Updates from EDGES

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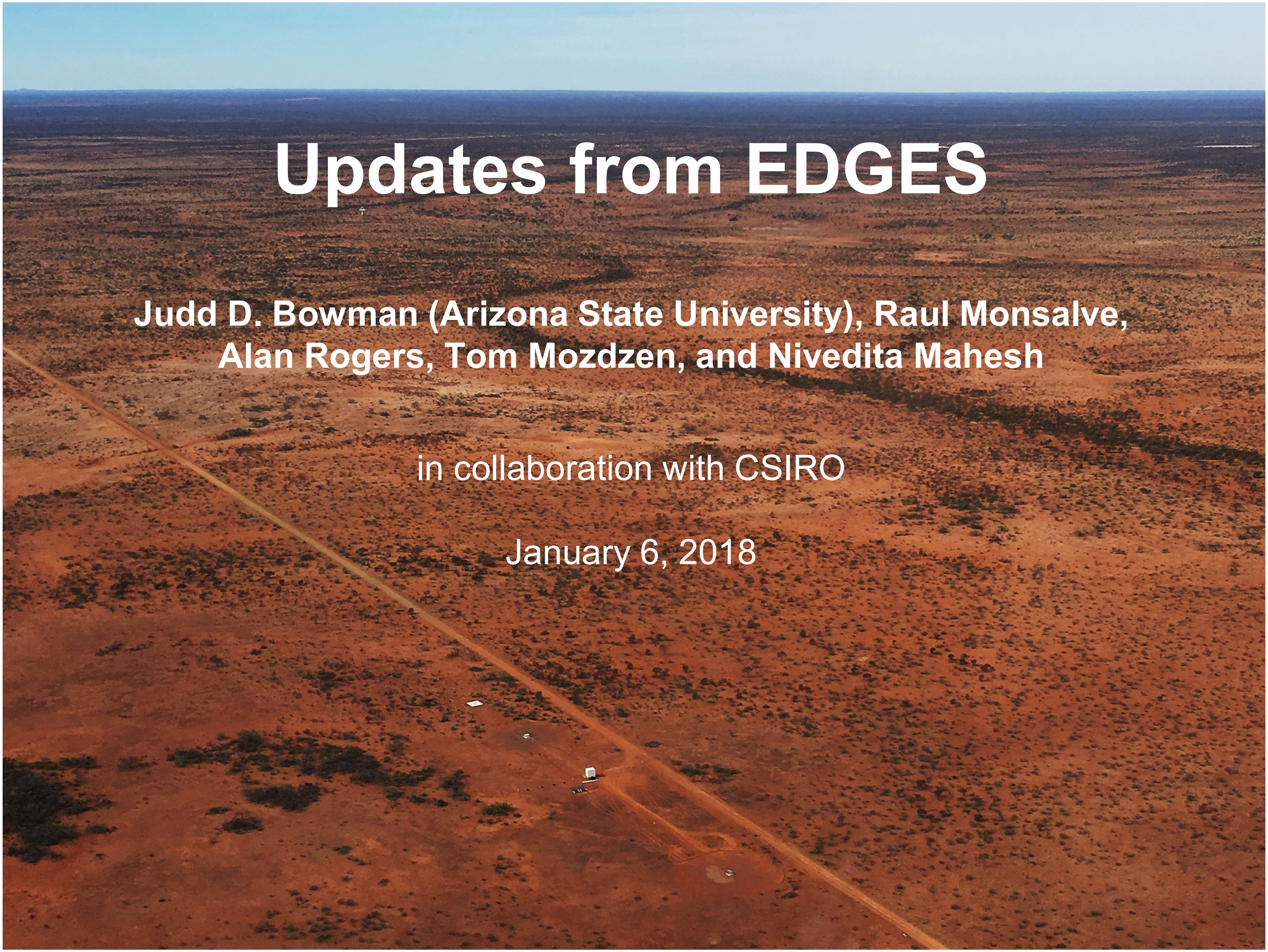
in collaboration with CSIRO

January 6, 2018



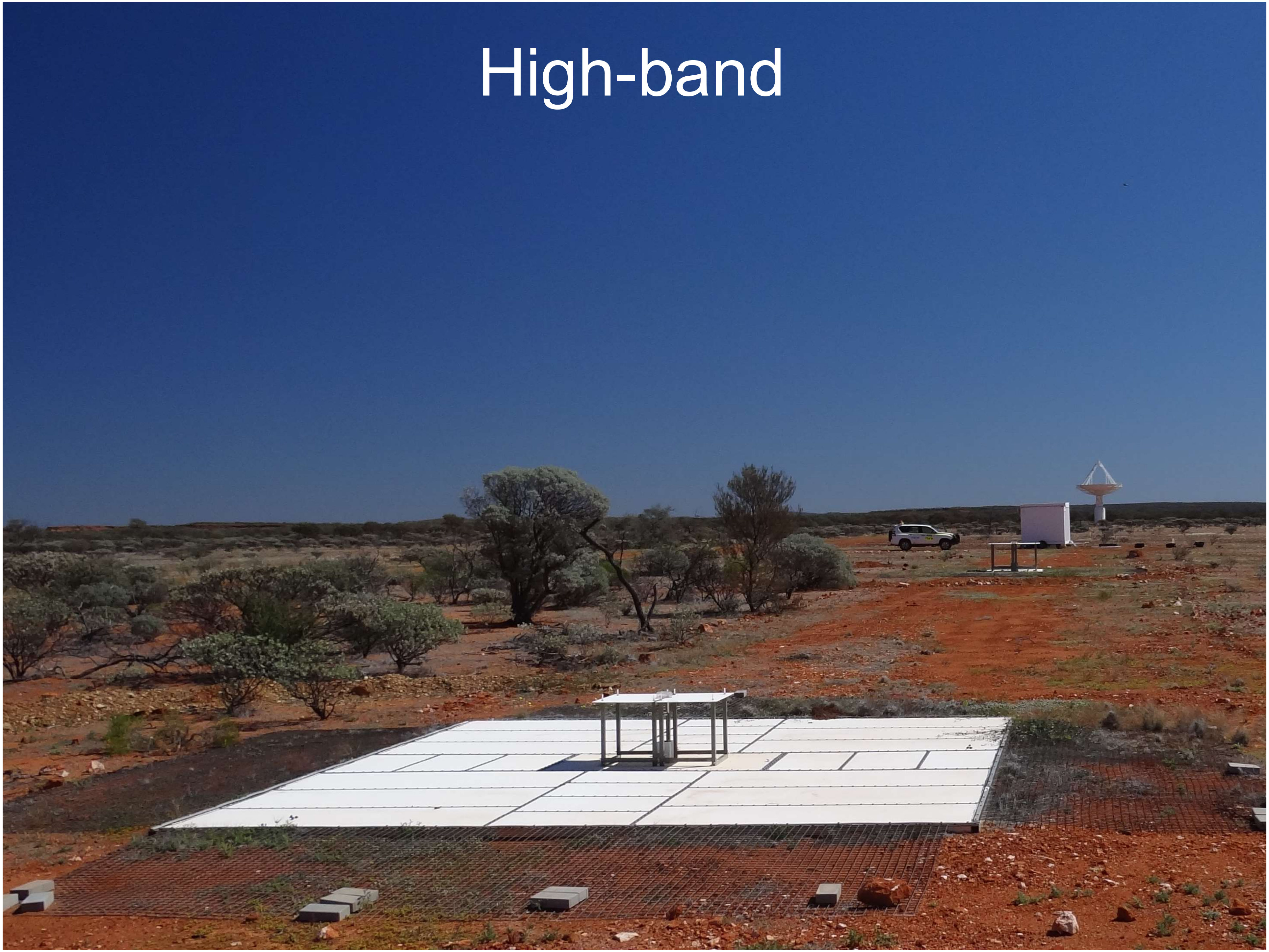
EDGES-2 (since 2012)

