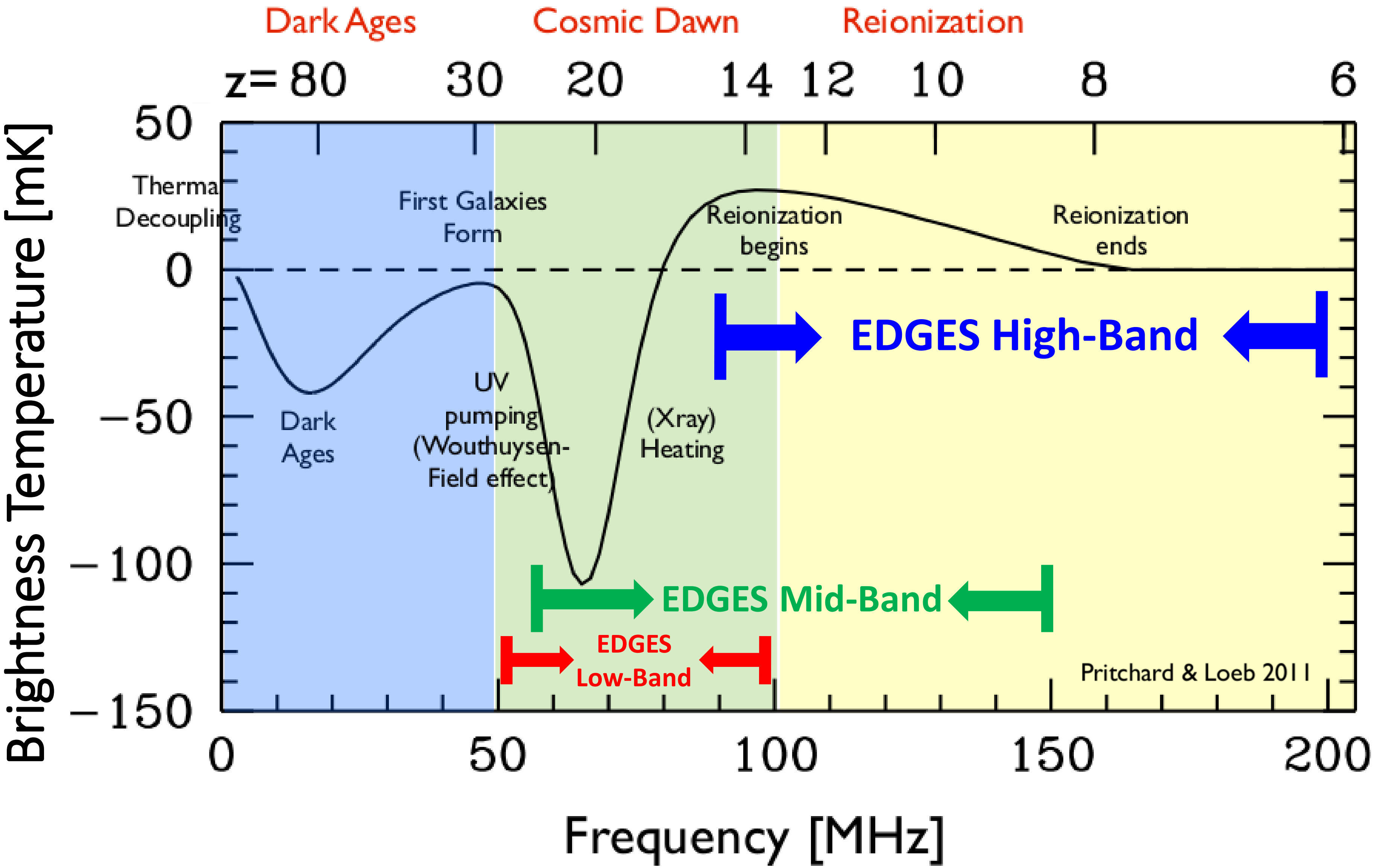
EDGES

Raul Monsalve on behalf of the EDGES team

Prof. Judd Bowman (PI)
Dr. Alan Rogers
Ms. Nivedita Mahesh
Dr. Steven Murray
Dr. John Barrett
Undergraduate Students

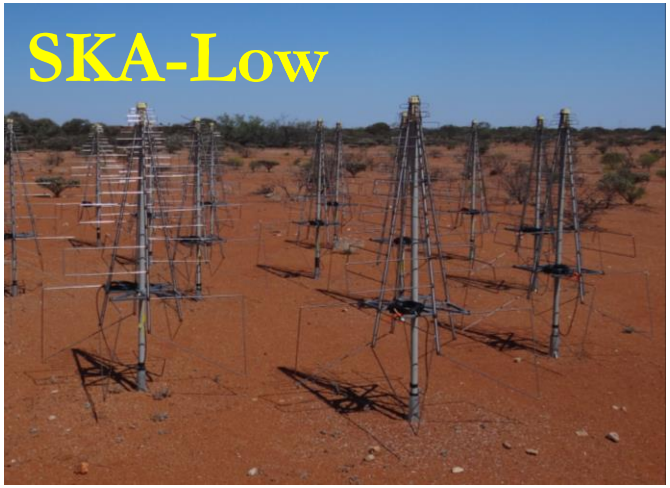
ARIZONA STATE UNIVERSITY
McGill UNIVERSITY
MIT HAYSTACK OBSERVATORY

EDGES Instruments

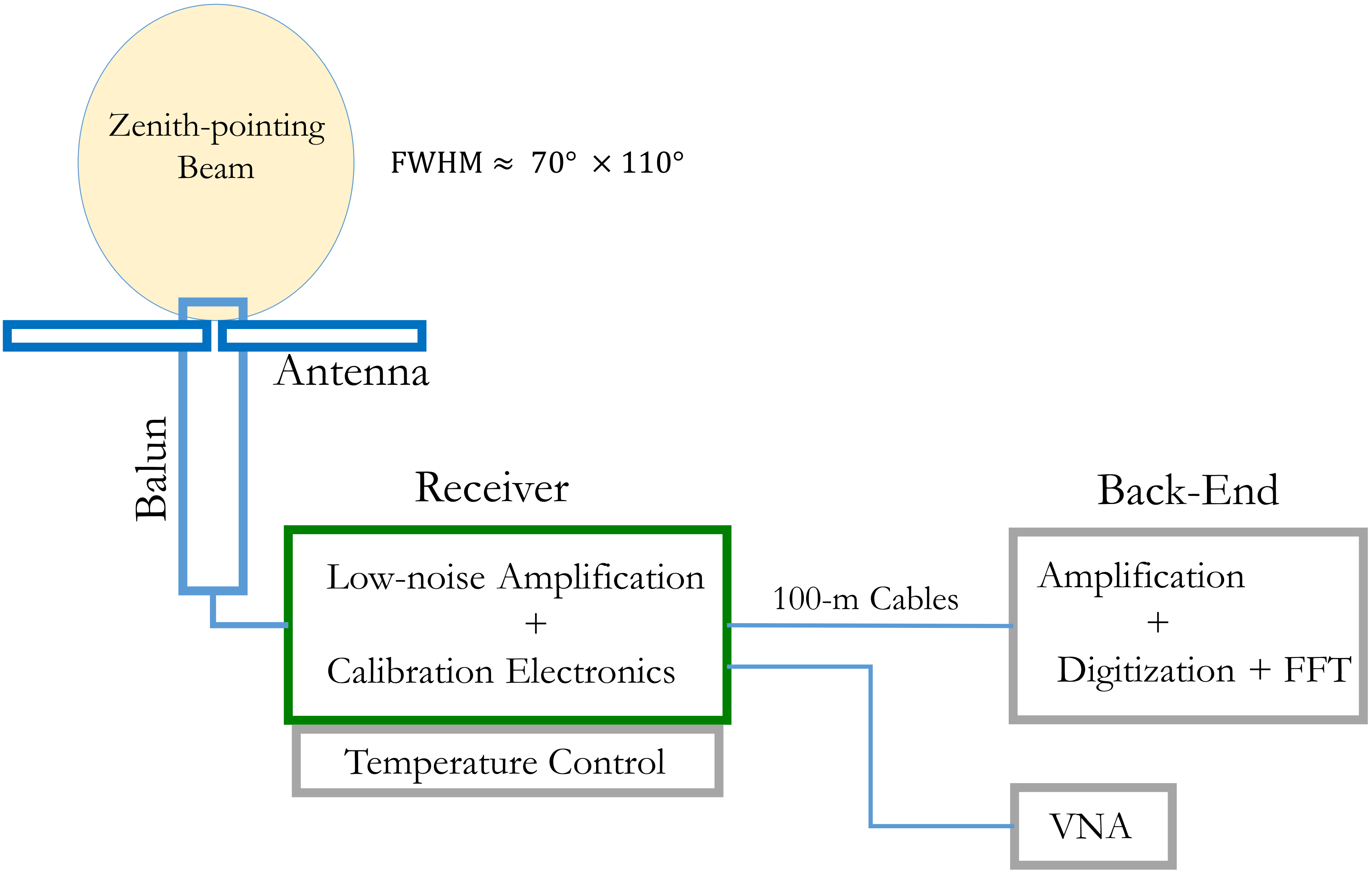


Western Australia

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

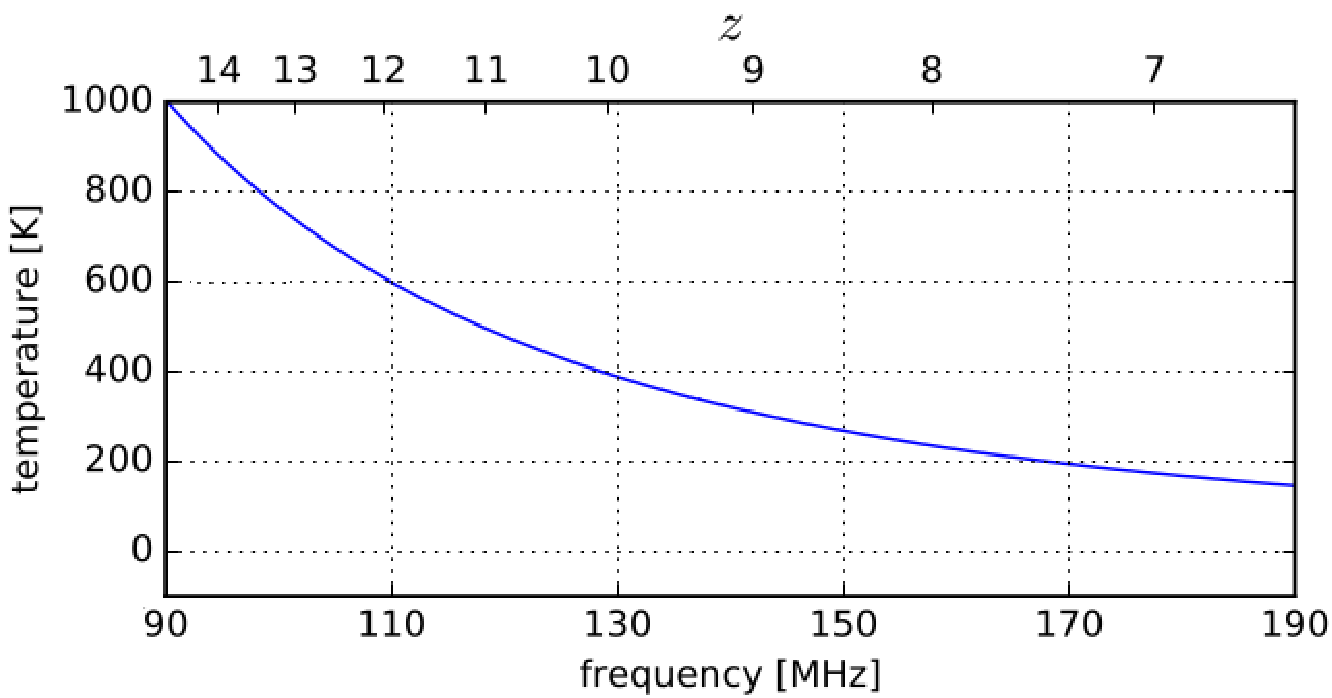


EDGES Block Diagram



EDGES **High-Band**

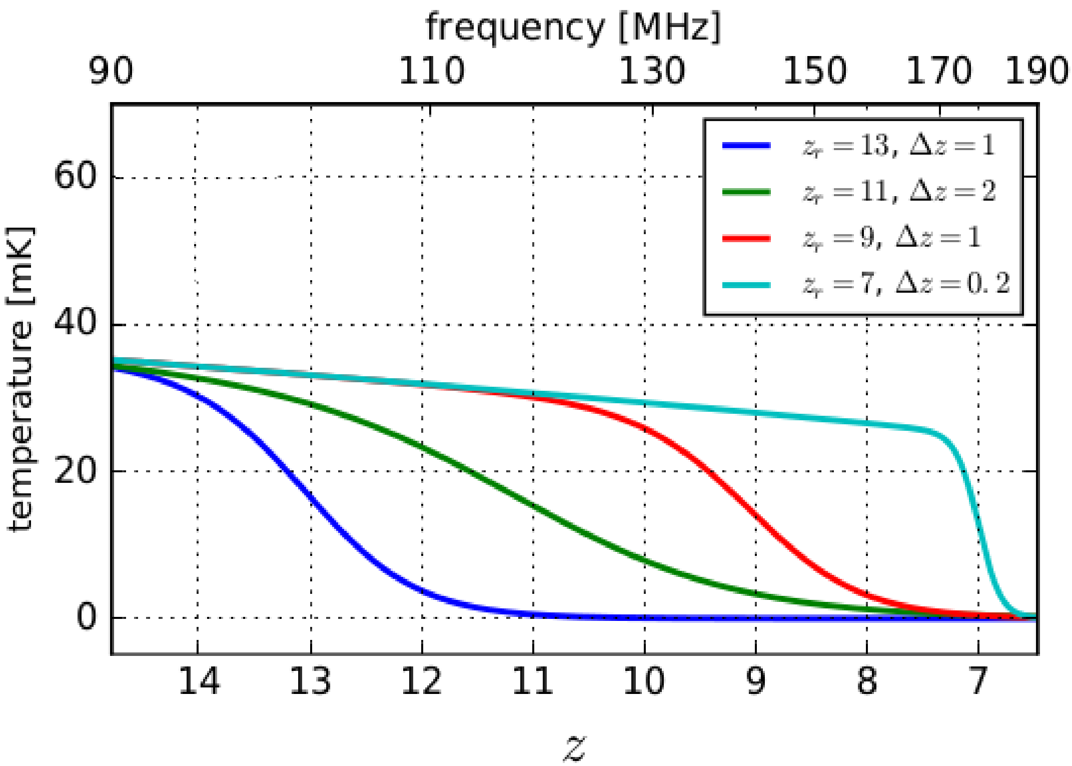
EDGES **High-Band** Spectrum



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

- **Noise of 6 mK** at 140 MHz.
- **No detection reported** in this frequency range.

