DARE

Cosmology from the Moon: The Dark Ages Radio Explorer

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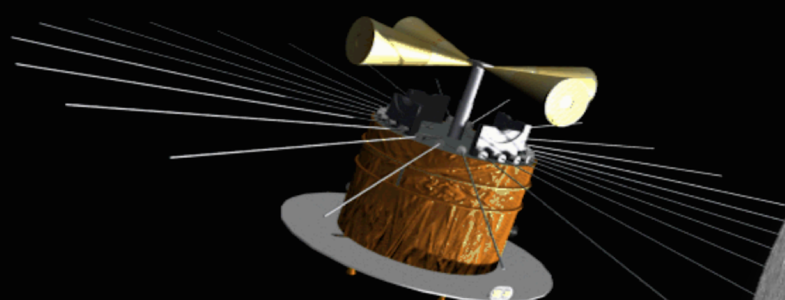

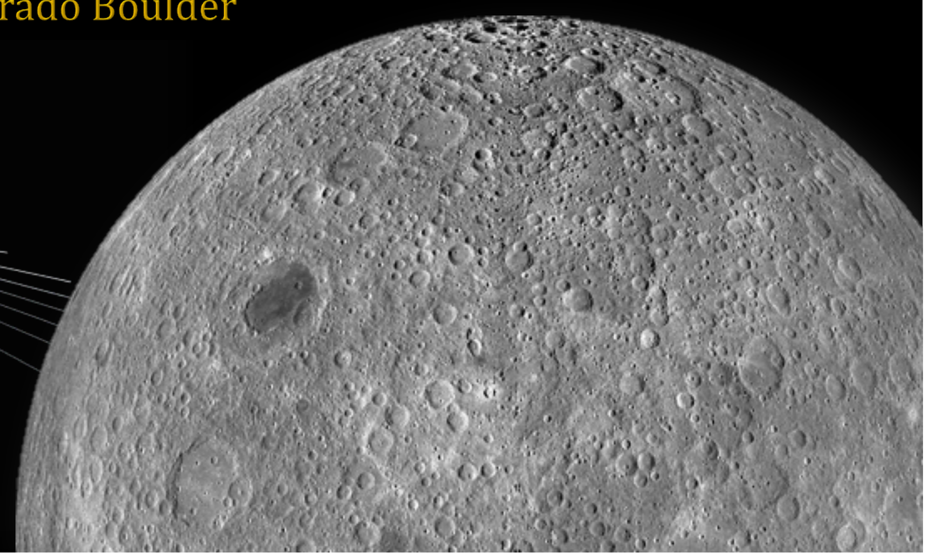

Science at Low Frequencies
Albuquerque, NM
2 December 2015

DARE Project Team

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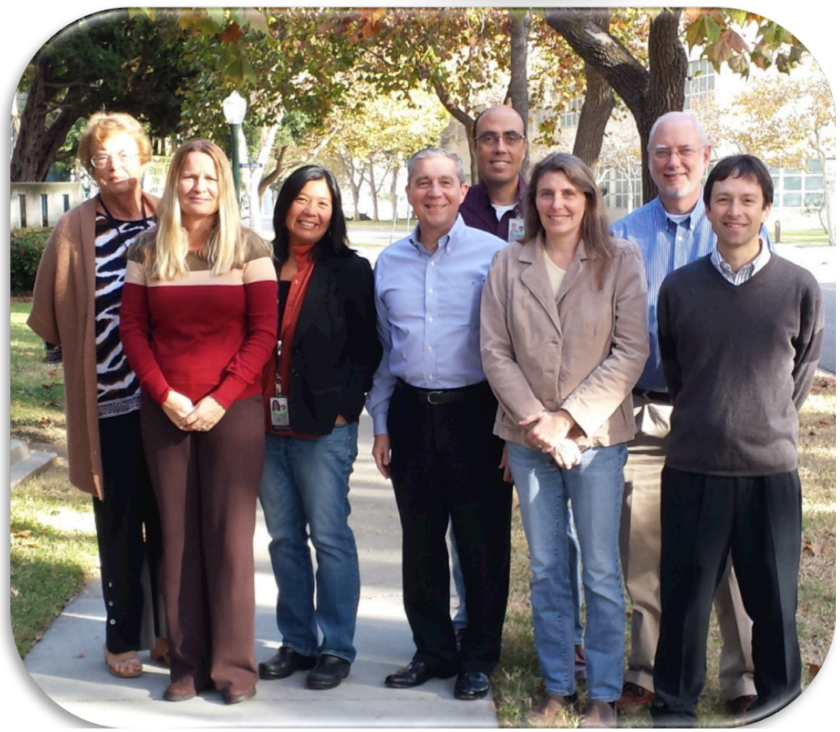
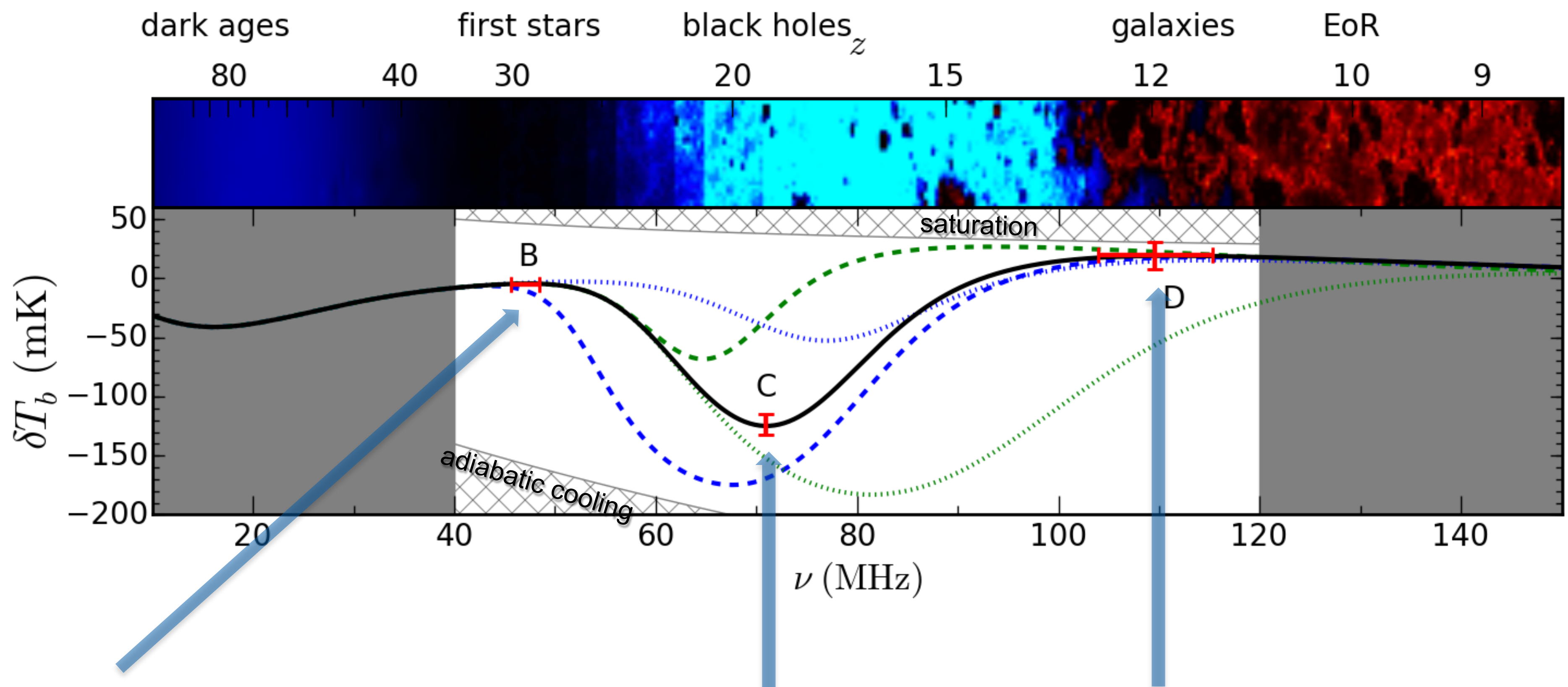


