Observational Limitations on the Duration of the Reionization Epoch

ASTR 6000 – The High-Redshift Universe
Spring 2012

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Reading:

- Bowman, J. & Rogers, A. "A lower limit of $\Delta z > 0.06$ for the duration of the reionization epoch"
- Bowman, J. & Rogers, A. "Supplementary Information: EDGES"
- Pritchard, J. & Loeb, A. "Hydrogen was not ionized abruptly"

Pritchard & Loeb

Overview: Reionization Epoch

400,000 yrs after Big Bang: Universe cool enough to for hydrogen to form

100's of Myr later: First stars + galaxies produce ionizing UV radiation

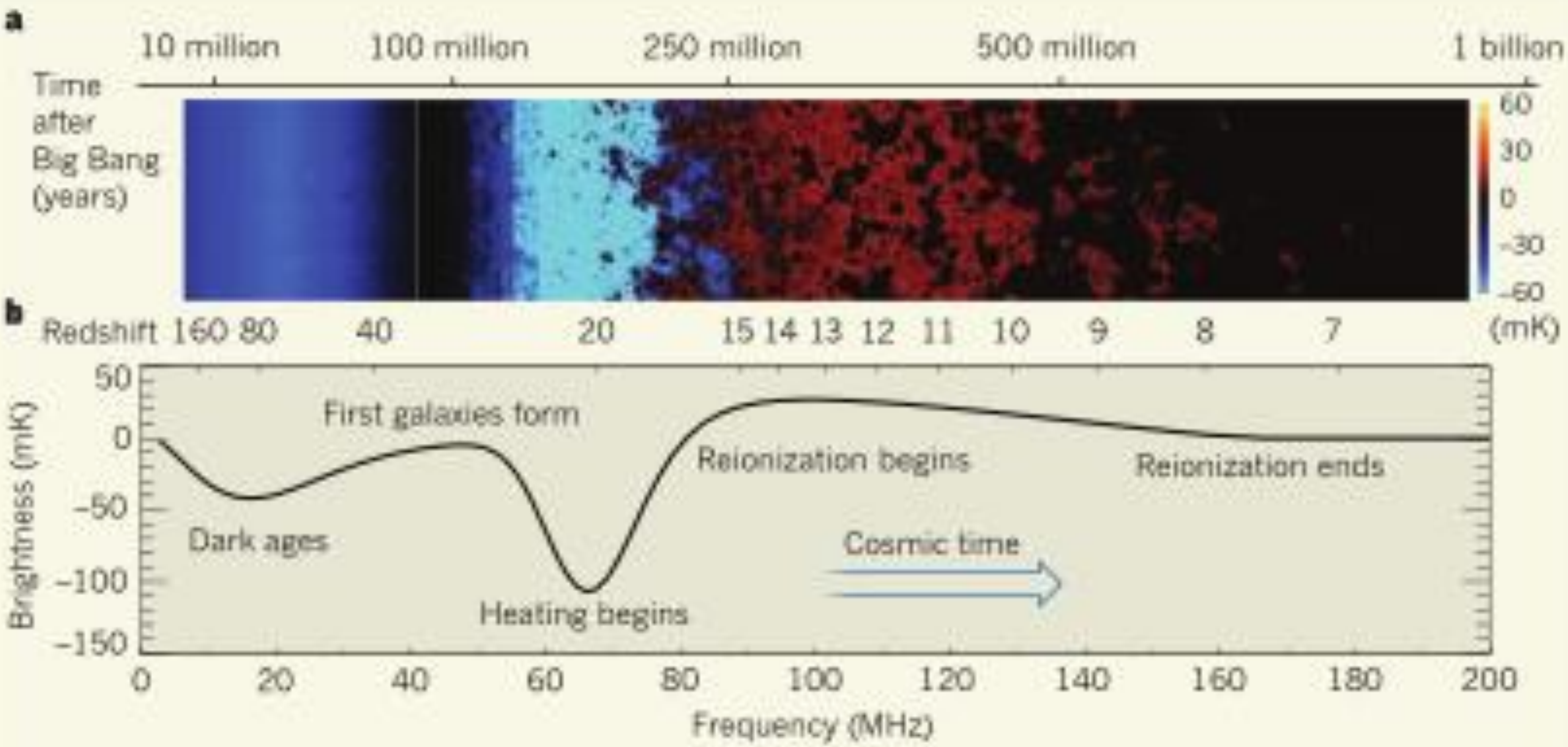
– Epoch of Reionization

How can we test this model?