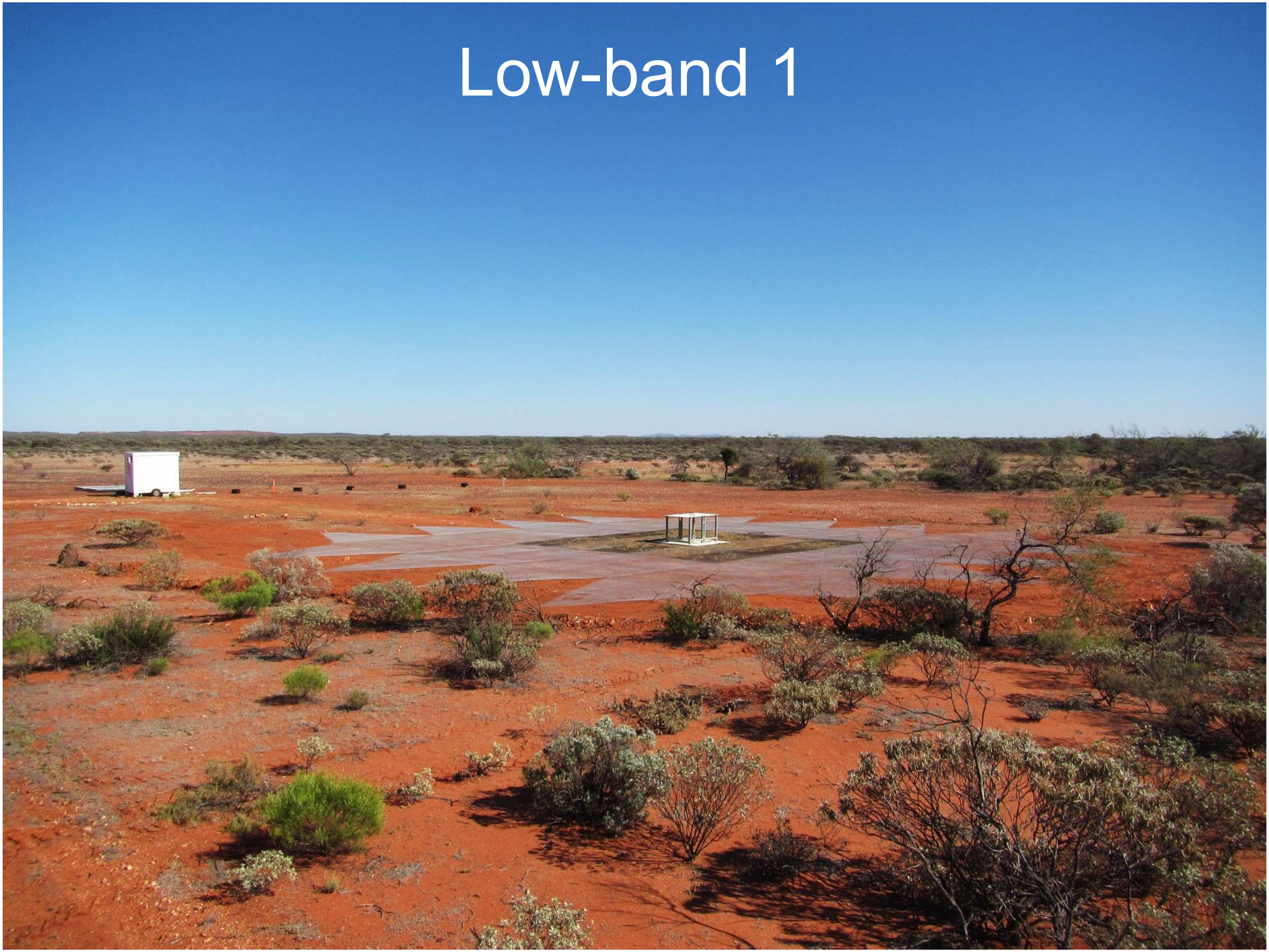
- Goal
  - Detect/constrain reionization durations less than $\Delta z \sim 1\text{-}2$
  - Detect/constrain Cosmic Dawn absorption trough
- Design
  - Two frequency bands, two instruments:
    - Low-band: 50-110 MHz (25>z>12)
    - High-band: 90-200 MHz (14>z>6)
    - Balance between antenna reflection coeff. and beam chromaticity
  - Absolute calibration of receiver and antenna
- Calibration procedure
  - In the lab: First-principle sources (cables, loads, reflection coeffs., varying temperatures, etc.)
  - In the field: Reflection measurement of antenna, 3-position switch
  - In processing: Galaxy up/down to provide a calibration signal for the entire system

Rogers & Bowman 2012

Recent history of configurations

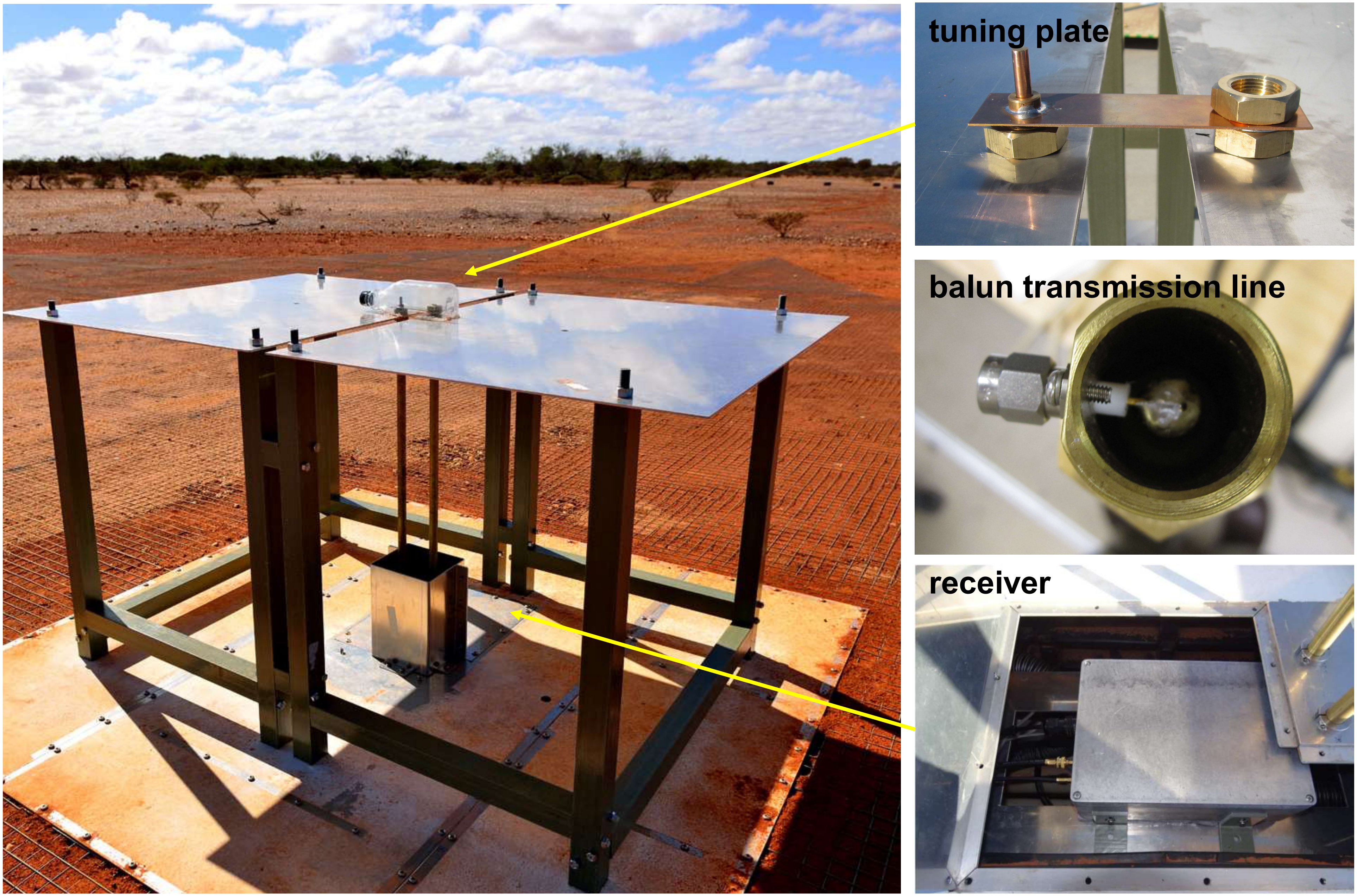
• High-band	2015 → 2016
• Low-1 with 10x10 meter ground plane	2015-07 → 2016-09
• Low-1 with 30x30 meter ground plane	2016-09 → 2017-04
• Low-1 with 30x30 meter ground plane and recalibrated receiver	2017-05 → 2017-07
• Low-2 with north-south dipole orientation	2017-03 → 2017-05
• Low-2 with east-west dipole orientation	2017-05 → 2017-06
• Low-2 with east-west dipole orientation and balun shield removed	2017-06 → present


