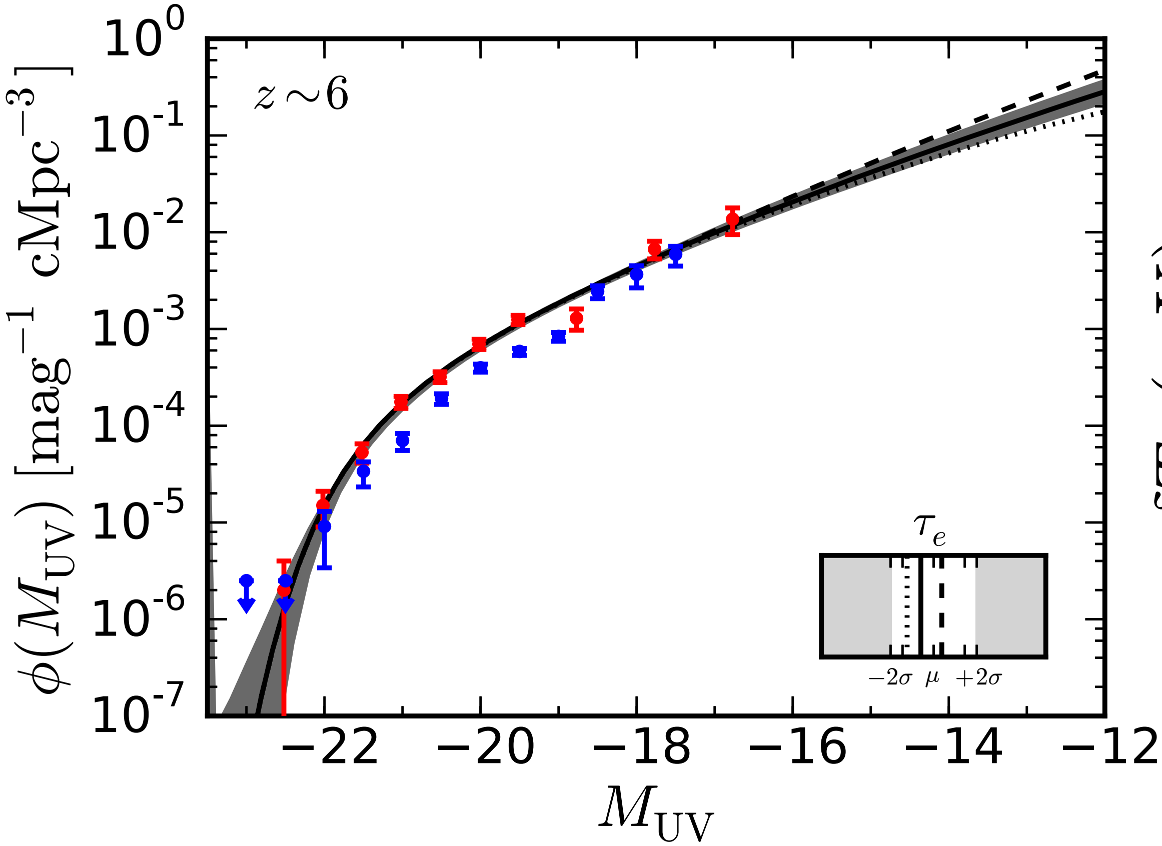
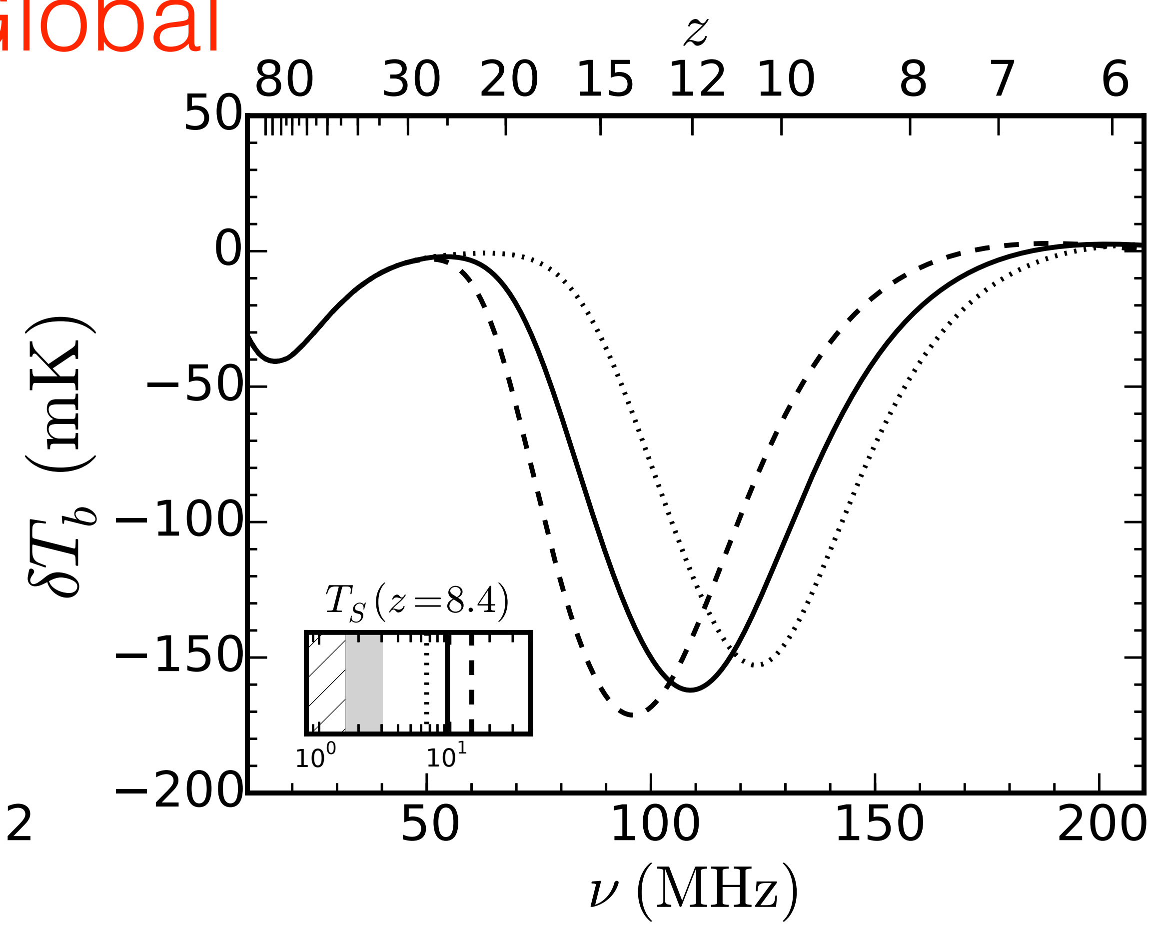
Metrics for Disentangling PopII and PopIII Contributions to the 21-cm Background

Global





Jordan Mirocha (UCLA)

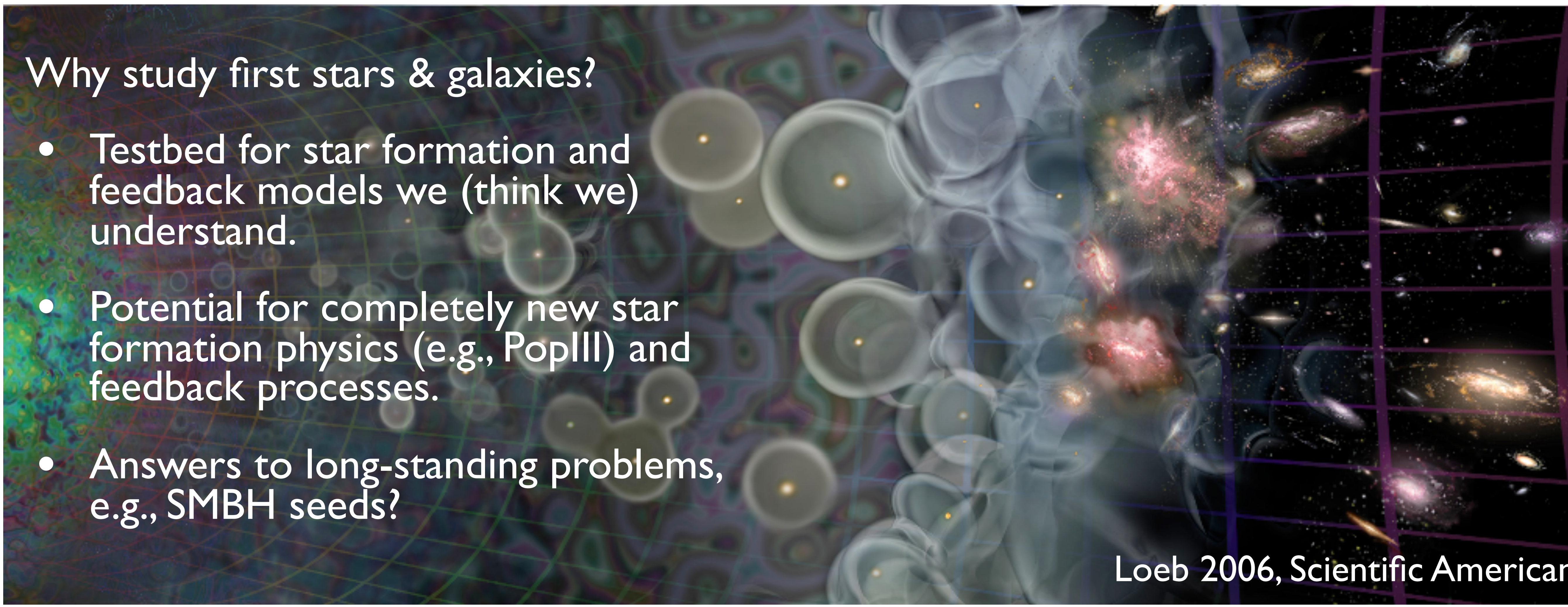
in collaboration with Steve Furlanetto (UCLA), Rick Mebane (UCLA), Jason Sun (Caltech), Krishma Singal (GaTech), and Donald Trinh (UCI)

Outline

- Motivation
- Preview of main results
- Background on the 21-cm…background
  - Part I: Global 21-cm in context of galaxy LF
  - Part II: Unique signatures of PopIII?
- Summary

Motivation

CMB ~ 100 Myr ~ 1 Gyr Today



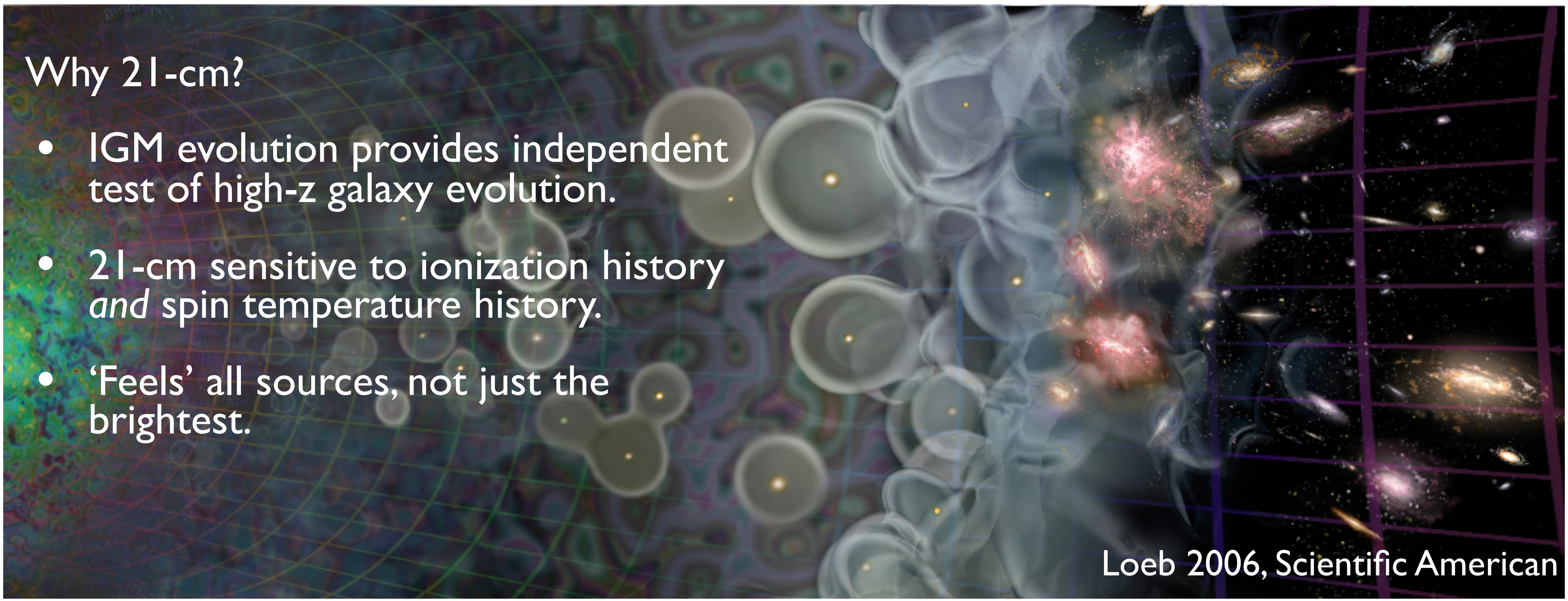
Why study first stars & galaxies?

- Testbed for star formation and feedback models we (think we) understand.
- Potential for completely new star formation physics (e.g., PopIII) and feedback processes.
- Answers to long-standing problems, e.g., SMBH seeds?

Loeb 2006, Scientific American

Motivation

CMB ~ 100 Myr ~ 1 Gyr Today



Why 21-cm?

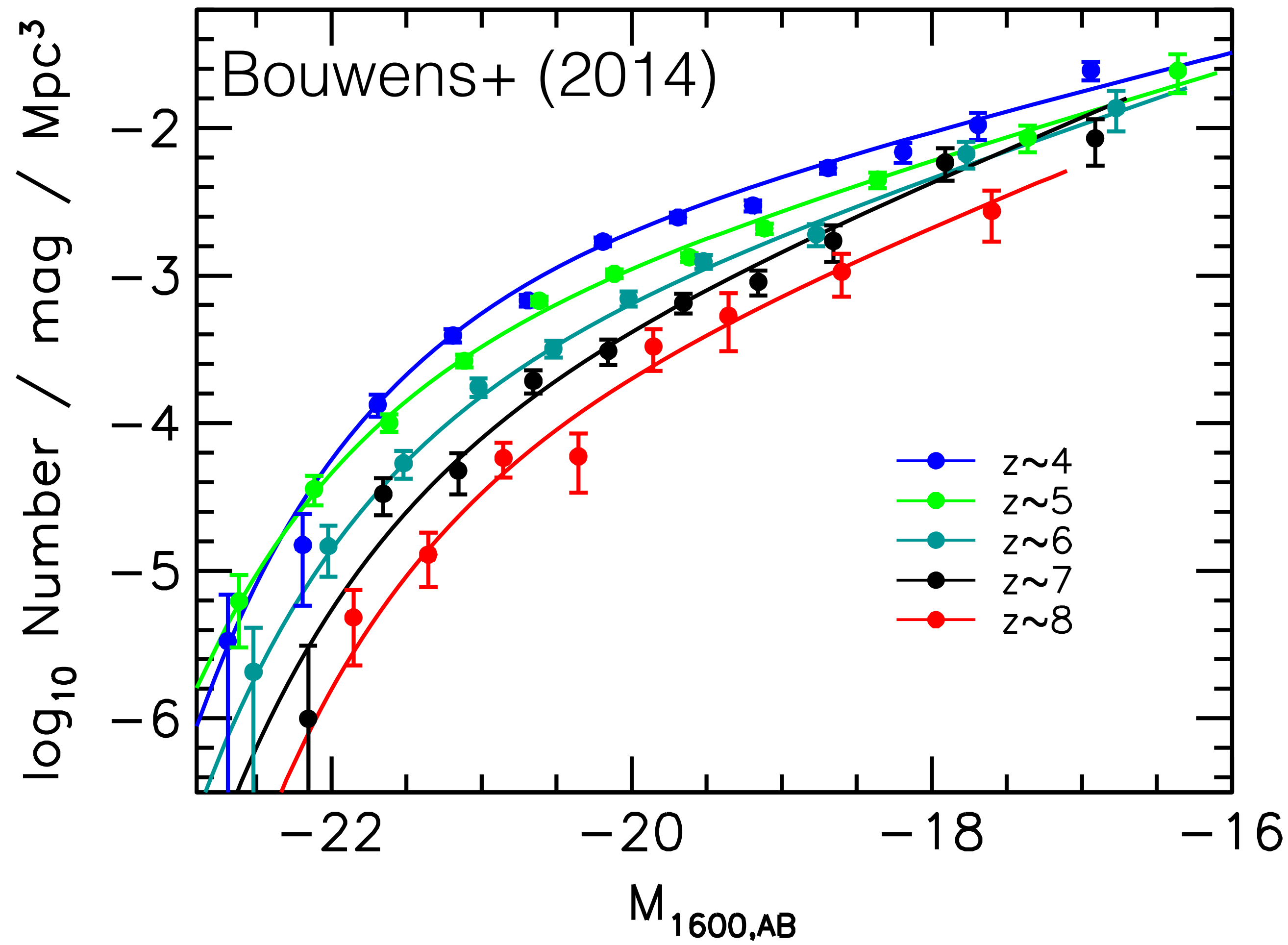
- IGM evolution provides independent test of high-z galaxy evolution.
- 21-cm sensitive to ionization history *and* spin temperature history.
- ‘Feels’ all sources, not just the brightest.

