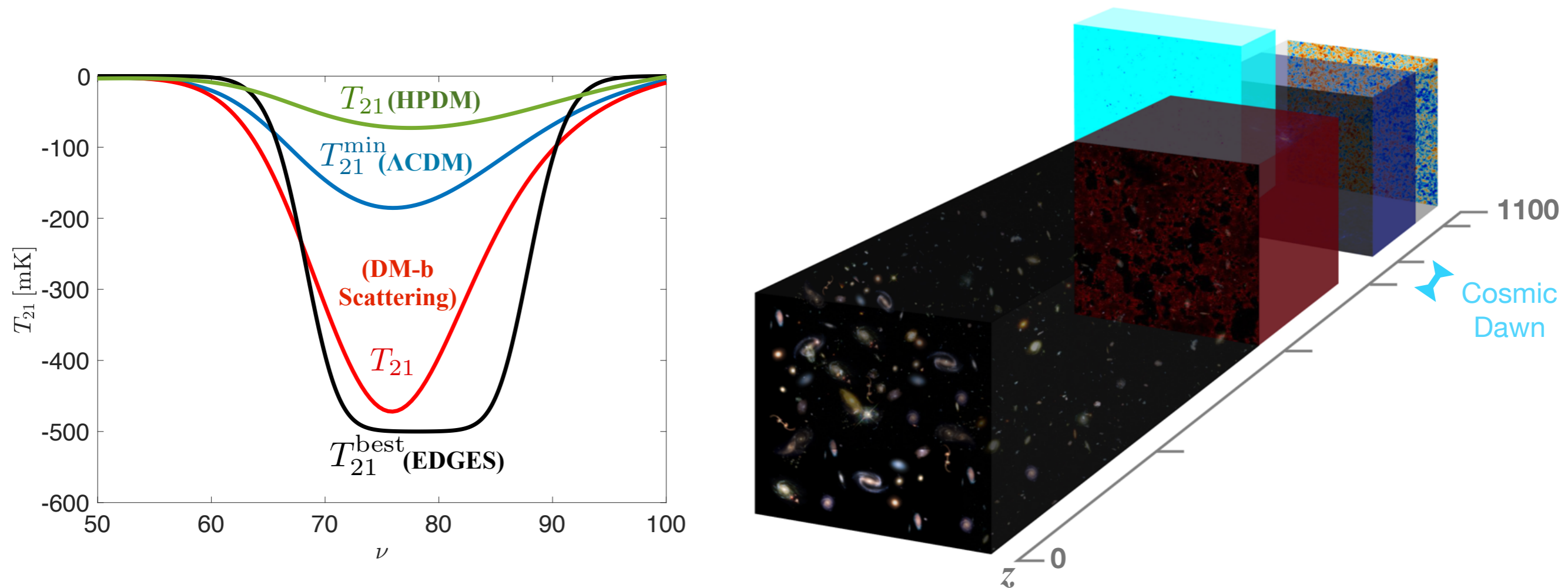


Dark Matter in Light of the 21cm EDGES Signal

Ely D. Kovetz
Ben-Gurion University



Based on arXiv:1509.00029, arXiv:1807.01139, arXiv:1808.00001, arXiv:1809.01139, arXiv:1903.09154:

Muñoz, **EDK** and Ali-Haïmoud, “Heating of Baryons due to Scattering with Dark Matter during the Dark Ages”

EDK, Poulin, Gluscevic, Boddy, Barkana and Kamionkowski, “Tighter Limits on Dark Matter Explanations of the Anomalous EDGES 21cm Signal”

Boddy, Gluscevic, Poulin, **EDK**, Kamionkowski and Barkana, “A Critical Assessment of CMB Limits on Dark Matter-Baryon Scattering”

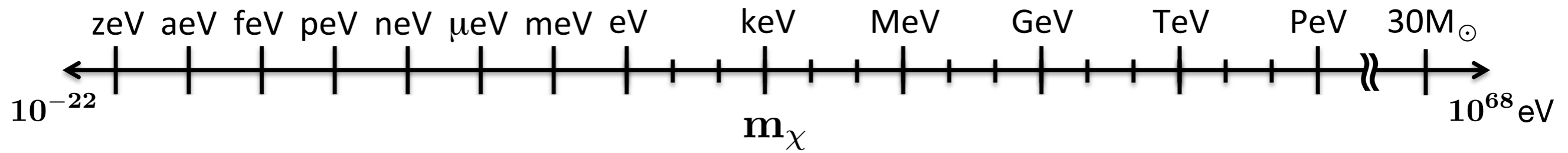
Creque-Sarbinowski, Ji, **EDK**, Kamionkowski, “Direct Millicharged Dark Matter Cannot Explain EDGES”

(**EDK**, Cholis and Kaplan, “Bounds on Ultra-Light Hidden-Photon Dark Matter from 21cm at Cosmic Dawn”)

The Dark Matter Landscape

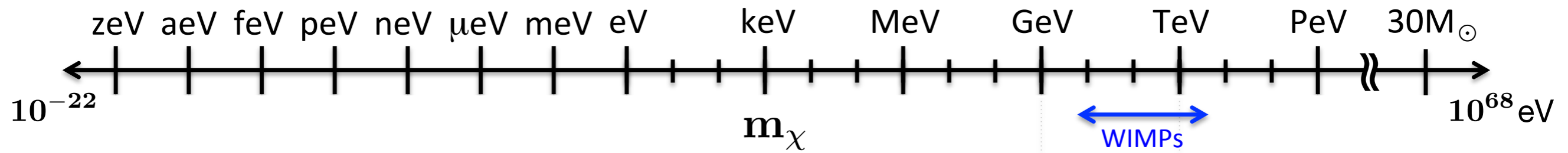
The Dark Matter Landscape

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



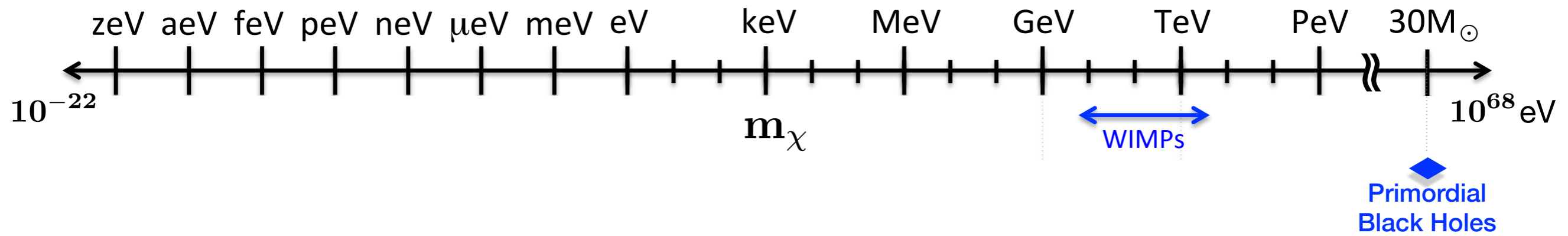
The Dark Matter Landscape

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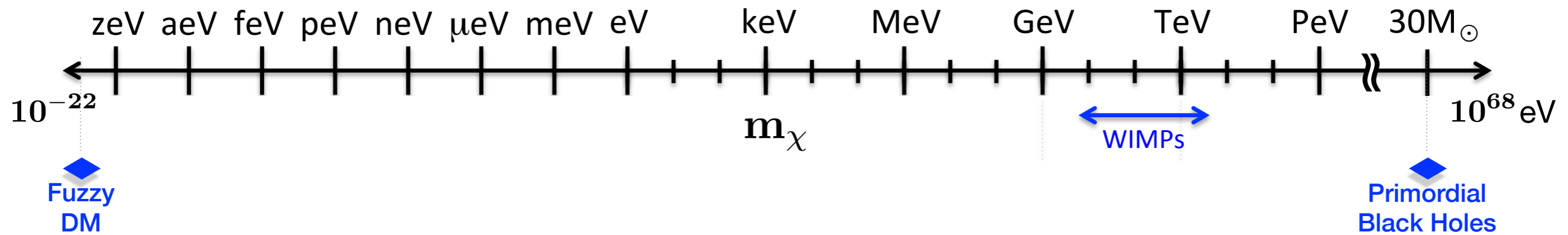
The Dark Matter Landscape

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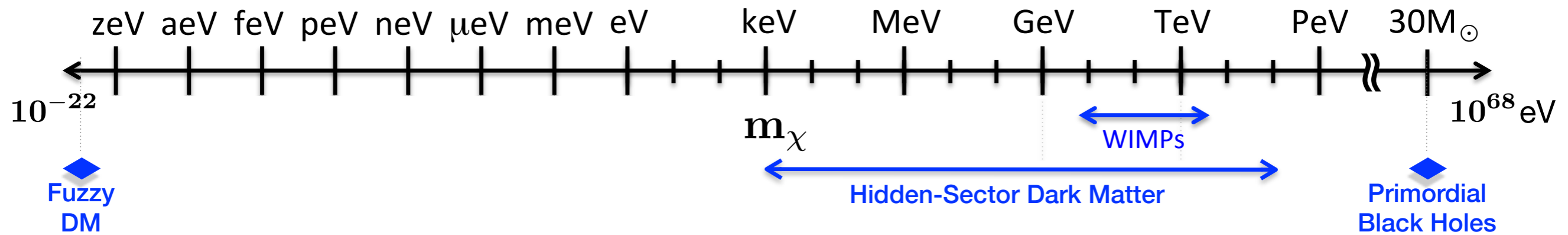
The Dark Matter Landscape

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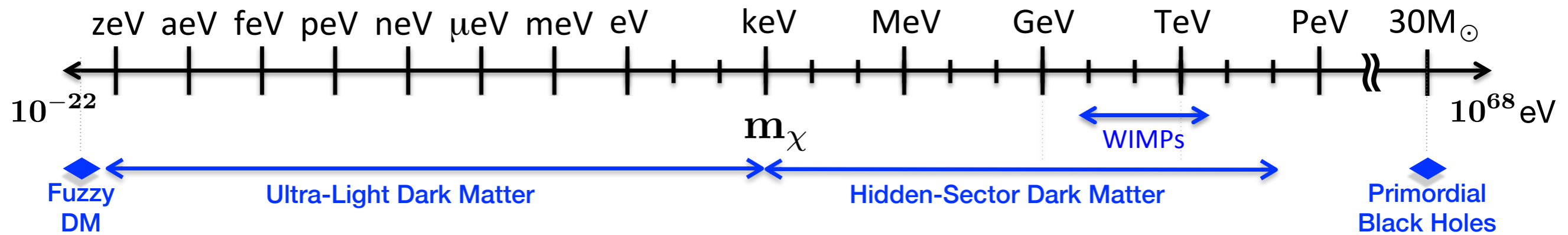
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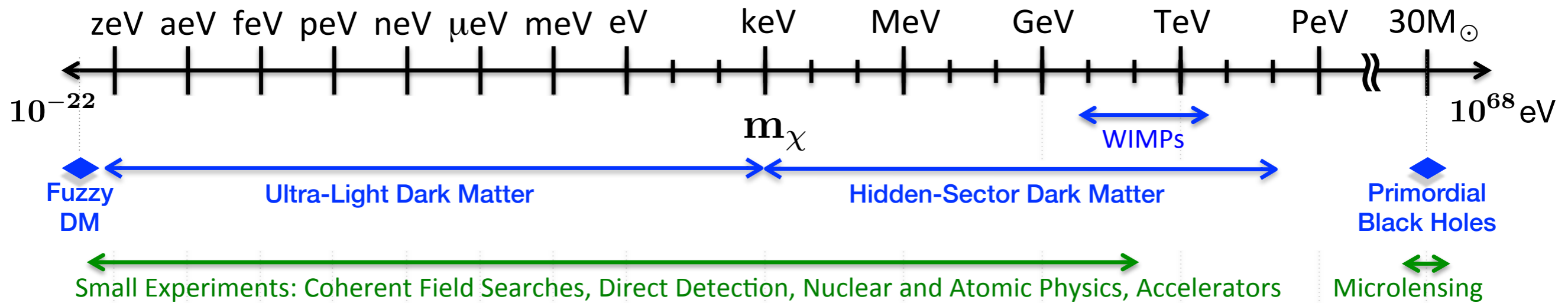
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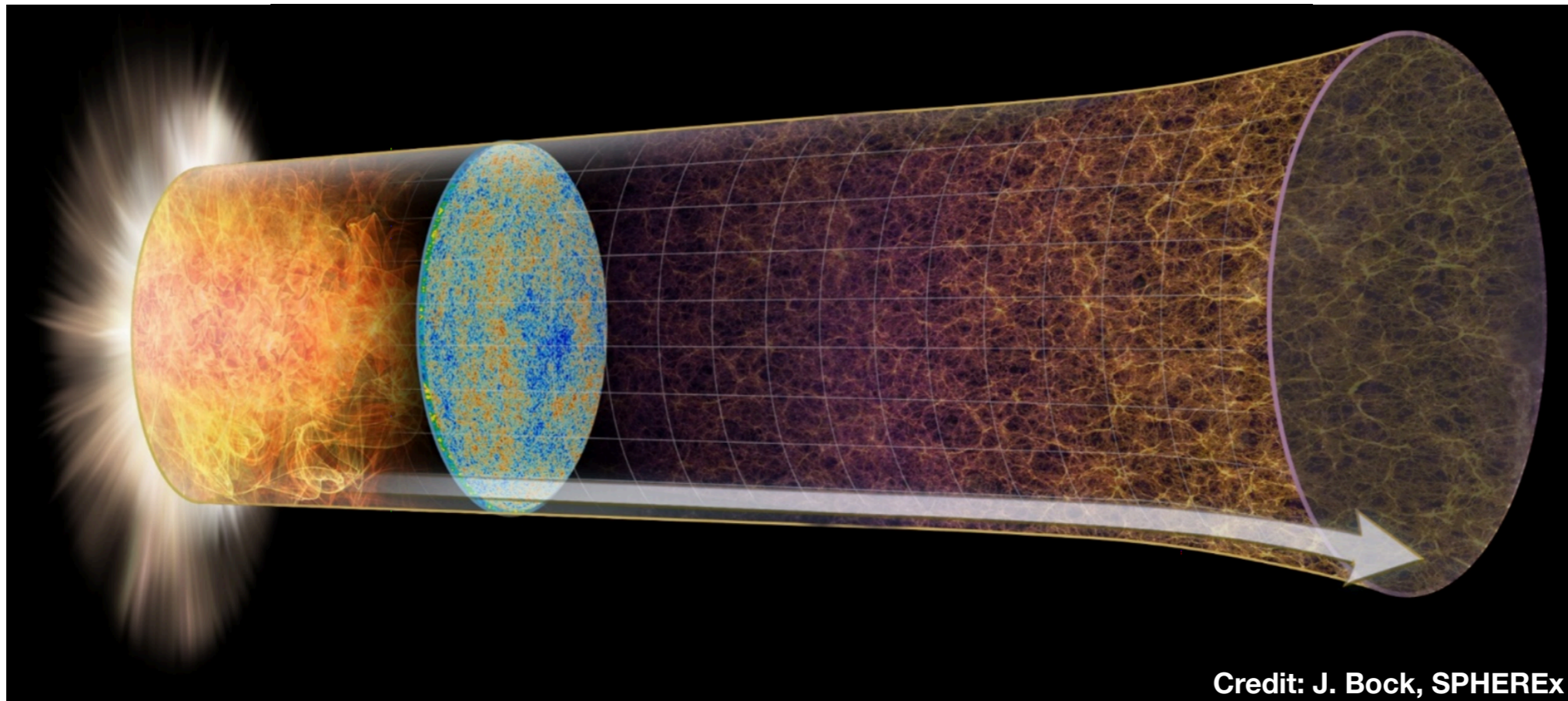
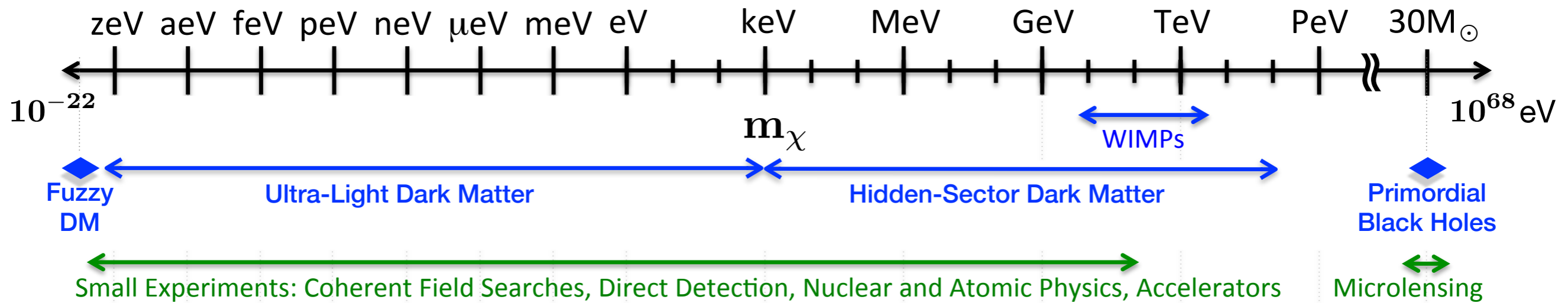
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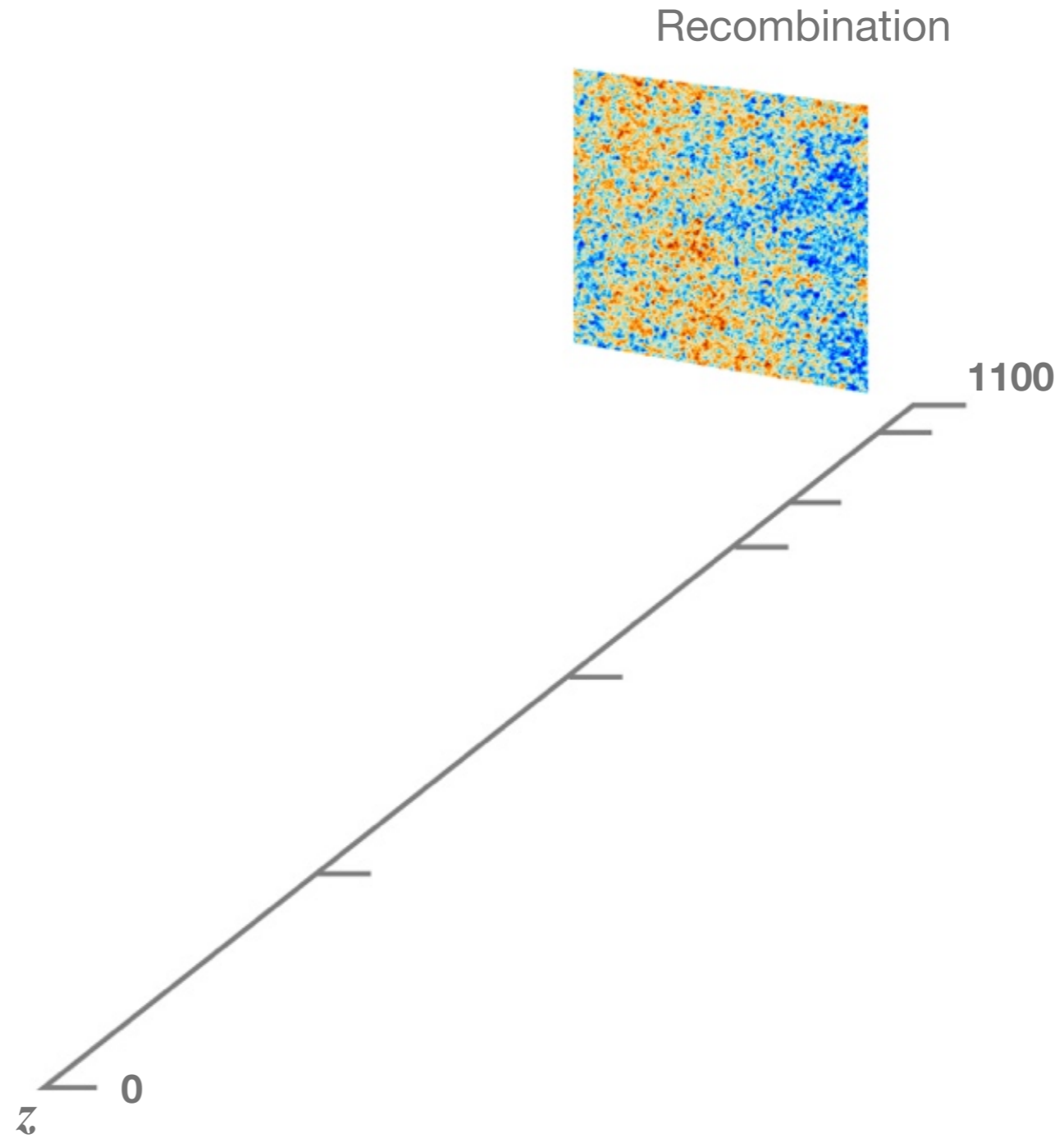
The Dark Matter Landscape

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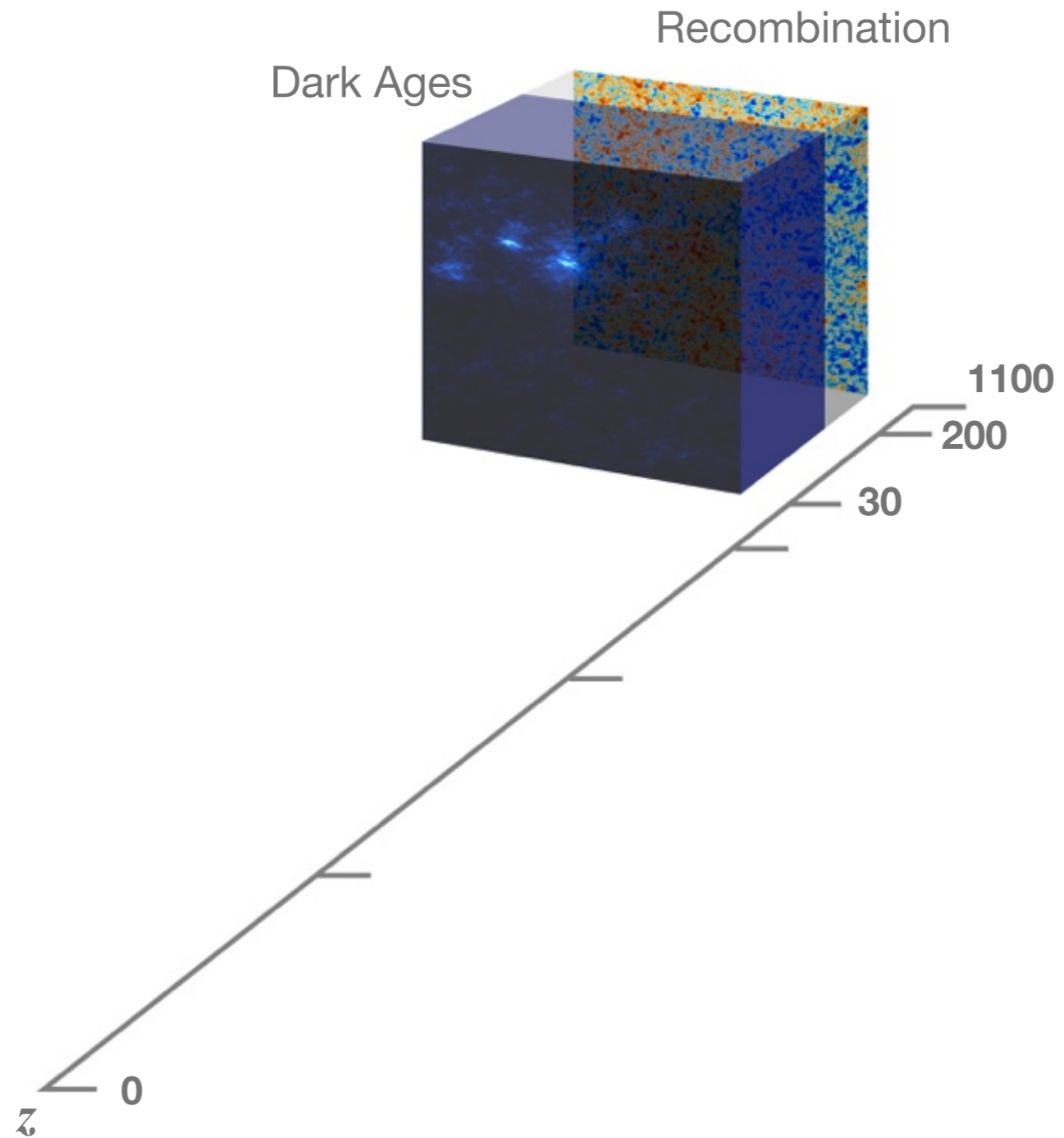


Credit: J. Bock, SPHEREx

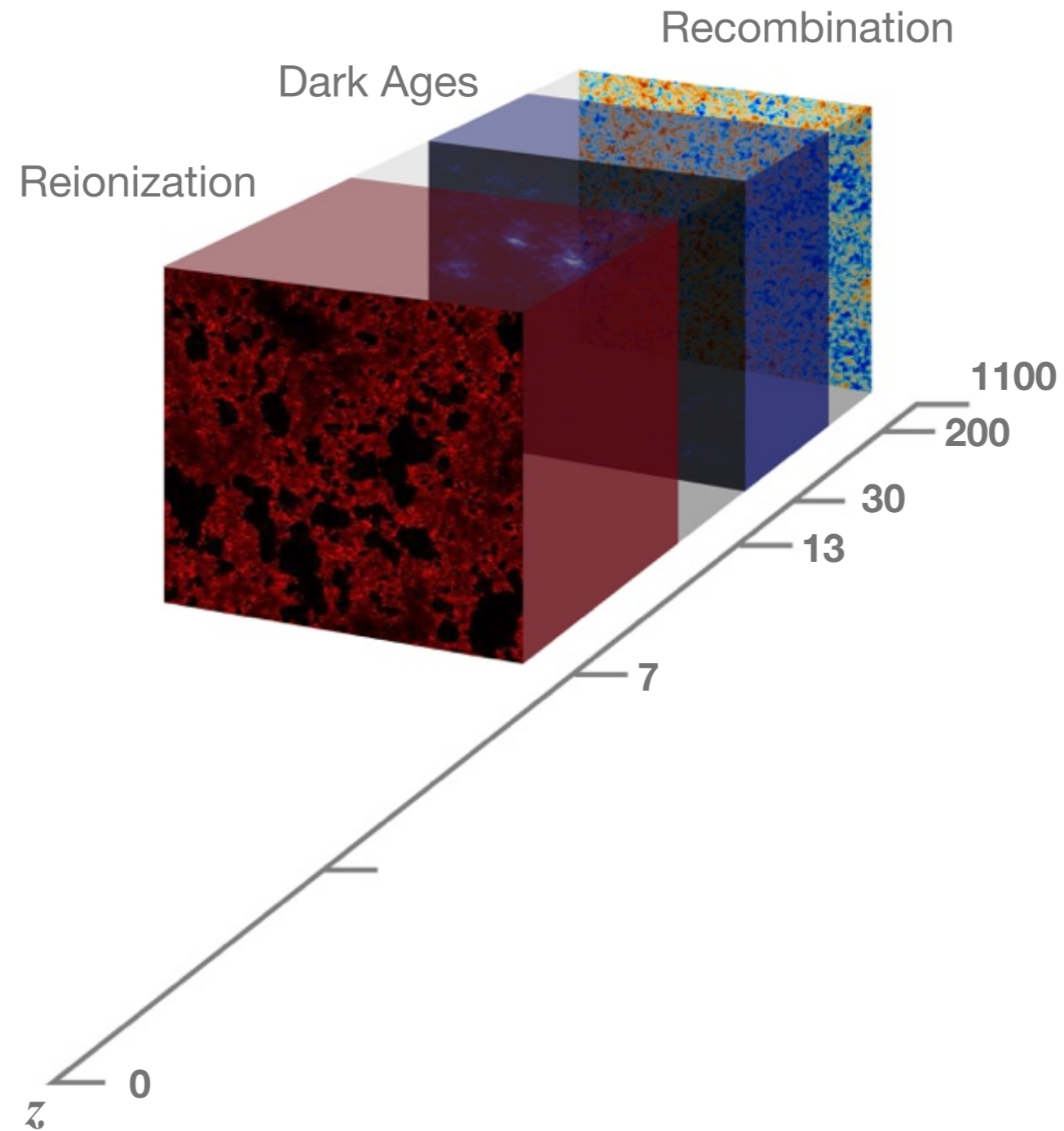
The Observable Universe: A Multi-Layer Detector



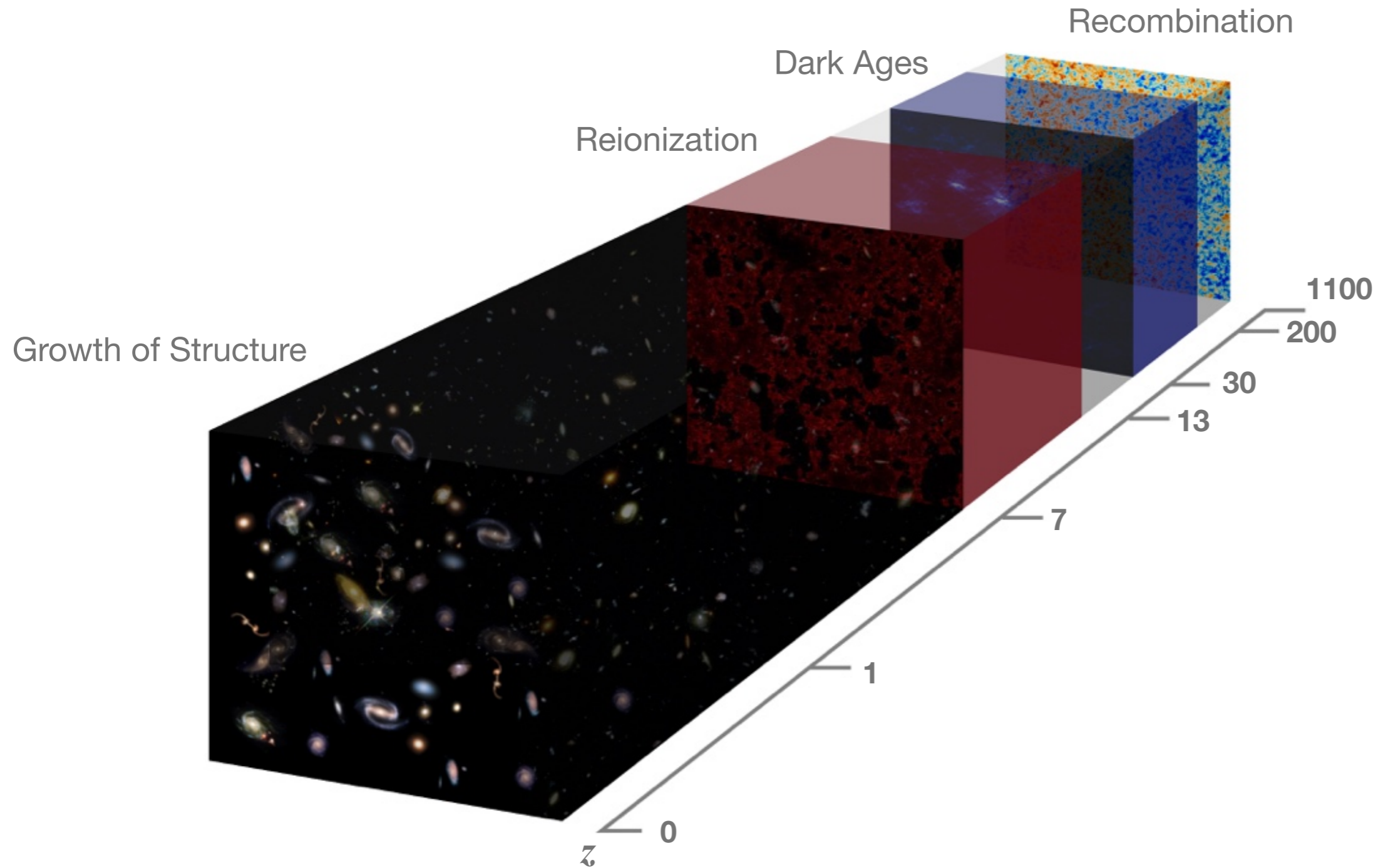
The Observable Universe: A Multi-Layer Detector



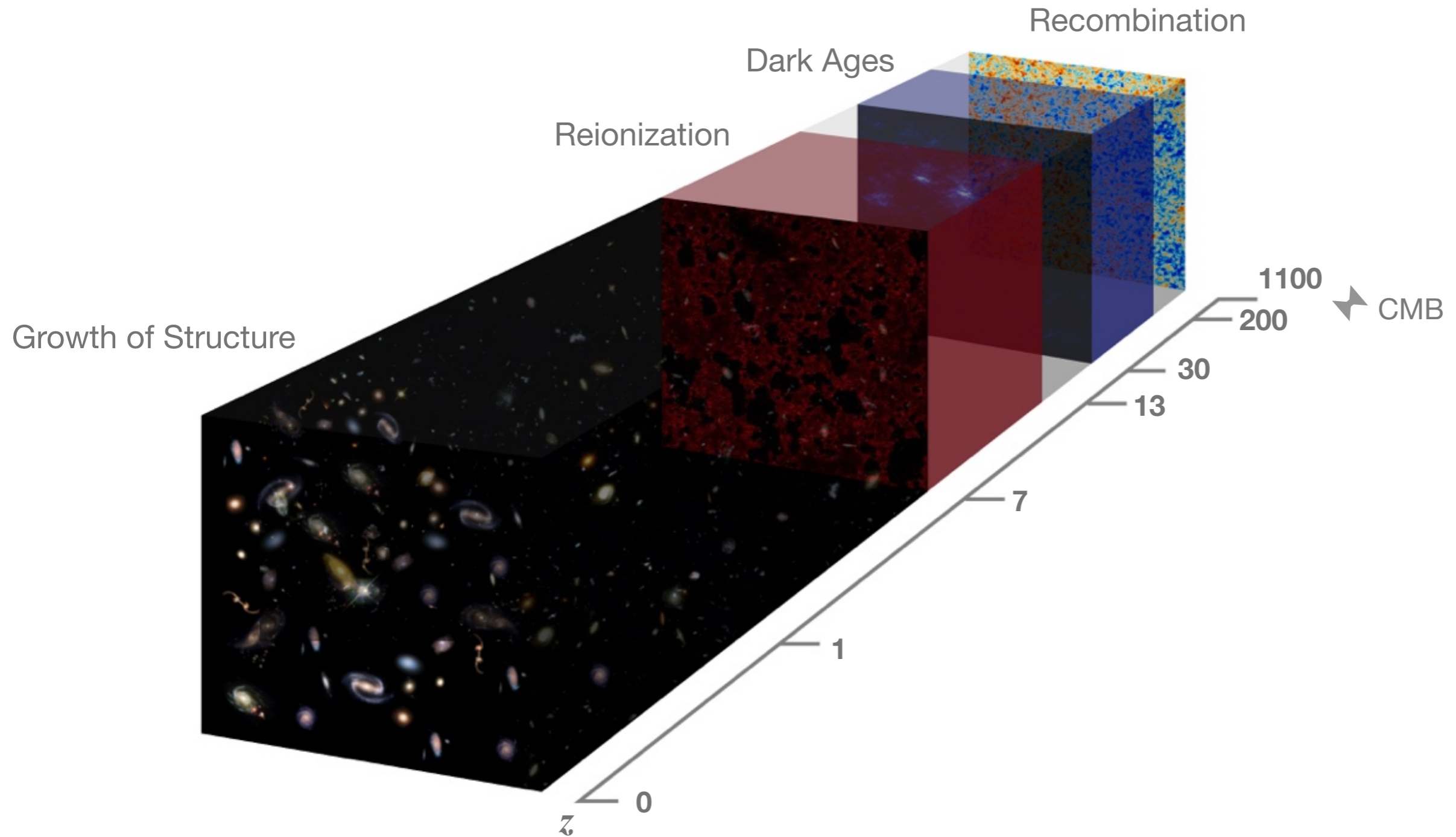
The Observable Universe: A Multi-Layer Detector



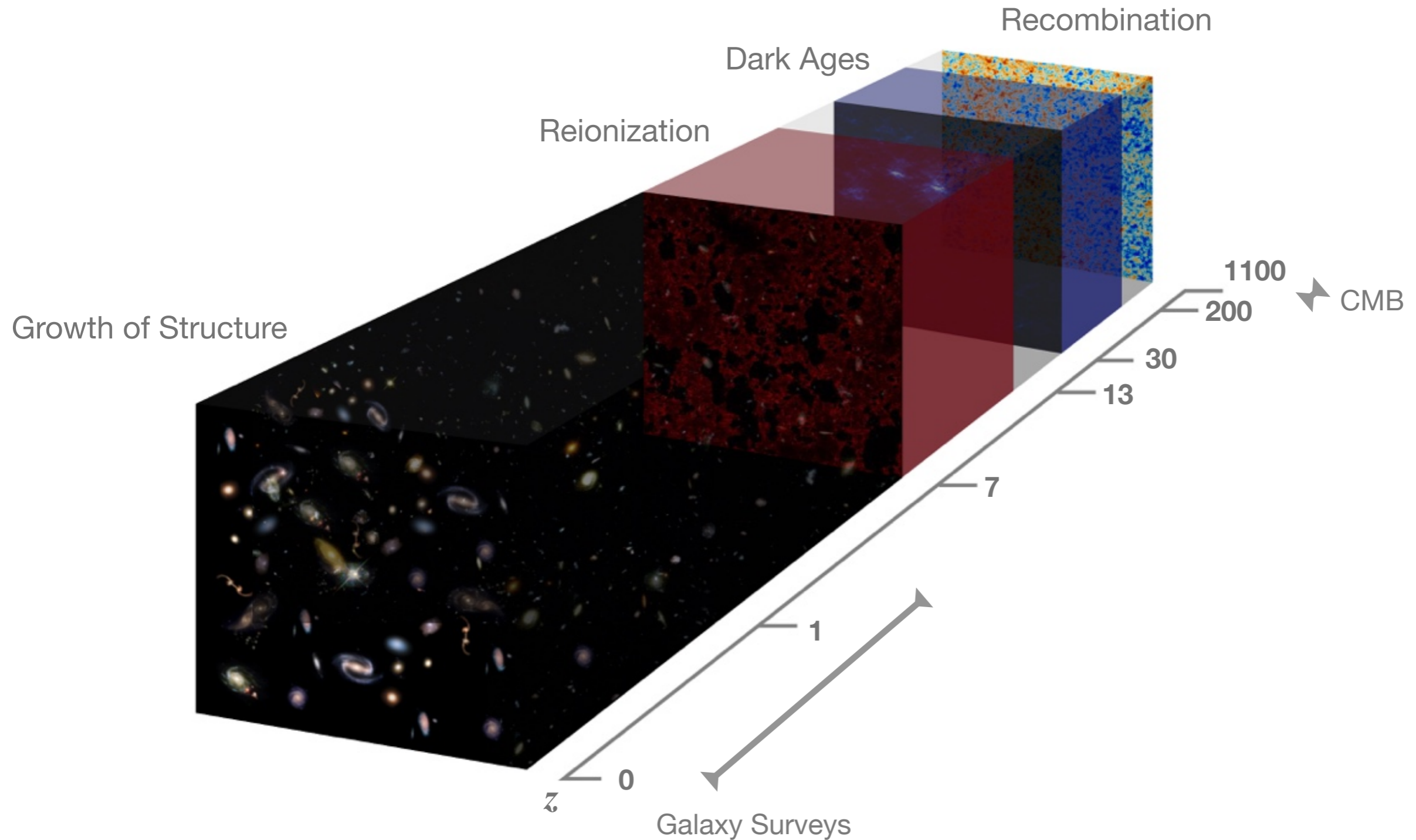
The Observable Universe: A Multi-Layer Detector



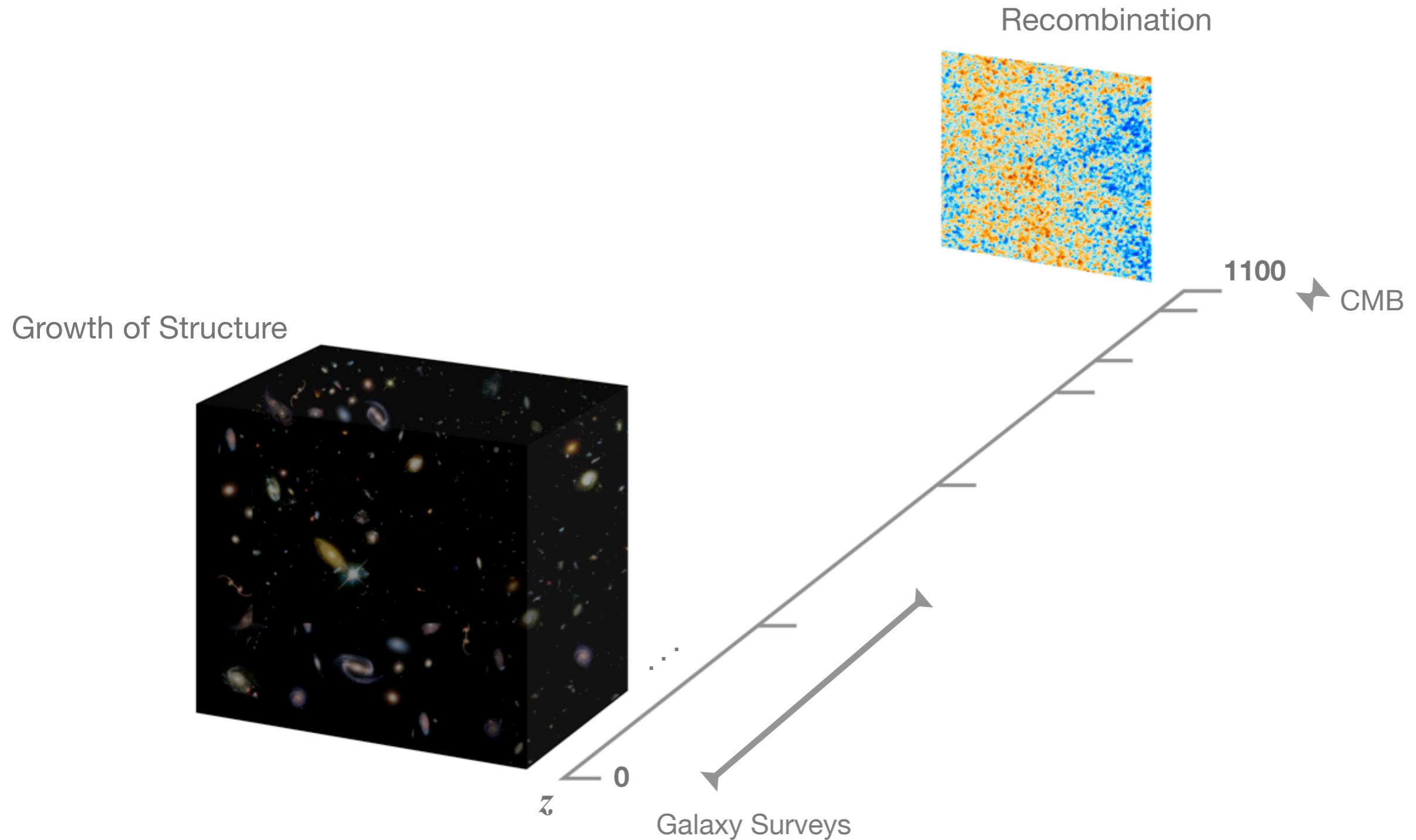
The Observable Universe: A Multi-Layer Detector



The Observable Universe: A Multi-Layer Detector

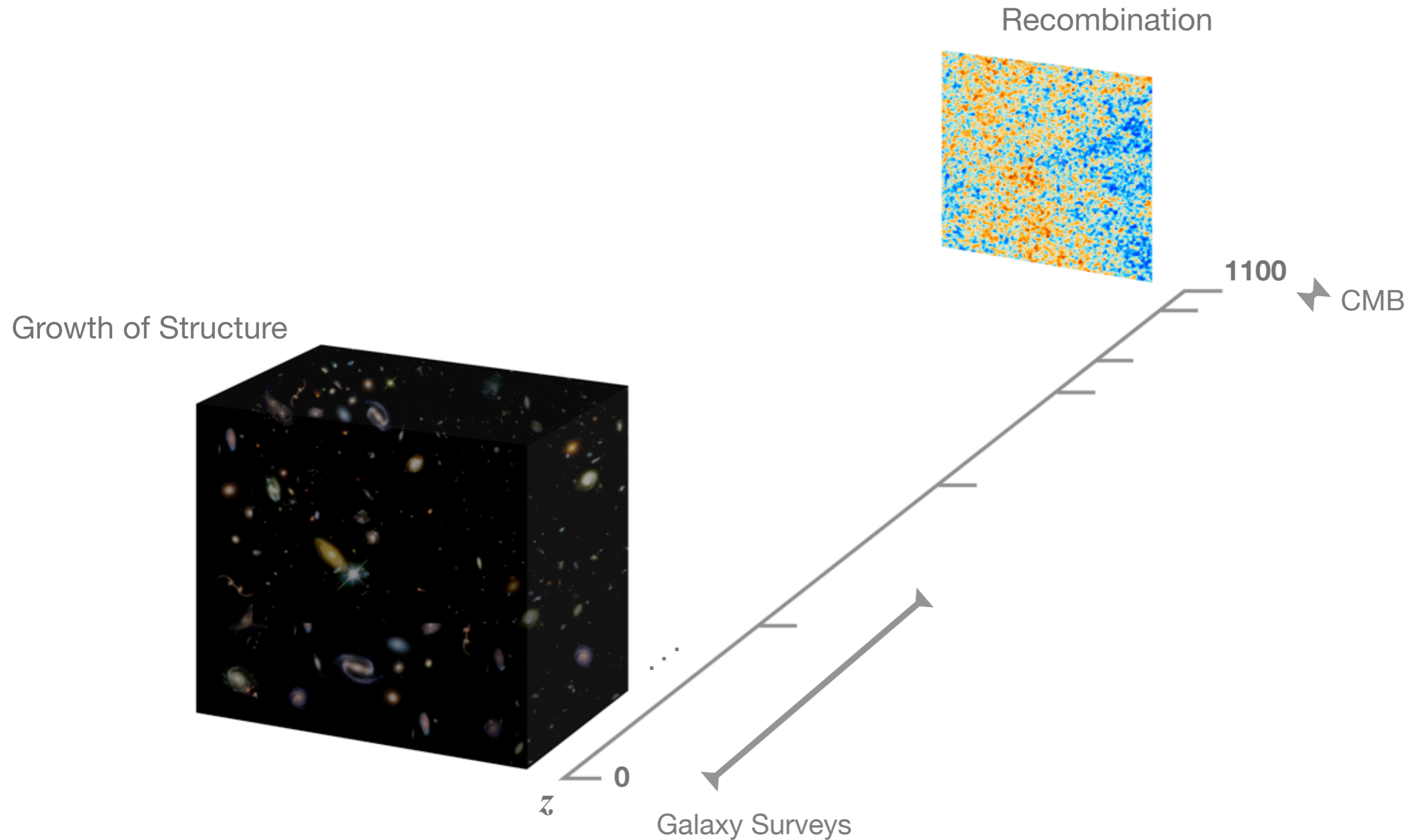


The Observable Universe: A Multi-Layer Detector



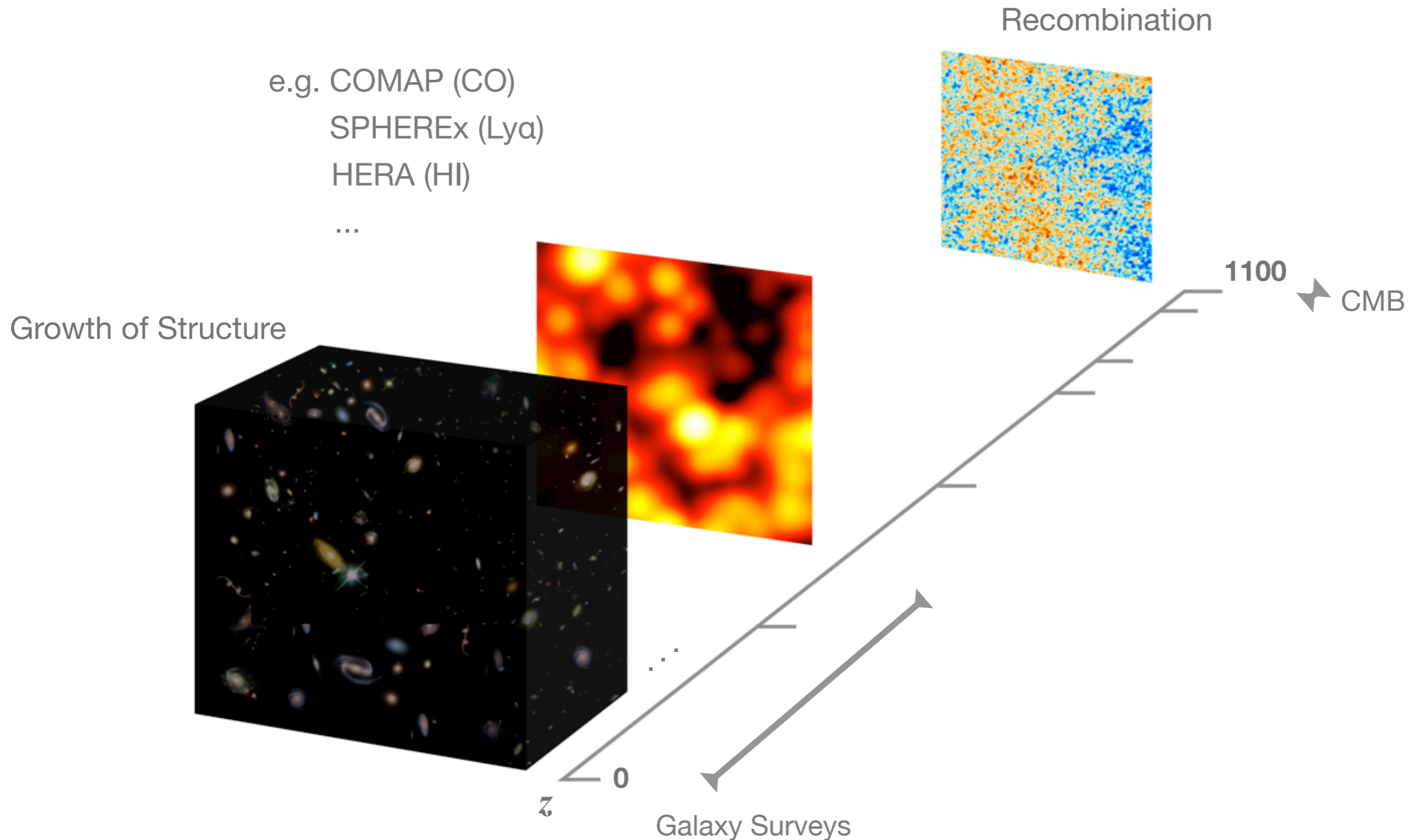
The Observable Universe: A Multi-Layer Detector

How do we access the rest?



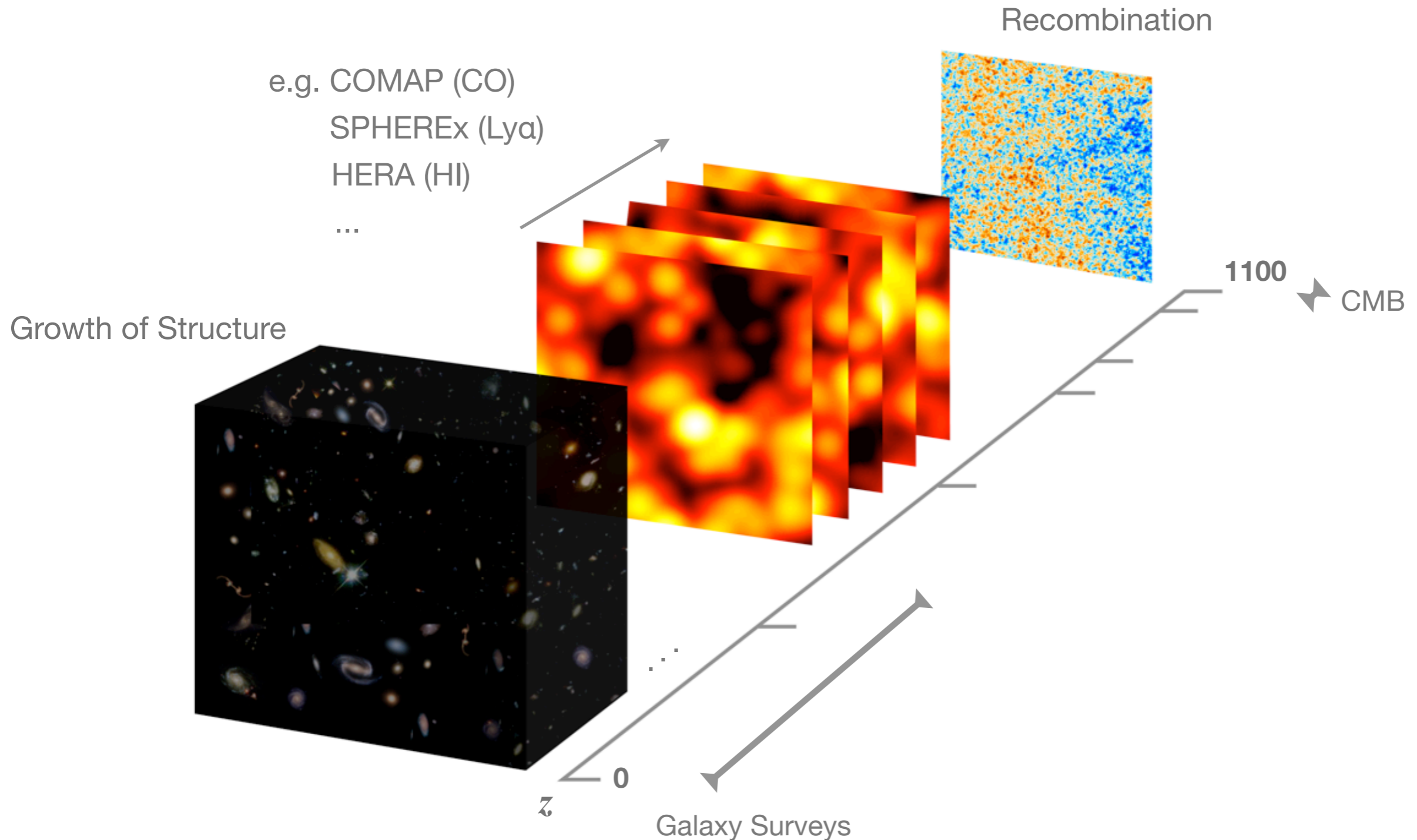
The Observable Universe: A Multi-Layer Detector

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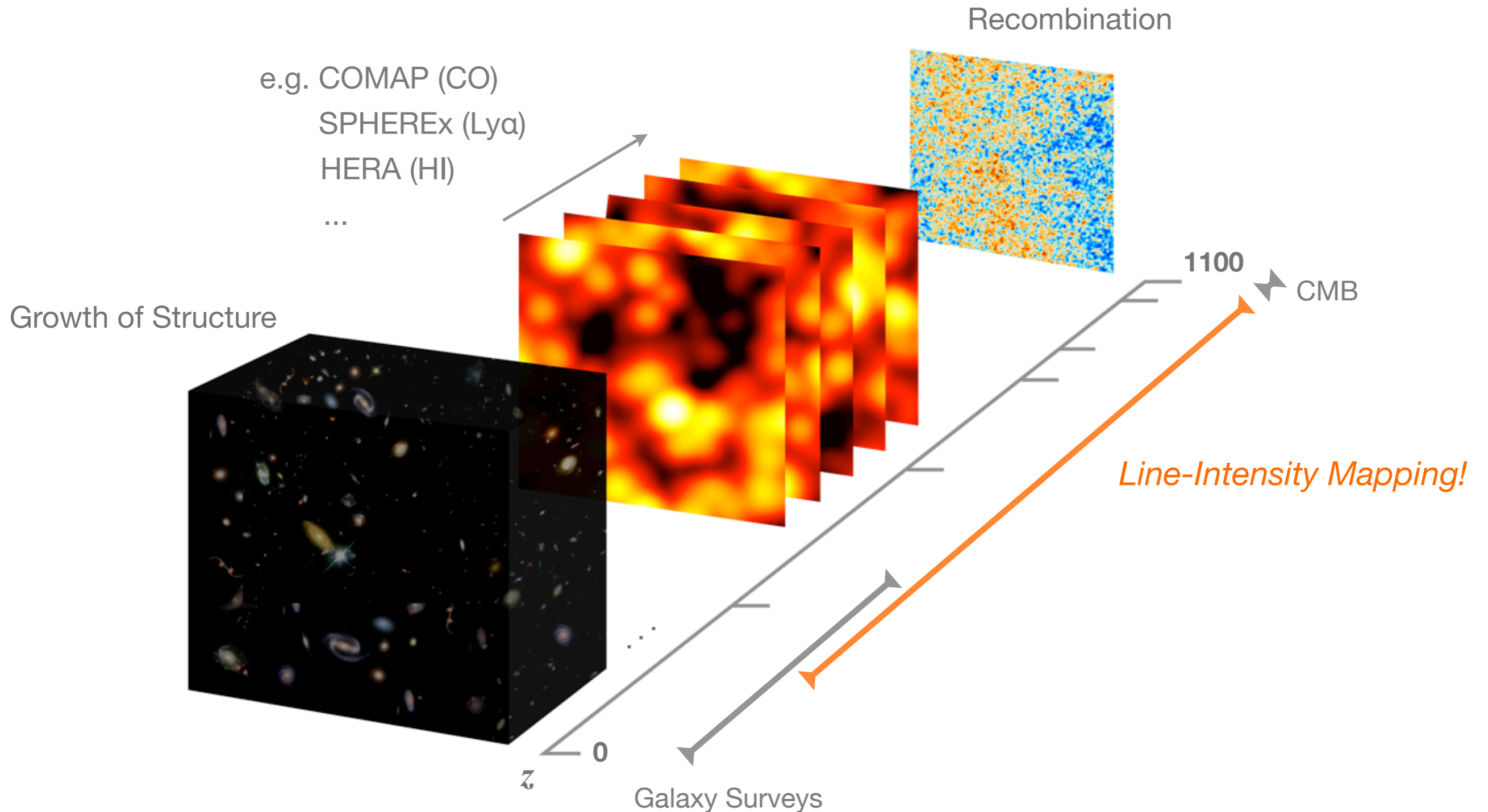
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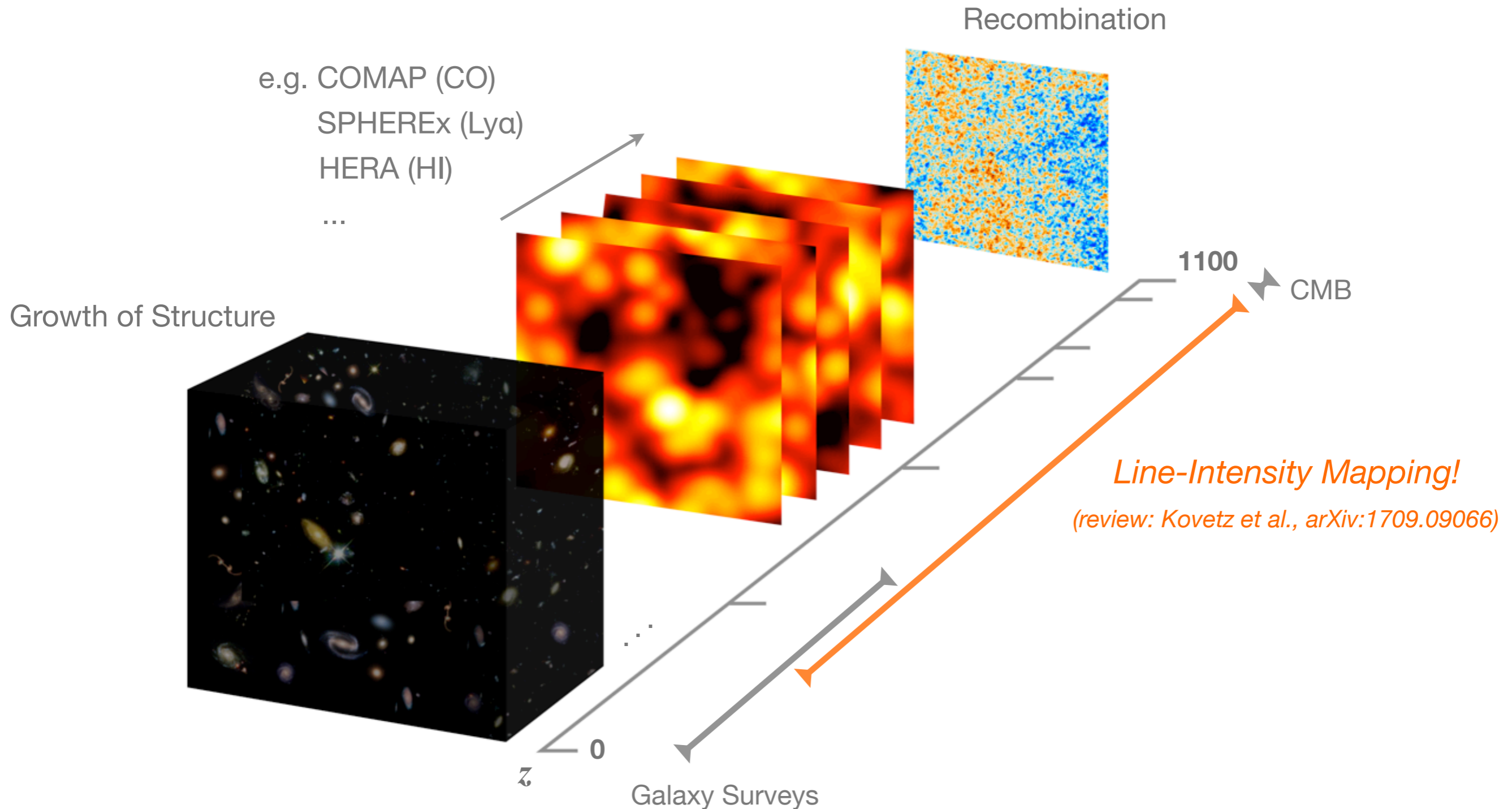
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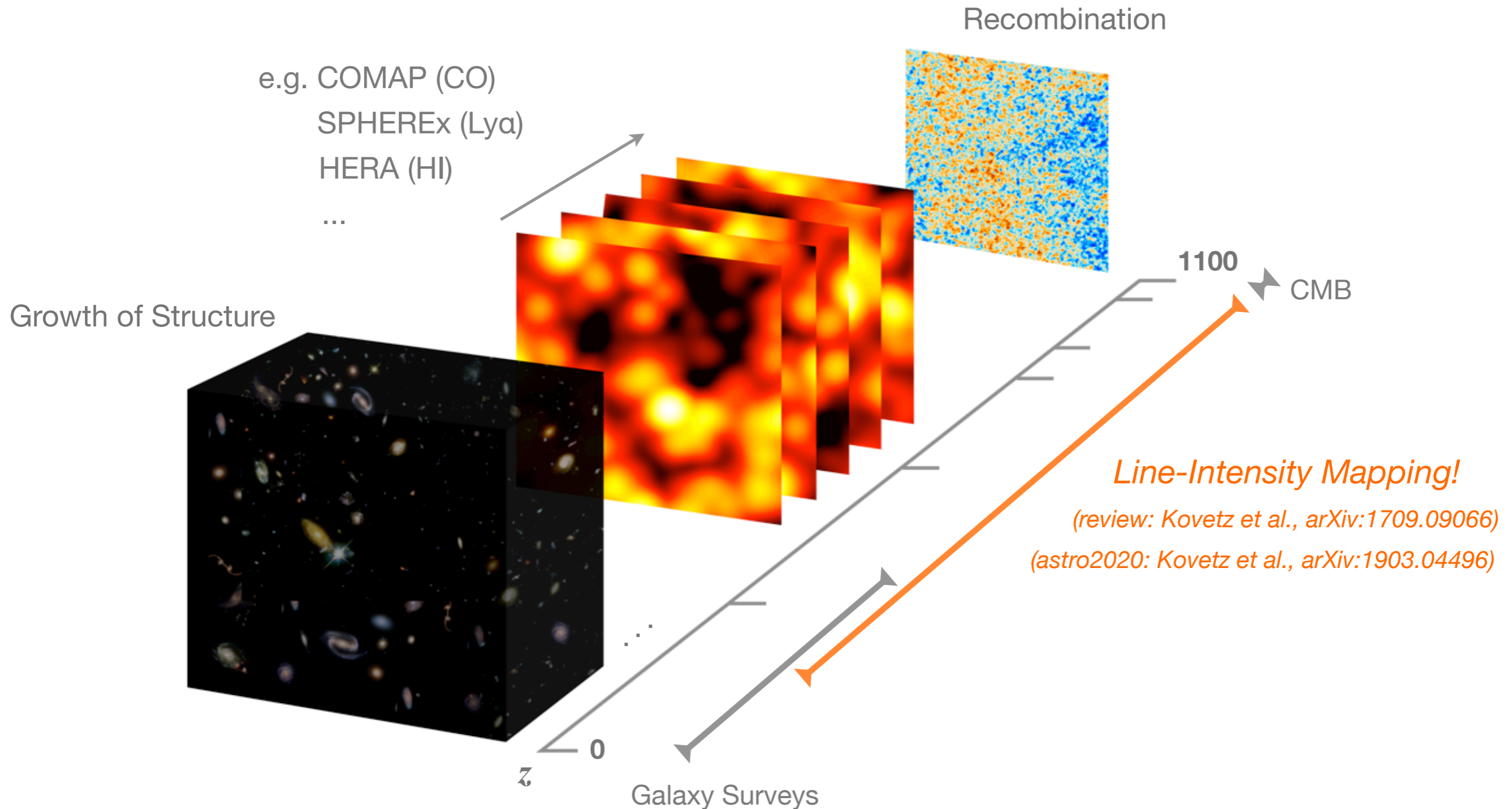
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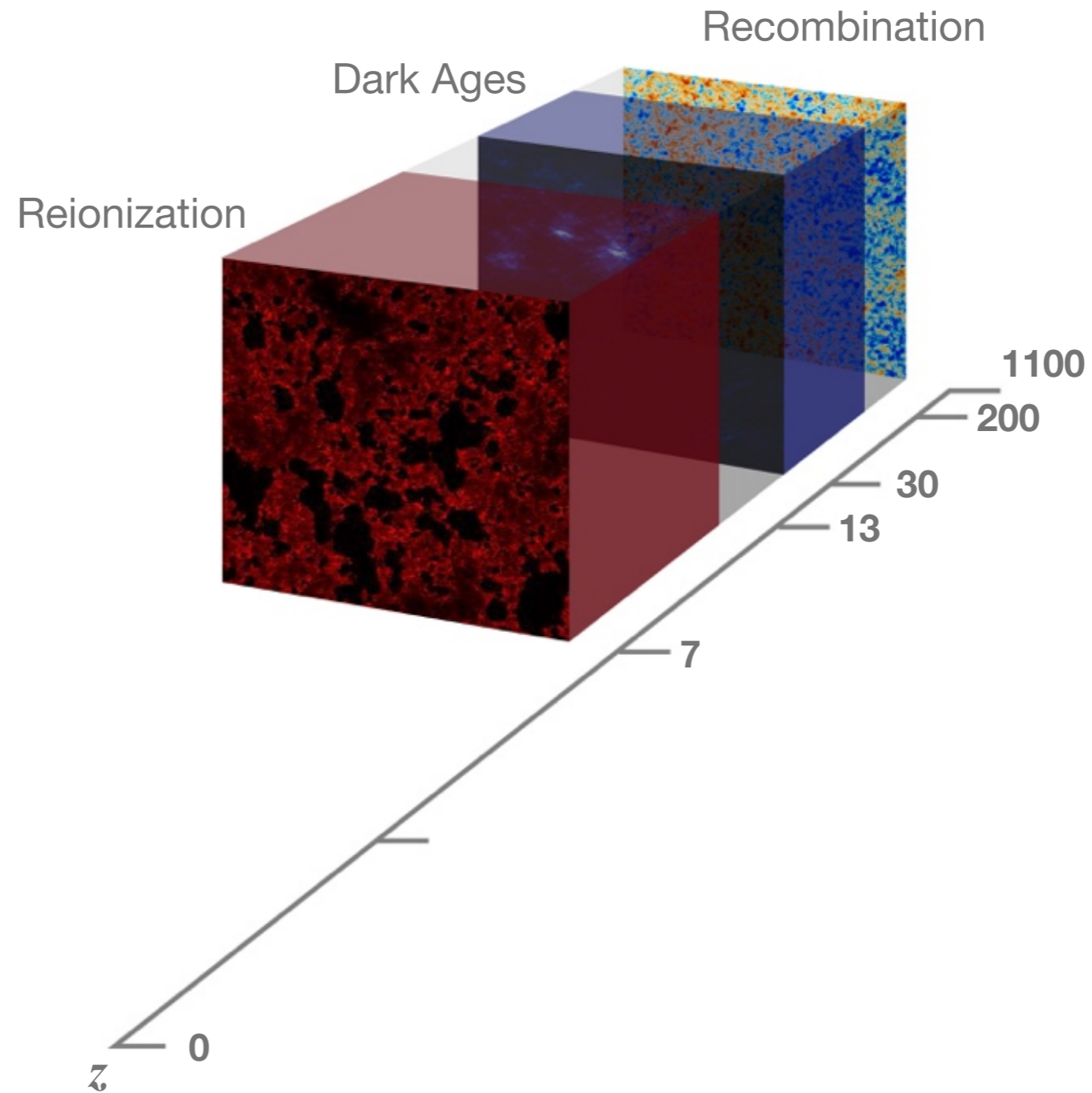


