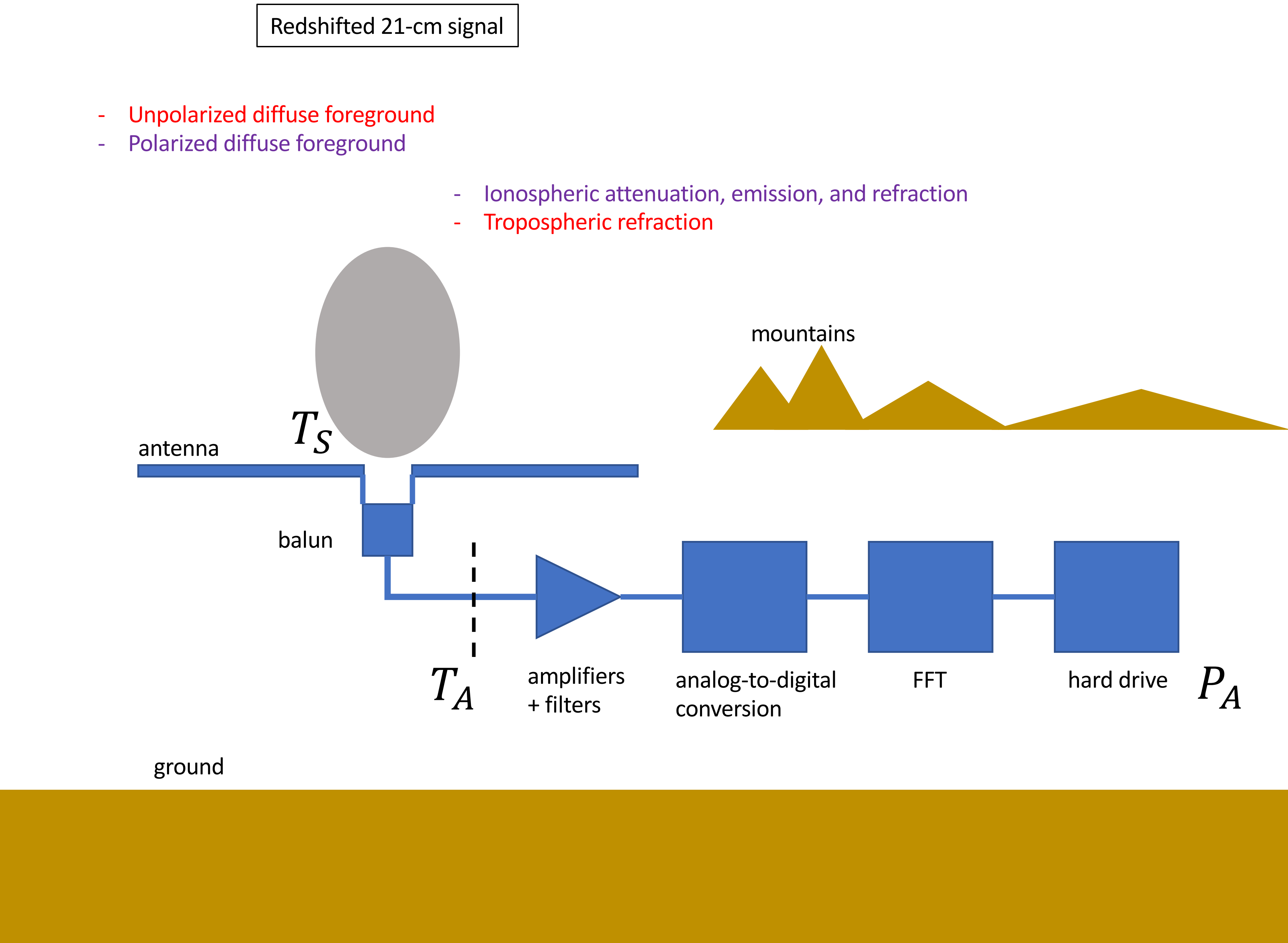
6th Global 21-cm Workshop
IFPU Focus Week, 21-cm Cosmology
IFPU, Trieste, Italy
Sept 12, 2023

Status of 21-cm Global Signal

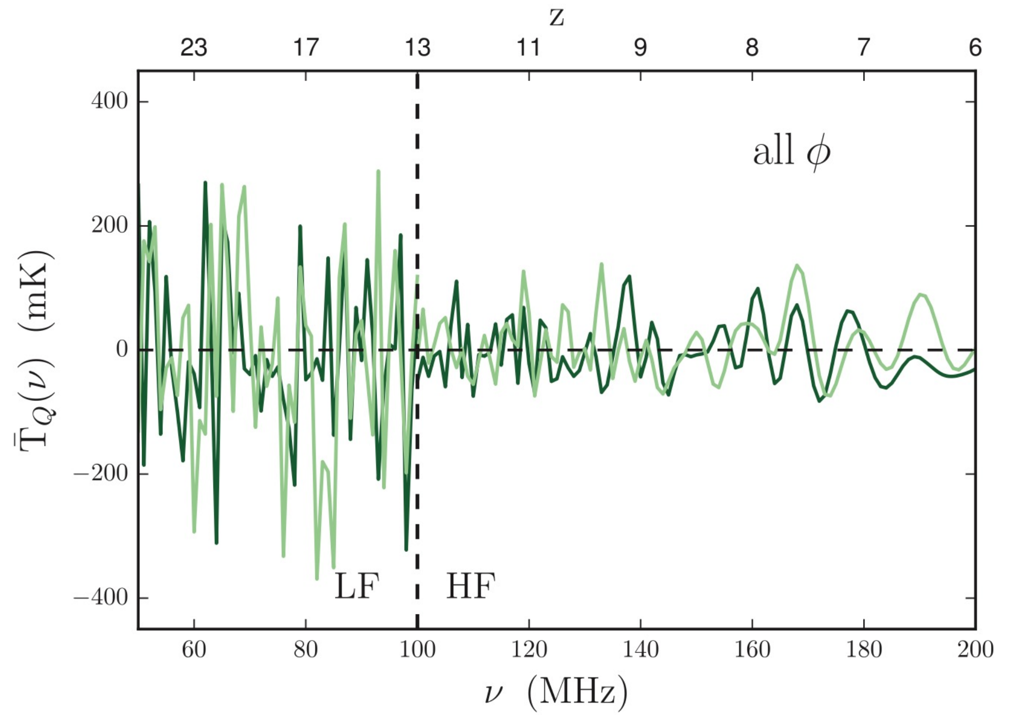
Raul Monsalve

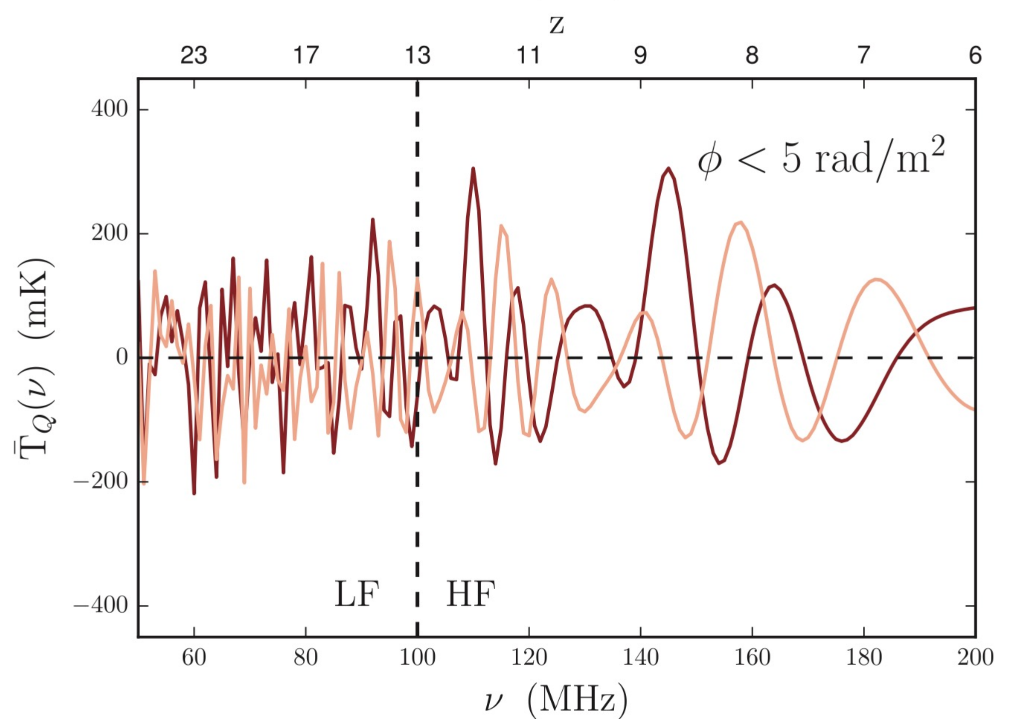
SSL
UC Berkeley


Redshifted 21-cm signal
- Unpolarized diffuse foreground
- Polarized diffuse foreground
- Ionospheric attenuation, emission, and refraction
- Tropospheric refraction
mountains
antenna
T_S
balun
T_A
amplifiers
+ filters
analog-to-digital
conversion
FFT
hard drive
P_A
ground

Polarized Foregrounds

Spinelli, Bernardi, Santos (2019)





Next:

Instrumental Stuff

Receiver Calibration

$$T_A(\nu) = \frac{P_A(\nu)}{g_R(\nu)} - T_R(\nu)$$

- Receiver gain and temperature
- Typically obtained from lab and field measurements of calibration standards
- Impedance mismatch between antenna and receiver input

(for single-polarization antenna)

$$T_S(\nu) = \frac{\int_0^{2\pi} \int_0^{\pi/2} T_{sky}(\theta, \phi, \nu) D(\theta, \phi, \nu) \sin\theta d\theta d\phi}{\int_0^{2\pi} \int_0^{\pi/2} D(\theta, \phi, \nu) \sin\theta d\theta d\phi}$$

Beam Chromaticity Correction

$$C(\nu, t) = \left(\frac{\int_0^{2\pi} \int_0^{\pi/2} T_{GSM}(\theta, \phi, \nu, t) D_c(\theta, \phi, \nu) \sin\theta d\theta d\phi}{\int_0^{2\pi} \int_0^{\pi/2} D_c(\theta, \phi, \nu) \sin\theta d\theta} \right) \times \left(\frac{\int_0^{2\pi} \int_0^{\pi/2} T_{GSM}(\theta, \phi, \nu, t) D_c(\theta, \phi, \nu_r) \sin\theta d\theta d\phi}{\int_0^{2\pi} \int_0^{\pi/2} D_c(\theta, \phi, \nu_r) \sin\theta d\theta} \right)^{-1}$$

Measurement Efficiency (1- Losses)

$$T_A(\nu) = \eta(\nu) T_S(\nu) + [1 - \eta(\nu)]\, T_{phys}$$

$$T_S = \frac{T_A - [1 - \eta_{rad}\eta_{beam}\eta_{balun}]\, T_{phys}}{\eta_{rad}\eta_{beam}\eta_{balun}}$$

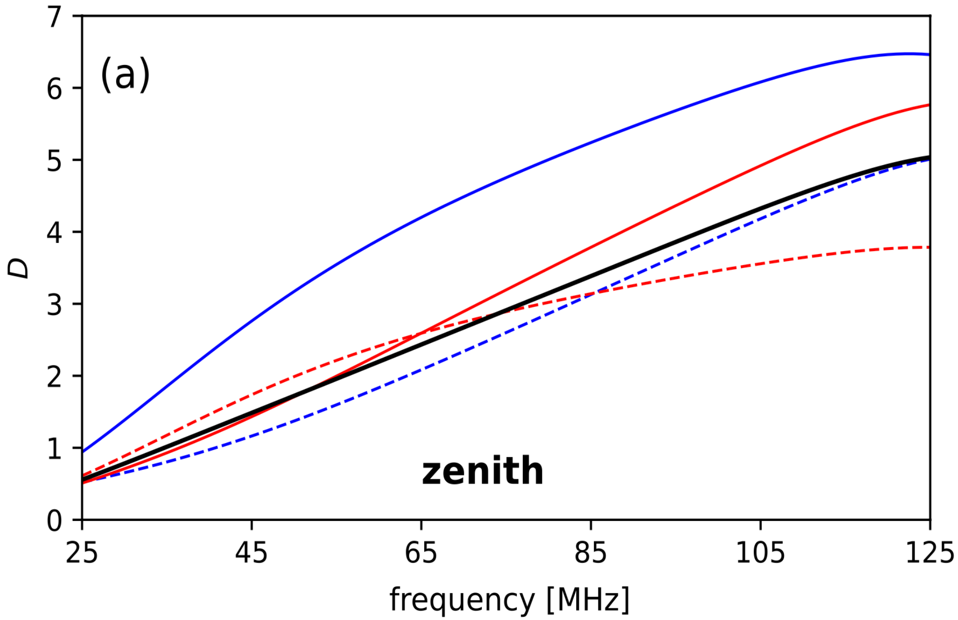
Radiation Efficiency

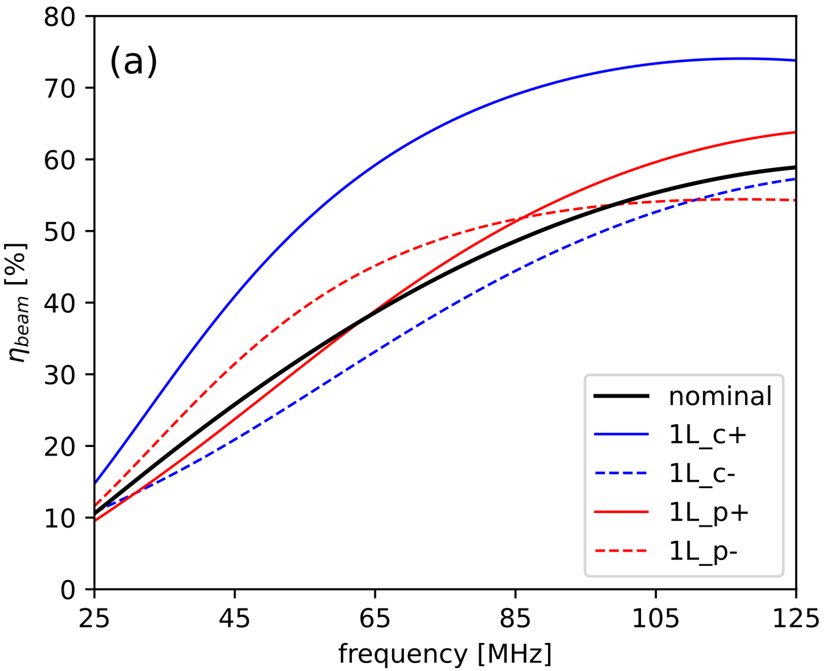
$$G(\theta, \phi, \nu) = \eta_{rad}(\nu) D(\theta, \phi, \nu)$$

Beam Efficiency

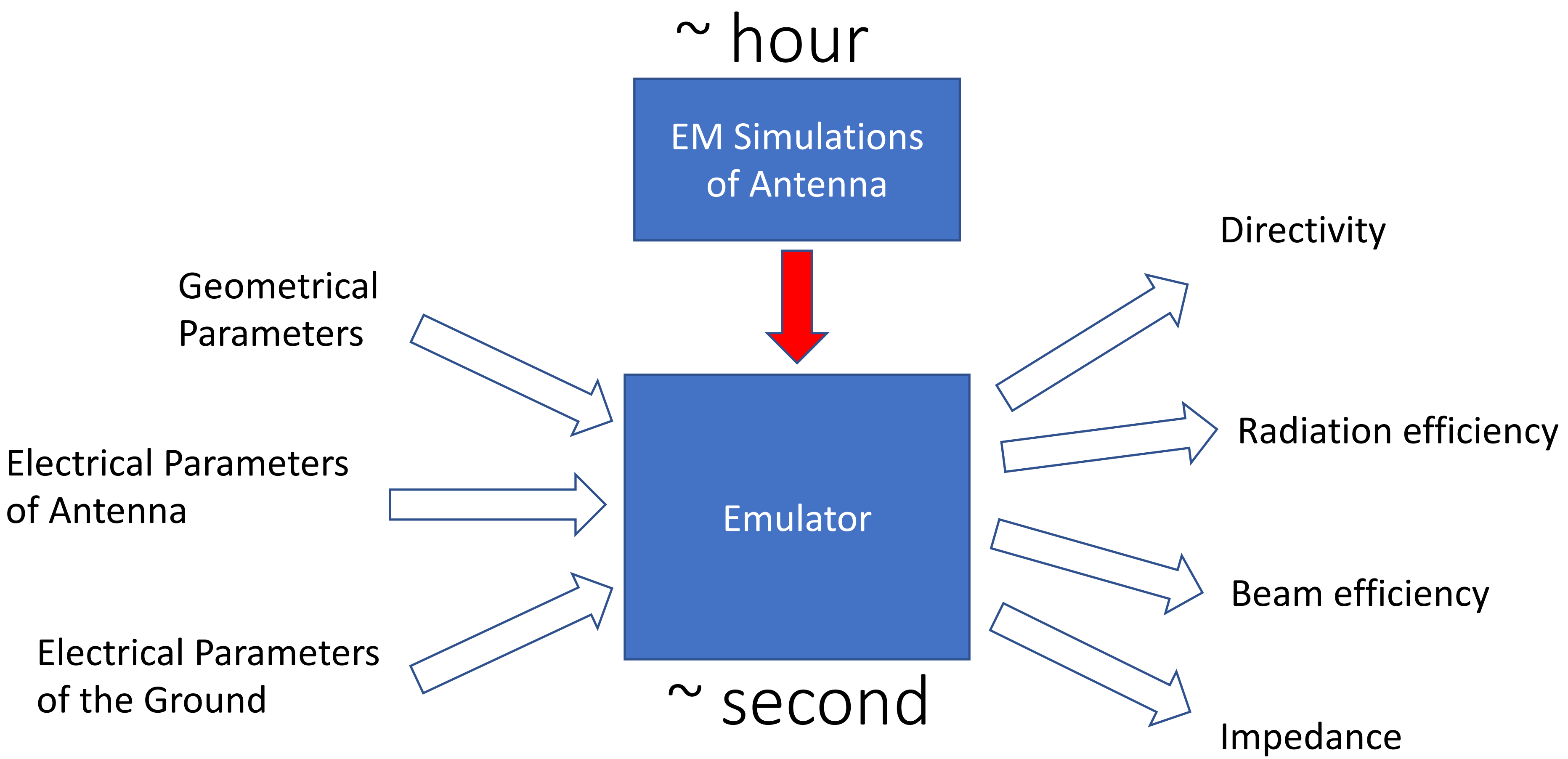
$$\eta_{beam}(\nu) = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi/2} D(\theta, \phi, \nu) \sin\theta d\theta d\phi$$

