Modeling the 21-cm Signal

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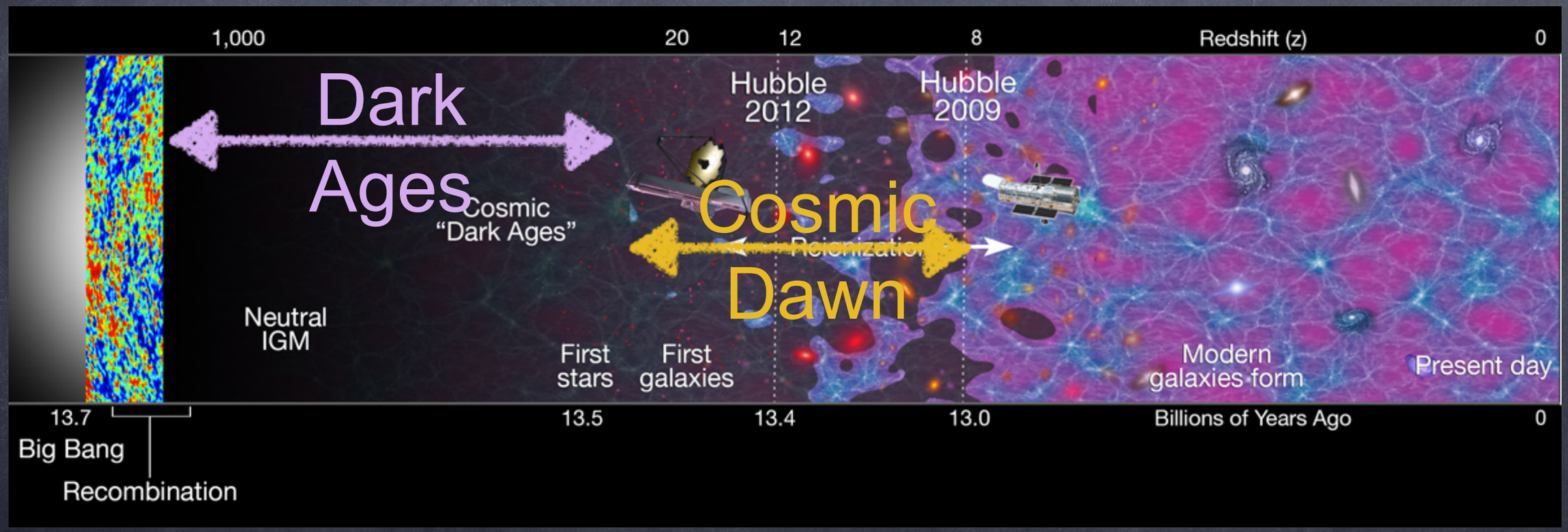
Outline

- Background and context
- Motivations for studying the Cosmic Dawn
- Motivations for studying the Dark Ages
- Ongoing work

Part I:

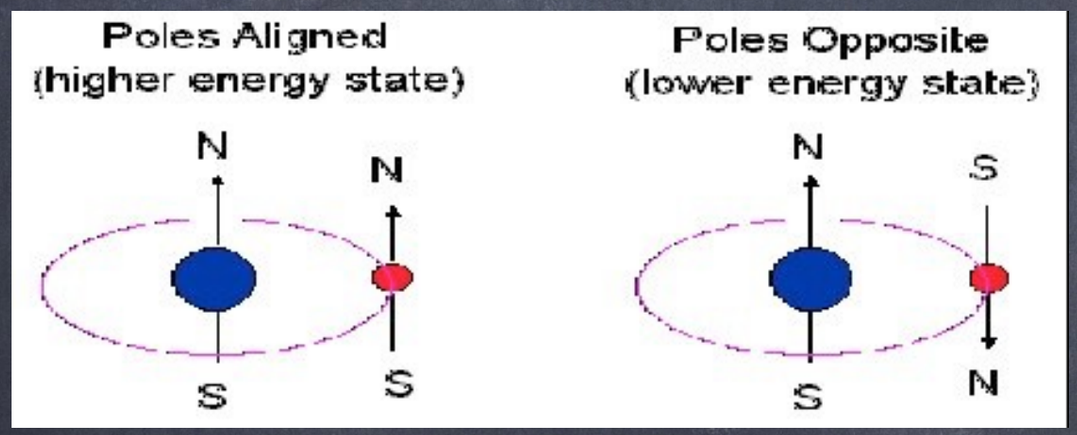
The 21-cm Signal

The Dark Ages and the Cosmic Dawn



Robertson et al. (2010)

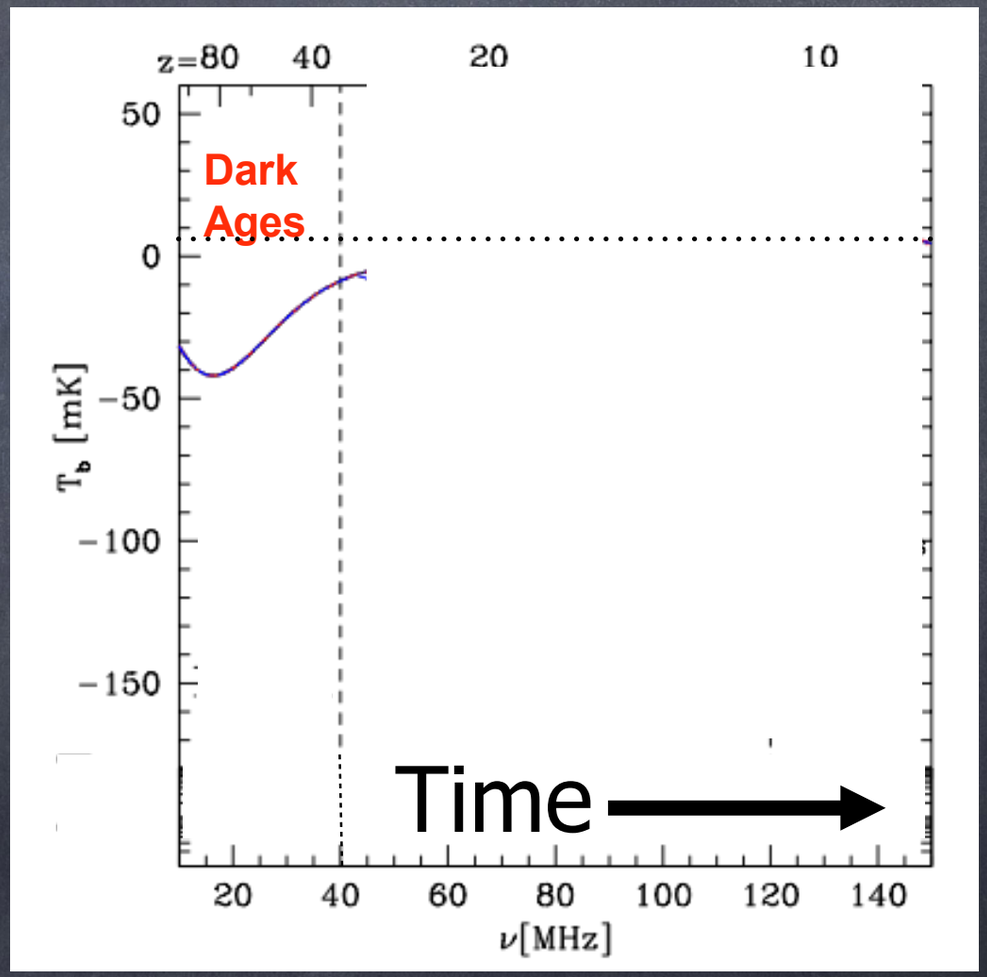
The 21-cm Line



- Protons and electrons both have spins and hence magnetic moments
- Transition between alignments corresponds to 21-cm (1420 MHz) photon

