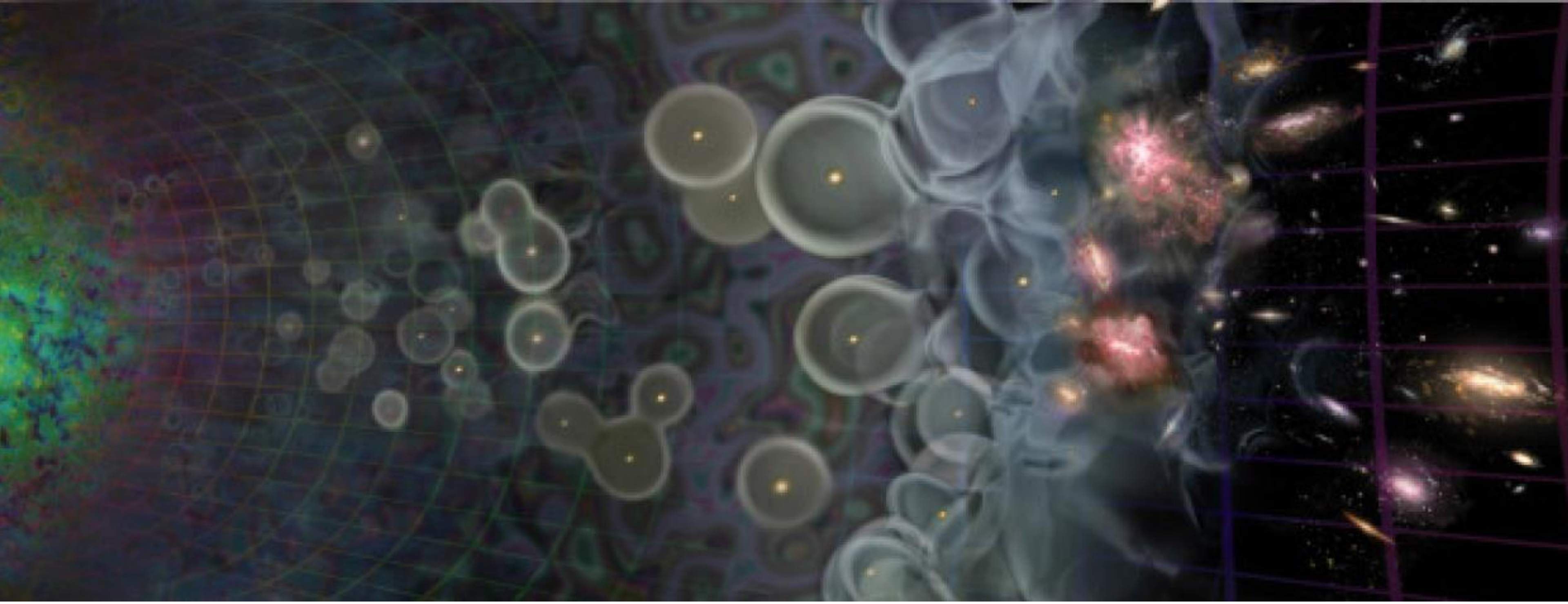
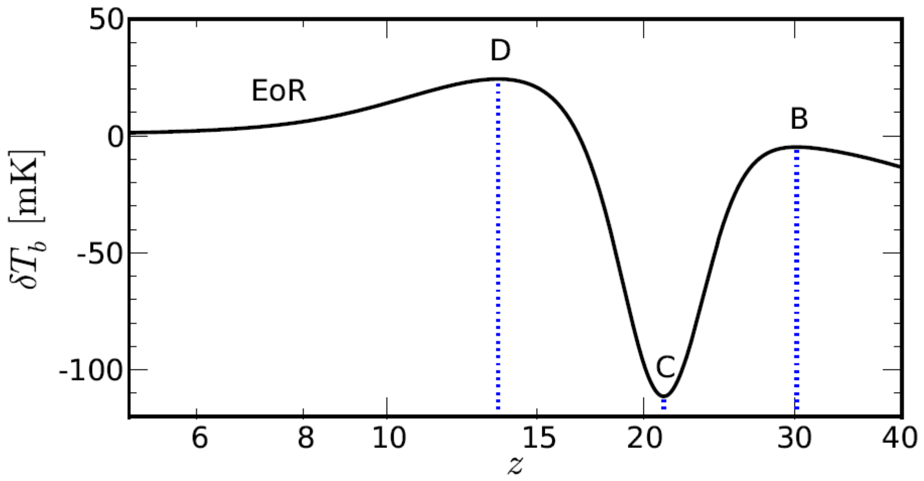
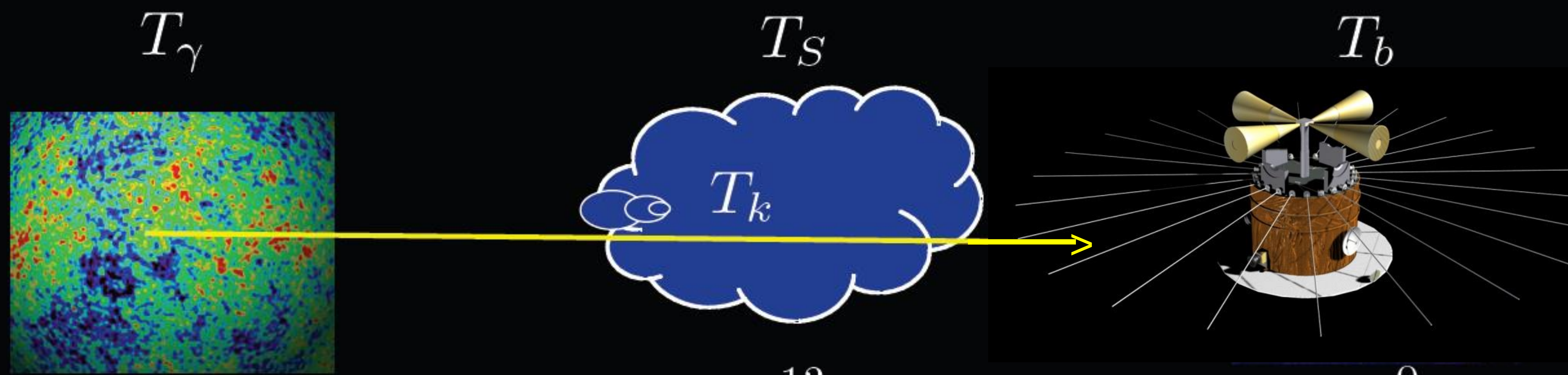