The Observable Universe: A Multi-Layer Detector

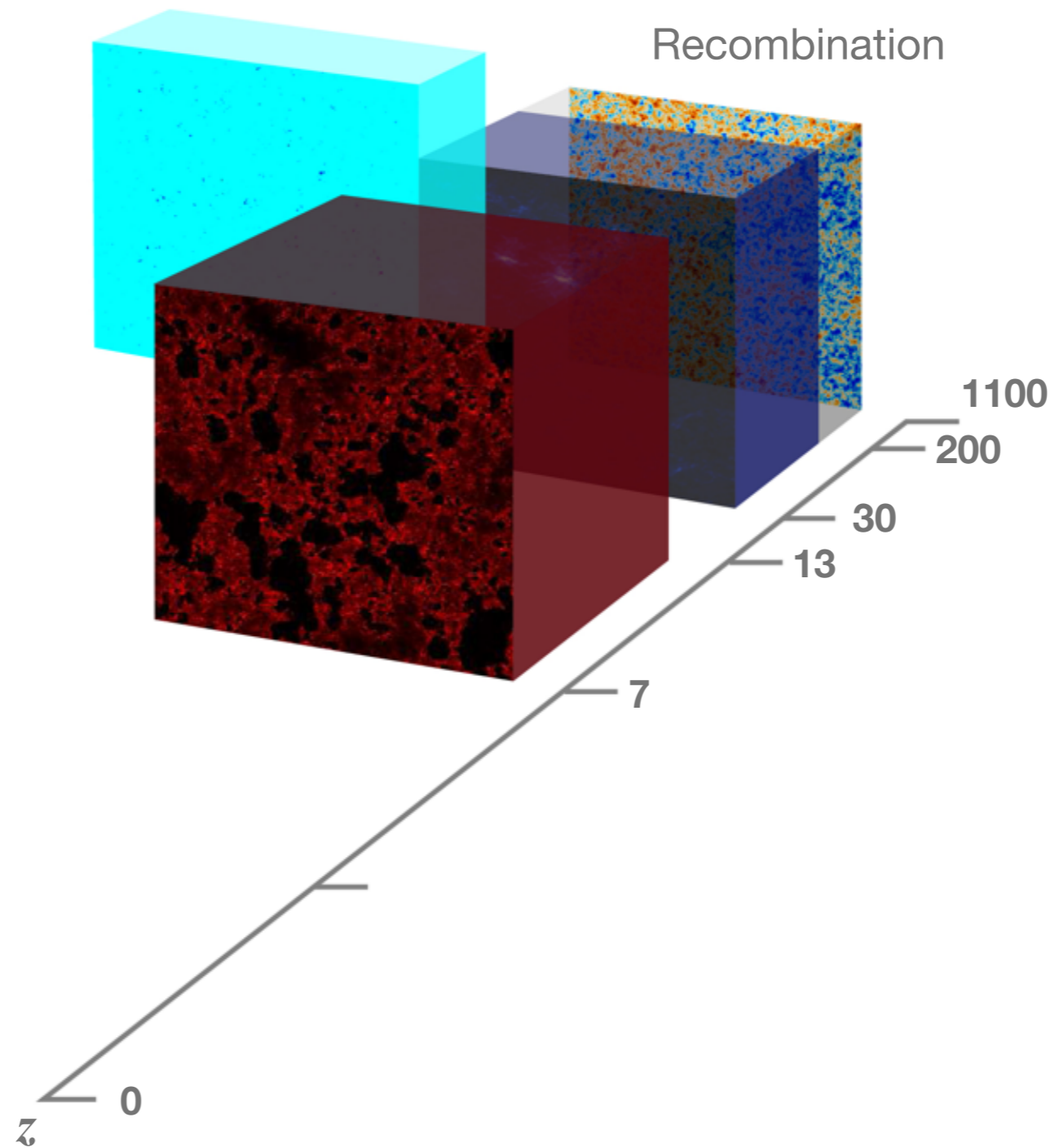
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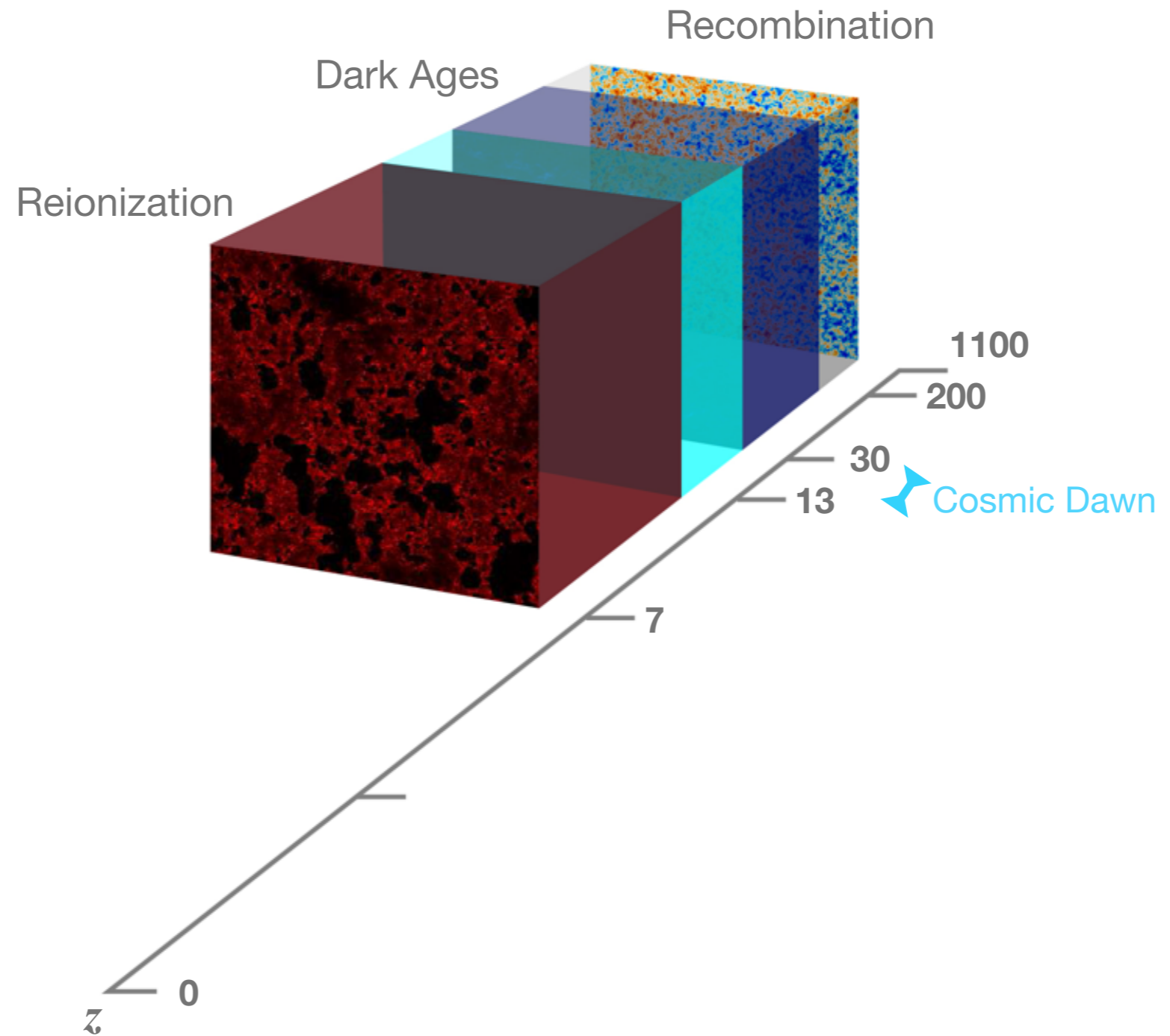
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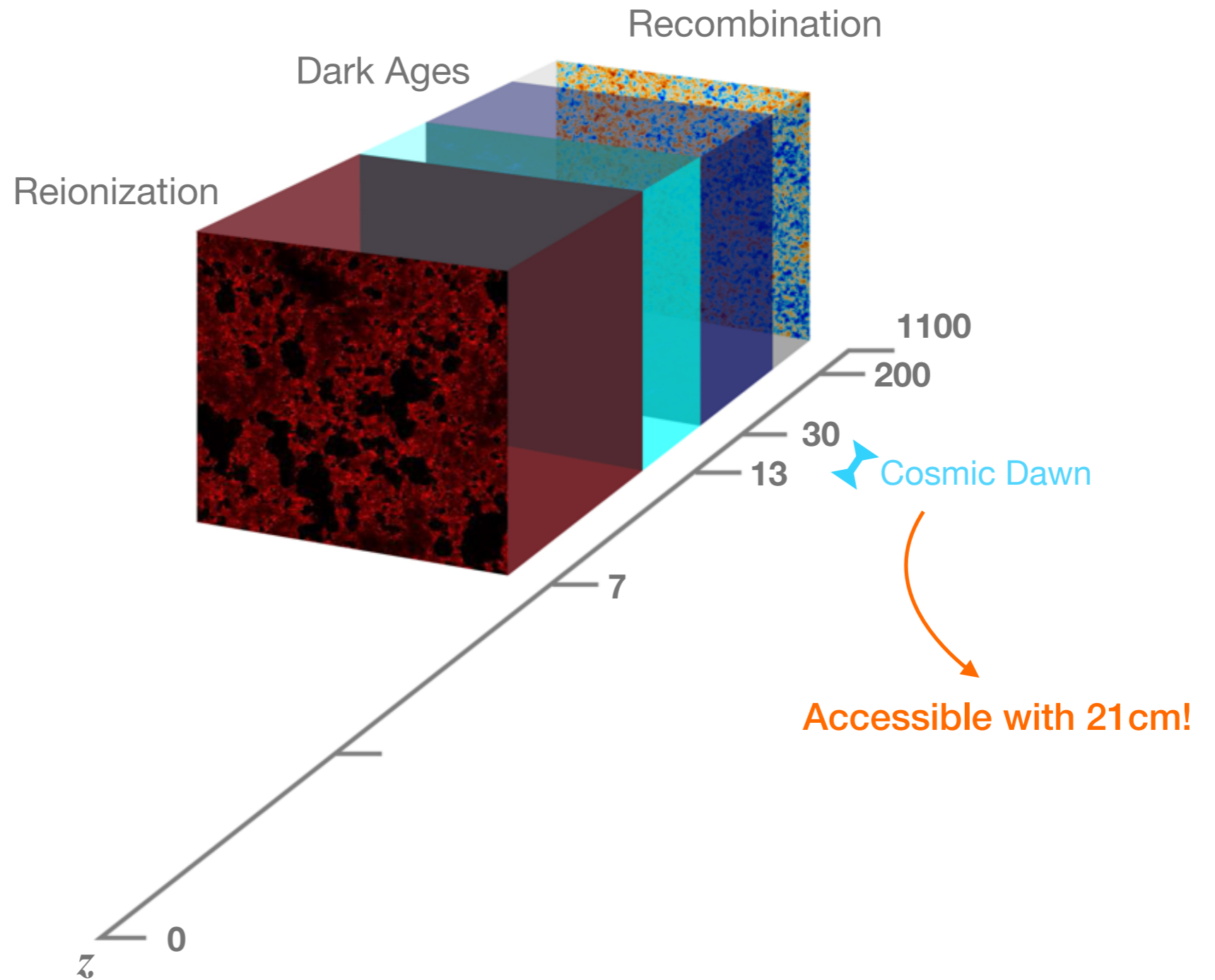
The Observable Universe: A Multi-Layer Detector



The Observable Universe: A Multi-Layer Detector

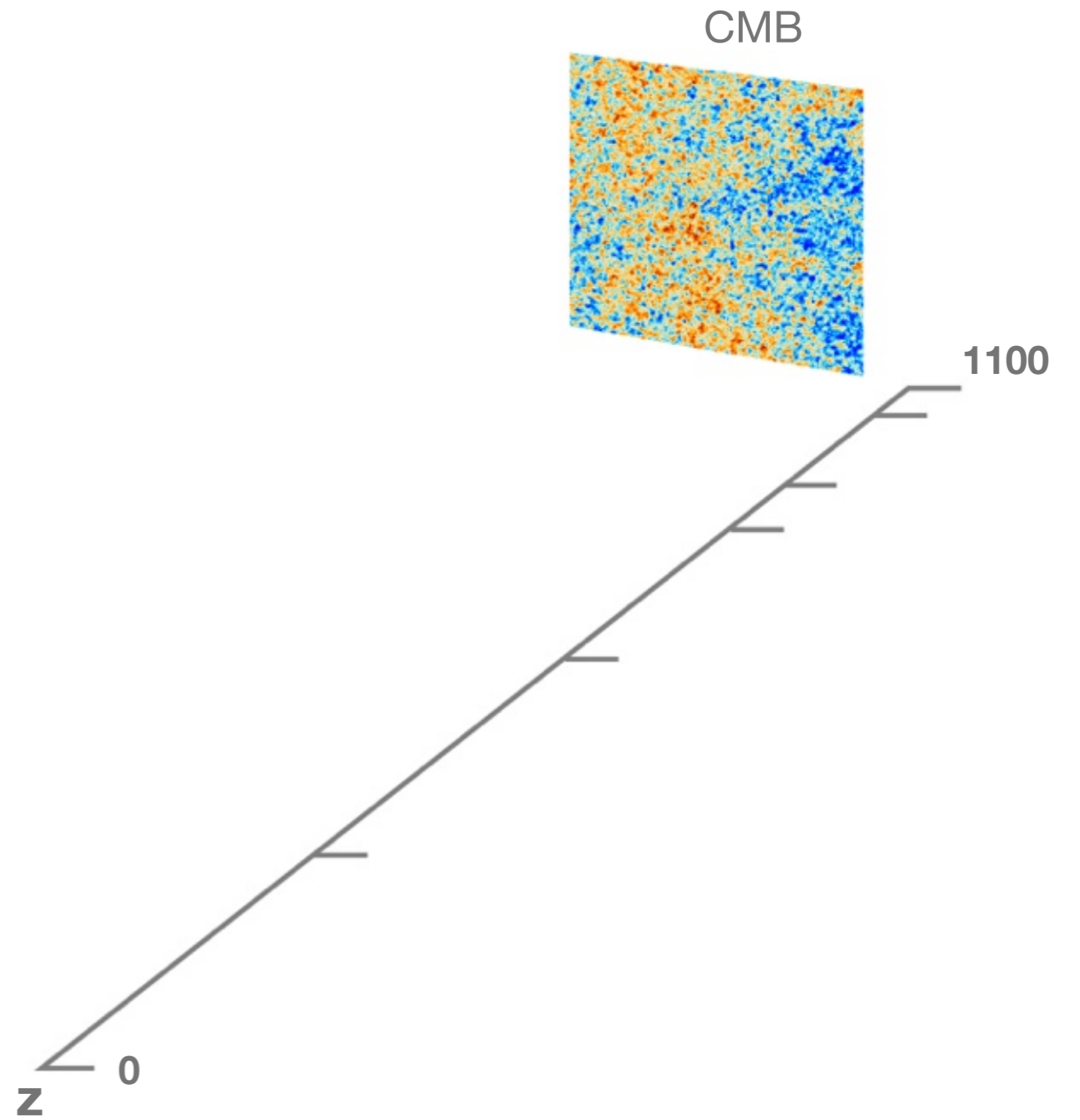


The Observable Universe: A Multi-Layer Detector

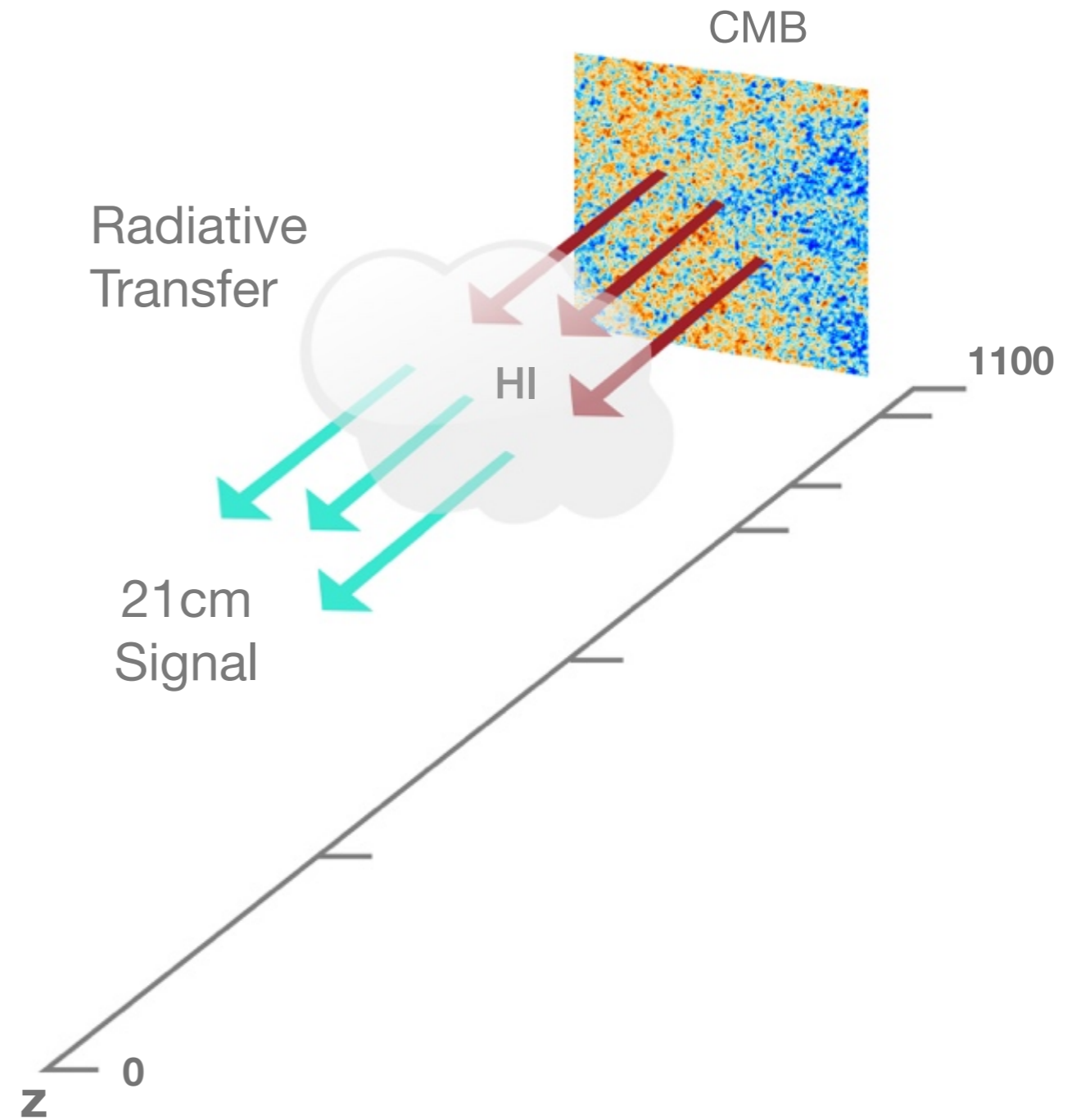


The Cosmological 21cm Signal: Lightning Review

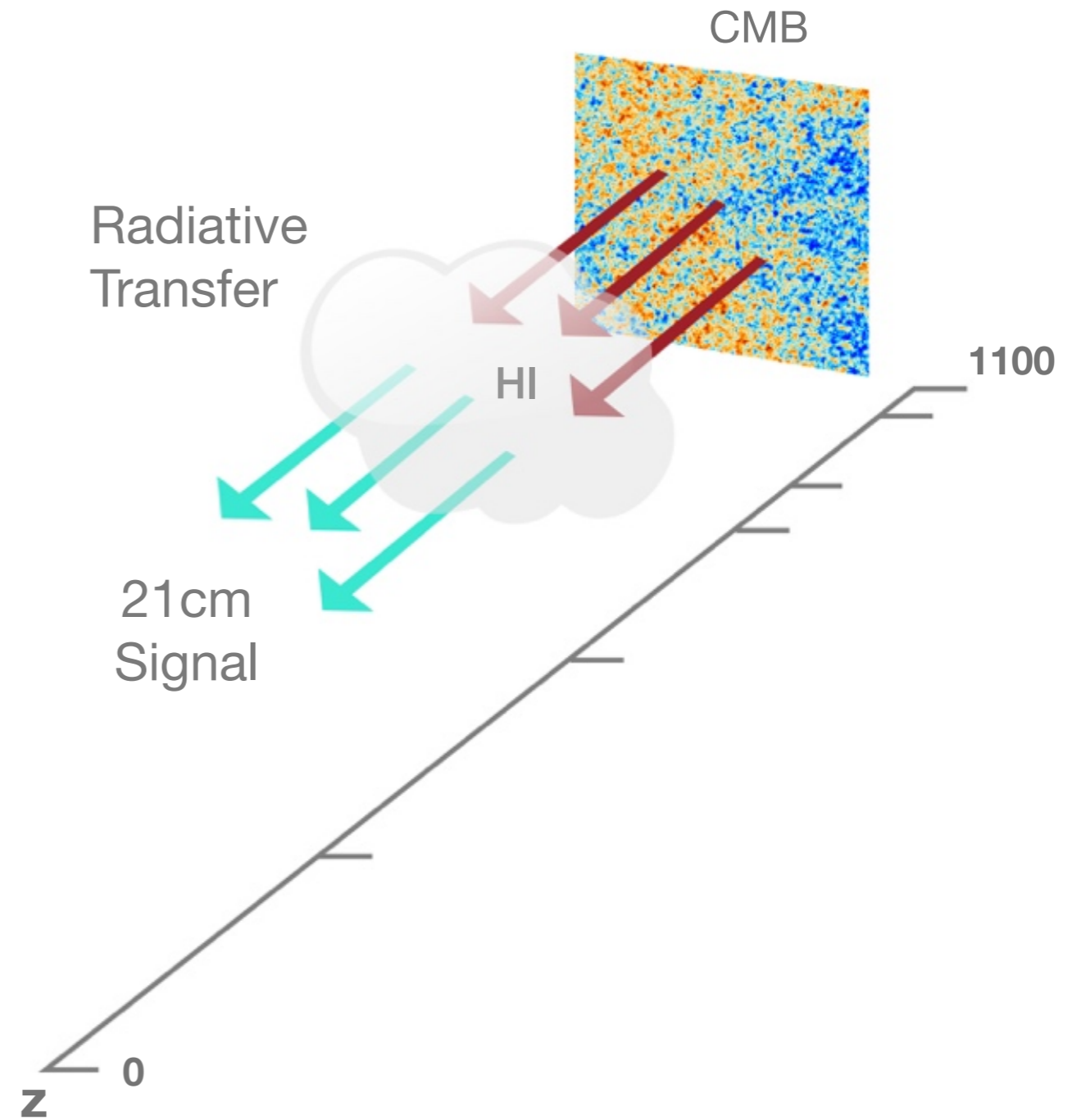
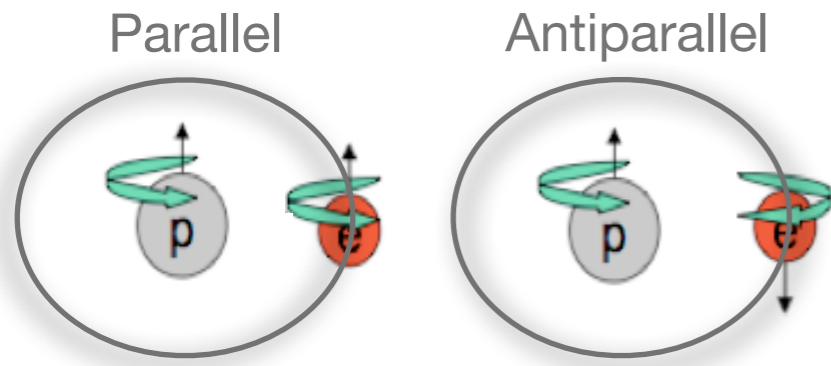
The Cosmological 21cm Signal: Lightning Review



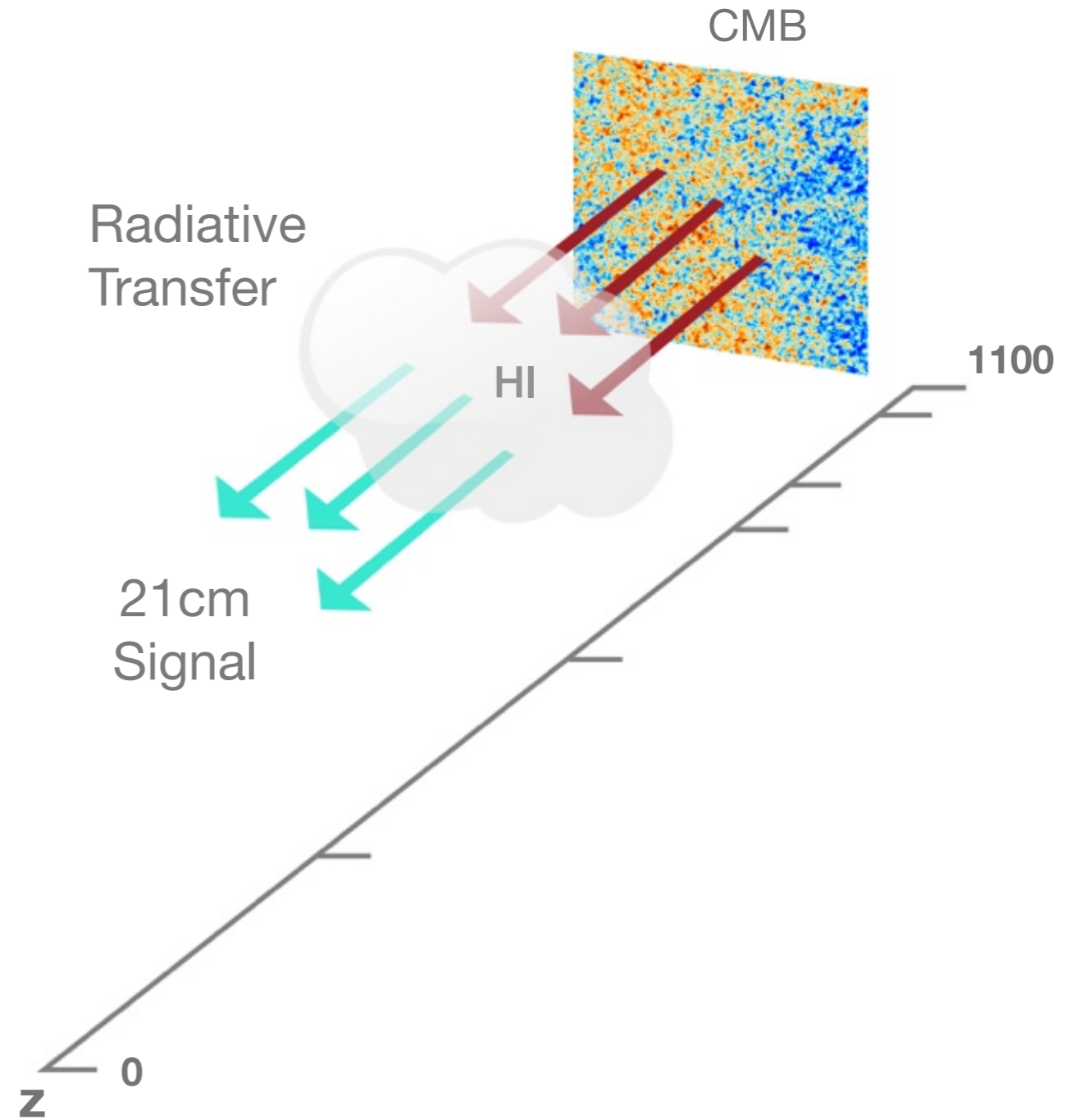
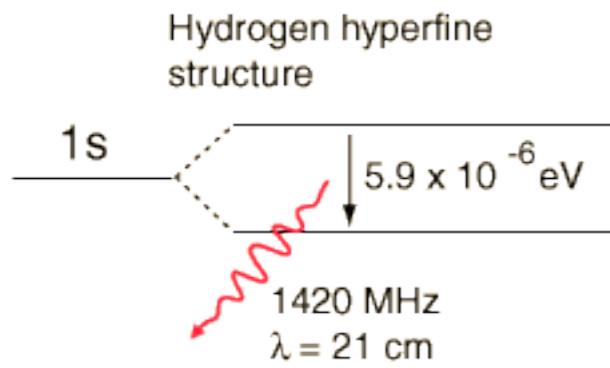
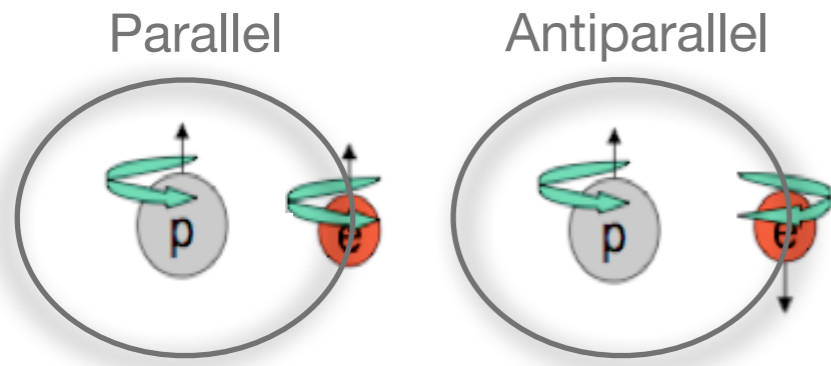
The Cosmological 21cm Signal: Lightning Review



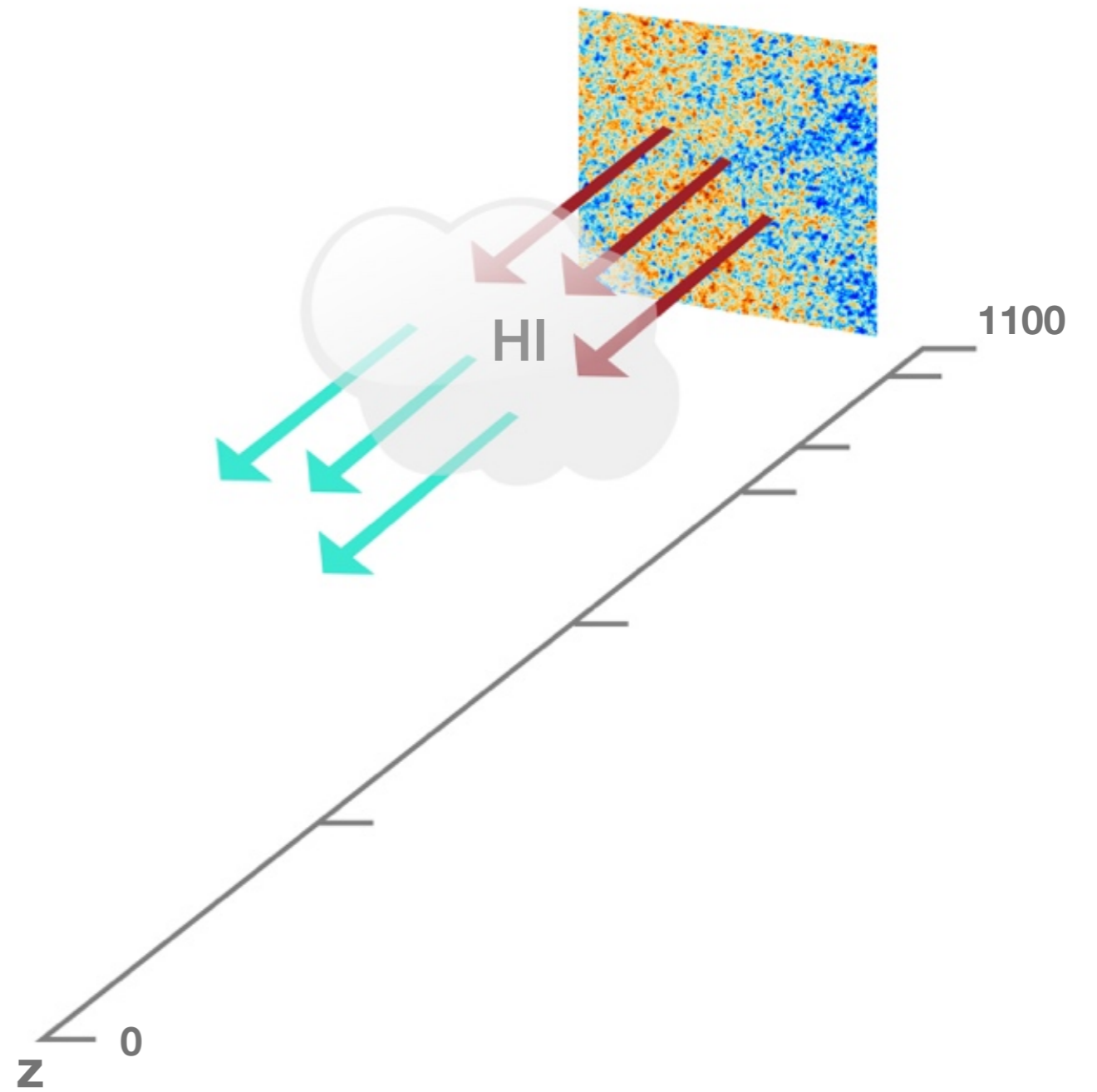
The Cosmological 21cm Signal: Lightning Review



The Cosmological 21cm Signal: Lightning Review

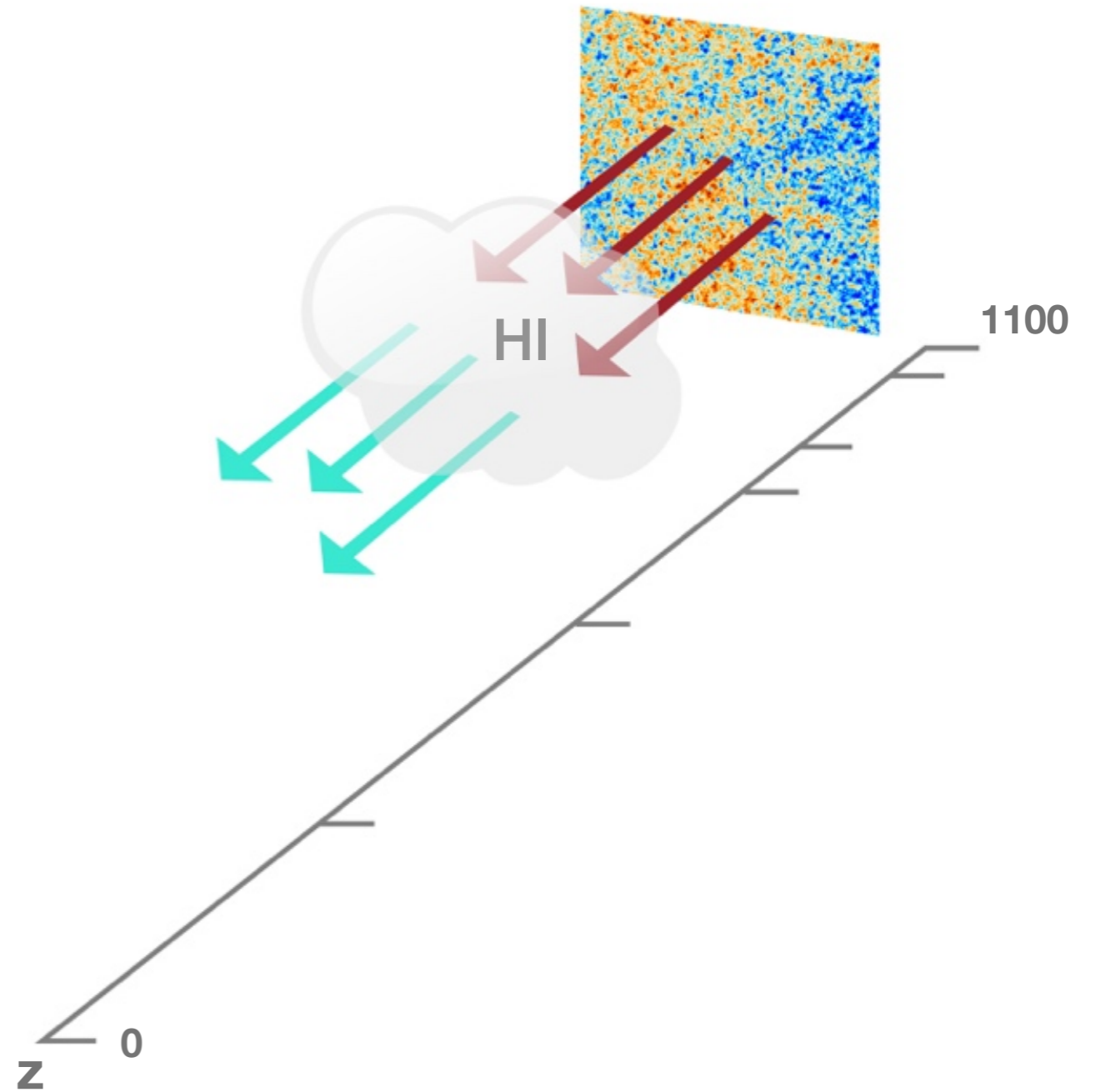


The Cosmological 21cm Signal: Lightning Review



The Cosmological 21cm Signal: Lightning Review

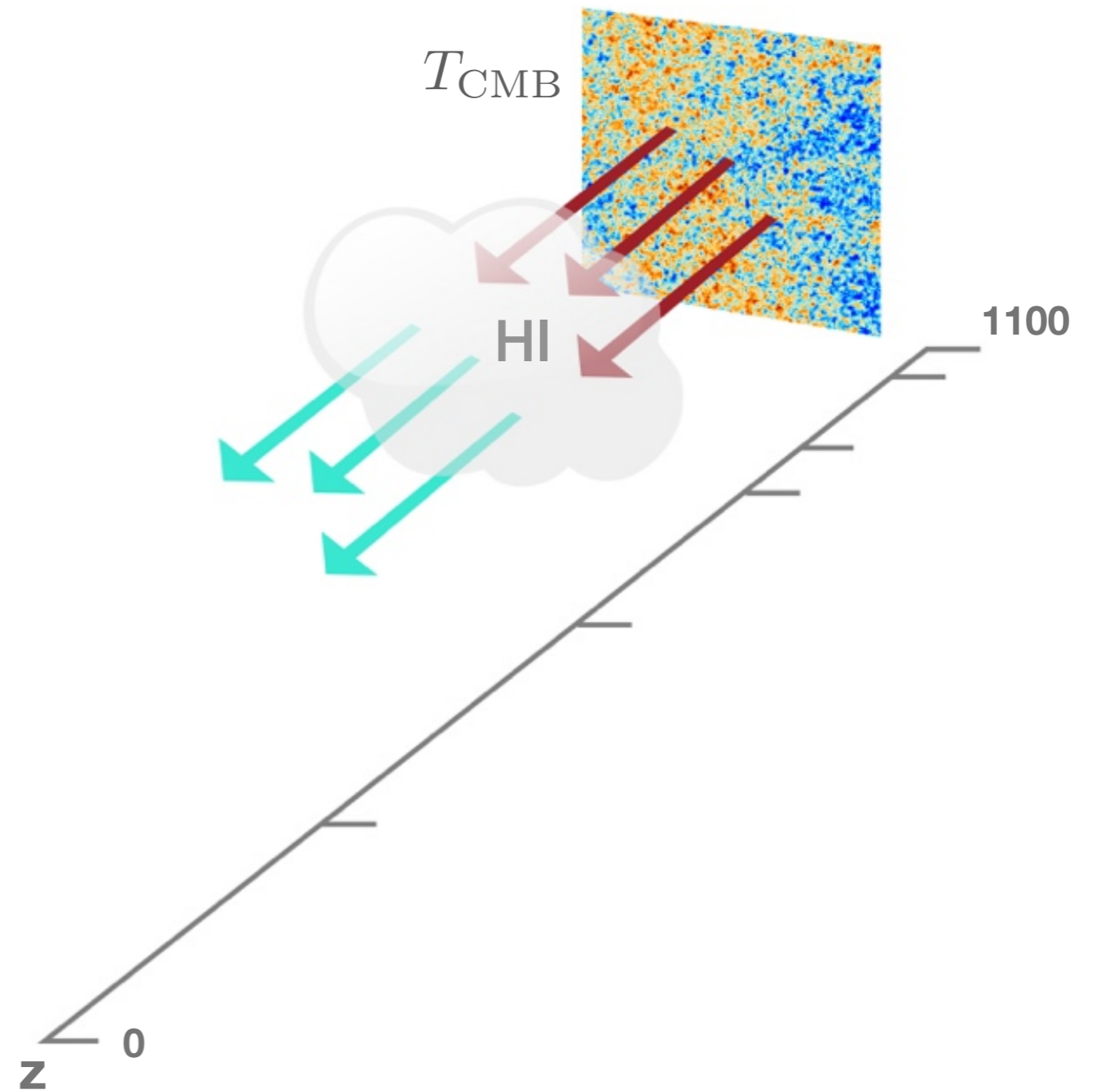
Game of “Temperatures”:



The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

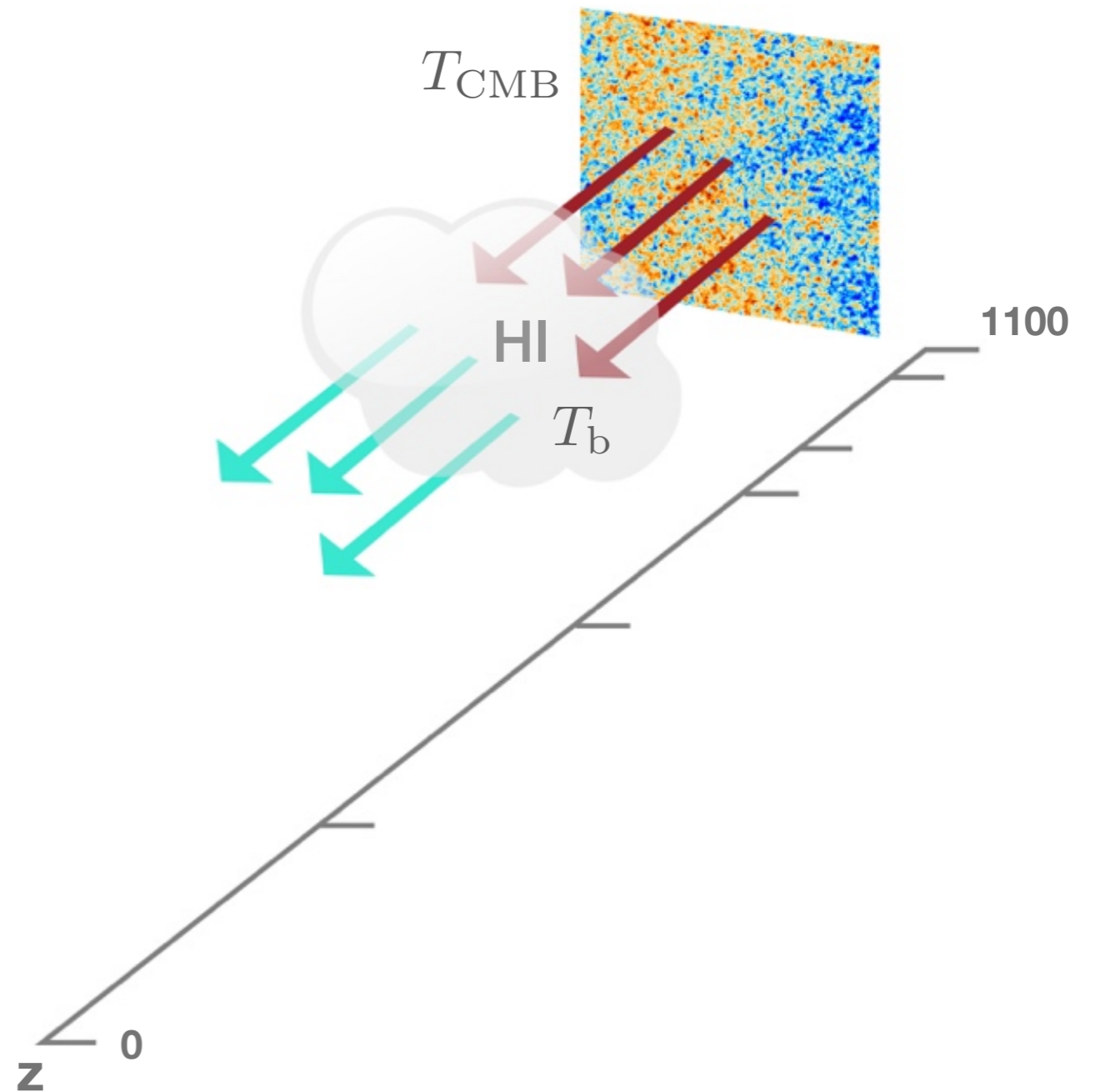
- CMB temperature (background)



The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

- CMB temperature (background)
- Gas (kinetic) temperature

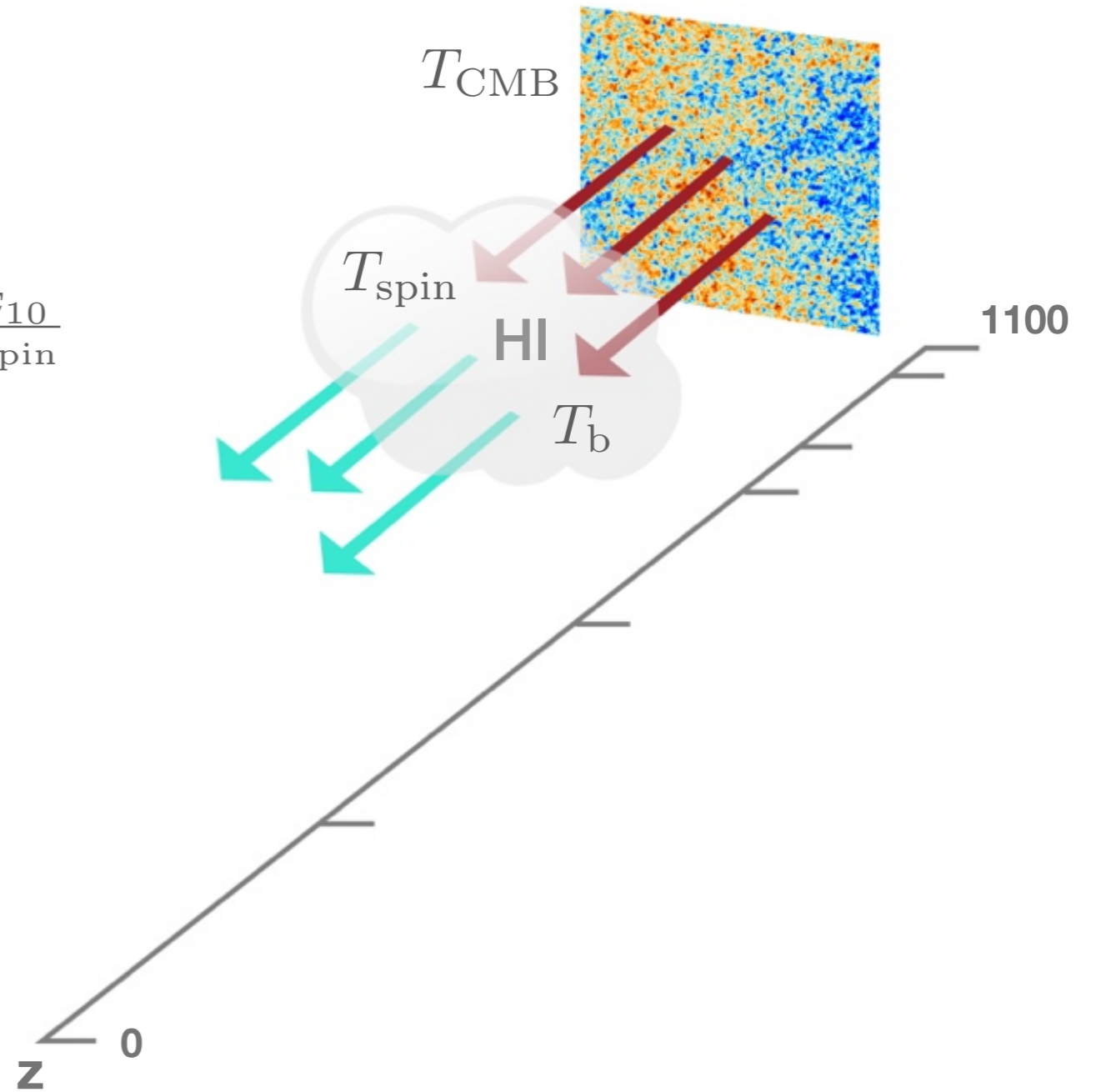


The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

- CMB temperature (background)
- Gas (kinetic) temperature
- Spin (excitation) temperature:

$$\frac{n_1}{n_0} \equiv 3e^{\frac{-E_{10}}{kT_{\text{spin}}}}$$

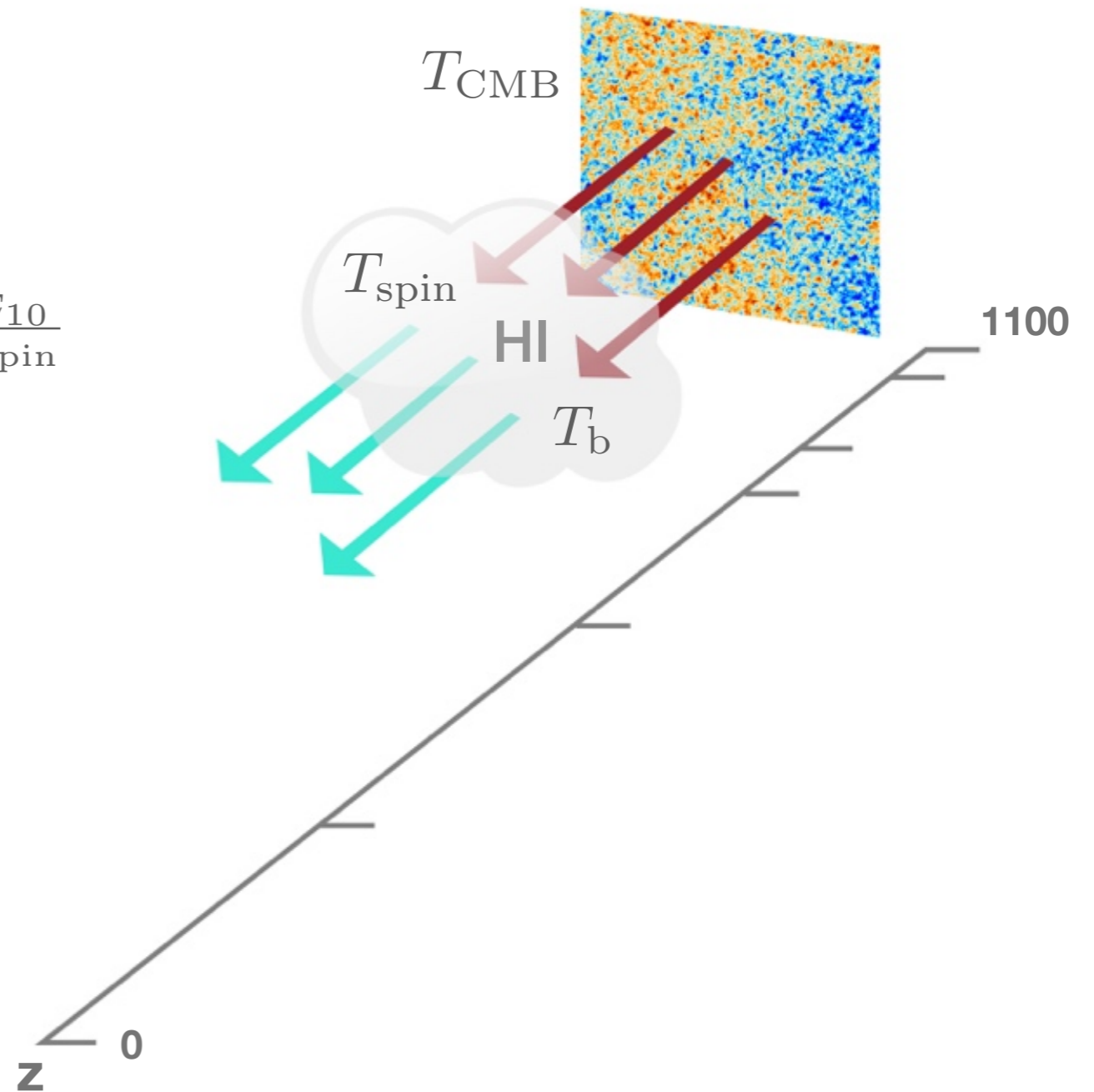


The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

- CMB temperature (background)
- Gas (kinetic) temperature
- Spin (excitation) temperature:
 - (i) Absorption of CMB photons

$$\frac{n_1}{n_0} \equiv 3e^{\frac{-E_{10}}{kT_{\text{spin}}}}$$



The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

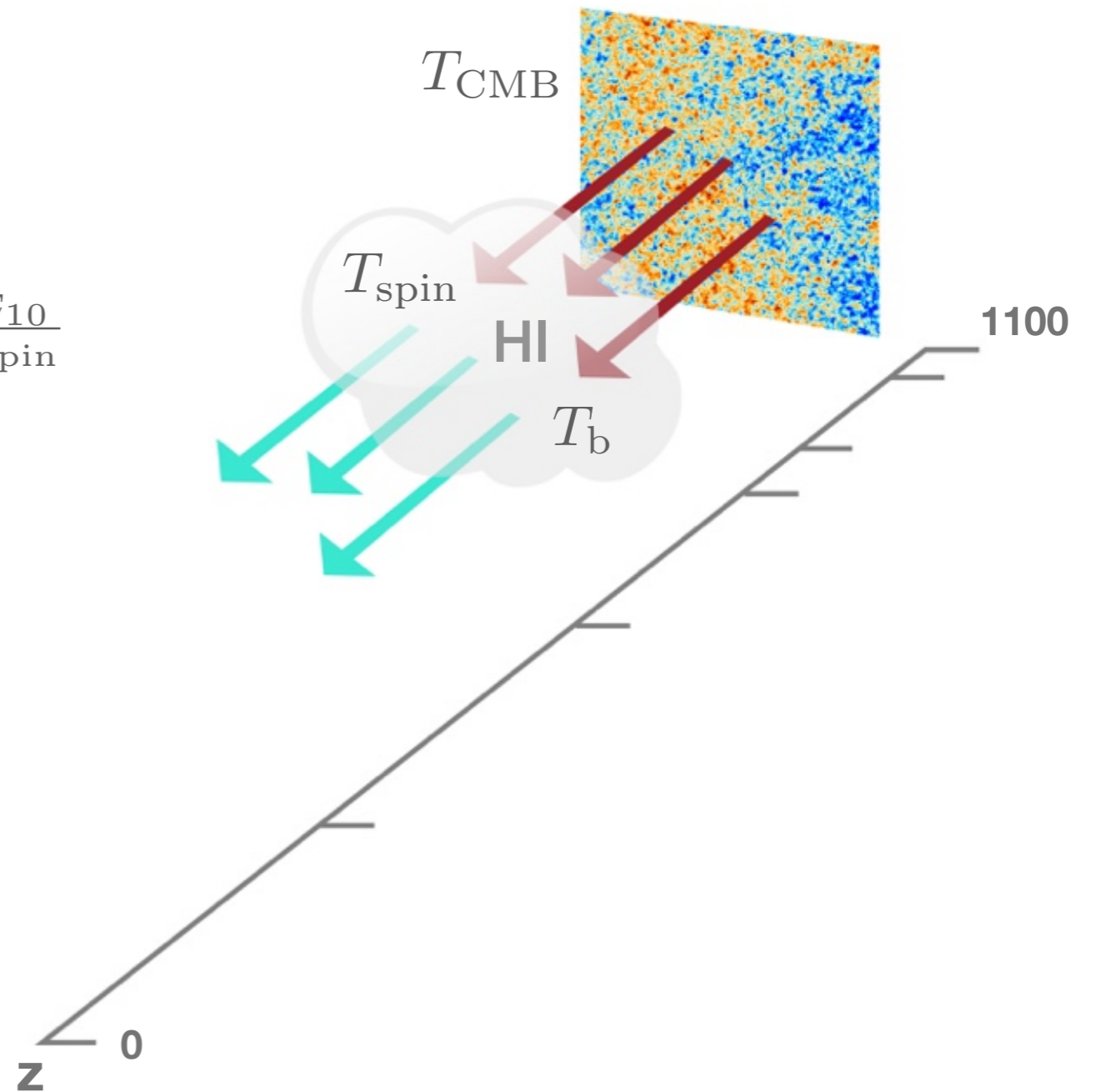
- CMB temperature (background)

