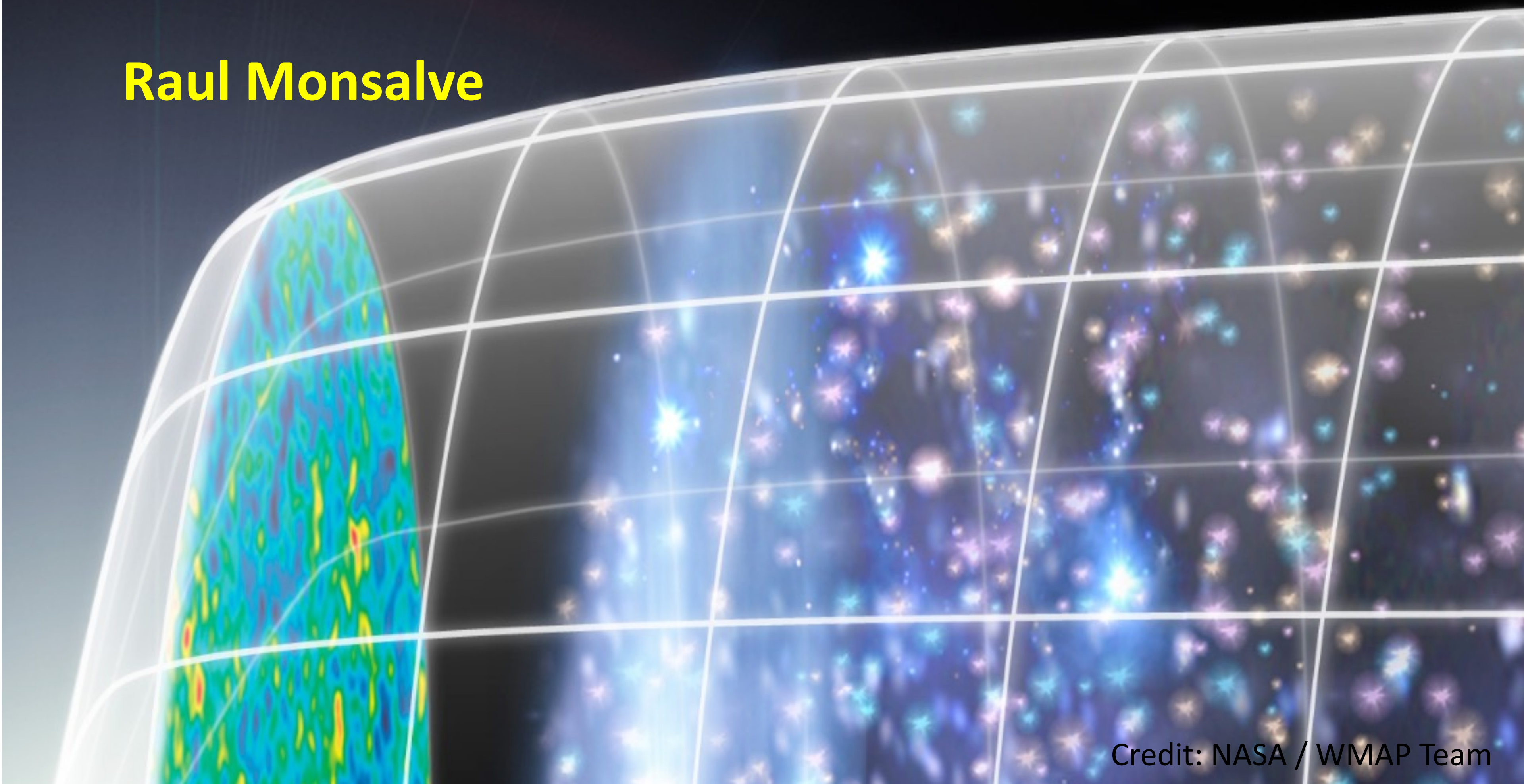
SSL
UC Berkeley

October 29, 2024
Space Sciences Laboratory, University of California Berkeley

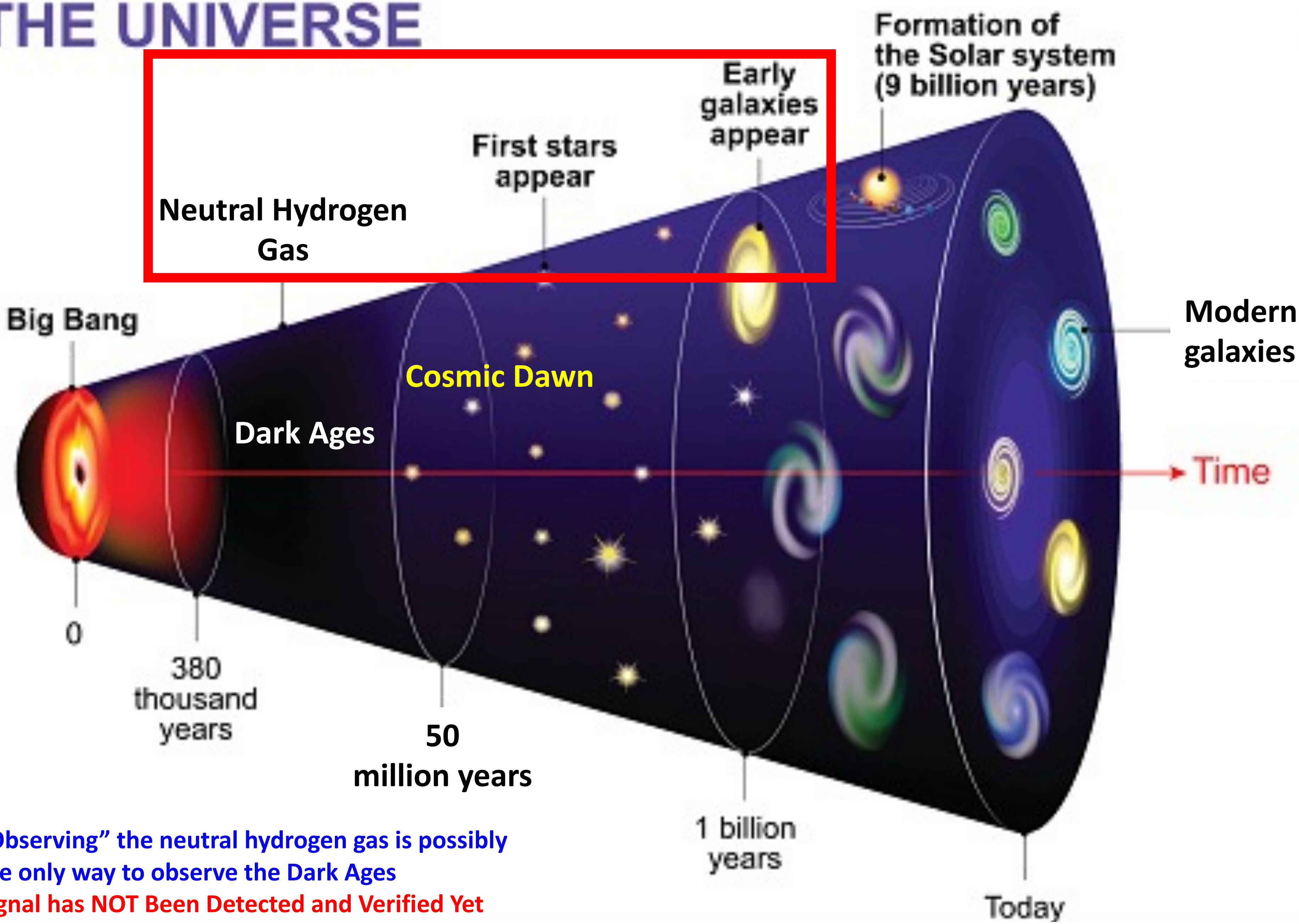
Observing the Universe's Dark Ages and First Stars Through Measurements of Distortions in the Global Radio Spectrum

Raul Monsalve



Credit: NASA / WMAP Team

EVOLUTION OF THE UNIVERSE

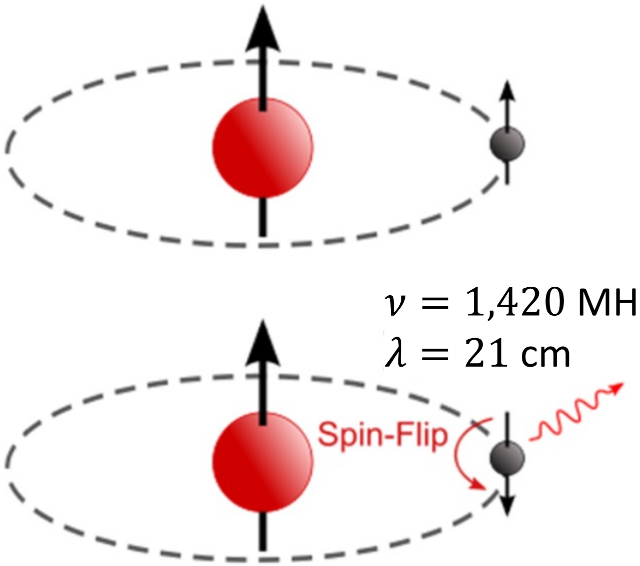


"Observing" the neutral hydrogen gas is possibly the only way to observe the Dark Ages

Signal has NOT Been Detected and Verified Yet

Emission at 21 cm from Hydrogen Atom

Ground state spin-flip transition



ν = 1,420 MHz

λ = 21 cm

Parallel spins

Upper ground state

Anti-parallel spins

Lower ground state

Spin Temperature (T_S)

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

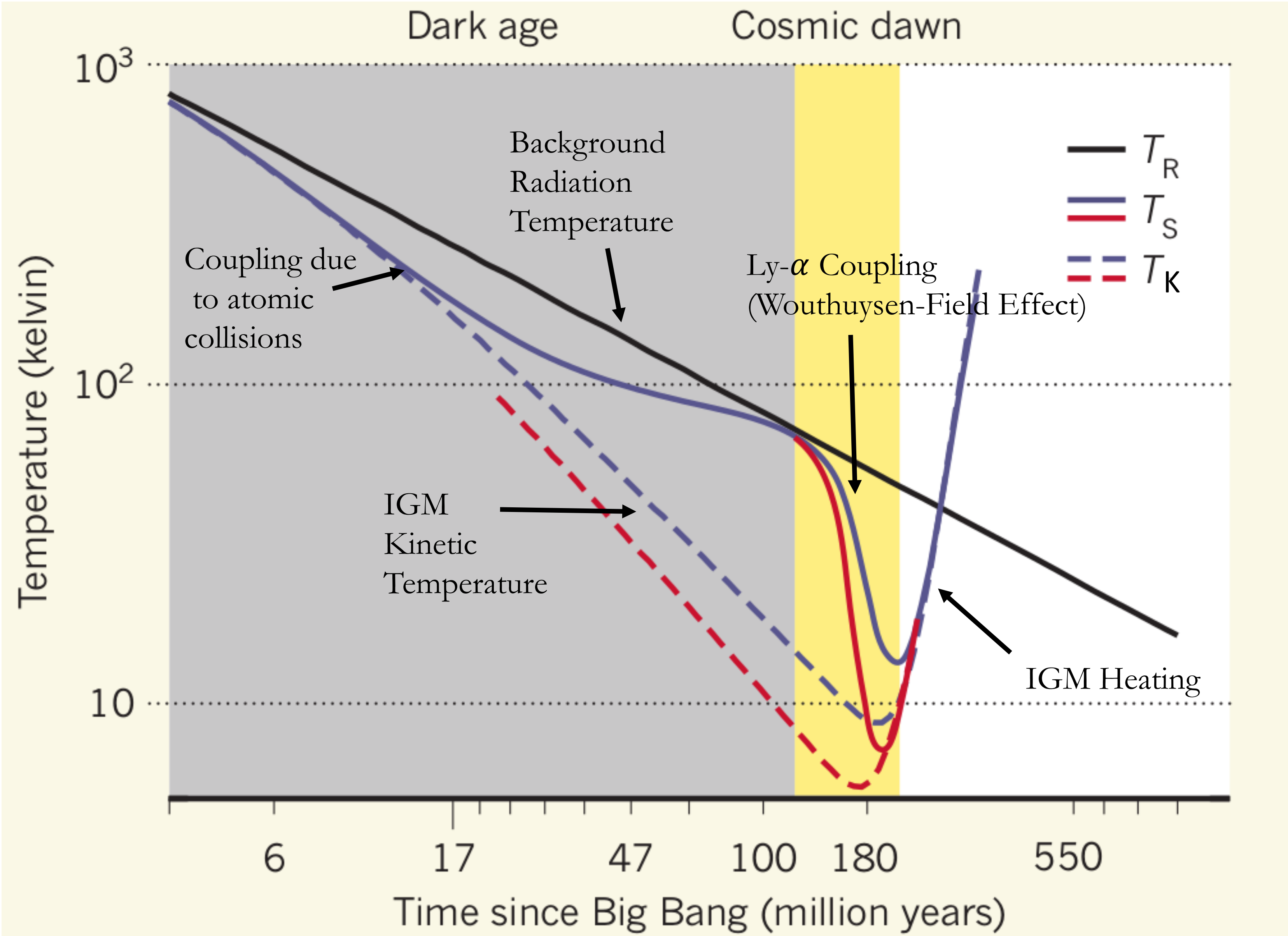
Relative abundance of ground states of hydrogen atoms

$$\frac{n_{\mathrm{upper}}}{n_{\mathrm{lower}}} = 3 \cdot exp\left(-\frac{h \cdot \nu_{21\mathrm{cm}}}{k_{\mathrm{b}} \cdot T_S}\right)$$

$\nu_{21\mathrm{cm}} = 1{,}420$ MHz
h : Planck constant
k_{b} : Boltzmann constant

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

Global Evolutions



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

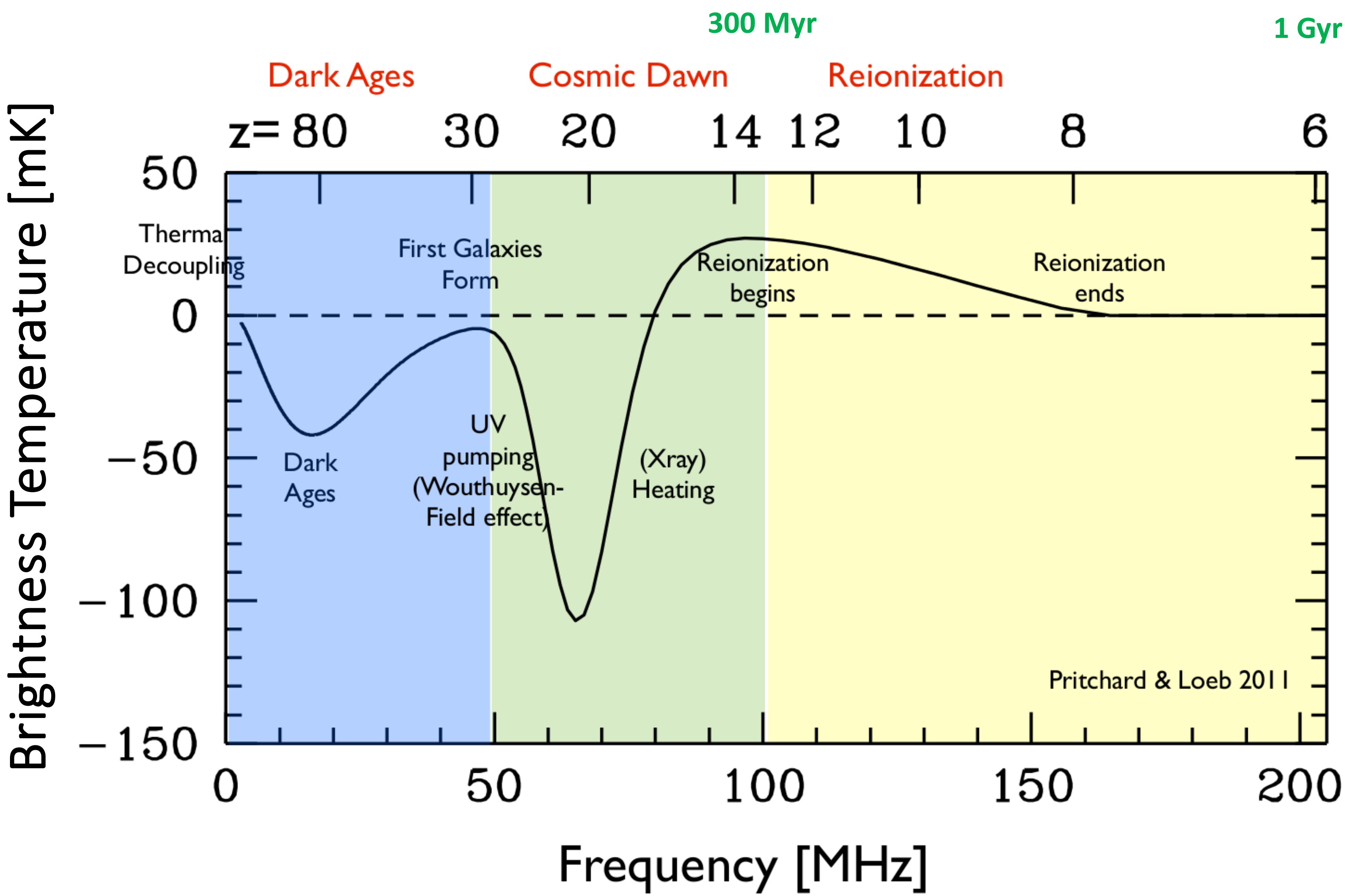
High Redshift of 21-cm Signal ⇨ Low Observation Frequency