High-band

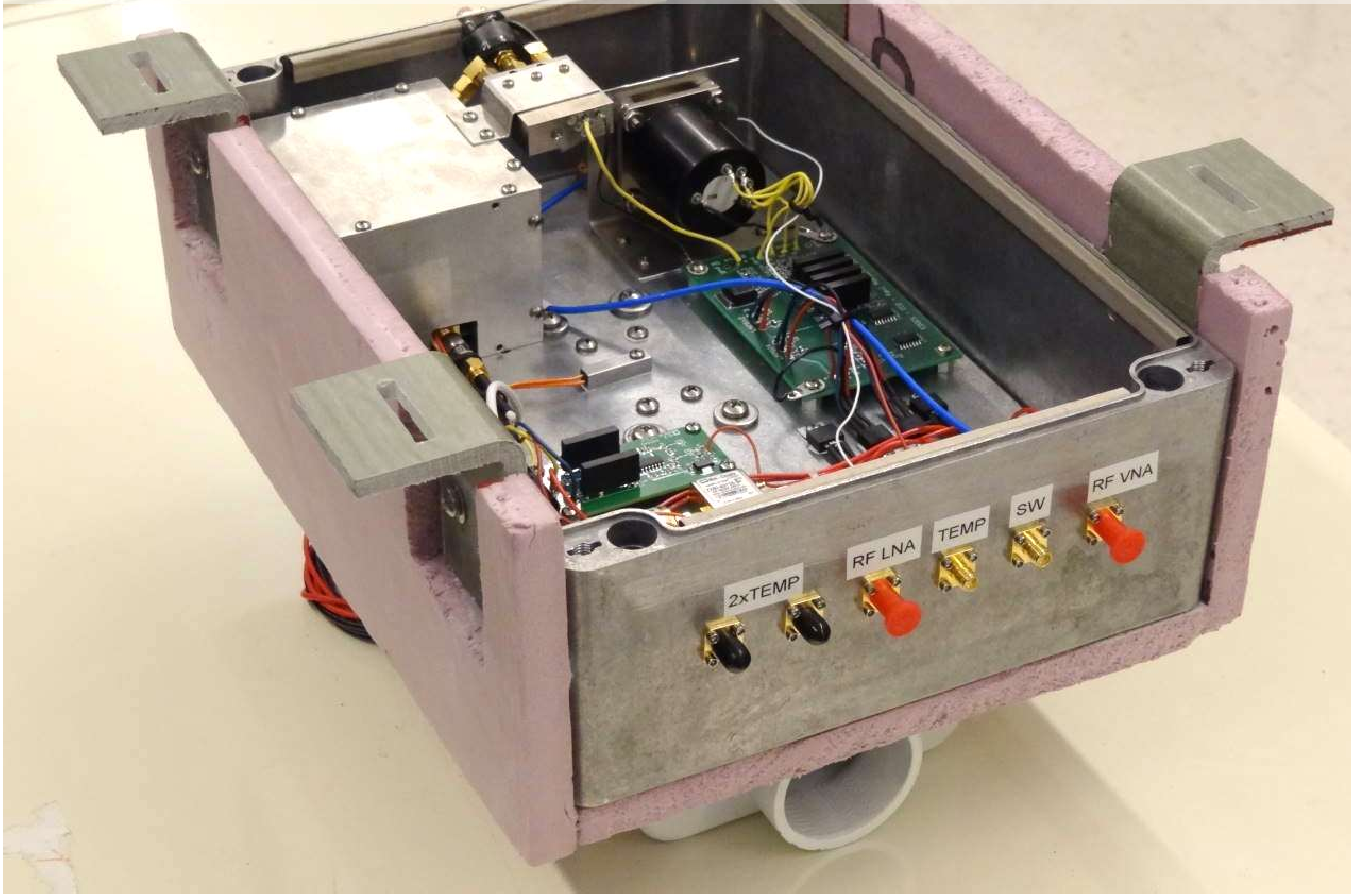

Low-band 1


Low-band 2

Antenna and balun

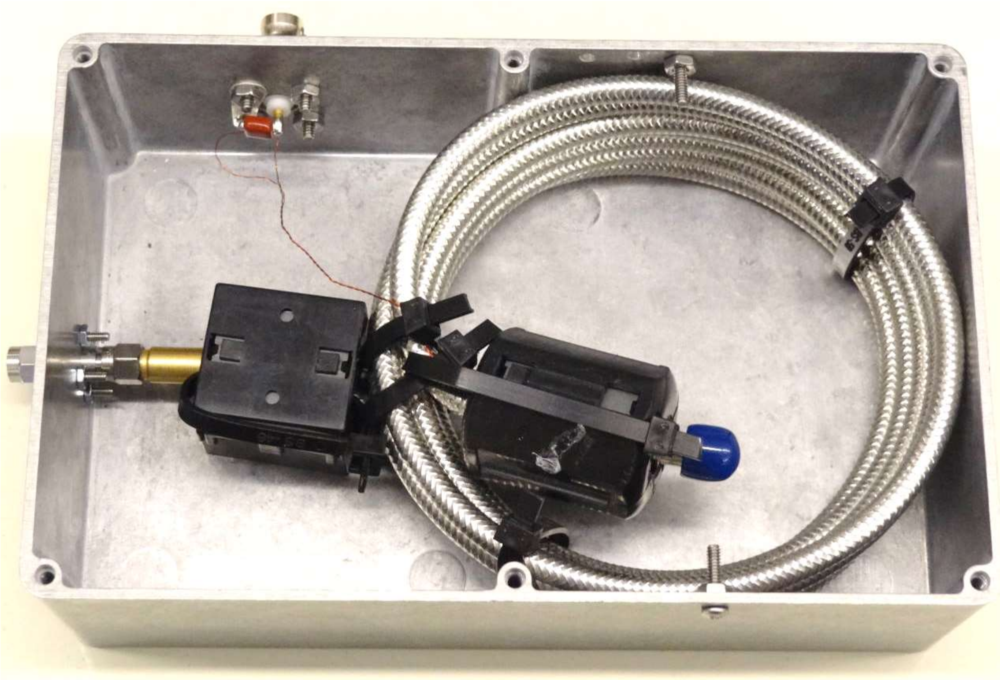


Receiver (high-band)



Laboratory calibration

External calibrator sources



(above) long cable

(right) ambient/hot load

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Calibration formalism

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

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

- Absolute calibration:

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

with:

