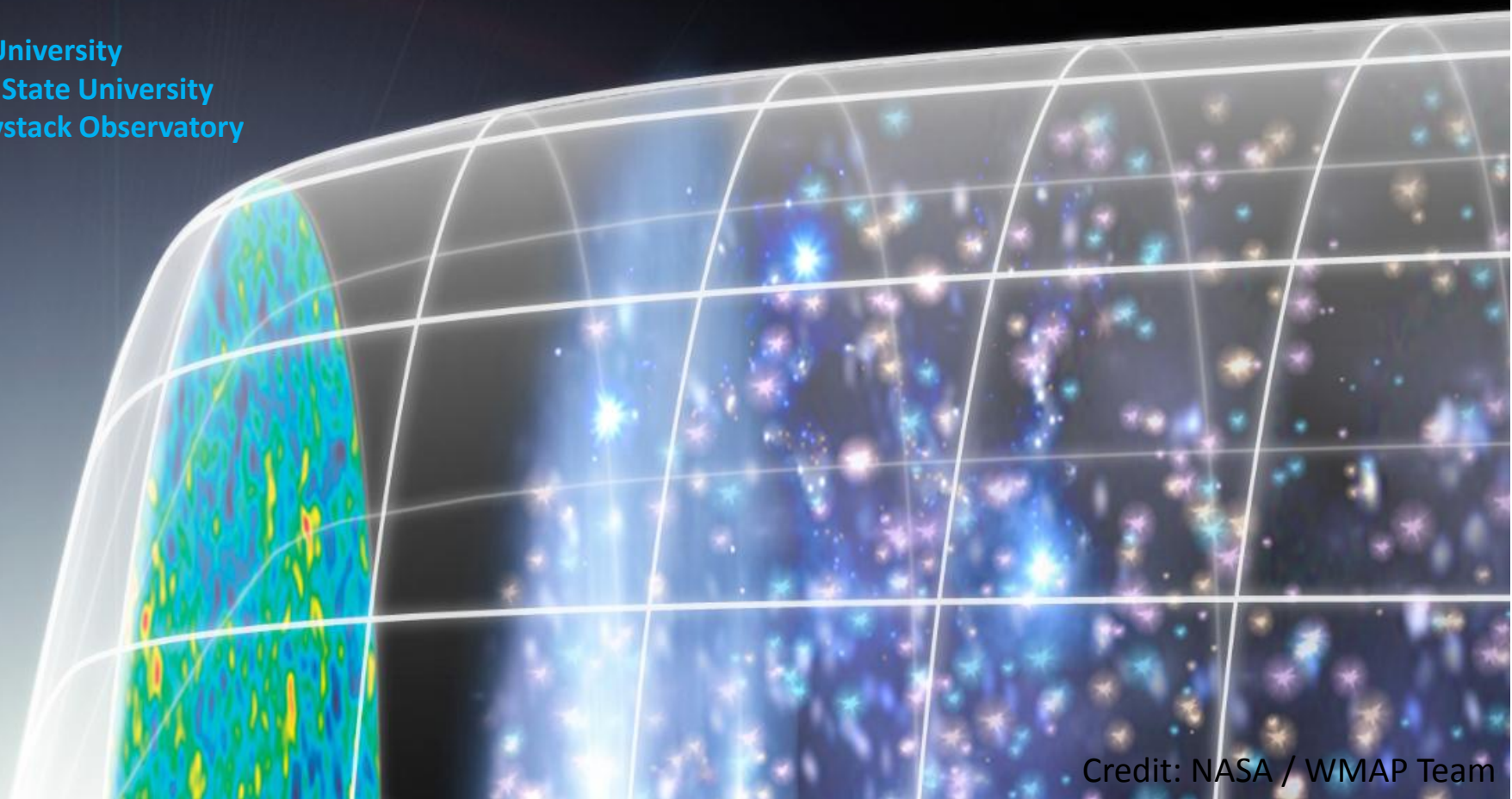
Thermal History of the Universe at Intermediate Redshift:
Progress with 21cm Absorption Measurements
CERN

June 26, 2018

# An Absorption Feature in the Sky-Averaged Radio Spectrum

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

[1]McGill University
[2]Arizona State University
[3]MIT Haystack Observatory



Credit: NASA / WMAP Team

# Summary

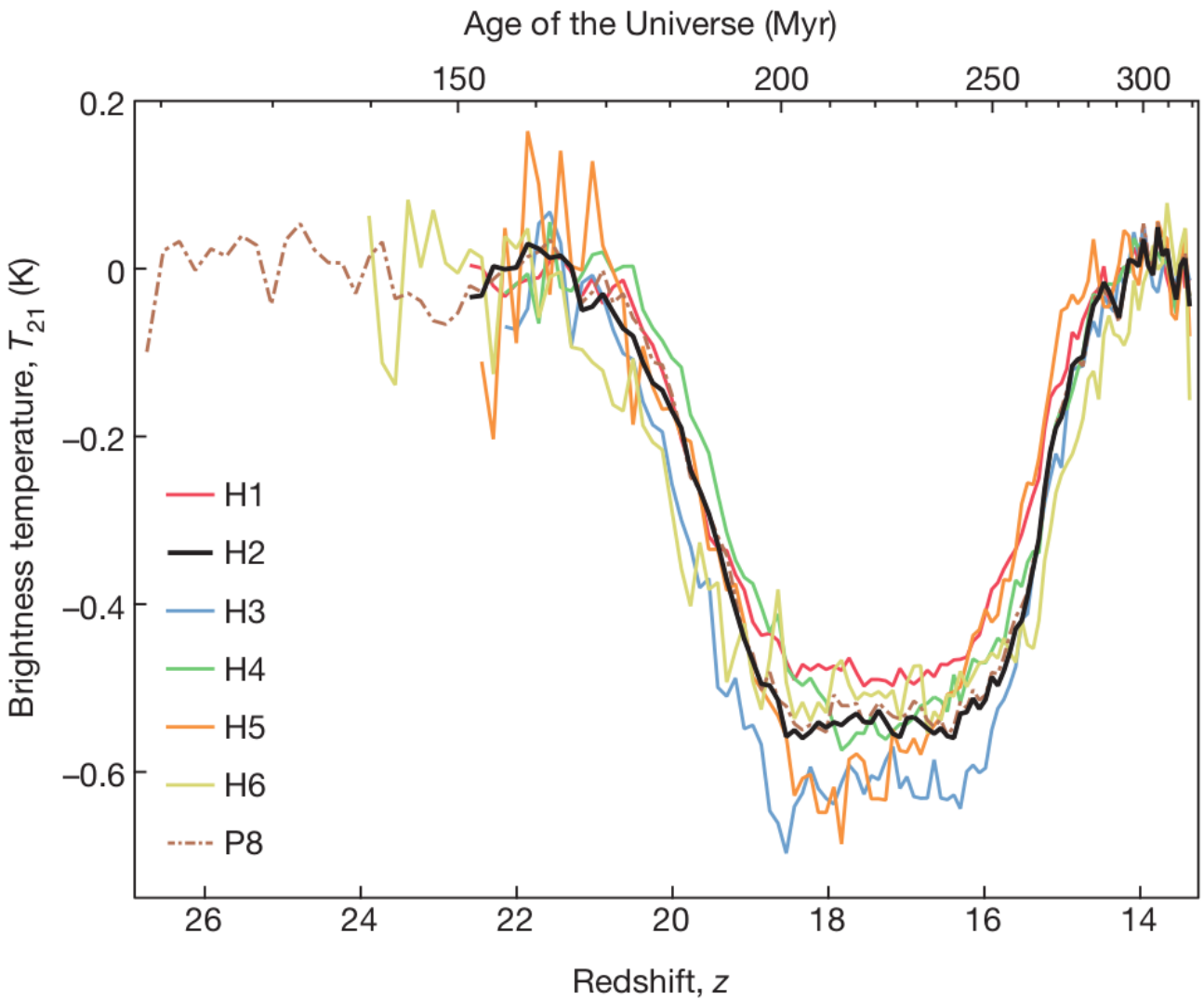
1) The **EDGES experiment** has **detected an absorption feature** in the sky-averaged spectrum centered at 78 MHz.

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**.




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

# EDGES

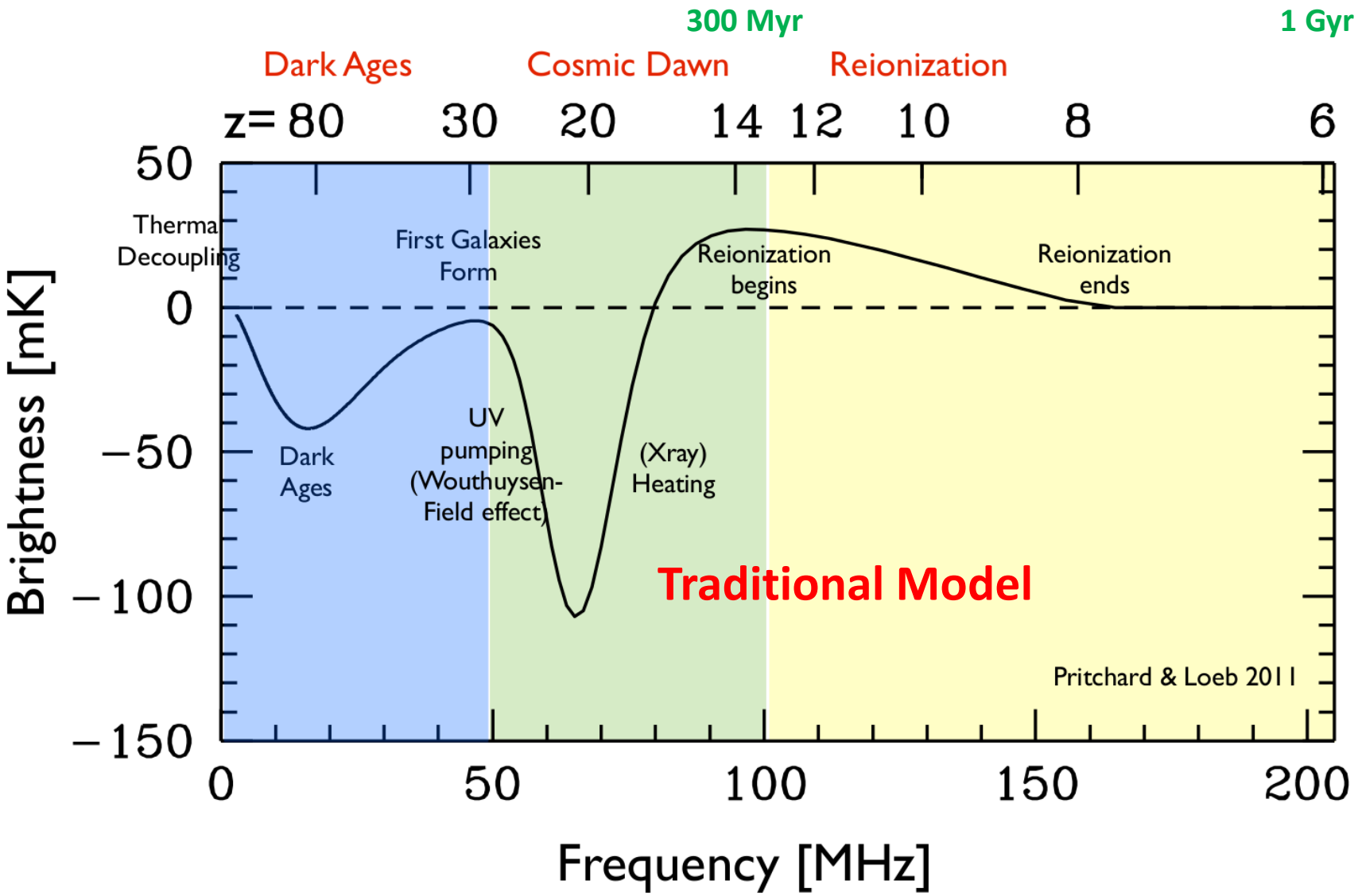
## Experiment to Detect the Global EoR Signature

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

Arizona State University

MIT Haystack Observatory

# Global (sky-average) 21-cm Signal



# Global 21-cm Measurement

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

2) **Experiment much smaller** than antenna arrays.

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

4) Provides constraints on:
   - **Timing** and **strength** of UV coupling by first sources, and IGM 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.**

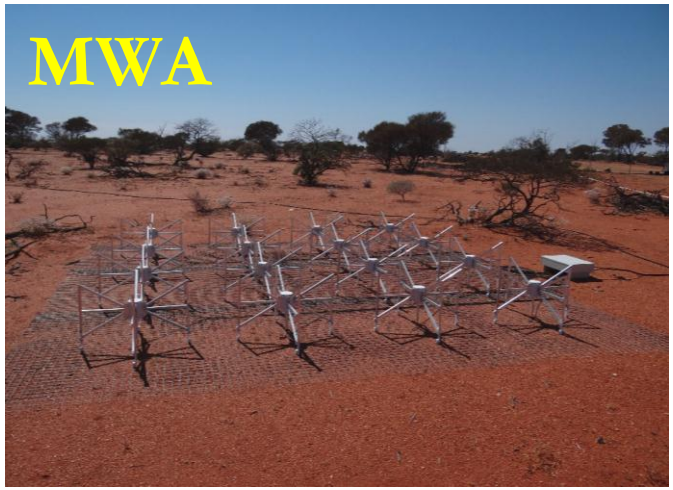
# Challenges

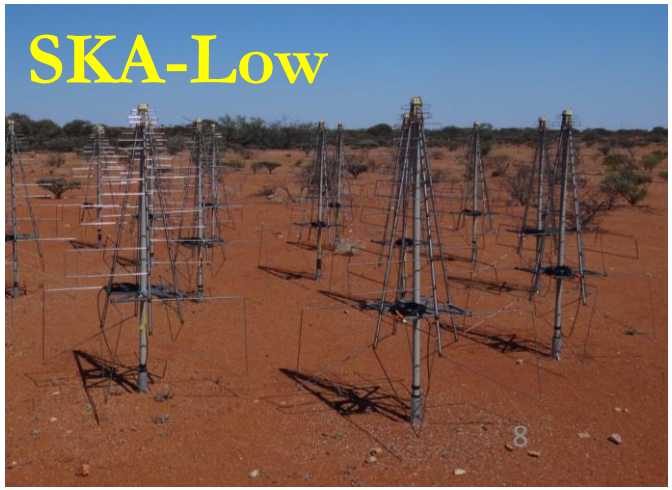
1) **Hard instrument calibration** problem.

