Rencontres du Vietnam, Windows on the Universe
Quy Nhon, Vietnam

August 9, 2018

An Absorption Signal in the Sky-Averaged Radio Spectrum

Raul Monsalve[1], Judd Bowman[2], Alan Rogers[3], Thomas Mozdzen[2], Nivedita Mahesh[2]

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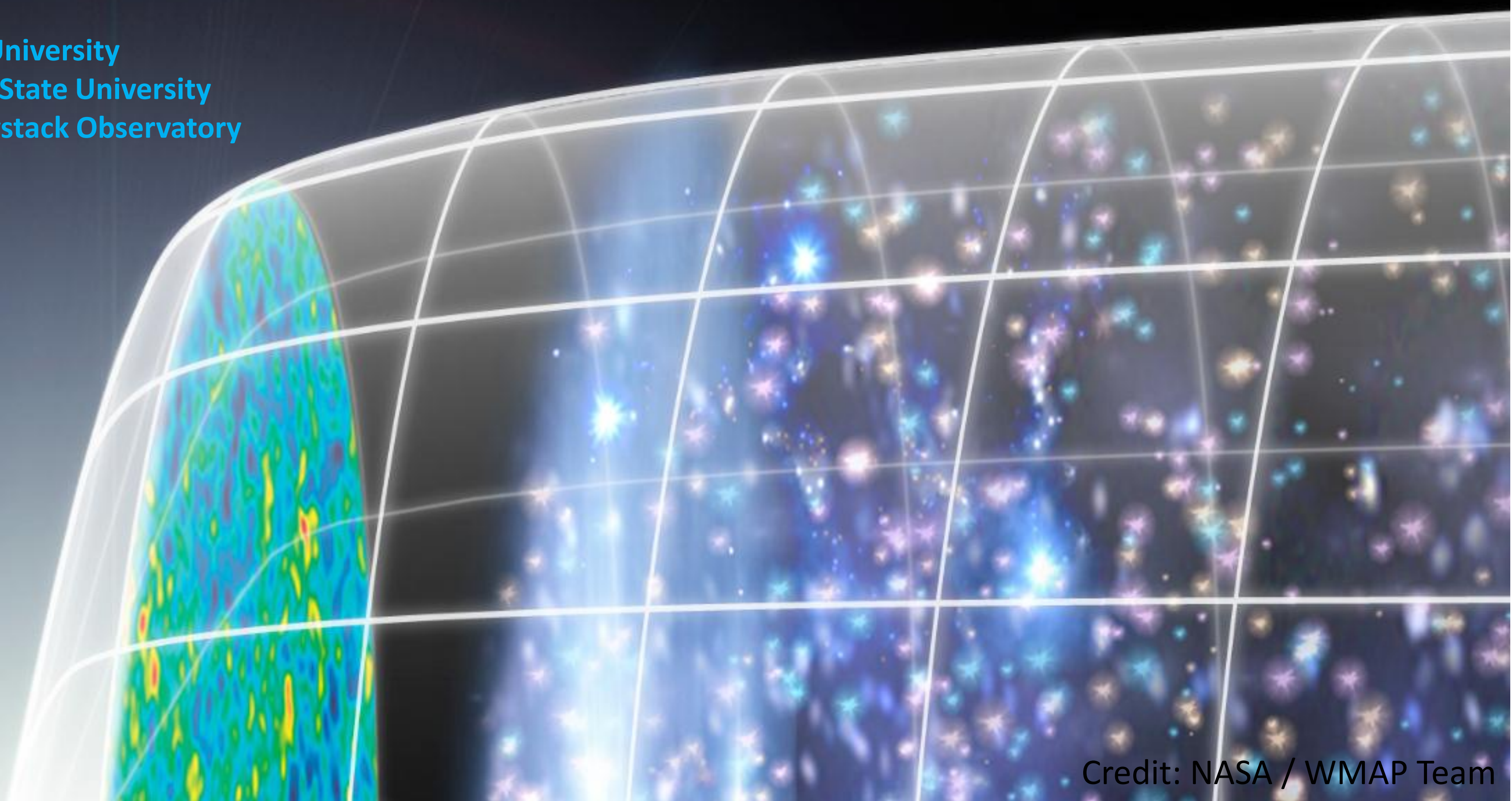


Credit: NASA / WMAP Team

Summary

1) The **EDGES experiment** has **detected an absorption feature** in the sky-averaged spectrum centered at 78 MHz.

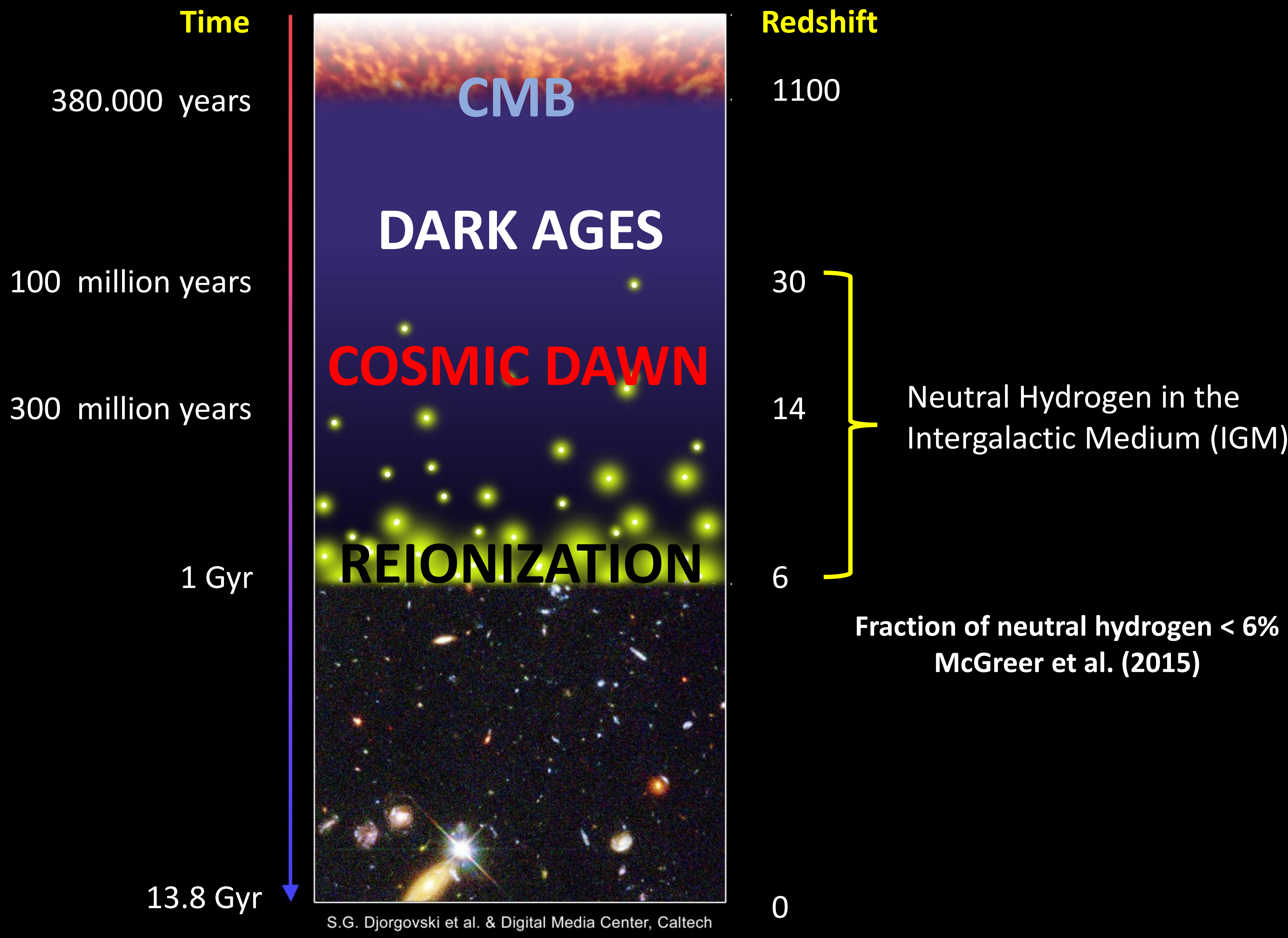
2) This is **consistent with stars forming by 180 Myrs after the Big Bang**.

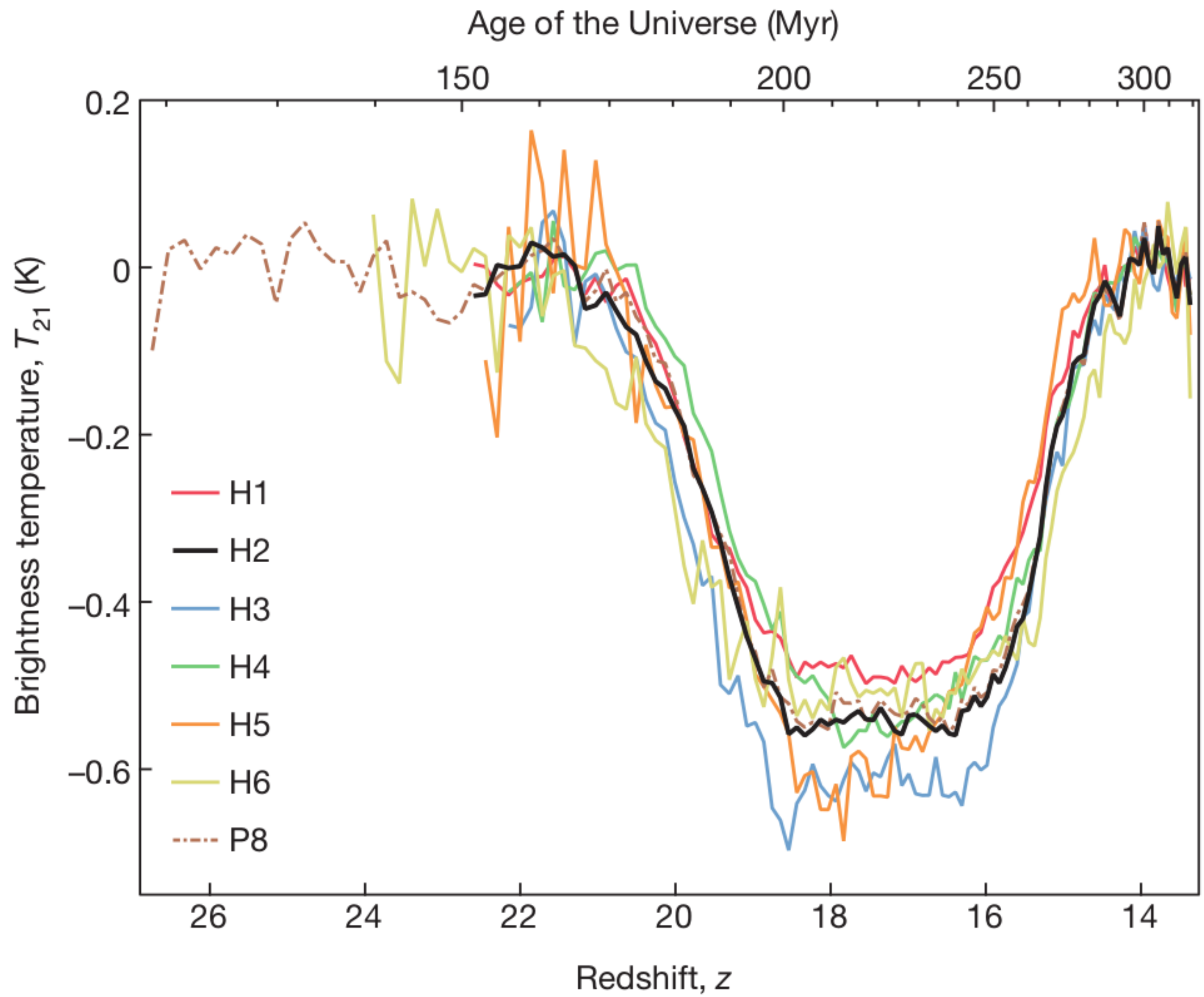
3) Feature is **deeper and sharper** than expected.

4) We **remain agnostic** regarding the **interpretation**.

5) We are **working to verify the measurement**.

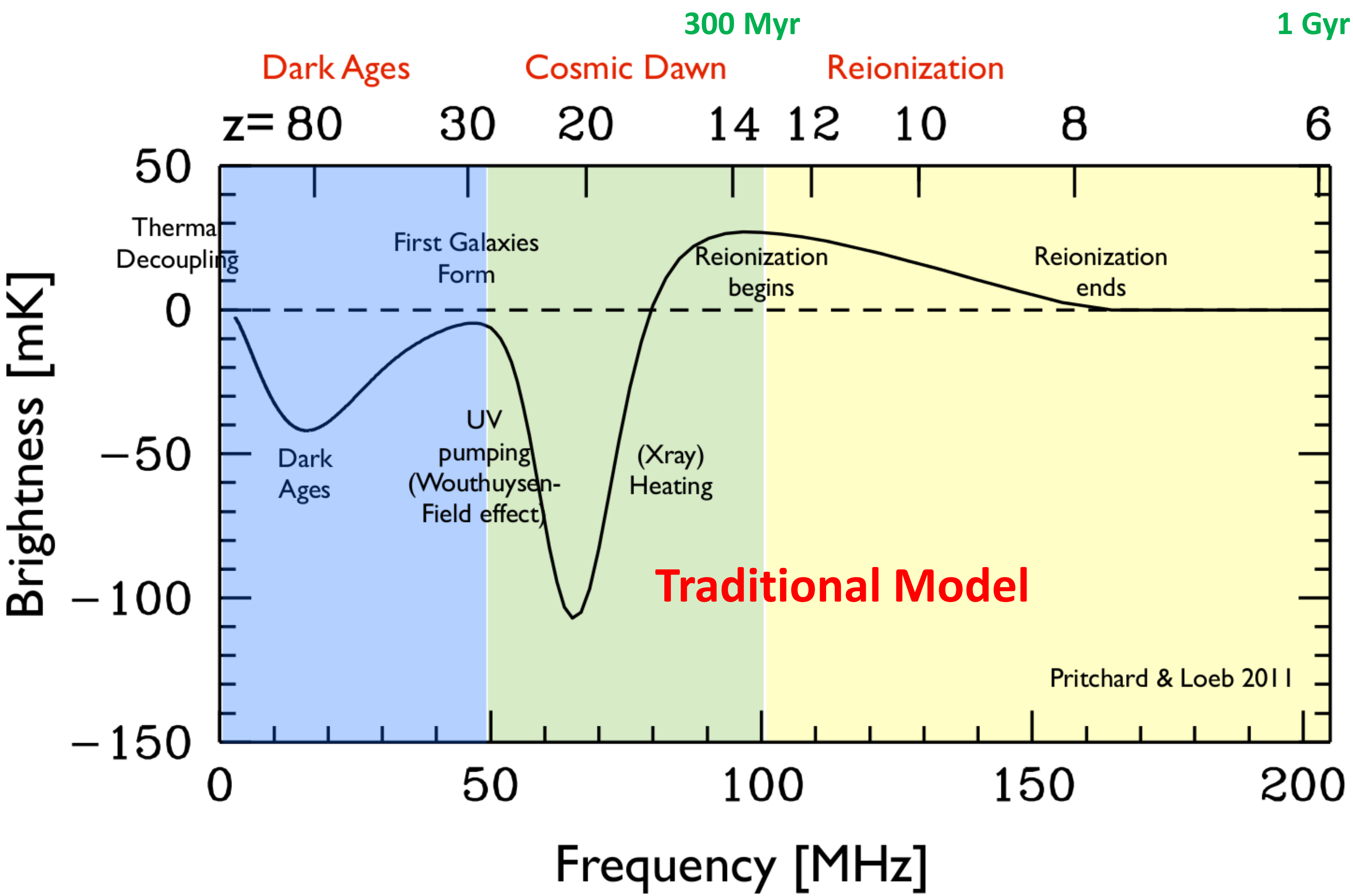
6) Also, **constraining high-z astrophysical parameters**, including properties of X-rays that heat the IGM.