- Gas (kinetic) temperature

- Spin (excitation) temperature: $\frac{n_1}{n_0} \equiv 3e^{\frac{-E_{10}}{kT_{\text{spin}}}}$

(i) Absorption of CMB photons

(ii) Collisions in the IGM (H, p, e)

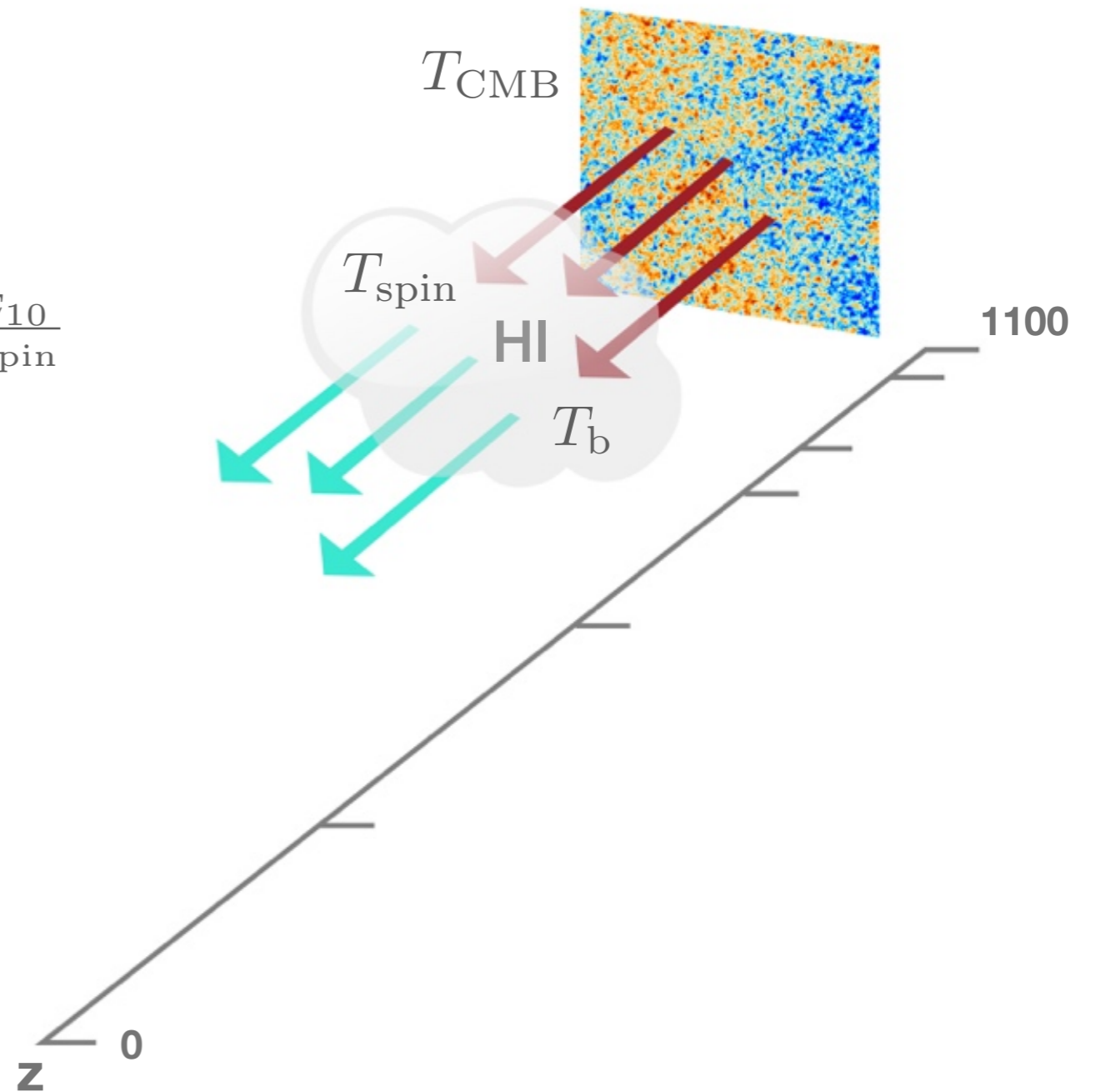


The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

- CMB temperature (background)
- Gas (kinetic) temperature
- Spin (excitation) temperature:
 - (i) Absorption of CMB photons
 - (ii) Collisions in the IGM (H, p, e)
 - (iii) Excitation by Ly α photons

$$\frac{n_1}{n_0} \equiv 3e^{\frac{-E_{10}}{kT_{\text{spin}}}}$$



The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

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- Gas (kinetic) temperature

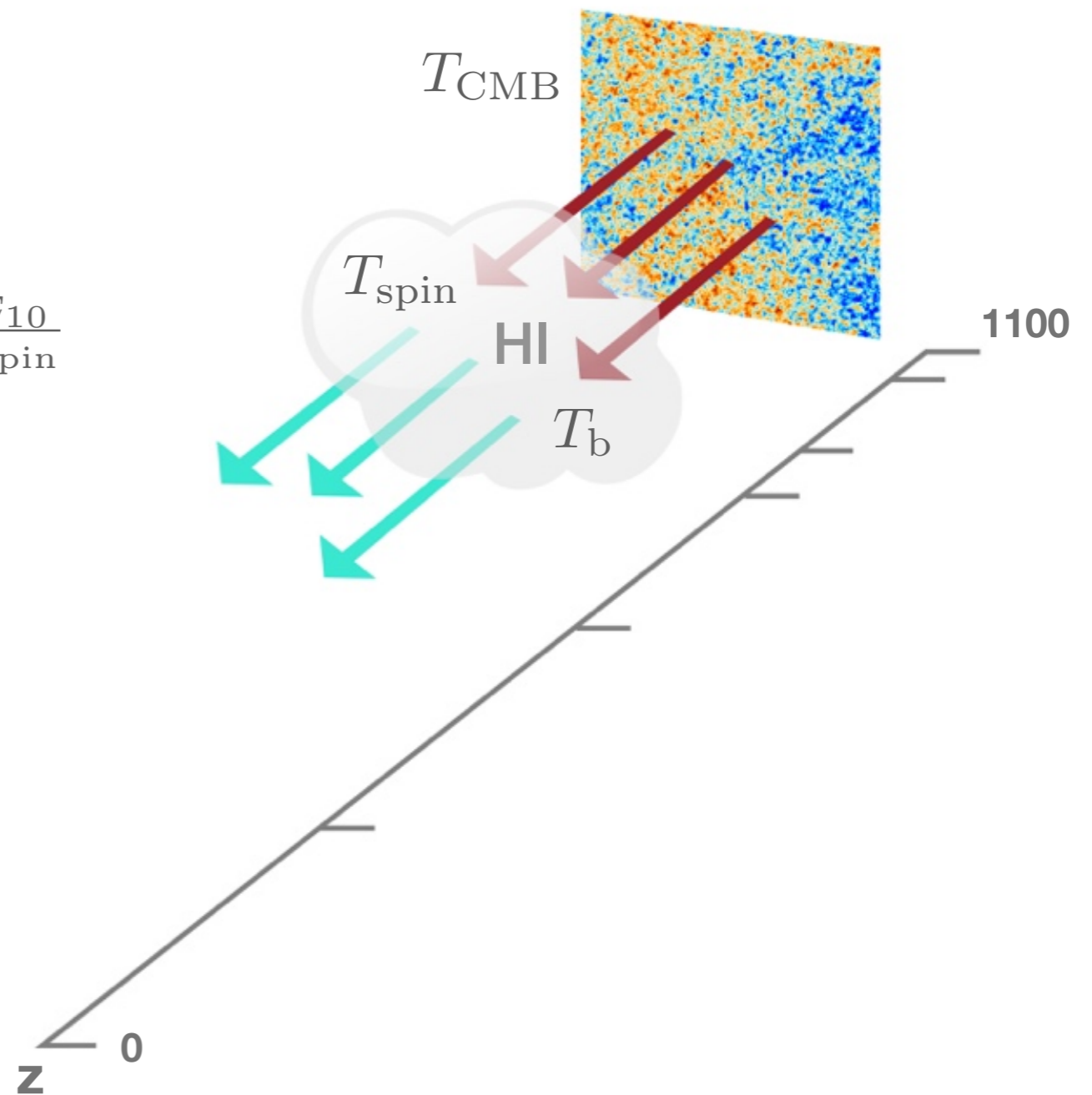
- Spin (excitation) temperature: $\frac{n_1}{n_0} \equiv 3e^{\frac{-E_{10}}{kT_{\text{spin}}}}$

(i) Absorption of CMB photons

(ii) Collisions in the IGM (H, p, e)

(iii) Excitation by Ly α photons

Determined by: $T_{\text{spin}}^{-1} \simeq \frac{T_{\text{CMB}}^{-1} + \sum_i x_i T_b^{-1}}{1 + \sum_i x_i}$



The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

- CMB temperature (background)

- Gas (kinetic) temperature

- Spin (excitation) temperature: $\frac{n_1}{n_0} \equiv 3e^{\frac{-E_{10}}{kT_{\text{spin}}}}$

(i) Absorption of CMB photons

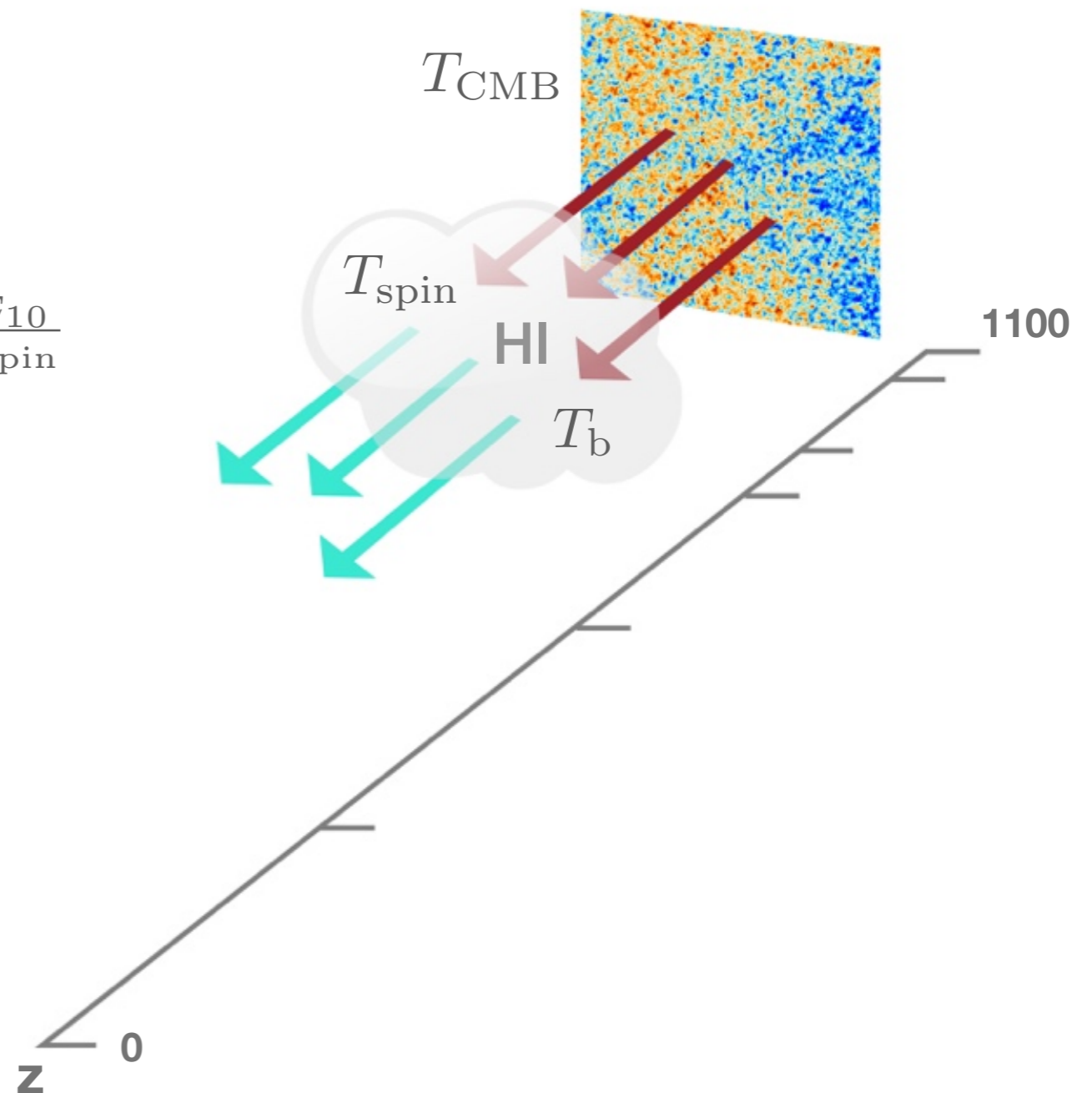
(ii) Collisions in the IGM (H, p, e)

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- Brightness temperature (radiative transfer):

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



The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

- CMB temperature (background)

- Gas (kinetic) temperature

- Spin (excitation) temperature: $\frac{n_1}{n_0} \equiv 3e^{\frac{-E_{10}}{kT_{\text{spin}}}}$

(i) Absorption of CMB photons

(ii) Collisions in the IGM (H, p, e)

(iii) Excitation by Ly α photons

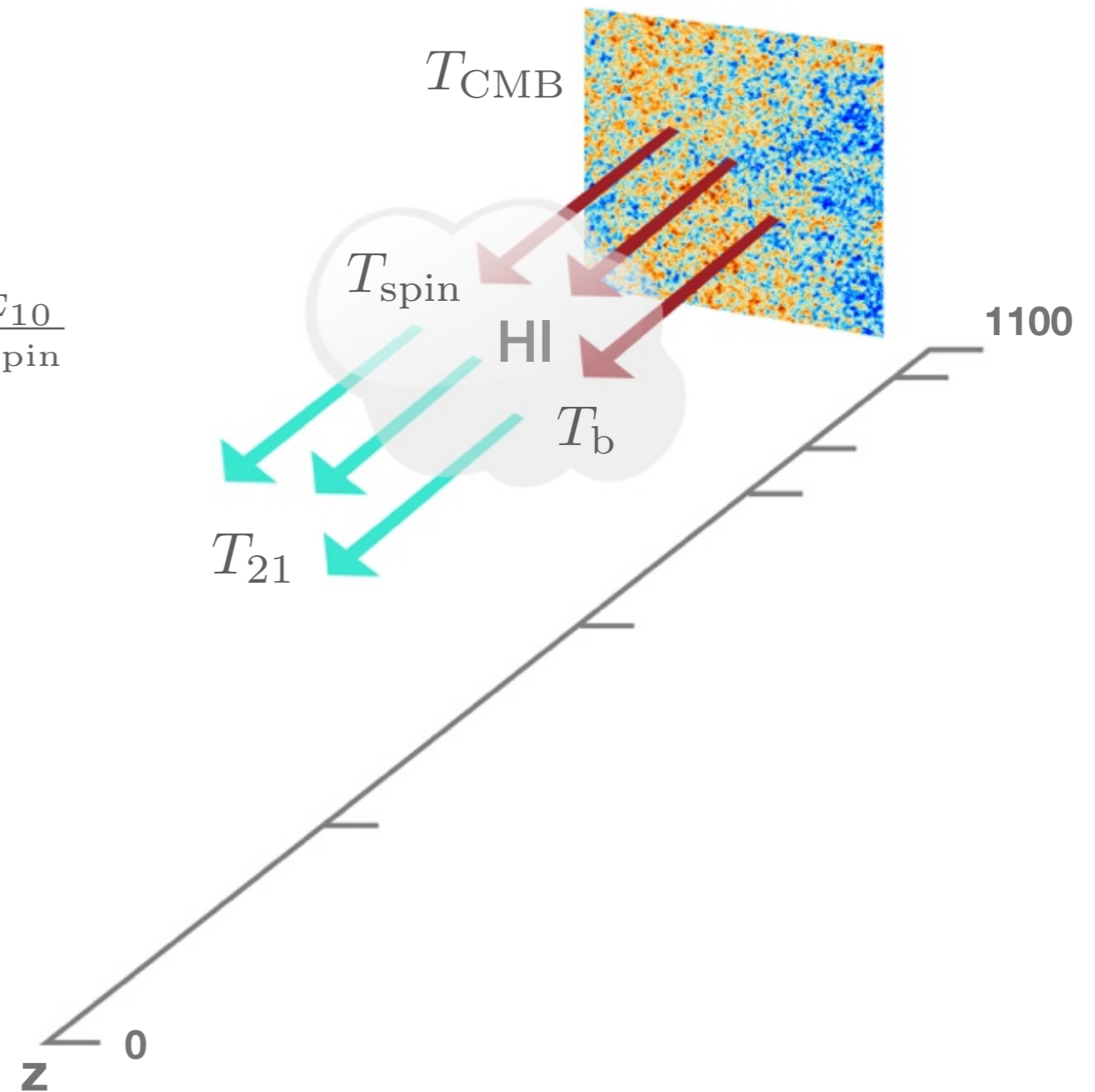
Determined by: $T_{\text{spin}}^{-1} \simeq \frac{T_{\text{CMB}}^{-1} + \sum_i x_i T_b^{-1}}{1 + \sum_i x_i}$

- Brightness temperature (radiative transfer):

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

- Brightness temperature contrast:

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



The Cosmological 21cm Signal: Lightning Review

Game of “Temperatures”:

- CMB temperature (background)

- Gas (kinetic) temperature

- Spin (excitation) temperature: $\frac{n_1}{n_0} \equiv 3e^{\frac{-E_{10}}{kT_{\text{spin}}}}$

(i) Absorption of CMB photons

(ii) Collisions in the IGM (H, p, e)

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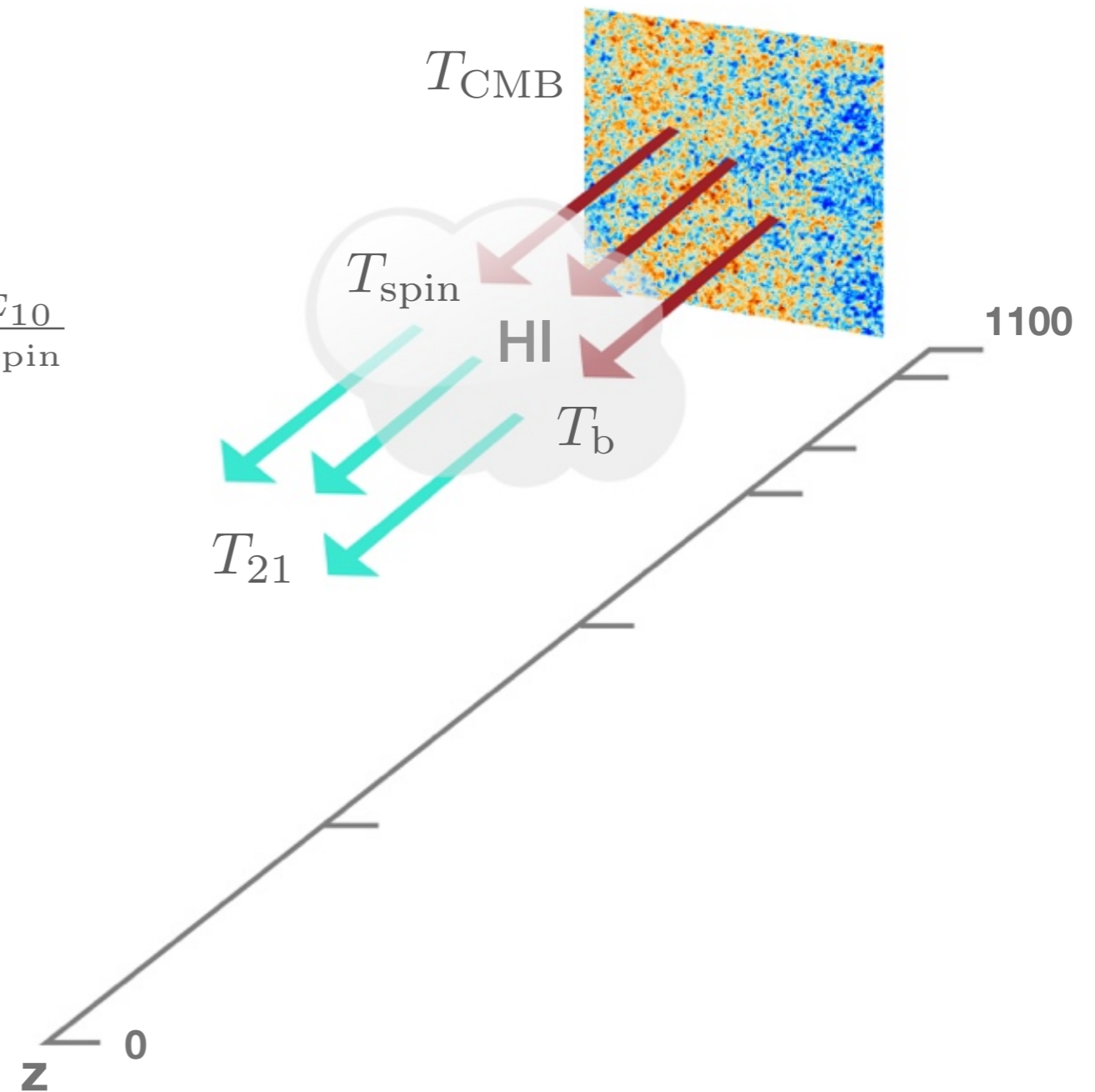
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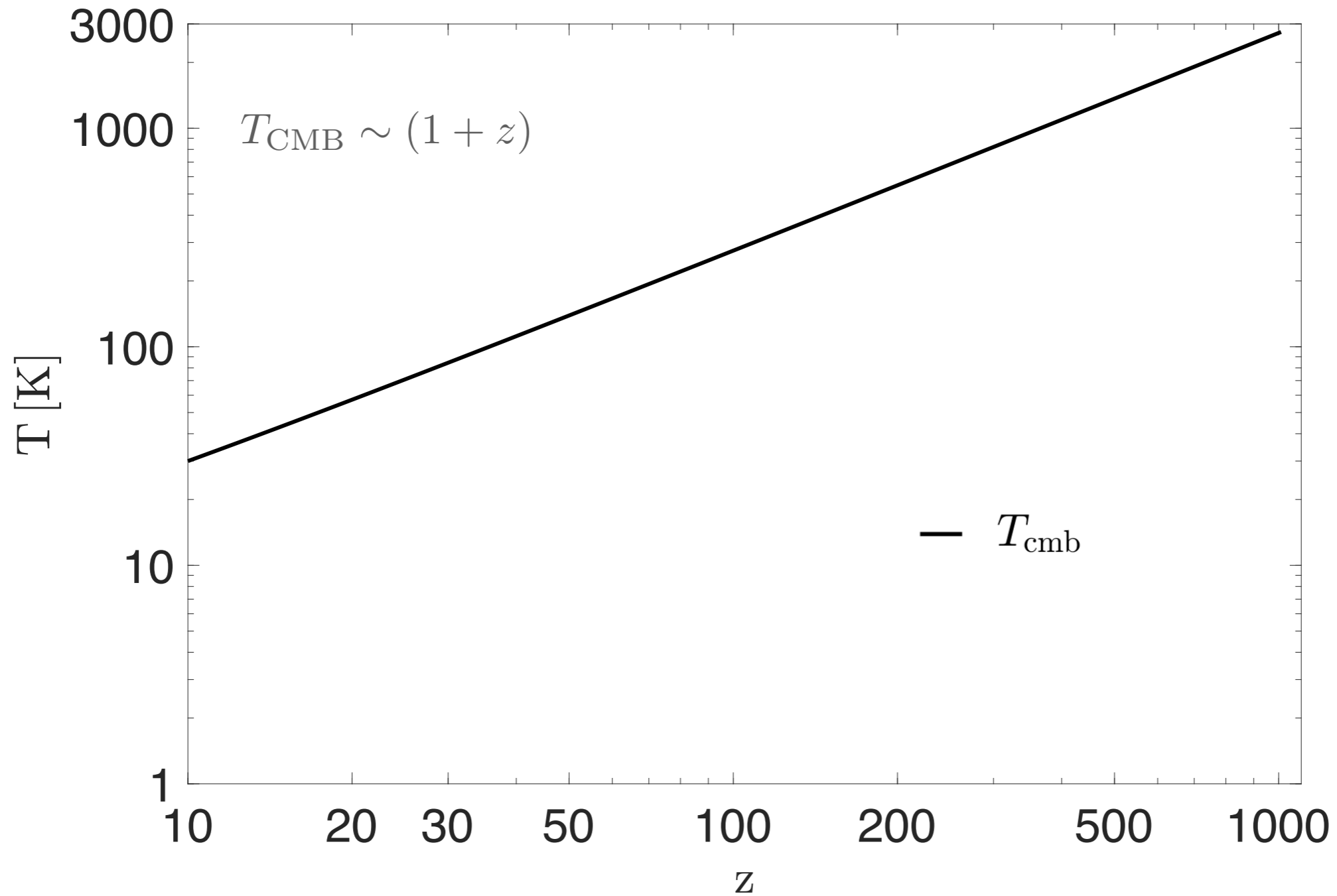
- Brightness temperature contrast:

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

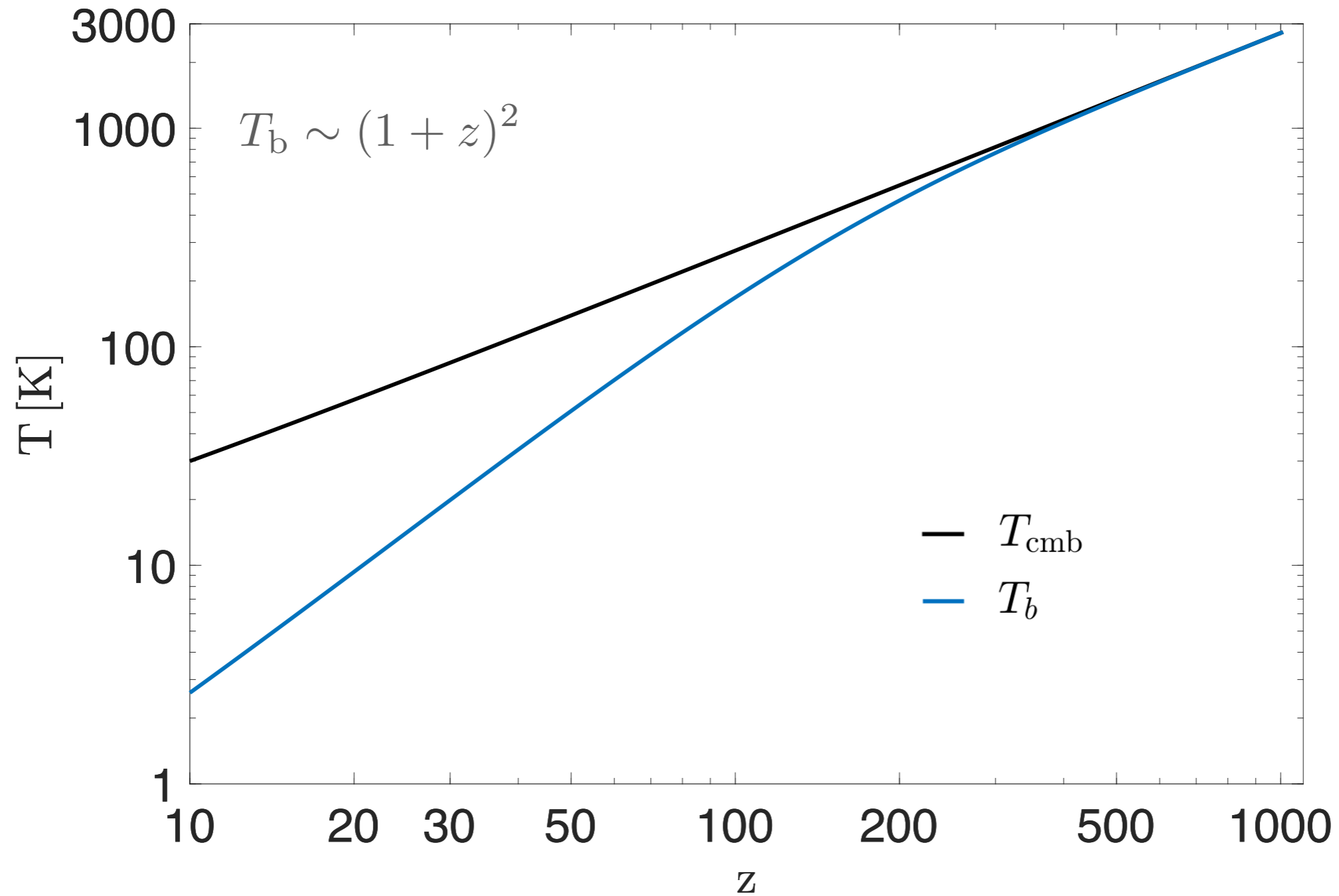


The Cosmological 21cm Signal: Lightning Review

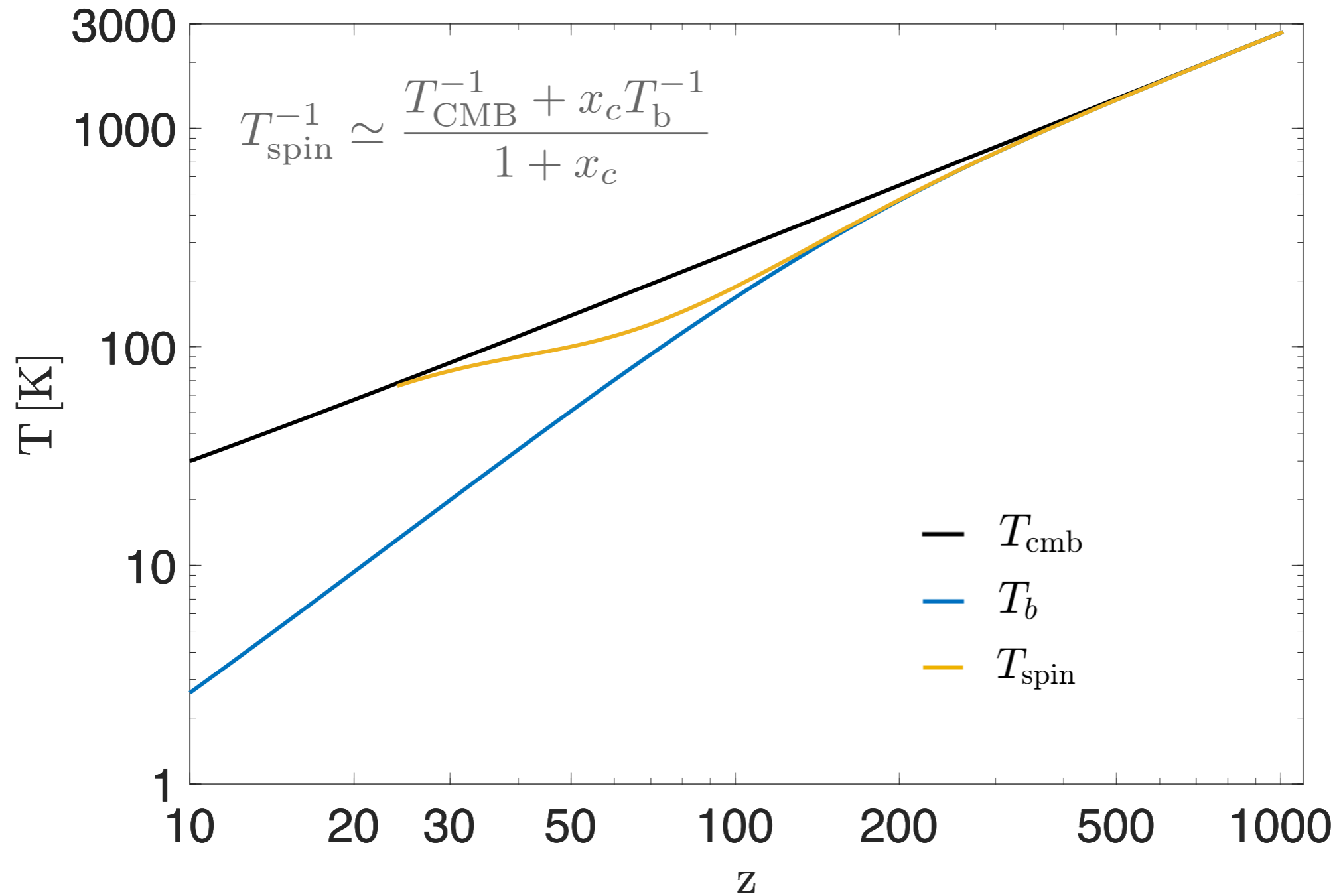
The Cosmological 21cm Signal: Lightning Review



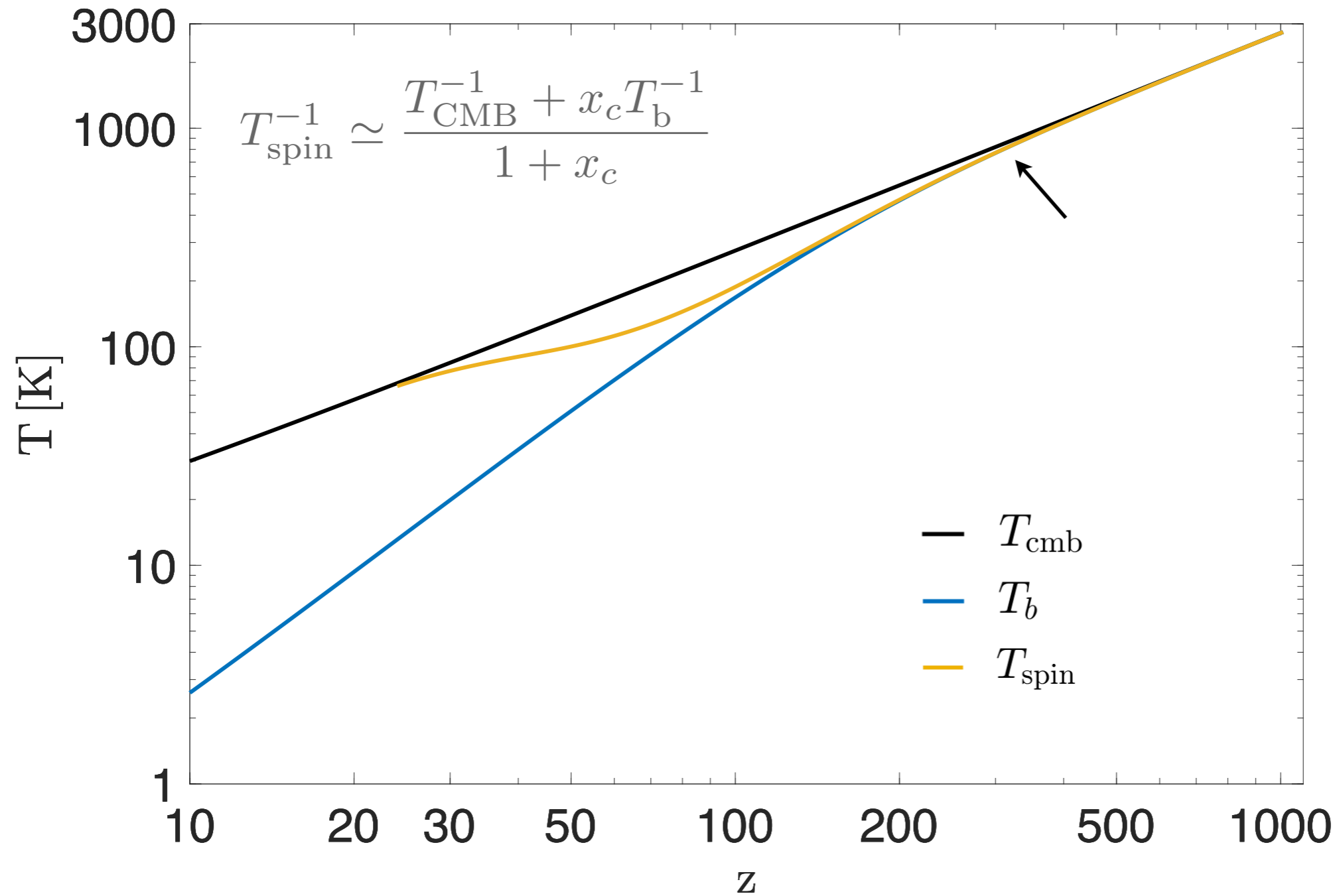
The Cosmological 21cm Signal: Lightning Review



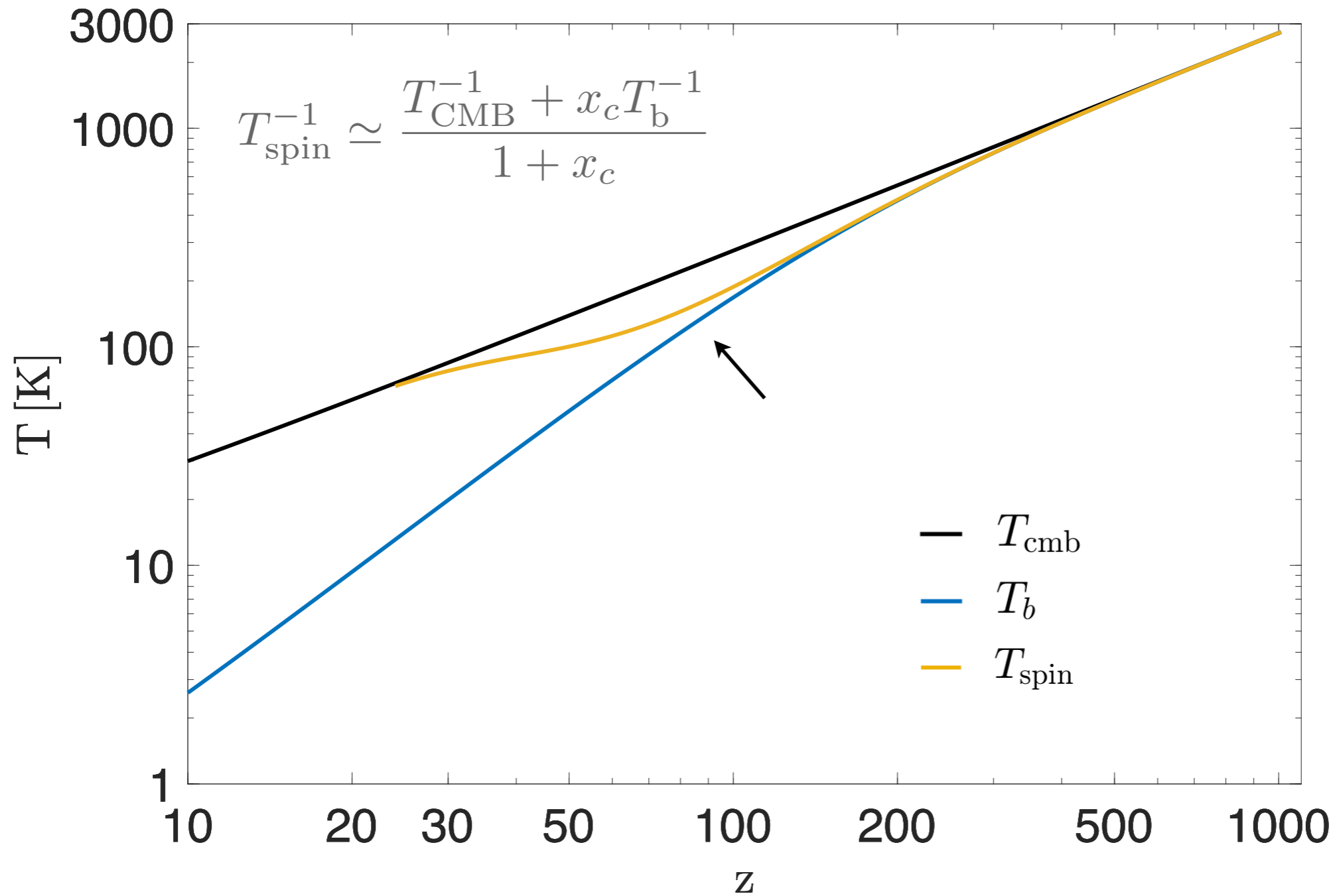
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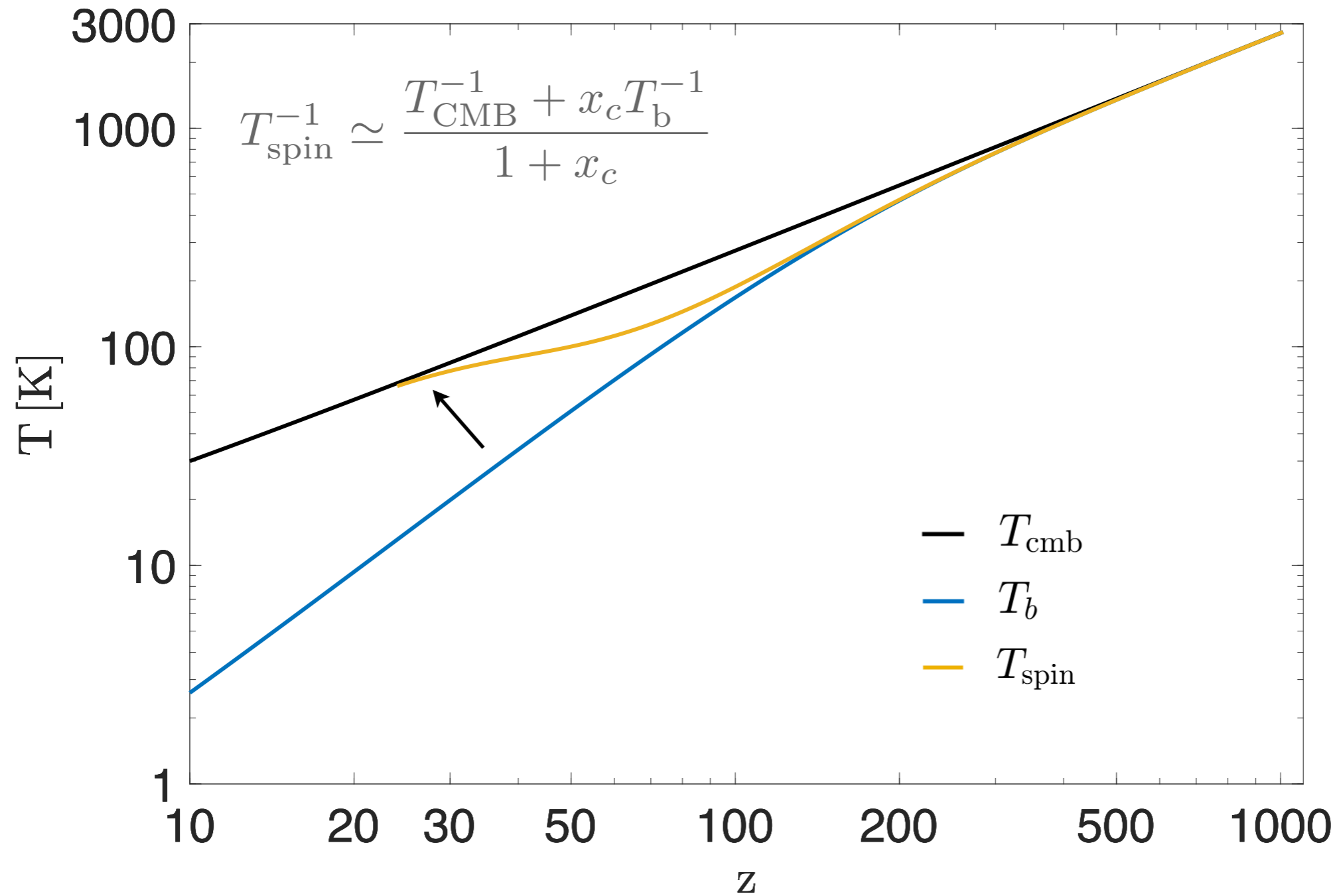
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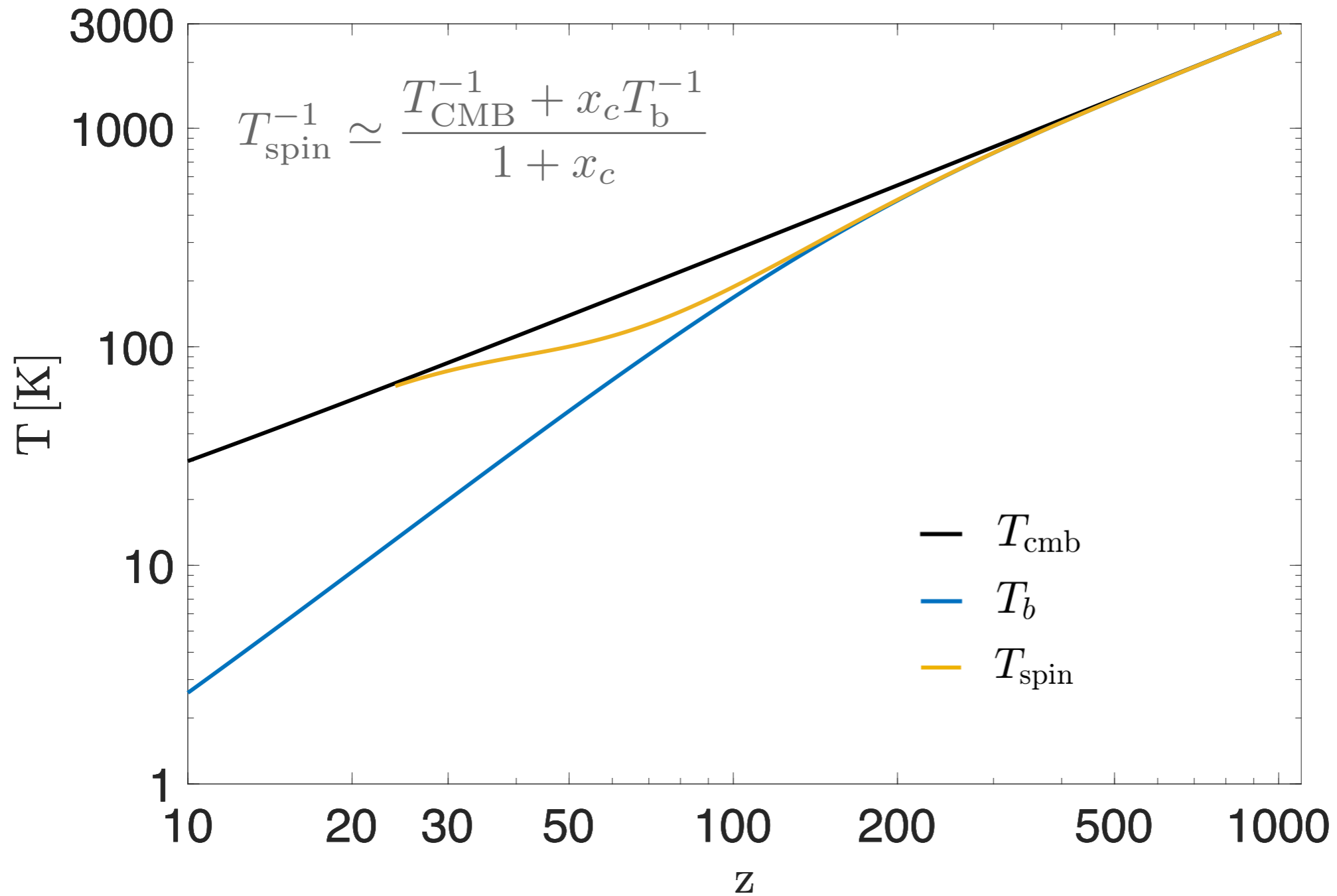
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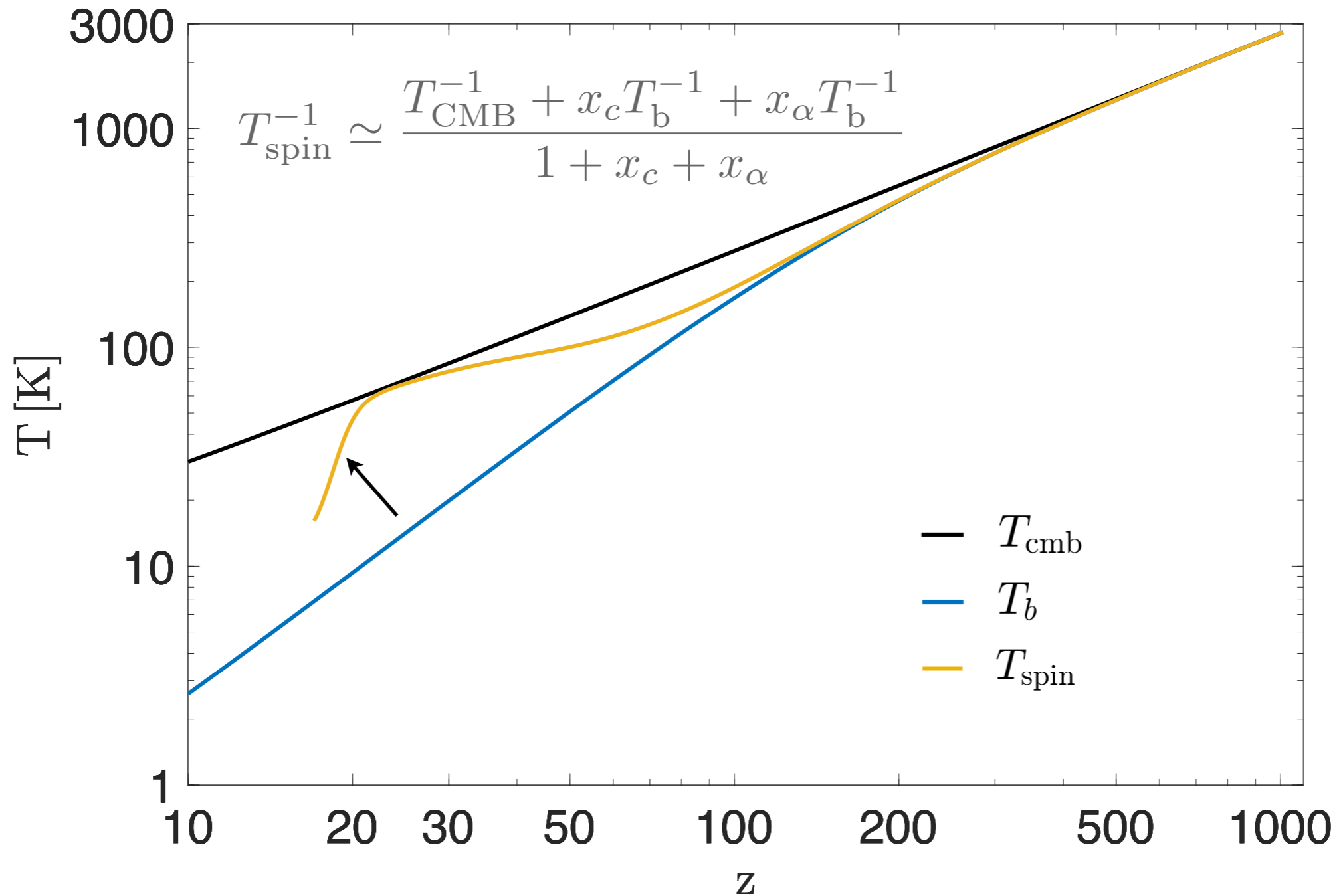


The Cosmological 21cm Signal: Lightning Review



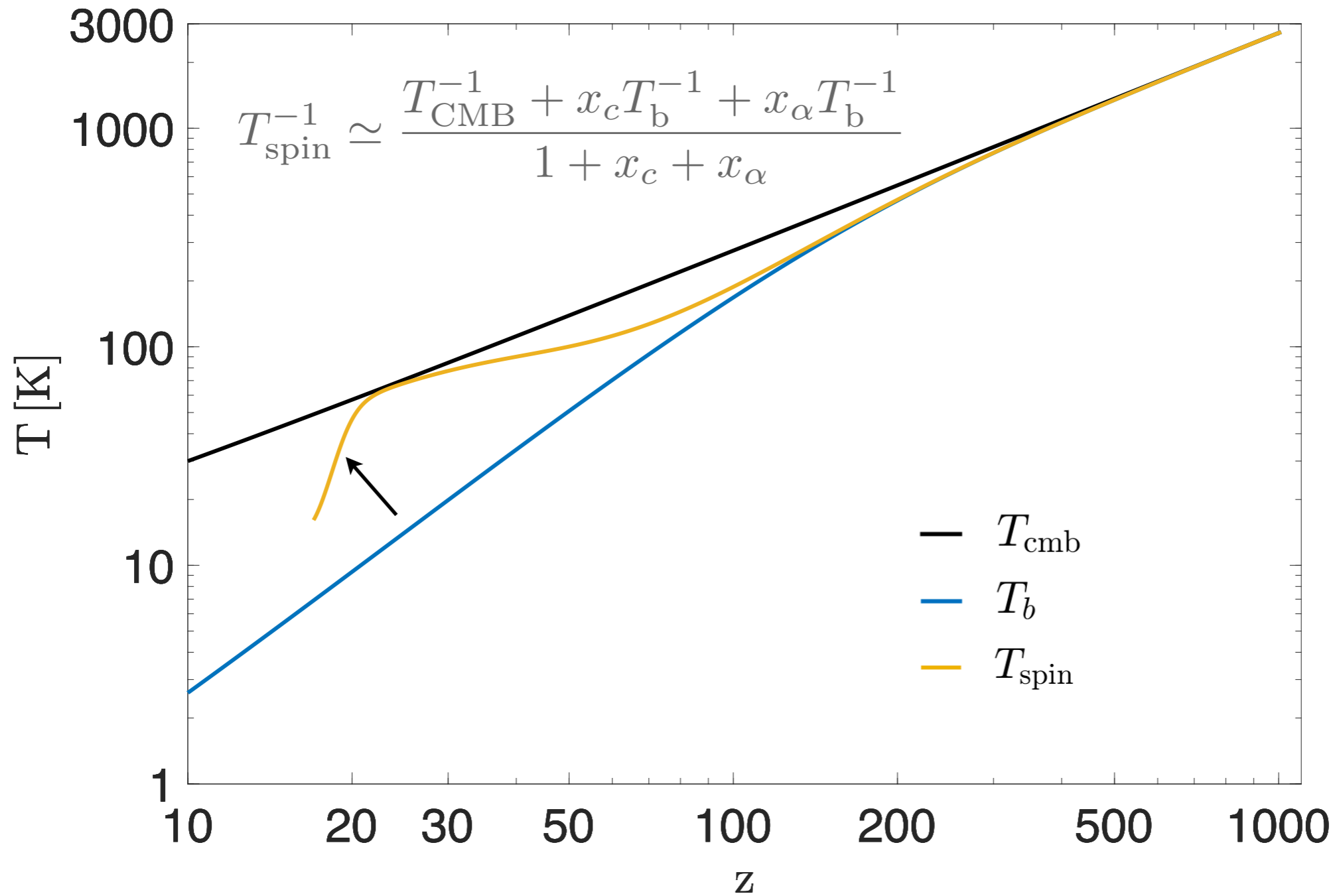
Absorption: (1) $T_{\text{spin}} < T_{\text{CMB}}$ (Dark Ages)

The Cosmological 21cm Signal: Lightning Review

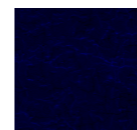


Absorption: (1) $T_{\text{spin}} < T_{\text{CMB}}$ (Dark Ages)

The Cosmological 21cm Signal: Lightning Review



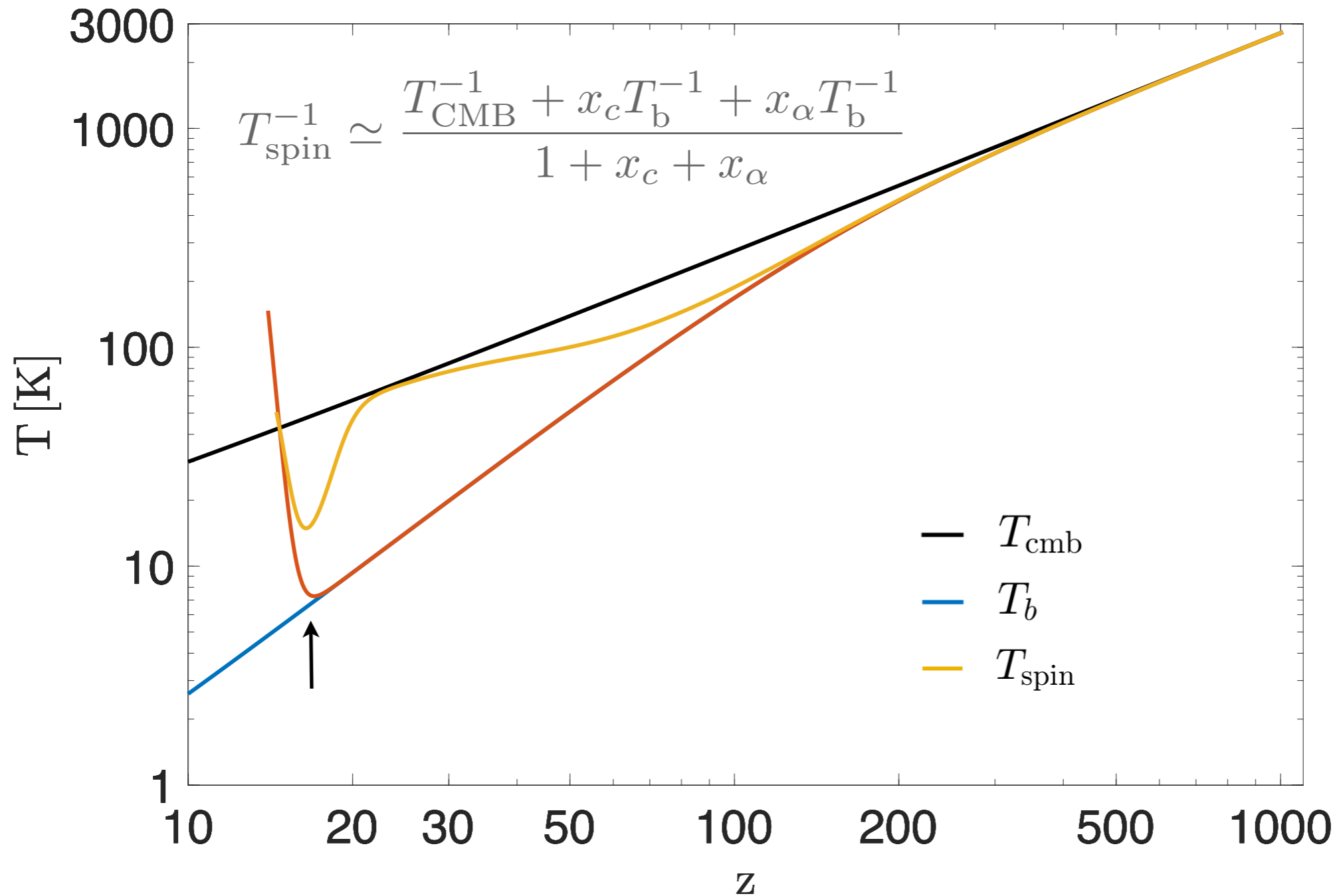
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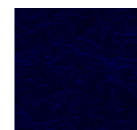
(2) $T_{\text{spin}} < T_{\text{CMB}}$ (Cosmic Dawn)



