Radio Cosmology without Interferometry

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Contents

Radiometric observations

Beginnings

Published: 08 July 1933

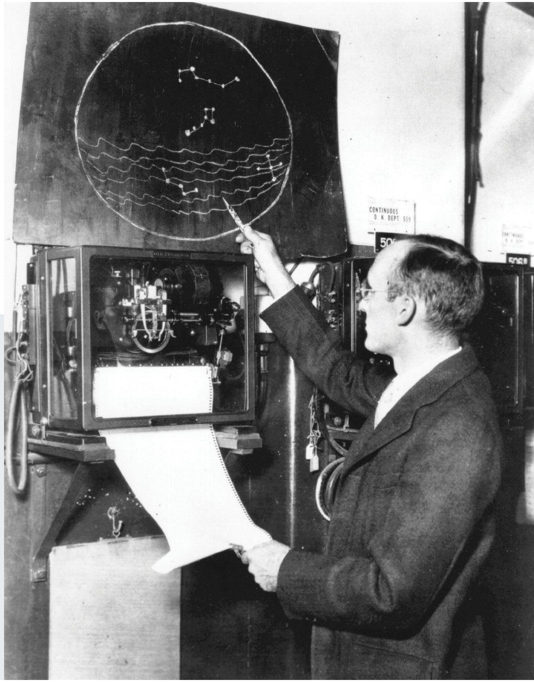
Radio Waves from Outside the Solar System

KARL G. JANSKY

Nature **132**, 66 (1933) | Cite this article

"I have taken more data which indicated definitely that the stuff, whatever it is, comes from something not only extraterrestrial, but from outside the solar system. It comes from a direction that is fixed in space and the surprising thing is that ...[it] is in the direction towards which the solar system is moving in space. According to Skellett... there are clouds of "cosmic dust" in that direction..."

Karl Jansky



CMB

COSMIC BLACK-BODY RADIATION*

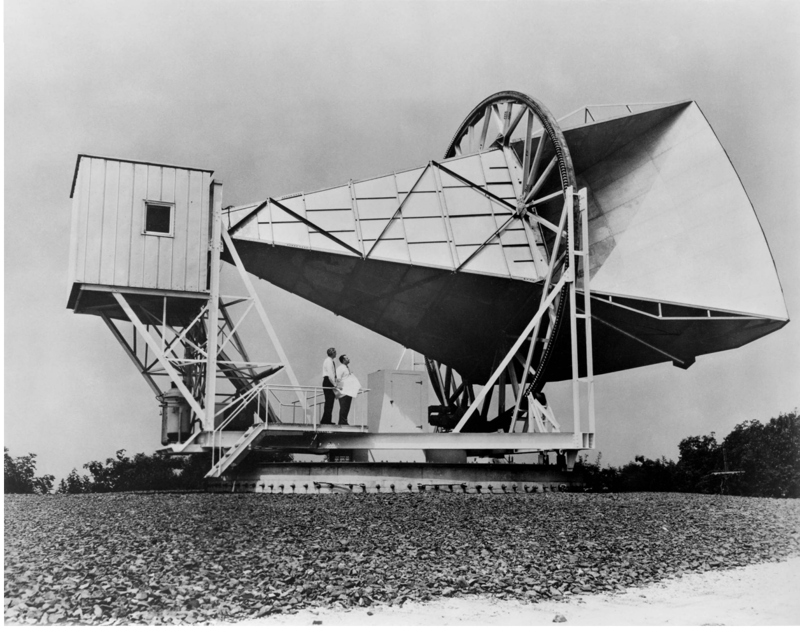
One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

1. The assumption of continuous creation (Bondi and Gold 1948; Hoyle 1948), which avoids the singularity by postulating a universe expanding for all time and a continuous but slow creation of new matter in the universe.

2. The assumption (Wheeler 1964) that the creation of new matter is intimately related to the existence of the singularity, and that the resolution of both paradoxes may be found in a proper quantum mechanical treatment of Einstein's field equations.

3. The assumption that the singularity results from a mathematical over-idealization,

* This research was supported in part by the National Science Foundation and the Office of Naval Research of the U.S. Navy.

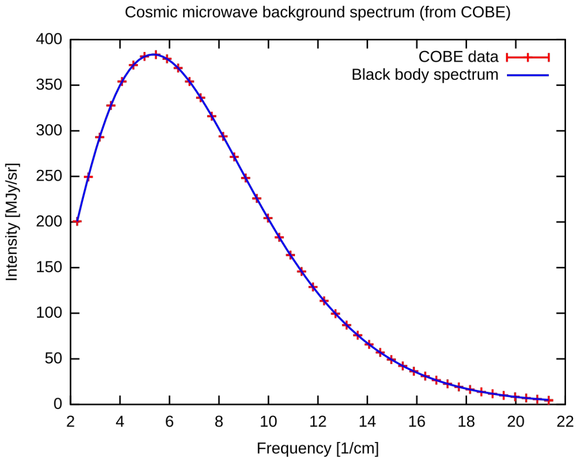


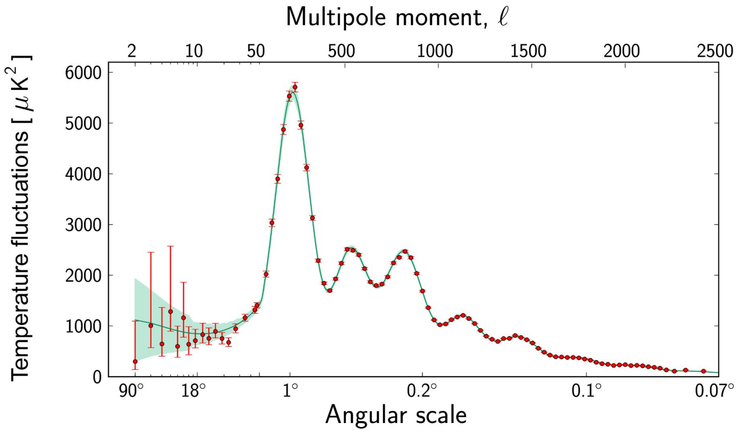
Sky (at zenith)	2.3 ± 0.2 K
Horn antenna	2.0 ± 1.0 K
Waveguide	7.0 ± 0.7 K
Maser assembly	7.0 ± 1.0 K
Converter	0.6 ± 0.2 K
Total System Temperature	**18.9 ± 3.0 K**

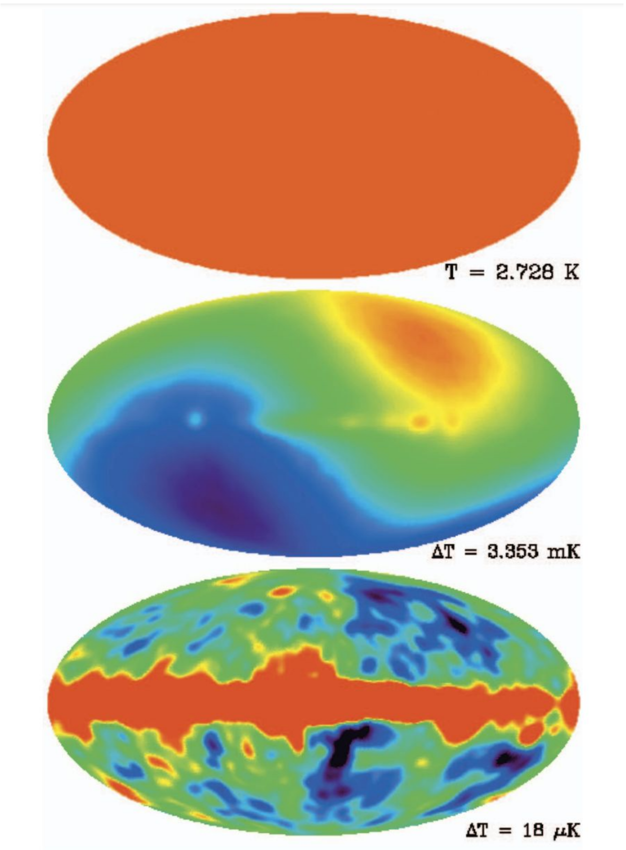
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

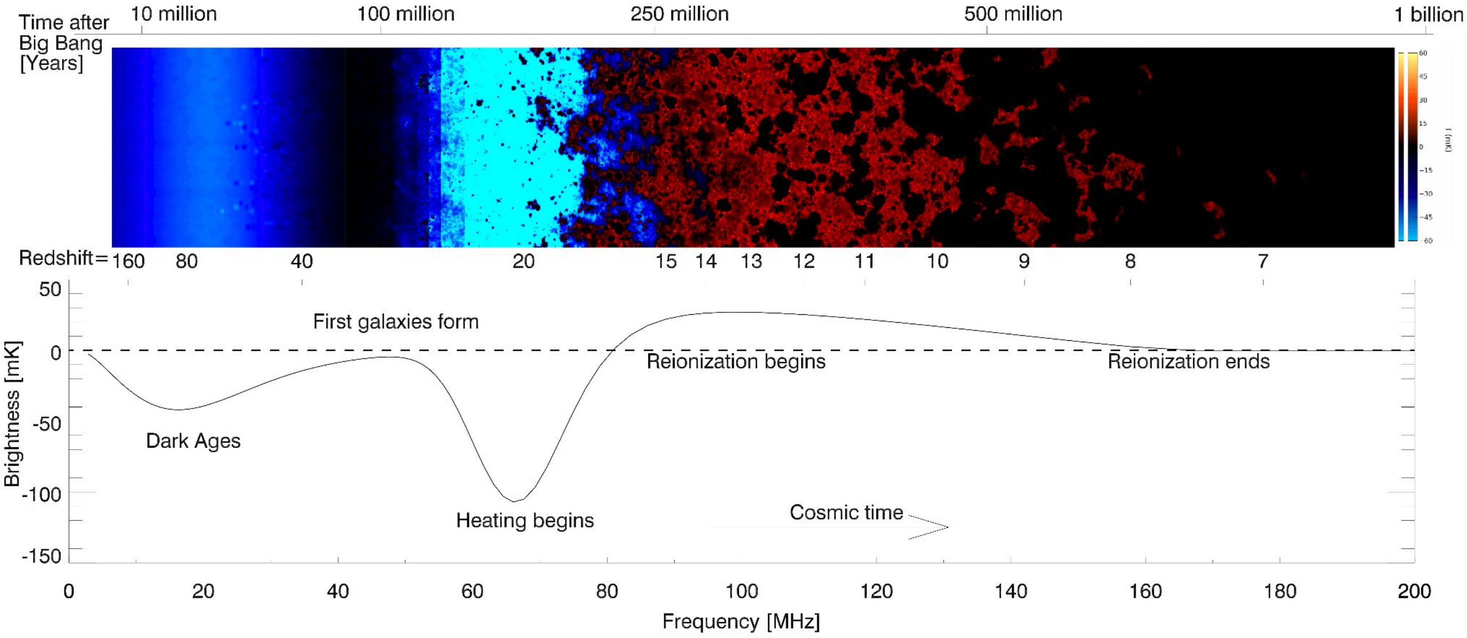
Interferometry vs radiometric measurements

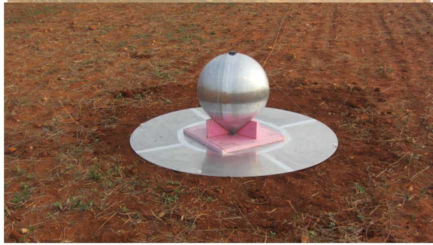






21-cm power spectrum and global 21-cm signal





Pritchard and Loeb, 2012

What does the “21-cm brightness” measure?

$$\delta T_b \approx 27 x_{\mathrm{HI}} \, (1+\delta_b) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10}\right)^{1/2} \times \boxed{\left(\frac{T_S - T_R}{T_S}\right)} \left[\frac{\partial_r v_r}{(1+z)H(z)}\right] \mathrm{mK}$$

Neutral fraction — *Traces ionization history*

Overdensity

Cosmological parameters

Spin temperature — *Traces thermal history*

Peculiar velocities

Distortion of the primordial radiation spectrum by the 21-cm hydrogen line at epochs $z = 150$–15

D. A. Varshalovich and V. K. Khersonskii

Ioffe Physics and Technology Institute, USSR Academy of Sciences, Leningrad

(Submitted March 9, 1977)

Pis'ma Astron. Zh. 3, 291–294 (July 1977)

A hydrogen absorption line will have developed in the primordial radiation spectrum because of the violation of local thermodynamic equilibrium during the adiabatic expansion of the universe at epochs $z = 150$–15. The line profile is calculated; its depth and position of minimum depend essentially on the mean density Ω of matter in the universe and on the parameter z_e, which specifies the epoch when the temperatures of radiation and matter were effectively decoupled. On this basis a method is proposed for determining Ω and z_e.

