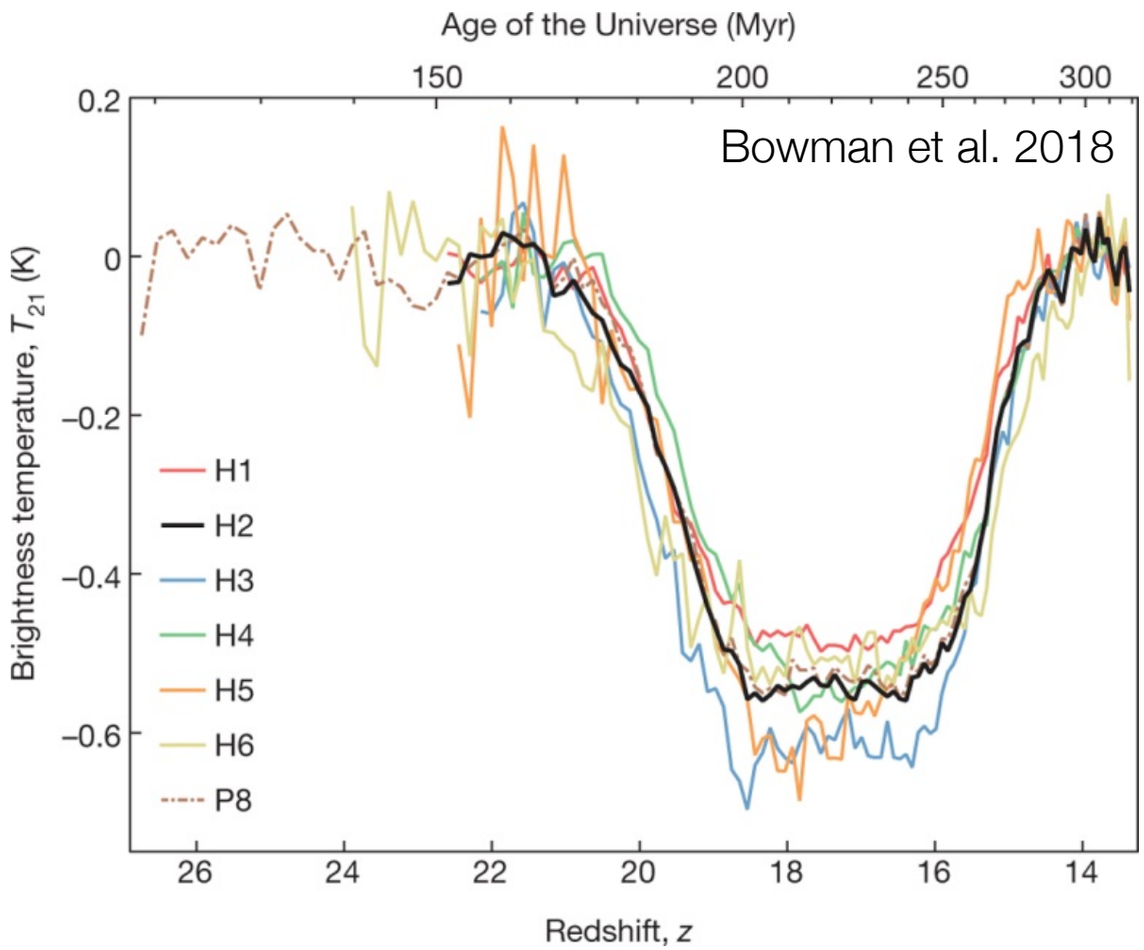
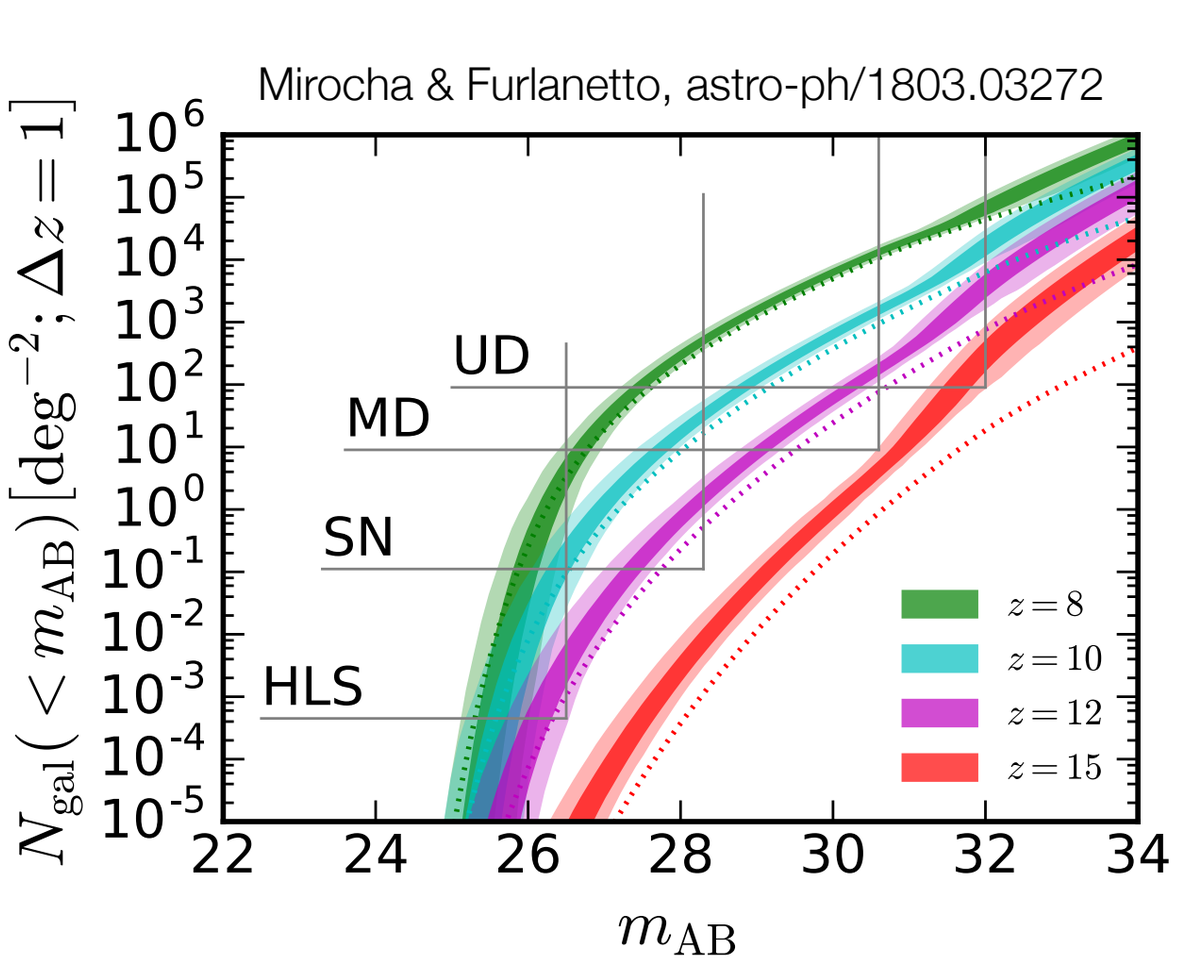
The first high-z 21-cm detection:
Implications for dark matter and galaxy formation

Jordan Mirocha (UCLA)
in collaboration with Steve Furlanetto (UCLA)



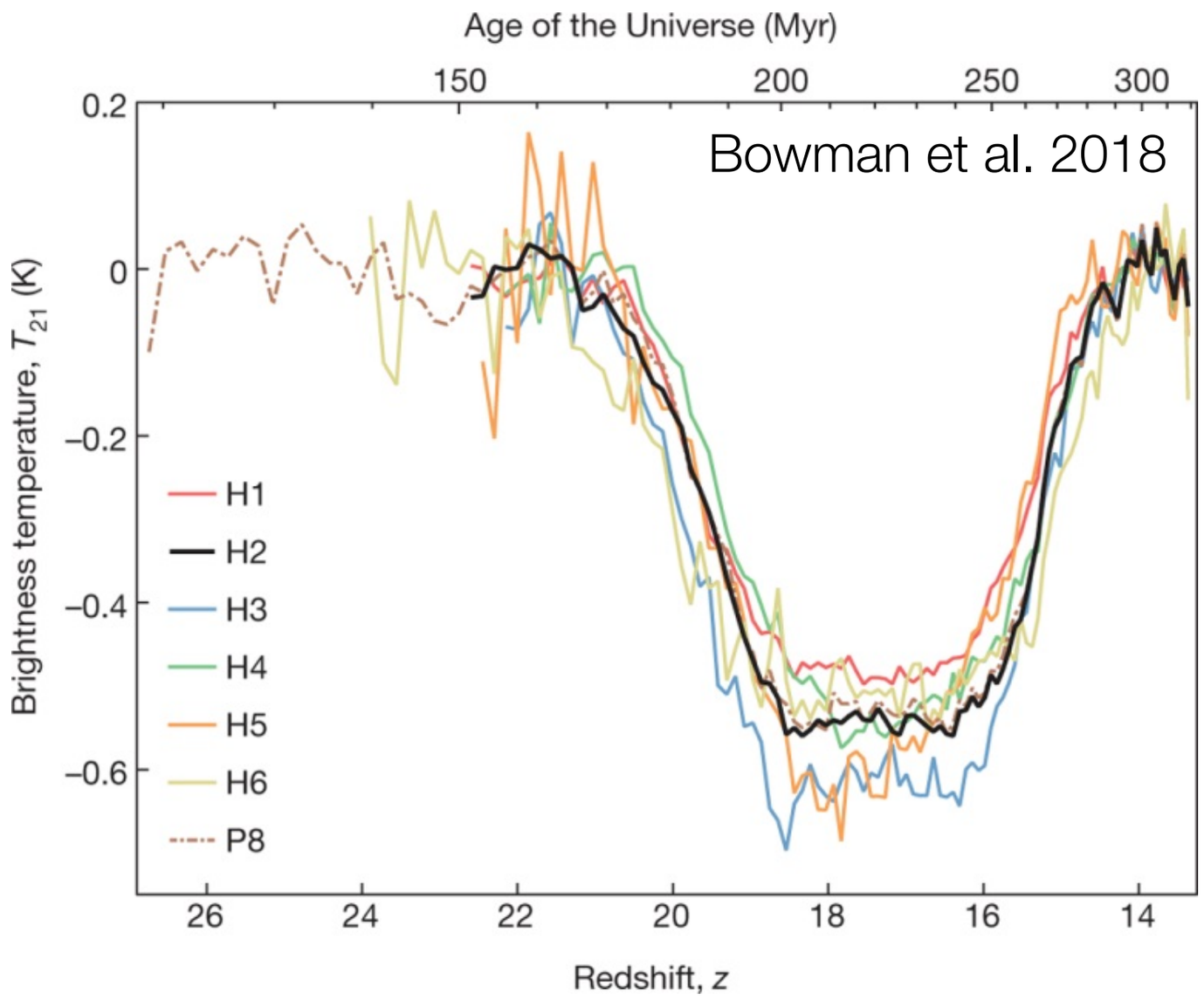


Outline

I. What is the global 21-cm signal? What is weird about the EDGES signal?

II. What are the leading ideas for the anomalous depth of the EDGES signal?

III. What does the EDGES signal tell us about galaxy formation?



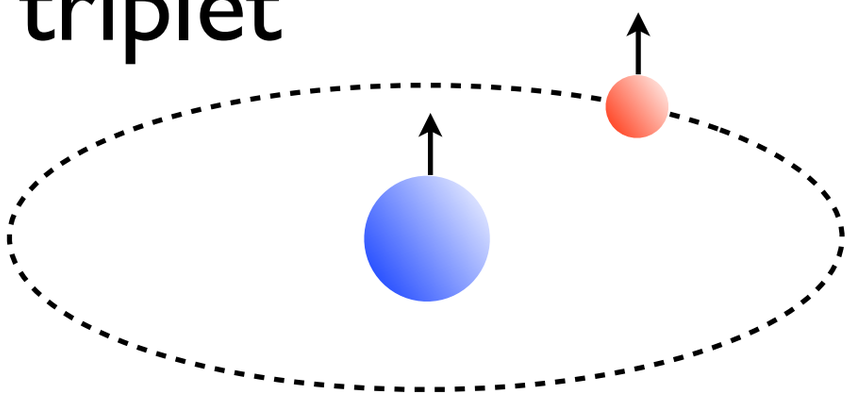
Part I:

The Global 21-cm Signal

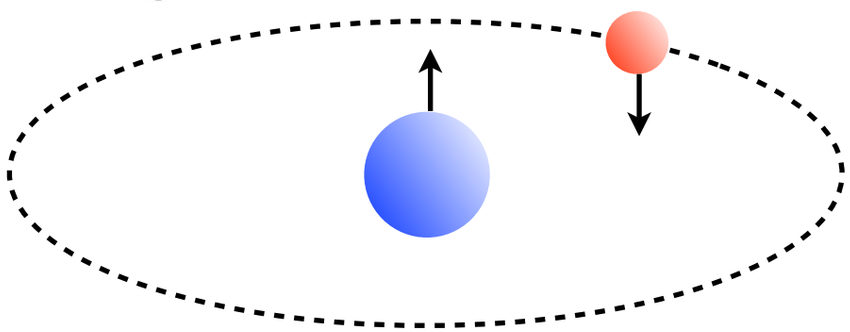
Tomography: Madau et al. (1997)
Monopole: Shaver et al. (1999)

21-cm Physics

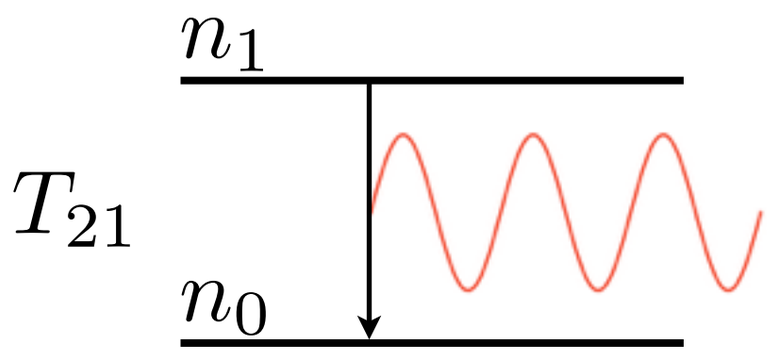
triplet



singlet



Ground-state hyper-fine splitting

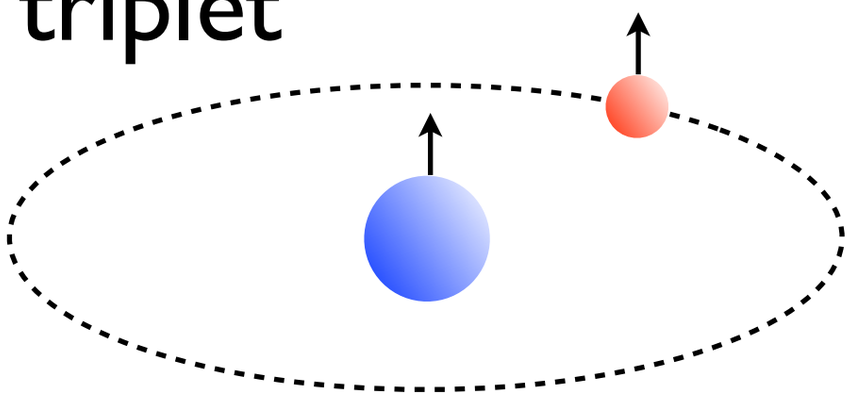


$\lambda = 21$ cm

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

21-cm Physics

triplet



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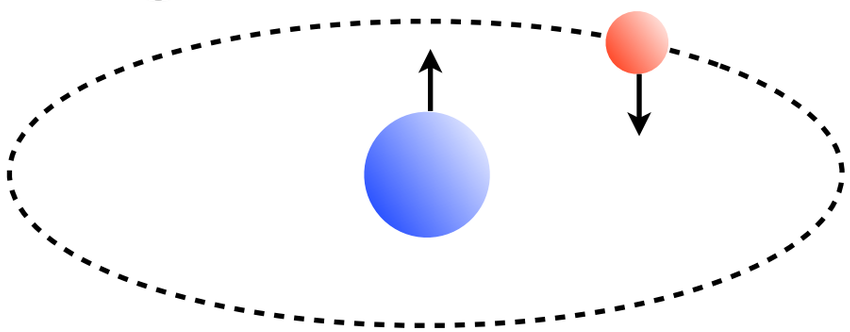

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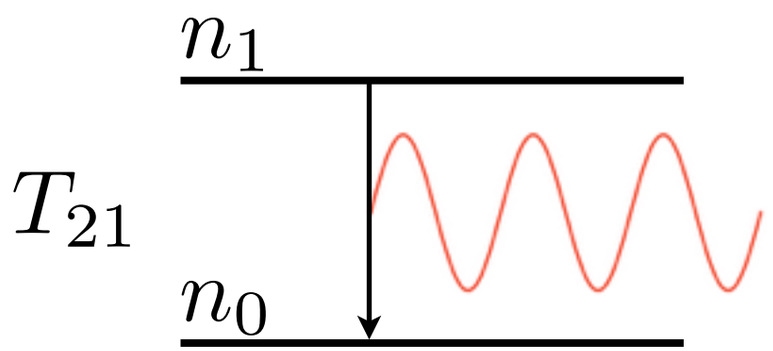


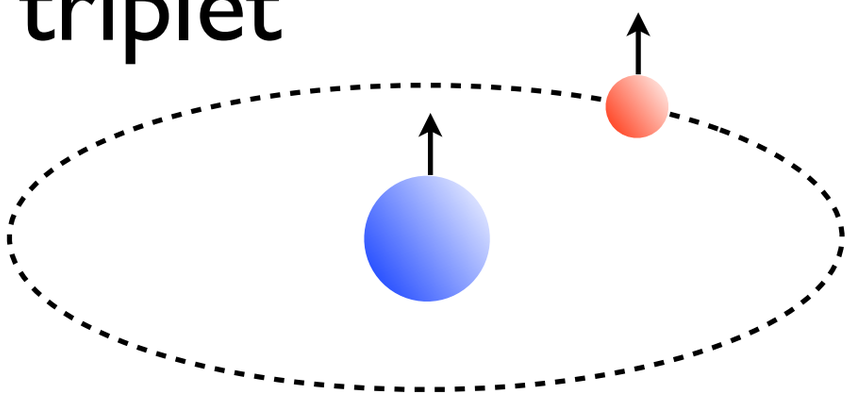
$\lambda = 21$ cm

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

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

21-cm Physics

triplet



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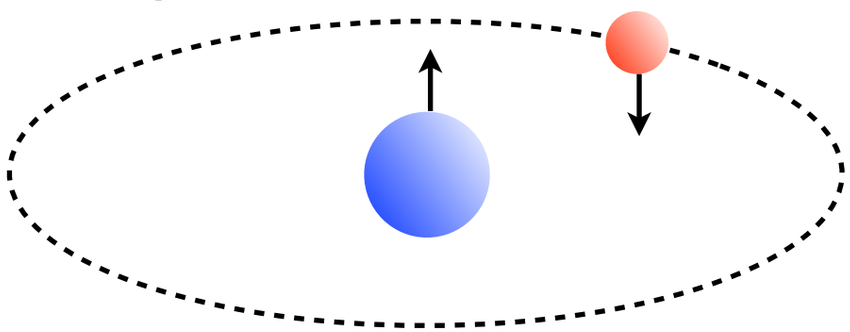
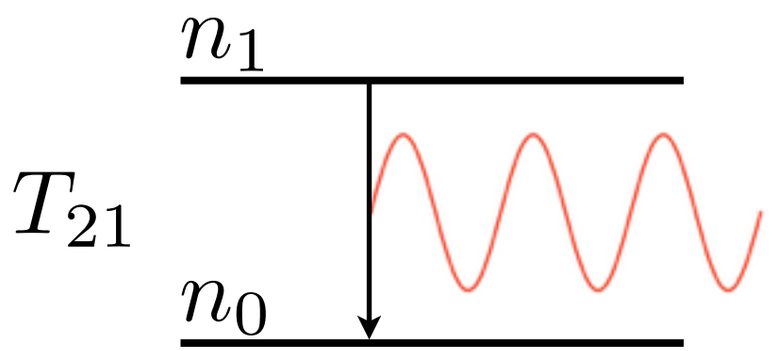


Ground-state hyper-fine splitting



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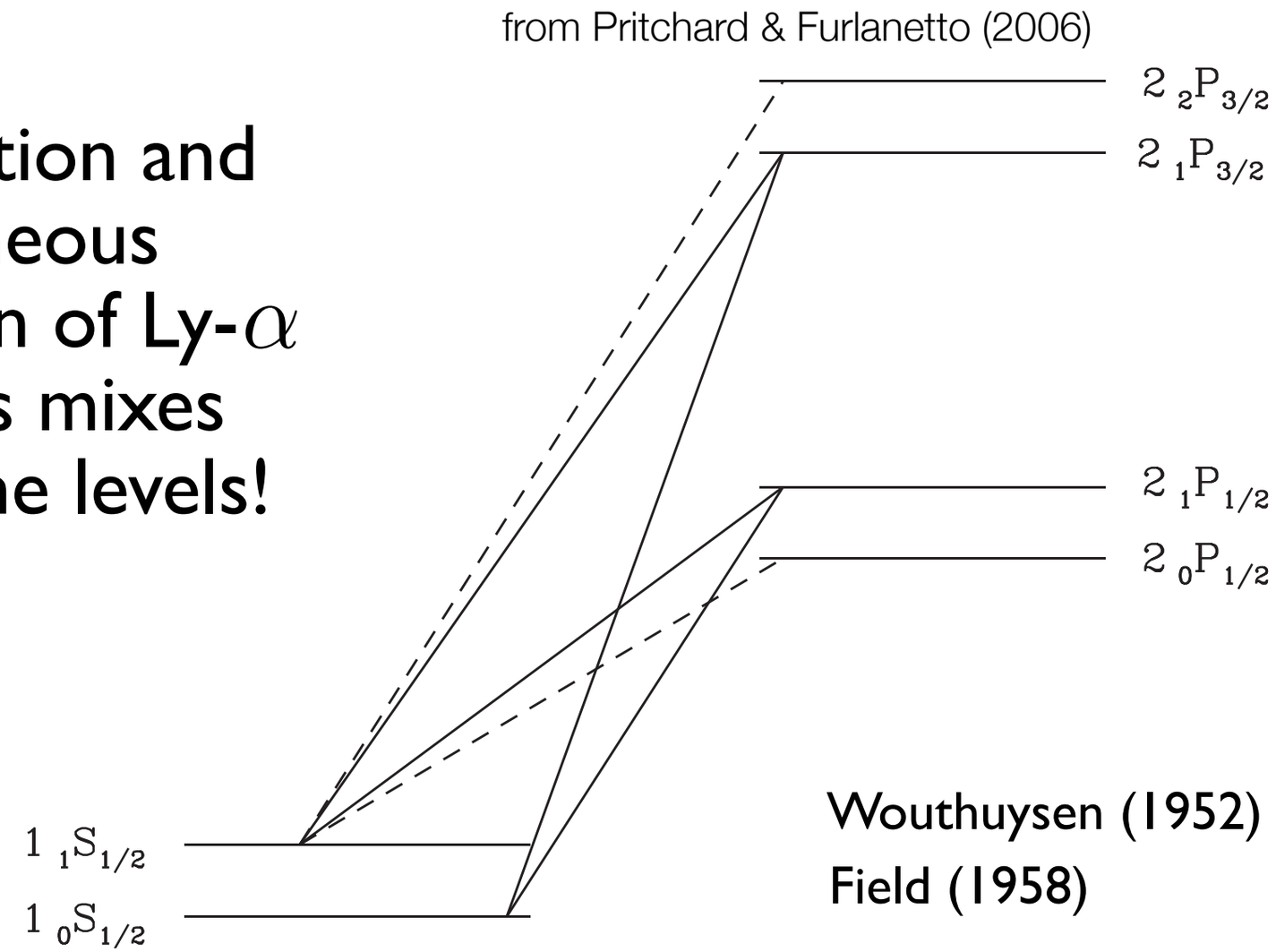
...?

Wouthuysen*-Field Effect

Absorption and spontaneous emission of Ly-α photons mixes hyperfine levels!



Wouthuysen (1952)
Field (1958)

*vowt-how-sen

Wouthuysen*-Field Effect

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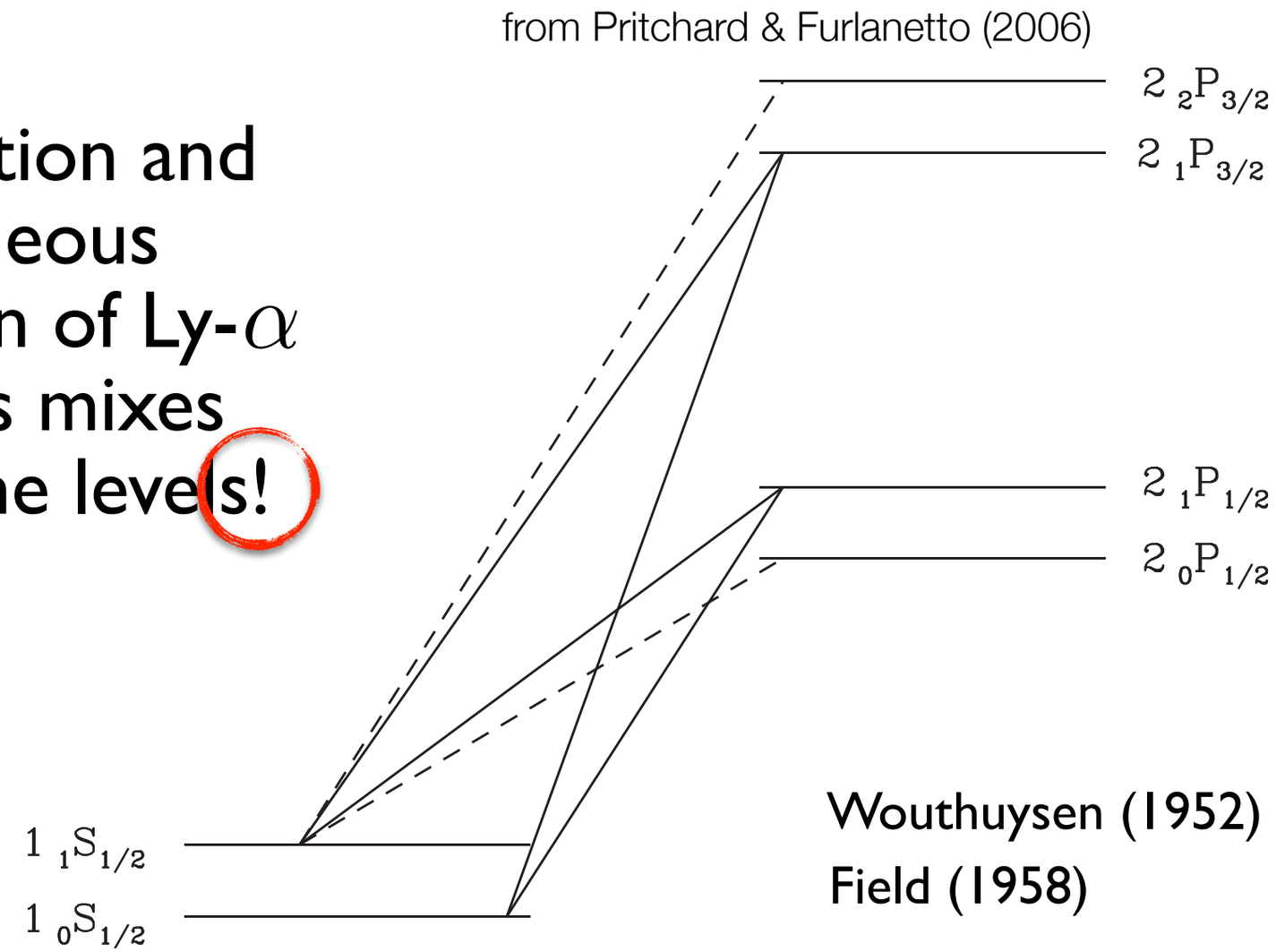
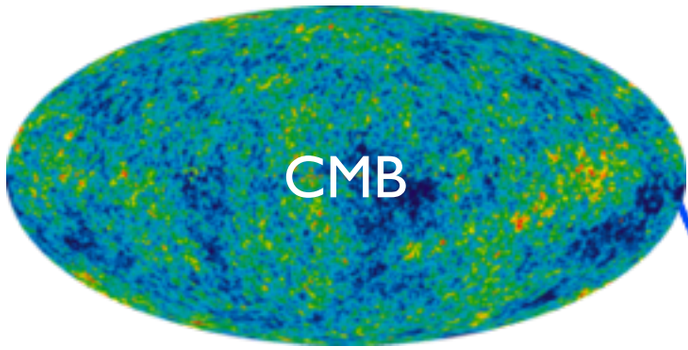
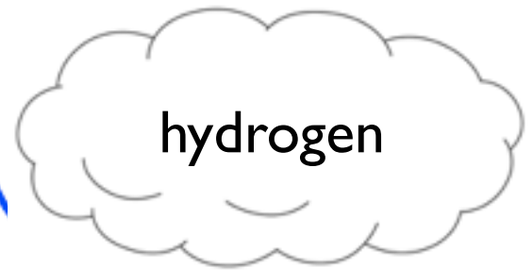


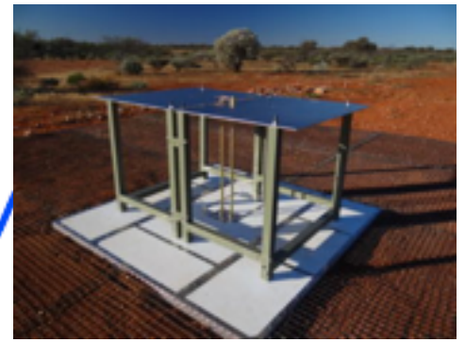
*vowt-how-sen

21-cm Physics

T_γ T_S δT_b







Adapted from J. Pritchard

e.g., EDGES

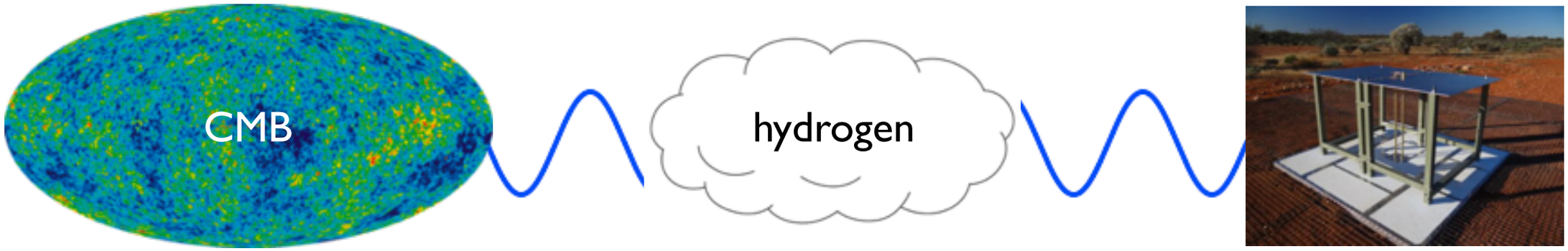
"Differential brightness temperature":

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

e.g., Furlanetto (2006)

21-cm Physics

T_γ T_S δT_b



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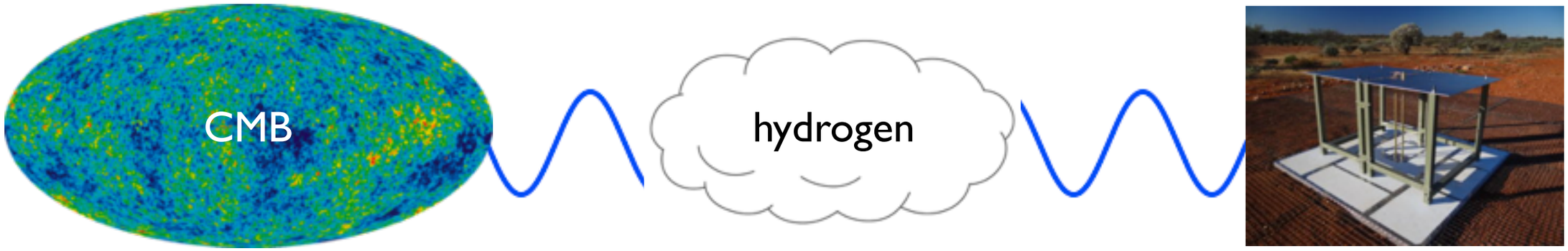

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0

for global signal

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21-cm Physics

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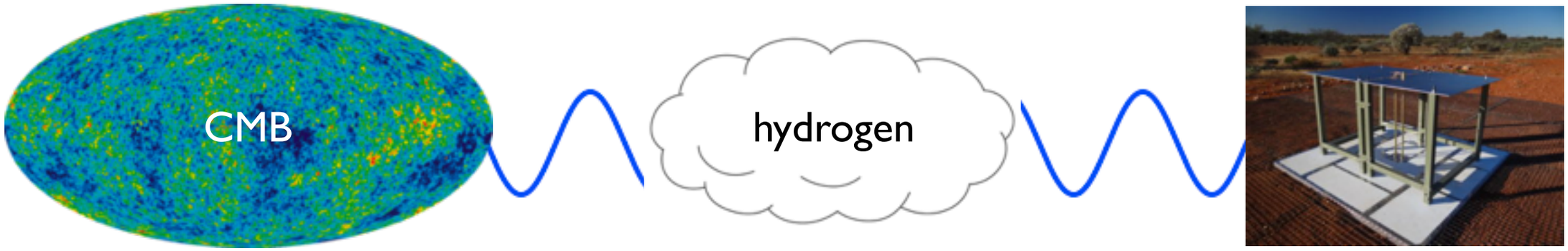

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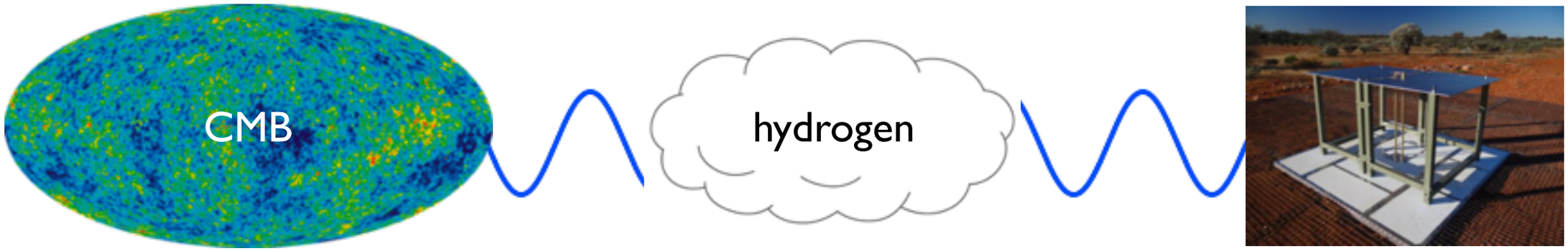

