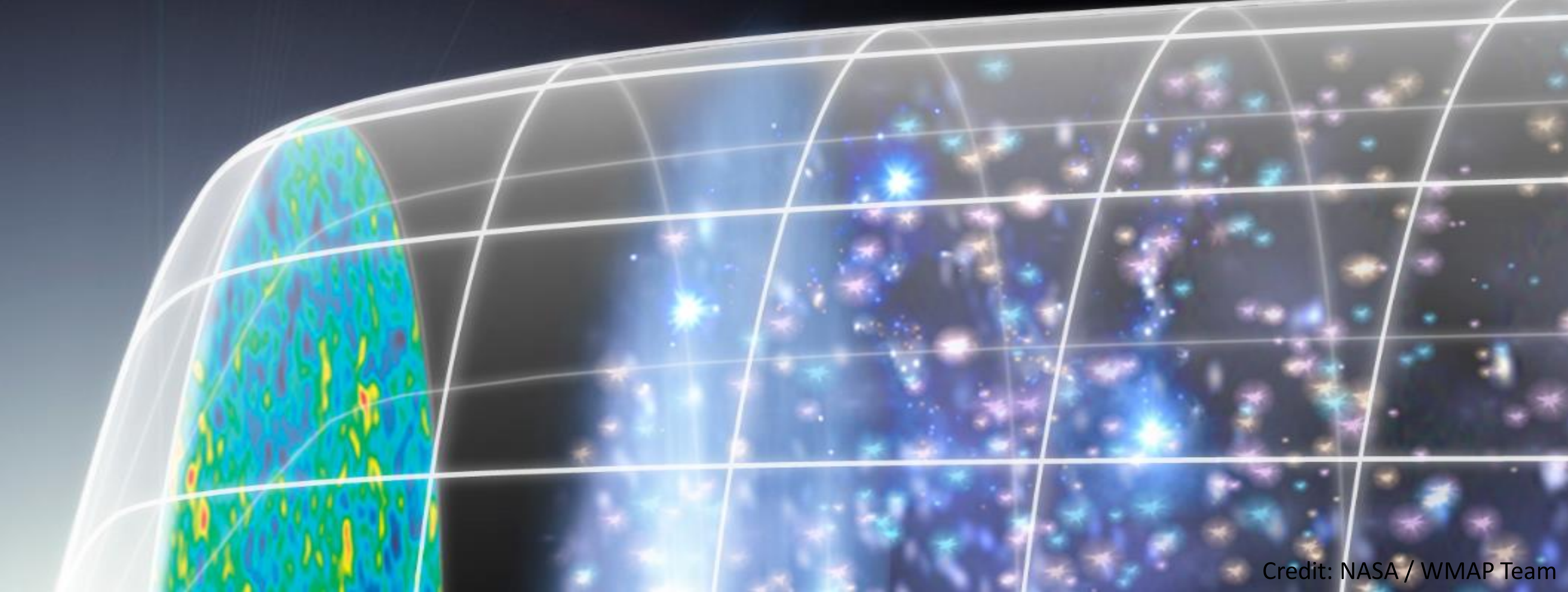
2022-01-18, Berkeley Cosmology Seminar

SSL UC Berkeley

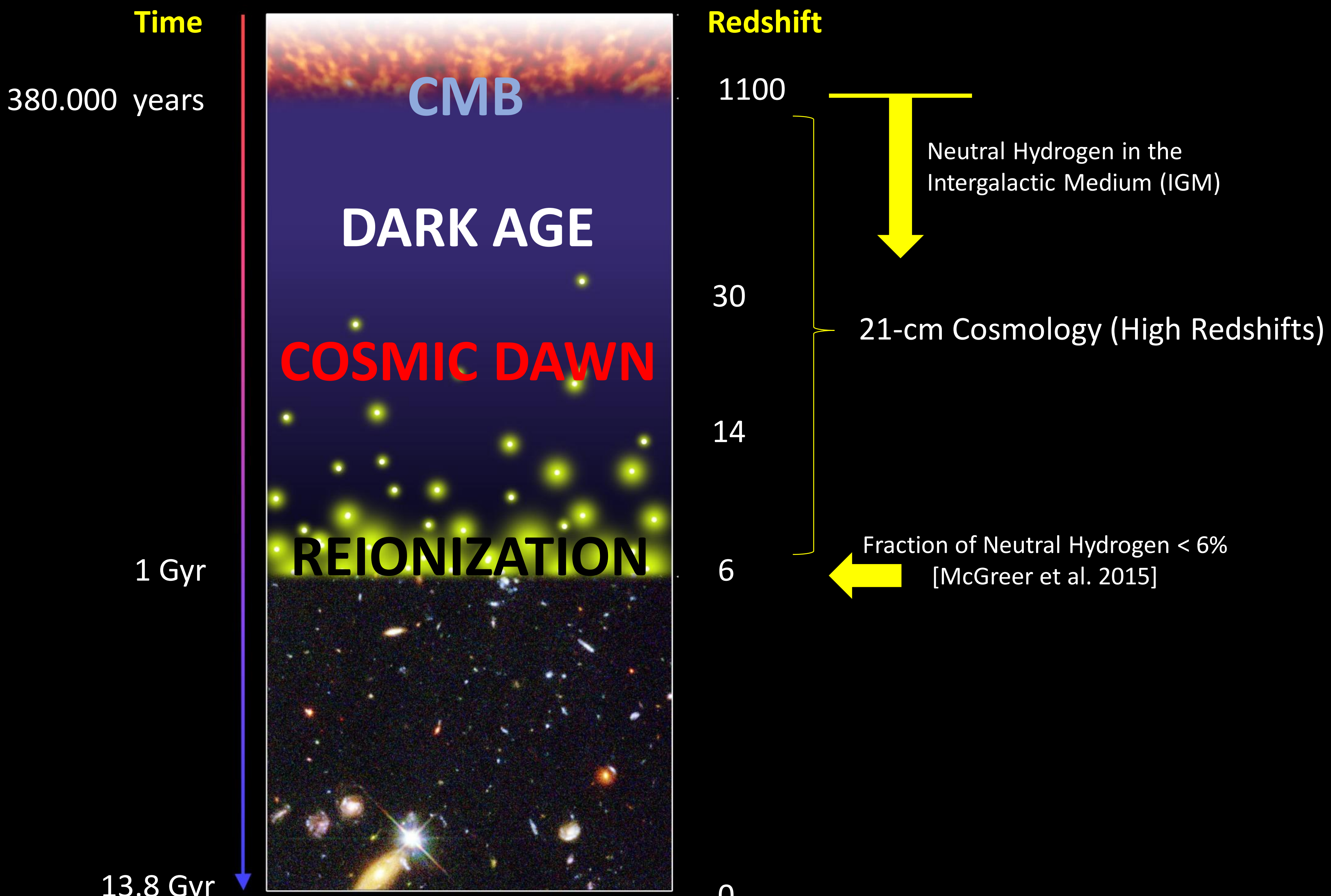
Studying the Early Universe with Radio Measurements of the Global 21-cm Signal

Raul Monsalve



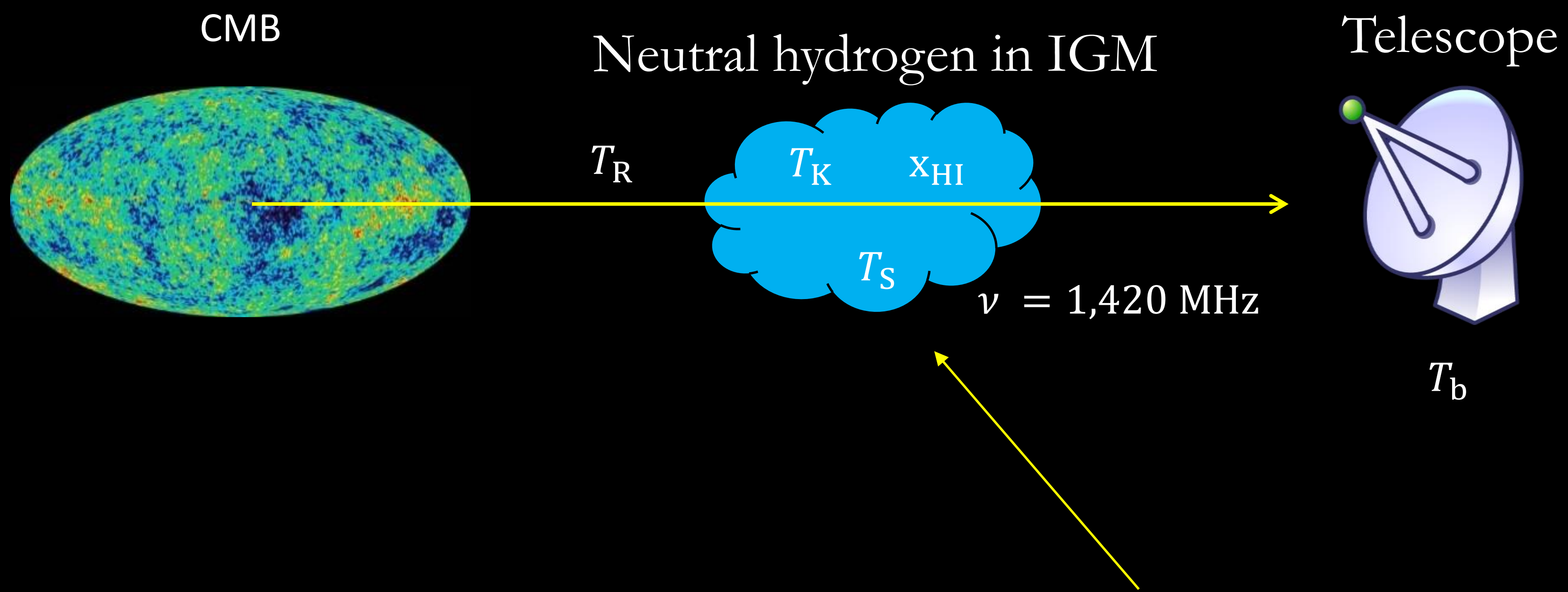
Credit: NASA / WMAP Team

1) Introduction



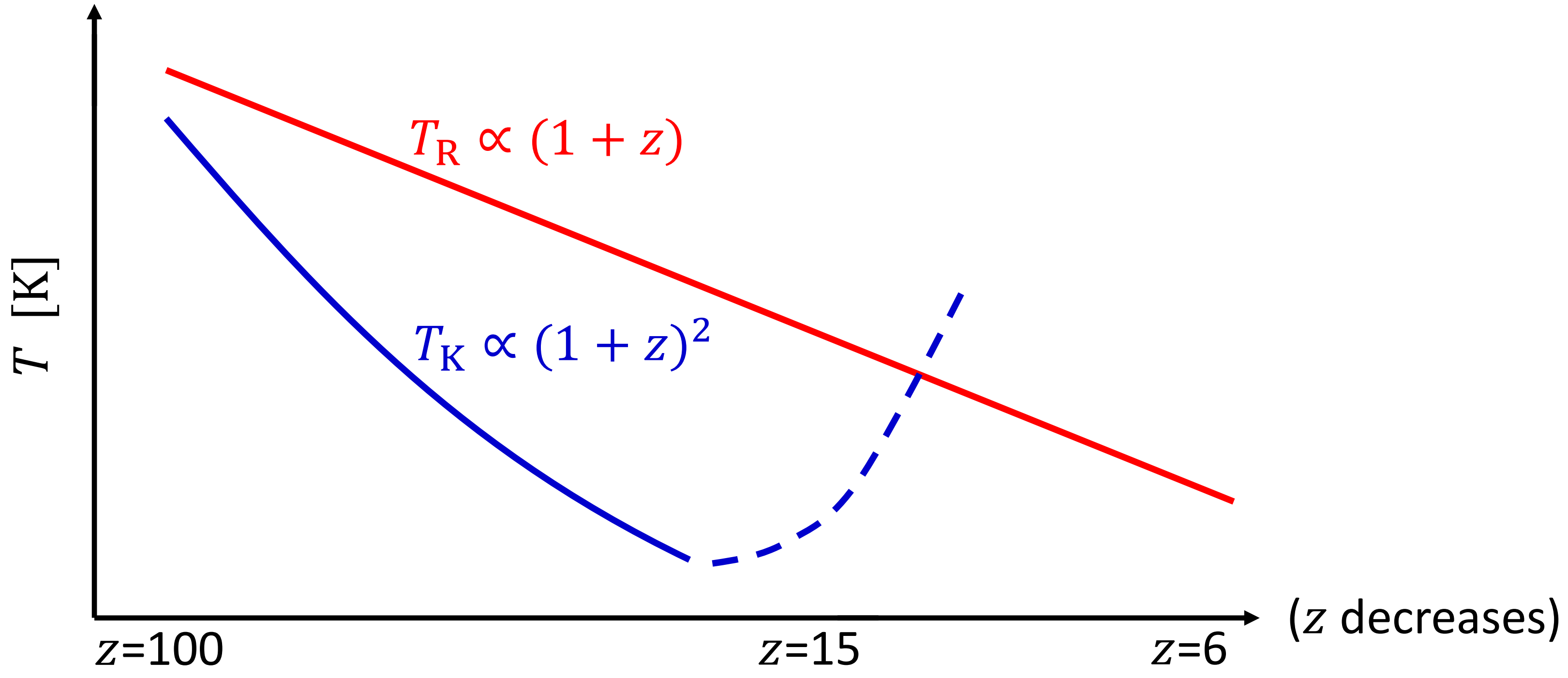
S.G. Djorgovski et al. & Digital Media Center, Caltech

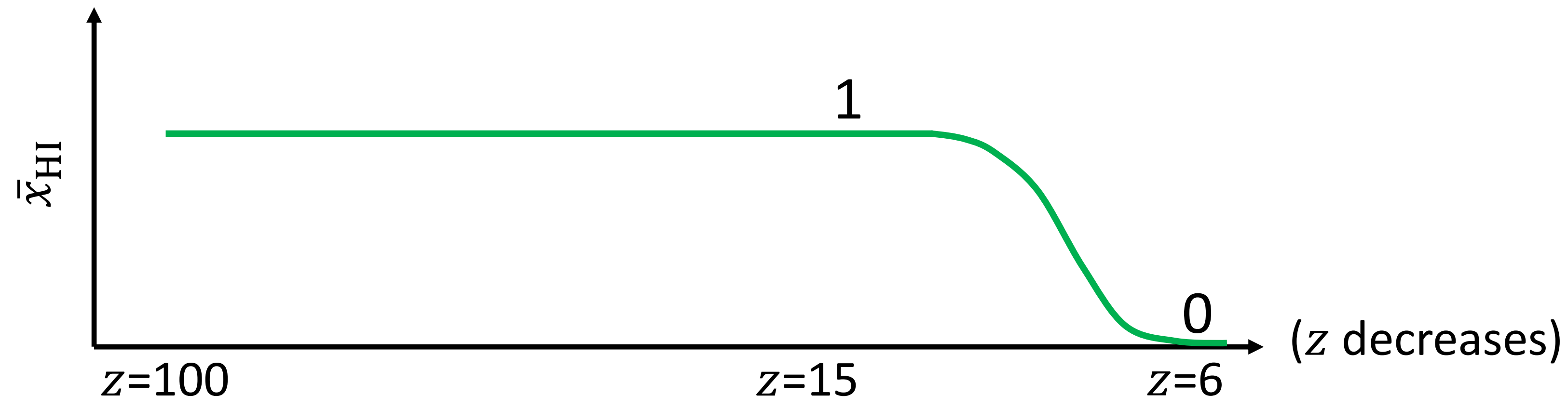
21-cm Cosmology



- Brightness temperature measured by radio-telescope captures **the interaction of these quantities as a function of redshift**.
- We can study **Spatial Fluctuations** of the brightness temperature or its **Sky-Averaged (or Global)** component.

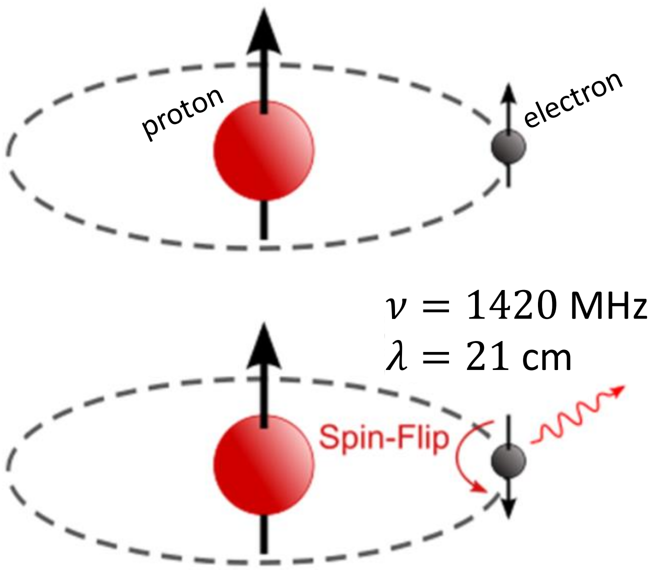
Global Evolutions





Emission at 21 cm from Hydrogen Atom

Change in ground state spin alignment



Parallel spins

Upper ground state (more energetic)

Anti-parallel spins

Lower ground state (lower ground state)

Spin Temperature (T_S)

Intensity of 21-cm radiation is expressed as a "**Spin Temperature**"

Relative abundance of ground states of hydrogen atoms

$$\frac{\boldsymbol{n}_{\mathbf{upper}}}{\boldsymbol{n}_{\mathbf{lower}}} = 3 \cdot exp\left(-\frac{h \cdot \nu_{21\mathrm{cm}}}{k_{\mathrm{b}} \cdot \boldsymbol{T}_{\mathbf{S}}}\right)$$

$\nu_{21\mathrm{cm}} = 1420$ MHz
h : Planck constant
k_{b} : Boltzmann constant

http://www.cv.nrao.edu/course/astr534/HILine.html

Spin Temperature (T_{S})

During Cosmic Dawn:

$$T_{\mathrm{S}}^{-1} \approx \frac{\boldsymbol{T_{\mathrm{R}}^{-1}} + x_{\mathrm{c}}\boldsymbol{T_{\mathrm{K}}^{-1}} + x_{\alpha}\boldsymbol{T_{\alpha}^{-1}}}{1 + x_{\mathrm{c}} + x_{\alpha}}$$