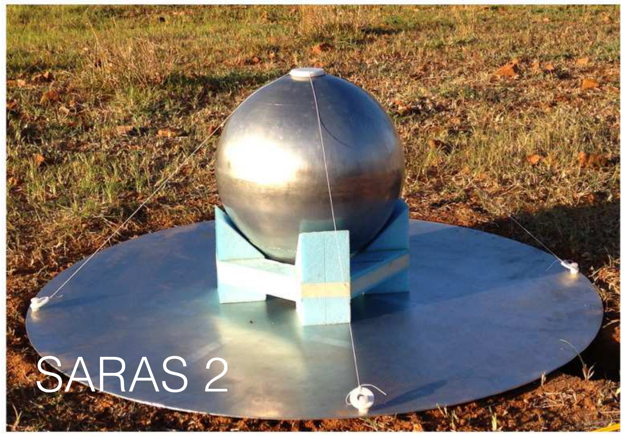
Loeb 2006, Scientific American

21-cm approach: probe galaxies indirectly through impact on IGM

Motivation

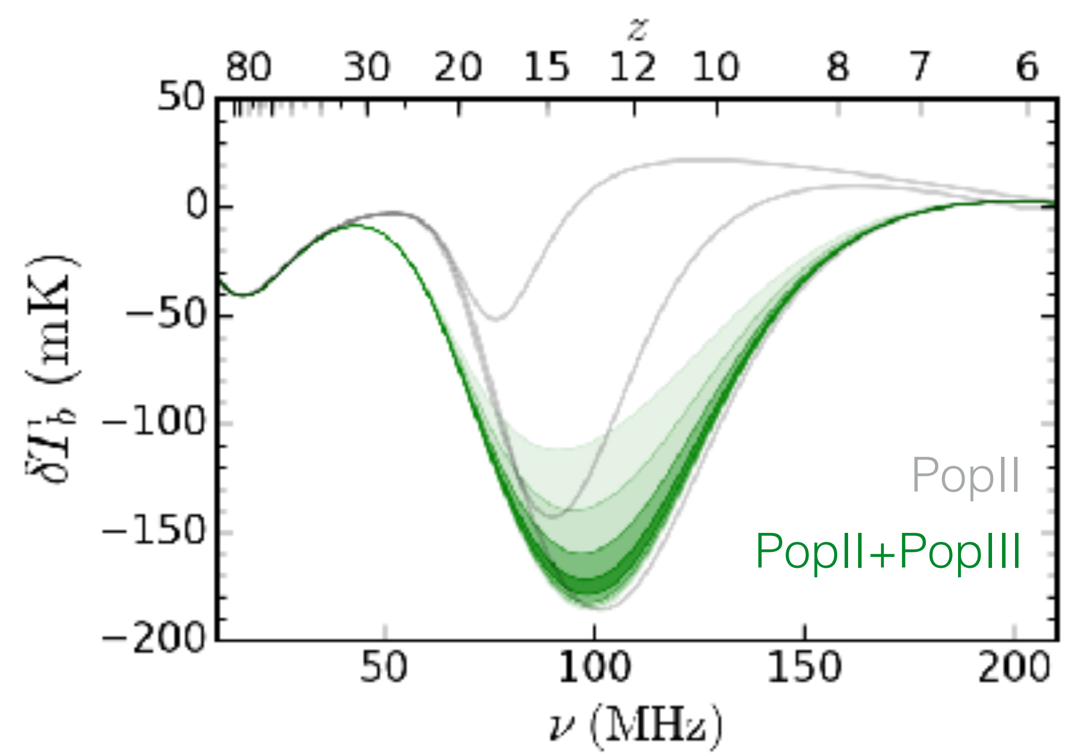
1. Simple models describe known high-z galaxy population quite well.
   - Many 21-cm predictions pre-date this progress.
2. Simple arguments thought to describe unseen 'PopIII' sources.
   - But can they ever be detected directly?
3. Experimental progress!
   - EDGES, SARAS, BIGHORNS, SCI-HI, LEDA, HYPERION,… more?





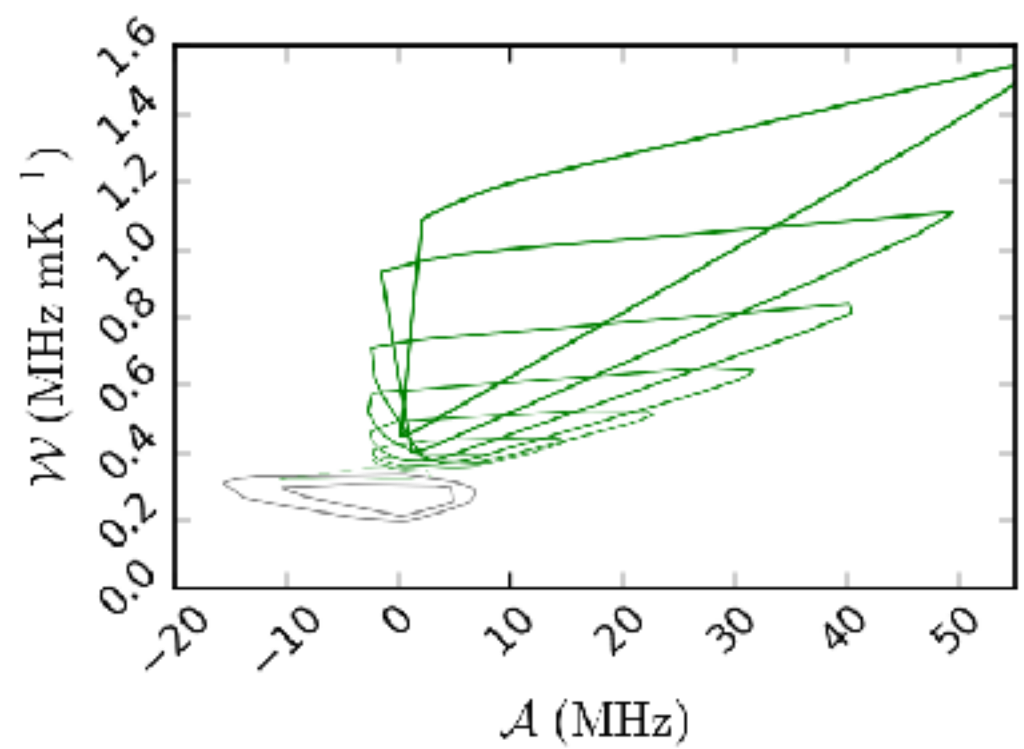
Main Results

1. Based on high-z LF measurements, low-frequency experiments targeting the sky-averaged 21-cm signal should expect a strong symmetrical signal near ~100 MHZ.



Mirocha, Furlanetto, & Sun (2017)

2. Unless small ($<10^8$ M_{sun}) halos can form multiple generations of metal free stars with a top-heavy IMF, in which case we predict a weaker — and asymmetric — signal.

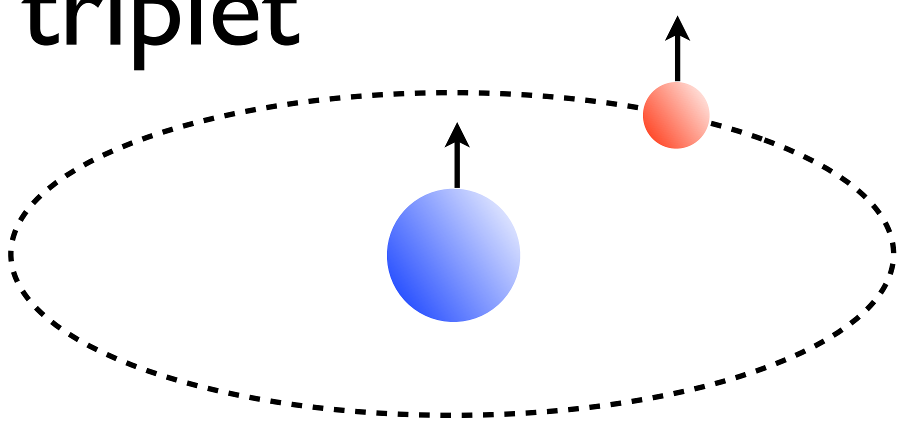


Mirocha et al., submitted

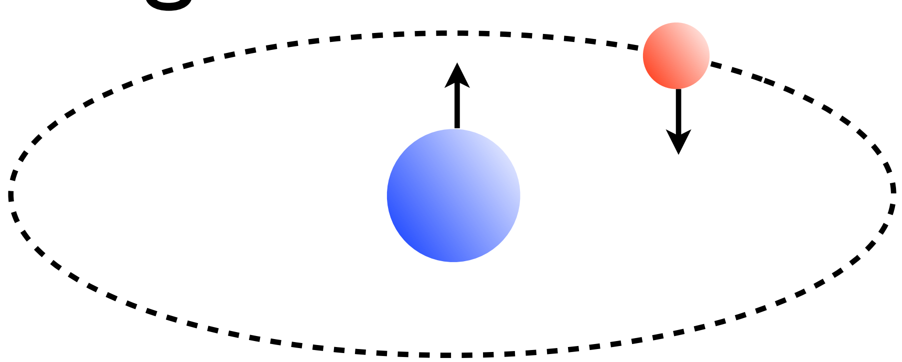
The 21-cm Background

21-cm Physics

triplet

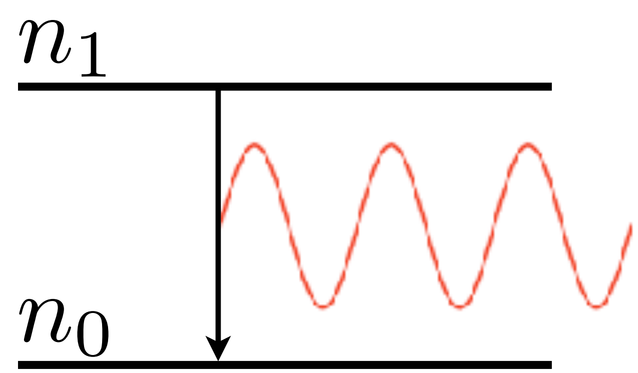


singlet



Ground-state hyper-fine splitting

T_{21}



$\lambda = 21 \text{ cm}$

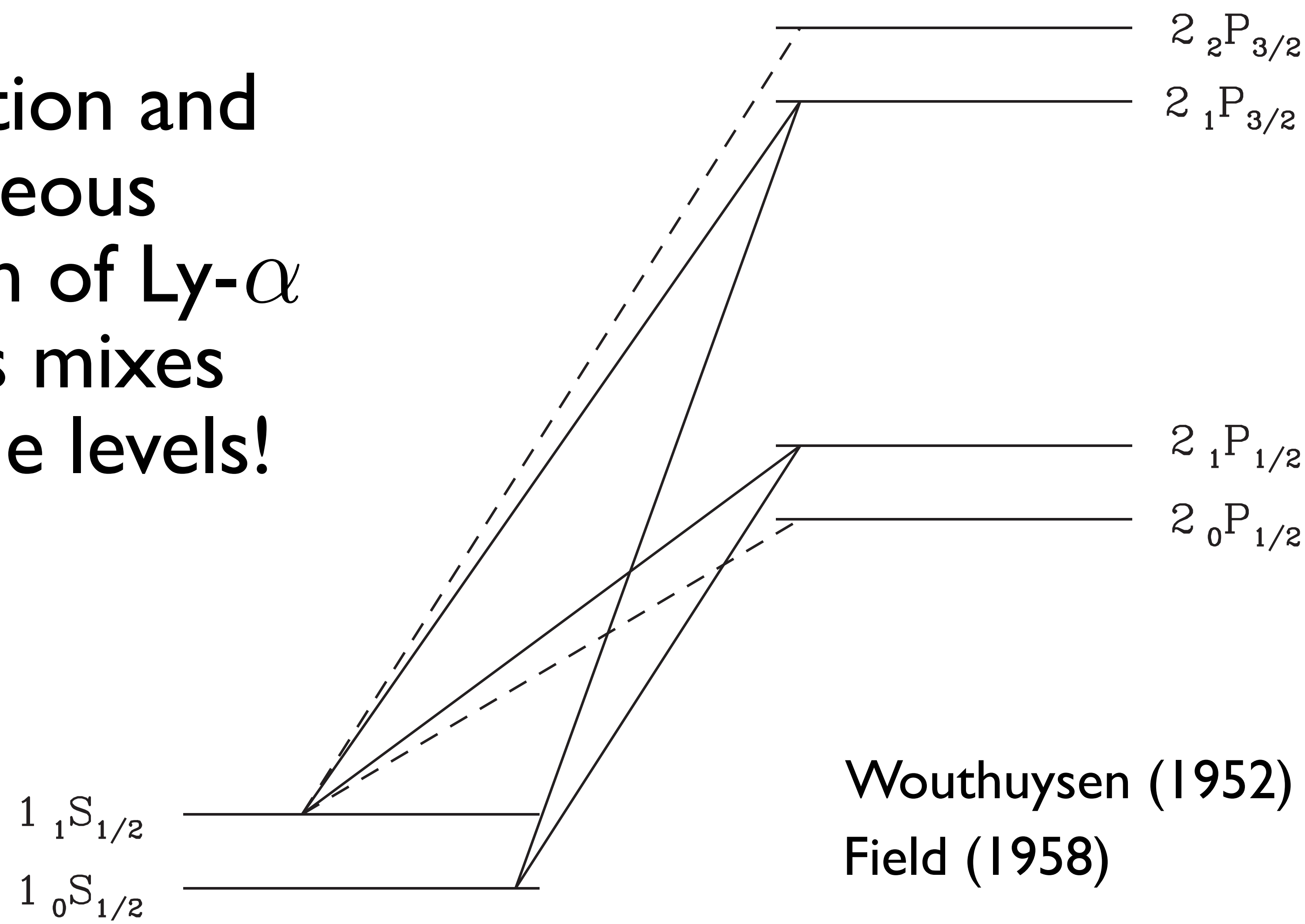
$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left[T_{21}/\boxed{T_S}\right]$$

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

...?

21-cm Physics

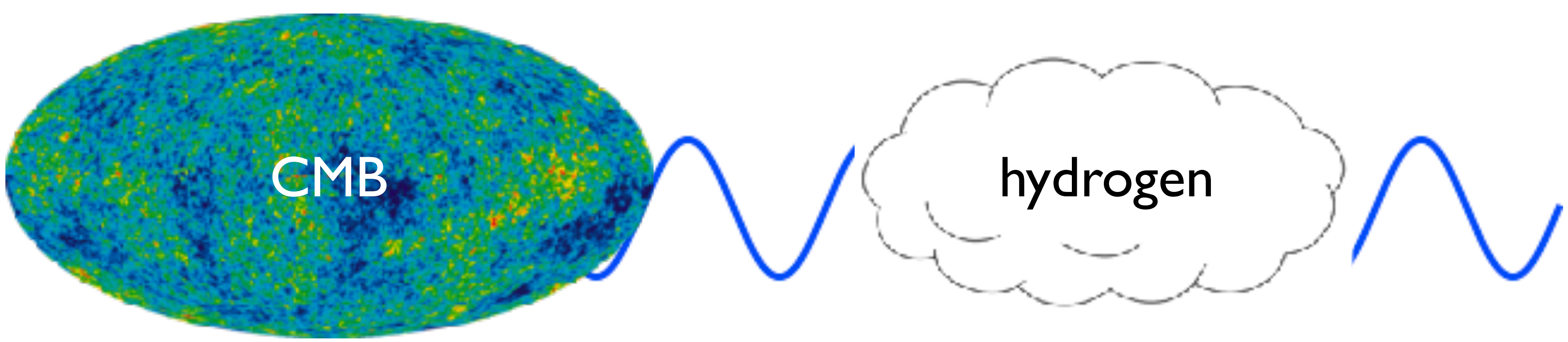
Absorption and spontaneous emission of Ly-α photons mixes hyperfine levels!



Wouthuysen (1952)
Field (1958)

21-cm Physics

T_γ T_S δT_b



Adapted from J. Pritchard

e.g., EDGES

“Differential brightness temperature”:

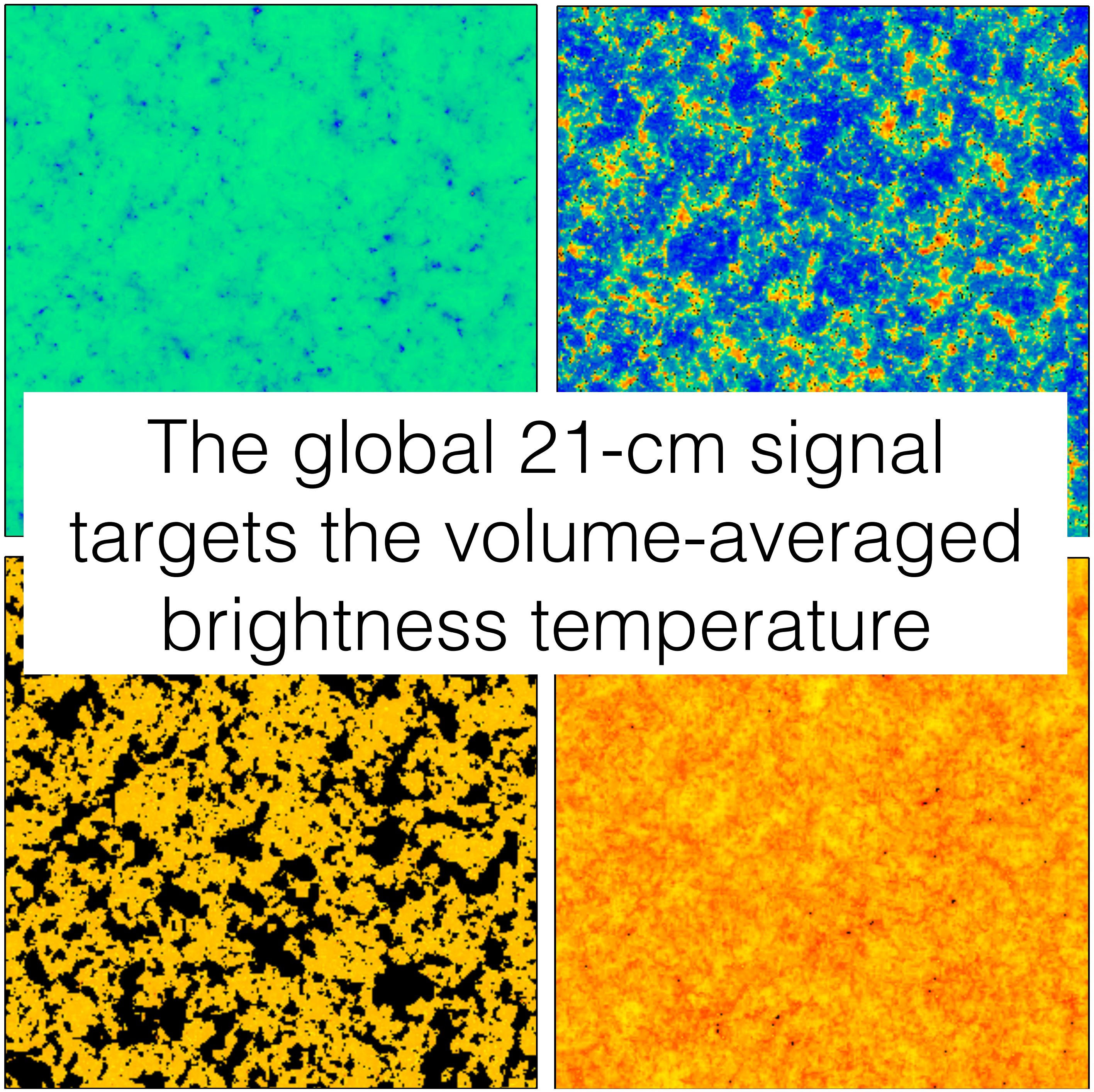
$$\delta T_b \approx 27\,\boxed{x_{\rm HI}}\,(1+\cancelto{0}{\delta})\left(\frac{1+z}{10}\right)^{1/2}\left[1-\boxed{\frac{T_\gamma}{T_S}}\right]\,\mathrm{mK}$$

for global signal

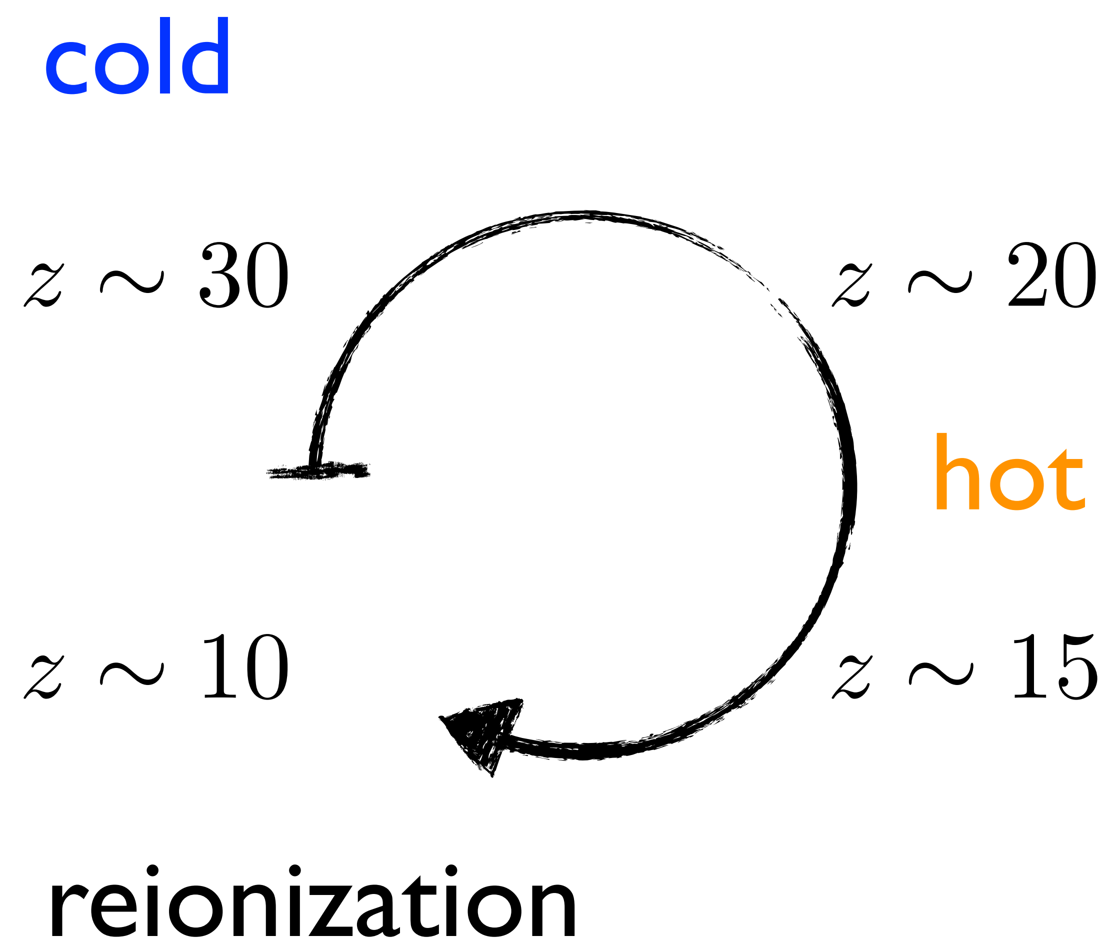
e.g., Furlanetto (2006)

