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Fingerprints of the First Stars in the Sky-Averaged Radio Spectrum

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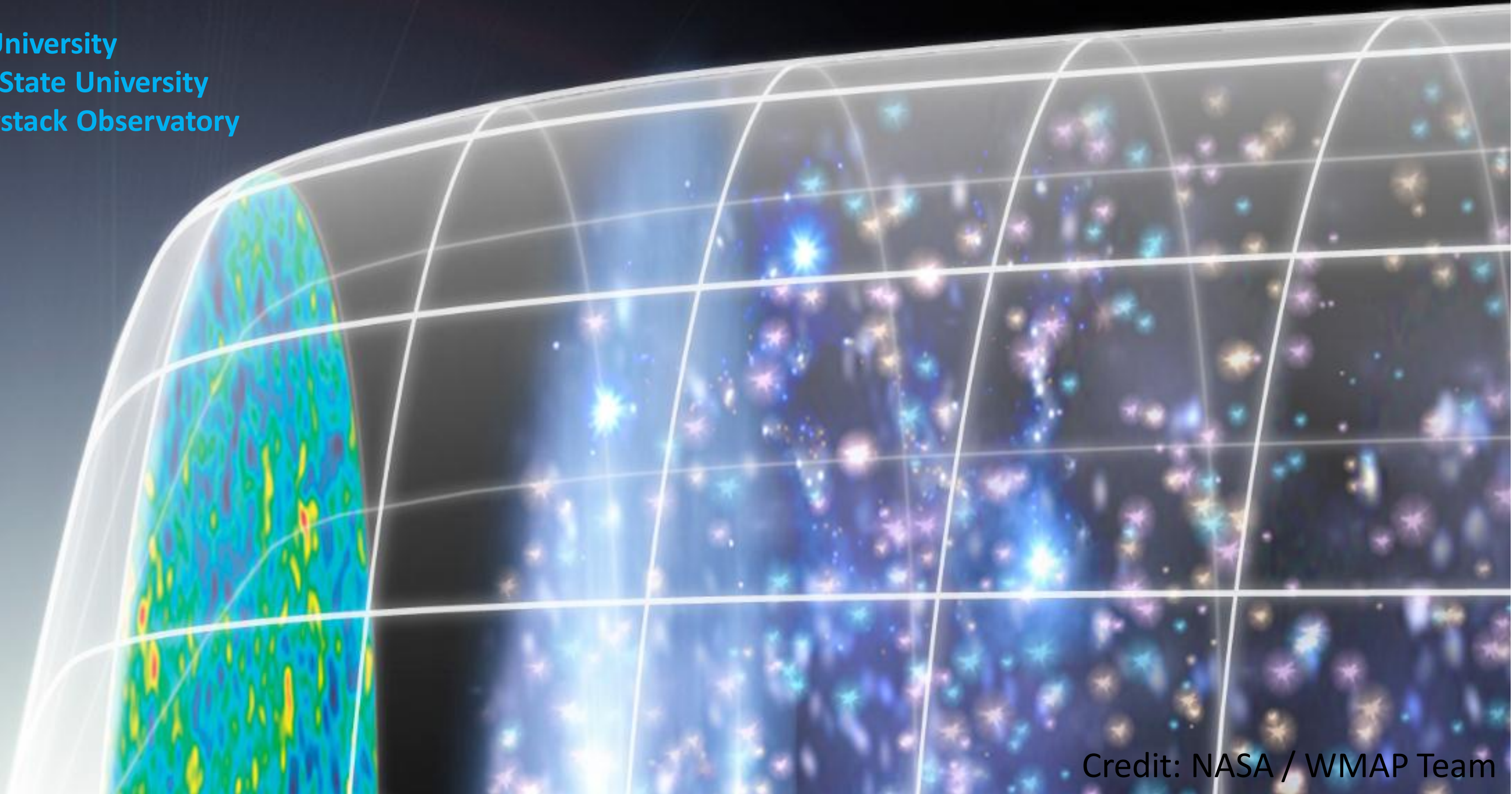


Credit: NASA / WMAP Team

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**.

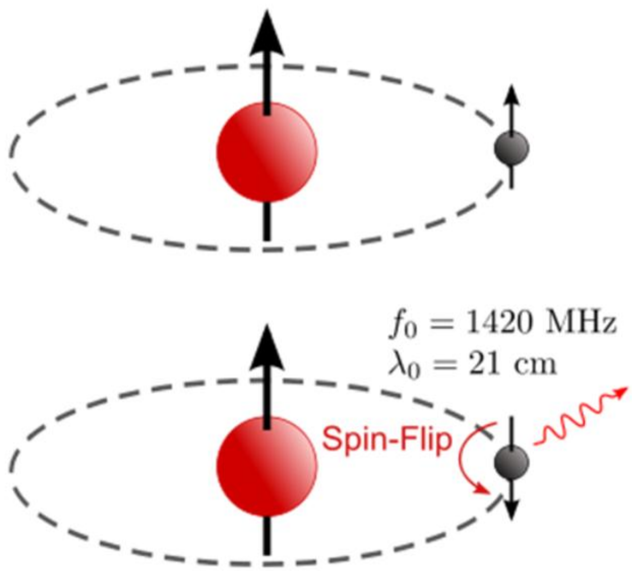
5) EDGES and other teams are **working to verify the measurement**.

Time		Redshift	
380.000 years		1100	
100 million years		30	Neutral Hydrogen in the Intergalactic Medium (IGM)
300 million years		14	
1 Gyr		6	
13.8 Gyr		0	

S.G. Djorgovski et al. & Digital Media Center, Caltech

Fraction of neutral hydrogen < 6%
McGreer et al. (2015)

Emission at 21 cm from Hydrogen Atom



Parallel spins

Upper ground state

Anti-parallel spins

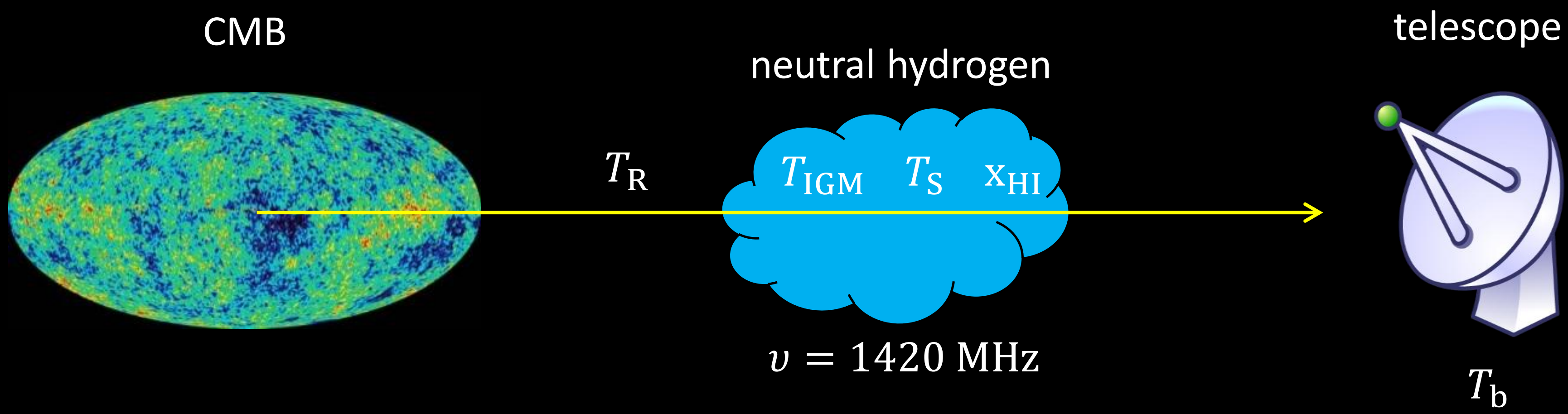
Lower ground state

Due to Cosmological Expansion

$$\upsilon_{\text{obs}} = \frac{\upsilon_{\text{emit}}}{(1+z)}$$

Redshift	Frequency
0	1420 MHz
6	200 MHz
13	100 MHz
140	10 MHz

21-cm Cosmology



21-cm Brightness Temperature

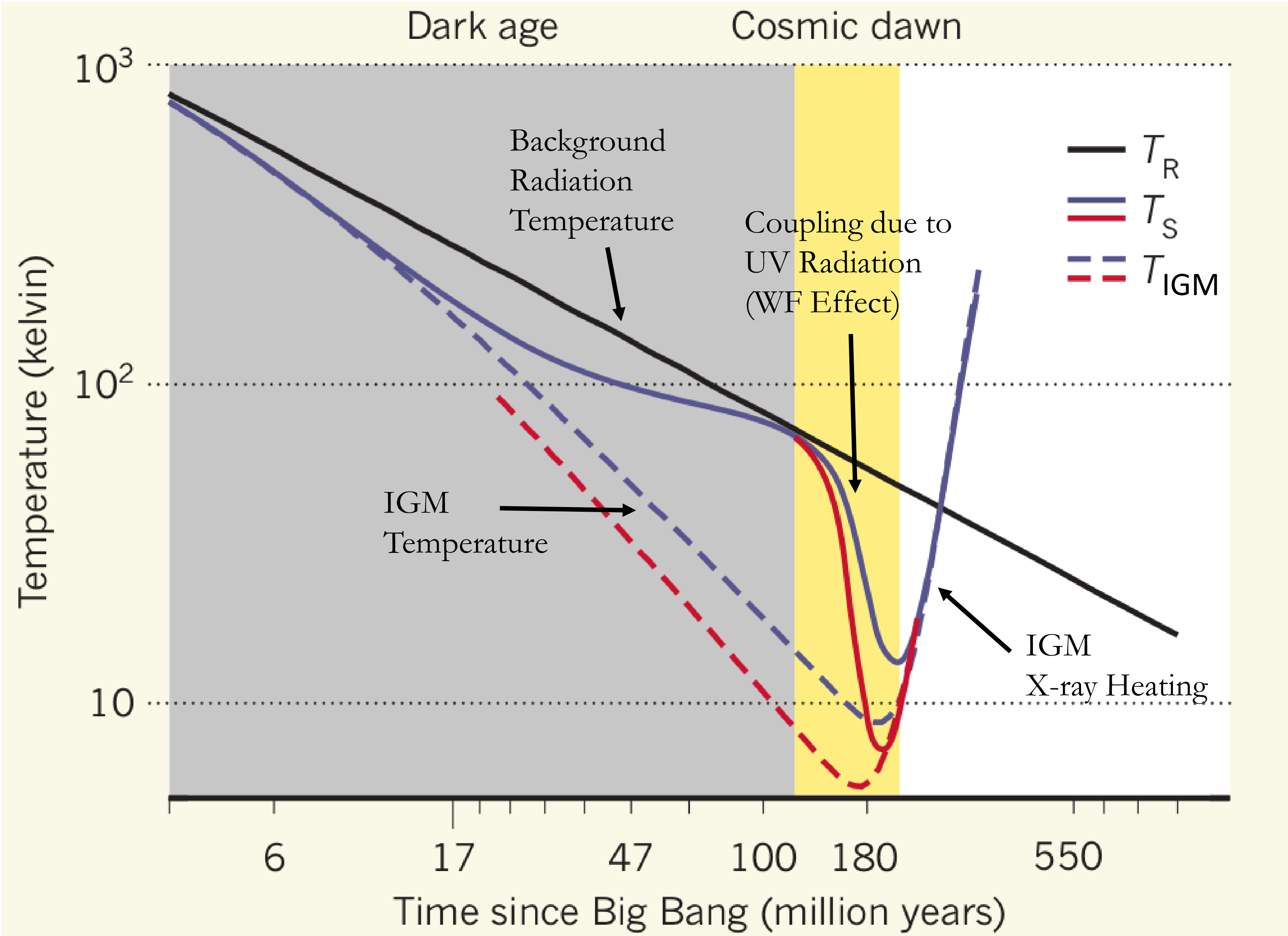
$$T_{21}(z) \approx 28\ \text{mK} \cdot \sqrt{\frac{1+z}{10}} \cdot x_{HI} \cdot \left(\frac{T_S - T_R}{T_S}\right)$$

