First stars and galaxies with FARSIDE

Jordan Mirocha (McGill)

The Renaissance Simulations
(see, e.g., O'Shea+ 2015)

Outline

I. The 21-cm Universe

What is the 21-cm signal and how does it probe astrophysics and cosmology?

II. Expectations

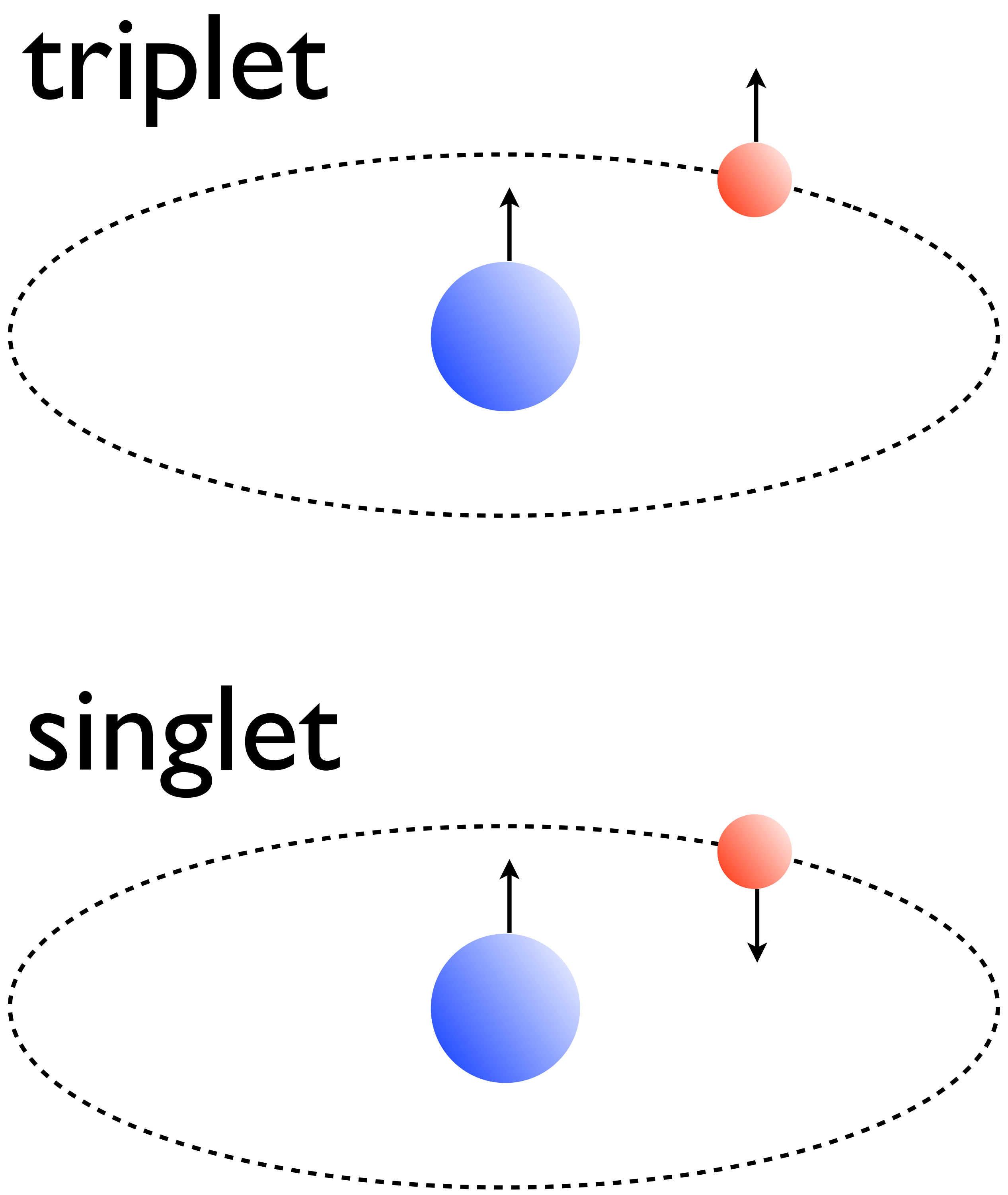
How solid are theoretical predictions, and what do we learn if they are wrong?

III. Broader context

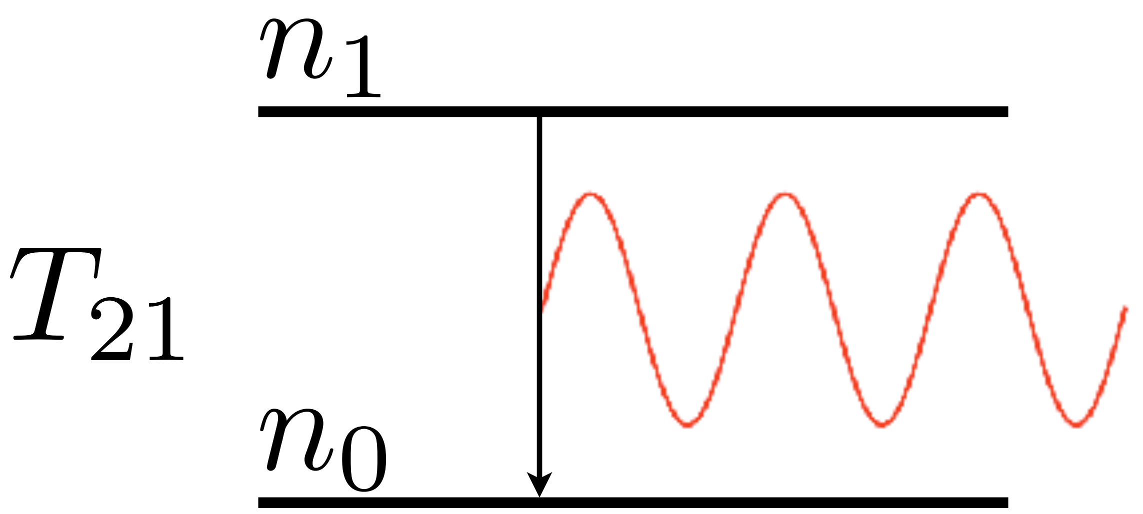
How is FARSIDE+ complementary to other upcoming facilities, like JWST?

The Renaissance Simulations (see, e.g., O'Shea+ 2015)

21-cm Physics



Ground-state hyper-fine splitting

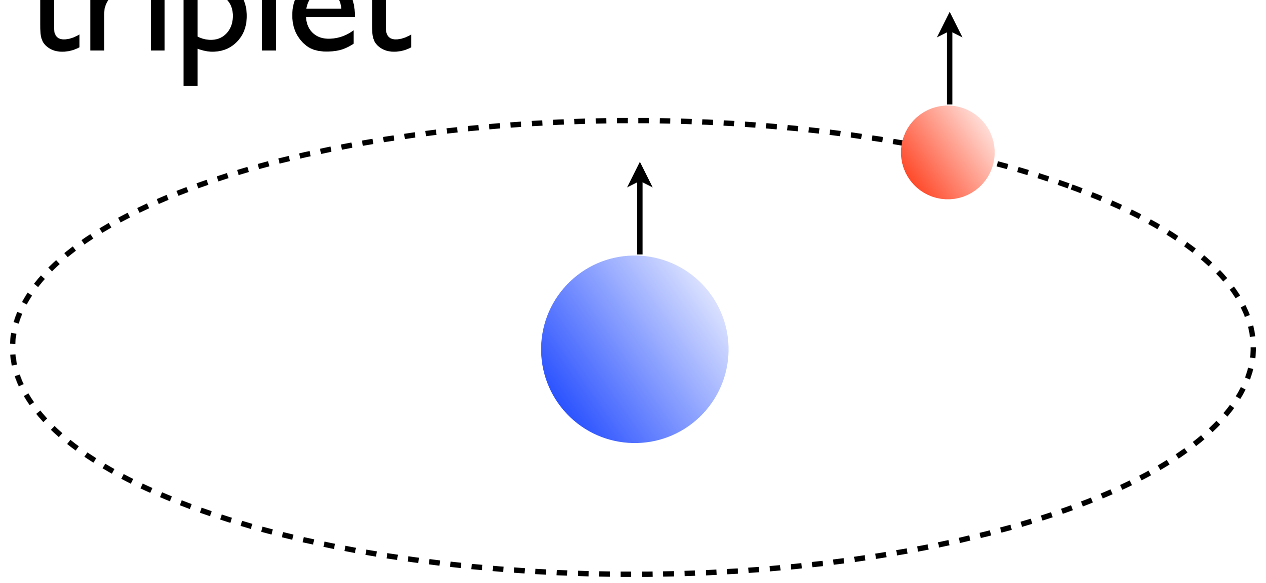


$$\lambda = 21 \text{ cm}$$

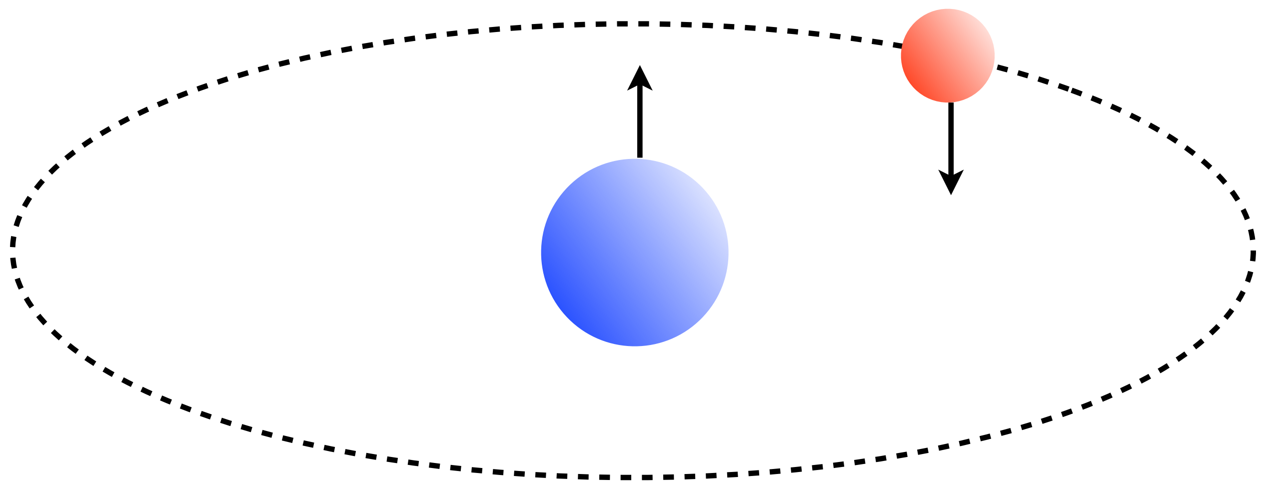
$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left[-T_{21}/T_{\rm S}\right]$$

21-cm Physics

triplet



singlet



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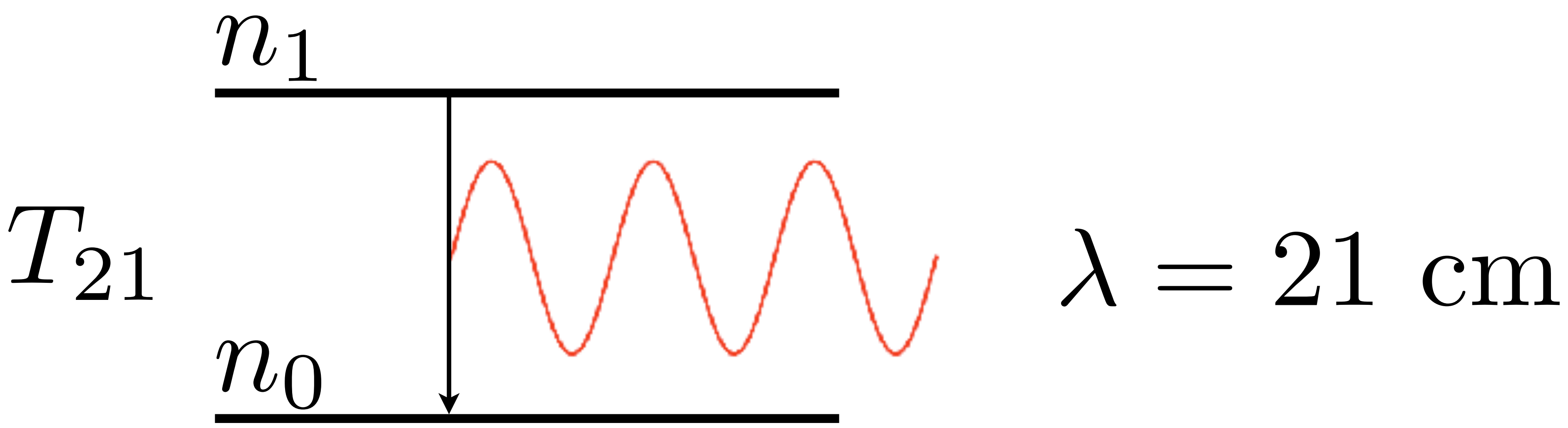


$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\,[-T_{21}\boxed{/T_\mathrm{S}]}$$

$$T_S = T_S(n_\mathrm{H}, n_e, T_K, T_\gamma, J_\alpha)$$

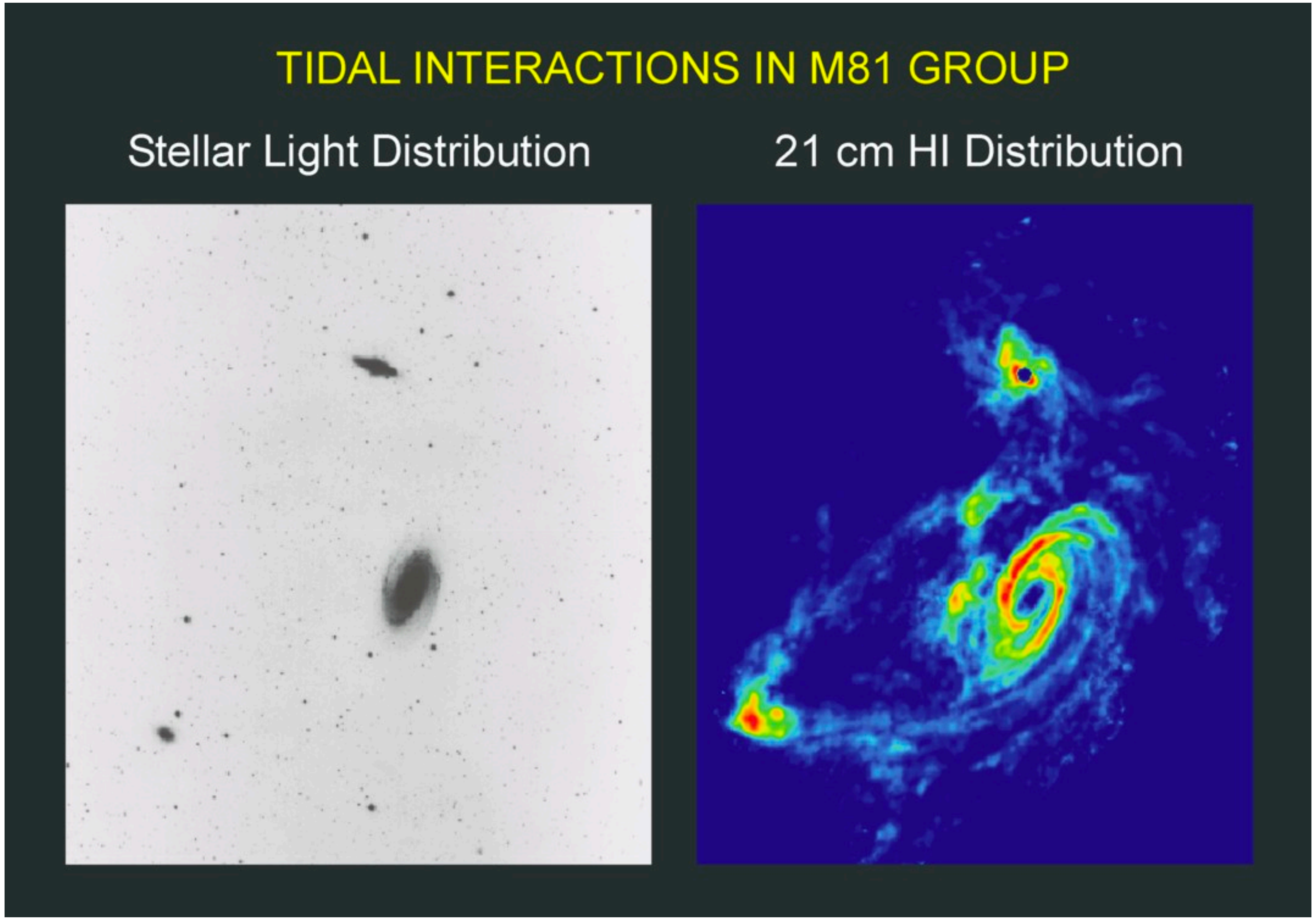
Big Picture

M101

THINGS (see, e.g., Walter+ 2008)

Most famous 21-cm application historically: mapping galaxy rotation curves via HI emission.