The 21-cm Sky

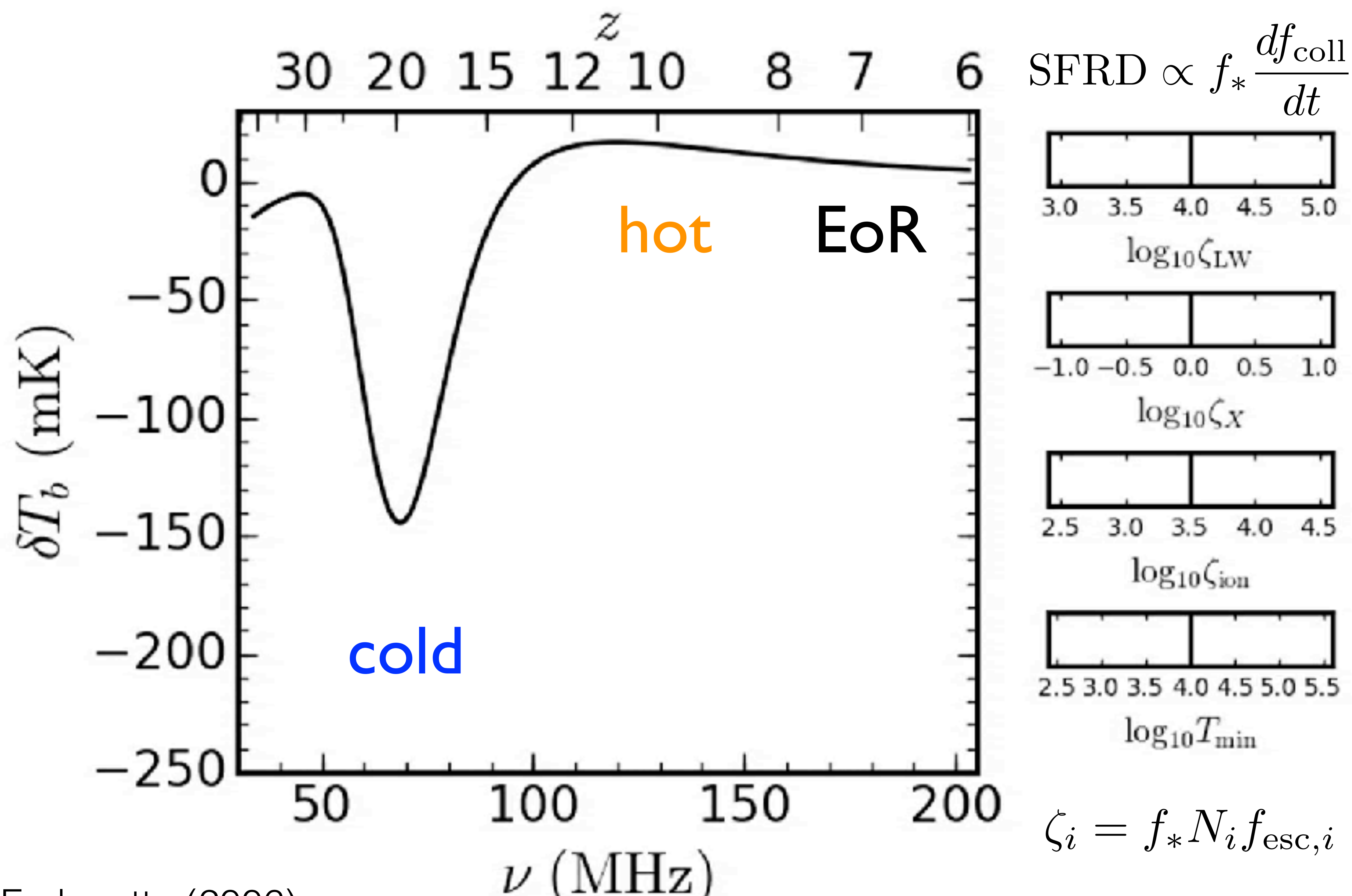
from Mesinger+ 2011



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



The Global 21-cm Signal

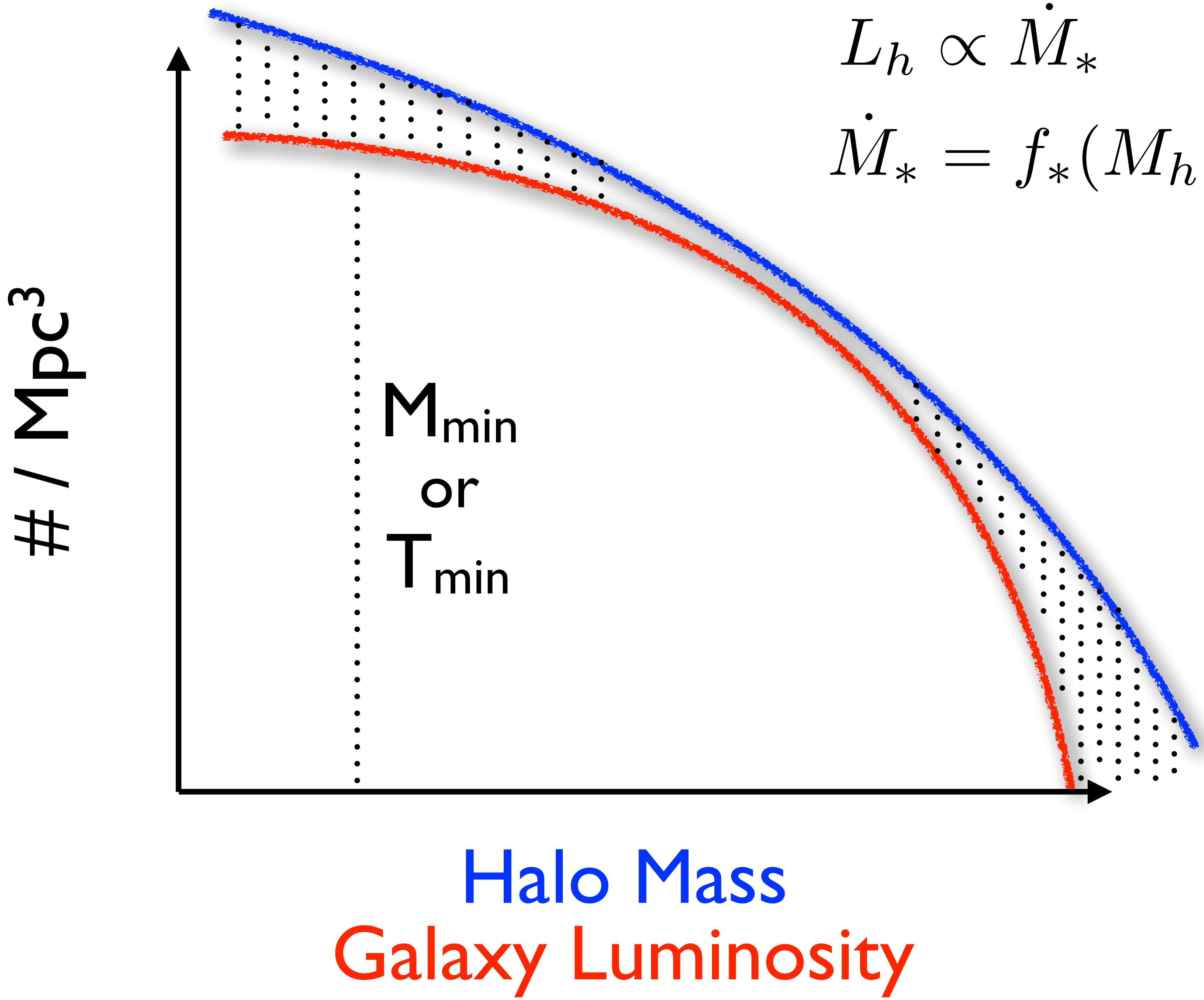


$$\zeta_i = f_* N_i f_{\mathrm{esc},i}$$

e.g., Furlanetto (2006)

Part I: Calibrating Models

LF-calibrated models



$$L_h \propto \dot{M}_*$$

$$\dot{M}_* = f_*(M_h, z)\dot{M}_h(M_h, z)$$

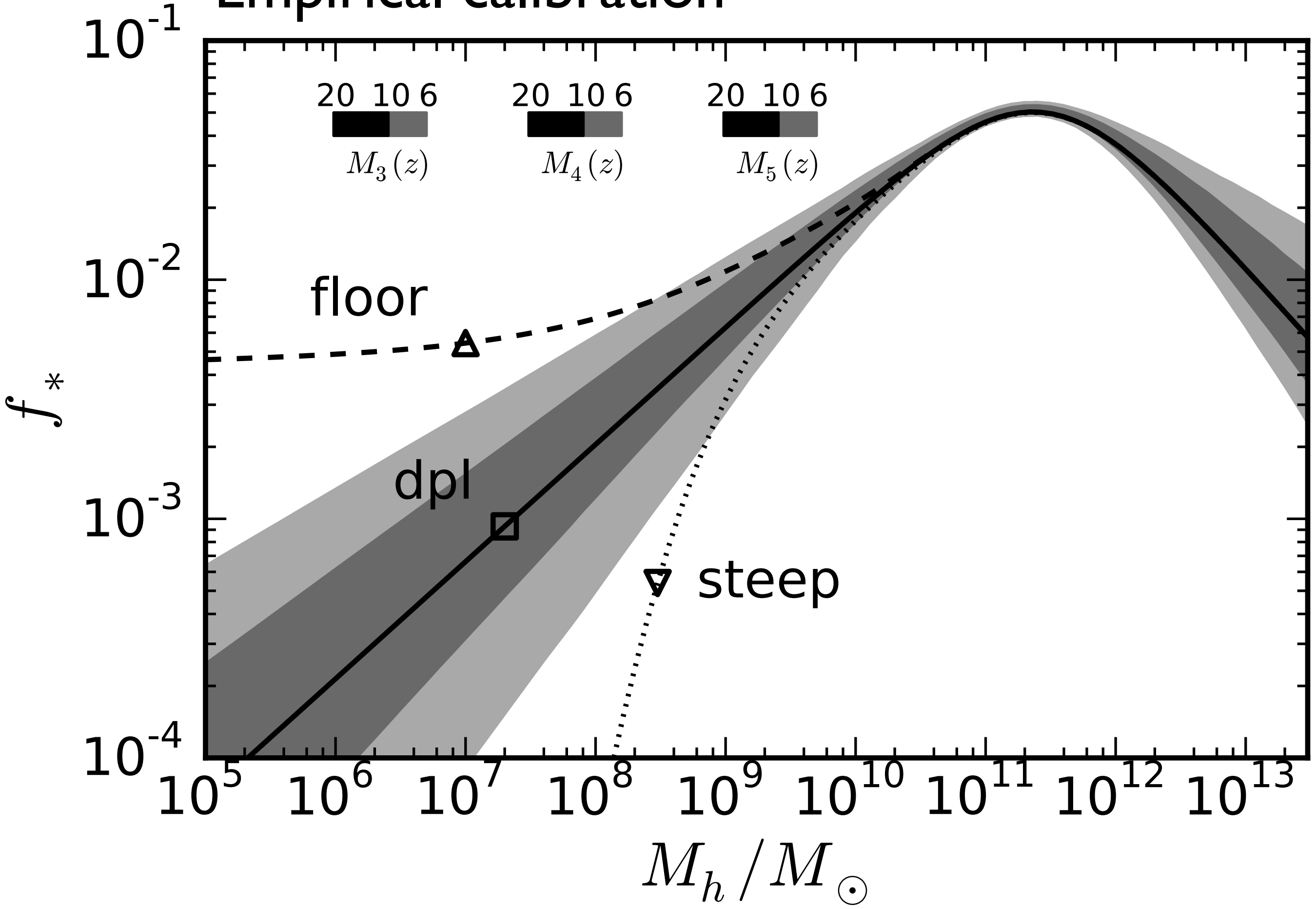
SFE is no longer a free parameter, it is tuned to match the LF.

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

Star formation efficiency

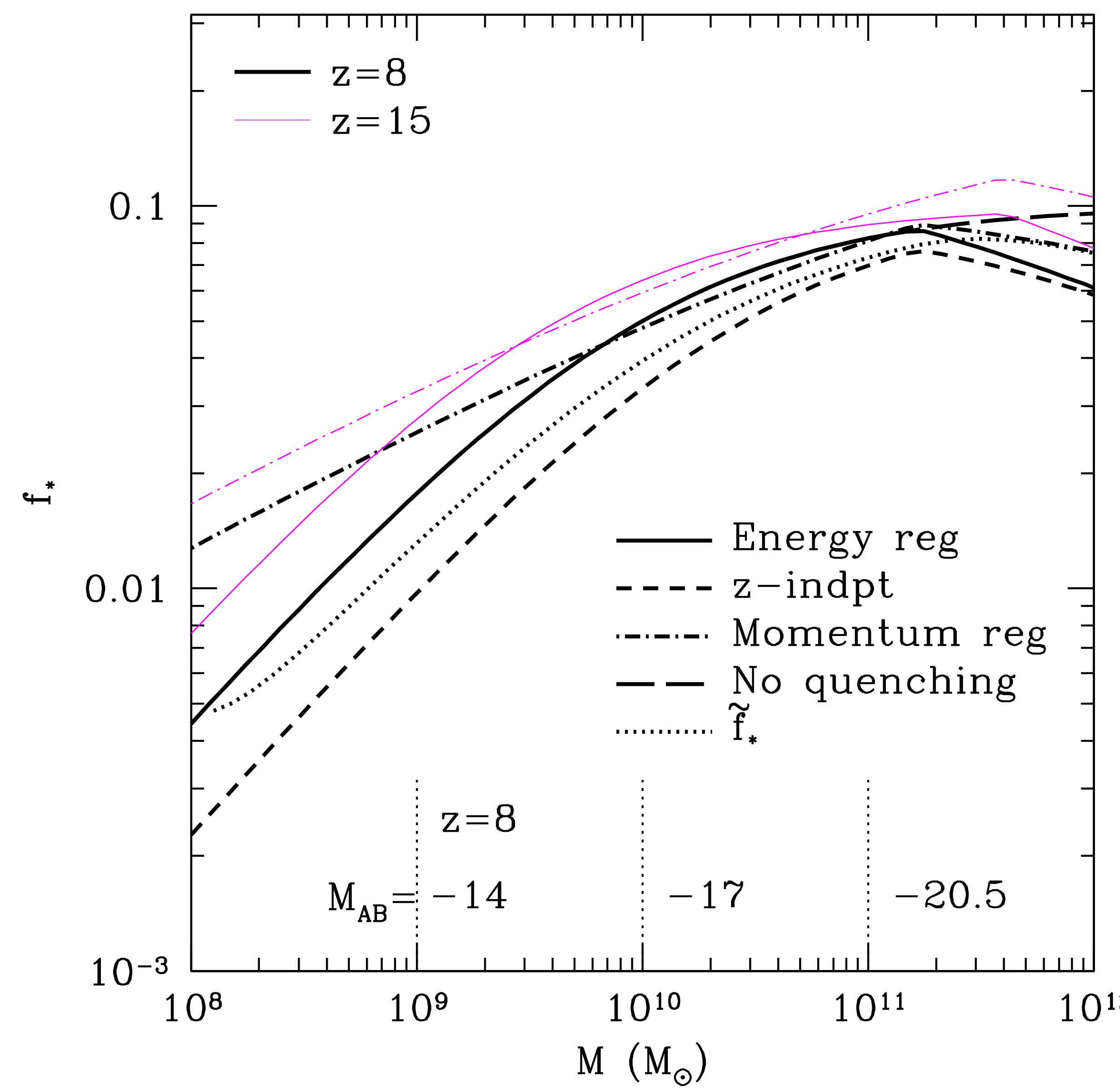
Not a constant! Typically < 10%.

