Seeing the cosmic dawn from lunar orbit with the sky-averaged 21-cm signal

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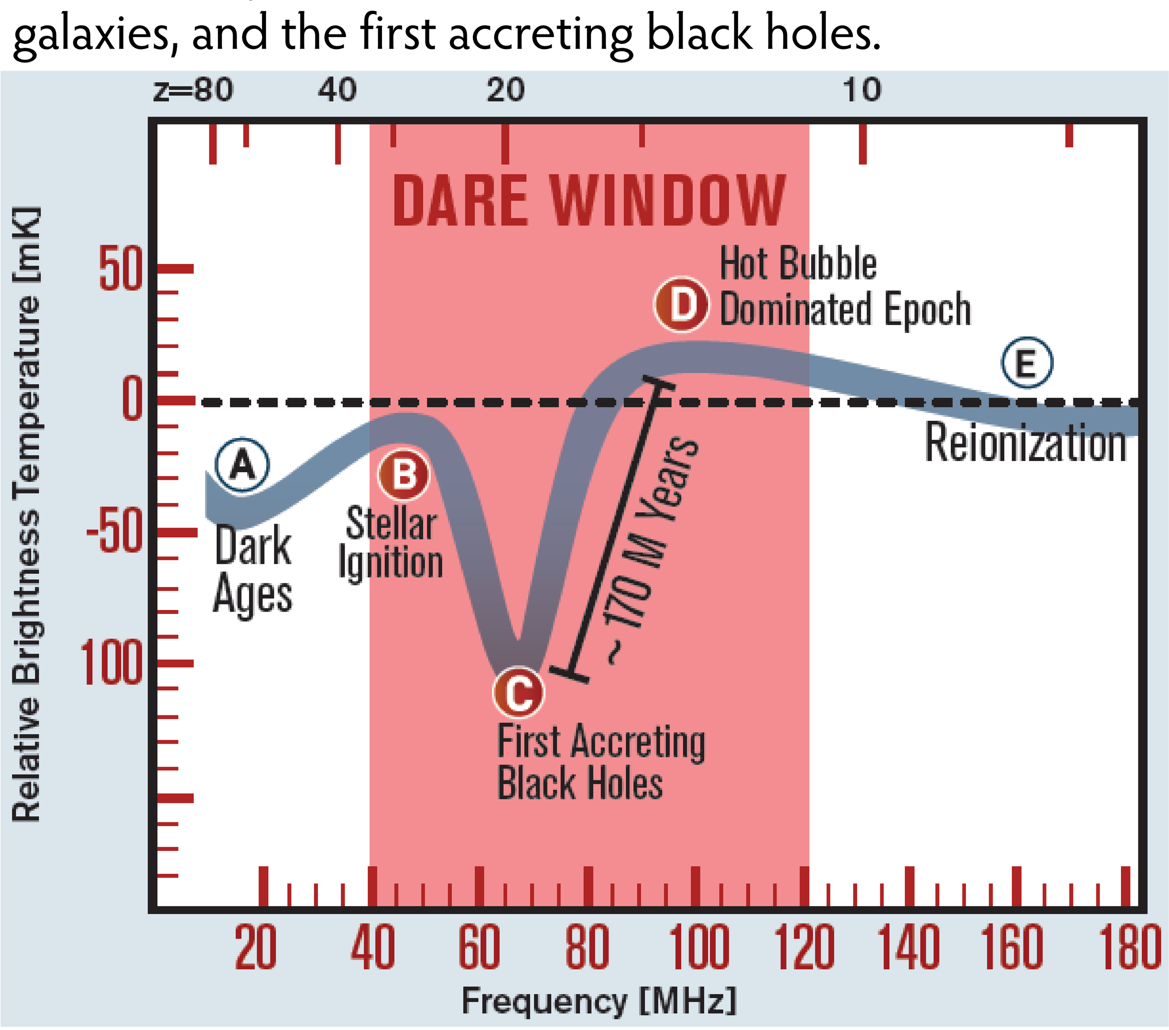
Summary

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.