radiation temperature

fraction of neutral hydrogen

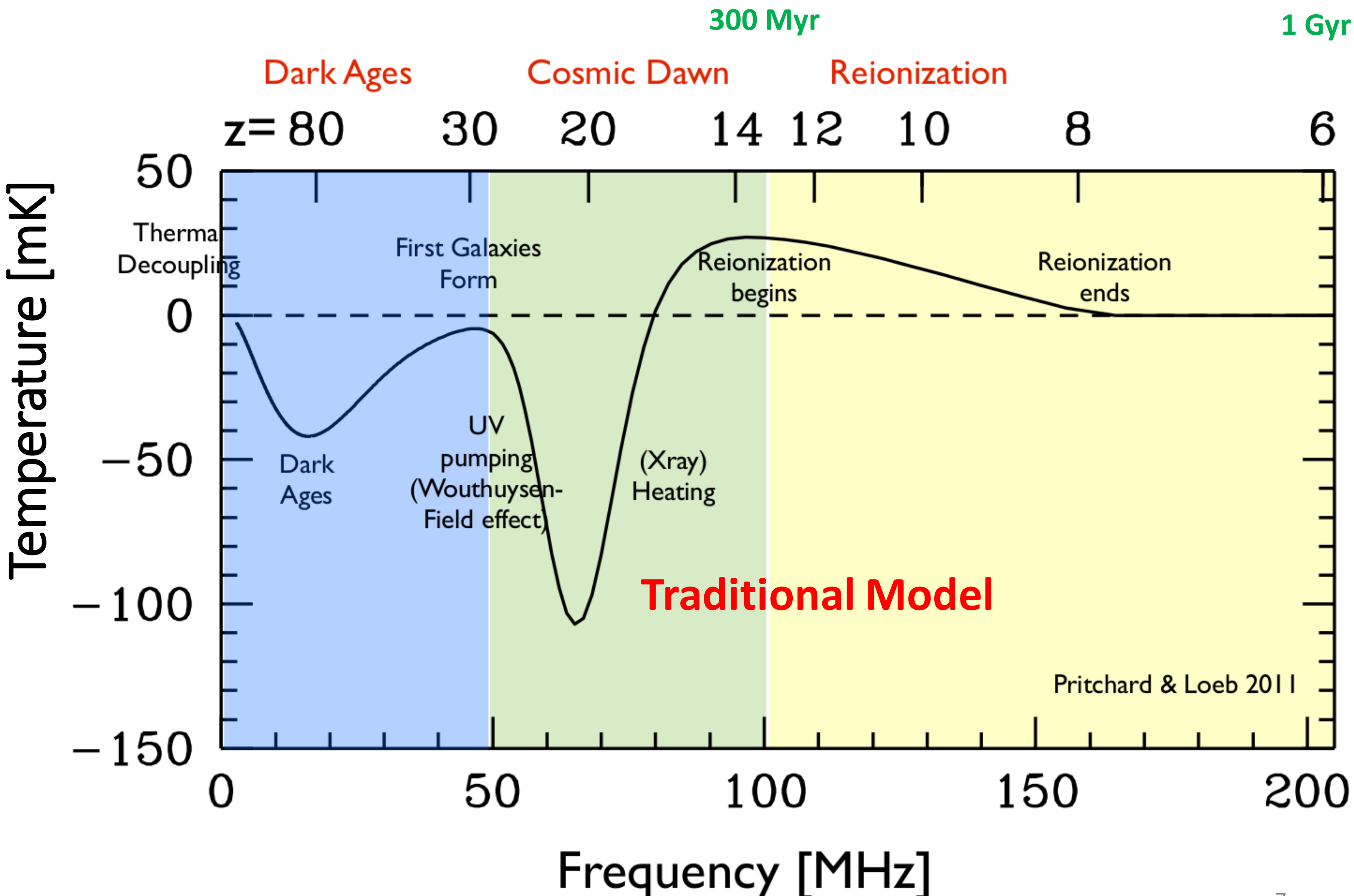
spin temperature

Global (Sky-Averaged) 21-cm Spin Temperature



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

Global 21-cm Signal



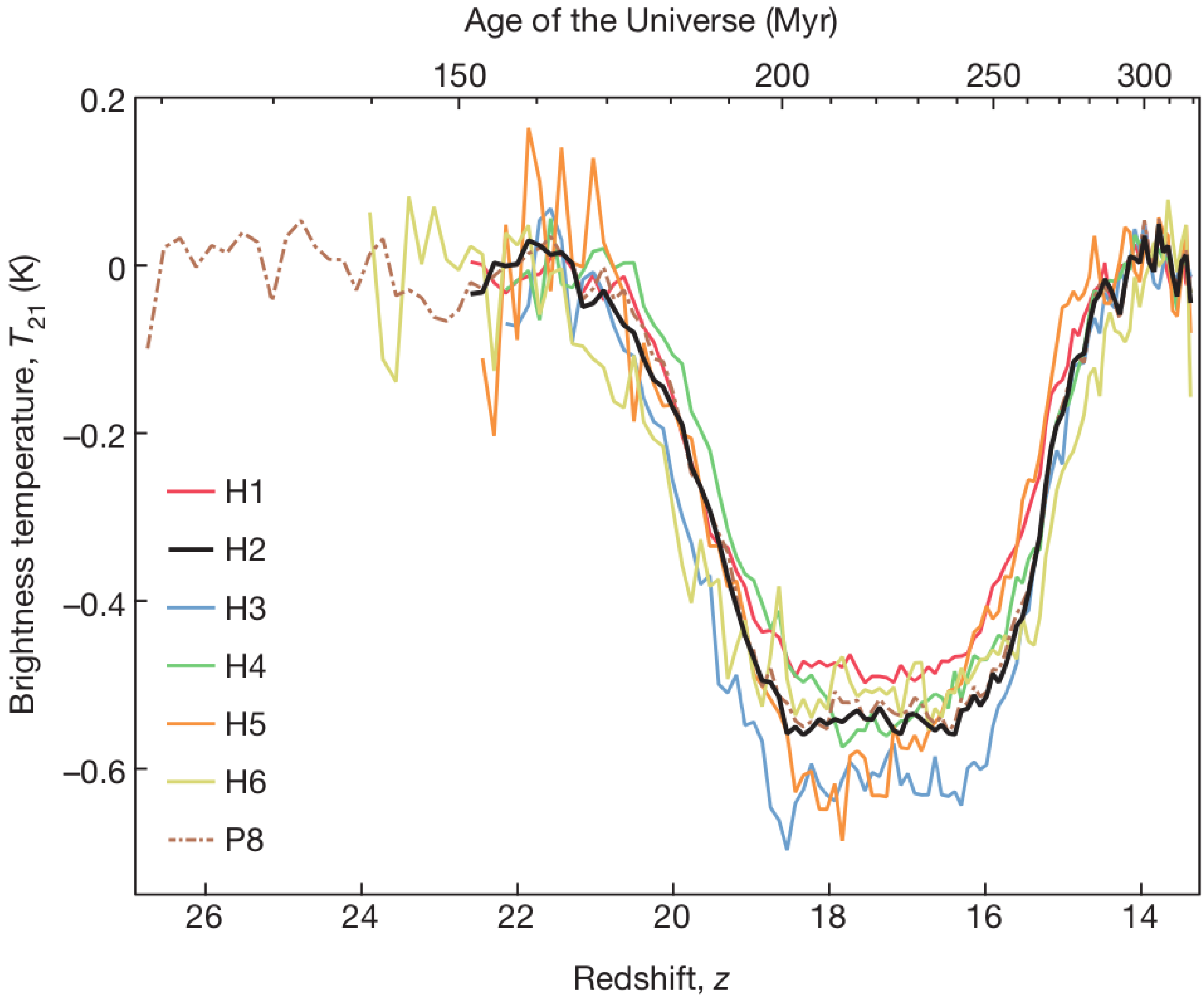
Global 21-cm Measurement

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

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**

EDGES Measurement



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