The 21-cm Global Signal Reveals the Birth & Characteristics of the First Stars & Galaxies



B: ignition of first stars

- When did the First Stars ignite? What were these First Stars?
- What surprises emerged from the Dark Ages?

C: heating by first black holes

- When did the first accreting black holes turn on? What was the characteristic mass?

D: the onset of reionization

- When did Reionization begin?

--- · · · uncertainties in 1st star models

--- · · · uncertainties in 1st black hole models

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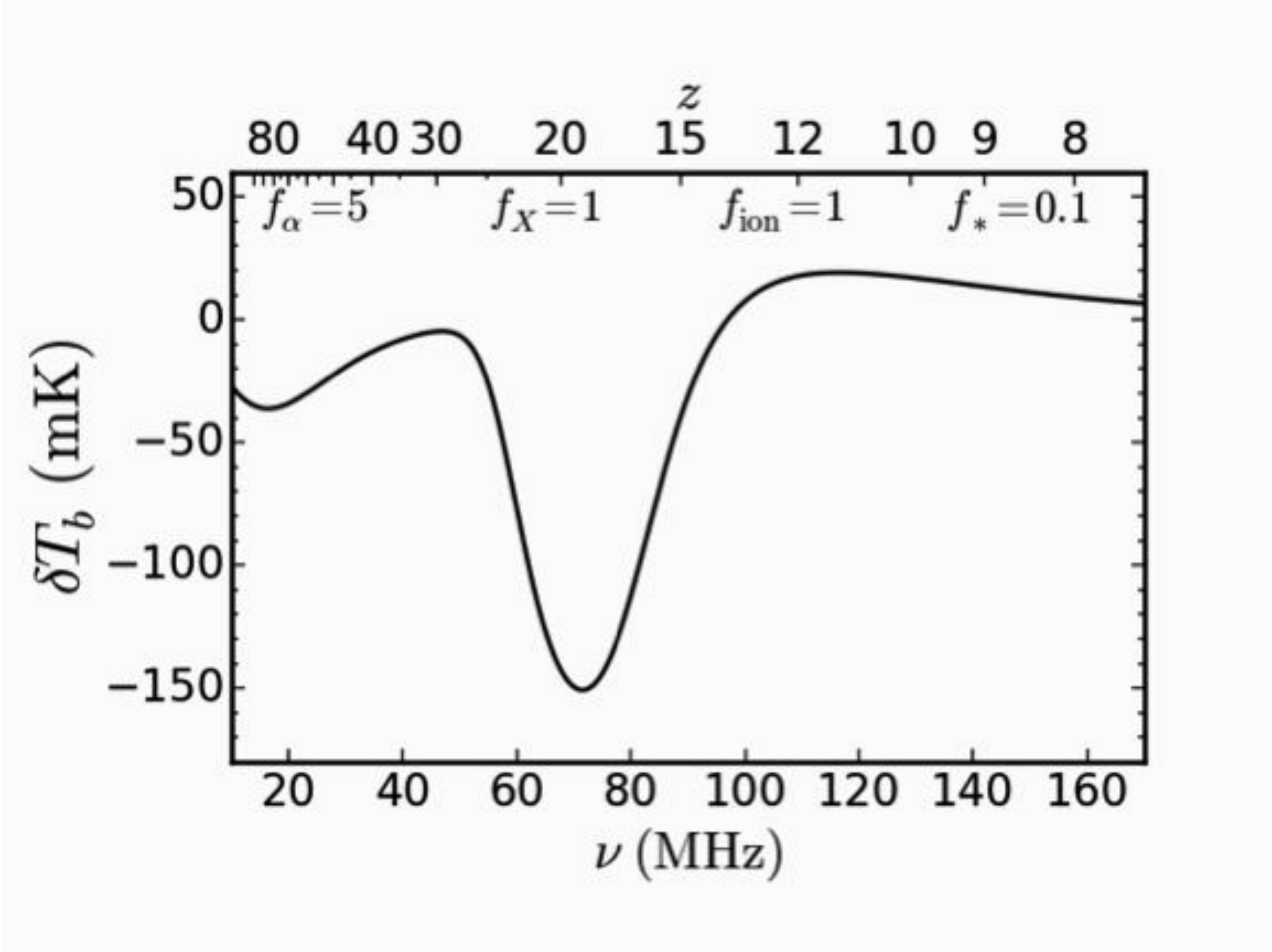
Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006
and Mirocha, Harker, & Burns, 2015, ApJ, 813, 11.