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



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

Global (sky-average) 21-cm Signal



Global 21-cm Measurement

1) **One of few current alternatives** to access **Cosmic Dawn** ($z > 14$) period.

2) Probes the (sky-averaged) interaction of :
   - **IGM Neutral Hydrogen Fraction**
   - **IGM Kinetic and 21-cm Spin Temperature**
   - **Background Radiation Temperature**

4) Provides constraints on:
   - **Timing** and **strength** of UV coupling and X-ray heating
   - **Type** of early sources (PopII vs PopIII, Black Holes, X-Ray Binaries, etc.)
   - Star formation **cooling and feedback mechanisms**
   - **Redshift** and **Duration** of epoch of **Epoch of Reionization**

Challenges

1) **Hard instrument calibration** problem.

2) **Strong diffuse foregrounds** compared to 21-cm signal.

EDGES

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

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Dr. Alan Rogers
Dr. Raul Monsalve
Dr. Thomas Mozdzen
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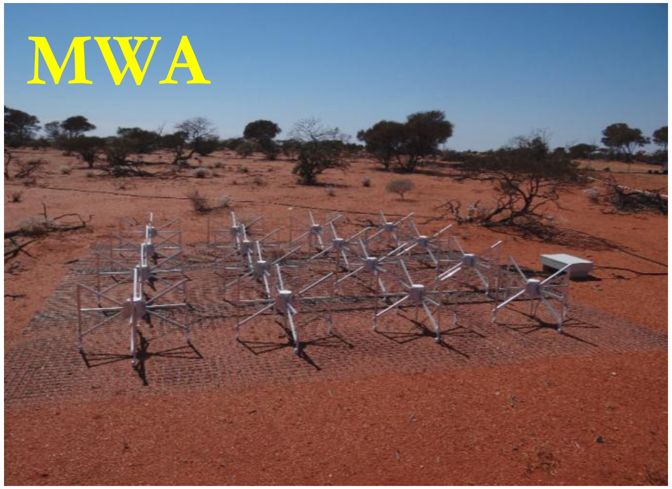
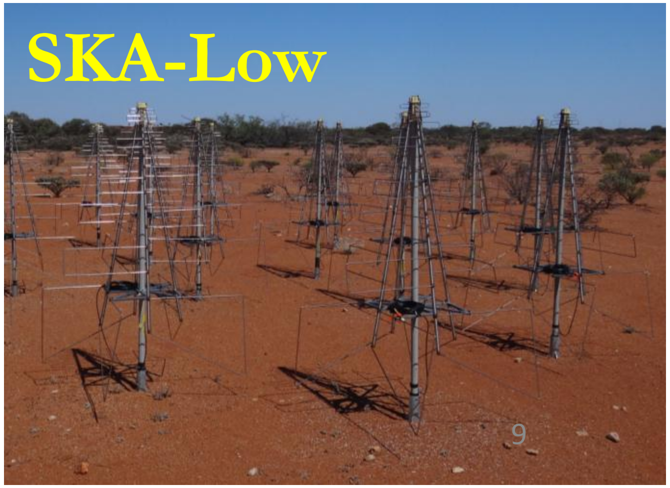
ASU
ARIZONA STATE UNIVERSITY

MIT HAYSTACK OBSERVATORY

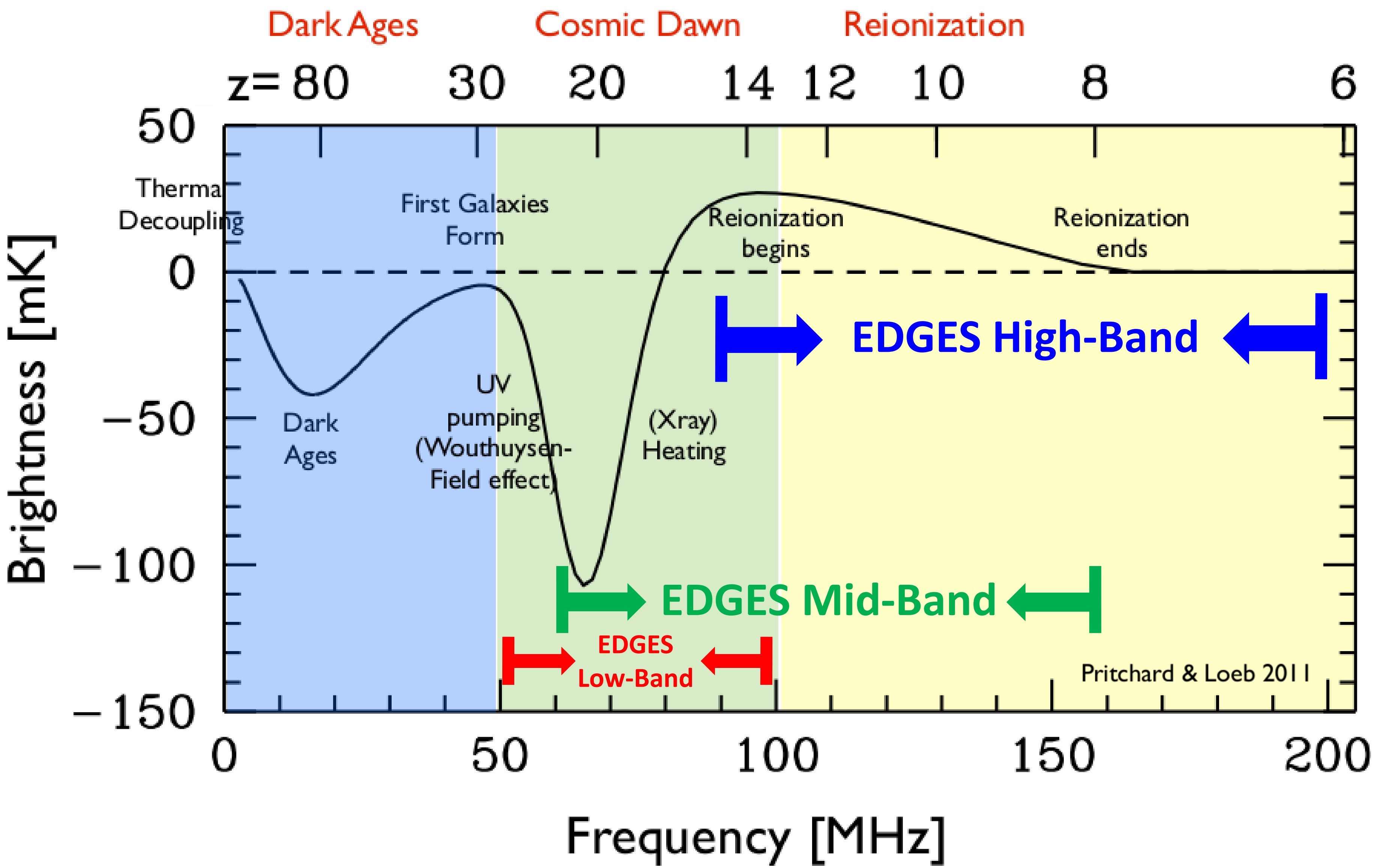
Western Australia

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

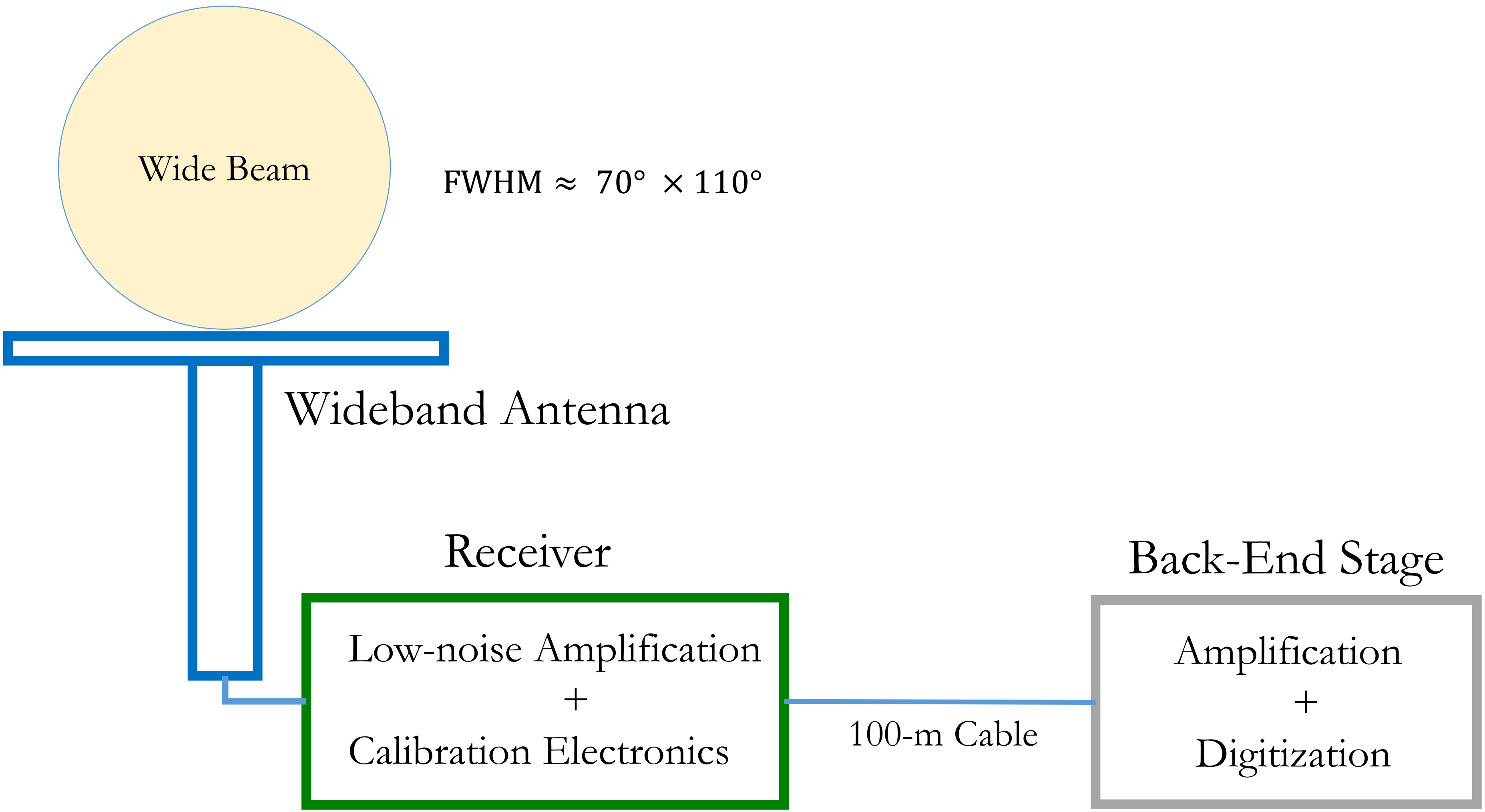




EDGES Instruments



EDGES Block Diagram



Instrumental Calibration

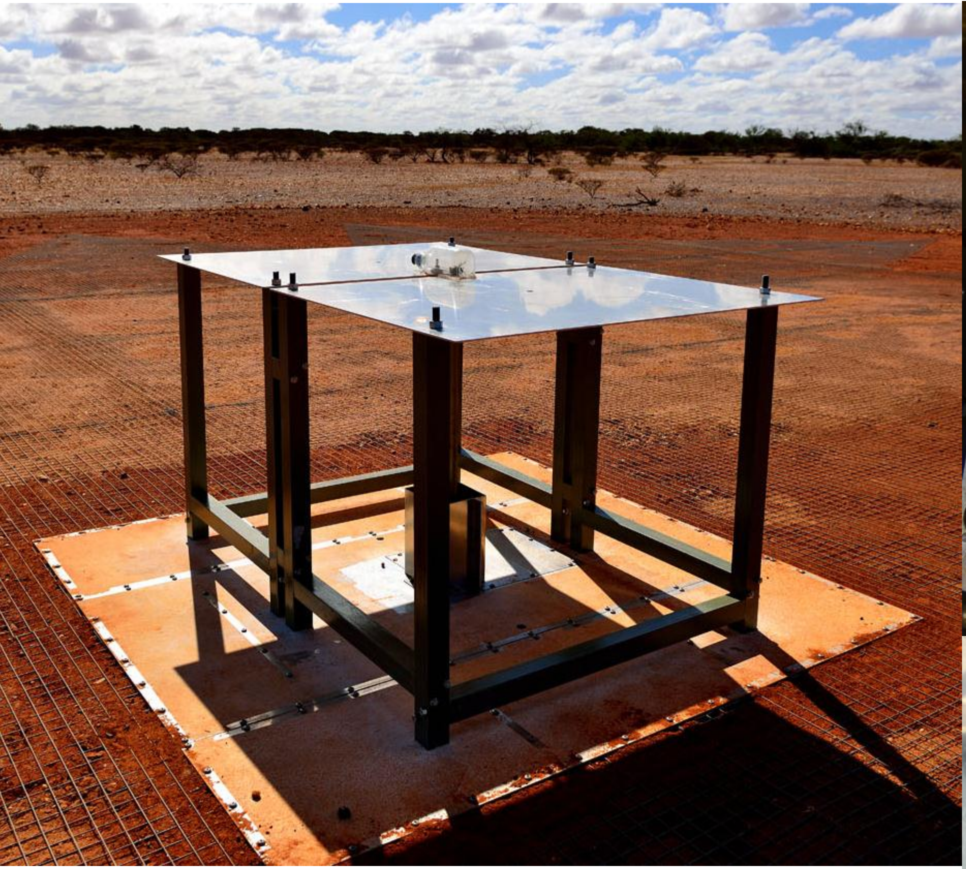
1) **Receiver gain and offset.**

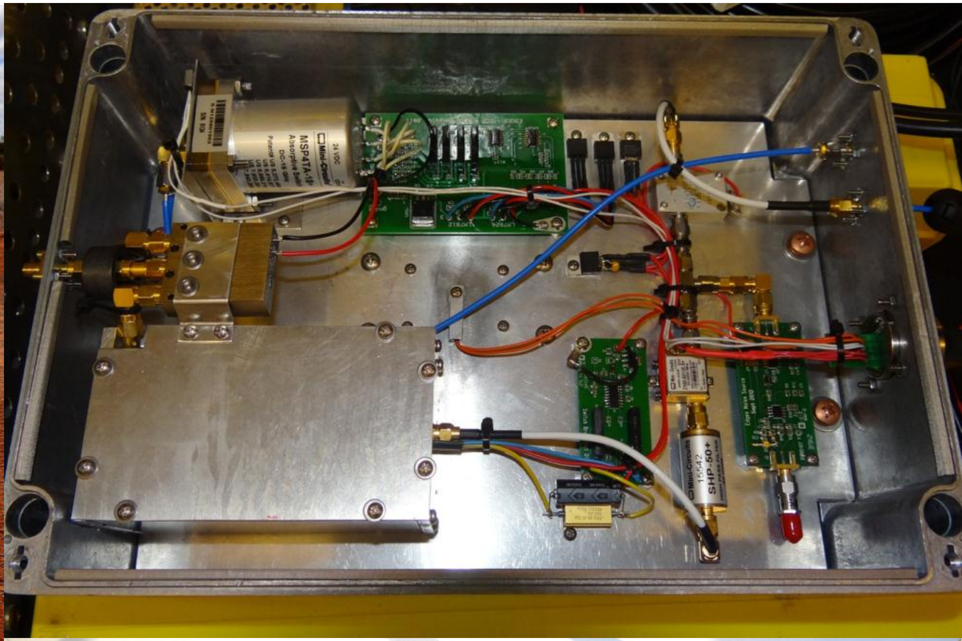
2) **Impedance mismatch between receiver and the antenna.**

