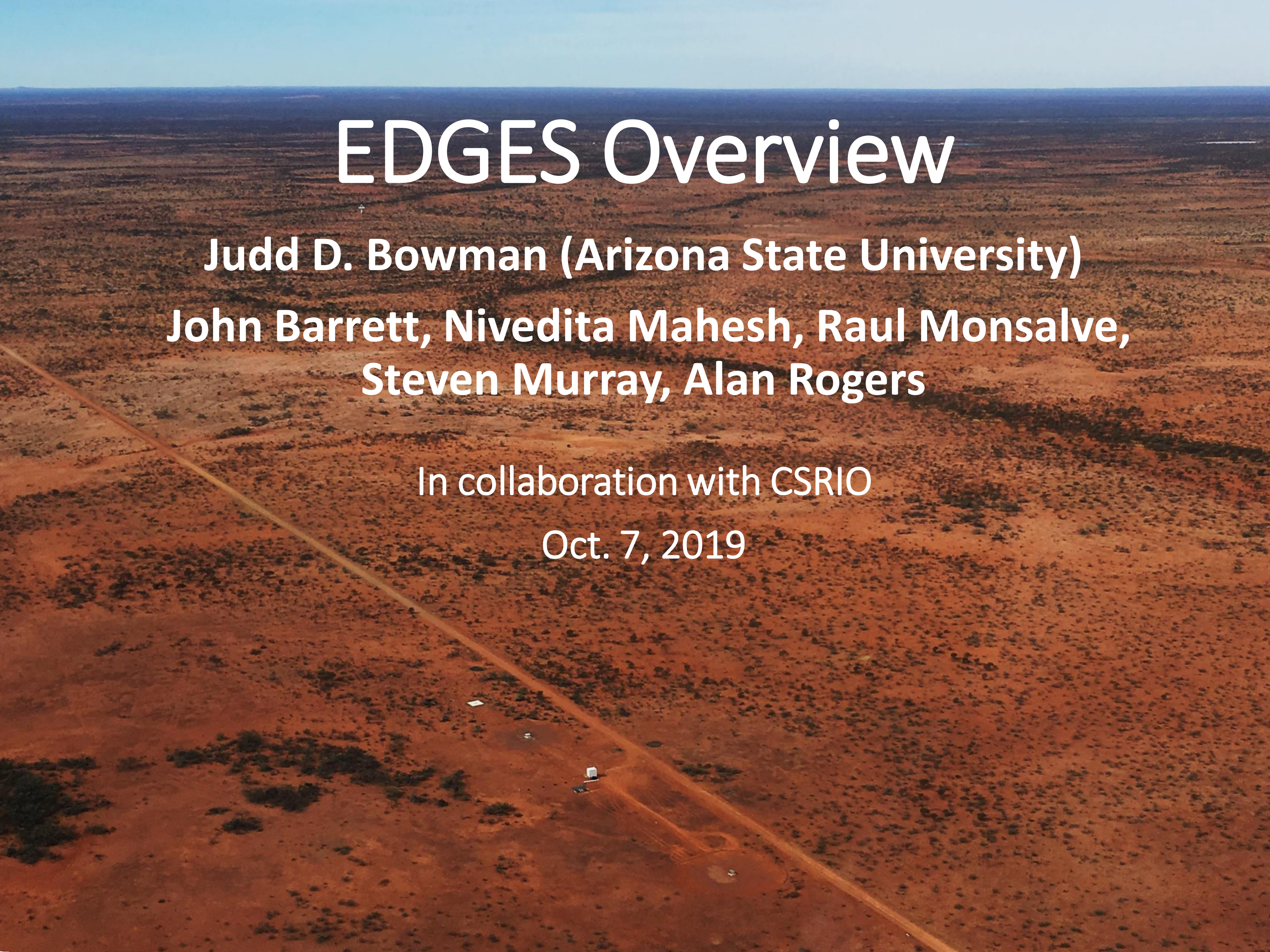


EDGES Overview

Judd D. Bowman (Arizona State University)

John Barrett, Nivedita Mahesh, Raul Monsalve, Steven Murray, Alan Rogers

In collaboration with CSRIO

Oct. 7, 2019

EDGES TEAM

Dr. Alan Rogers
MIT / Haystack

Dr. Raul Monsalve
McGill University

Nivedita Mahesh
ASU (Ph.D. student)

Dr. Steven Murray
ASU

Dr. John Barrett
MIT / Haystack

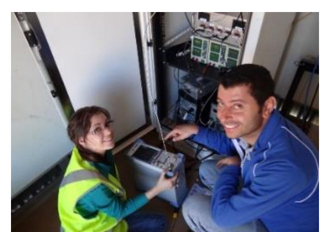
Dr. Tom Mozdzen
ASU (Ph.D. '17)

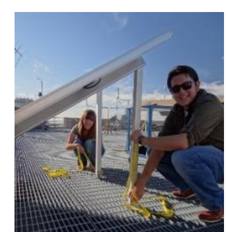
<u>Technicians/engineers</u>

- Mark Derome
- Hamdi Mani
- Jim Traffie
- Ken Wilson
- Titu Sampson
  (staring soon!)

And on-site support from the CSIRO MRO team

*** Now hiring! ***





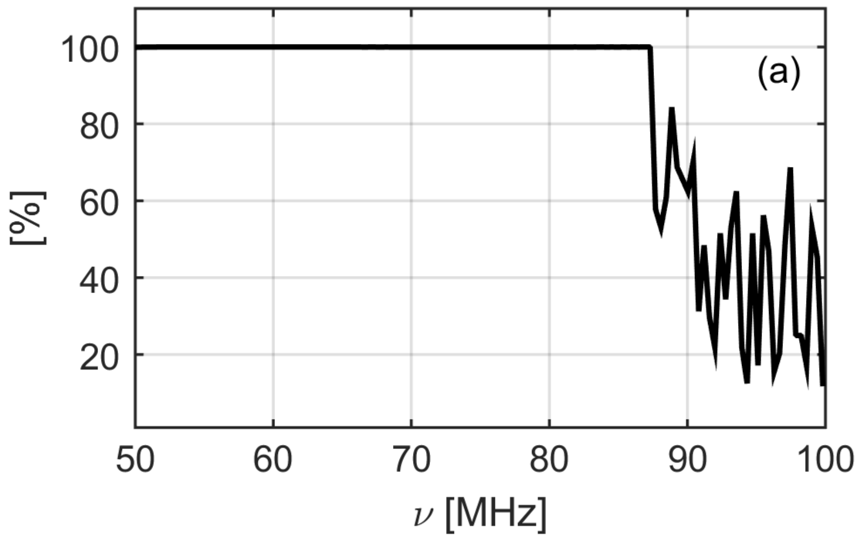
<u>Undergraduate students</u>: Kali, Lauren, Leroy, David, Sarah, Hamdi, Breana, Jose, Delani, Ethan

Curtin University

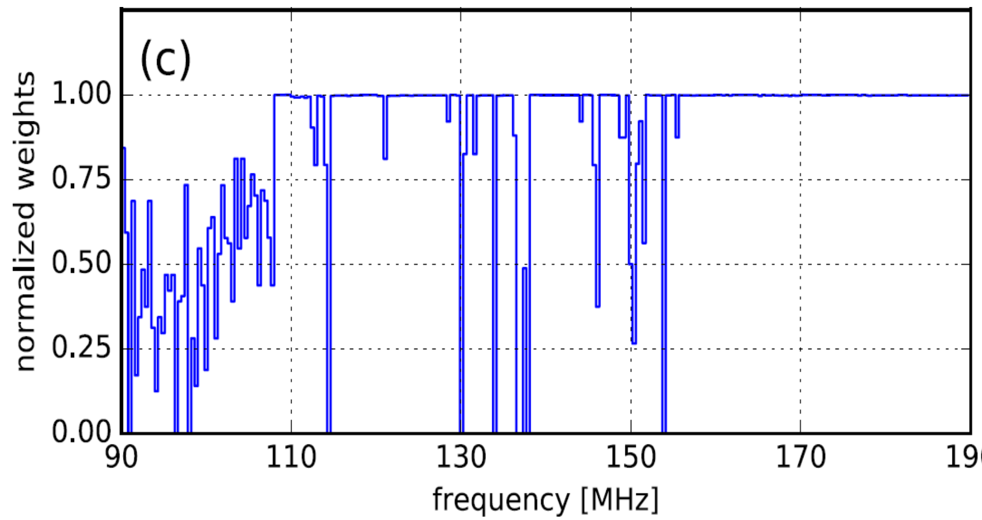
MRO site is a good balance

Fraction of data used per channel

Low-band



High-band



- Infrastructure, accessibility, low RFI
- Hundreds of nights in each band
- Very clean below FM band