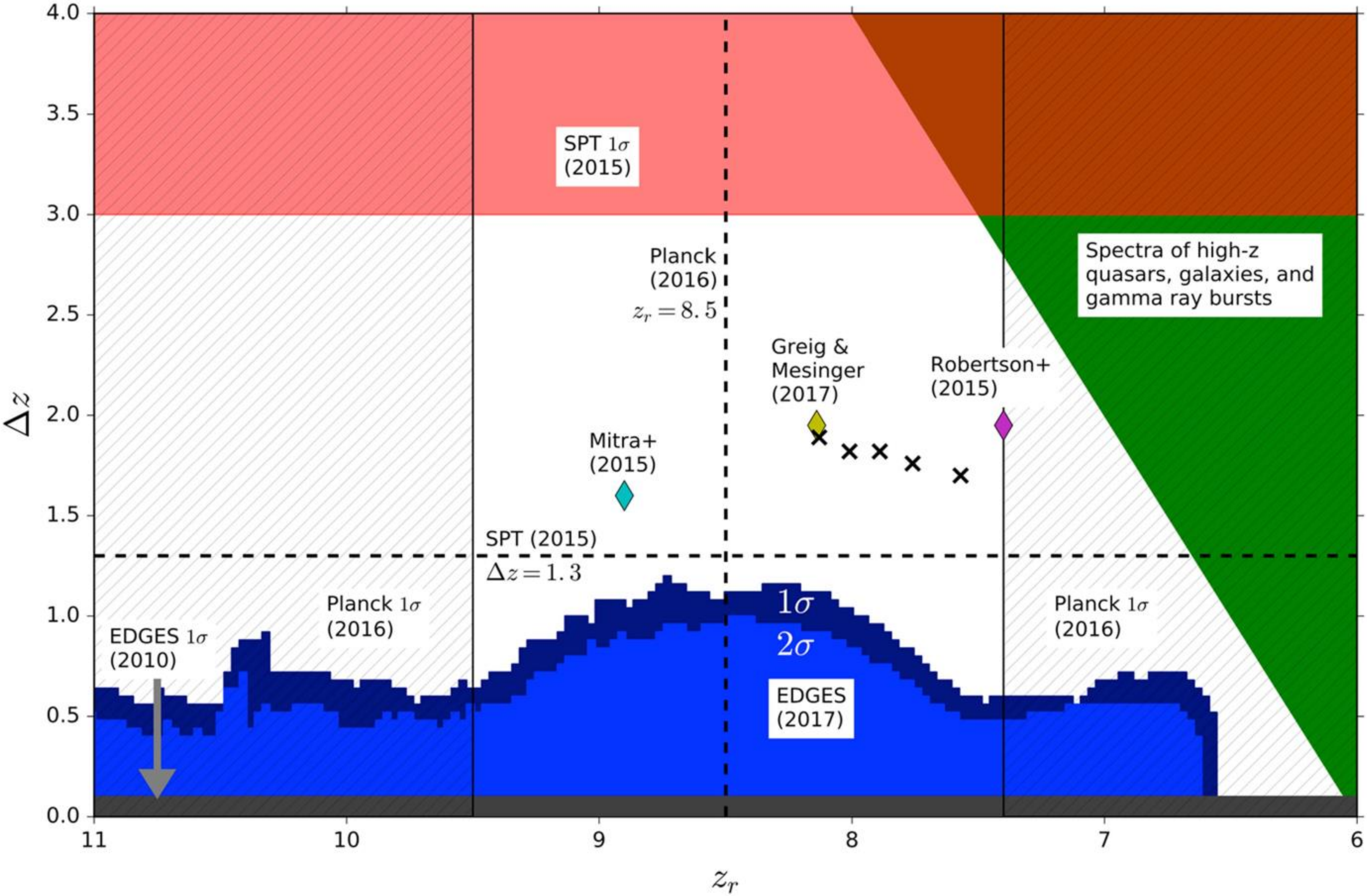
Epoch of Reionization Constraints (Hot IGM)



- 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)

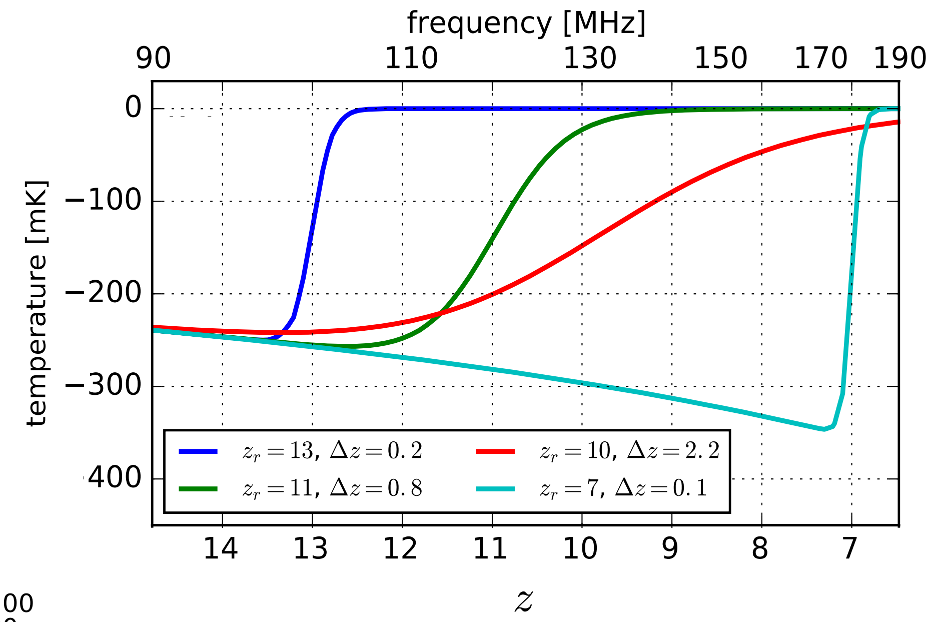
Epoch of Reionization Constraints (Hot IGM)



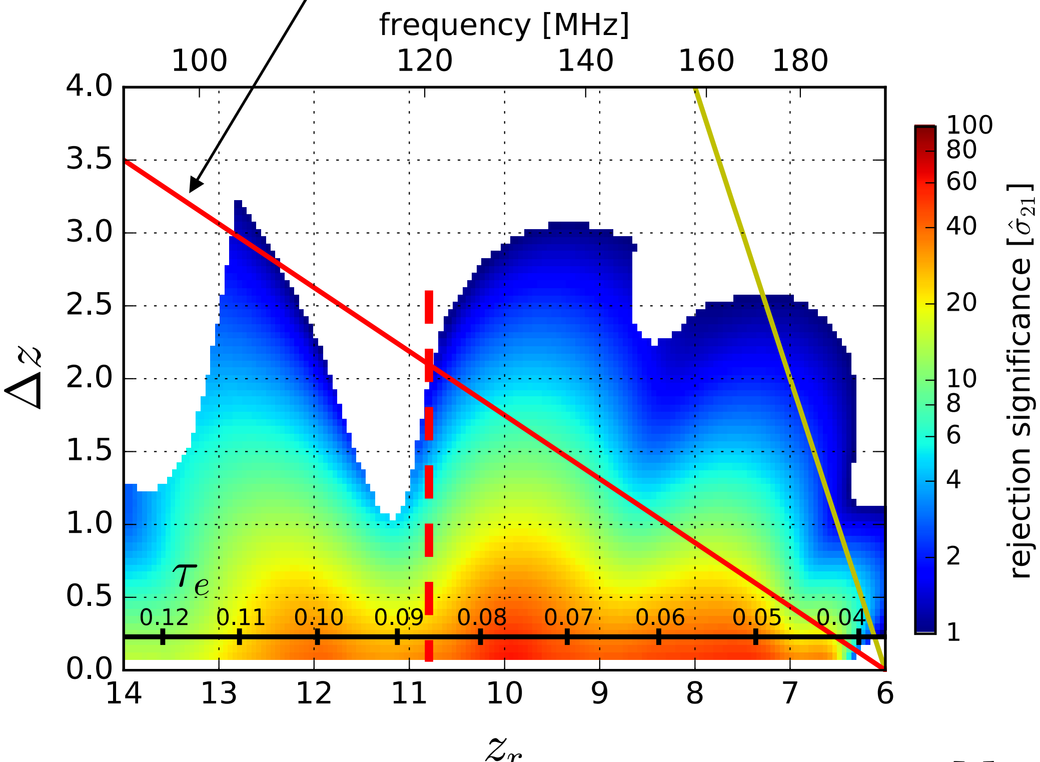
Monsalve, Rogers, Bowman, & Mozdzen (2017b)

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:

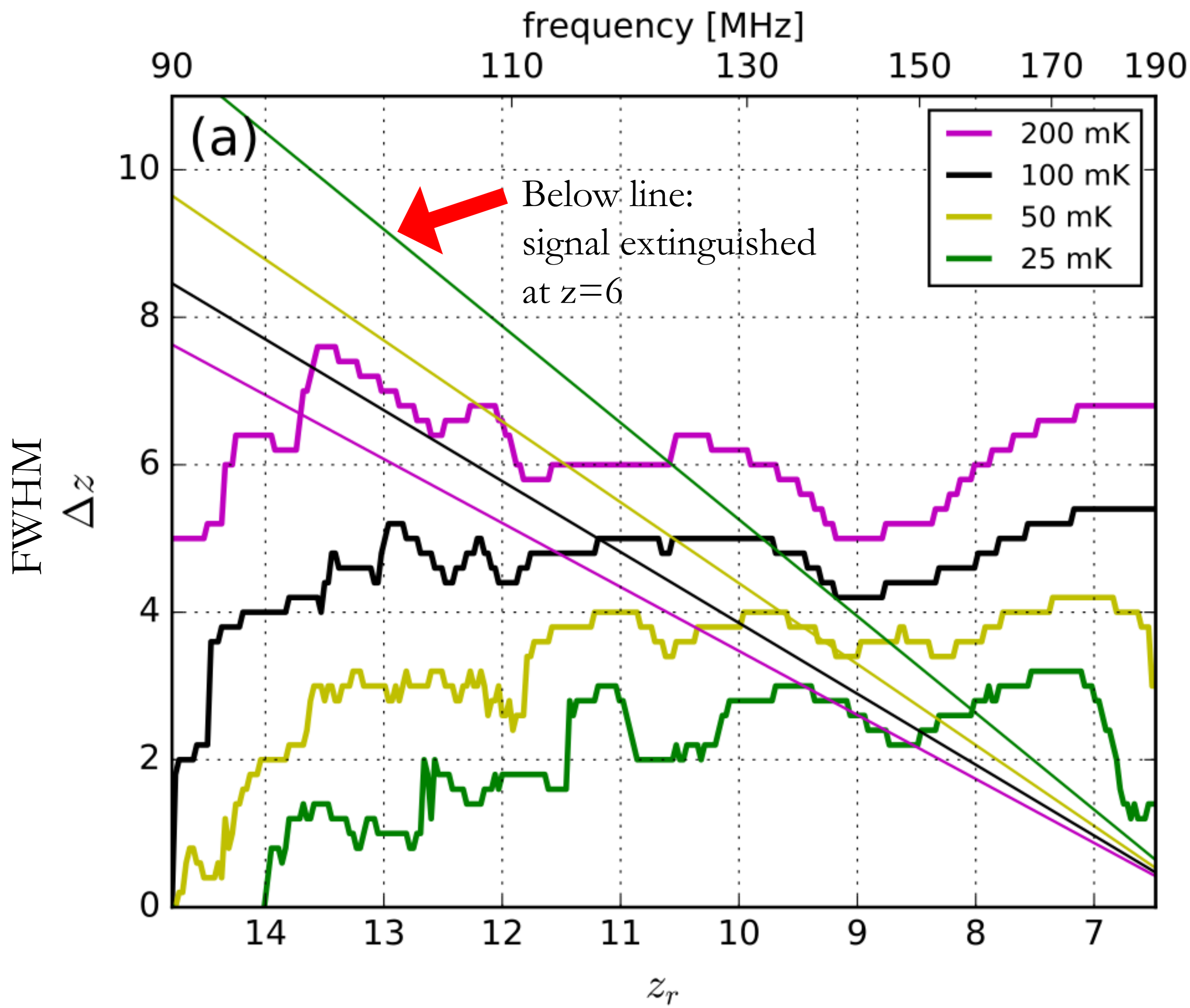
- $0.086 \geq \tau_e \geq 0.038$
- $\bar{x}_{HI} \leq 1\%$ at $z = 6$

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

NO IGM Heating prior to Reionization

This is the **only result so far** from 21-cm measurements that **excludes** reionization scenarios with **no prior IGM heating**, which are consistent with the optical depth from Planck.

Gaussian Absorption Troughs



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

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

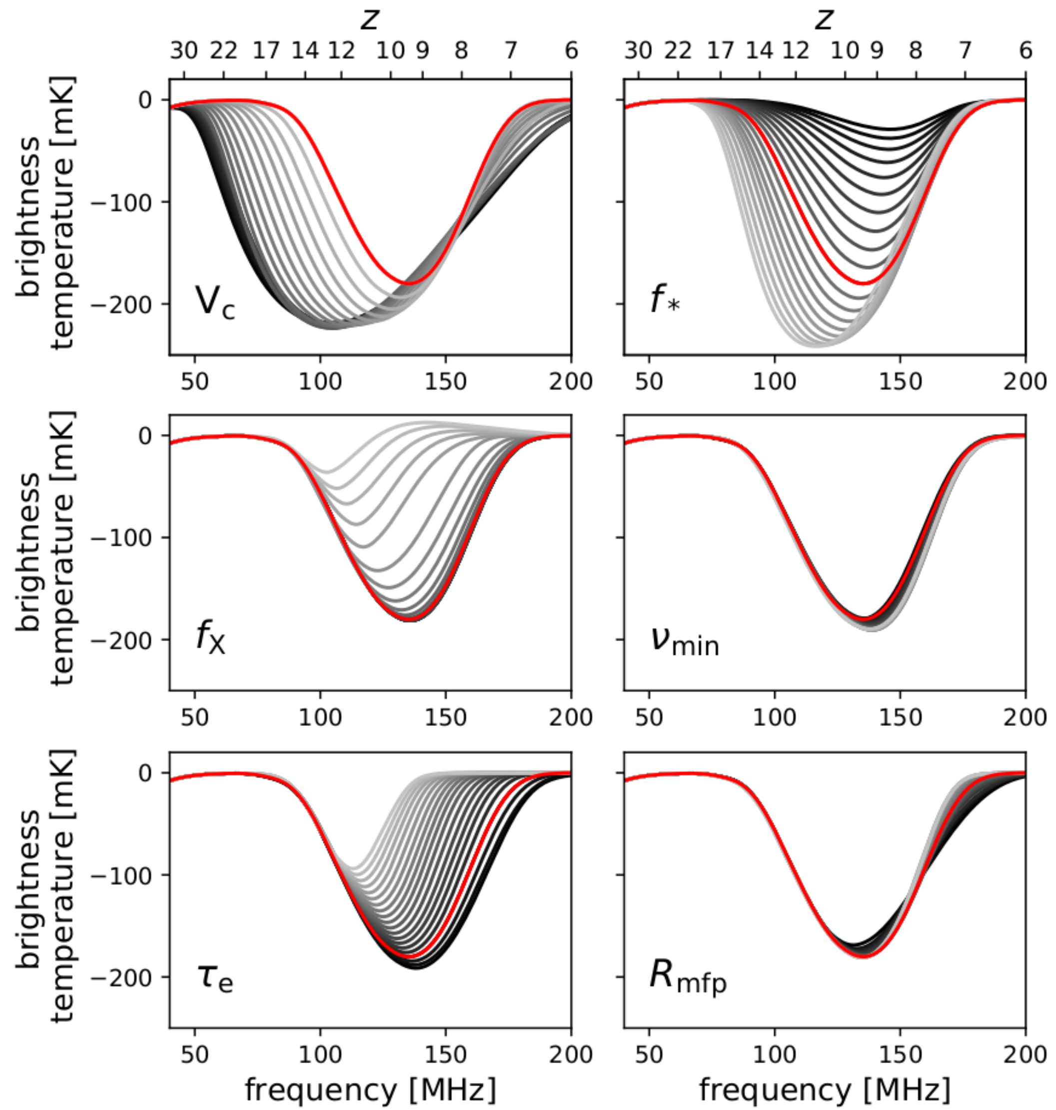
$\boldsymbol{\nu_{min}}$: minimum energy of X-rays

Reionization

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

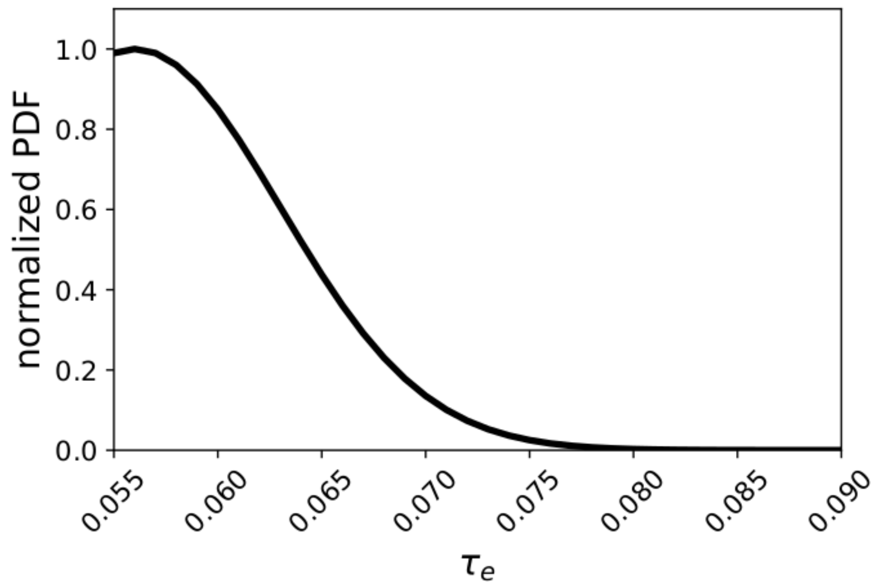
$\boldsymbol{\tau_e}$: CMB optical depth

Foreground parameters are marginalized

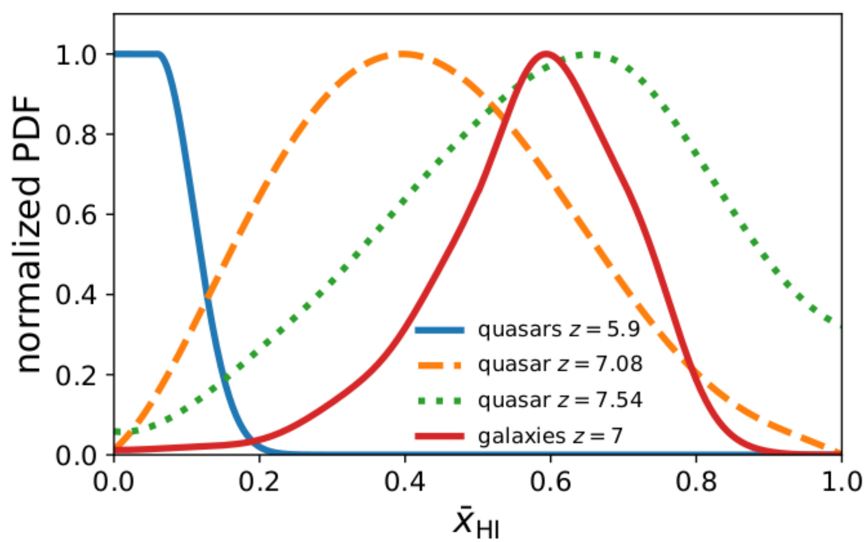


Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh (2019)

