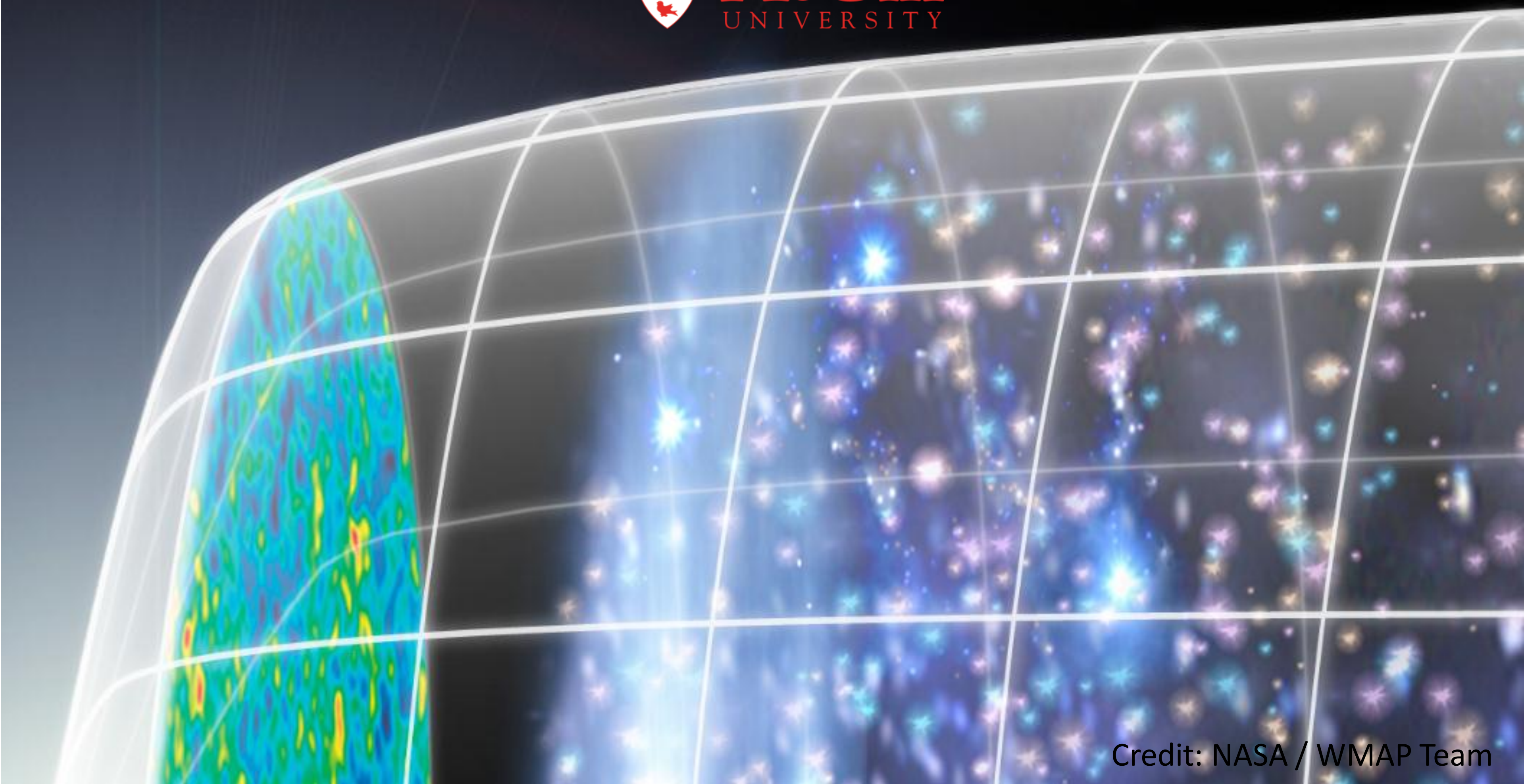
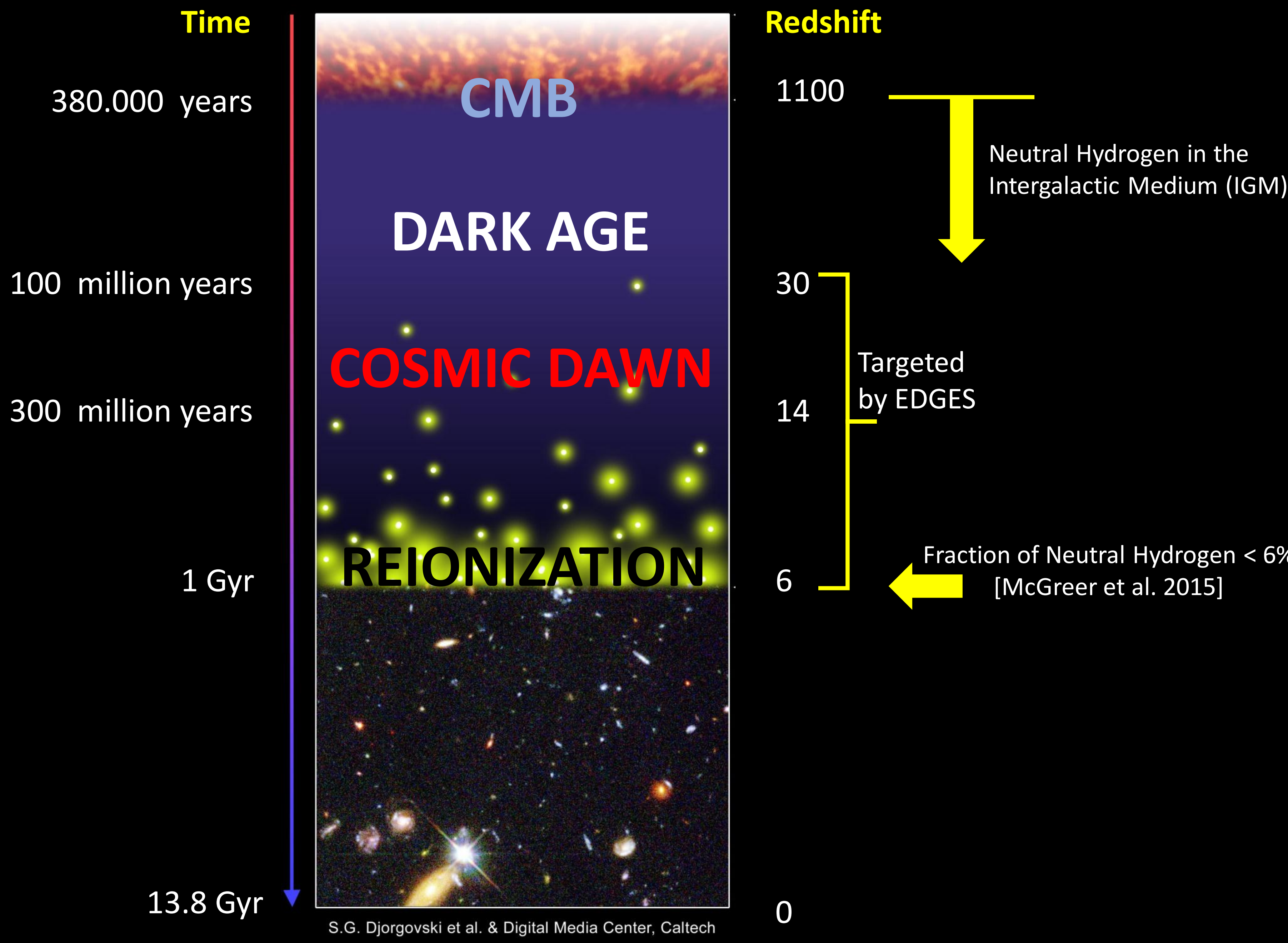
An Absorption Feature in the All-Sky Radio Spectrum

Raul Monsalve

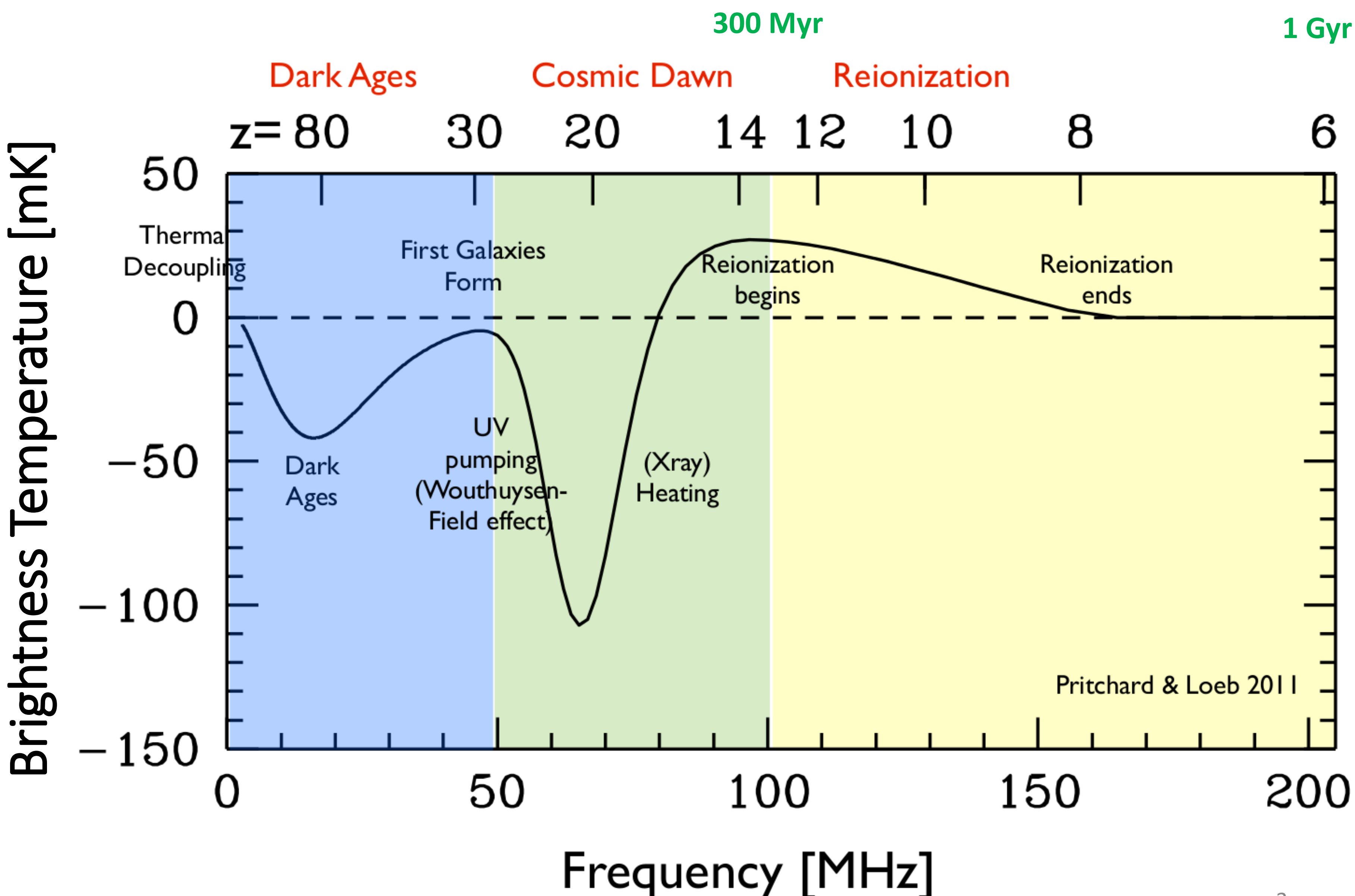
McGill University



Credit: NASA / WMAP Team


Time
380.000 years
100 million years
300 million years
1 Gyr
13.8 Gyr
CMB
DARK AGE
COSMIC DAWN
REIONIZATION
S.G. Djorgovski et al. & Digital Media Center, Caltech
Redshift
1100
30
14
6
0
Neutral Hydrogen in the Intergalactic Medium (IGM)
Targeted by EDGES
Fraction of Neutral Hydrogen < 6%
[McGreer et al. 2015]

Standard Prediction for Global 21-cm Signal



EDGES

Experiment to **D**etect the **G**lobal **E**oR **S**ignature

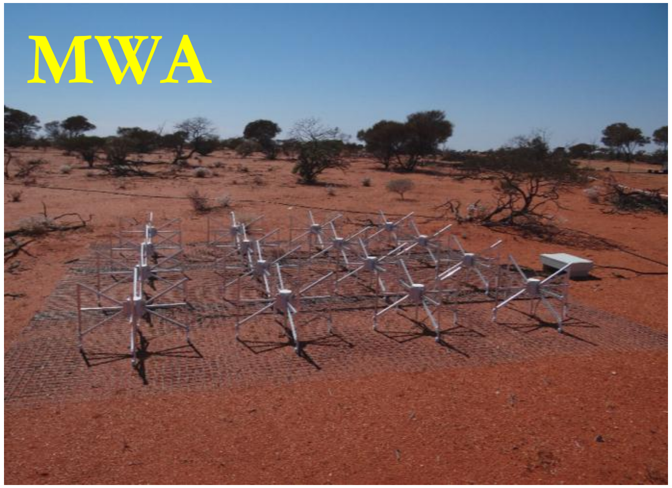
Prof. Judd Bowman (PI)
Dr. Alan Rogers
Dr. Raul Monsalve
Dr. Thomas Mozdzen
Ms. Nivedita Mahesh

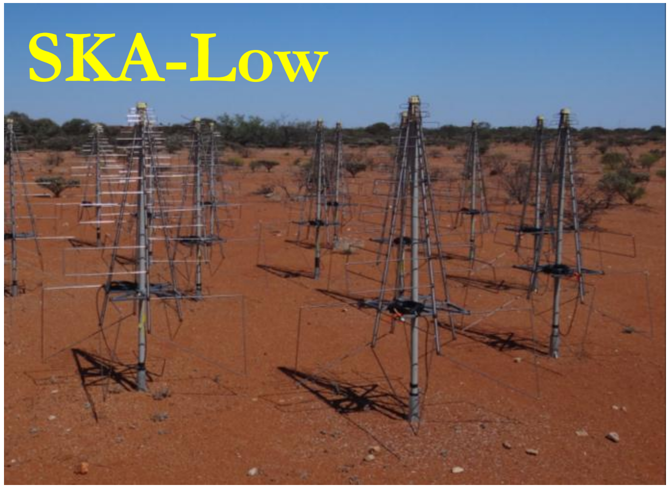
Arizona State University

MIT Haystack Observatory

Western Australia

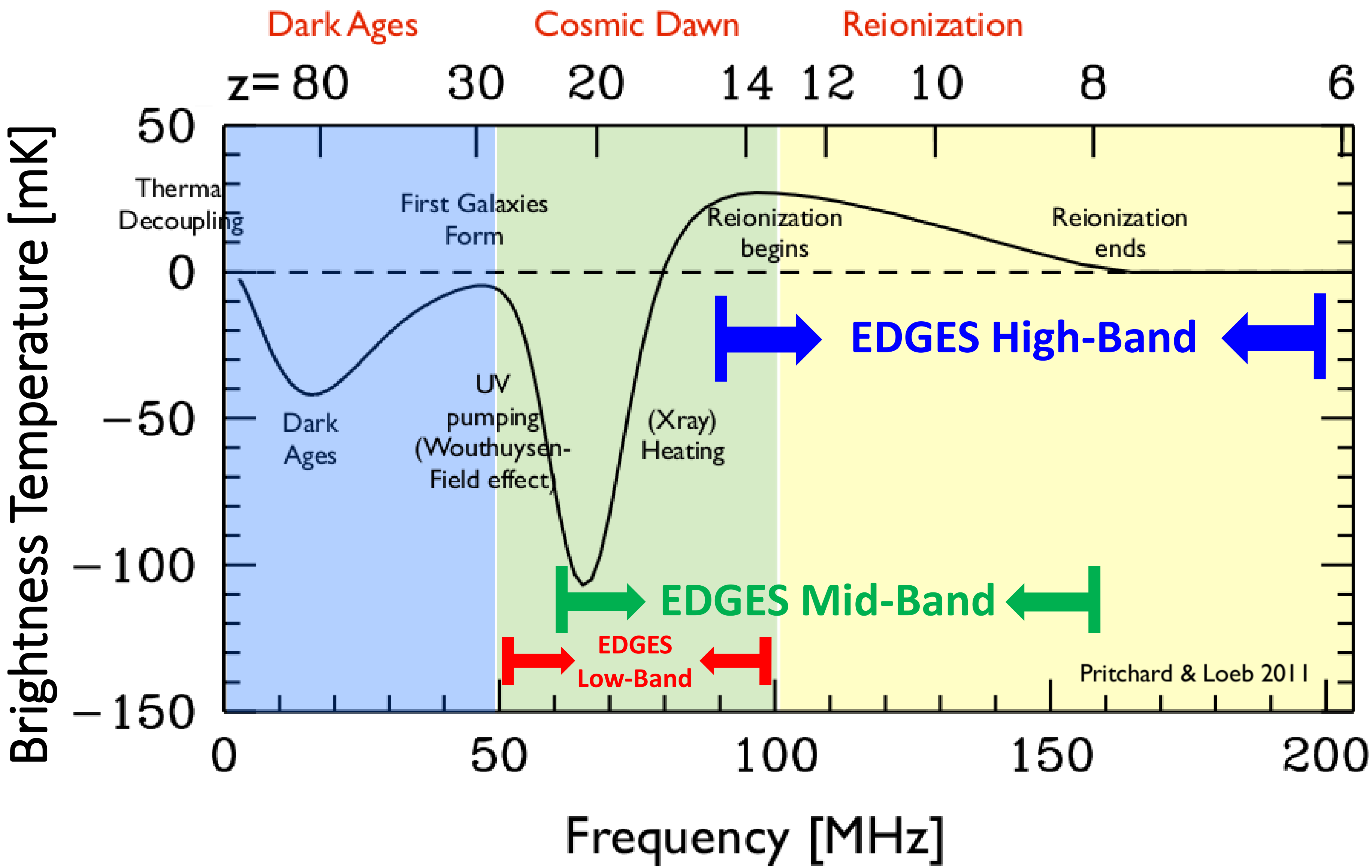
Murchison Radio-astronomy Observatory (MRO)
Radio-Quiet Site





