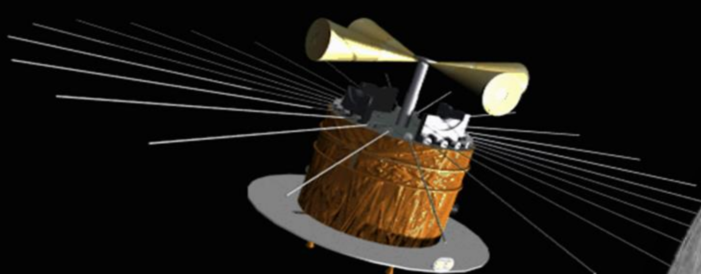
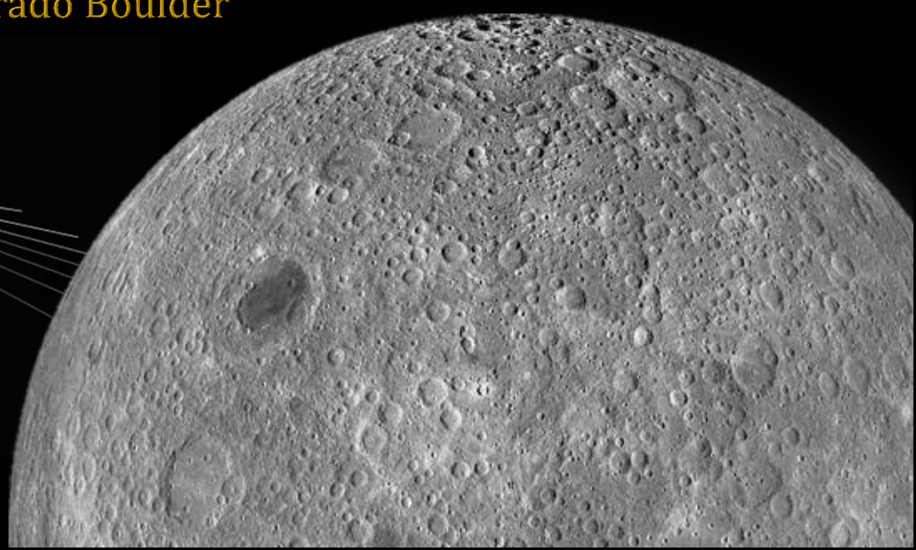
# DARE

# Detecting the First Galaxies with the Global 21-cm Signal: The Dark Ages Radio Explorer


**Jack Burns for the DARE Team**

Center for Astrophysics & Space Astronomy
University of Colorado Boulder



*The Reionization Epoch:*
*New Insights and Future Prospects*
Aspen, CO
March 6-12, 2016

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# DARE Project Team

Principal Investigator: Jack Burns, University of Colorado Boulder
Project Management & Mission Operations: NASA Ames Research Center: B. Hine & J. Bauman
Observatory Project Management: Ball Aerospace & Technologies Corp.: W. Purcell & D. Newell

Science Co-Investigators:

- Robert MacDowall, NASA GSFC, Project Scientist
- Richard Bradley, NRAO, Deputy Project Scientist
- Judd Bowman, Arizona State University
- Abhirup Datta, University of Colorado Boulder
- Anastasia Fialkov, CfA
- Steven Furlanetto, UCLA
- Dayton Jones, Space Science Institute, Boulder
- Justin Kasper, University of Michigan
- Joseph Lazio, JPL/Caltech
- Abraham Loeb, Harvard University
- Raul Monsalve, ASU & U. Colorado
- Jordan Mirocha, UCLA

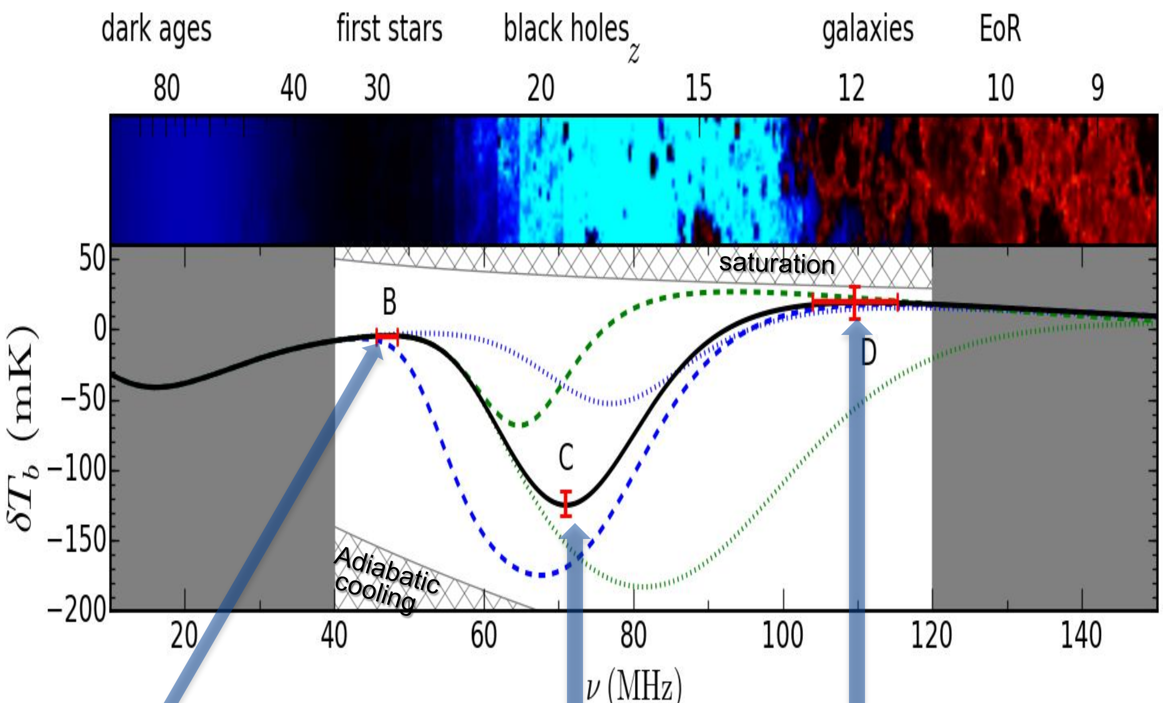
Collaborators:

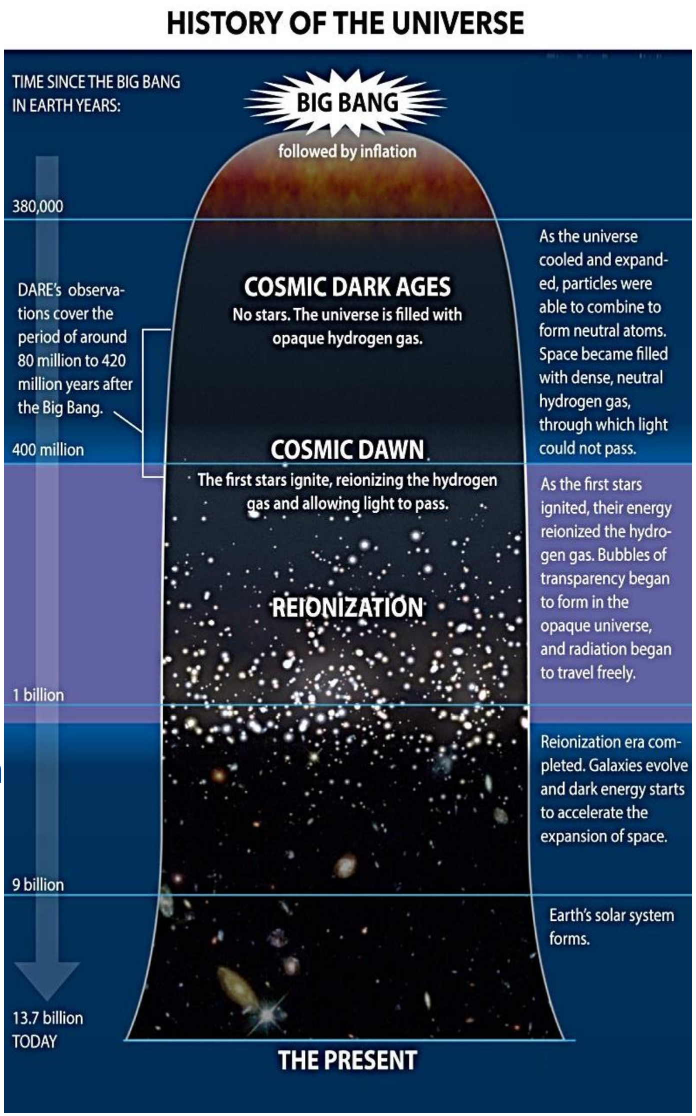
- Michael Bicay, NASA Ames
- William Farrell, NASA GSFC
- Jonathan Pritchard, Imperial College
- Eric Switzer, NASA GSFC
- Edward Wollack, NASA GSFC

Graduate Students:

- Bang Nhan, University of Colorado
- Keith Tauscher, University of Colorado

# The 21-cm Global Signal Reveals the Birth & Characteristics of the First Stars & Galaxies




**B: ignition of first stars**

**C: heating by first black holes**

**D: the onset of reionization**

--- … uncertainties in 1st star models

--- … uncertainties in 1st black hole models

DARE operates at ν = 40-120 MHz, probing redshifts z = 11-35

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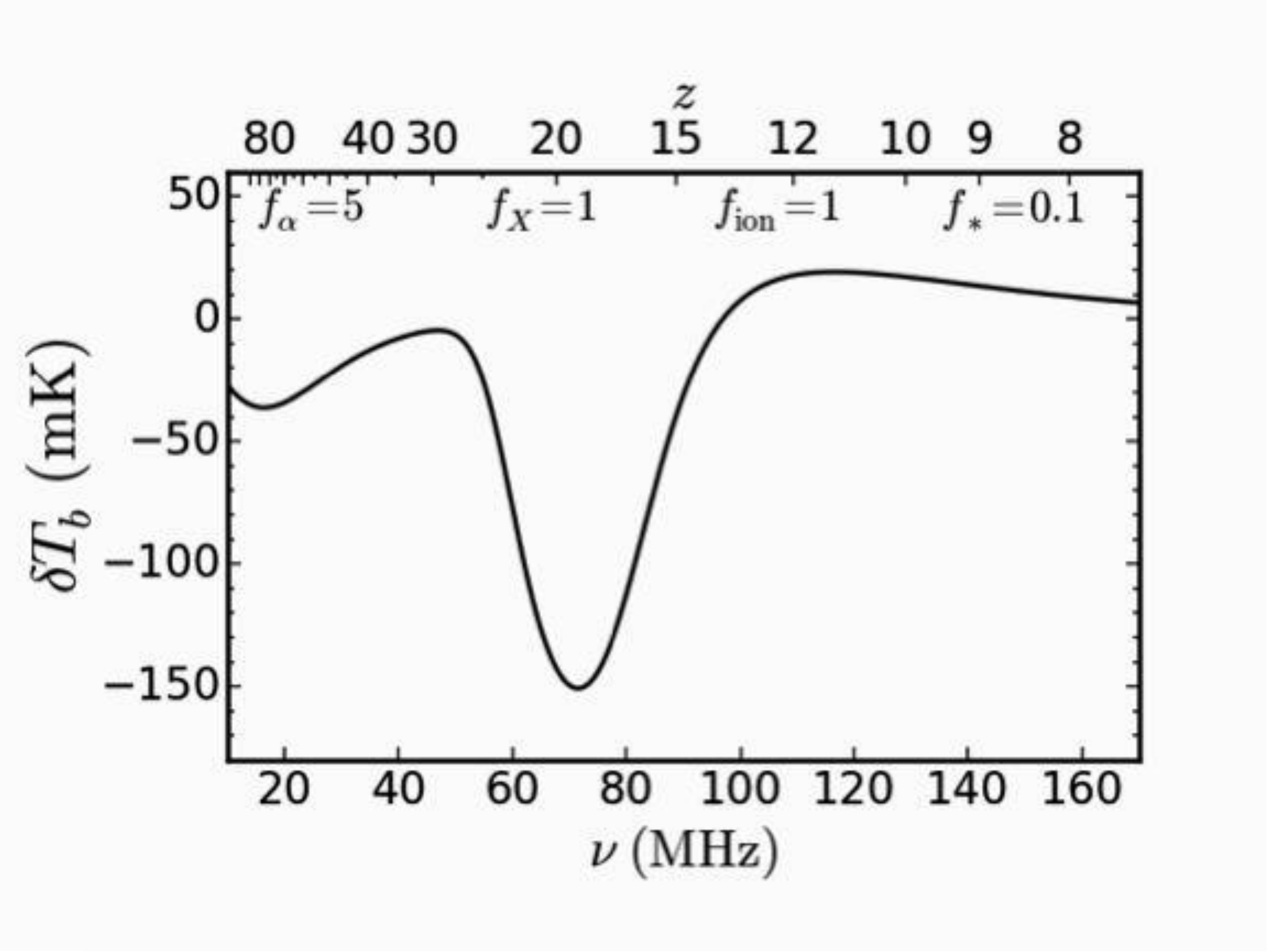
Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006
and Mirocha, Harker, & Burns, 2015, ApJ, 813, 11.