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

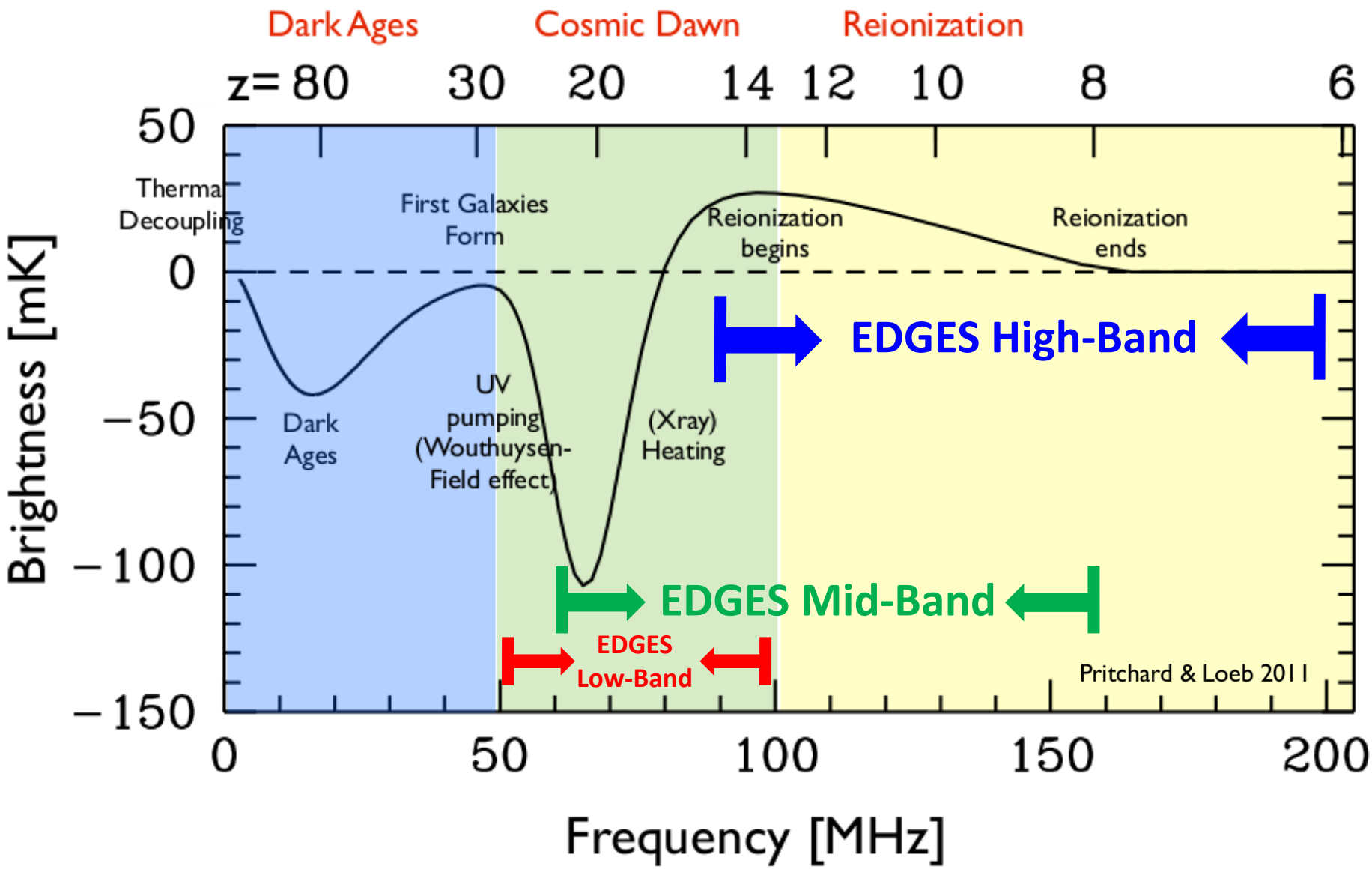
# Western Australia

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

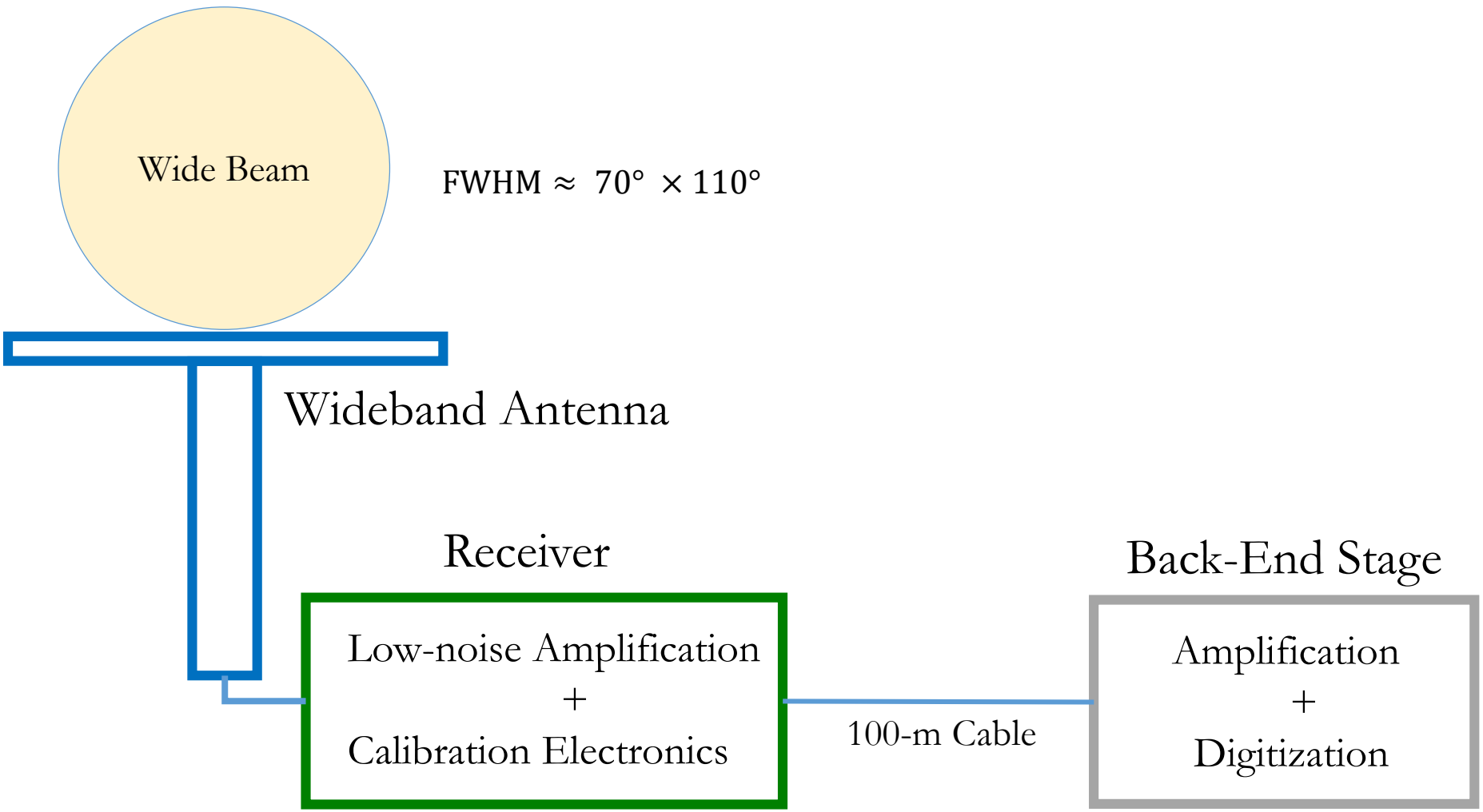


# EDGES Instruments



# EDGES Block Diagram



# Instrumental Calibration

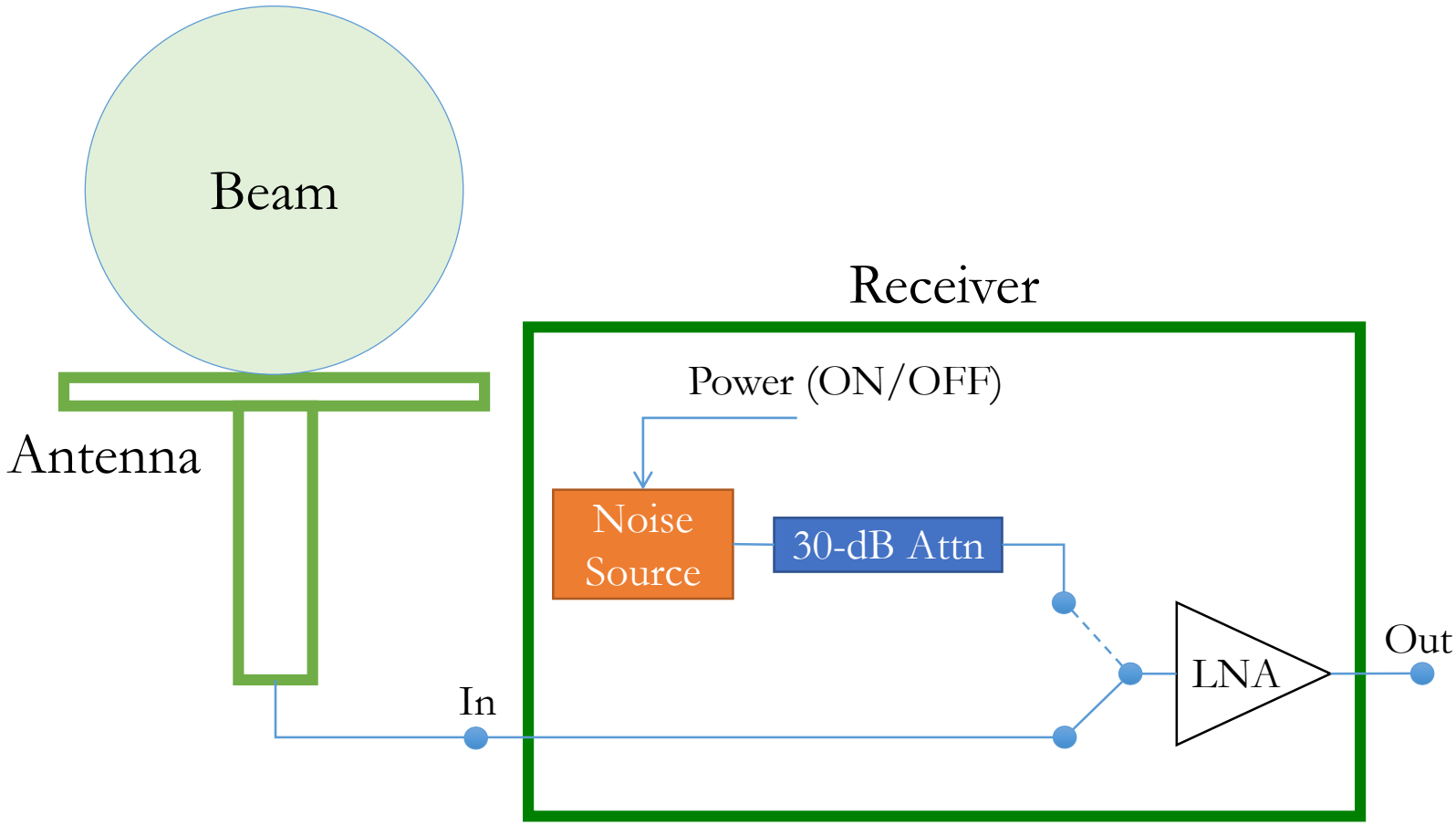
1) **Receiver gain and offset.**

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

3) **Antenna and ground losses.**

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

# Field Relative Calibration

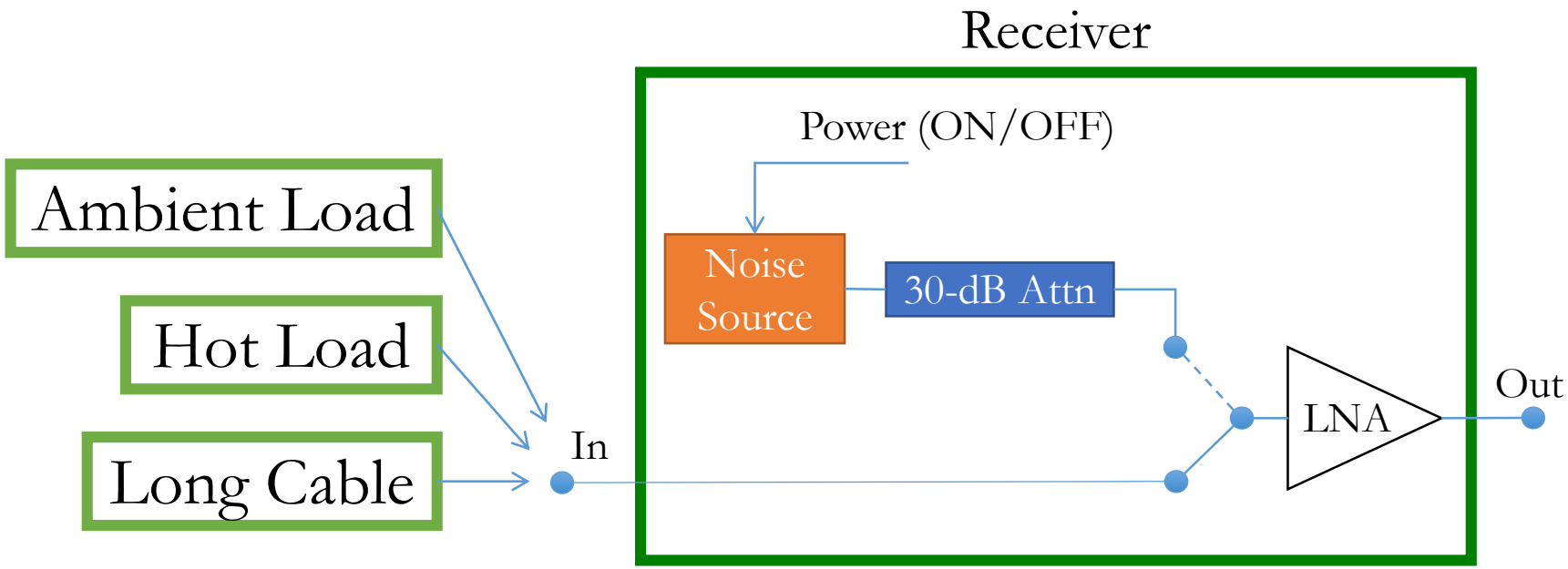



This calibration is **applied every 40 seconds. It removes time variability.**

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**.

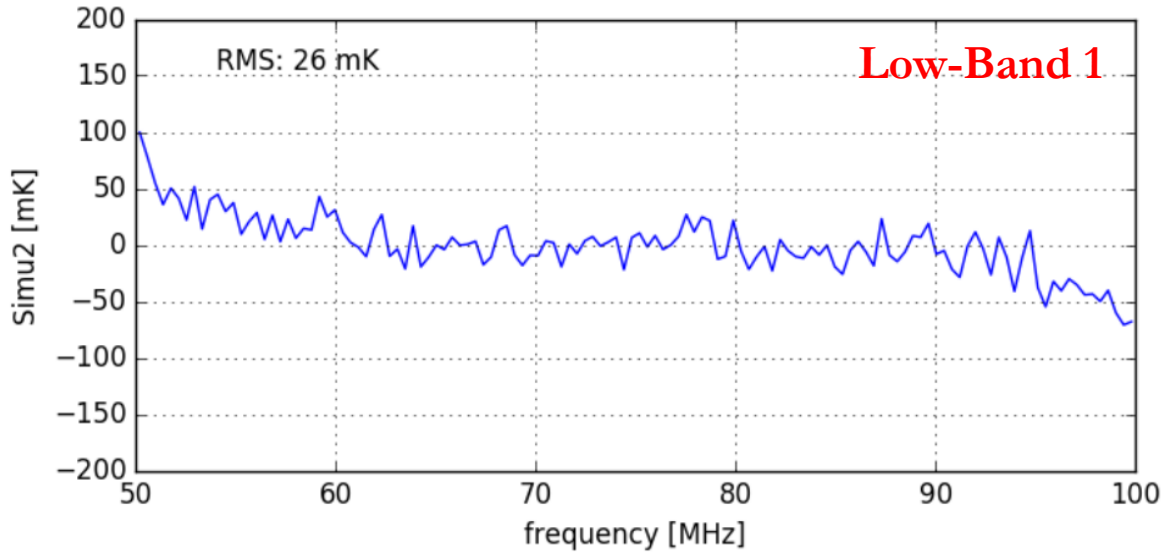
We measure with high precision and accuracy the **spectrum, reflection, and temperature of the standards**.