EDGES

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

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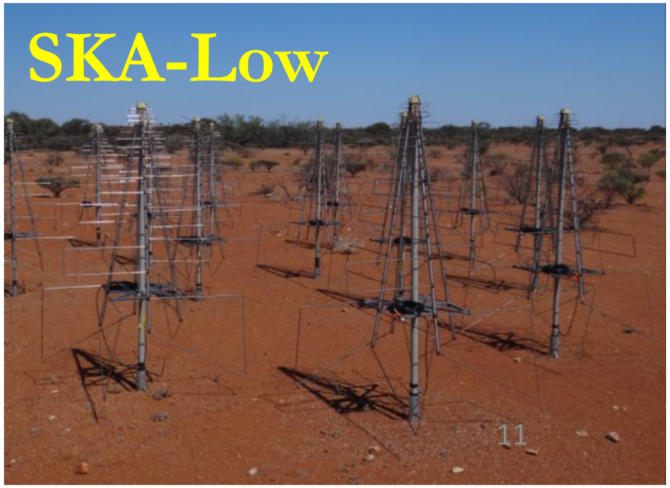
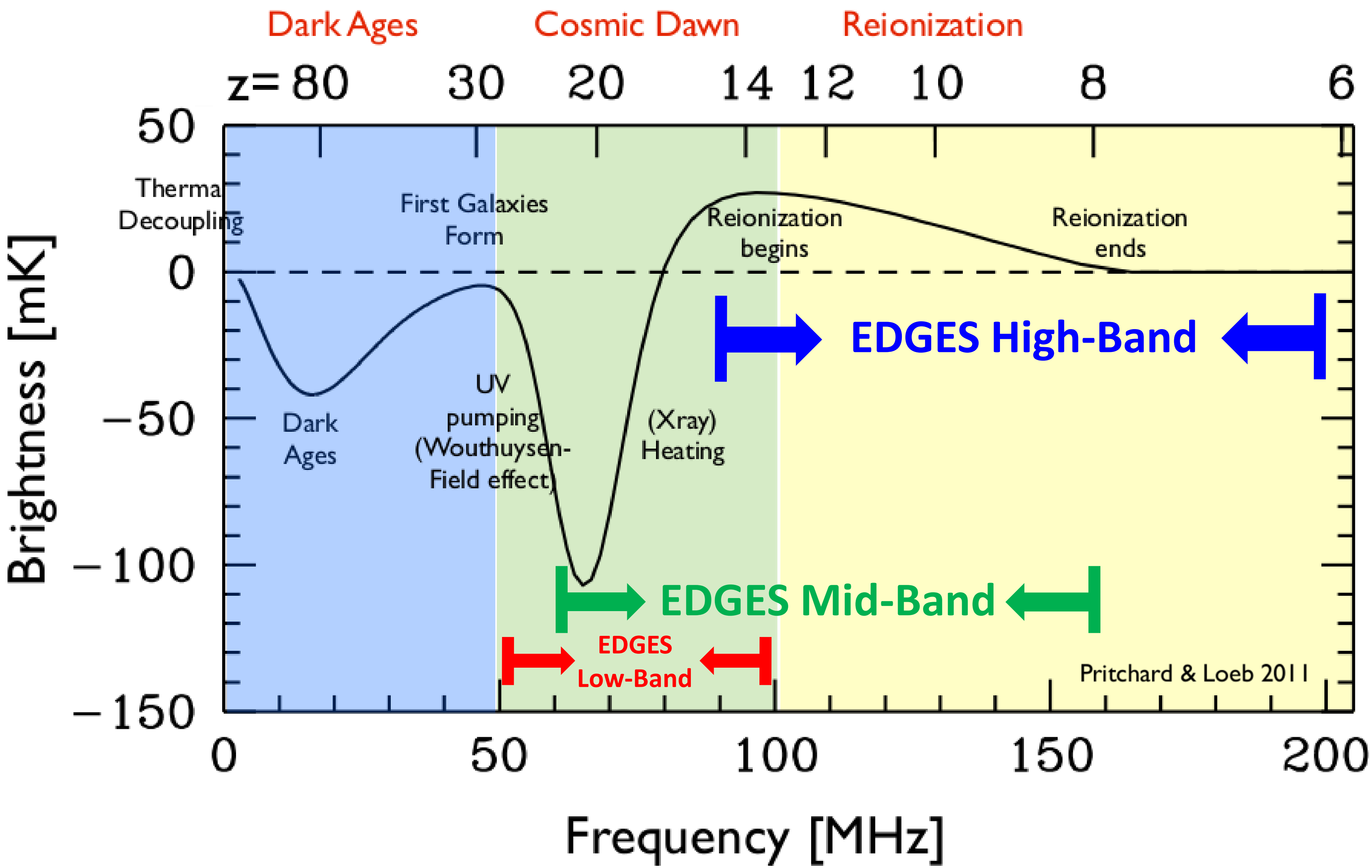
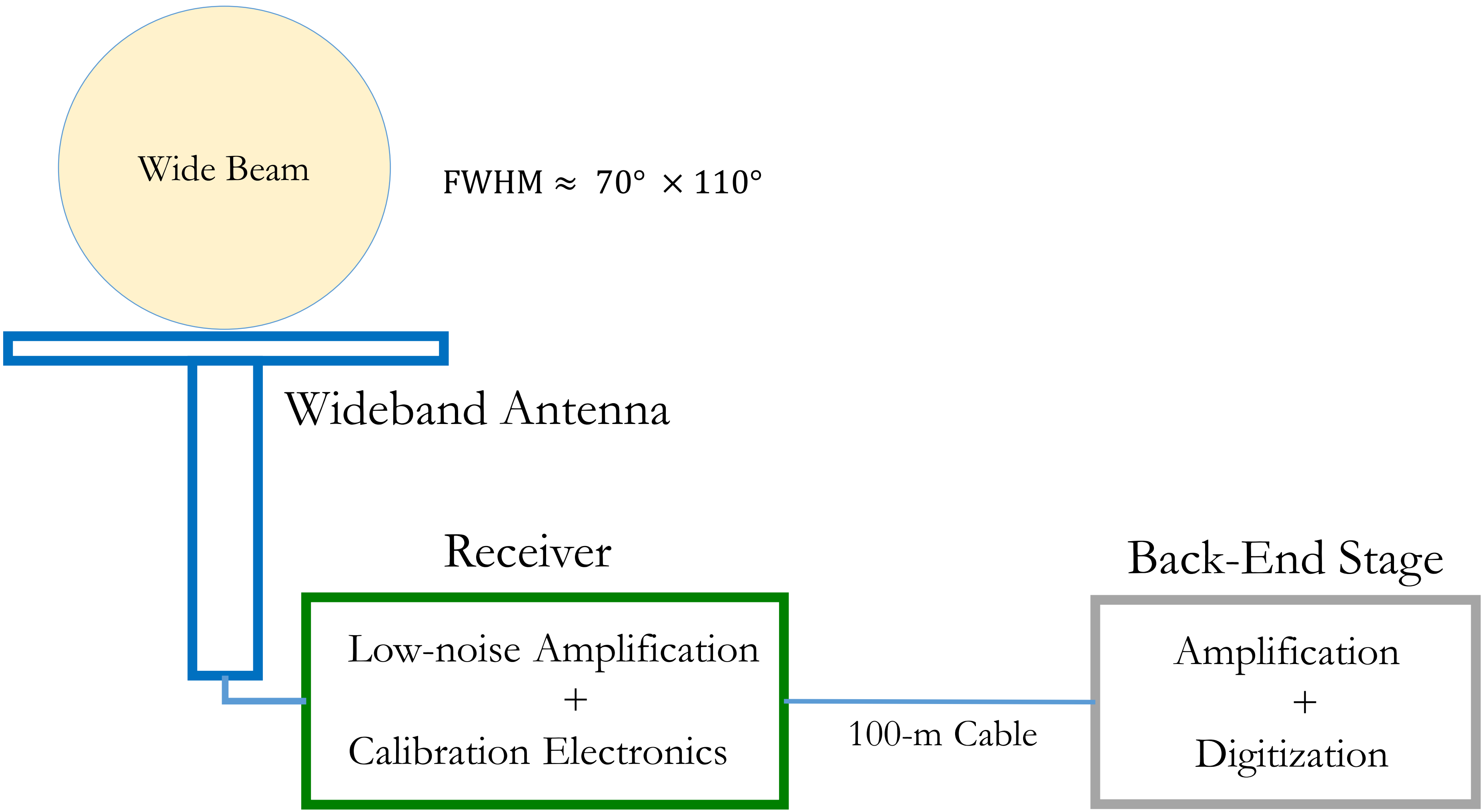
Radio-Quiet Site
Murchison Radio-astronomy Observatory (MRO)



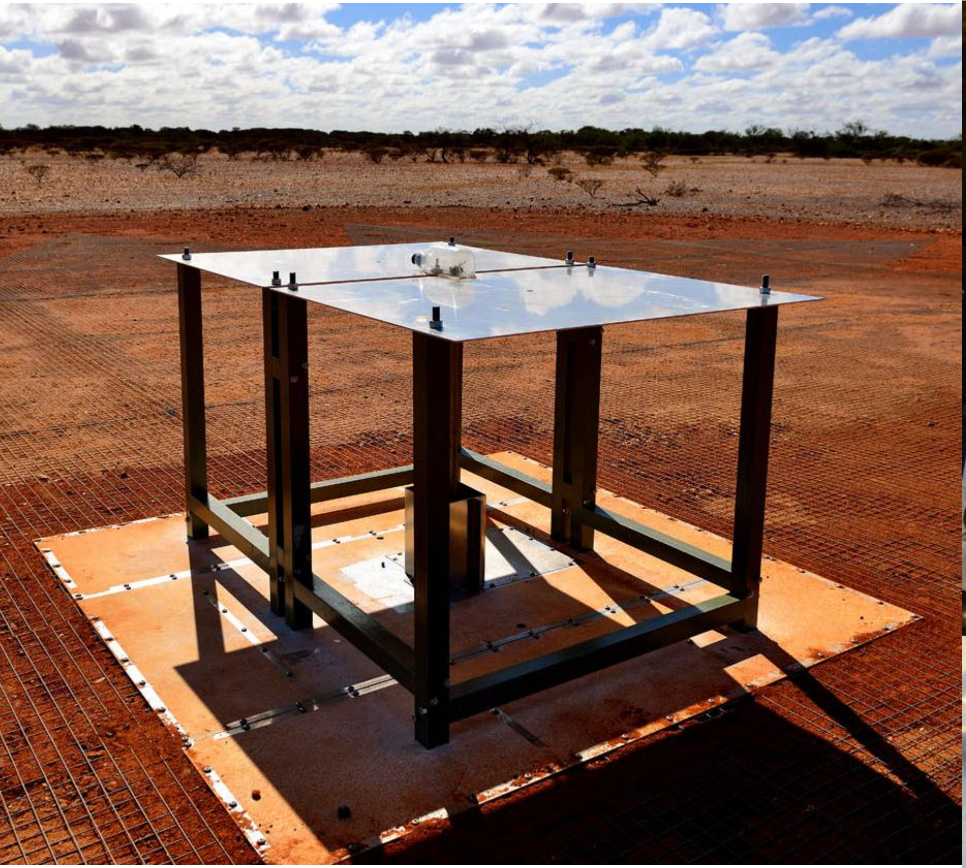
EDGES Instruments

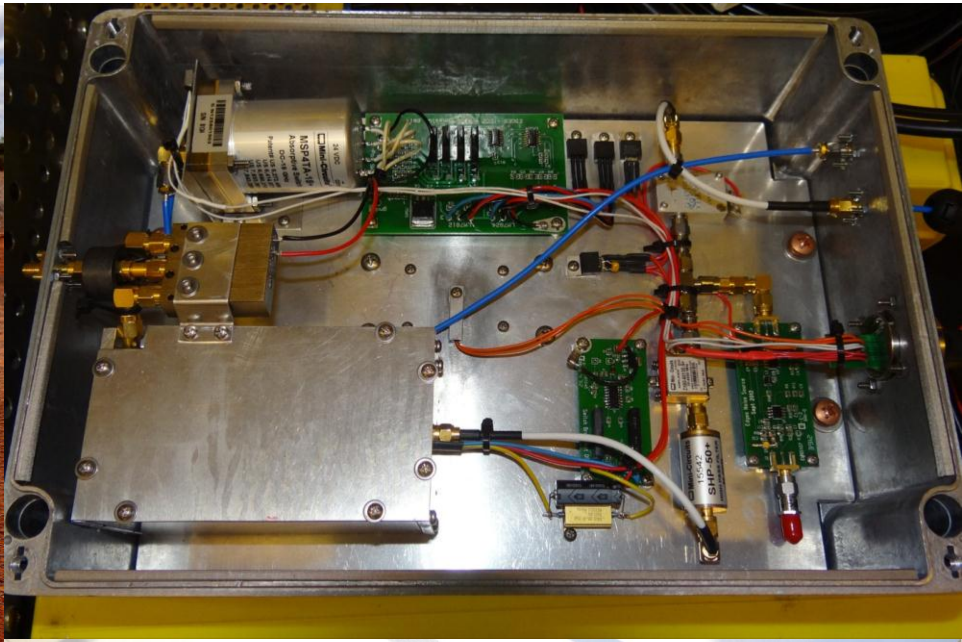


EDGES Block Diagram



EDGES **Low-Band**





Antenna size:

2m long / 1m high

Two **Low-Band** Instruments

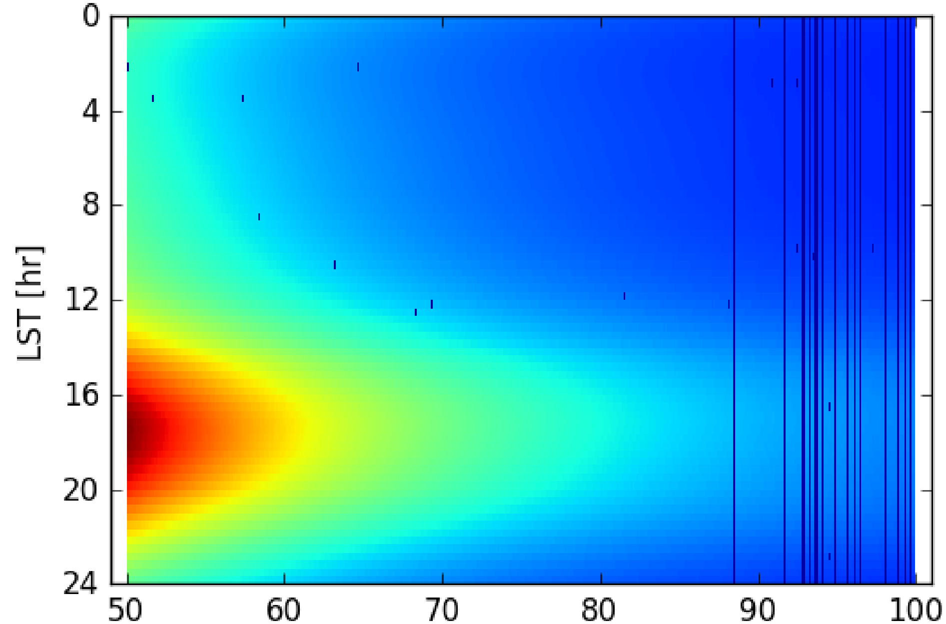
Challenges

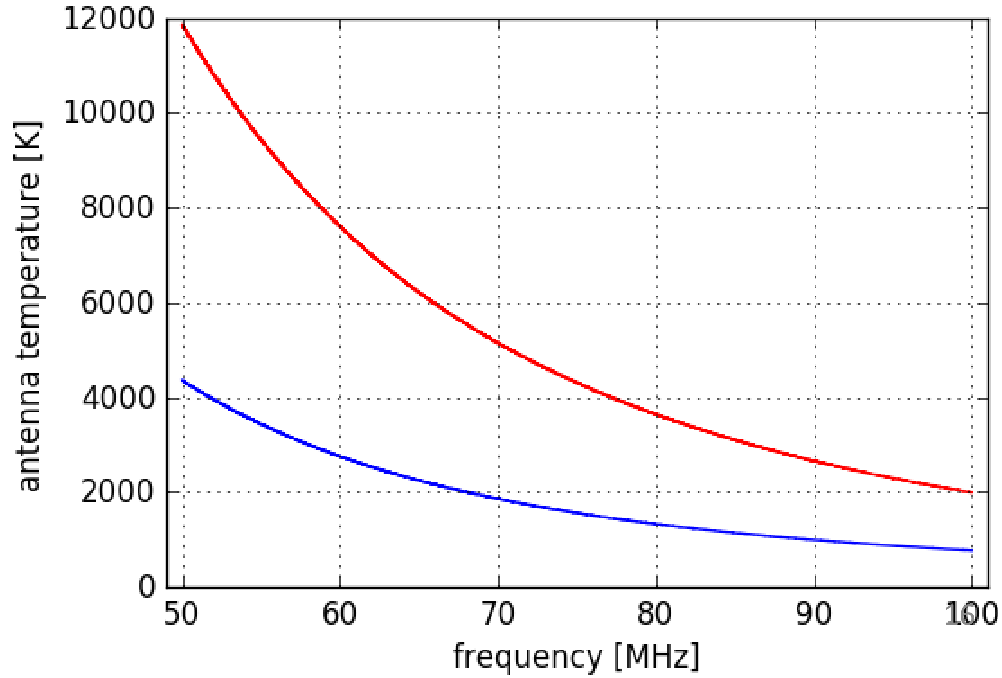
1) **Hard instrument calibration** problem.

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

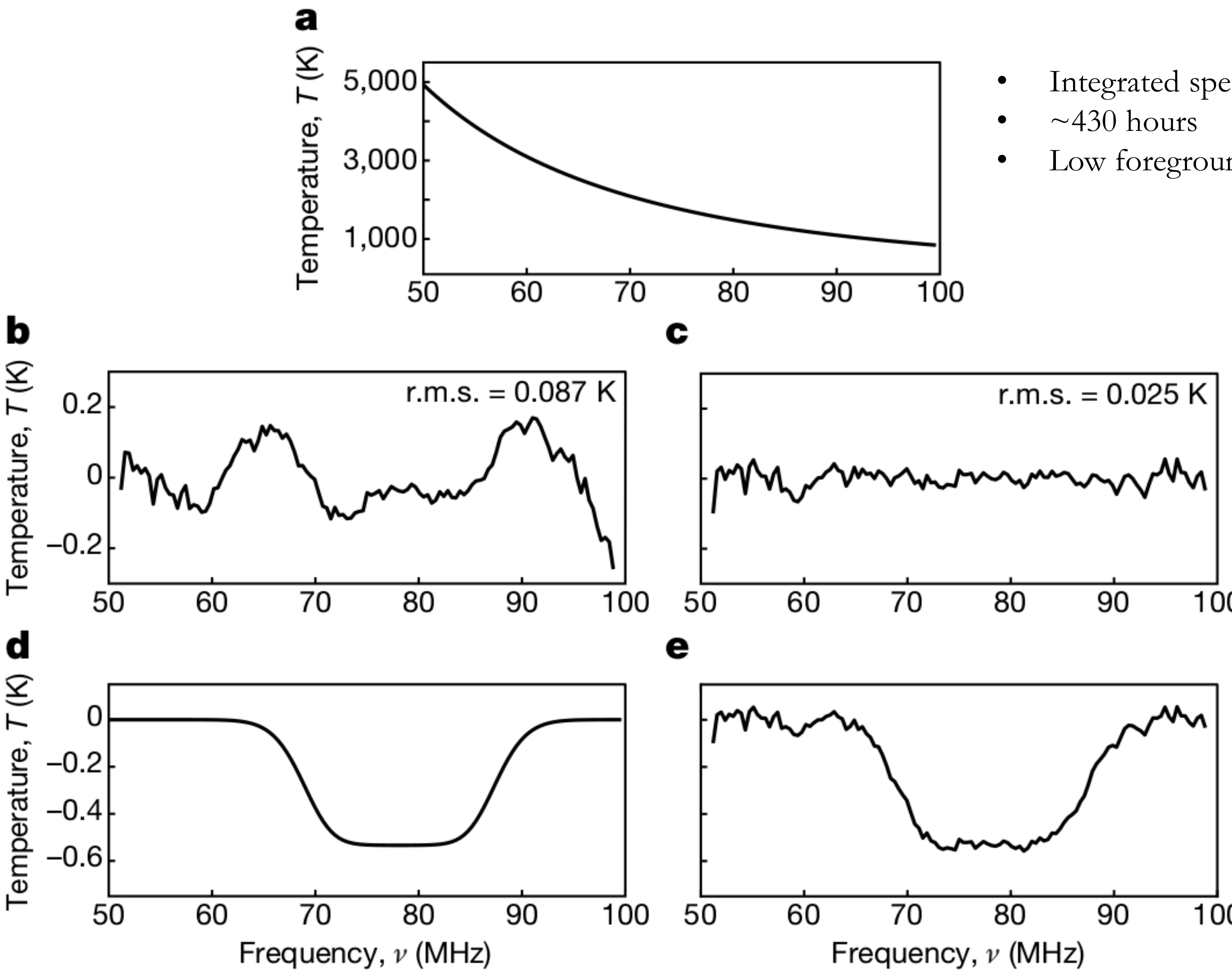
Daily Observations

EDGES Low-Band





Summary of the Detection



- Integrated spectrum
- ~430 hours
- Low foreground regions

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

Phenomenological 21-cm Model
"Flattened Gaussian"

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

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

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

"Foreground" Models

Linearized version of Physically-Motivated foreground model

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

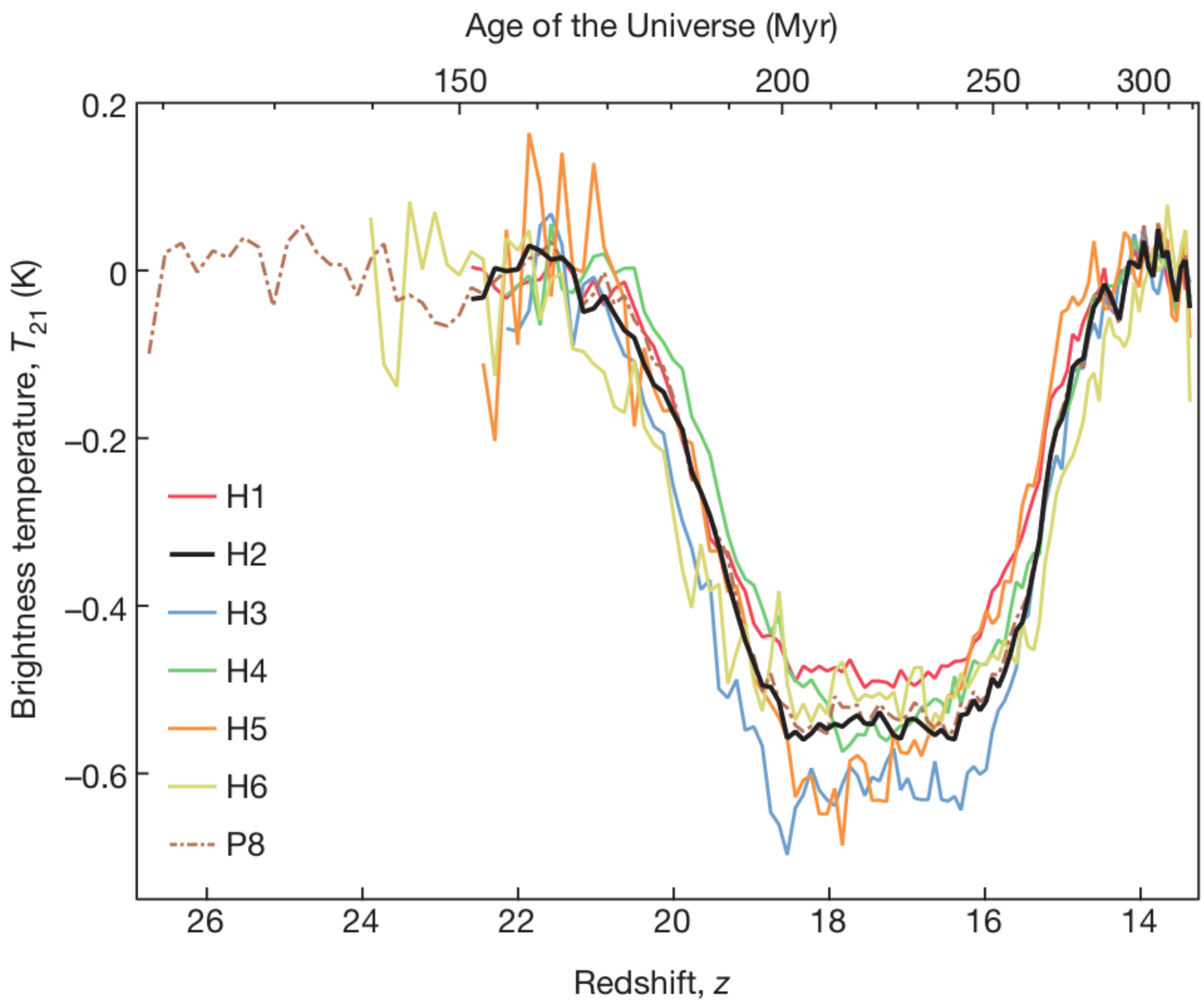
Alternative Polynomial Model

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

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**.