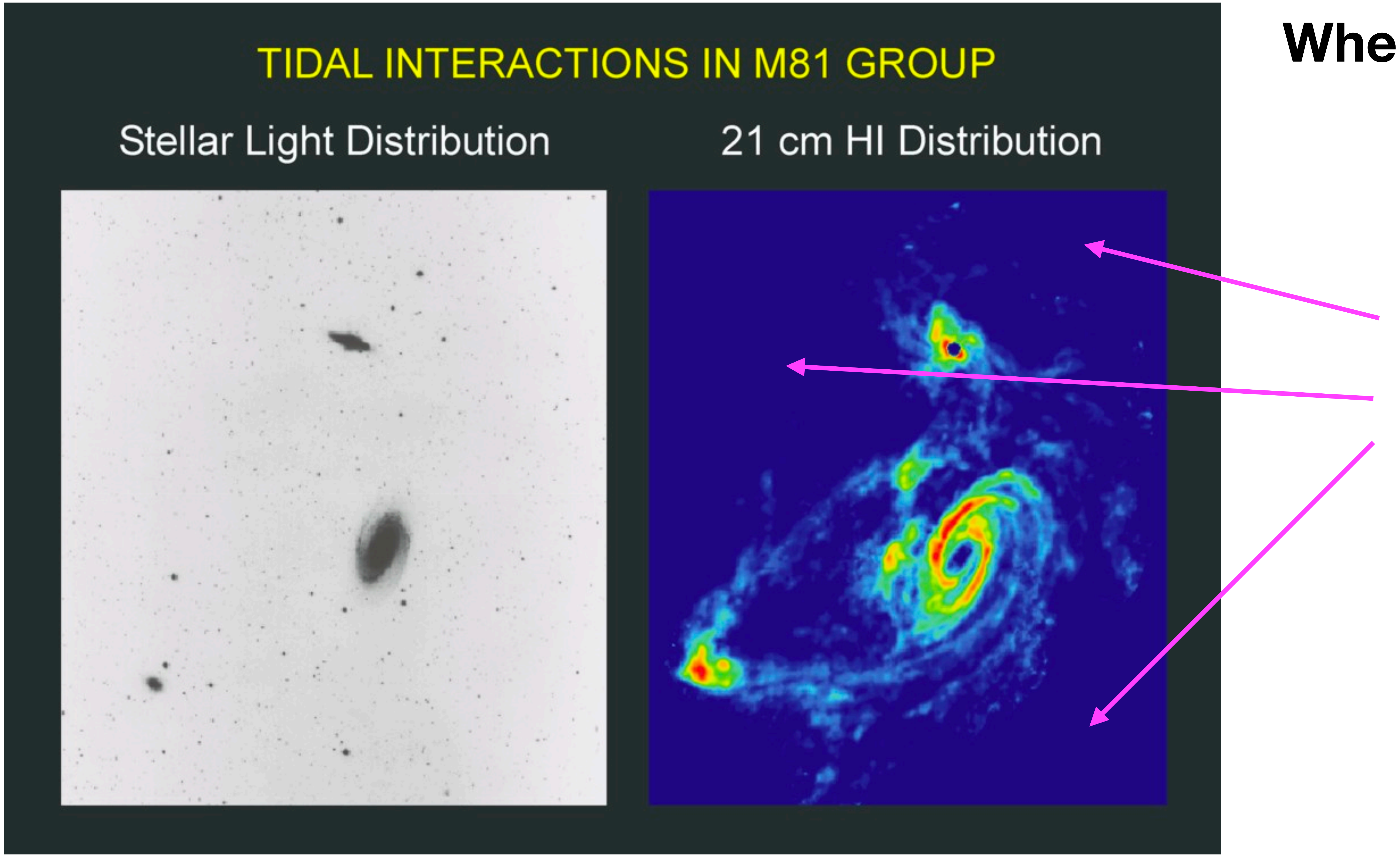
Big Picture



Images courtesy NRAO

Where's "the rest" of the H?

Big Picture



Images courtesy NRAO

Where's "the rest" of the H?

These regions aren't empty, they are *ionized*.

This "intergalactic medium" (IGM) hasn't always been ionized!

Big Picture

CMB ~ 100 Myr ~ 1 Gyr **Today**

Madau et al. (1997), Shaver et al. (1999)

Loeb 2006, Scientific American

Big Picture

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Loeb 2006, Scientific American

Big Picture

CMB $\sim 100\ \mathrm{Myr}$ $\sim 1\ \mathrm{Gyr}$ Today

21-cm signal is a cosmic "negative" as it traces space outside bubbles.

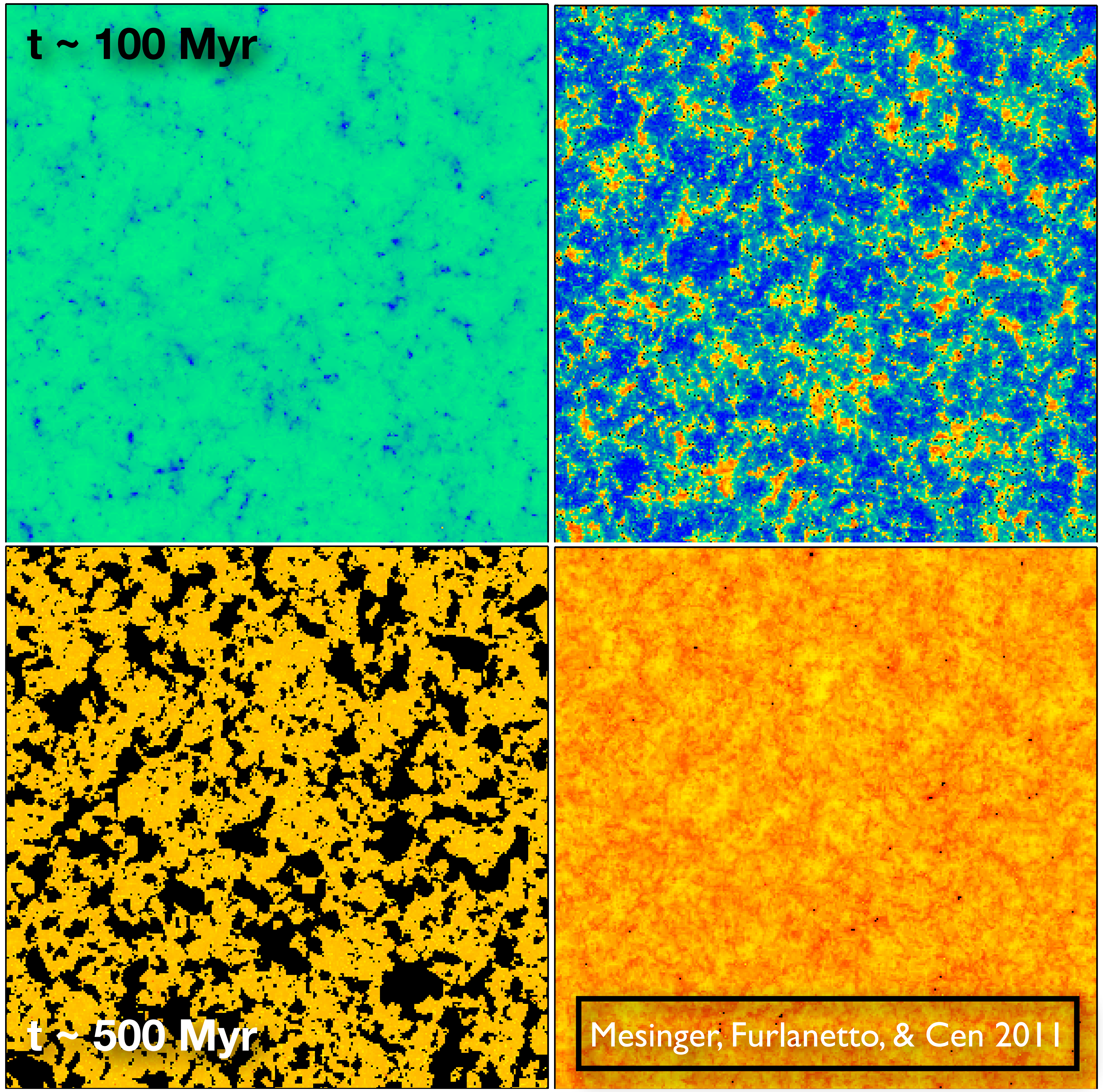
Overall amplitude encodes volume of space filled by bubbles, but also temperature of the IGM.

As a result, traces stars (UV ionizes gas), compact objects (X-rays heat gas), exotic physics can affect ionization and temperature.

Madau et al. (1997), Shaver et al. (1999)