# Range of Model Parameters for 1st Stars & Galaxies






courtesy Jordan Mirocha

# Observational Approaches for Detection of Global 21-cm Monopole

## Single Antenna Radiometers

- EDGES (Bowman & Rogers)
- SARAS (Patra et al.)
- LEDA (Greenhill, Bernardi et al.)
- SCI-HI (Peterson, Voytek et al.)
- BIGHORNS (Sokolowski et al.)
- DARE (Burns et al.)

Challenges include systematics arising from stability issues, accurate calibration, polarization leakage, foregrounds.

## Small, Compact Interferometric Arrays

- Vadantham et al.
- Mahesh et al.
- Presley, Parsons & Liu
- Subrahmanyan, Singh et al.

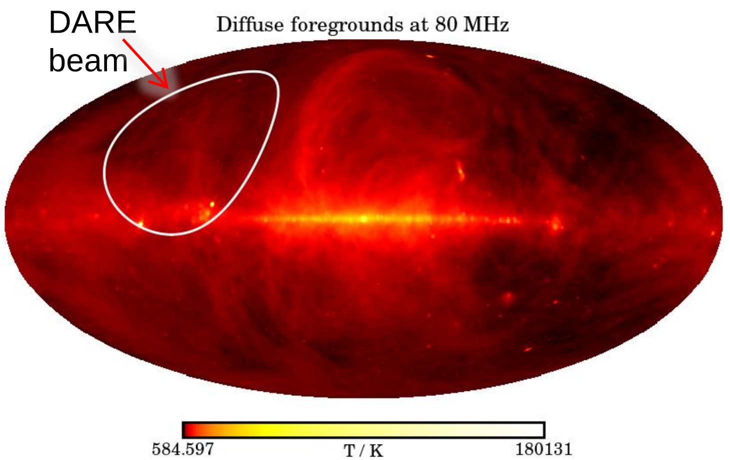
Challenges include cross-talk among antenna elements, mode-coupling of foreground continuum sources into spectral confusion, sensitivity.

# Foregrounds: Major Challenge

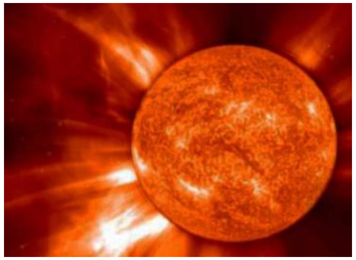
- **Earth's Ionosphere** (e.g., Vedantham et al. 2014; Datta et al. 2016; Rogers et al. 2015; Sokolowski et al. 2015)
  - Refraction, absorption, & emission
  - Spatial & temporal variations related to forcing action by solar UV & X-rays => 1/f or flicker noise acts as another systematic or bias.
  - Effects scale as $\nu^{-2}$ so they get much worse quickly below ~100 MHz.
- **Radio Frequency Interference (RFI)**
  - RFI particularly problematic for FM band (88-110 MHz).
  - Reflection off the Moon, space debris, aircraft, & ionized meteor trails are an issue everywhere on Earth (e.g., Tingay et al. 2013; Vedantham et al. 2013).
  - Even in LEO ($10^8$ K) or lunar nearside ($10^6$ K), RFI brightness $T_B$ is high.
- **Galactic/Extragalactic**
  - Mainly synchrotron with expected smooth spectrum (~3rd order log polynomial, $\log T_{\text{fg}} = \sum_{i=0}^{N_{\text{poly}}} a_i \log\left(\frac{\nu}{\nu_0}\right)^i$, although it is corrupted by antenna beam; e.g., Bernardi et al. 2015).
  - EDGES finds spectral structure at levels <8 mK in foreground at 100-200 MHz.
- **Other Foregrounds -** lunar thermal emission & reflections; Jupiter; Recombination lines.