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e.g., EDGES

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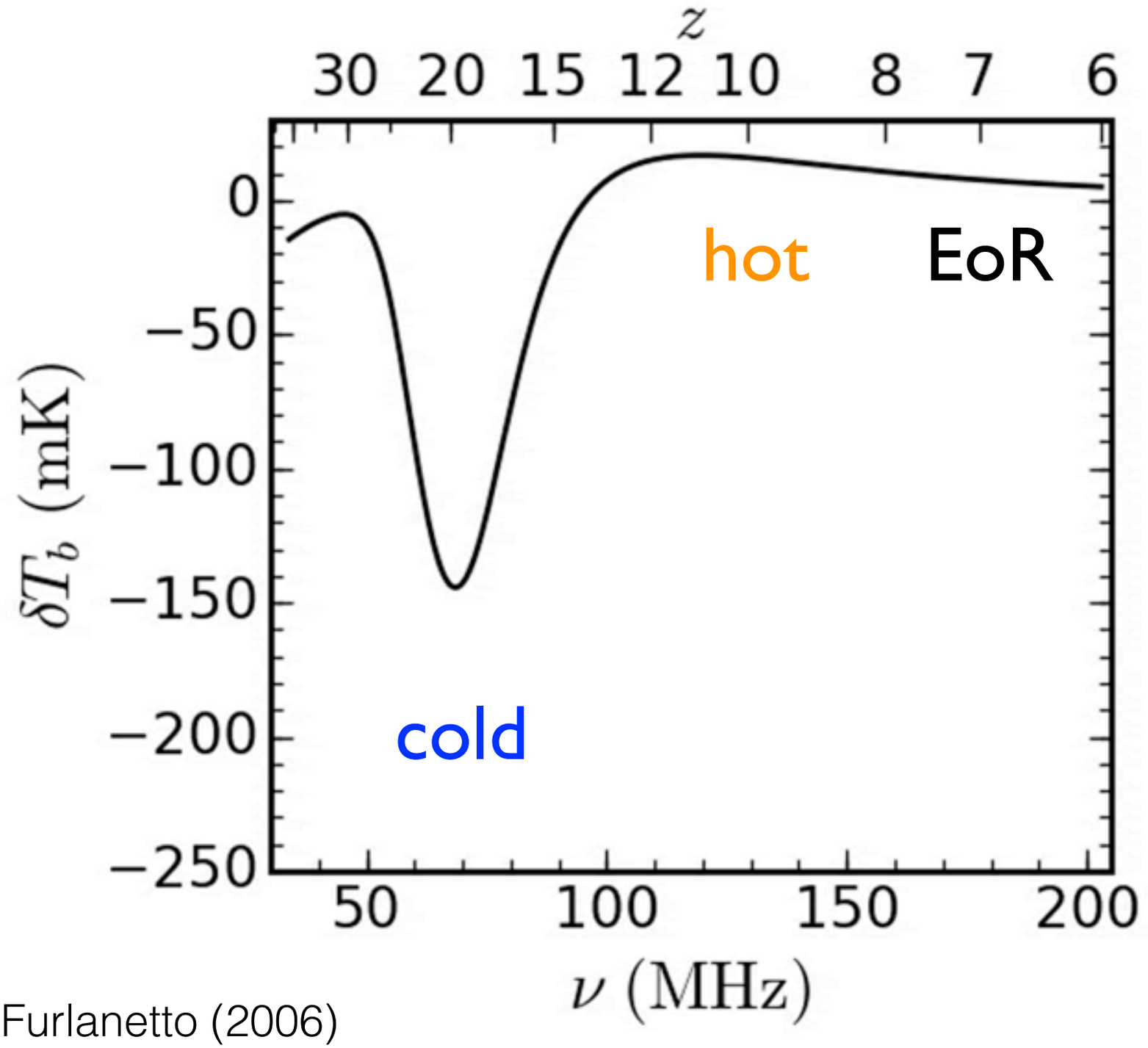
0 → for global signal

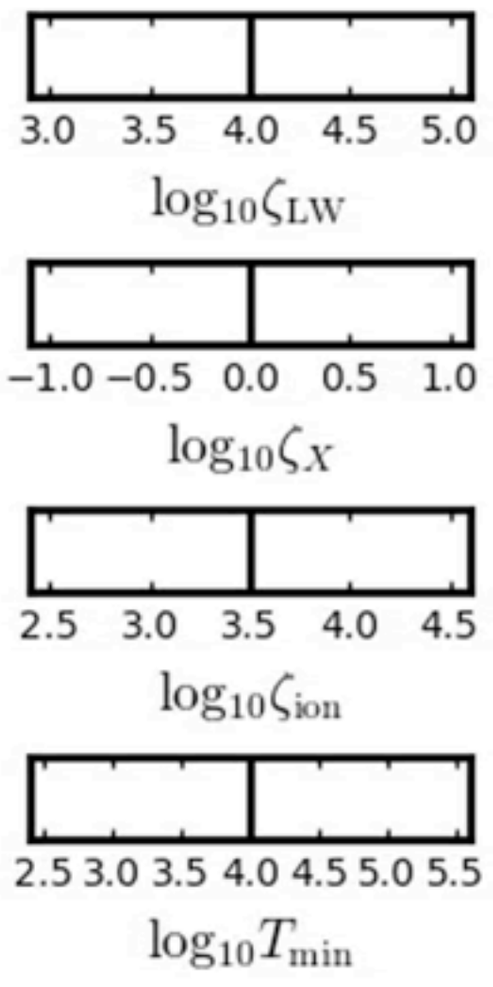
T_R

e.g., Furlanetto (2006)

The Global 21-cm Signal



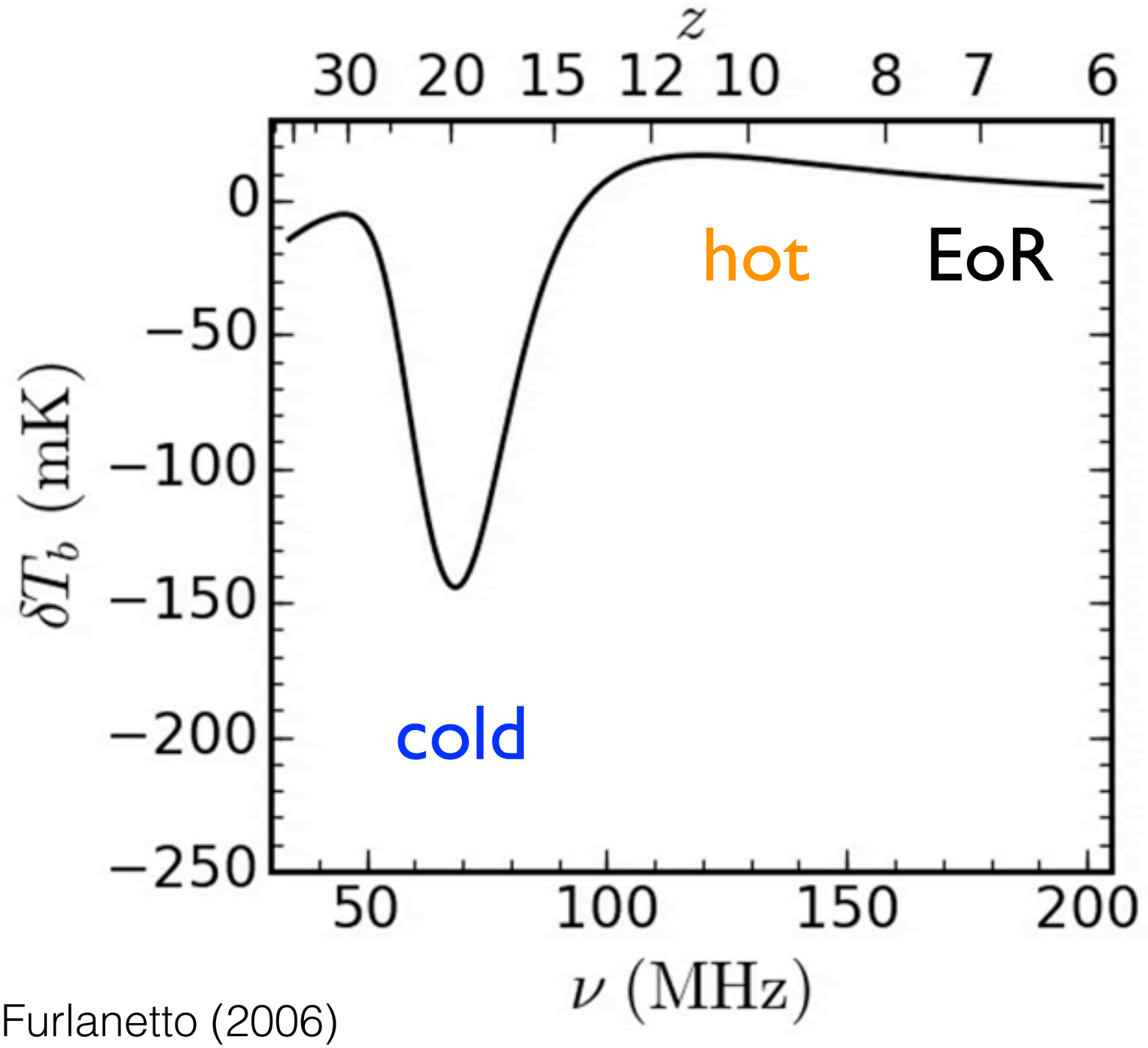
$$\mathrm{SFRD} \propto f_* \frac{df_{\mathrm{coll}}}{dt}$$



$$\zeta_i = f_* N_i f_{\mathrm{esc},i}$$

e.g., Furlanetto (2006)

The Global 21-cm Signal



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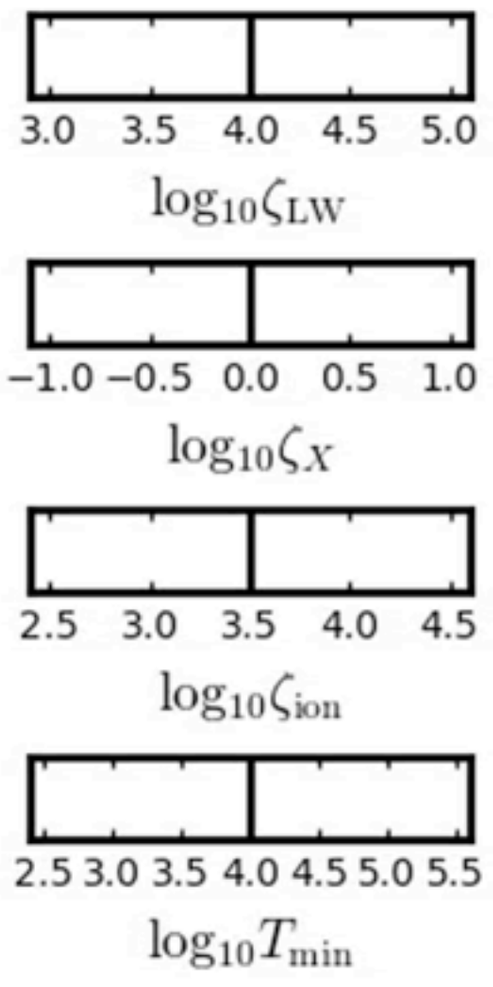

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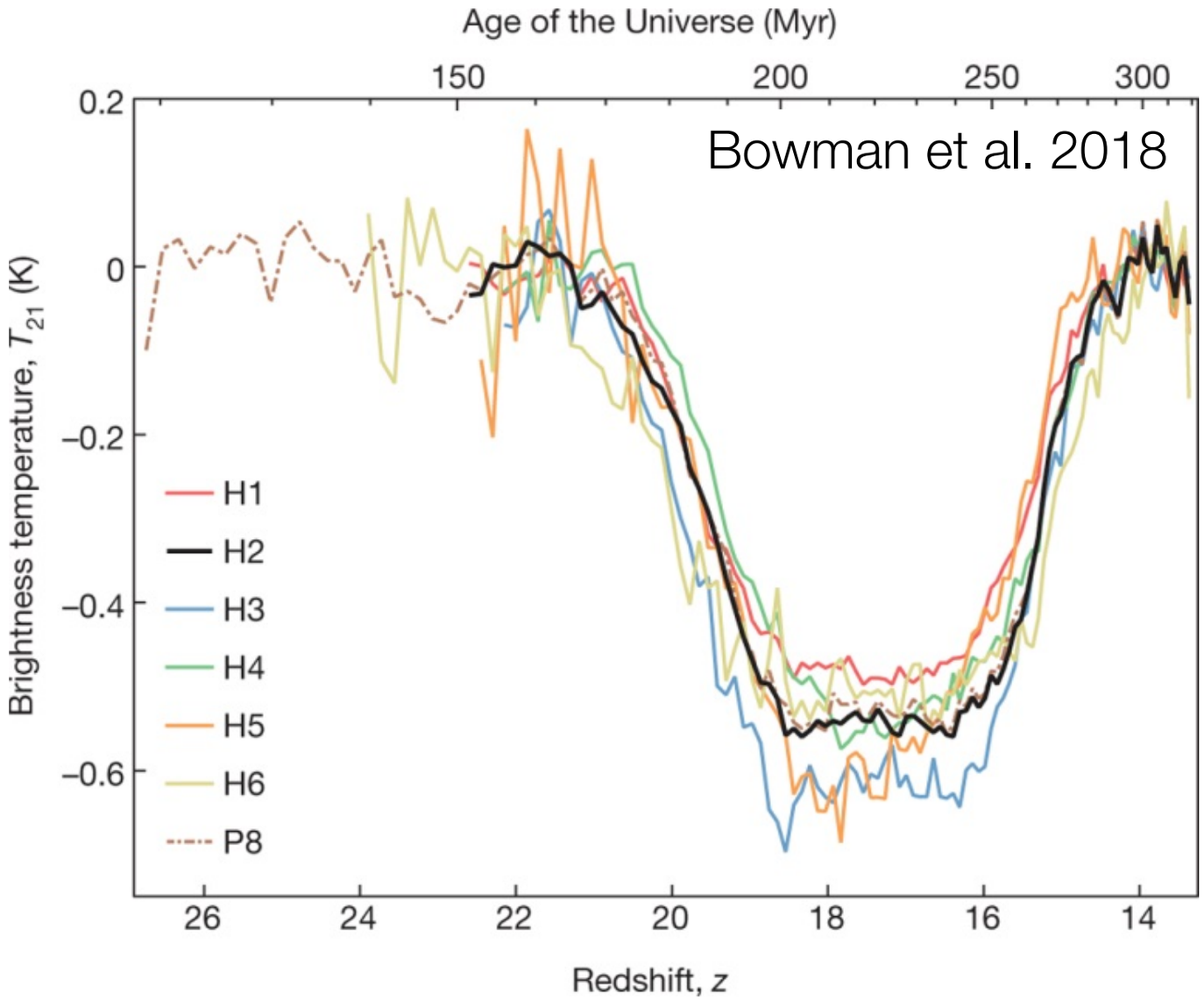
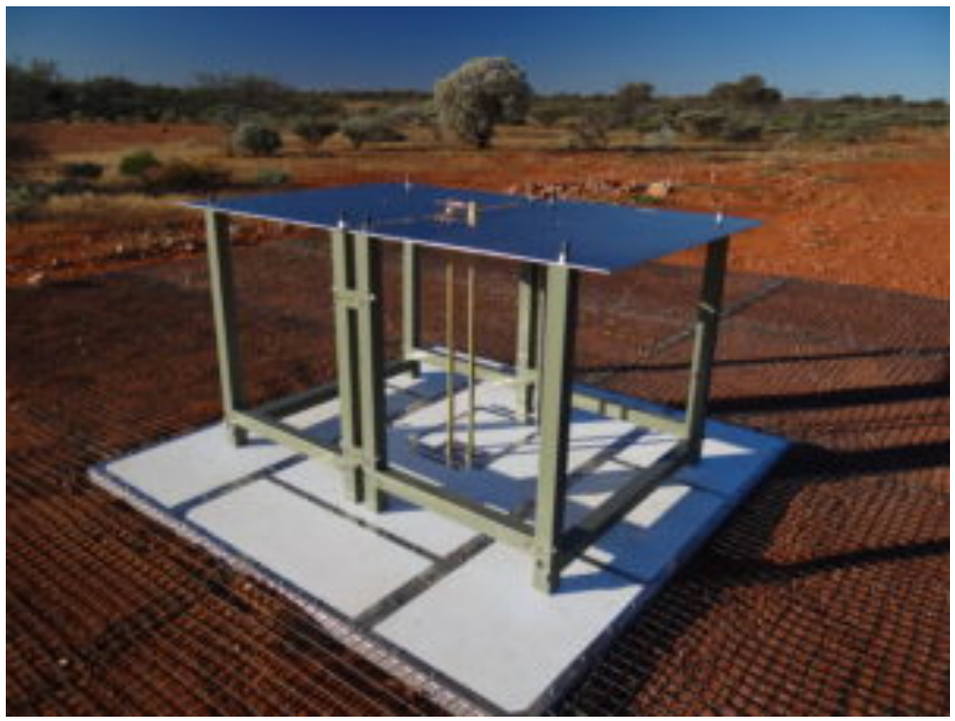
e.g., Furlanetto (2006)

Enter: EDGES



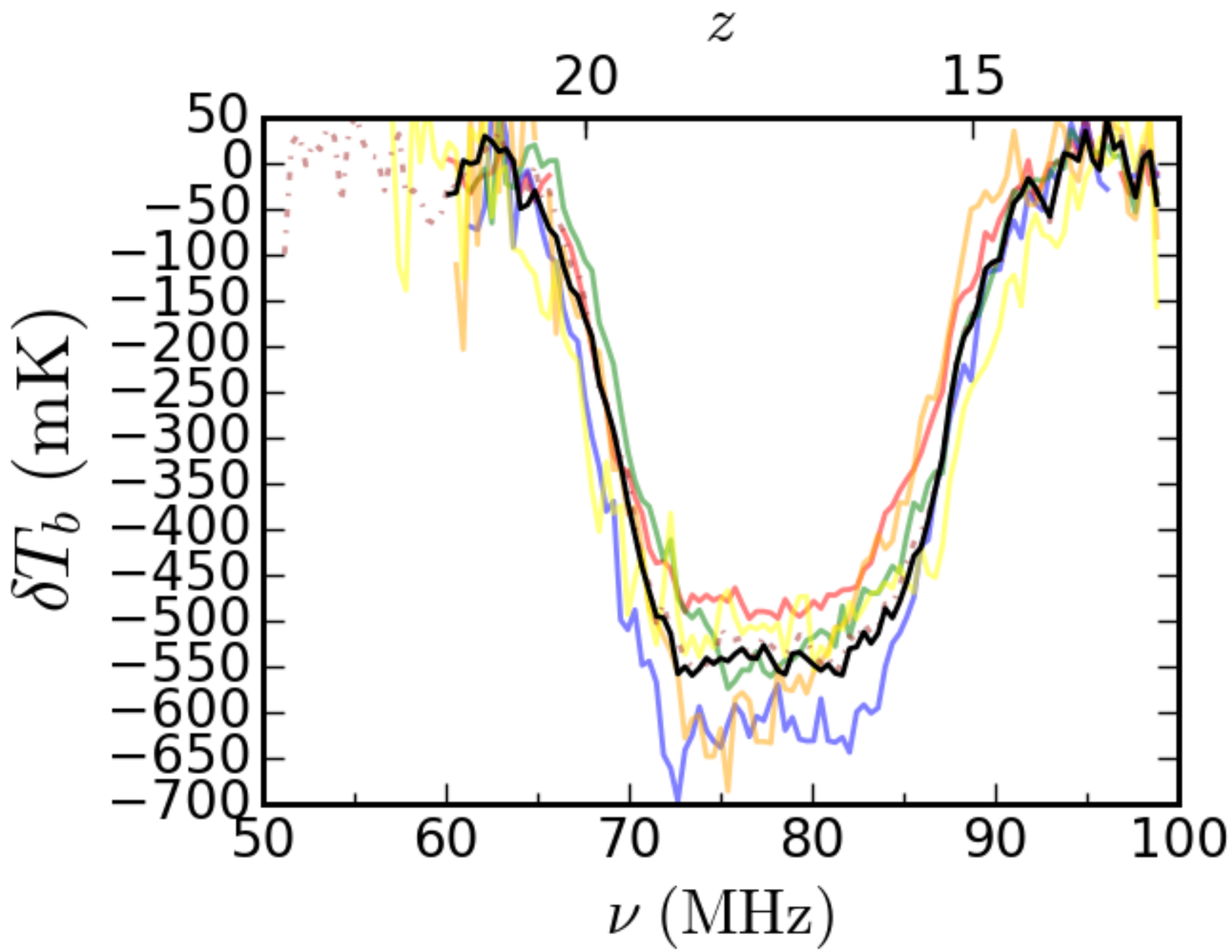
Published in Nature, March 1, 2018

Observing site:
Murchison Radio Observatory (W. Australia)



See also, e.g., Bowman & Rogers (2010), Monsalve et al. (2017)

EDGES: Key Features



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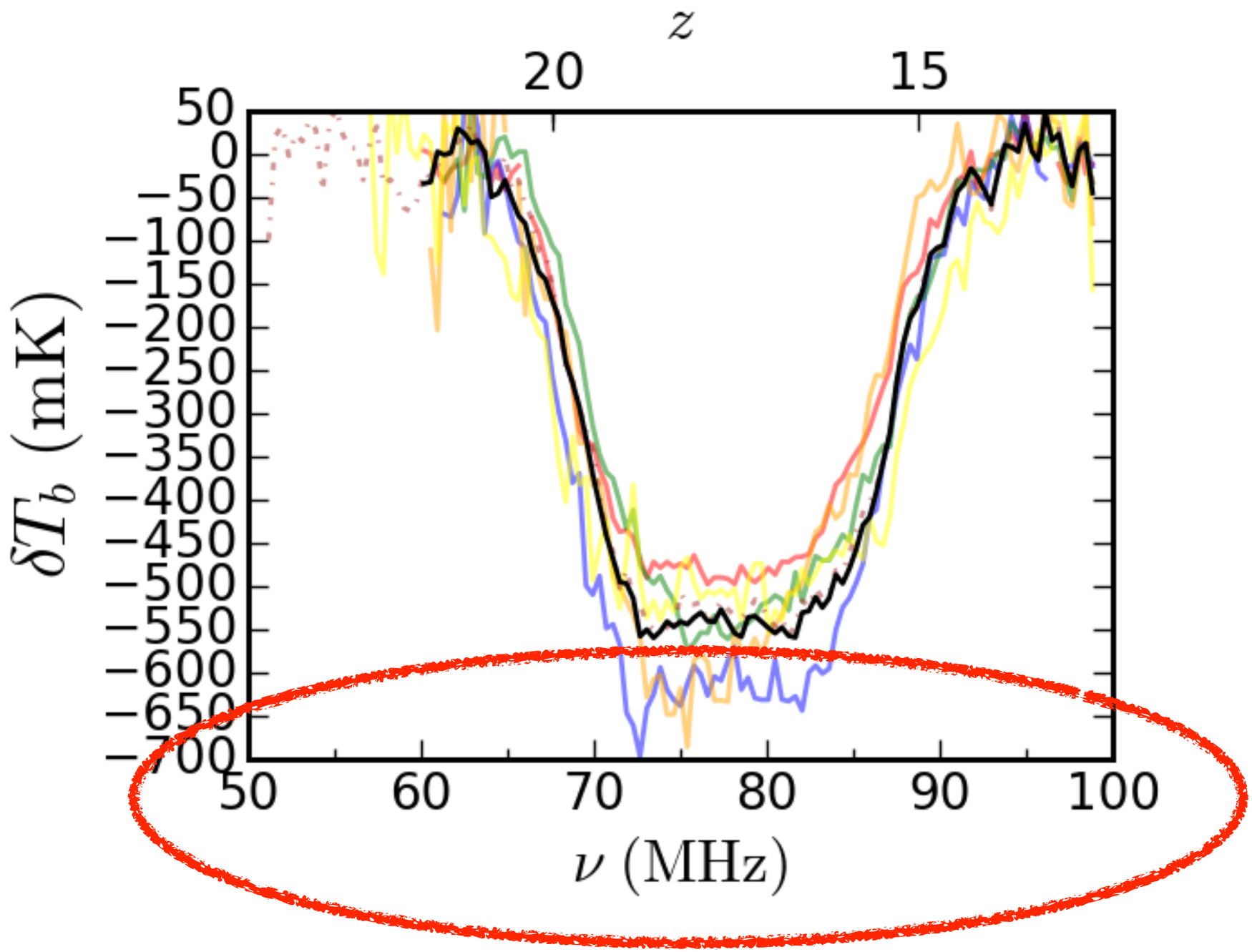

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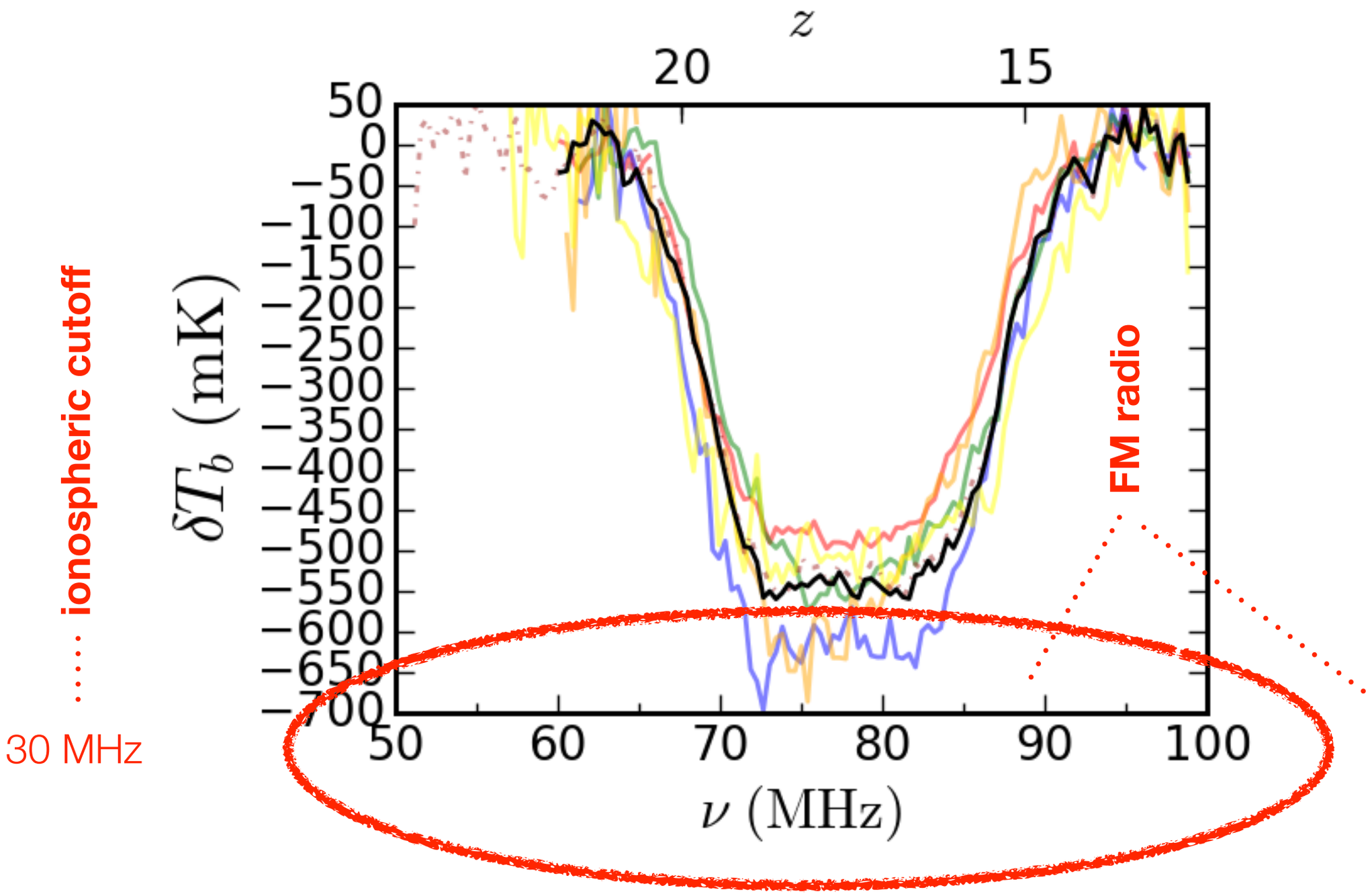

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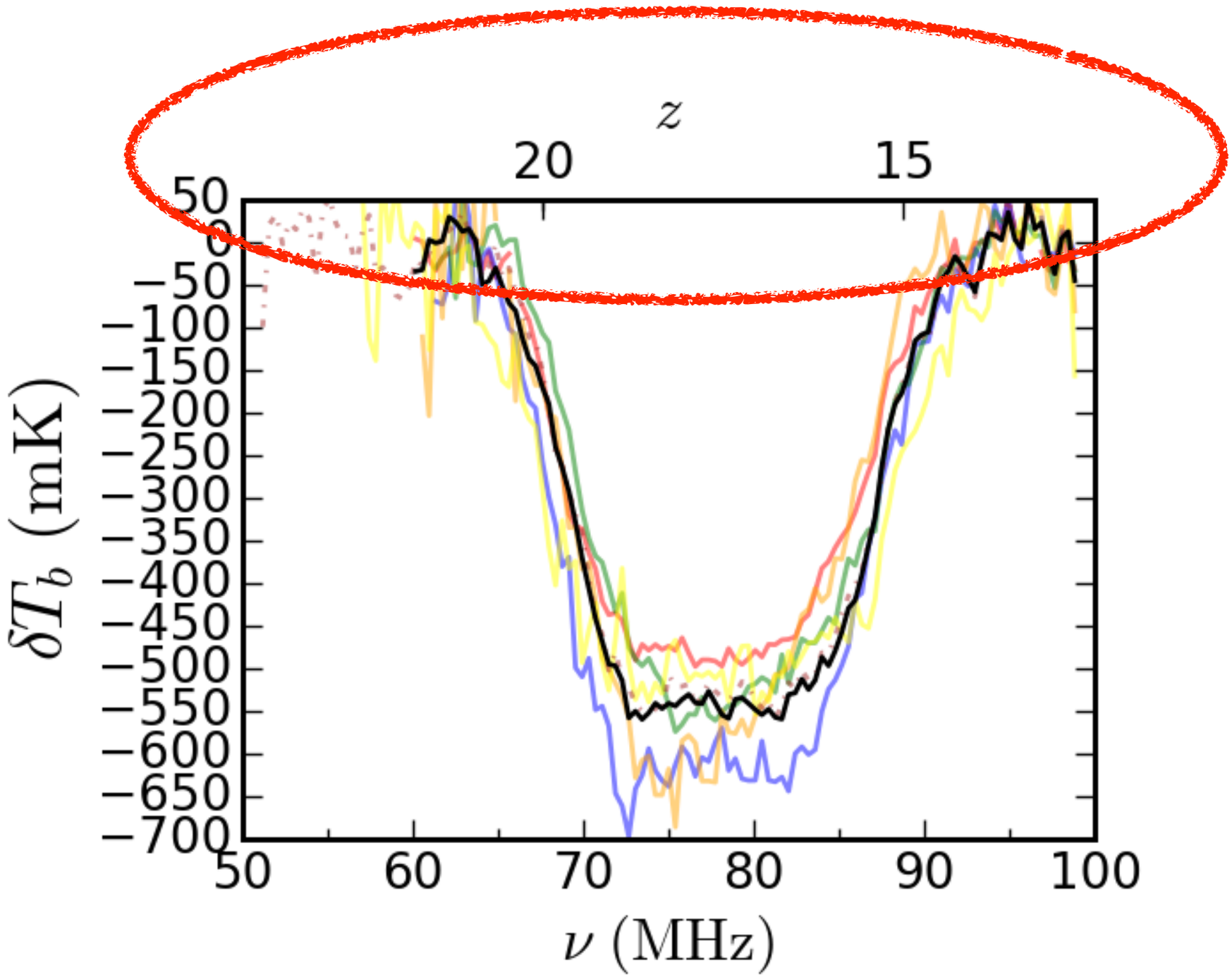

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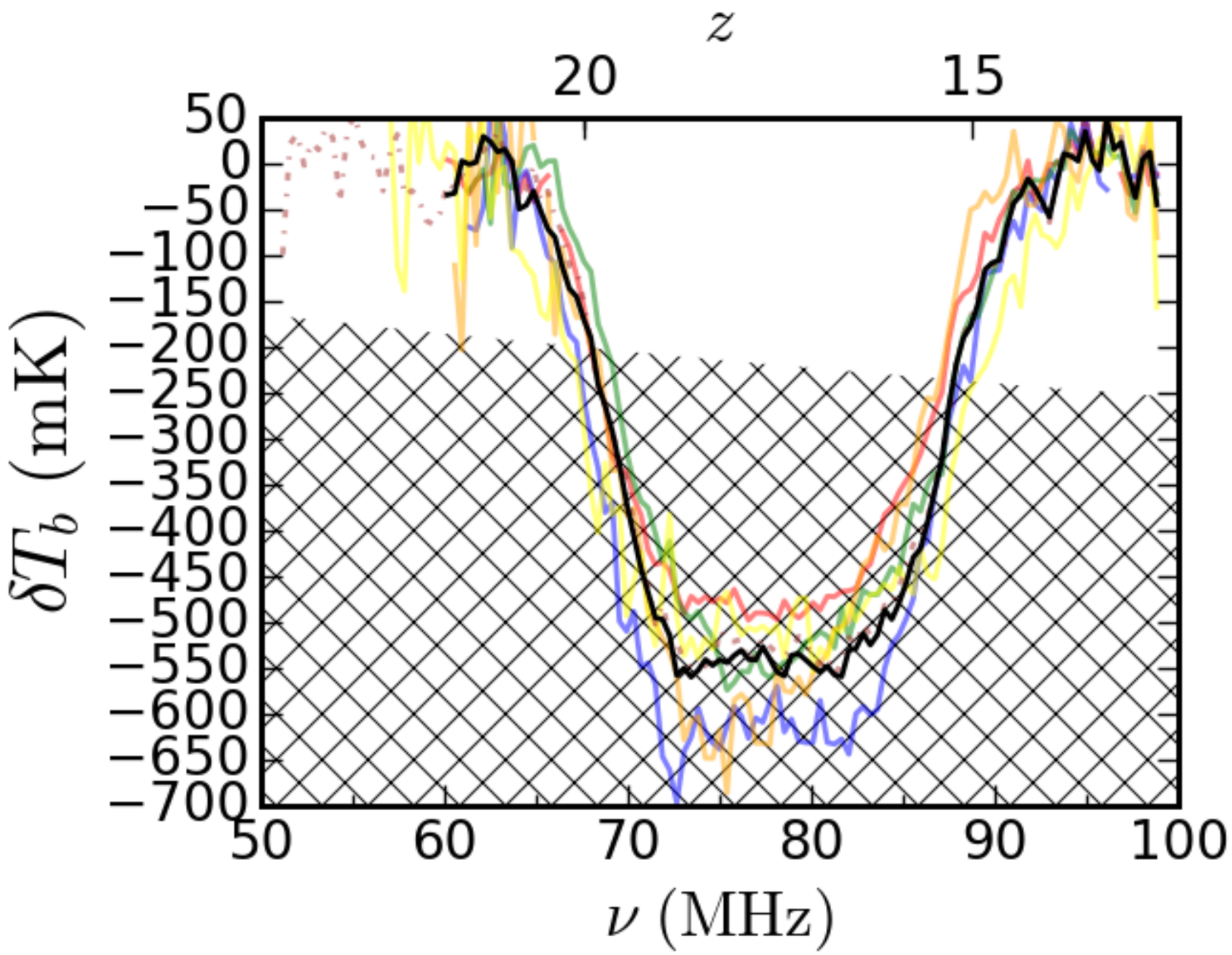
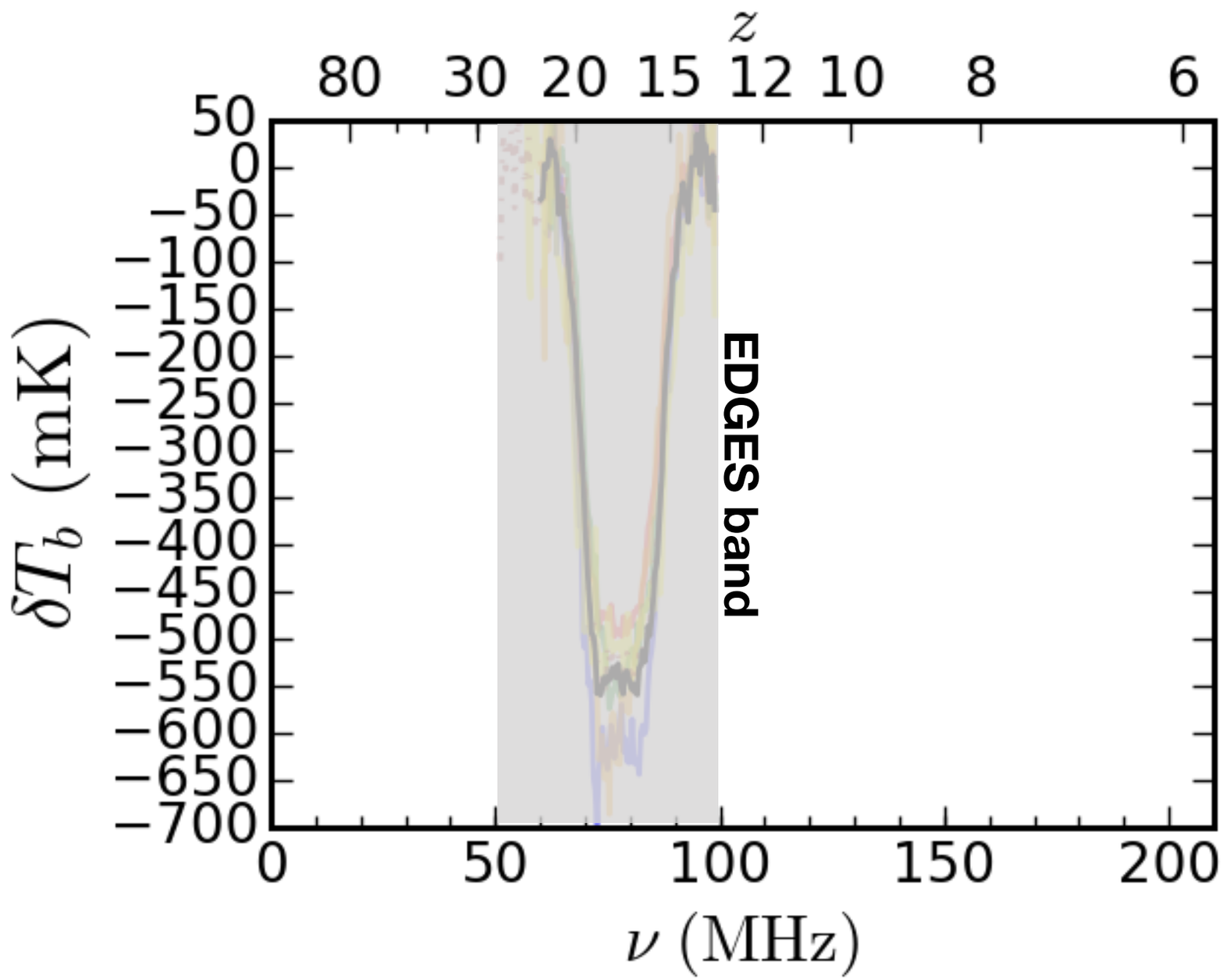