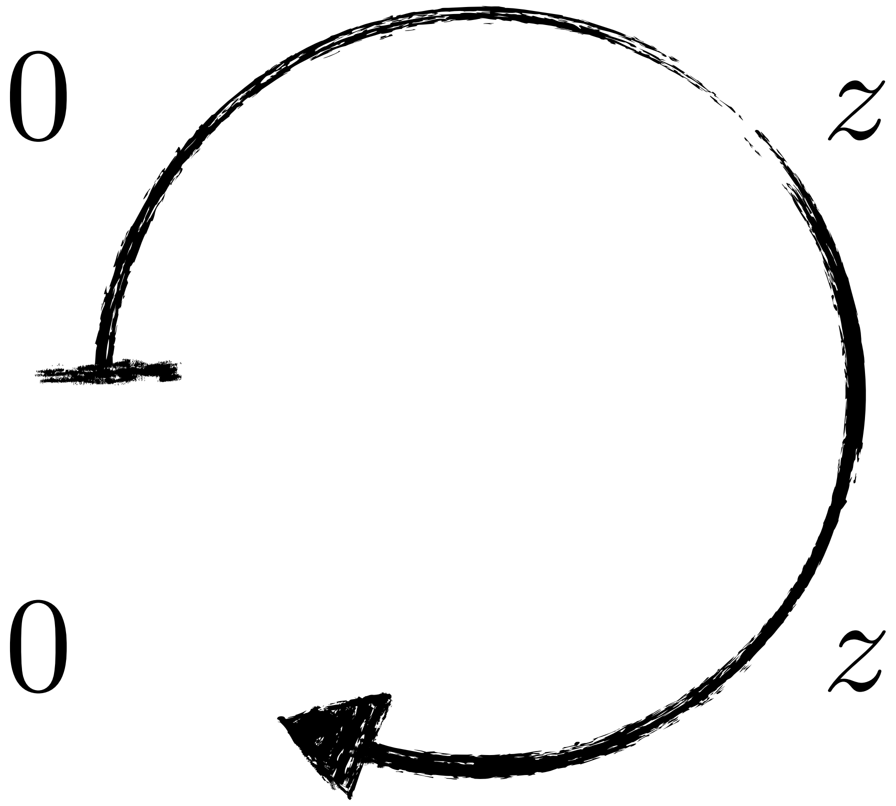
Loeb 2006, Scientific American

Observed wavelength indicates cosmic epoch



Mesinger, Furlanetto, & Cen 2011

$$\boxed{\lambda_{\mathrm{obs}} = 21\mathrm{cm} \times (1 + z)}$$



cold

$z \sim 30$

$z \sim 20$

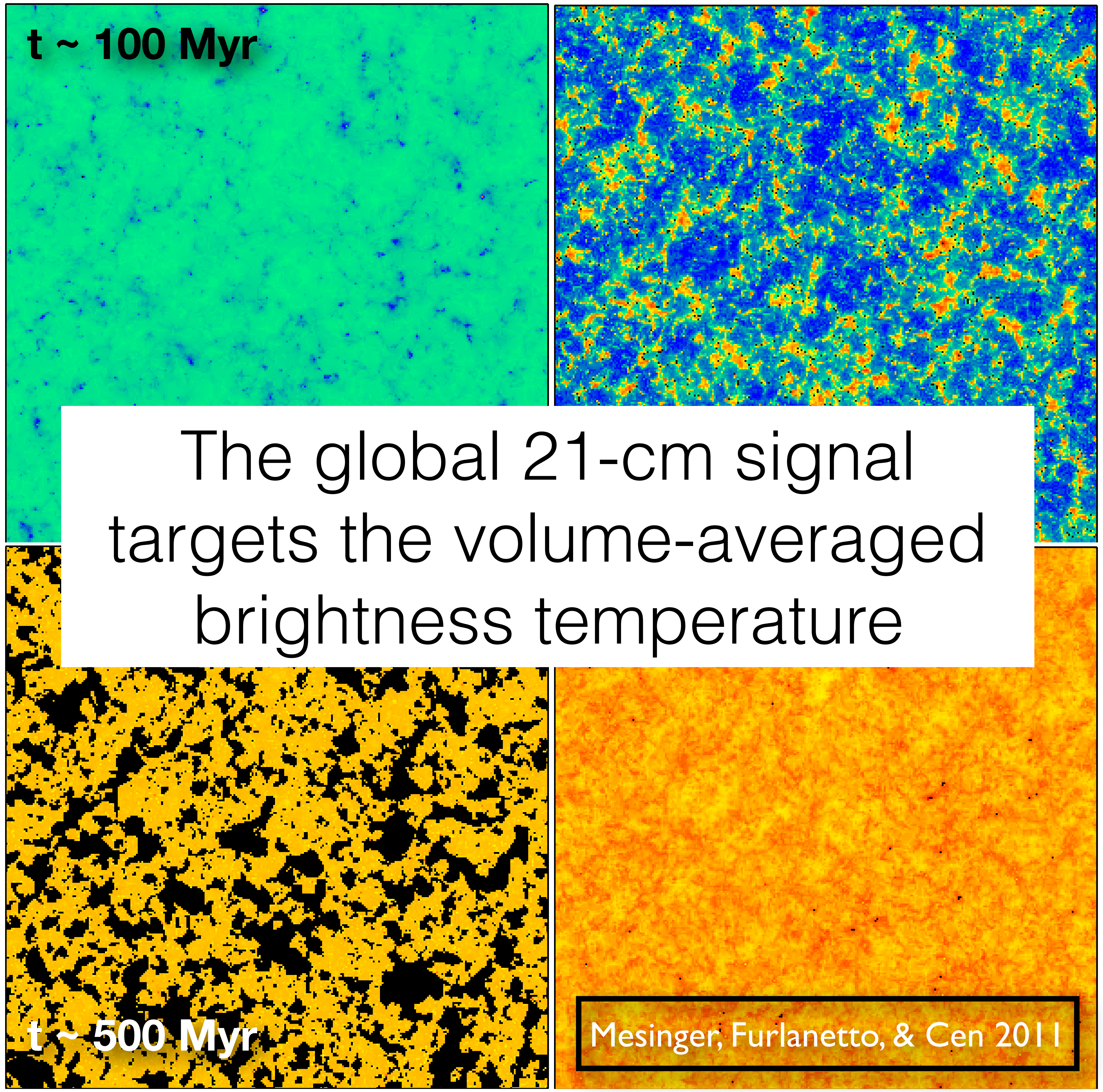
hot

$z \sim 15$

$z \sim 10$

reionization

Observed wavelength indicates cosmic epoch



The global 21-cm signal targets the volume-averaged brightness temperature

Mesinger, Furlanetto, & Cen 2011

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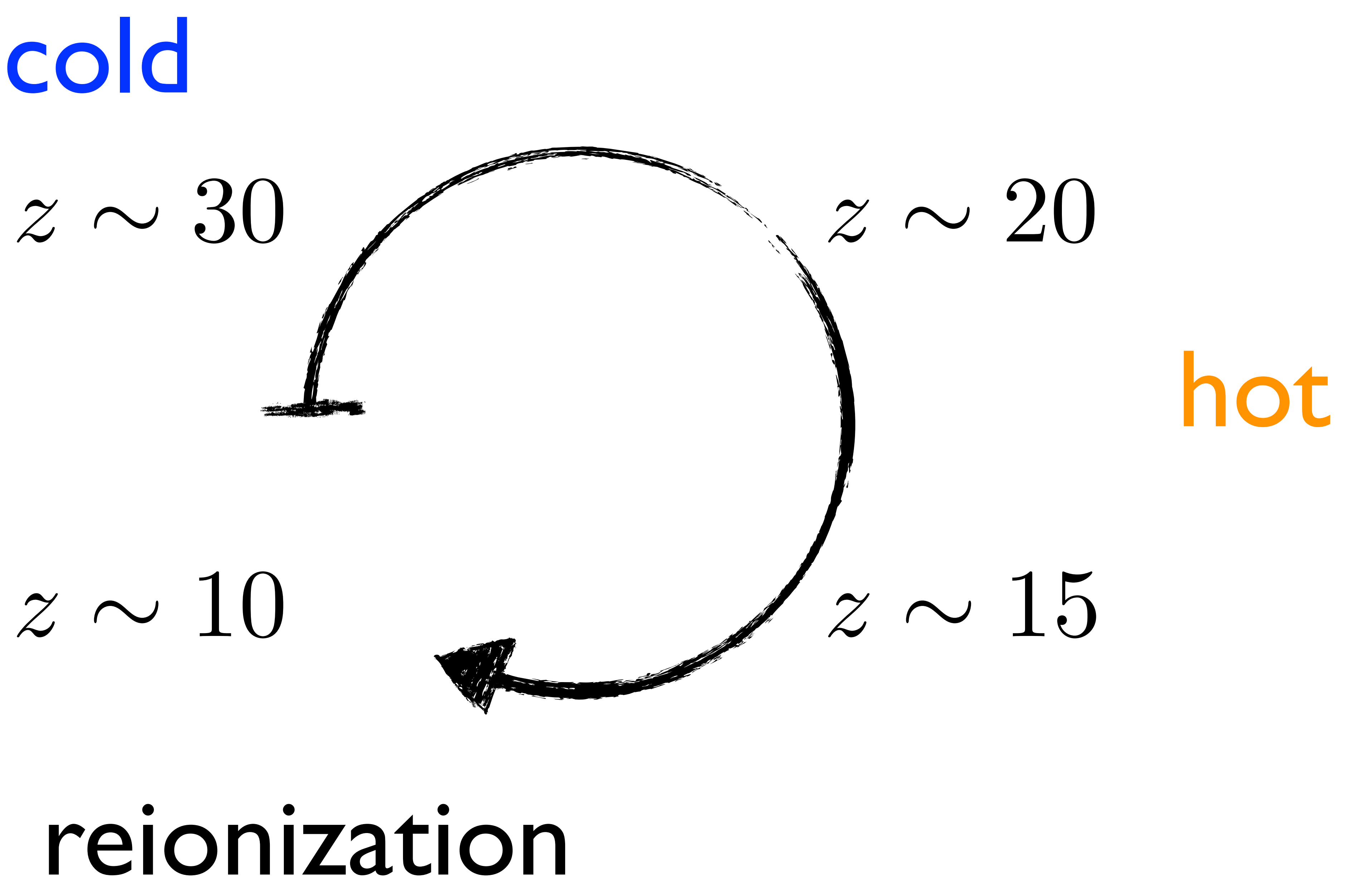

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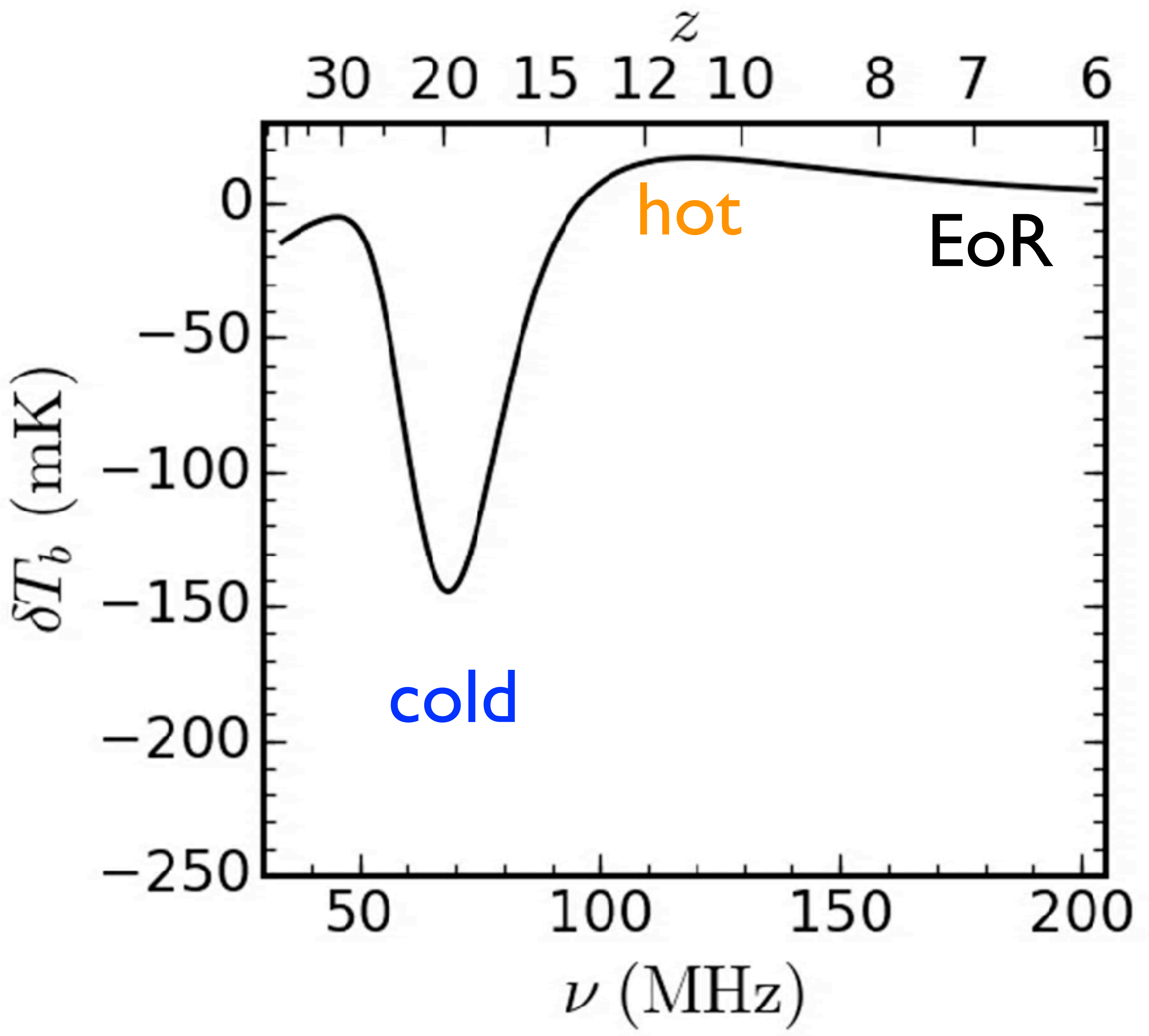
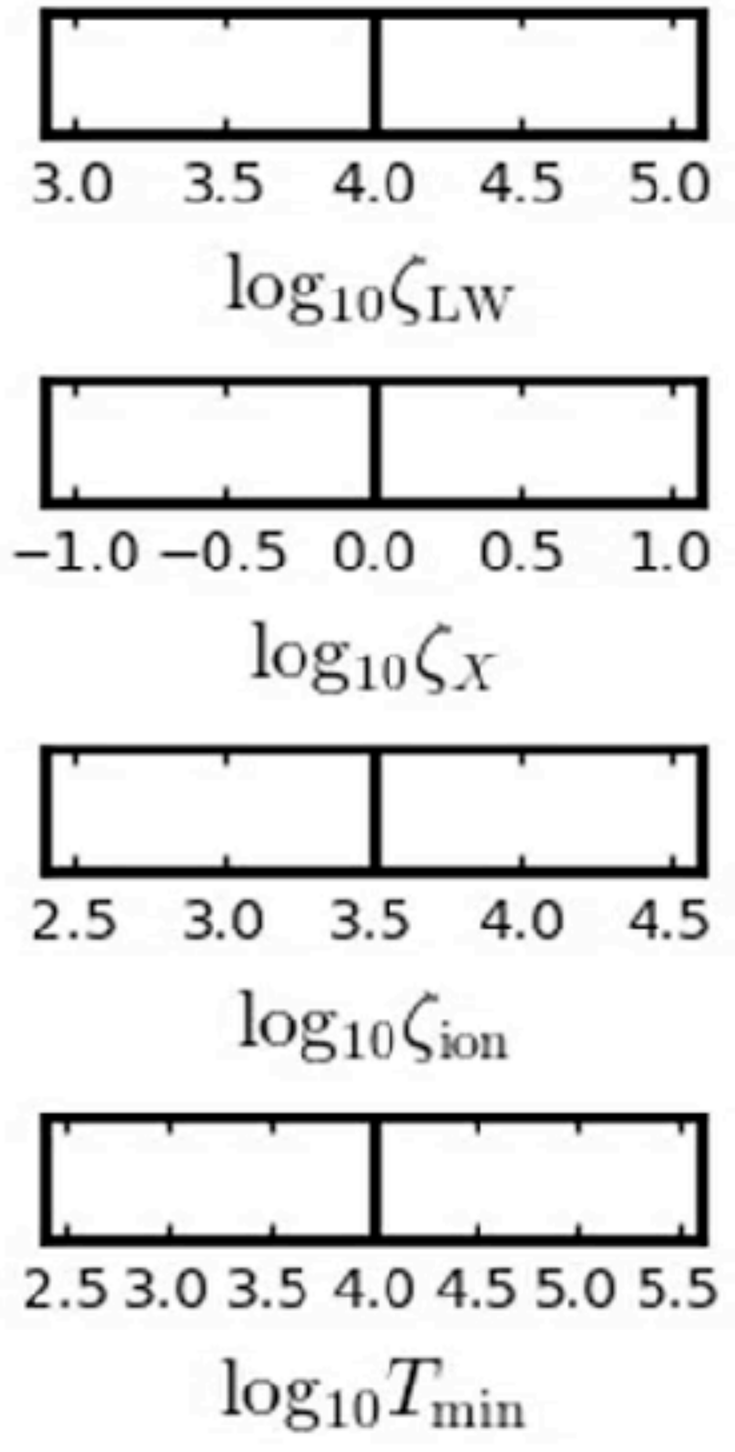
The Global 21-cm Signal





Efficiency of 11.2-13.6 eV photon production

Efficiency of ~0.2-2 keV photon production

Efficiency of 13.6-24.6 eV photon production

Proxy for typical mass of early galaxies

see, e.g., Furlanetto (2006), **J.M.**, Harker, & Burns (2015)

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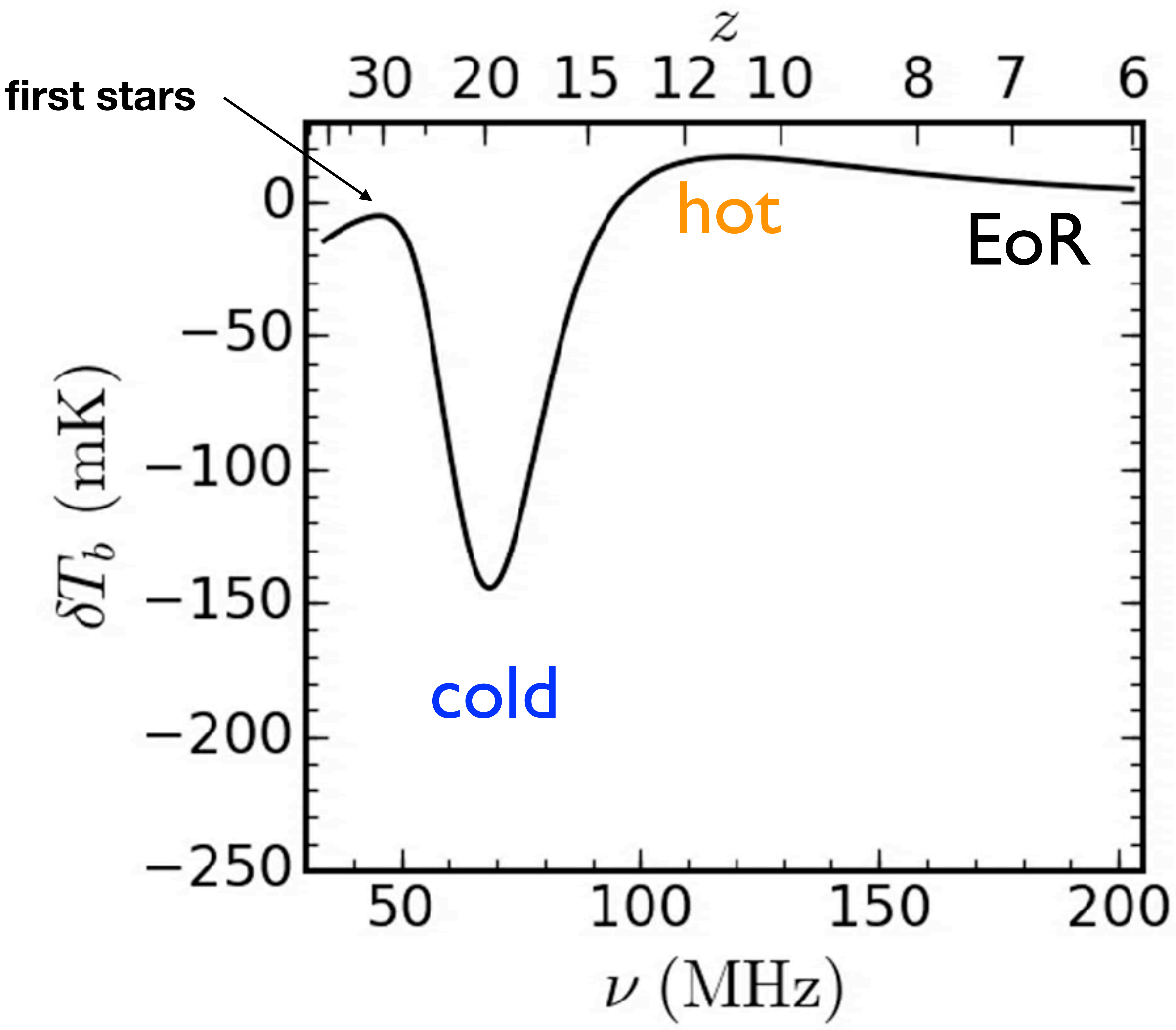

