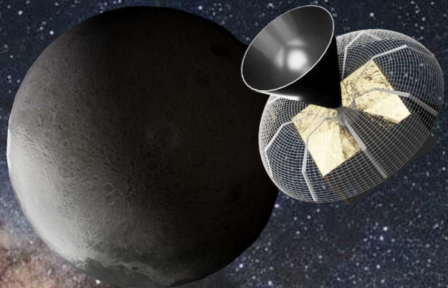


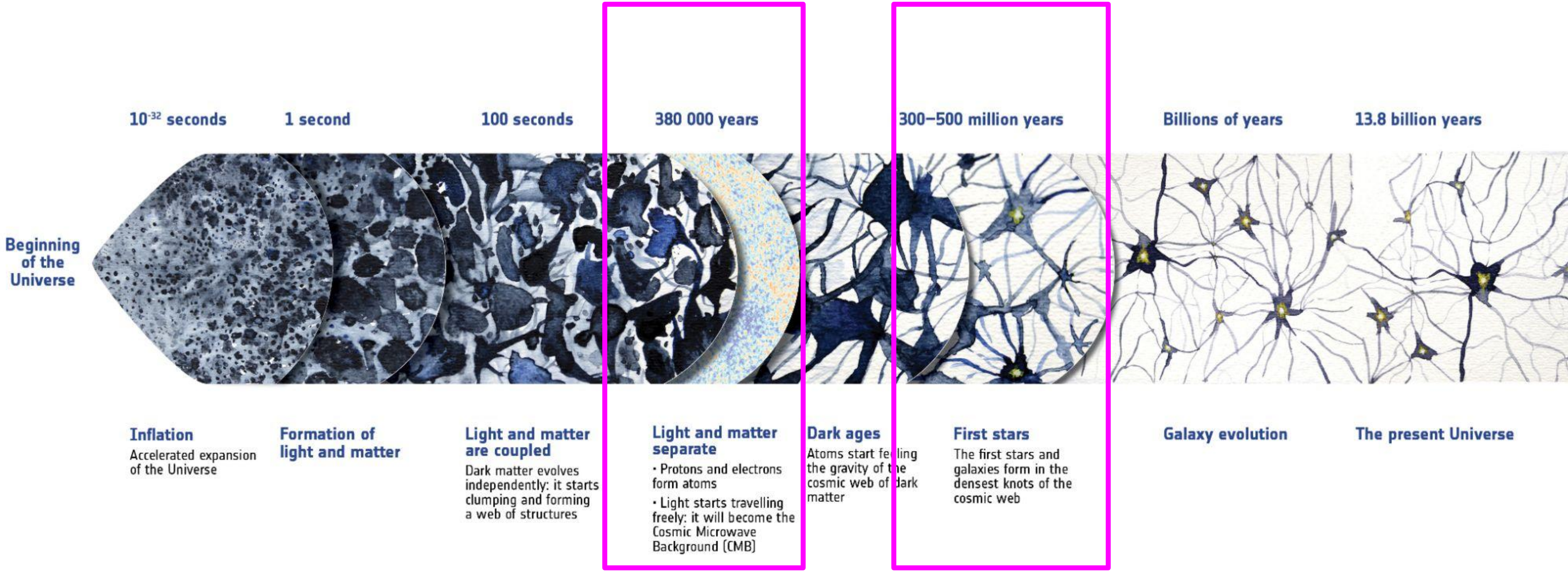
APSERa & PRATUSH

Mayuri S. Rao

Challenges at the CMB Frontier

29 June 2026

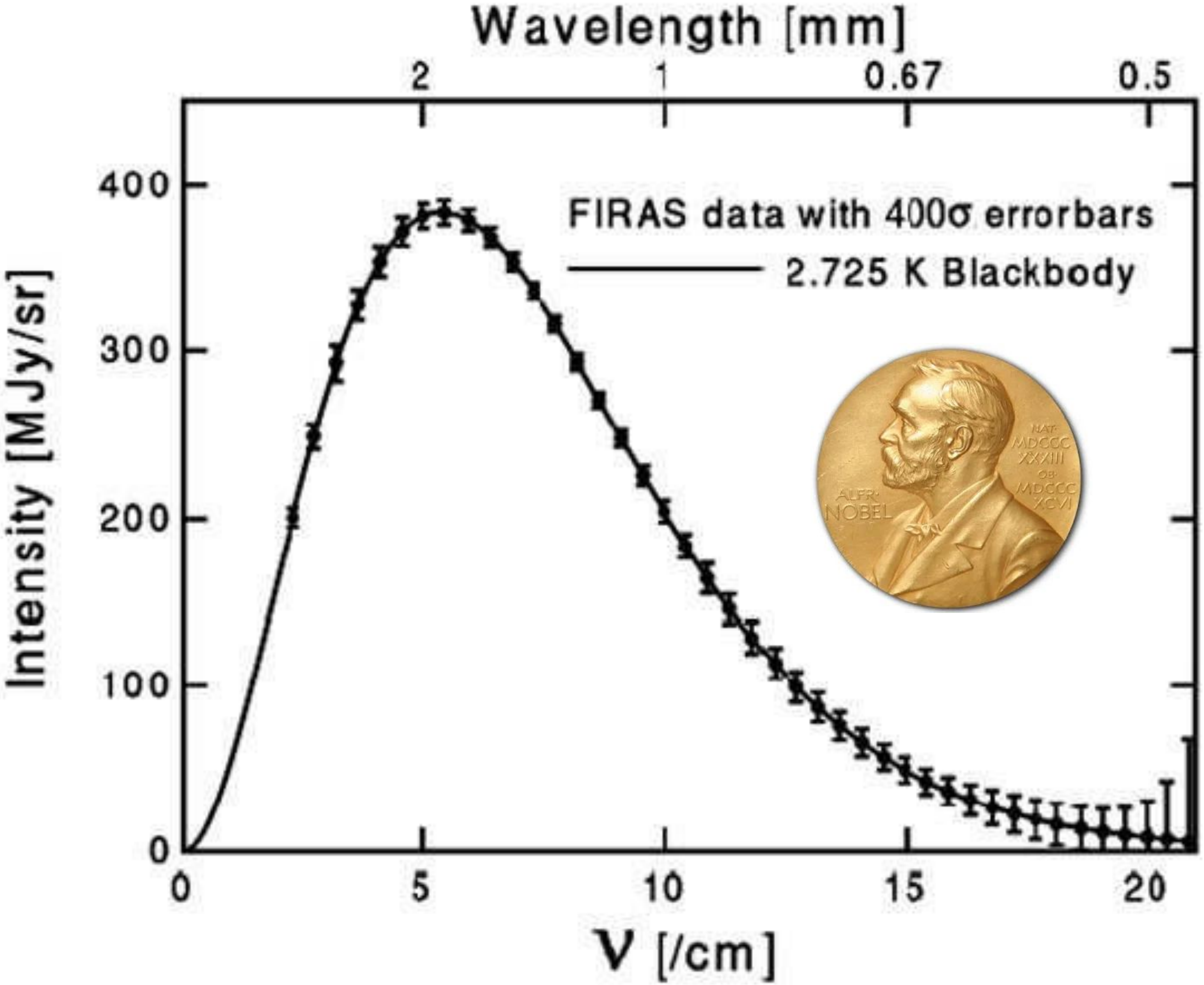
The Cosmic Timeline



APSERa:
FIRST ATOMS

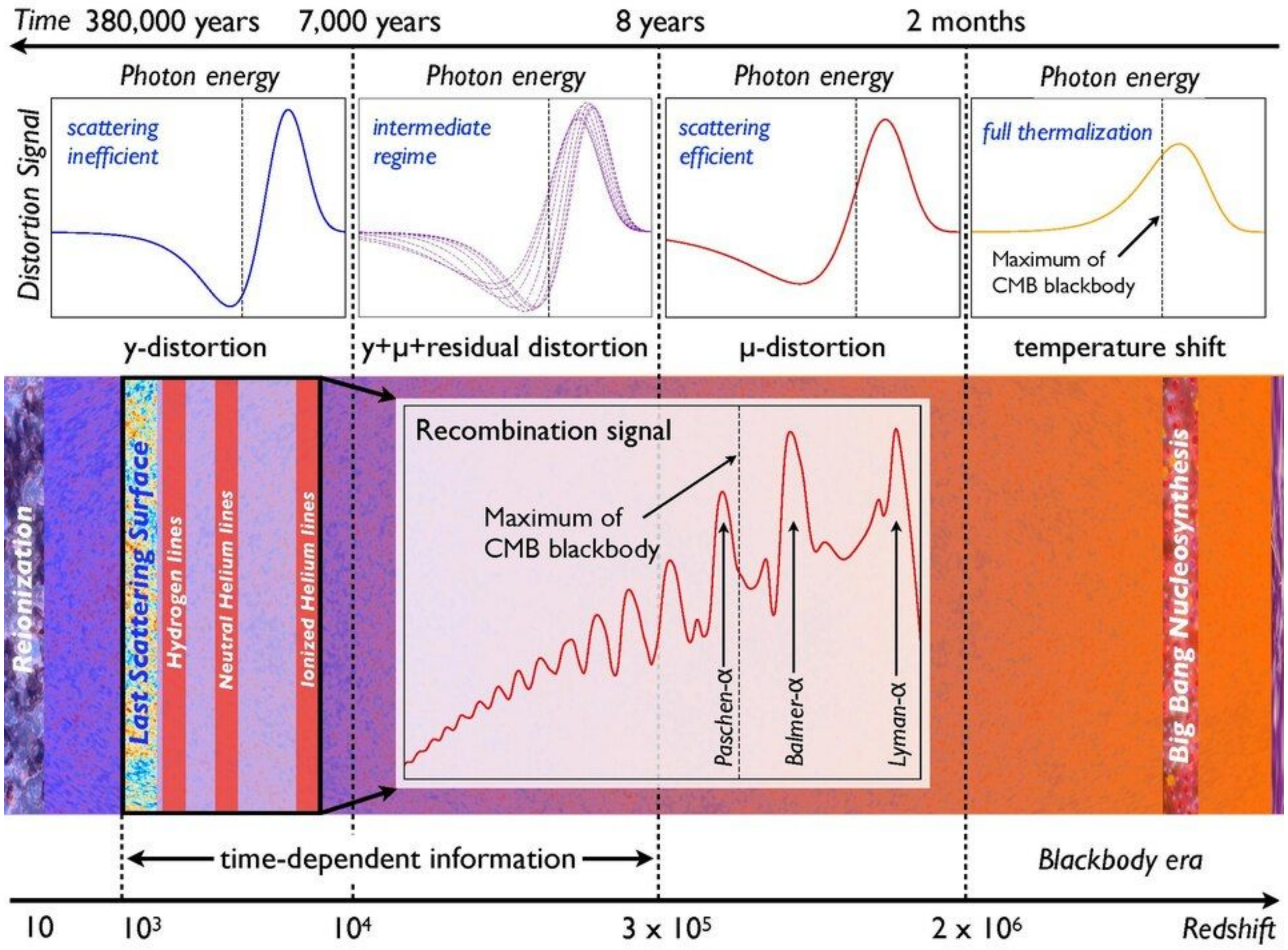
PRATUSH:
FIRST STARS

Courtesy : ESA



Battistelli et al, 2000

Cosmological CMB spectral distortions



$|\mu|<9\times10^{-5}$

$|y|<1.5\times10^{-5}$

Fig courtesy - Jens Chluba

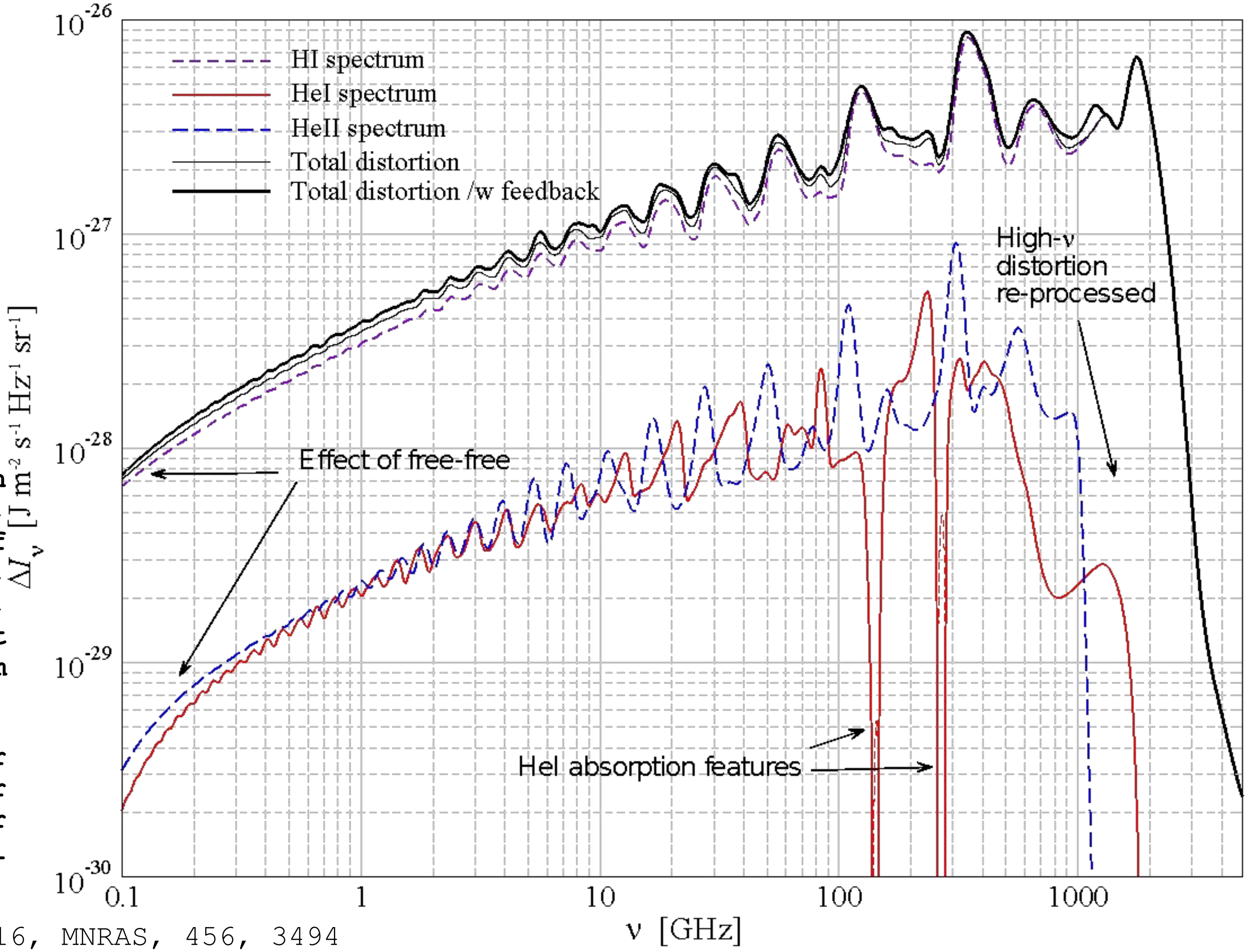
APSERa - an upcoming S-band cosmology experiment

500 <~ z <~ 2000 for hydrogen, 1600 <~ z <~ 3500 for He II → He I and 5000 <~ z <~ 8000 for He III → He II recombination

Free-bound, and bound-bound transitions emit photons that are additive distortions to the CMB spectrum

Why? - Confirmation of thermal, ionization history of the Universe, independent measure of cosmological parameters, exotic energy injection, experimental measurement of prestellar Helium abundance.

Requires a receiver sensitivity of 1 part per billion. Advantage, clear and rich spectral signature predicted!