T_{S} : spin temperature

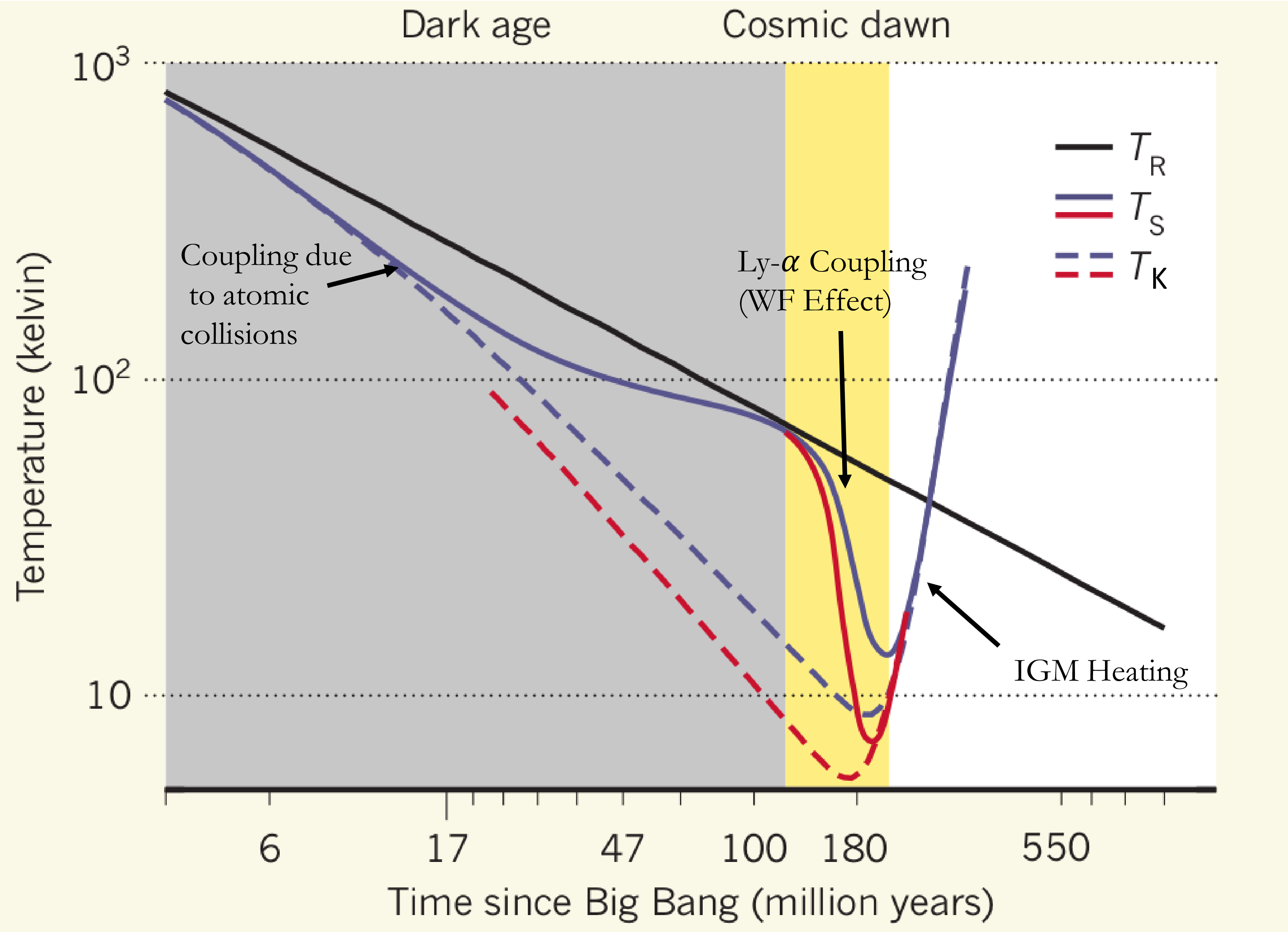
T_{R} : background radiation temperature

T_{K} : IGM kinetic temperature

T_{α} : Lyman-α background temperature

x_{c} , x_{α} : coupling factors

Global Evolutions



Adapted from Greenhill 2018, **Nature**, 555, 38

Global 21-cm Brightness Temperature

radiation temperature

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

spin temperature

fraction of neutral hydrogen

High redshift $\Rightarrow$ Low frequency

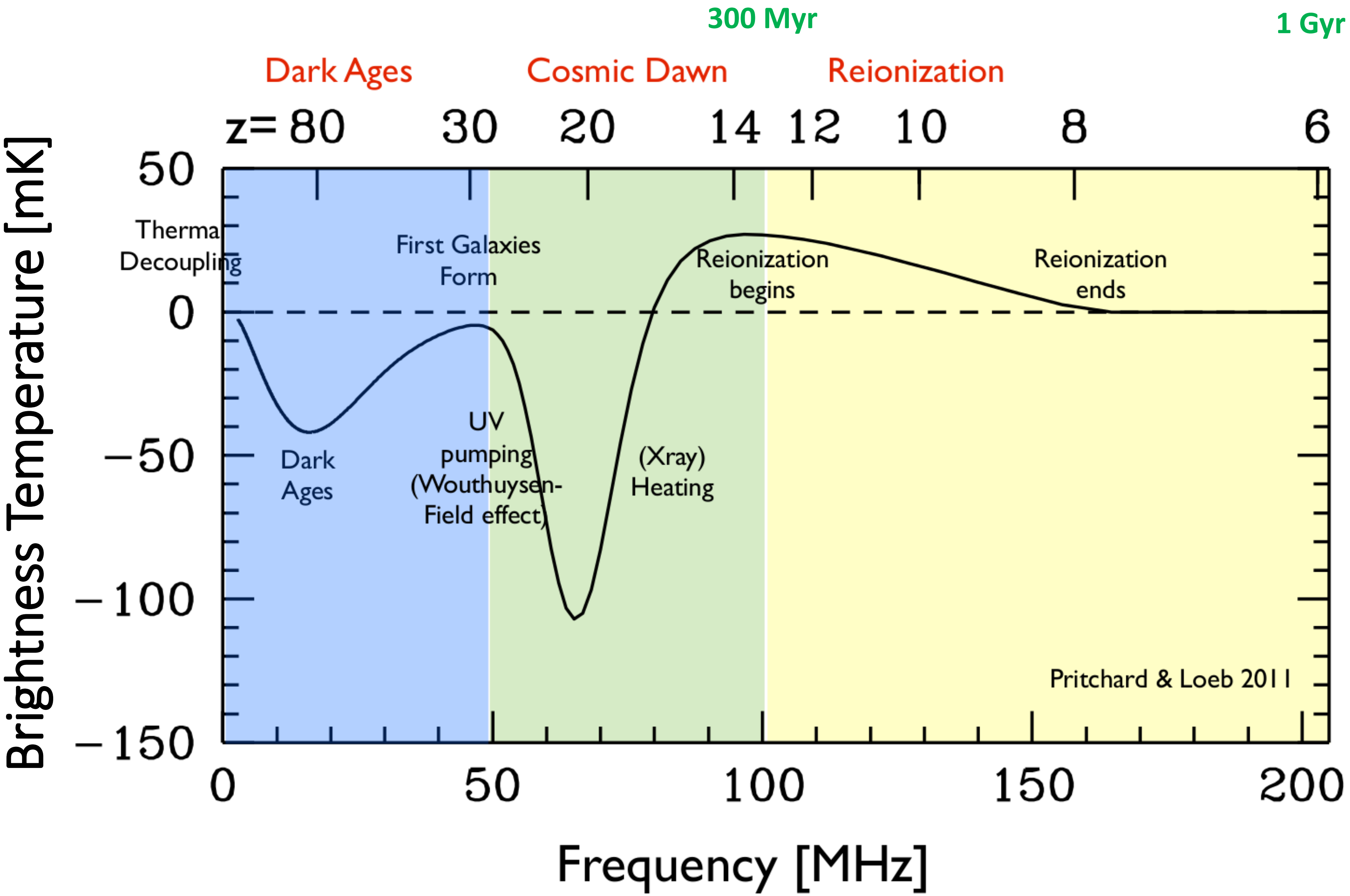
1420 MHz

$$\boxed{\nu_{\text{obs}} = \frac{\nu_{\text{rest frame}}}{(1+z)}}$$

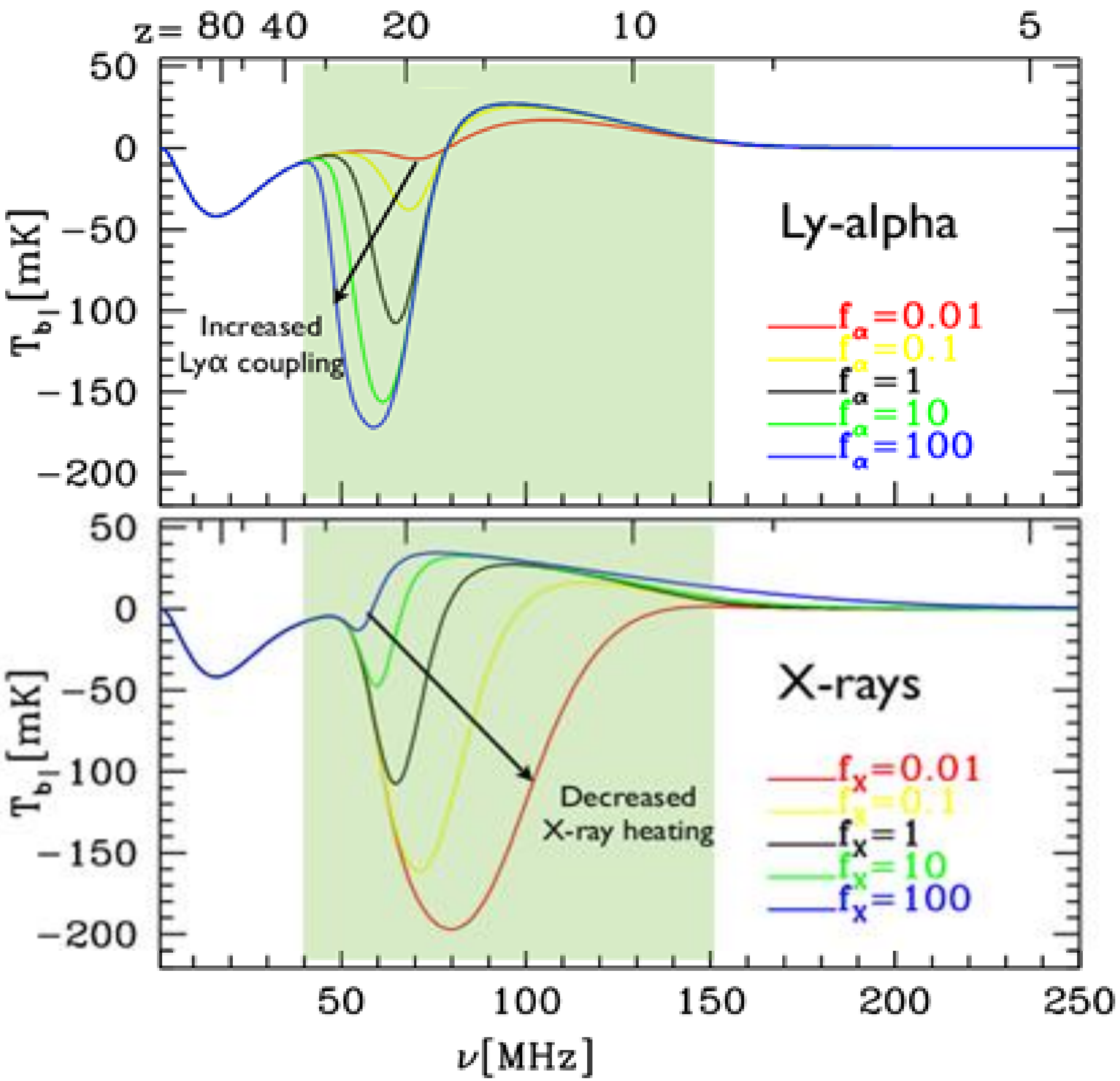
200 MHz $\quad \boldsymbol{z = 6}$

50 MHz $\quad \boldsymbol{z = 28}$

Standard Prediction for Global 21-cm Signal



Understand Nature and Timing of First Sources on Large Scales



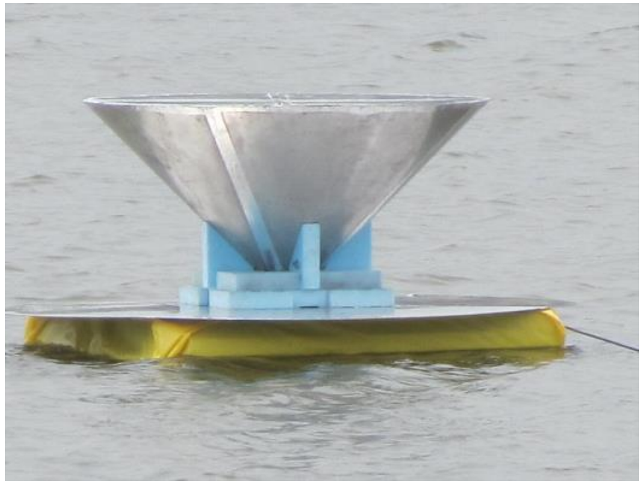
Dark Ages signal does not depend on astrophysics

From Pritchard & Loeb (2011)

Global 21-cm Experiments

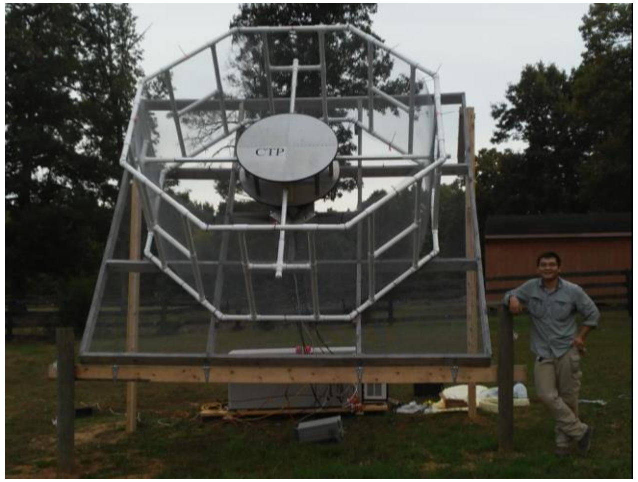
PRI^{Z}M
(McGill, Sievers et al.)

SARAS 3
(RRI, Subrahmanyan et al.)



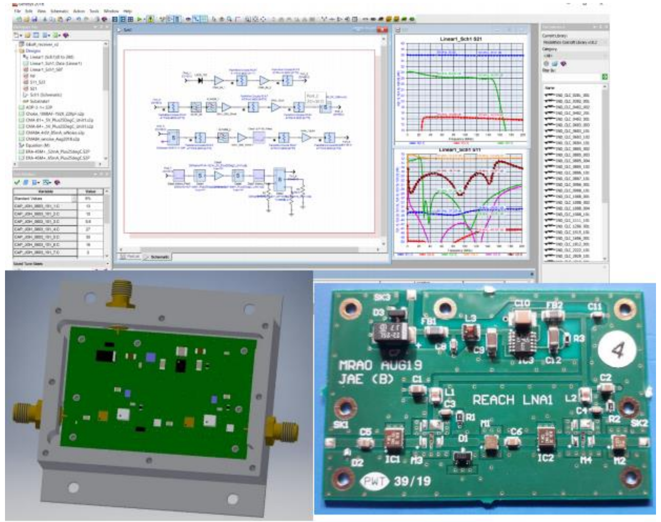
LEDA
(Harvard, Greenhill et al.)

CTP
(NRAO, Bradley et al.)

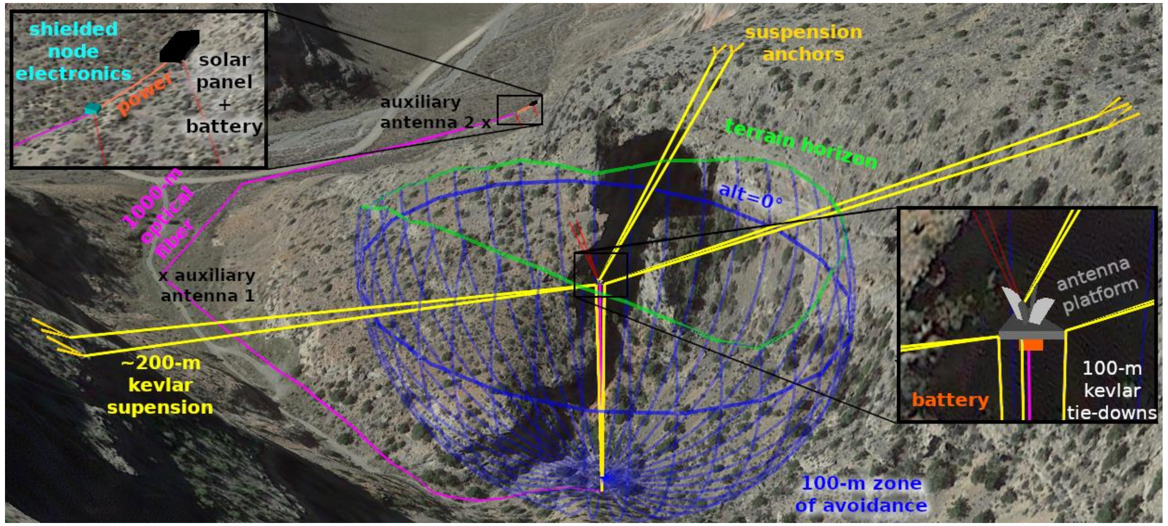


High-Z
(CMU, Peterson et al.)

REACH
(Cambridge, De Lera Acedo et al.)



EIGSEP
(UC Berkeley, Parsons et al.)



2) EDGES

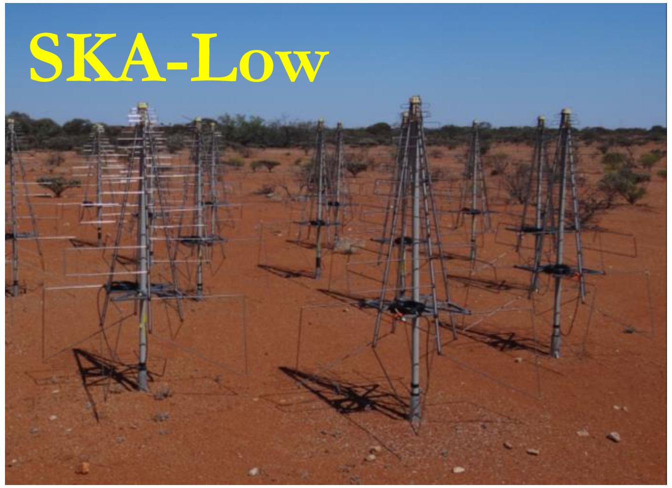
EDGES

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

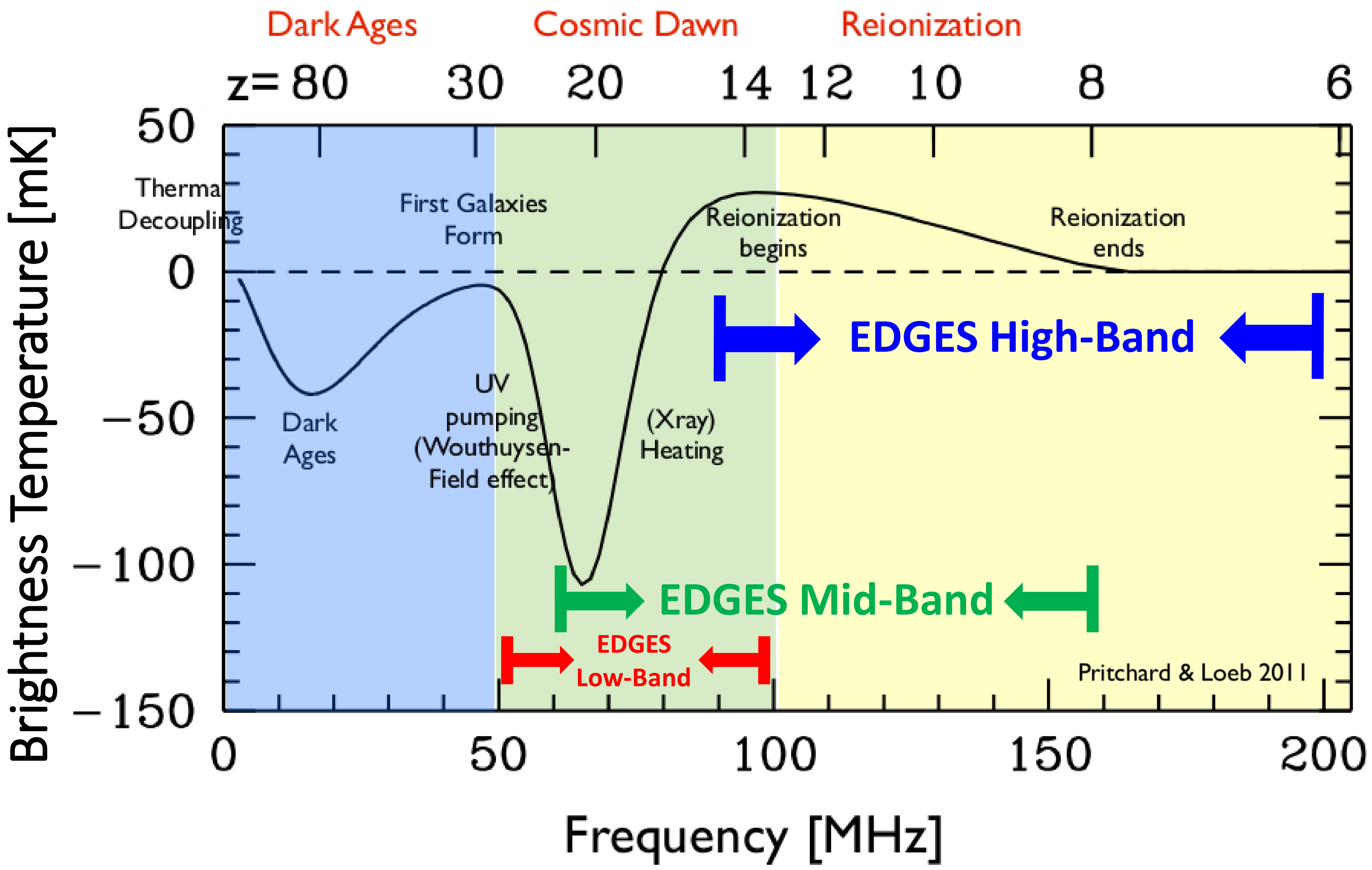
Judd Bowman (PI)
Alan Rogers
Raul Monsalve
Steven Murray
John Barrett
Colin Lonsdale
Thomas Mozdzen
Nivedita Mahesh
Leroy Johnson
Titu Samson
David Lewis
Akshatha Vydula
Peter Sims