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

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

See Monsalve et al. 2017a; Rogers & Bowman 2012; Bowman et al. 2008; Meys 1978

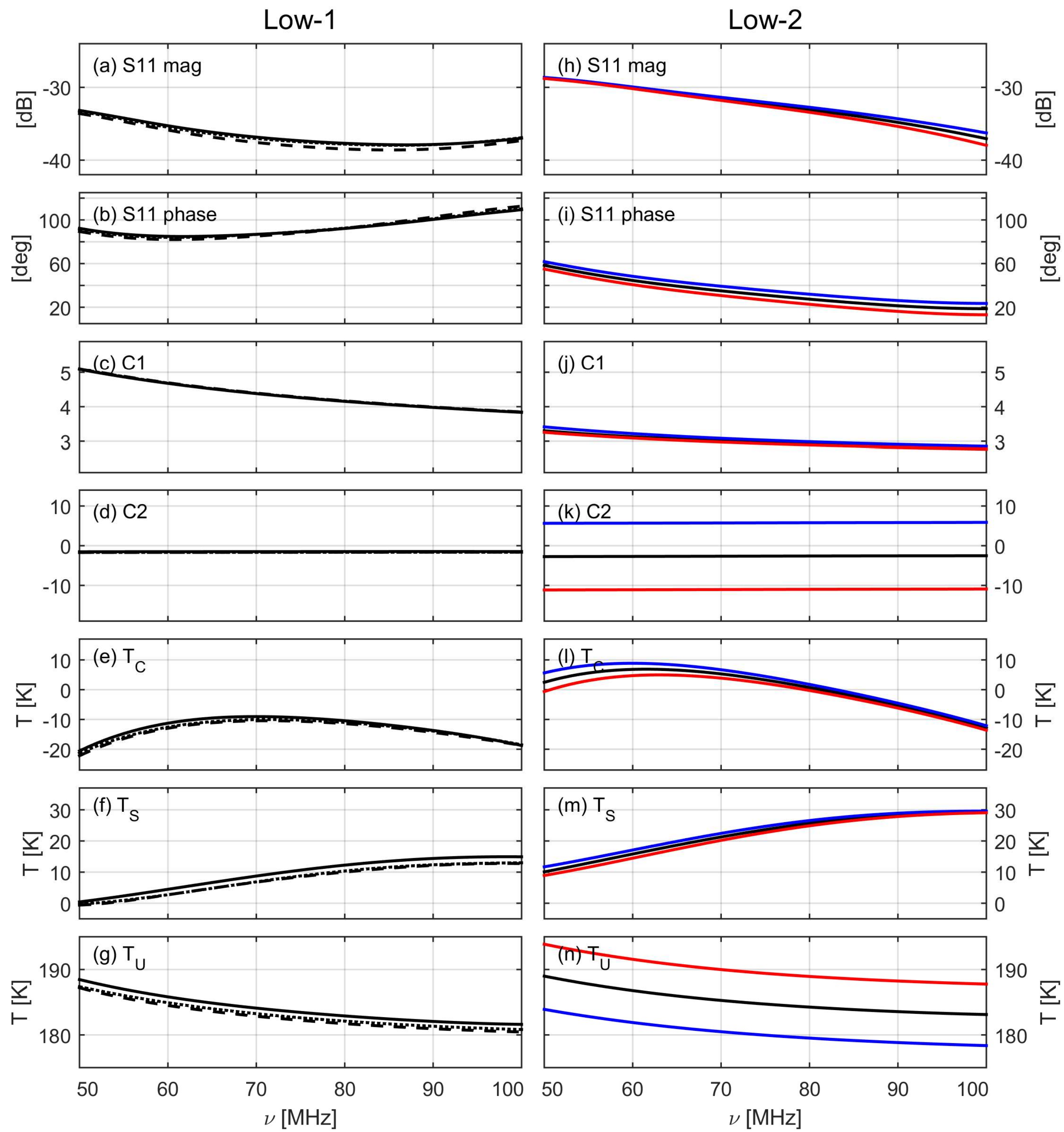
Calibration solutions

Low-1 (left): three different calibration measurements

- August 2015
- May 2017
- September 2017

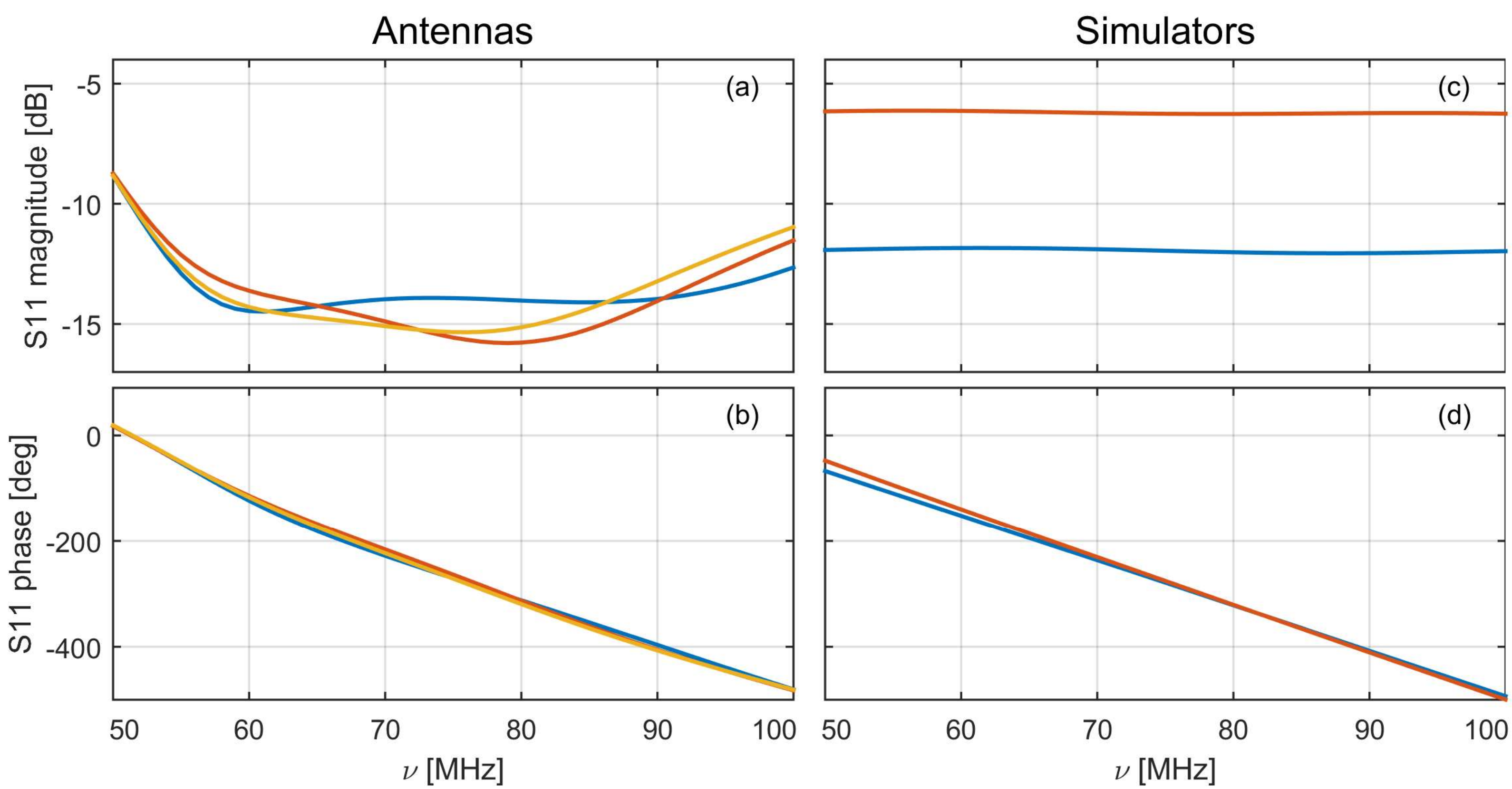
Low-2 (right): three receiver set-point temperatures:

- 15°C (blue)
- 25°C (black)
- 35°C (red)



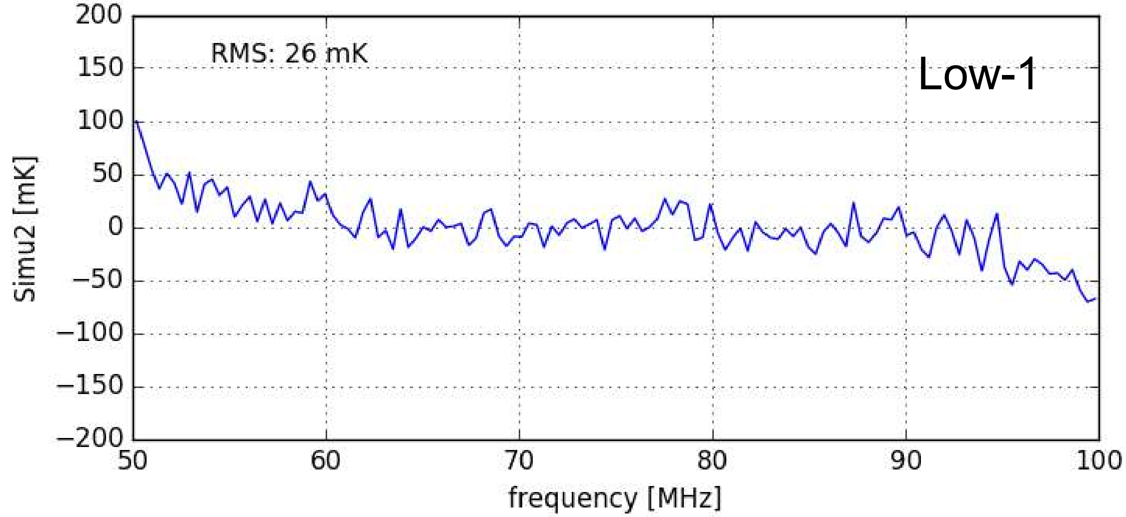
Antenna S11

- Measured in-situ using VNA pathway in receiver:
  - Low-1 (blue), Low-2 (green), and Low-2 no balun shield (red)
  - Identically designed, but each antenna tuned manually during installation
- Simulators used in laboratory for validation tests
  - 300 K 6dB attenuator connected through cable for phase (blue)
  - 10,000 K noise source connected through 3dB attenuator and cable for phase (red)

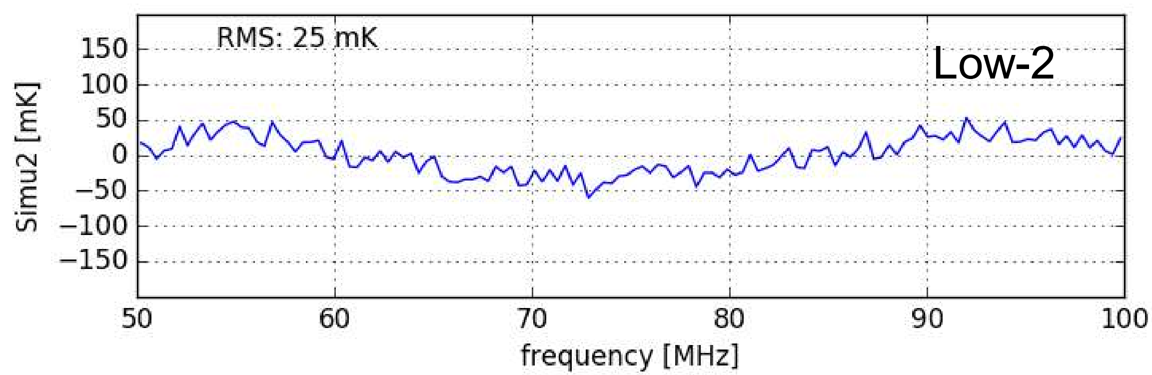


Example antenna simulator tests

- 300 K 6dB attenuator
  - Corrected for simulator S11 (previous slide)
  - Residuals after removing best-fit constant



- Similar test performed with 10,000 K noise source simulator (not shown)



