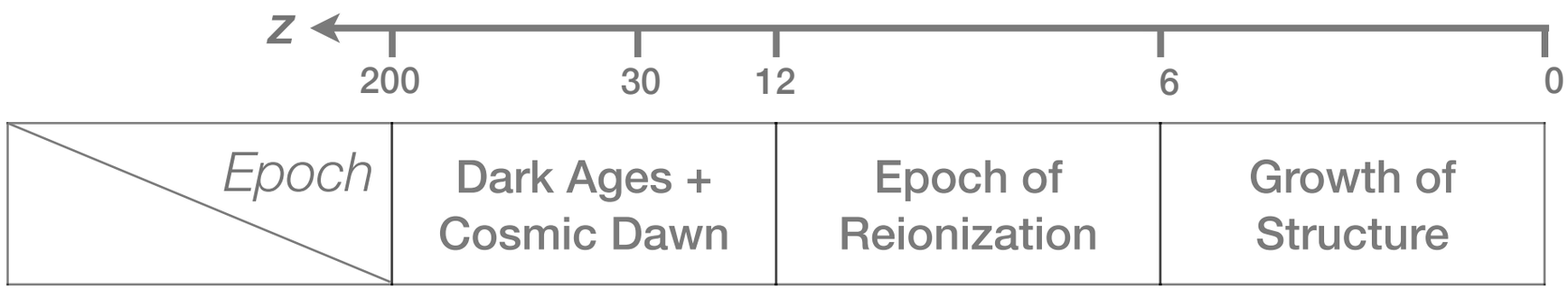

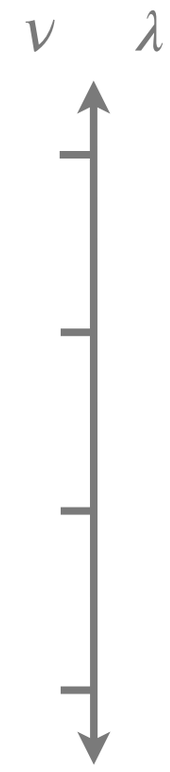

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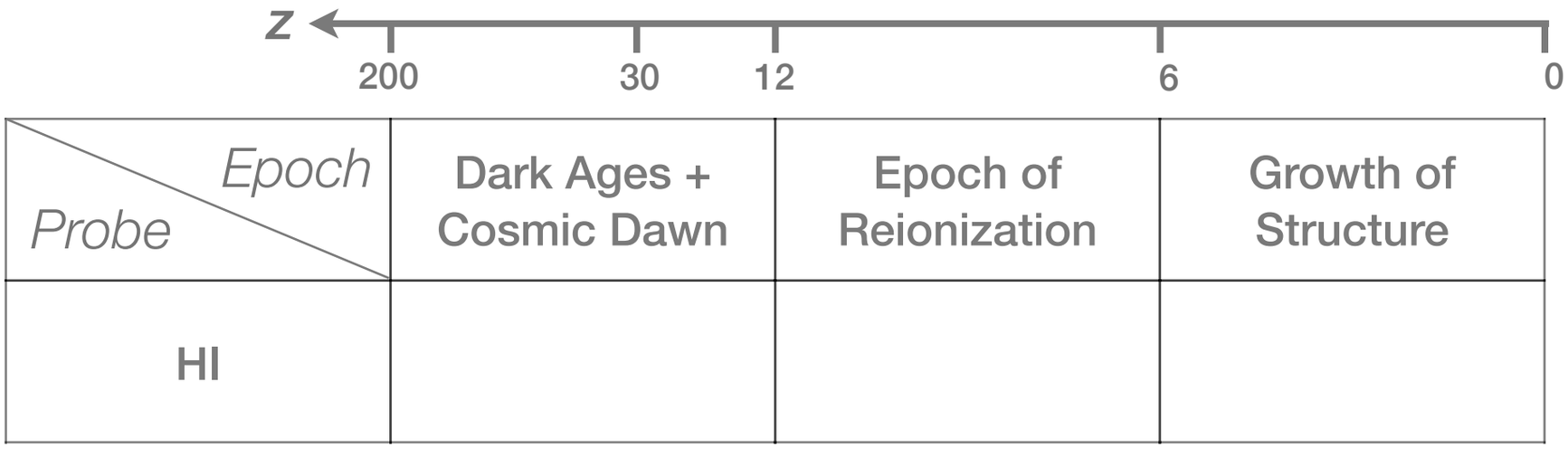
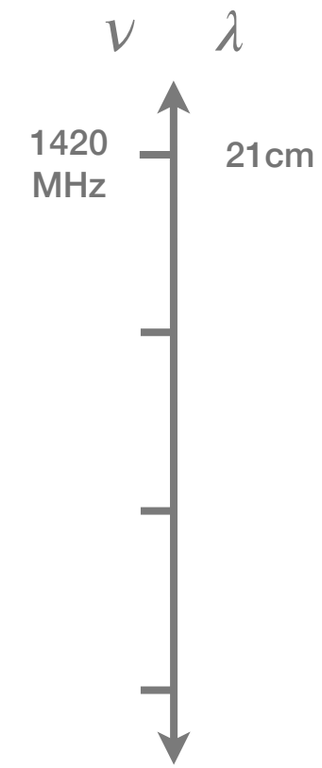


Probe \ Epoch	Dark Ages + Cosmic Dawn	Epoch of Reionization	Growth of Structure
HI			



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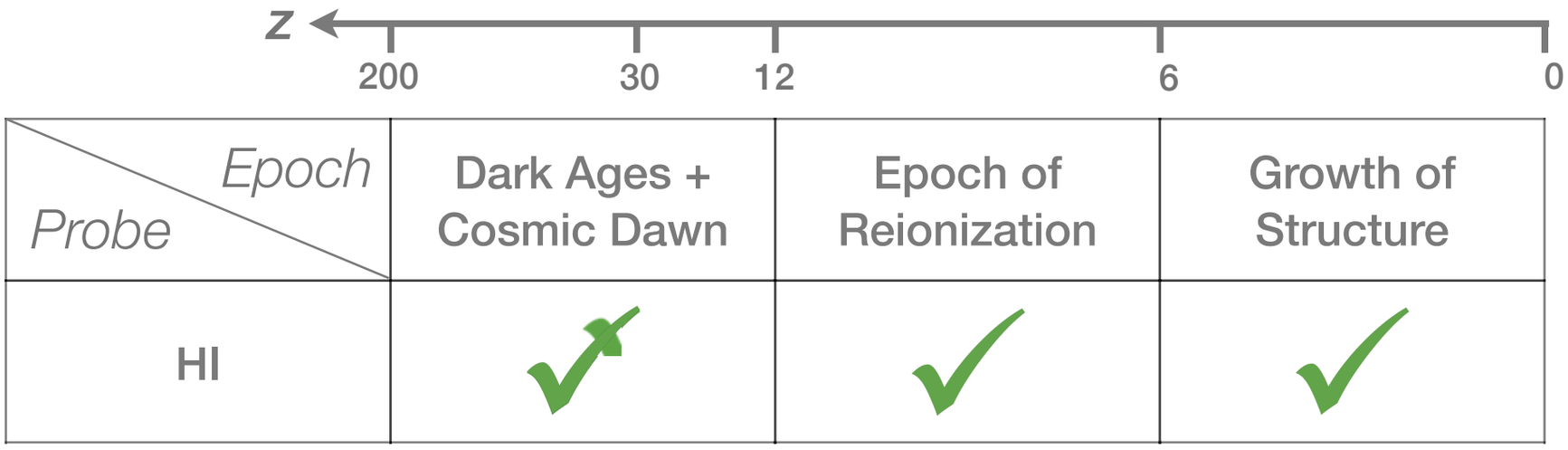
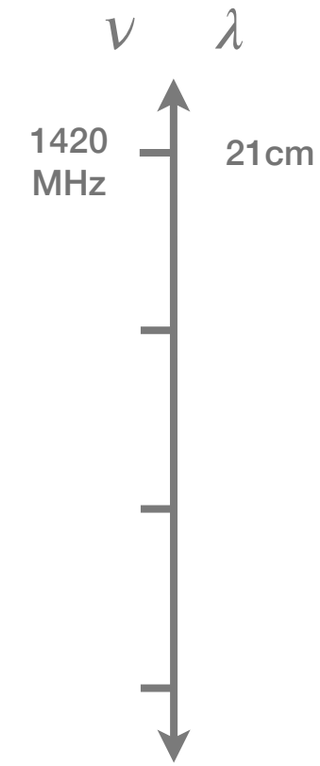


Probe \ Epoch	Dark Ages + Cosmic Dawn	Epoch of Reionization	Growth of Structure
HI	✓	✓	✓



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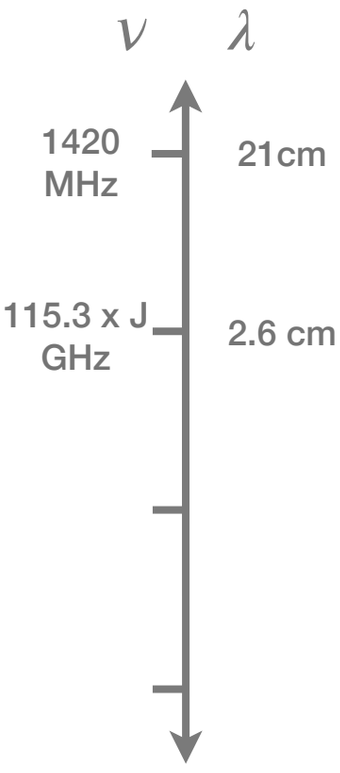
Probe \ Epoch	Dark Ages + Cosmic Dawn	Epoch of Reionization	Growth of Structure
HI	✓	✓	✓
CO			



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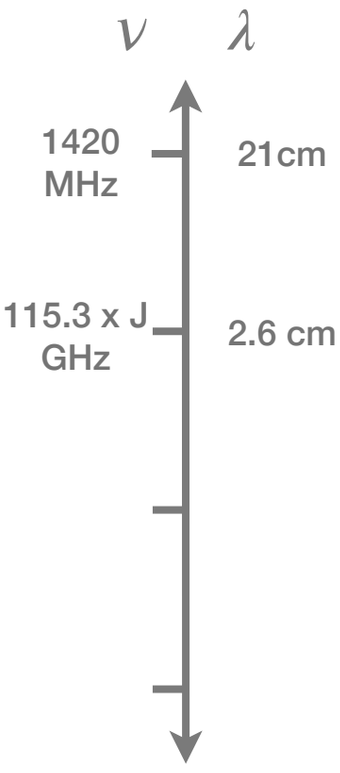

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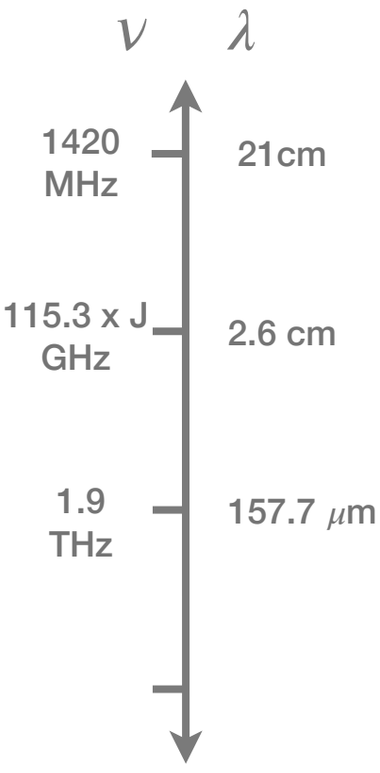

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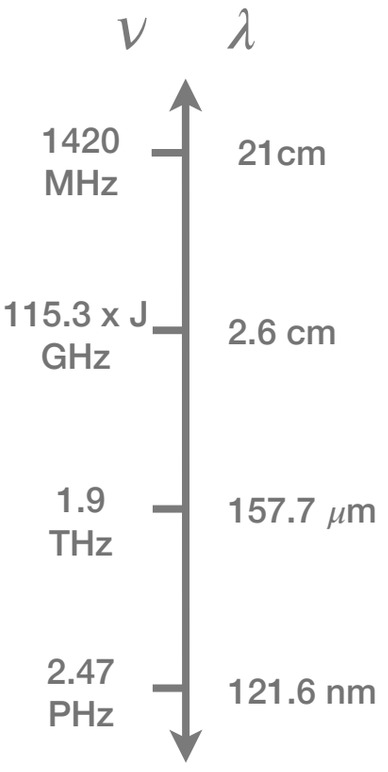

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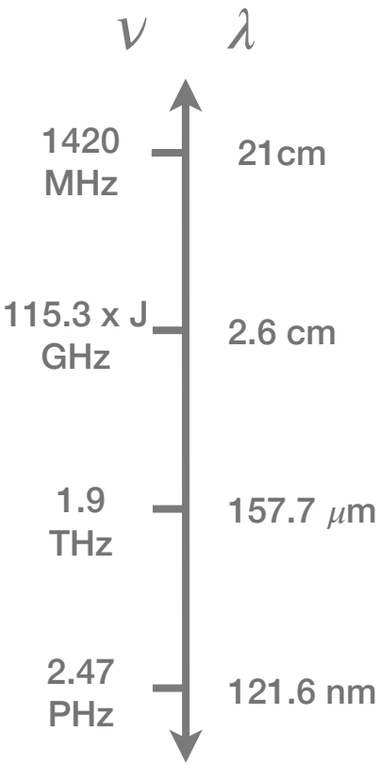
Lyα		✓	✓
Hα ⋮			



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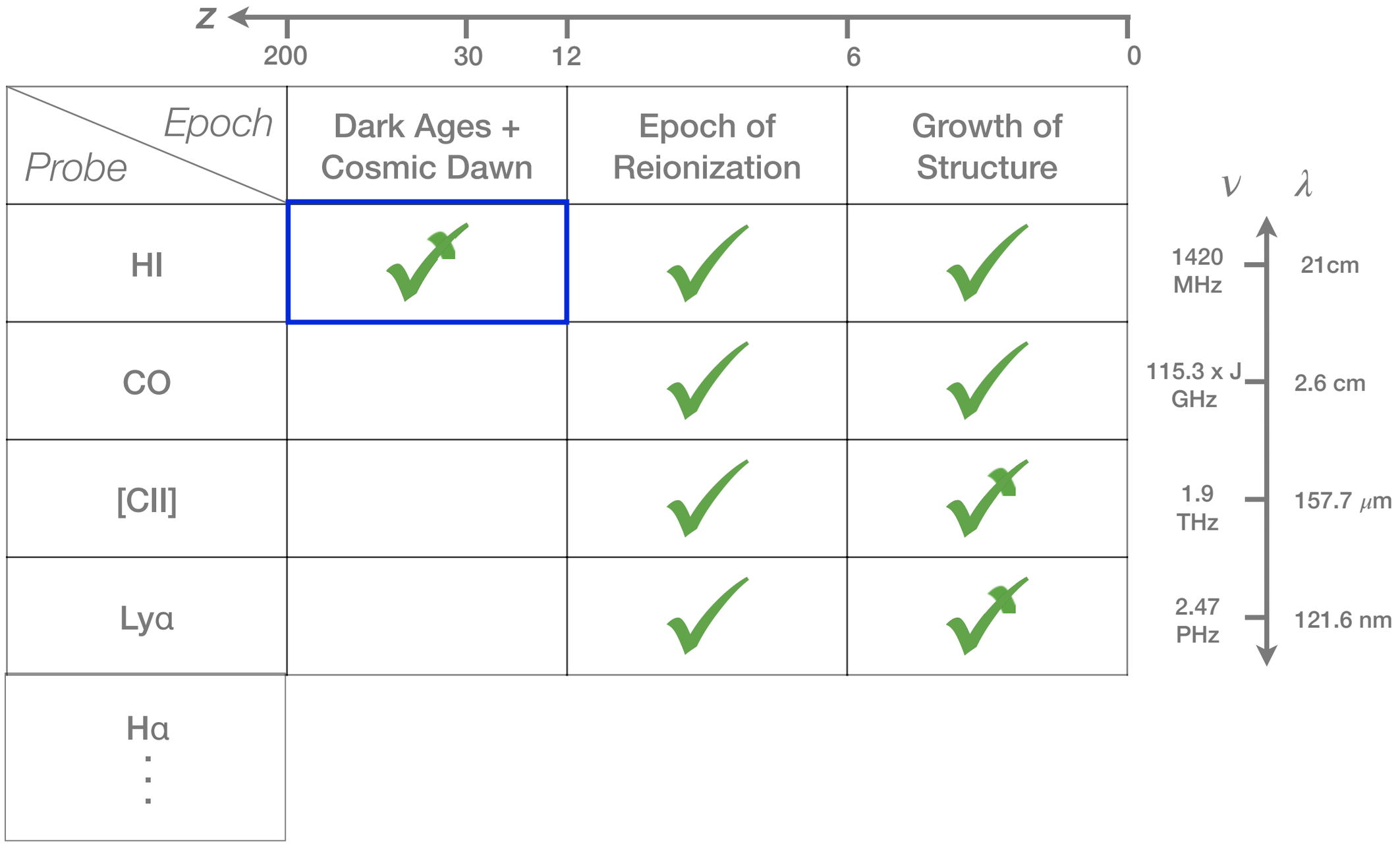

Line-Intensity Mapping: Experimental Landscape

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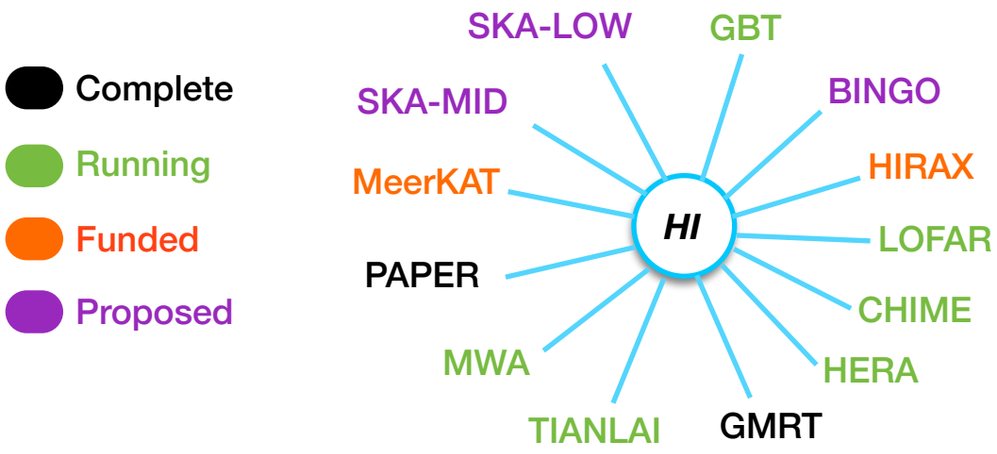

(Astro2020: Kovetz et al., arXiv:1903.04496)

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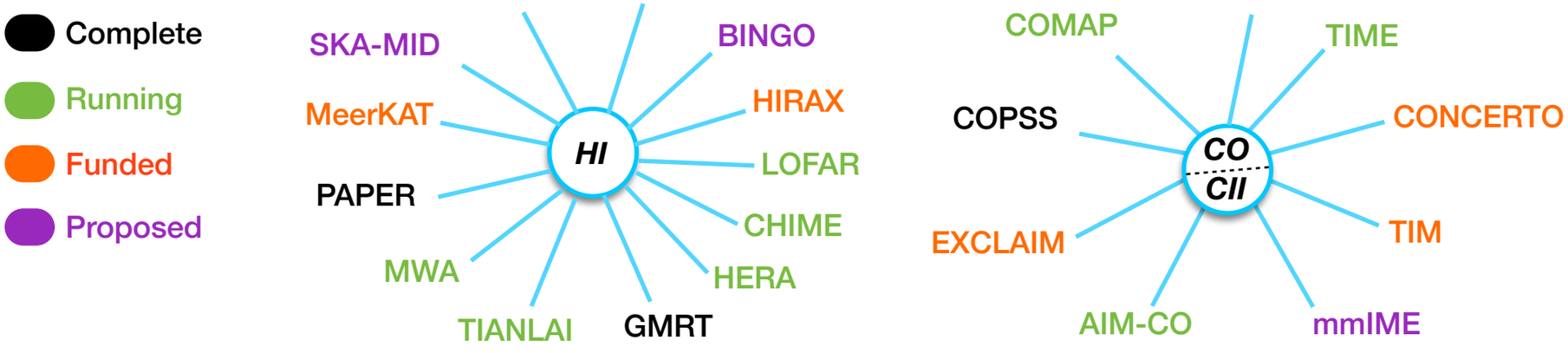

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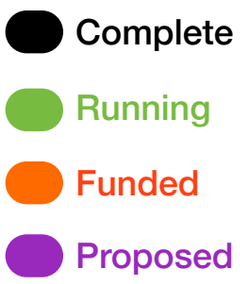

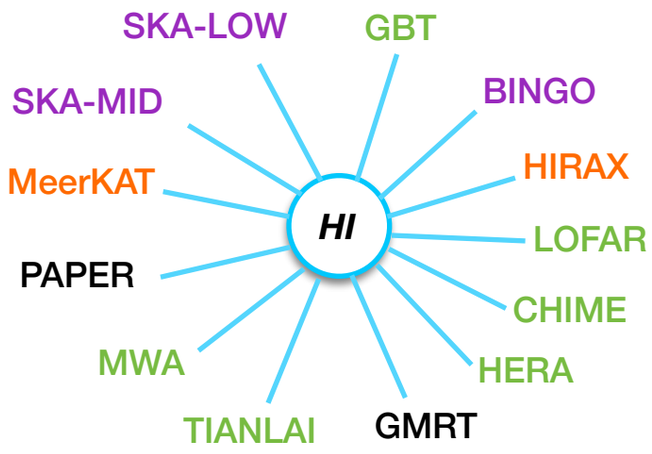

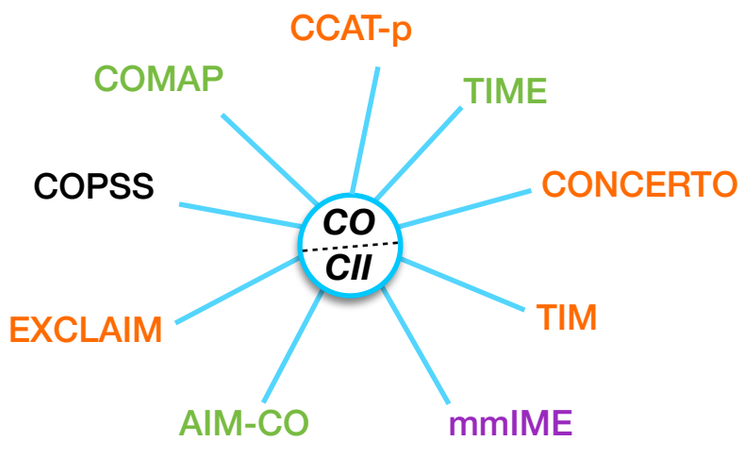

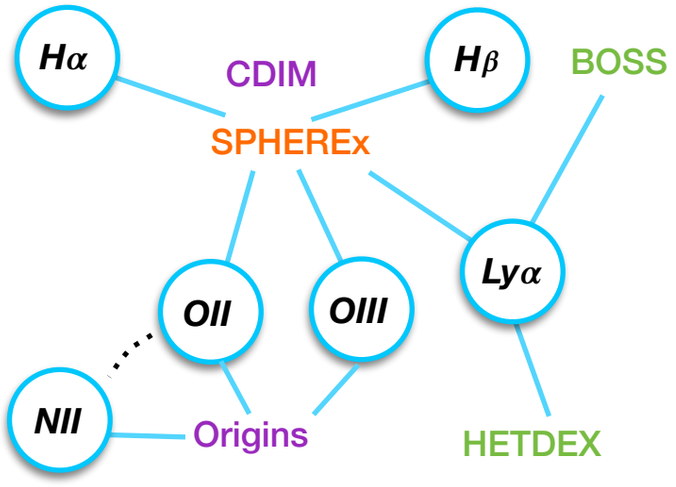

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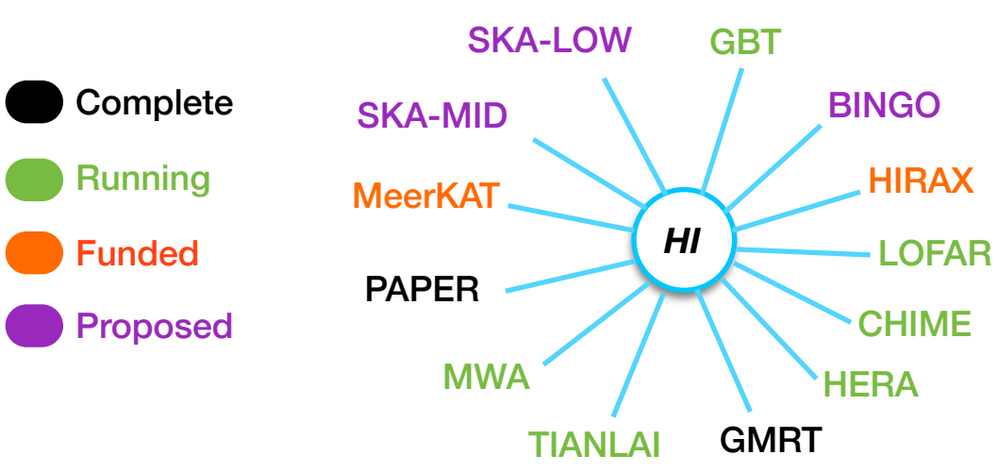

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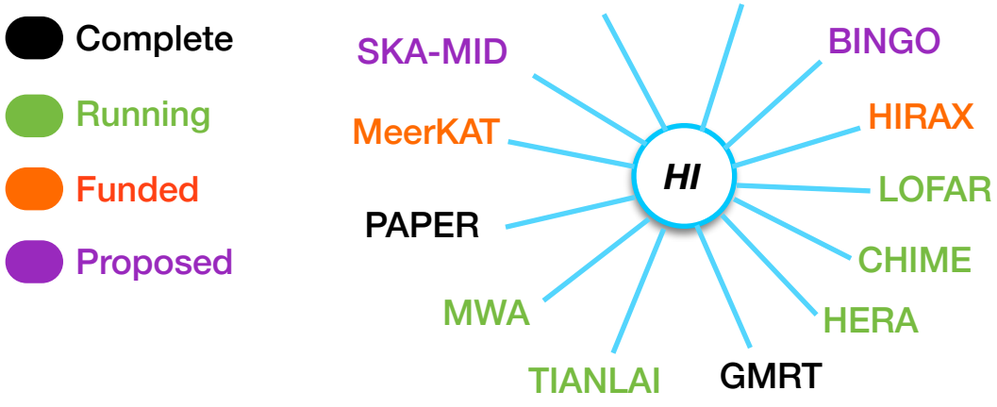

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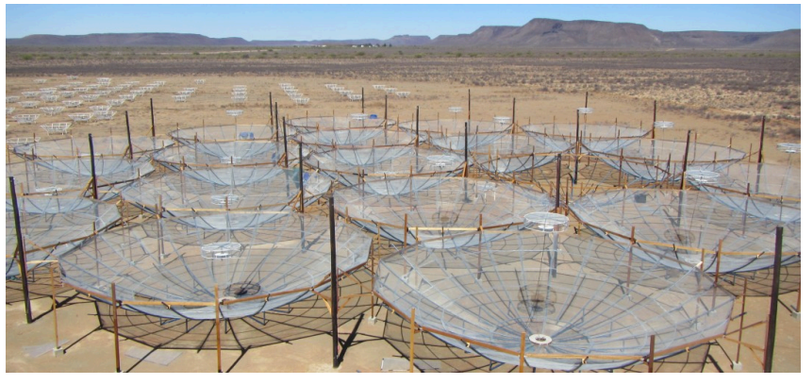

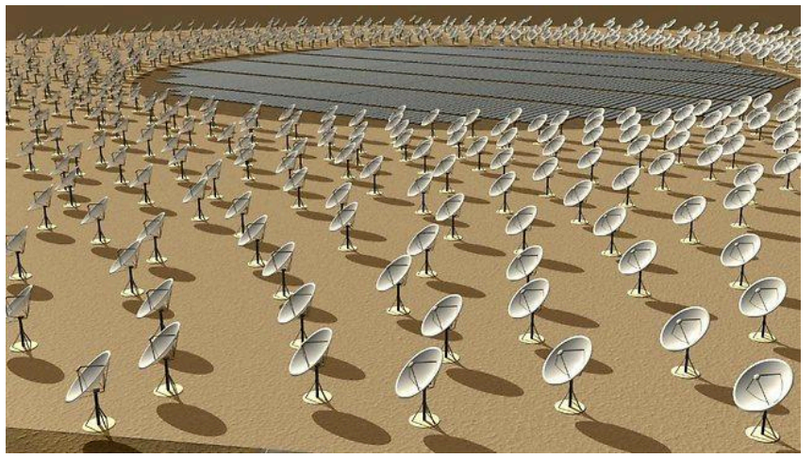

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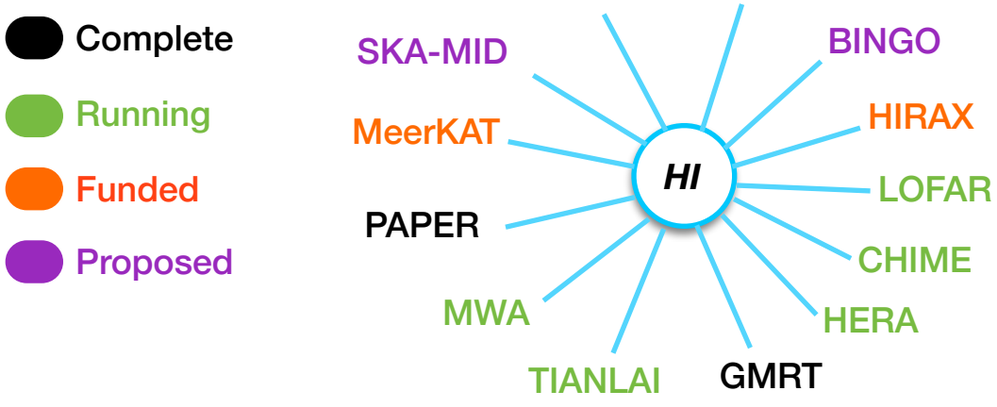

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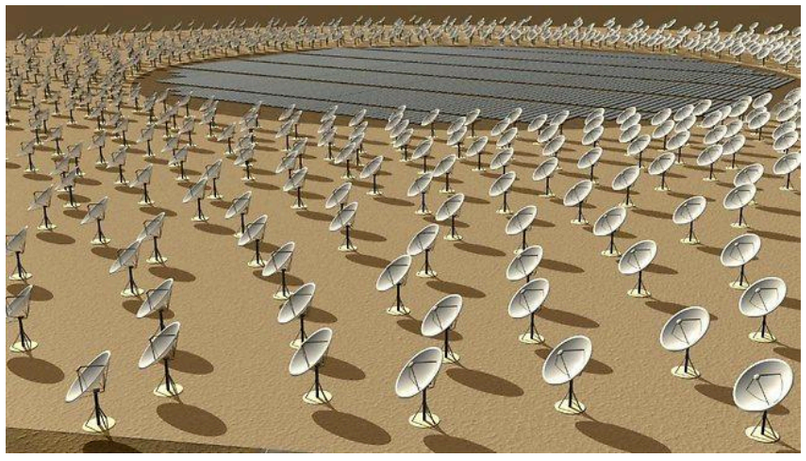
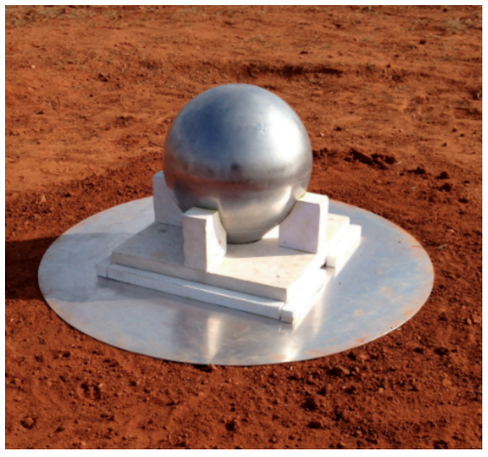
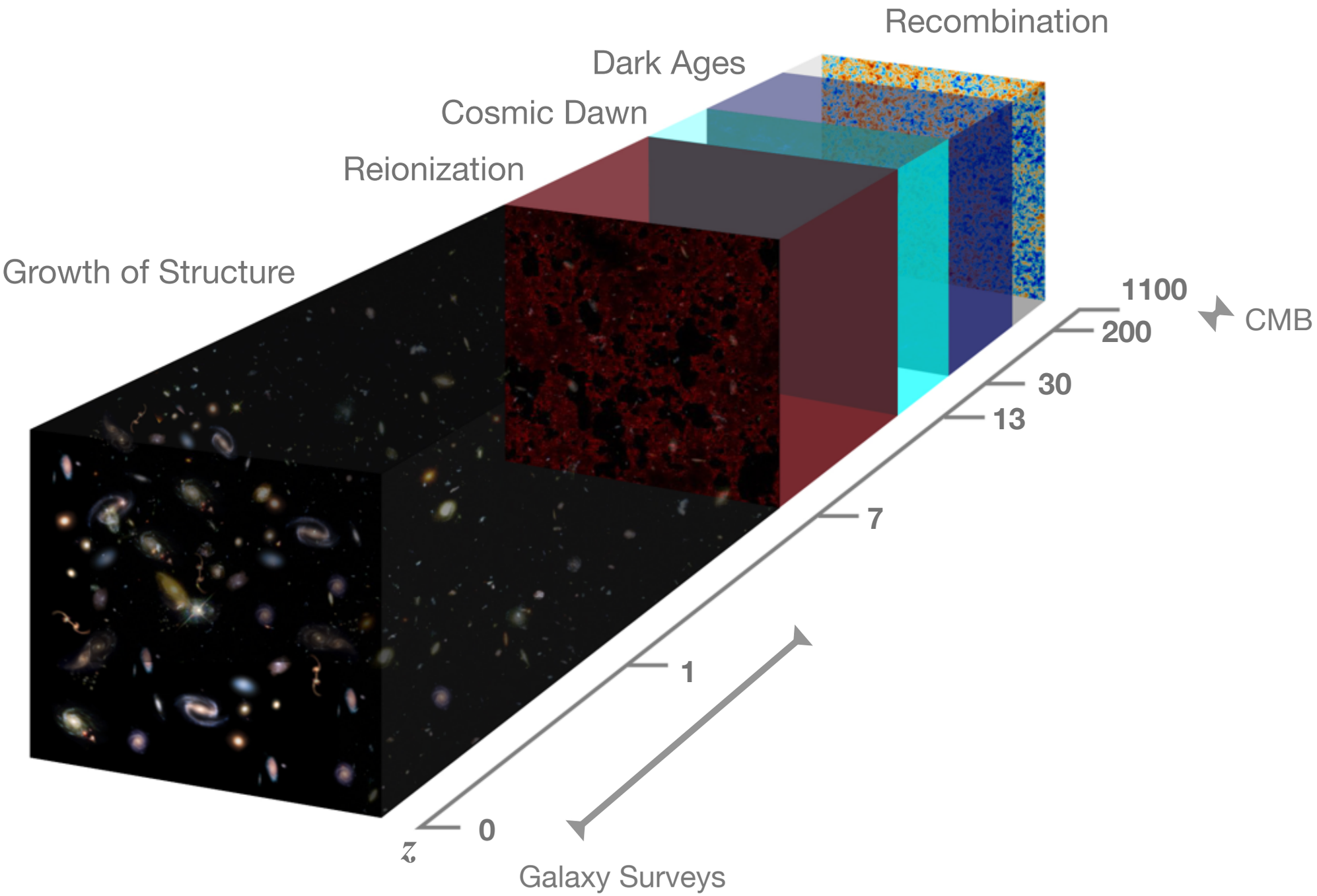




The Observable Universe: A Multi-Layer Detector!



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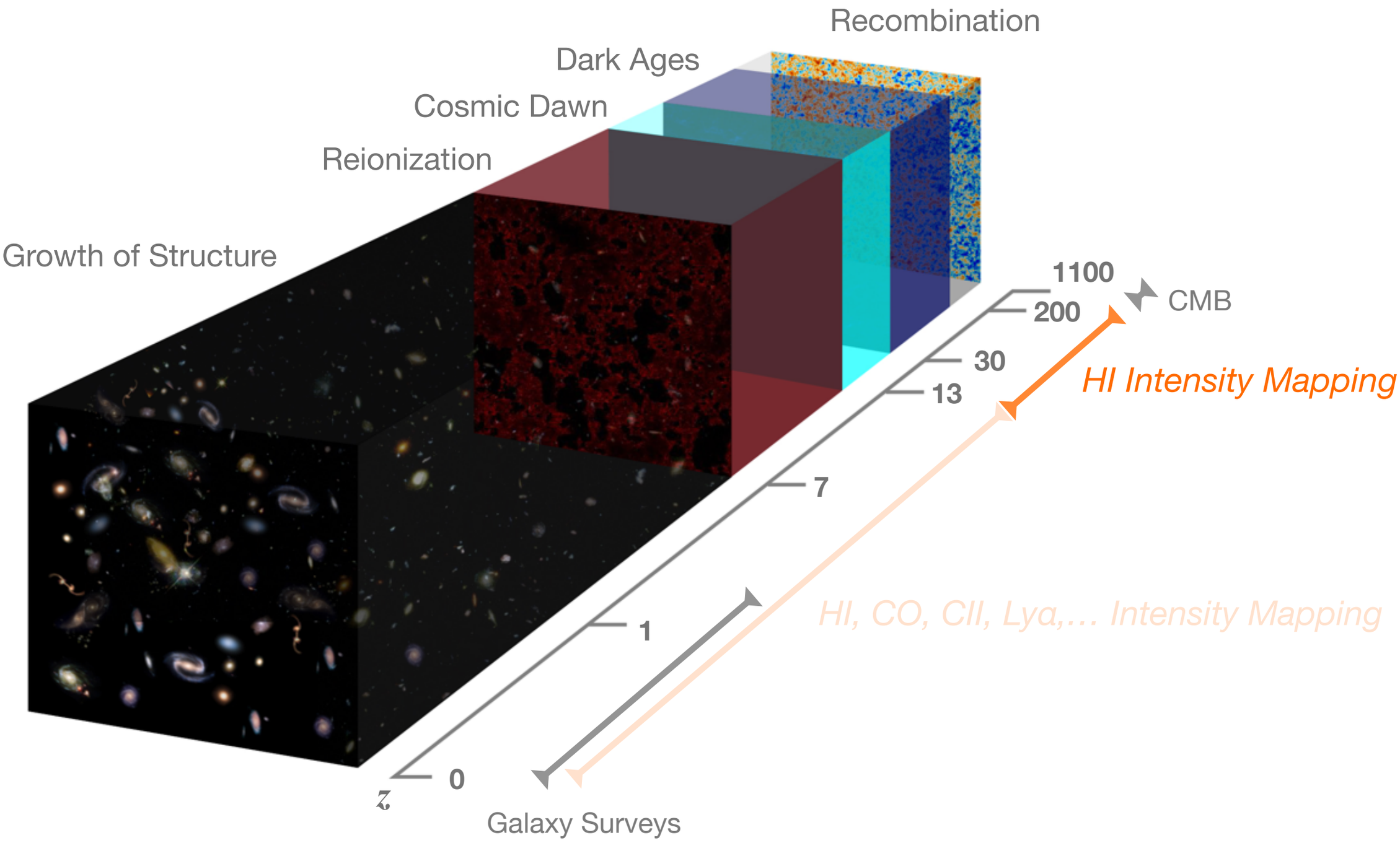

The Dark Matter (Mass) Landscape

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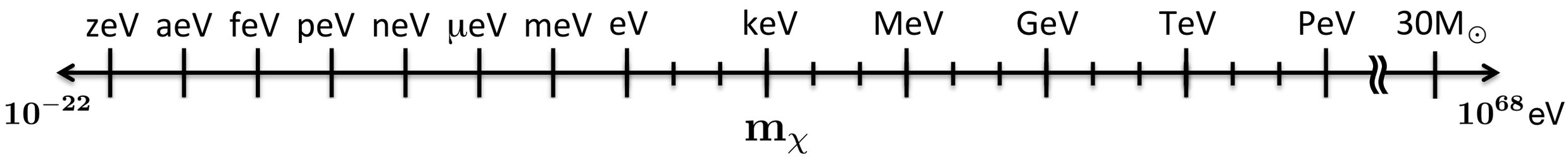
(adapted from “US Cosmic Visions” 2017 Report: Battaglieri et al., arXiv:1707.04591)



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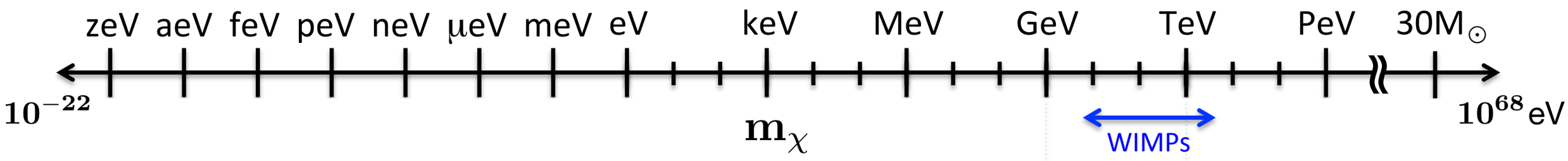

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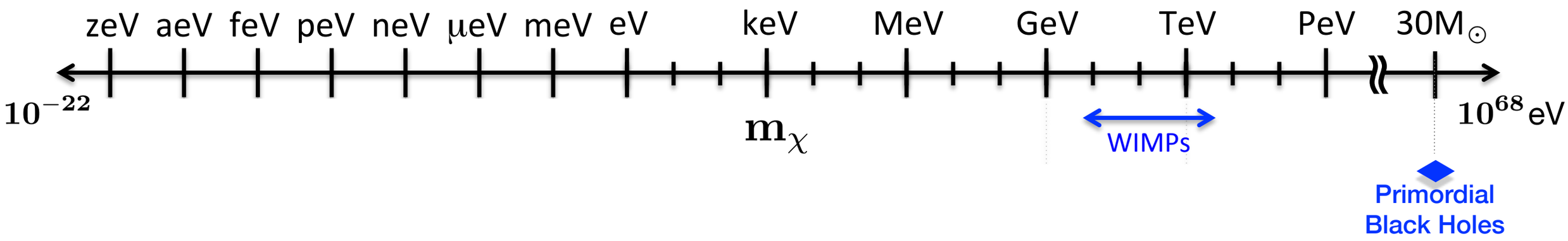

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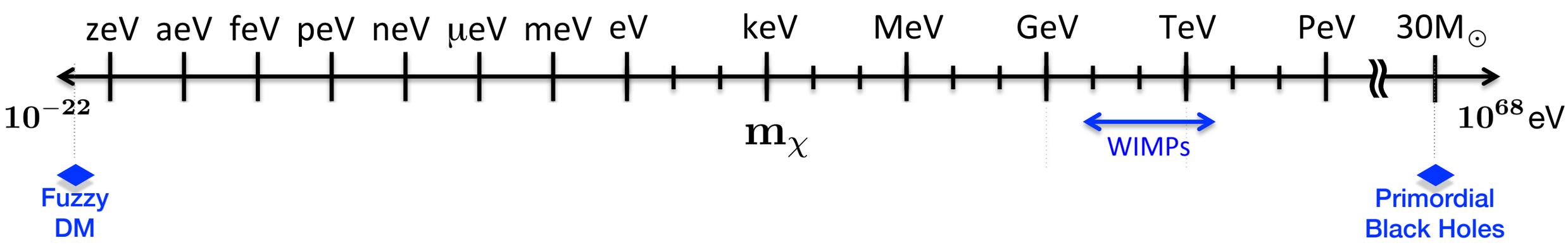

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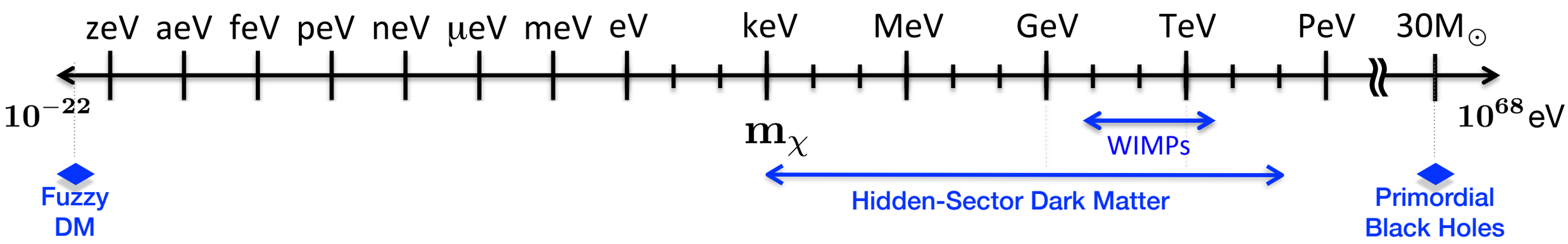

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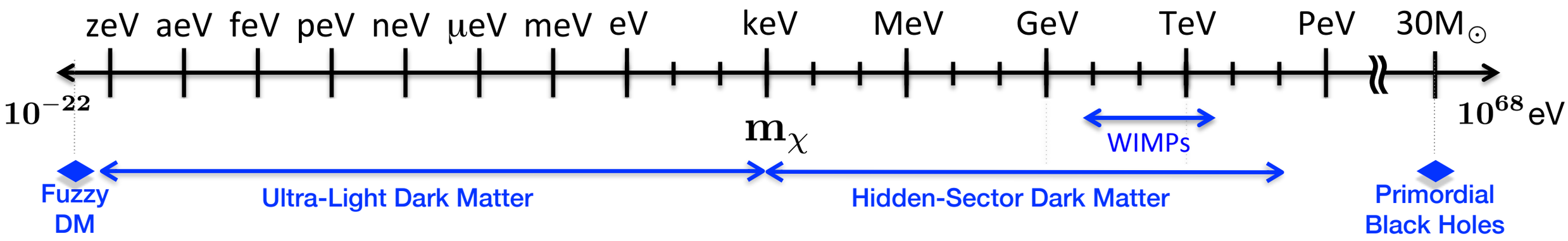

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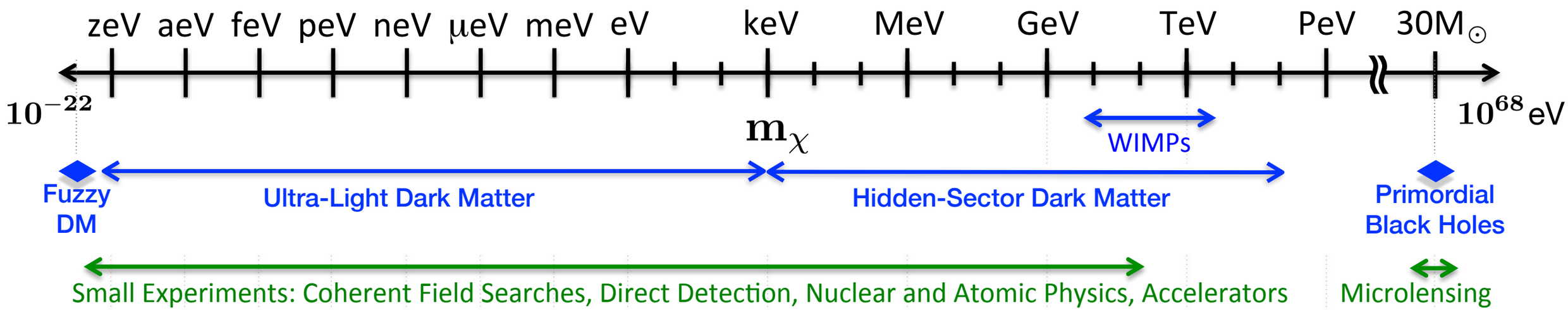

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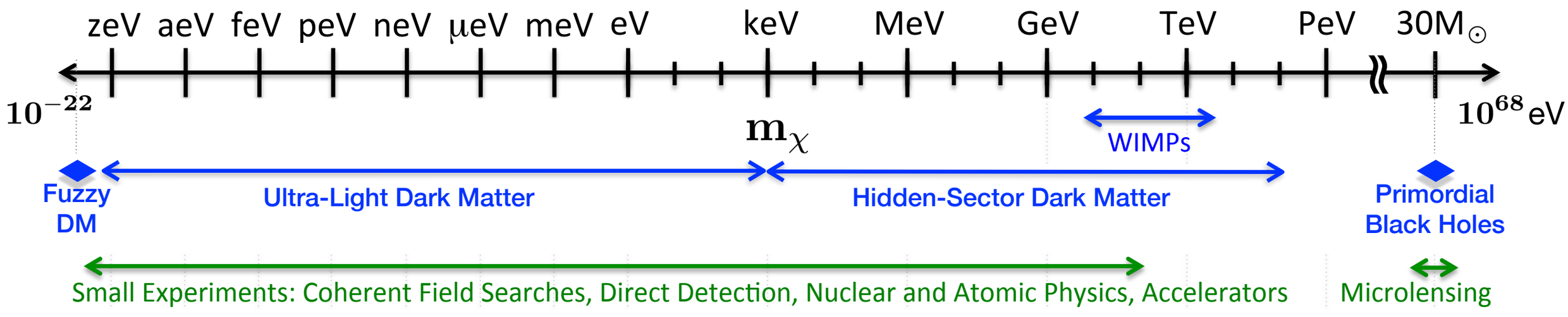
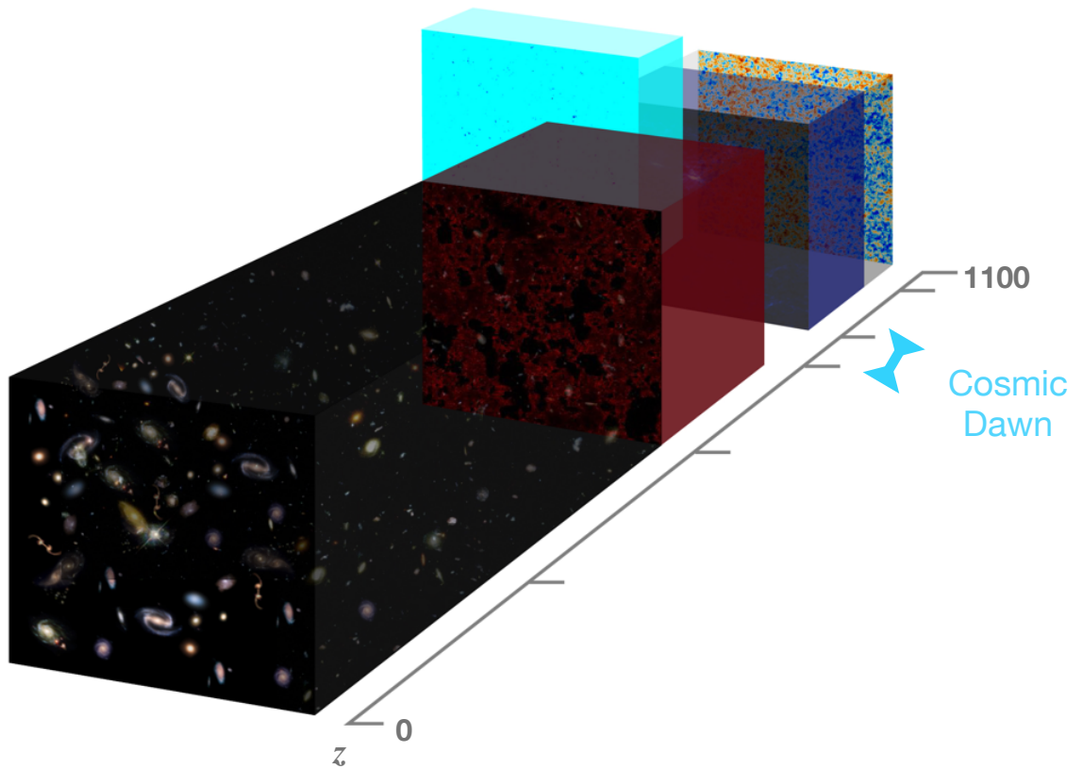


This talk: What can we do with HI LIM?



Outline

Ely Kovetz
MPIK, Feb. 2022

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- The future of 21cm as a Dark Matter probe

The Cosmological 21cm Signal: Lightning Review

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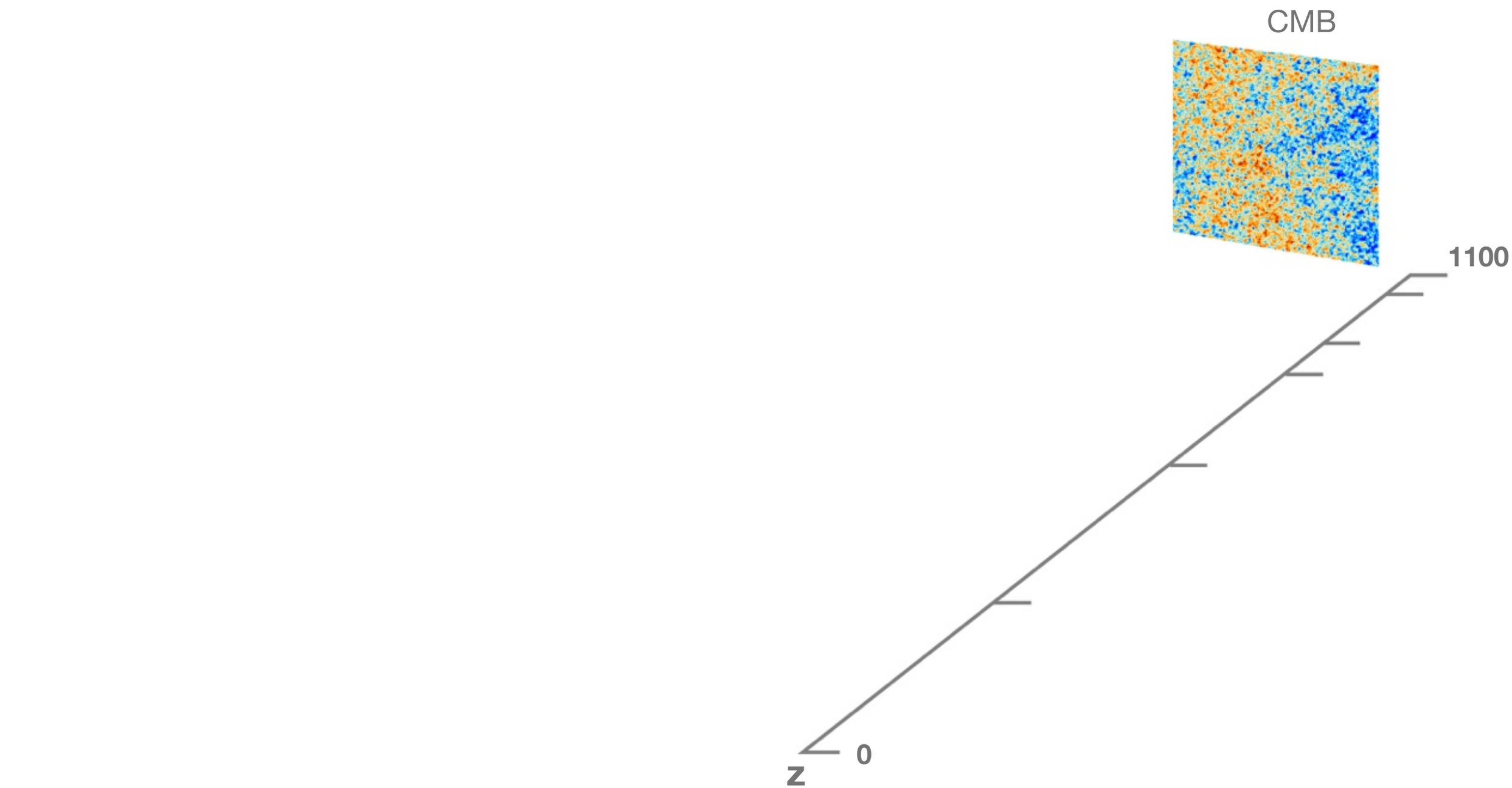

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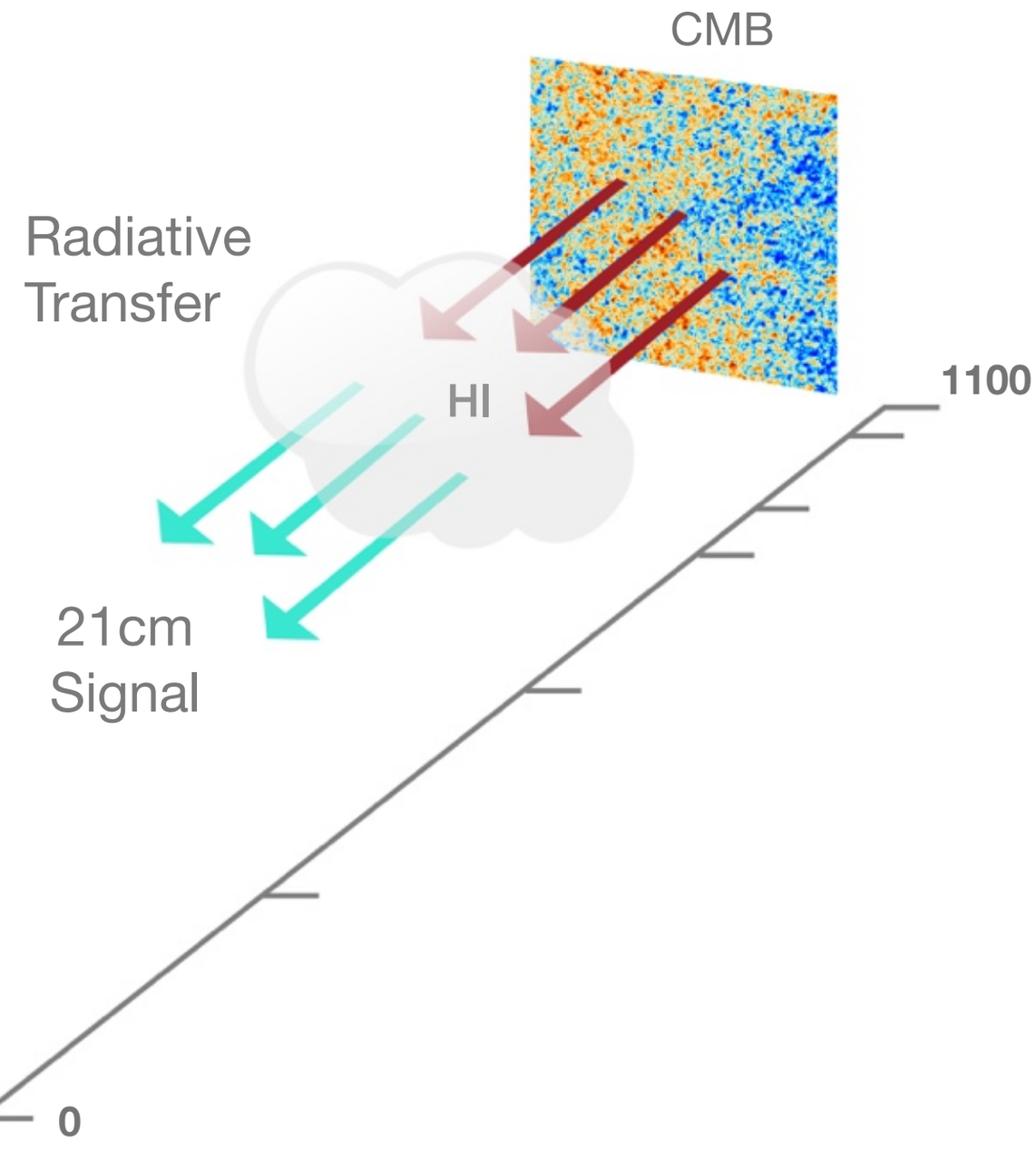

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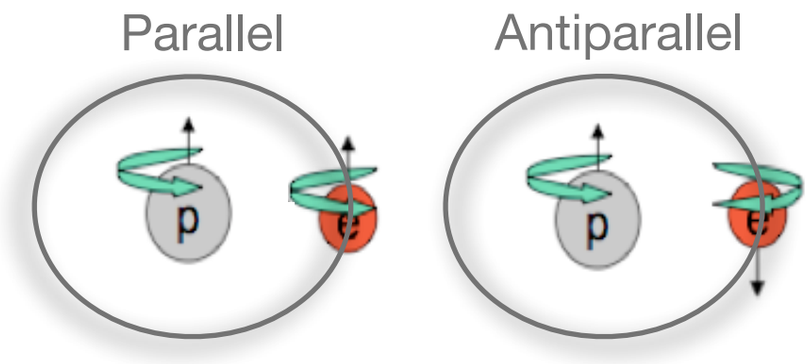

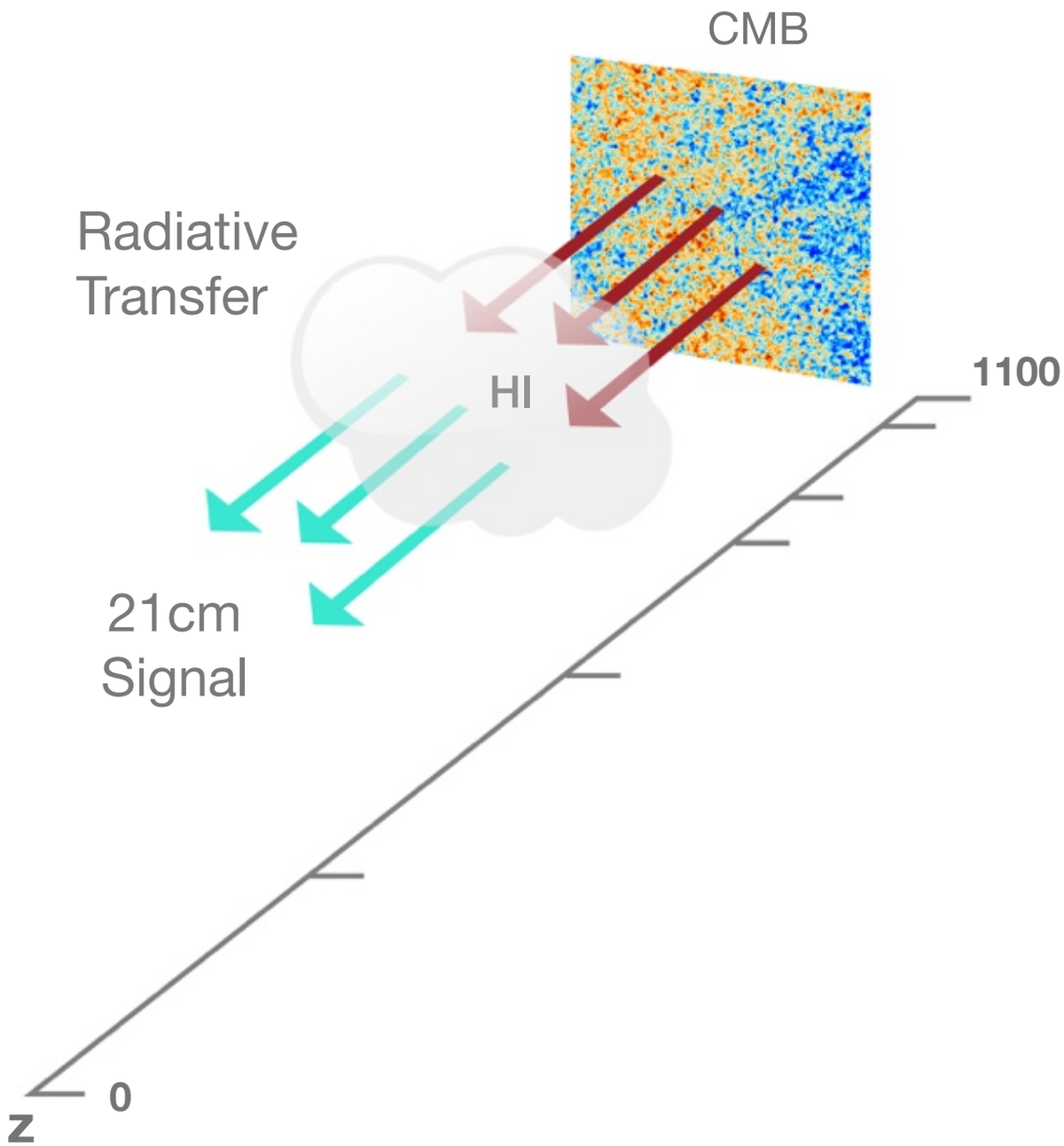

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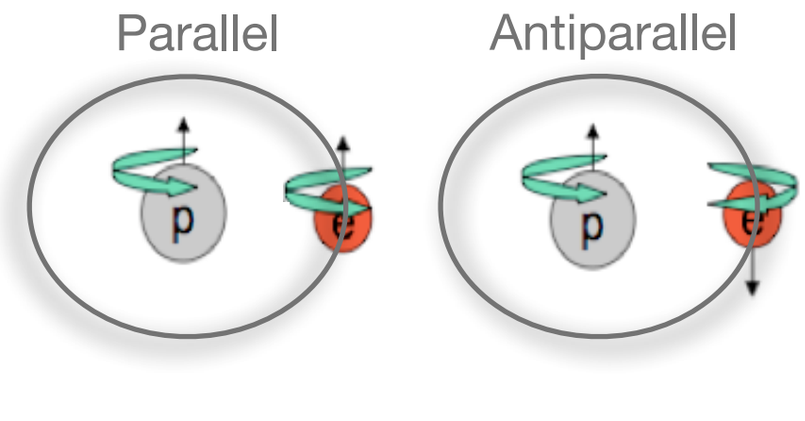

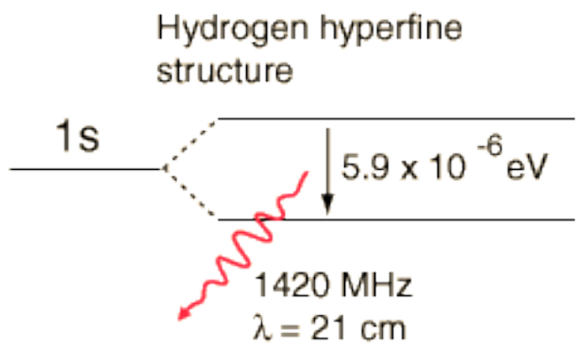

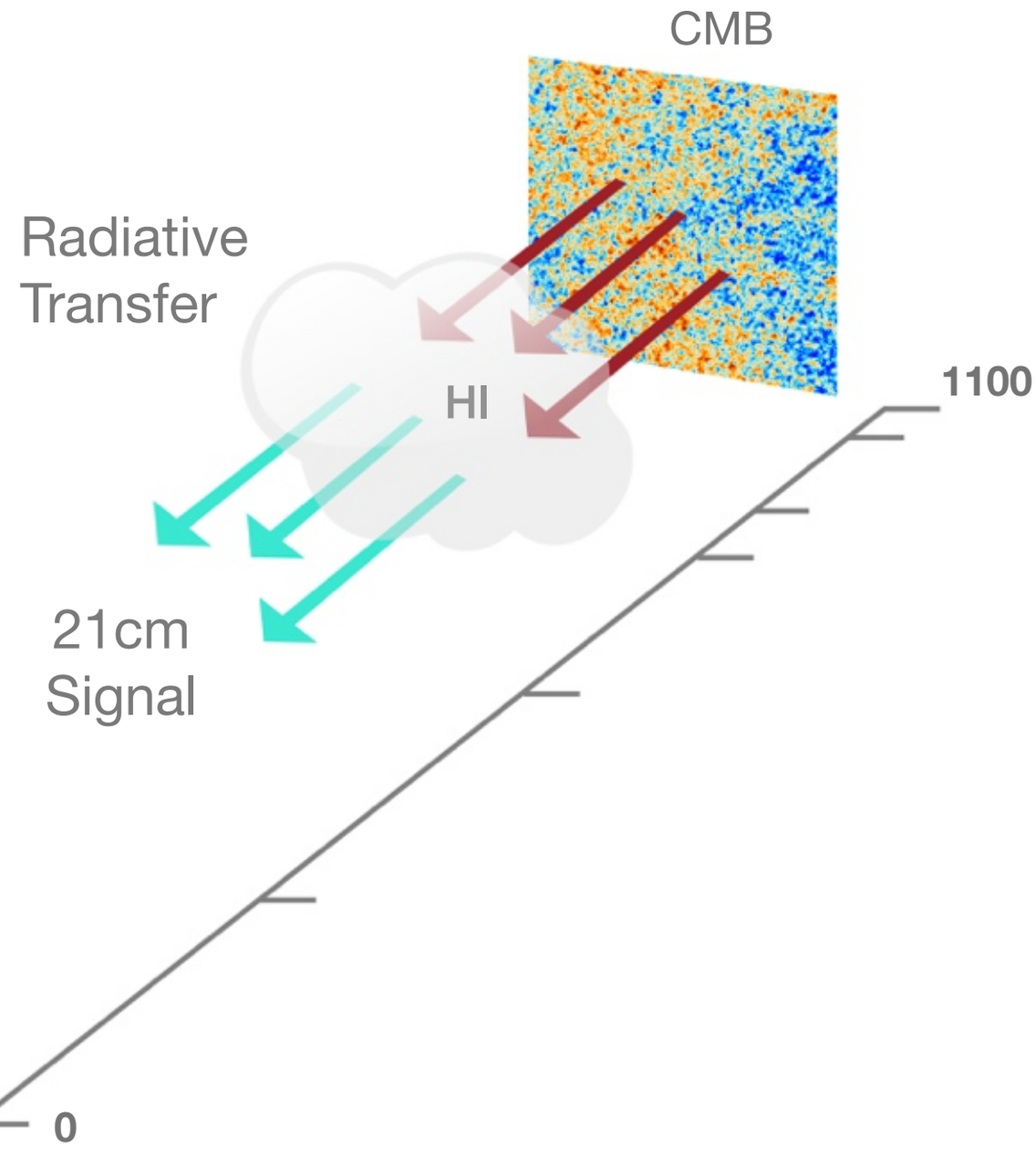

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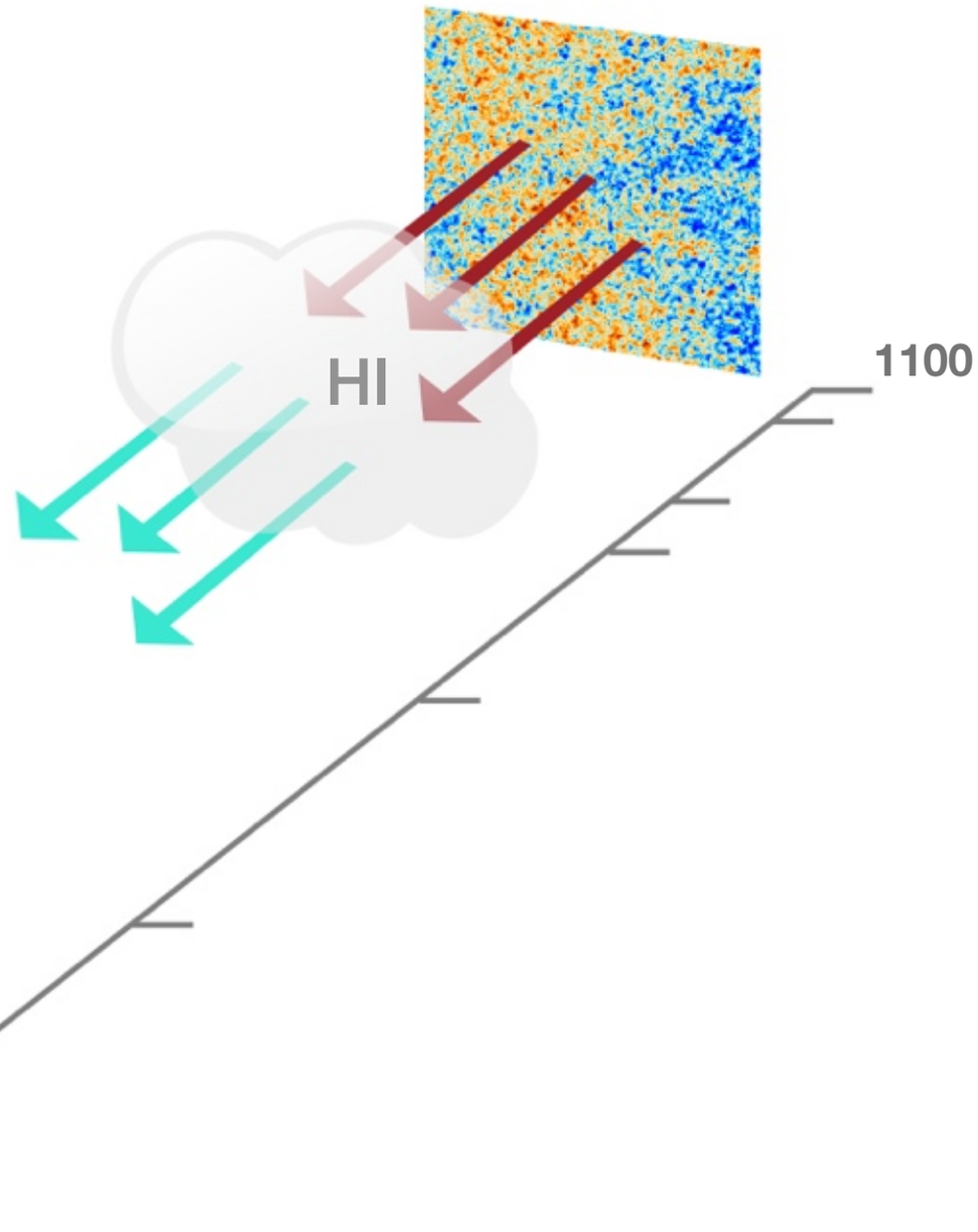