Probing the First Galaxies & Their Environs with the Global 21-cm Spectrum



Jack Burns
University of Colorado Boulder
Jordan Mirocha
U. Colorado Boulder & UCLA
Geraint Harker
University College London

The 21-cm Line in Cosmology



CMB acts as back light	Neutral gas imprints signal	Redshifted signal detected
	$z = 13$ $\nu = 1.4\,\mathrm{GHz}$	$z = 0$ $\nu = 100\,\mathrm{MHz}$

neutral fraction — baryon density — spin temperature — peculiar velocities

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

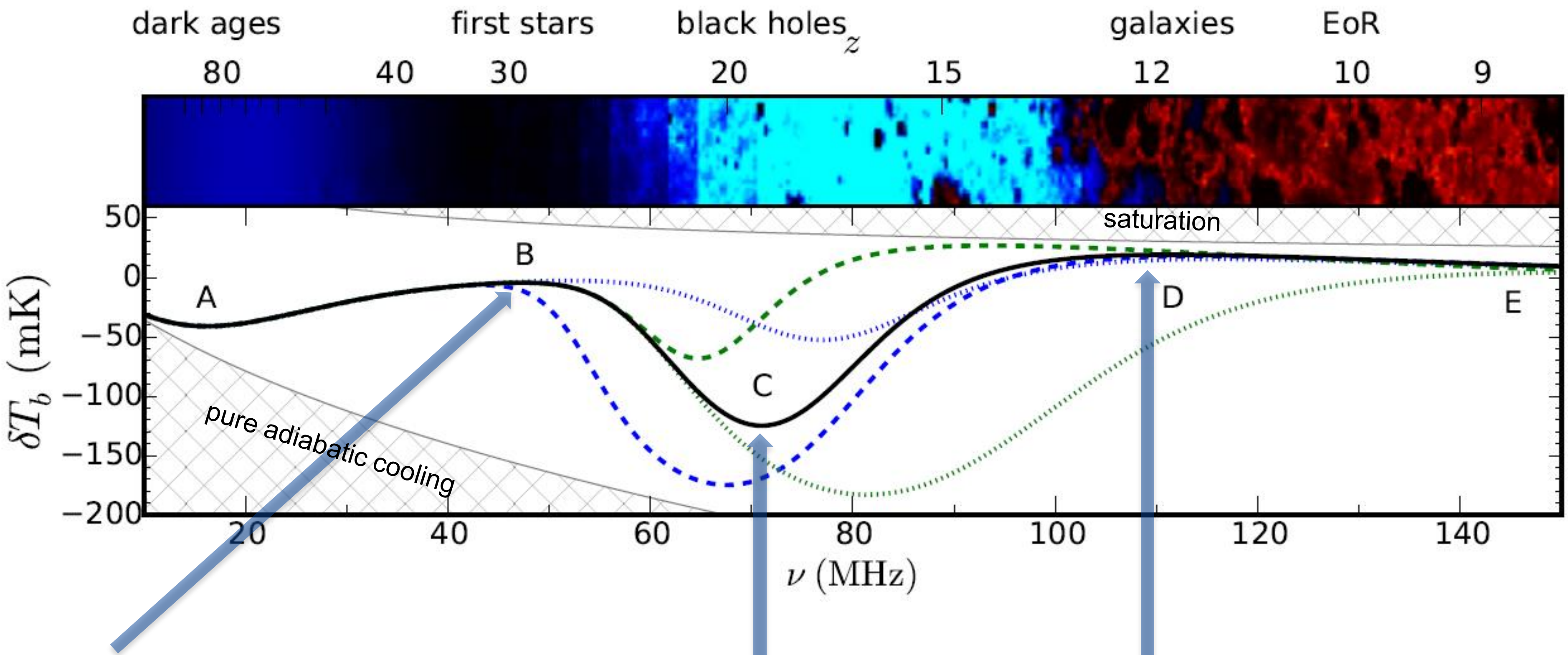
$$T_b = 27 x_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\ \mathrm{mK}$$