PACS numbers: 98.80.—k

sources would track each other closely. Contrariwise, there would be no correlation between the 21-cm contributions, because the two frequencies would be probing "shells" in redshift space whose radial separation would exceed the correlation length. Consequently, it is not necessarily unfeasible to distinguish the 21-cm background, utilizing a radio telescope with a large collecting area. That line radiation allows three-dimensional tomography of the high-z HI renders this a specially interesting technique.

Rees, 1997

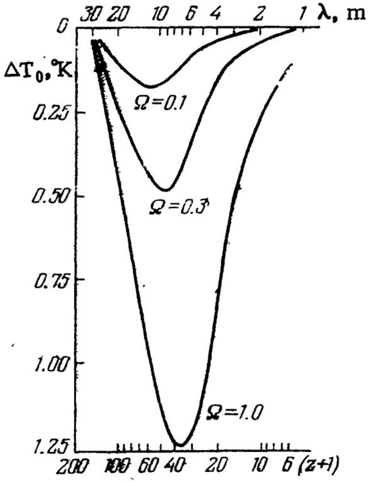


FIG. 1. Profile of the absorption band in the primordial radiation spectrum. The amount of absorption $\Delta T_0^{(R)}$ is shown as a function of the wavelength λ of the radiation or the parameter $z + 1 = \lambda/\lambda_0$ for three values of the density of matter (Ω = 0.1, 0.3, 1.0) at z_e = 150.

A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
12.03.1; 12.03.3; 12.04.2, 12.05.1

ASTRONOMY AND ASTROPHYSICS

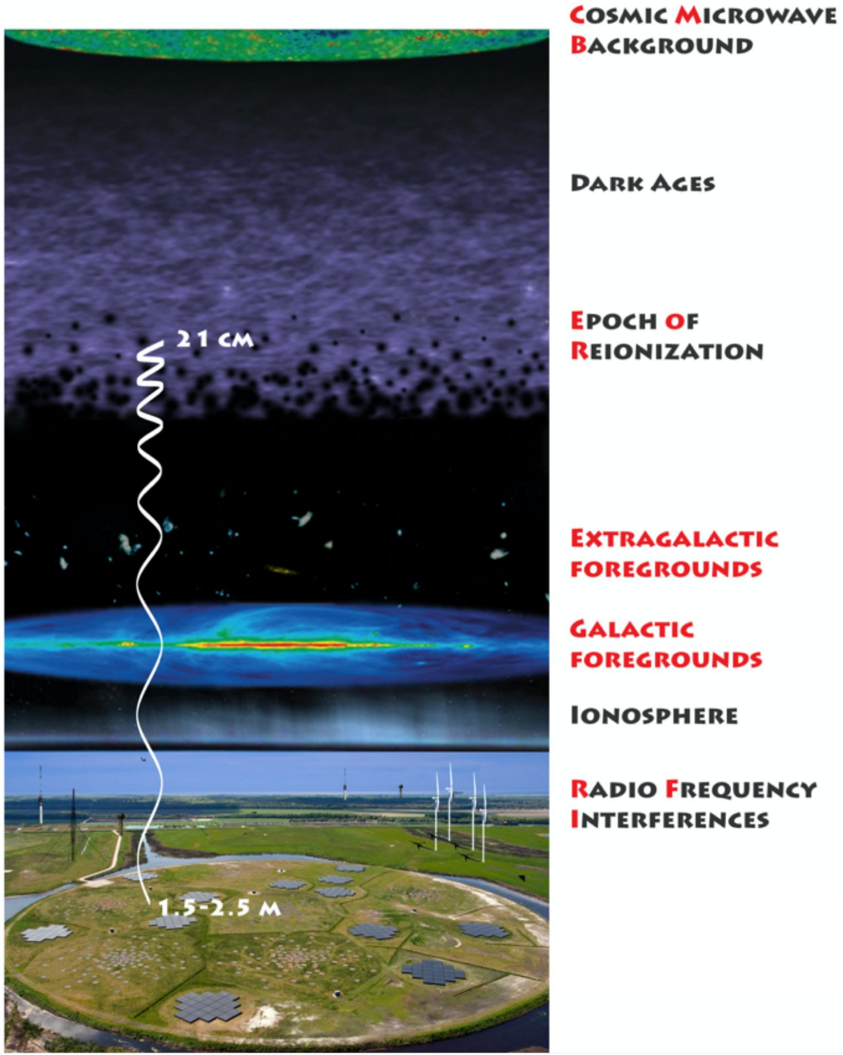
Can the reionization epoch be detected as a global signature in the cosmic background?

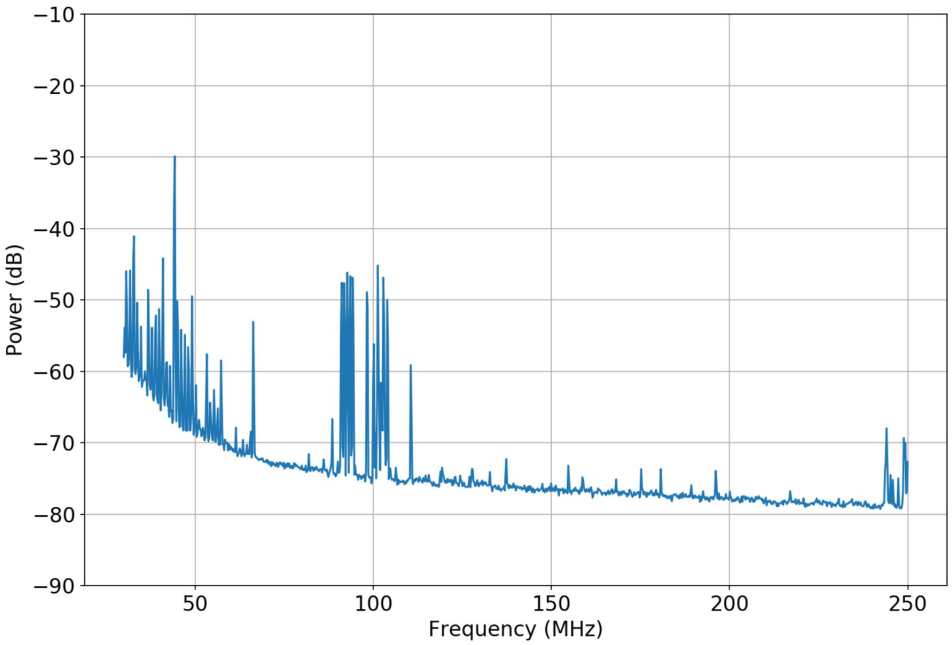
P.A. Shaver[1], R.A. Windhorst[2], P. Madau[3], and A.G. de Bruyn[4]

[1] European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
[2] Arizona State University, Dept. of Physics & Astronomy, Tempe, AZ 85287-1504, U.S.A.
[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, U.S.A.
[4] Netherlands Foundation for Research in Astronomy, Postbus 2, NL-7990 AA Dwingeloo, The Netherlands and Kapteyn Astronomical Institute, Postbus 800, NL-9700 AV Groningen, The Netherlands

Received 5 October 1998/ Accepted

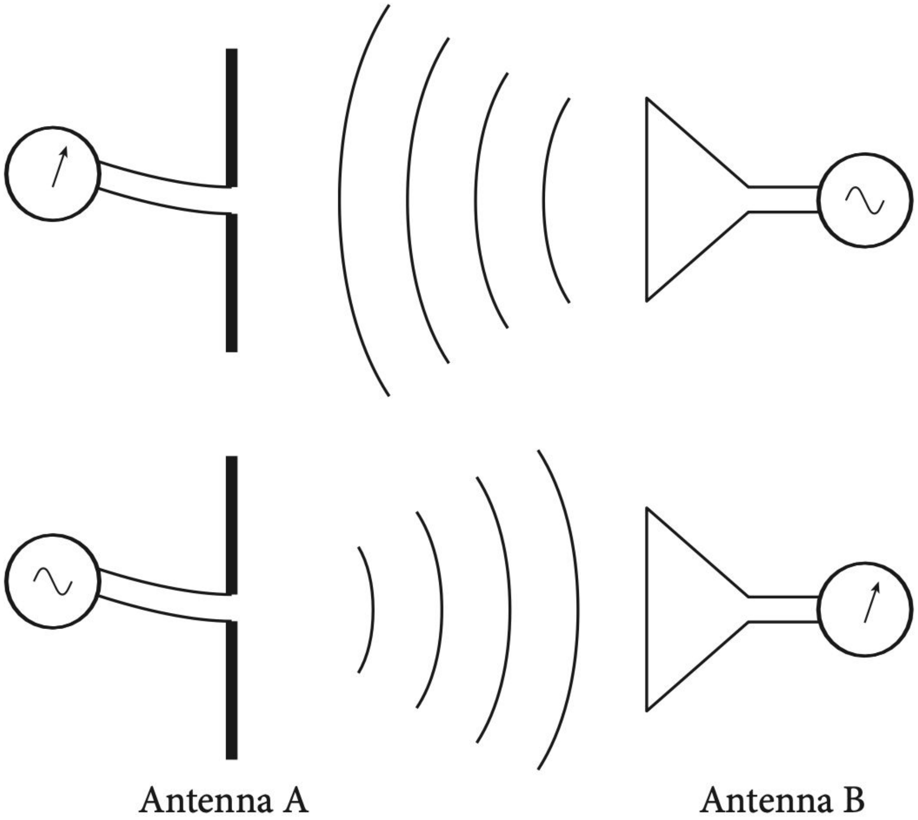
Major Challenges





What does an antenna measure?