The Cosmological 21cm Signal: Lightning Review



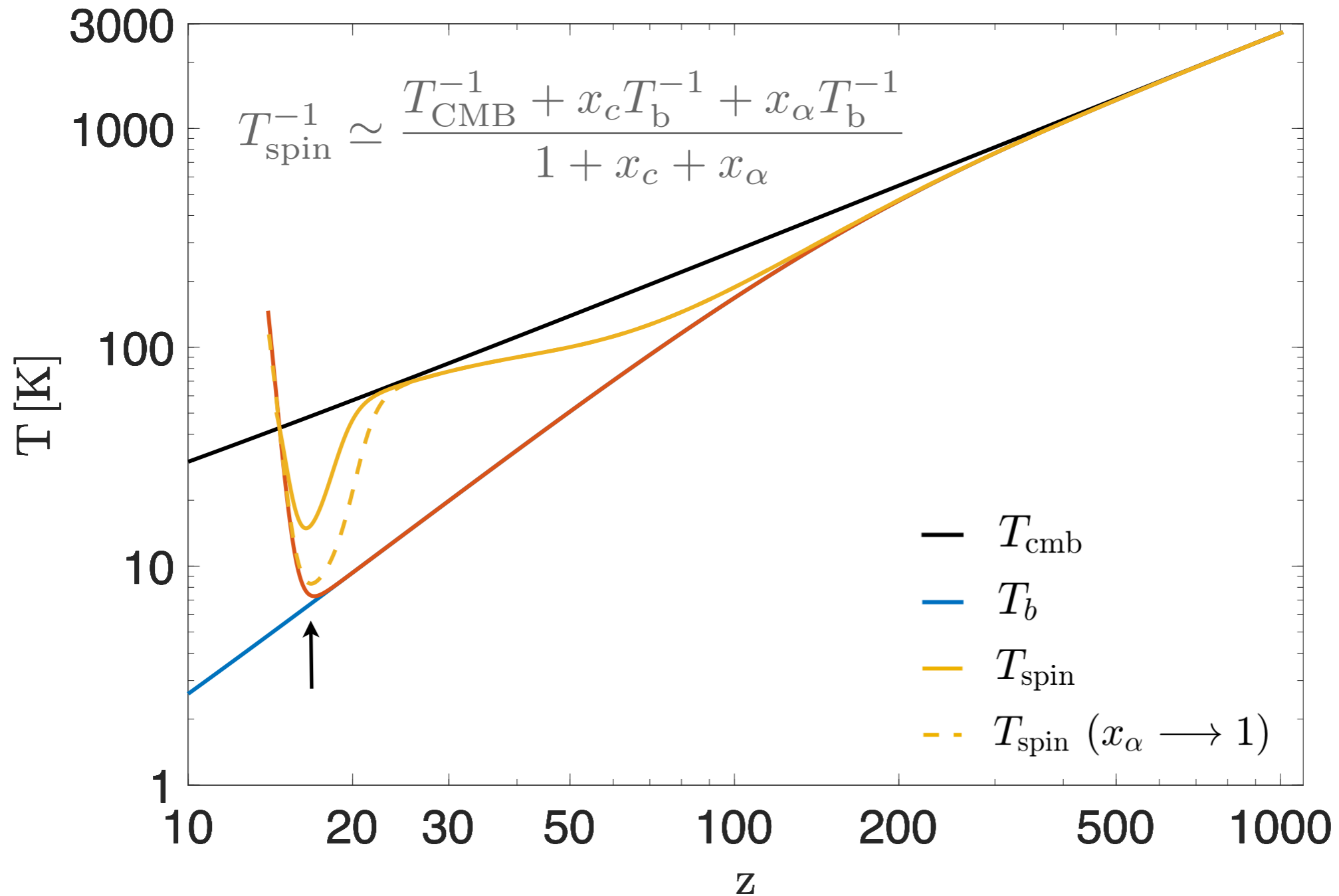
Absorption: (1) $T_{\text{spin}} < T_{\text{CMB}}$ (Dark Ages)



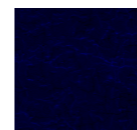
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The Cosmological 21cm Signal: Lightning Review



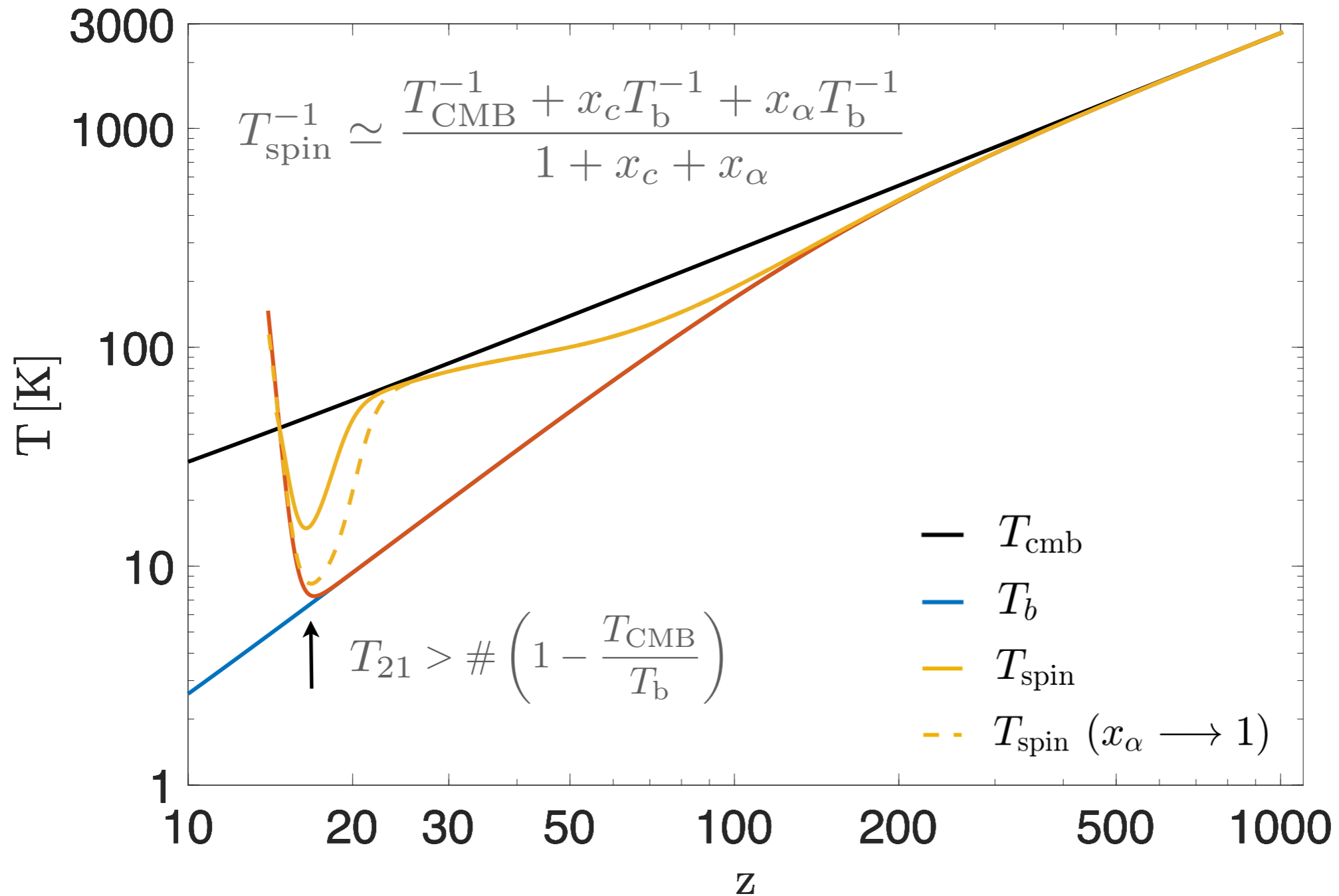
Absorption: (1) $T_{\text{spin}} < T_{\text{CMB}}$ (Dark Ages)



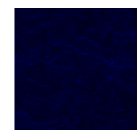
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The Cosmological 21cm Signal: Lightning Review



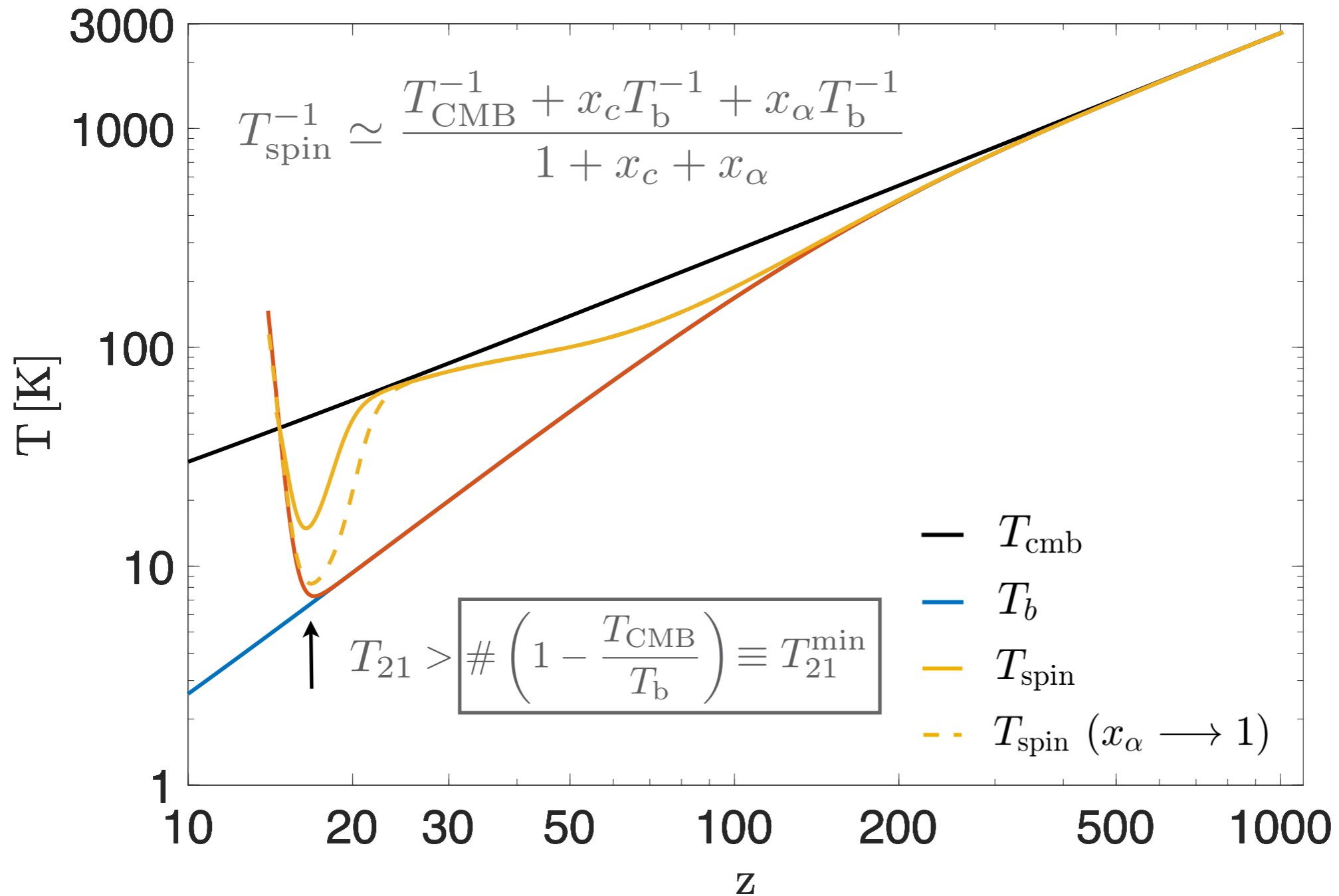
Absorption: (1) $T_{\text{spin}} < T_{\text{CMB}}$ (Dark Ages)



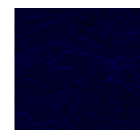
(2) $T_{\text{spin}} < T_{\text{CMB}}$ (Cosmic Dawn)



The Cosmological 21cm Signal: Lightning Review



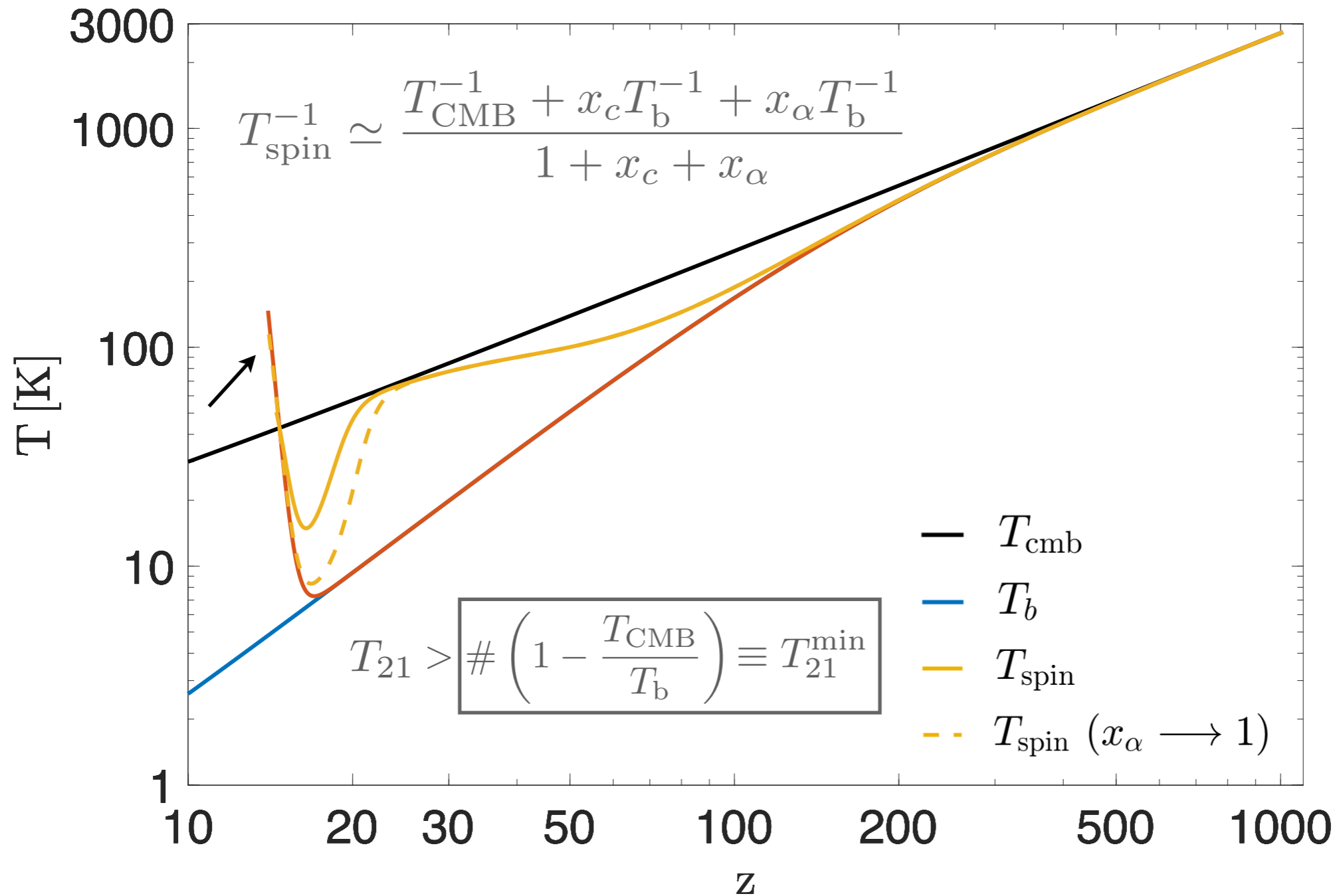
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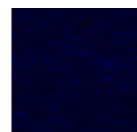
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The Cosmological 21cm Signal: Lightning Review



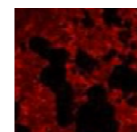
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Emission: $T_{\text{spin}} > T_{\text{CMB}}$ (Reionization)



Measuring the Cosmic Dawn Global 21 cm Signal

Measuring the Cosmic Dawn Global 21 cm Signal

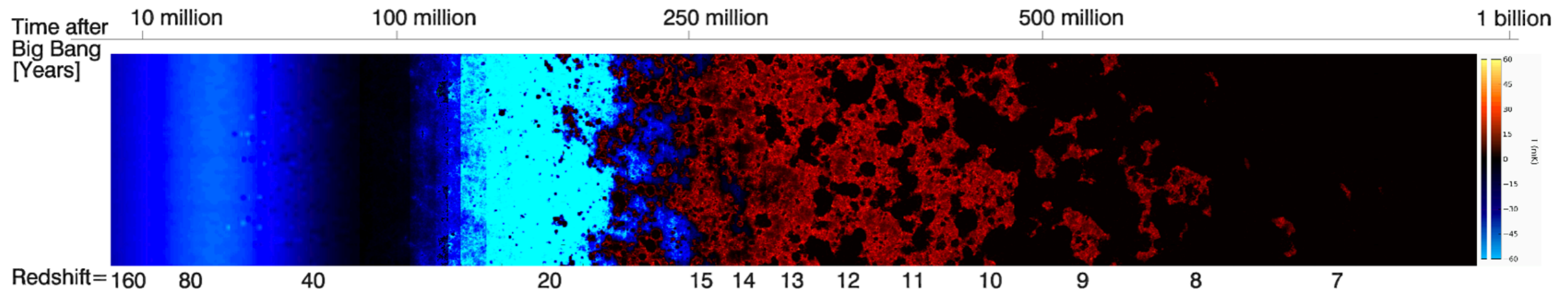
The observable:

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

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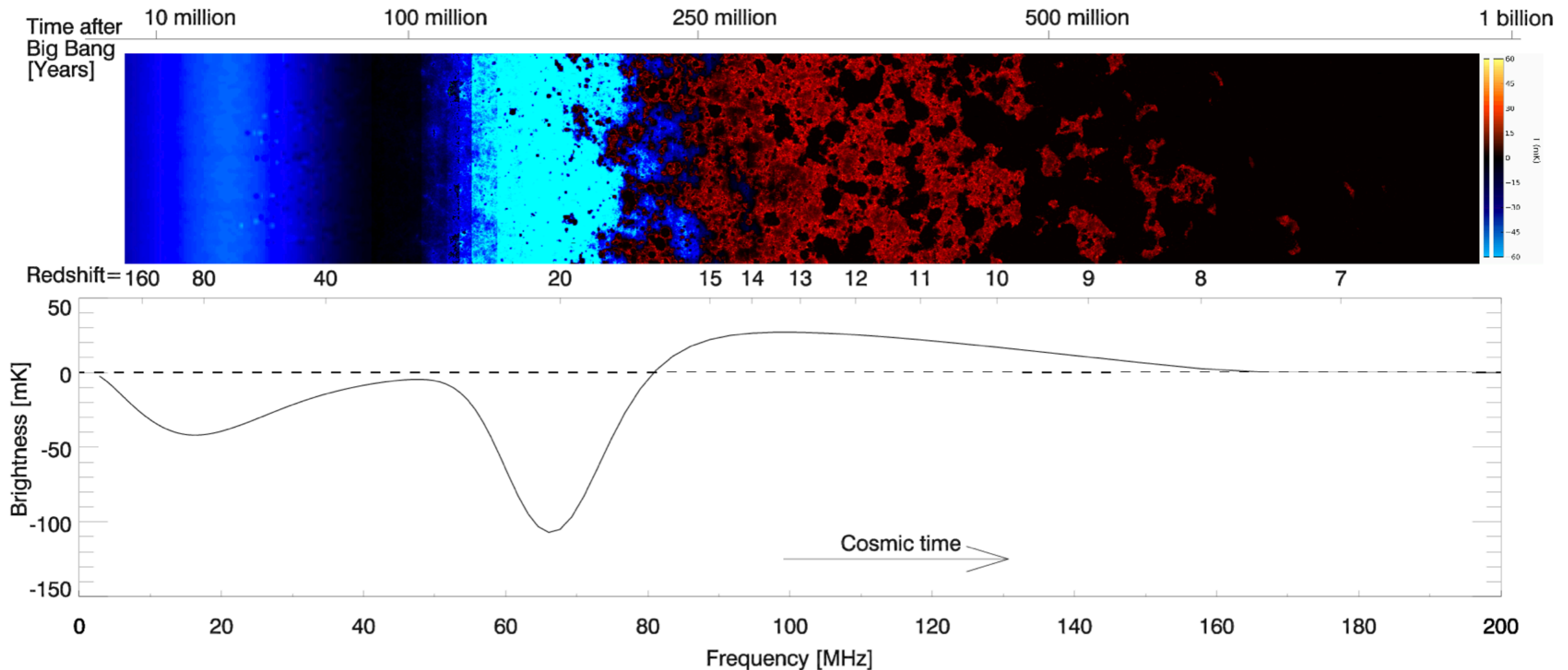
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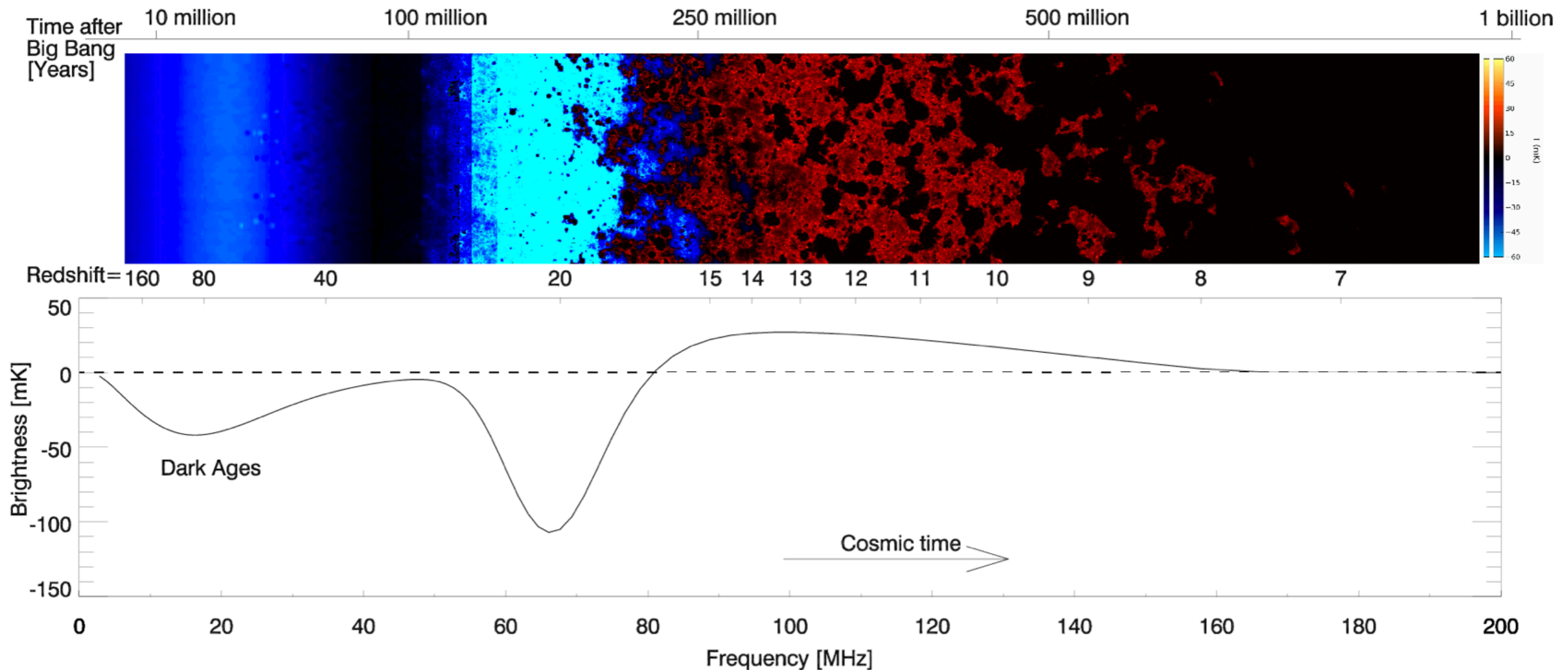


Credit: J. Pritchard

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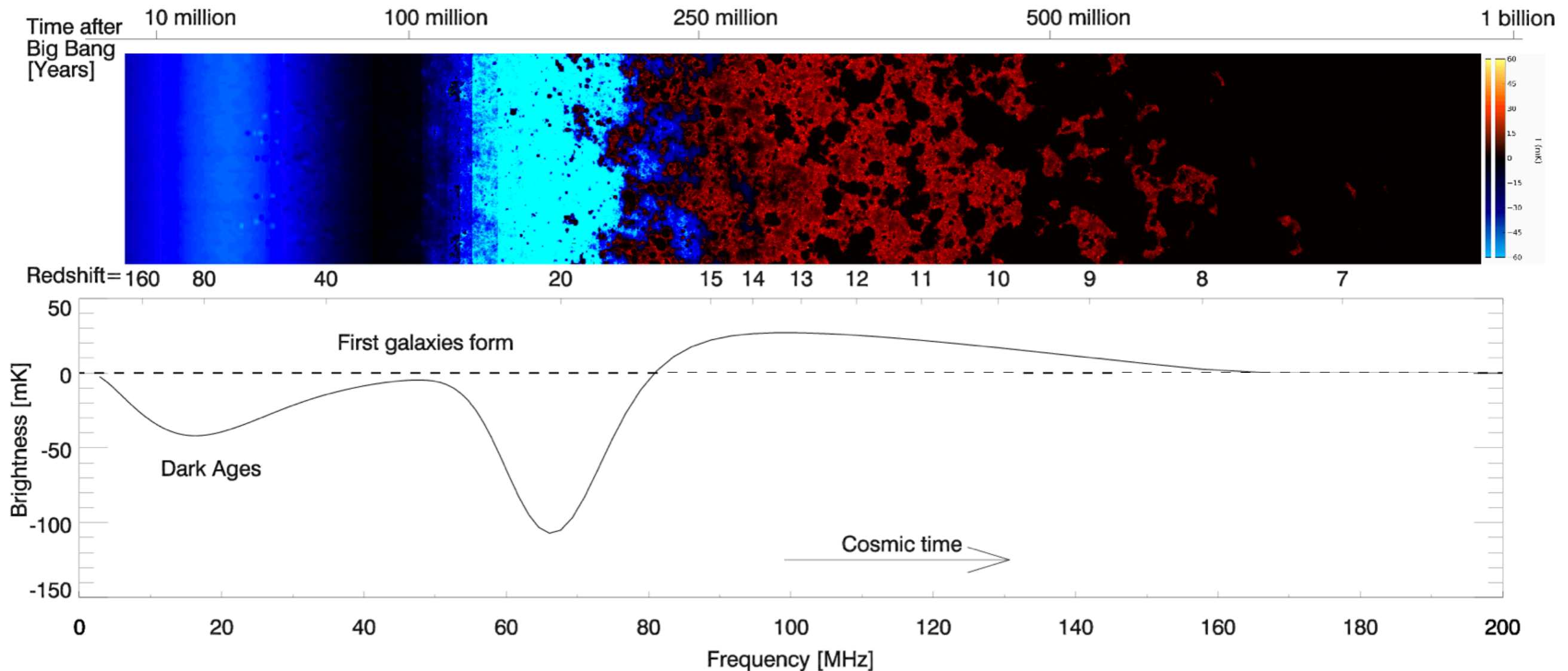


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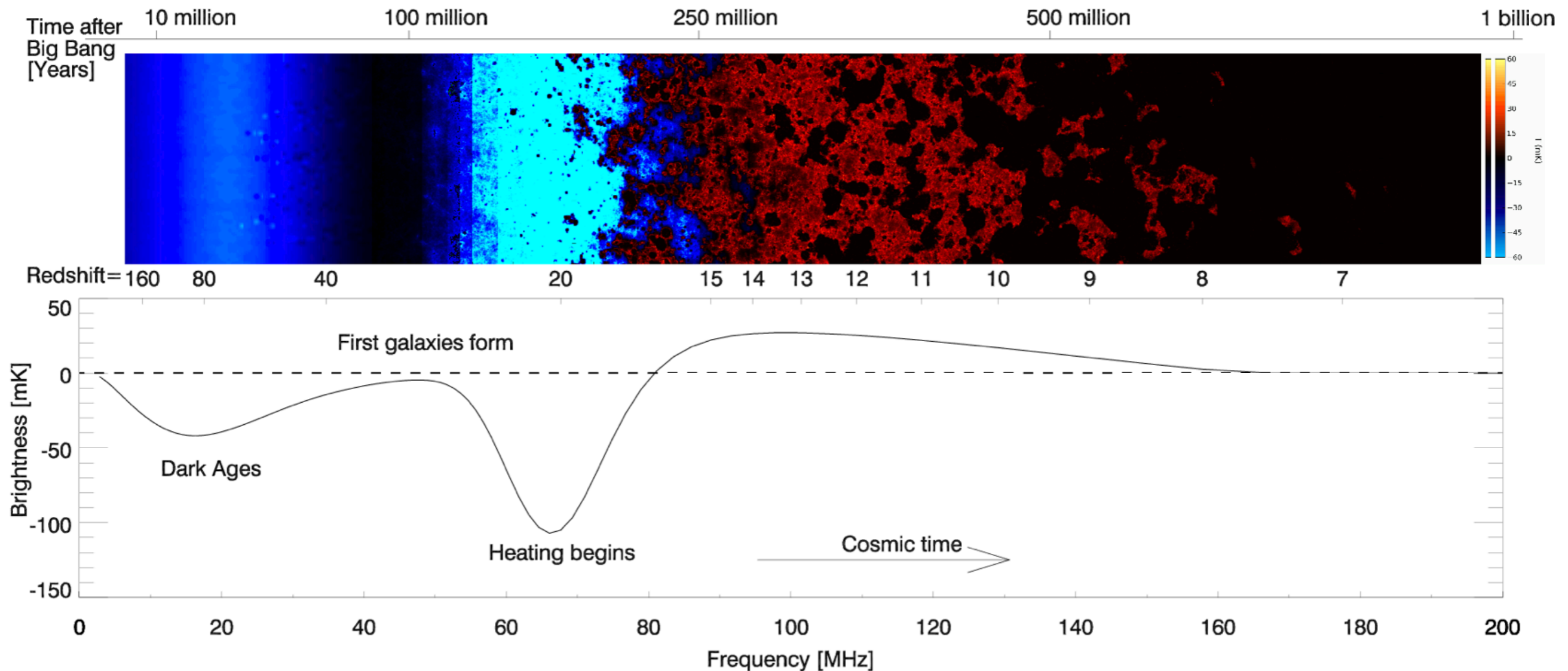


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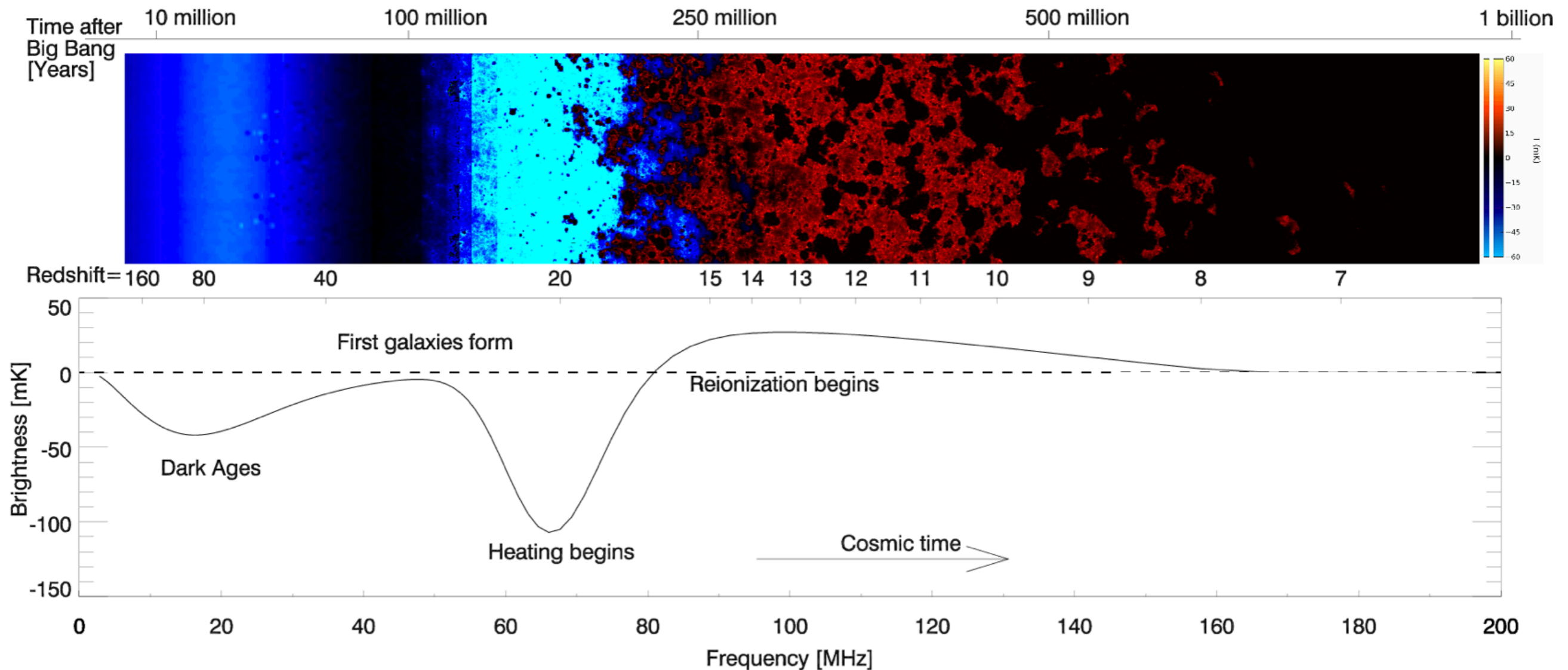


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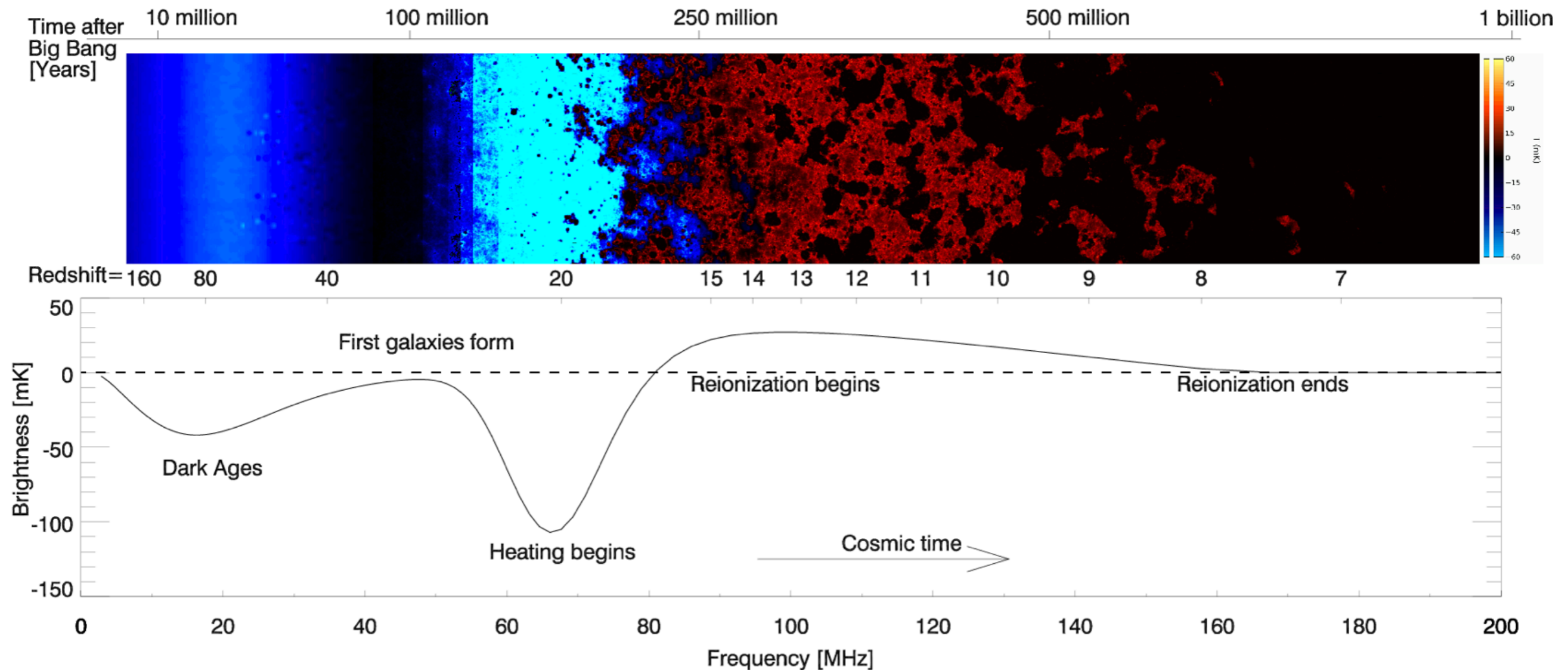


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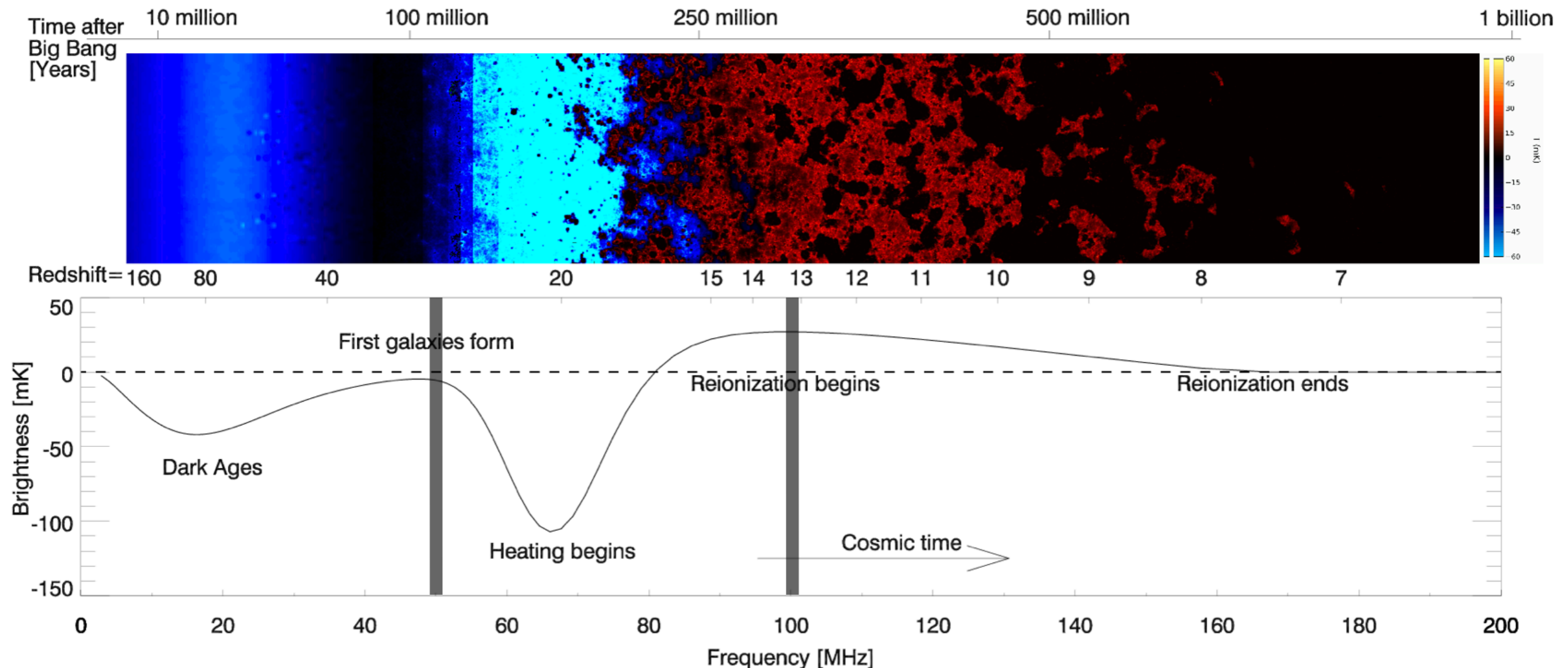


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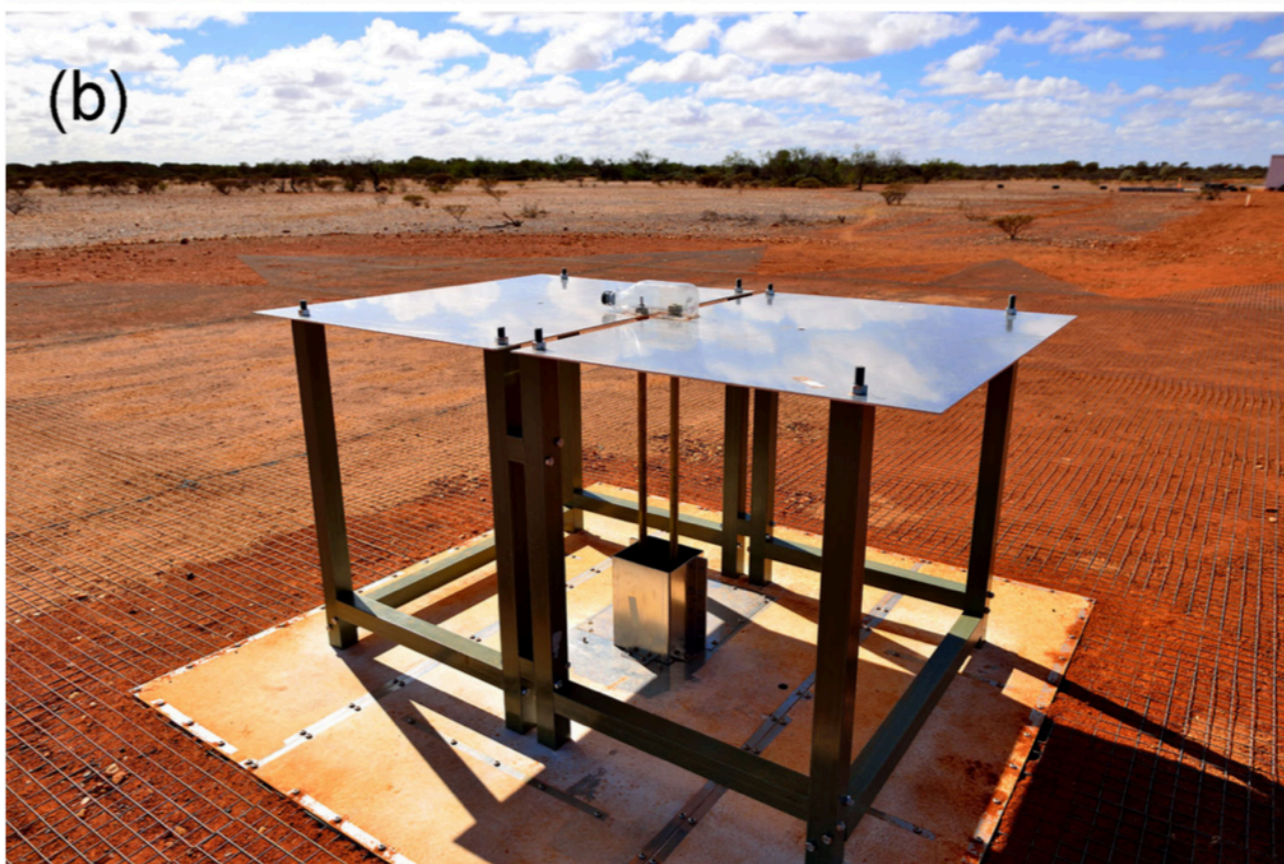
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EDGES Low-Band

Credit: J. Pritchard

Experiment to Detect the Global Epoch of Reionization Signature



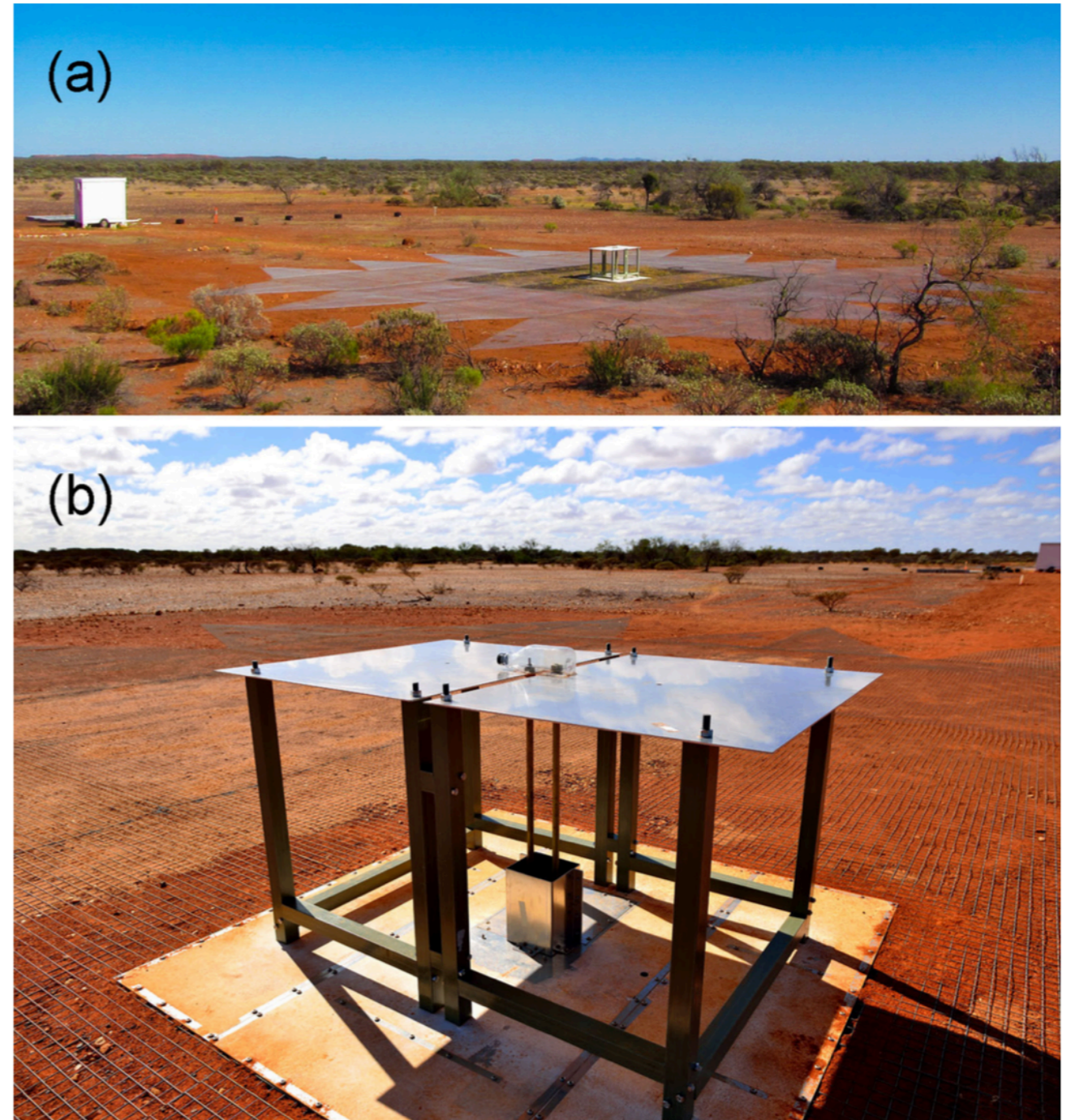
Experiment to Detect the Global Epoch of Reionization Signature



Credit: Bowman et al. 2018

Experiment to Detect the Global Epoch of Reionization Signature

Led by Bowman (ASU), Rogers (MIT):



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Led by Bowman (ASU), Rogers (MIT):

- Located in western Australia (low RFI)



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Experiment to Detect the Global Epoch of Reionization Signature

Led by Bowman (ASU), Rogers (MIT):

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- Cheap instrument (roughly \$2M price tag)

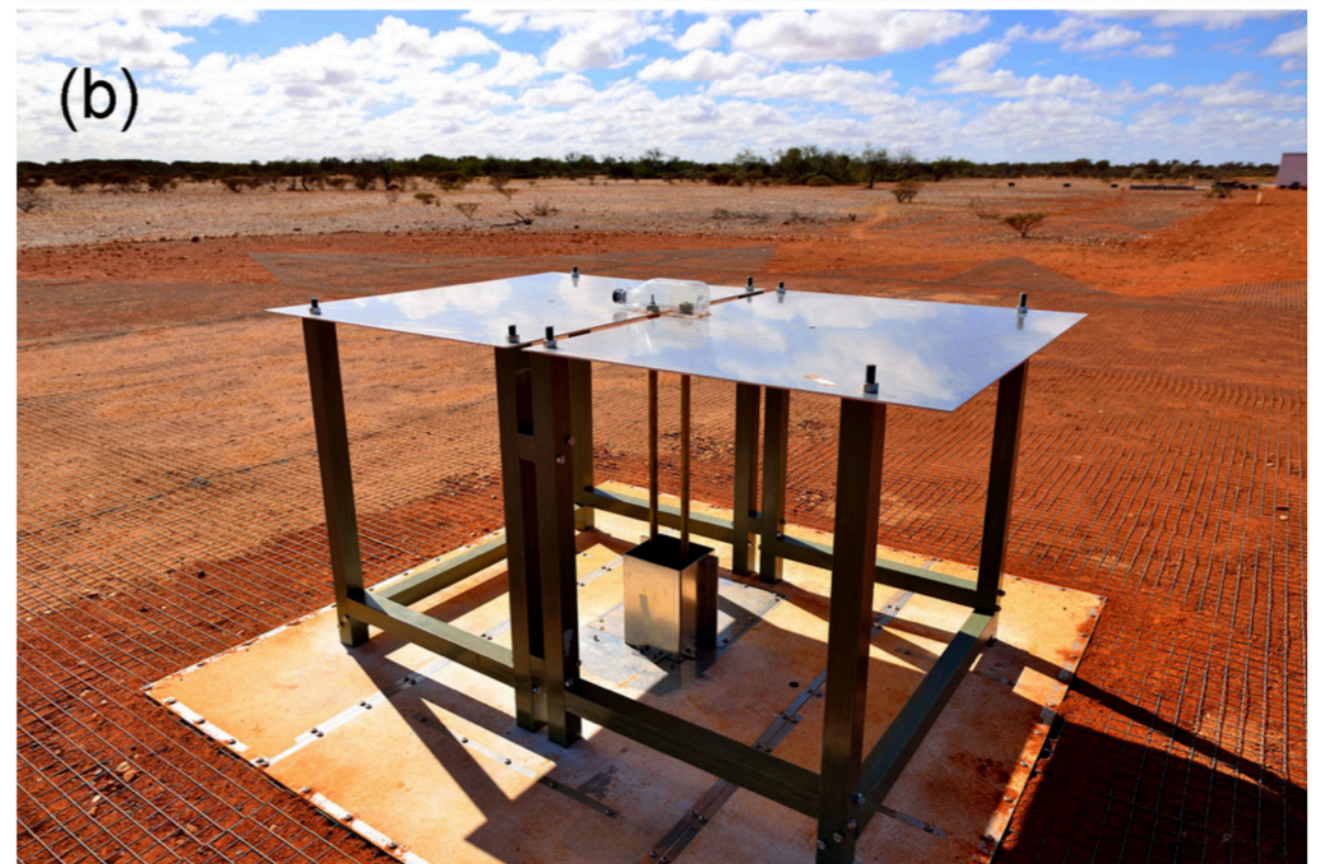


Credit: Bowman et al. 2018

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Led by Bowman (ASU), Rogers (MIT):

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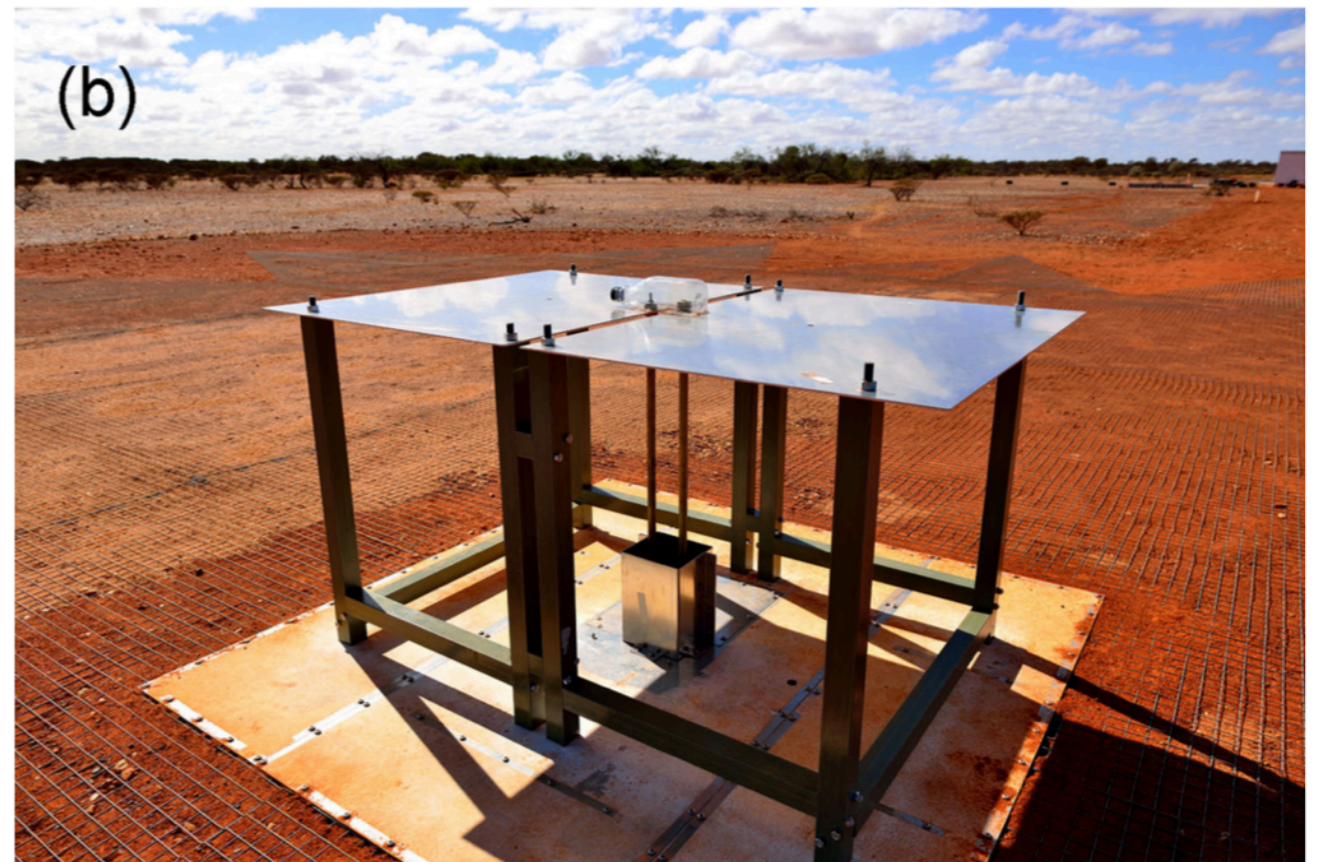


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- Two identical instruments, placed 150m apart



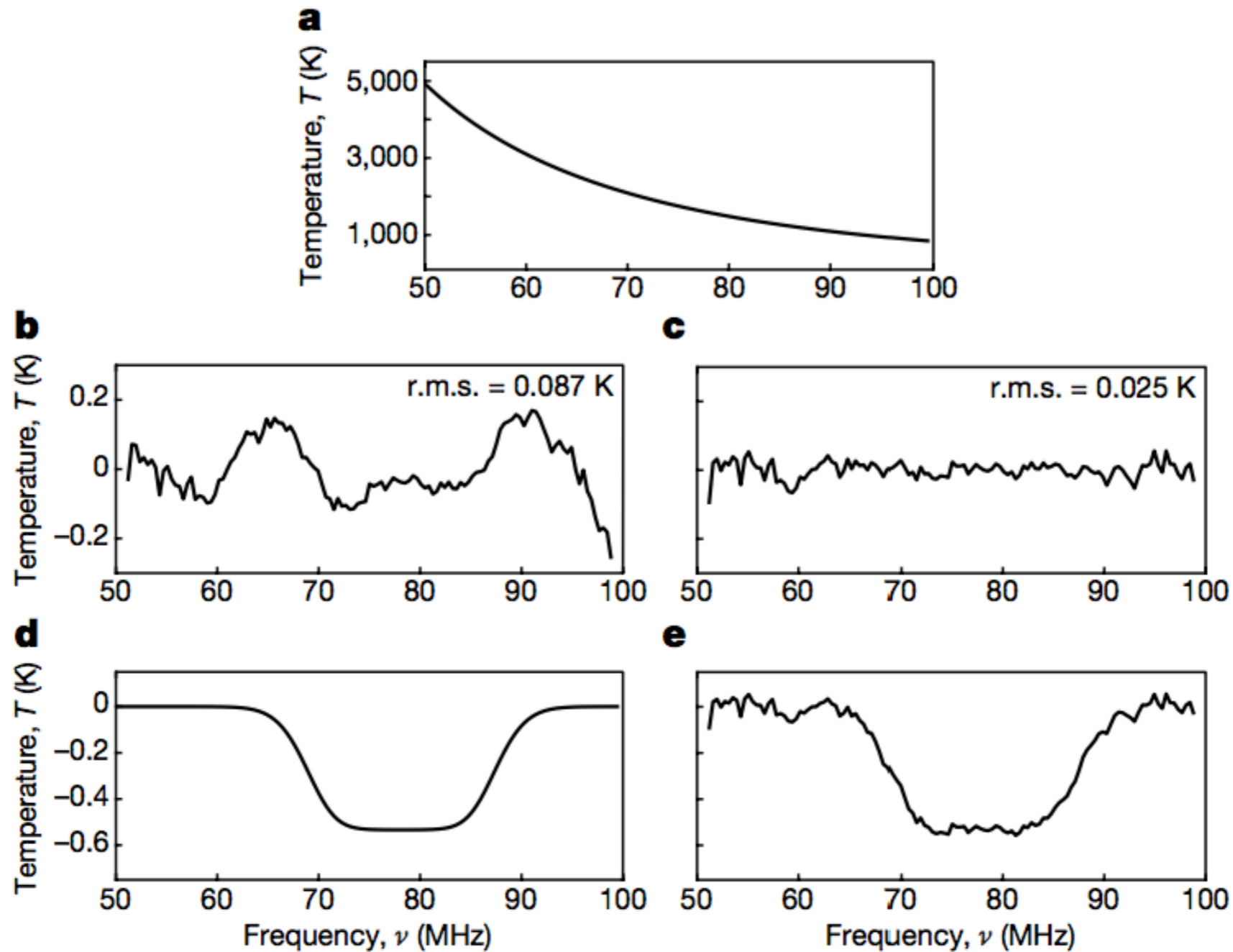
Credit: Bowman et al. 2018

EDGES: First Claimed Detection of Cosmic Dawn

And it measured this:

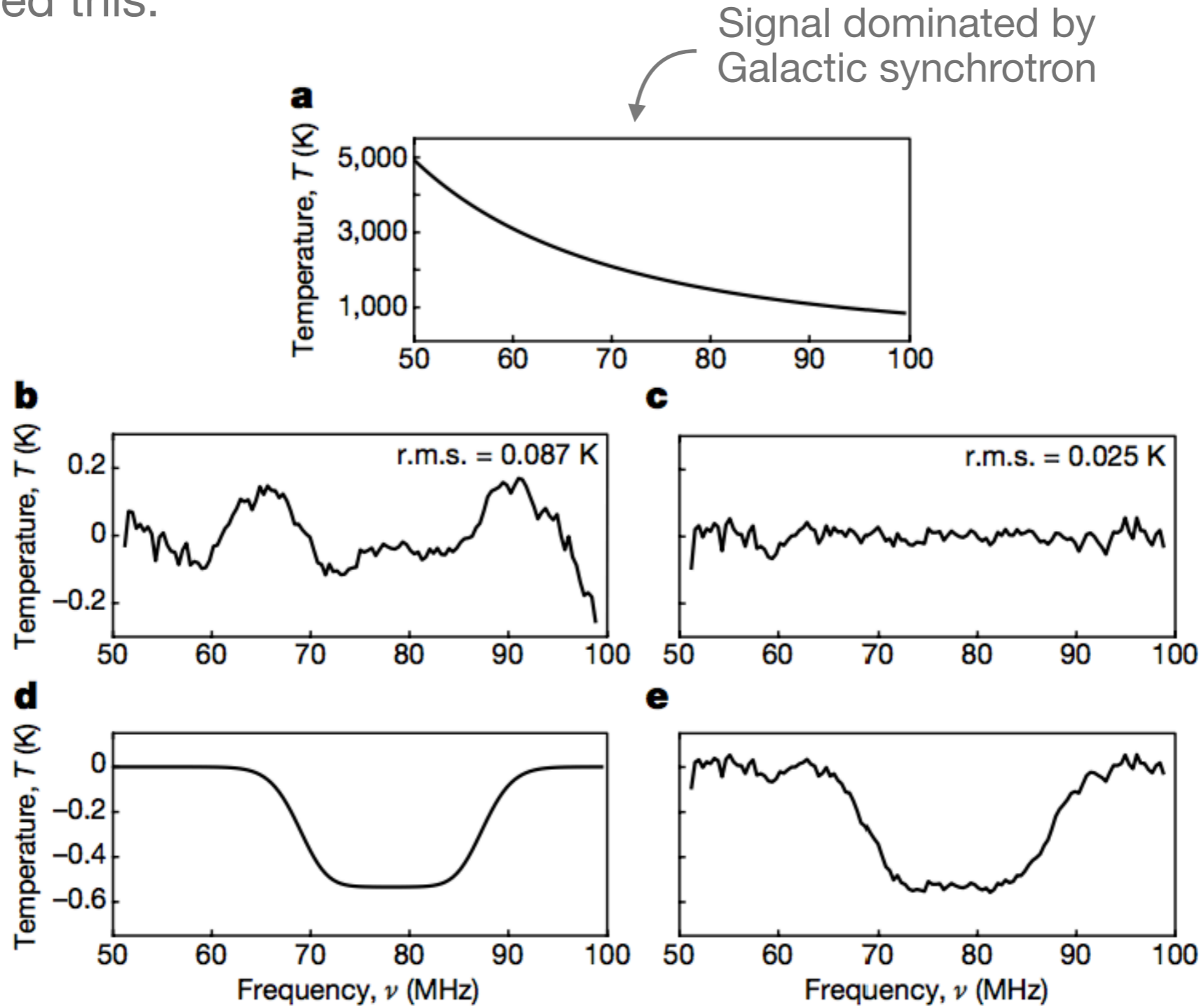
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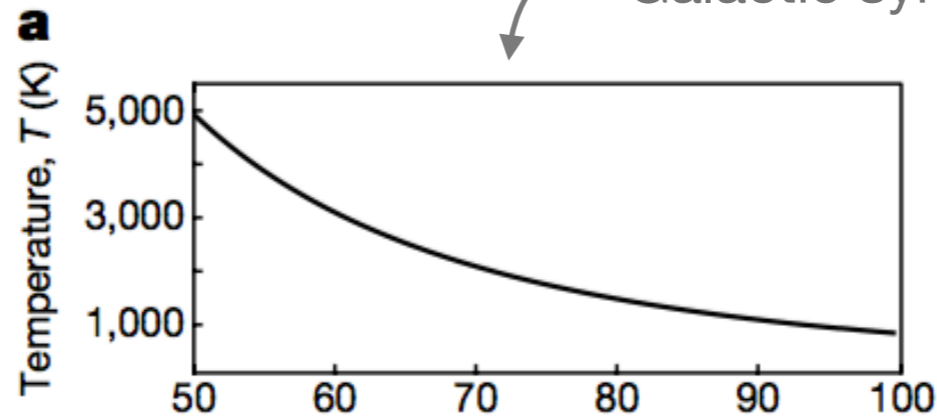
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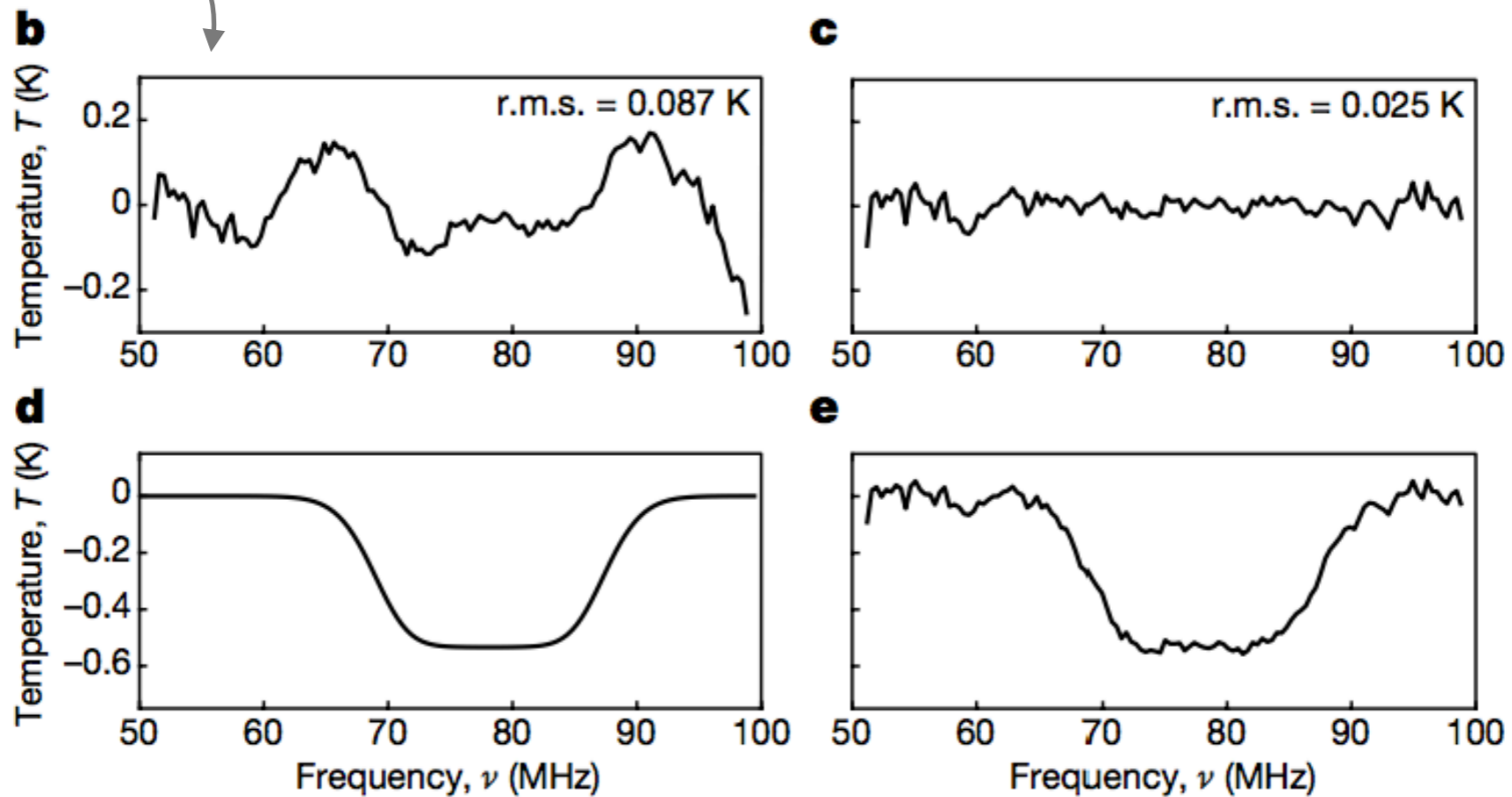
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Signal dominated by Galactic synchrotron