spin temperature set by different mechanisms:

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

Courtesy of J. Pritchard

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

Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006;
Mirocha, Harker, & Burns, 2015, *ApJ*, in press, arXiv:1509.07868.

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.

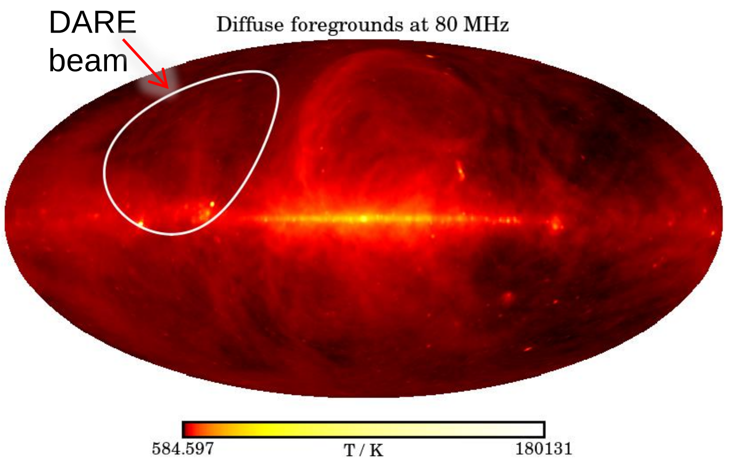
Challenges include cross-talk among antenna elements, mode-coupling of foreground continuum sources into spectral confusion, sensitivity.

Foregrounds: Major Challenge

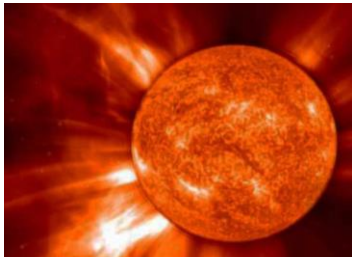
- **Earth's Ionosphere** (e.g., Vedantham et al. 2014; Datta et al. 2015; Rogers et al. 2015; Sokolowski et al. 2015)
  - Refraction, absorption, & emission
  - Spatial & temporal variations related to forcing action by solar UV & X-rays => 1/f or flicker noise acts as another systematic or bias.
  - 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 T_B is high.
- **Galactic/Extragalactic**
  - Mainly synchrotron with expected smooth spectrum (~3rd order log polynomial, $\log T_{\rm fg} = \sum_{i=0}^{N_{\rm poly}} a_i \log\left(\frac{\nu}{\nu_0}\right)^i$, 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