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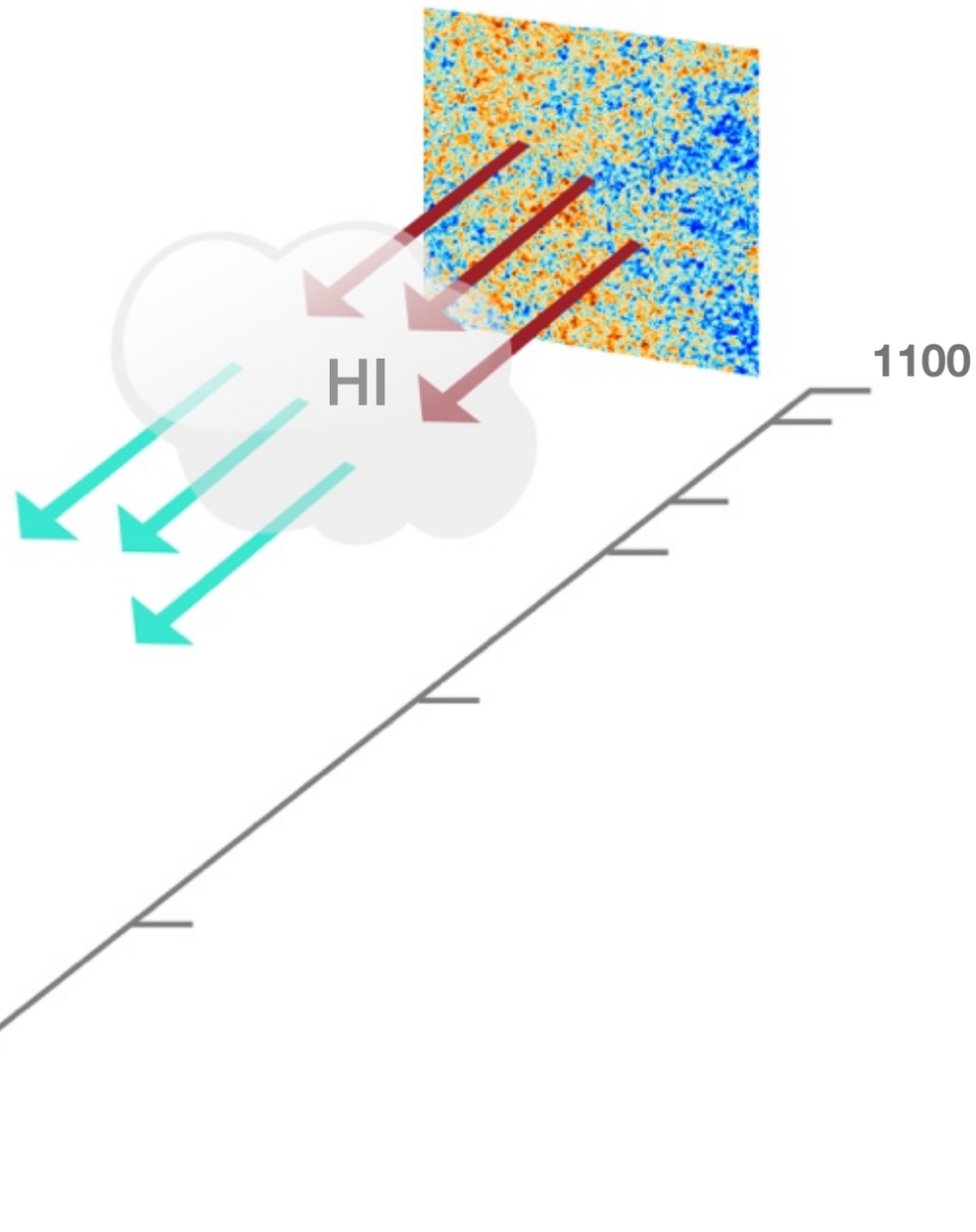
Game of *Temperatures*:



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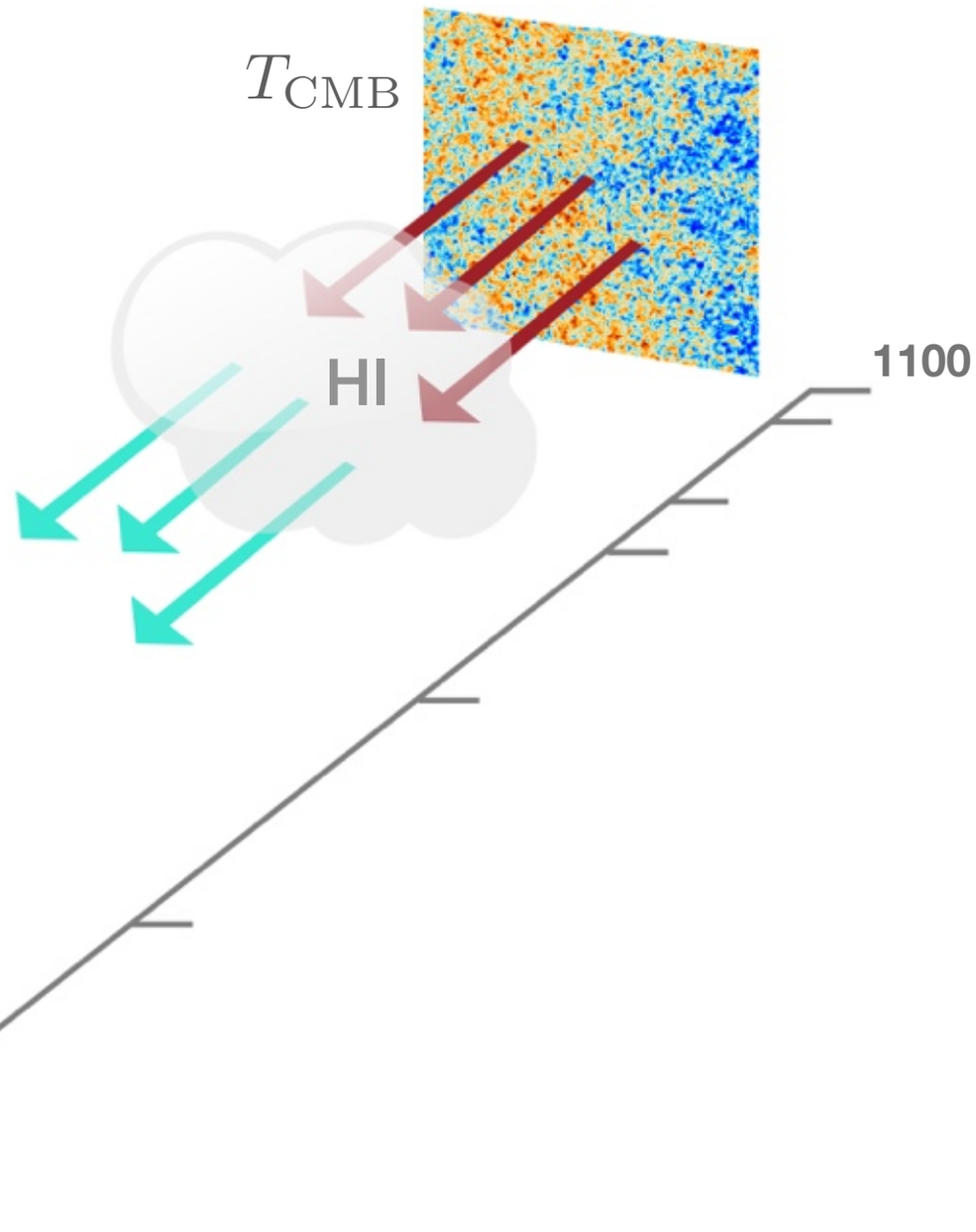

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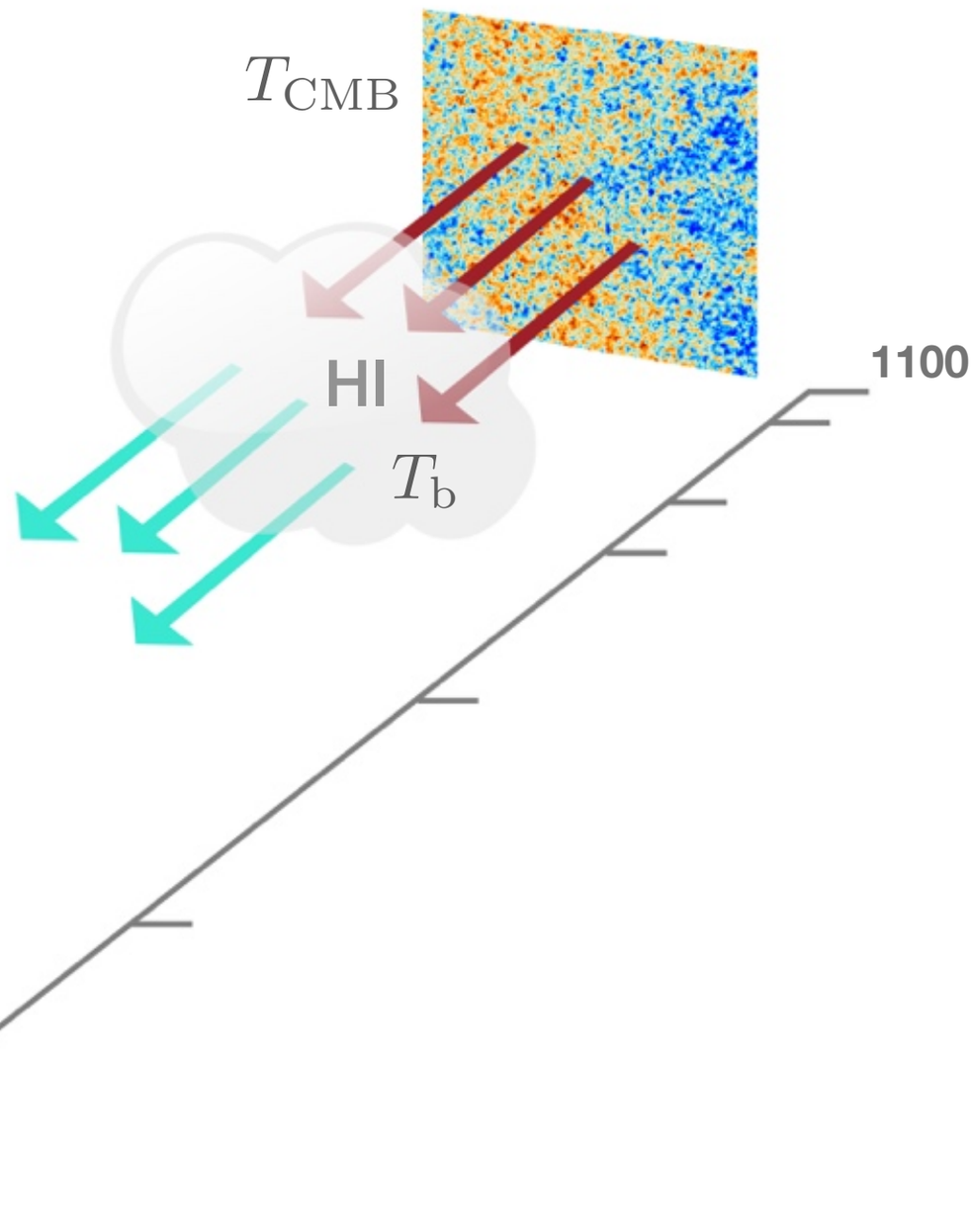

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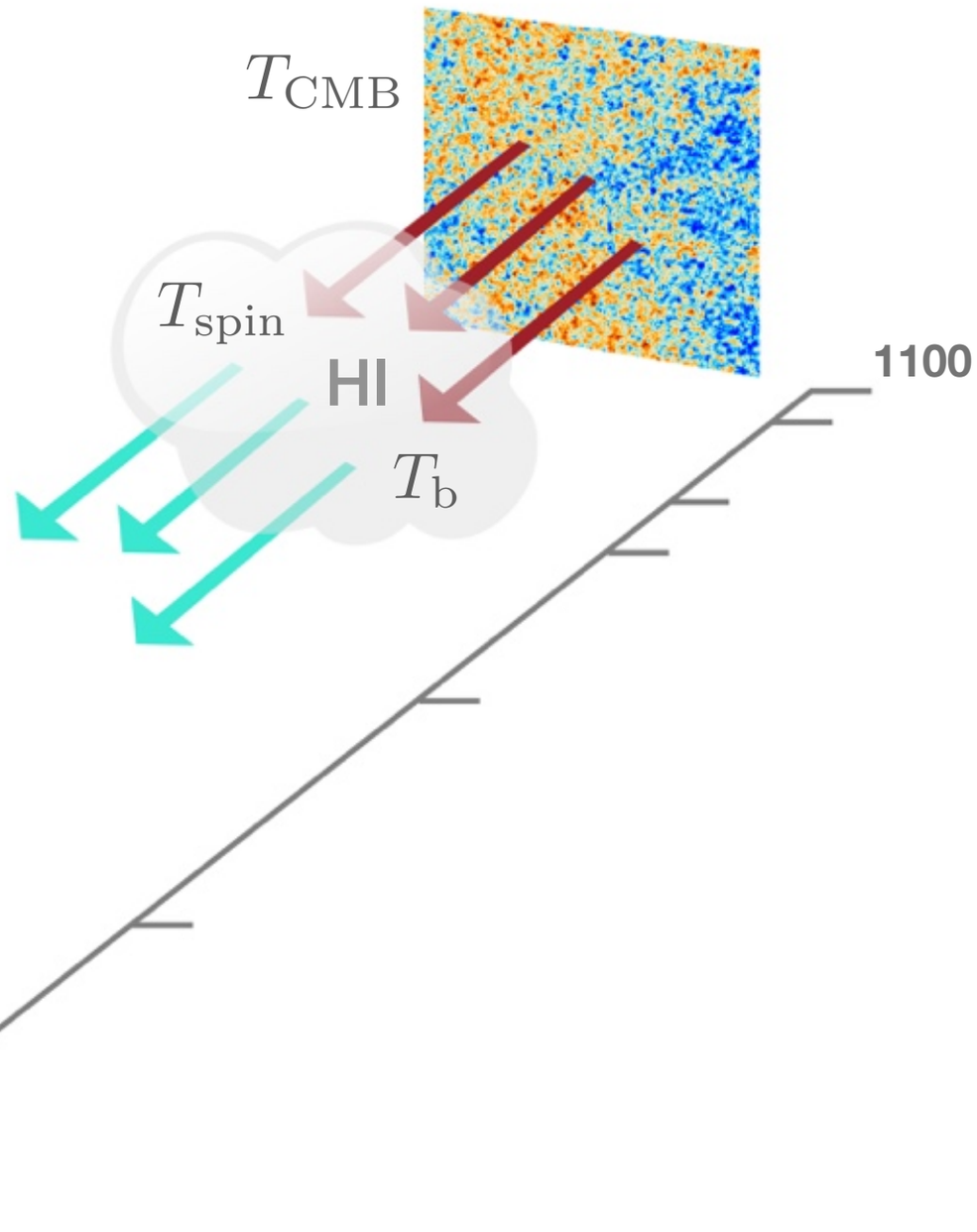

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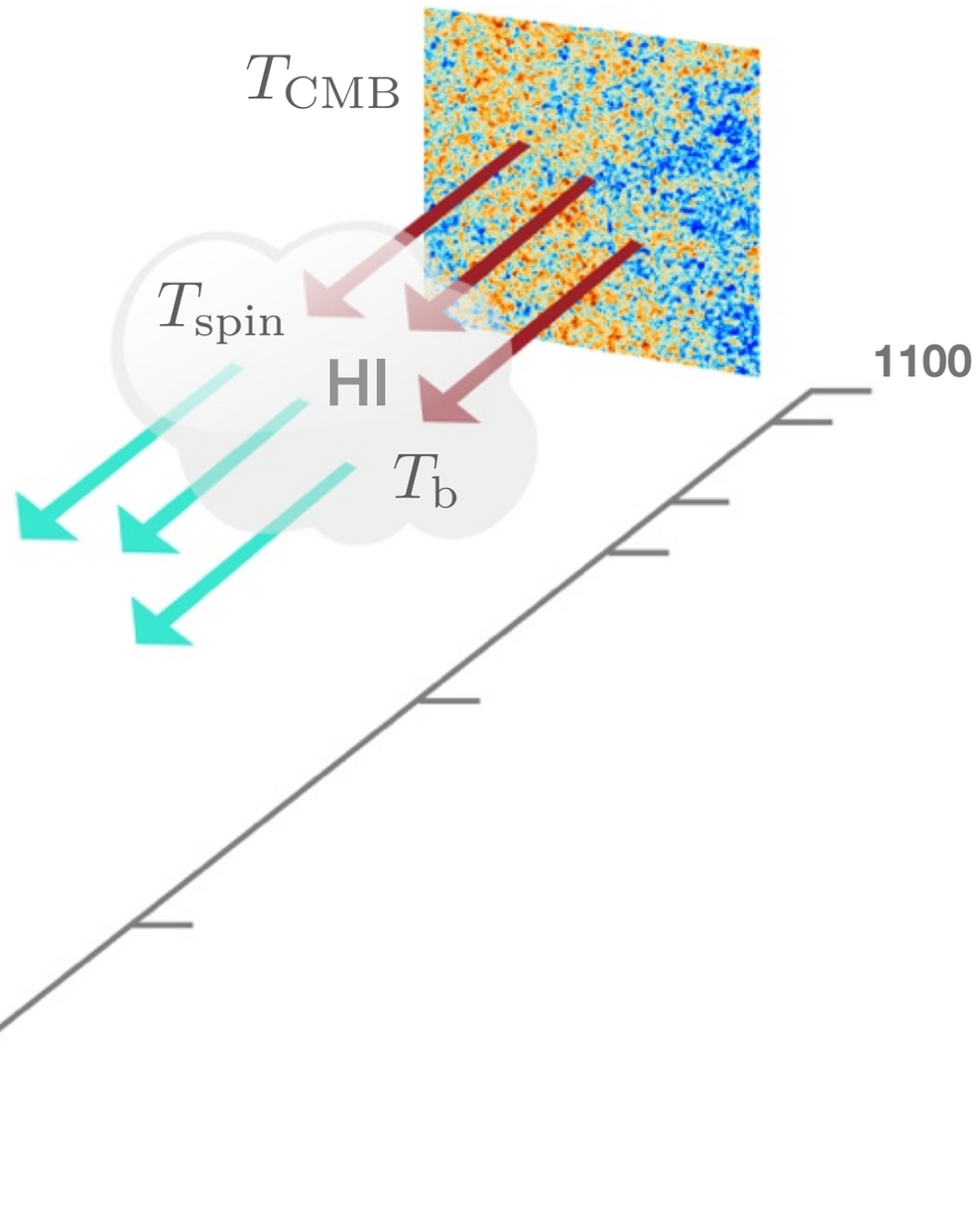

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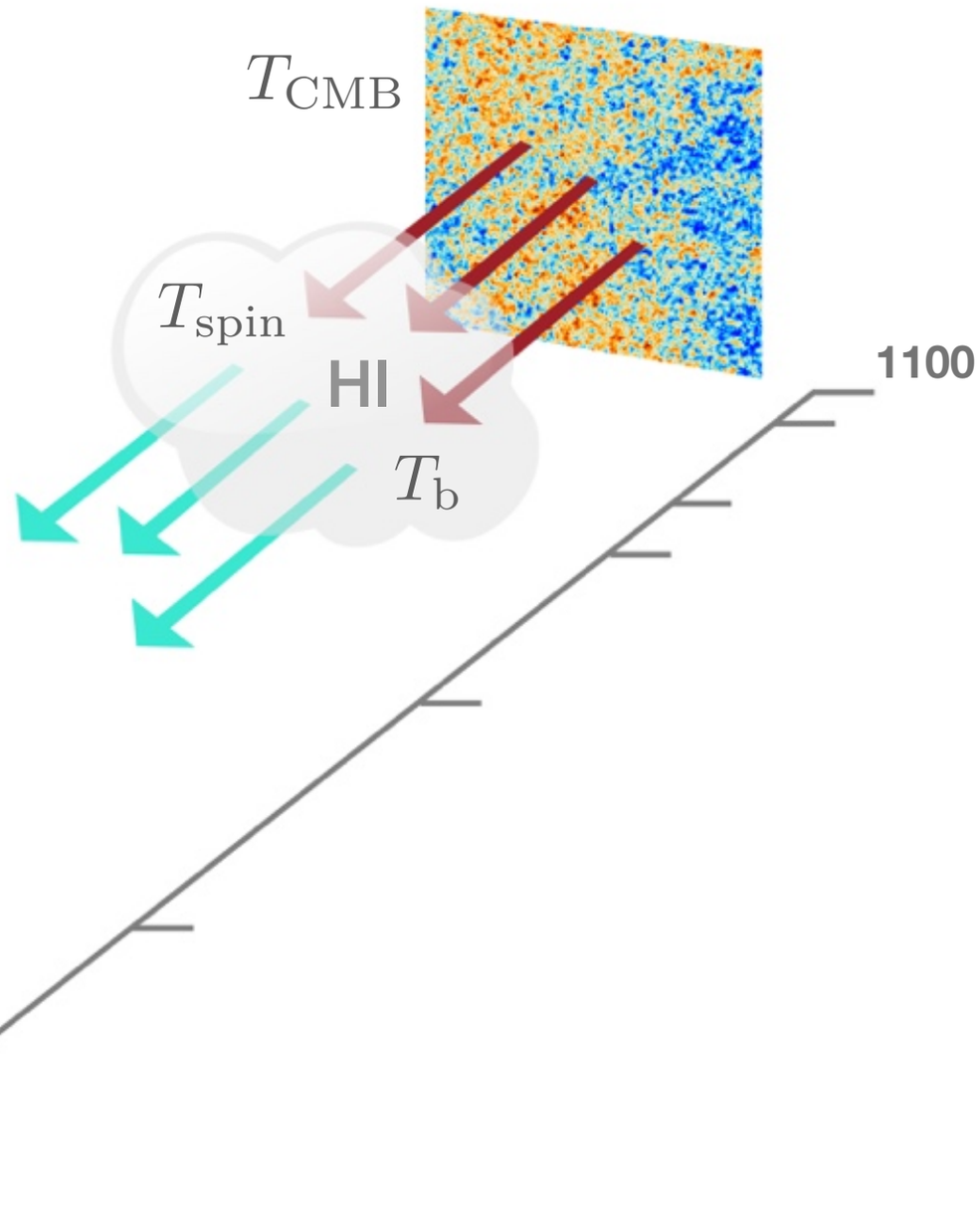

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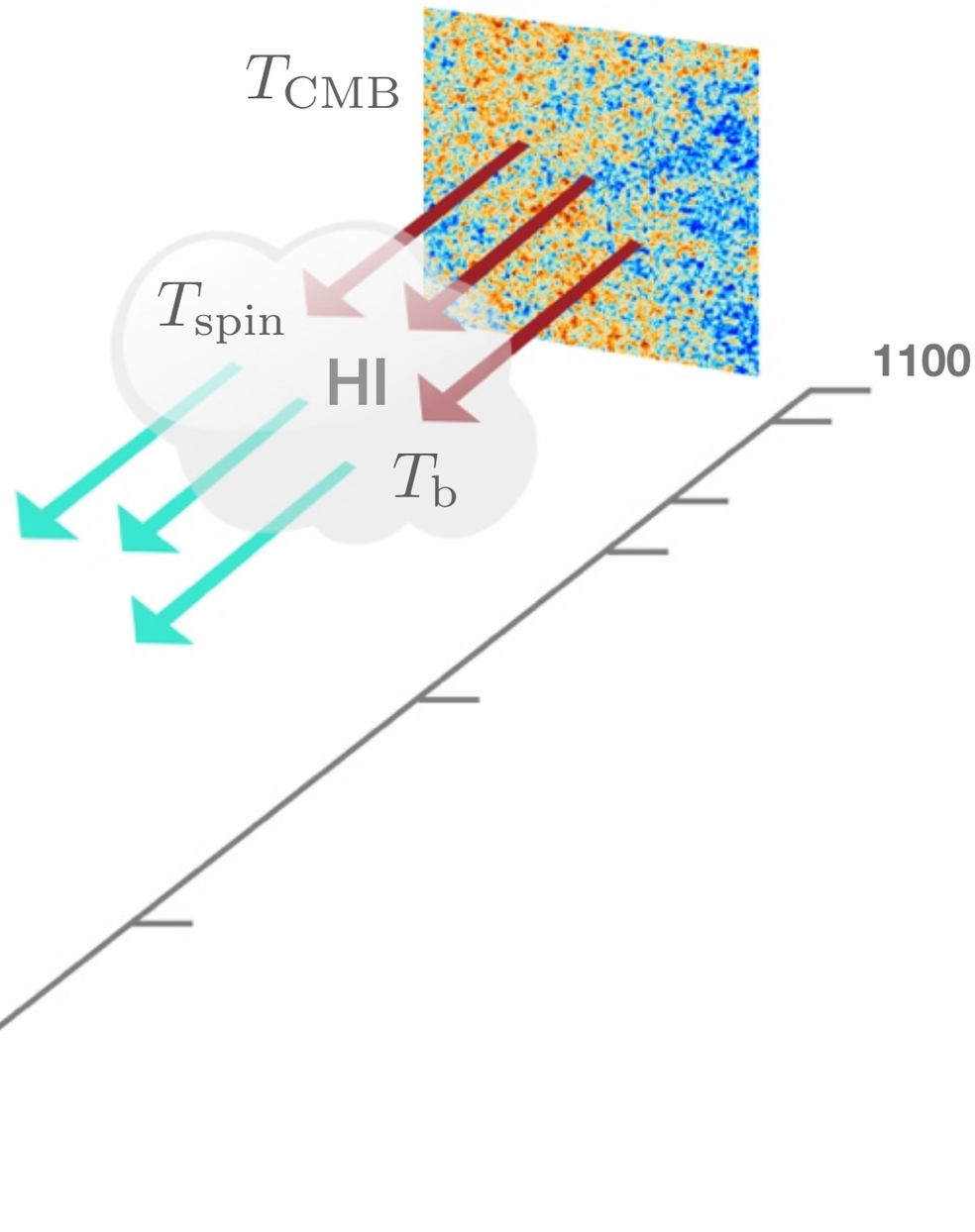

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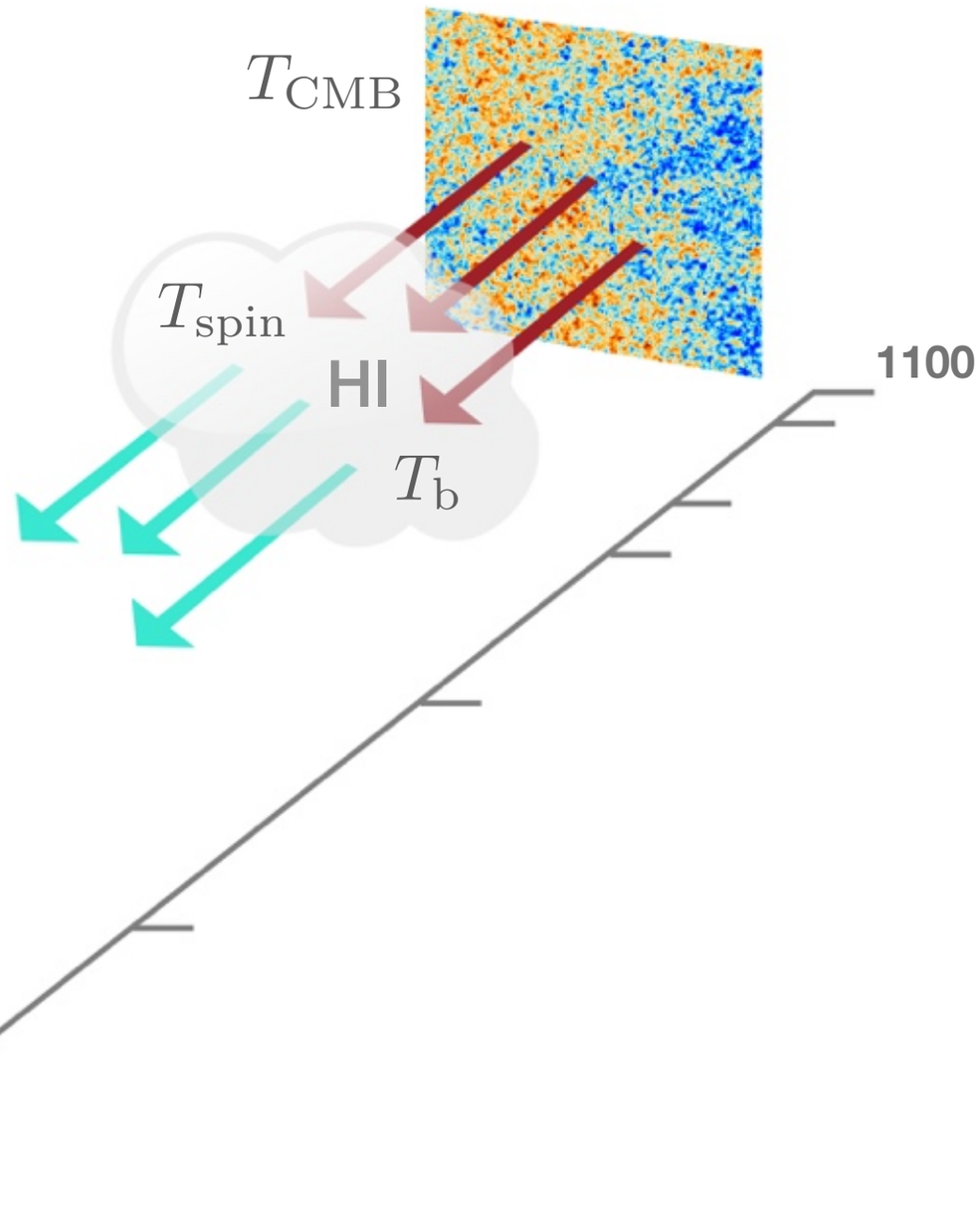

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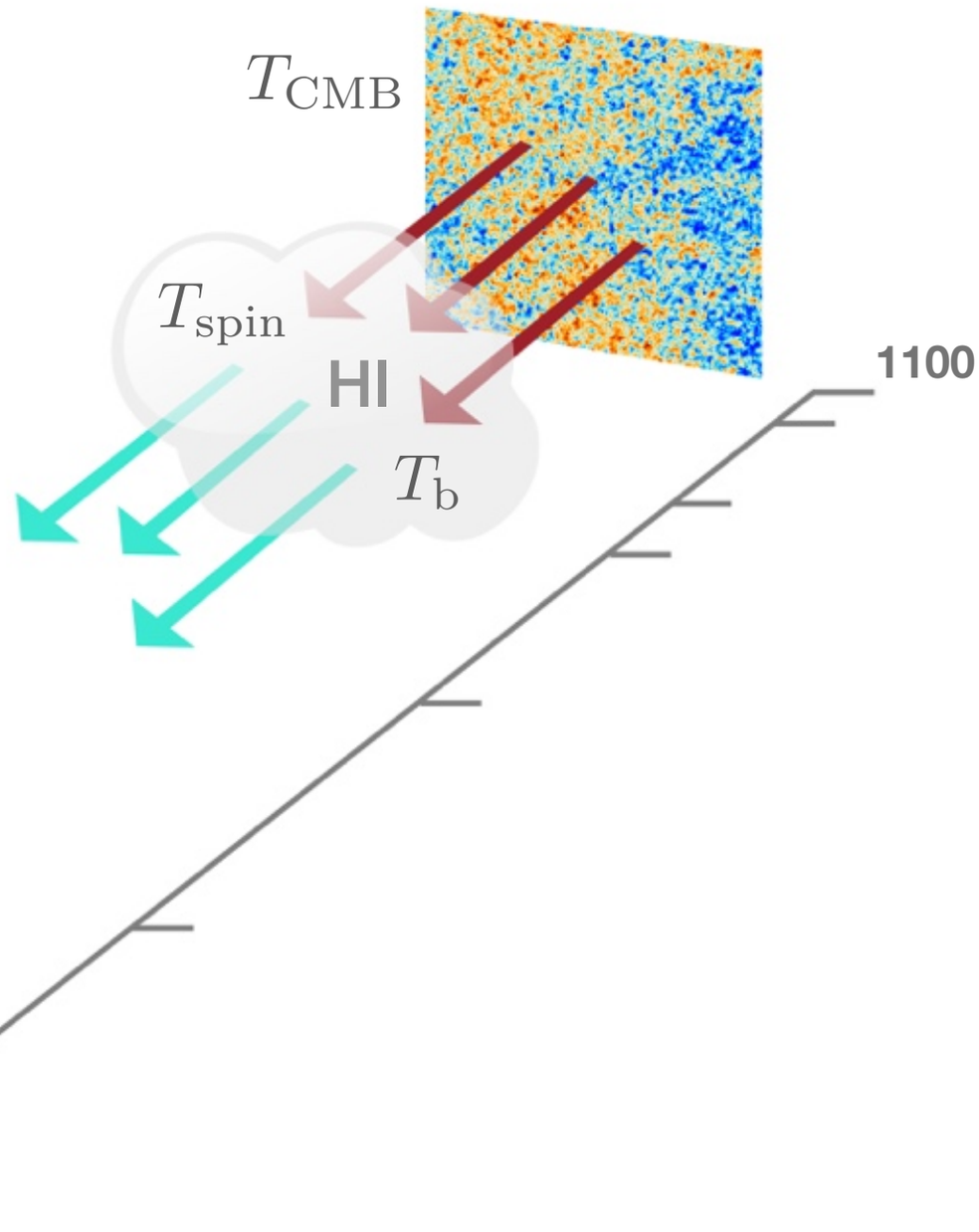

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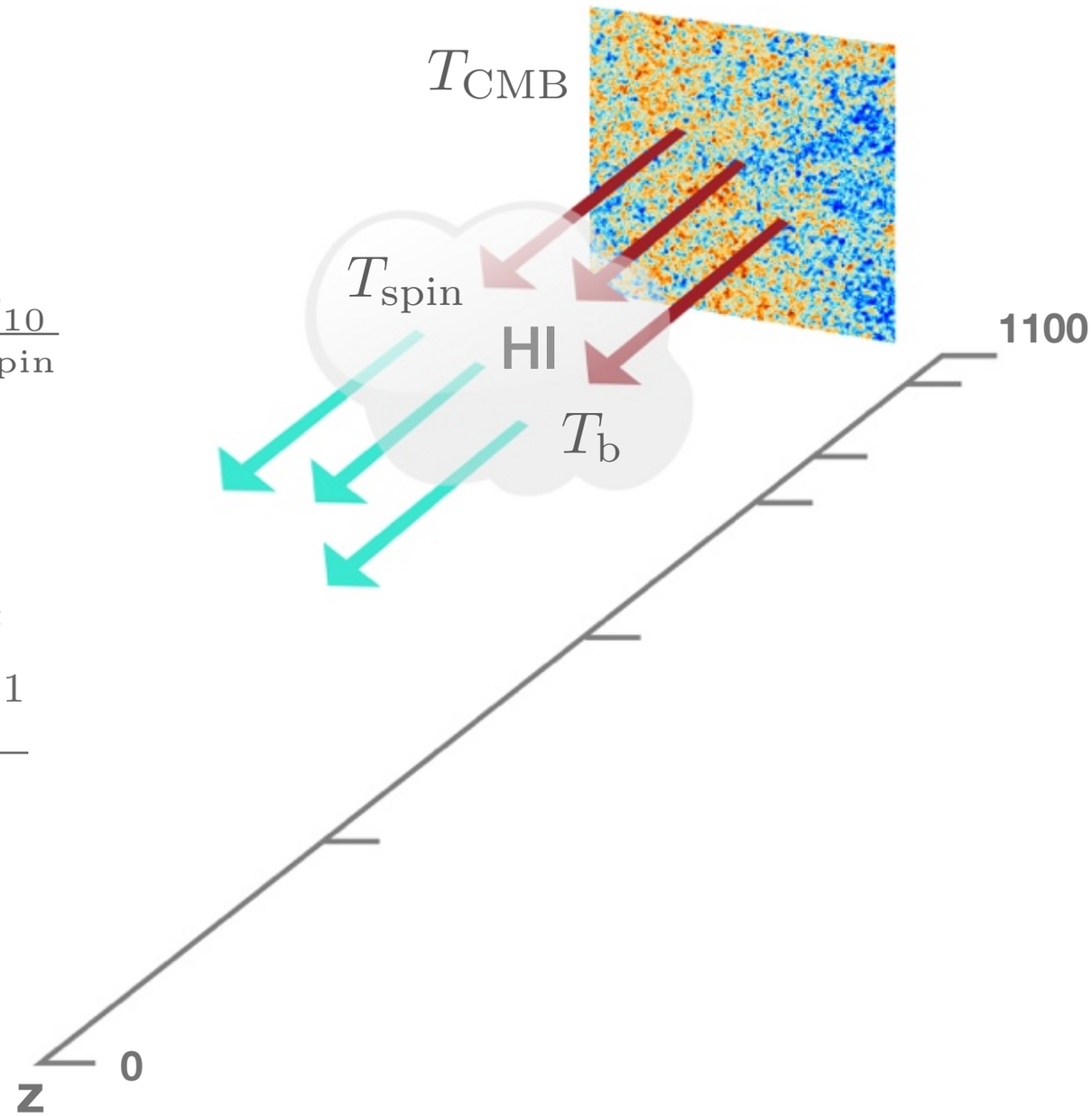

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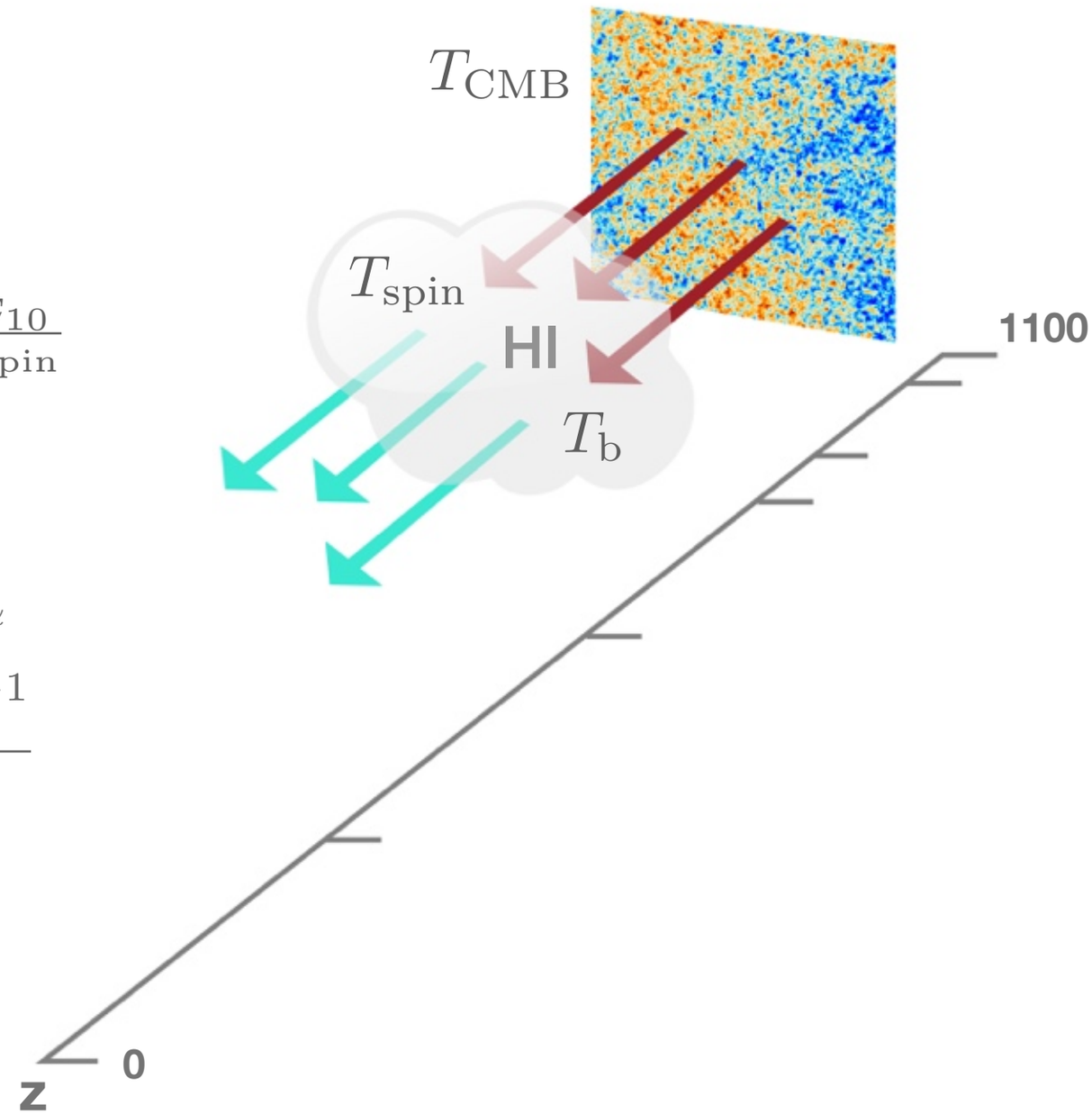

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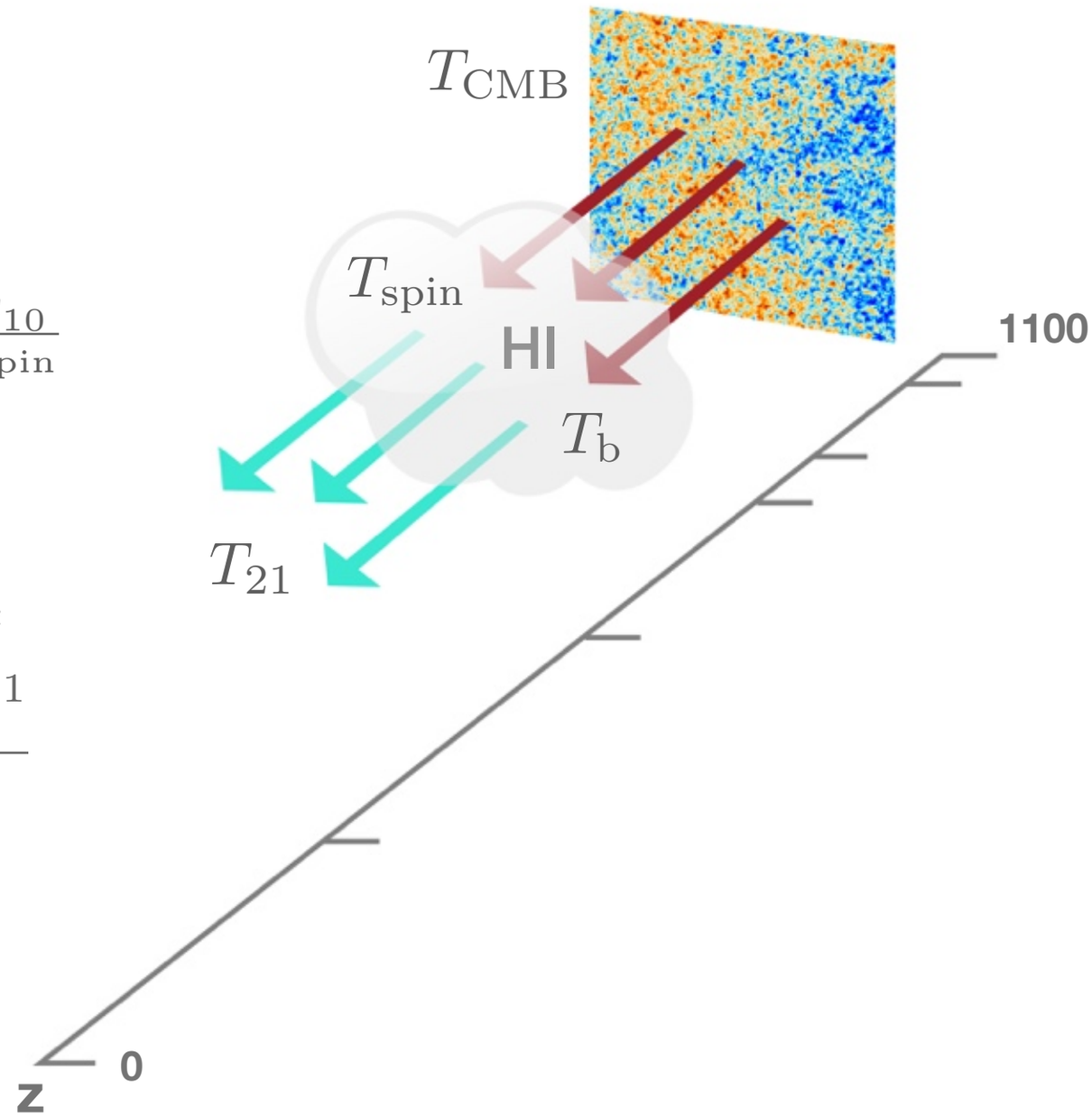

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$$T_{\rm bright} = T_{\rm spin}\left(1 - e^{-\tau}\right) + T_{\rm CMB} e^{-\tau}$$

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

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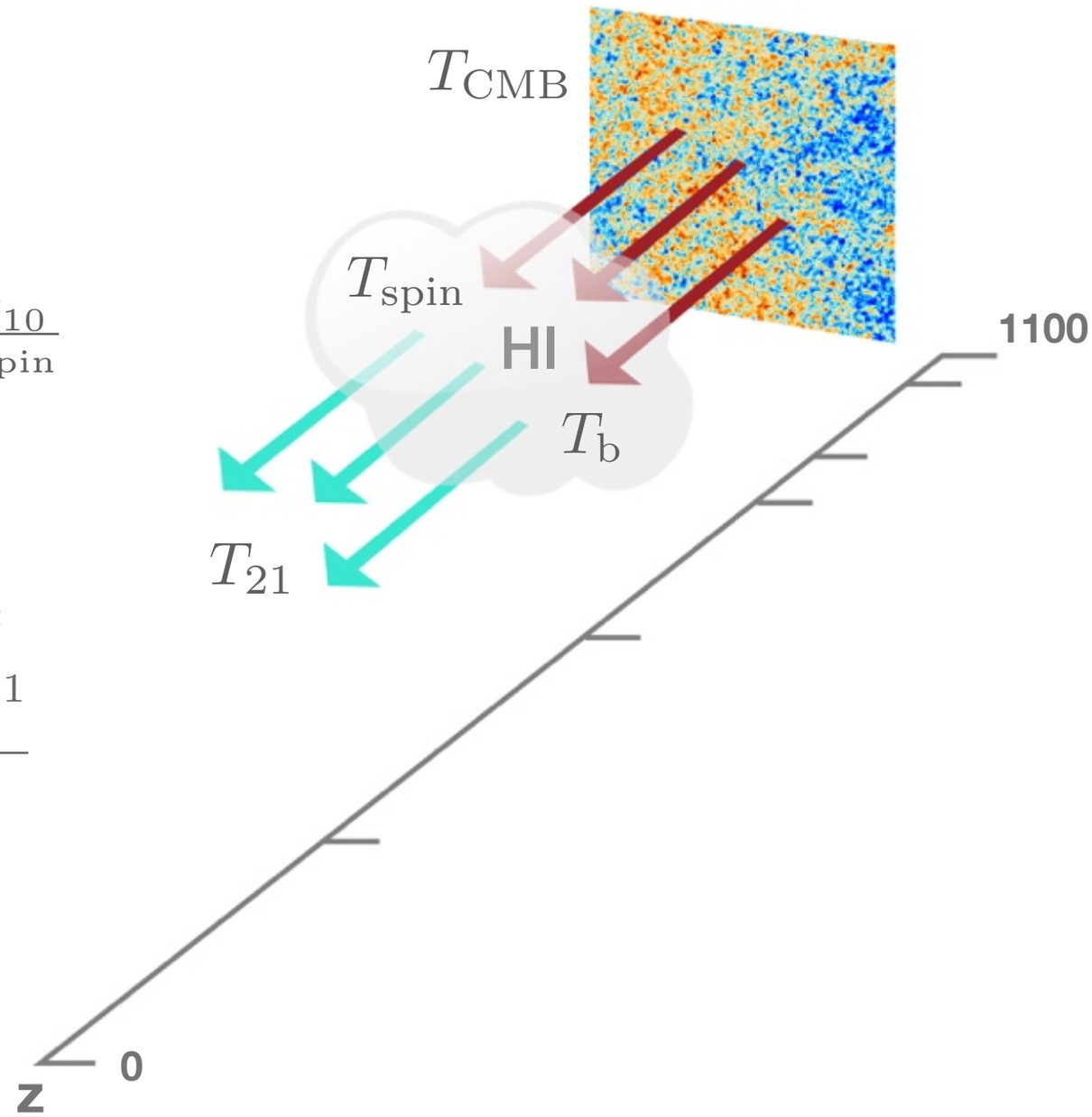

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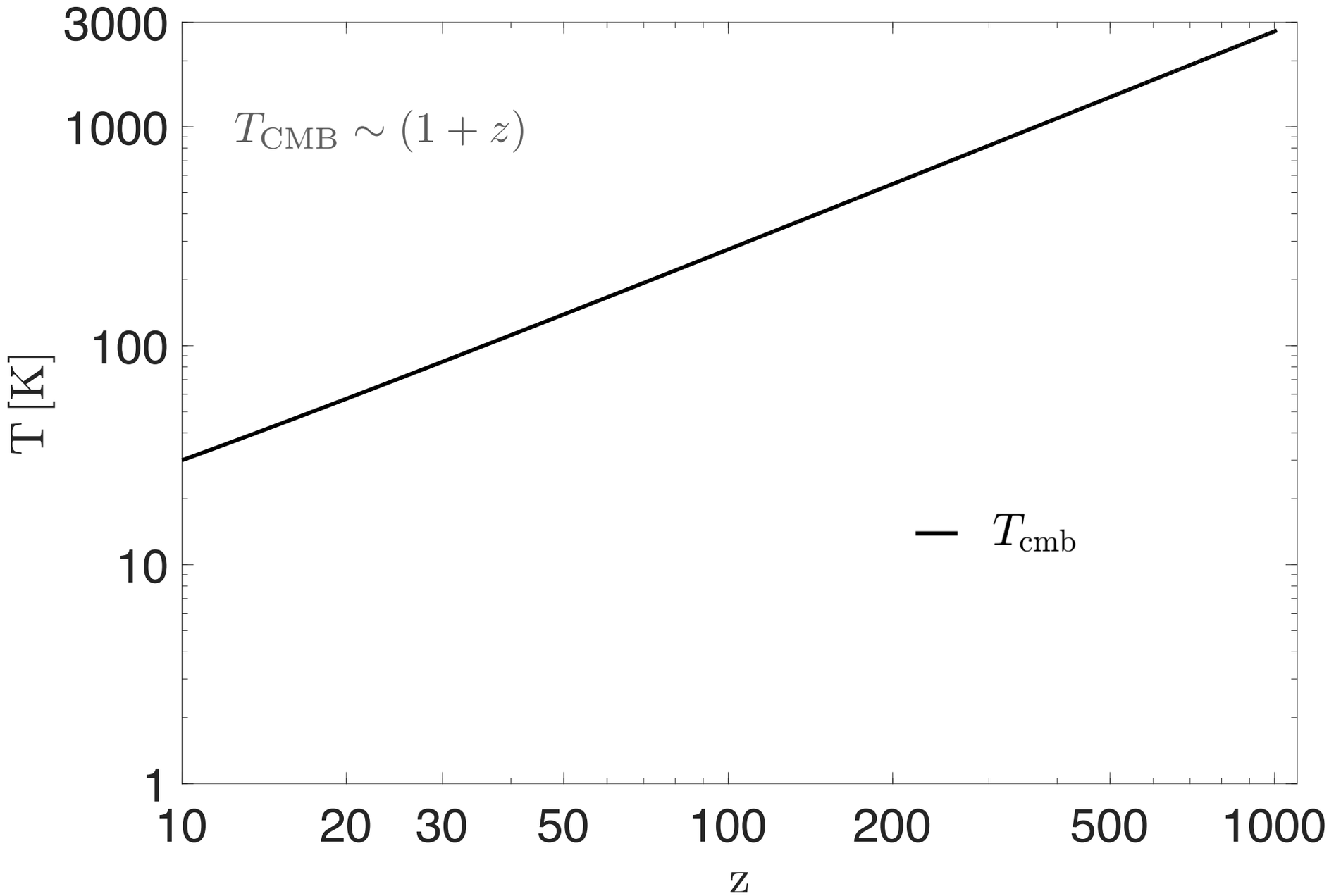

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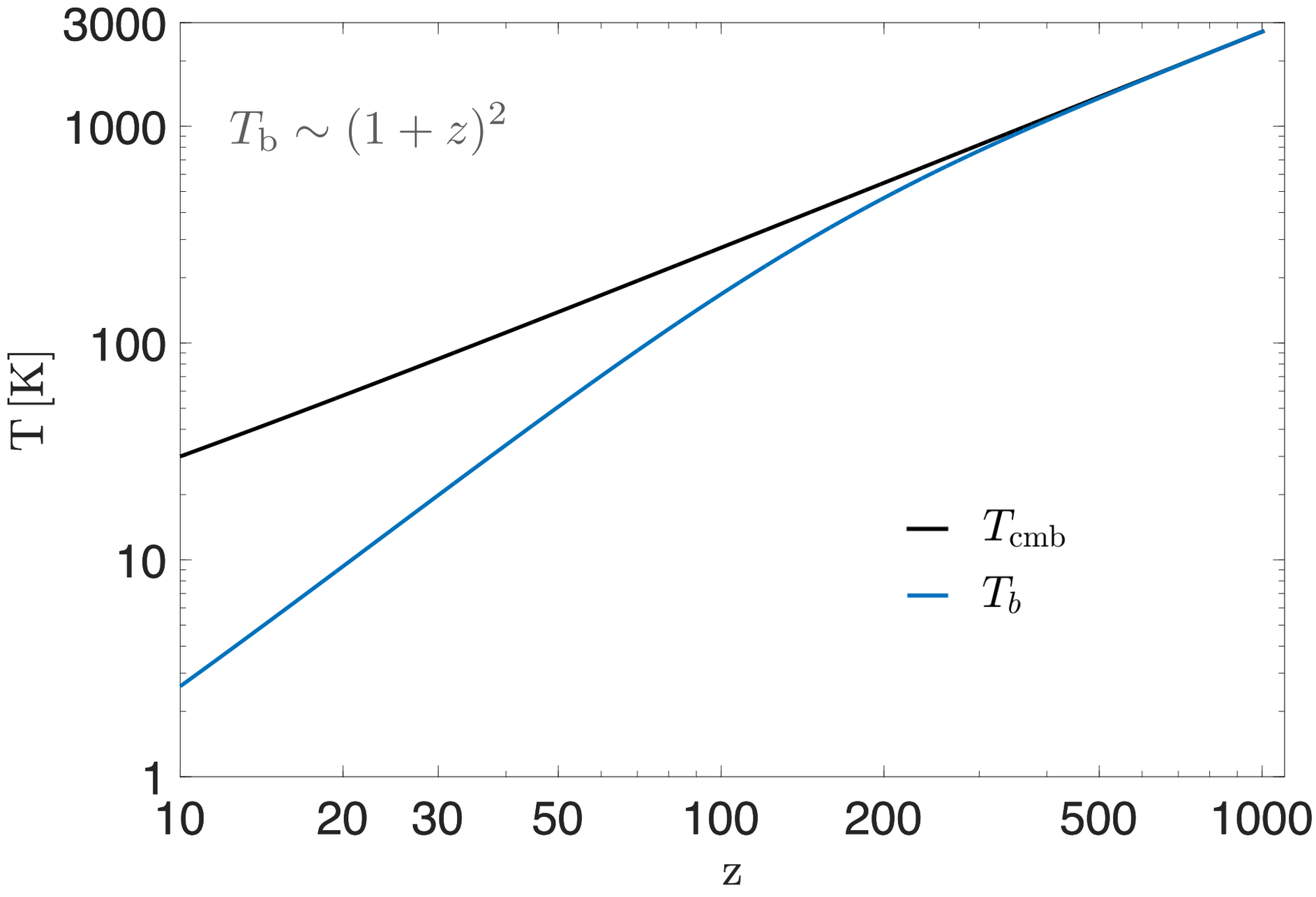

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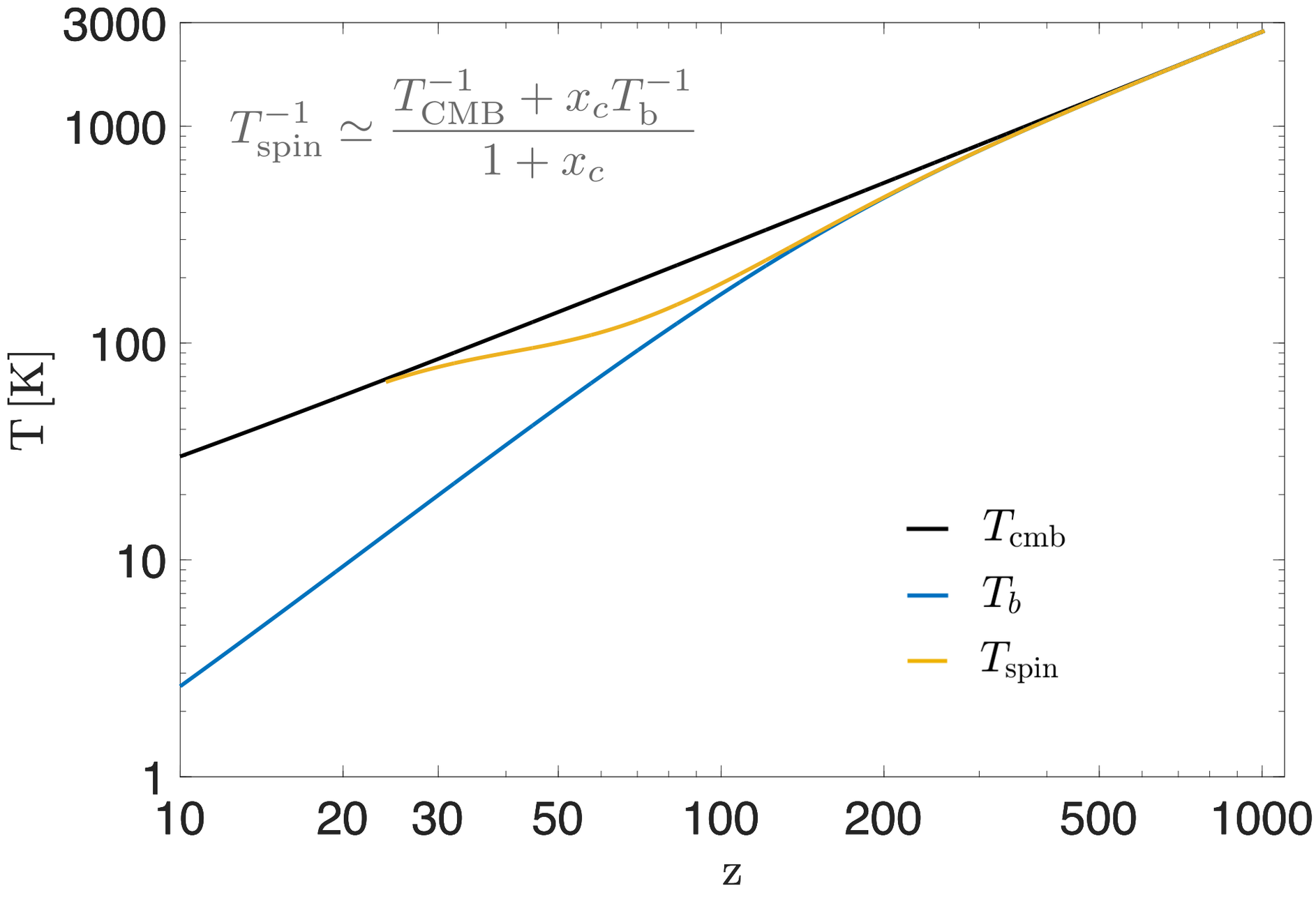

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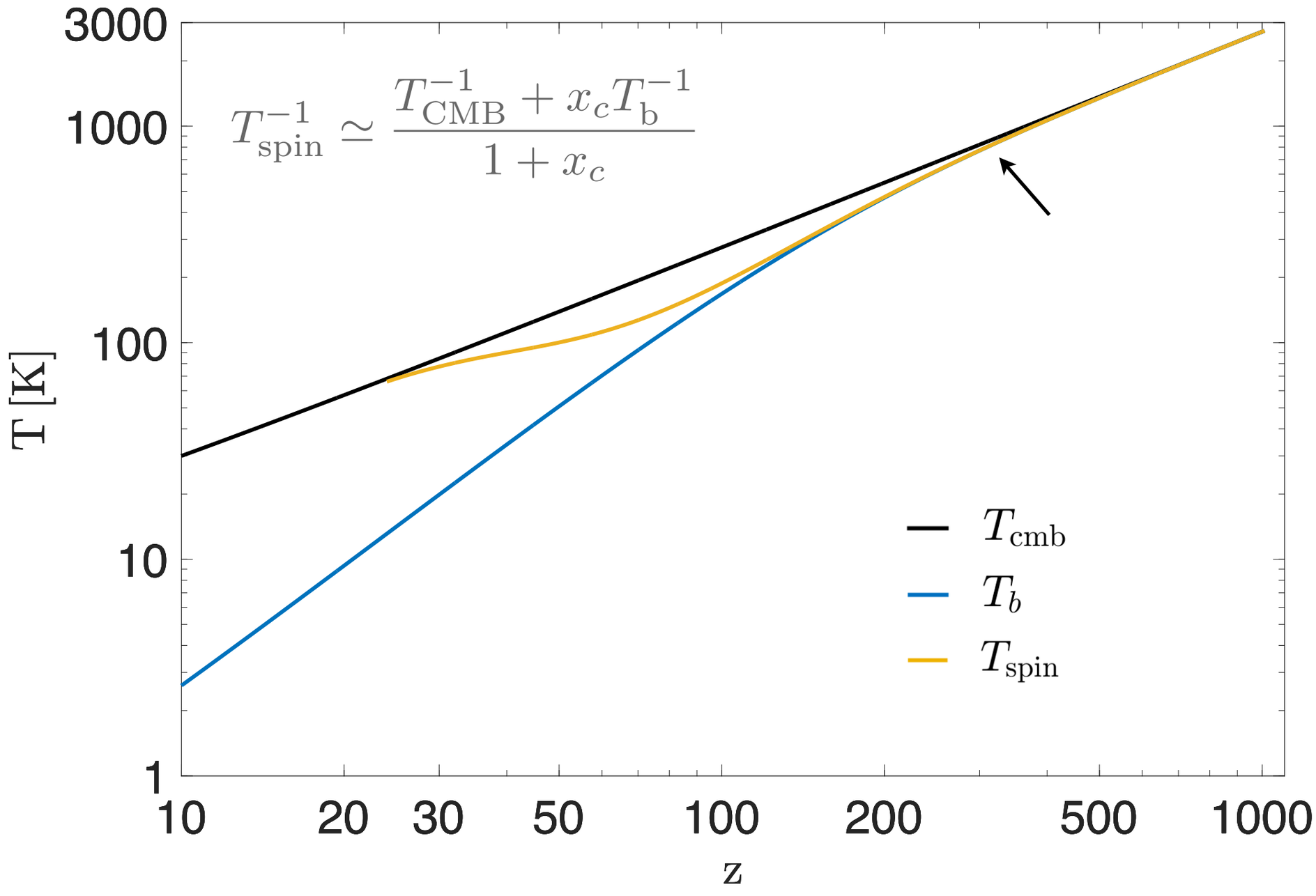

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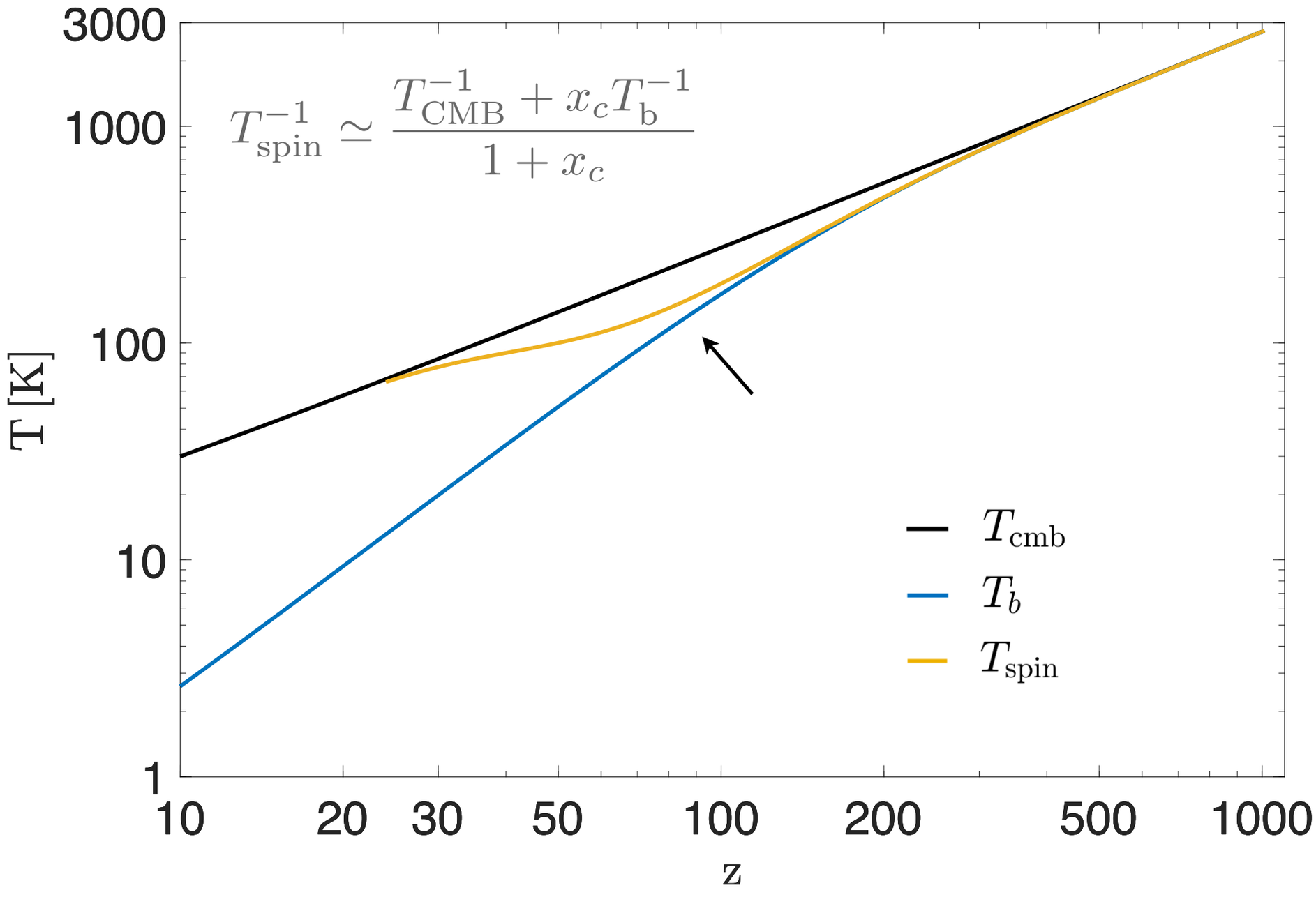

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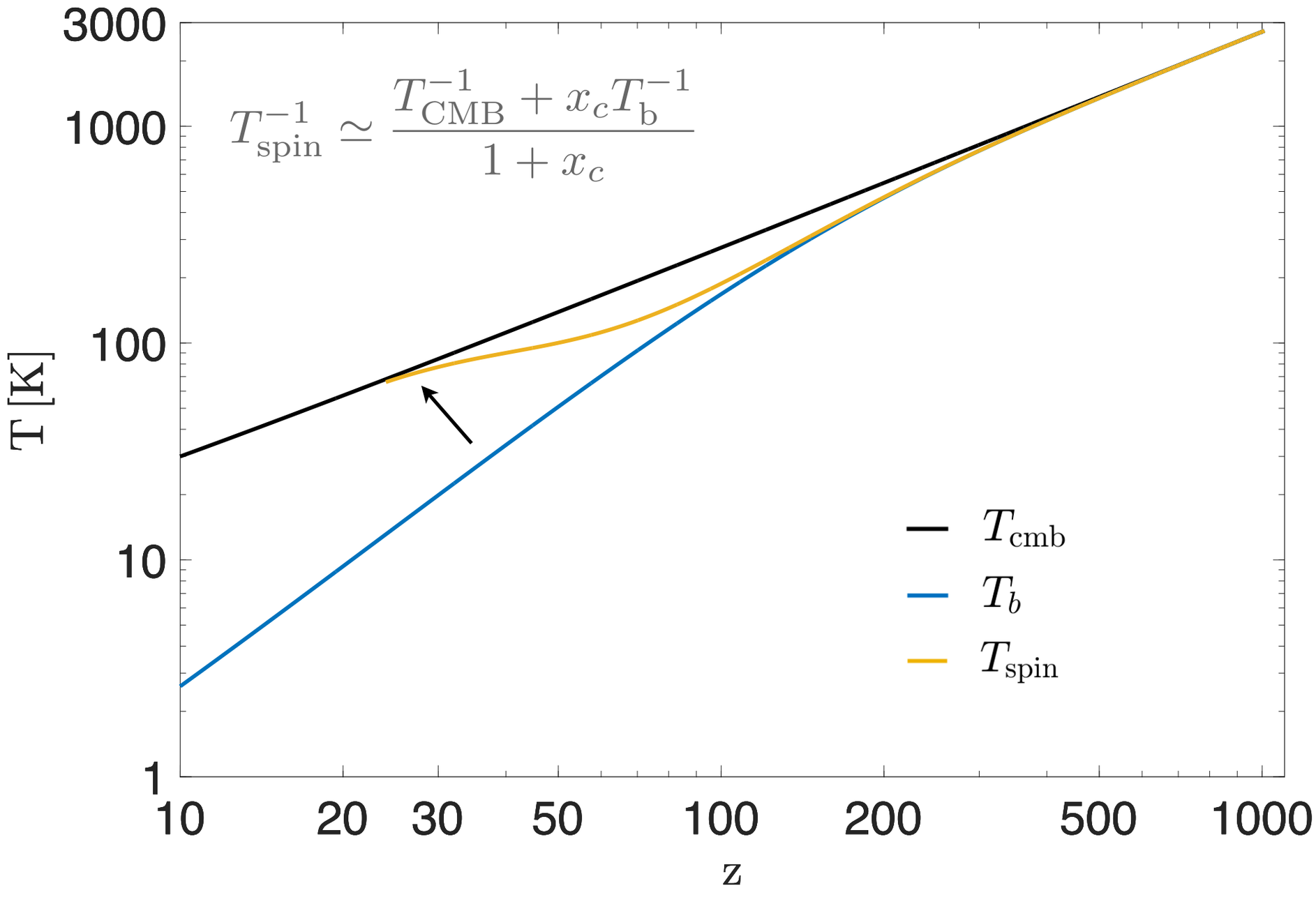

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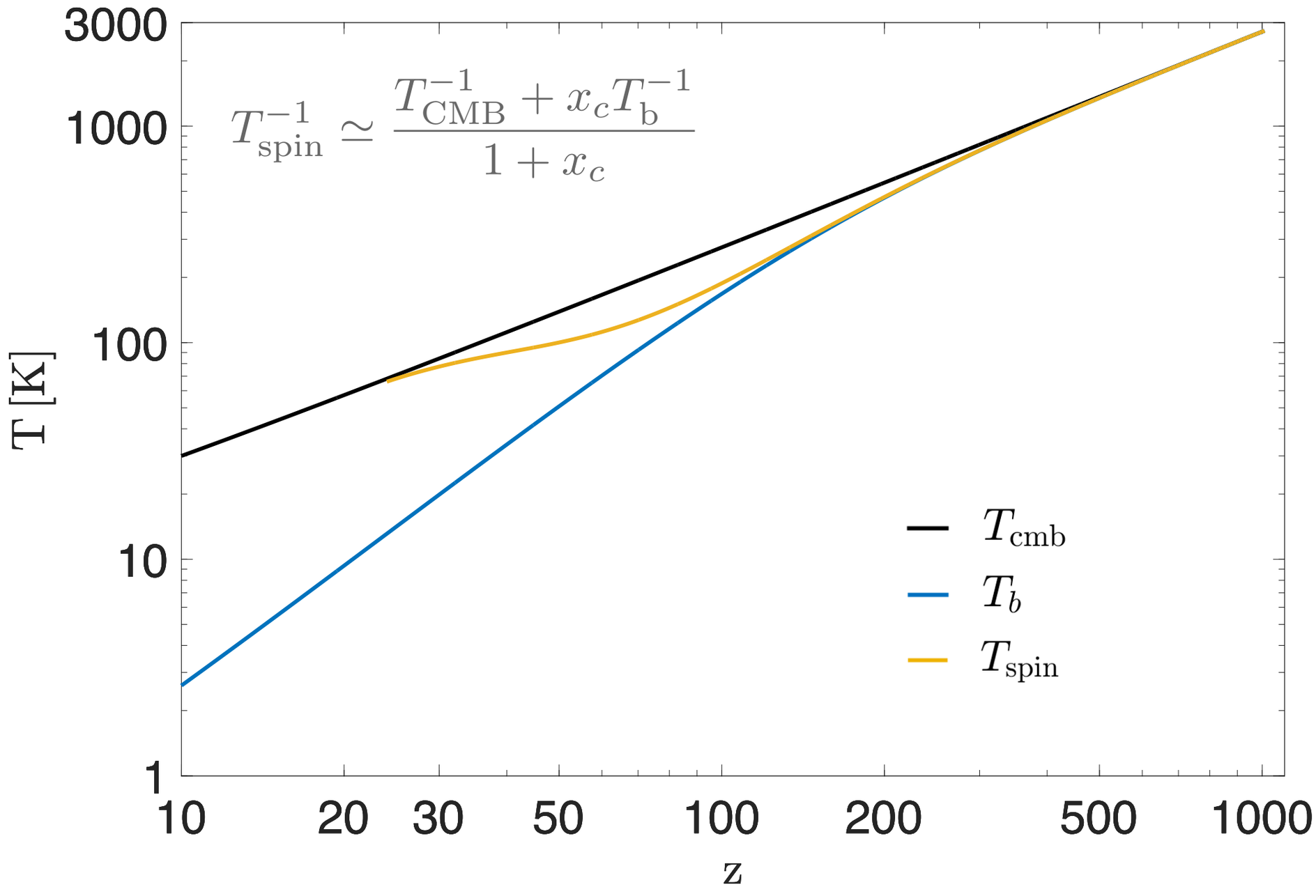

