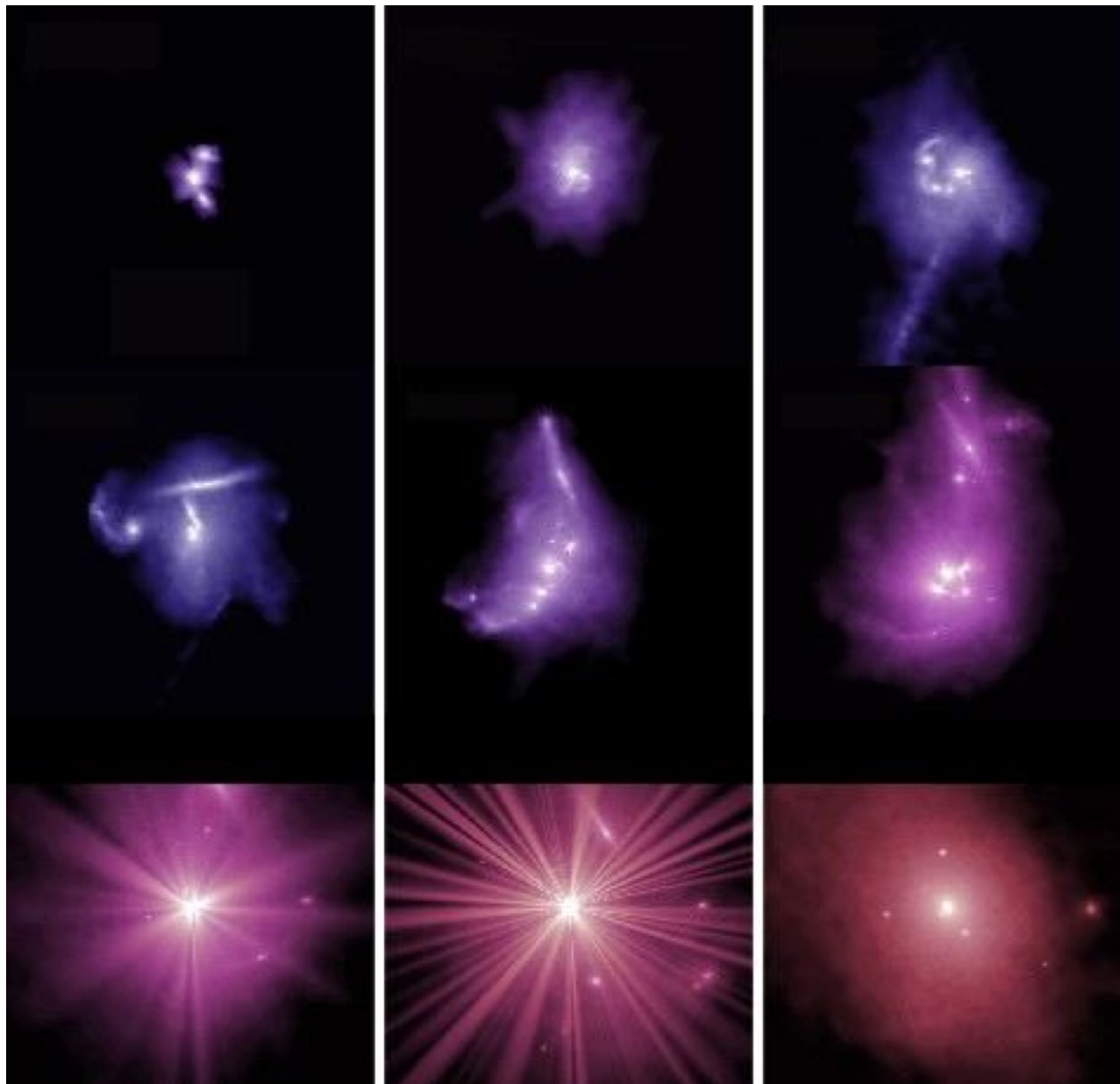
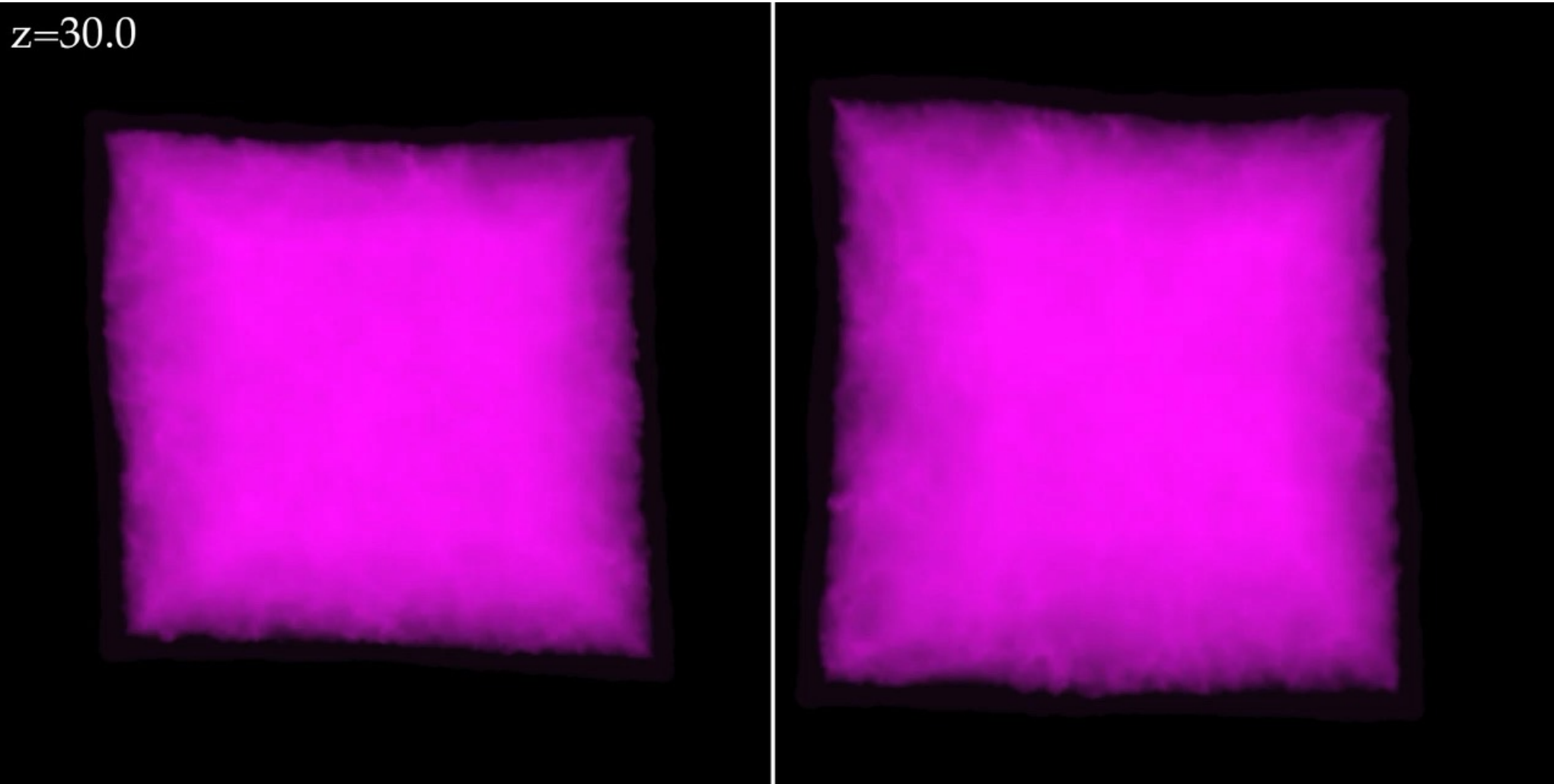


Astronomy 537



FIRE simulation of the creation of a disk galaxy

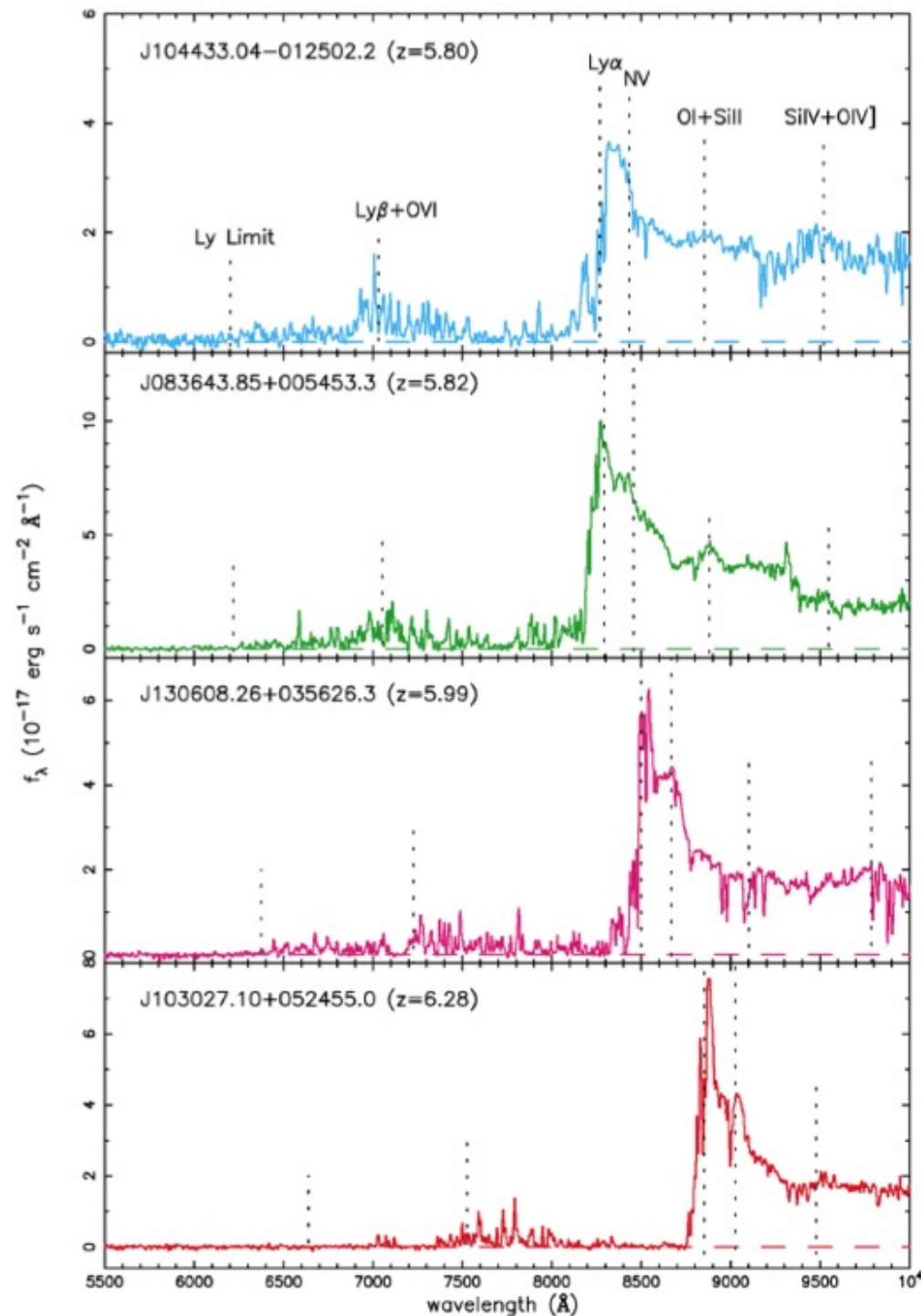


Journal Class

- **Probing diffuse radio emission in bridges between galaxy clusters with uGMRT**
- Pignataro et al. 2024

Discussion leader: **Shane Li**

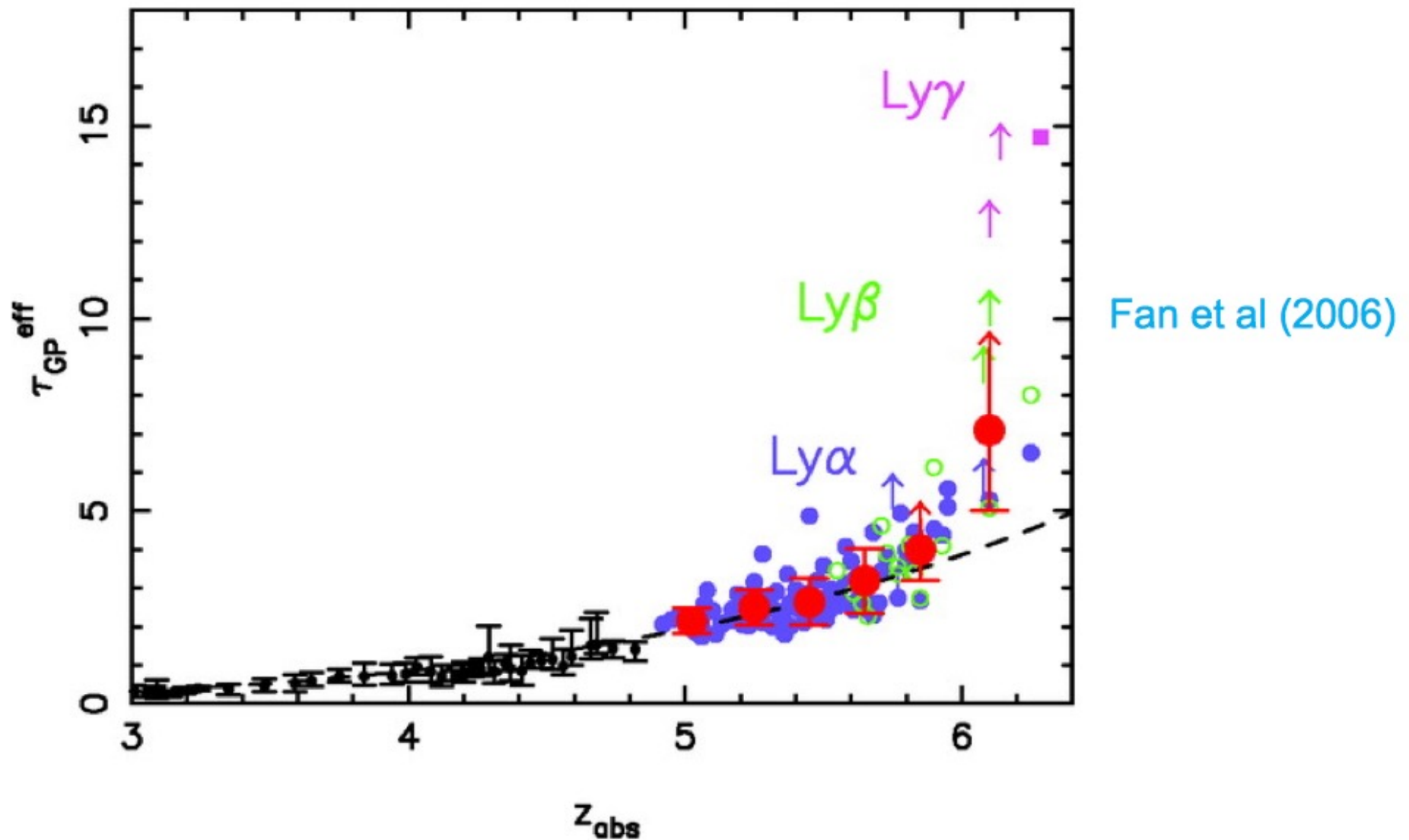
Note: To encourage discussion everybody must pose at least one question during the group discussion



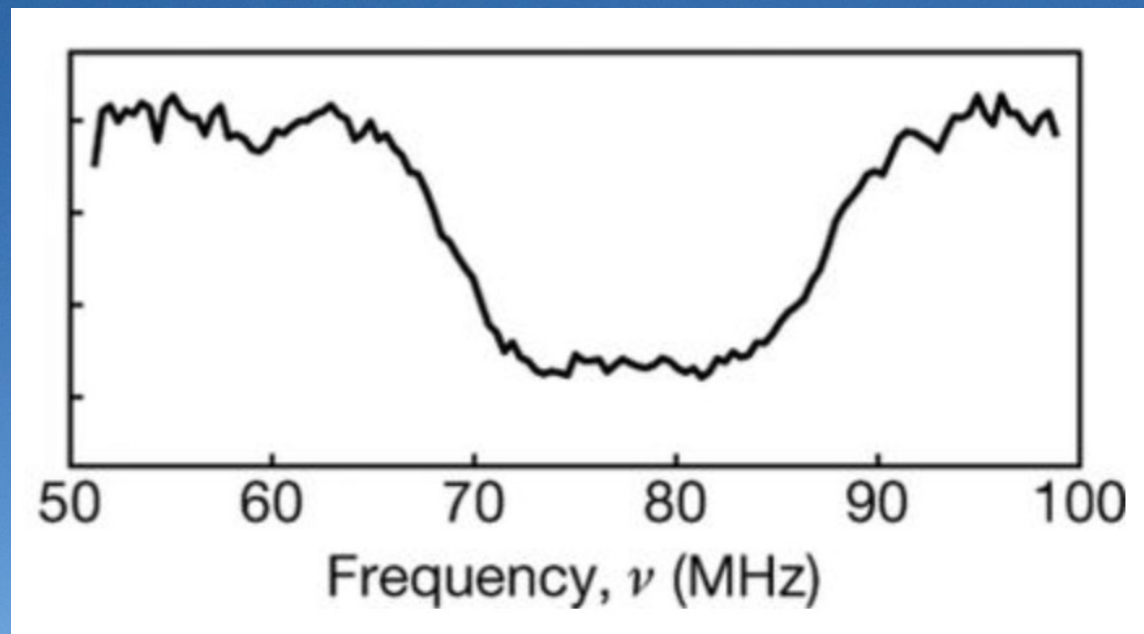
Detection of Gunn-Peterson Troughs in $z \sim 6$ Quasars in 2001