Planck

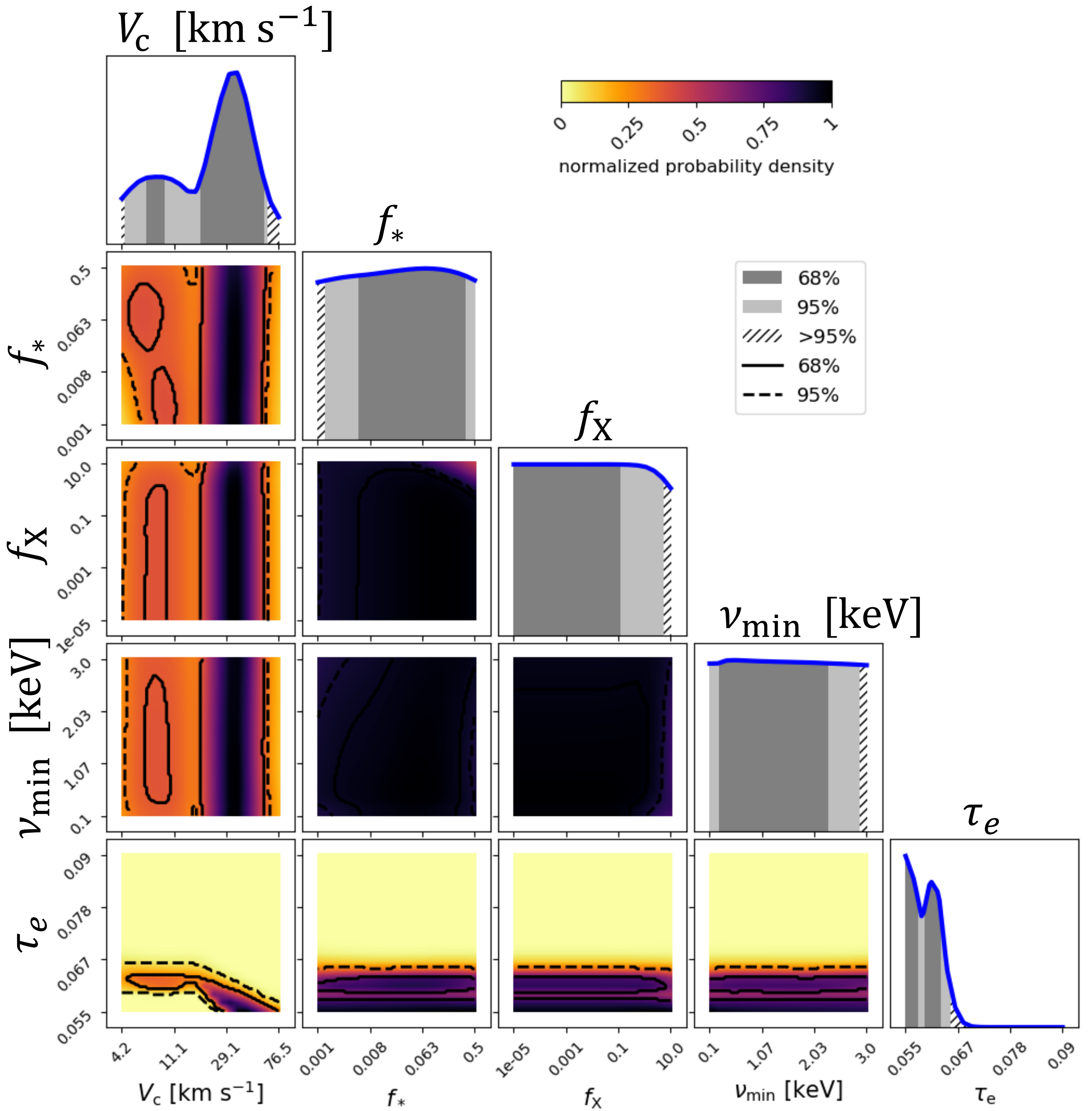


High-z Quasars and Galaxies



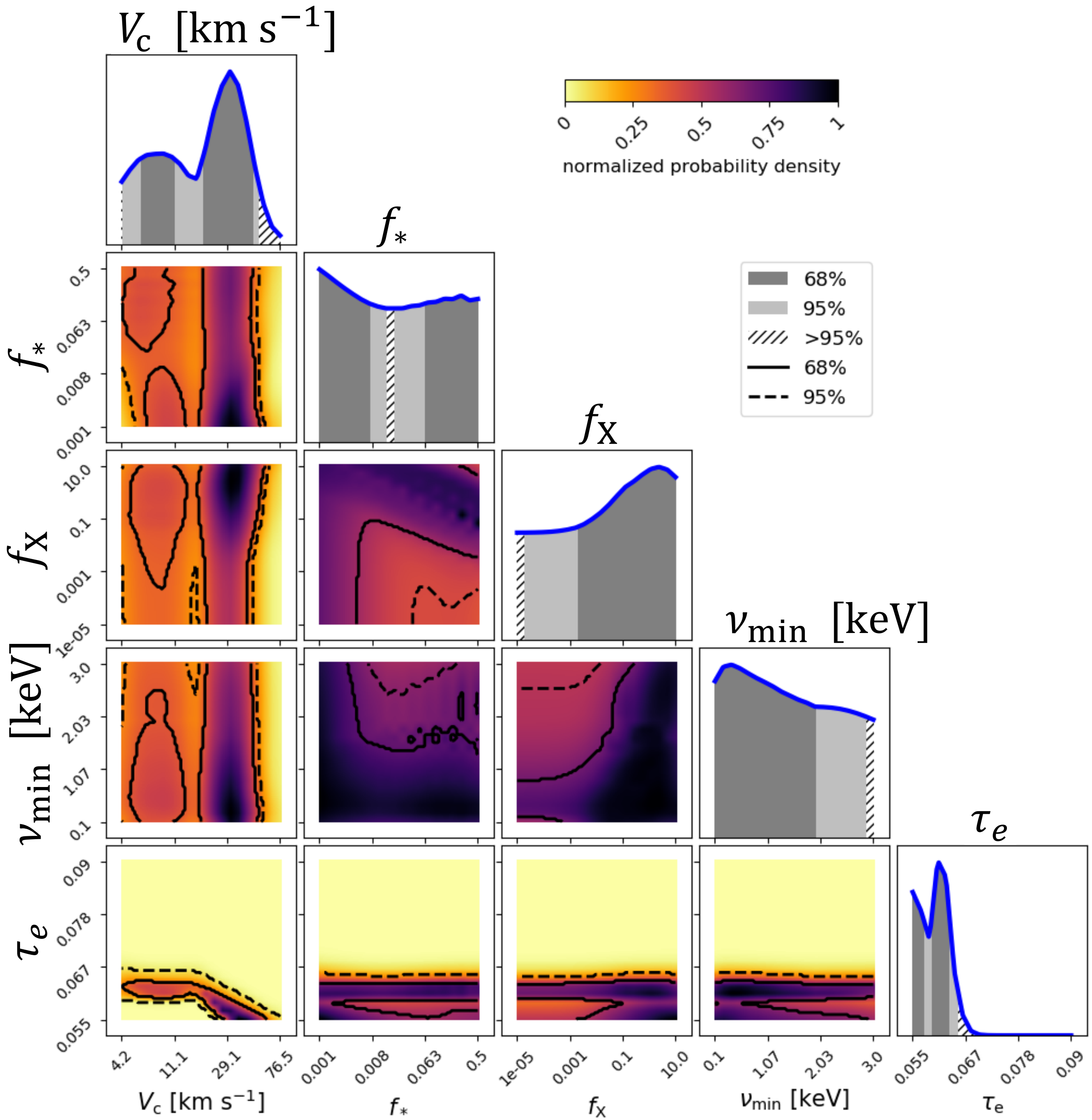
Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh (2019)

Planck + High-z Quasars + Galaxies



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

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

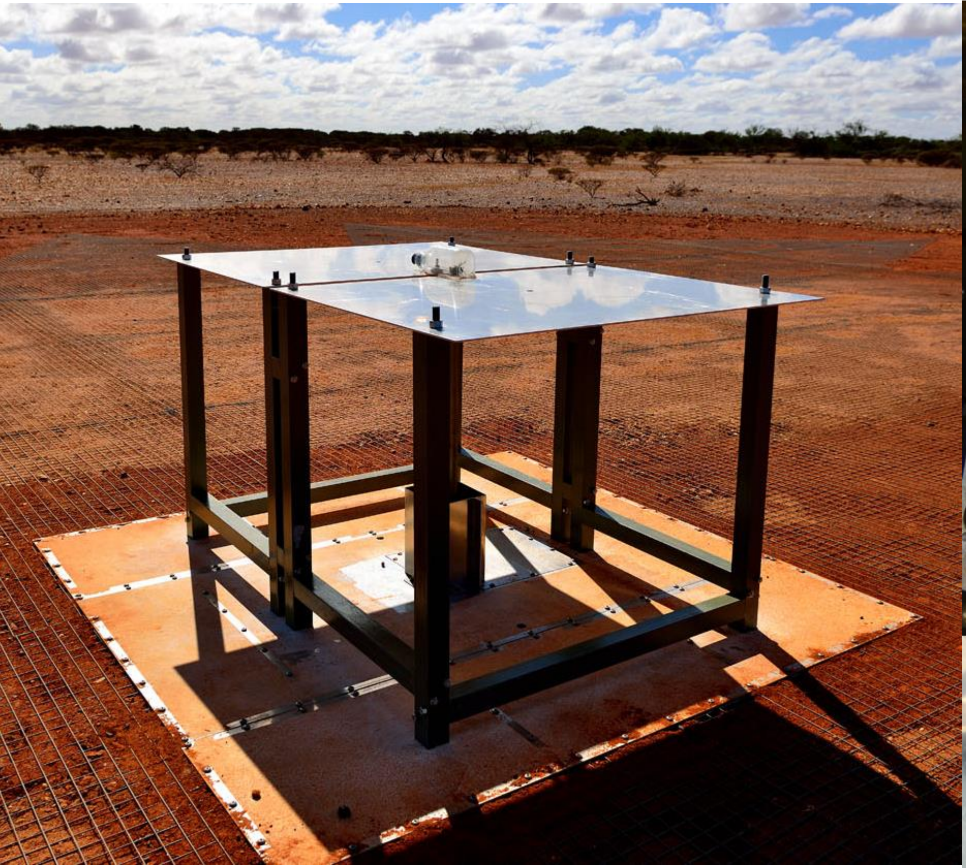


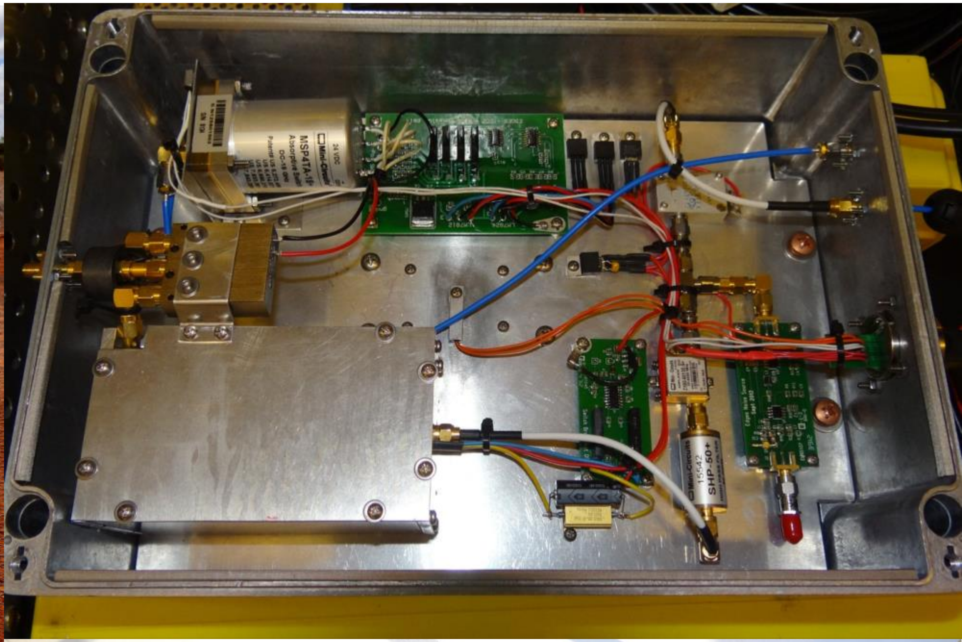
Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh (2019)

High-Band constraints are independent from **Low-Band** data

EDGES **Low-Band**

EDGES **Low-Band**





Antenna size:

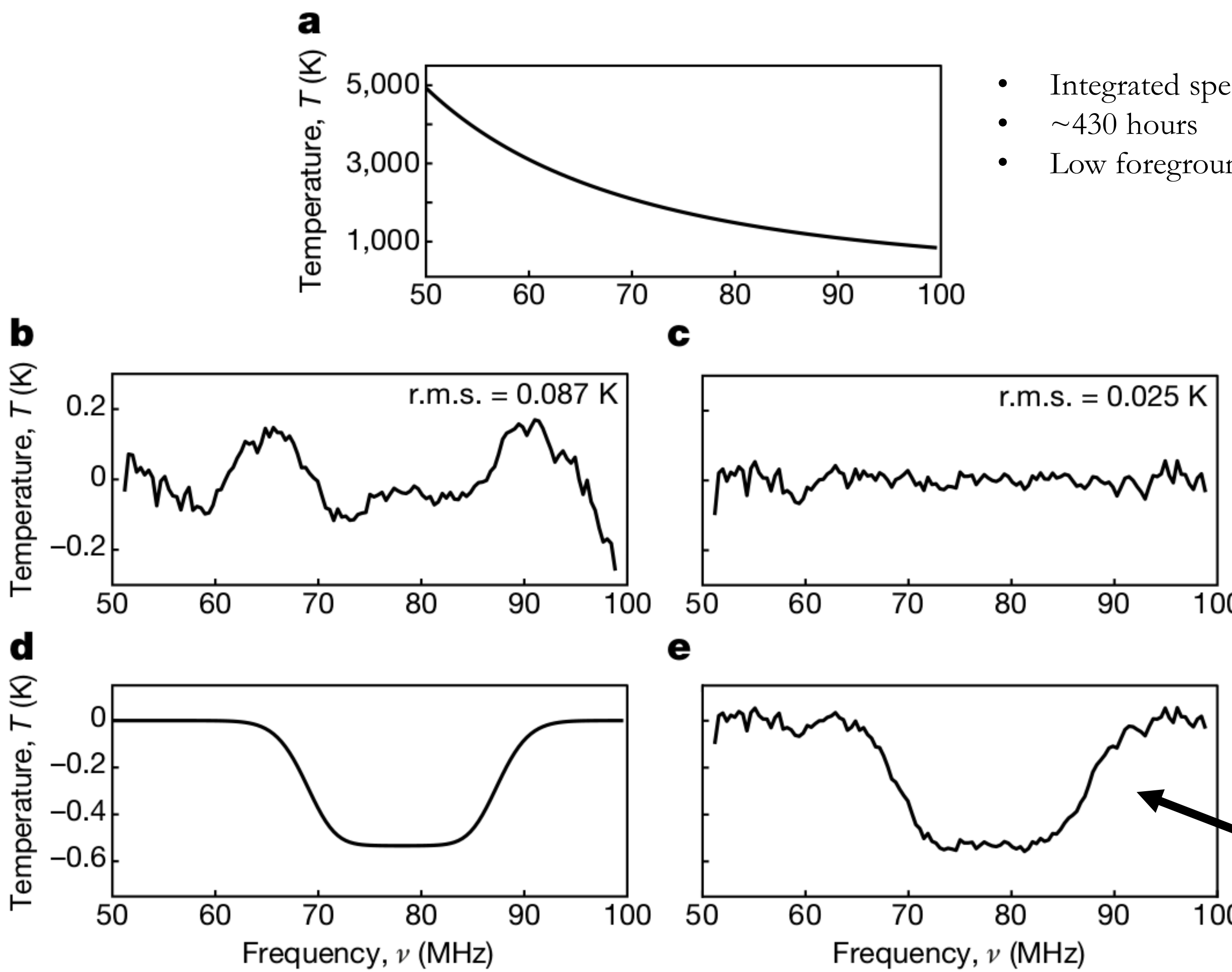
2m long / 1m high

TWO **Low-Band** Instruments

Low-Band 1

Low-Band 2

Summary of the Low-Band Detection

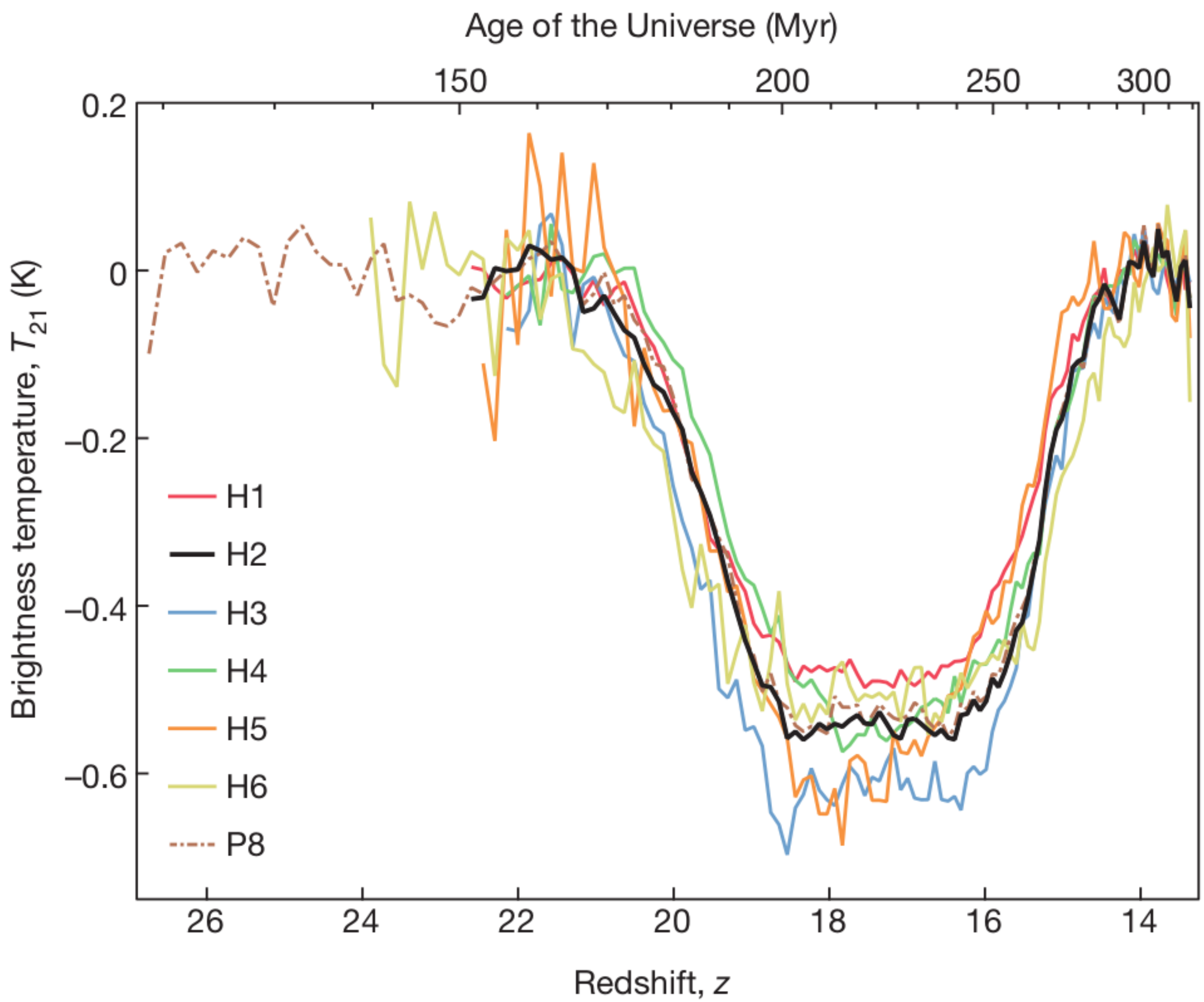


- Integrated spectrum
- ~430 hours
- Low foreground regions

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

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

How to Explain Deep Absorption?

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

Suggested sources:

- Radio emission from **early black holes** [i.e., Ewall-Wice et al. 2018]
- Decay of **unstable particles** [Pospelov et al. 2018] [Aristizabal Sierra & Sheng Fong 2018]

Lower than expected

$\boldsymbol{T_{\mathrm{IGM}}}$ **Lower than expected**

Suggested source:

- Baryon-Dark matter **particle interactions** [i.e., Muñoz and Loeb 2018]

IOP Publishing

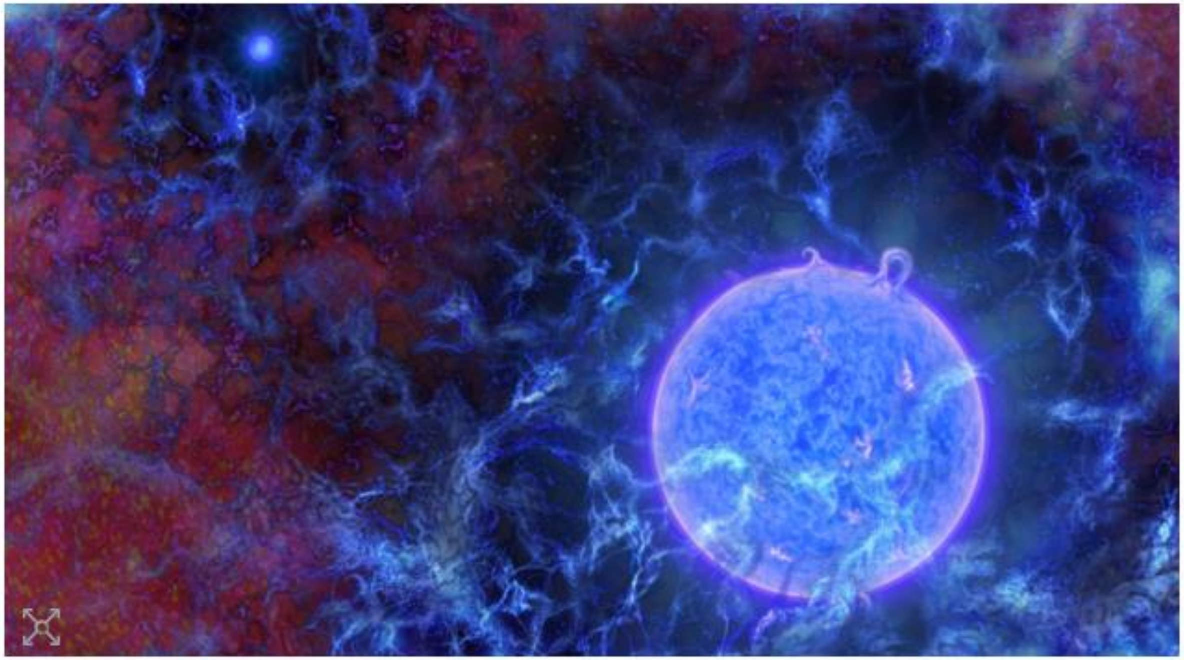
physicsworld

TOP 10 Breakthrough in 2018

Dec 13, 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

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**.

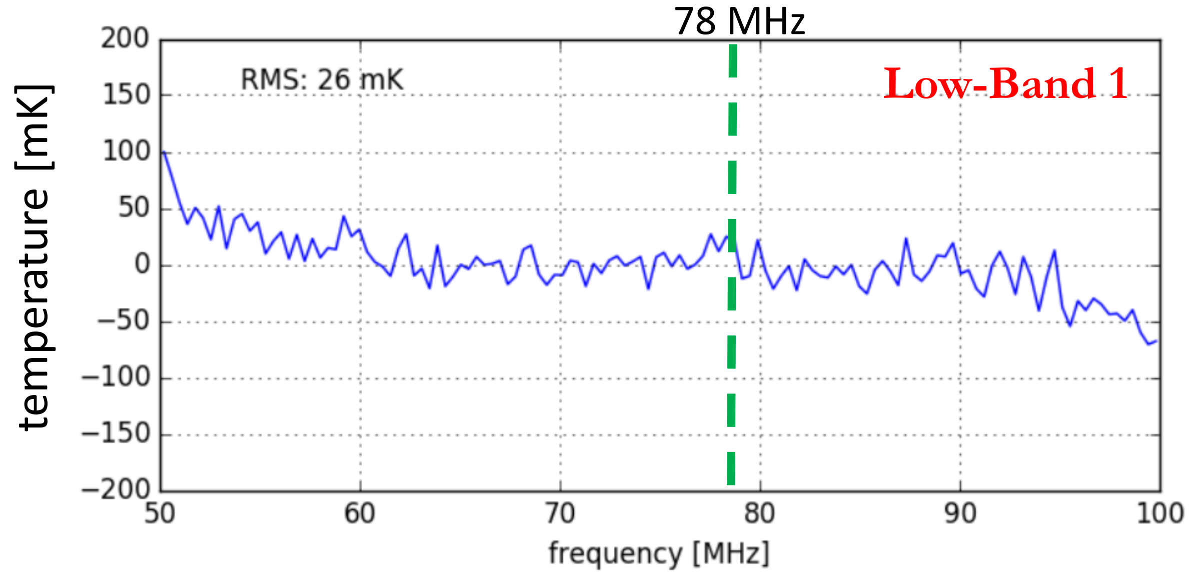
Tests Addressing Antenna Beam Effects (**feature should be found**)

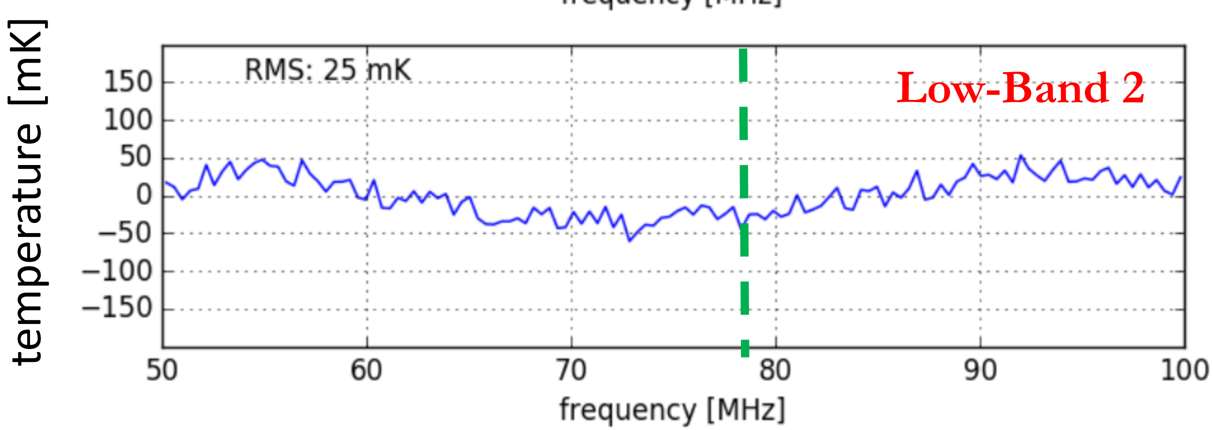
1) Using **smaller Mid-Band antenna** covering 60-160 MHz.
2) Using Low-Band antenna over a **smaller 9m x 9m ground plane**. We call this **Low-Band 3**.

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

Verification Using ~300K Passive Noise Sources

Residuals After Removing a Constant





EDGES **Mid-Band**

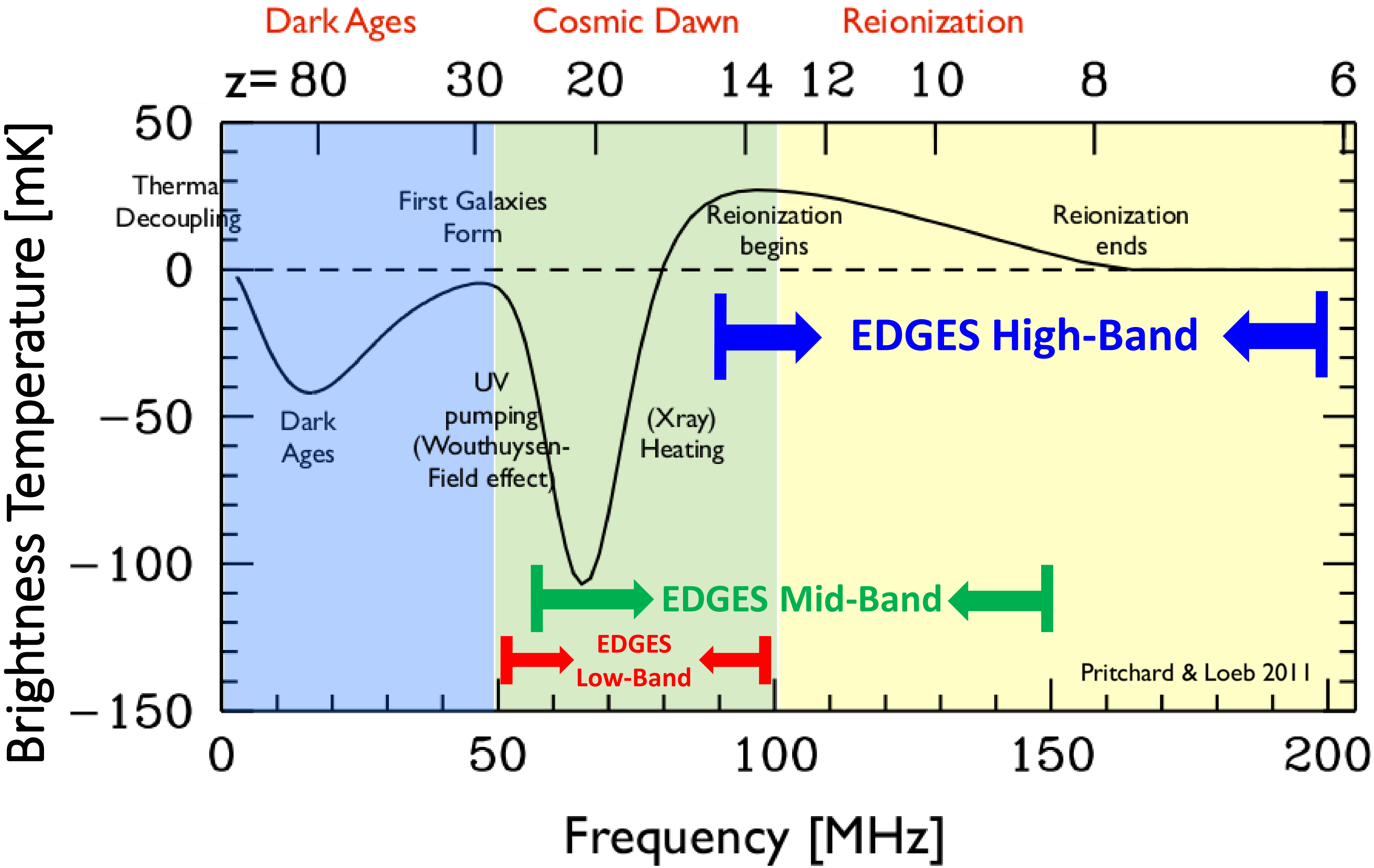
Motivation for EDGES **Mid-Band**

- Contribute to verifying the Low-Band detection by measuring with an **antenna 25% smaller** than Low-Band and a recalibrated receiver.

- This would test for antenna **effects that scale with antenna size**.

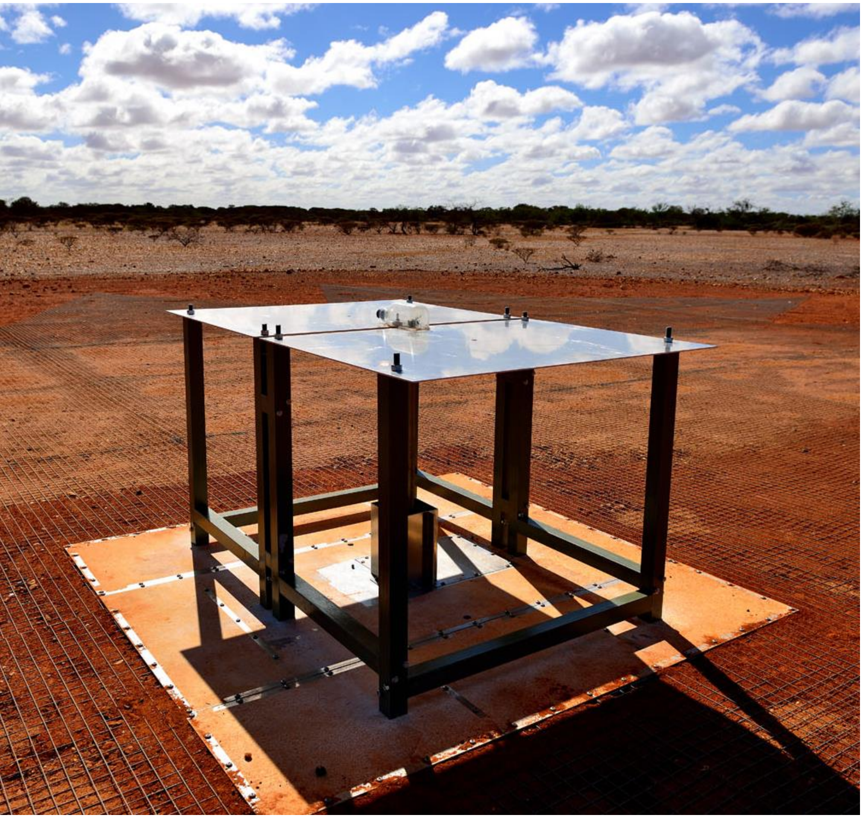
- This might **not test for all** antenna effects, or effects from the ground plane that are independent from the antenna.