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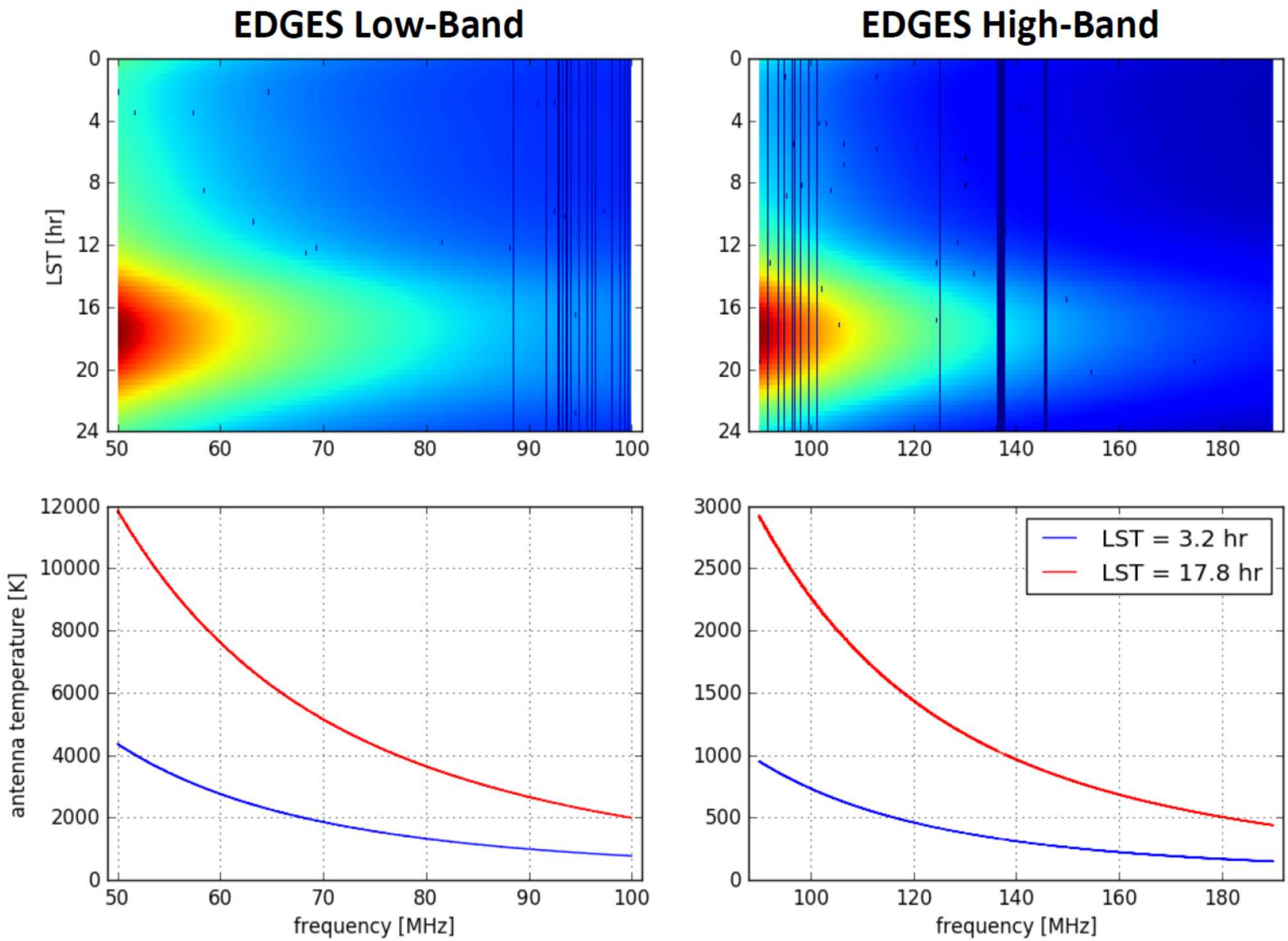
EDGES Low-Band
EDGES High-Band
LST [hr]
antenna temperature [K]
frequency [MHz]
frequency [MHz]
LST = 3.2 hr
LST = 17.8 hr

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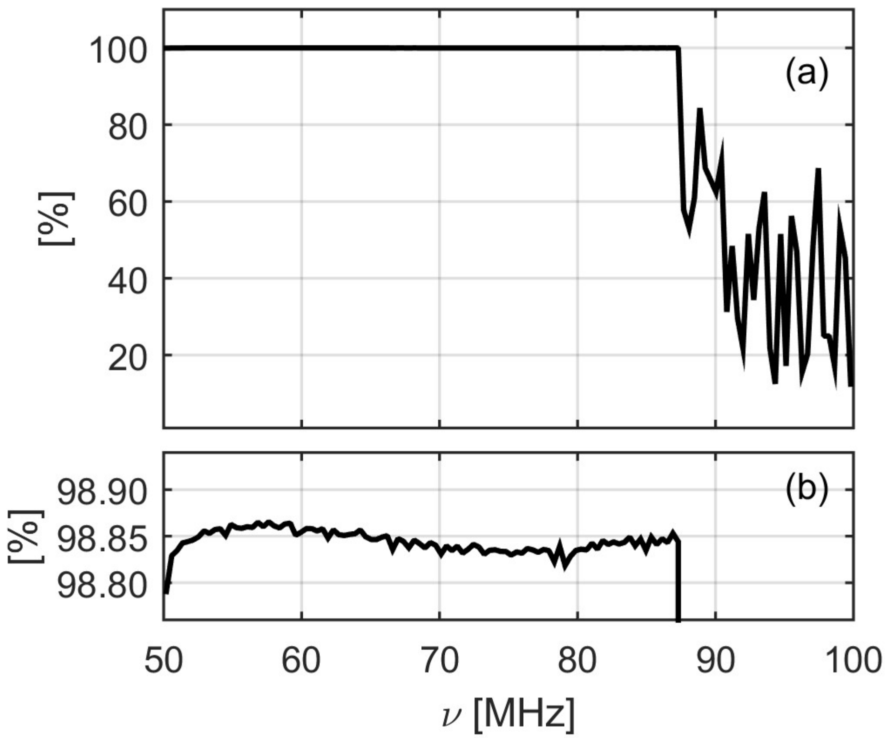
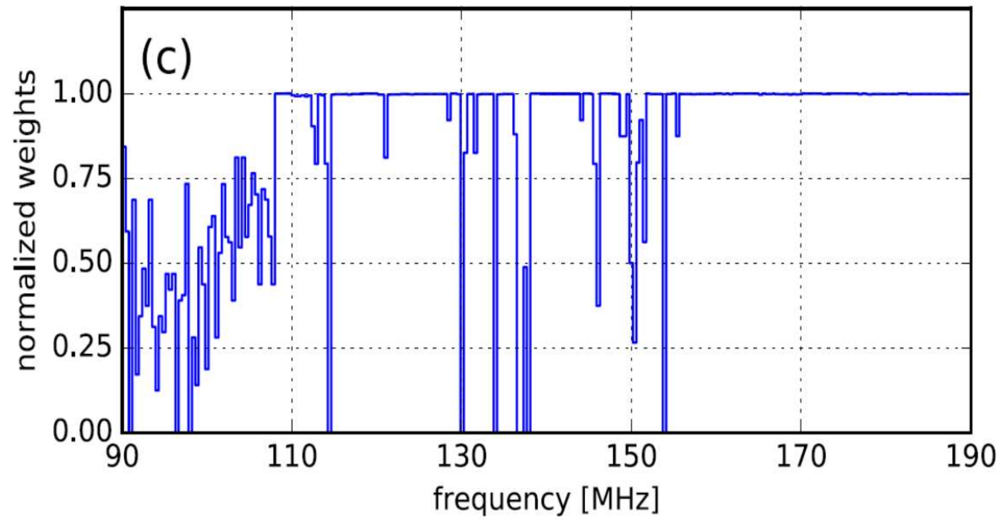
Channel weights (RFI occupancy)

Low-band



High-band



- Hundreds of nights in each band
- Very clean below FM band

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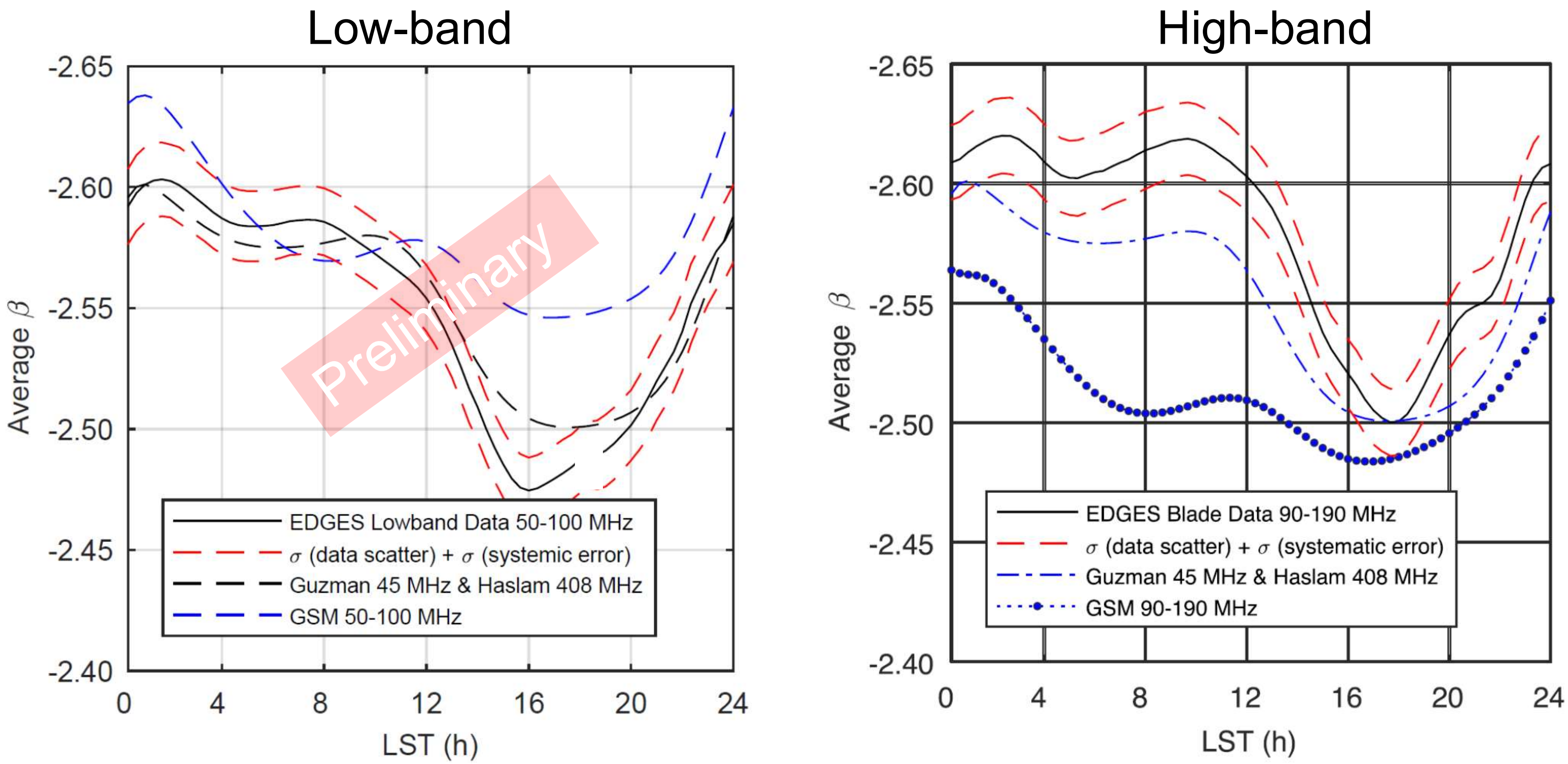
Diffuse spectral index