Requires temperatures colder than those predicted in ~adiabatically cooling IGM

EDGES: Key Features



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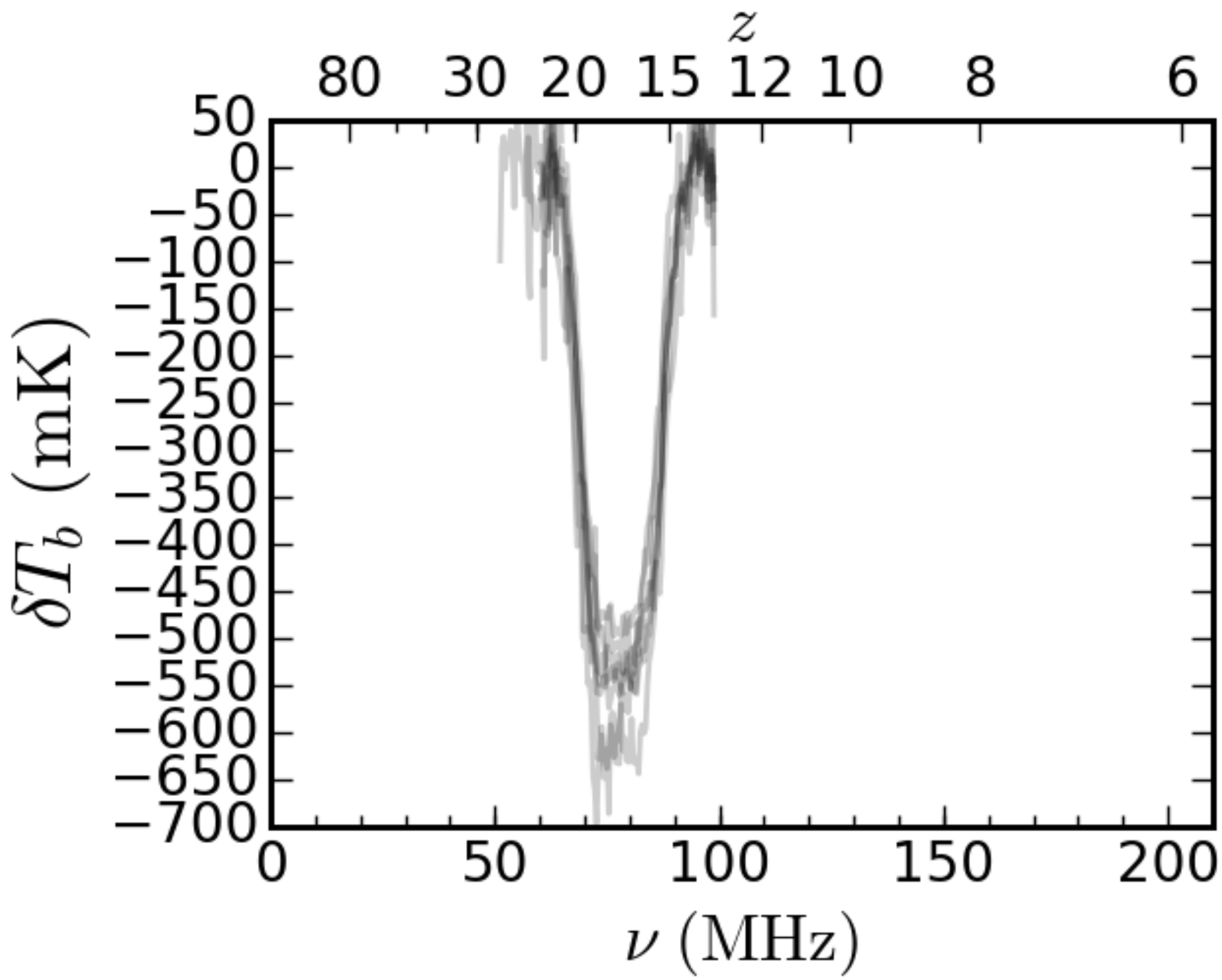

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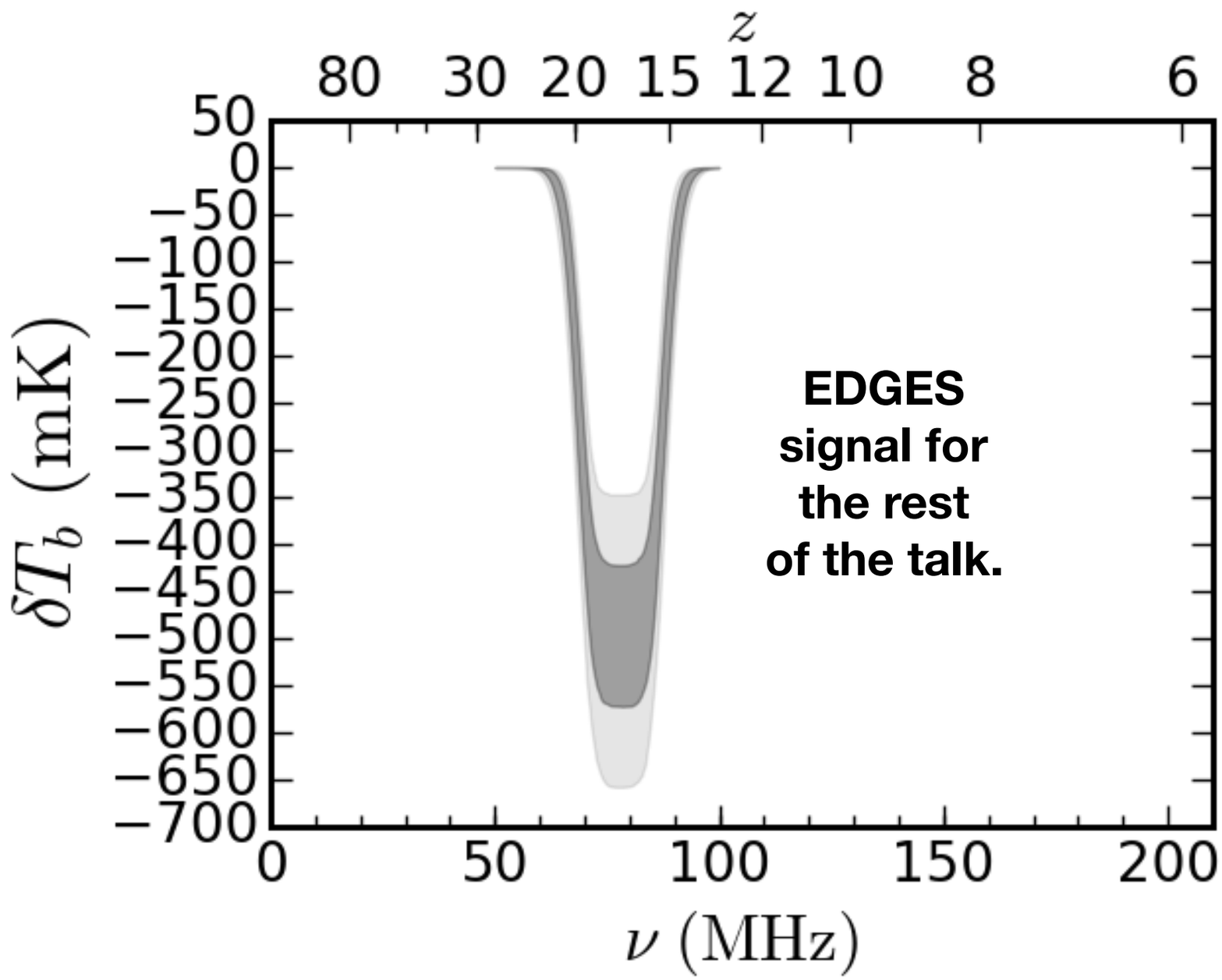

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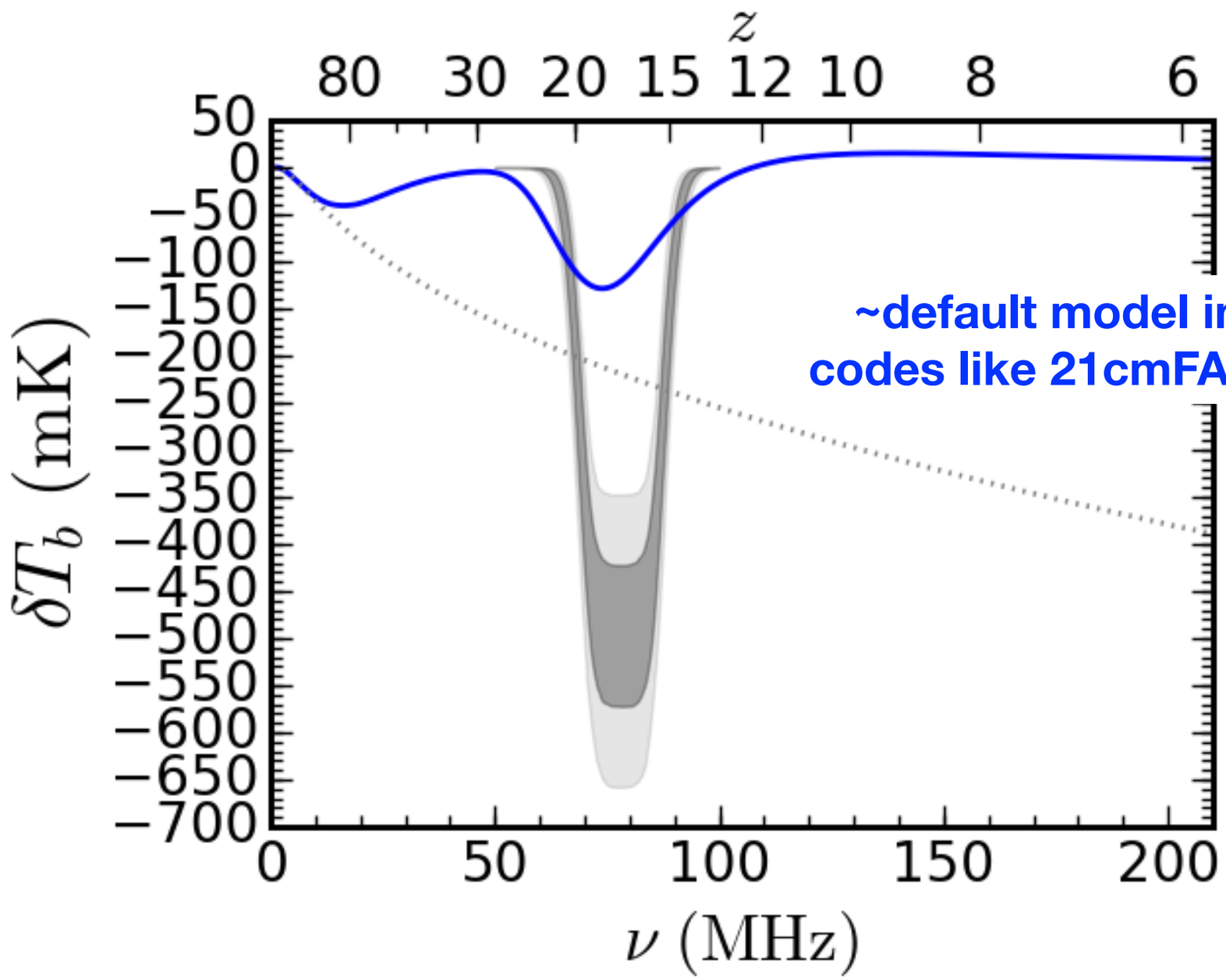

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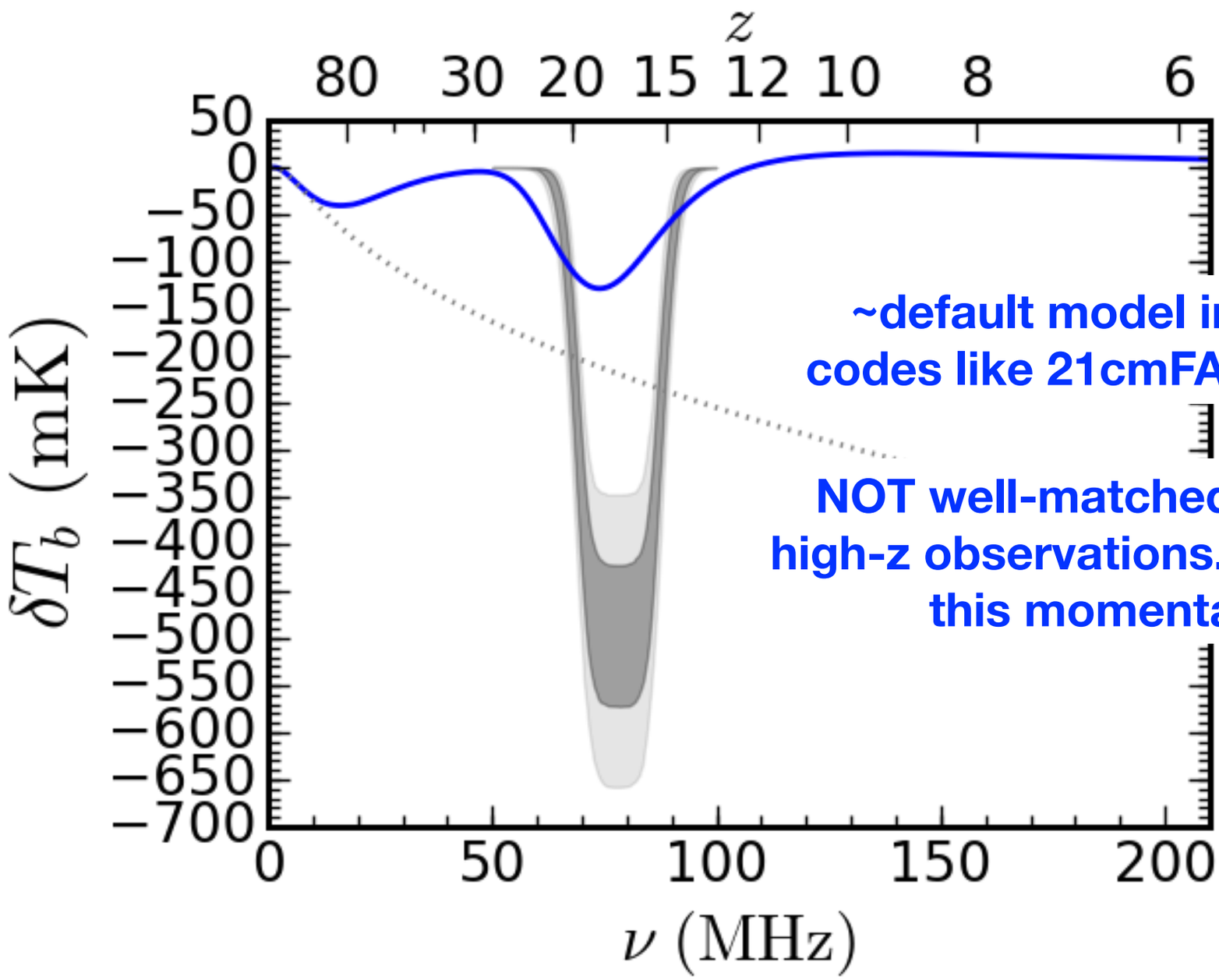

~default model in public codes like 21cmFAST, ARES

NOT well-matched to other high-z observations. Will revisit this momentarily.

Part II:

Explanations for the anomalous EDGES amplitude

Initial Considerations

$$\delta T_b \simeq 27\, \overline{x}_{\mathrm{H\ I}}(1+\delta) \left(\frac{\Omega_{b,0}h^2}{0.023}\right) \left(\frac{0.15}{\Omega_{m,0}h^2}\frac{1+z}{10}\right)^{1/2} \left(1-\frac{T_{\mathrm{R}}}{T_{\mathrm{S}}}\right)\ \mathrm{mK}$$

Q. How to amplify signal by a factor of 2-3?

Initial Considerations

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Q. How to amplify signal by a factor of 2-3?

1. Decrease T_S via baryon-DM interactions.

- Barkana, Munoz & Loeb, Fialkov et al., Berlin et al., Slatyer & Wu

Note: inclusion in these lists does not imply authors' endorsement of the solution!

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2. Increase T_R via DM decay or synchrotron from BHs, galaxies.
   - Feng & Holder, Ewall-Wice et al., Fraser et al., Mirocha & Furlanetto

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2. Increase T_R via DM decay or synchrotron from BHs, galaxies.
   - Feng & Holder, Ewall-Wice et al., Fraser et al., Mirocha & Furlanetto
3. Alter the cosmology.
   - McGaugh, Costa et al., Hill et al.

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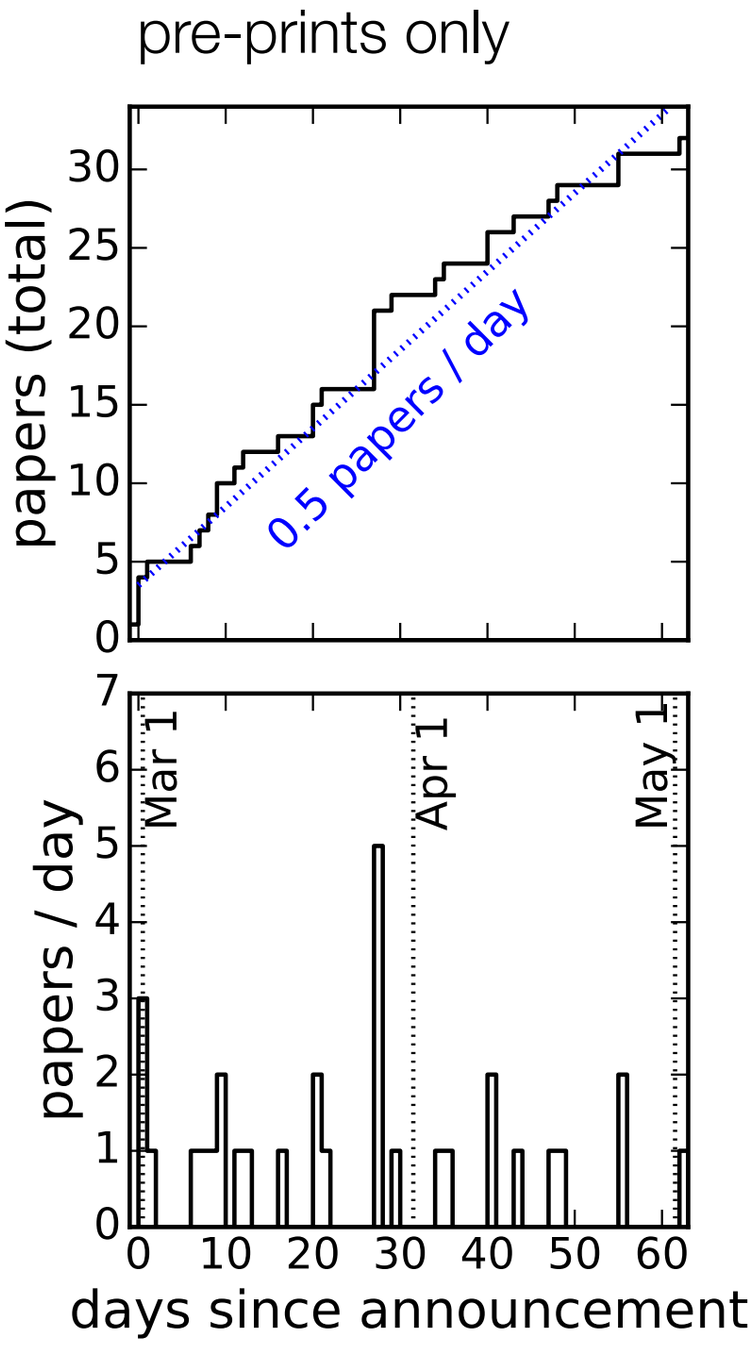
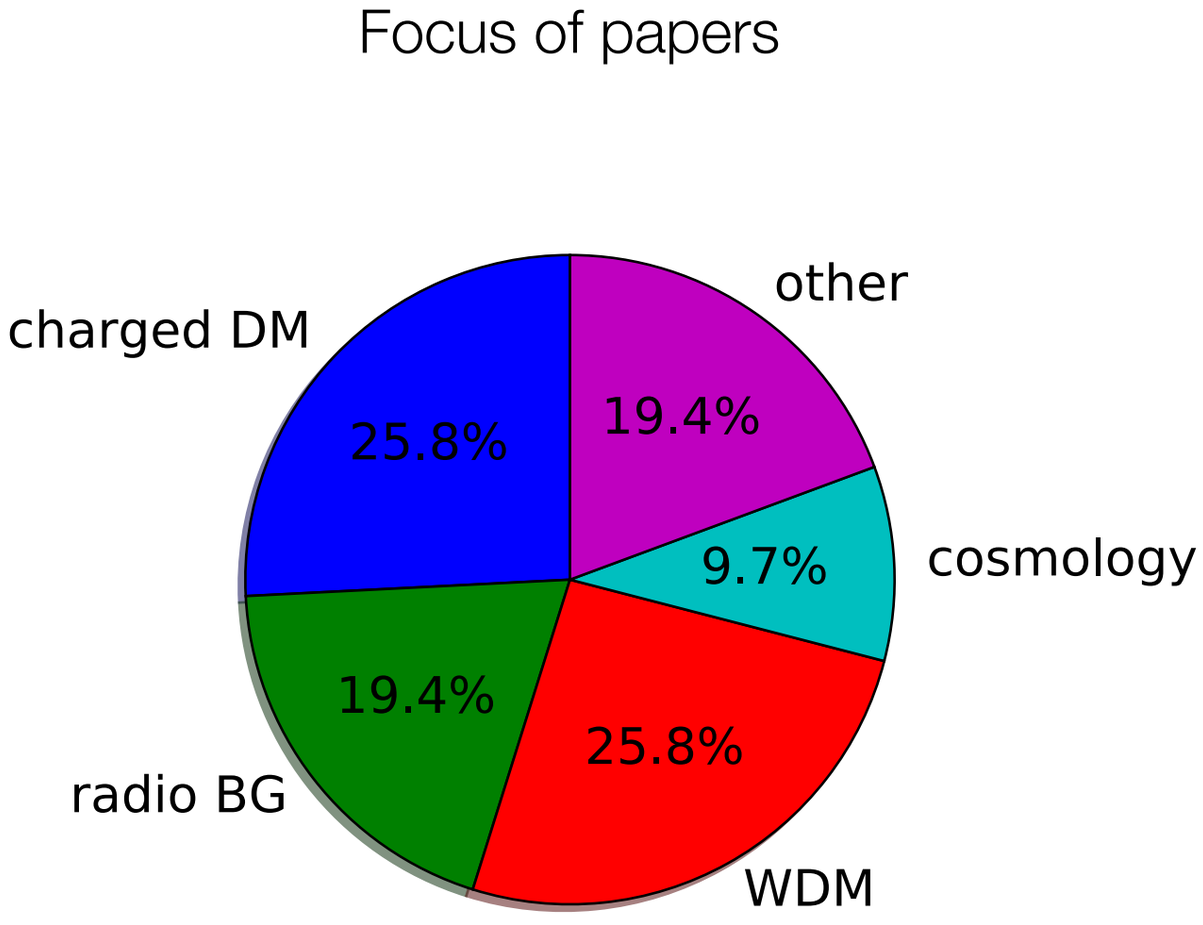
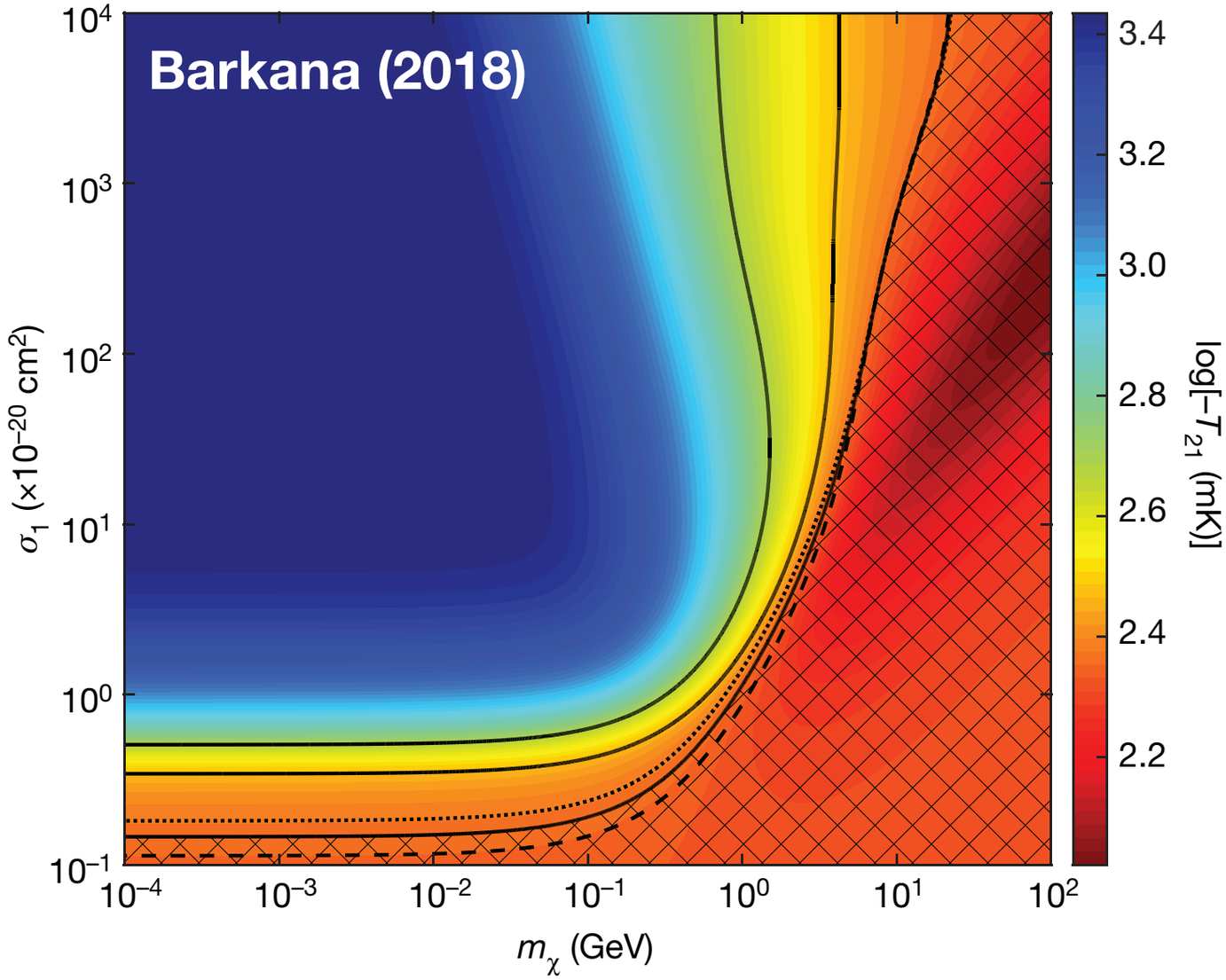
Responses to EDGES





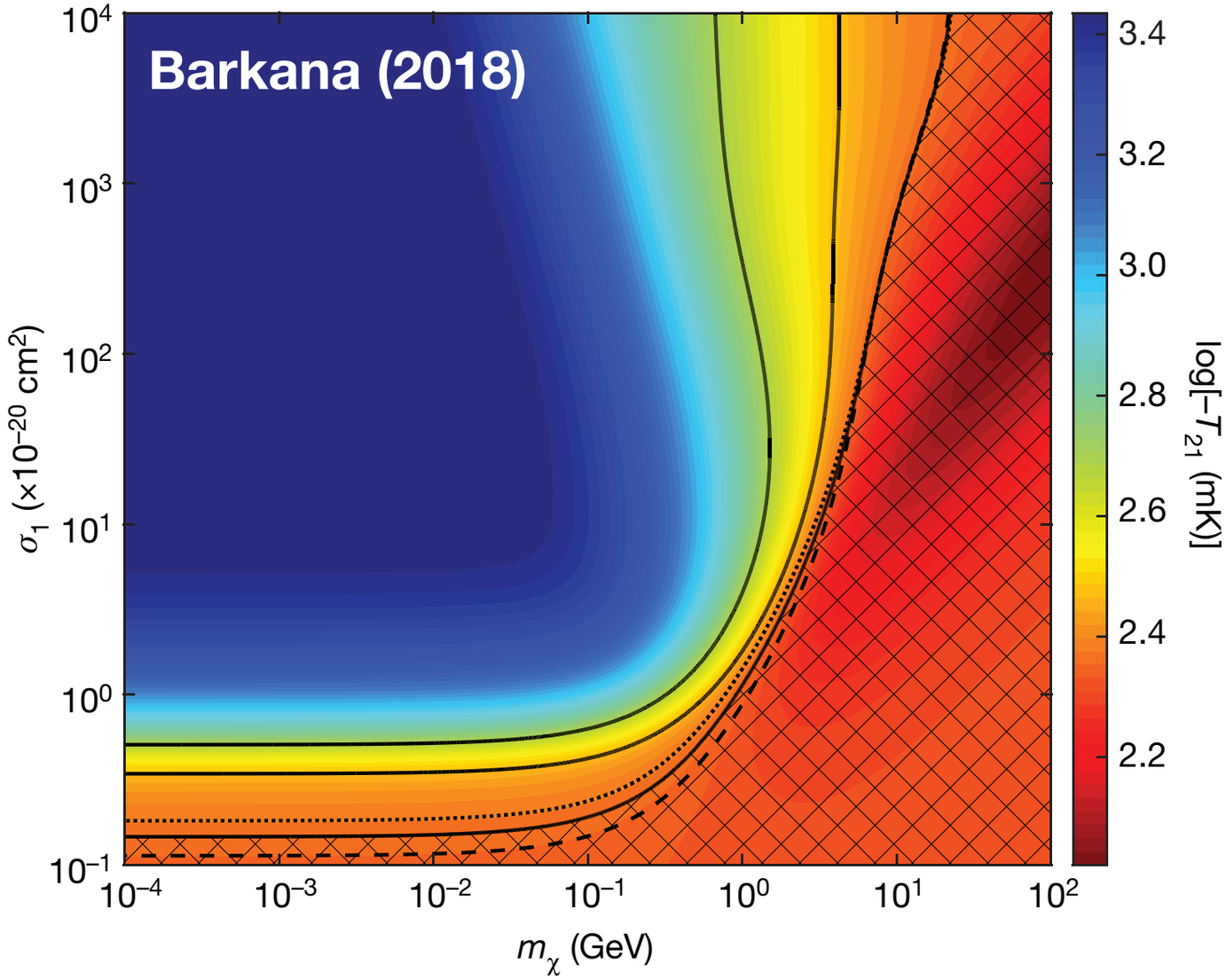
Includes explanations for signal amplitude and use of its timing to constrain WDM.

DM as a coolant



DM as a coolant

- Initial suggestion of milli-charged DM from Barkana (2018).