Sensitivity of the Ground





Urgently Needed: Accurate Emulator of Antenna Performance



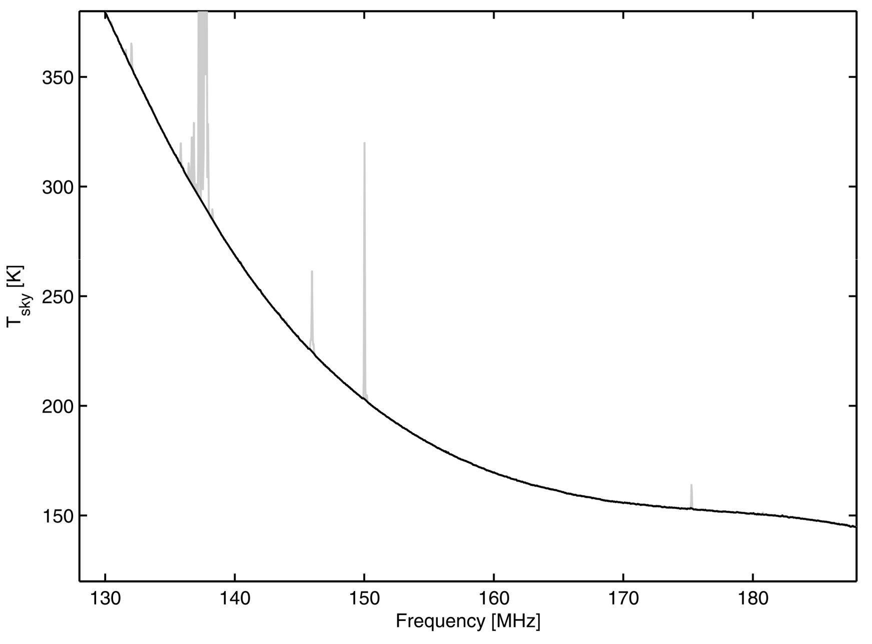
Next:

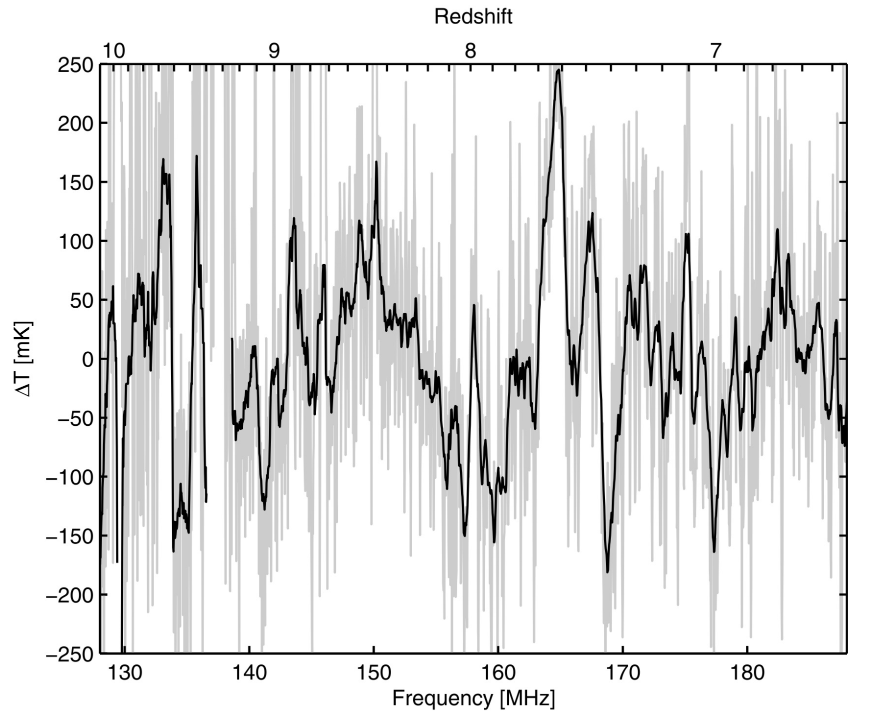
Data Calibrated Differently

Models Constraints Differently

Results Reported Differently

Bowman, Rogers, Hewitt (2008) -EDGES



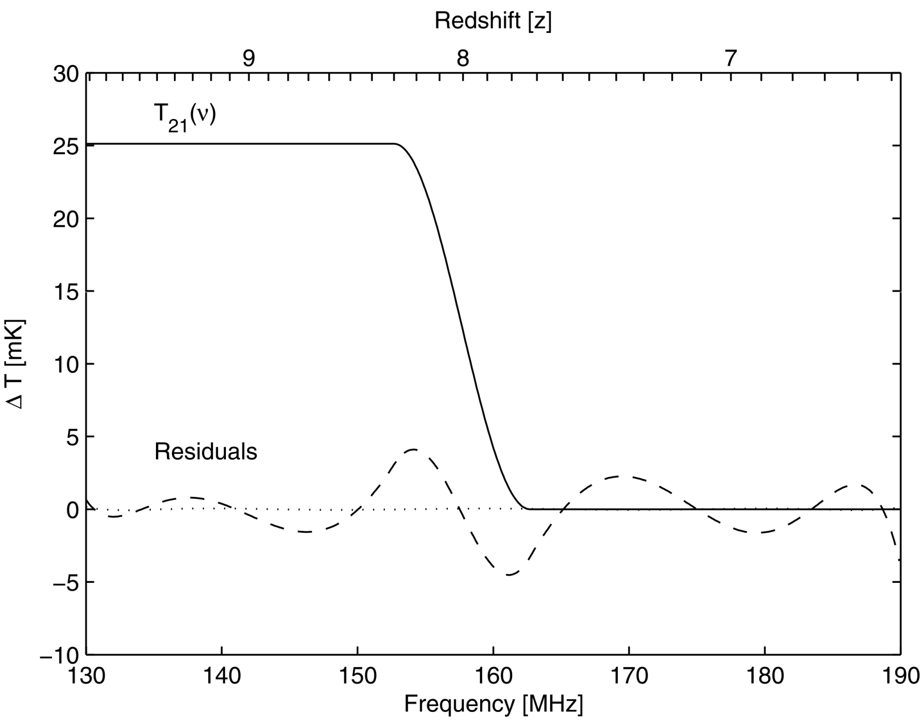


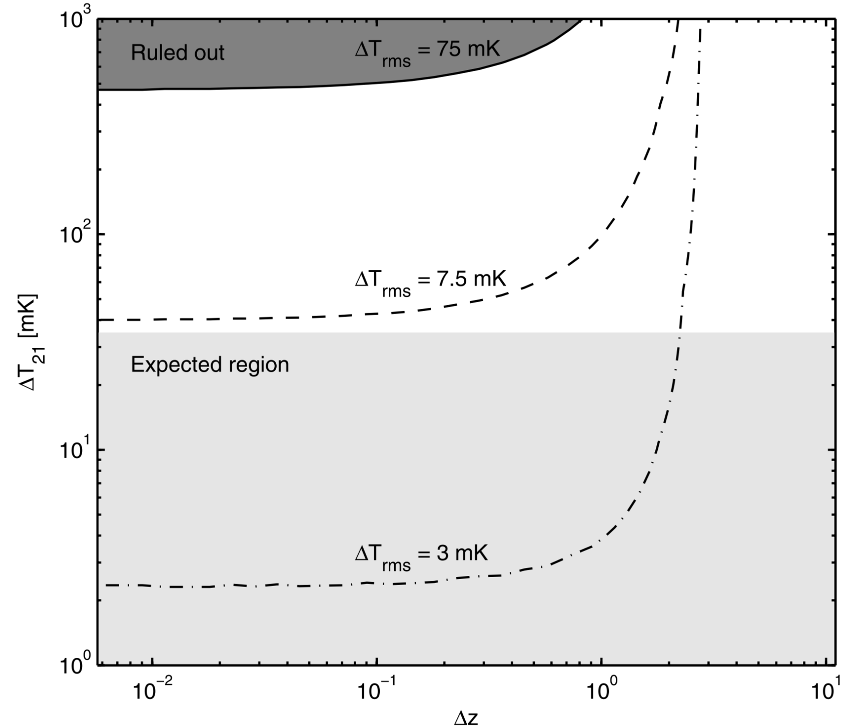
- ~4 hours of observations
- 3-position switching
- 130 – 190 MHz

- 8-term polynomial
- 75 mK residuals (after smoothing)

Bowman, Rogers, Hewitt (2008) -EDGES

$$T_{21}(z) = \Delta T_{21} \frac{1}{2} \left\{ 1 + \cos\left[\frac{\pi(z_r - z - \Delta z/2)}{\Delta z} \right] \right\}$$

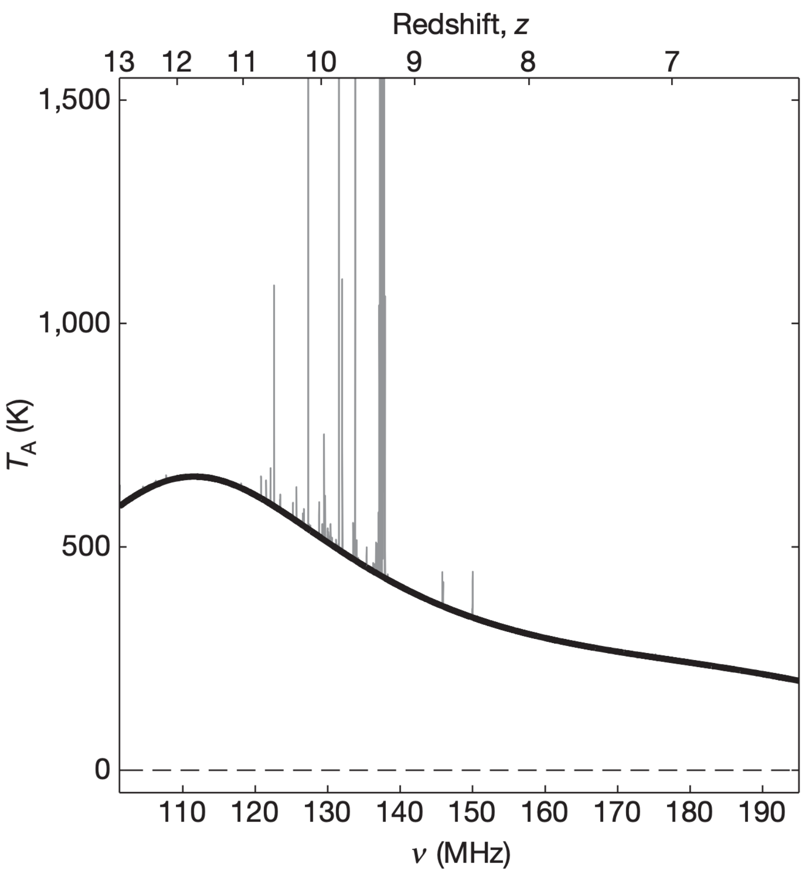




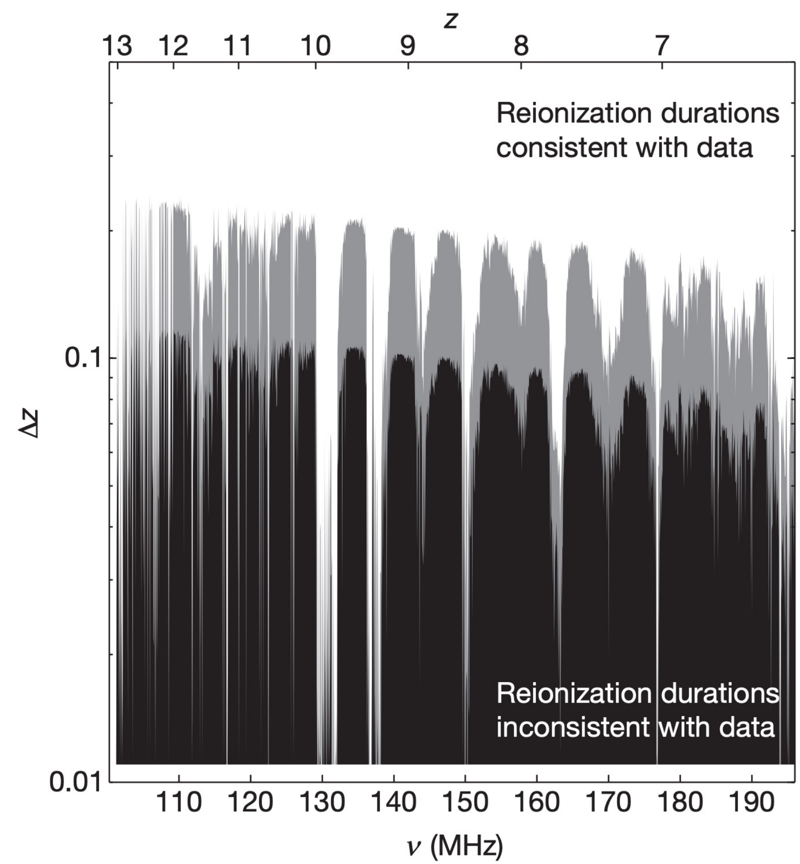
- Analytical EoR model centered at z=8
- Amplitude and duration varied

Bowman and Rogers (2010) -EDGES

$$\delta\bar{T}_{21}(z)\approx 27\left(\frac{1+z}{10}\right)^{1/2}\bar{x}_{H\,I}(z)\ \mathrm{mK} \qquad \tilde{x}_{\mathrm{H\,I}}(z)=\frac{1}{2}\left[\tanh\left(\frac{z-z_{\mathrm{r}}}{\Delta z}\right)+1\right]$$



- 3 months of observations
- Noise 6 mK at 150 MHz and 1 MHz

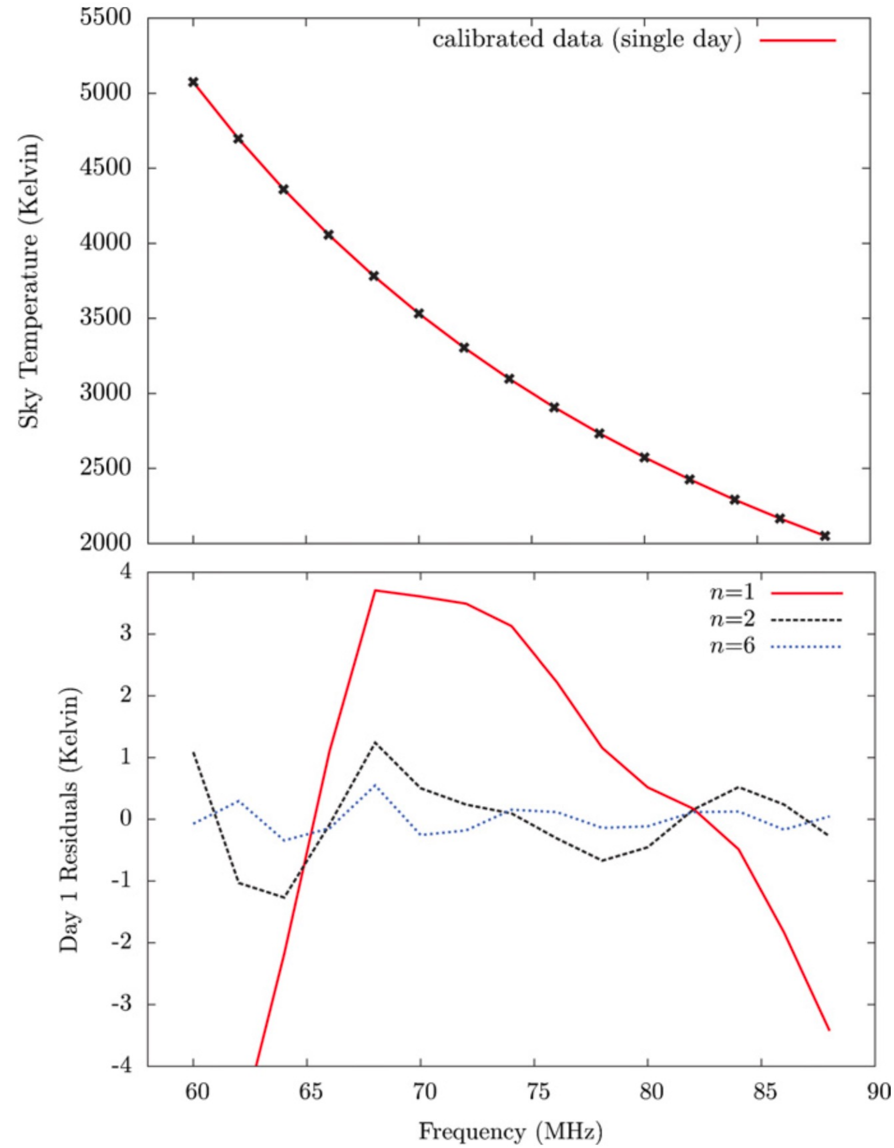


- Sweeping 20 MHz windows
- Fitting 5 or 6 term polynomials + 21 cm signal
- 21-cm transition centered at vr
- Amplitude fixed, free parameter only duration

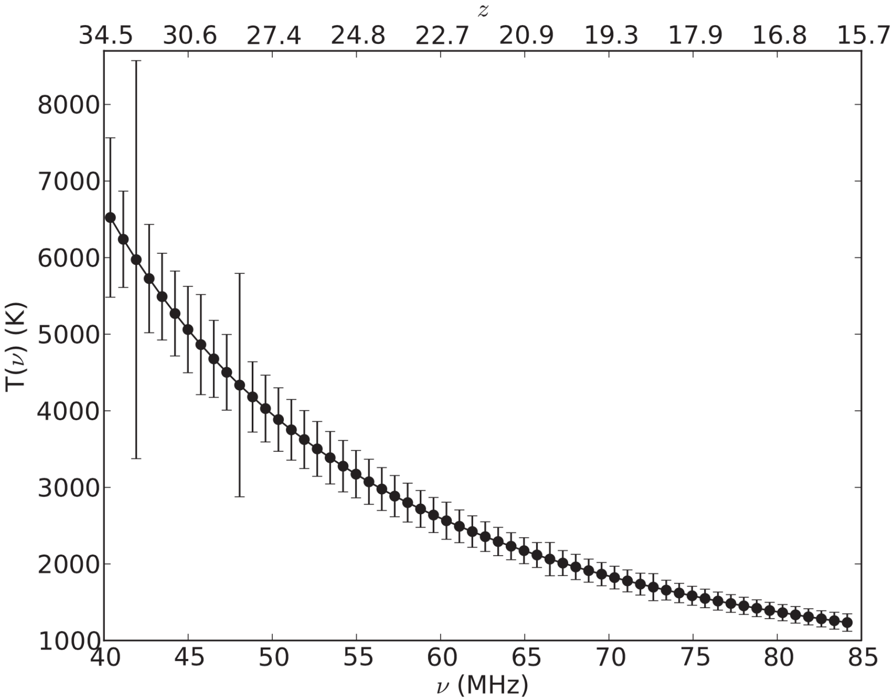
Voytek et al. (2014) -SCI-HI

- 60-87 MHz (Lowest frequencies to date)
- 50-minute integration per day
- 9 days of data
- 2-MHz resolution
- 3 calibration approaches (2 approaches using Global Sky Model)
- 3-term Log-Log foreground model

