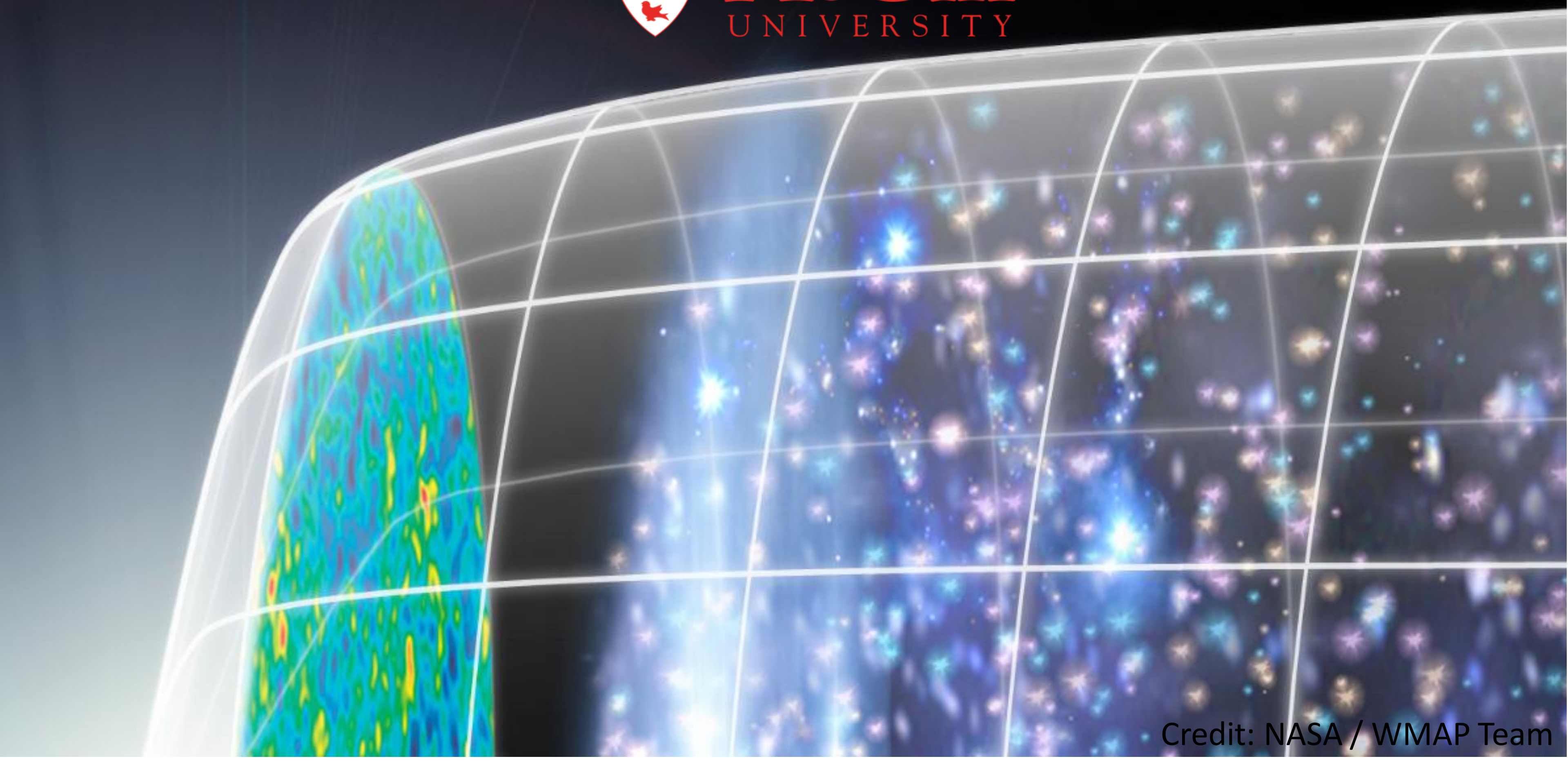
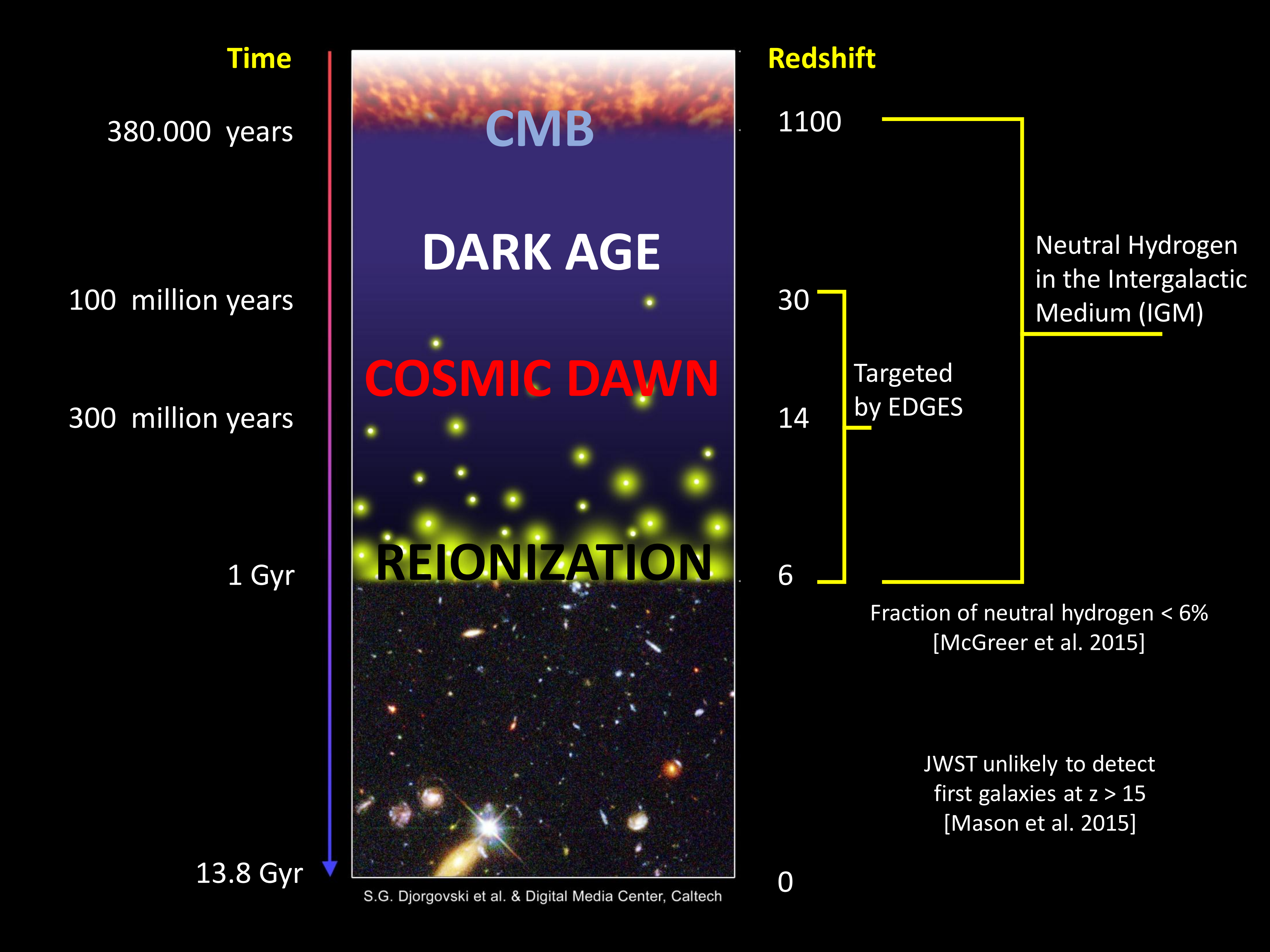
An Absorption Feature in the Sky-Averaged Radio Spectrum

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]
JWST unlikely to detect first galaxies at z > 15
[Mason et al. 2015]