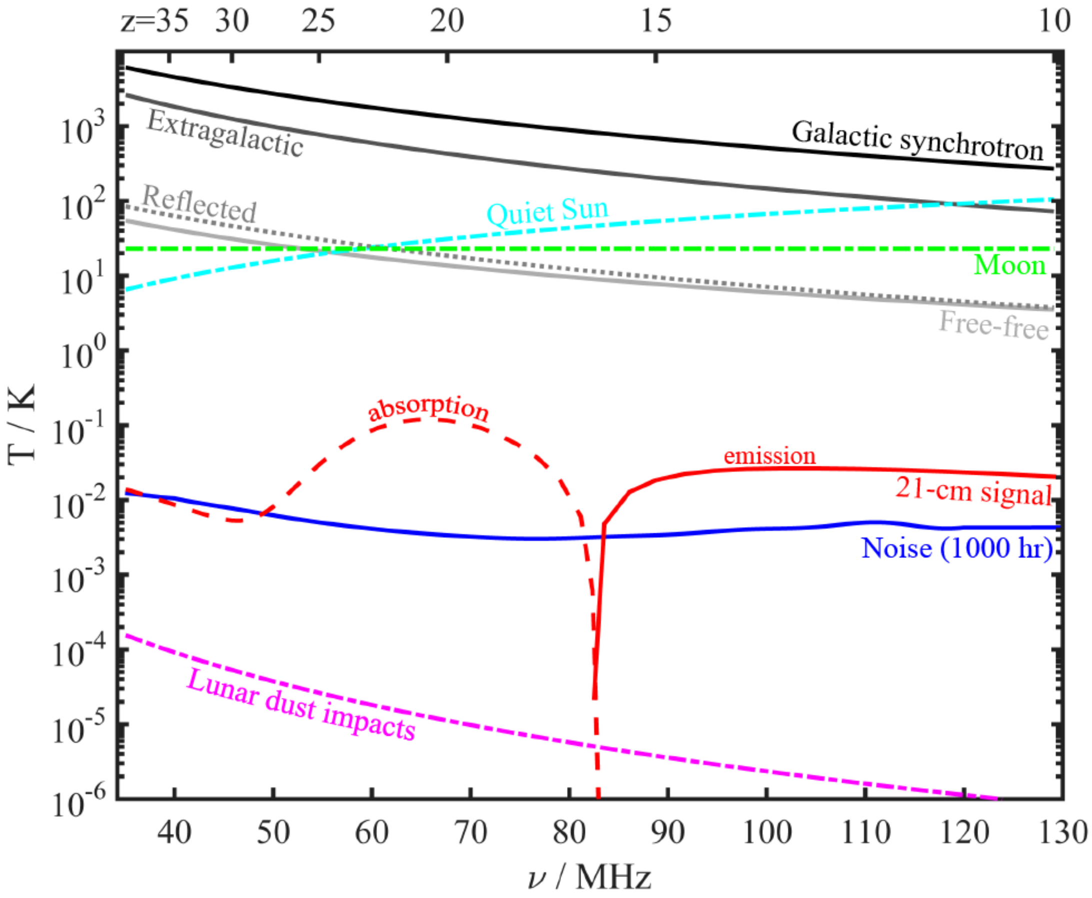
1) Milky Way synchrotron emission + "sea" of extragalactic sources.



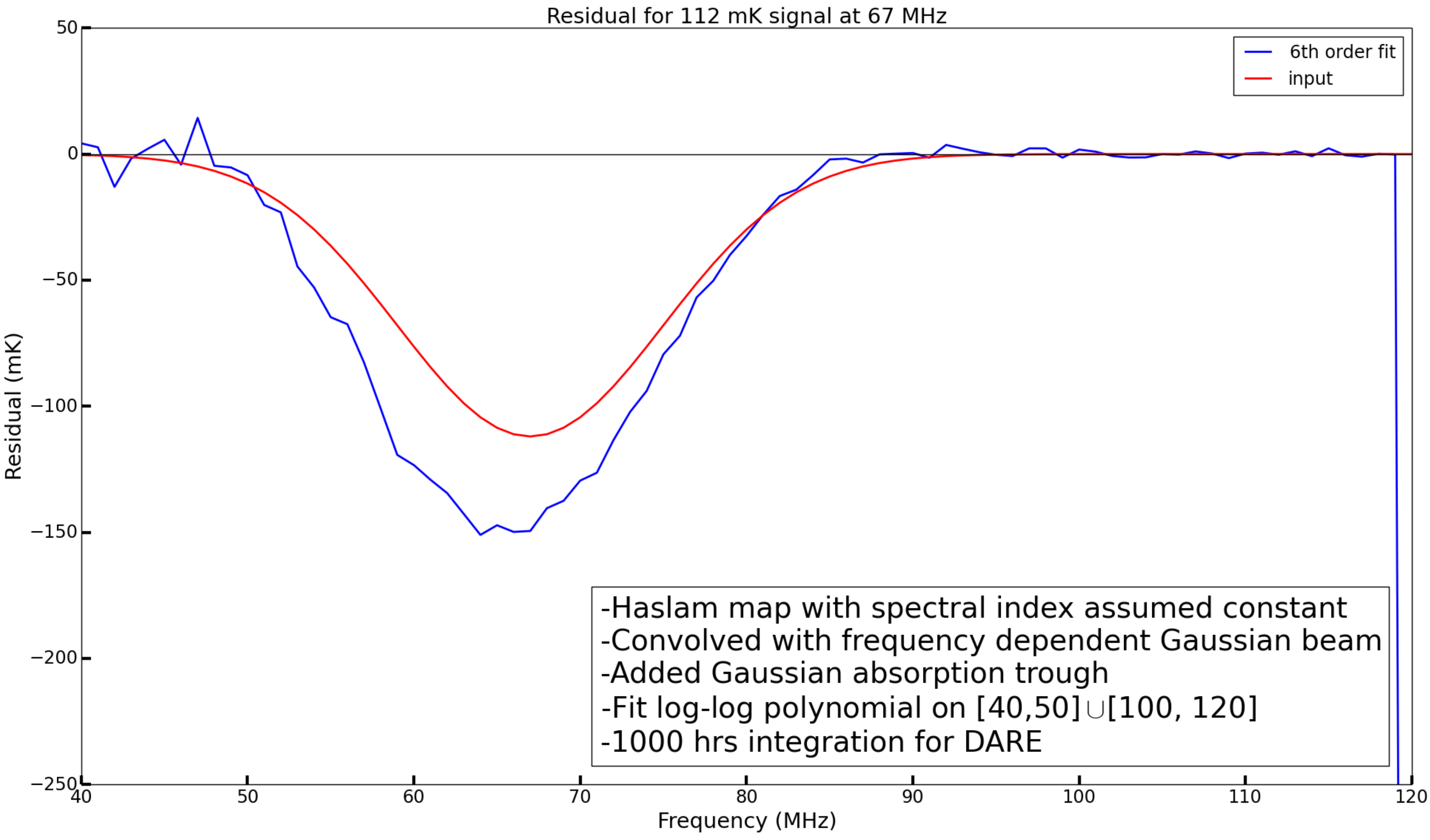
2) Solar system objects: Sun, Jupiter, Moon.