Antenna: Reciprocity



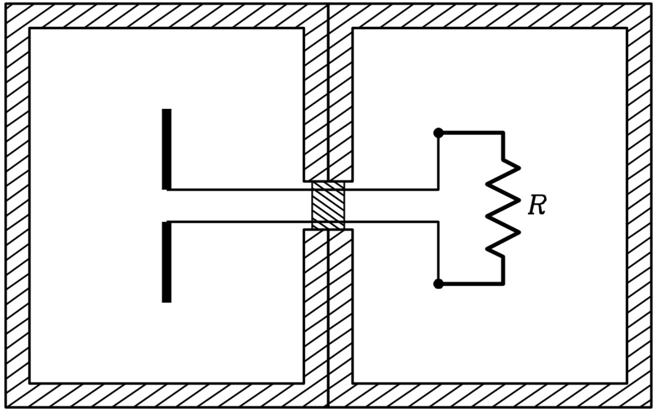
Basic antenna terms

- Antenna Gain: Power radiated compared to isotropic antennas

$$\int_{\text{sphere}} \mathrm{G}\, d\Omega = 4\pi.$$

$$\Omega_A \equiv \frac{4\pi}{G_0}$$

- Effective Area:



$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2}$$

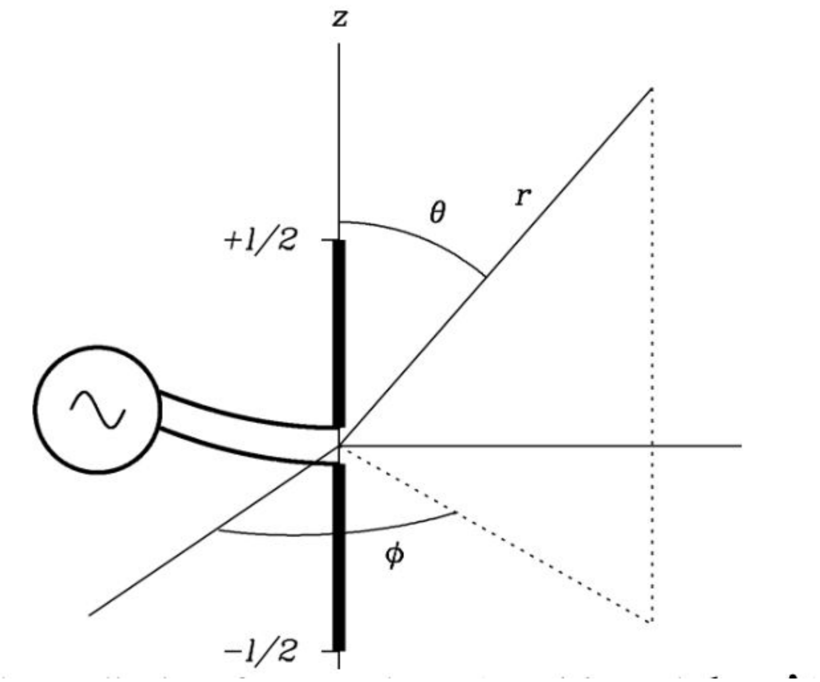
$$A_e(\theta, \phi) = \frac{\lambda^2 G(\theta, \phi)}{4\pi}$$

Units of Measurement — temperature

Brightness and flux density

$$I_\nu \equiv \frac{dP}{(\cos\theta\, d\sigma)\, d\nu\, d\Omega}$$

$$S_\nu \approx \int_{\text{source}} I_\nu(\theta, \phi) d\Omega .$$

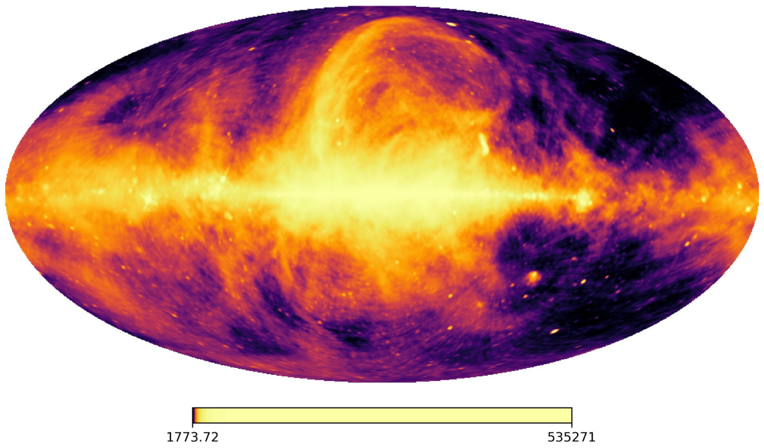


What does an antenna measure?

$$T_A(t,\nu) = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi/2} \mathrm{d}\theta \sin\theta \, T_f(t,\nu,\theta,\phi) B(\nu,\theta,\phi)$$

1. When source is extended
2. When source is compact

Why does it matter for 21 cm?



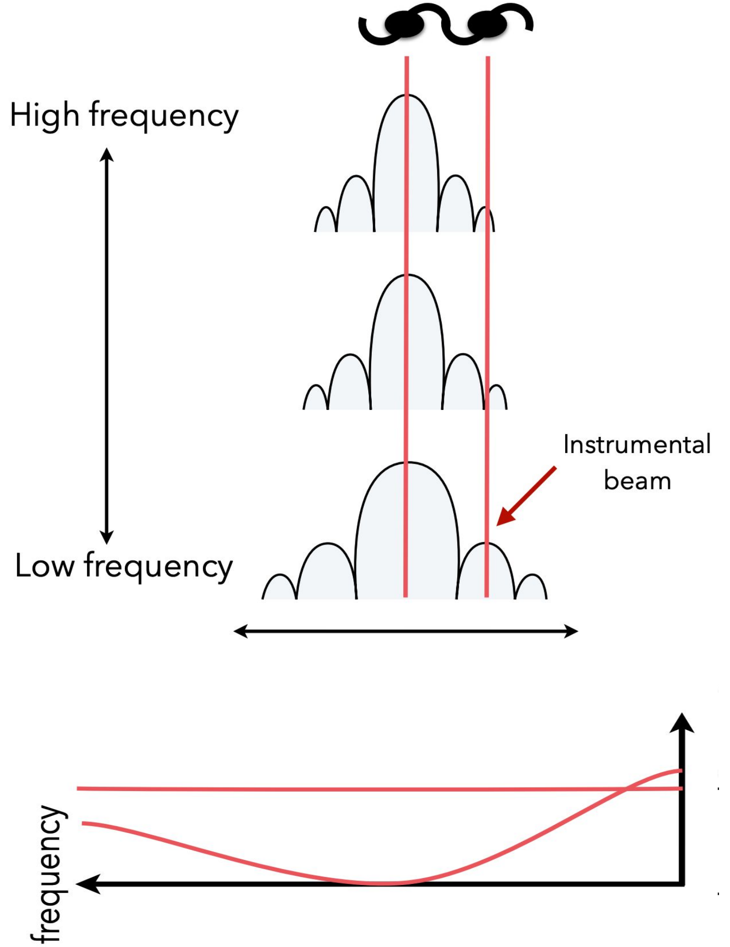
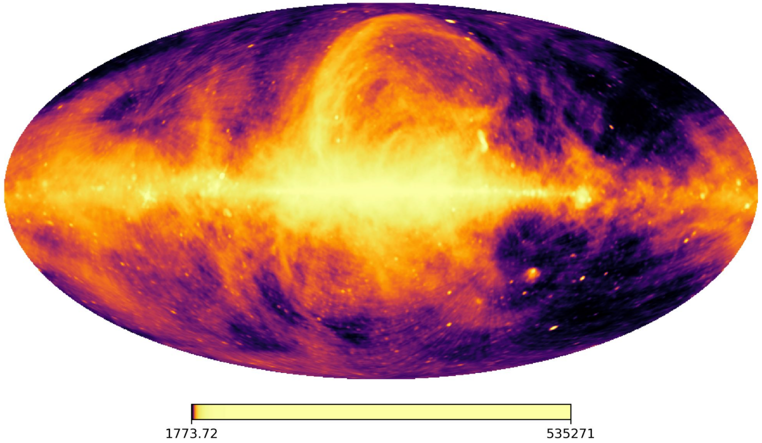
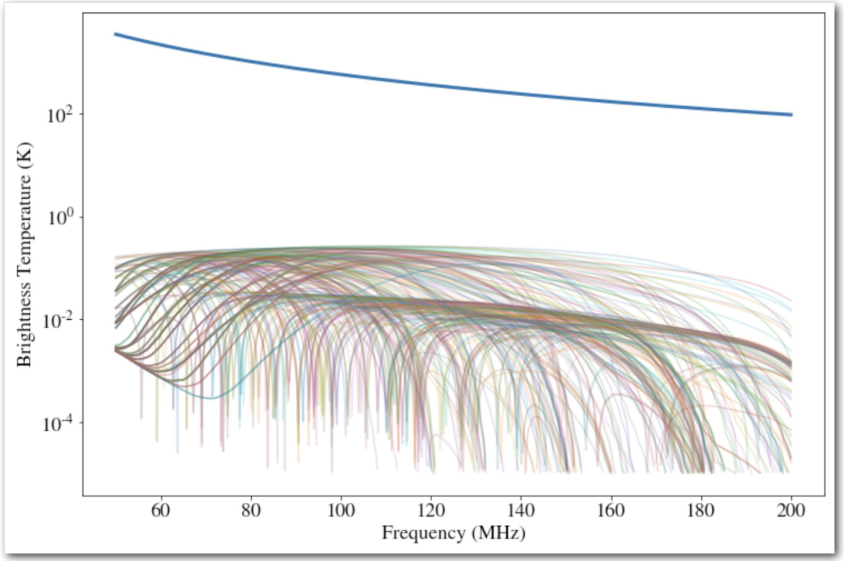


Figure Courtesy: Richard Shaw

Why does it matter for 21 cm?