Different Instruments/Hardware Cases



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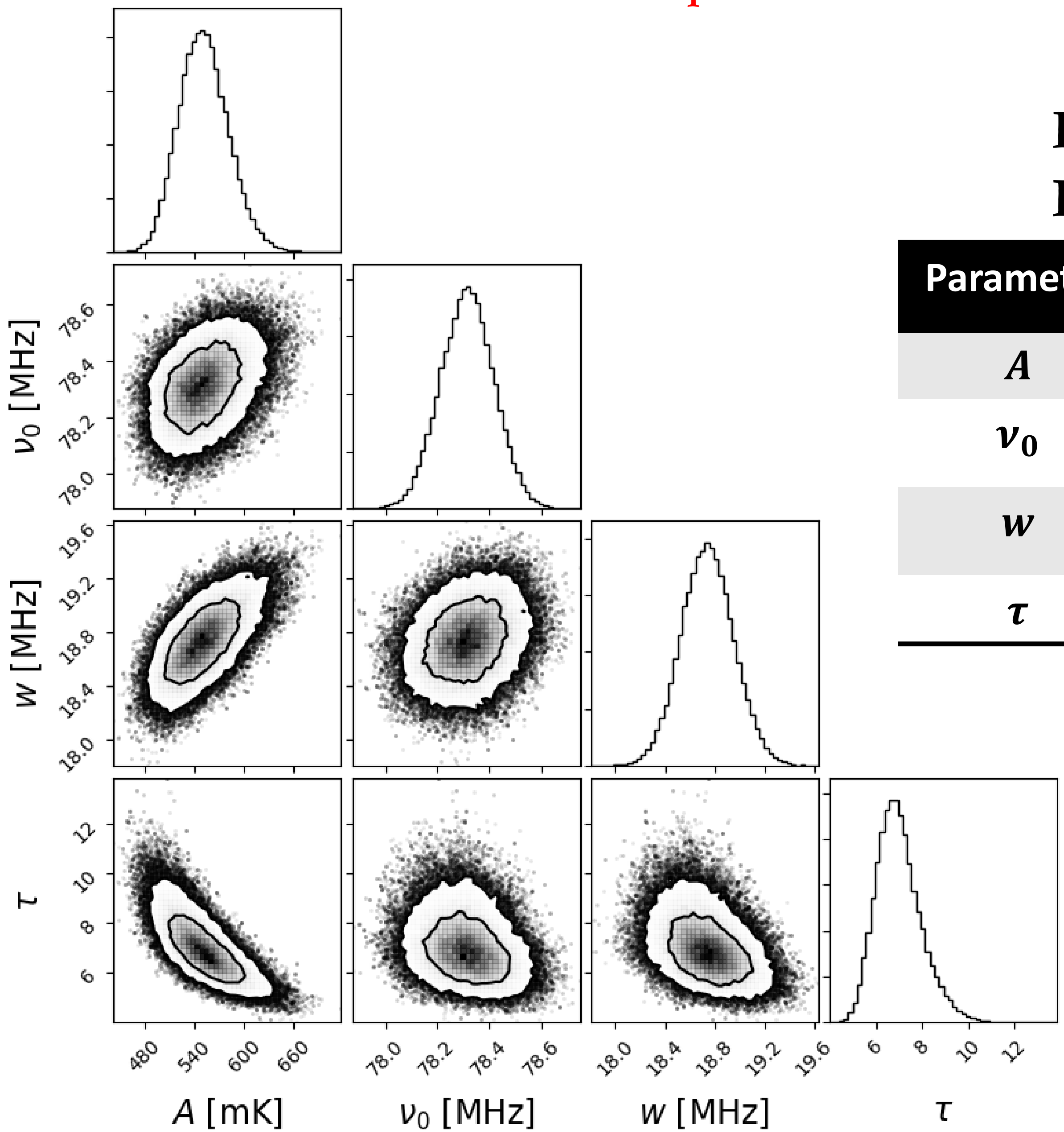
Parameter Estimates

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

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?

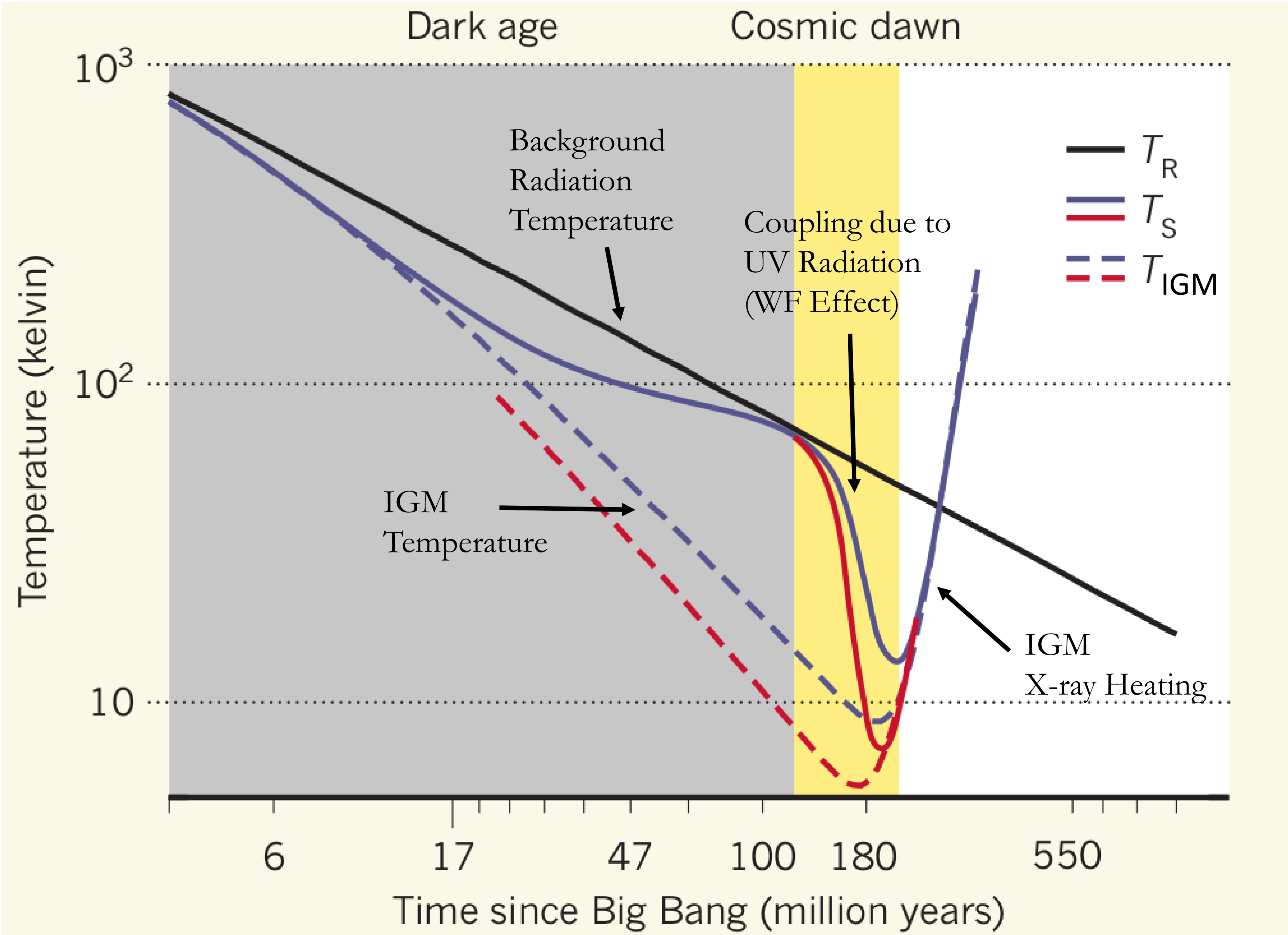
$$T_{21}(z) \propto \left(1 - \frac{T_{\rm CMB} + \boldsymbol{T}_{\mathbf{EXCESS}}}{\boldsymbol{T}_{\mathbf{S}}}\right)$$

Higher than zero

Lower than expected

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

Global (Sky-Averaged) 21-cm Spin Temperature



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

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

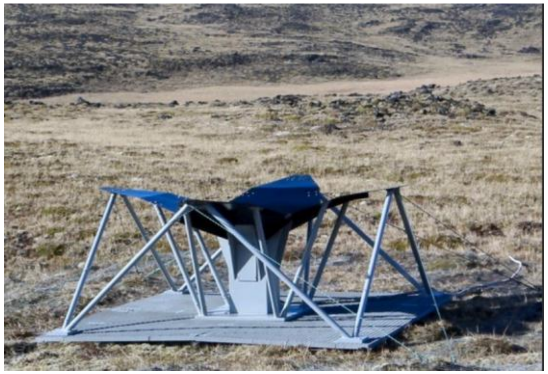
1) Enough IGM cooling achieved if **small fraction (<1%) of DM particles** posses **electric mini-charge (~10^{-6} the charge of an electron)**.

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

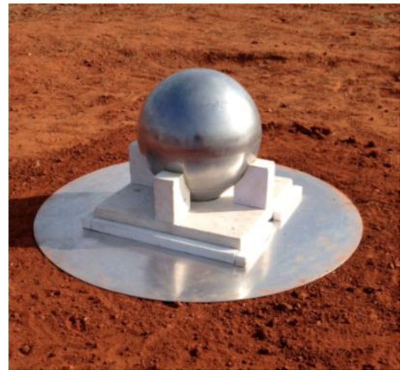
In EDGES **we remain agnostic** about the cosmological/astrophysical explanations, and focused on the verification of our measurement.