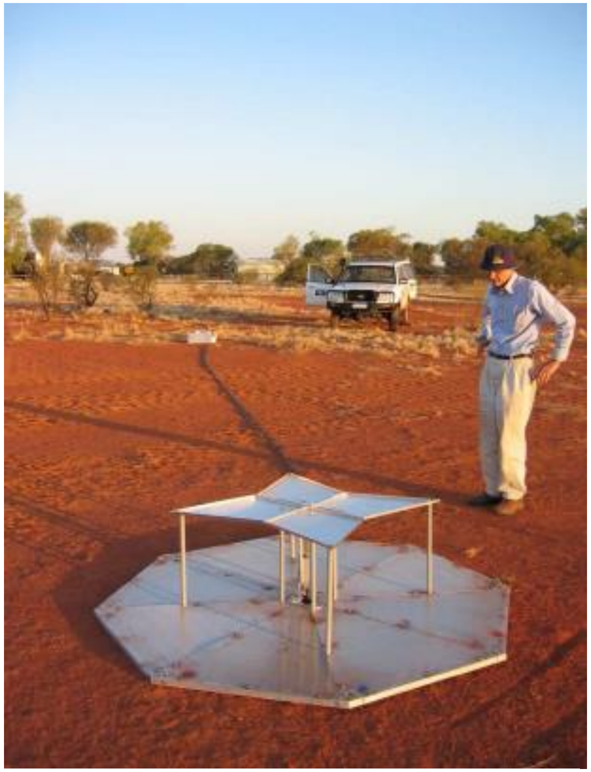
R. Monsalve

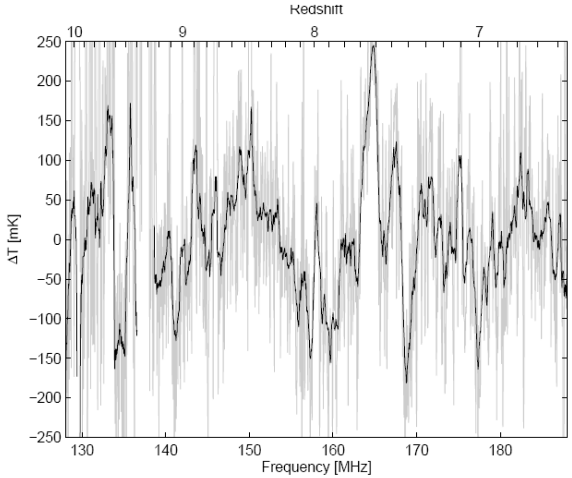
EDGES hardware configurations

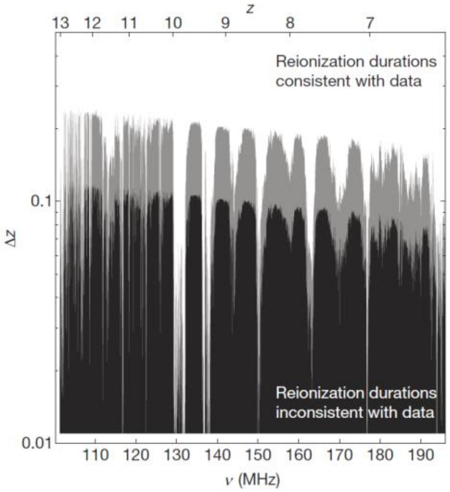
EDGES-0	**2005-2008**
EDGES-1	**2009-2012**
EDGES-2	**2012-2018**
• High-band	2015 → 2016
• Low-1 with 10x10 meter ground plane	2015-07 → 2016-09
• Low-1 with 30x30 meter ground plane	2016-09 → 2017-04
• Low-1 with 30x30 meter ground plane and recalibrated receiver	2017-05 → 2017-07
• Low-2 with north-south dipole orientation	2017-03 → 2017-05
• Low-2 with east-west dipole orientation	2017-05 → 2017-06
• Low-2 with east-west dipole orientation and balun shield removed	2017-06 → 2018-08
• Mid-band on low-1 ground plane with rcvr-3	2017-11 → 2018-02
• Mid-band on low-1 ground plane with rcvr-1	2018-05 → 2018-08
EDGES-3 (see Alan's talk)	**2019-2022**

EDGES-0 (2006)

EDGES-1 (2009)







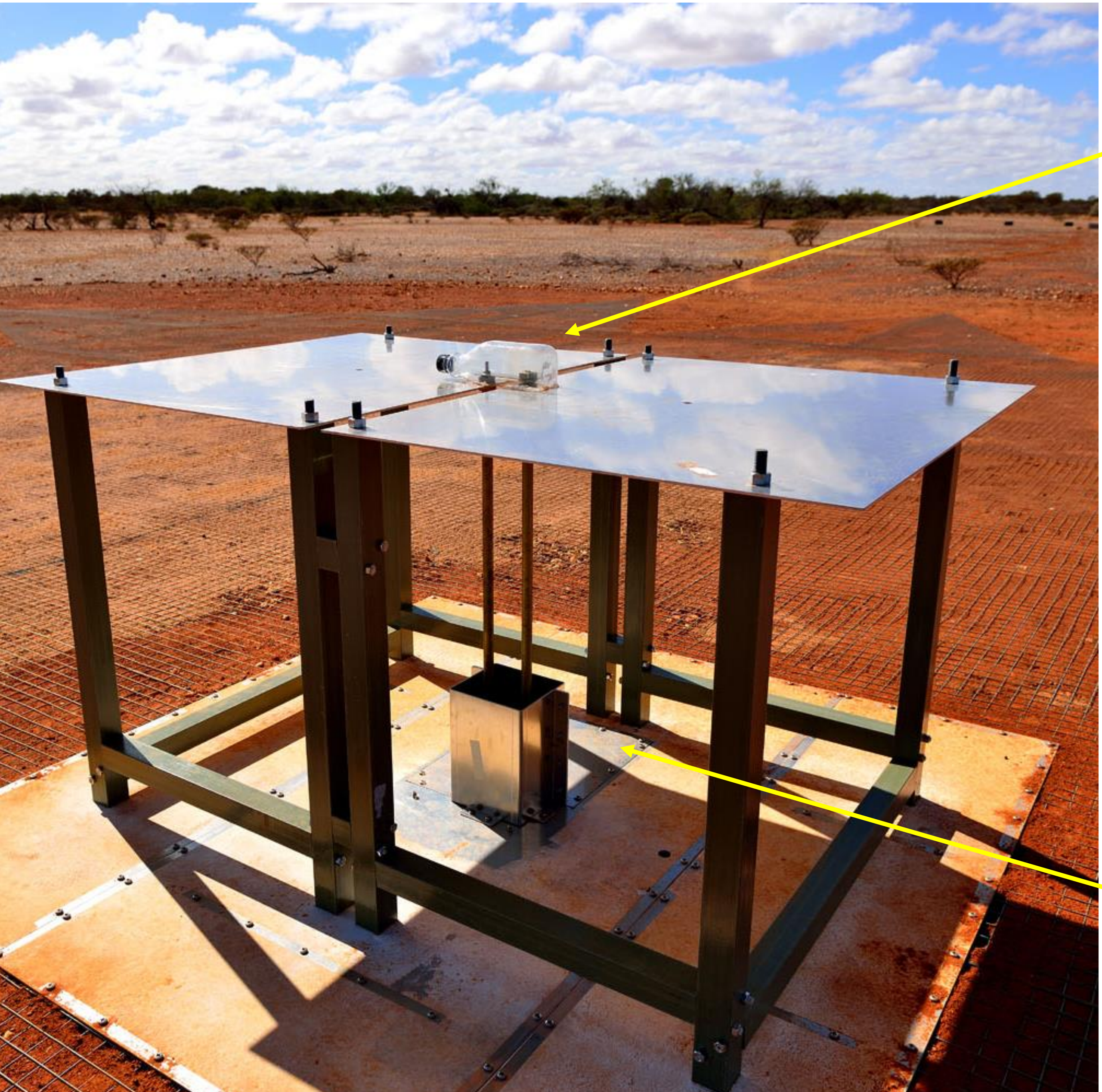
Bowman et al. 2008, Rogers & Bowman 2008, Bowman & Rogers 2010