Empirical calibration



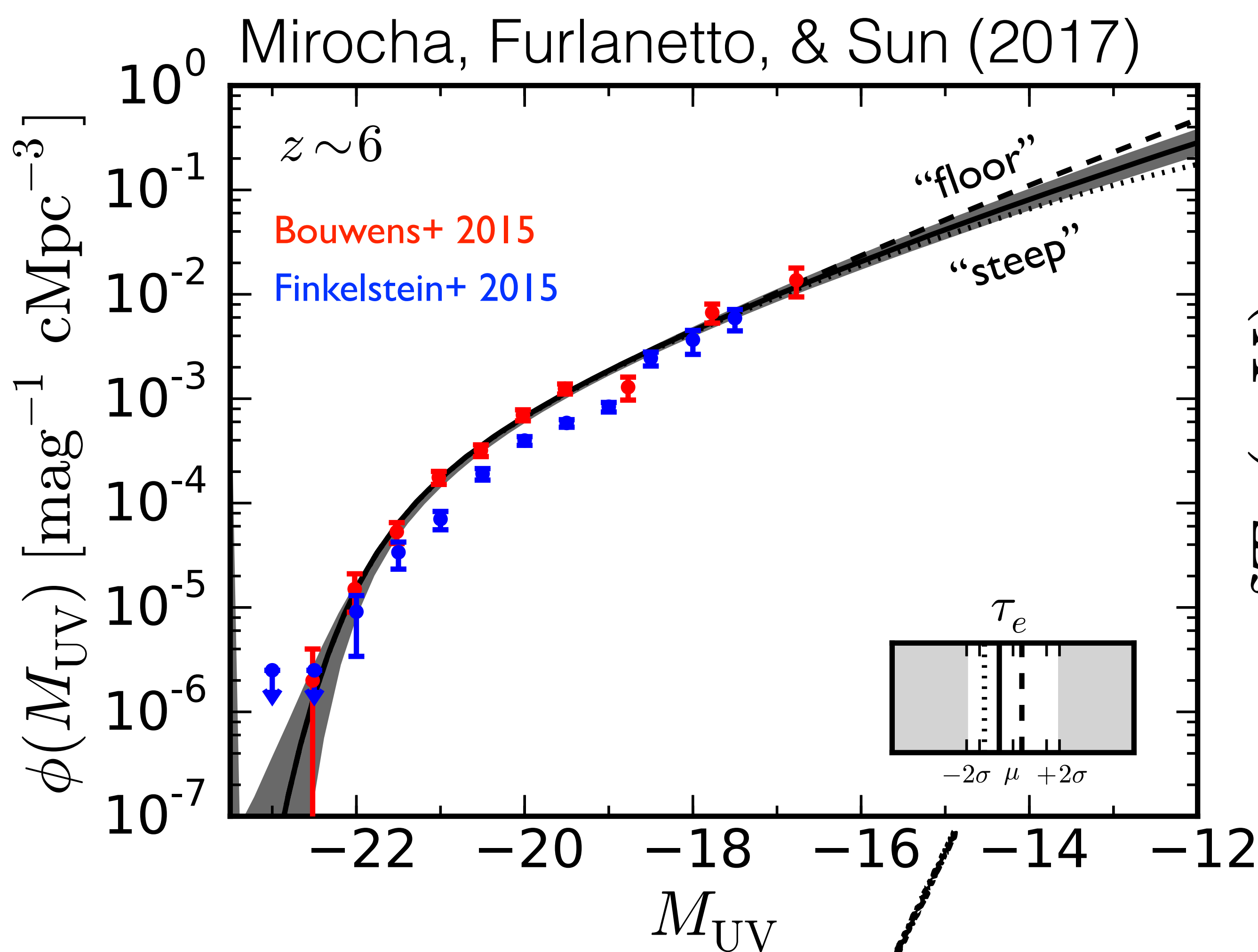
Mirocha, Furlanetto, & Sun (2017)

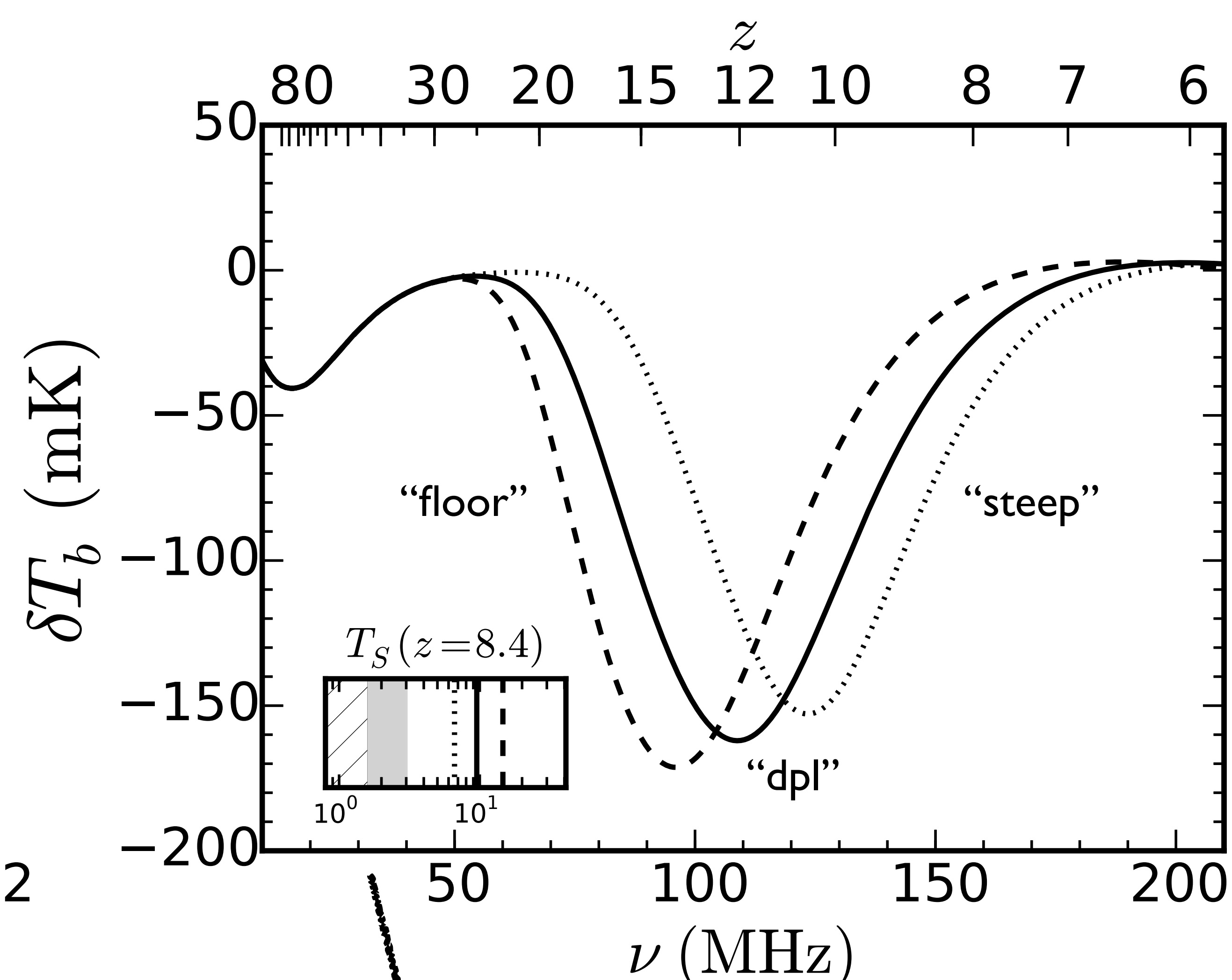
"Minimalist" physical model



Furlanetto, Mirocha+ (astro-ph/1611.01169)

“Best” Guess Model?



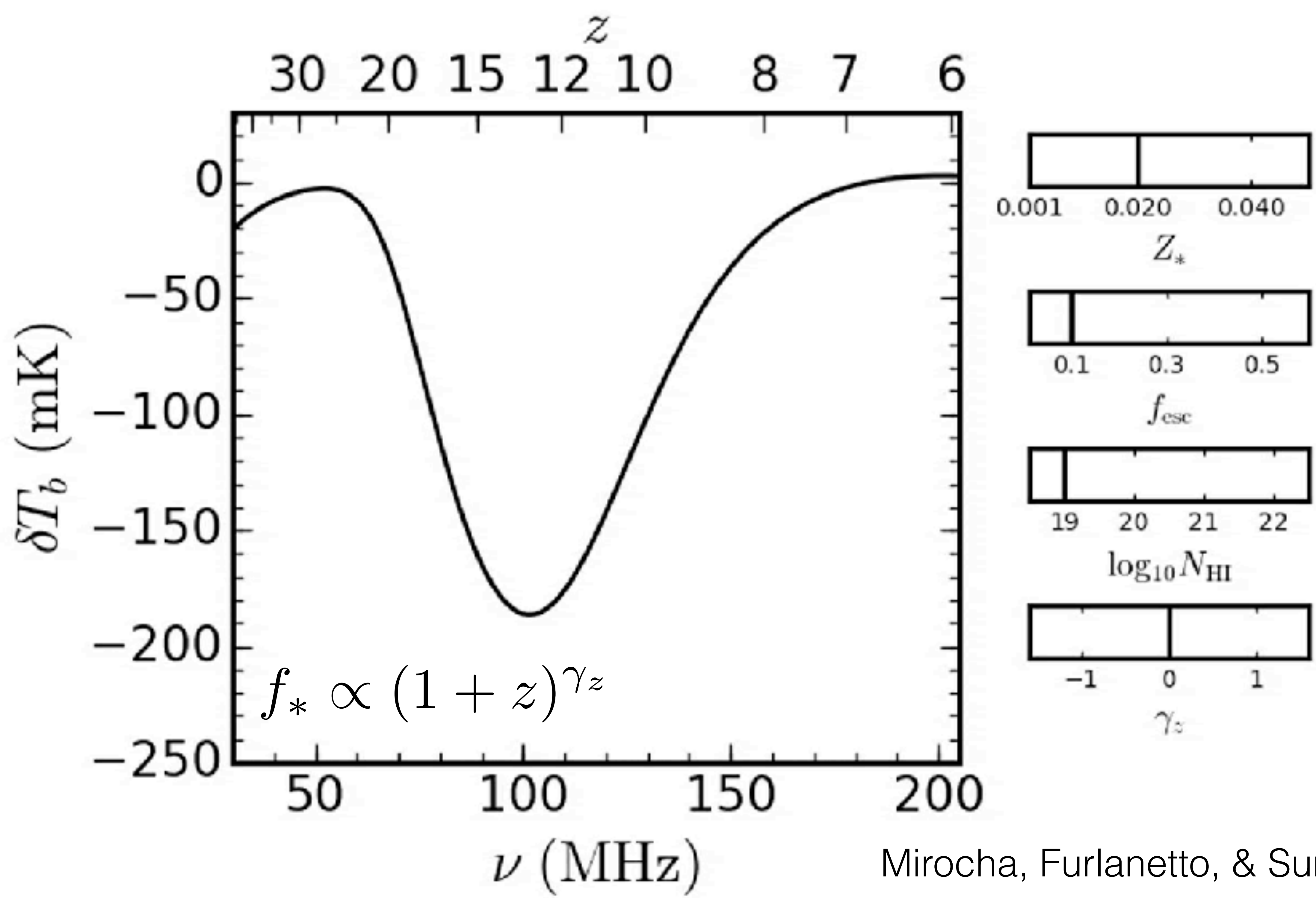


Planck: $\tau_e = 0.055 \pm 0.009$

PAPER: $T_S(z = 8.4) \gtrsim 3$ K

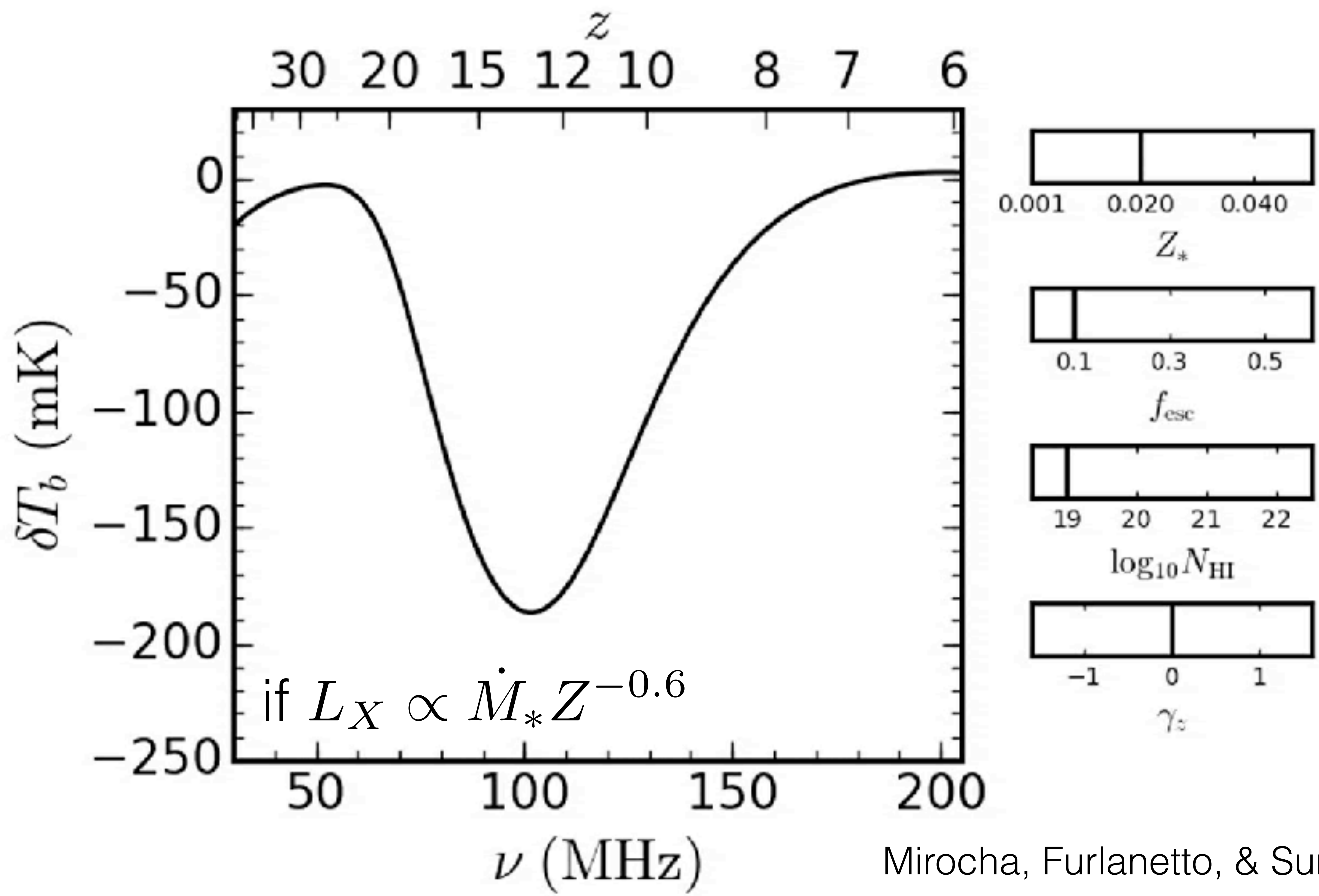
Parsons+ (2014), Ali+(2015), Pober+(2015), Greig+ (2016)

LF-Calibrated Models



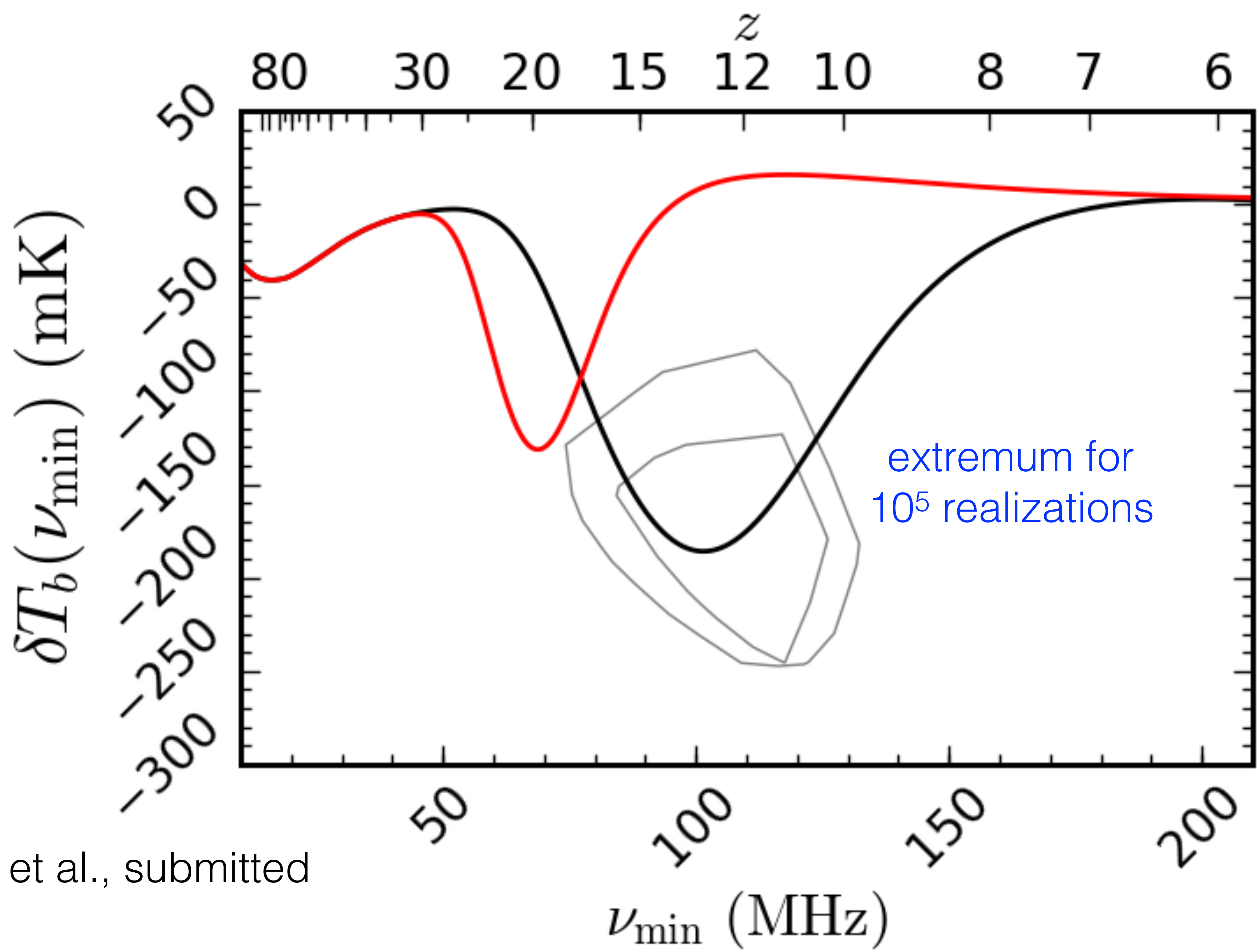
Mirocha, Furlanetto, & Sun (2017)

LF-Calibrated Models



Mirocha, Furlanetto, & Sun (2017)

Expanded PopII Model Set



Mirocha et al., submitted

Summary: Part I

- Galaxy LFs provide solid anchor for global 21-cm predictions.
- Deep, ~100 MHz trough is a generic feature.
- Caveat: completely neglected smallest halos.
- Bright side: rule out these models, strong evidence of new sources?
- *How important are very small halos likely to be? Hope of unique signature?*

Part II: PopIII Signatures

Quick Estimate

Assume 1 star-forming site per halo:

$$\dot{M}_* = \frac{\overset{1}{N_*}\,\overset{100\ \mathrm{M_{sun}}}{M_*}}{\underset{5\ \mathrm{Myr}}{\tau_{\rm ms}} + \underset{0\ \mathrm{Myr}}{\tau_{\rm recov}}} \approx 2 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$$

How many PopIII host halos at high-z? ~1-10 cMpc^{-3}, so

$$\dot{\rho}_{*,\rm III} \lesssim 2 \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{cMpc}^{-3}$$

That's not great news. 100-1000x less than SFRD at z~6.