*Chluba & Ali-Haimoud, 2016, MNRAS, 456, 3494

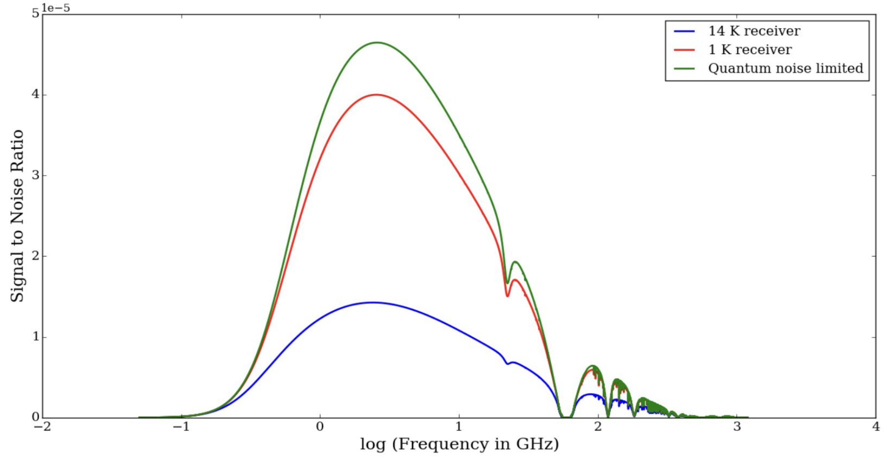


Fig. 3.6 Signal-to-noise ratio vs. nominal observing frequency (in log(GHz) scale) for the detection of spectral-line signatures from recombination epoch with an octave bandwidth. The green line shows the ratio assuming ideal quantum-noise-limited receivers; the blue line shows the ratio for the more realistic case of receivers with 14 K receiver noise. The red line shows this ratio for a receiver that is cryogenically cooled to 1 K. The observing time is assumed to be 1 s.

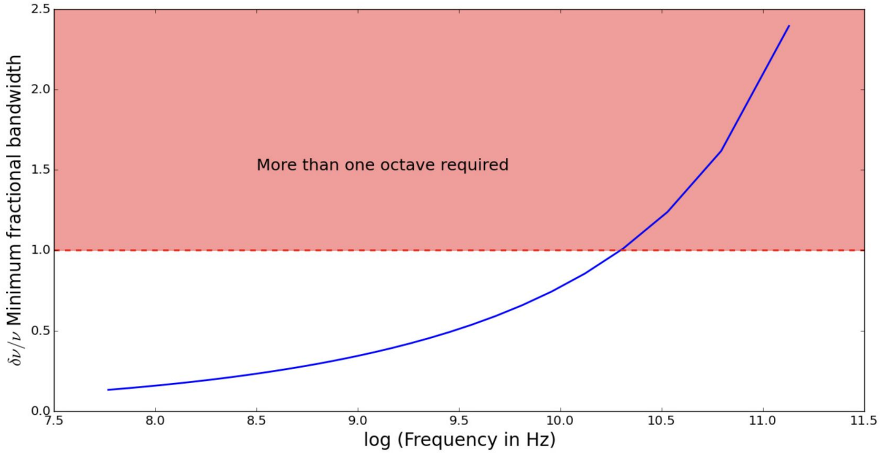
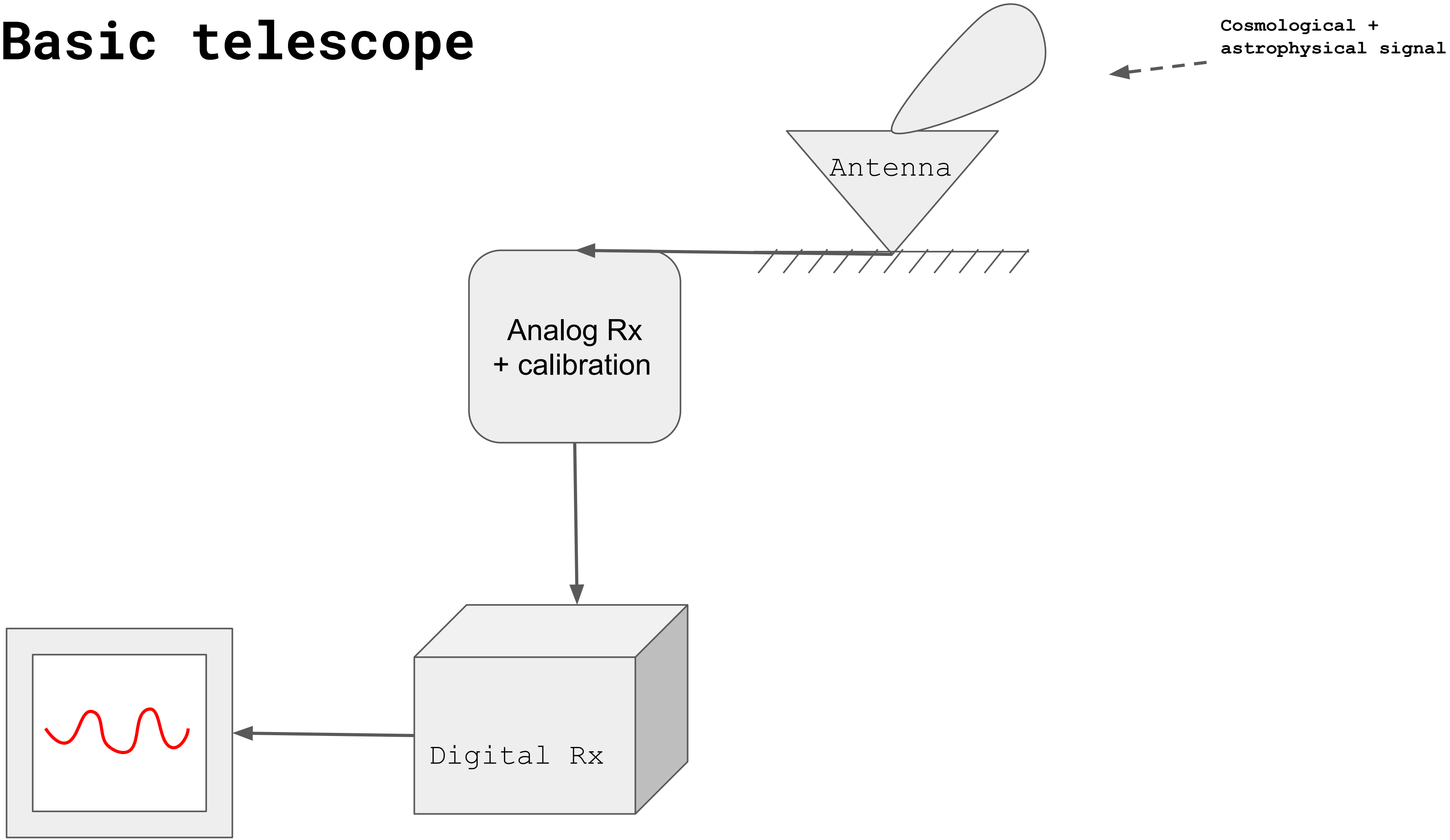
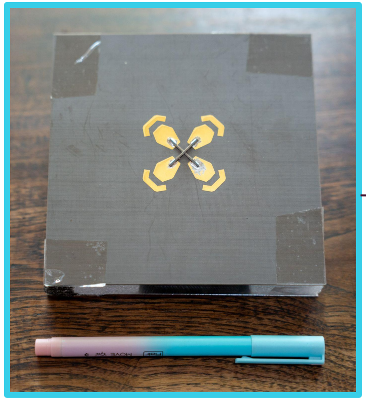
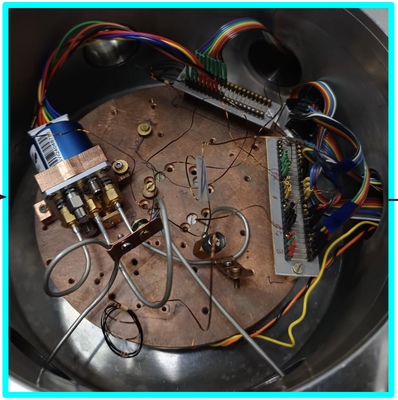


Fig. 3.4 Ratio of spacing between peaks of α transitions from n and $n+2$ quantum shells of hydrogen to the nominal frequency vs. nominal observing frequency in log(Hz) units.