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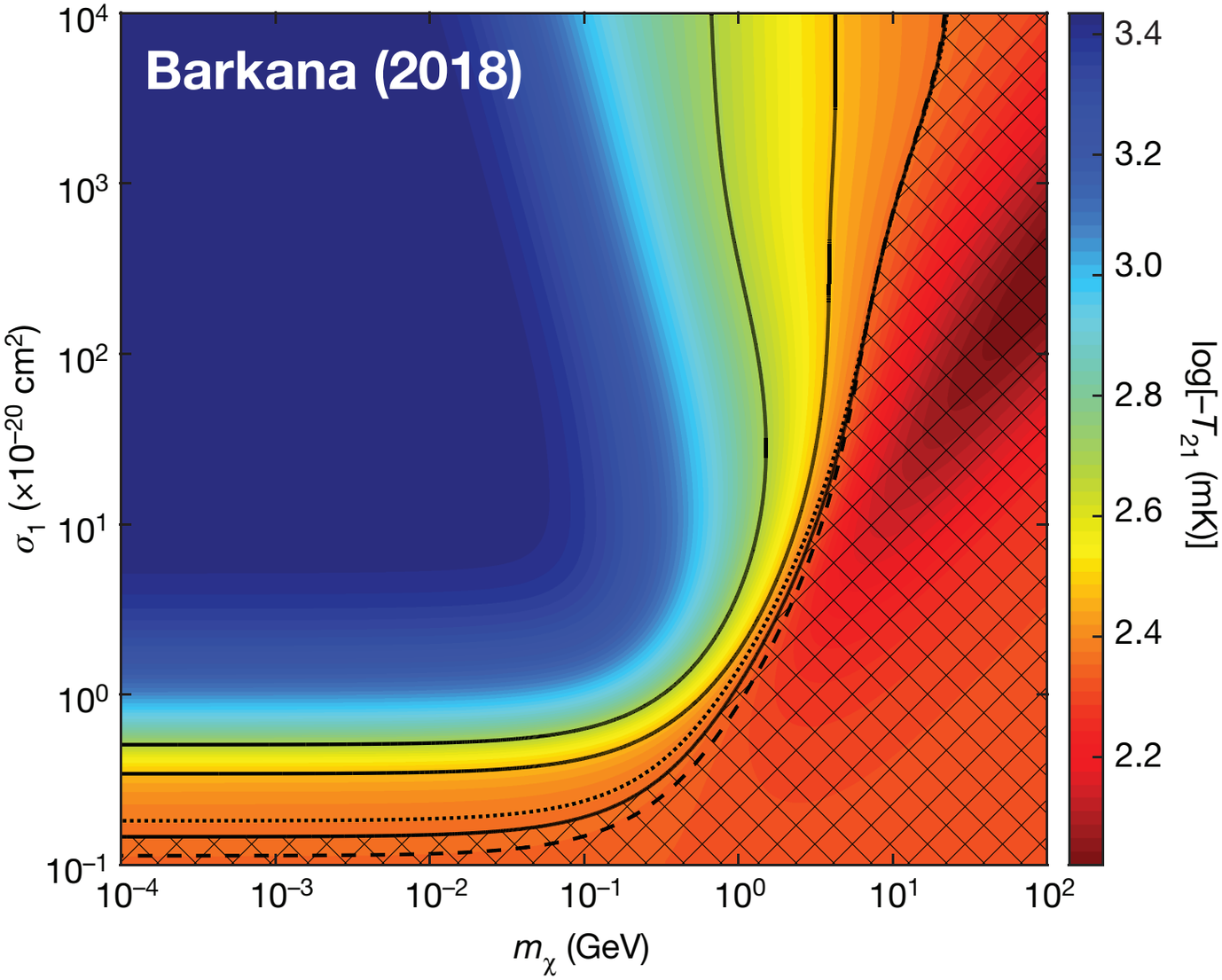

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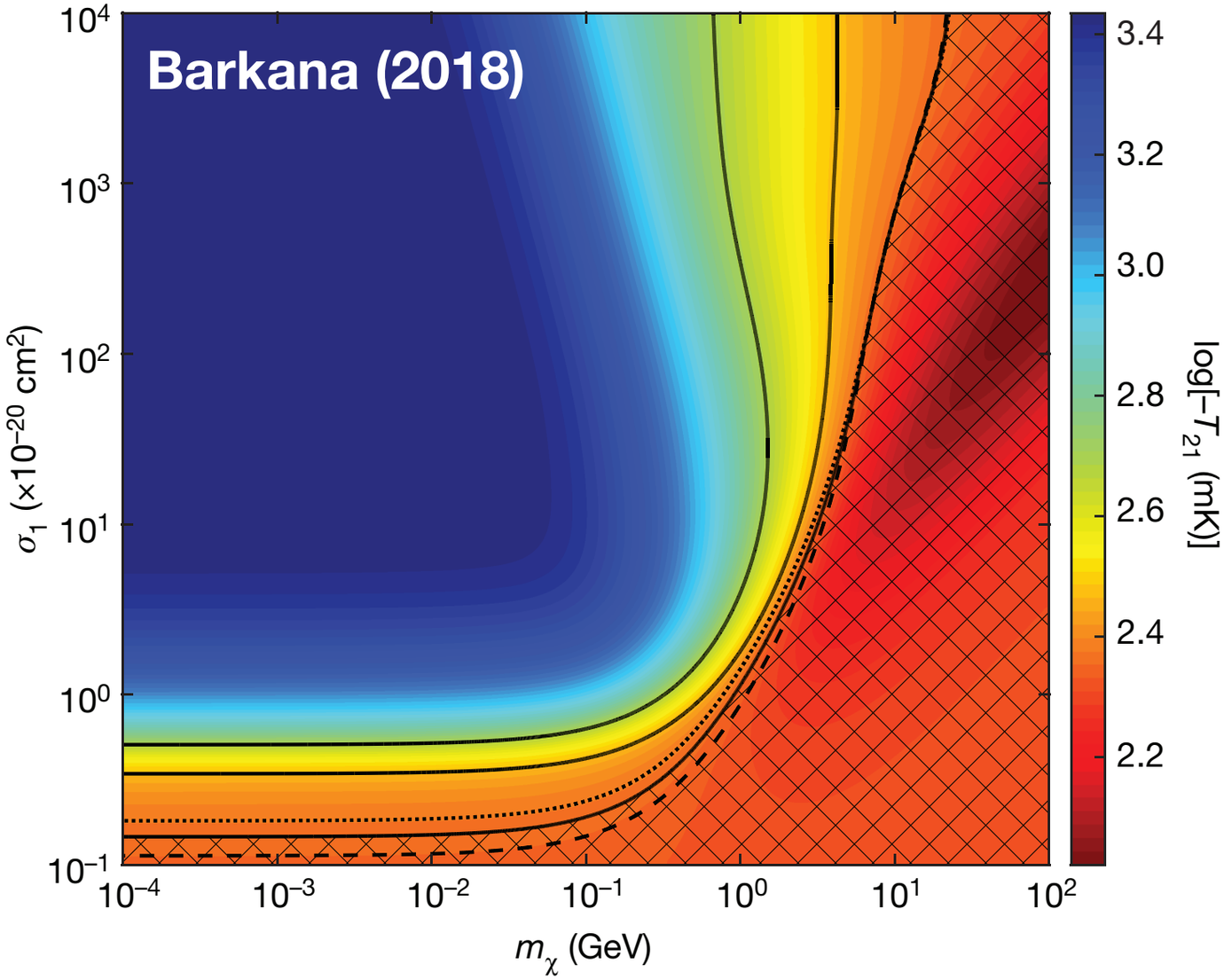
- Revision to $f_{DM} \sim 0.01$ by Berlin et al. (2018).



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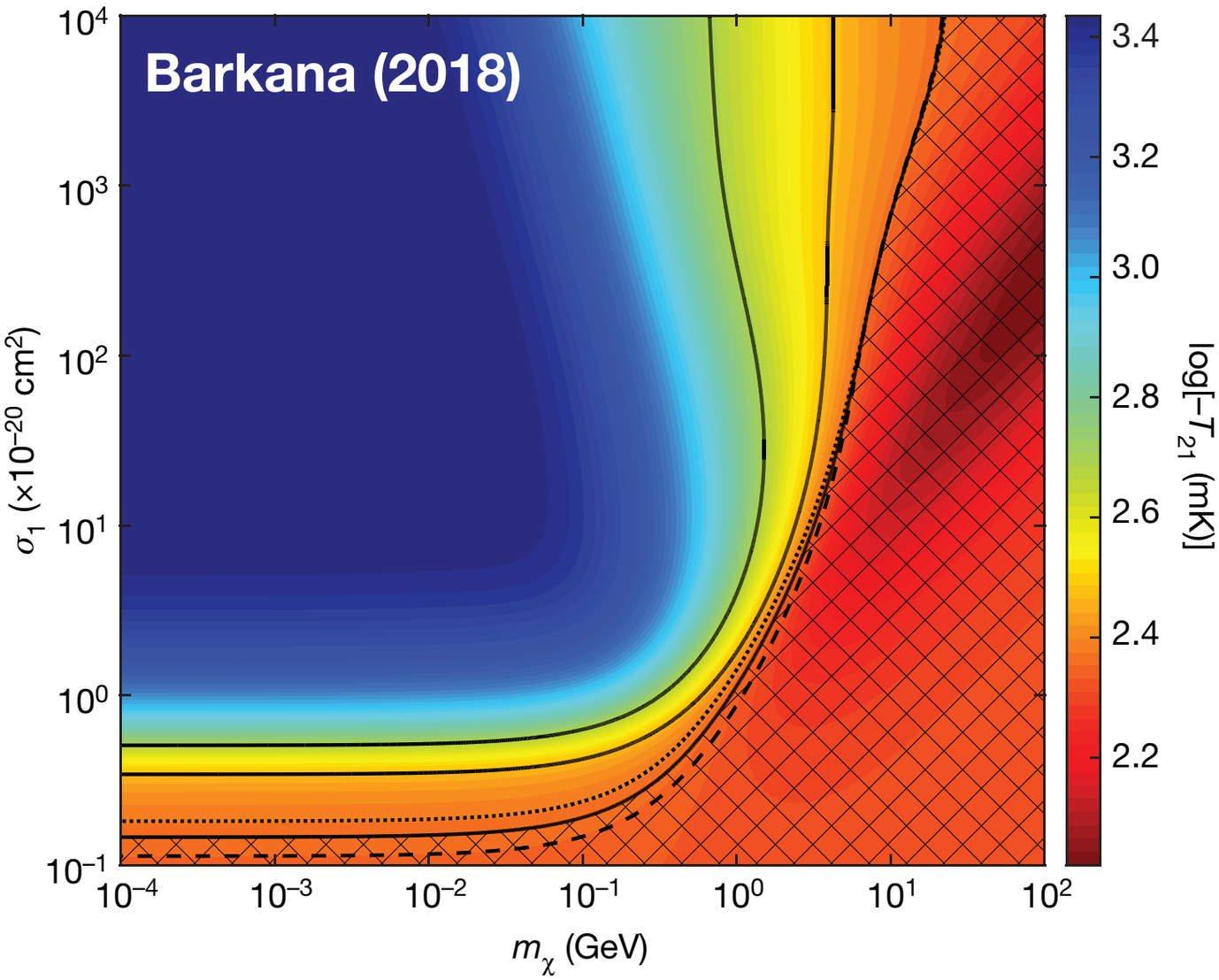
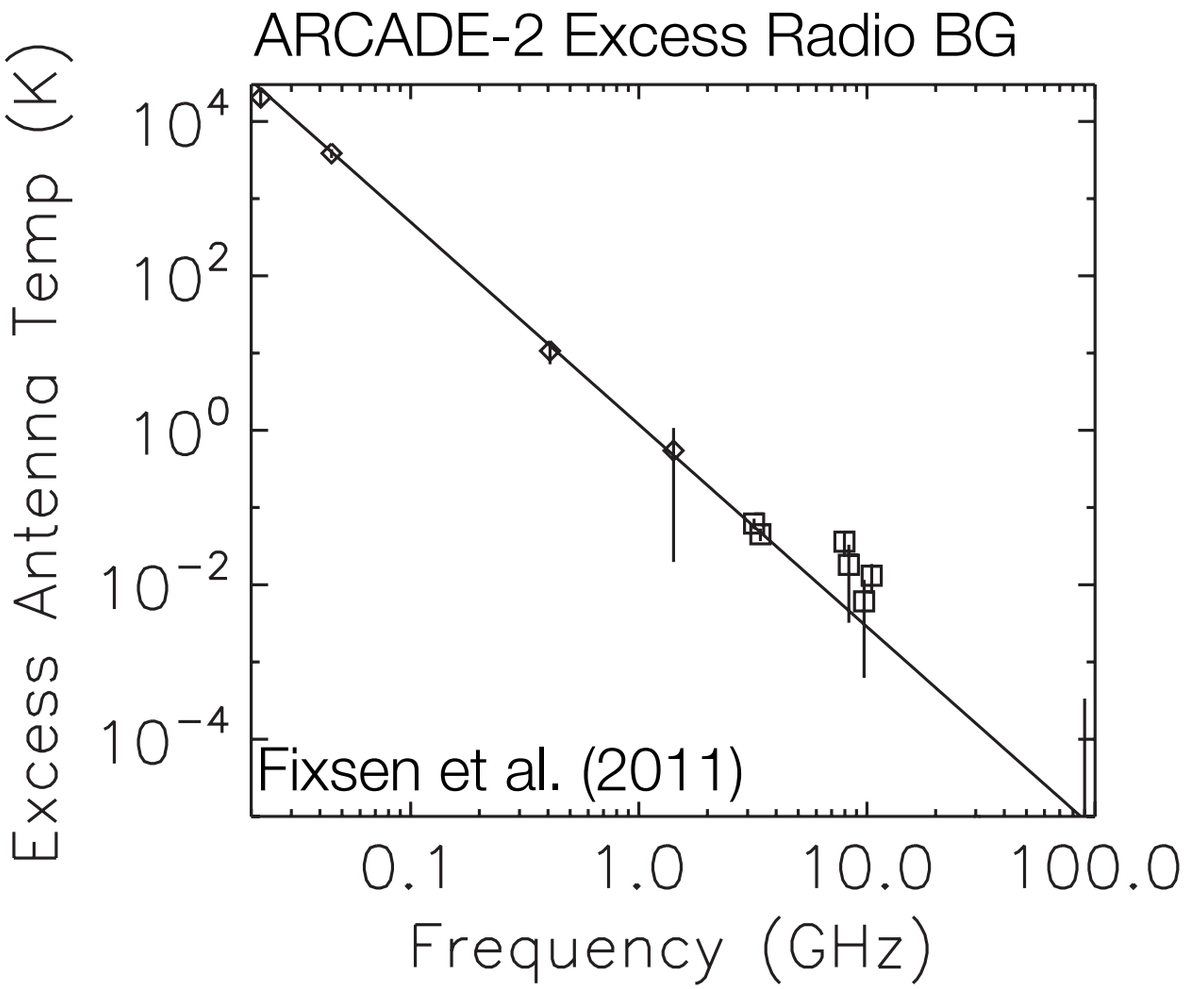
- Revision to $f_{DM} \sim 0.01$ by Berlin et al. (2018).
- See talk by Vera Glusevic Friday re: CMB constraints on these models.



Alternative: non-CMB radio BG



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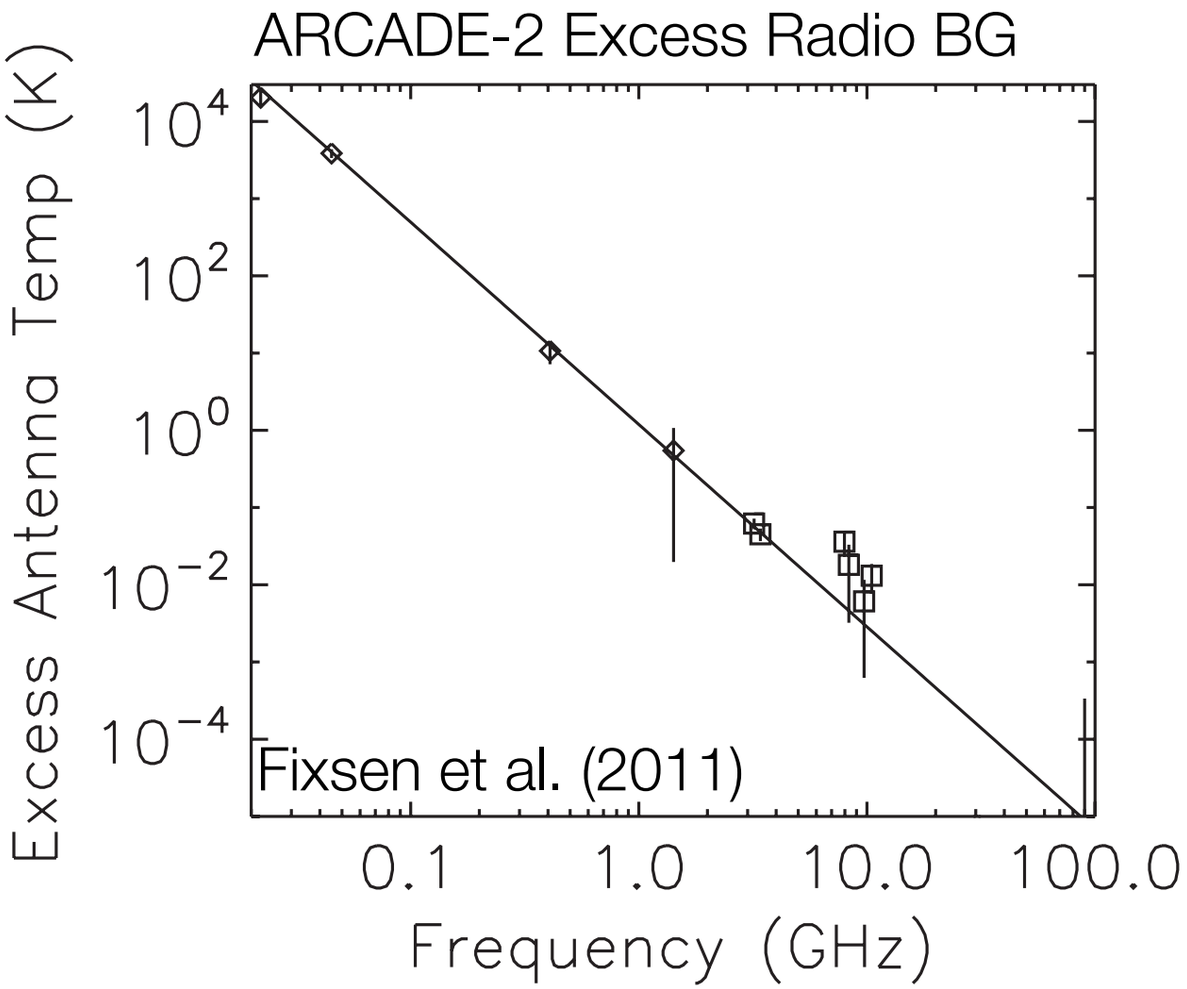

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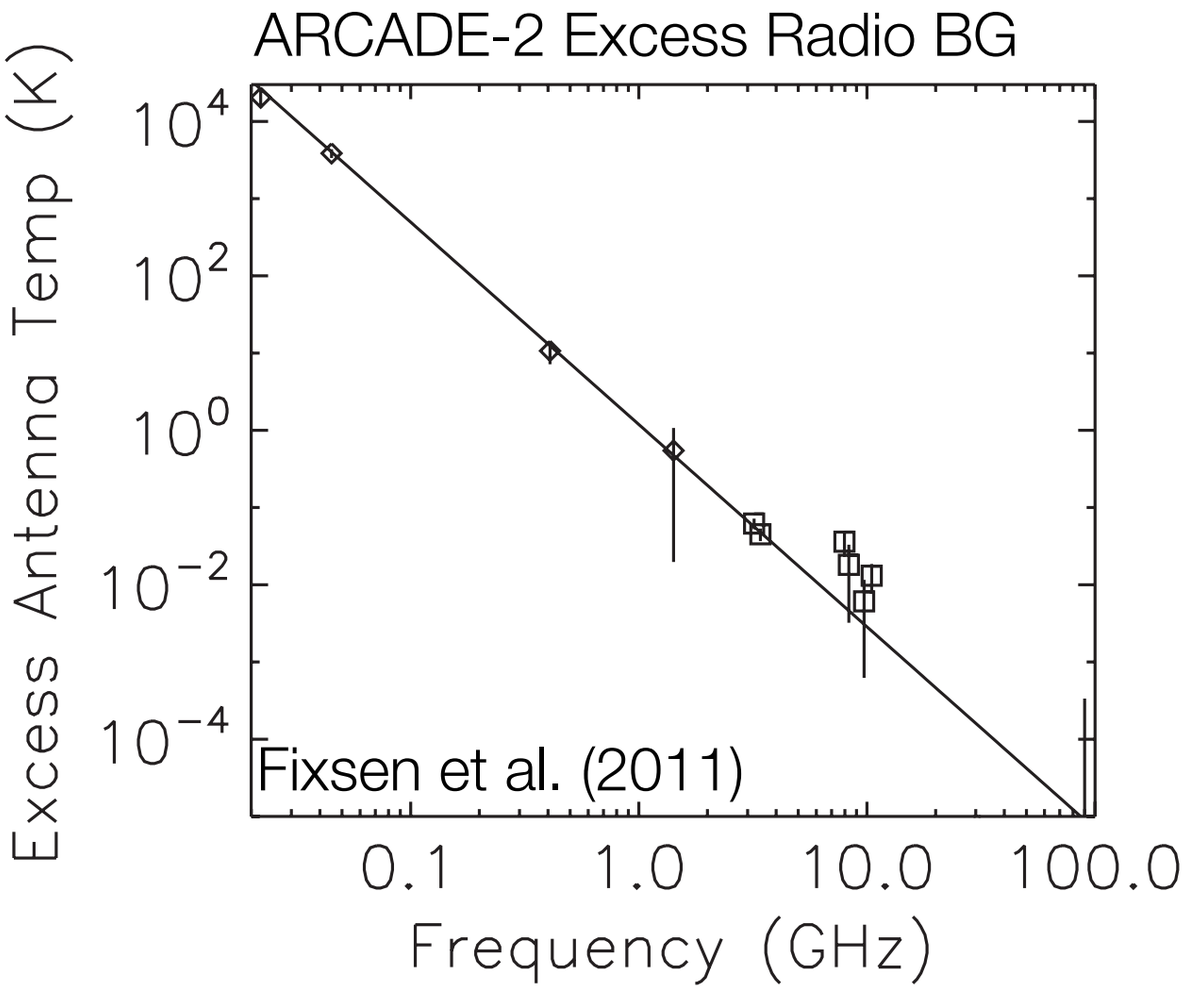

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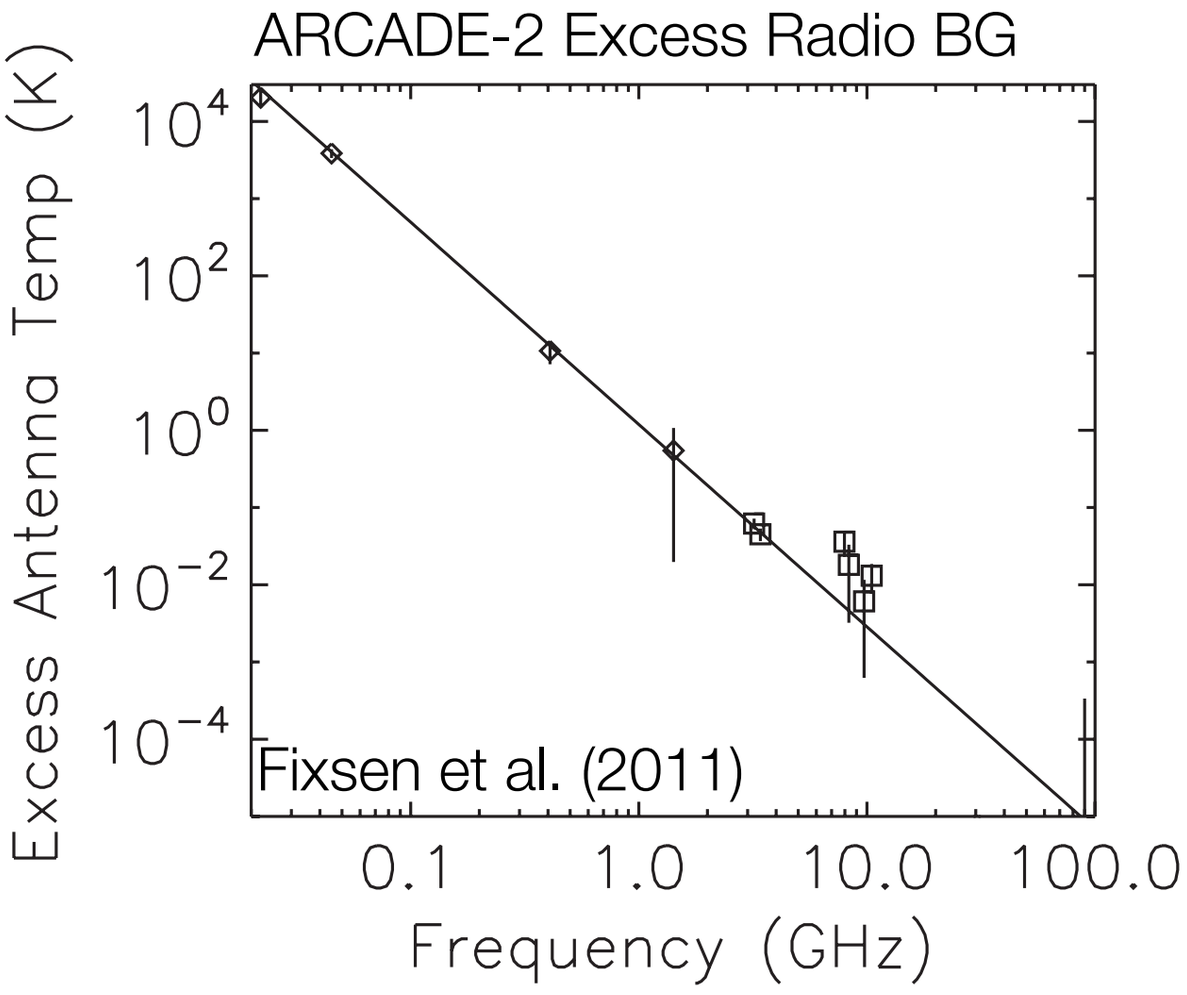

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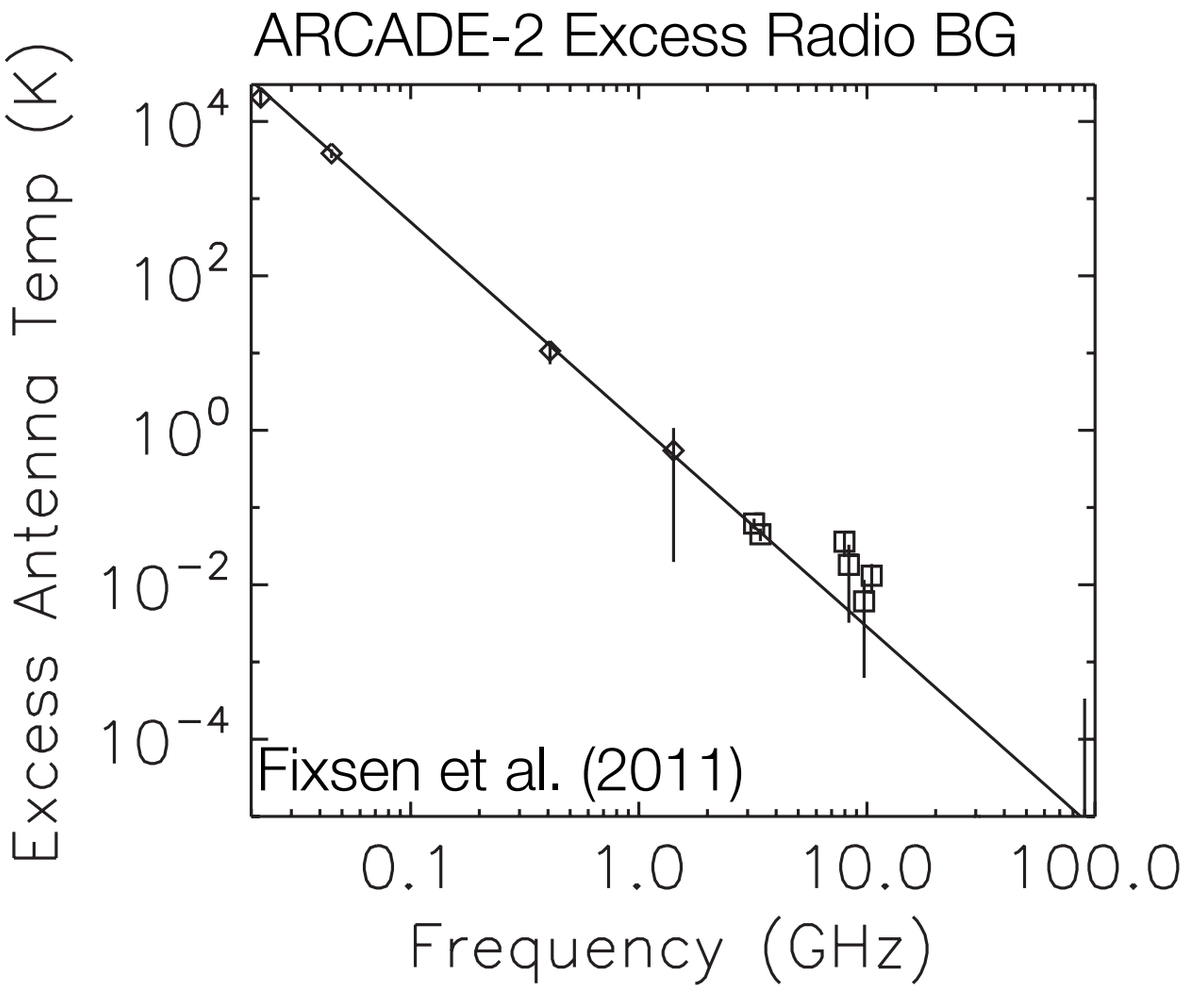

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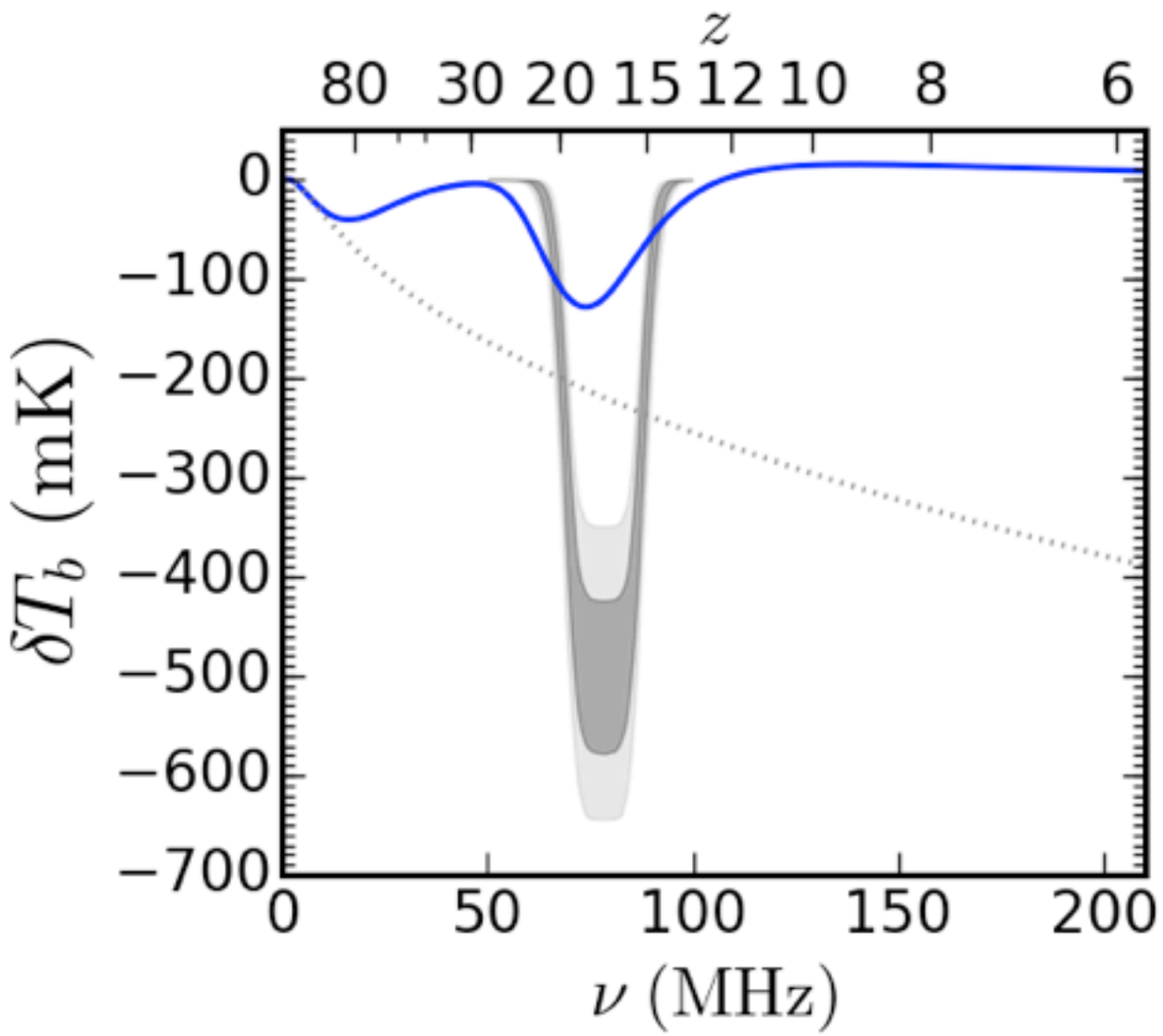
- If associated with star formation, require ~10^3x boost in low-frequency production efficiency per SFR (Mirocha & Furlanetto).

Part III:

New hints about galaxy formation as well?