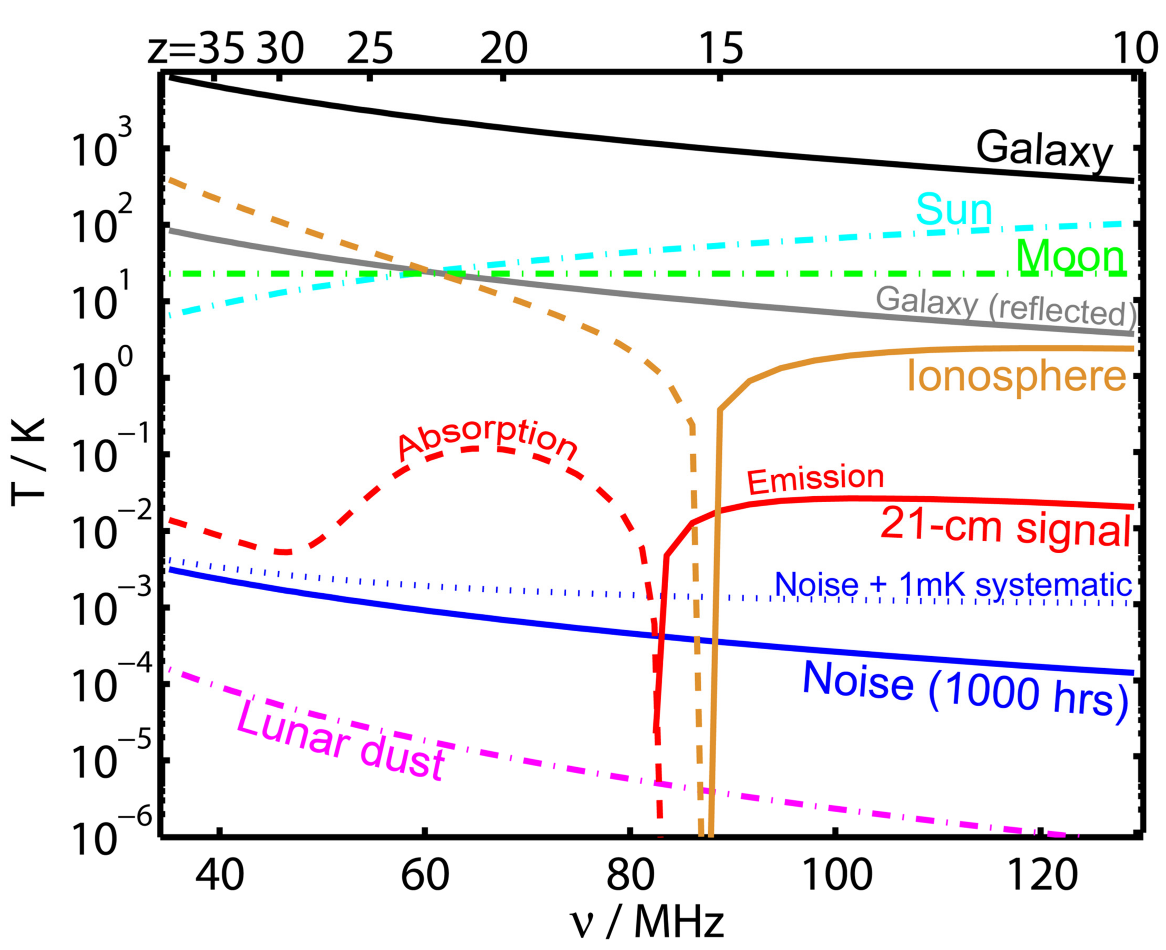
Introduction

Sky-averaged observations of the highly redshifted 21-cm line will yield information on the first stars and galaxies, and the first accreting black holes.



Foregrounds

Astrophysical sources at the redshifted 21-cm signal frequency exceed it by ≈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.