Global 21-cm Brightness Temperature

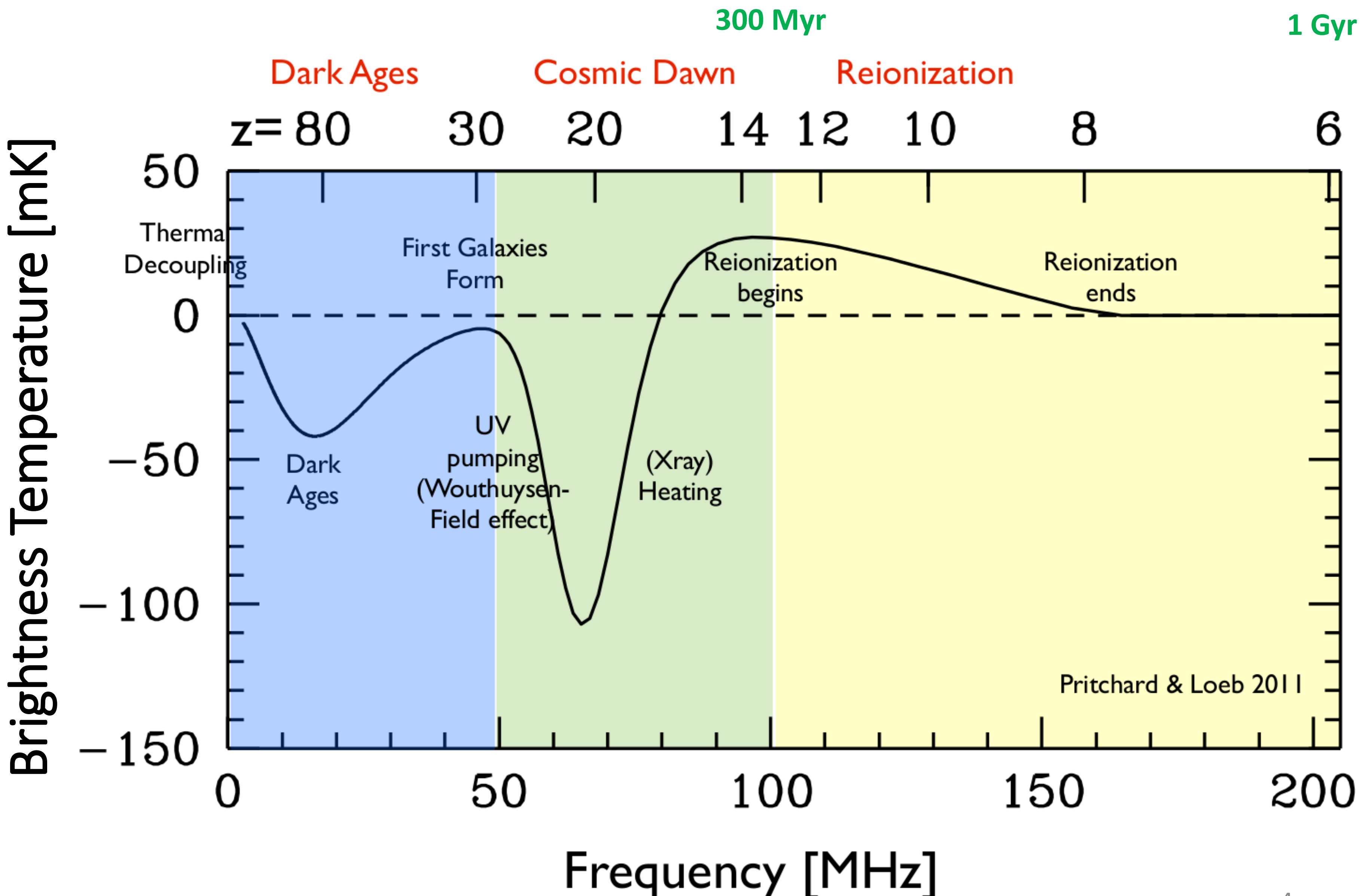
radiation temperature

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

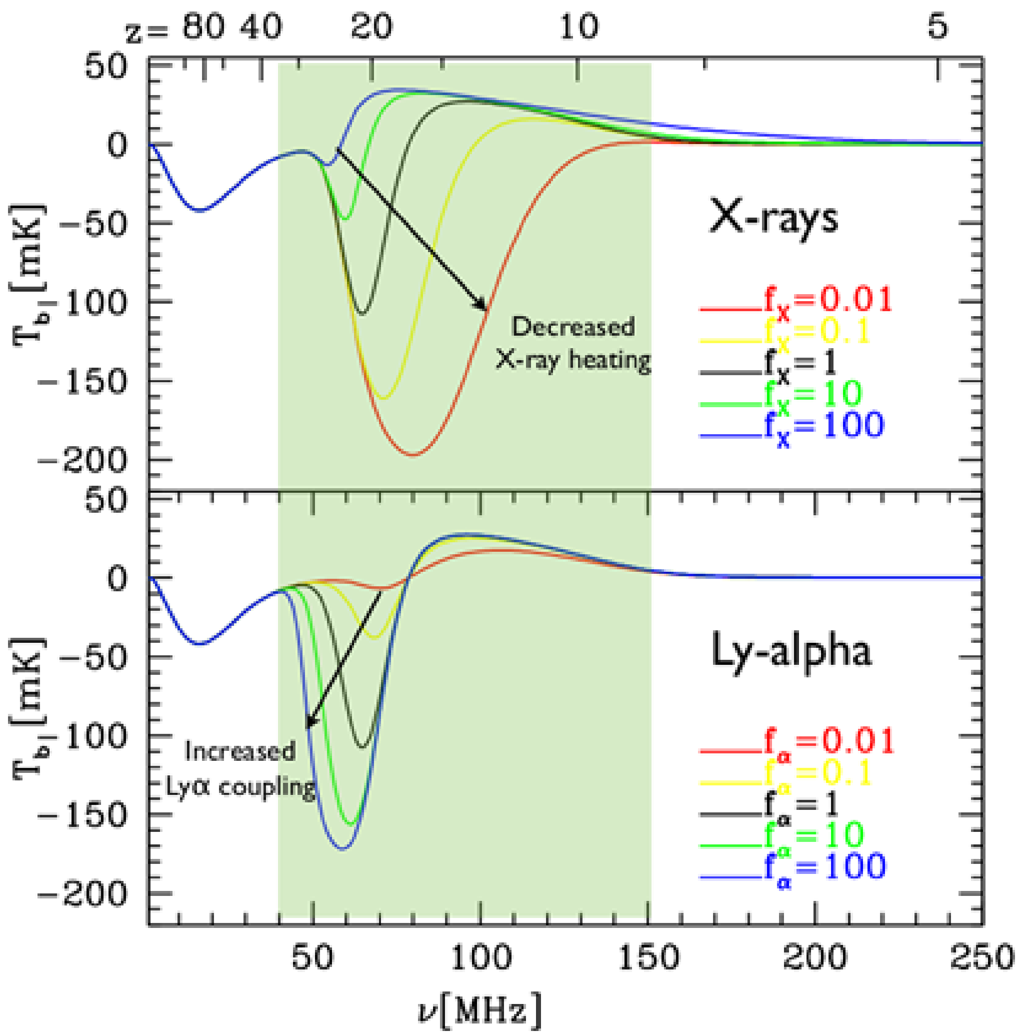
fraction of neutral hydrogen

spin temperature

Standard Prediction

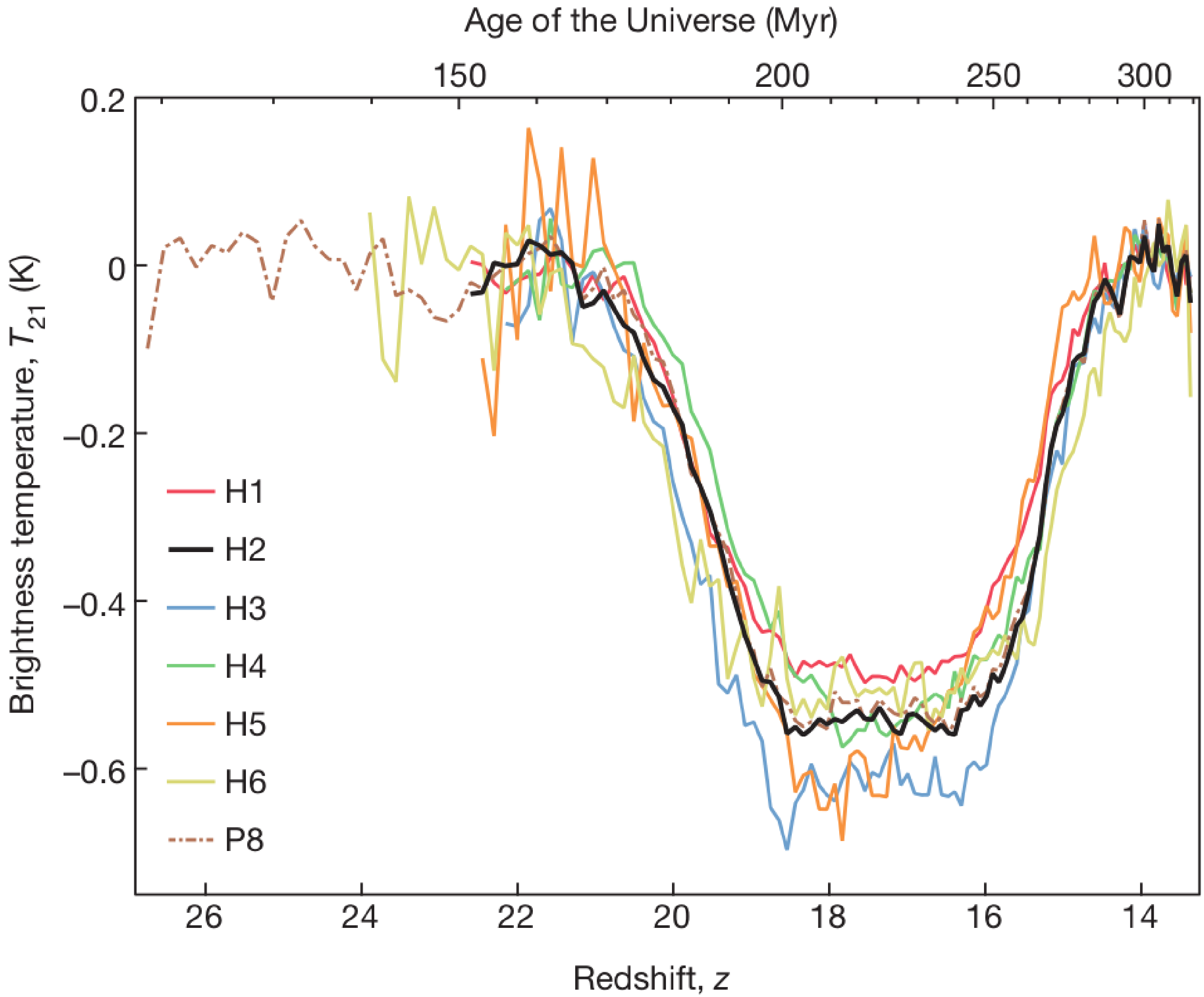


Nature and Timing of First Sources



Pritchard & Loeb (2011)

EDGES Measurement



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

EDGES

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

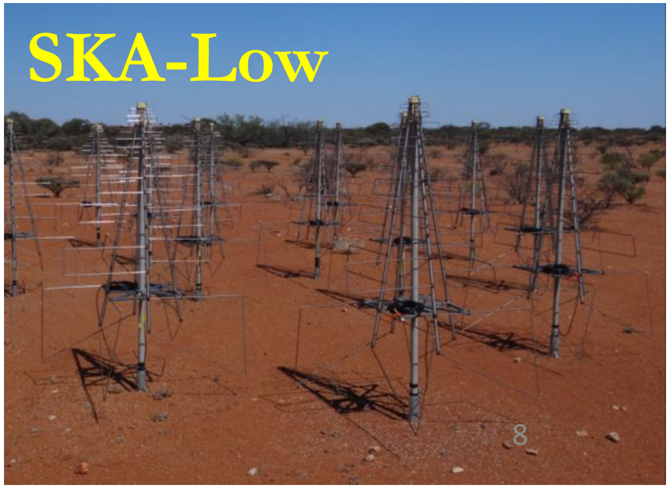
Prof. Judd Bowman (PI)
Dr. Alan Rogers
Dr. Raul Monsalve
Dr. Thomas Mozdzen
Ms. Nivedita Mahesh