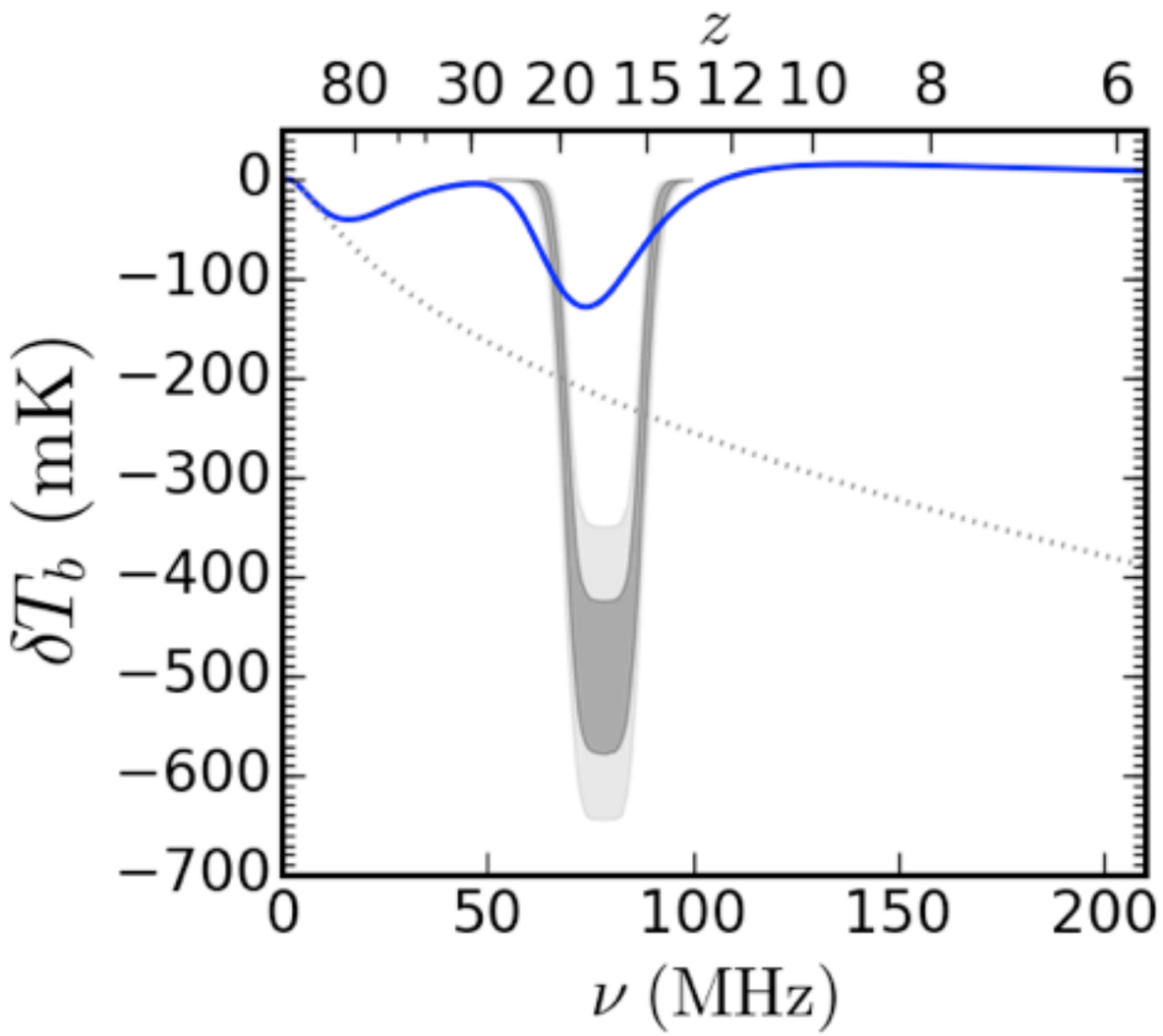
EDGES in Context



Mirocha & Furlanetto (2018), astro-ph/1803.03272

EDGES in Context

Assumes flat SFE



Mirocha & Furlanetto (2018), astro-ph/1803.03272

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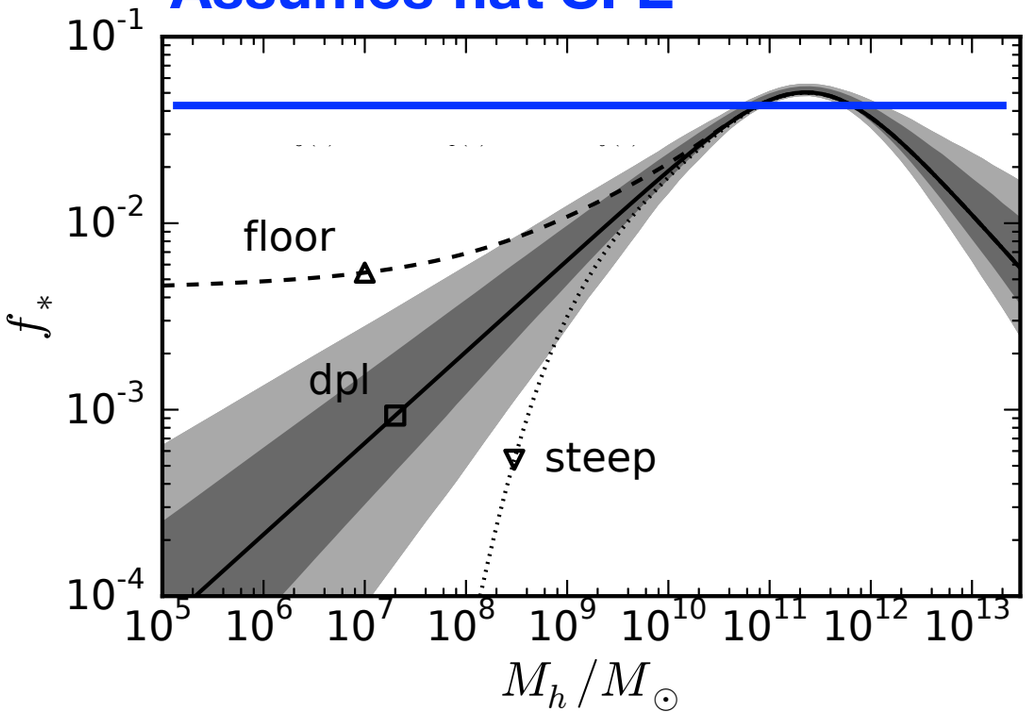
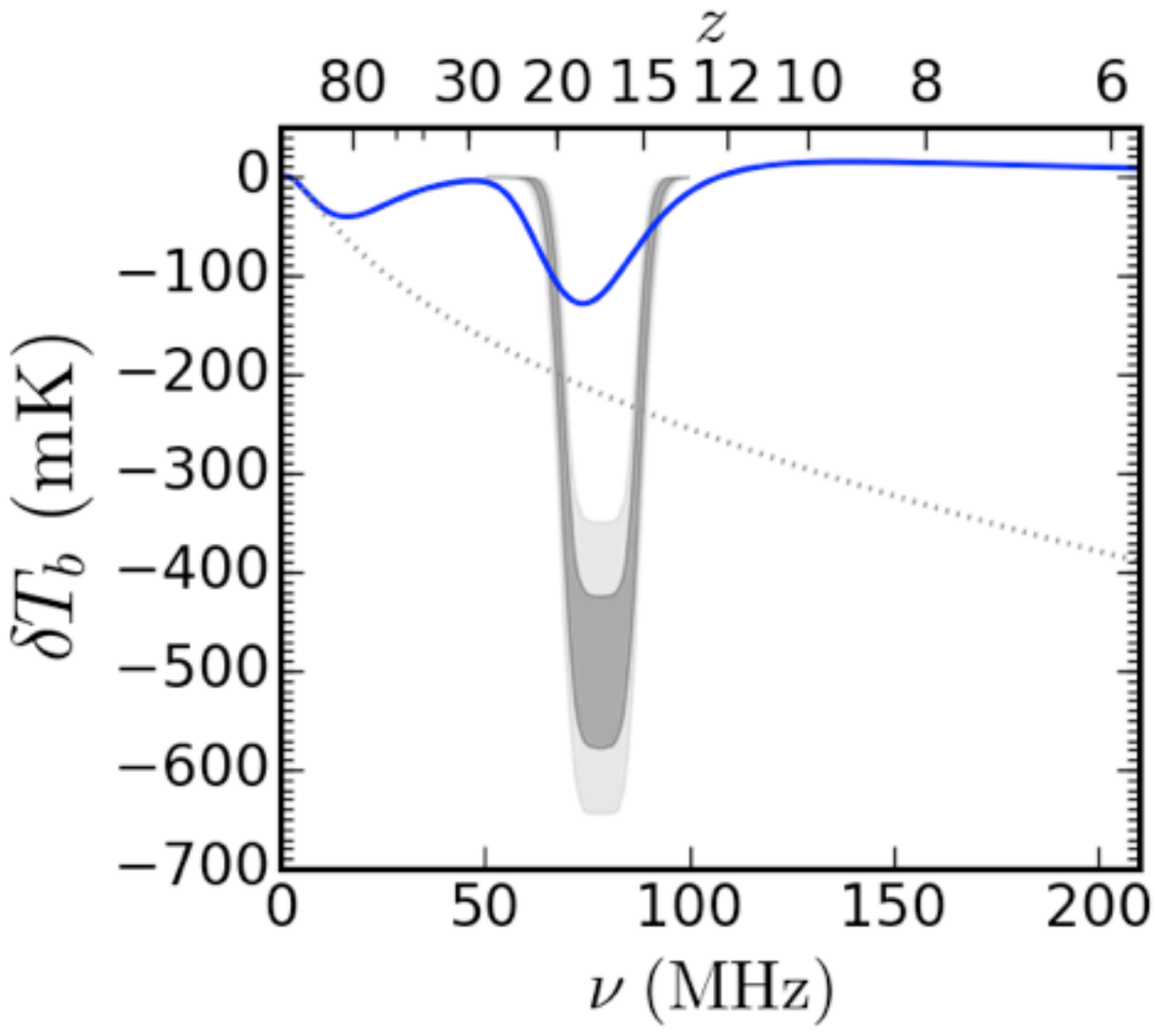
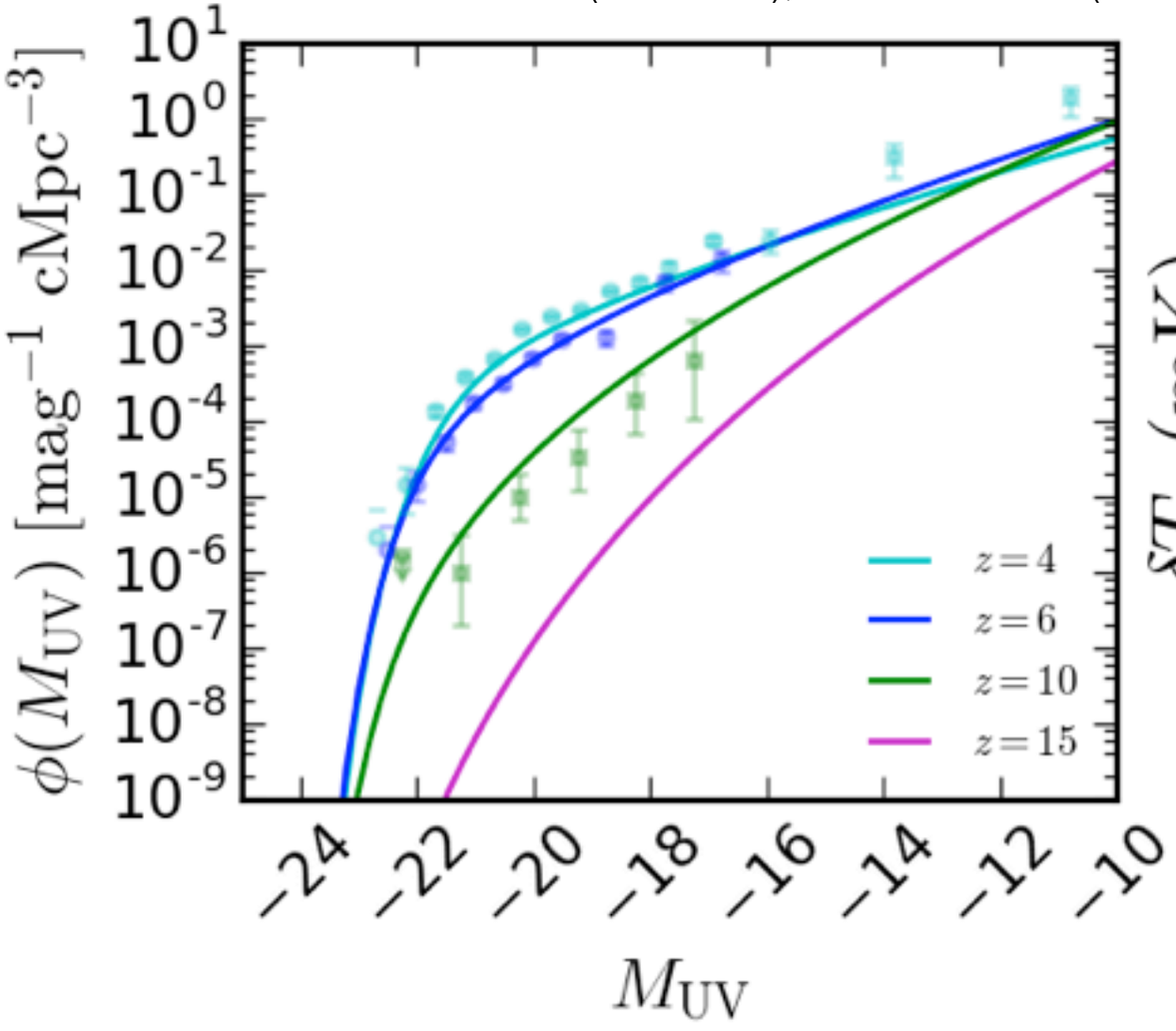


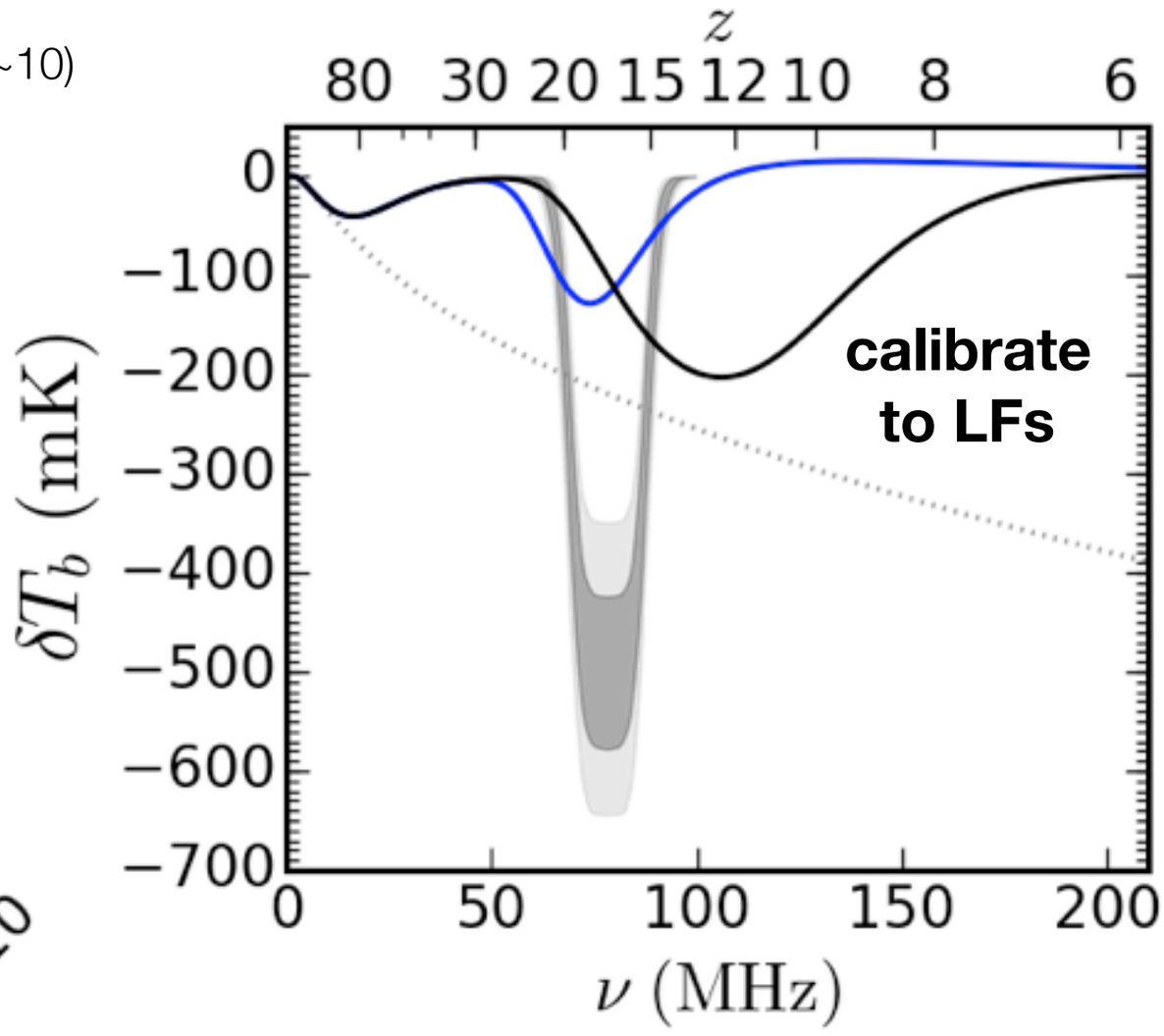


Mirocha & Furlanetto (2018), astro-ph/1803.03272

EDGES in Context

High-z galaxy luminosity functions from
Bouwens+ 2015 ($4 < z < 8$), Oesch+ 2018 ($z \sim 10$)





Mirocha, Furlanetto, & Sun (2017)

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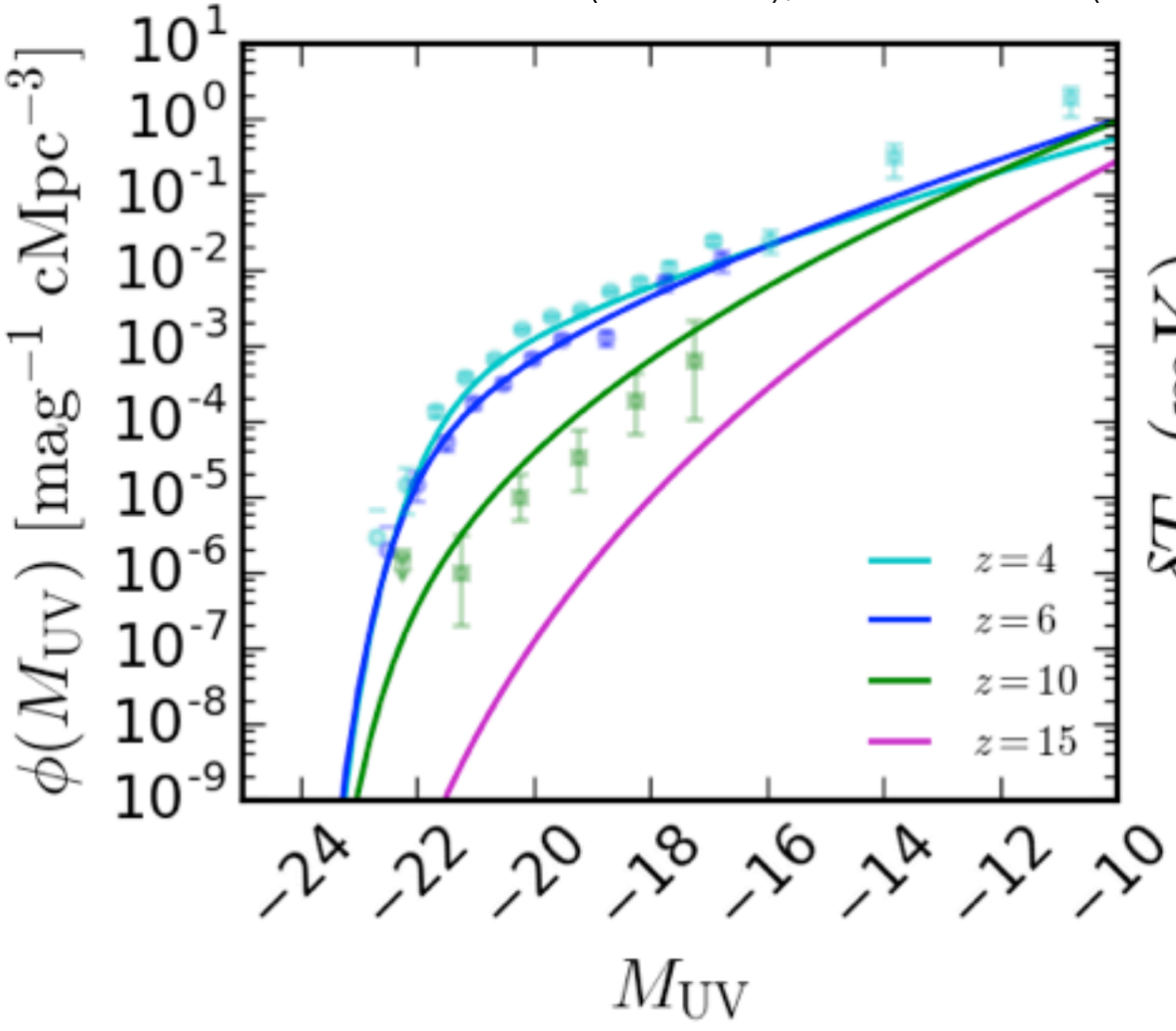

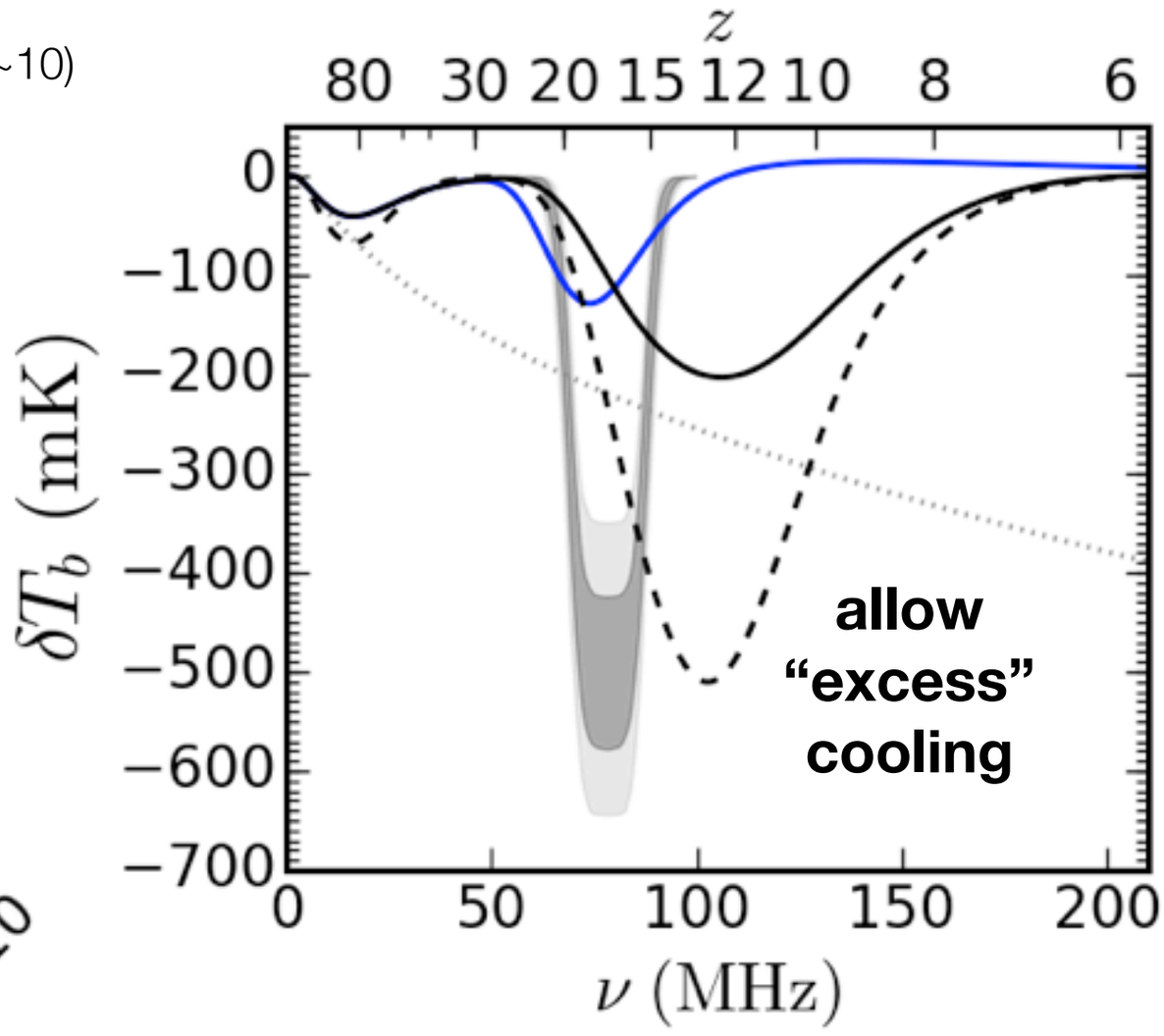

Mirocha & Furlanetto (2018), astro-ph/1803.03272

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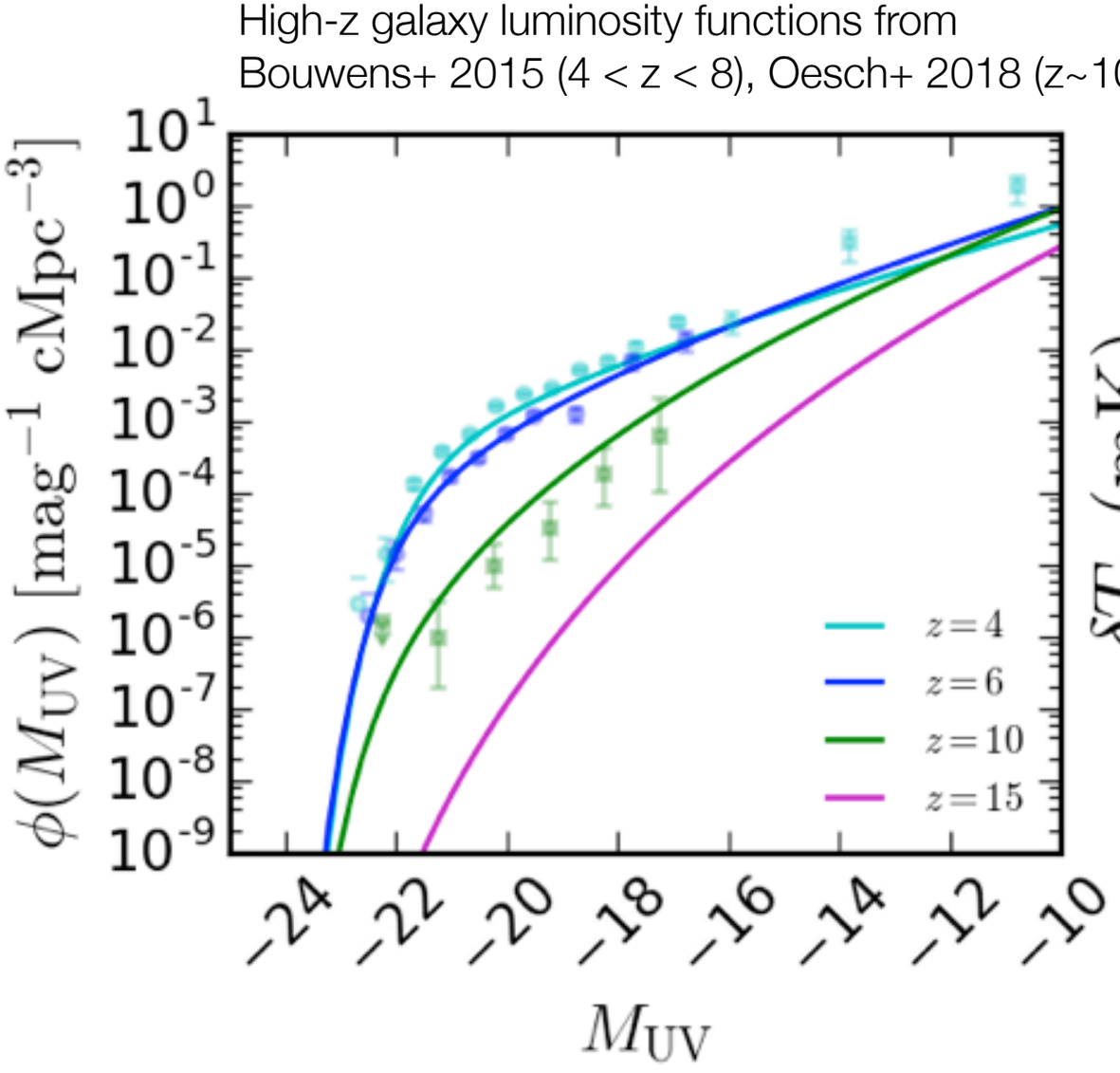
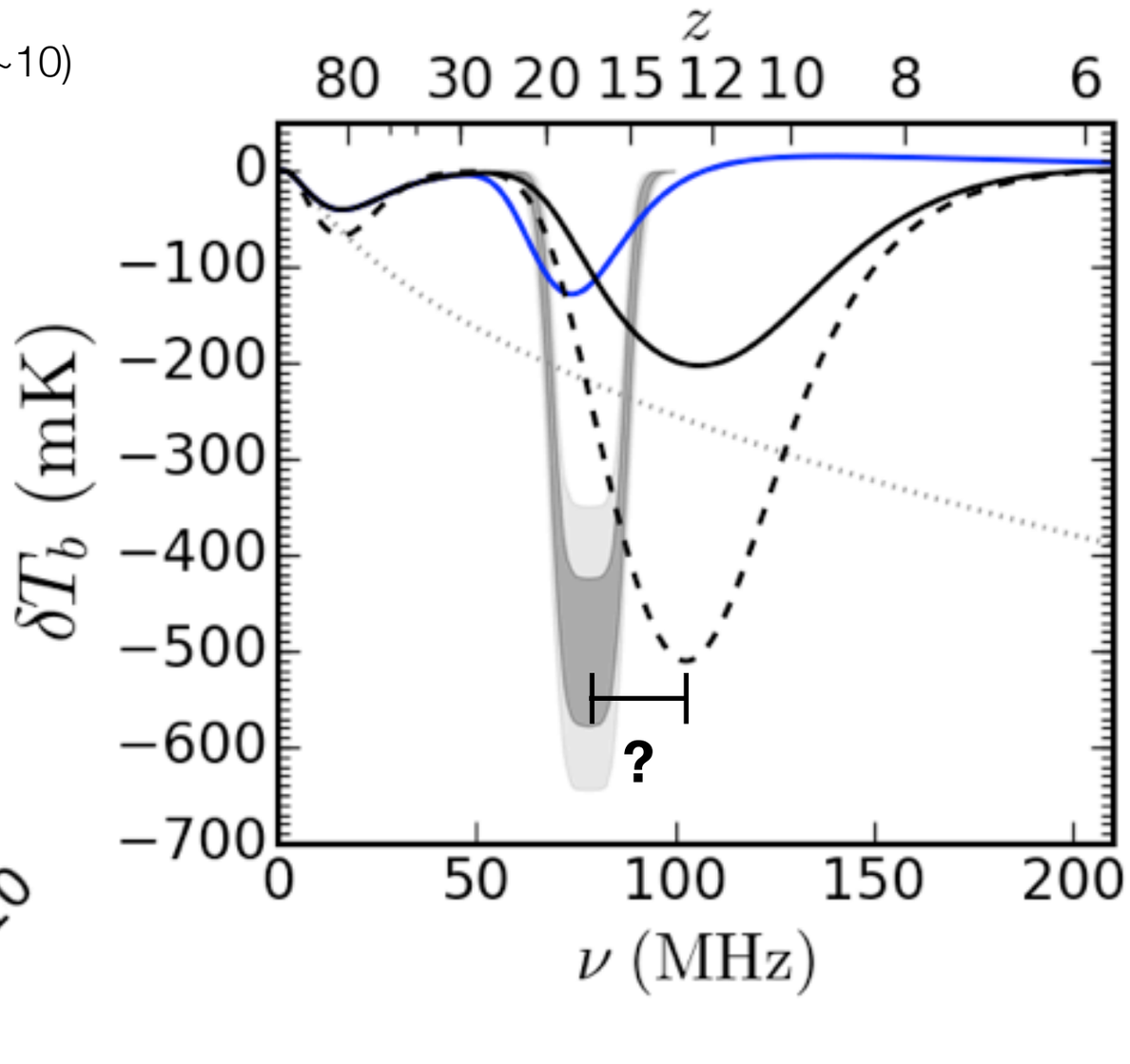
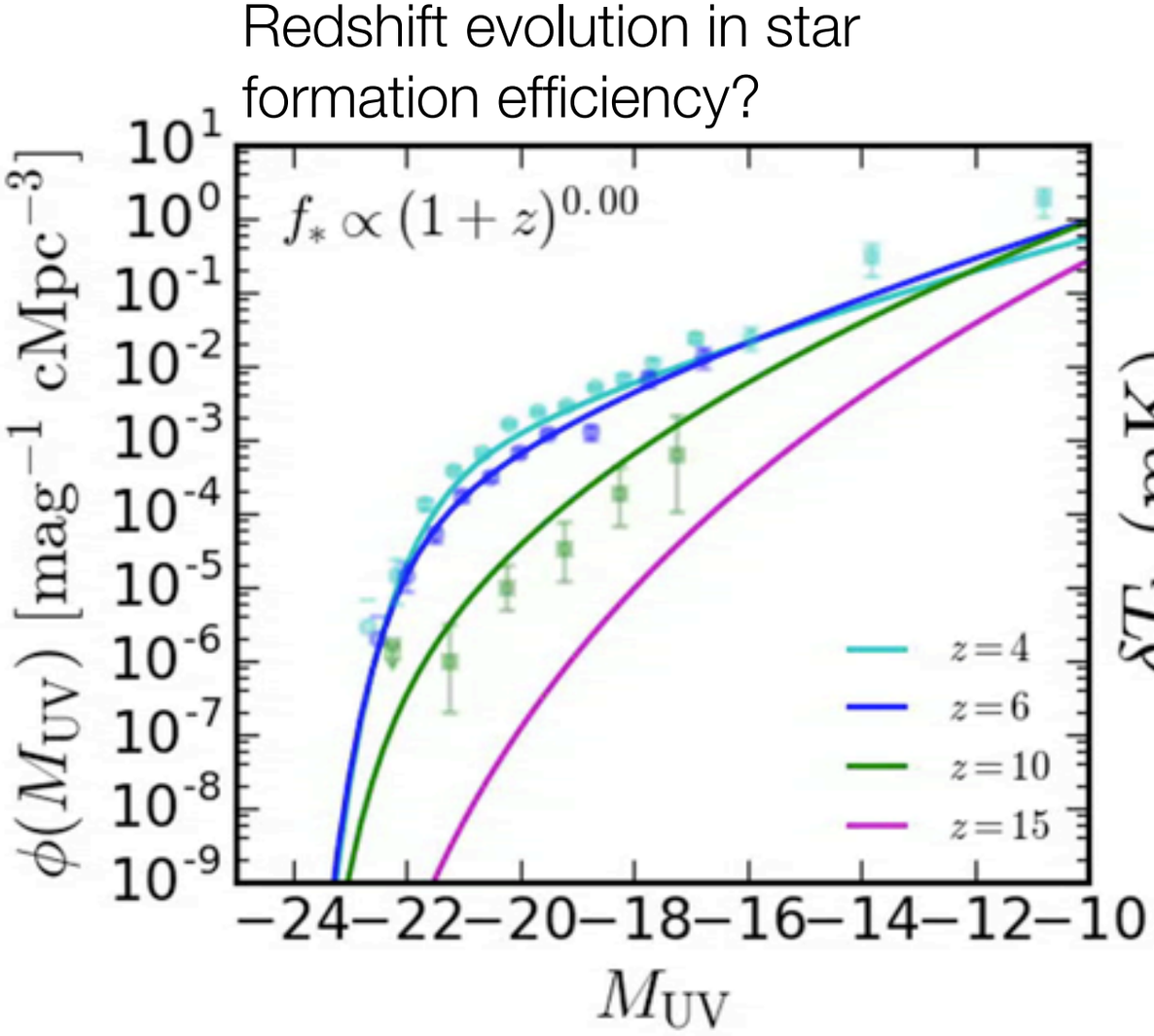


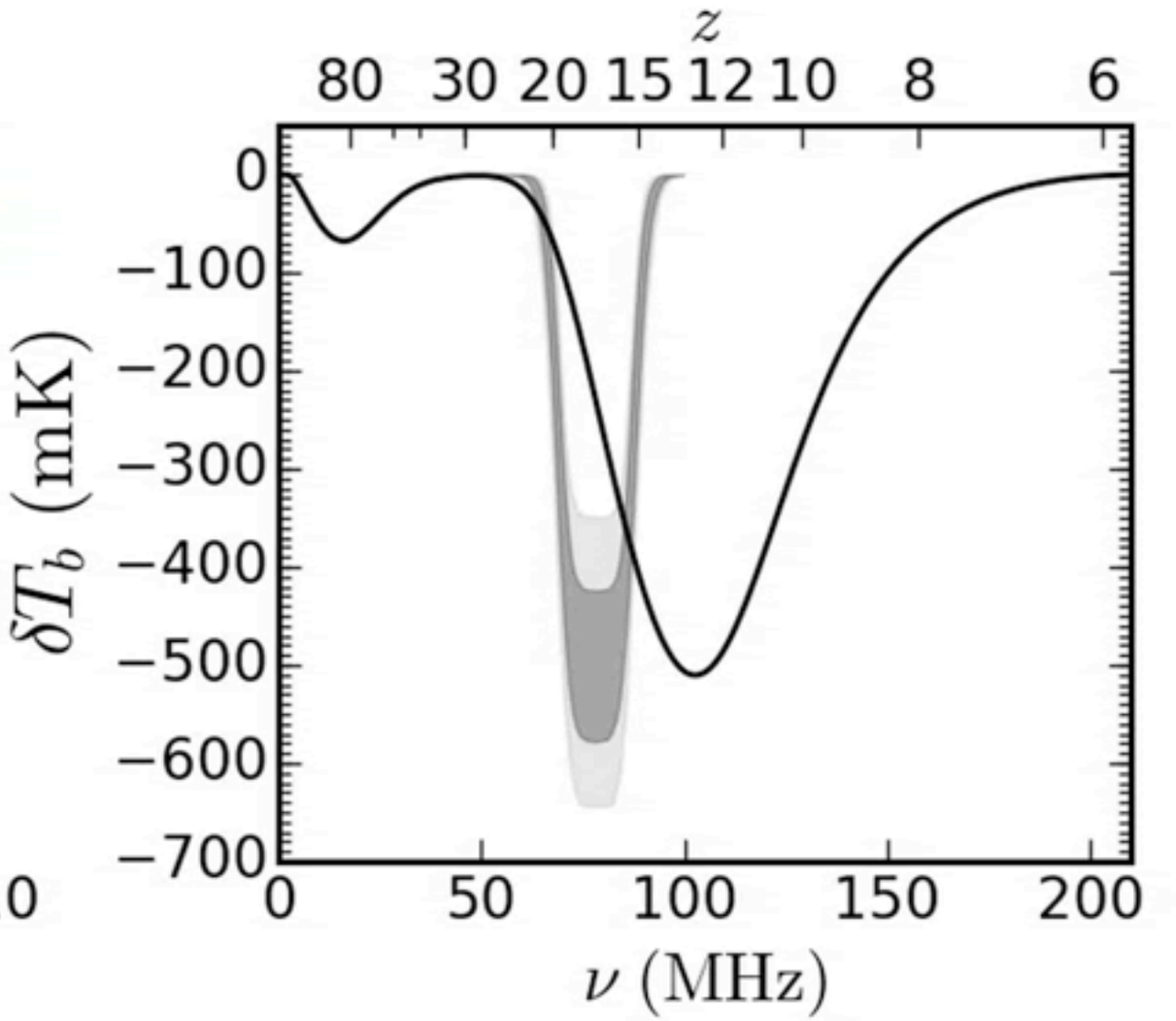


Mirocha & Furlanetto (2018), astro-ph/1803.03272

Getting to 80 MHz

Redshift evolution in star formation efficiency?