Range of Model Parameters for 1st Stars & Galaxies



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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. 2015; 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 ν^{-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 TB is high.

Galactic/Extragalactic

Mainly synchrotron with expected smooth spectrum (~3rd order log polynomial,

$$\log T_{\mathrm{fg}} = \sum_{i=0}^{N_{\mathrm{poly}}} a_i \log\left(\frac{\nu}{\nu_0}\right)^i$$

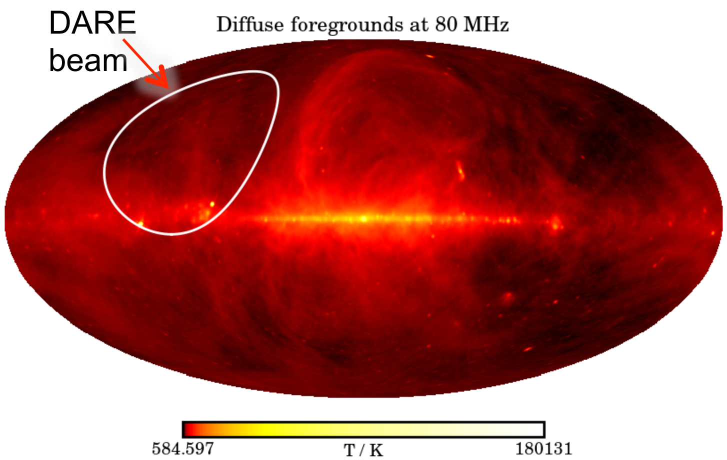
, although it is corrupted by antenna beam; e.g., Bernardi et al. 2015).

EDGES finds spectral structure at levels <12 mK in foreground at 100-200 MHz.

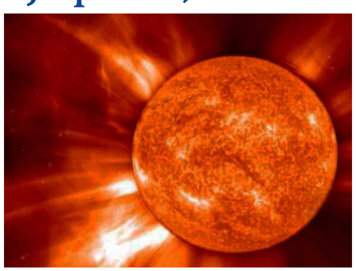
Other Foregrounds - lunar thermal emission & reflections; Jupiter; Recombination lines.

Extraterrestrial Foregrounds

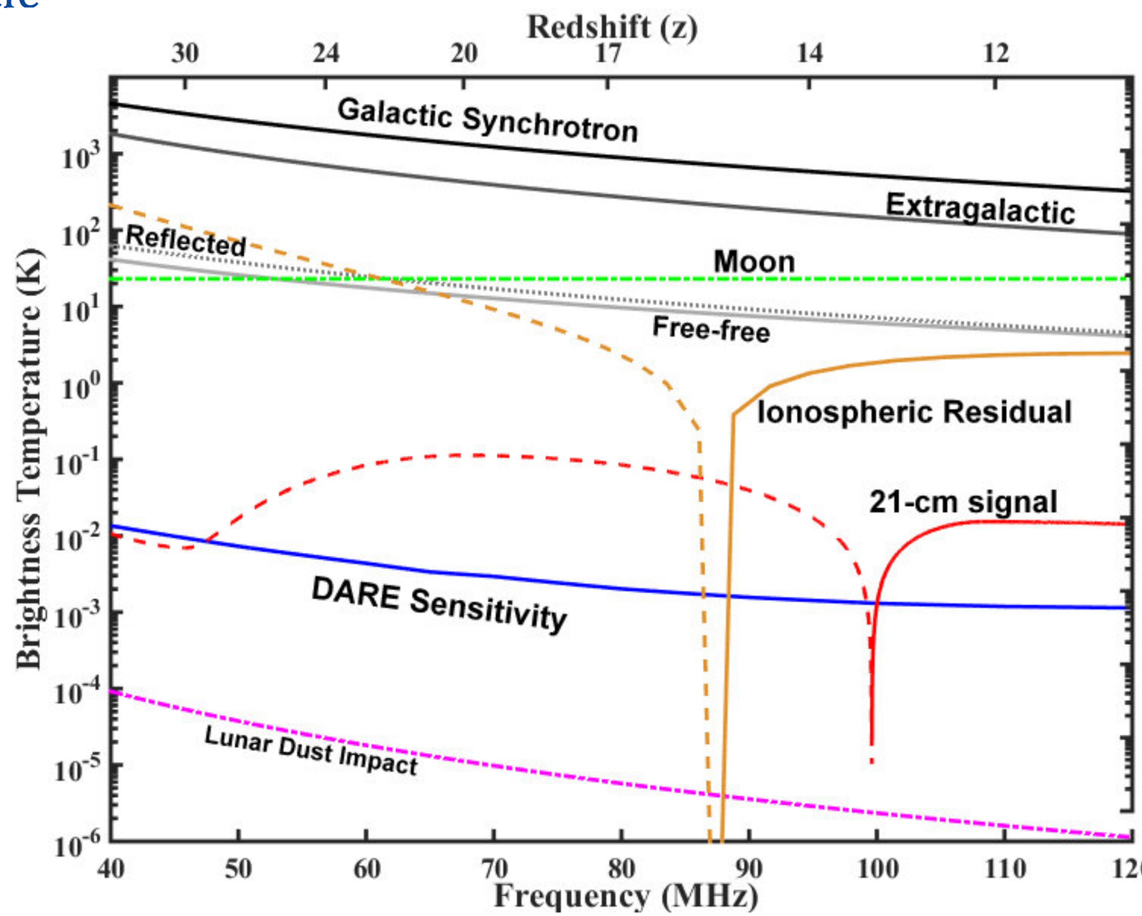
1) Milky Way synchrotron emission + “sea” of extragalactic sources.