But…

$$L_X \sim 2\times 10^{39}\mathrm{erg\ s^{-1}}\left(\frac{\dot{M}_*}{M_\odot\ \mathrm{yr}^{-1}}\right)$$

HMXBs observed locally, e.g., Mineo+ 2012

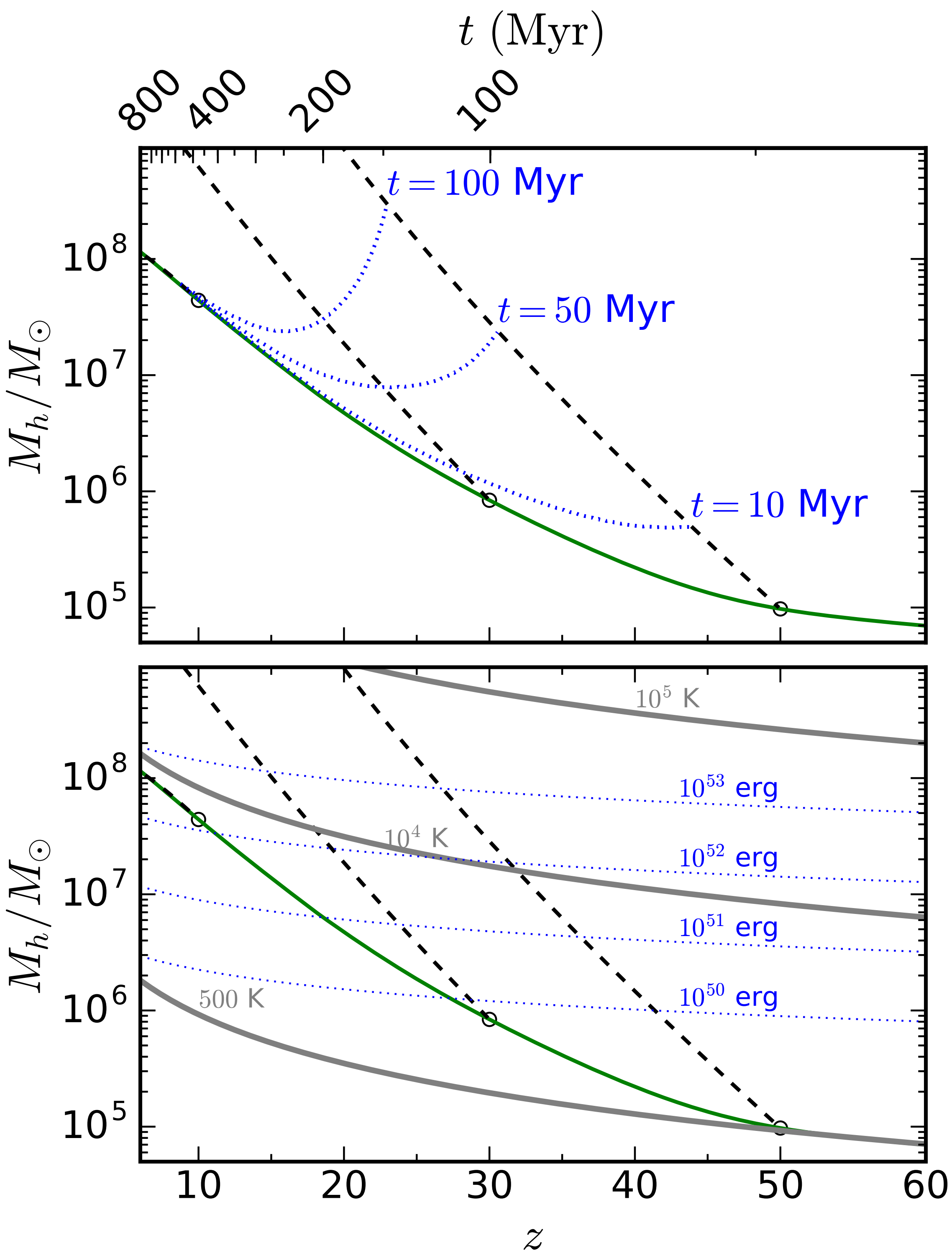
$$f_{X,\mathrm{III}} \equiv \underbrace{\times\left(\frac{\epsilon}{0.1}\right)\boxed{\left(\frac{f_\bullet}{10^{-3}}\right)}\left(\frac{f_{\rm bin}}{0.5}\right)\left(\frac{\tau}{20\ \mathrm{Myr}}\right)\left(\frac{f_{\rm sur}}{0.2}\right)\left(\frac{f_{\rm act}}{0.1}\right)}$$

for PopIII: $f_\bullet \sim 1$?

e.g., Mirabel+ 2011

so you're sayin' there's a chance…

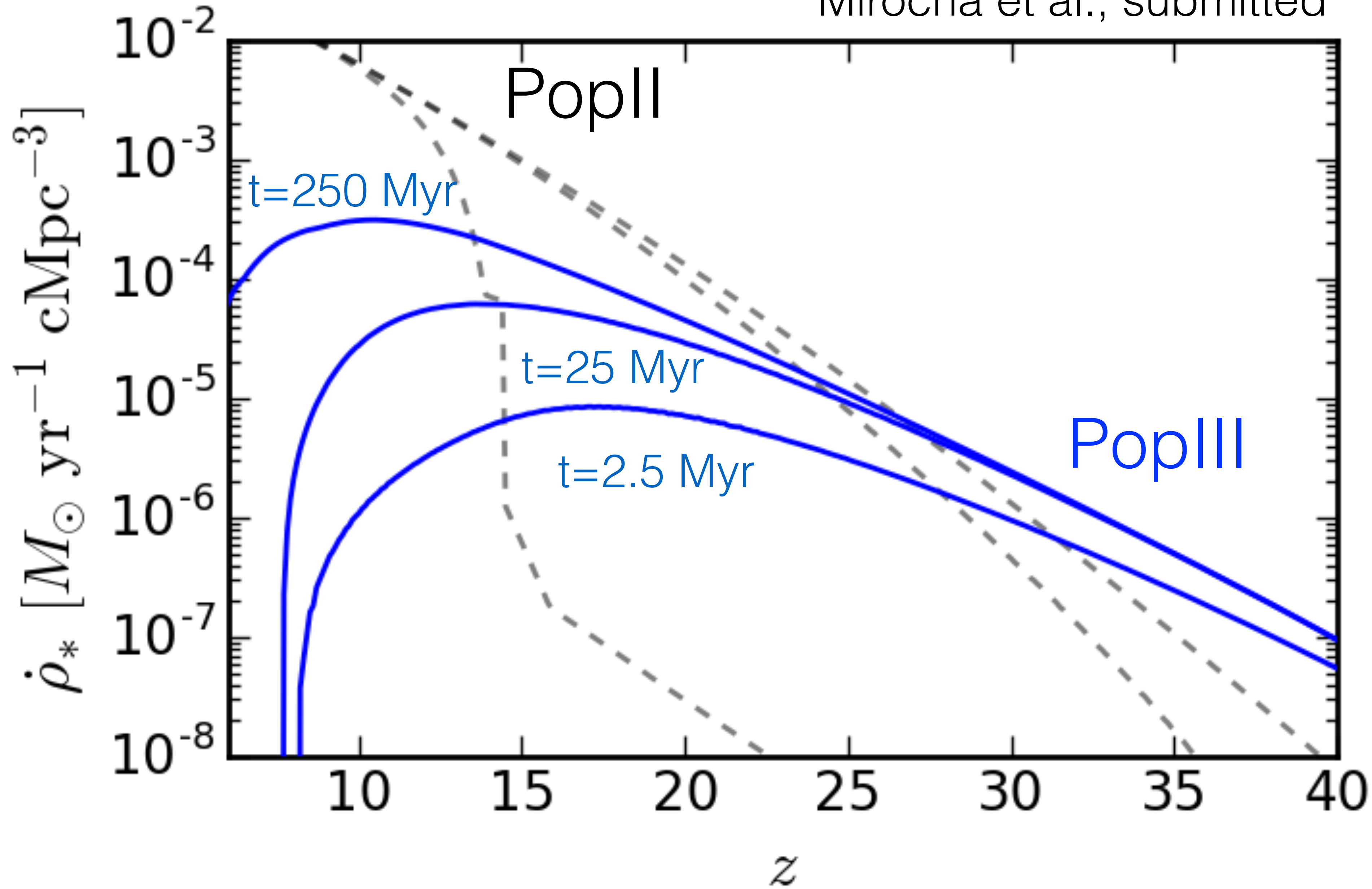
Simple PopIII SF Model



- PopIII stars begin forming in halos with $M_h > M_{min}$, M_{min} set by J_{LW}.
- Assume single site of star formation per halo, SFR is free parameter.
- Transition to PopII occurs after fixed time interval or when critical binding energy surpassed (both free parameters).
  - Metal production vs. retention hack.

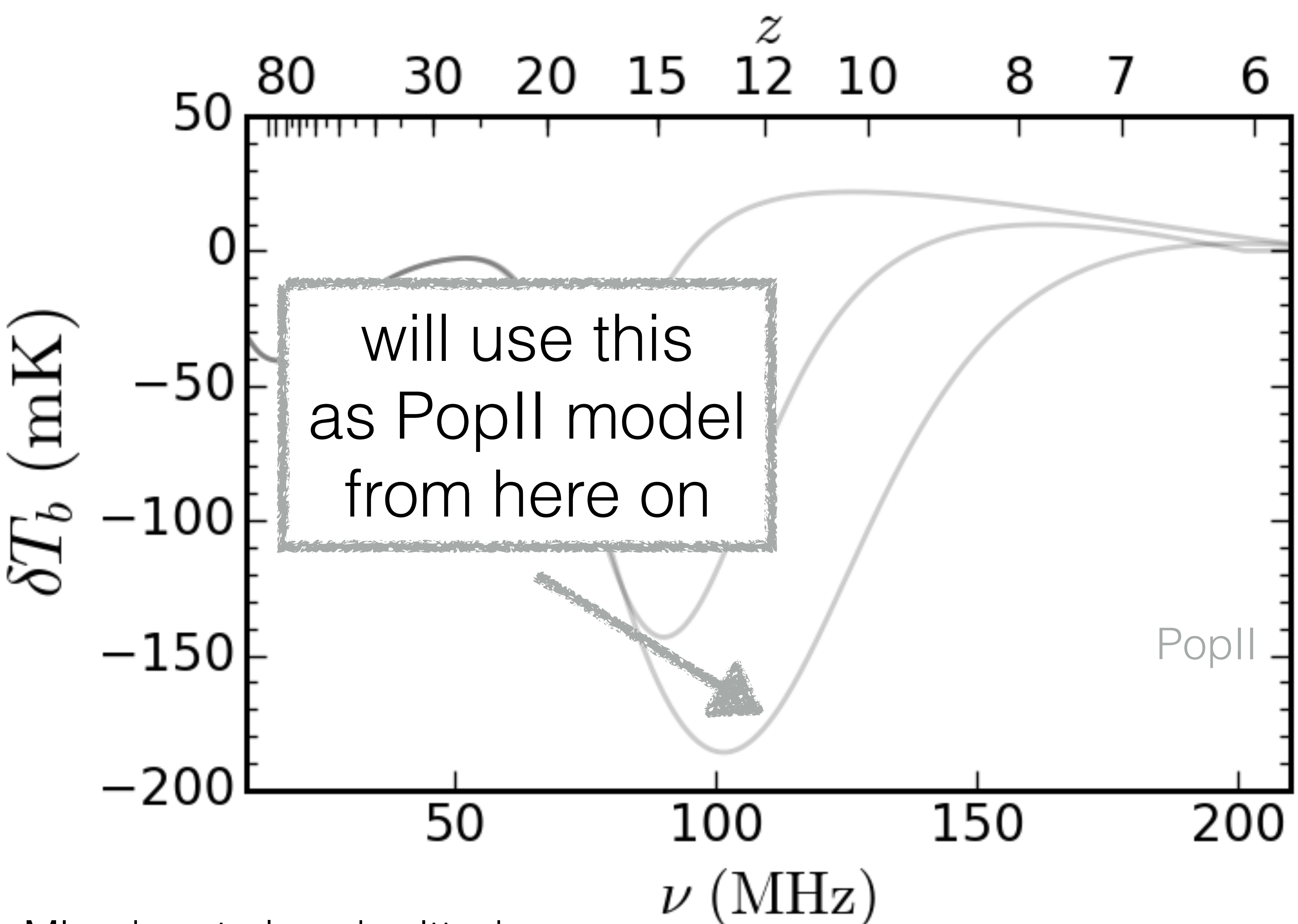
Characteristics of PopIII

Mirocha et al., submitted



see also, e.g.,
Trenti & Stiavelli (2009), Xu+ (2016), Mebane+, in prep.