- Red-shifted, 21-cm hydrogen signal:
  - Expected to cut off at short, observed wavelengths in the radio regime
  - EDGES => new technique to pinpoint progressive ionization of neutral hydrogen gas
    => use of a simple radio antenna operating at low frequencies

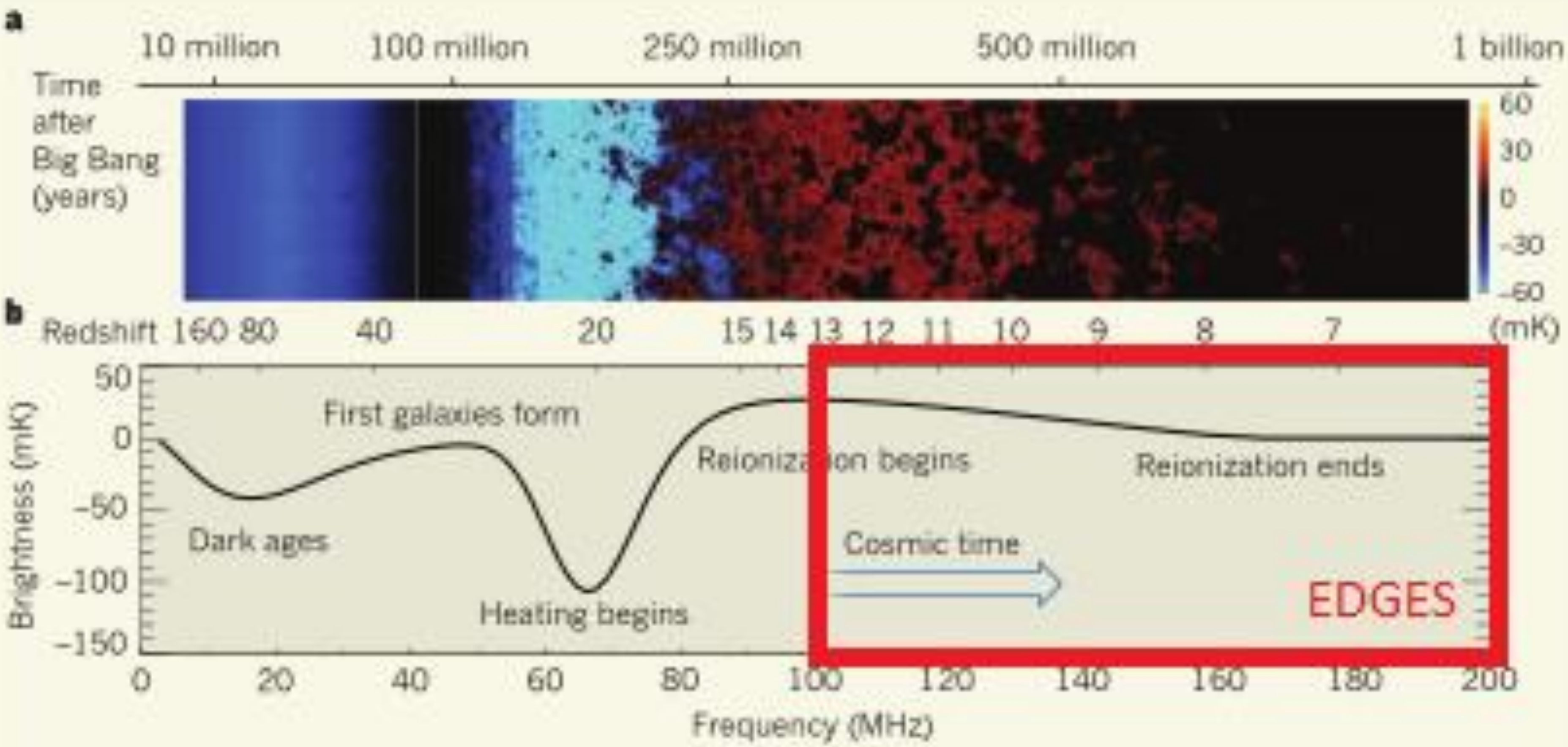
Pritchard & Loeb

21-cm cosmic hydrogen signal



Pritchard & Loeb

21-cm cosmic hydrogen signal



Supplementary, Bowman & Rogers

EDGES Experiment

- Low-frequency radio spectrometer
  - Measures all-sky spectrum (100- 200 MHz)
  - T ~ 100 – 10,000 K
- Dominant emission source: Milky Way
  - 70% of emission detected
  - What is this source?
- Other source of contamination:
  - Free-free emission
  - Discrete galactic/continuum extragalactic source
  - RRLs from ISM: exception to smooth spectrum
    - Why would these be easy to account for?

Spectrometer Requirements:

1. Instrument artifacts & systematic errors must be eliminated below 1 mK
   - Typically, use a blank reference field to precisely calibrate the instrument response
     - Why can’t we use this method?
   - Used an internal comparison source between antenna and spectrometer receiver
2. Separation of foreground spectrum must be better than $1/10^4$