Becker et al (2001)

Rapid increase in H I Opacity at $z \sim 6$



Cosmic Dawn



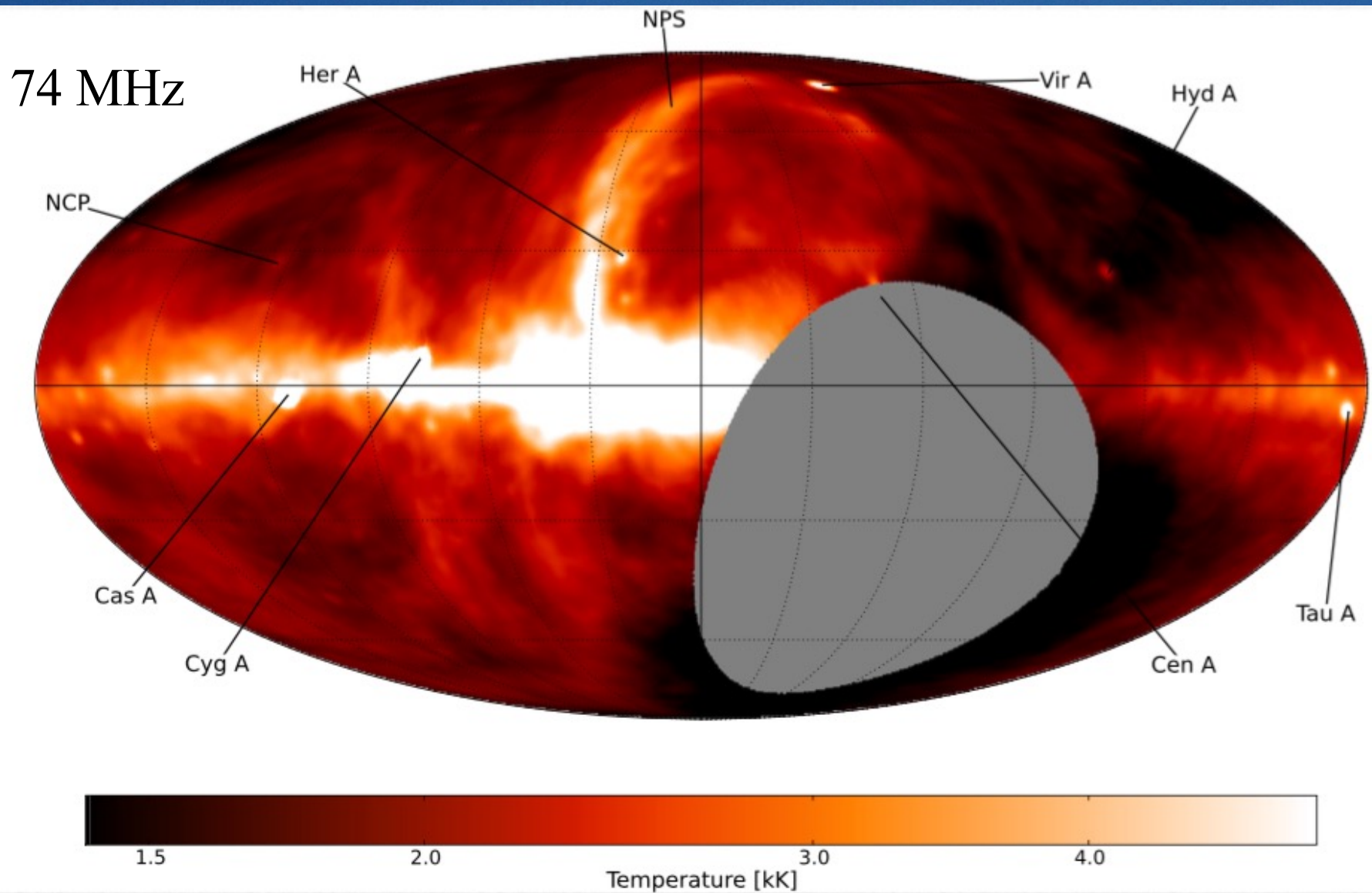
Bowman et al. 2018

Outline

- Introduction to Cosmic Dawn
- How to get it wrong
- How to get it right
- Efforts to confirm the detection



THE SKY

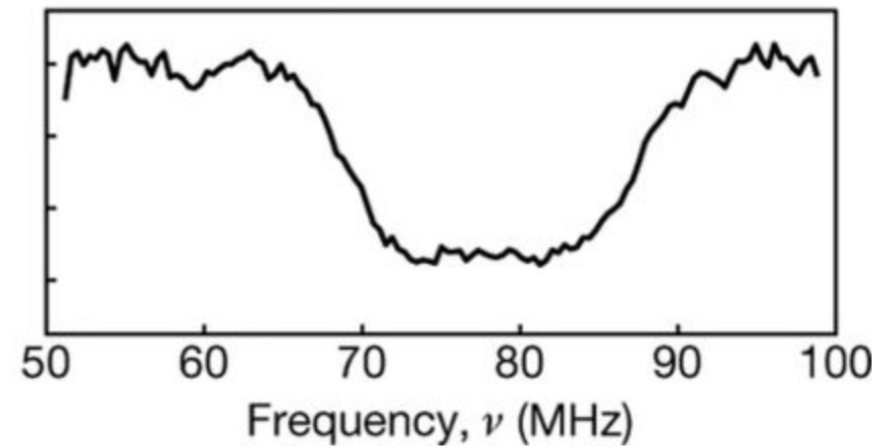
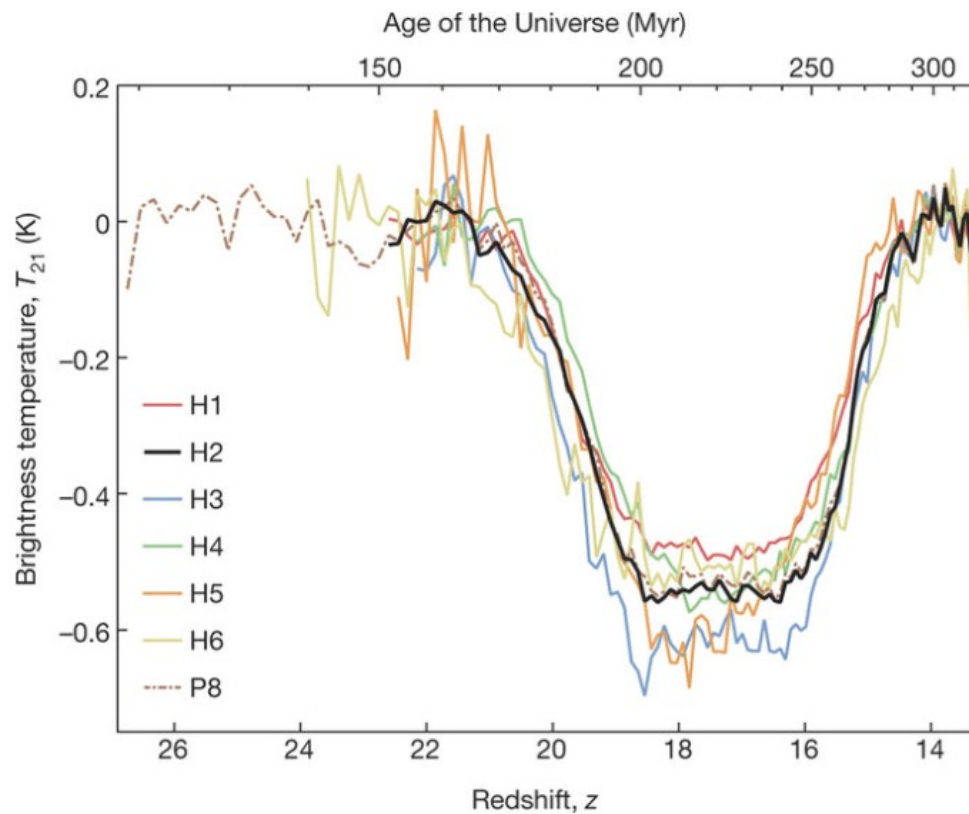


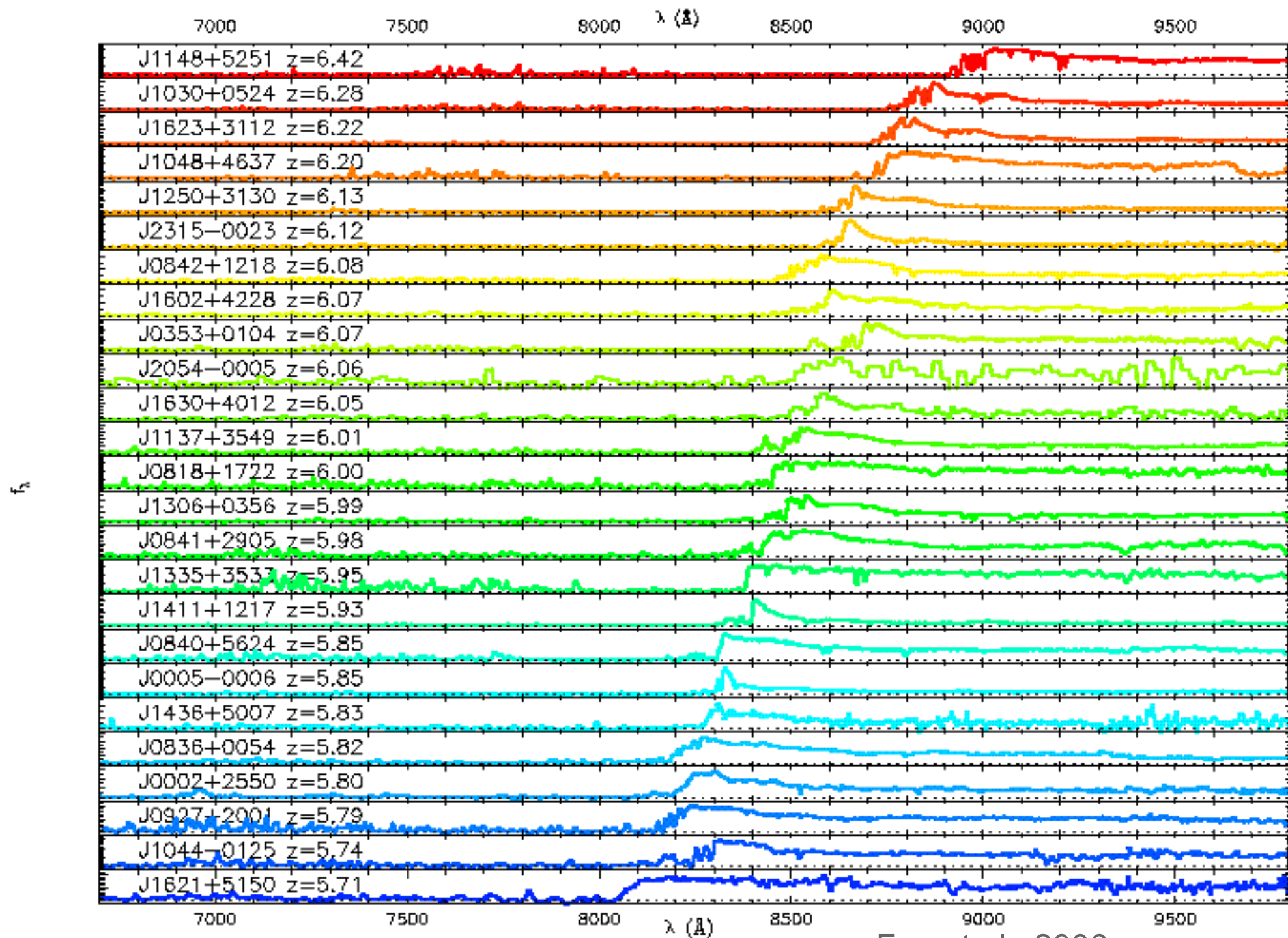
11.09.2014

Dowell et al. 2017

Detection of HI at $z=17$

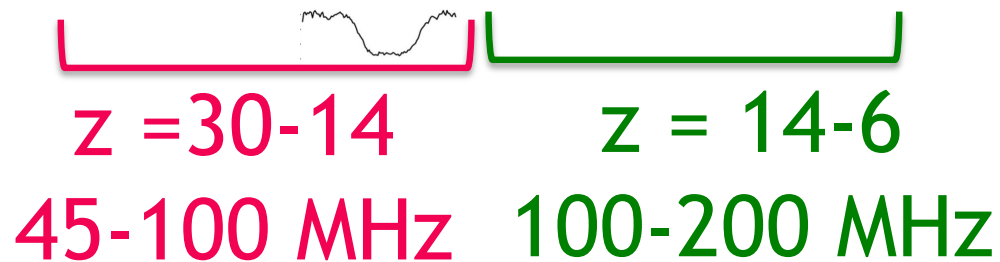
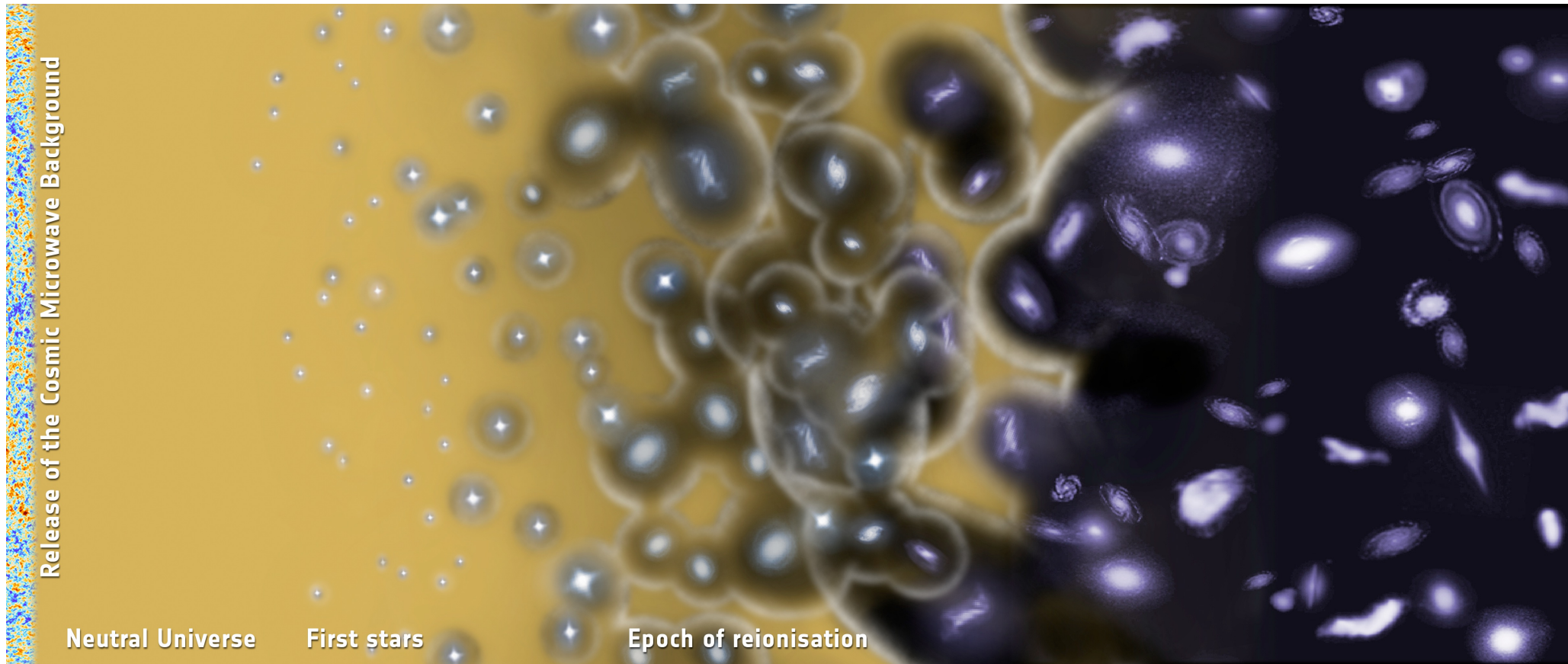
Bowman et al. 2018