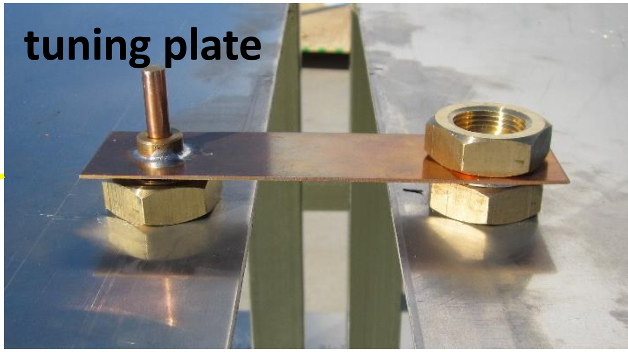
EDGES-2: High-band

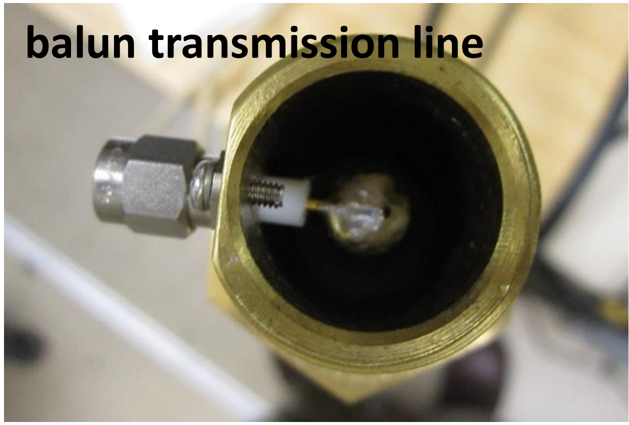
EDGES-2: Low-band 1

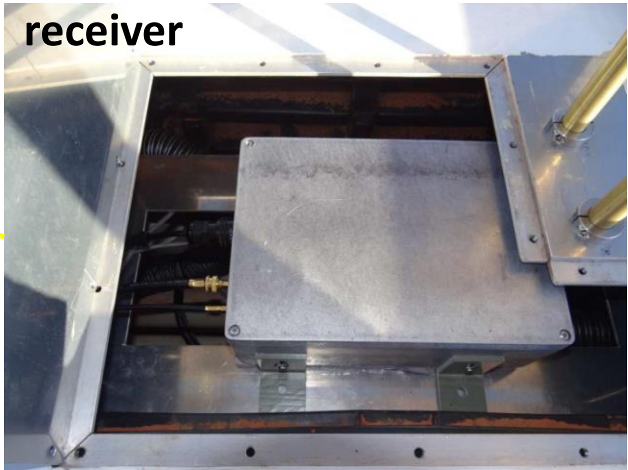
EDGES-2: Low-band 2

EDGES-2: Antenna and balun

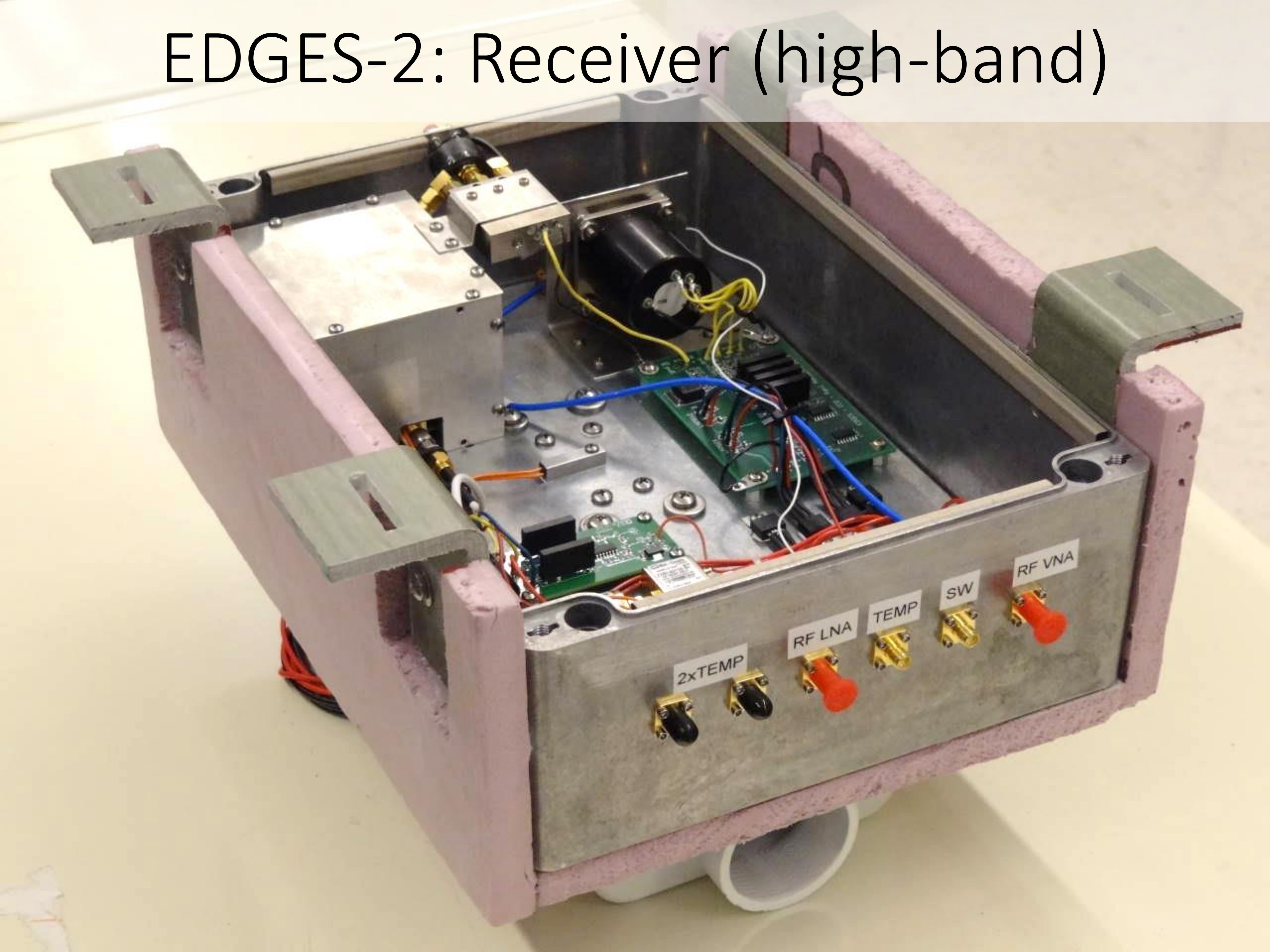








EDGES-2: Receiver (high-band)



EDGES-2: Backend and hut

Calibration formalism

- Initial correction using 3-position switch and internal noise states:

$$T^*_{\text{ant}} = T_{\text{NS}} \frac{(P_{\text{ant}} - P_{\text{L}})}{(P_{\text{L+NS}} - P_{\text{L}})} + T_{\text{L}}$$

- Absolute calibration:

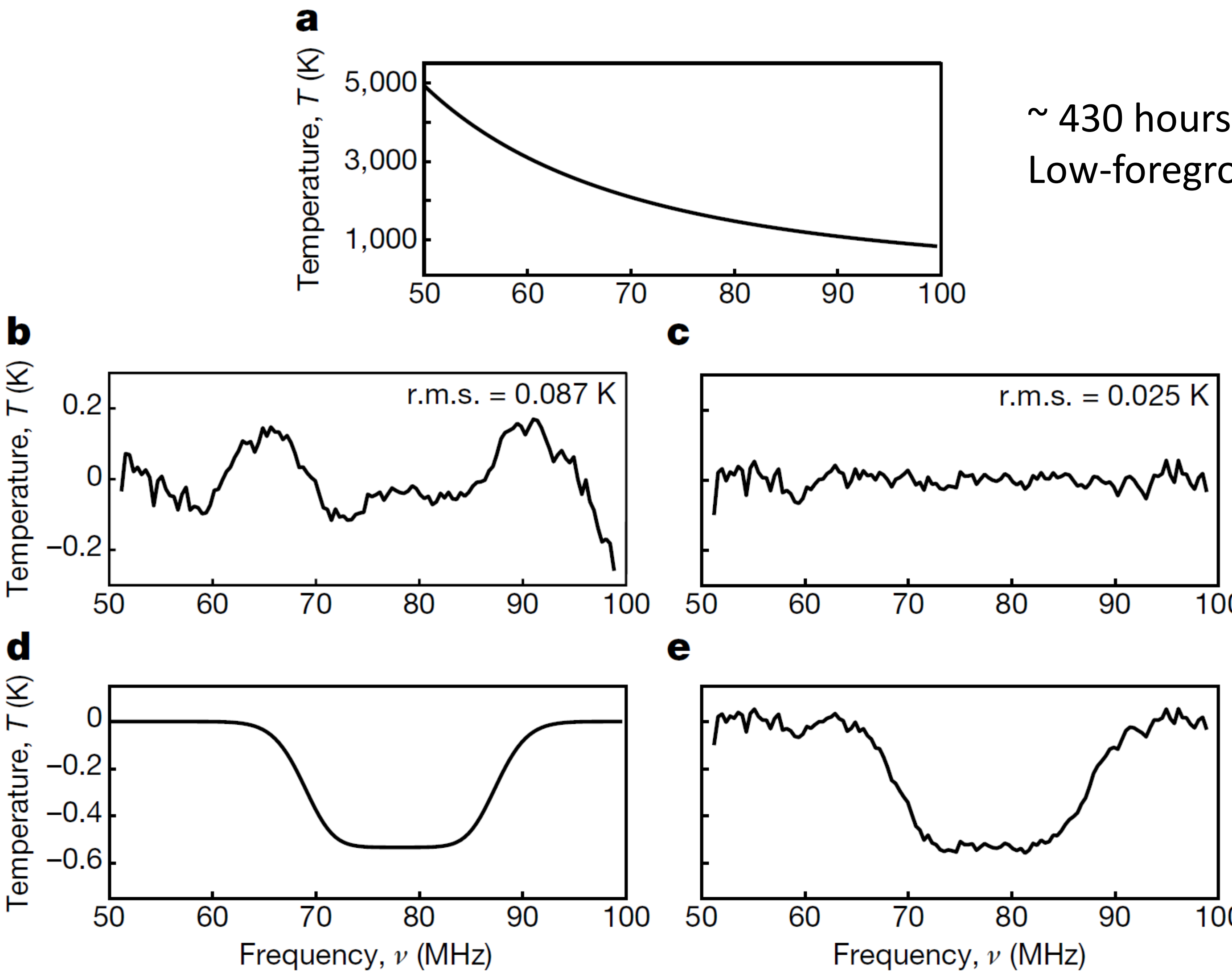
$$\begin{aligned}(T^*_{\text{ant}} - T_{\text{L}})C_1 + (T_{\text{L}} - C_2) = {} & T_{\text{ant}}\left[\frac{(1 - |\Gamma_{\text{ant}}|^2|\ F|^2}{(1 - |\Gamma_{\text{rec}}|^2)}\right] \\ & + T_{\text{unc}}\left[\frac{|\Gamma_{\text{ant}}|^2|F|^2}{(1 - |\Gamma_{\text{rec}}|^2)}\right] \\ & + T_{\cos}\left[\frac{|\Gamma_{\text{ant}}||F|}{(1 - |\Gamma_{\text{rec}}|^2)}\cos\alpha\right] \\ & + T_{\sin}\left[\frac{|\Gamma_{\text{ant}}||F|}{(1 - |\Gamma_{\text{rec}}|^2)}\sin\alpha\right].\end{aligned}$$

with: $$F = \frac{\sqrt{1 - |\Gamma_{\text{rec}}|^2}}{1 - \Gamma_{\text{ant}}\Gamma_{\text{rec}}}$$

$$\alpha = \arg(\Gamma_{\text{ant}} F).$$

Meys 1978
Rogers & Bowman 2012
Monsalve et al. 2017a

Evidence for 21cm detection



~ 430 hours
Low-foreground sky

Bowman et al. 2018

EDGES verification tests

Four primary concerns:

- Physical foreground interpretation (Hills et al. 2019)
- Alternative models and goodness of model fits (Hills et al. 2019)
- Ground plane resonances (Bradley et al. 2019)
- Chromatic beam effects

Previously reported tests:

- 6 instrument configurations
- 18 data cuts and processing variations
- 6 injection, modeling, and laboratory null-result tests

New tests and analyses:

✓ Was our model selection appropriate?
  - Diffuse spectral index consistent with other surveys and models (Mozdzen et al. 2019)
  - BIC supports model/band selection used in Bowman et al. 2018 (EDGES report #122)

✓ Are unmodeled ground plane effects responsible?
  - Verification of DC electrical conductivity
  - Low-band antenna over different inner structure (although sensitivity to assumptions of soil properties)

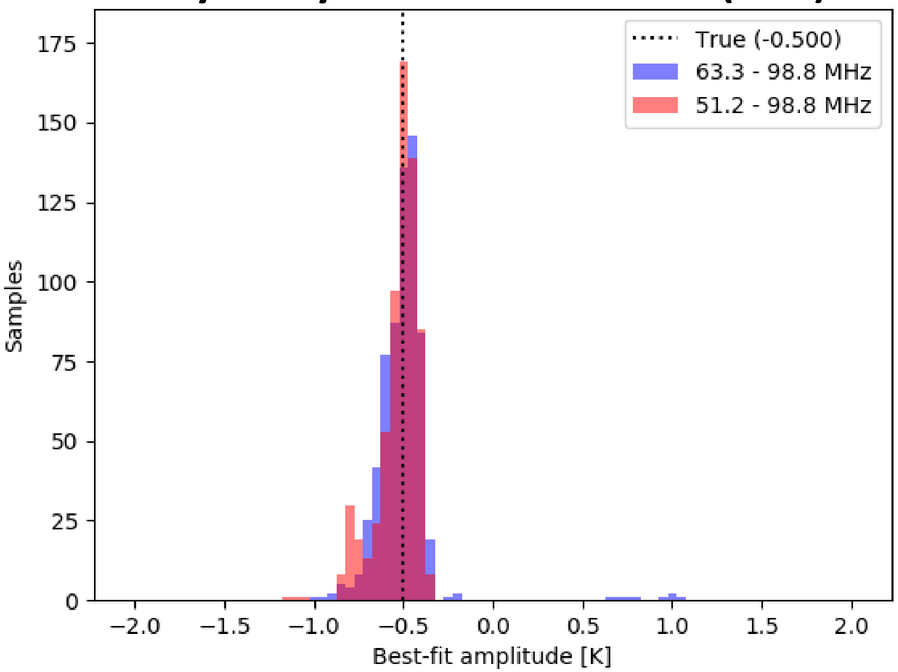
✓ Are unmodeled chromatic antenna beam effects responsible?
  - Mid-band antenna (60-160 MHz; more in Raul's talk)
  - Comparison of simulated observations to data (more in Nivedita's talk)

Bayesian-based model selection

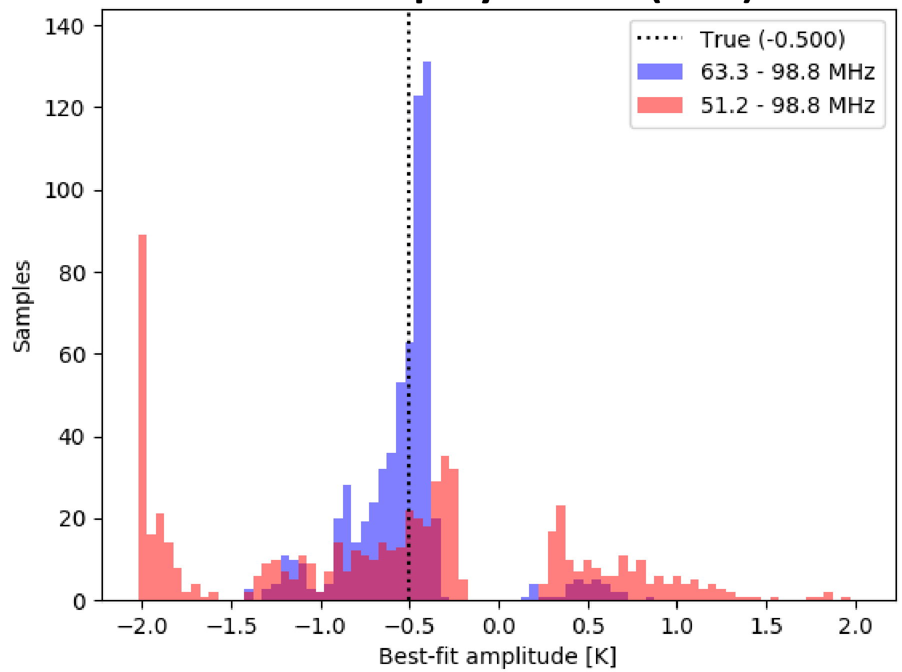
BIC (lower is better)

	Log expansion (linear)		"Physically motivated model"		EDGES polynomial	
N+4=k	**51-99 MHz**	**63-99 MHz**	**51-99 MHz**	**63-99 MHz**	**51-99 MHz**	**63-99 MHz**
3+4=7	-24	-132	--	--	44	-97
4+4=8	-223	-264	--	--	-115	-235
5+4=9	**-375**	**-277**	**-372**	**-277**	**-275**	**-275**
6+4=10	-373	-275	--	--	-363	-275
7+4=11	-371	-273	--	--	-371	-273

"Physically motivated model" (N=5)

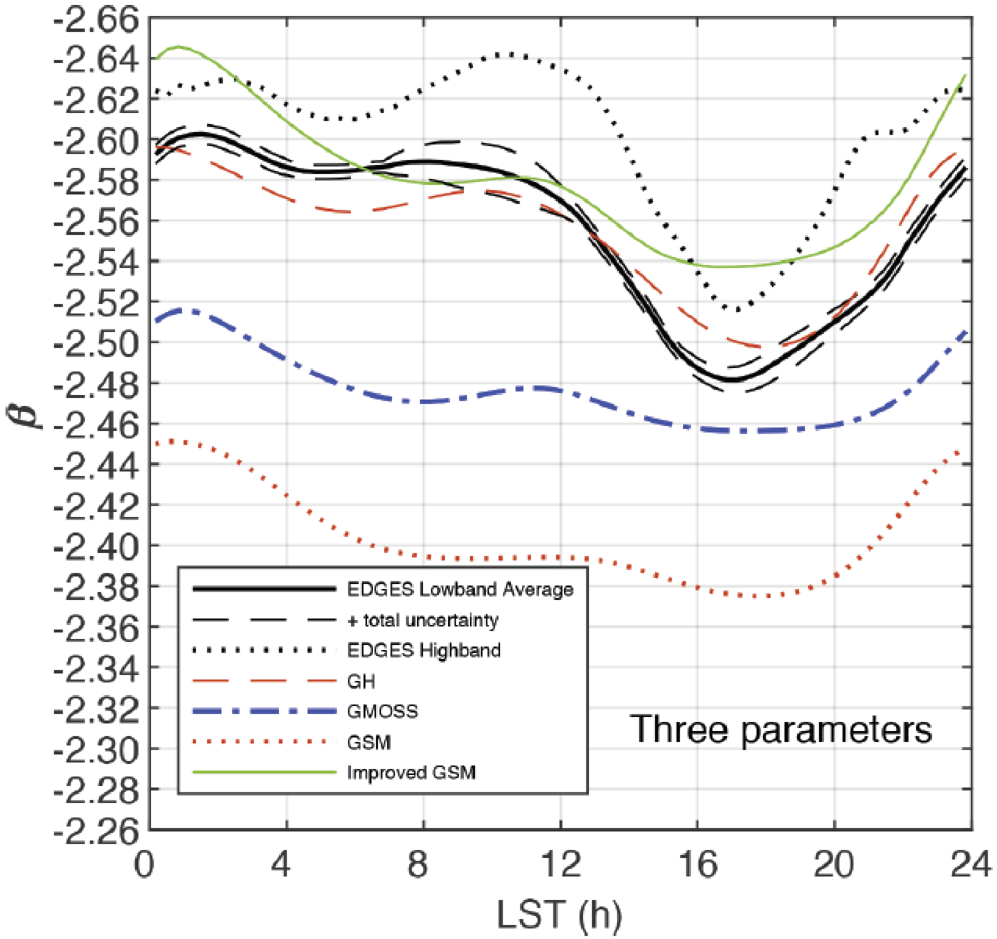


EDGES polynomial (N=5)



Diffuse spectral index

$$T_{\rm ant} = T_{75}\left(\frac{\nu}{\nu_{75}}\right)^{\beta+\gamma\ln(\frac{\nu}{\nu_{75}})+a_4[\ln(\frac{\nu}{\nu_{75}})]^2+a_5[\ln(\frac{\nu}{\nu_{75}})]^3} + T_{\rm CMB}$$