EDGES at Murchison Radio-Astronomy Observatory: Western Australia

EDGES System

1. Antenna
   - Modified dipole
2. Amplifier & comparison switching module
   - 3 switches: antenna
ambient load
ambient load + calibration noise source
3. Digital backend
   - Off-the-shelf digitizer

Calibration & Data

$$T_{ant}(v) = T_{cal}(v)\left[\frac{p_2(v) - p_0(v)}{p_1(v) - p_0(v)}\right] + T_{load}$$

$$p_0(v) = g(v)[p_{load}(v) + p_{rcv}(v)]$$
$$p_1(v) = g(v)[p_{cal}(v) + p_{load}(v) + p_{rcv}(v)]$$
$$p_2(v) = g(v)[p_{ant}(v) + p_{rcv}(v)]$$

p0, p1, p2 = power spectra from 3 switch positions

g = collective gain of amplifiers & bandpass filters

pload = ambient temperature load

prcv = first-stage low-noise amplifier in receiver

pcal = calibrated noise source

pant = sky noise after propagating through antenna

Calibration

- Removes signals produced by digital electronics
  - Independent of switch state
    - Cancel out in $T_{ant}(\upsilon)$
- Removes unknown constant gain contribution
    - Divides out in $T_{ant}(\upsilon)$
- DOES NOT calibrate antenna transmission properties
  - Lack of a method for taking this out

Data Analysis

- Angle-averaged observable differential brightness temperature caused by red-shifted 21-cm line:

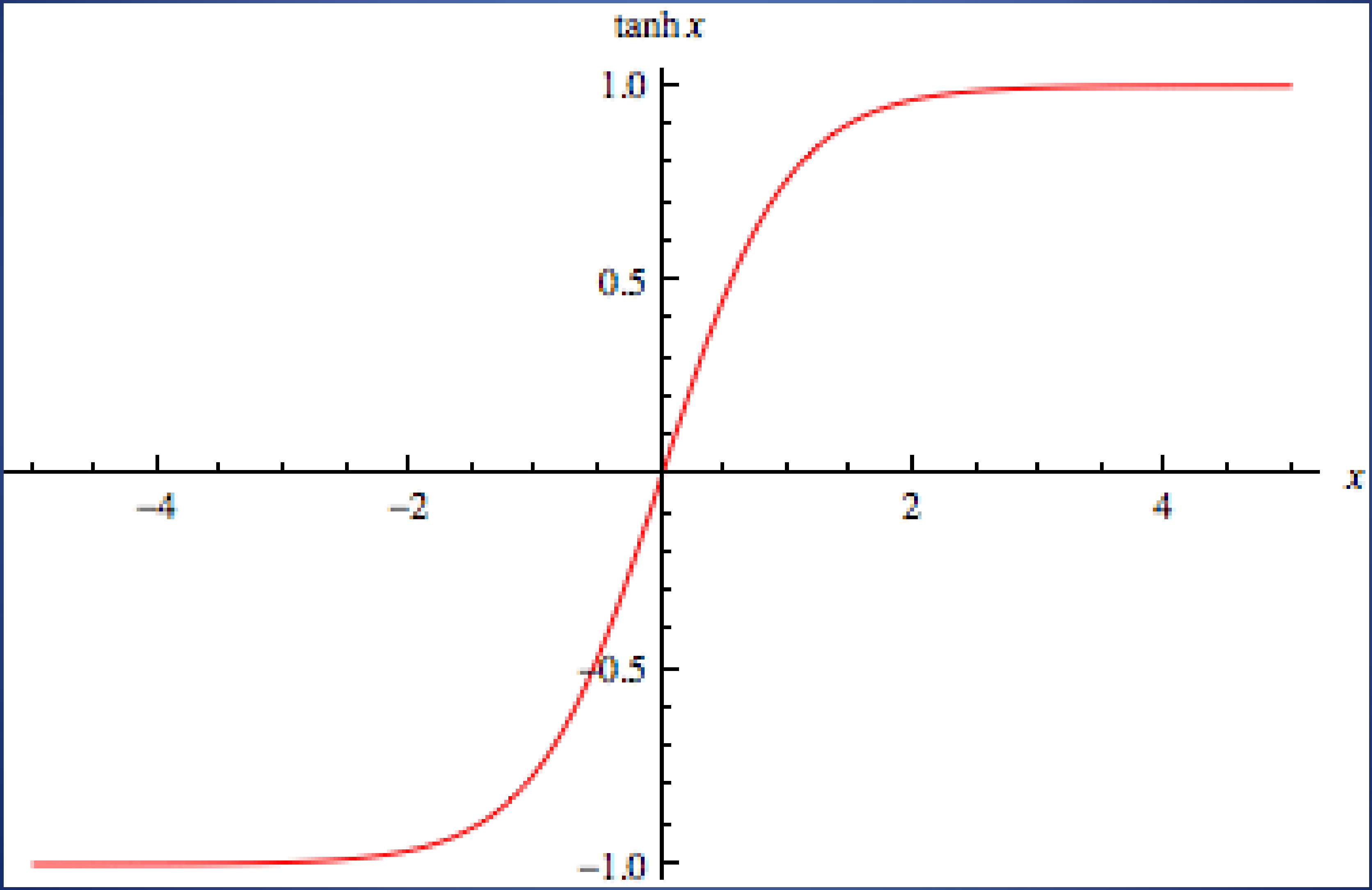
$$< \delta T_{21}(\theta, z) >_0 = 27\left(\frac{1+z}{10}\right)^{\frac{1}{2}} \bar{x}_{HI}(z) \text{ mK}$$

- 21-cm term fitted by:

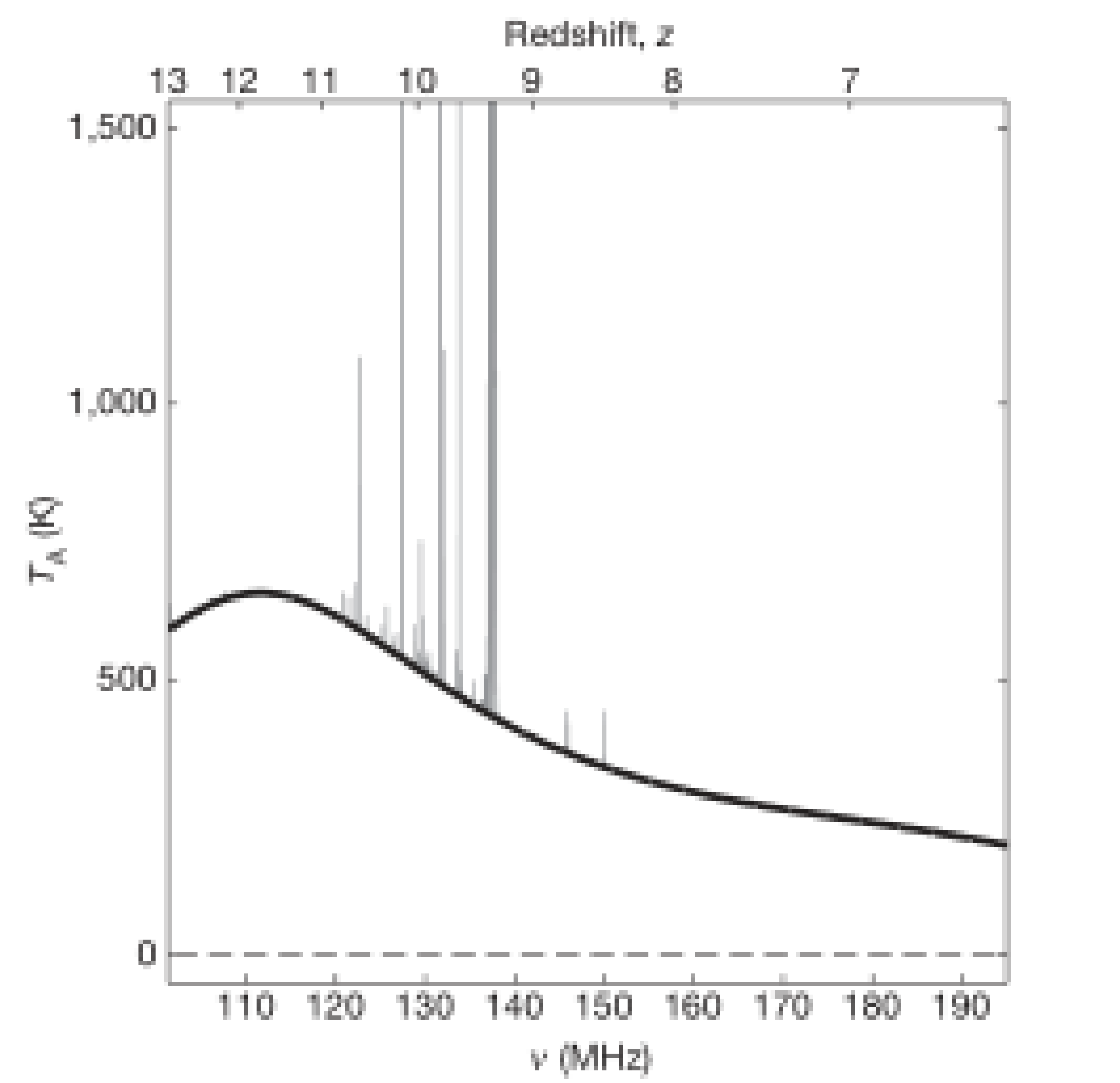
$$\bar{x}_{HI}(z) = \frac{1}{2}\left[\tanh\left(\frac{z - z_r}{\Delta z}\right) + 1\right]$$

$$T_{obs}(z) = \delta \bar{T}_{21}(z) + T_F(z)$$

$$\bar{x}_{HI}(z) \propto \left[\tanh\left(\frac{z - z_r}{\Delta z}\right)\right]$$