The Four Phases of the 21-cm Signal

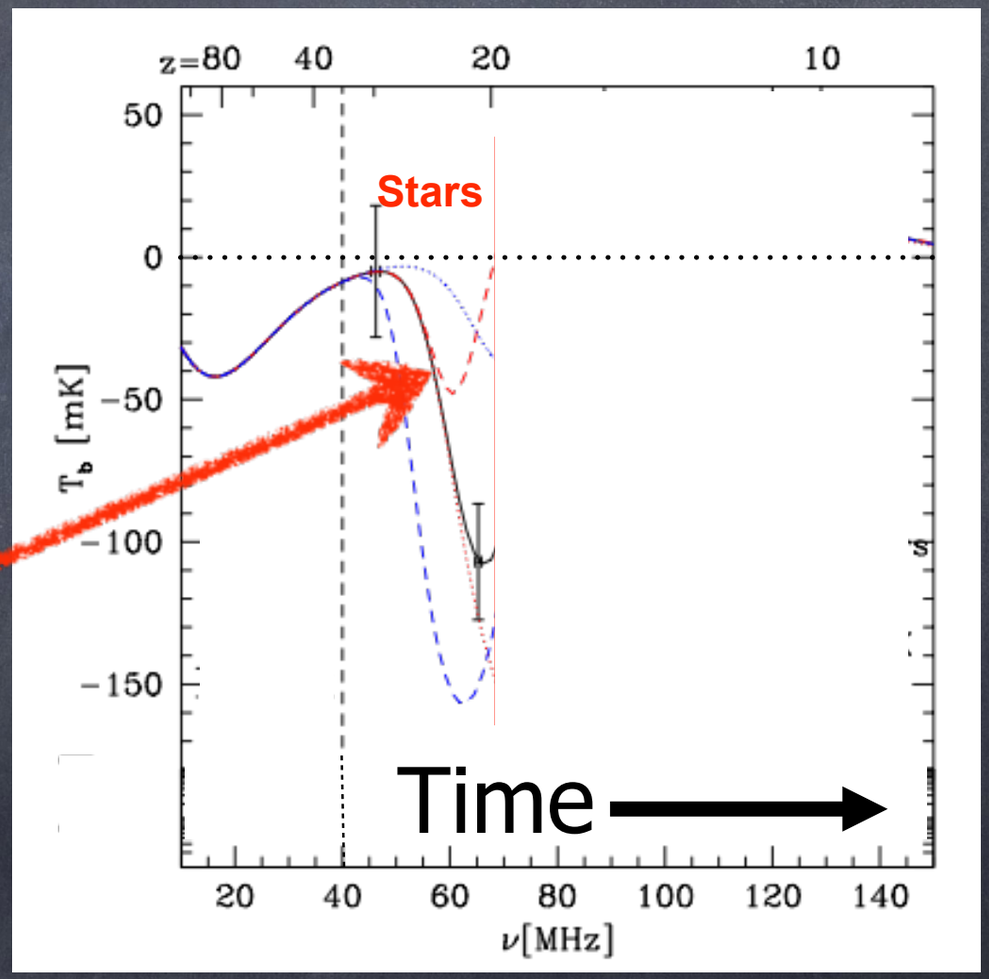
- Before the first sources: absorption from cold gas



J. Pritchard

The Four Phases of the 21-cm Signal

- Before the first sources: absorption from cold gas
- Cosmic Dawn: UV light triggers stronger absorption



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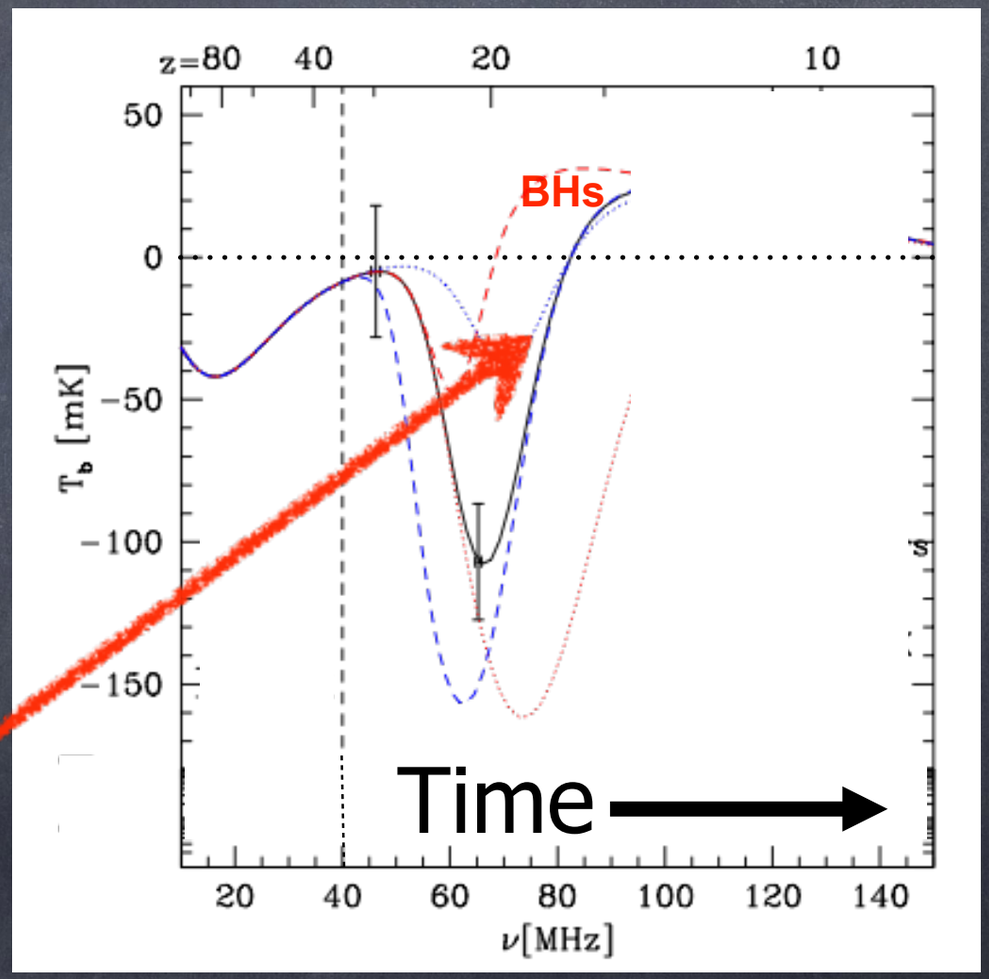
The Four Phases of the 21-cm Signal

- Before the first sources: absorption from cold gas
- Cosmic Dawn: UV light triggers stronger absorption
- First black holes: X-ray heating transitions to emission