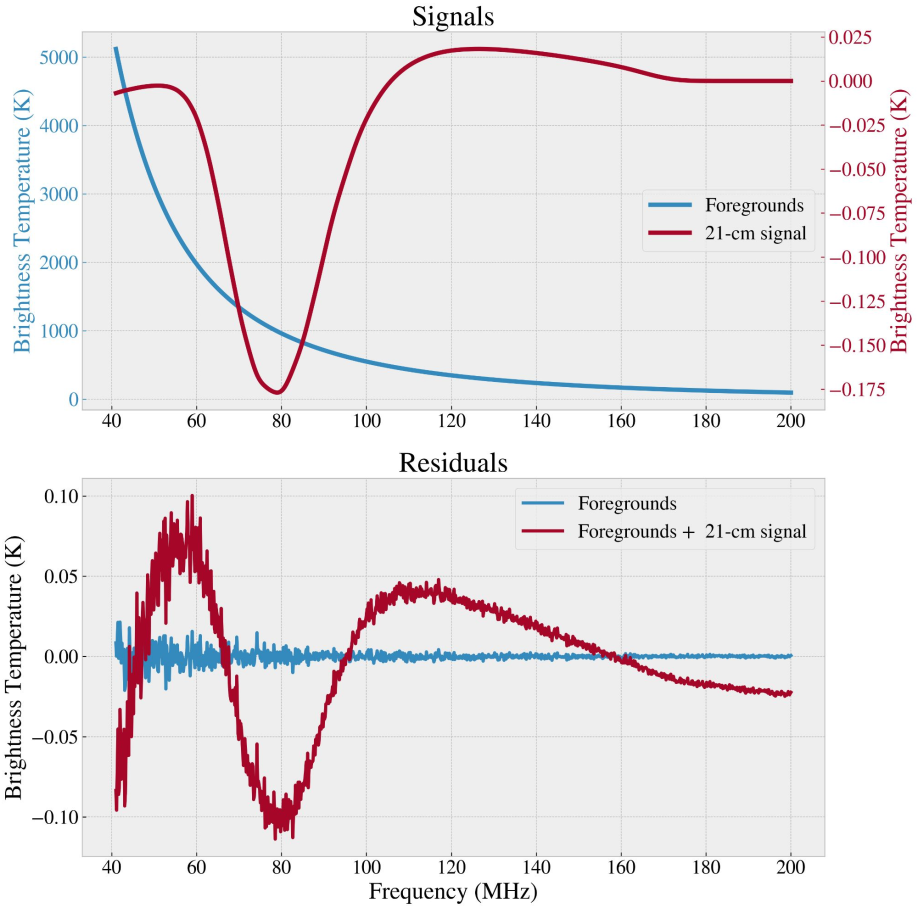




Dealing with ideal foregrounds

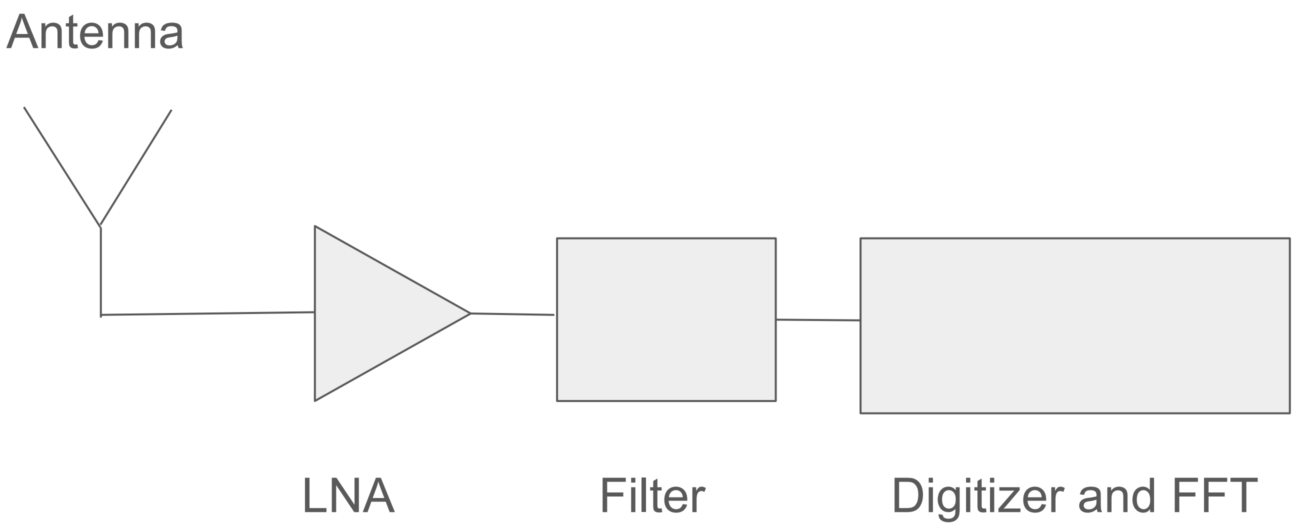
$$f(x) = p_0 + p_1(x - x_0) + p_2(x - x_0)^2 + p_3(x - x_0)^3$$

$$\frac{\mathrm{d}^m f(x)}{\mathrm{d}x^m} = \sum_{i=0}^{n-m} \{(m+i)!/i!\} p_{m+i}(x - x_0)^i$$

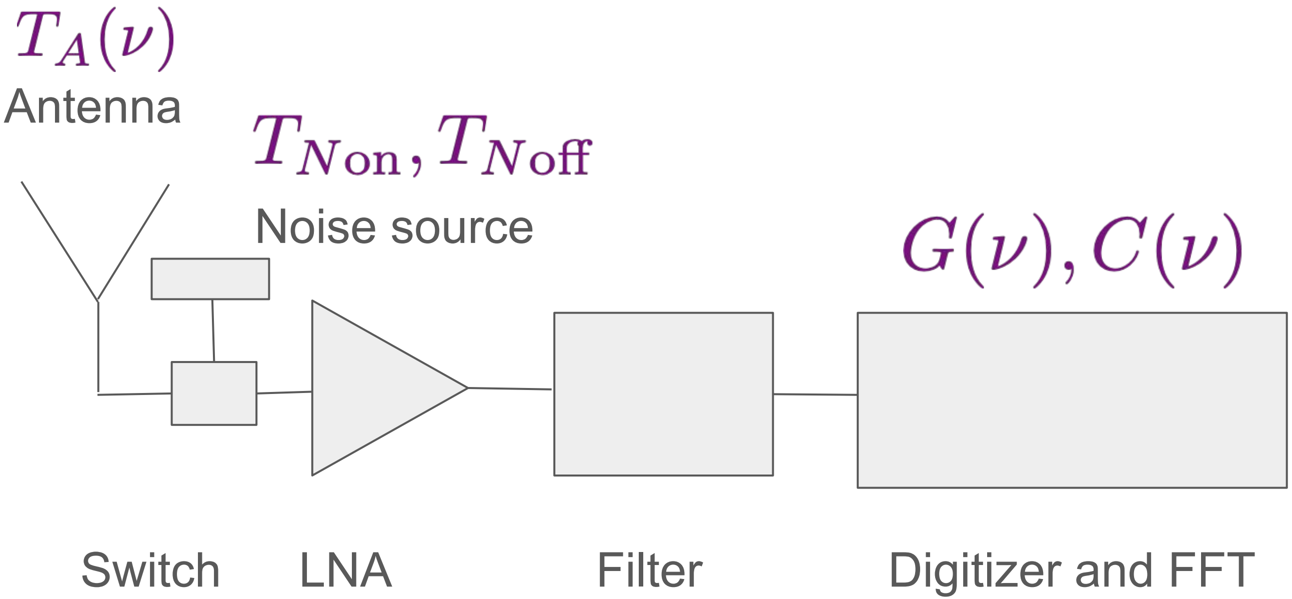


Radiometers and their calibration

Our own basic radiometer!



Usual calibration scheme



Challenges: Instrument

- Antenna beam
- Antenna transfer function

} Often not calibratable
Needs to be
modeled externally

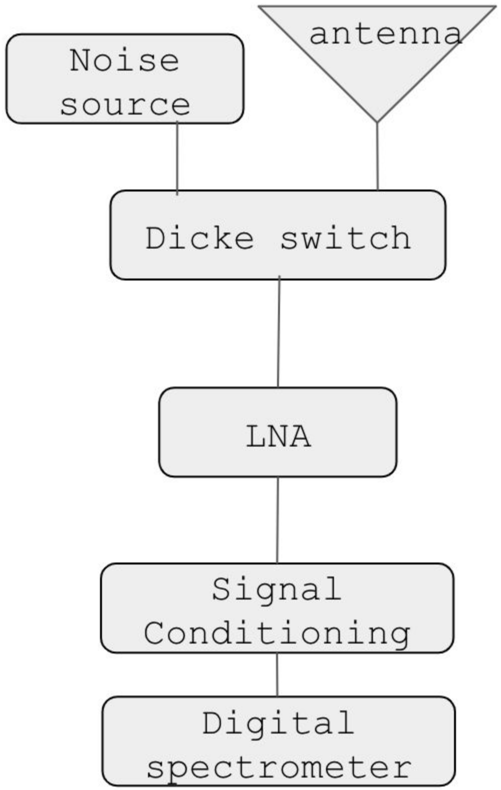
- Bandpass transfer function (analog + digital chain)

} Mostly corrected with
noise source injection

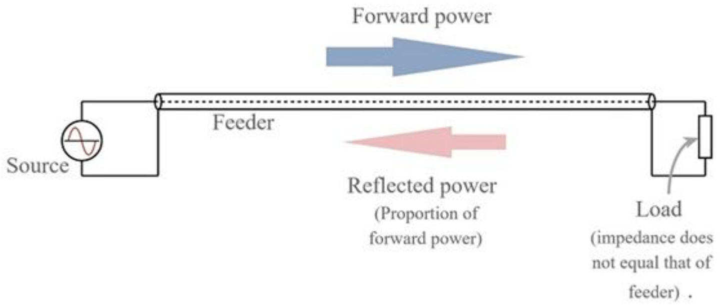
- Additives from amplifiers + ground coupling

} Often not calibratable
Needs to be
modeled externally

All these characteristics are frequency and (more or less) time/temperature dependent

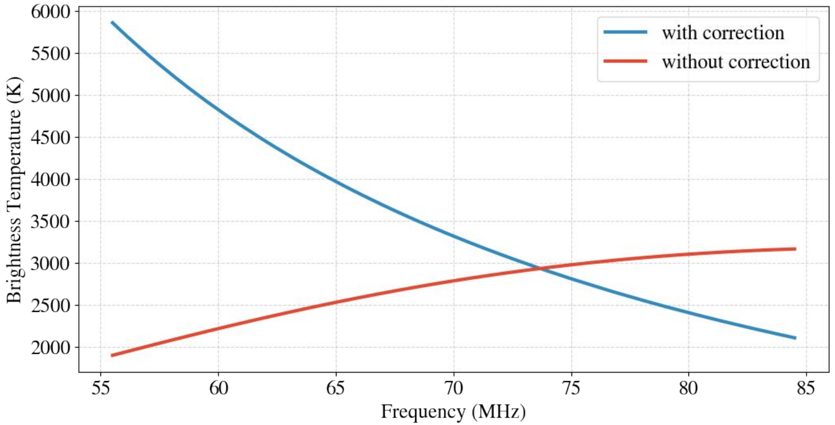


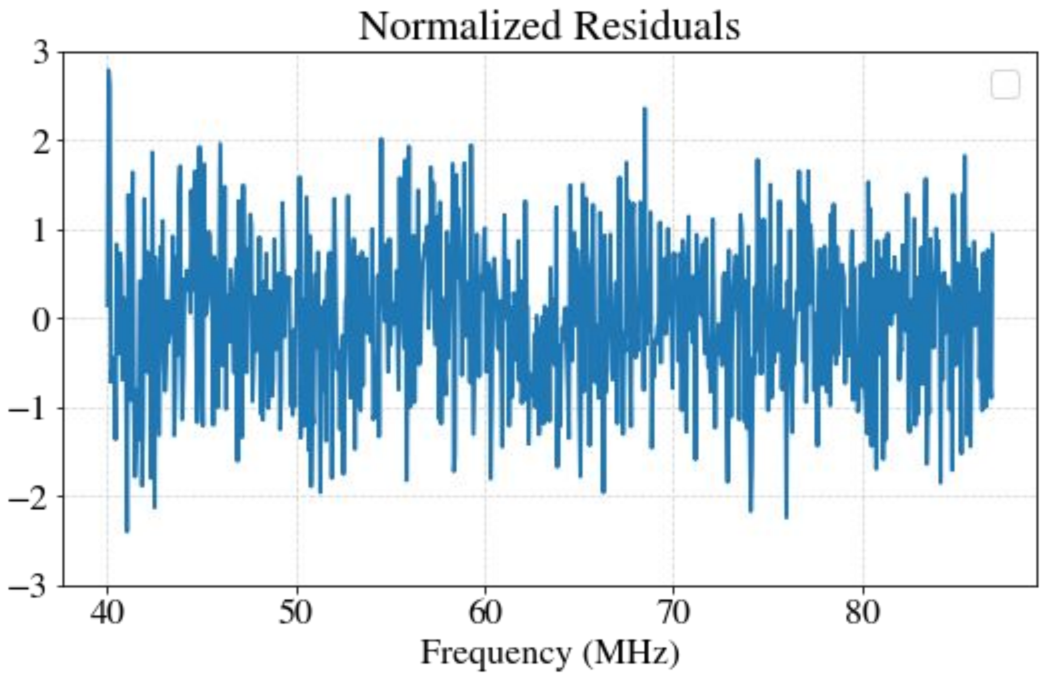
Modeling radiometric contributions

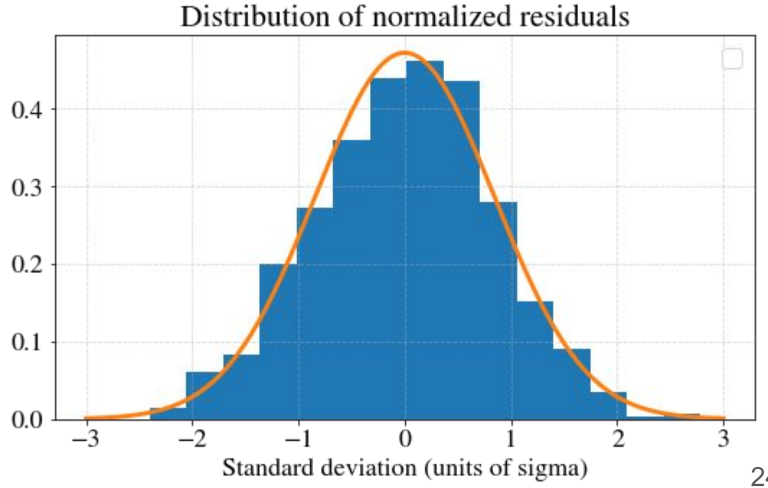


$$T_{\mathrm{sky}} = \frac{T_{\mathrm{meas}} + T_{\mathrm{ref}}}{\eta_{\mathrm{rad}}(1 - |\Gamma|^2)} - \frac{T_{\mathrm{rec}}}{\eta_{\mathrm{rad}}(1 - |\Gamma|^2)} - \frac{T_{\mathrm{w}}(1 - \eta_{\mathrm{rad}})}{\eta_{\mathrm{rad}}}$$