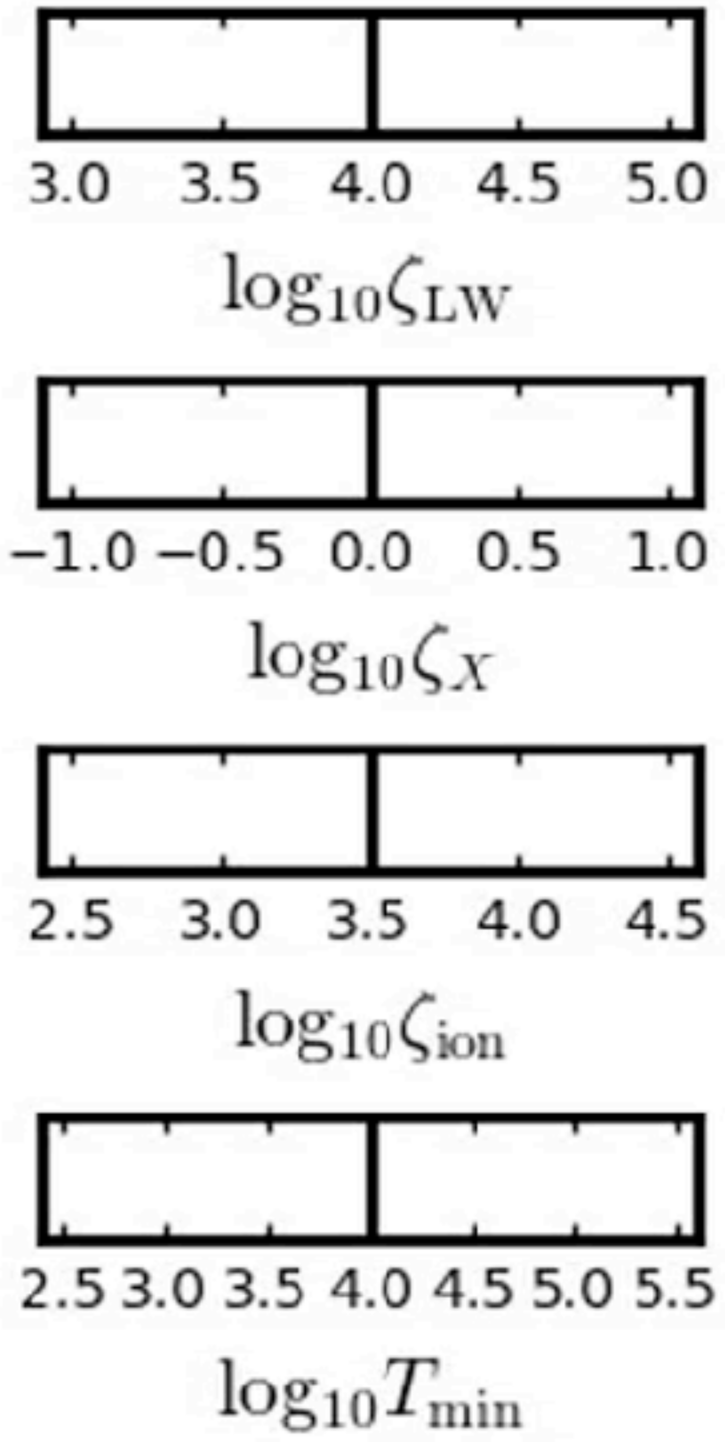

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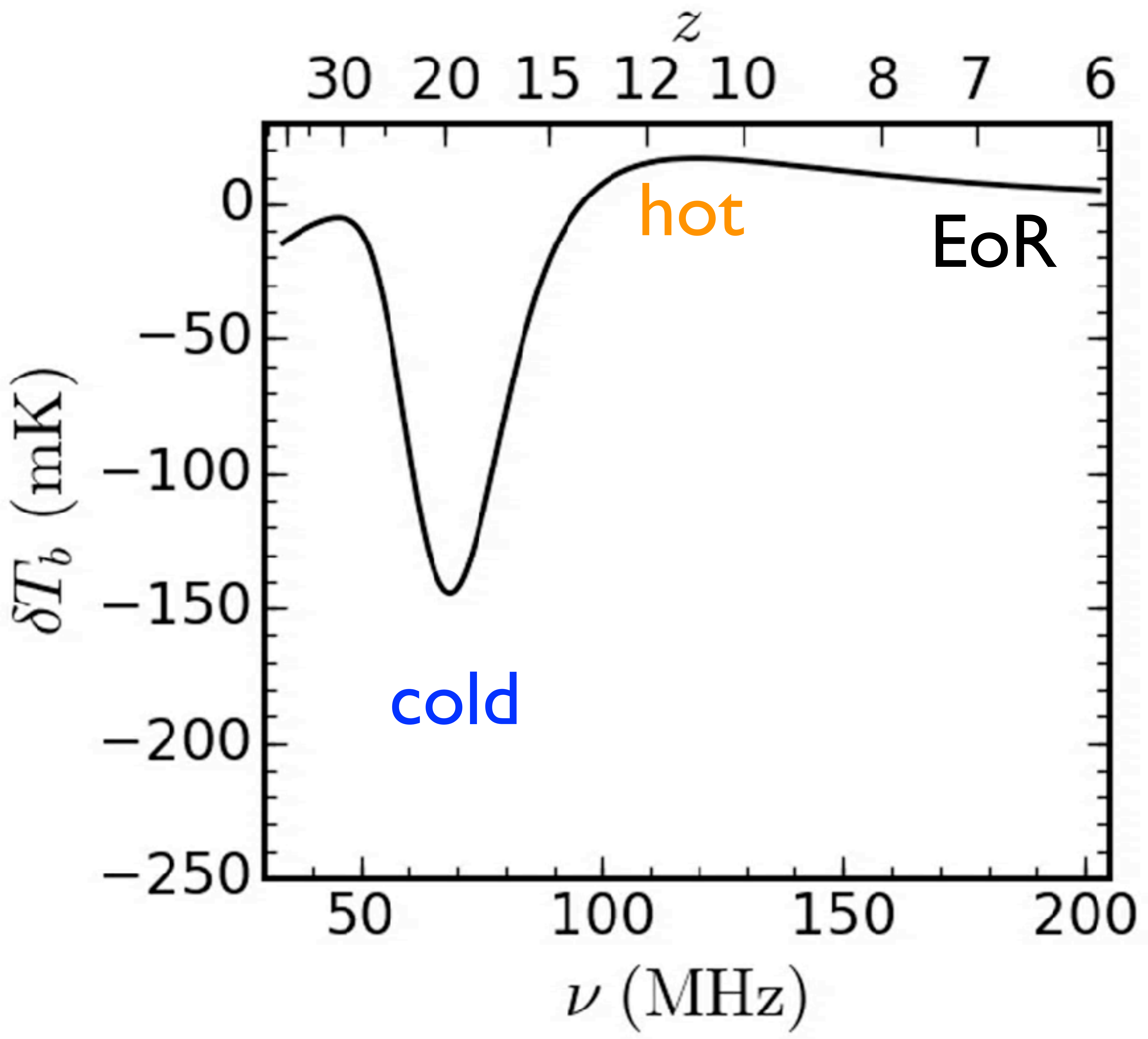

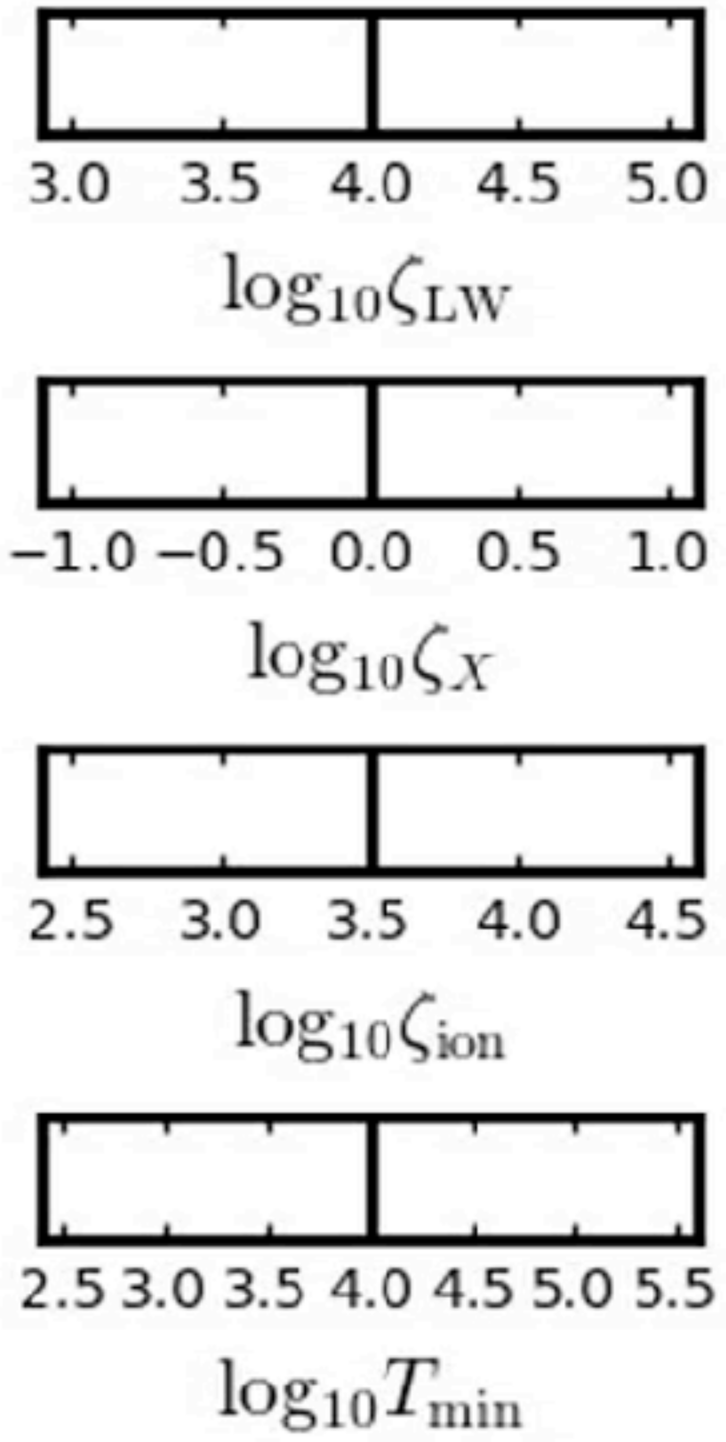

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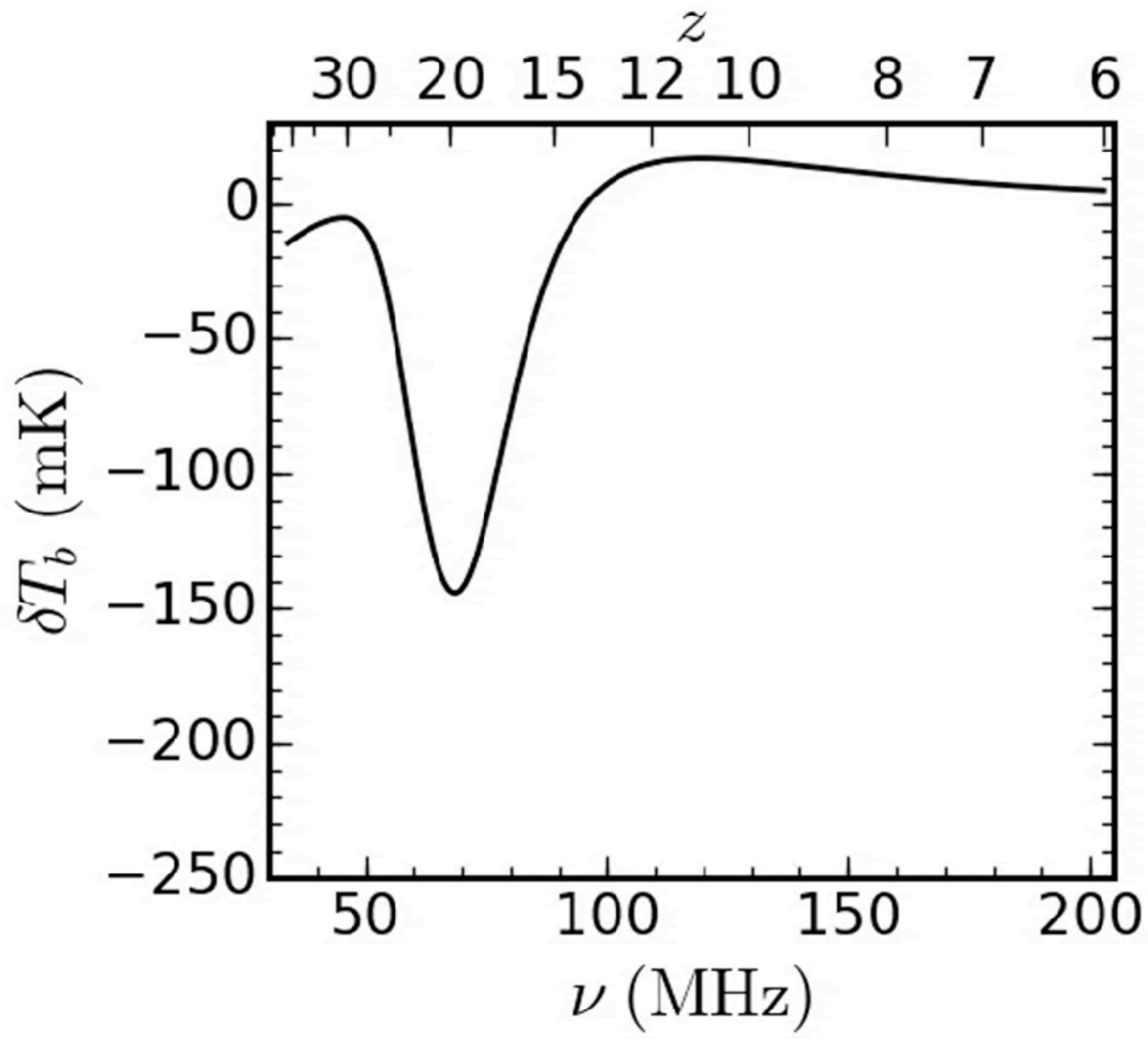