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

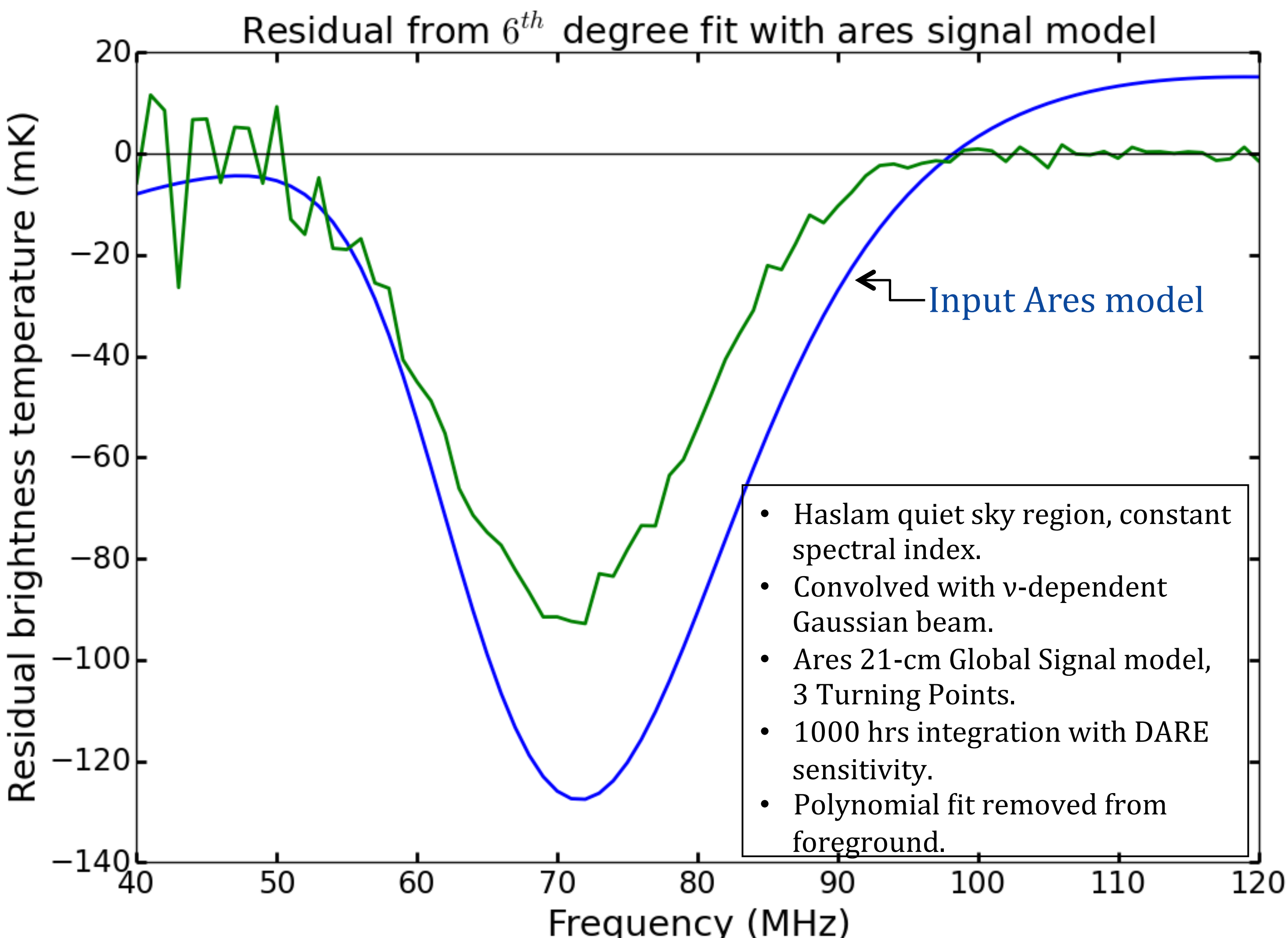


Spectra of Foregrounds



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

Can we detect the strongest spectral feature in the presence of the Galactic foreground?