Fan et al. 2006

Epoch of Reionization



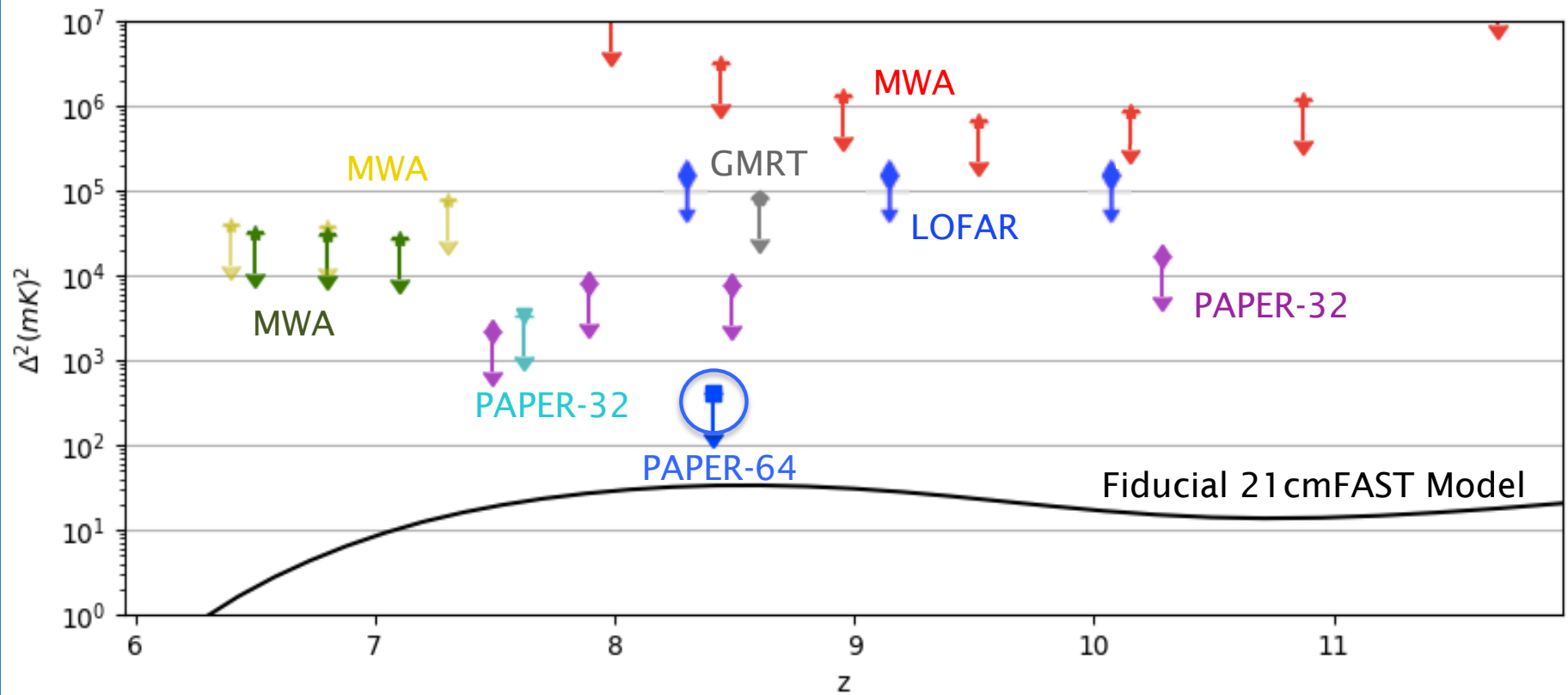
Precision Array for Probing the Epoch of Reionization

- ▷ Interferometer located in the Karoo Desert, South Africa
- ▷ PAPER-64: 2012-2013
- ▷ PAPER-128: 2013-2015
- ▷ Main challenge: foregrounds & systematics are $\sim 10^4$ - 10^5 times brighter than the predicted EoR signal
- ▷ One PAPER technique to increase sensitivity: *fringe-rate filtering*

Carina Cheng (UCB)



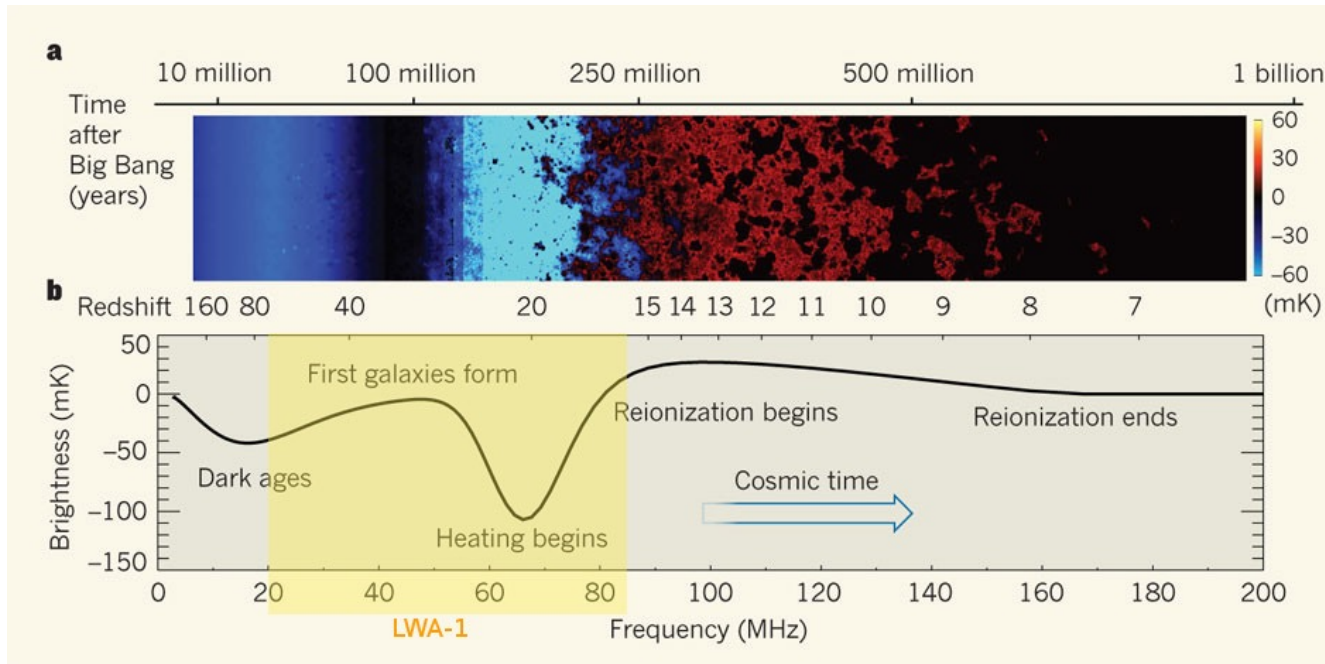
Status of Field



Carina Cheng (UCB)

- | | |
|-----------------|-------------------|
| ● Paciga, 2013 | ★ Beardsley, 2016 |
| ★ Dillon, 2014 | ◆ Jacobs, 2015 |
| ★ Dillon, 2015 | ◆ Patil, 2017 |
| ▼ Parsons, 2014 | ■ Ali, 2015 |

LWA 1 Science Program: Dark Ages



The predicted brightness temperature of the 21cm line from the HI gas is displayed as a function of time, redshift & frequency.

Figure 1 from Pritchard & Loeb, 2010 Nature 469 772

The Dark Ages through Cosmic Dawn encompasses the formation of the 1st galaxies & black holes. LWA1 offers a unique window into this era.

- **LEDA** (PI Greenhill): Constrain Dark Ages signal

- Probe thermal history & Ly α output of 1st stars & galaxies by characterizing HI trough – only means to detect IGM @ $z > 15$
- New correlator, total power hardware & data reduction pipeline

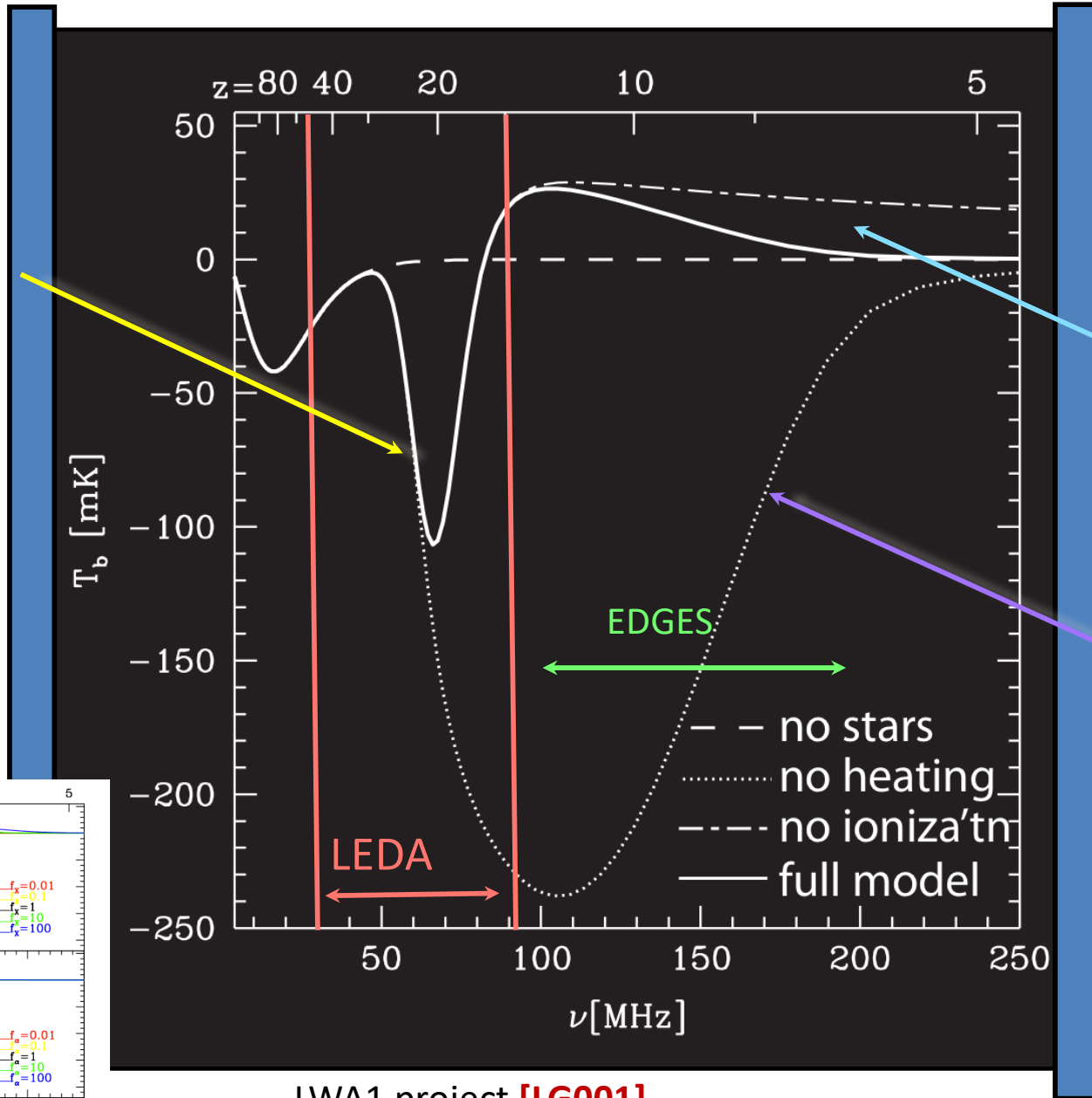
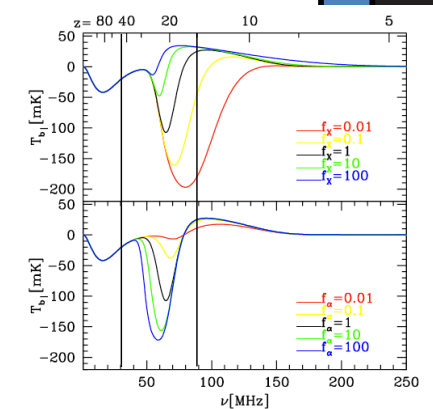


LEDA: Inference

Lyman- α
photon
production
(likely from
stars)
determines
magnitude of
decoupling
from the
dashed curve

Production of
ionizing photons
determines the
difference between
dash-dot and solid
curves

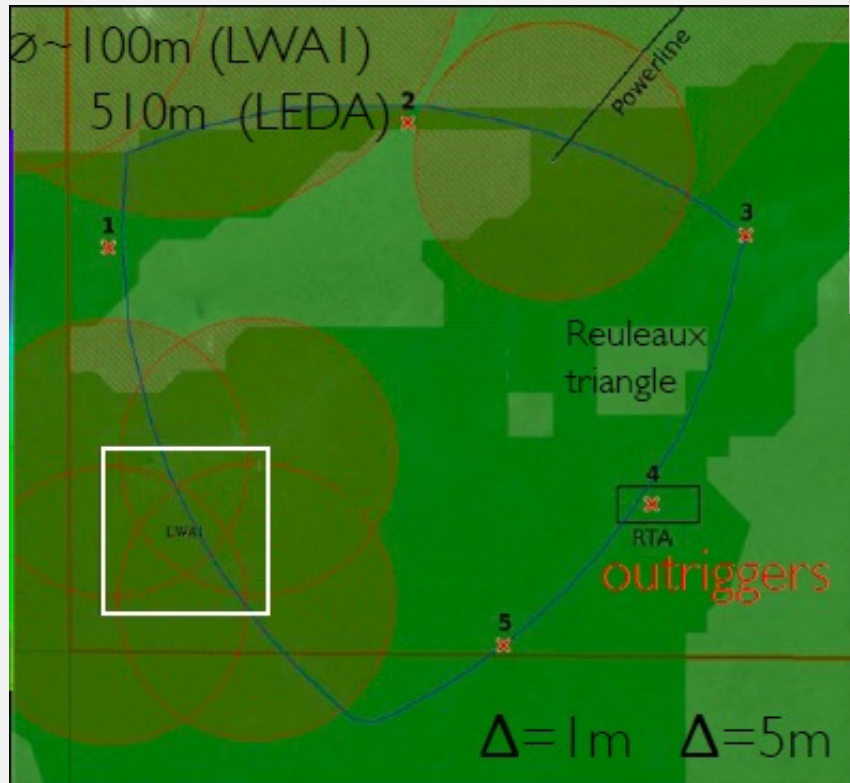
Case where IGM
not reheated prior
to reionization. It
takes just 10^{-3} eV
per baryon to
significantly change
this curve.