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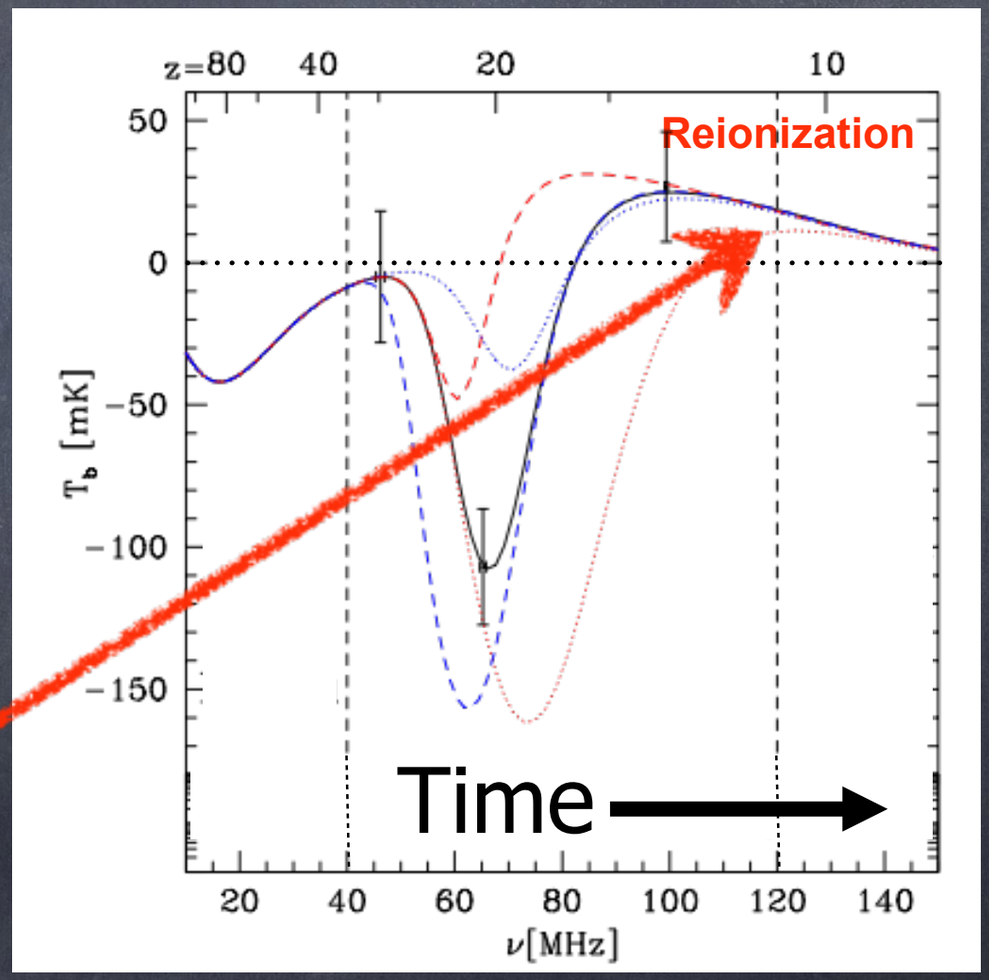
The Four Phases of the 21-cm Signal

- Before the first sources: absorption from cold gas
- Cosmic Dawn: UV light triggers stronger absorption
- First black holes: X-ray heating transitions to emission
- Reionization: signal fades



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The Four Phases of the 21-cm Signal

Mesinger, Furlanetto, & Cen (2011)

Astro2020

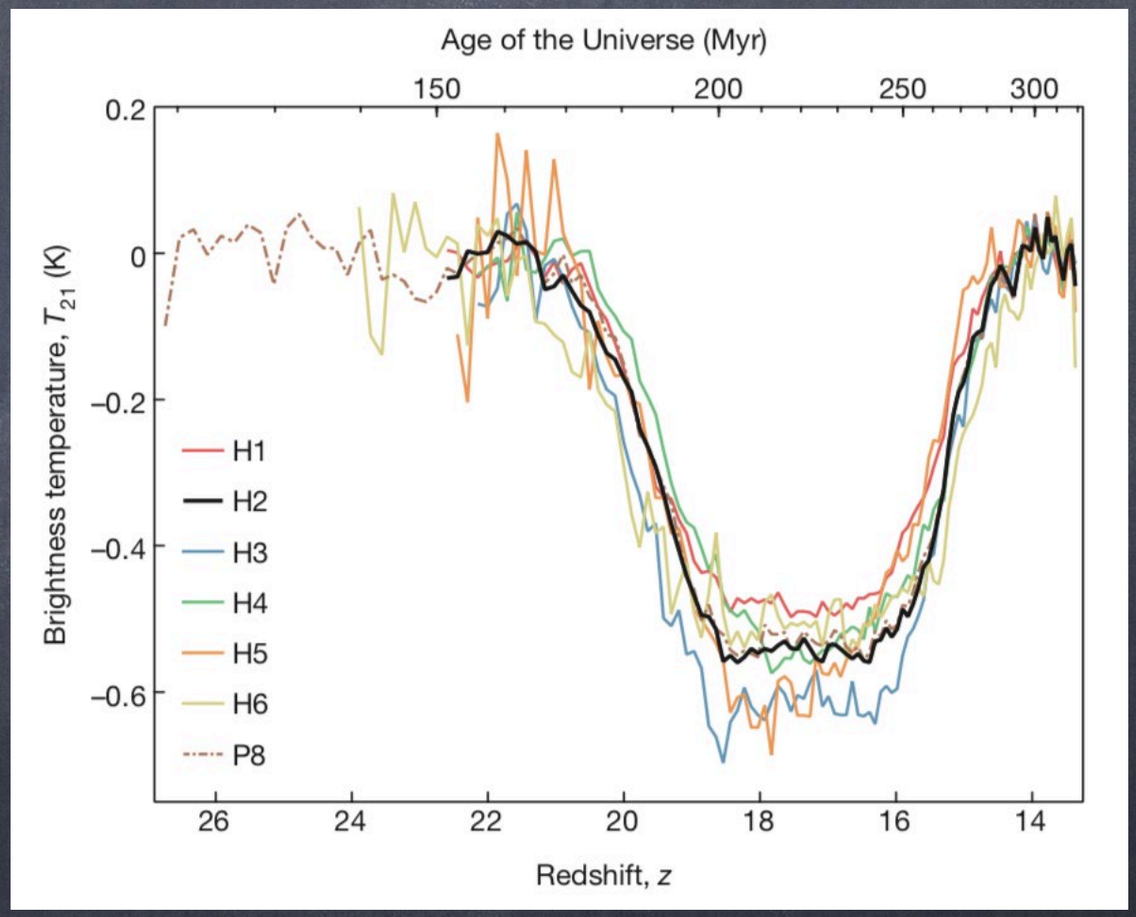
- **SIX** 21-cm white papers were submitted with a focus on 21-cm:
  - "Cosmology with the Highly Redshifted 21cm Line," (Liu et al., arXiv.org/1903.06240)
  - "First Stars and Black Holes at Cosmic Dawn with Redshifted 21-cm Observations," (Mirocha et al., arXiv.org/1903.06218)
  - "Fundamental Cosmology in the Dark Ages with 21-cm Line Fluctuations," (Furlanetto et al., arXiv.org/1903.06212)
  - "Insights into the Epoch of Reionization with the Highly-Redshifted 21-cm Line," (Furlanetto et al., arXiv.org/1903.06204)
  - "Synergies Between Galaxy Surveys and Reionization Measurements," (Furlanetto et al., arXiv.org/1903.06197)
  - "Dark Cosmology: Investigating Dark Matter & Exotic Physics in the Dark Ages Using the Redshifted 21-cm Global Spectrum," (Burns et al., arXiv.org/1902.06147)
- Several others referencing the probe as well!

Part II:

Motivations for Studying the Cosmic Dawn

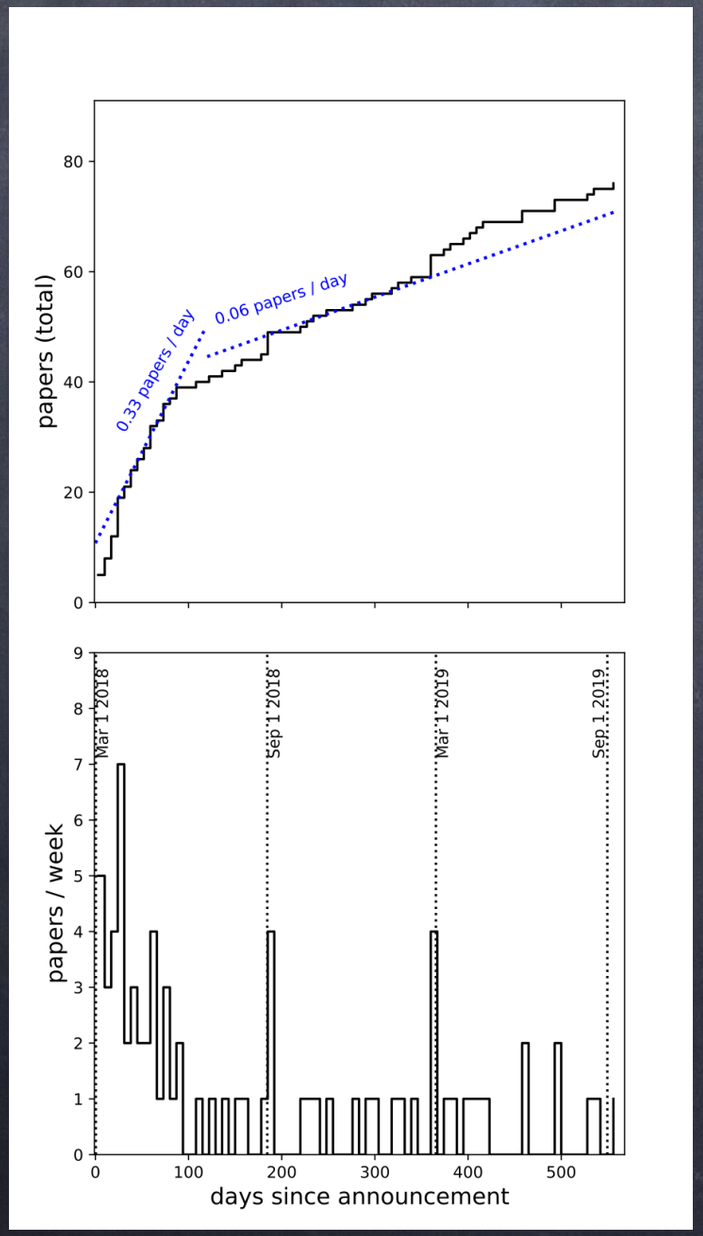
The EDGES Detection

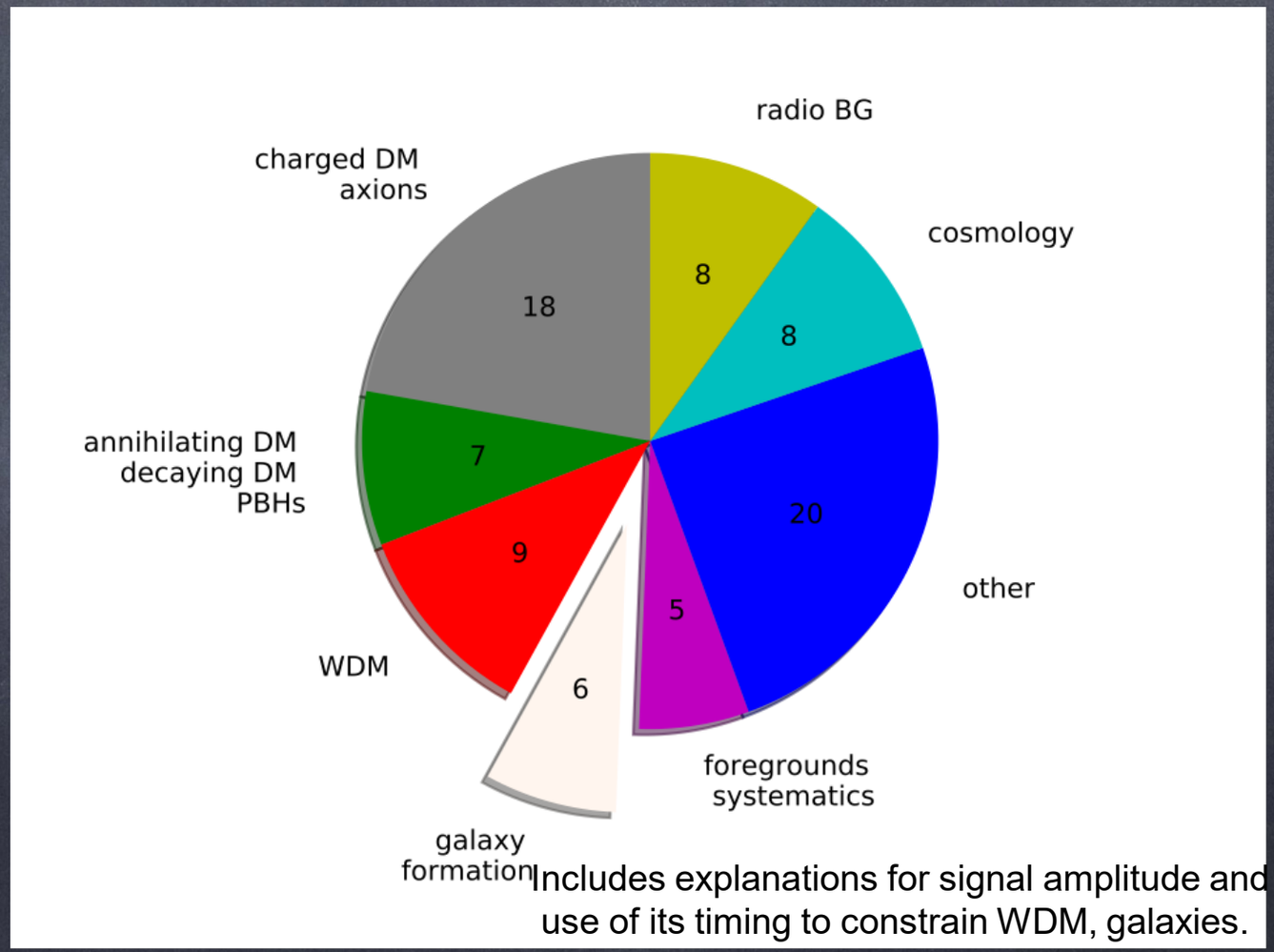
- In Feb. 2018, Bowman et al. announced the first detection of the 21-cm signal!
- The claim is very controversial - but it is AT LEAST an example of what we can learn from the 21-cm signal



Bowman et al. (2018)

The Landscape After EDGES

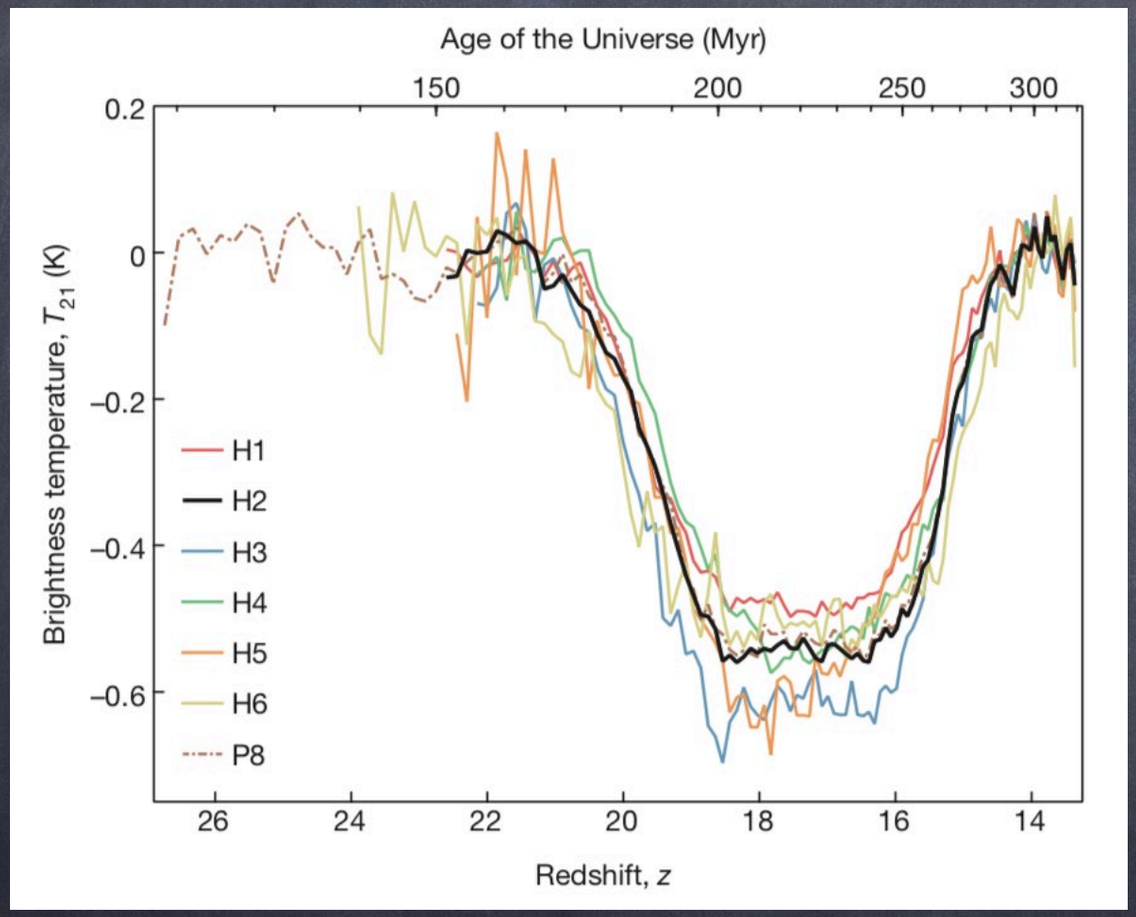




Includes explanations for signal amplitude and use of its timing to constrain WDM, galaxies.