# Extraterrestrial Foregrounds

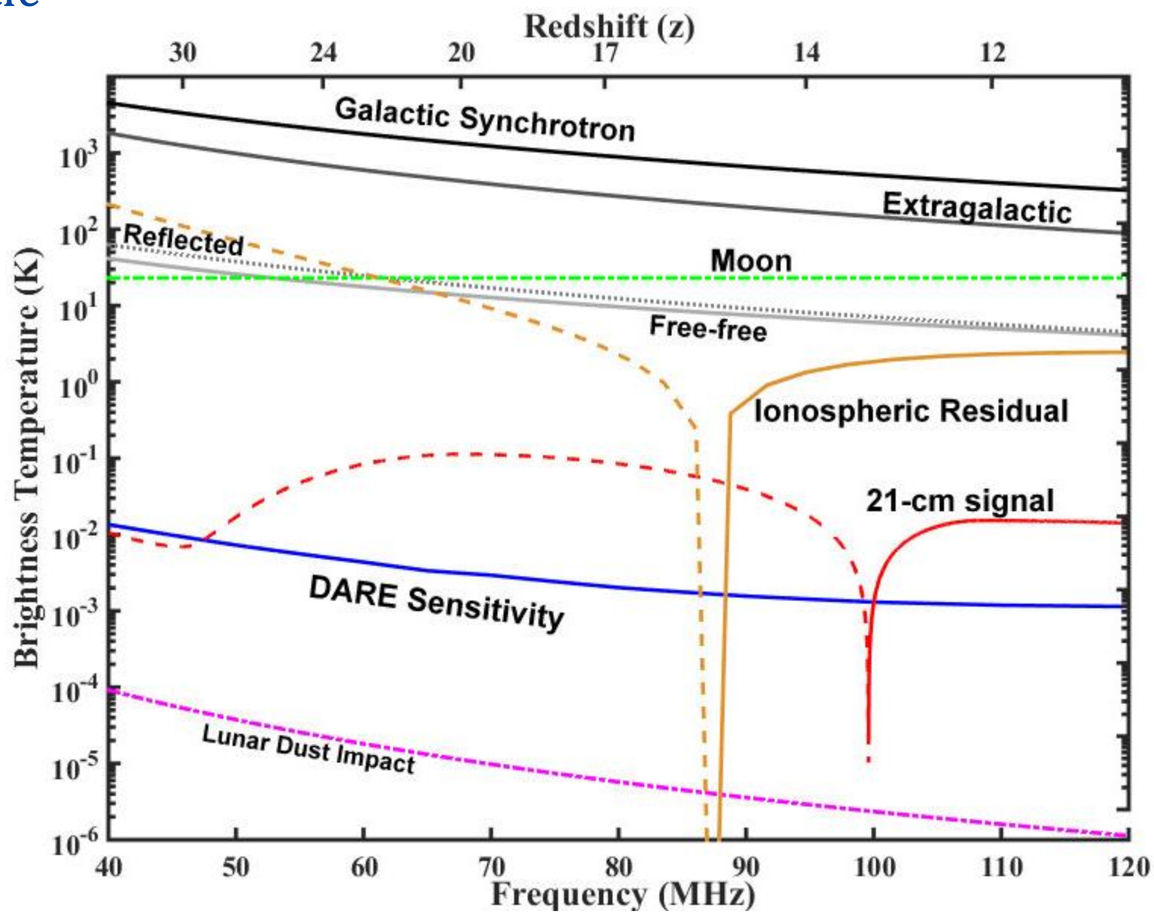
1) Milky Way synchrotron emission + “sea” of extragalactic sources.




2) Solar system objects: Sun, Jupiter, Moon.

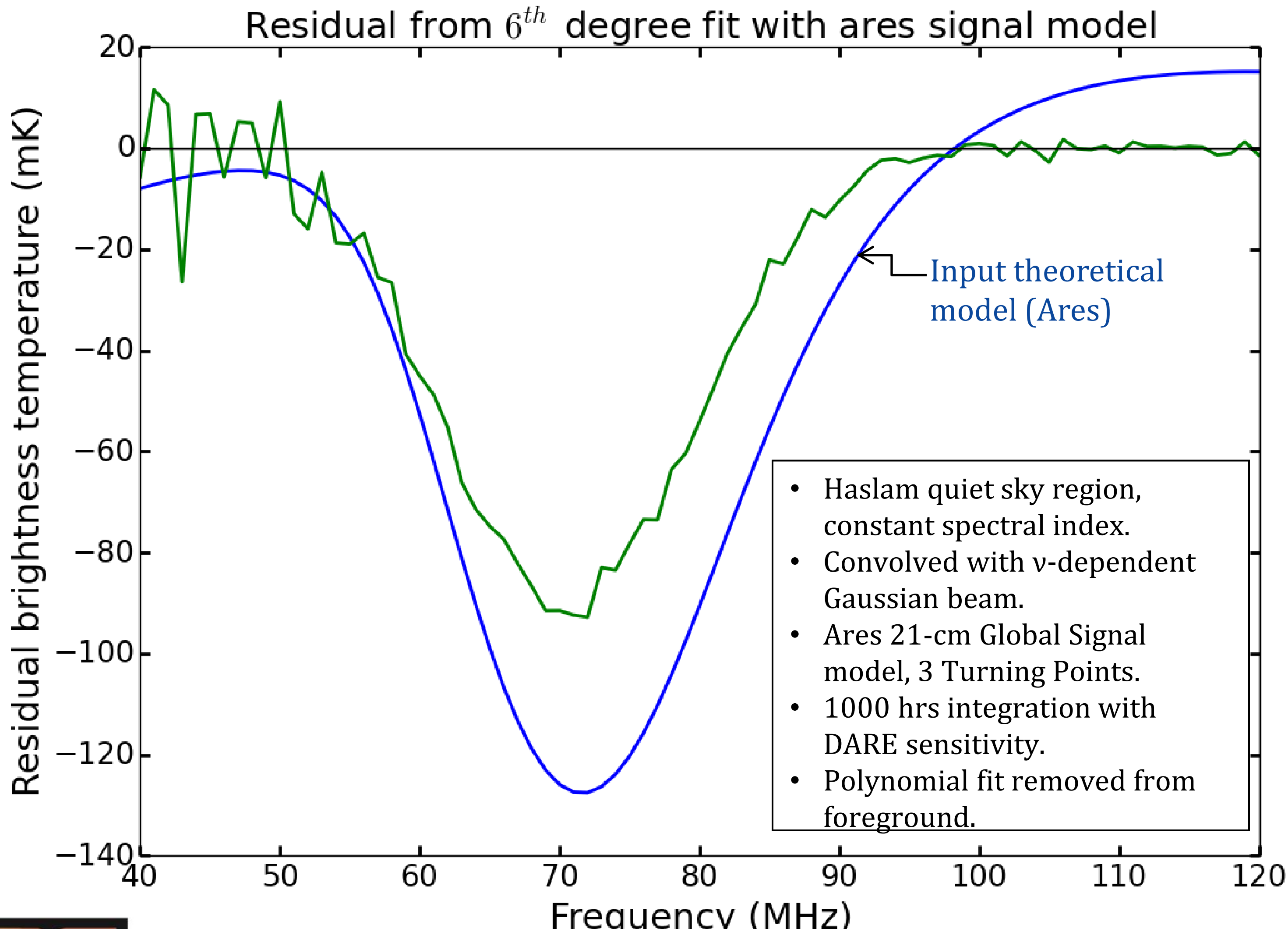


## Spectra of Foregrounds




=>Must employ advanced statistical techniques to simultaneously fit signal, foregrounds, & instrument parameters