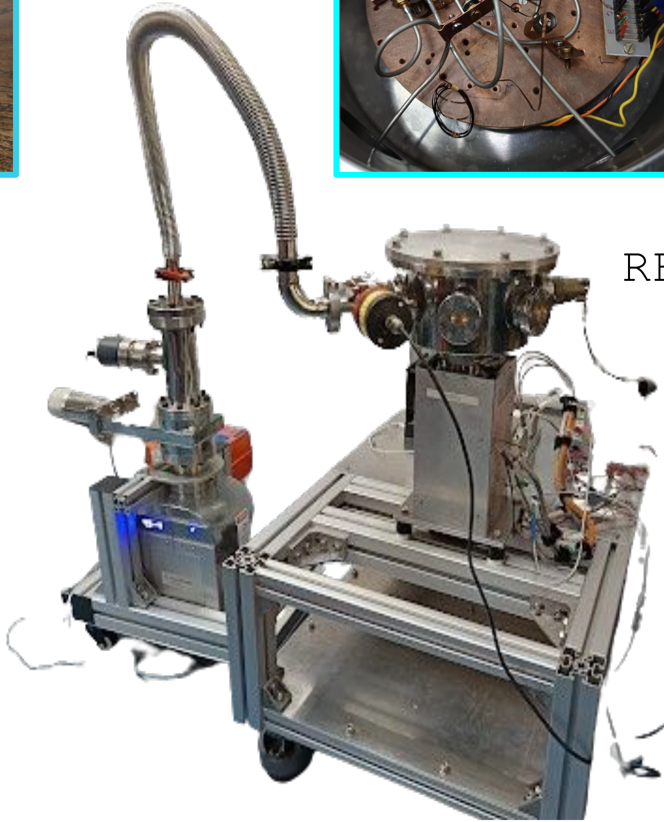
Basic telescope







Antenna

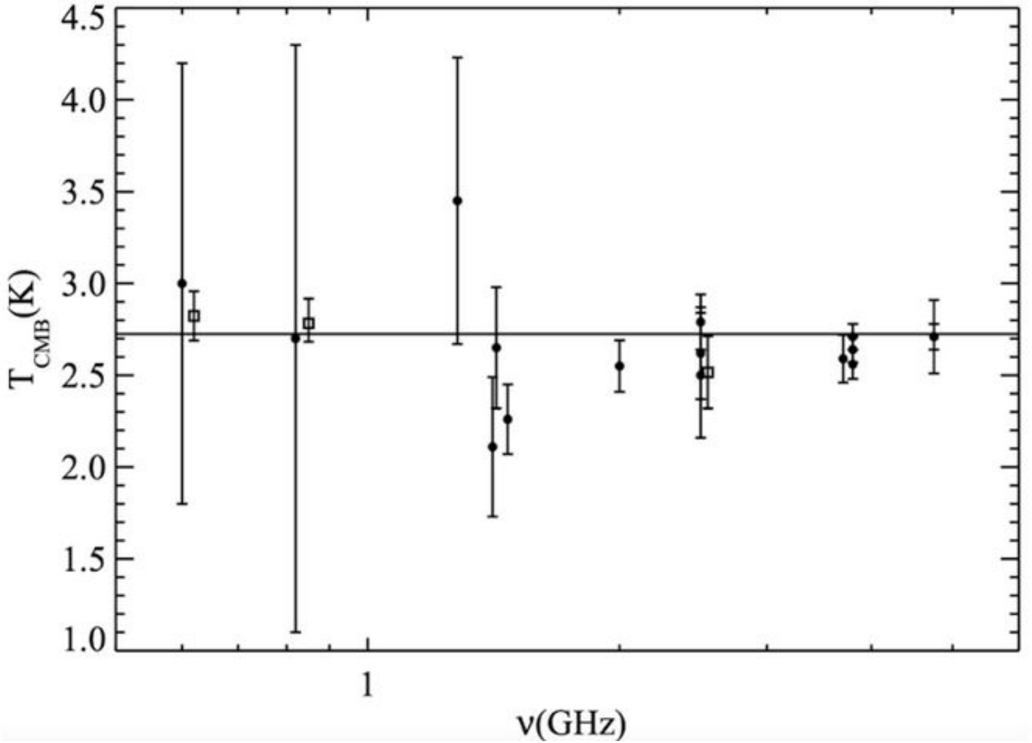


RF

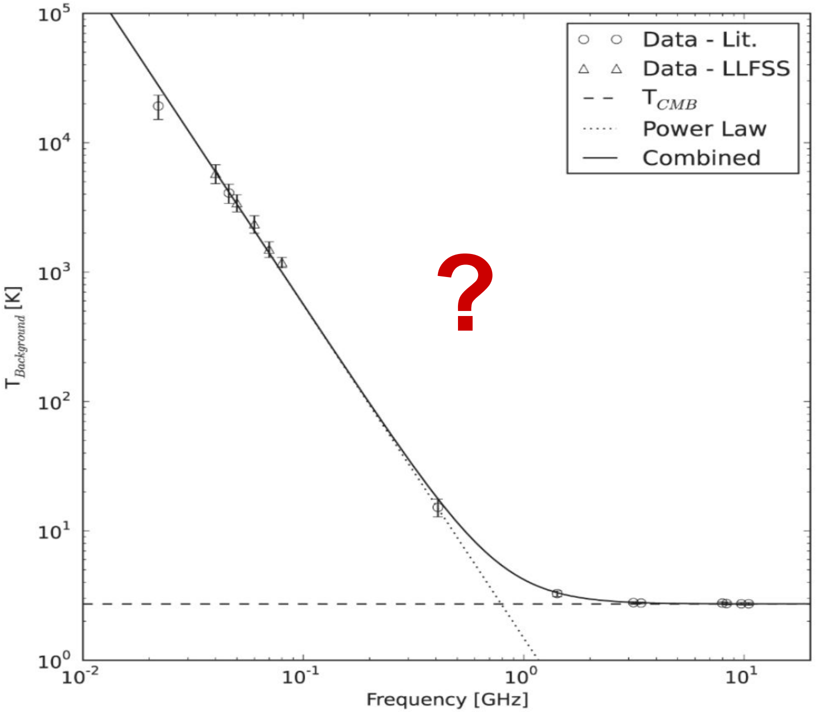
Cryogenics

Digital

Absolute sky-temperature measurement and excess radio background

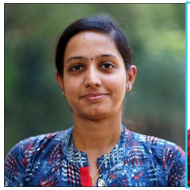


Gervasi et al ApJ, 2008, TRIS collaboration

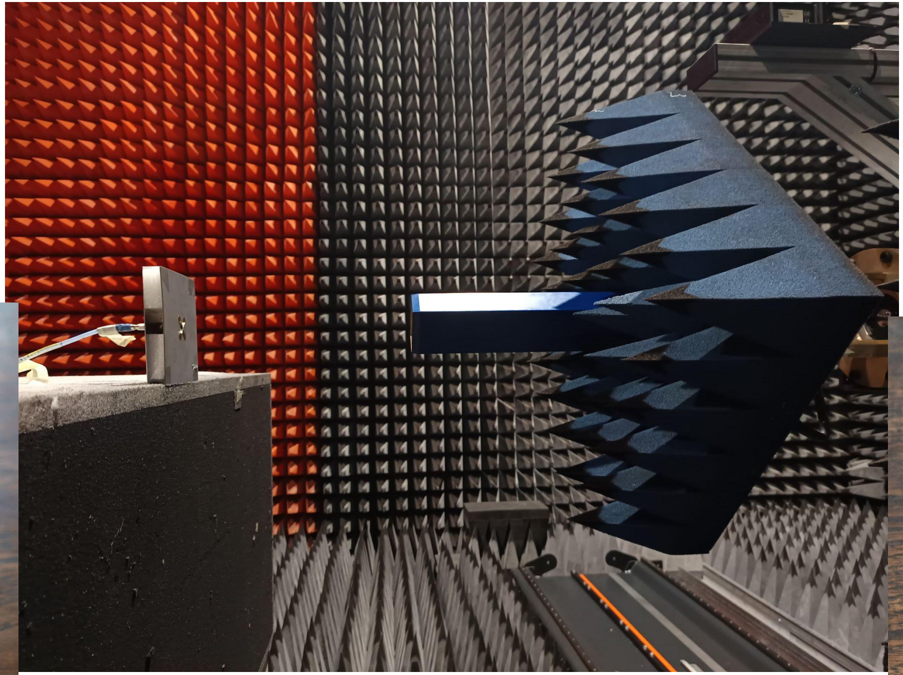


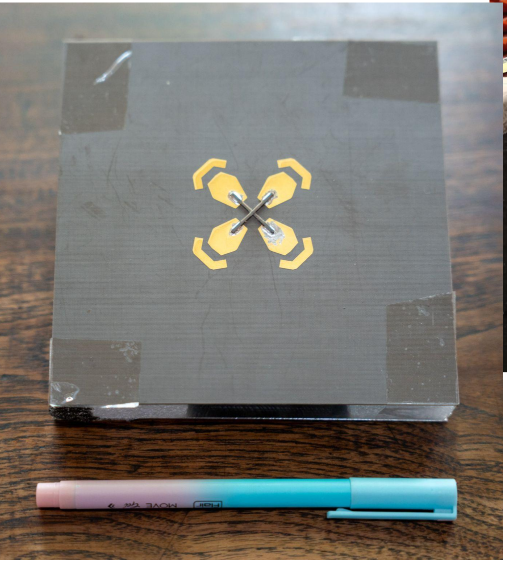
Poorly constrained CMB spectrum at frequencies 1-5 GHz (top). Modelled extragalactic background temperature as a function of frequency (plot from Dowell & Taylor, 2018)