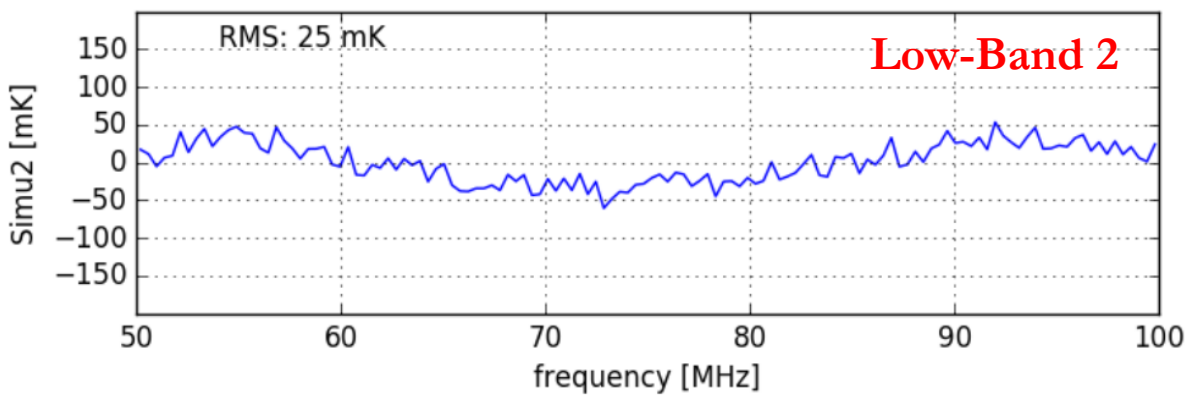
# Verification Using ~300K Antenna Simulators

At 75 MHz

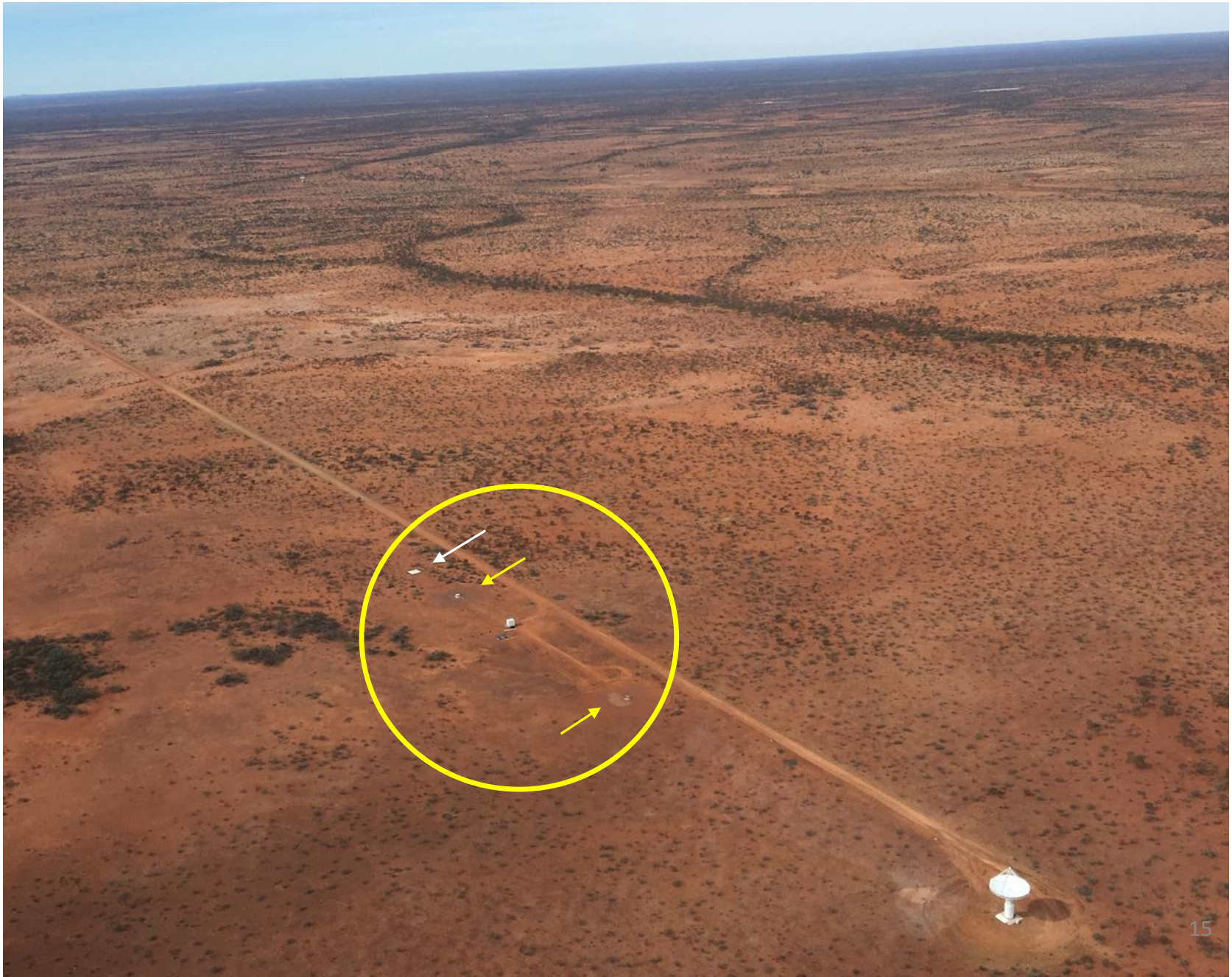
$$\frac{1{,}500\ \mathrm{K}}{300\ \mathrm{K}} = 5$$

Residuals After Removing a Constant

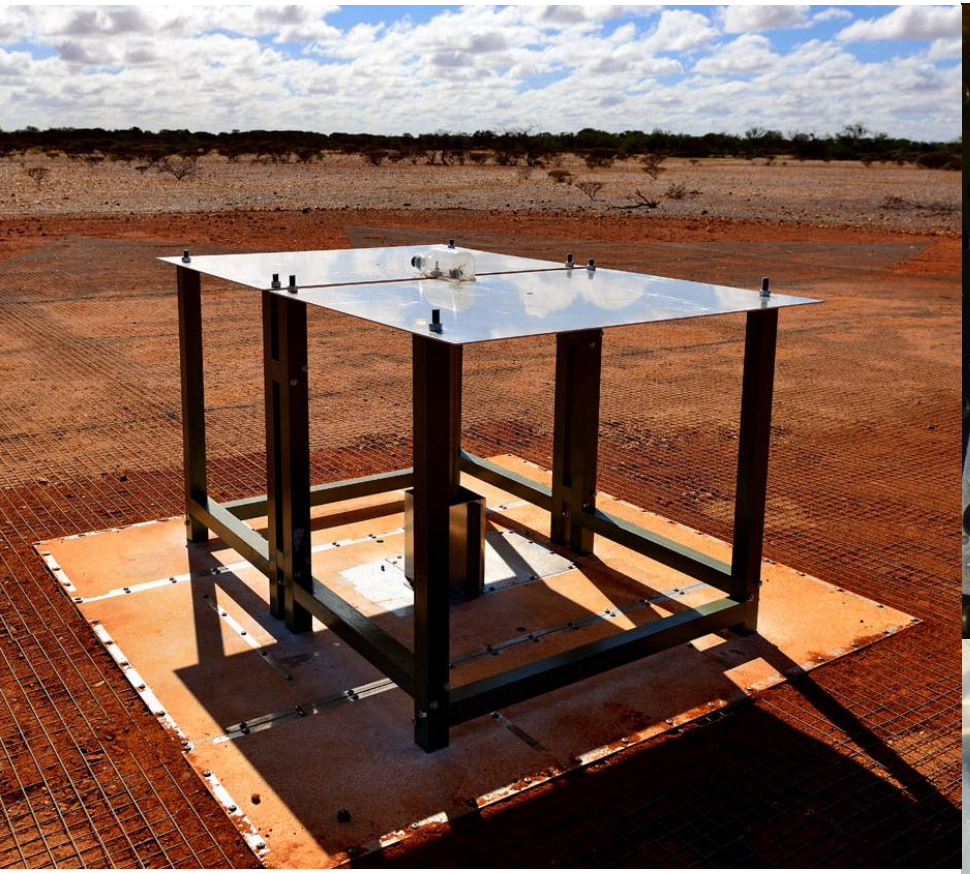


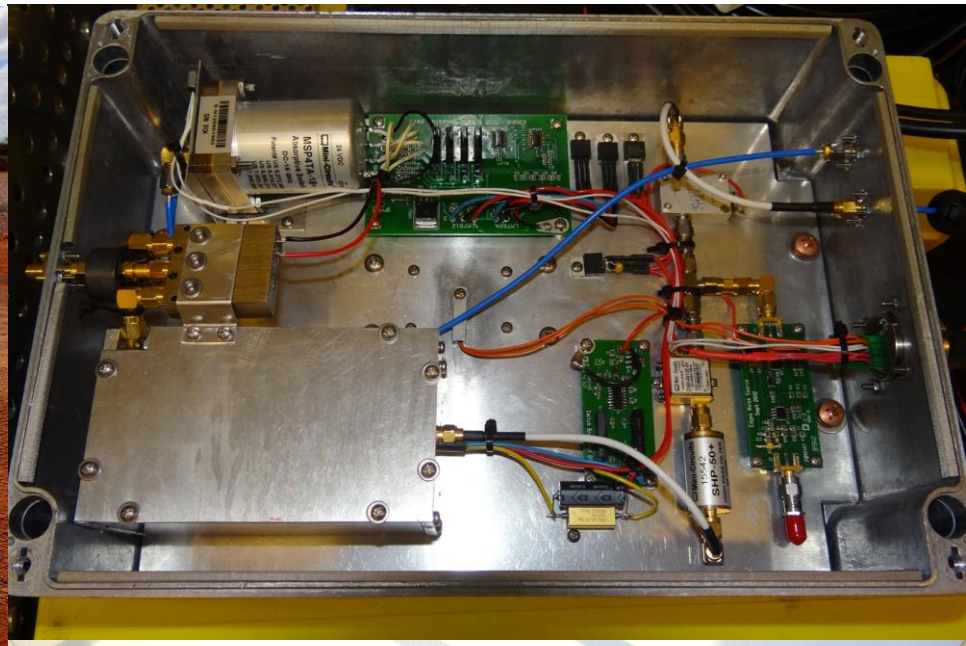



# EDGES Instruments



# EDGES Low-Band



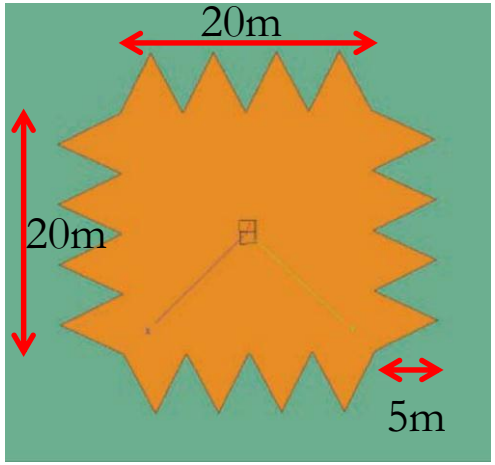


**Antenna size:**

**2m long / 1m high**

# Low-Band Antenna Ground Plane

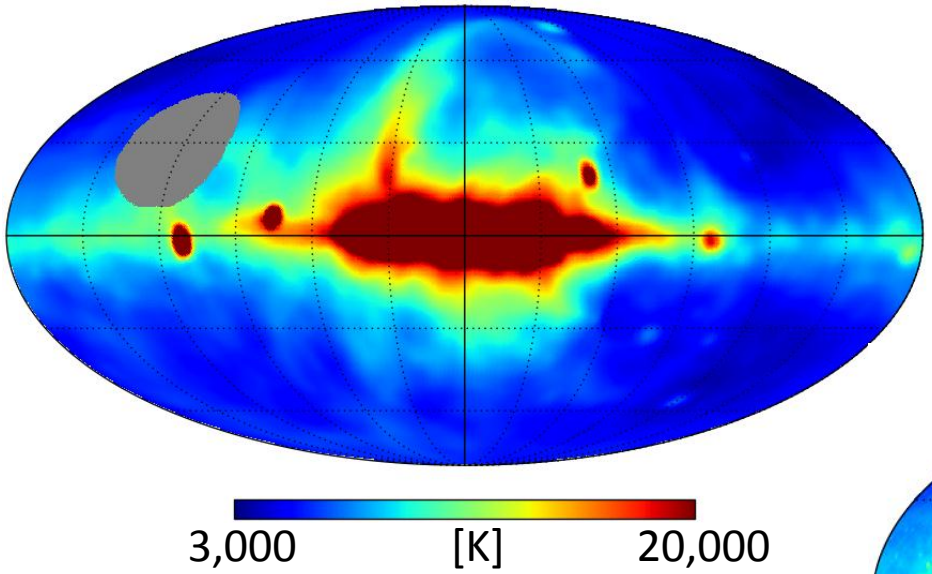
**Extended Ground Plane:**
**Central Square: 20m x 20m**
**16 Triangles: 5m-long**



# Diffuse Foregrounds

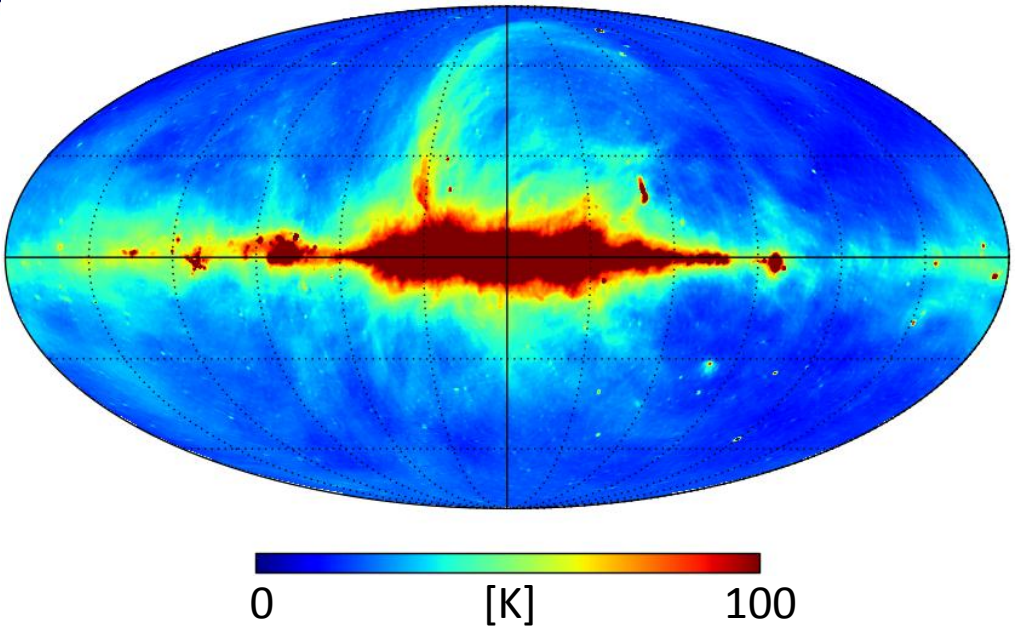
## 45-MHz Map

Guzmán et al. (2011)




## 408-MHz Map

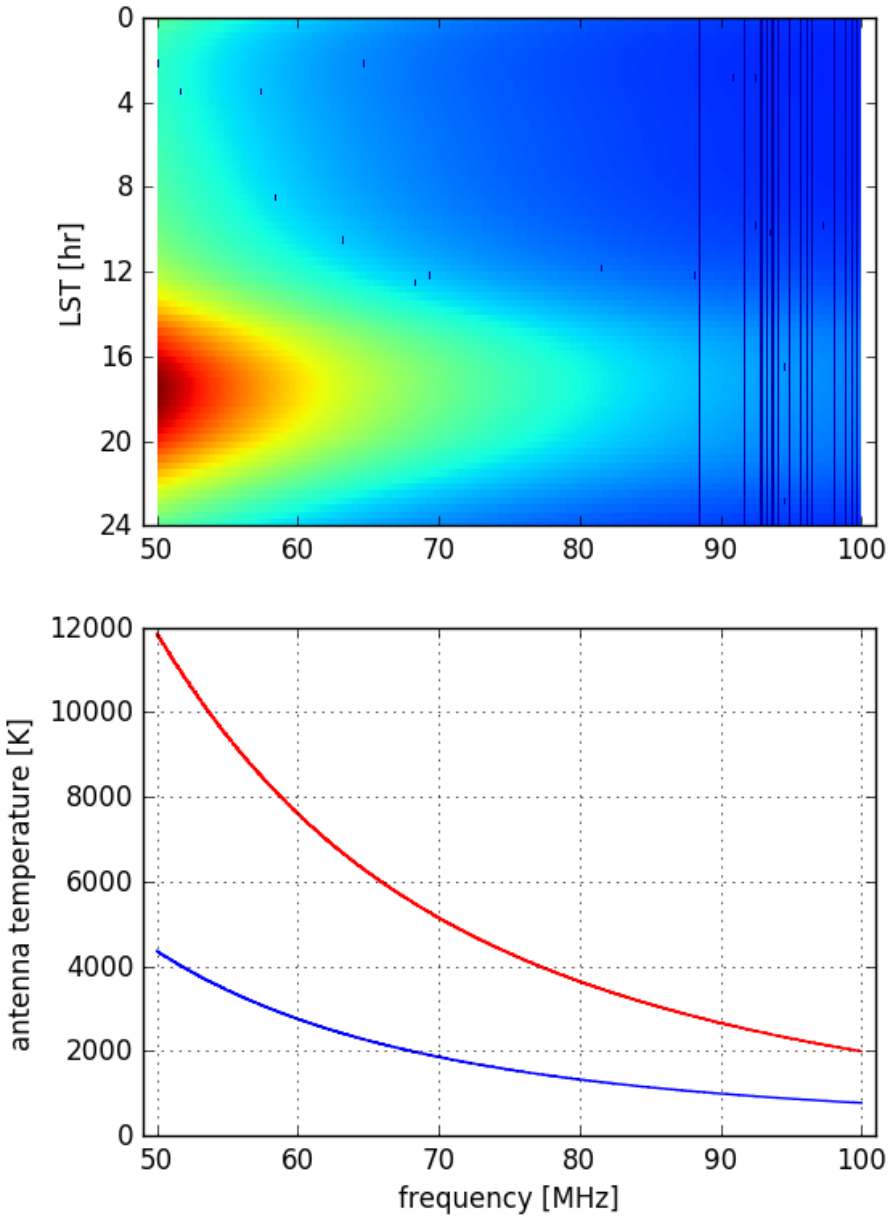
Haslam et al. (1982)