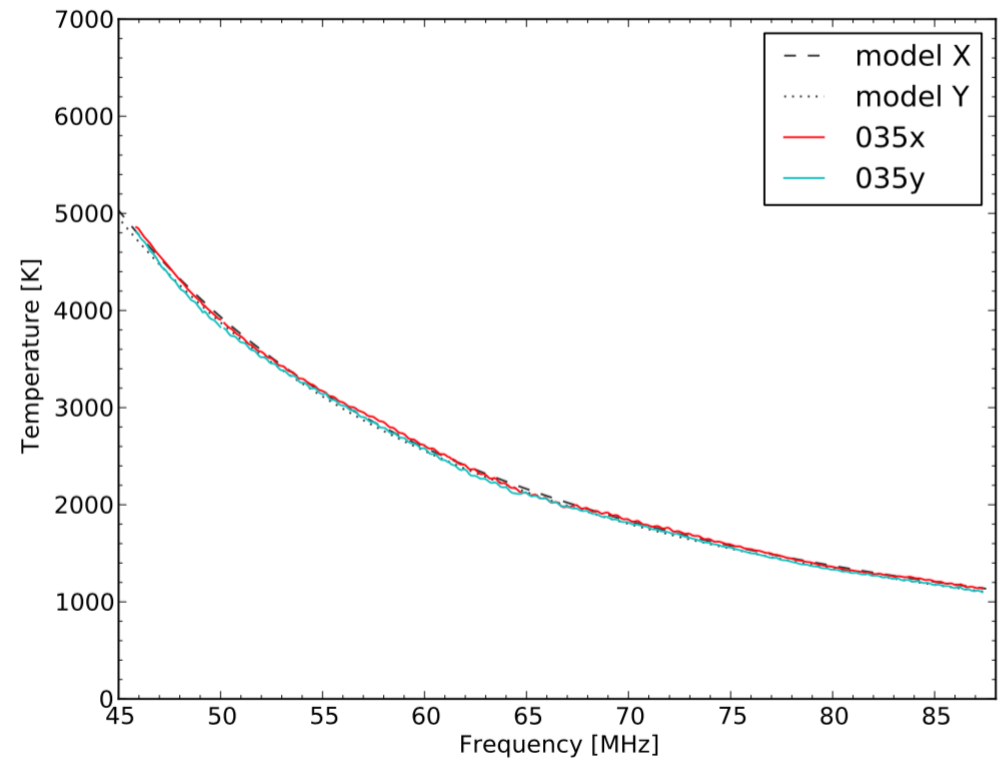
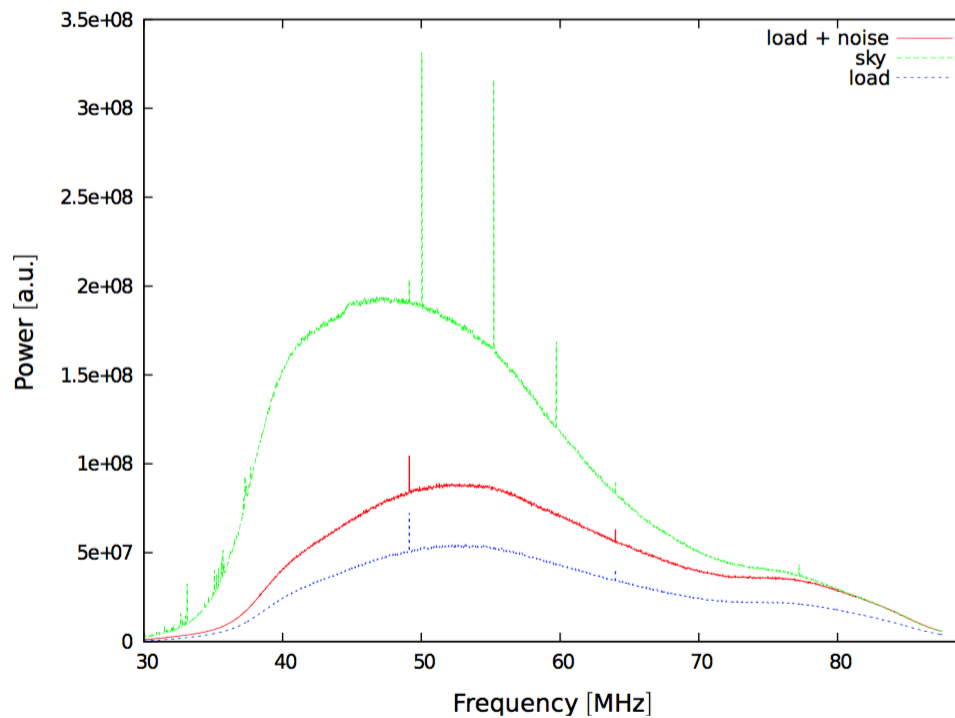
LWA1 project [LG001]

LEDA –outriggers for LWA1

Construction of 4 additional outriggers.