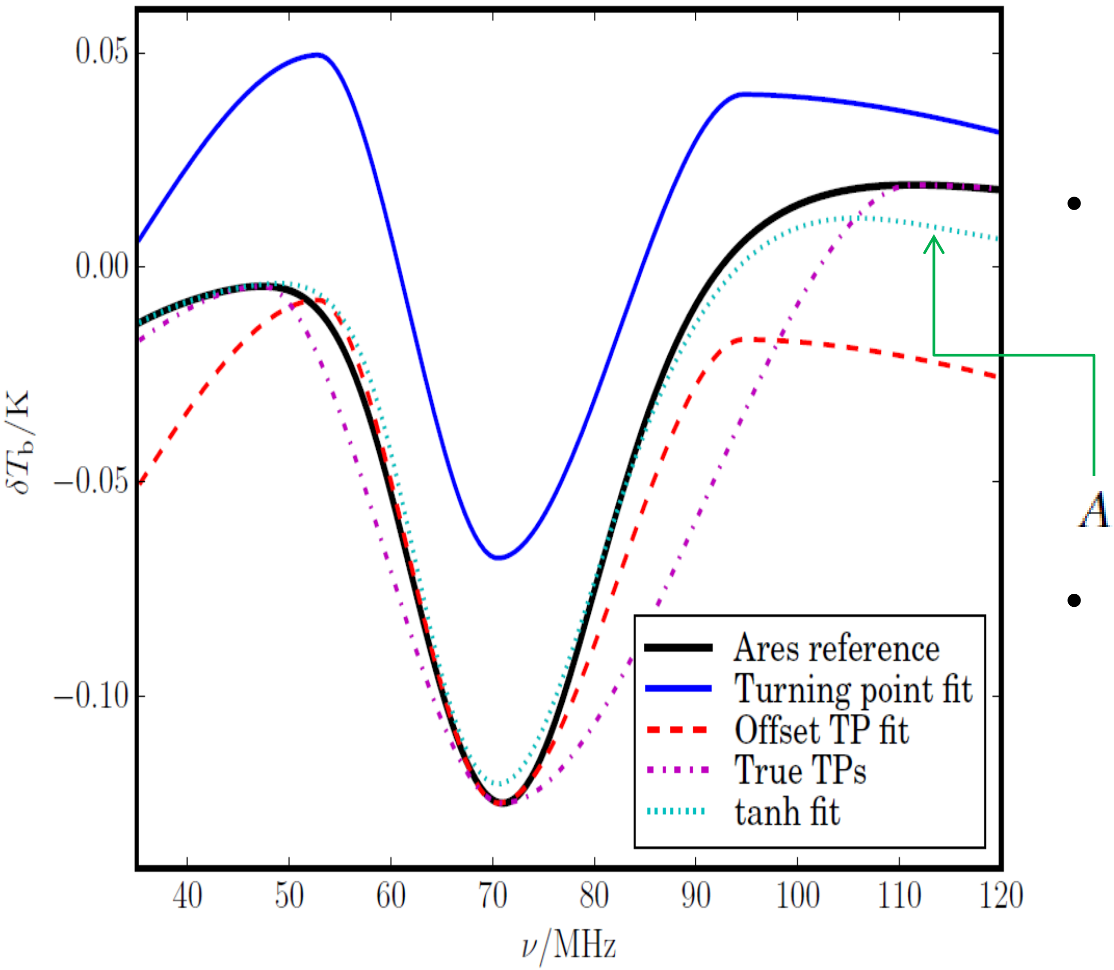
Spectra of Foregrounds



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



Parameterizing the 21-cm Model



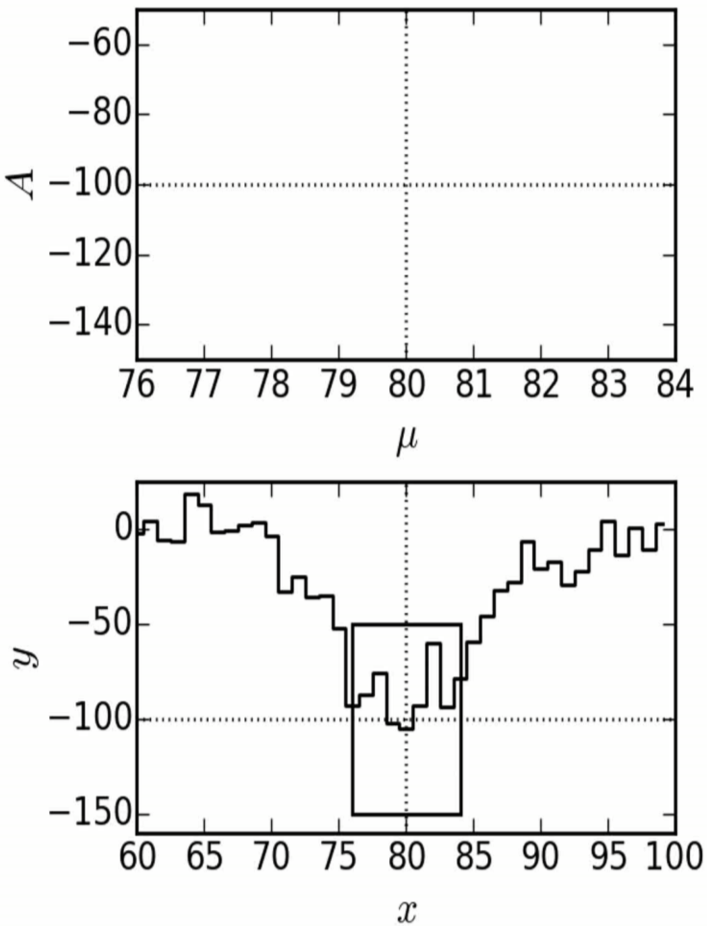
- Previous studies parameterized signal from just the 3 Turning Points.