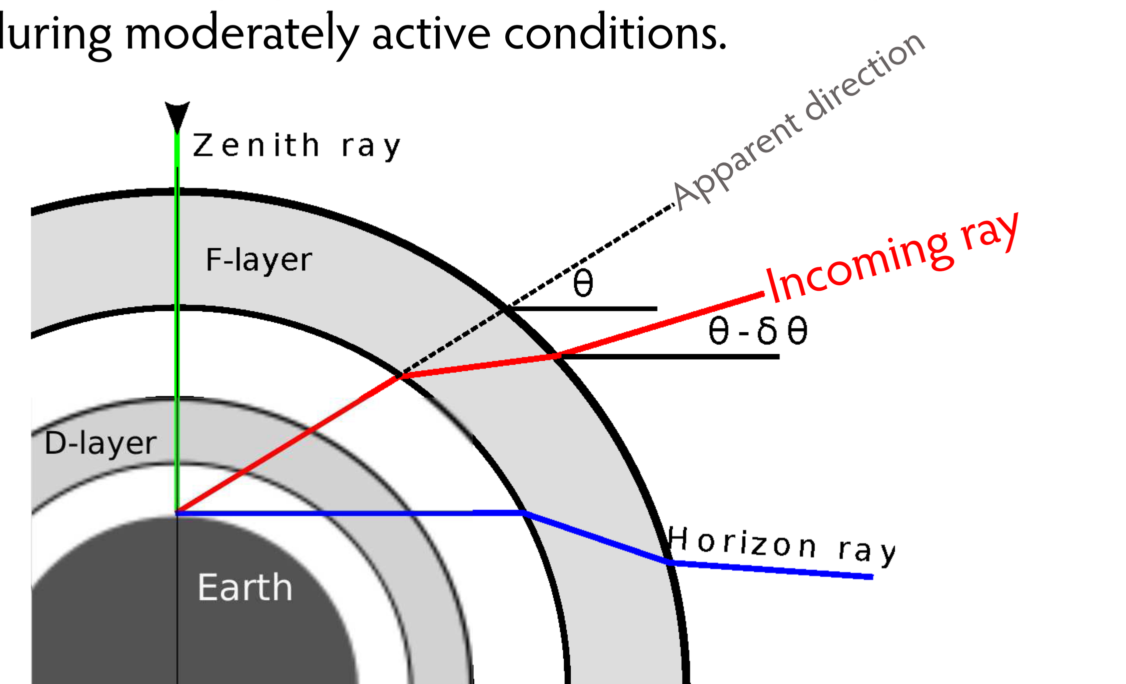
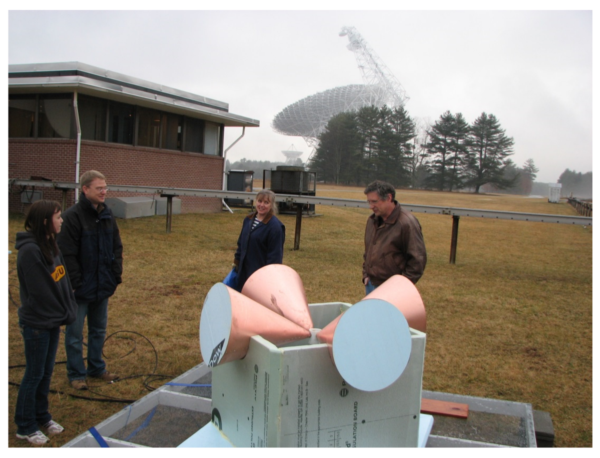


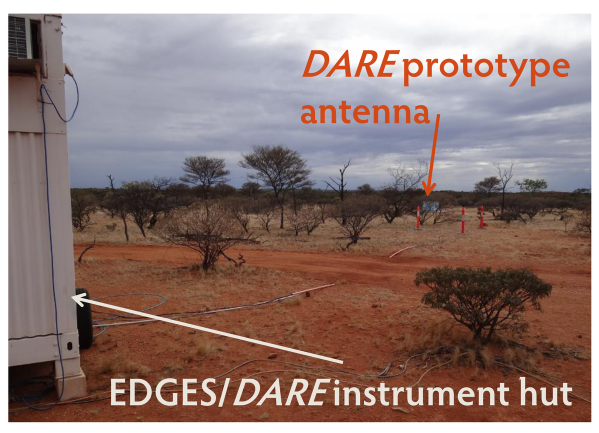
Figure from Vedantham et al. (2013)