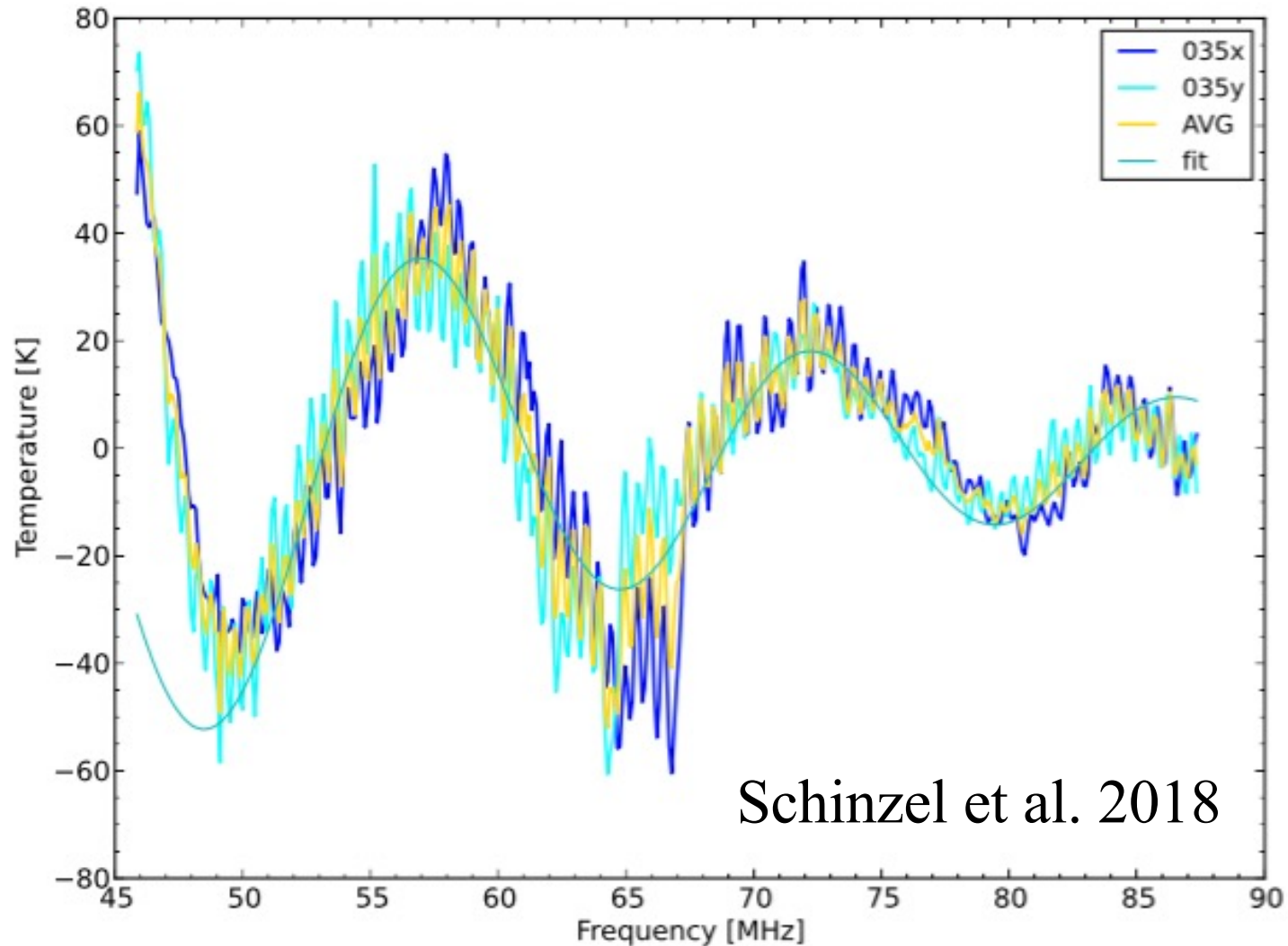


LEDA – results from NM

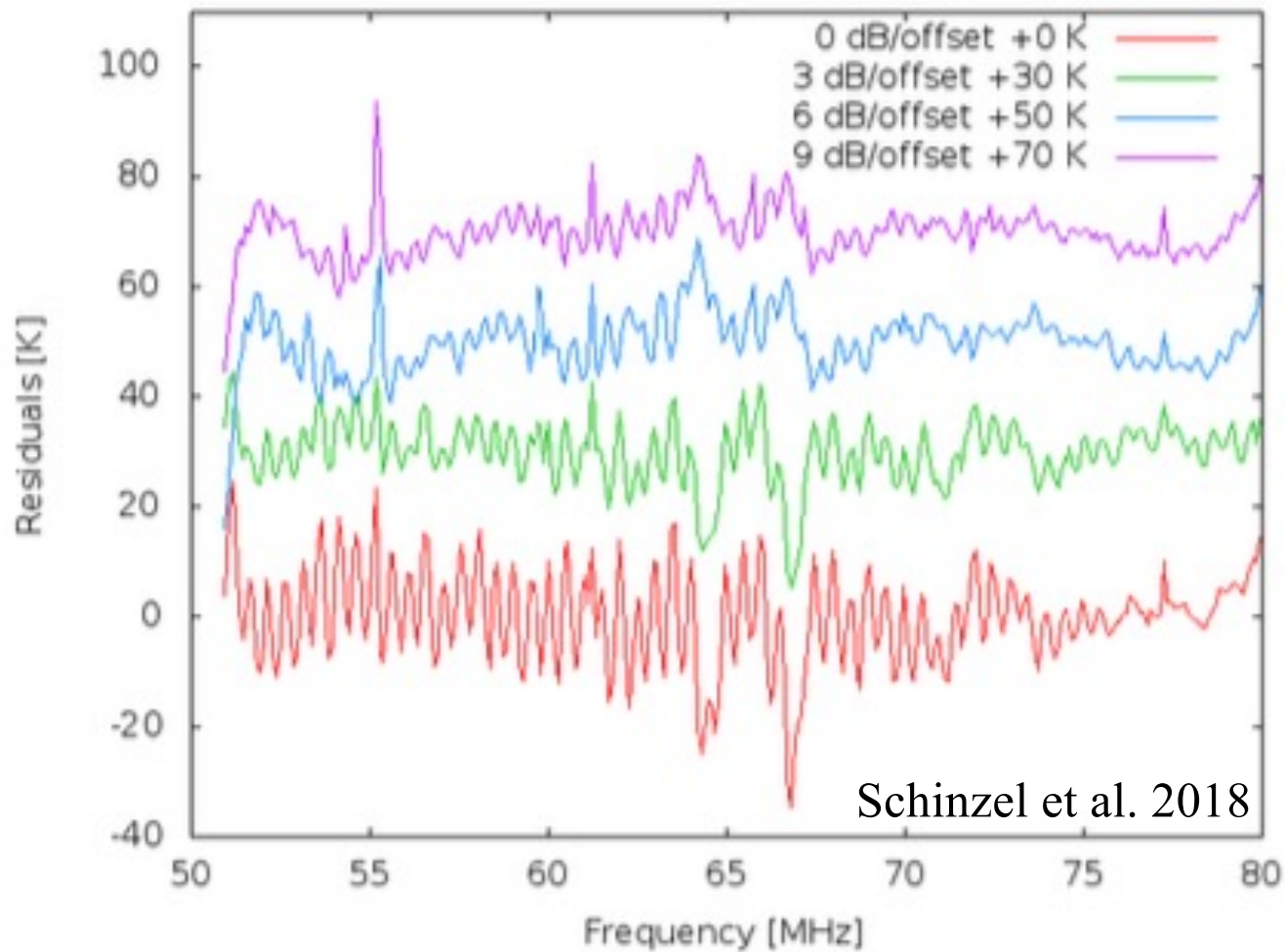


Schinzel et al. 2018

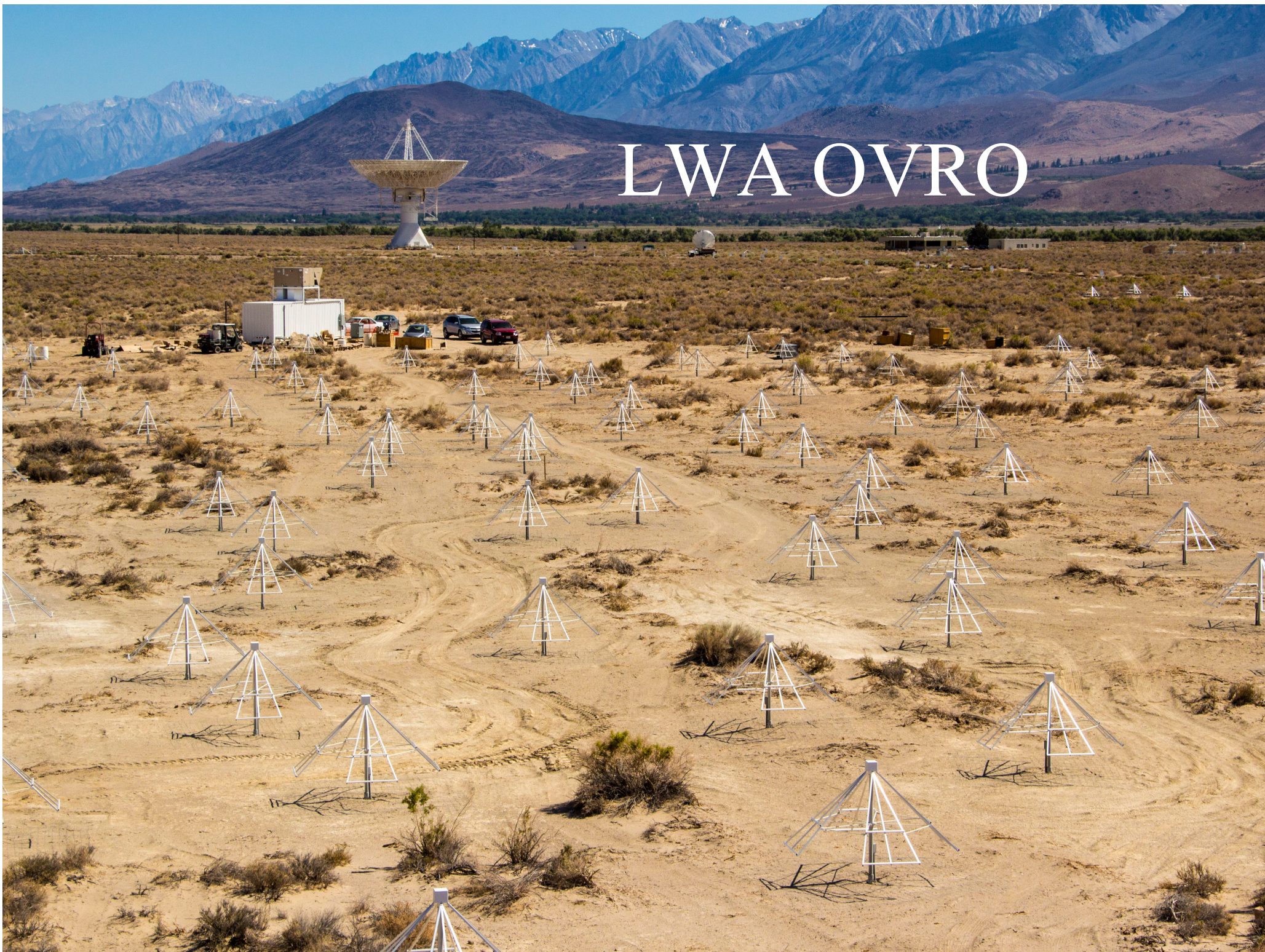
LEDA – results from NM



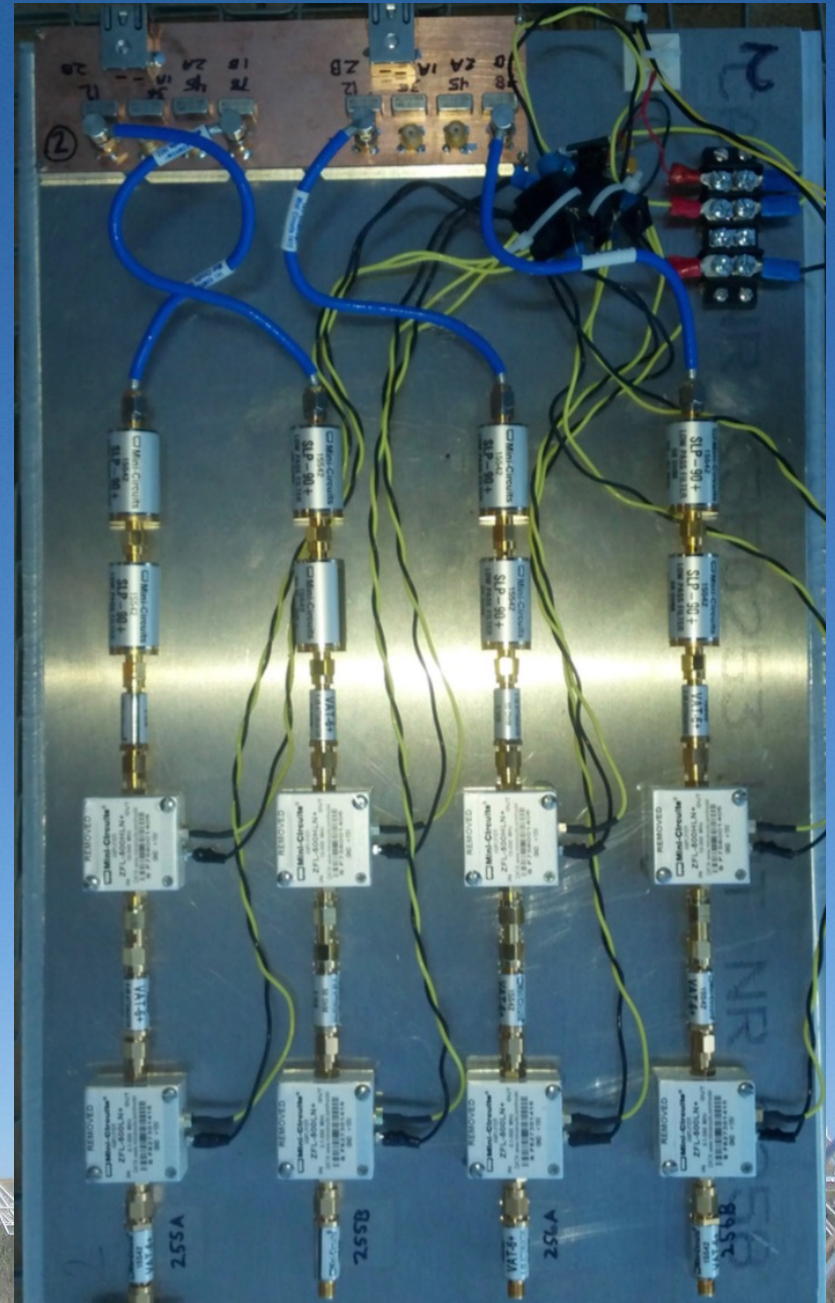
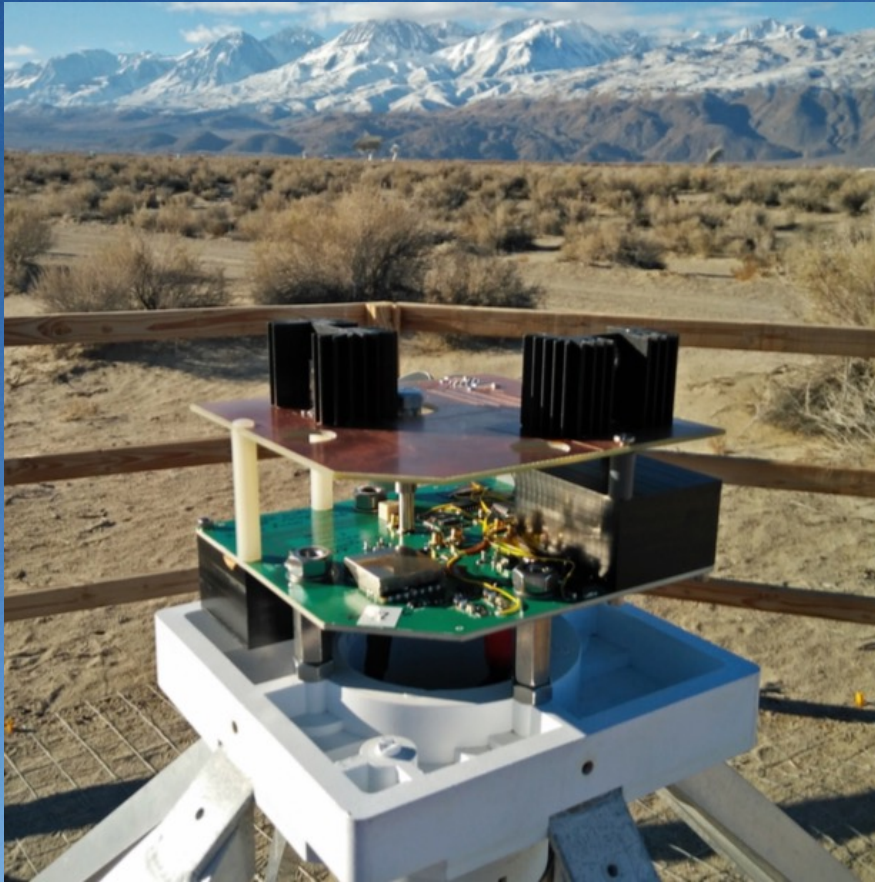
LEDA – results from NM



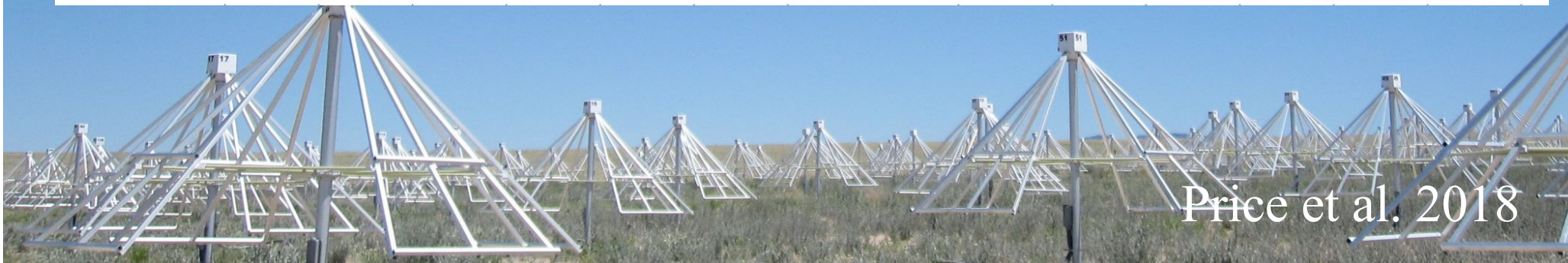
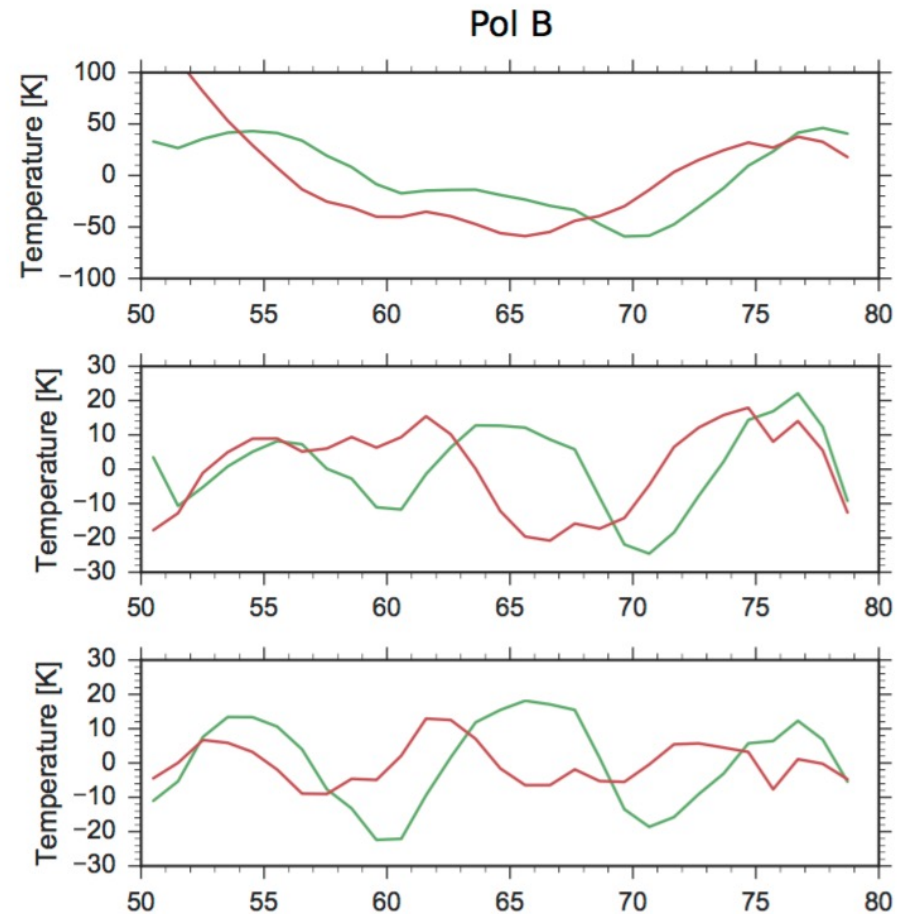
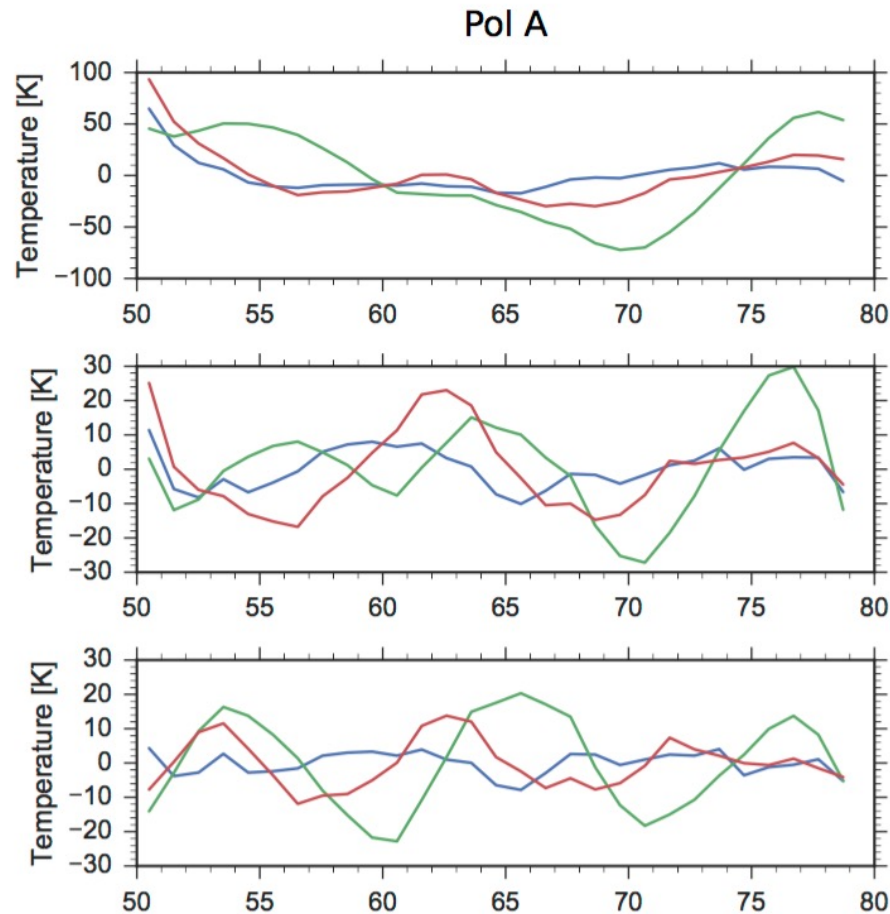
LWA OVRO



LEDA at OVRO

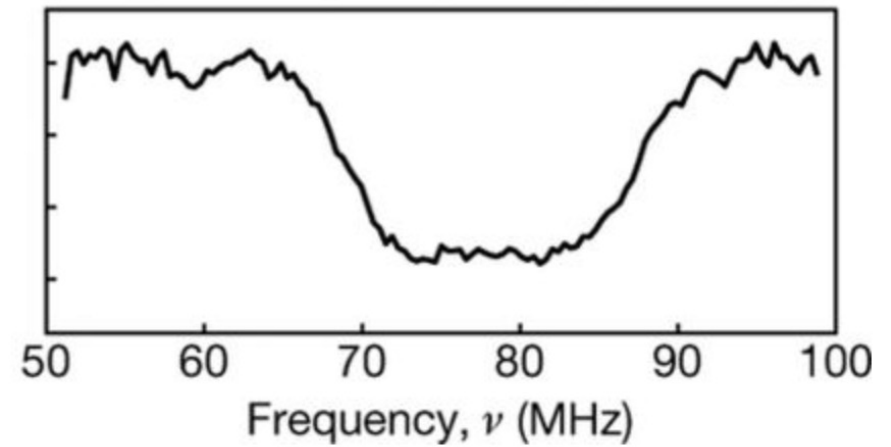
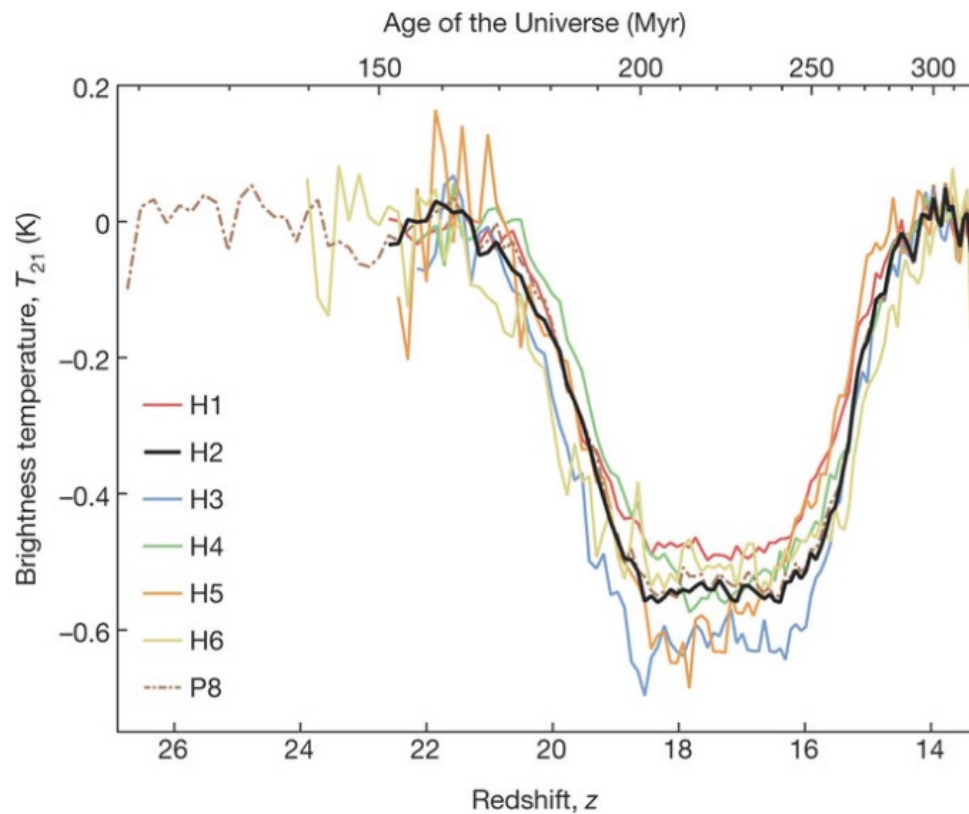