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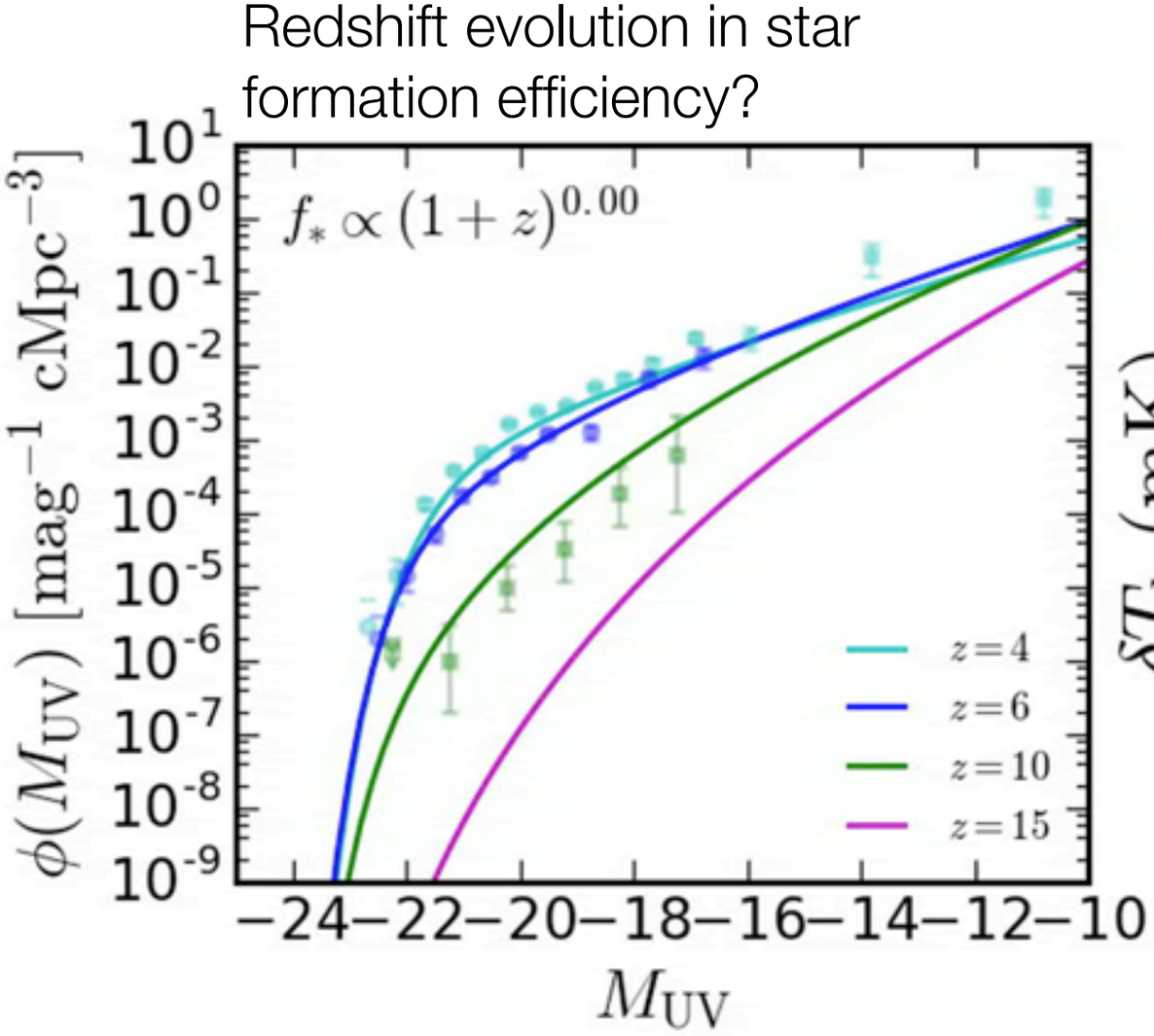

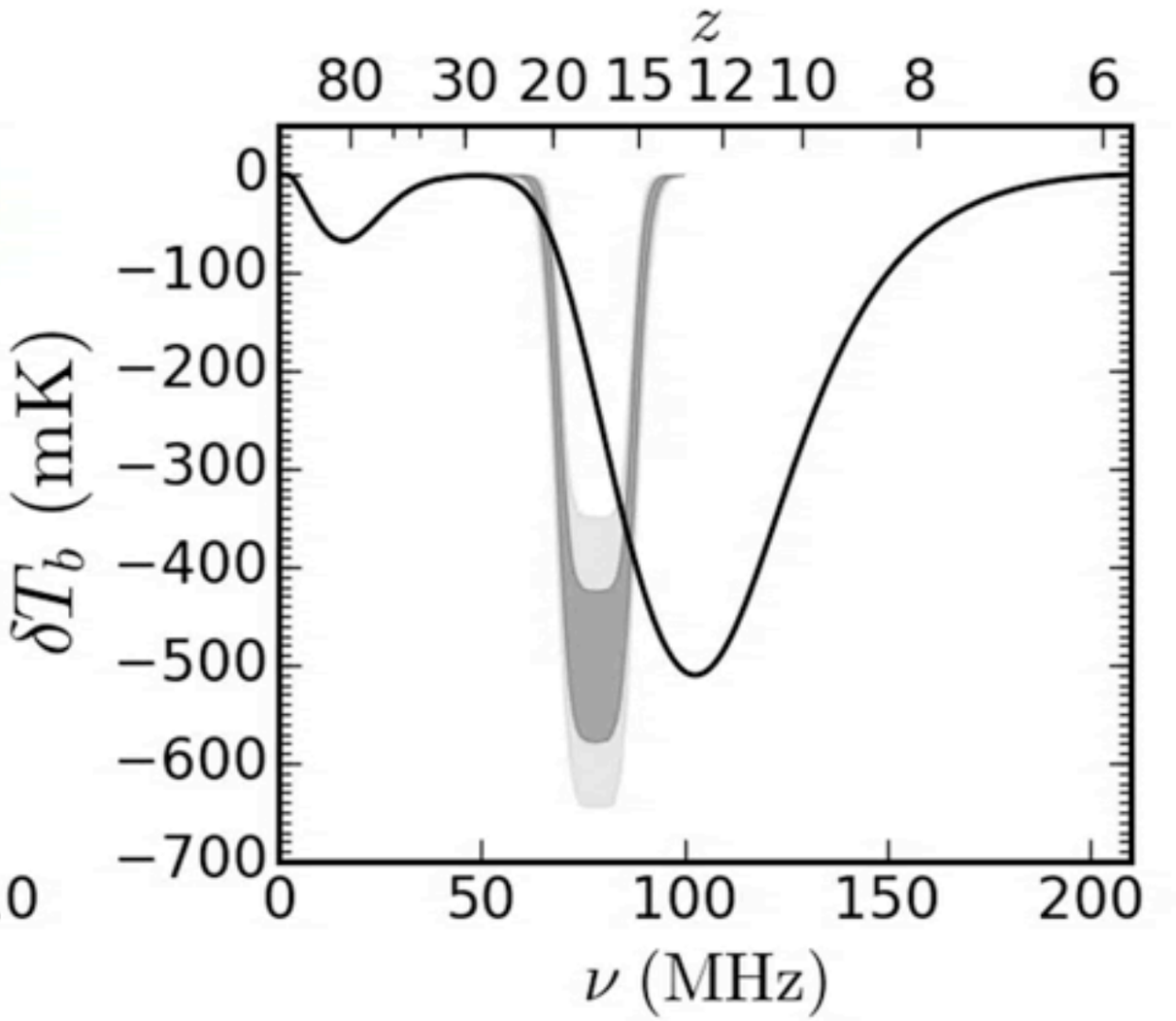

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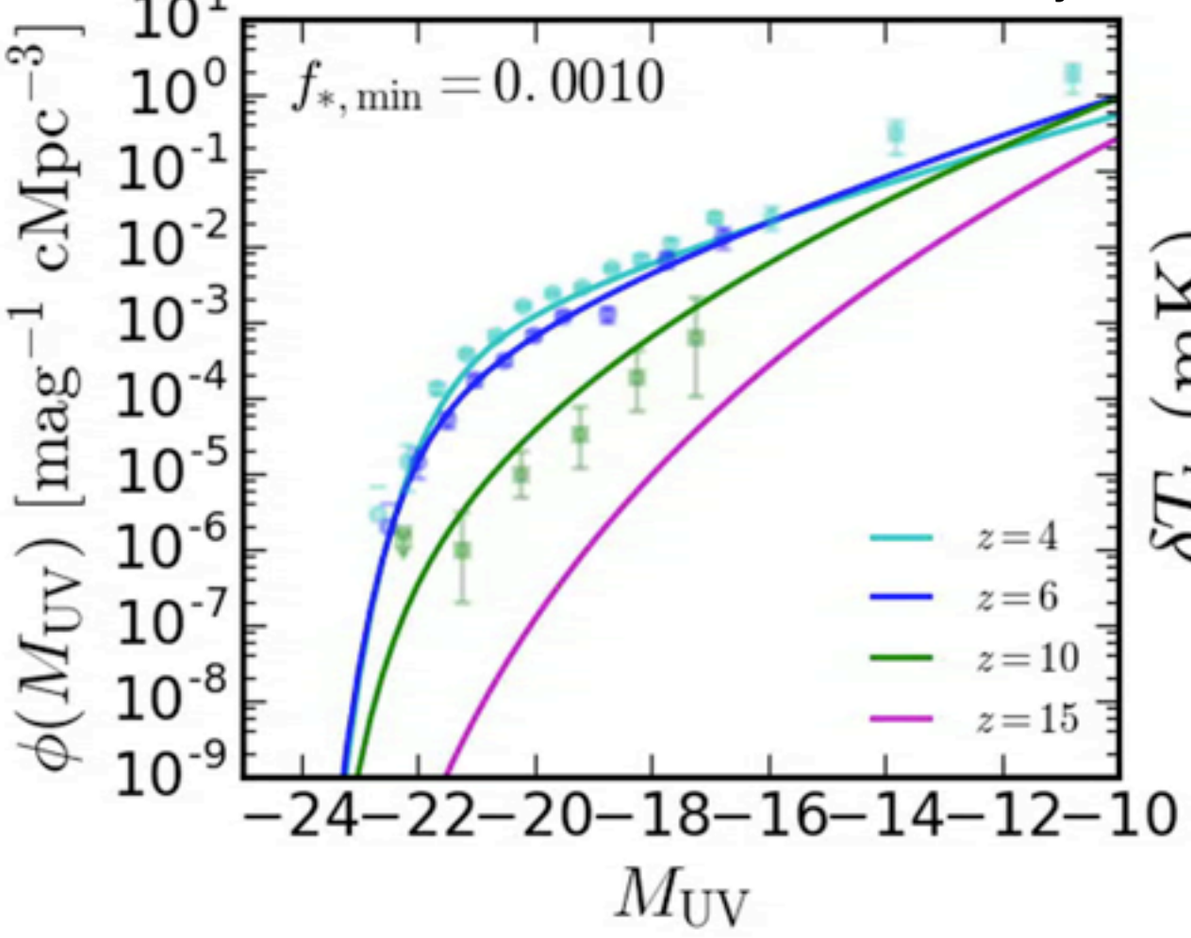

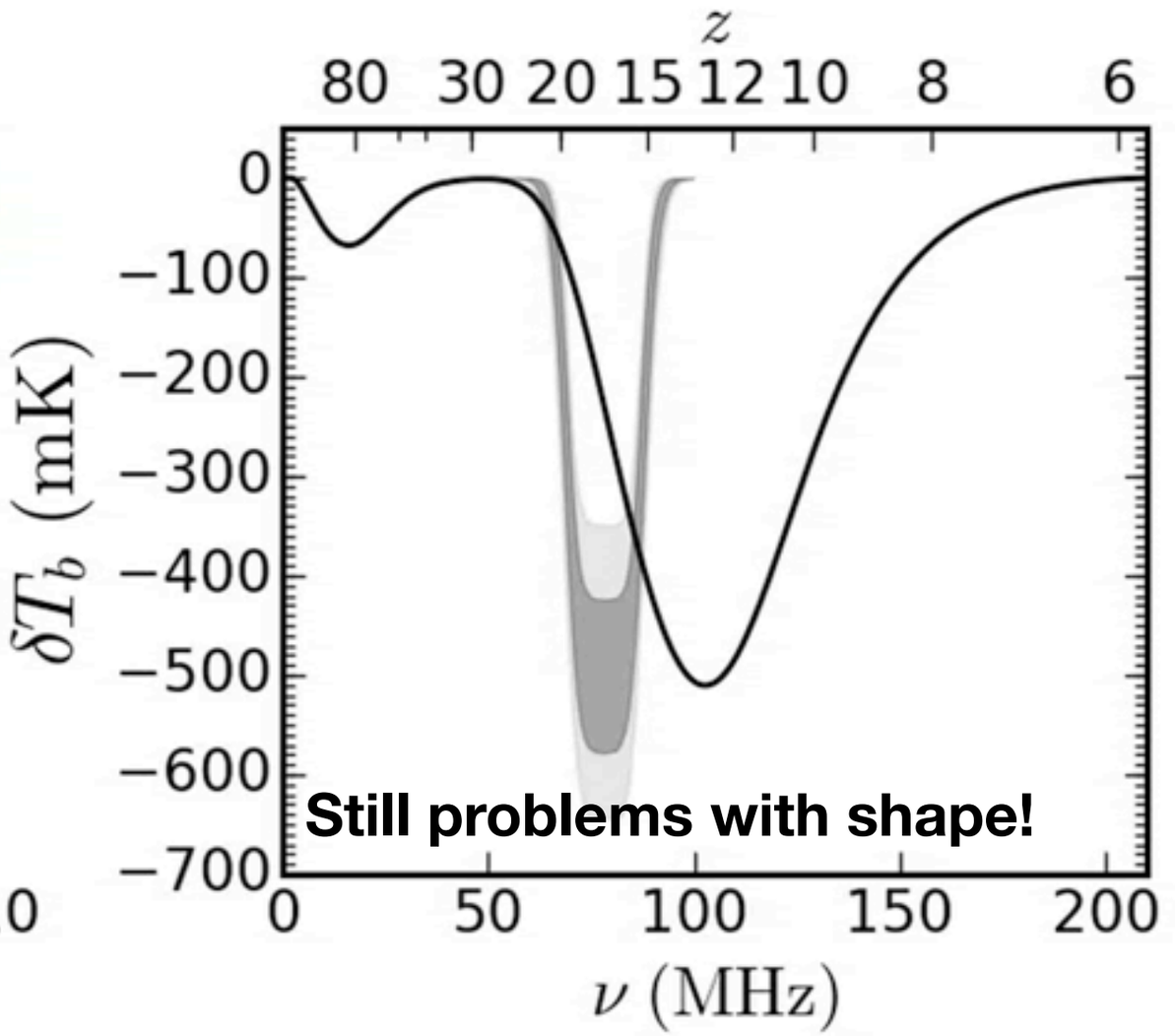

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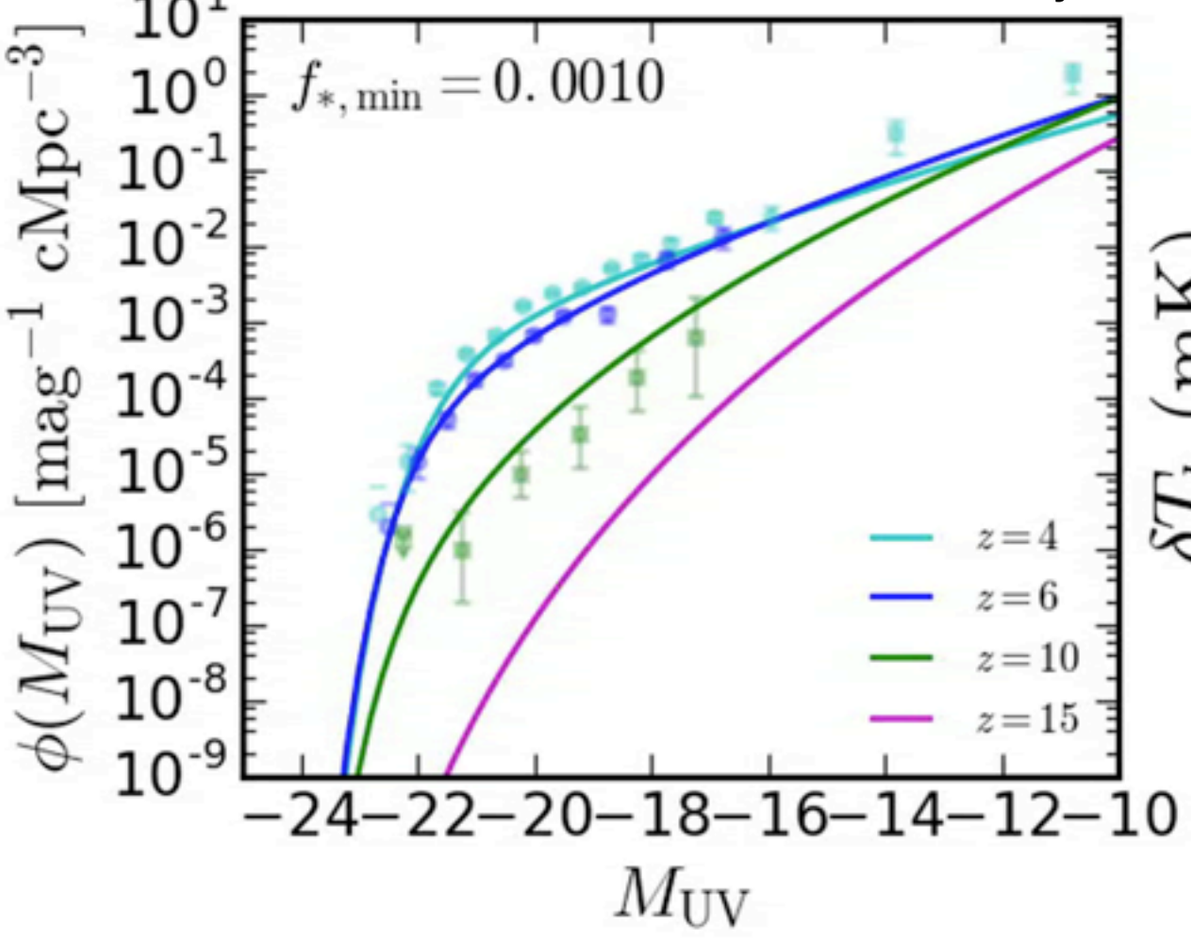

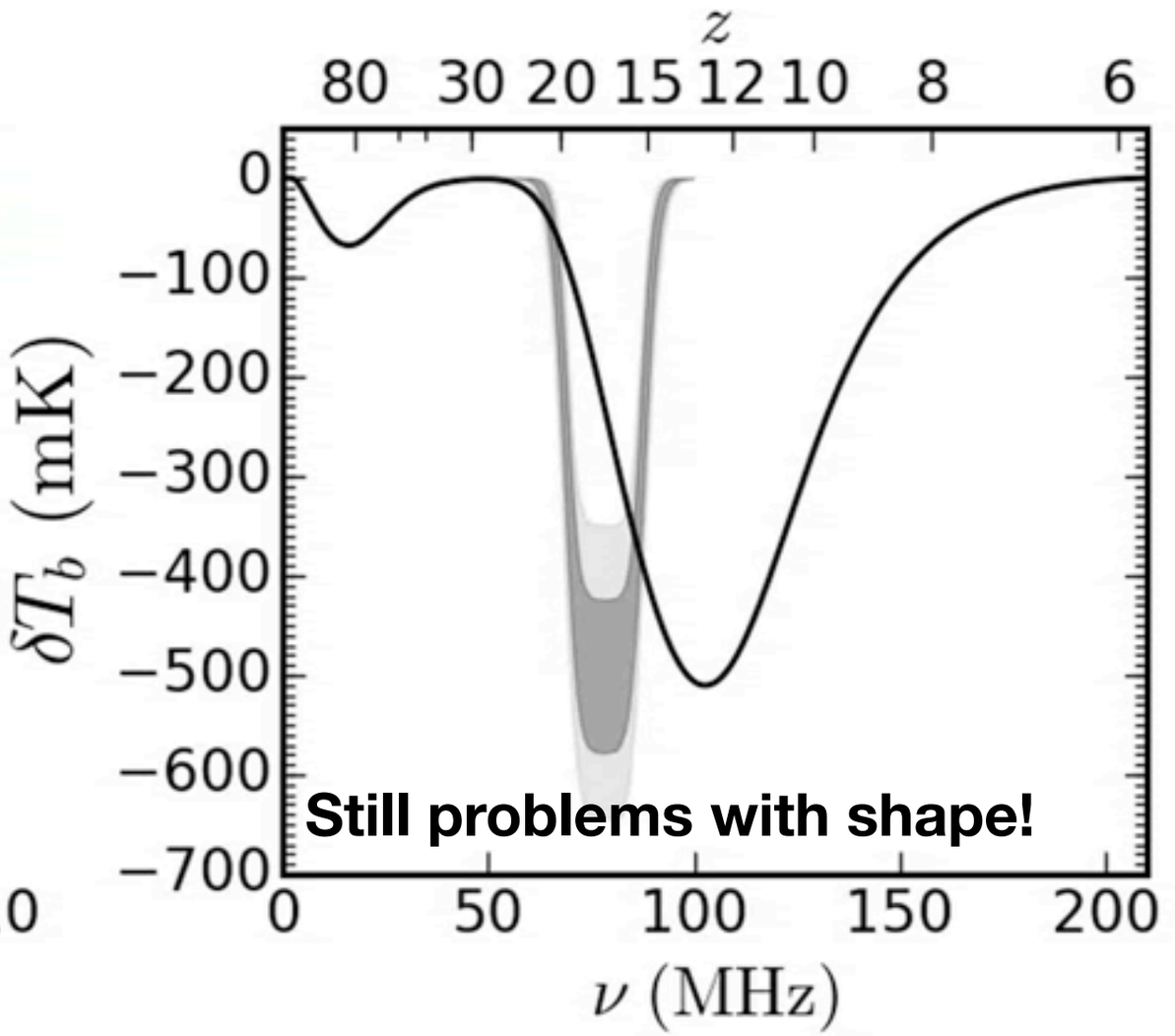

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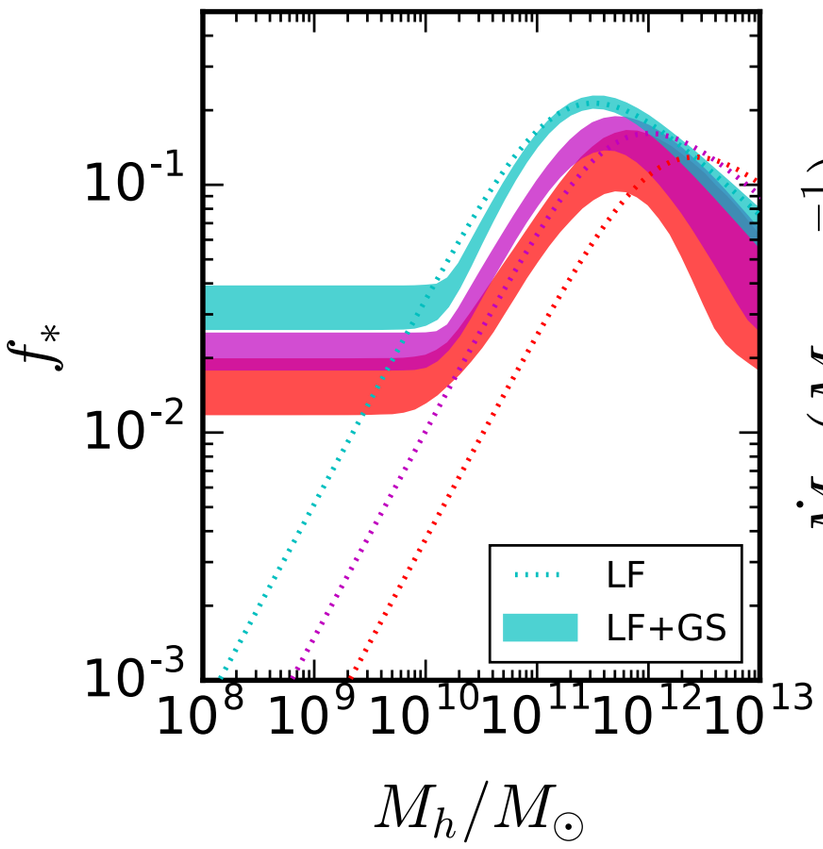
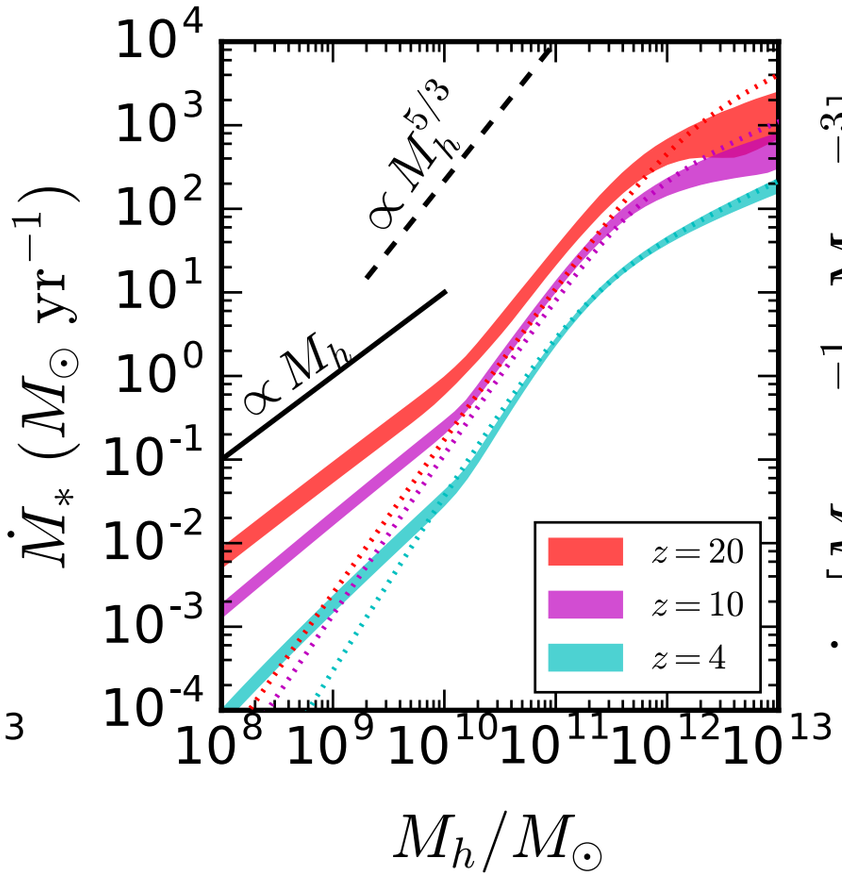
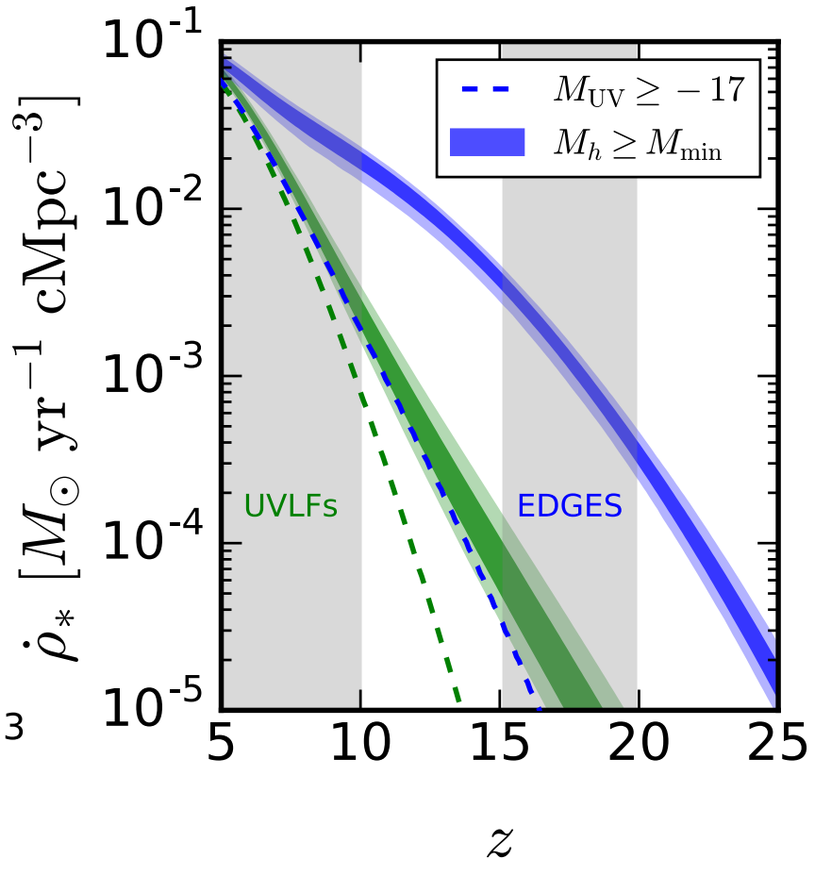
Engineering a Solution

Q. What must SFE be to fit EDGES signal?







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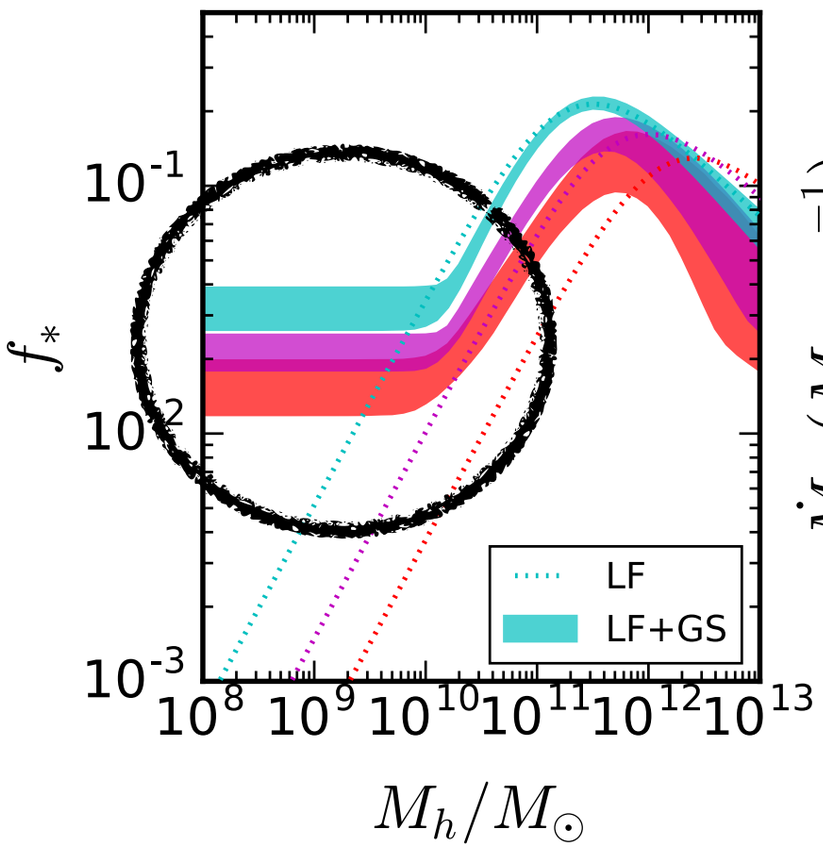