$\upsilon_{21\text{cm}}$ **rest frame**: 1,420 MHz

$$\upsilon_{obs} = \frac{\upsilon_{21\text{cm rest } frame}}{(1+z)}$$

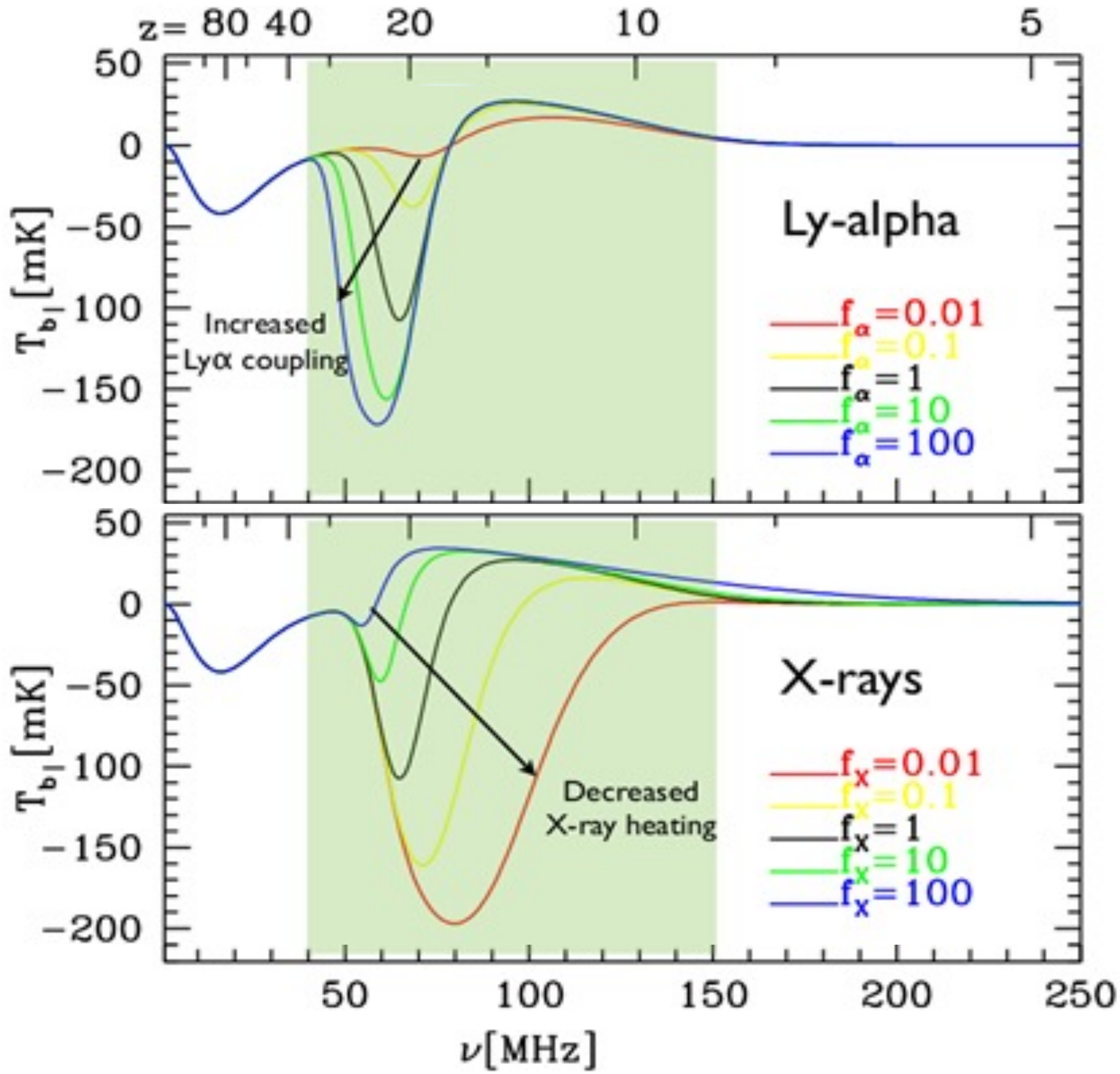
	υ_{obs}
$z = 6$	200 MHz
$z = 30$	45 MHz
$z = 100$	15 MHz
$z = 300$	5 MHz

Standard Prediction for Global 21-cm Signal



Nature and Timing of First Sources

Dark Ages signal does not depend on astrophysics

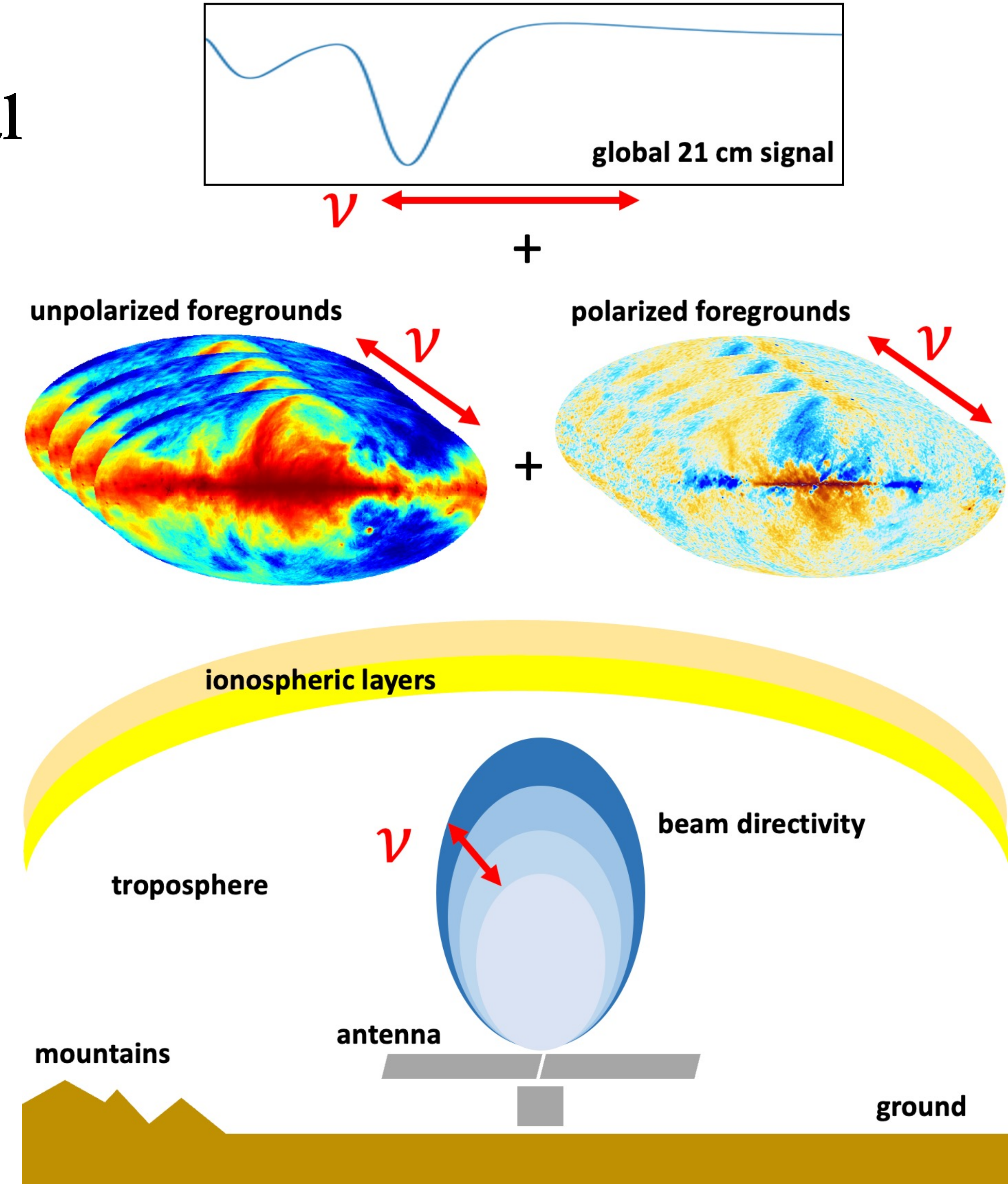


From Pritchard & Loeb (2011)

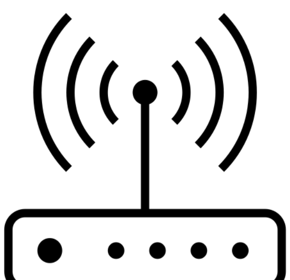
Observation of Global 21-cm Signal

Foregrounds are >4 orders of magnitude stronger than 21-cm signal

Dominated by synchrotron radiation

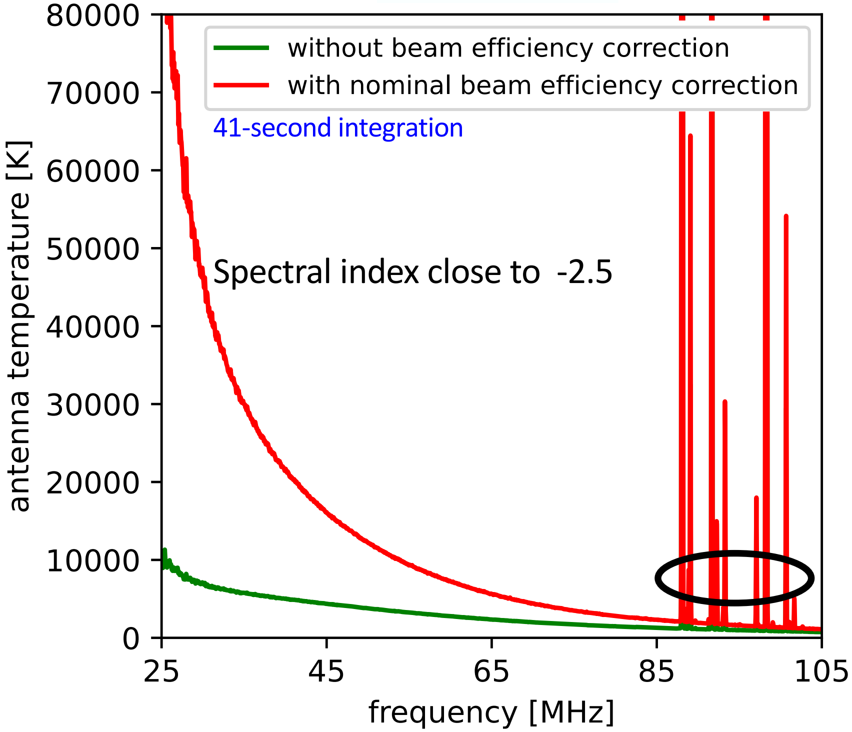


radio-frequency interference (RFI) from artificial transmitters



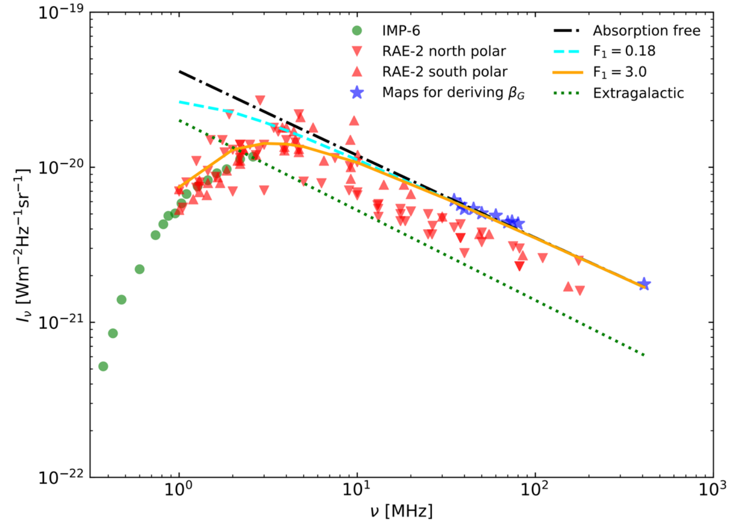
"Foreground" Spectrum

MIST

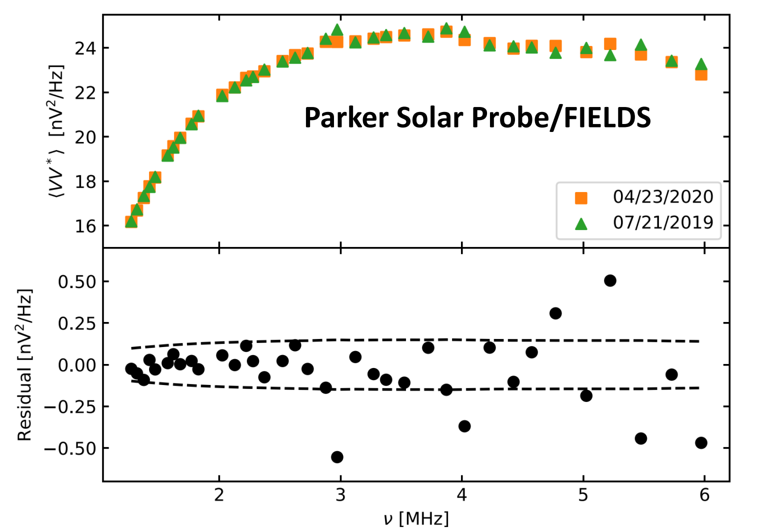


Monsalve et al (2024a)
arXiv:2309.02996

Many experiments show free-free absorption below 3 MHz

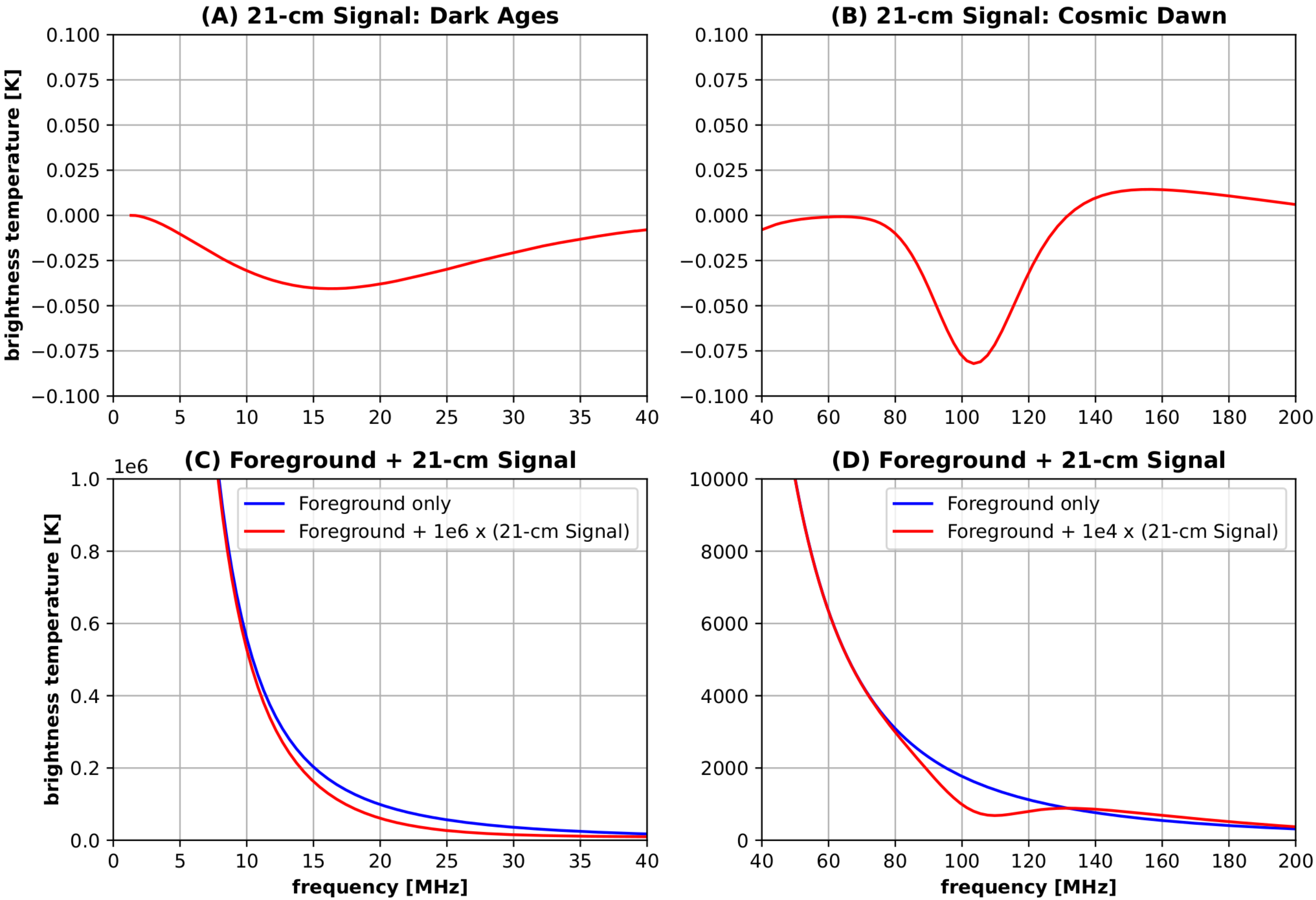


Cong et al (2021)
arXiv:2104.03170



Bassett et al (2023)
arXiv:2301.09612

Big Challenge!