CUSTOM ANTENNAS

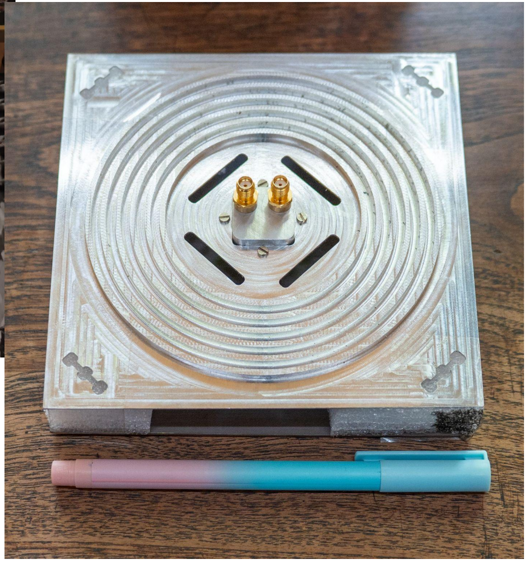



Sathish, MSR, Sarkar 2024 AJ
Anand, Sathish, MSR ++ 2026 (in review)



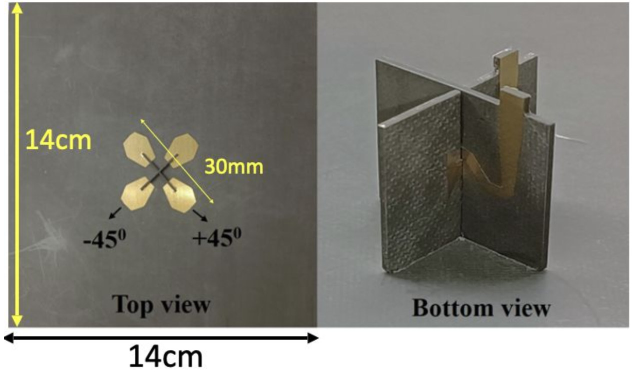


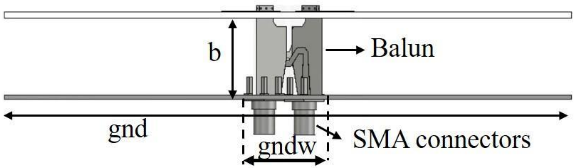
Custom dual-pol wideband (2.5 - 4 GHz) planar antennas, antenna arrays, cryo-antennas



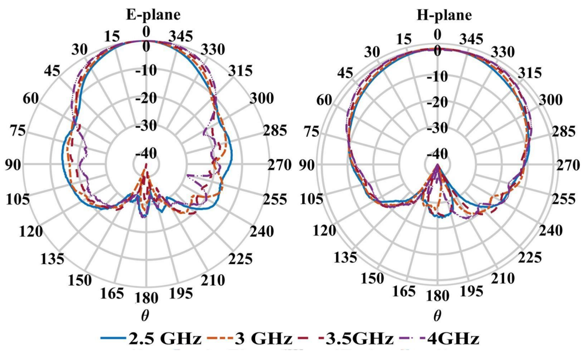
Antenna

- Planar fantail shaped dual polarised dipole antenna was developed and tested (Satish, MSR et al., 2024), which has near smooth response across band.
- Residues with measured pattern in anechoic chamber with finite ground plane: 31mK; and simulation residuals over soil: 60 mK.
- For an absolute measurement of sky to look for ERB, we are designing a new antenna, with narrower beam and resonance at multiple points within 2-4 GHz.

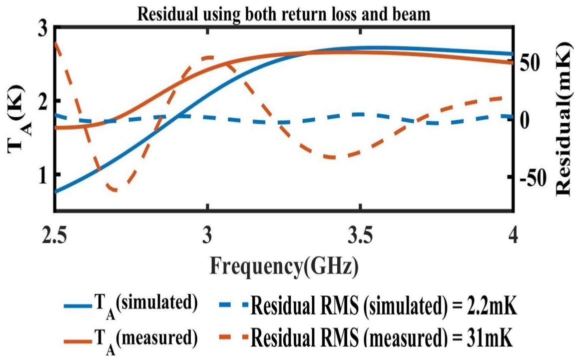




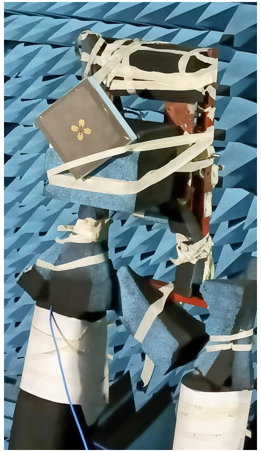
Measured radiation pattern (normalized) variation across frequency



ANTENNA ON FINITE GROUND PLANE (MEASURED)



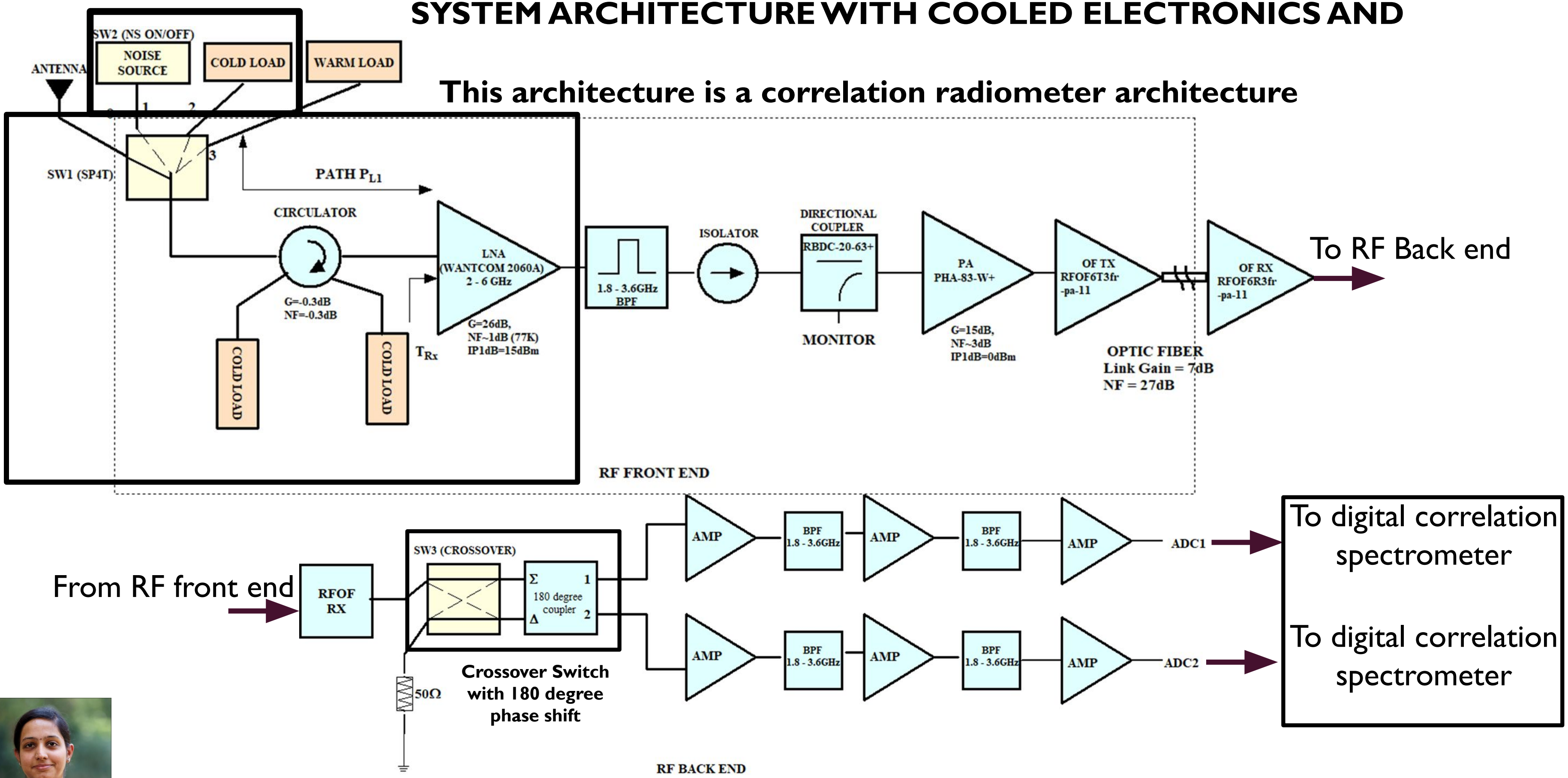
(Mismatch likely due to interpolation errors)