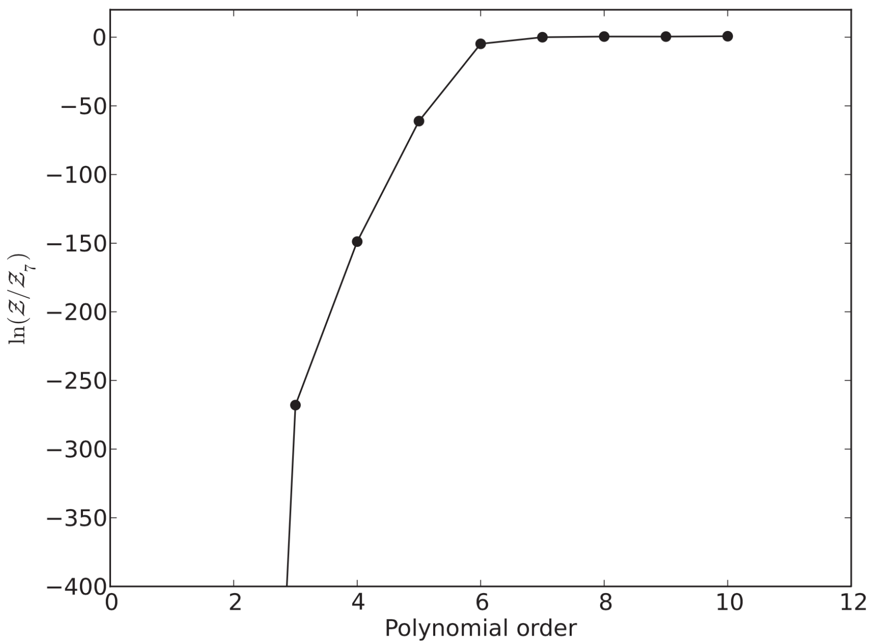
$$\log_{10} T_{\mathrm{GM}}(\nu) = \sum_{k=0}^{n} a_k \left[\log_{10}\left(\frac{\nu}{70\ \mathrm{MHz}}\right)\right]^k$$



Bernardi et al. (2016) -LEDA

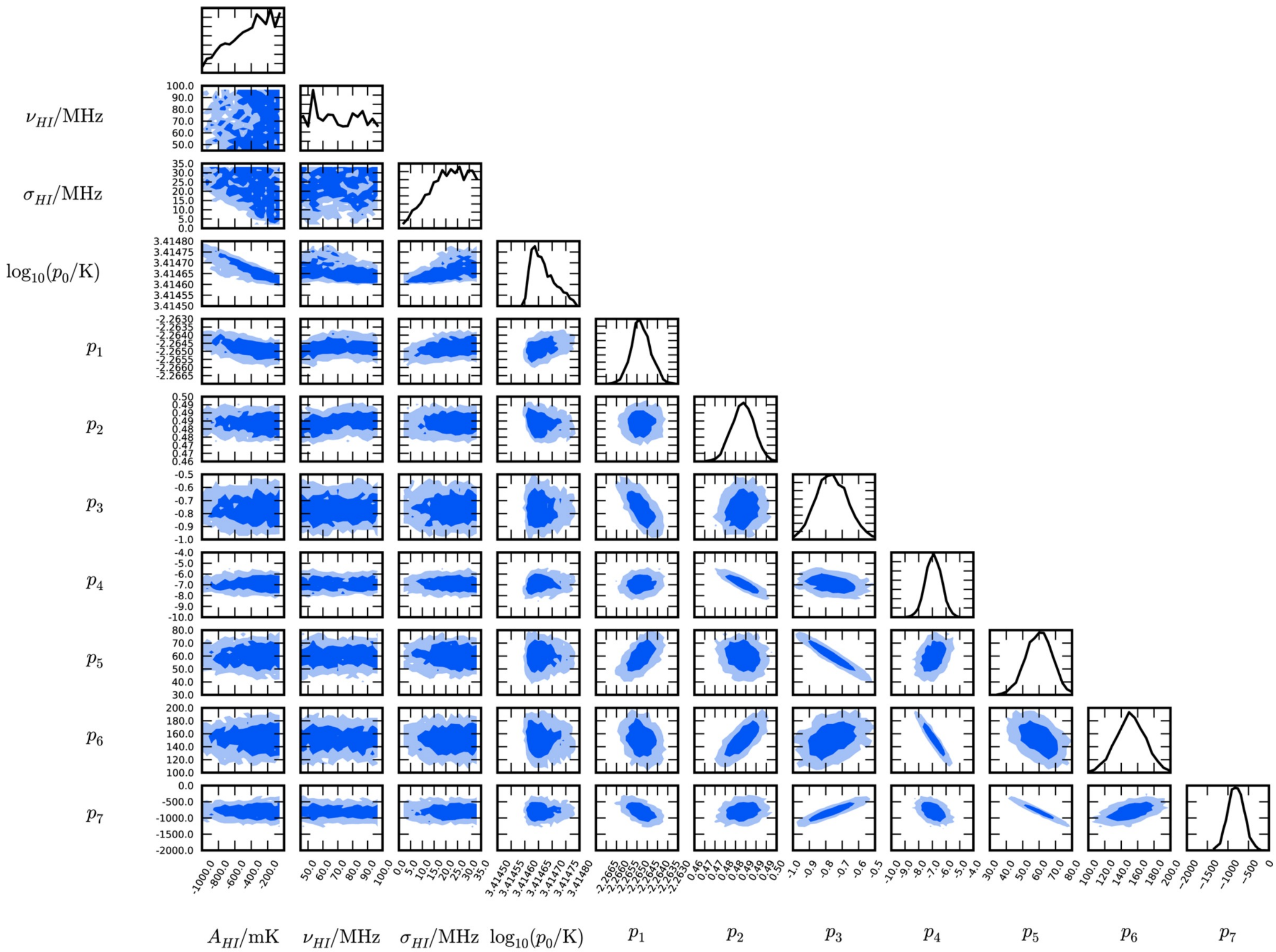


2-h of data (19-minute effective integration time)

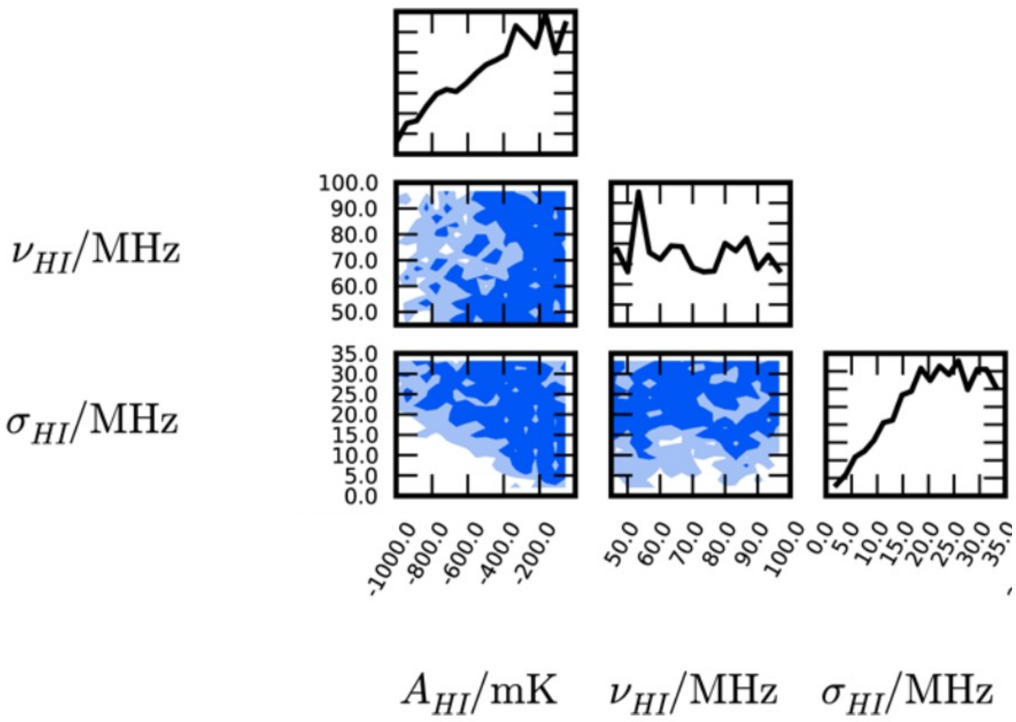


- 50-85 MHz
- Gaussian model for cosmic dawn feature
- 8-term log-log polynomial
- Bayesian analysis

Bernardi et al. (2016) -LEDA



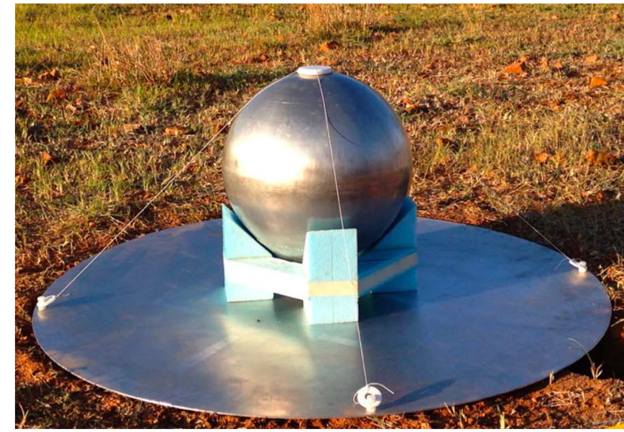
Bernardi et al. (2016) -LEDA

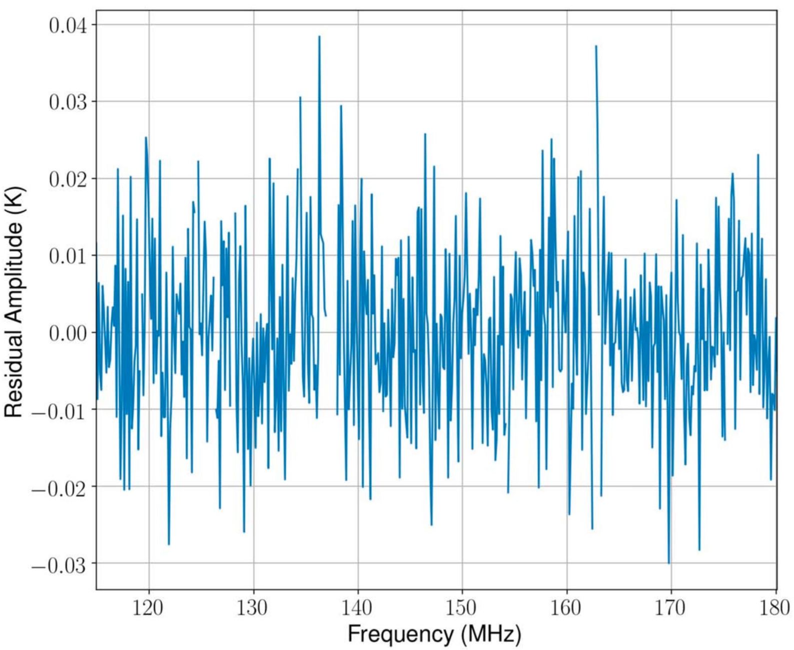


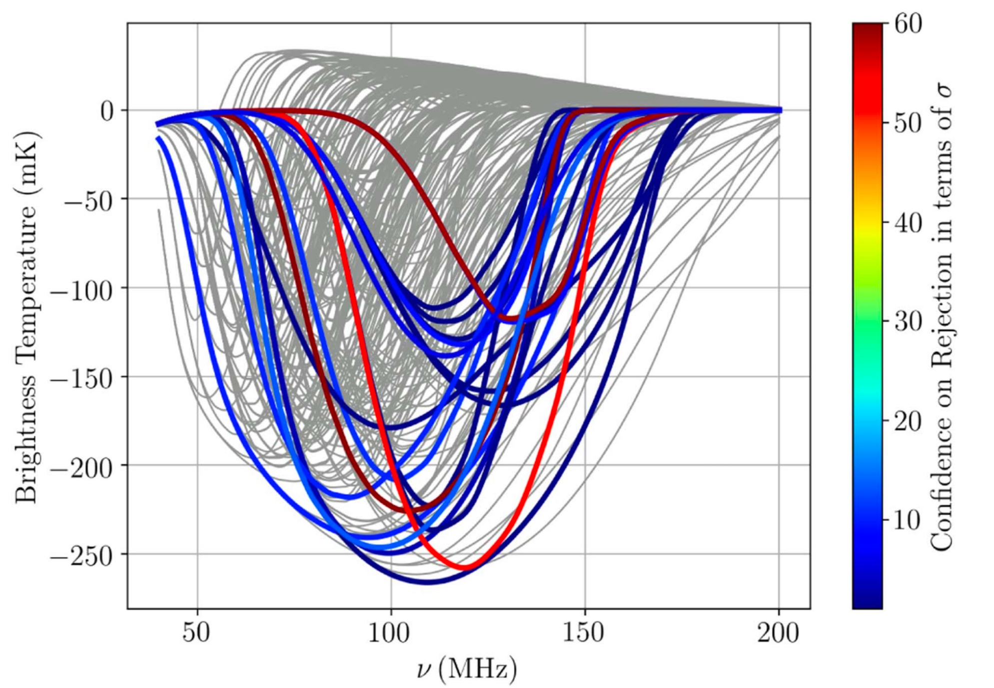
$-890 < A_{\mathrm{H\,I}} < 0$ mK and $\sigma_{\mathrm{H\,I}} > 6.5$ MHz at 95% confidence

Singh et al. (2017,2018) -SARAS 2

- Spherical monopole antenna
- Correlation spectrometer
- Estimating the total efficiency using GMOSS foreground model
- 63 h of data
- Removing polynomial within range 110-200 MHz
- Probing semi-numerical models from Cohen et al (2017)
- 2 methods: Likelihood ratio and fitting a scale

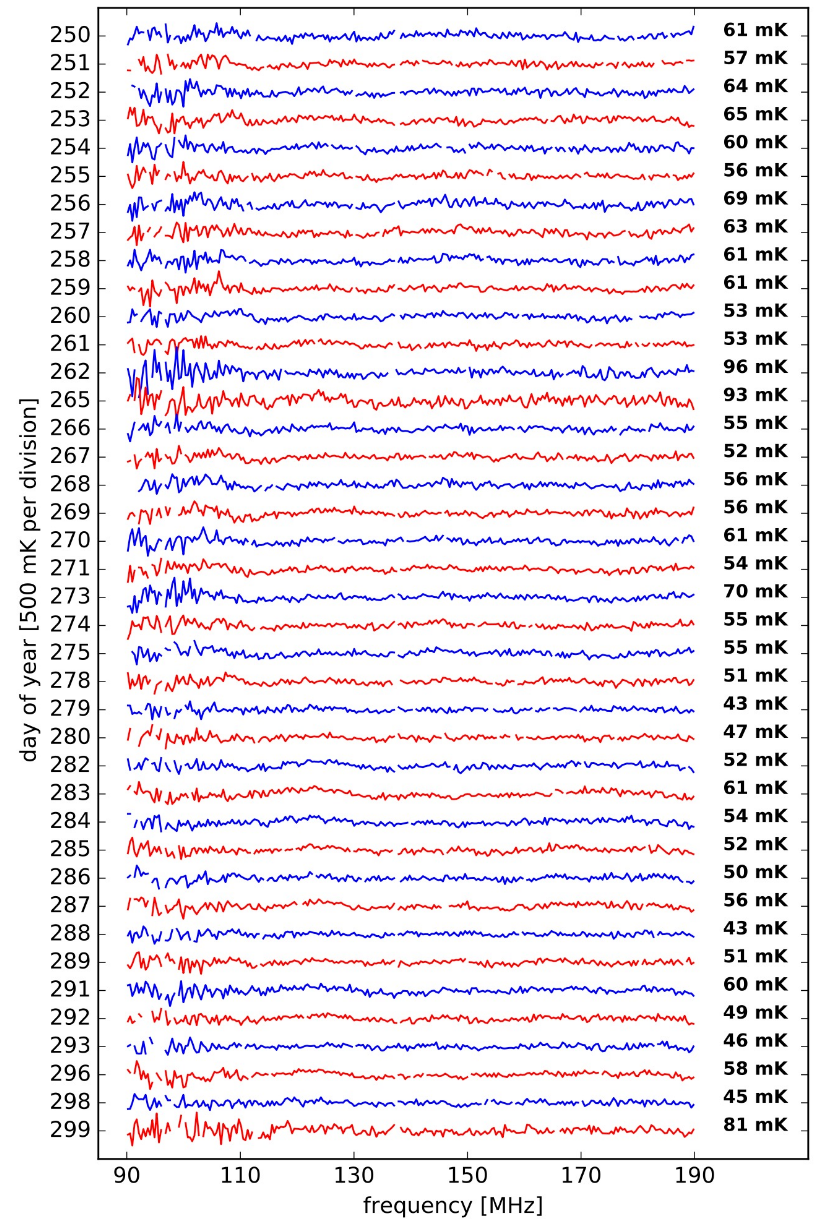






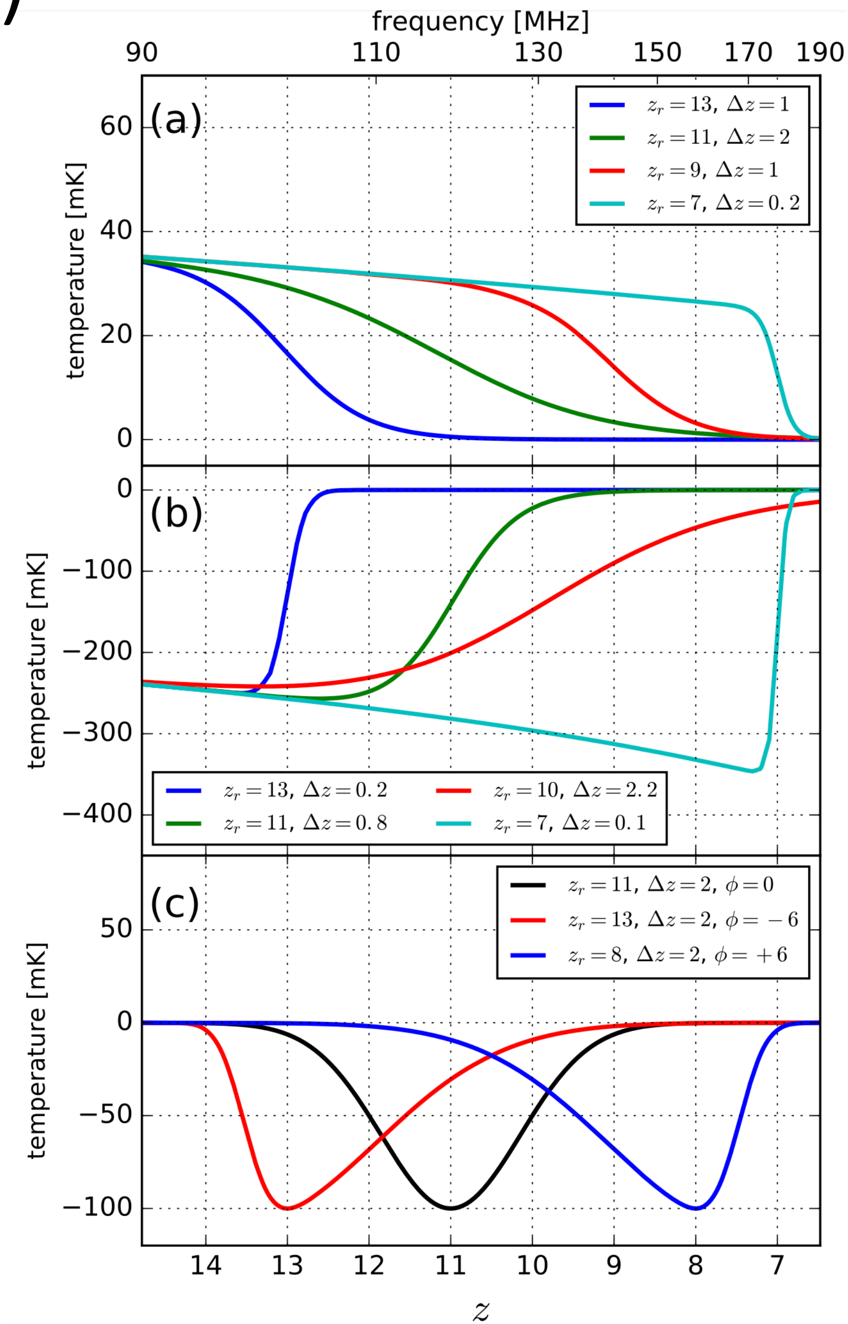
Monsalve et al. (2017,2018,2019) EDGES High-Band