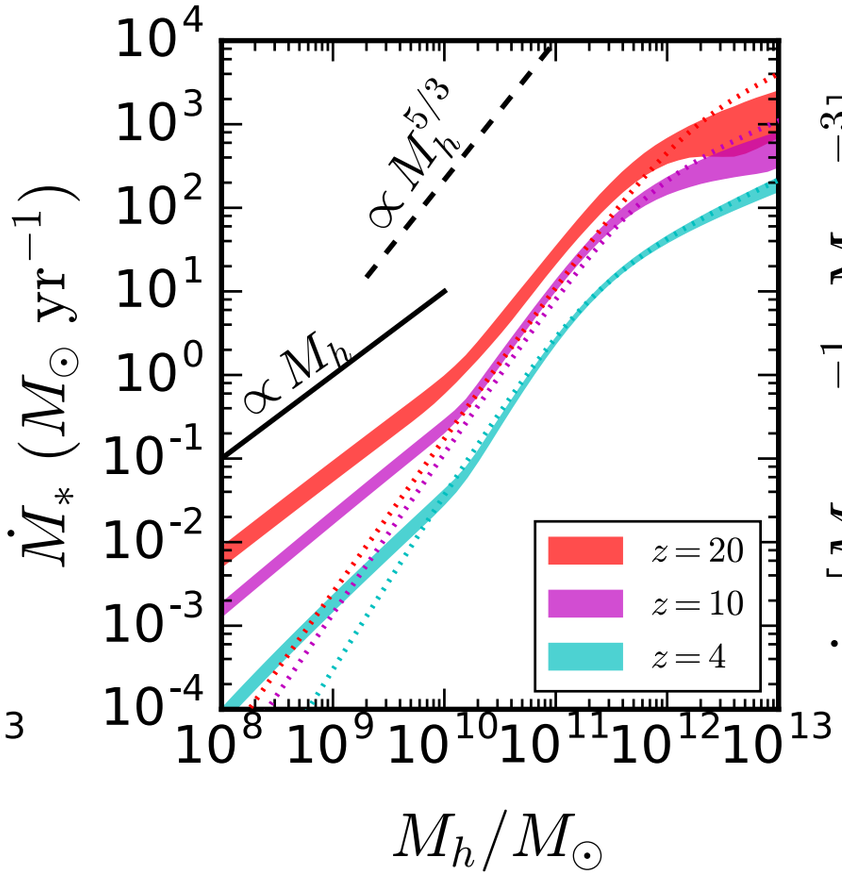

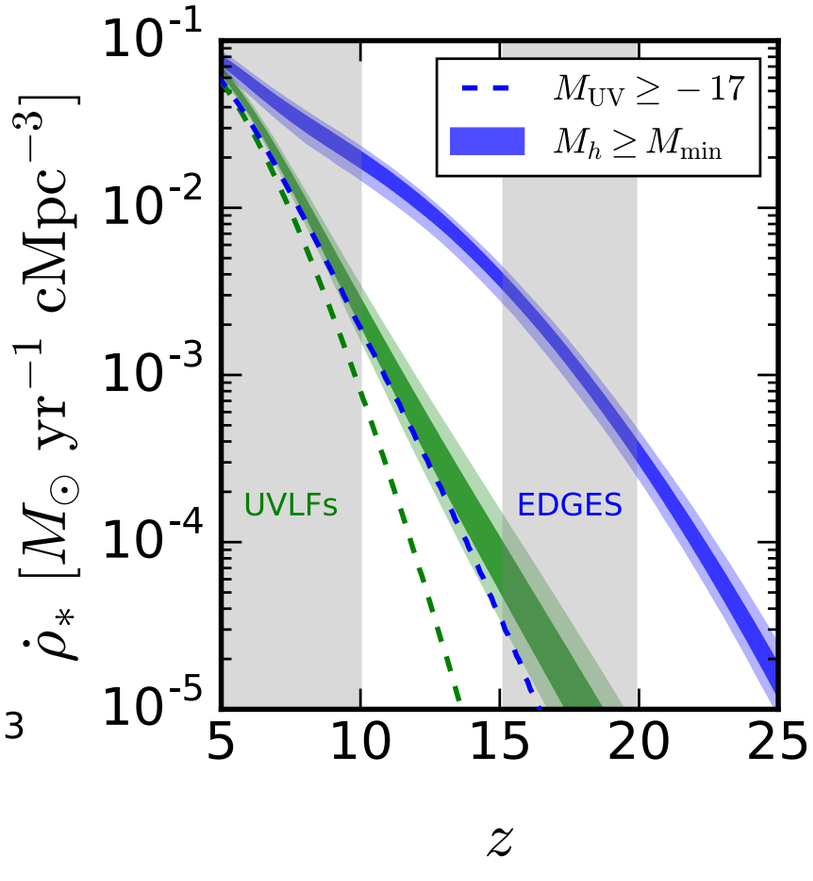

***Flattened SFE need not persist to late times.**

Mirocha & Furlanetto (2018), astro-ph/1803.03272

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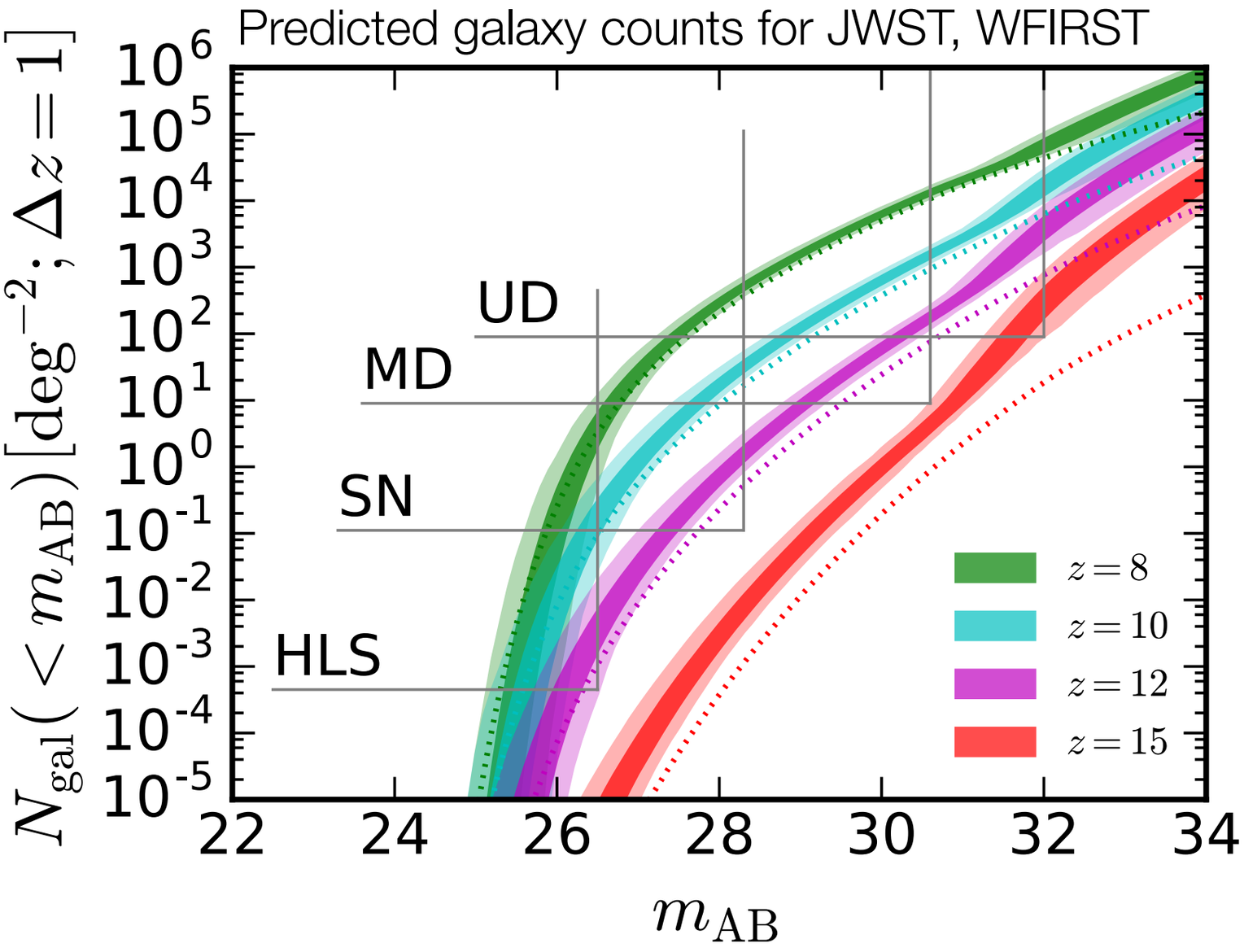

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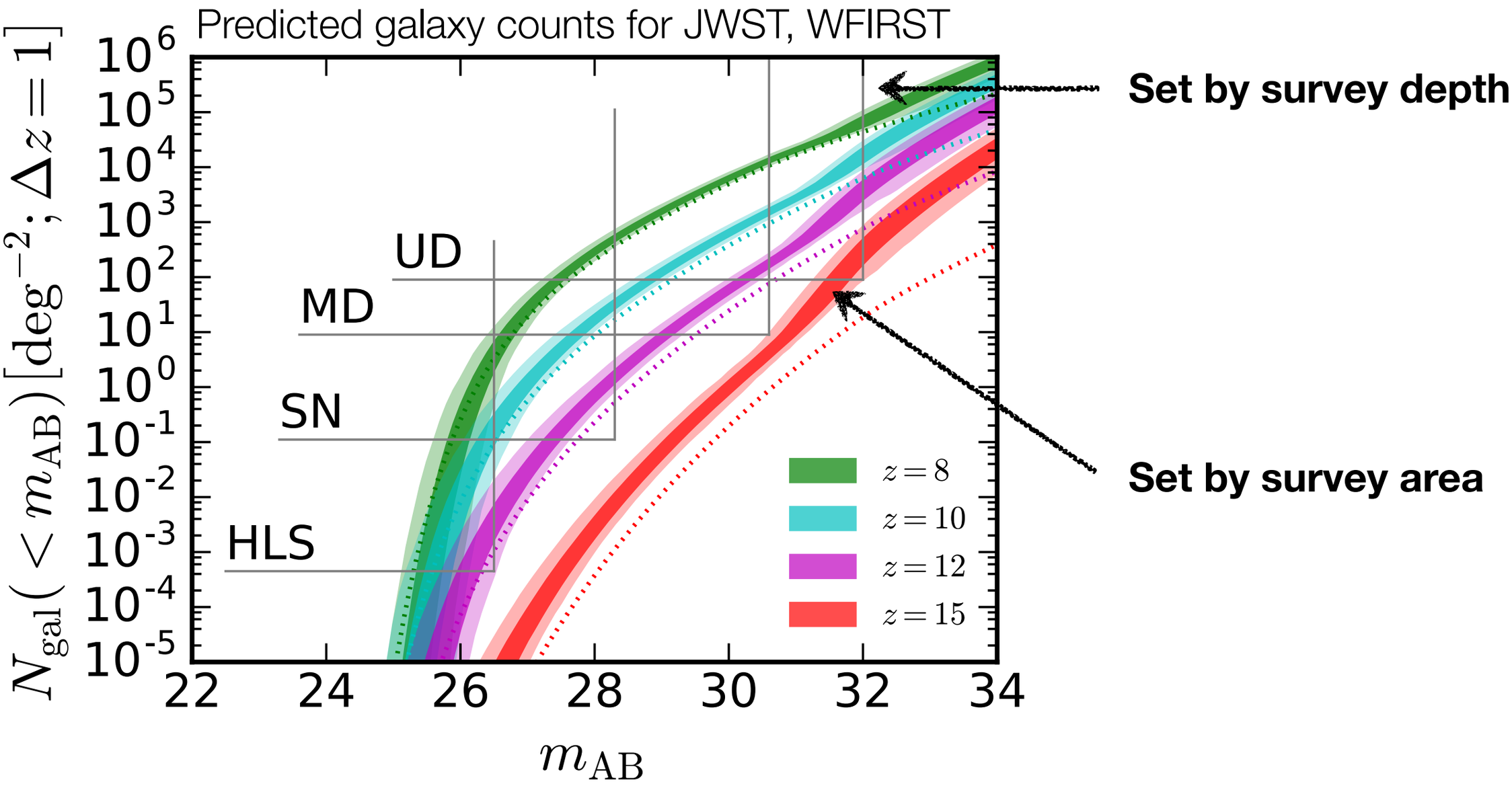

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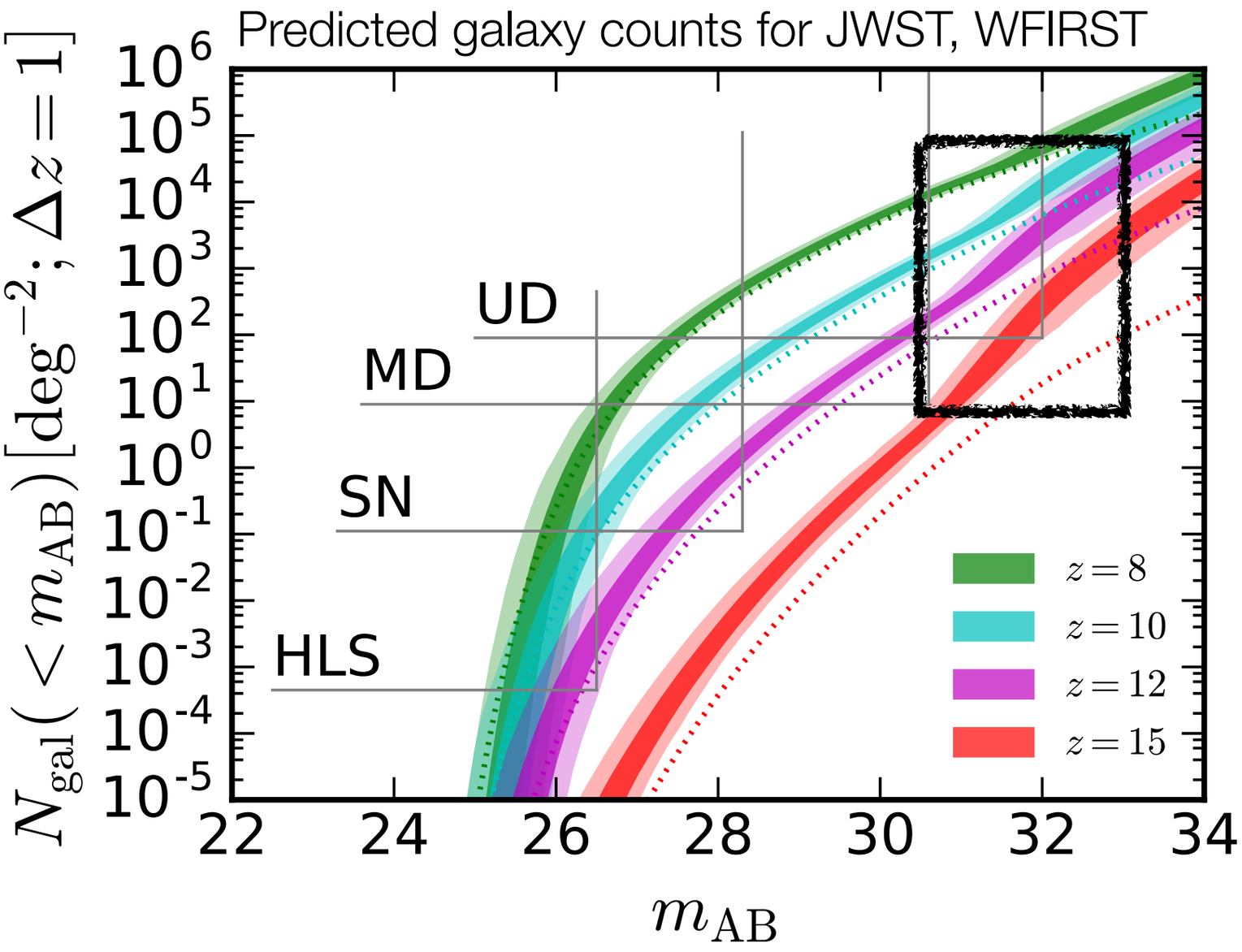


If a JWST UDF sees anything at z~12-15, maybe this isn't crazy.

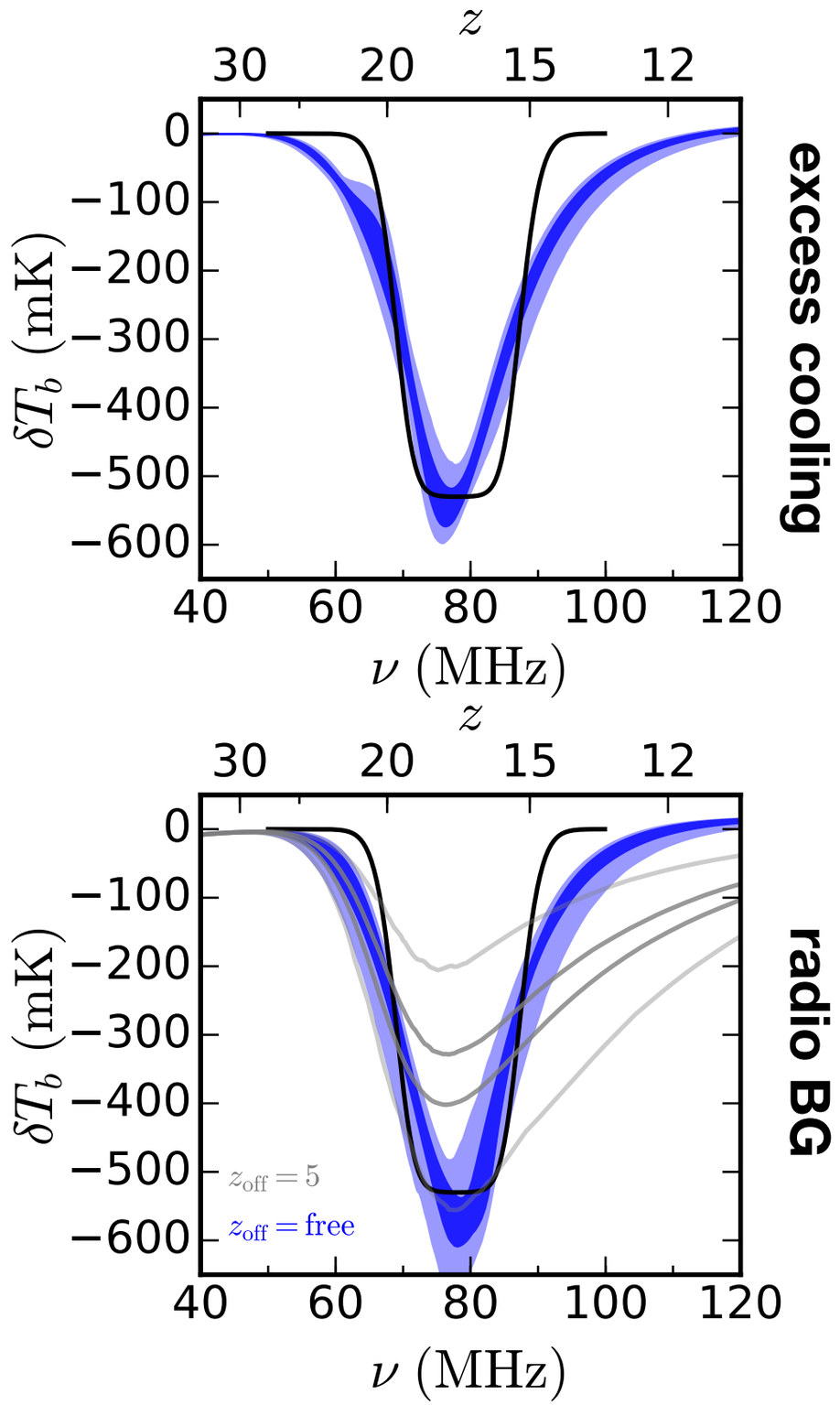
Mirocha & Furlanetto (2018), astro-ph/1803.03272

Shape Problems

- Fit UVLF and EDGES simultaneously, vary SFE parameters, L_X-SFR relation. Limit to atomic cooling halos.

- Allow excess cooling (parametric approach)

- Generate radio background assuming L_R ~ f_R x SFR.



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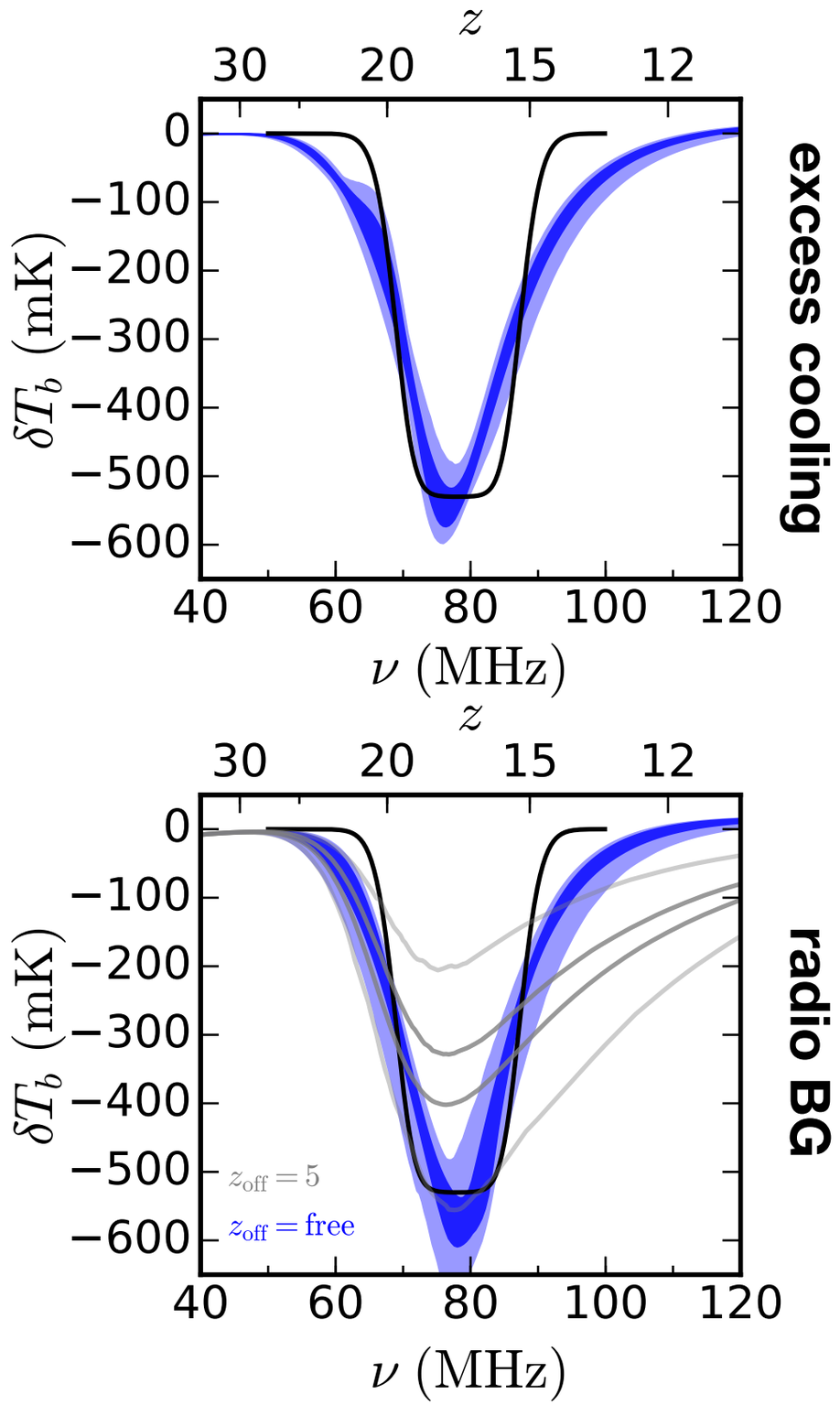

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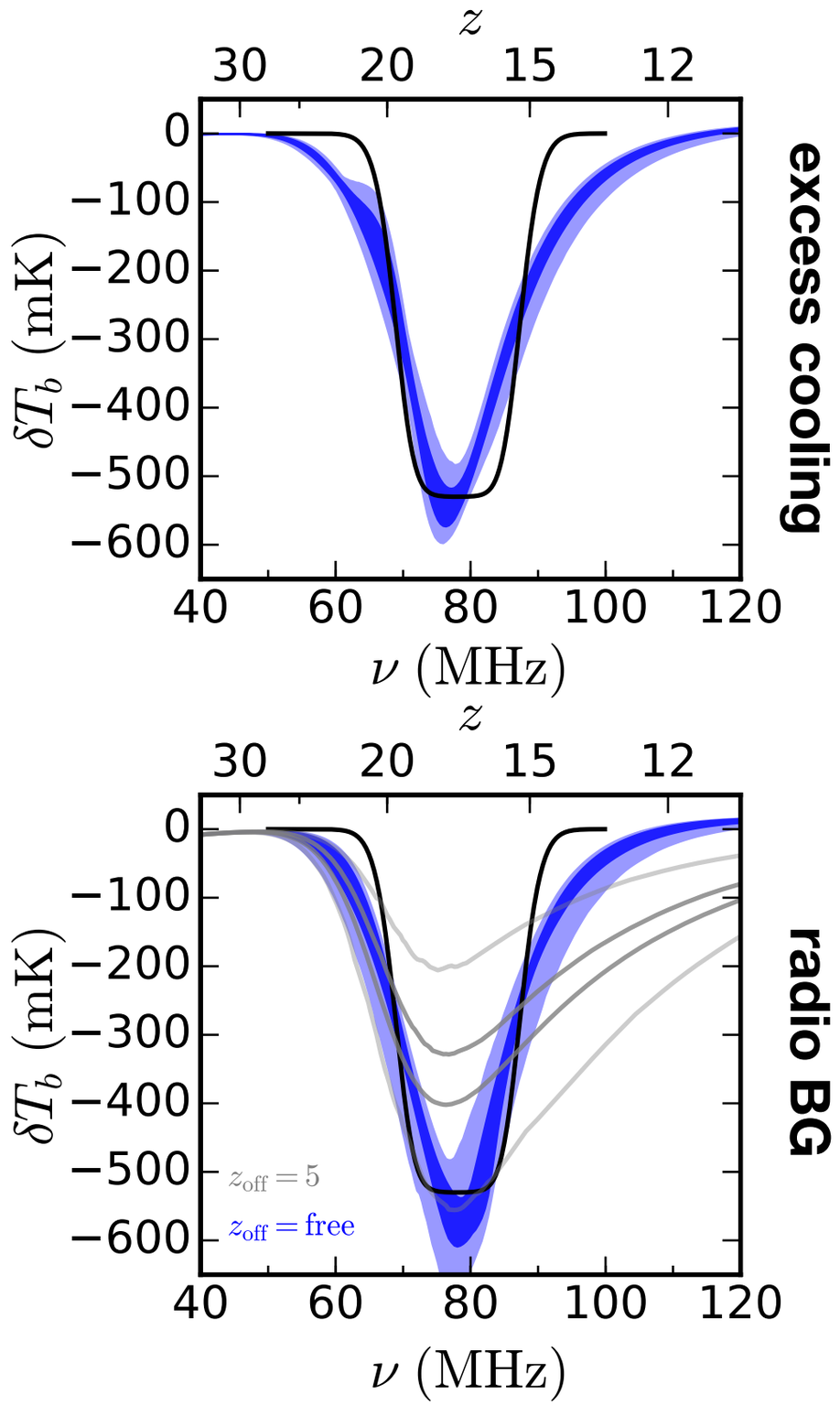

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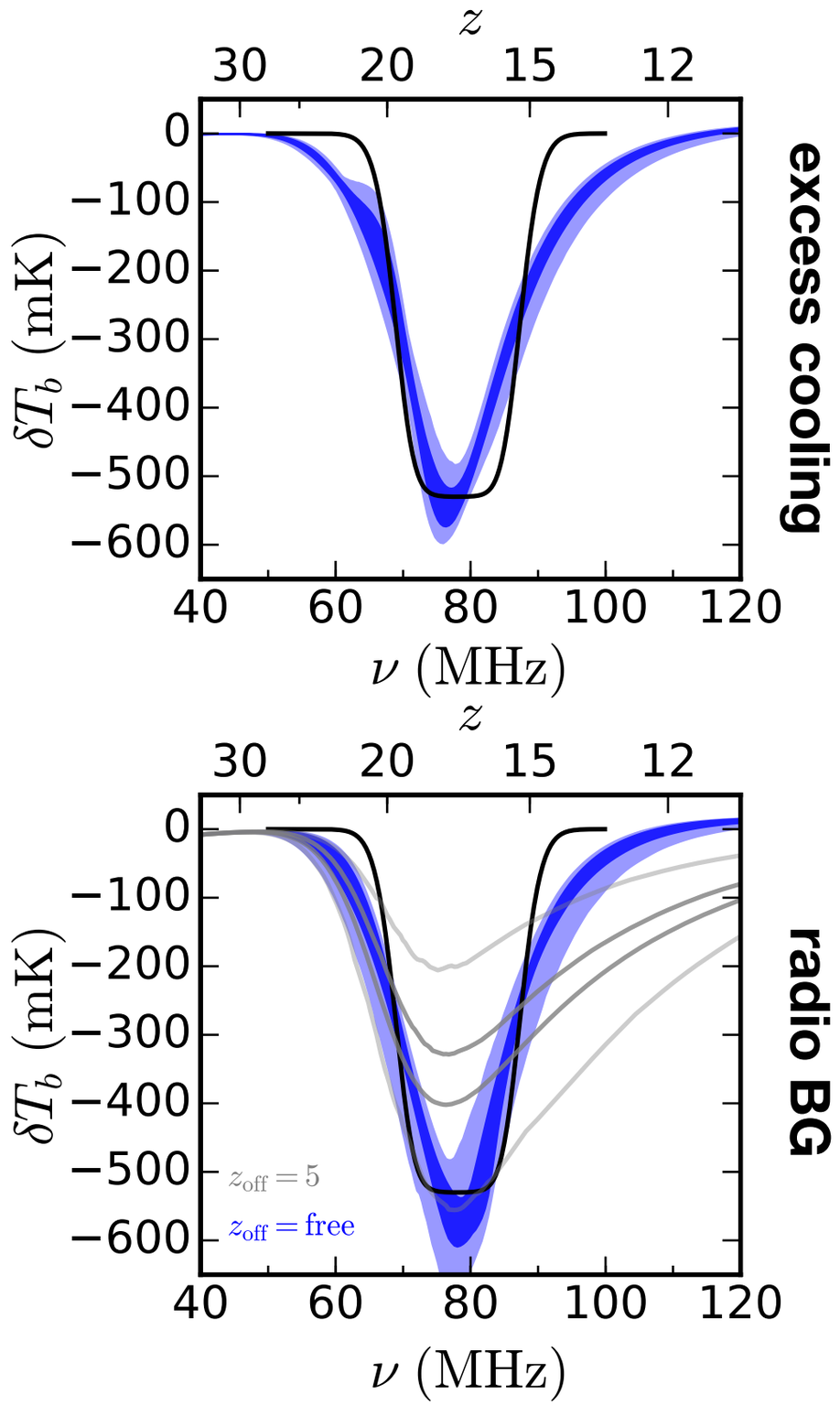
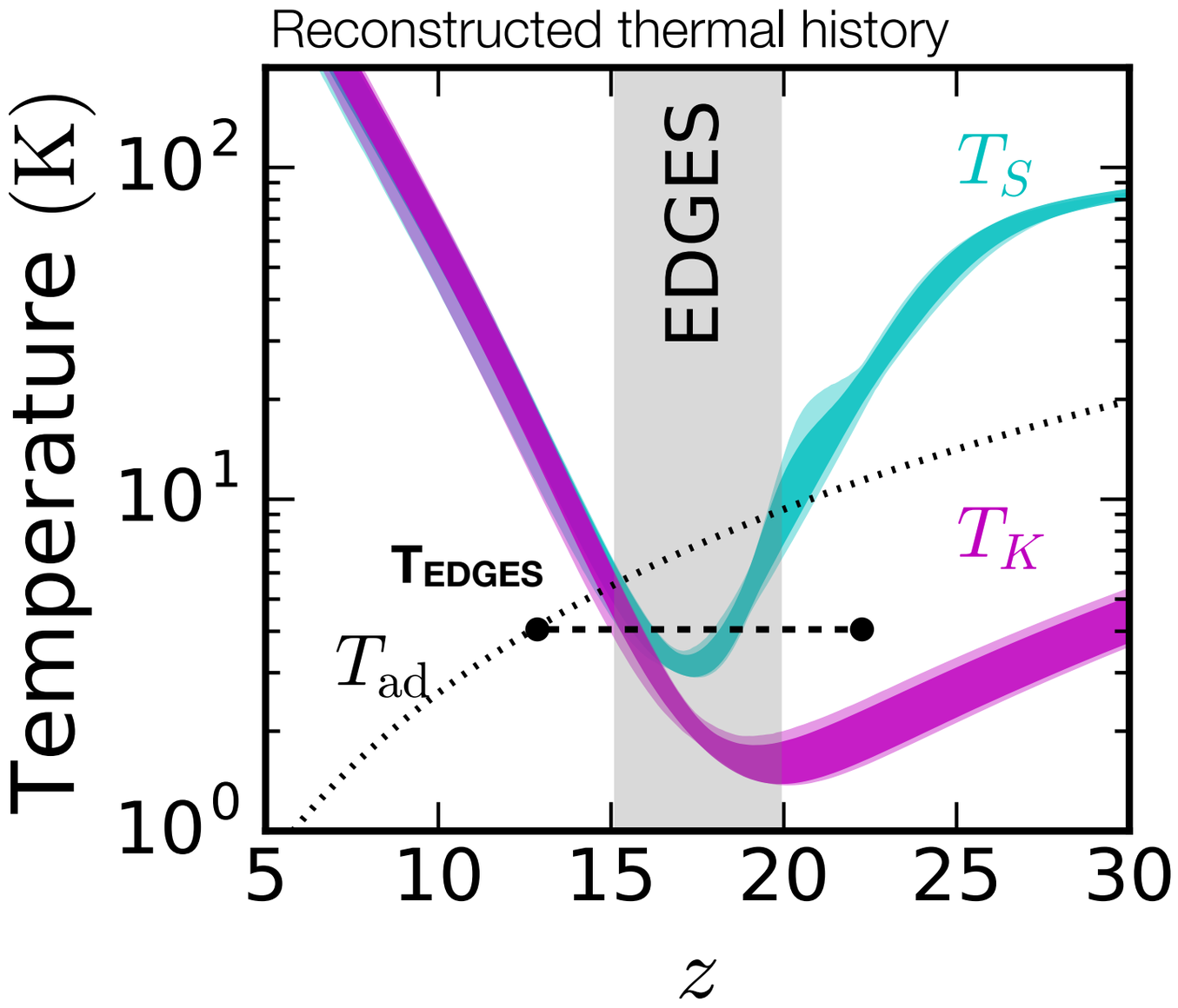


Mirocha & Furlanetto (2018), astro-ph/1803.03272

Words of Caution



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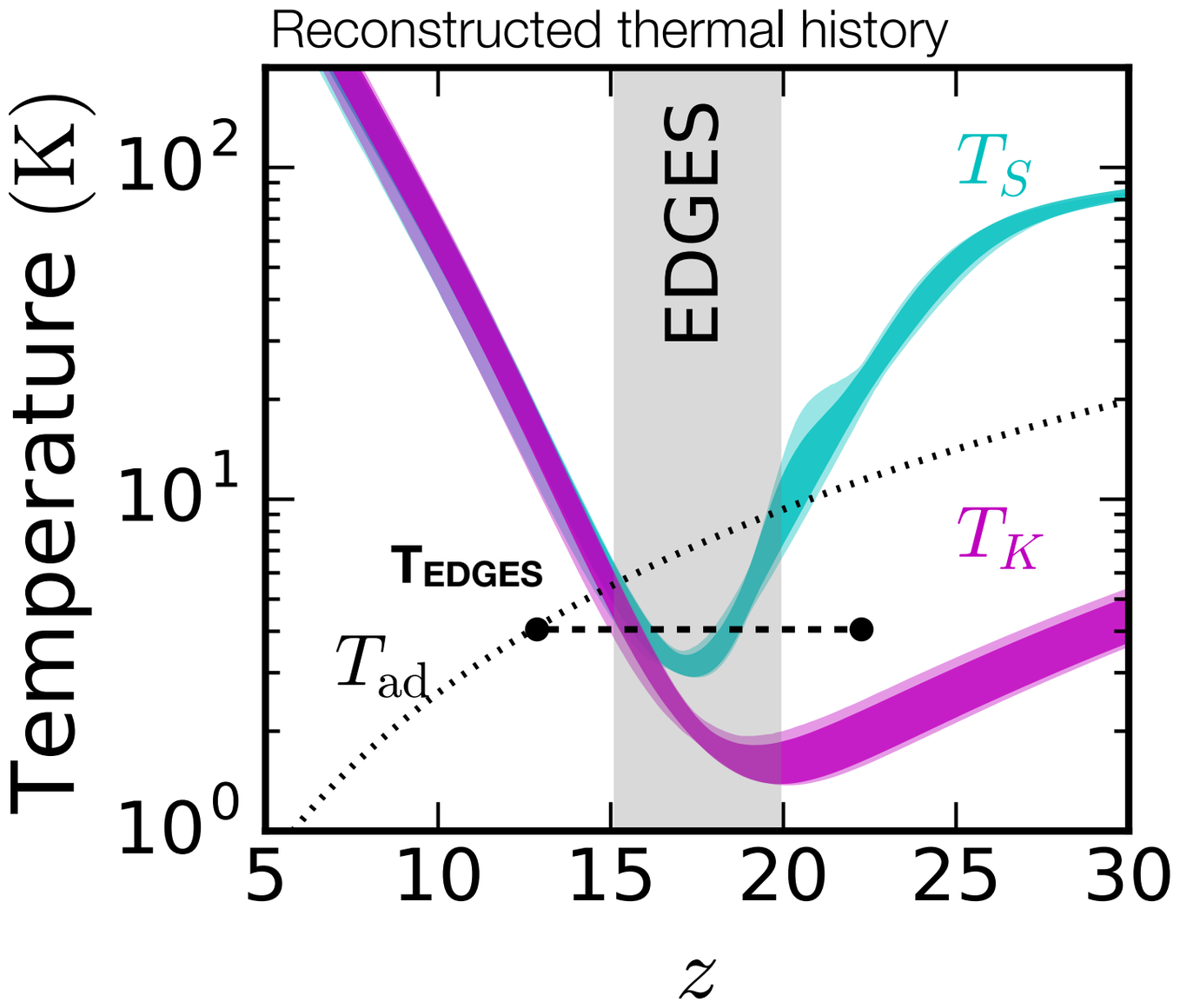

- T_S is not fully coupled to T_K at peak of signal!