LEDA at OVRO



Detection of HI at $z=17$

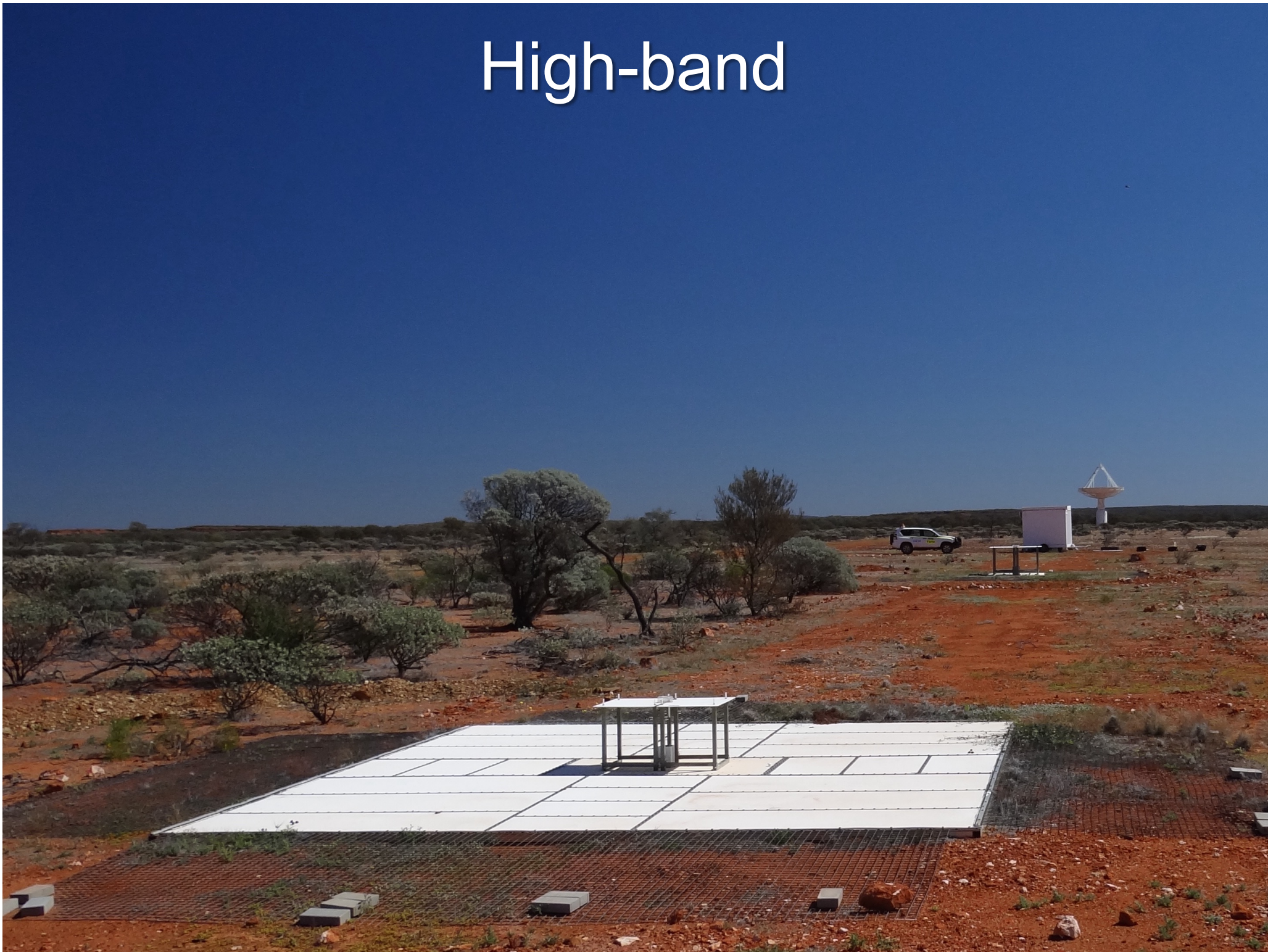
Bowman et al. 2018



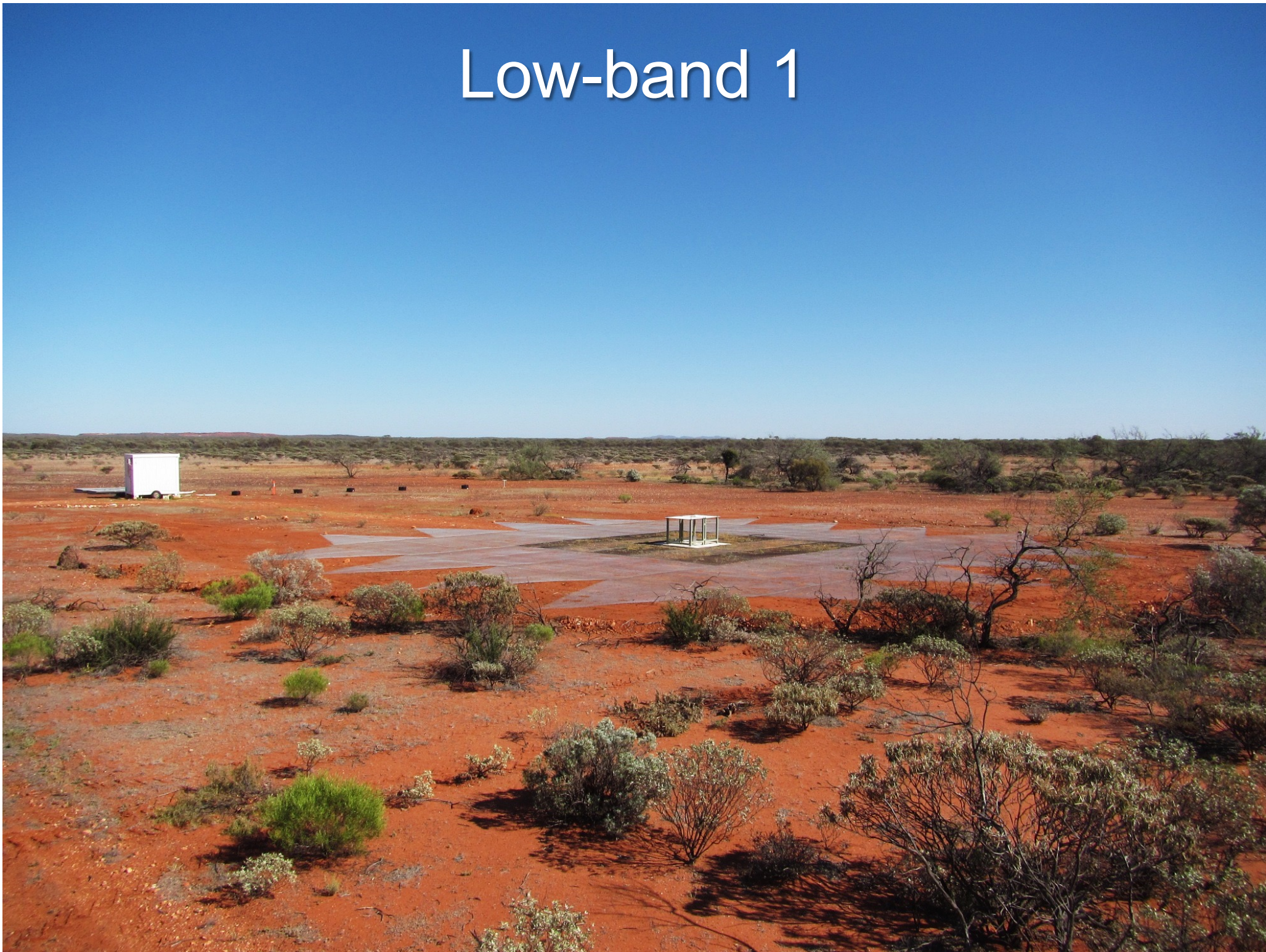
EDGES

- Goal
 - Detect/constrain reionization durations less than $\Delta z \sim 1-2$
 - 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

High-band



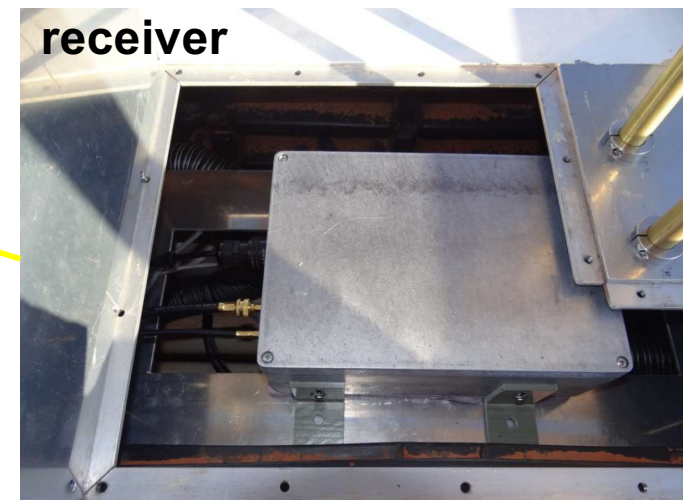
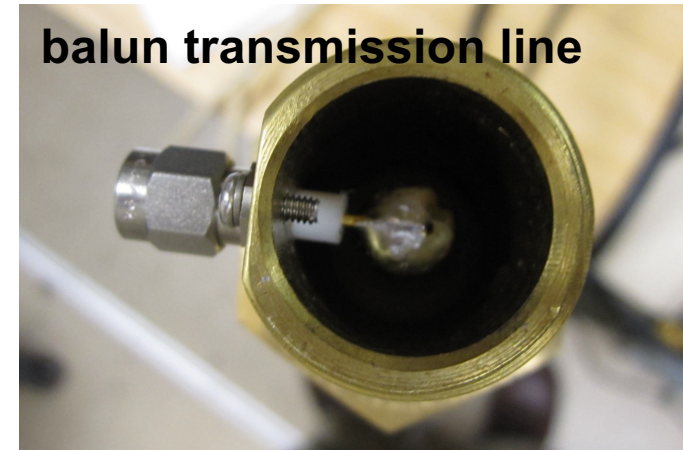
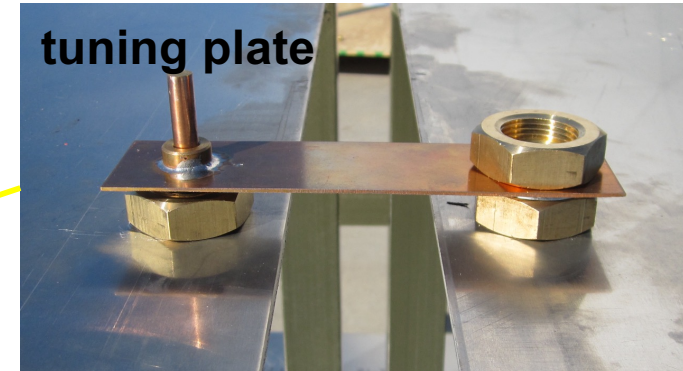
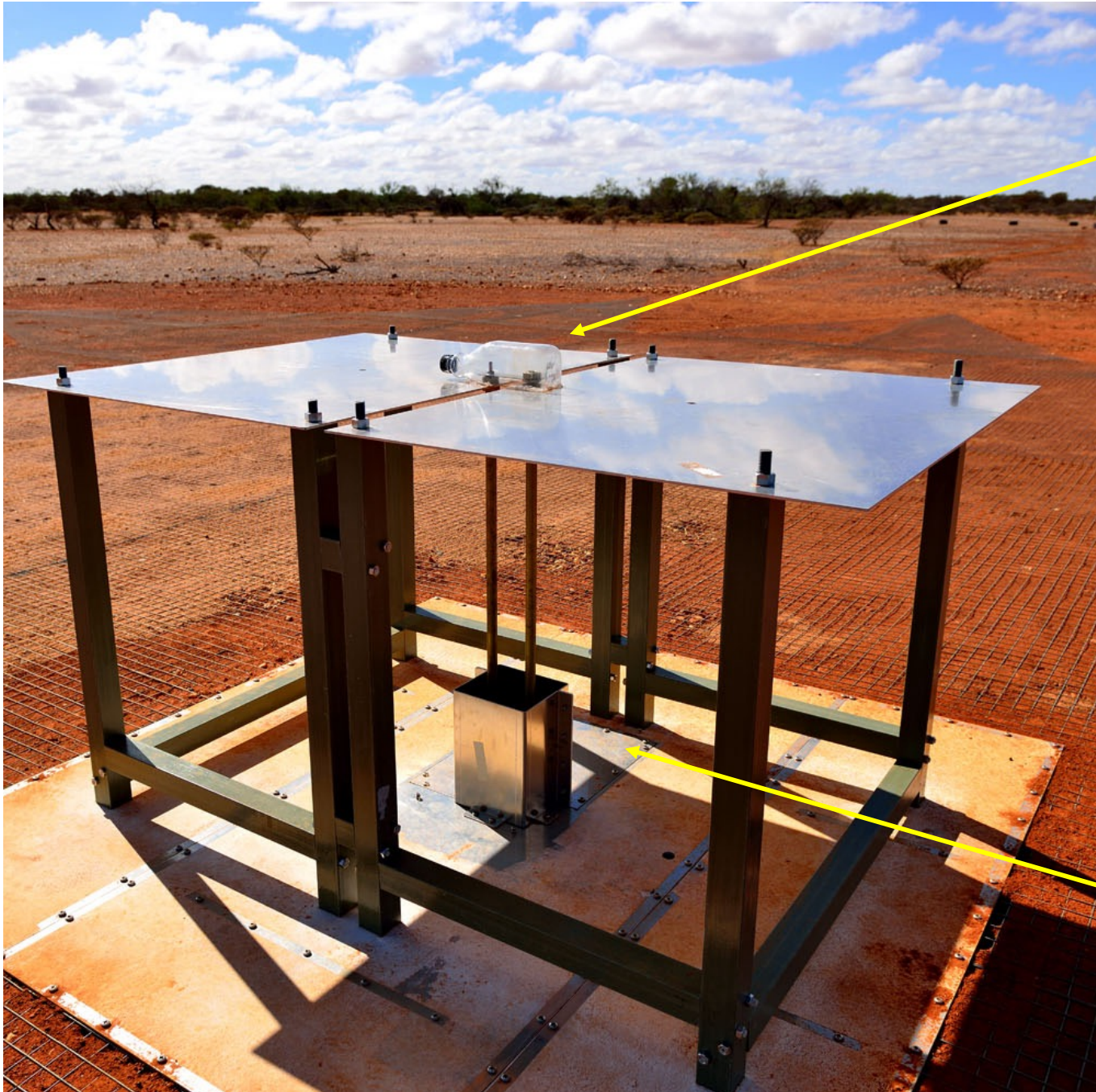
Low-band 1



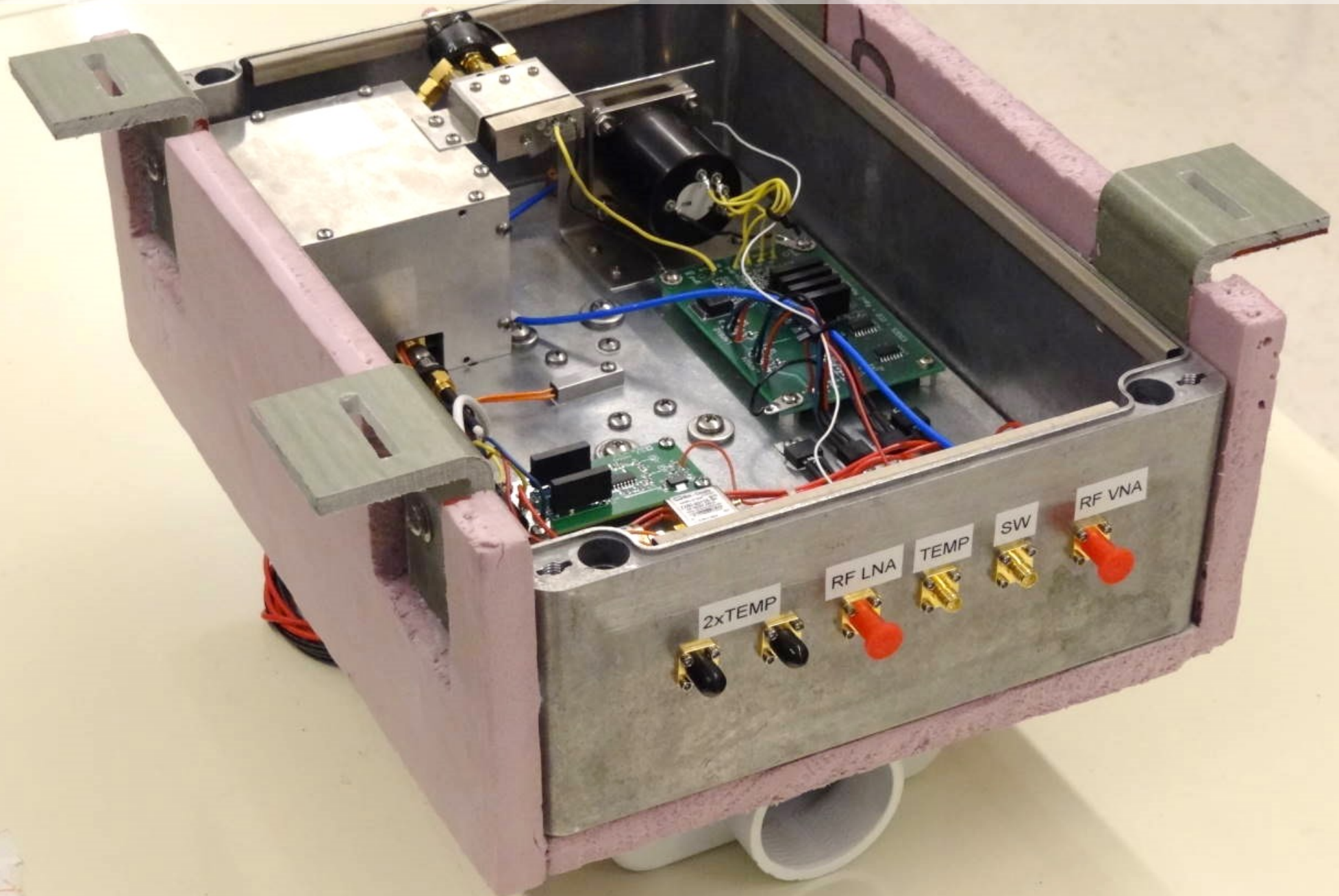
Low-band 2



Antenna and balun



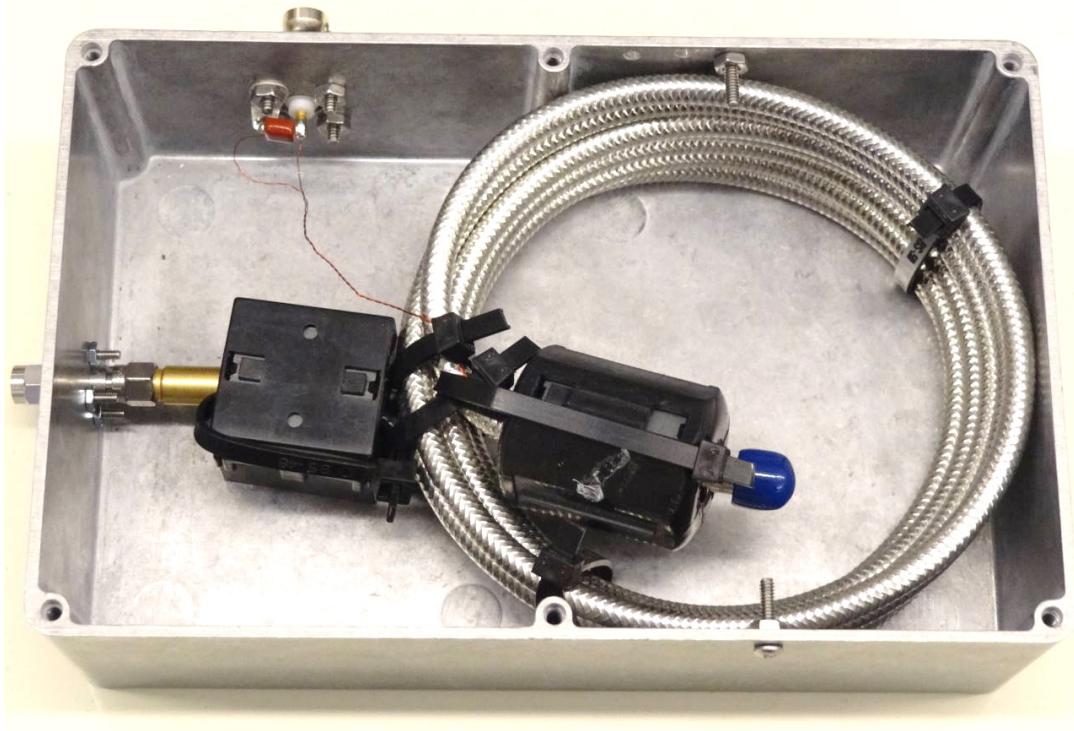
Receiver (high-band)