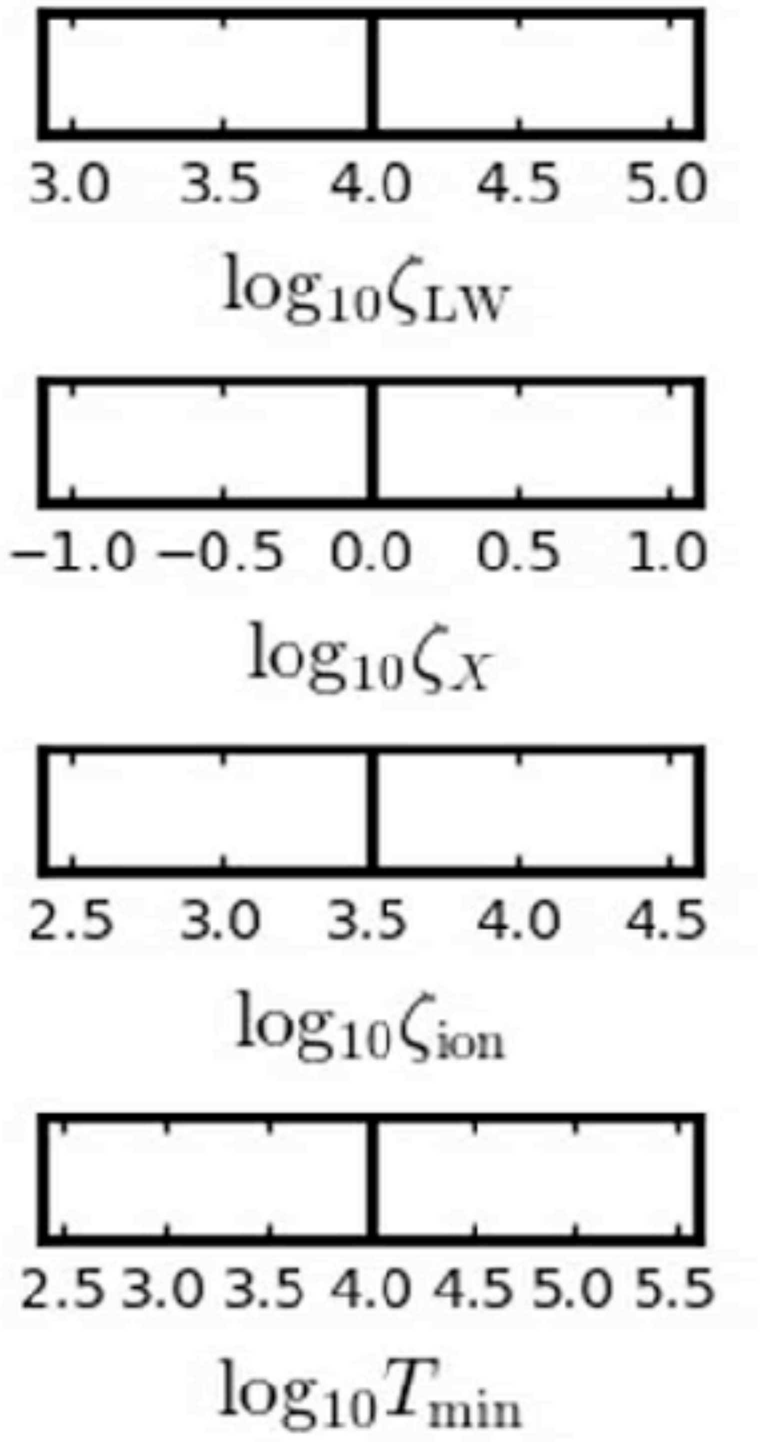

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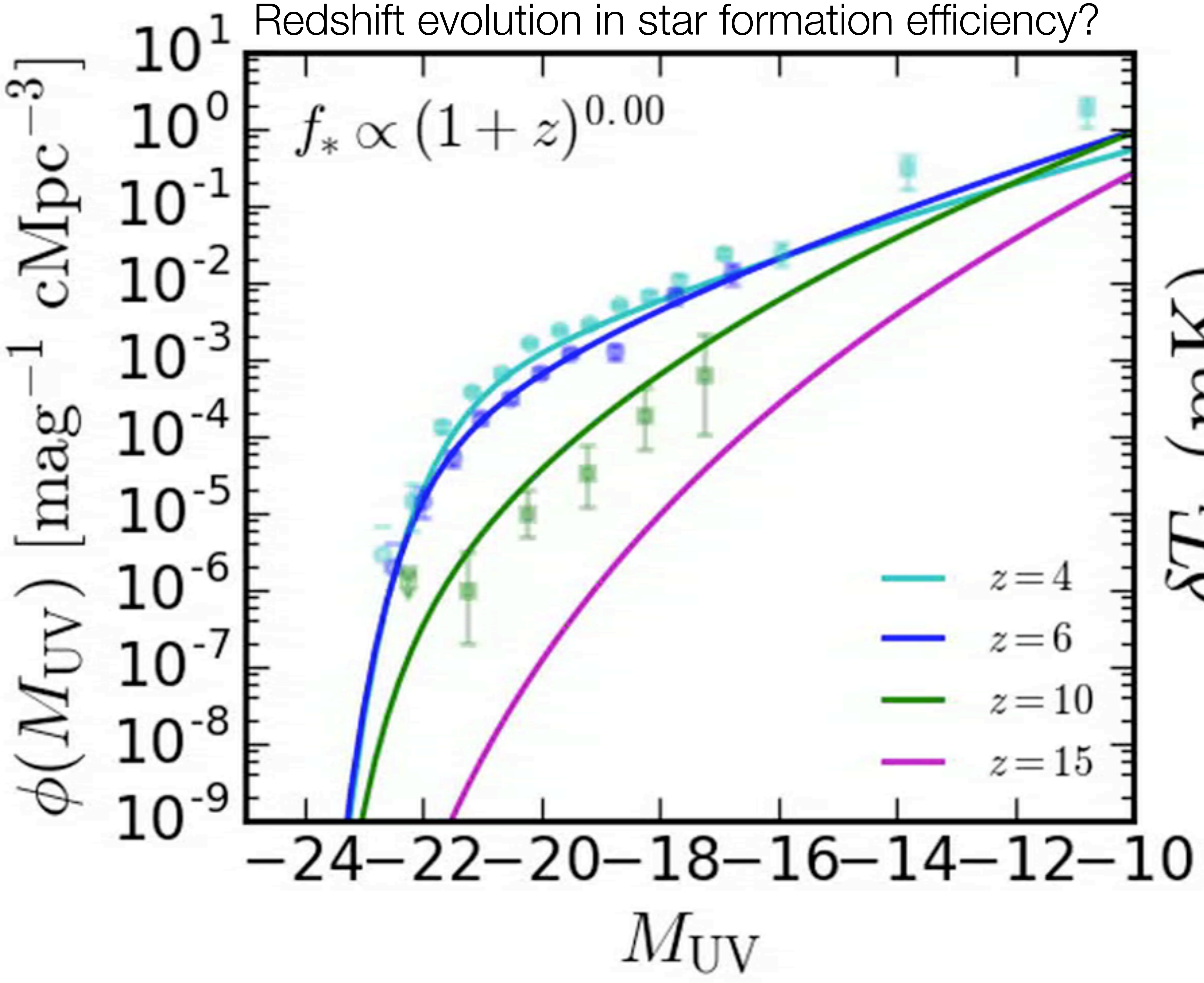
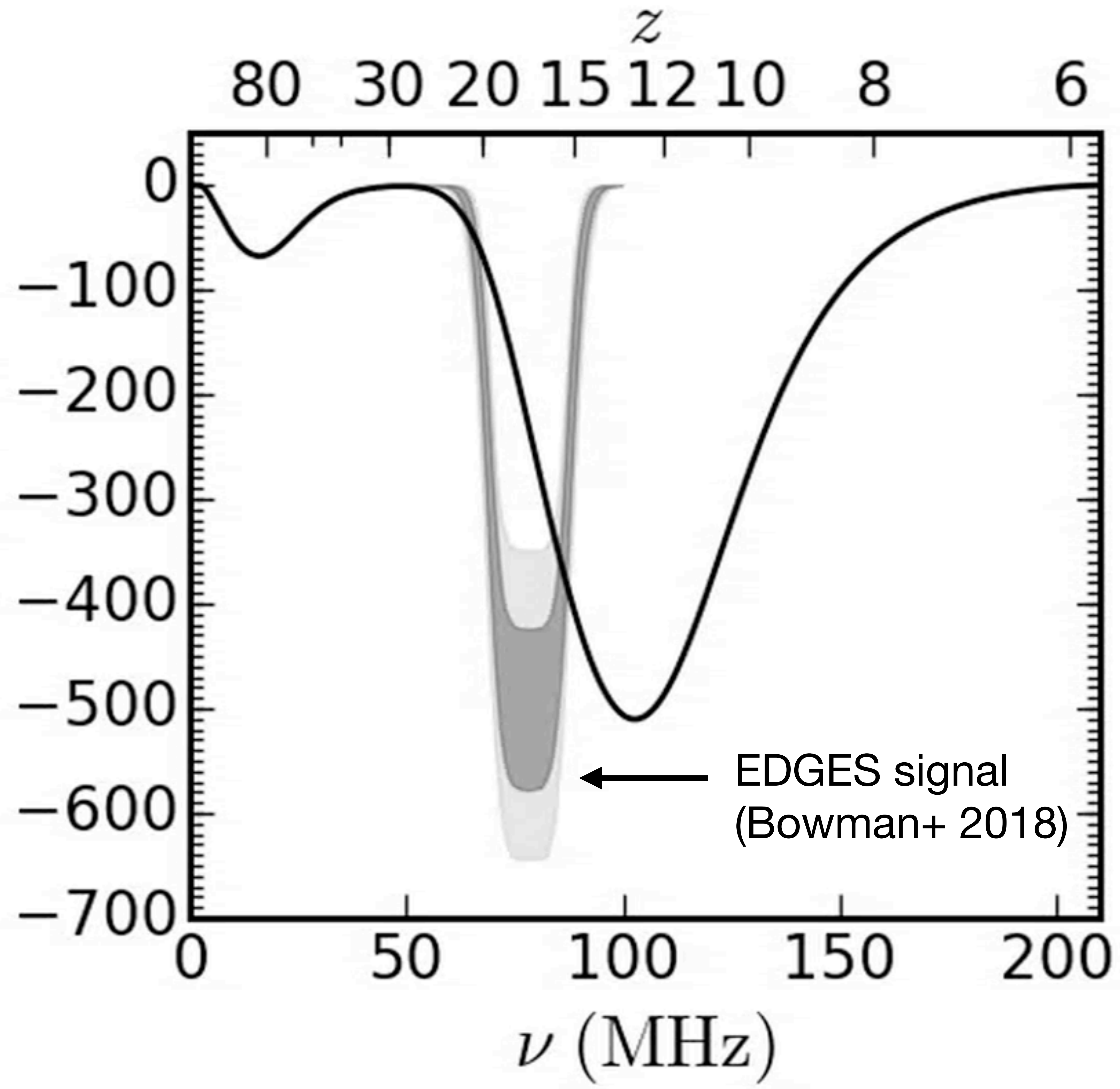
Synergy with Hubble, JWST

Redshift evolution in star formation efficiency?





EDGES signal (Bowman+ 2018)

J.M. & Furlanetto (2019)