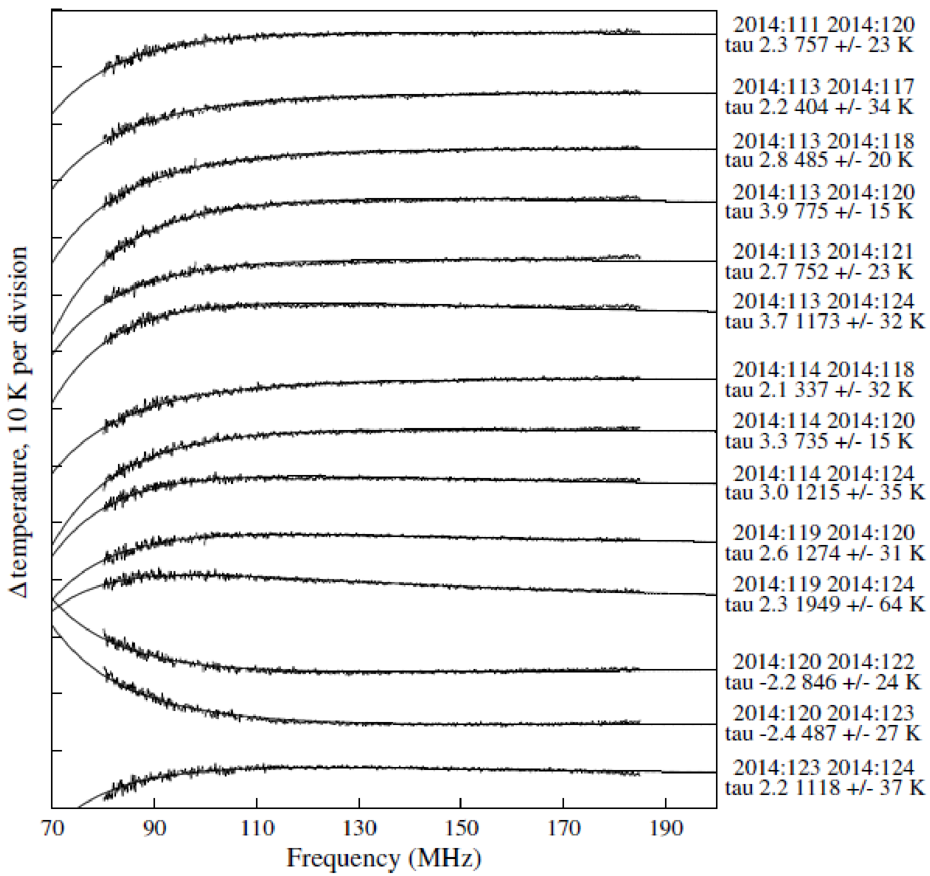


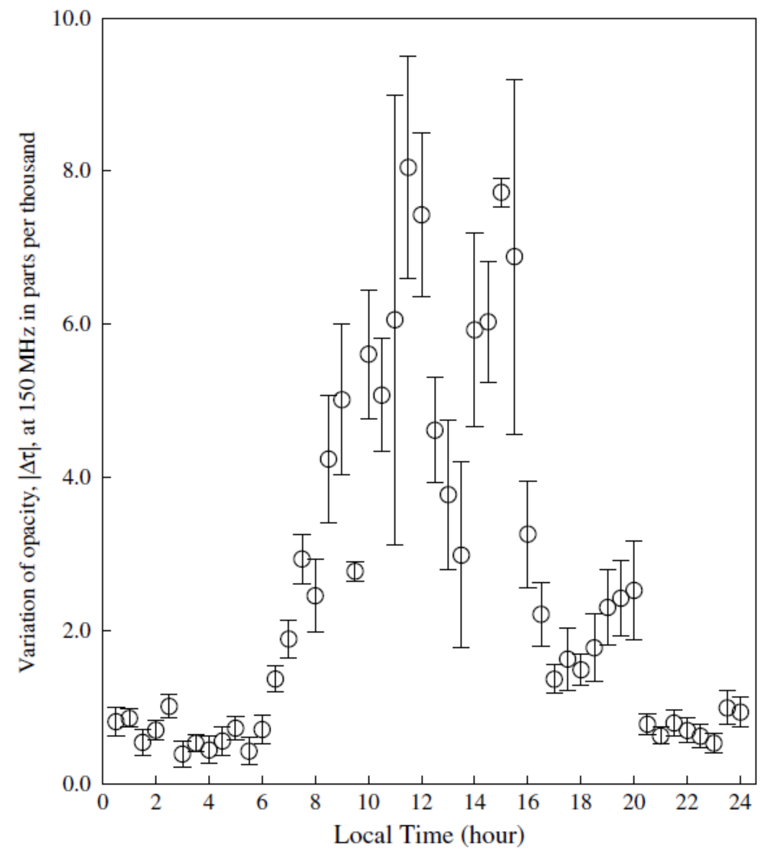
Param.	2 terms	3 terms	5 terms
T_{75}	1673 K	1673 K	1673 K
β	-2.571	-2.585	-2.585
γ	---	-0.47	-0.41
a_4	---	---	-0.004
a_5	---	---	-0.031

LST = 6h

Mozdzen, Mahesh, et al. 2019
Mozdzen et al. 2018

Ionosphere variability (high-band)