Bowman & Rogers

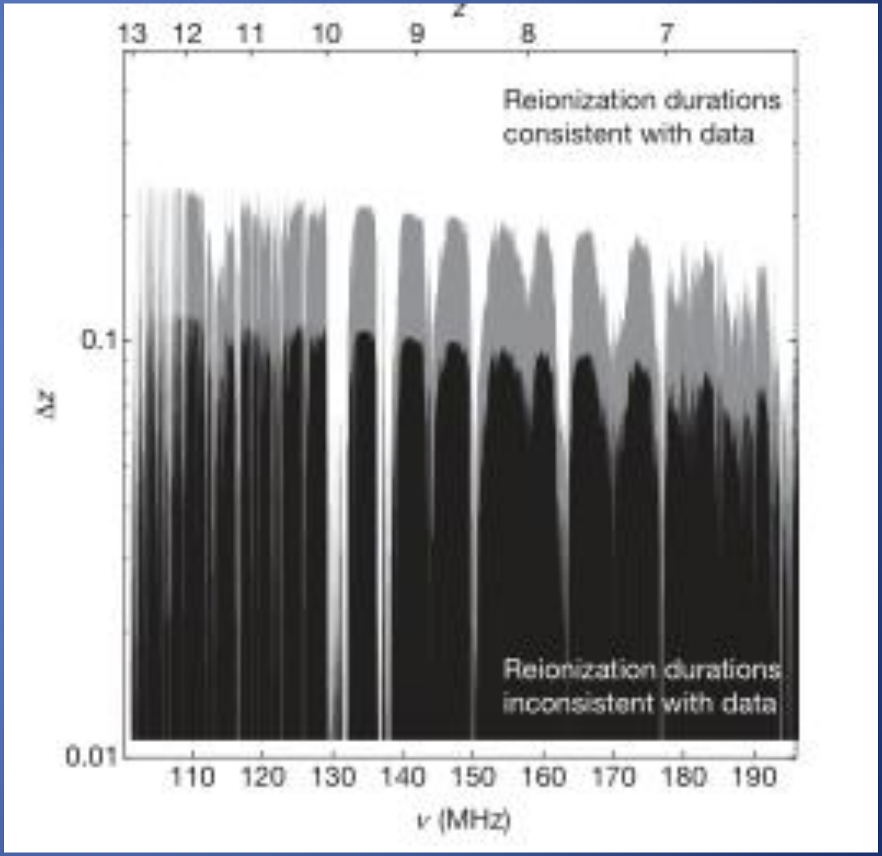


Bowman & Rogers

Confidence Bounds on the duration of Reionization transition

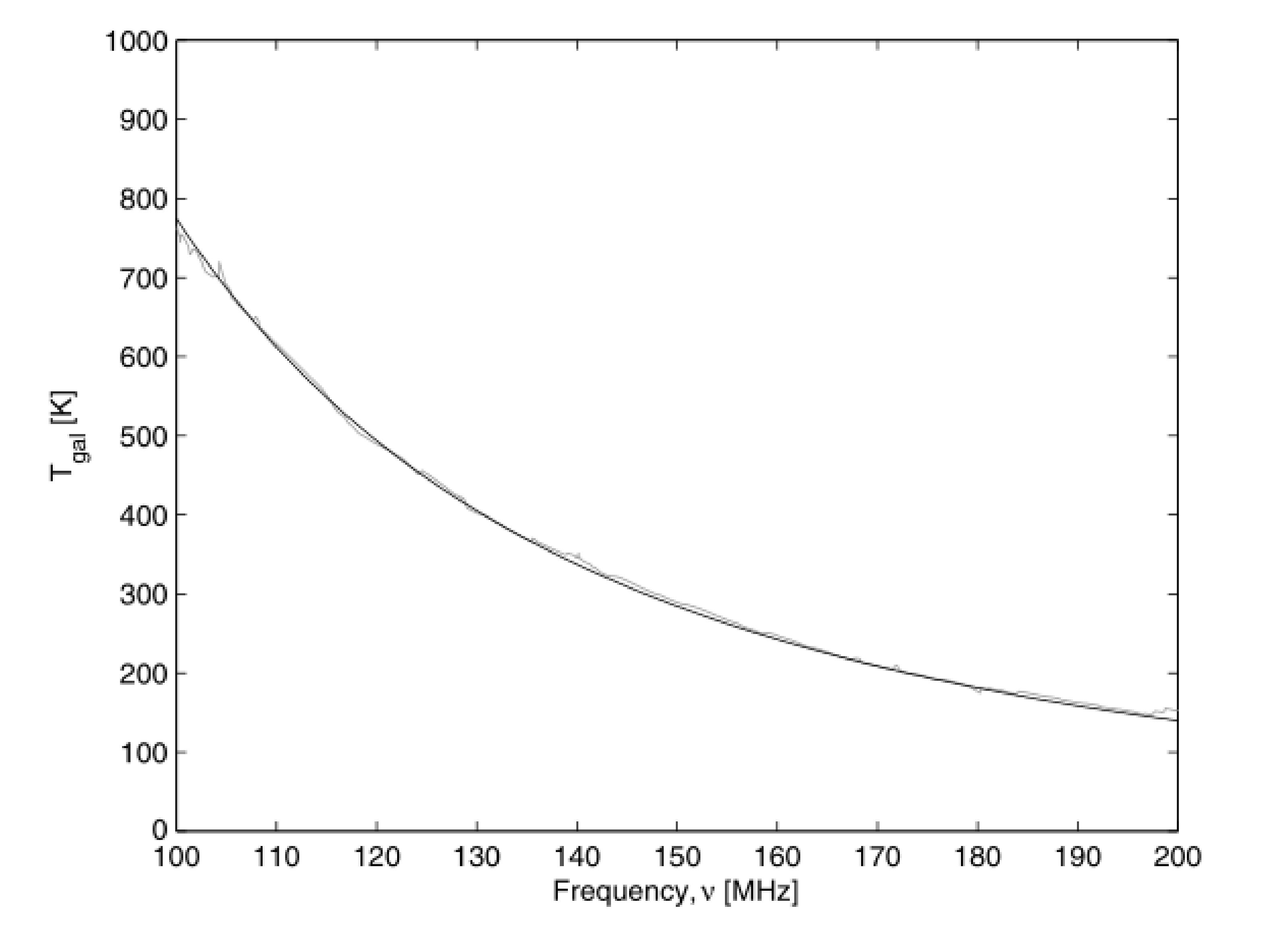
- Null hypothesis: distribution peaks at $\Delta z^{-1} = 0$
  - Systematics: $\Delta z < 0.21$ (68% confidence)
- Reionization equally likely to occur anywhere between ($6 < z < 13$)
  - Observations exclude Reionization histories shorter than $\Delta z < 0.19$ (68% confidence)

– Combining statistical + systematics: $\Delta z < 0.13$ (68% confidence), $\Delta z < 0.06$ (95% confidence)



Rogers & Bowman (2008)

Spectral Index Constrained by EDGES Experiment:

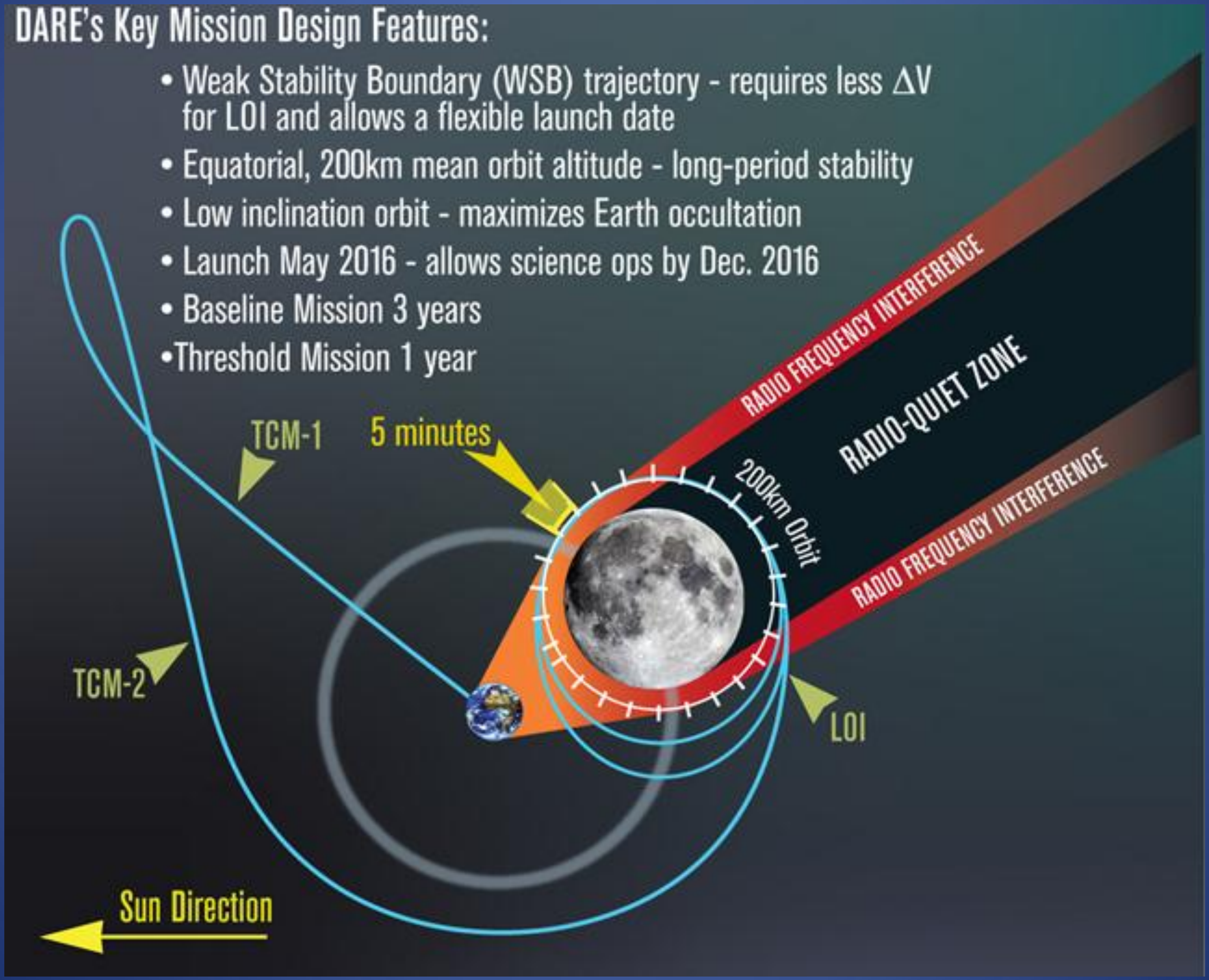


Pritchard & Loeb

After EDGES

- Enhancements to EDGES = improved constraints by an order of magnitude
- Observational techniques may be used to higher redshifts (lower frequencies) z ~ 20
- Low-frequency radio interferometers targeting spatial fluctuations in 21-cm
  - – MWA, LOFAR, PAPER

DARE – Dark Ages Radio Explorer



Technical problems for ground-based experiments	DARE
Complex environment Prevents transferring laboratory calibration of the antenna impedance and beam pattern to the deployed instrument, limits the accuracy of in situ calibration, and increases frequency of calibration operations.	**Simple environment** Simple, compact, stable geometry of S/C enables accurate modeling of the antenna and facilitates in-situ calibration.
Multipath reflections Trees, mountains, and other structures can reflect sky noise, resulting in complicated constructive and destructive spectral interference patterns in the spectrum above the 1 mK threshold.	**No multipath** No external structures are in proximity to the S/C.
RFI is always present!	**No RFI from Earth** Full RF spectrum is usable for science with low-EMI from DARE S/C environment. Sources of other RFI is predictable and calibrated out
Dynamic range is difficult to achieve A/D converters must use large bit-depths and be highly linear to accommodate RFI. Particularly susceptible to internal clock stability errors and digital noise. EDGES receiver modeled to have 6 mK artifacts.	**Easy to achieve needed dynamic range** A/D converter can use low bit-depth, industry standard specifications. Receiver based on 50 years of proven RF flight hardware.
The Earth's ionosphere Radio waves from terrestrial emitters can be reflected from meteor trails or ionospheric density structures	**No effective ionosphere**

DARE Observing Window