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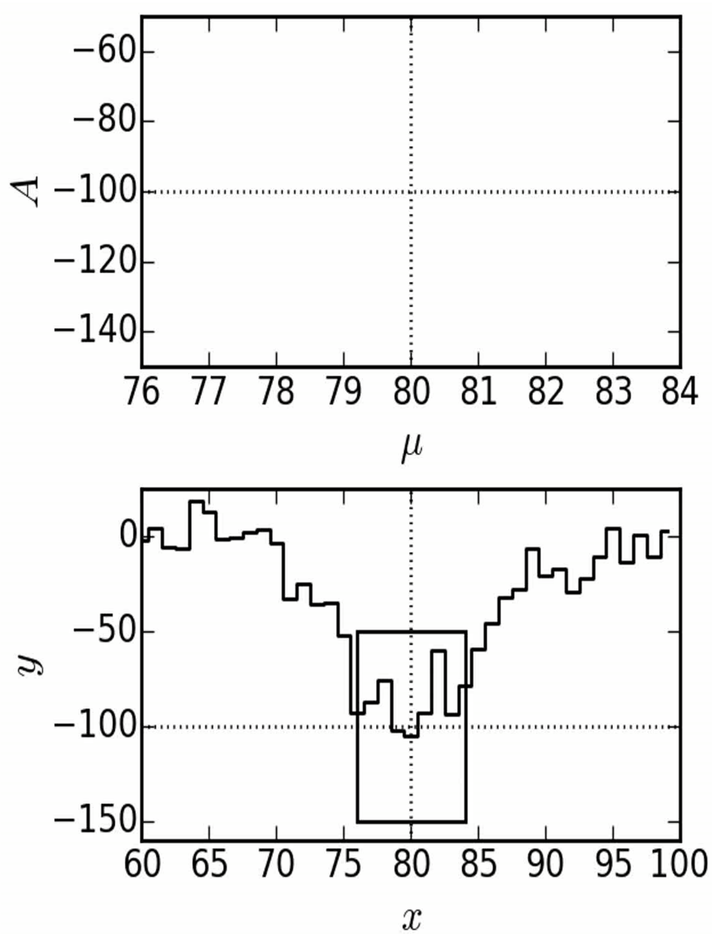
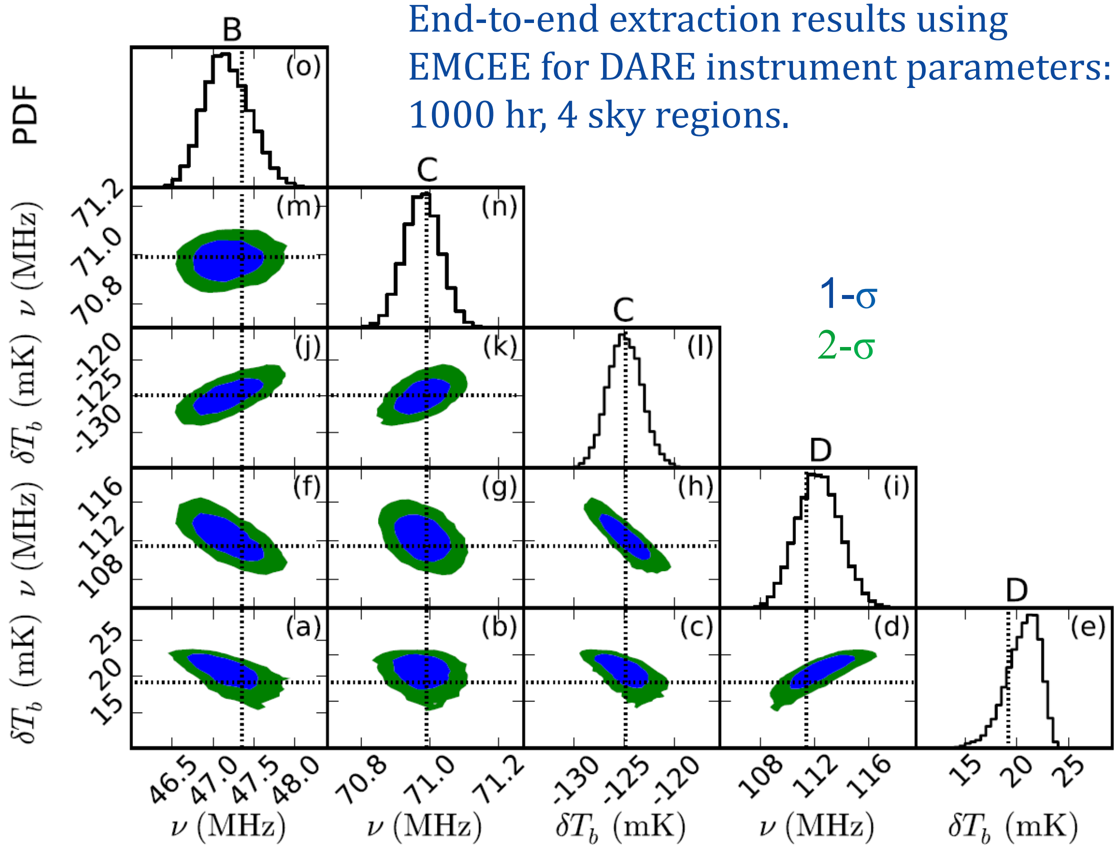
- Instrument Requirement: Minimal Chromatic beam effects

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.