Fit Model:
Two-parameter Power Law:

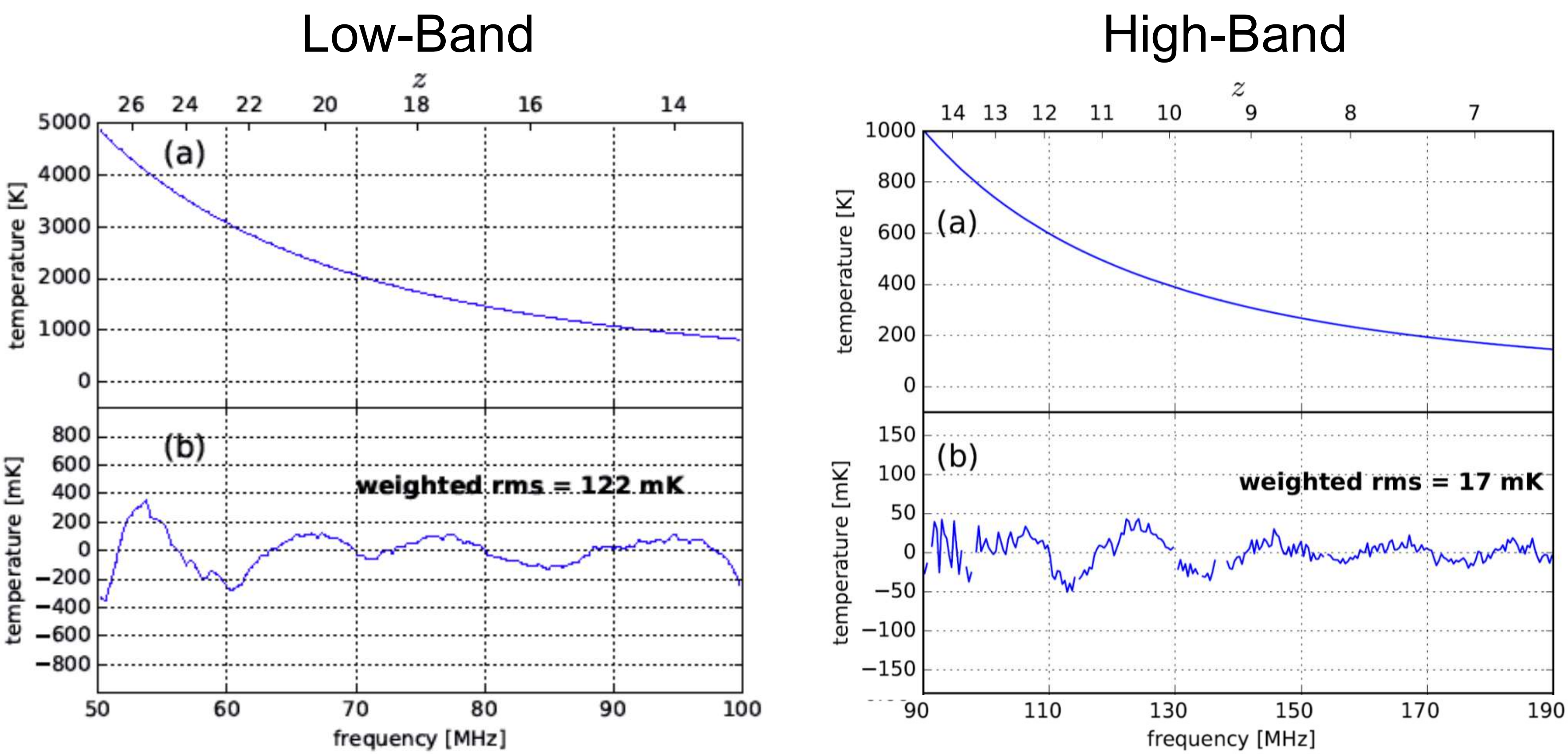
$$T_{\mathrm{sky}}(\upsilon) = \boldsymbol{T_{150}} \left(\frac{\upsilon}{150\ \mathrm{MHz}}\right)^{+\boldsymbol{\beta}} + T_{\mathrm{CMB}}$$



- Typical residuals ~ 0.1%
- GSM (de Oliveira-Costa et al. 2008) poor fit at high latitudes
- Still assessing ionosphere impact in low-band

Mozdzen et al. 2017
Mozdzen & Mahesh, in prep

Long integration residuals (typical)



- 5-term polynomial fit and removed, RMS < 0.01% sky power
- Hundreds of nights in each band

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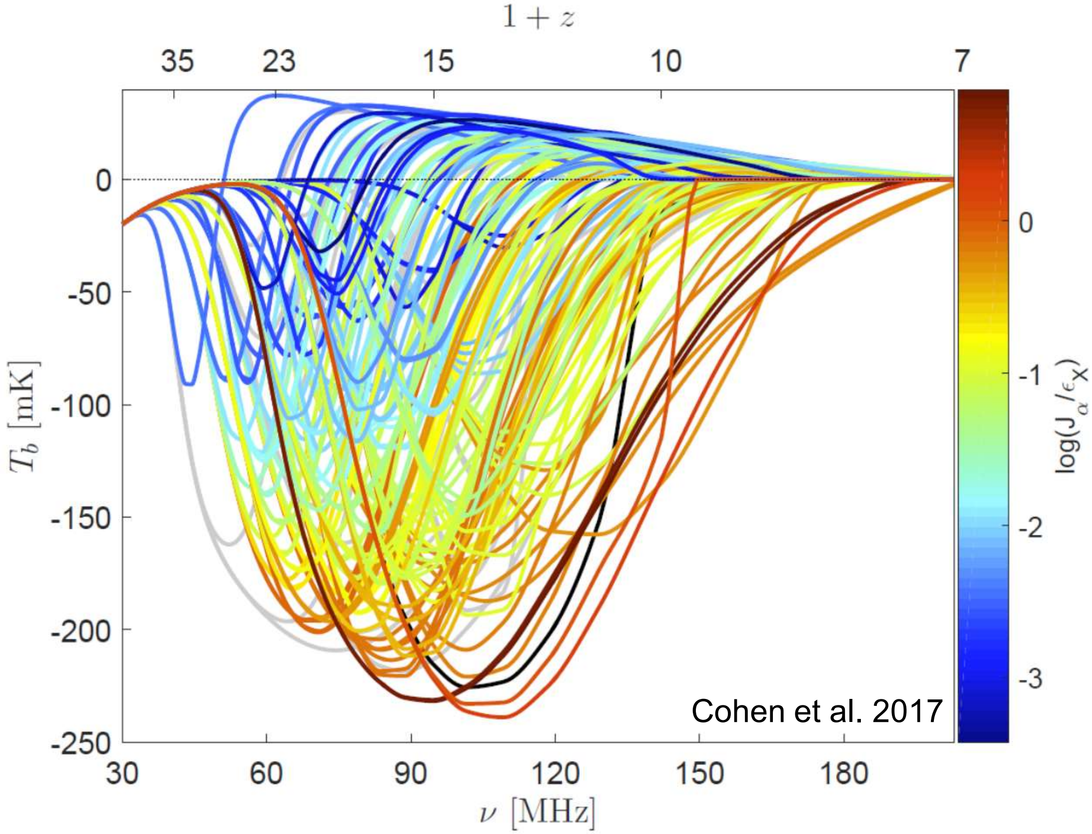
EDGES reionization analysis

- Three general scenarios
  - High X-ray emission – gas is *hot* during reionization (blue curves)
  - Low X-ray emission – gas is *cold* during reionization (red curves)
  - Low X-ray and late UV – late Gaussian-like absorption feature
- Sample of specific astrophysical models



Phenomenological models

<u>21 cm model</u>

$$T_{21}(z) = a_0 \; x_{HI}(z) \left[\frac{1+z}{10}\right]^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)}\right] \text{mK}$$