Laboratory calibration



External calibrator sources



(above) long cable



(right) ambient/hot load

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:

$$(T_{\text{ant}}^* - T_{\text{L}})C_1 + (T_{\text{L}} - C_2) = T_{\text{ant}} \left[\frac{(1 - |\Gamma_{\text{ant}}|^2 |F|^2)}{(1 - |\Gamma_{\text{rec}}|^2)} \right]$$

$$+ T_{\text{unc}} \left[\frac{|\Gamma_{\text{ant}}|^2 |F|^2}{(1 - |\Gamma_{\text{rec}}|^2)} \right]$$

with:

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

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

$$+ T_{\cos} \left[\frac{|\Gamma_{\text{ant}}| |F|}{(1 - |\Gamma_{\text{rec}}|^2)} \cos \alpha \right]$$

$$+ T_{\sin} \left[\frac{|\Gamma_{\text{ant}}| |F|}{(1 - |\Gamma_{\text{rec}}|^2)} \sin \alpha \right].$$

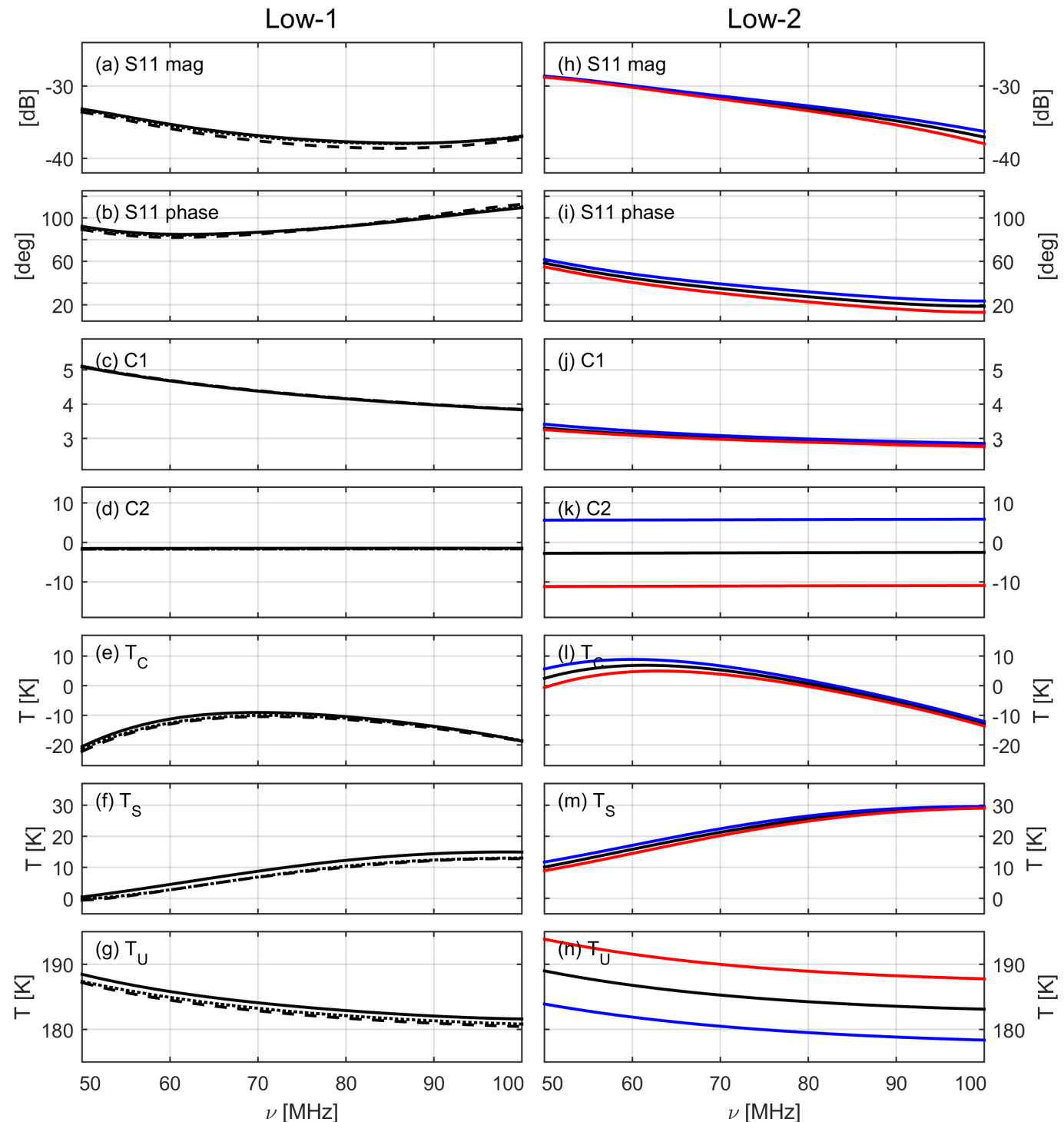
Calibration solutions

Low-1 (left): three different calibration measurements

- August 2015
- May 2017
- September 2017

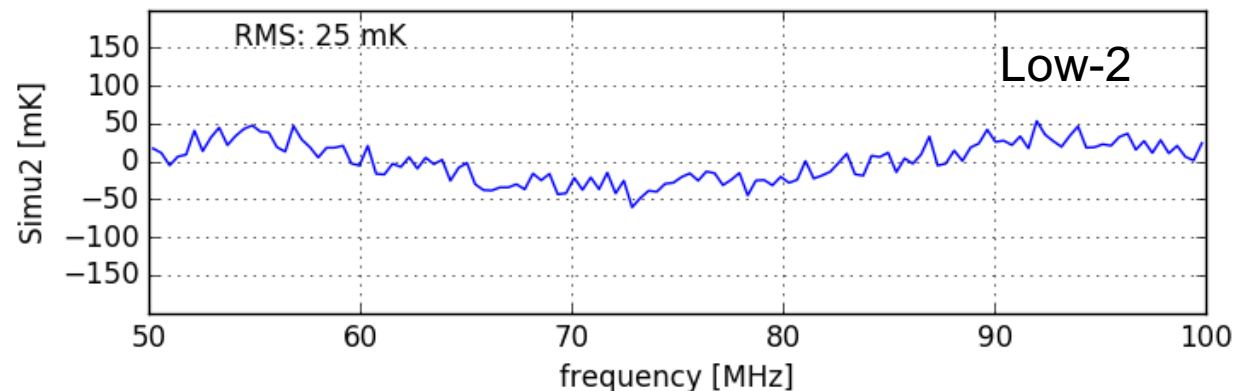
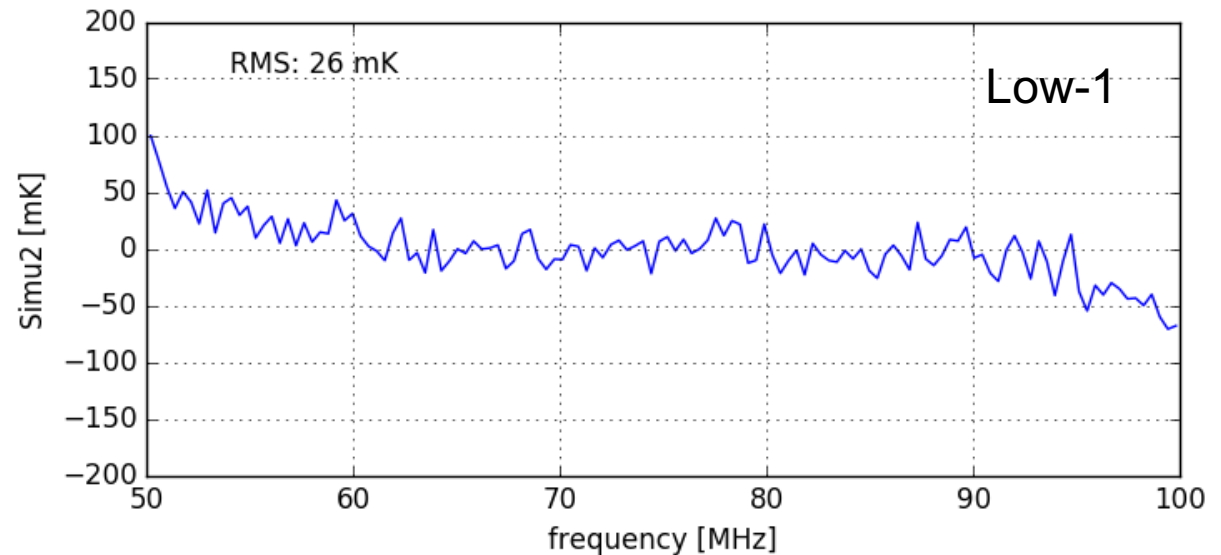
Low-2 (right): three receiver set-point temperatures:

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

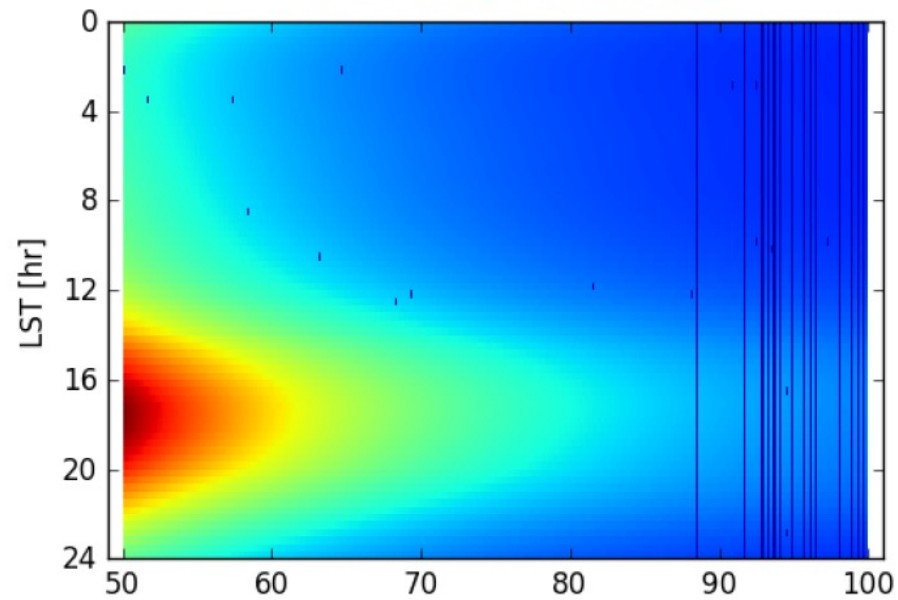


Example antenna simulator tests

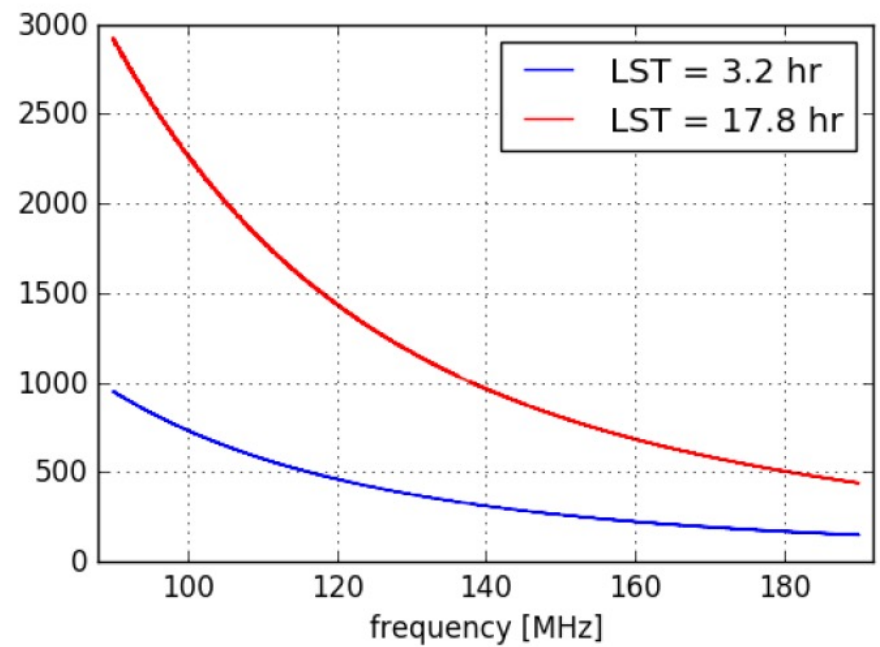
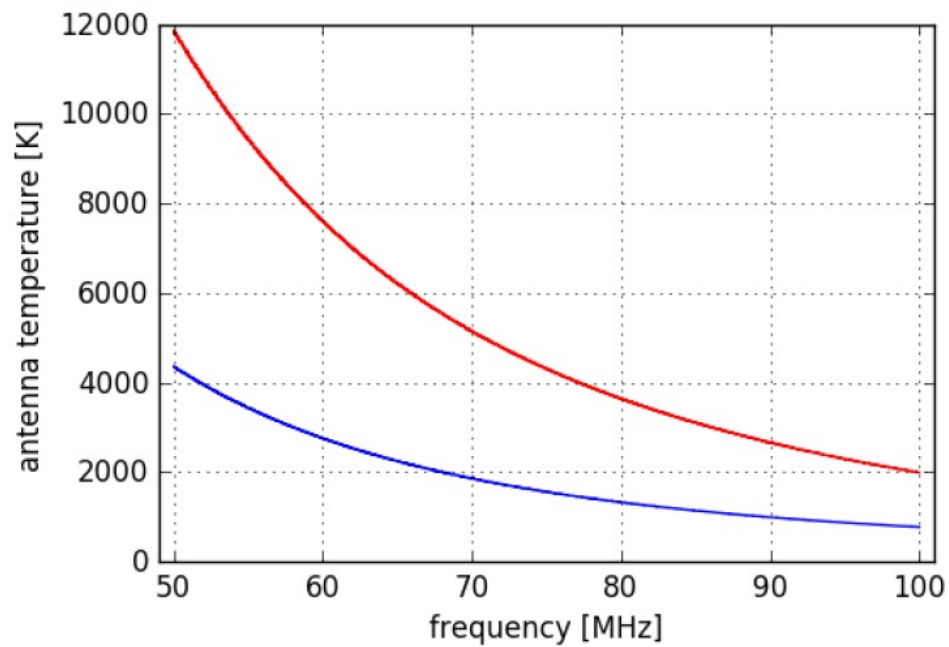
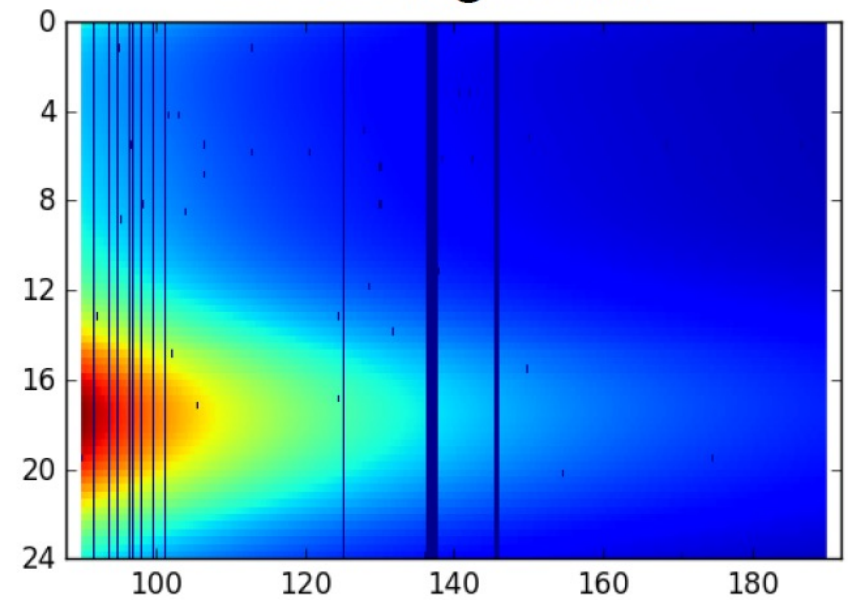
- 300 K 6dB attenuator
 - Corrected for simulator S11 (previous slide)
 - Residuals after removing best-fit constant
- Similar test performed with 10,000 K noise source simulator (not shown)