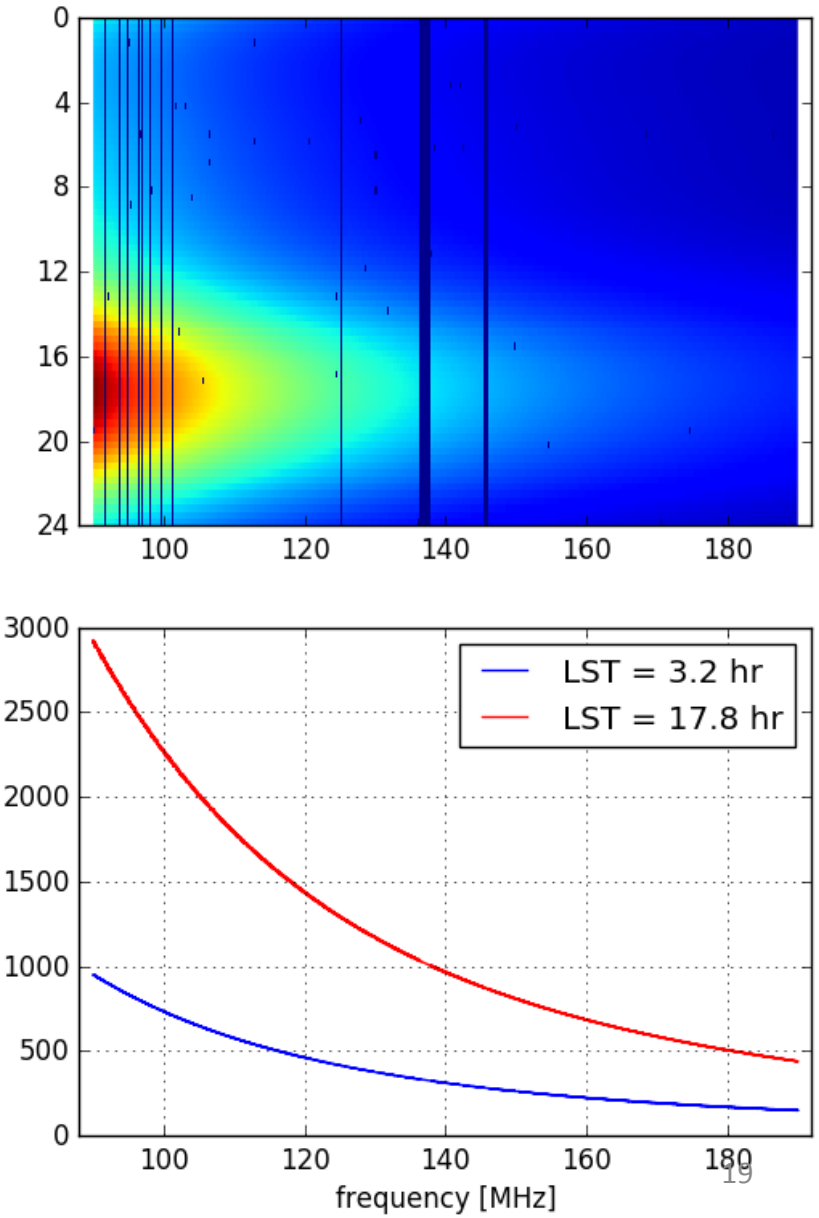

1) From **hundreds to thousands of Kelvins**.
2) **Spectrally smooth** but might need **several terms** to model (Bernardi et al. 2015)
3) Large **spatial gradients**.

# Observations

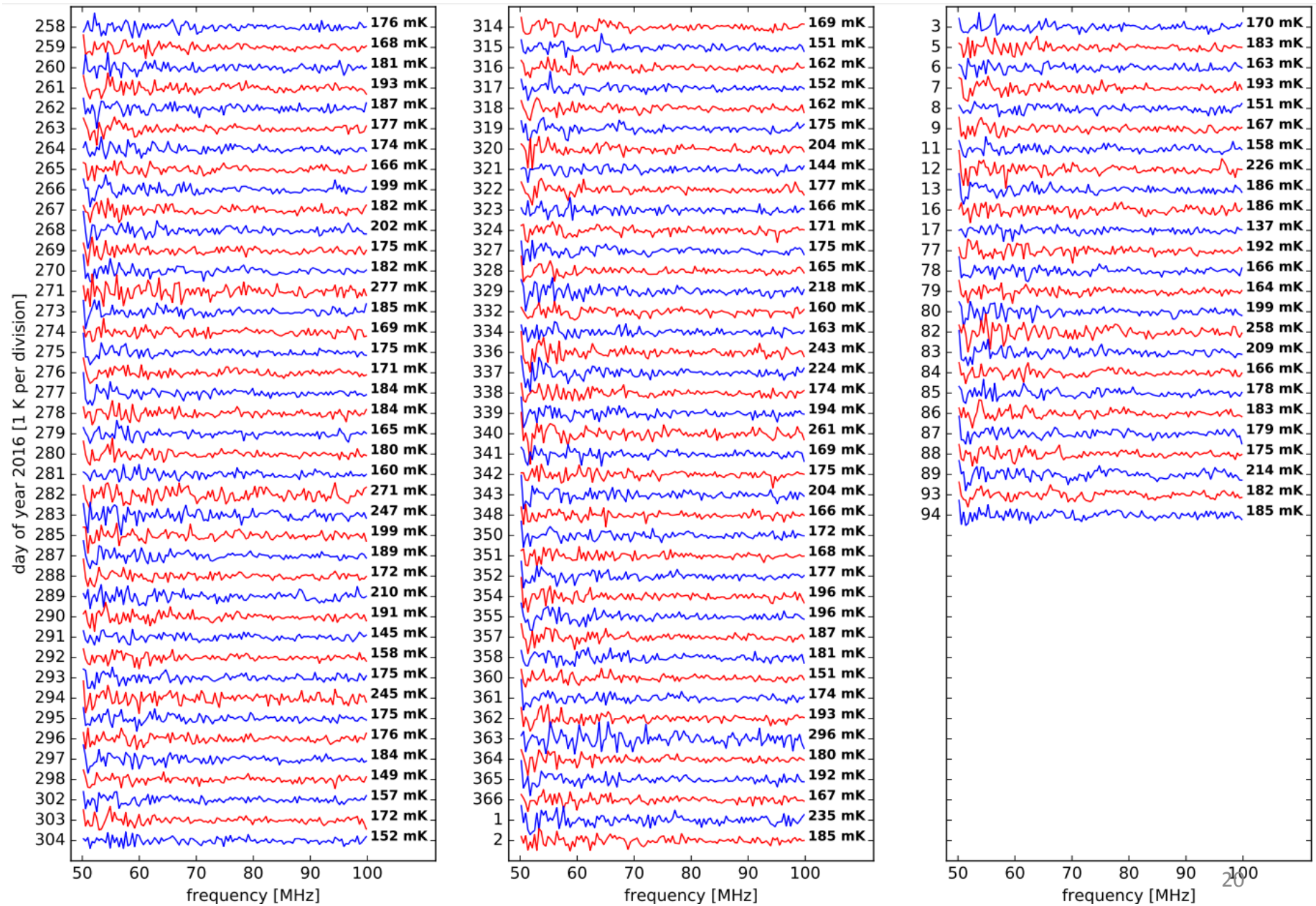
**EDGES Low-Band**



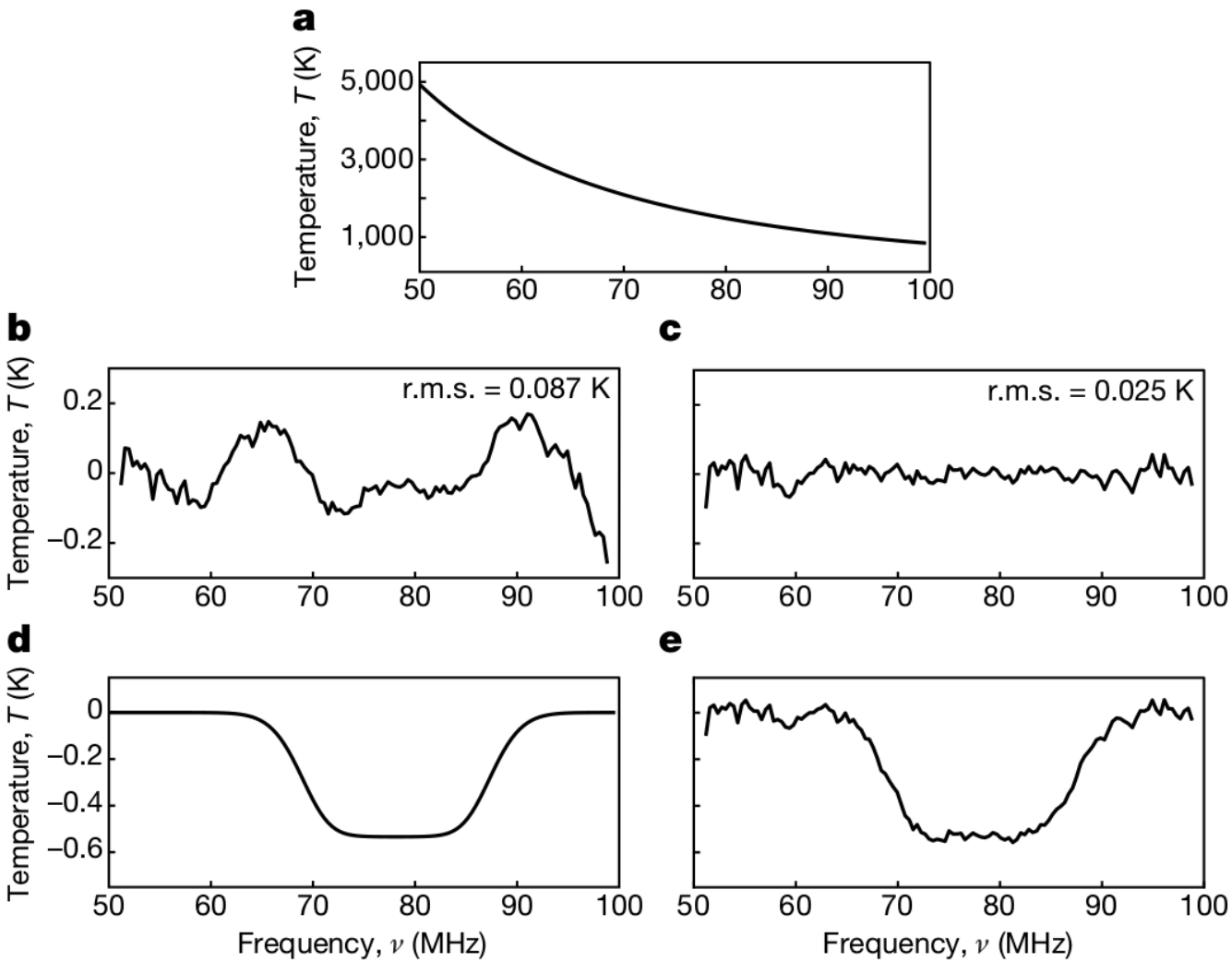

**EDGES High-Band**



# Daily Low-Band Residuals



# Summary of the Detection




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

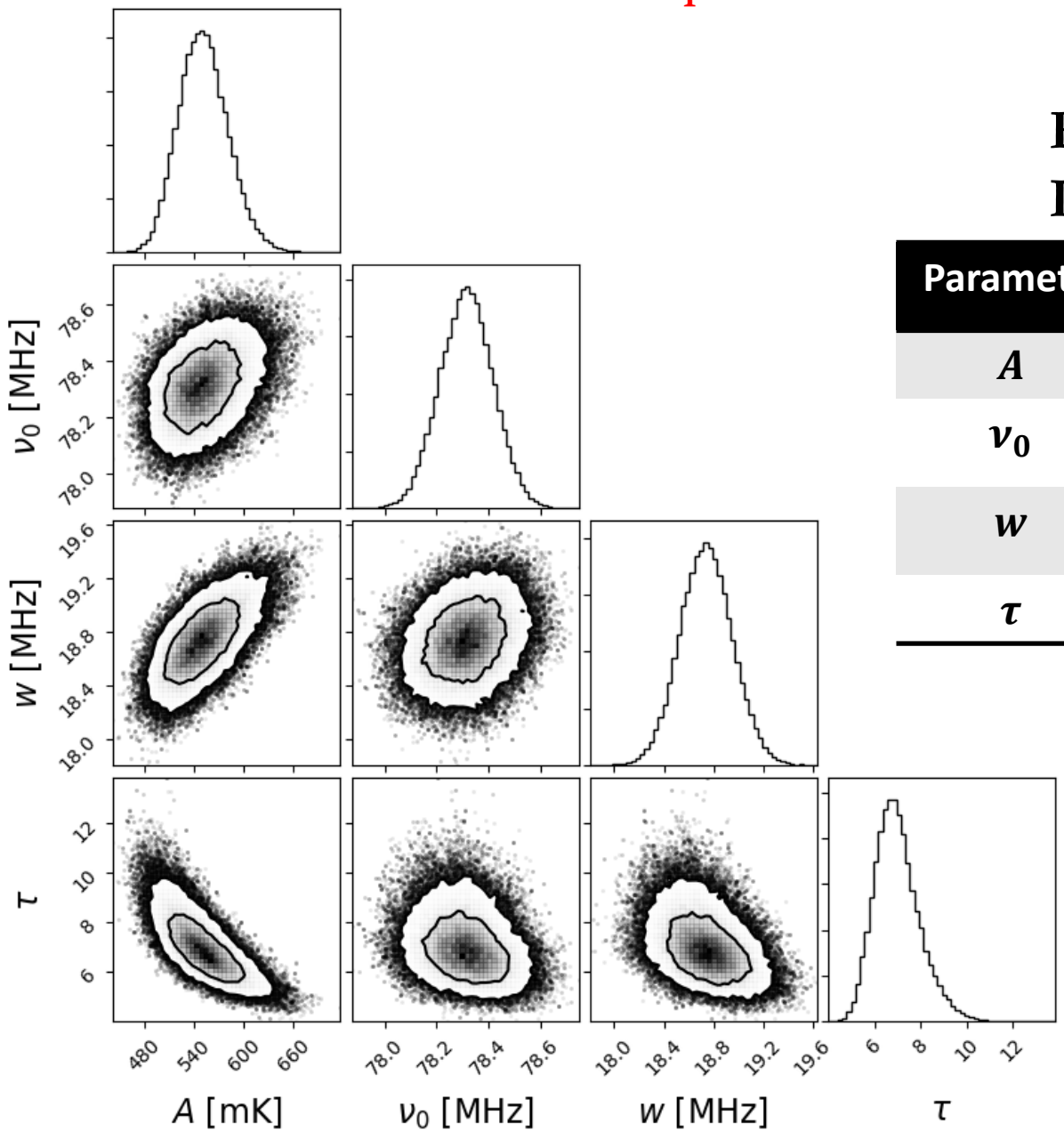
$$m_{\mathrm{fg}}(\boldsymbol{a_i}) = \left(\frac{\nu}{\nu_n}\right)^{-2.5} \sum_{i=0}^{N_{\mathrm{fg}}-1} \boldsymbol{a_i}\left(\frac{\nu}{\nu_n}\right)^{i}$$