# Detecting the strongest spectral feature in the presence of the Galactic foreground

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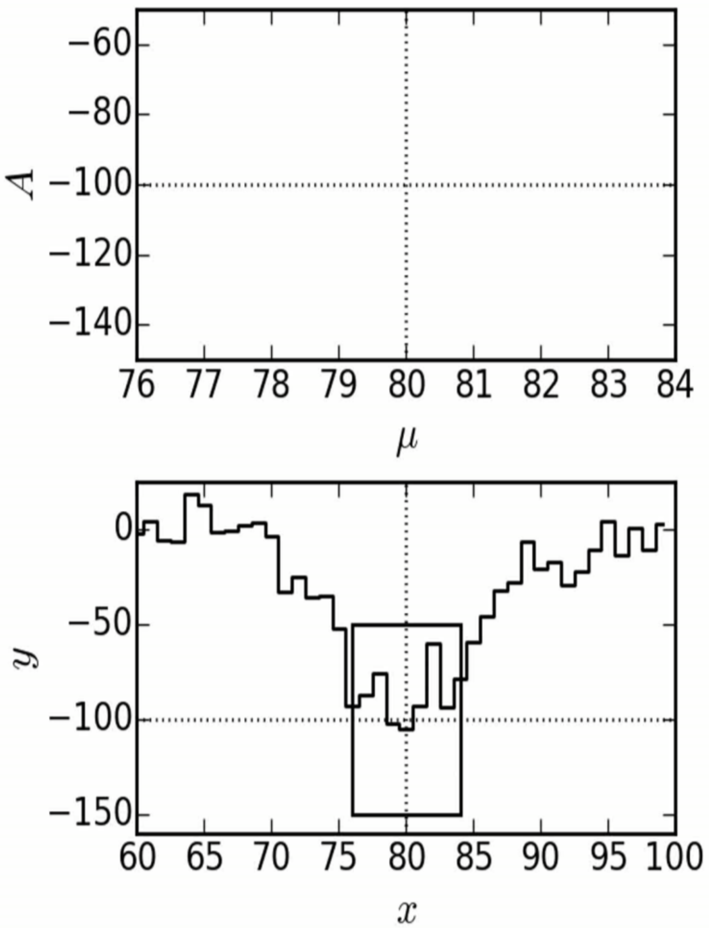
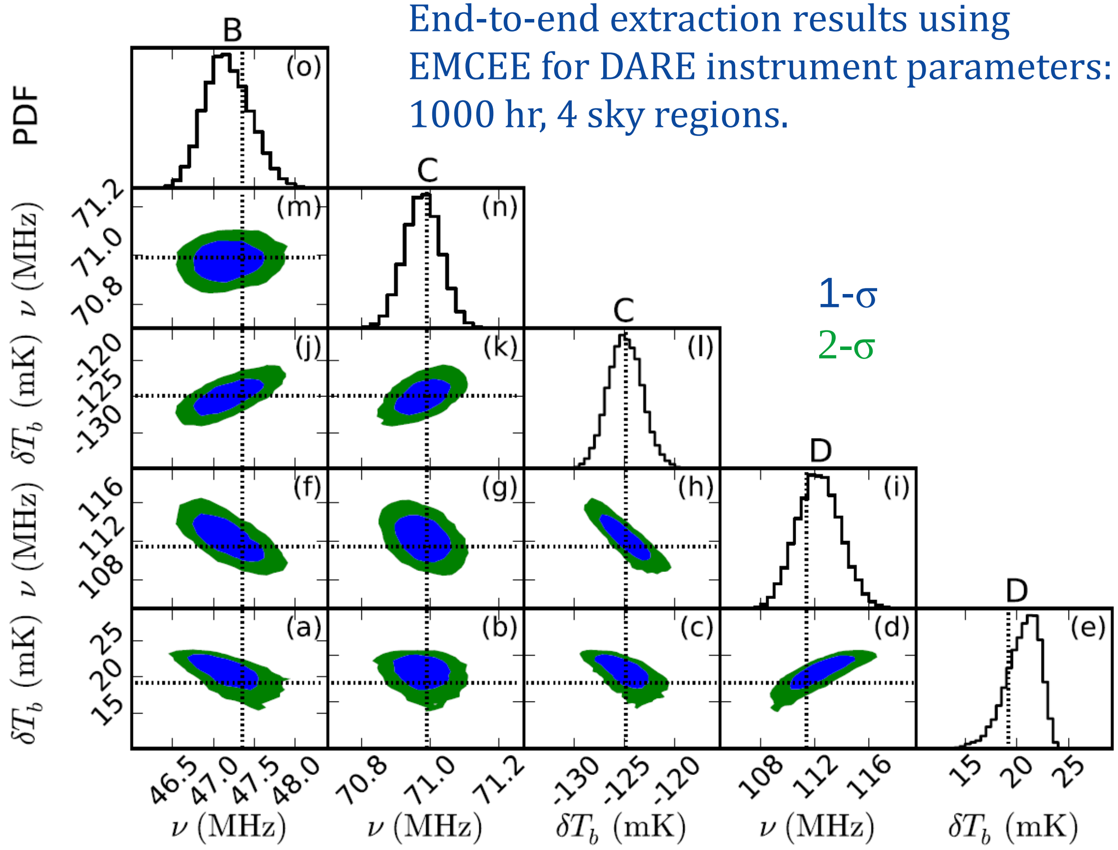
- Instrument Requirement: Minimal Chromatic beam effects

Keith Tauscher & J. Burns

# Signal Extraction using MCMC




End-to-end extraction results using EMCEE for DARE instrument parameters: 1000 hr, 4 sky regions.