From J. Mirocha

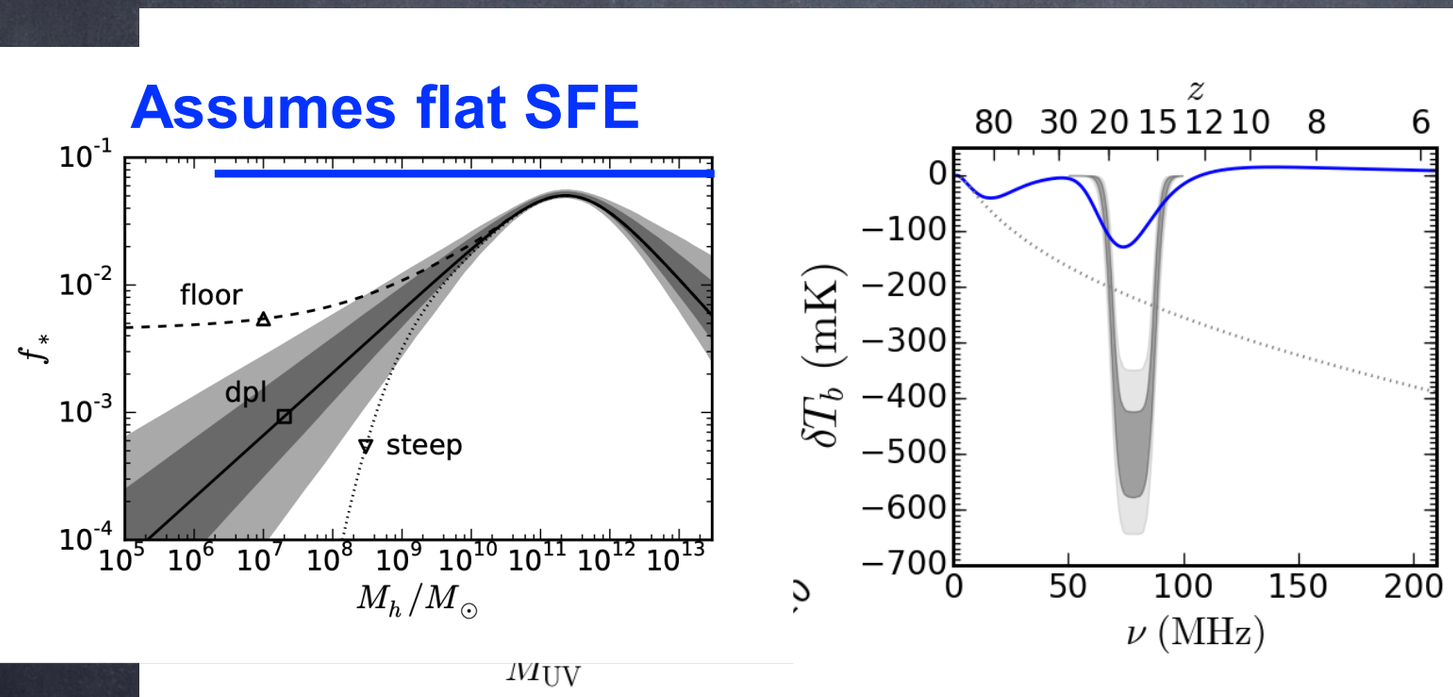
EDGES and Galaxies



Bowman et al. (2018)

- With a "vanilla" calibration to galaxies, EDGES signal is weird in three ways…
  - Depth
  - Shape
  - Timing

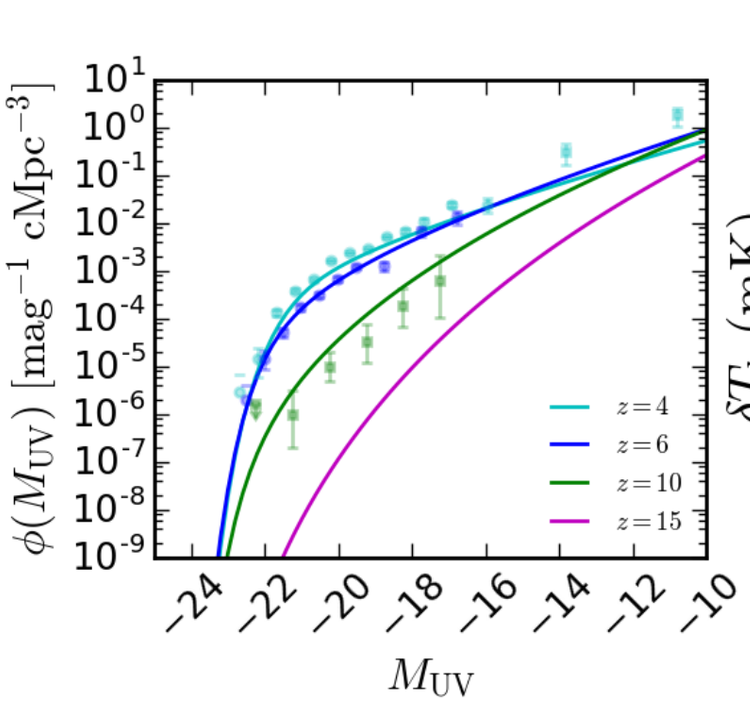
The "Classic" Picture of the 21-cm Signal

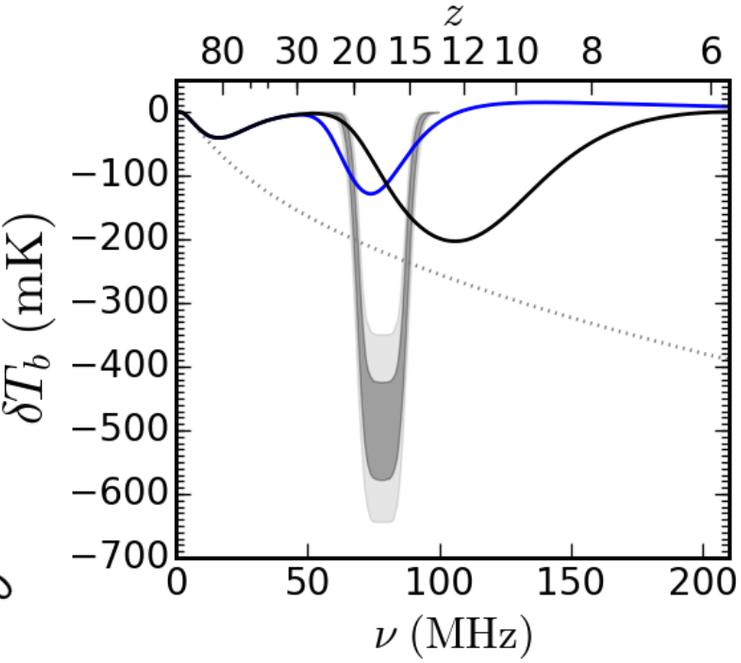


- Without empirical knowledge of high-z galaxies, make simplest possible assumptions…
- Star formation efficiency and all other relevant quantities independent of halo mass!
- But DOESN'T fit any known galaxy population!
- In last few years, "robust" measurements of high-z UV luminosity functions have emerged