EDGES Instruments



Mid-Band Antenna

Low-Band

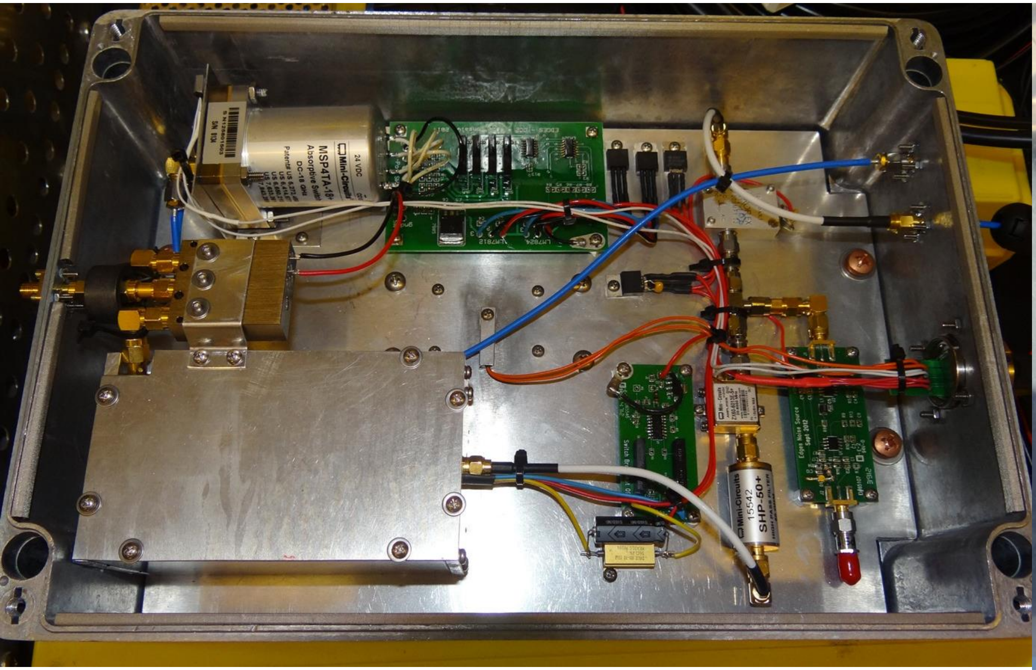


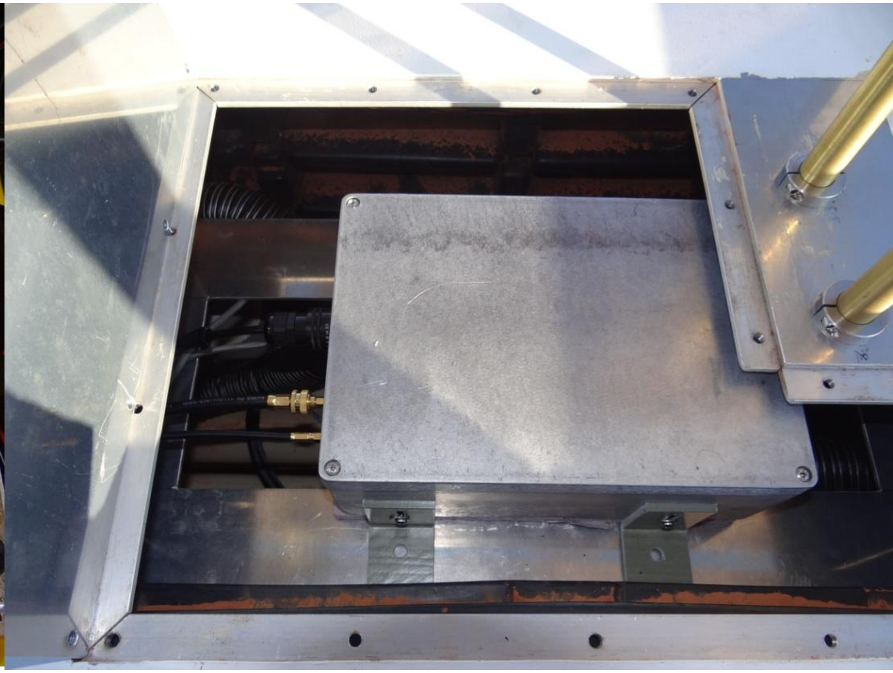
Mid-Band (~25% smaller)

Antenna size:
Length: 2 m
Width: 1.25 m
Height: 1 m

Antenna size:
Length: 1.5 m
Width: 0.95 m
Height: 0.79 m

Same Receiver as **Low-Band 1**



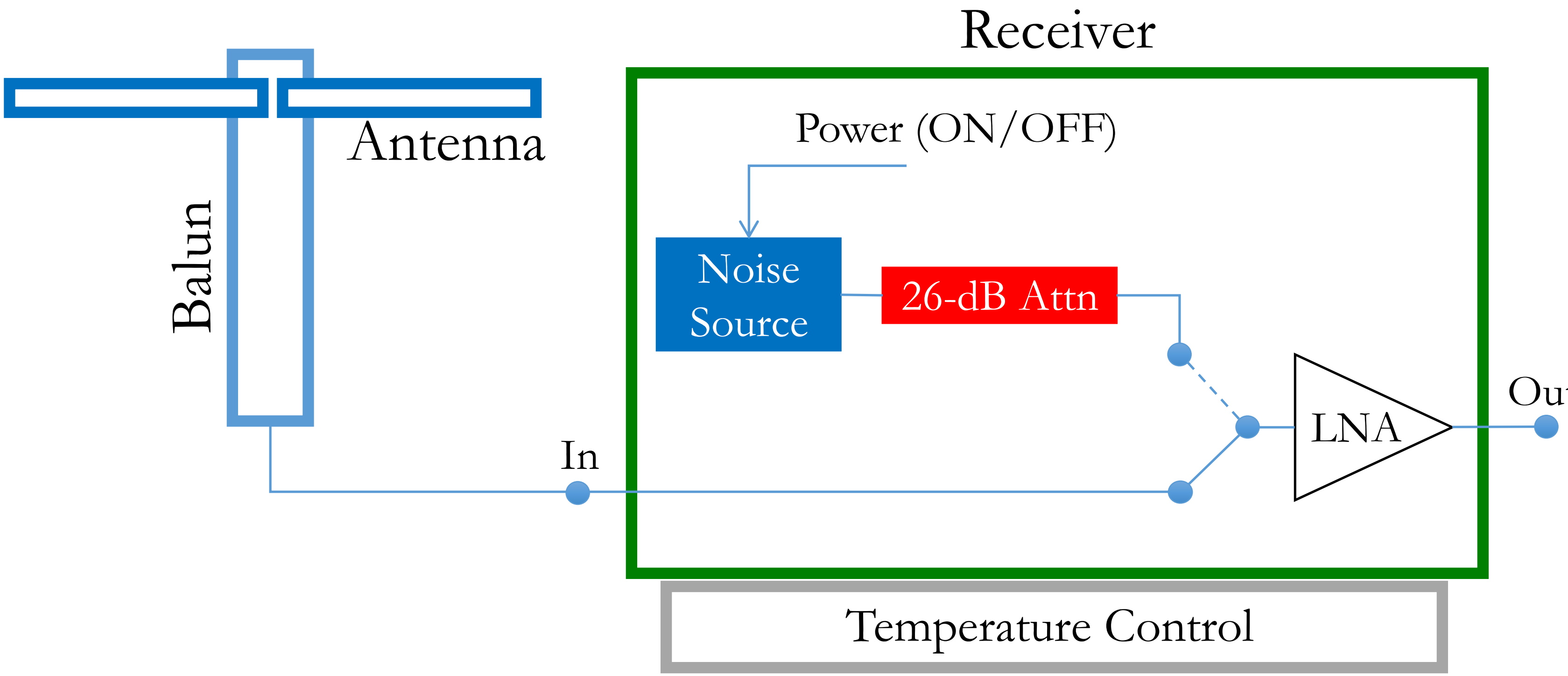


Same Ground Plane as **Low-Band 1**

Instrumental Calibration

1) **Instrument gain and noise offset.**
2) **Impedance mismatch between receiver and antenna.**
3) **Antenna and ground losses.**
4) **Antenna beam chromaticity.**

Field Relative Calibration

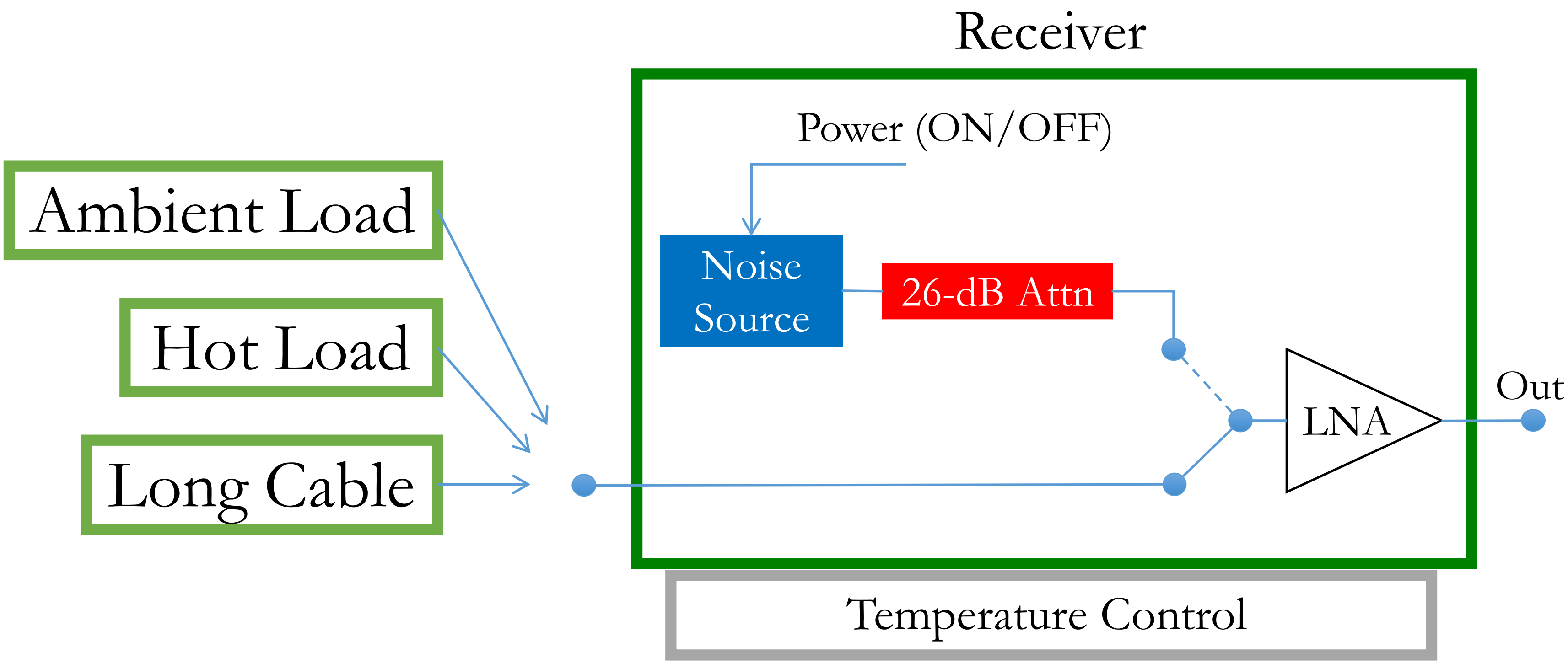


3-position switching **removes time variable instrument gain + noise offset.**

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

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

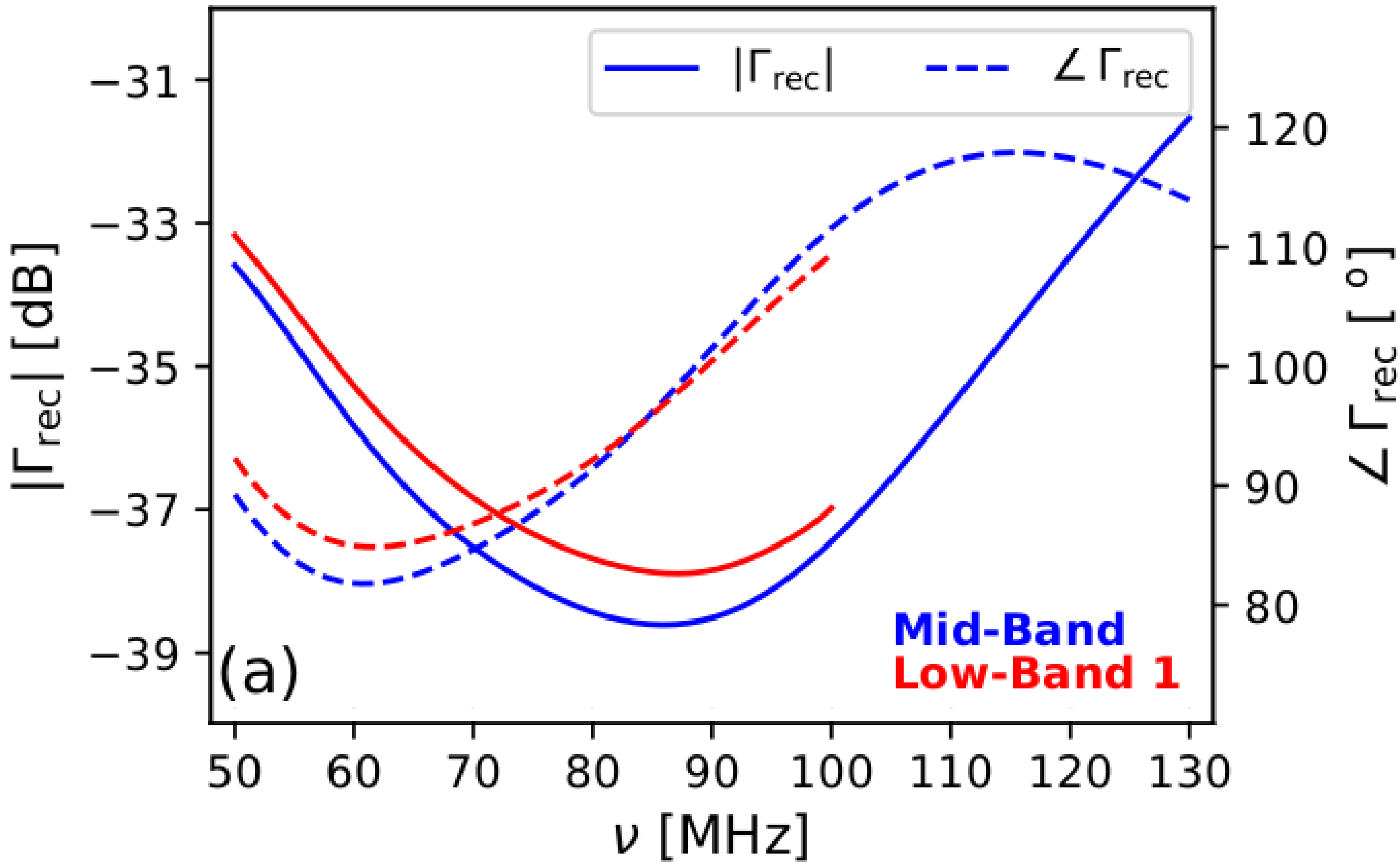
Lab Absolute Calibration



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**.