**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

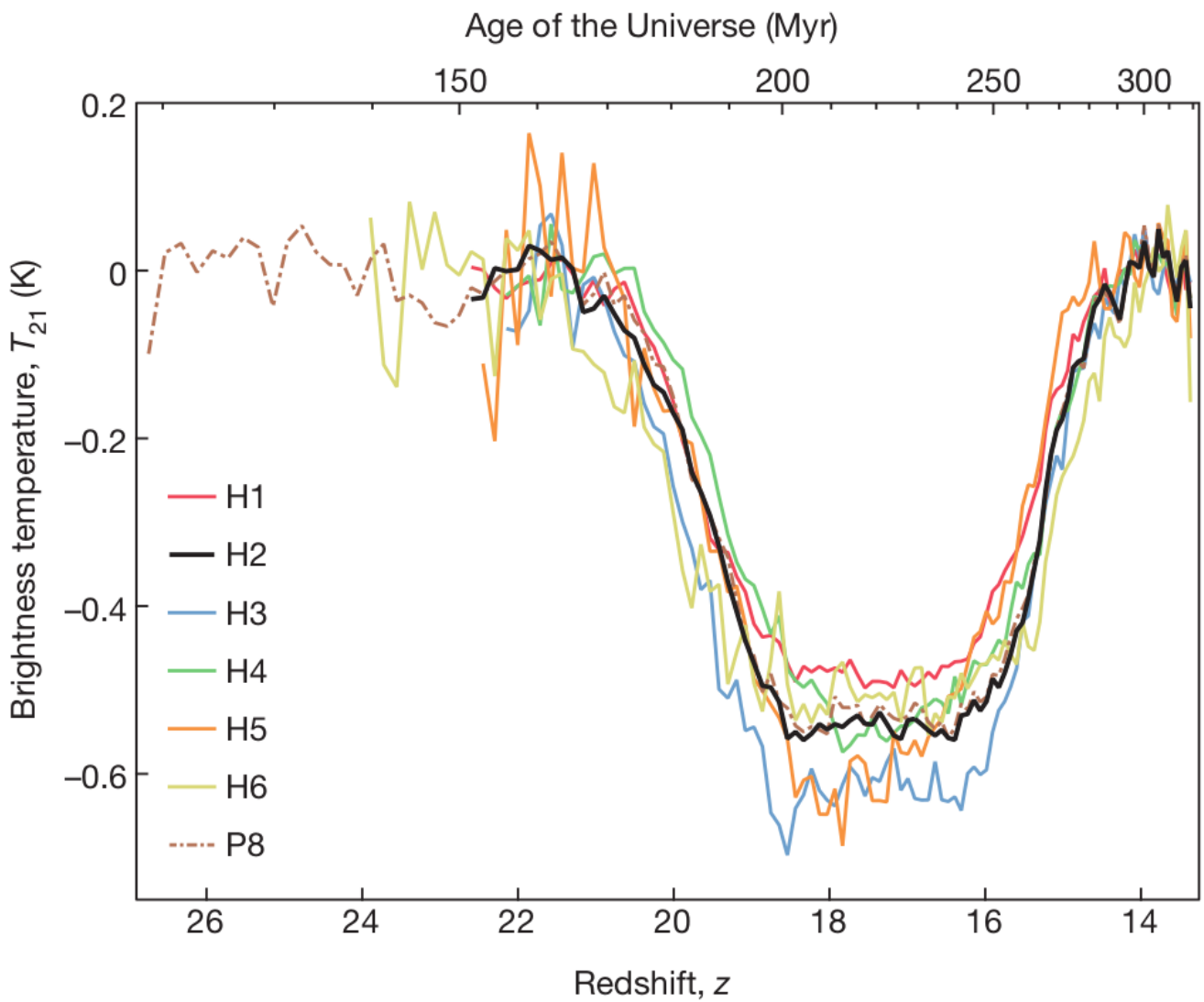
| Parameter | Best Fit | Uncertainty ($3\sigma$) |
|---|---|---|
| $A$ | 0.5 K | +0.5/-0.2 K |
| $\nu_0$ | 78 MHz | +/-1 MHz |
| $w$ | 19 MHz | +4/-2 MHz |
| $\tau$ | 7 | +5/-3 |

# 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

# Different Instruments/Hardware Cases




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

# 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?

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

**Higher than zero**

**Lower than expected**

# 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

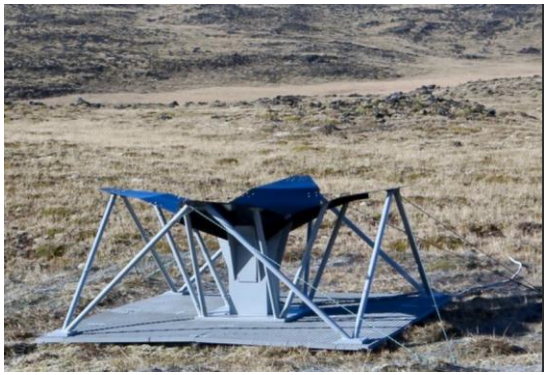
1) Enough IGM cooling achieved if **small fraction (<1%) of DM particles** posses **electric mini-charge (~$10^{-6}$ the charge of an electron)**.

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

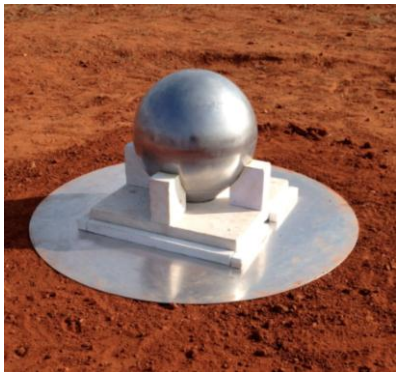
In EDGES **we remain agnostic** about the cosmological/astrophysical explanations, and focused on the verification of our measurement.

# Global 21-cm Experiments

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



SARAS 2
(RRI, Subrahmanyan et al.)



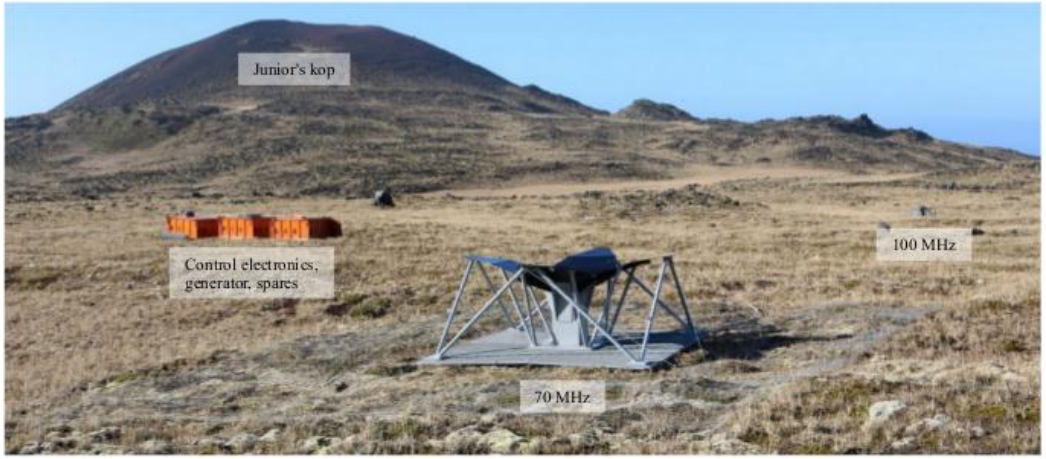
LEDA
(Harvard, Greenhill et al.)

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

HYPERION
(Berkeley, Parsons et al.)

CTP
(NRAO, Bradley et al.)

# Probing Radio Intensity at high-Z from Marion (PRI$^{Z}$M) *Philip et al. 2018*



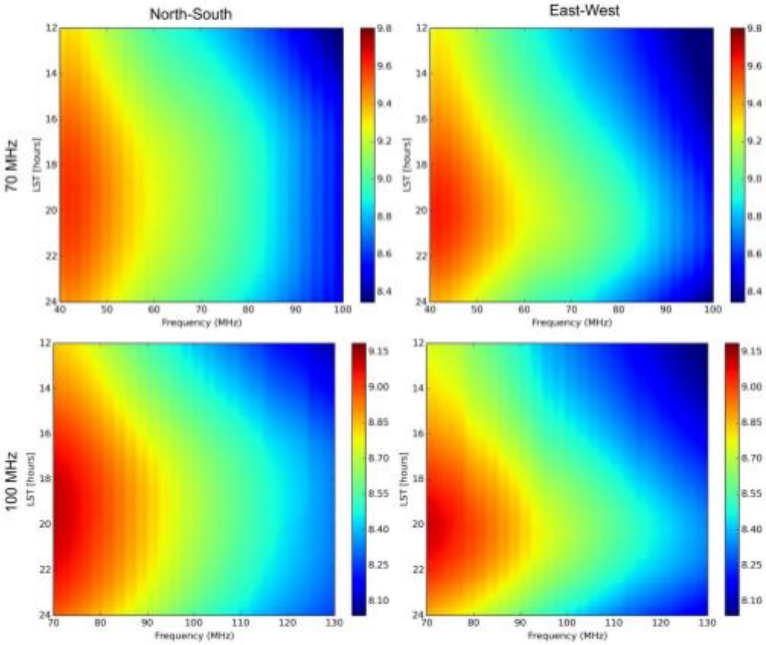

Dual-polarization antenna

Operating frequency 30—200 MHz

Two antennas with centre frequencies of 70 and 100 MHz

Uses Smart Network ADC Processor (SNAP) boards

Data rate ~900 MB per day for both antennas



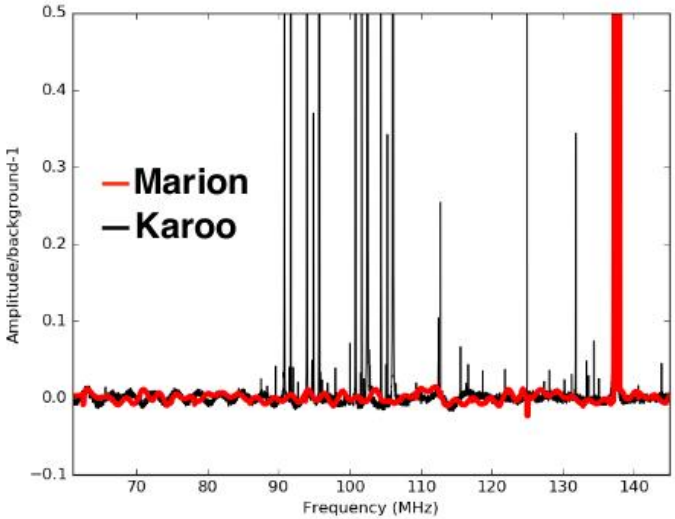

raw, uncalibrated data

No visible FM interference

No visible meteor scatter

PRIZM is deployed for the 2018-19 season on Marion

Marion Island is an excellent site for low-frequency observations




RFI environment

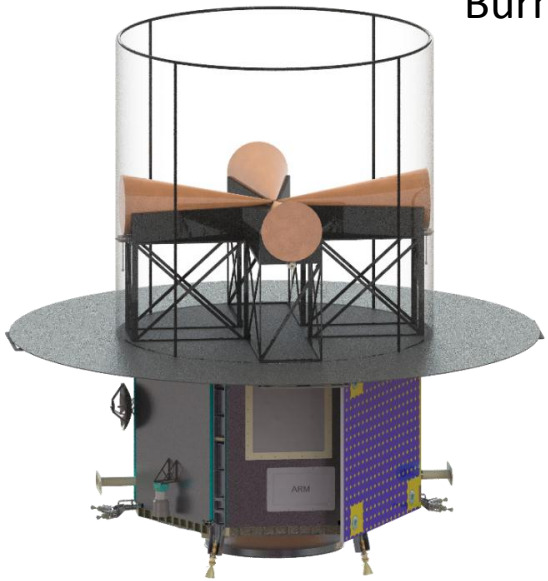
https://arxiv.org/abs/1806.09531

# Space-based Instrument Concepts

## Dark Ages Radio Explorer (DARE)

Proposed to NASA MIDEX program in Dec 2016

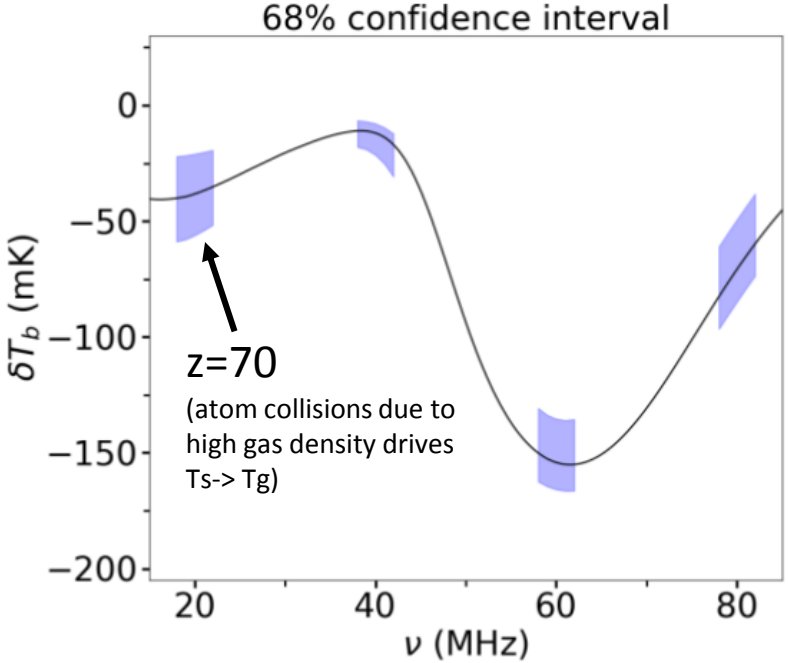
Burns et al. (2017)



- ~ 40-120 MHz
- 3-m dual dipole
- Orbit above lunar farside
- Foreground rotation modulation
- 1000 hrs of integration
- 2-yr mission

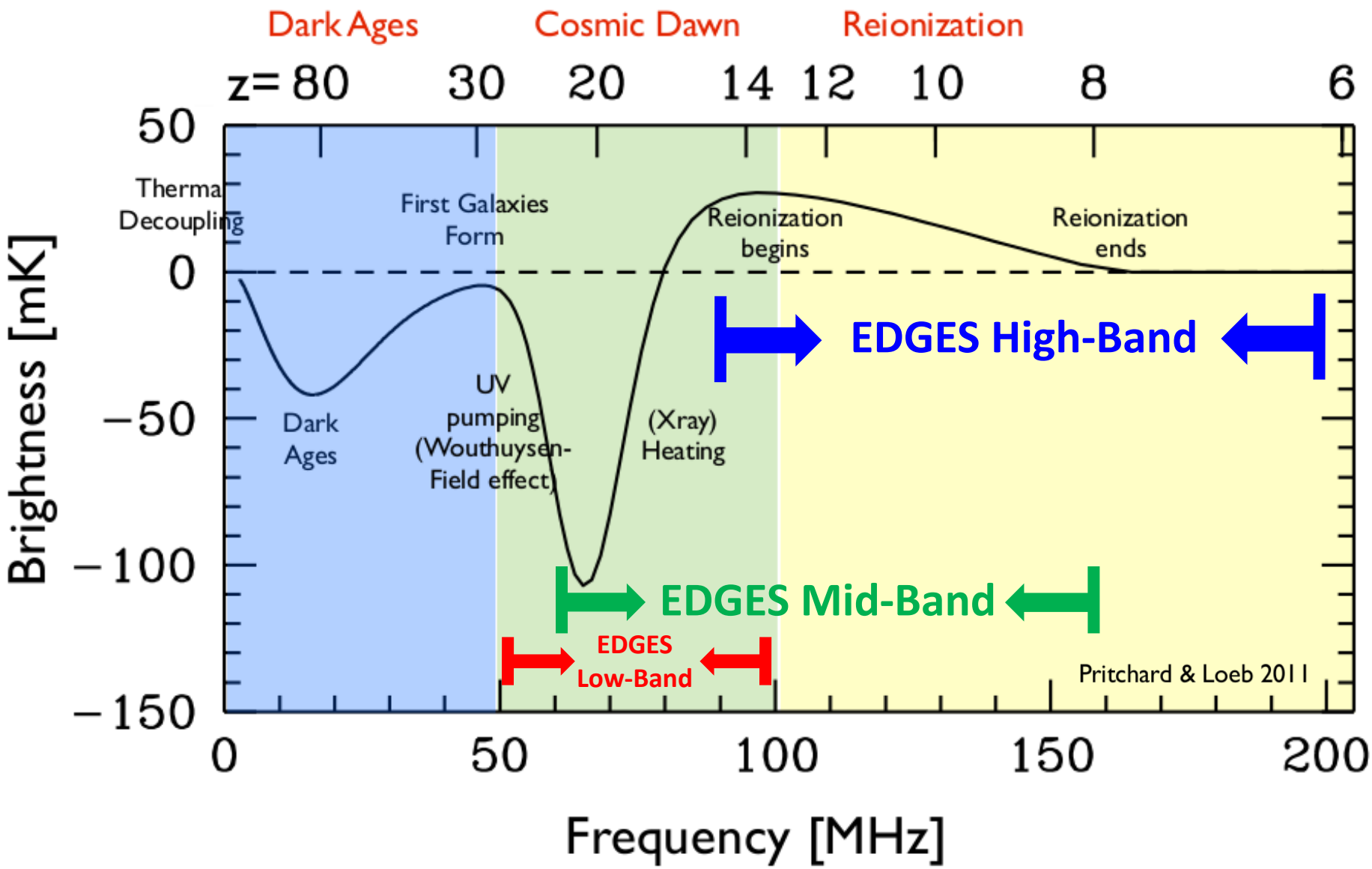
## Dark Ages Polarimeter PathfindER (DAPPER)