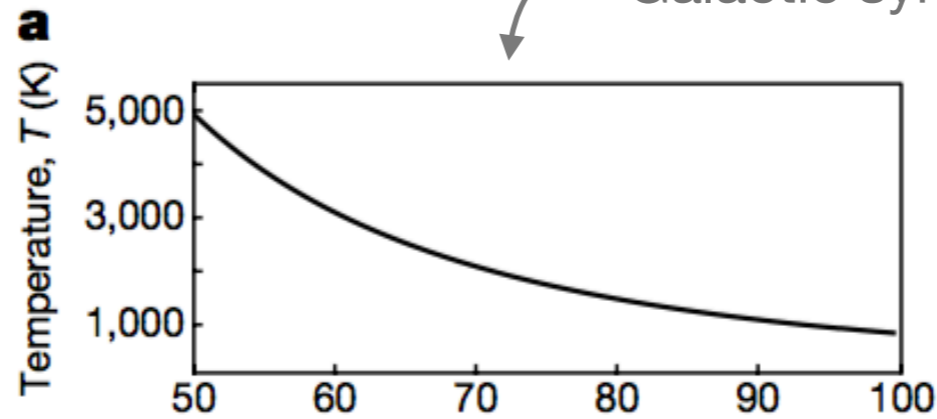
Residuals After Foreground Removal



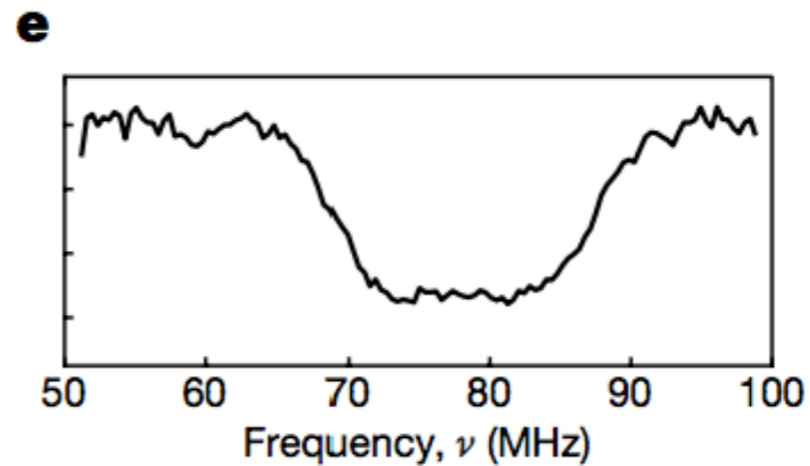
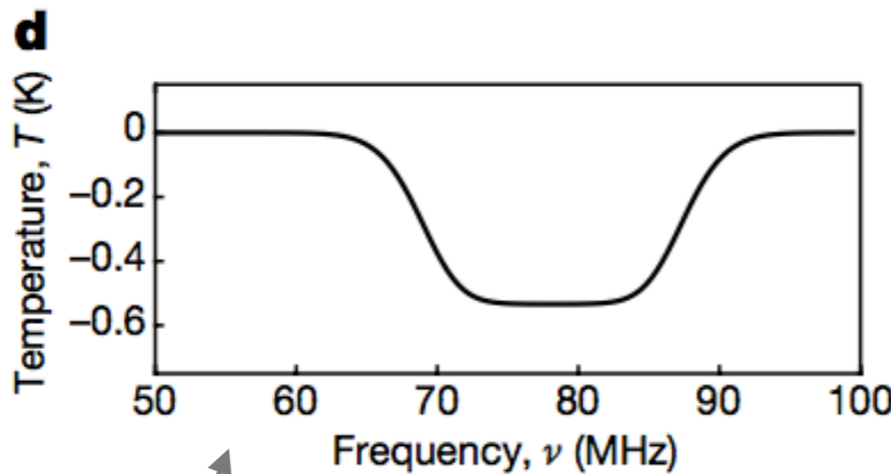
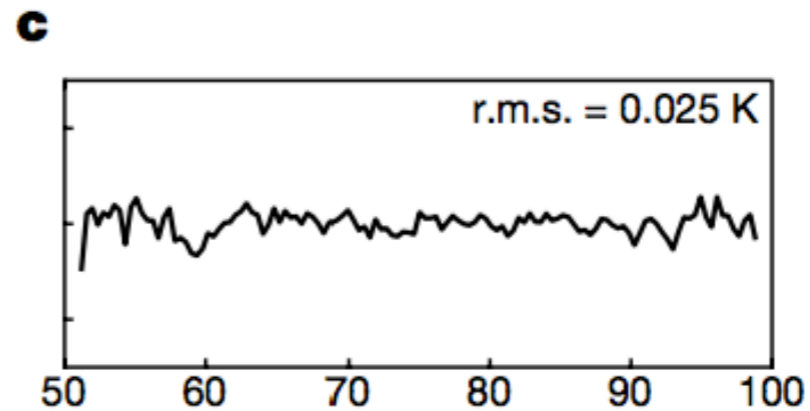
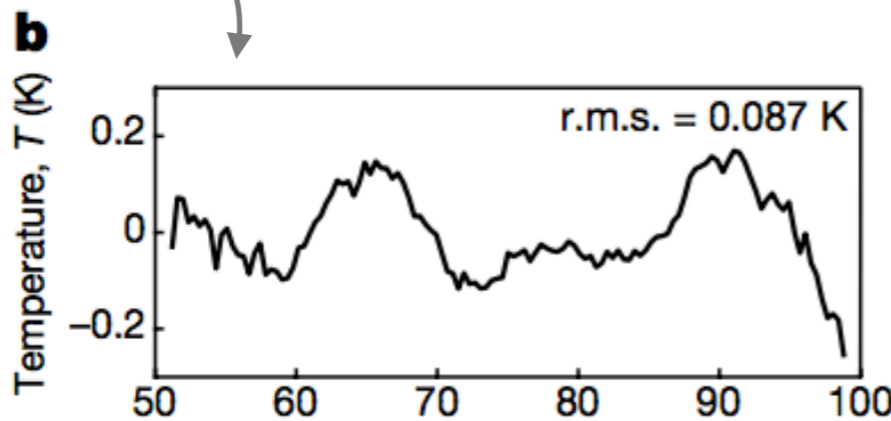
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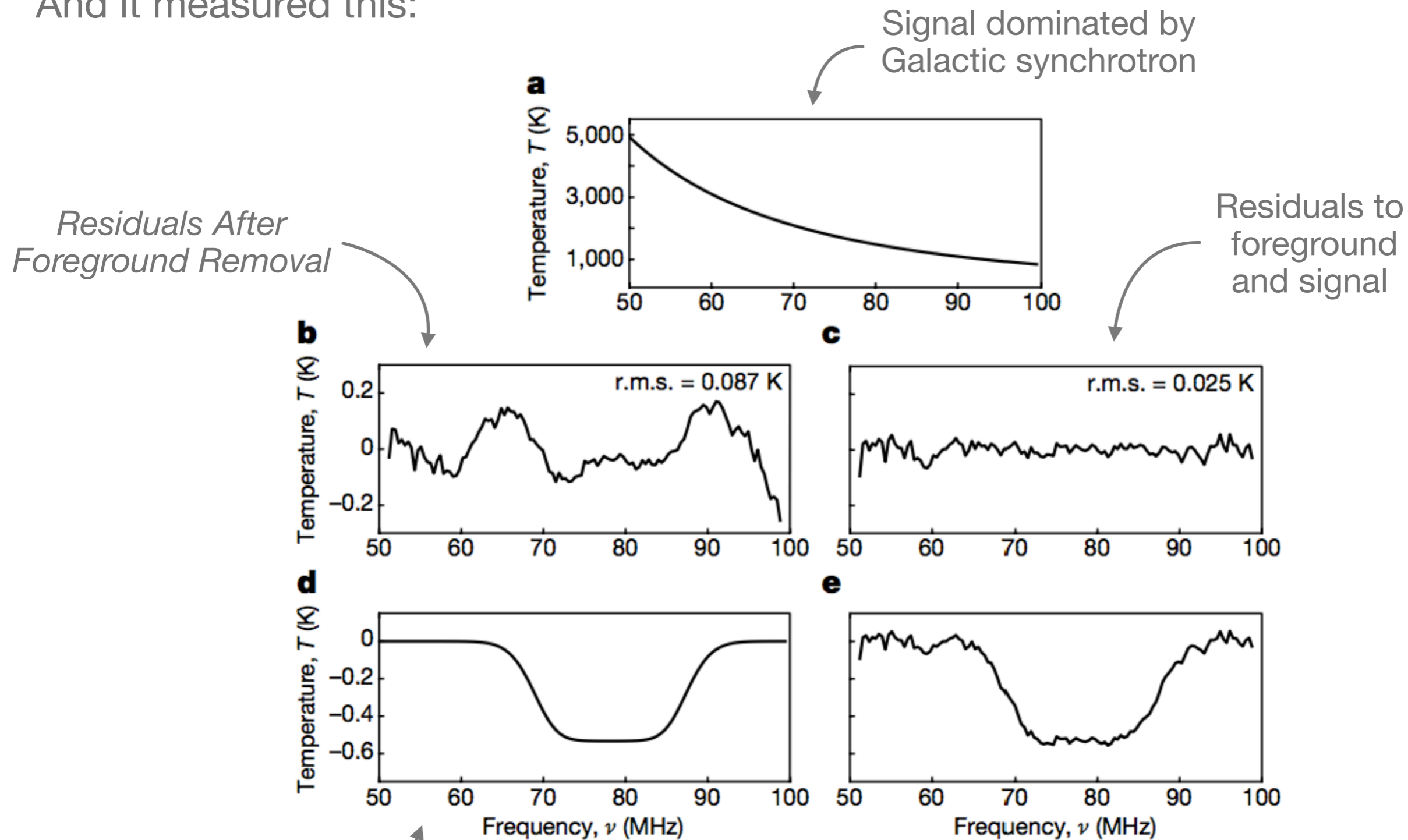


Best-fit 21cm model

Bowman et al., Nature (2018)

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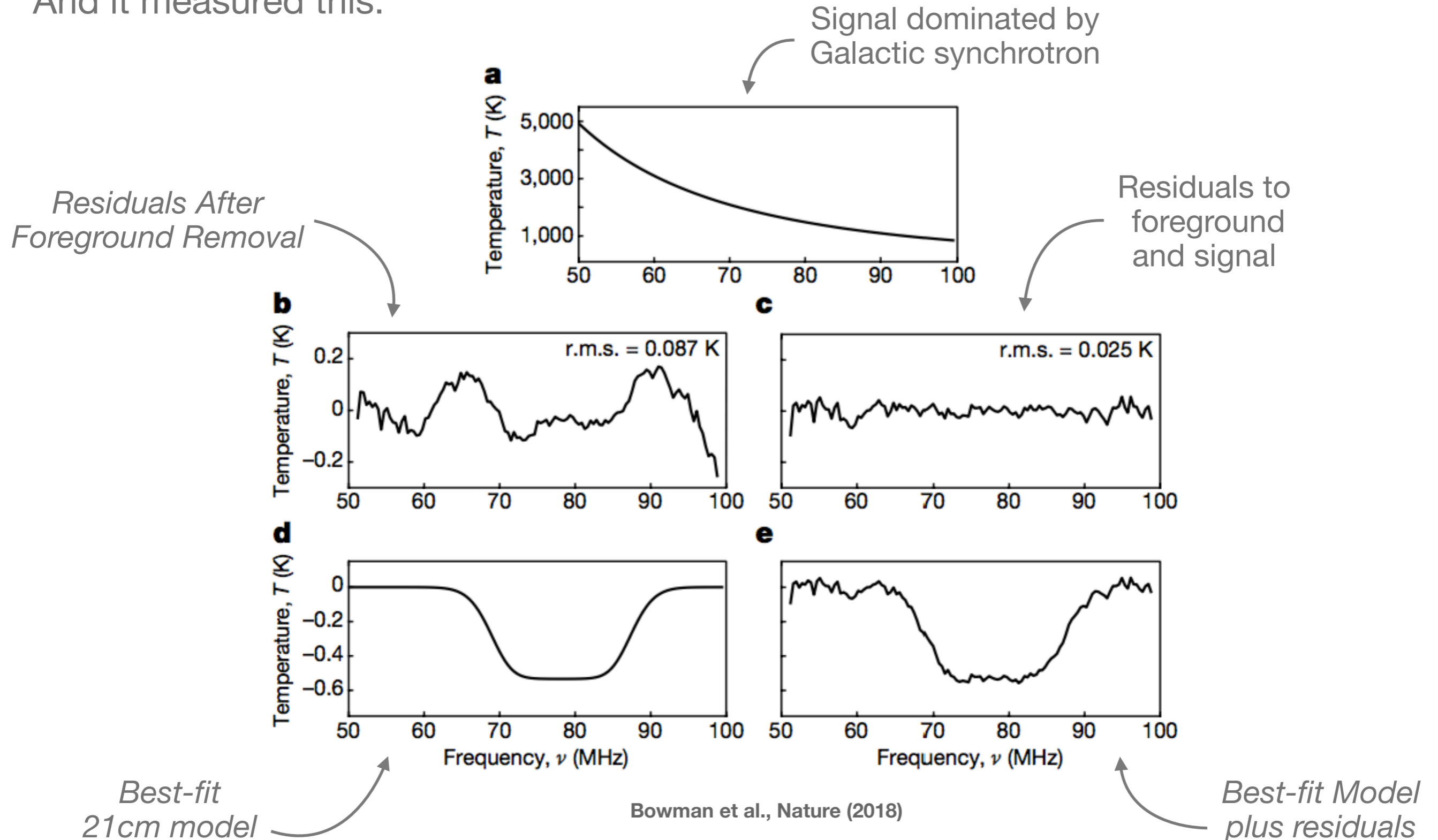
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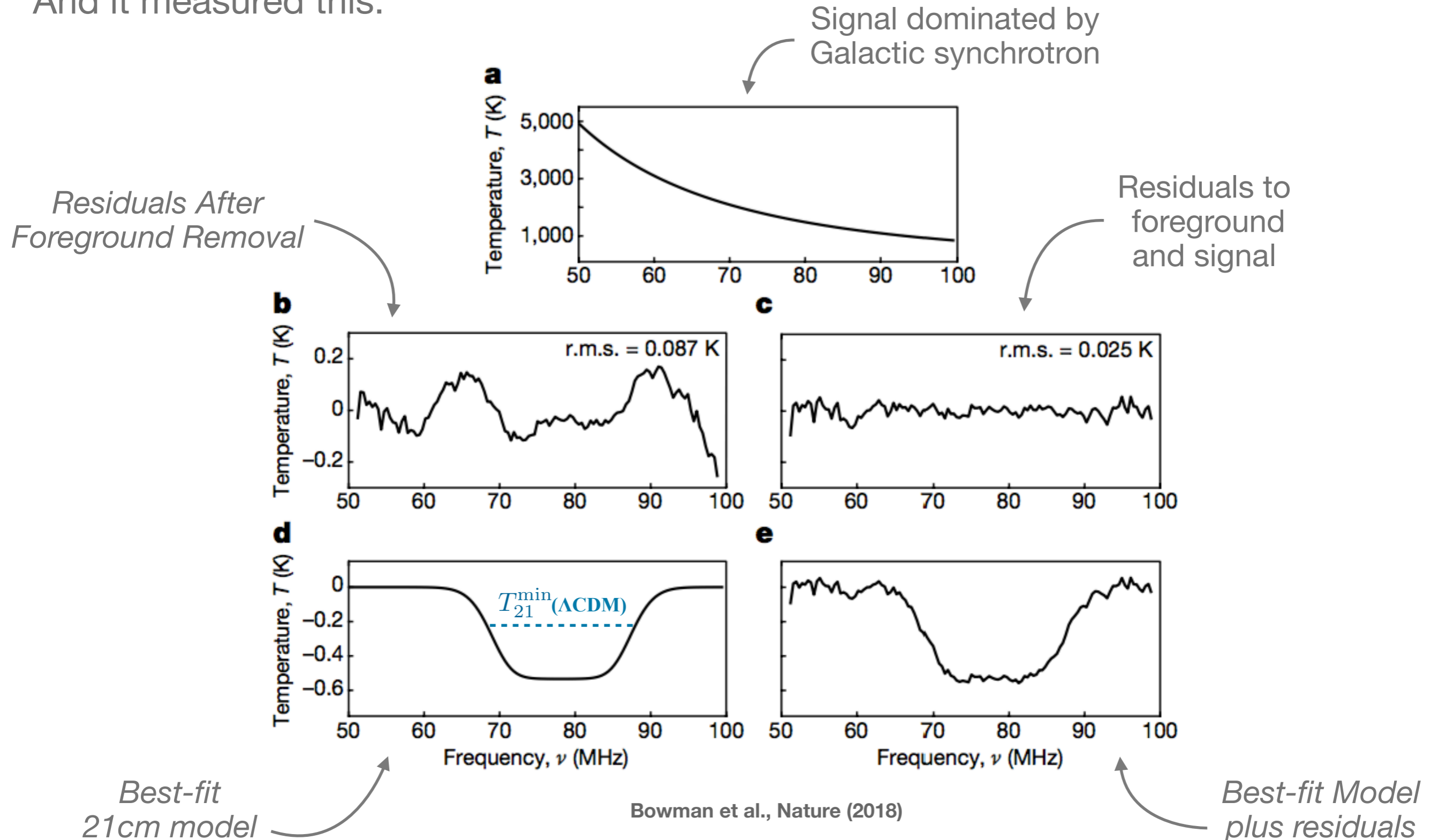
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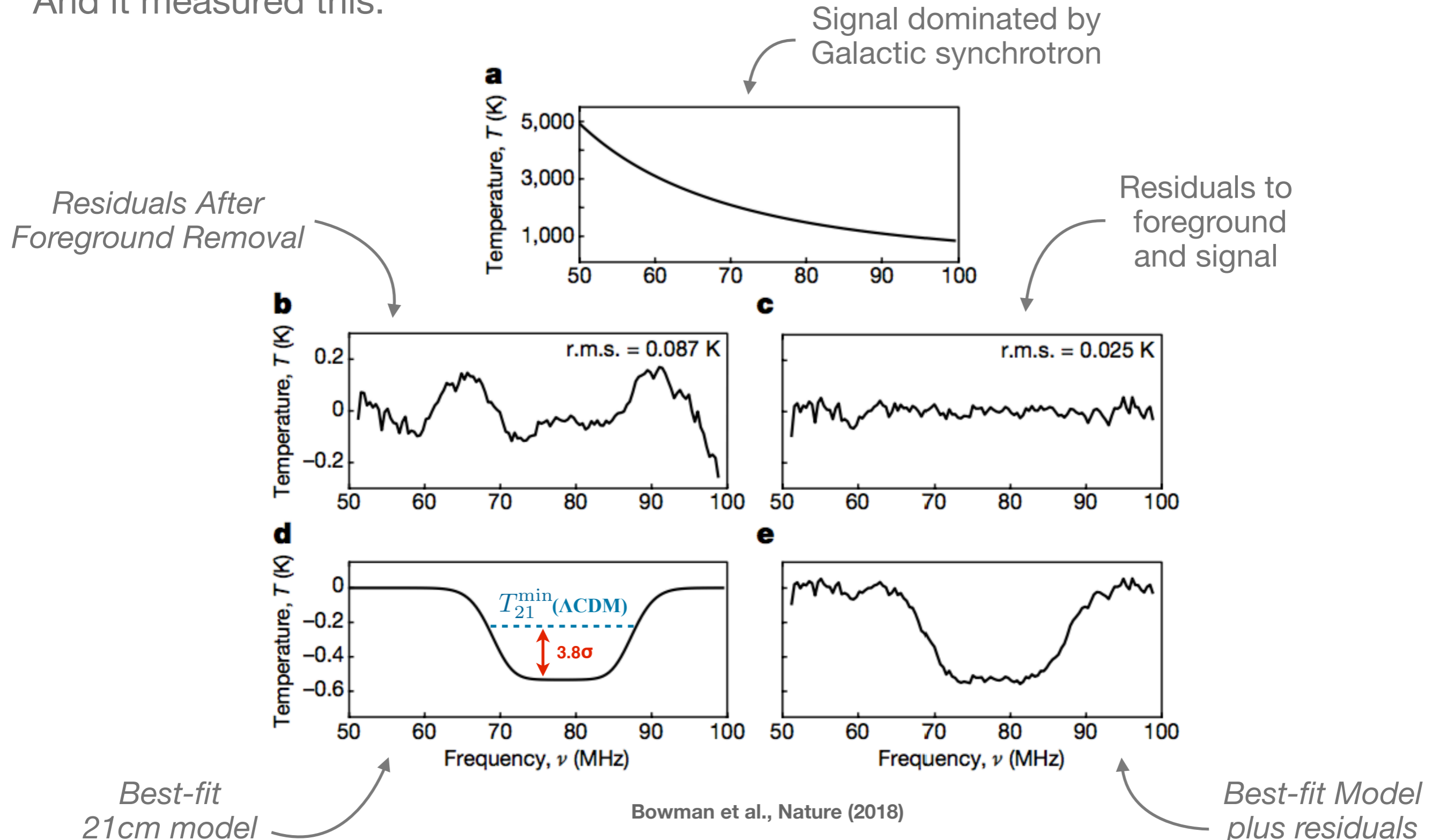
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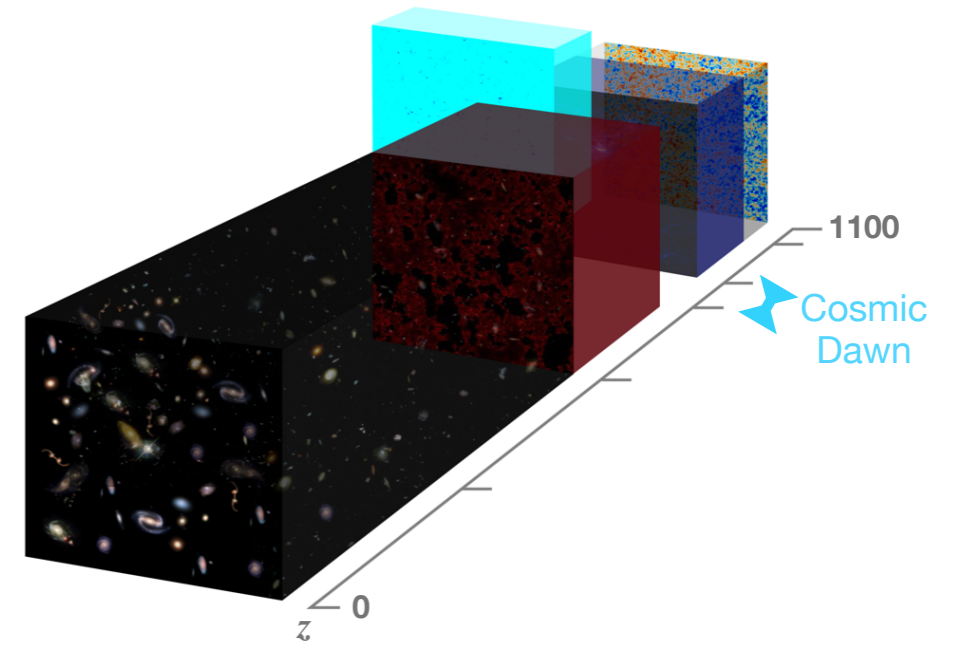
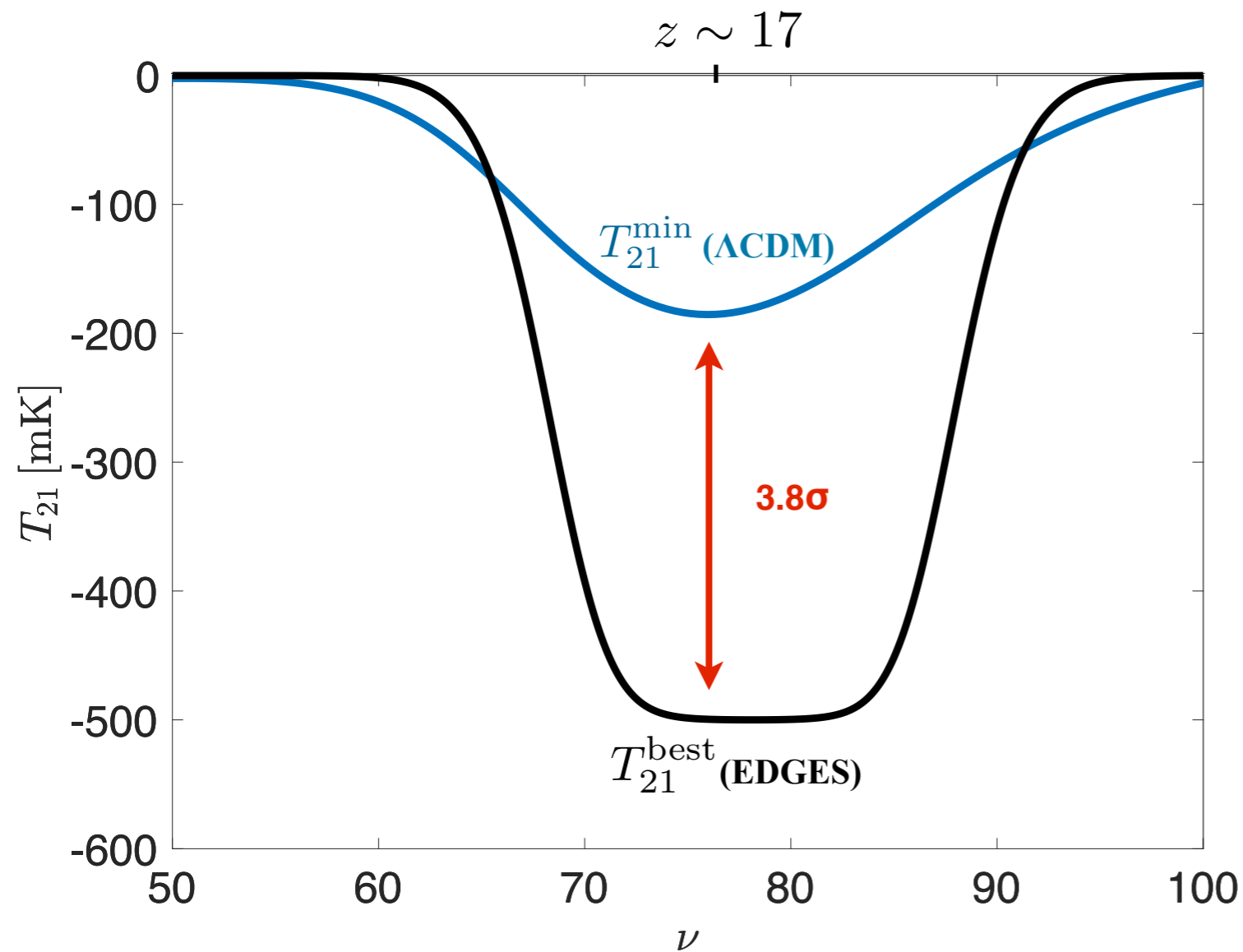


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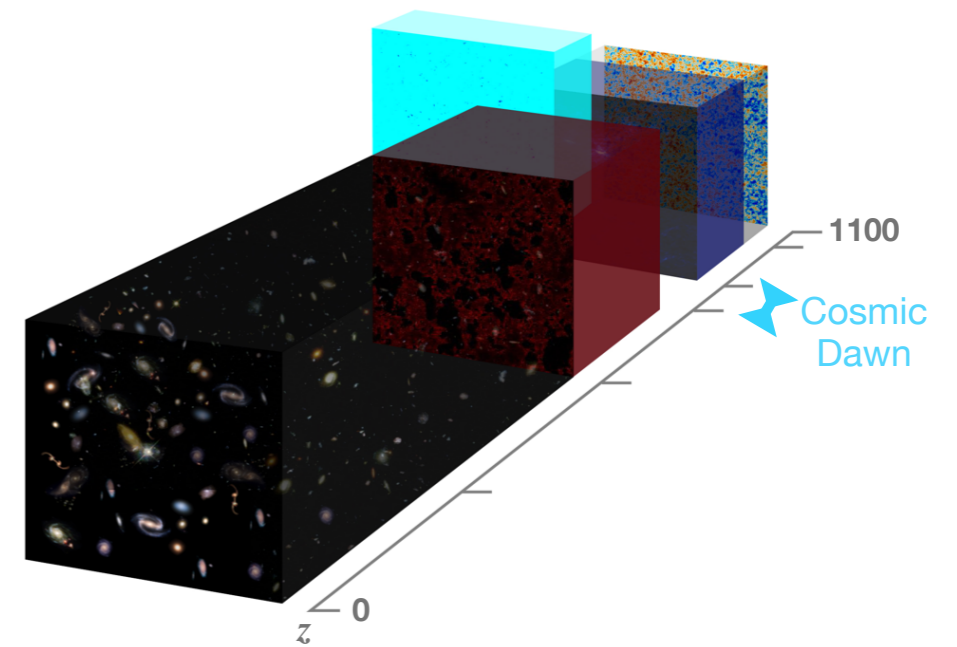
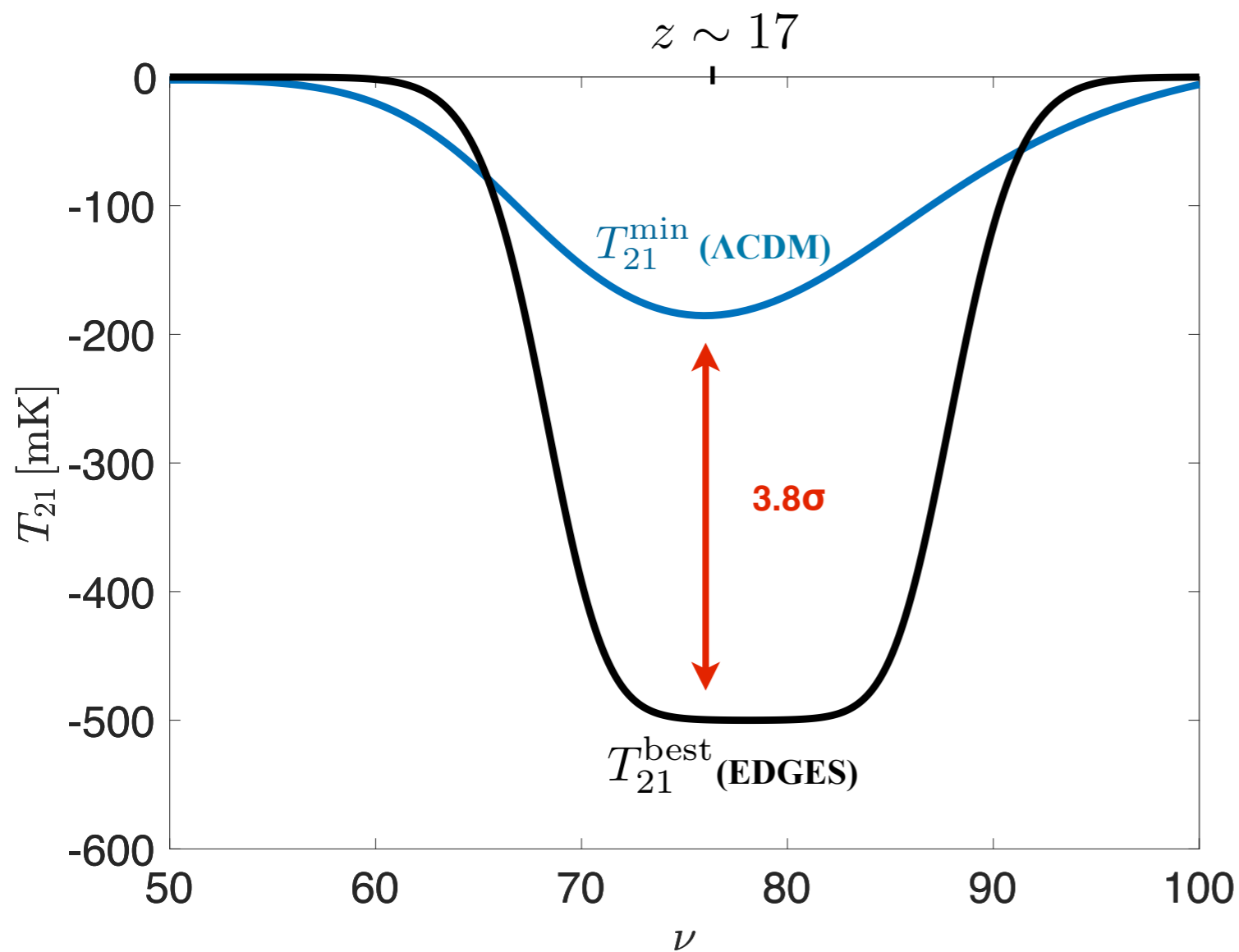
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Q: Can Dark Matter Explain the EDGES Signal?

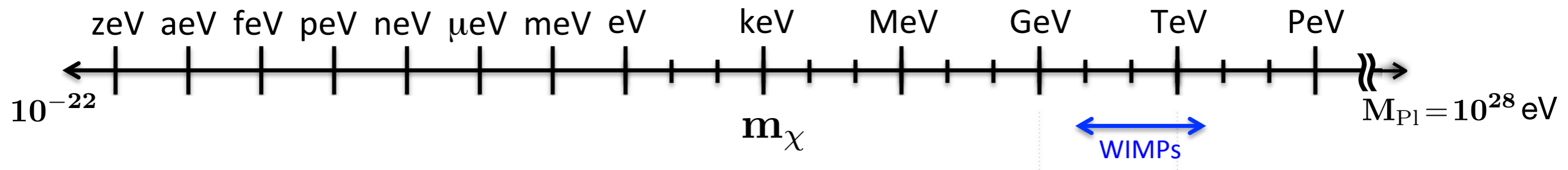


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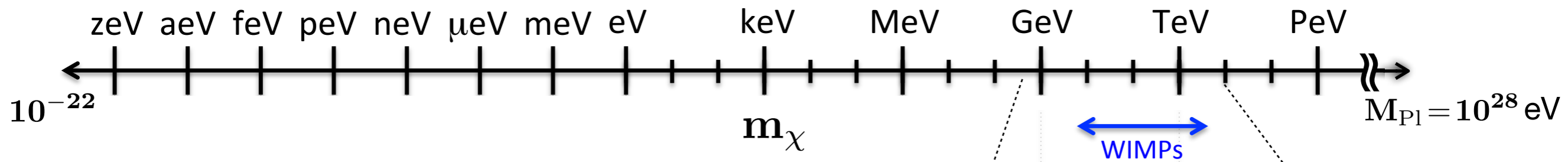
Signatures of Dark Matter-Baryon Scattering

(Muñoz, EDK and Ali-Haïmoud, PRD 2015)

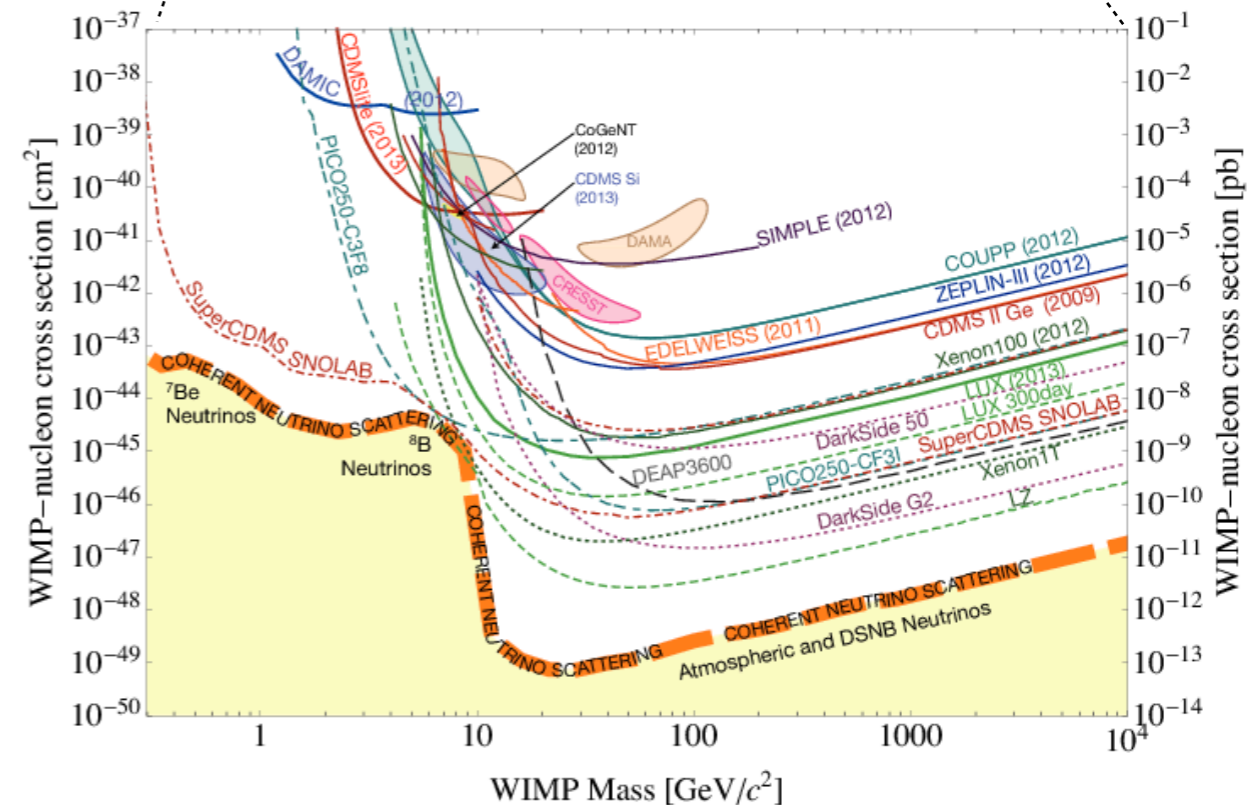


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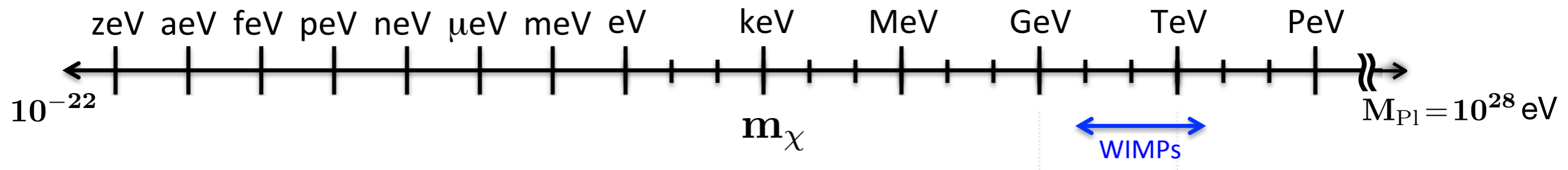


Billard et al., arXiv:1307.5458



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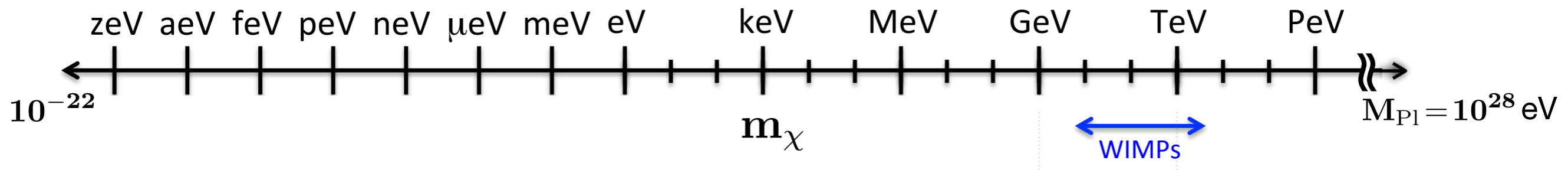
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Consider a cross-section: $\sigma = \sigma_0 v^n$

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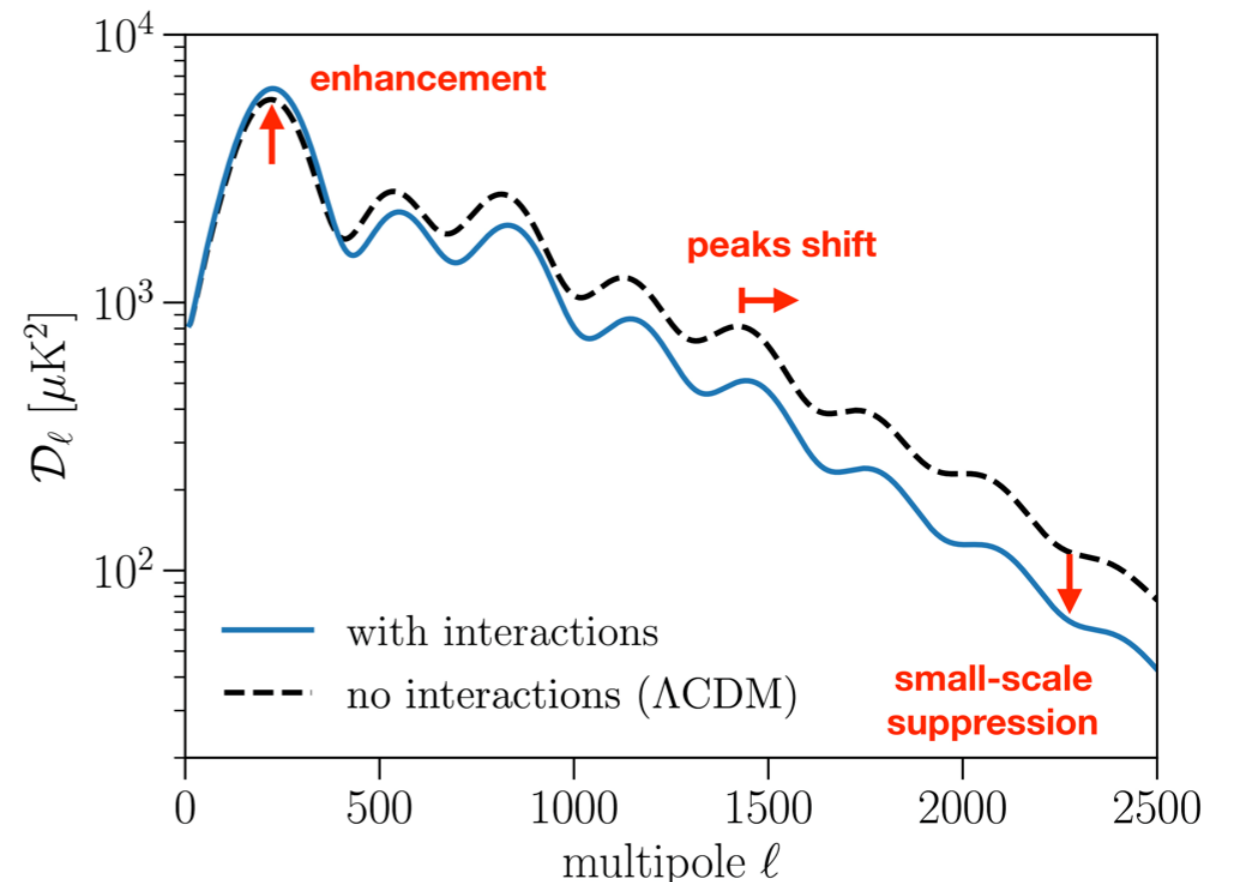
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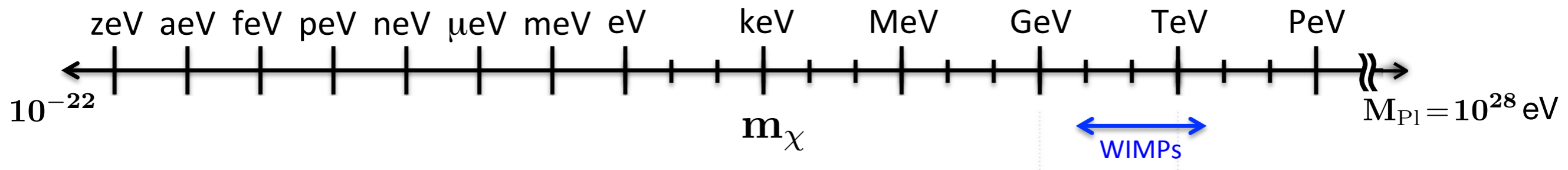
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Cosmology remains sensitive at $m_\chi \ll \text{GeV}$:



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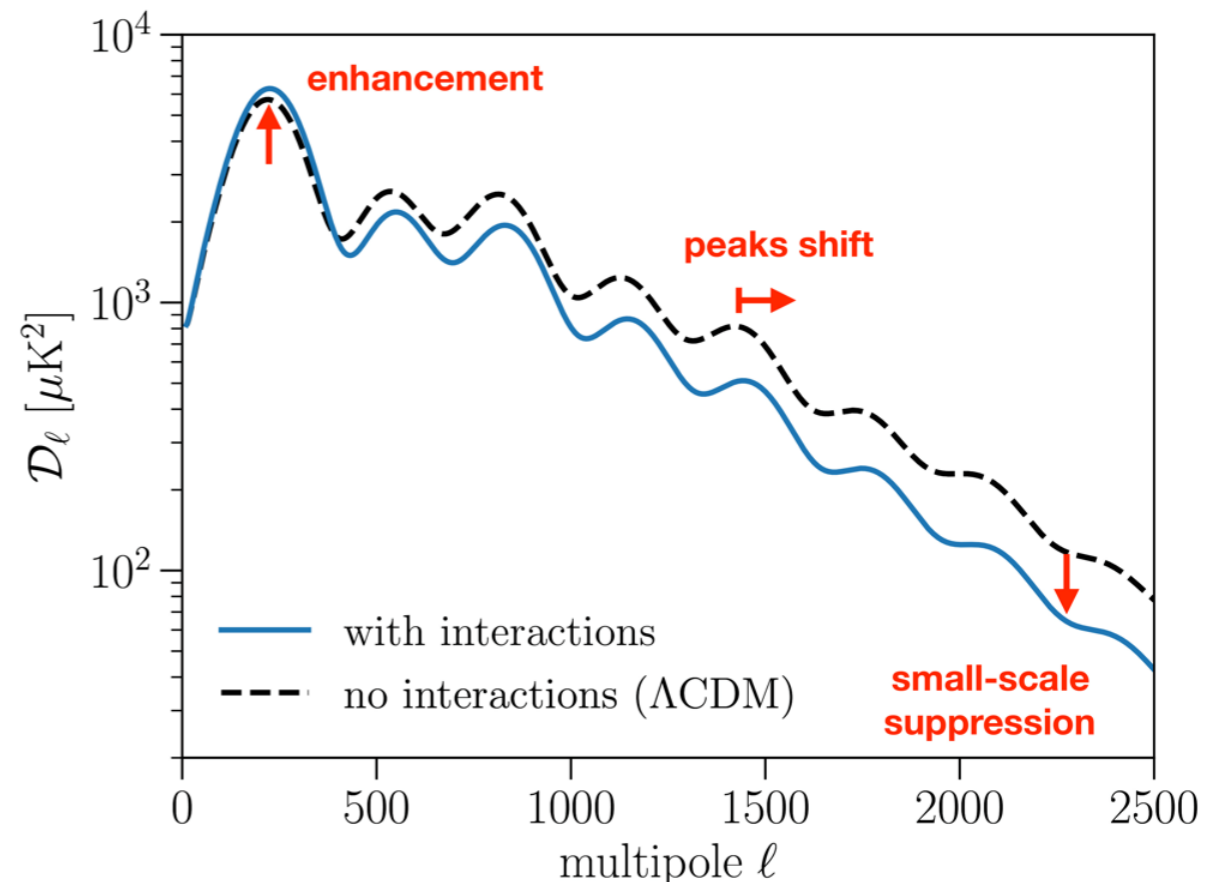


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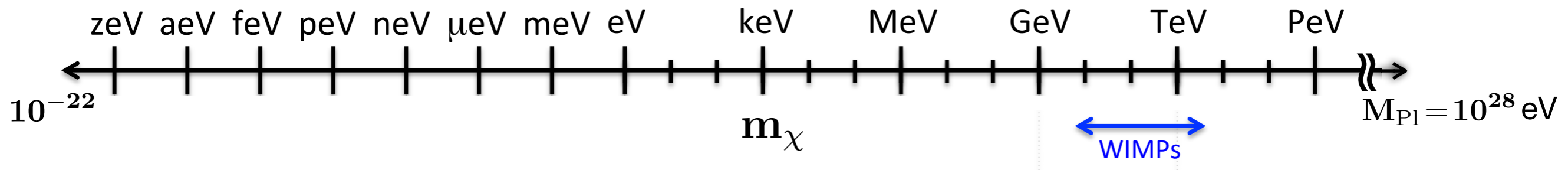
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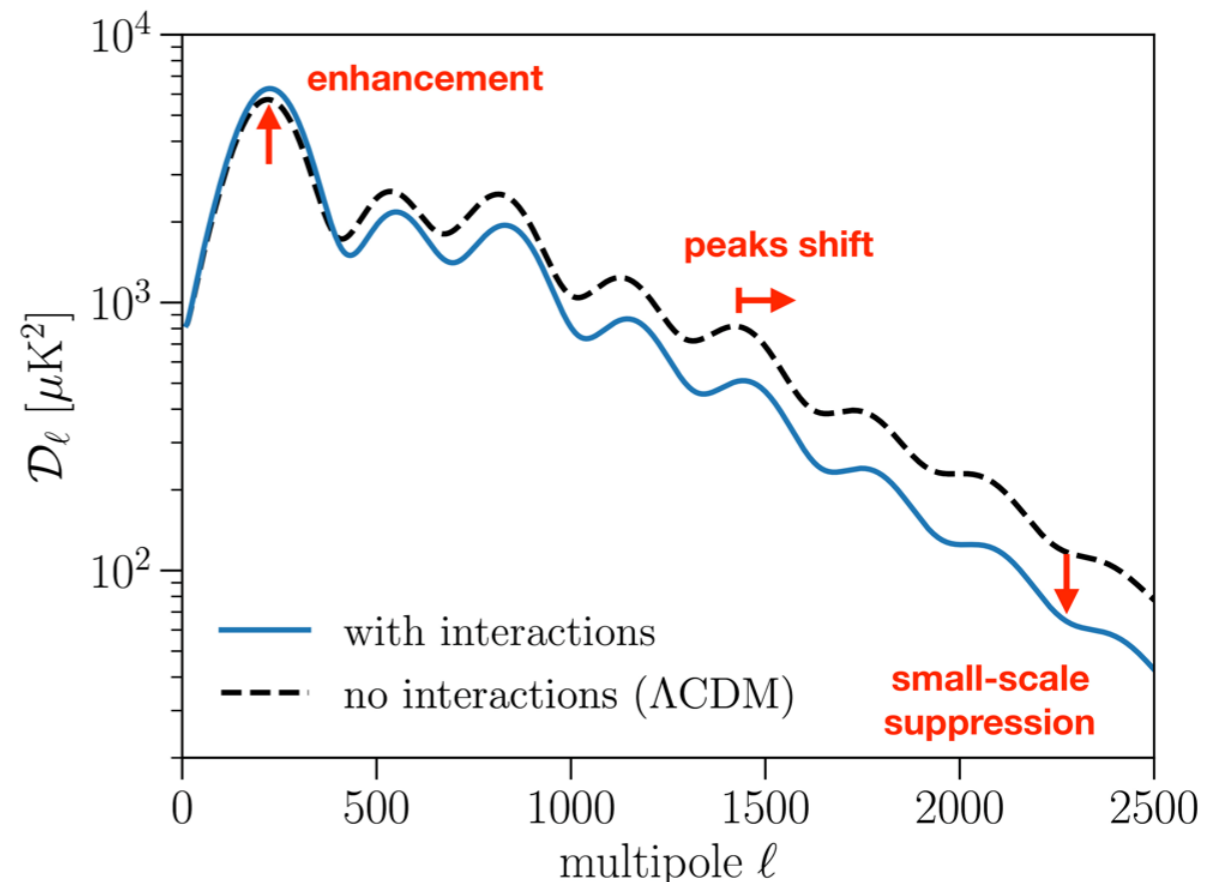
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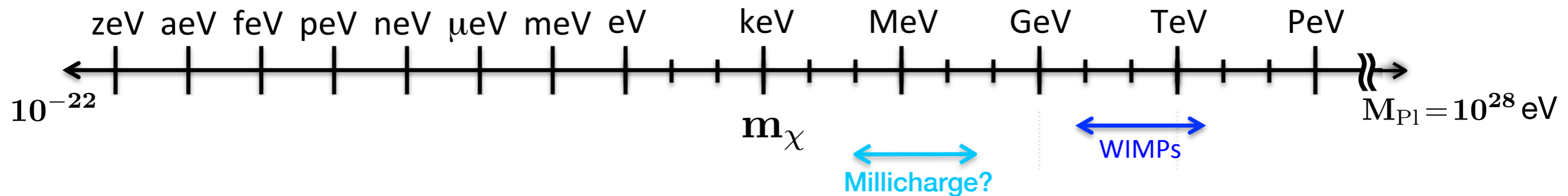
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Let's examine the case: $\sigma(v) = \sigma_c \left(\frac{v}{c}\right)^{-4}$



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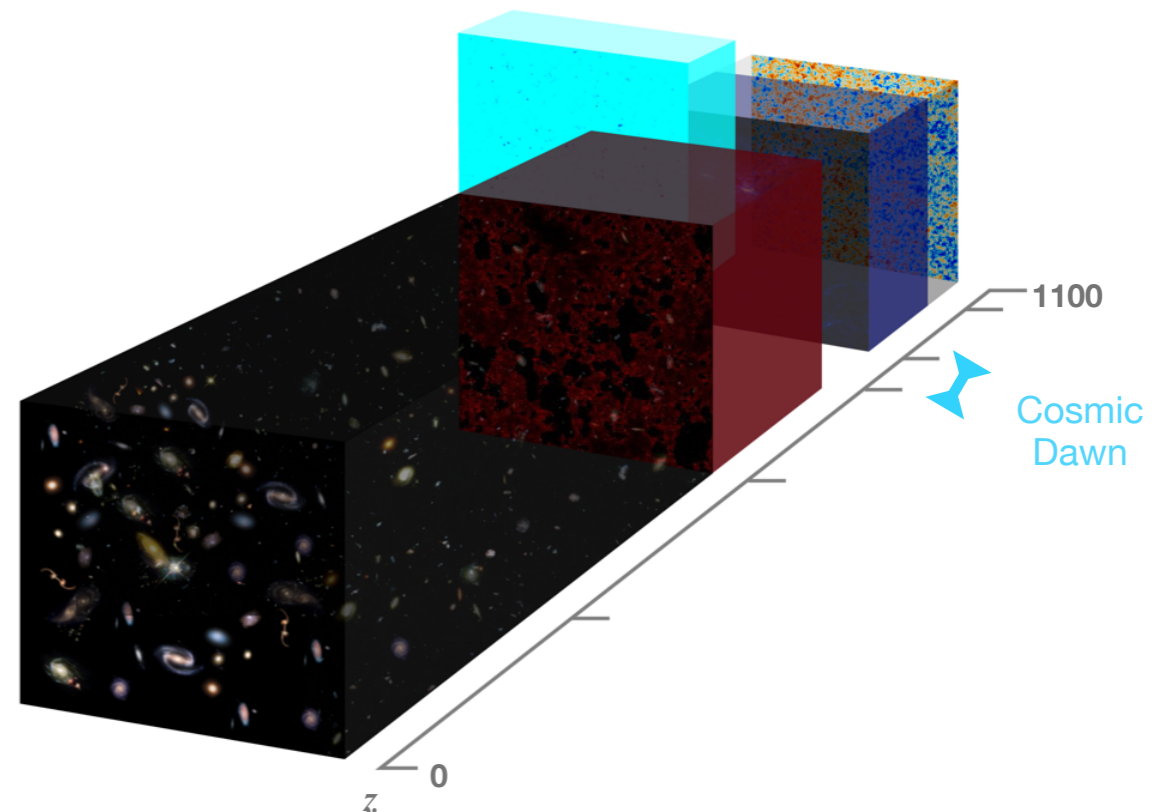


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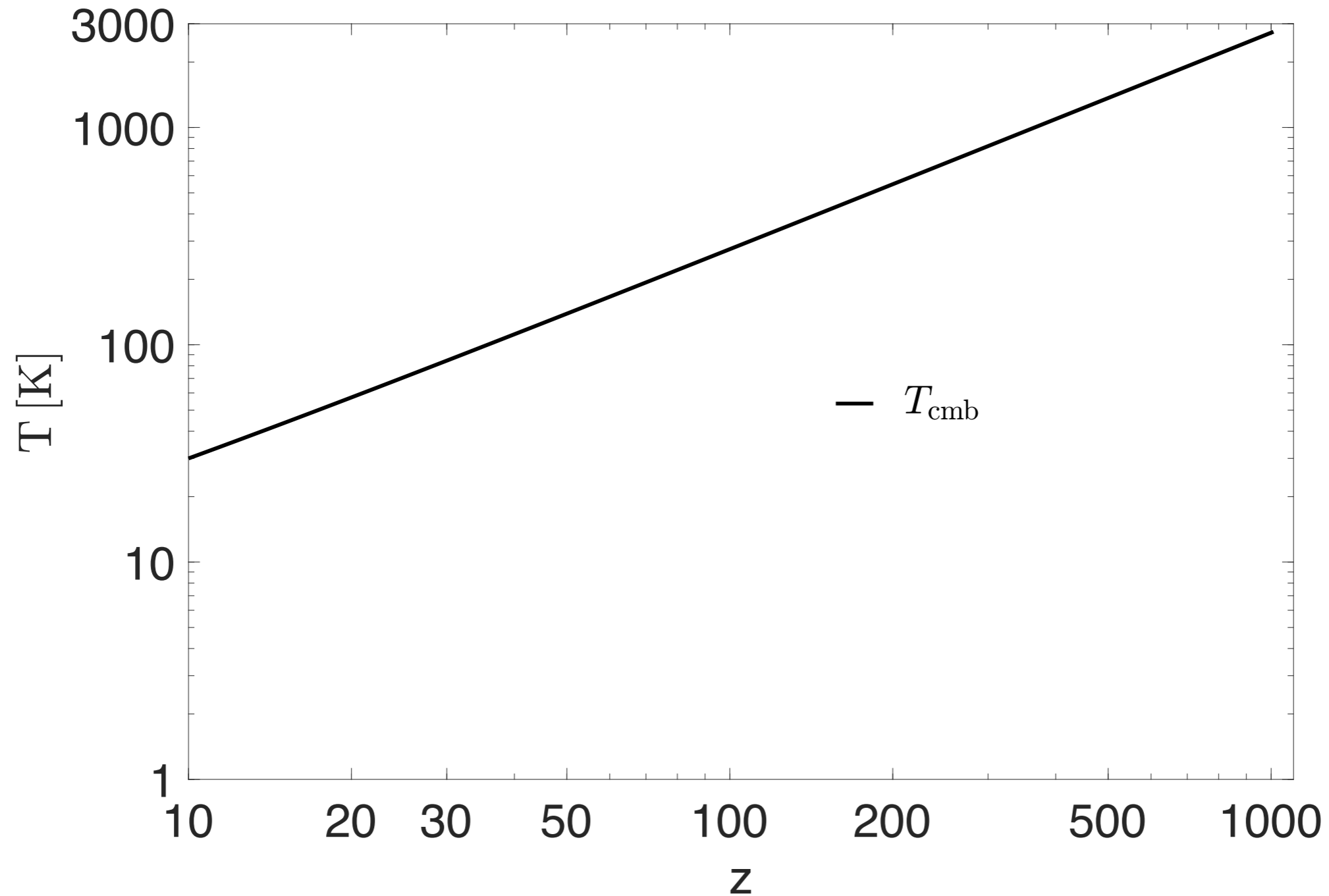


DM-Baryon $\propto v^{-4}$ Scattering: Late-Time Cooling!