Absorption: (1) $T_{\rm spin} < T_{\rm CMB}$ (Dark Ages)

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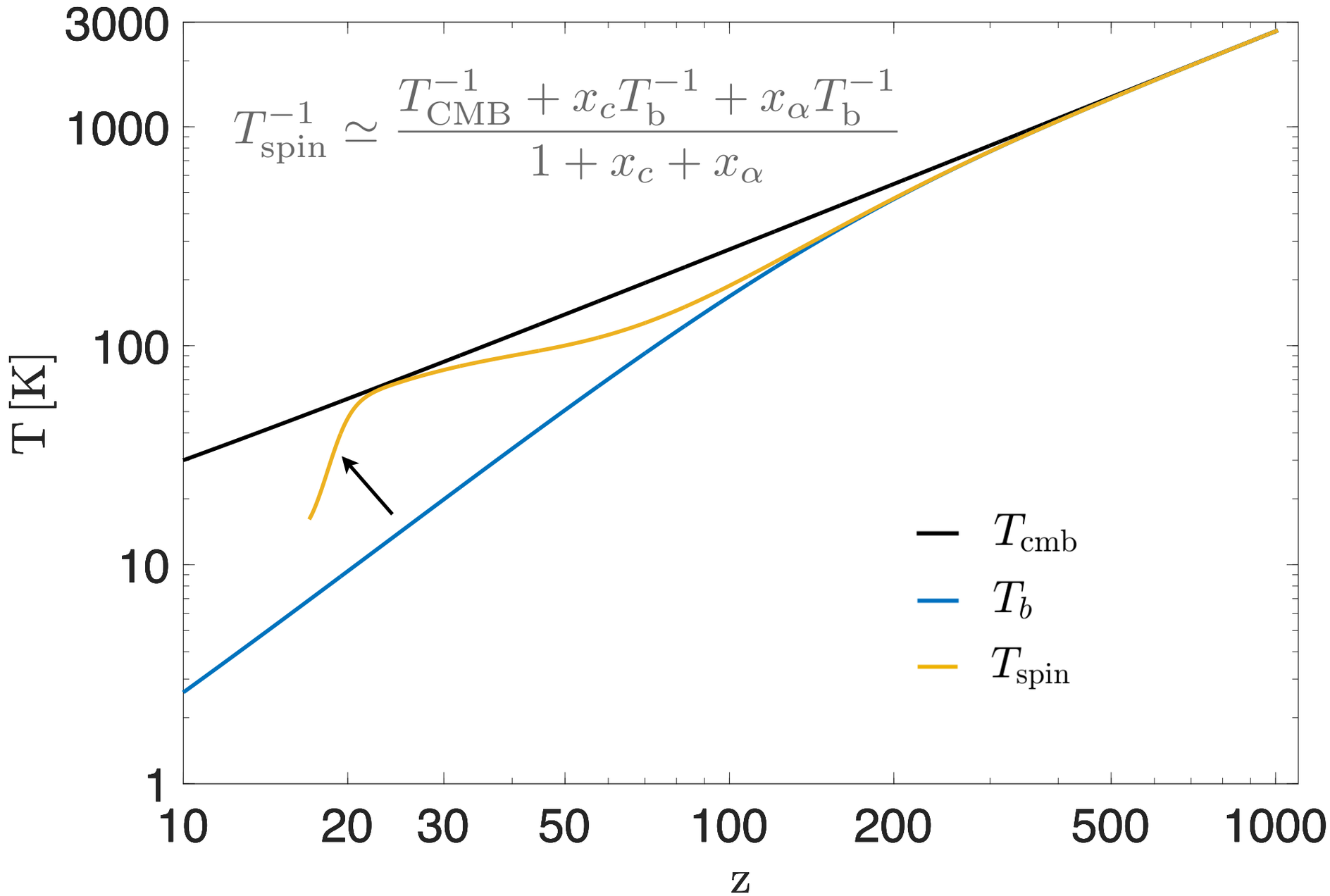

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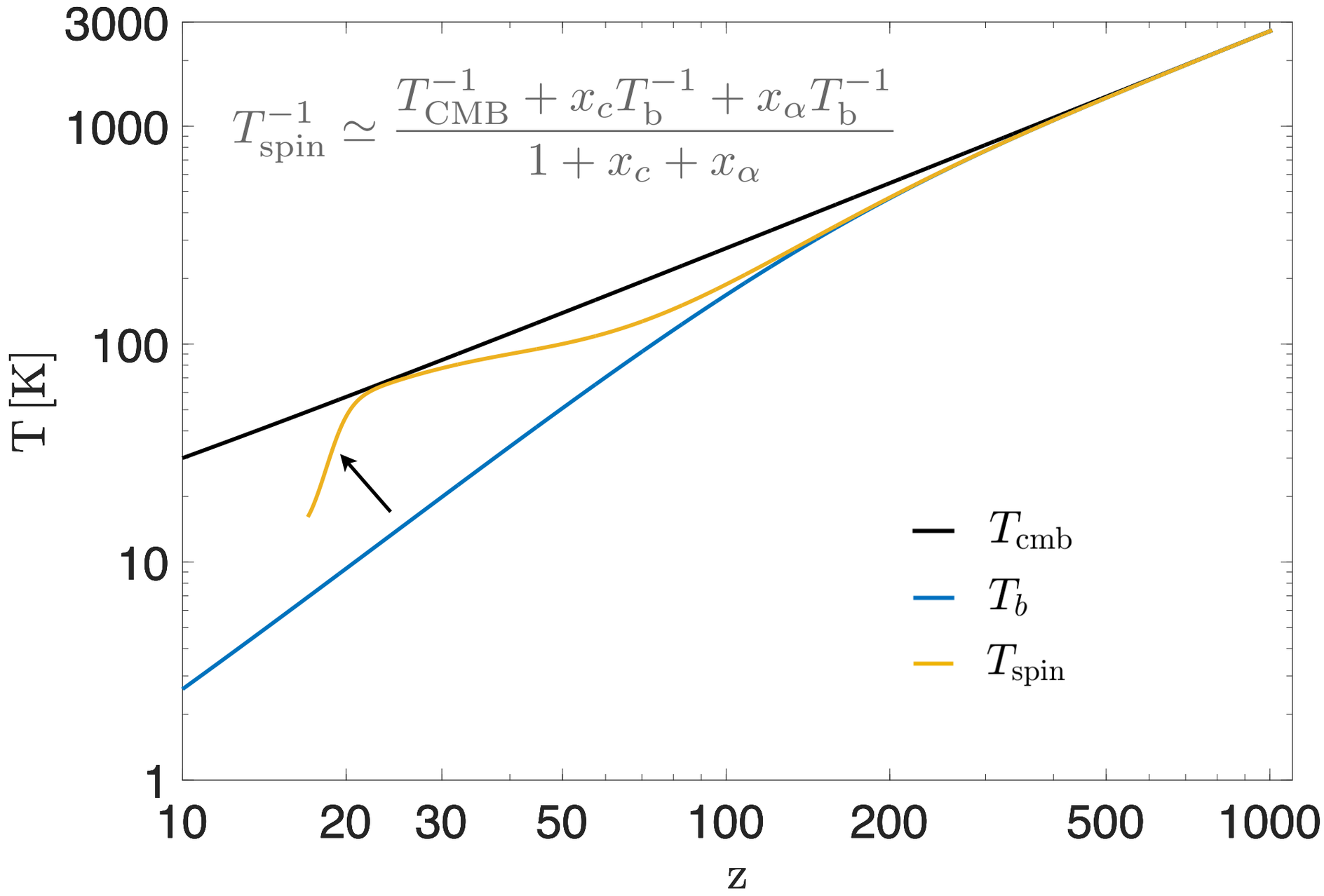

Absorption: (1) $T_{\rm spin} < T_{\rm CMB}$ (Dark Ages) (2) $T_{\rm spin} < T_{\rm CMB}$ (Cosmic Dawn)

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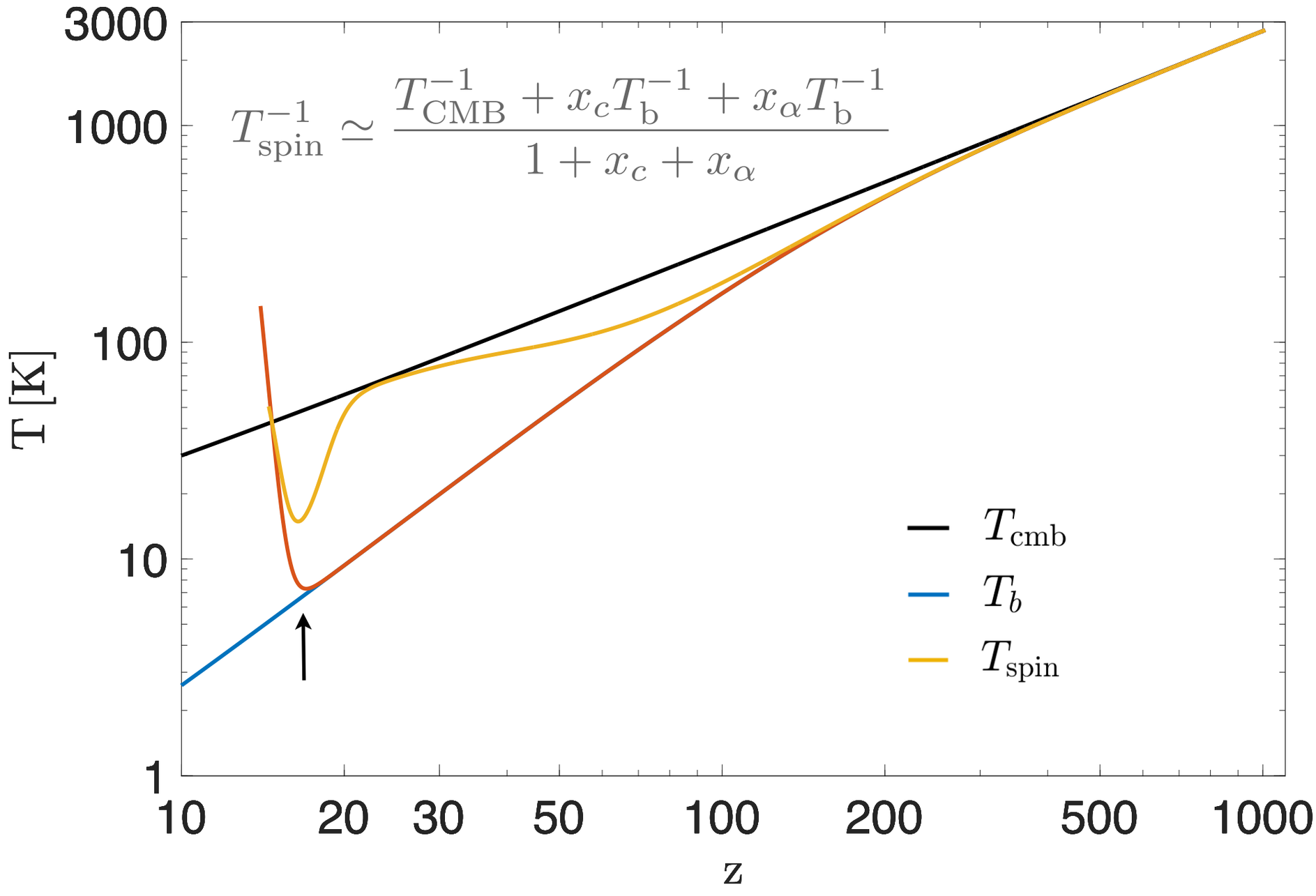

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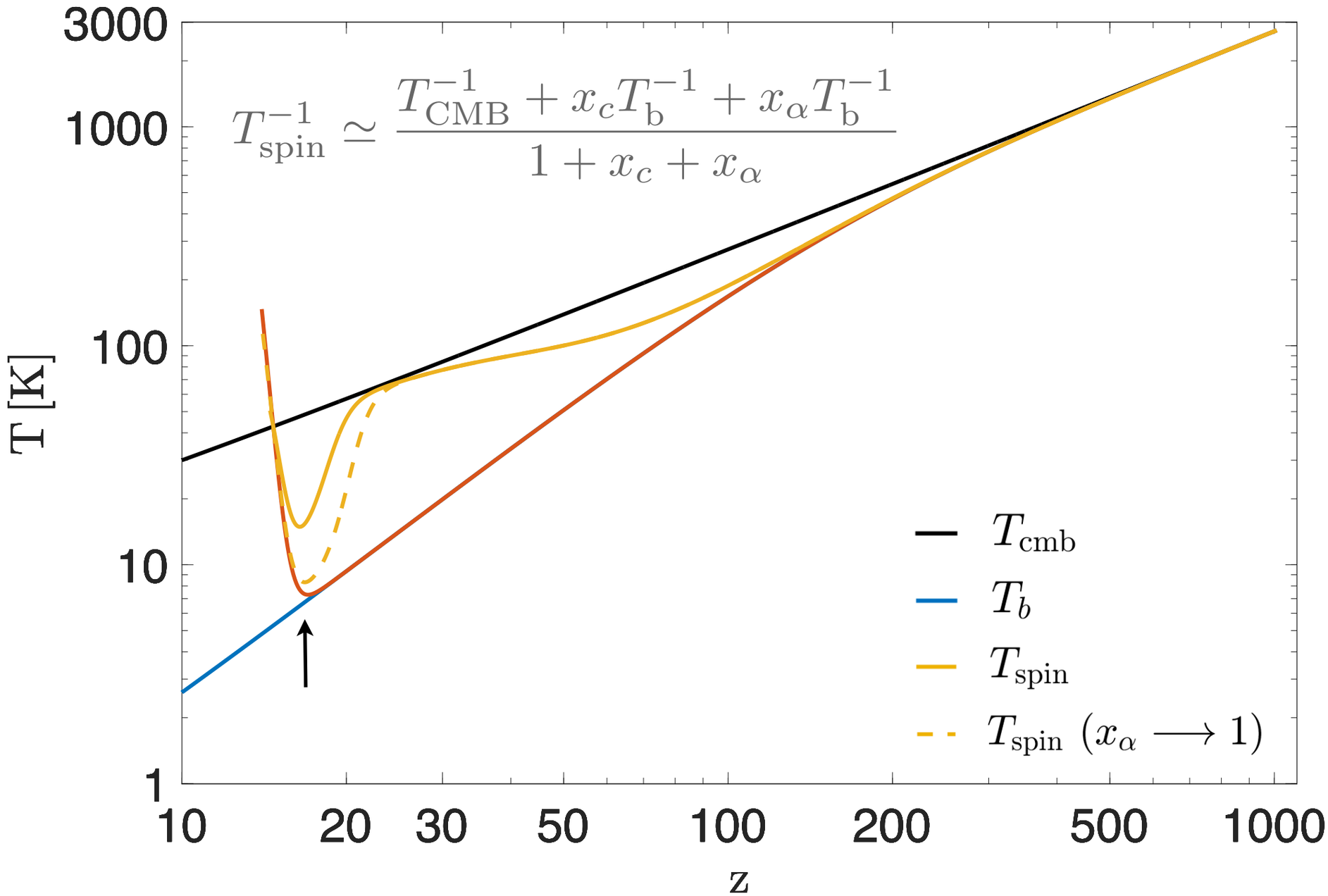

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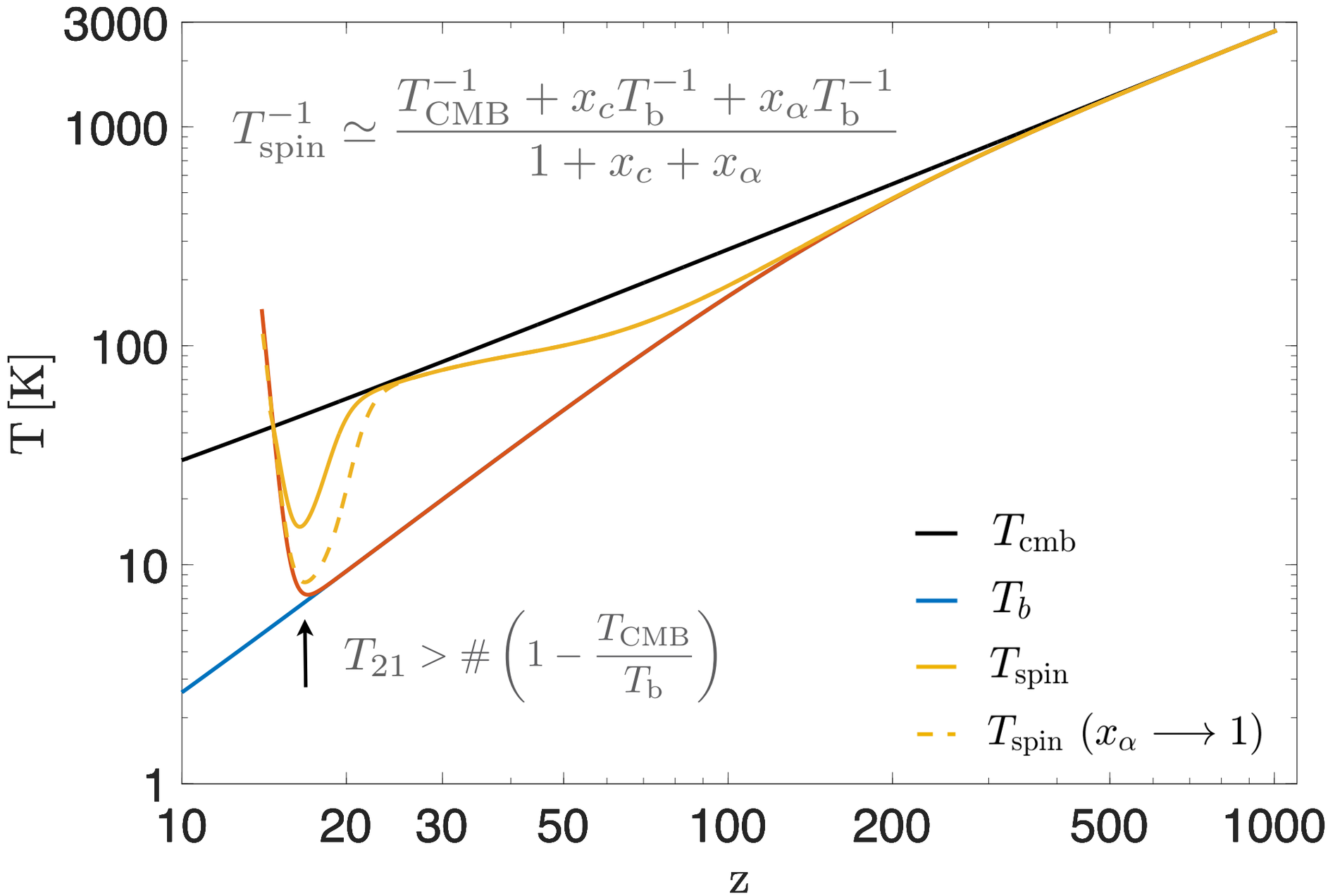

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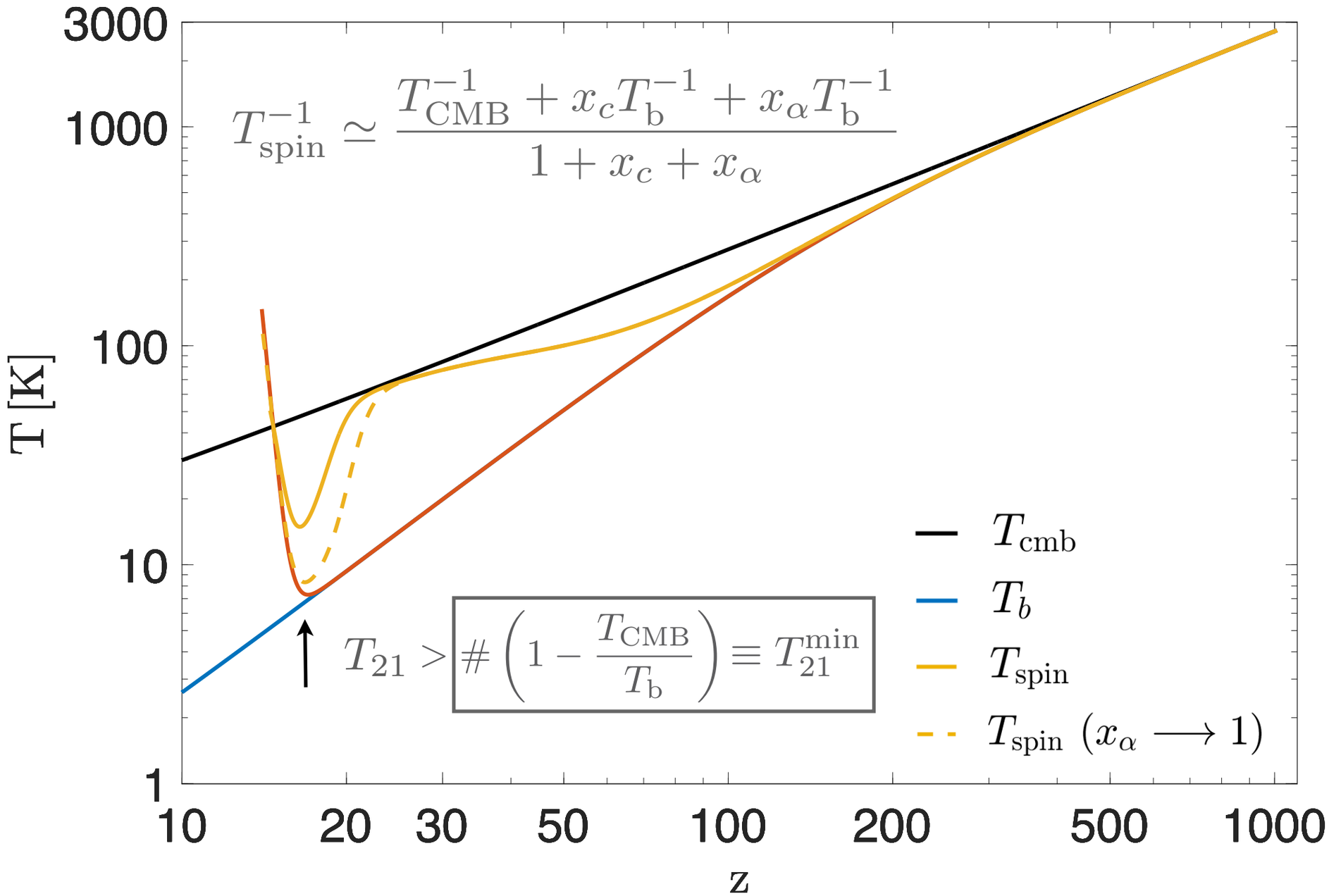

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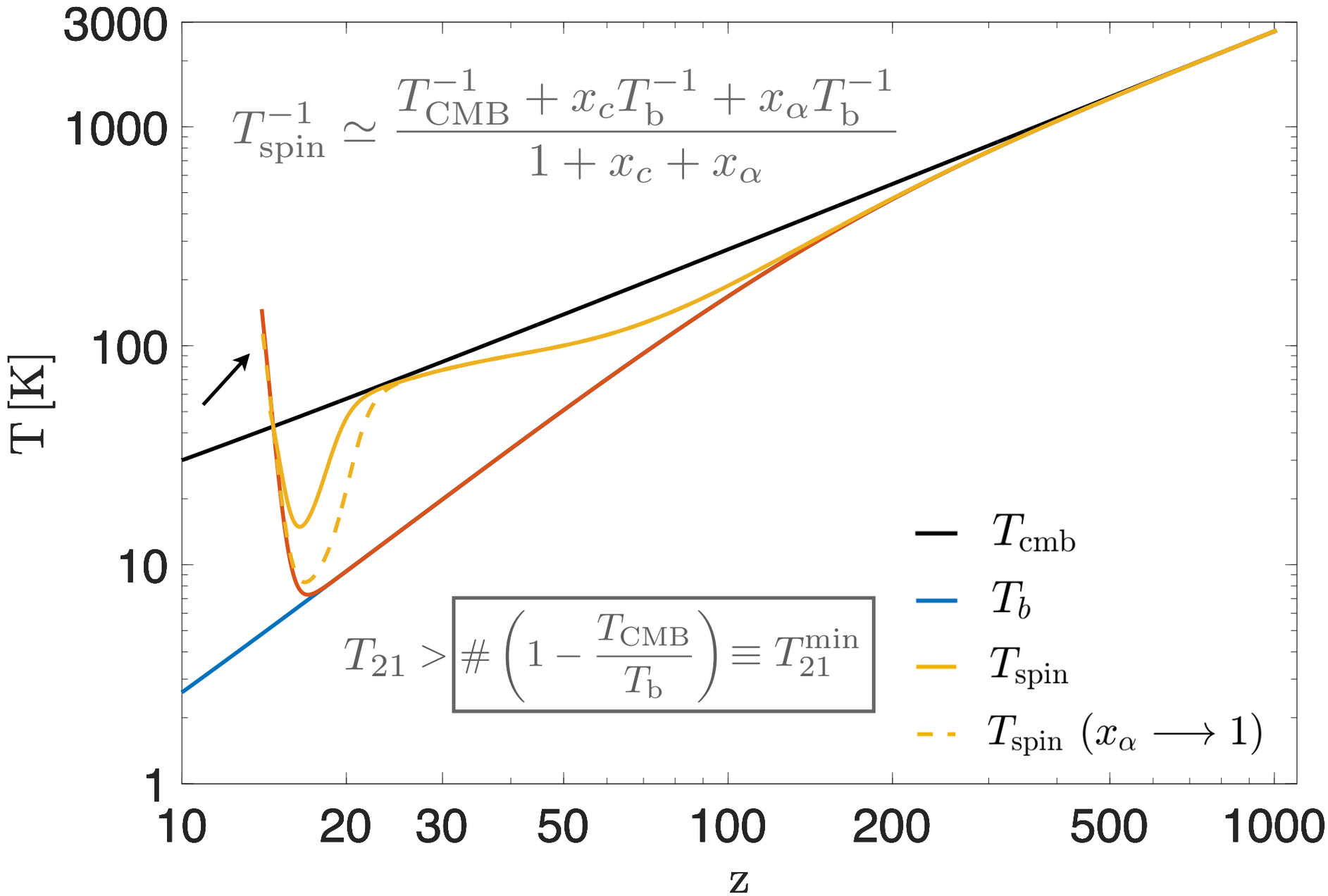
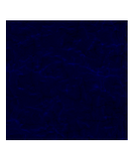
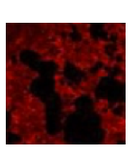


Absorption: (1) $T_{\rm spin} < T_{\rm CMB}$ (Dark Ages)  (2) $T_{\rm spin} < T_{\rm CMB}$ (Cosmic Dawn) 

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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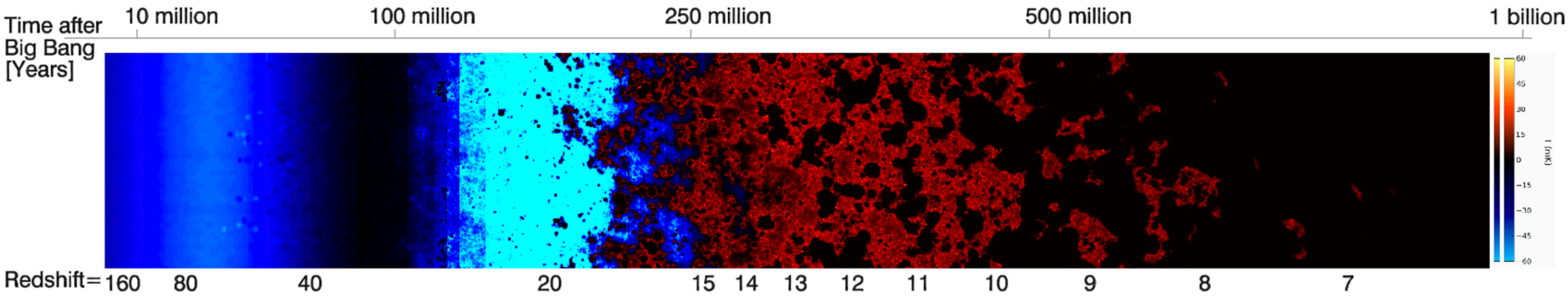

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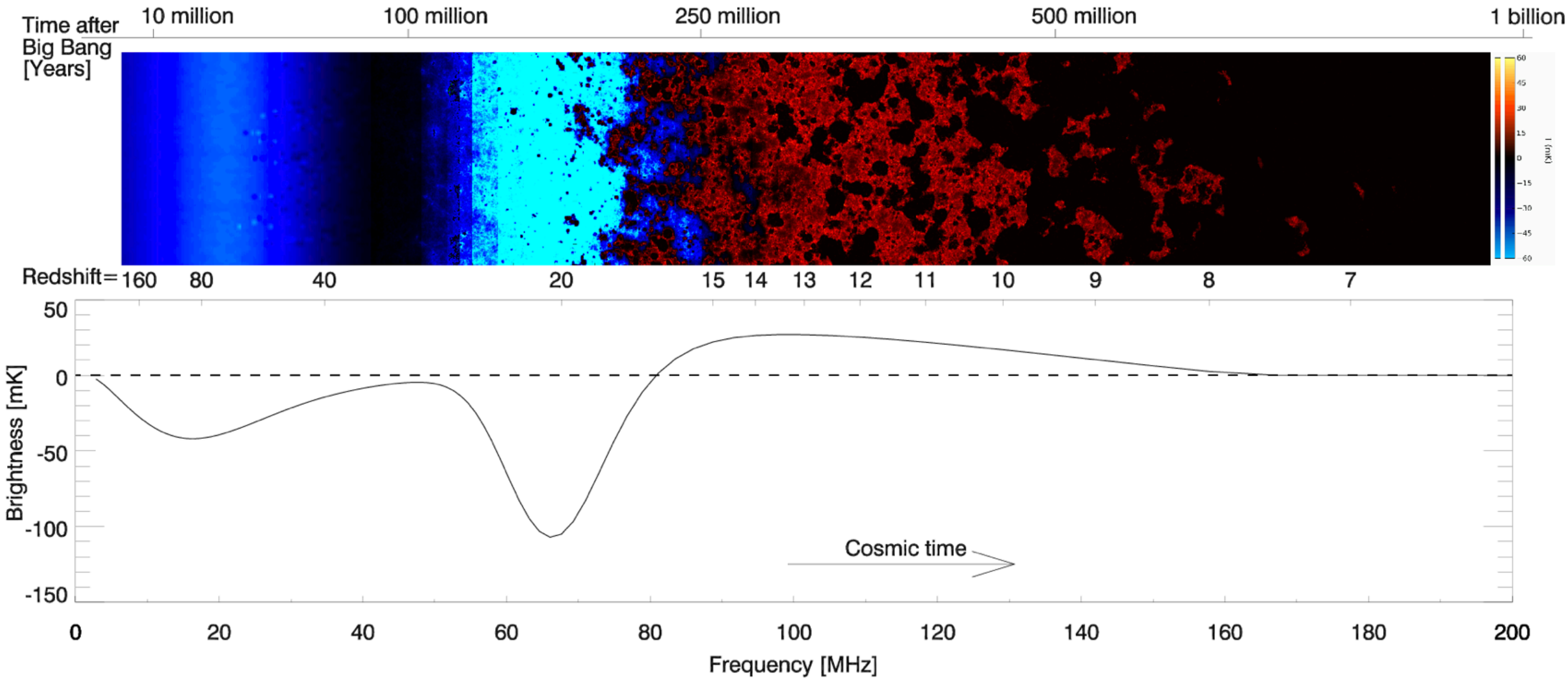

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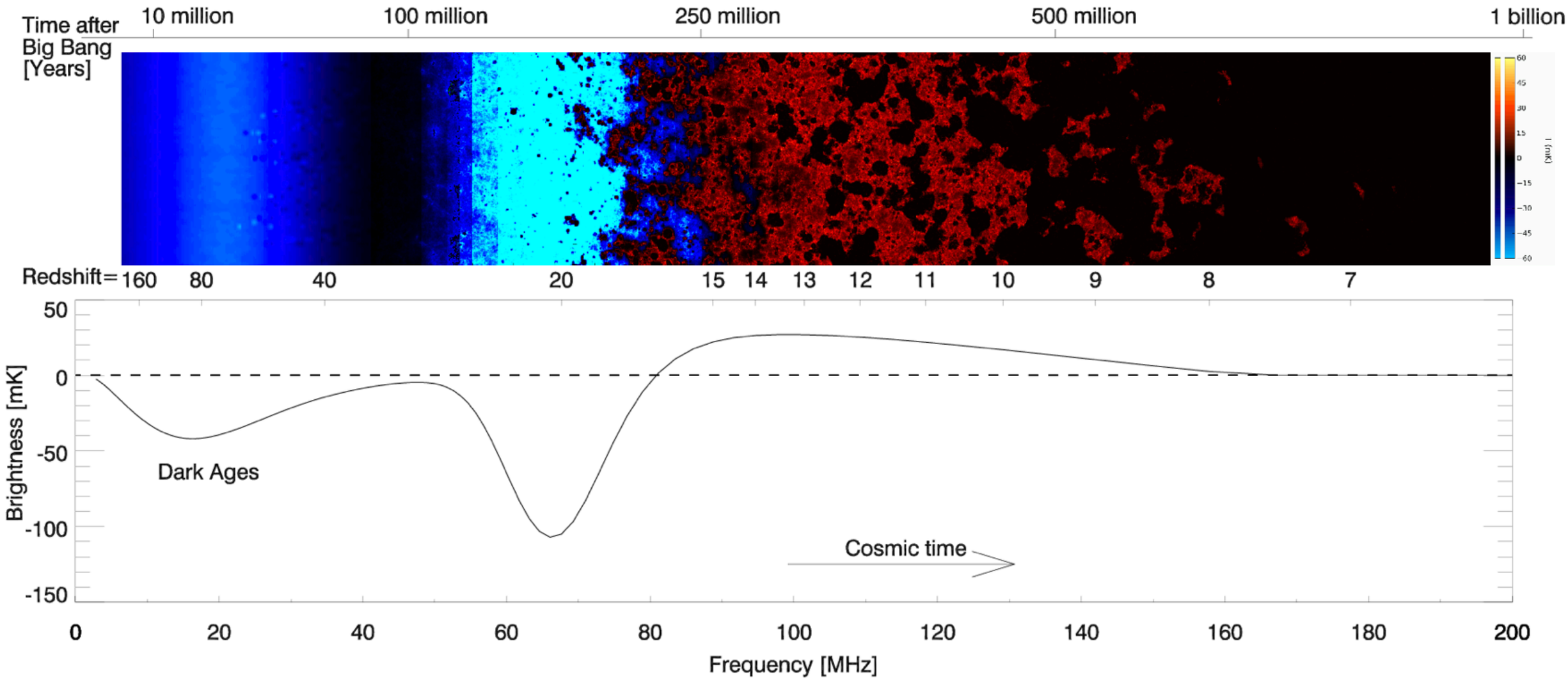

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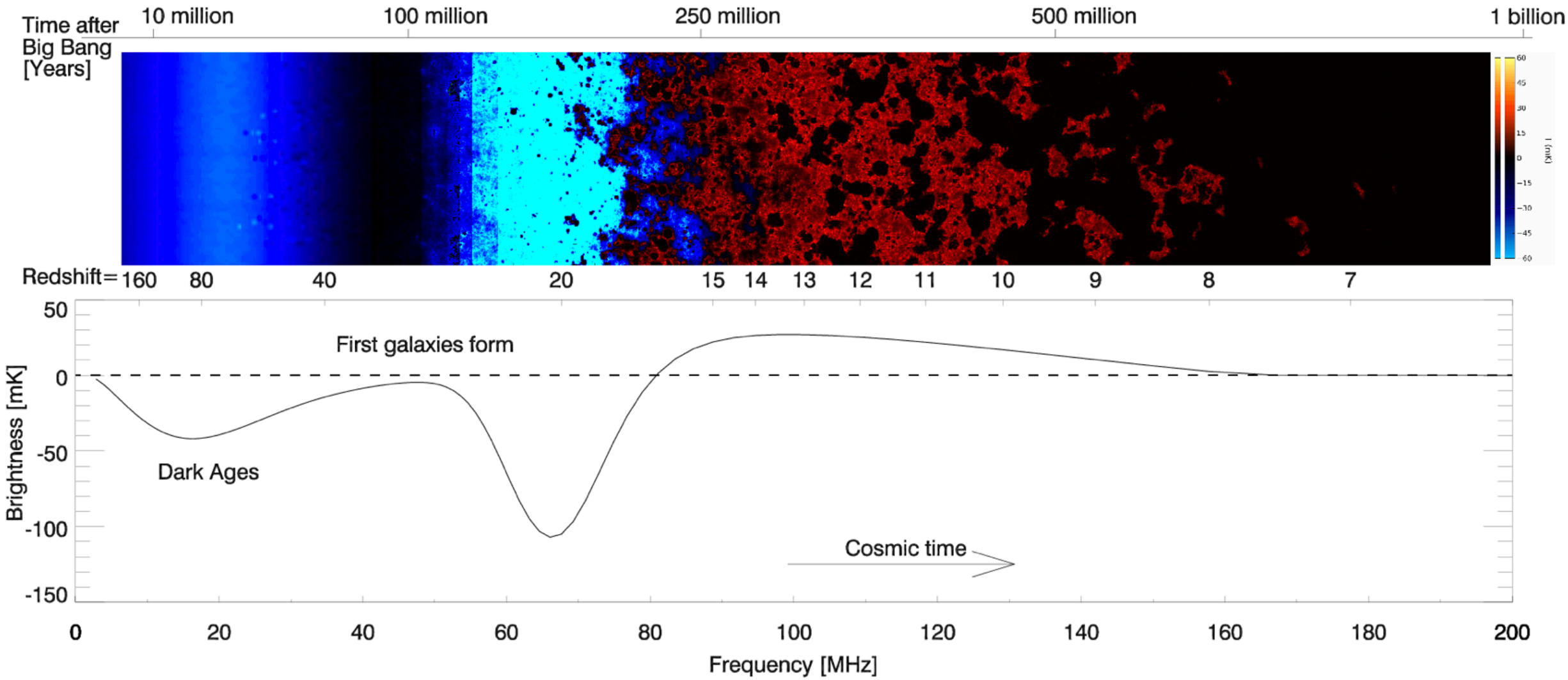

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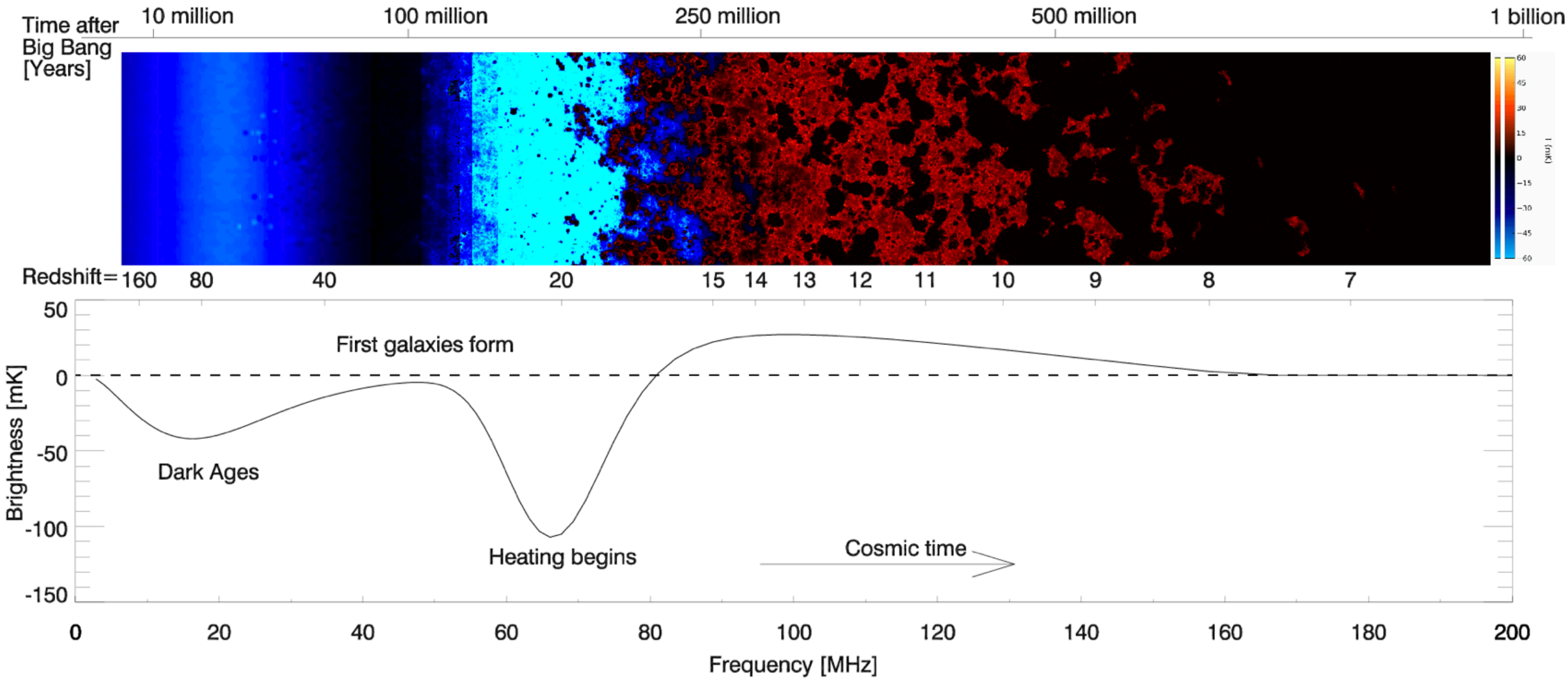

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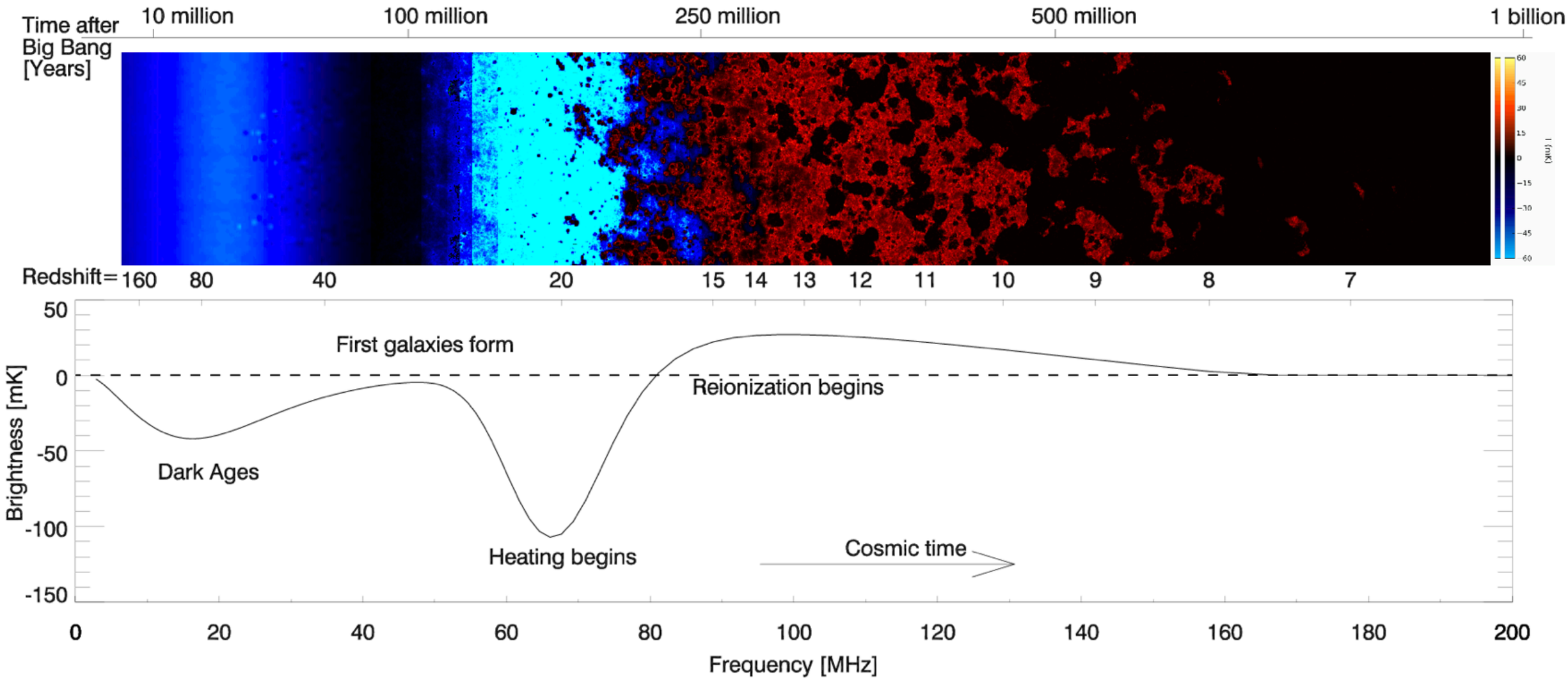

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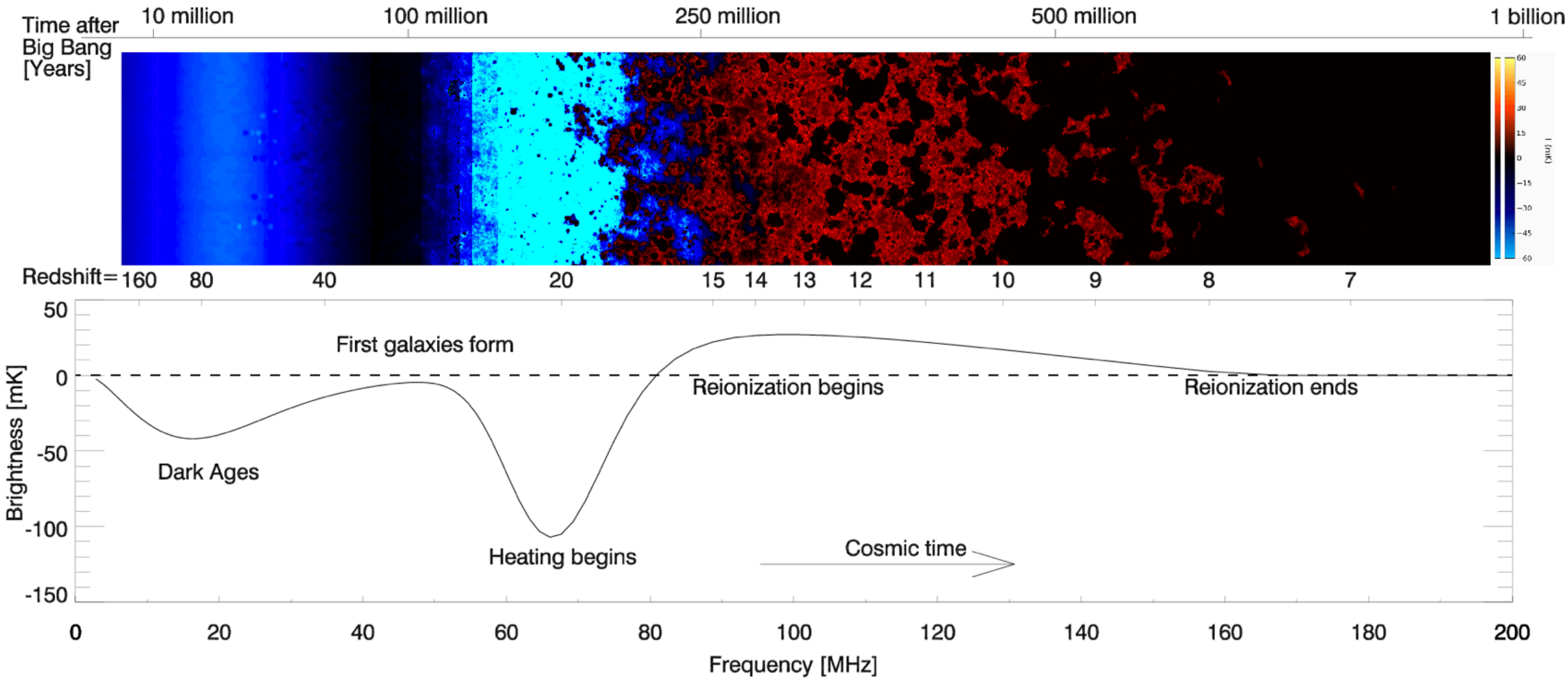

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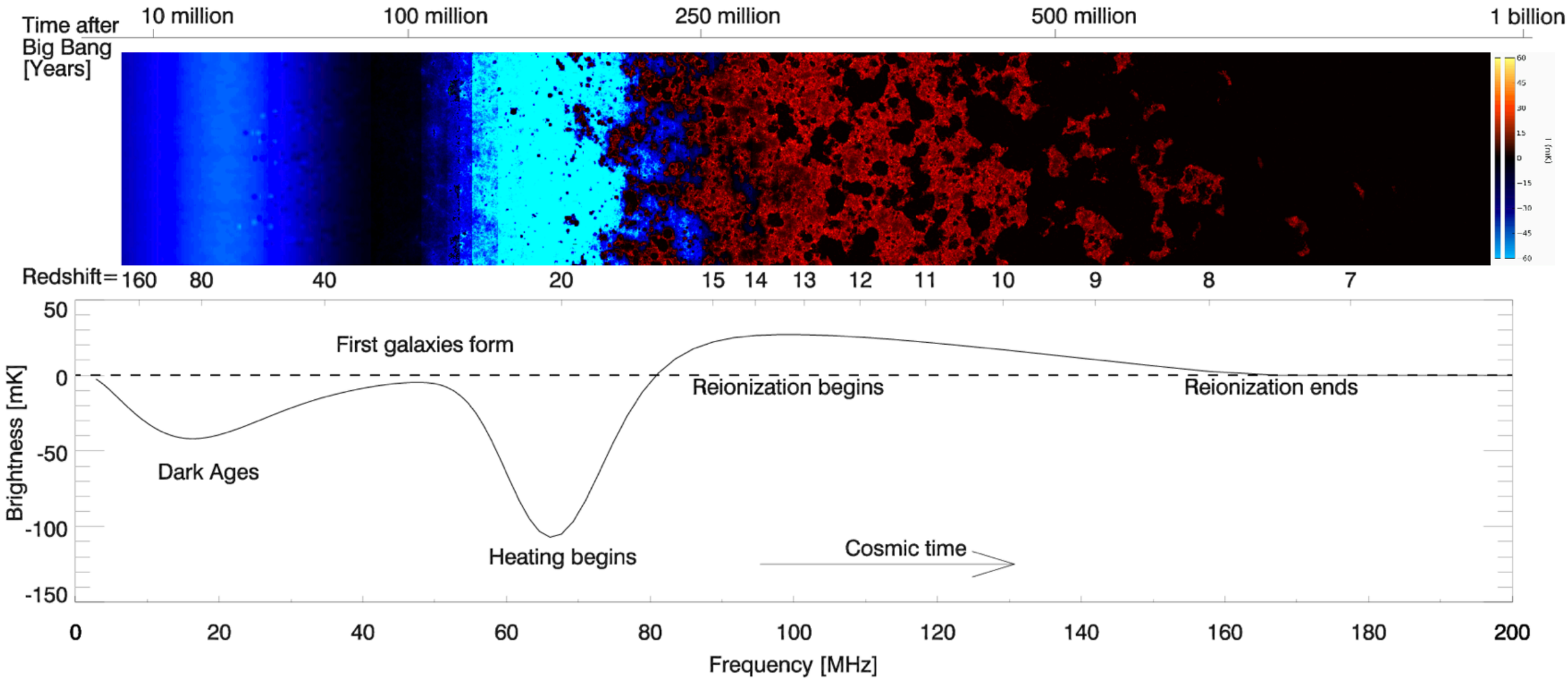

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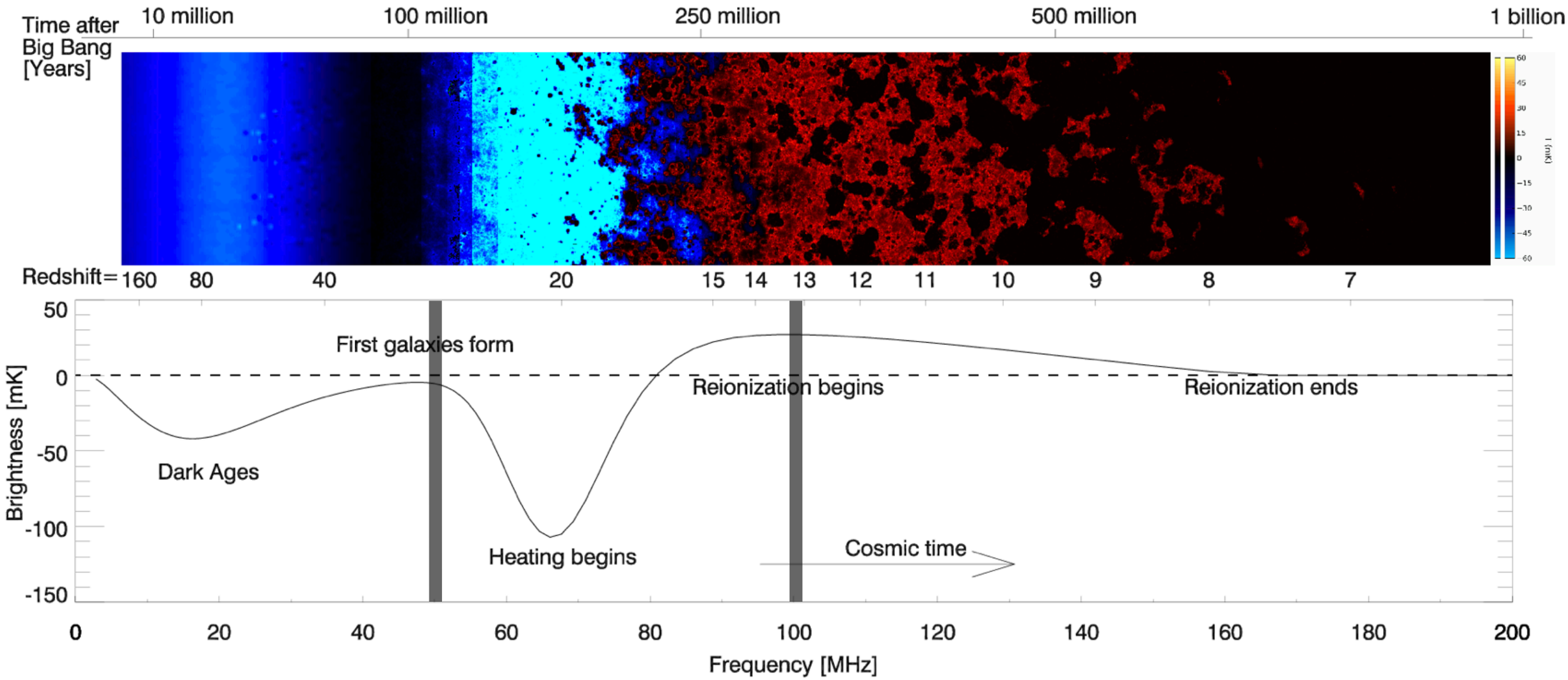

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EDGES Low-Band

Outline

Ely Kovetz
MPIK, Feb. 2022

- Brief review of the cosmic 21cm Signal

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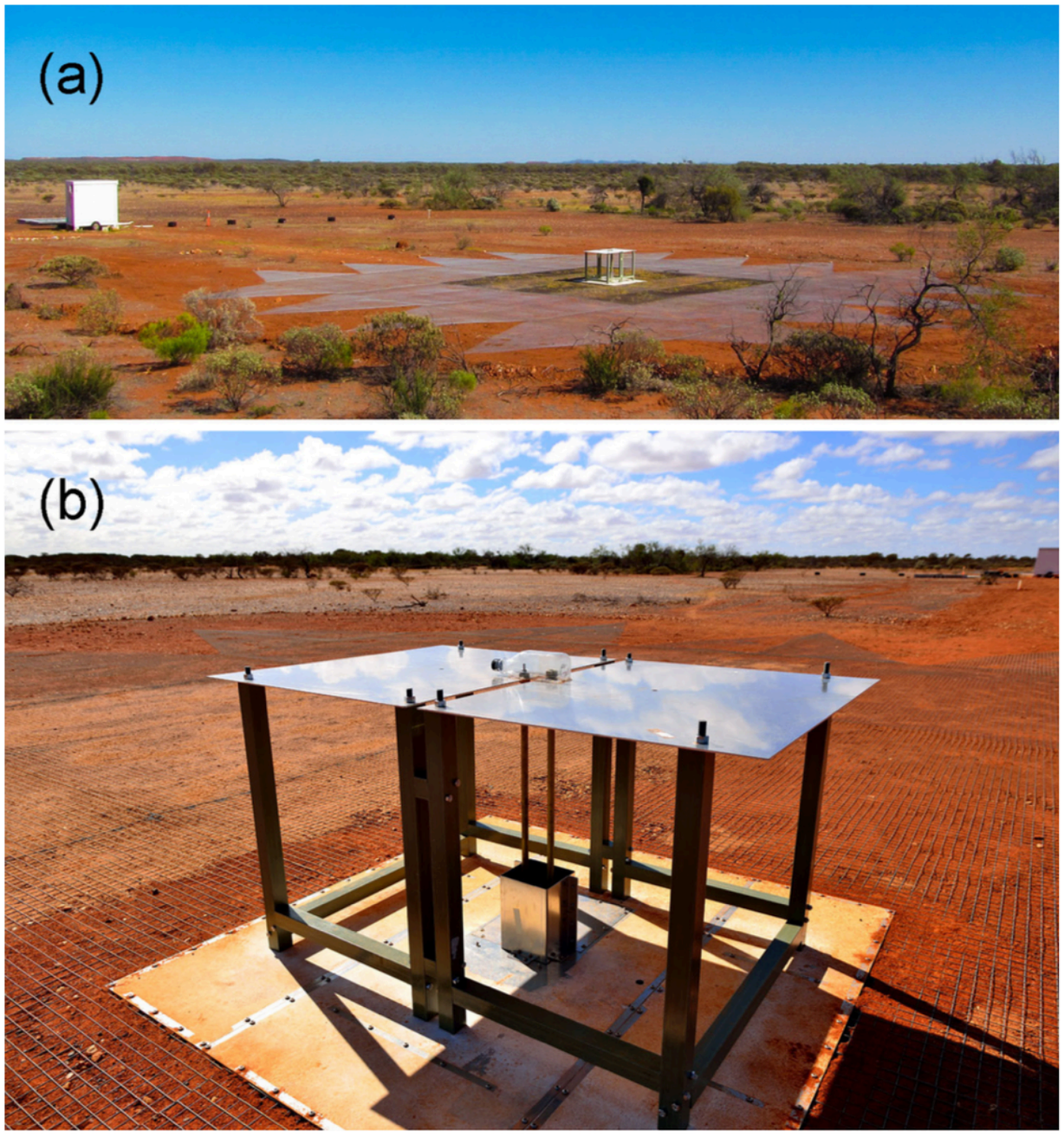
- The EDGES “detection” and Dark Matter

Experiment to Detect the Global Epoch of Reionization Signature



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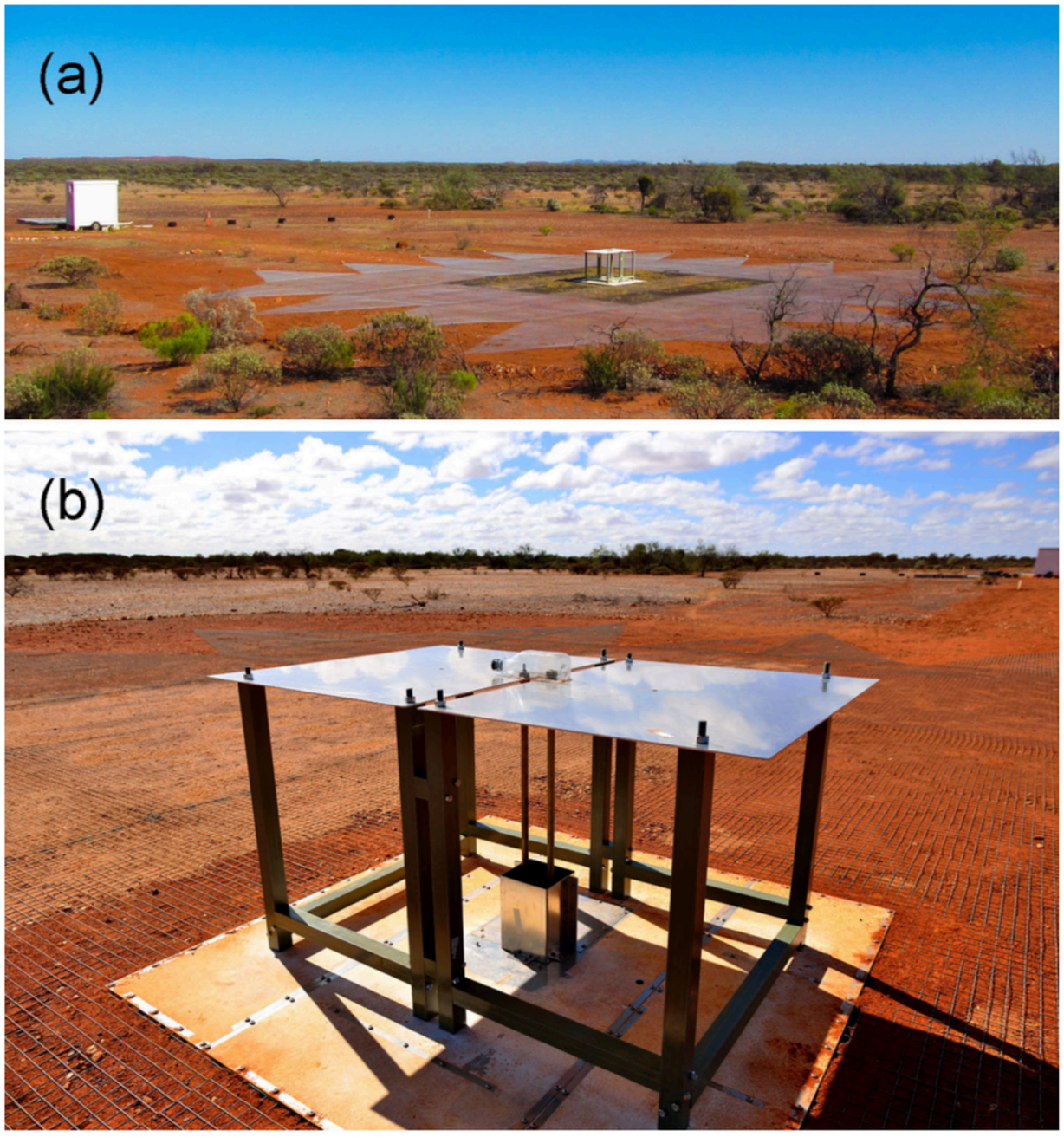

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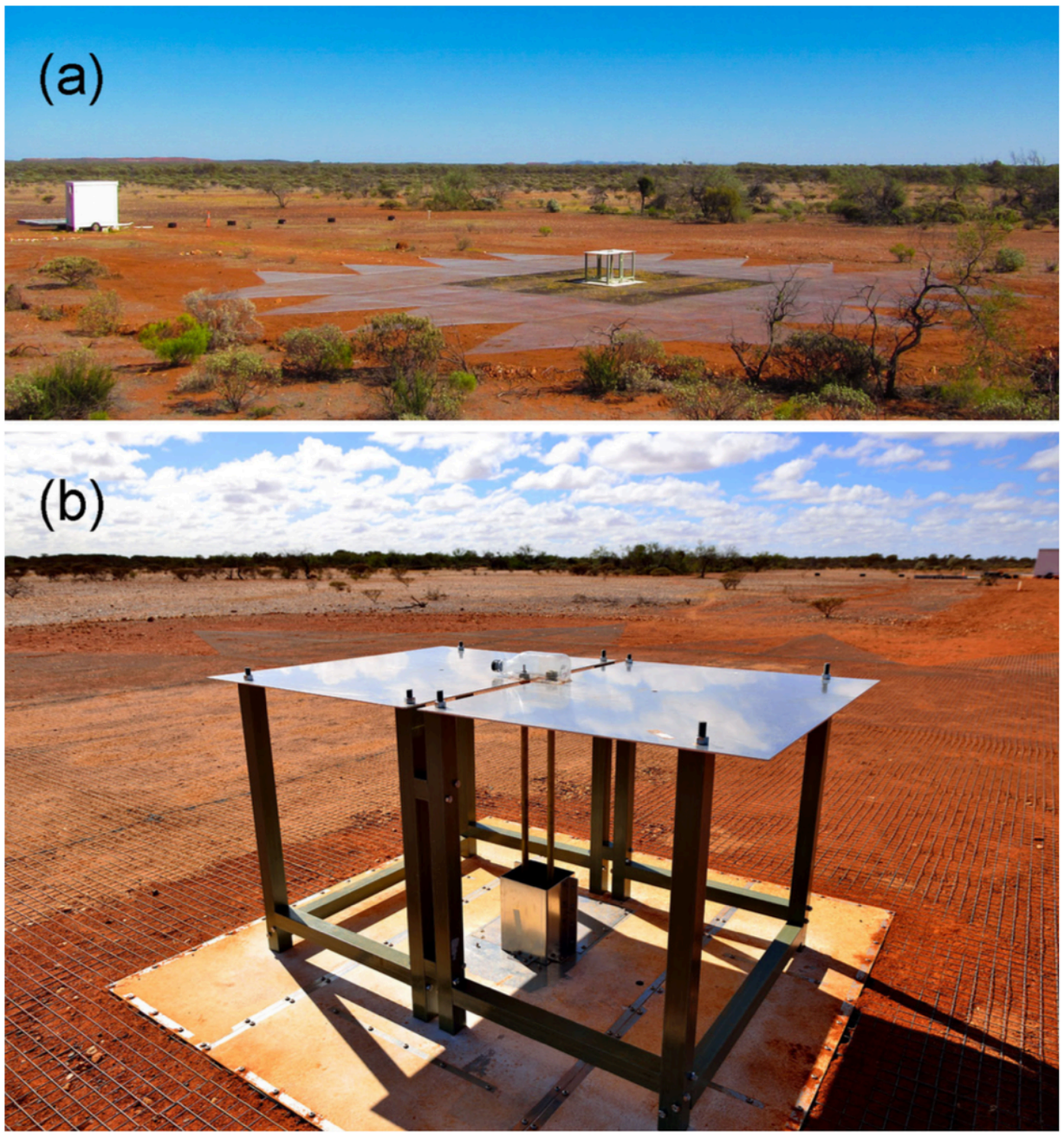

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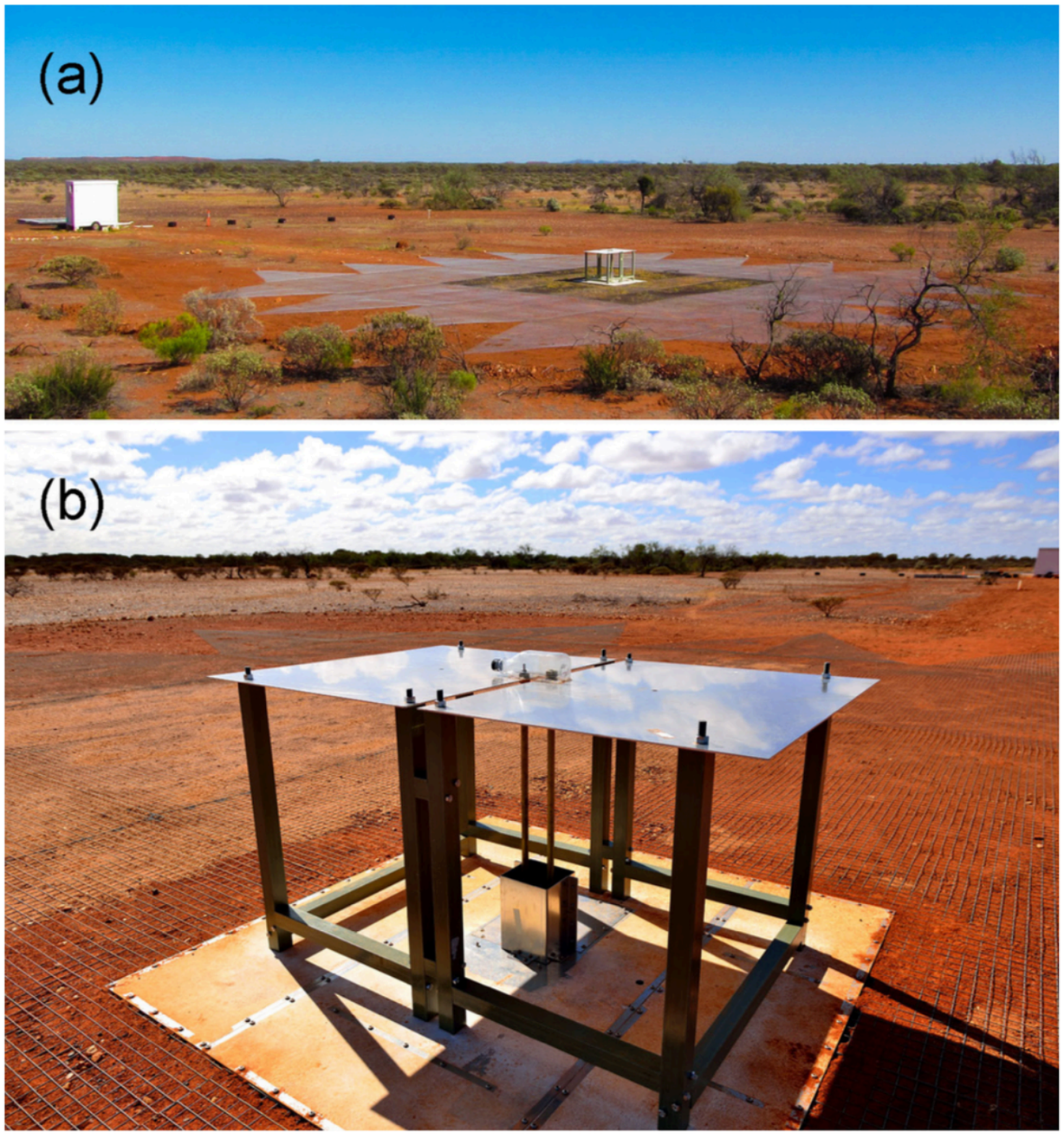

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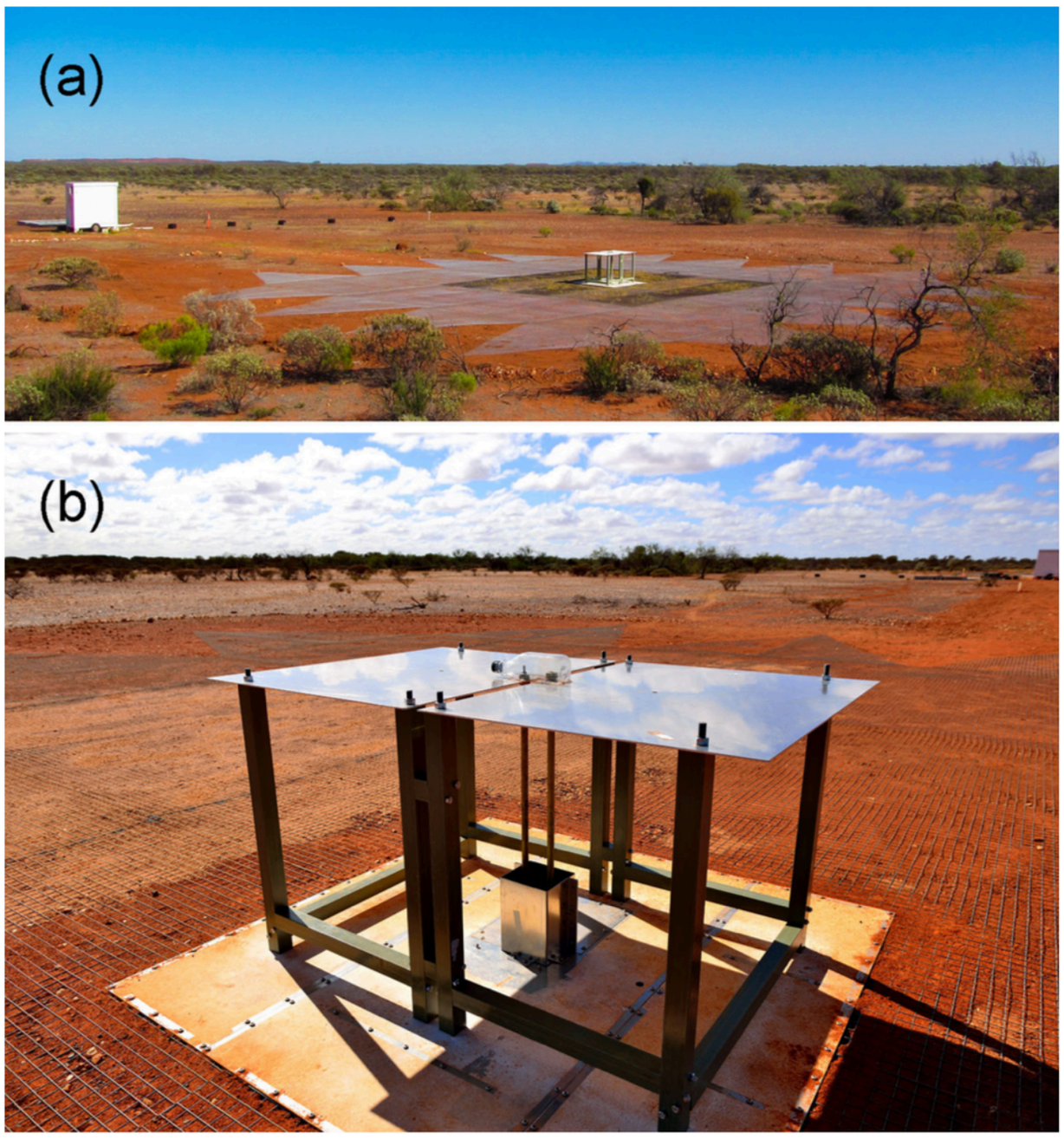