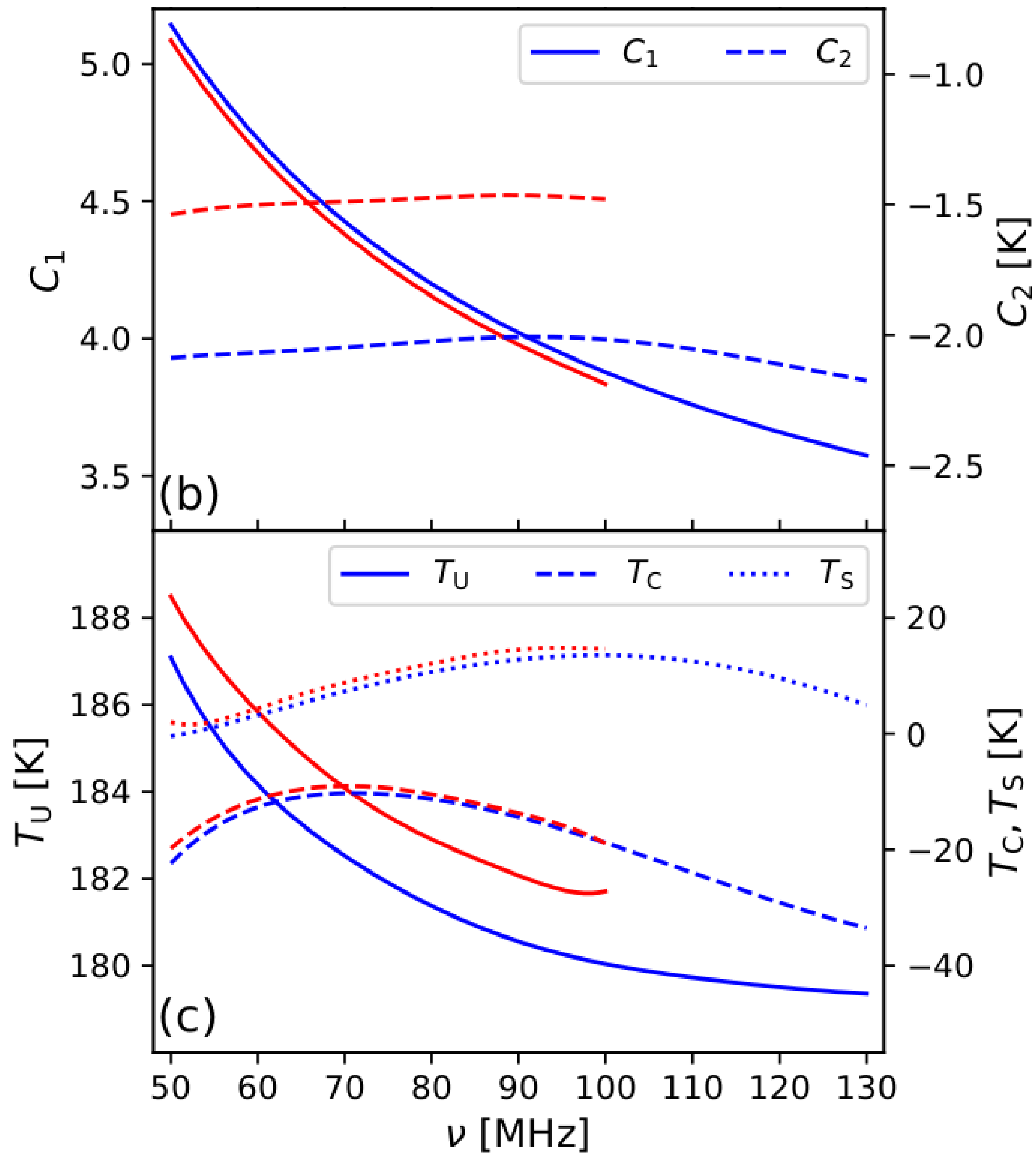
Mid-Band Receiver Parameters



Monsalve et al (2019, in preparation)

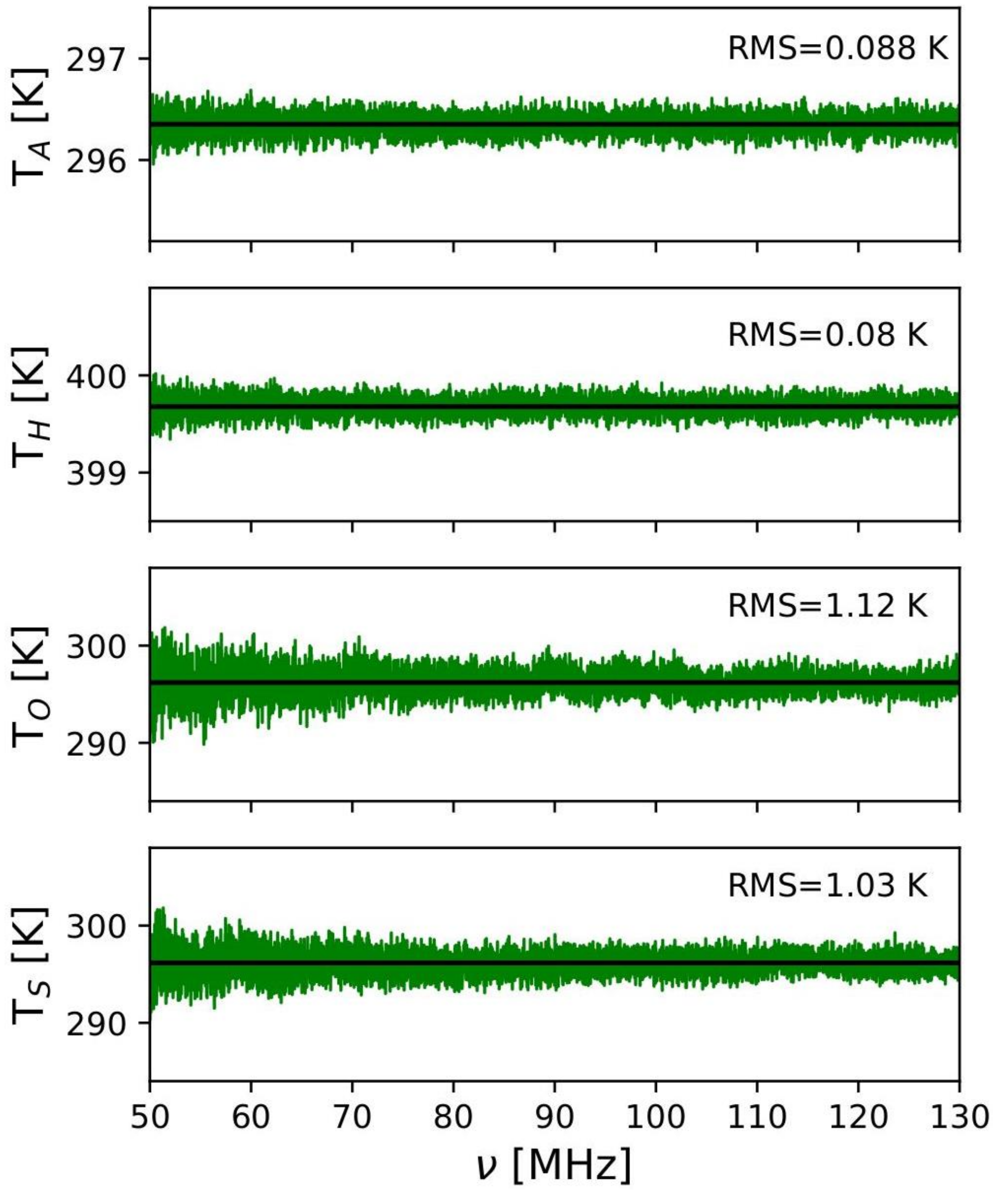
Mid-Band Receiver Parameters

Mid-Band
Low-Band 1



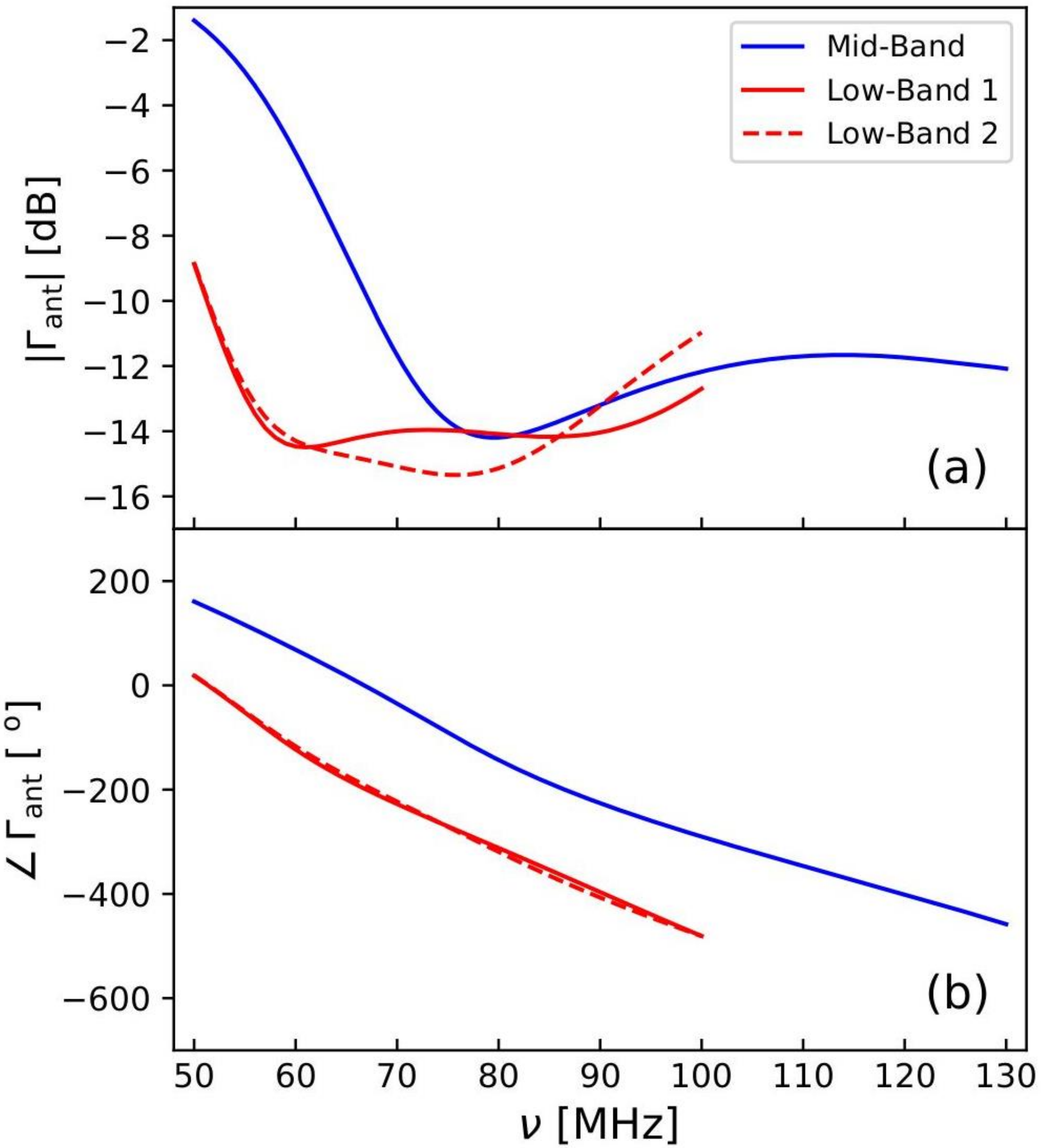
Monsalve et al (2019, in preparation)

Mid-Band Receiver Cross-Check



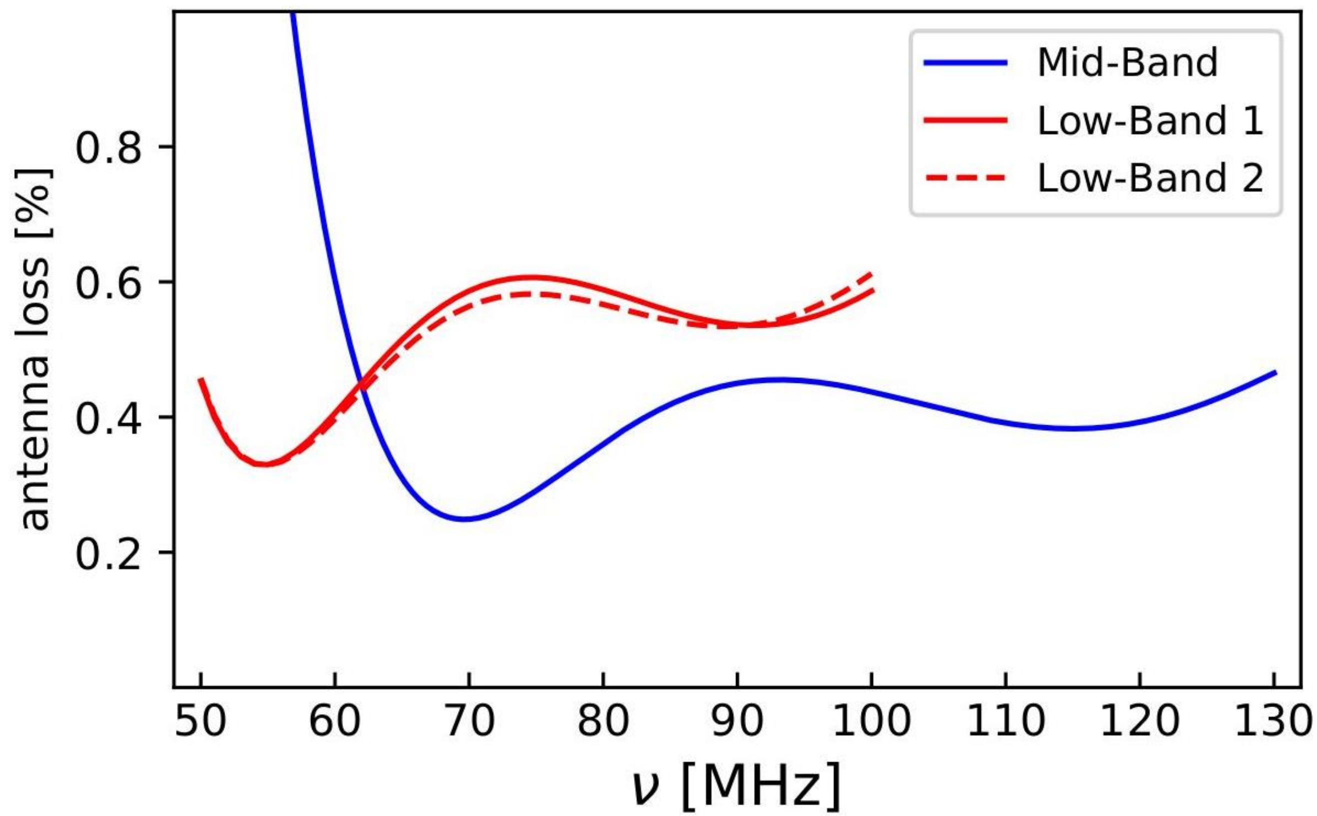
Monsalve et al (2019, in preparation)

Mid-Band Antenna Reflection



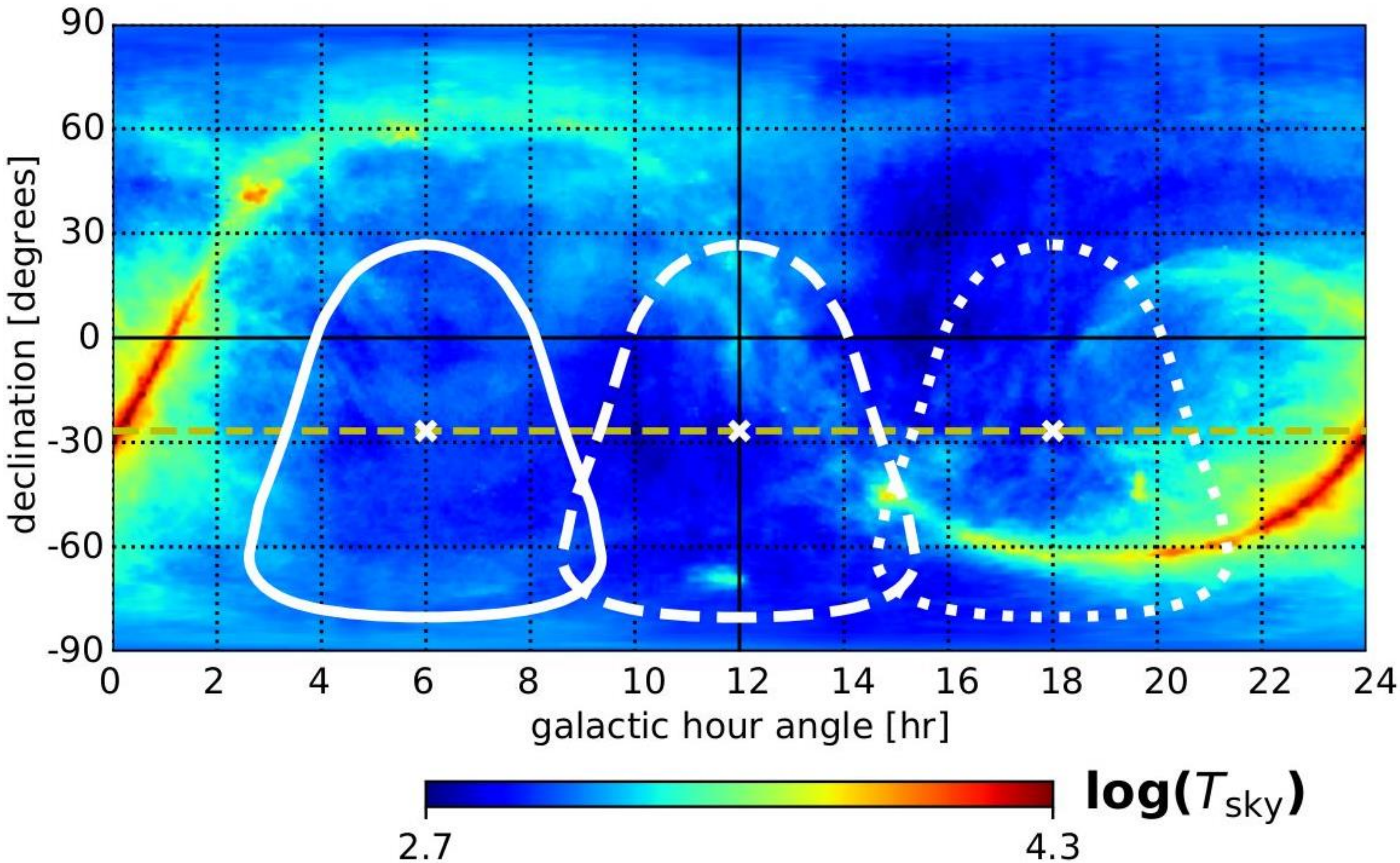
Monsalve et al (2019, in preparation)

Mid-Band Antenna Loss



Monsalve et al (2019, in preparation)

Mid-Band Beam FWHM Projected onto Sky



Monsalve et al (2019, in preparation)