ASU Arizona State University

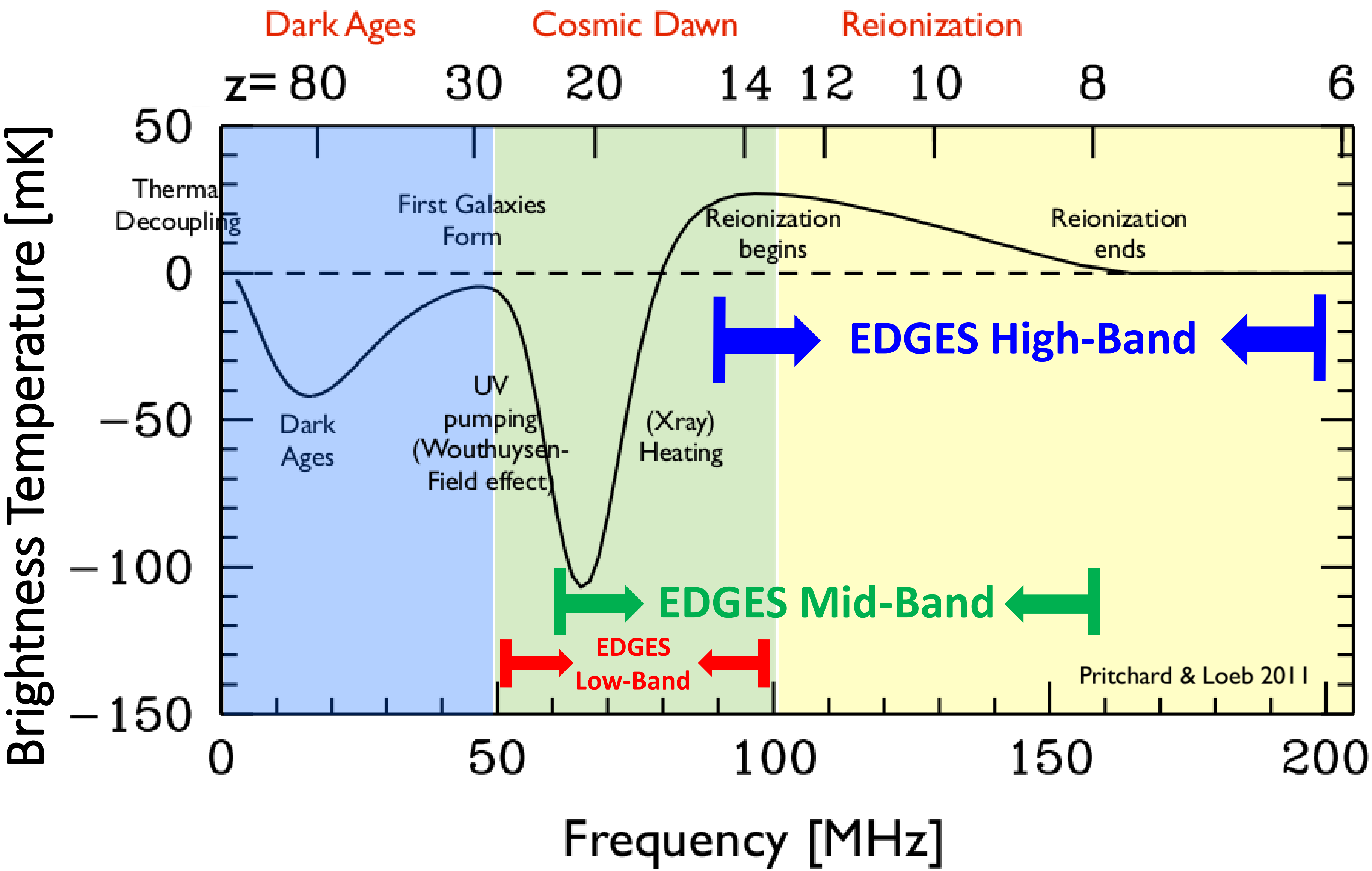
MIT Haystack Observatory

Western Australia

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

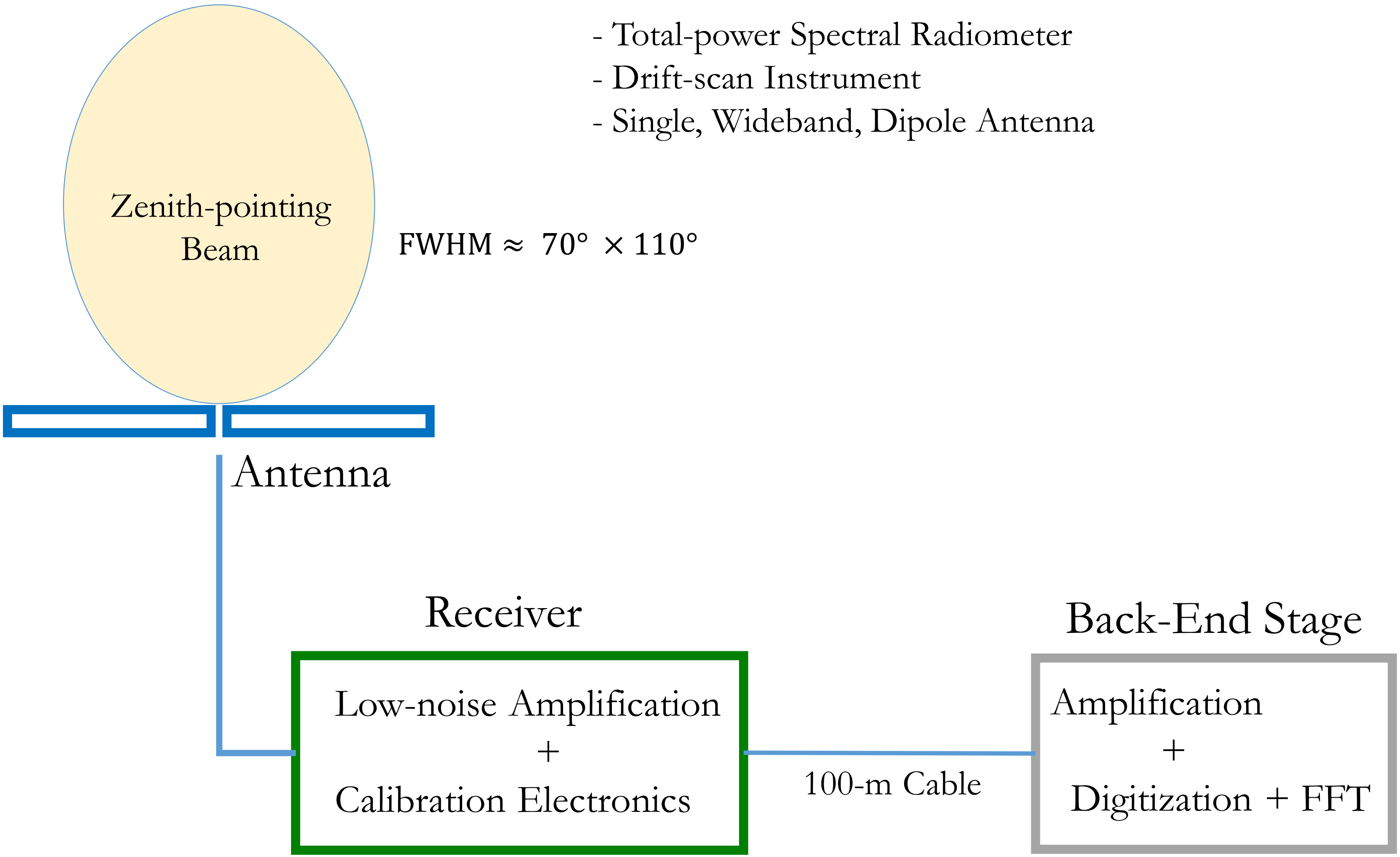


EDGES Instruments

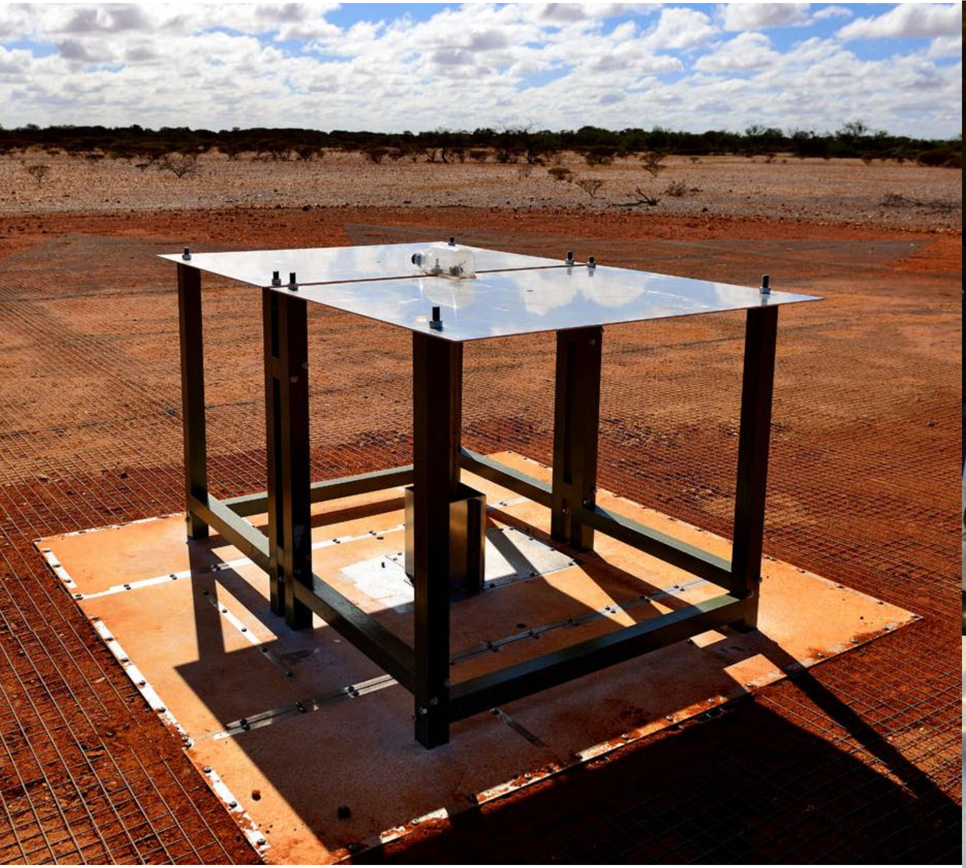


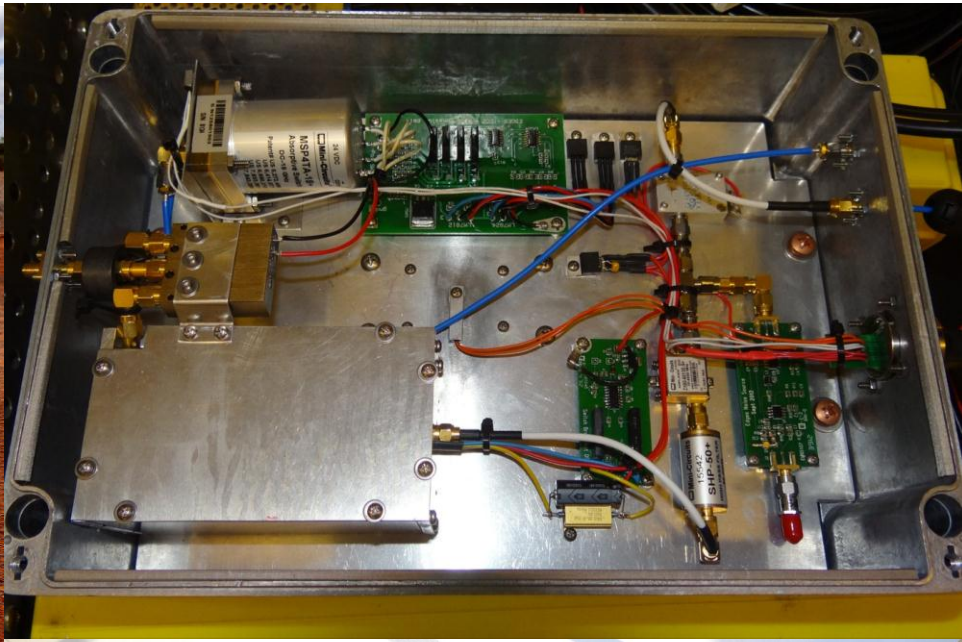
EDGES Instrument Block Diagram

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



EDGES Low-Band



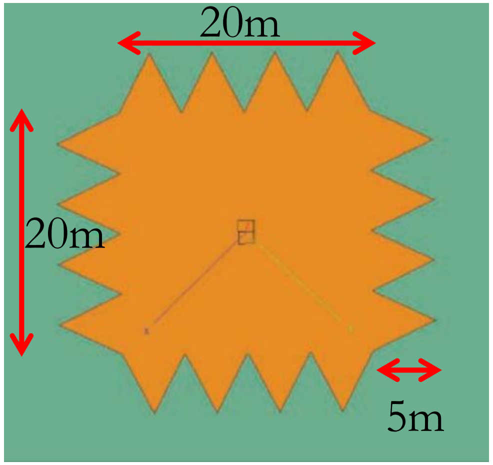


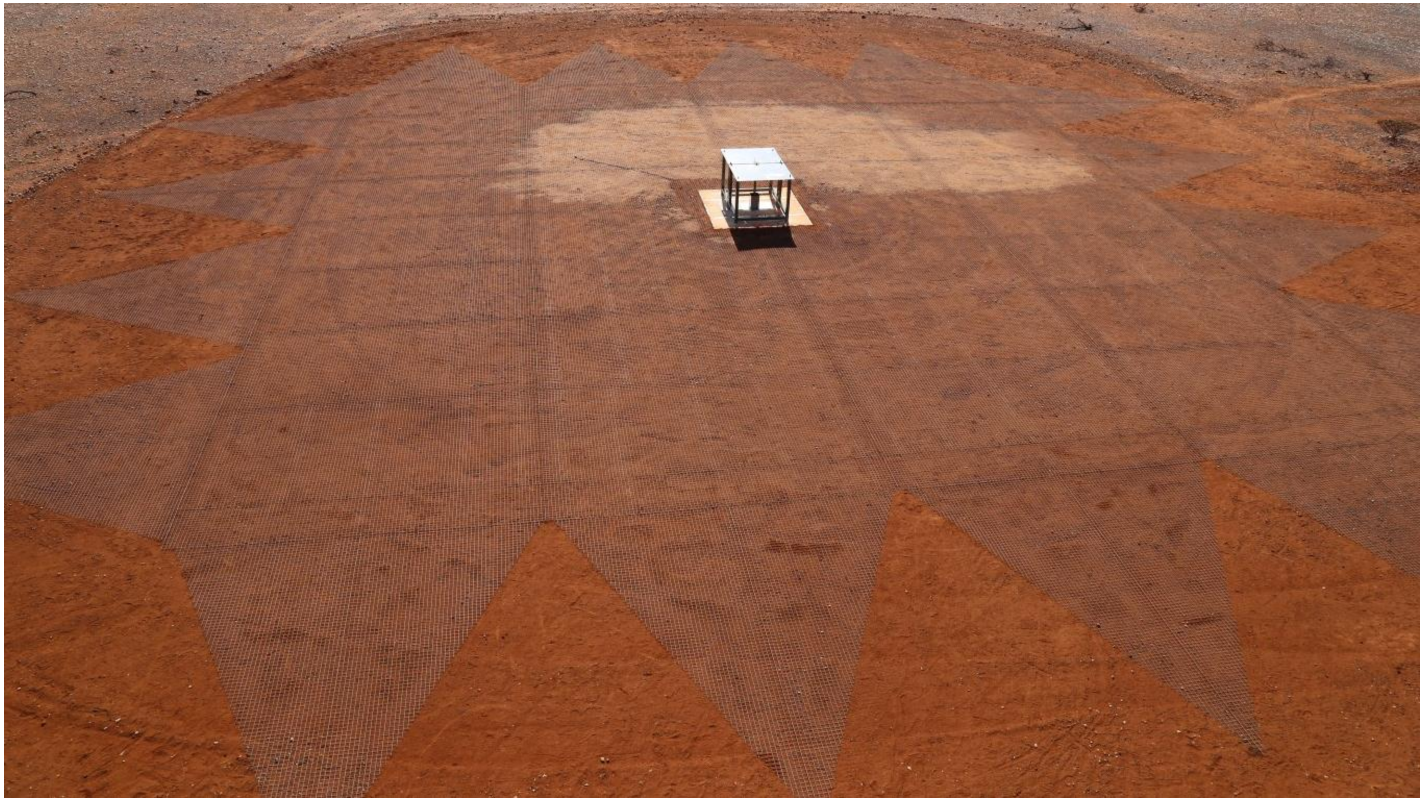
Antenna size:
2m long / 1m high

TWO **Low-Band** Instruments

Low-Band Ground Plane

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





Instrumental Calibration

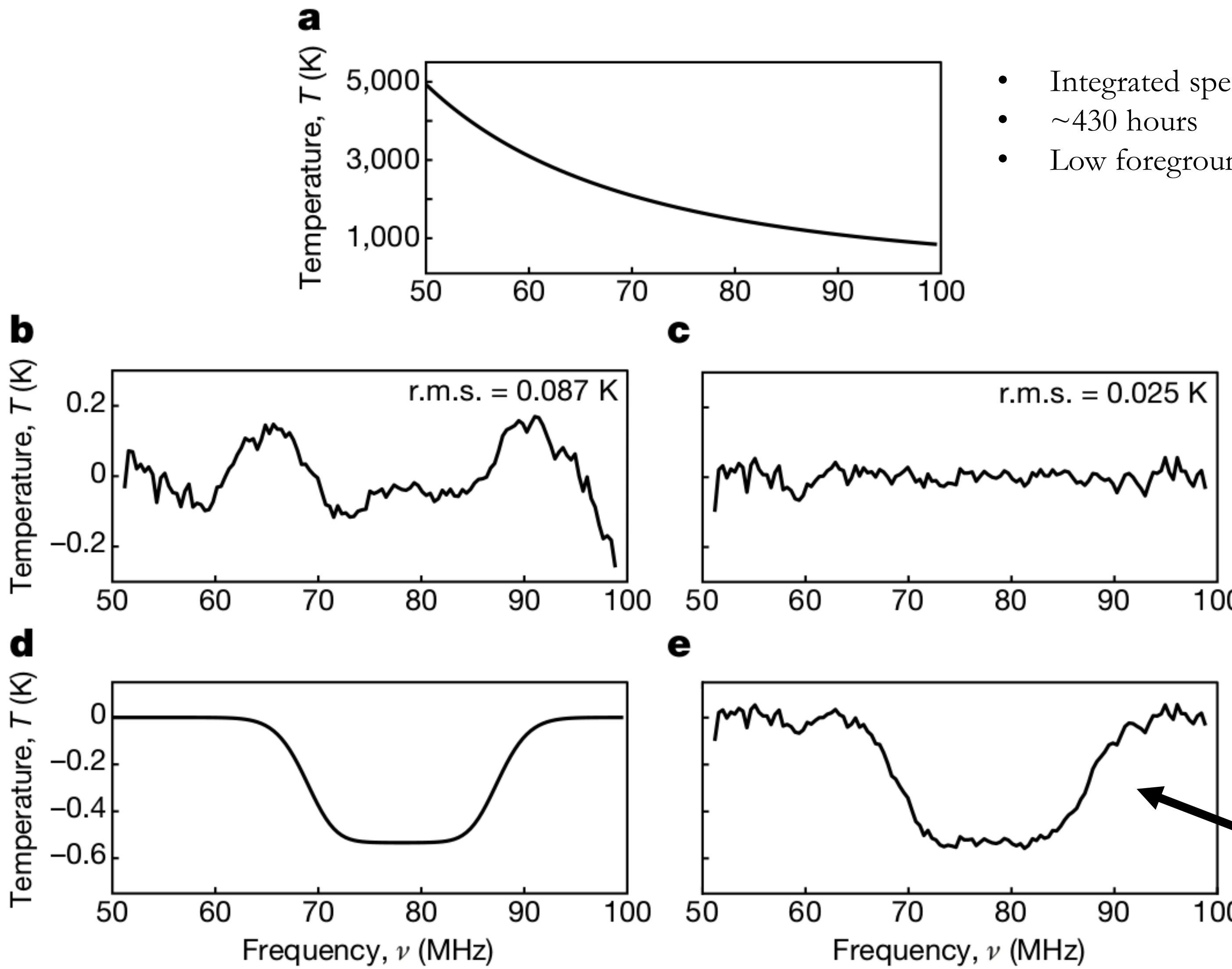
1) **Receiver gain and offset.**

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

3) **Antenna and ground losses.**

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

Summary of the EDGES Detection



- Integrated spectrum
- ~430 hours
- Low foreground regions

Absorption deeper than expected by factor > 2

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

Model of the Spectrum

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

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**.

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

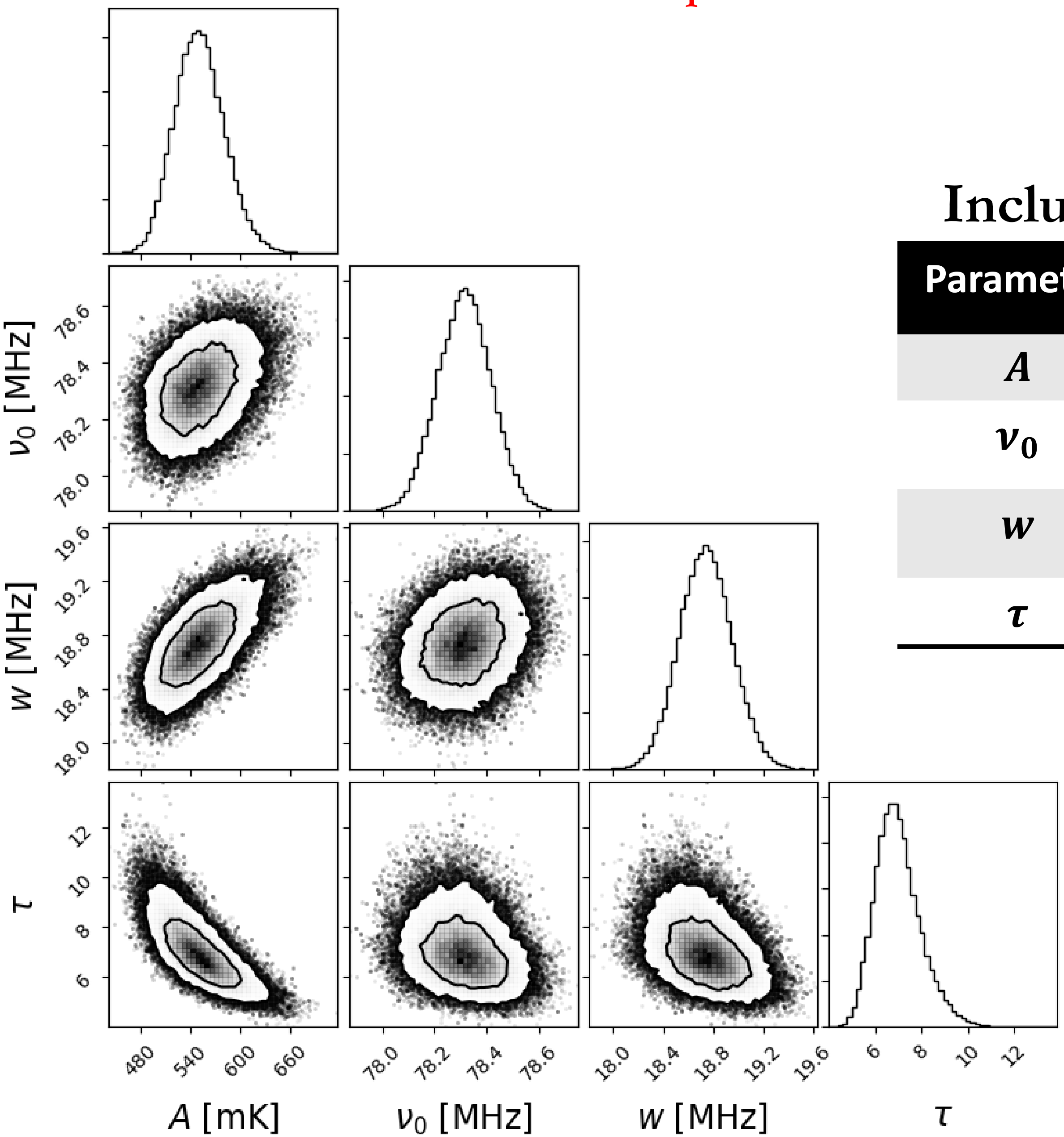
Galactic Hour Angle (GHA)	SNR	Amplitude (K)	Sky Temperature (K)
6-hour bins			
0	8	0.48	3999
6	11	0.57	2035
12	23	0.50	1521
18	15	0.60	2340
4-hour bins			
0	5	0.45	4108
4	9	0.46	2775
8	13	0.44	1480
12	21	0.57	1497
16	11	0.59	1803
20	9	0.66	3052

Total temperature varies by a factor of up to 3.