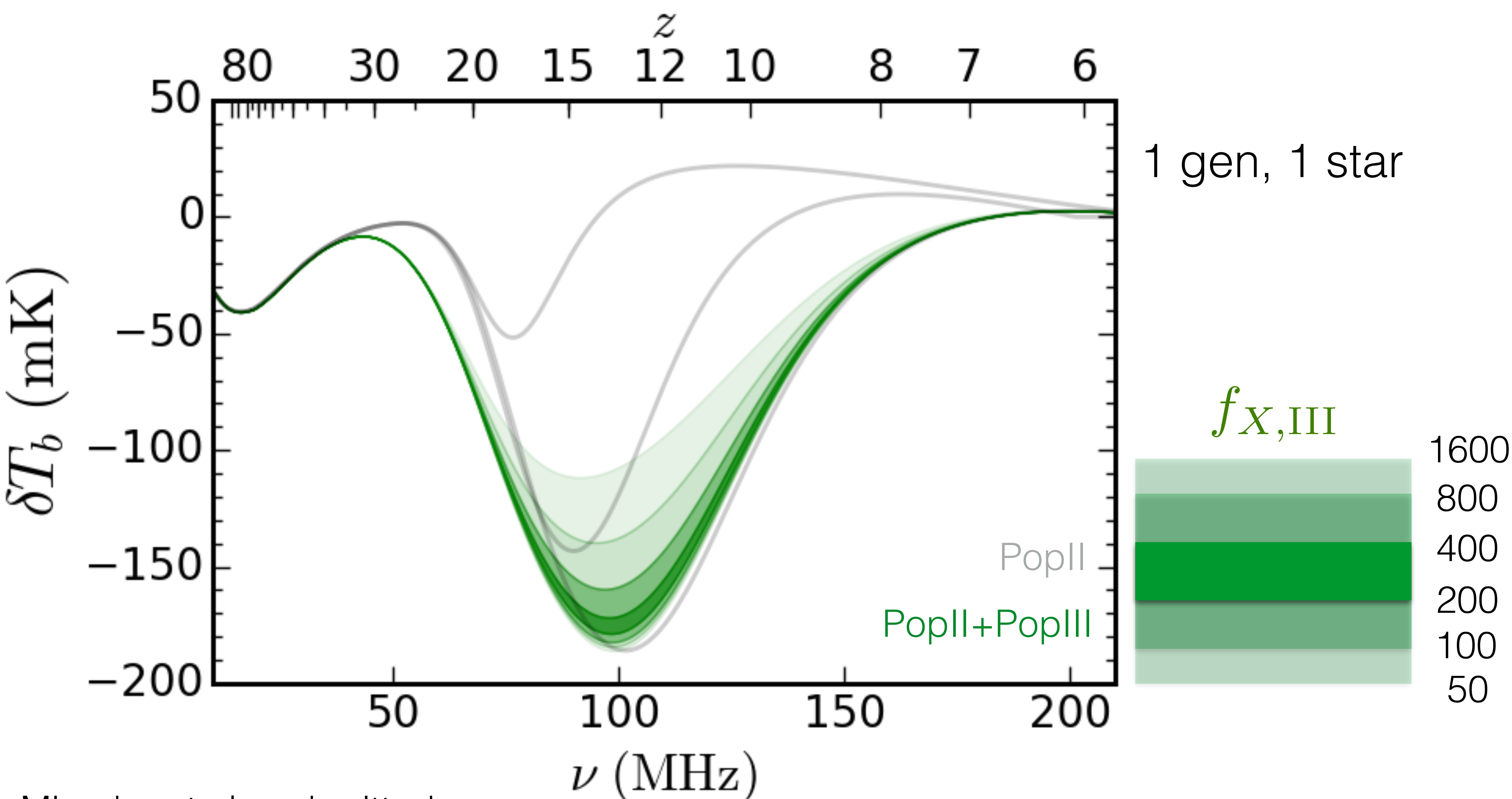
Basic Features of PopII



Shallow troughs = stronger emission peaks

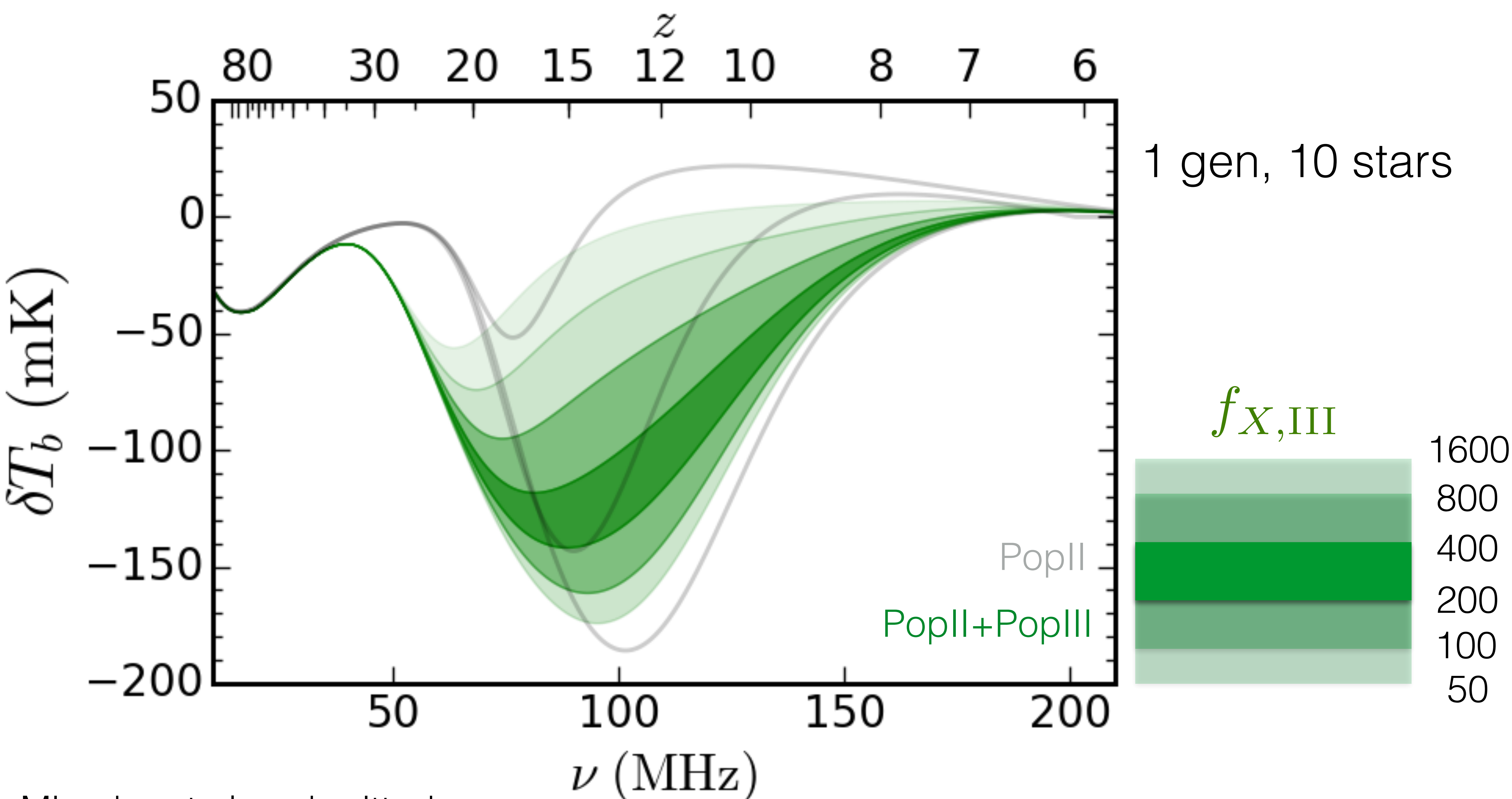
Mirocha et al., submitted

Impact of PopIII



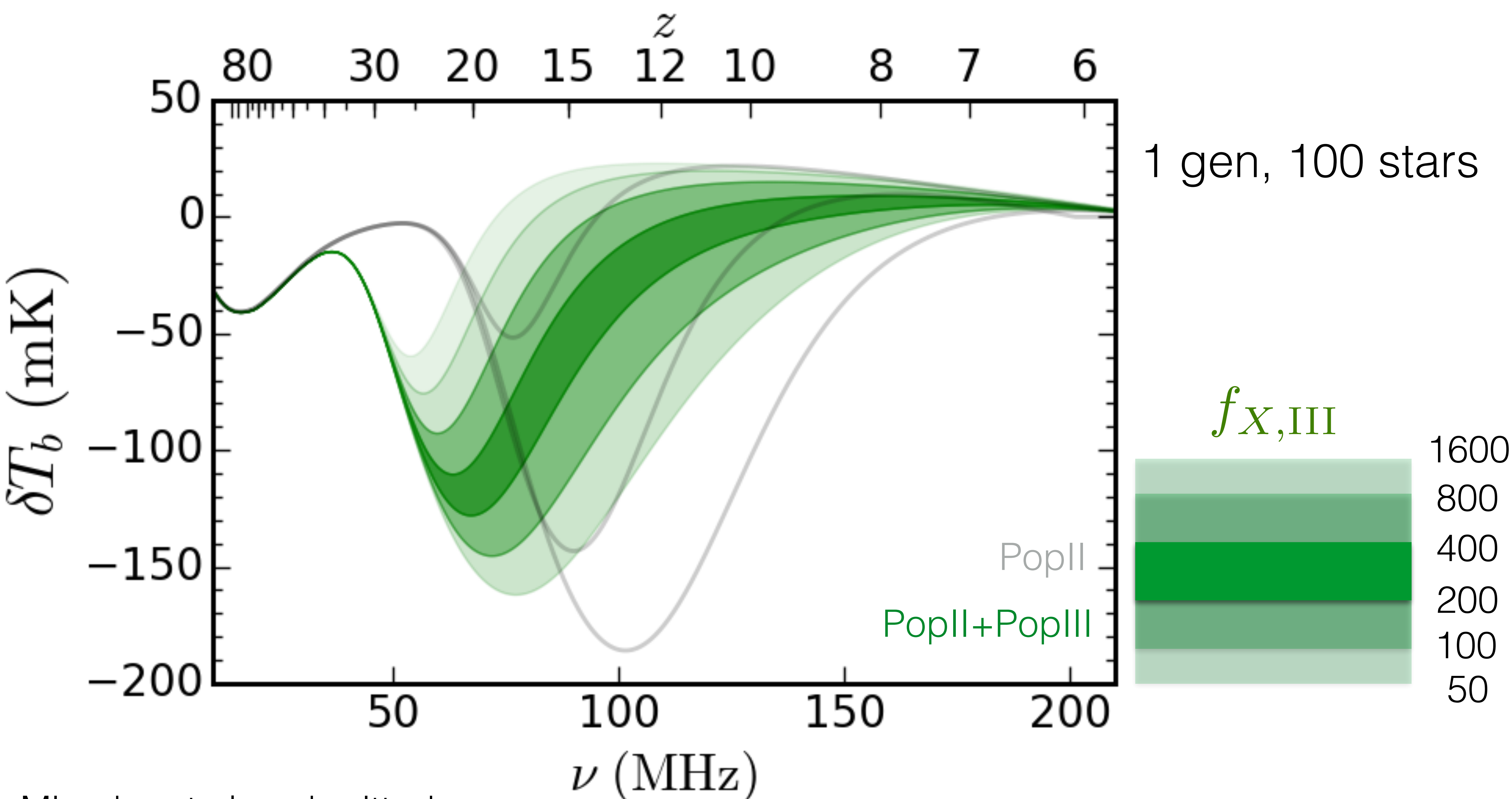
Mirocha et al., submitted

Impact of PopIII



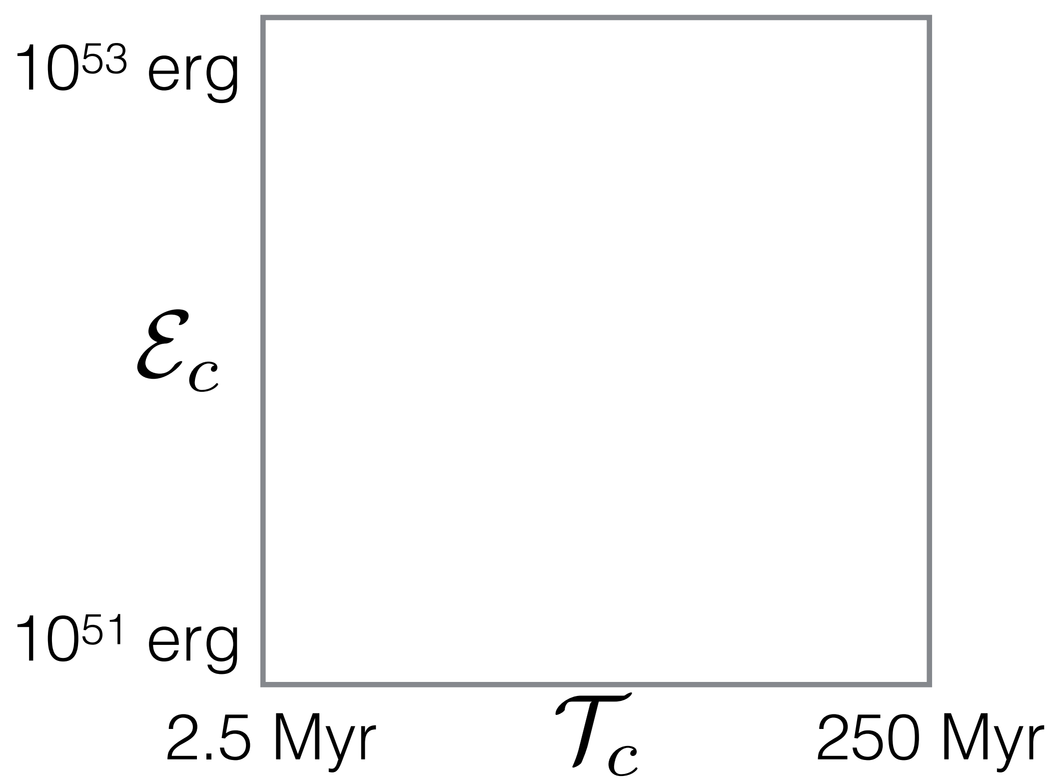
Mirocha et al., submitted

Impact of PopIII

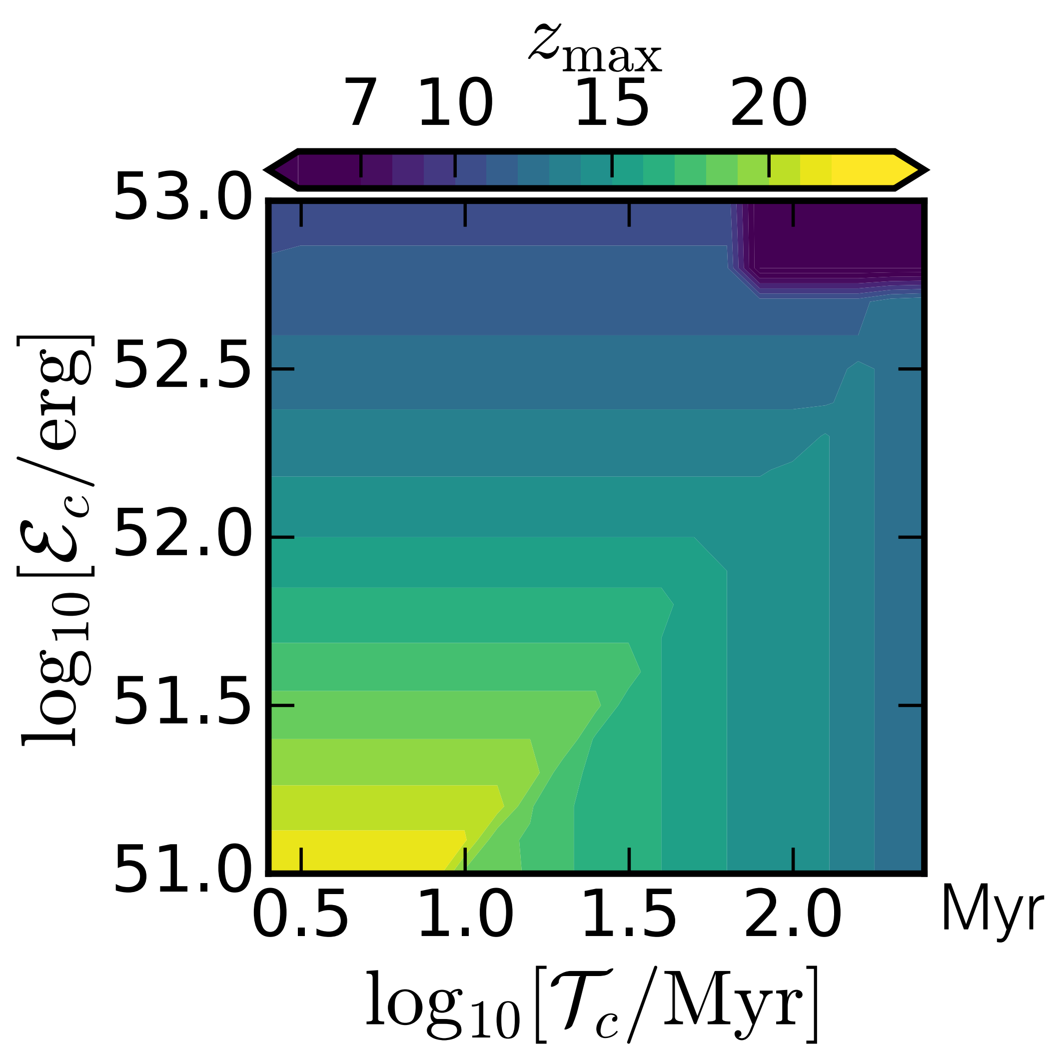


Mirocha et al., submitted

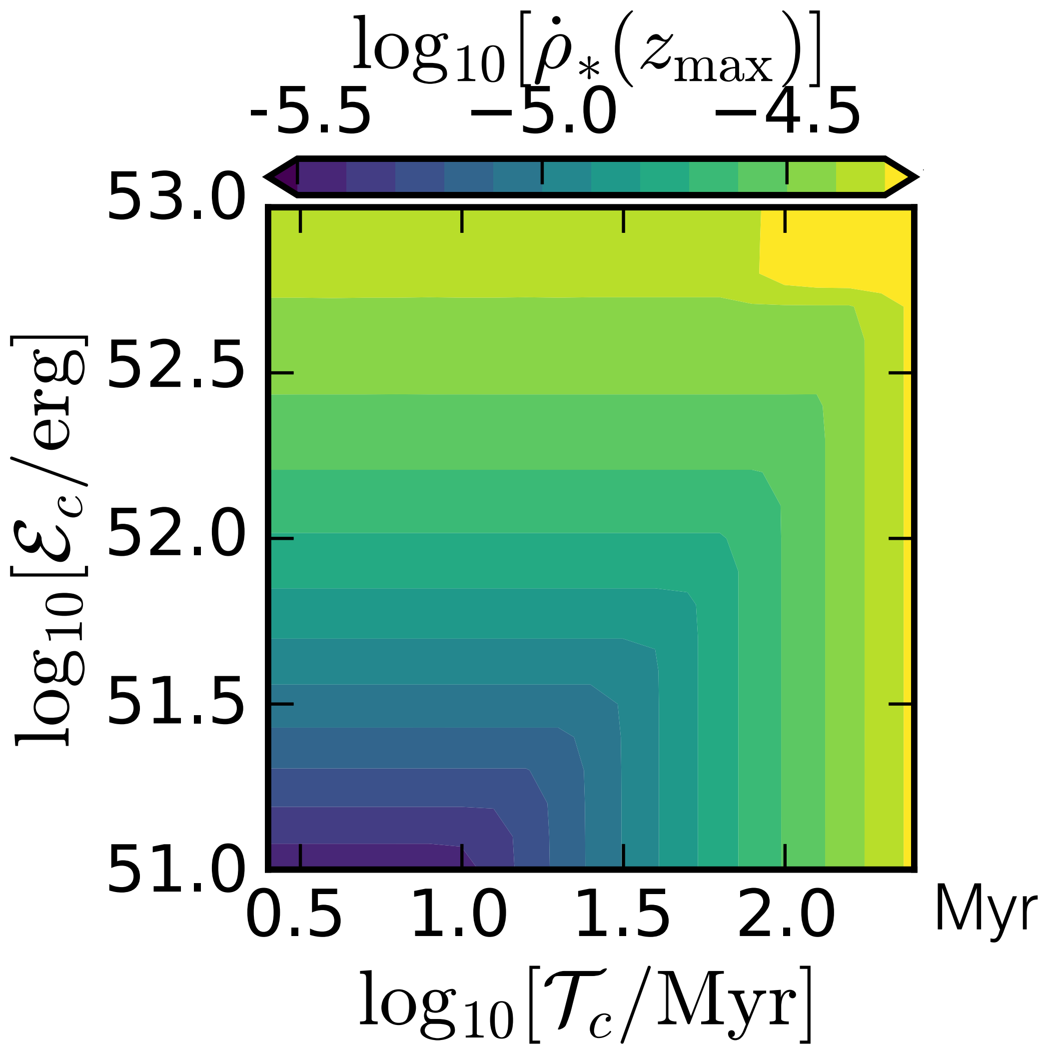
Expanded PopIII Model Set



Expanded PopIII Model Set



Expanded PopIII Model Set



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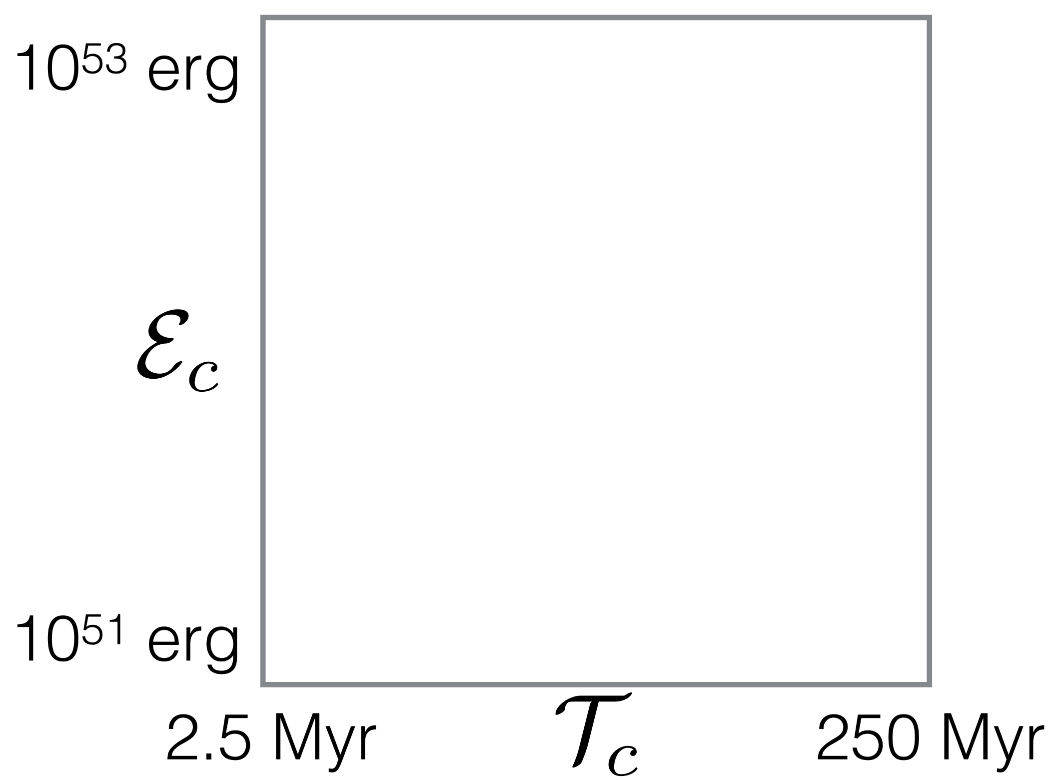
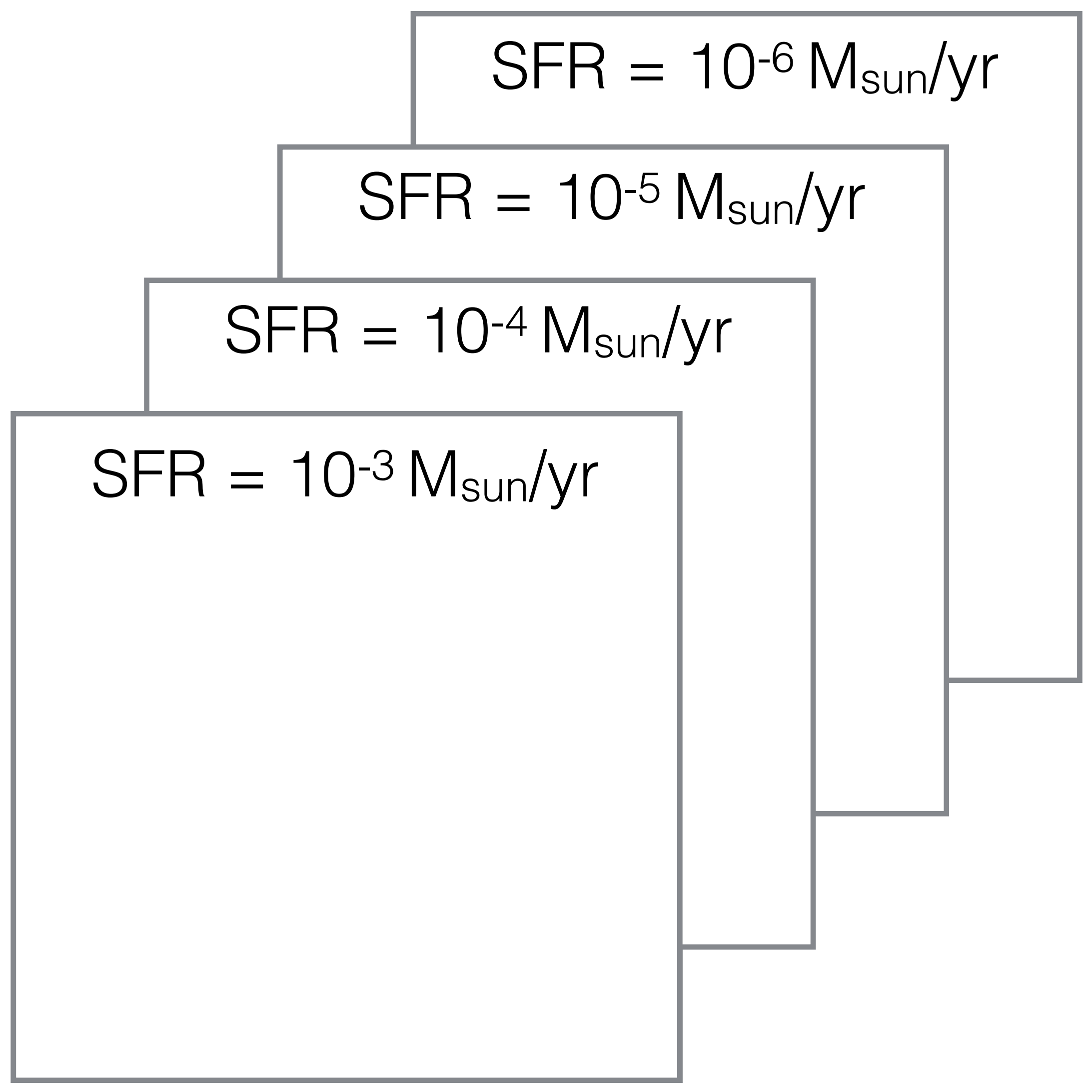
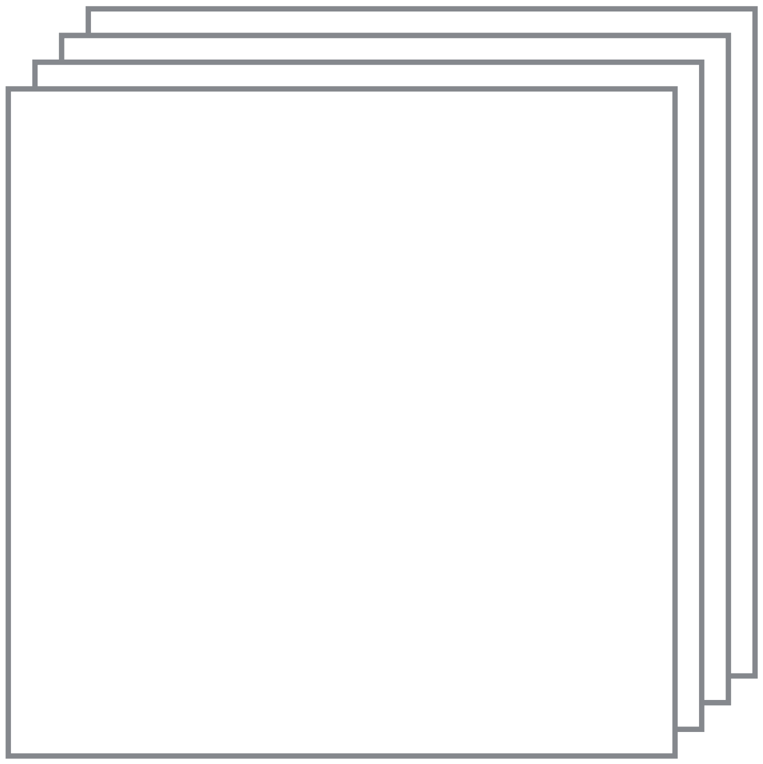