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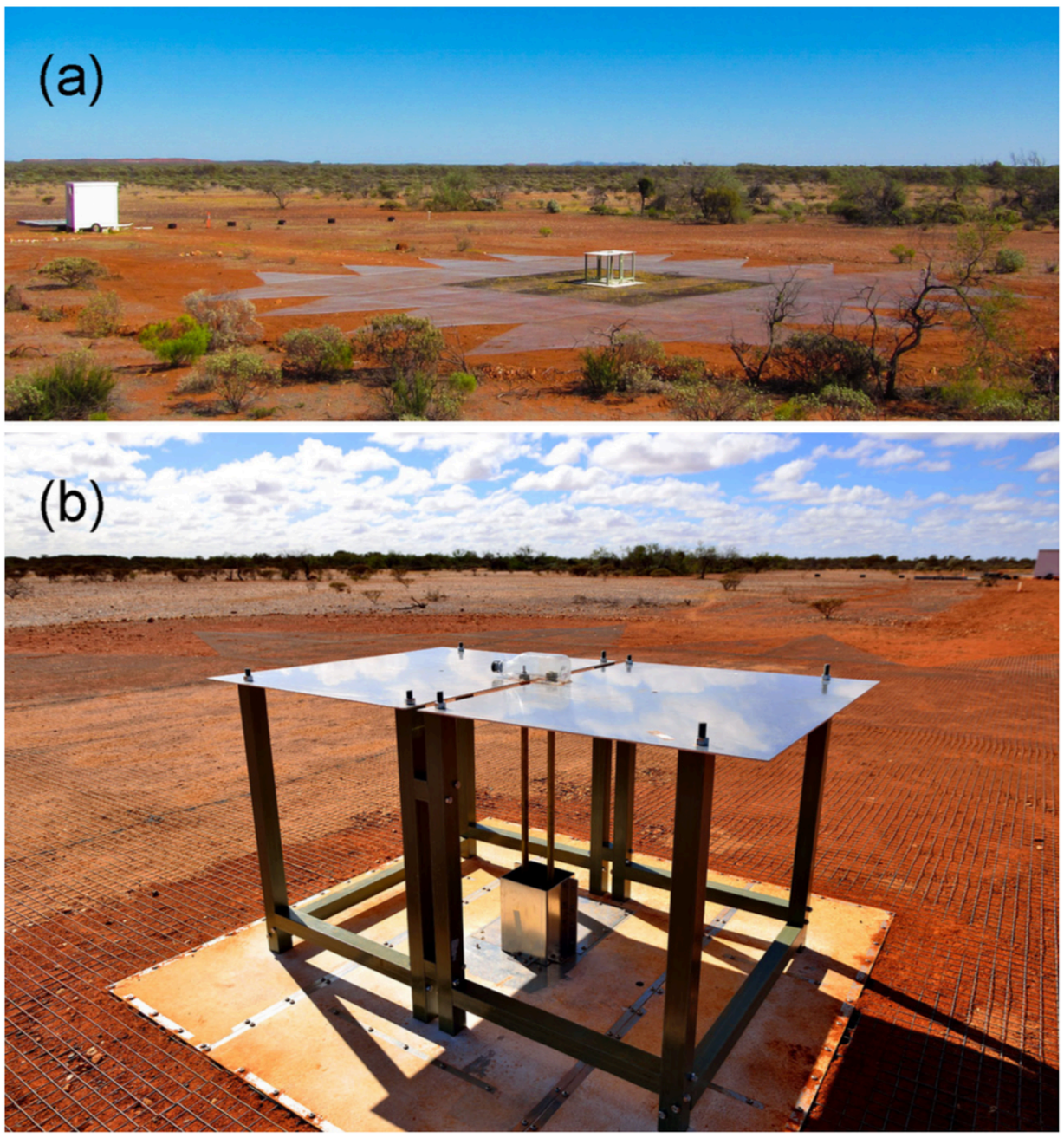

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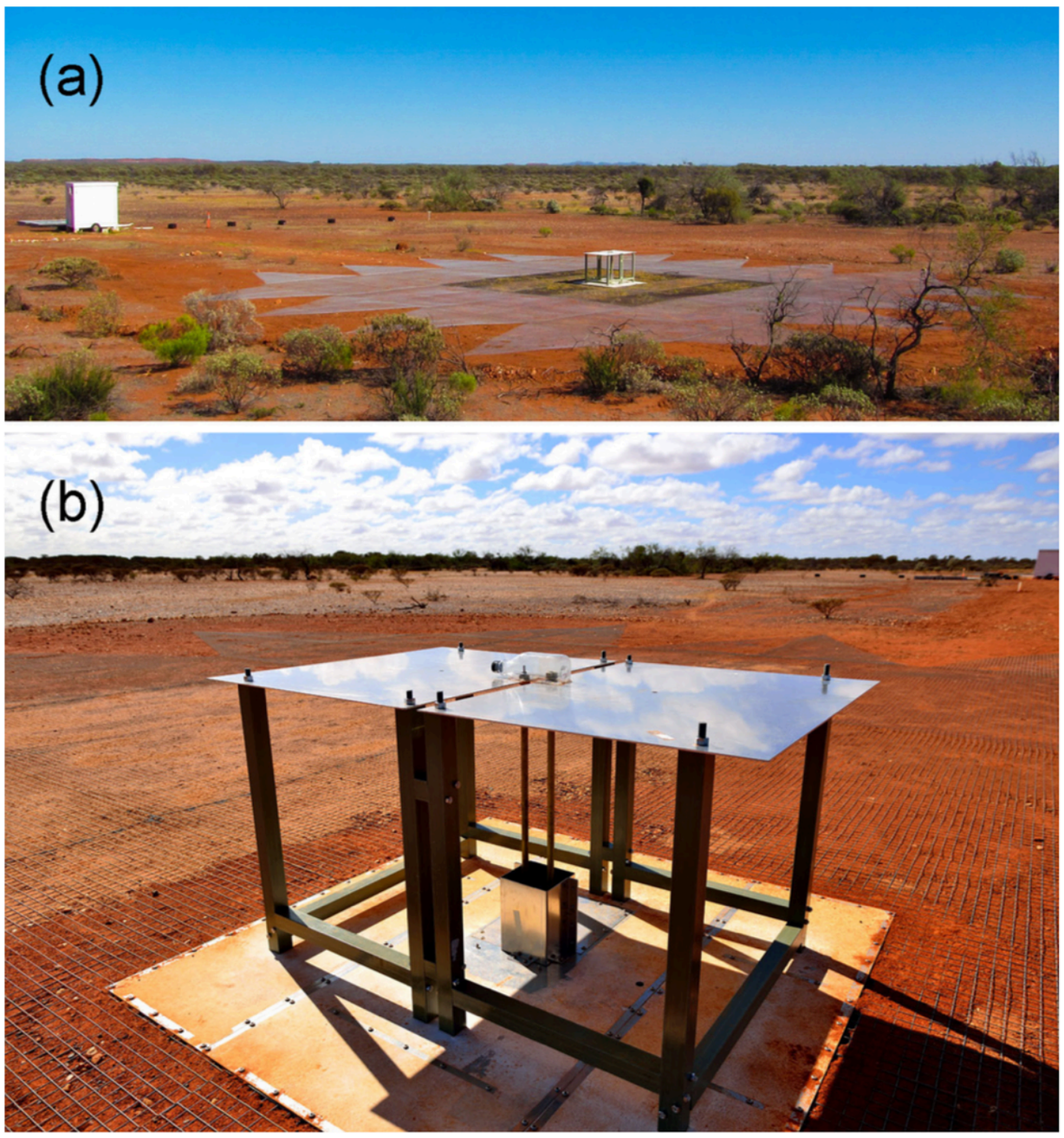

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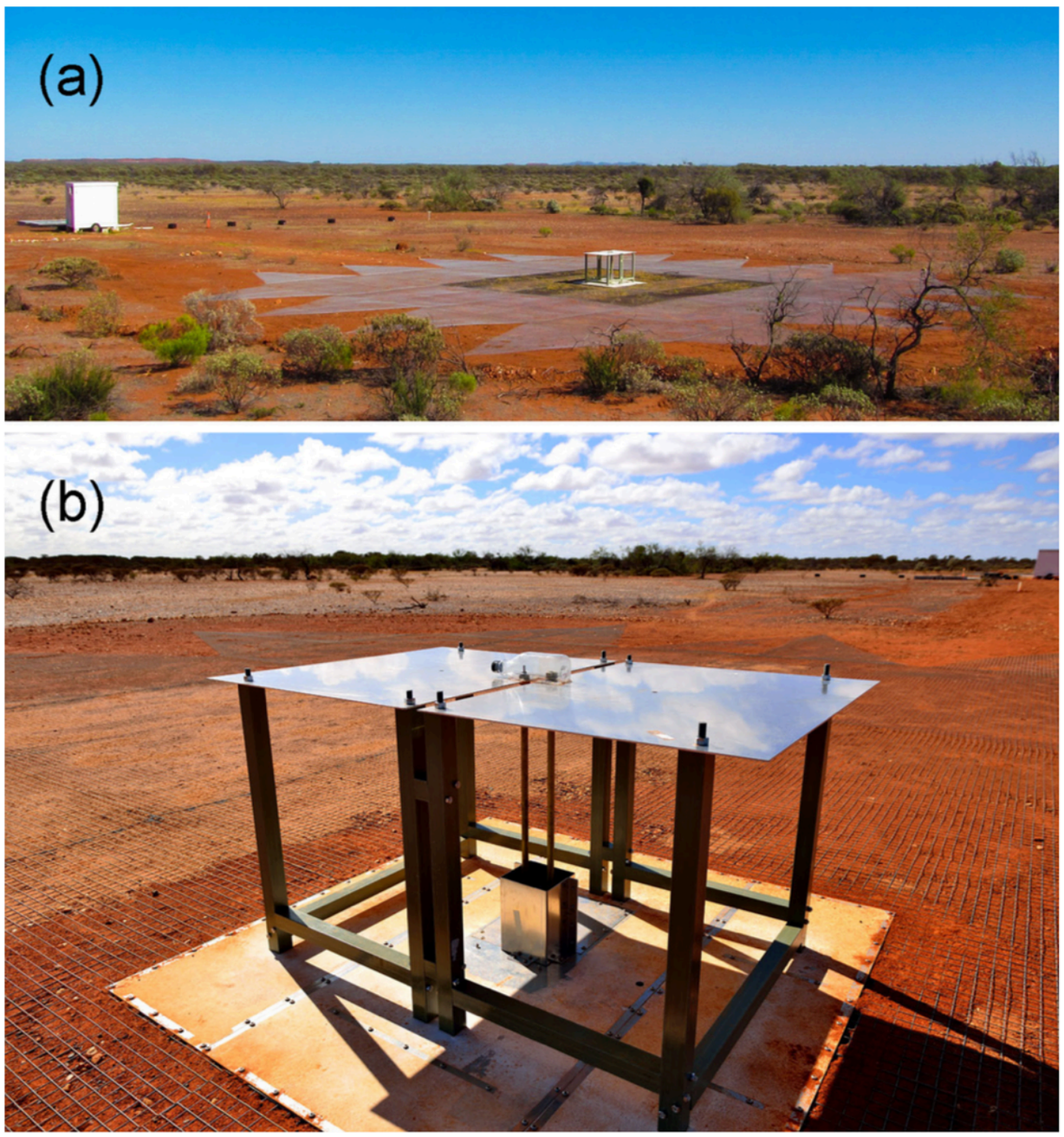

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EDGES: First *Claimed* Detection of Cosmic Dawn

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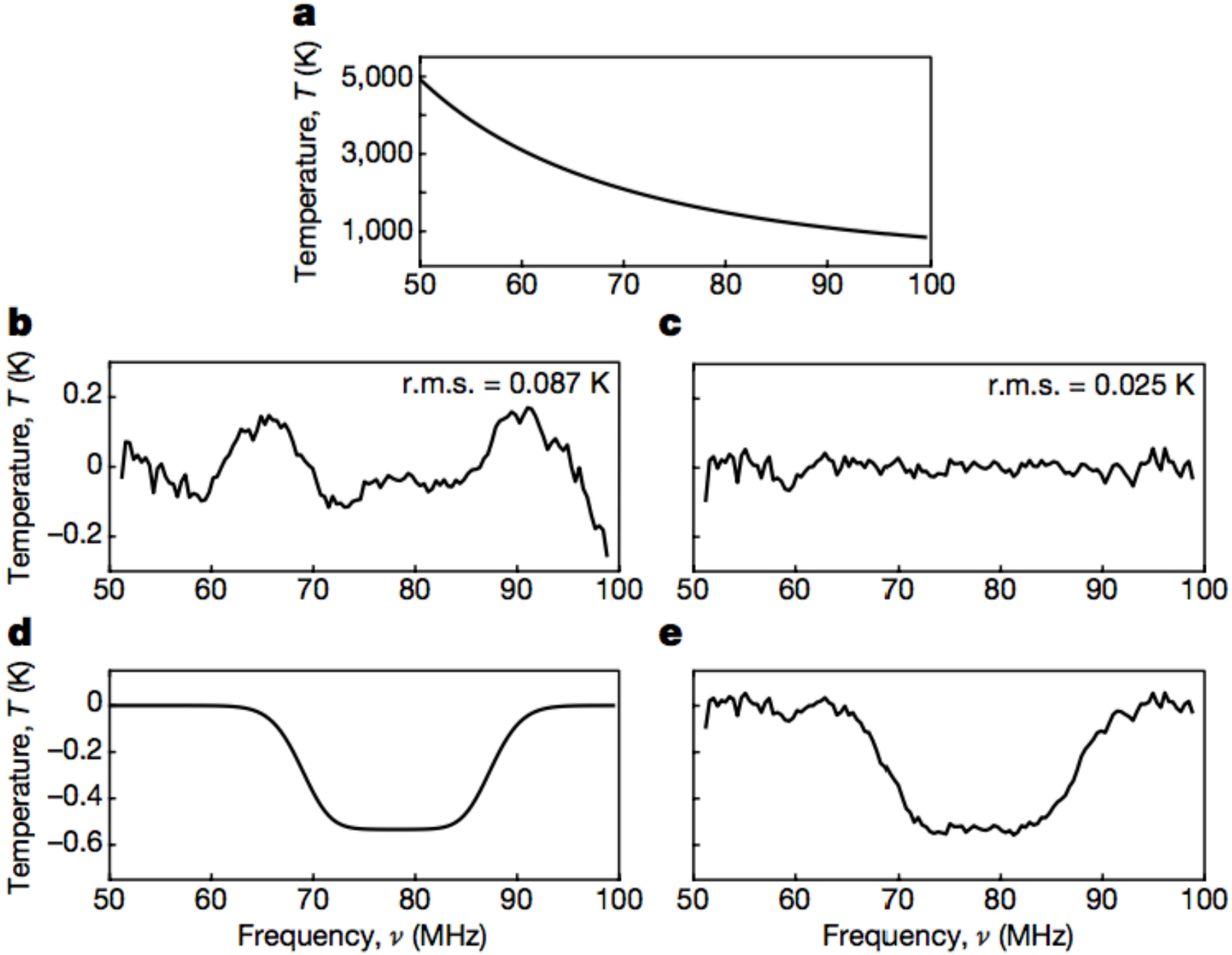

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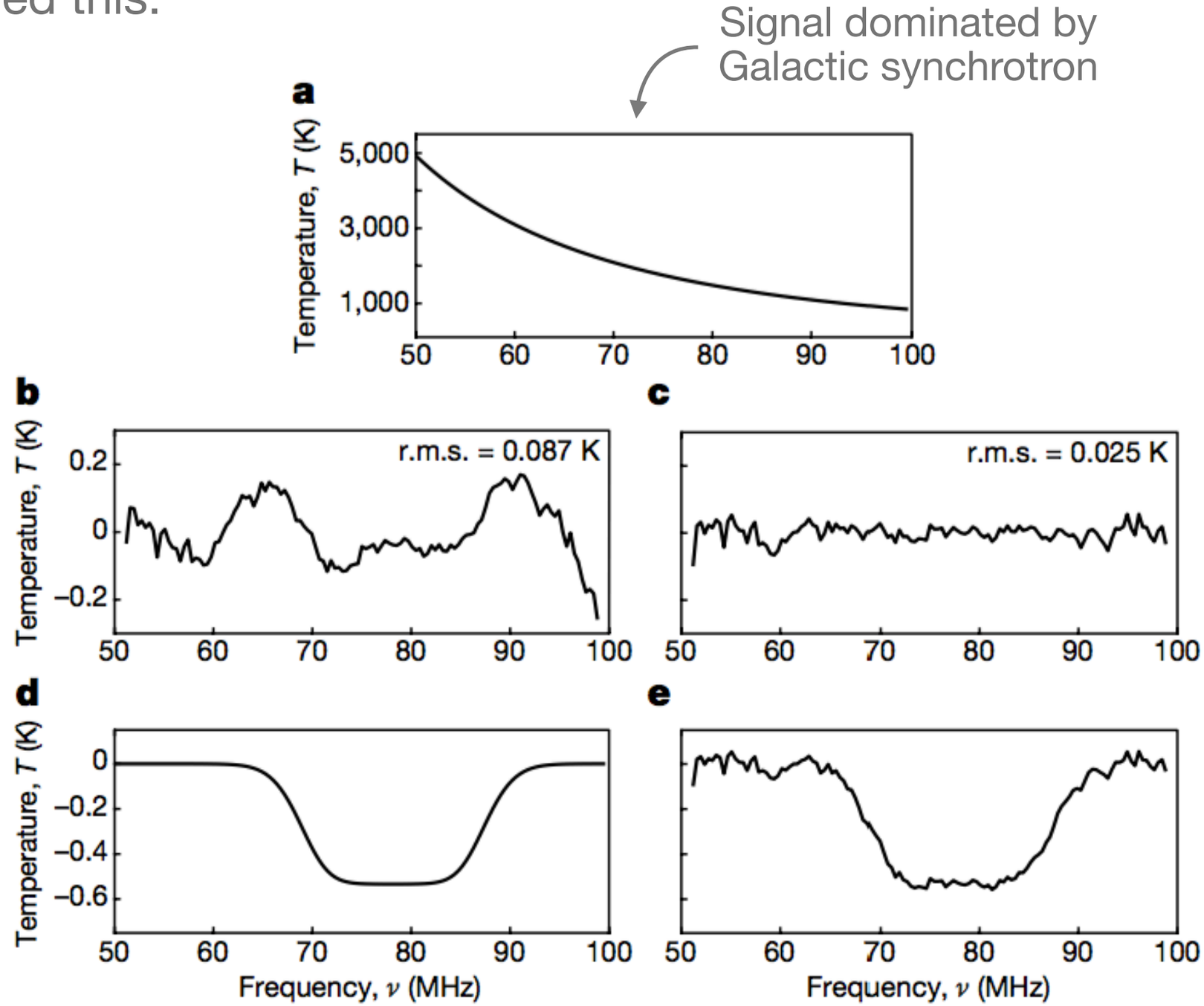

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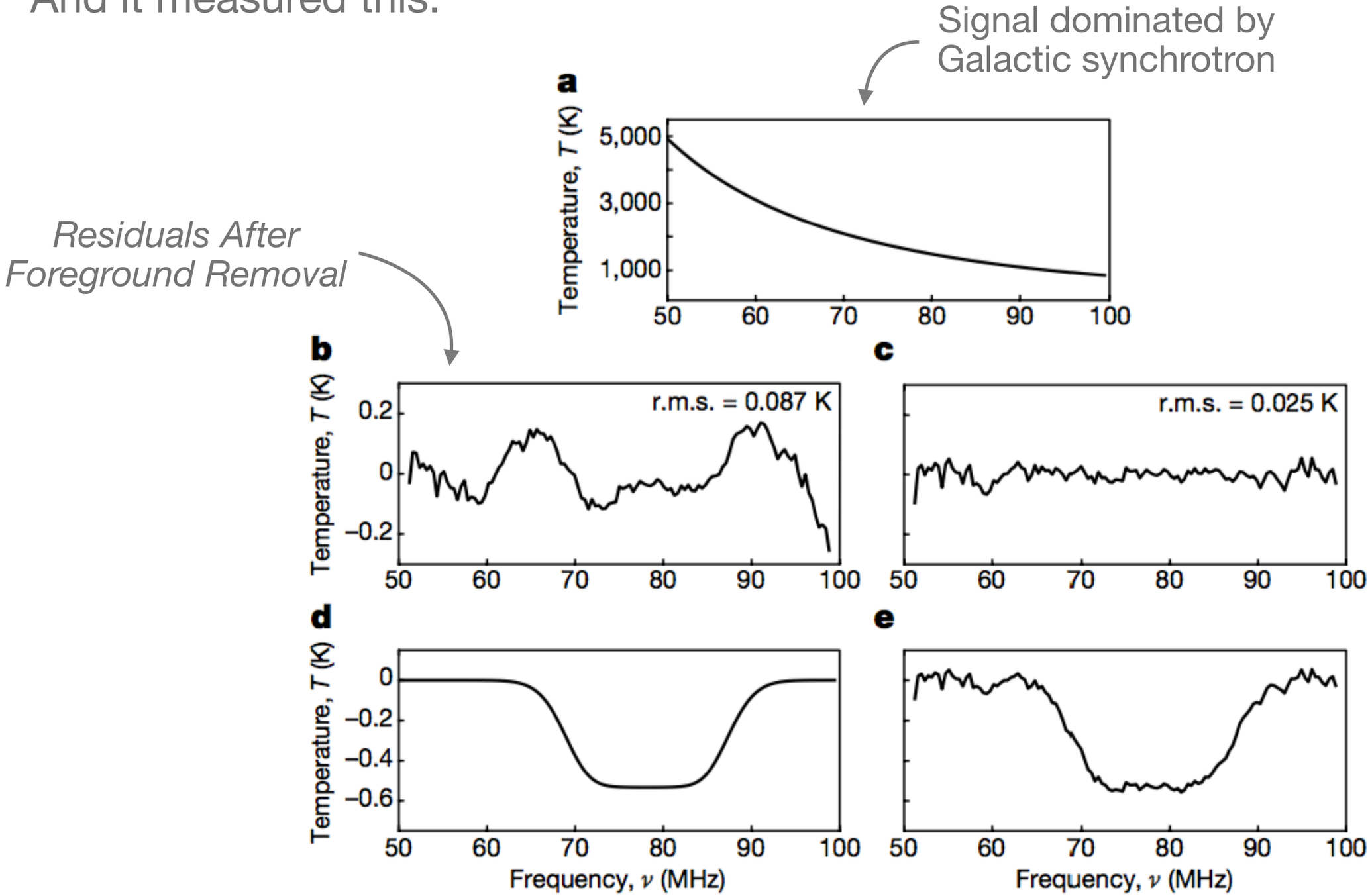

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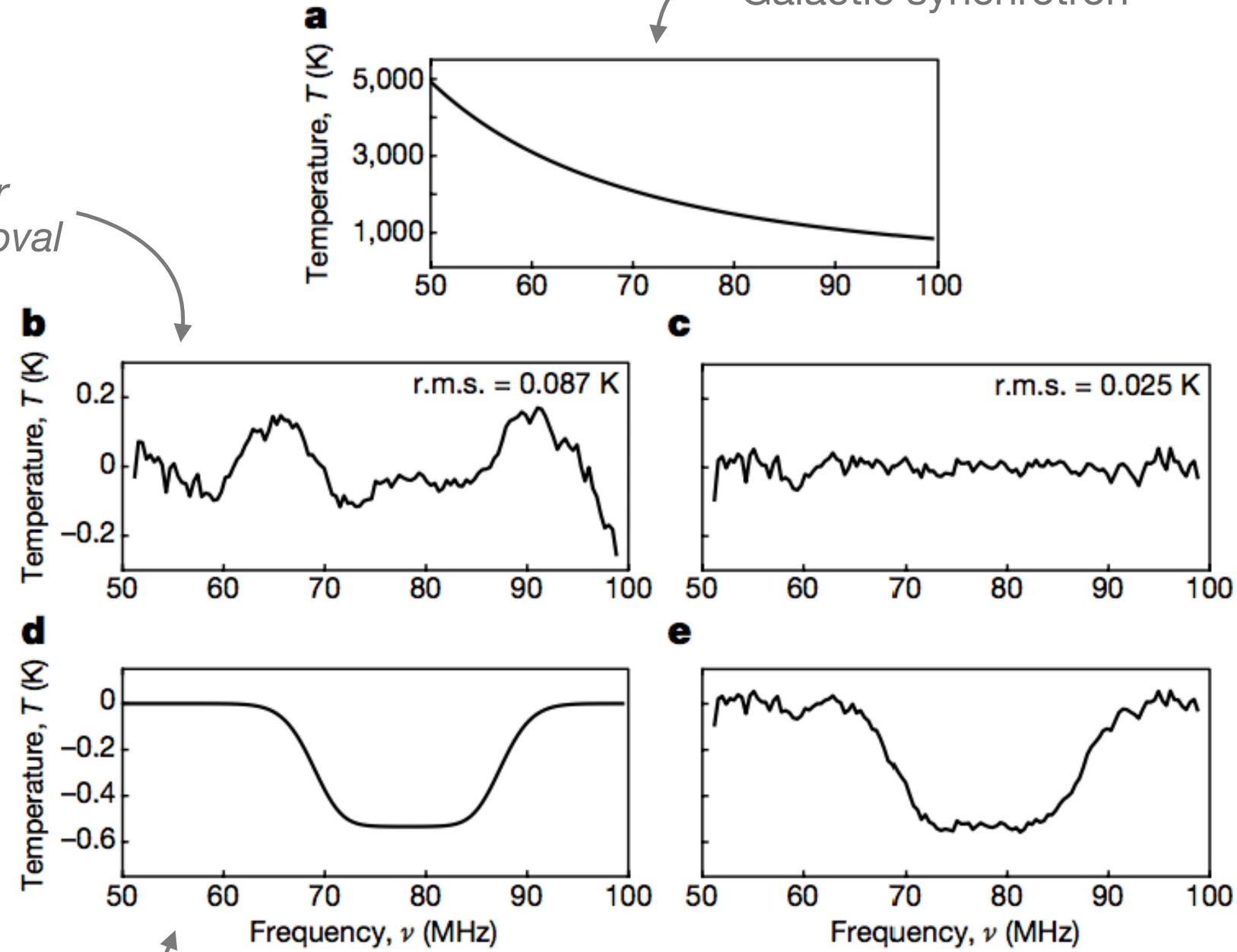
Residuals After Foreground Removal



Best-fit 21cm model

Bowman et al., Nature (2018)

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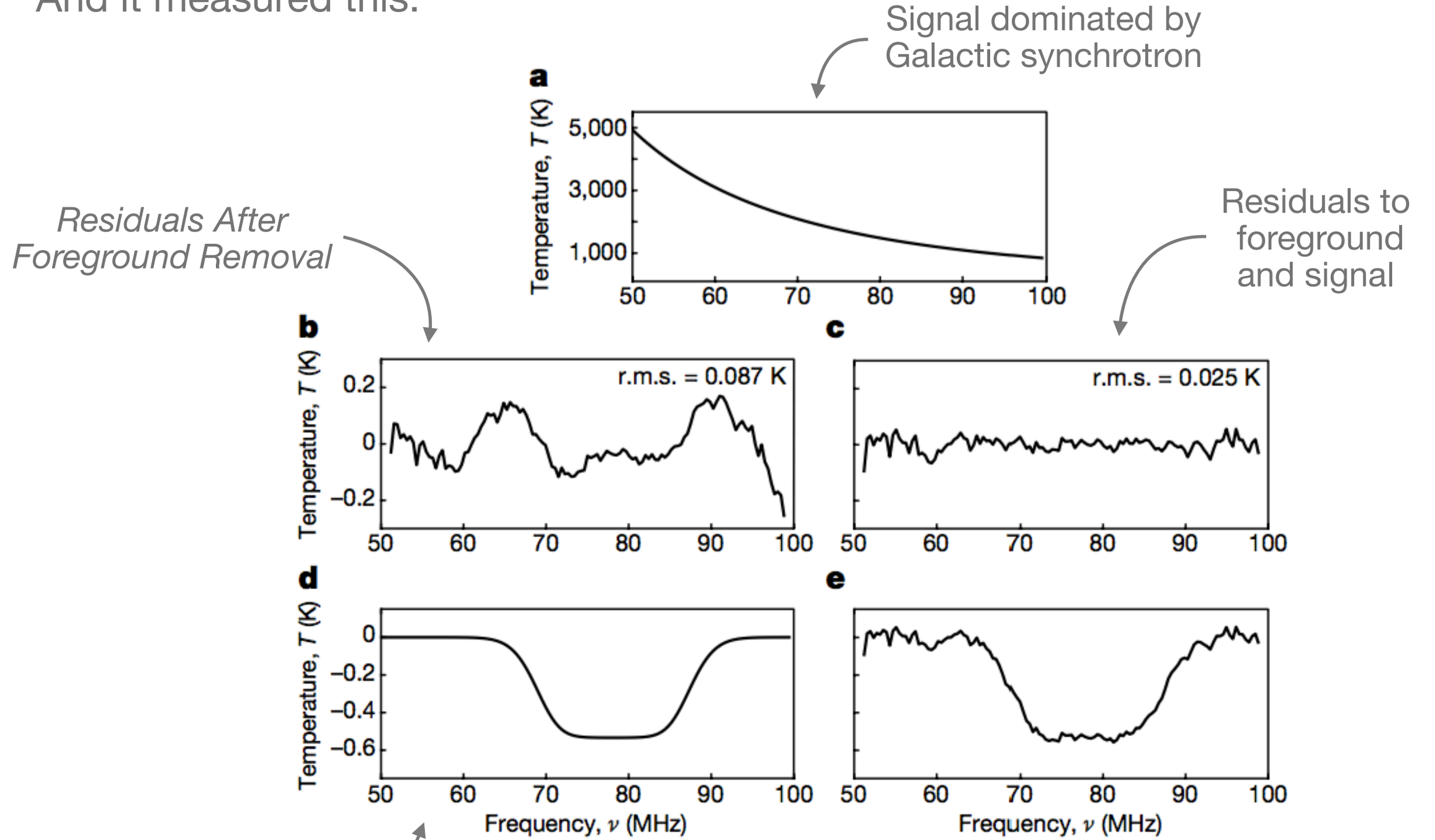

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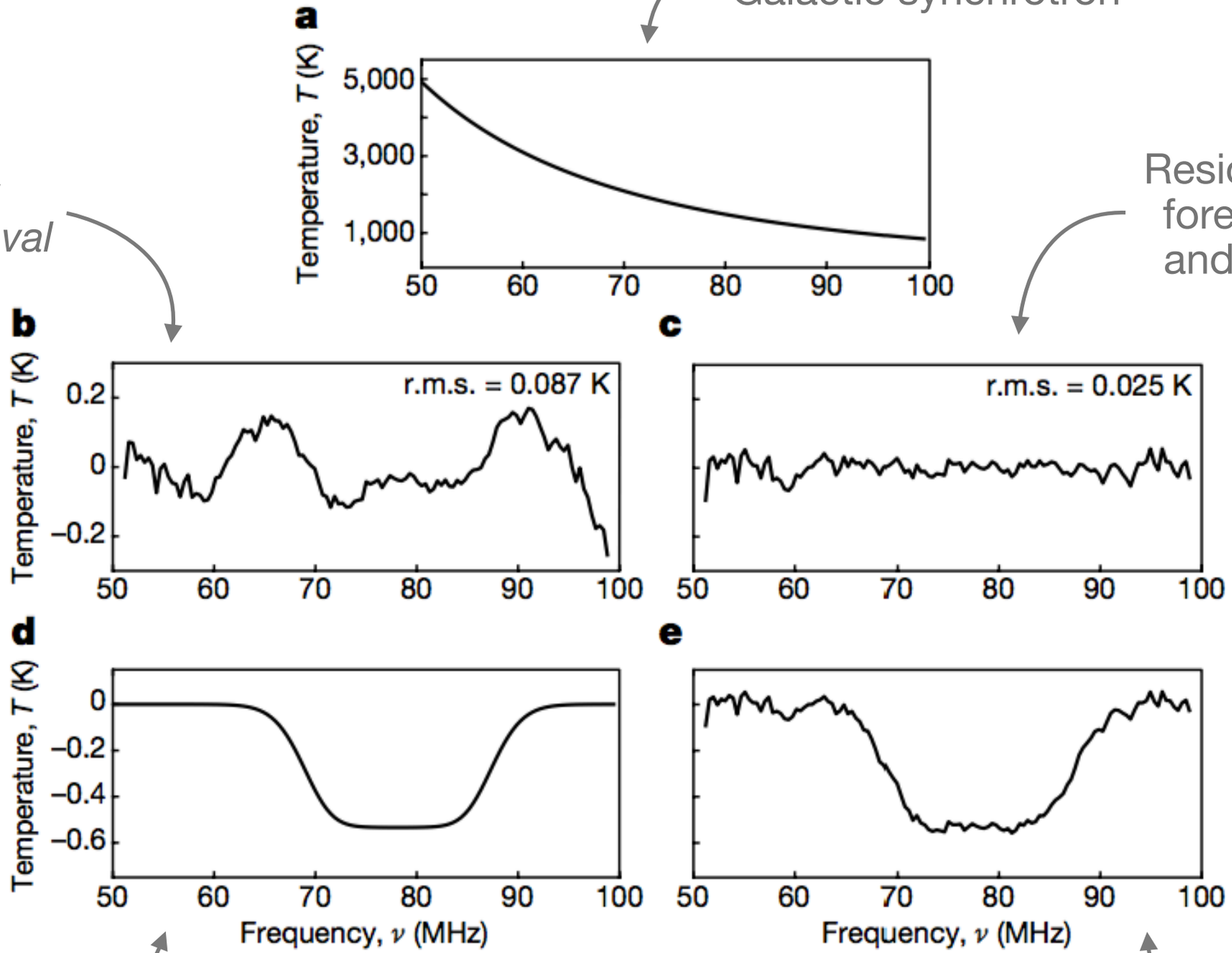

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Best-fit Model plus residuals

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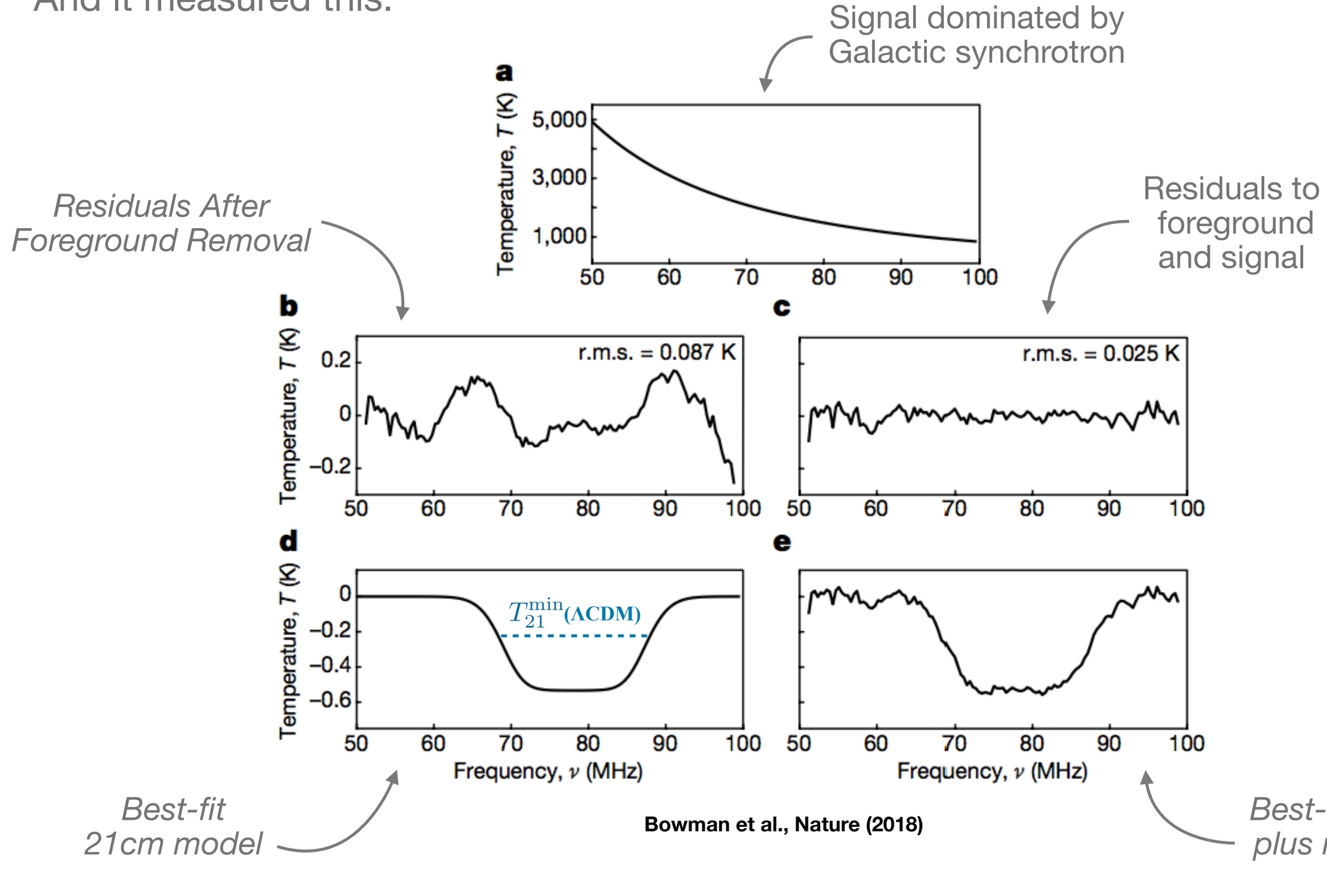

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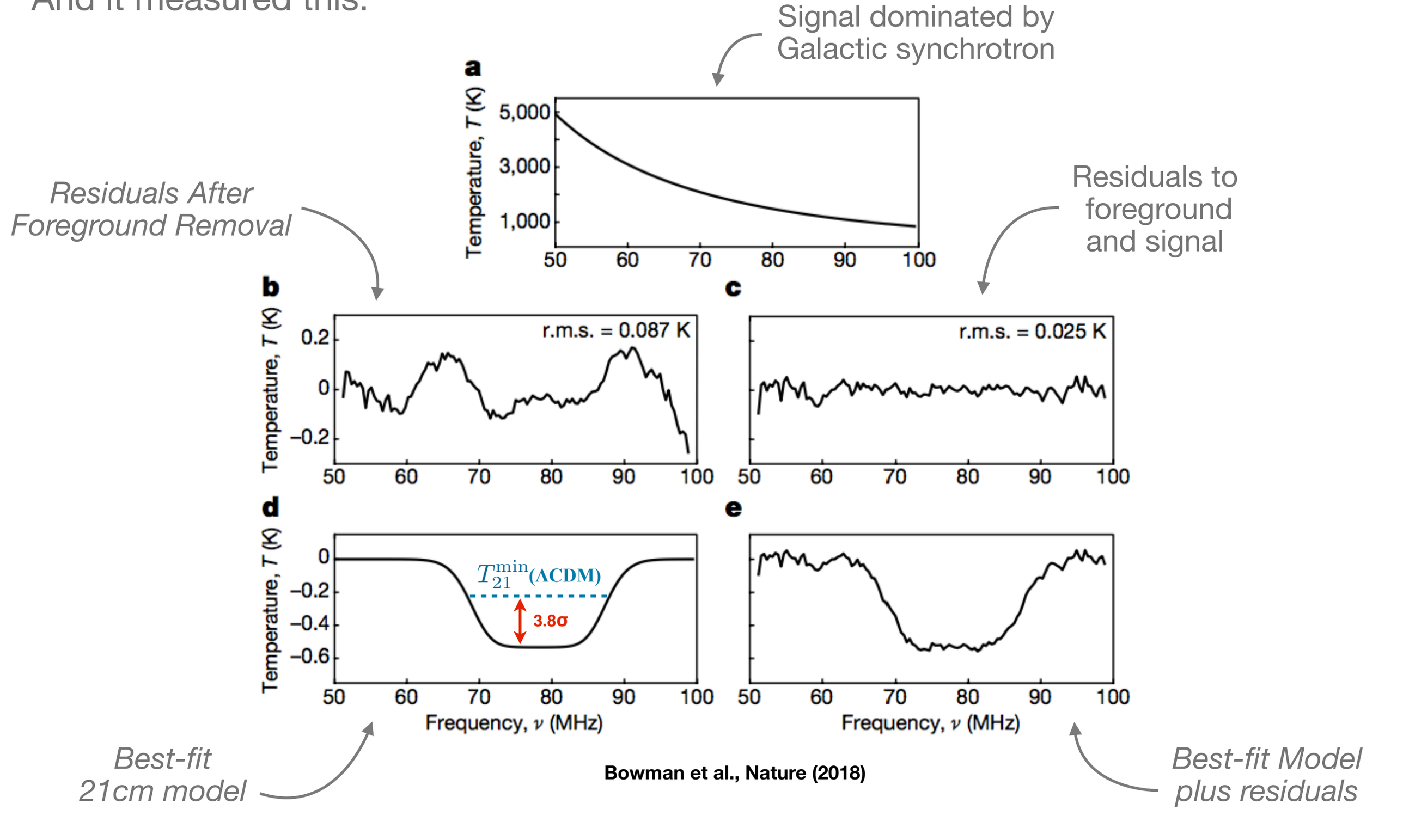

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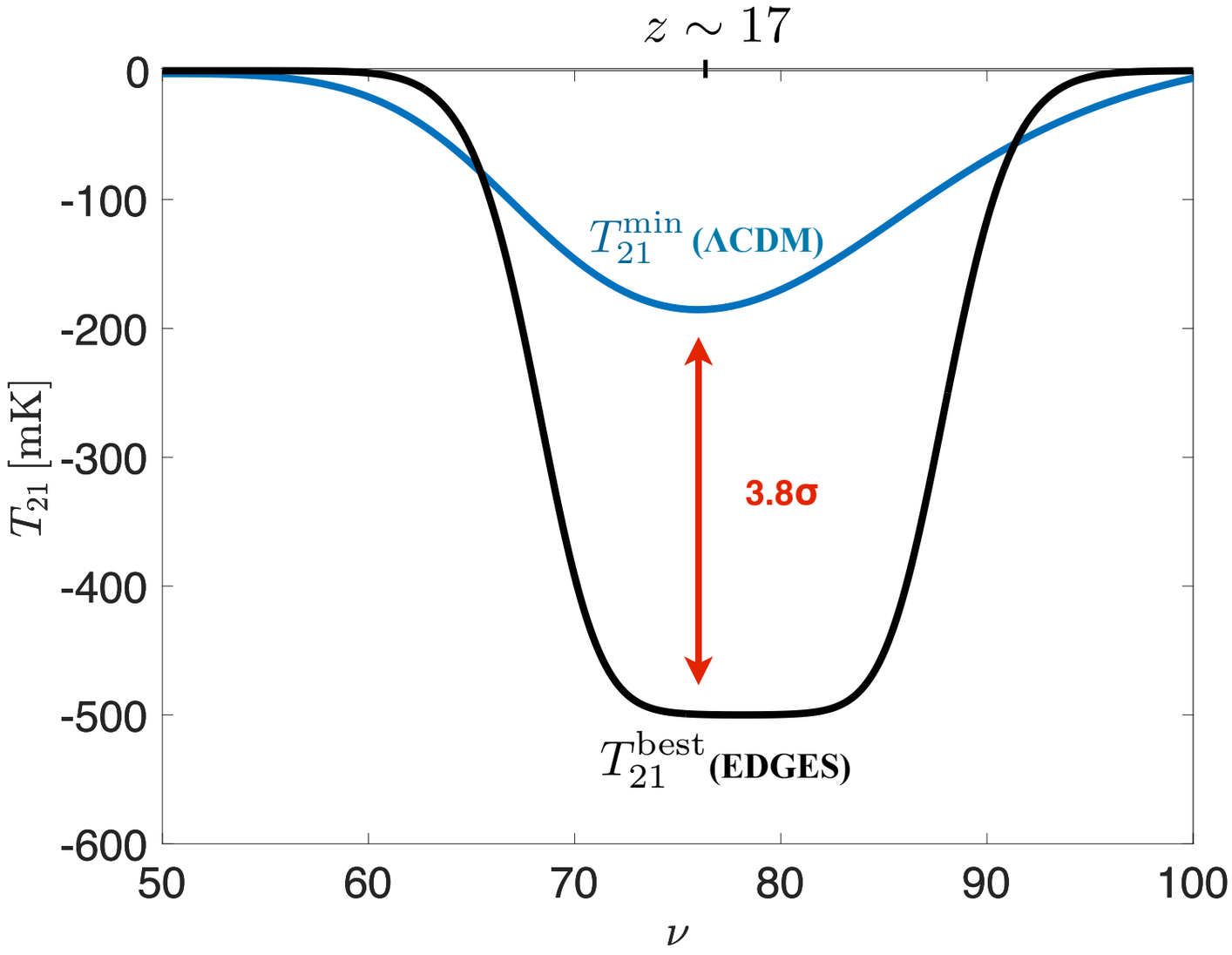
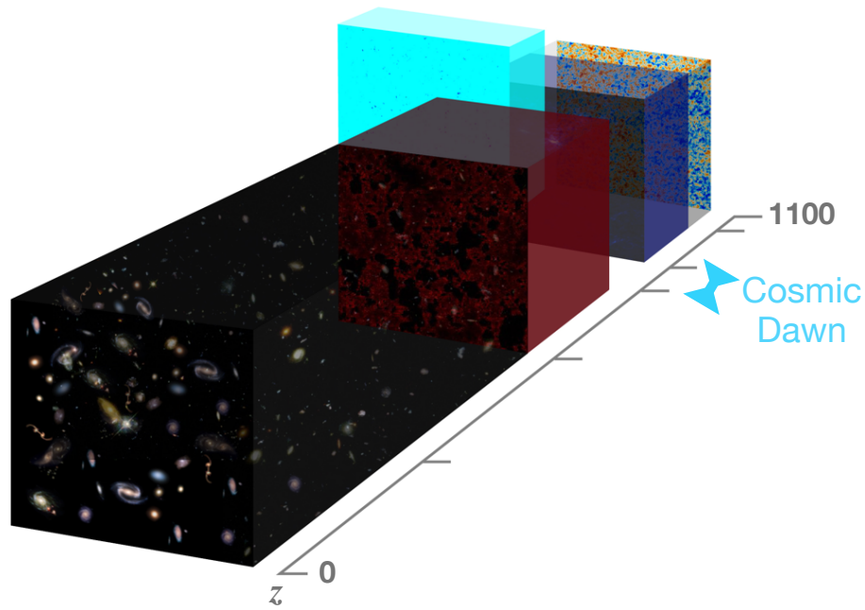
Q: Can Dark Matter Explain the EDGES Signal?





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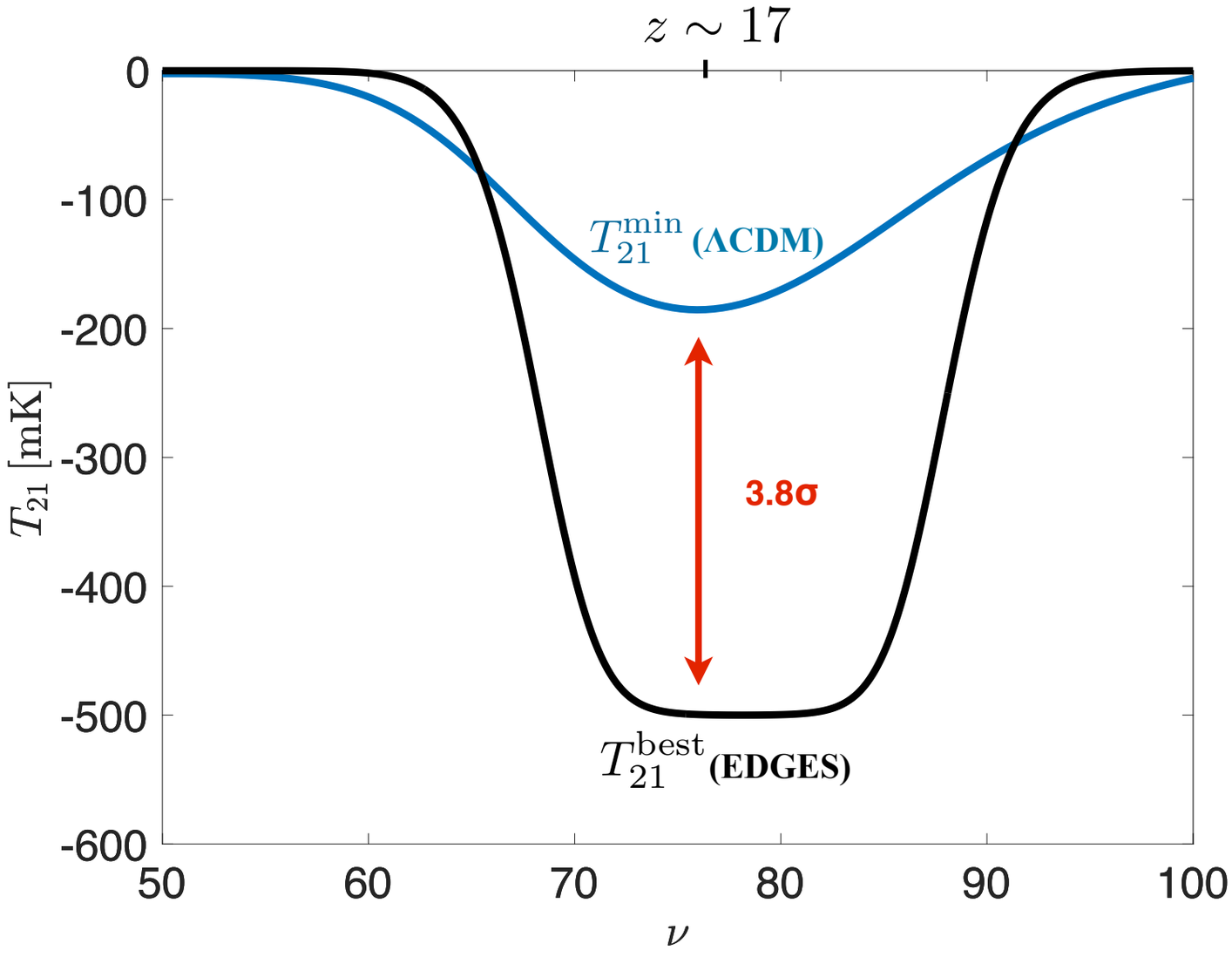
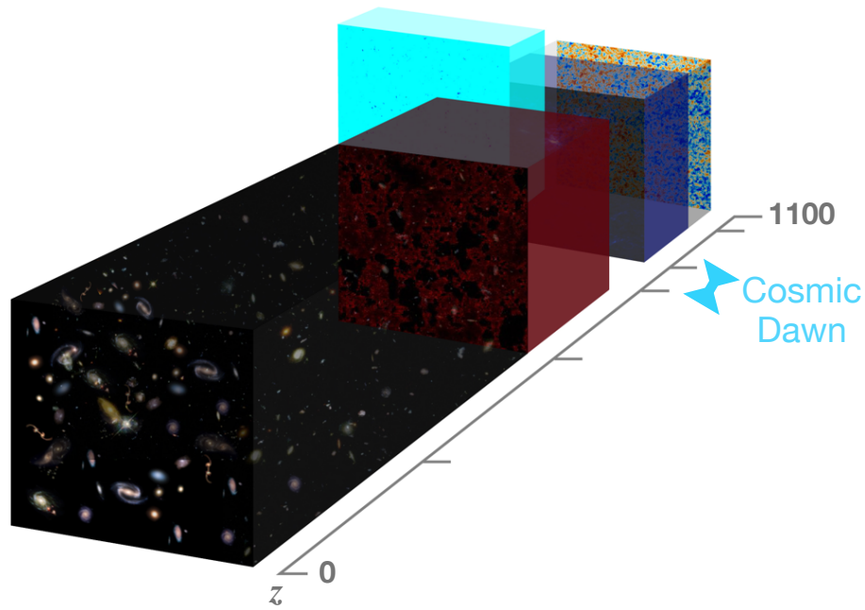
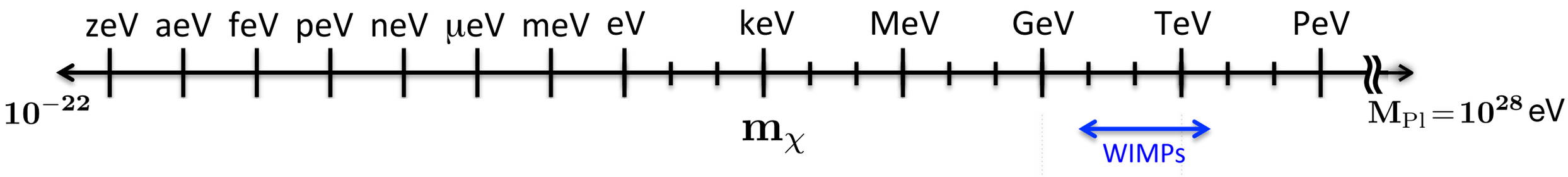




Signatures of Dark Matter-Baryon Scattering



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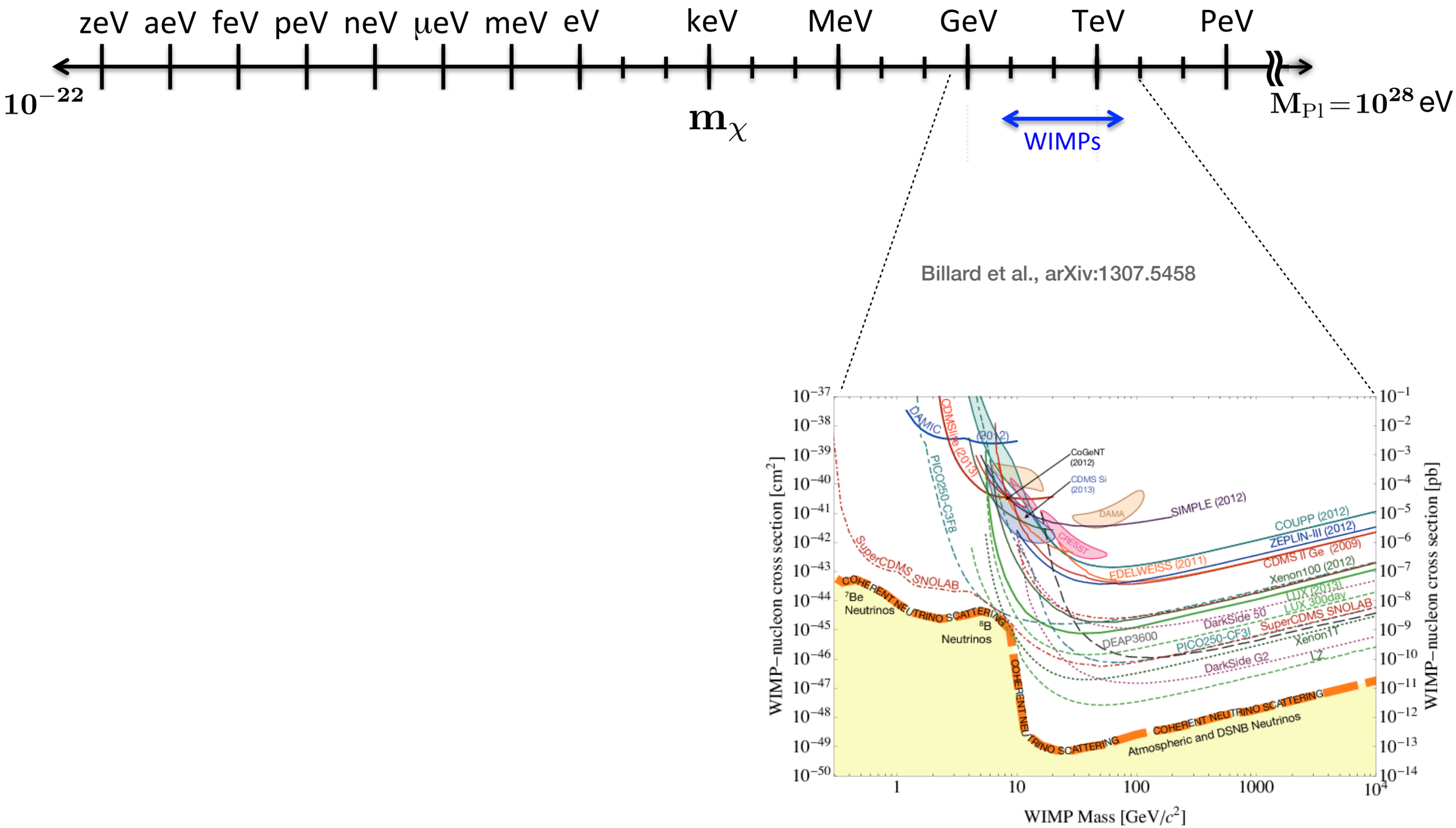

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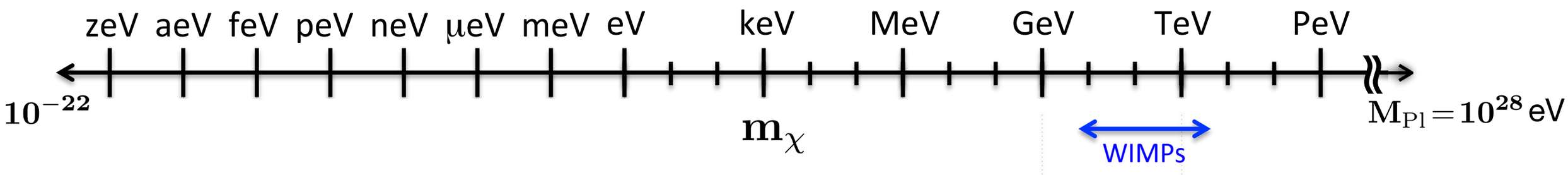

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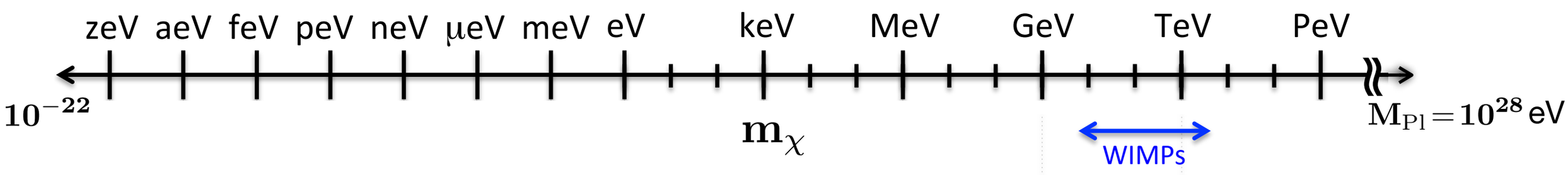

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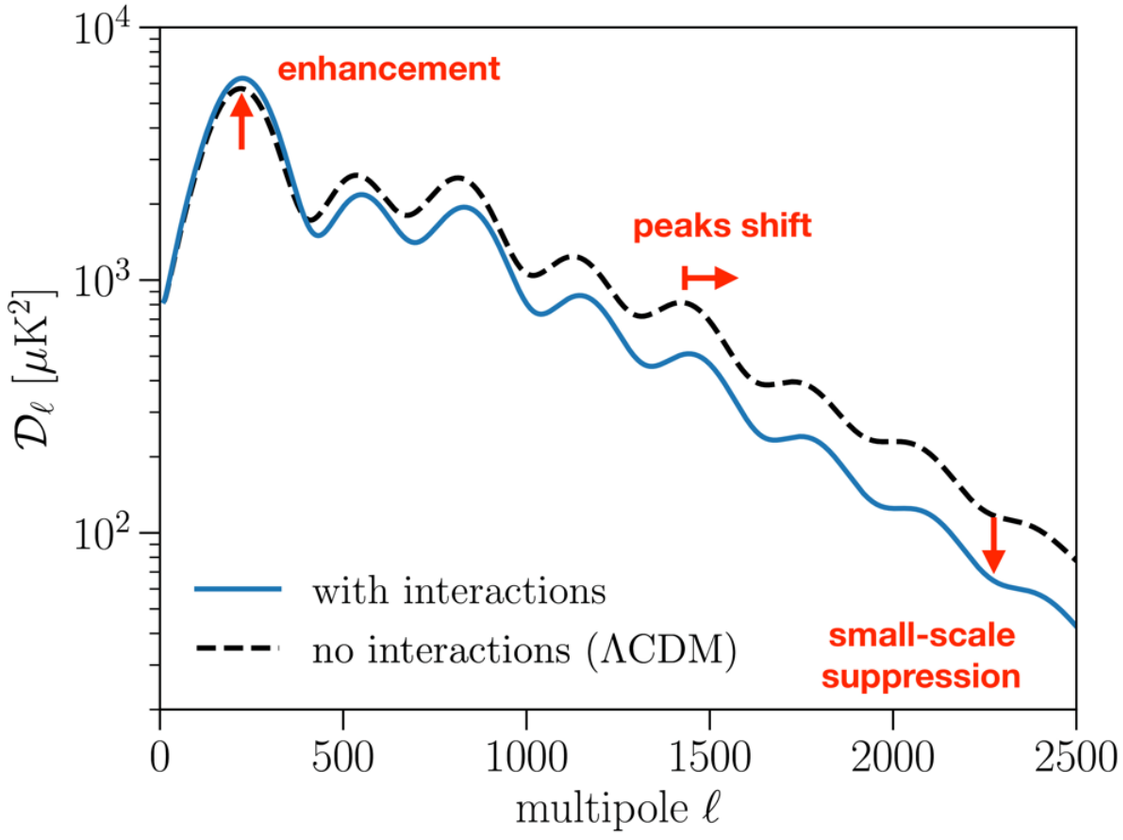
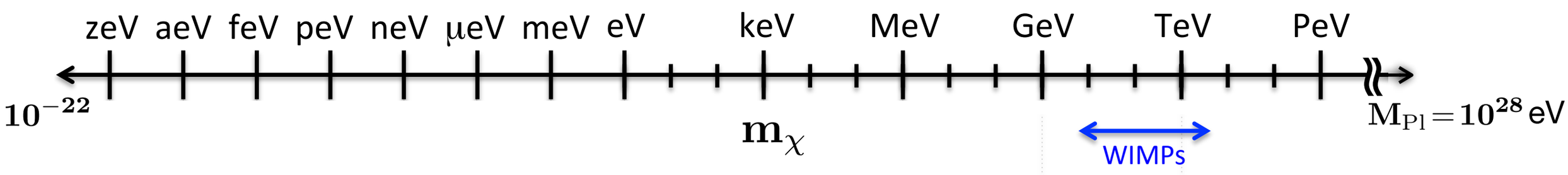


Signatures of Dark Matter-Baryon Scattering



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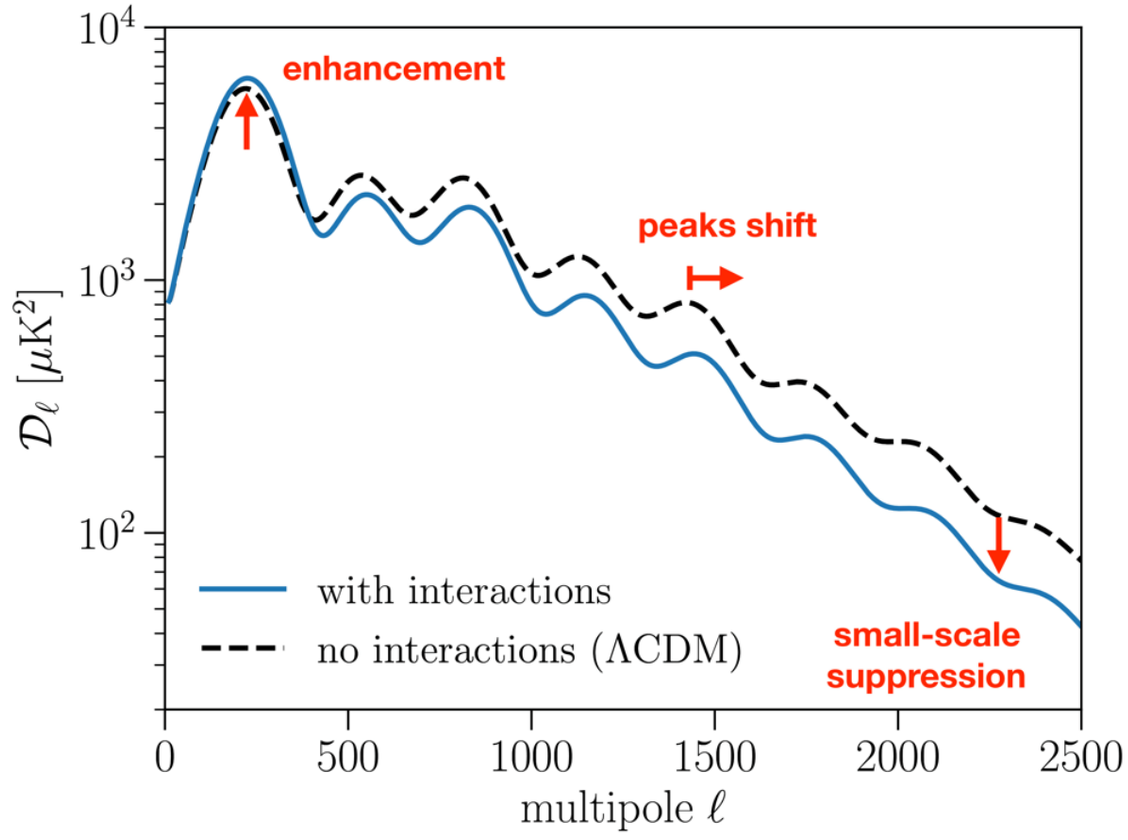

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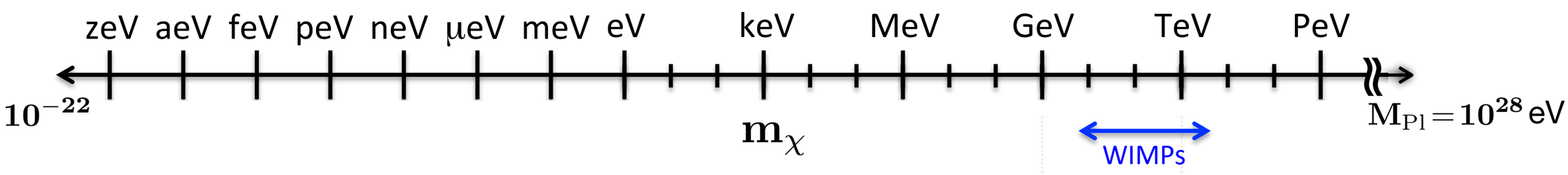

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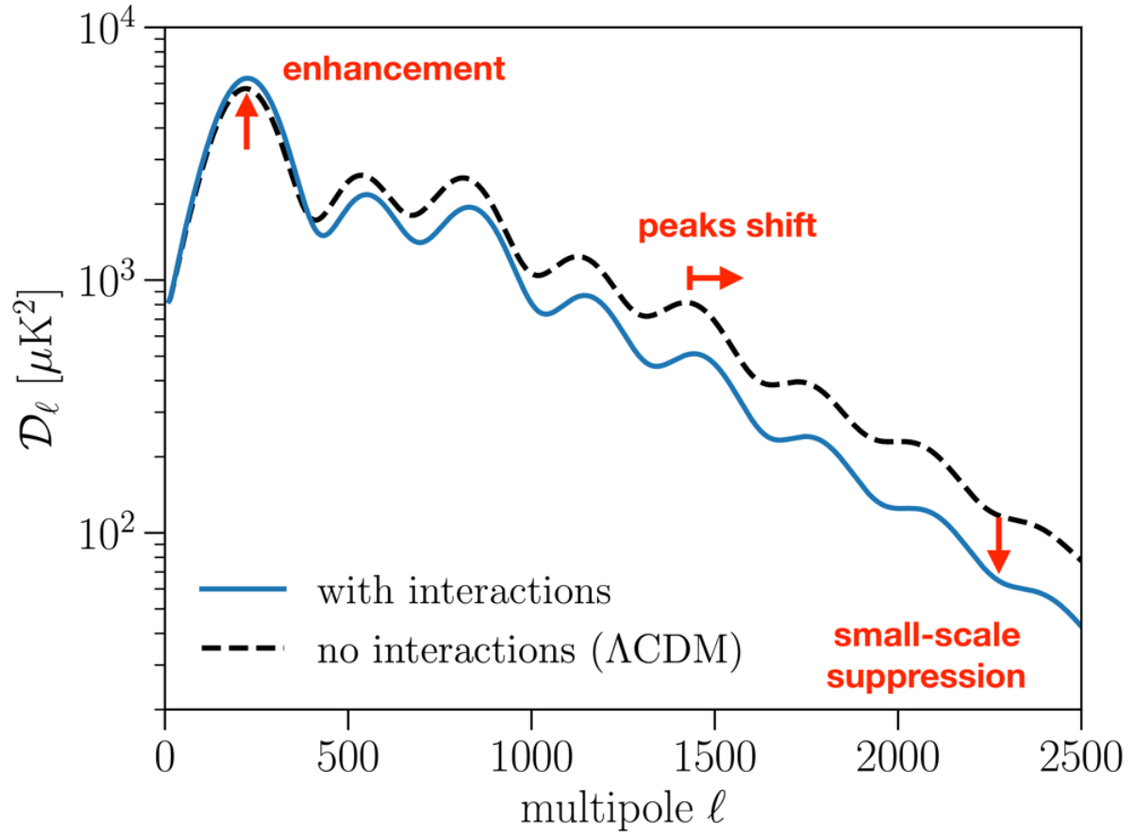

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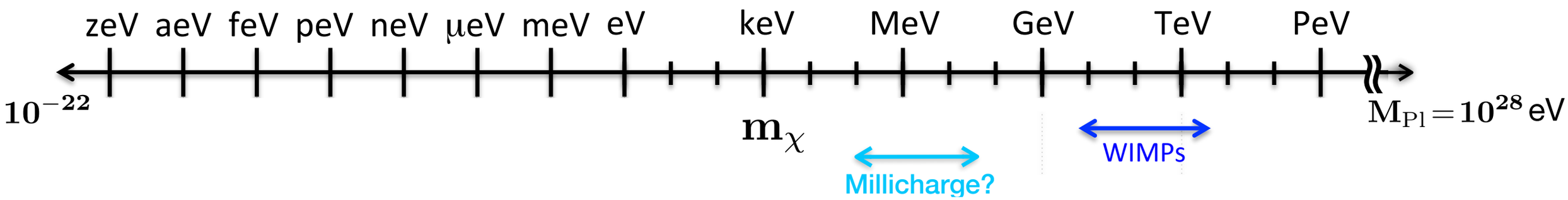