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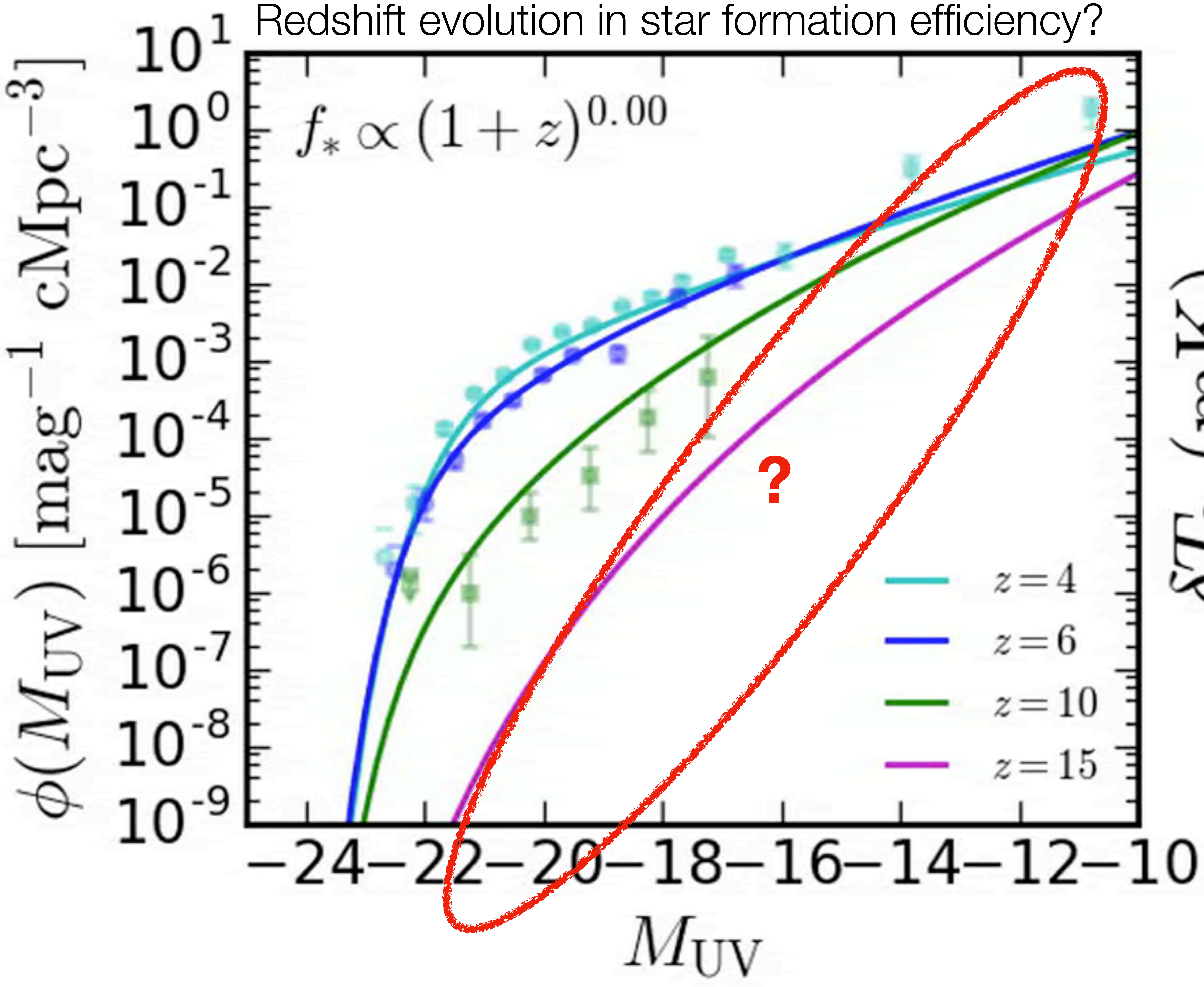
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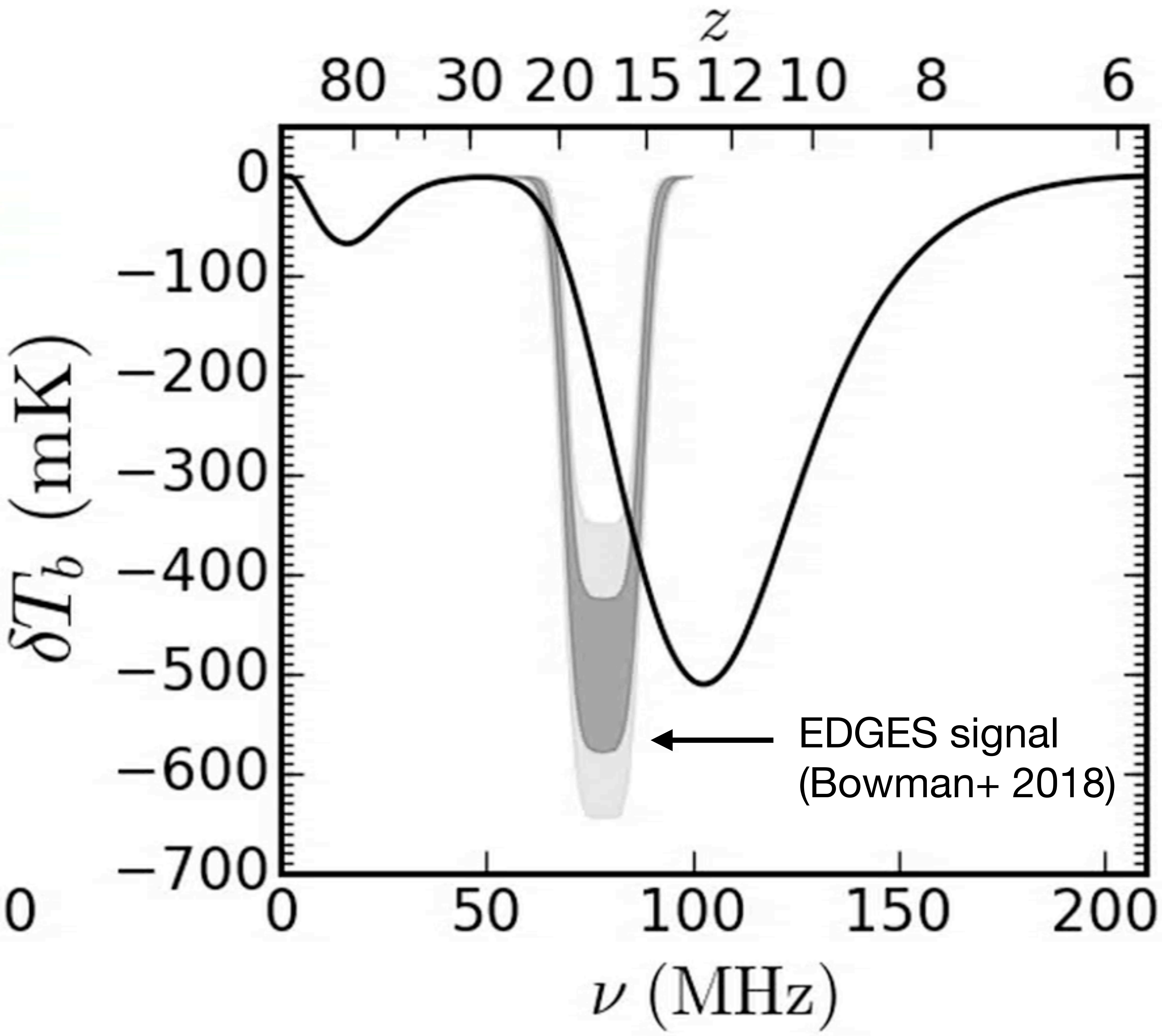
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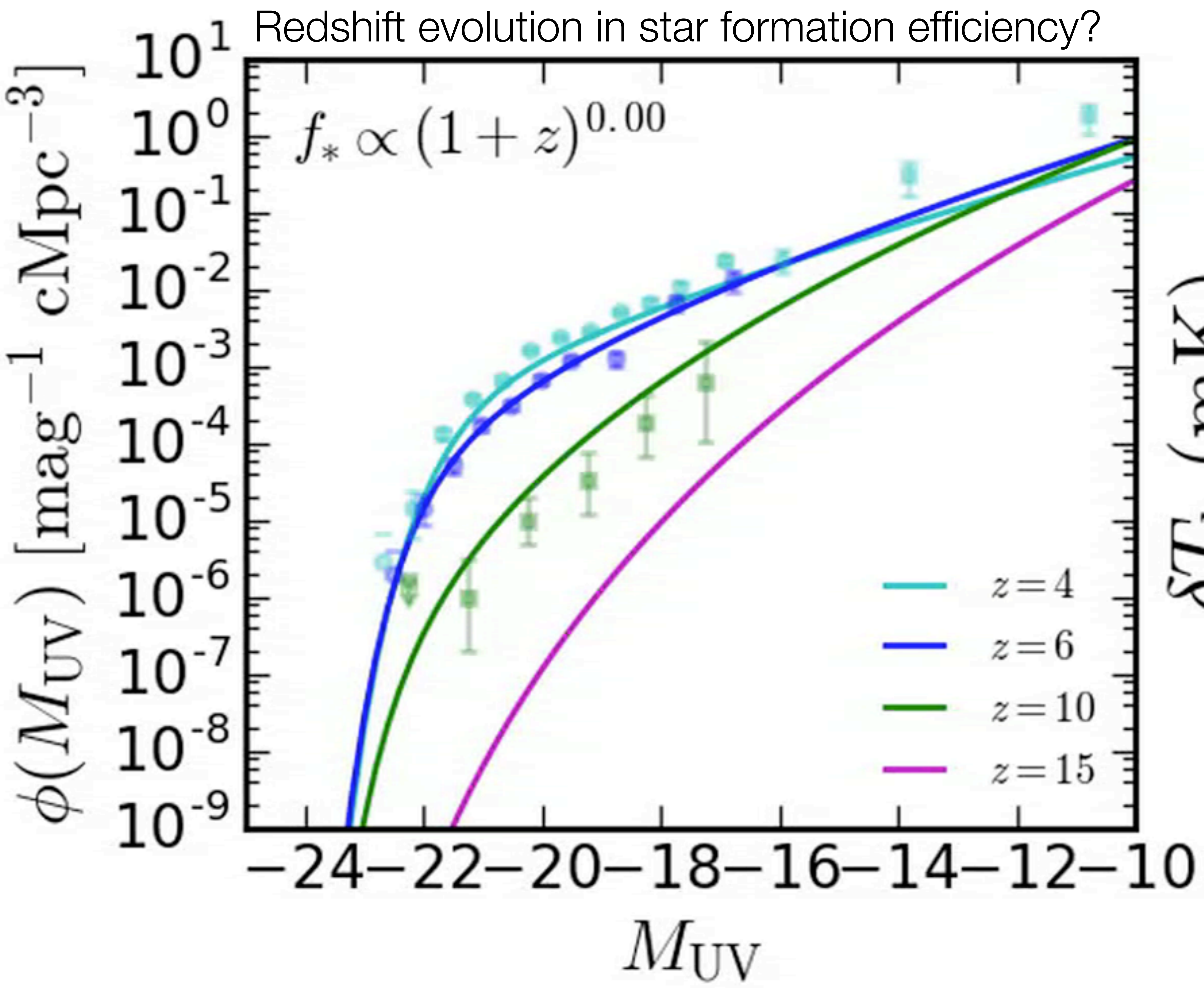
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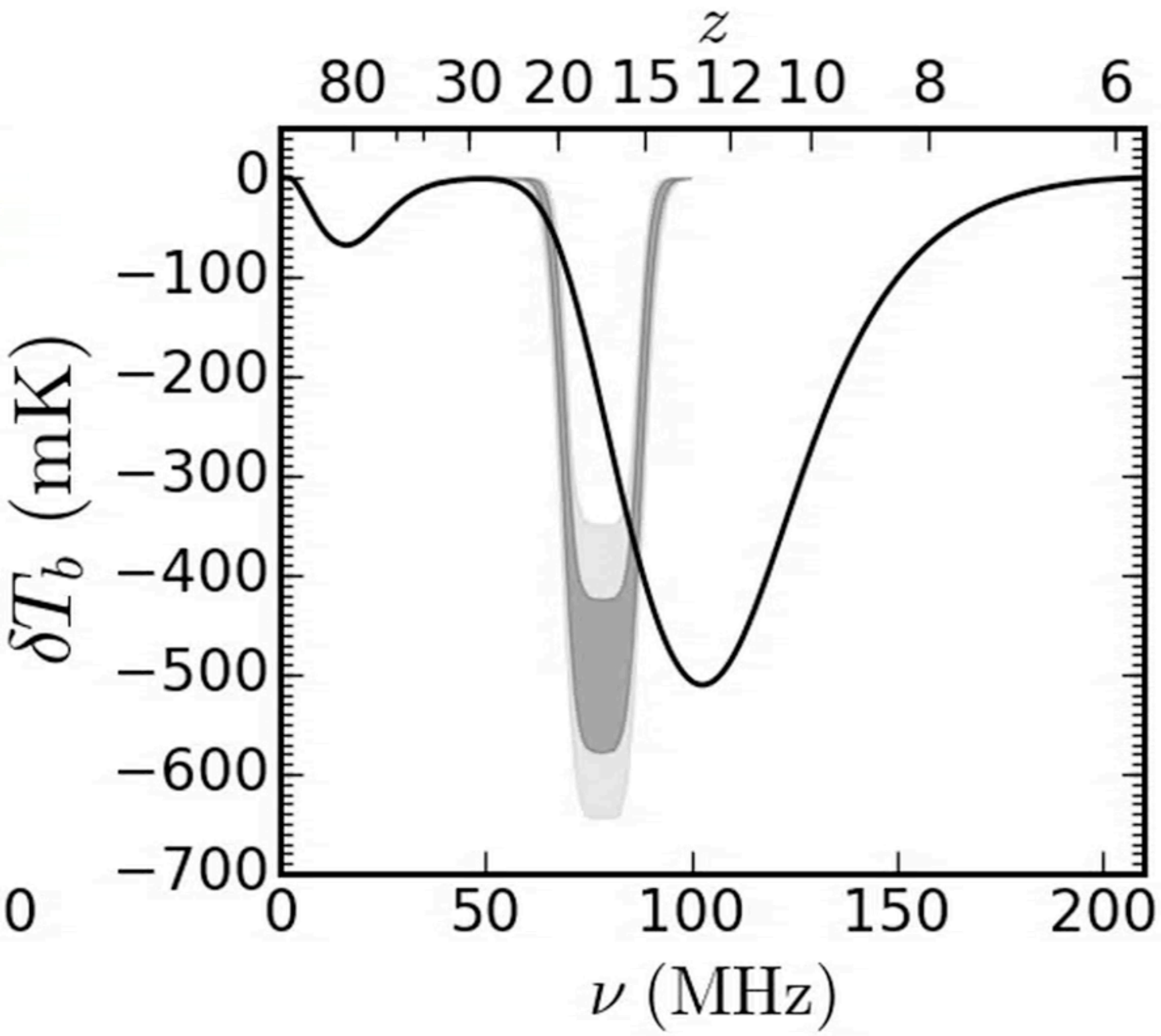

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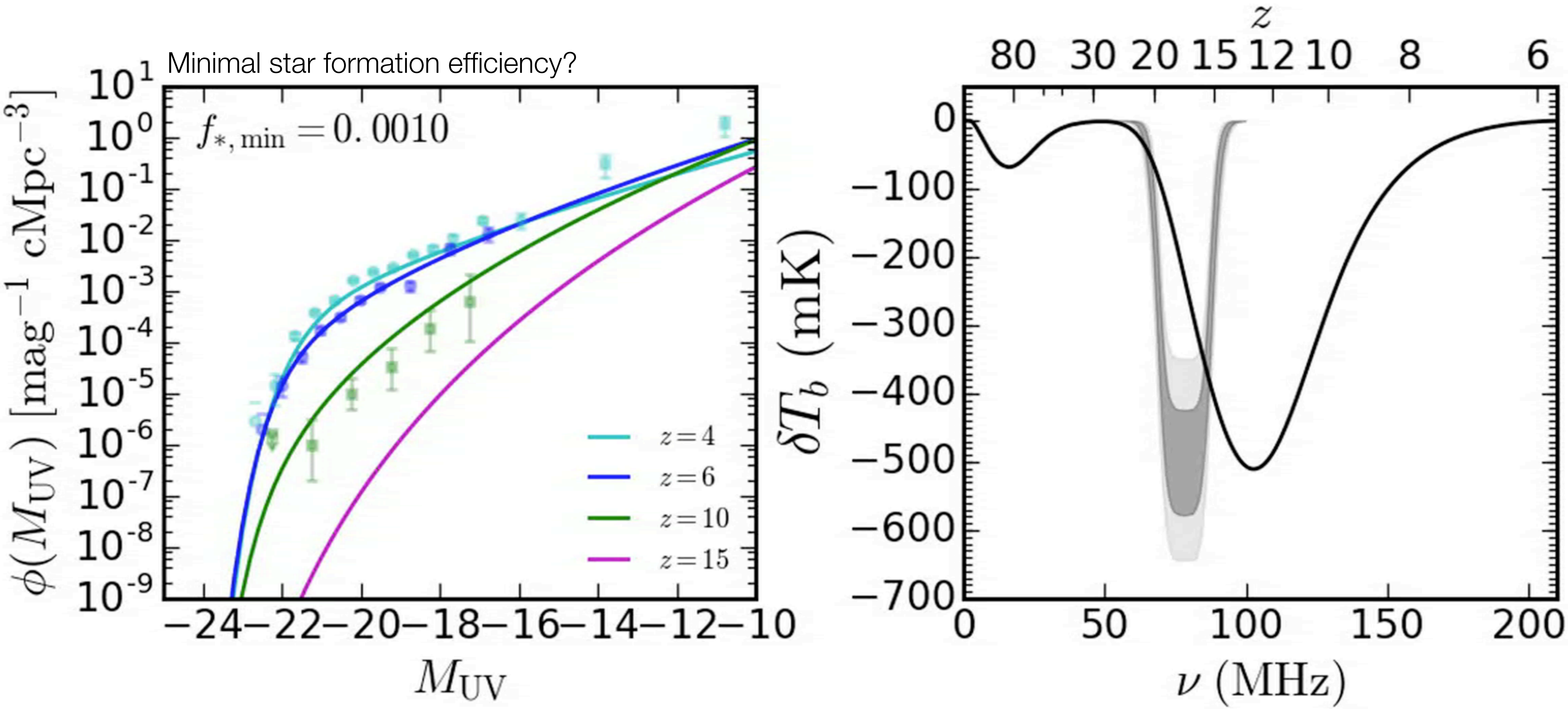

Minimal star formation efficiency?