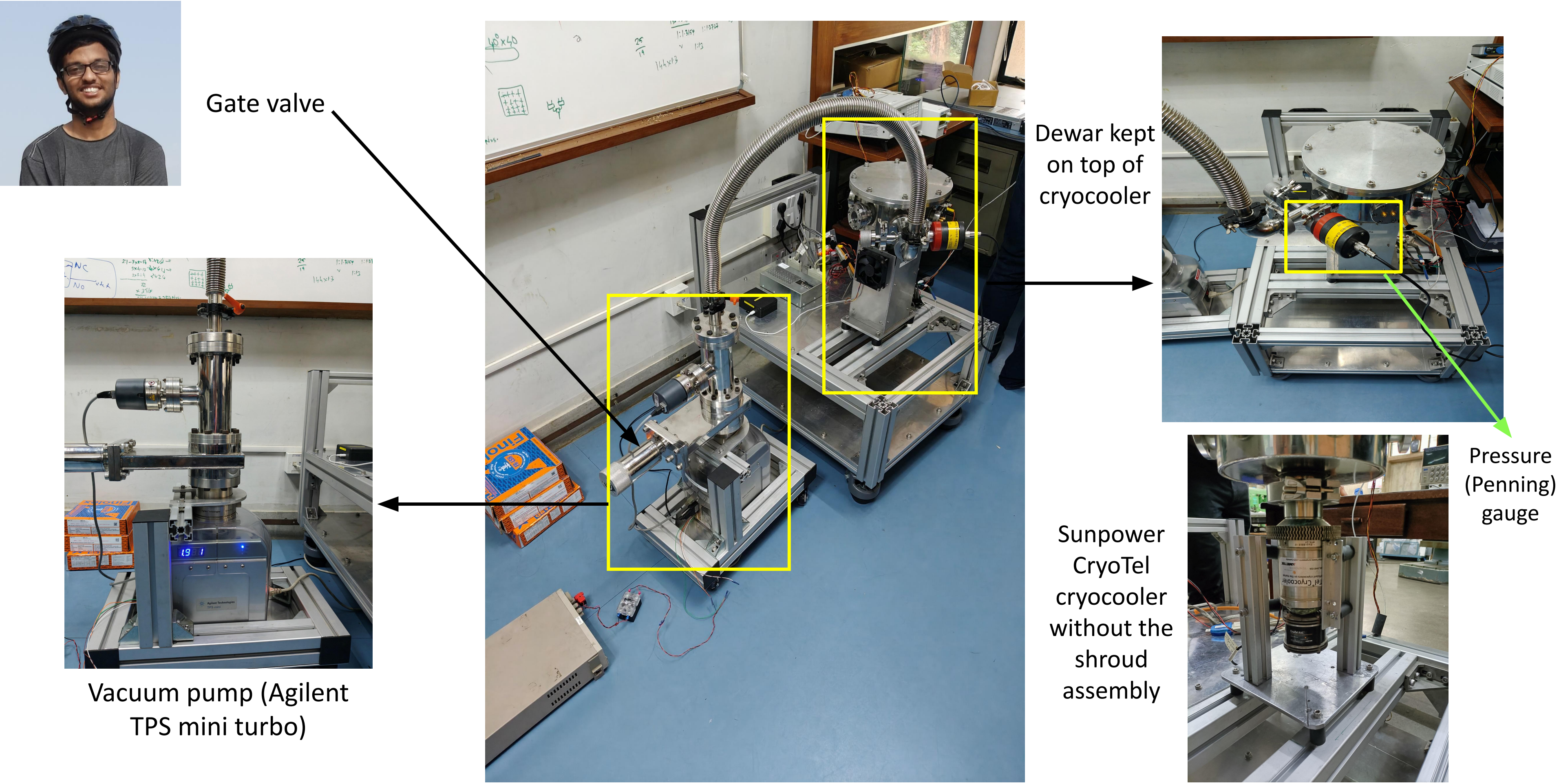
APSERA RADIOMETER SYSTEM ARCHITECTURE

SYSTEM ARCHITECTURE WITH COOLED ELECTRONICS AND

This architecture is a correlation radiometer architecture

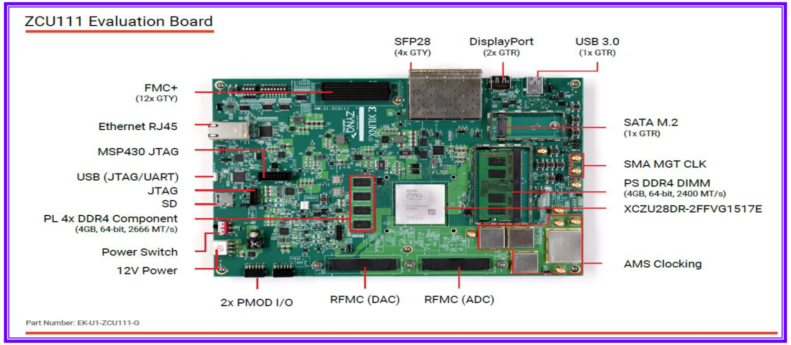


Gain of the system = 70dB, Noise figure <0.3dB, Input compression point >-25dBm



Present set-up of APSERa first element receiver - Vacuum pump for ultra high vacuum (left) and cryo-cooler setup with dewar to house frontend electronics to be cooled to 77 K

ZCU111-APSERa DIGITAL RECEIVER





ZCU111 for APSERa

- GEN1 ZU28DR RFSoC, up to 6 GHz RF input,
- Direct RF sampling
- 12-bit, 8 ADCs at up to 4GSPS
- calibration of TI ADCs for offset, gain & phase
- 18-layer stack up, PCB : 11.31″ x 7.87″ ,
- 1 GbE , SFP, USB3.0 interfaces
- On-board DDR4 - 4GB, 64-bit, PL and PS side