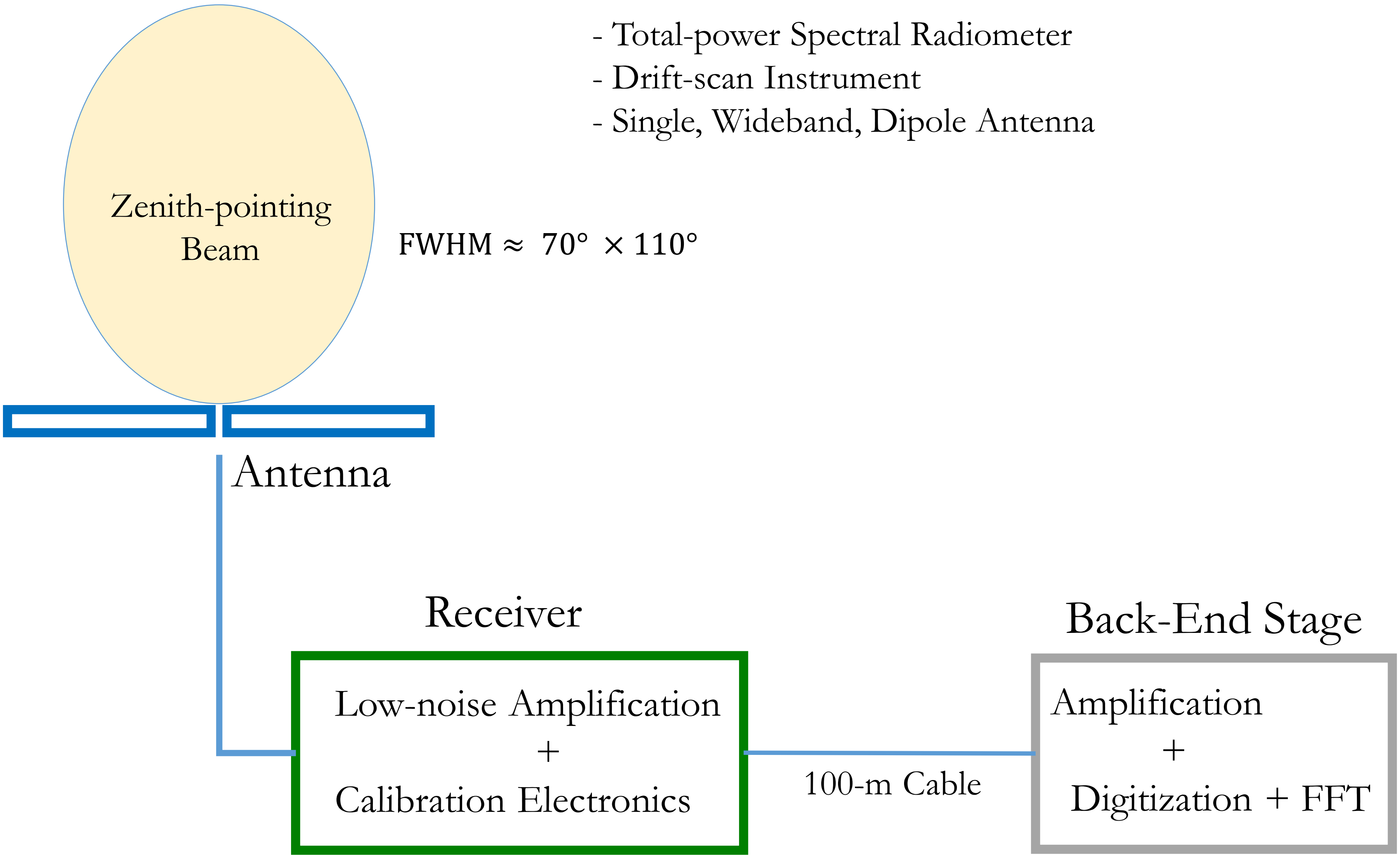



EDGES Instruments

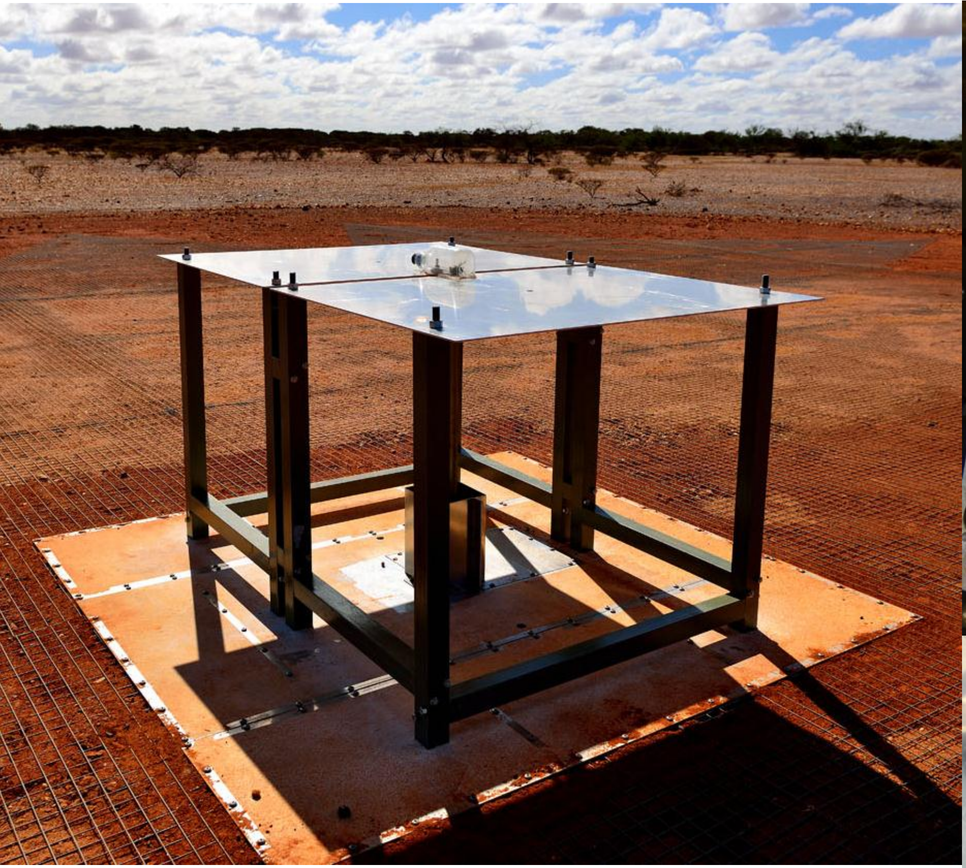


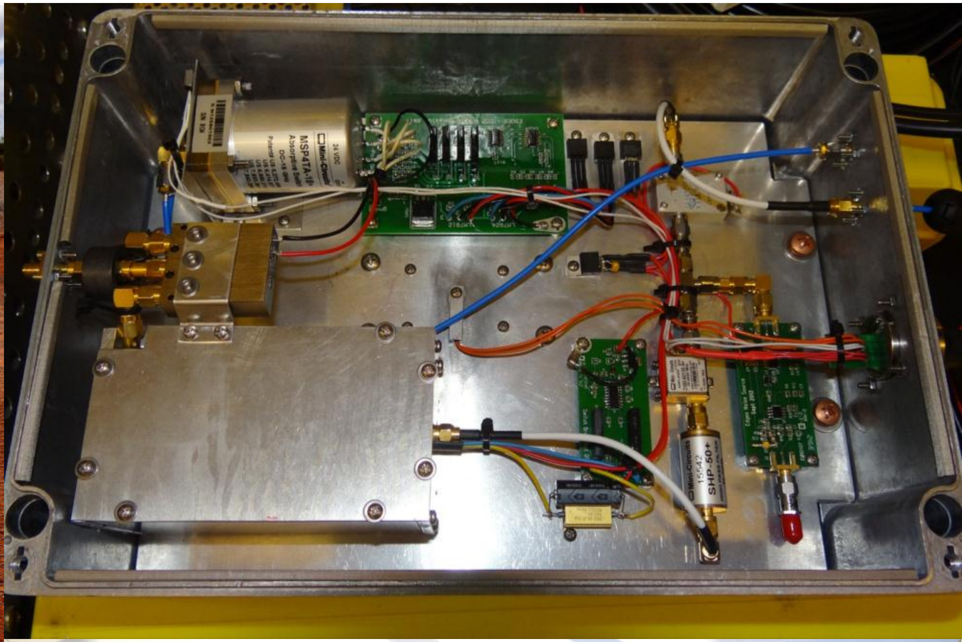
EDGES Instrument Block Diagram

- Total-power Spectral Radiometer
- Drift-scan Instrument
- Single, Wideband, Dipole Antenna



EDGES Low-Band





Antenna size:

2m long / 1m high

TWO **Low-Band** Instruments

Main Challenges

1) **Hard instrument calibration** problem.

2) **Strong diffuse foregrounds (Galactic and Extragalactic)** compared to cosmological 21-cm signal.

Instrumental Calibration

1) **Instrument gain and noise offset.**

2) **Impedance mismatch between receiver and the antenna.**

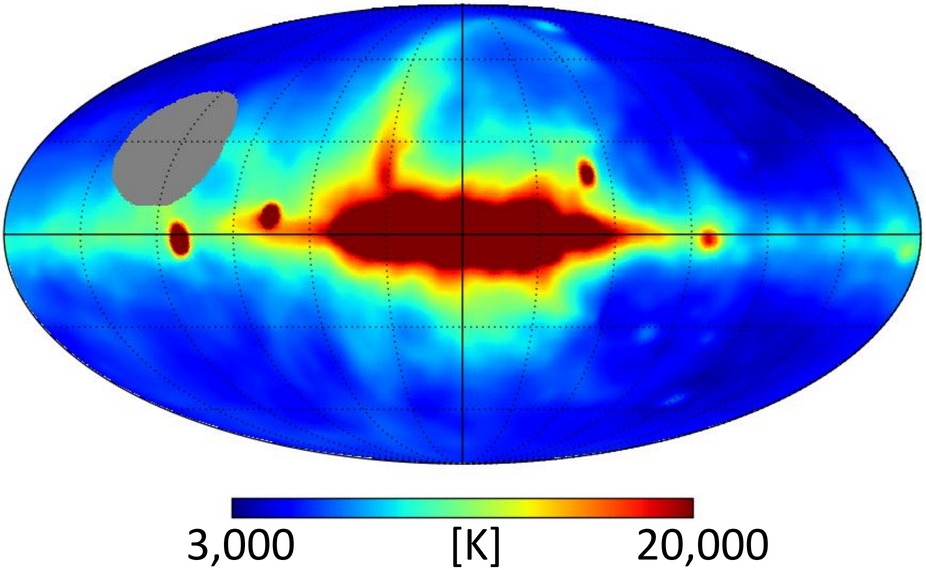
3) **Antenna and ground losses.**

4) **Frequency-dependence of the antenna beam.**

Diffuse Foregrounds

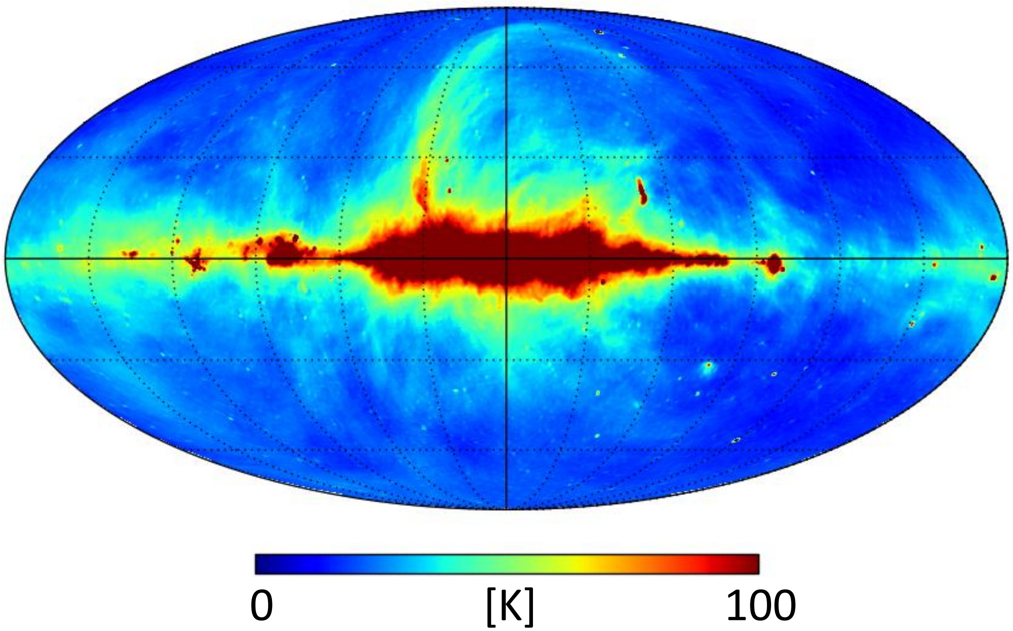
45-MHz Map

Guzmán et al. (2011)



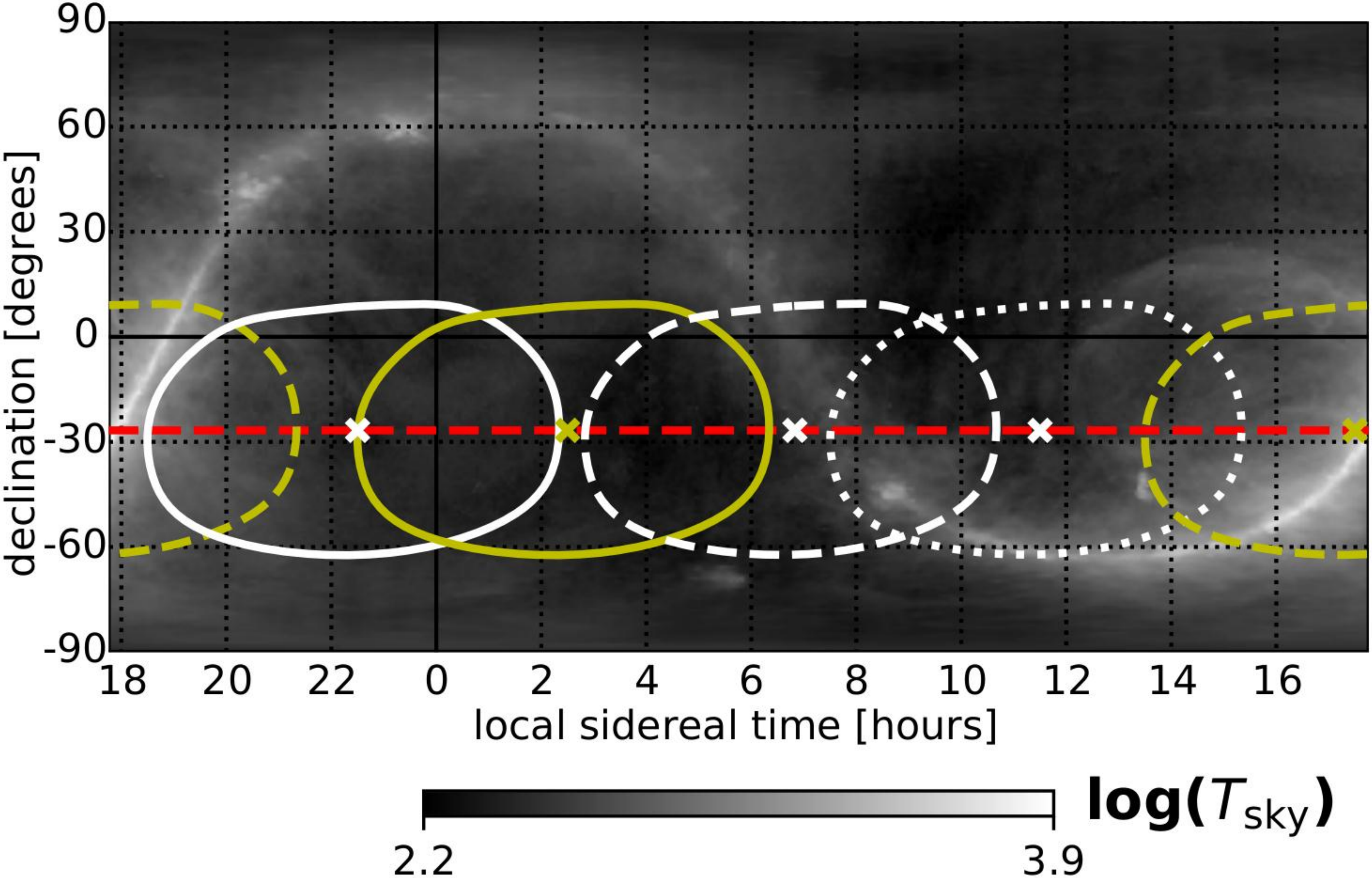
408-MHz Map

Haslam et al. (1982)



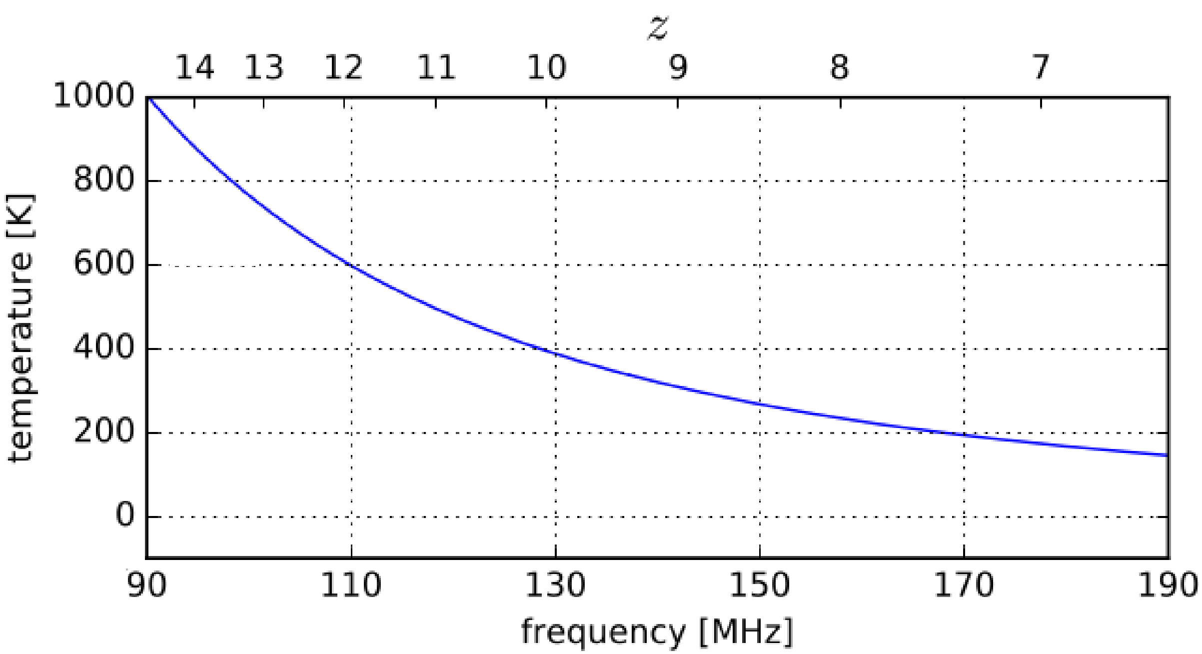
1) From **hundreds to thousands of Kelvins**.
2) Include **Galactic and Extragalactic**.
3) Mostly **Galactic synchrotron radiation**.
4) **Smooth** spectral dependence expected.

Beam Projected onto the Sky



Constraining Standard Models with the EDGES **High-Band** Spectrum

EDGES **High-Band** Spectrum



Monsalve, Rogers, Bowman, & Mozdzen (2017b)

No detection claimed in this frequency range

<u>Integration</u>

- 40 days
- 6 hrs of low foreground regions
- Noise of 6 mK at 140 MHz.

Physical 21cm Models from Fialkov et al.

Early star formation

$\boldsymbol{V_c}$: minimum virial circular velocity of halos

$\boldsymbol{f_*}$: star formation efficiency

IGM X-ray heating

$\boldsymbol{f_X}$: X-ray heating efficiency

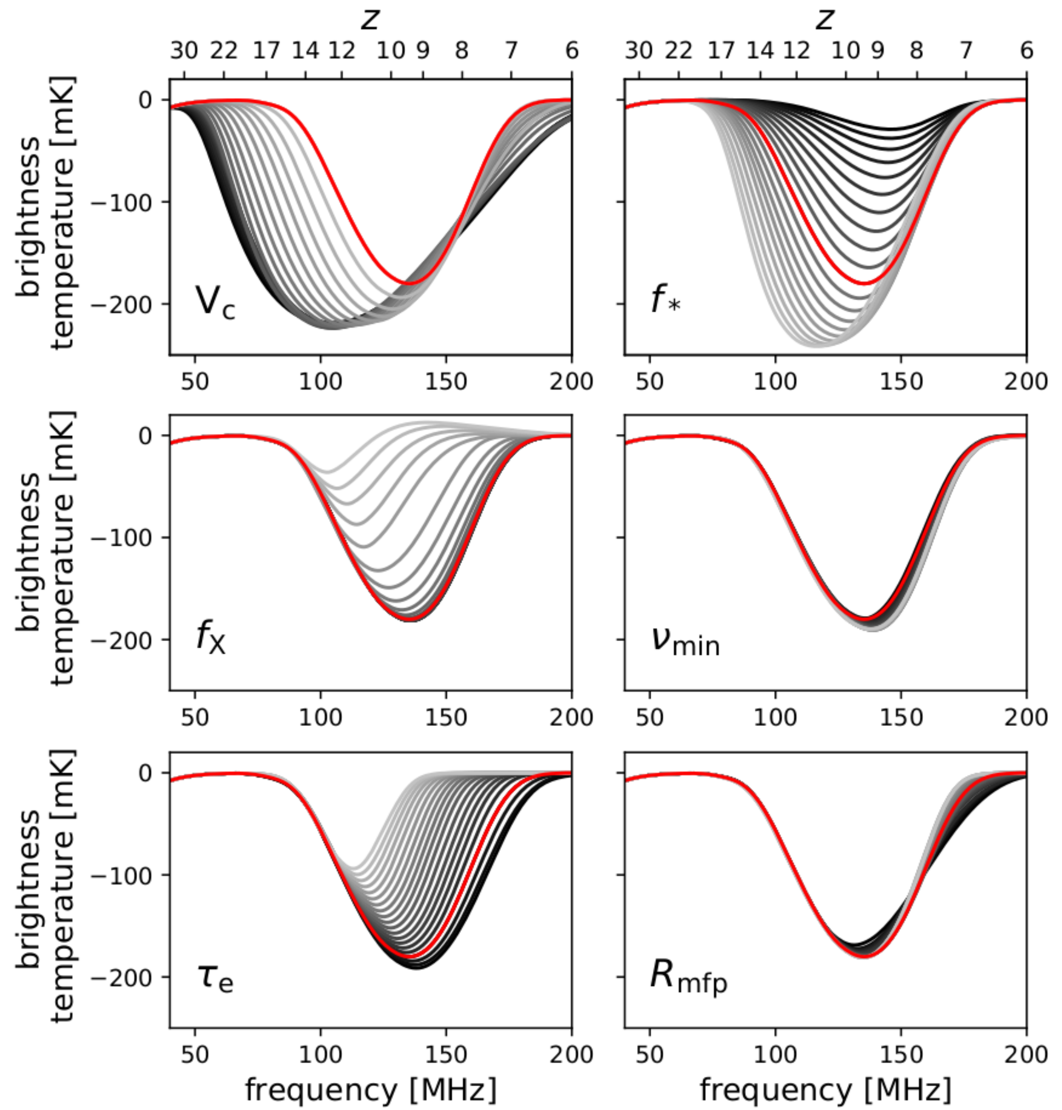
$\boldsymbol{\nu_{min}}$: minimum energy of X-rays