Required Observation Time

Noise Standard Deviation:

$$\sigma_{T_b} = \frac{T_b}{\sqrt{\Delta\upsilon \cdot \Delta t}}$$

total brightness temperature

frequency resolution

integration time

Required Observation Time:

$$\Delta t = \frac{1}{\Delta\upsilon} \cdot \left(\frac{T_b}{\sigma_{T_b}}\right)^2$$

Example:

$\sigma_{T_b} = 0.01$ K

$\Delta\upsilon = 1\times10^6$ Hz

Dark Ages:

$T_b = 100{,}000$ K

$\Delta t = 1\times10^8$ sec $\approx 1{,}200$ days ≈ 3.2 years

Cosmic Dawn:

$T_b = 10{,}000$ K

$\Delta t = 1\times10^6$ sec ≈ 12 days

LuSEE-Night

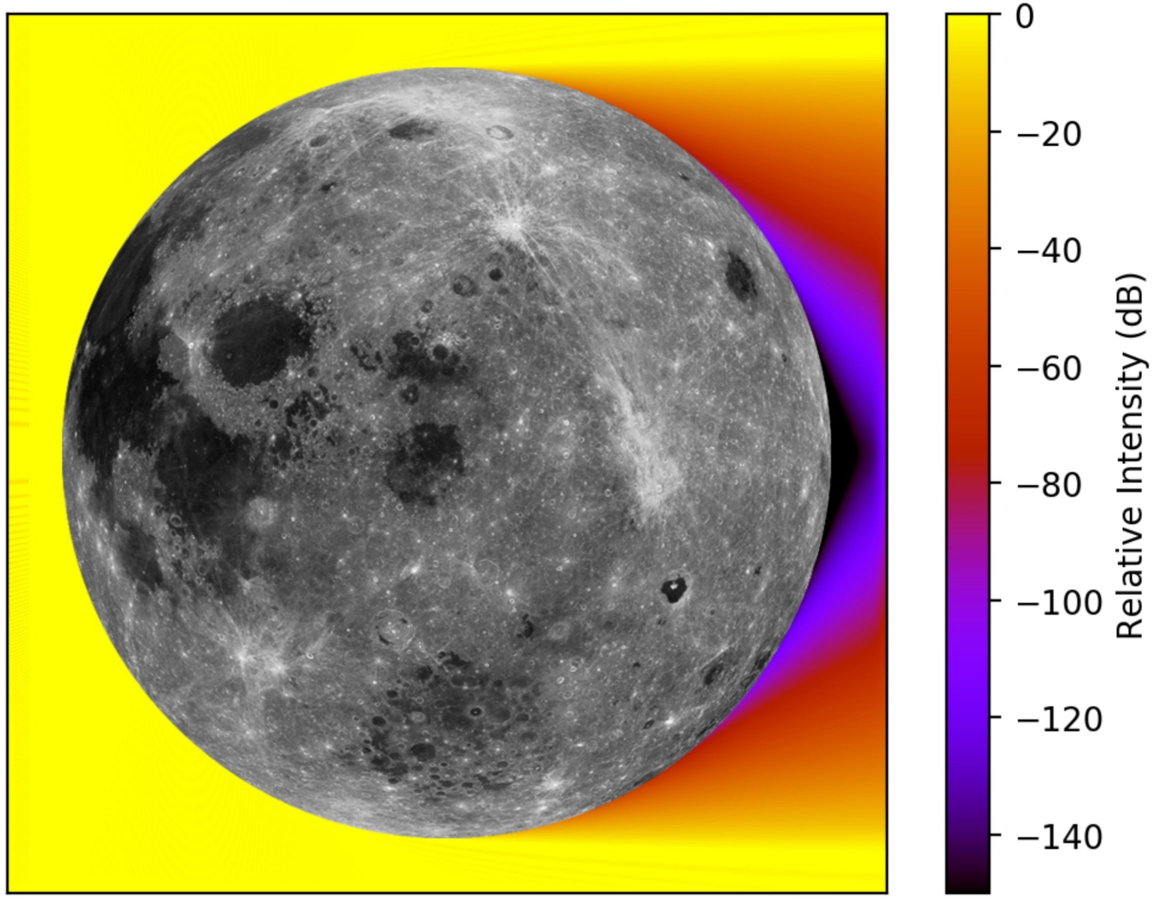
Far Side of the Moon

Most radio-quiet site in the inner Solar System

Very weak ionosphere

Attenuation of Terrestrial RFI on Lunar Far Side

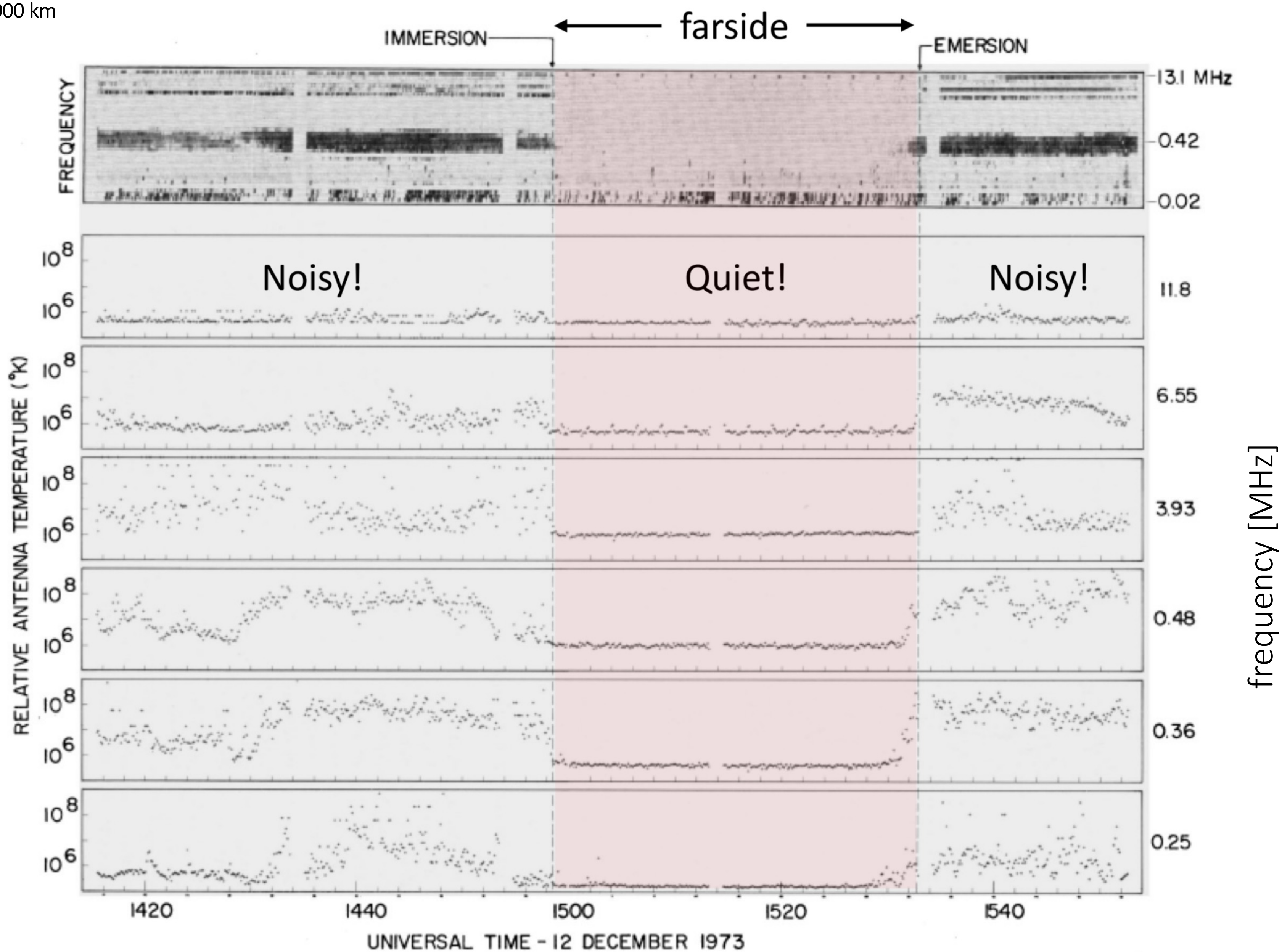
At 30 kHz



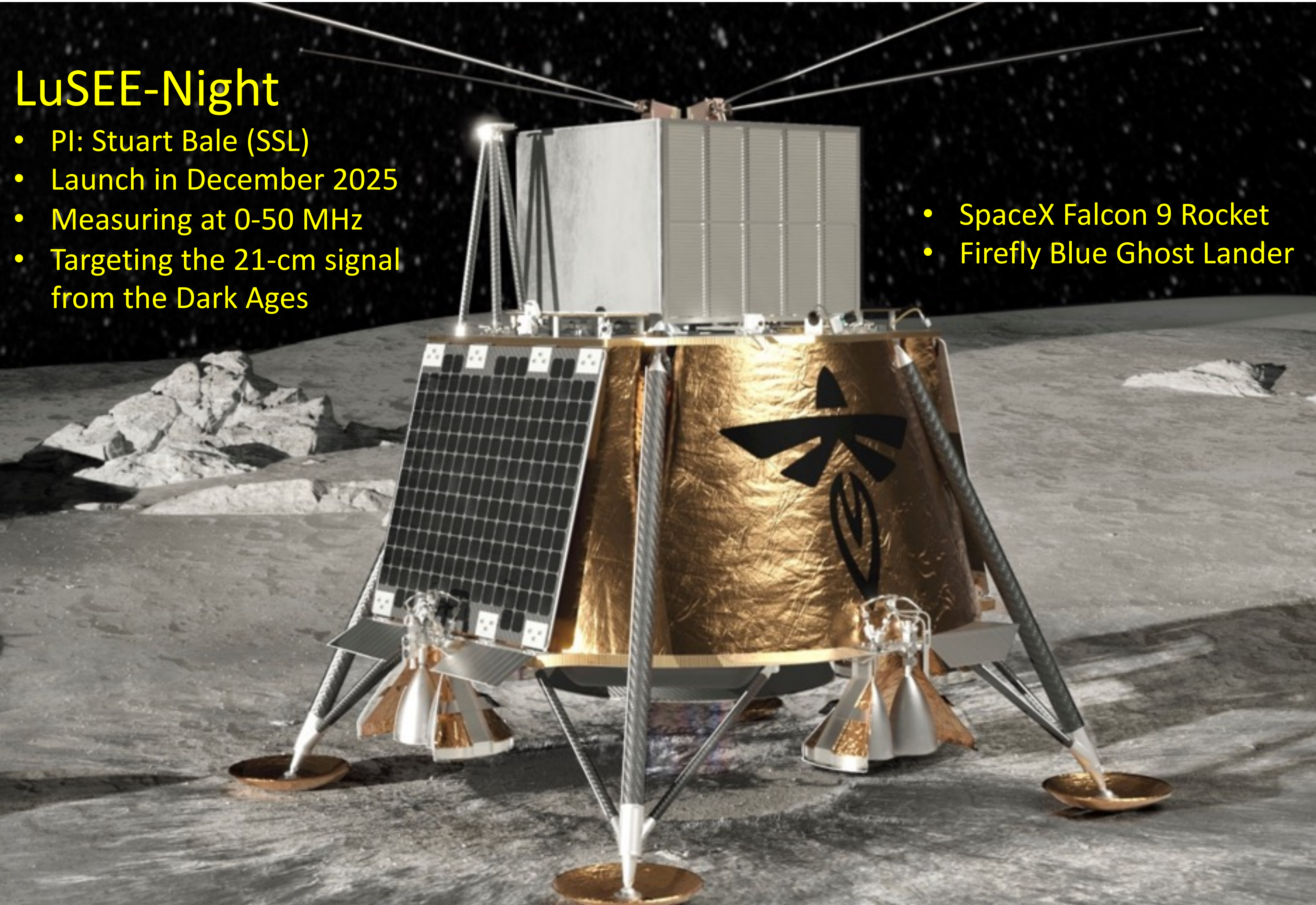
Bassett et al (2020)
arXiv:2003.03468

Data from the **Radio Astronomy Explorer 2 (RAE-2)** spacecraft (Alexander et al. 1975)

Antenna length: 230 m
Altitude: 1,000 km



Lunar Surface Electromagnetics Experiment (LuSEE)



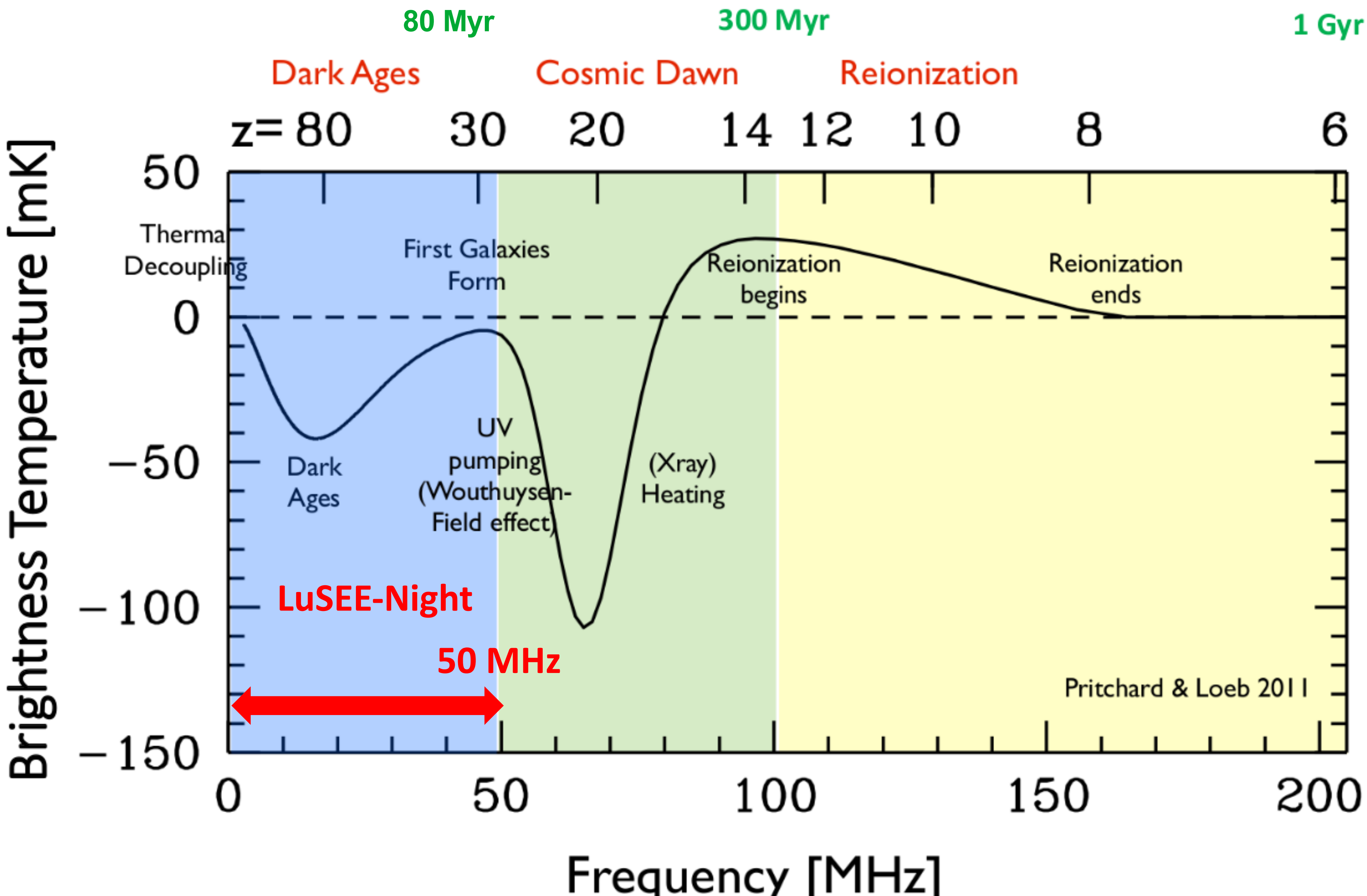
LuSEE-Night

- PI: Stuart Bale (SSL)
- Launch in December 2025
- Measuring at 0-50 MHz
- Targeting the 21-cm signal from the Dark Ages