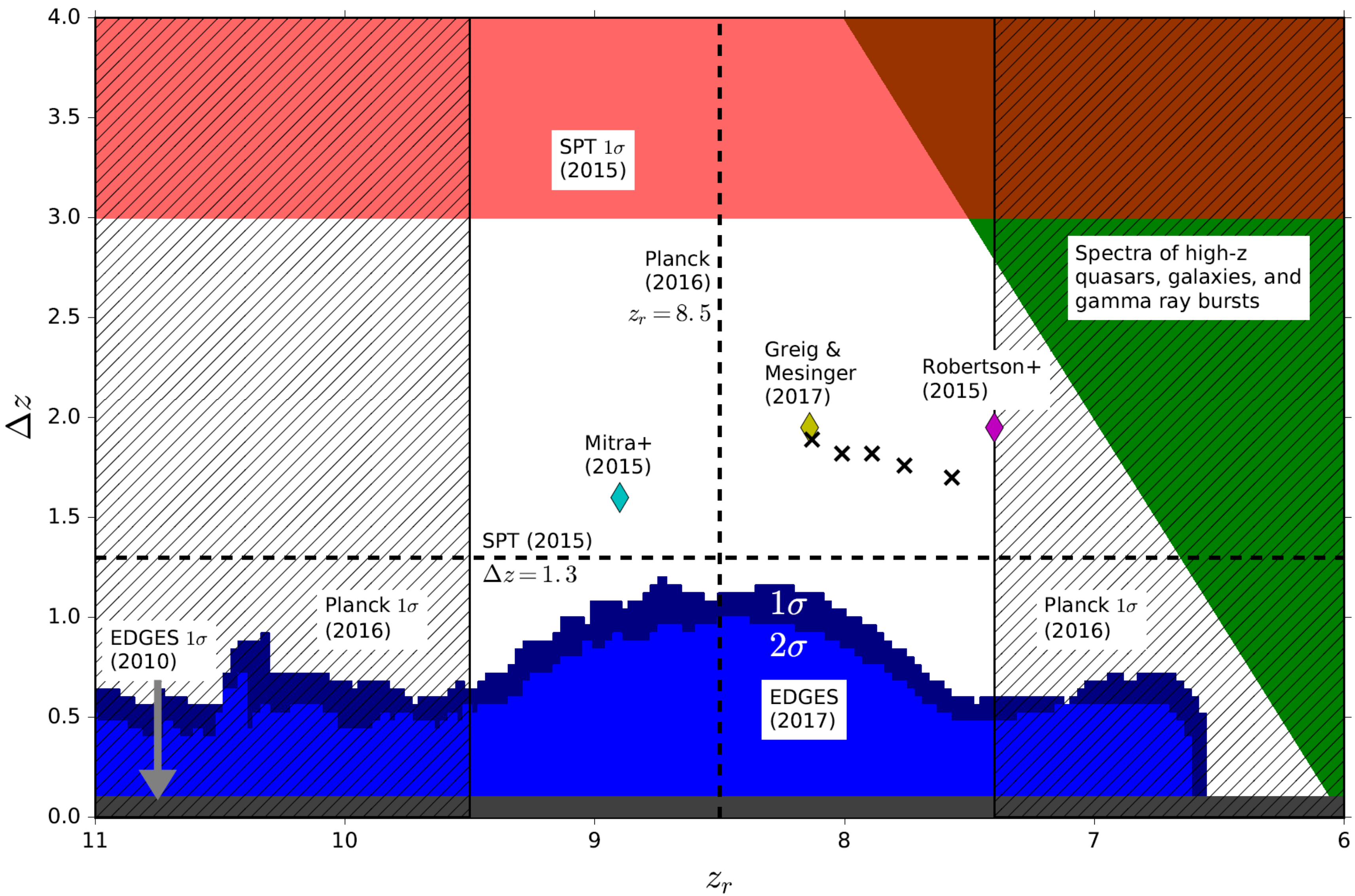




~8K effect at 75 MHz

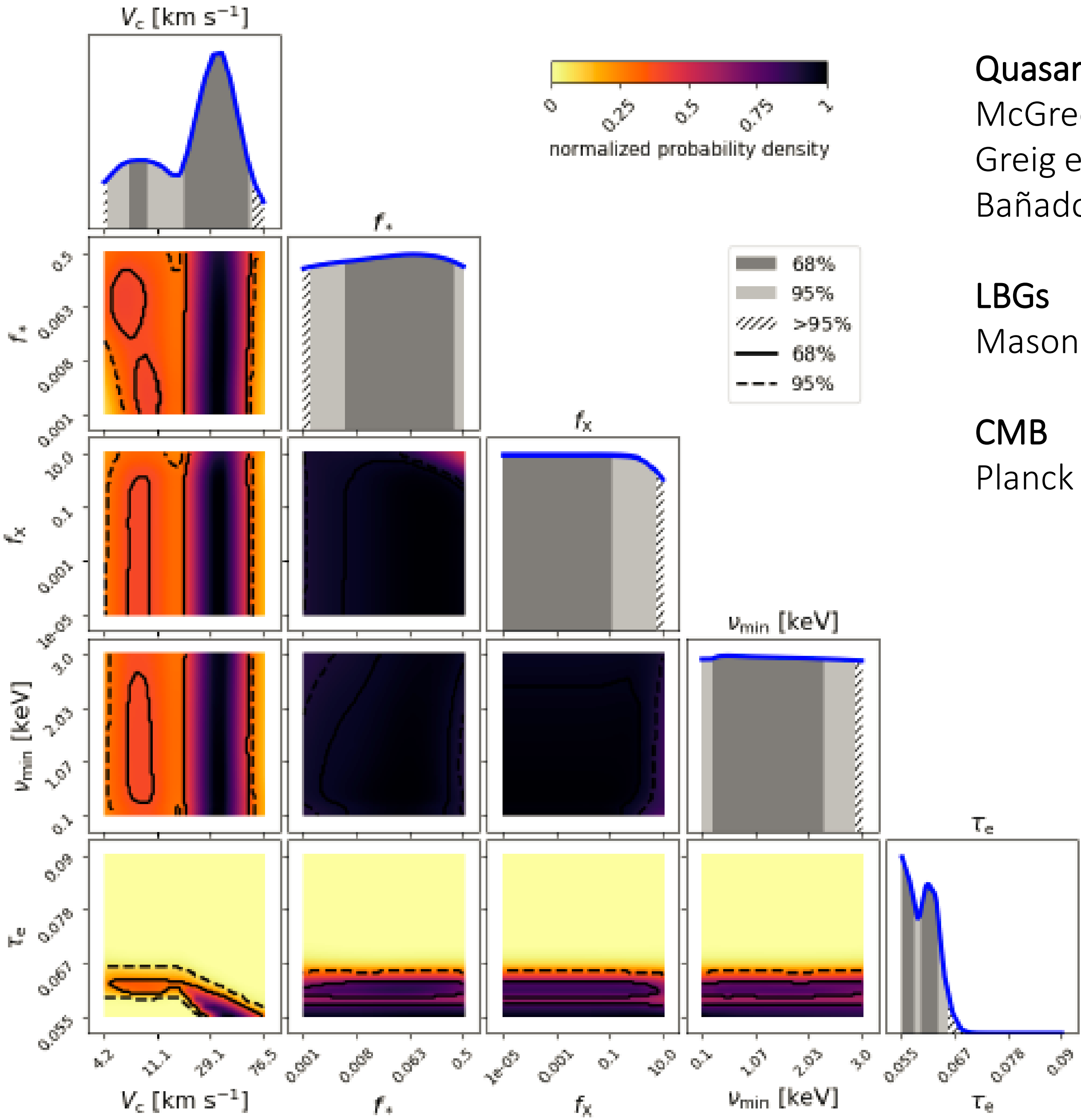
Rogers et al. 2015

EDGES high-band reionization



Monsalve et al. 2017b

CMB/high-z τ_e alone



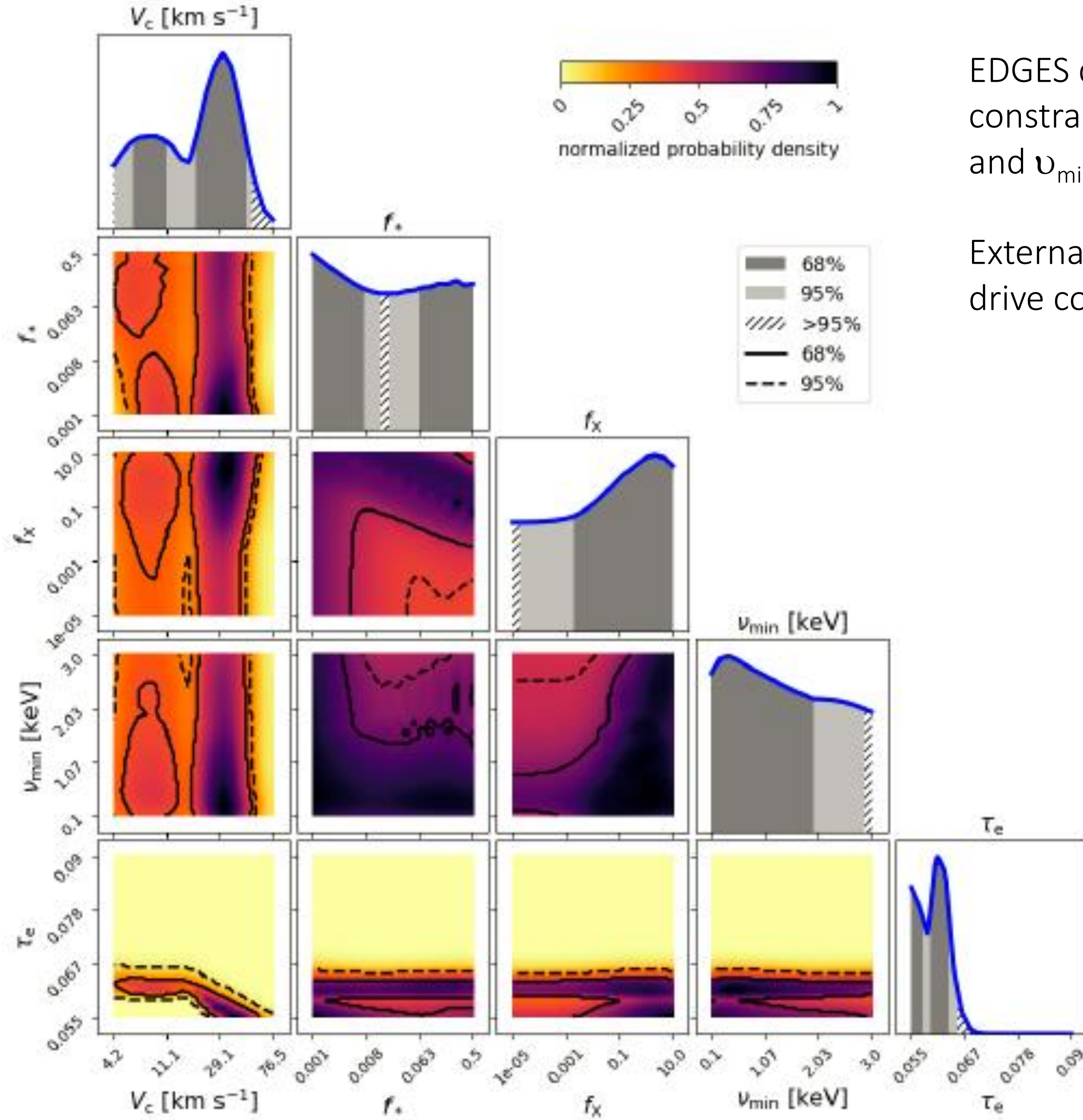
Quasars
McGreer et al. 2015
Greig et al. 2017
Bañados et al. 2018

LBGs
Mason et al. 2018

CMB
Planck VI 2018

Monsalve et al. 2019

CMB/high-z τ_e and EDGES-high



EDGES drives constraints on: f_*, f_X, and υ_{min}

External observations drive constraint on: τ_e

Monsalve et al. 2019

Next generation: EDGES-3

Funded by NSF ATI (2019-2022)

<u>Goal: Improve performance over current system by 3x - 10x</u>

- Address two largest sources of uncertainty based on error modeling:
    - Minimize propagation path delays and losses by removing balun and embedding receiver in antenna (3x)
    - Reduce beam chromaticity by using larger, terminated, or no ground plane (2-4x)
- Maintain MRO site (with extended ground plane)
- Temporary sites in southeast Oregon, possibly elsewhere