(Muñoz, EDK and Ali-Haïmoud, PRD 2015; Barkana, Nature 2018)

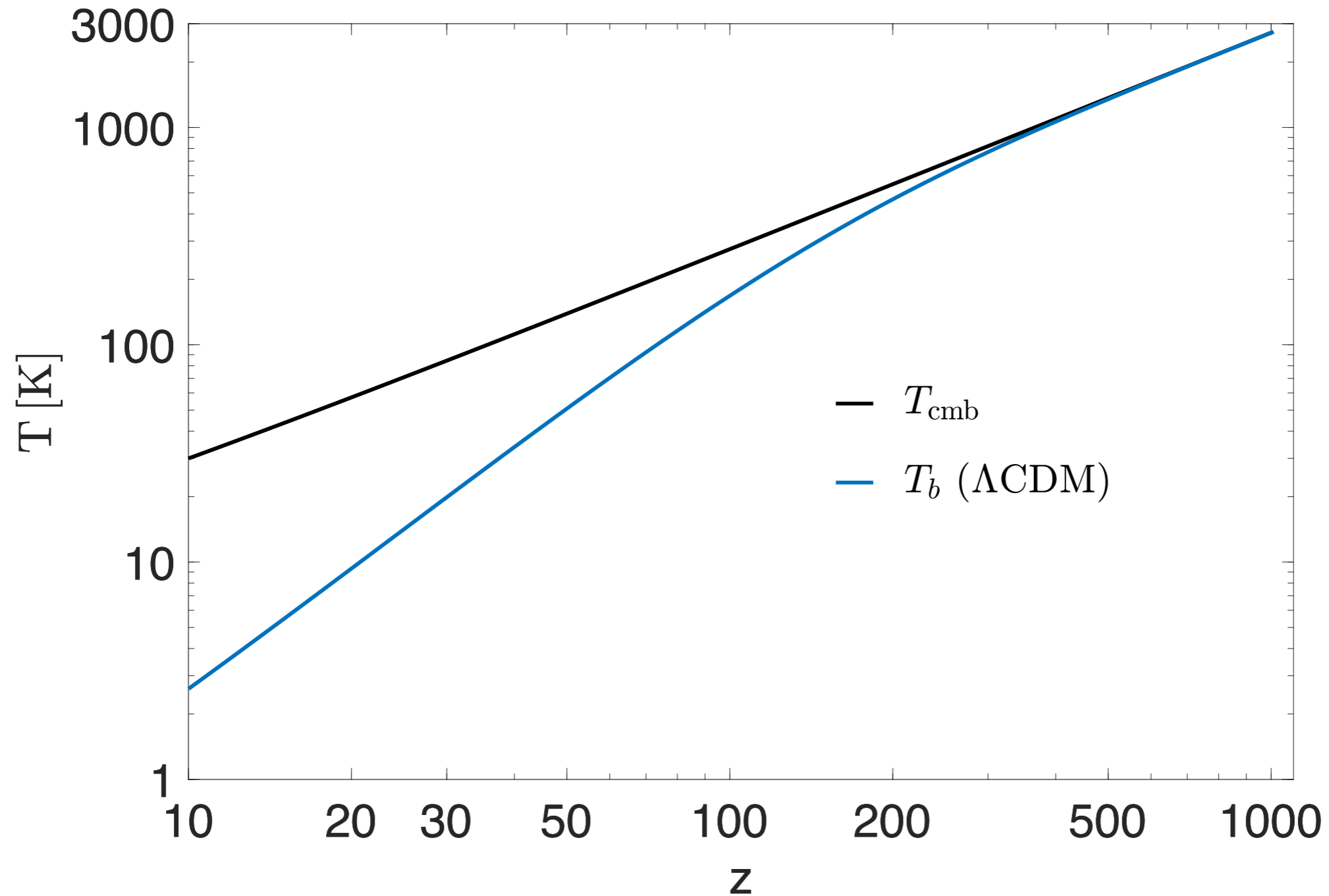
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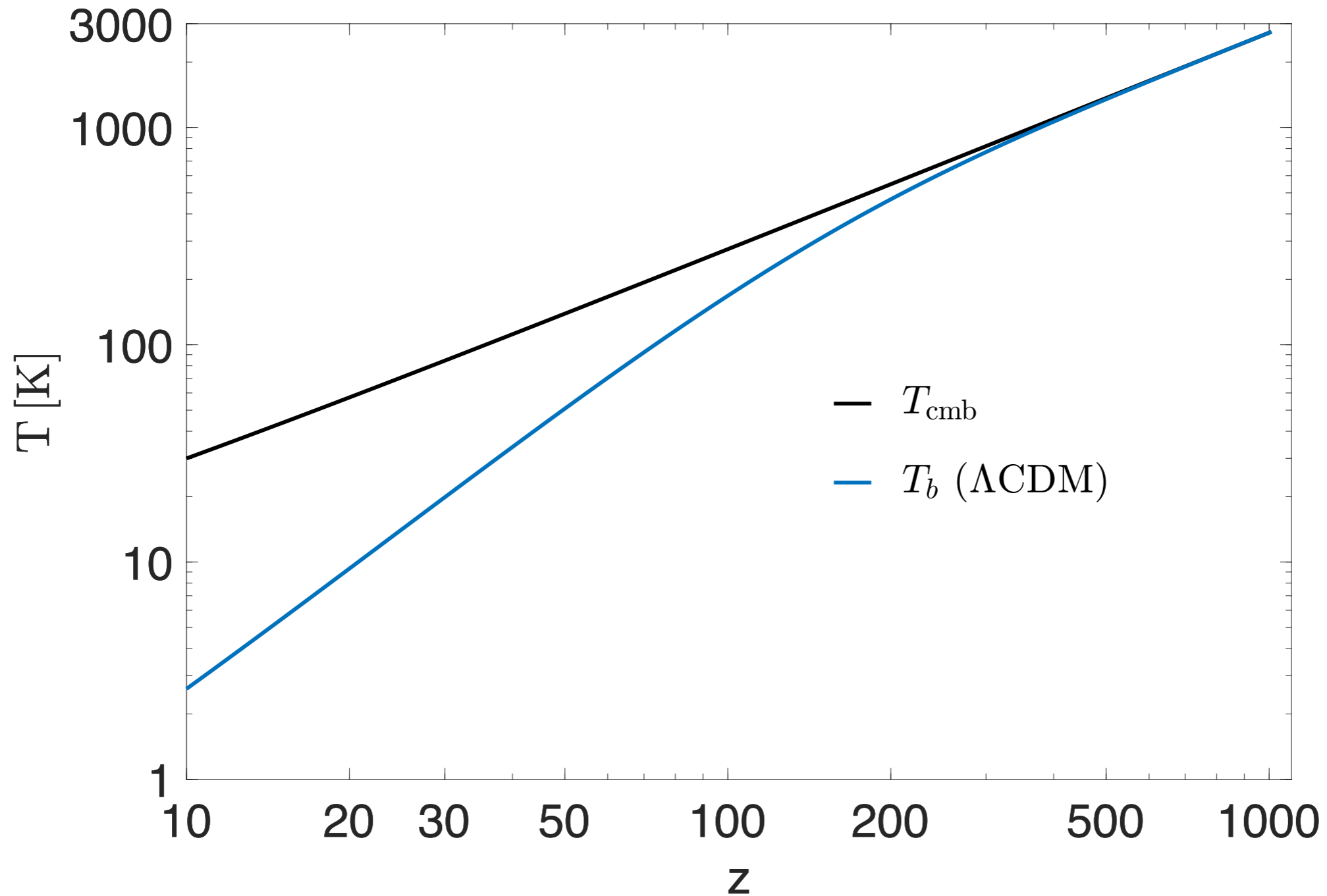
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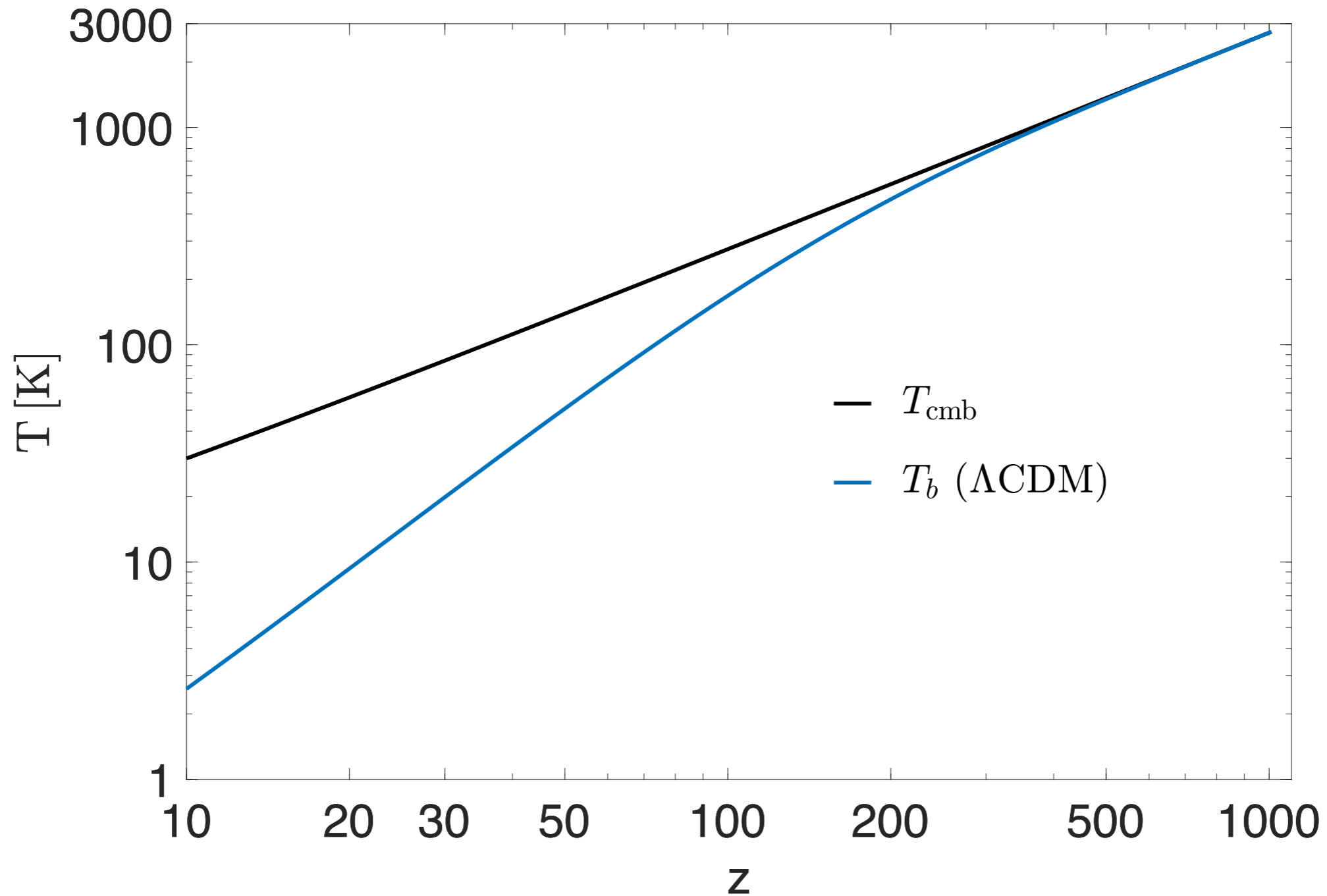


DM-baryon
interactions:

$$\dot{T}_b = -2HT_b + \Gamma_C(T_\gamma - T_b) + \Gamma_{\chi b}(T_\chi - T_b)$$

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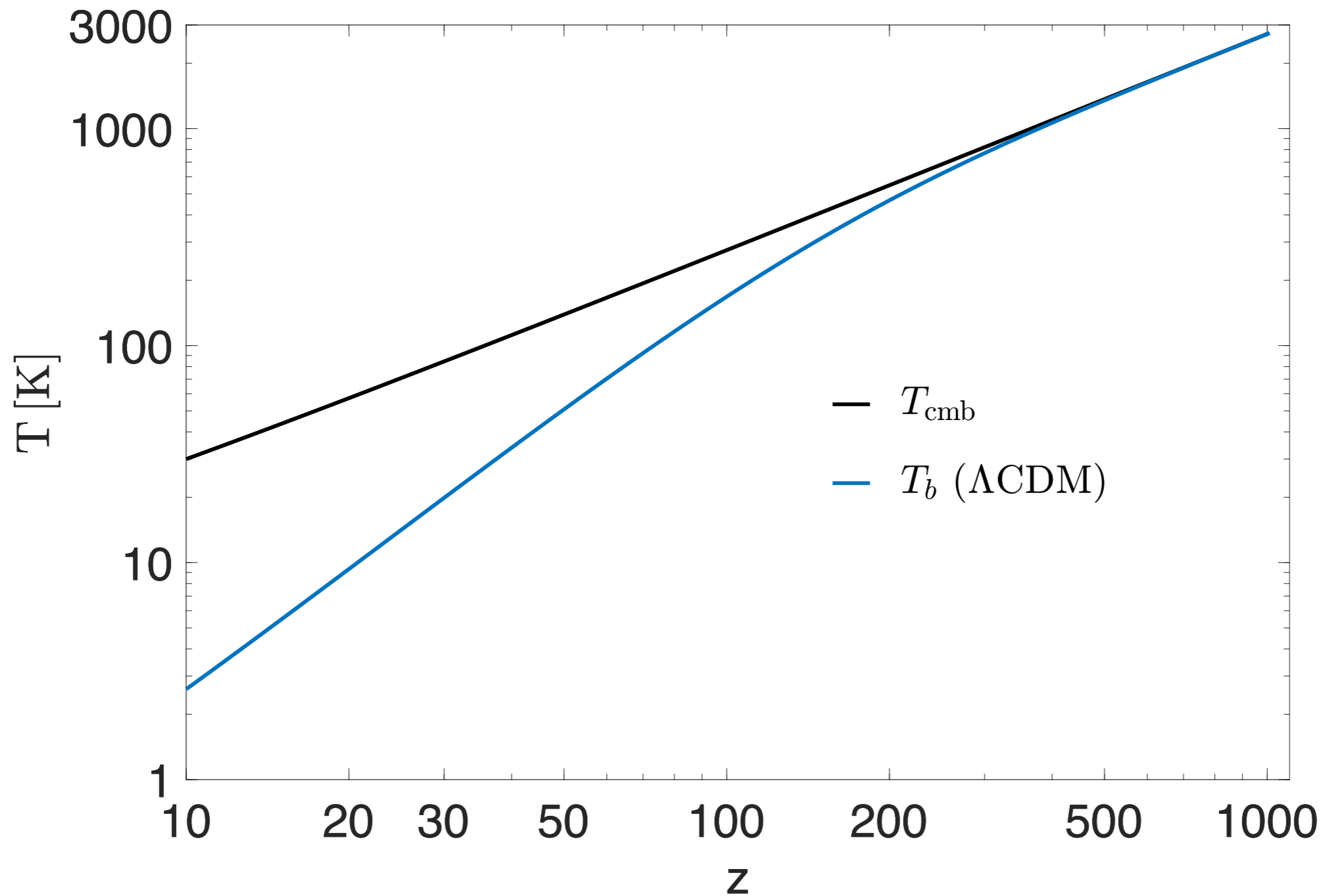


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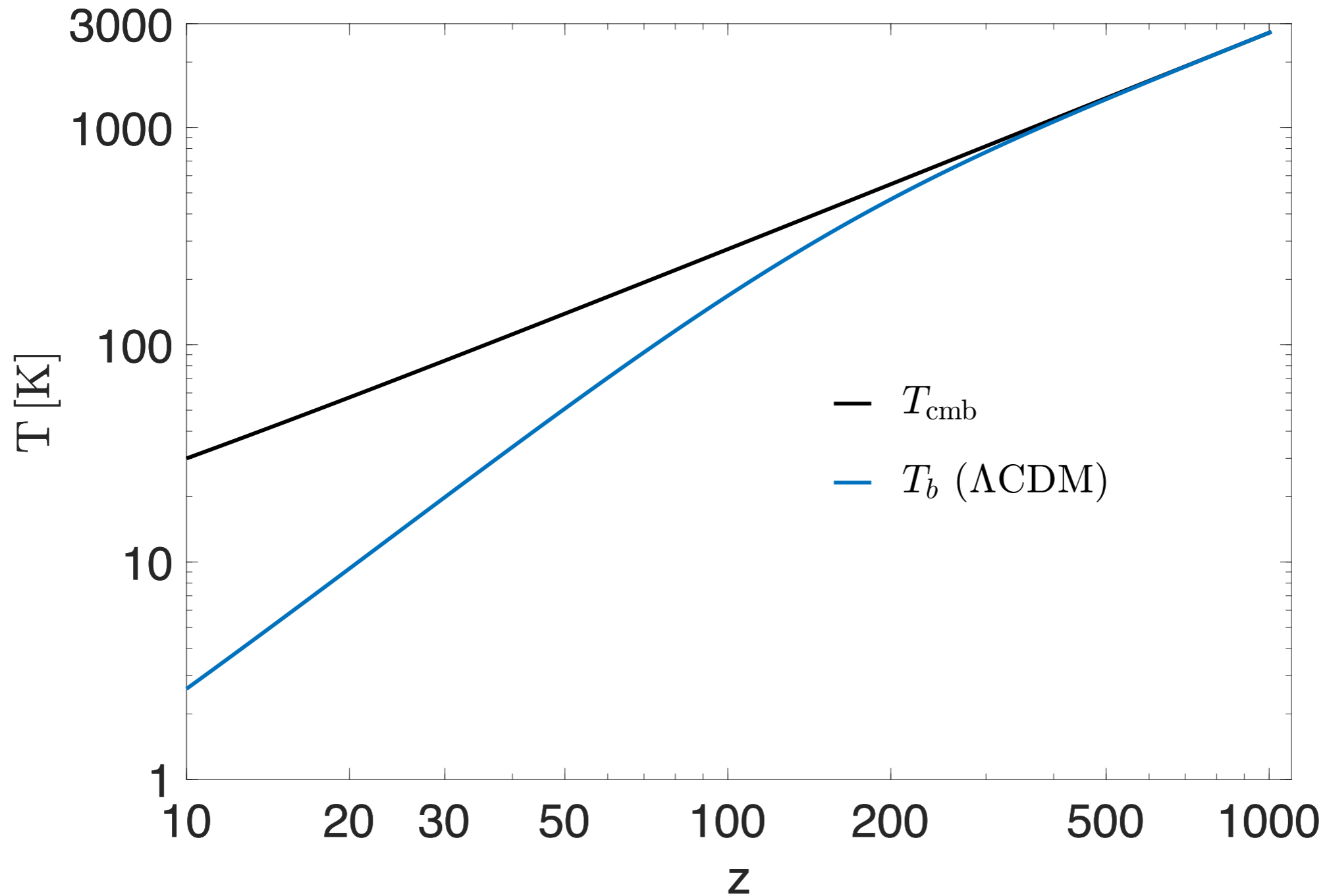


DM-baryon
interactions:

$$\dot{T}_b = \underbrace{-2HT_b}_{\text{blue}} + \underbrace{\Gamma_C(T_\gamma - T_b)}_{\text{red}} + \Gamma_{\chi b}(T_\chi - T_b)$$

DM-Baryon $\propto v^{-4}$ Scattering: Late-Time Cooling!

(Muñoz, EDK and Ali-Haïmoud, PRD 2015; Barkana, Nature 2018)

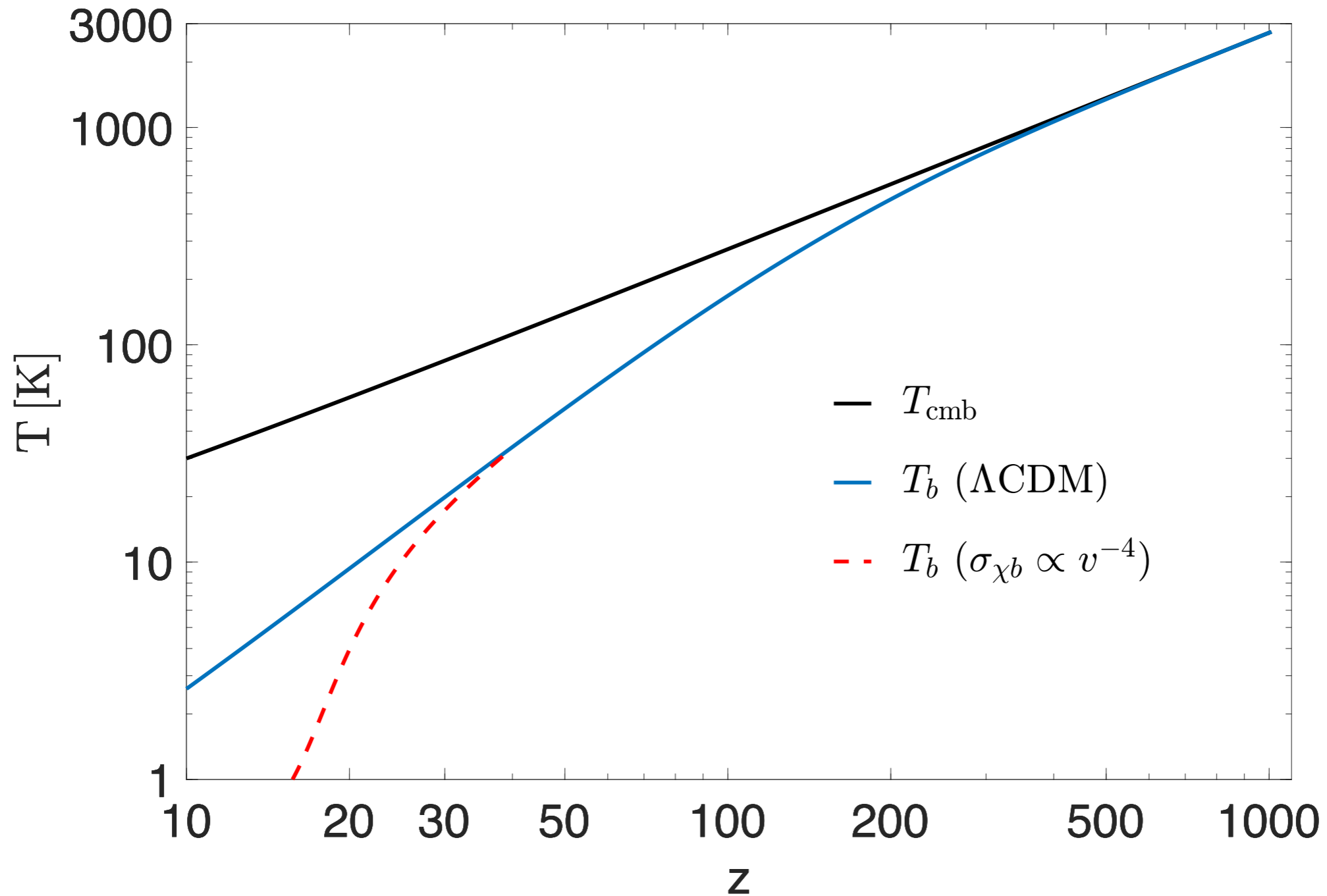


DM-baryon
interactions:

$$\dot{T}_b = \underbrace{-2HT_b}_{\text{blue}} + \underbrace{\Gamma_C(T_\gamma - T_b)}_{\text{red}} + \underbrace{\Gamma_{\chi b}(T_\chi - T_b)}_{\text{blue}}$$

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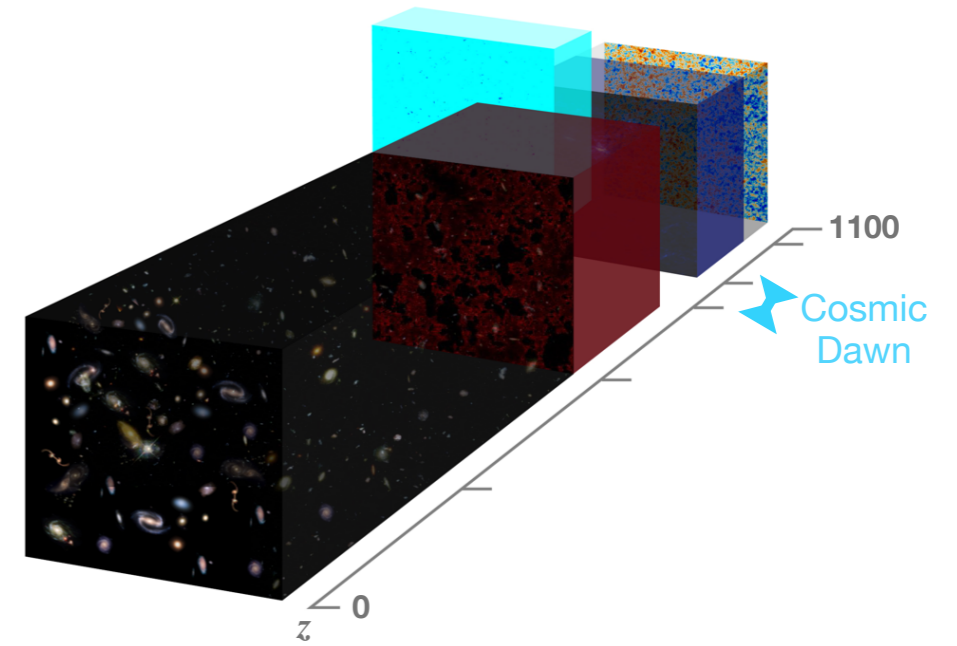
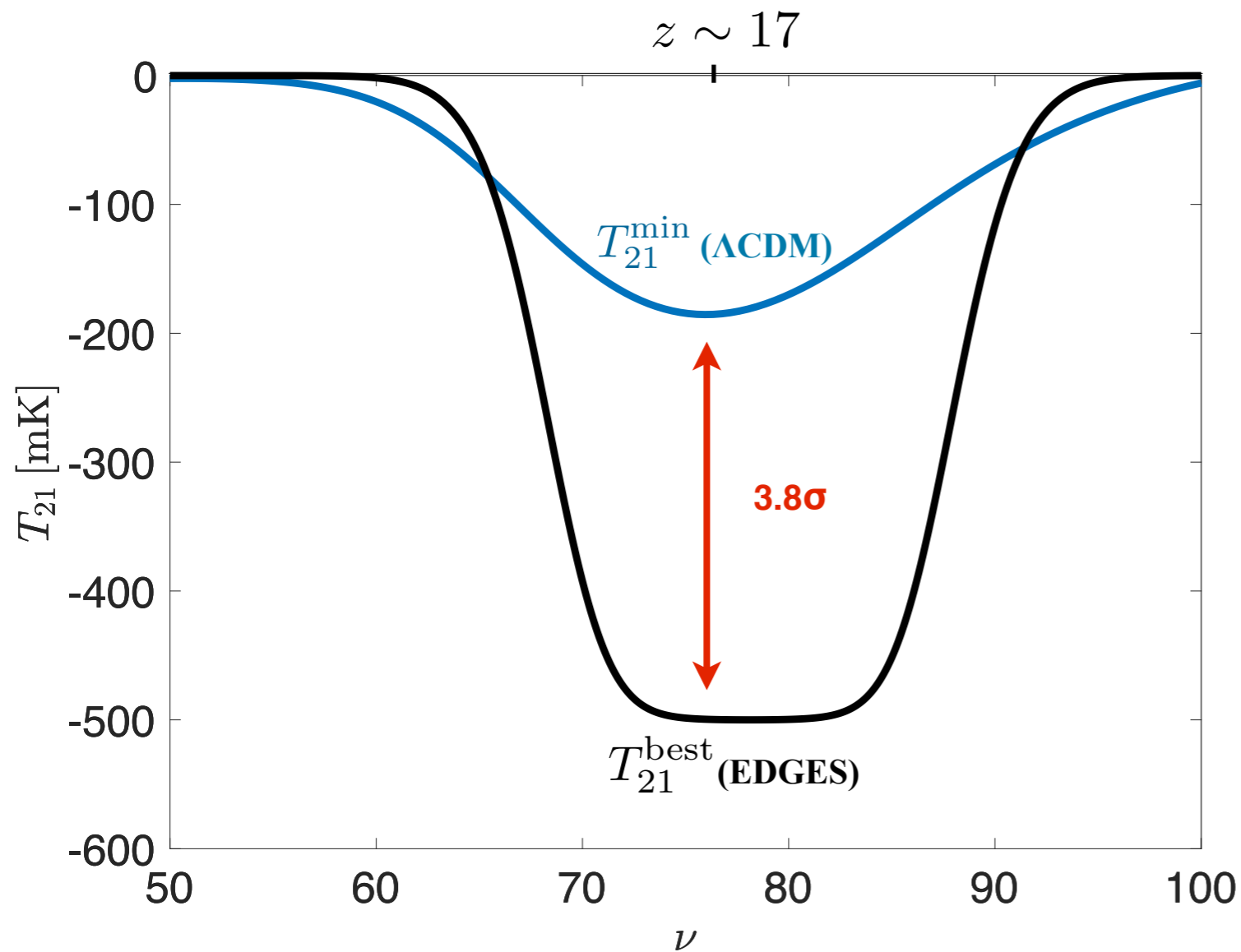


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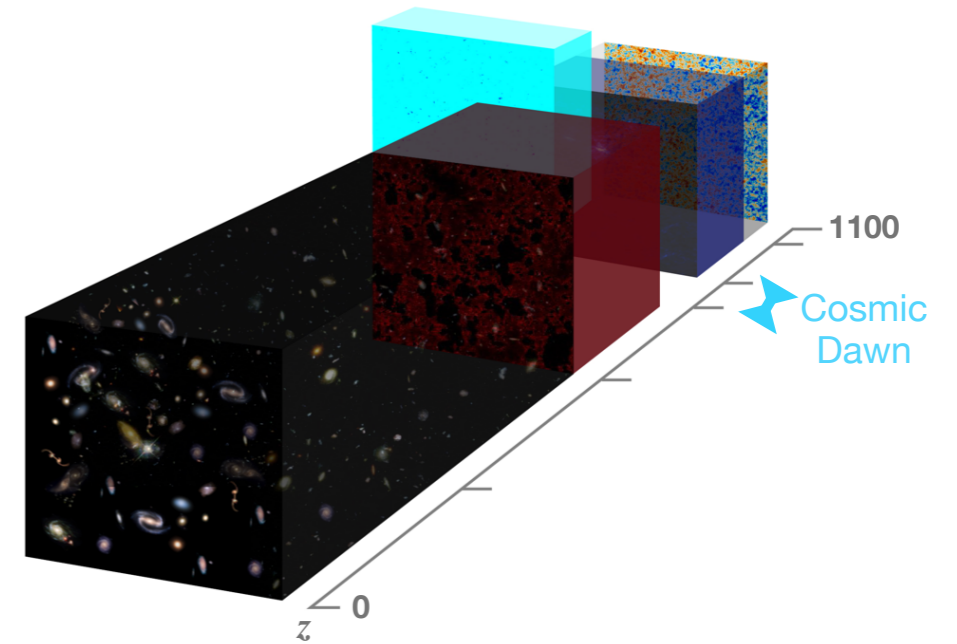
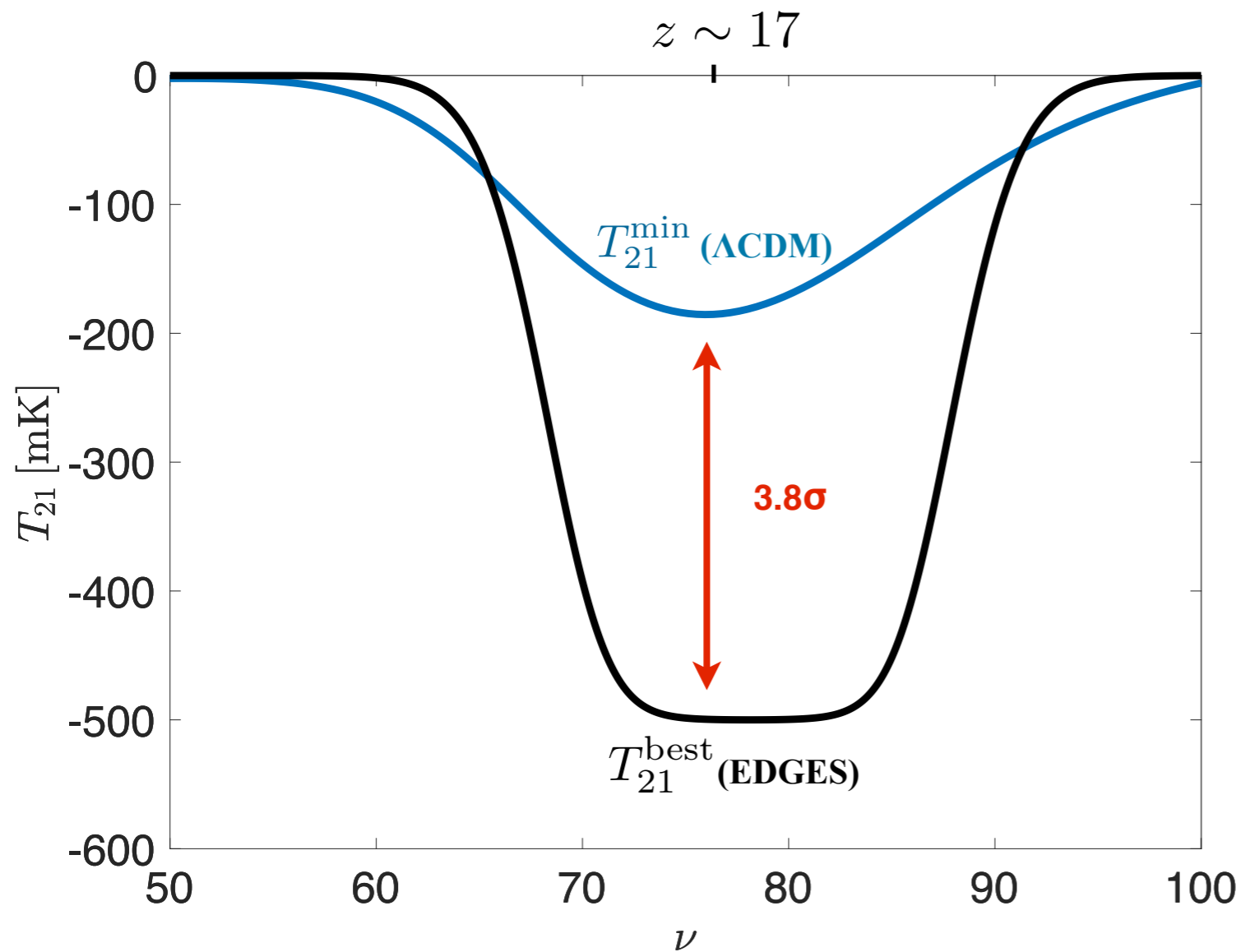
Q: Can Dark Matter Explain the EDGES Signal?

(Muñoz, EDK and Ali-Haïmoud, PRD 2015; Barkana, Nature 2018)



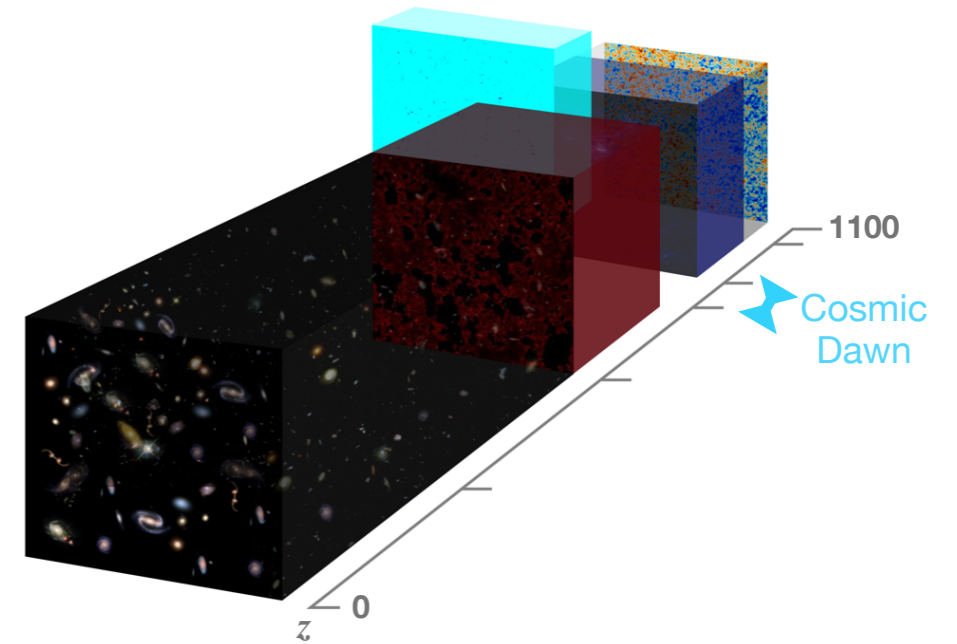
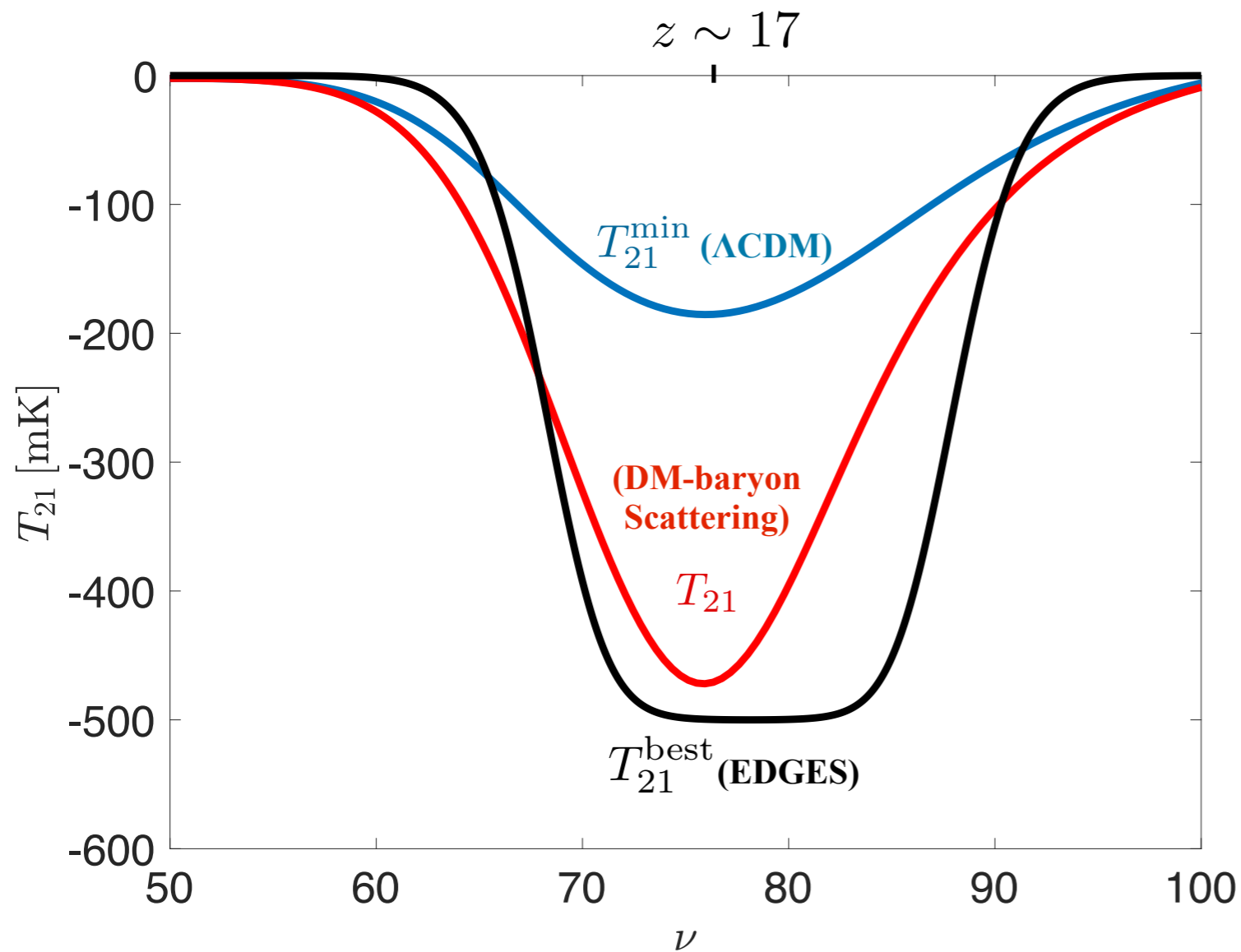
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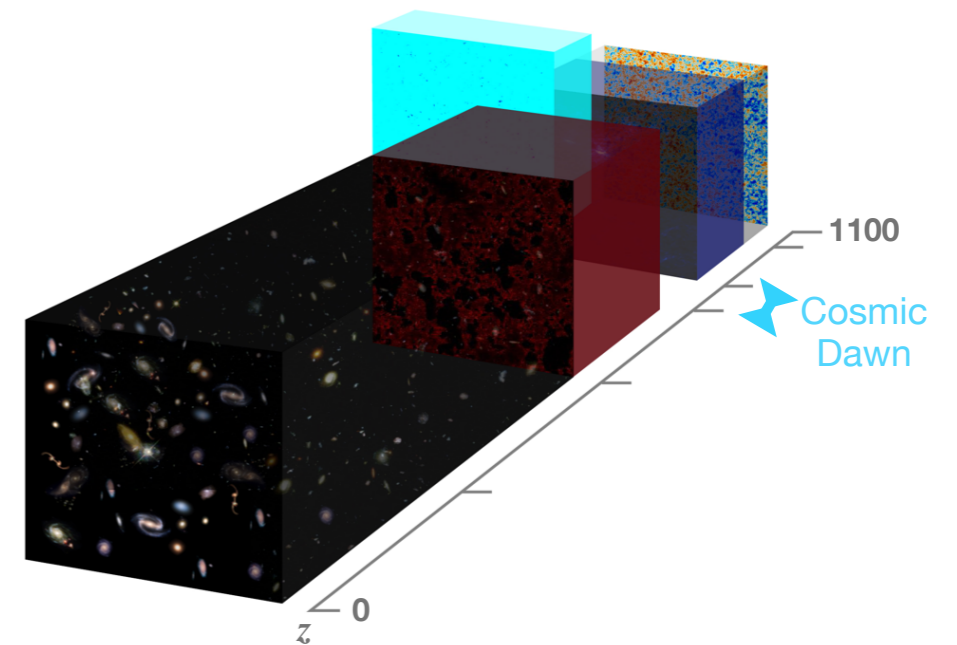
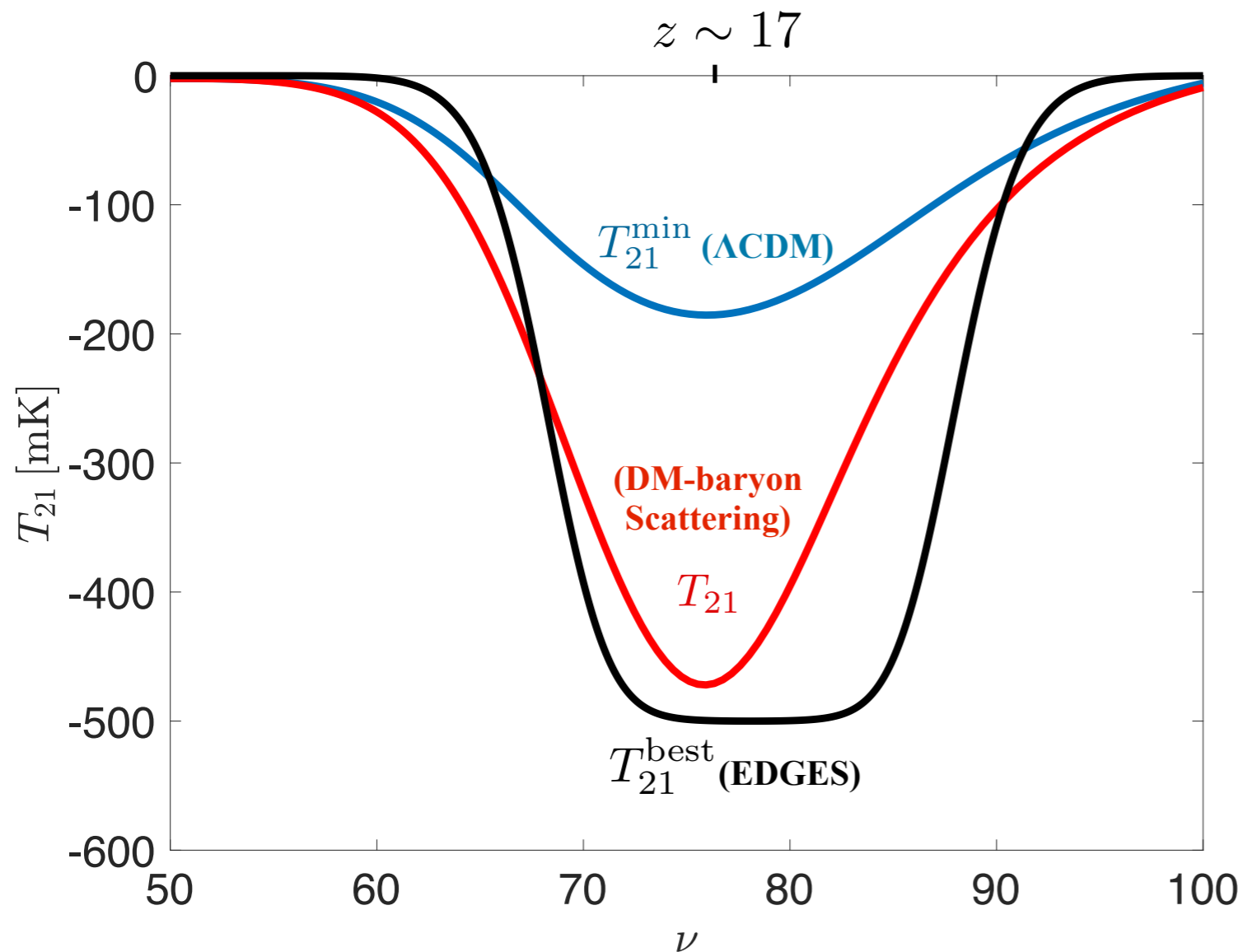
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But it's not that simple...

Muñoz and Loeb, Nature (2018)

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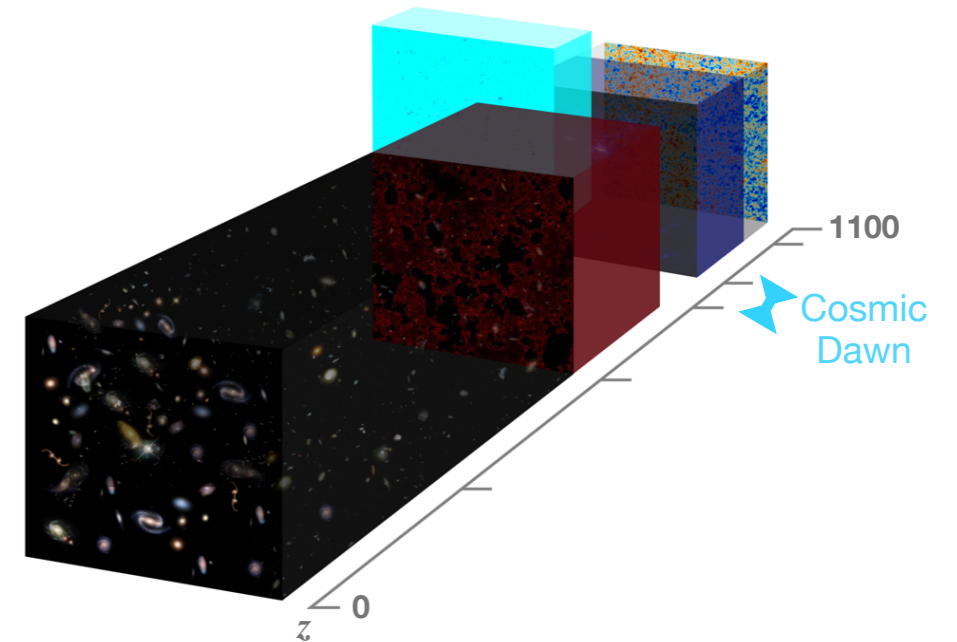
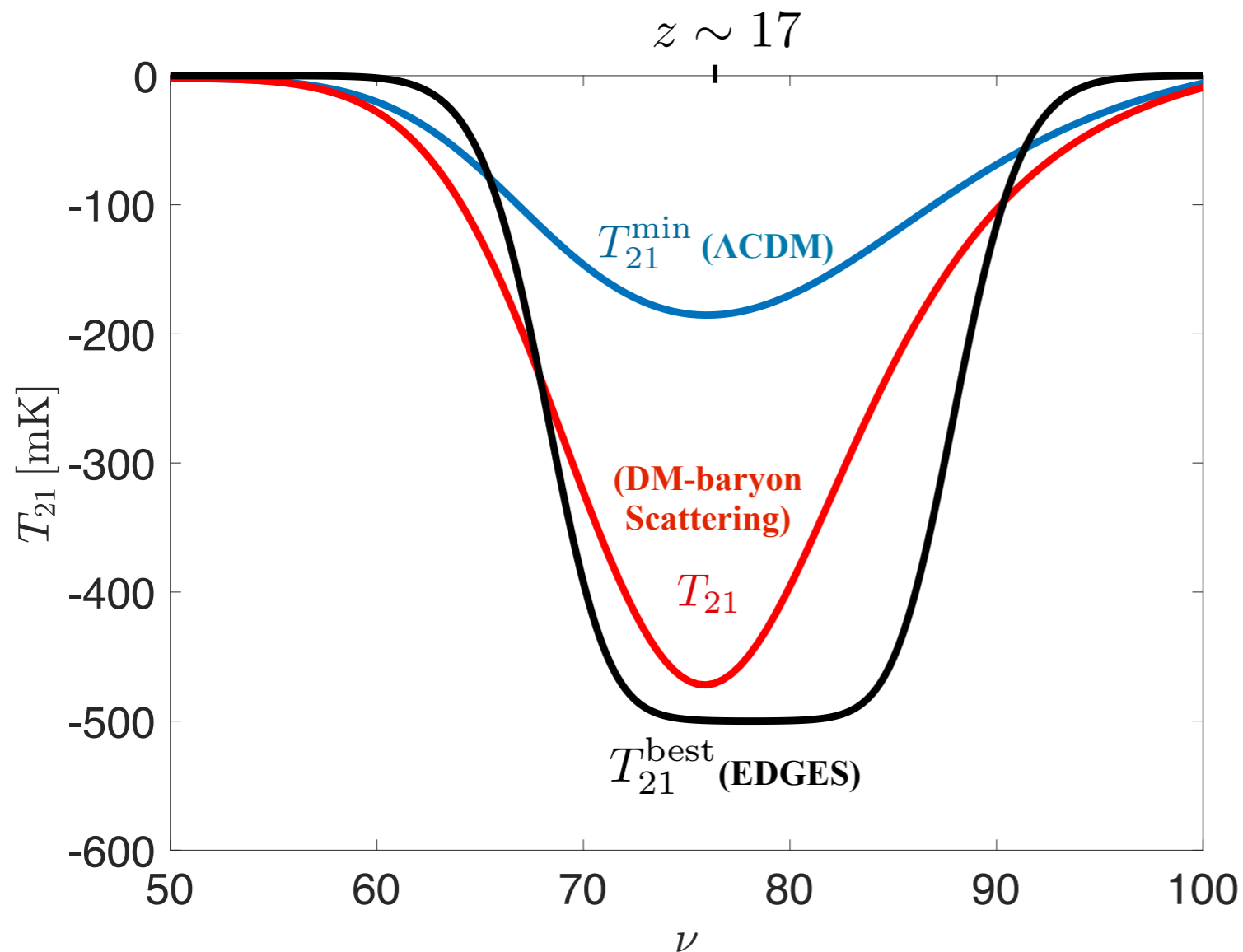
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Could maybe work with $f_\chi \sim 1\%$.