- SpaceX Falcon 9 Rocket
- Firefly Blue Ghost Lander

Frequency Range: 0-50 MHz

$z > 27$



Far Side of the Moon

Best radio-quiet site in the inner Solar System
Very weak ionosphere

Ground-based Experiments

EDGES

Experiment to Detect the Global EoR Signature

ARIZONA STATE UNIVERSITY

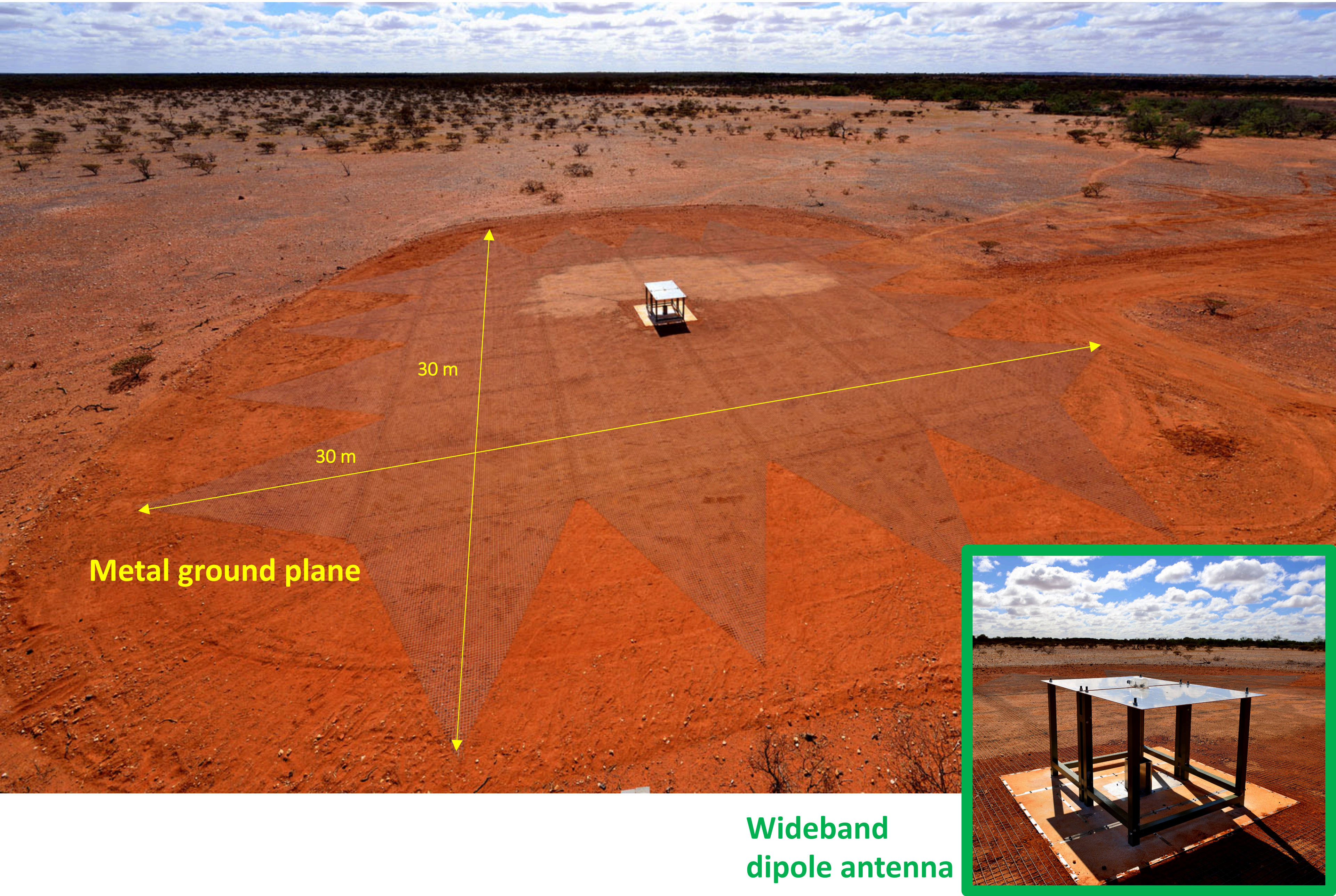
MIT HAYSTACK OBSERVATORY

SSL UC Berkeley

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

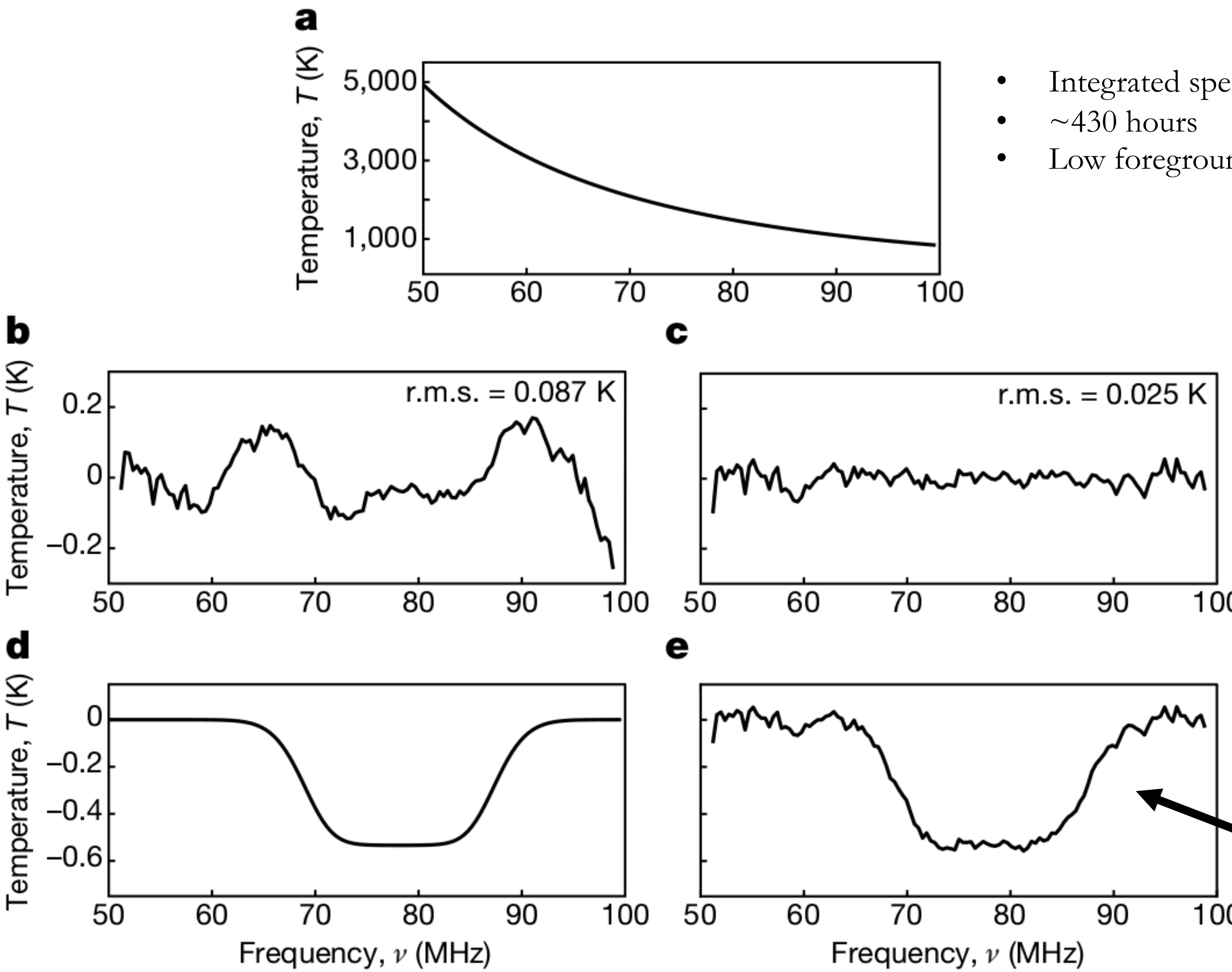
SCUOLA NORMALE SUPERIORE

EDGES Low-Band



Wideband
dipole antenna

Absorption Feature Reported by EDGES in 2018

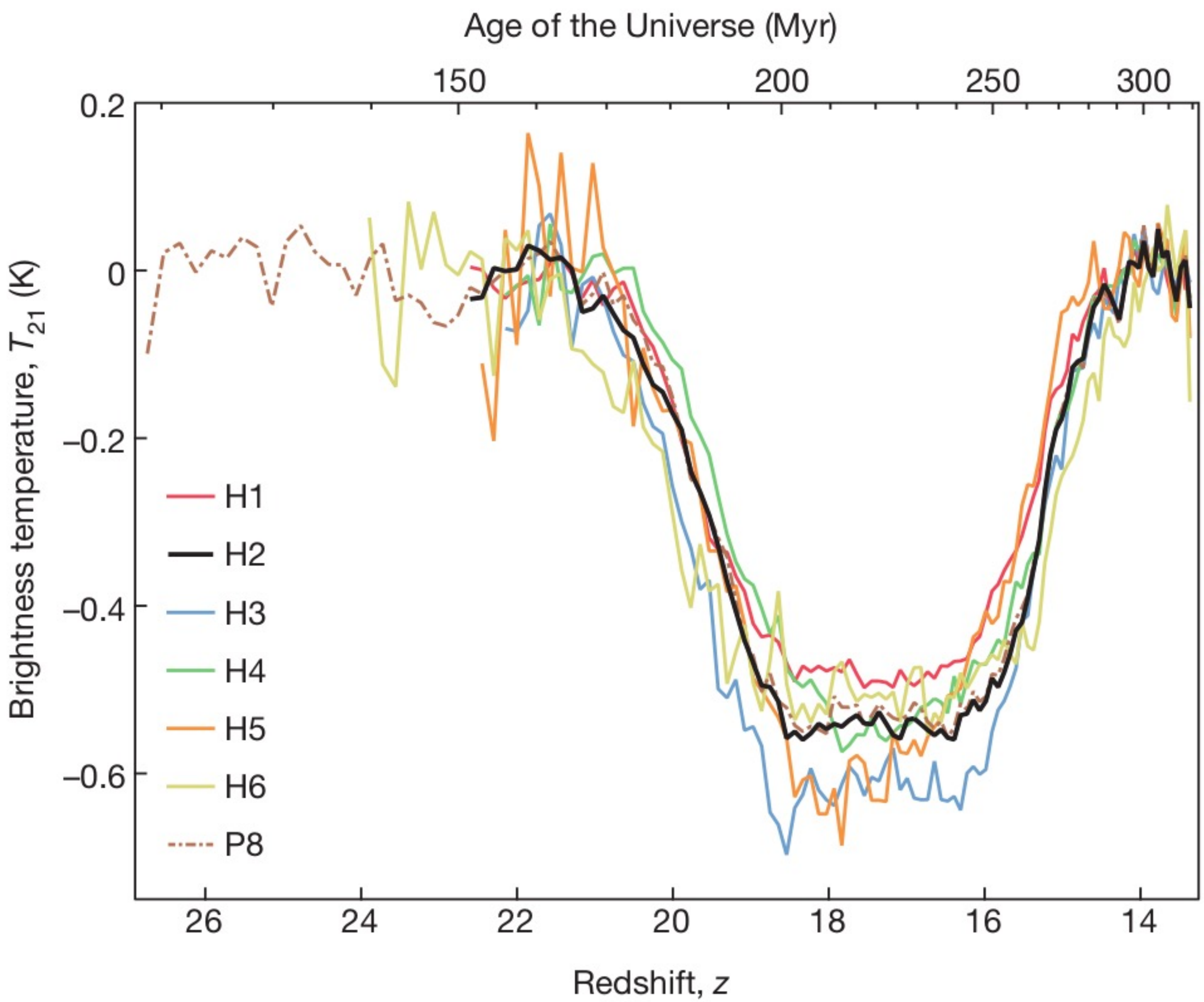


- Integrated spectrum
- ~430 hours
- Low foreground regions

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

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

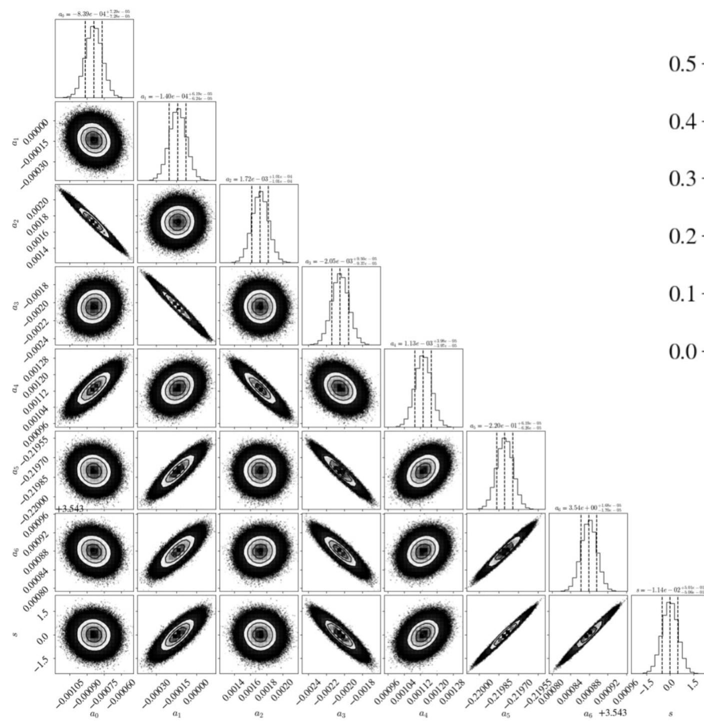
A **Ground Plane Artifact** that Induces an Absorption Profile in Averaged Spectra from Global 21-cm Measurements - with Possible Application to EDGES

Richard F. Bradley, Keith Tauscher, David Rapetti, and Jack O. Burns, ApJ, 874, 153 (2018)

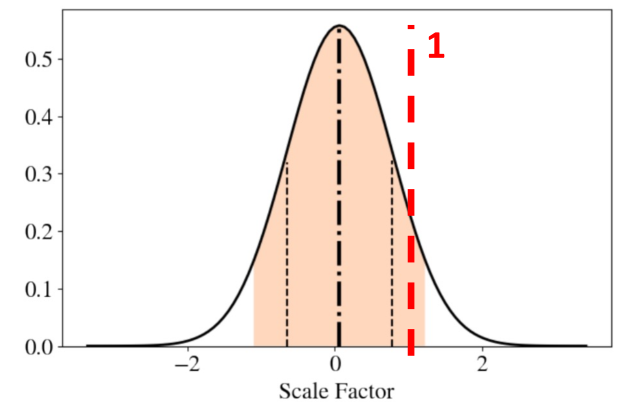
On the detection of a cosmic dawn signal in the radio background (2022)

Saurabh Singh[1,2,3] ✉, Jishnu Nambissan T.[1,4], Ravi Subrahmanyan[1,5], N. Udaya Shankar[1], B. S. Girish[1], A. Raghunathan[1], R. Somashekar[1], K. S. Srivani[1] and Mayuri Sathyanarayana Rao[1]

SARAS 3 in a lake in India



The value of 1 is within 90% confidence range.



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

- 55-85 MHz band modeled with:
  7-term log-log polynomial
  + 1 scale factor for best-fit EDGES signal

Mapper of the IGM Spin Temperature (MIST)