Expanded PopIII Model Set

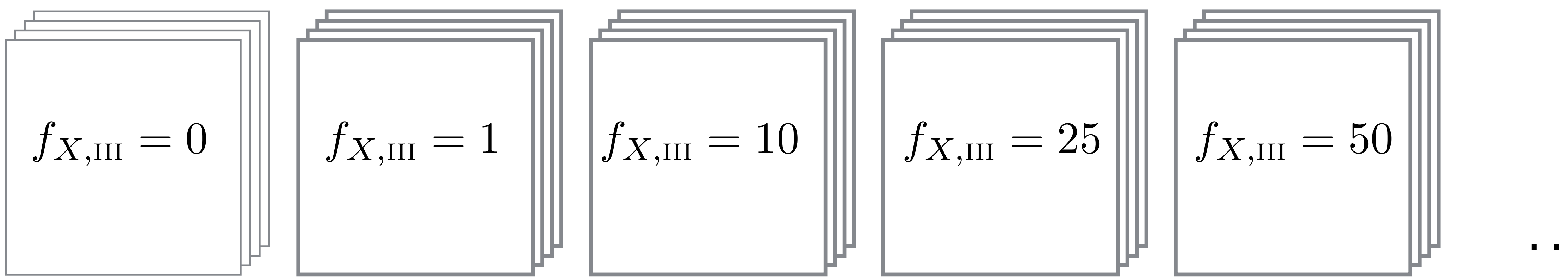


Expanded PopIII Model Set



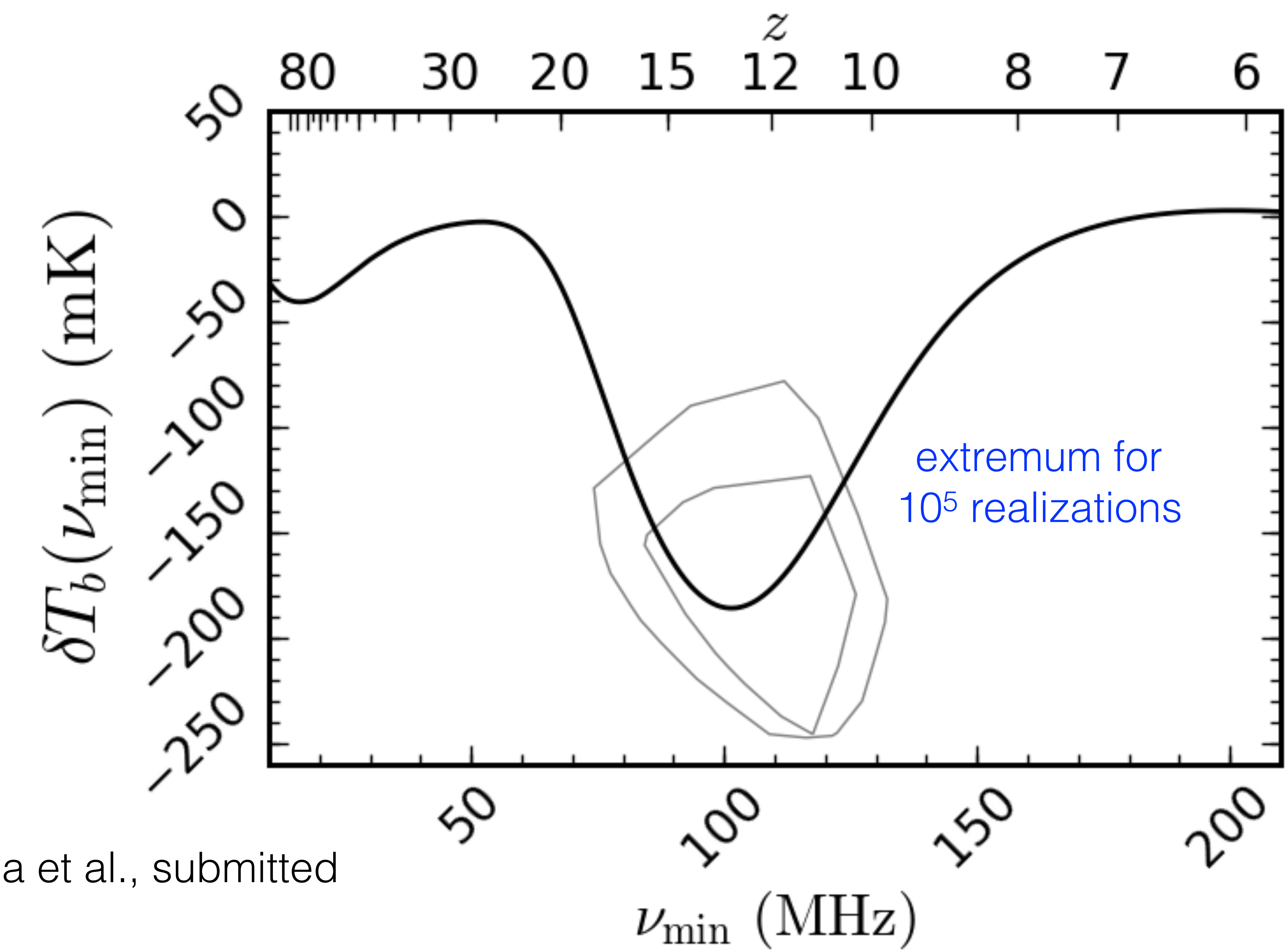
Expanded PopIII Model Set

Final set: 4-D grid, $\sim 10^5$ total models.



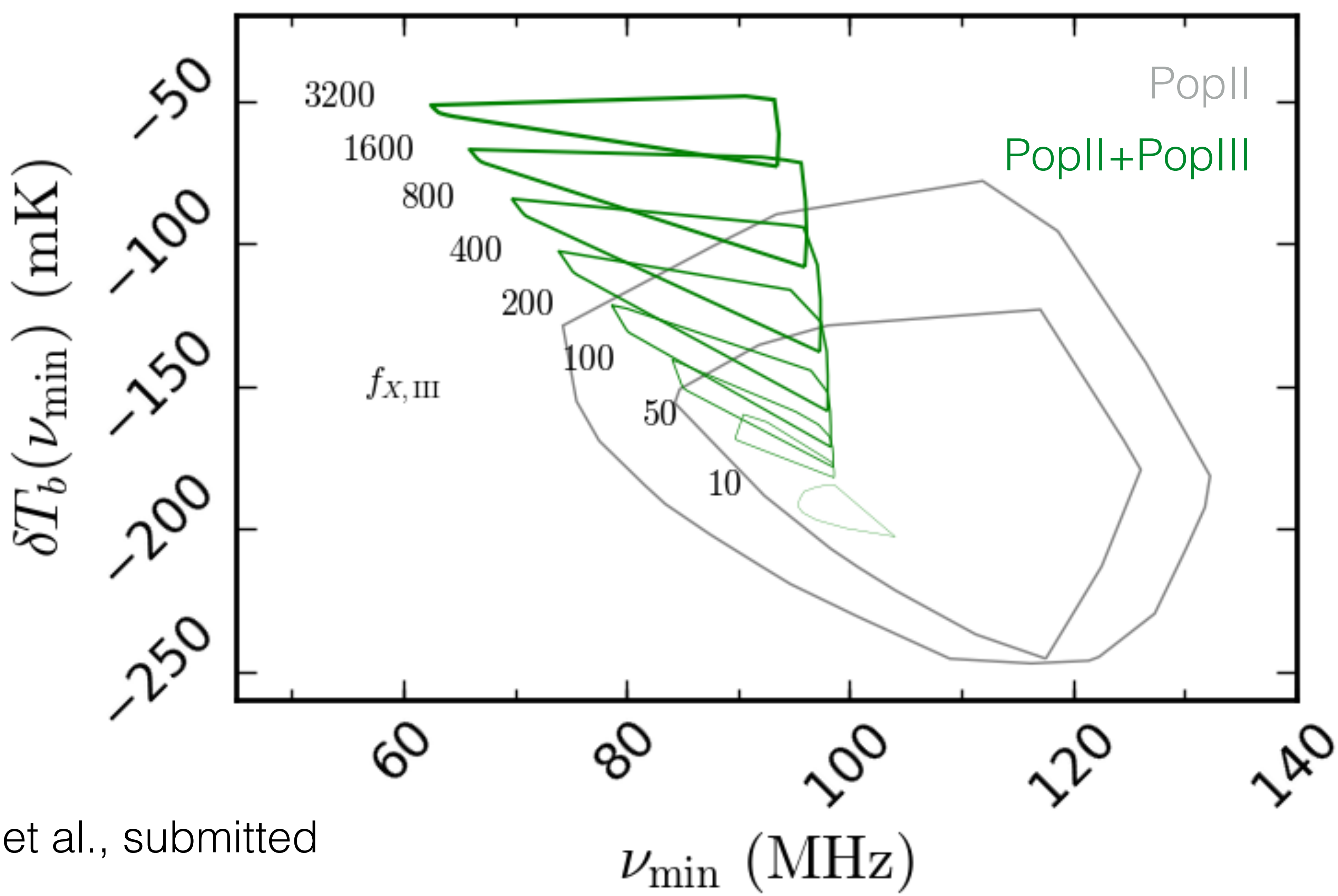
Will now slice through grid, re-project into variety of diagnostic spaces.

Expanded PopII Model Set



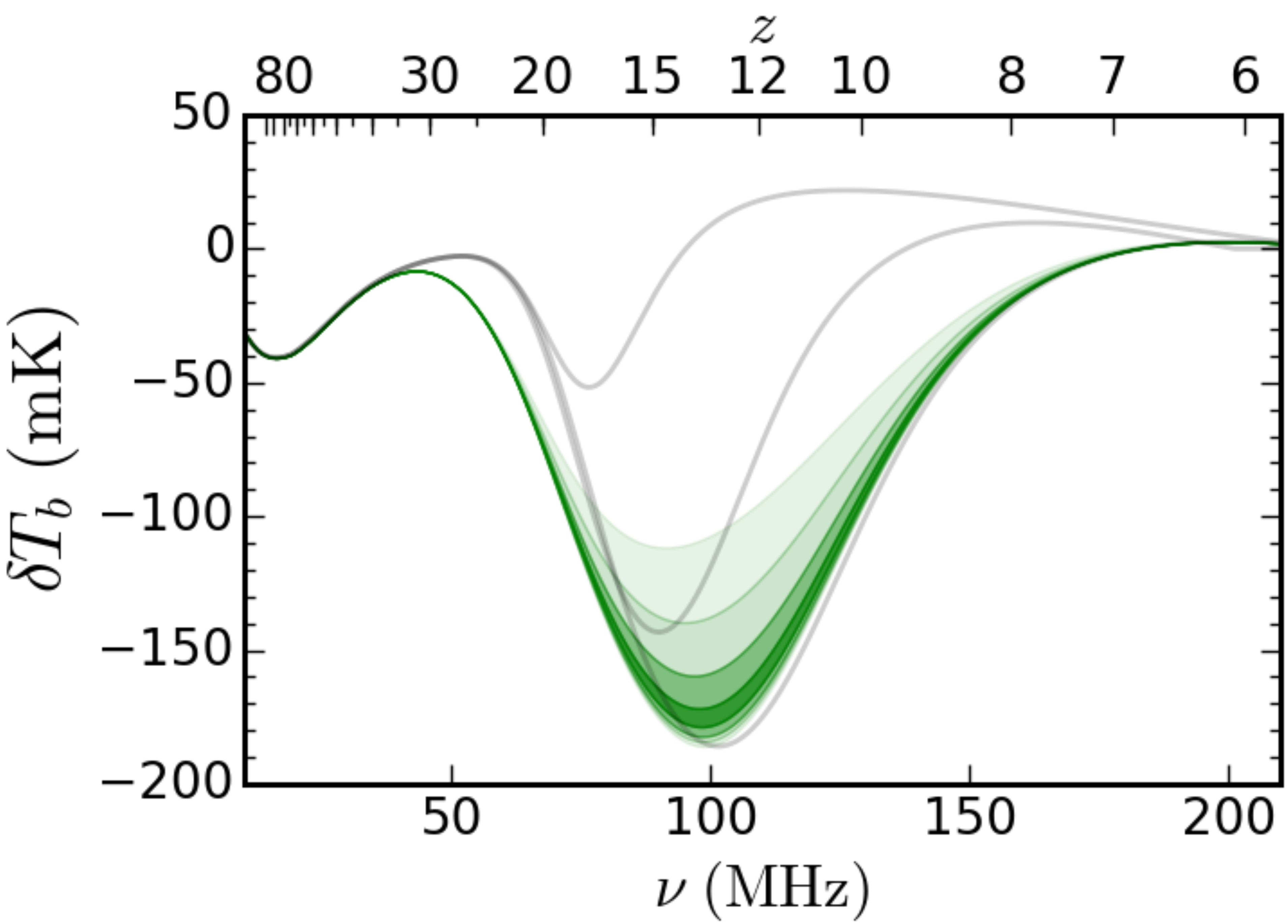
Mirocha et al., submitted

PopII vs. PopIII



Mirocha et al., submitted

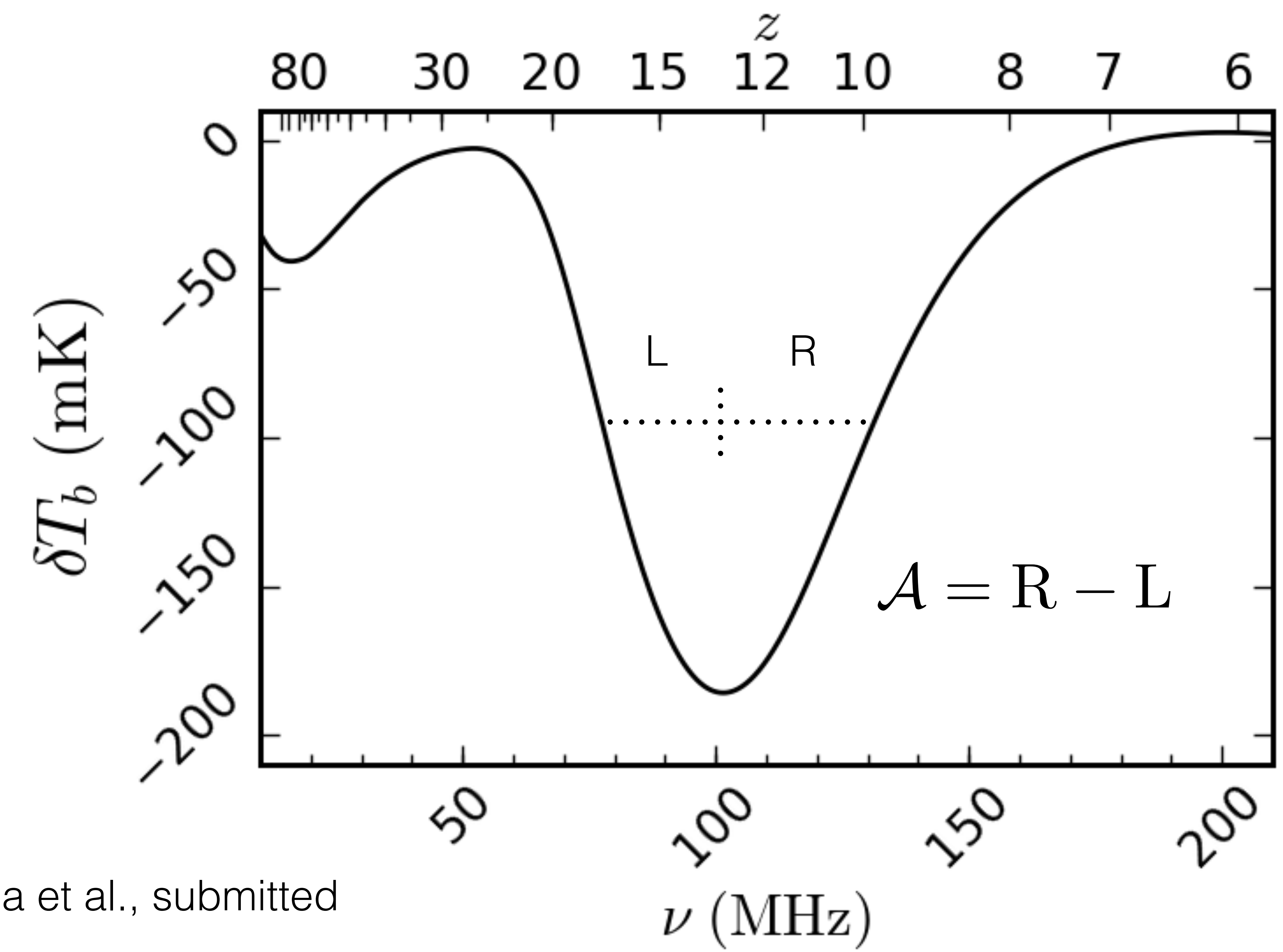
PopII vs. PopIII



Remember it's really that the *shape* is different, not just the amplitude.