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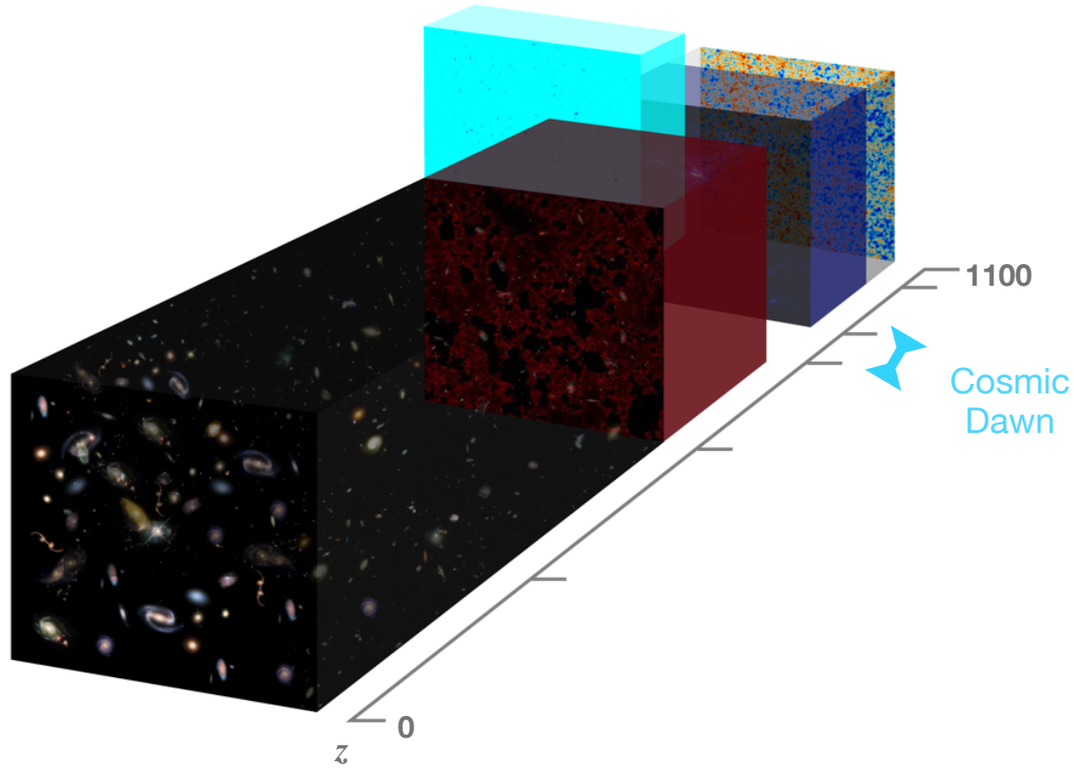

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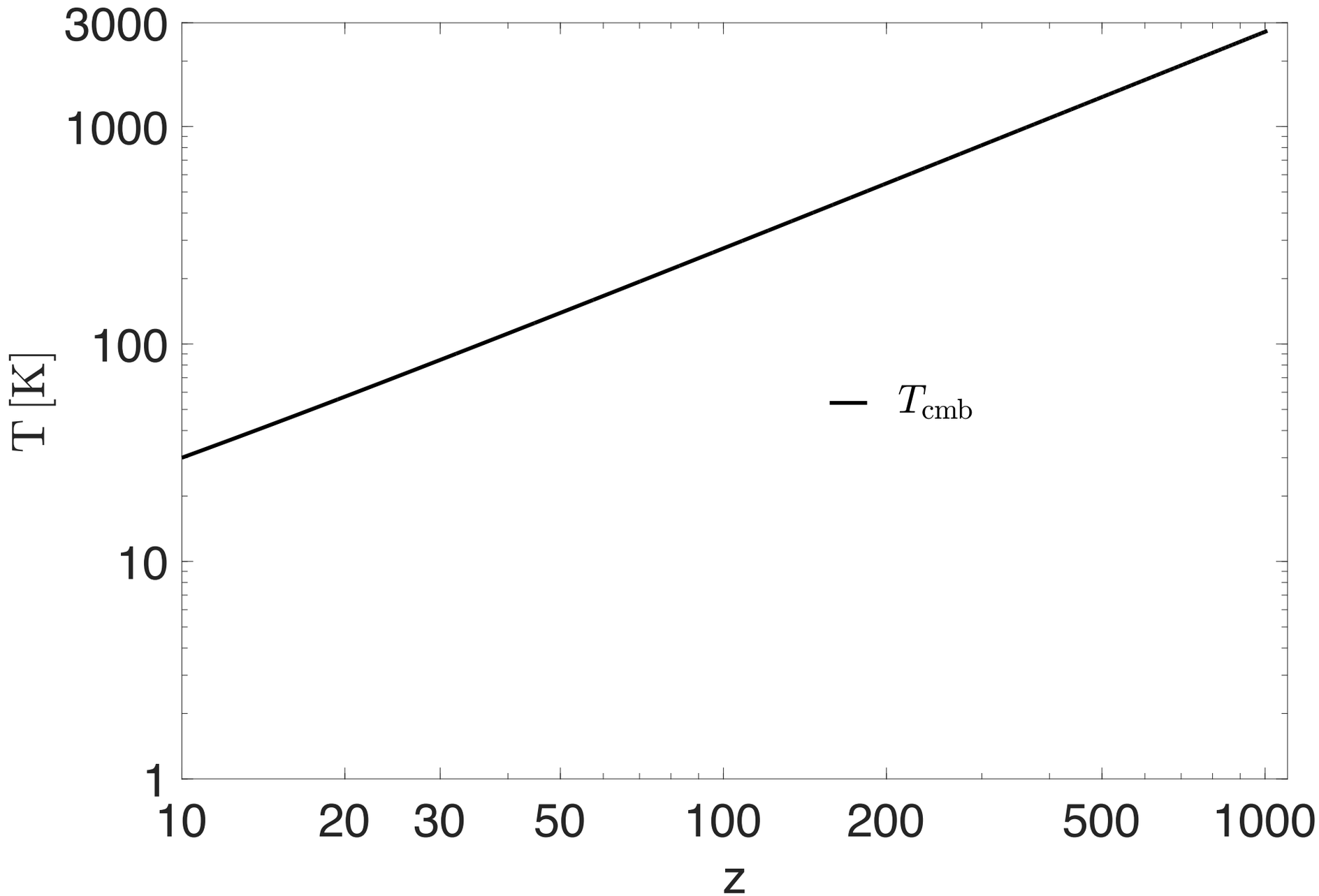

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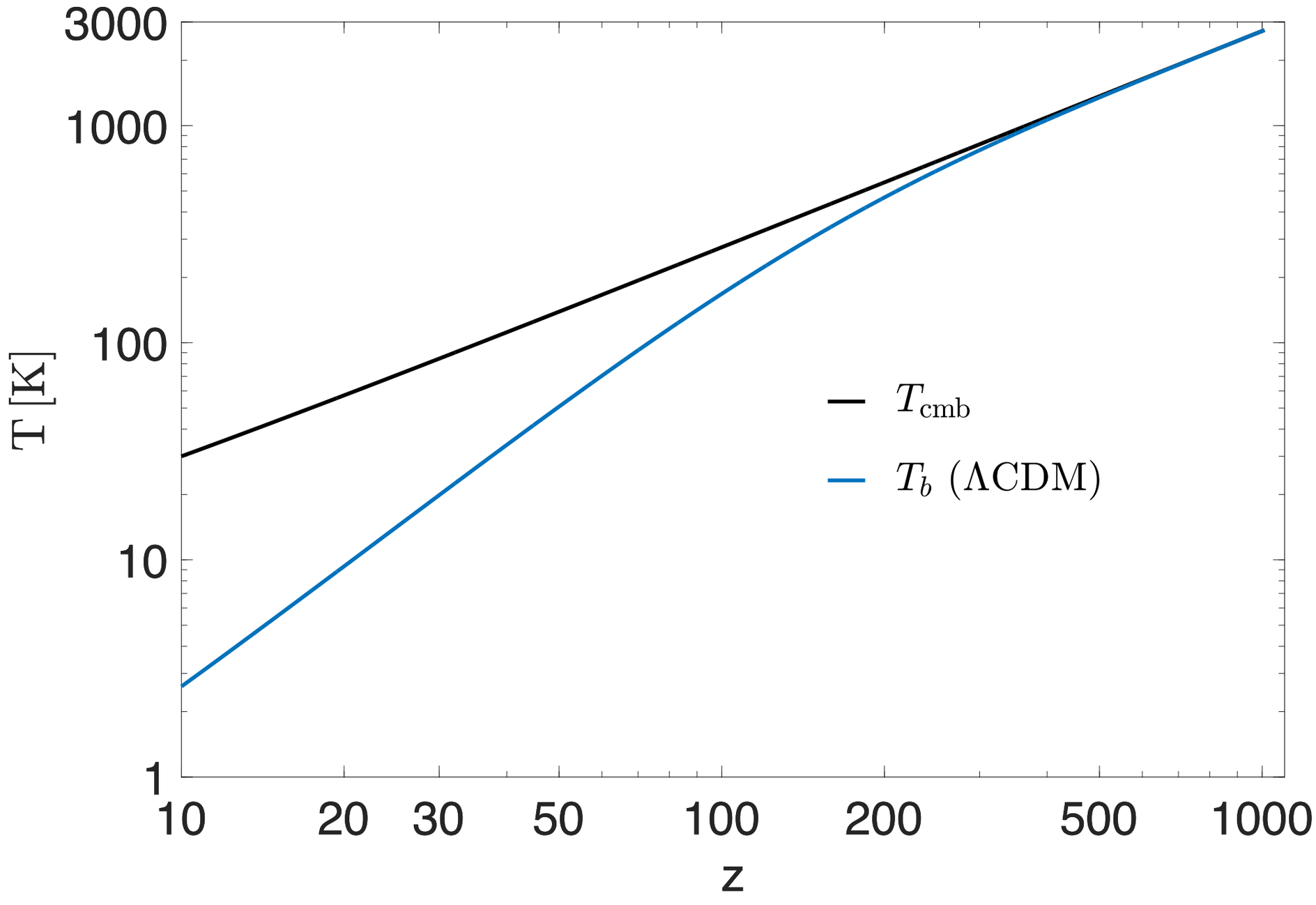

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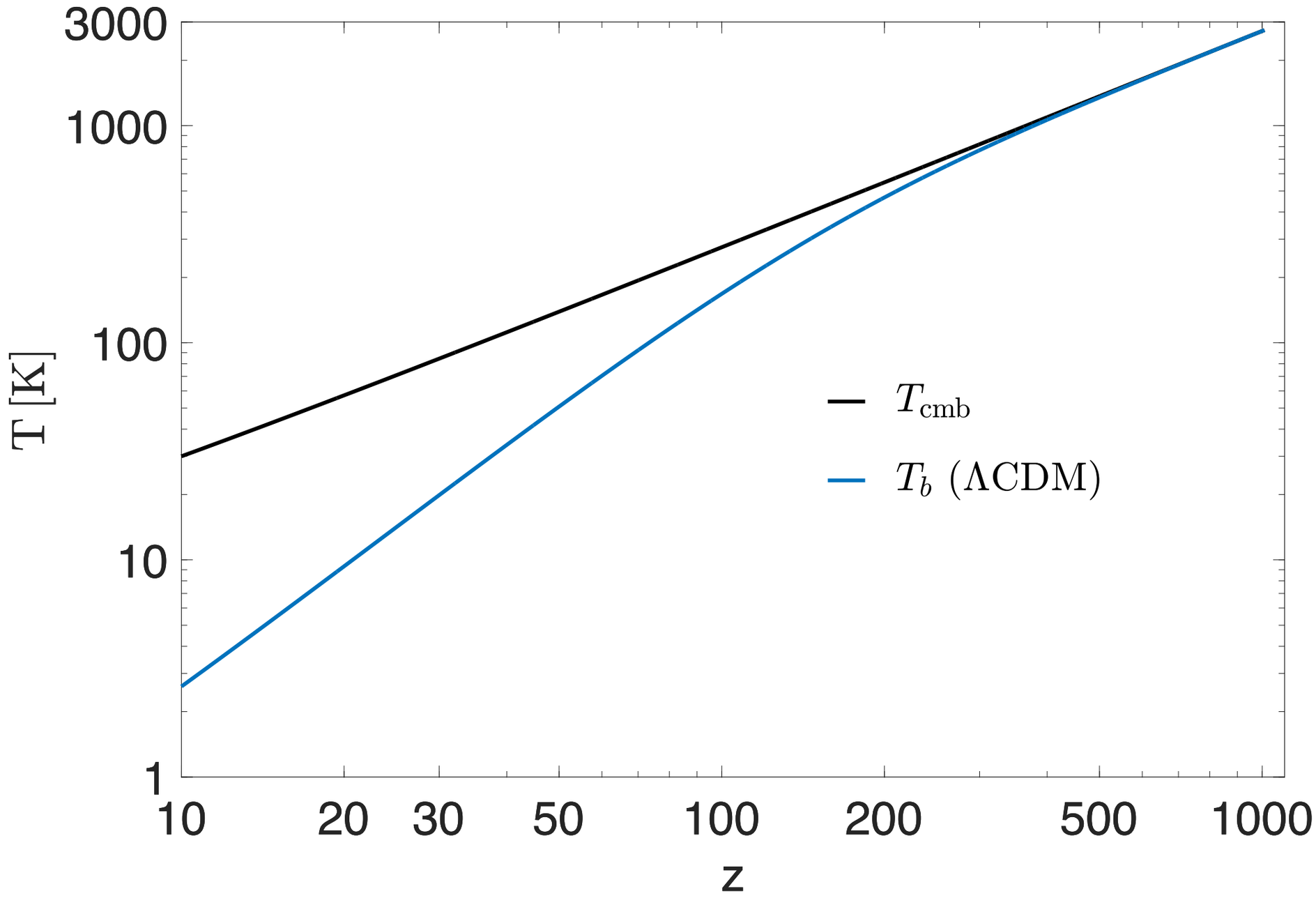

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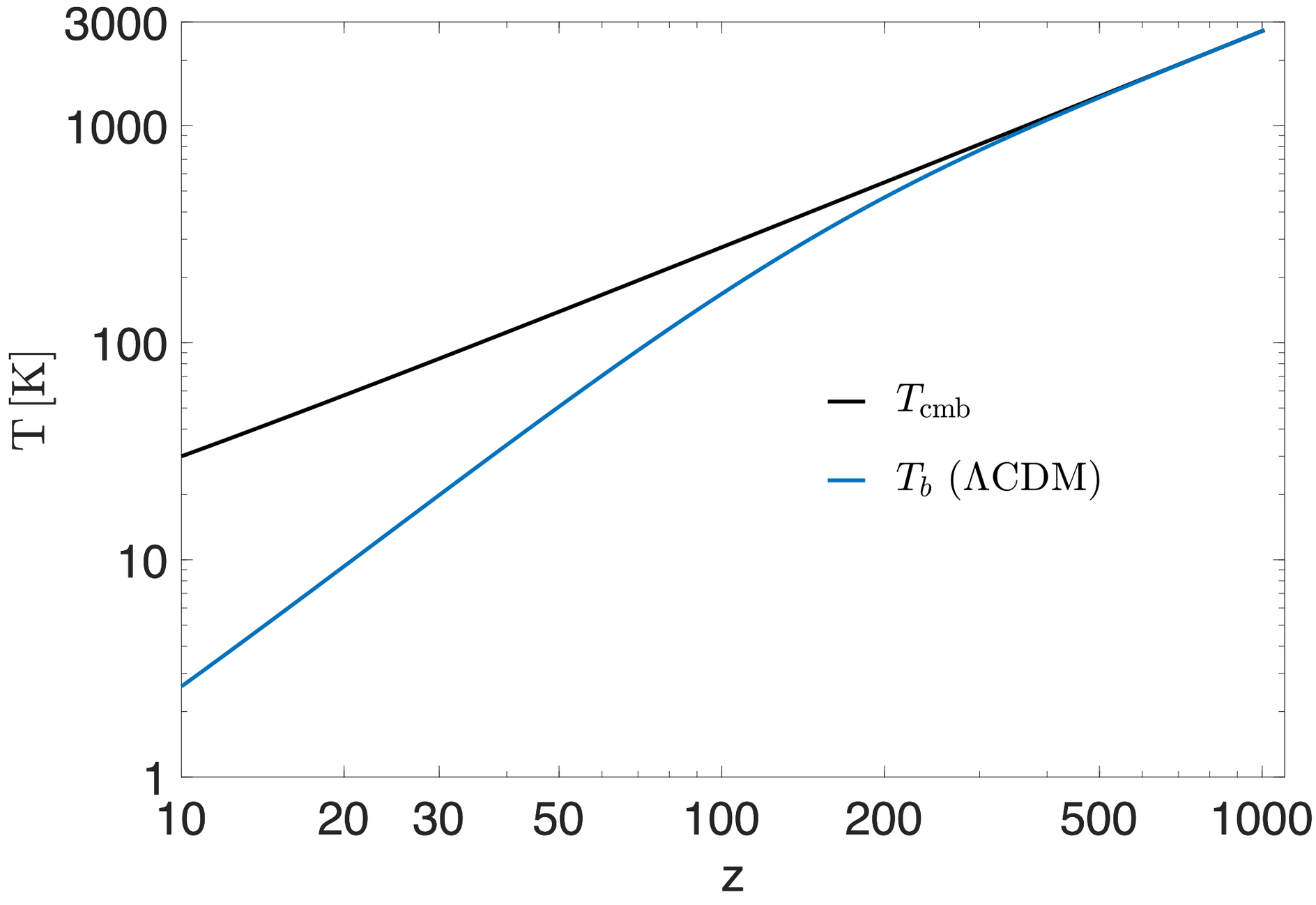

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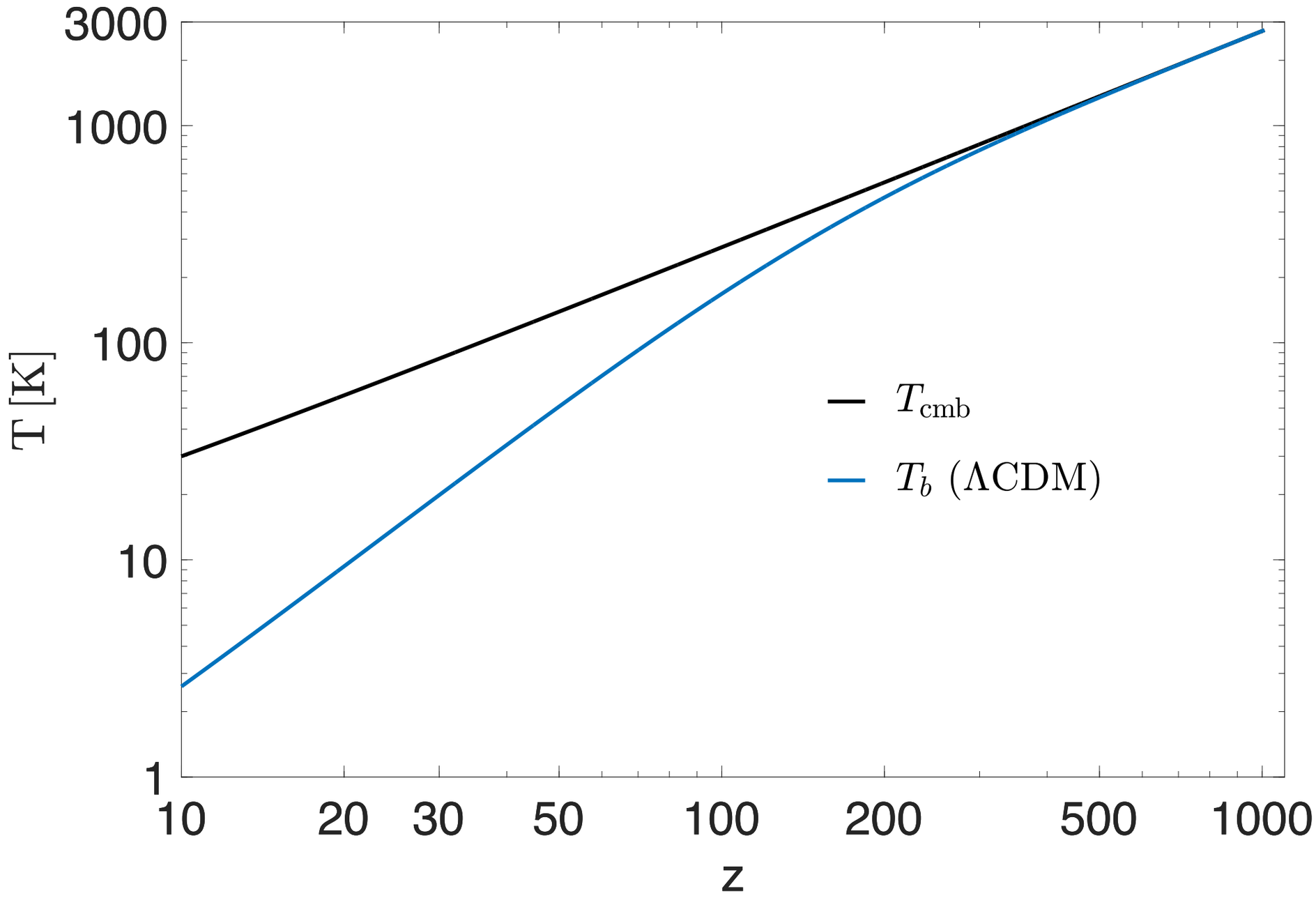

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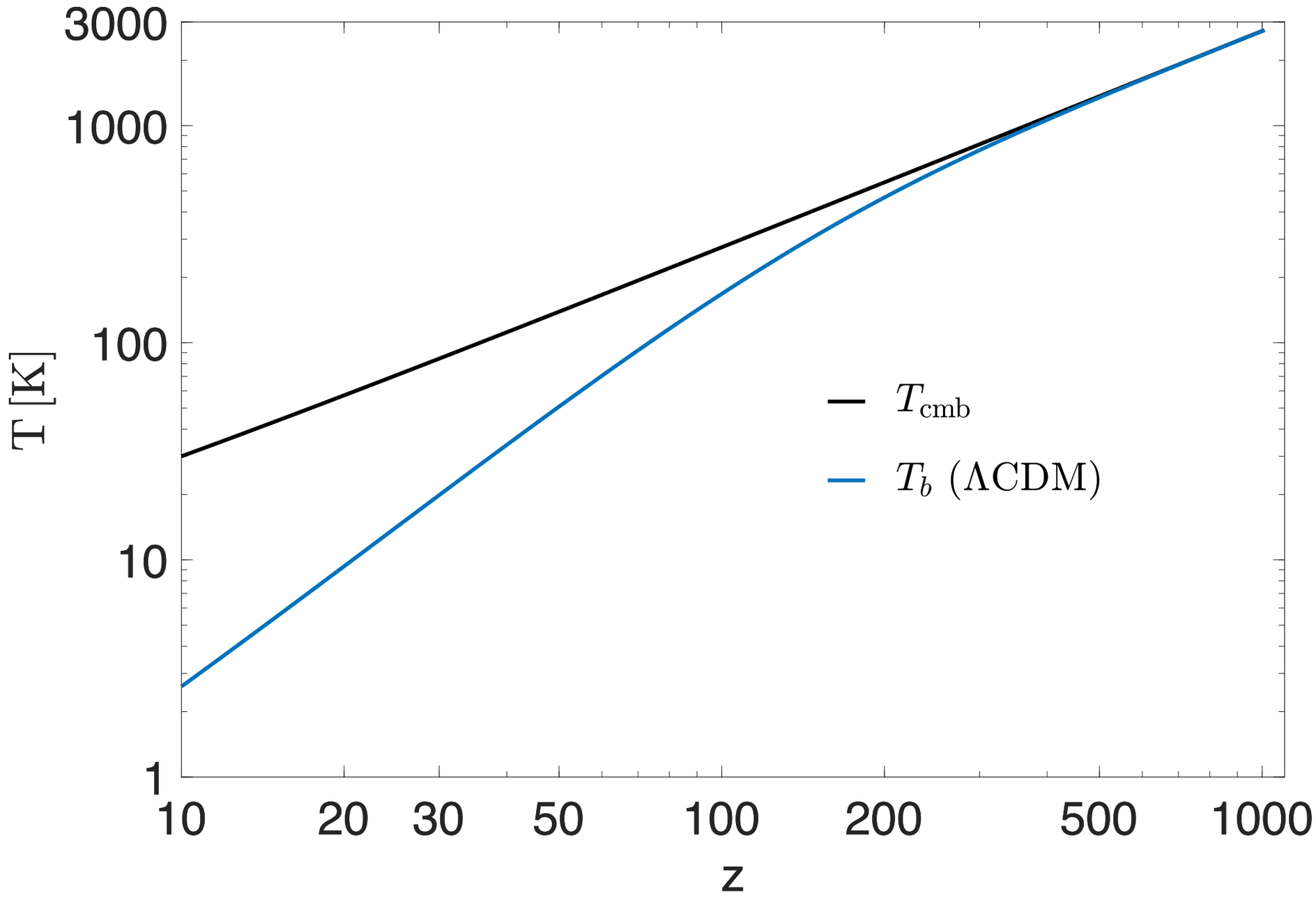

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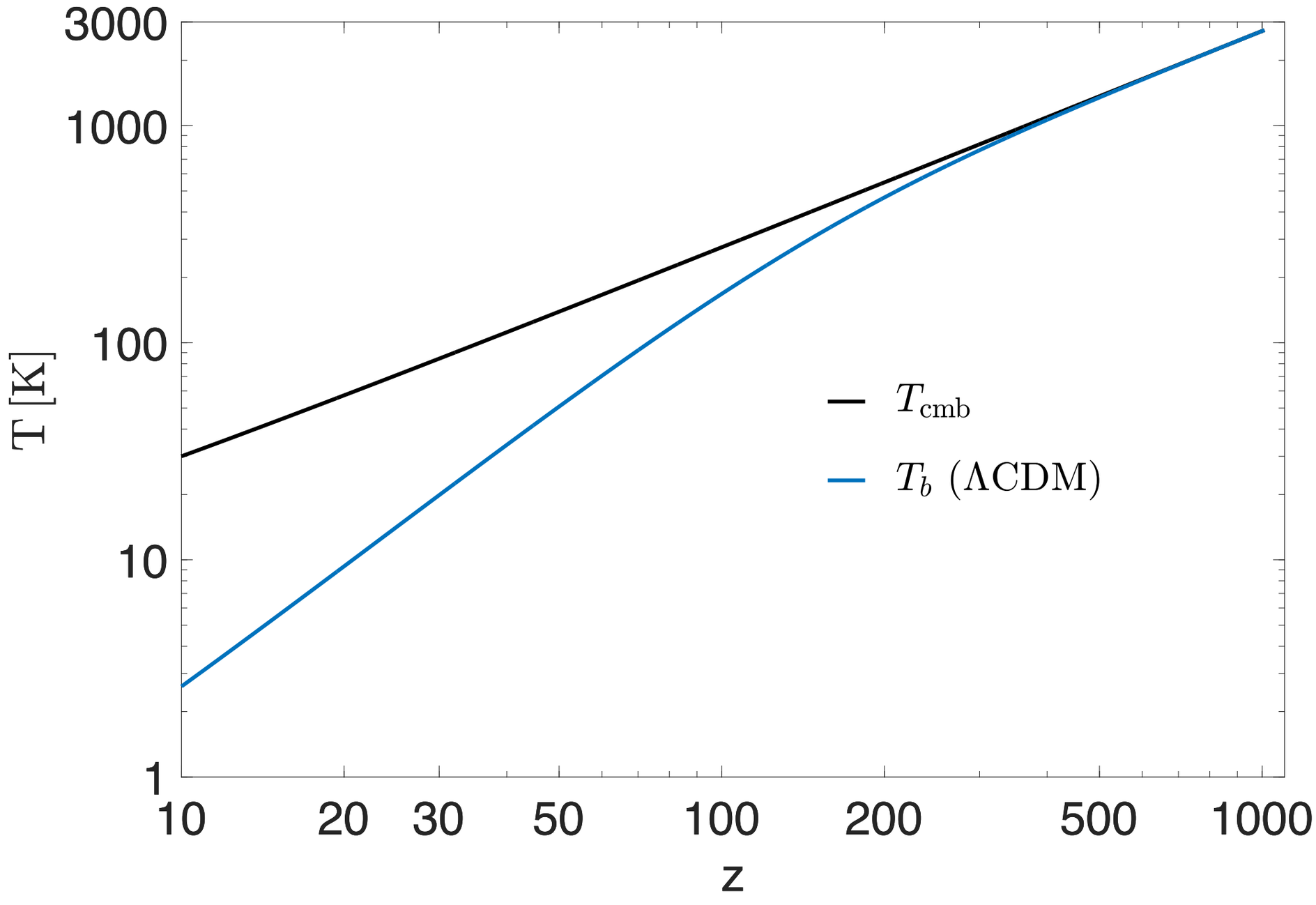

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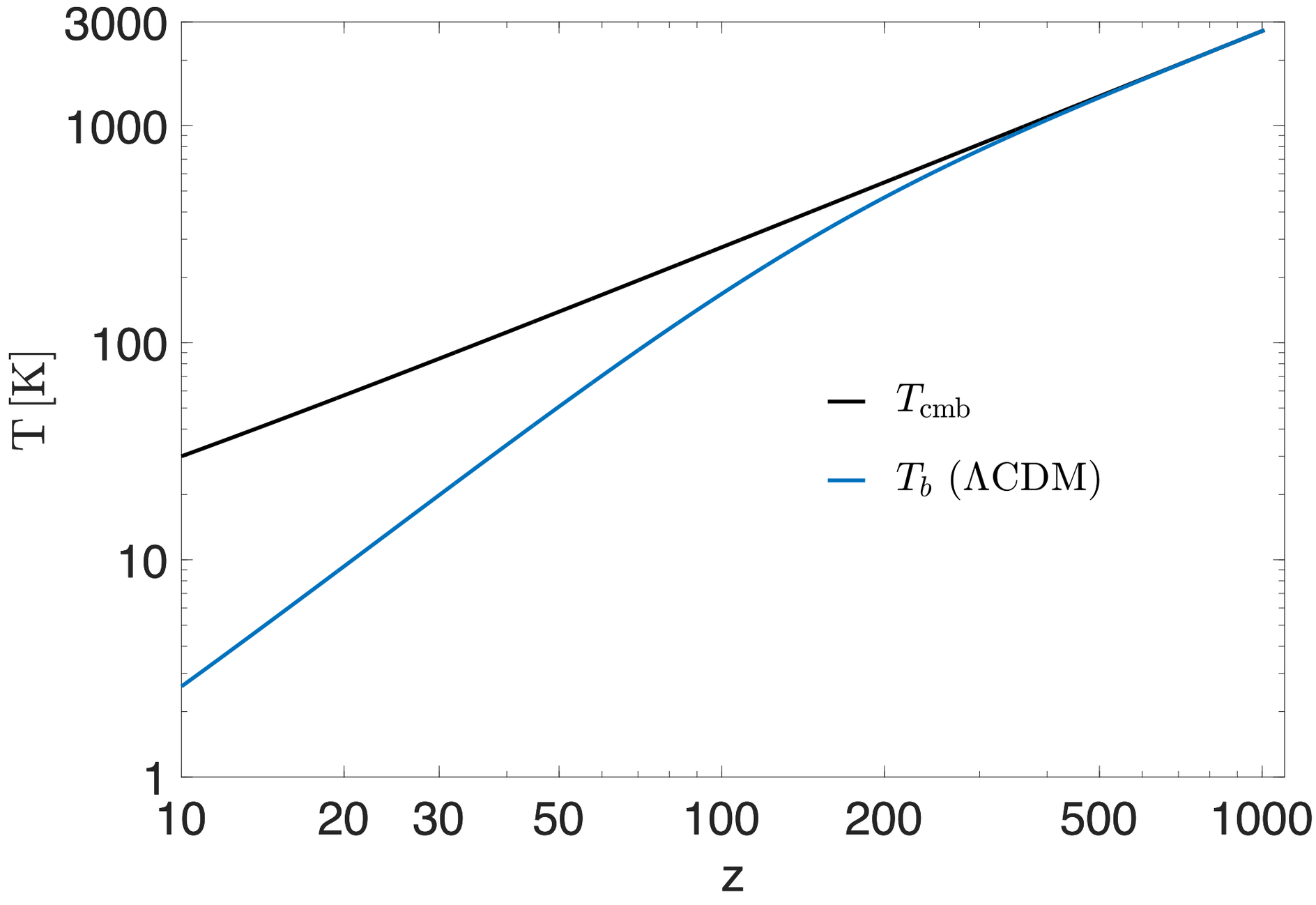

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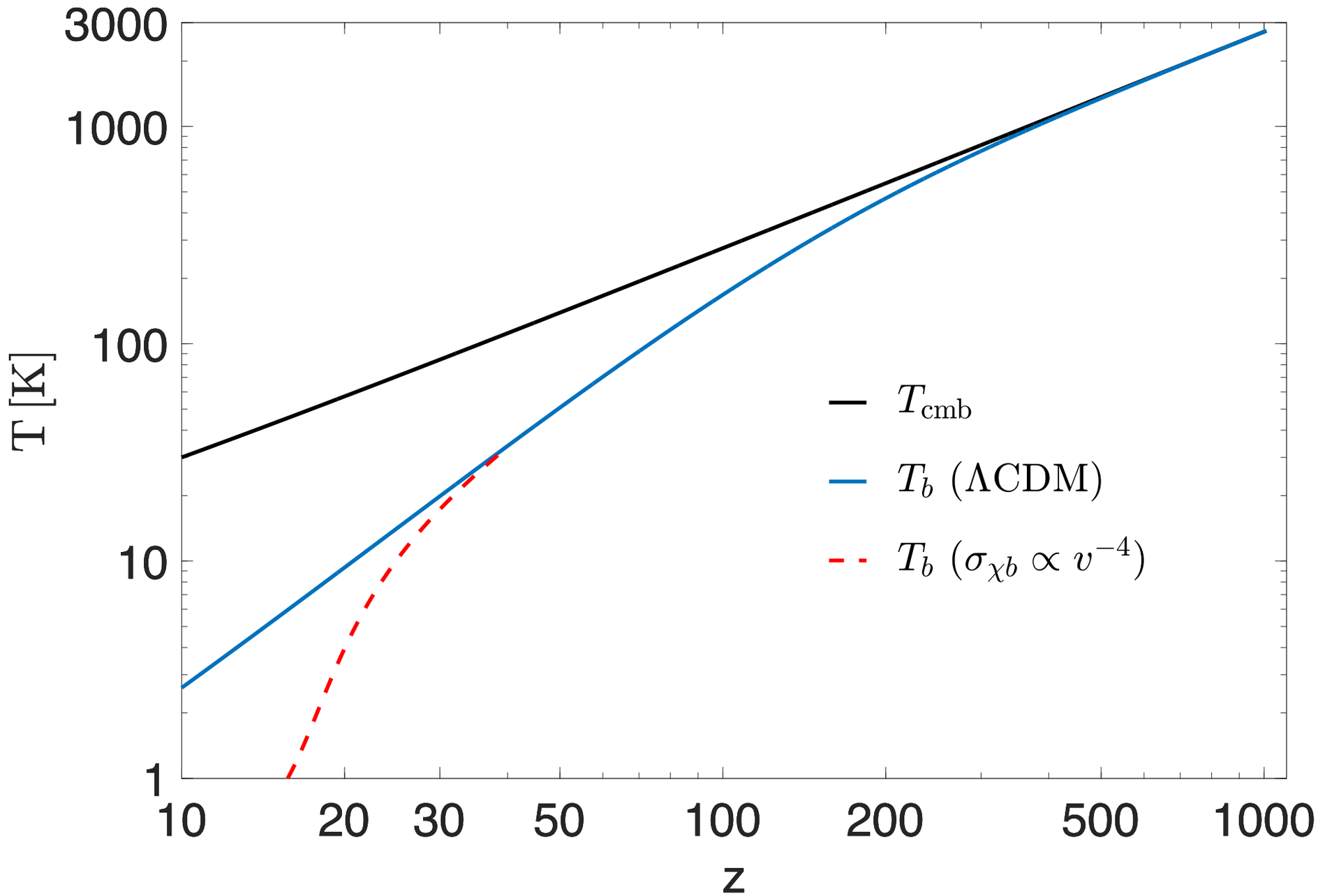

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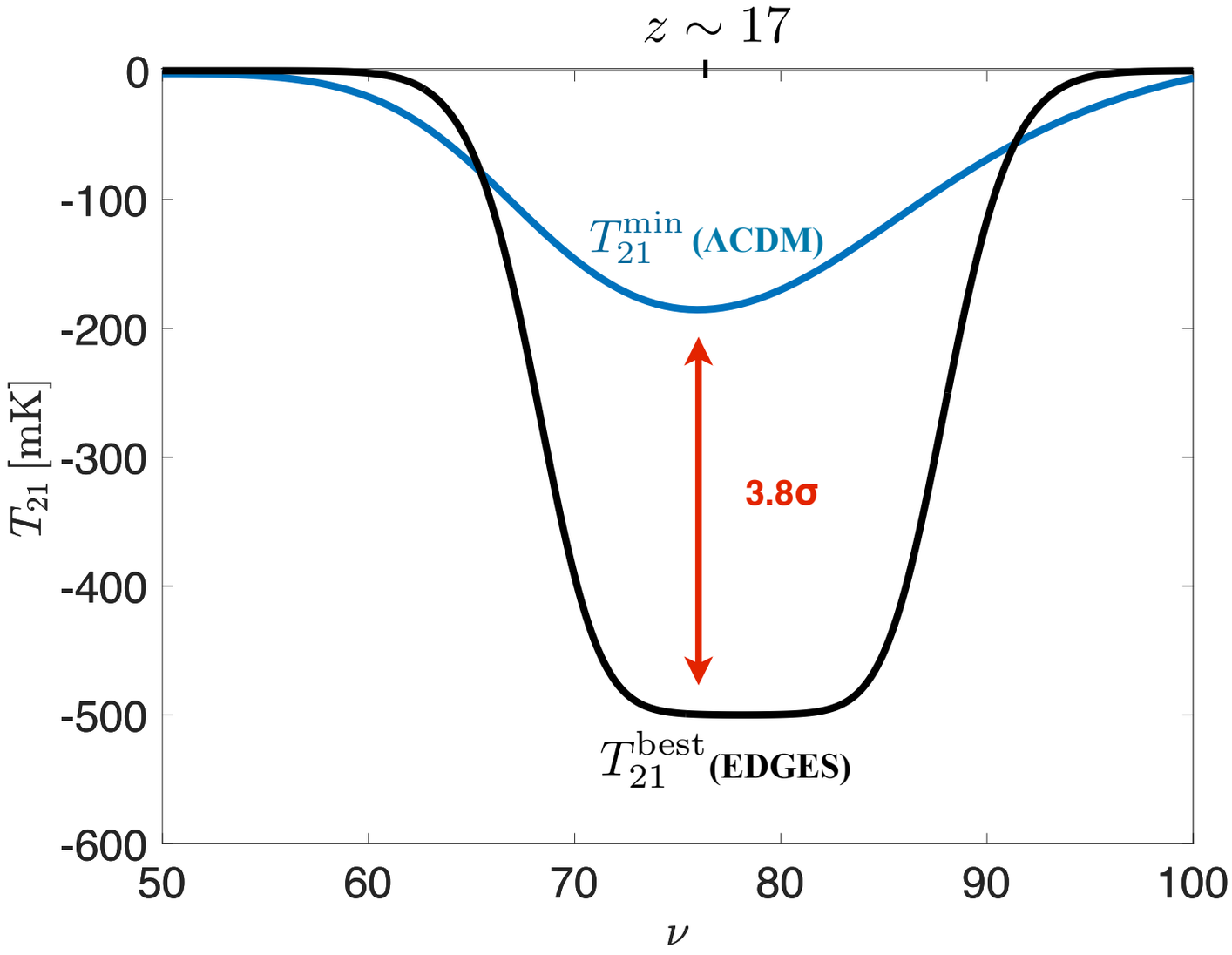

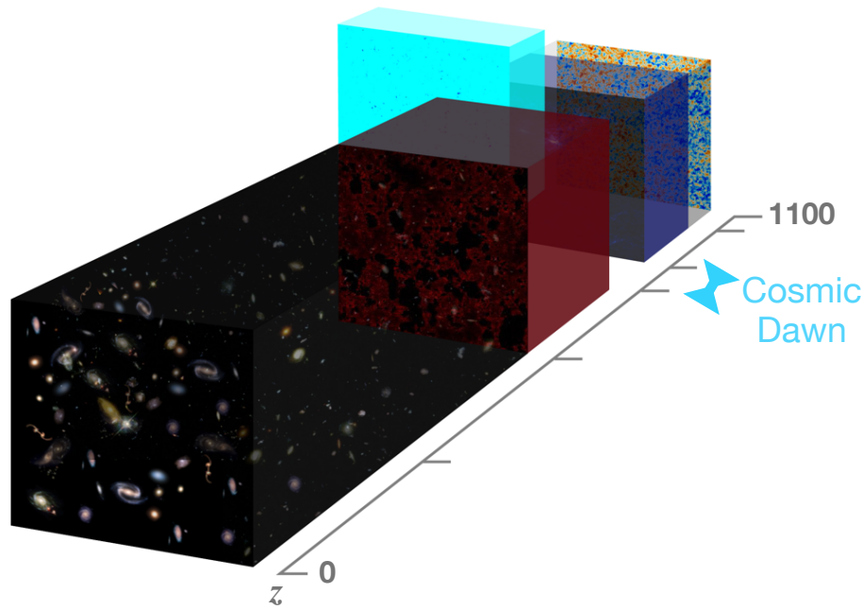

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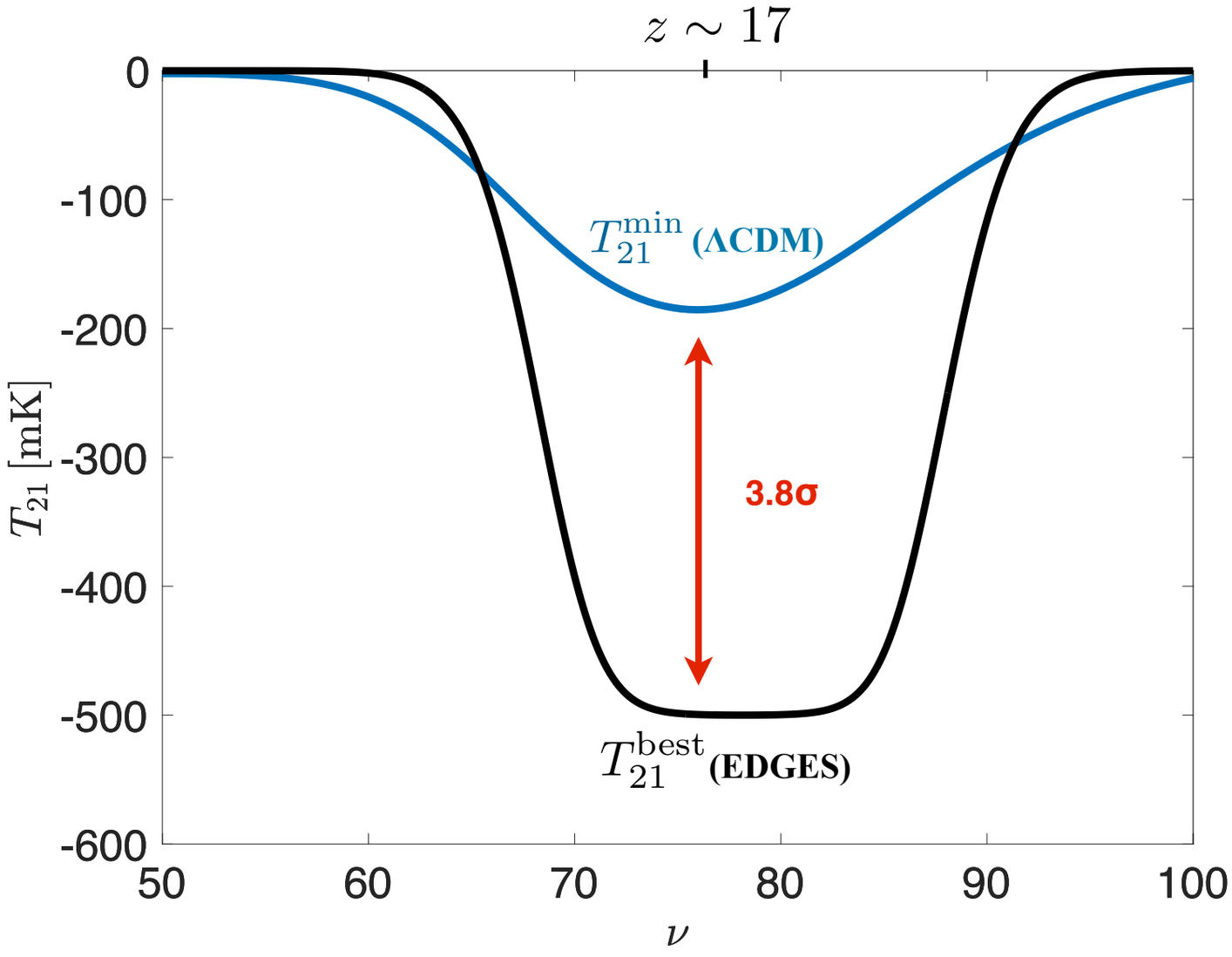

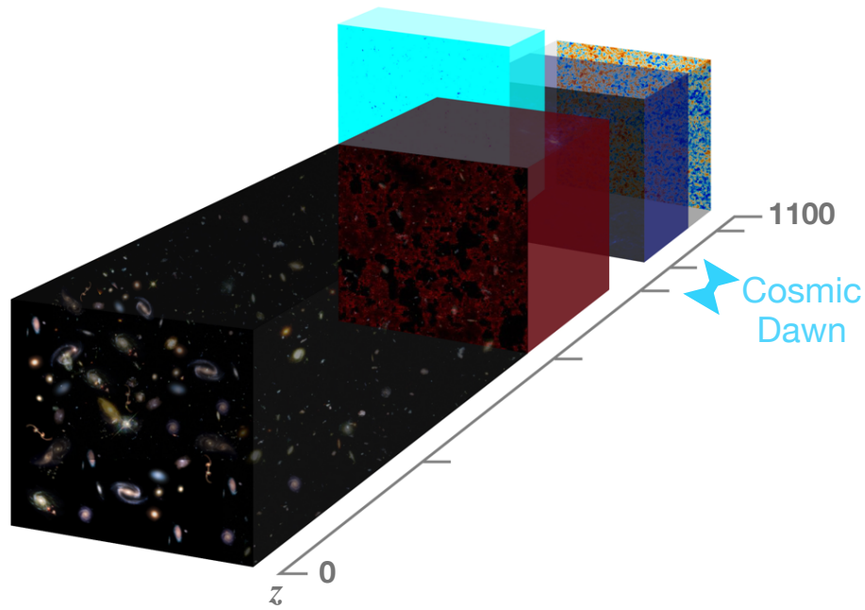

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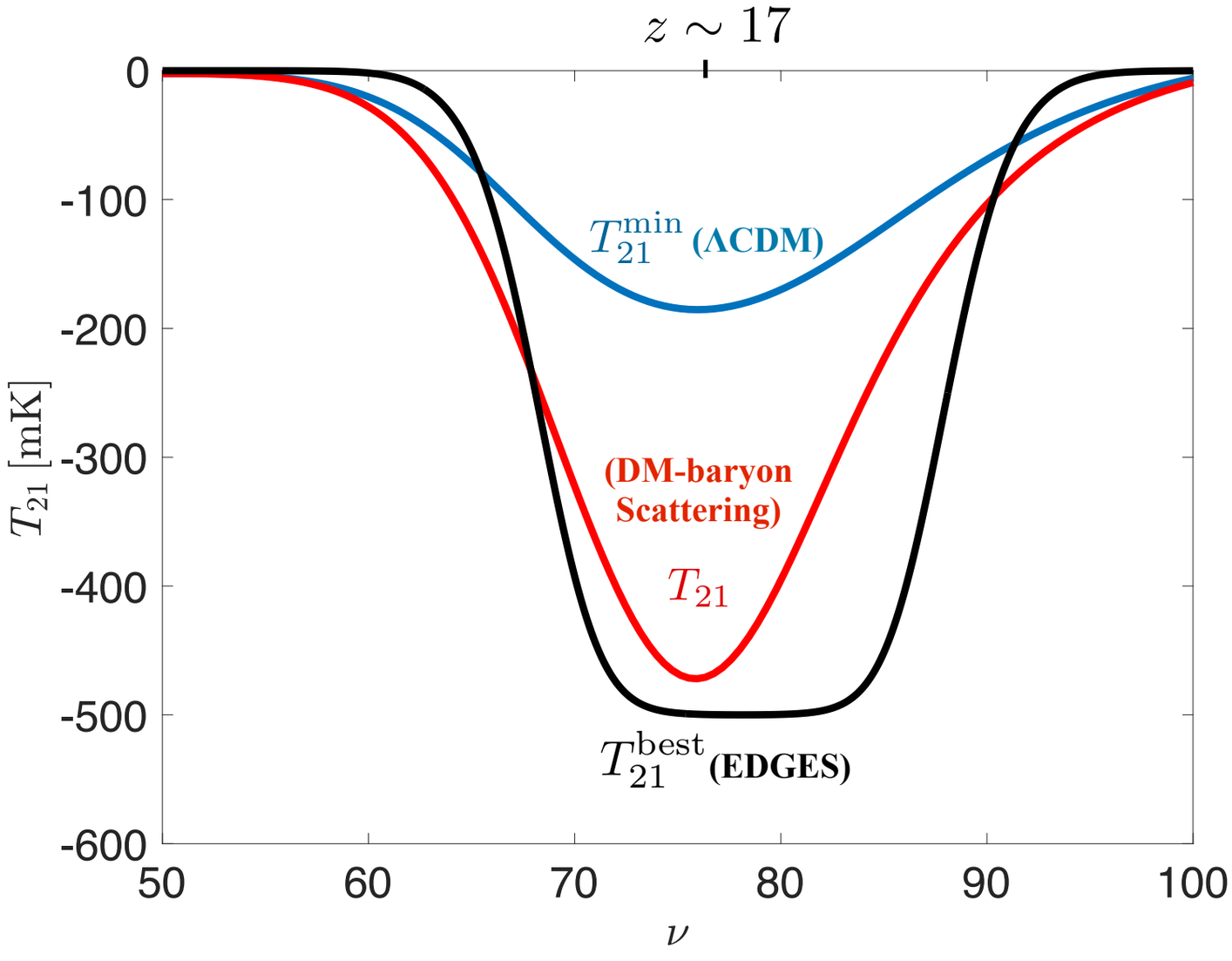

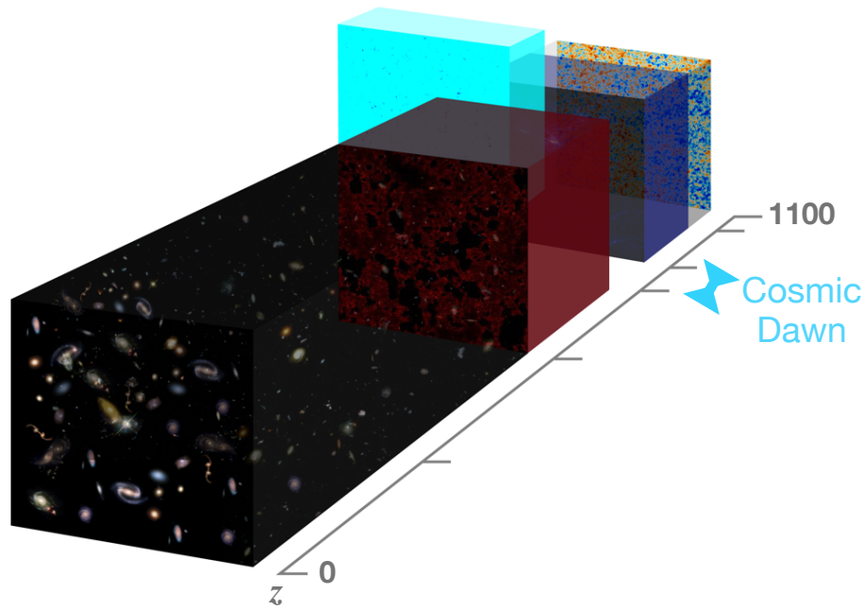

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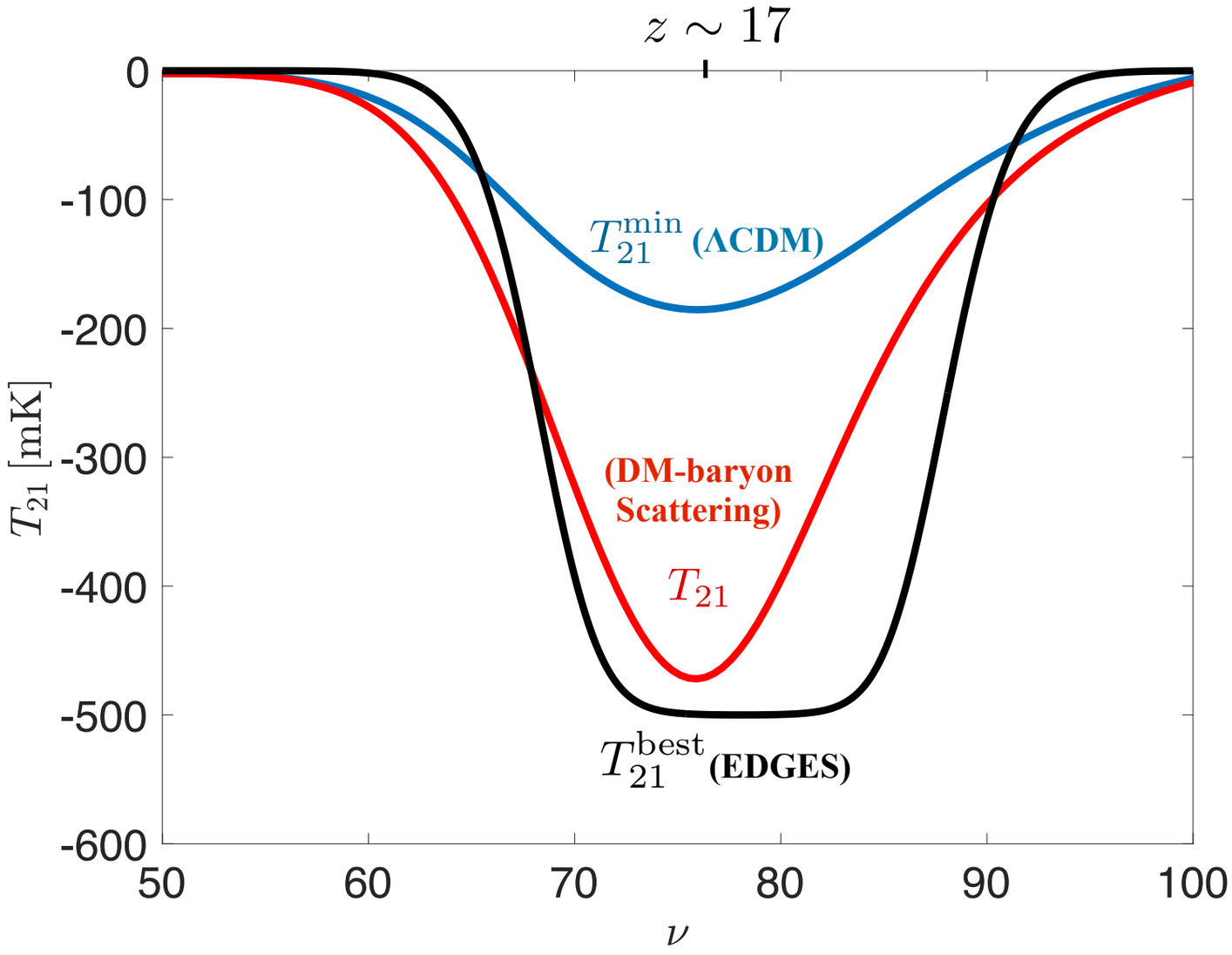

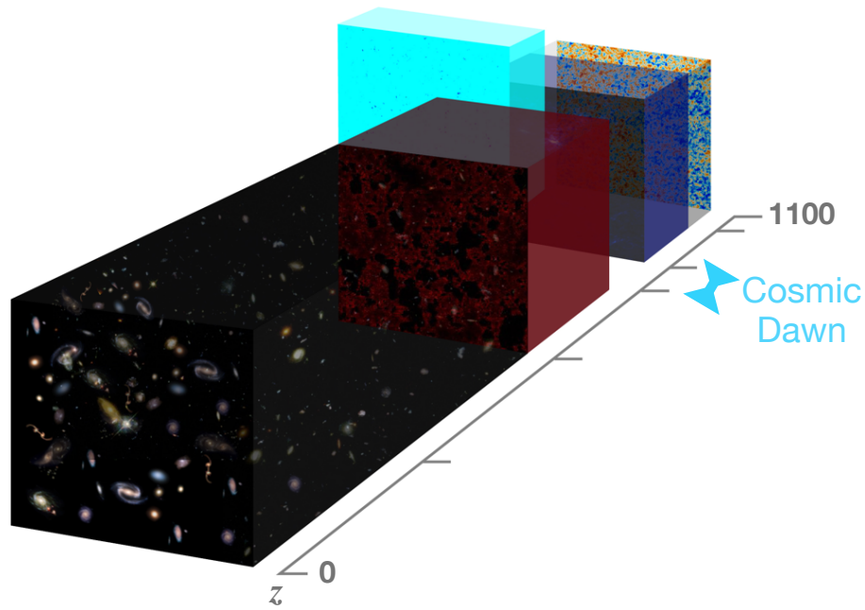

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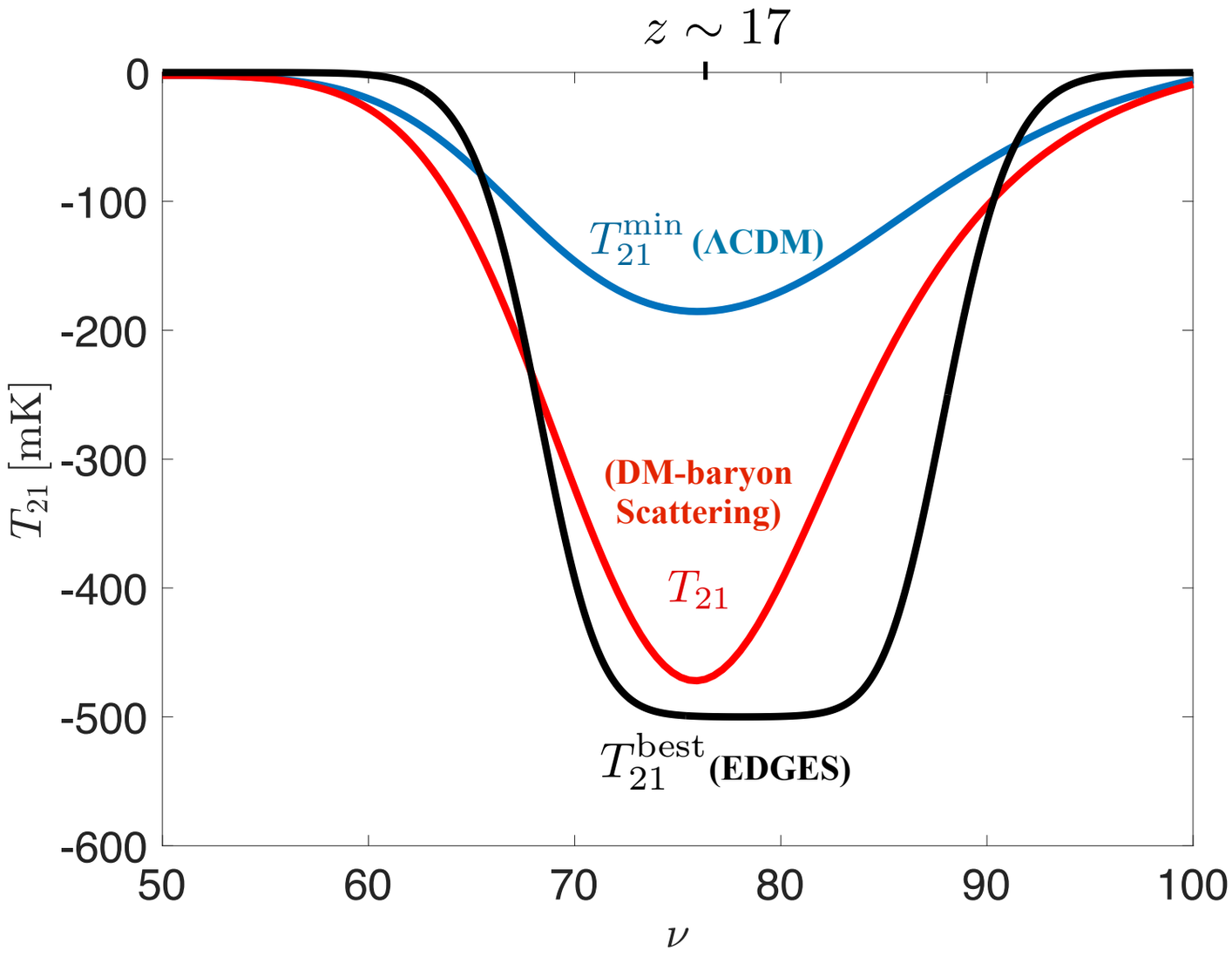

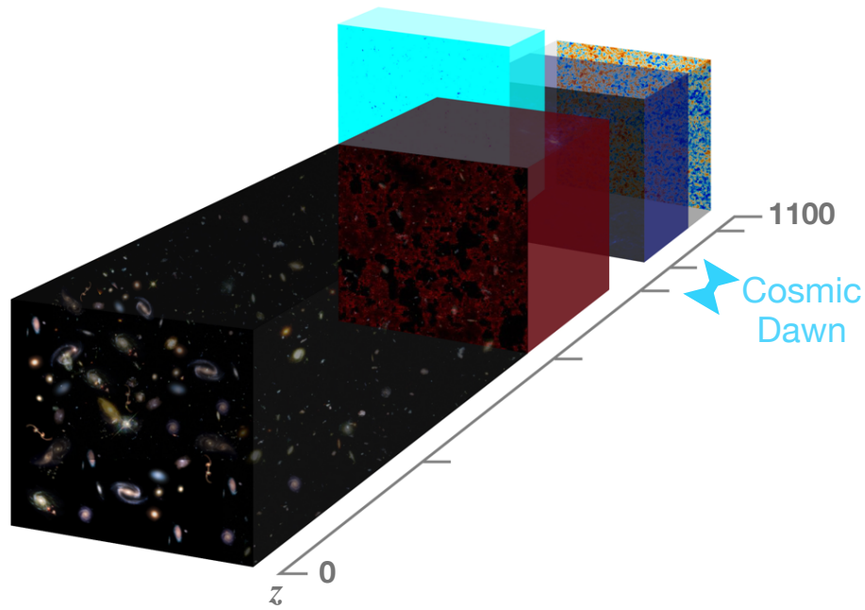

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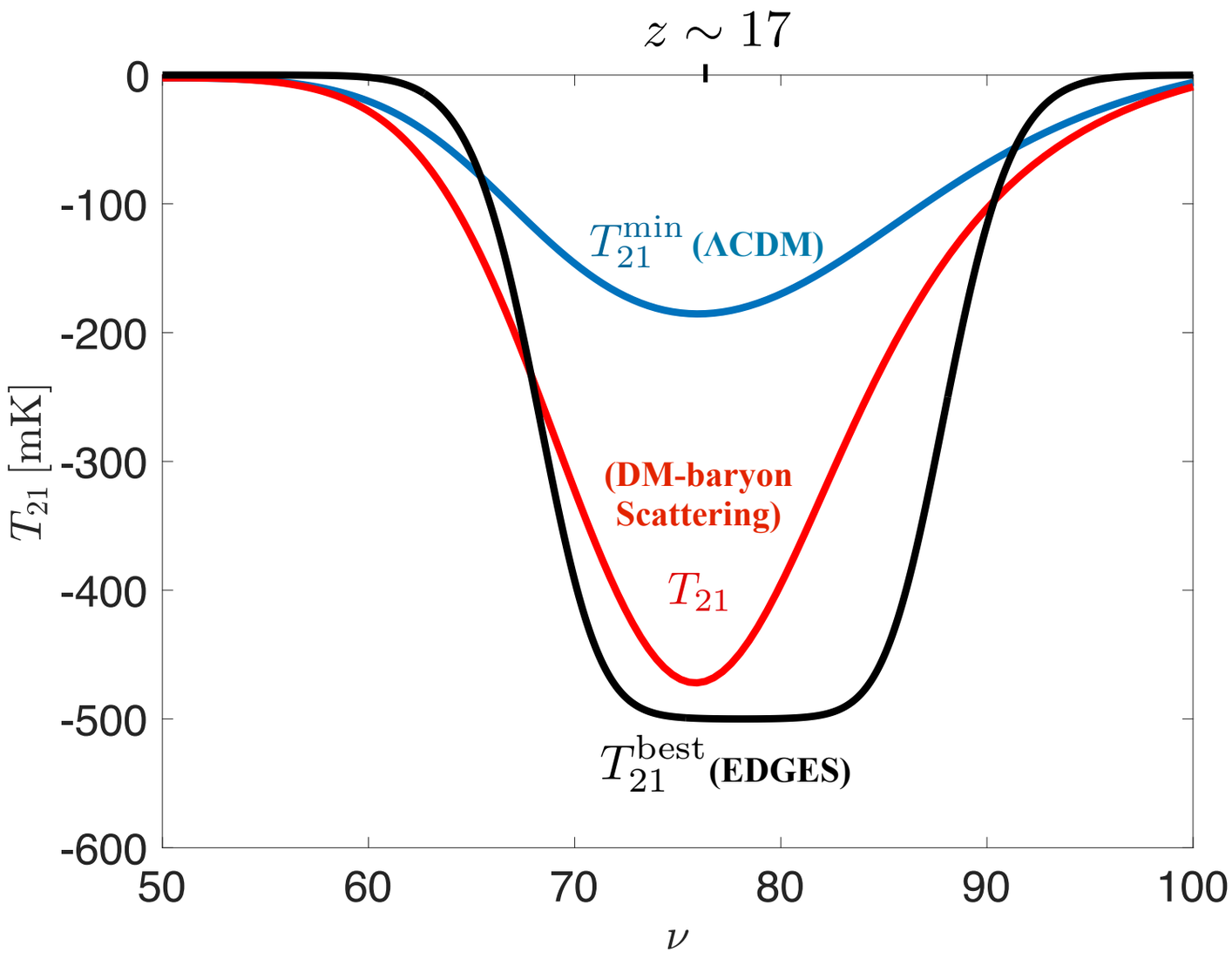

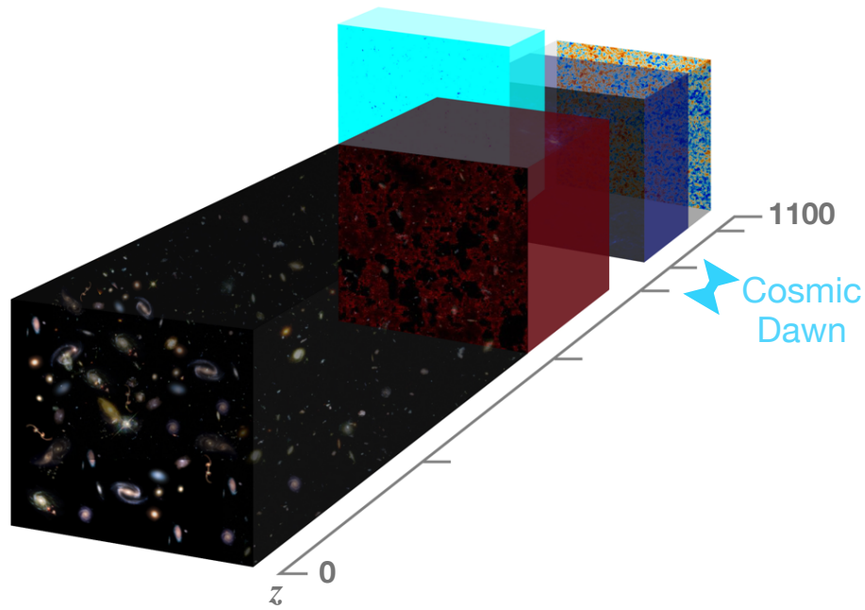

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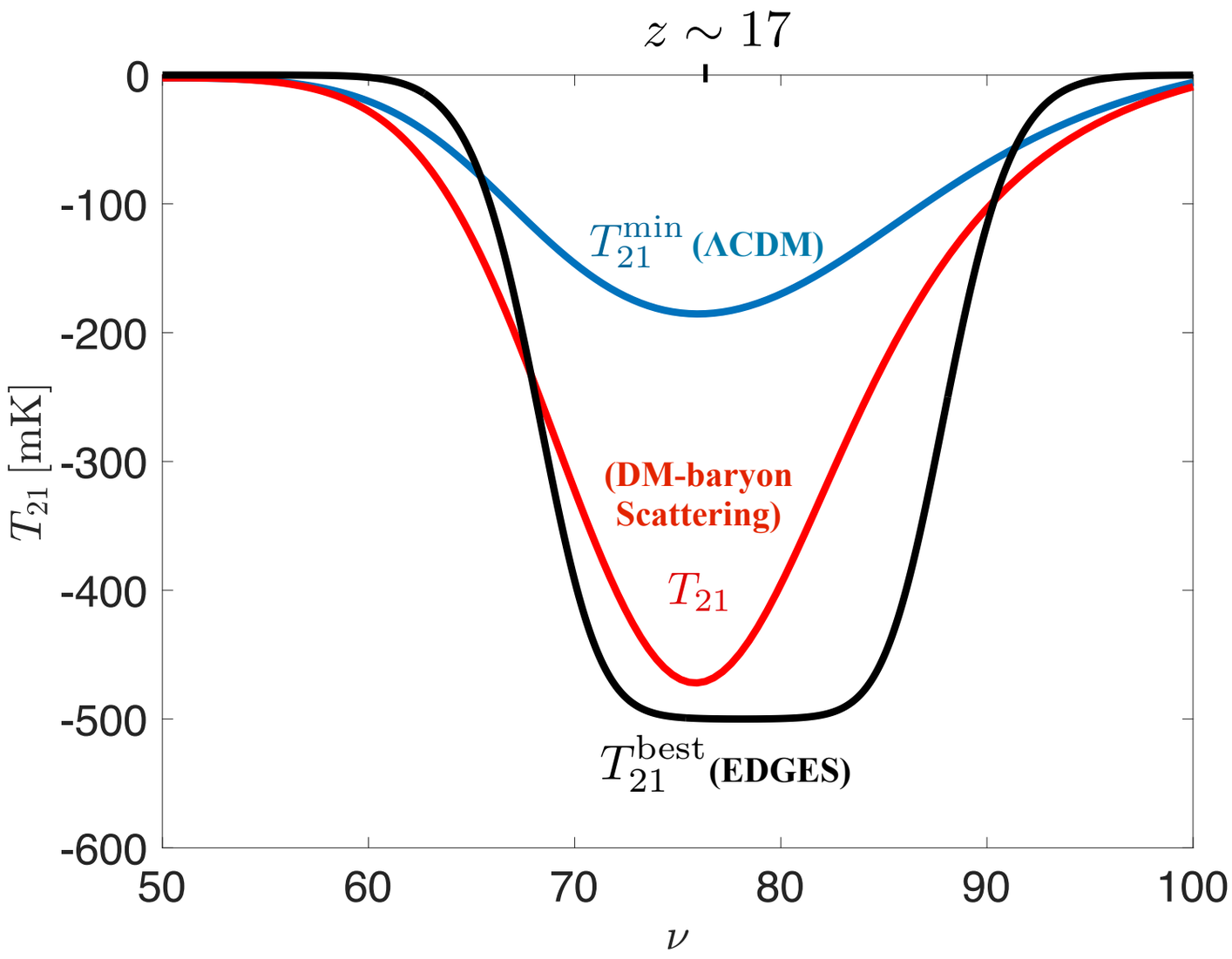
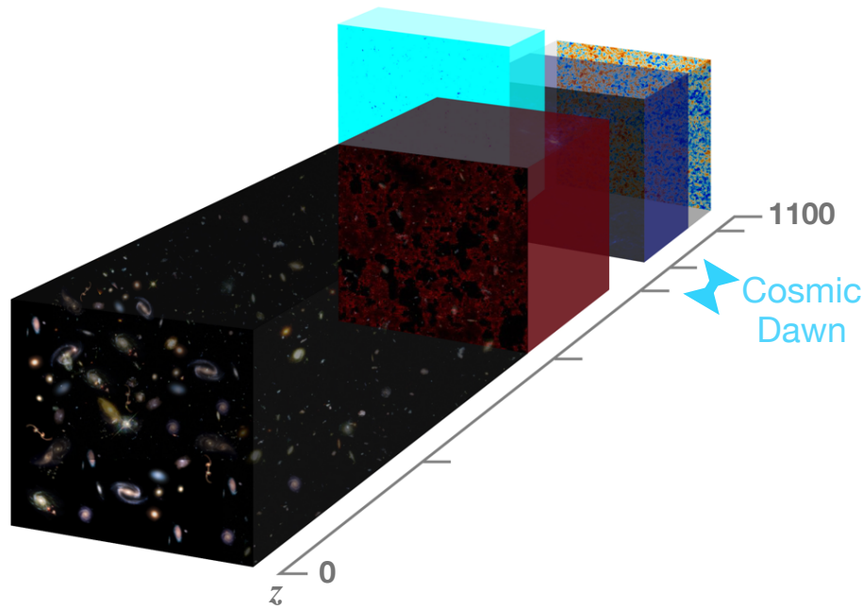




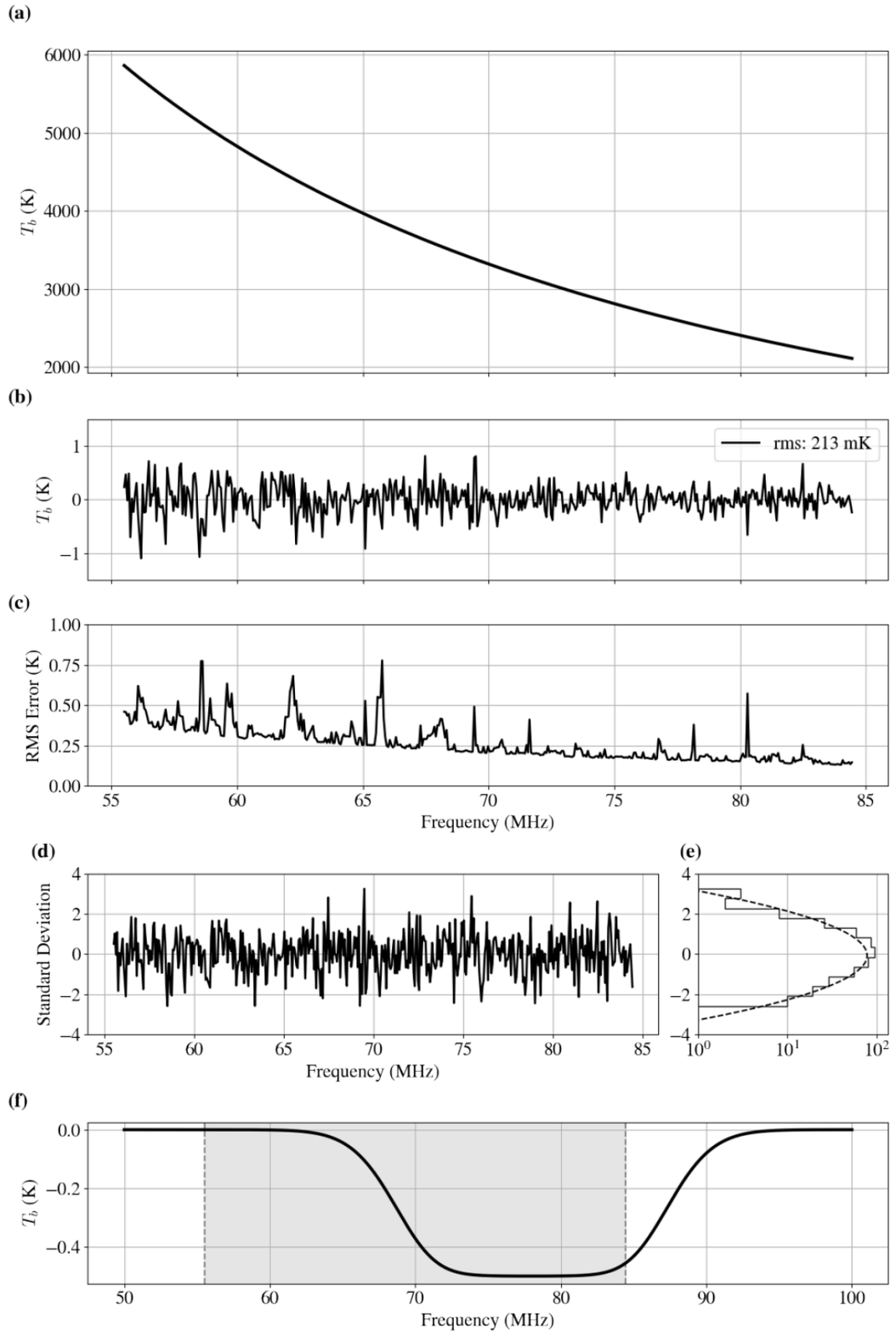
R.I.P. EDGES Signal?

