Inferring the properties of the first stars and galaxies from a radiometer in lunar orbit

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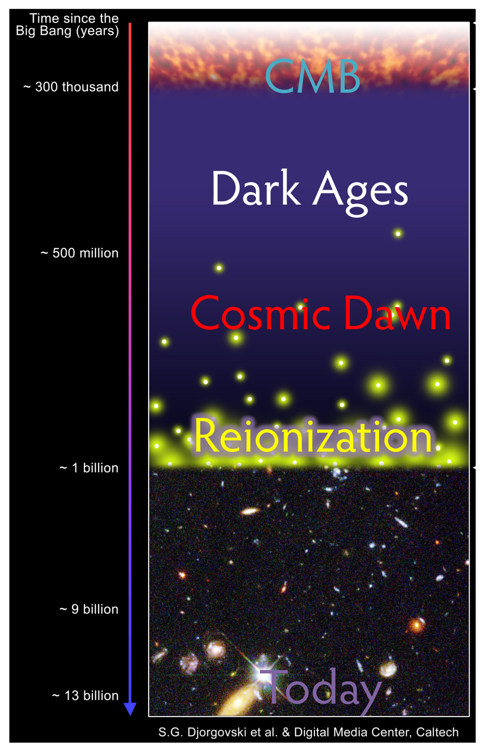
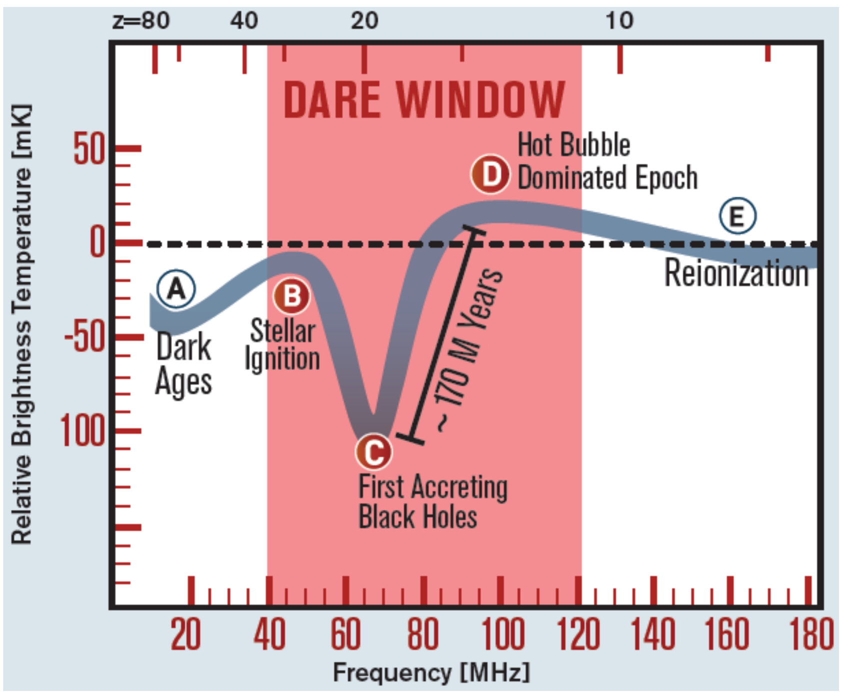


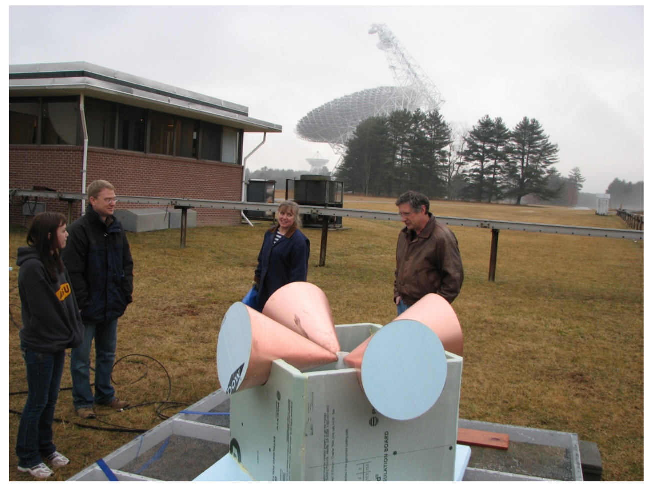
Summary

The sky -averaged 21-cm signal is perhaps the most promising near-term probe of the 'cosmic dawn', when the first stars and galaxies began to heat and ionize the Universe.. Measurements are still challenging, however, because of the intense foregrounds at the relevant low radio frequencies, the exquisite instrumental calibration this necessitates, anthropogenic radio frequency interference (RFI), and the Earth's ionosphere. The latter three problems can be greatly mitigated by studying the cosmic dawn from the far side of the Moon. The proposed *Dark Ages Radio Explorer (DARE)* would do so by carrying a dipole antenna in a low lunar orbit. We outline this mission, show the constraints it can put on the physics of the cosmic dawn, and demonstrate how the ionosphere puts a fundamental limit on the sensitivity of similar, ground-based experiments.