3) **Antenna and ground losses.**

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

EDGES **Low-Band**





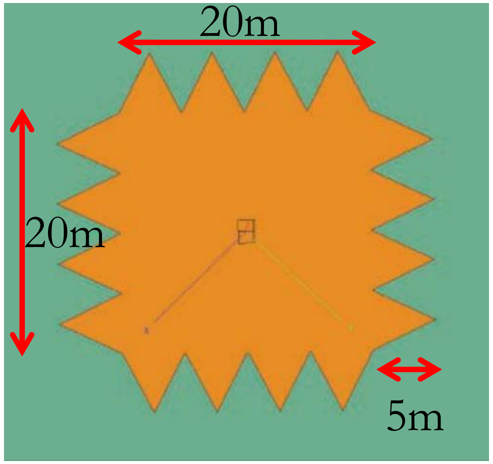
Antenna size:

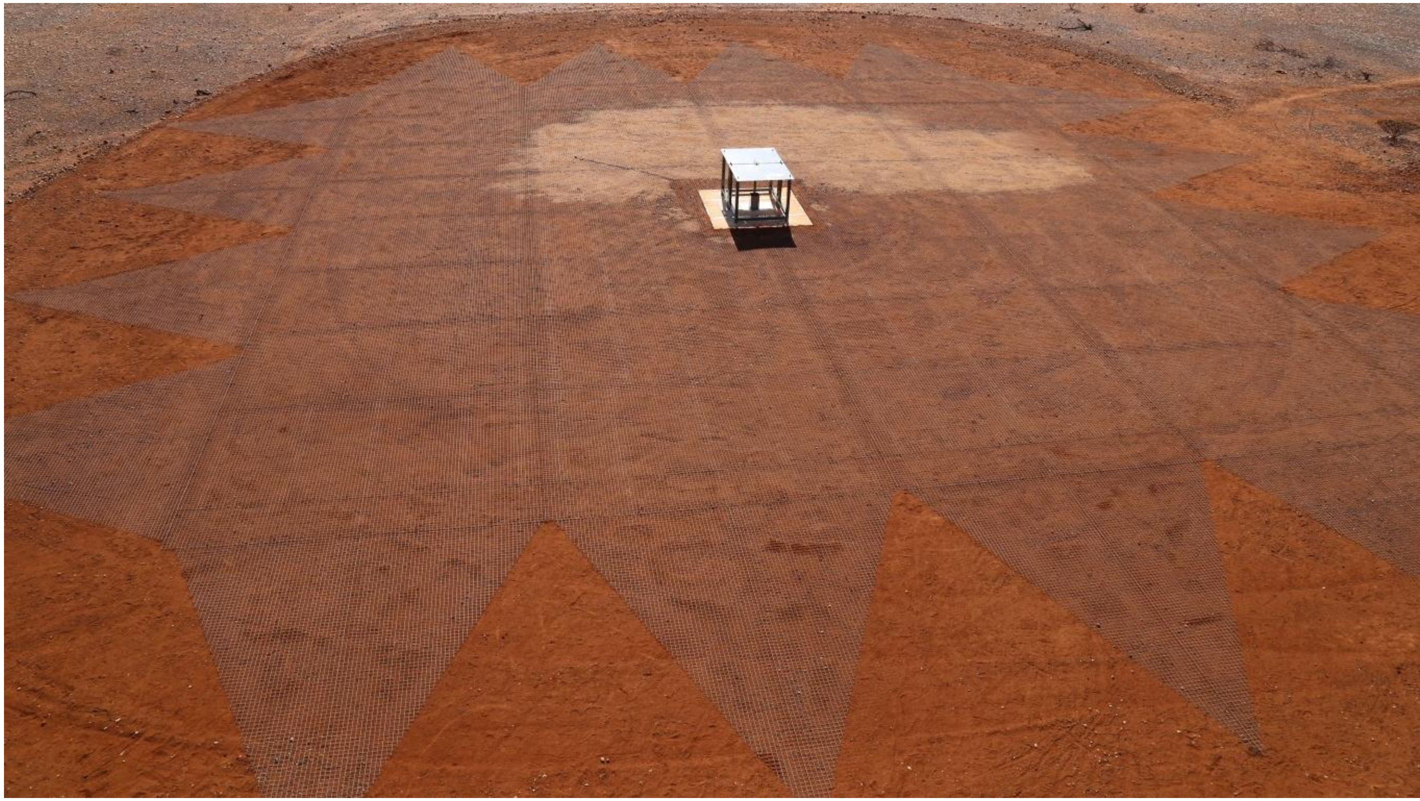
2m long / 1m high

Two **Low-Band** Instruments

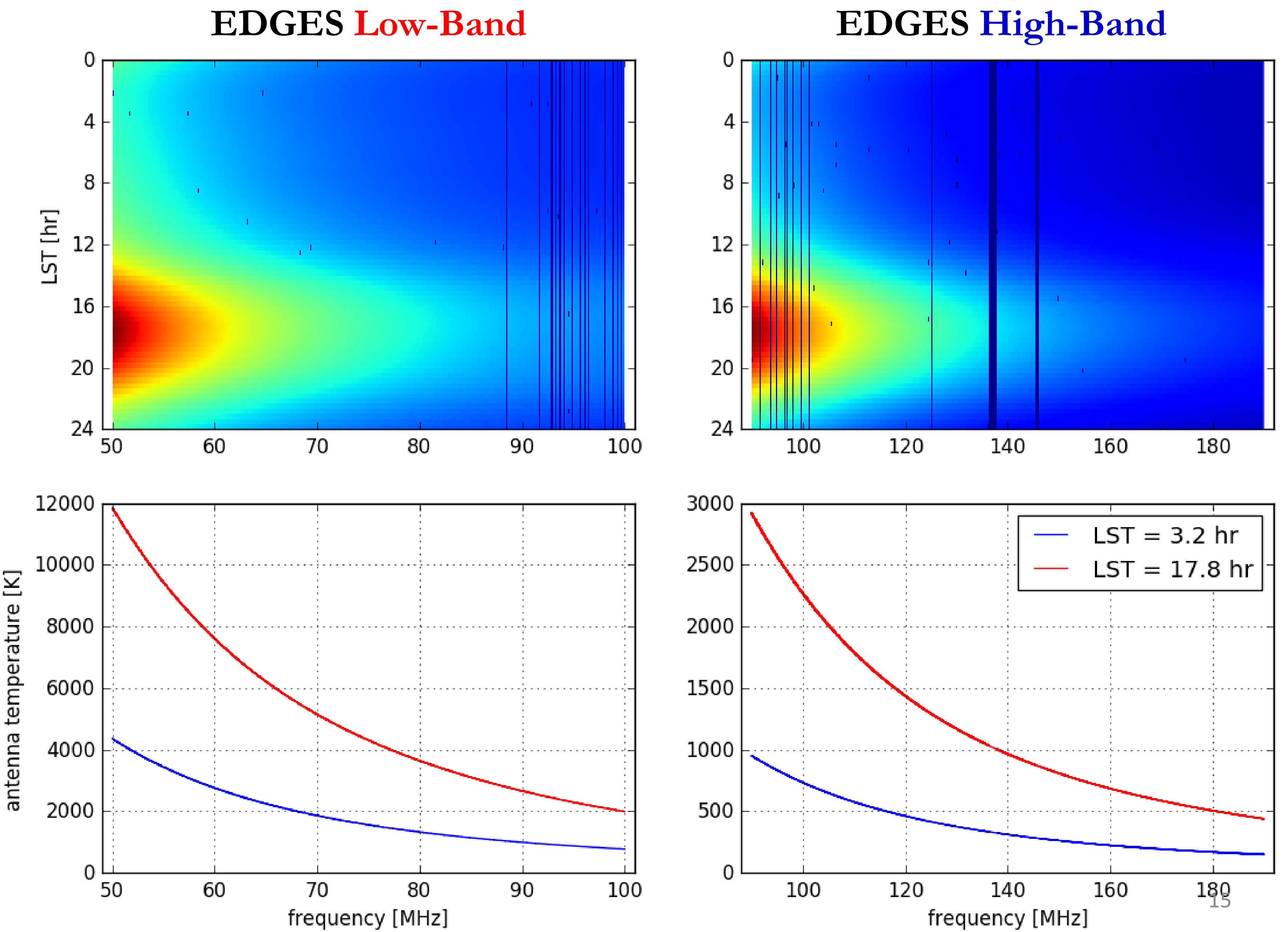
Low-Band Ground Plane

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

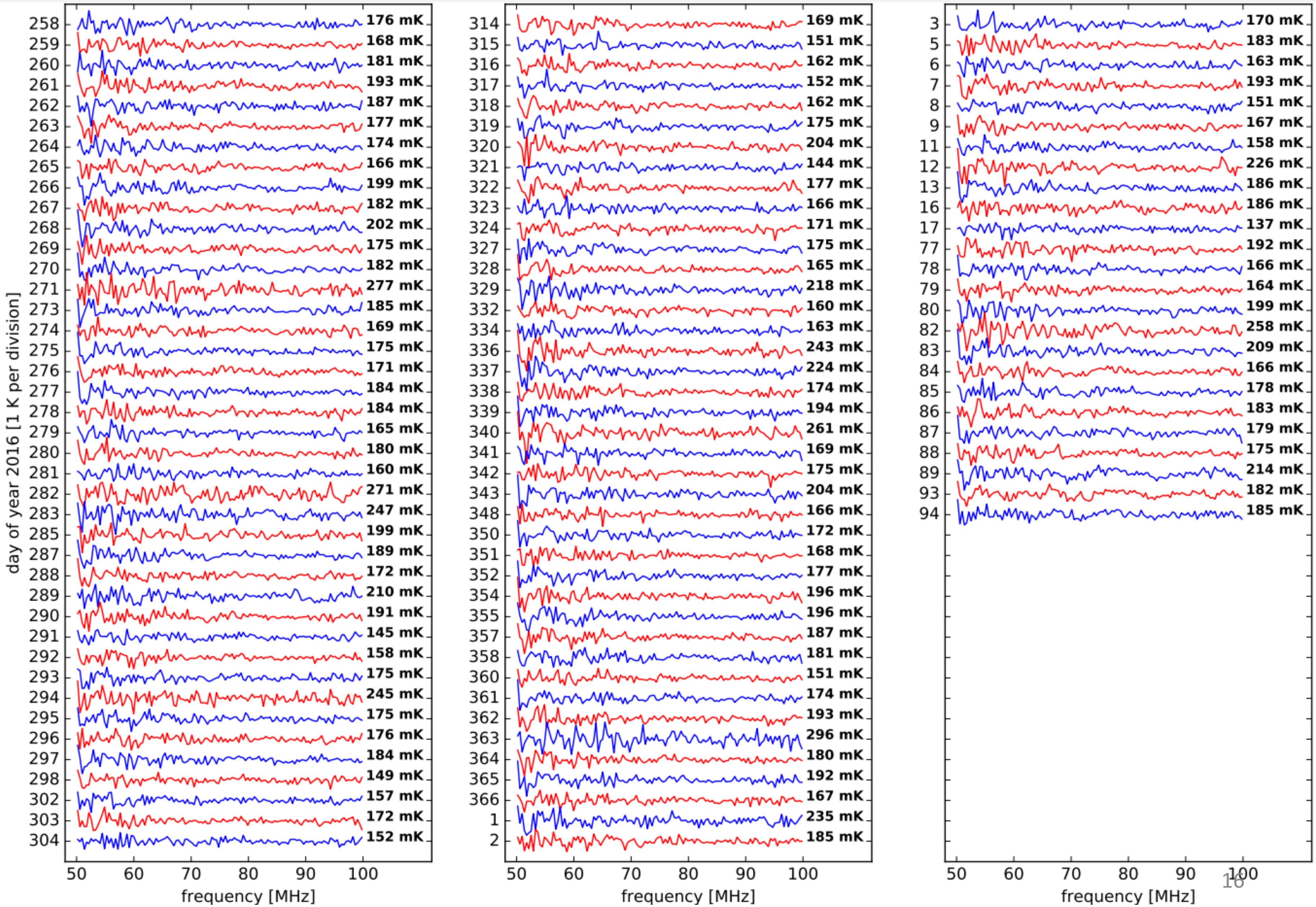




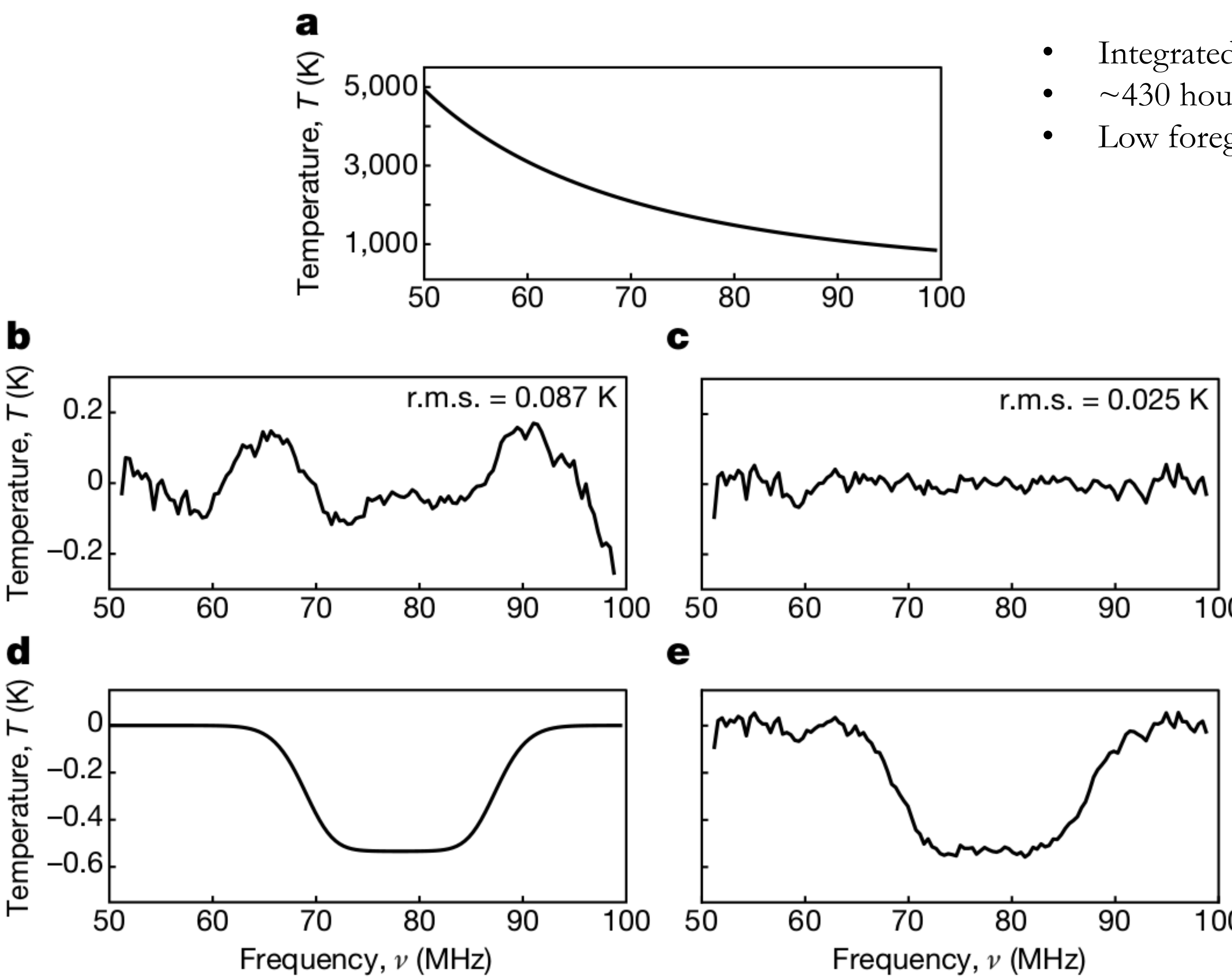
Observations



Daily **Low-Band** Residuals



Summary of the Detection



- Integrated spectrum
- ~430 hours
- Low foregrounds

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

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

$$m_{\mathrm{fg}}(\boldsymbol{a_i}) = \boldsymbol{a_0}\left(\frac{\nu}{\nu_n}\right)^{-2.5} + \boldsymbol{a_1}\left(\frac{\nu}{\nu_n}\right)^{-2.5}\left[\log\left(\frac{\nu}{\nu_n}\right)\right] + \boldsymbol{a_2}\left(\frac{\nu}{\nu_n}\right)^{-2.5}\left[\log\left(\frac{\nu}{\nu_n}\right)\right]^2 + \boldsymbol{a_3}\left(\frac{\nu}{\nu_n}\right)^{-4.5} + \boldsymbol{a_4}\left(\frac{\nu}{\nu_n}\right)^{-2}$$