SARAS 3

R.I.P. EDGES Signal?

SARAS 3

Singh et al., Nature (2022)



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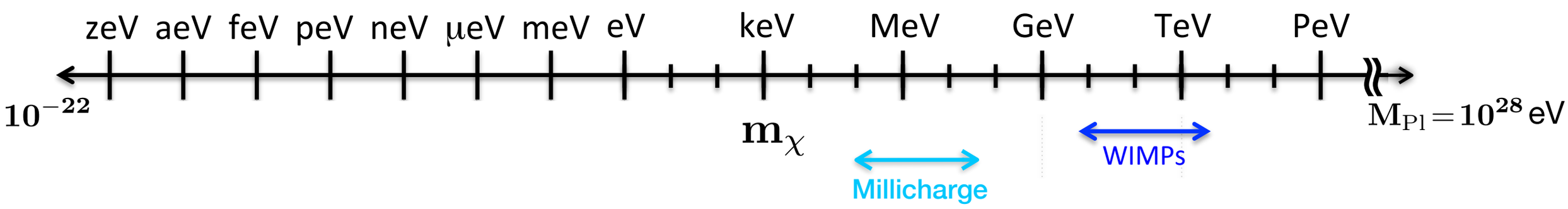

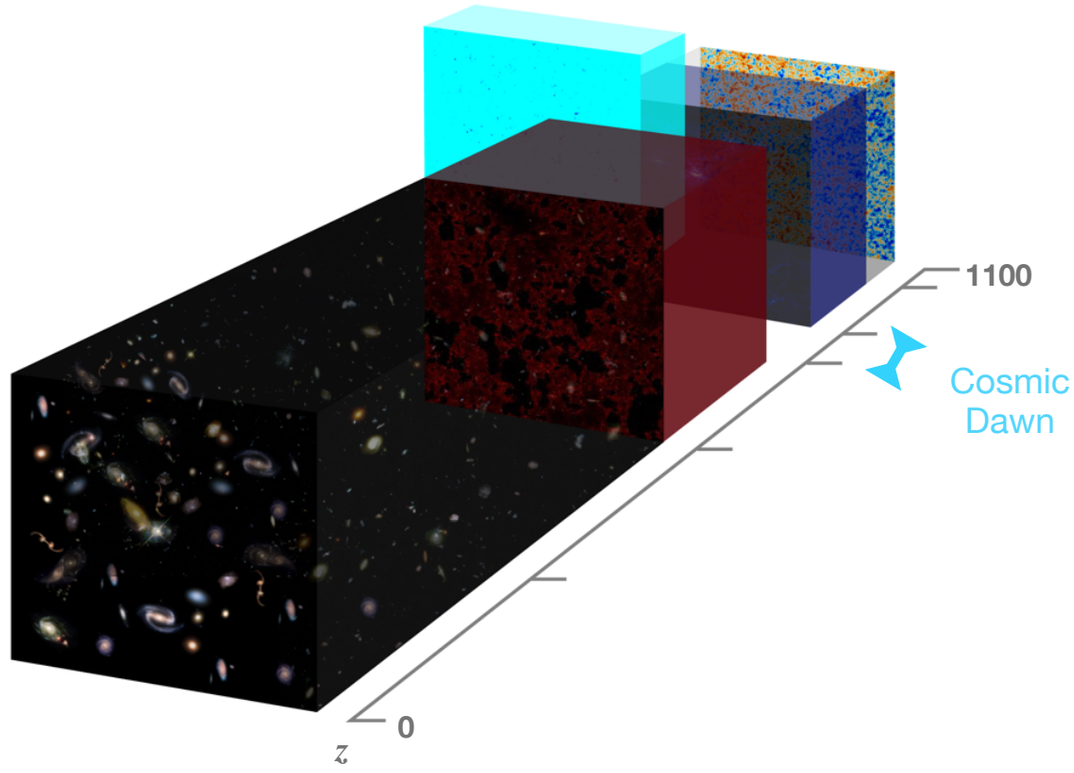

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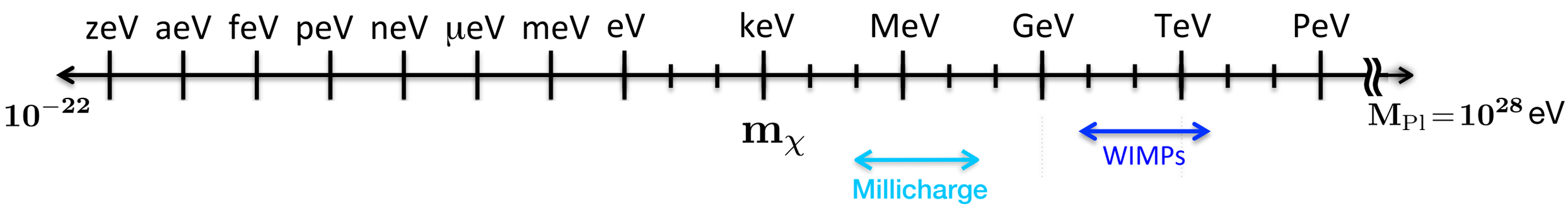

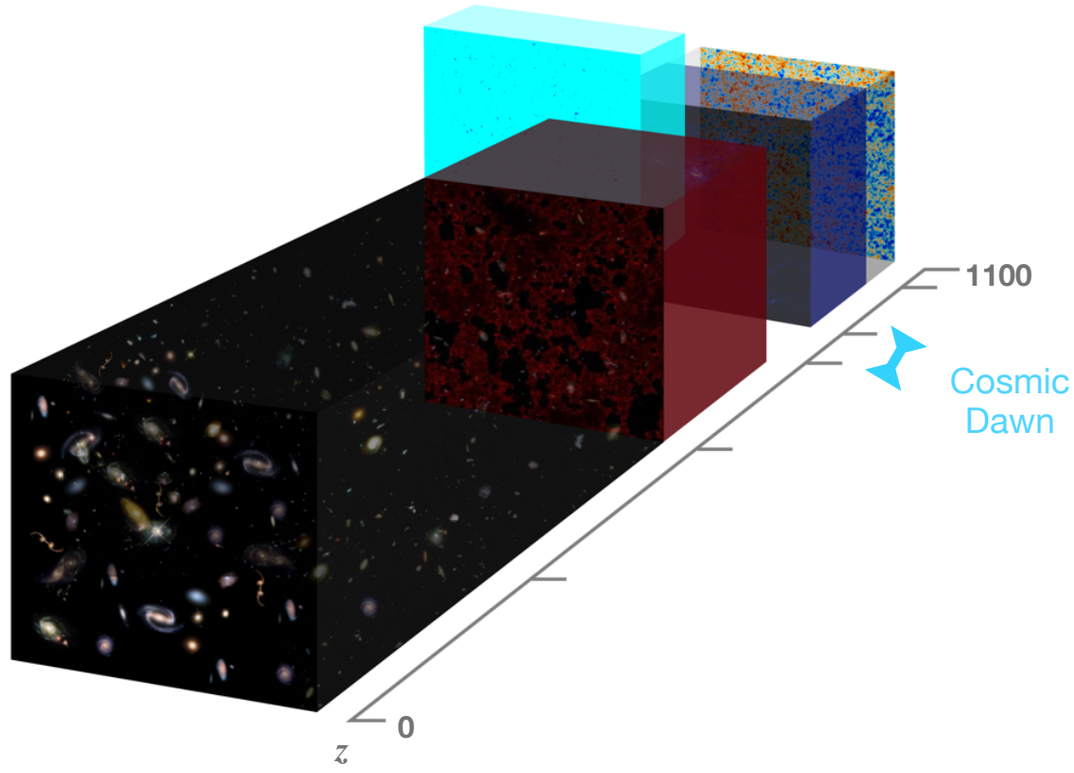

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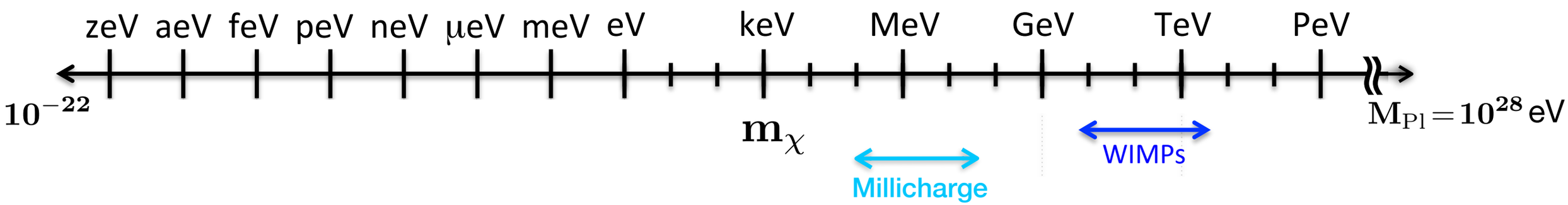

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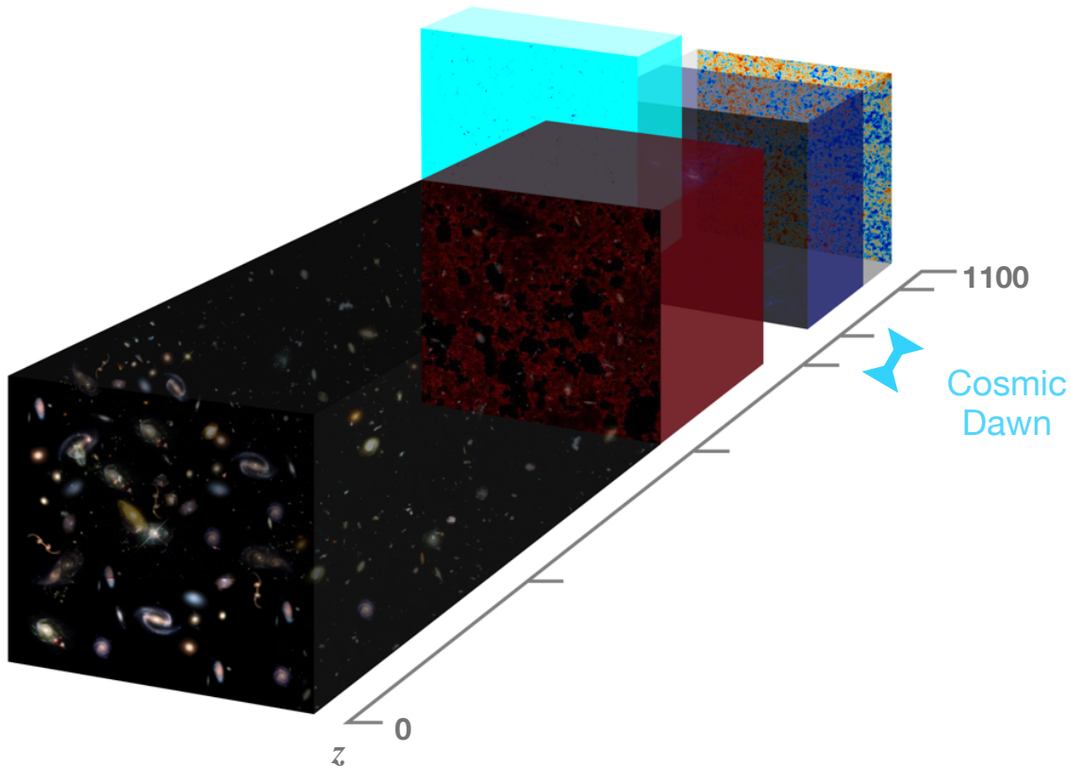

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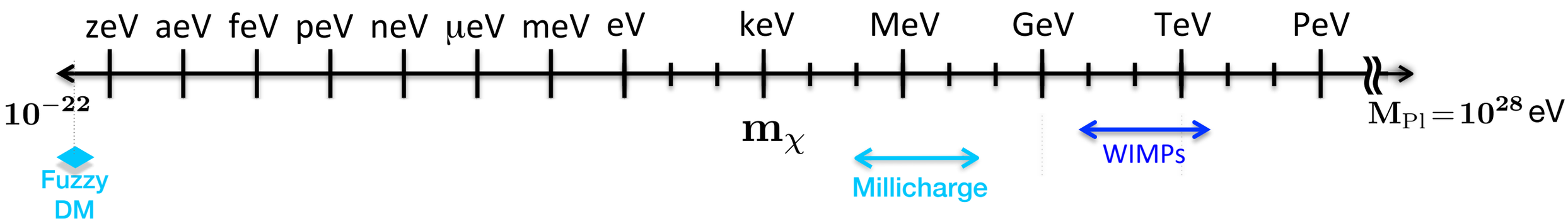

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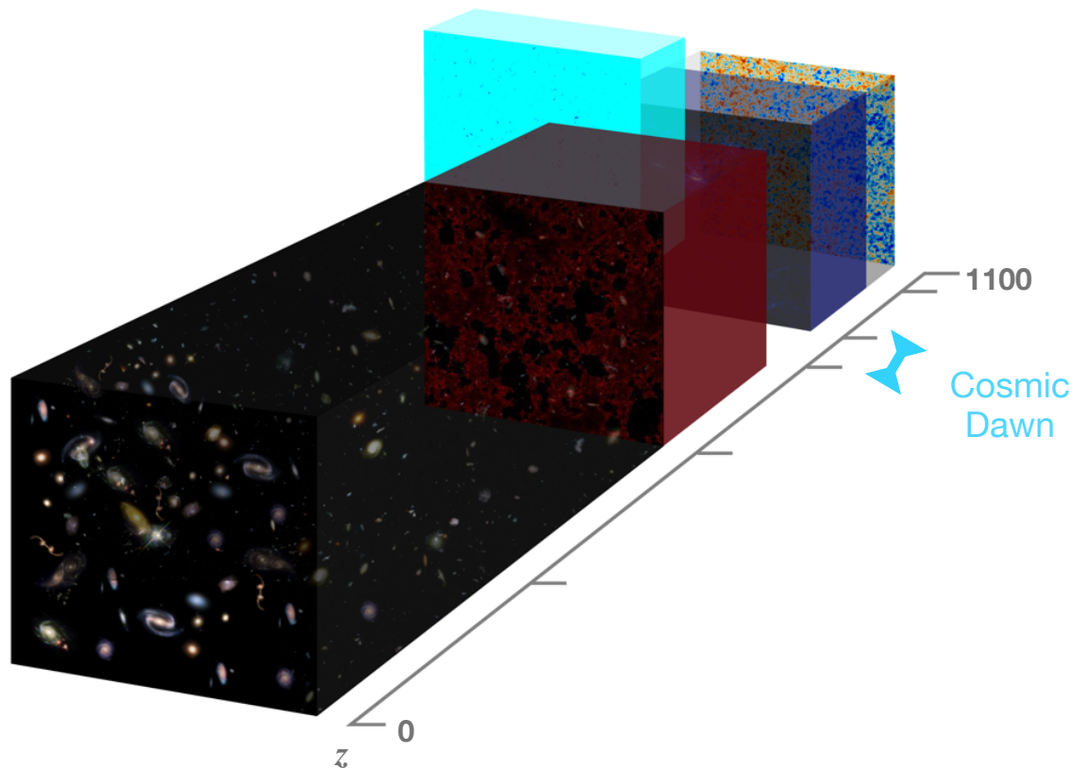

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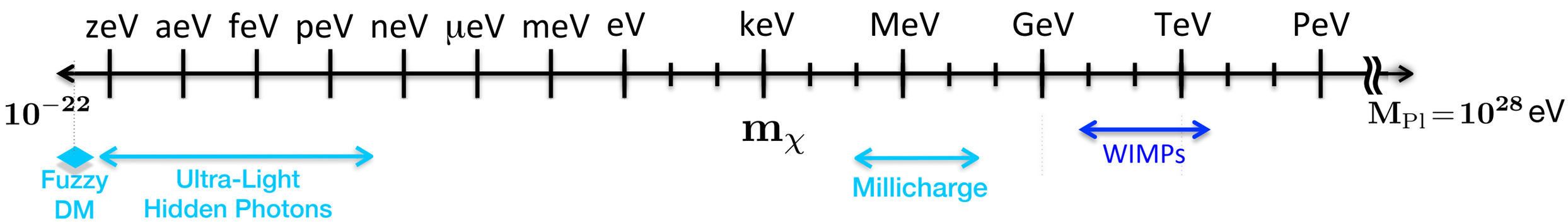

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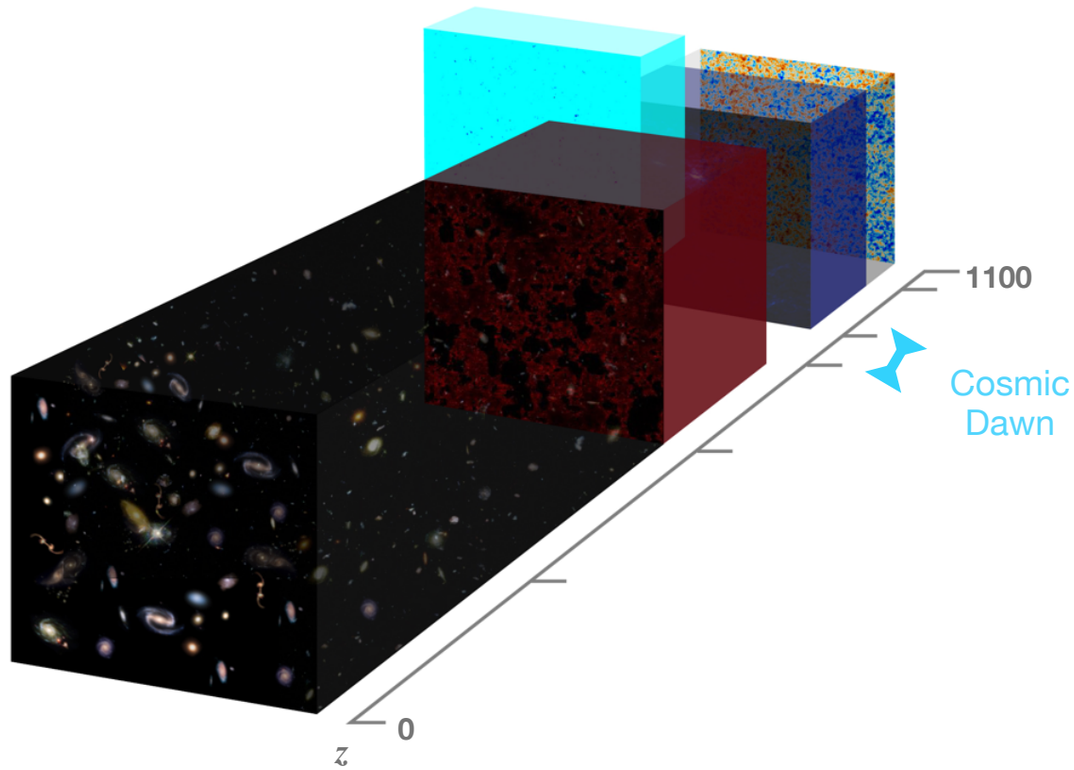

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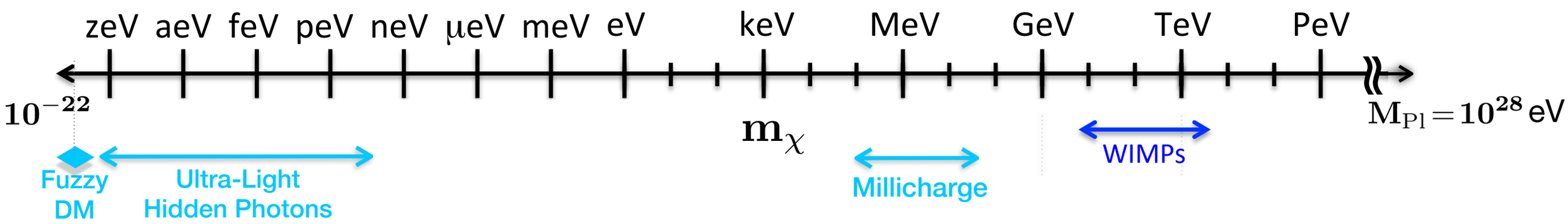

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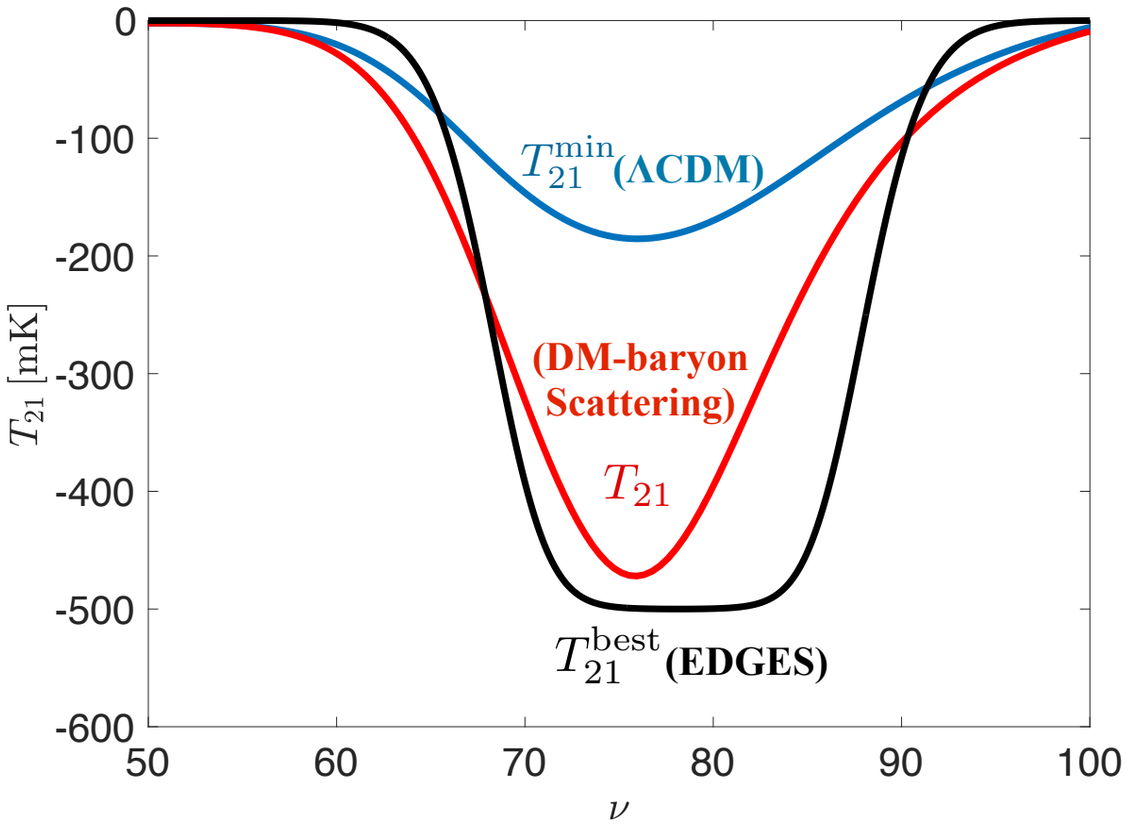

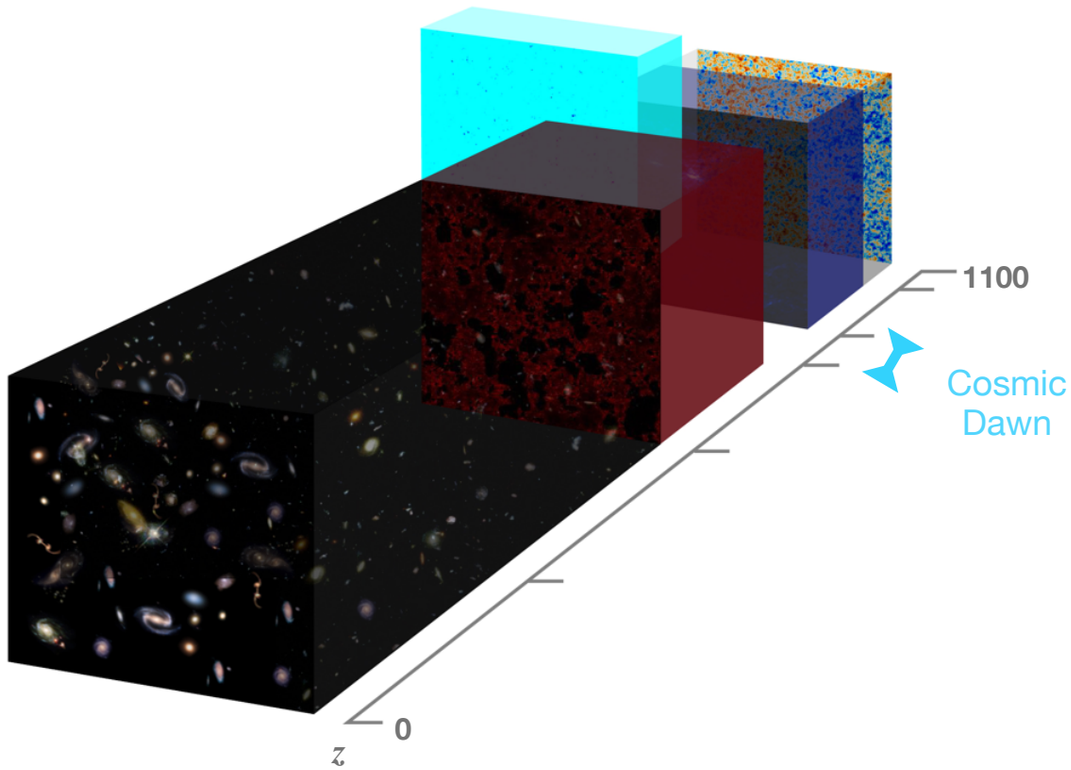

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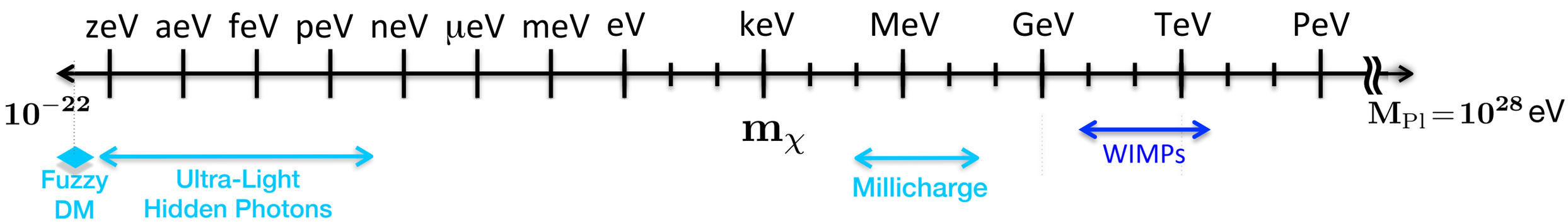

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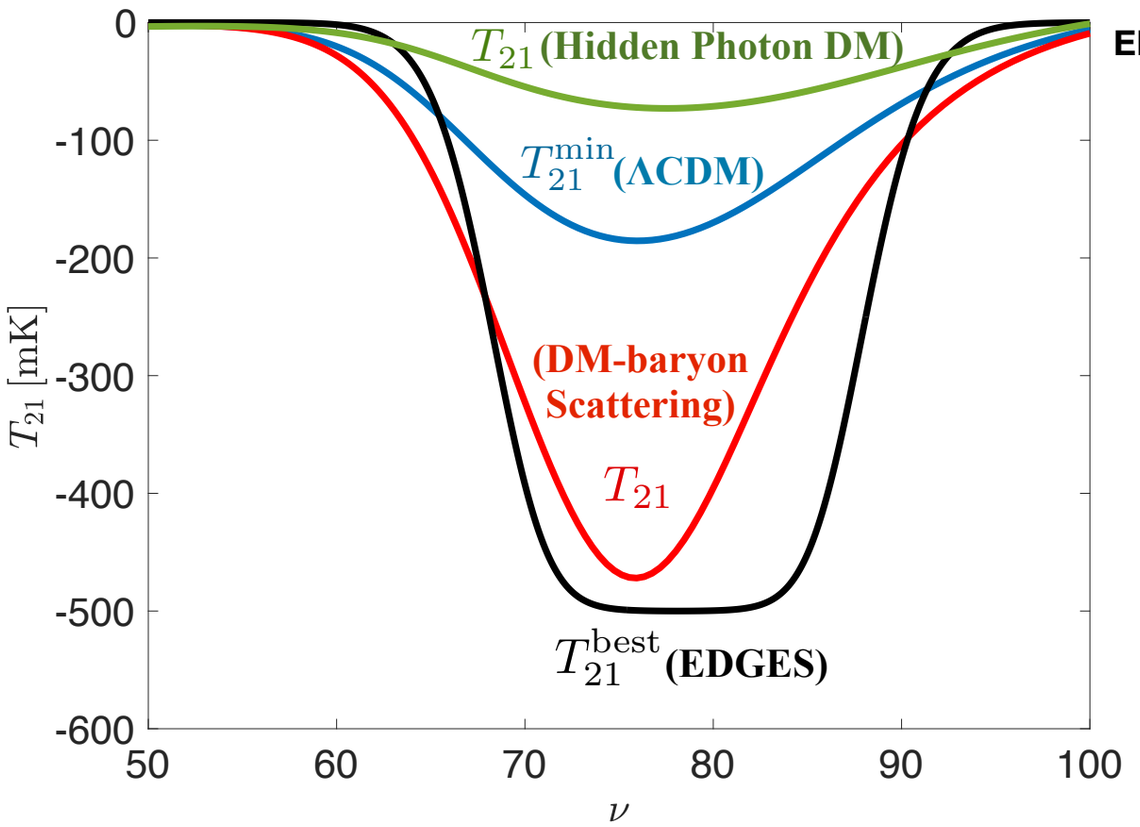
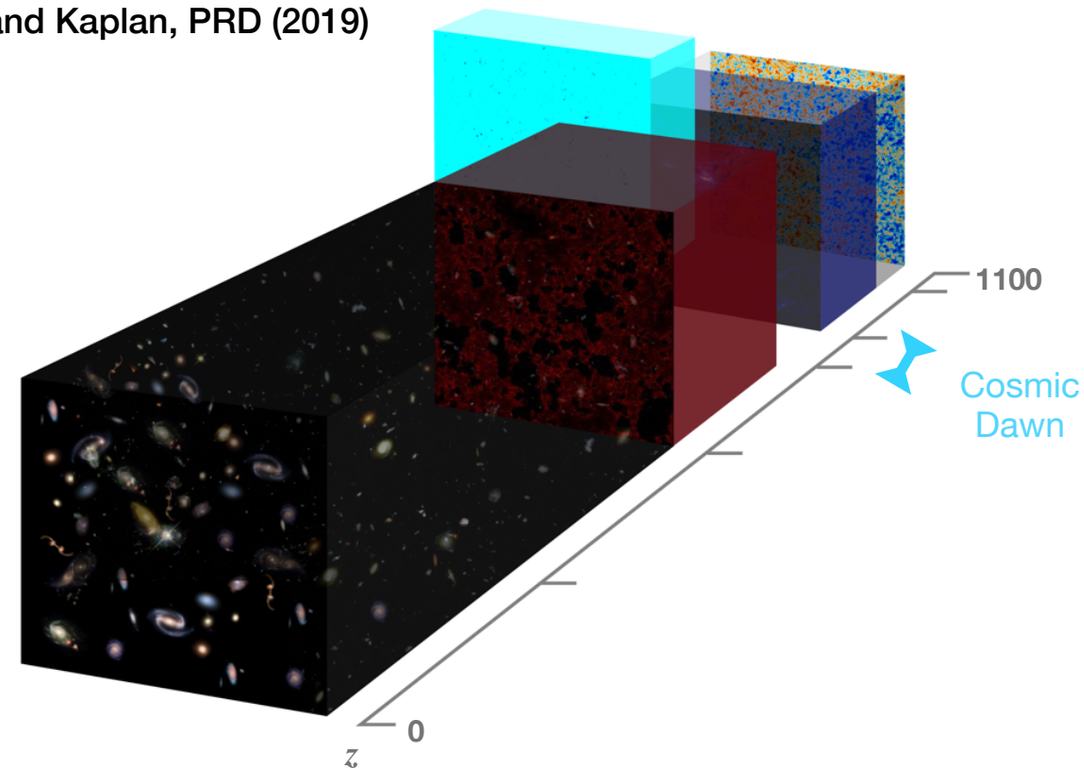


EDK, Cholis and Kaplan, PRD (2019)



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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- The baryon temperature is then:

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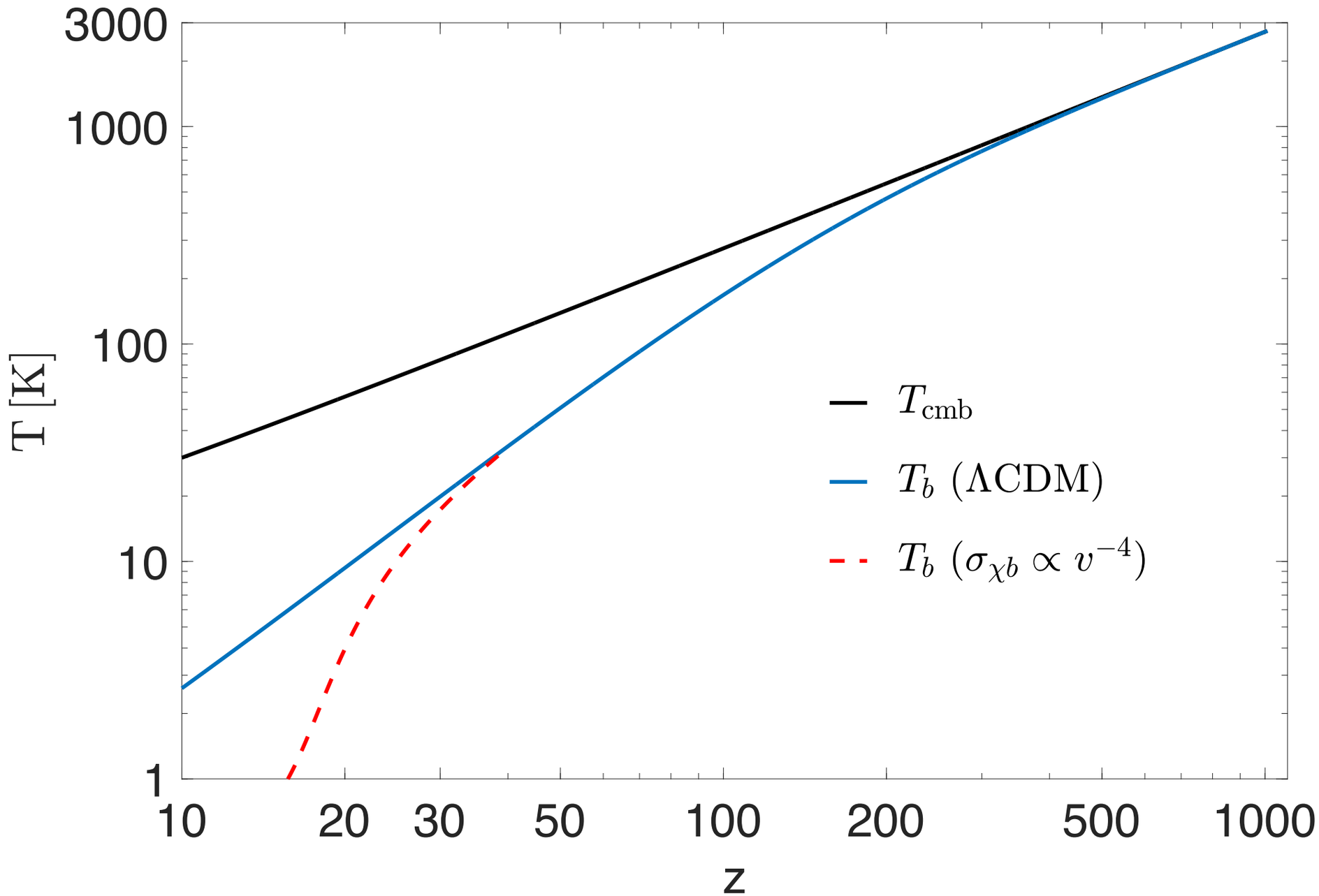

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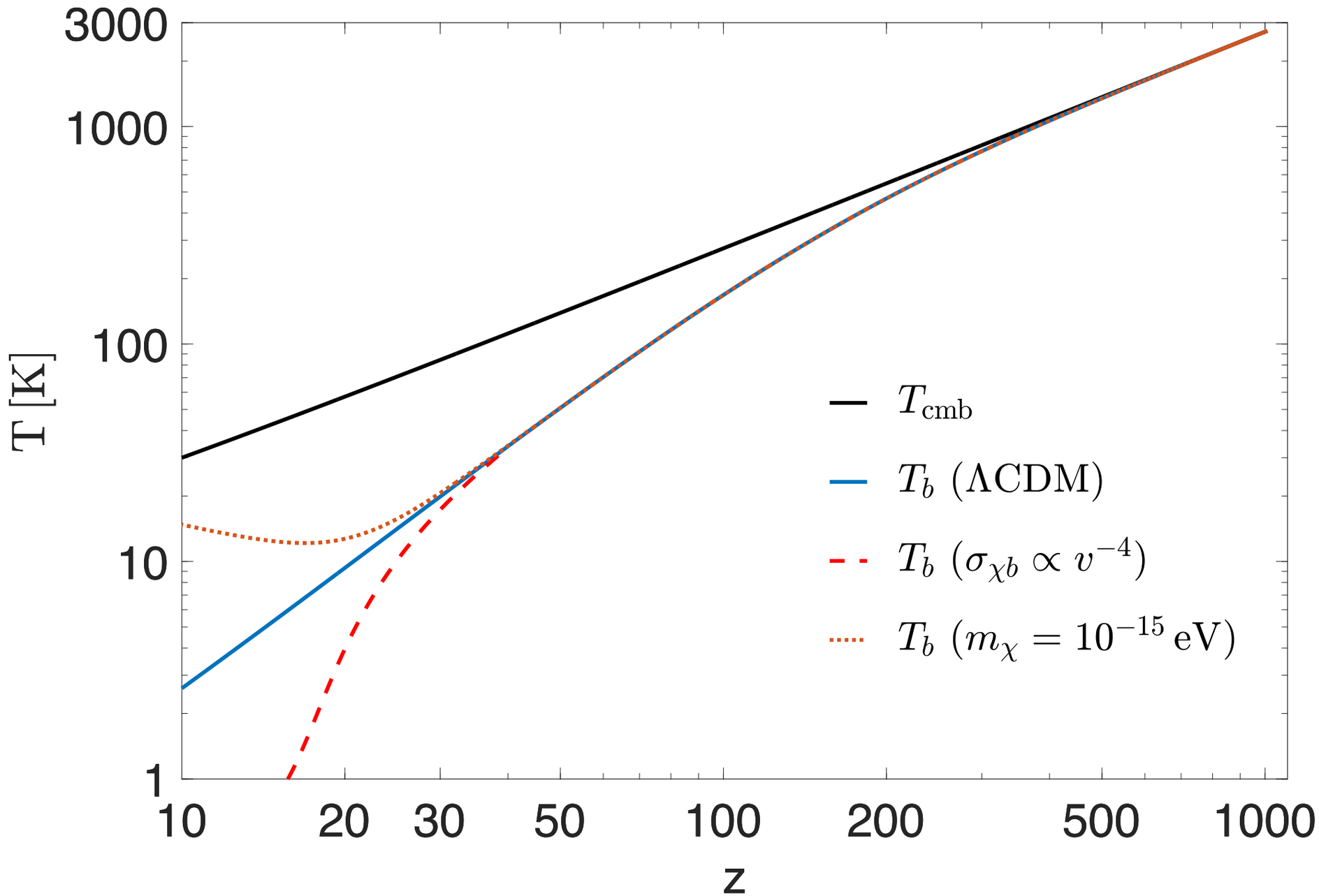

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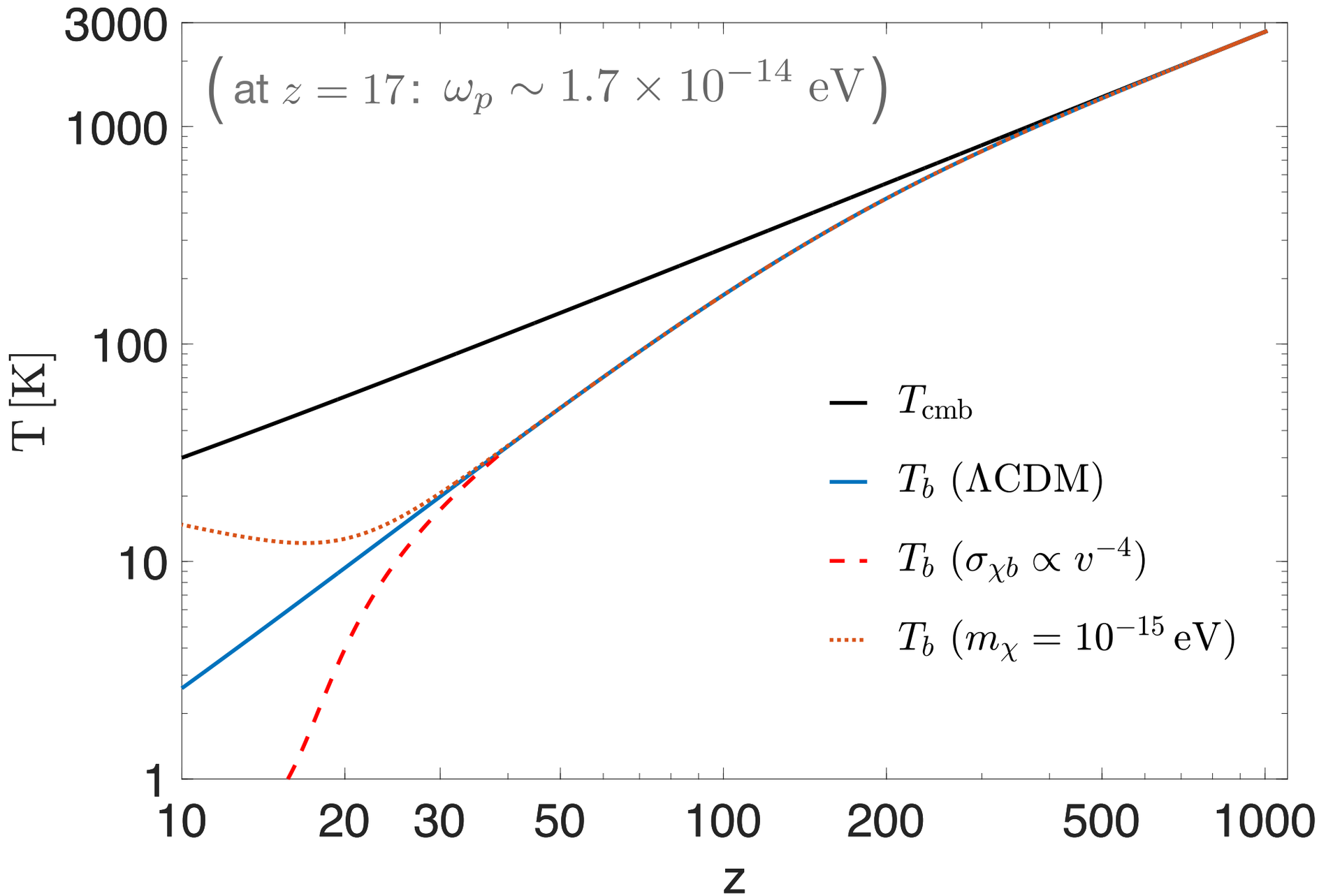

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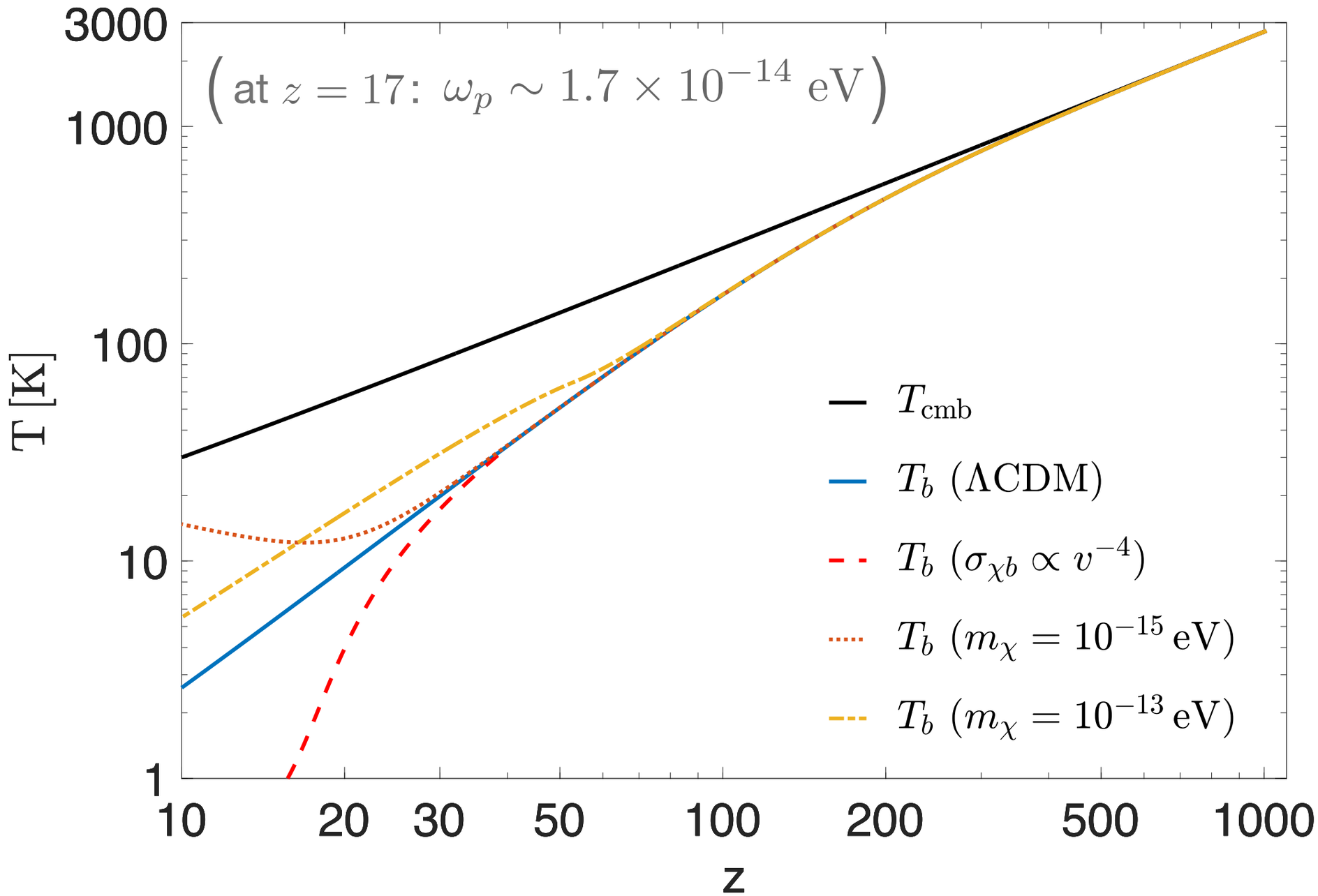

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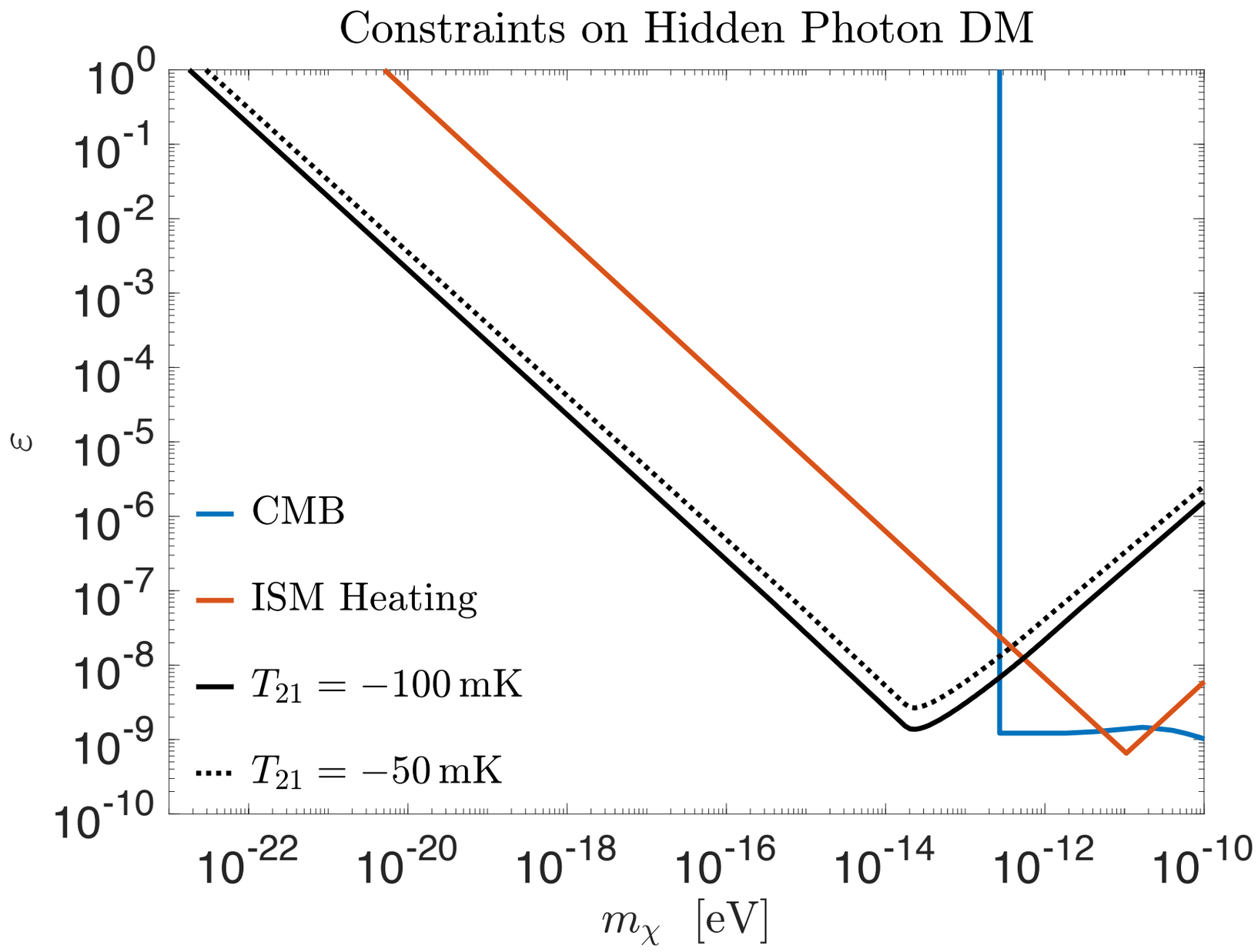

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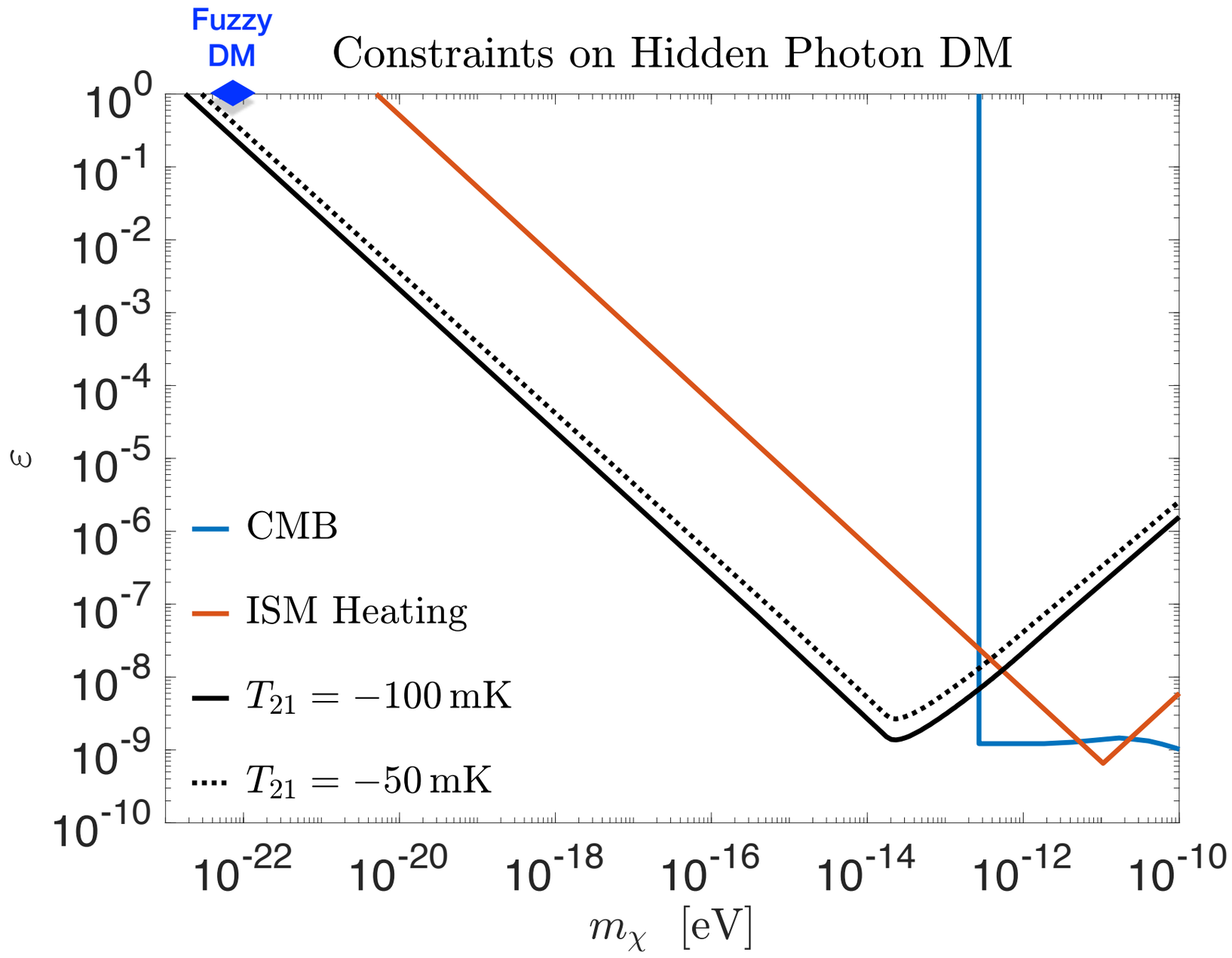

Outline

Ely Kovetz
MPIK, Feb. 2022

- Brief review of the cosmic 21cm Signal
- The EDGES “detection” and Dark Matter

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- The future of 21cm as a Dark Matter probe

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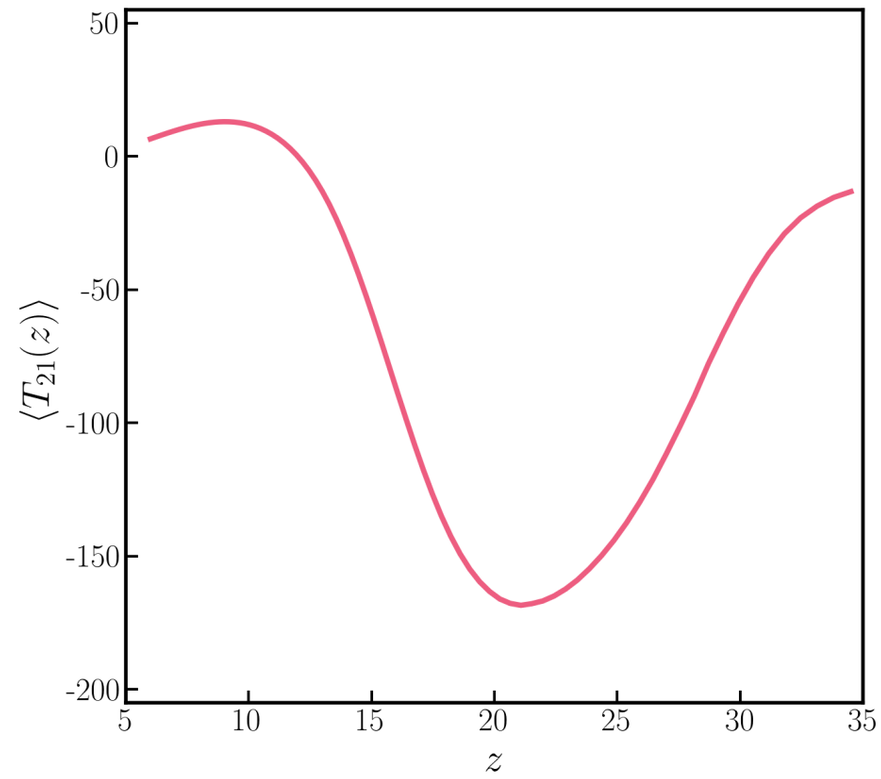

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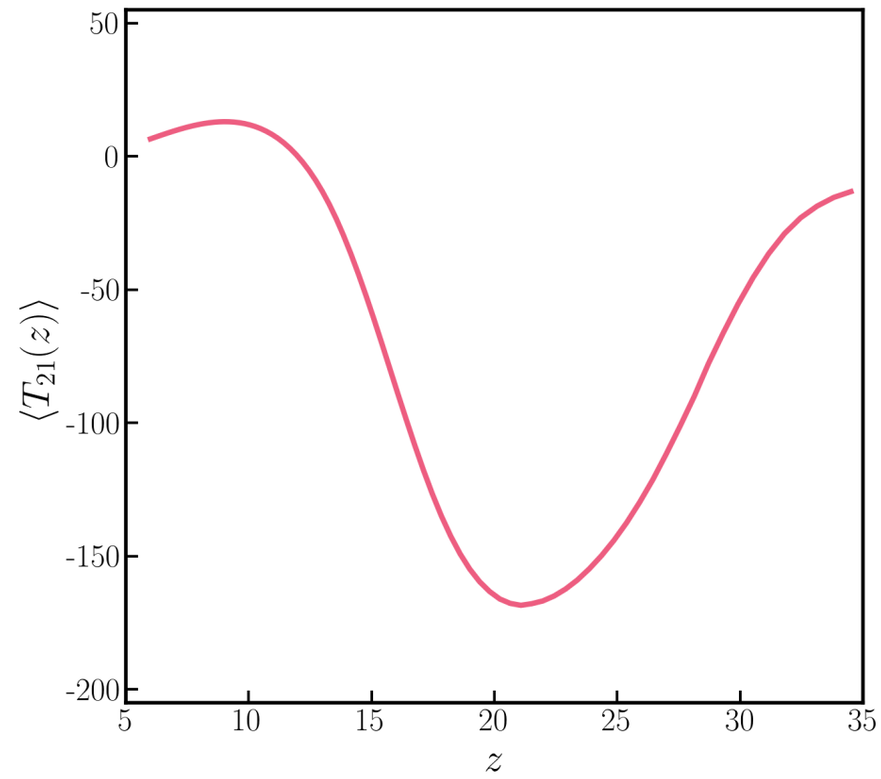

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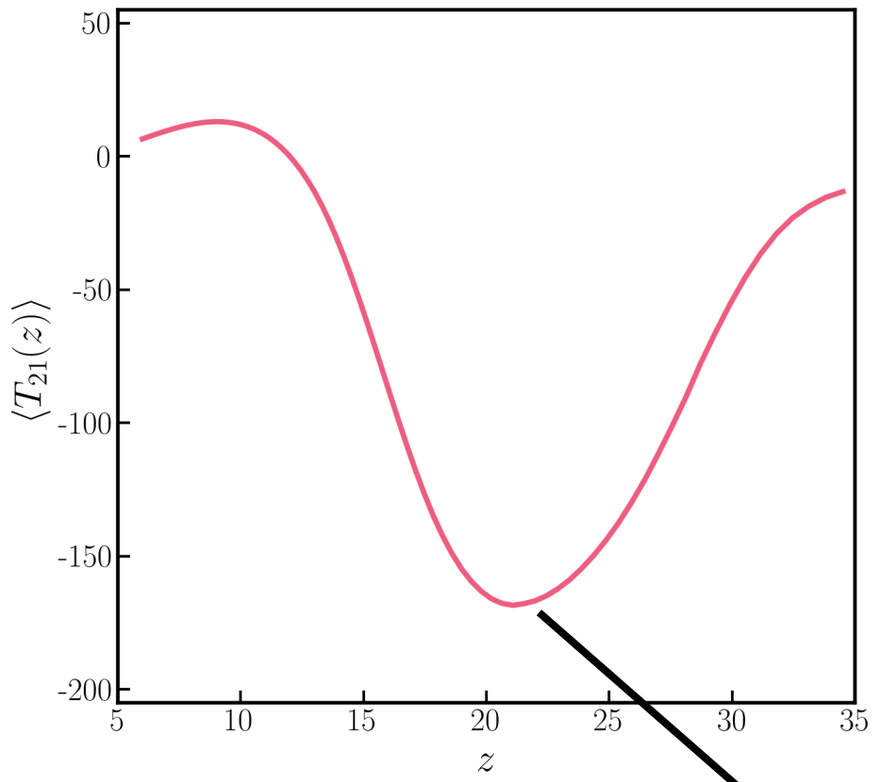

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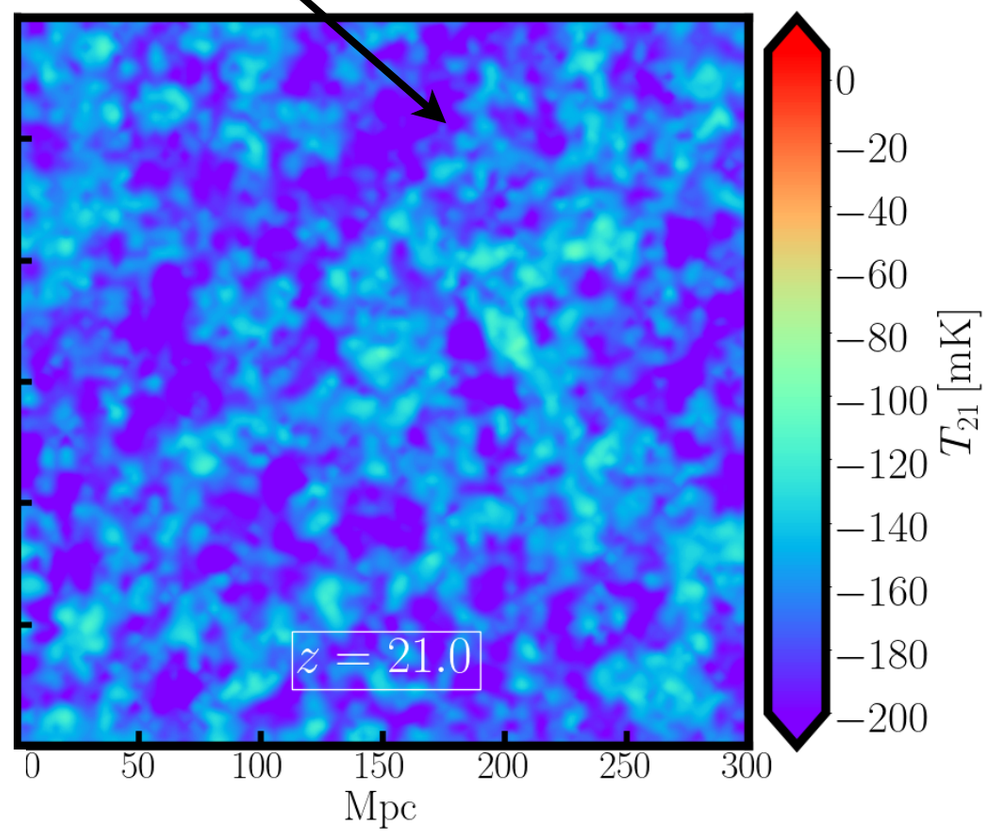

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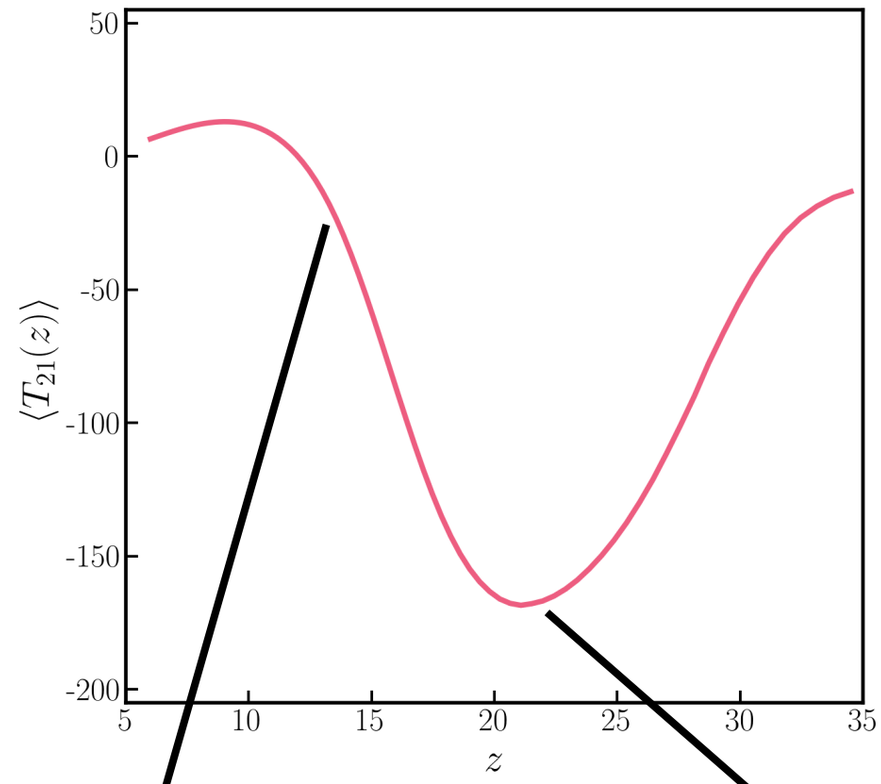

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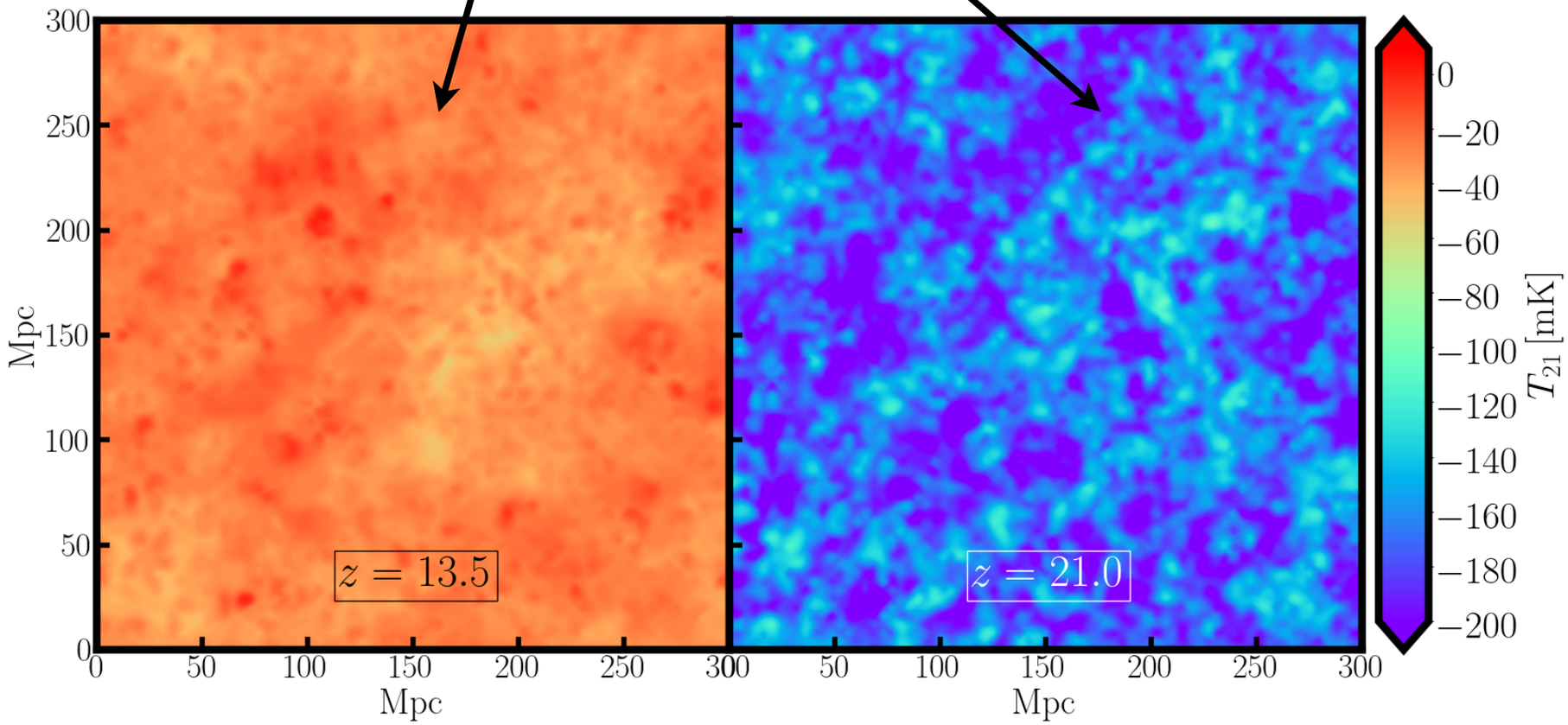

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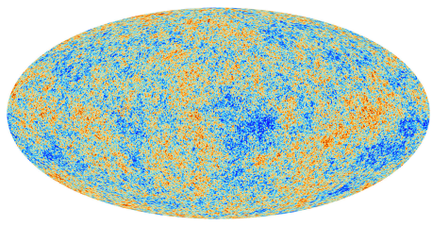

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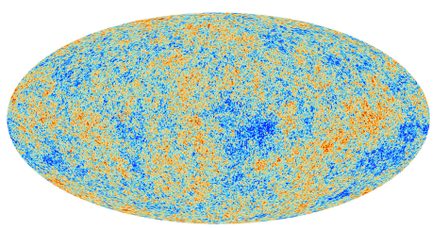