- A more physically-motivated approach to model the Ly-α, IGM thermal, & ionization history is a tanh model:

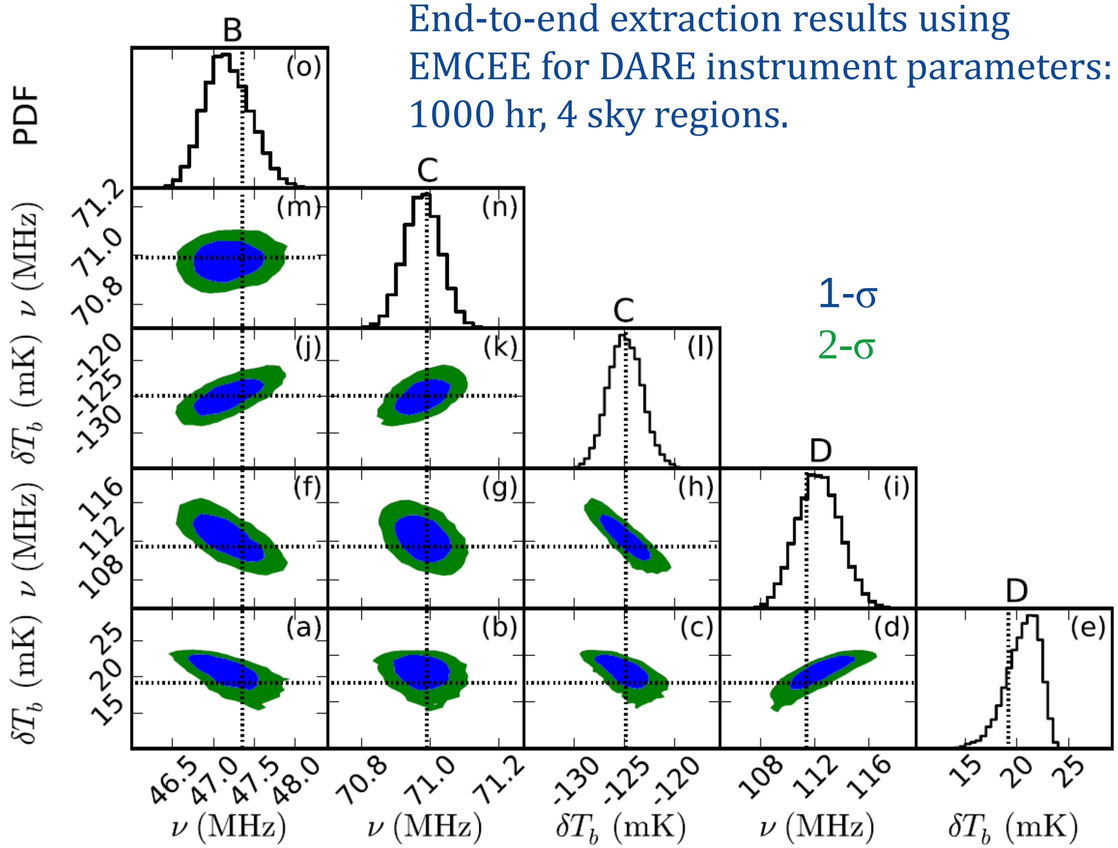
$$A(z) = \frac{A_{\text{ref}}}{2}\{1 + \tanh[(z_0 - z)/\Delta z]\}$$

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

Harker, Mirocha, Burns, & Pritchard (2015), *MNRAS,* submitted.