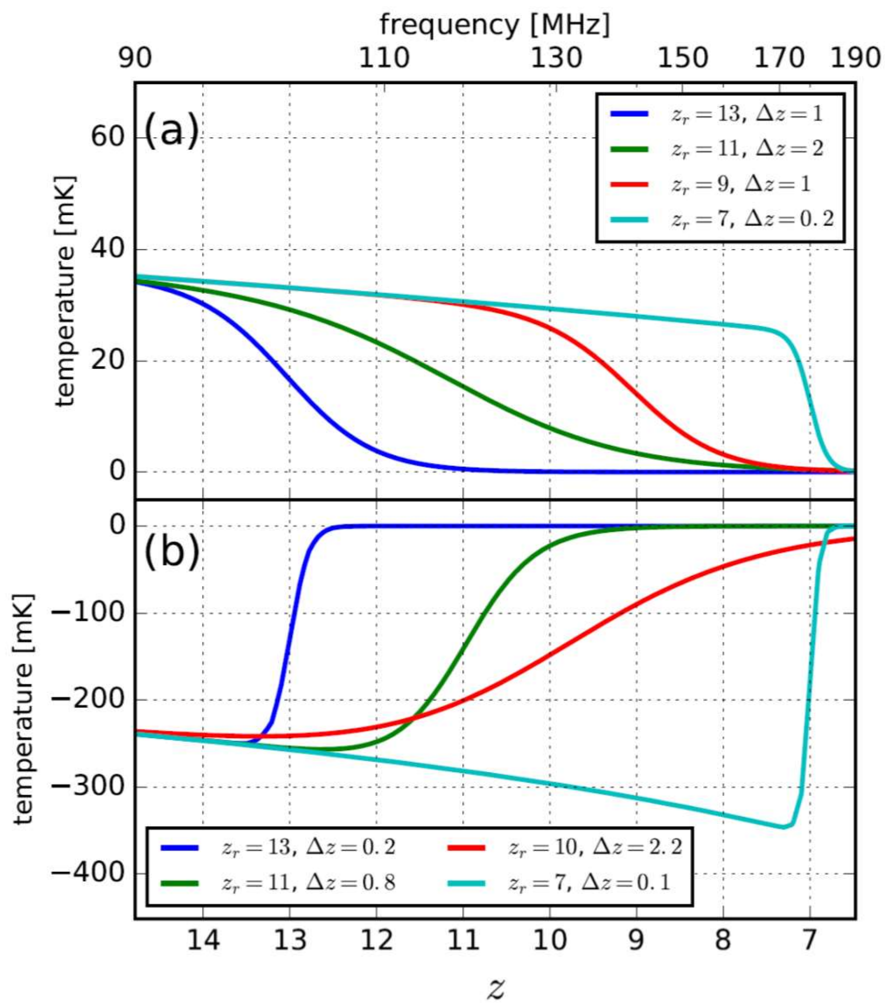
Hot and cold IGM models (cases a and b) assume:

- Saturated spin temperature (T_s = T_{gas})
- *tanh* reionization

$$x_{\mathrm{HI}}(z) = \frac{1}{2}\left[\tanh\left(\frac{z - z_r}{\Delta z}\right) + 1\right]$$