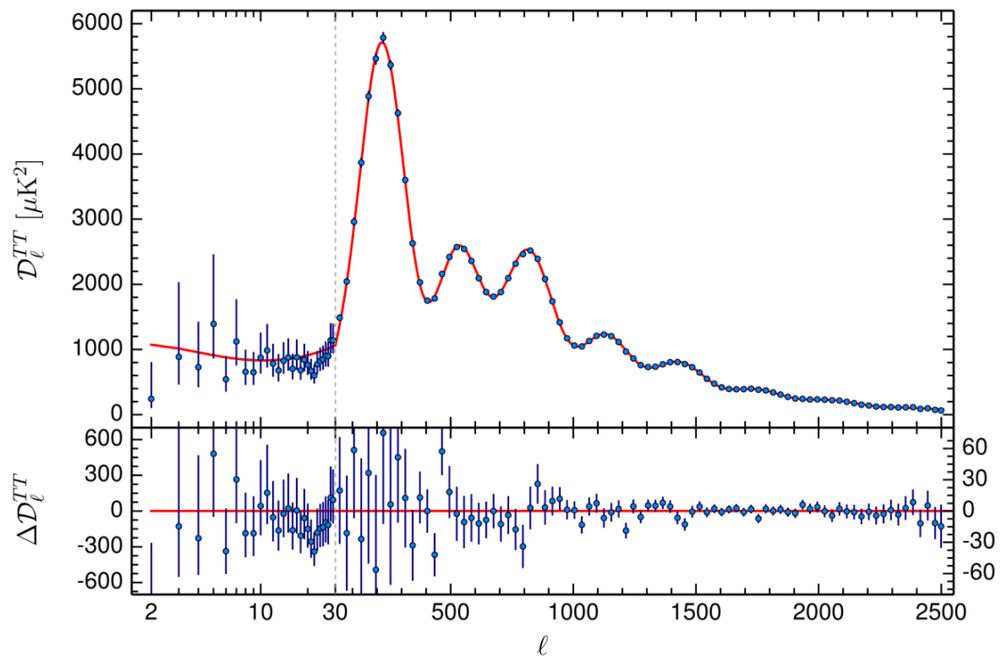

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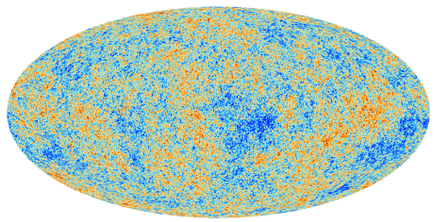
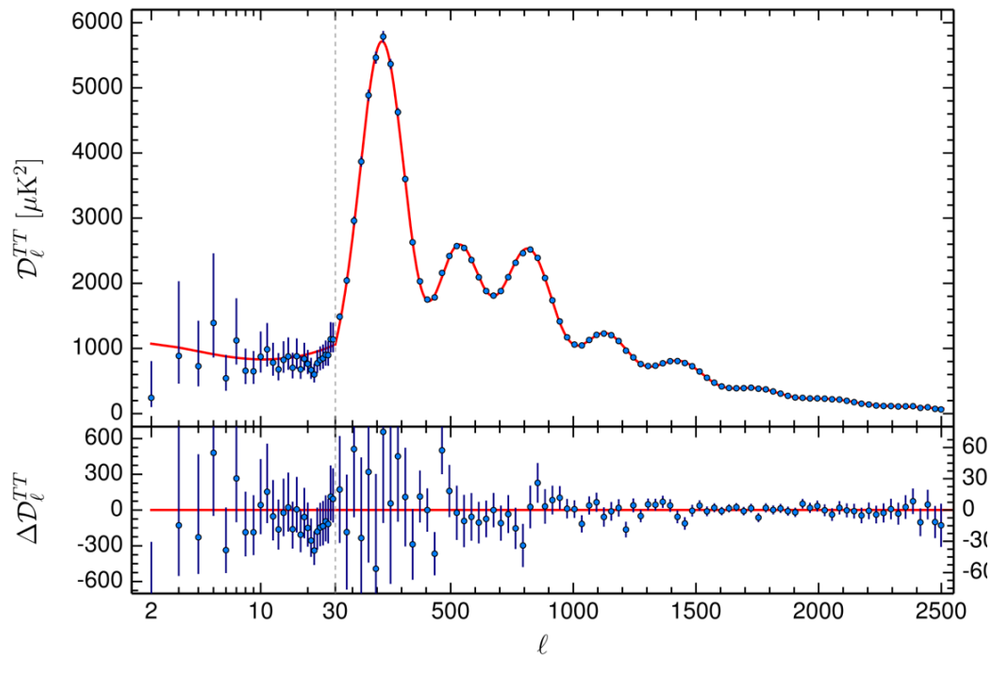
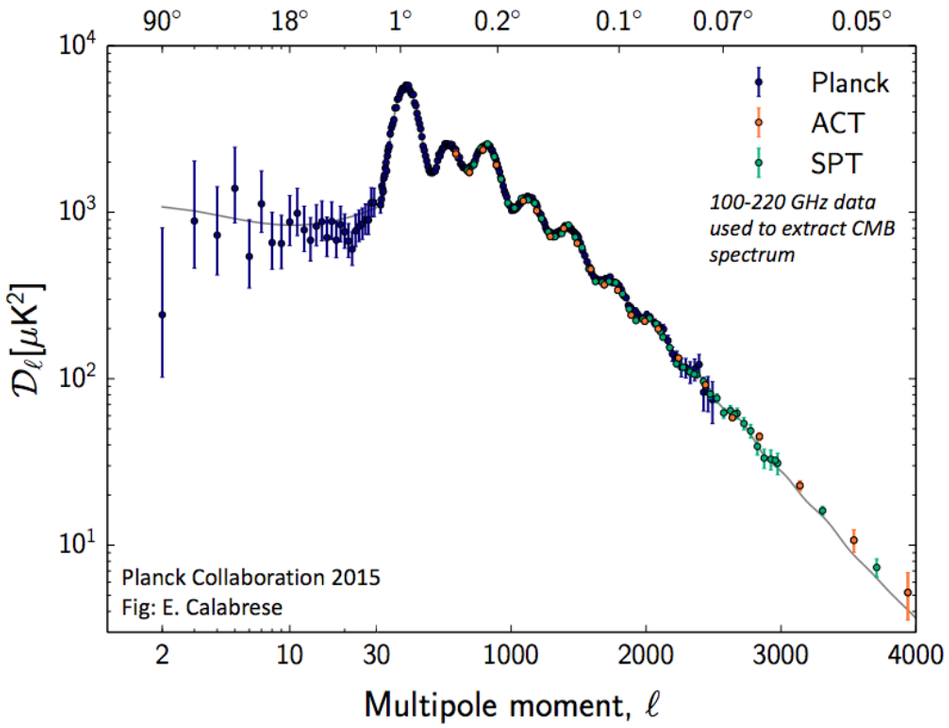




Angular power



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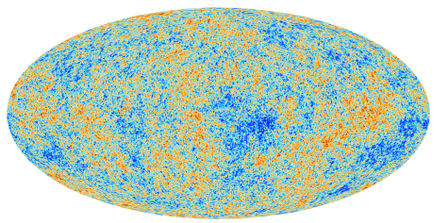

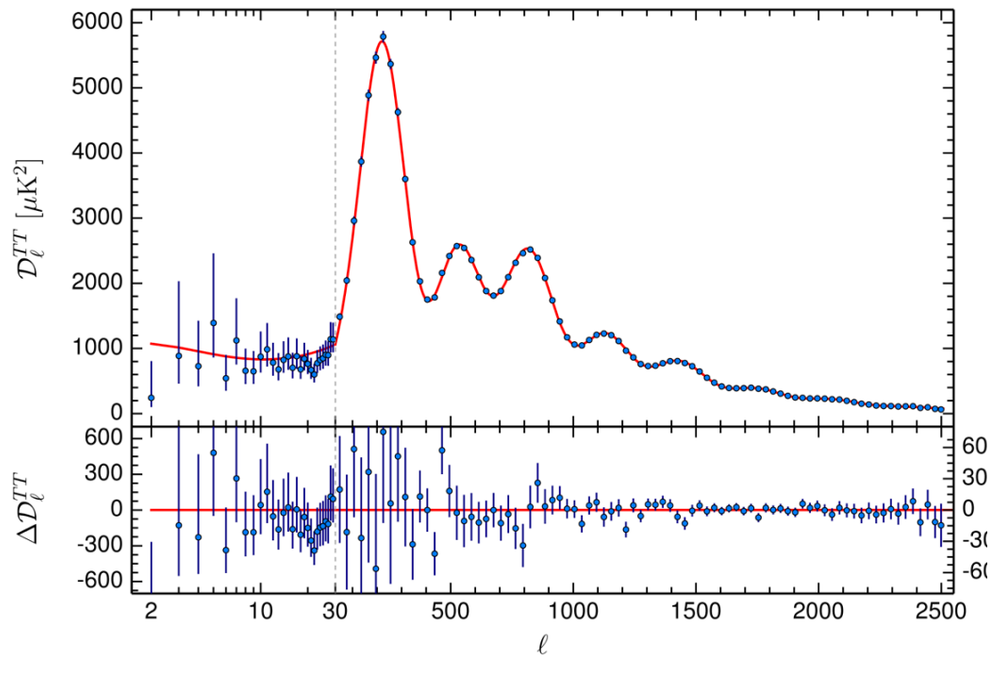

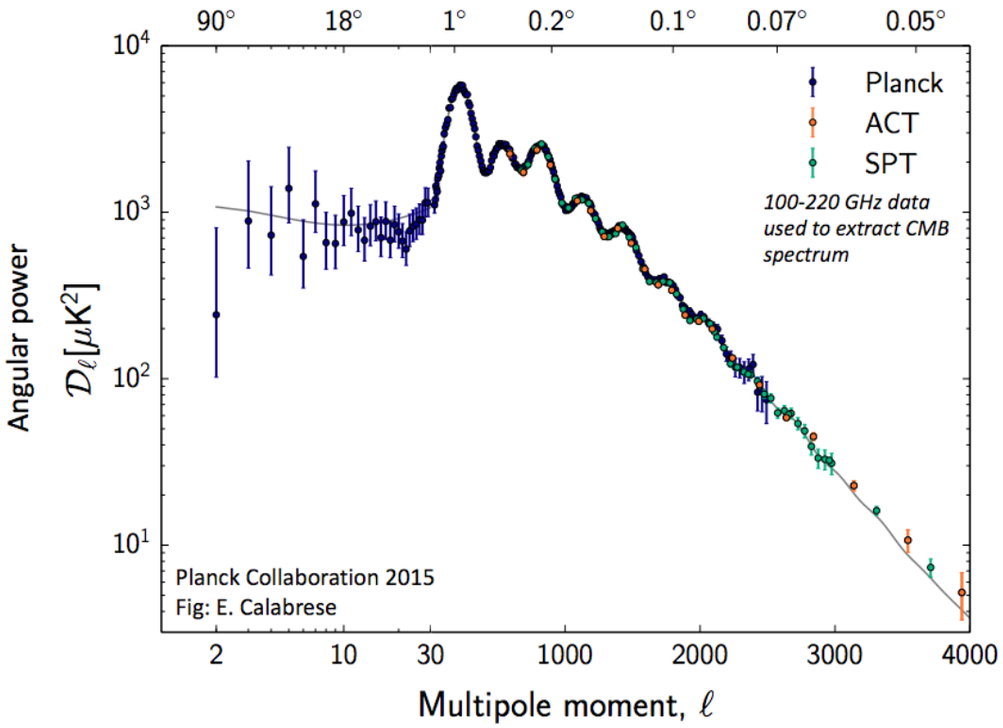

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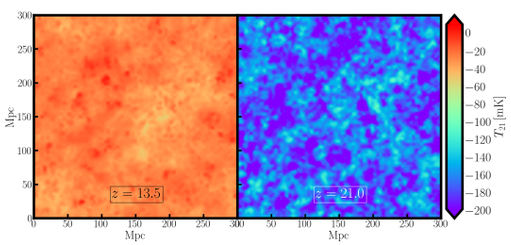

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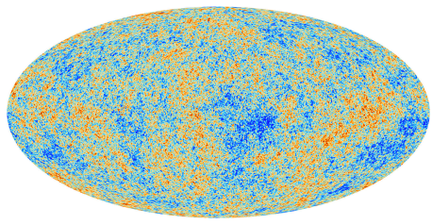

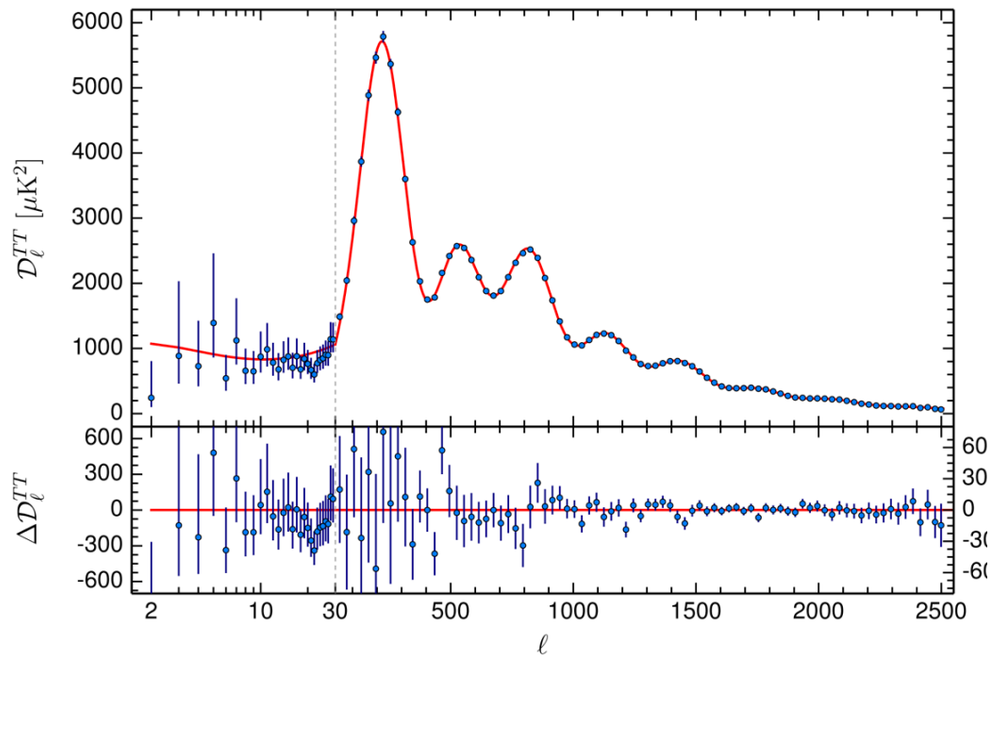

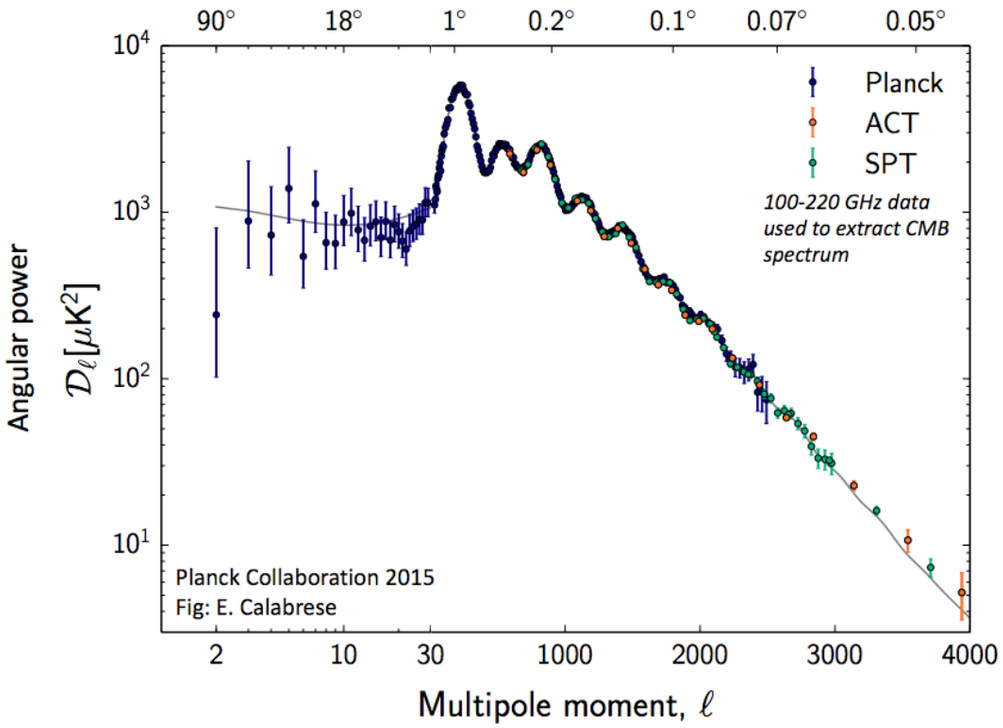

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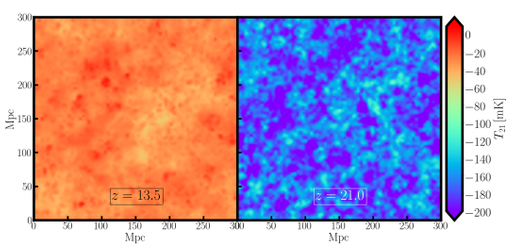
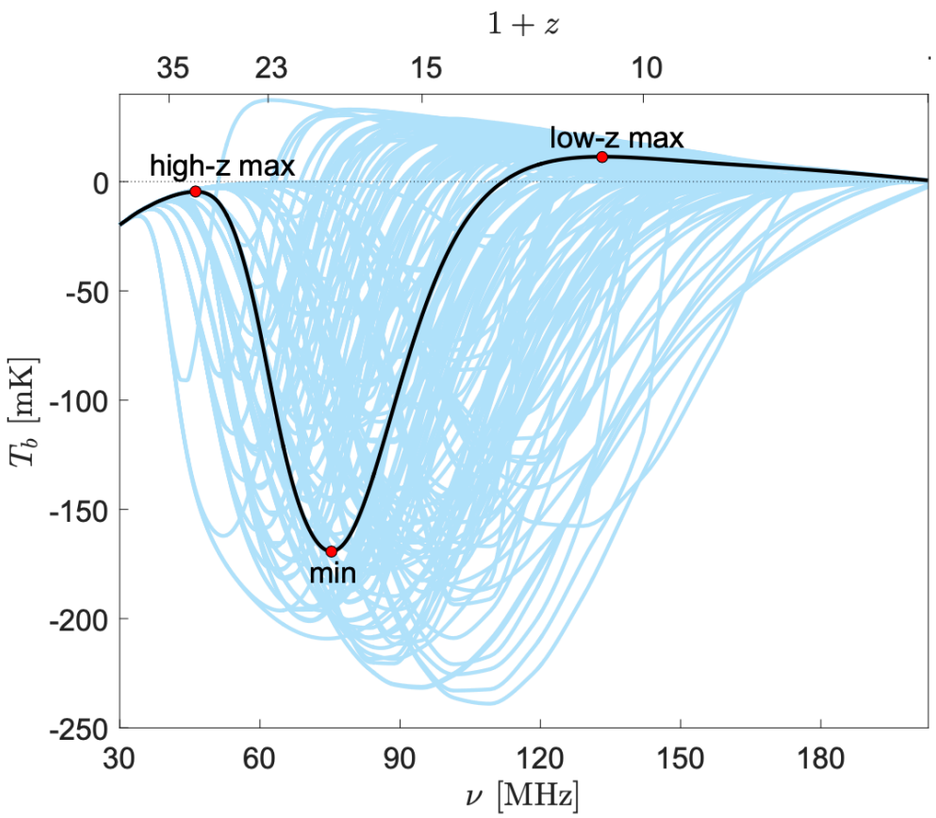
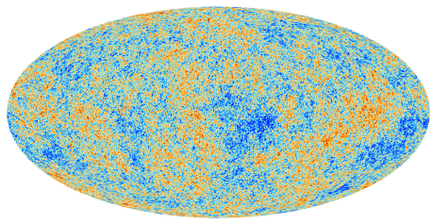
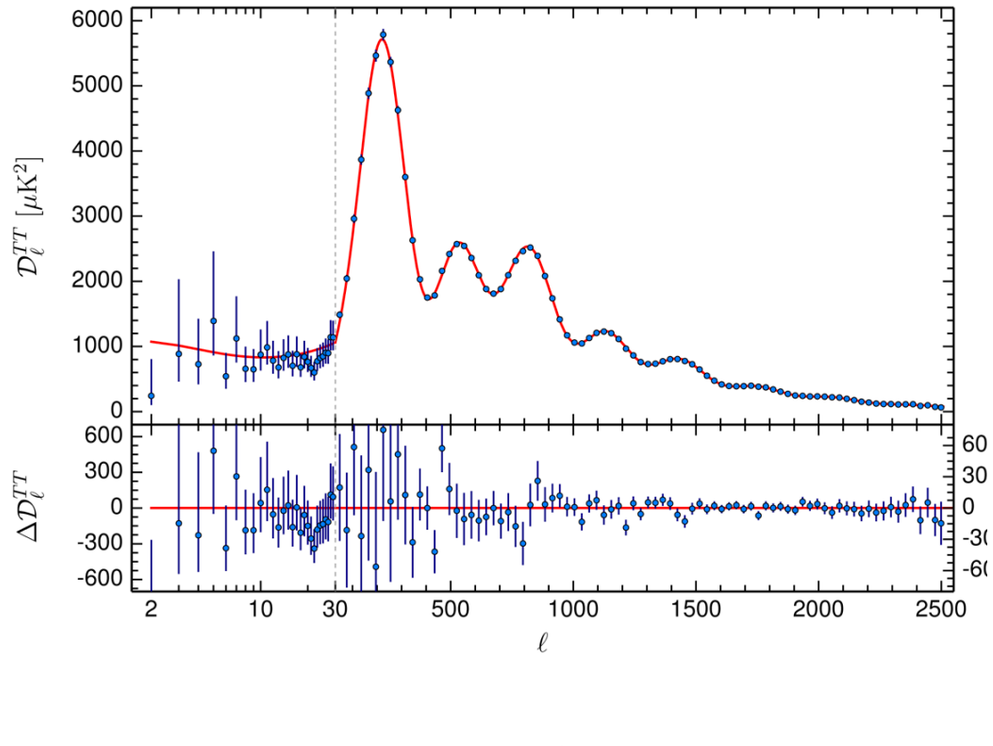


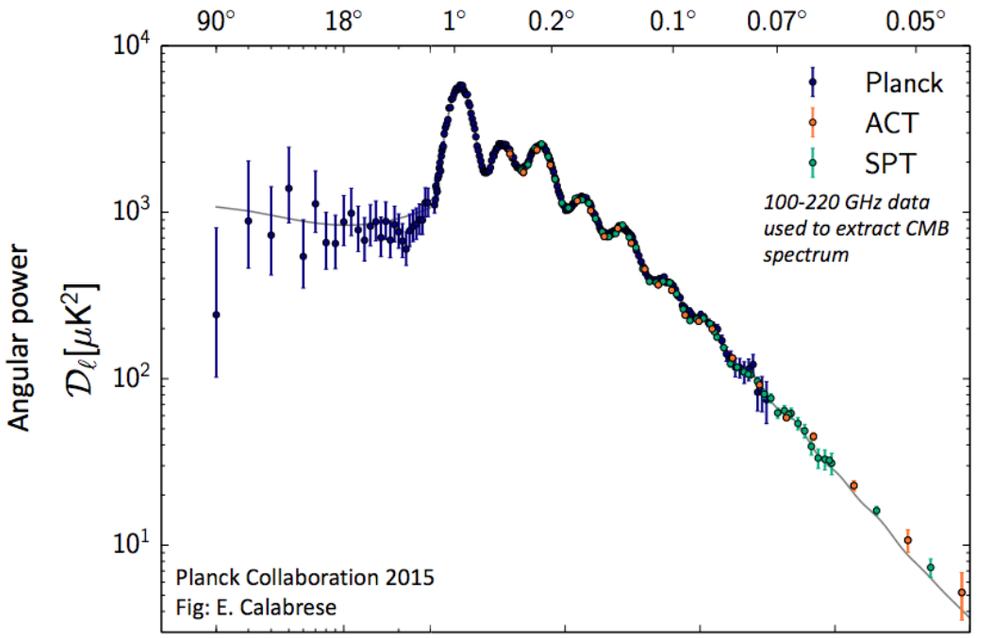


Goal 2: Combine CMB and 21cm Observations

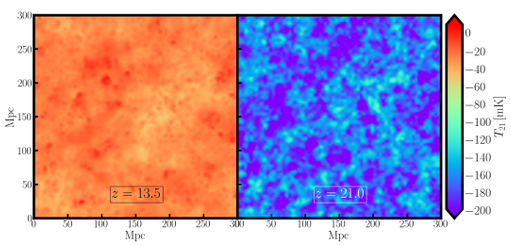
CMB

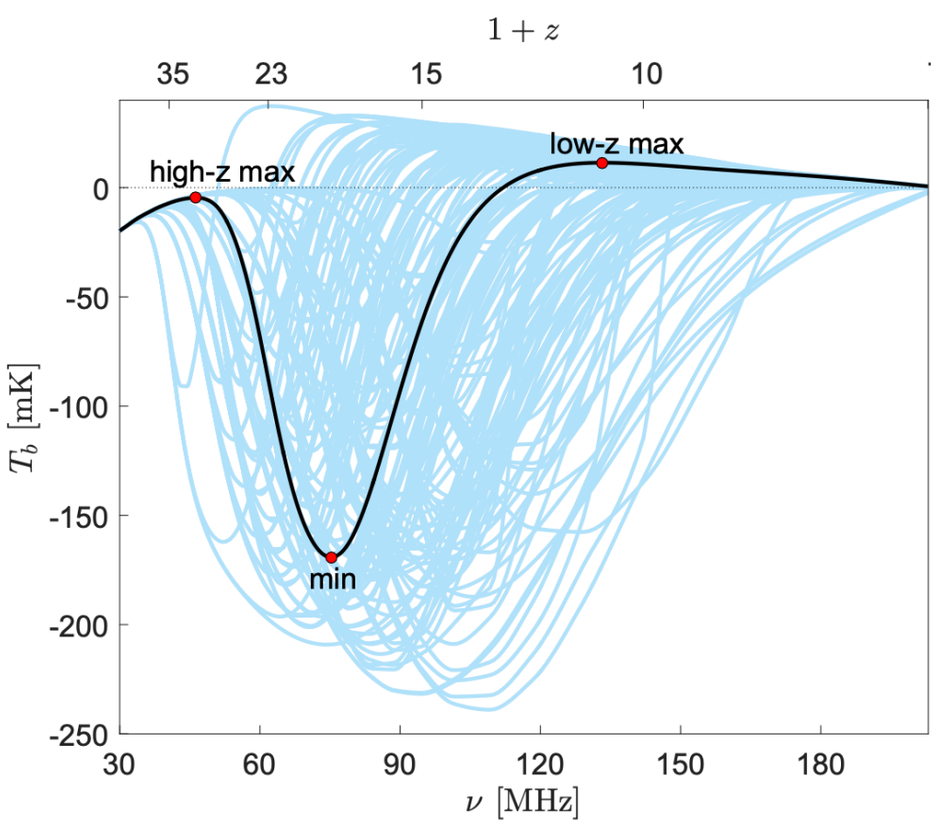


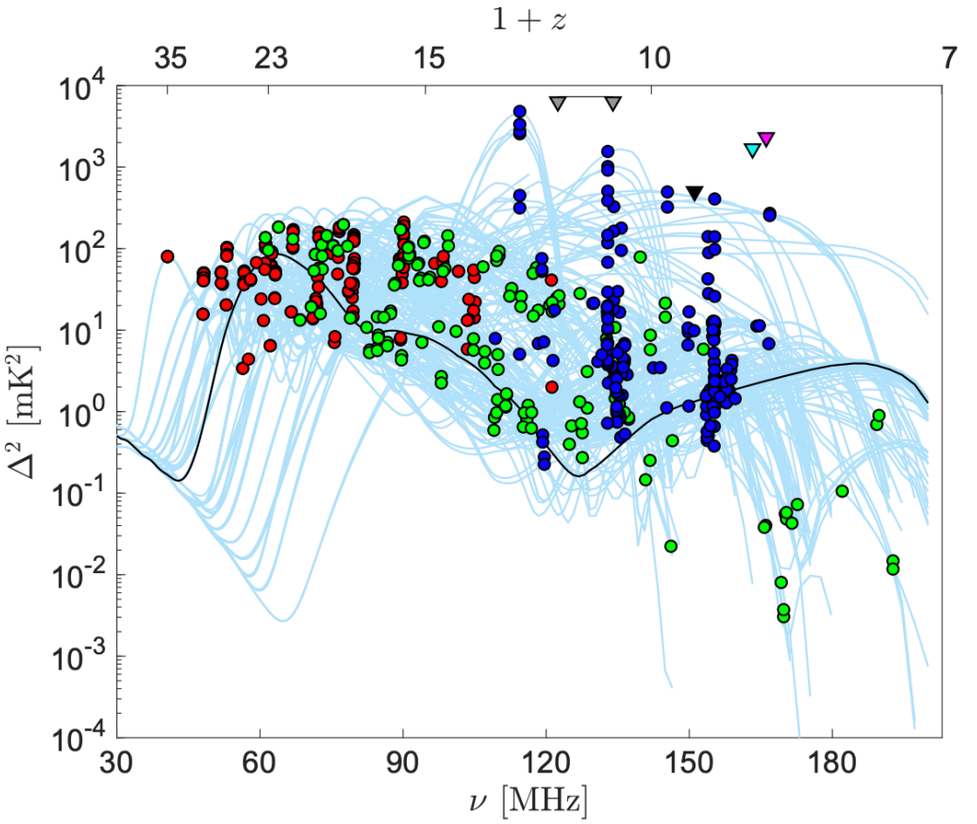




21cm







Goal 3: Track the Full Cosmic History

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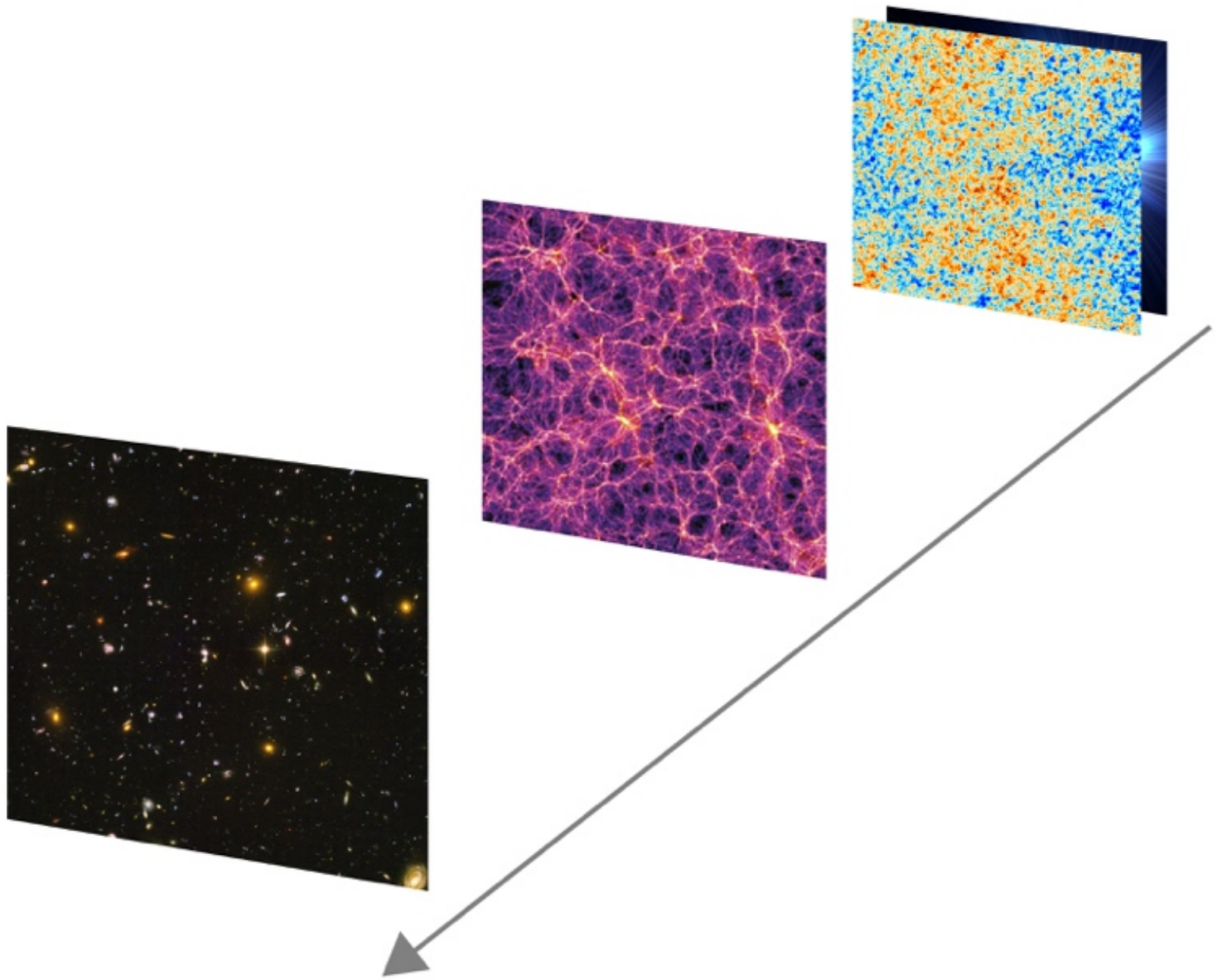

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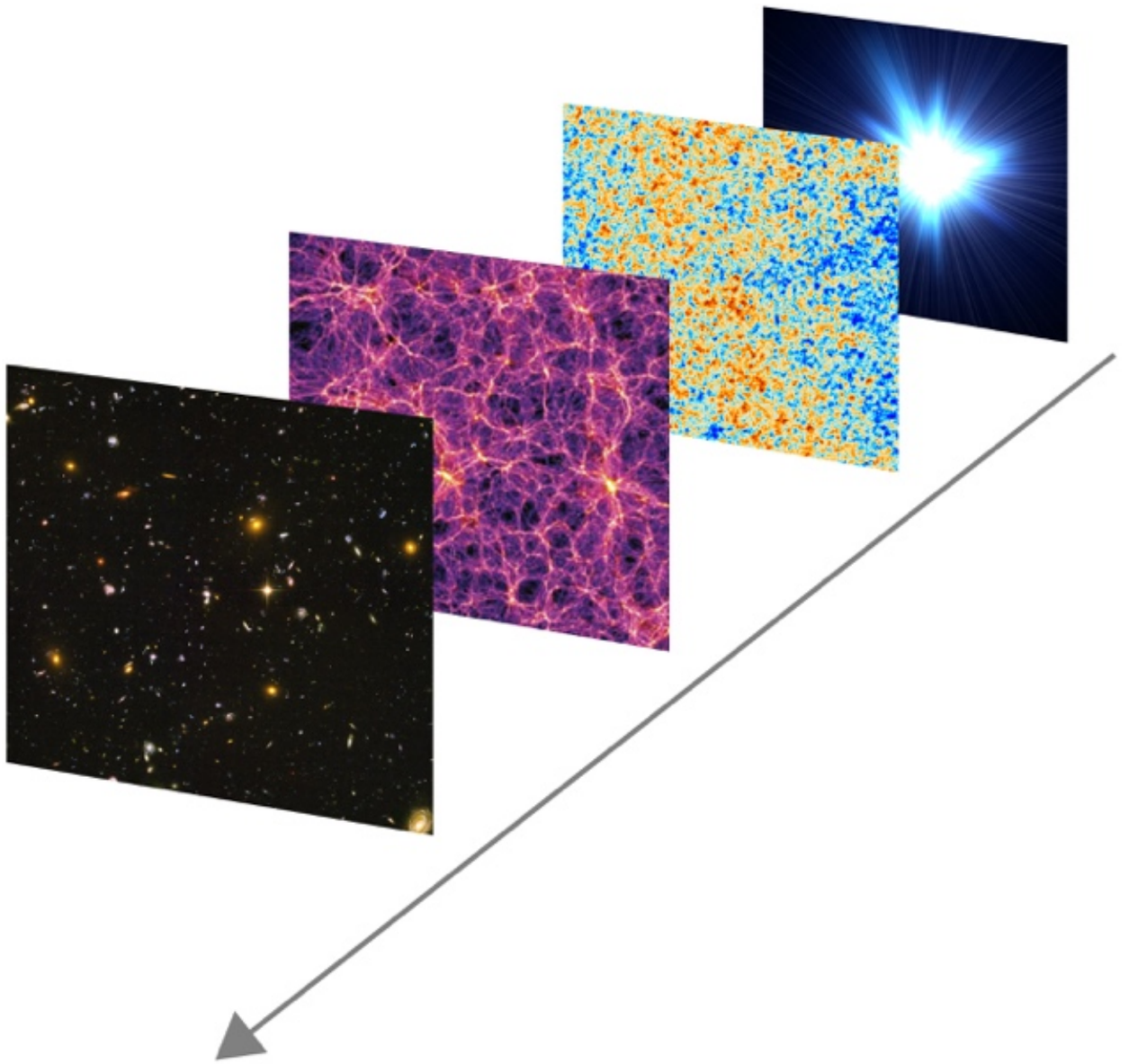

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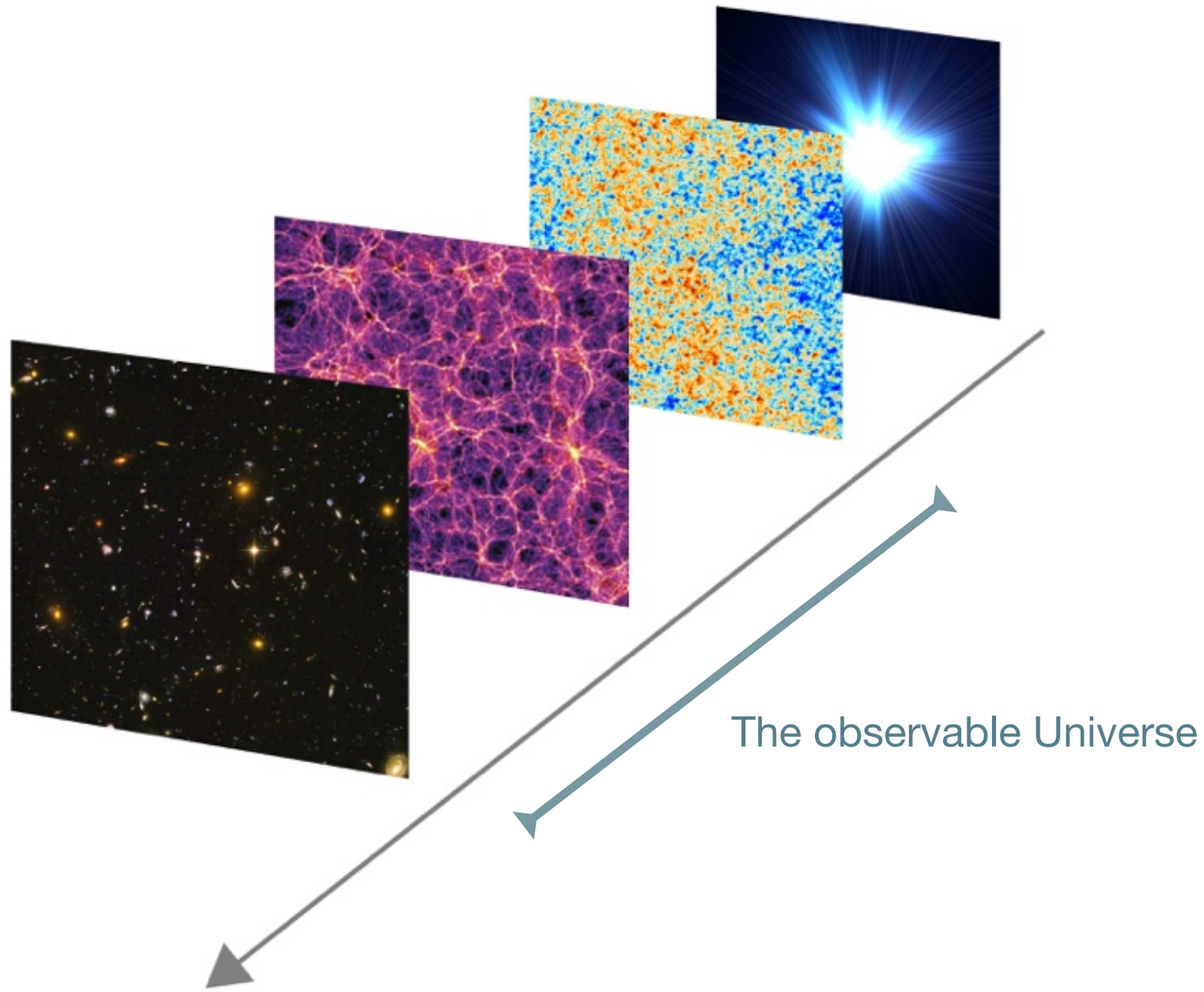

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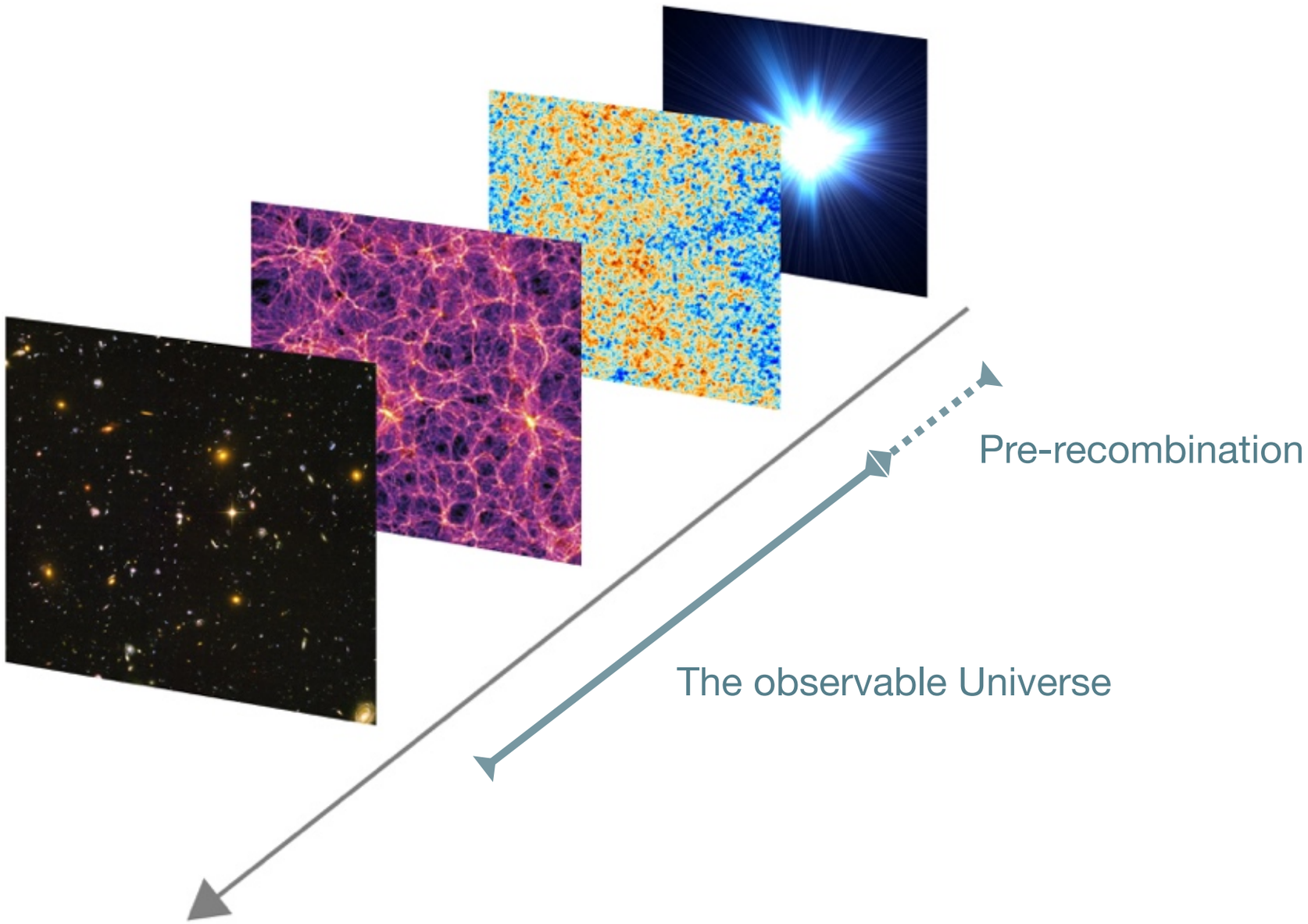

Solution: Self-Consistent CMB+21cm Calculation

(Sarkar, Flitter and **EDK**, arXiv:2201.03355)

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CLASS

Programs

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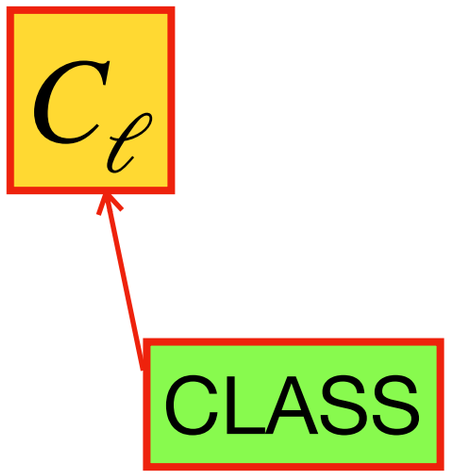

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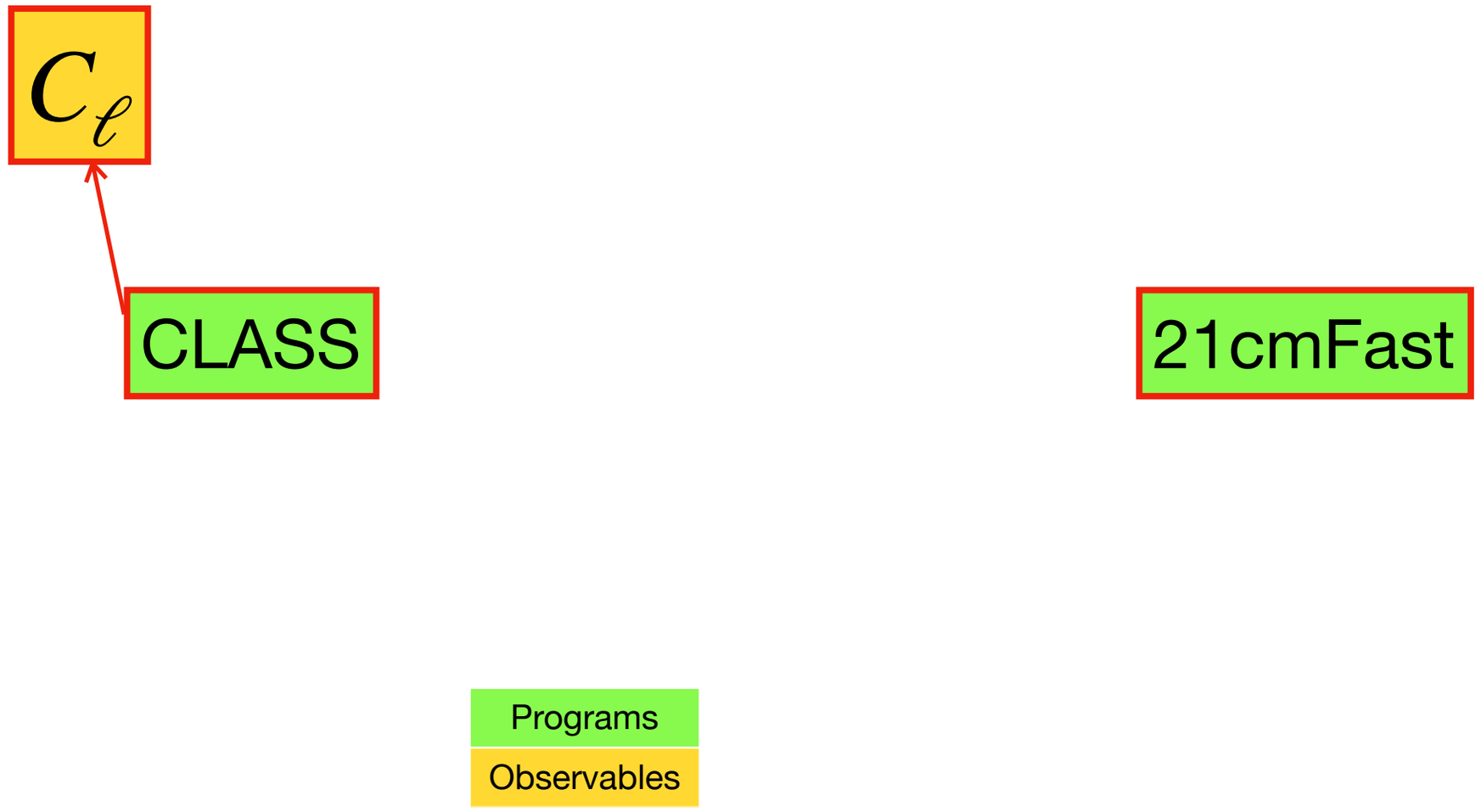

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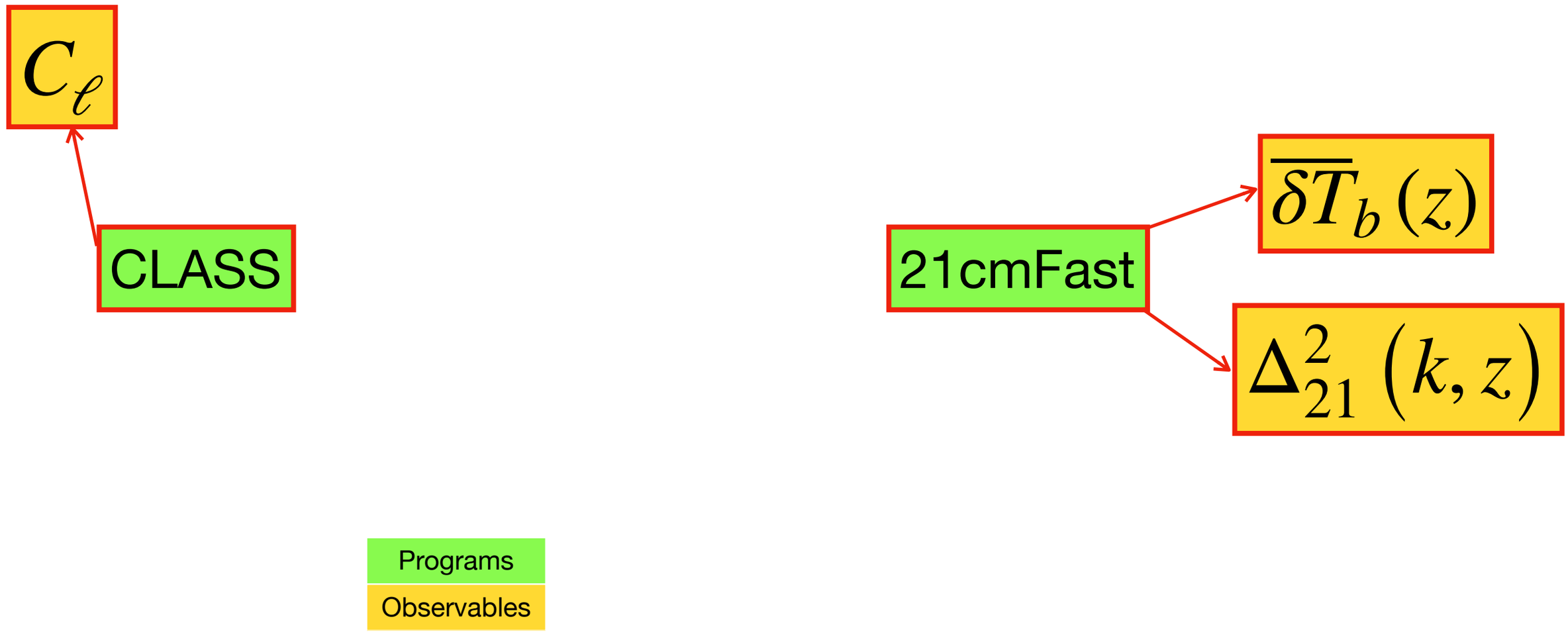

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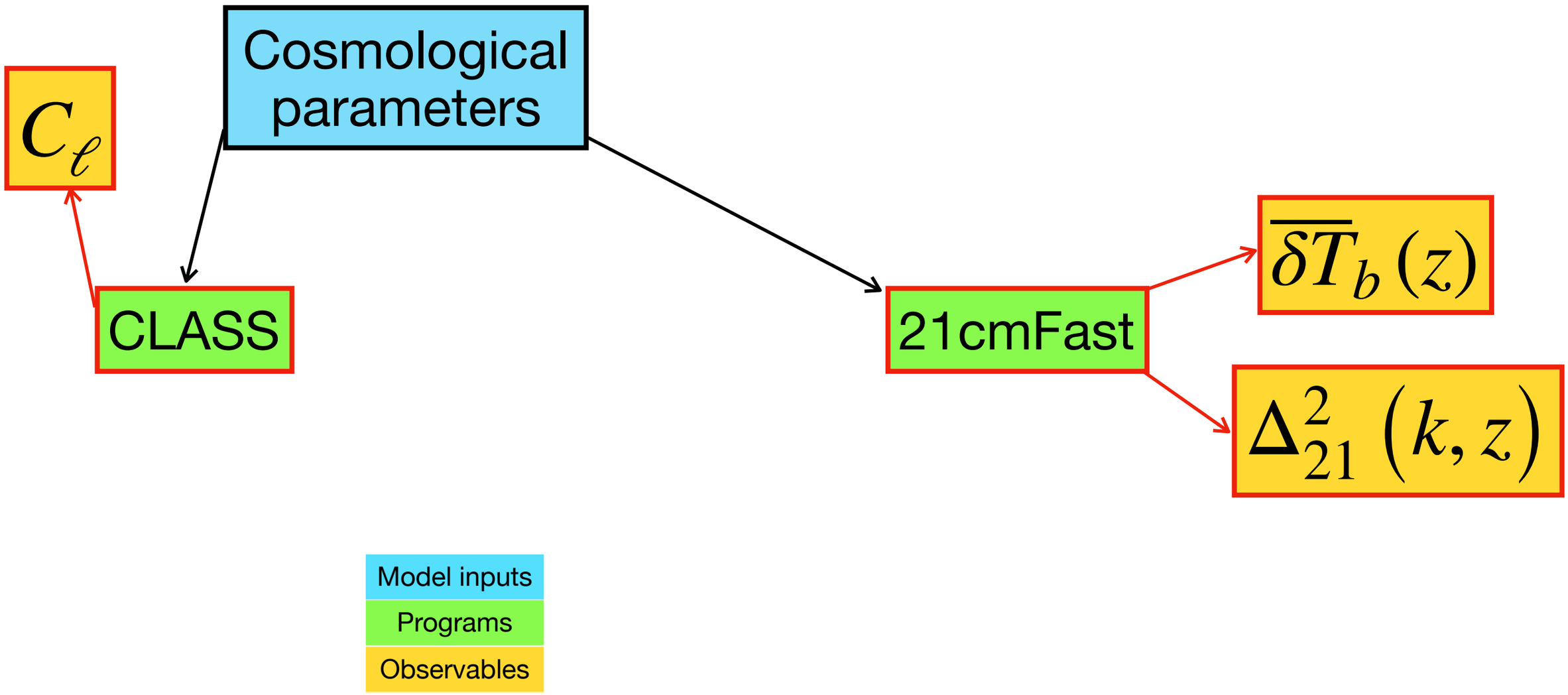

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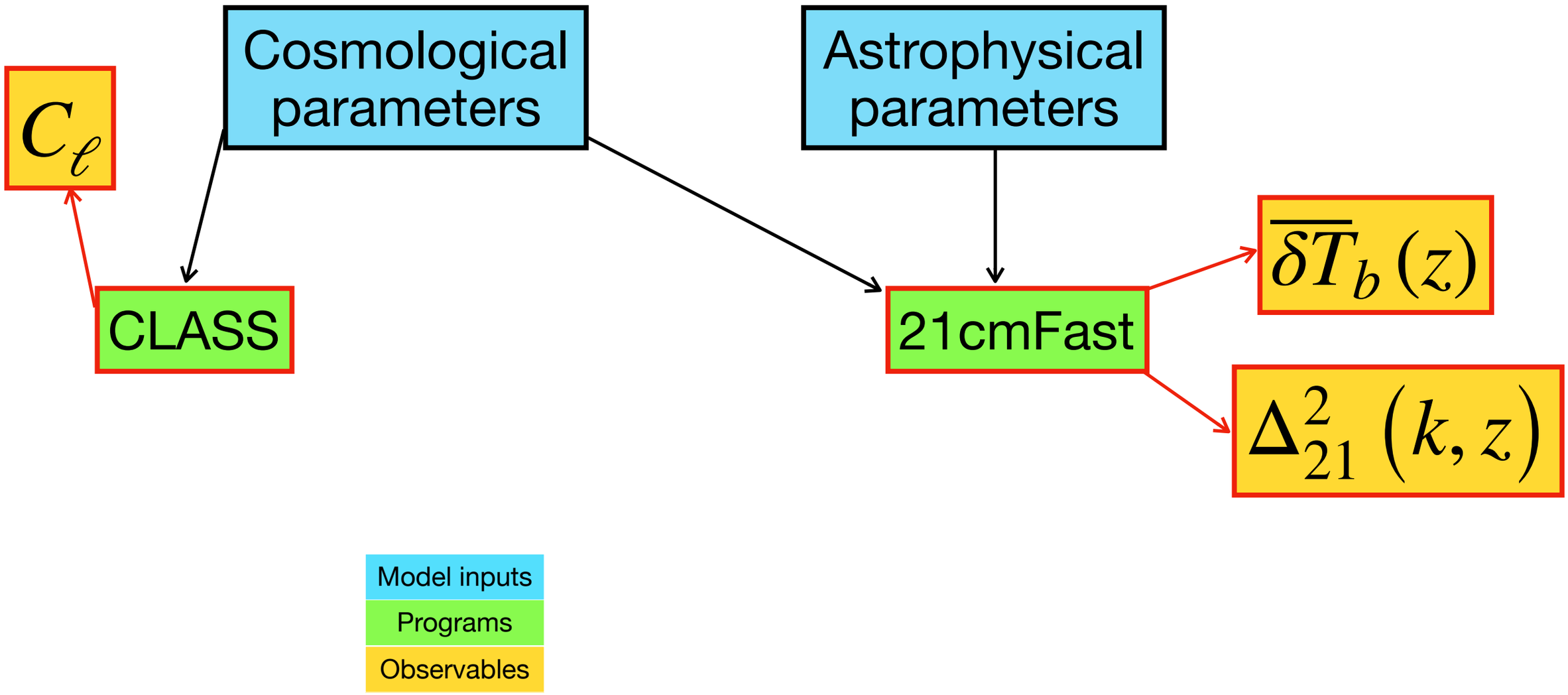

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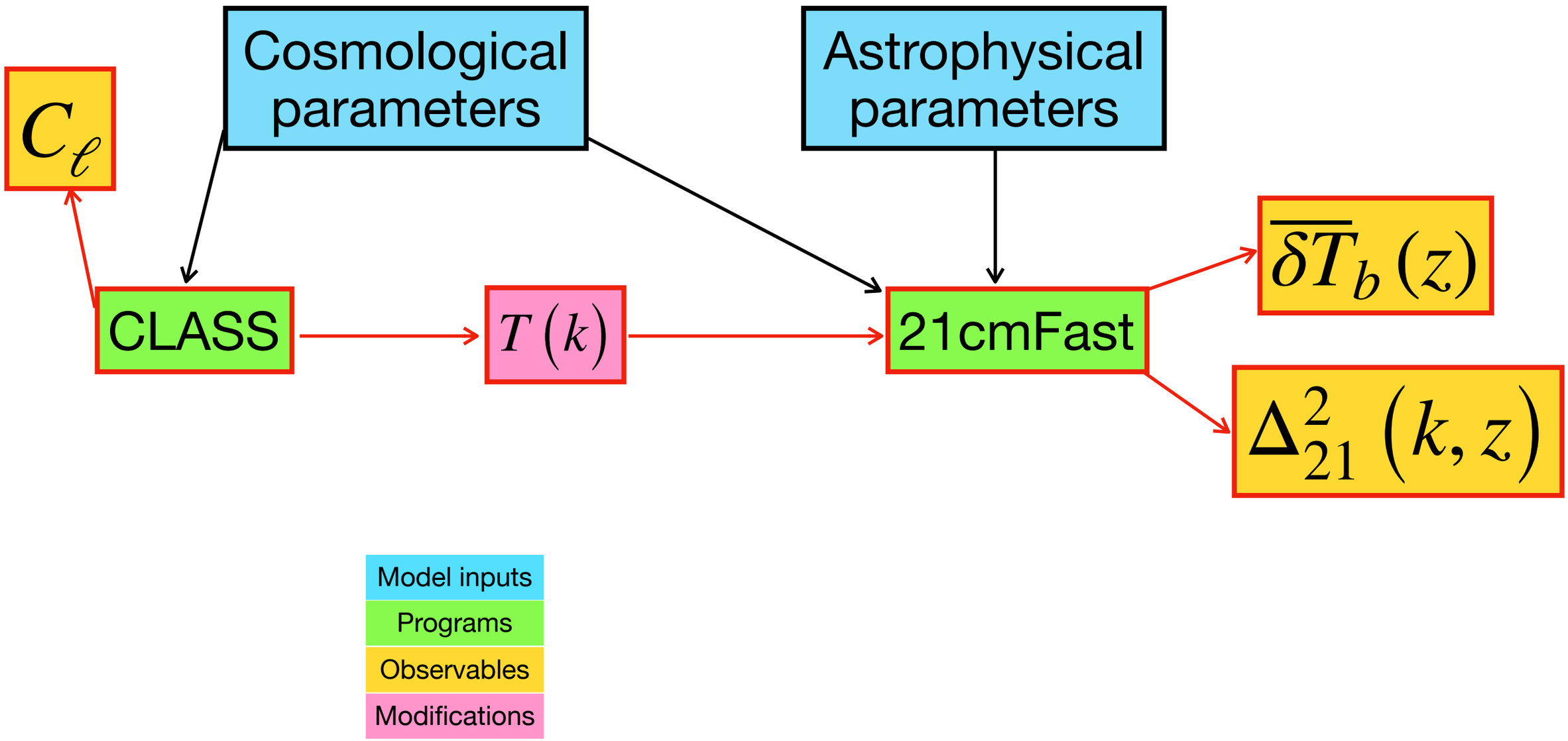

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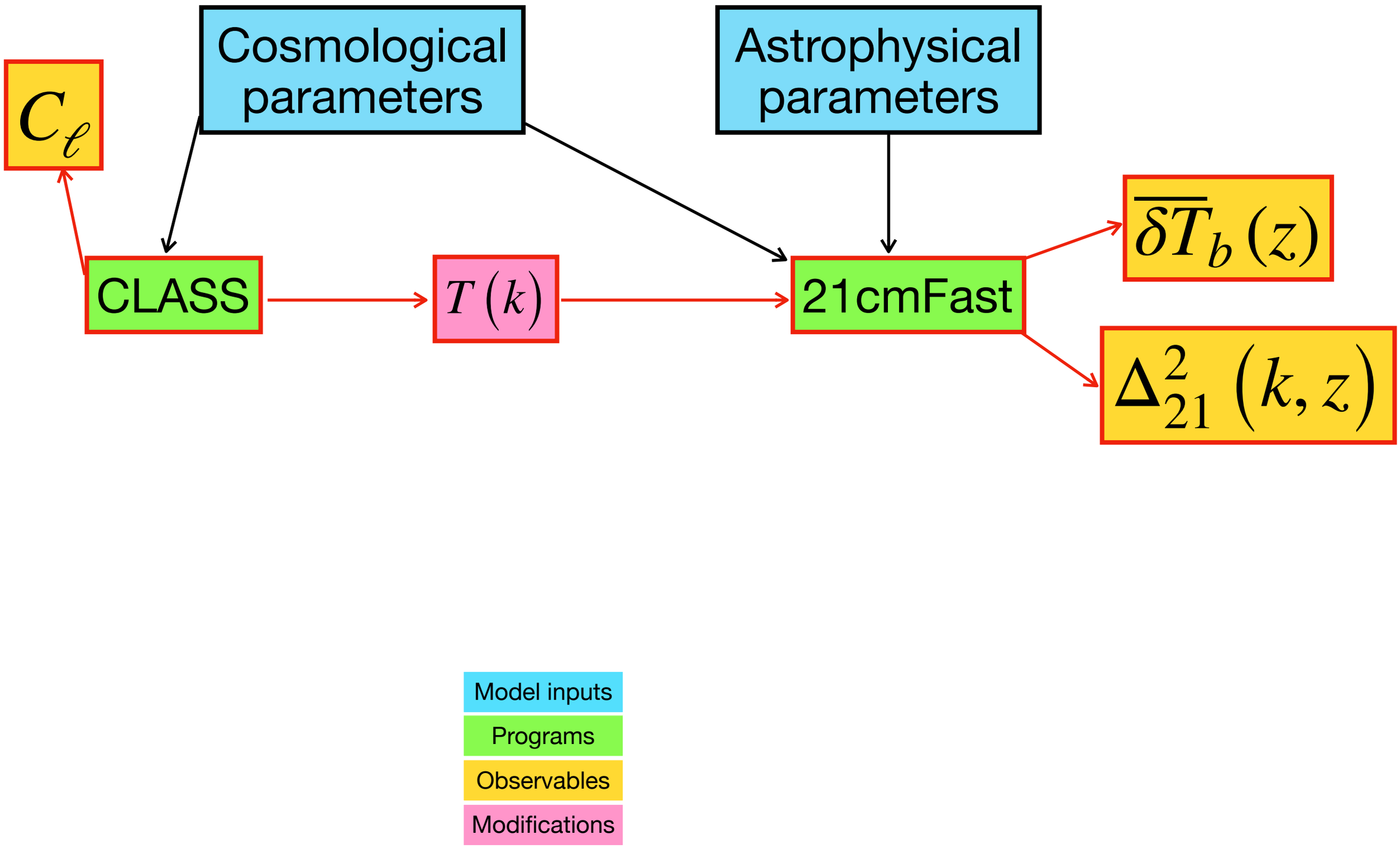

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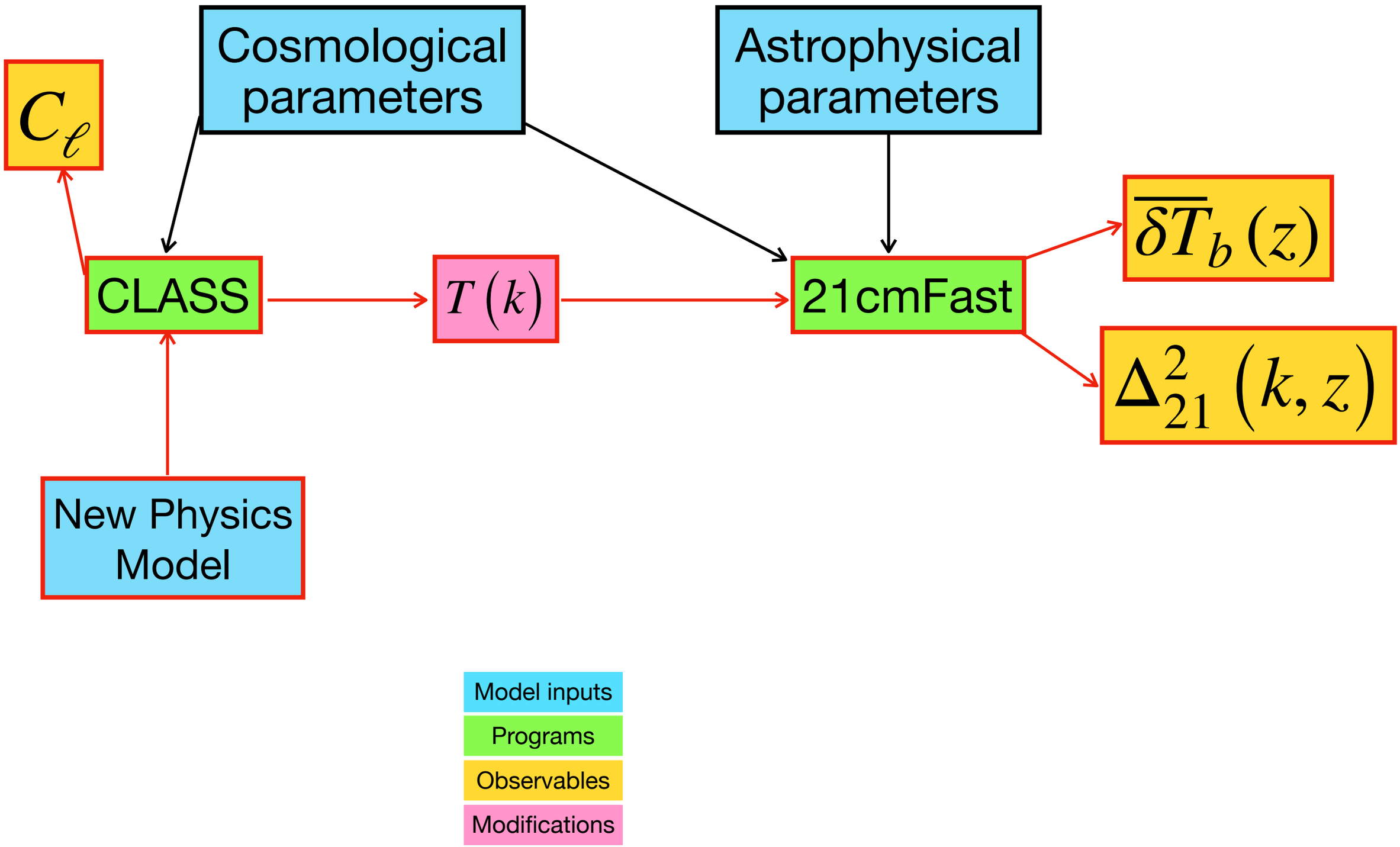

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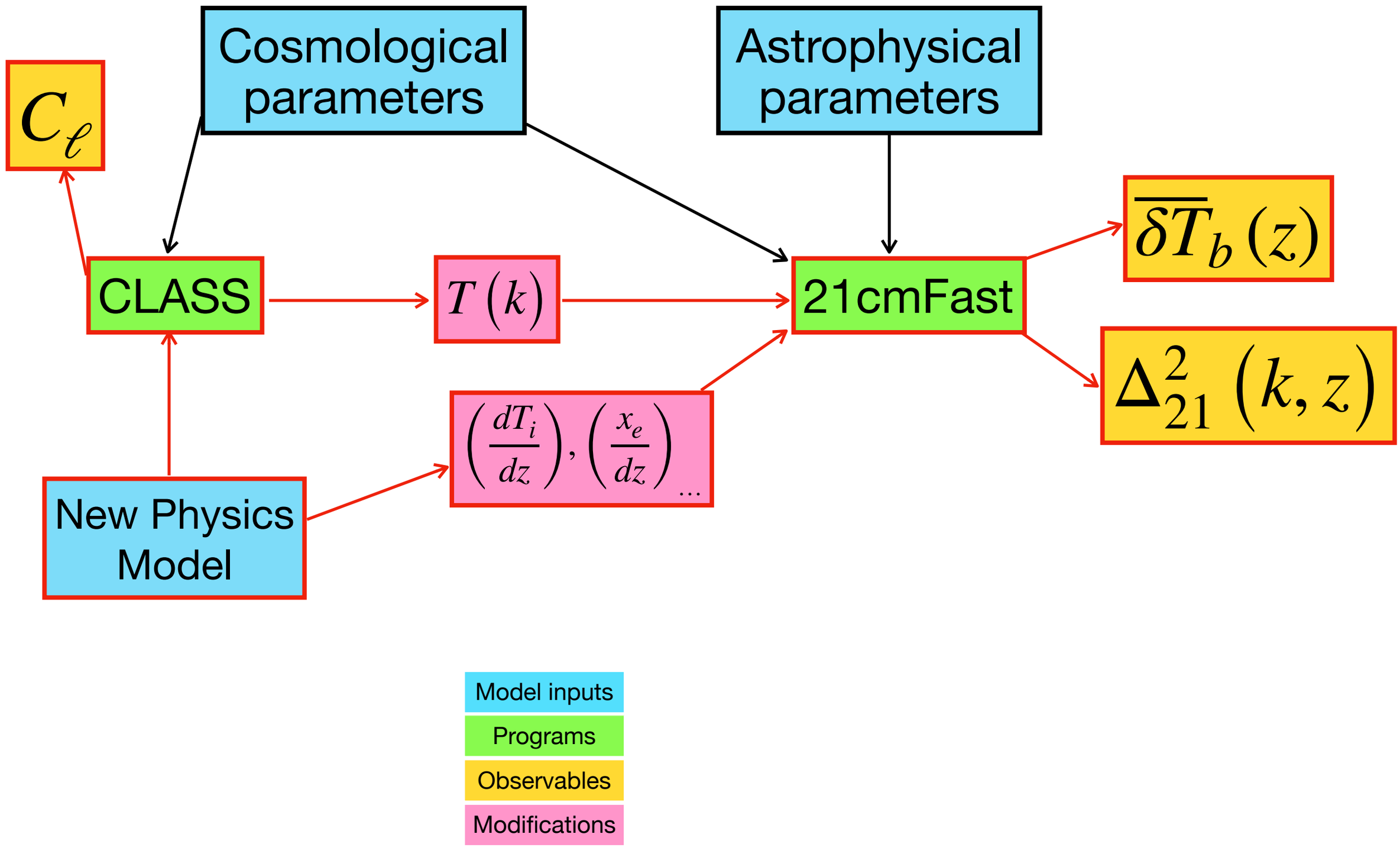