$$\hat{T}_{\mathrm{fg}}(\nu) = \sum_{i=0}^{4} a_i \nu^{-2.5+i}$$

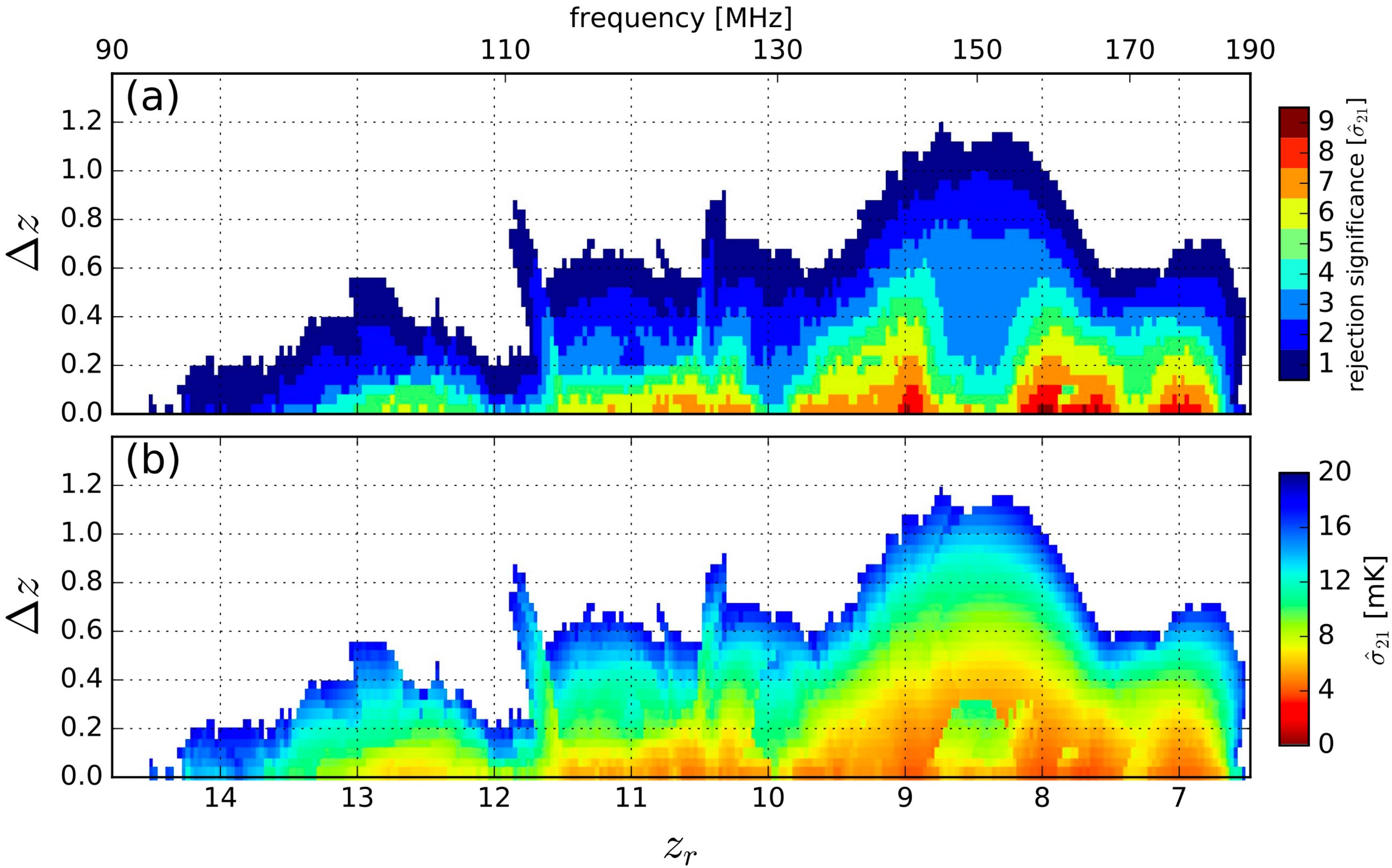


Monsalve et al. (2017)
EDGES High-Band

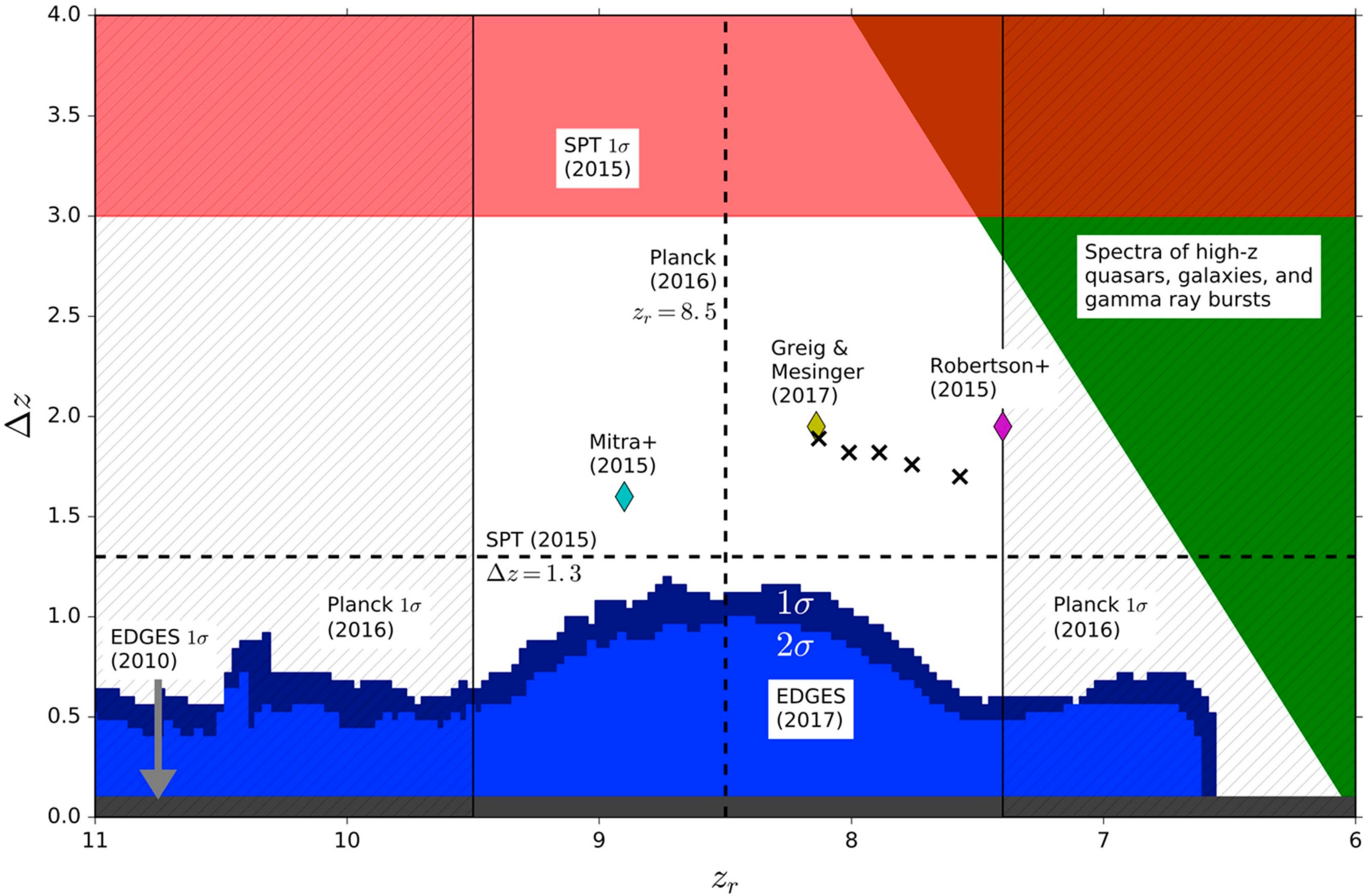
- Phenomenological signals
- Hot EoR, Tanh evolution of neutral fraction
- Cold EoR, Tanh evolution, strong Ly-alpha, NO IGM heating, only EoR. Provided by Jordan Mirocha
- Gaussian absorption models, with and without asymmetry



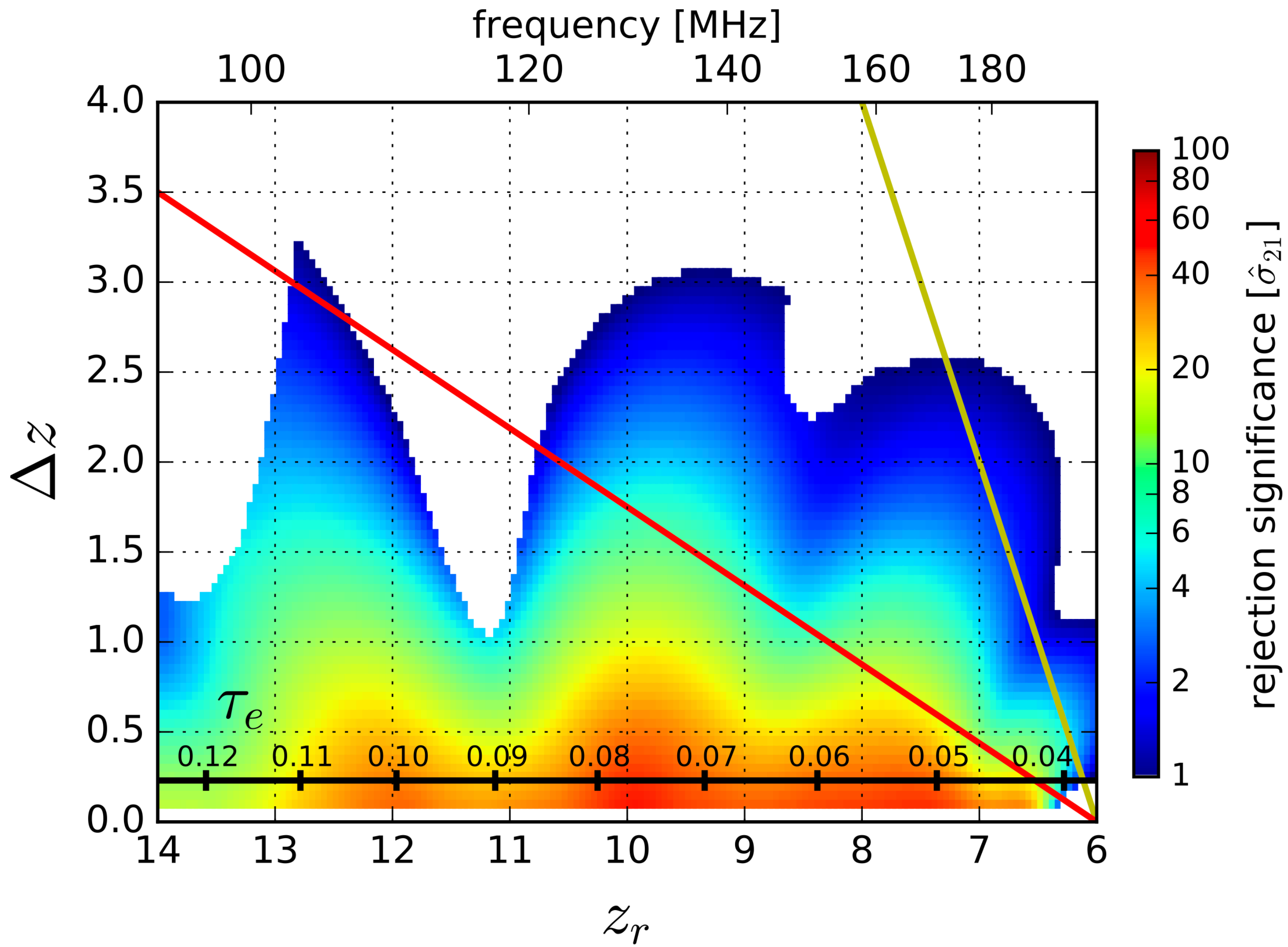
Monsalve et al. (2017)
EDGES High-Band



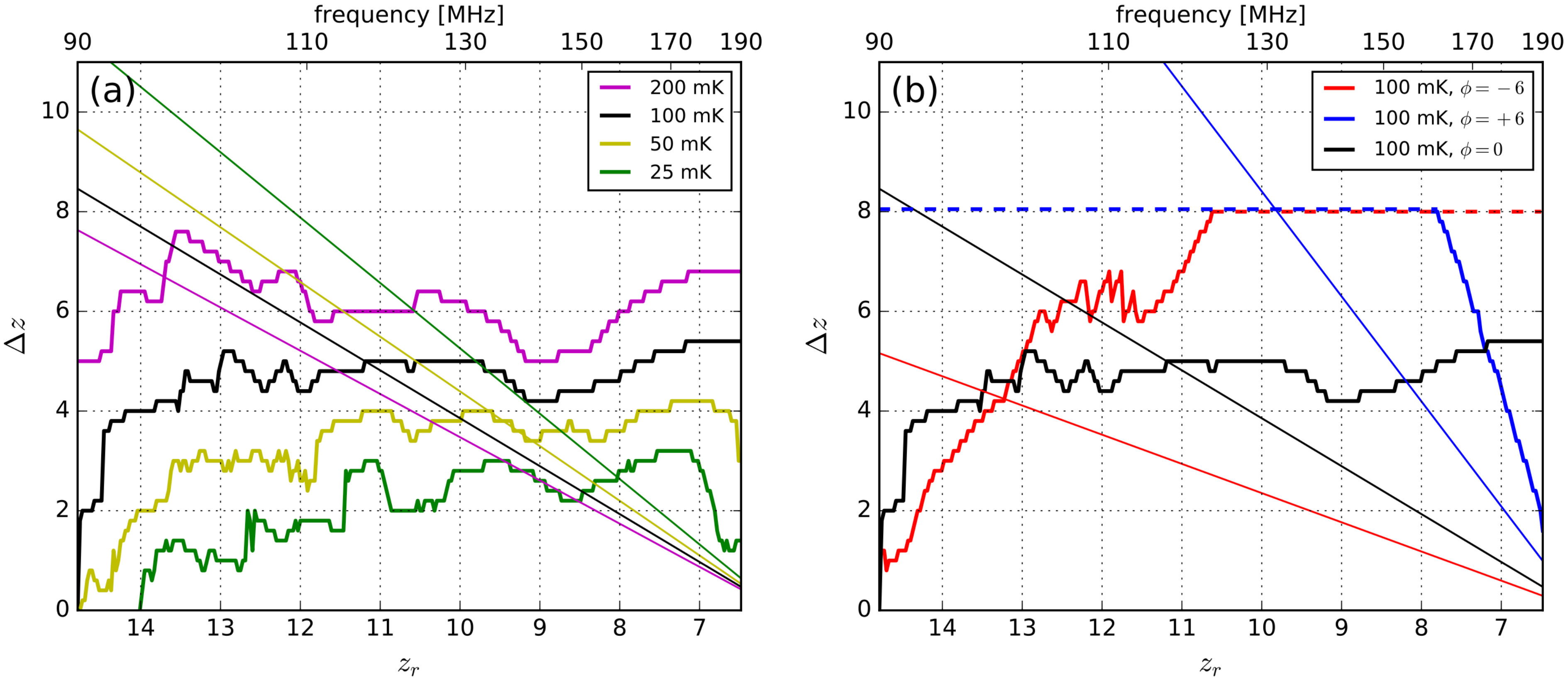
Monsalve et al. (2017)
EDGES High-Band



Monsalve et al. (2017)
EDGES High-Band

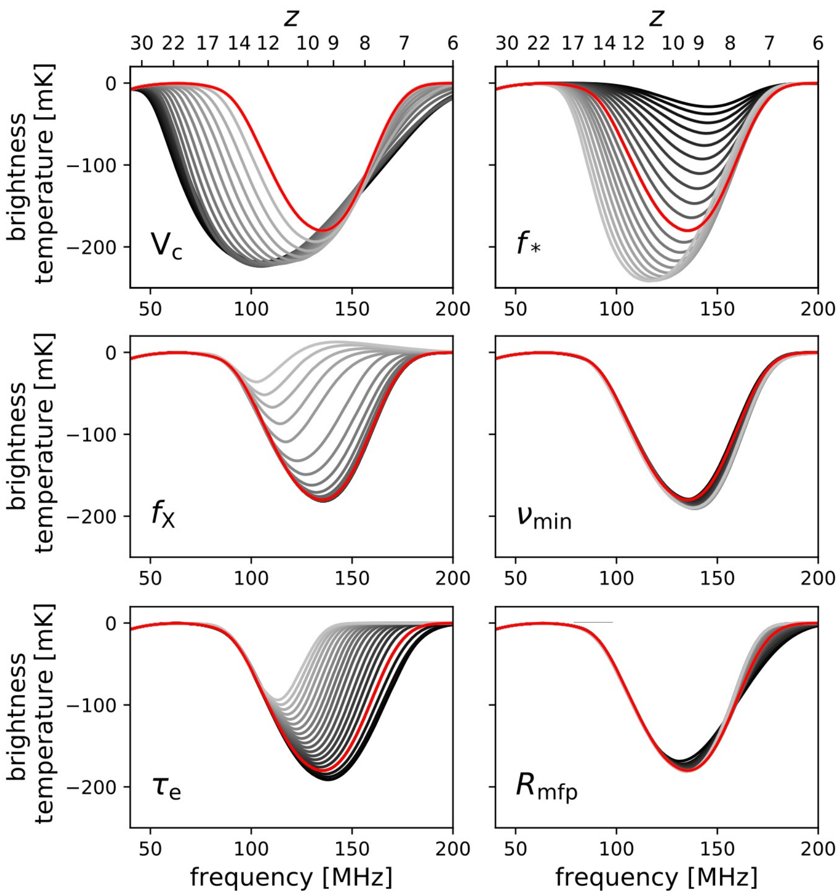


Monsalve et al. (2017)
EDGES High-Band



Monsalve, Fialkov, et al. (2019) EDGES High-Band

21cmGEM



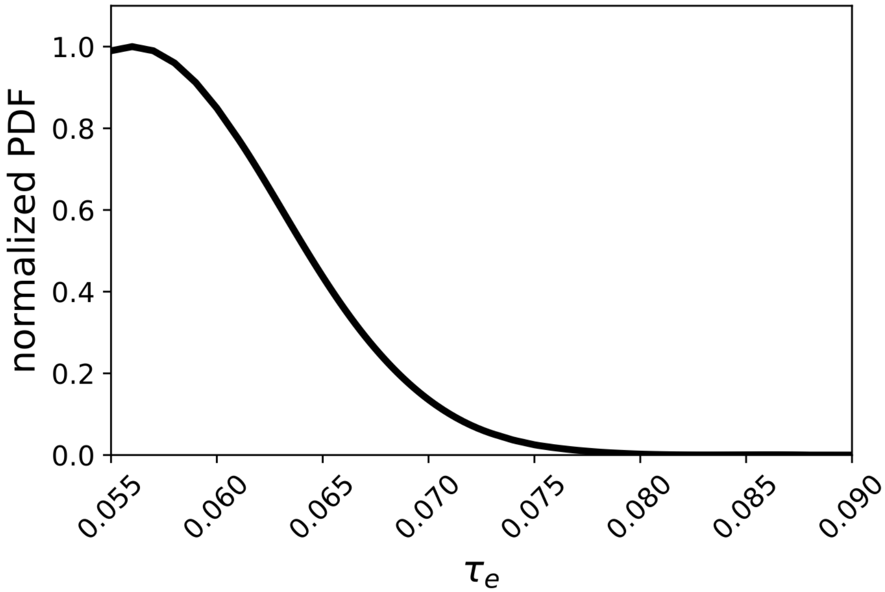
$$\hat{T}_{\rm fg}(\nu) = \sum_{i=0}^{4} a_i \nu^{-2.5+i}$$