Alternative Polynomial Model

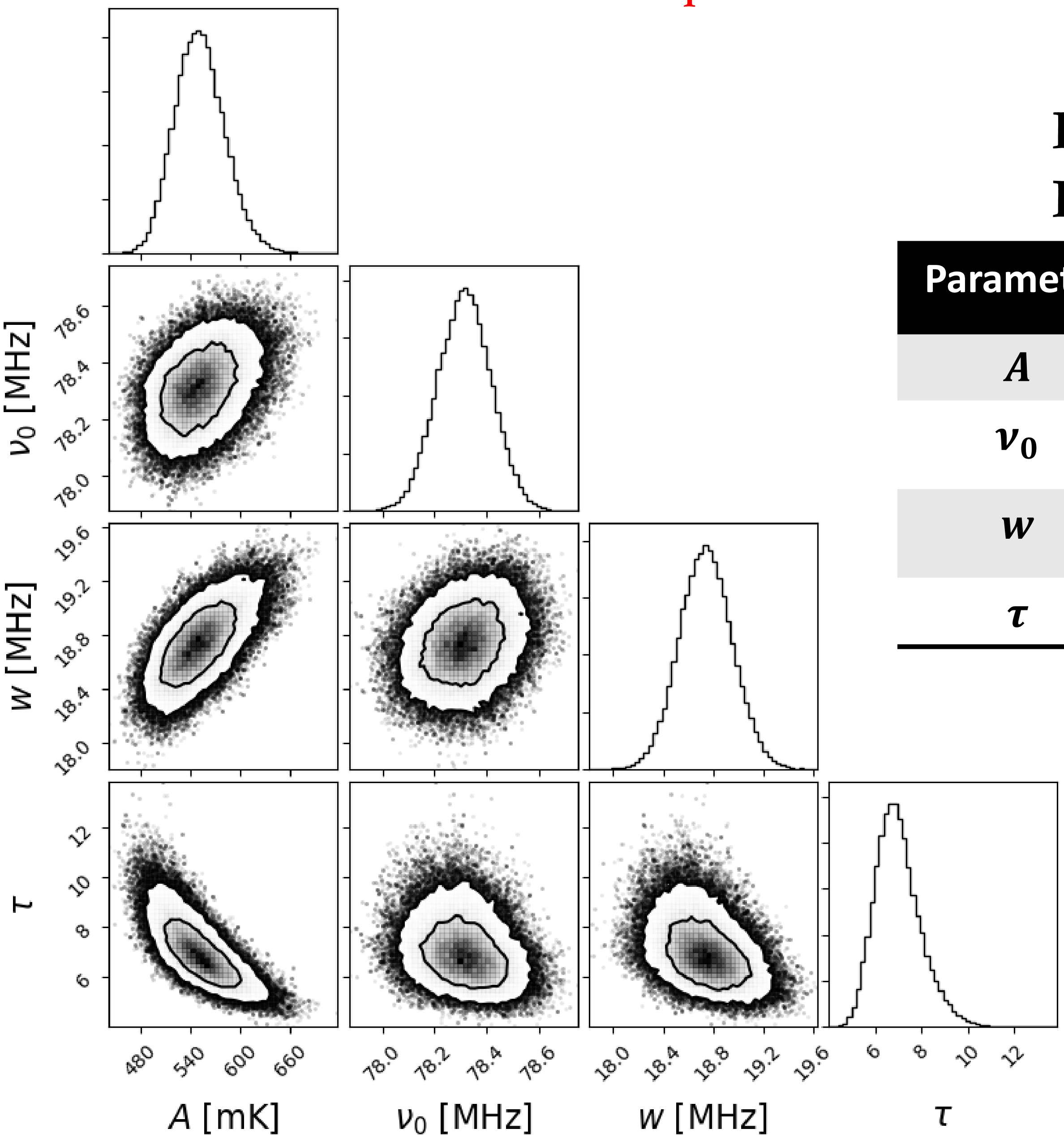
$$m_{\mathrm{fg}}(\boldsymbol{a_i}) = \left(\frac{\nu}{\nu_n}\right)^{-2.5} \sum_{i=0}^{N_{\mathrm{fg}}-1} \boldsymbol{a_i}\left(\frac{\nu}{\nu_n}\right)^{i}$$

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**.

Parameter Estimates

Estimates from Nominal Spectrum



Reported Estimates Including All Cases

Parameter	Best Fit	Uncertainty (3σ)
A	0.5 K	+0.5/-0.2 K
ν_0	78 MHz	+/-1 MHz
w	19 MHz	+4/-2 MHz
τ	7	+5/-3

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

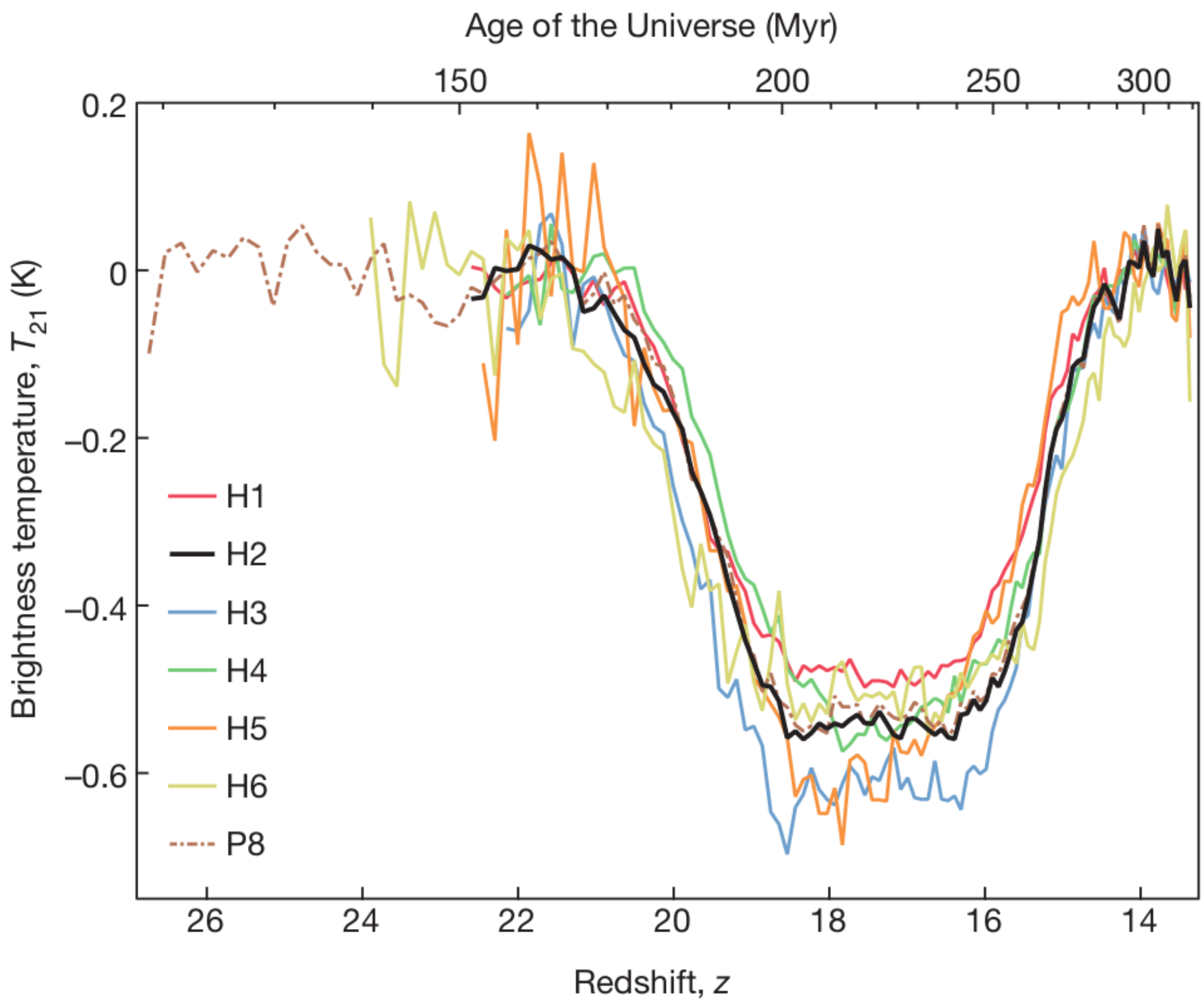
Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, **Nature**, 555, 67

Hardware and Processing Cases

Configuration		Sky Time (hours)	SNR	Centre Frequency (MHz)	Width (MHz)	Amplitude (K)
Hardware configurations (all P6)						
H1 – low-1 10x10 ground plane		528	30	78.1	20.4	0.48
H2 – low-1 30x30 ground plane		428	52	78.1	18.8	0.54
H3 – low-1 30x30 ground plane and recalibrated receiver		64	13	77.4	19.3	0.43
H4 – low-2 NS		228	33	78.5	18.0	0.52
H5 – low-2 EW		68	19	77.4	17.0	0.57
H6 – low-2 EW and no balun shield		27	15	78.1	21.9	0.50
Processing configurations (all H2 except P17)						
P3 –	No beam correction		19	78.5	20.8	0.37
	No beam correction (65-95 MHz)		25	78.5	18.6	0.47
	HFSS beam model		34	78.5	20.8	0.67
	FEKO beam model		48	78.1	18.8	0.50
P4 –	No loss corrections		25	77.4	18.6	0.44
P7 –	5-term foreground polynomial (60-99 MHz)		21	78.1	19.2	0.47
P8 –	Physical foreground model (51-99 MHz)		37	78.1	18.7	0.53
P14 –	Moon above horizon		44	78.1	18.8	0.52
	Moon below horizon		40	78.5	18.7	0.47
P17 –	15°C calibration (61-99 MHz, 5-term)		25	78.5	22.8	0.64
	35°C calibration (61-99 MHz, 5-term)		16	78.9	22.7	0.48

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

Different Instruments/Hardware Cases



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

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

How to Explain Deep Absorption?