Experiment began in 2018

McGill

Berkeley
UNIVERSITY OF CALIFORNIA

NRAO

UCSC

CSIRO

Raul Monsalve, co-PI
Ricardo Bustos, PI

We acknowledge support from

Gobierno de Chile

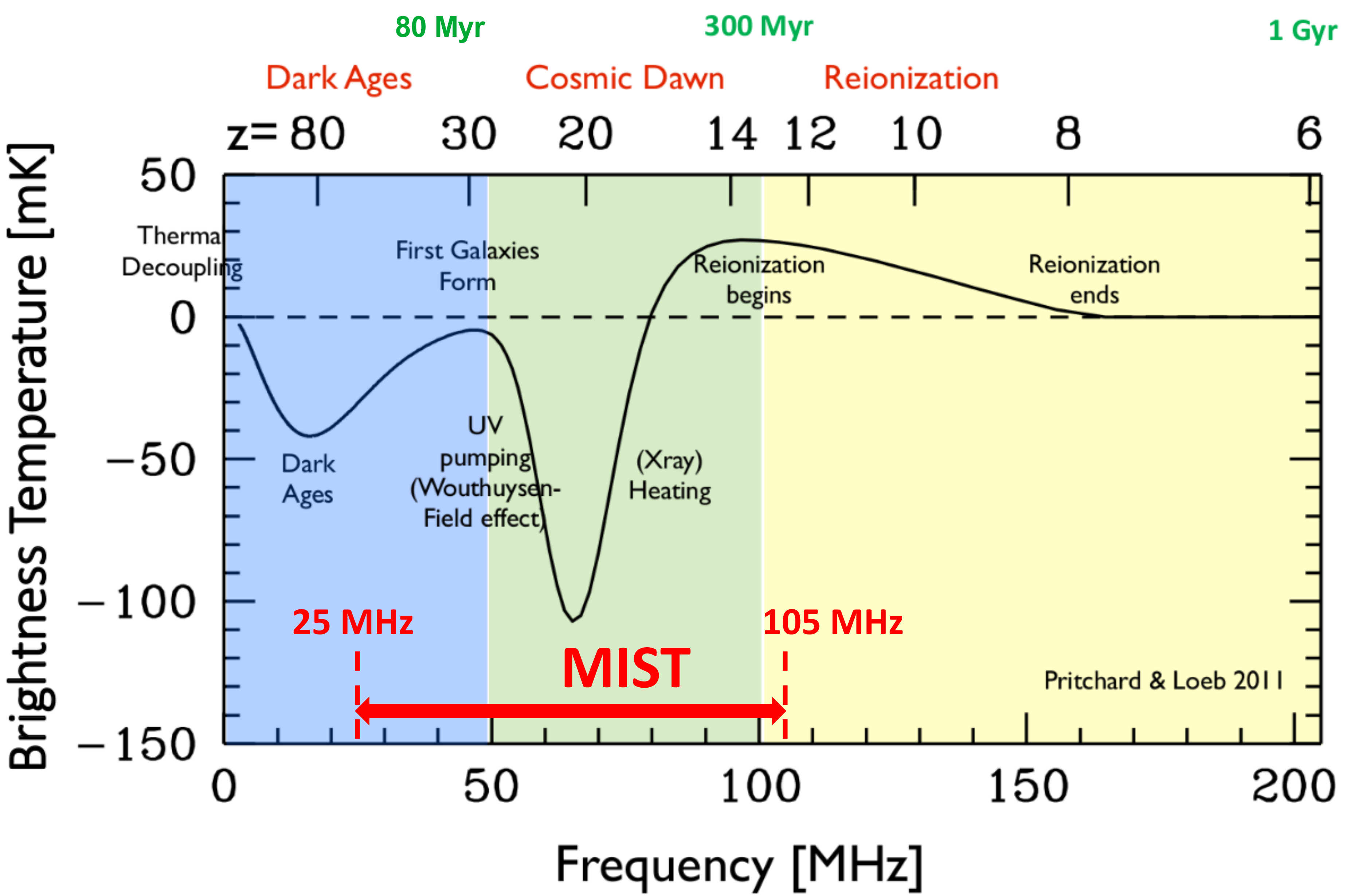
UCSC

NSERC
CRSNG

CSA ASC
Canadian Space Agency

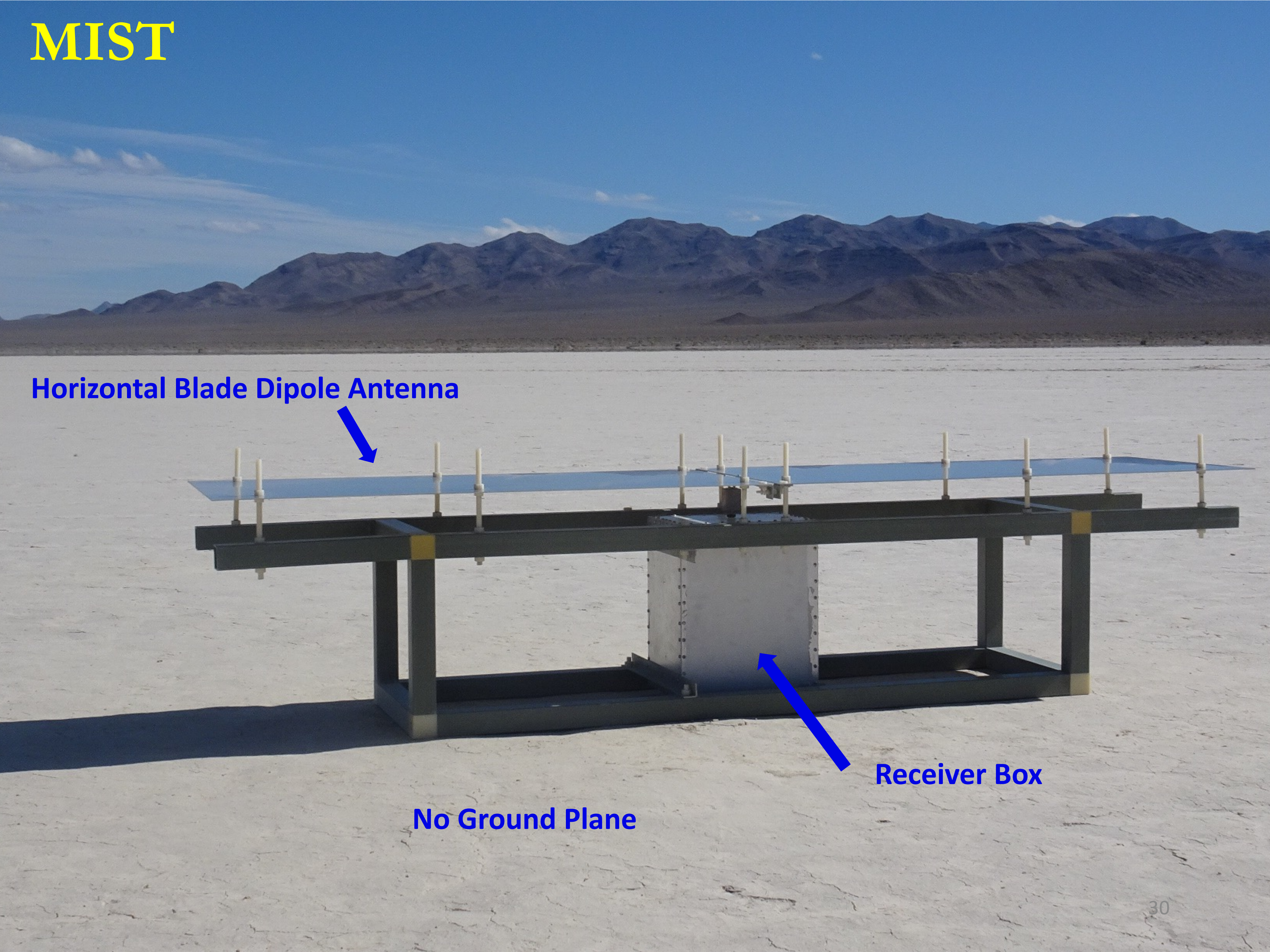
Frequency Range: 25-105 MHz

$55.5 > z > 12.5$

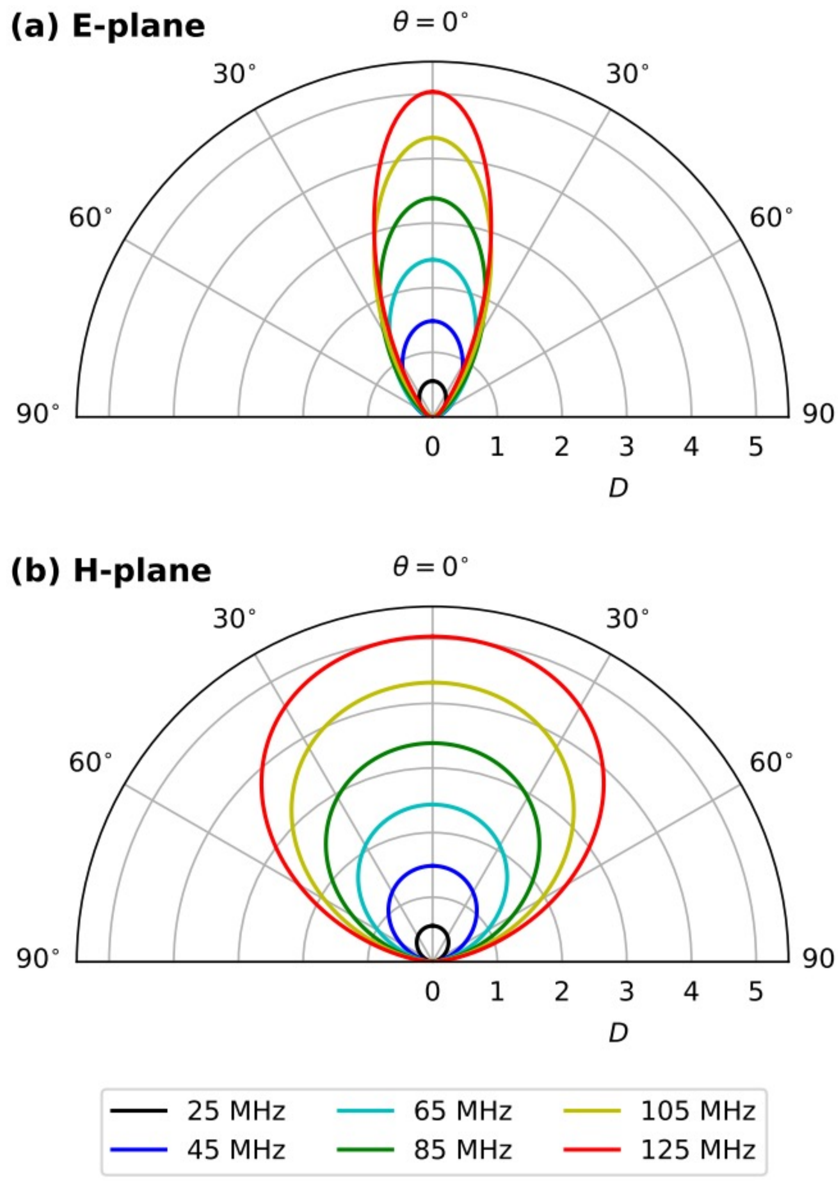


Two MIST Instruments Built in 2022

- Single-antenna, **total-power radiometers**
- Frequency range **25-105 MHz**
- Horizontal **blade dipole** antennas
- **No metal ground plane**
- Field measurements of **spectra** and **impedance** of **antenna**
- **Small and portable** for deployment at remote locations
- Power consumption of **15 watts**
- Powered by **12 V batteries**


MIST
Horizontal Blade Dipole Antenna
Receiver Box
No Ground Plane

Beam Directivity From EM Simulations



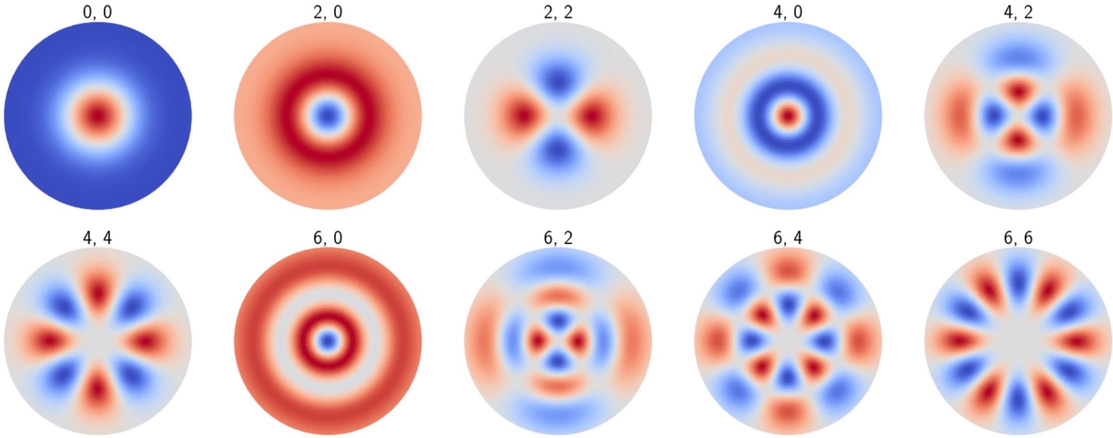
Monsalve et al (2024a)
arXiv:2309.02996

Decomposition of Beam into Analytical Functions

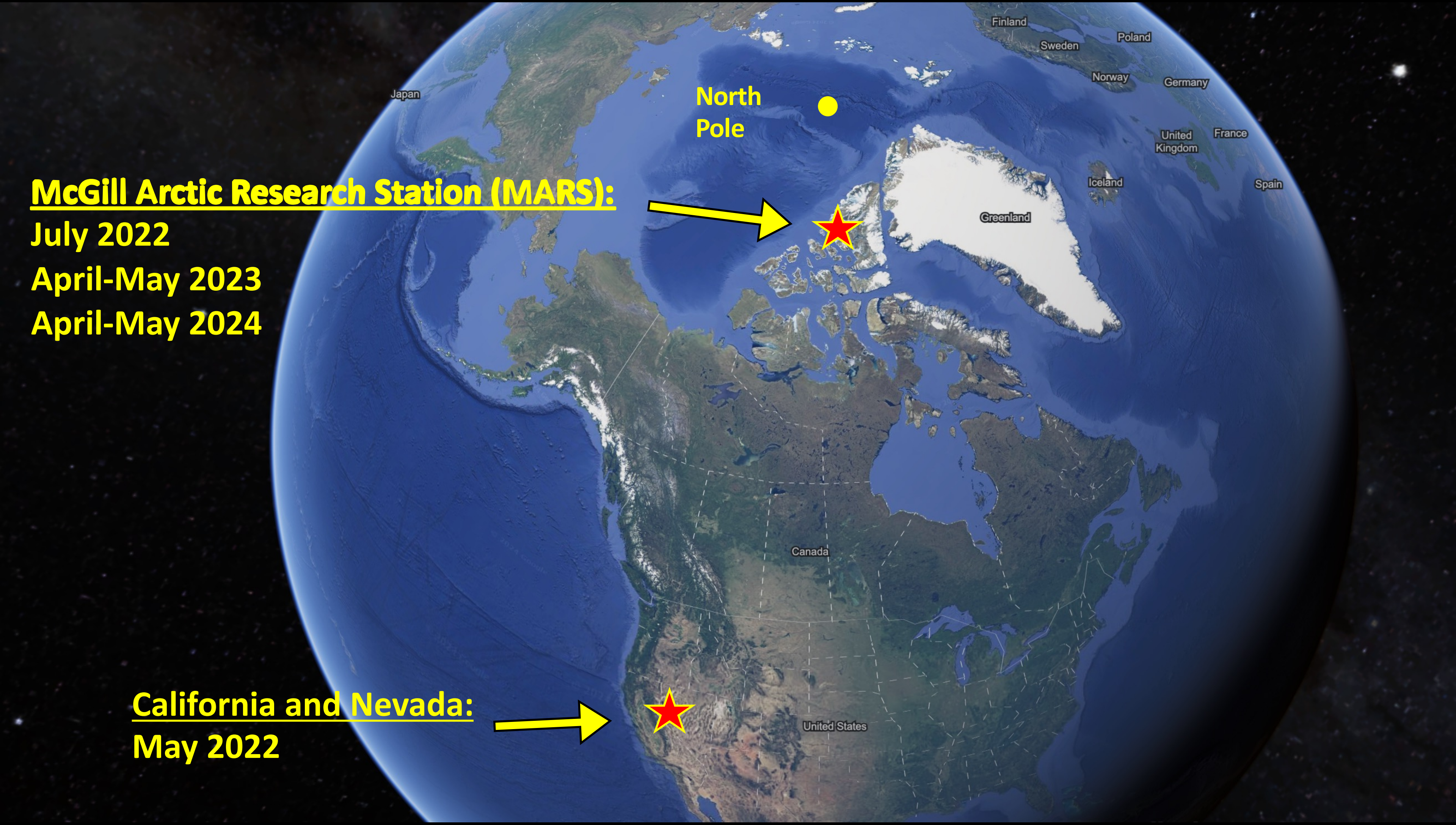
Xinze "Sunny" Guo

UC Berkeley Undergrad Student

Sample of Analytical Basis Functions



MIST Observation Sites



MIST in 2022

MIST in 2022: Deep Springs Valley, California

MIST in 2022: Death Valley, Nevada

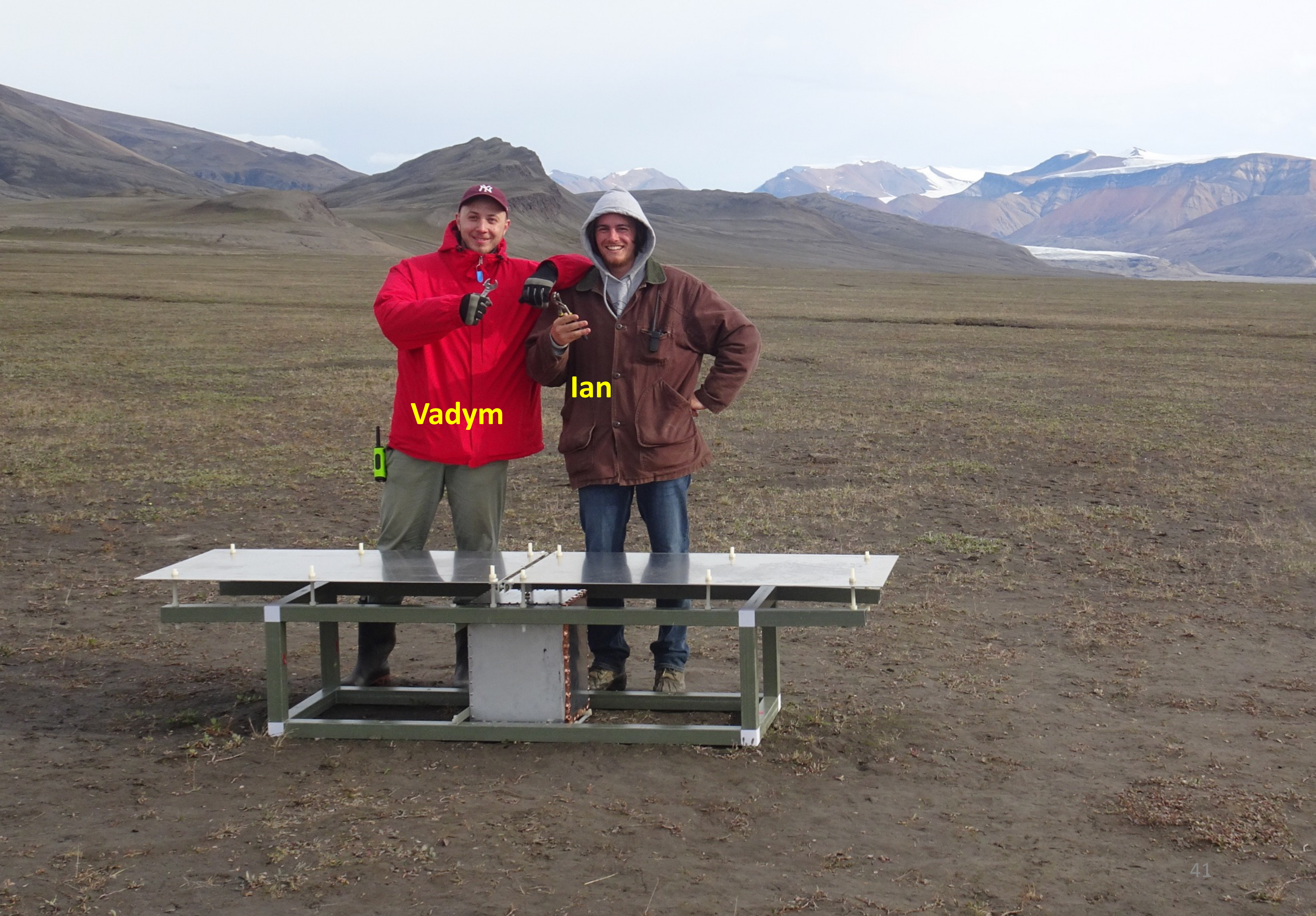
McGill Arctic Research Station (MARS): Twin Otter Plane

McGill Arctic Research Station (MARS): Facilities

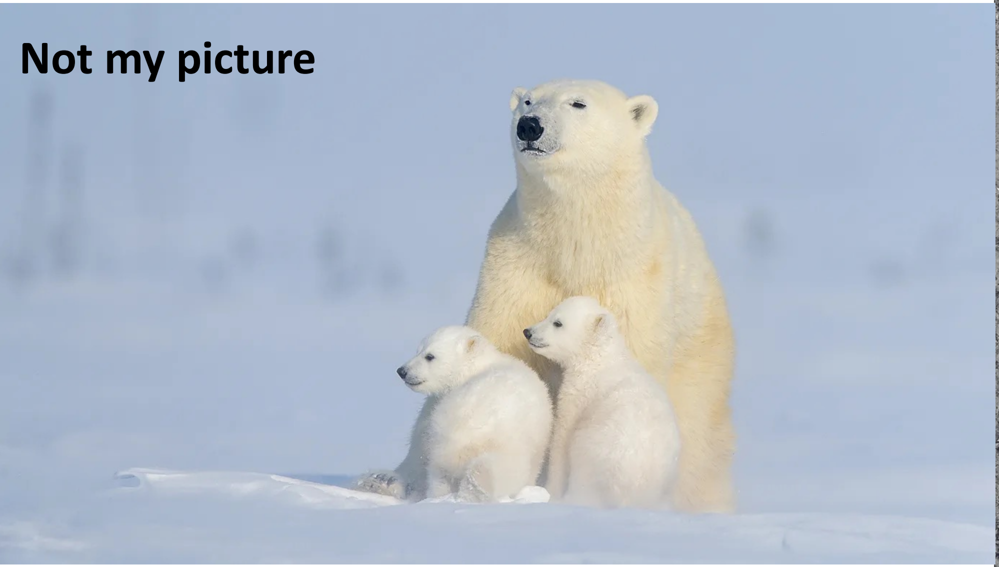
McGill Arctic Research Station (MARS): Expedition Fjord