Other 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.)

Summary

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

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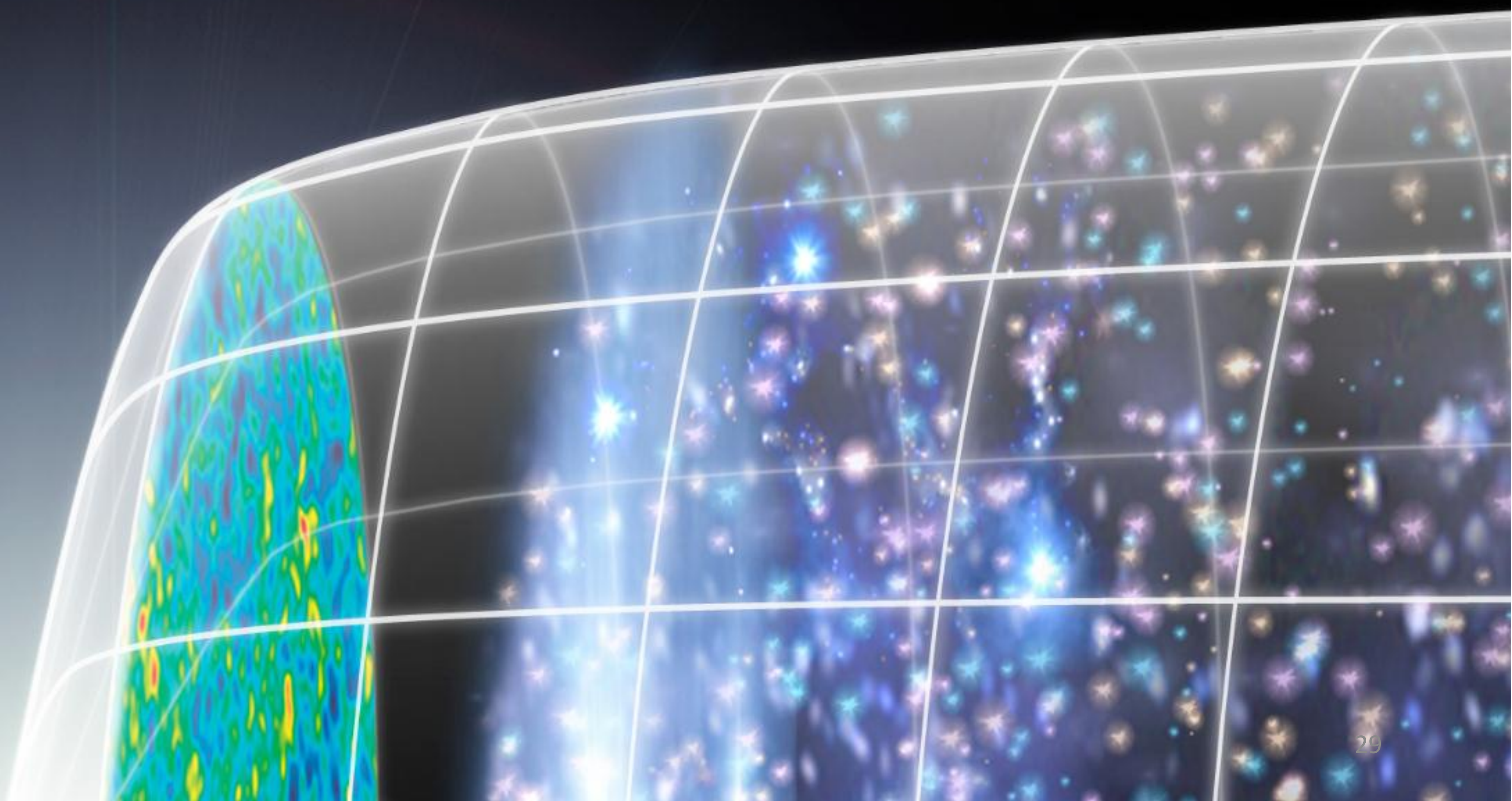
Thank You



Instrumental Calibration

1) **Receiver gain and offset.**

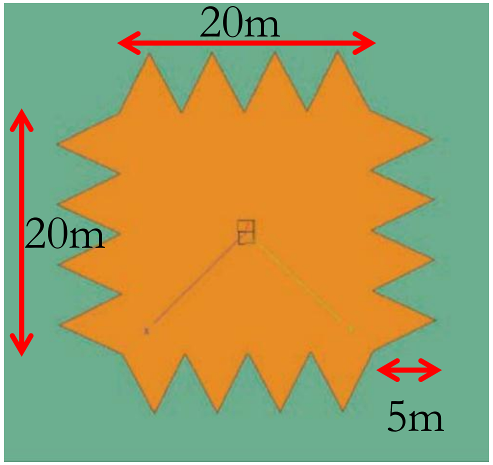
2) **Impedance mismatch between receiver and the antenna.**