Antenna — Additives — Medium

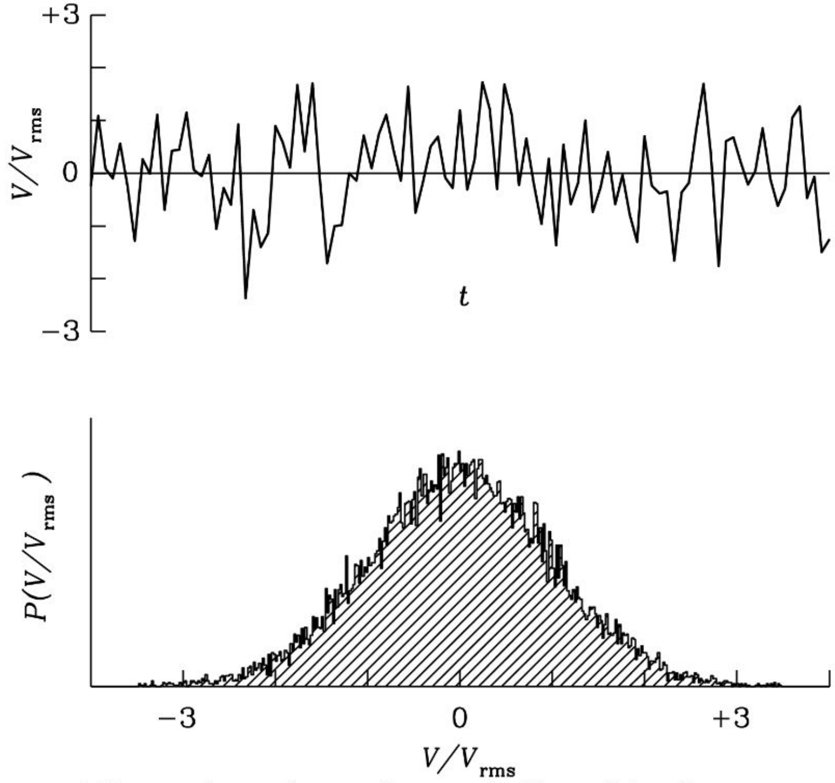



Normalized Residuals
3
2
1
0
−1
−2
−3
40
50
60
70
80
Frequency (MHz)


Distribution of normalized residuals
0.4
0.3
0.2
0.1
0.0
−3
−2
−1
0
1
2
3
Standard deviation (units of sigma)

Sensitivity of radiometers

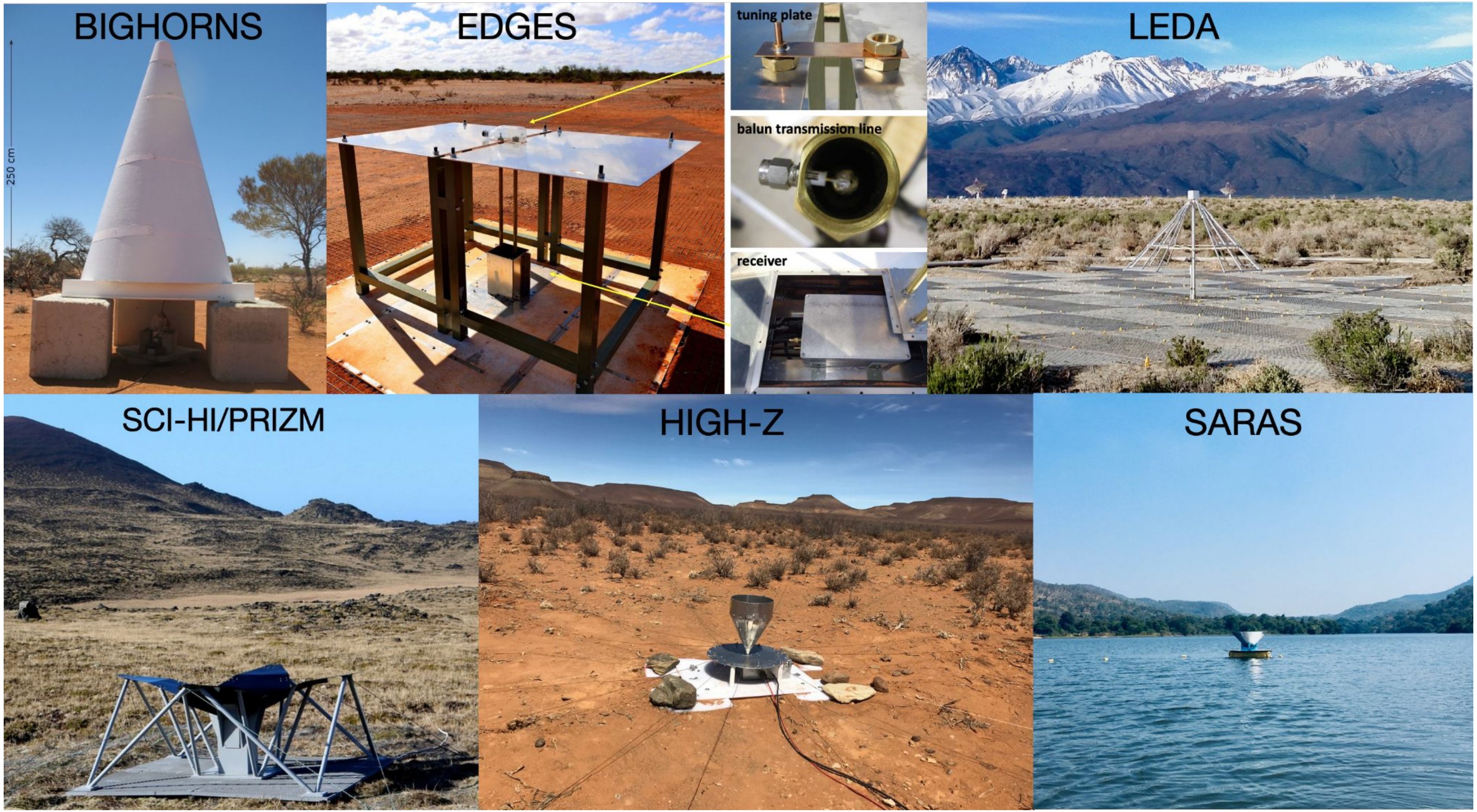
$$\sigma_T = \frac{T_{sys}}{\sqrt{Bt}}$$



$$T_s = T_{cmb} + T_{rsb} + \Delta T_{source} + [1 - \exp(-\tau_A)]\, T_{atm} + T_{spill} + T_r + \cdots.$$

Where are we?

Global 21-cm experiments



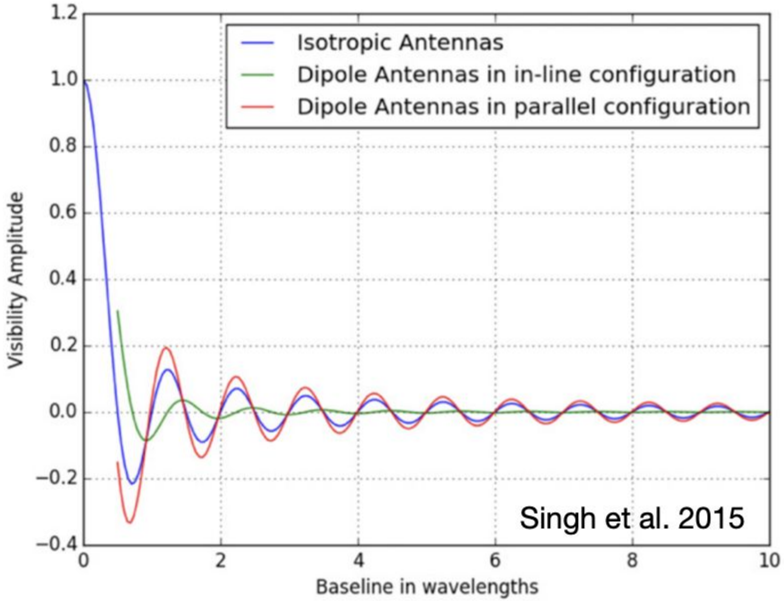
MIST

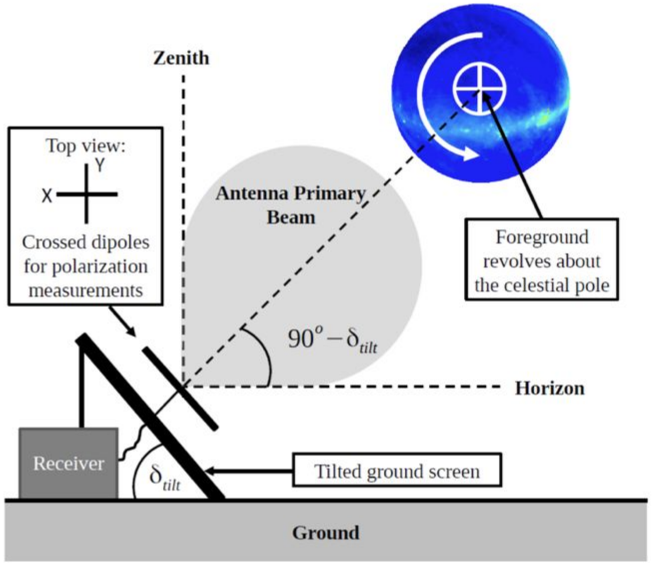
REACH

RHINO

And many more on the horizon…

Other ways to measure: interferometers, polarimetry



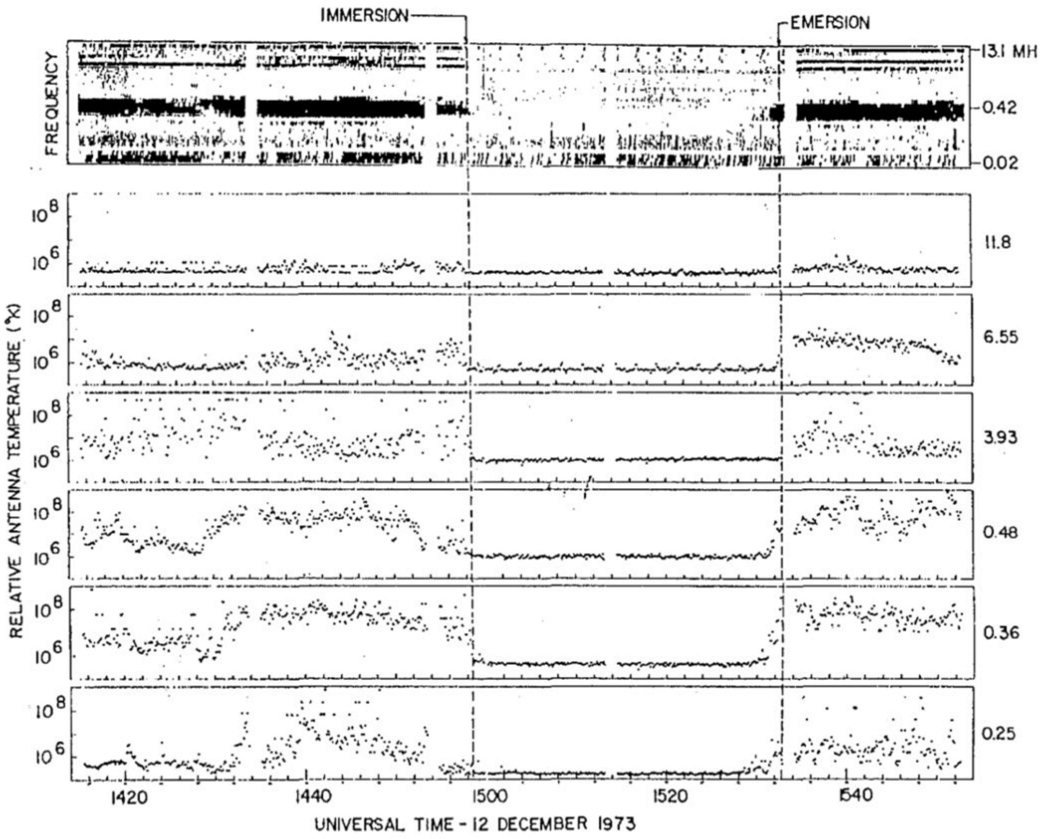


- Interferometers have a diminished, but a non-zero response to the monopole
- Immune to many systematics that affect single dish experiments
- Experiment: ASSASIN (McKinley et al. 2020)