McGill Arctic Research Station (MARS): Expedition Fjord

MIST in 2022: Arctic



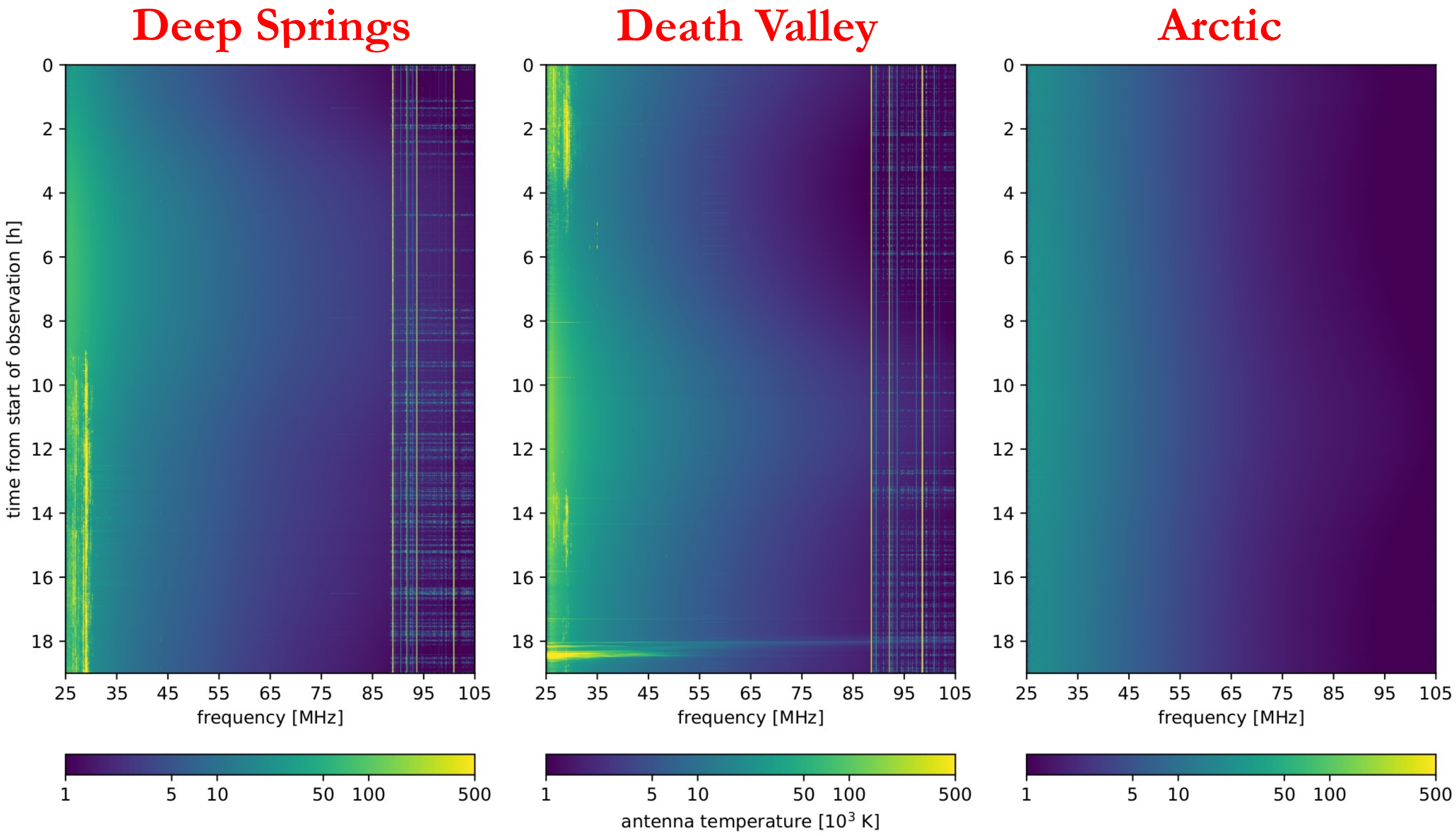
Polar Bears


Not my picture

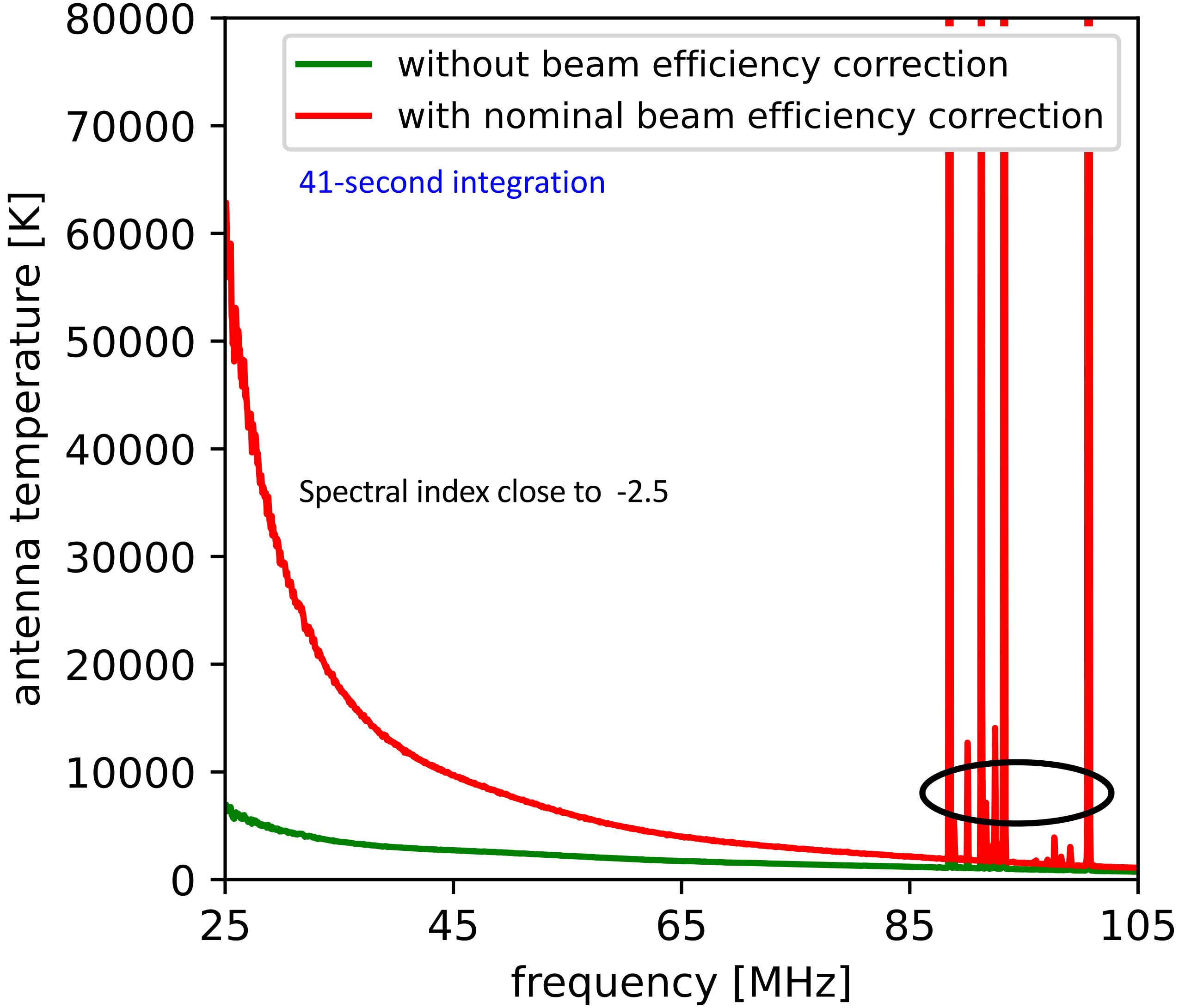

My picture
Polar bear prints at MIST site in the Arctic

Arctic Wolves

Antenna Temperature, 19 hours

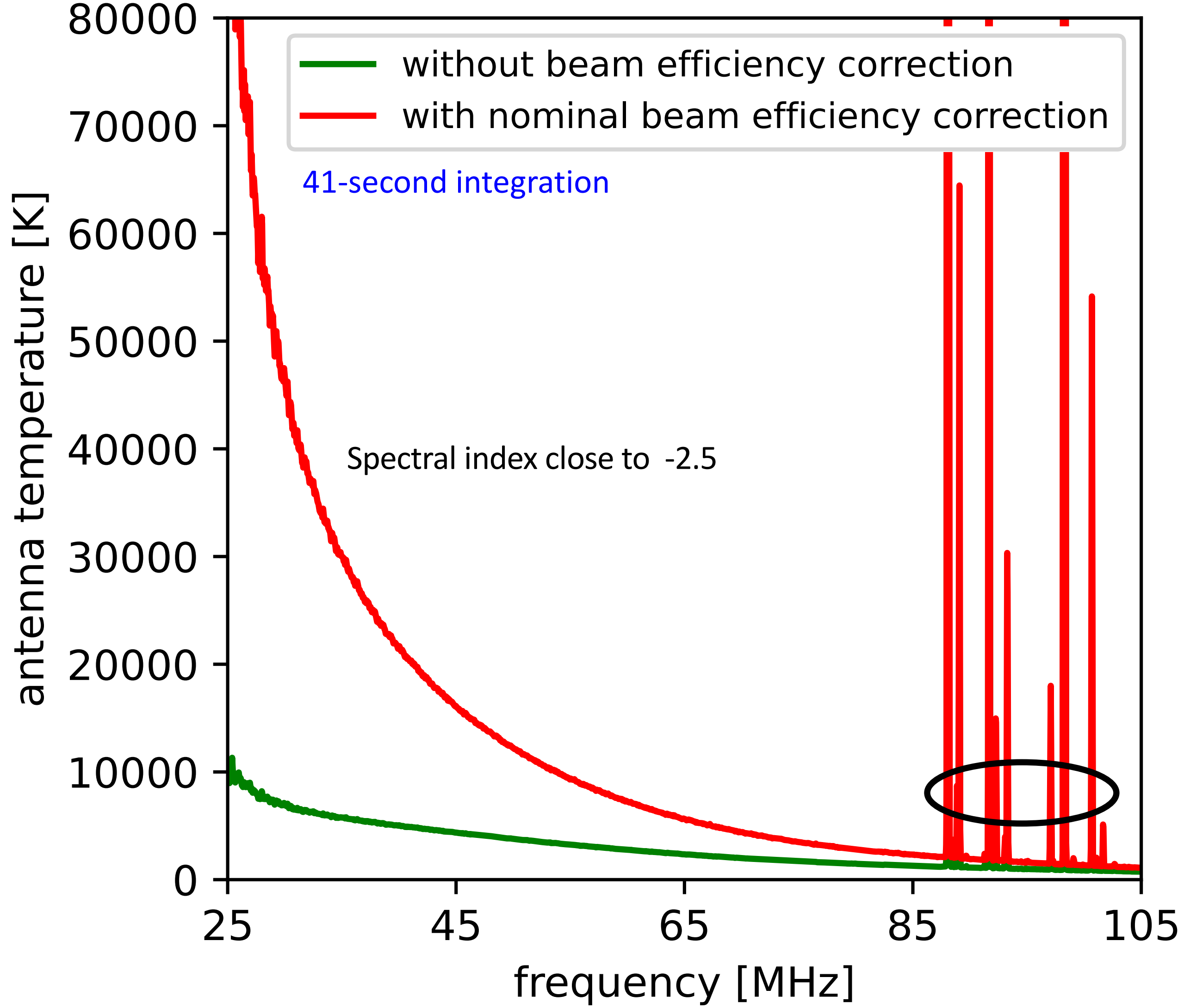


Deep Springs Valley



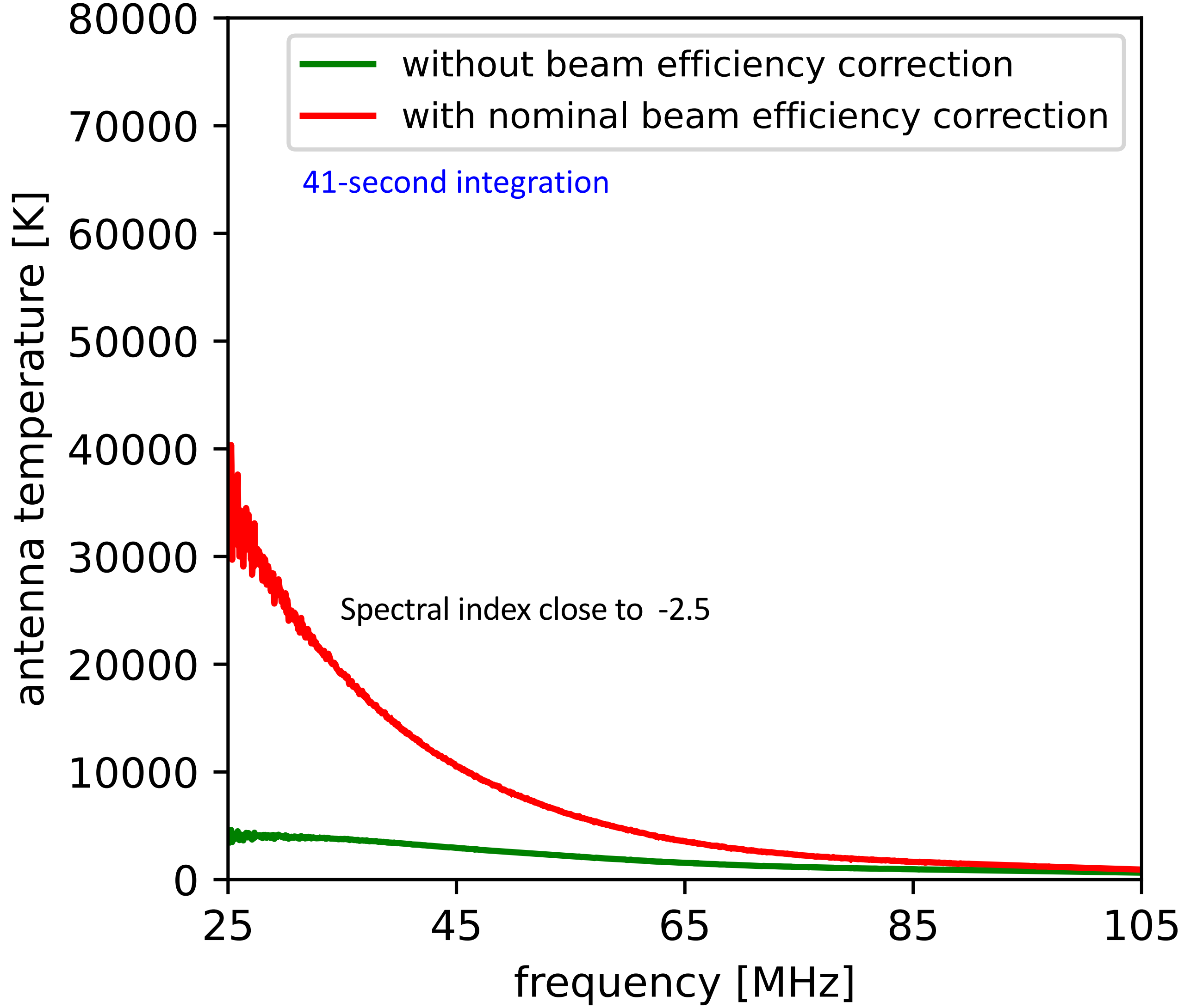
Monsalve et al (2024a)
arXiv:2309.02996

Death Valley



Monsalve et al (2024a)
arXiv:2309.02996

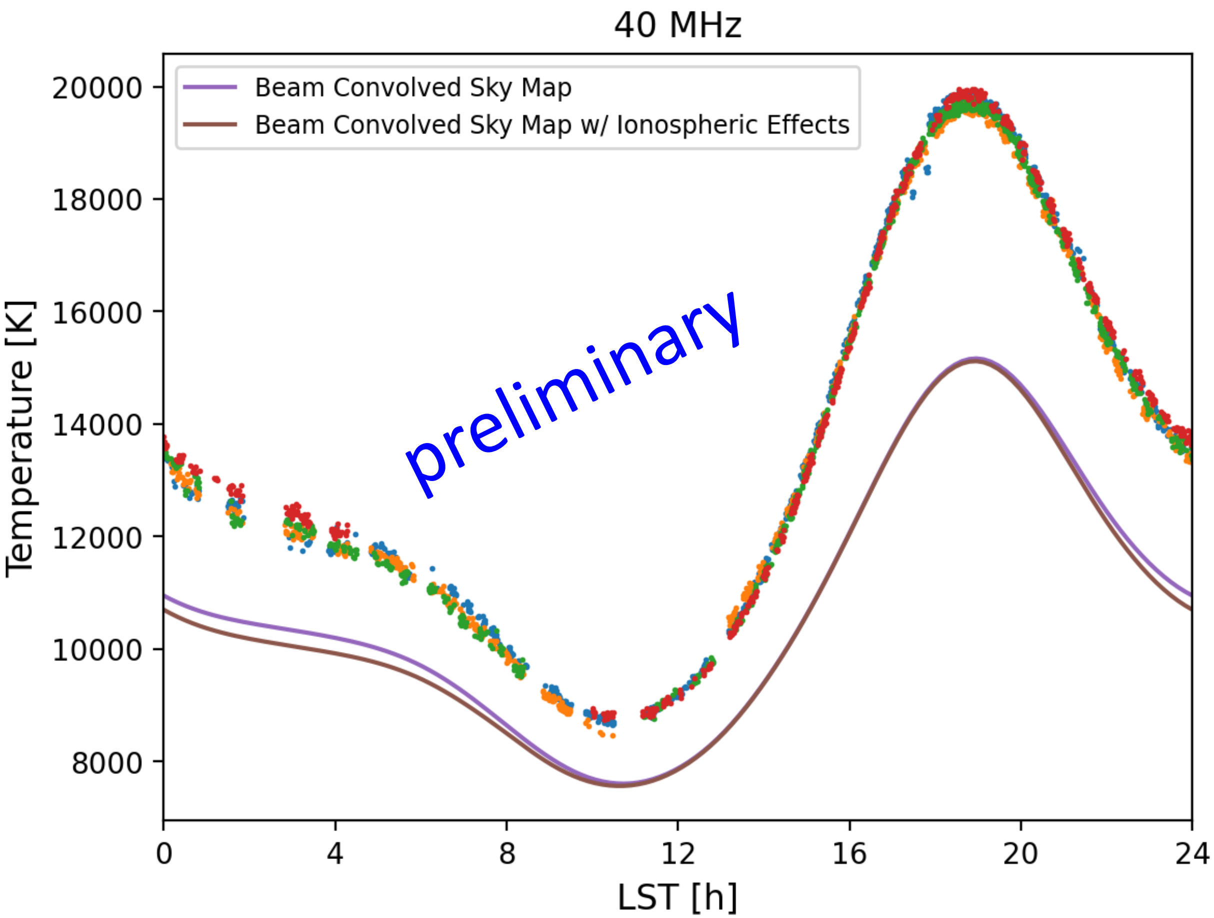
McGill Arctic Research Station



Monsalve et al (2024a)
arXiv:2309.02996

Foreground Characterization

Example: Death Valley



Lisa Nasu-Yu

McGill Graduate Student

MIST in 2023

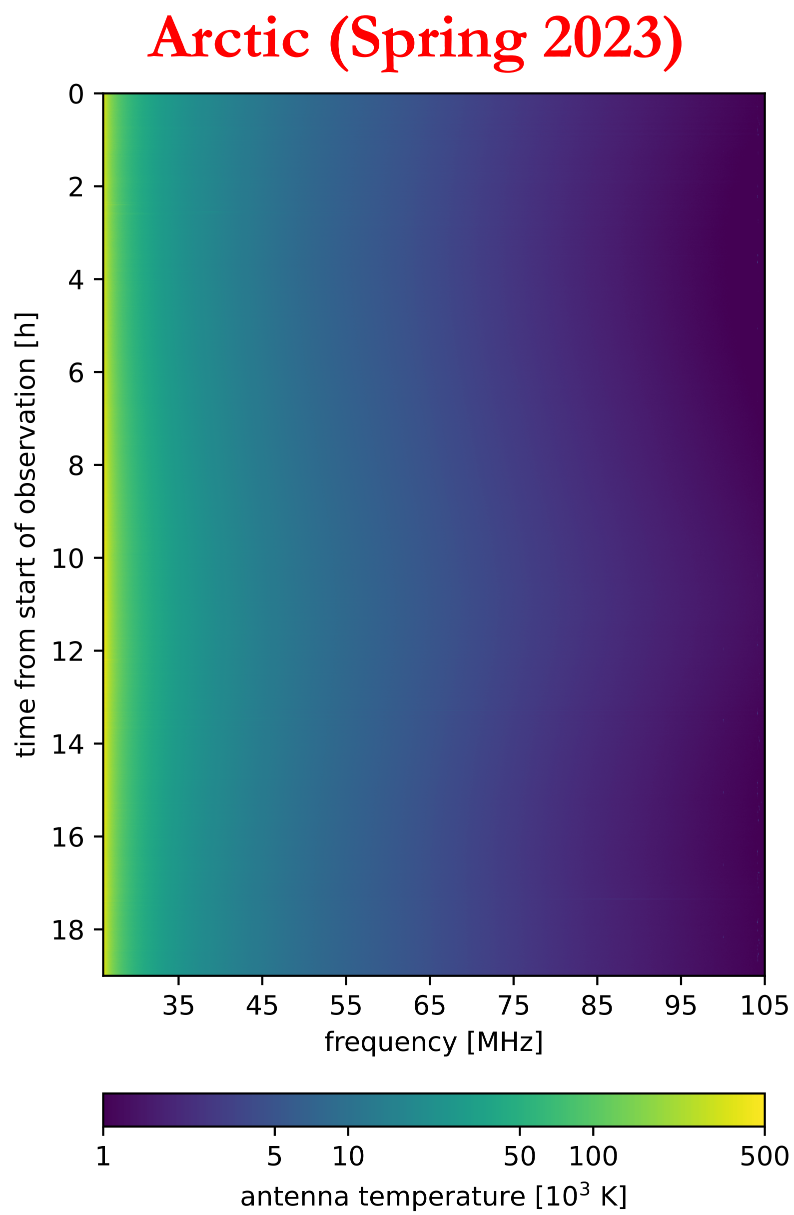

Spring 2023
Glaciologists and Cosmologists
Ian
Raul
Wonderful Glaciologists Friends