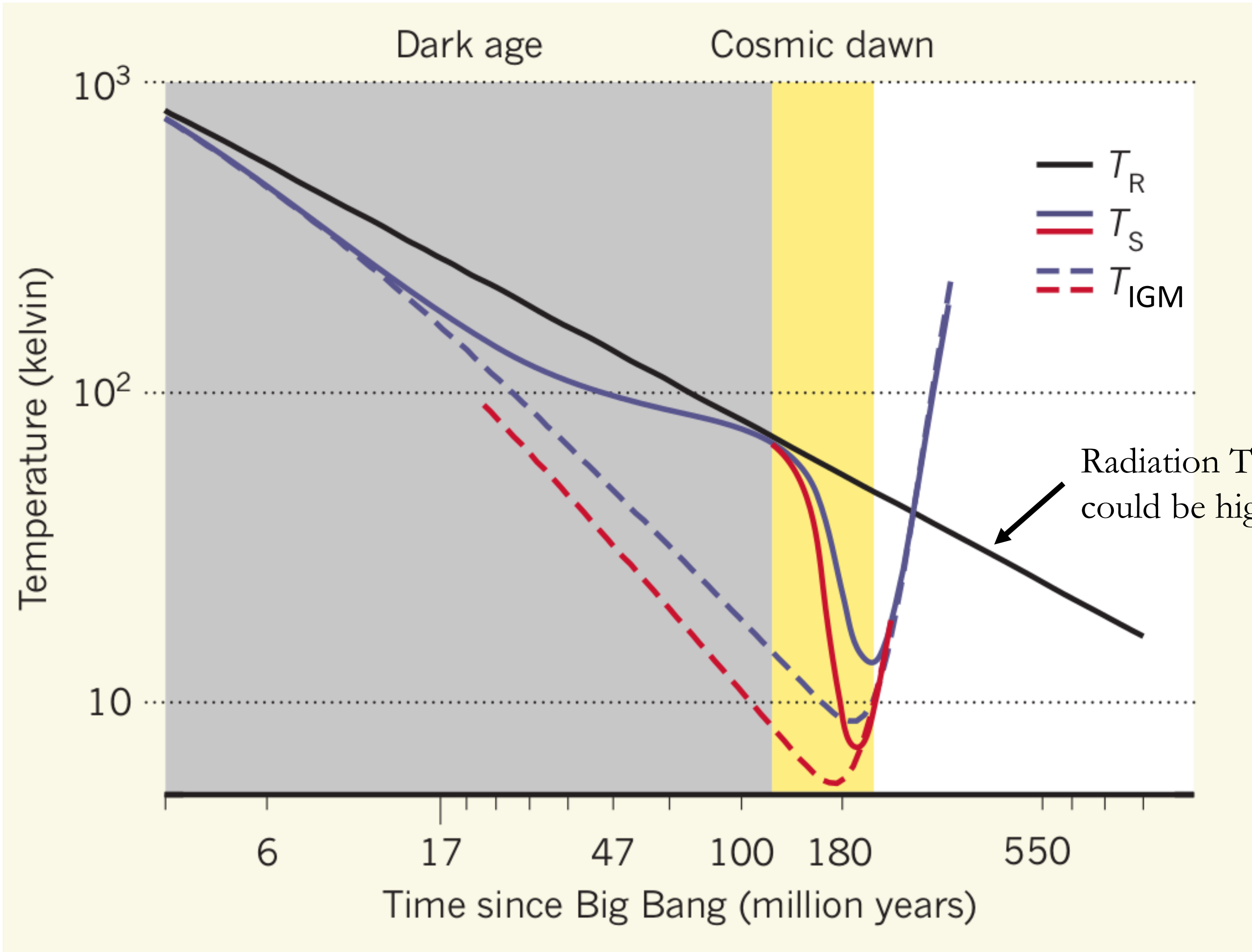
Higher than zero

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

Lower than expected

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

Producing a Deep Absorption



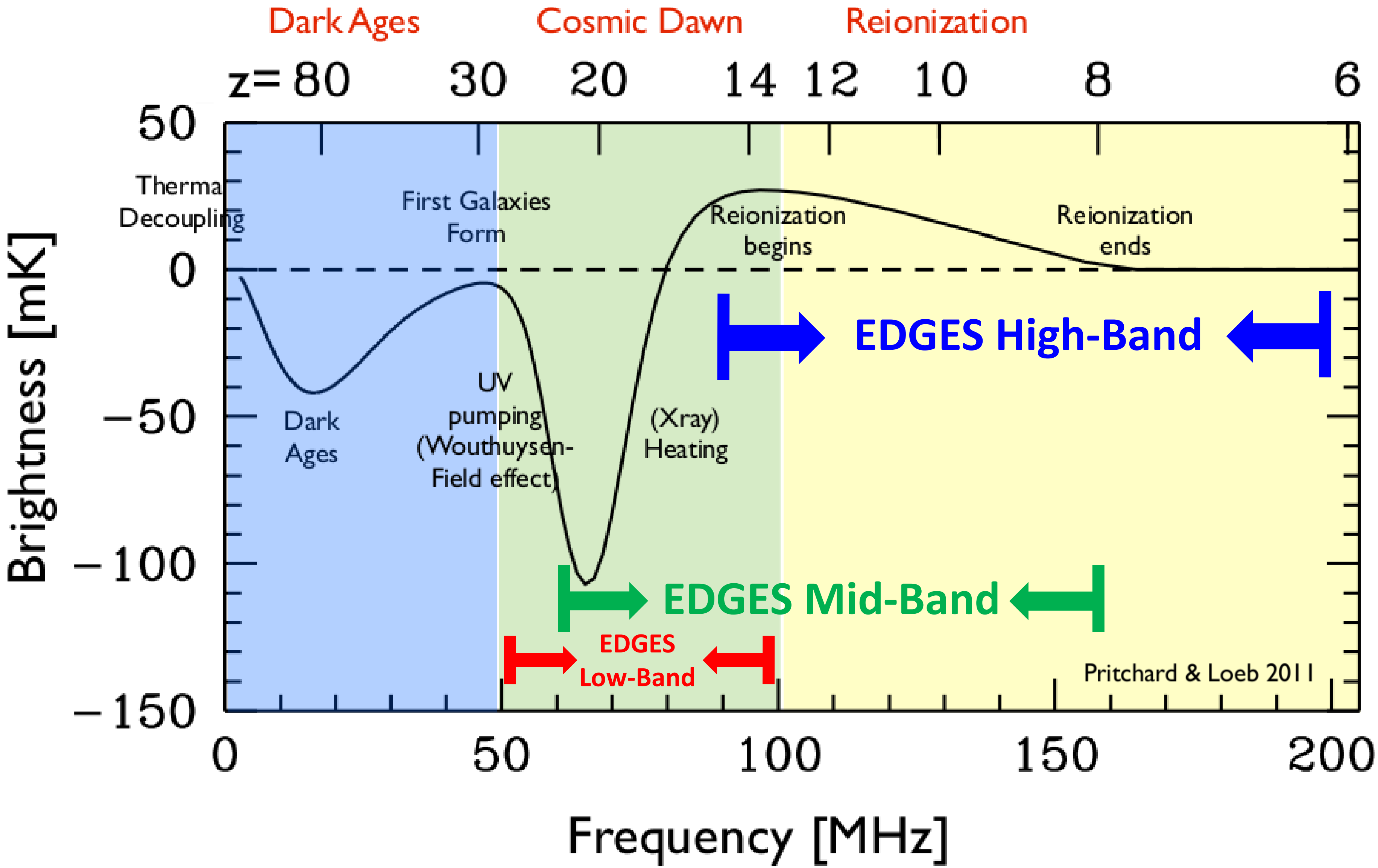
Radiation Temperature could be higher than CMB

Greenhill 2018, **Nature**, 555, 38

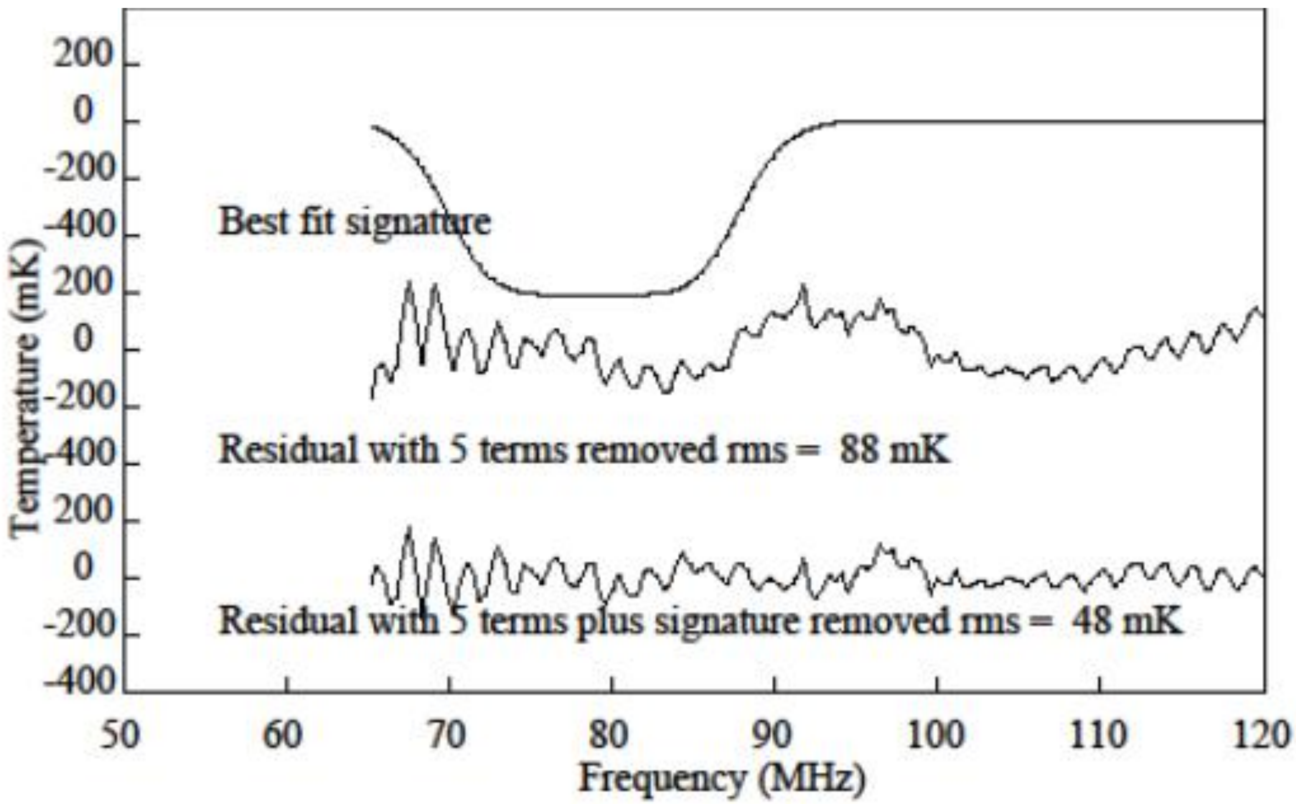
With EDGES **we remain agnostic** about the cosmological/astrophysical explanations, and focused on the verification of our measurement.

Other experiments trying to verify the measurement include PRI^{Z}M, LEDA, and SARAS 2

EDGES Instruments



Preliminary Mid-Band Results with Imperfect Data



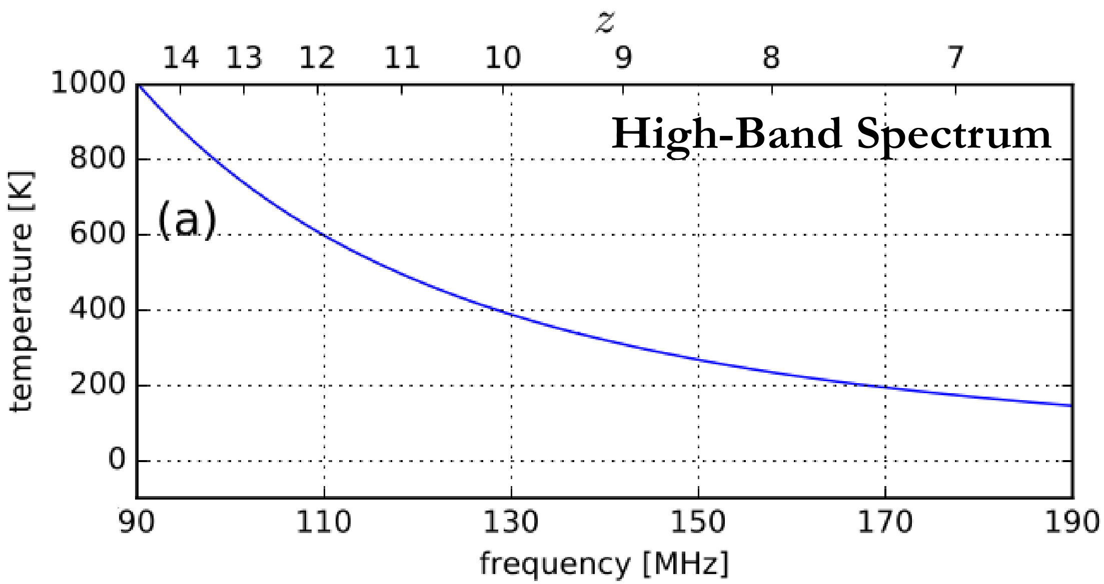
1) Data from **November 2017-February 2018.**
2) **Imperfect calibration** (noise source level too low).
3) Frequency range **65-120 MHz**.
4) **5-term linear "physical" foreground model**.

Best-fit parameters:

- $\boldsymbol{A}$: 0.61 K
- $\boldsymbol{\nu_0}$: 78.9 MHz
- $\boldsymbol{\omega}$: 18.2 MHz
- $\boldsymbol{\tau}$: 7

Recent EDGES High-Band Analyses

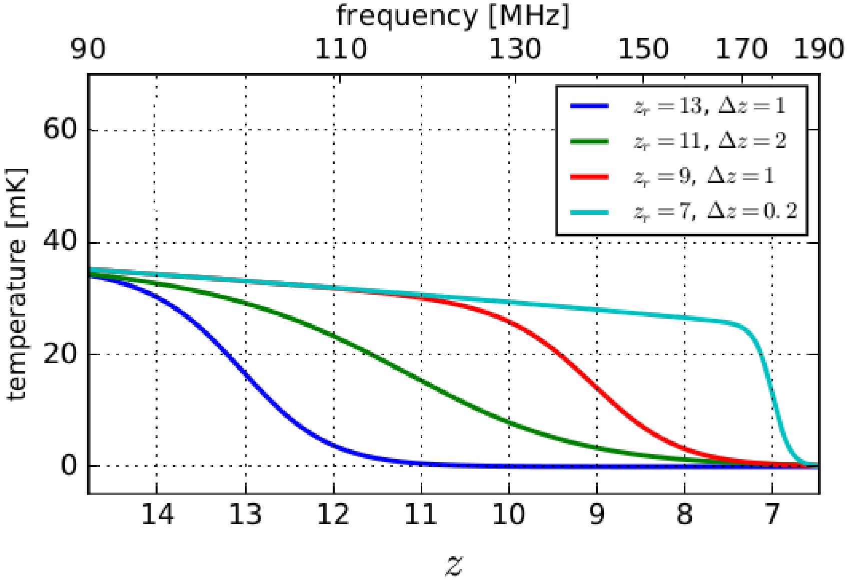
Monsalve, Rogers, Bowman, & Mozdzen (2017b)



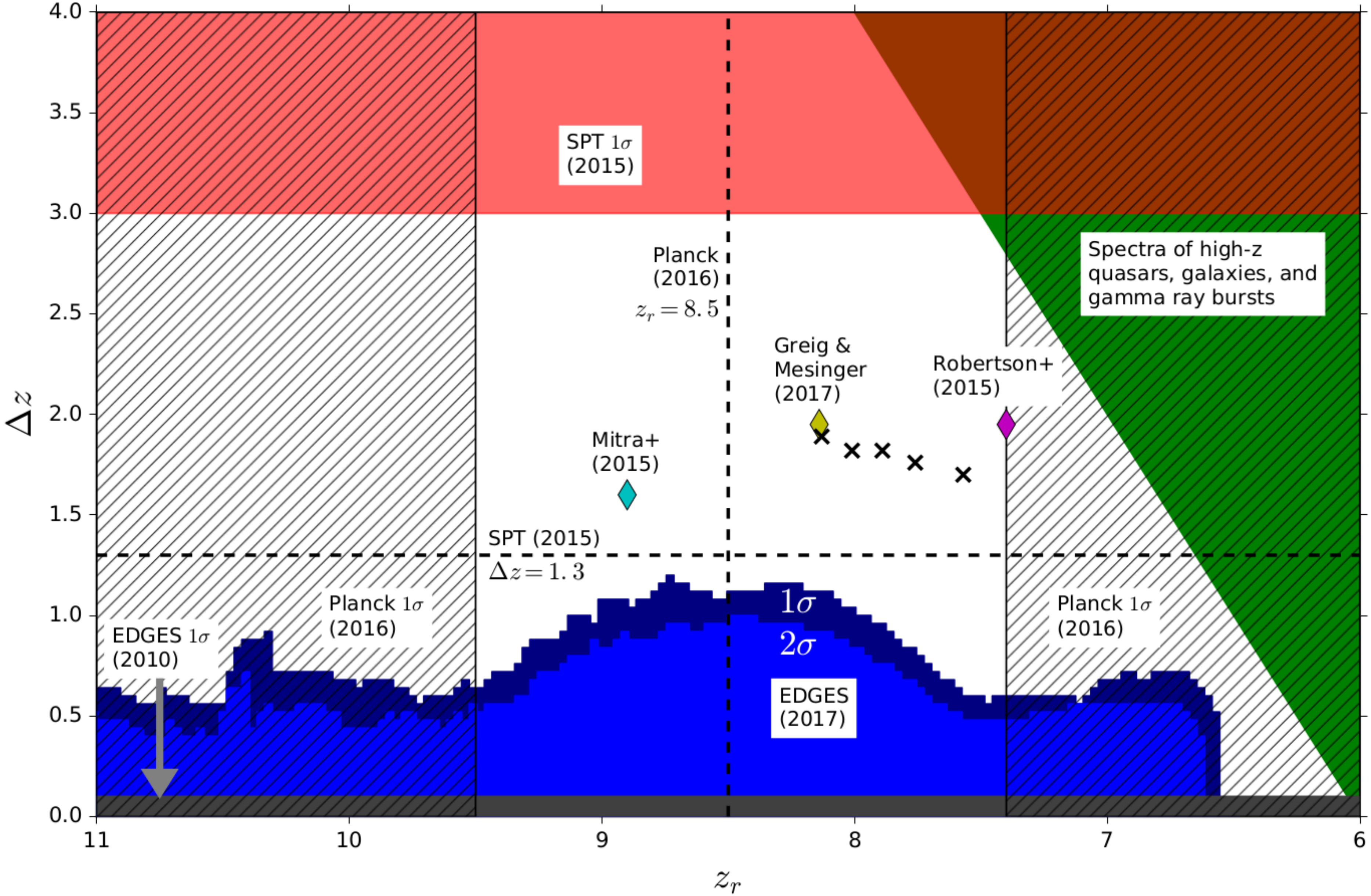
1) Evaluate **EoR models** based on **Tanh function**

2) Emission **amplitudes < 40 mK**

3) Parameters probed are **Redshift (z_r) and Duration (Δz)**



Epoch of Reionization Constraints (Hot IGM)



Monsalve, Rogers, Bowman, Mozdzen (2017)

Constraining High-z Astrophysical Parameters

1) We test **traditional models** that assume **standard temperatures** for the **IGM and radiation background** in the Early Universe.