Western Australia

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

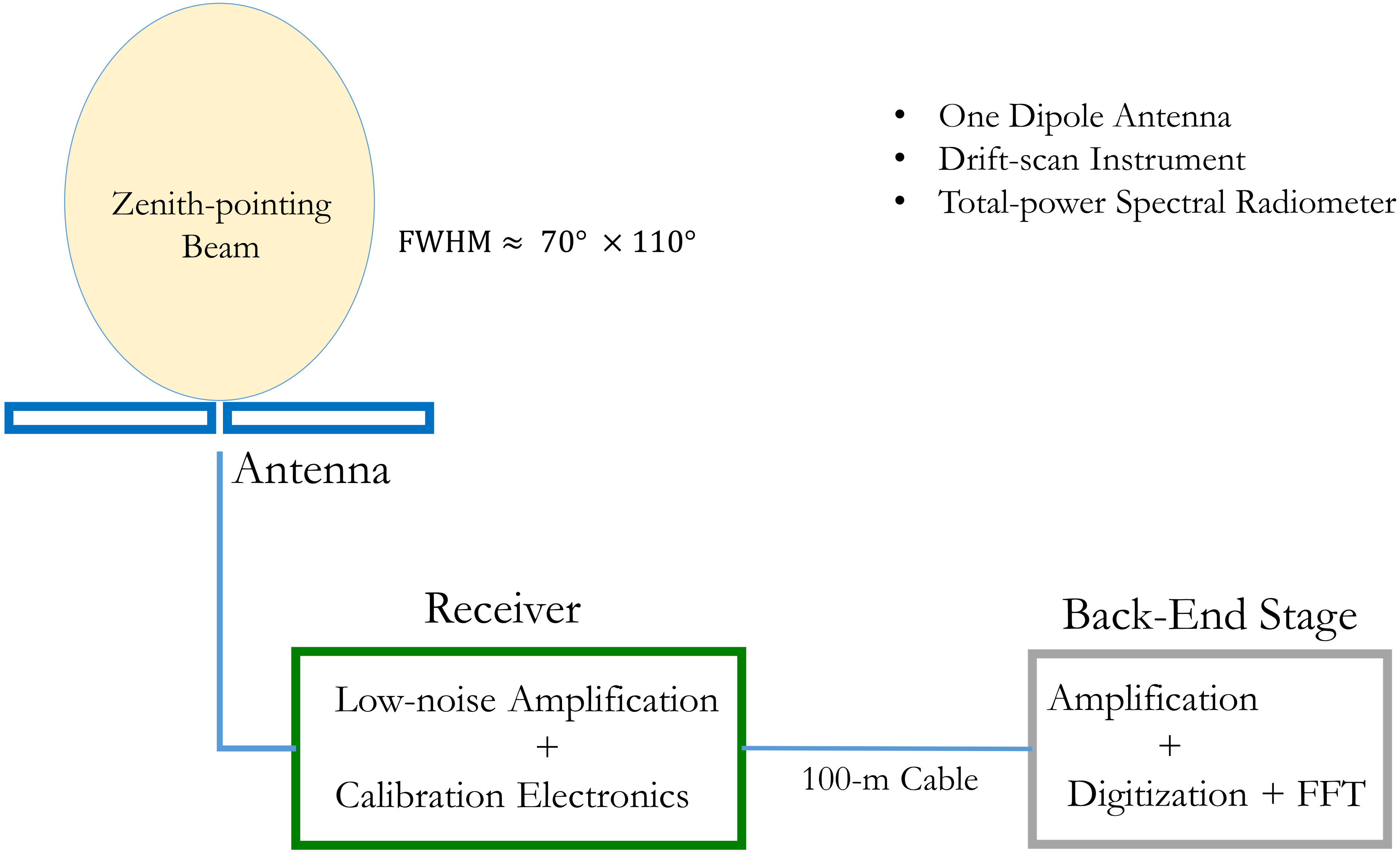


EDGES 2 Instruments

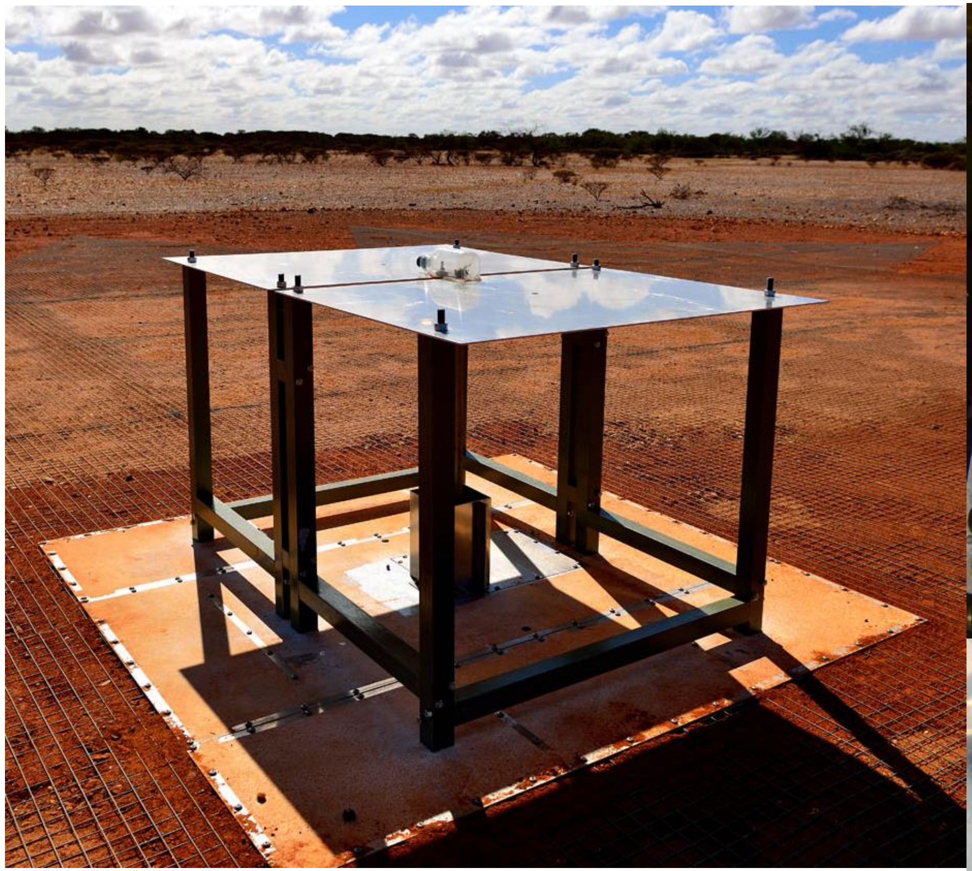


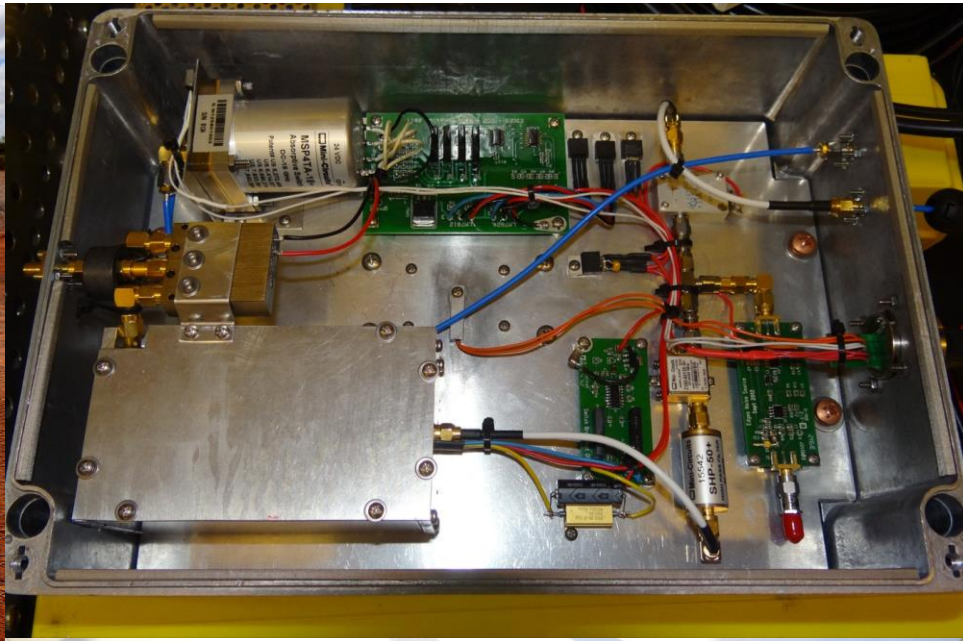
EDGES Instrument Block Diagram

- One Dipole Antenna
- Drift-scan Instrument
- Total-power Spectral Radiometer



EDGES **Low-Band**





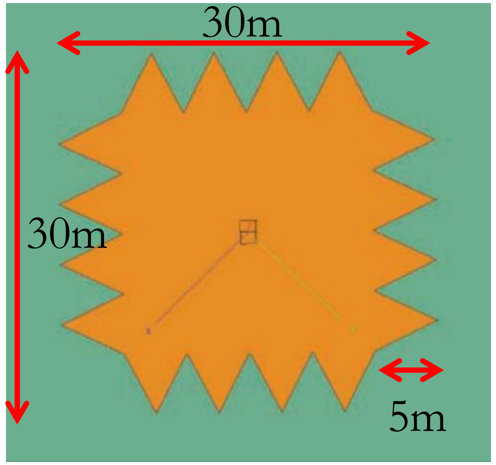
Antenna size:

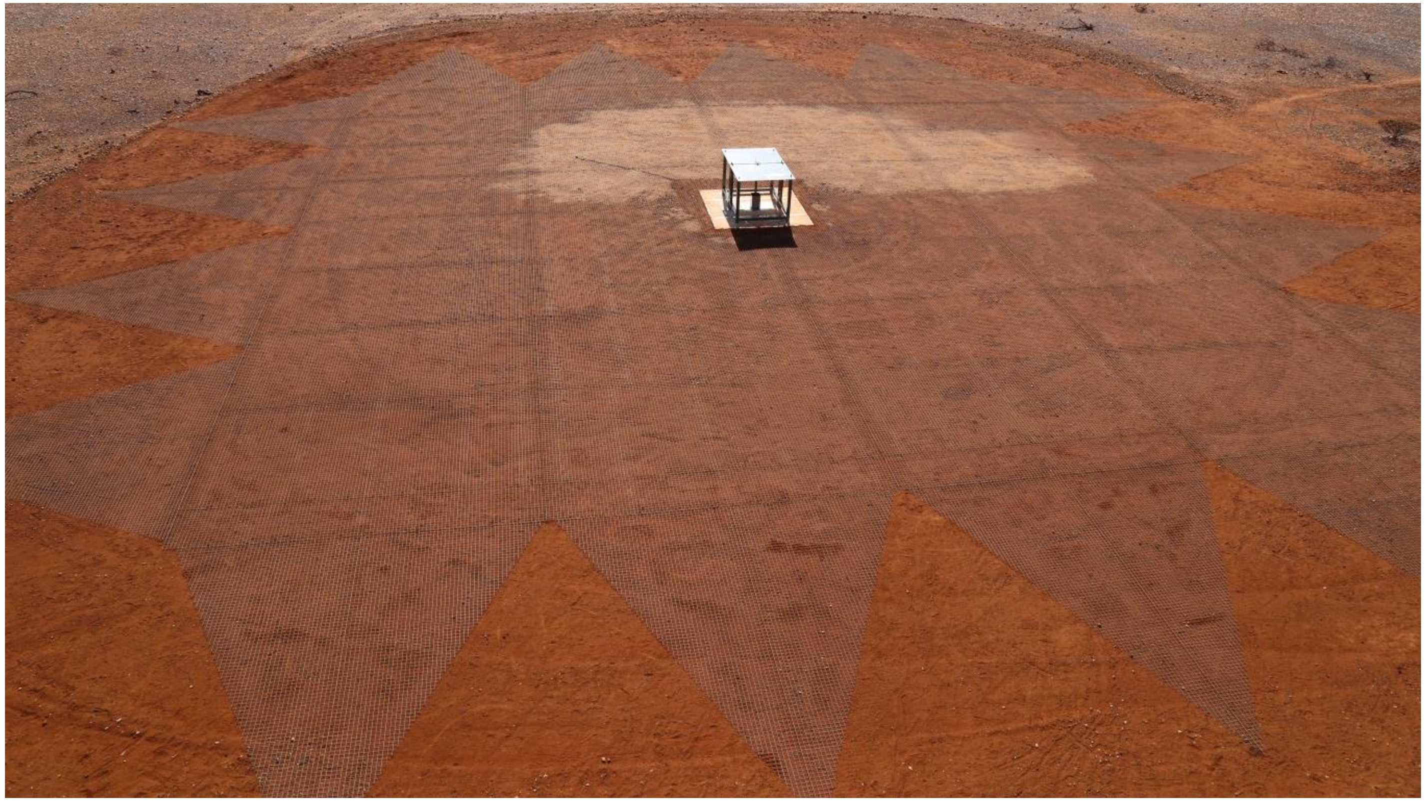
2m long / 1m high

TWO **Low-Band** Instruments

Low-Band Ground Plane

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

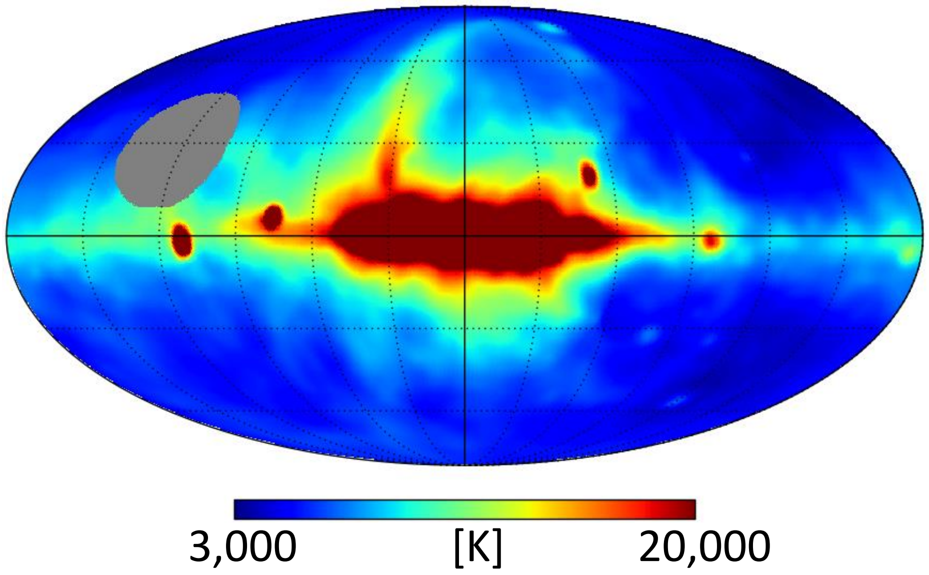




Diffuse Foregrounds

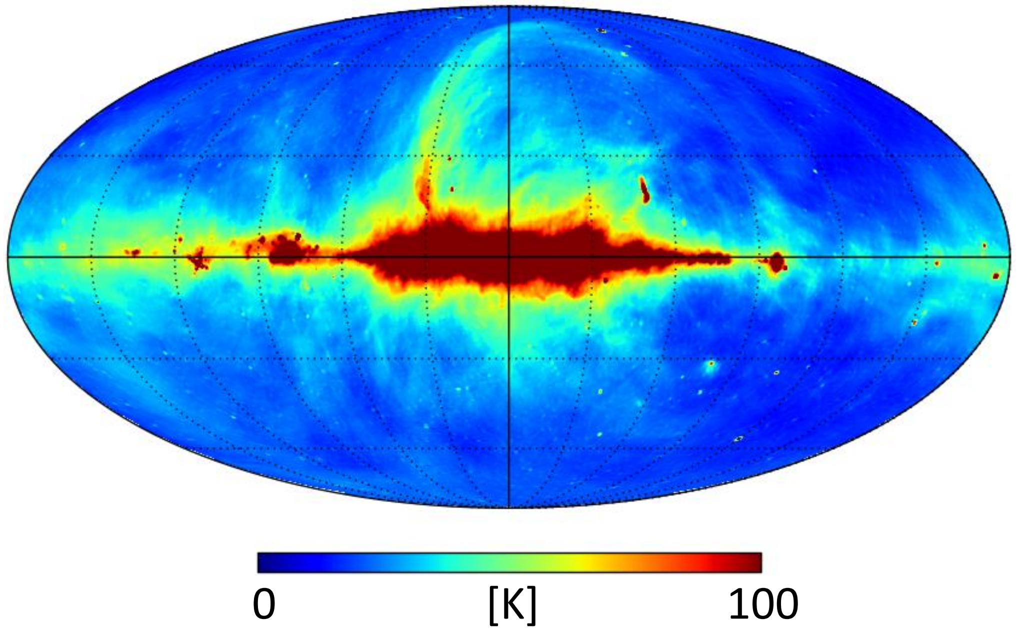
45-MHz Map

Guzmán et al. (2011)