McGill Arctic Research Station (MARS)


Raul
TUNDRA

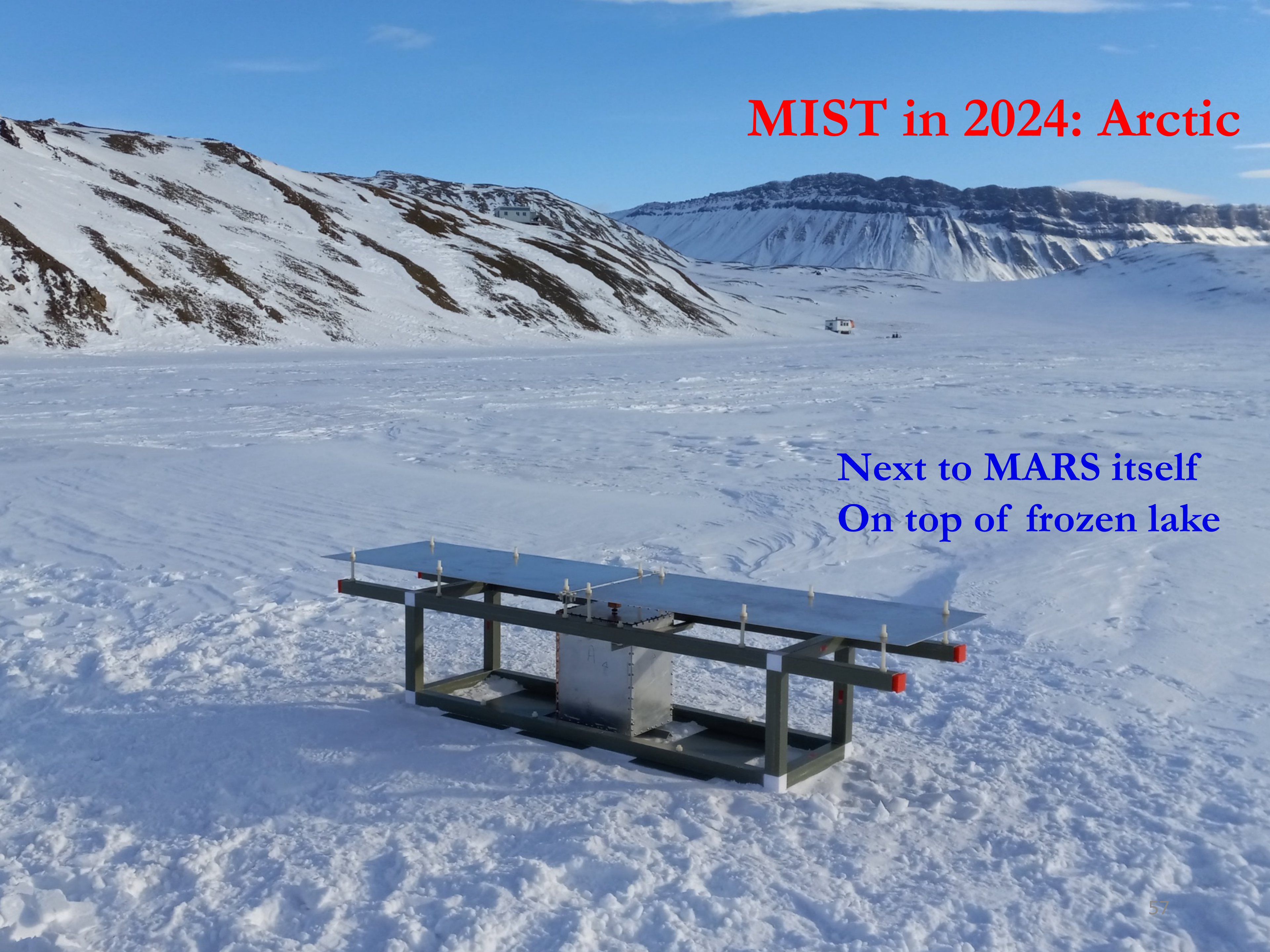
MIST in 2023: Arctic

Antenna Temperature, 19 hours



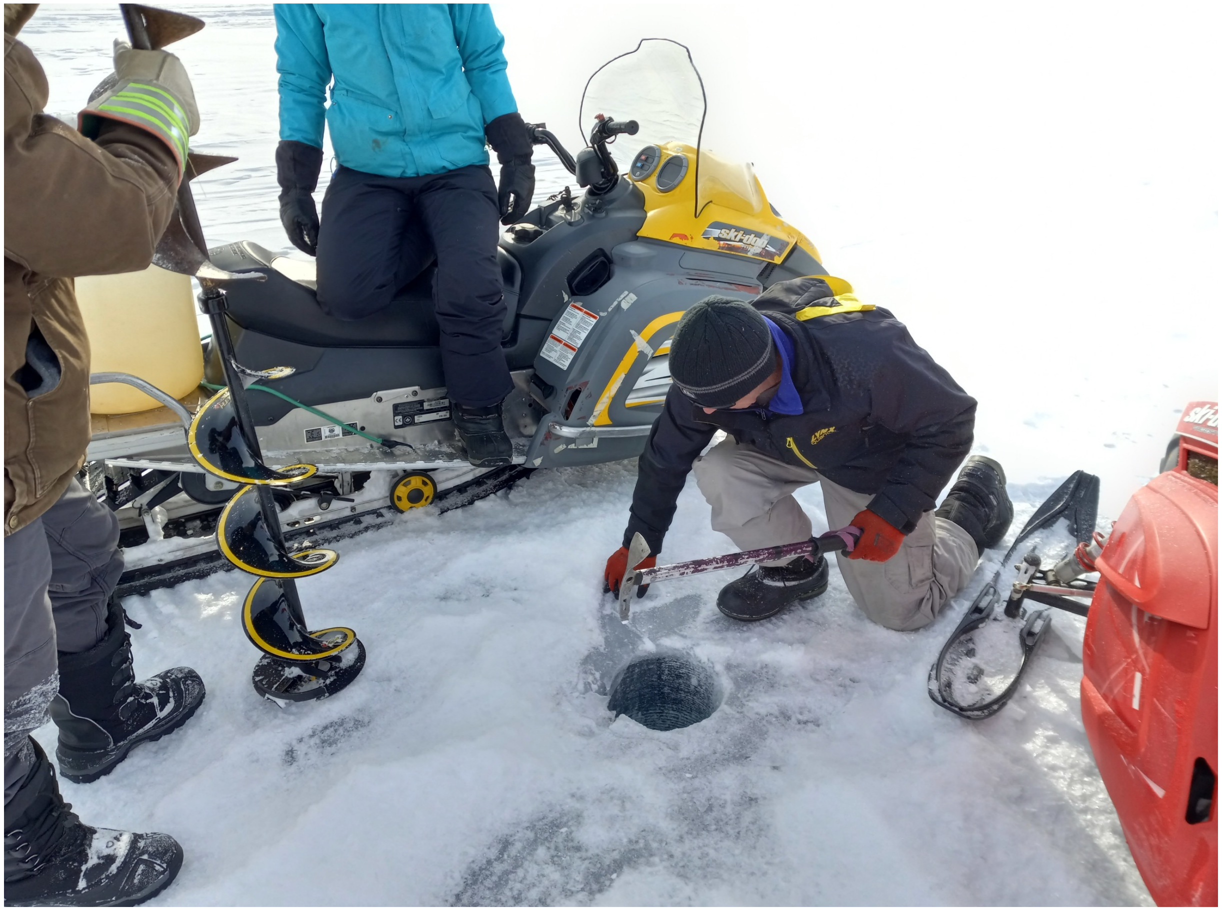
MIST in 2024

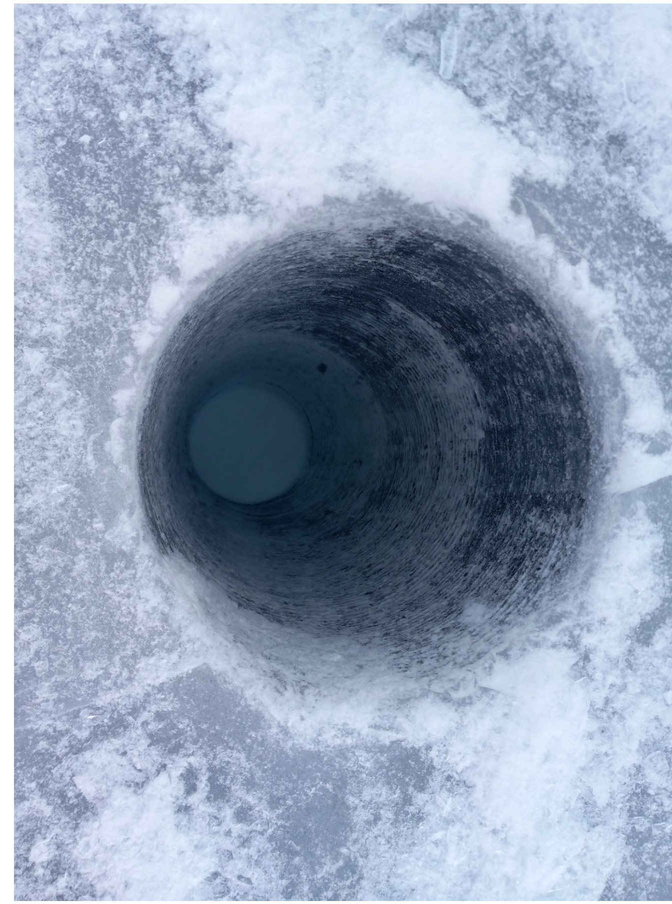

Spring 2024
Glaciologists and Cosmologists
Kenn Borek Air
Raul
Ian
Tristan
Wonderful Glaciologists Friends


MIST in 2024: Arctic
Next to MARS itself
On top of frozen lake

This is the lake we perforate to get water in the Spring

Ice thickness ~2 meters





MIST in 2024: Arctic

Second instrument: “MIST-Low”
Located 8 km west of MARS

Compared to “Standard” MIST:
Panel width: **60 cm -> 140 cm**
Panel height: **52 cm -> 75 cm**

MIST in 2024: Arctic

MIST-Low

Receiver Calibration in the Arctic at -30 degC

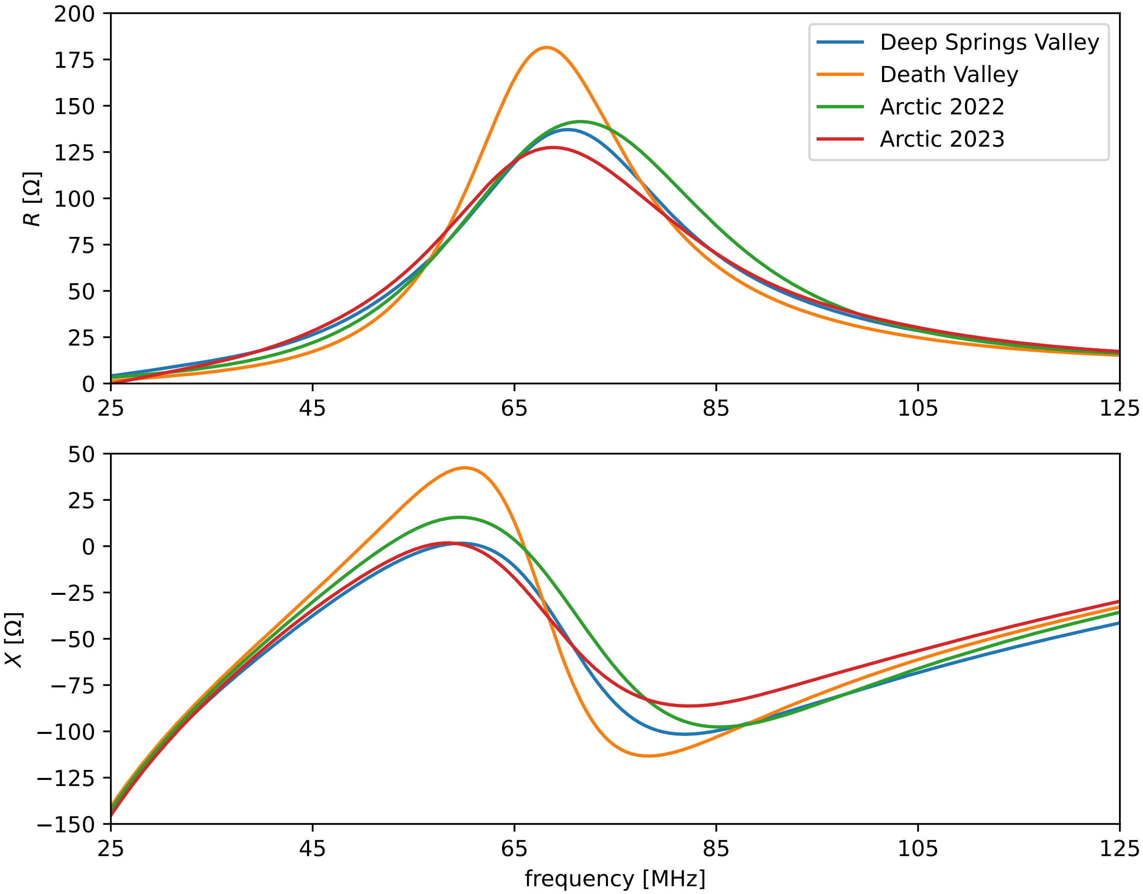
MIST has gathered 30 days of observations from the Arctic between 2022 and 2024

Sufficient SNR to test the presence of EDGES signal

Focusing on understanding soil effects

MIST Antenna Impedance

- MIST antenna impedance strongly depends on soil properties
- Solve inverse problem and use impedance to estimate soil parameters



Ian Hendricksen

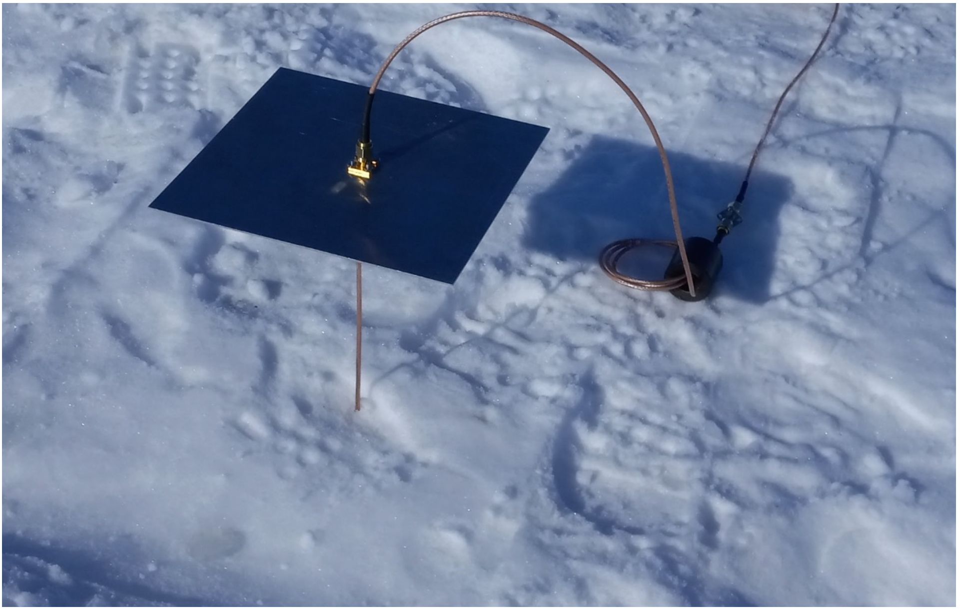
McGill Graduate Student

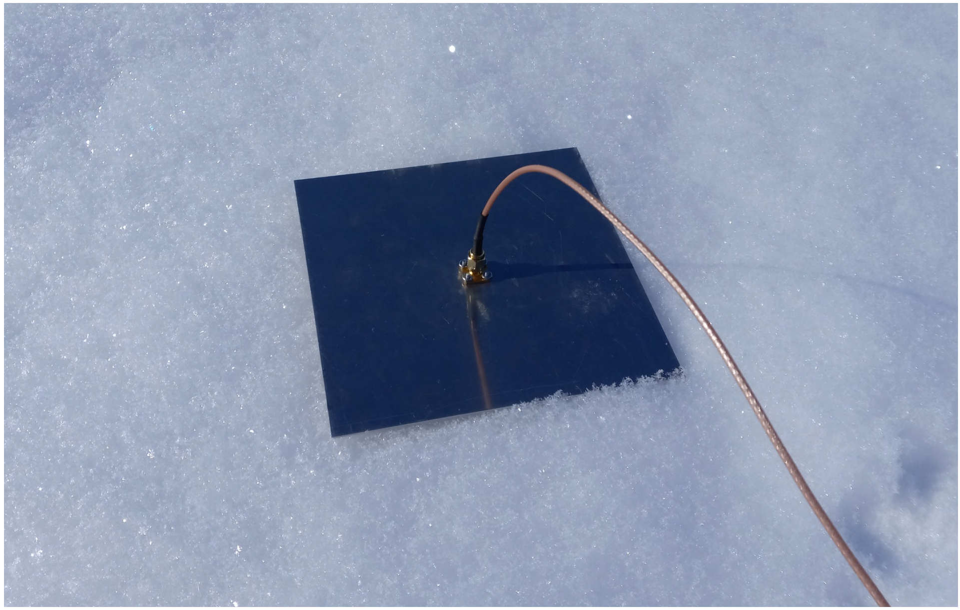
Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) measurement
100 m x 100 m area centered at the MIST antenna
Area was swept by pulling GPR with skidoo