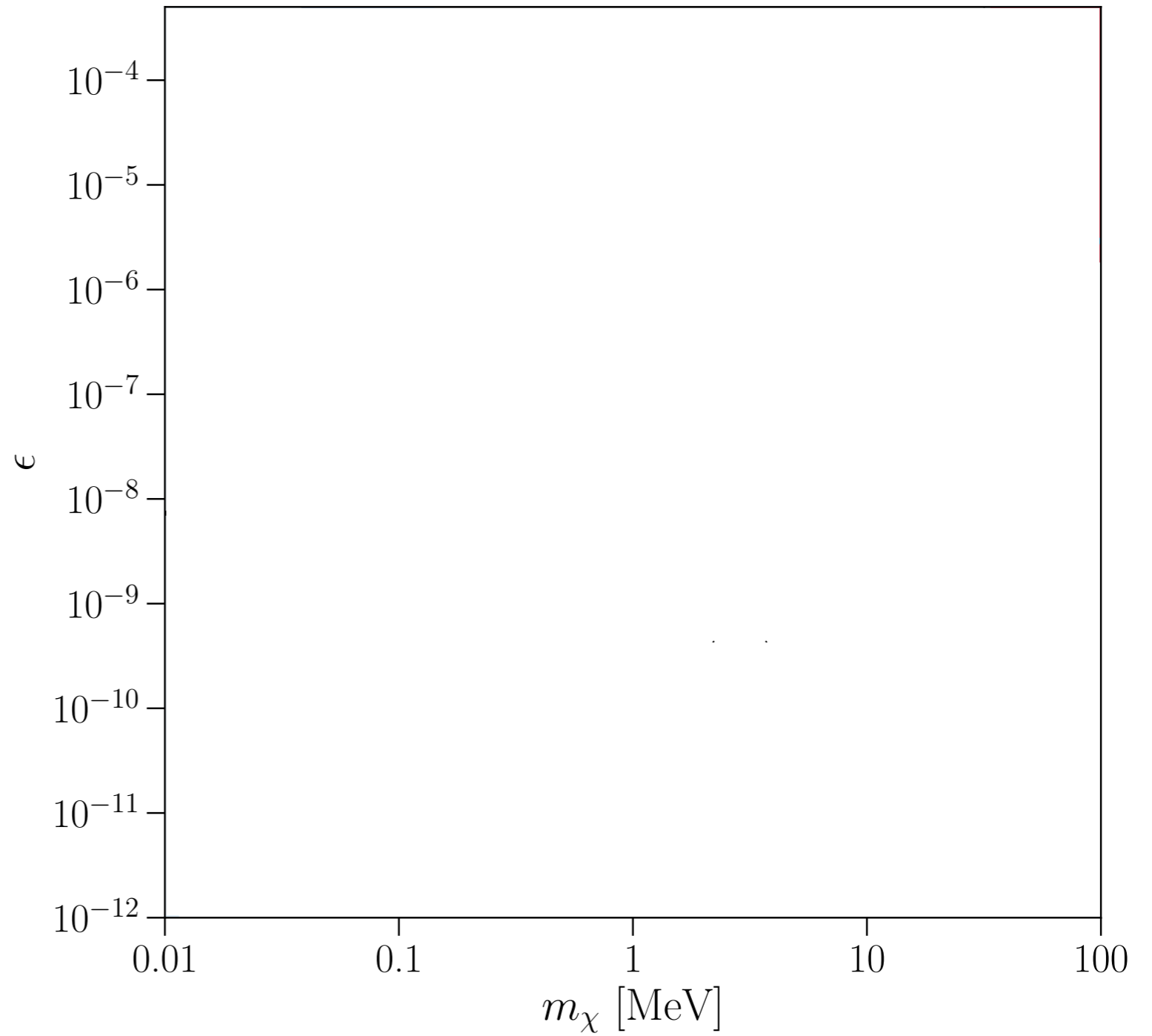


Millicharged DM: Tight Constraints

(EDK, Poulin, Gluscevic, Boddy, Barkana and Kamionkowski, PRD 2018)

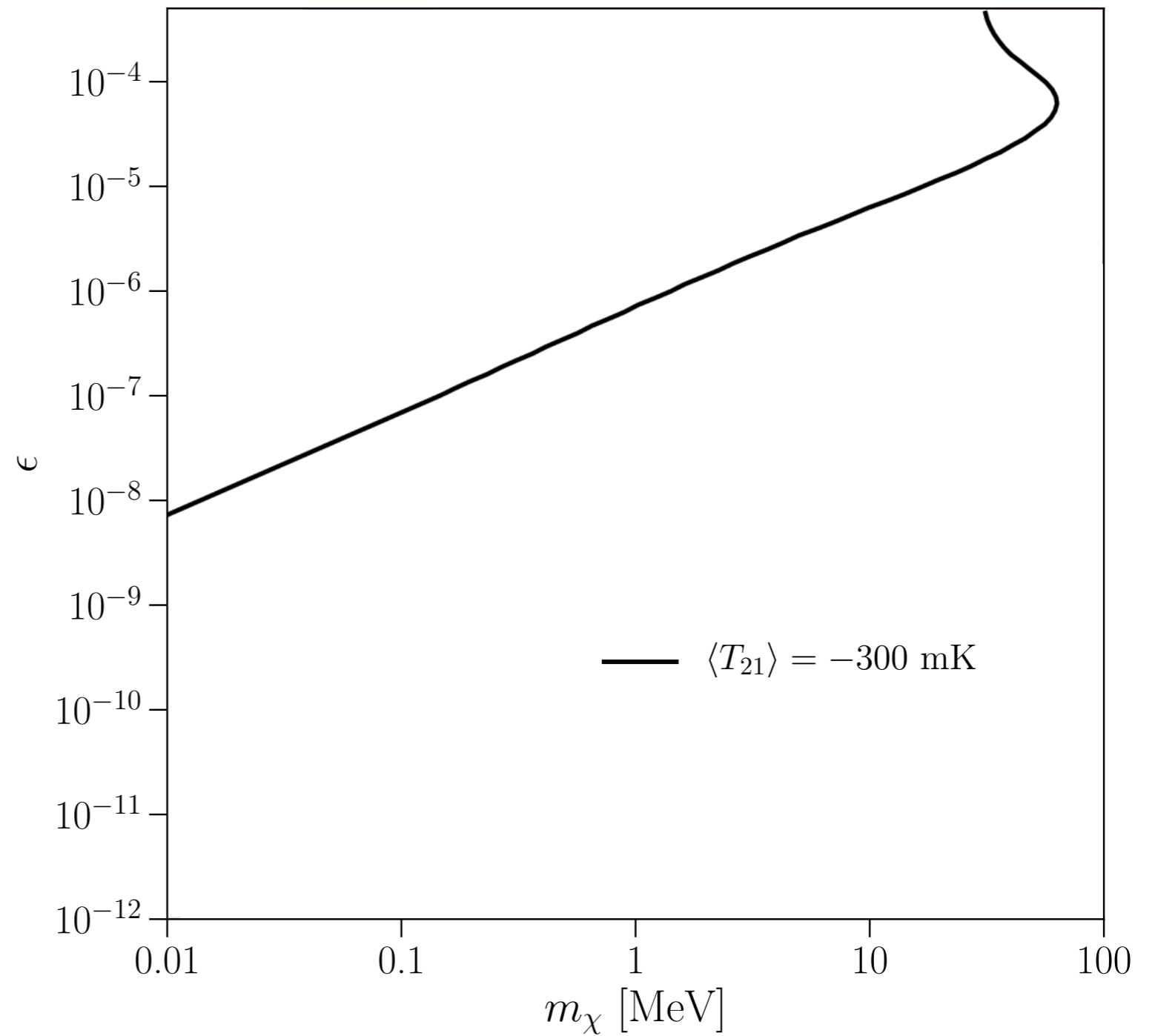
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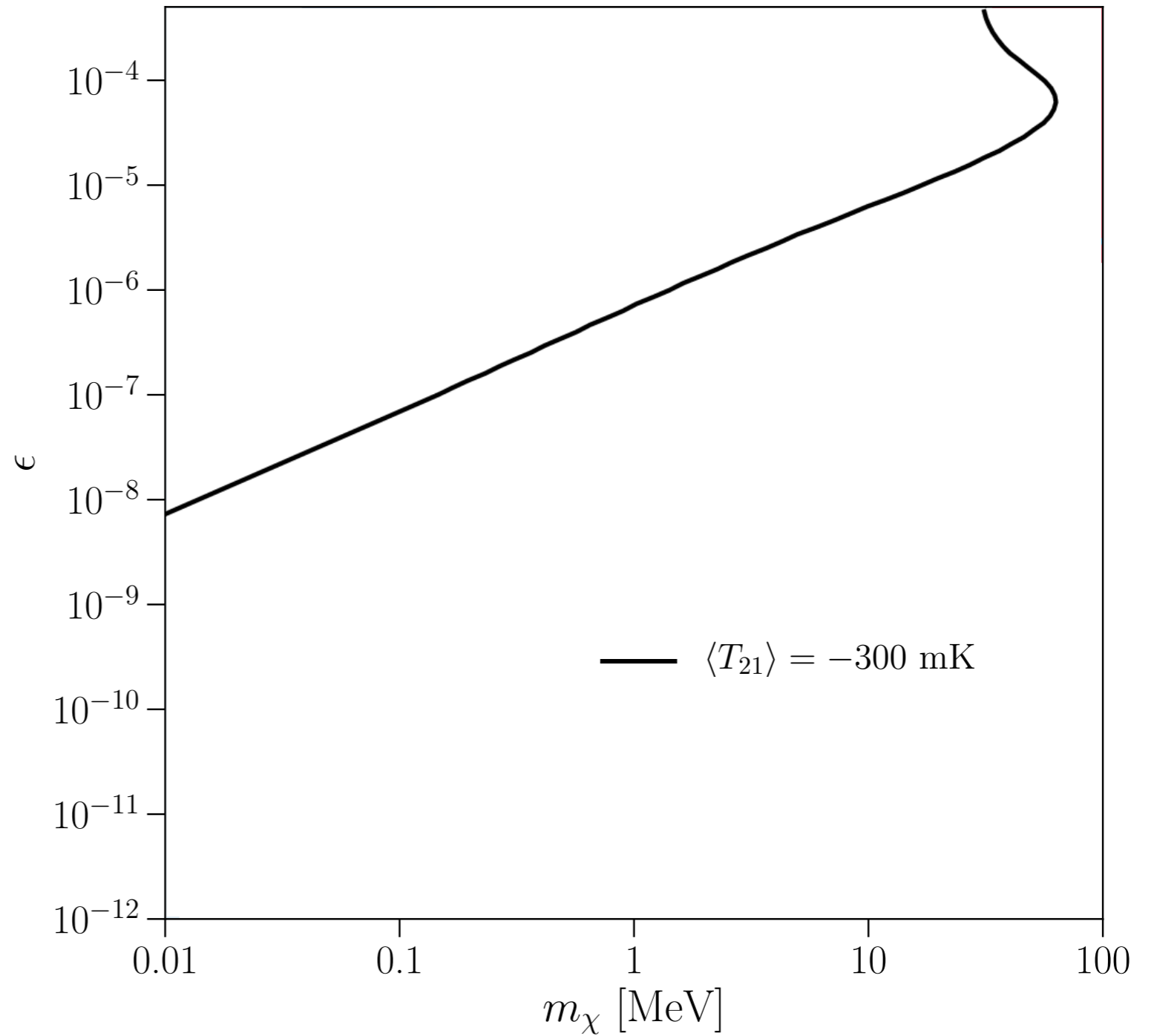
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Constraints from DM production:

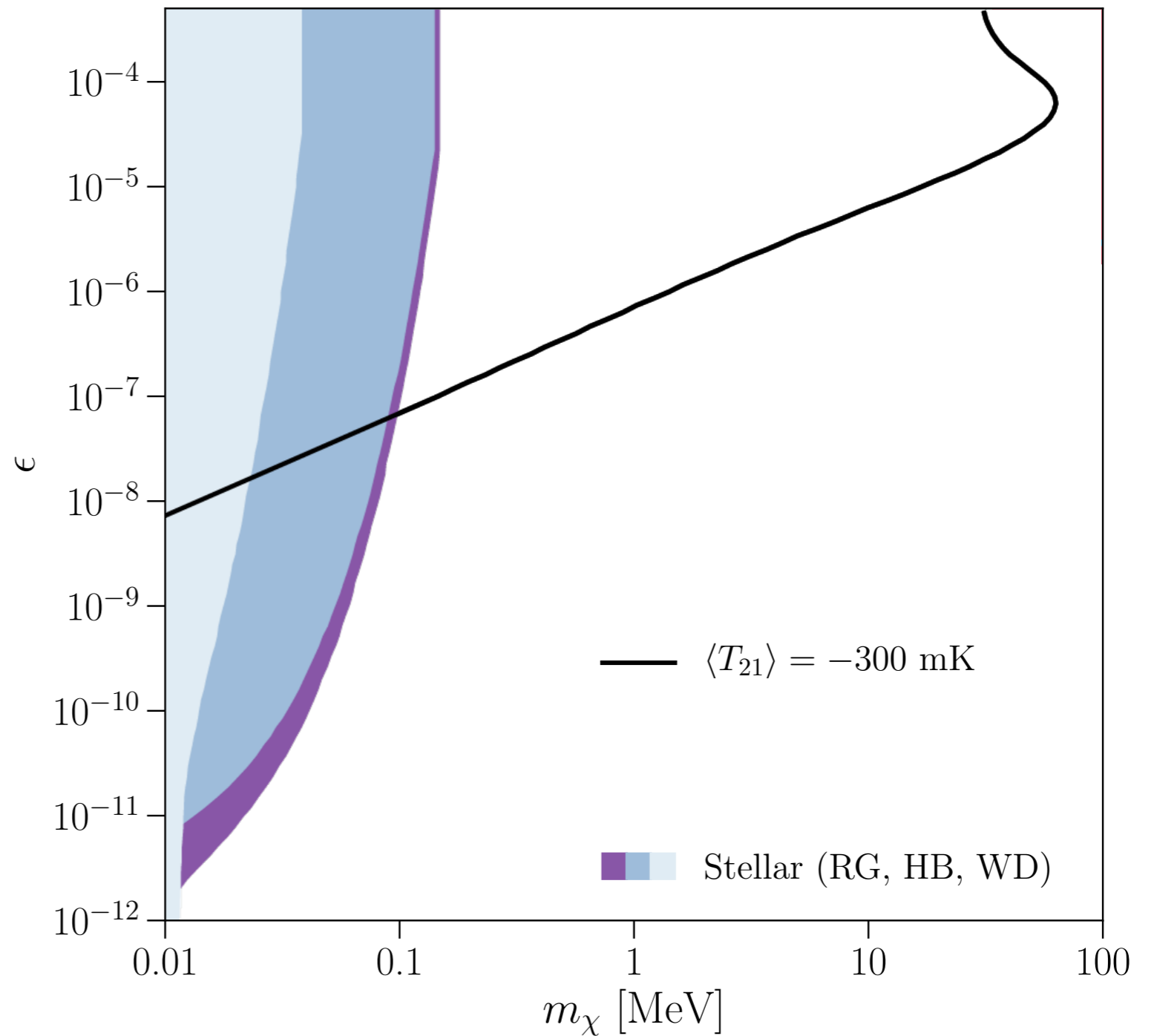


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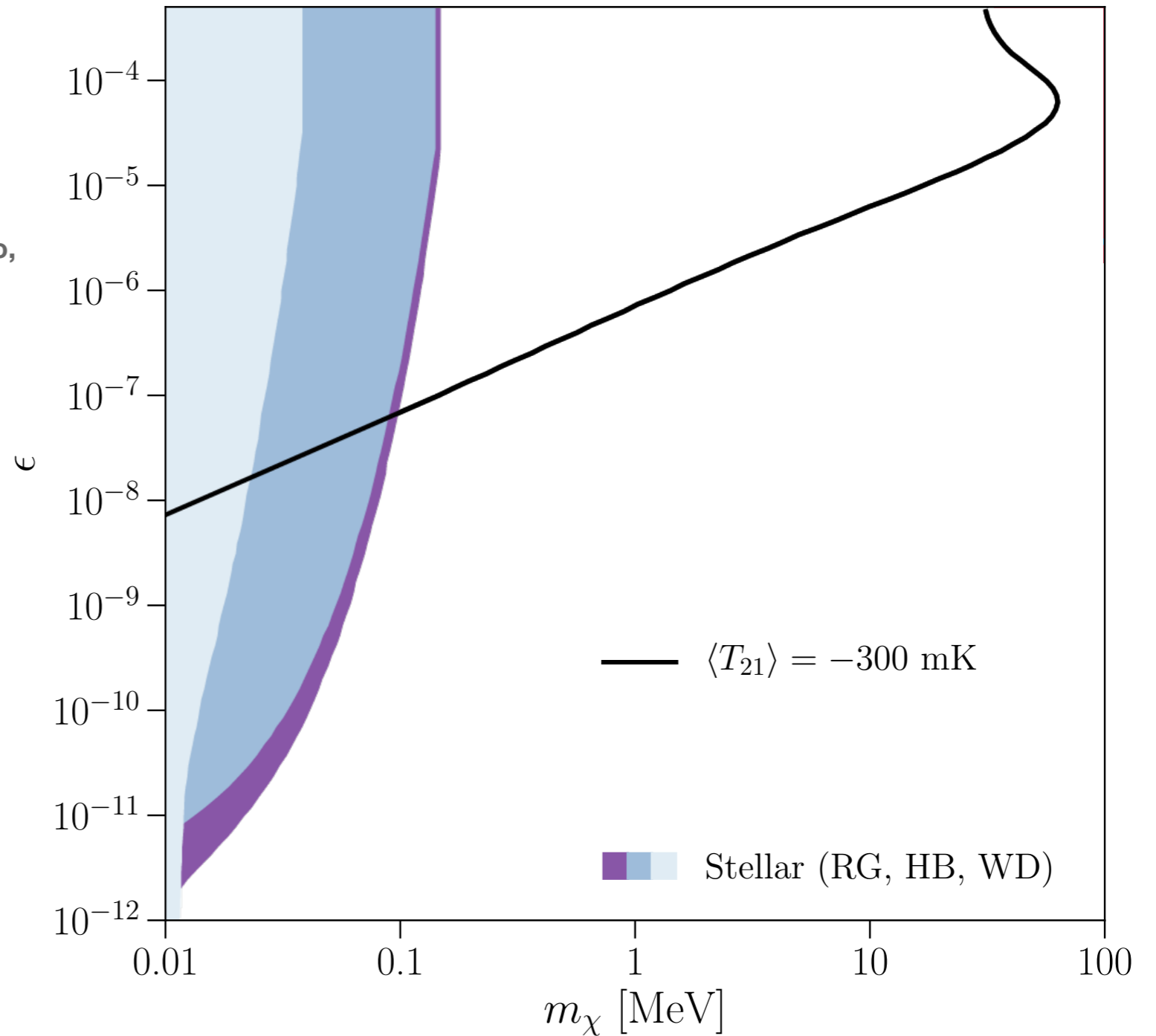
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Constraints from DM production:

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- White dwarfs
- Helium-burning stars
- Red giants

Vogel & Redondo,
JCAP (2014)

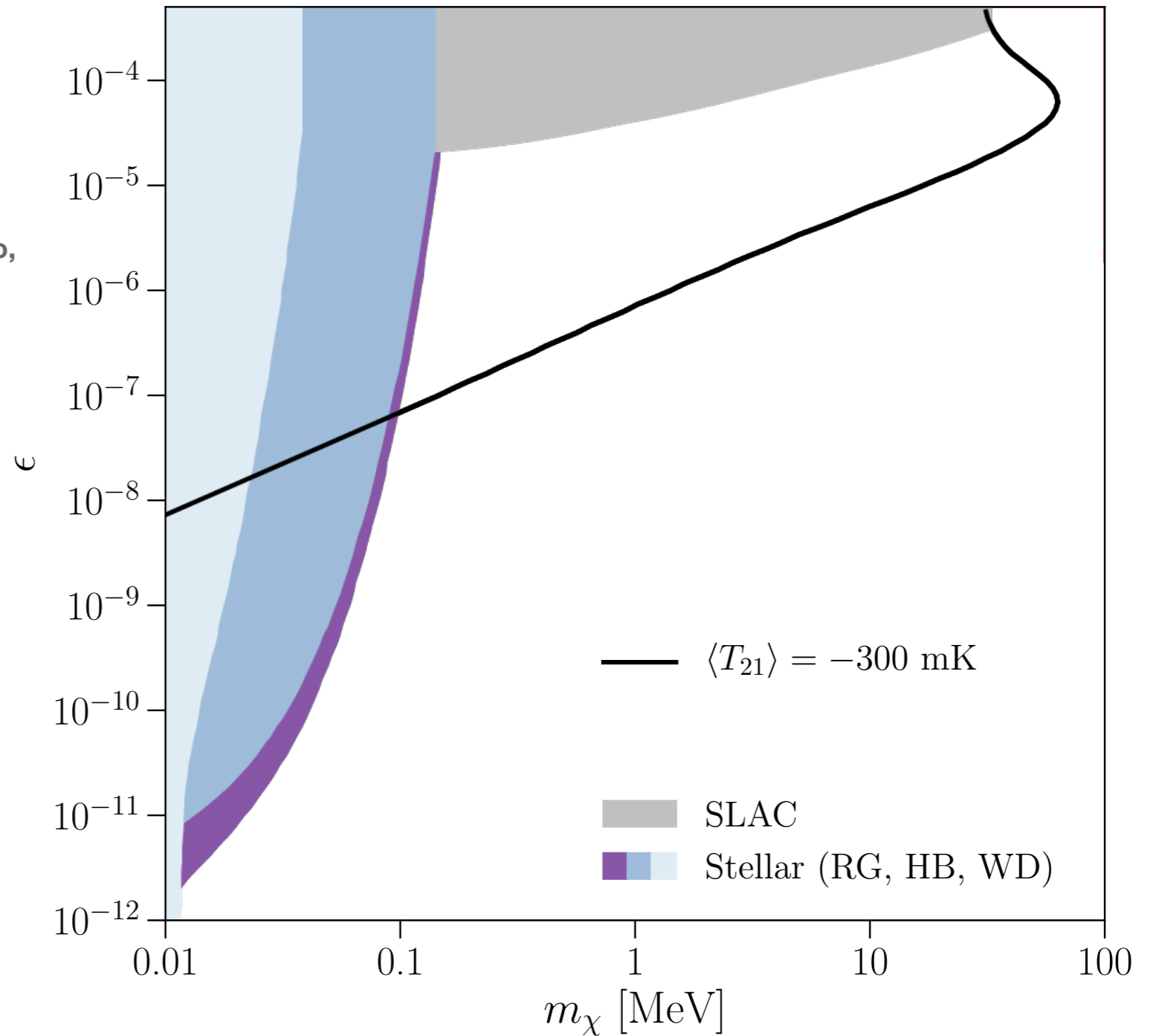


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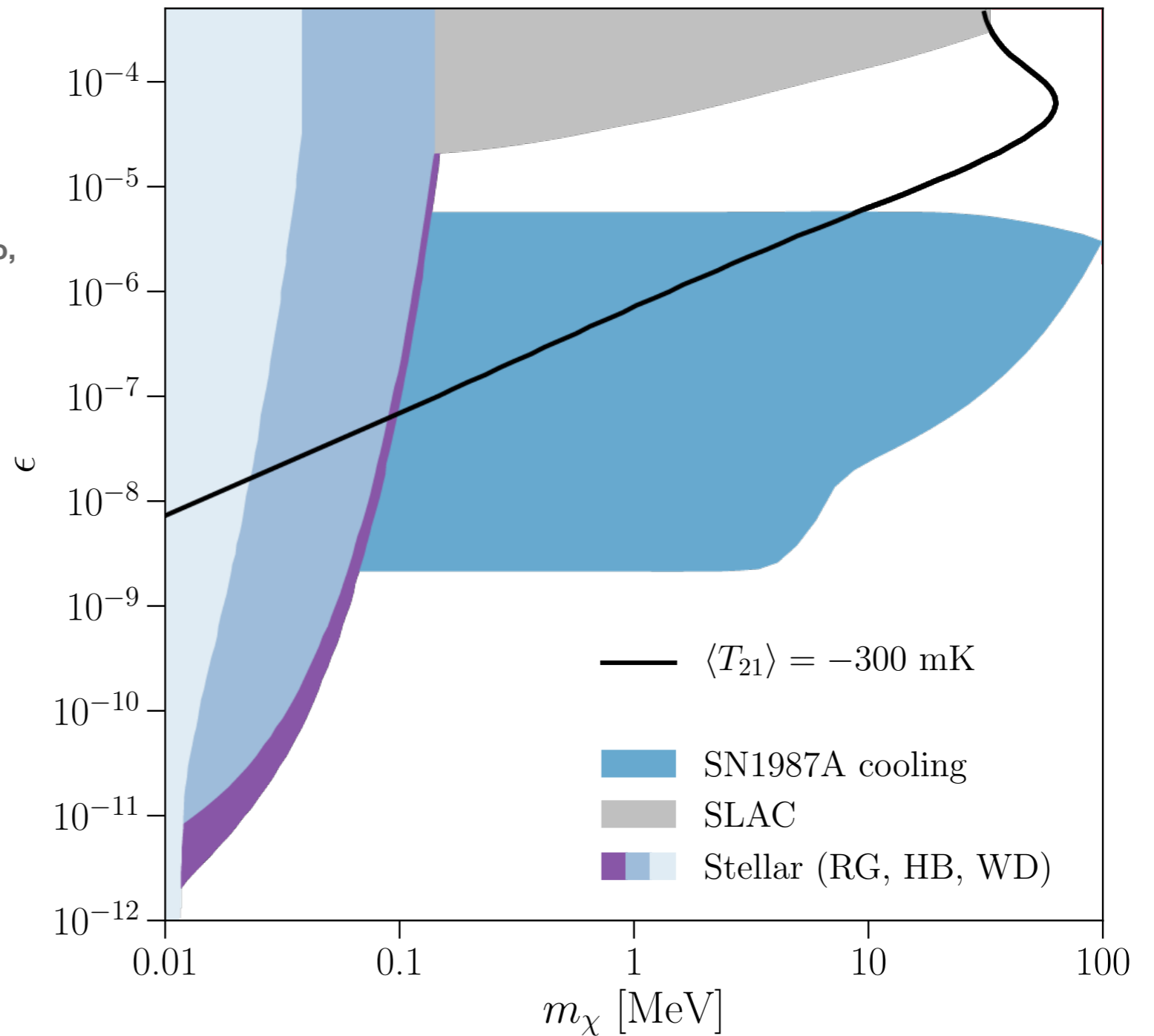


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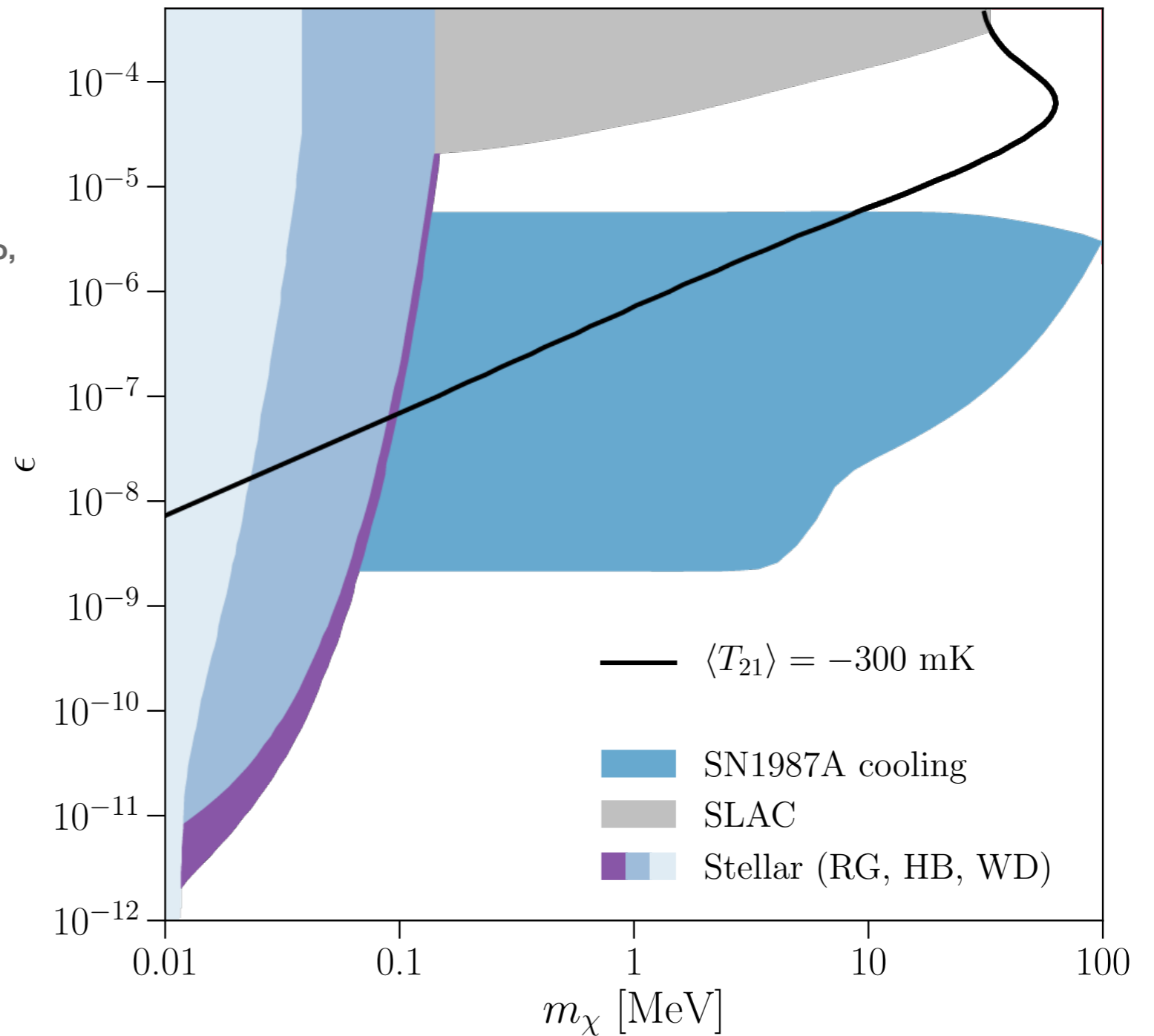
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Viable region for $f_\chi = 1\%$?



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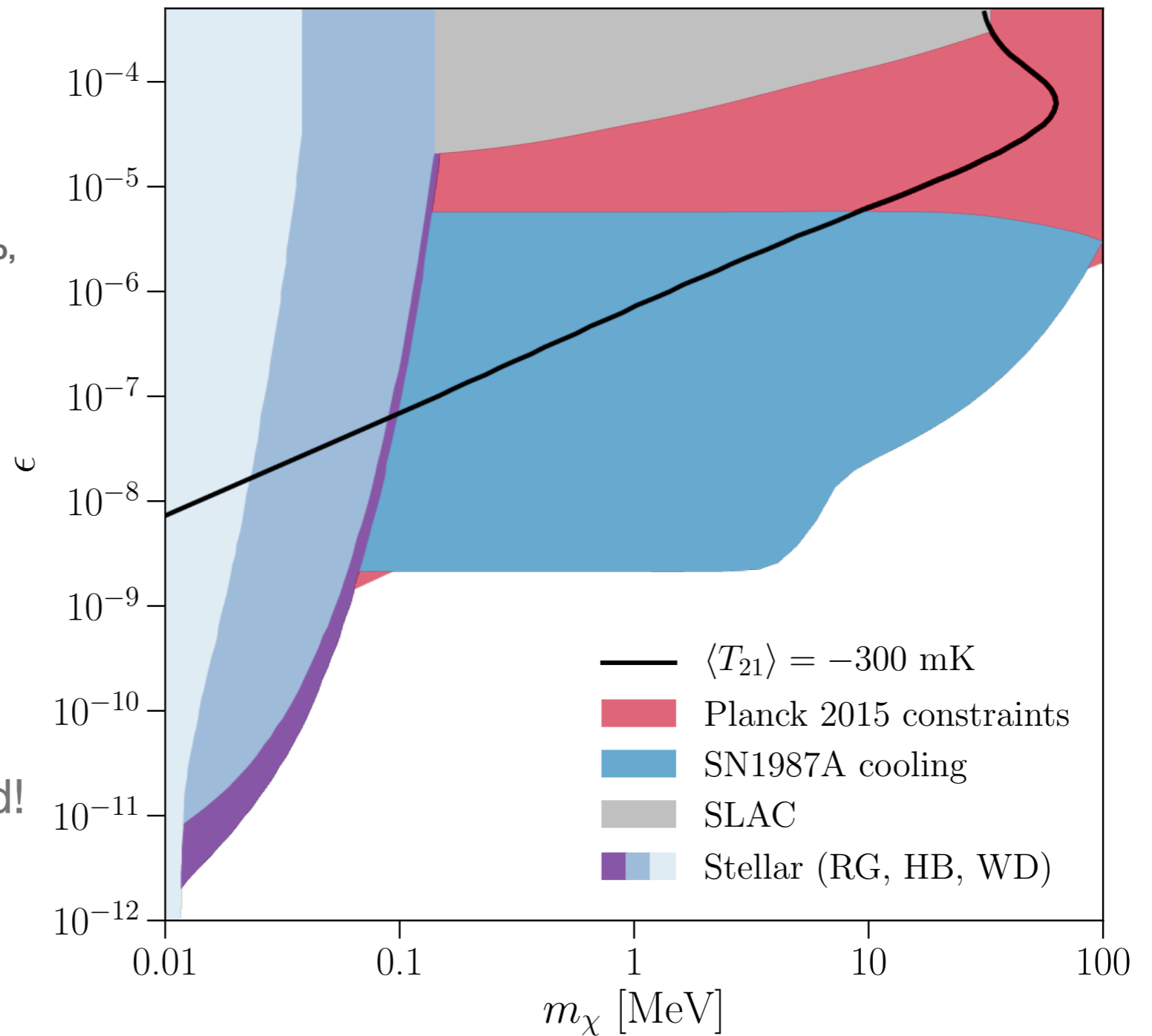
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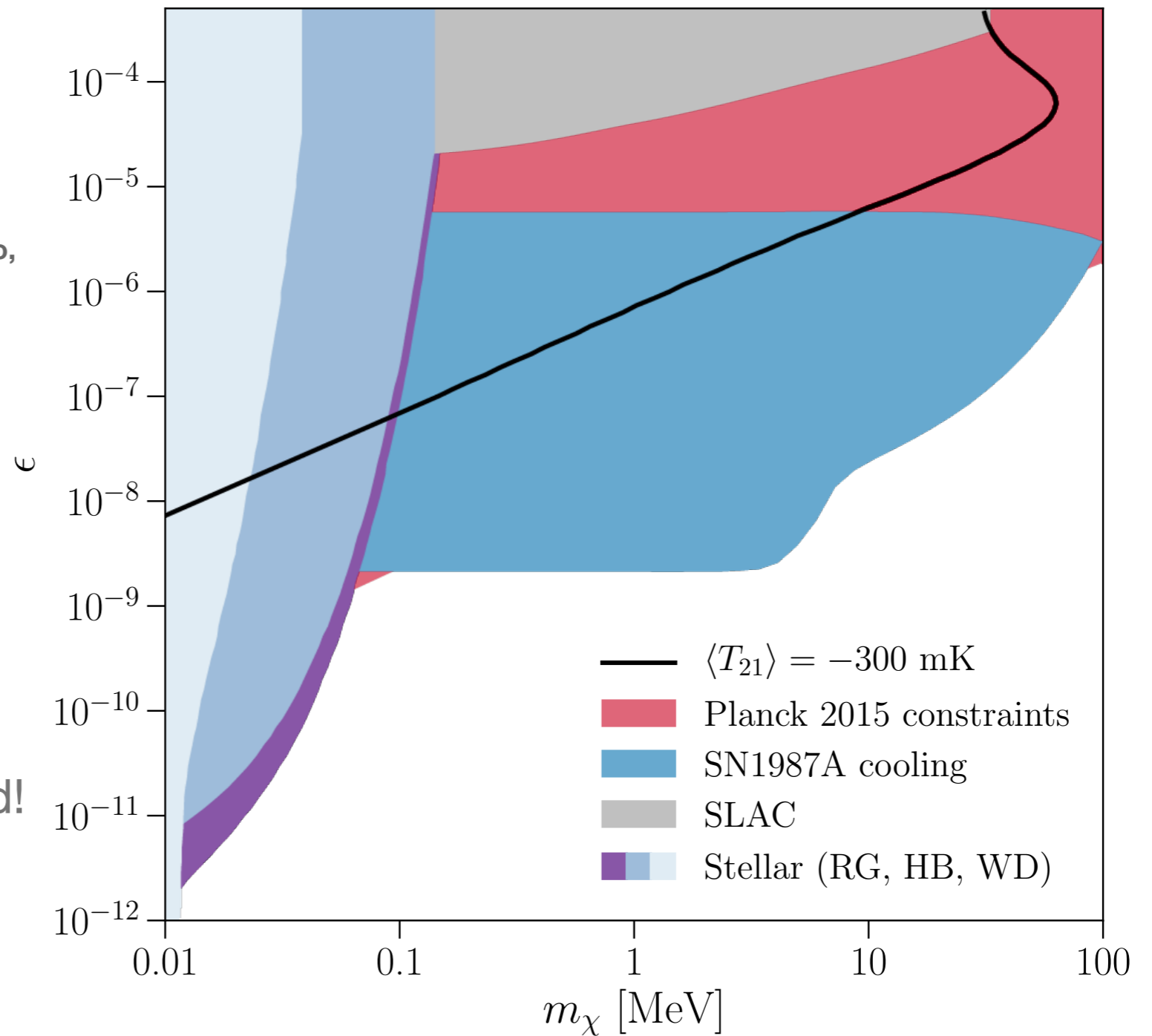
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What about lower fractions?



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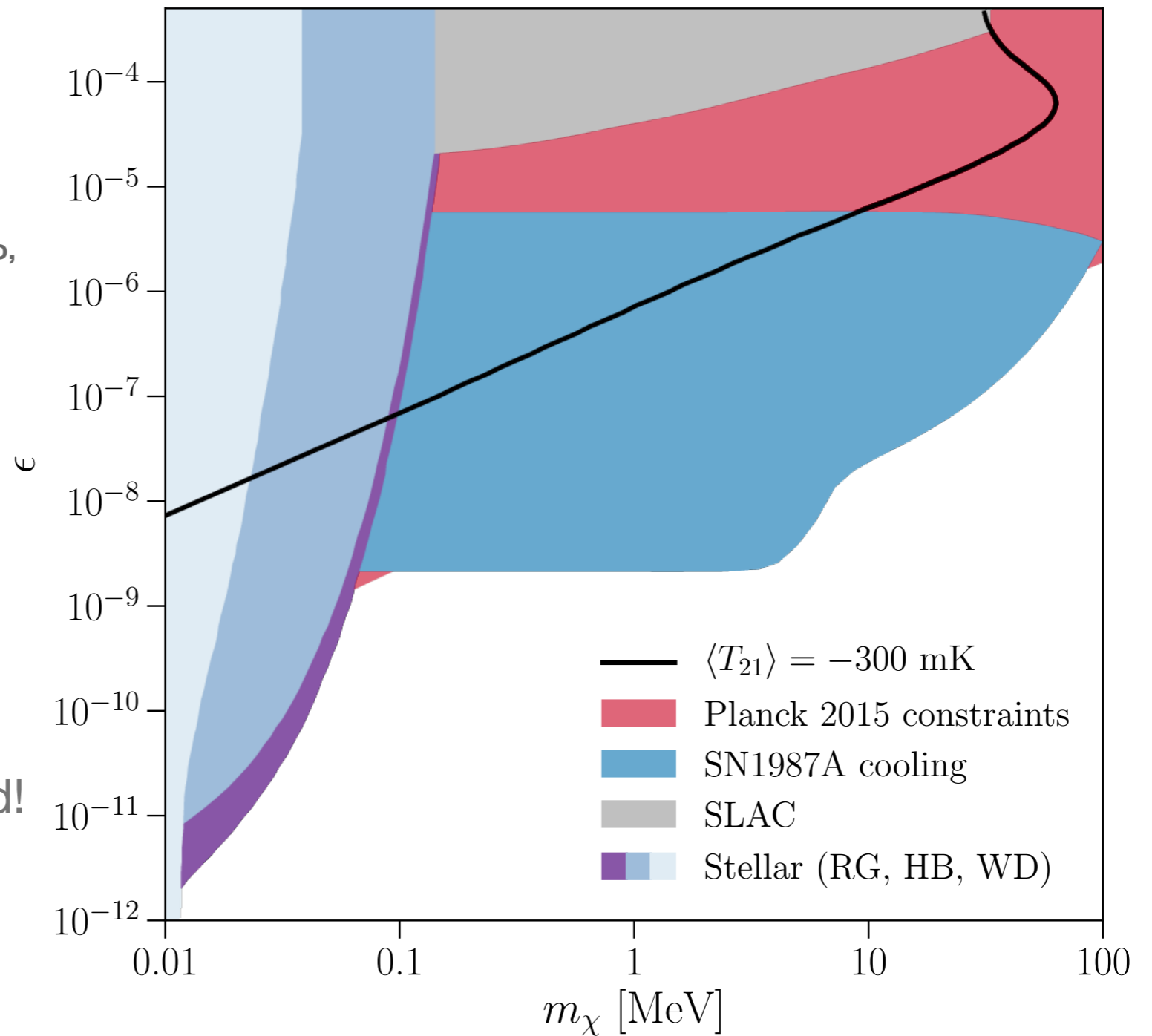
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- Stronger cross sections are needed.

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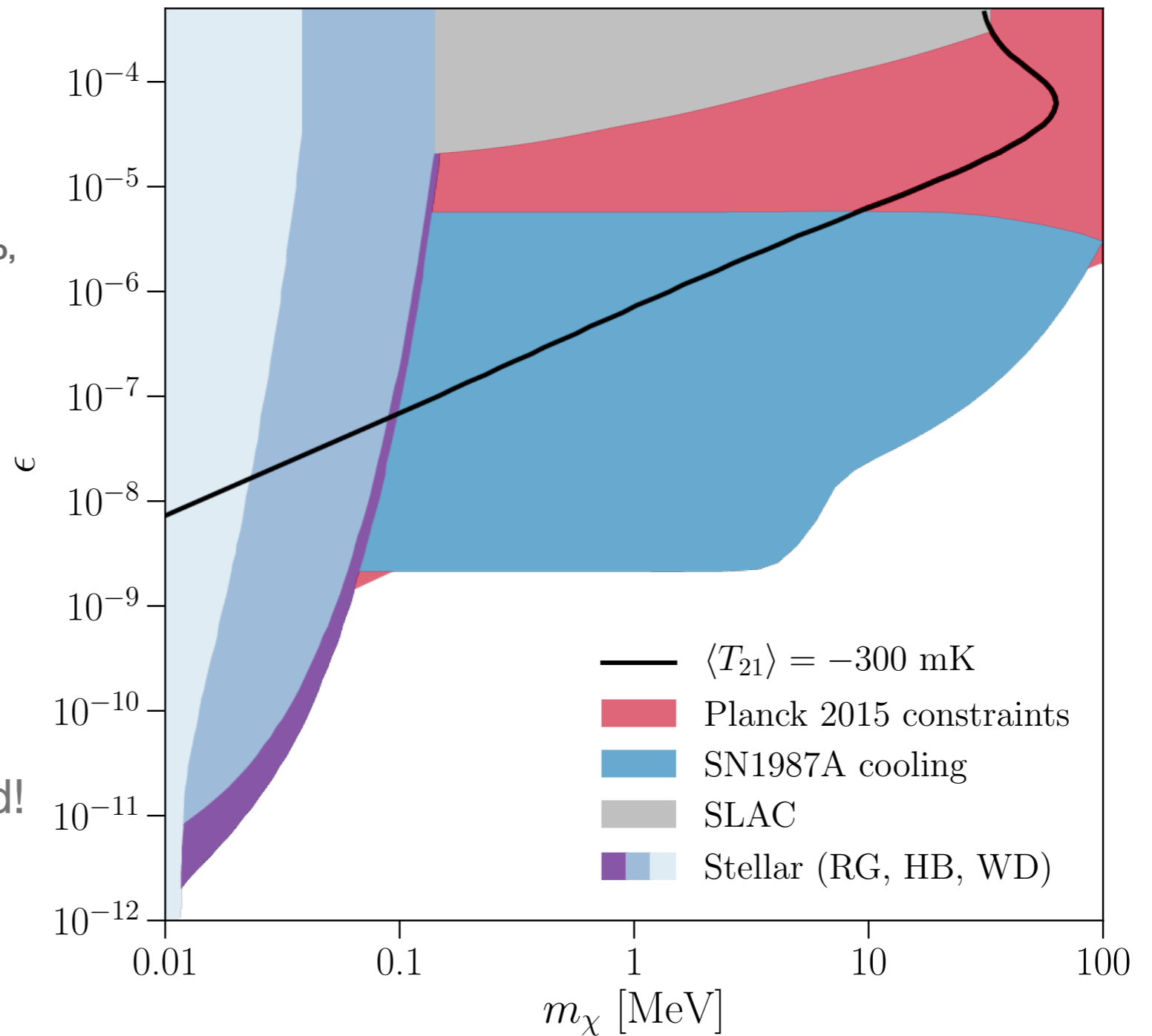
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What about lower fractions?

- Stronger cross sections are needed.
- At some point, CMB becomes ineffective (tightly-coupled DM obscured by $\Delta\Omega_b$).

Millicharged DM: Viable Parameter Space?

(EDK, Poulin, Gluscevic, Boddy, Barkana and Kamionkowski, PRD 2018)

Millicharged DM: Viable Parameter Space?

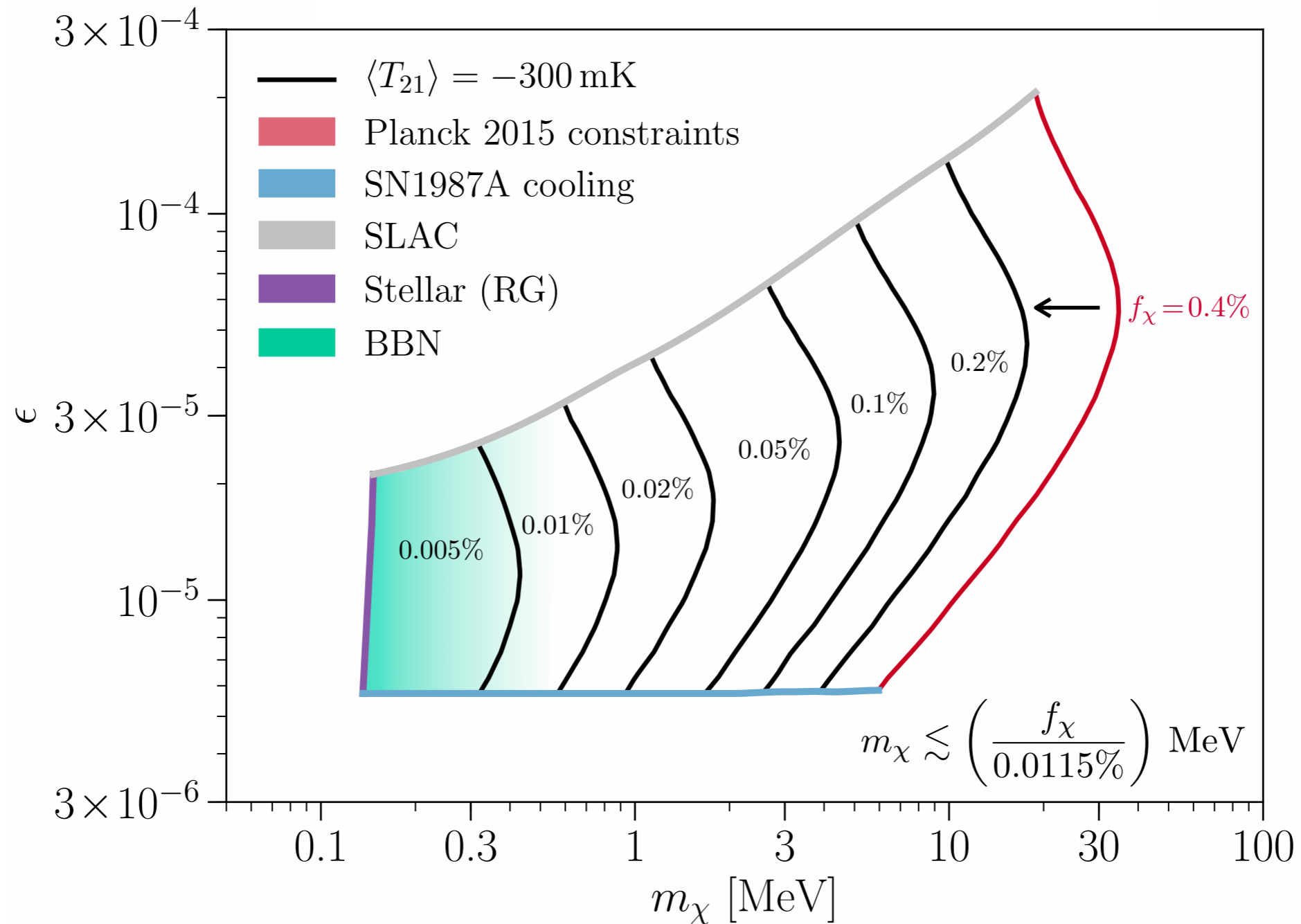
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Taking all constraints into account, we are left with:

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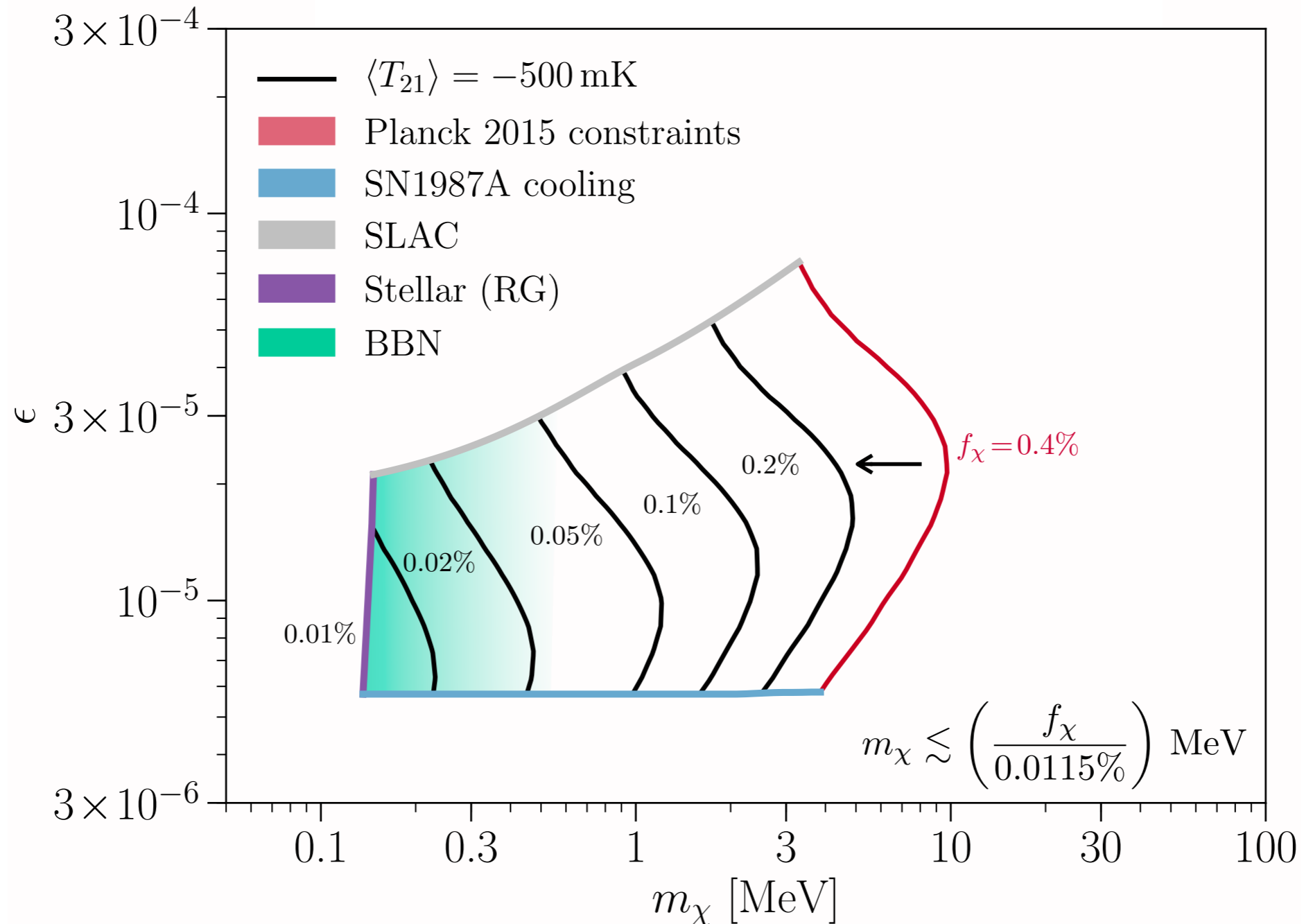


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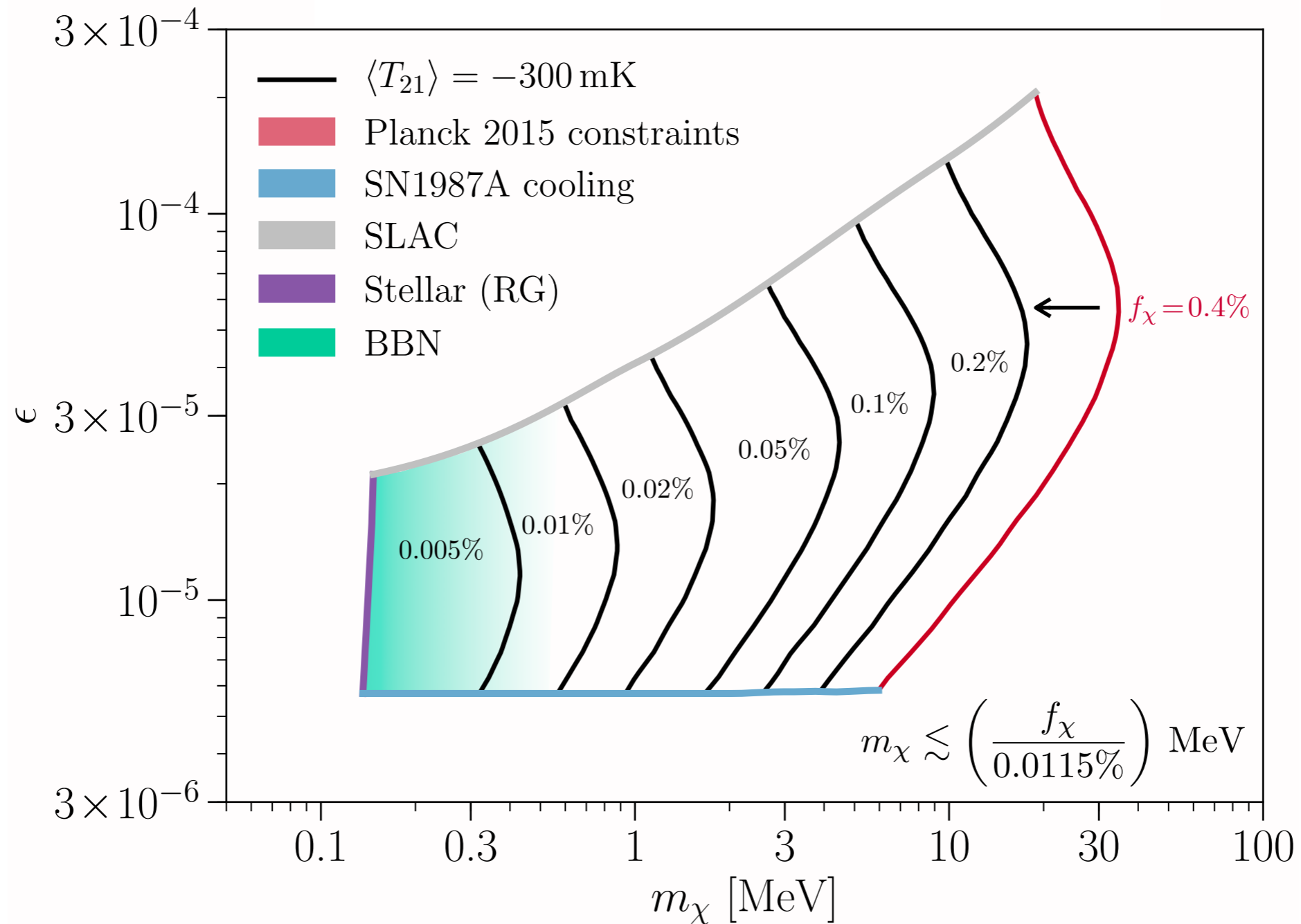


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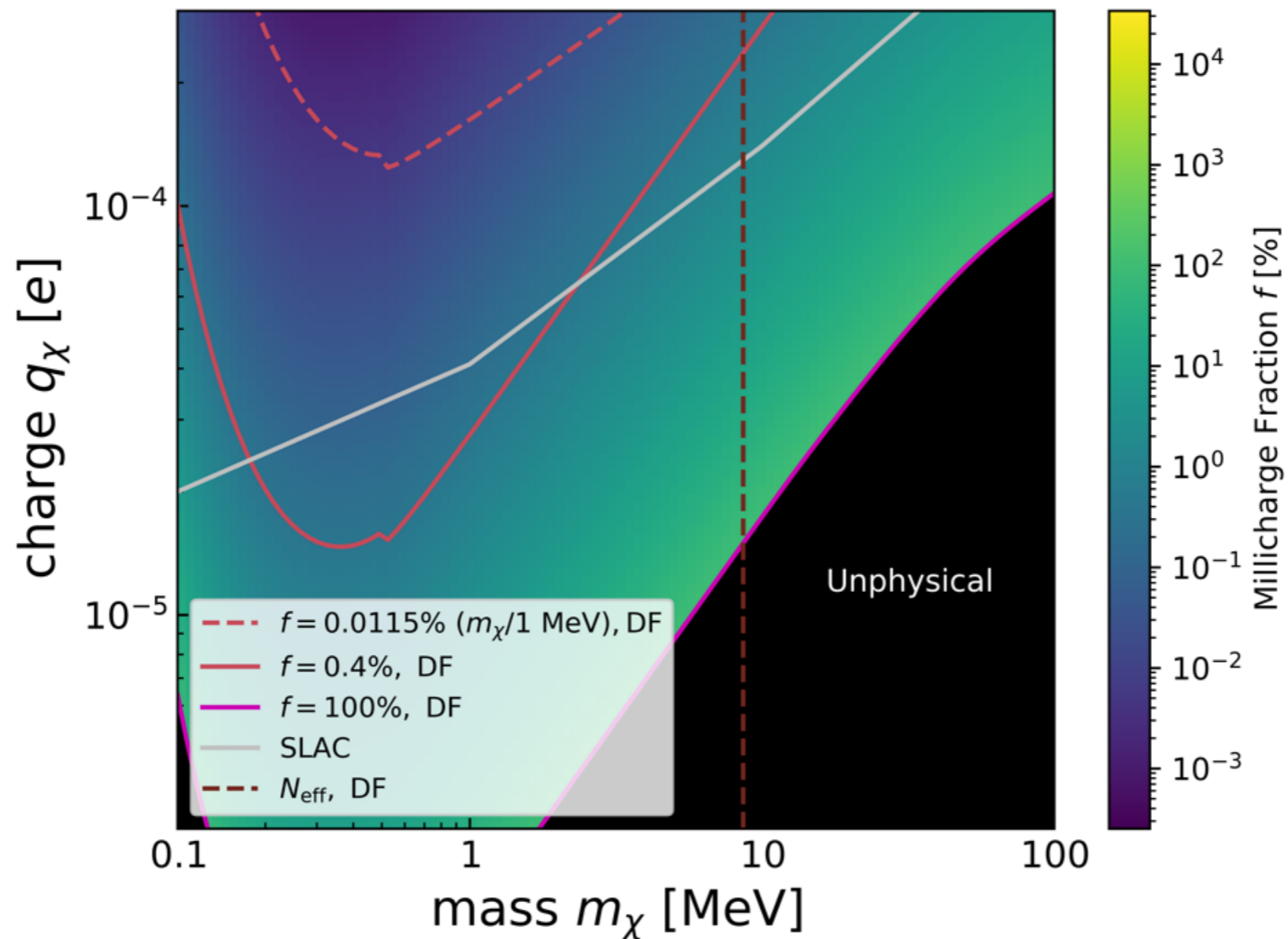
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Taking into account the thermal history, no room for the standard scenario:

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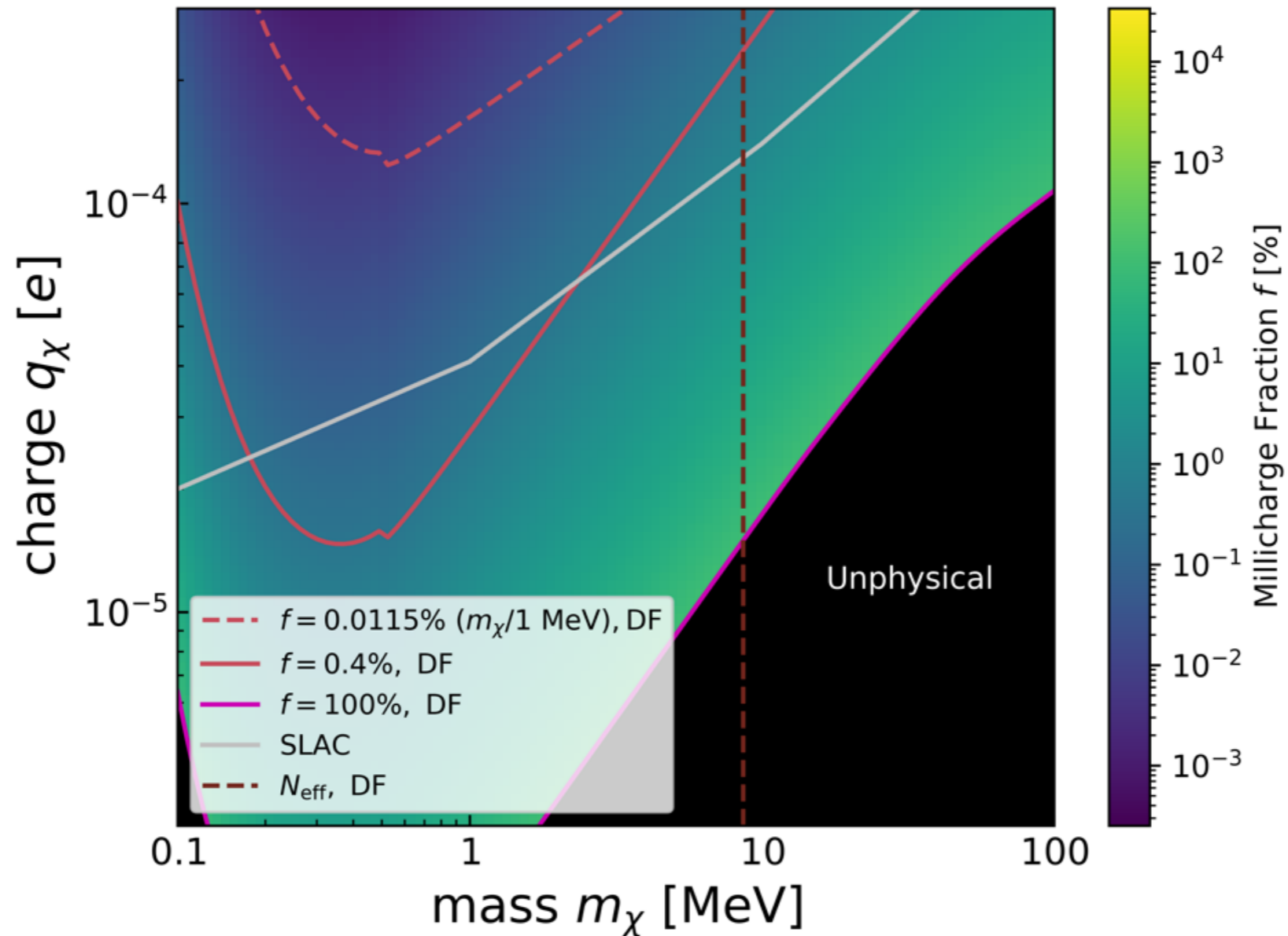
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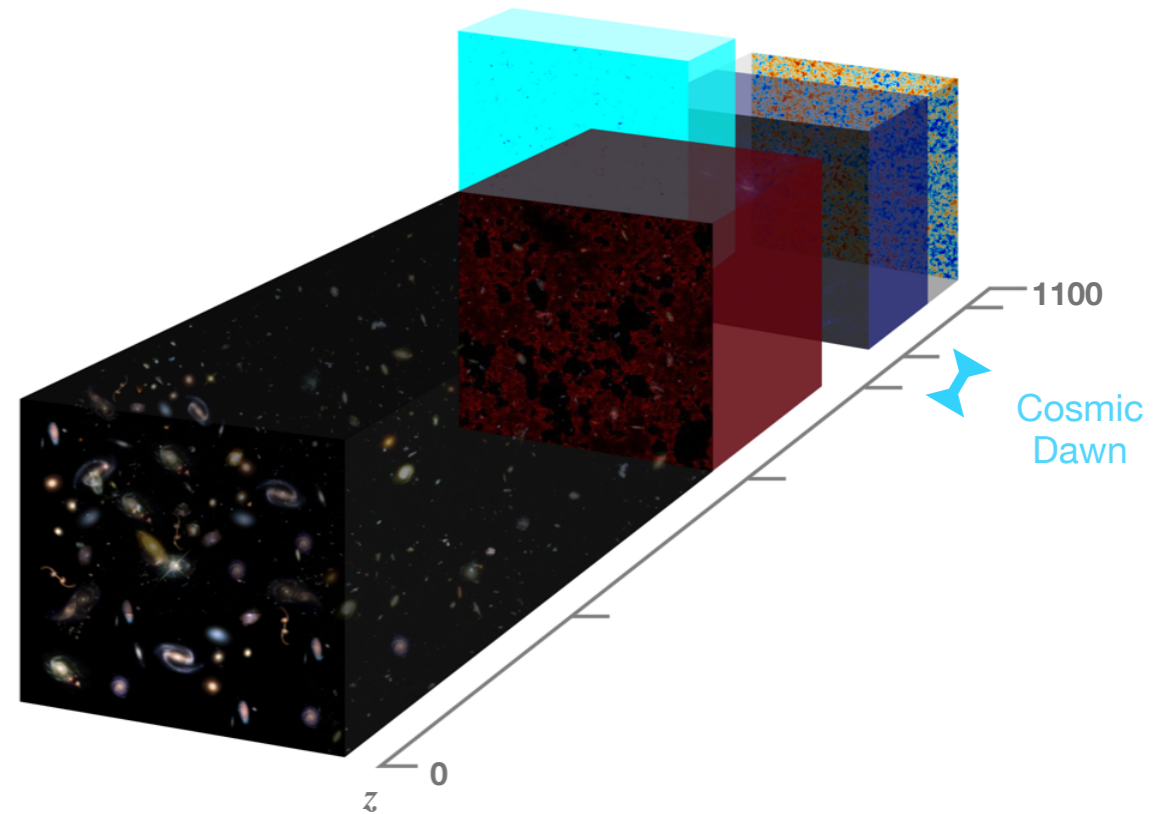
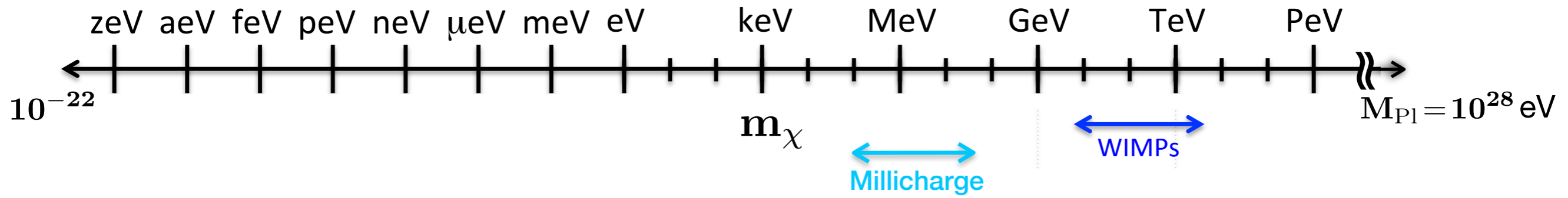
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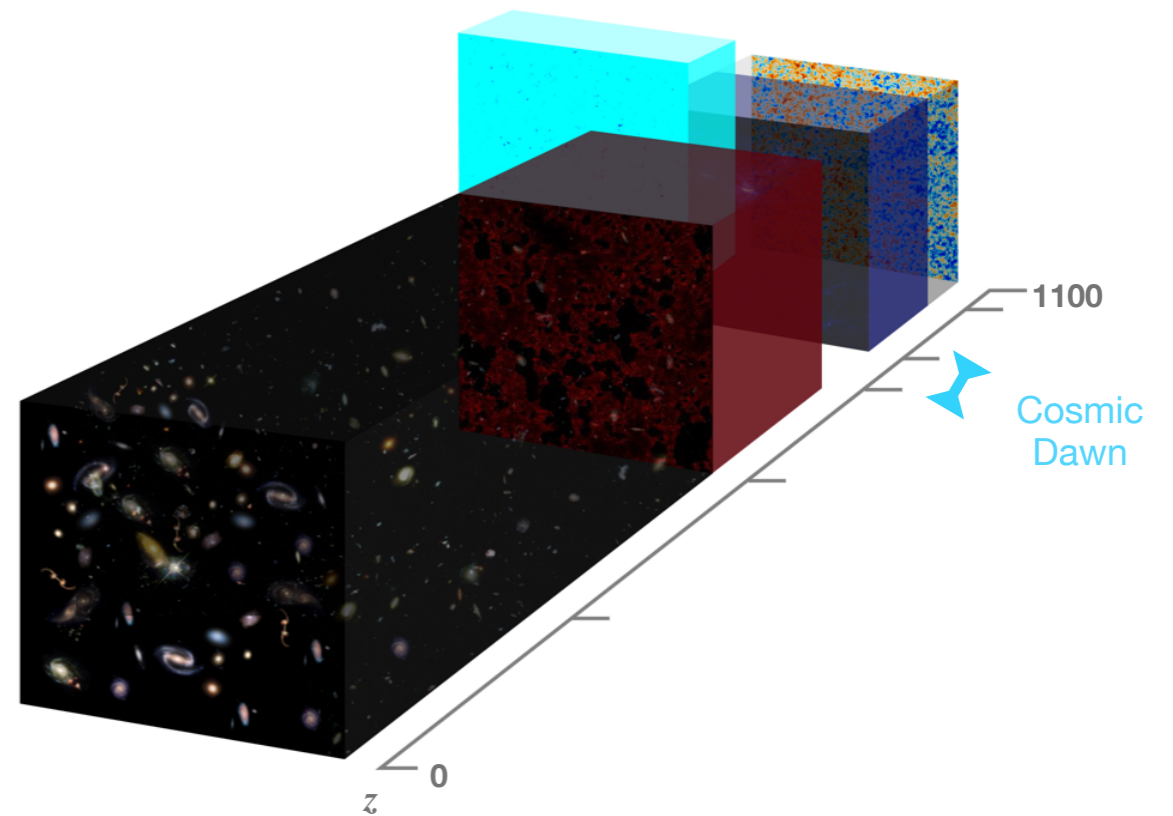
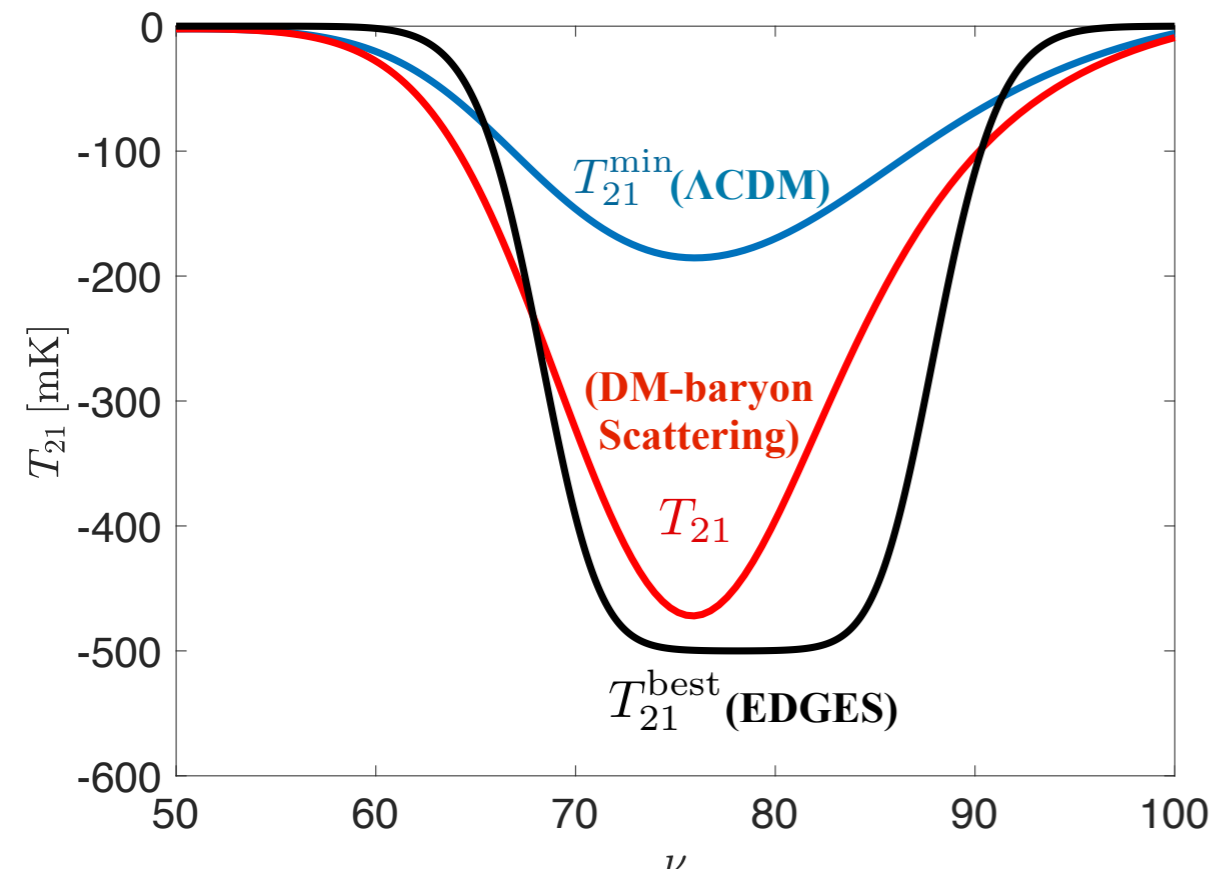
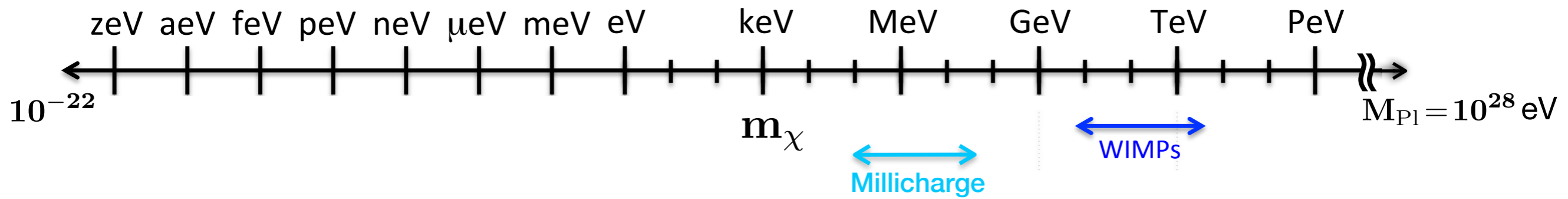


(Way out: atomic dark matter?)