408-MHz Map

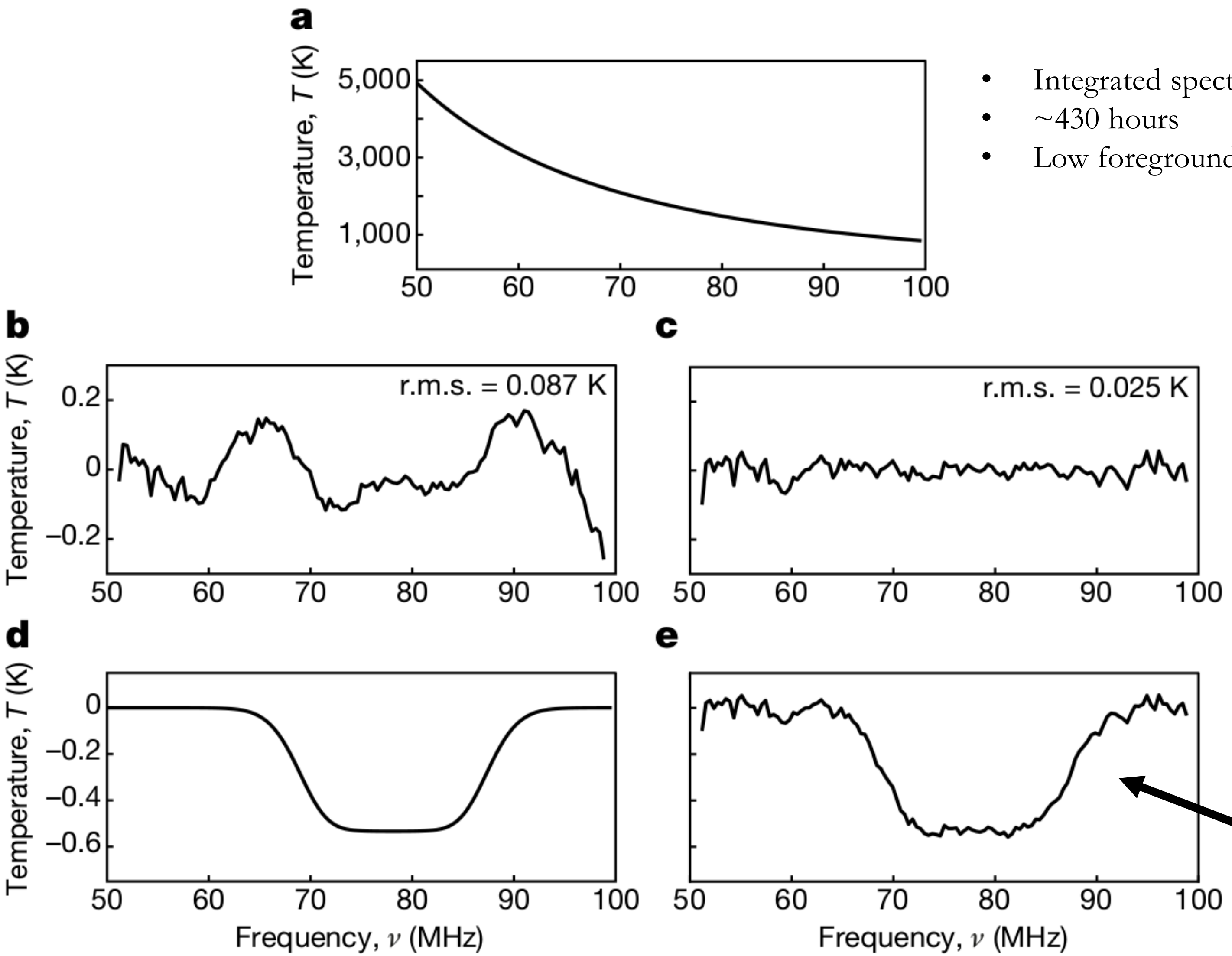
Haslam et al. (1982)



1) From **hundreds to thousands of Kelvins**.
2) **Galactic and Extragalactic** contributions.
3) Mostly **Galactic synchrotron radiation**.
4) **Smooth** spectral dependence expected.

Absorption Feature in EDGES **Low-Band** Data

Summary of Detection

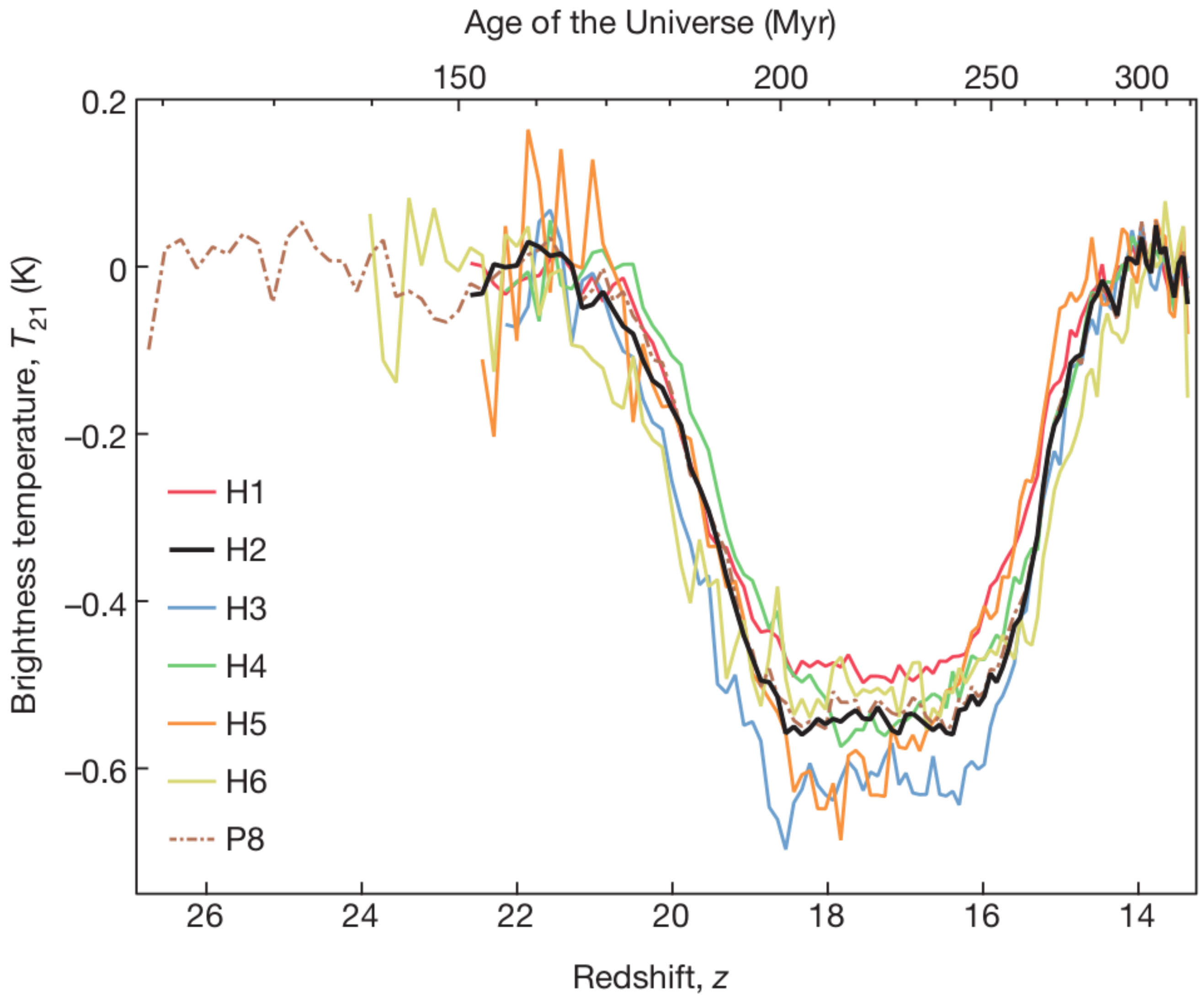


- Integrated spectrum
- ~430 hours
- Low foreground regions

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

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

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

Larger amplitude than allowed by standard models, even considering uncertainties

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] [Aristizabal Sierra & Sheng Fong 2018]

Lower than expected

$\boldsymbol{T}_{\mathbf{K}}$ **Lower than expected**

Suggested source:

- Interactions between **Baryons and Dark Matter** particles [Muñoz and Loeb 2018]

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

Null Tests (**cosmological feature should not be found)**

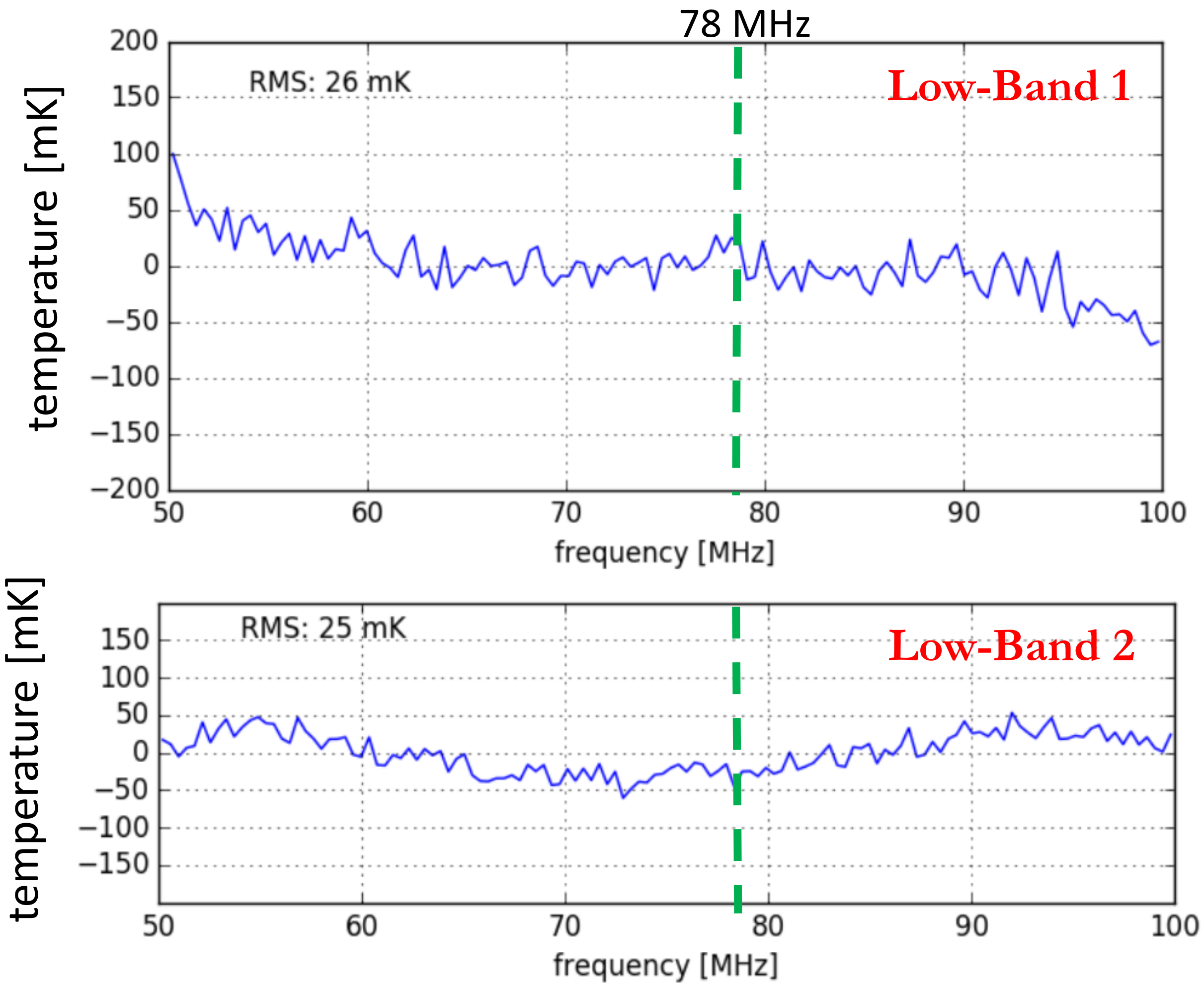
1) Measuring noise sources that produce a **flat spectrum**.
2) Measuring noise sources that produce a spectrum **resembling the diffuse foregrounds**.

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

1) Using **smaller Mid-Band antenna** on the Low-Band ground plane.
2) Using **rotated Low-Band antenna 45 degrees** relative to ground plane and sky.

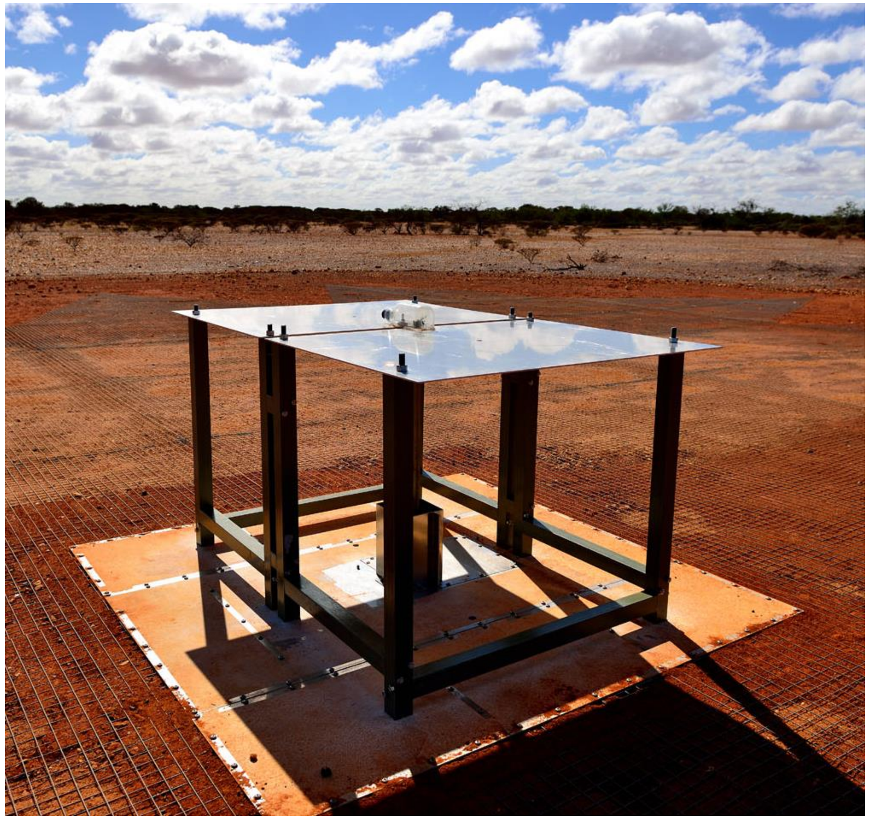
Verification Using ~300K Passive Noise Sources

Residuals After Removing a Constant



Verification with EDGES Mid-Band

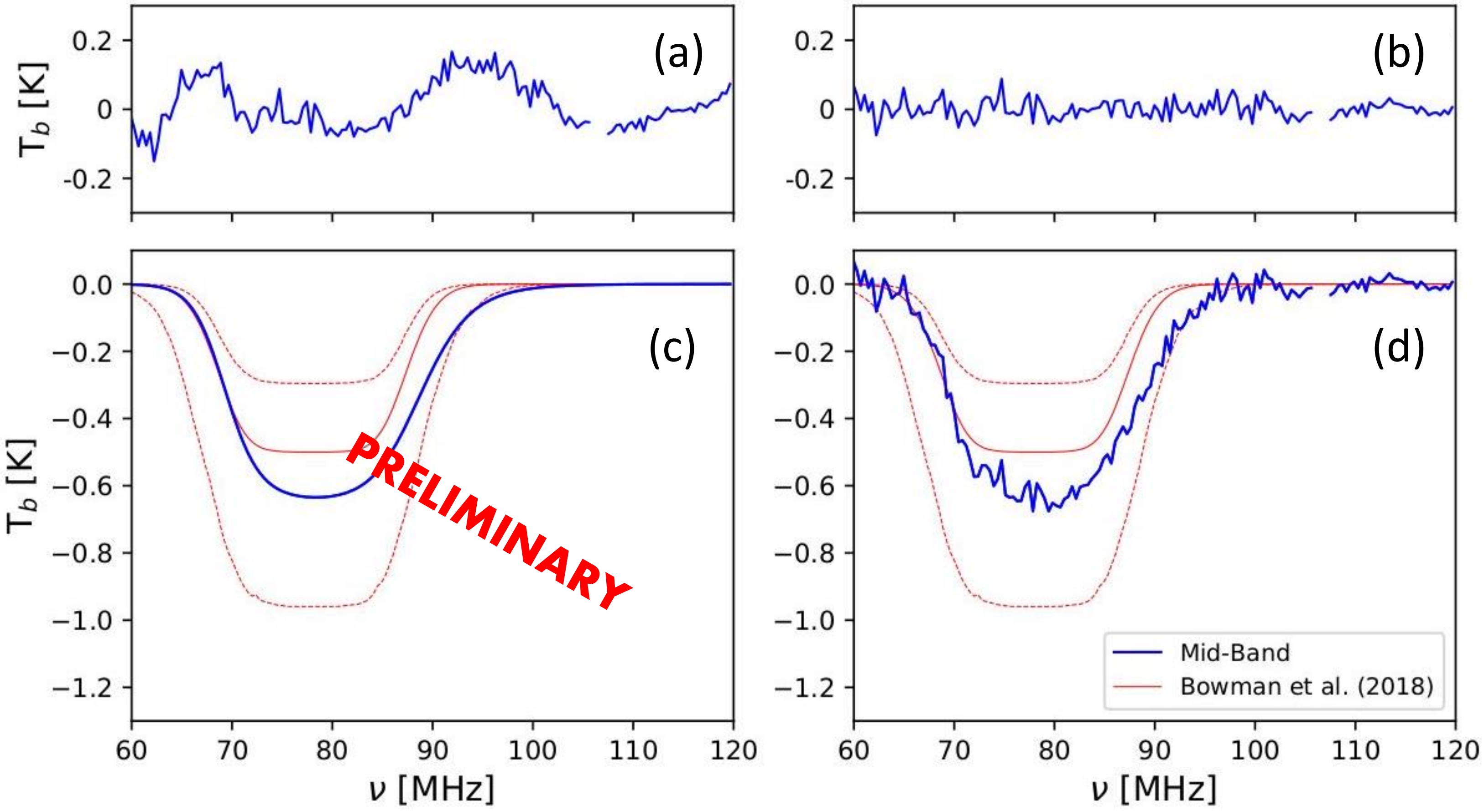
Low-Band



Mid-Band (~25% smaller)