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

Parameter Estimates

Estimates from Nominal Spectrum



Including All Cases Processed

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

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]

Lower than expected

$\boldsymbol{T}_{\mathbf{IGM}}$ **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

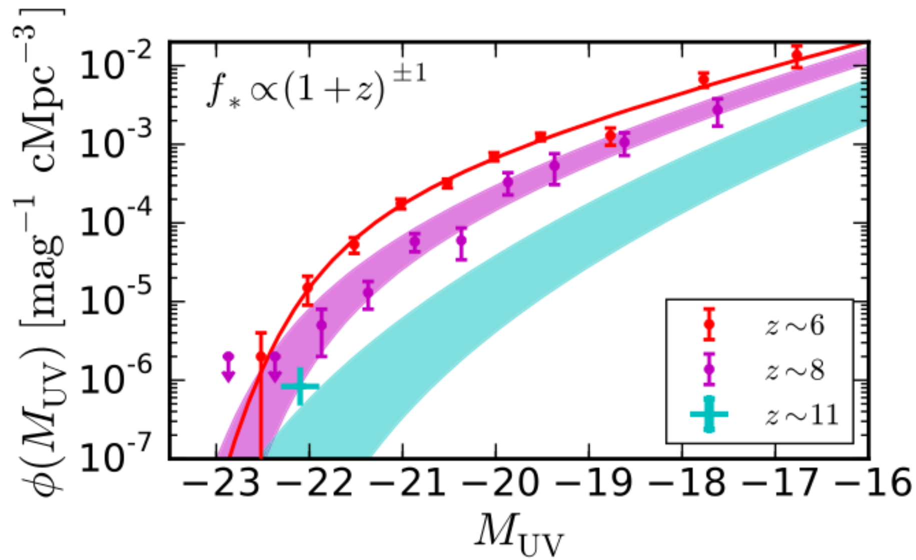
Julian B. Muñoz[1]* & Abraham Loeb[2]

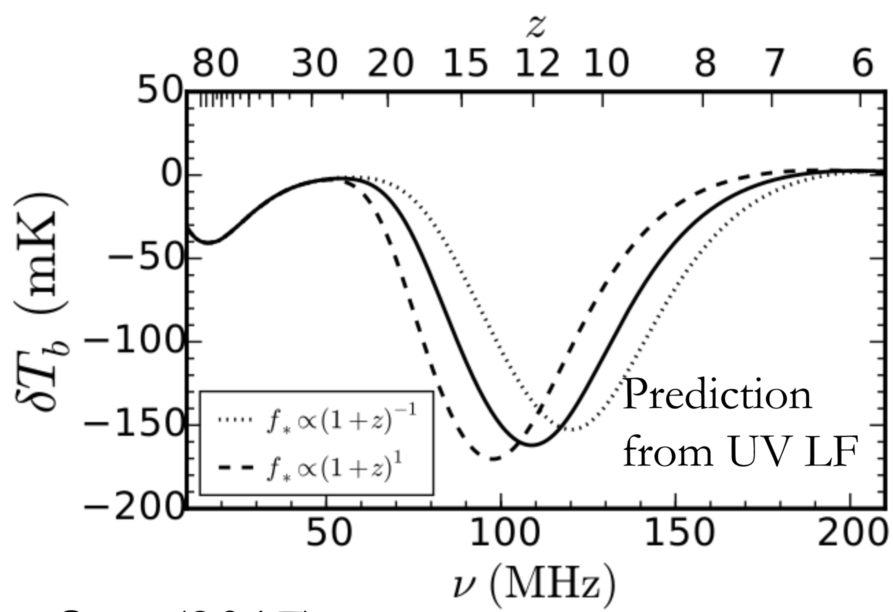
NATURE, 557, 31 MAY 2018

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**.

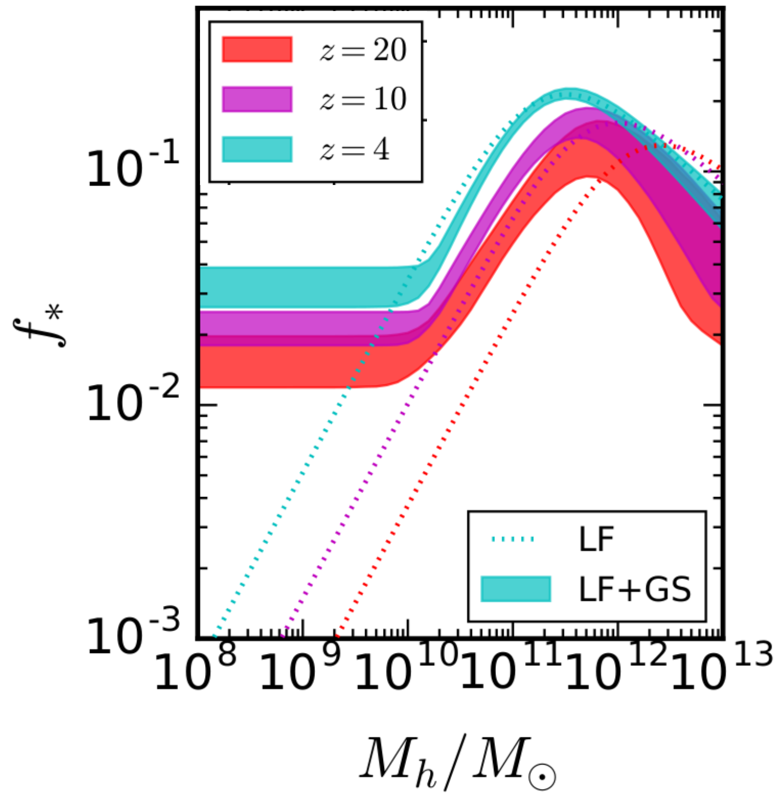
Implications of Absorption Frequency (78 MHz)





Mirocha, Furlanetto, & Sun (2017)

Implications of Absorption Frequency (78 MHz)



Mirocha & Furlanetto (2018)

"A mass of $10^{10} M_\odot$ corresponds roughly to current sensitivity limits, which, coupled with the flat SFE we infer, means the optimal fit to the UVLF and EDGES data is one that maximizes the amount of star formation occurring in small objects beyond current detection limits."

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

Recent Tests in the Field

Null Tests (**feature not found)**

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

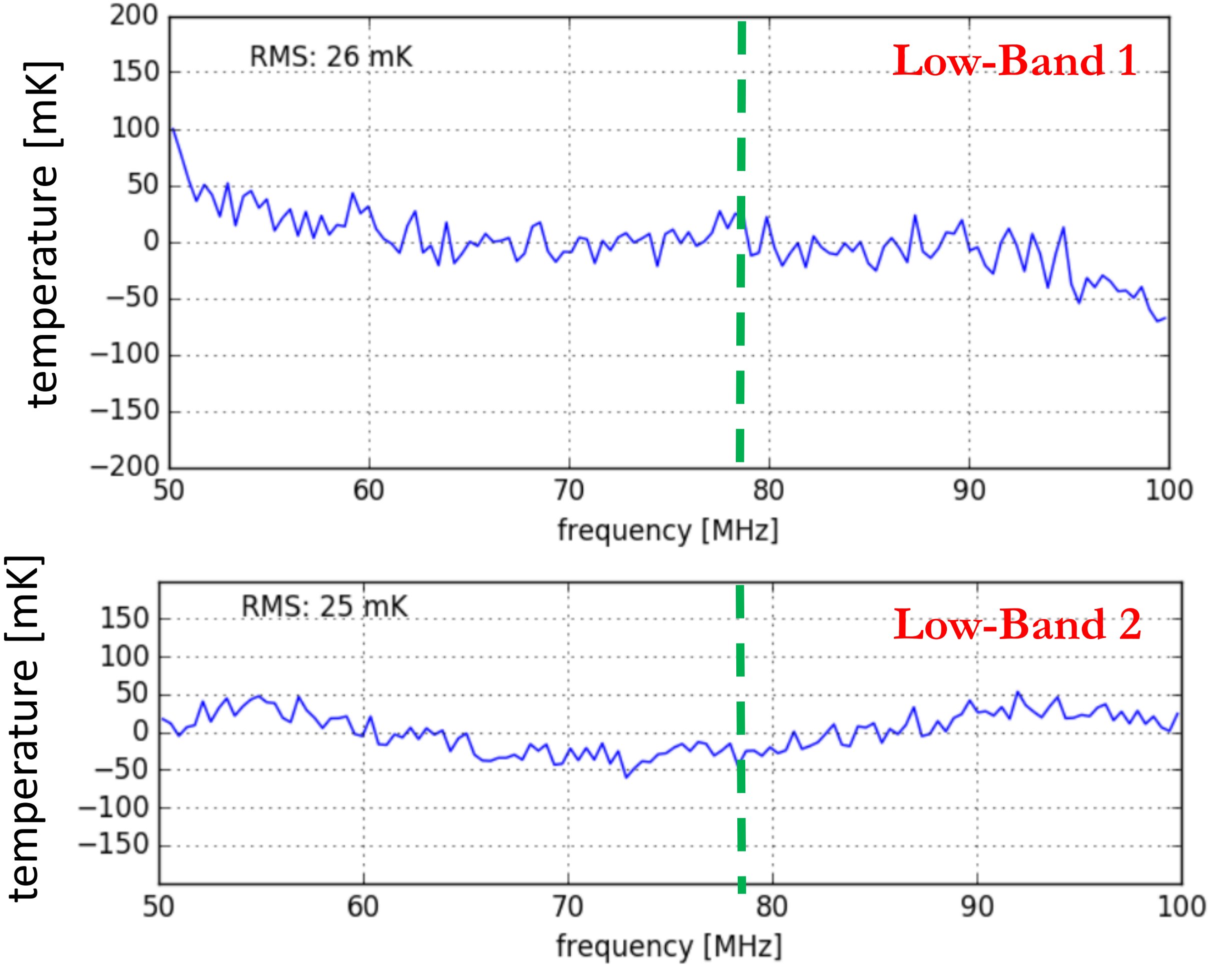
Tests Addressing Antenna Beam Effects (**feature found**)

1) Using **Mid-Band antenna** over 60-160 MHz.
2) Using Low-Band antenna over a **smaller 5m x 5m ground plane**.

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

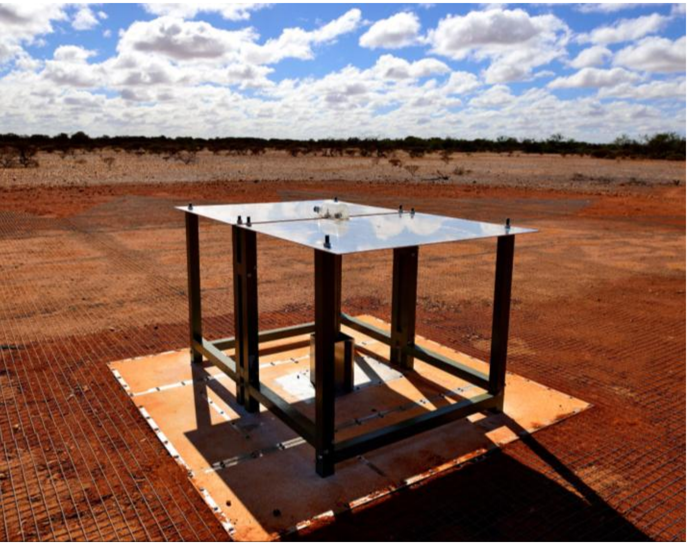
Verification Using ~300K Passive Noise Source