BW= 2GHz, Fs= 4 GSPs
16384 channel spectrometer
ADCS = 12 bit , 2 channels

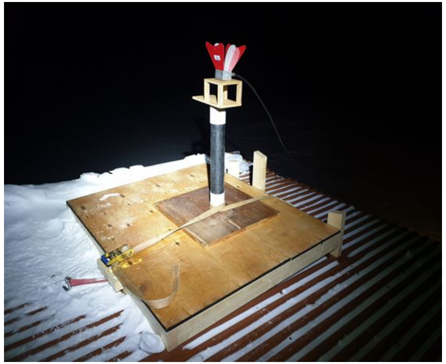
RFI SURVEY SETUP IN VARIOUS LOCATIONS

Setup in Gauribidanur Observatory

Setup in Hanle Observatory

Setup in Thamchung giri

Setup in Himadri Arctic station



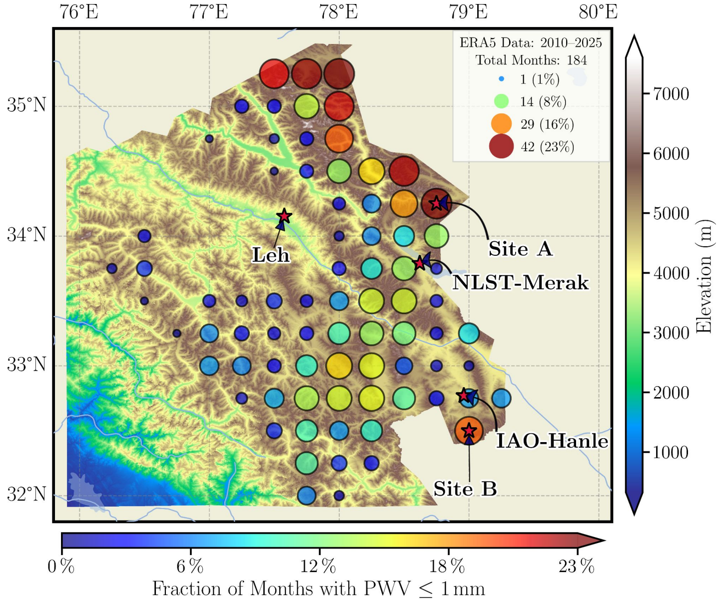
Picture credit: B.S. Girish, RRI

Shielding cage to enclose the Laptop, Spectrum analyzer and the receiver

Observations were carried out during day and night each for 3 hours duration

Sathish, MSR, ++ IEEE WAMS 2024

PRECIPITABLE WATER VAPOUR



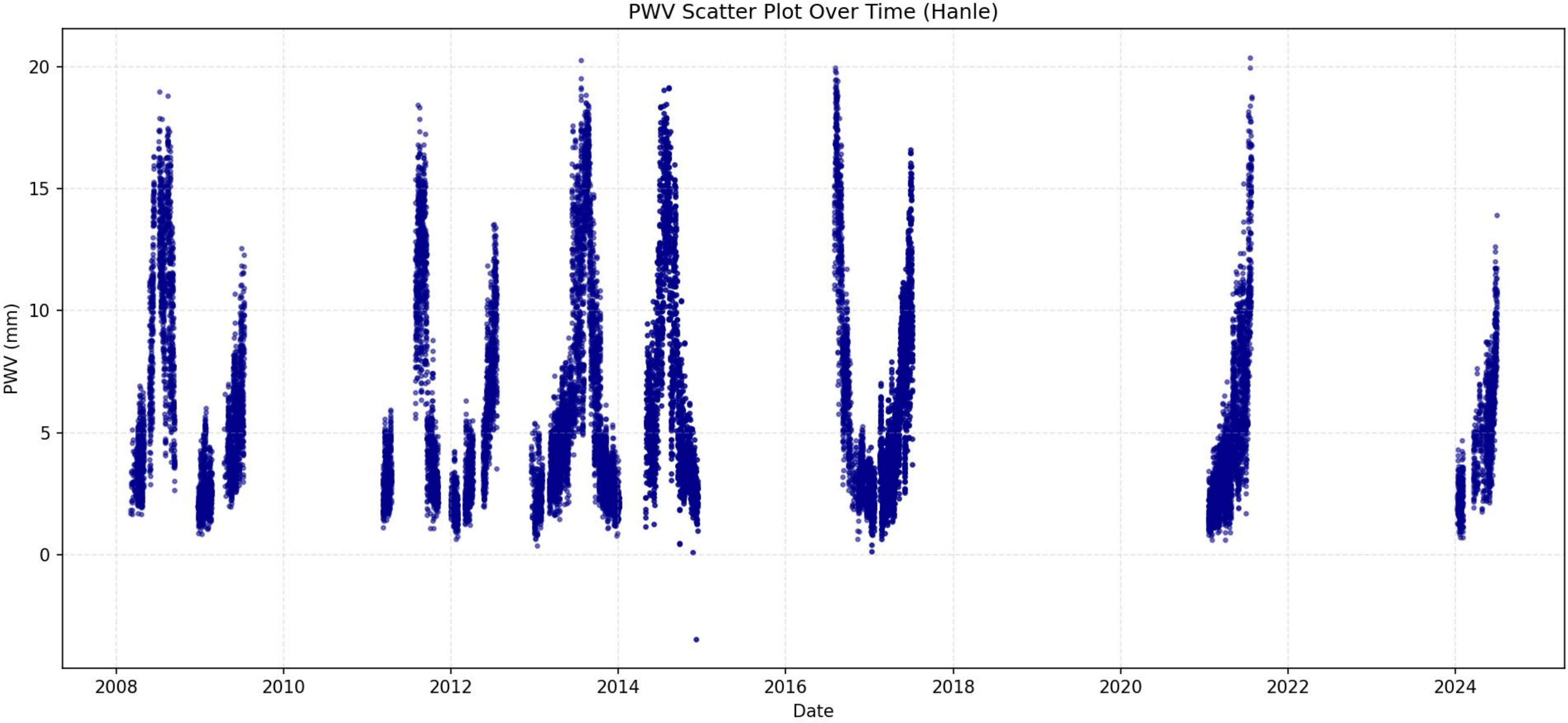
- We have conducted a reanalysis based study over the Ladakh plateau over 2010-2025, at monthly resolution and 27 x 27 km spatial resolution
- Bigger and redder the circle, better the site – many such sites
- Ladakh has very favorable conditions for sub-mm astronomy, Transmittance of 0.8 up to ~300 GHz enables sub-mm science
- Average elevation – 3000 m

Site name	Elevation	Notes
IAO, Hanle	4500 m	Observatory
Nurbula- Top	5310 m	Greenfield site

Technique in Sugiyama, Nishino, Kusaka. MNRAS, 2024

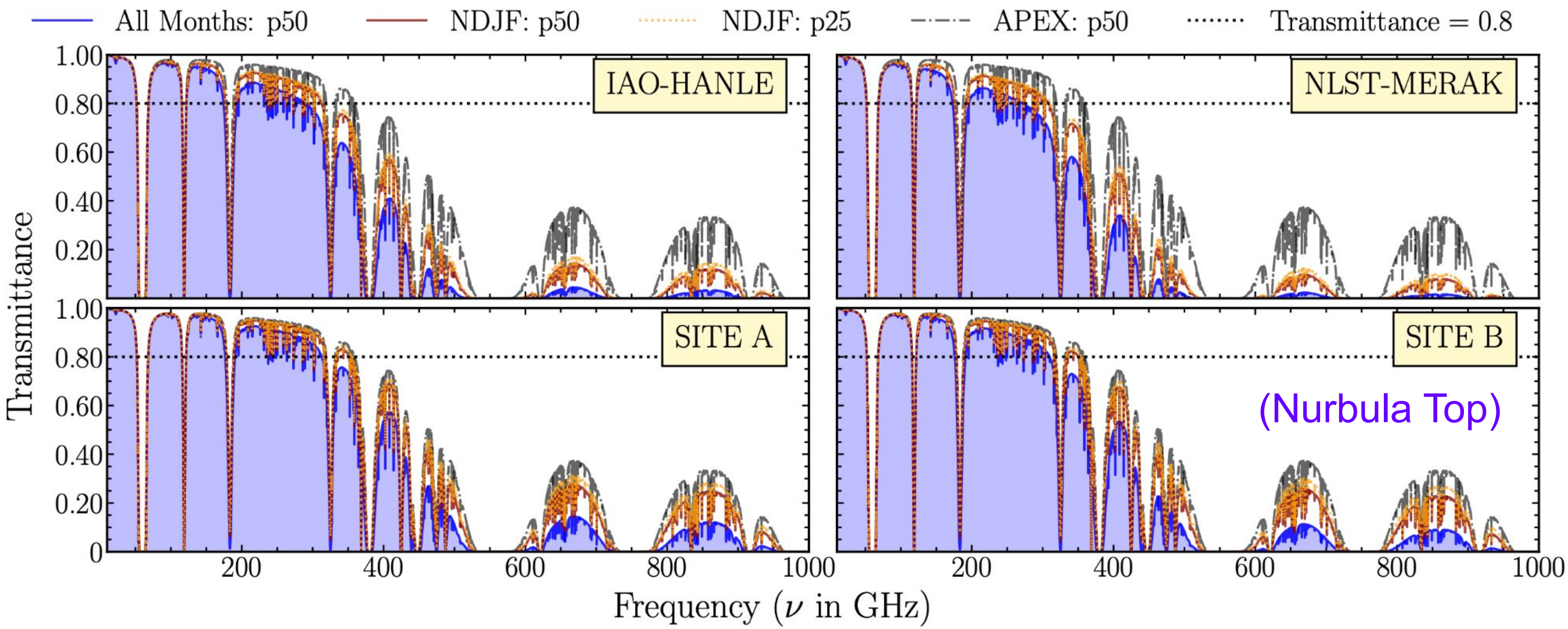
T. Singh, MSR, Basu Thakur 2026 AJ 171 331