Signal Extraction using MCMC





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

1-σ

2-σ

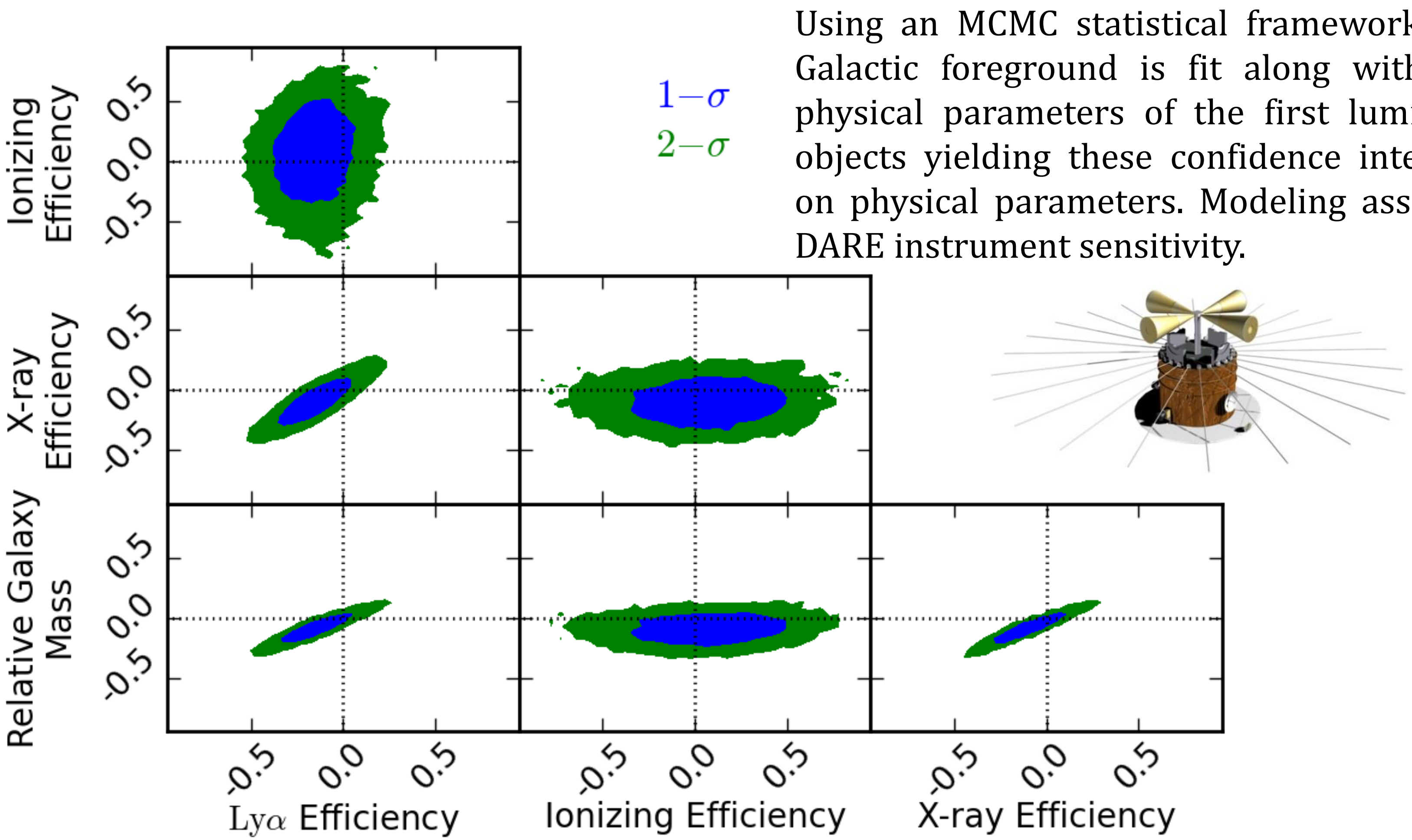
This technique captures degeneracies & covariances between parameters, including those related to signal, foregrounds, & the instrument.

DARE DARK AGES RADIO EXPLORER

For details see Harker et al. (2012), MNRAS, 419, 1070; and Harker et al. (2015), MNRAS, submitted.