The *DARE* mission: status and timeline

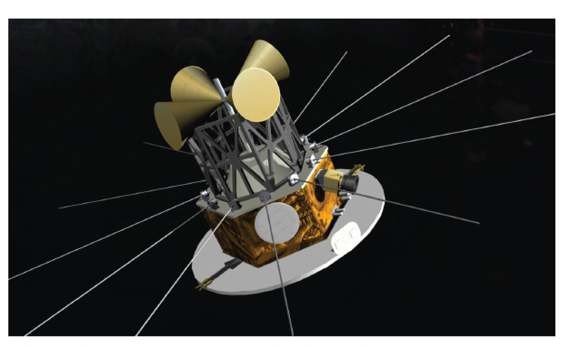
In February 2011 we proposed an Explorer mission to carry a system sensitive at 40-120 MHz in a 200 km lunar orbit for up to three years. It was not chosen for a Phase A study but was deemed 'selectable'.



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.

New calibration approach

Single-load calibration scheme (Bradley, R. et al., in prep.) based on detailed circuit modelling is being implemented in prototype data. Requires very high precision lab measurements of the parameters.

$$T_{ant} = T_{cal}\frac{P_{on}}{P_{off}}\frac{G_{amp_0}}{G_{amp_1}}\left[T_{amb} + T_{amp_0} + \frac{T_{Rx}}{G_{amp_0}}\right] - T_{amp_1} - \frac{T_{Rx}}{G_{amp_1}}$$

Simulating *DARE* data

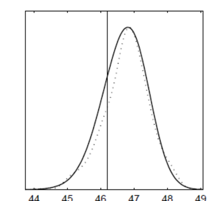
The *DARE* antenna will have enough directivity to gather spectra from several (~8) independent regions of the sky. This independent information helps us to constrain the properties of our instrument and the foregrounds. We simulate the noisy spectra using the low-frequency sky model of de Oliveira-Costa et al. (2008), simple models for the Moon's emission and reflection and the quiet Sun, and a sophisticated parametrized model of the antenna and the instrument.

Parameter inference

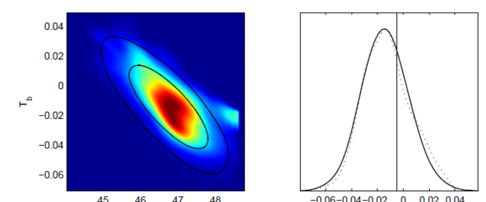
We make use of the April 2013 release of the widely-used Markov Chain Monte Carlo code, CosmoMC [Lewis, A. & Bridle, S., *Phys. Rev. D*, **66**, 103511 (2002)], running on the Janus supercomputer at CU Boulder, to infer parameters of the signal, foregrounds and instrument model from the spectra. A typical 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.