Secondary goal: Automated in-situ absolute calibration

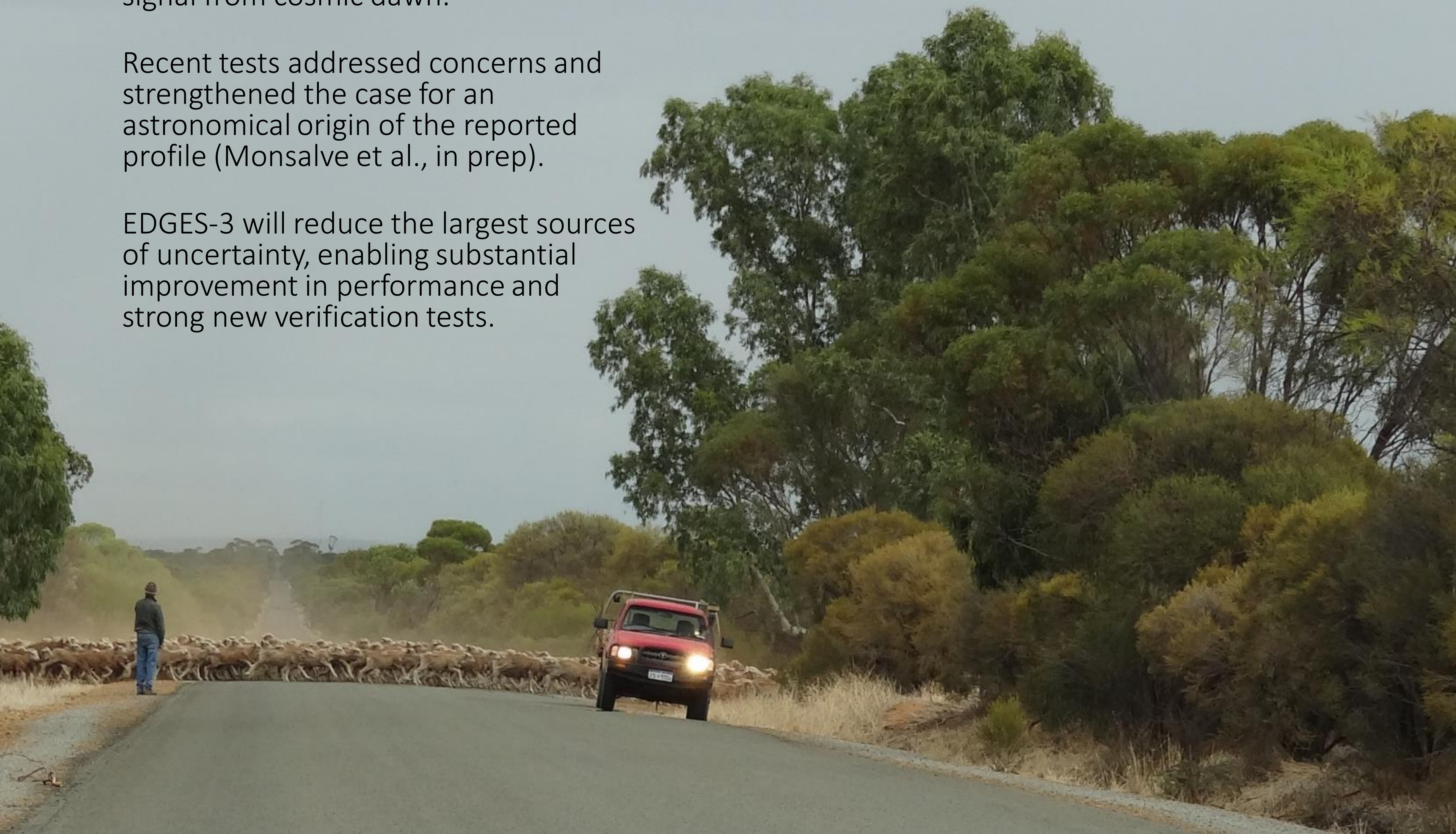
Challenges: Self-interference

Conclusion

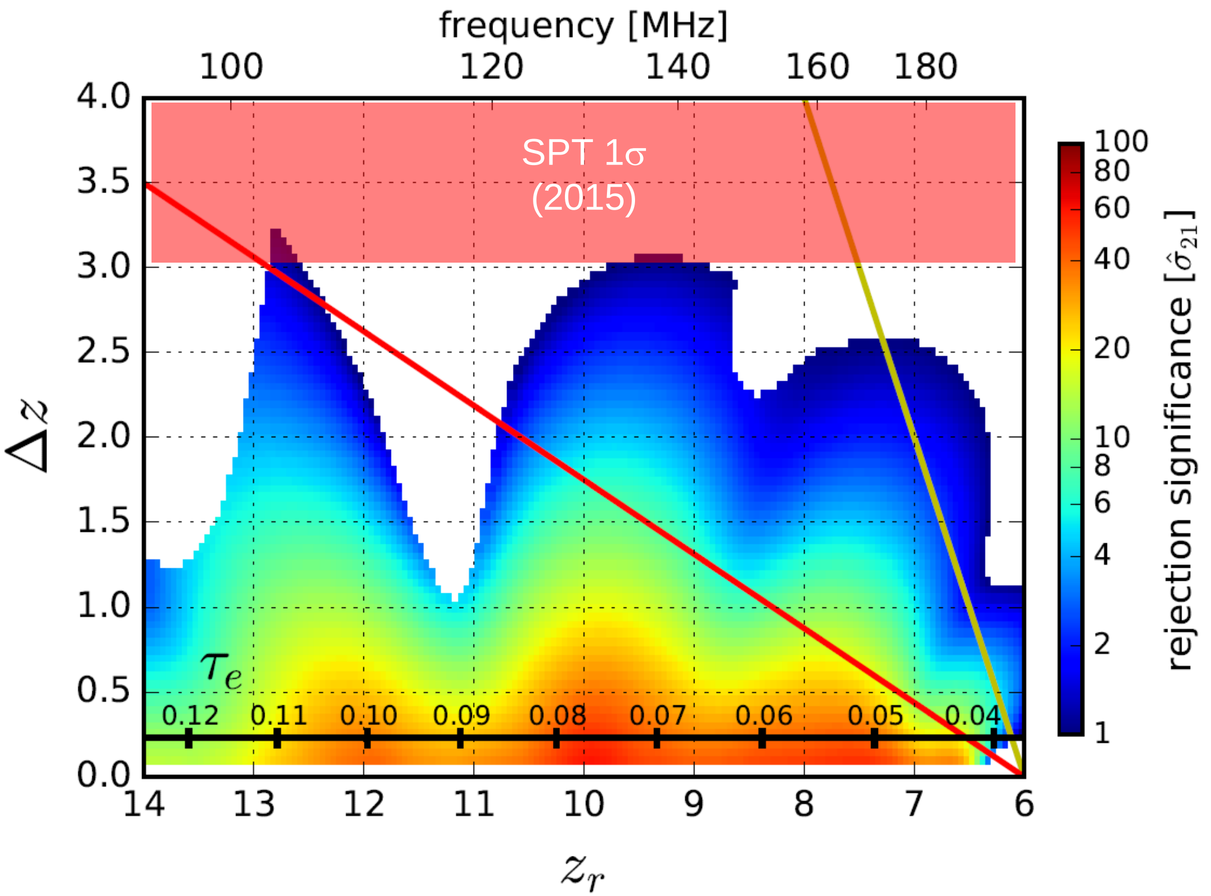
EDGES has pioneered global 21cm measurements and reported the first evidence for detection of the 21cm signal from cosmic dawn.

Recent tests addressed concerns and strengthened the case for an astronomical origin of the reported profile (Monsalve et al., in prep).

EDGES-3 will reduce the largest sources of uncertainty, enabling substantial improvement in performance and strong new verification tests.



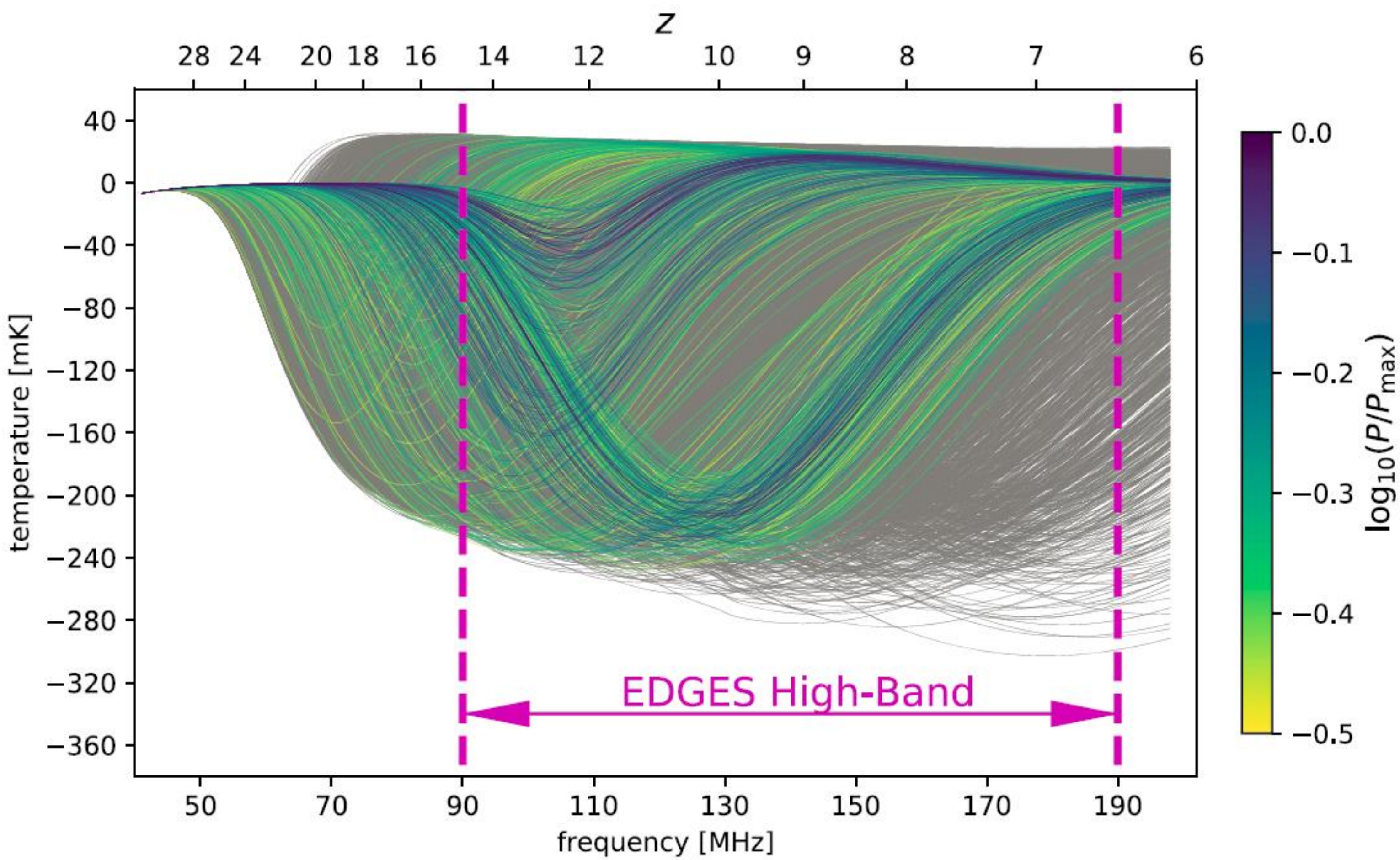
Cold gas: constraints on duration



- Many scenarios ruled-out, including best estimates from Planck, SPT, Greig & Mesinger, Robertson, etc.
- Disfavors lack of X-ray heating (cold IGM) with saturated spin temperature at time of reionization