Same Ground Plane as **Low-Band**

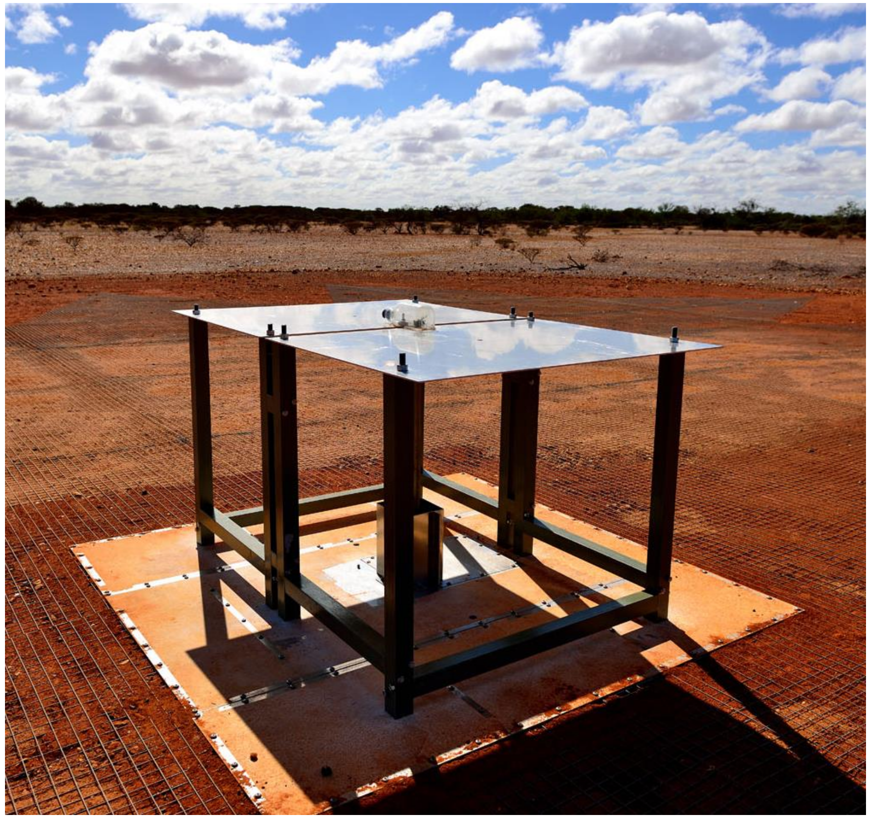
Preliminary **Mid-Band** Results



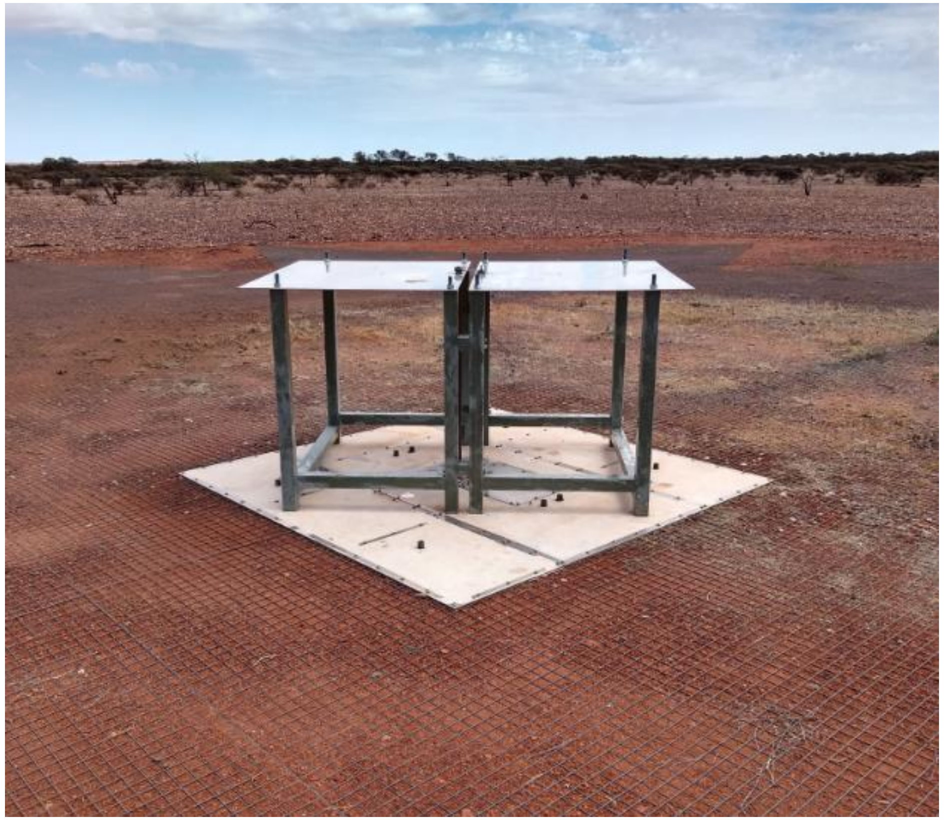
Data taken in 2018, 2020, and 2021

Verification with **Rotated Low-Band**

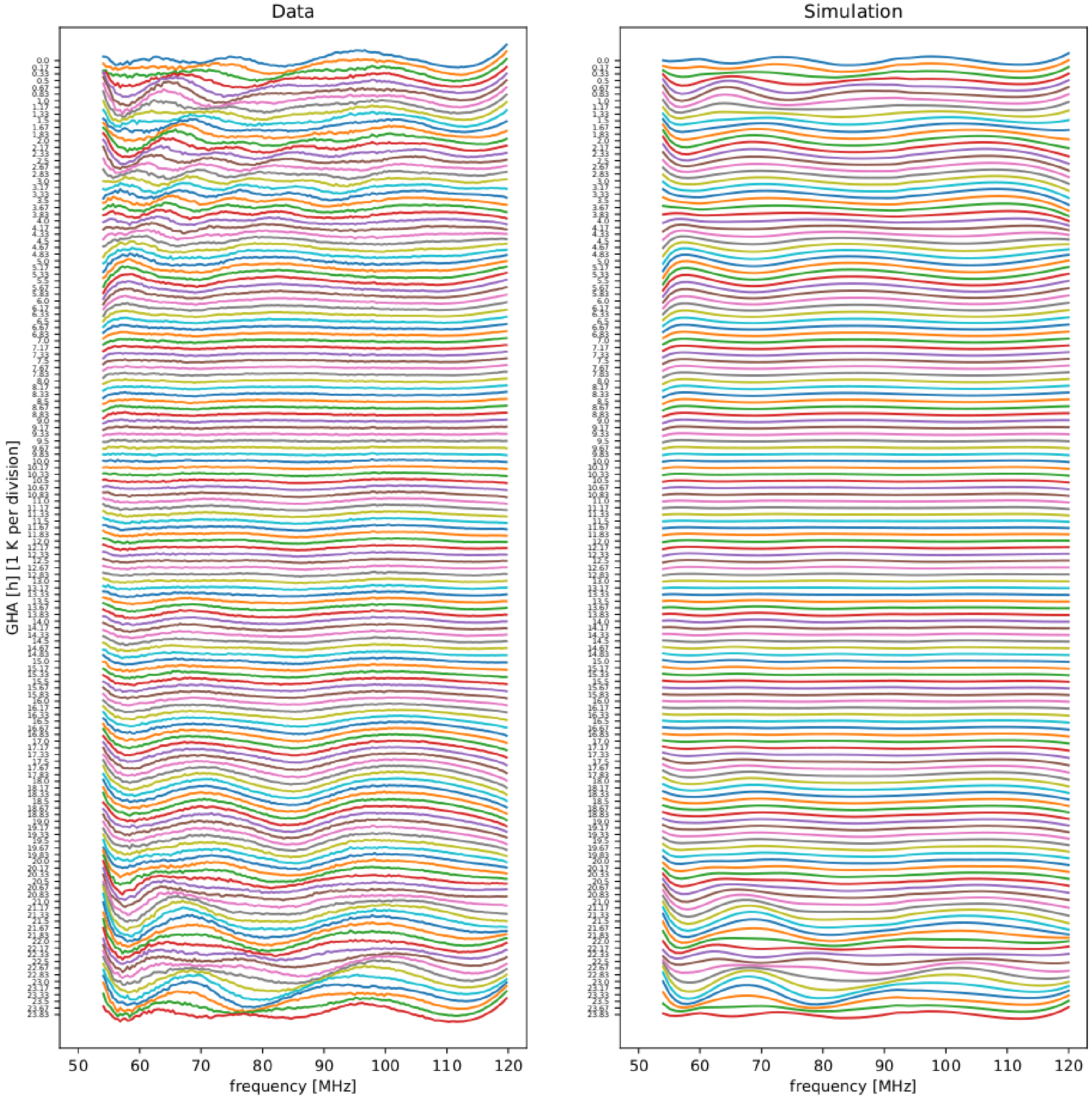
Low-Band



45-deg Rotated Low-Band



Preliminary **Rotated Low-Band** Results



Data taken in
2020, 2021, and 2022

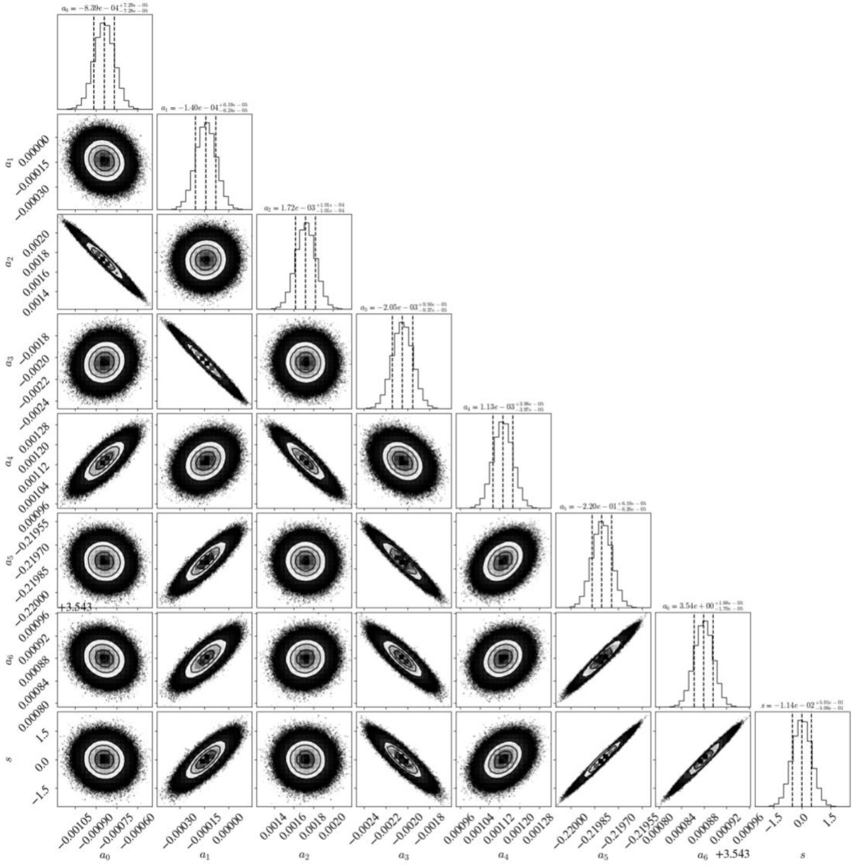
Work in Progress

Recent SARAS 3 Result

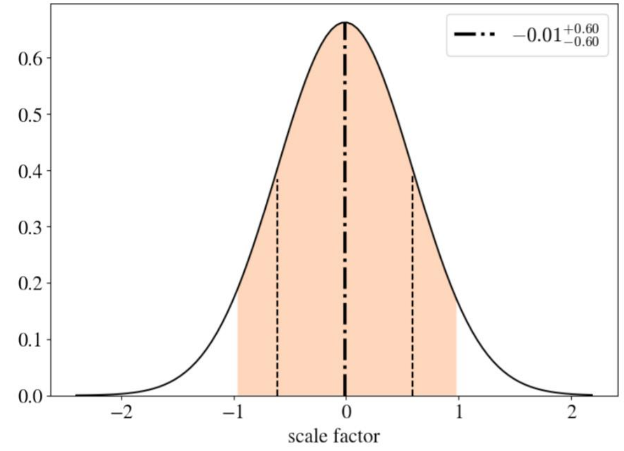
SARAS 3 on a lake in India

Singh et al. (2021)

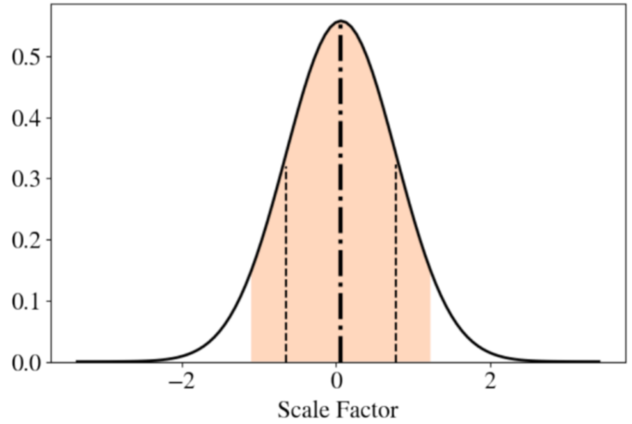
https://arxiv.org/abs/2112.06778



- 55-85 MHz
- 30-MHz band modeled with 7 foreground terms + 1 scale term for best-fit EDGES signal

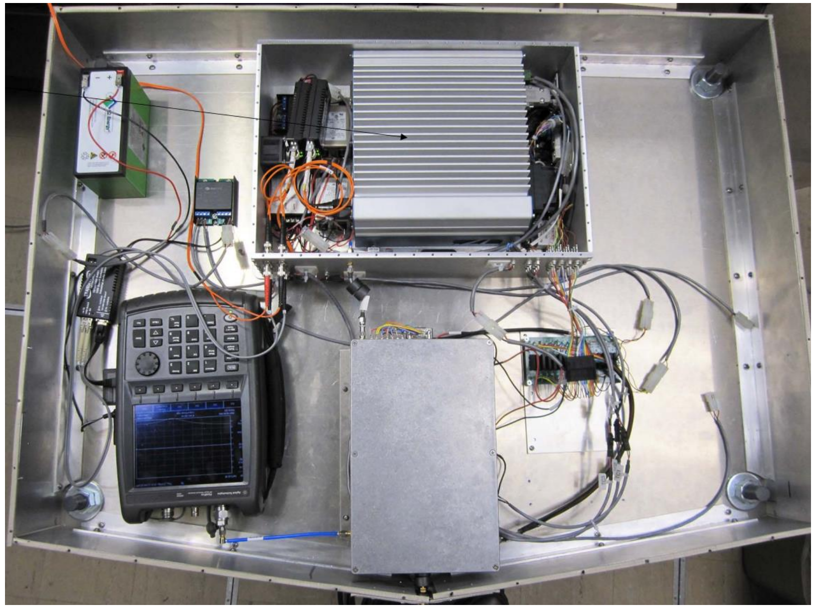


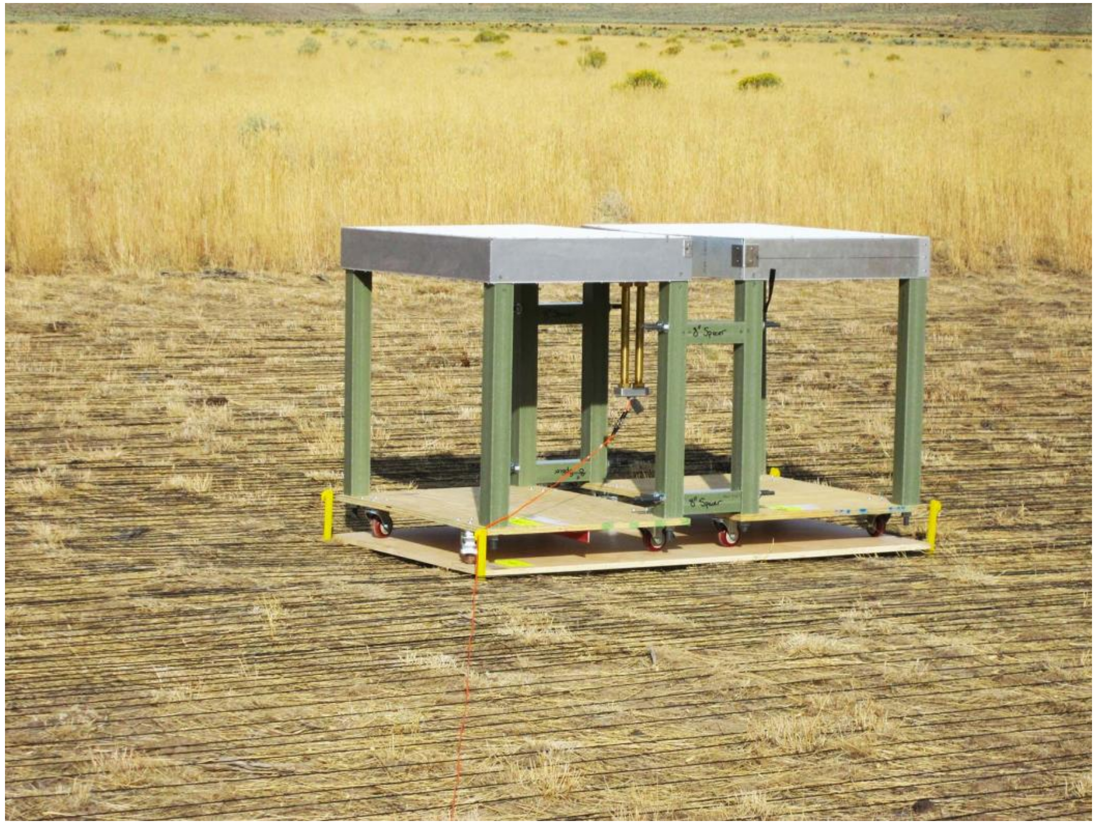
90% confidence range for scale, considering reported SARAS systematics.



90% confidence range for scale, considering systematics and range of EDGES signals.

EDGES-3





1) Improved hardware.

2) More **portable design**.

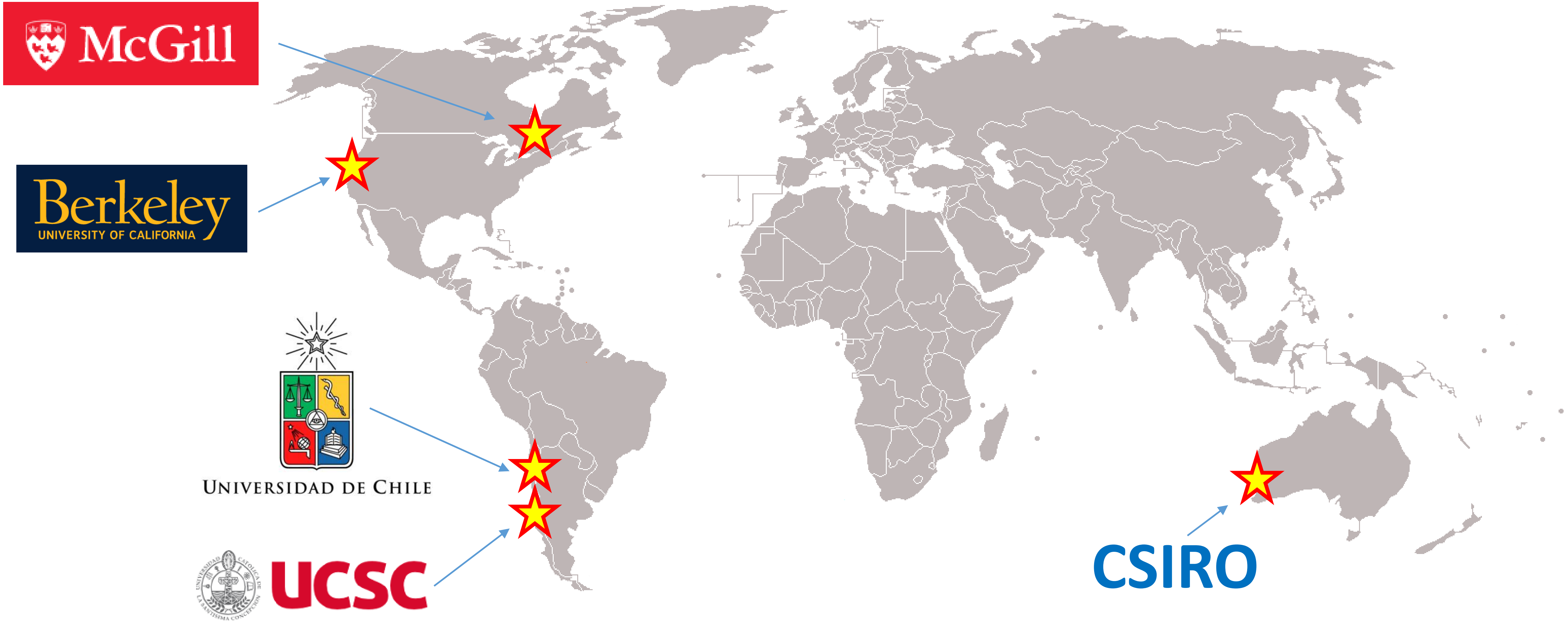
3) Electronics **within antenna**.

4) Prototype observed from **Oregon, USA**.