2) **Do NOT assume** that absorption feature of Bowman et al. (2018) **is the cosmological signal**.

3) 10,000 models from semi-numerical simulations with the **21cmFAST** code.

High-z Astrophysical Parameters:

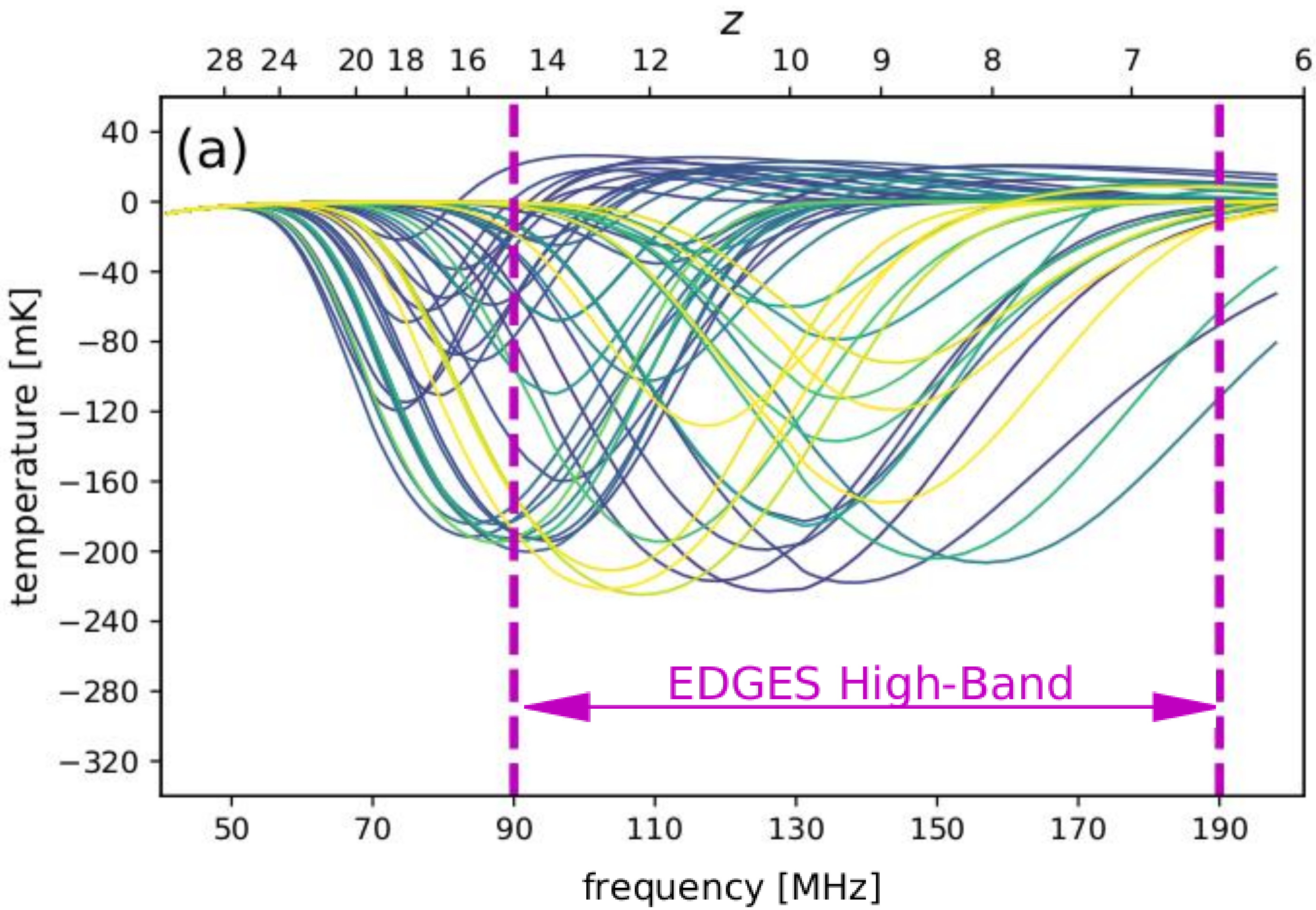
ζ: Ionizing efficiency of halos that host galaxies

$T_{\mathrm{vir}}^{\mathrm{min}}$: Minimum virial temperature of halos that host star-forming galaxies

L_X/SFR: X-ray luminosity per star-formation rate from galaxies (up to 2 keV)

E_0: Minimum energy of X-rays

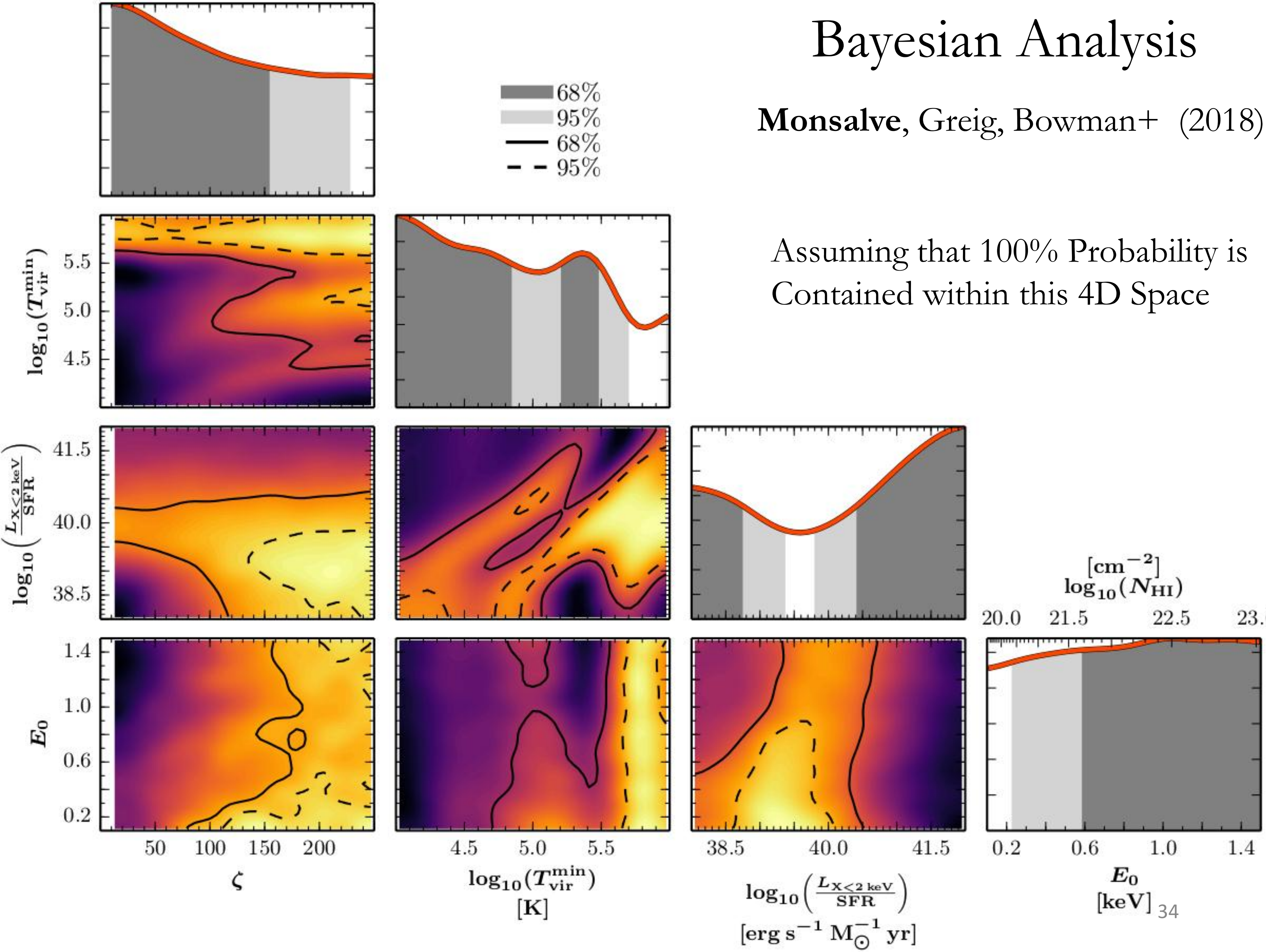
Sample of Models from 21cmFAST



Bayesian Analysis

Monsalve, Greig, Bowman+ (2018)

Assuming that 100% Probability is Contained within this 4D Space



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2) This is **consistent with stars forming by 180 Myrs after the Big Bang**.

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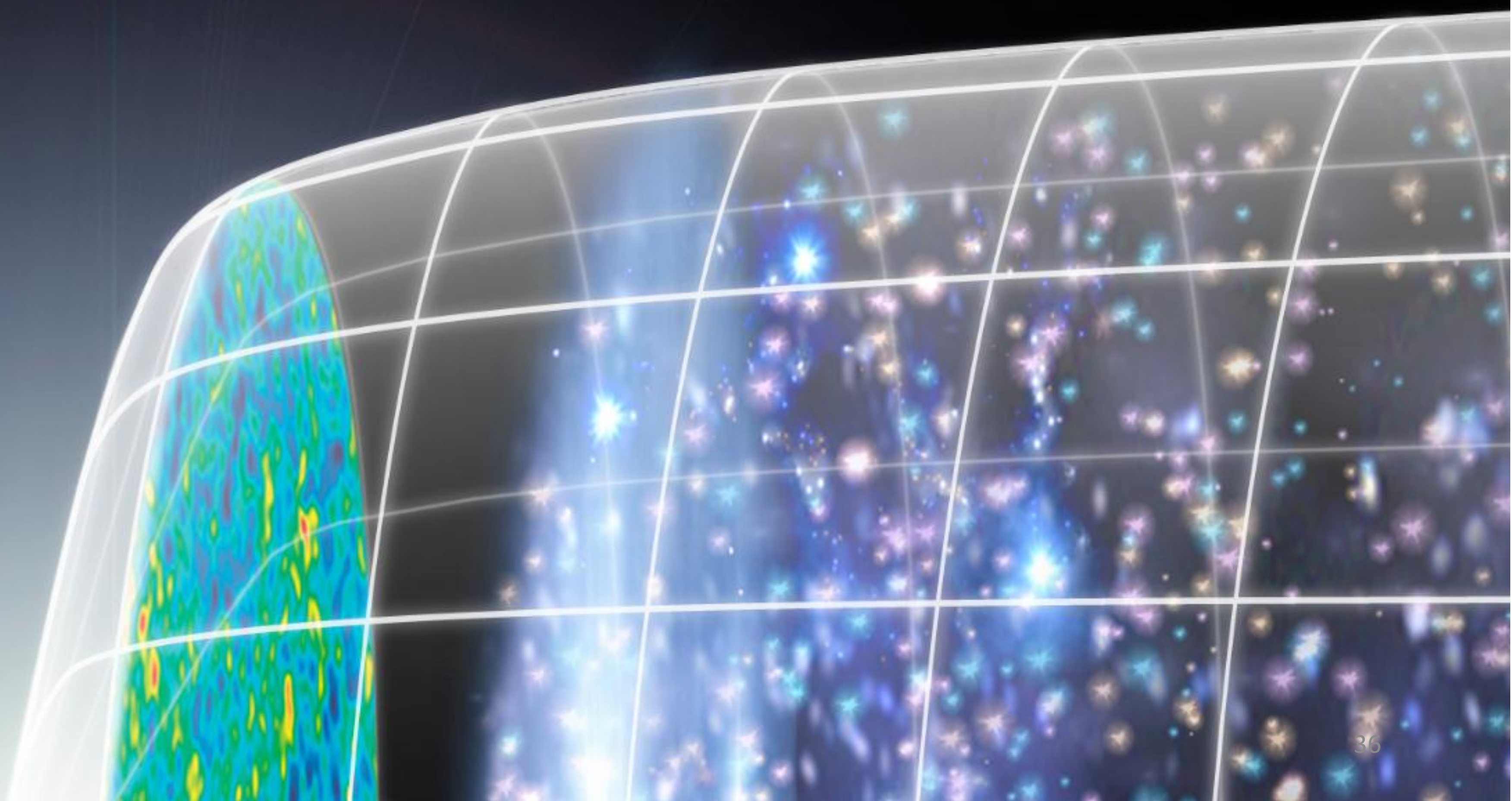
Thank You



Bayesian Analysis

$$m(\boldsymbol{\theta}) = m_{21}(\boldsymbol{\theta}_{21}) + m_{\text{fg}}(\boldsymbol{\theta}_{\text{fg}})$$

$$\mathcal{L}(d|\boldsymbol{\theta}) = \frac{1}{\sqrt{(2\pi)^{N_\nu}|\Sigma|}} \times e^{\left\{-\frac{1}{2}[d-m(\boldsymbol{\theta})]^T\Sigma^{-1}[d-m(\boldsymbol{\theta})]\right\}}$$

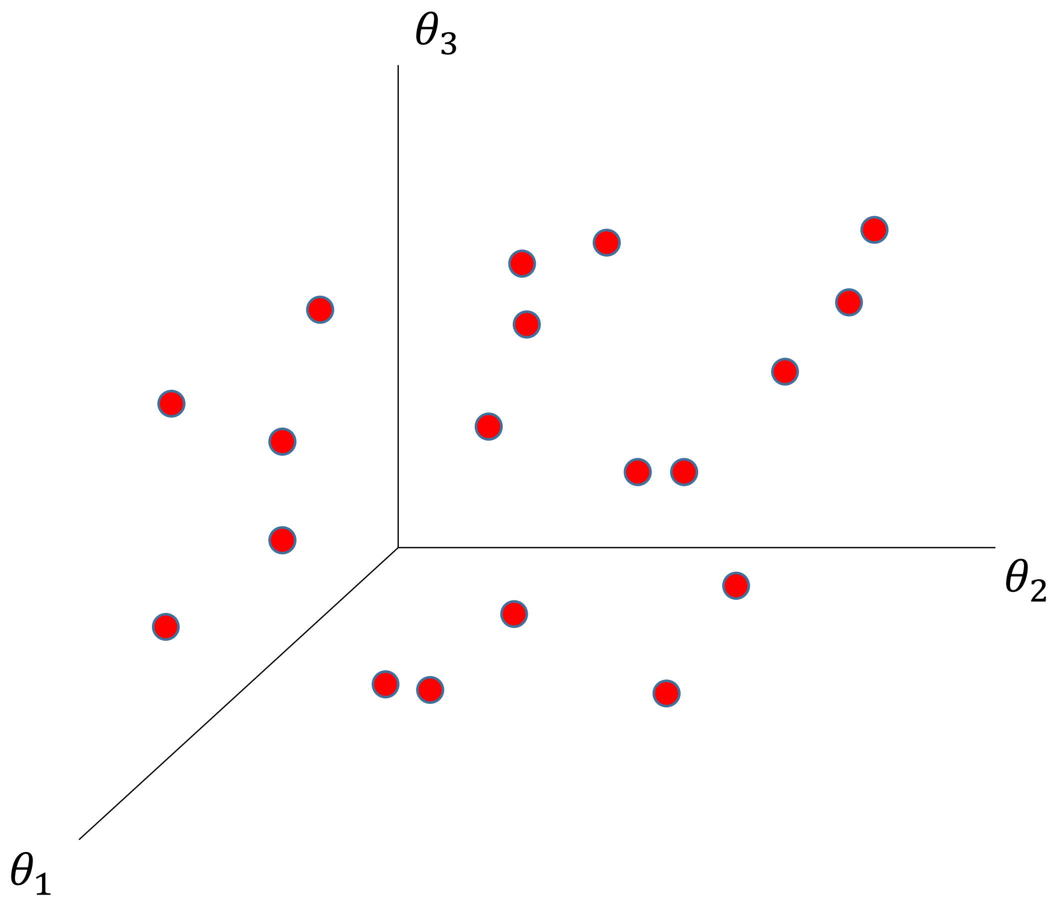
d: data
m: model
Σ: covariance matrix of data (Noise + Systematic Uncertainty)
N_ν: number of spectral channels