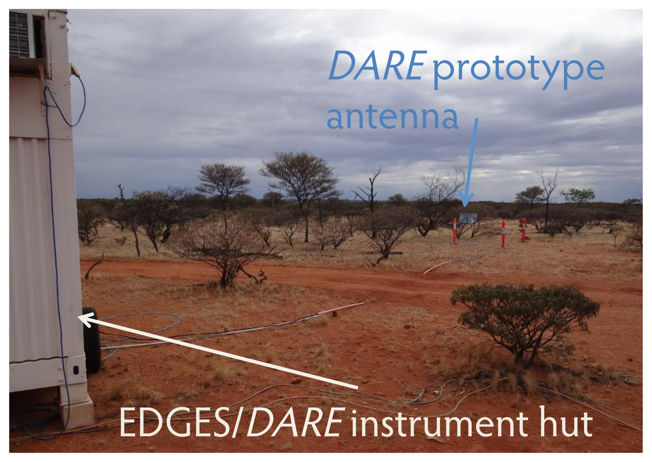
The DARE mission: status and timeline



In February 2011 we proposed an Explorer mission to carry a system sensitive at 40-120 MHz in a 200 km lunar orbit for up to three years. It was not chosen for a Phase A study but was deemed 'selectable'.



1st-gen prototype testing in Green Bank; Mar. 2012. Validated antenna, front-end and spectrometer performance and showed effects of ionosphere and RFI (especially FM band).



Prototype was deployed at MRO site in Western Australia; fewer problems with FM, but low-frequency RFI (probably naval radar) required extra filters and attenuation.

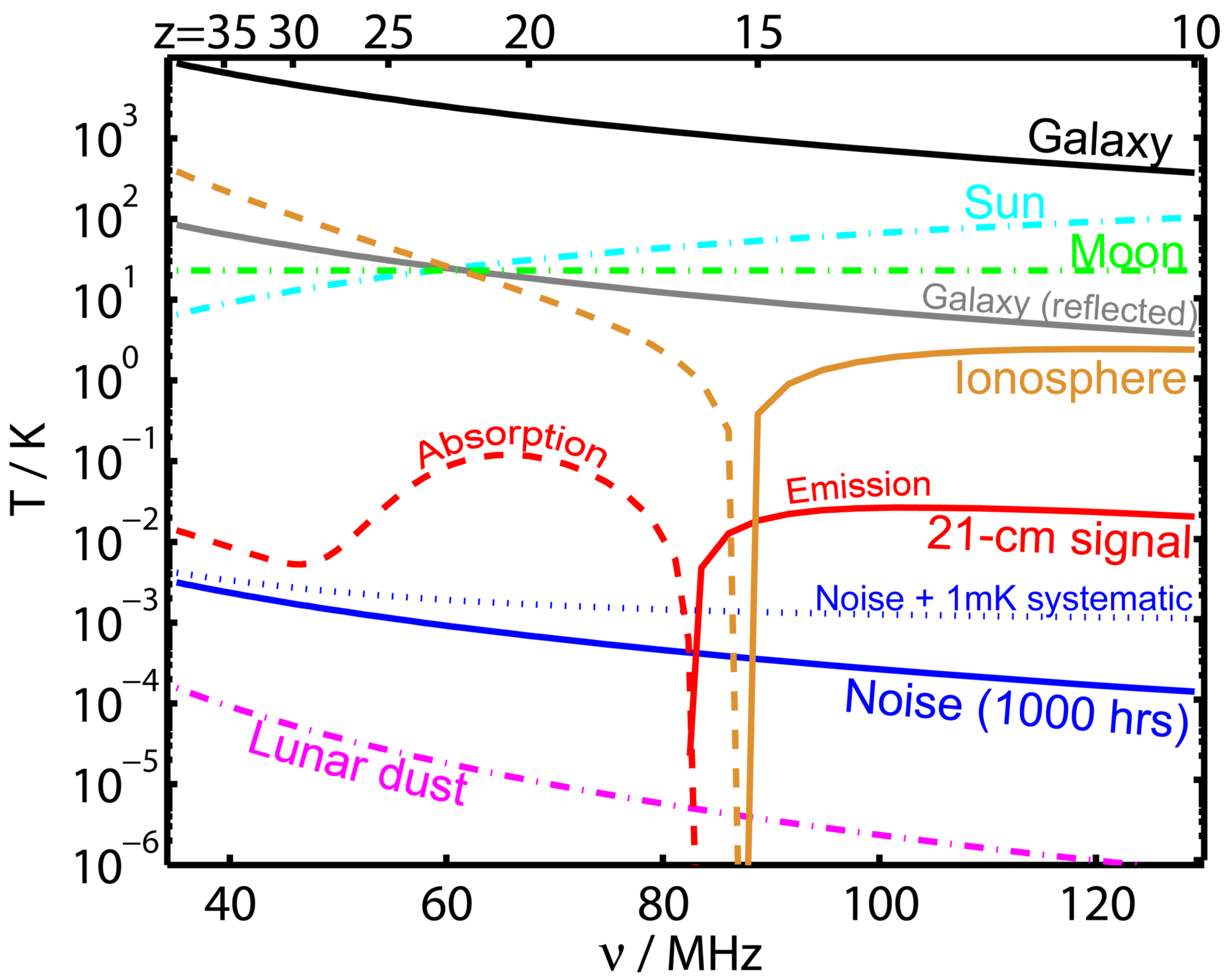
2nd-gen. prototype to be deployed Oct. 2013 in Green Bank – larger biconical antenna with higher gain at low frequency, improved balun assembly, better receiver isolation. Results critical for reproposing DARE for a SMEX mission in late2014.