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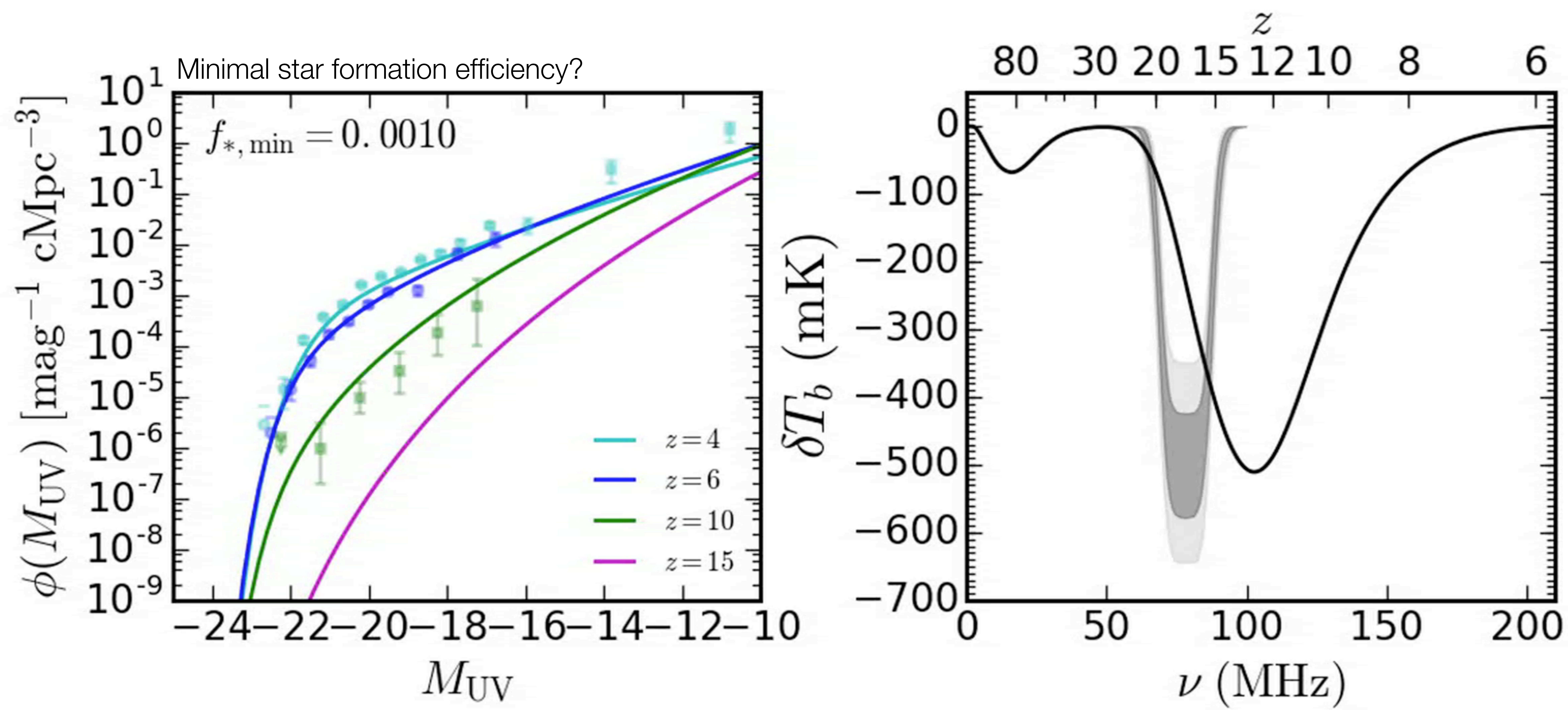
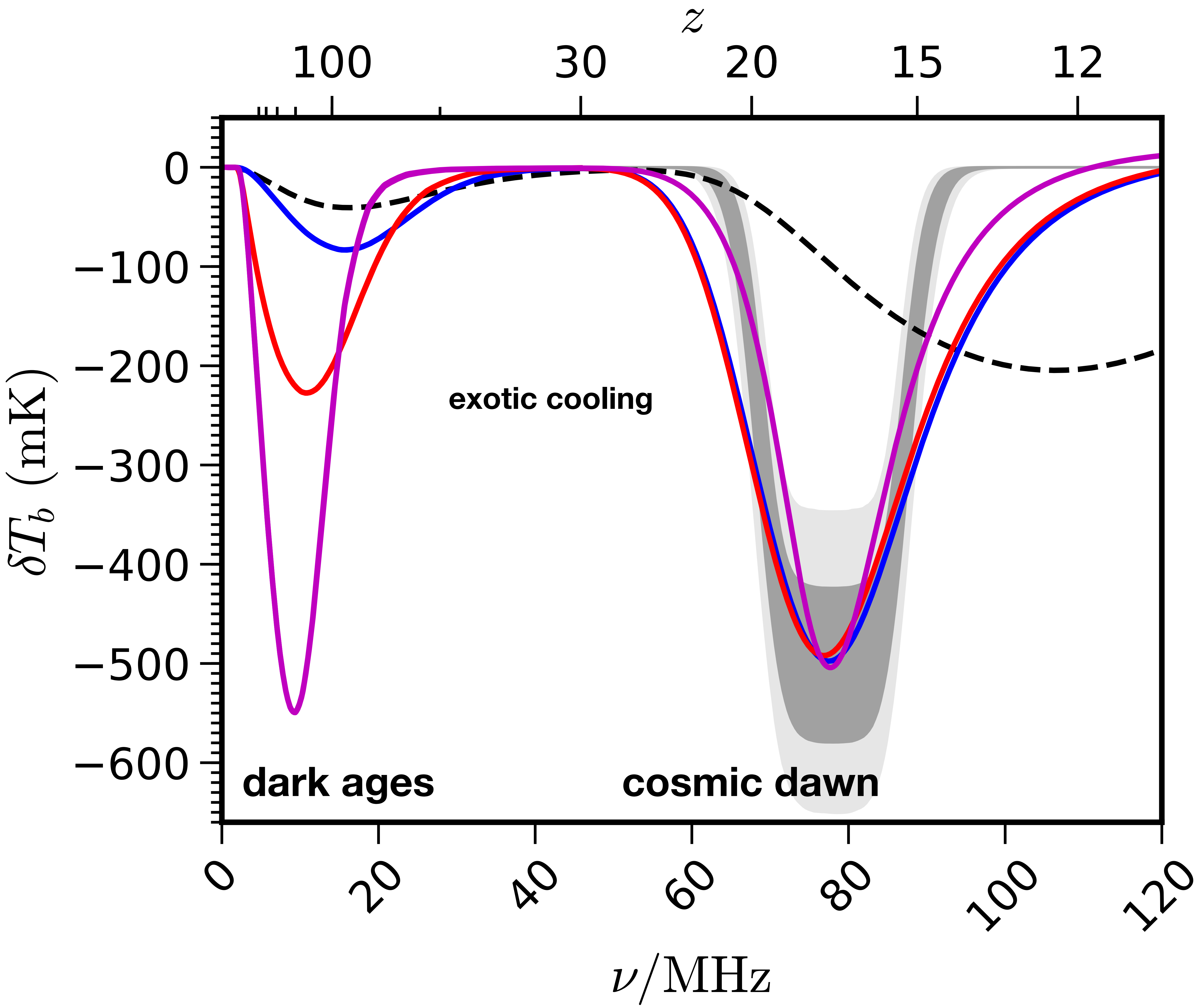


J.M. & Furlanetto (2019)

Importance of low frequencies



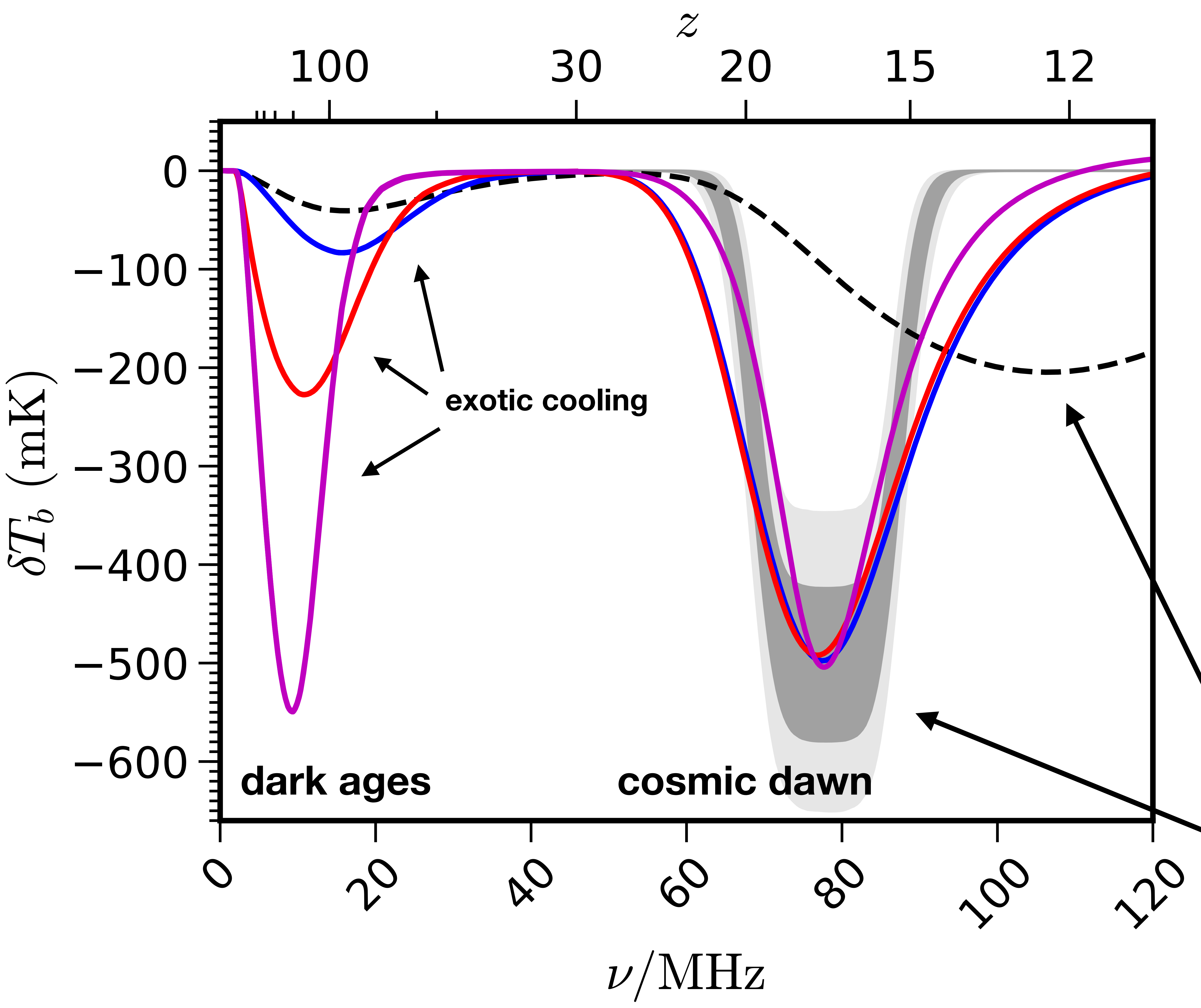
The cosmic "dark ages" free of astrophysics: clean probe of cosmology and dark matter physics.

Constraints at earliest epoch break degeneracies between astrophysics and cosmology during the "cosmic dawn."

standard models (**J.M.** & Furlanetto 2017,2019)

EDGES signal (Bowman+ 2018; see talk at 12:20 MST)

Importance of low frequencies



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EDGES signal (Bowman+ 2018; see talk at 12:20 MST)

Summary

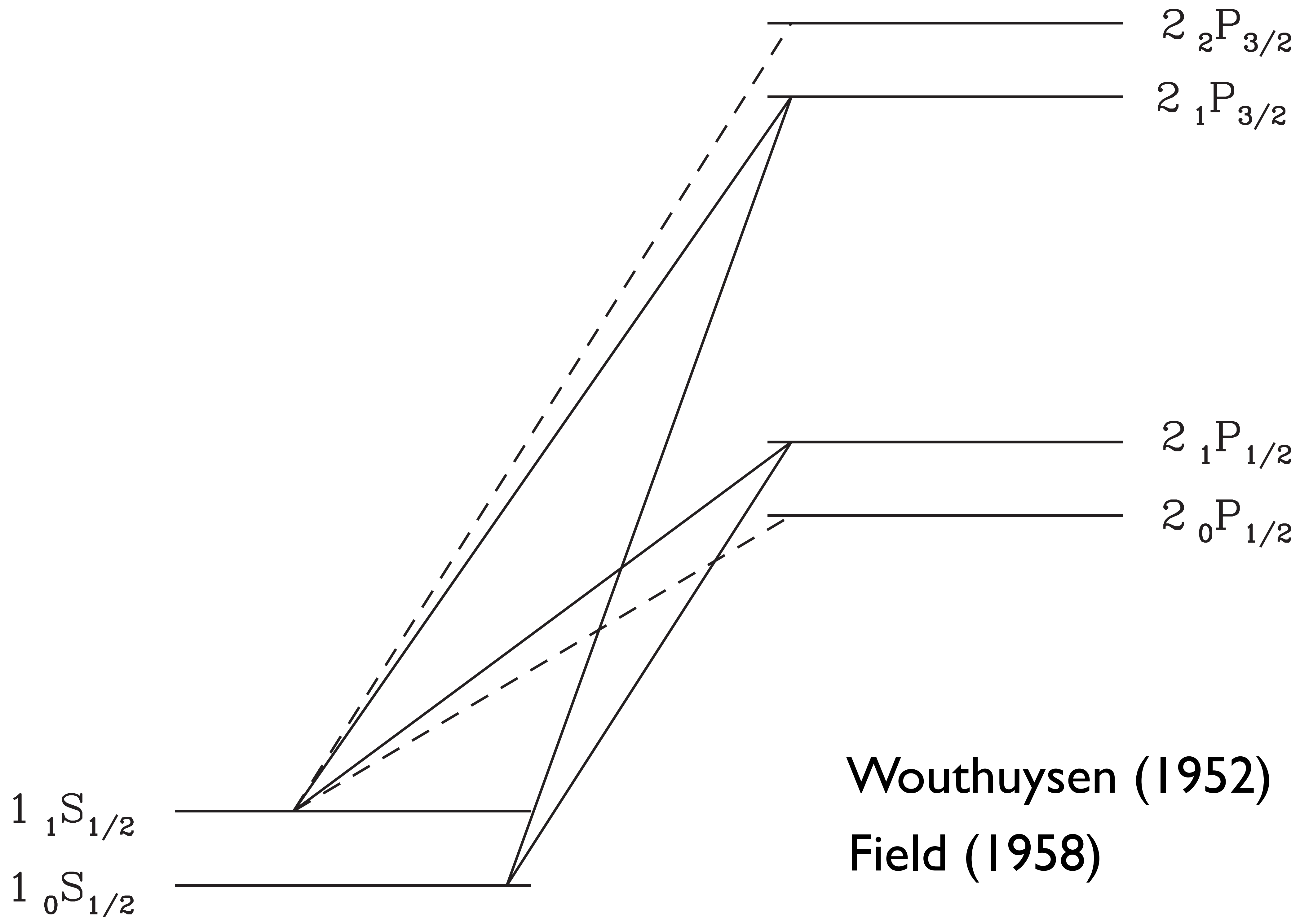
- 21-cm background rich source of information on first galaxies, cosmology, and dark matter.
- Low frequencies — best accessed from Moon — vital for breaking degeneracies.
- EDGES non-standard in more ways than one. Hint of the very first stars and black holes?

The Renaissance Simulations
(see, e.g., O’Shea+ 2015)

Backup slides

Wouthuysen*-Field Effect

from Pritchard & Furlanetto (2006)



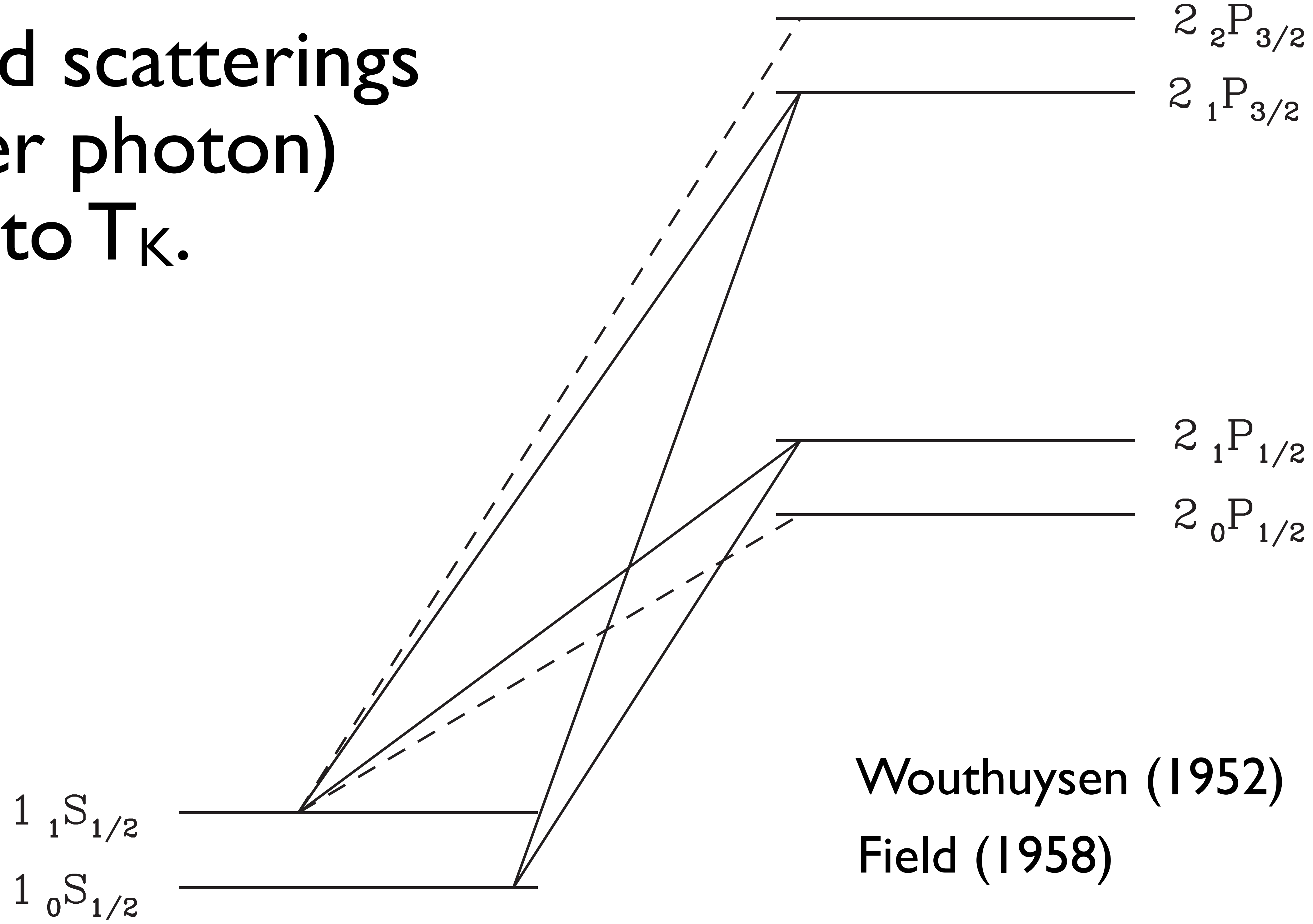
Wouthuysen (1952)