Reionization

$\boldsymbol{R_{mfp}}$: mean-free path of ionizing photons

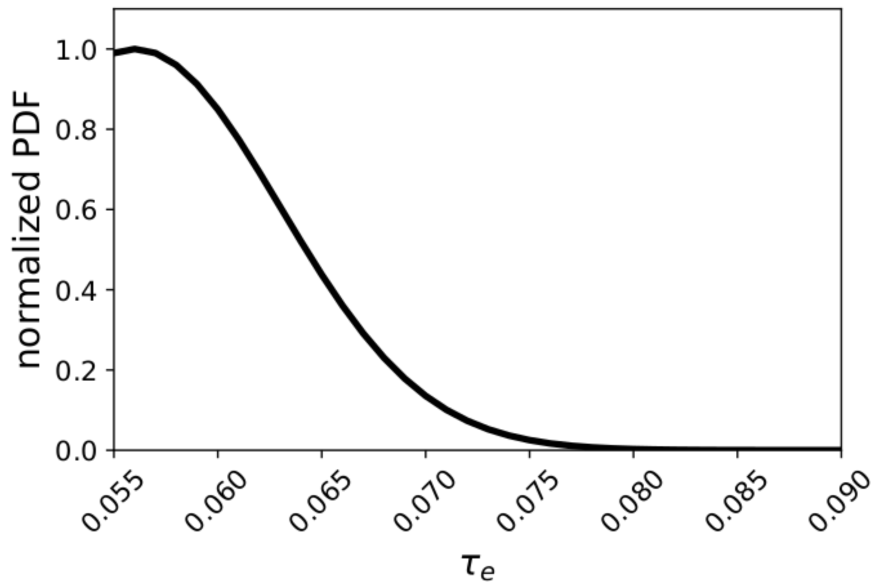
$\boldsymbol{\tau_e}$: CMB optical depth

Foreground parameters are marginalized

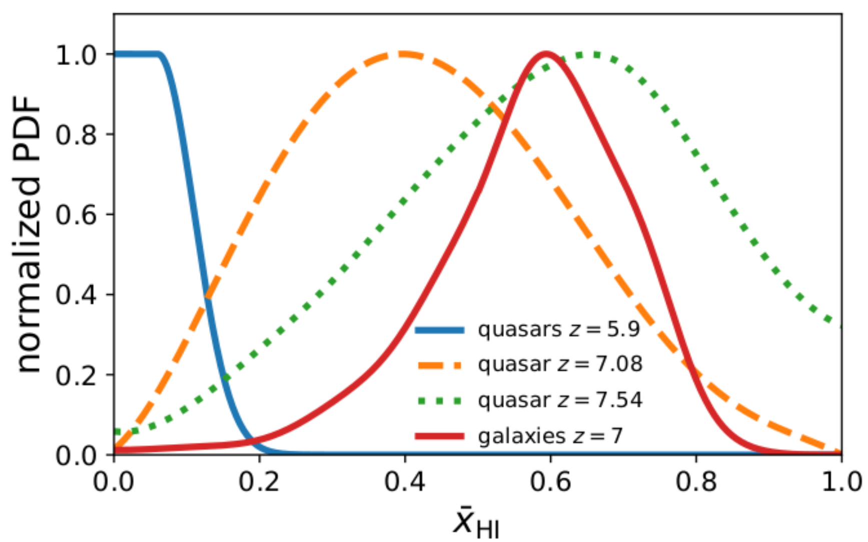


Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019

Planck

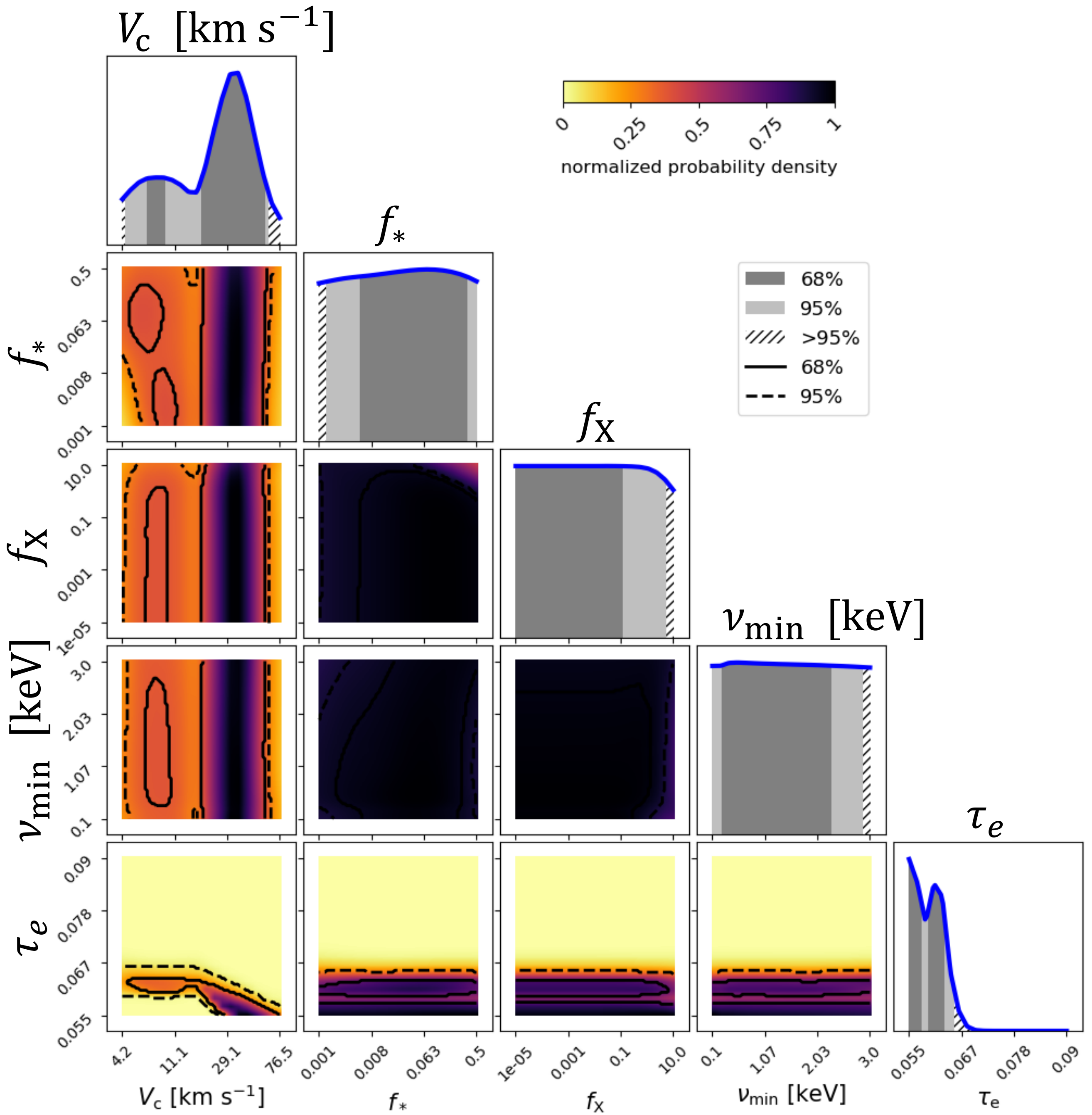


High-z Quasars and Galaxies



Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019

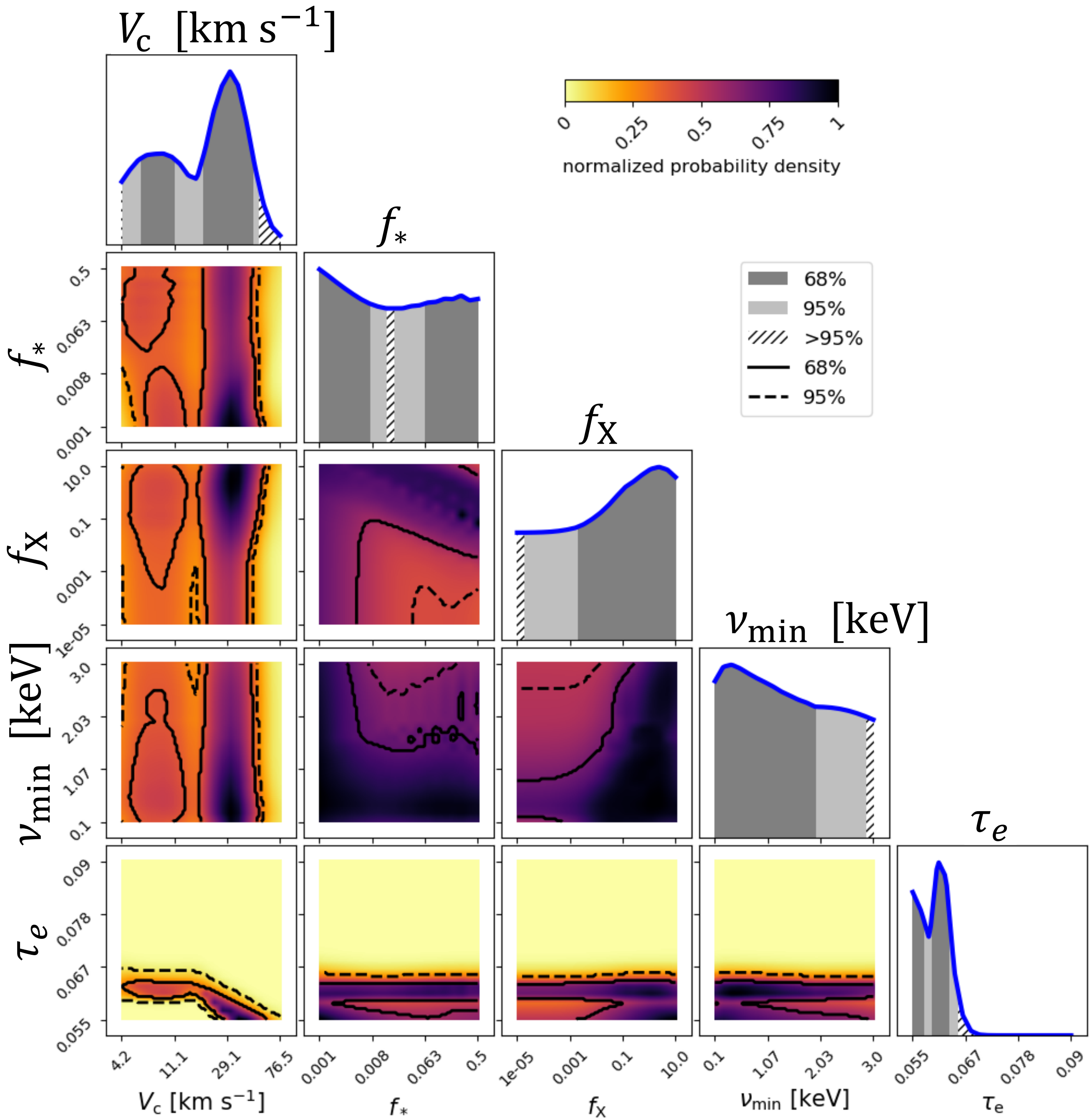
Planck + High-z Quasars + Galaxies



Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019

Planck + High-z Quasars + Galaxies + EDGES **High-Band**

Constraints independent from **Low-Band** data



Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019

EDGES **Low-Band**

Detection of an Absorption Feature

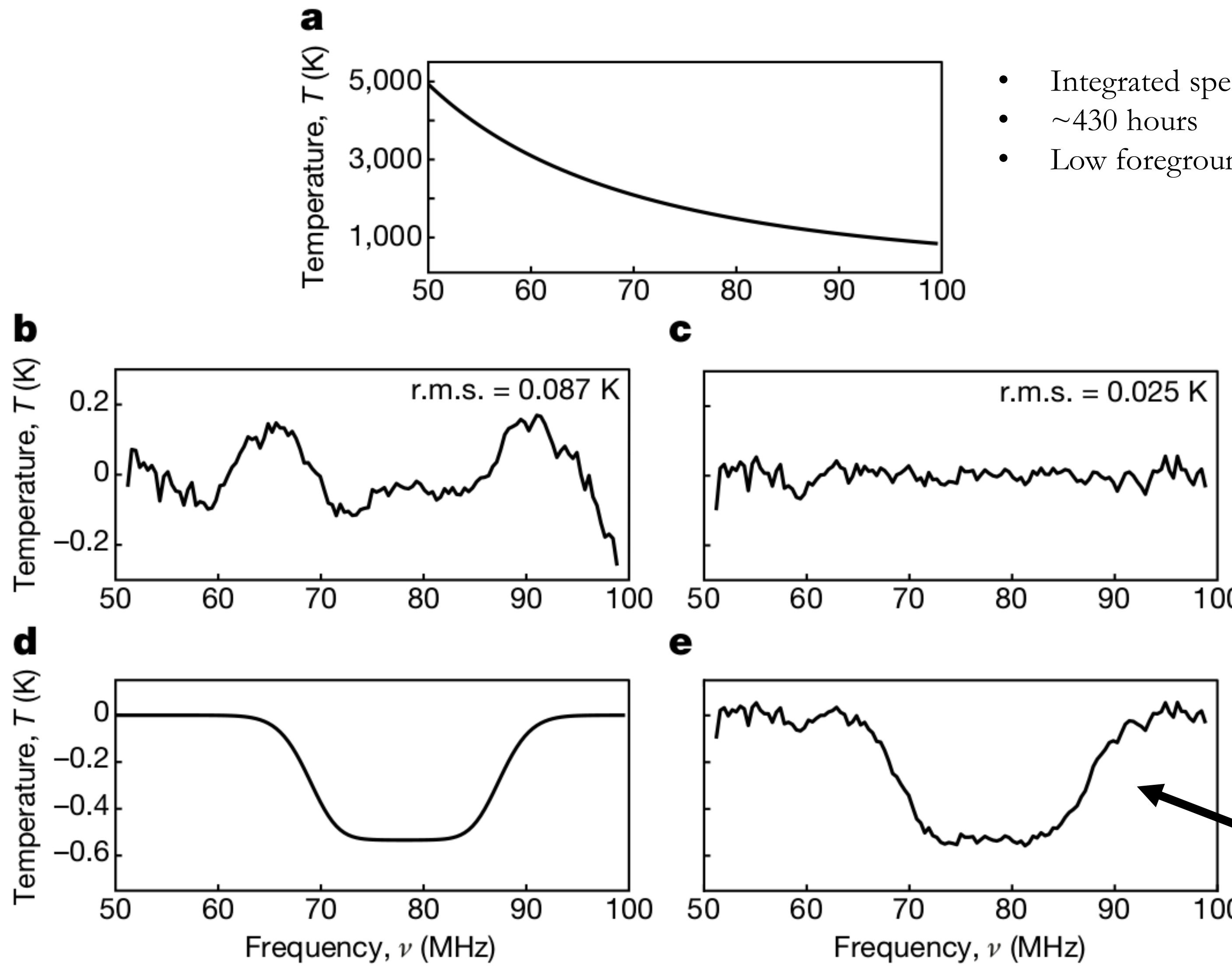
LETTER

doi:10.1038/nature25792

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

Summary of Detection

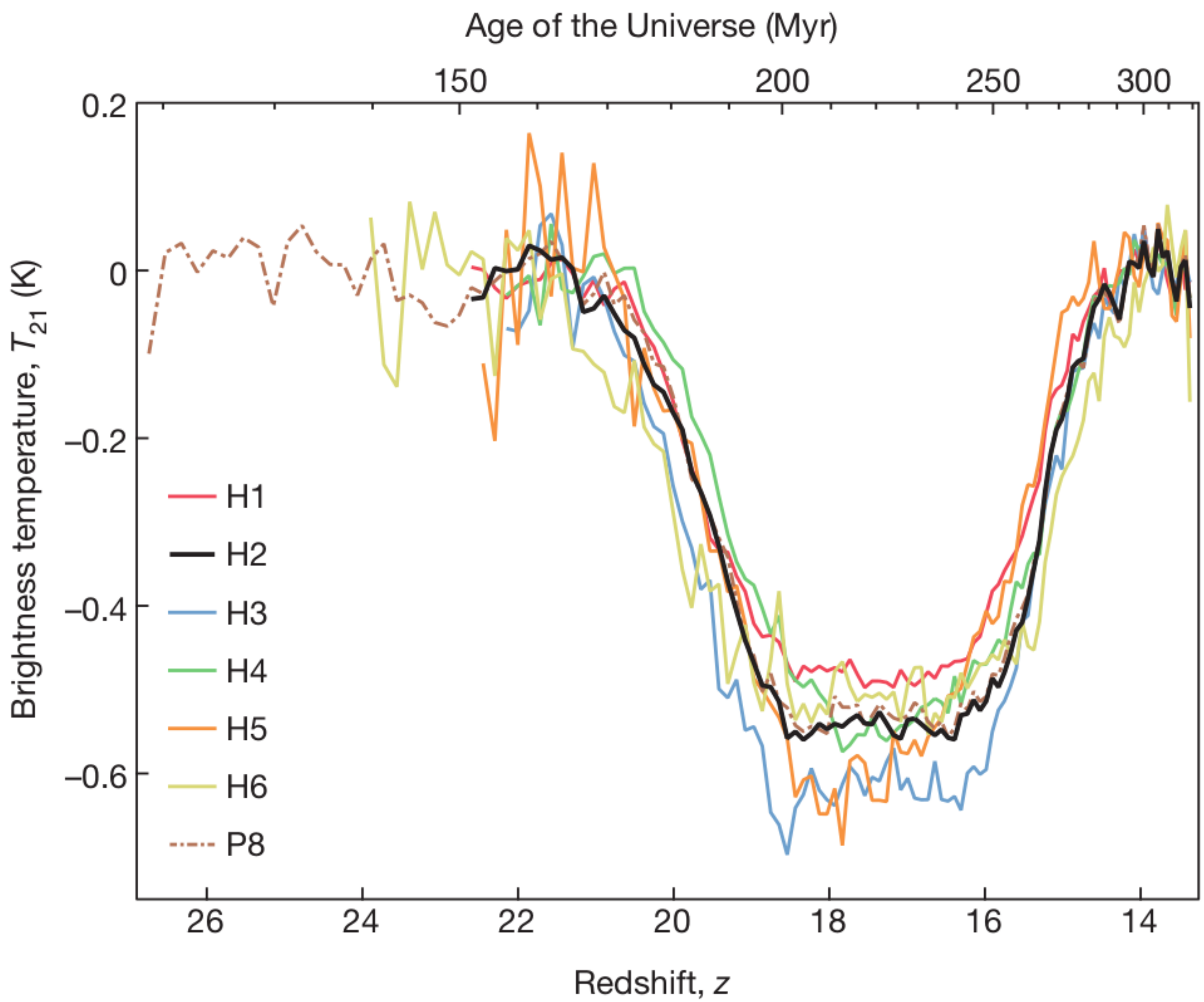


- Integrated spectrum
- ~430 hours
- Low foreground regions

Absorption deeper than expected by factor > 2

Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, **Nature**, 555, 67

Two Instruments / Several Configurations



Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, **Nature**, 555, 67

Sensitivity to Possible Calibration Errors

Error source	Estimated uncertainty	Modelled error level	Recovered amplitude (K)
LNA S11 magnitude	0.1 dB	1.0 dB	0.51
LNA S11 phase (delay)	20 ps	100 ps	0.48
Antenna S11 magnitude	0.02 dB	0.2 dB	0.50
Antenna S11 phase (delay)	20 ps	100 ps	0.48
No loss correction	N/A	N/A	0.51
No beam correction	N/A	N/A	0.48

Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, **Nature**, 555, 67

Absorption Amplitude for Various GHA

Galactic Hour Angle (GHA)	SNR	Amplitude (K)	Sky Temperature (K)
6-hour bins			
0	8	0.48	3999
6	11	0.57	2035
12	23	0.50	1521
18	15	0.60	2340
4-hour bins			
0	5	0.45	4108
4	9	0.46	2775
8	13	0.44	1480
12	21	0.57	1497
16	11	0.59	1803
20	9	0.66	3052

Total temperature varies by a factor of up to 3.

Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, **Nature**, 555, 67

Parameter Estimates

From All Cases Processed

Parameter	Best Fit	Uncertainty (3σ)
Amplitude	0.5 K	+0.5/-0.2 K
Center	78 MHz	+/-1 MHz
Width	19 MHz	+4/-2 MHz
Flatness	7	+5/-3

Amplitude is in tension with standard models by $\geq \mathbf{3.5}\boldsymbol{\sigma}$

How to Explain Deep Absorption?

$$T_{21}(z) \propto \left(1 - \frac{T_{\mathrm{CMB}} + \boldsymbol{T}_{\mathbf{EXCESS}}}{\boldsymbol{T}_{\mathbf{S}}}\right)$$

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]

Lower than expected

$\boldsymbol{T}_{\mathbf{IGM}}$ **Lower than expected**

Suggested source:

- Interactions between **Baryons and Dark Matter** particles [Muñoz and Loeb 2018]

IOP Publishing

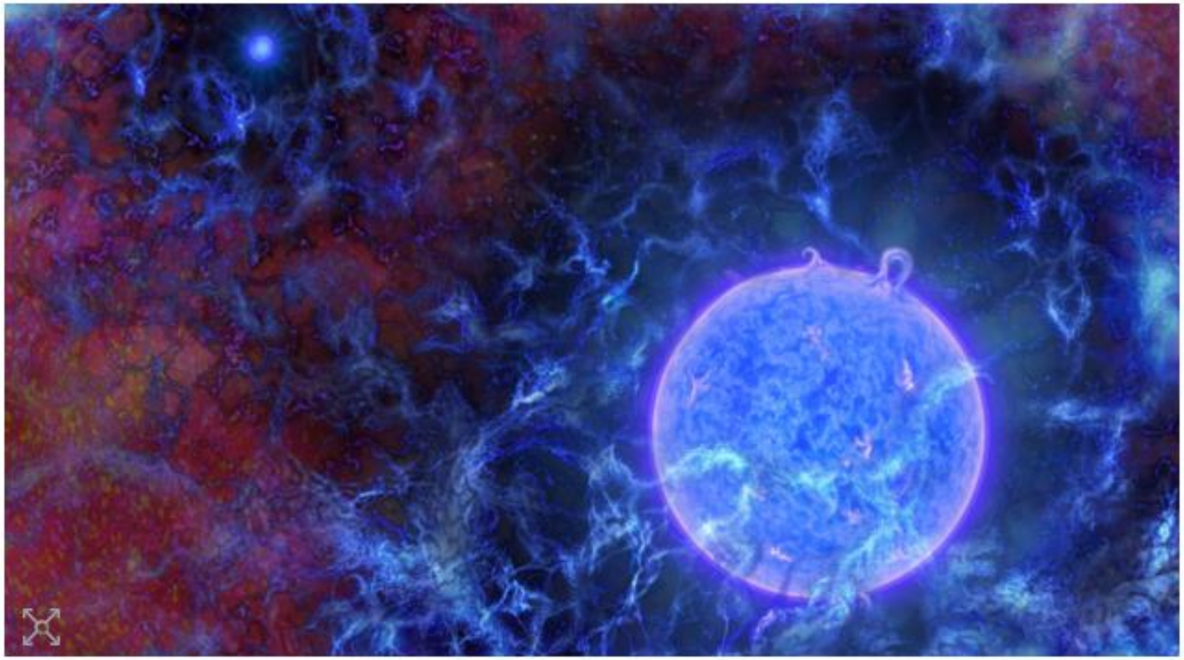
physicsworld

Dec 13, 2018

TOP 10 Breakthrough in 2018

Ancient hydrogen reveals clues to dark matter's identity

To Judd Bowman, Raul Monsalve, Thomas Mozdzen and Nivedita Mahesh of Arizona State University Arizona State University and Alan Rogers of the Massachusetts Institute of Technology for using the EDGES radio telescope to observe colder-than-expected hydrogen gas that existed just 180 million years after the Big Bang; and Rennan Barkana, of Tel Aviv University for calculating that this could be the first direct observation of a non-gravitational interaction between dark matter and conventional matter. While further observations are needed to back-up this hypothesis, the research could help resolve one of the most important unsolved mysteries of physics: what is the nature of dark matter?



Light and dark: did dark matter cool ancient hydrogen?

BRIEF COMMUNICATIONS ARISING

Concerns about modelling of the EDGES data

ARISING FROM J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen & N. Mahesh *Nature* **555**, 67–70 (2018); https://doi.org/10.1038/nature25792

A Ground Plane Artifact that Induces an Absorption Profile in Averaged Spectra from Global 21-cm Measurements - with Possible Application to EDGES

Richard F. Bradley, Keith Tauscher, David Rapetti, and Jack O. Burns

Addressing Concerns: Recent Tests in the Field

Null Tests (**feature should not be found)**

1) Measuring noise sources that produce a **flat spectrum**.
2) Measuring noise sources that produce a spectrum **resembling the diffuse foregrounds**.

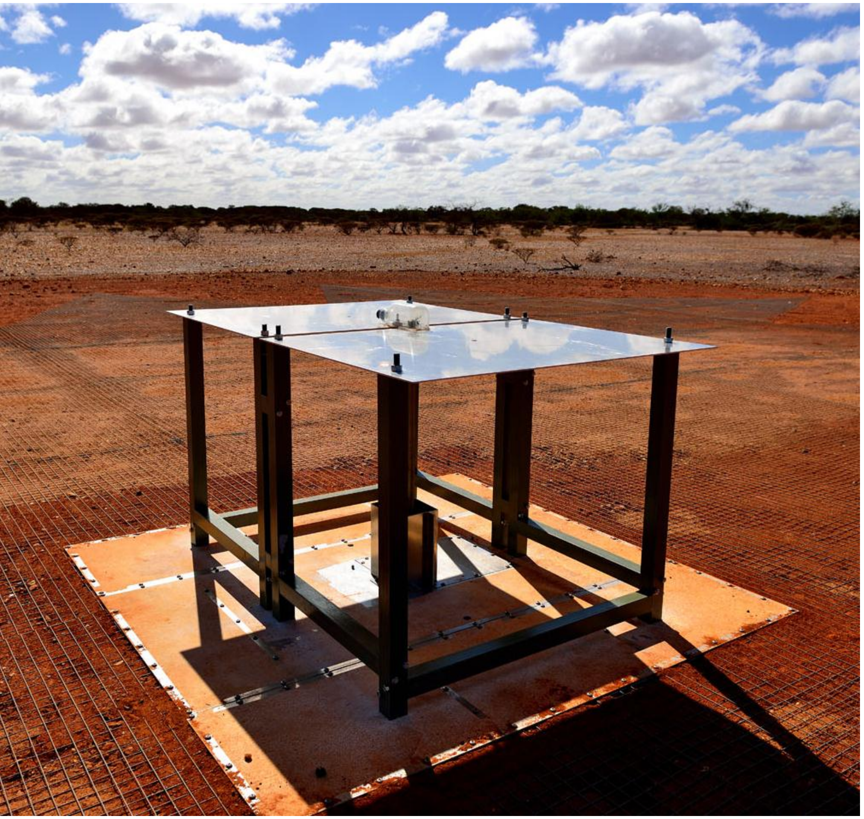
Tests Addressing Antenna Beam Effects (**feature should be found**)

1) Using **smaller Mid-Band antenna** covering 60-160 MHz.
2) Using Low-Band antenna over a **smaller 9m x 9m ground plane**. We call this **Low-Band 3**.

These **tests have been passed successfully**. This supports a **spectral feature from the sky**.

Verification with EDGES **Mid-Band**

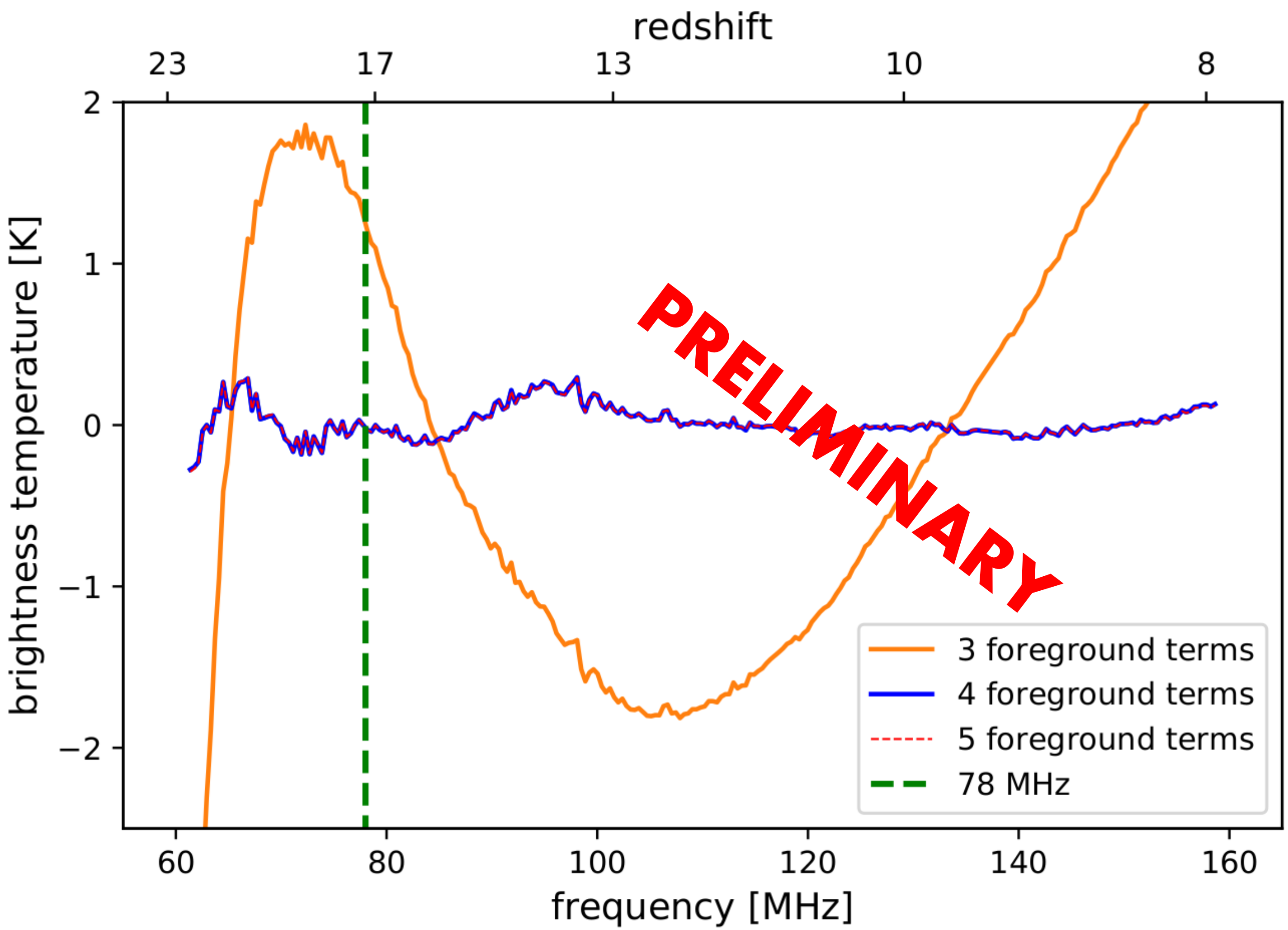
Low-Band



Mid-Band (~25% smaller)

Same Ground Plane as **Low-Band**

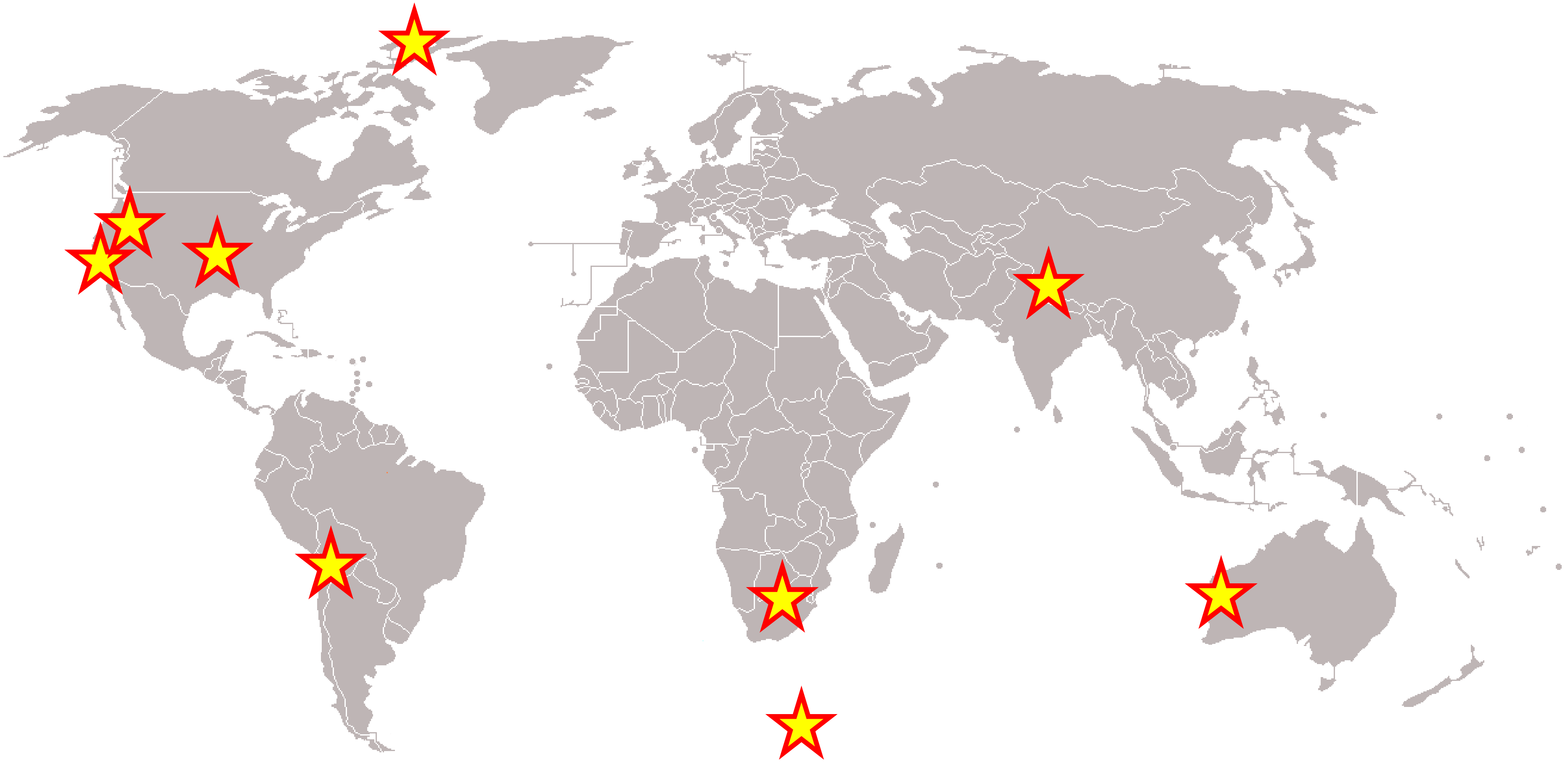
Preliminary **Mid-Band** Results



1) Data from **May - August 2018.**
2) **Low foregrounds**.
3) Best-fit absorption **consistent with Bowman et al. (2018)**.
4) Some alternative models suggested **can be disfavored**.

Monsalve, Mahesh, Rogers, Bowman, Mozdzen, & Johnson (in preparation)

Worldwide Effort

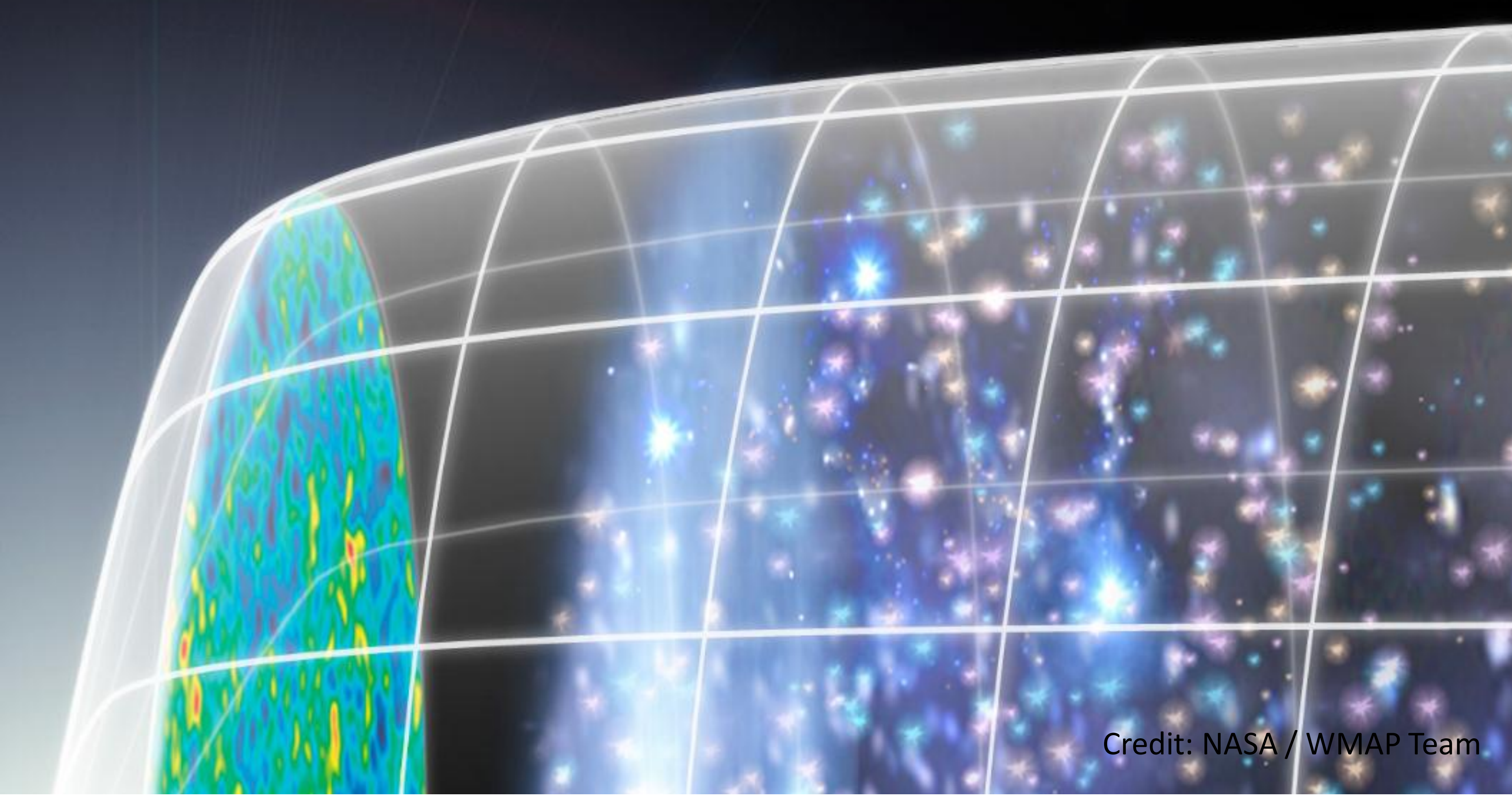


+ a few Space-Based Efforts

- Continue favoring a spectral feature in the sky spectrum

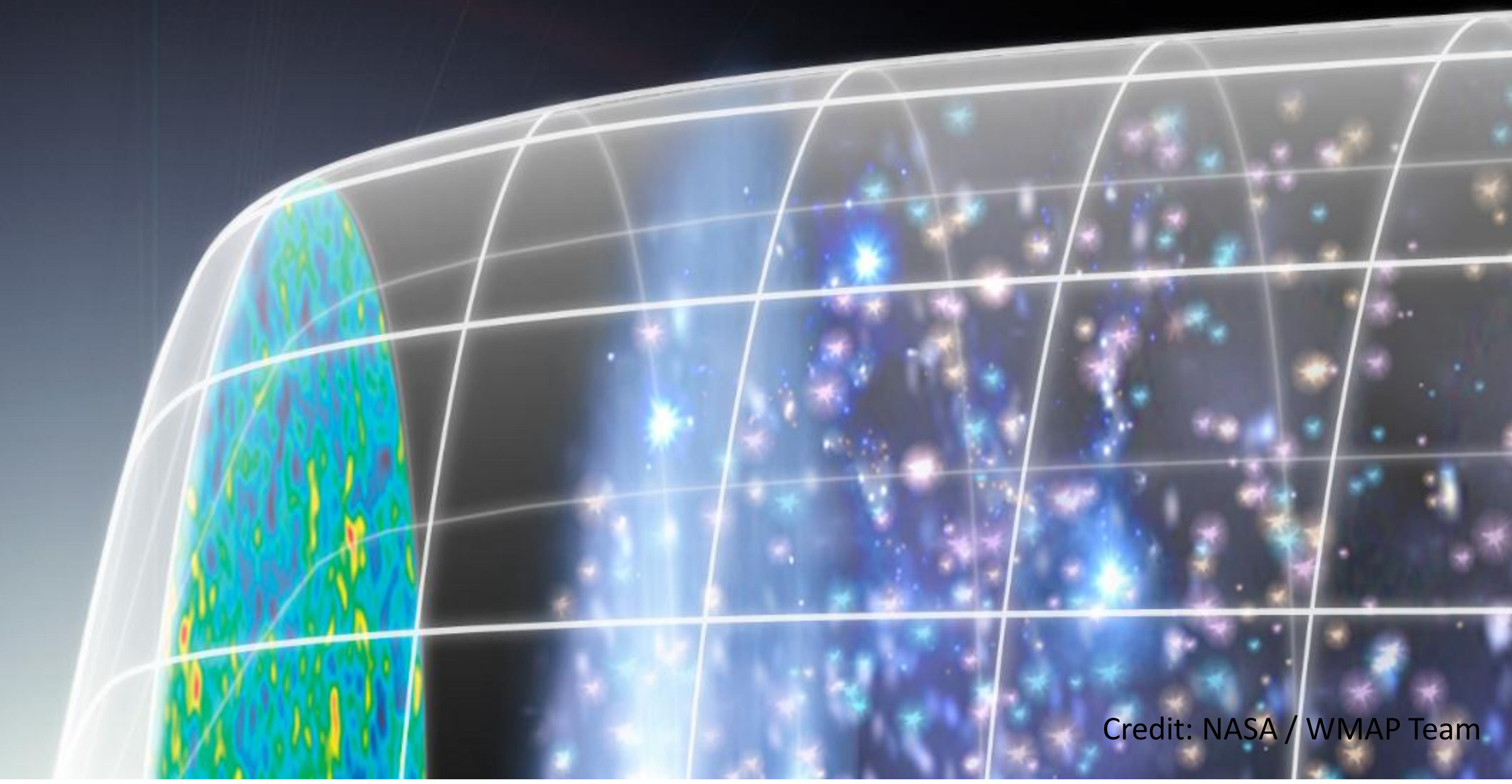
- Constraining models and parameters of the early Universe