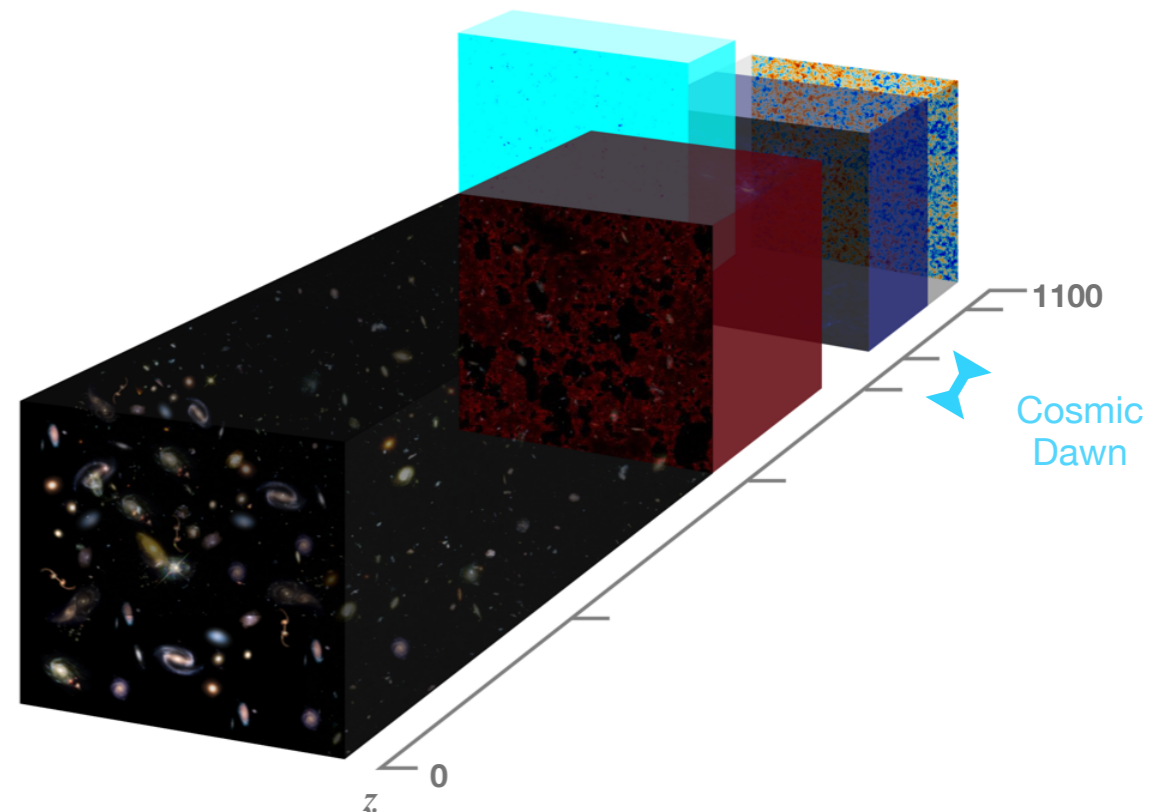
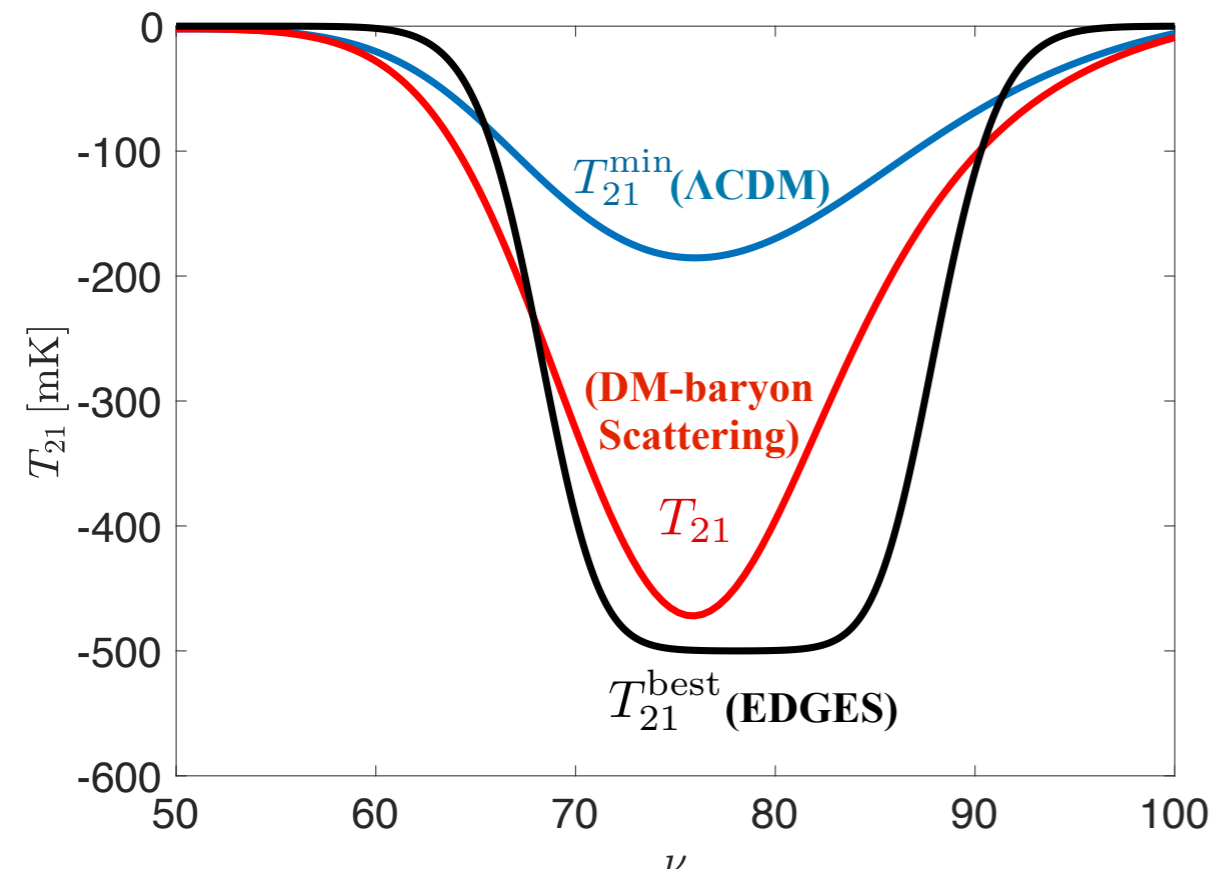
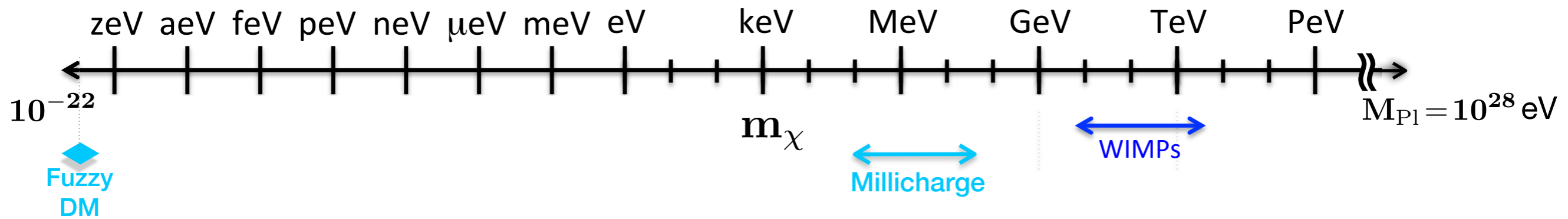
Takeaway:



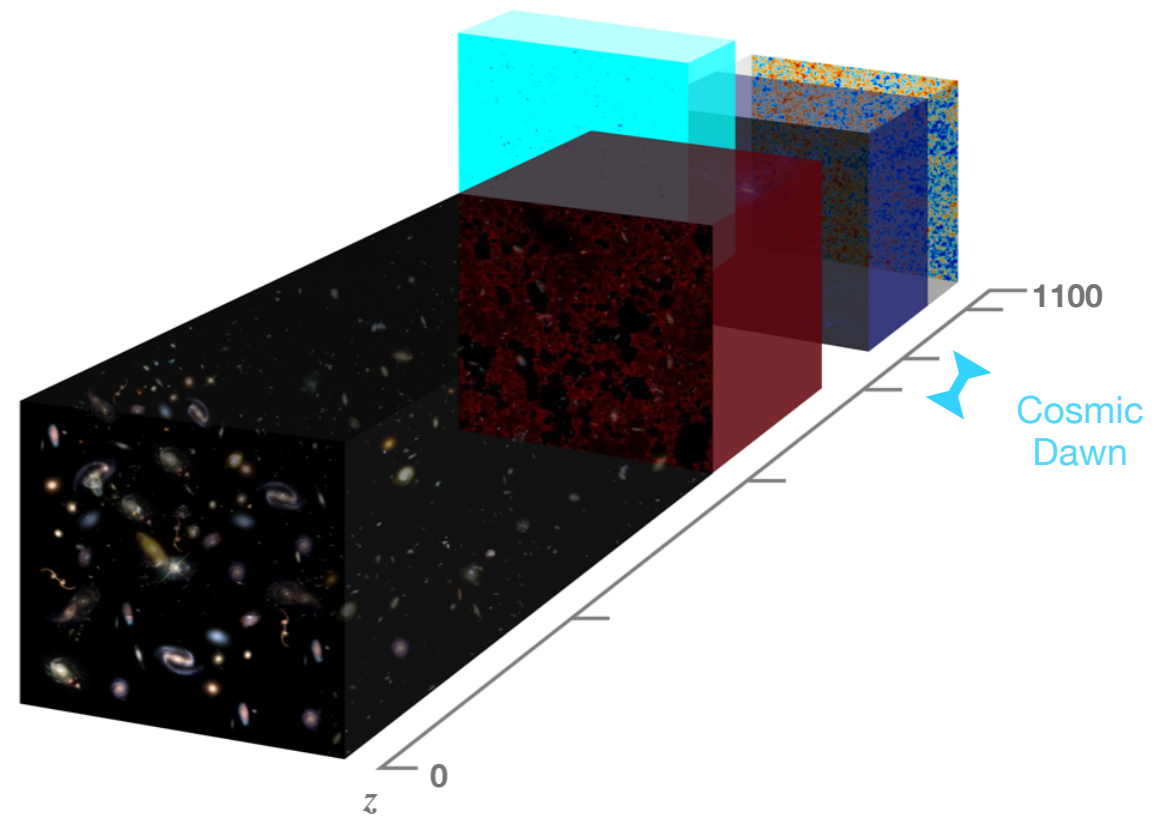
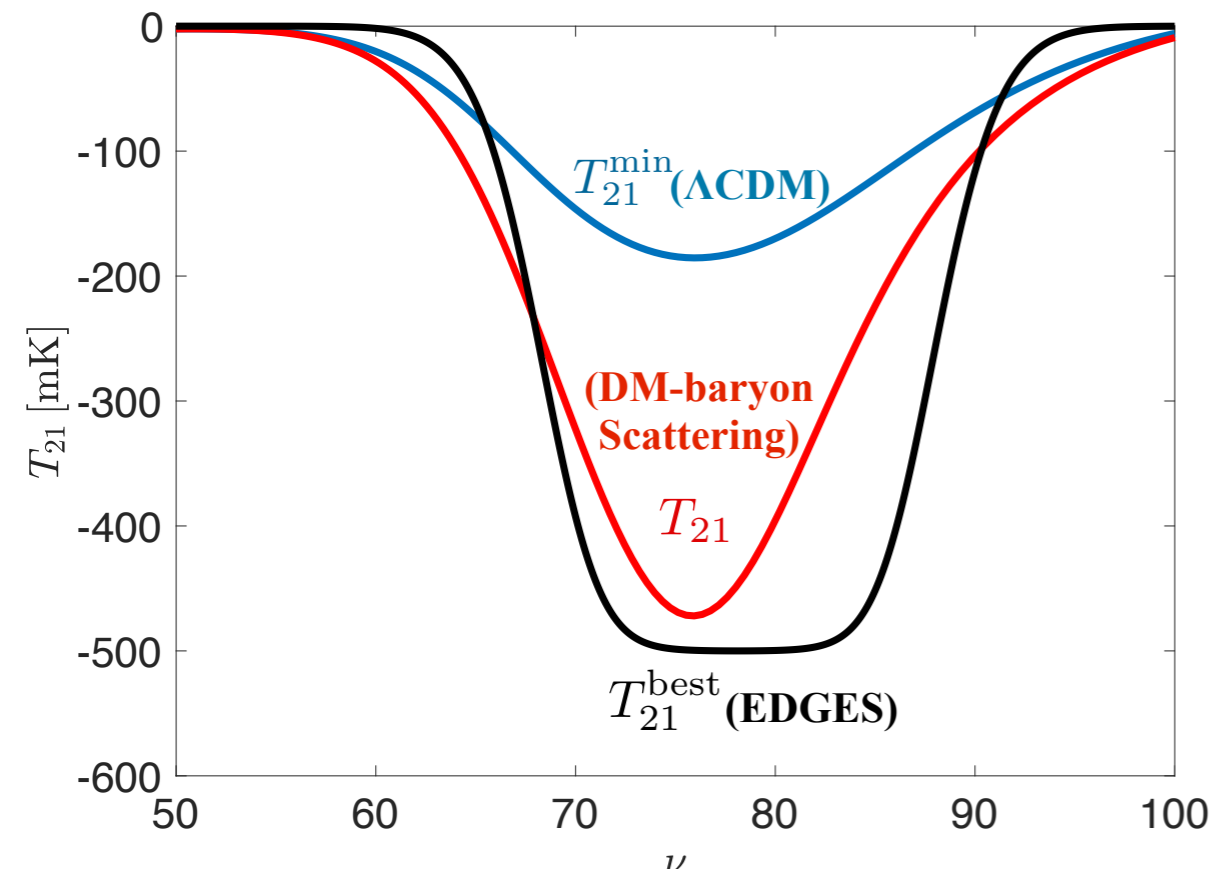
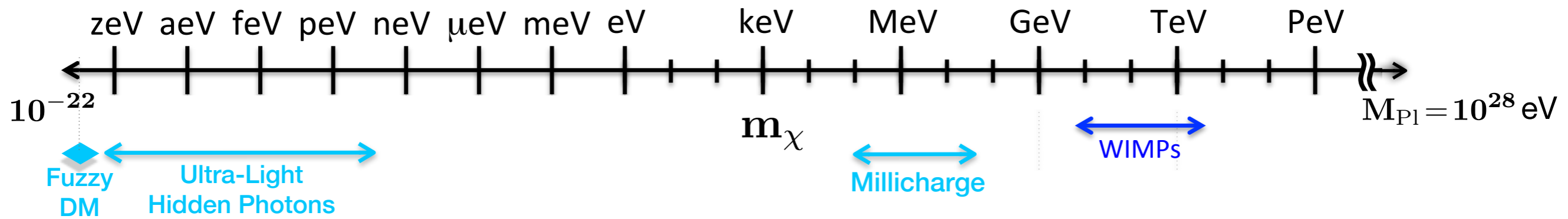
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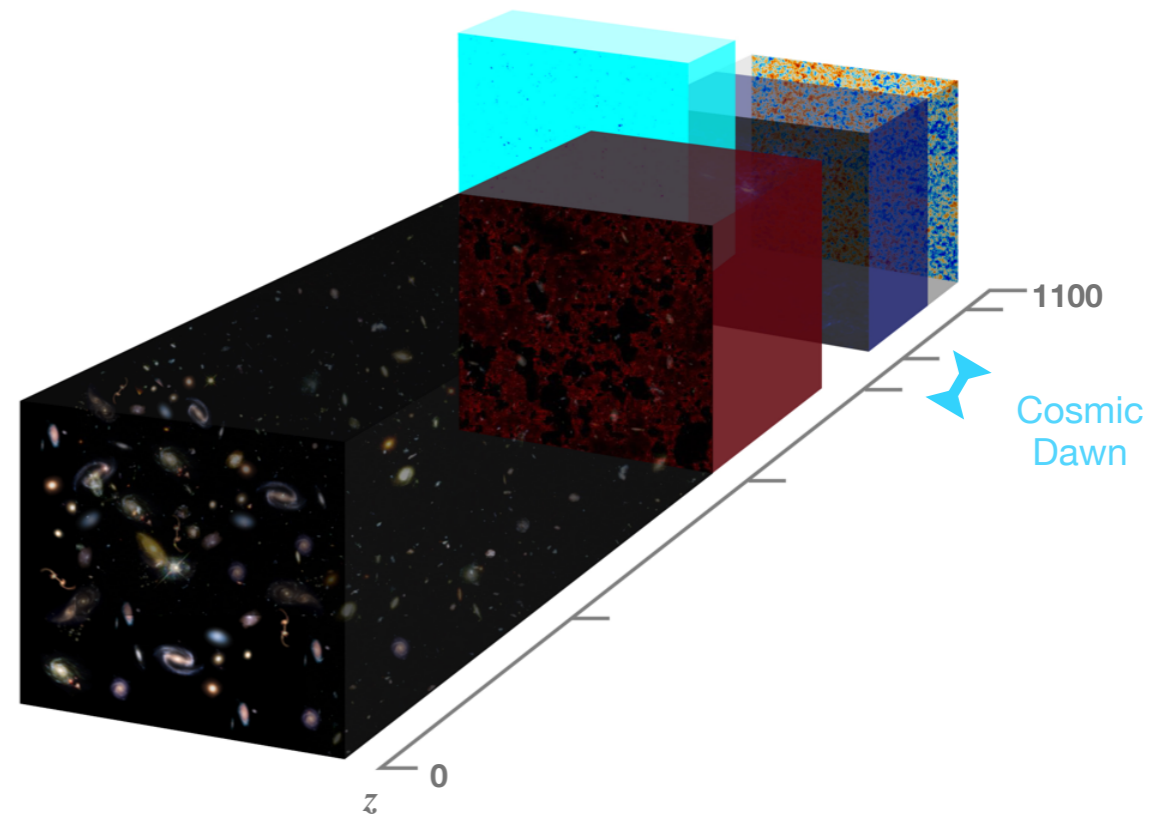
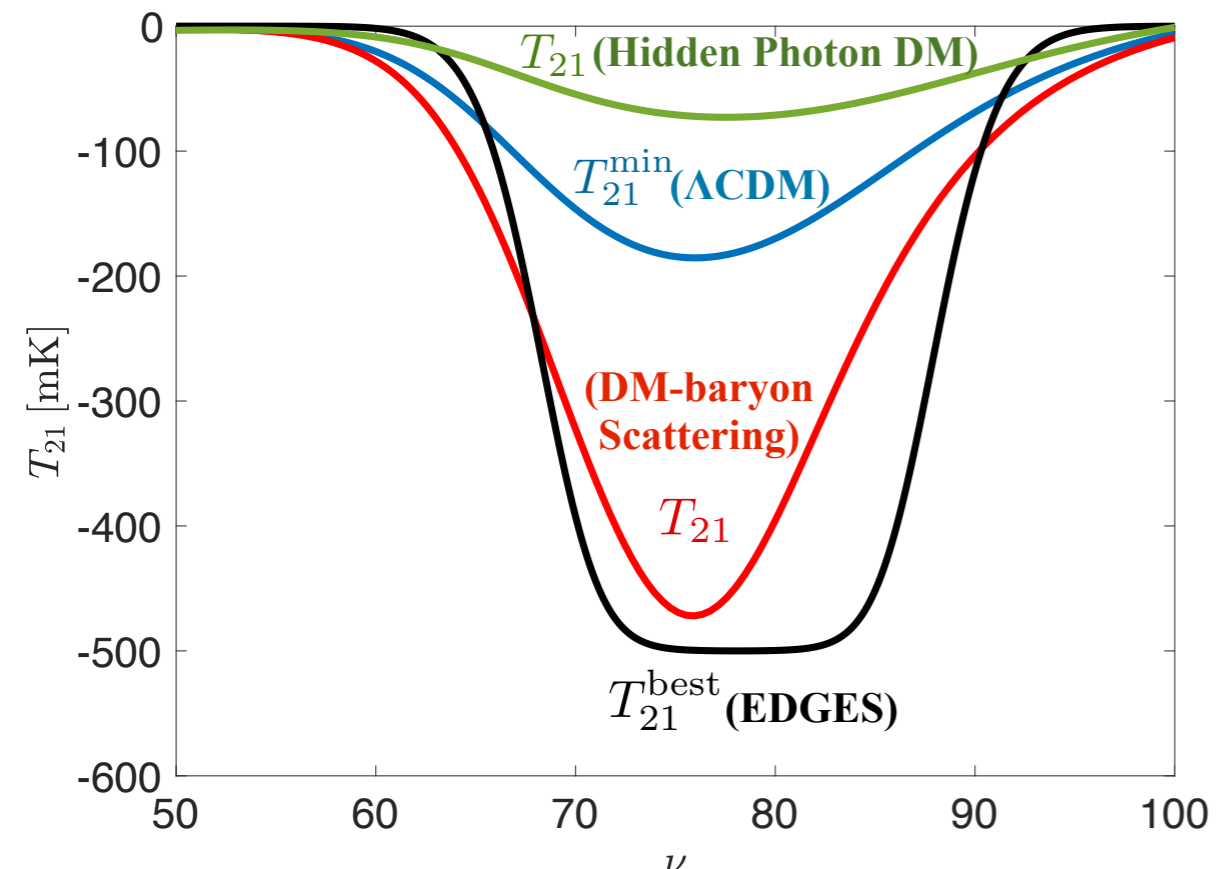
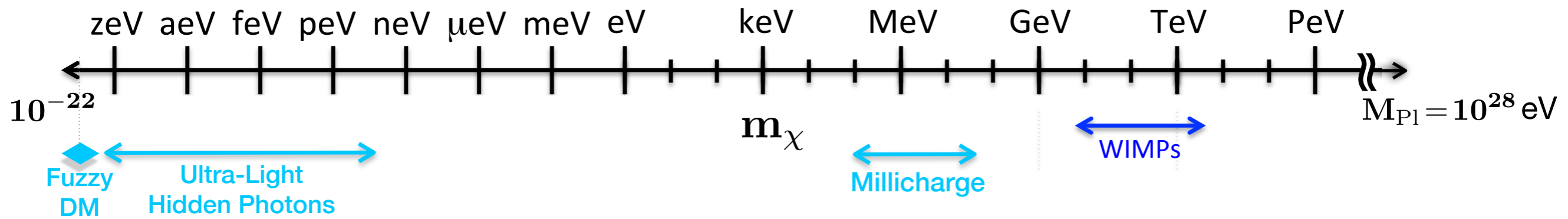
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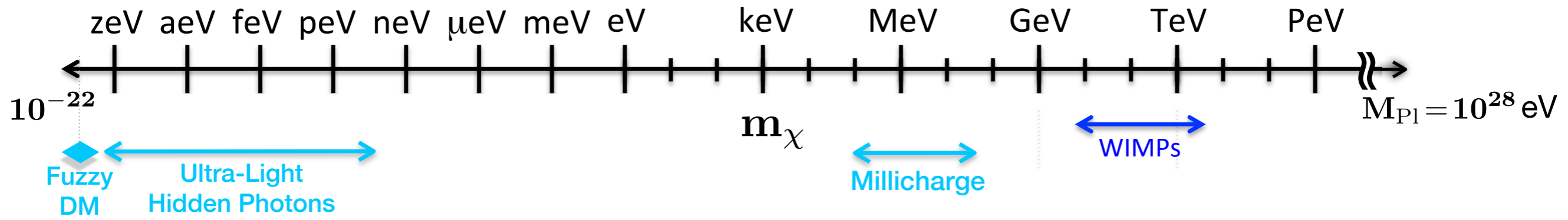
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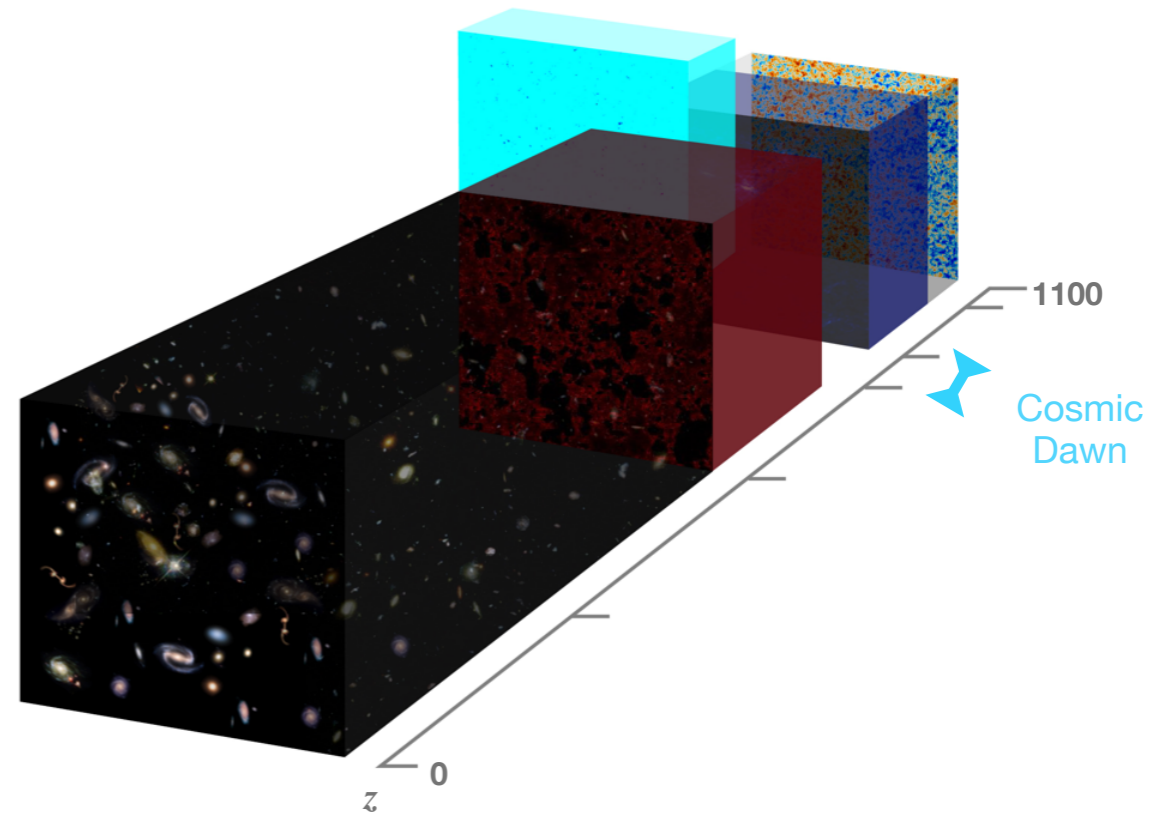
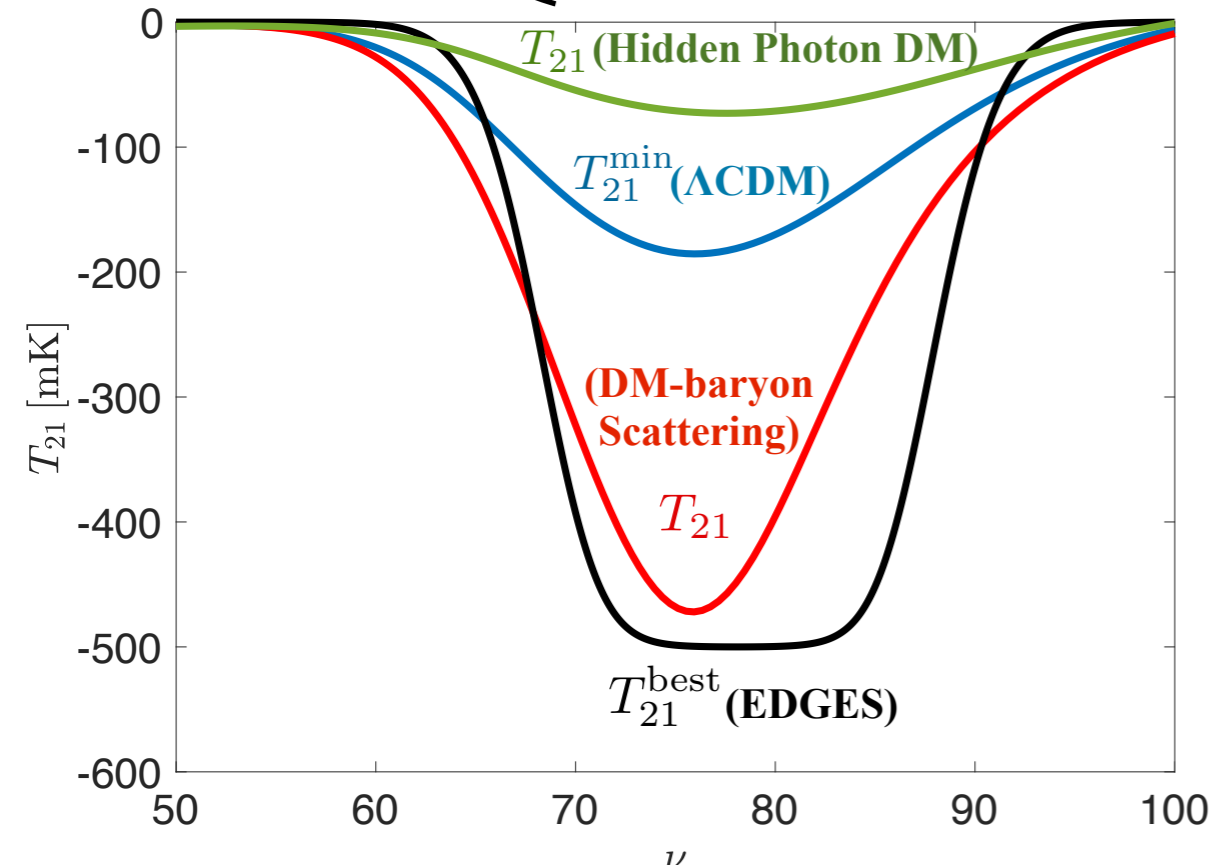
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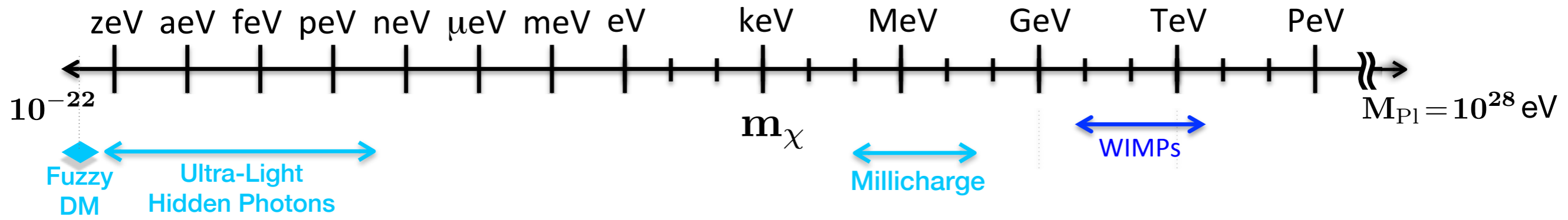
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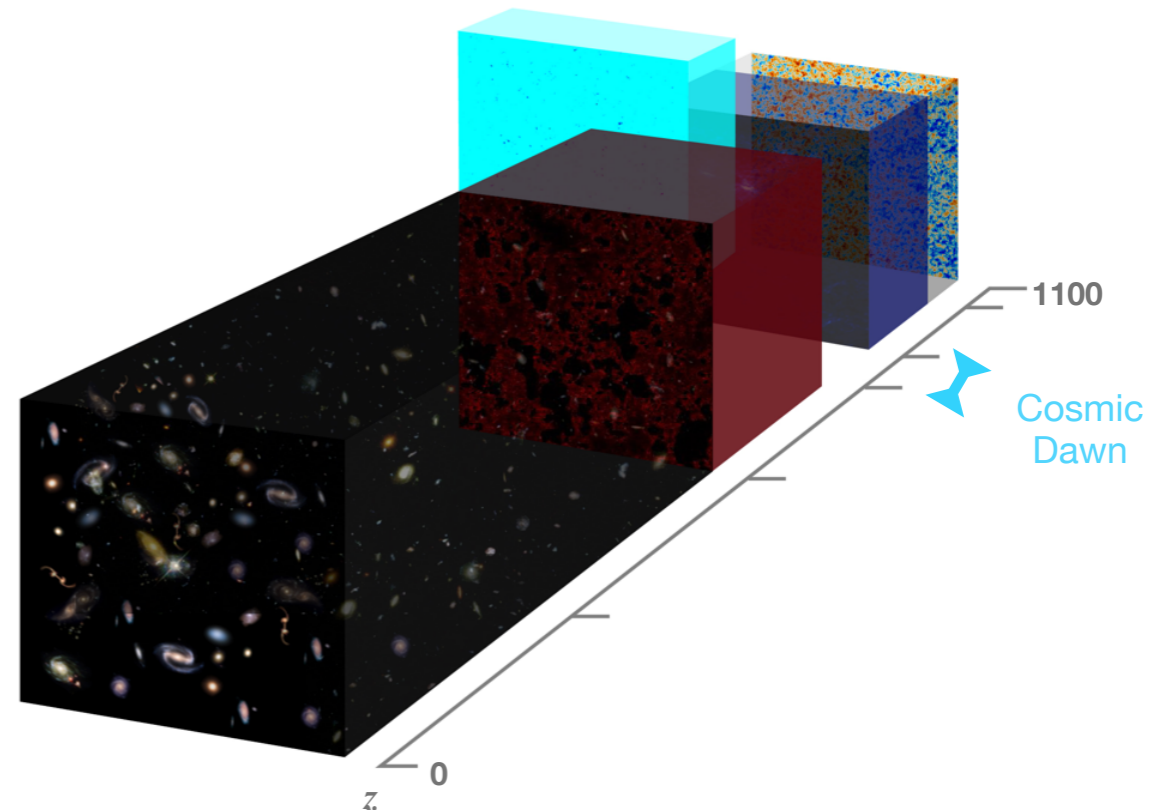
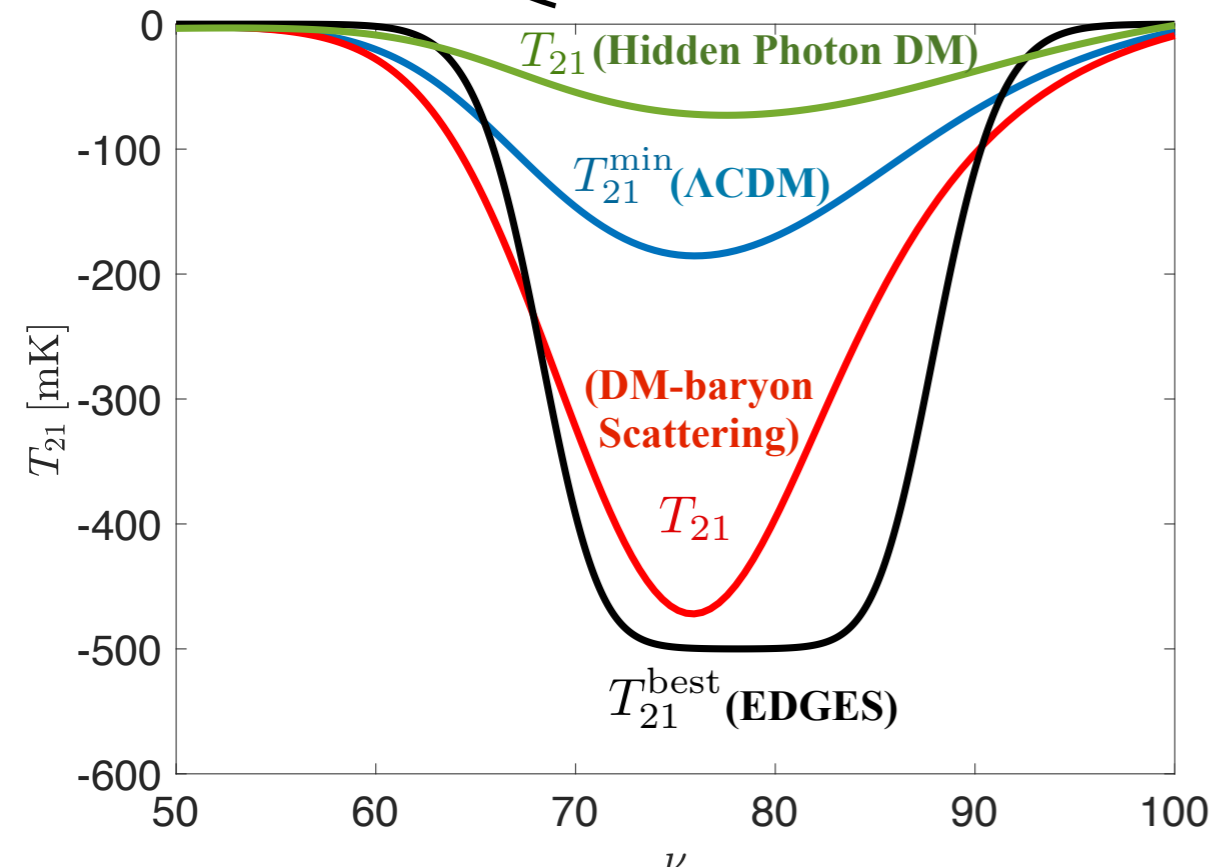
EDK, Cholis and Kaplan, PRD 2019



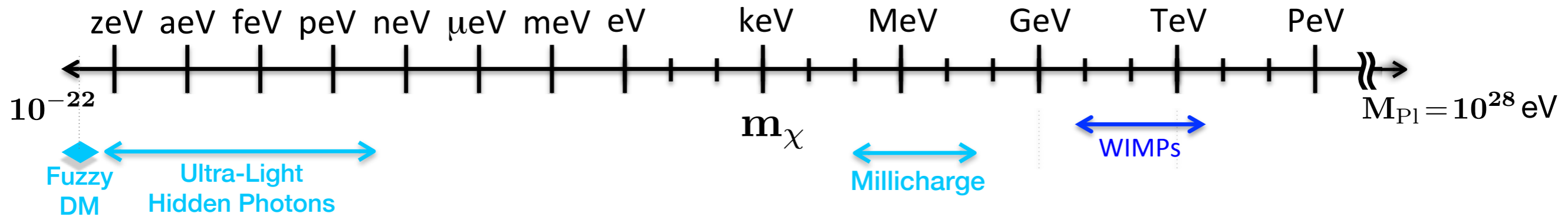
Takeaway: Cosmic Dawn can shed light on DM!



EDK, Cholis and Kaplan, PRD 2019

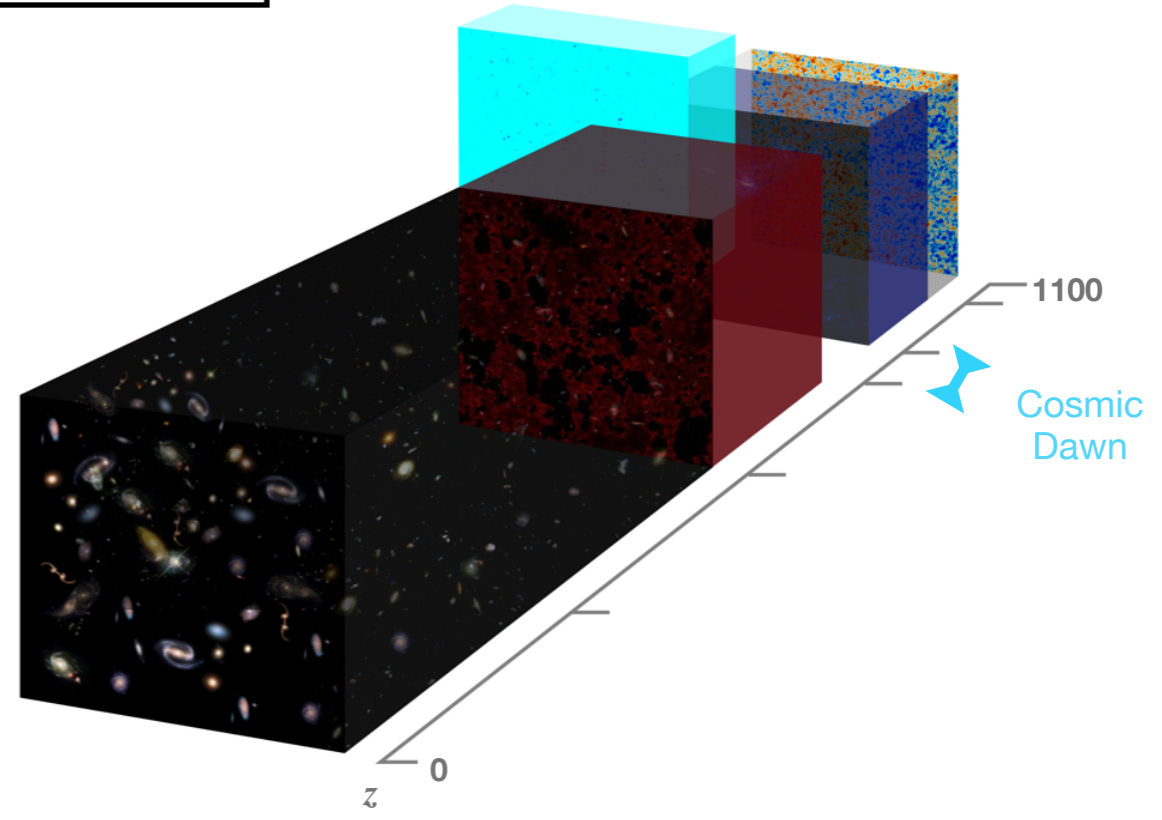
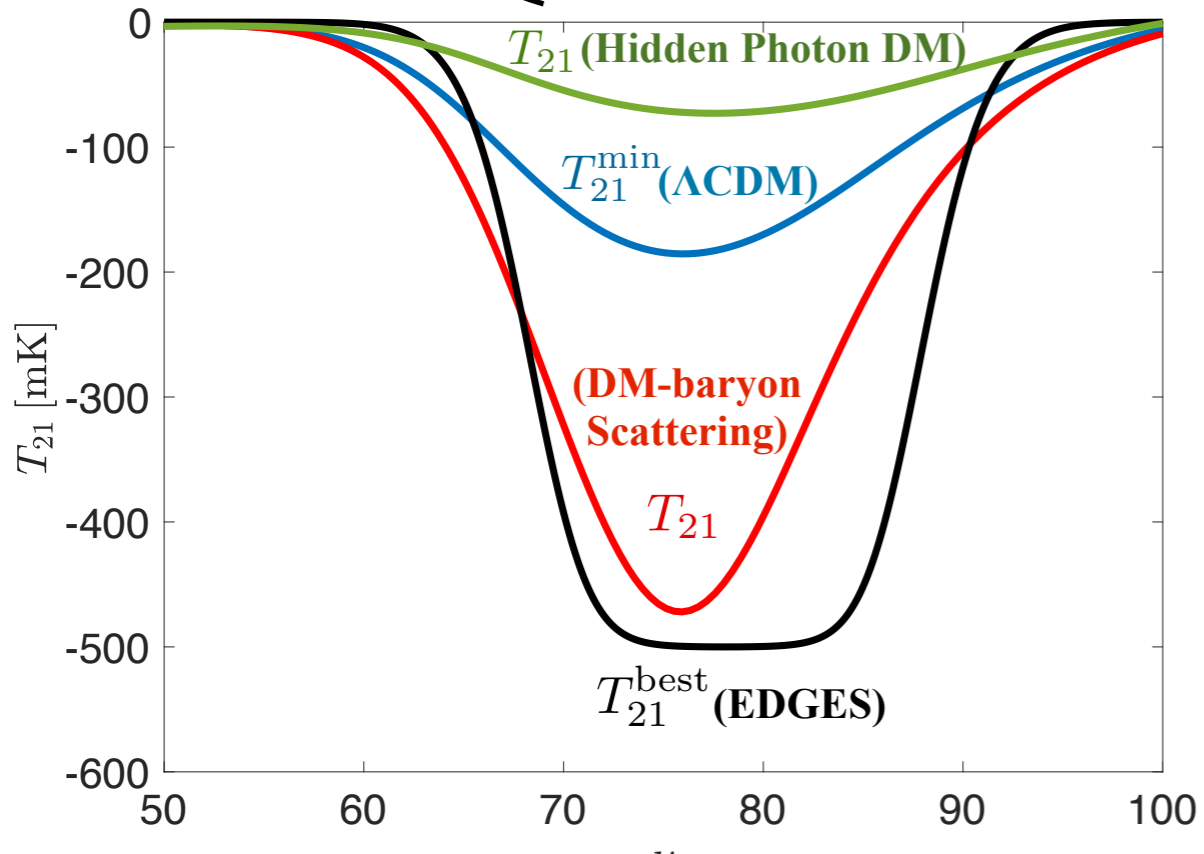


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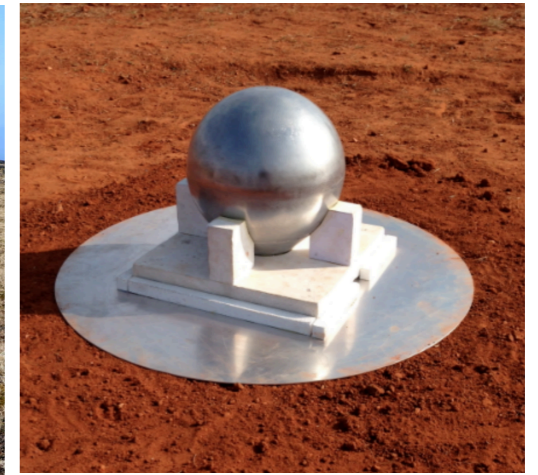
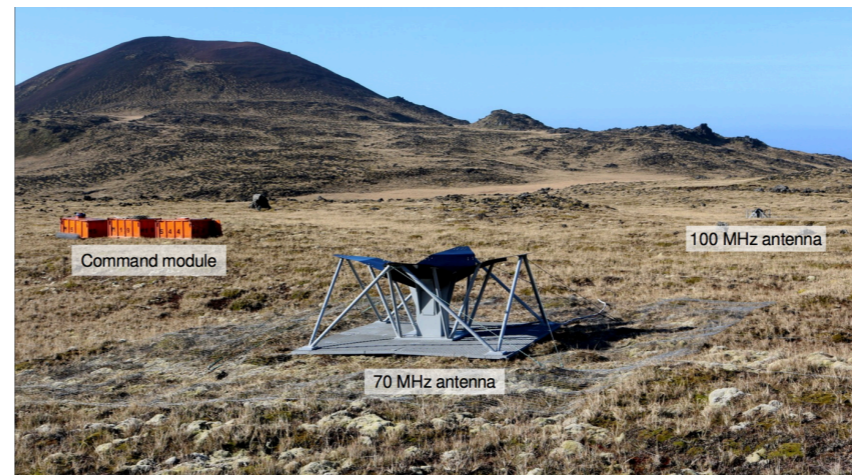
We used one number!



Cosmic Dawn 21 cm: Observational Outlook

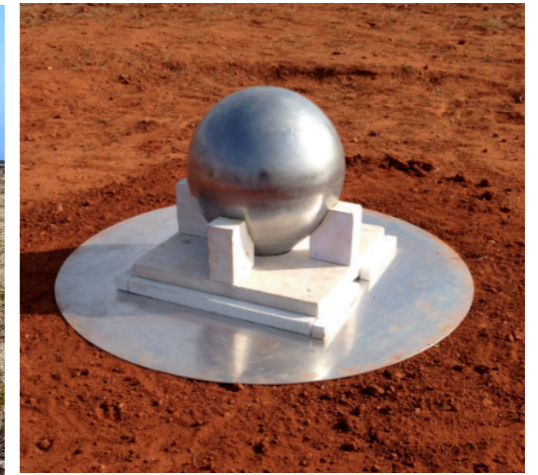
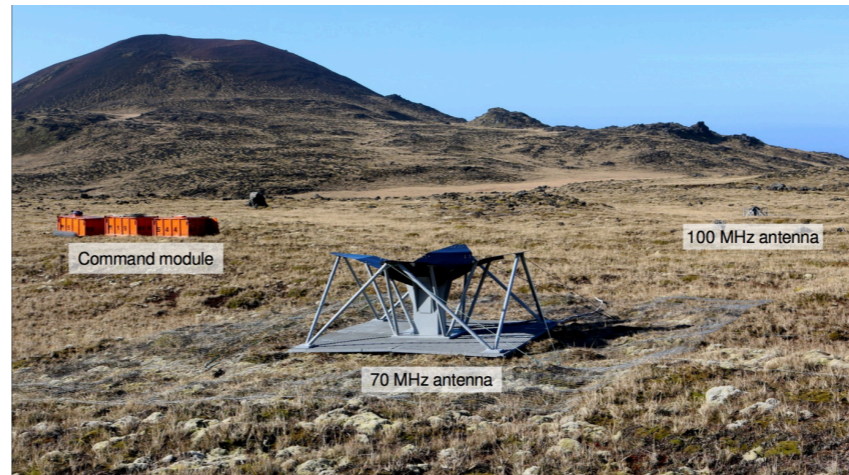
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- 21cm global signal: LEDA, PRIZM, SARAS2...



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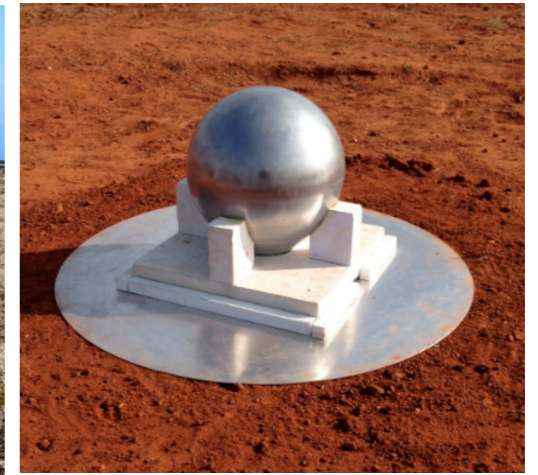
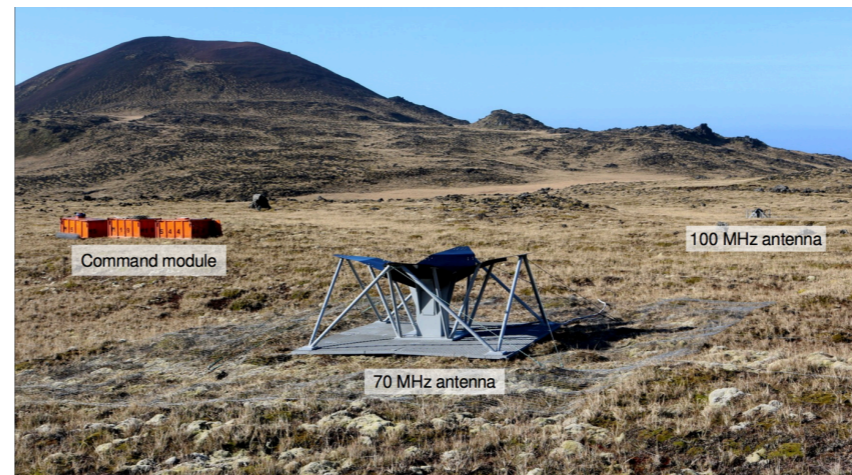
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Earliest results could show up before the end of 2019!

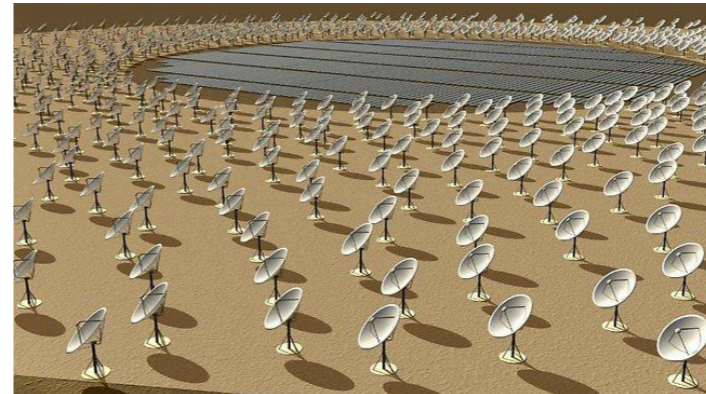
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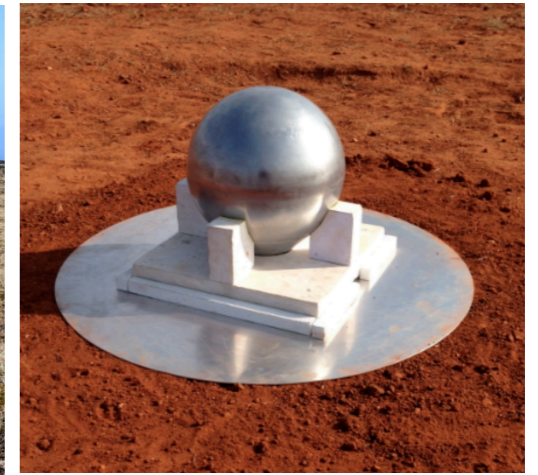
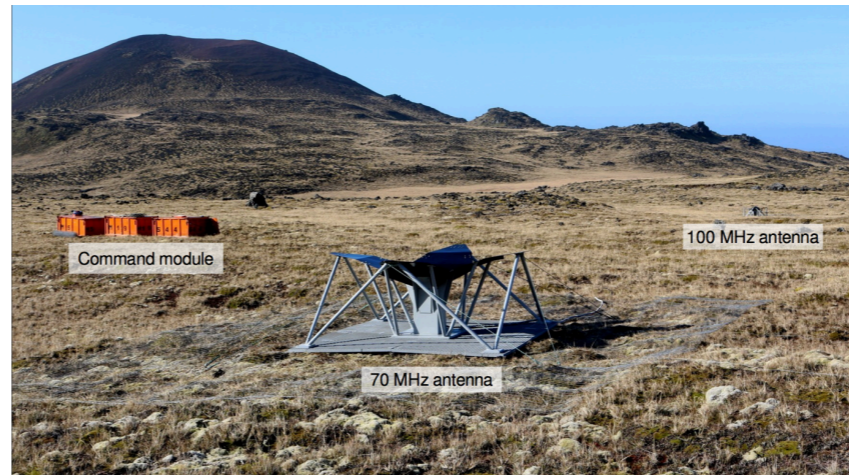
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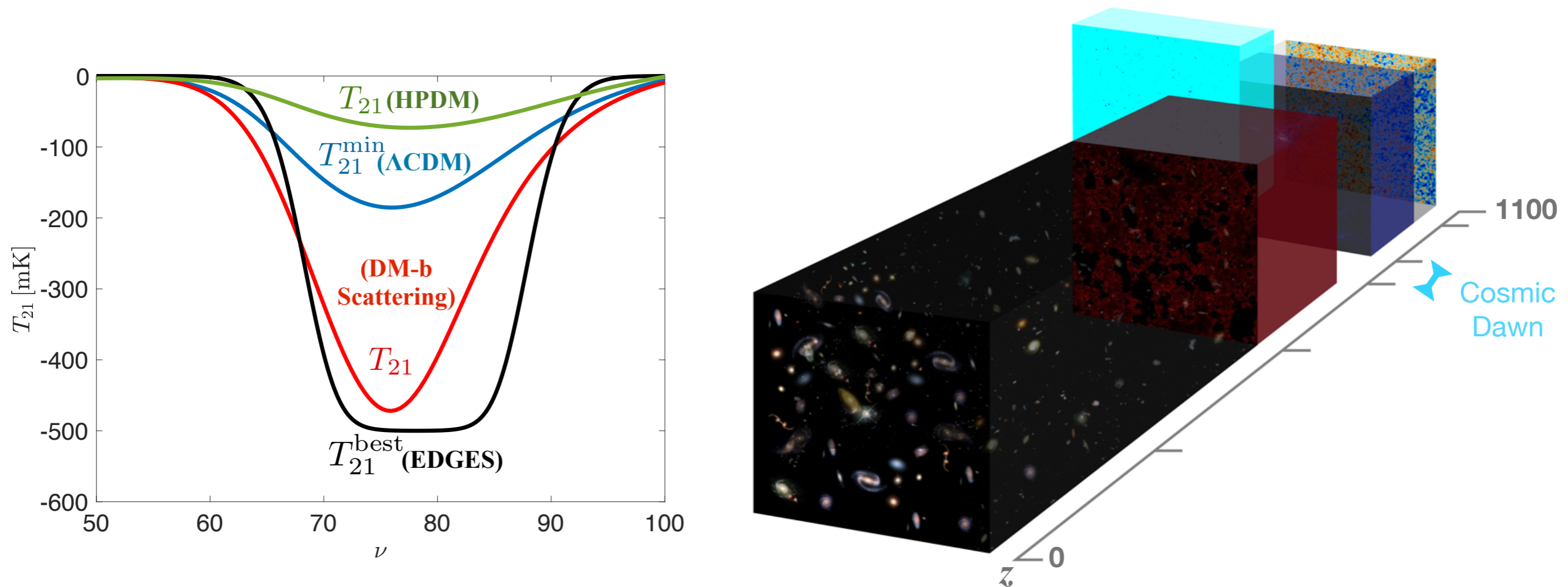
- 21 power spectrum: HERA, SKA.... coming in the next decade!



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

Thank You!

Ely D. Kovetz
Ben-Gurion University



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