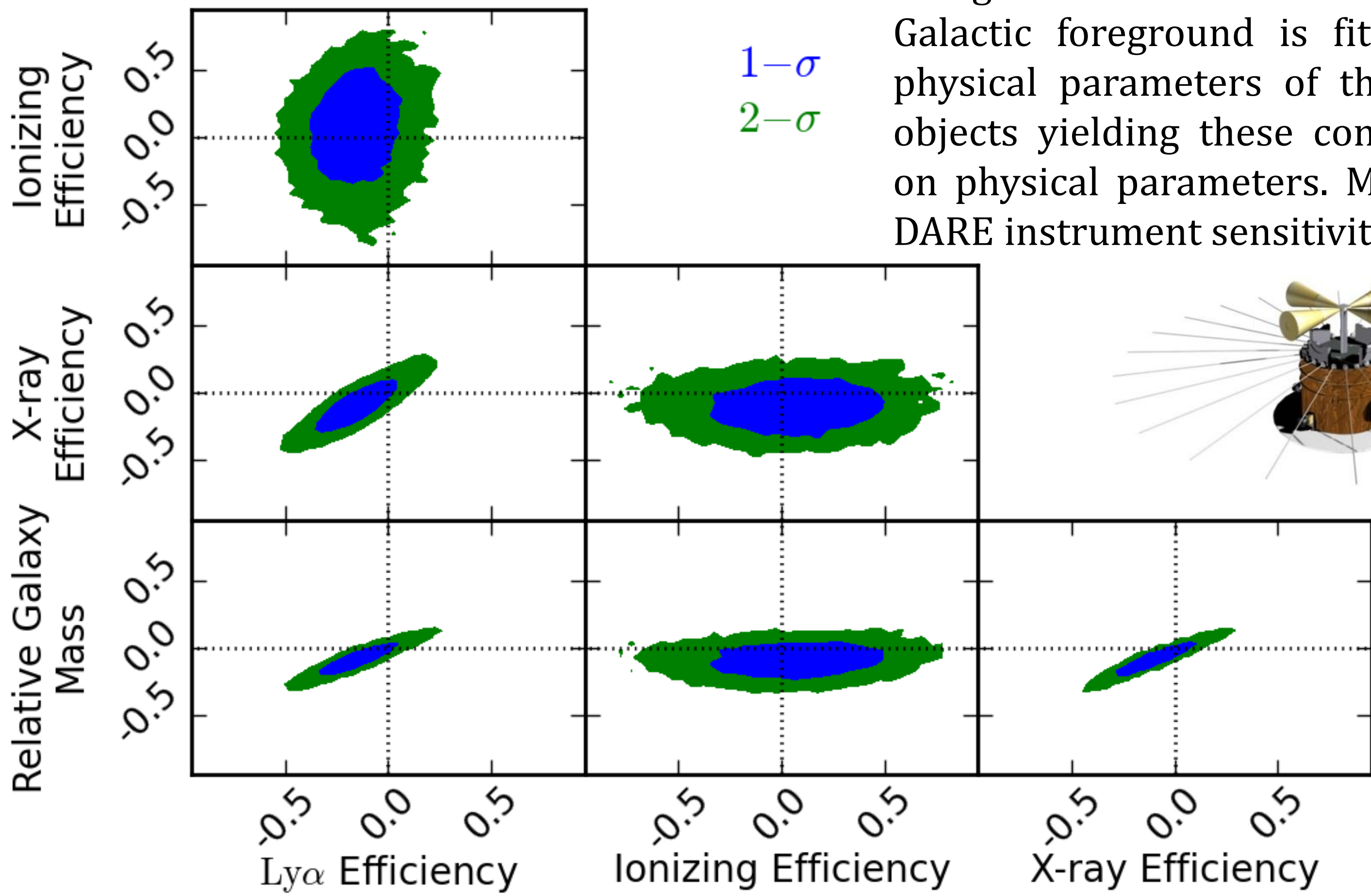


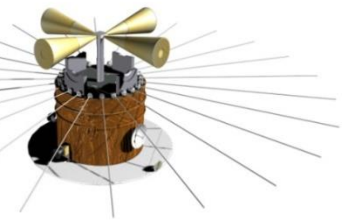

This technique captures degeneracies & covariances between parameters, including those related to signal, foregrounds, & the instrument. Extensive heritage from CMB observations by WMAP & Planck.

For details, see Harker, Mirocha, Burns, & Pritchard (2016), MNRAS, 455, 3829.

# Characterizing the First Stars & Galaxies

Using an MCMC statistical framework, the Galactic foreground is fit along with the physical parameters of the first luminous objects yielding these confidence intervals on physical parameters. Modeling assumes DARE instrument sensitivity.



Global Experiments have the potential to bound the properties (e.g., mass, spectra) of the first generation of stars, black holes, & galaxies for the first time (0.1-0.2 dex).

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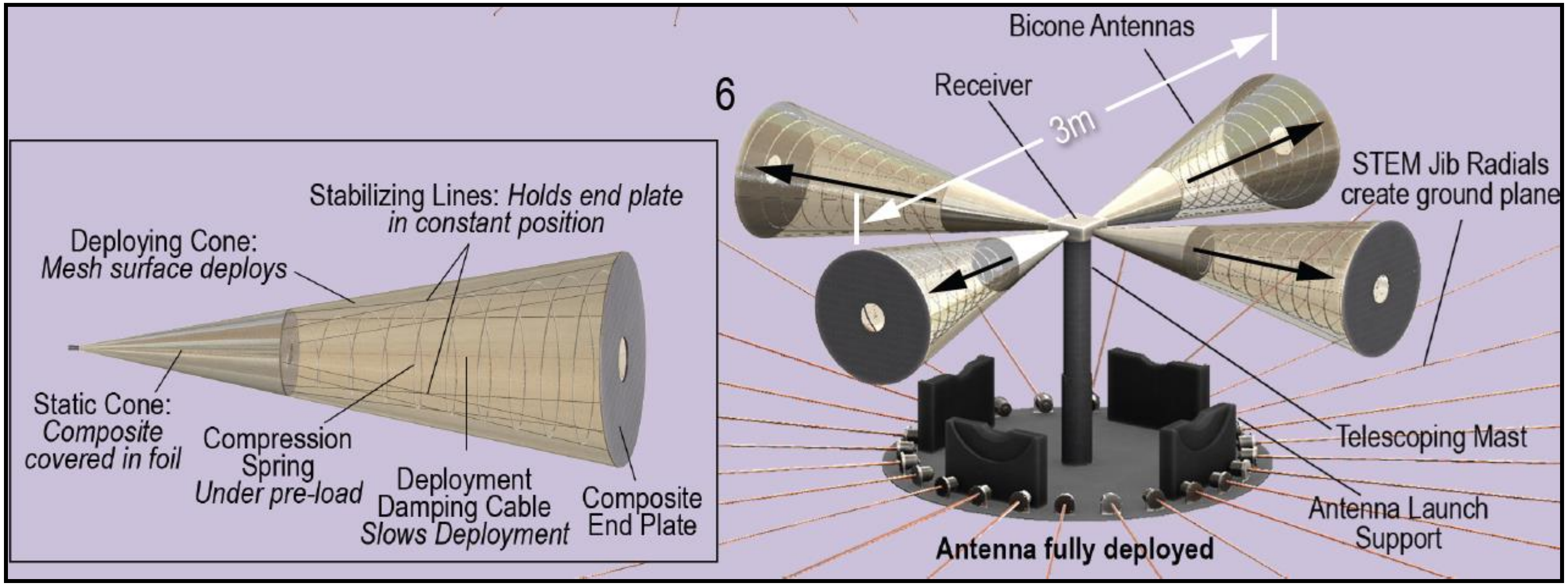
Mirocha, Harker, & Burns (2015), *ApJ*, 813, 11.