Mirocha et al. (2017)

The New Picture of the 21-cm Signal





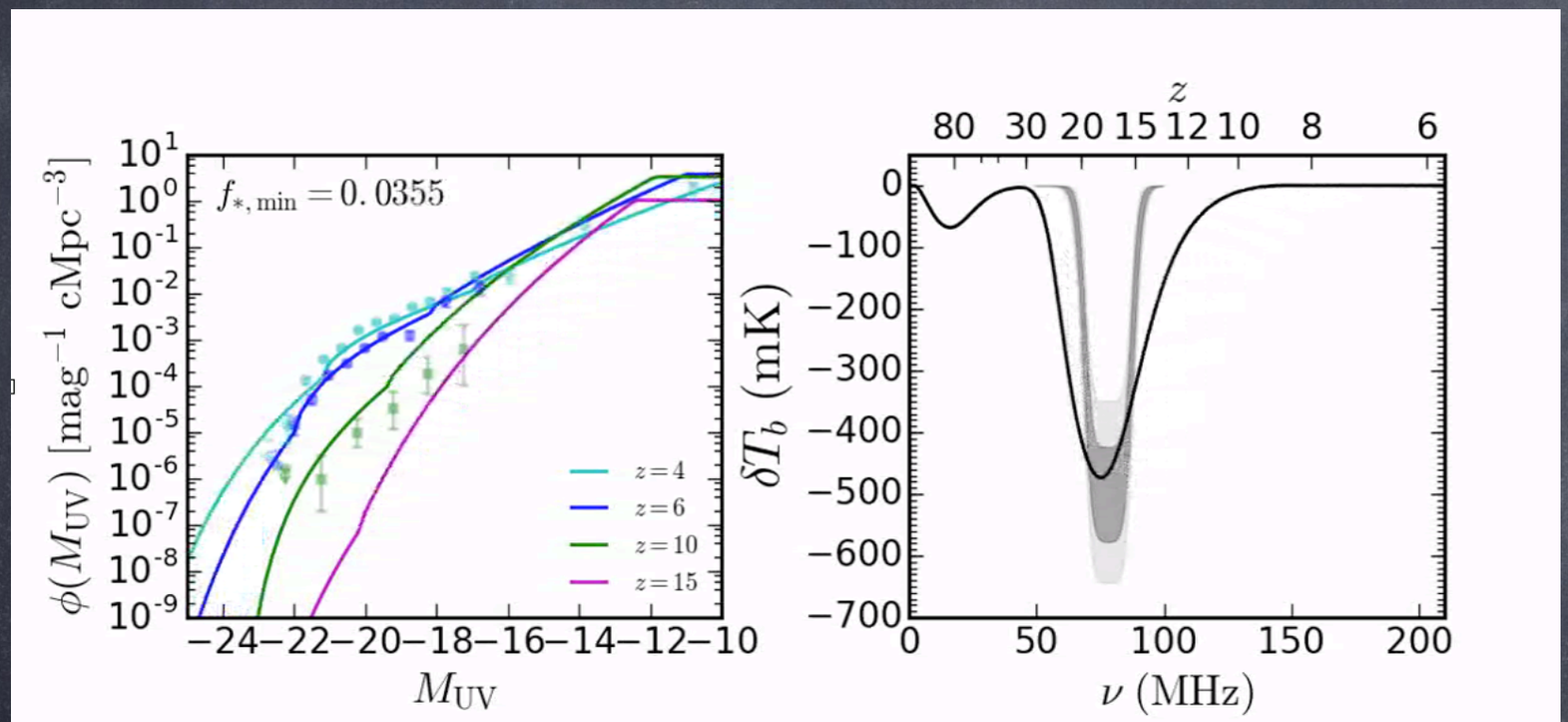
Calibrate with LFs:

- **Assume HMF**
- **1 galaxy per halo**
- **SFR ∝ SFE x MAR**
- **Lh ∝ SFR**

Mirocha et al. (2017)

- Assume…
  - SFE varies with halo mass
  - LX-SFR relation comparable to nearby galaxies
  - IMF, ionizing efficiency, etc. comparable to local galaxies
- Results: significantly later 21-cm features!
  - Heating and reionization can EASILY overlap!

EDGES and Galaxies



Mirocha & Furlanetto (2018)

- Timing is most important for galaxy formation
- Early signal requires EITHER
  - More efficient star formation at higher redshifts
  - More efficient star formation in (very) small halos
  - (Or both)

A Solution - The First Stars?

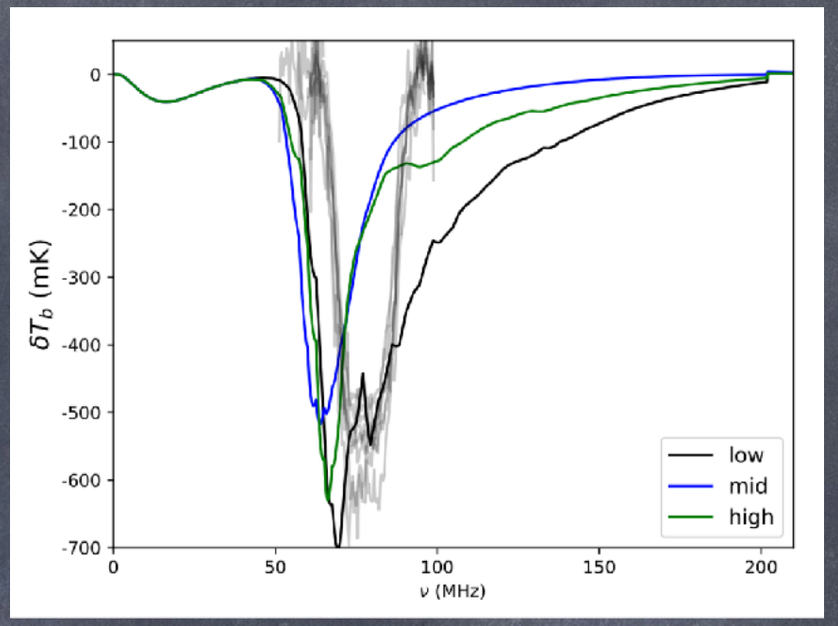
- The first "Population III" stars form in tiny dark matter clumps through an entirely different mode
- Transition to "normal" star formation as heavy elements form and halos grow
- Can these Pop III stars provide the extra UV background?

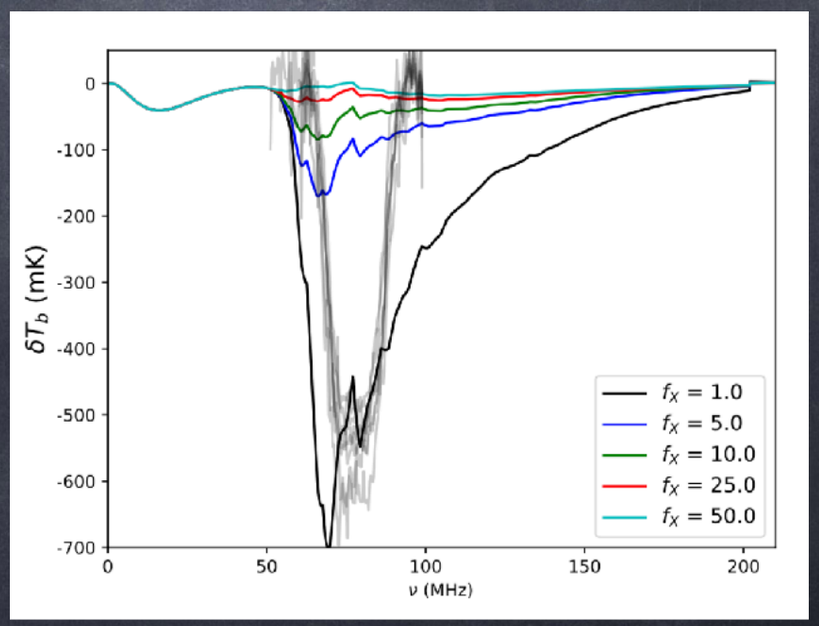
R. Hurt

A Solution - The First Stars?