- Expecting results soon from other experiments

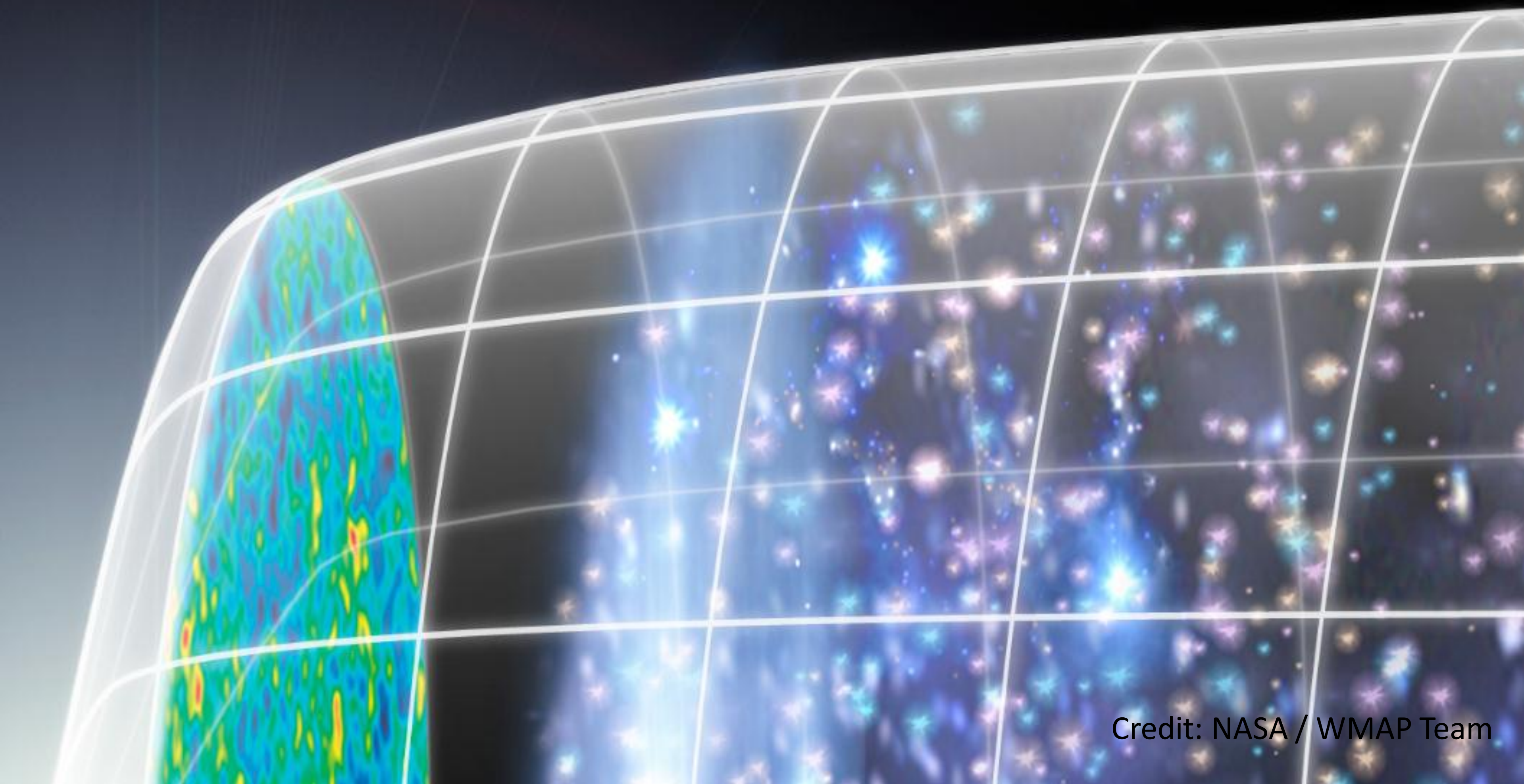


Credit: NASA / WMAP Team

We are Witnessing the Dawn of 21-cm Cosmology



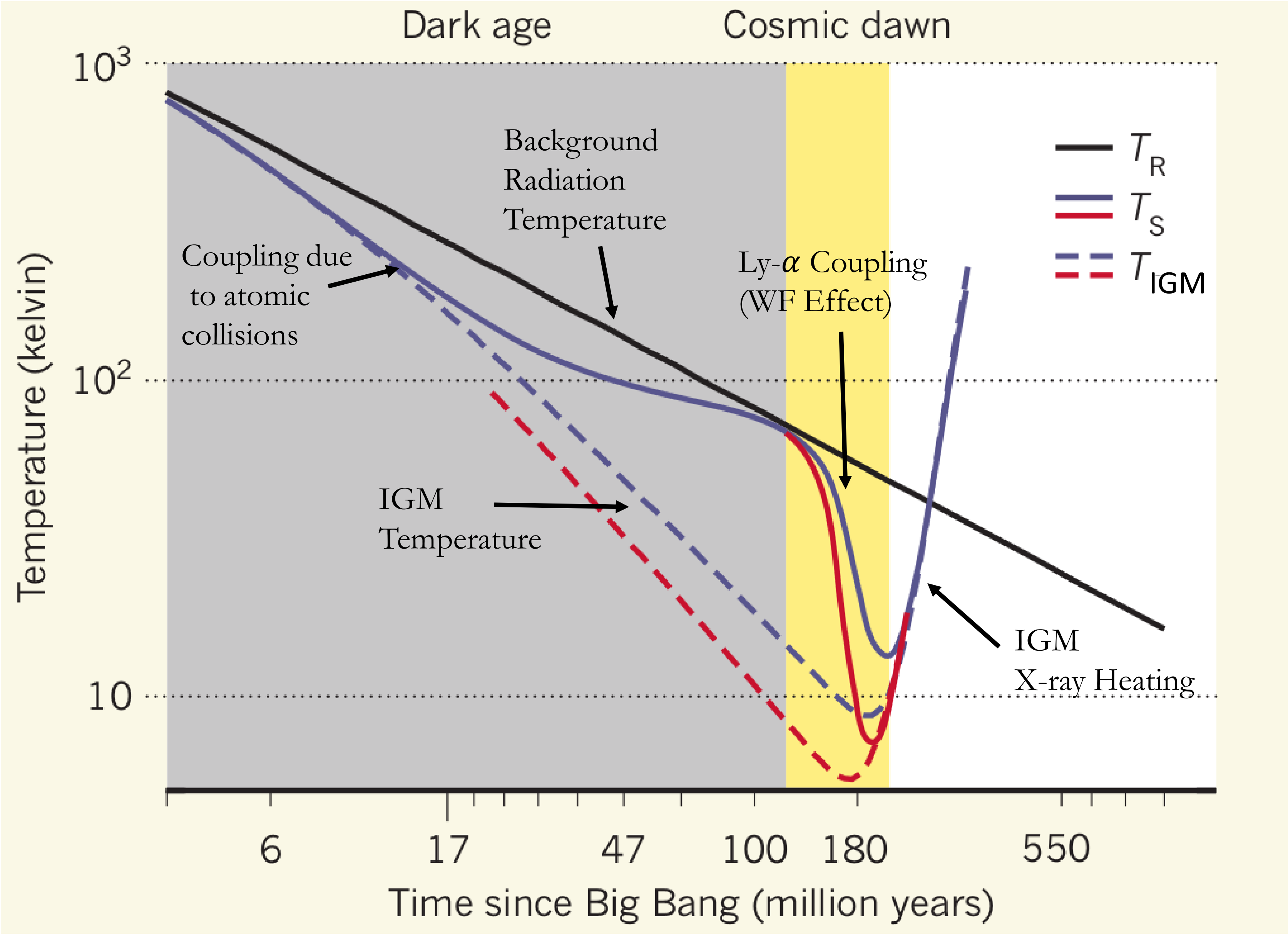
Thank you



Credit: NASA / WMAP Team

Extra Slides

Global Interaction



Adapted from Greenhill 2018, **Nature**, 555, 38

Global 21-cm Brightness Temperature

radiation
temperature

$$T_{\mathrm{b}}(z) \approx 28\ \mathrm{mK} \cdot \sqrt{\frac{1+z}{10}} \cdot \bar{x}_{\mathrm{HI}} \cdot \left(\frac{T_{\mathrm{S}} - T_{\mathrm{R}}}{T_{\mathrm{S}}}\right)$$

fraction
of neutral
hydrogen

spin
temperature

High redshift -> Low frequency

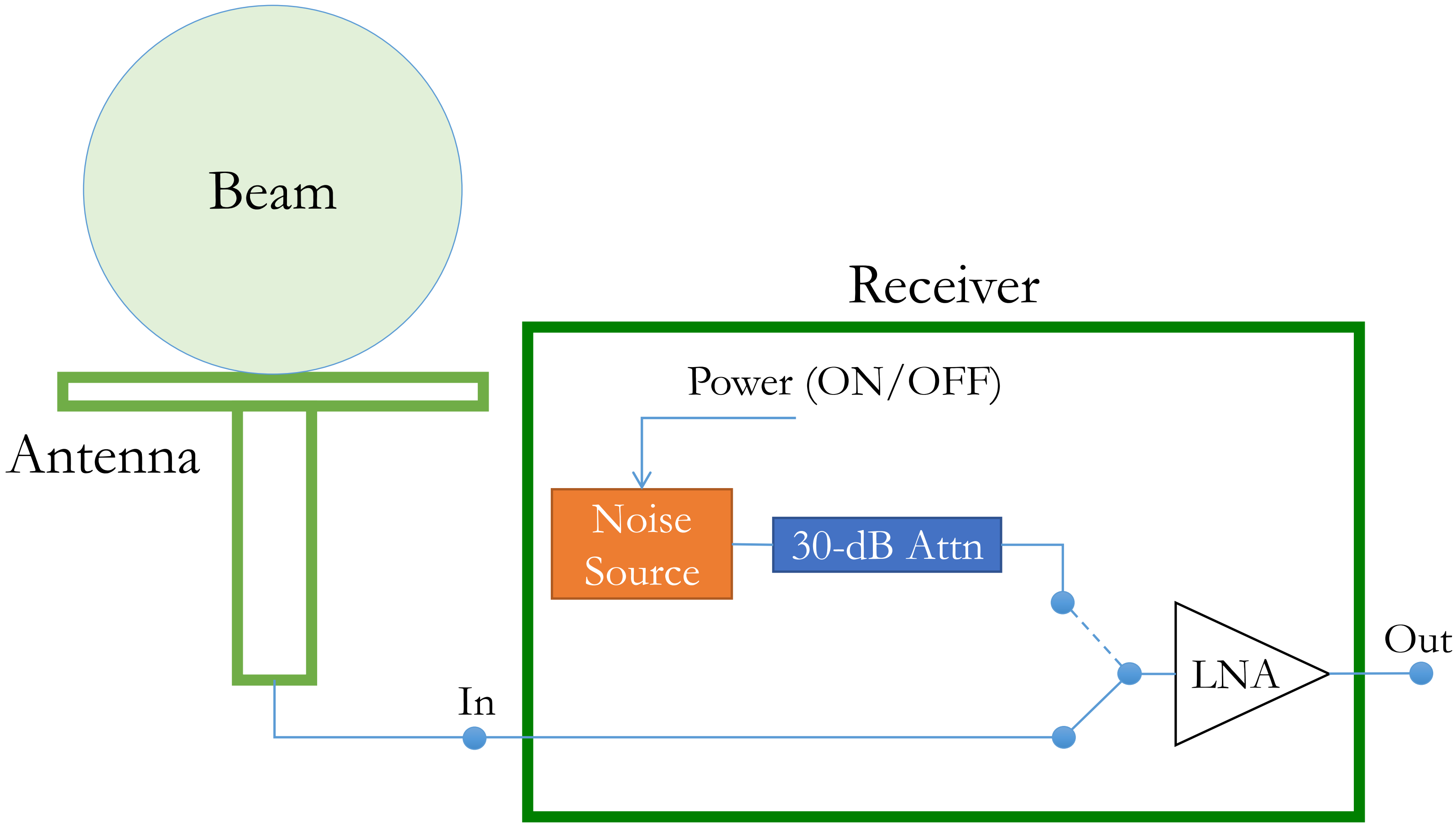
$$\nu_{\text{rest frame}} = 1420 \text{ MHz}$$

Due to Cosmological Expansion

$$\nu_{\text{obs}} = \frac{\nu_{\text{rest frame}}}{(1+z)}$$

Redshift	Frequency	
0	1420 MHz	
6	200 MHz	First Billion Years
13	100 MHz	
140	10 MHz	

Field Relative Calibration

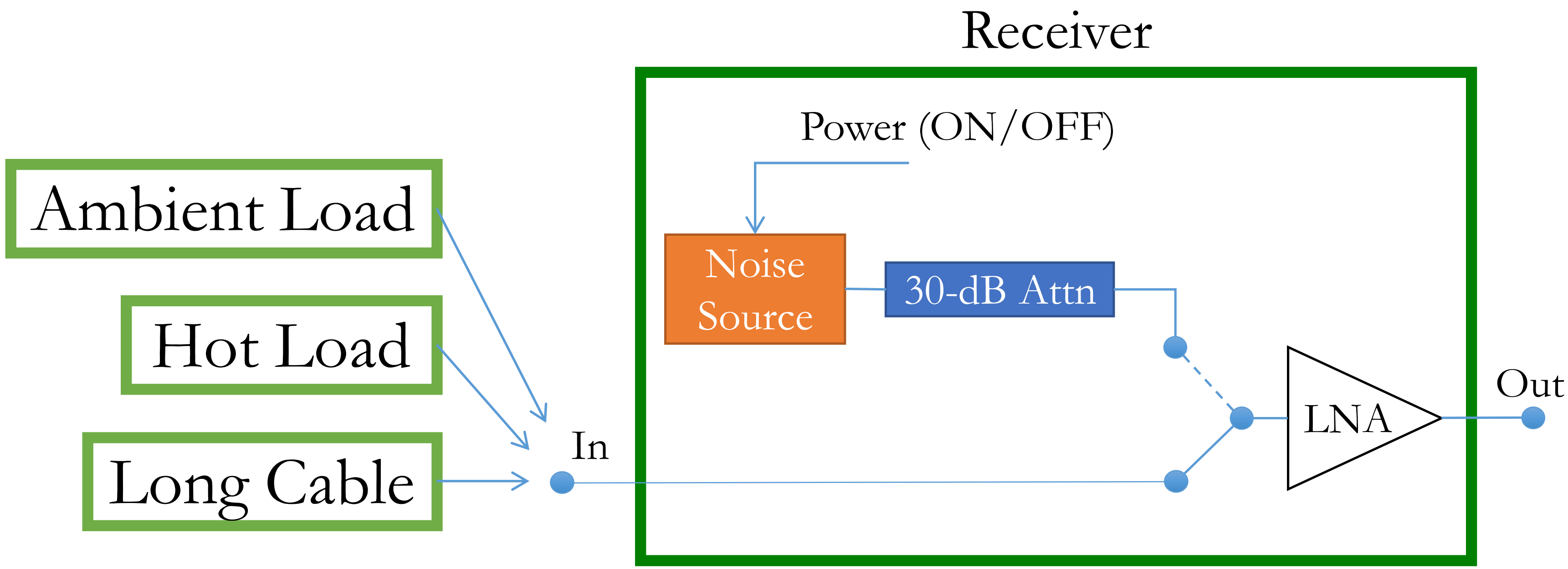


3-position switching **removes time variability.**

In each 3-position switching cycle we measure **power spectral density** from:

1) **Antenna**
2) **Ambient Load**
3) **Ambient Load + Noise Source**

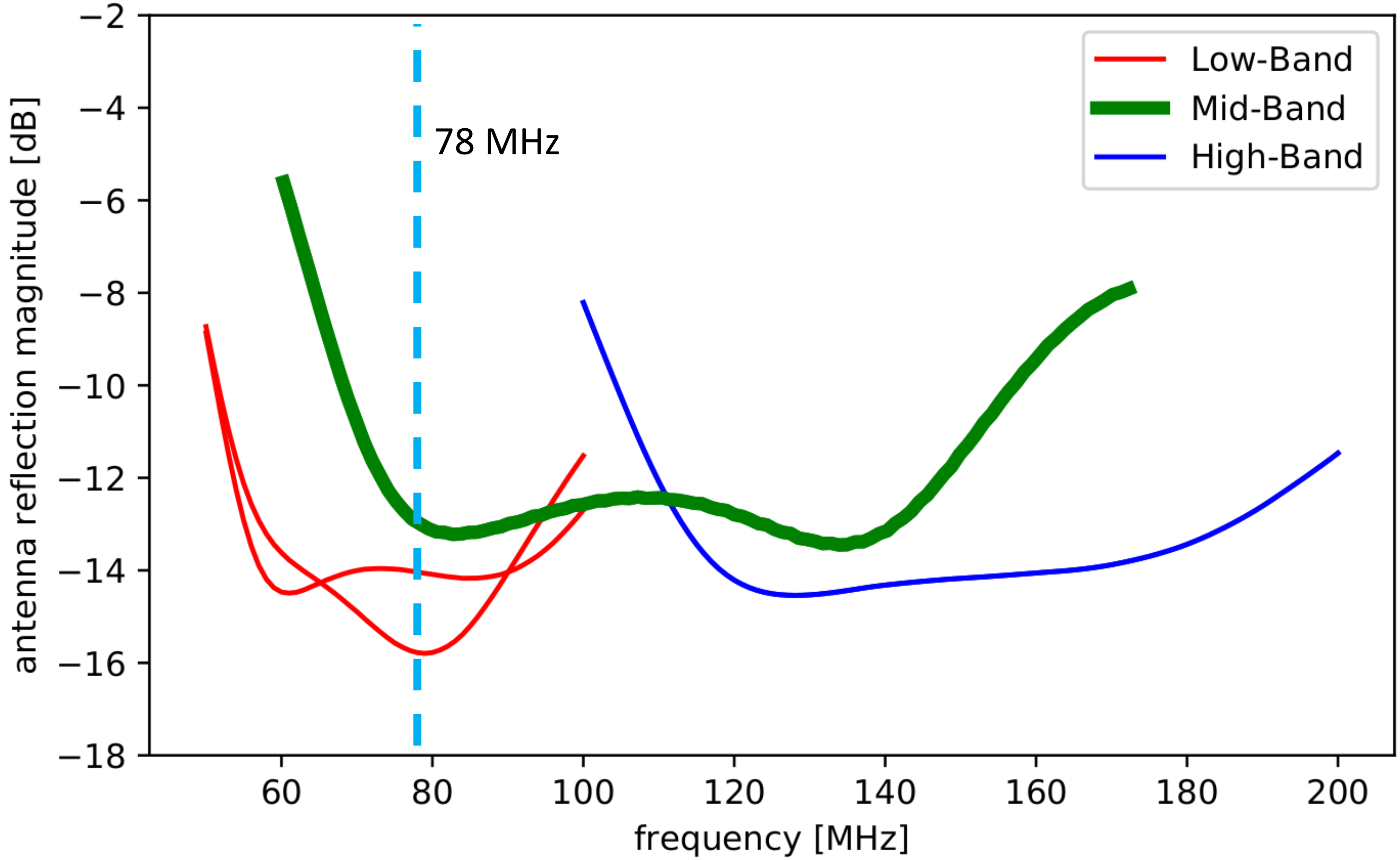
Absolute Lab Calibration



Receiver parameters are obtained measuring **calibration standards in the lab**.