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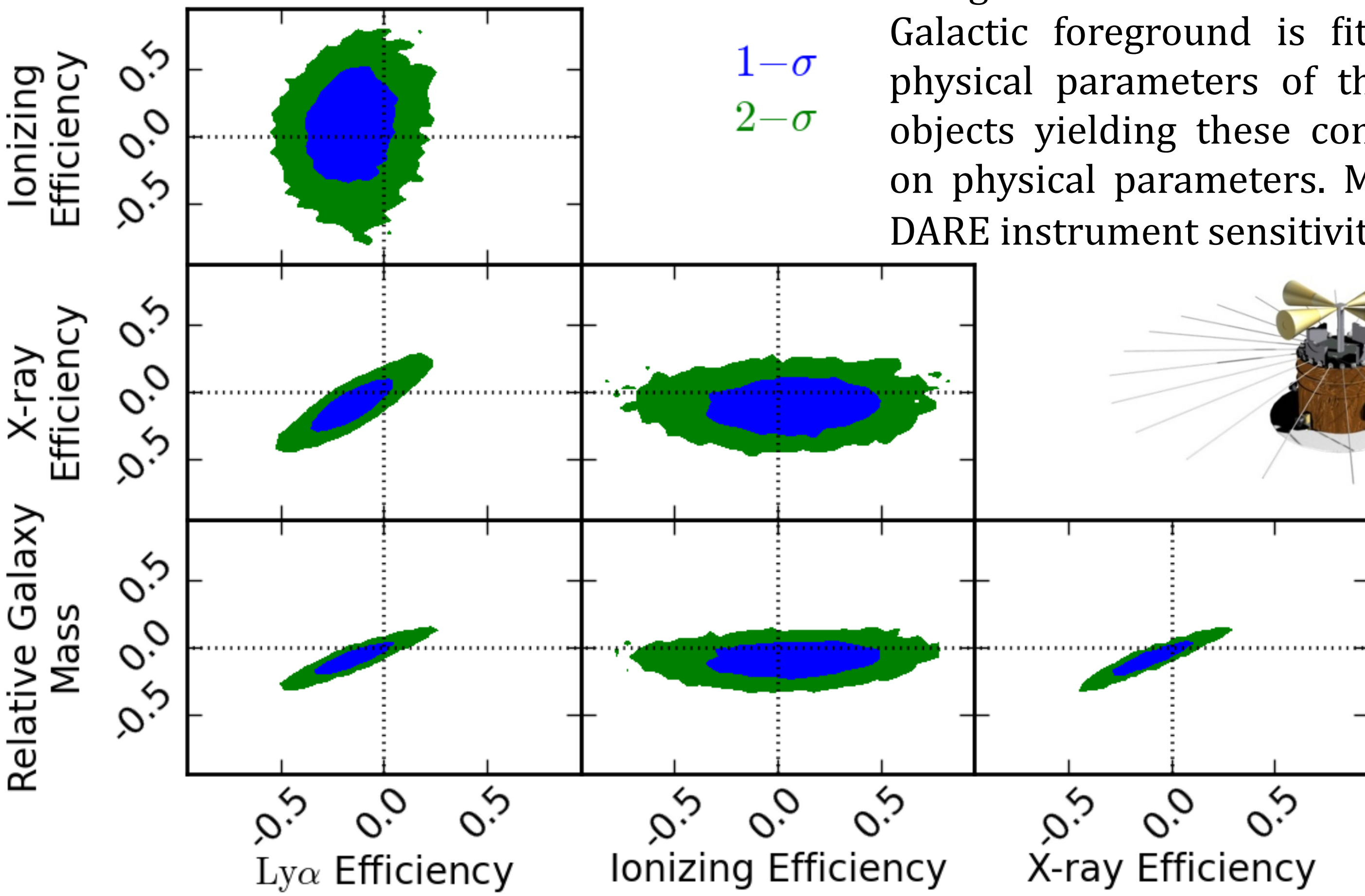
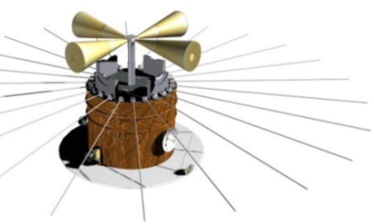
For details see Harker et al. (2012), MNRAS, 419, 1070;
and Harker et al. (2015), MNRAS, in press, arXiv:151000271H.

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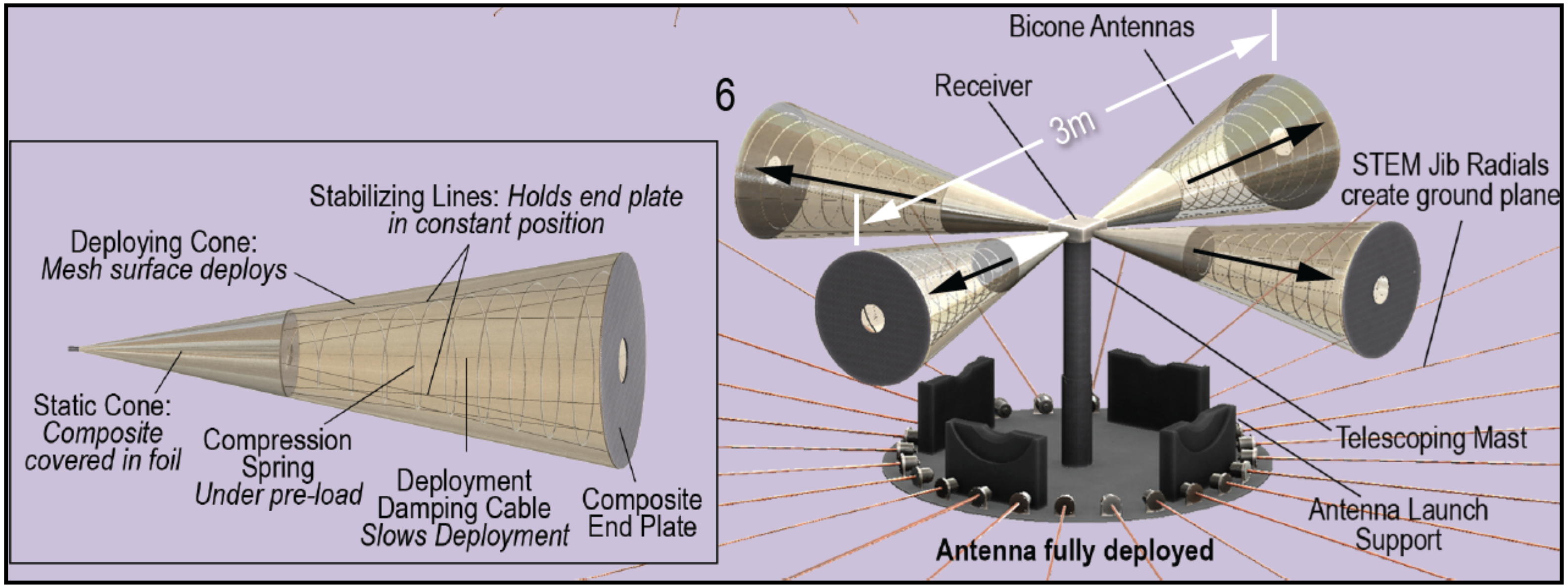
Mirocha, Harker, & Burns (2015), *ApJ*, 813, 11.