# Science Instrument




**Antenna: Dual, deployable bicones to accommodate launch volume**

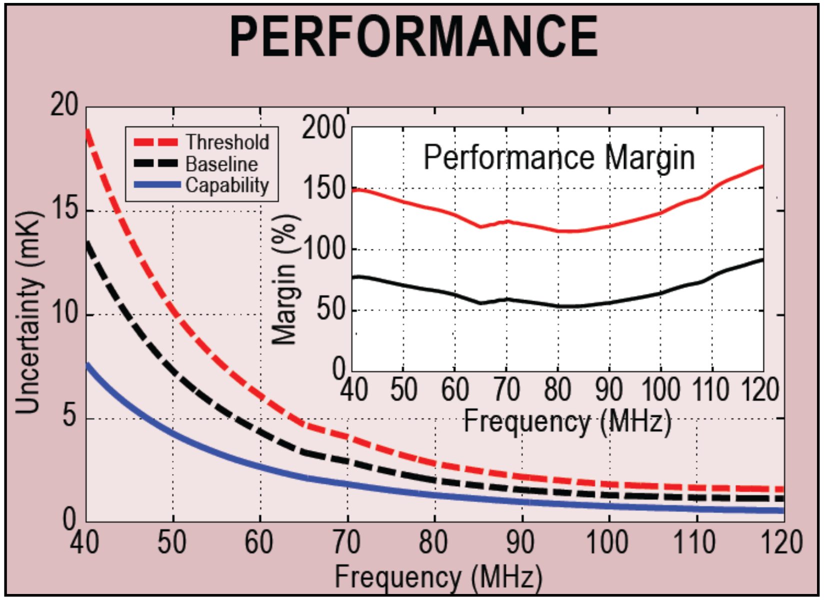
- Mast deploys bicones above S/C deck
- Bicones deploy to achieve length
- Jib Radials deploy to form ground plane

**Receiver: Pseudo-correlation Architecture + Reflectometer**

- Heritage from WMAP, Planck, Microwave Limb Sounder on UARS.
- Thermally controlled front-end receiver electronics enclosure

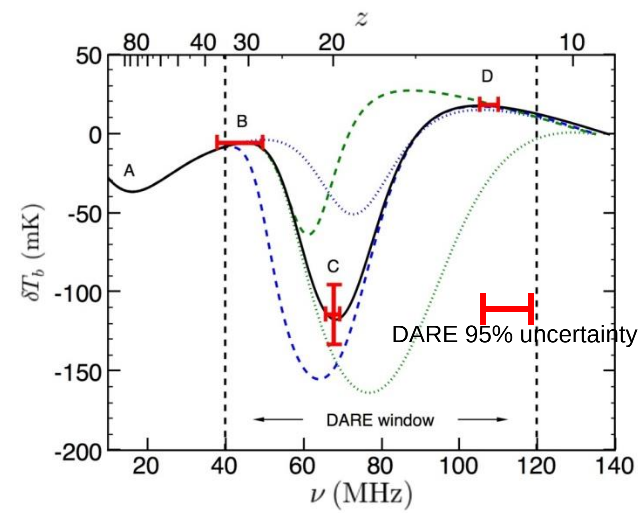
**Spectrometer**

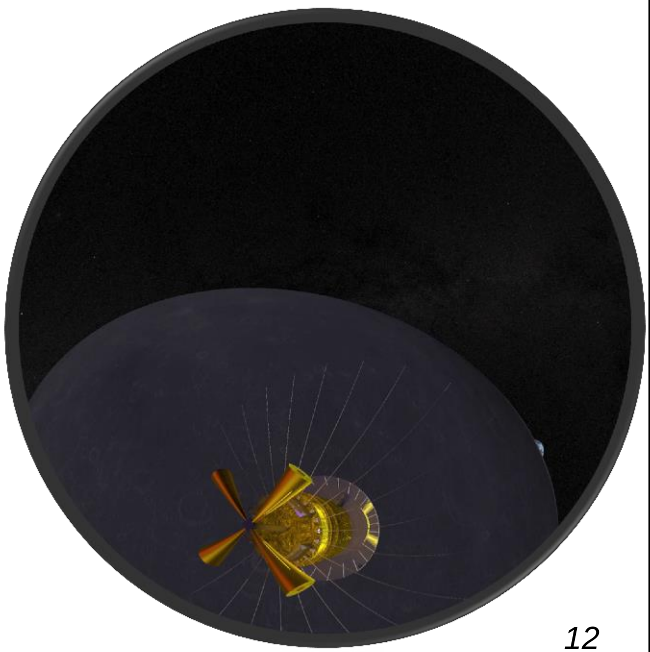
- Achieves $10^6$ dynamic range
- Uses space-qualified FPGAs.



# Summary and Conclusions

- The Global 21-cm Monopole signal is a powerful tool to explore the first luminous objects in the Universe and their environs at z>10.
- *DARE science instrument*: broad-band dipole antenna, pseudo-correlation receiver, digital spectrometer, radial ground screen.
- *MCMC fits set meaningful constraints on:* Ly-α, ionizing, & X-ray backgrounds along with minimum virial temperatures of halos.
- DARE will be proposed  in response to the NASA Explorer AO in late 2016.