Parameter inference

We make use of the widely-used Markov Chain Monte Carlo code, emcee, to infer parameters of the signal, foregrounds and instrument model from the spectra. A typical run using spectra from two sky regions and including fits to ionospheric parameters requires us to search a 44-dimensional parameter space. This increases rapidly if we use more sky regions, as would be the case for a space-based experiment.

Foregrounds

Astrophysical sources at the redshifted 21-cm signal frequency exceed it by $\approx 10^4$–10^6.



The ionospheric contribution shown here is due to absorption and emission. In reality, we must also deal with refraction, which effectively makes the beam frequency- and time-dependent. Horizon cutoff can lead to sharp (problematic) features in the spectrum during moderately active conditions.

To escape the ionosphere, we must escape the surface of the Earth; to escape radio frequency interference too, the only viable location in the inner solar system is the lunar farside!

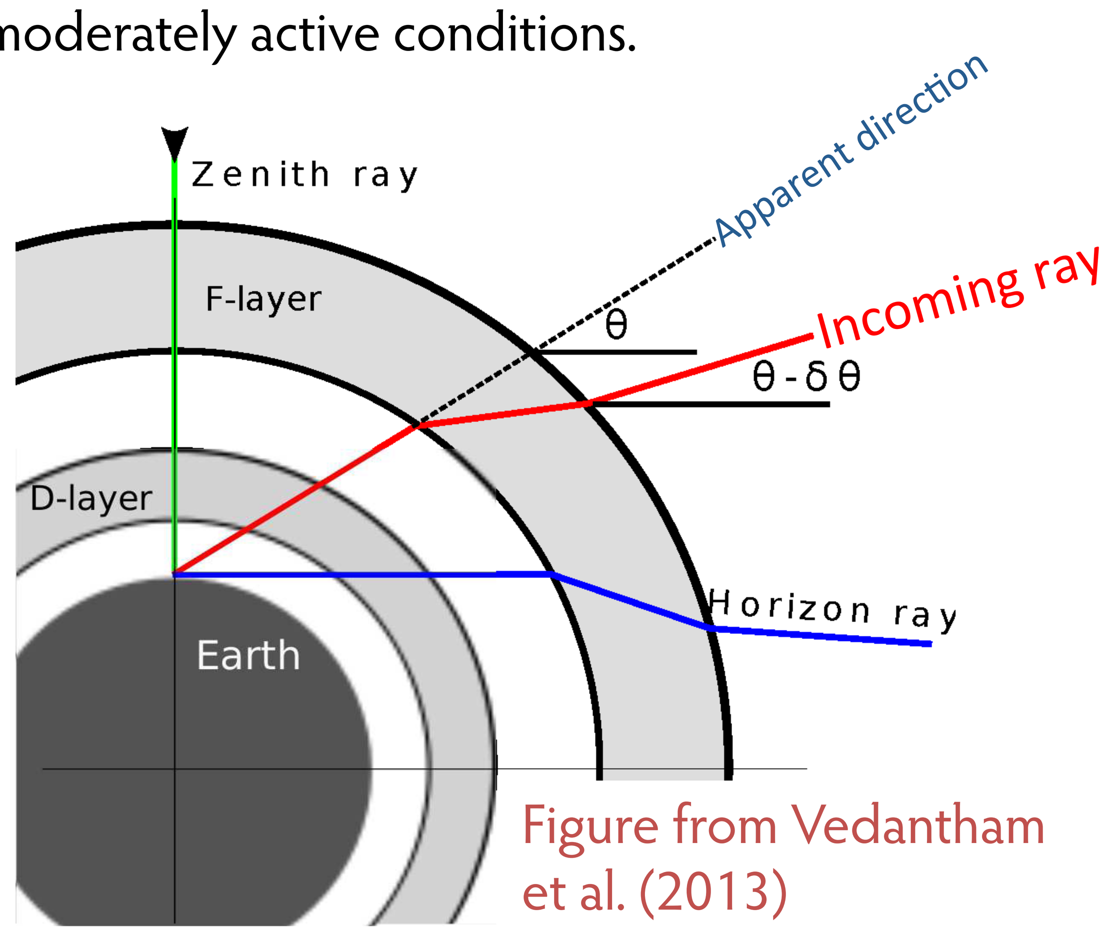
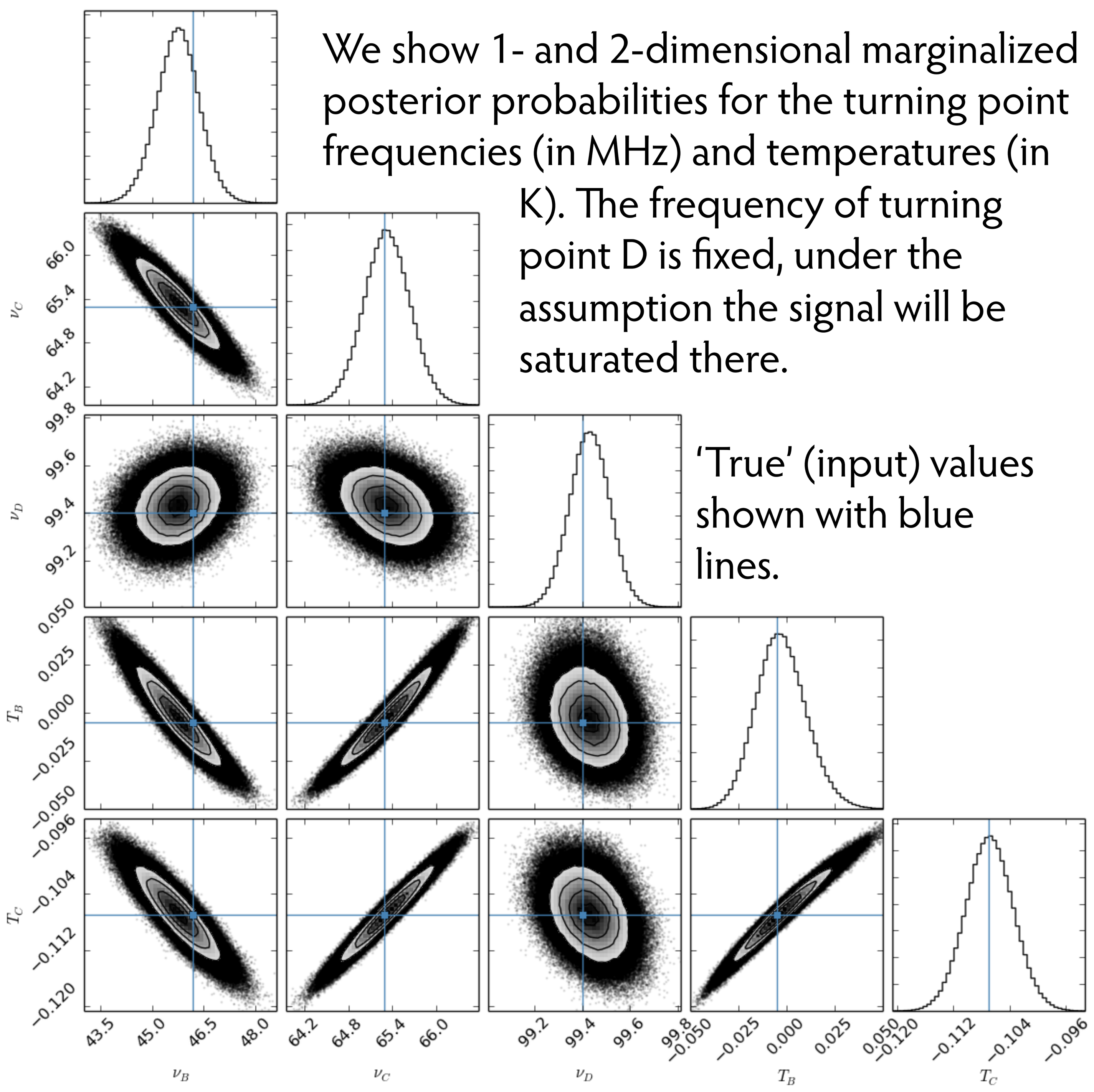