Impedance of Monopole Antenna Inserted into the "Soil"

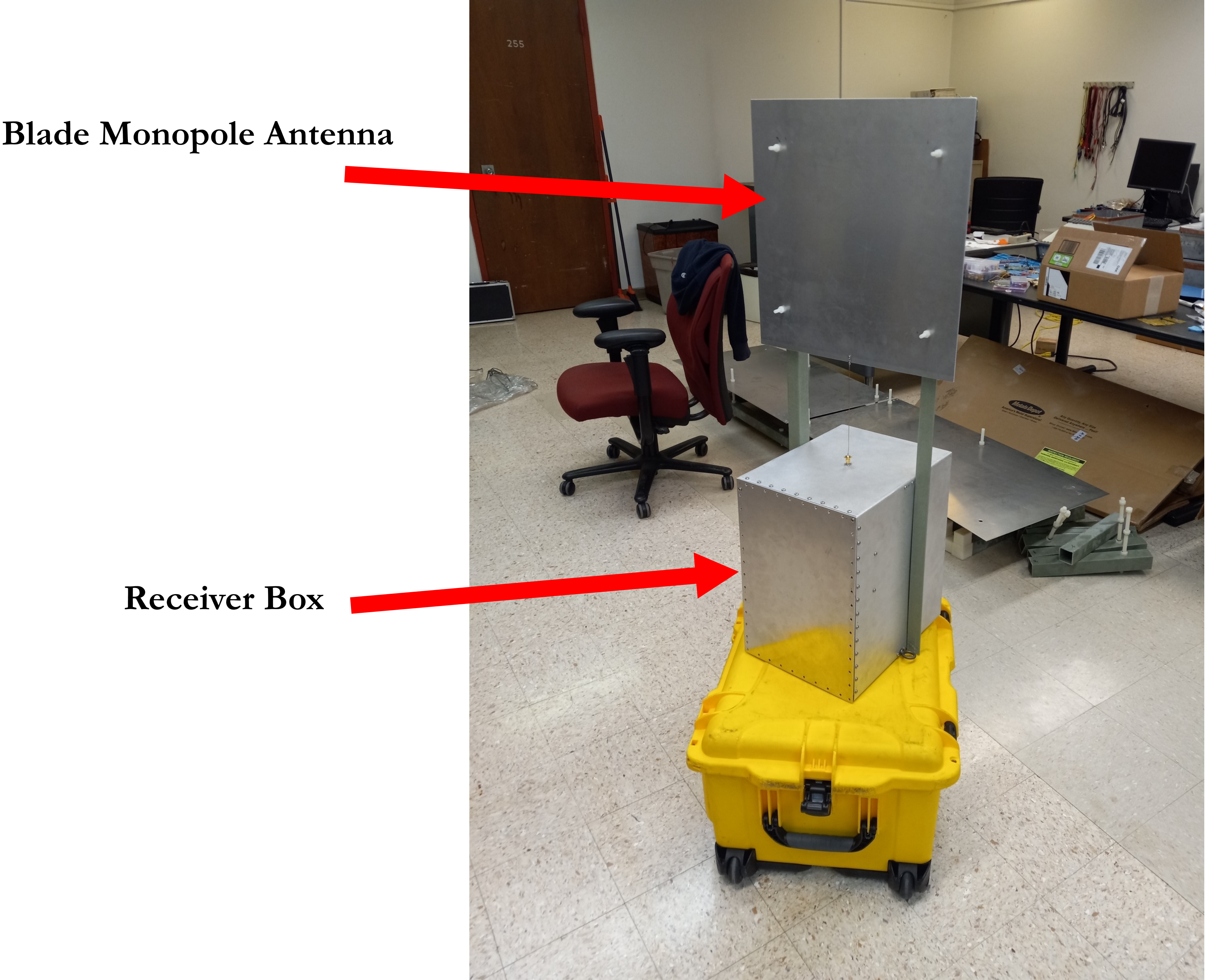




Effort led by Ian Hendricksen

10 Days Ago: Trip to Utah


EIGSEP Global 21-cm Experiment
Prof. Aaron Parsons


Blade Monopole Antenna
Receiver Box

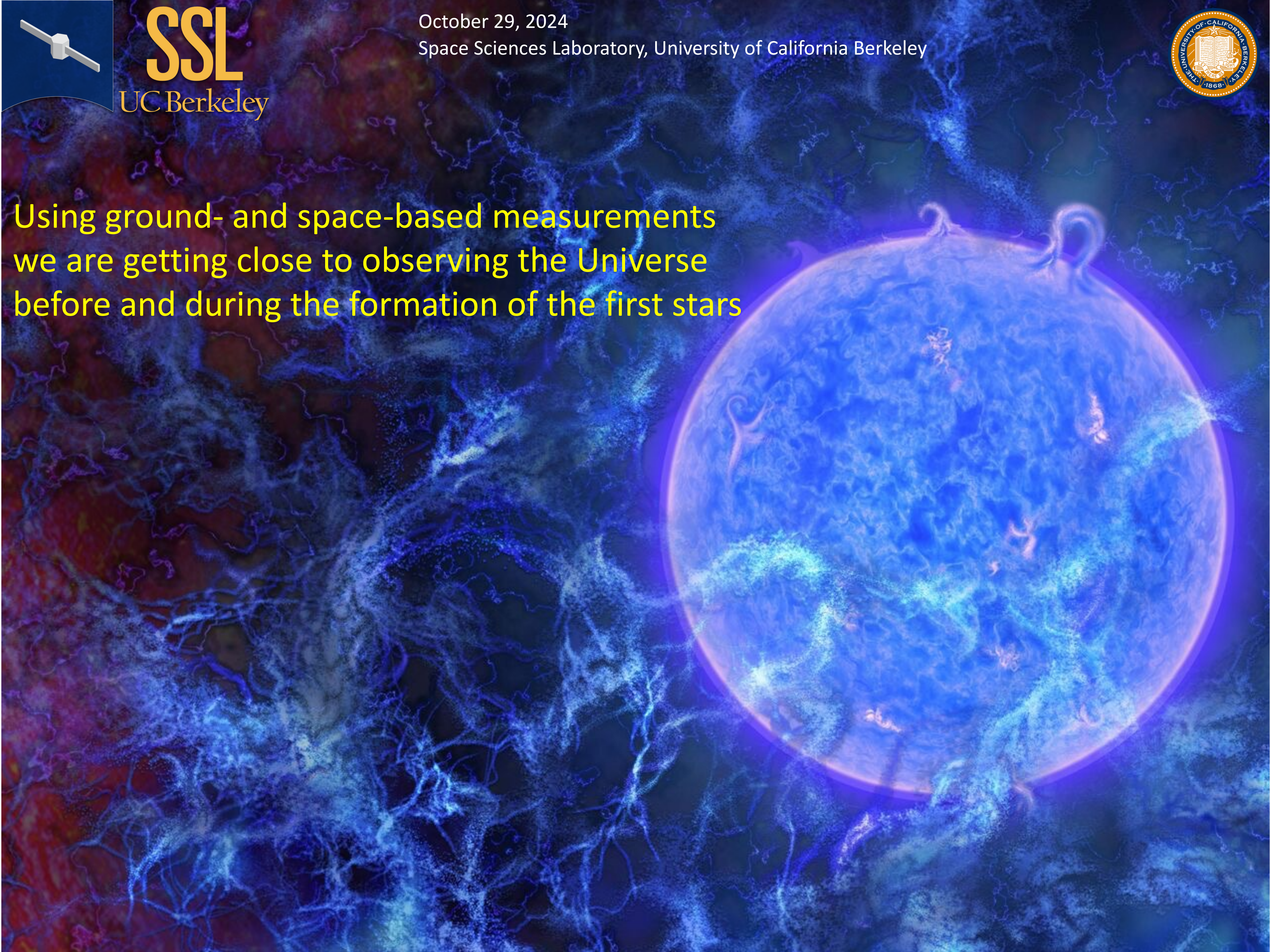
MIST In a Canyon (MISTIC)

- Hanging at 25 meters above the ground
- Took 1.5 days of observations
- Starting to analyze the data

MIST In a Canyon (MISTIC)


EIGSEP Antenna

EIGSEP Antenna at 90-95 m Above the Ground



SSL UC Berkeley

October 29, 2024
Space Sciences Laboratory, University of California Berkeley

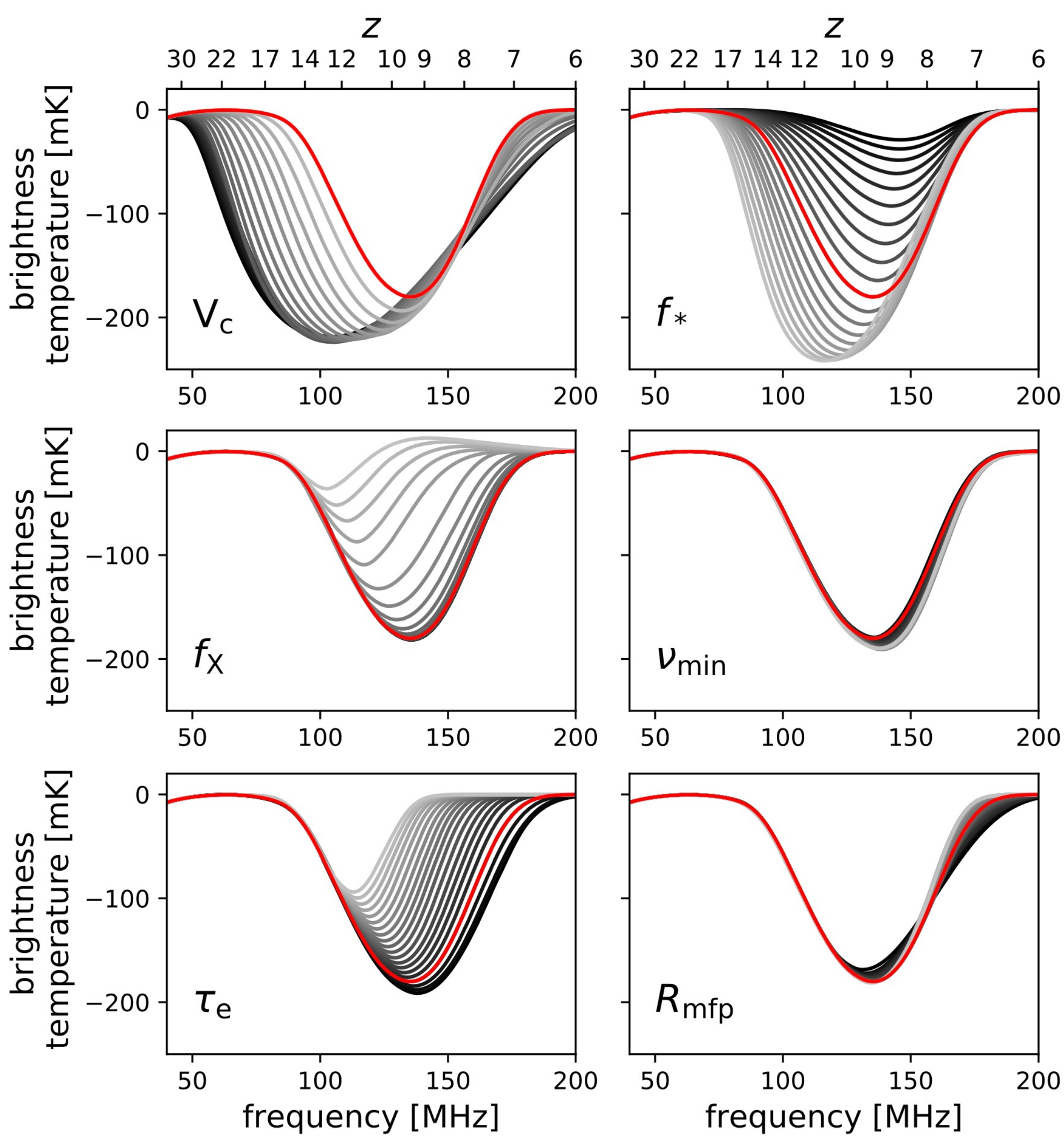
Using ground- and space-based measurements we are getting close to observing the Universe before and during the formation of the first stars


SSL
UC Berkeley
October 29, 2024
Space Sciences Laboratory, University of California Berkeley
Thank you very much

Extra Slides

One parametrization used for the Cosmic Dawn

seven astrophysical parameters were varied in the widest possible range: the minimum virial circular velocity of star-forming halos (V_c), the star formation efficiency (SFE) (f_*), the X-ray heating efficiency of early sources (f_X), the low-energy cutoff (ν_{min}) of the X-ray spectral energy distribution (SED), the slope (α) of the X-ray SED, the mean-free path of ionizing photons (R_{mfp}), and τ_e.



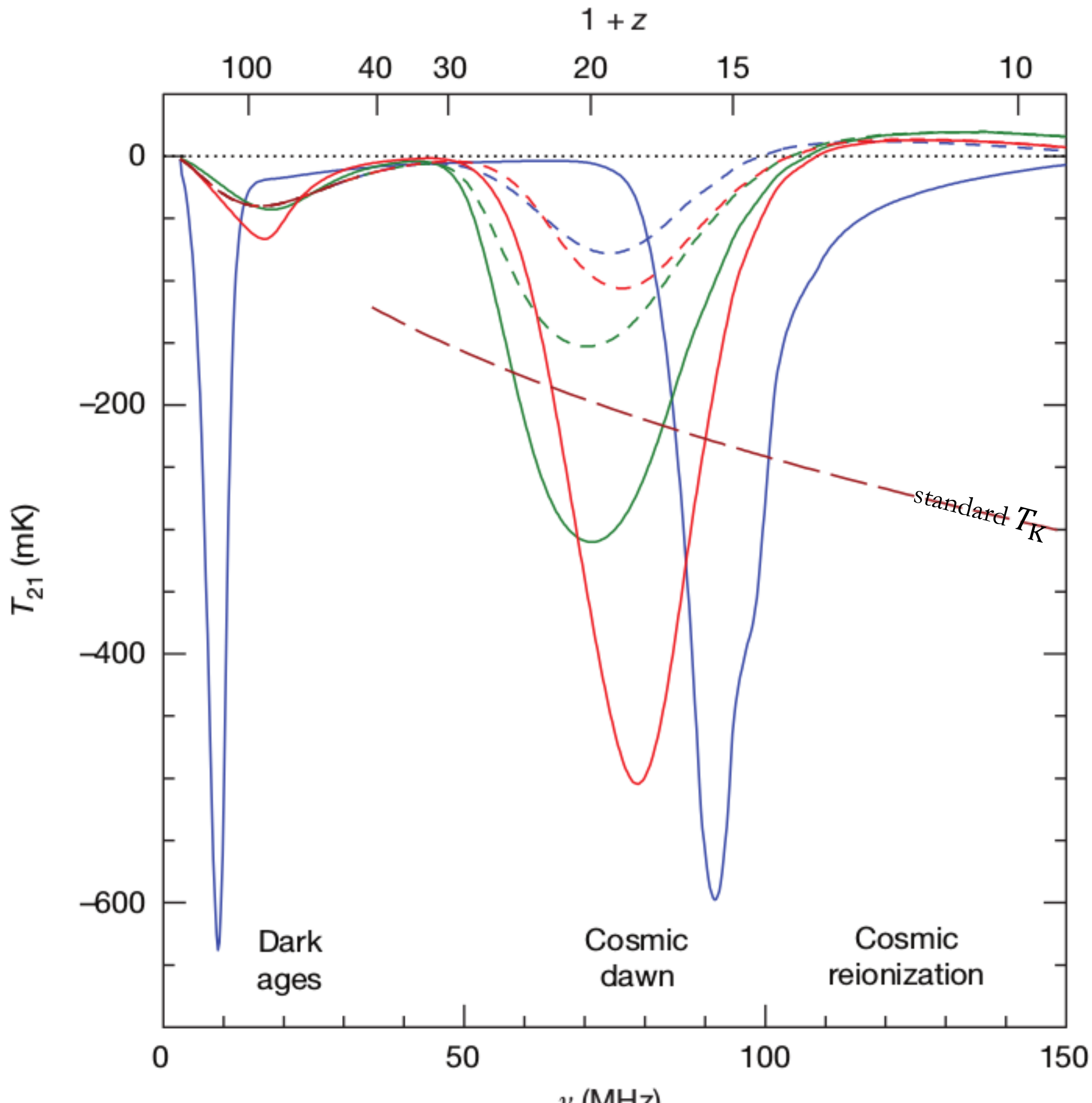
Monsalve et al (2019)
arXiv:1901.10943

Interaction of Baryons with Dark Matter?

Enough IGM cooling to explain EDGES can be achieved if (Muñoz & Loeb 2018):

- **~ 1%** of DM particles
- have mass **~ 1-60 MeV**
- and posses electric mini-charge, **$\sim 10^{-6}$ the charge of an electron**

Possibility of non-gravitational interaction between baryons and dark matter.



R. Barkana 2018, **Nature**, 555, 71

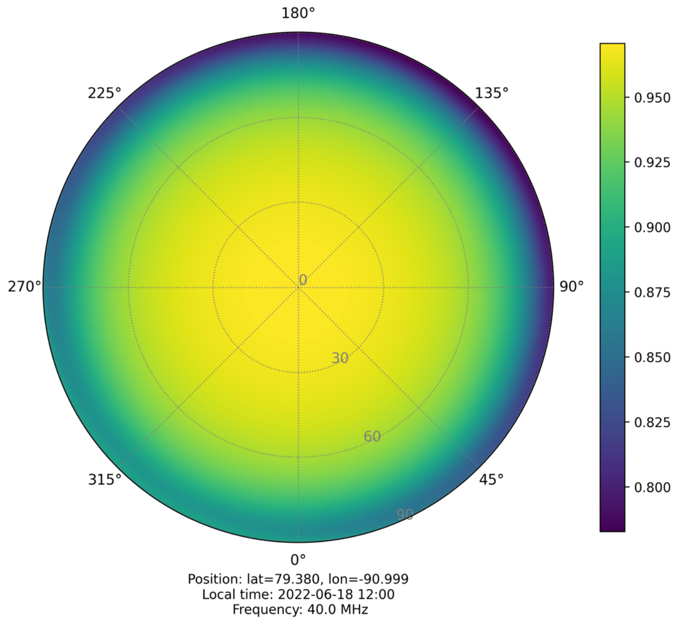
DionPy: Dynamic Ionospheric Model in Python

Based on IRI (International Reference Ionosphere)

https://pypi.org/project/dionpy/

Vadym Bidula

Transmission Fraction



Refraction Angle