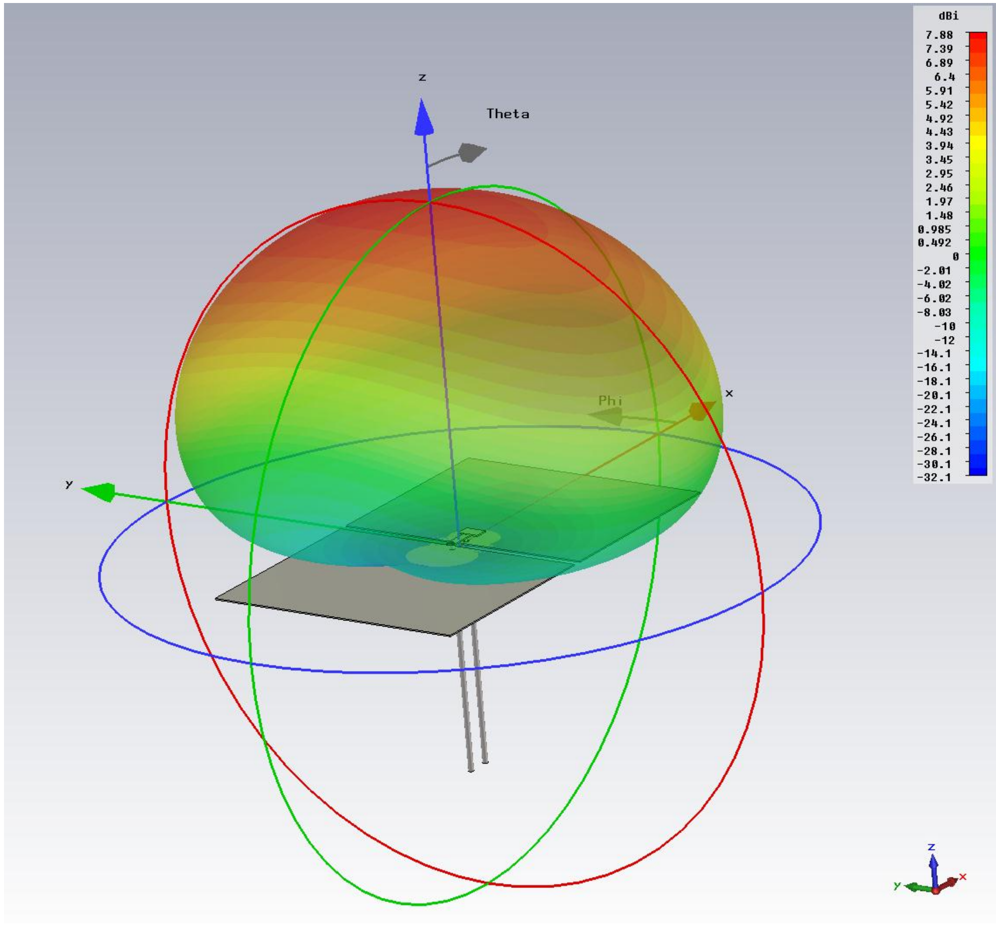
We measure with high precision and accuracy the **spectrum, reflection, and temperature of the standards**.

Antenna Reflection Coefficients



Beam Chromaticity

Simulated Antenna Beam



Antenna-to-Sky Temperature

$$\langle\, T_{\mathrm{ant}}(\nu, \mathrm{LST})\,\rangle_{\Omega} = \int T_{\mathrm{sky}}(\nu, \mathrm{LST}, \Omega) \cdot B(\nu, \mathrm{LST}, \Omega)\; d\Omega$$

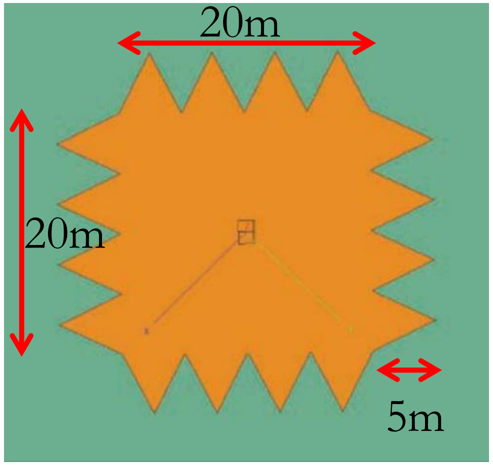
$$\langle\, T_{\mathrm{ant}}(\nu, \mathrm{LST})\,\rangle_{\Omega} = C(\nu, \mathrm{LST}) \;\cdot \big\langle\, T_{\mathrm{sky}}(\nu, \mathrm{LST})\,\big\rangle_{\Omega}$$

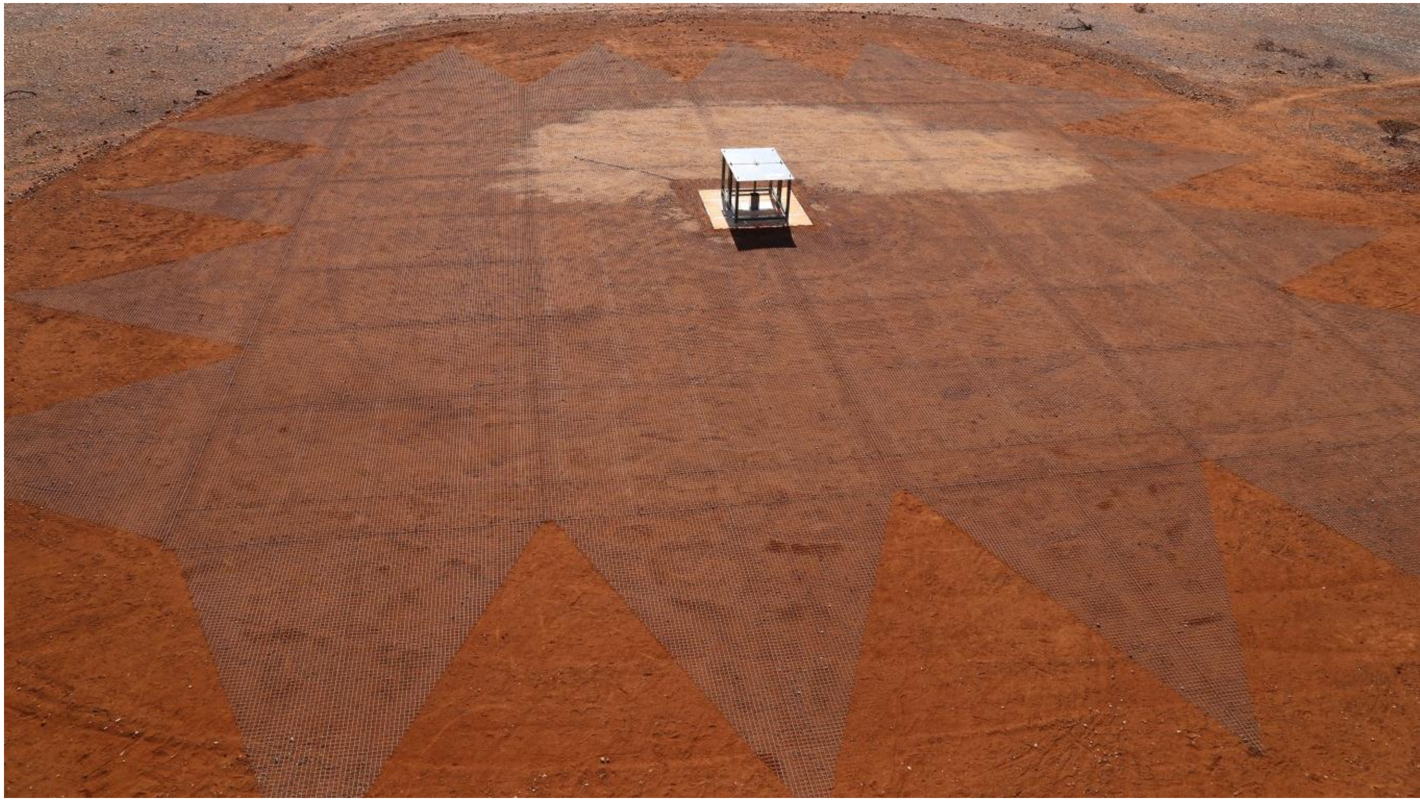
Chromaticity Correction

$$C(\nu, \mathrm{LST}) = \frac{\int T_{\mathrm{sky}}(\boldsymbol{\nu}_{\mathbf{ref}}, \mathrm{LST}, \Omega) \cdot B(\boldsymbol{\nu}, \mathrm{LST}, \Omega)\; d\Omega}{\int T_{\mathrm{sky}}(\boldsymbol{\nu}_{\mathbf{ref}}, \mathrm{LST}, \Omega) \cdot B(\boldsymbol{\nu}_{\mathbf{ref}}, \mathrm{LST}, \Omega)\; d\Omega}$$

Low-Band Ground Plane

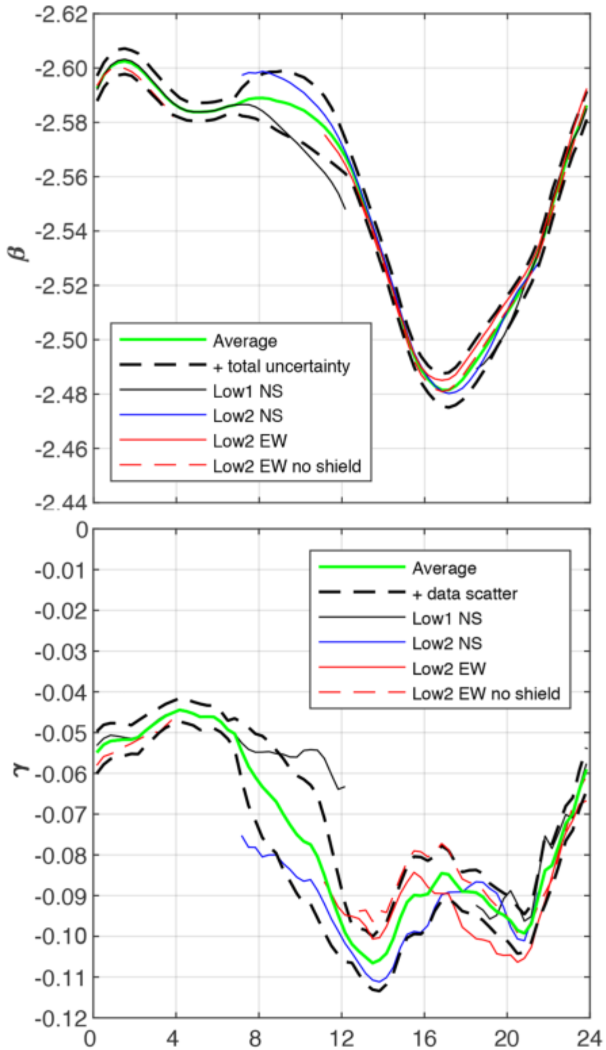
Extended Ground Plane:
Central Square: 20m x 20m
16 Triangles: 5m-long





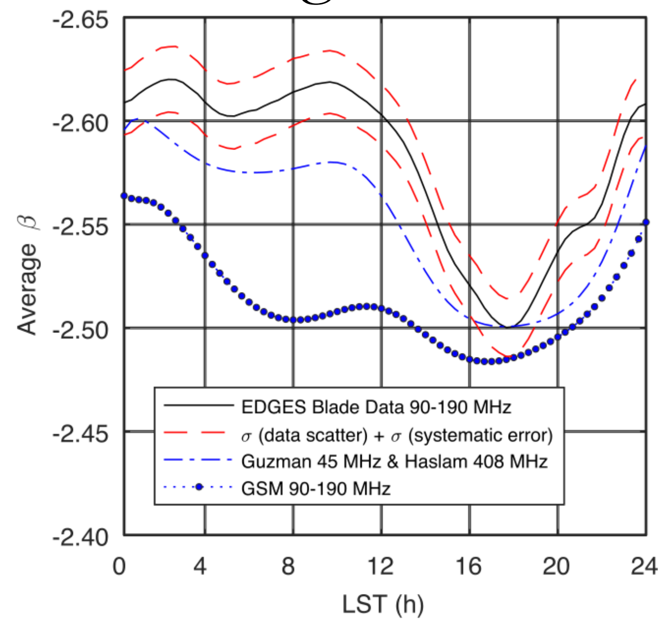
Foreground Spectral Index

Low-Band



LST (h)

High-Band



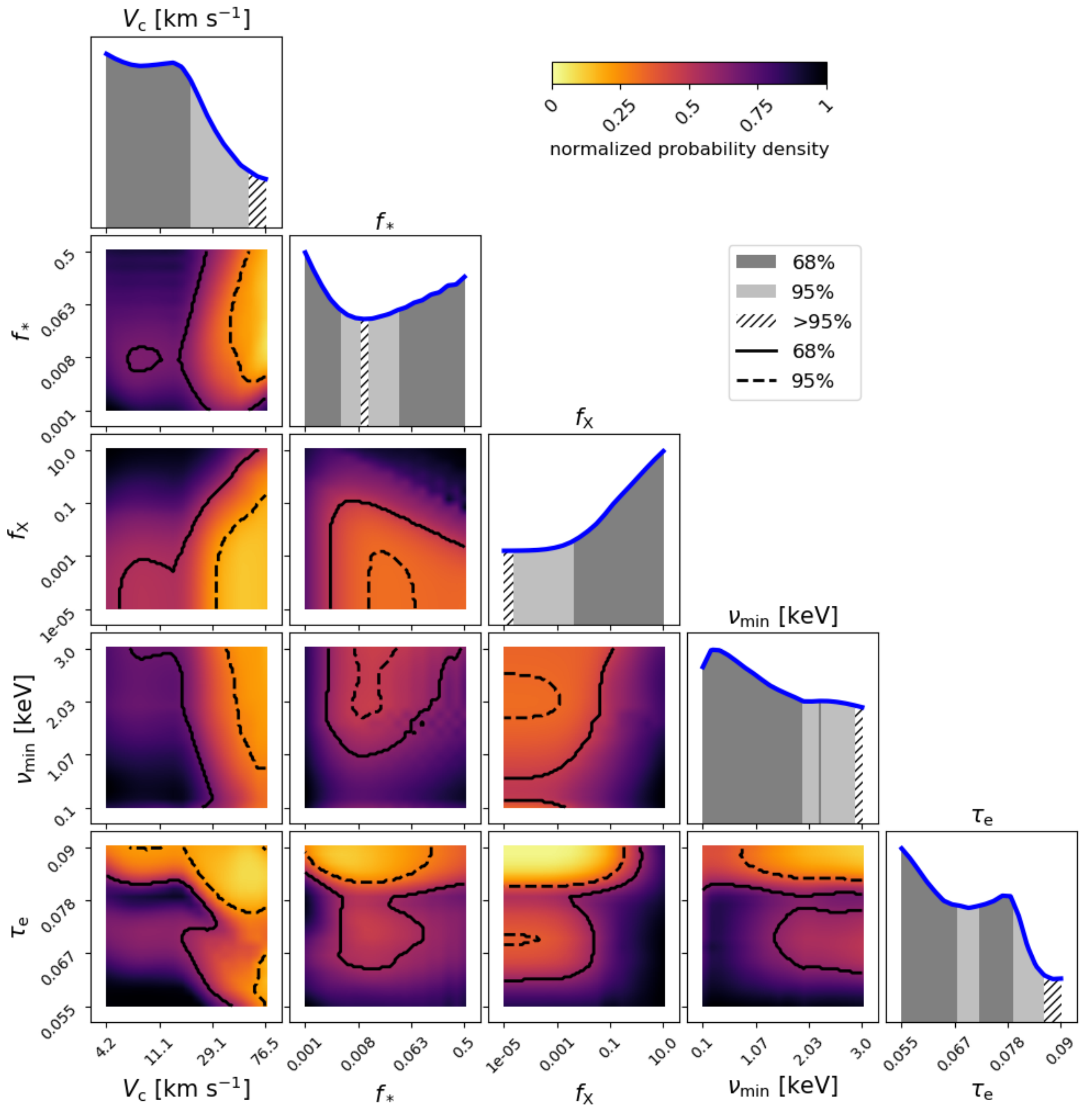
Bayesian Approach

Posterior **Likelihood** **Prior**

$$P(\theta|D) \propto P(D|\theta) \cdot P(\theta)$$

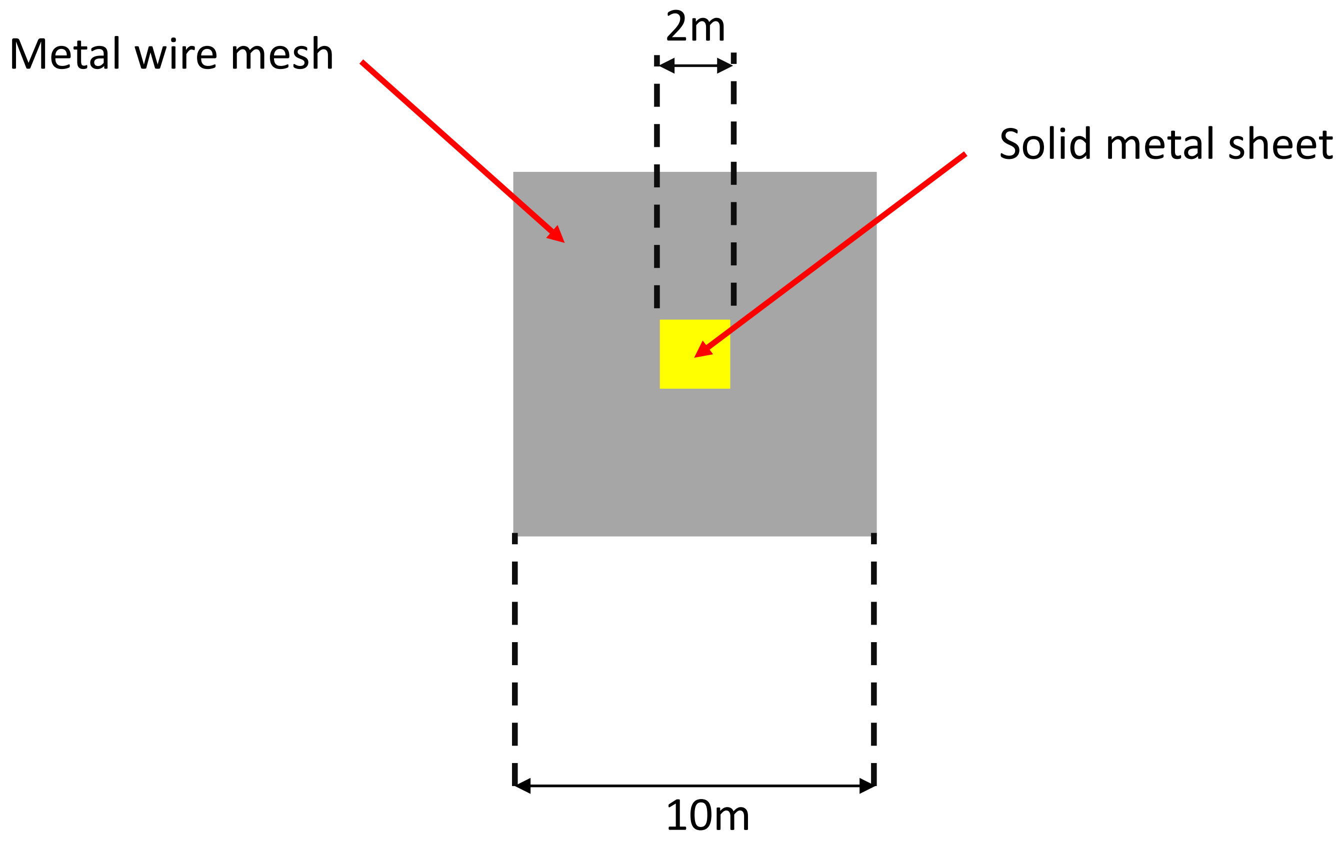
$$\propto P(D_1|\theta) \cdot P(D_2|\theta) \cdot P(D_3|\theta) \cdot P(\theta)$$