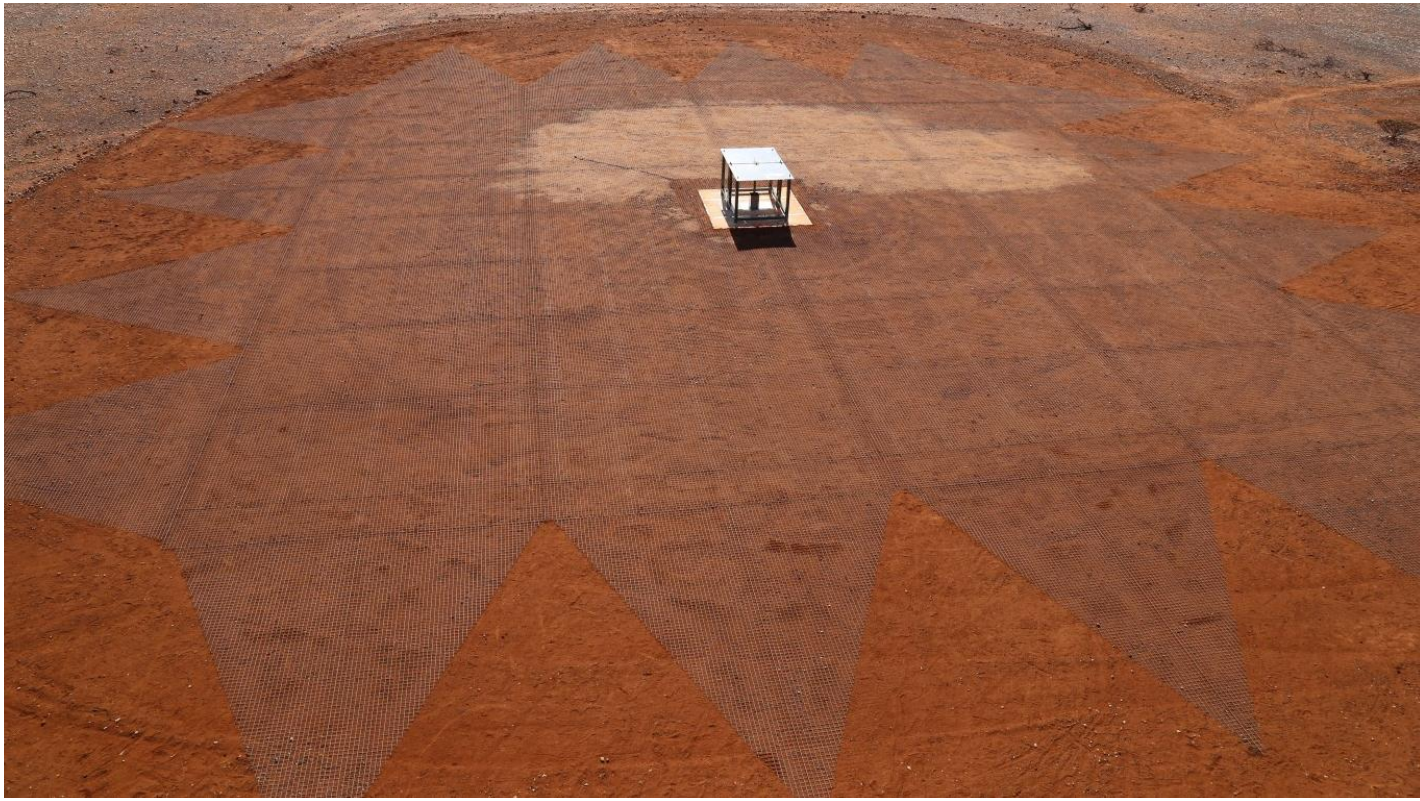
3) **Antenna and ground losses.**

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

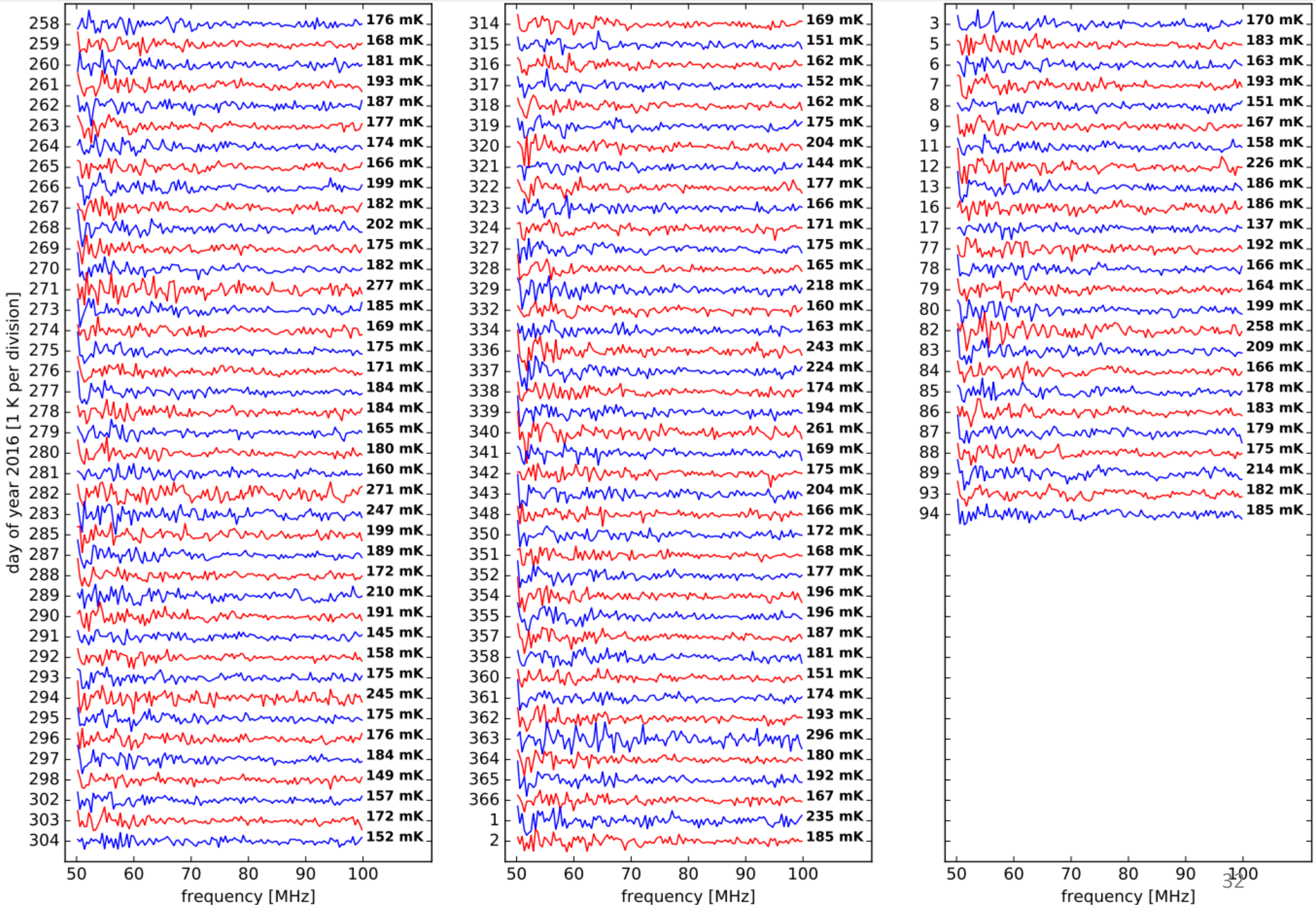
Low-Band Ground Plane

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





Daily **Low-Band** Residuals



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

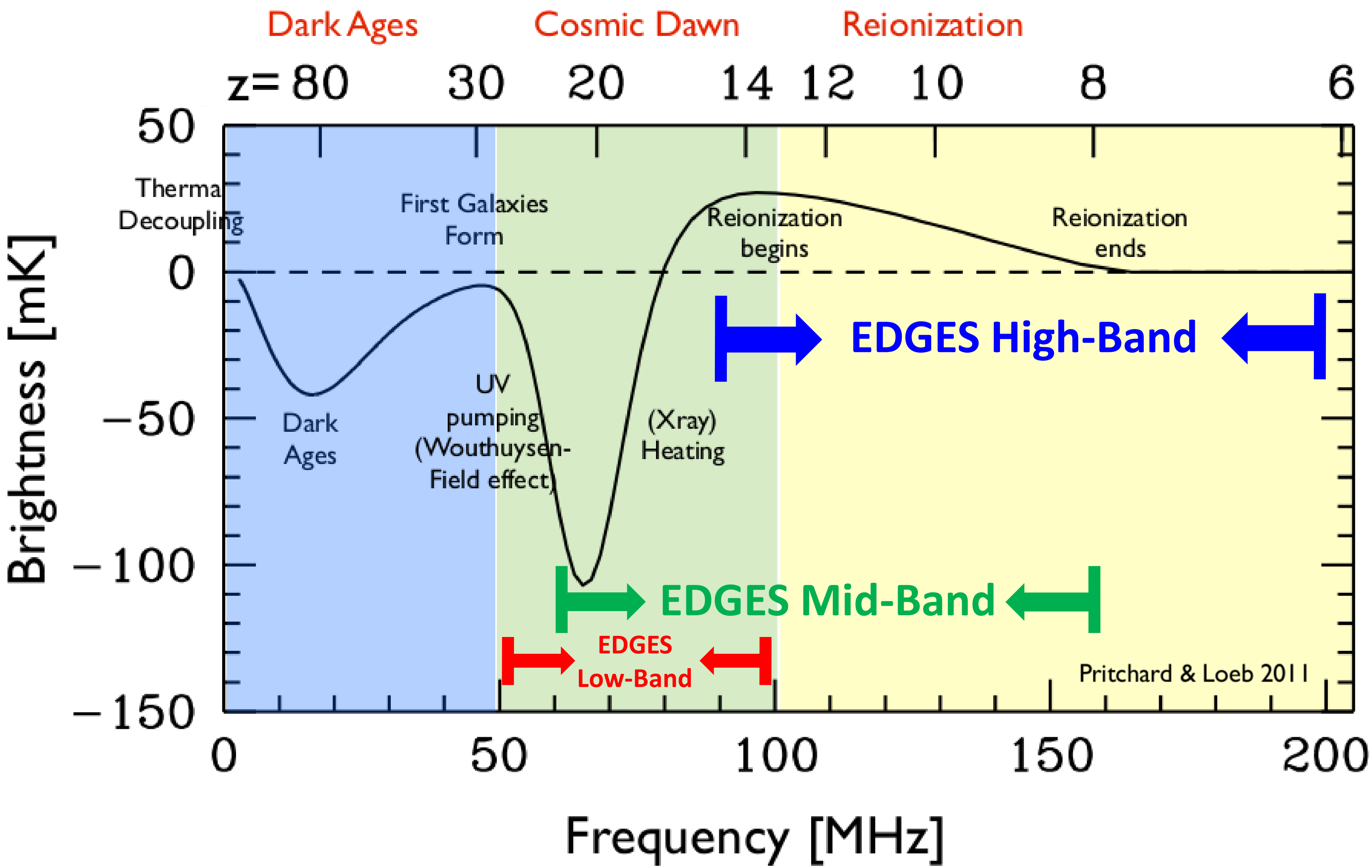
Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, **Nature**, 555, 67

Hardware and Processing Cases

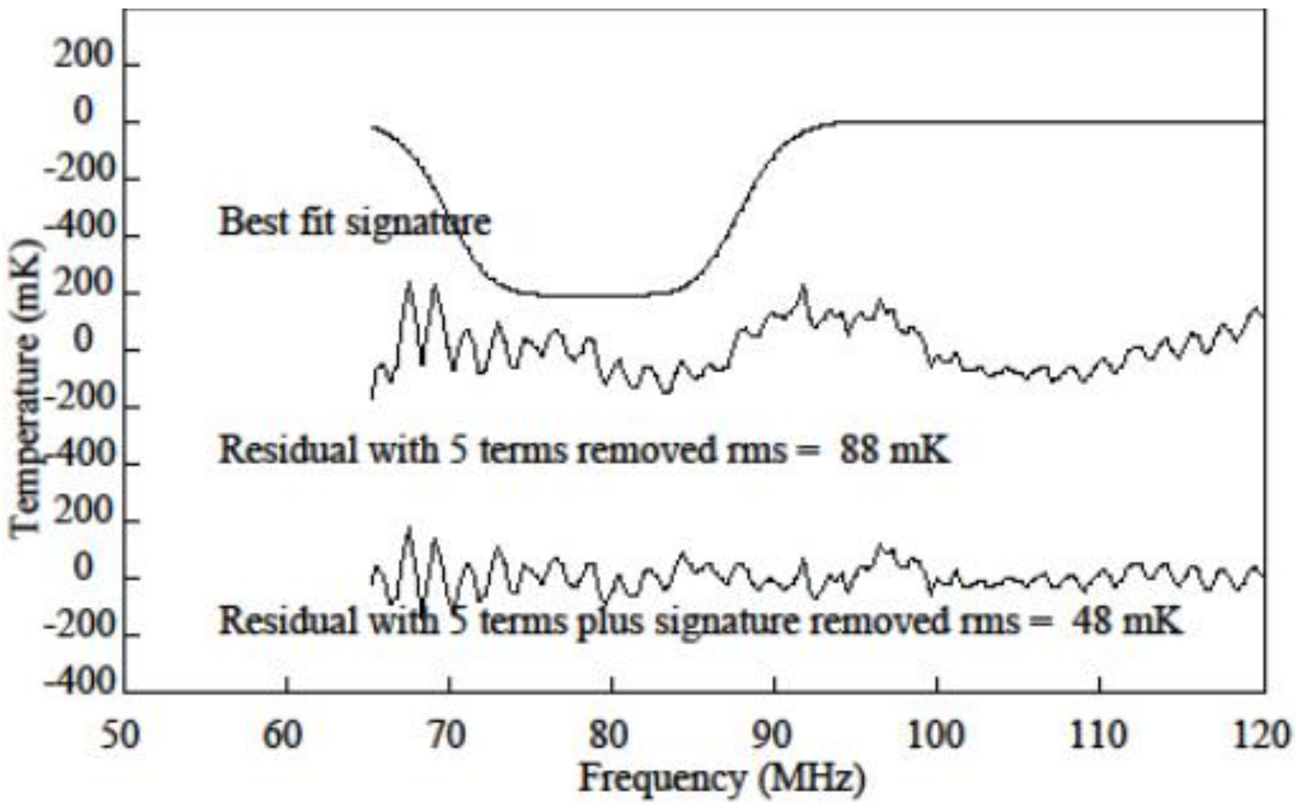
Configuration		Sky Time (hours)	SNR	Centre Frequency (MHz)	Width (MHz)	Amplitude (K)
Hardware configurations (all P6)						
H1 – low-1 10x10 ground plane		528	30	78.1	20.4	0.48
H2 – low-1 30x30 ground plane		428	52	78.1	18.8	0.54
H3 – low-1 30x30 ground plane and recalibrated receiver		64	13	77.4	19.3	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

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**.

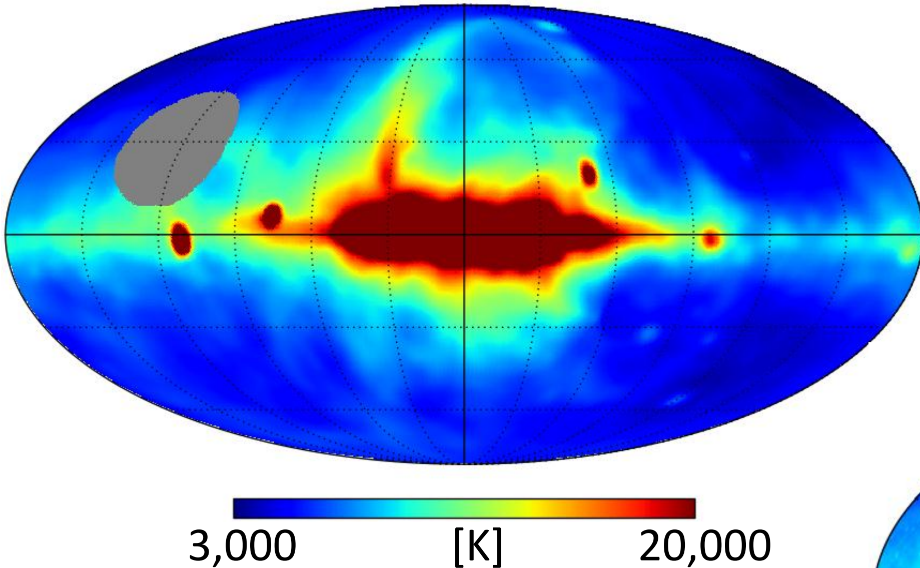
Best-fit parameters:

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

Diffuse Foregrounds

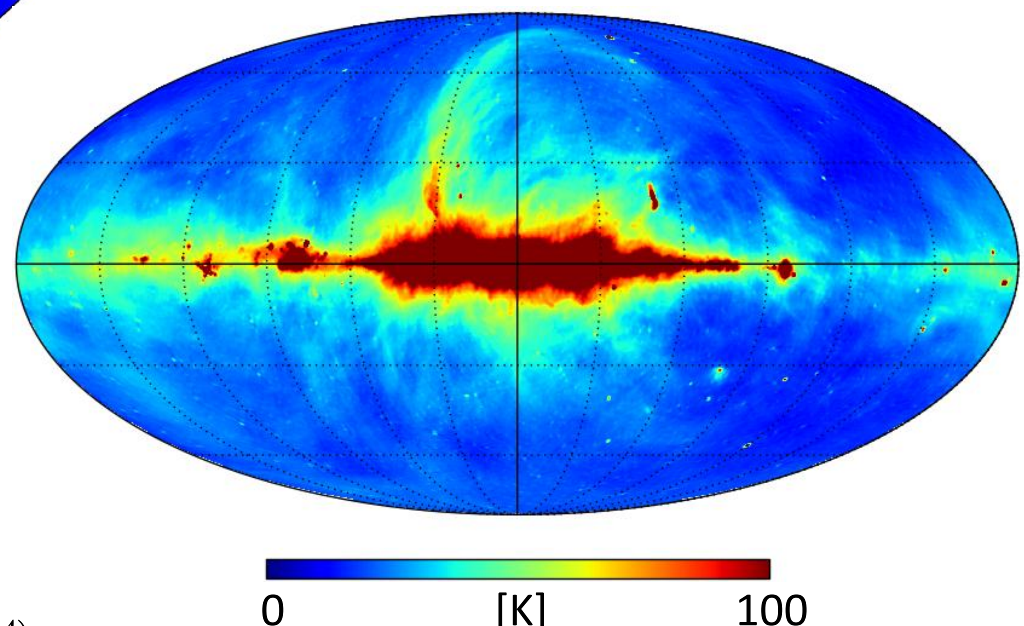
45-MHz Map

Guzmán et al. (2011)



408-MHz Map

Haslam et al. (1982)



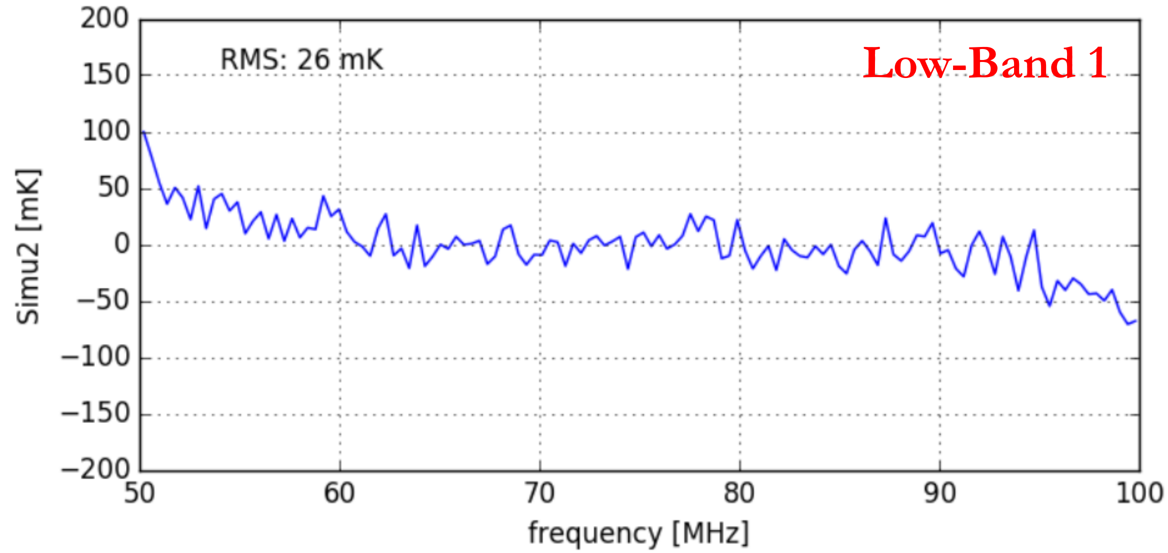
1) From **hundreds to thousands of Kelvins**.
2) Include **Galactic and Extragalactic**.
3) Mostly **Galactic synchrotron radiation**.
4) **Spectrally smooth** (e.g., Fornengo et al. 2014)
5) Might need **several terms** to model (Bernardi et al. 2015)
6) Large **spatial gradients**.

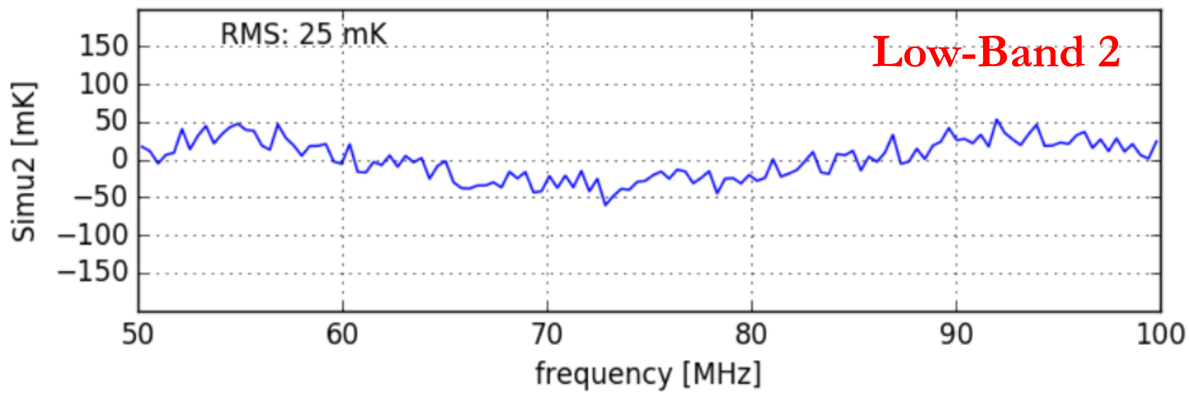
Verification Using ~300K Antenna Simulators

At 75 MHz

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

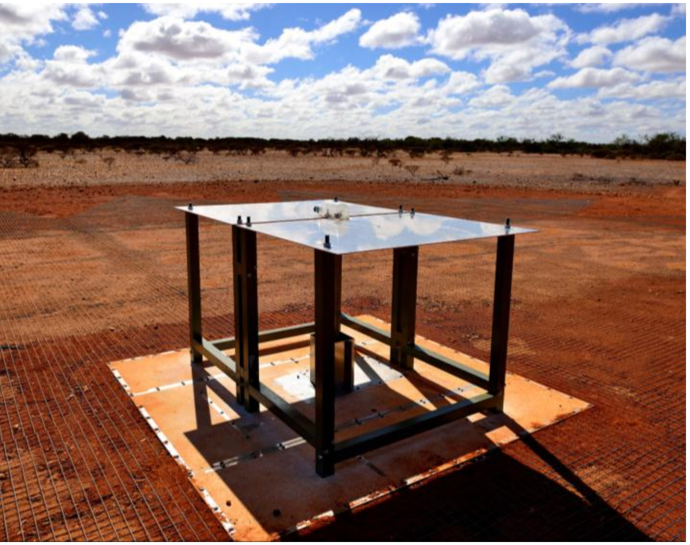
Residuals After Removing a Constant





EDGES Mid-Band

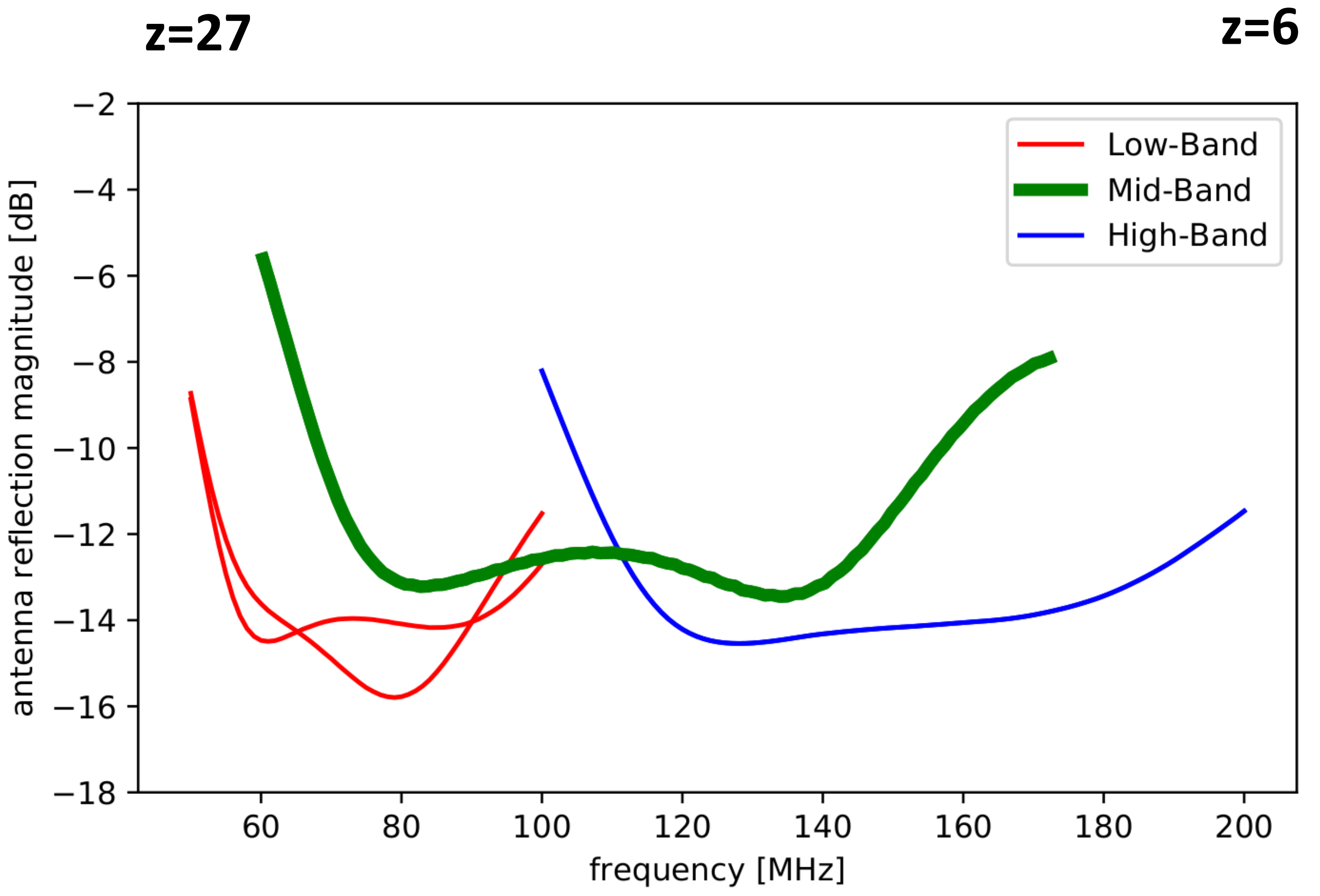
Low-Band



High-Band

Mid-Band

Antenna Reflection Coefficients



Preliminarily …..