Field (1958)

*vowt-how-sen

Wouthuysen*-Field Effect

Repeated scatterings (~10^6 per photon) drive T_S to T_K.



from Pritchard & Furlanetto (2006)

Wouthuysen (1952)

Field (1958)

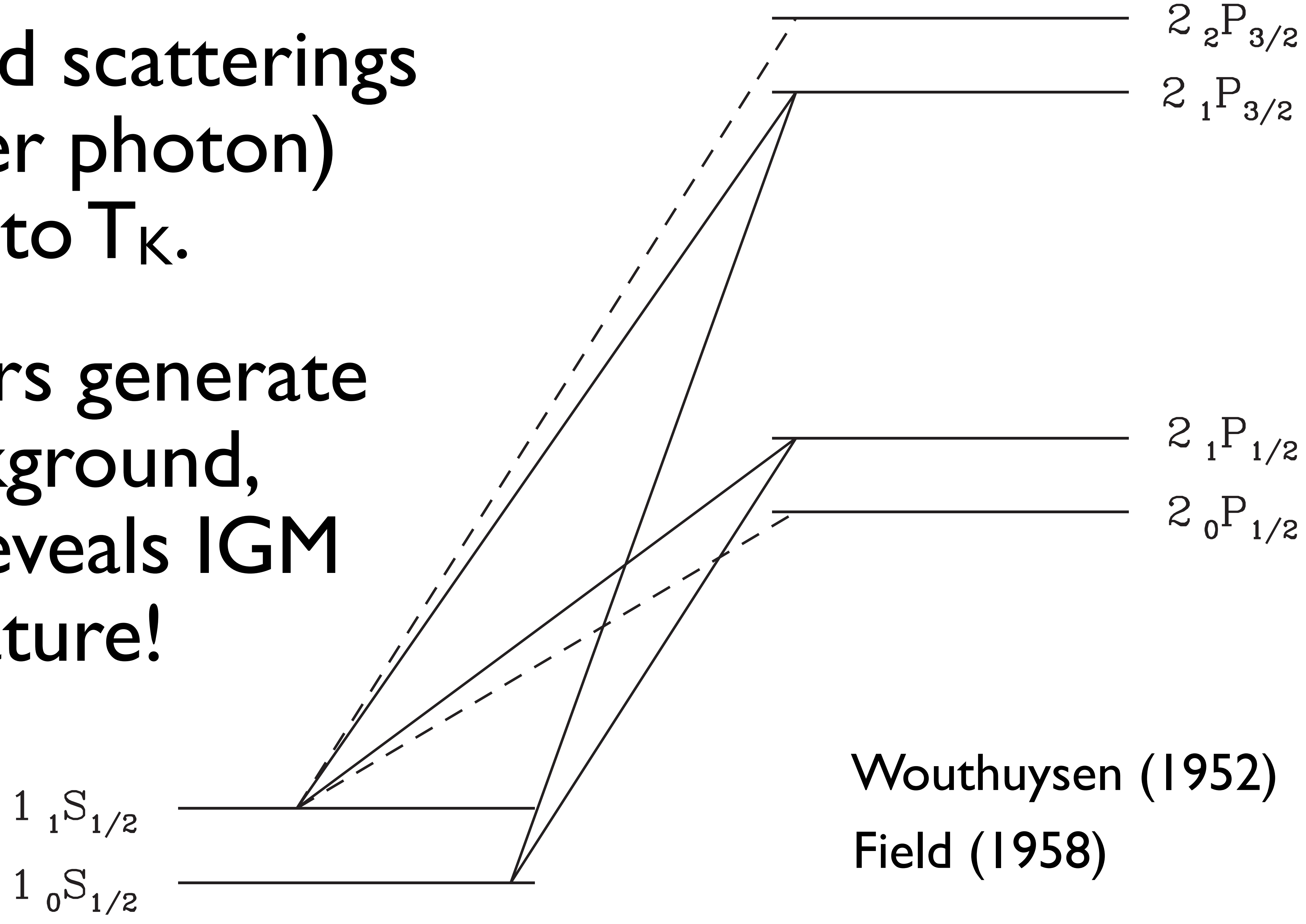
*vowt-how-sen

Wouthuysen*-Field Effect

Repeated scatterings ($\sim 10^6$ per photon) drive T_S to T_K.

First stars generate UV background, which reveals IGM temperature!

from Pritchard & Furlanetto (2006)



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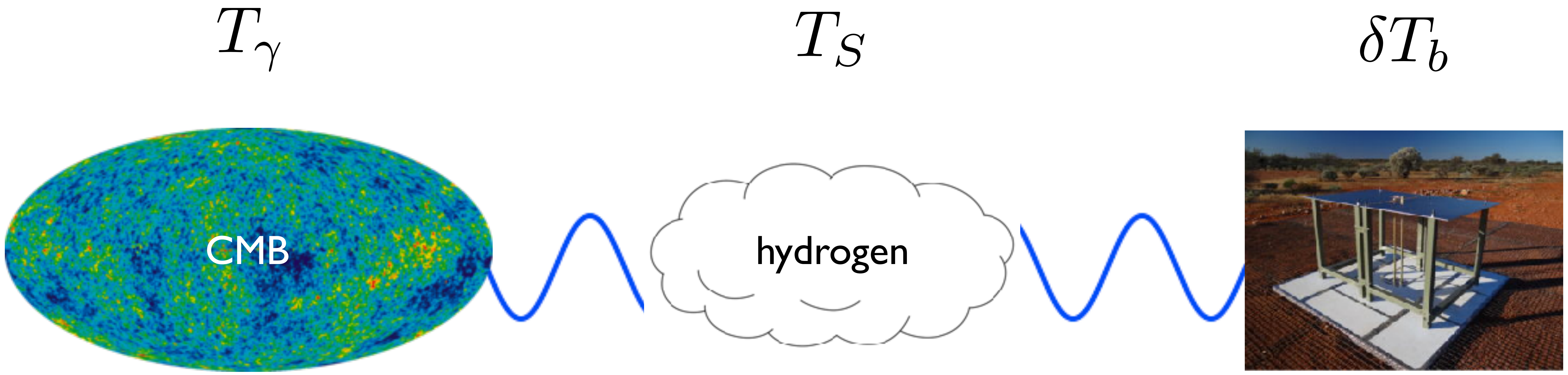


Adapted from J. Pritchard

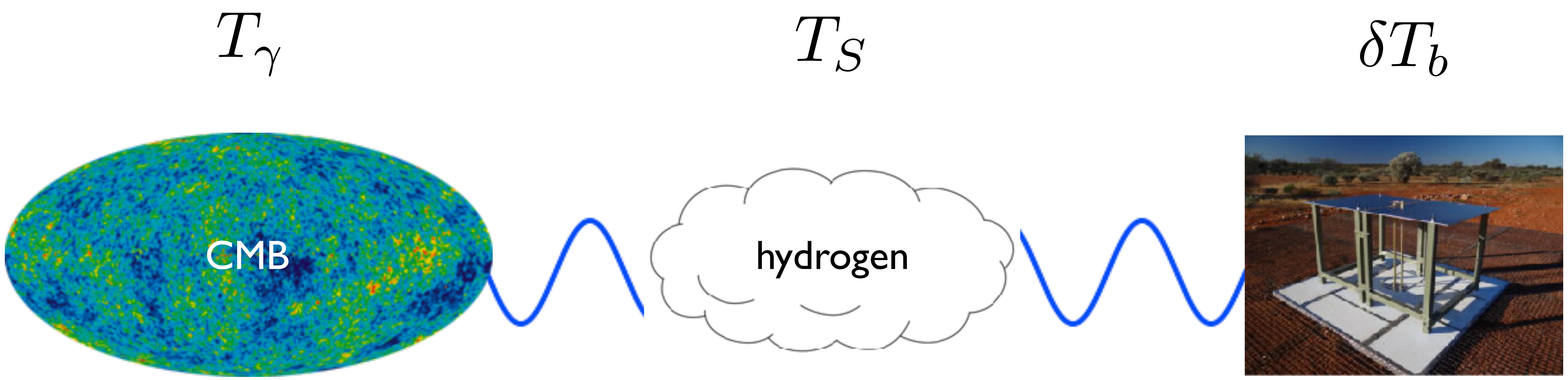
e.g., EDGES

"Differential brightness temperature":

$$\delta T_b \simeq 27\ \bar{x}_{\rm H\,I}(1+\delta)\left(\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right)\ \mathrm{mK}$$

e.g., Furlanetto (2006)

21-cm Physics



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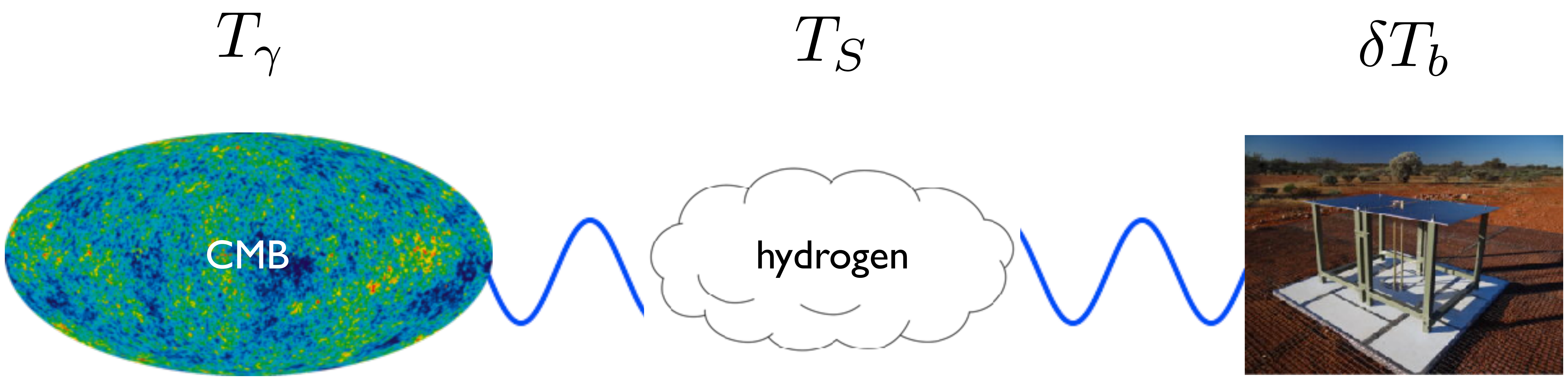

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for global signal

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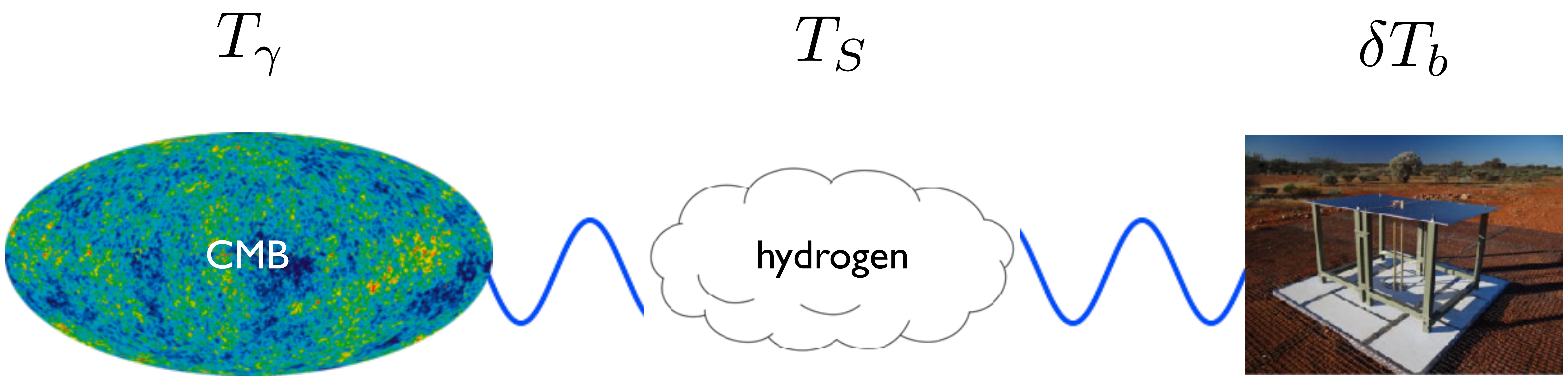

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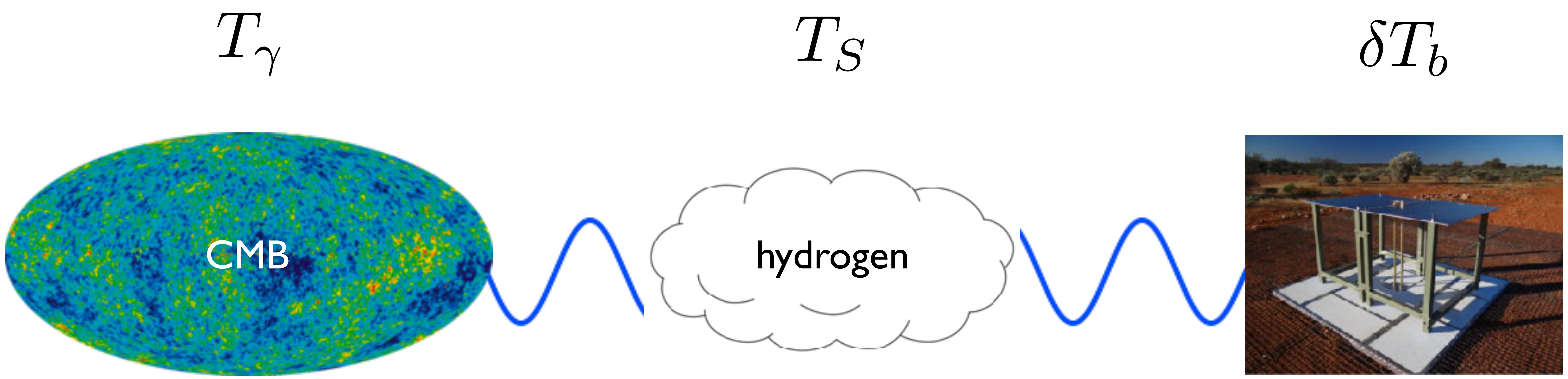

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