- Anisotropic brightness distribution of the foregrounds can create modulations in the polarization measurement
- This is absent for 21-cm signal, making the signal separation easier
- Experiment: Cosmic Twilight Polarimeter (Nhan et al. 2019)

Experiments/Proposals for space

- Major motivations:
  - Ionospheric effects
  - RFI
  - Coupling with the environment
- Not to forget the additional challenges:
  - Shielding from self-generated RFI
  - Electromagnetic footprints of other systems in the spacecraft
  - Restricted mass/power/volume



As measured from Radio Astronomy Explorer

Telescope
SARAS1
SARAS2
SARAS3
SCI-HI
BIGHORNS
EDGES
PRIZM
REACH
MIST
GINAN
EIGSEP
RHINO

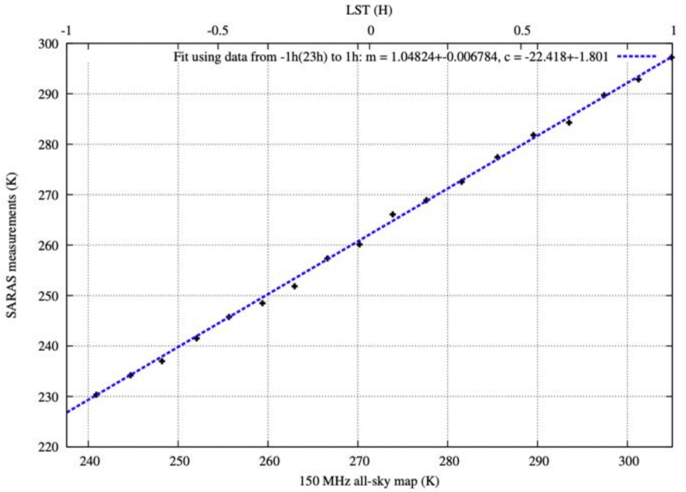
Telescope
GMRT
21CMA/PAST
NenuFAR
SKA-LOW
MWA
PAPER
LOFAR
HERA
OVRO-LWA/LEDA

LCRT
FARSIDE
DALI
ALO
FarView
DAPPER
ROLSES
ROLSES-2
DARE
PRATUSH
LuSee-Night
DEX
Hongmeng/DSL
CosmoCube
SEAMS

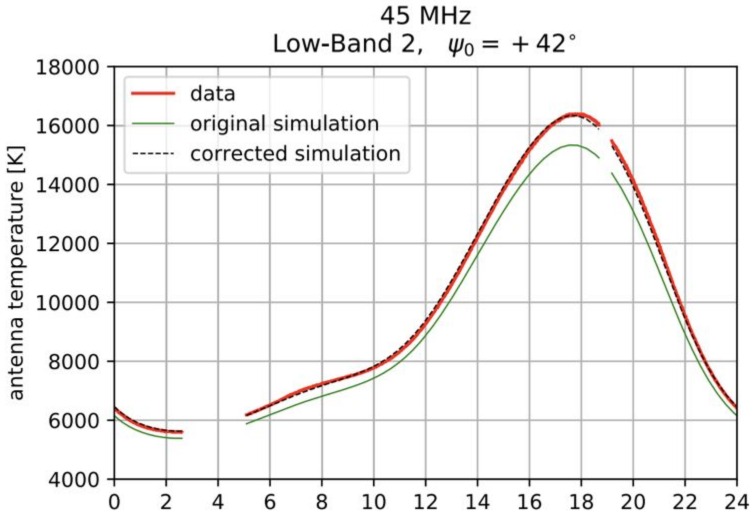
https://docs.google.com/spreadsheets/d/1ivpOBFxBW_3guvNMOkRfU7e-hFXRtjXCTbr4aTJcPdY/edit?usp=sharing

Bonus science: foregrounds

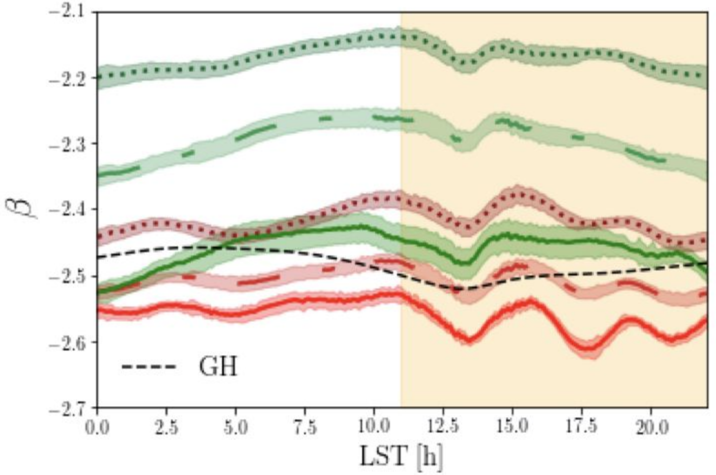
- Correction to the existing maps
- Spectral index variation in different regions of the sky
- Recombination lines!



SARAS 1



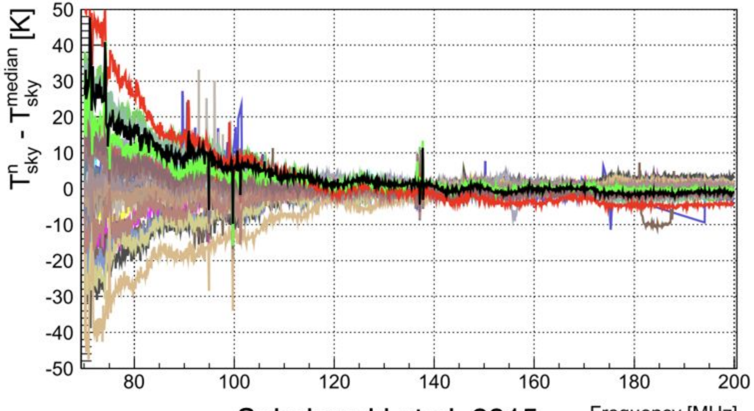
EDGES



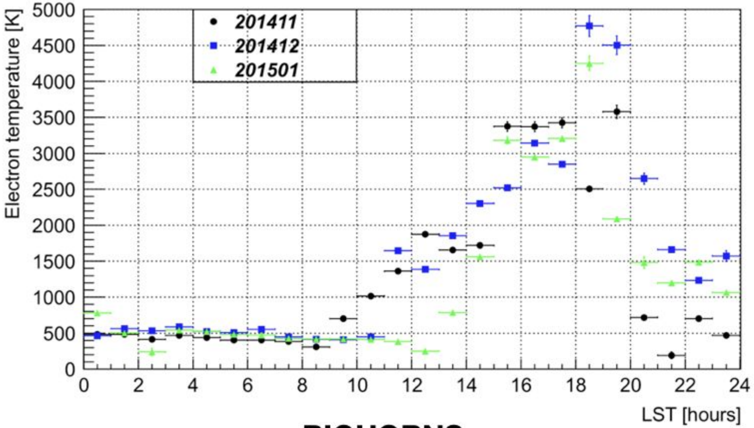
LEDA

Bonus science: ionosphere

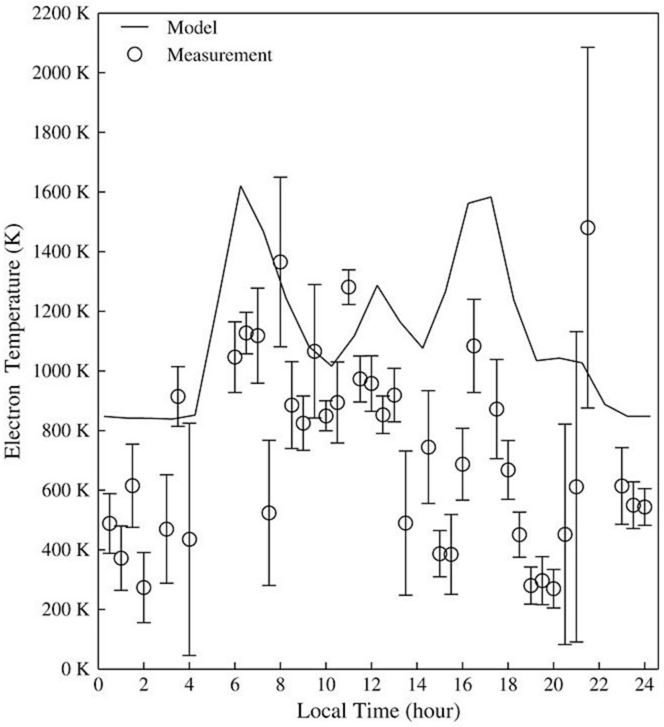
- Ionospheric effects are degenerate with foreground models!
- Variation of the spectrum over long timescales can be modeled with ionospheric emissions and absorption