Response to 2017 NASA Request for Information for SmallSats



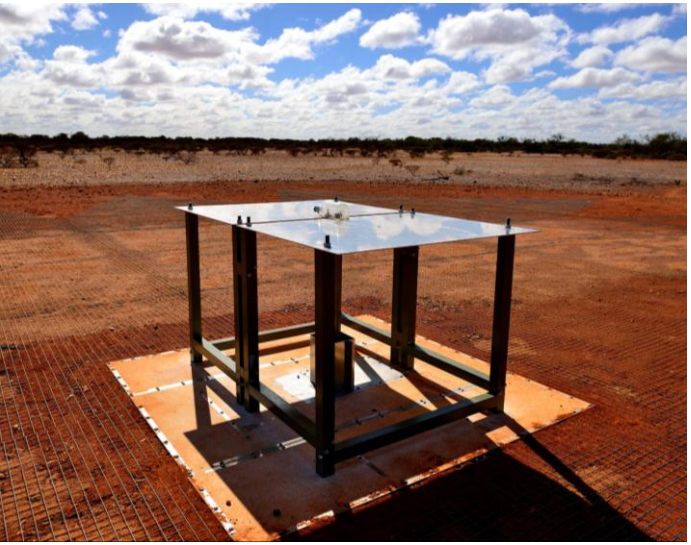

- ~ 10-100 MHz
- 7-m dual dipole
- Orbit above lunar farside
- Foreground rotation modulation
- 1000 hrs of integration
- 6-month mission
- Key instrument to access Dark Age (low frequencies)

# EDGES Instruments



# EDGES Instruments

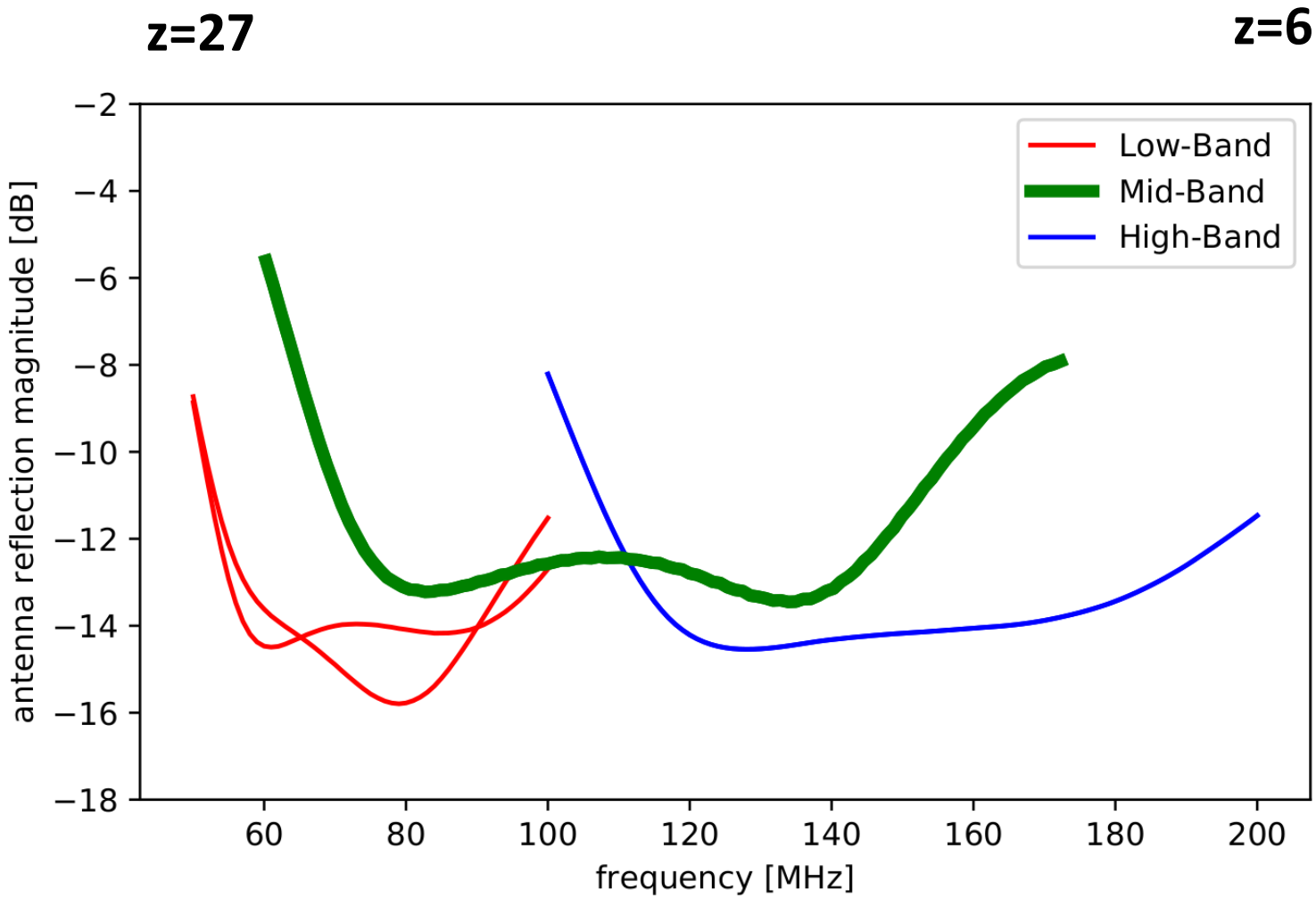
**Low-Band**



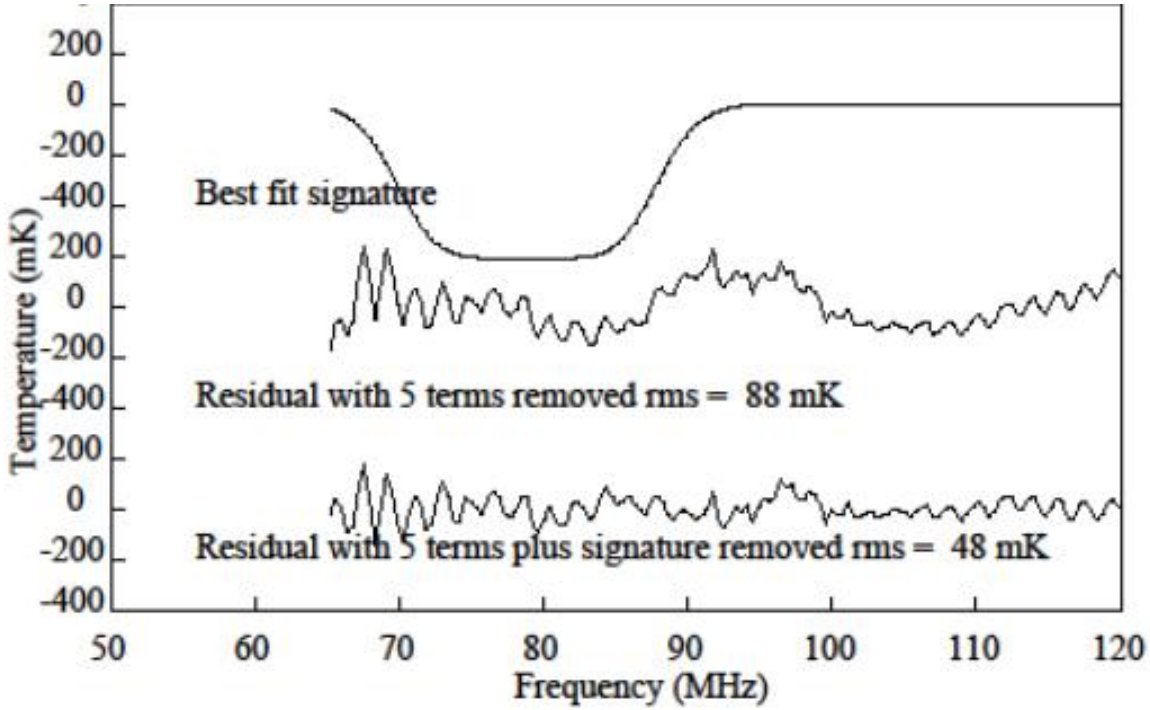
**High-Band**

**Mid-Band**

# Antenna Reflection Coefficients



# 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 model.

Best-fit parameters:

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

# Summary

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

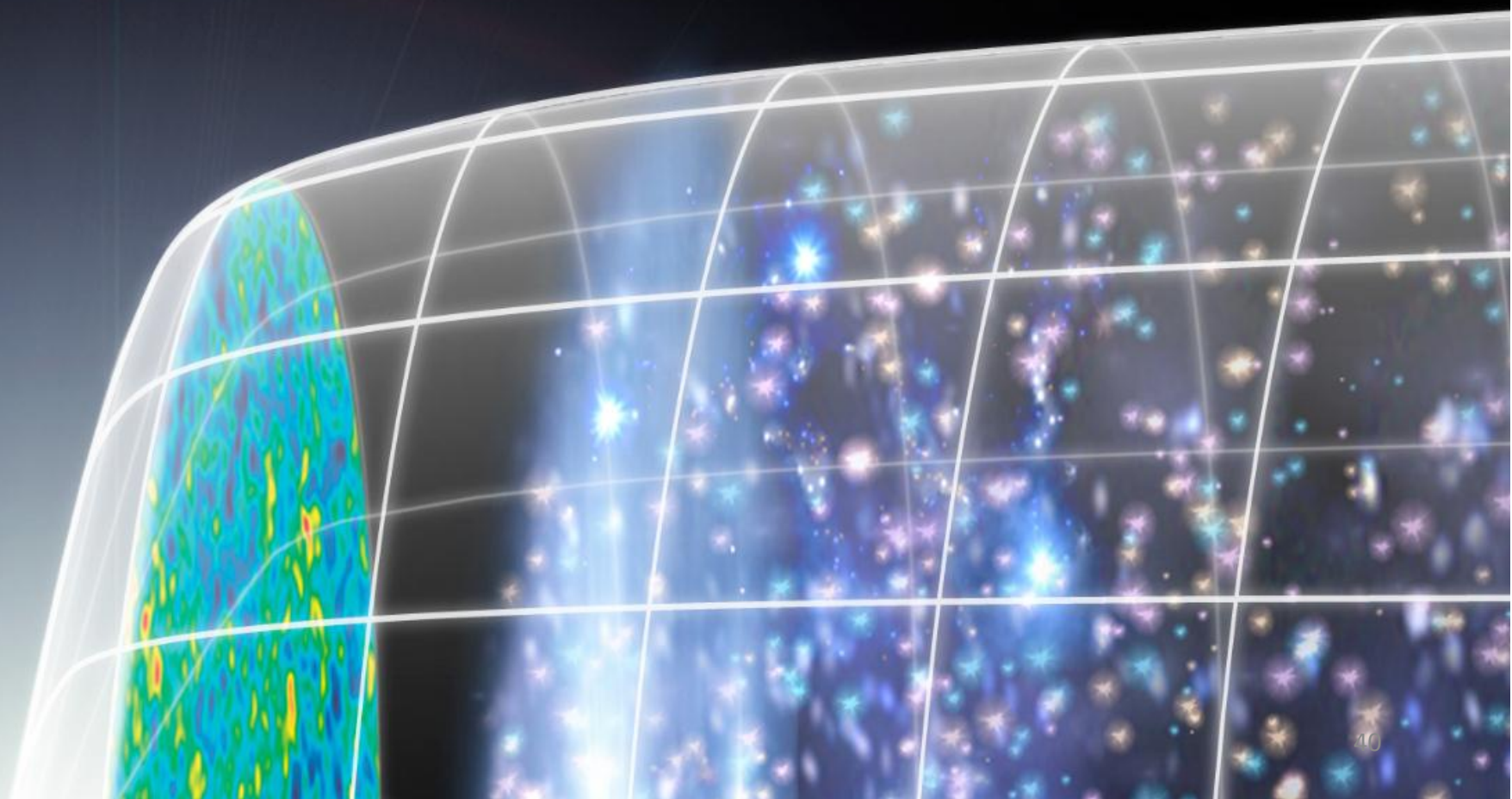
2) This is **consistent with stars forming by 180 Myrs after the Big Bang**.

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

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

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

# Extra Slides



# Concerns About Foreground Modeling

1) EDGES measures spatially-integrated signals from **astrophysical foregrounds, ionosphere, and low-level calibration effects**.

2) Astrophysical foregrounds **not known with precision**.

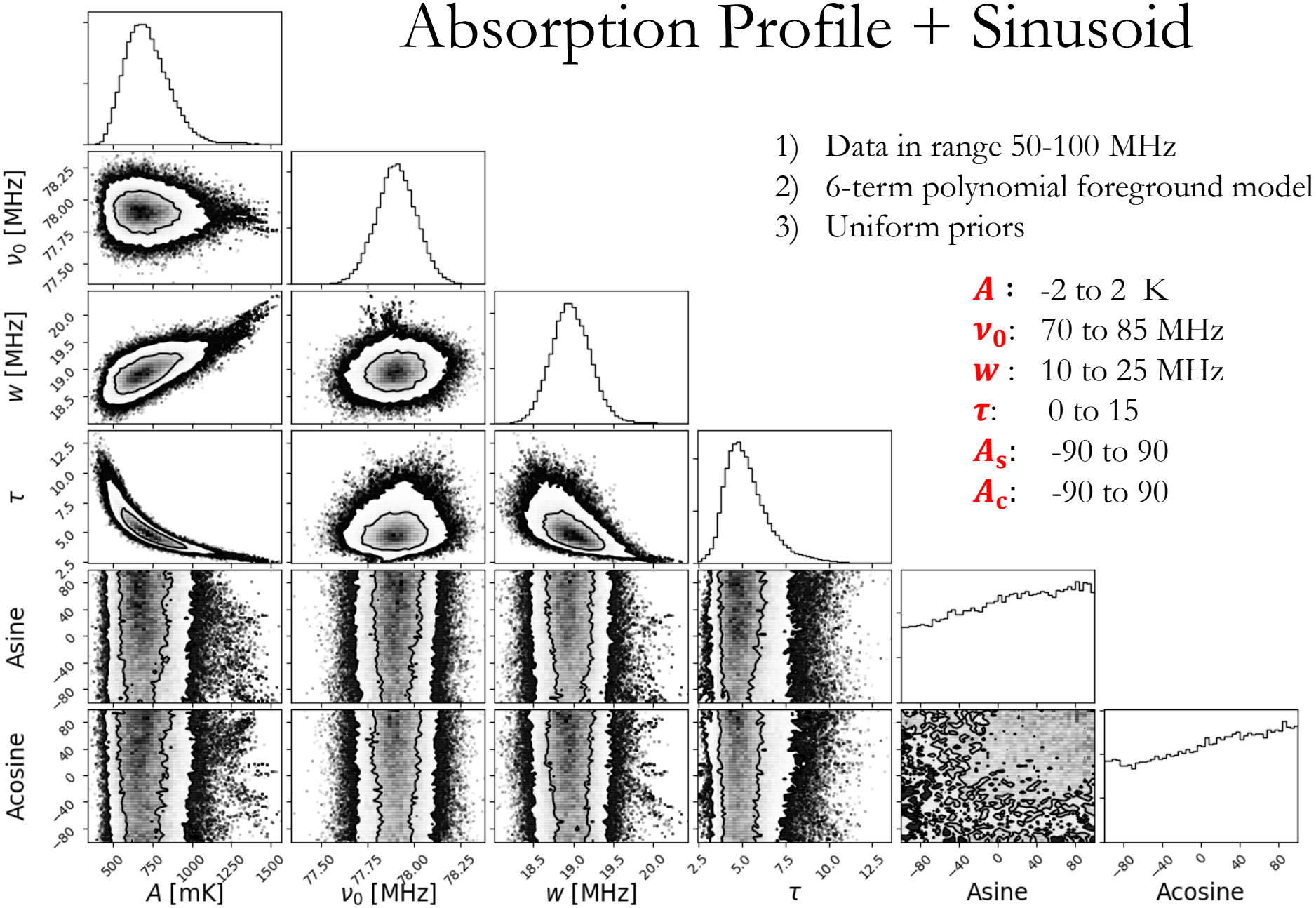
3) Foregrounds could be **more complicated than assumed** (eg., Bernardi et al. 2015)

4) Tight priors **could easily bias parameter estimates**.