We Marginalize Uncertainty in the Foreground Model Parameters

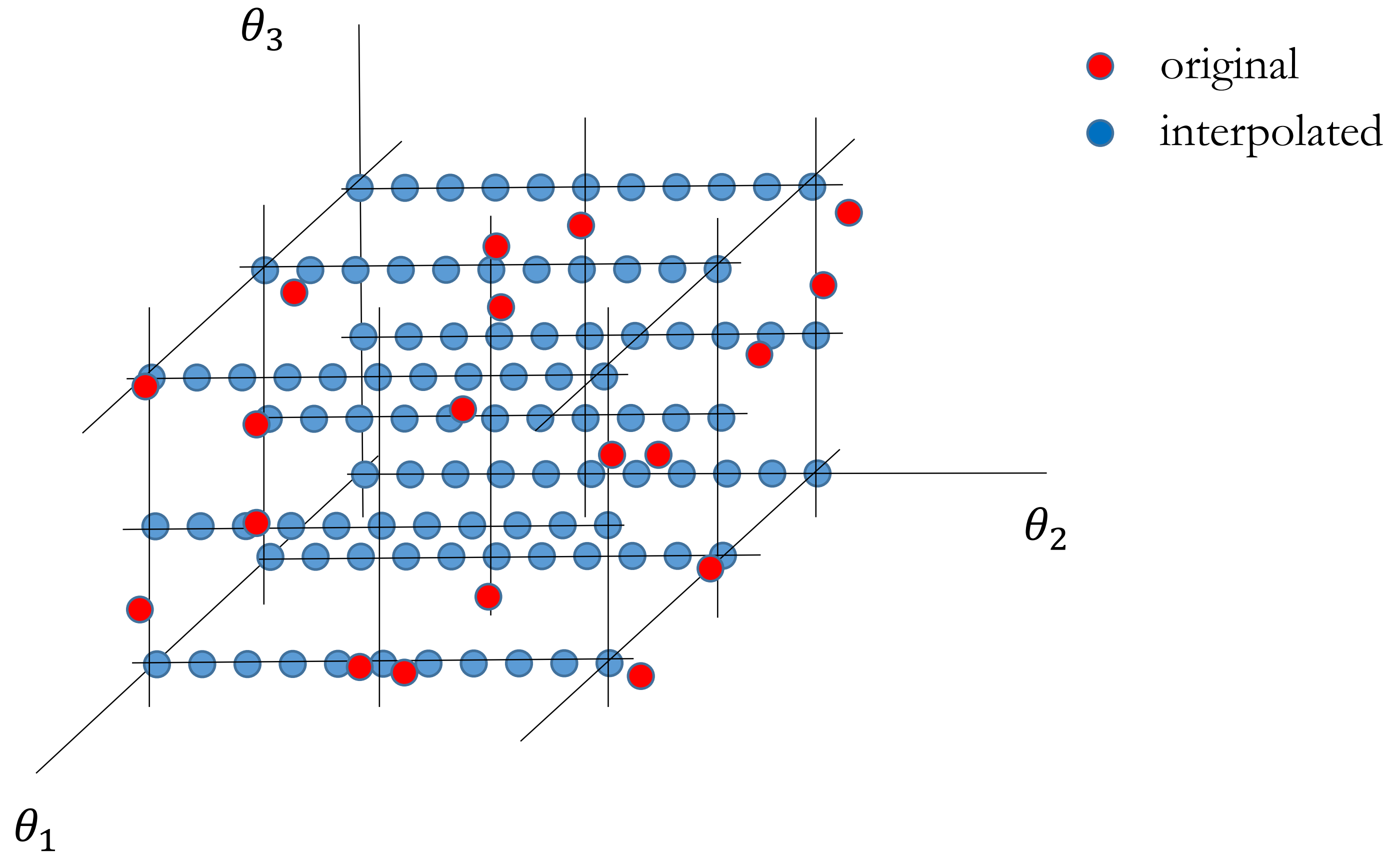
and Obtain:

Likelihood of each 21-cm Model: $\mathcal{L}(d|\boldsymbol{\theta}_{21})$

Likelihood for Original Models



Interpolation of Likelihood onto Regular Grid

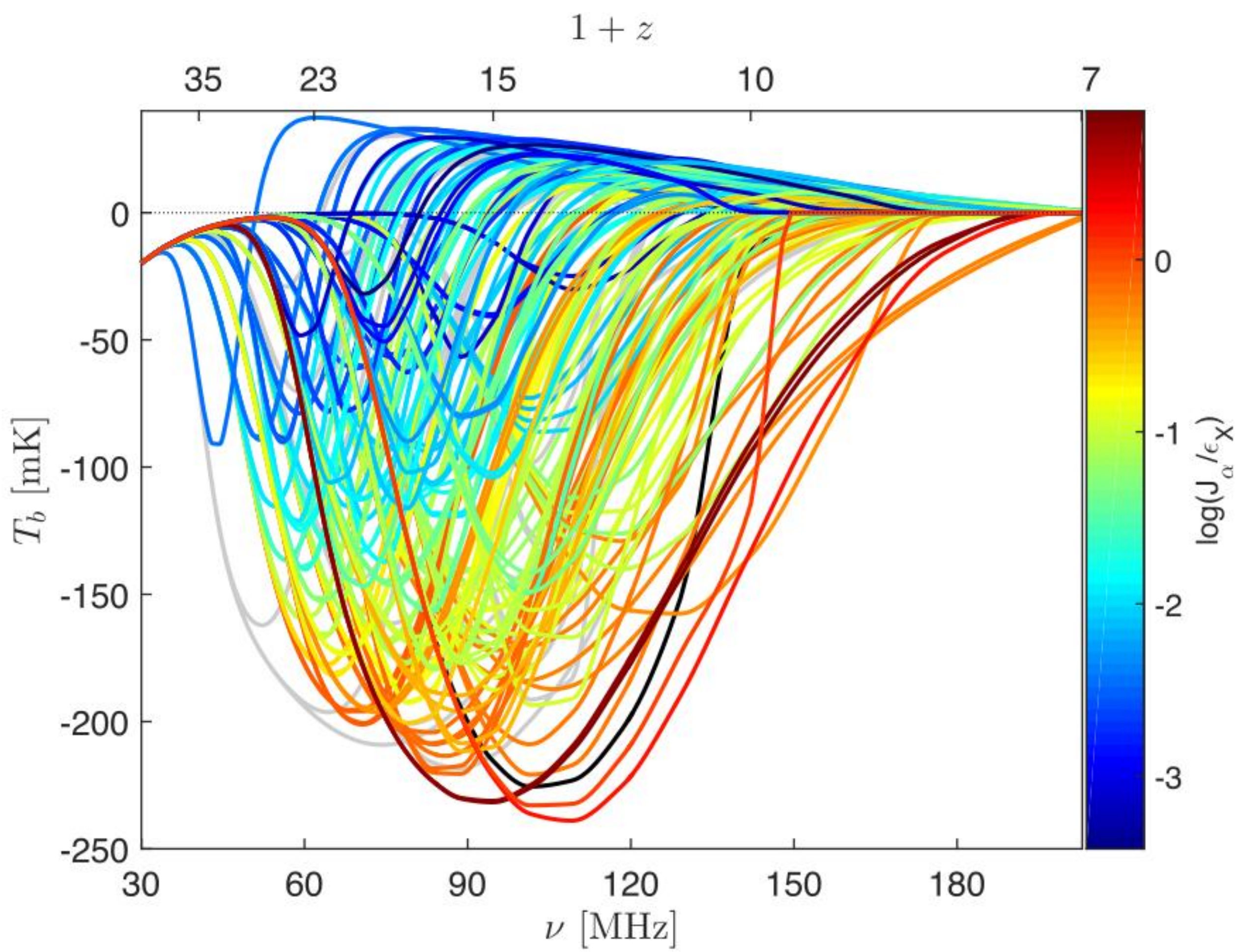


This Enables Rigorous Marginalization Over Parameters.

New Model Set

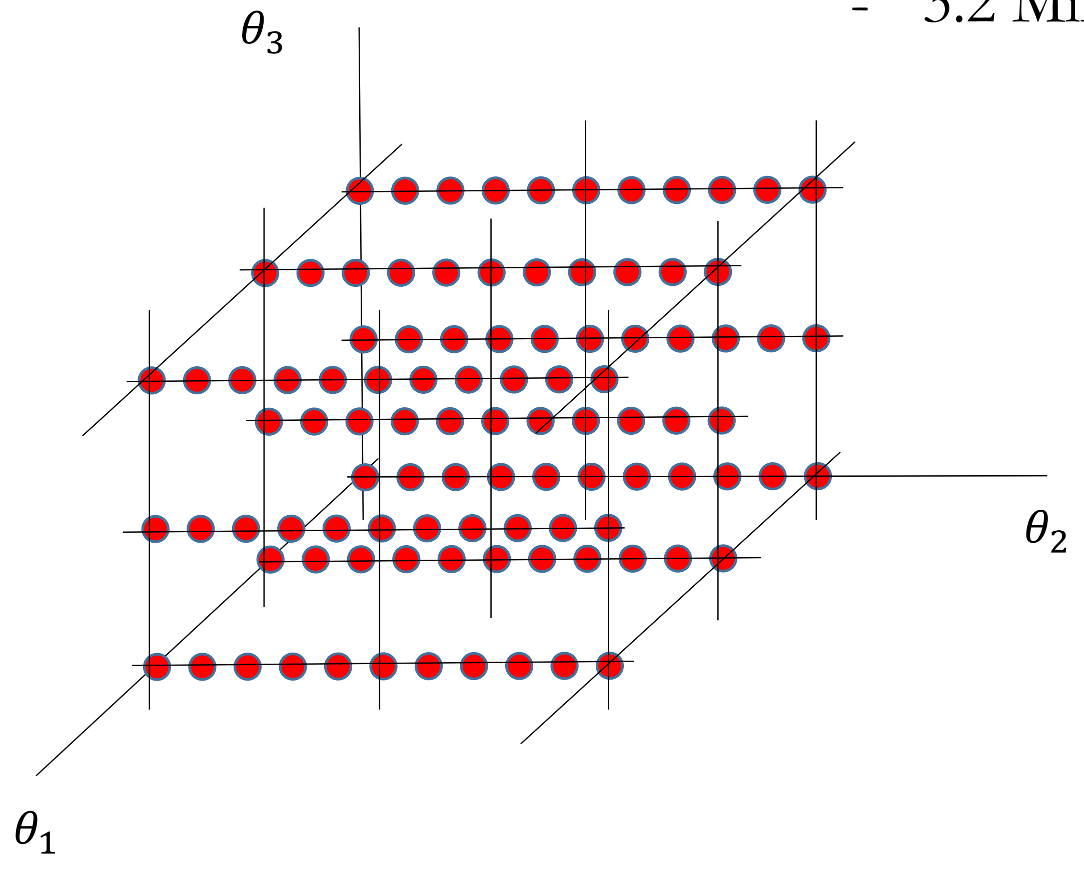
Interpolation of Standard Semi-Numerical Models from Cohen+ (2017)

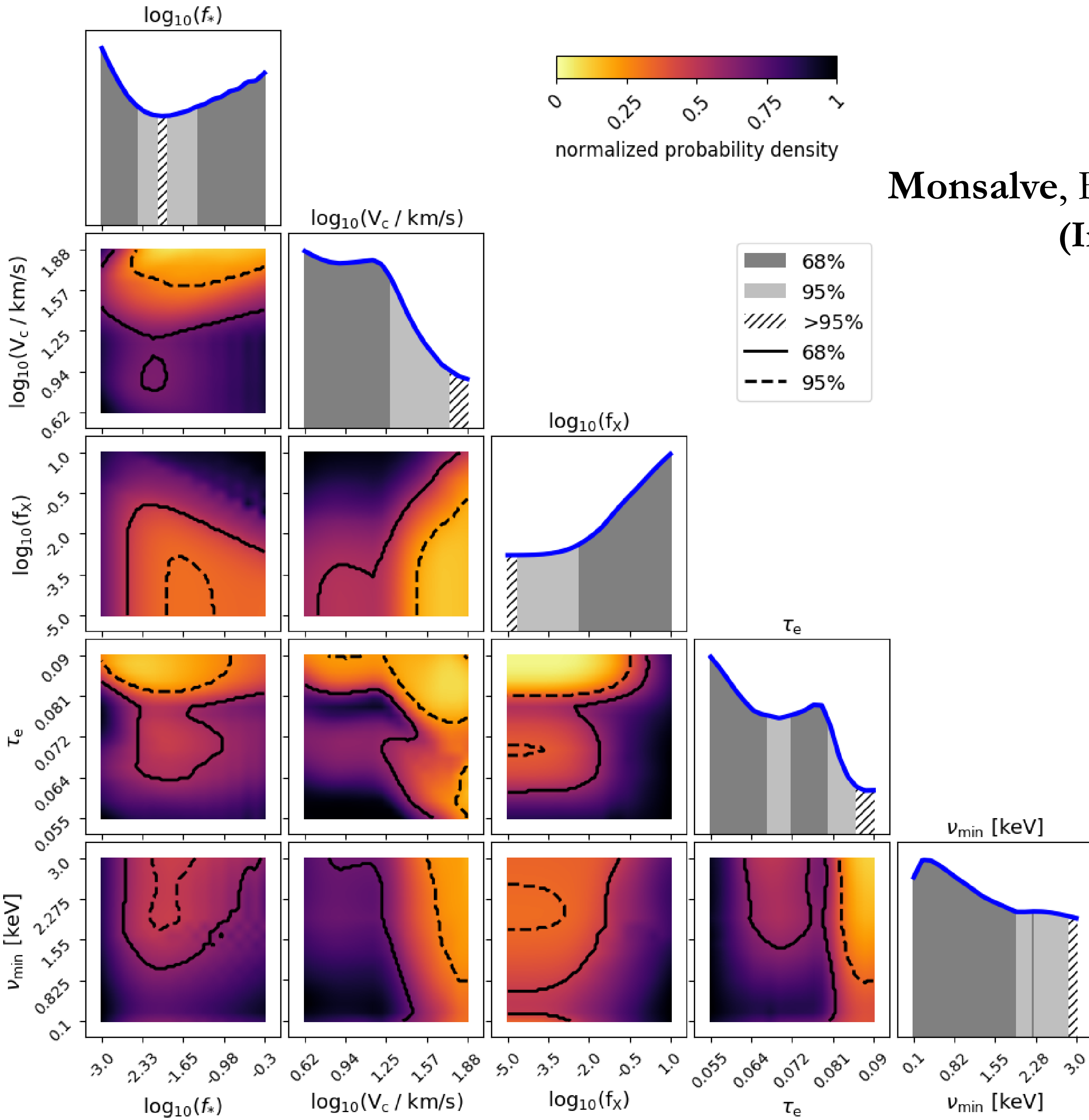
Description of Interpolation Code in Cohen+ (2018)