Residuals After Removing a Constant



EDGES **Mid-Band**

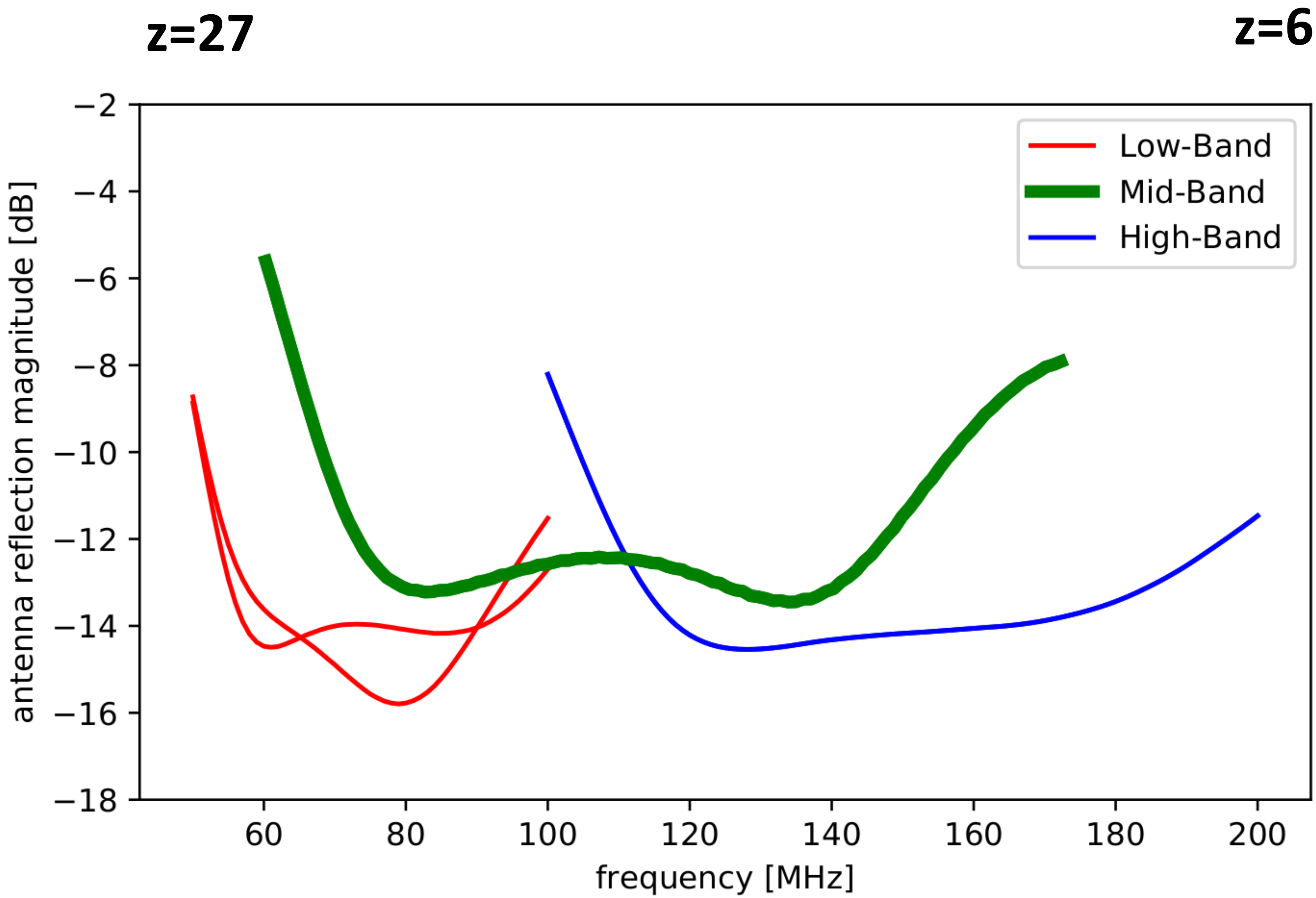
Low-Band



High-Band

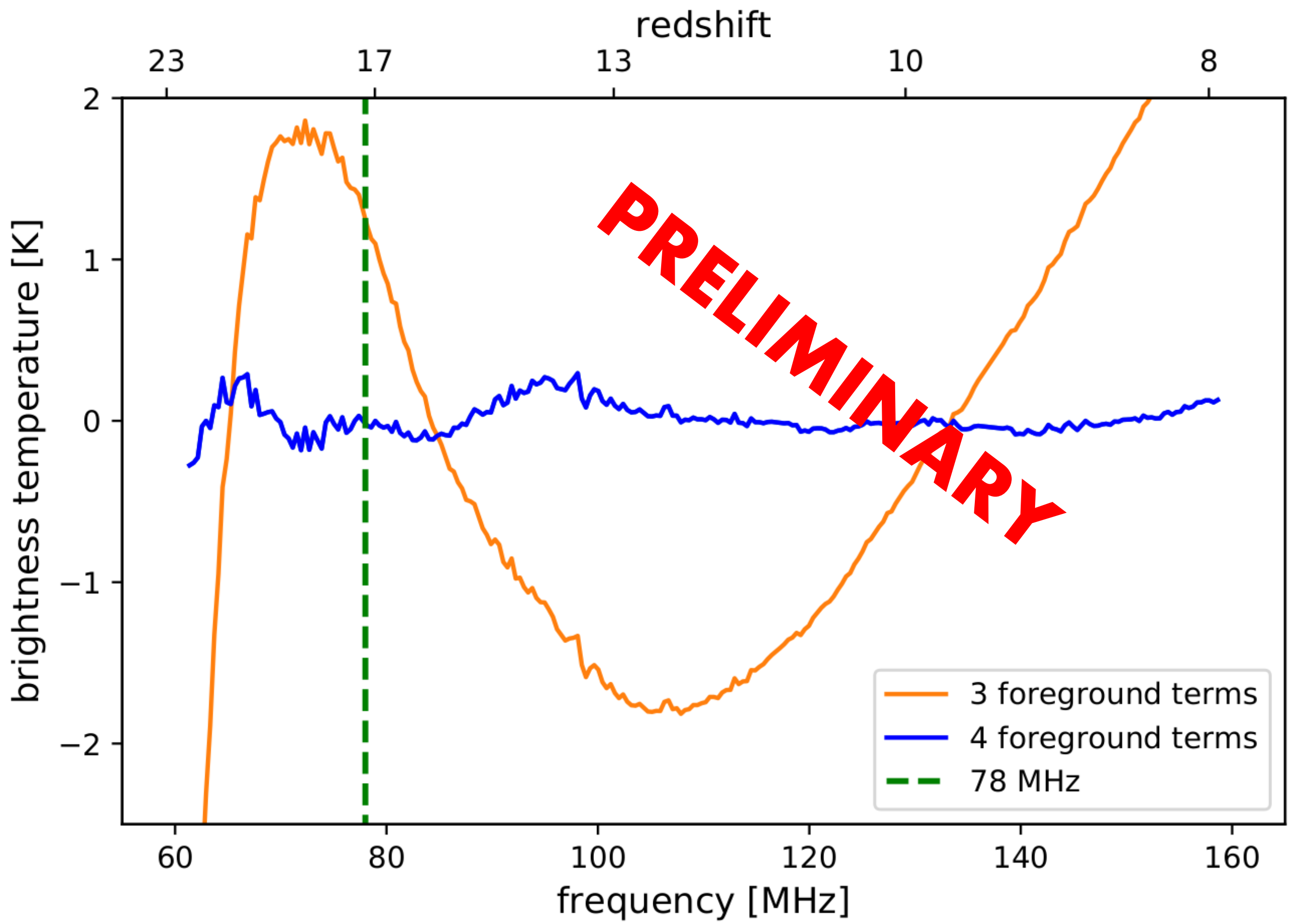
Mid-Band

Antenna Reflection Coefficients



Preliminarily …..

Preliminary Mid-Band Results



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

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

Constraints on
Standard Astrophysical Parameters

Standard Models from Semi-Numerical Simulations

Monsalve, Fialkov, Bowman et al. (2018) (Submitted)

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

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

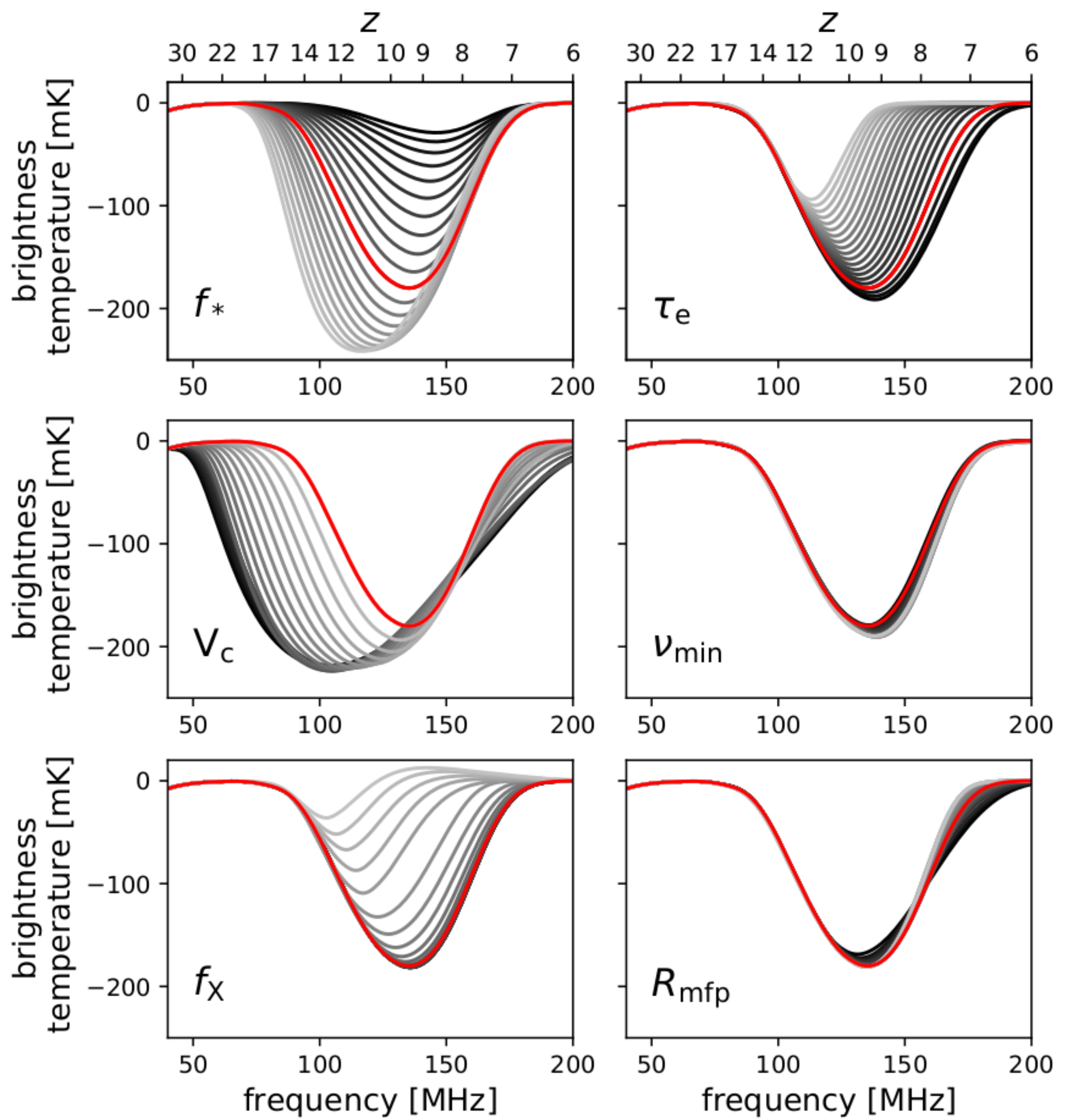
$\boldsymbol{f_X}$: X-ray heating efficiency

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

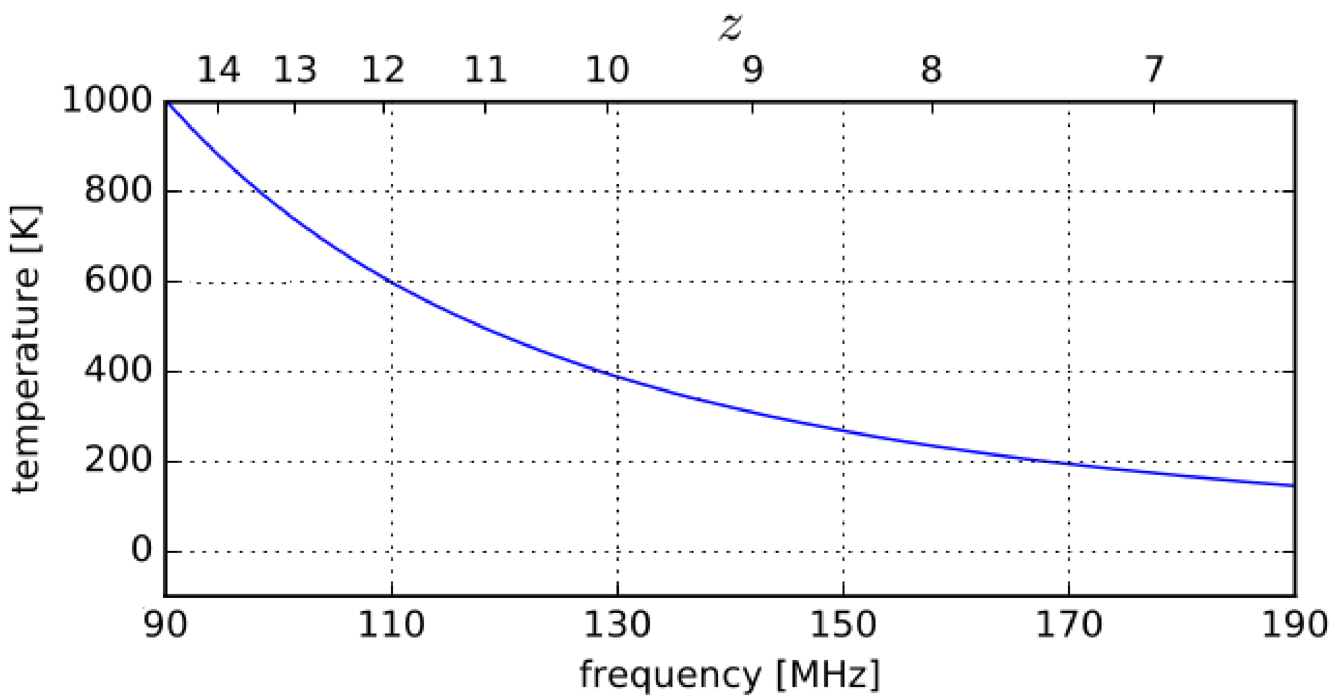
$\boldsymbol{R_{mfp}}$: mean-free path of ionizing photons