Science Instrument



Antenna: Dual, deployable bicones to accommodate launch volume

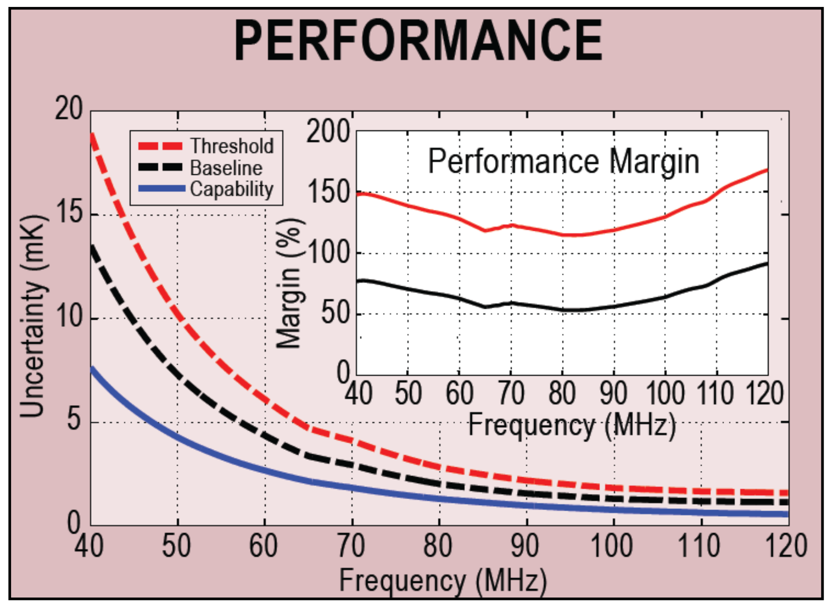
- Mast deploys bicones above S/C deck
- Bicones deploy to achieve length
- Jib Radials deploy to form ground plane

Receiver: Pseudo-correlation Architecture + Reflectometer

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

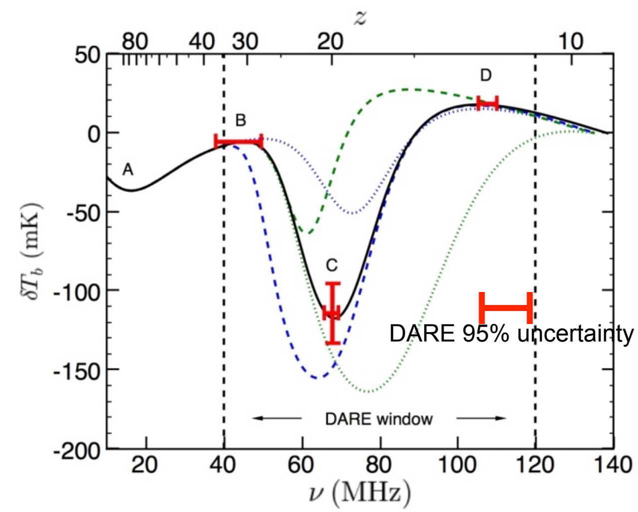
Spectrometer

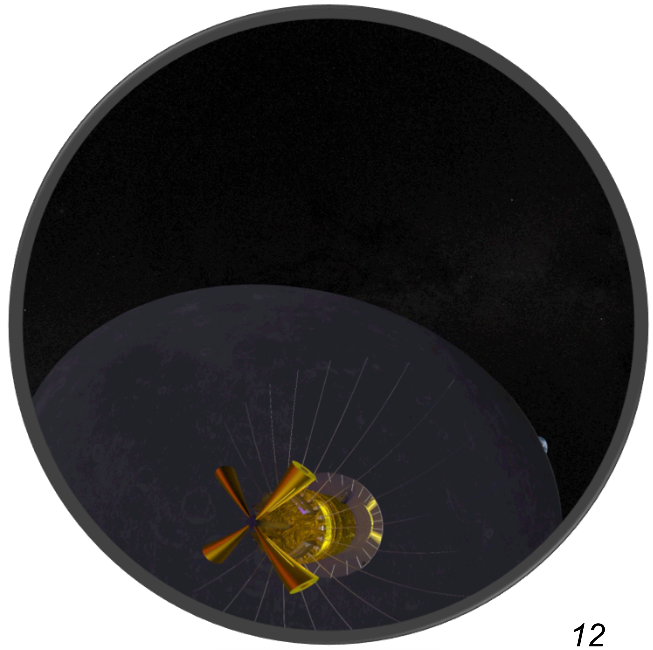
- Achieves 10^6 dynamic range
- Uses space-qualified FPGAs.