Direct Evaluation of Likelihood at High Resolution Grid Points

- 5 Parameters
- 3.2 Million Signals





Monsalve, Fialkov, Bowman+(2018)

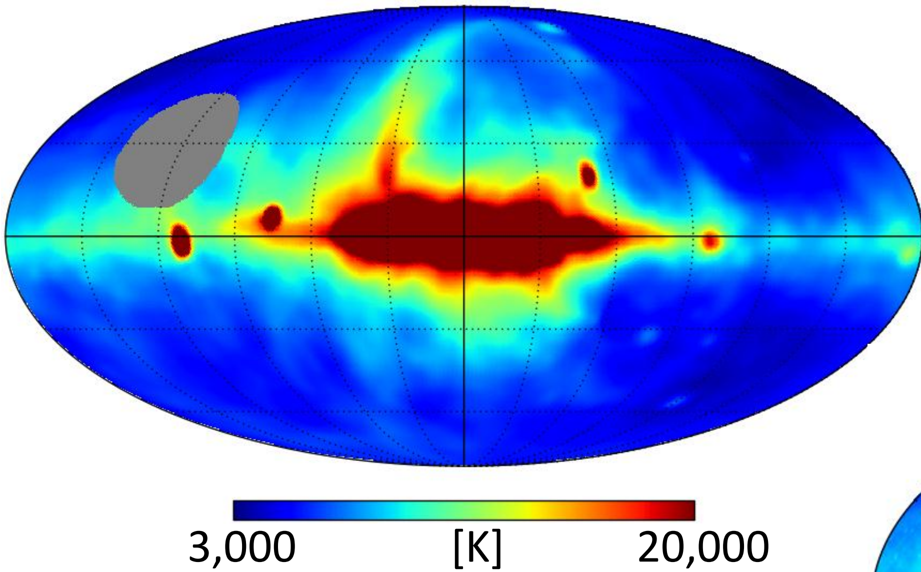
(In Preparation)

Expecting to Conduct **Similar Analyses Using Low- and Mid-Band Data** once Large Physical Model Sets are Available.

Diffuse Foregrounds

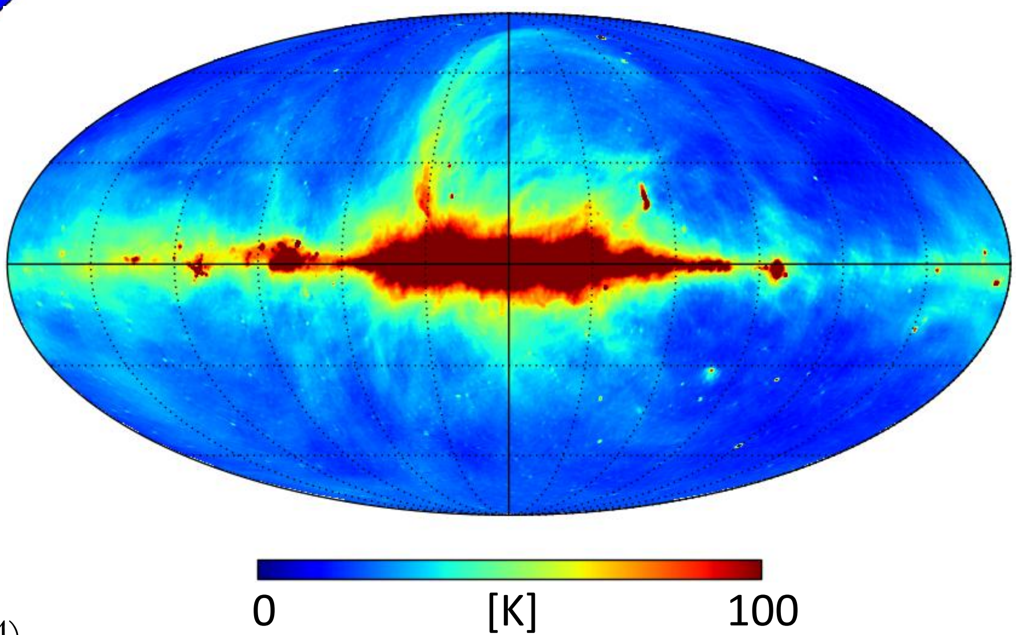
45-MHz Map

Guzmán et al. (2011)



408-MHz Map

Haslam et al. (1982)



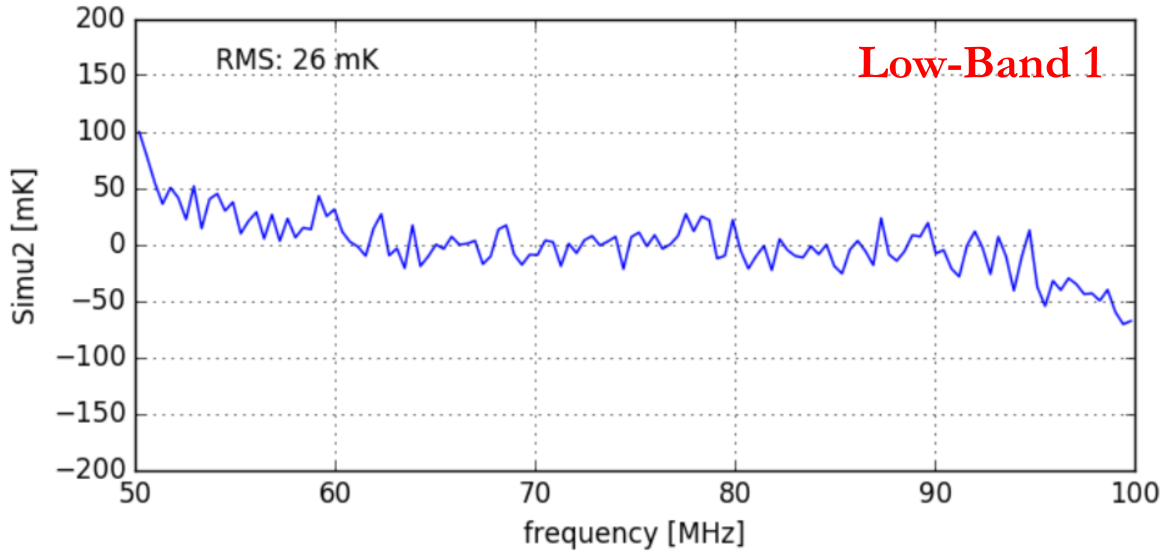
1) From **hundreds to thousands of Kelvins**.
2) Include **Galactic and Extragalactic**.
3) Mostly **Galactic synchrotron radiation**.
4) **Spectrally smooth** (e.g., Fornengo et al. 2014)
5) Might need **several terms** to model (Bernardi et al. 2015)
6) Large **spatial gradients**.

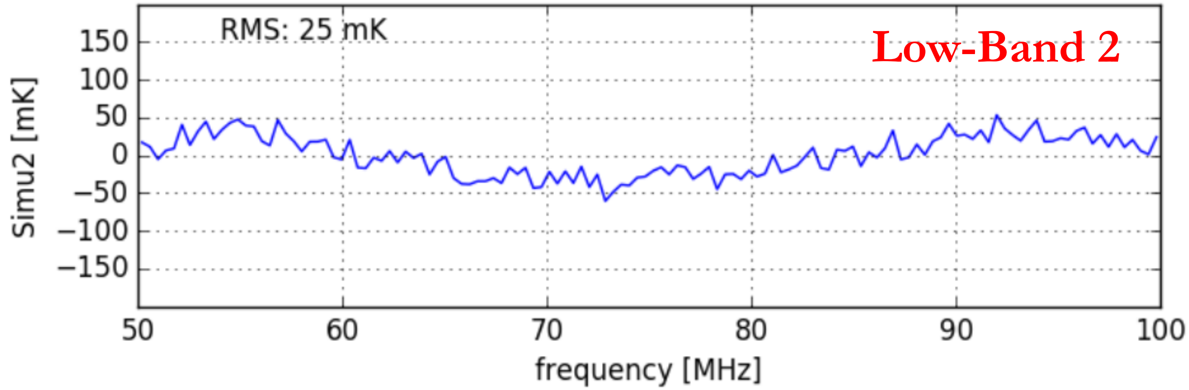
Verification Using ~300K Antenna Simulators

At 75 MHz

$$\frac{1{,}500\ \text{K}}{300\ \text{K}} = 5$$

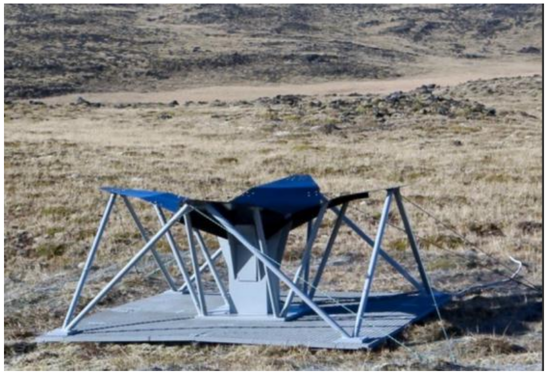
Residuals After Removing a Constant



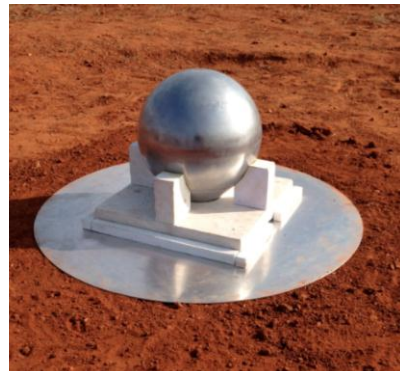


Global 21-cm Experiments

PRI^{Z}M
(Kwazulu-Natal, Sievers et al.)



SARAS 2
(RRI, Subrahmanyan et al.)



LEDA
(Harvard, Greenhill et al.)

SCI-HI
(Carnegie Mellon, Peterson et al.)

HYPERION
(Berkeley, Parsons et al.)

CTP
(NRAO, Bradley et al.)

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]

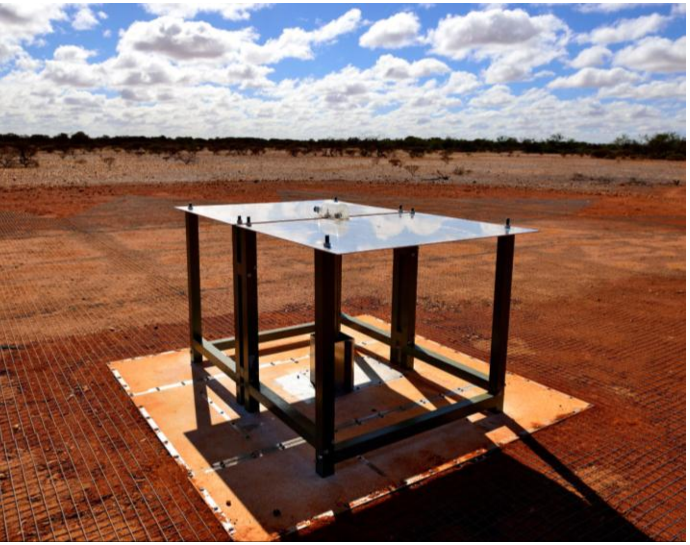
NATURE, 557, 31 MAY 2018

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**.

EDGES Mid-Band

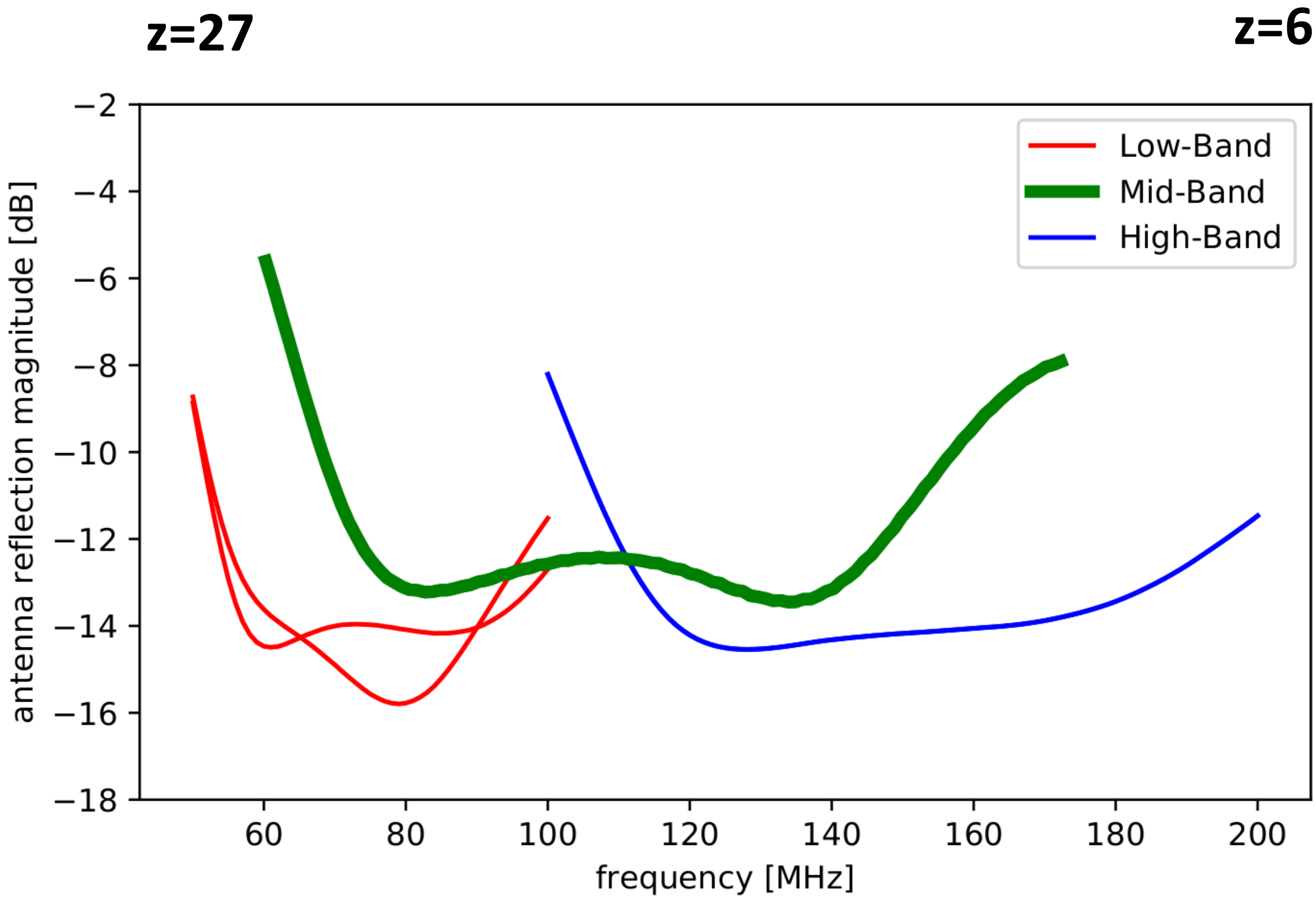
Low-Band



High-Band

Mid-Band

Antenna Reflection Coefficients



Preliminarily …..