Sokolowski et al. 2015

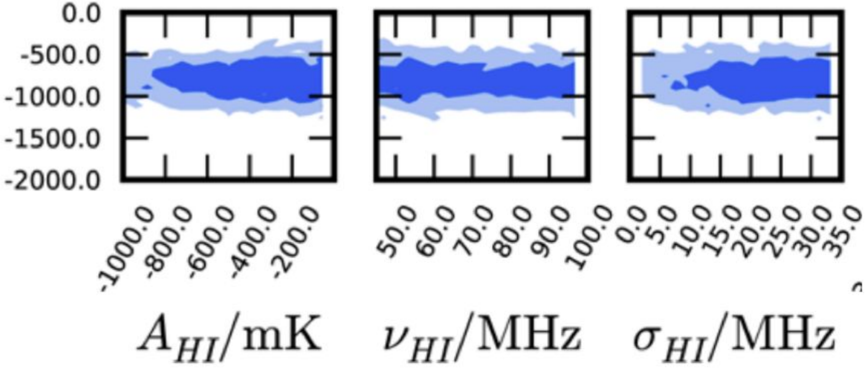


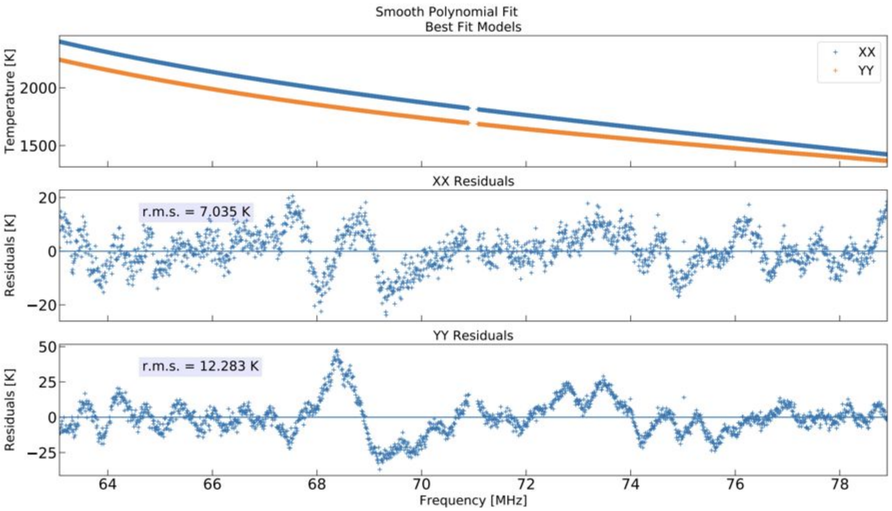
BIGHORNS



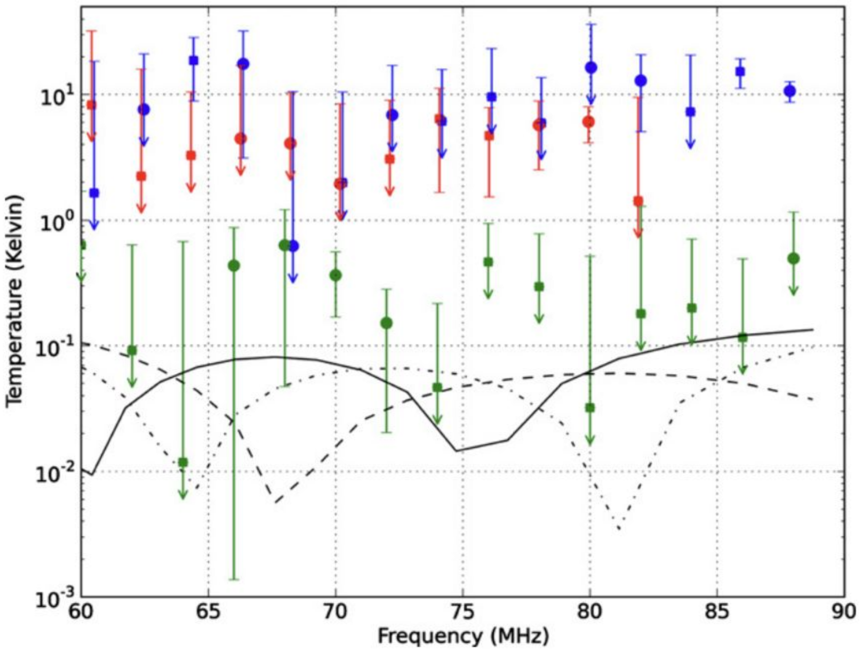
EDGES

Constraints on the signal/upper limits





LEDA

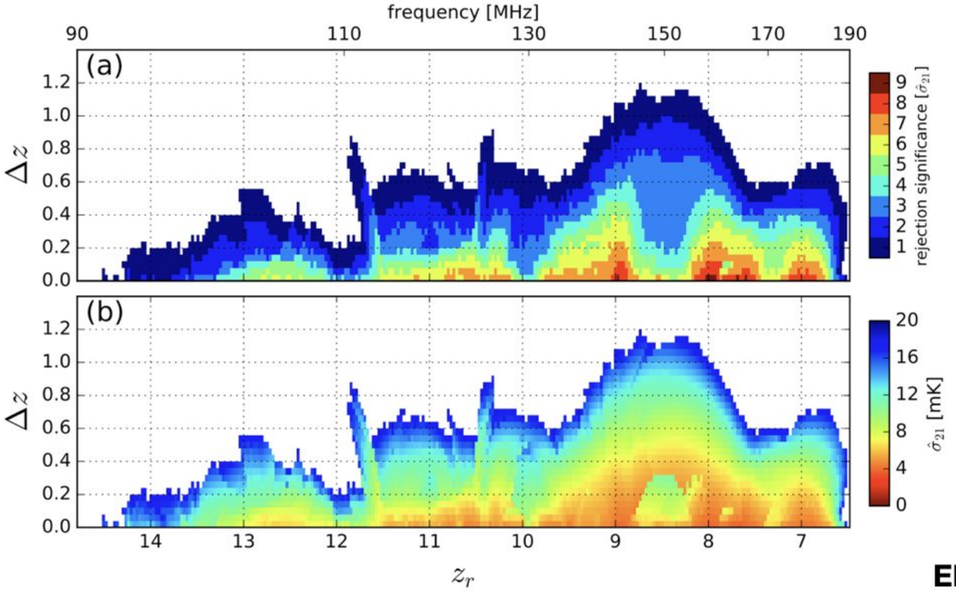


SCI-HI

Constraints on reionization

Global 21-cm experiments are sensitive to rapid reionization scenarios

$$\tilde{x}_{\mathrm{H\,I}}(z) = \frac{1}{2}\left[\tanh\left(\frac{z - z_{\mathrm{r}}}{\Delta z}\right) + 1\right]$$



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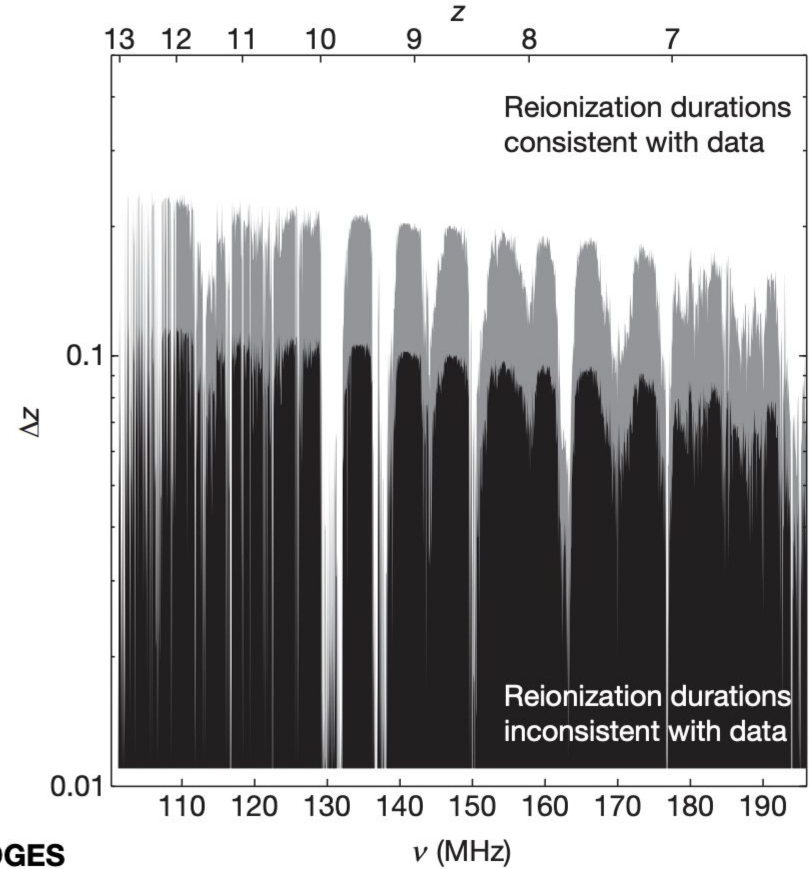
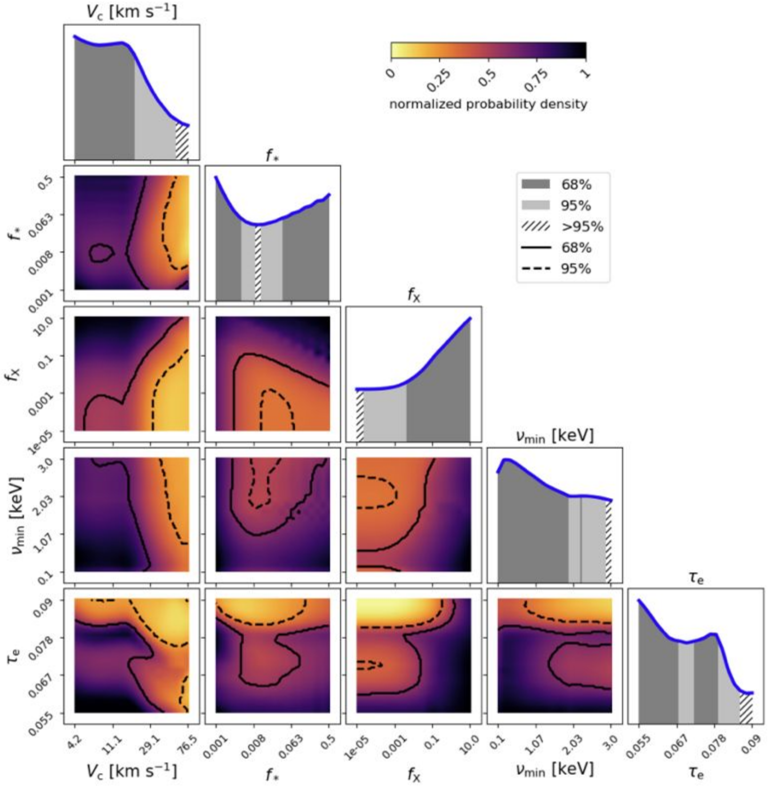


Constraints on astrophysics

Late/no heating and rapid reionization models are strongly disfavored



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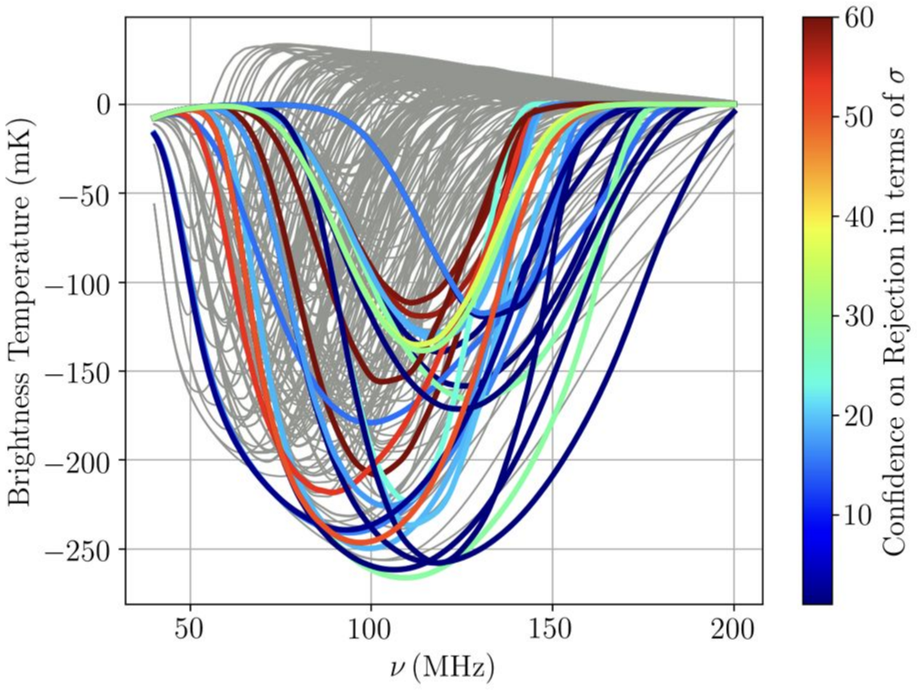
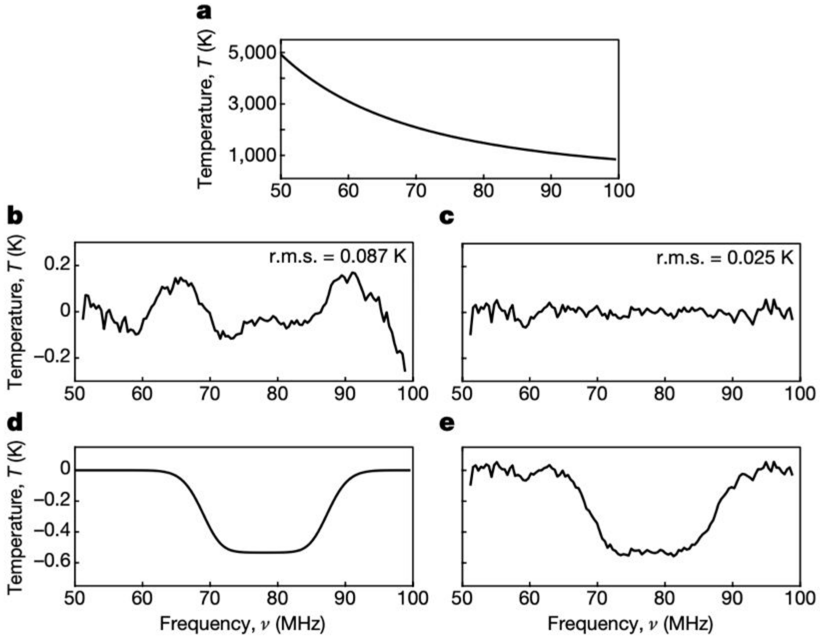