Summary and Conclusions

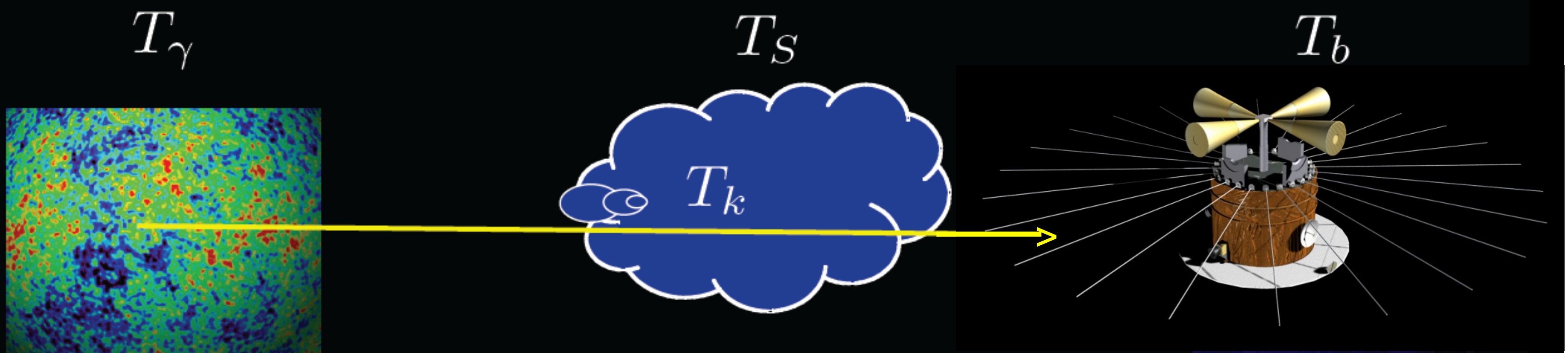
- The Global 21-cm Monopole signal is a powerful tool to explore the first luminous objects in the Universe and their environs at z>10.
- *DARE science instrument*: biconical dipole antenna, pseudo-correlation receiver, digital spectrometer, radial ground screen.
- *MCMC fits set meaningful constraints on:* Ly-α, ionizing, & X-ray backgrounds along with minimum virial temperatures of halos.
- *Work in Progress:* Nested Sampling codes have the potential to measure the structure in the beam-convolved Foreground & differentiate between different physical model of the first galaxies.





Supplemental Slides

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 ($P=kT_b\Delta\nu$)

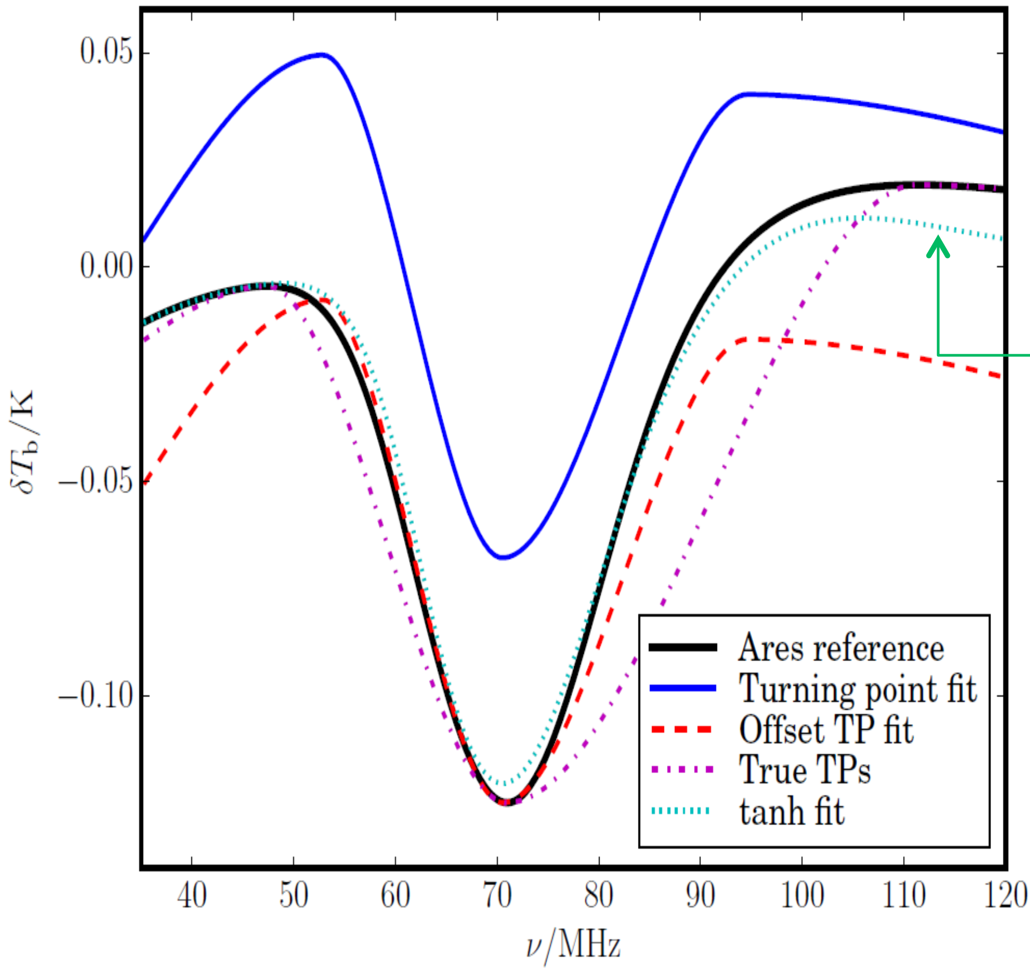
$$T_b = 27 x_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\ \mathrm{mK}$$

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 (2015), *MNRAS,* in press, arXiv:151000271H.