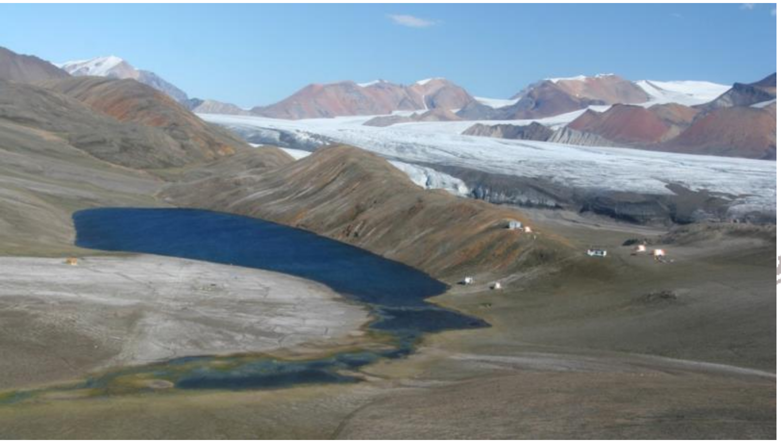
5) Plan to observe from **Australia** but also other sites, potentially in **North America**.

3) MIST

Mapper of the IGM Spin Temperature (MIST)

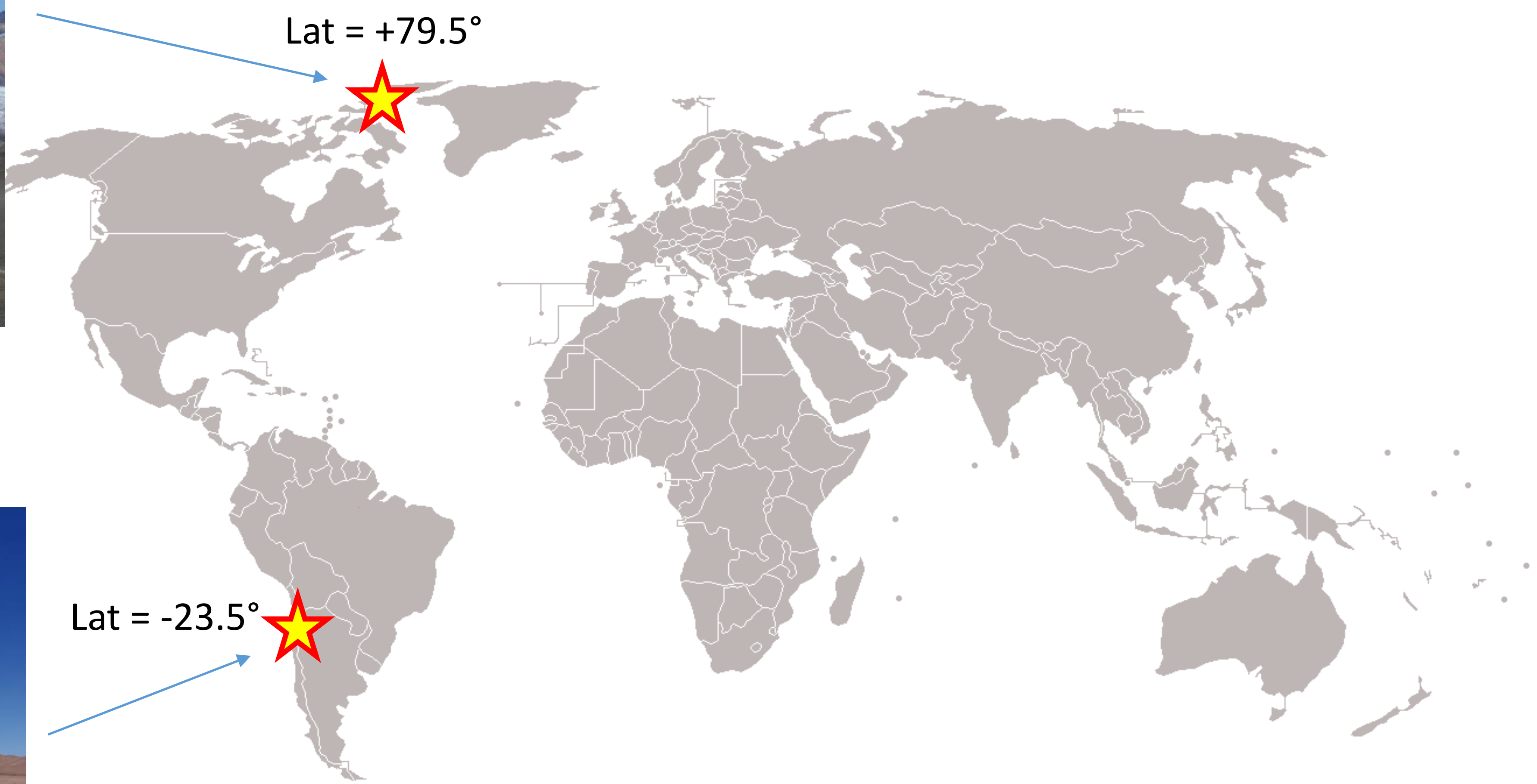


Nominal Observation Sites



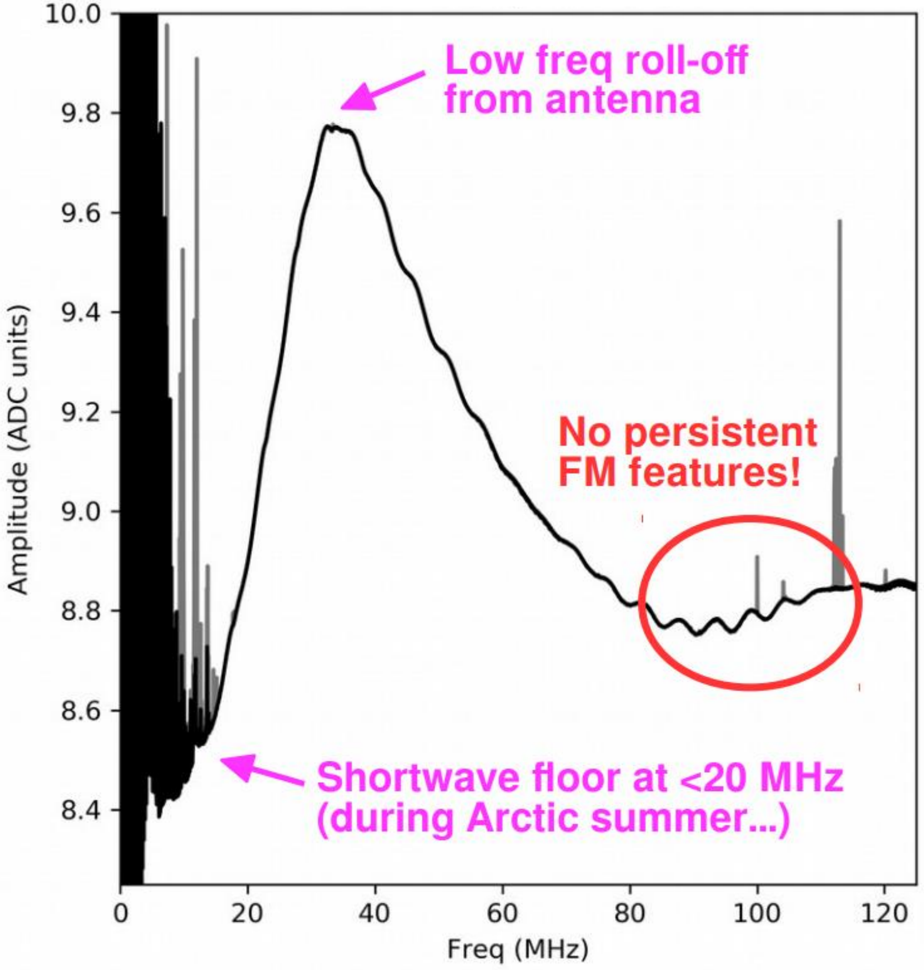
McGill Arctic Research Station

Atacama Desert

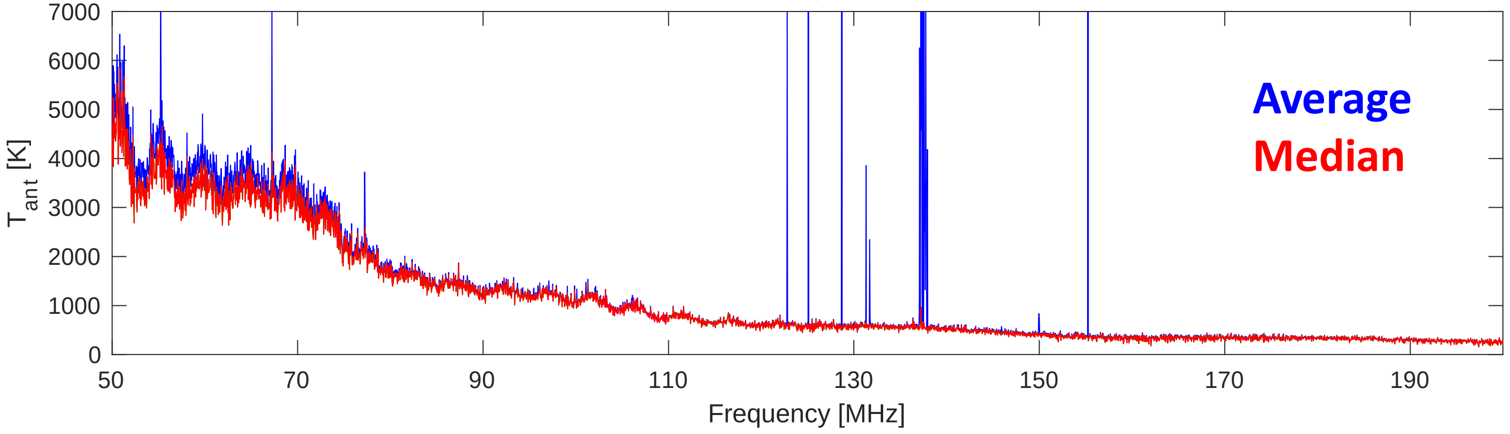


Will try to also observe from other radio-quiet sites

RFI in Arctic (Trip in 2019)

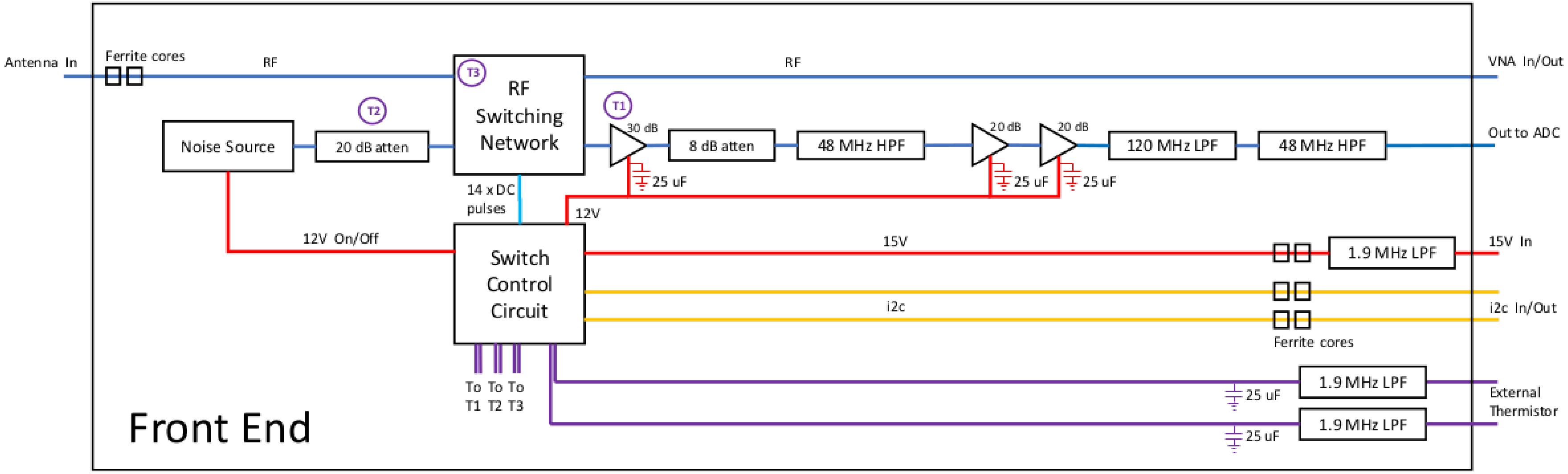


RFI in Atacama Desert (Trip in 2015)

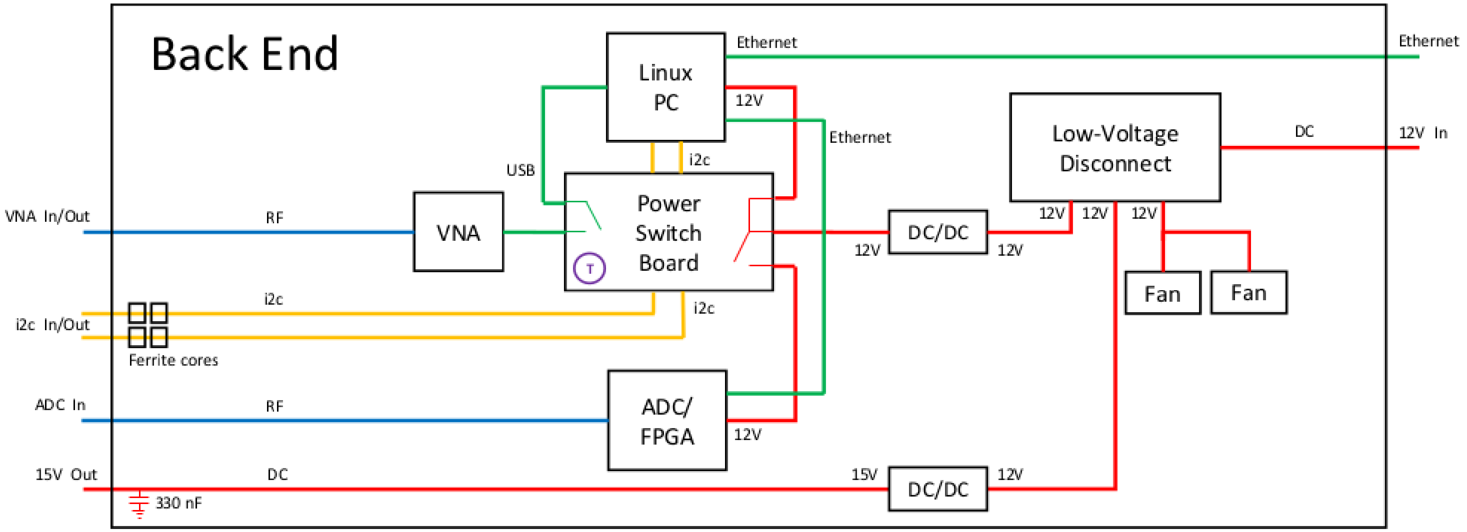


Block Diagram

- Amplifiers, filters
- RF switches
- Noise standards

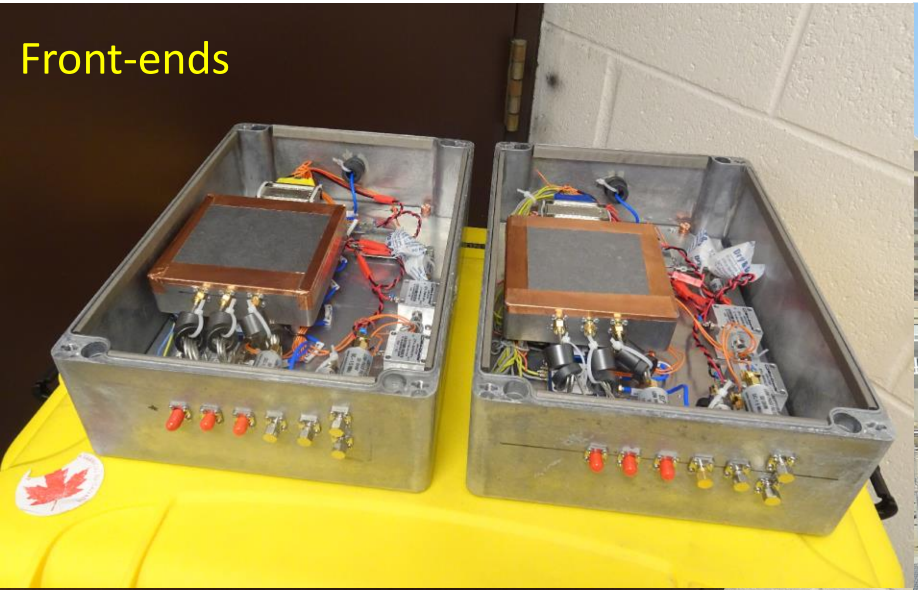


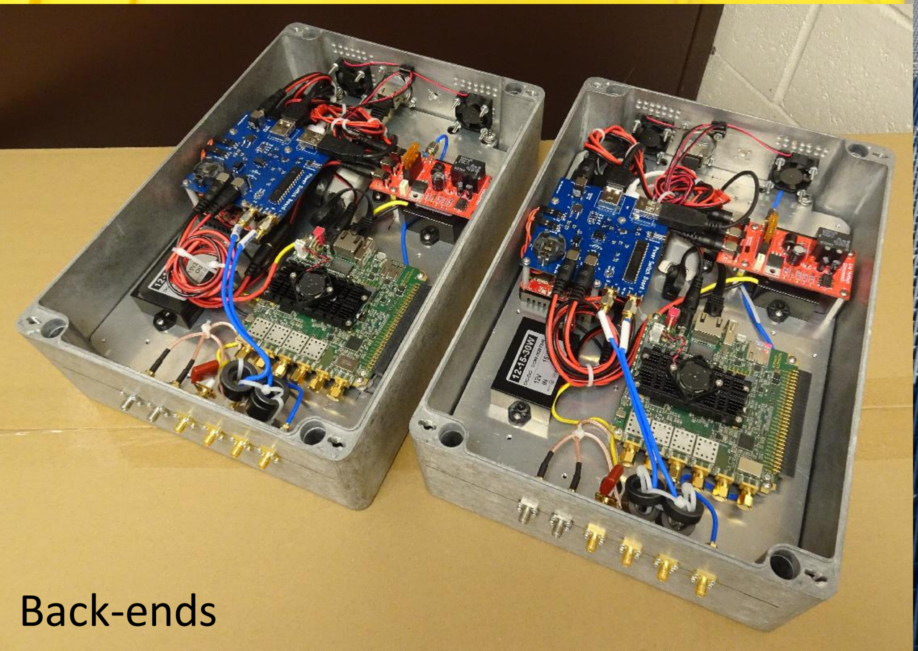
- ADC/FPGA
- VNA
- Control computer
- 20W Power consumption