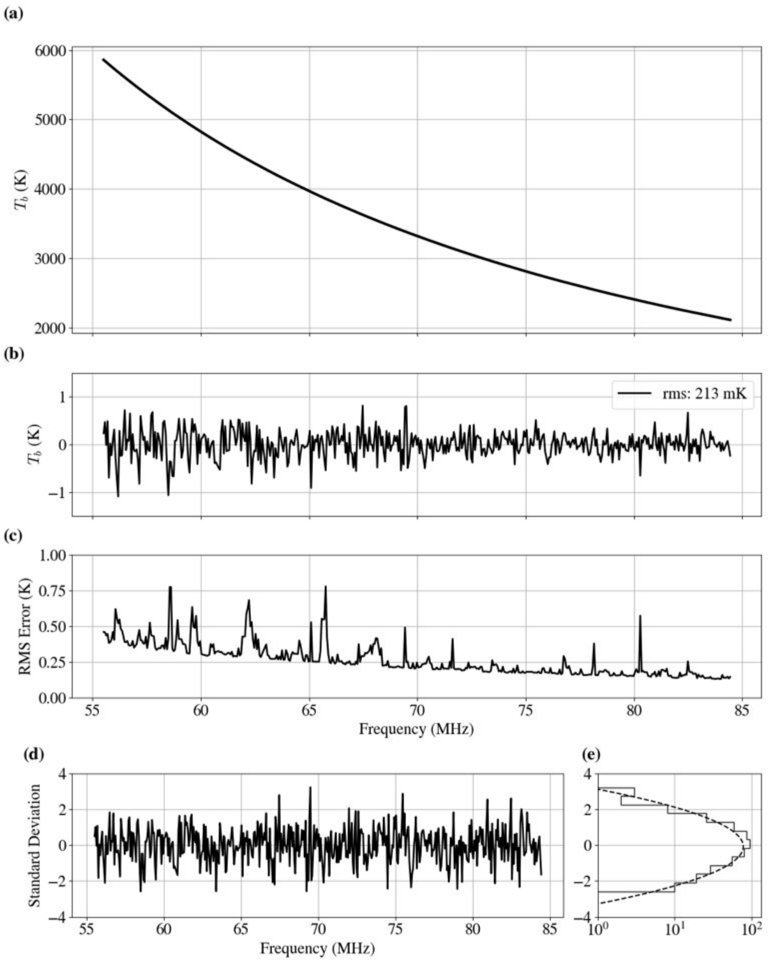
SARAS 2

Claimed Detection!

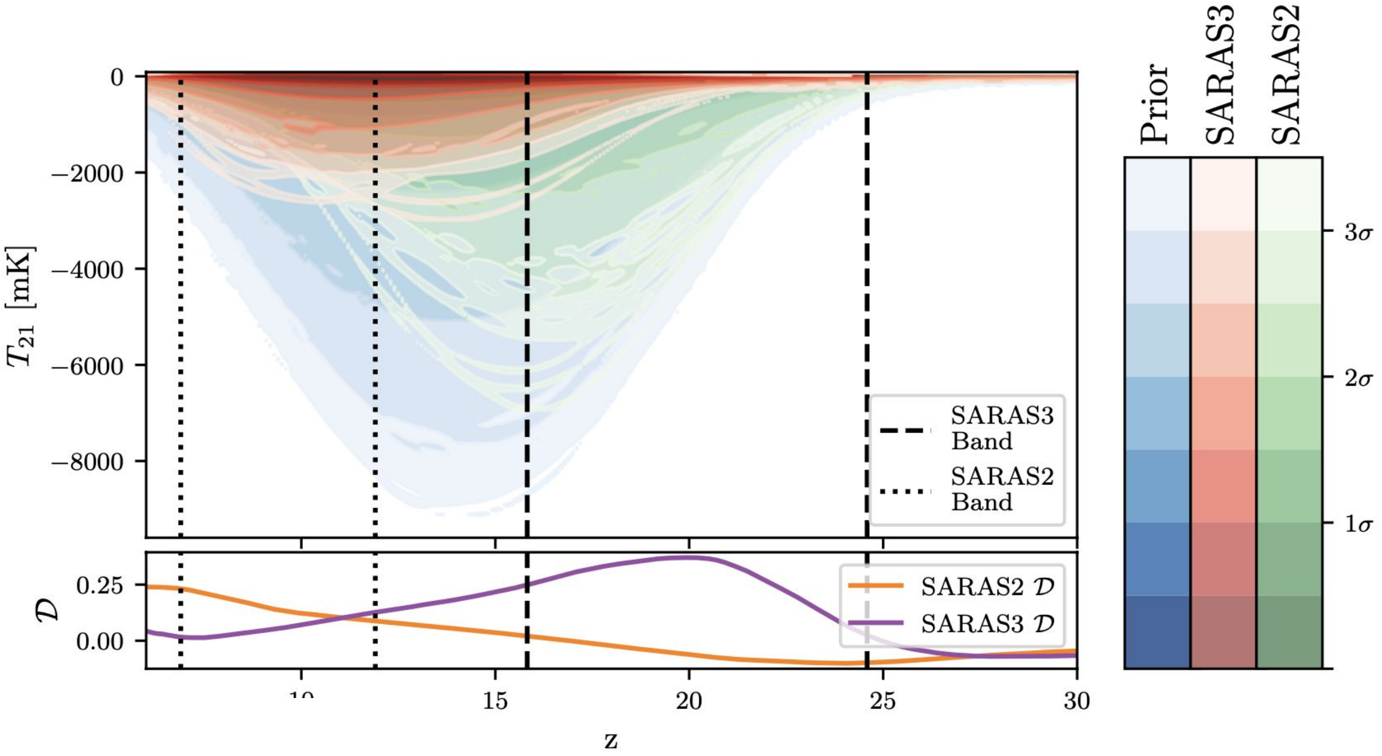


EDGES

Averaged Spectrum



SARAS 3: towards constraining the first stars



nature astronomy

Article

https://doi.org/10.1038/s41550-022-01825-6

Astrophysical constraints from the SARAS 3 non-detection of the cosmic dawn sky-averaged 21-cm signal

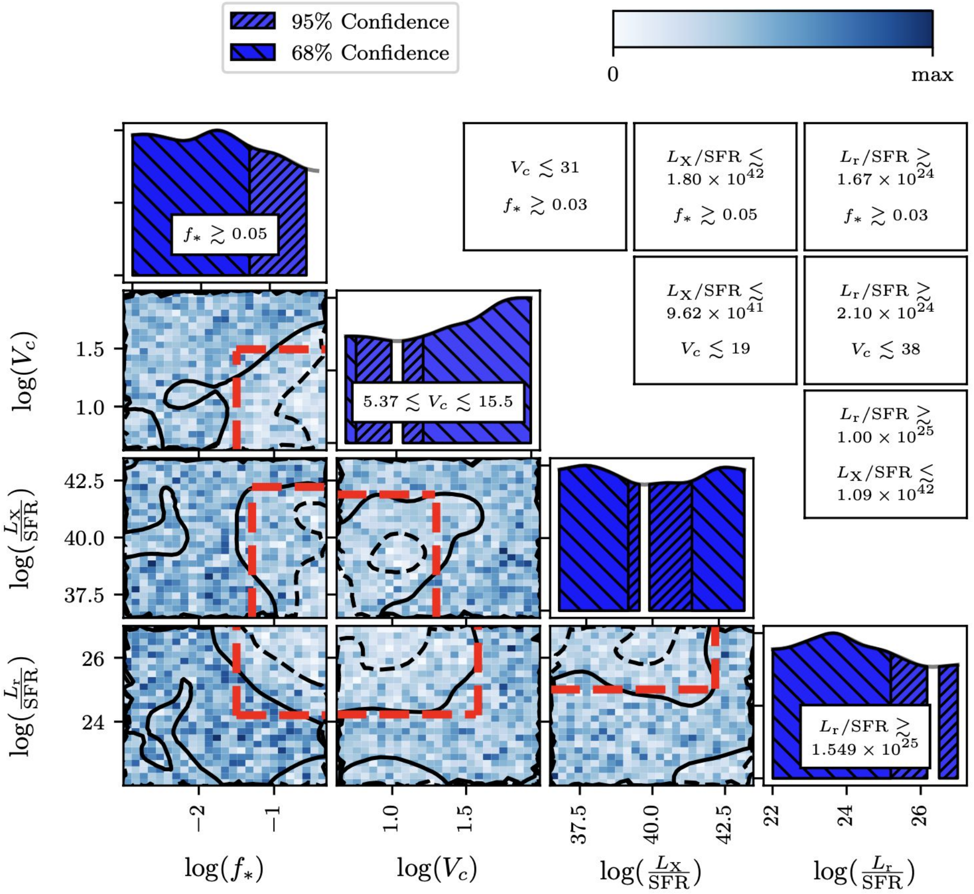
A joint model:

- Foreground
- Systematics
- Noise
- 21-cm signal ($f_{\rm radio}, f_*, V_c, f_X, \tau$)

	SARAS3
Signal type	Global
Redshift range	$z \approx 15 - 25$
L_r/SFR	$\gtrsim 1.549 \times 10^{25}$
$L_r/\mathrm{SFR} \cap L_X/\mathrm{SFR}$	$\gtrsim 1 \times 10^{25} \cap \lesssim 1.09 \times 10^{42}$
M	$4.4 \times 10^5 \lesssim M \lesssim 1.1 \times 10^7$
f_*	$\gtrsim 0.05$
$f_* \cap M$	$\gtrsim 0.03 \cap \lesssim 8.53 \times 10^8$

$$L_{\rm Radio}(\nu, z) = f_{\rm Radio} 10^{22} \left(\frac{\nu}{150\,\mathrm{MHz}}\right)^{-\alpha_{\rm Radio}} \frac{\mathrm{SFR}}{M_\odot \mathrm{yr}^{-1}}$$

$$\frac{L_X}{\mathrm{SFR}} = 3 \times 10^{40} f_X \ \mathrm{erg\ s^{-1}\ M_\odot^{-1}\ yr}$$



Ongoing work

- Better instrumentation
  - Designing optimal radiometers
  - Improving calibration strategy
  - Radio Quiet Locations
- Efficient data analysis algorithms
  - Better algorithms for flagging, calibration etc.
  - Minimum assumption foreground models
  - Bayesian/ML models for systematics
  - Quicker parameter space exploration for 21-cm signals
  - Synergy with other observations