Beam Chromaticity

Antenna to Sky Temperature

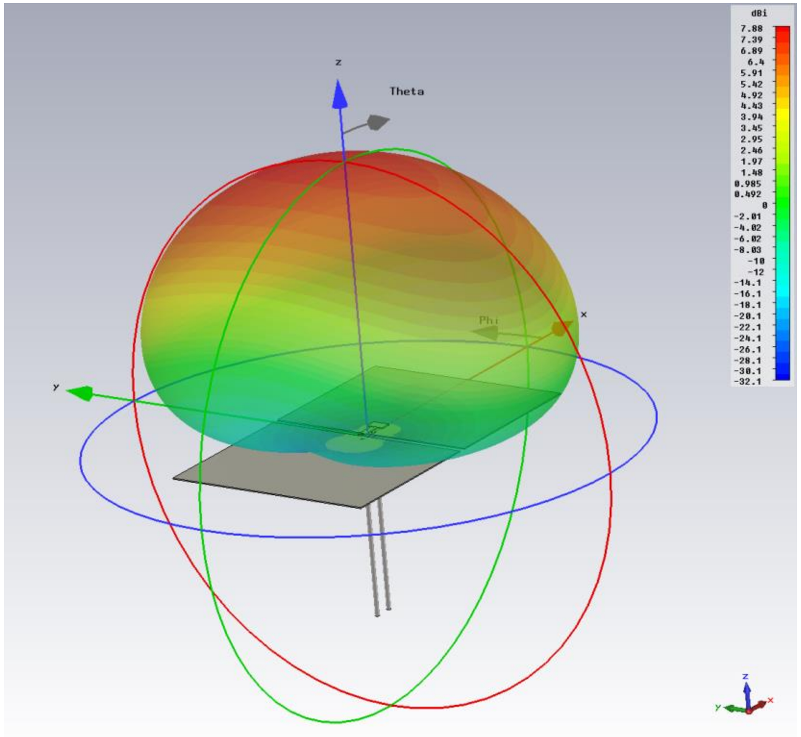
$$T_{\text{ant}}\,(\upsilon, \text{GHA}) = \int T_{\text{sky}}(\upsilon, \text{GHA}; \theta, \varphi) \cdot D(\upsilon, \text{GHA}; \theta, \varphi)\; d\Omega$$

$$T_{\text{ant}}\,(\upsilon, \text{GHA}) = C(\upsilon, \text{GHA}) \cdot T_{\text{sky}}\,(\upsilon, \text{GHA})$$

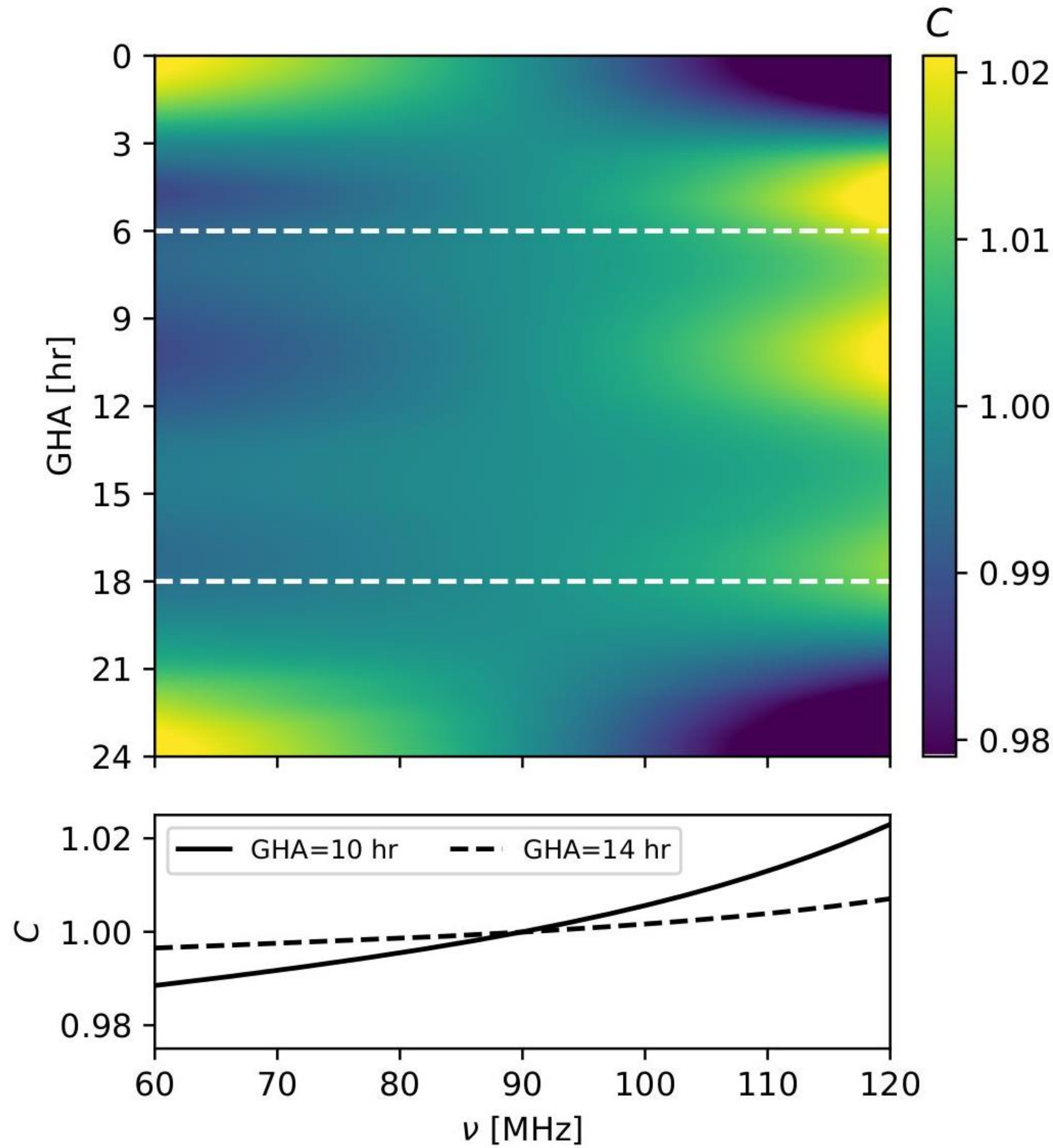
Chromaticity Correction

$$C(\boldsymbol{\upsilon}, \text{GHA}) = \frac{\int T_{\text{sky}}(\boldsymbol{\upsilon}_{\textbf{ref}}, \text{GHA}; \theta, \varphi) \cdot D(\boldsymbol{\upsilon}, \text{GHA}; \theta, \varphi)\; d\Omega}{\int T_{\text{sky}}(\boldsymbol{\upsilon}_{\textbf{ref}}, \text{GHA}; \theta, \varphi) \cdot D(\boldsymbol{\upsilon}_{\textbf{ref}}, \text{GHA}; \theta, \varphi)\; d\Omega}$$

Antenna Directive Gain from Simulation



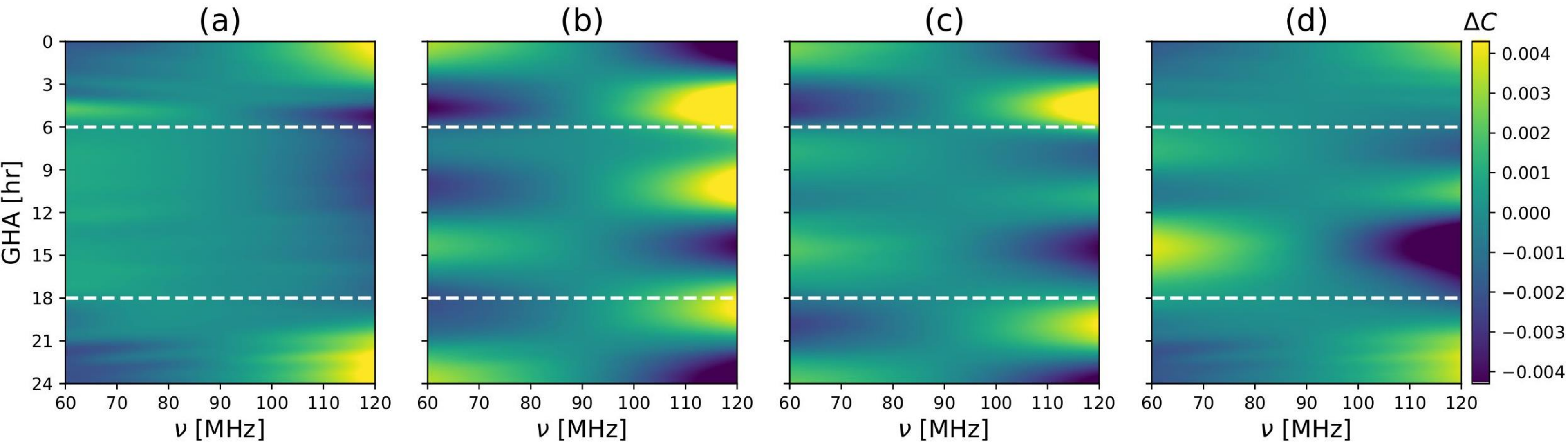
Mid-Band Chromaticity Correction



Monsalve et al (2019, in preparation)

Mid-Band Chromaticity Correction

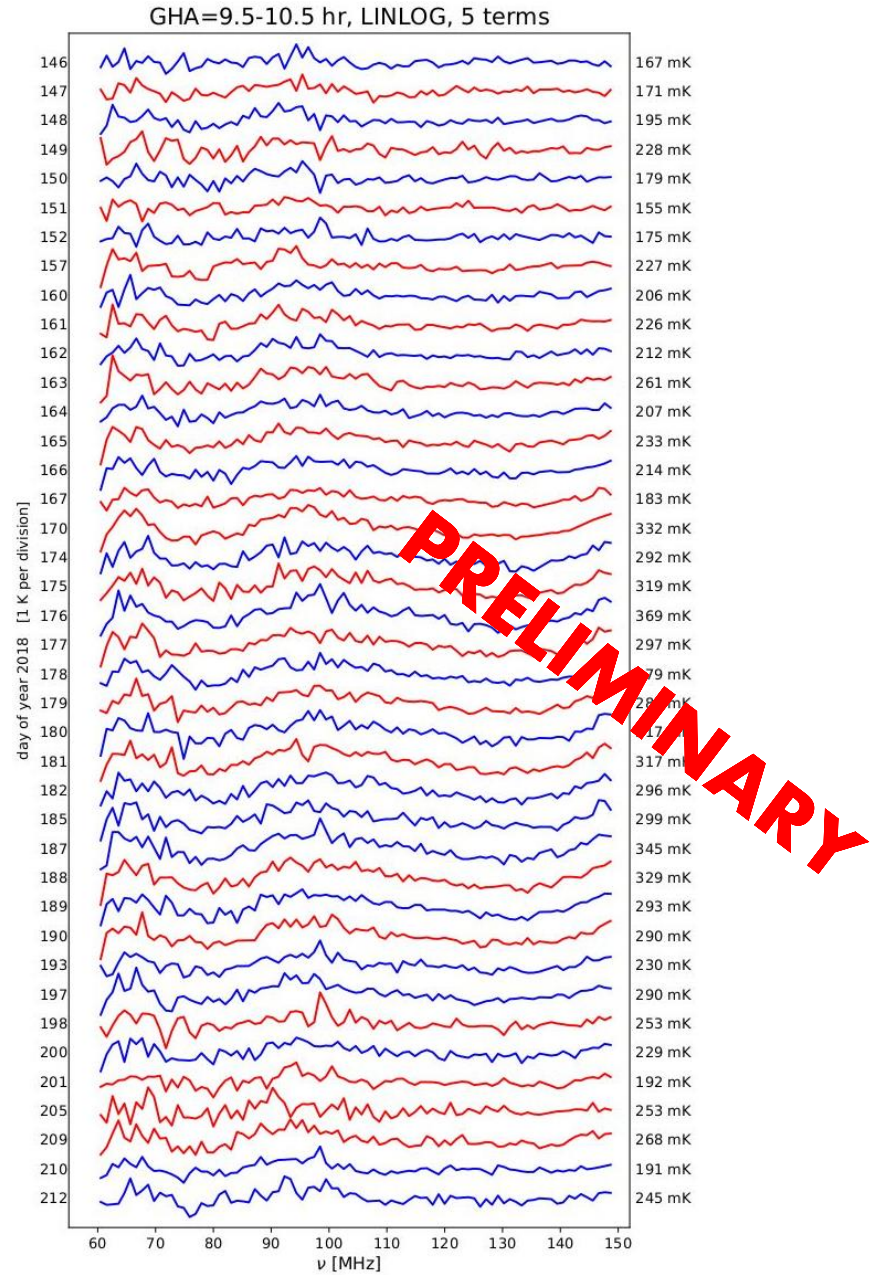
Infinite metal ground plane	Haslam 408 MHz map flat spectral index	LW 150 MHz map (Landecker & Wielebinski 1970)	Guzman 45 MHz map (Guzman et al 2011)



Monsalve et al (2019, in preparation)

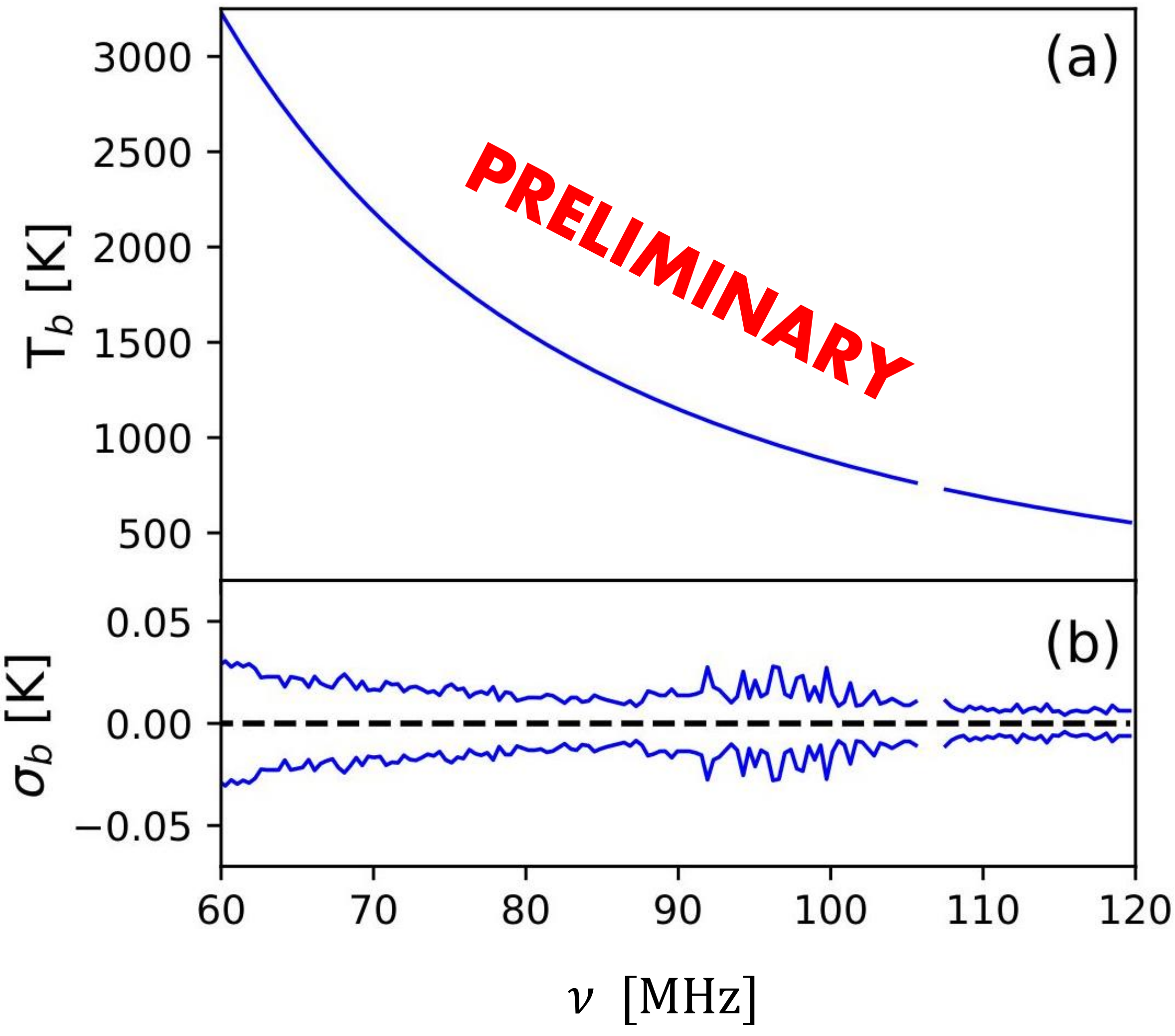
Sample of Daily **Mid-Band** Residuals for 1hr Integrations

May-August 2018



Monsalve et al (2019, in preparation)

Integrated **Mid-Band** Spectrum



GHA 6-18 hr

Monsalve et al (2019, in preparation)