Monsalve et al. 2017b

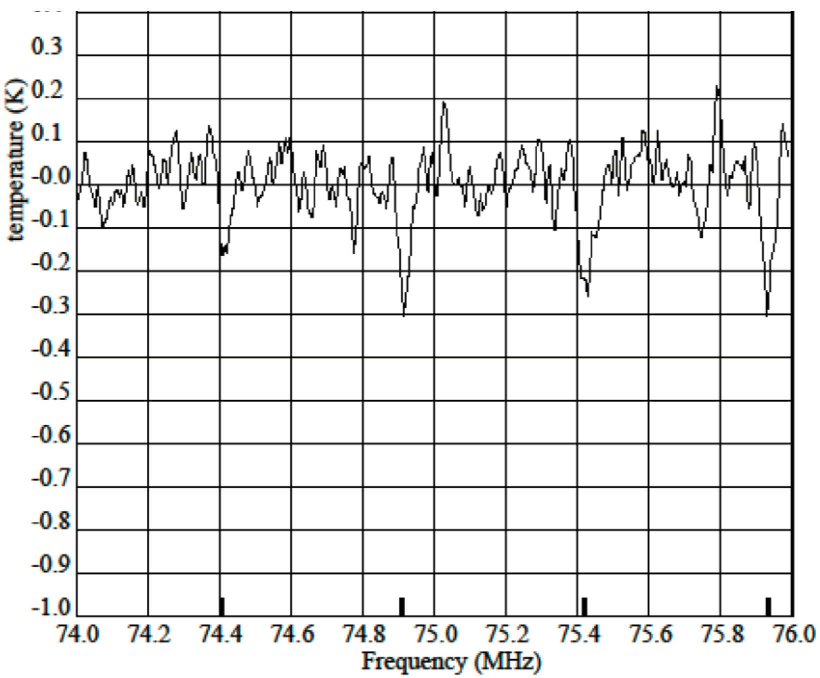
Additional constraints from EDGES



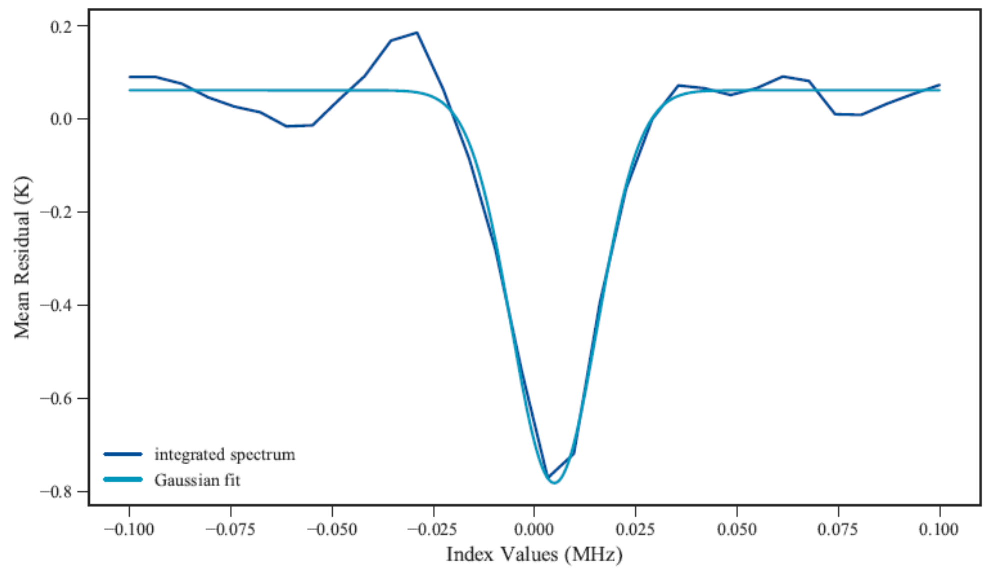
Example top 5% of parameter combinations most-consistent with data

Monsalve et al. 2017, 2018, 2019

(Galactic) radio recombination lines



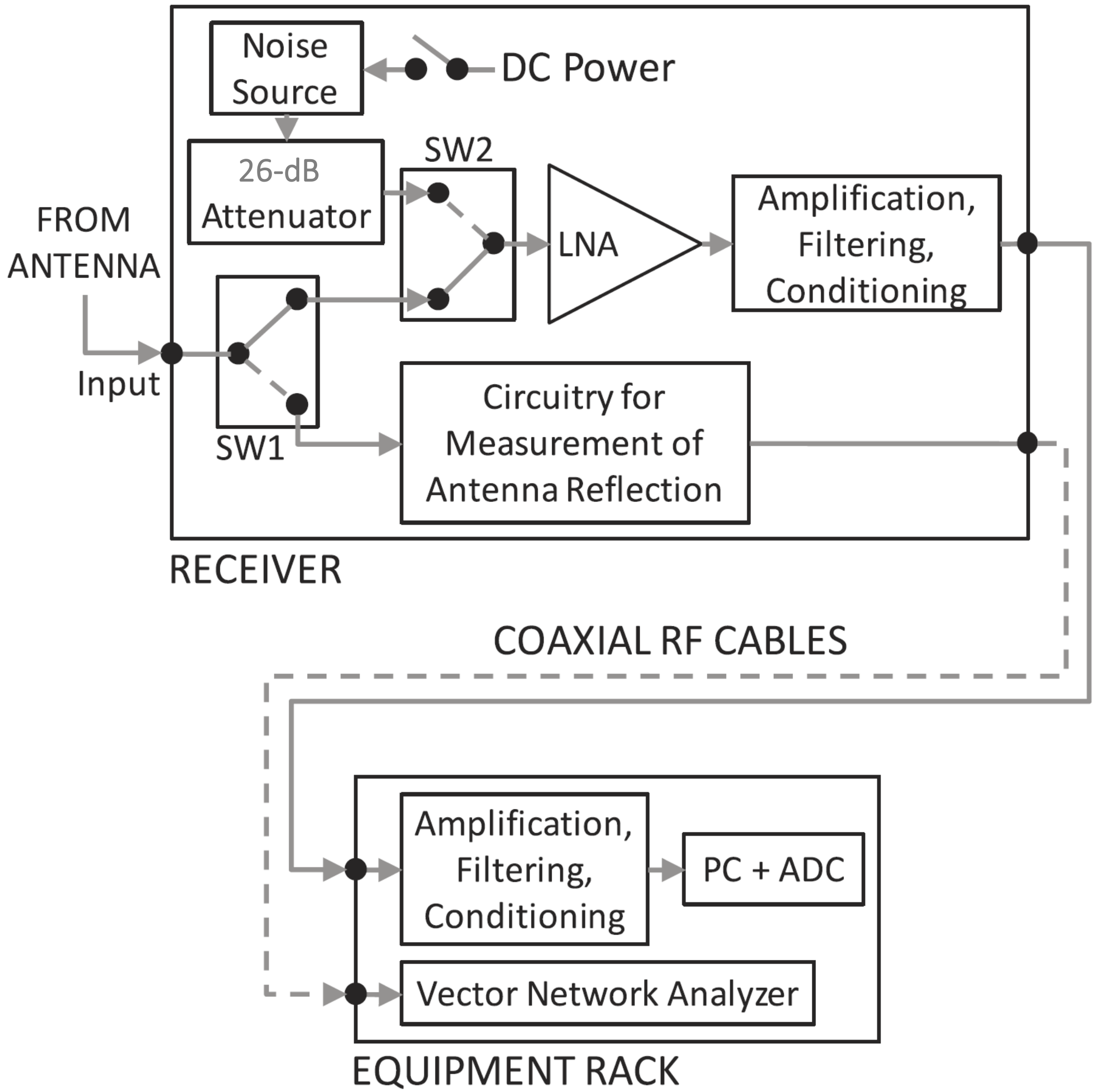
- Carbon lines with n=445, 444, 443 and 442
- GHA=-6 to +6 hours



- Stacked from 50 to 86 MHz
- 85 lines
- GHA = -1 to +1 hours
- Small bump from hydrogen alpha emission? (30 kHz less than carbon)

A. Rogers & K. Crawford

EDGES-2: Block diagram



R. Monsalve

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