Instrumental Developments

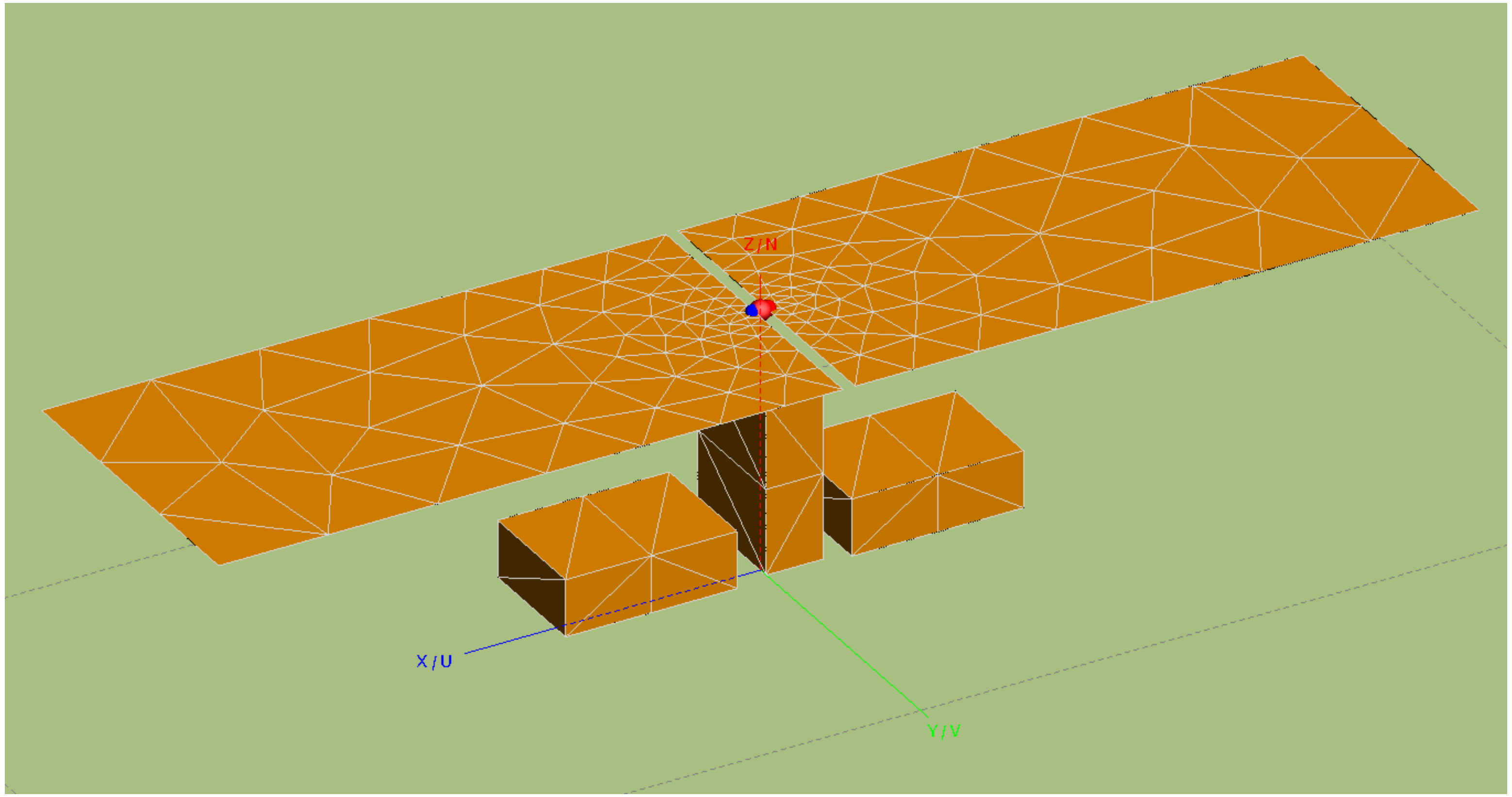
2 Instruments Built





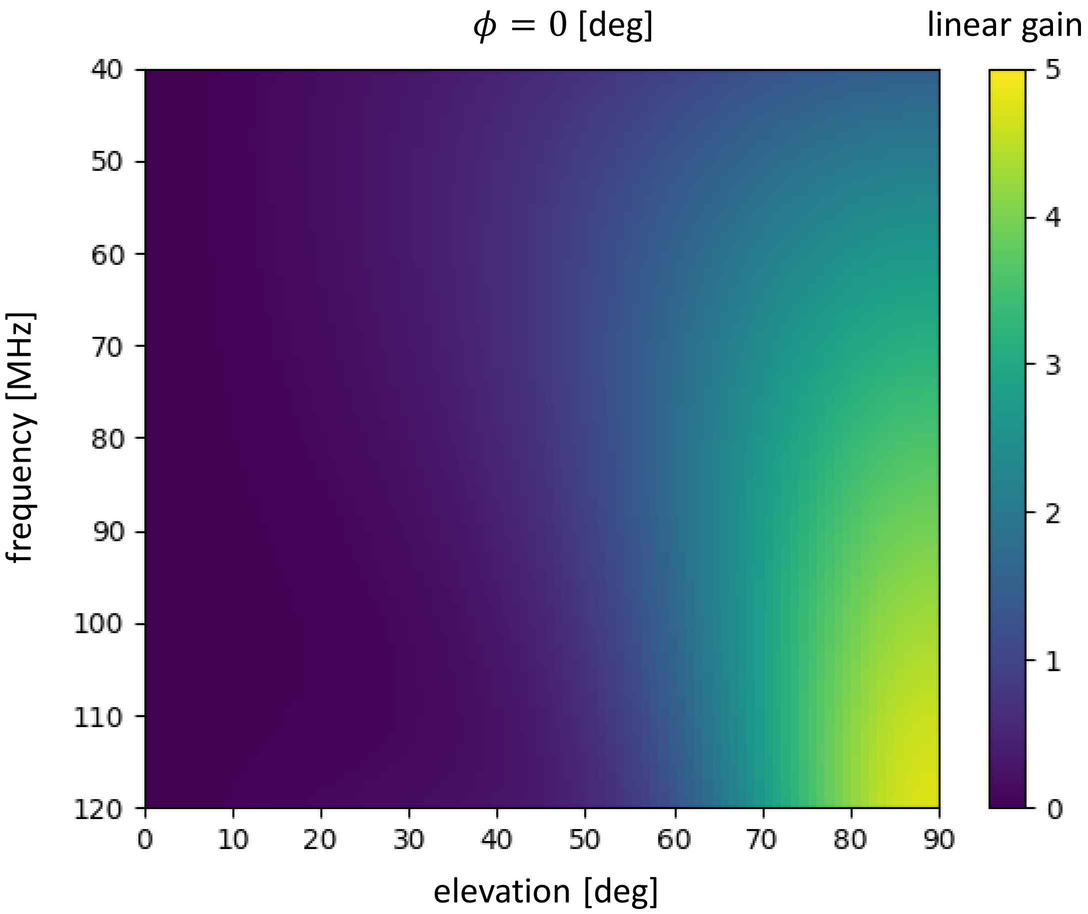
Antenna EM Simulations

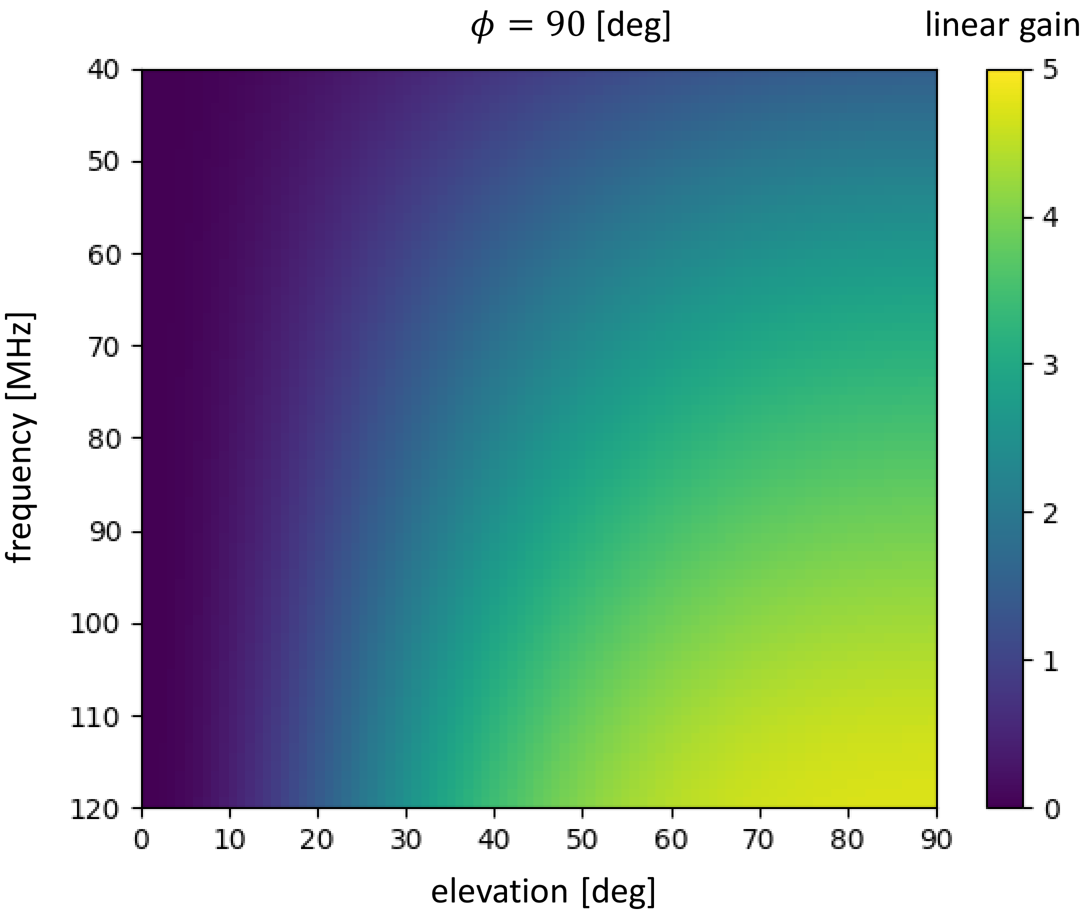
Blade Dipole, Panel Size 60cm x 120cm



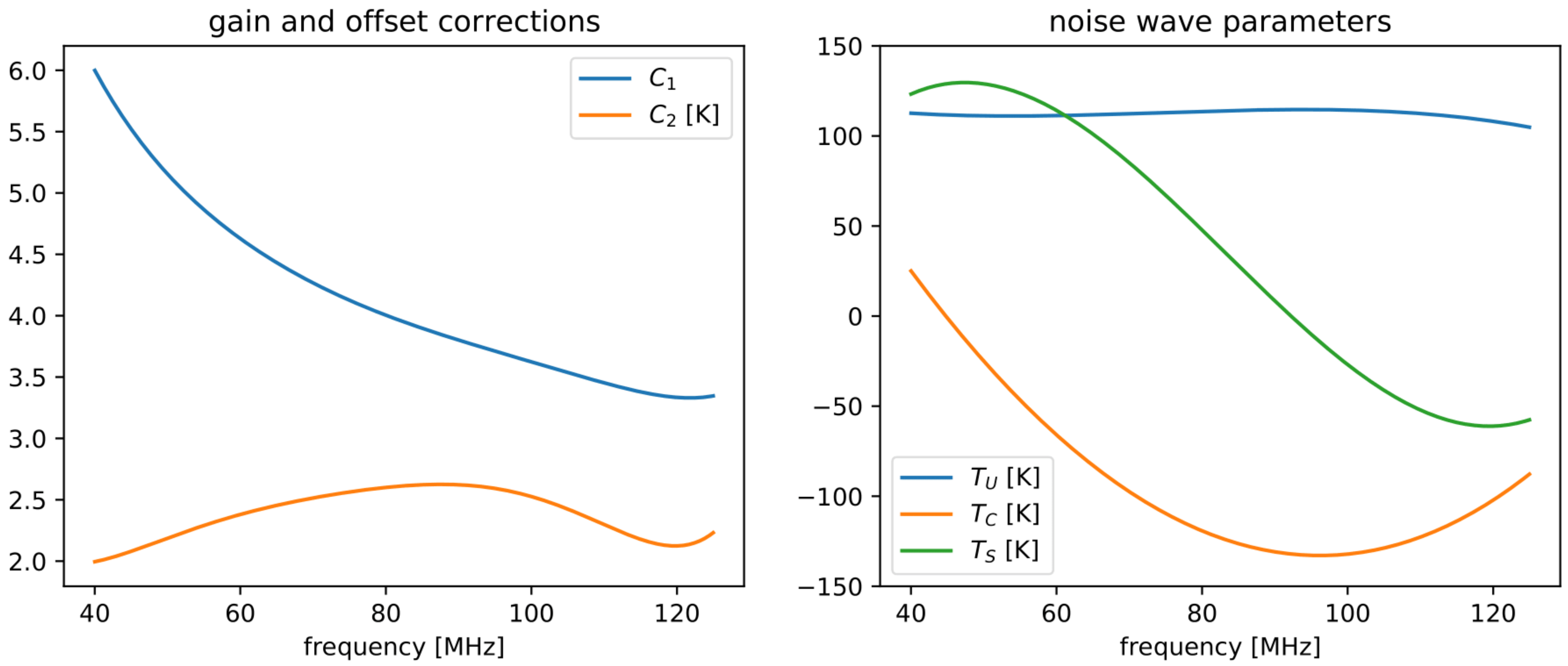
<u>Design Objective</u>
3:1 bandwidth ratio, 40-125 MHz

Antenna Beam Model

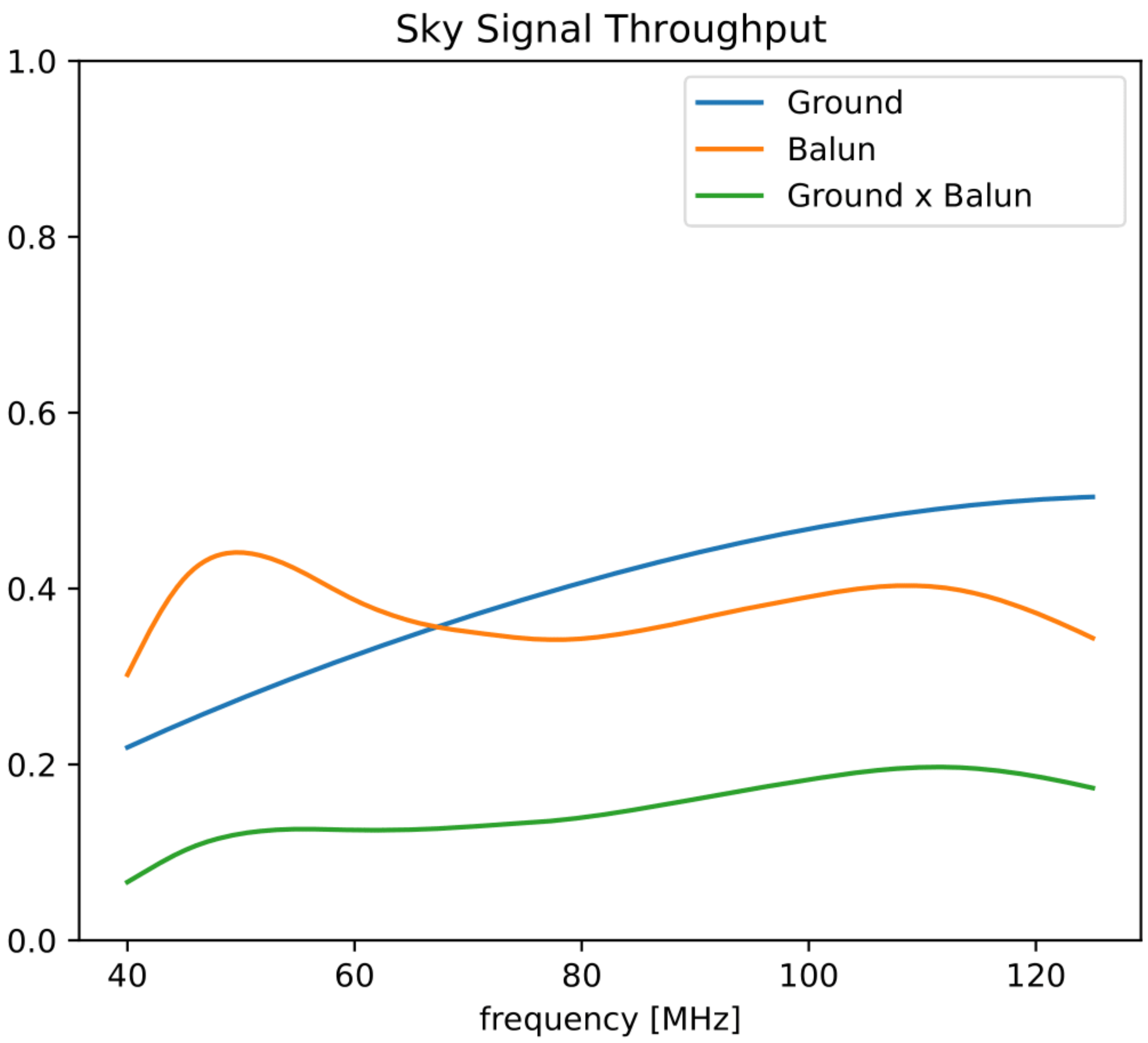




Receiver Parameters



Efficiency

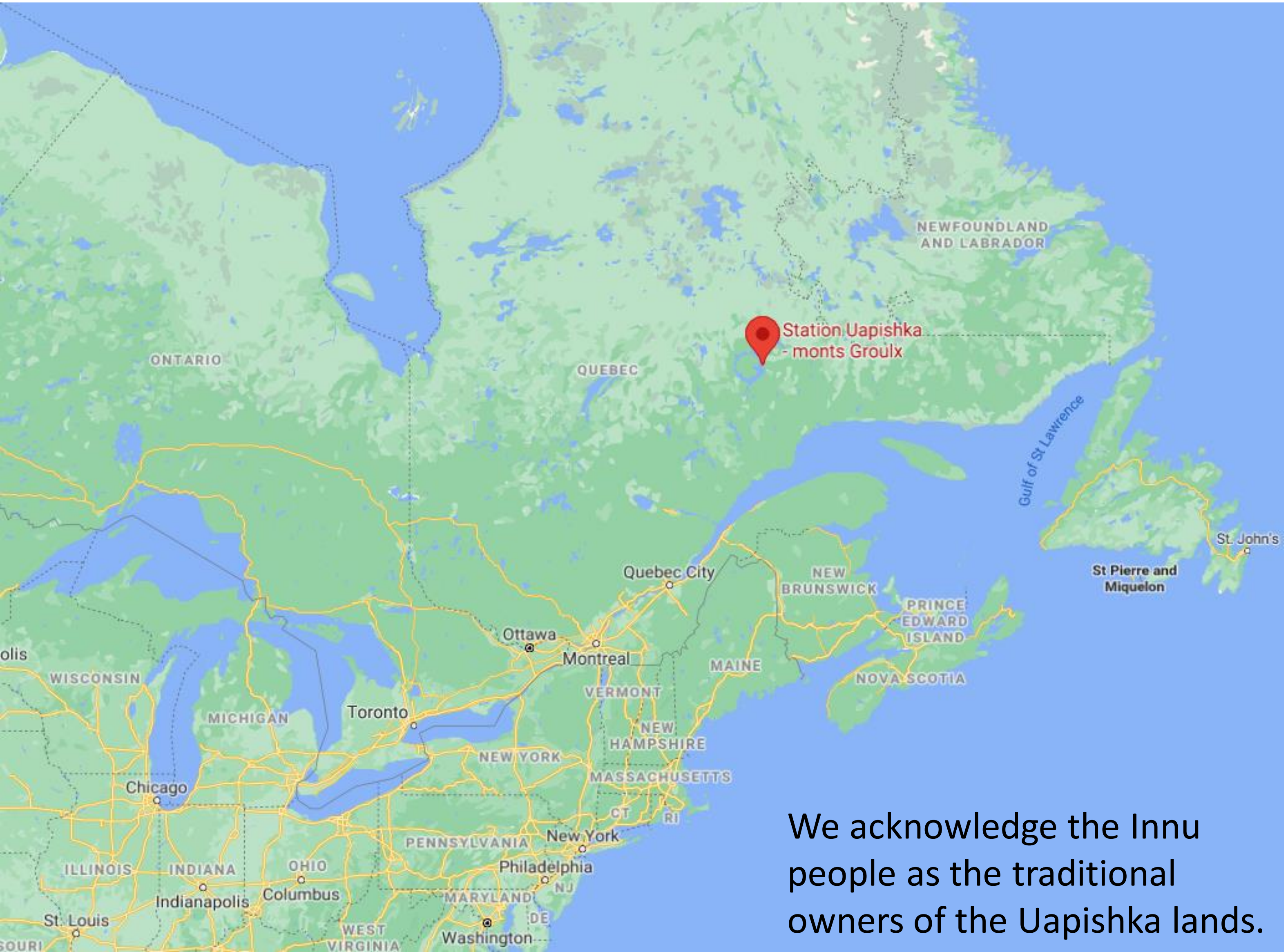


$\sigma = 0.005\ Sm^{-1}$
$\epsilon_r = 3.5$

We are developing techniques to produce more realistic soil models (see other MIST presentations)