- Shown are a variety of Pop III models that all reproduce the rough timing of EDGES

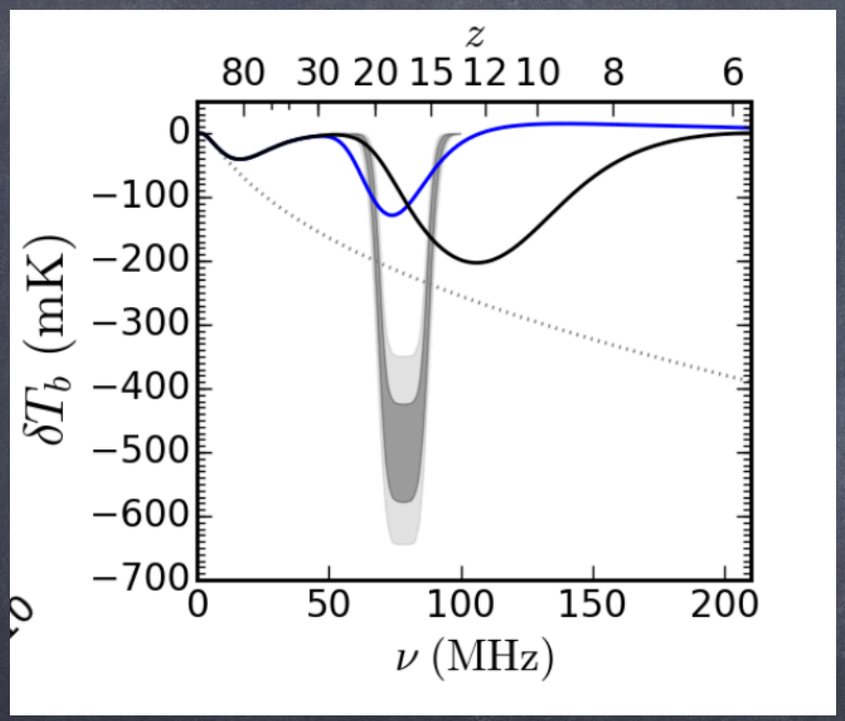
- This provides a "natural" solution to the timing - but it is also not a guarantee!





Mebane et al. (in prep)

The Depth Problem

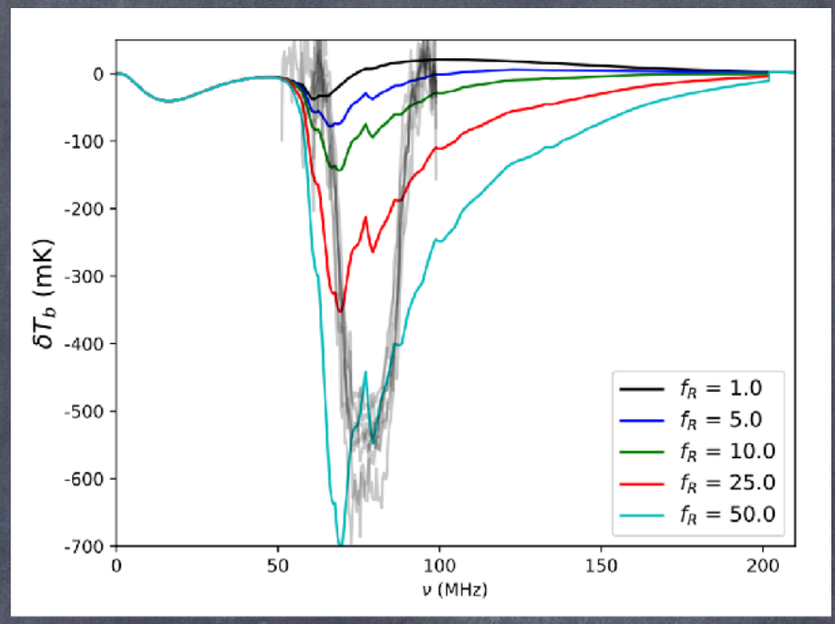


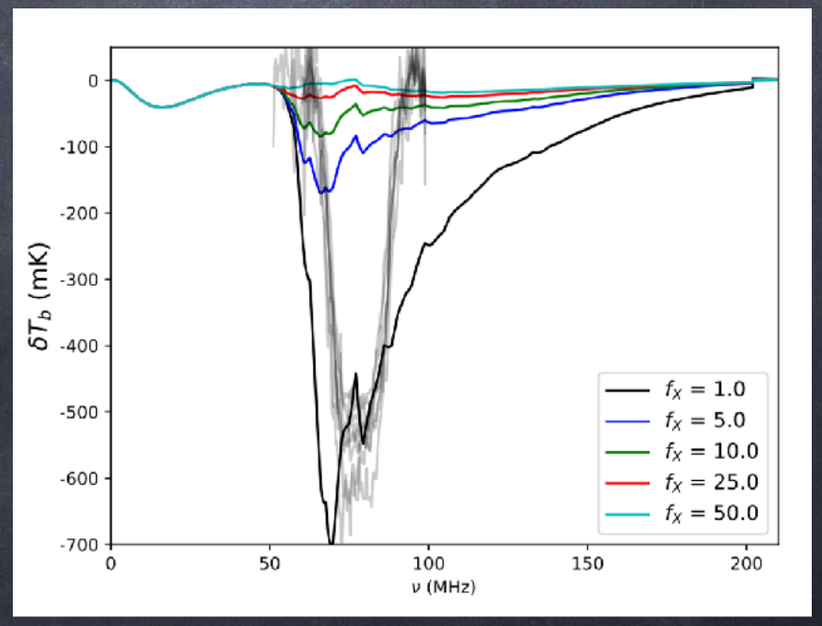
Mirocha et al. (2017)

- Two potential classes of explanations:
  - COOLER gas than expected - hard, because it should be thermally isolated!
  - BRIGHTER radio background than expected - so absorption is stronger even though gas is the same

What about the amplitude?

- The biggest problem with EDGES: the huge amplitude
- Requires either:
  - Excess cooling of intergalactic gas (exotic physics - study with DAPPER!)
  - Excess radio background - either exotic physics or self-generated by these sources?
- An entirely Pop III solution is POSSIBLE but NOT EASY





Mebane et al. (in prep)

Some Key Motivations: Cosmic Dawn

- Likely our only opportunity to observe the (effects of the) first stars and black holes at z>20!
- Unique information on unresolved populations of sources - highly complementary to galaxy surveys
- Tracing IGM baryons as fuel for galaxy formation and to understand later structures
- Possibility of cosmological information…