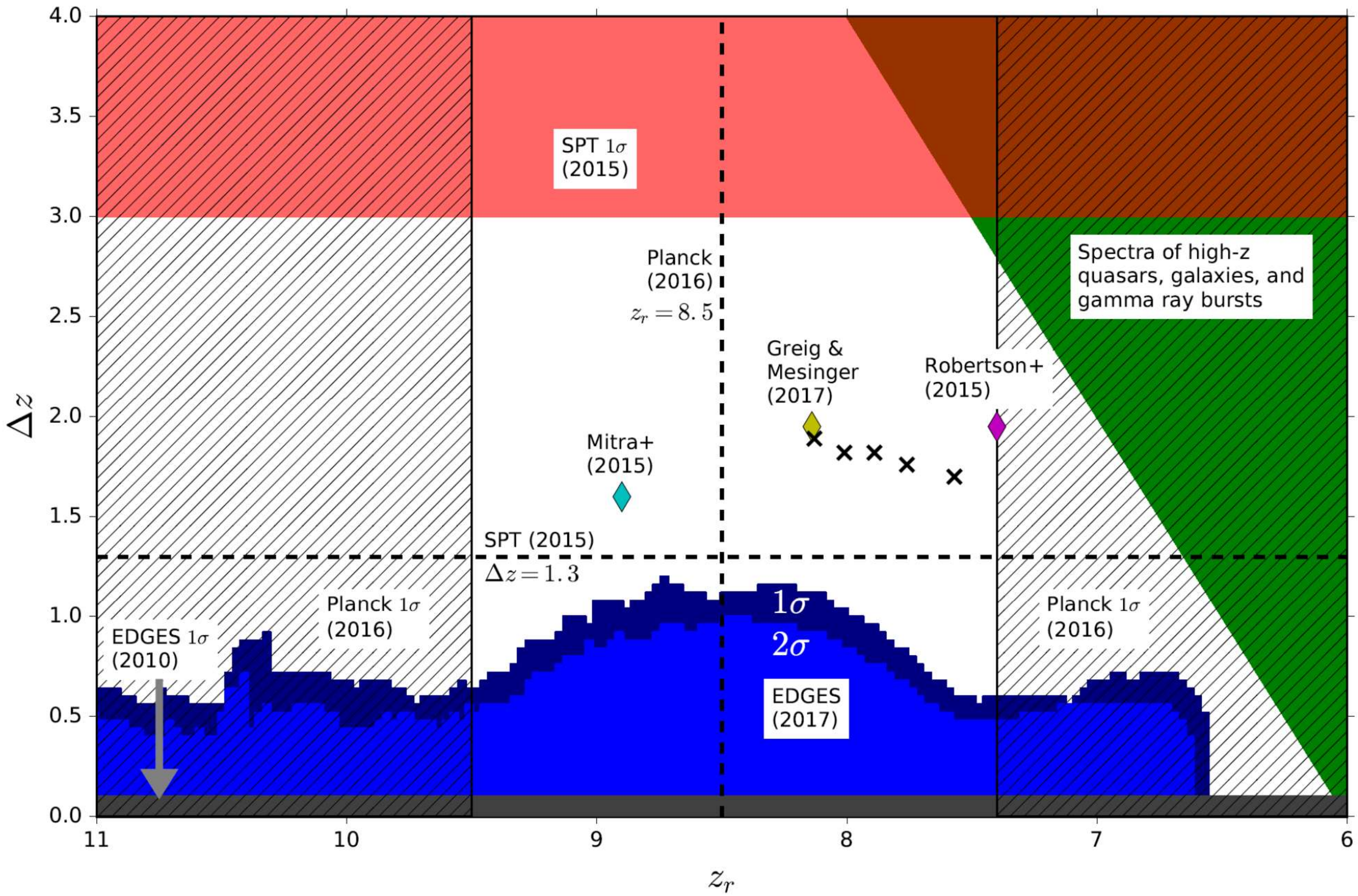
<u>Foreground model:</u>

$$\hat{T}_{\mathrm{fg}}(\nu) = \sum_{i=0}^{4} a_i \nu^{-2.5+i}$$



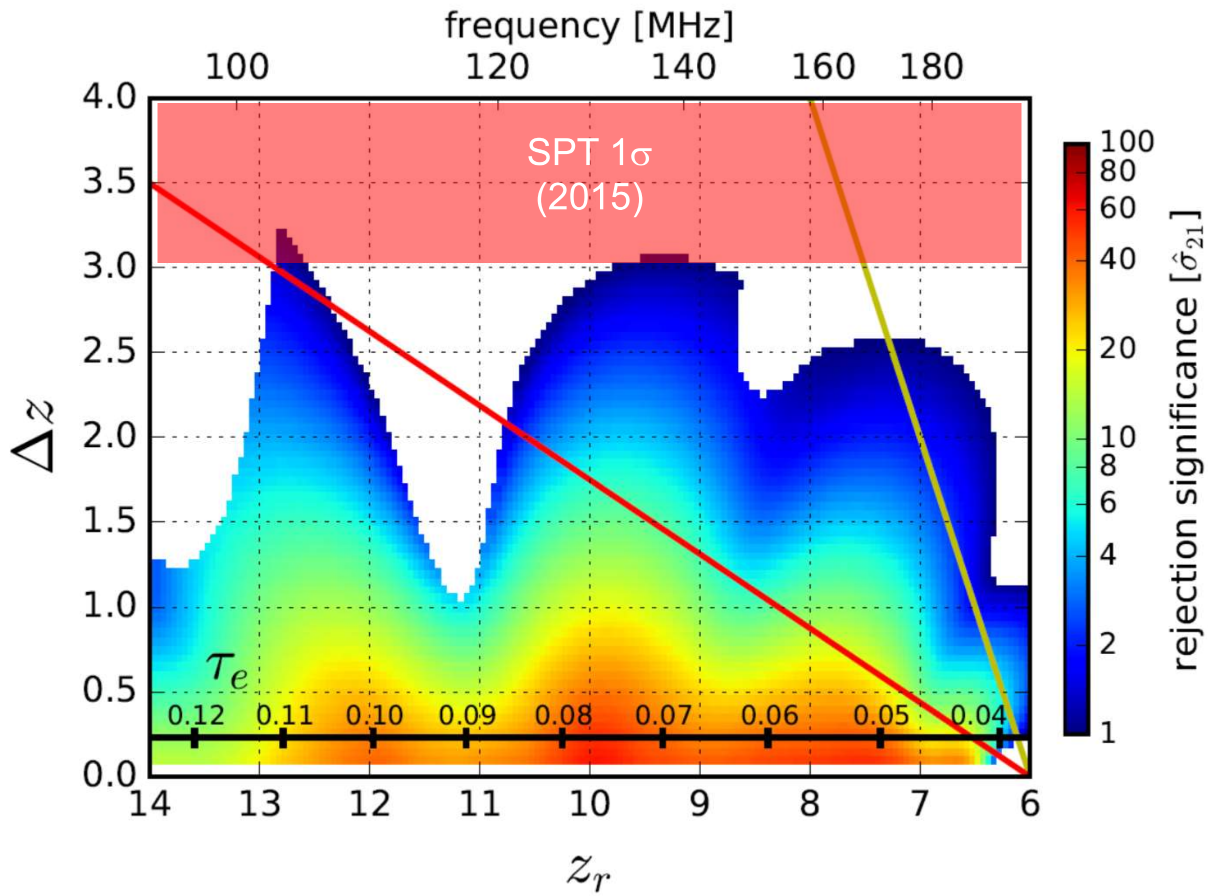
Monsalve et al. 2017b

Hot gas: EDGES plus external limits



Monsalve et al. 2017b

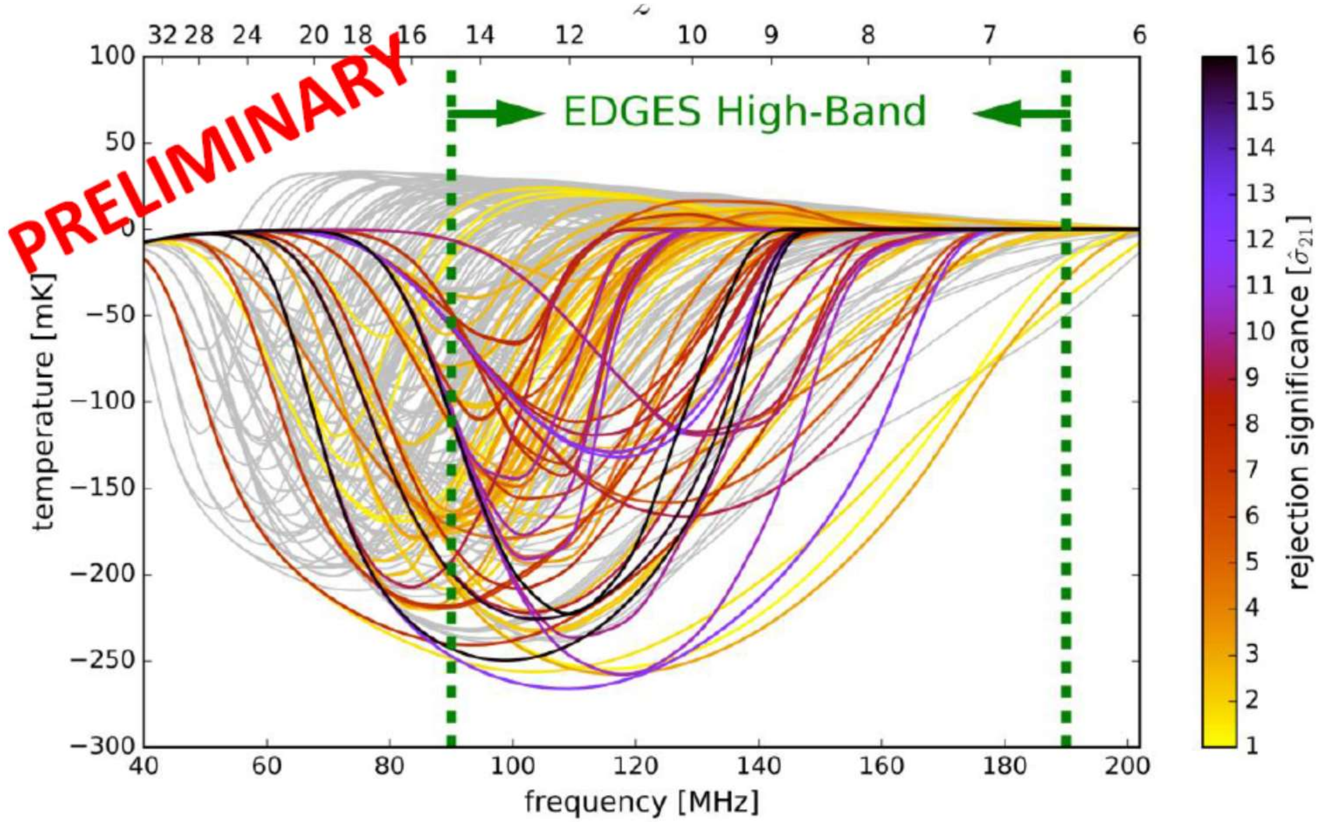
Cold gas: constraints on duration



- 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

Disfavored astrophysical models

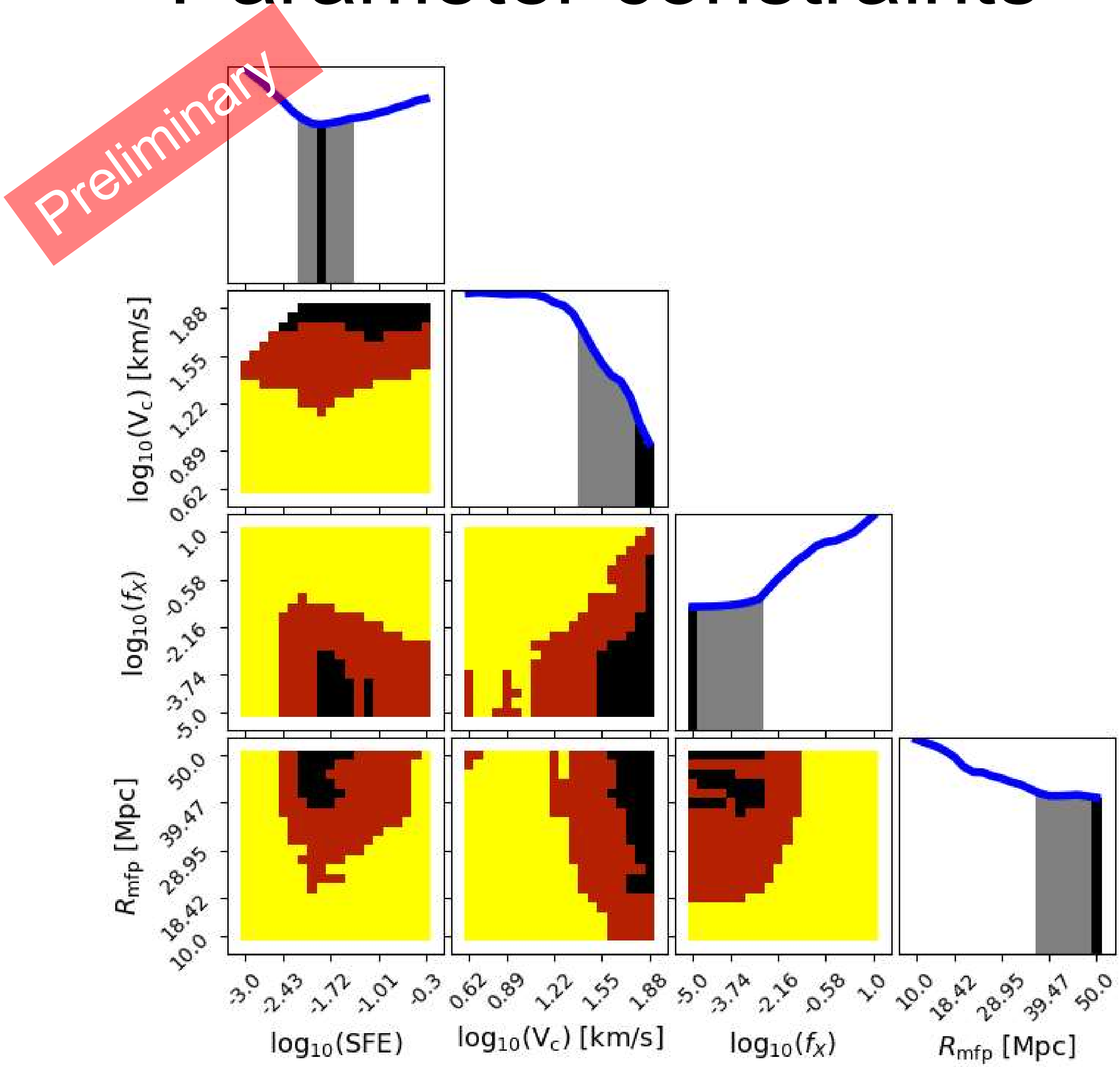


- Numerical simulations from Fialkov et al. (2016), Cohen et al. (2017)
  - Probing: star formation efficiency, minimal mass of star-forming halos, efficiency and spectral distribution of X-ray sources, reionization history

- Also investigating Mirocha et al. and Greig & Mesinger (21CMFast) models

Monsalve et al., *in prep*

Parameter constraints



Monsalve et al., *in prep*

Conclusion

- EDGES-2 based on absolute calibration and antenna trade-off design
  - Improved calibration and characterization of VNAs at low-frequencies (Monsalve et al. 2016)
  - Antenna simulators and laboratory calibration standards
  - Detailed error propagation analysis (Monsalve et al. 2017a)
  - Antenna design and EM model verification (Mozdzen et al. 2016, Mahesh et al., in prep)

- Science results:
  - Reionization constraints (Monsalve et al. 2017b)
    - Constrained “standard” reionization duration to Δz > ~1
    - Disfavored “cold” reionization models
  - Astrophysical parameter constraints during reionization (Monsalve et al., in prep)
  - Improved spectral index measurements of diffuse radio emission (Mozdzen et al. 2017, Mozdzen & Mahesh, in prep)

- Ongoing/future work:
  - Low-band analysis
  - Ongoing antenna and receiver improvements
  - Continue annual cadence of deployments and observing