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

Foreground parameters also explored



EDGES **High-Band** Spectrum

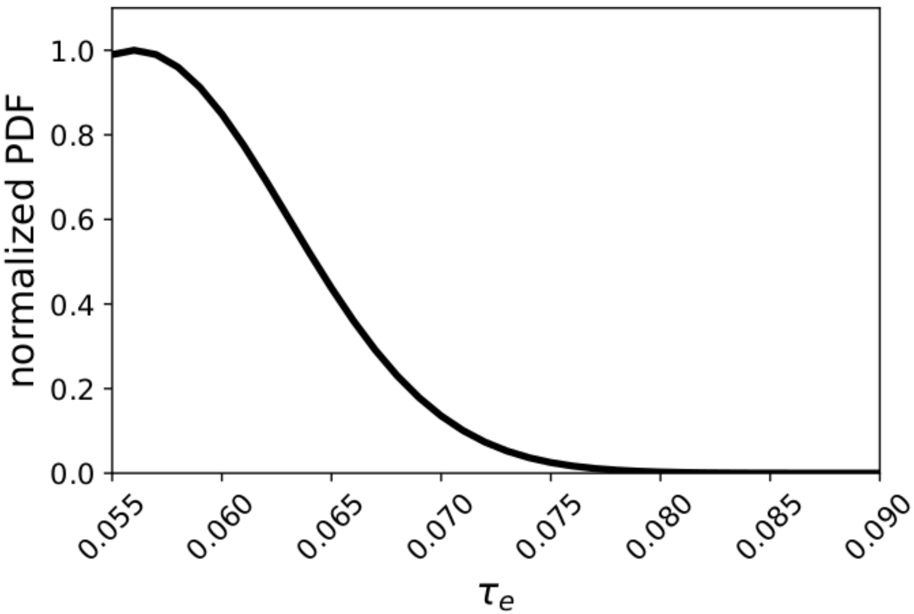


Monsalve, Rogers, Bowman, & Mozdzen (2017b)

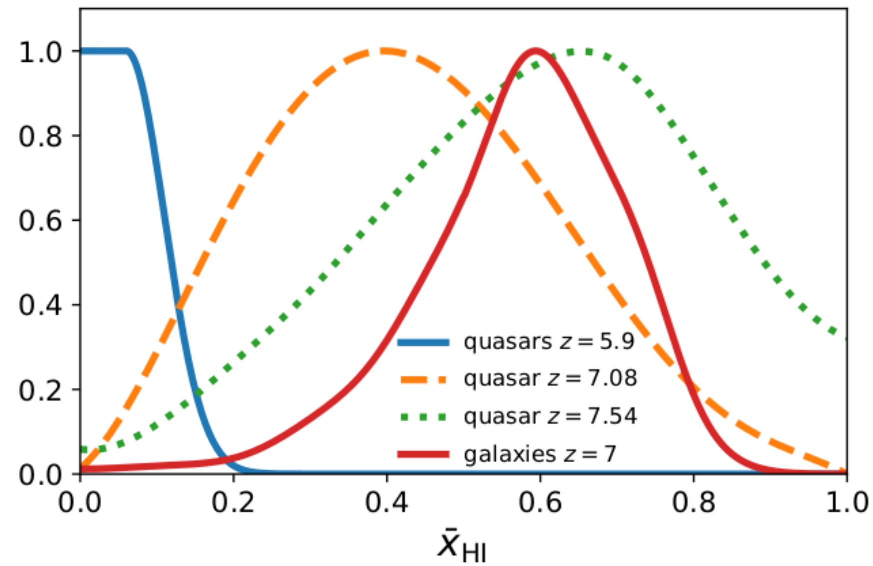
- **Noise of 6 mK** at 140 MHz.
- **No detection reported** in this frequency range.
- Used to **constrain models and parameters**.

External Data

Estimate of $\boldsymbol{\tau_e}$ from Planck

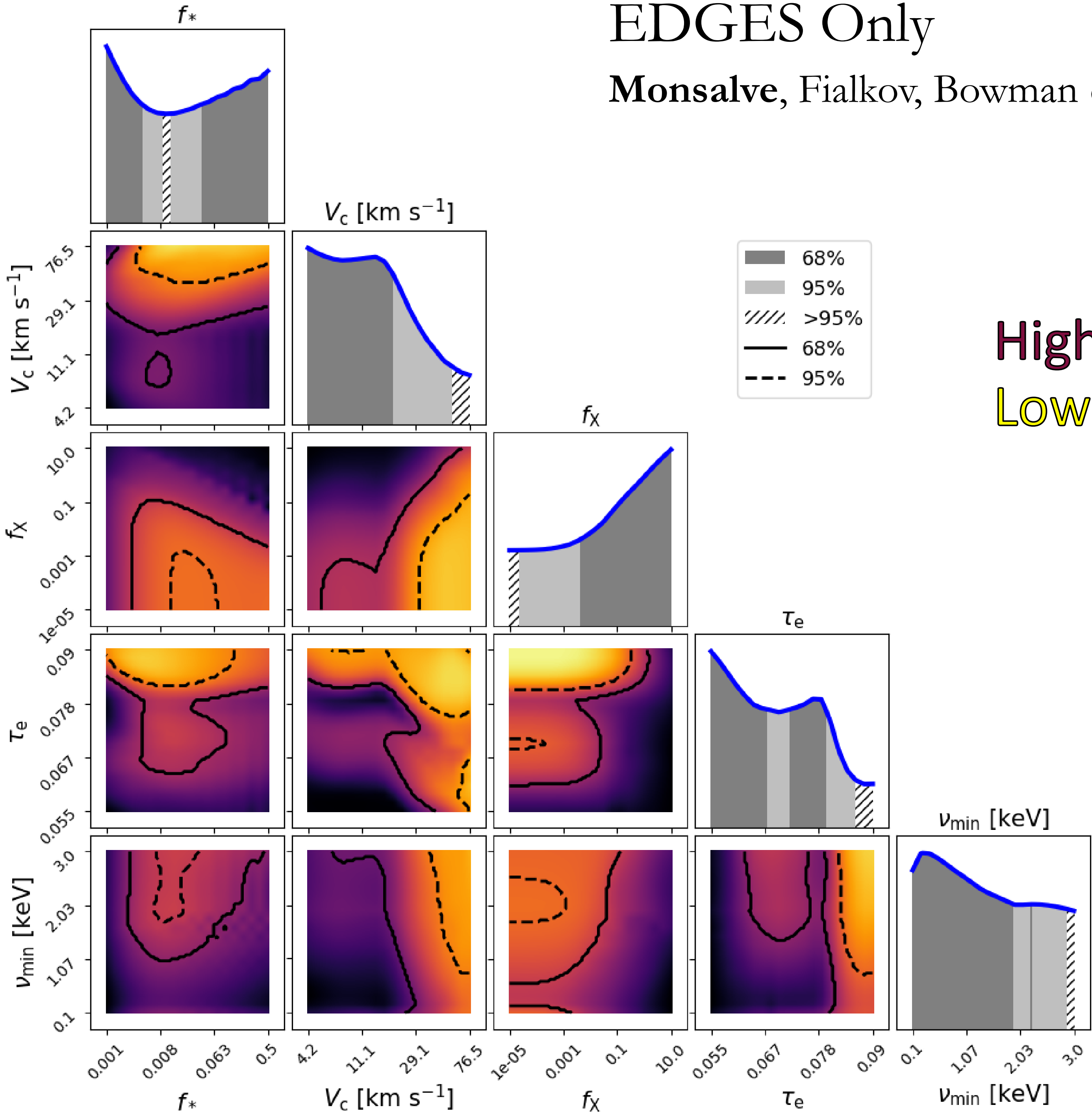


Estimate of $\boldsymbol{\bar{x}_{HI}}$ from
High-z Quasars and Galaxies



EDGES Only

Monsalve, Fialkov, Bowman et al. (2018) (Submitted)

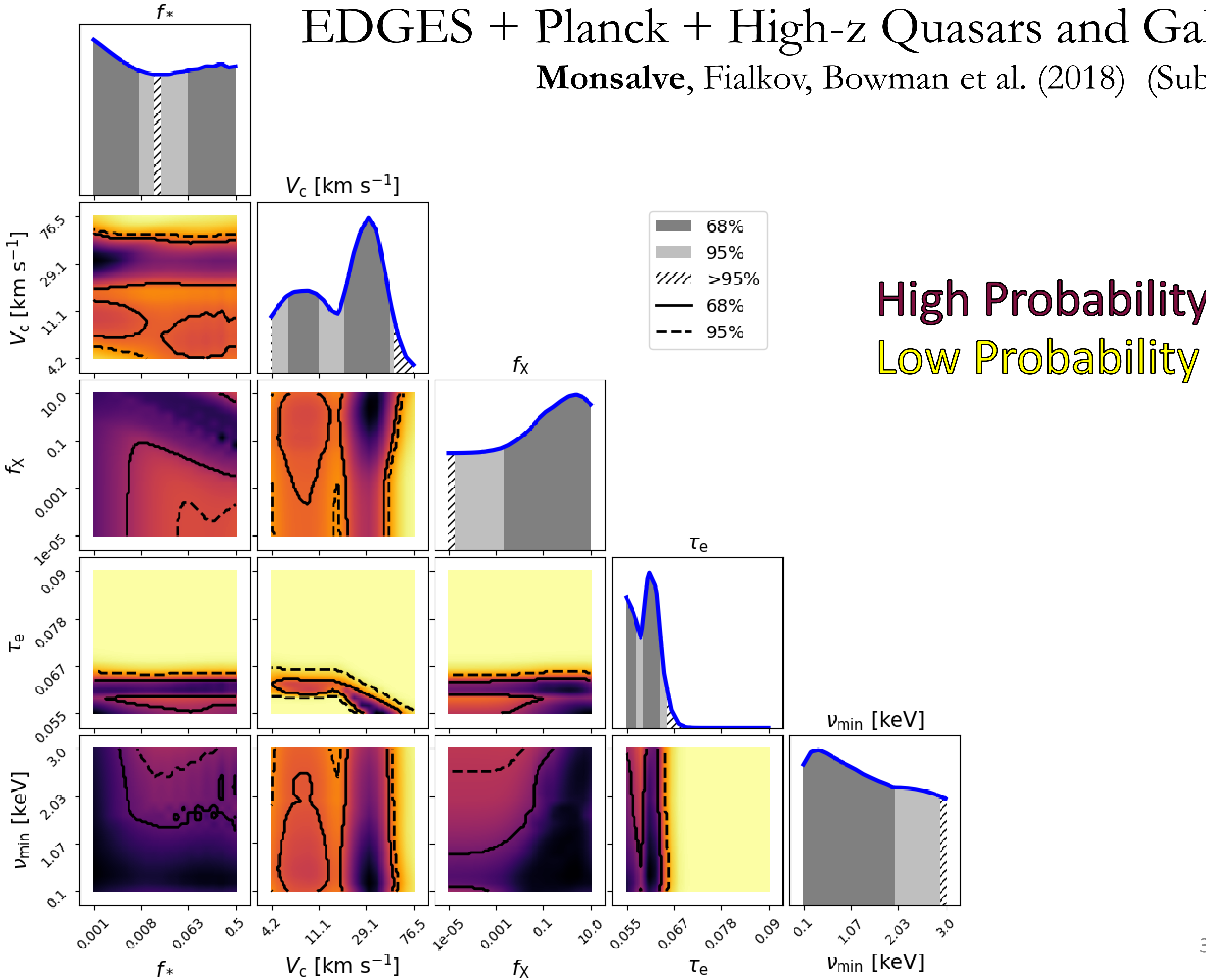


High Probability

Low Probability

EDGES + Planck + High-z Quasars and Galaxies

Monsalve, Fialkov, Bowman et al. (2018) (Submitted)



New Global 21-cm Experiment

MIST: Mapper of the IGM Spin Temperature

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

UCSC

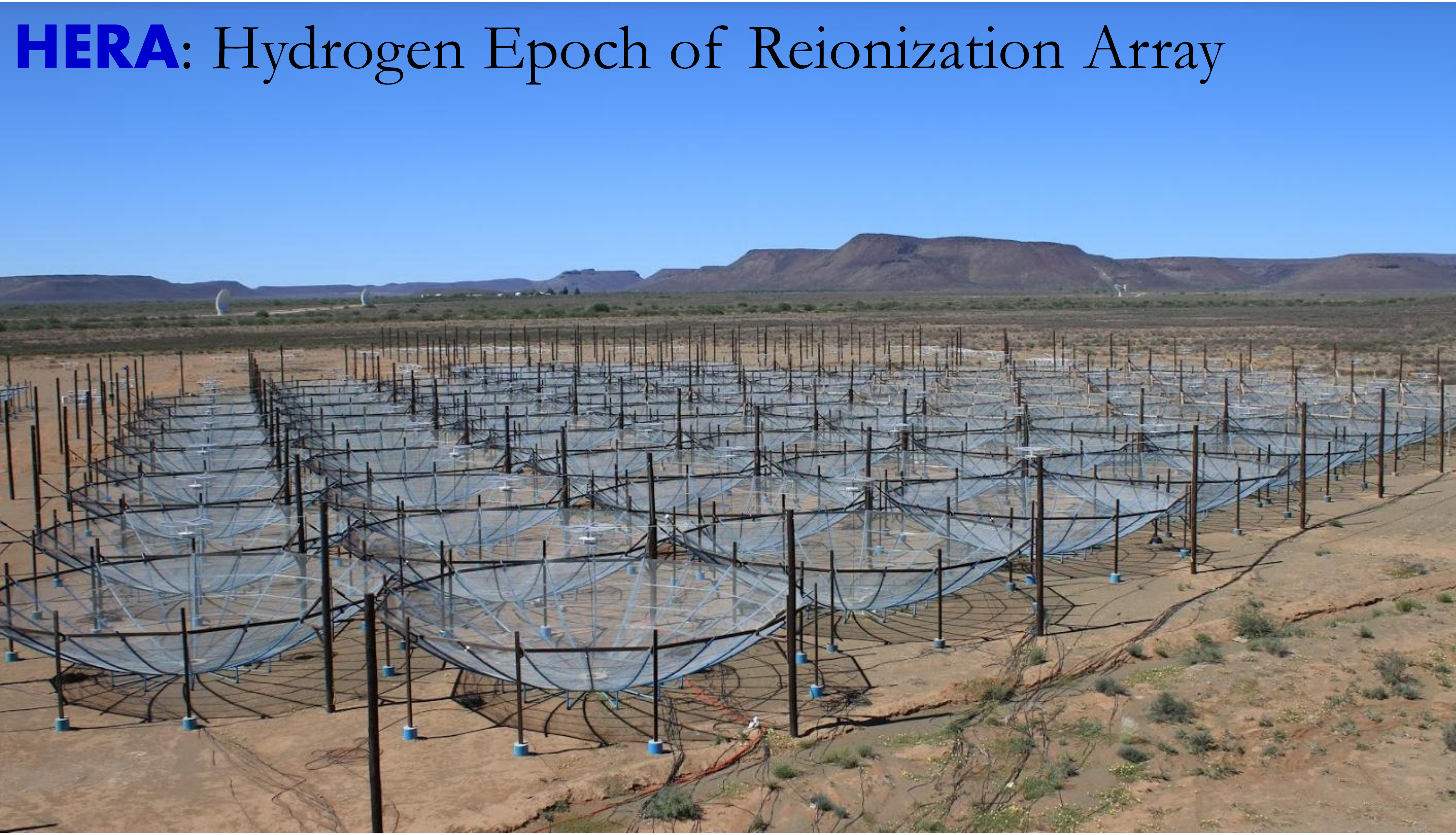
Universidad de Chile

NRAO

McGill University

Independent Verification
Through the Spatial Fluctuations

HERA: Hydrogen Epoch of Reionization Array



Summary

1) The **EDGES experiment** has **reported 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** and could correspond to the **Signature from the Cosmic Dawn**.