EDGES Low-Band

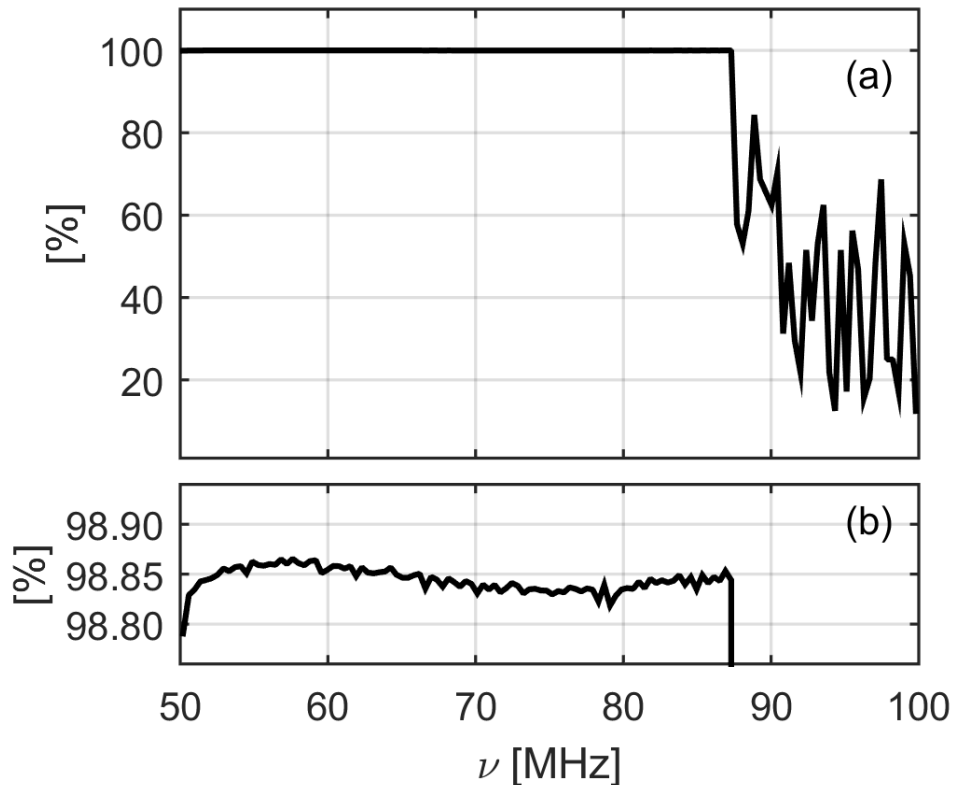


EDGES High-Band

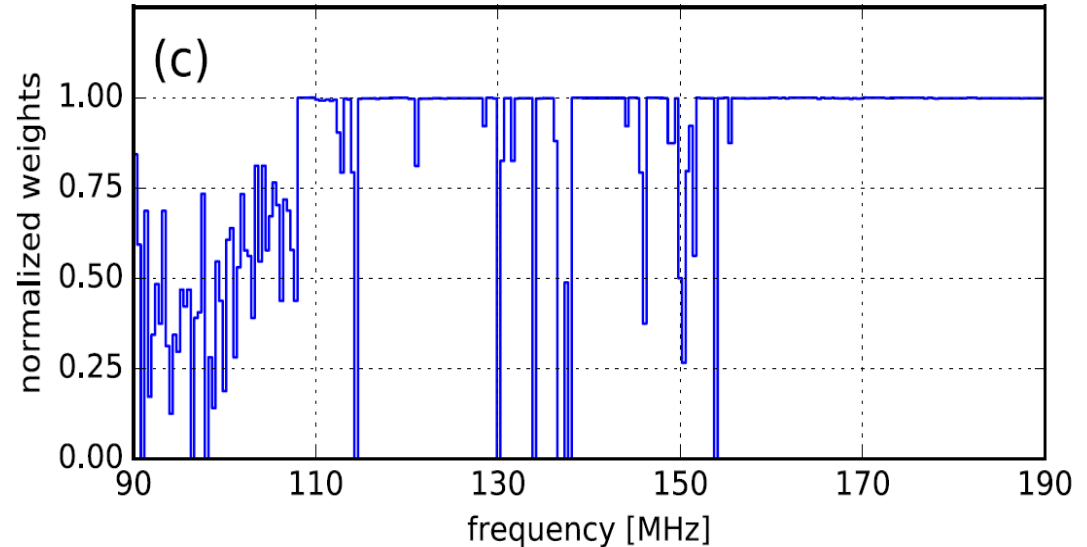


Channel weights (RFI occupancy)

Low-band



High-band



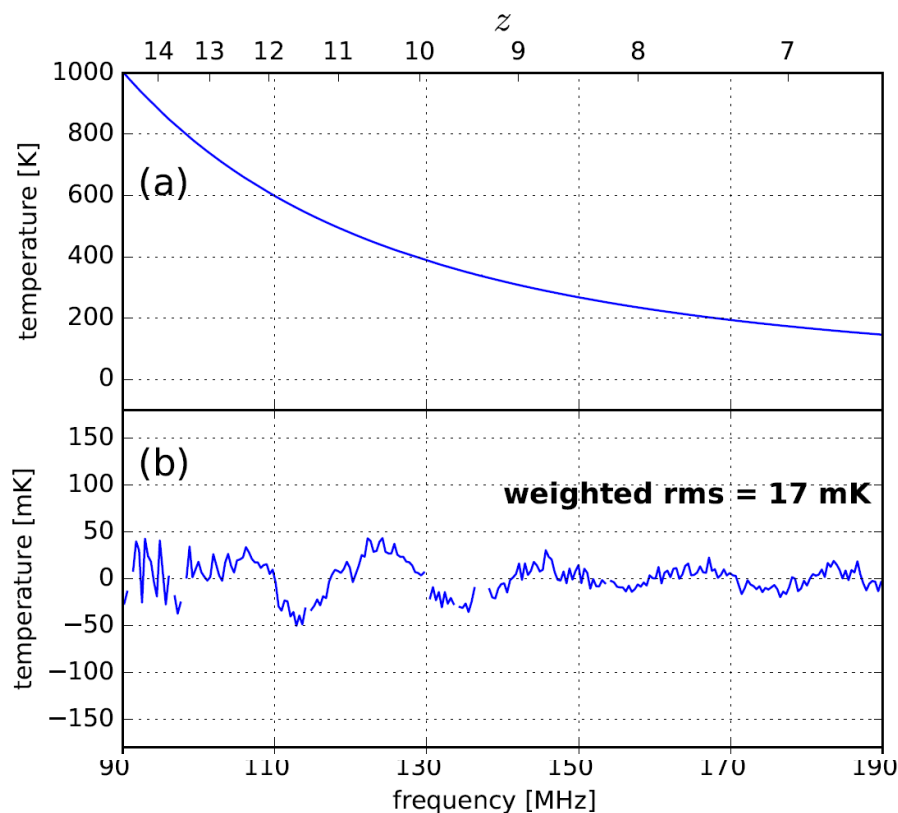
- Hundreds of nights in each band
- Very clean below FM band

Long integration residuals (typical)

Low-Band

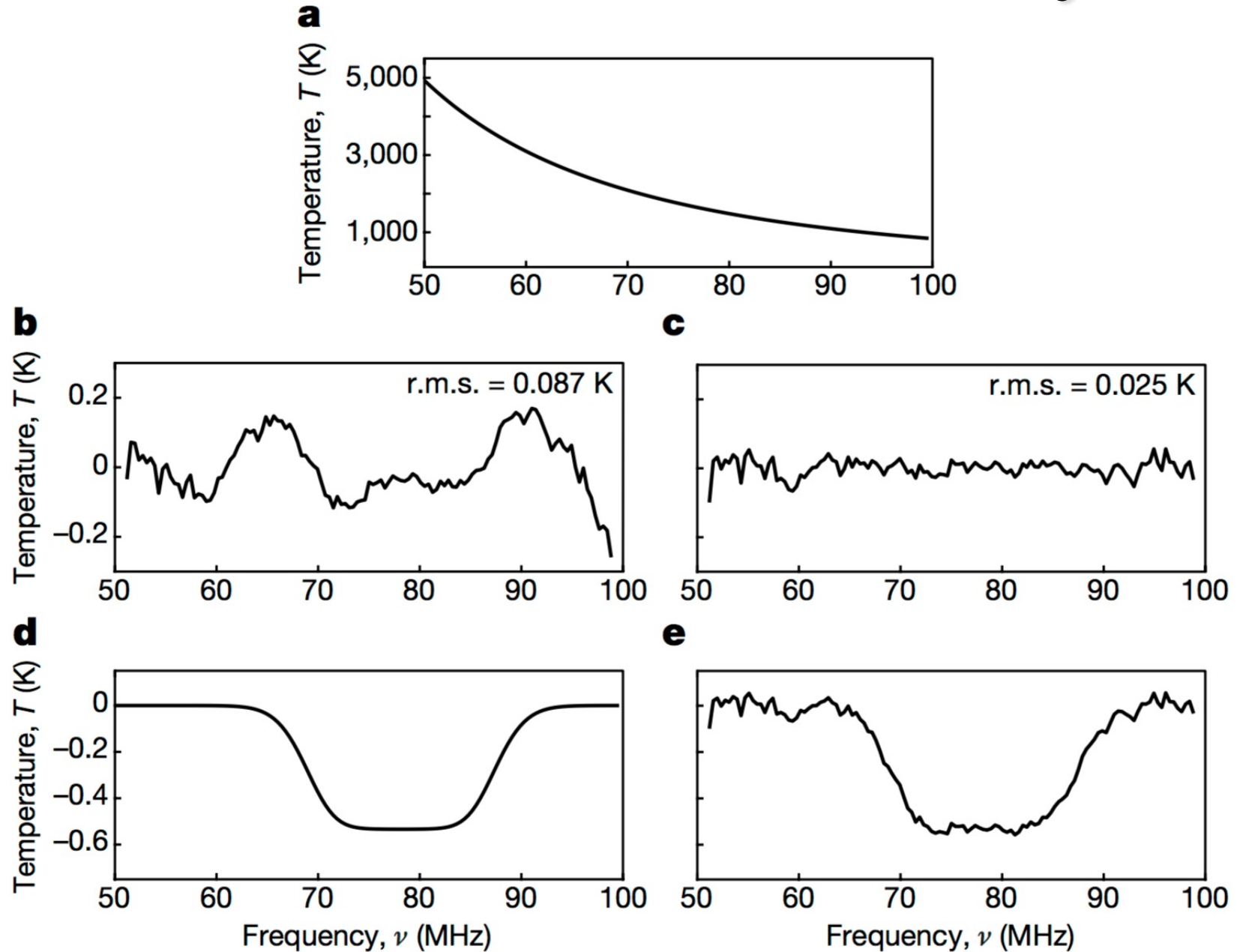


High-Band



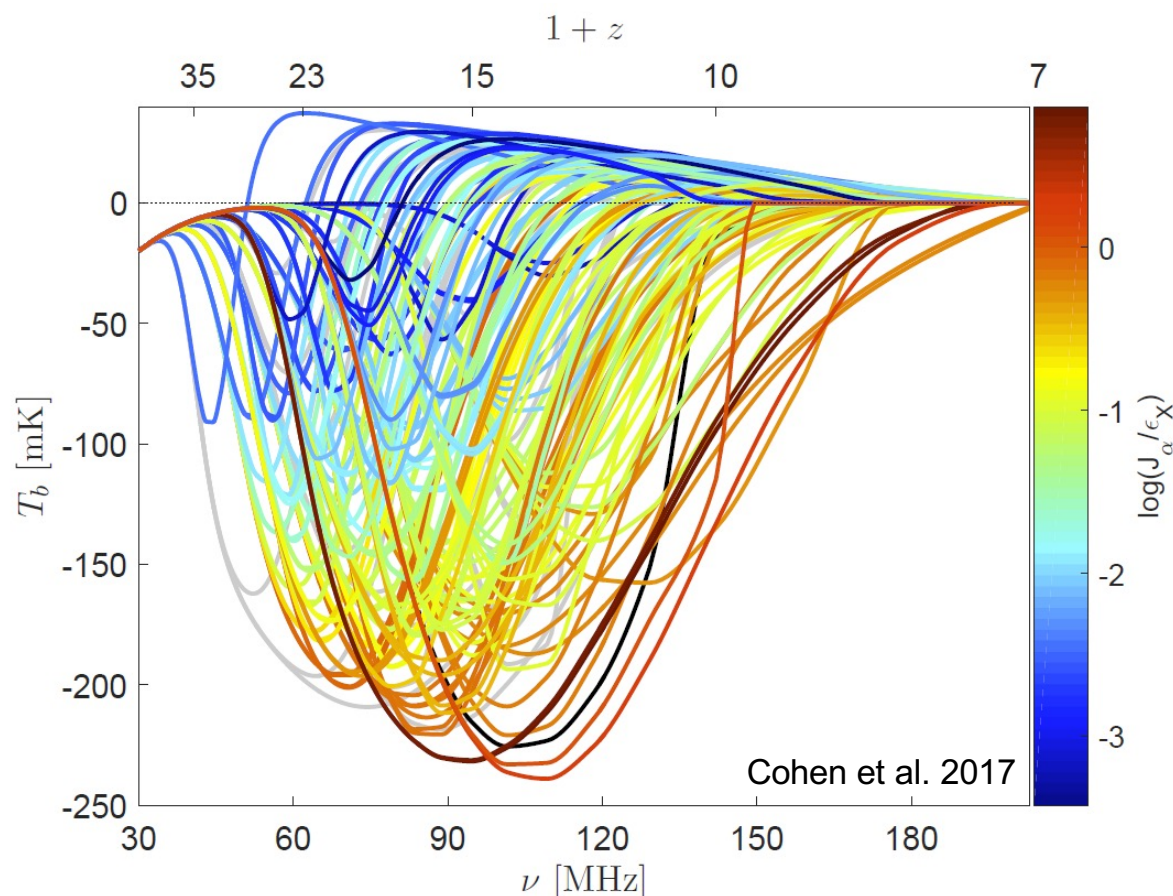
- 5-term polynomial fit and removed, RMS < 0.01% sky power
- Hundreds of nights in each band

Final results from ~200 days



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



Efforts to Confirm the 78 MHz line

LEDA - Greenhill et al. (Harvard, Caltech, UNM)

SCI-HI/PRIZM – Peterson et al. (CMU)

BigHorns – Wayth, Tremblay et al. (Curtin)

Hyperion – Kundert et al. (UCB)

HERA 2.0 – Paarsons et al. (UCB)

LWA – DiLullo et al. (UNM)



What we have Learned

- The number density of quasars drops dramatically at $z > 3$
- Billion solar mass black holes can form within a billion years of the big bang
- Cosmic Dawn begins at $z \sim 17$ (maybe). Strong foregrounds and the ionosphere make detection challenging
- The Epoch of Reionization (EoR) ends around $6 < z < 8$ after which the Universe is fully ionized (again)