Results

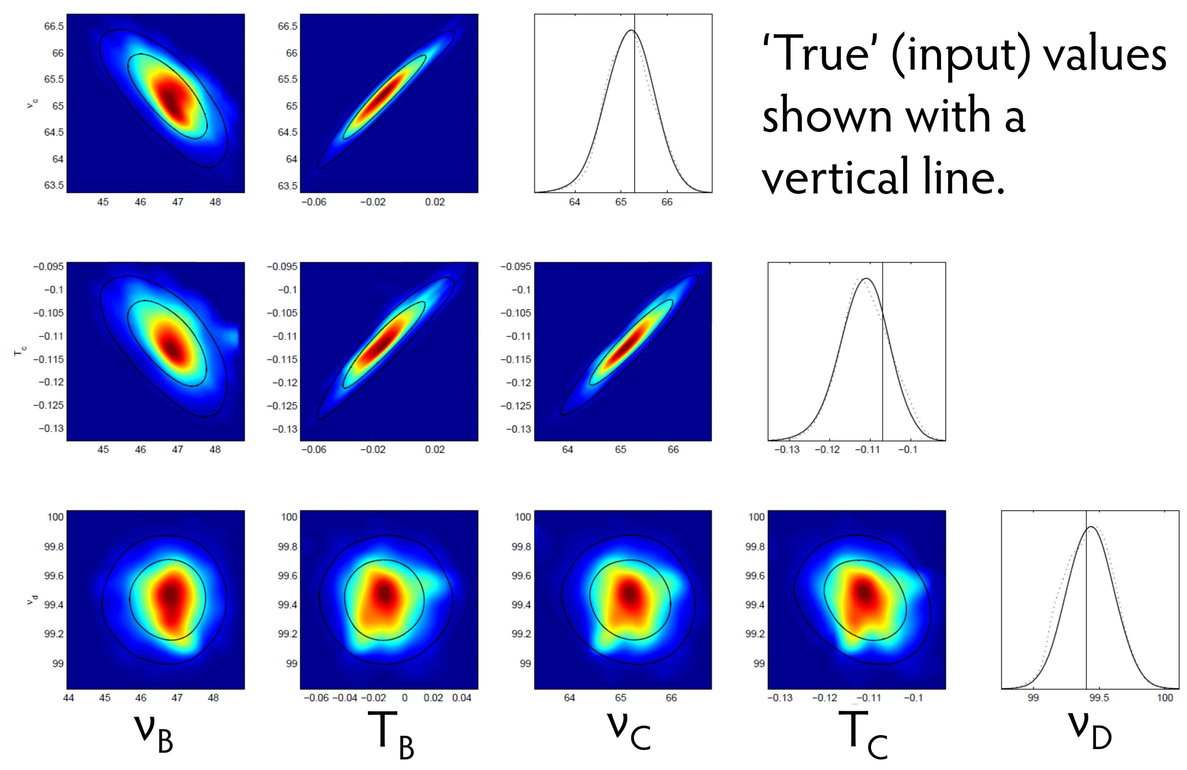
DARE should obtain 1000 hrs of data in the RFI shadow of the Earth and with the Sun occluded by the Moon. In this case we can obtain tight constraints on the positions of all three in-band turning points of the signal.



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.



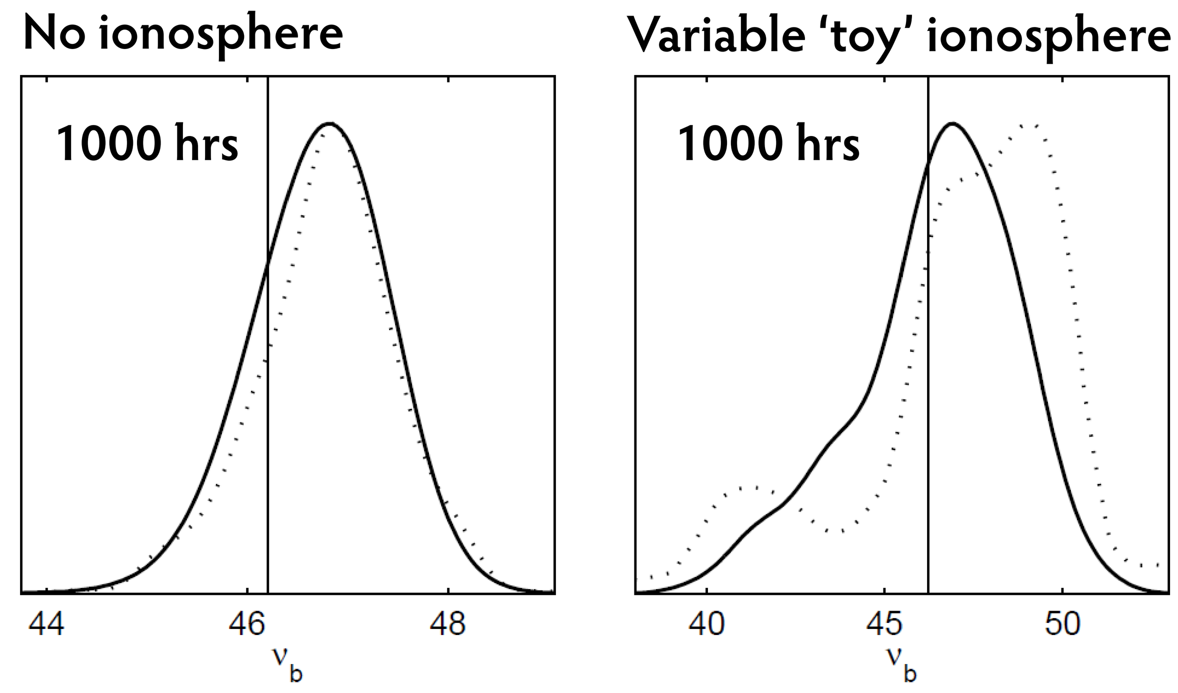
'True' (input) values shown with a vertical line.