Model of the Spectrum

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

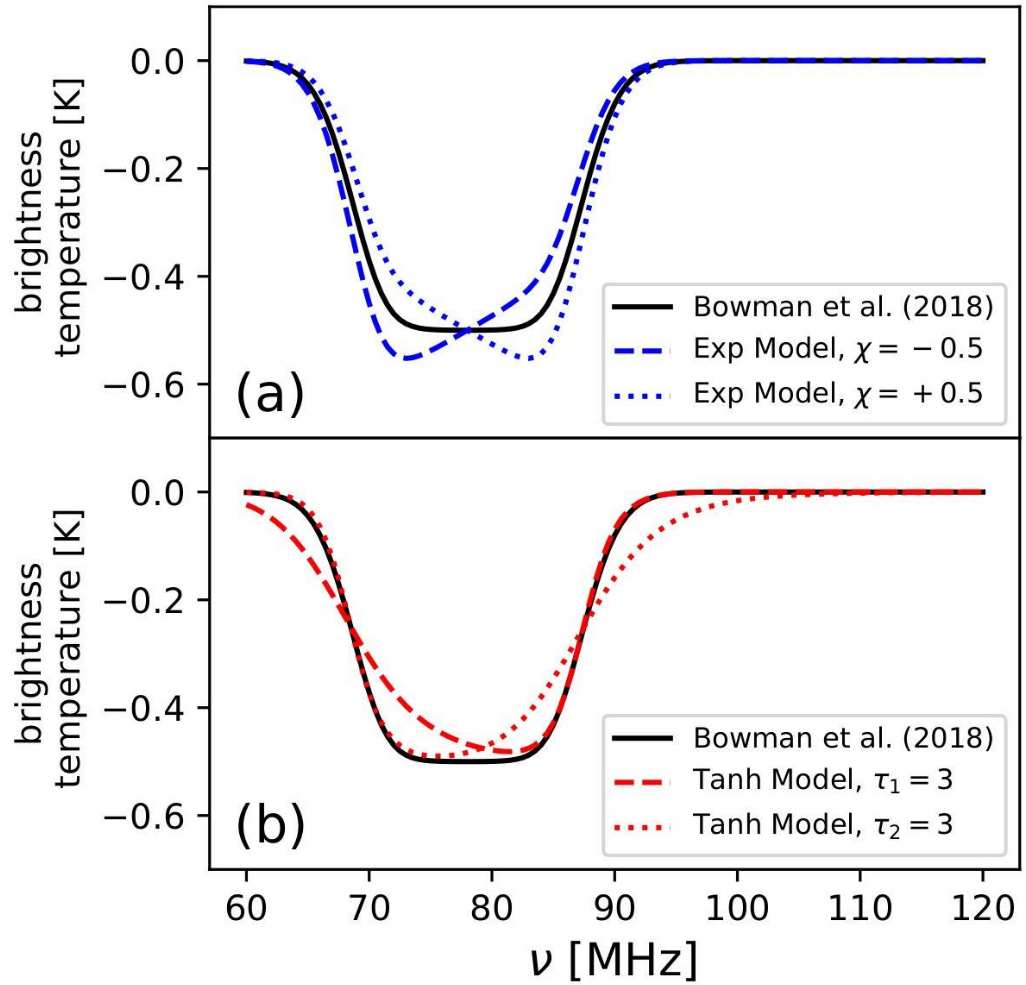
Absorption Model: “Flattened Gaussian”

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

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

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

Extended "Flattened Gaussian"



Monsalve et al (2019, in preparation)

Foreground Models

PowerLog:

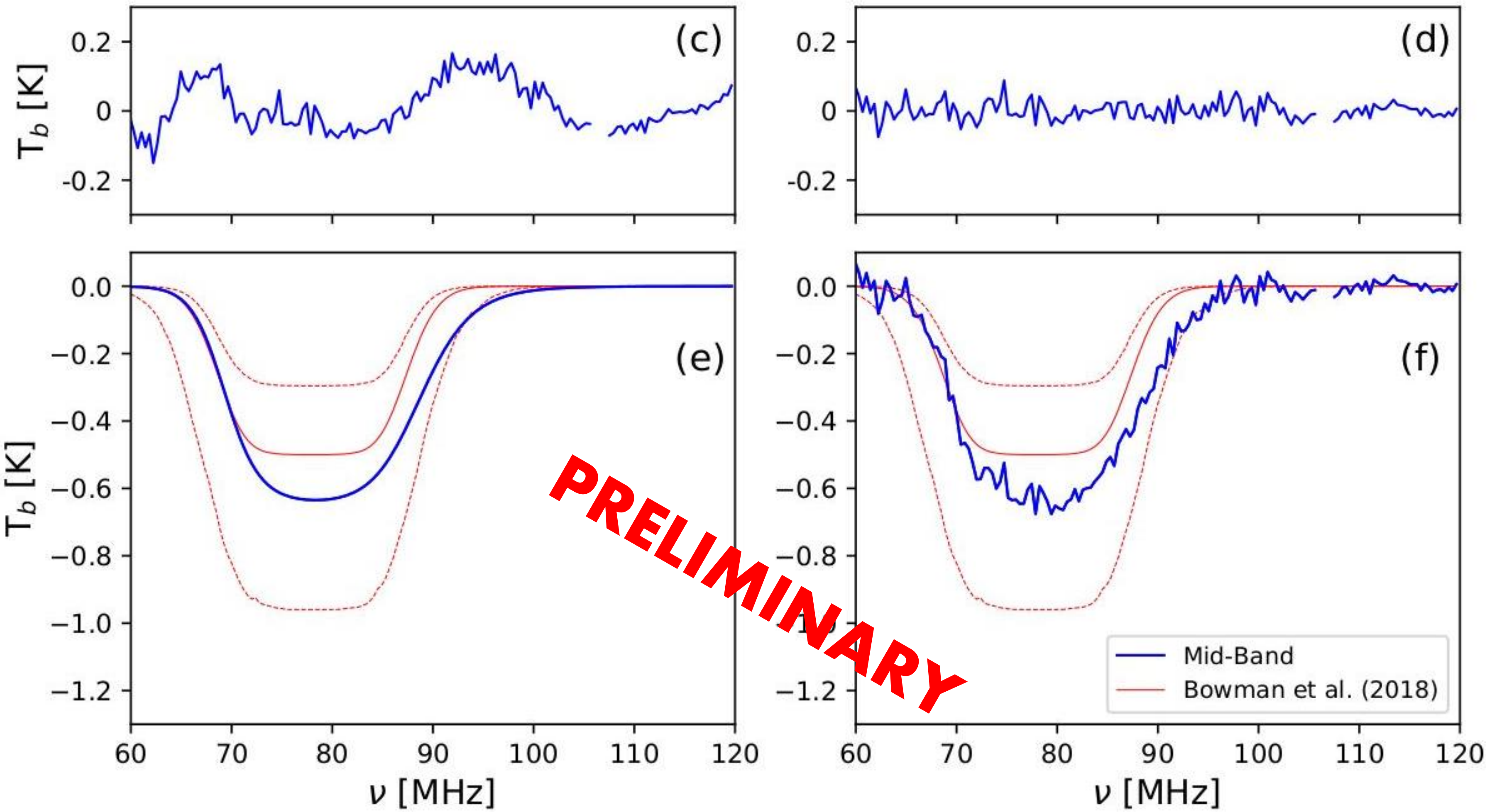
$$m_{\mathrm{fg}}(\nu) = \boldsymbol{a_0} \left(\frac{\nu}{\nu_0}\right)^{\sum_{i=1}^{N_{\mathrm{fg}}-1} \boldsymbol{a_i} \left[log\left(\frac{\nu}{\nu_0}\right)\right]^{i-1}}$$

LinLog Model:

$$m_{\mathrm{fg}}(\nu) = \left(\frac{\nu}{\nu_0}\right)^{-2.5} \sum_{i=0}^{N_{\mathrm{fg}}-1} \boldsymbol{a_i} \left[log\left(\frac{\nu}{\nu_0}\right)\right]^{i}$$

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

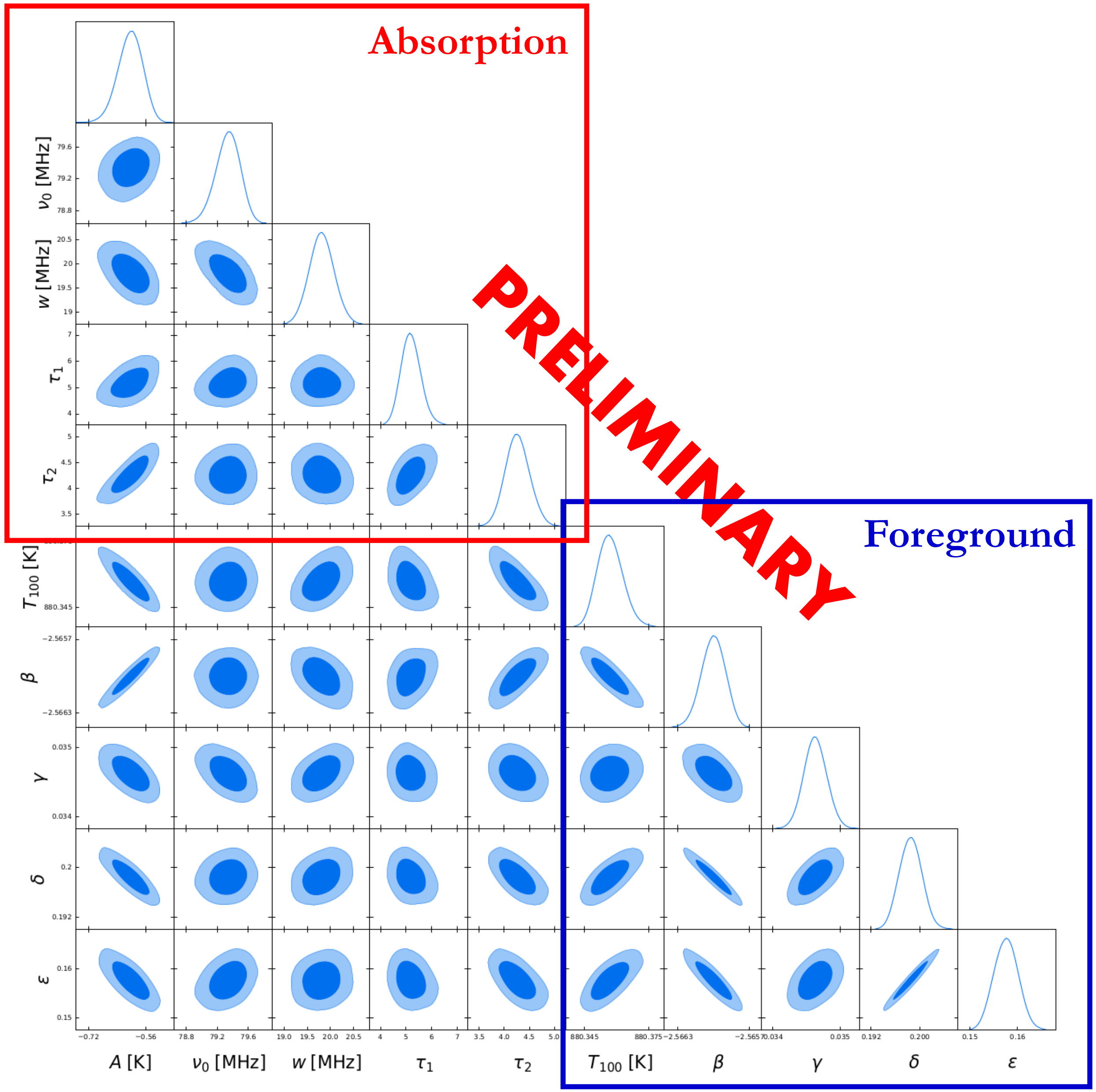
Preliminary **Mid-Band** Results



Monsalve et al (2019, in preparation)

- Not identical but consistent with Bowman et al (2018).
- Rising slope less steep than Bowman et al (2018).

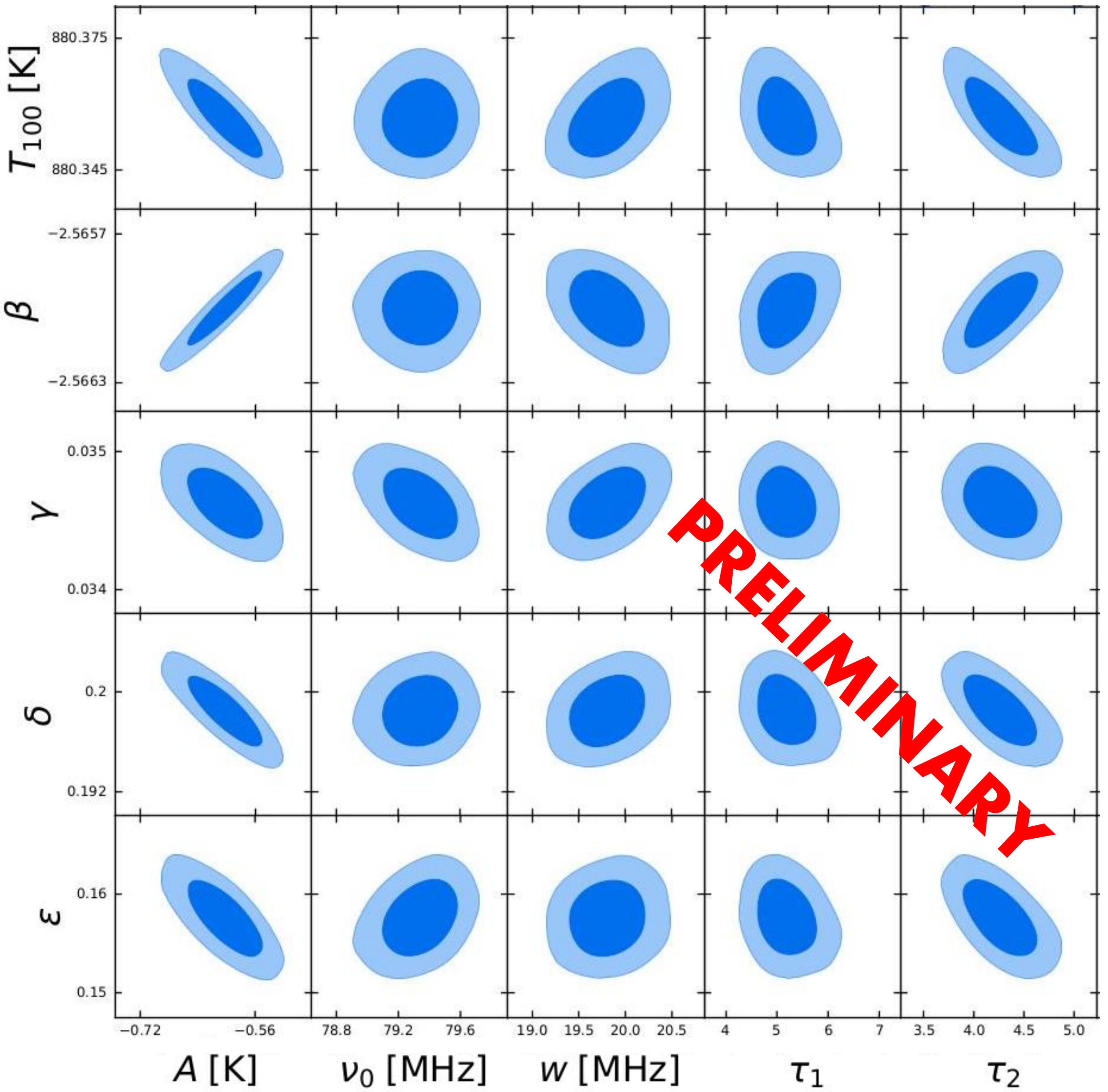
Preliminary **Mid-Band** Results



- Using Polychord Nested Sampling algorithm
- PowerLog foreground model
- Extended flattened Gaussian

Monsalve et al (2019, in preparation)

Preliminary **Mid-Band** Results



Monsalve et al (2019, in preparation)

Current **Mid-Band** Efforts

1) **Data selection**:

- Relatively **small dataset**, with **low-foreground region available during daytime**. Ionosphere and ambient temperature **less stable than at night**. Data selection is important.
- Working on **developing robust filters** that select for analyses the most representative observations.

2) **New lab receiver calibration**:

- Evaluating the **sensitivity** of the integrated spectrum to the **receiver calibration** solution.
- In **2018** we carried out the nominal receiver calibration, **before observations**.
- In **2019** we carried out a receiver calibration **after observations**.
- **Currently** carrying out a **second receiver calibration after observations**.

3) **Beam models**:

- To determine correctly the antenna beam chromaticity, the **antenna gain** has to be computed **over the full sphere**, and not only above the horizon.
- The **gain below the horizon is very hard to compute** reliably **when including a realistic model of the soil** below the ground plane.
- Currently computing antenna gain using **different software packages** for comparison.

Next Generation: EDGES-3

- **Funded** by NSF ATI (2019-2022).
- **Address** two largest sources of uncertainty based on error modeling.
- Minimize antenna delay by **removing balun**.
- Reduce beam chromaticity by **using larger or no ground plane**.
- **Automated in-situ** absolute calibration.
- Challenge: **self interference**.
- Possibly **observe from Oregon and MRO**.

Summary

- **Nominal analysis** of **Mid-Band** observations yield an **absorption feature consistent with Bowman et al (2018)**.

- Currently we are:

1) refining the **data selection**,

2) evaluating the **receiver calibration stability**, and the **sensitivity** of the spectrum to small variations, and

3) verifying our **antenna beam model** over the full sphere using **several** software packages.

- Starting EDGES-3

Extra Slides

Bayesian Approach

Posterior **Likelihood** **Prior**

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

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

EDGES **Planck** **Quasars and Galaxies**

Canadian Arctic: ~80 deg Latitude

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