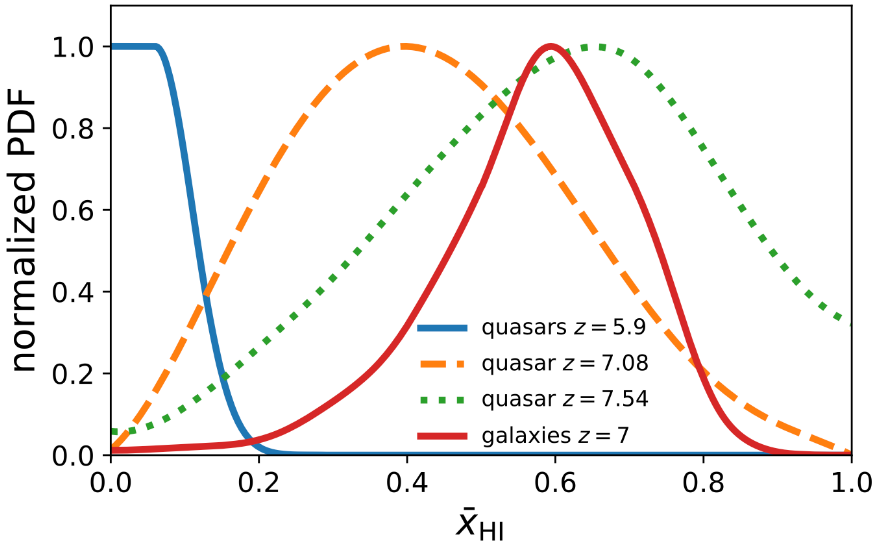
Parameter Ranges and Sampling Scale

Parameter	Min	Max	Unit	Scale
V_c	4.2	76.5	km s^{-1}	$\log_{10}$
f_*	10^{-3}	0.5	⋯	$\log_{10}$
f_X	10^{-5}	10	⋯	$\log_{10}$
ν_{min}	0.1	3	keV	linear
τ_e	0.055	0.09	⋯	linear
R_{mfp}	10	50	Mpc	linear

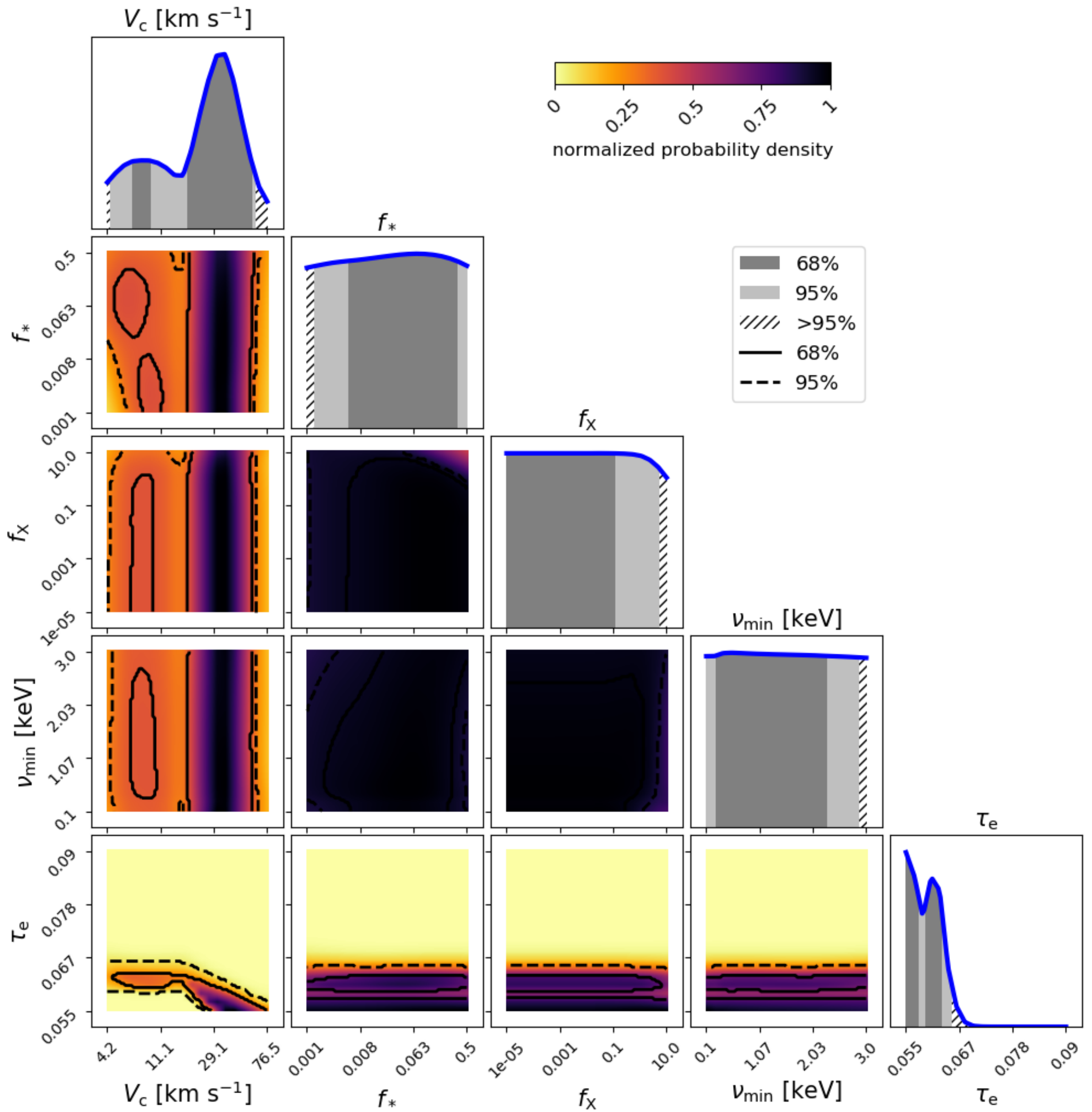
Monsalve, Fialkov, et al. (2019)
EDGES High-Band

External Priors

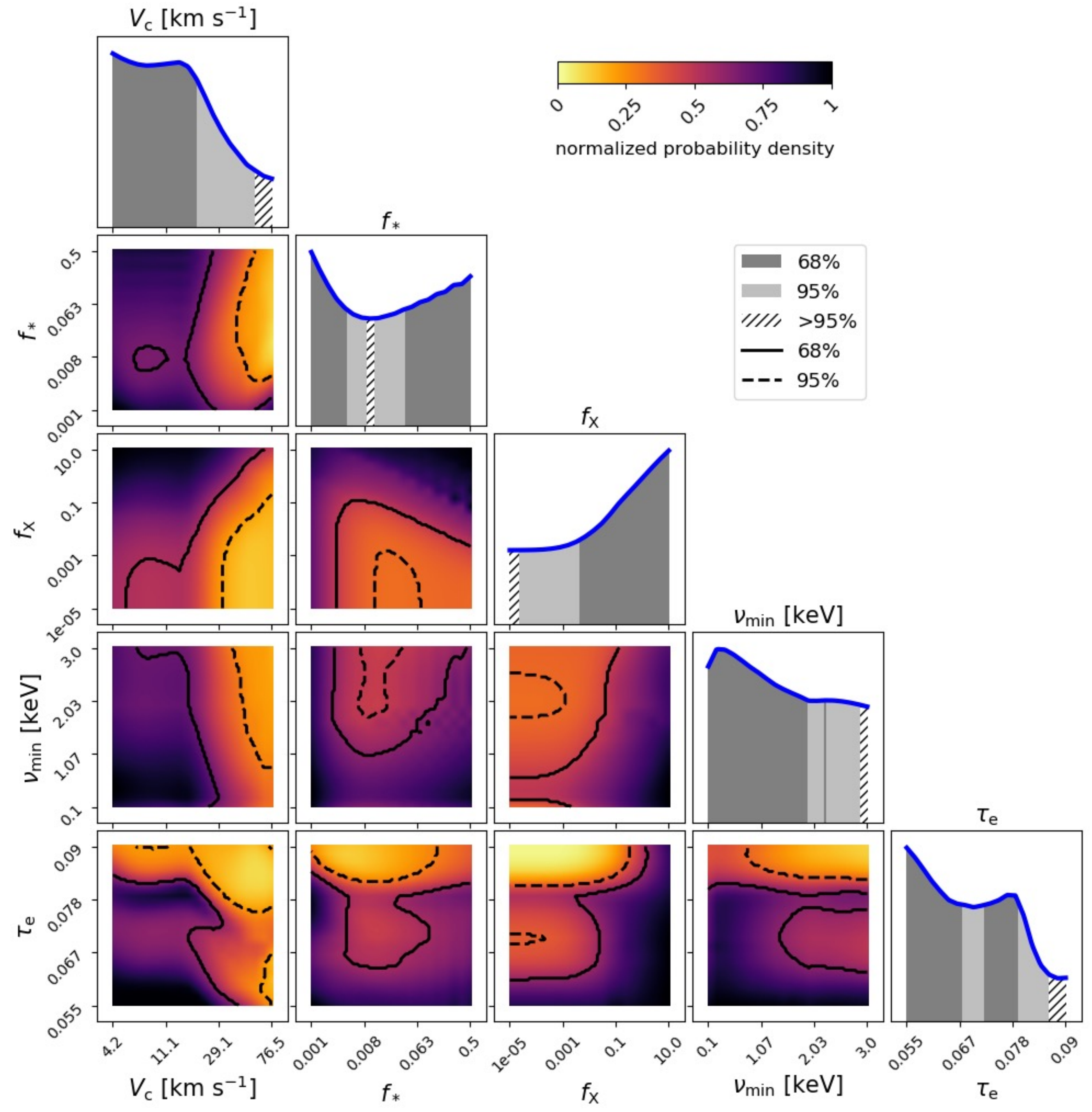




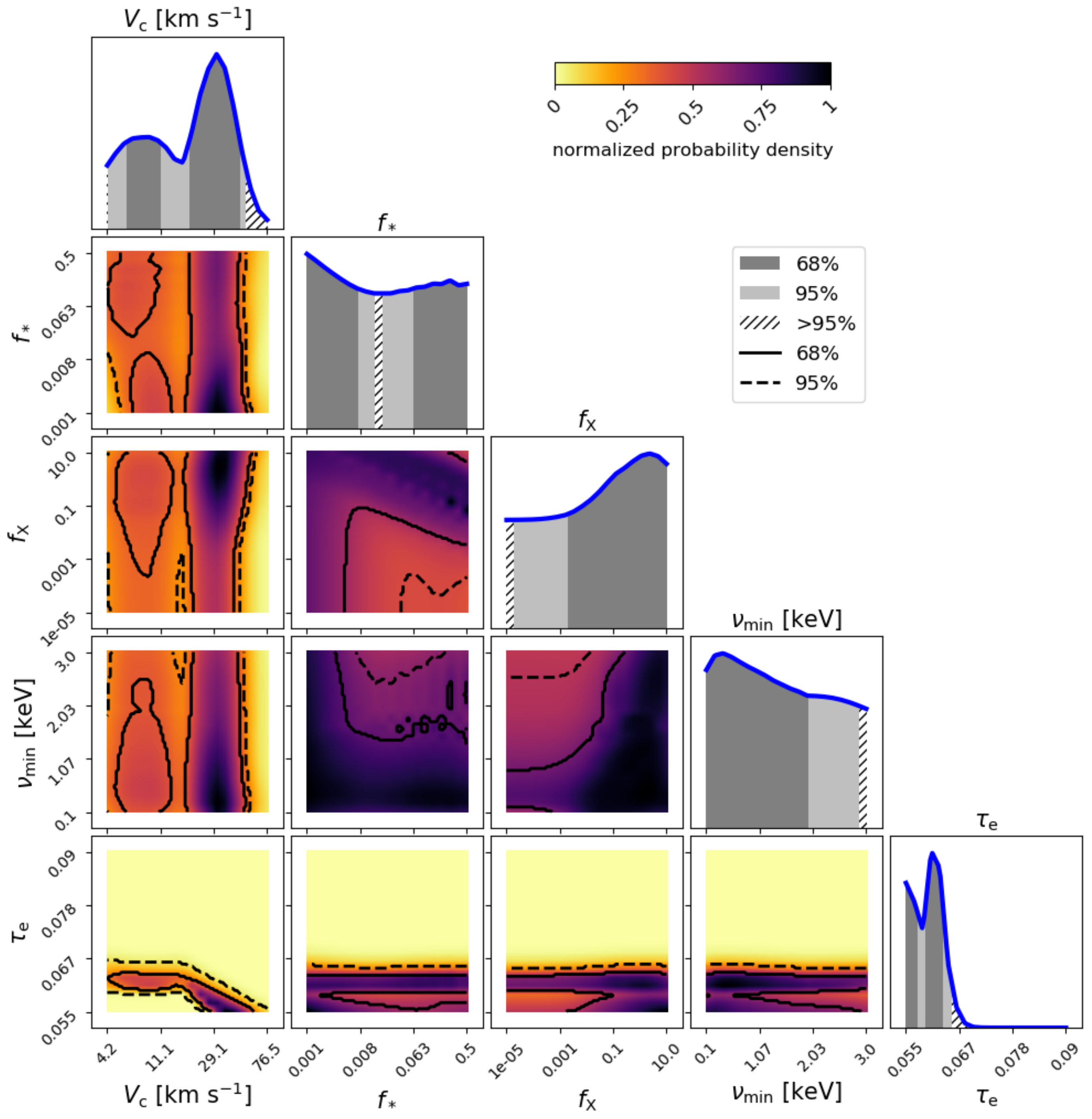
Constraints from External Priors



Constraints from EDGES High-Band



Constraints from External Priors + EDGES High-Band



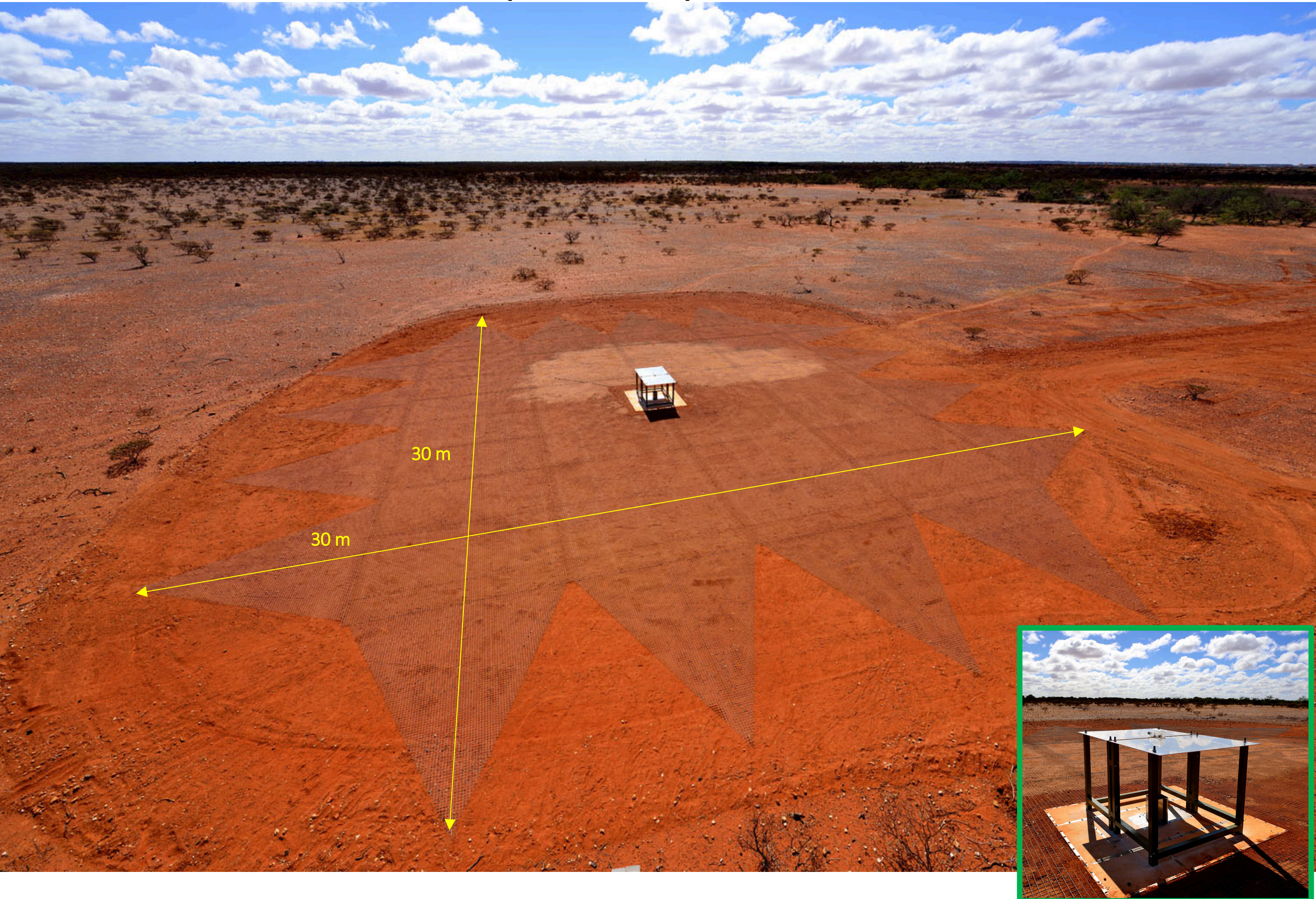
Monsalve, Greig, et al. (2018)

Likelihood of 21-cm models computed after marginalizing over linear foreground parameters

$$\mathcal{L}(d|\boldsymbol{\theta}_{21}) = \int \mathcal{L}(d|\boldsymbol{\theta}_{21},\, \boldsymbol{\delta}_{\rm fg})\, d\boldsymbol{\delta}_{\rm fg}$$