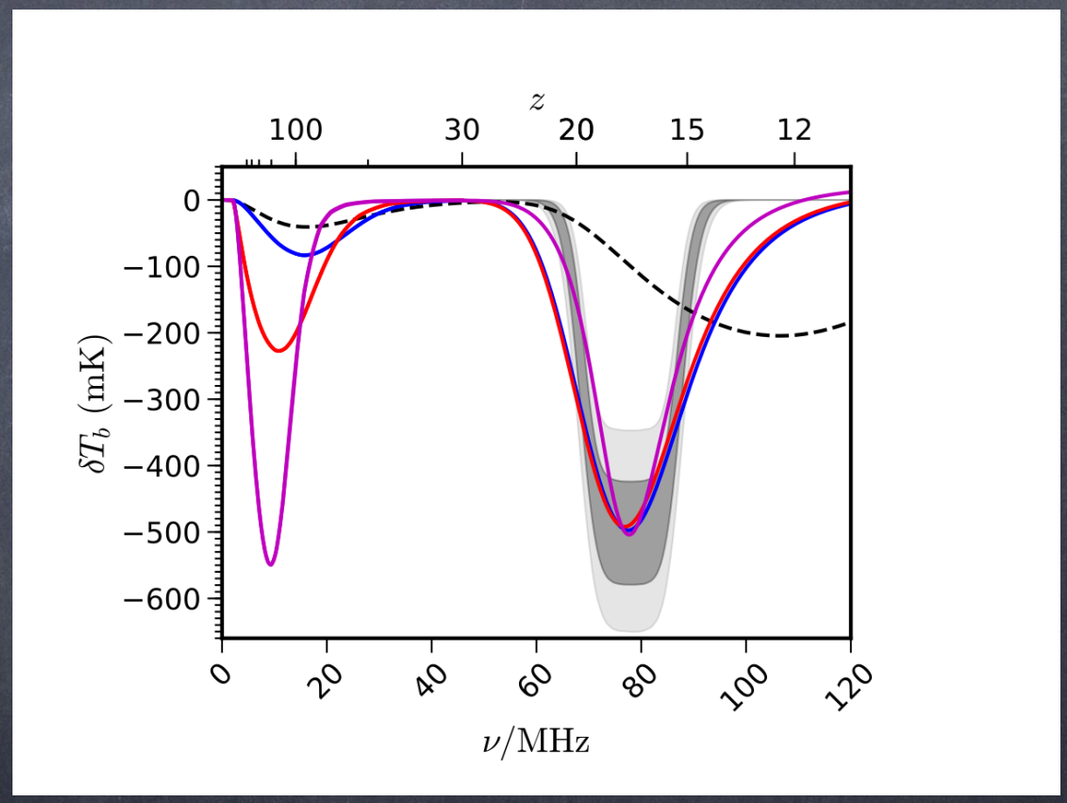
Part III:

Motivations for Studying the Dark Ages

Some Key Motivations: The Dark Ages

- Free from astrophysical "contamination"

- Sensitive calorimeter for exotic heating/cooling mechanisms (many now proposed since EDGES!)



J. Mirocha

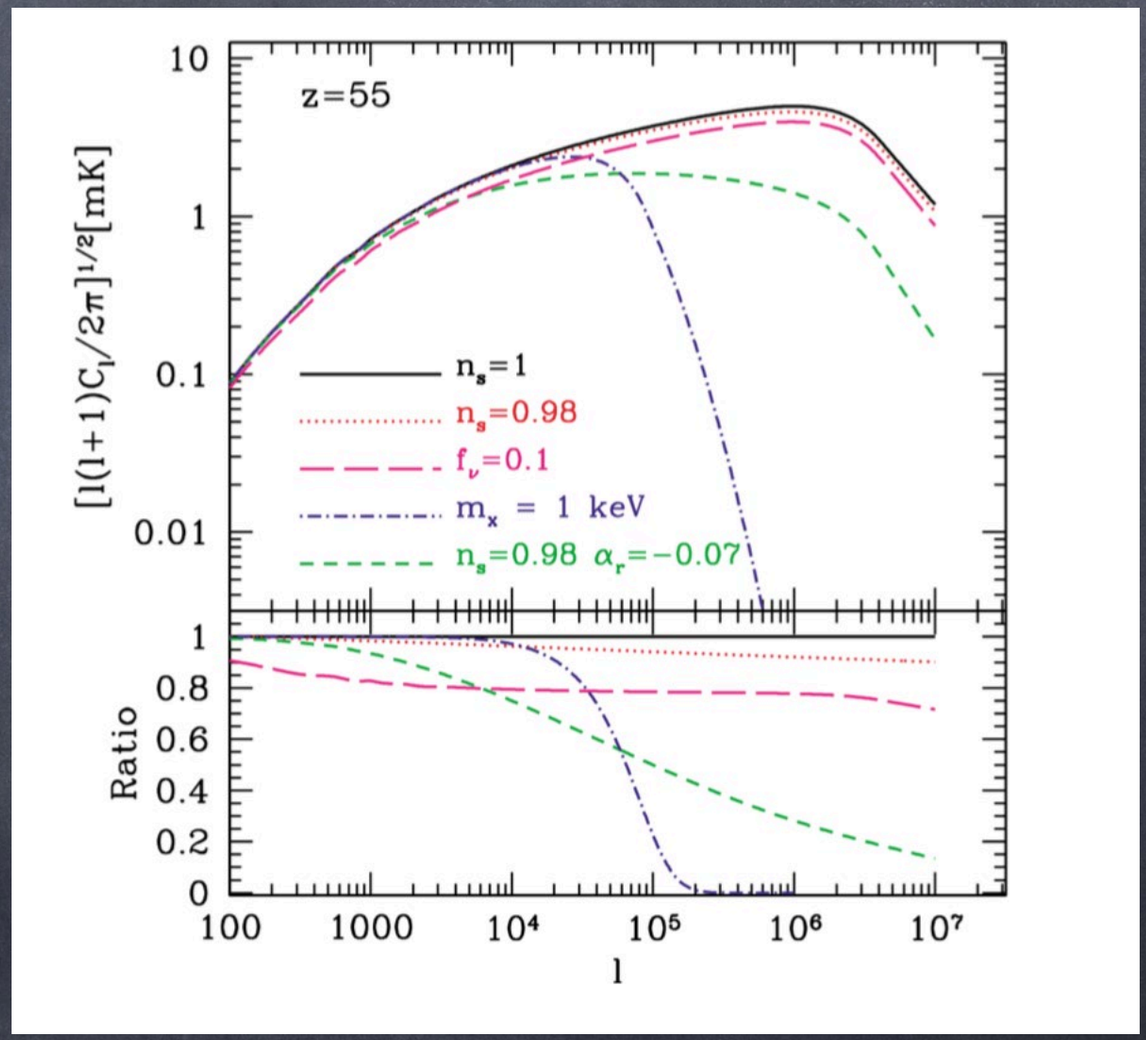
Some Key Motivations: The Dark Ages

- Free from astrophysical "contamination"
- Sensitive calorimeter for exotic heating/cooling mechanisms (many now proposed since EDGES!)
- Massive volume means lots of statistical power (compare with $N_{CMB}\sim10^7$)

$$N_{21\mathrm{cm}} \sim 8\times10^{11}\left(\frac{k_{\mathrm{max}}}{3\ \mathrm{Mpc}^{-1}}\right)^3\left(\frac{\Delta\nu}{\nu}\right)\left(\frac{1+z}{100}\right)^{-1/2}$$

Some Key Motivations: The Dark Ages

- Free from astrophysical "contamination"
- Sensitive calorimeter for exotic heating/cooling mechanisms (many now proposed since EDGES!)
- Massive volume means lots of statistical power
- Excellent dynamic range enables unique cosmology: neutrino mass, curvature, inflation parameters



Loeb & Zaldarriaga (2004)

Part IV:
Ongoing Work

Ongoing Work

- Finish analysis of effect of Pop III stars on 21-cm signal (likely by mid-October) [Mebane]
- Incorporate Pop III models into power spectrum calculations with 21cmFAST (already in process) [Mebane]
  - Are there distinct features in the power spectrum?
  - Allows us to incorporate new physics (inhomogeneous radiation backgrounds and inhomogeneous metal enrichment)

Ongoing Work

- Improve galaxy models in a fast, physically-motivated framework (already in process) [Furlanetto]
  - Mostly relevant for lower redshifts, but crucial for understanding feedback effects on Pop III phases
- A valiant effort to model the 21-cm power spectrum analytically [Mirocha]
  - It's hard - but if it works would be extremely useful for broadening the parameter space we can constrain
- Outreach: build a website explaining all this cool astrophysics to the public! [Furlanetto + ???]

Summary

- The 21-cm line offers an unprecedented window into cosmology and the Cosmic Dawn, with UNIQUE power to constrain luminous sources and the parameters of our Universe.