Test Deployment in August 2021

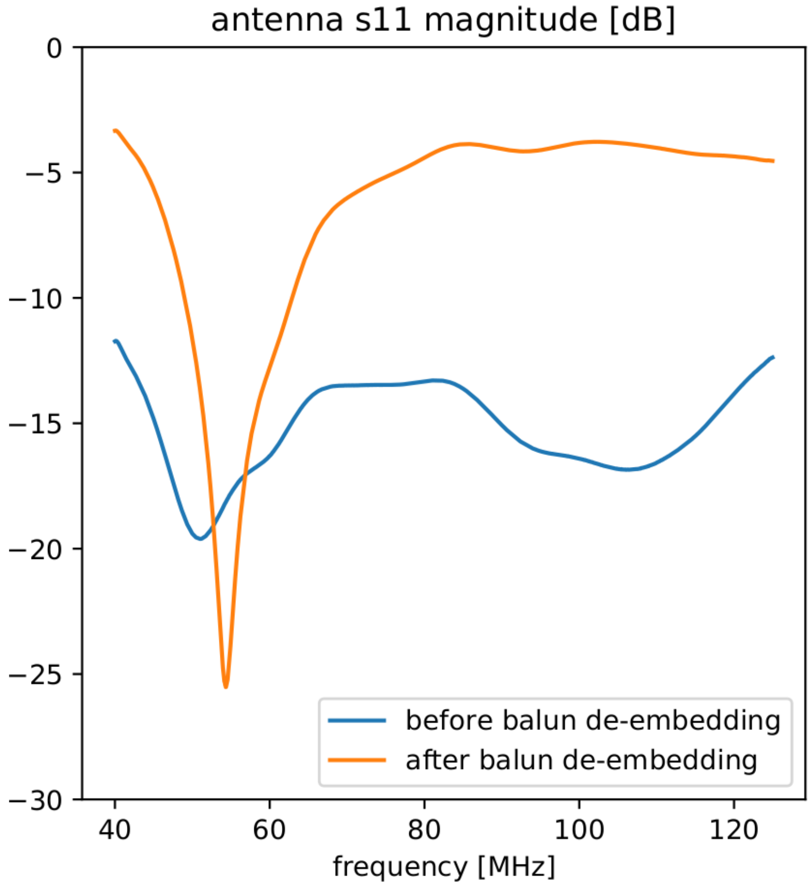
Uapishka Natural Reserve



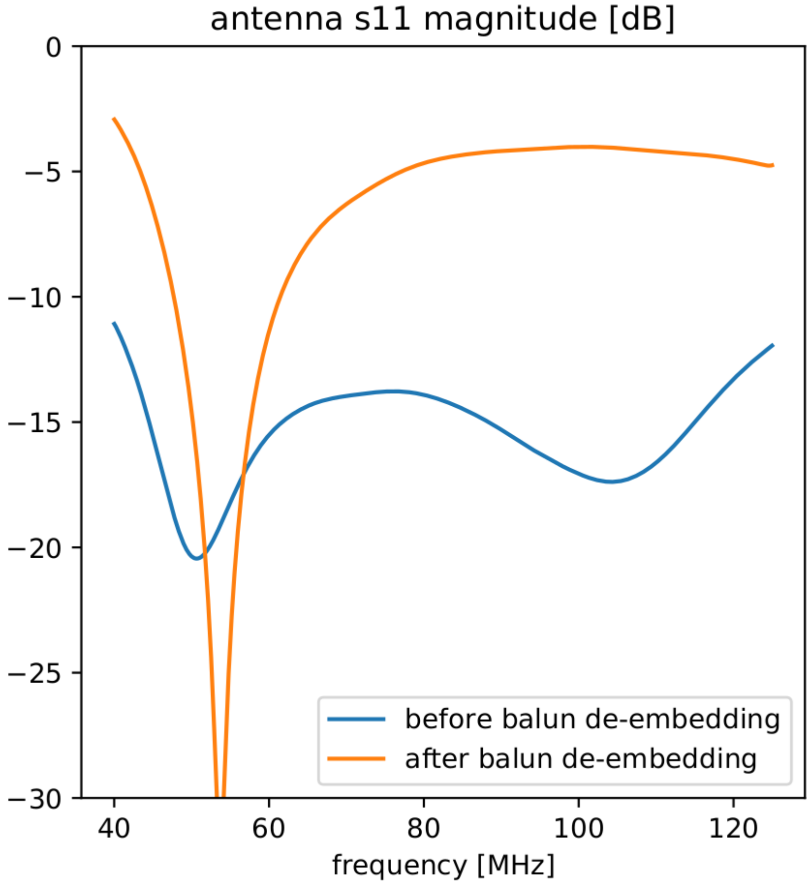
We acknowledge the Innu people as the traditional owners of the Uapishka lands.

Sample Antenna S11

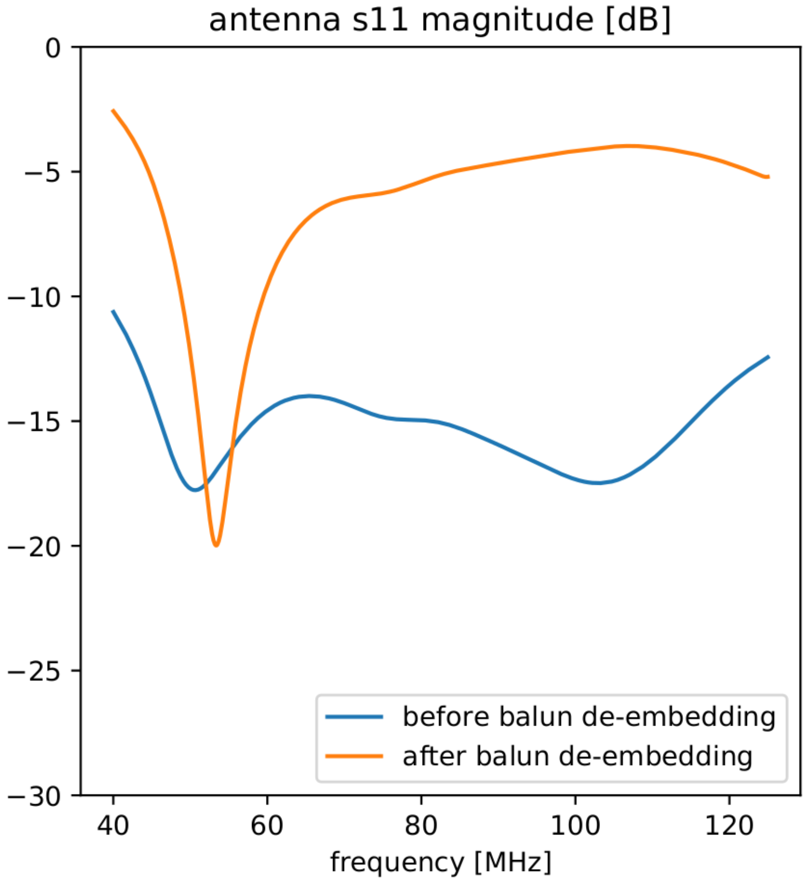
Site 1



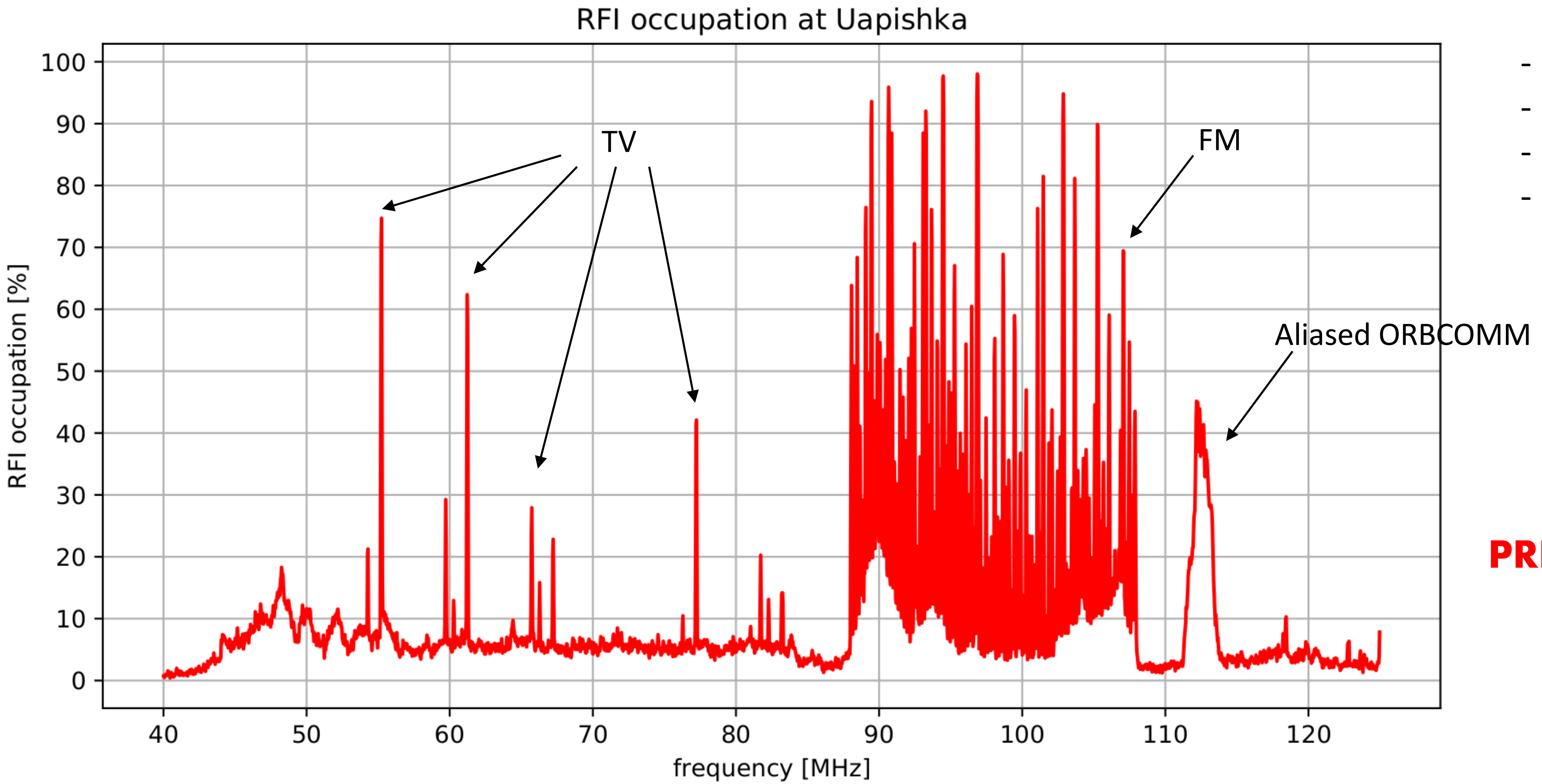
Site 2



Site 3



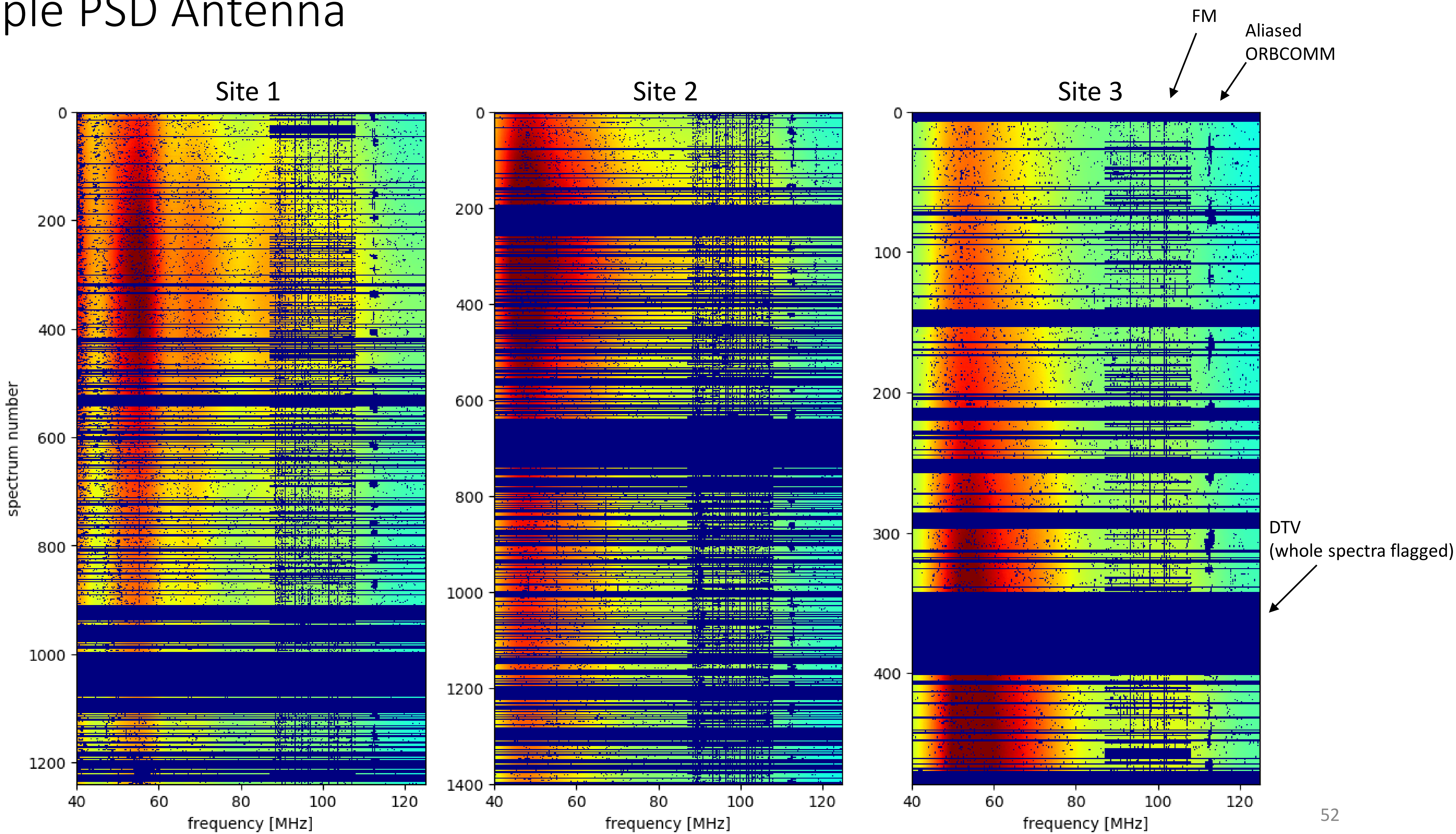
Occupation for Analog RFI



- 11 hours of data
- 12-second integrations
- 36-second cadence
- 30-kHz freq. resolution

PRELIMINARY

Sample PSD Antenna



Status

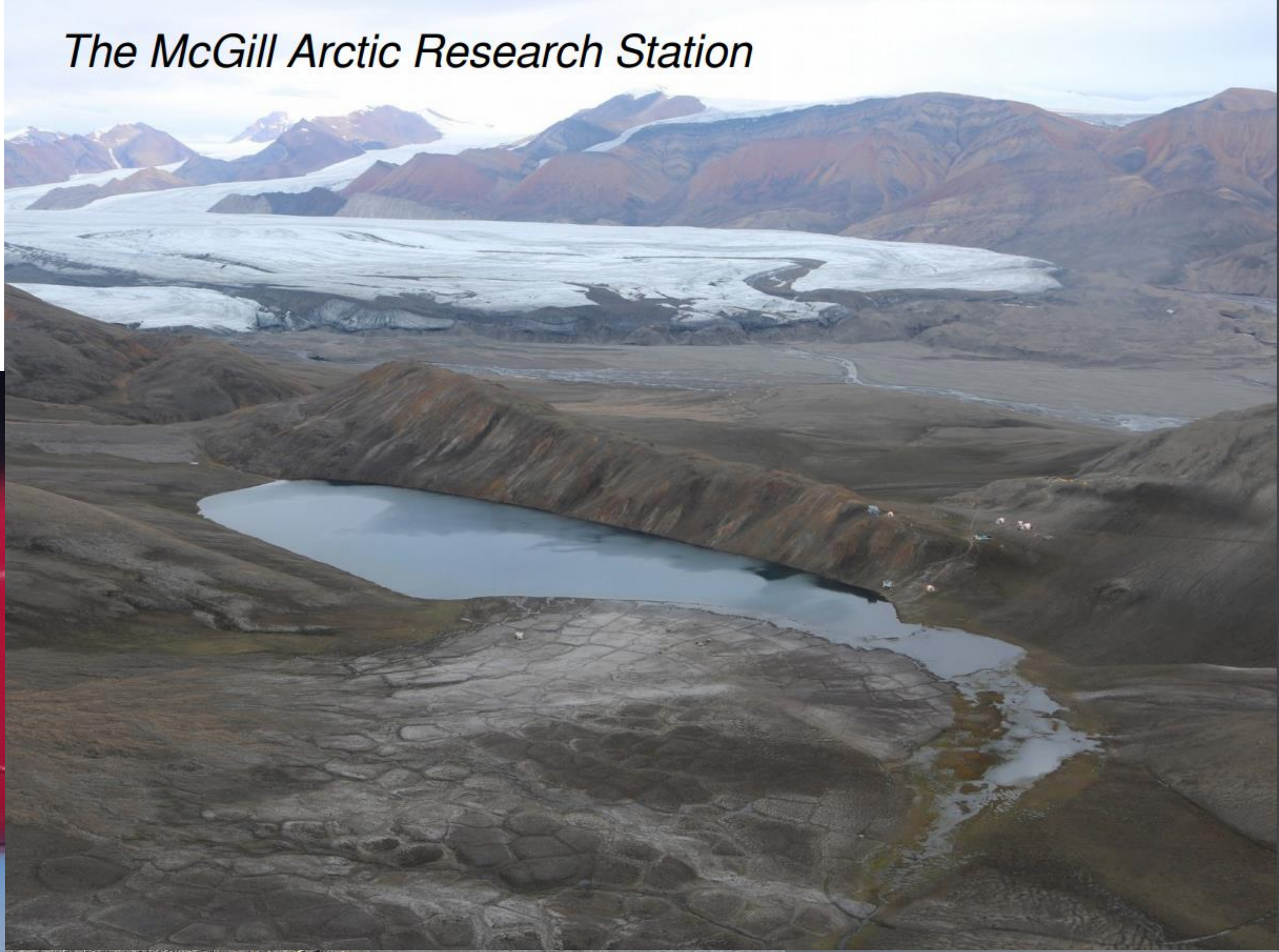
- Analyzing data from Uapishka to maximize its usefulness

- Implementing refinements to the instrument from lessons learned at Uapishka

- Eliminating low-level self-RFI and effects from boxes with electronics under antenna

- Implementing solar power system following tests at Uapishka

Looking forward to observe from the Arctic this summer !



Summary

1) **Analyzing EDGES data from 2018-2022** to determine presence of absorption feature in new instrumental configurations. Considering wide range of options when interpreting spectral structure.

2) **Developing EDGES-3**, to observe as soon as possible from Australia and North America.

3) **MIST experiment is almost ready** to be taken to remote places for sky measurements after implementing lessons learned from Uapishka.

Thank you Very Much