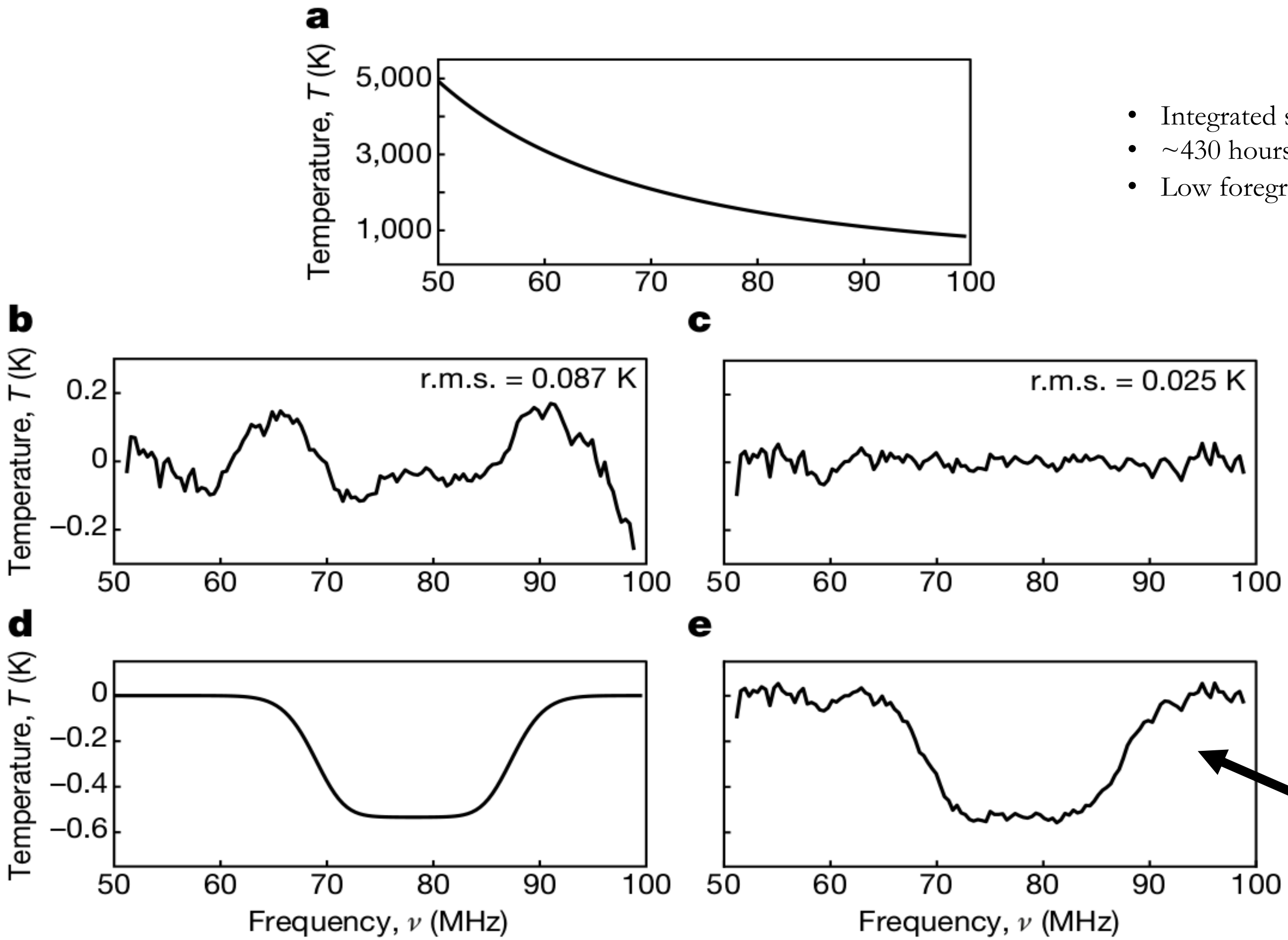
$$= \sqrt{\frac{(2\pi)^{N_{\rm fg}-N_\nu}}{|\Sigma||C^{-1}|}}\, \exp\left\{-\frac{1}{2} d_\star^T (\Sigma + V)^{-1} d_\star\right\}$$

Bowman et al. (2018)



Bowman et al. (2018)

Nominal

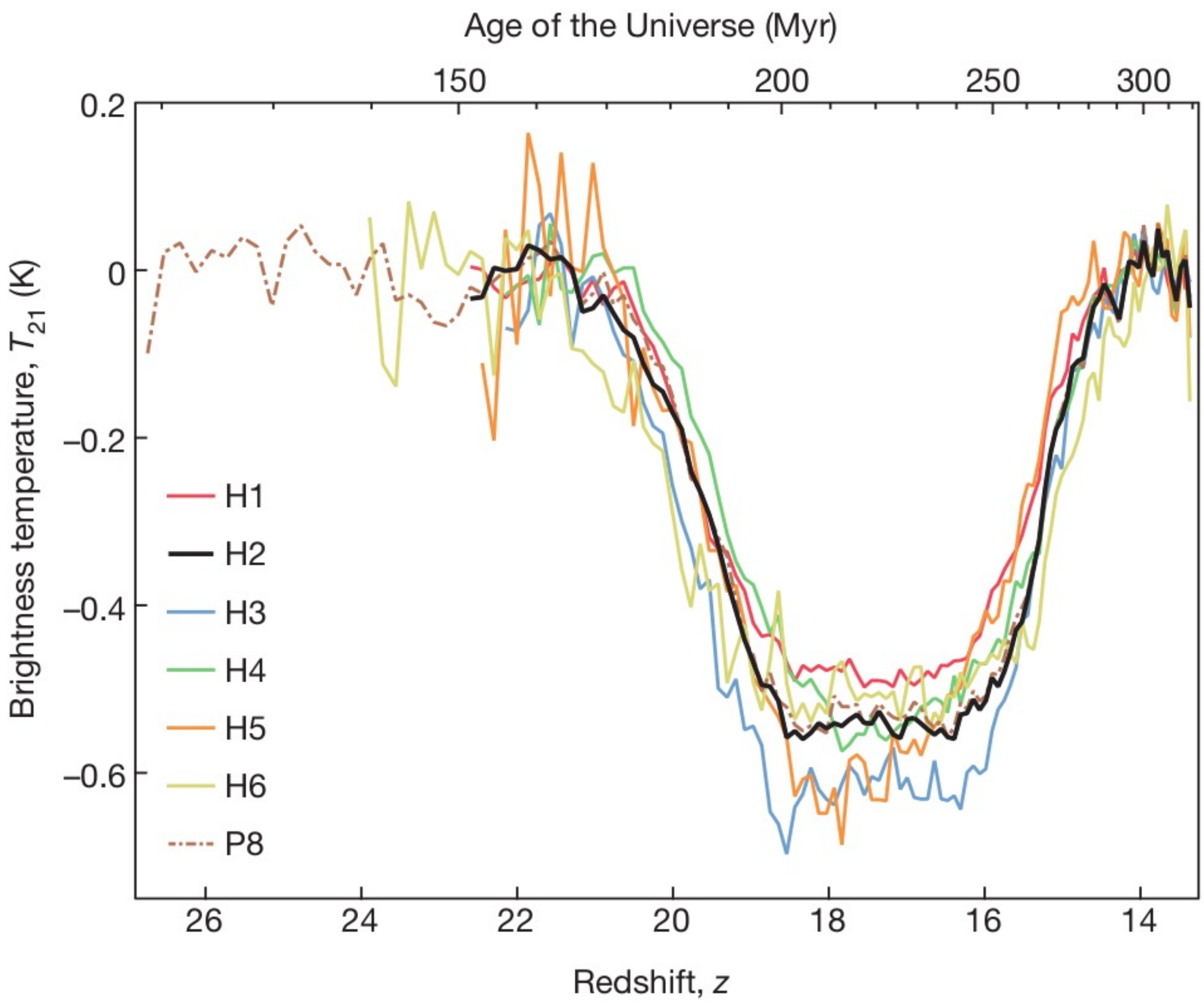


- Integrated spectrum
- ~430 hours
- Low foreground regions

Absorption deeper than expected by factor > 2

Bowman et al. (2018)

Two Instruments / Several Configurations



Bowman et al. (2018)

How to Explain Deep Absorption?

$$T_b(z) \propto \left(1 - \frac{T_{CMB} + \boldsymbol{T_{EXCESS}}}{\boldsymbol{T_S}}\right)$$

Suggested sources:

- Radio emission from **early black holes** (Ewall-Wice et al. 2018)
- Decay of **unstable particles** (Pospelov et al. 2018) (Aristizabal Sierra & Sheng Fong 2018)

T_S: **Lower than expected**

↓

$\boldsymbol{T_K}$ **Lower than expected**

Suggested source:

- Interactions between **Baryons and Dark Matter** particles (Muñoz & Loeb 2018)

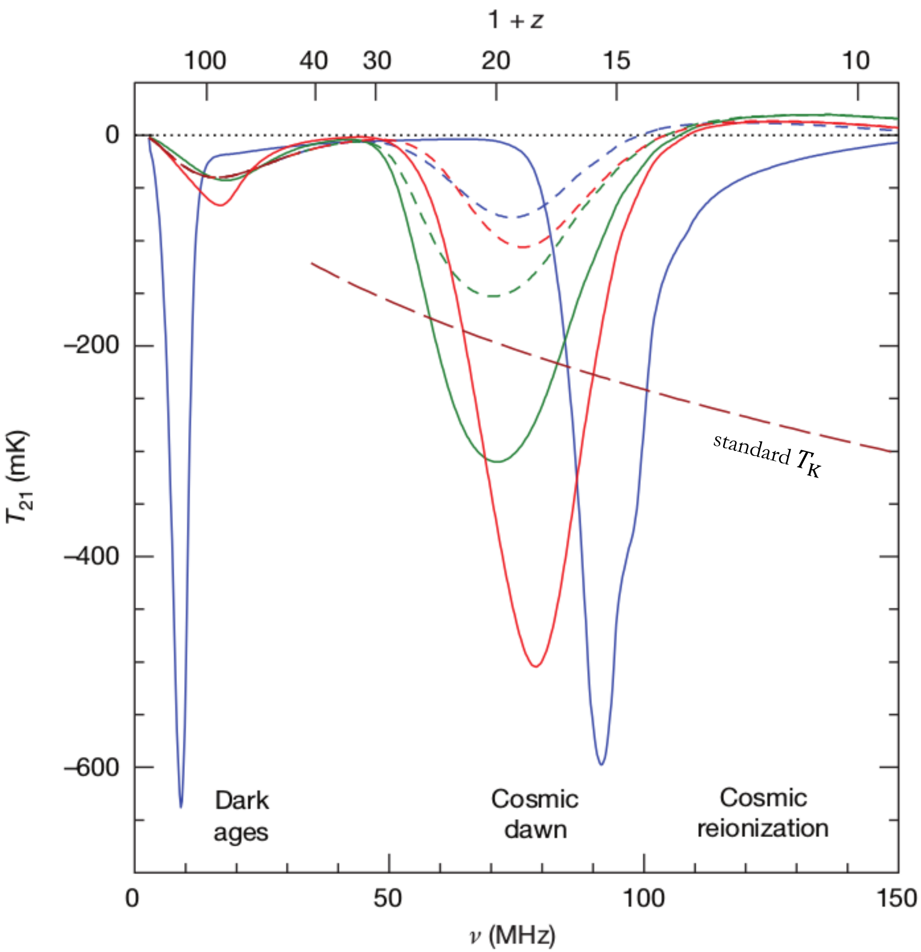
Bowman et al. (2018)

Interaction of Baryons with Dark Matter?

Enough IGM cooling can be achieved if (Muñoz & Loeb 2018):

- **~ 1%** of DM particles
- have mass **~ 1-60 MeV**
- and posses electric mini-charge, **$\sim 10^{-6}$ the charge of an electron**

Possibility of non-gravitational interaction between baryons and dark matter.



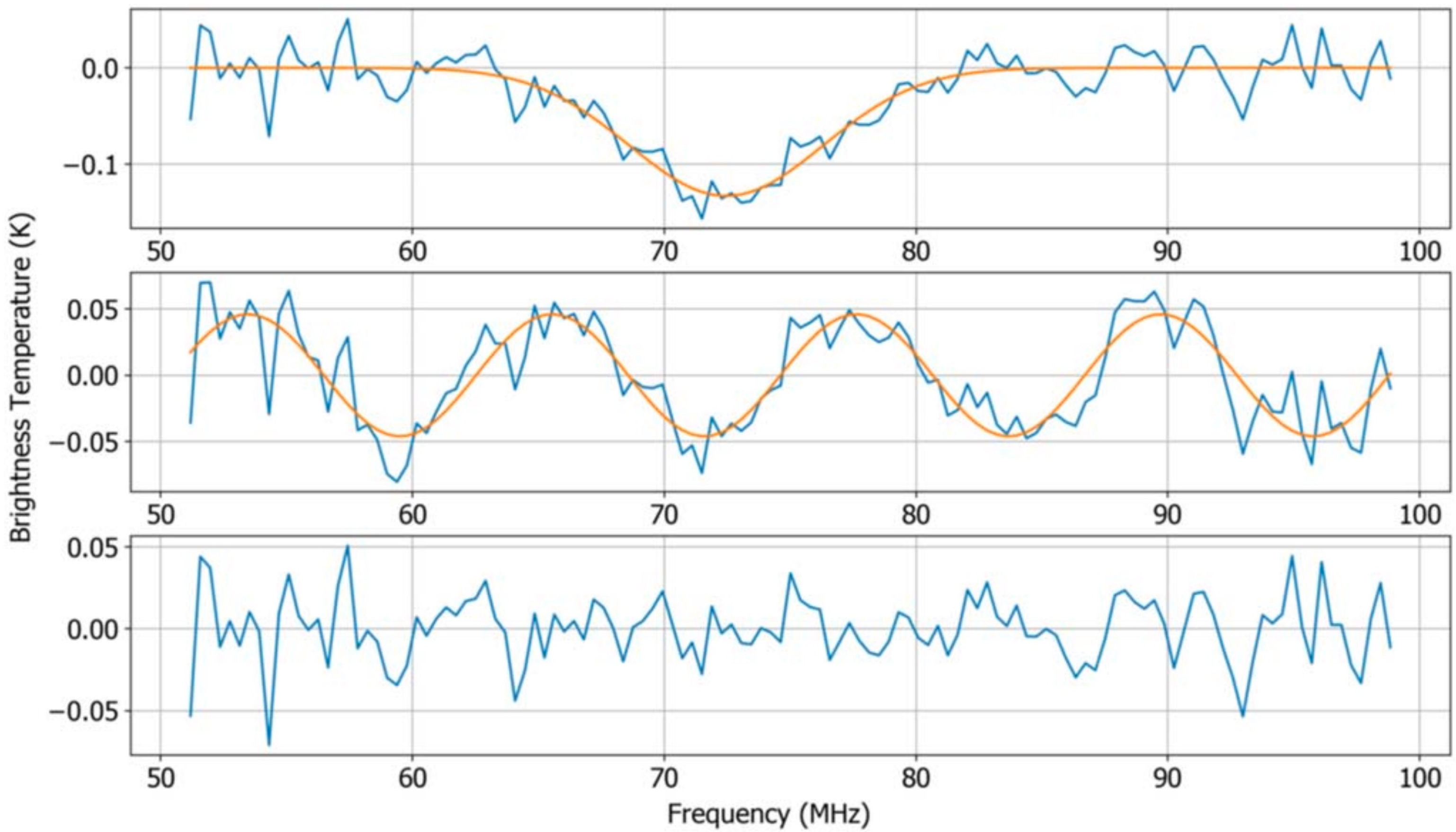
R. Barkana 2018, **Nature**, 555, 71

The Redshifted 21 cm Signal in the EDGES Low-band Spectrum

Saurabh Singh[1,2,3] and Ravi Subrahmanyan[3]

(2019)

- MS + Sinusoid + Gaussian
- Best-fit Gaussian has “standard” amplitude
- Lower residuals RMS
- Lower BIC

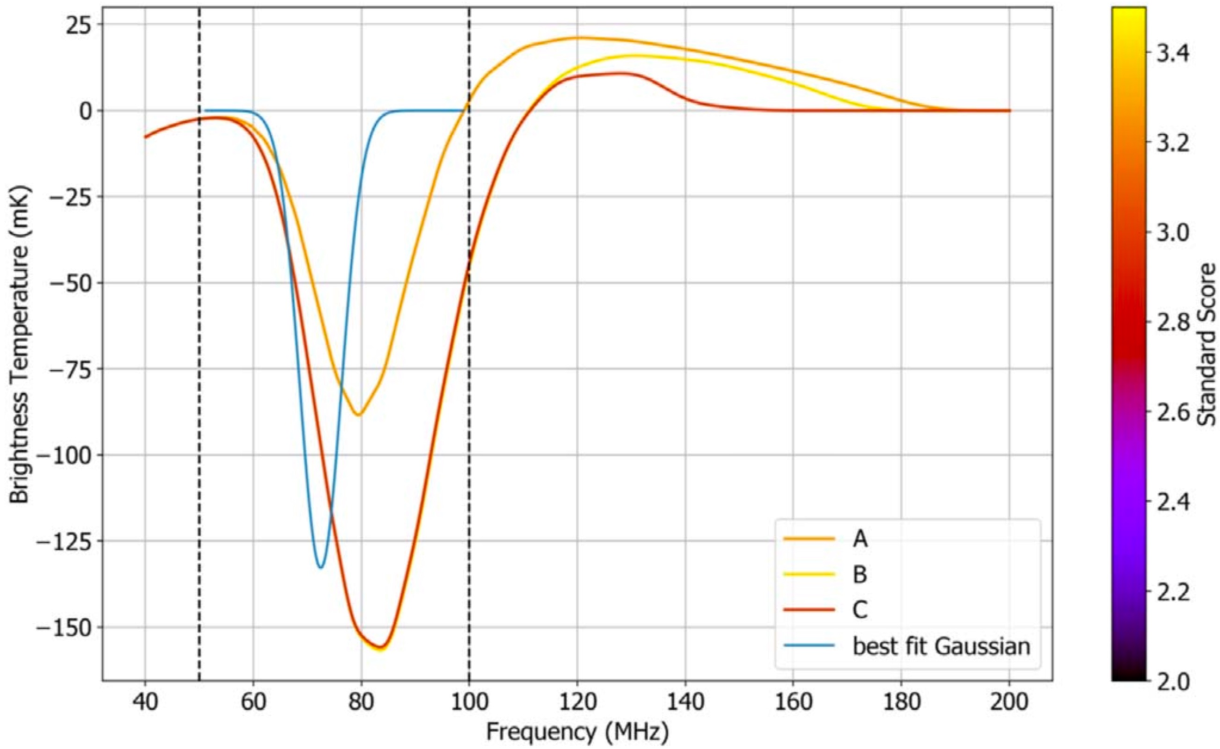


The Redshifted 21 cm Signal in the EDGES Low-band Spectrum

Saurabh Singh[1,2,3] and Ravi Subrahmanyan[3]

(2019)

- MS + Sinusoid + (scale x template)
- Template from Cohen et al. (2017)