Constraints from EDGES **High-Band**

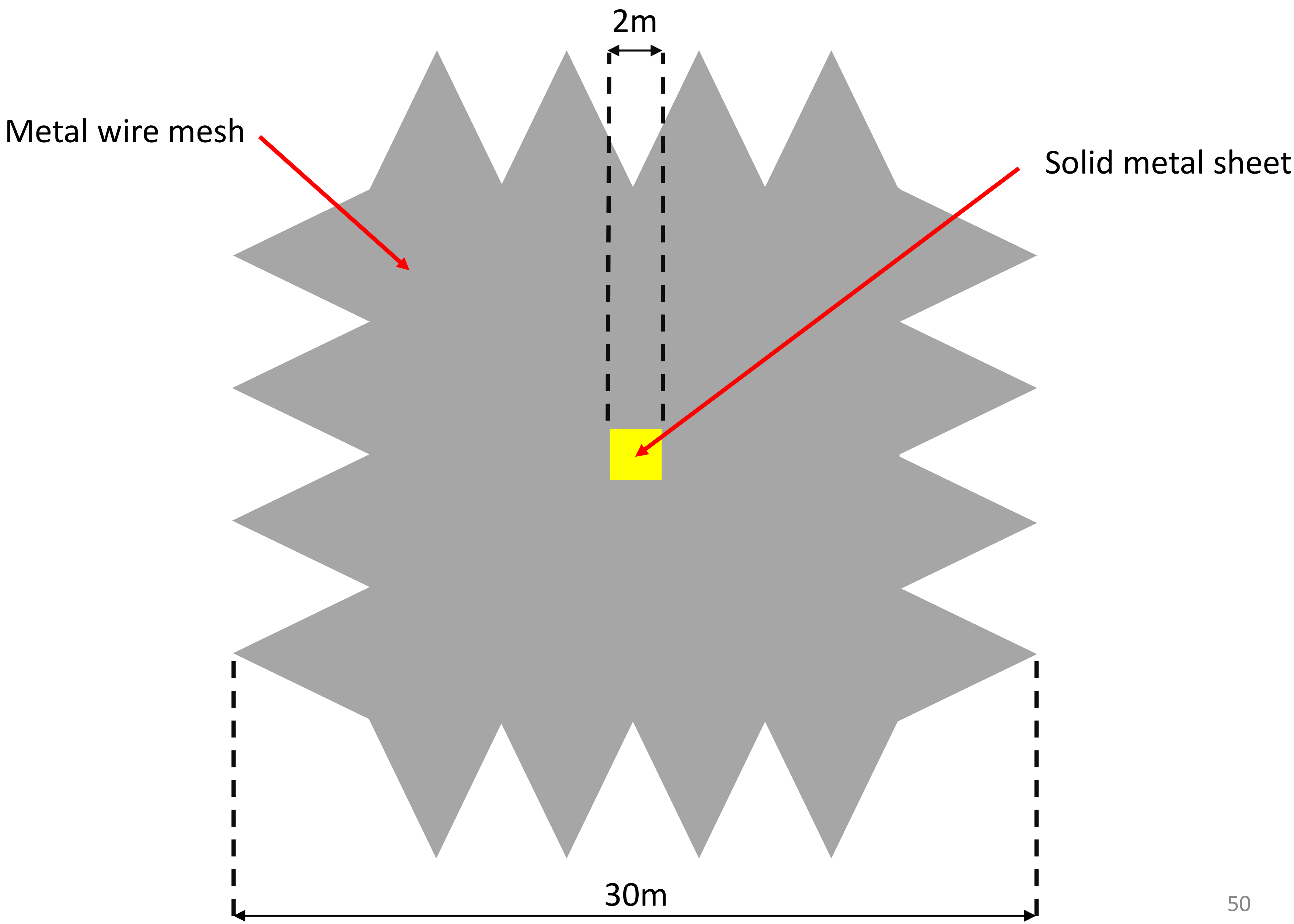


Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019

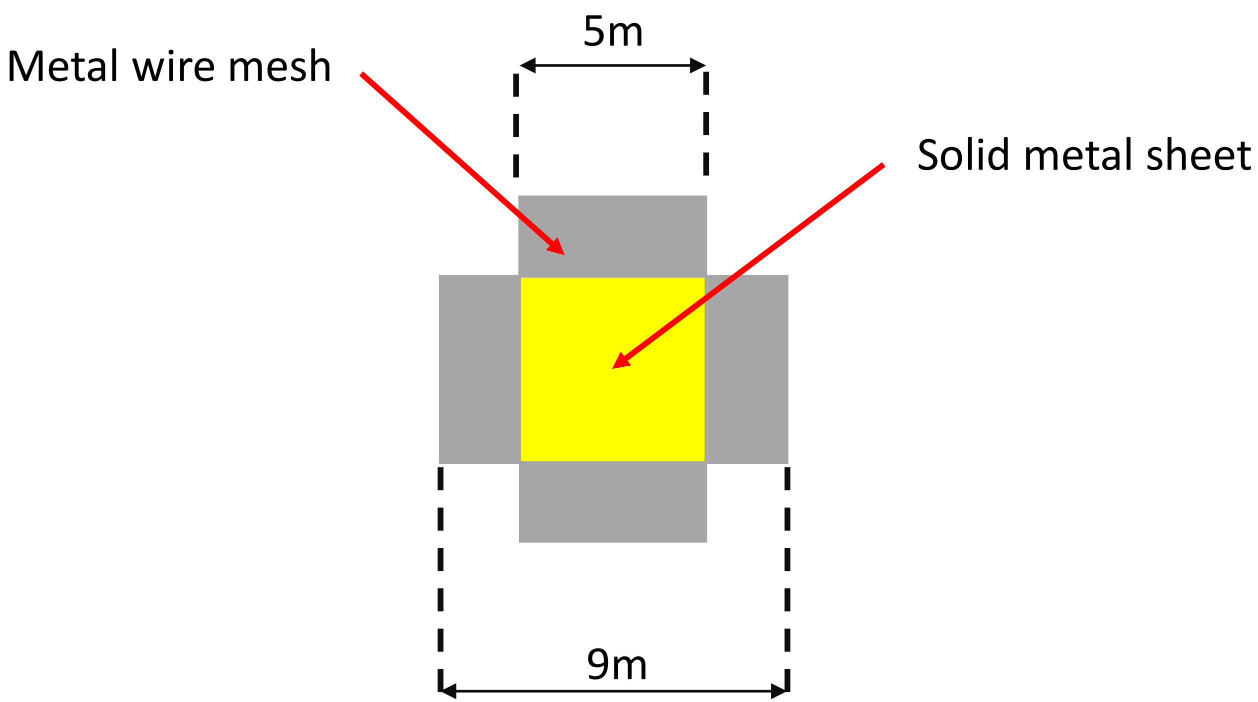
Low-Band Ground Plane: 2015-2016



Same Ground Plane as **Low-Band**



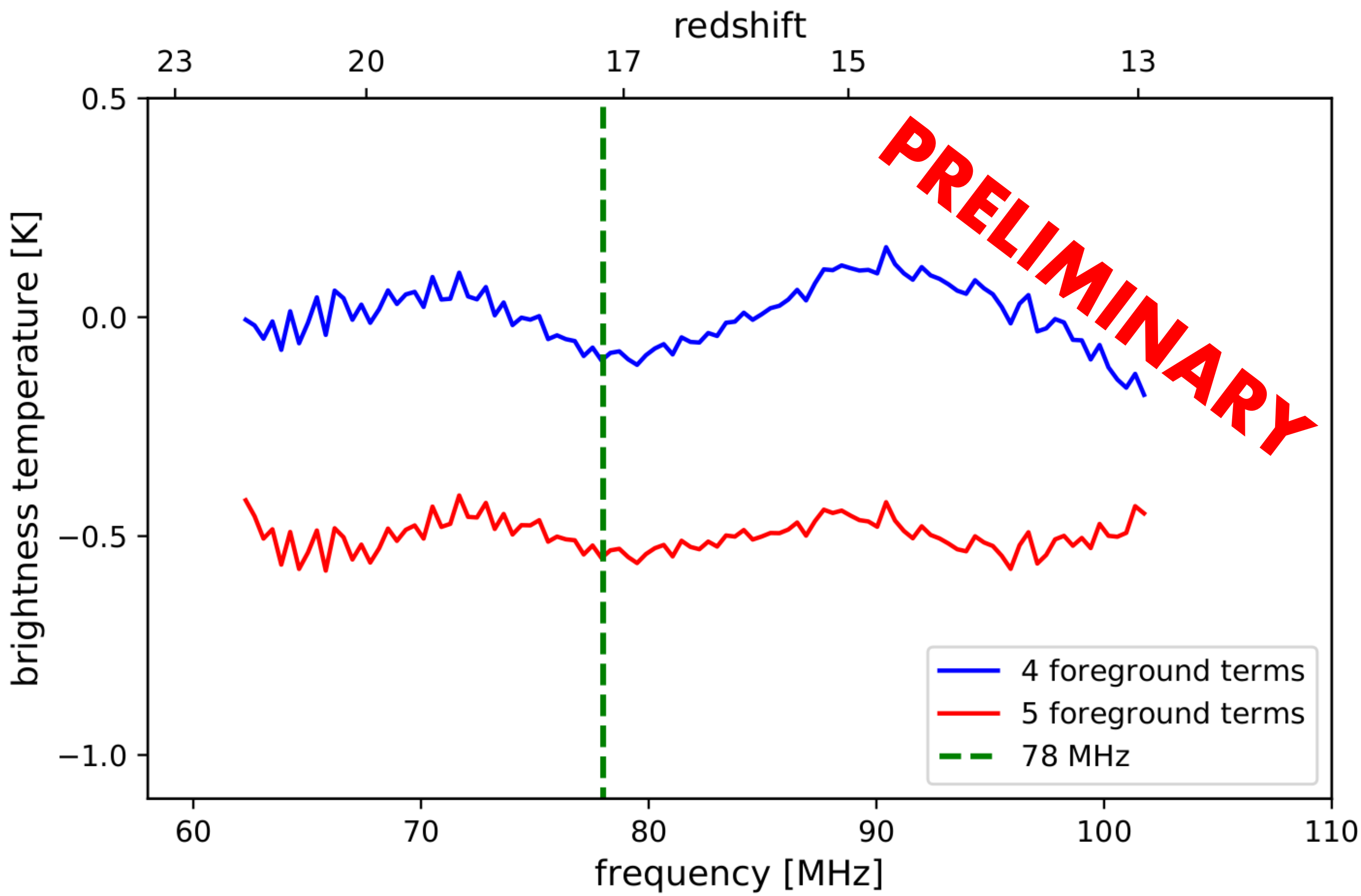
Low-Band Ground Plane: 2018-2019



We call this configuration

"Low-Band 3"

Preliminary **Low-Band 3** Results



Monsalve, Mahesh, Rogers, Bowman, Mozdzen, & Johnson (in preparation)

1) Data from **August - October 2018.**
2) **Low foregrounds**.
3) Best-fit absorption parameters **consistent with Bowman et al. (2018)**.

Model of the Spectrum

$$m(\nu) = m_{21}(\nu) + m_{\text{fg}}(\nu)$$

Phenomenological 21-cm Model
"Flattened Gaussian"

$$m_{21}(\nu, \boldsymbol{\theta_{21}}) = -\boldsymbol{A} \left(\frac{1 - e^{-\boldsymbol{\tau}\, e^{B}}}{1 - e^{-\boldsymbol{\tau}}} \right)$$

$$B = \frac{4\,(\nu - \boldsymbol{\nu_0})^2}{\boldsymbol{w}^2} \quad \ln\left[-\left(\frac{1}{\boldsymbol{\tau}}\right) \ln\left(\frac{1 + e^{-\boldsymbol{\tau}}}{2} \right) \right]$$

$\boldsymbol{A}$: absorption amplitude
$\boldsymbol{\nu_0}$: center frequency
$\boldsymbol{w}$: width
$\boldsymbol{\tau}$: flattening parameter

“Foreground” Models

Linearized Version of Physically-Motivated Foreground Model

$$m_{\mathrm{fg}}(\nu, \boldsymbol{a_i}) = \nu^{-2.5}\left\{\boldsymbol{a_0} + \boldsymbol{a_1}[\log\nu] + \boldsymbol{a_2}[\log\nu]^{\mathbf{2}} + \boldsymbol{a_3}\nu^{-2.0} + \boldsymbol{a_4}\nu^{0.5}\right\}$$

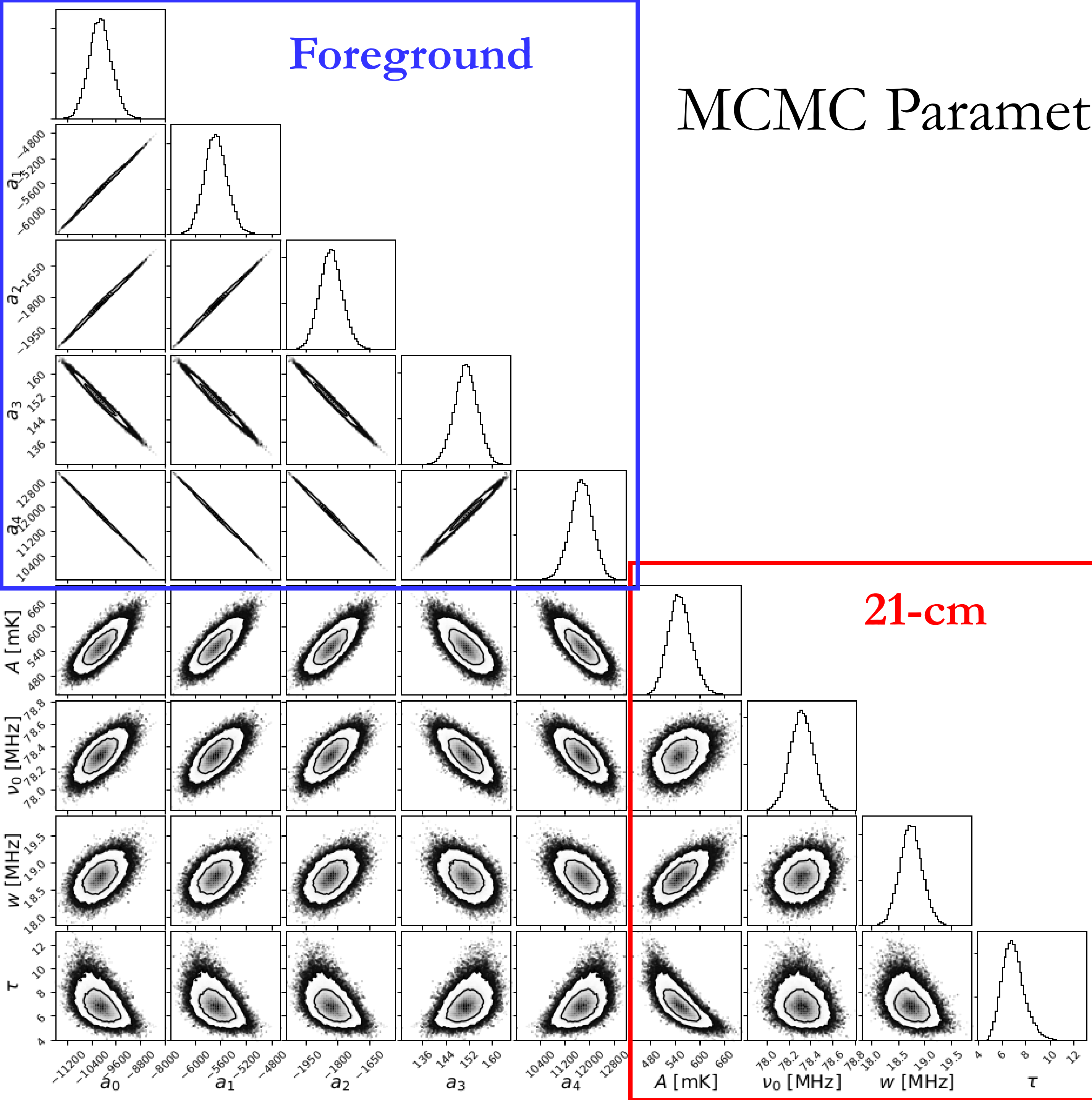
Alternative Polynomial Model

$$m_{\mathrm{fg}}(\nu, \boldsymbol{a_i}) = \nu^{-2.5}\sum_{i=0}^{N_{\mathrm{fg}}-1} \boldsymbol{a_i}\nu^{i}$$

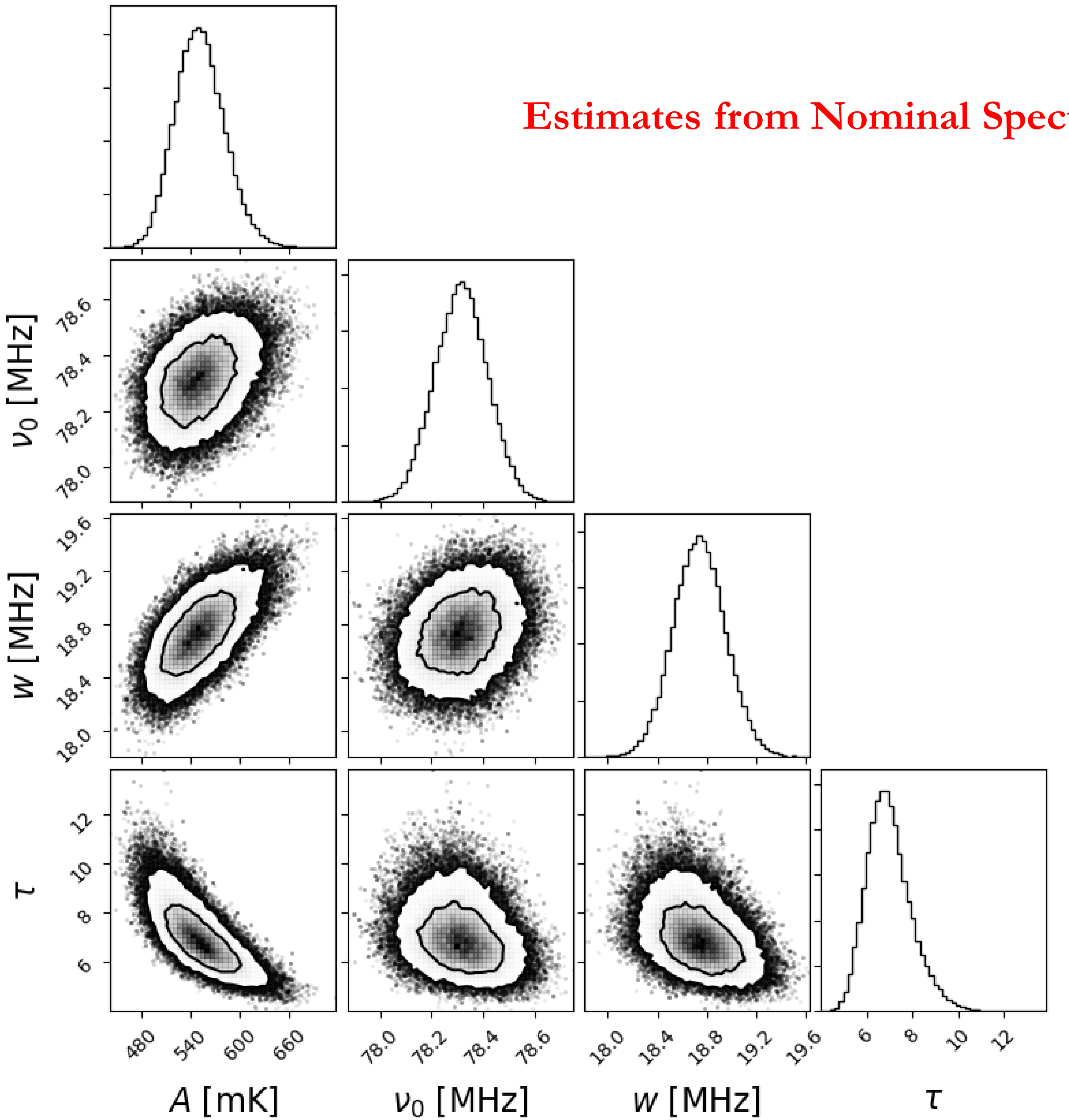
Smooth sets of basis functions that model well, with few terms, the spectrum over wide frequency ranges.

Linear fit coefficients **not intended to be assigned physical interpretation**.

MCMC Parameter Estimation



Parameter Estimates



Estimates from Nominal Spectrum

Interactions of Baryons with Dark Matter?

LETTER

https://doi.org/10.1038/s41586-018-0151-x

A small amount of mini-charged dark matter could cool the baryons in the early Universe

Julian B. Muñoz[1]* & Abraham Loeb[2]

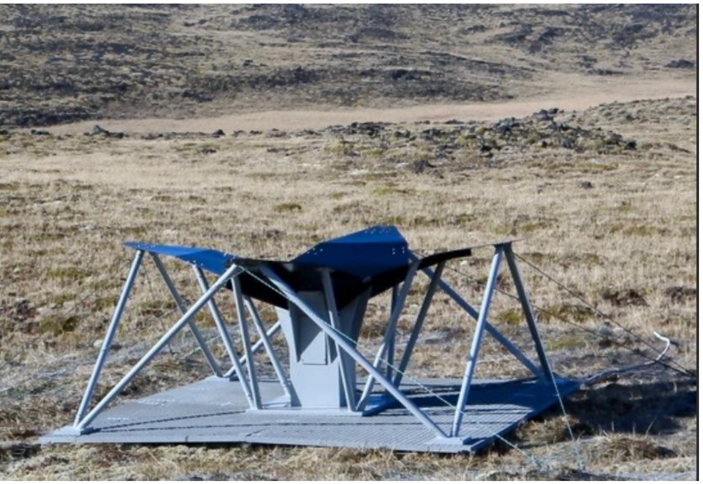
NATURE, 557, 31 MAY 2018

1) Enough IGM cooling achieved if **small fraction (<1%) of DM particles** posses **electric mini-charge (~10^{-6} the charge of an electron)**.