5) 5-term polynomial model is appropriate only on analysis of **restricted frequency range**.

6) Sinusoidal ripple **is not significantly present**, when fitted simultaneously with nominal absorption profile.

# Absorption Profile + Sinusoid

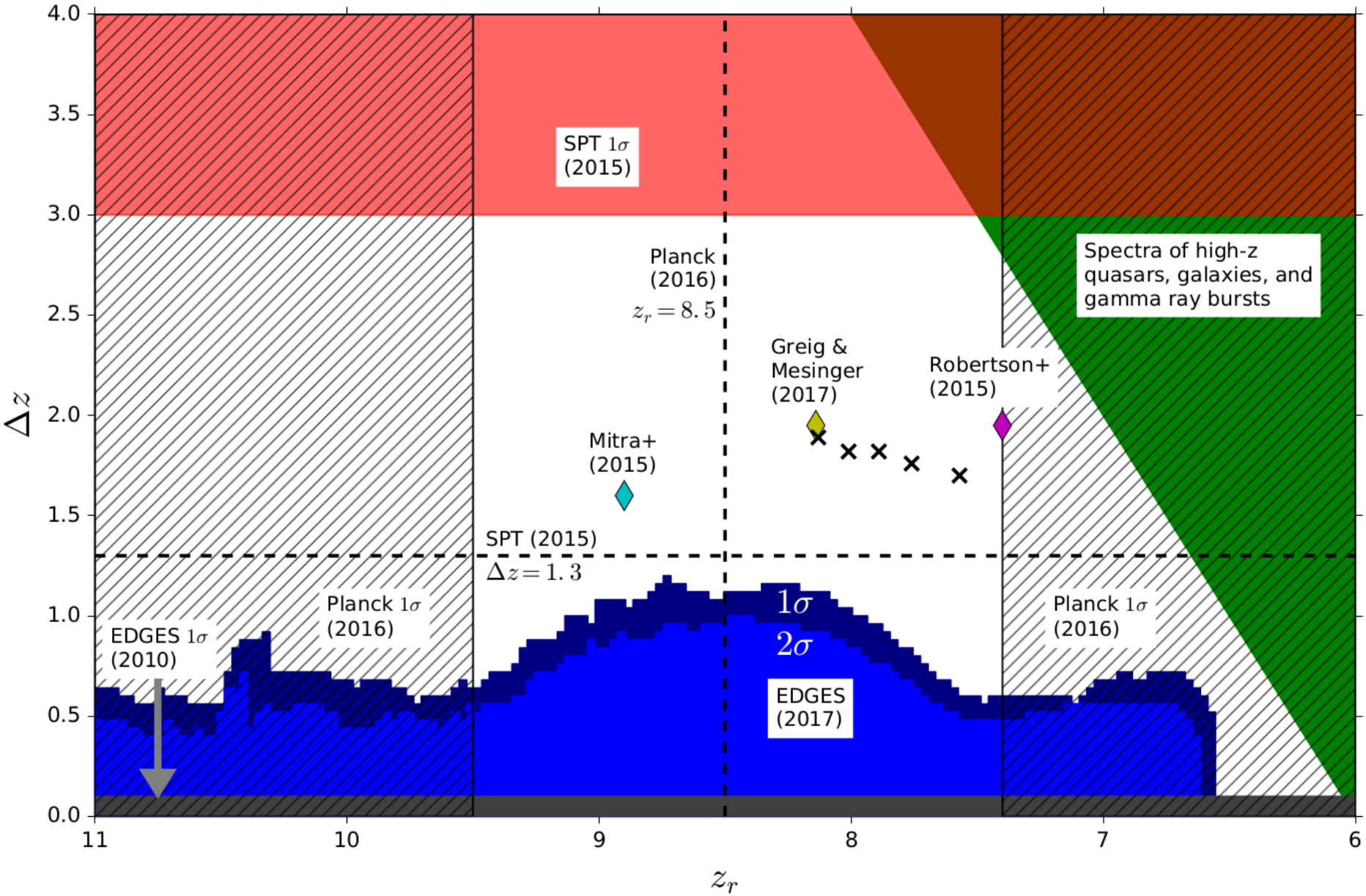



1) Data in range 50-100 MHz
2) 6-term polynomial foreground model
3) Uniform priors

$\boldsymbol{A}$ : -2 to 2 K
$\boldsymbol{\nu_0}$: 70 to 85 MHz
$\boldsymbol{w}$ : 10 to 25 MHz
$\boldsymbol{\tau}$: 0 to 15
$\boldsymbol{A_s}$: -90 to 90
$\boldsymbol{A_c}$: -90 to 90

# Recent EDGES High-Band Analyses

# Epoch of Reionization Constraints (Hot IGM)




**Monsalve**, Rogers, Bowman, Mozdzen (2017)

# Constraining Astrophysical Models and Parameters

**Standard Models assuming Traditional Temperatures for IGM and Radiation in the Early Universe.**

10,000 Random Semi-numerical Simulations from **21cmFAST** Code.

**<u>Astrophysical Parameters:</u>**

$\mathfrak{z}$: Ionizing efficiency

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

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

$E_0$: Minimum energy of X-rays

# Bayesian Analysis

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

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

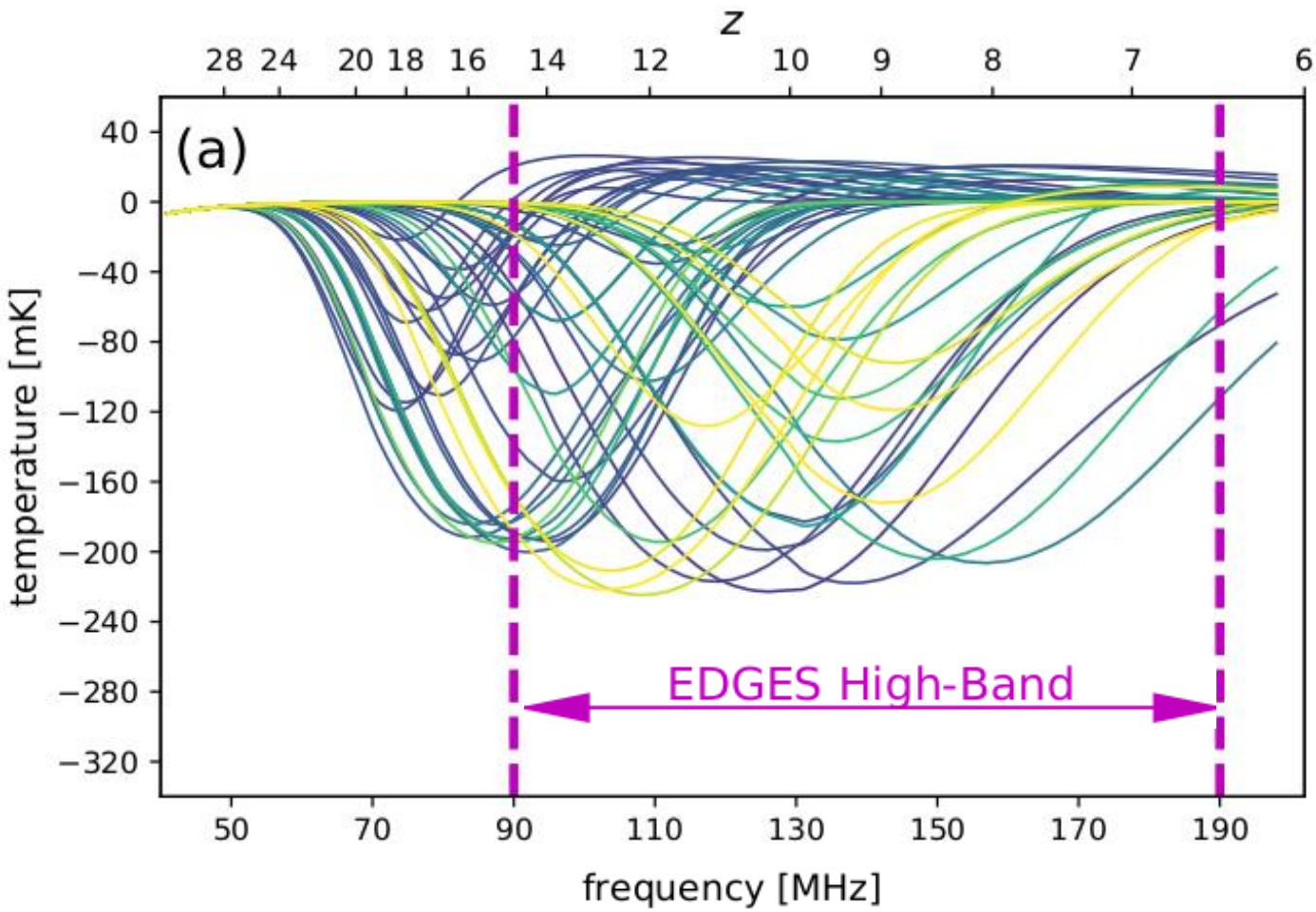
$d$: data
$m$: model
$\Sigma$: covariance matrix of data (Noise + Systematic Uncertainty)
$N_\nu$: number of spectral channels

We Marginalize Uncertainty in the Foreground Model Parameters

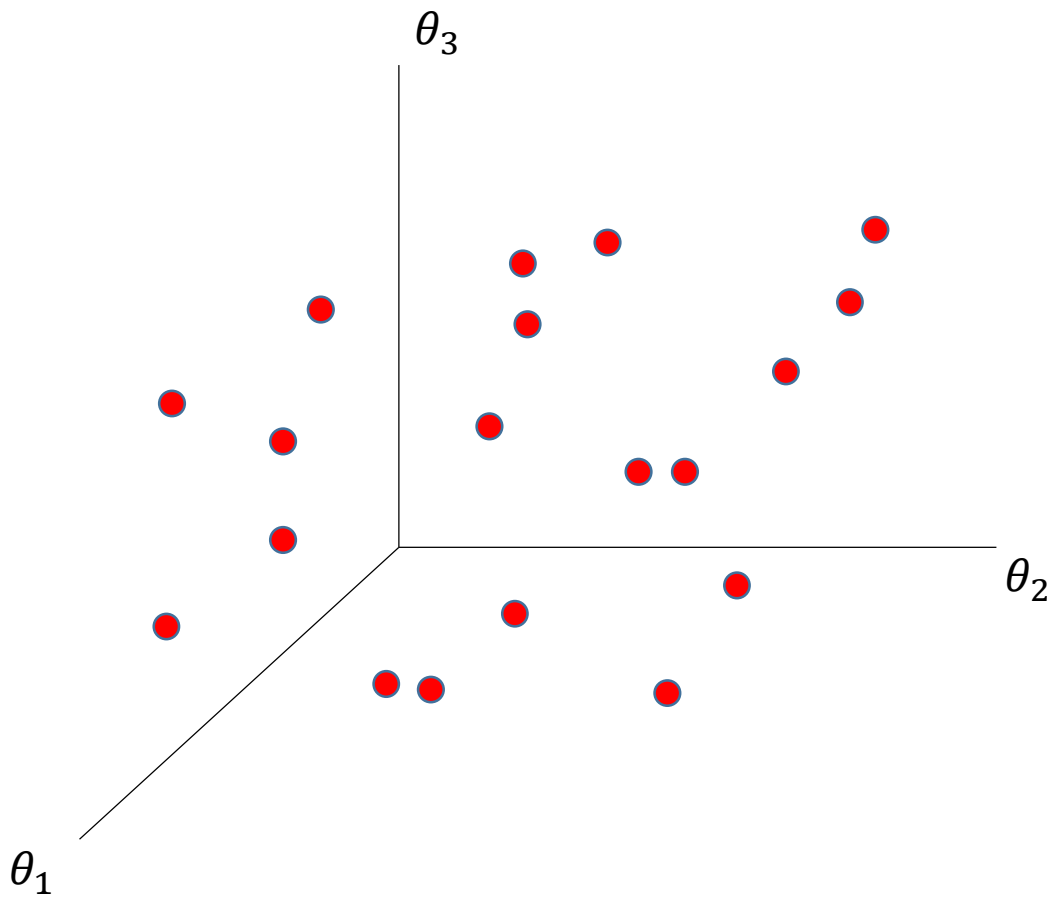
and Obtain:

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

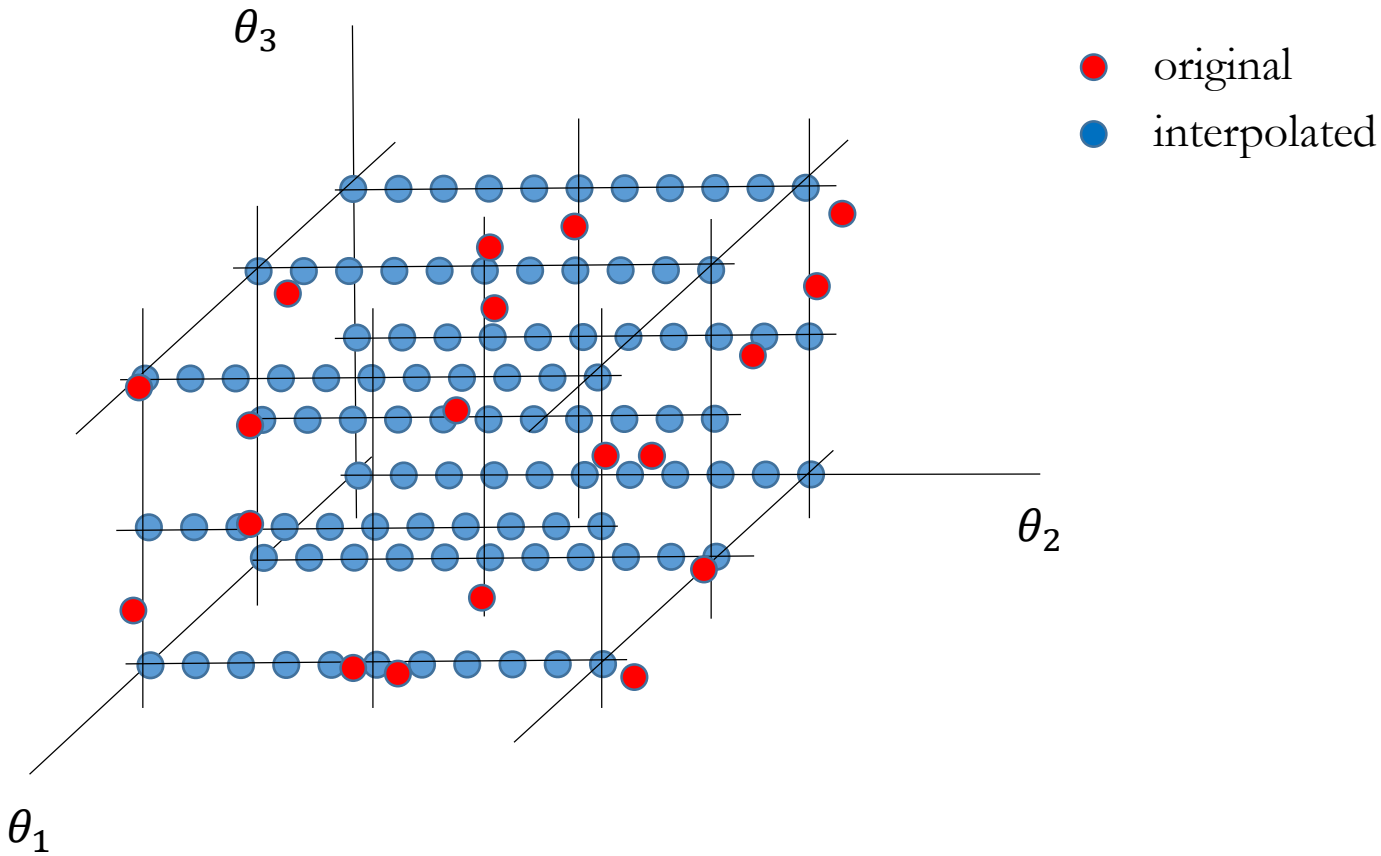
# Sample of Models from 21cmFAST



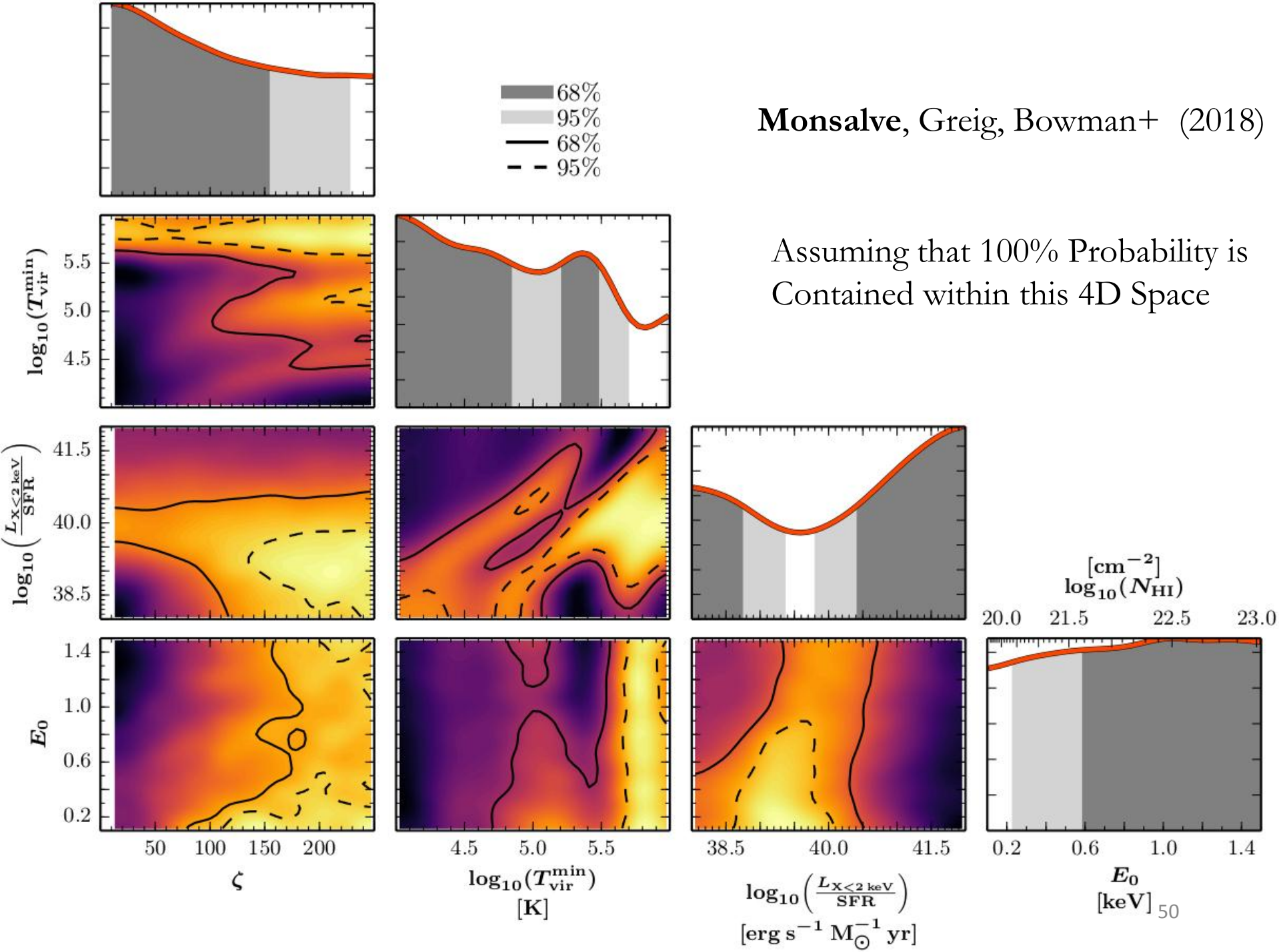
# Likelihood for Original Models



# Interpolation of Likelihood onto Regular Grid




This Enables Rigorous Marginalization Over Parameters.



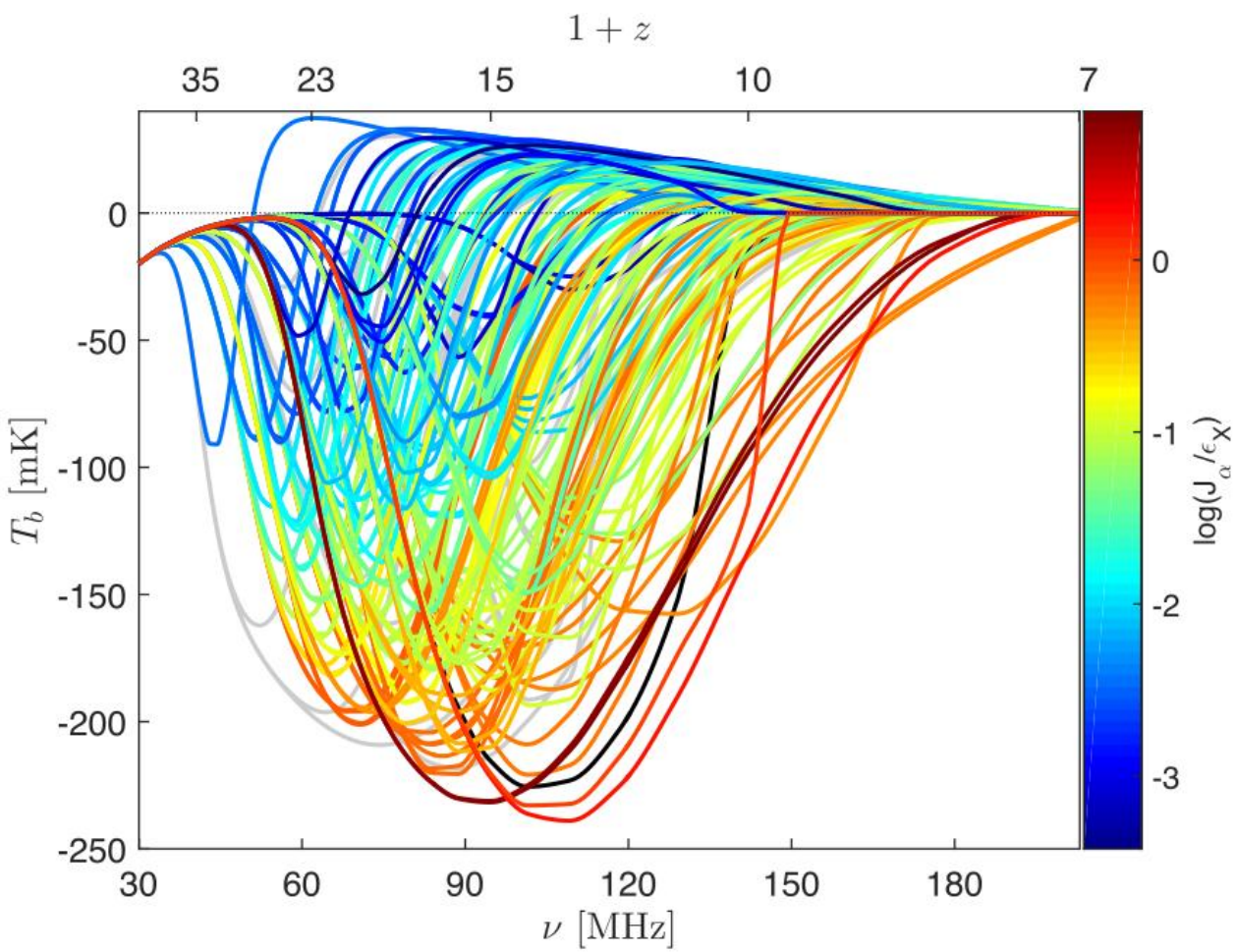

**Monsalve**, Greig, Bowman+ (2018)

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

# New Model Set

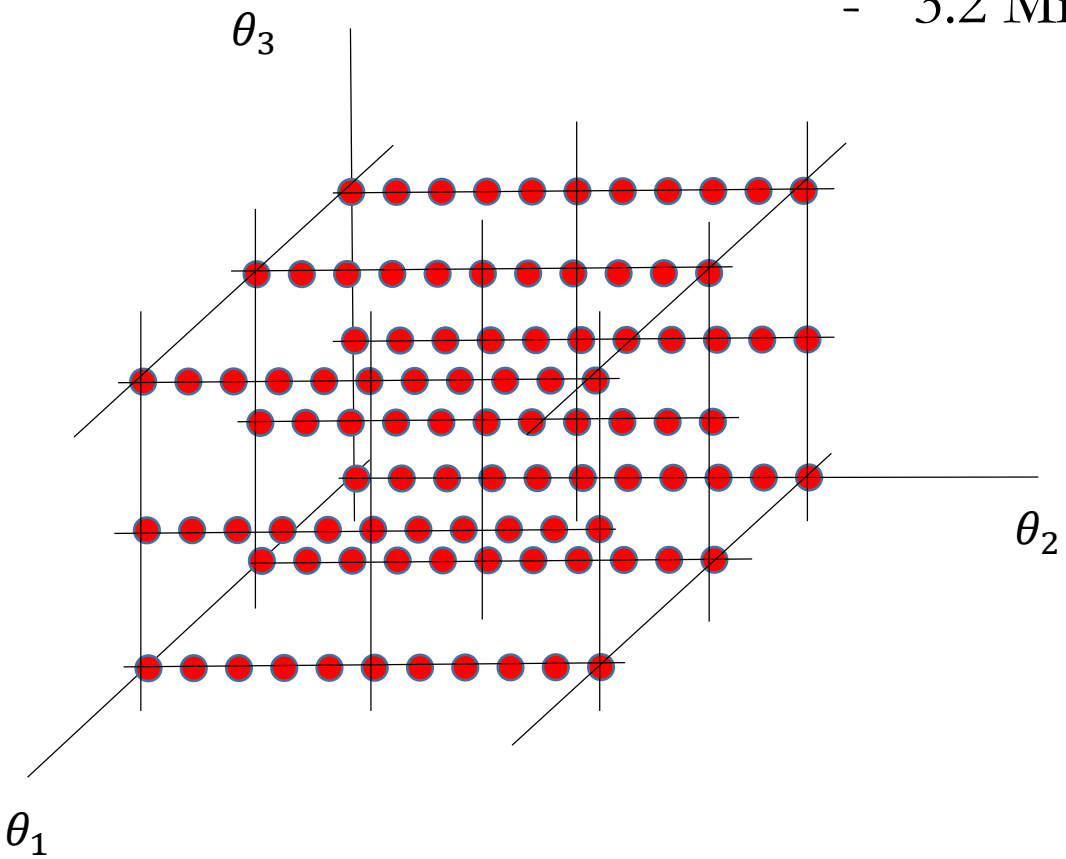
Interpolation of Standard Semi-Numerical Models from Cohen+ (2017)

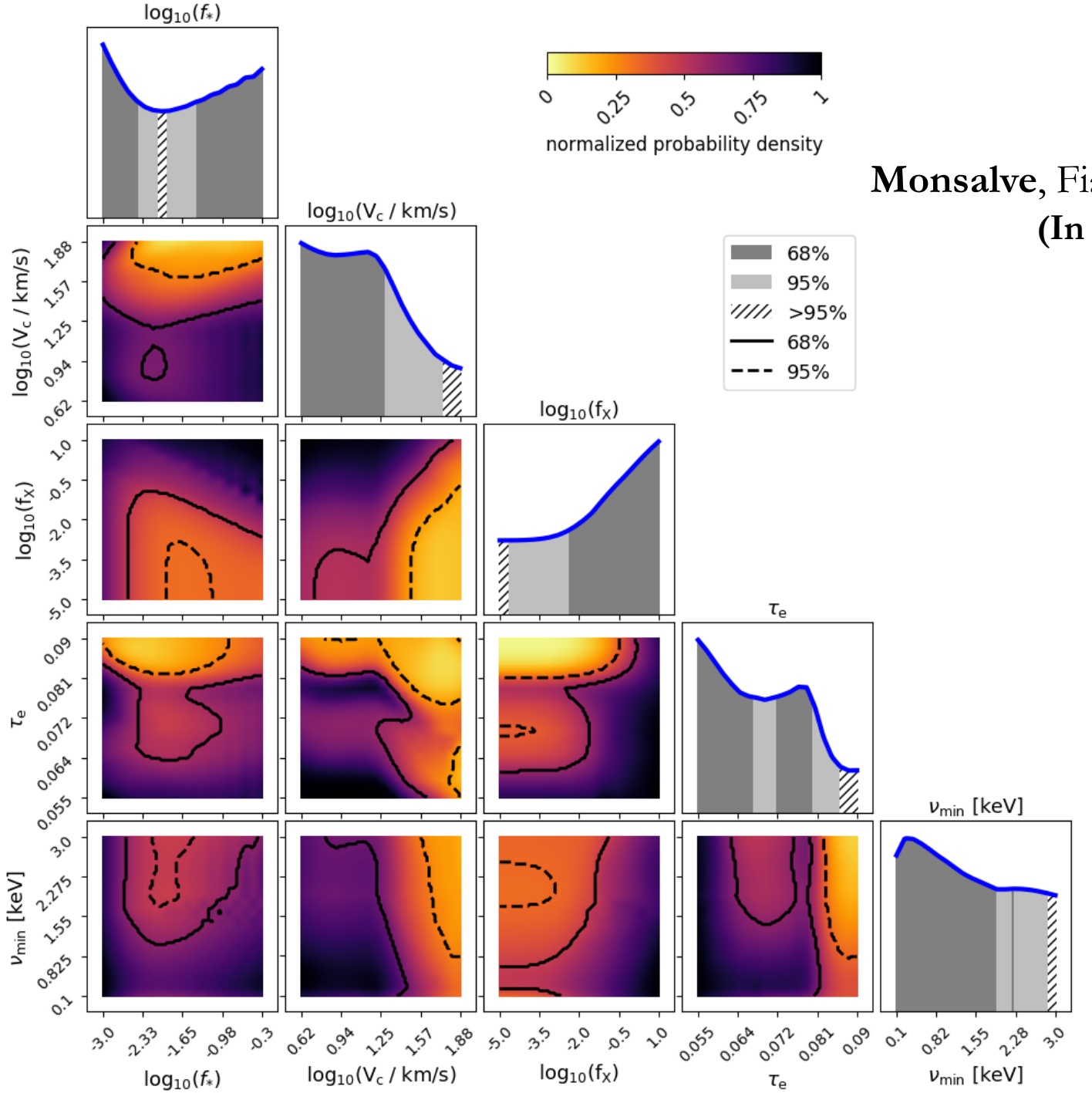
Description of Interpolation Code in Cohen+ (2018)



# 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.