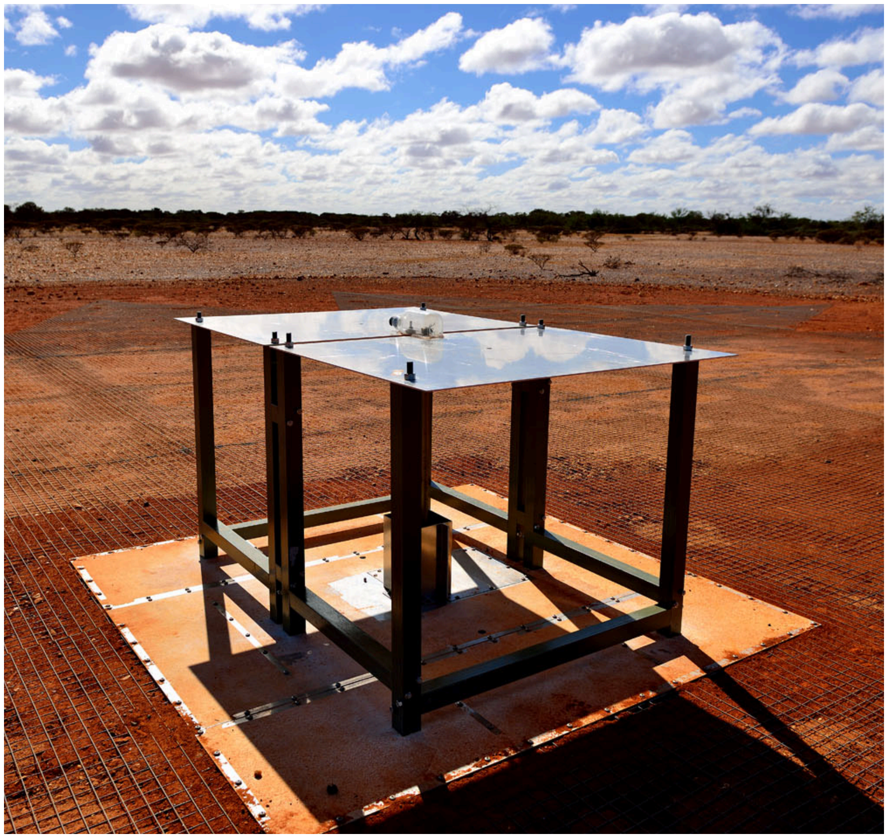
Parameters of the 21 cm Signals Favored by the Data

Case	f_*	V_c (km s^{-1})	f_X	τ	R_{mfp} (Mpc)
A	0.05	35.50	14.7	0.061	70
B	0.158	35.50	1.58	0.066	70
C	0.158	35.50	1.58	0.082	70

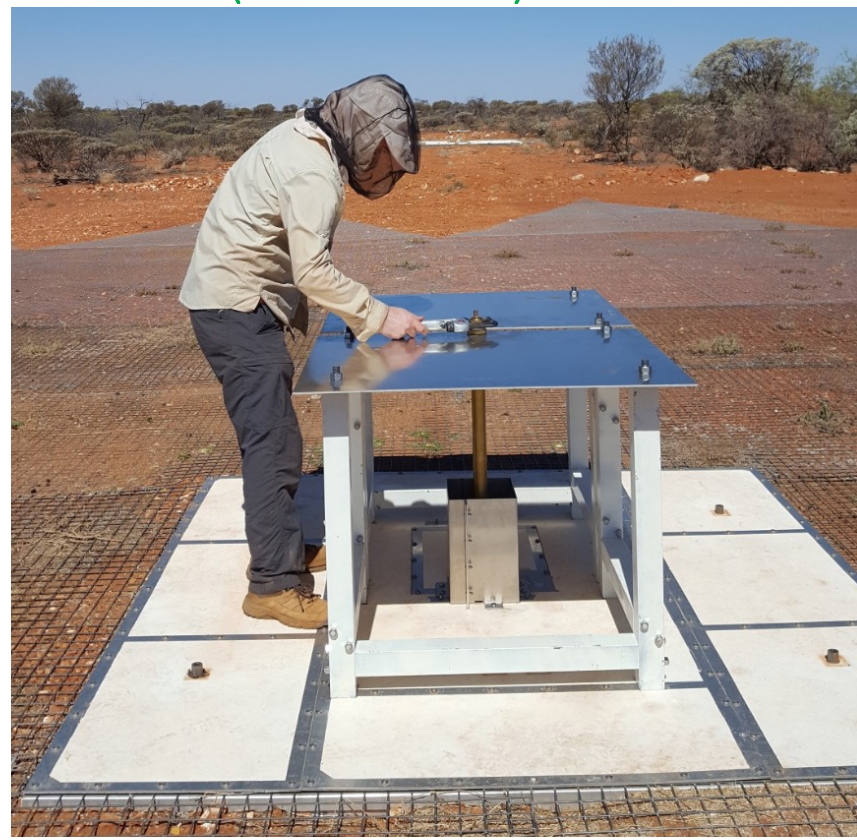
EDGES-2 in 2018-2020

Verification with EDGES-2 Mid-Band

Low-Band



Mid-Band (~25% smaller)



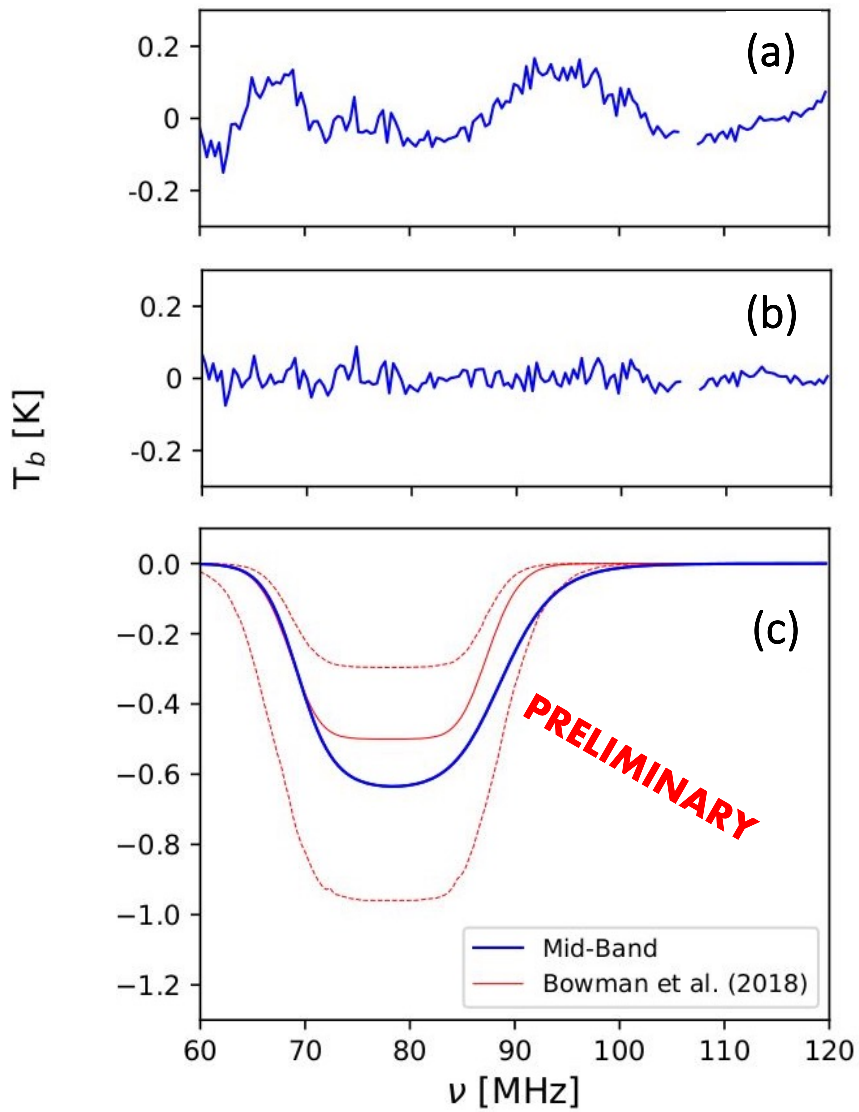
Same Ground Plane as Low-Band

Objective:

Shift some of the spectral structures from the instrument to higher frequencies

EDGES-2 in 2018-2020

Verification with EDGES-2 Mid-Band



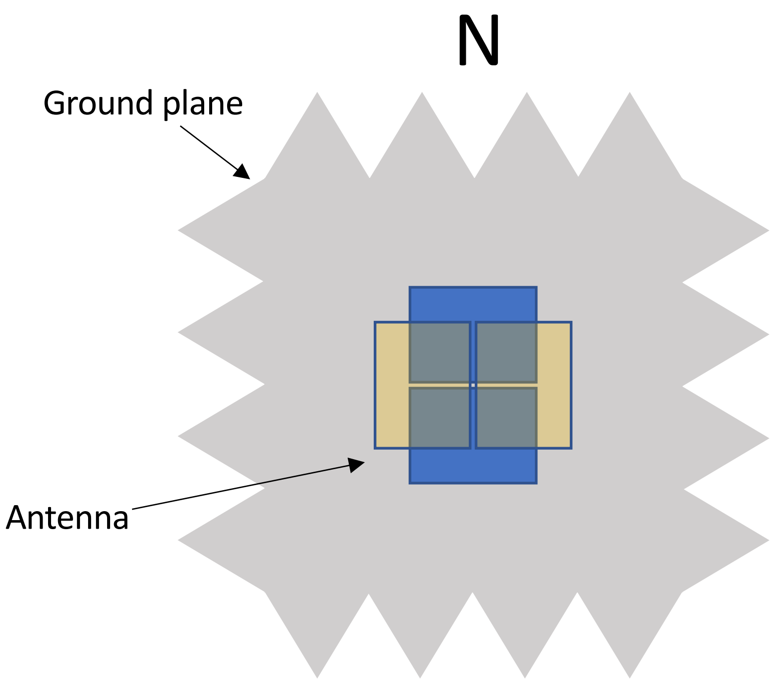
For many data cuts,
adding a flattened Gaussian absorption model
consistent with Bowman et al. (2018) ***improves the fit****.*

Bayesian pipeline *is being written to analyze all the aspects of the experiment in a statistically robust and self consistent way*

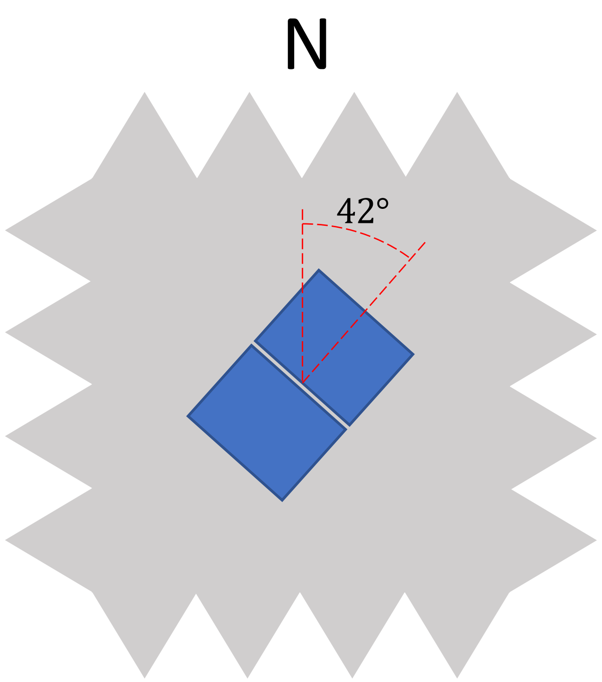
EDGES-2 in 2018-2020

Verification with EDGES-2 Rotated Low-Band

Low-Band **before 2020**



Low-Band **in 2020**

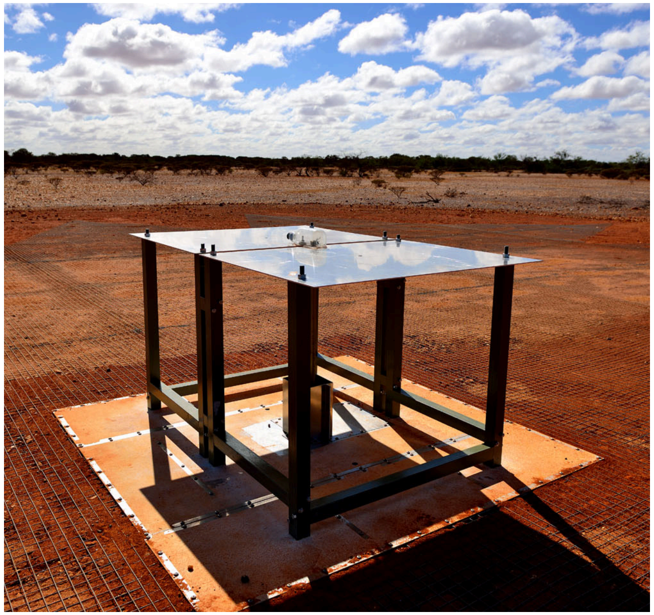


Different EM interaction between antenna and ground plane

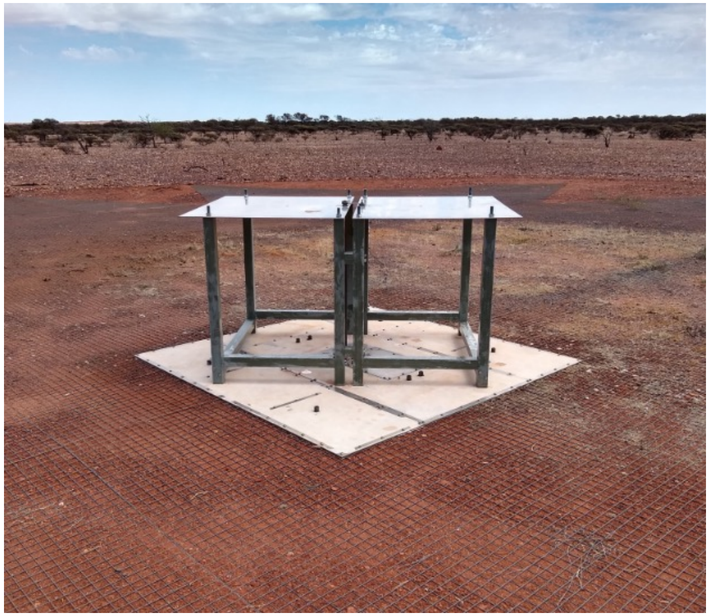
EDGES-2 in 2018-2020

Verification with EDGES-2 Rotated Low-Band

Low-Band



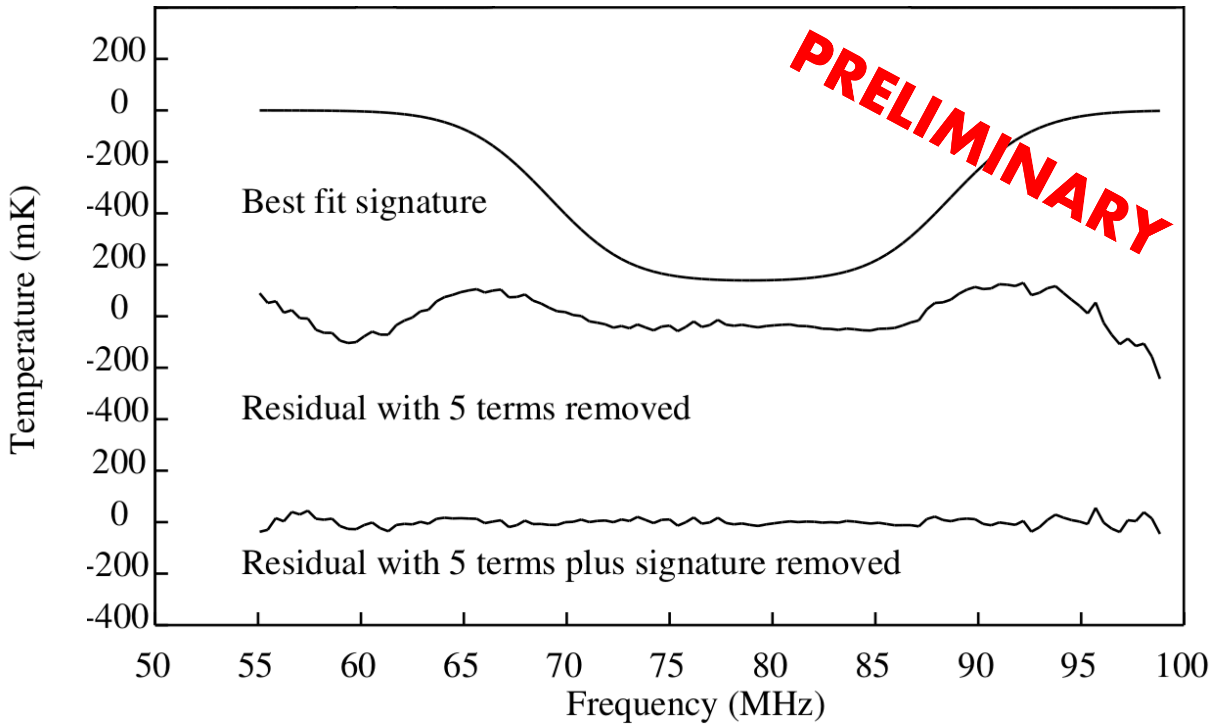
Rotated Low-Band



Objective:
Change the spectral structures from interaction between antenna and ground plane

EDGES-2 in 2018-2020

Verification with EDGES-2 Rotated Low-Band



Best-fit Parameters

$A = 660$ mK
$\nu_0 = 78.9$ MHz
$w = 19.7$ MHz
$\tau = 4$

RMS $= 71$ mK

RMS $= 16$ mK

For many data cuts,
adding a flattened Gaussian absorption model consistent with Bowman et al. (2018) ***improves the fit****.*

Bayesian pipeline *is being written to analyze all the aspects of the experiment in a statistically robust and self consistent way*

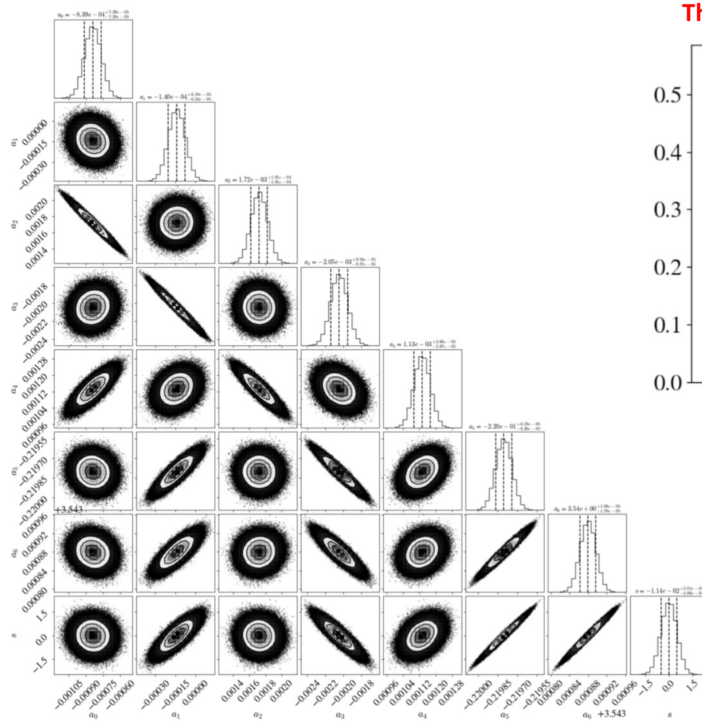
Recent progress by SARAS+

On the detection of a cosmic dawn signal in the radio background

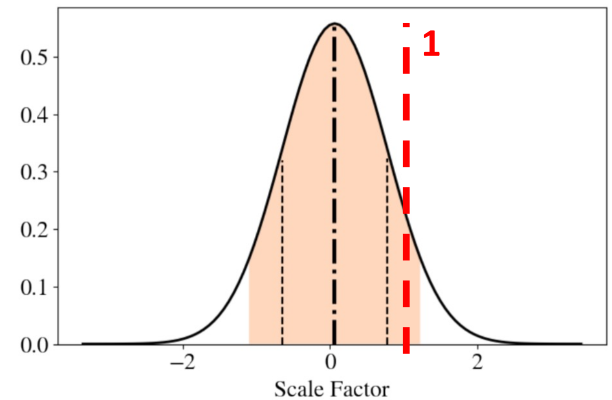
(2022)

Saurabh Singh[1,2,3] ✉, Jishnu Nambissan T.[1,4], Ravi Subrahmanyan[1,5], N. Udaya Shankar[1], B. S. Girish[1], A. Raghunathan[1], R. Somashekar[1], K. S. Srivani[1] and Mayuri Sathyanarayana Rao[1]

SARAS 3 on a lake in India



The value of 1 is within 90% confidence range.