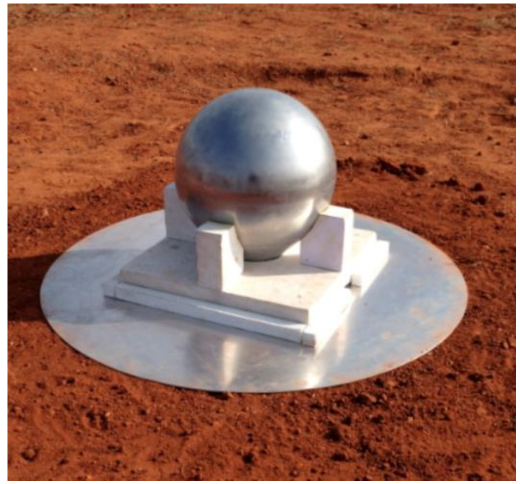
2) **Mass of these DM particles constrained to ~ 1-60 MeV**.

Global 21-cm Experiments

PRI^{Z}M
(McGill, Sievers et al.)



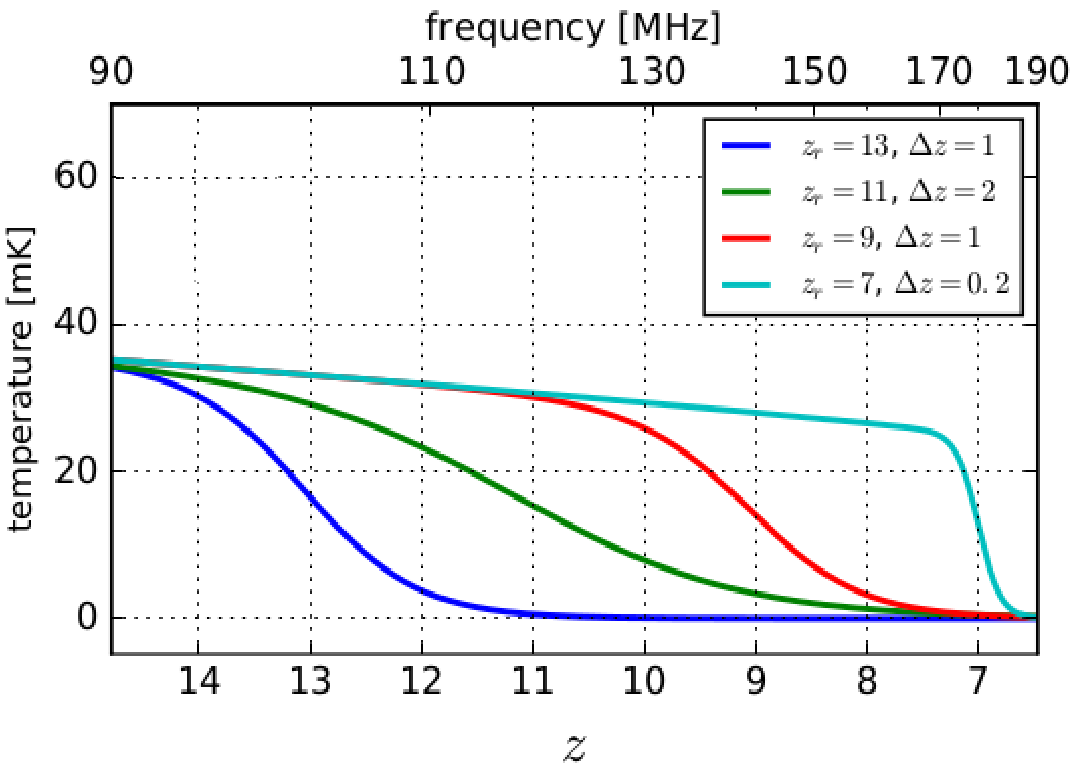
SARAS 2
(RRI, Subrahmanyan et al.)



LEDA
(Harvard, Greenhill et al.)

CTP
(NRAO, Bradley et al.)

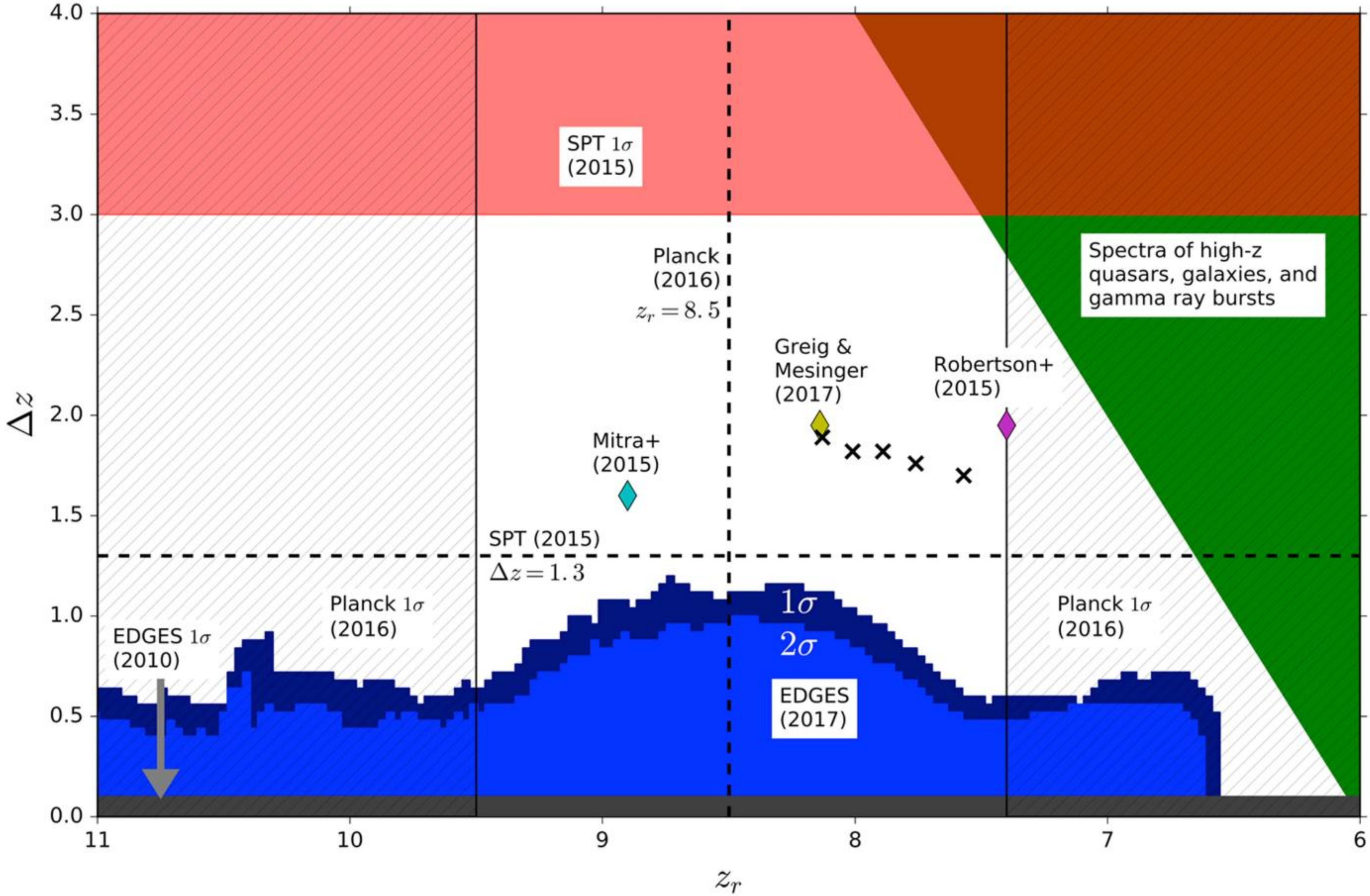
Epoch of Reionization Constraints (Hot IGM)



- TANH model for the evolution of the average neutral hydrogen fraction ($\bar{x}_{\mathrm{HI}}$).
- Parameters are EoR center (z_r) and duration (Δz).

Monsalve, Rogers, Bowman, & Mozdzen (2017b)

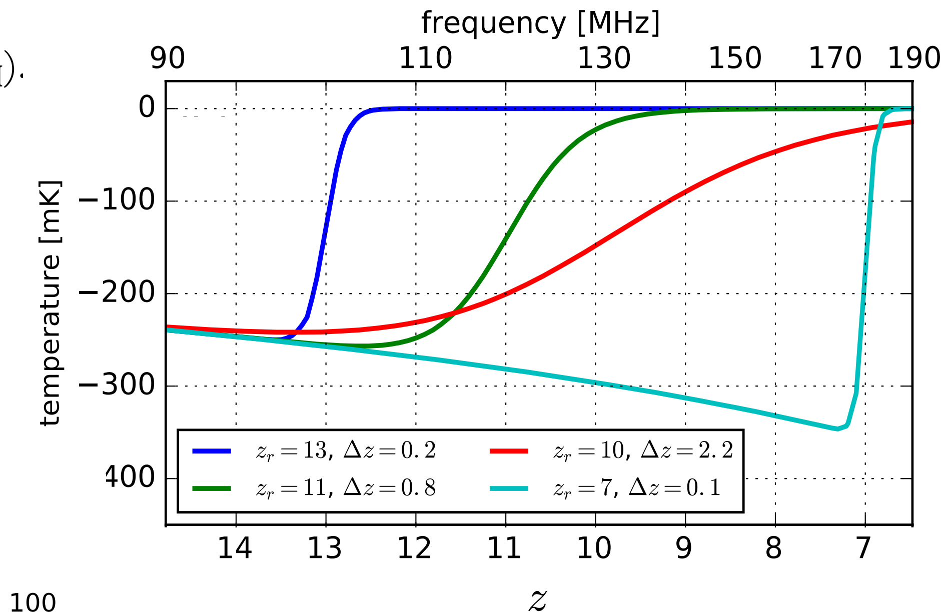
Epoch of Reionization Constraints (Hot IGM)



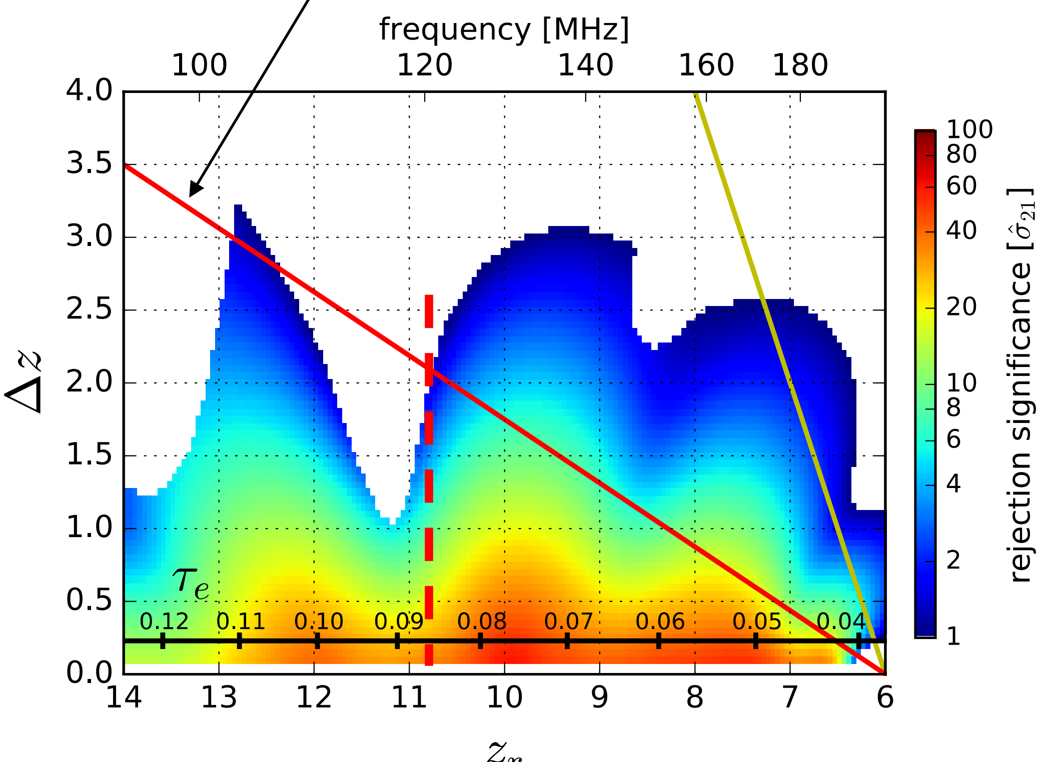
Monsalve, Rogers, Bowman, & Mozdzen (2017b)

NO IGM Heating prior to Reionization

1) Perfect Lyman-α coupling at early times ($T_S = T_{IGM}$).
2) No X-ray heating. IGM cools adiabatically.
3) Only reionization.
4) TANH model for $\bar{x}_{HI}$.



$\bar{x}_{HI} < 1\%$ at $z = 6$



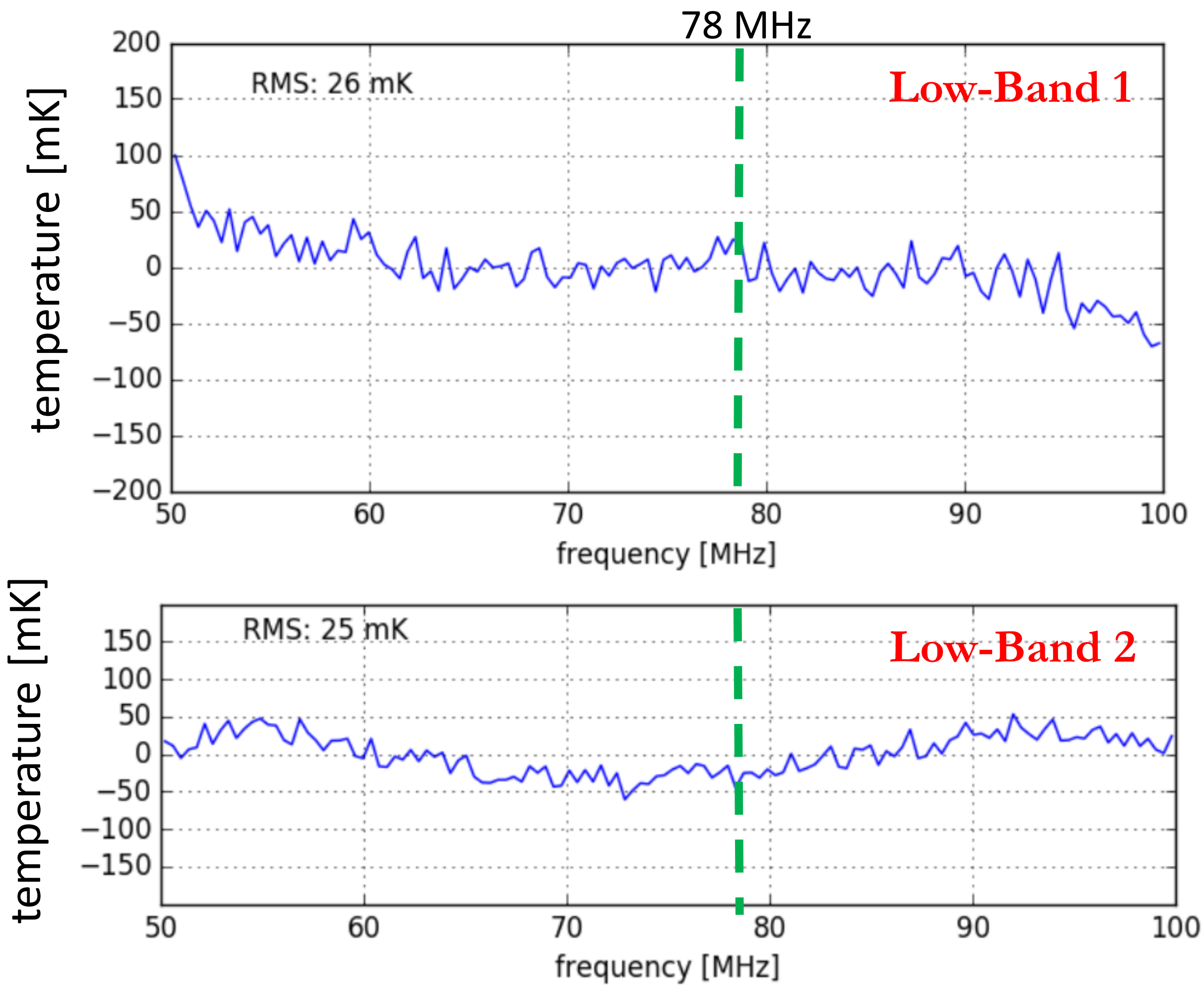
We rule out at $\geq 2\sigma$ all models with:

- $\bar{x}_{HI} \leq 1\%$ at $z = 6$
- $0.086 \geq \tau_e \geq 0.038$

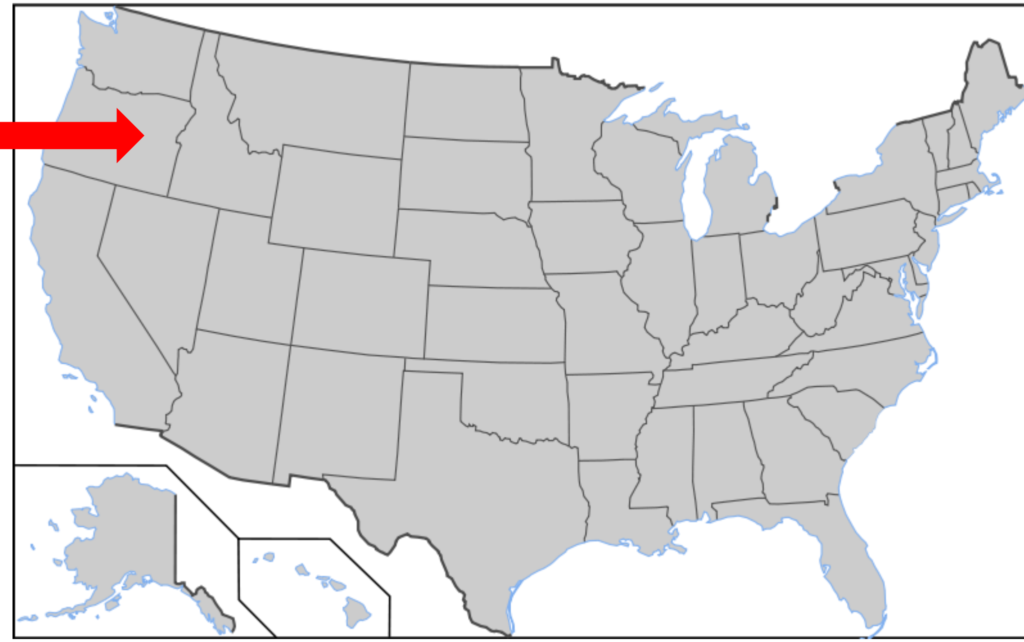
Monsalve, Rogers, Bowman, & Mozdzen (2017b)

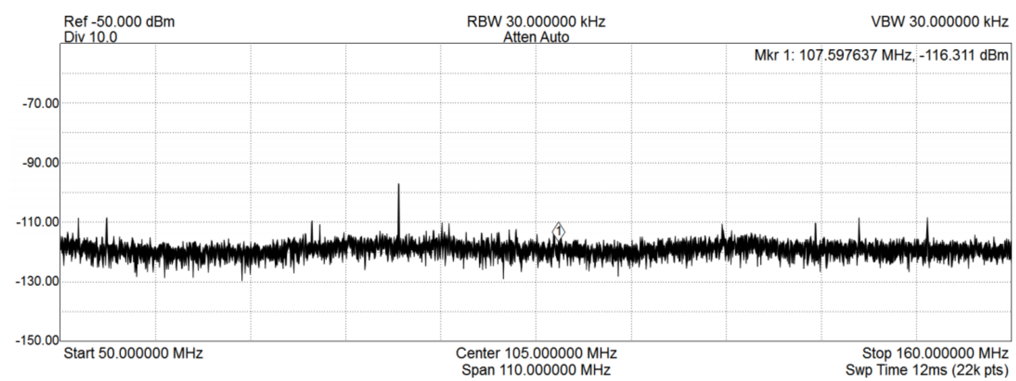
Verification Using ~300K Passive Noise Sources

Residuals After Removing a Constant



EDGES-3 Recently Proposed to NSF-ATI





1) Observe from **Oregon, USA**.

2) **Improved** hardware.

3) More **portable design**.

4) Electronics **within antenna**.

ARIZONA STATE UNIVERSITY

MIT HAYSTACK OBSERVATORY

New Global 21-cm Experiment

MIST: Mapper of the IGM Spin Temperature

PI: Ricardo Bustos **Chilean Andes** Site elevation: 4,500 m

McGill UNIVERSITY
UCSC
NRAO
UNIVERSIDAD DE CHILE