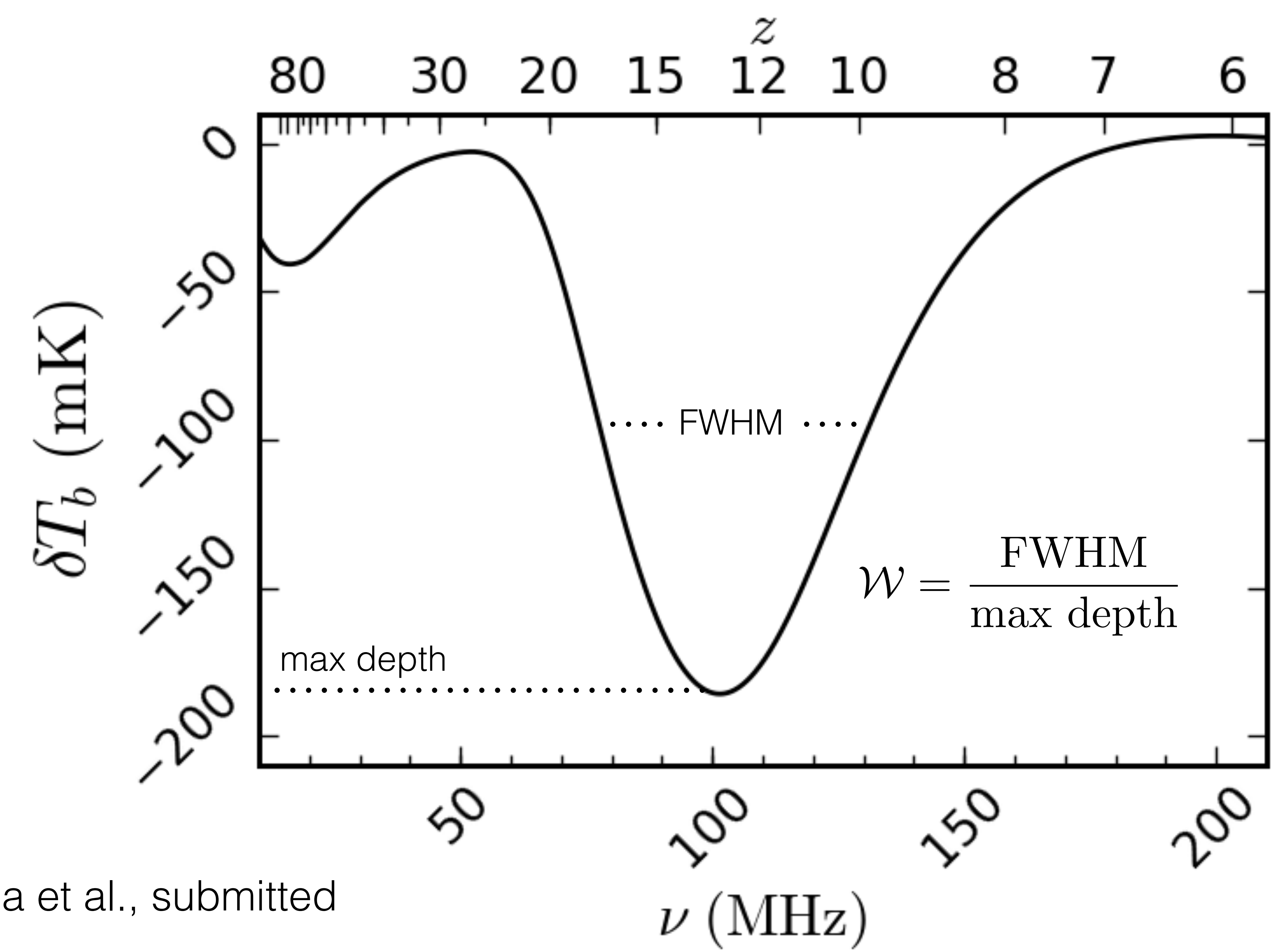
Mirocha et al., submitted

Shape Diagnostic: $\mathcal{A}$



Mirocha et al., submitted

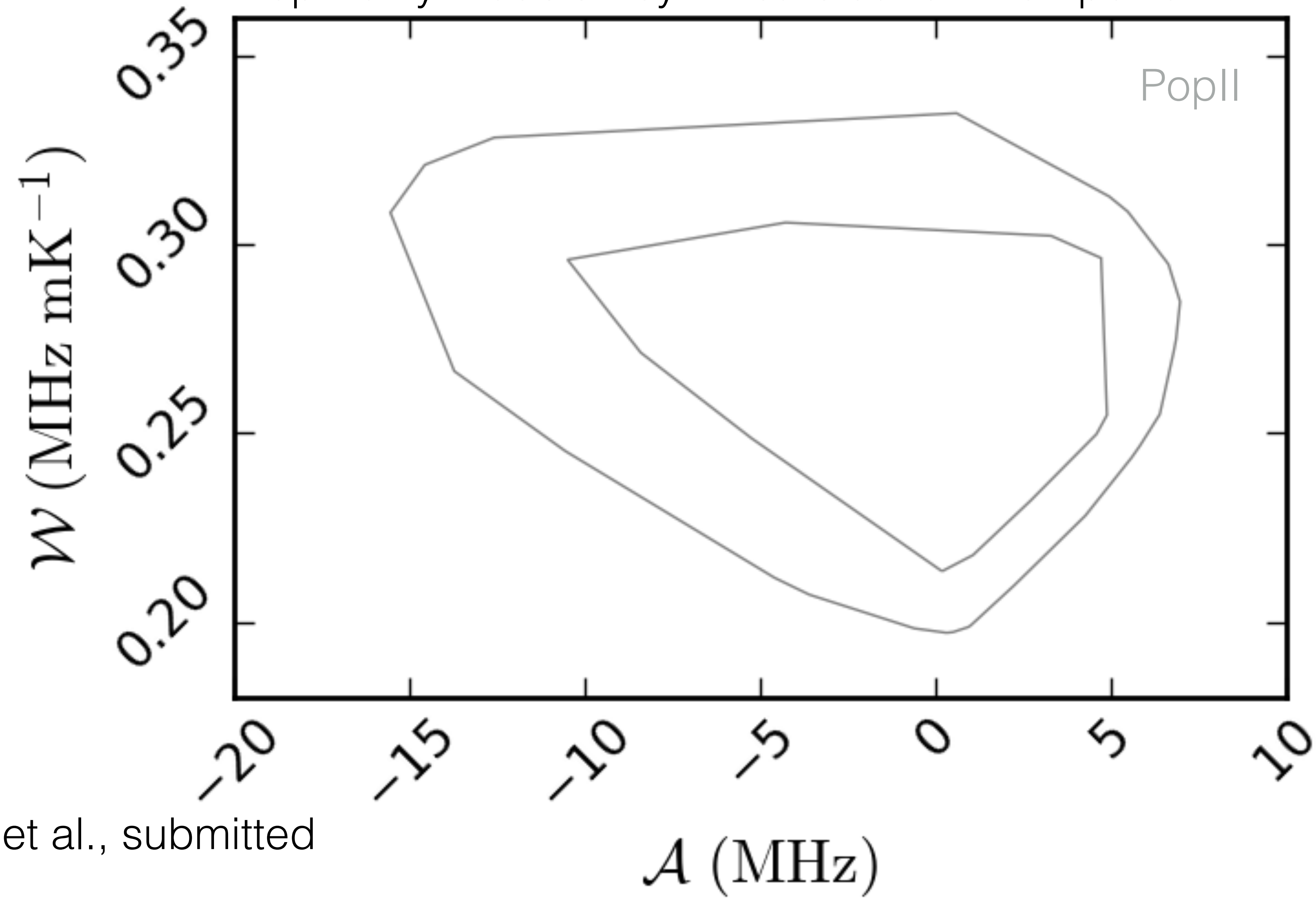
Shape Diagnostic: $\mathcal{W}$



Mirocha et al., submitted

PopII vs. PopIII

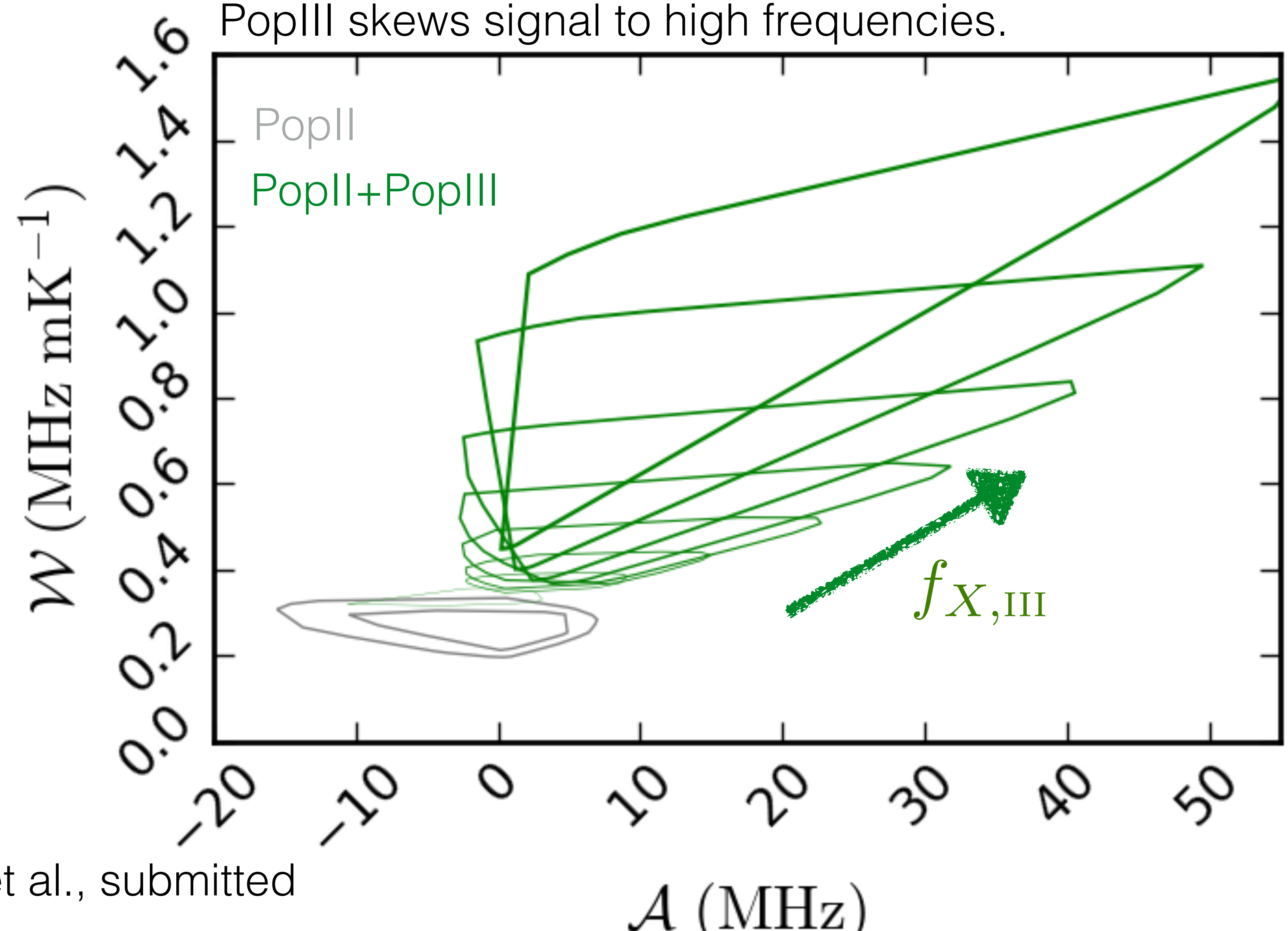
PopII-only models ~symmetric at half-max point



Mirocha et al., submitted

PopII vs. PopIII

PopIII skews signal to high frequencies.



Mirocha et al., submitted

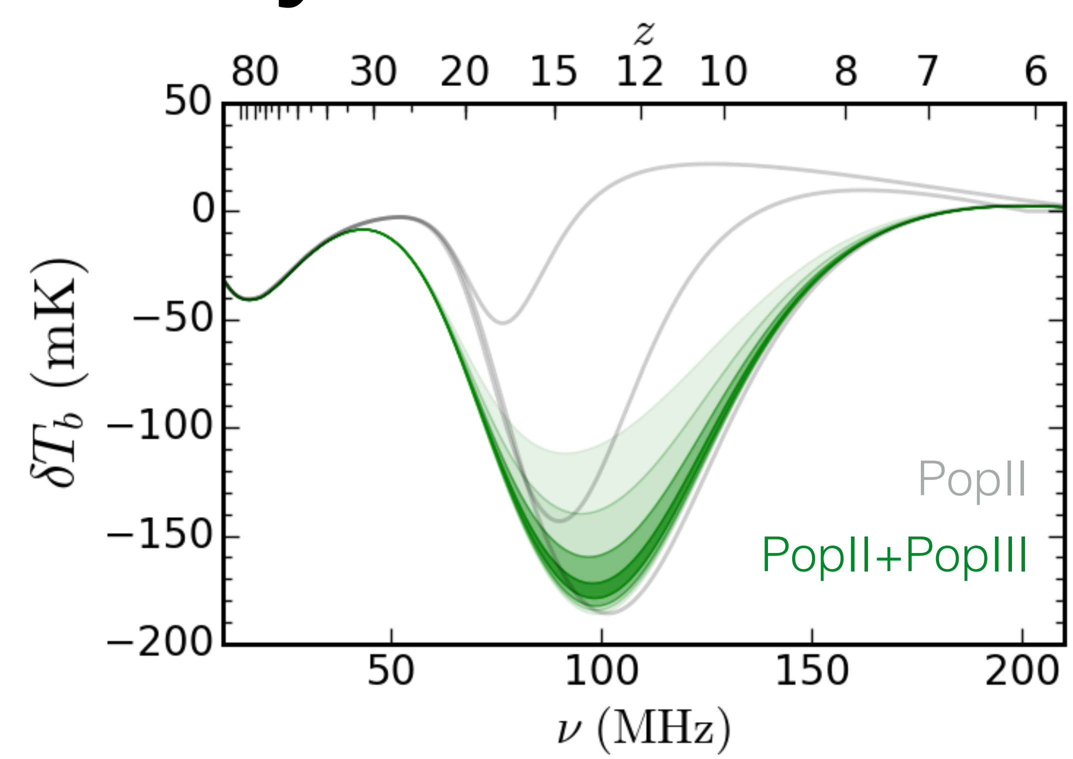
Summary: Part II

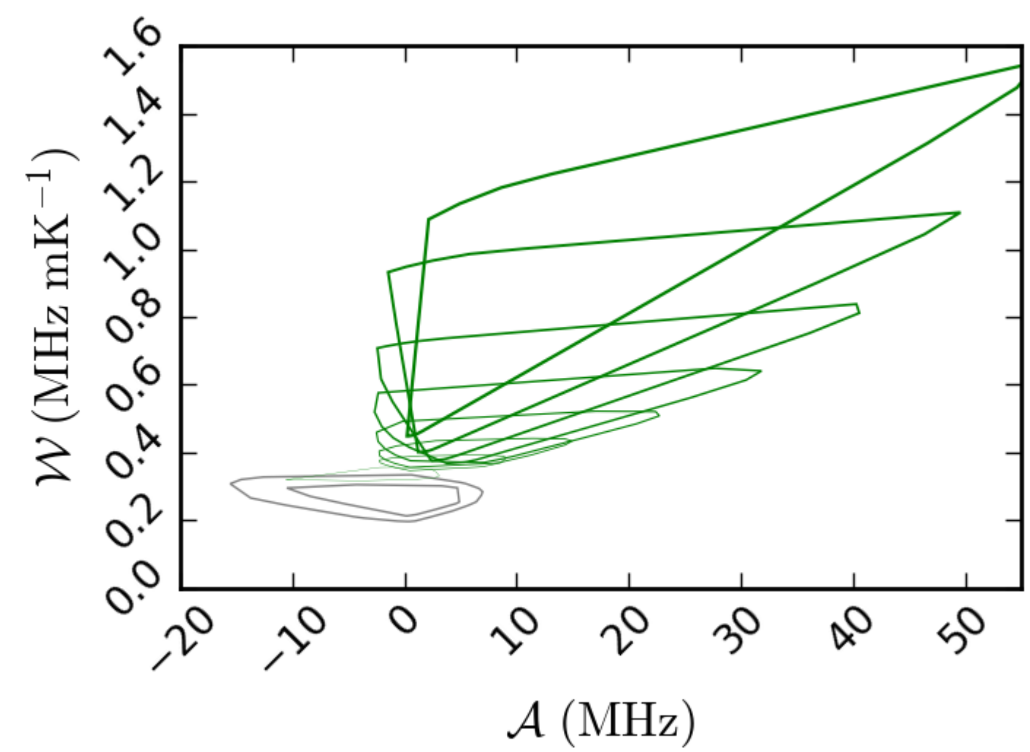
- Addition of PopIII only changes ~100 MHz trough result under extreme circumstances.
- However, the resultant signals are more asymmetric, with characteristic ~10-20 MHz skew toward high frequencies.
    - Due to slowly evolving heating rate density of IGM.
    - Potential competition: DM heating?

Summary

- PopII-only models: deep, ~100 MHz, and *symmetric* troughs.
- PopIII indicator: asymmetry in global 21-cm signal absorption trough.
- Observational limits are creeping into the ~100 MHz -200 mK range, so stay tuned!

  Monsalve+ accepted (EDGES)
  Singh+ submitted (SARAS)





Questions?