Figure from Vedantham et al. (2013)

Results

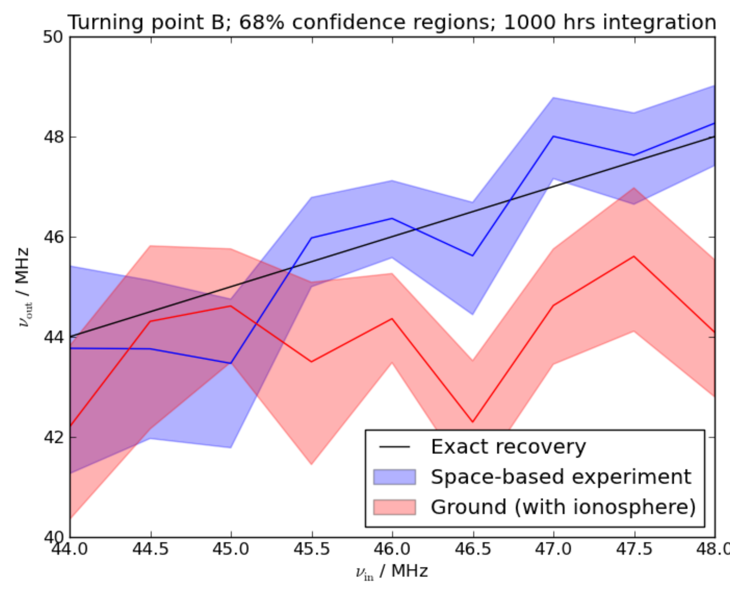
DARE should obtain 1000 hrs of data in the RFI shadow of the Earth and with the Sun occluded by the Moon. In this case we can obtain tight constraints on the positions of all three in-band turning points of the signal.



We show 1- and 2-dimensional marginalized posterior probabilities for the turning point frequencies (in MHz) and temperatures (in K). The frequency of turning point D is fixed, under the assumption the signal will be saturated there.

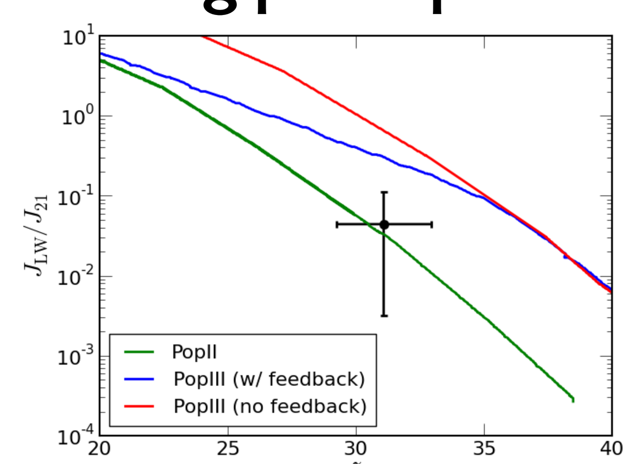
'True' (input) values shown with blue lines.

Isolating the impact of the ionosphere



Turning point B is worst affected by observing from the ground (especially if stars turn on early), even for the very simple ionospheric model used here, since its effects scale as ν^{-2}. Refraction will only make things worse!

Turning point positions → physical constraints



From the position of turning point B we can obtain limits on the Lyman-α flux and its rate of change, constraining models of the first stars (shown here for a 2% measurement of ν_B).

Turning point C gives limits on the heating rate density – for more, see J. Mirocha, GH & J. Burns, *ApJ*, **777**, 118 (2013).

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Further information

- An MCMC approach to extracting the global 21-cm signal during the cosmic dawn from sky-averaged radio observations; Harker G.J.A., Pritchard J.R., Burns J.O., Bowman J.D.; *Mon. Not. R. Astron. Soc.*, **419**, 1070 (2012)
- Probing the first stars and black holes in the early Universe with the Dark Ages Radio Explorer (DARE); Burns J.O. et al.; *Adv. Space Res.*, **49**, 433 (2012)
- emcee: The MCMC Hammer; Foreman-Mackey D. et al., *Publ. Astron. Soc. Pac.*, **925**, 306 (2013)

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