DARE DARK AGES RADIO EXPLORER

Characterizing the First Stars & Galaxies

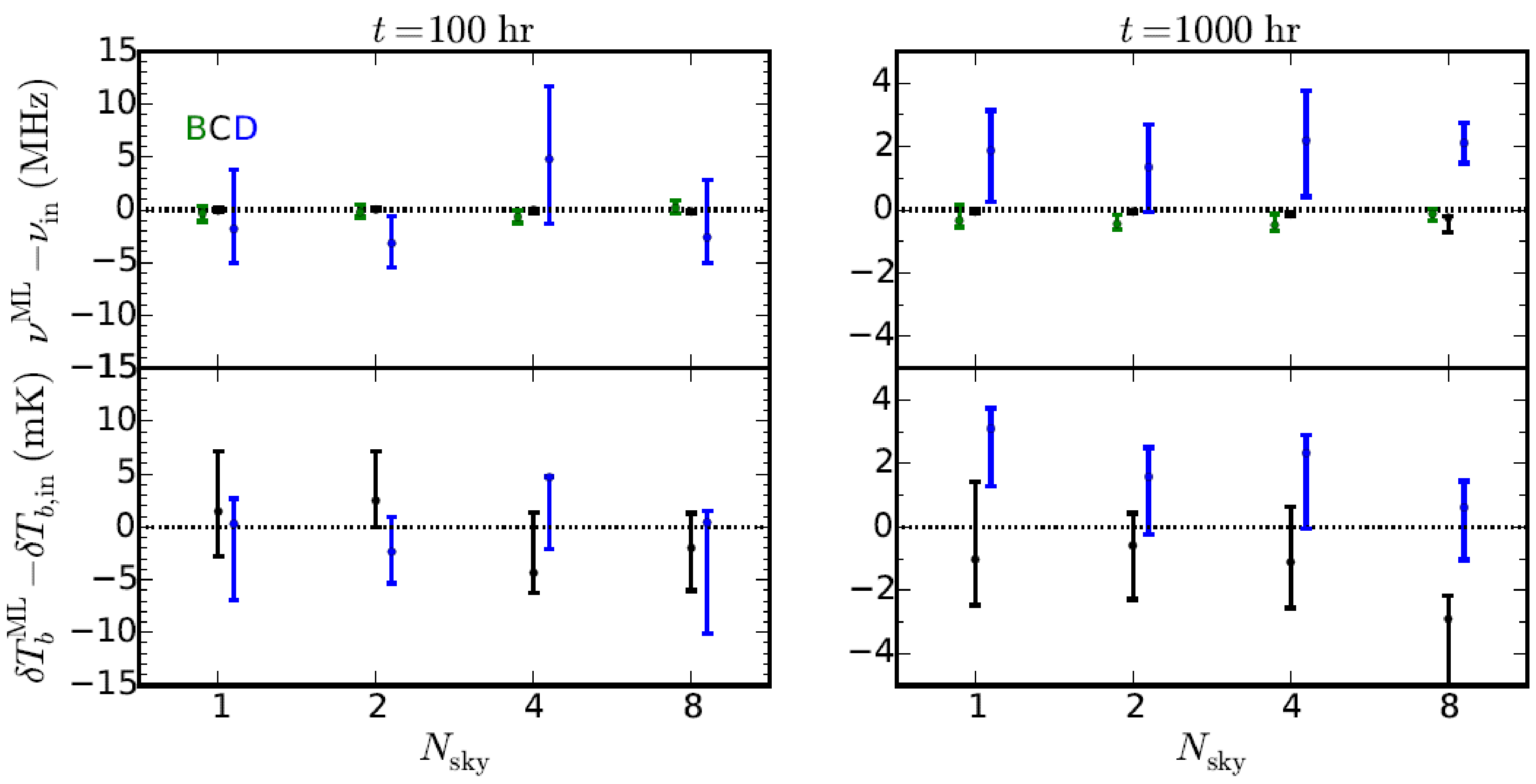


Using an MCMC statistical framework, the Galactic foreground is fit along with the physical parameters of the first luminous objects yielding these confidence intervals on physical parameters. Modeling assumes DARE instrument sensitivity.

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).

See poster by Mirocha, Harker, & Burns;
Mirocha, Harker, & Burns (2015), *ApJ*, in press, arXiv:1509.07868.

Constraints on Turning Points: # Sky Regions & Integration Time



Increasing the integration time has a much more substantial impact than increasing the # of sky regions. Bias for Turning Point D persists due to degeneracy with Foreground spectral shape.

Harker, Mirocha, Burns, & Pritchard (2015), *MNRAS,* submitted.

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.
- Parameterizing the 21-cm signal with a tanh function is (1) more physically motivated, (2) improves the extraction of the signal relative to the Foreground, and (3) reduces biases.
- Possible observational strategy: Observe fewer carefully selected sky regions (colder, smoother) for longer integrations.
- MCMC fits set meaningful constraints on Ly-α, ionizing, & X-ray backgrounds along with minimum virial temperatures of halos.
- Nested Sampling codes have the potential to measure the structure in the beam-convolved Foreground & differentiate between different physical model of the first galaxies.