Mirocha & Furlanetto (2018), astro-ph/1803.03272

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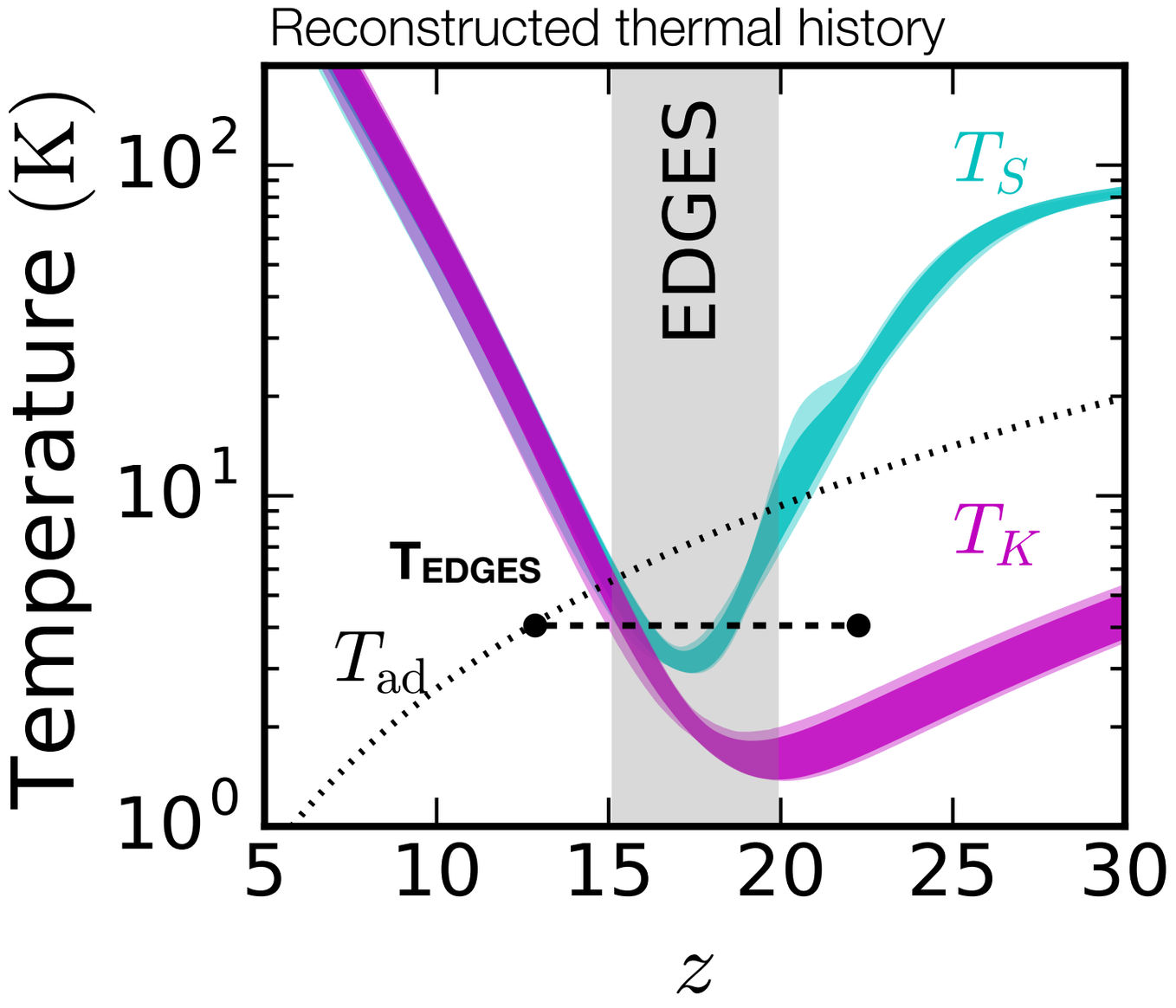

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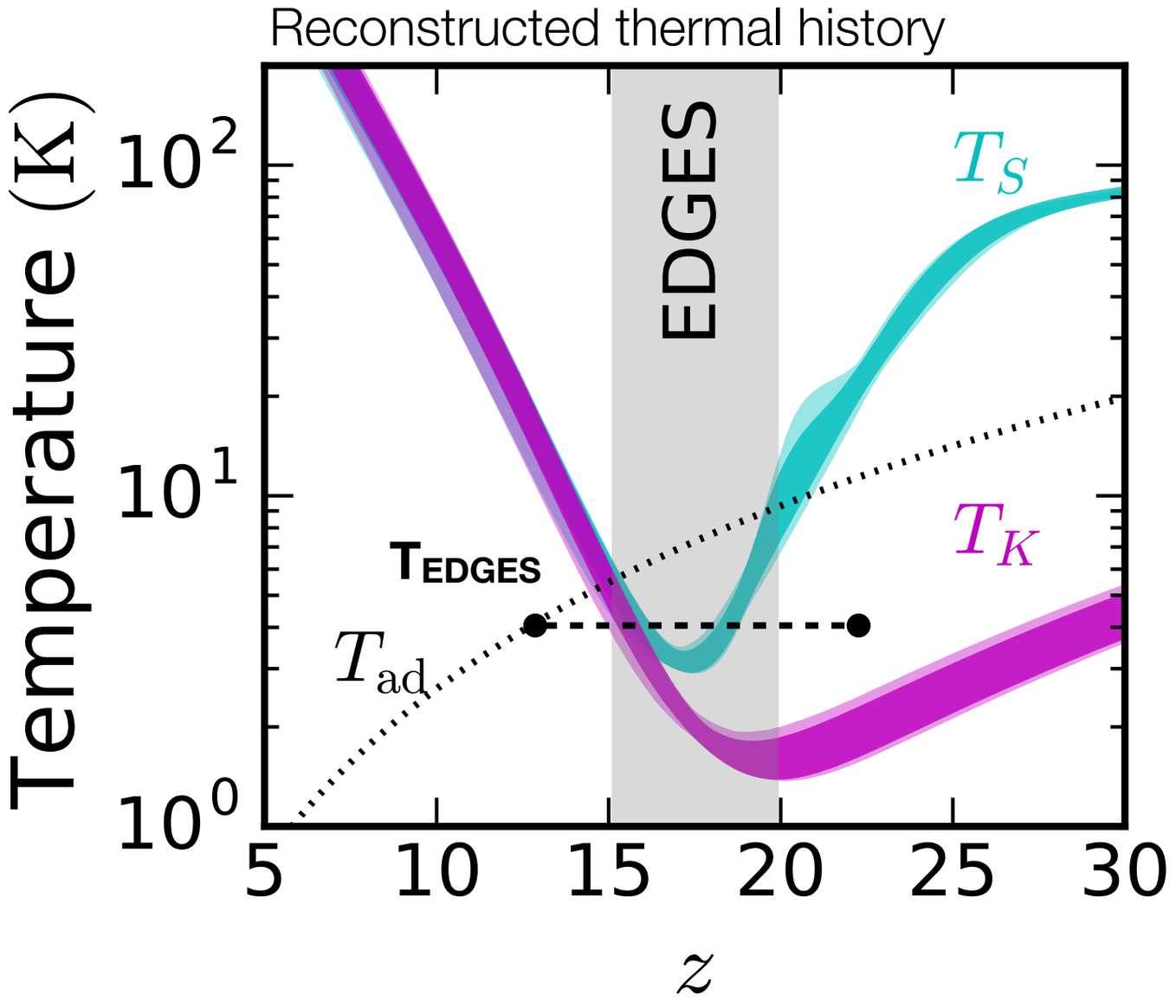
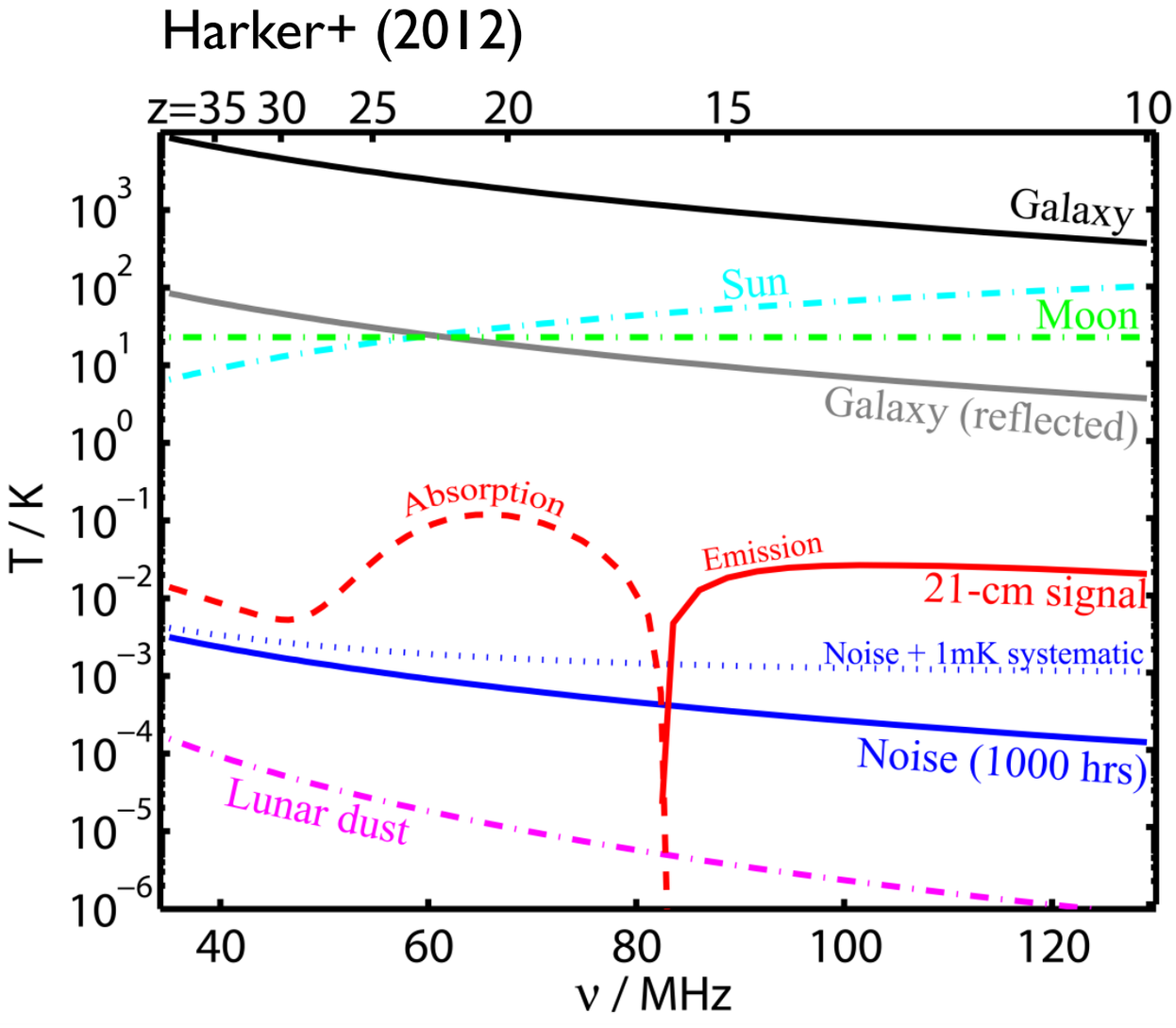
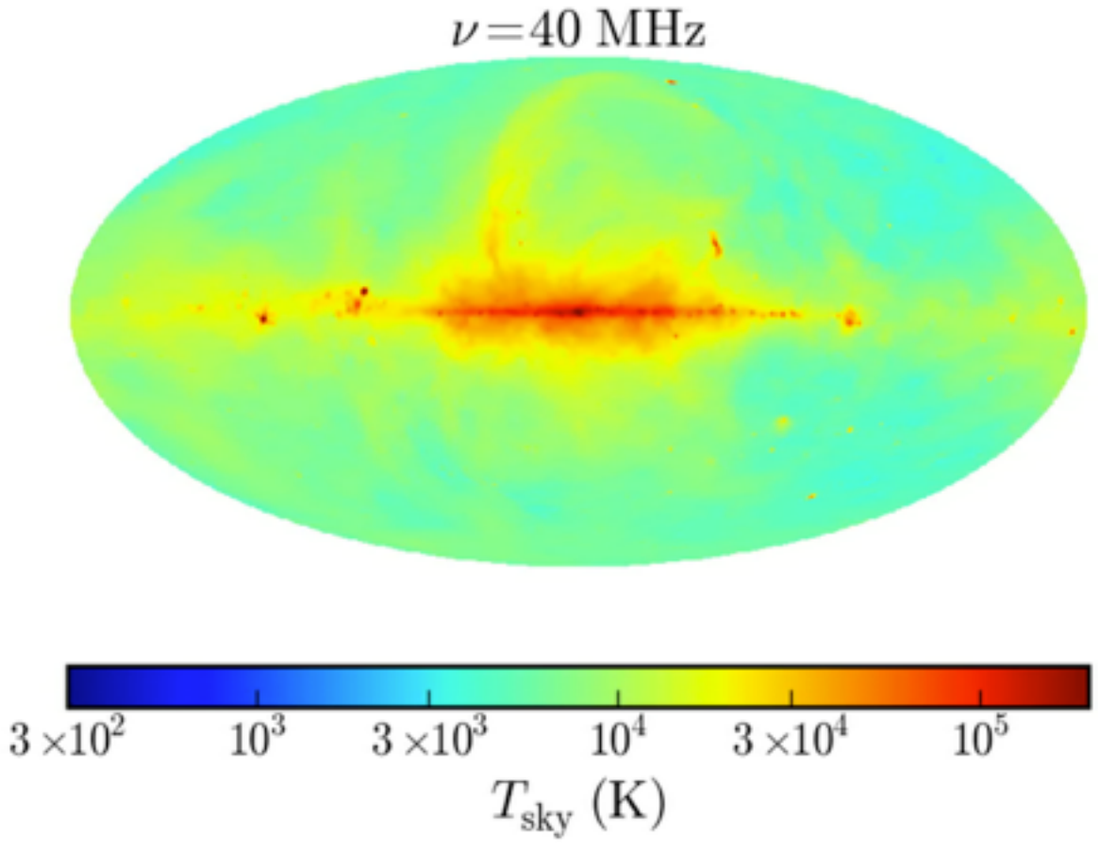


- T_S is not fully coupled to T_K at peak of signal!
- T_K has already been affected by sources!
- i.e., another situation in which galaxy formation physics may be a nuisance for DM-focused inference.

Mirocha & Furlanetto (2018), astro-ph/1803.03272

Words of Caution





This is a *really hard* measurement.

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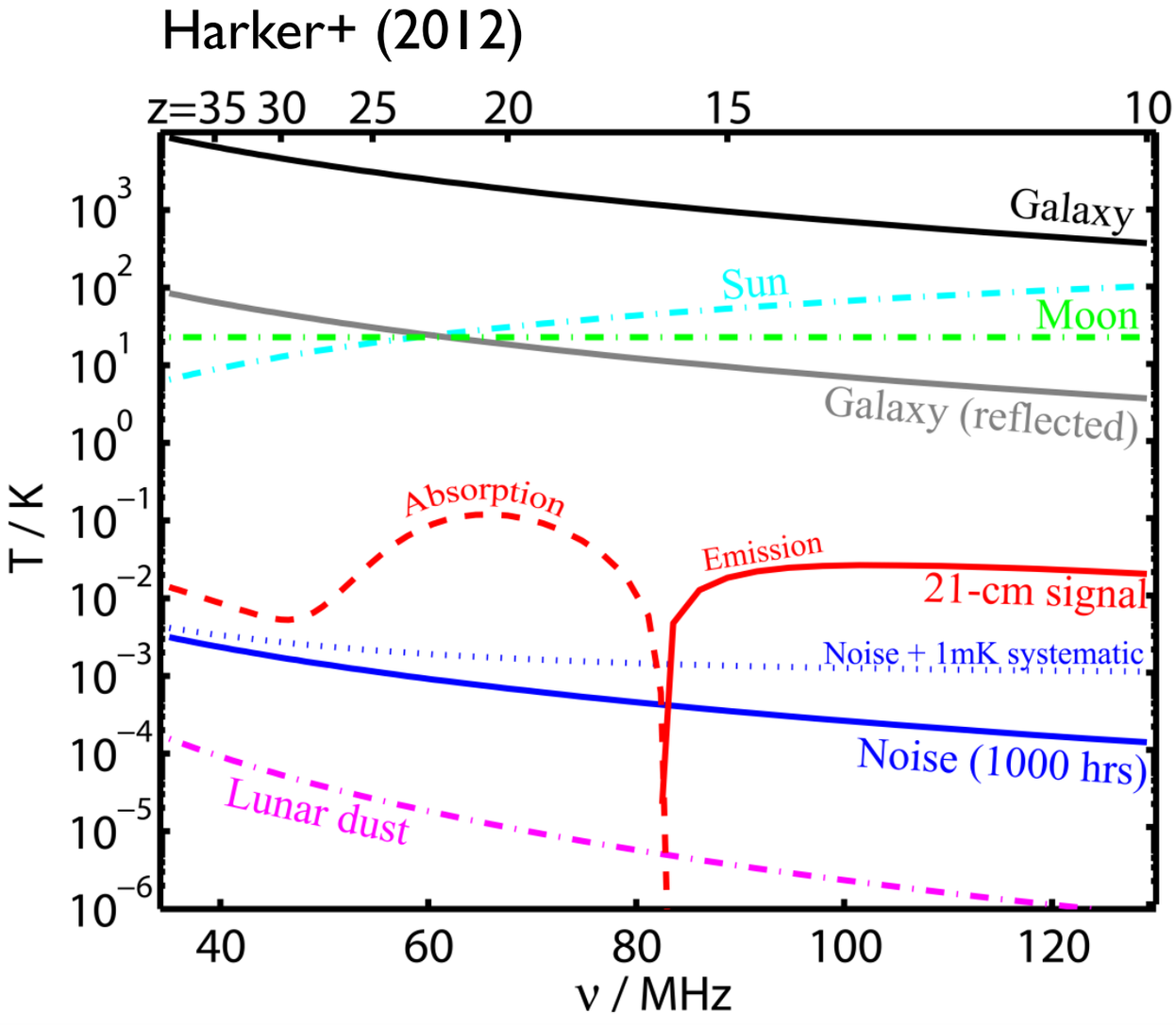

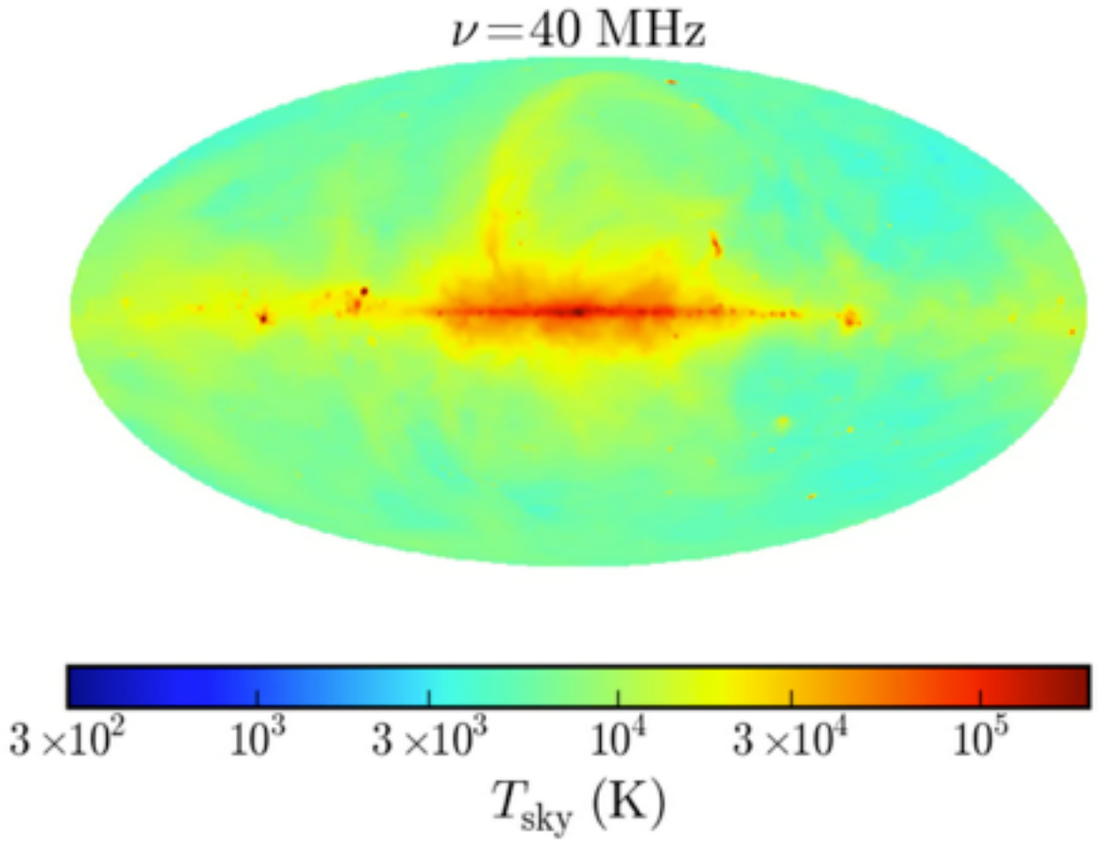

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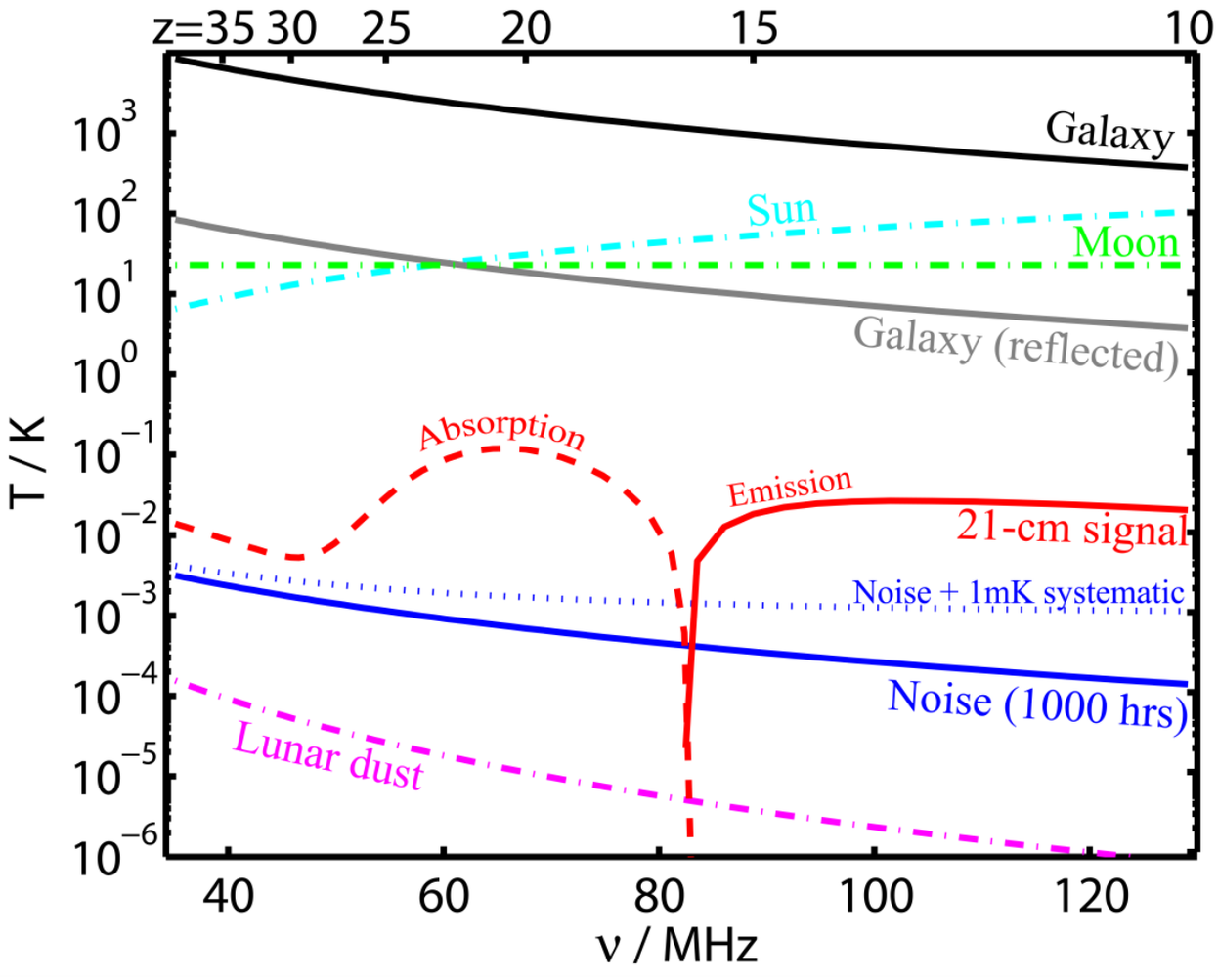
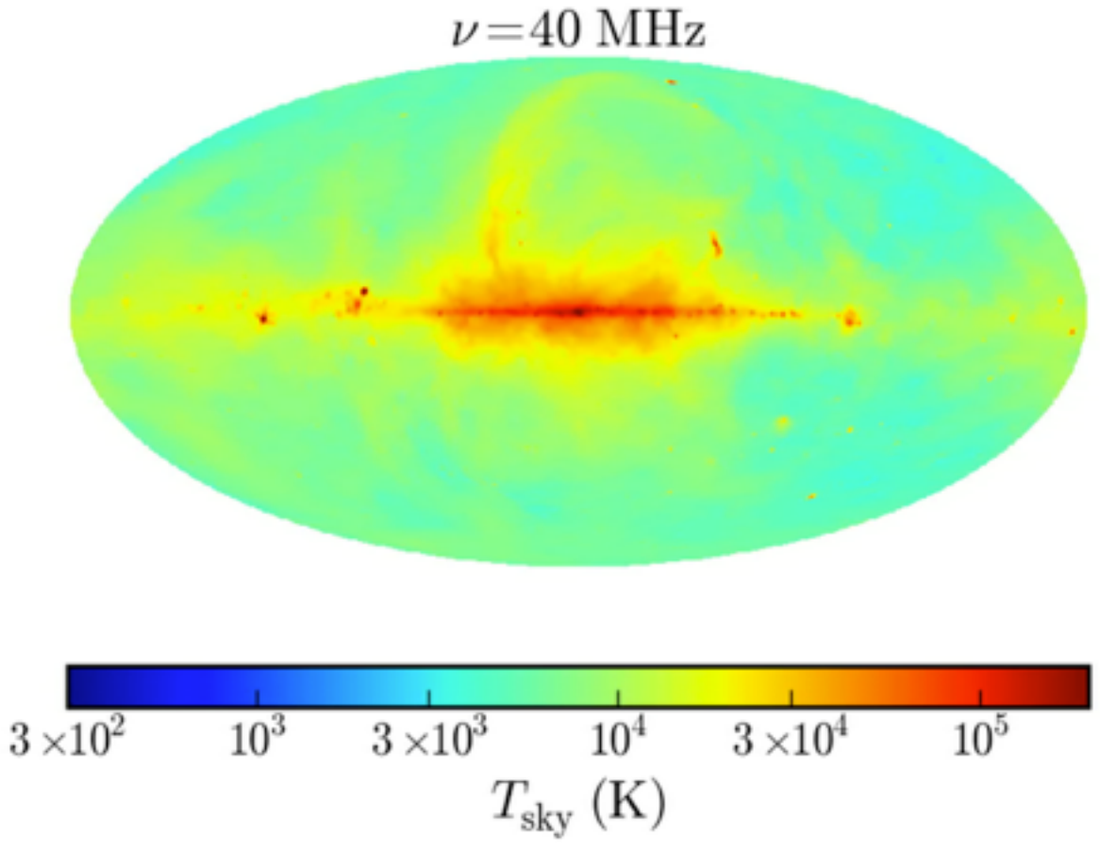
Words of Caution

Harker+ (2012)



deOliveira-Costa+ (2008) sky model



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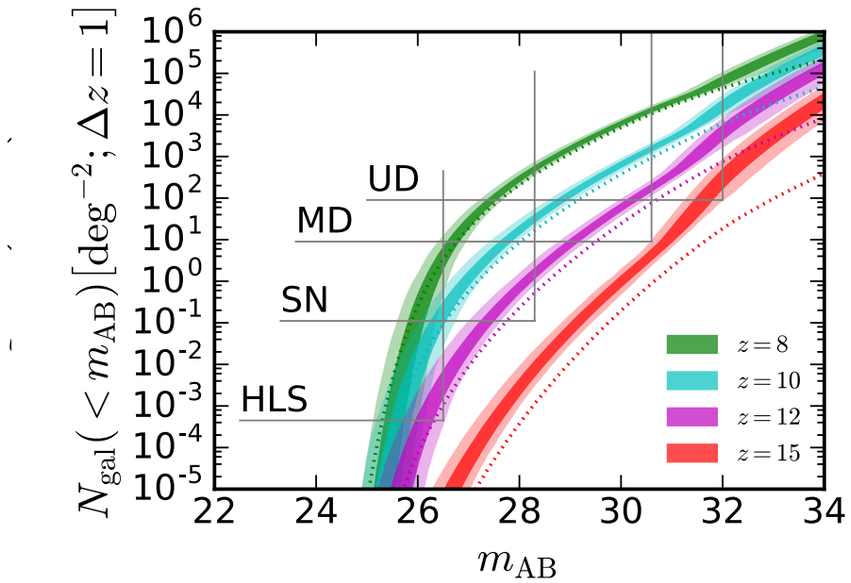
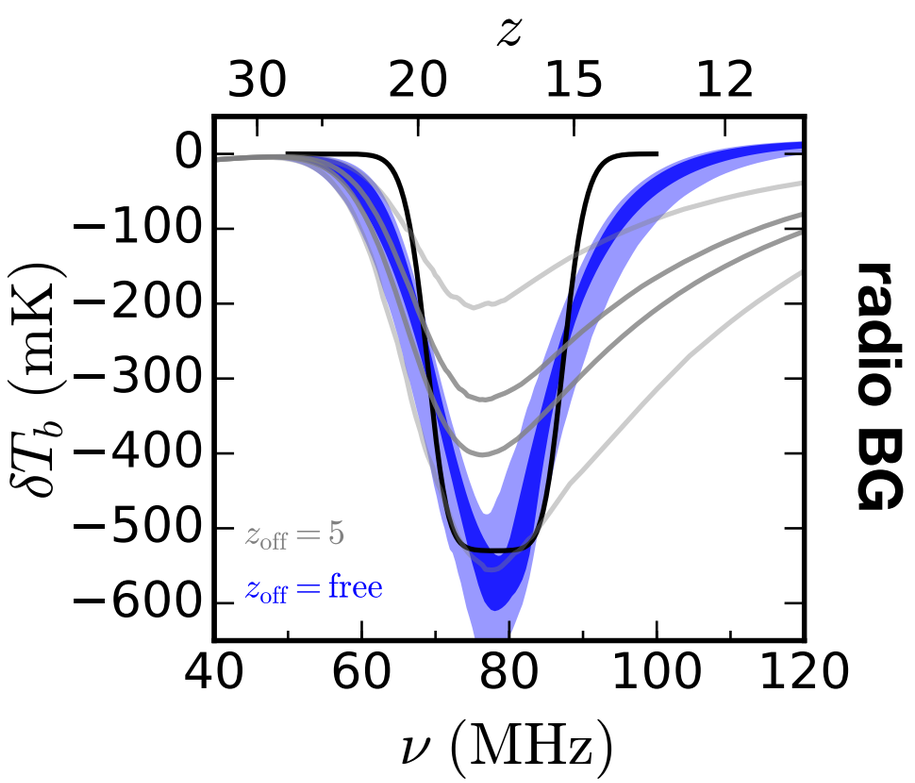
Conclusions

- Viable charged DM parameter space is likely quite limited.

- Radio background explanation puts a lot of pressure on astrophysical sources, both to generate a strong enough background at z > 20 and to shut down beyond z ~ 10-15.

- The timing of the EDGES signal is also odd, implying there is more star formation at z > 10 than simple models predict, independent of amplification mechanism.



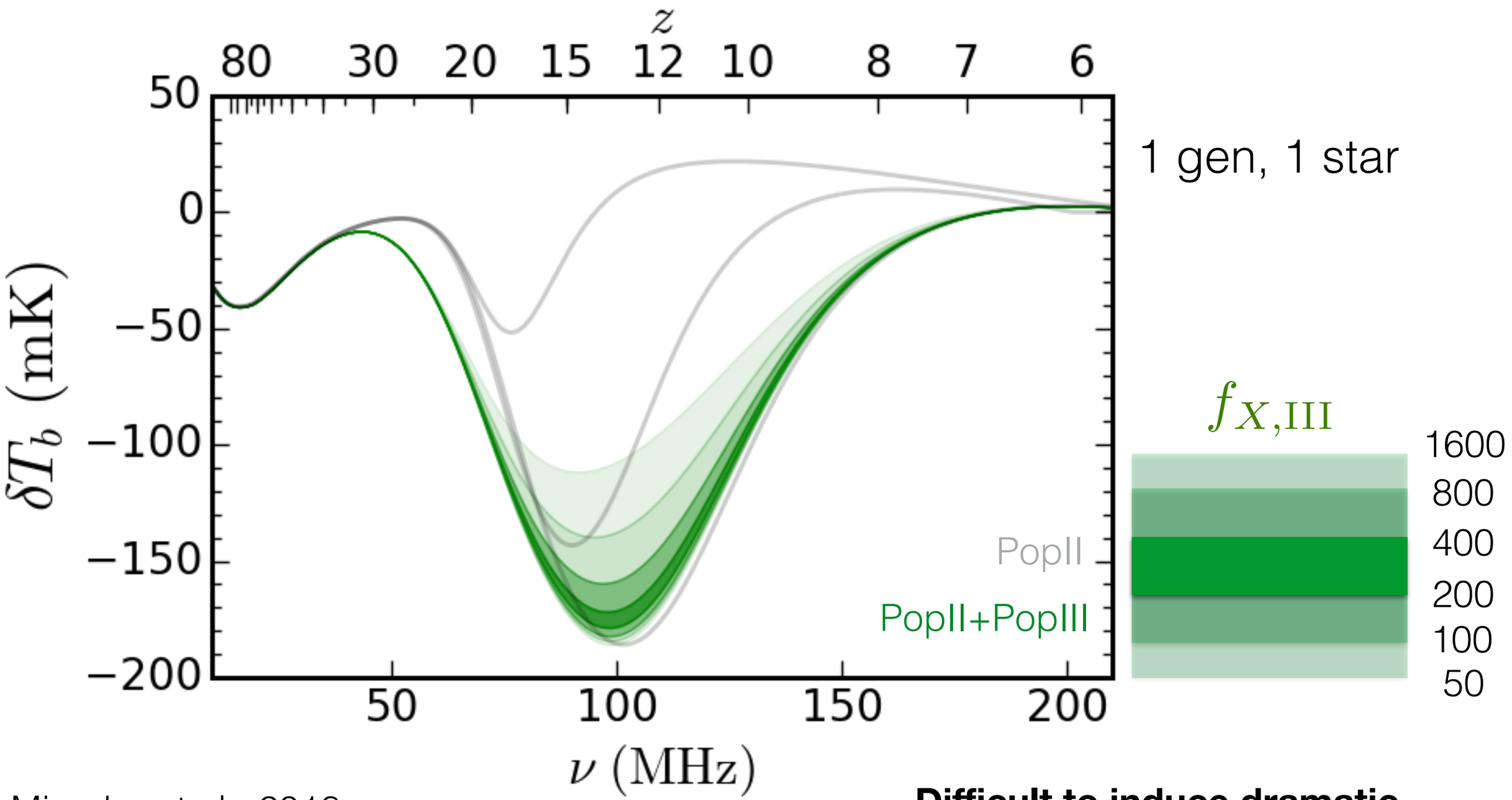


Tweetable Conclusions

The #EDGES global 21-cm signal is weird -- in amplitude, shape, *and* timing. This might be evidence of exciting new physics and astrophysics, or, depending on your inclination, reason to be skeptical. Excited to see what #HERA, #PRIZM, #SARAS, #JWST, and #SKA will find!

Backup Slides

Quick Aside: PopIII



Mirocha et al., 2018

Mebane, Mirocha, & Furlanetto (2018)

Difficult to induce dramatic change with minihalos!