90% confidence range for scale, considering systematics and range of EDGES signals.

- 55-85 MHz band modeled with:
  7-term log-log polynomial
  + 1 scale factor for best-fit EDGES signal

A comprehensive Bayesian reanalysis of the SARAS2 data from the epoch of reionization

(2022)

H. T. J. Bevins [1★], E. de Lera Acedo [1,2], A. Fialkov,[2,3] W. J. Handley,[1,2] S. Singh,[4,5,6]
R. Subrahmanyan[7] and R. Barkana [8,9]

Fitting the foreground with a "partially smooth function" suggests that there is a sinusoidal systematic

	Parameter	Prior	Prior type
Systematic	α_{sys}	0–10	Uniform
	A	0–1 K	
	P	10–70 MHz	
	ϕ	0–2π rad	
Signal	τ	0.026–0.1 (STA) / 0.035–0.077 (ERB)	Uniform
	α	1.3 (STA only)	
	E_{min}	0.1–3 keV (STA only)	
	R_{mfp}	30 (STA) / 40 (ERB) Mpc	
	f_*	0.001–0.5	Log-Uniform
	V_c	4.2–100 km s^{-1}	
	f_X	0.0001–1000	
	f_{radio}	1–99 500 (ERB only)	

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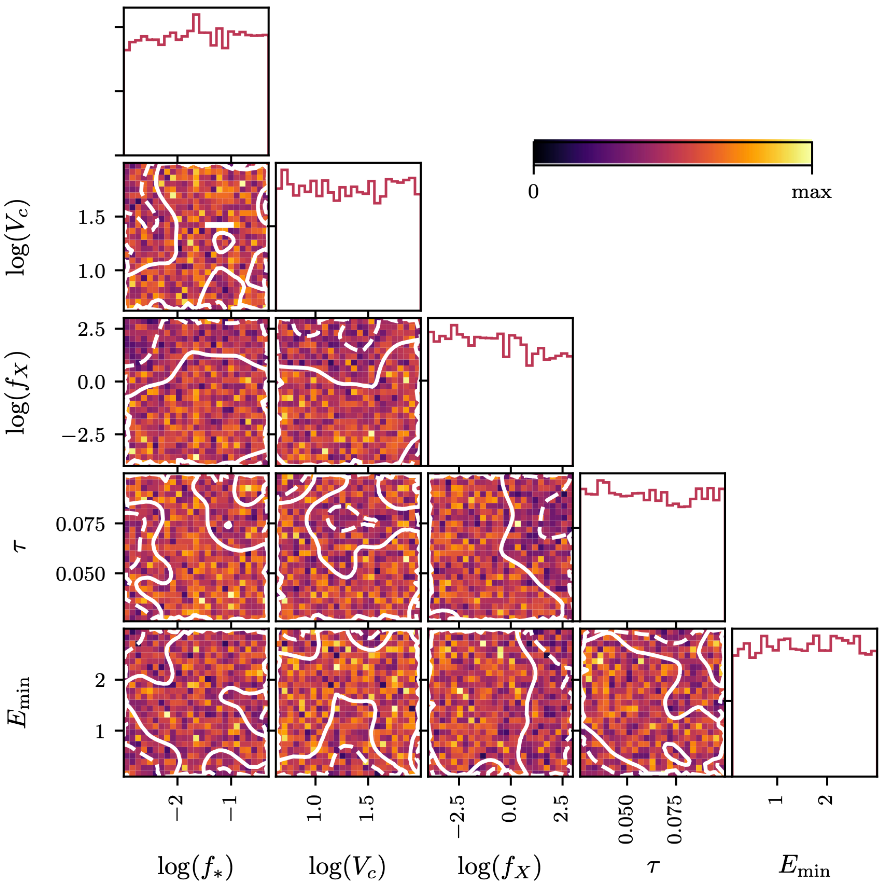

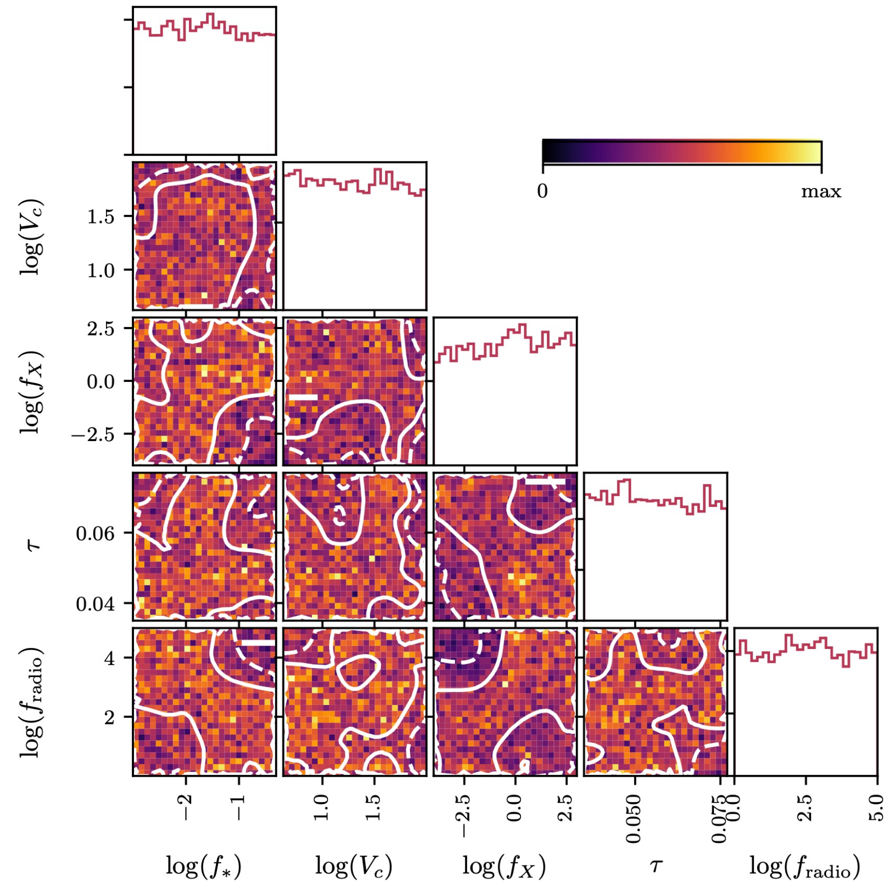

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Astrophysical constraints from the SARAS 3 non-detection of the cosmic dawn sky-averaged 21-cm signal

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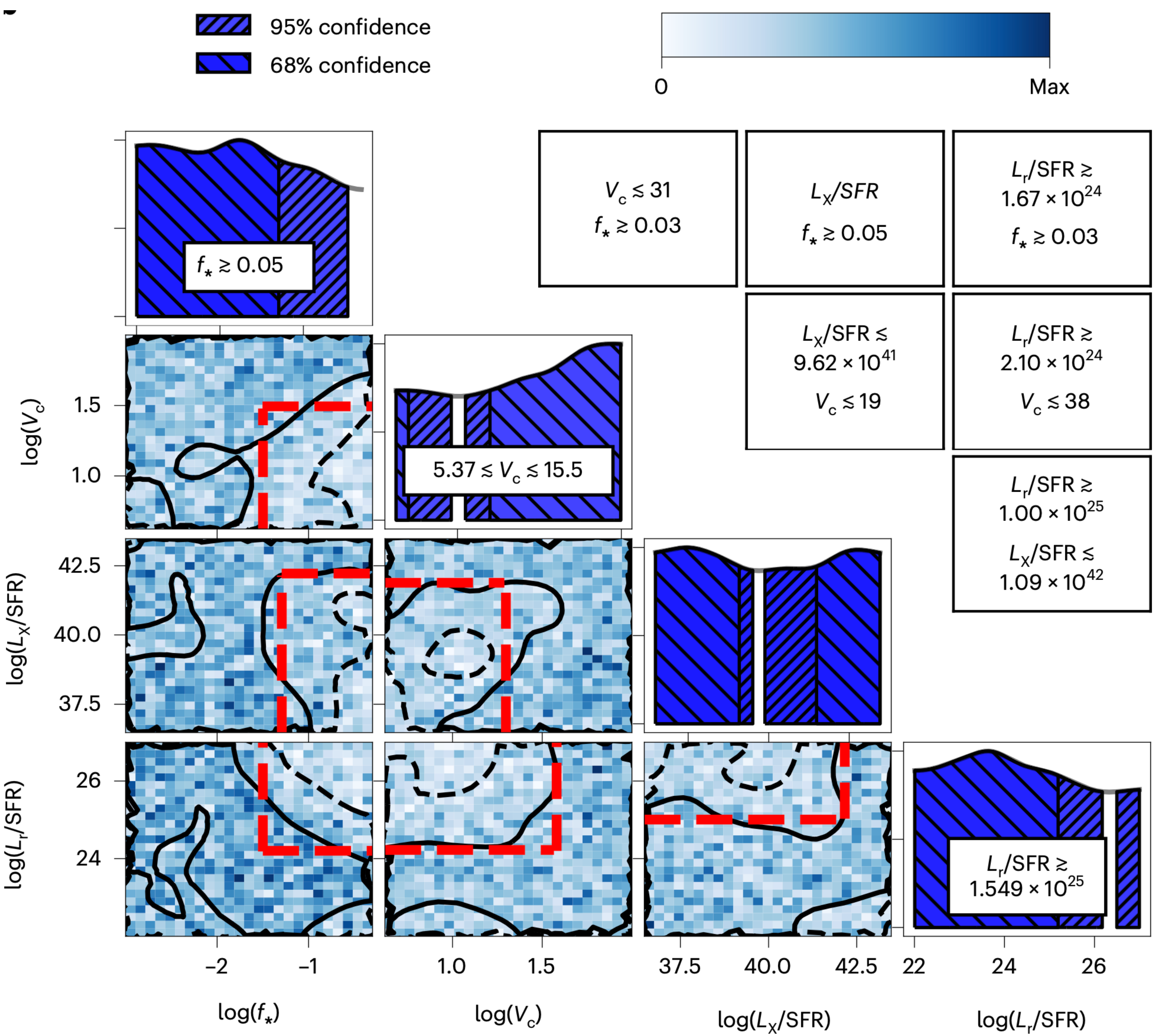
Accepted: 21 September 2022

H. T. J. Bevins[1,2], A. Fialkov[2,3], E. de Lera Acedo[1,2], W. J. Handley[1,2], S. Singh[4], R. Subrahmanyan[5] & R. Barkana[6,7,8]

Fitting the foreground with a 7-term log-log polynomial

Table 2 | The astrophysical priors

Parameter	Radio background	Range
f_*	CMB only, synchrotron, radio galaxies	0.001–0.5
V_c (km s^{-1})	CMB only, synchrotron, radio galaxies	4.2–100
f_X	CMB only, synchrotron, radio galaxies	0.001–1,000
f_{radio}	Radio galaxies	1.0–99,500
$A_r^{1,420}$	Synchrotron	0–47
τ	CMB only	0.026–0.103
	Synchrotron	0.016–0.158
	Radio galaxies	0.035–0.077
α	CMB only	1.0–1.5
E_{min} (keV)	CMB only	0.1–3.0
R_{mfp} (Mpc)	CMB only, synchrotron, radio galaxies	Fixed at 30, 40 and 40



95% confidence
68% confidence
0
Max
$f_* \gtrsim 0.05$
$V_c \lesssim 31$
$f_* \gtrsim 0.03$
L_X/SFR
$f_* \gtrsim 0.05$
$L_r/SFR \gtrsim 1.67 \times 10^{24}$
$f_* \gtrsim 0.03$
$L_X/SFR \lesssim 9.62 \times 10^{41}$
$V_c \lesssim 19$
$L_r/SFR \gtrsim 2.10 \times 10^{24}$
$V_c \lesssim 38$
$L_r/SFR \gtrsim 1.00 \times 10^{25}$
$L_X/SFR \lesssim 1.09 \times 10^{42}$
$5.37 \lesssim V_c \lesssim 15.5$
$L_r/SFR \gtrsim 1.549 \times 10^{25}$
$\log(V_c)$
$\log(L_X/SFR)$
$\log(L_r/SFR)$
$\log(f_*)$
1.5
1.0
42.5
40.0
37.5
26
24
−2
−1
1.0
1.5
37.5
40.0
42.5
22
24
26

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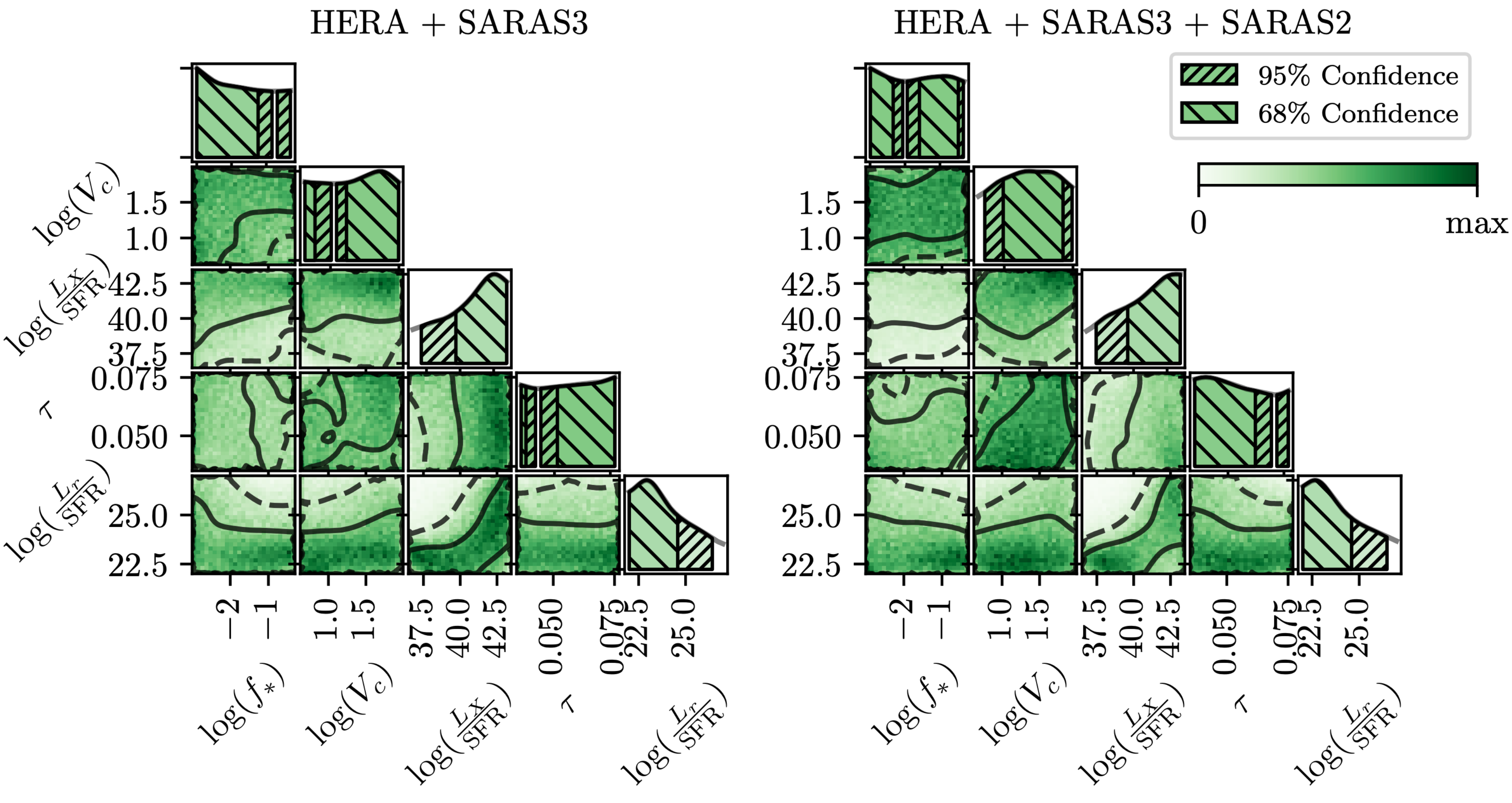
Table 3 | Summary of key constraints from SARAS 3 (this work), HERA and SARAS 2 experiments

	SARAS 3	HERA	SARAS 2
Signal type	Global	Power spectrum	Global
Redshift range	$z \approx 15$–25	$z \approx 8$ and $z \approx 10$	$z \approx 7$–12
L_r/SFR (W Hz$^{-1}M_\odot^{-1}$yr)	$\gtrsim 1.549\times10^{25}$	$\gtrsim 4.00\times10^{24}$	–
L_r/SFR$\cap L_X$/SFR (erg s$^{-1}M_\odot^{-1}$yr)	$\gtrsim 1\times10^{25} \cap \lesssim 1.09\times10^{42}$	$\gtrsim 4.00\times10^{24} \cap \lesssim 7.60\times10^{39}$	$\gtrsim 4.07\times10^{24} \cap \lesssim 6.3\times10^{39}$
M ($M_\odot$)	$4.4\times10^5 \lesssim M \lesssim 1.1\times10^7$	–	–
f_*	$\gtrsim 0.05$	–	–
$f_* \cap M$ ($M_\odot$)	$\gtrsim 0.03 \cap \lesssim 8.53\times10^8$	–	–

Joint analysis constraints on the physics of the first galaxies with low frequency radio astronomy data

(2023)

Harry T. J. Bevins[1,2]⋆, Stefan Heimersheim[3], Irene Abril-Cabezas[3], Anastasia Fialkov[2,3], Eloy de Lera Acedo[1,2], William Handley[1,2], Saurabh Singh[4] and Rennan Barkana[5,6]



Thank You Very Much