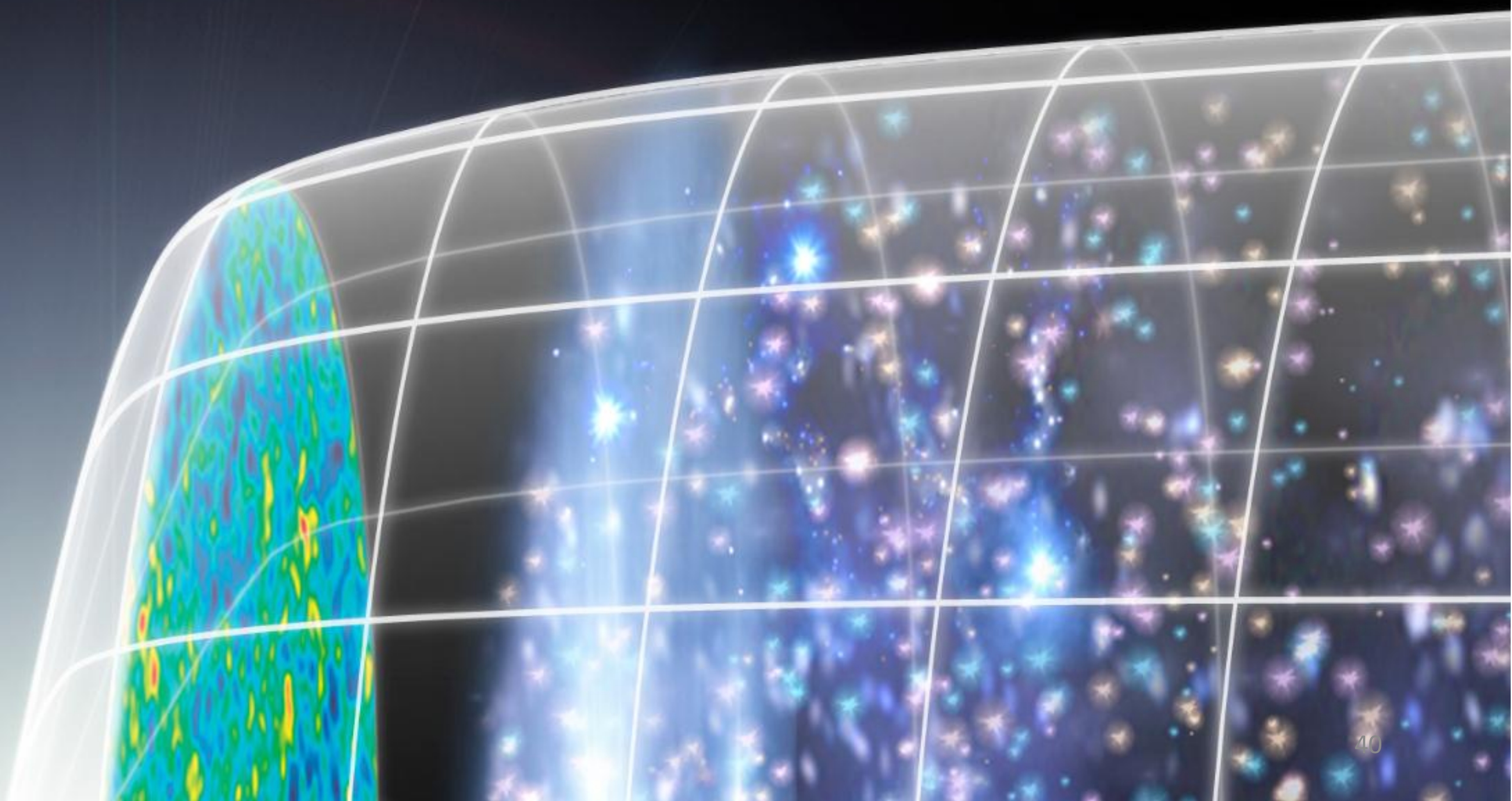
3) Feature is **deeper and sharper** than expected.

4) In EDGES, we **remain agnostic** regarding the **interpretation**.

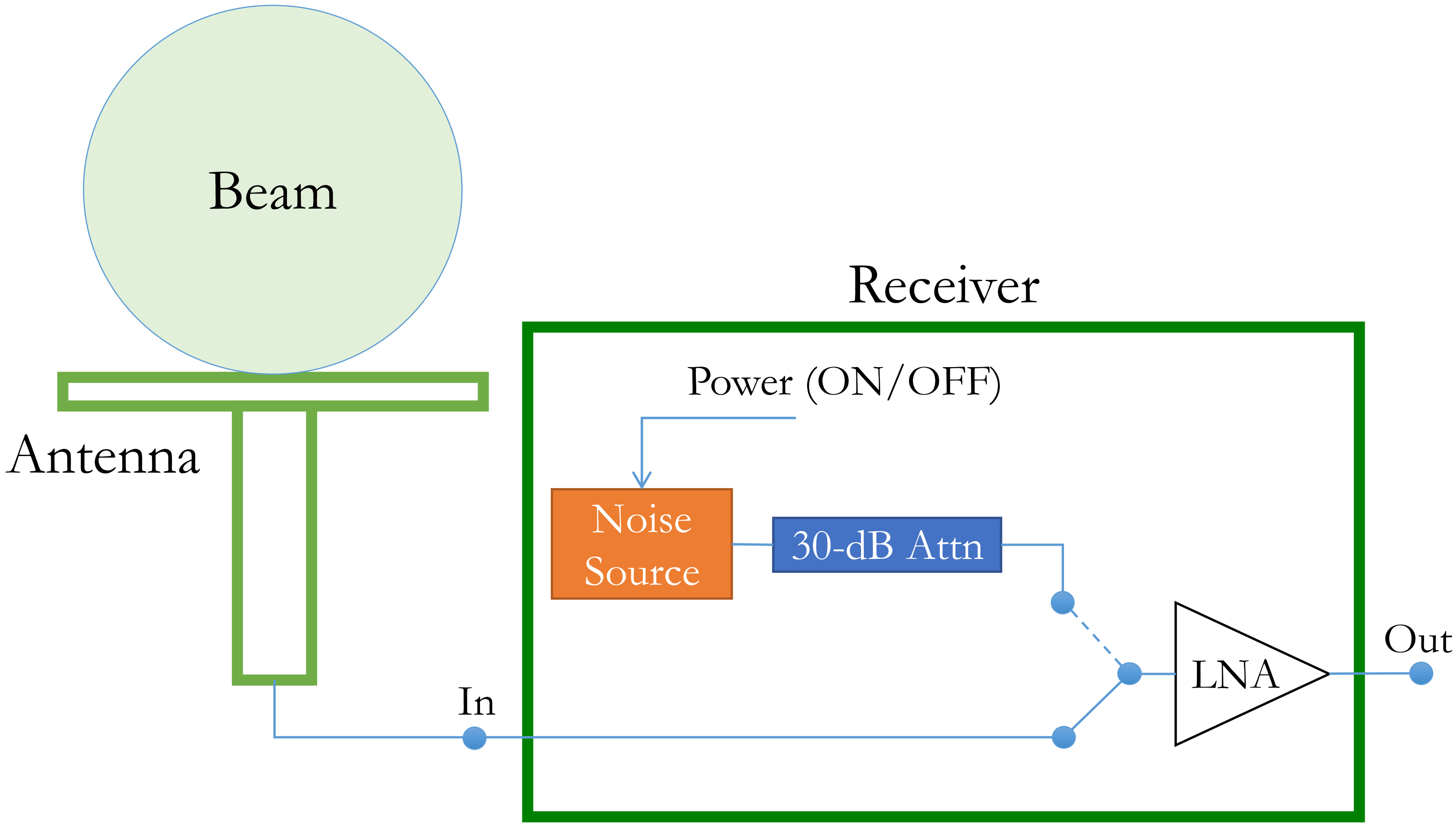
5) EDGES and other teams are **working to verify the measurement**.

6) Using other datasets, in EDGES we are **constraining parameters** of the **Cosmic Dawn** and **Reionization**.