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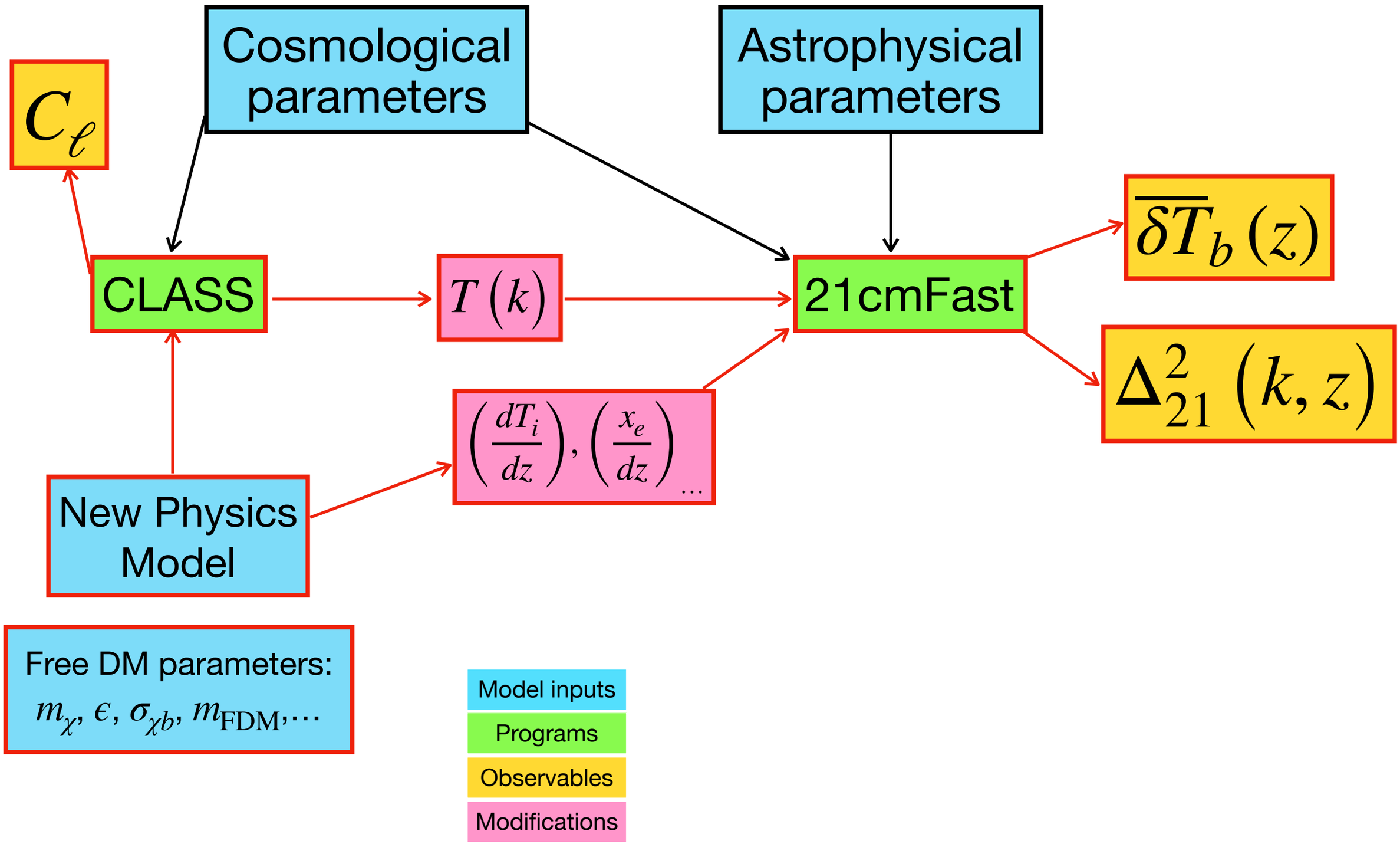

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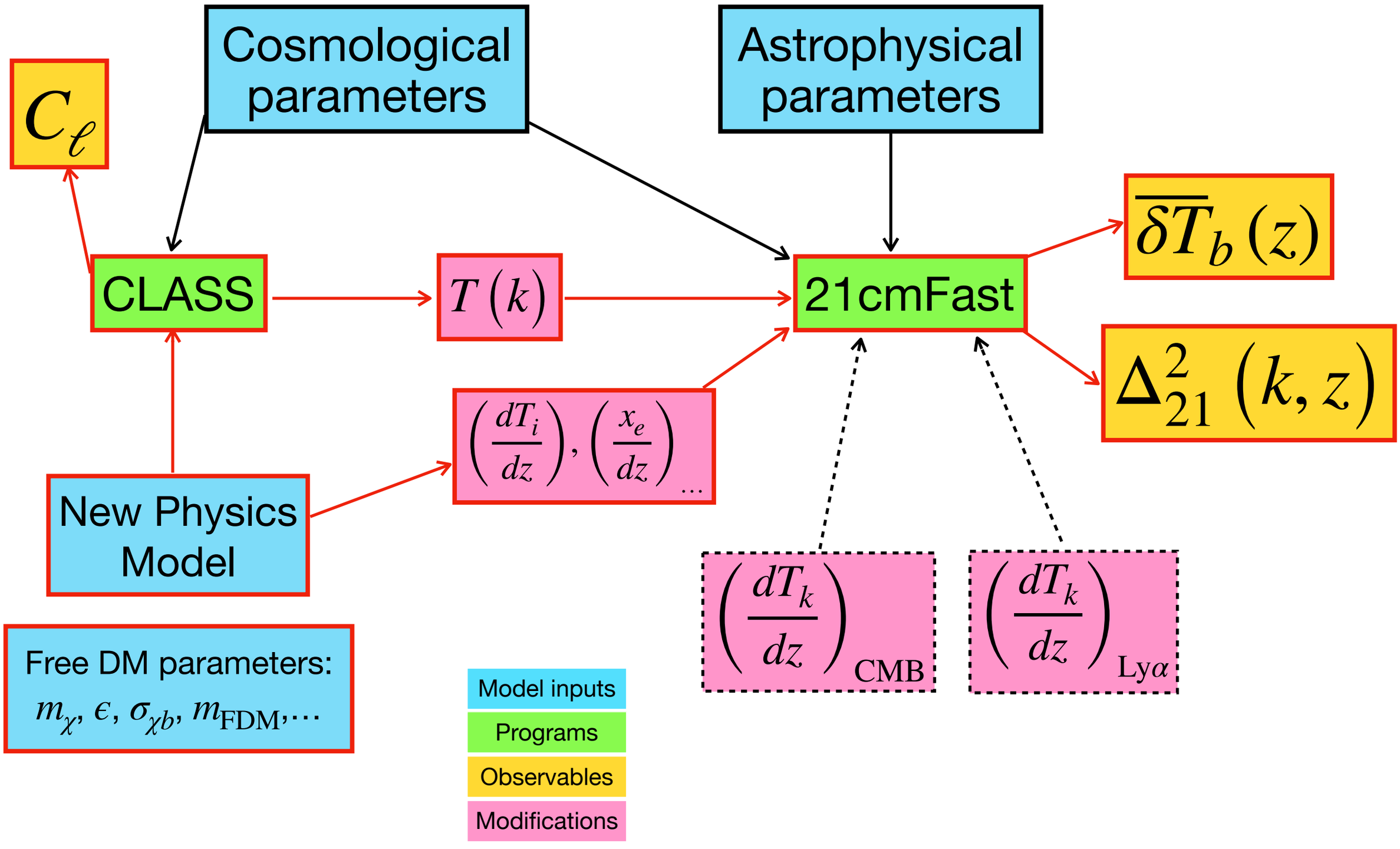
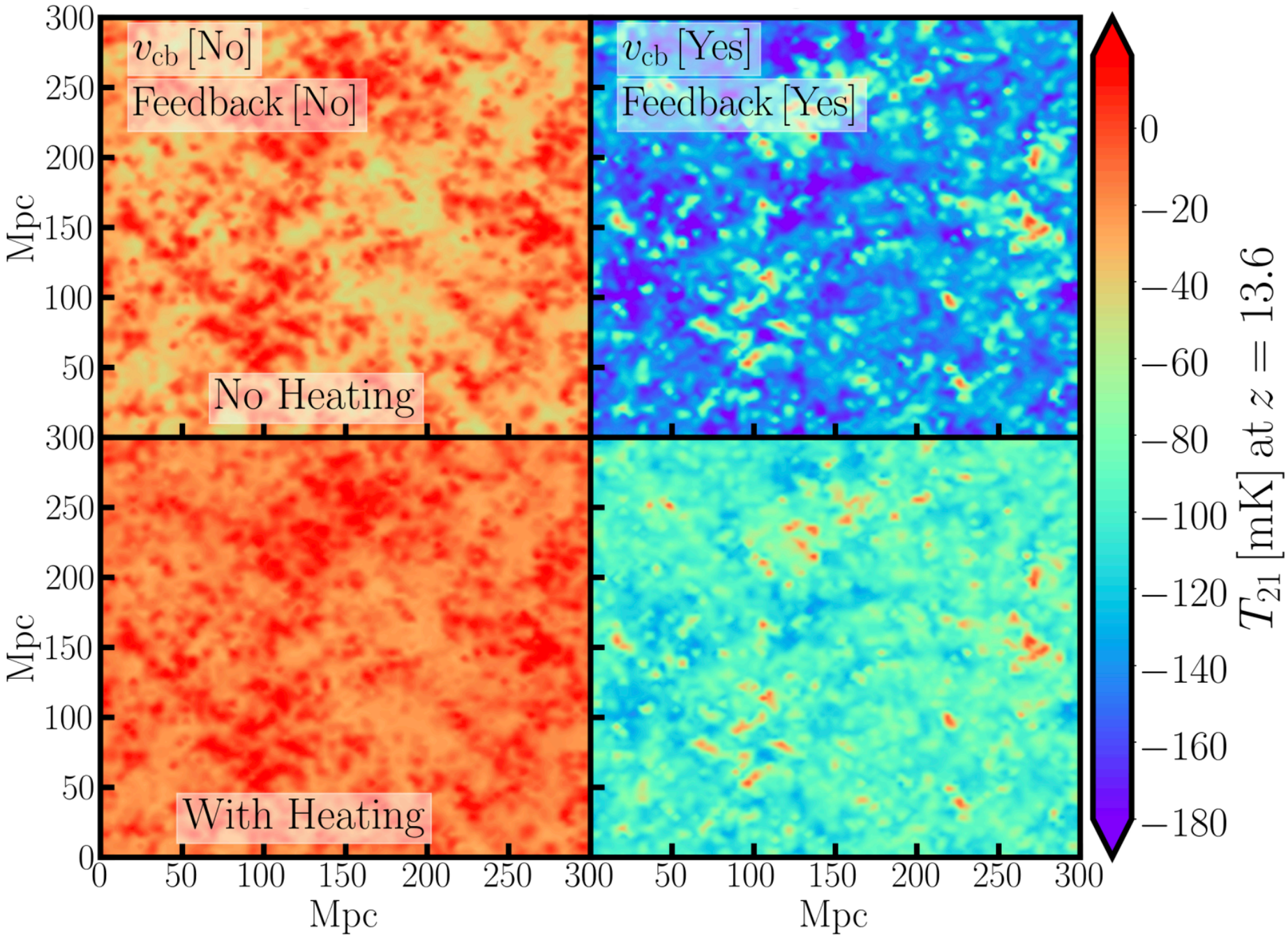


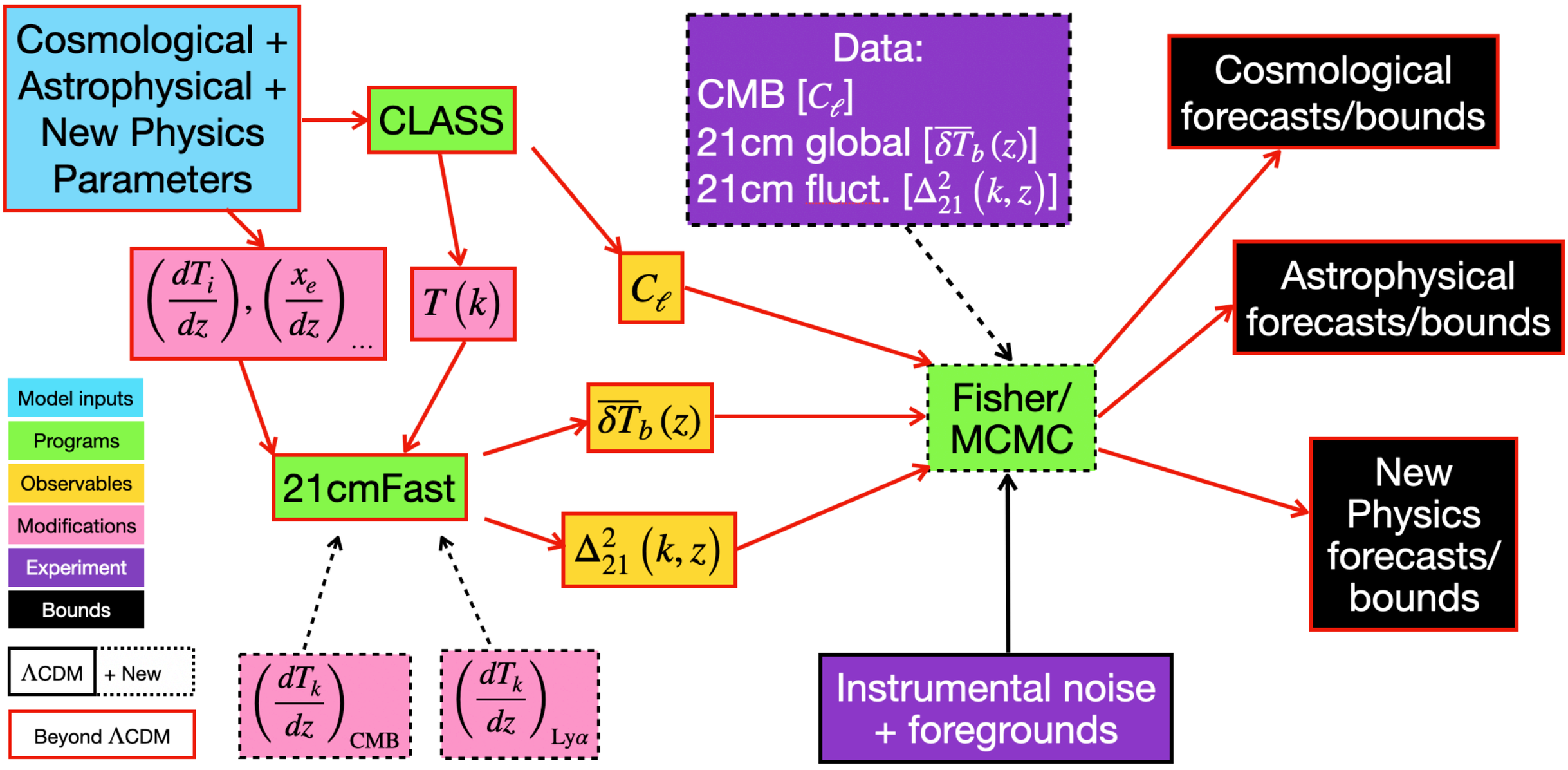
Solution: Importance of Heating + Delaying Effects

(Sarkar, Flitter and EDK, arXiv:2201.)



Solution: Joint CMB+21cm Analysis

(Sarkar, Flitter and **EDK**, arXiv:2201.03355)



(Toy?) Example: Fuzzy Dark Matter (FDM)

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$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_{\mathrm{FDM}}^2\phi^2$$

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FDM: Empirical Motivation

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Solves long-standing problems in cosmology:

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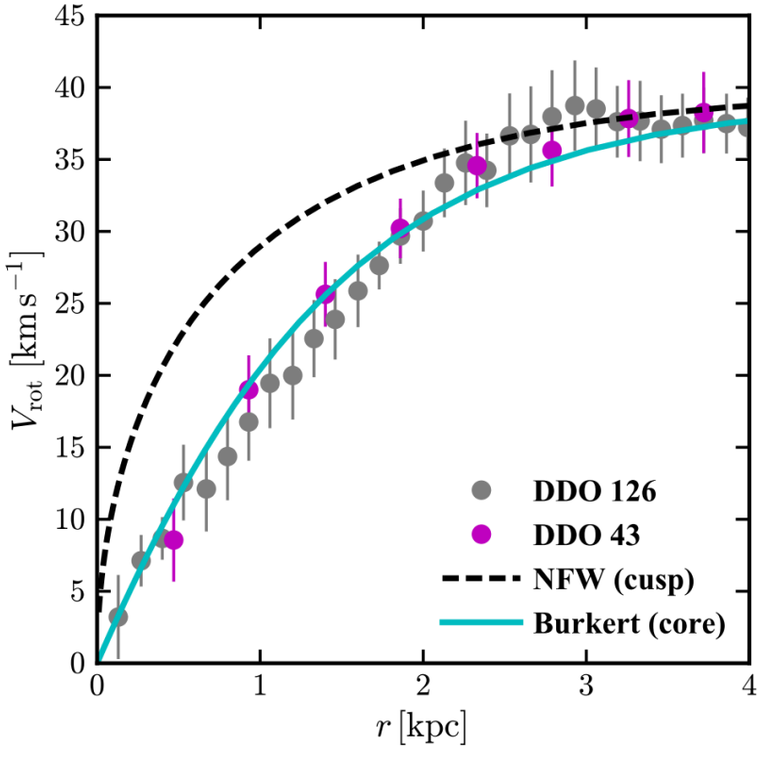
- Core-Cusp problem

Bullock & Boylan-Kolchin (arXiv: 1707.04256)



FDM: Empirical Motivation

Solves long-standing problems in cosmology:

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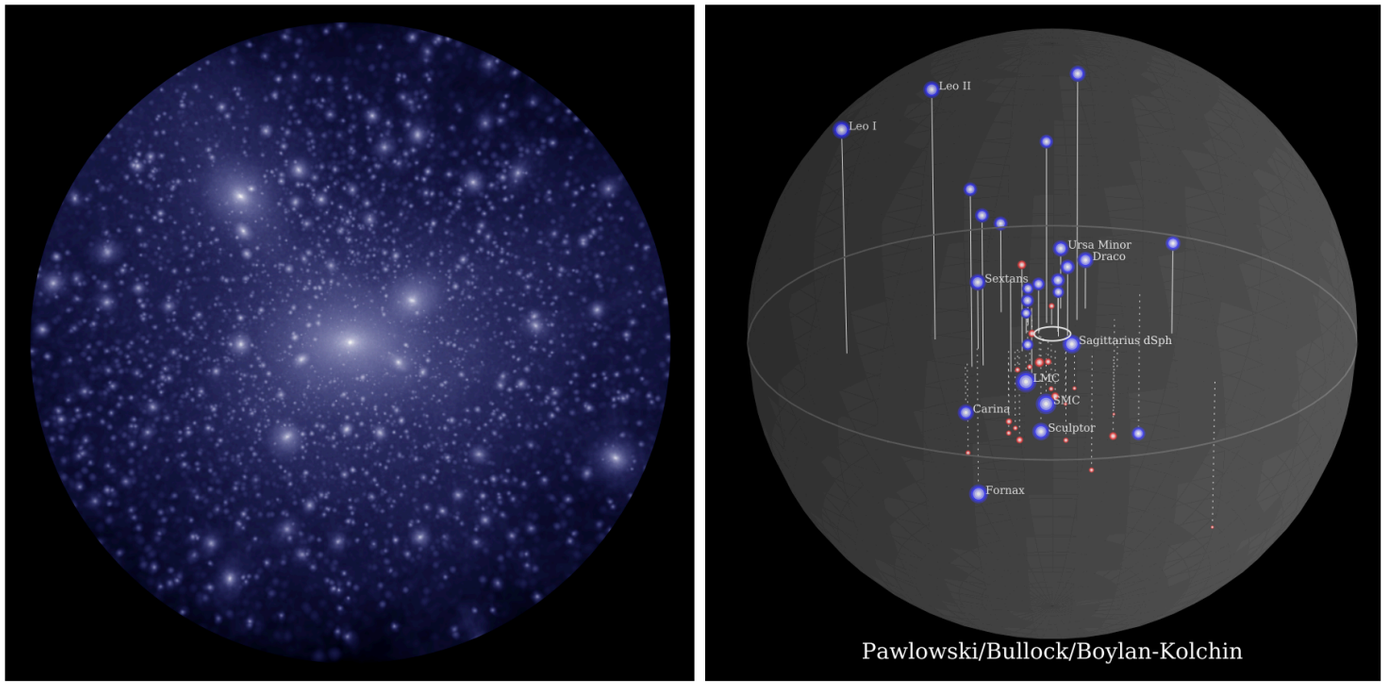
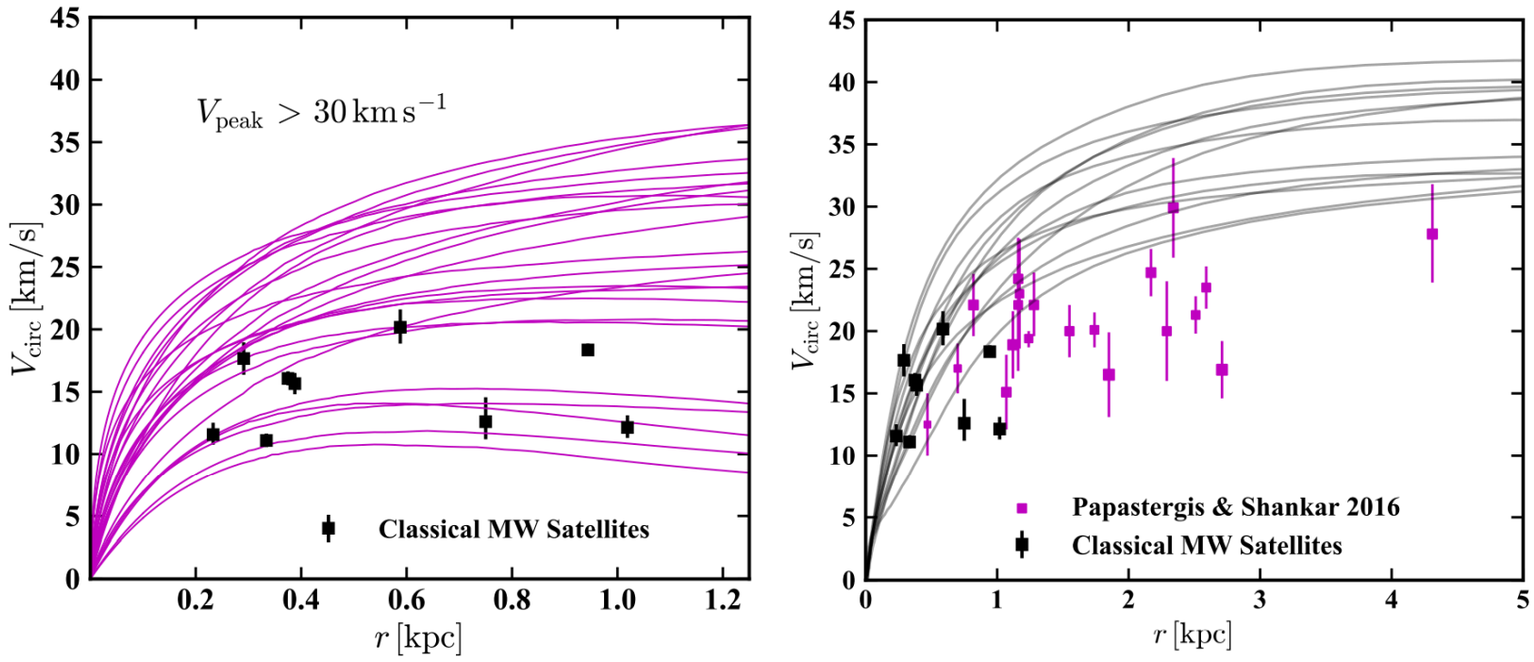


FDM: Empirical Motivation

Solves long-standing problems in cosmology:

- Too big to fail problem

Bullock & Boylan-Kolchin (arXiv: 1707.04256)



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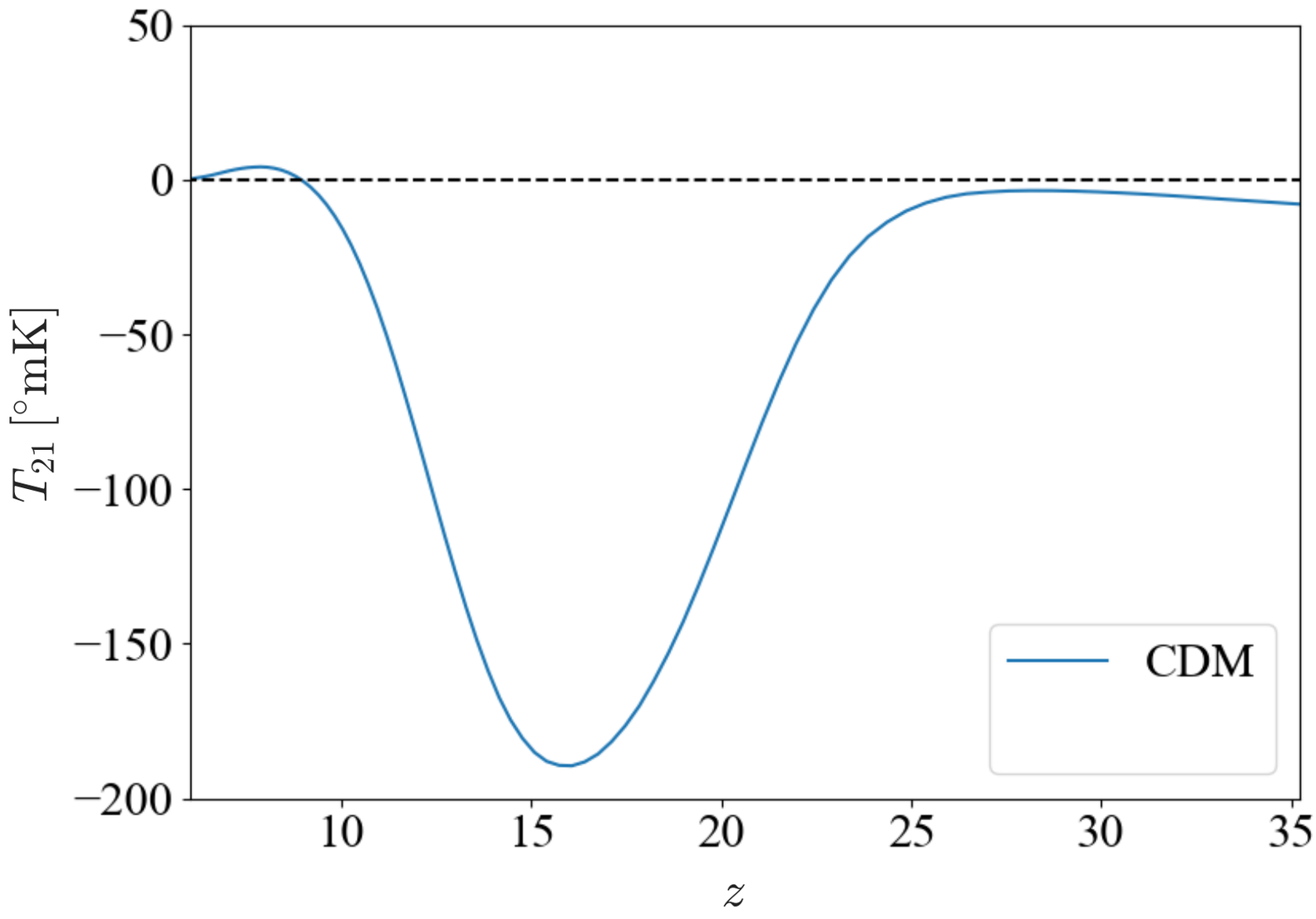
The 21cm signal is delayed!

FDM vs. CDM: 21cm Global Signal

(Sarkar, Flitter and **EDK**, arXiv:2201.)



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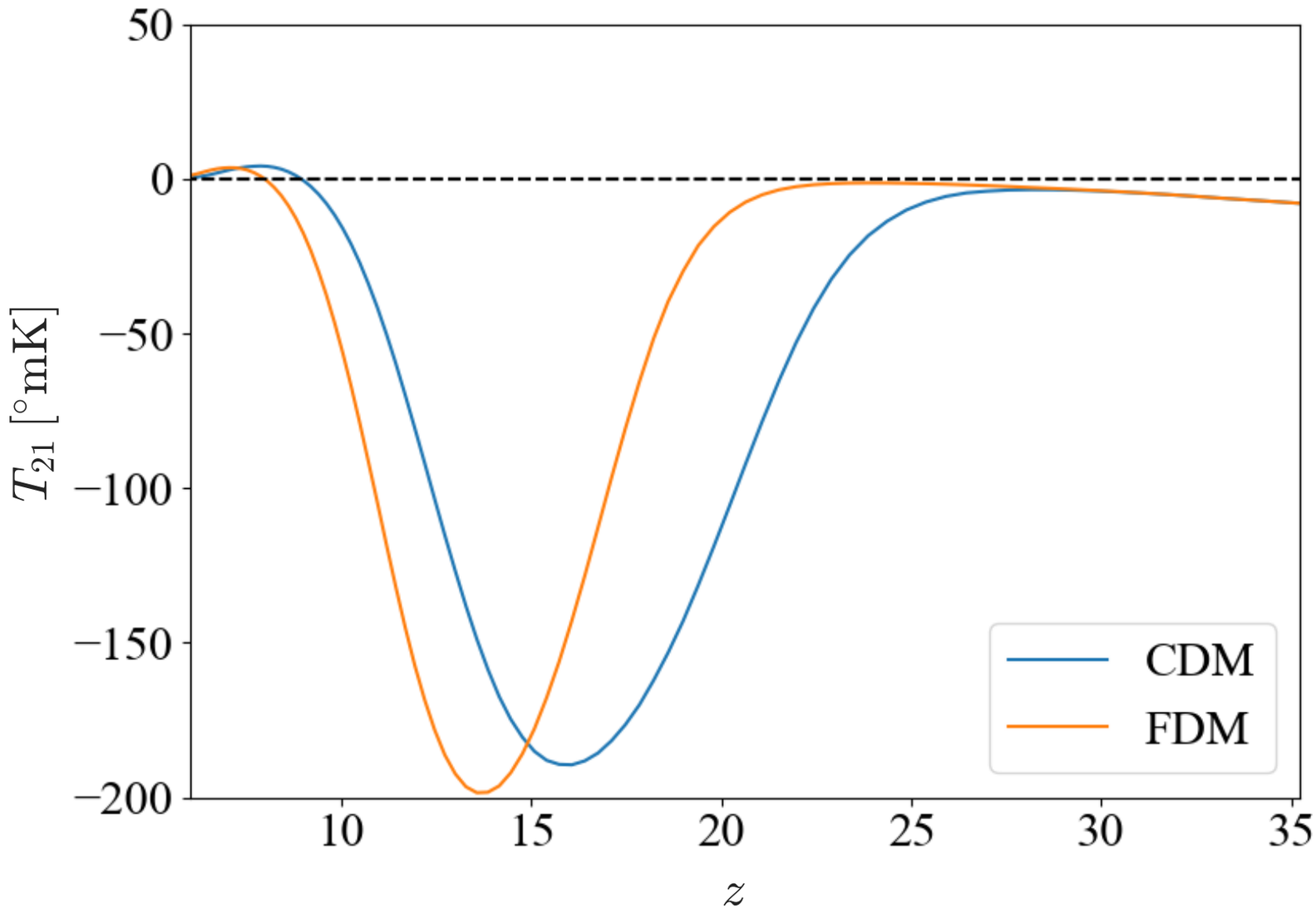

FDM vs. CDM: 21cm Global Signal - Ambiguous?

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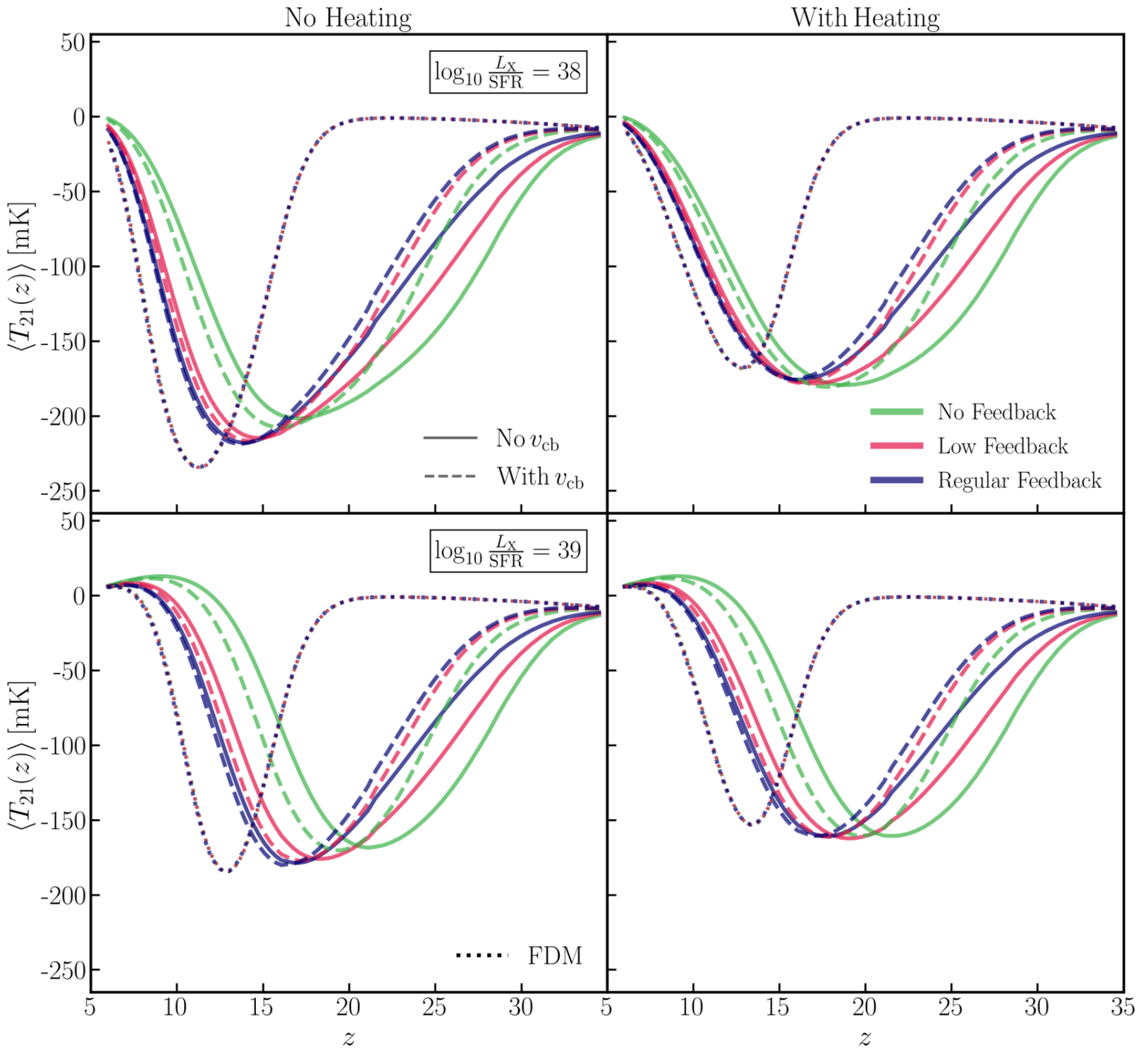

FDM vs. CDM: 21cm Fluctuations

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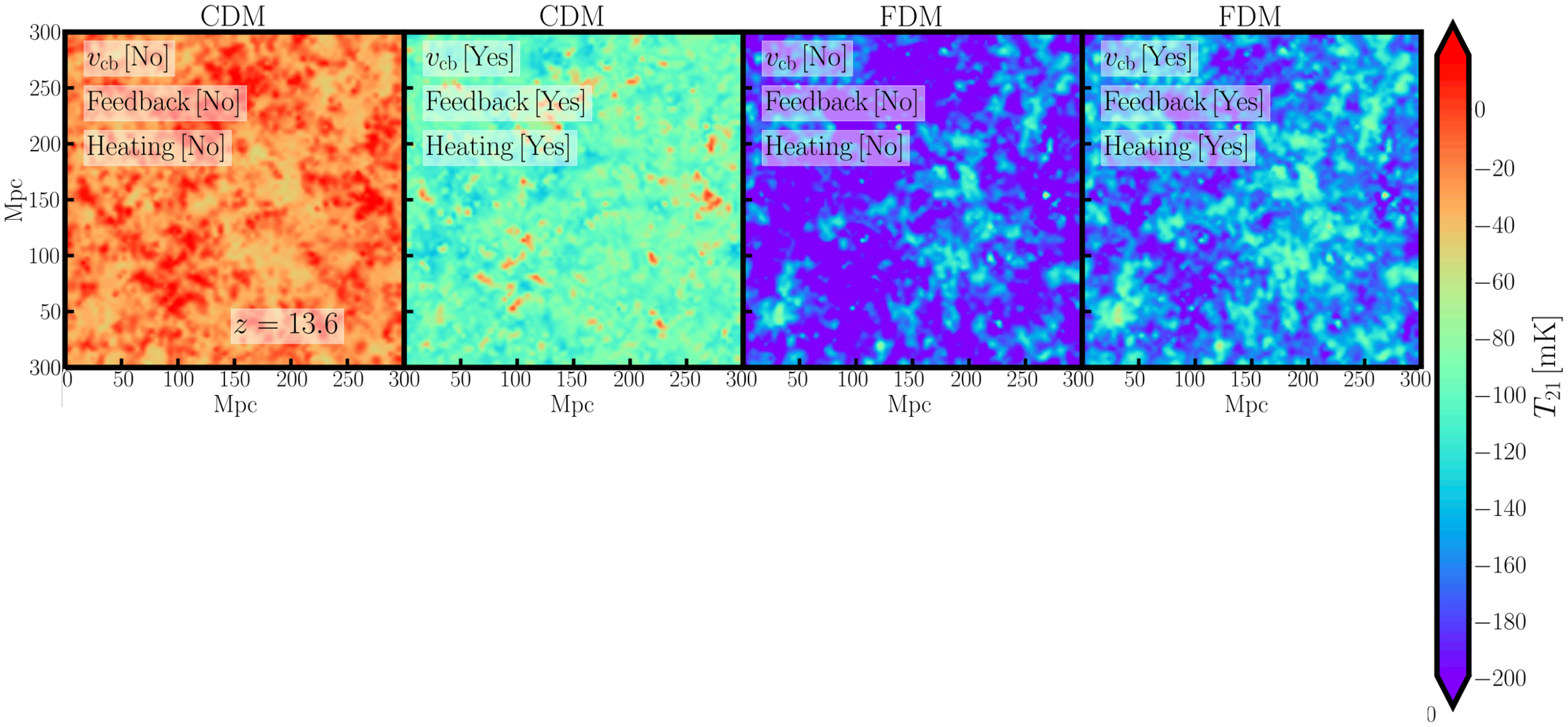

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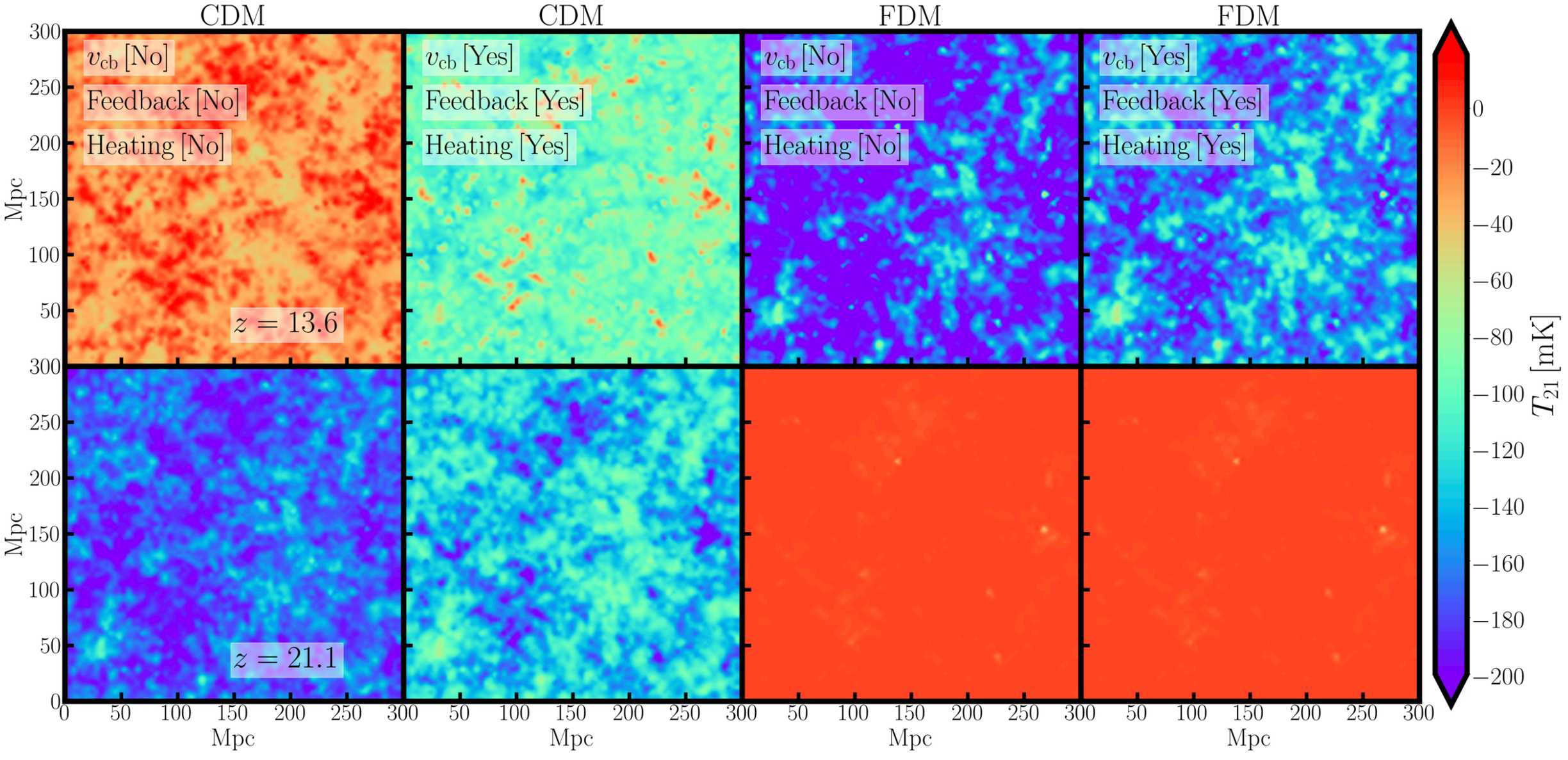

FDM vs. CDM: Detectability Forecast

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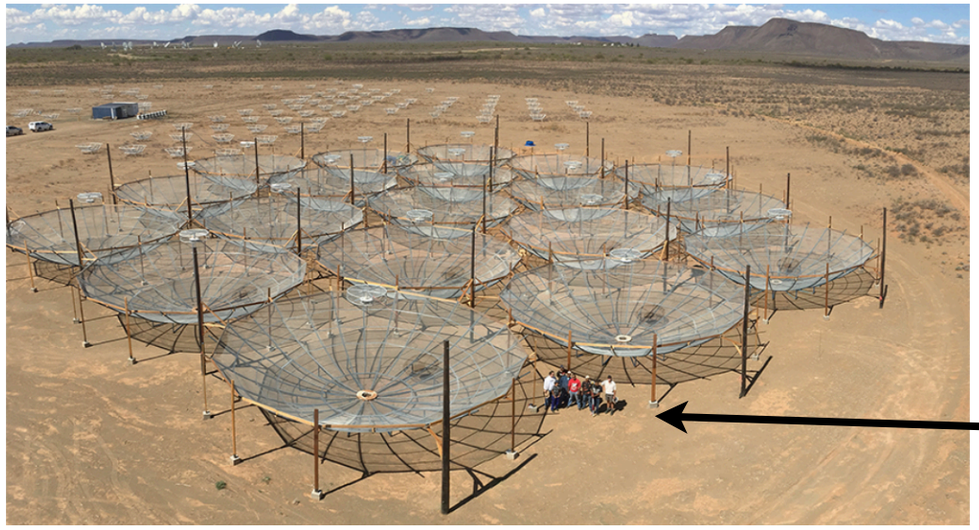
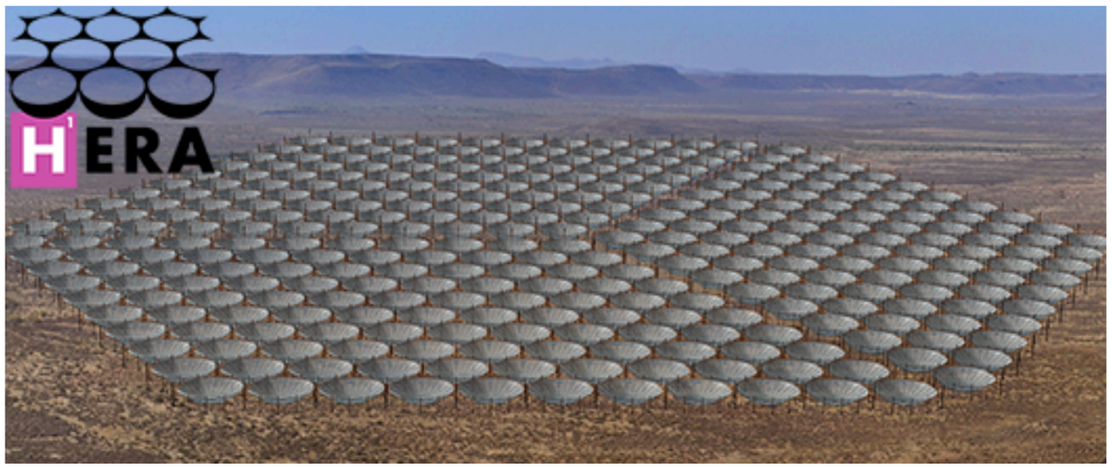
The HERA Experiment

DeBoer et al. (arXiv: 1606.07473)





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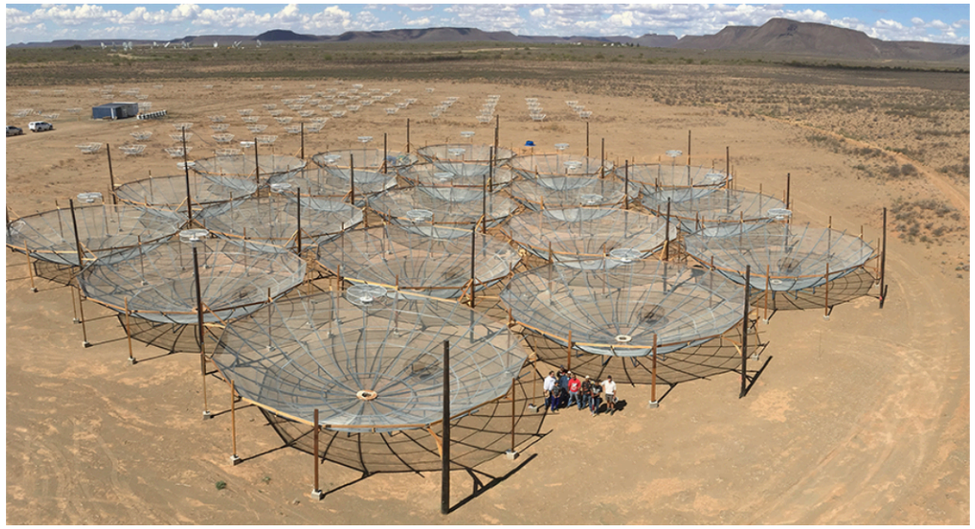
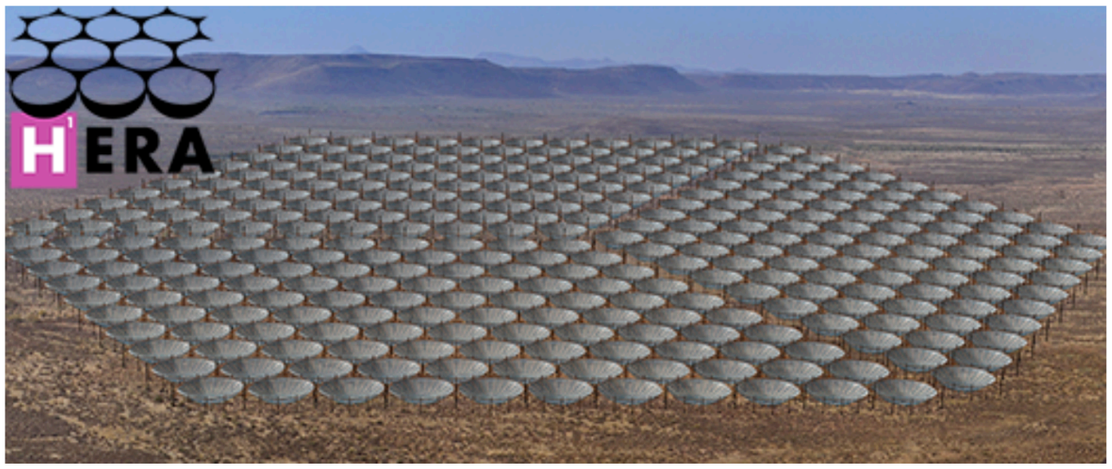
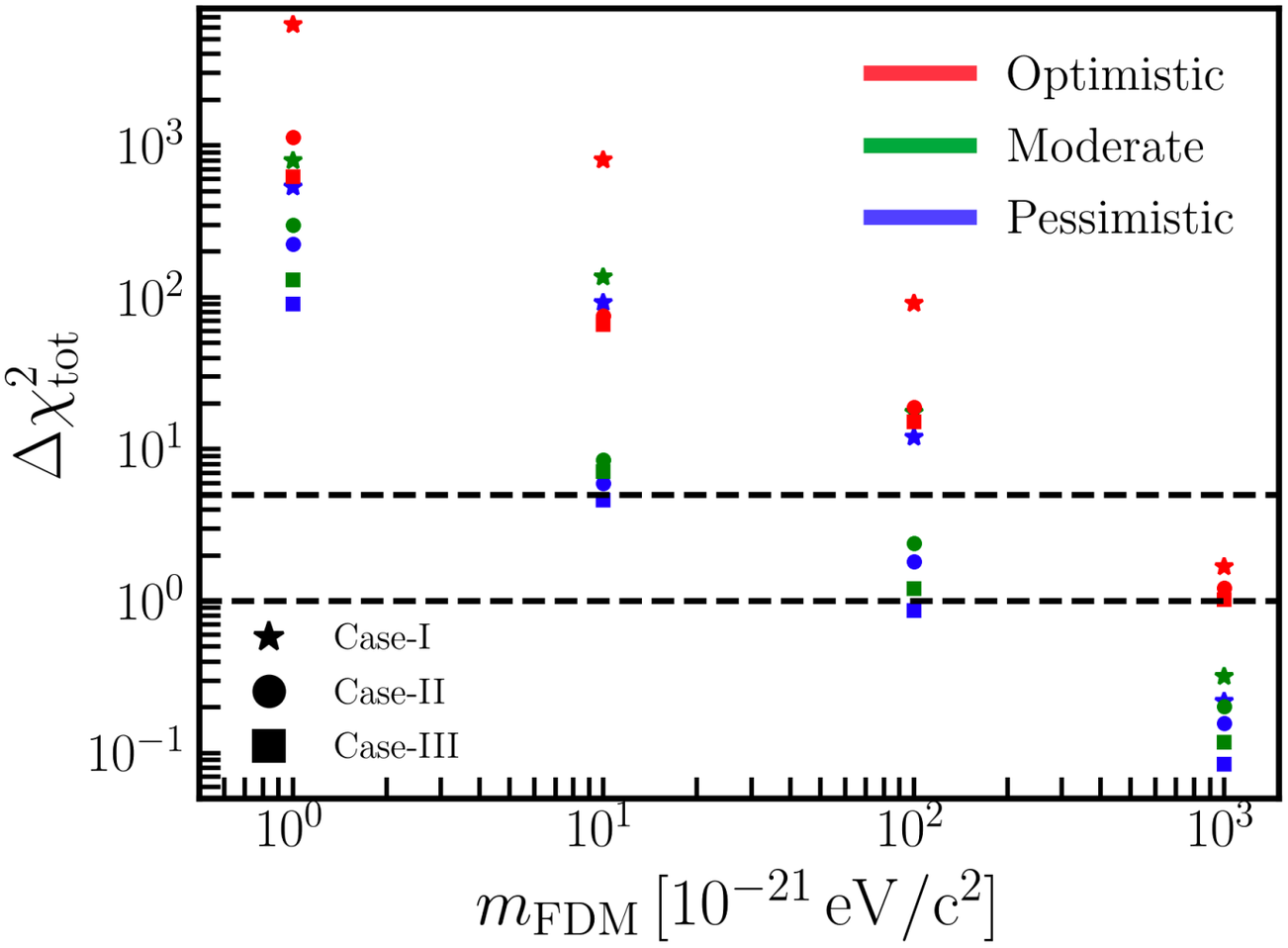


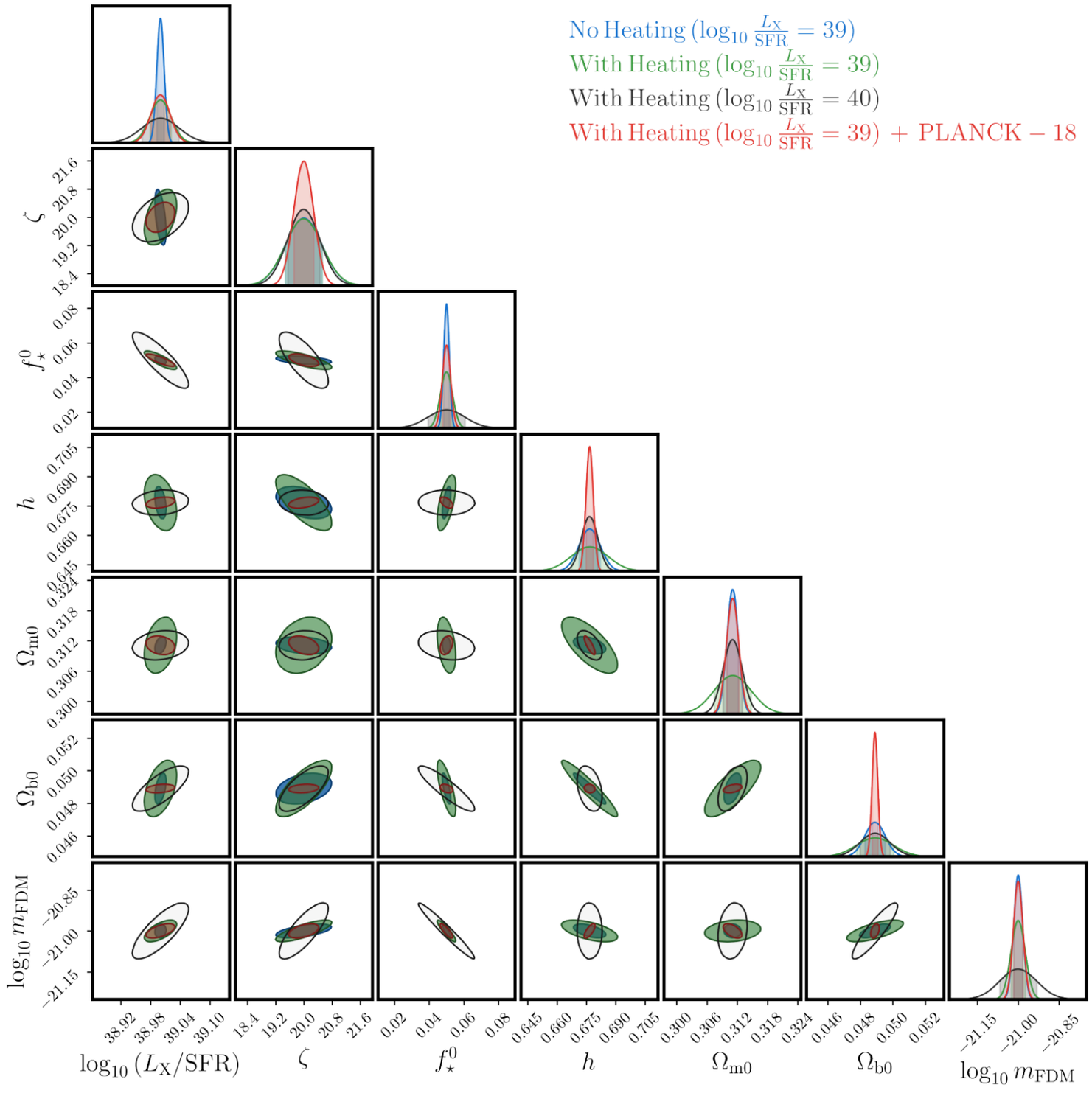


Signal to Noise

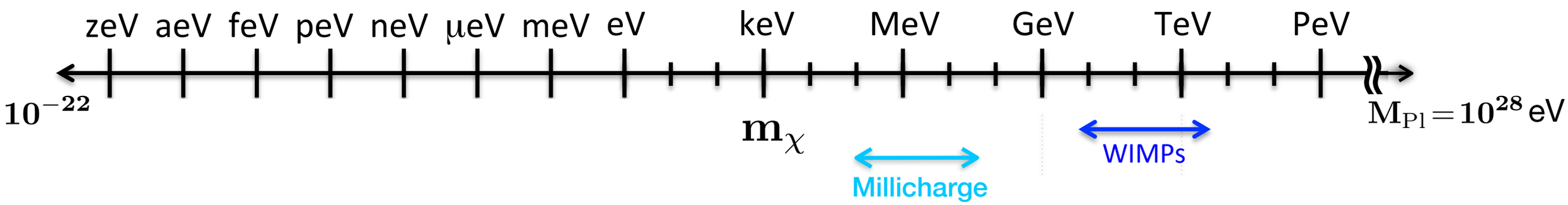


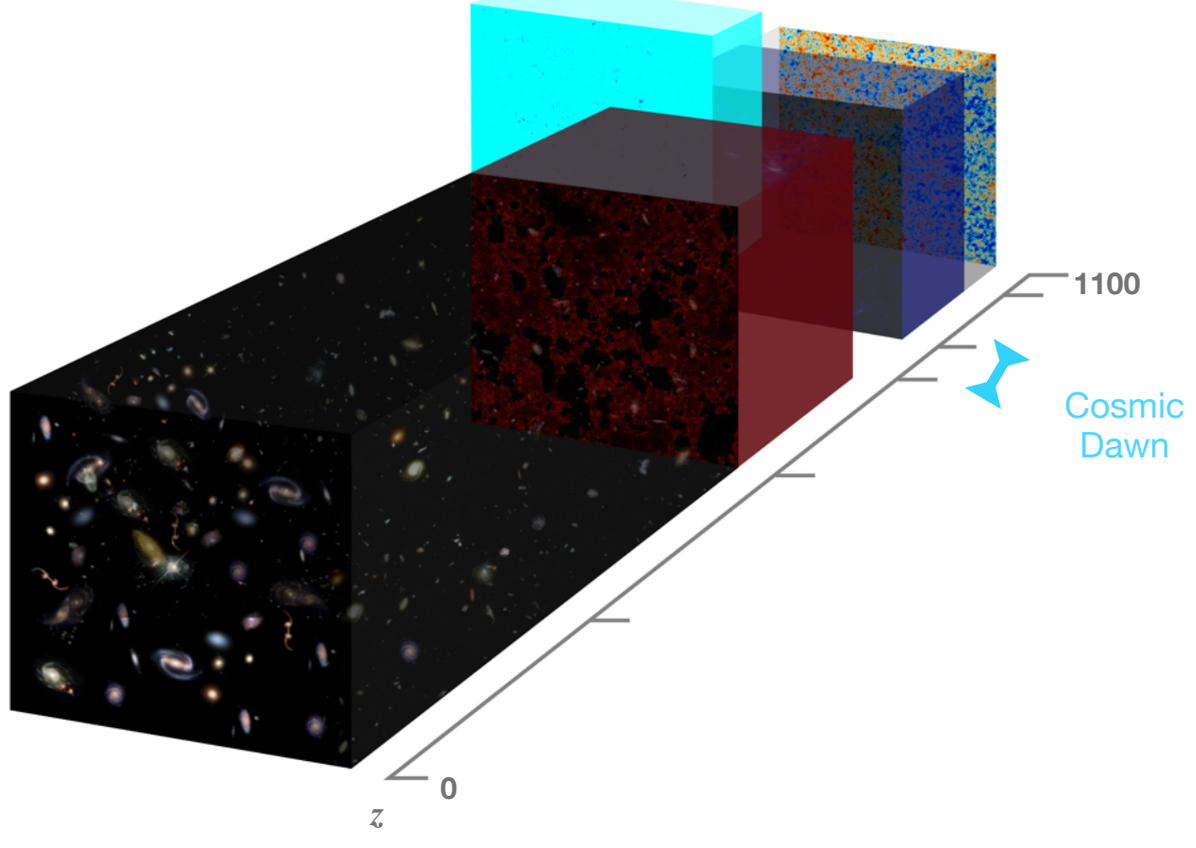
FDM: Cosmo/Astro Parameter Degeneracies

(Sarkar, Flitter and EDK, arXiv:2201.03355)



Takeaway: Cosmic Dawn 21cm a unique DM probe!





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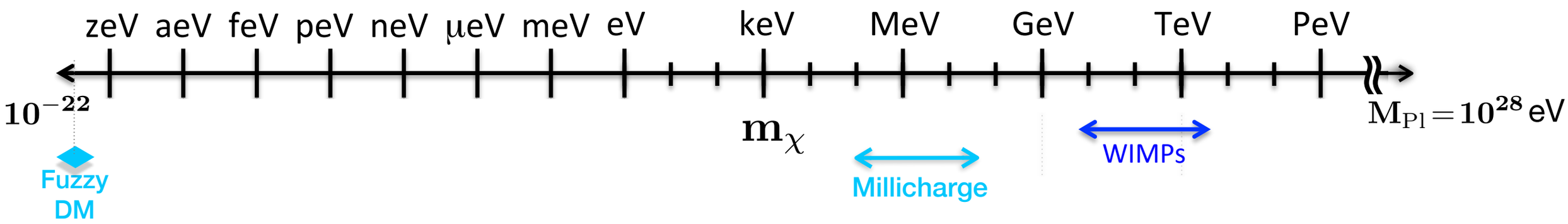

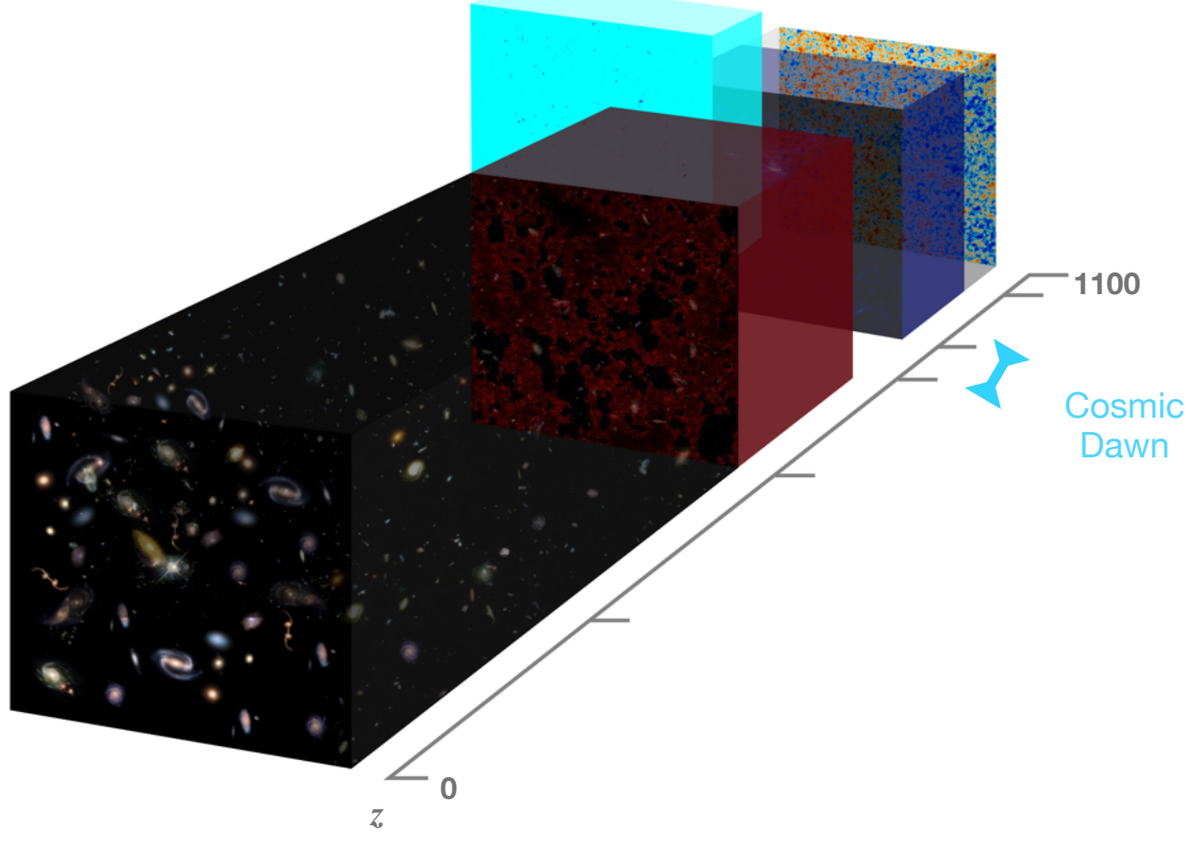

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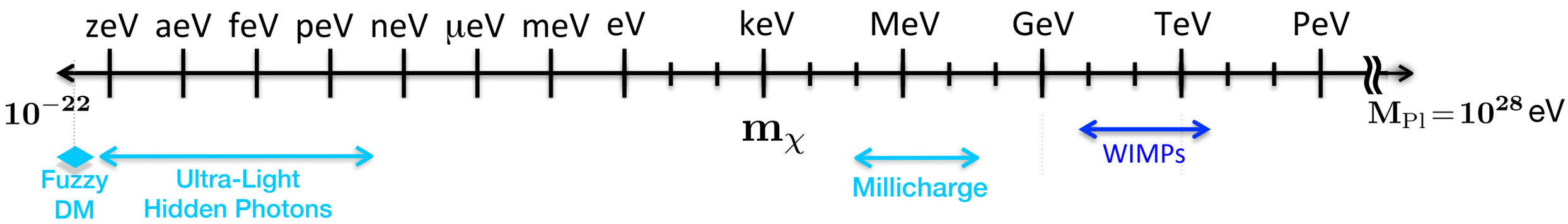
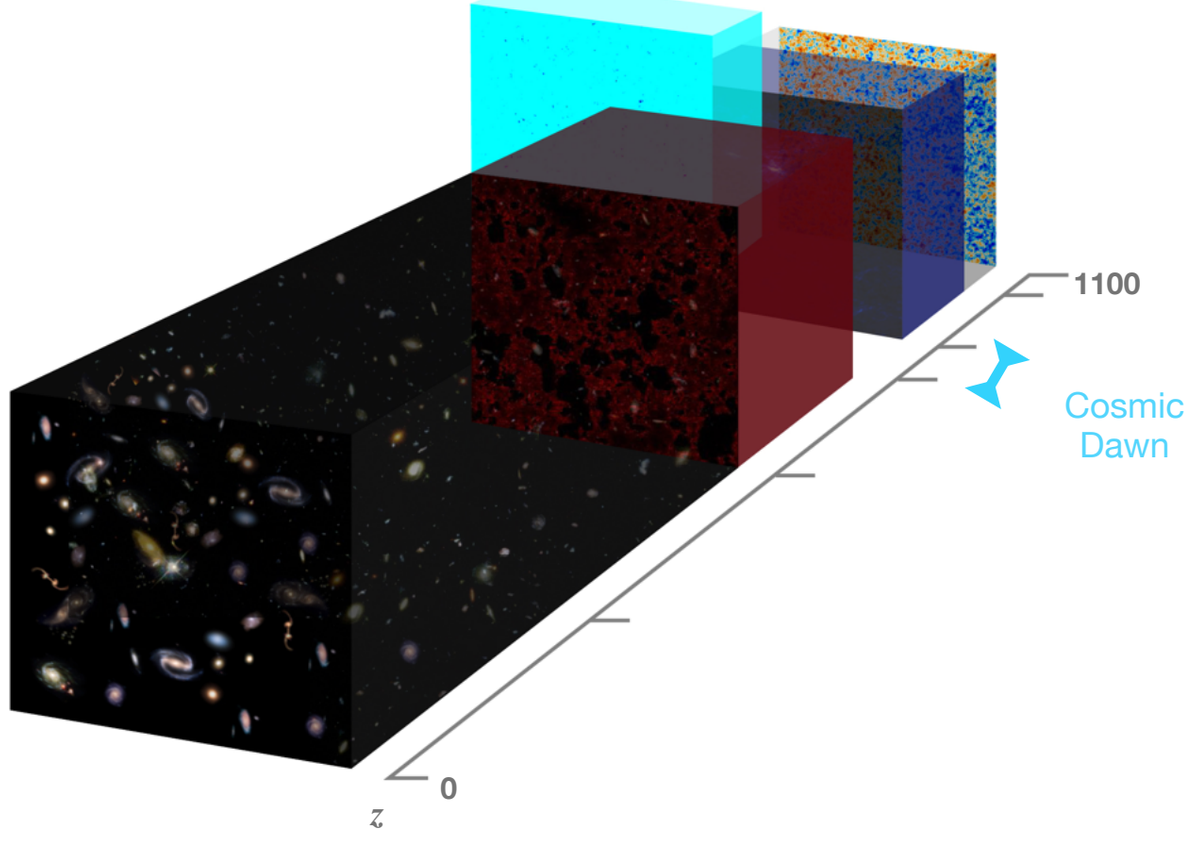
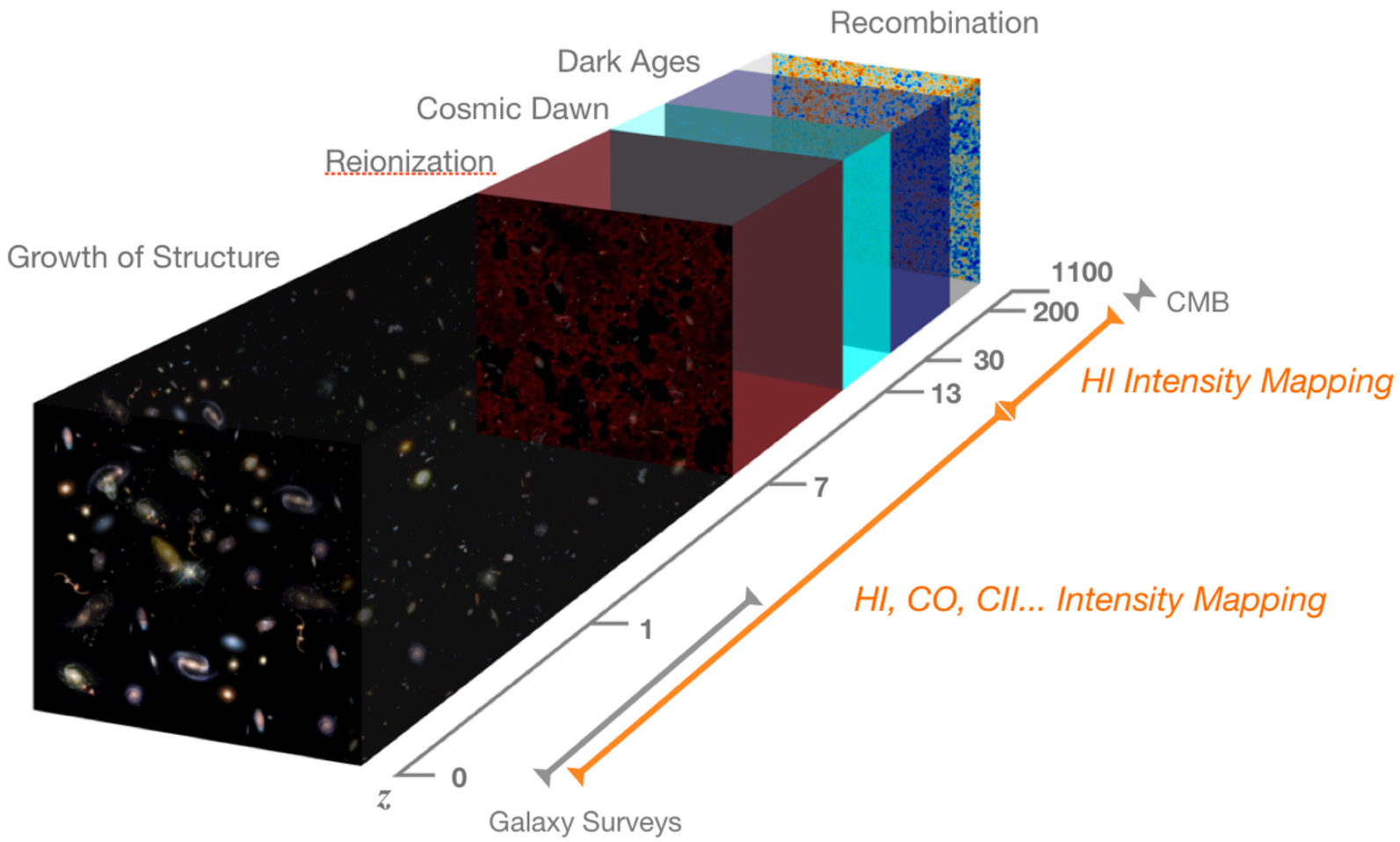




Thank You!

Ely D. Kovetz
Ben-Gurion University



MPIK Colloquium
Feb 23rd, 2022