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# Supplemental Slides


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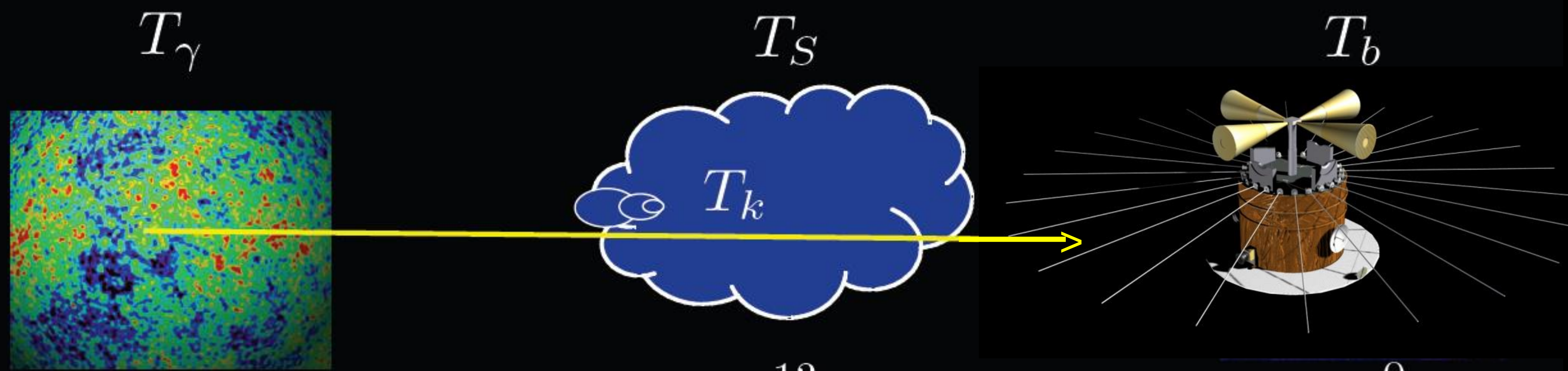
# The 21-cm Line in Cosmology




$z = 13$

$\nu = 1.4\,\mathrm{GHz}$

$z = 0$

$\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

neutral fraction

baryon density

spin temperature

peculiar velocities

brightness temperature (P=k$T_b\Delta\nu$)

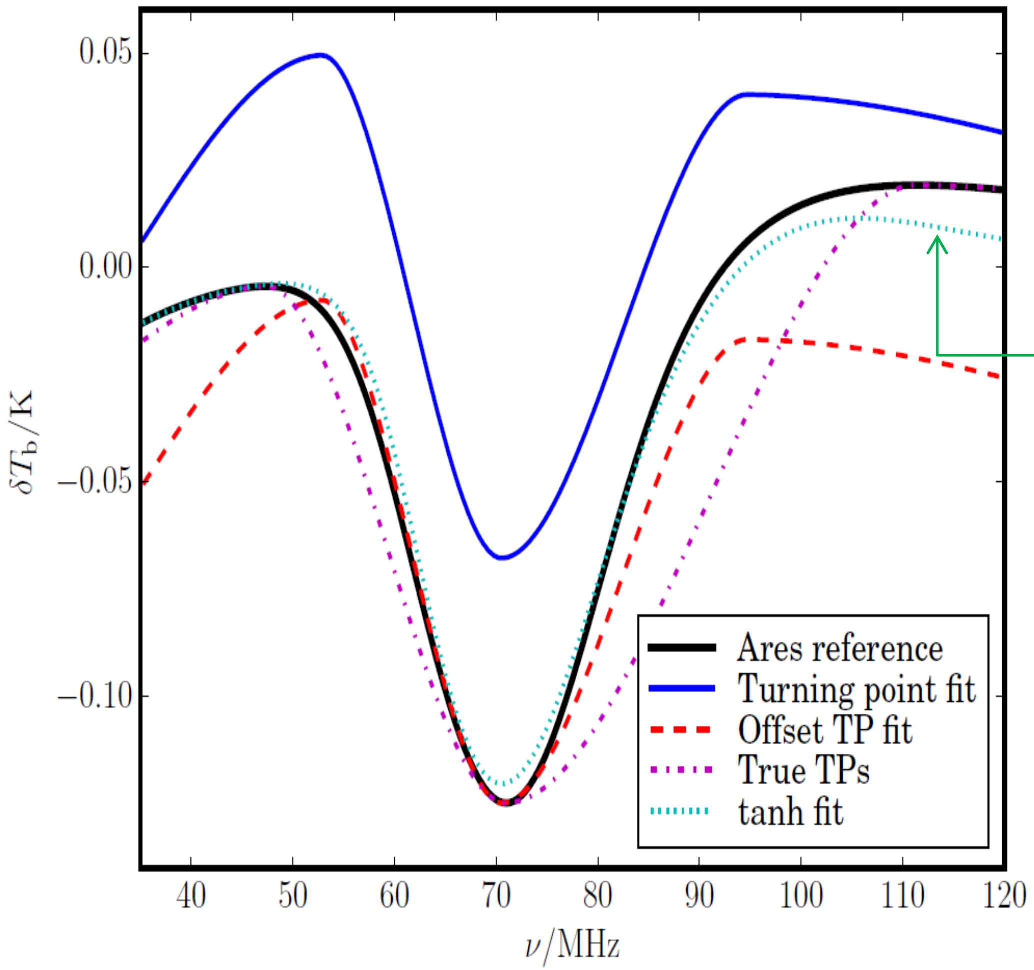
$$T_b = 27 x_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\,\mathrm{mK}$$

spin temperature set by different mechanisms:

- Radiative transitions (CMB)
- Collisions
- Wouthysen-Field effect

Courtesy of J. Pritchard

# Parameterizing the 21-cm Model




- Previous studies parameterized signal from just the 3 Turning Points.
- A more physically-motivated approach to model the Ly-α, IGM thermal, & ionization history is a *tanh* model:

$$A(z) = \frac{A_{\rm ref}}{2}\{1 + \tanh[(z_0 - z)/\Delta z]\}$$

- Significantly improves extraction of 21-cm signal from Foregrounds, reducing biases.

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Harker, Mirocha, Burns, & Pritchard (2016), MNRAS, 455, 3829.