We are Witnessing the Dawn of 21-cm Cosmology



Field Relative Calibration

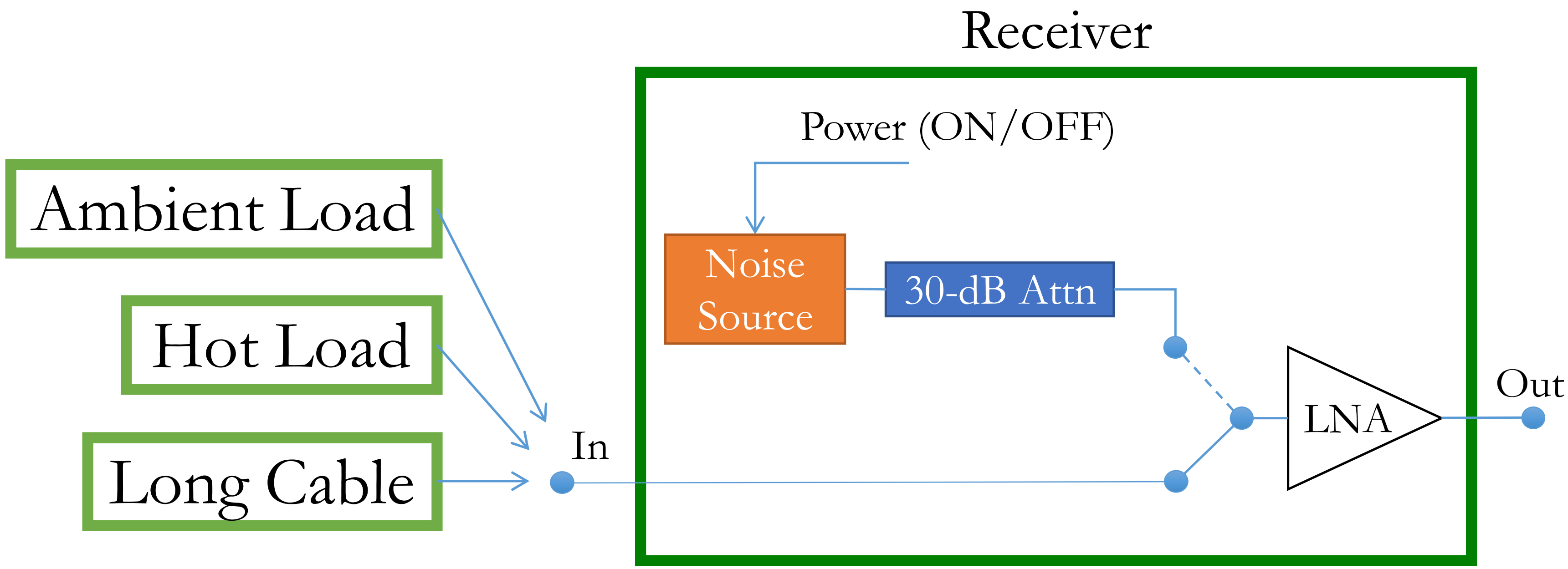


This calibration is **applied every 40 seconds. It removes time variability.**

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

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

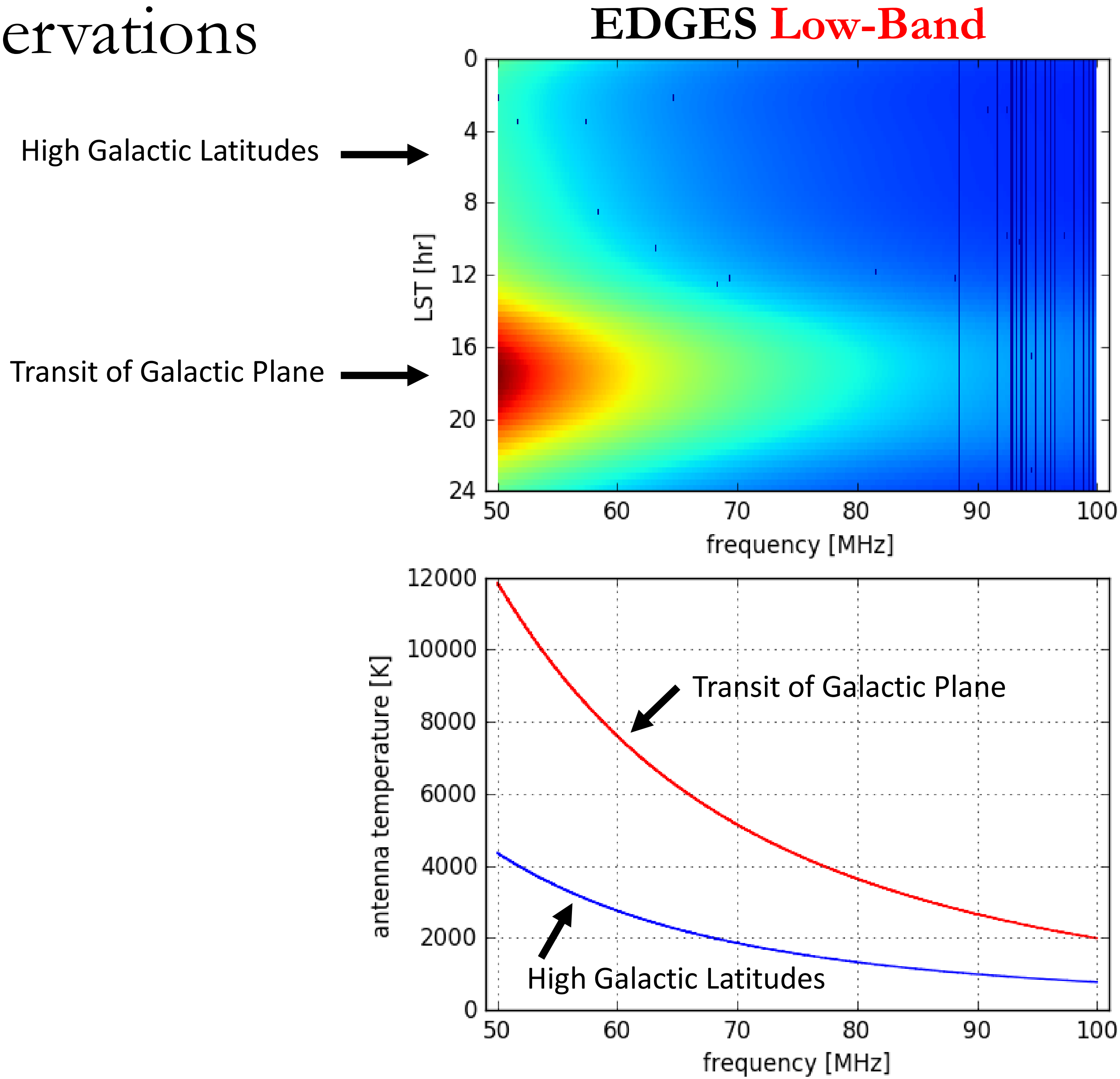
Absolute Lab Calibration



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

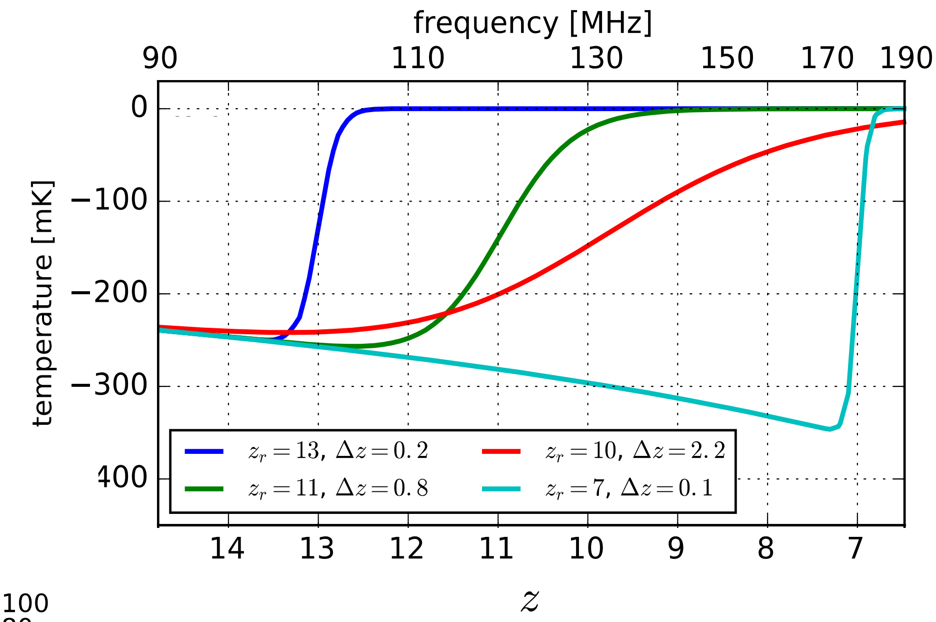
We measure with high precision and accuracy the **spectrum, reflection, and temperature of the standards**.

Daily Observations

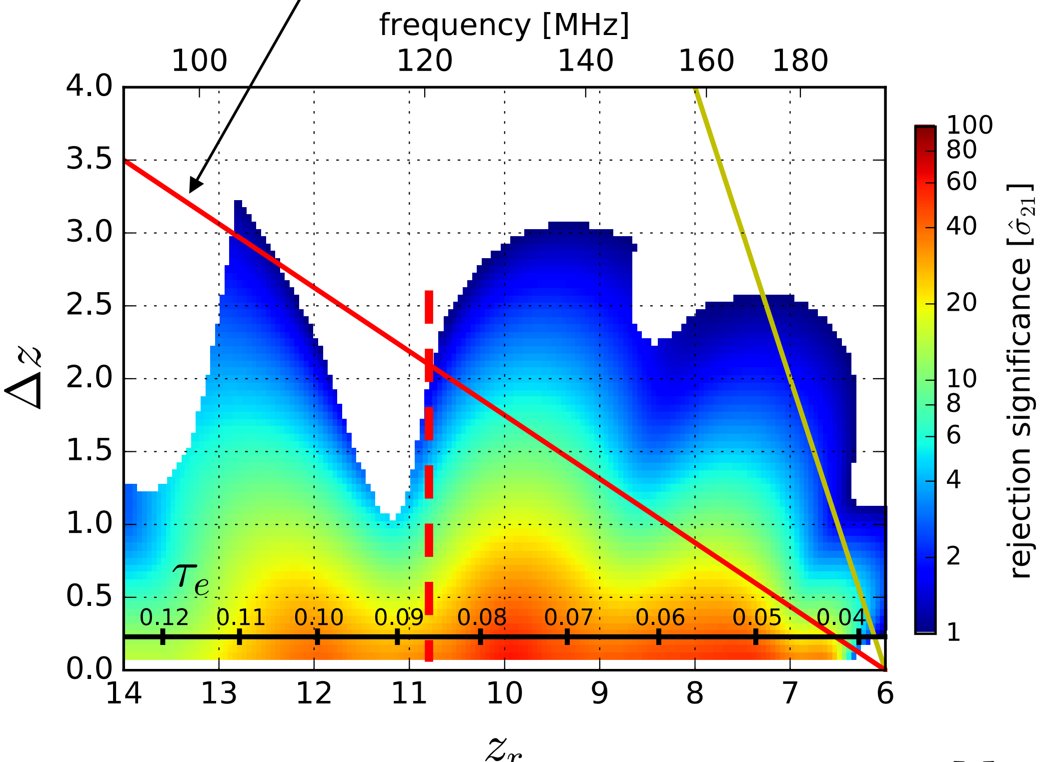


NO IGM Heating prior to Reionization

1) Perfect Lyman-α coupling at early times ($T_S = T_{IGM}$).
2) No X-ray heating. IGM cools adiabatically.
3) Only reionization.
4) Reionization modeled with TANH expression.



$x_{HI} < 1\%$ at $z = 6$



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

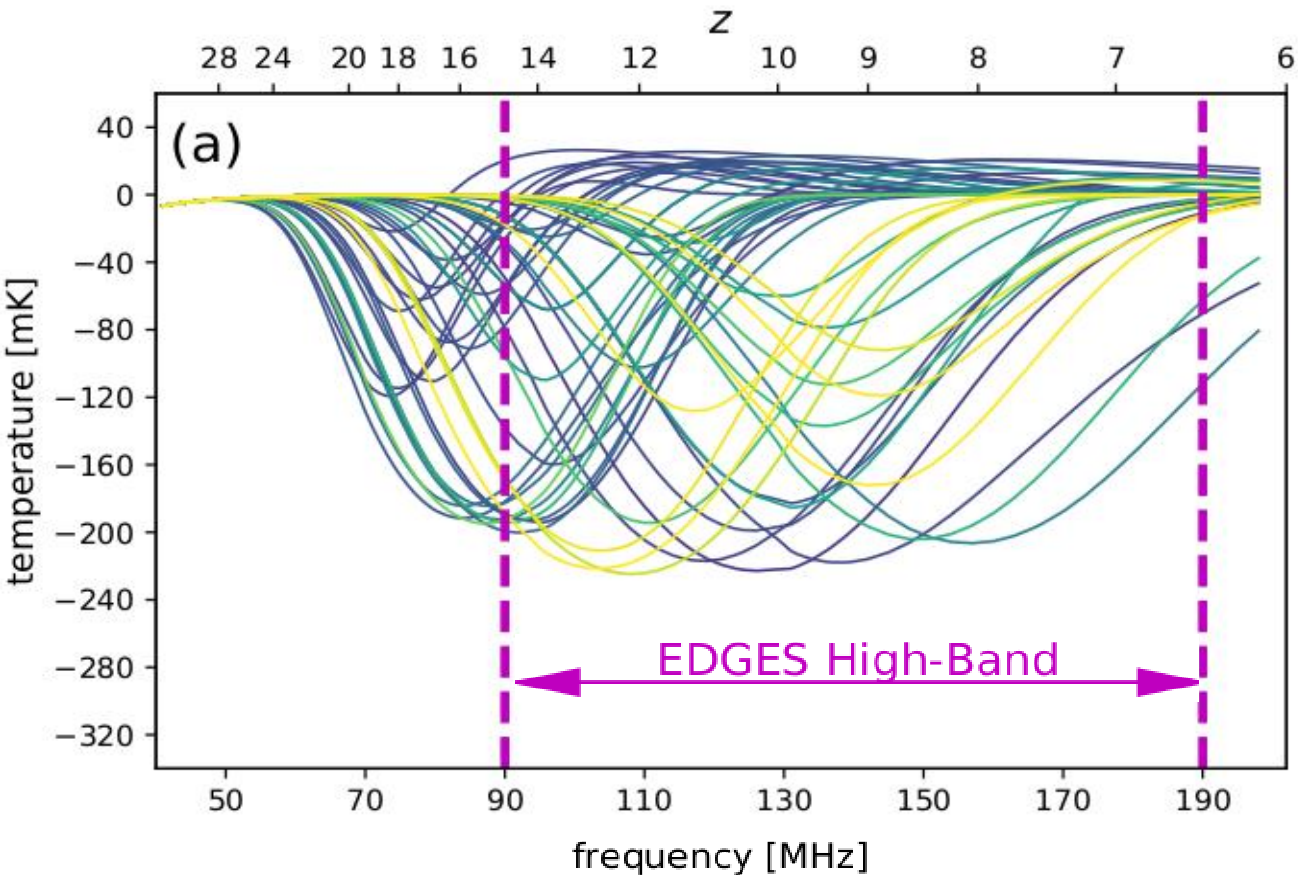
- Perfect Lyman-α coupling
- No X-ray heating
- $x_{HI} \leq 1\%$ at $z = 6$
- $0.086 \geq \tau_e \geq 0.038$

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

NO IGM Heating prior to Reionization

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

Constraints of High-z Astrophysical Parameters Using 21cmFAST Models



Sample of 50 models out of 10,000

High Likelihood

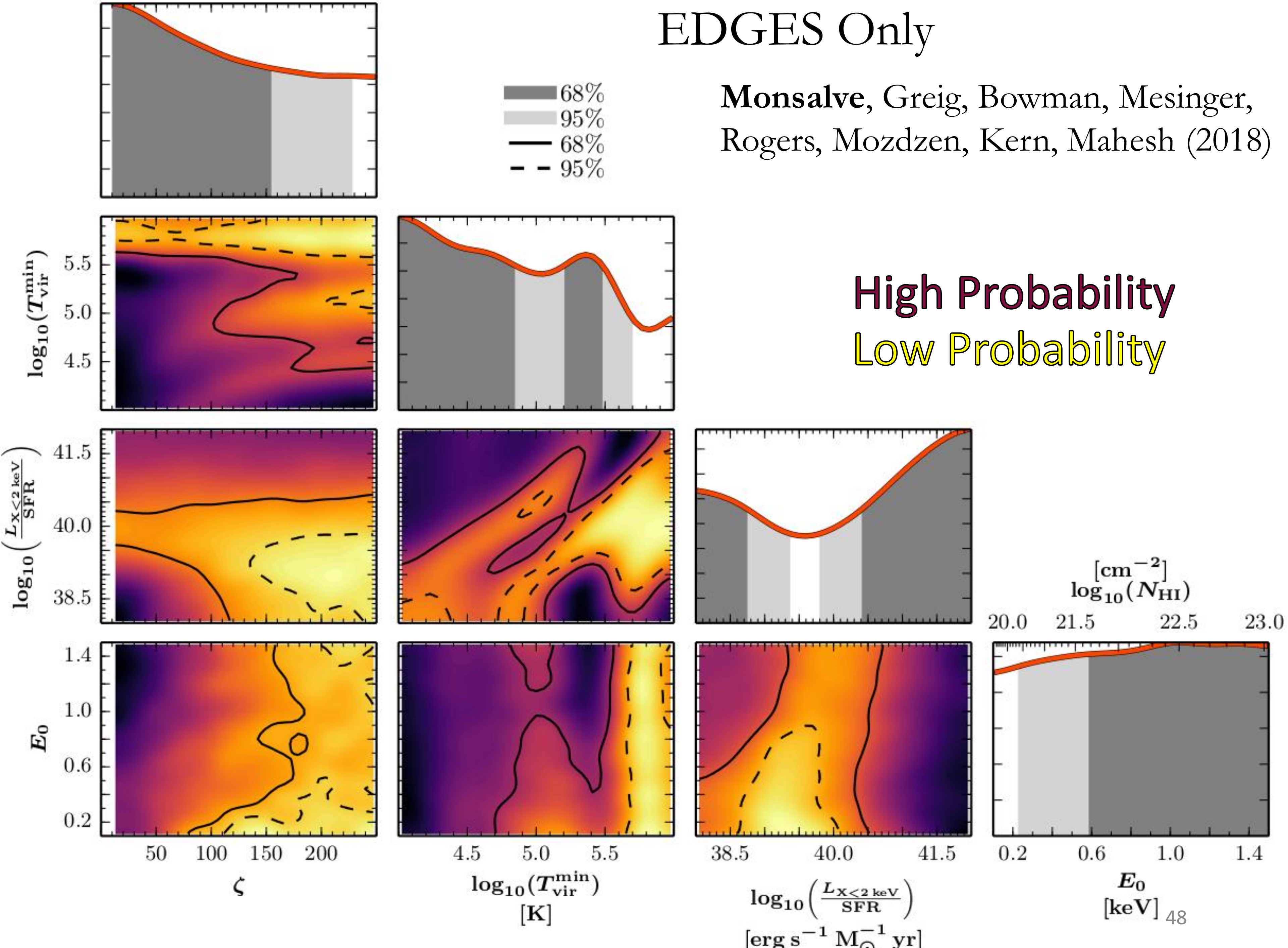
Low Likelihood

$T_{\mathrm{vir}}^{\mathrm{min}}$:	Minimum virial temperature of star-forming halos
ζ:	Ionizing efficiency of halos hosting galaxies
L_X/SFR:	X-ray luminosity per SFR of galaxies
E_0:	Minimum energy of X-rays

Monsalve, Greig, Bowman, Mesinger, Rogers, Mozdzen, Kern, Mahesh (2018)

EDGES Only

Monsalve, Greig, Bowman, Mesinger, Rogers, Mozdzen, Kern, Mahesh (2018)



EDGES+Planck+High-z Quasars

Monsalve, Greig, Bowman, Mesinger, Rogers, Mozdzen, Kern, Mahesh (2018)