Isolating the impact of the ionosphere

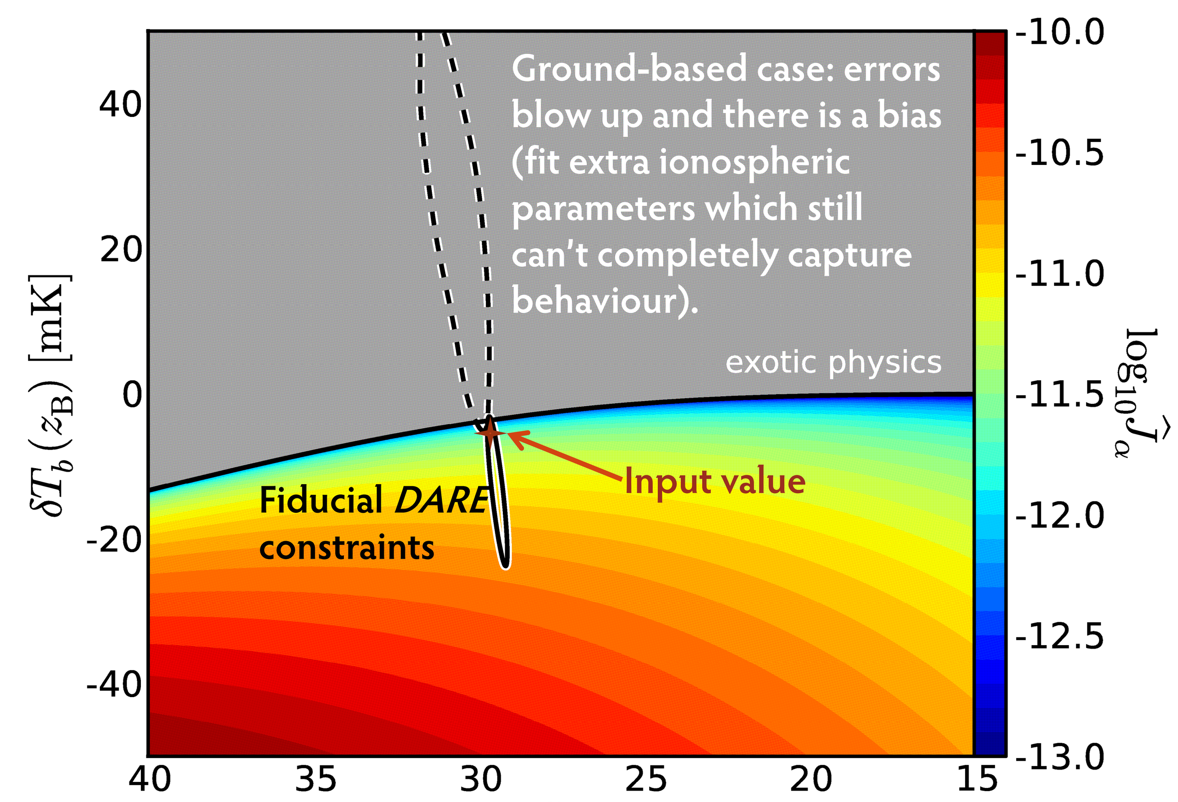
Turning point B is especially badly affected by observing from the ground, since the effects of the ionosphere scale as ν^{-2}. We have a very simple model for the emission and absorption of the ionosphere, with variations motivated by GPS data from Western Australia. Refraction will only make things worse!

No ionosphere | **Variable 'toy' ionosphere**



From turning point positions to physical constraints

From the position of turning point B we can obtain limits on the Lyman-α flux and its rate of change. Turning point C gives limits on the heating rate density – for more, see Jordan Mirocha's paper recently submitted to ApJ (Mirocha, J., Harker, G.J.A. & Burns, J.O.). These lead to information on the emissivities of the first sources: see our imminent followup paper.



Acknowledgements

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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)

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