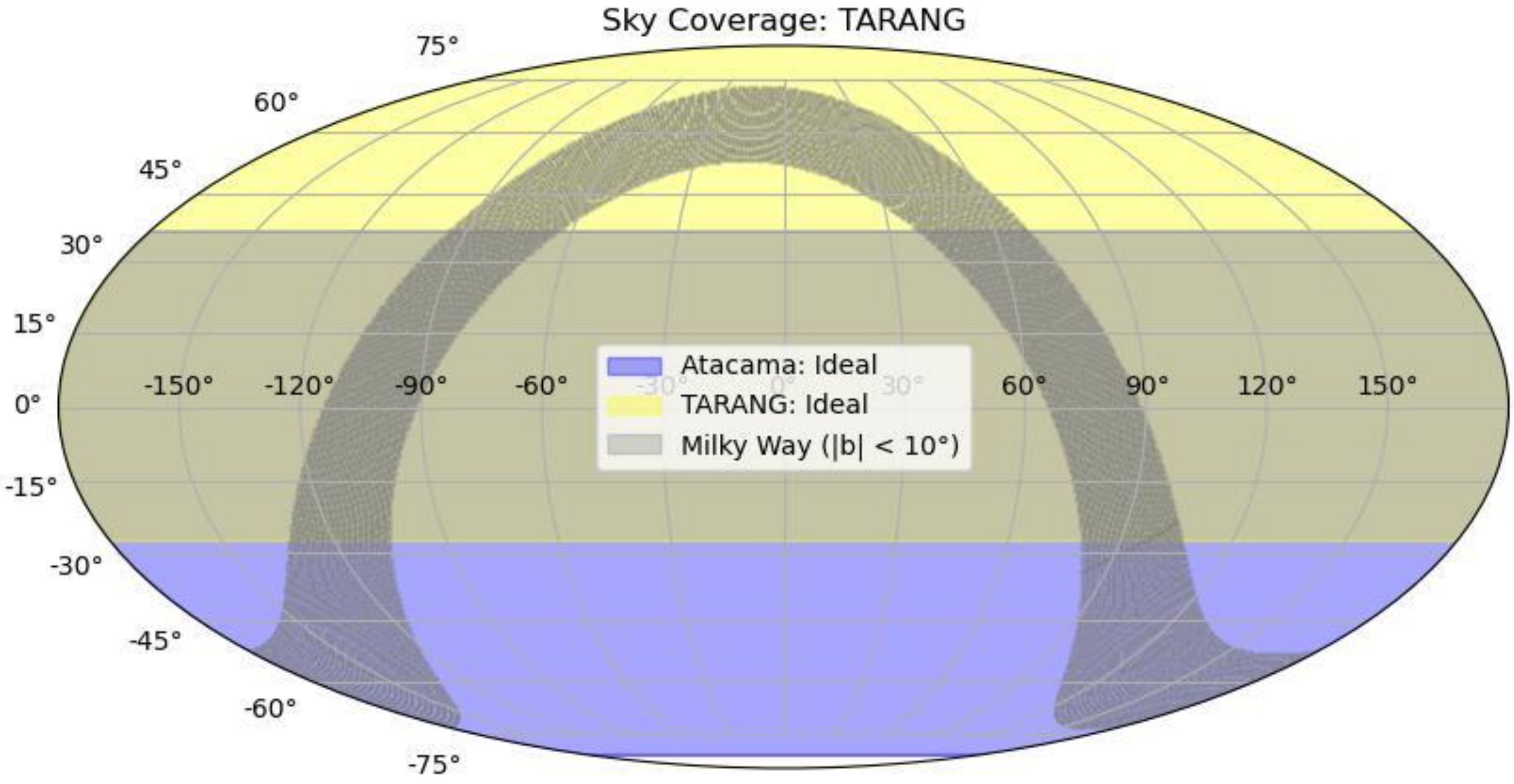
GNSS measured PWV at IAO, Hanle

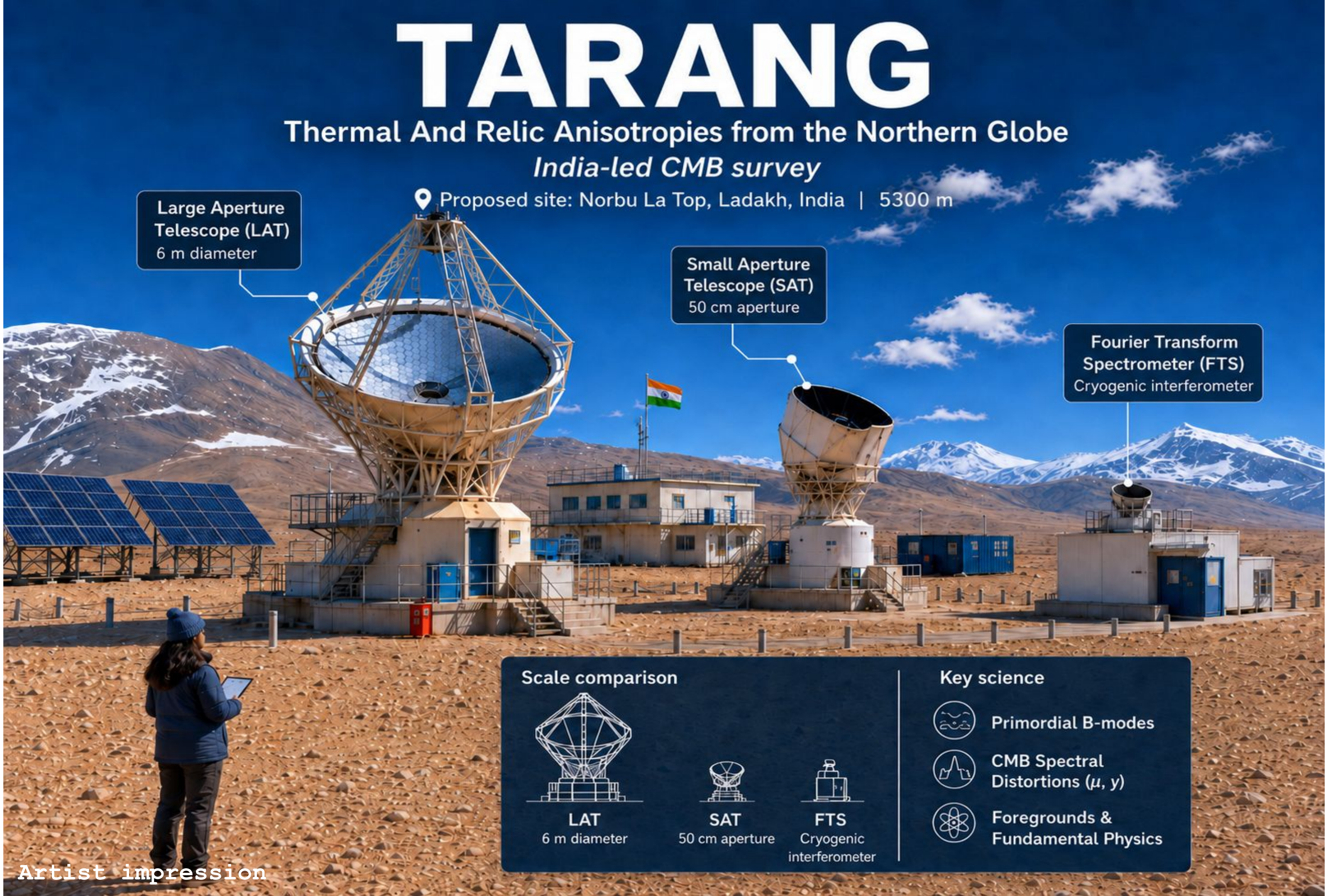


Courtesy, CSIR-National Institute Of Data Science And AI (formerly CSIR -4PI)

Transmittance based on monthly time resolution ERA5 reanalysis

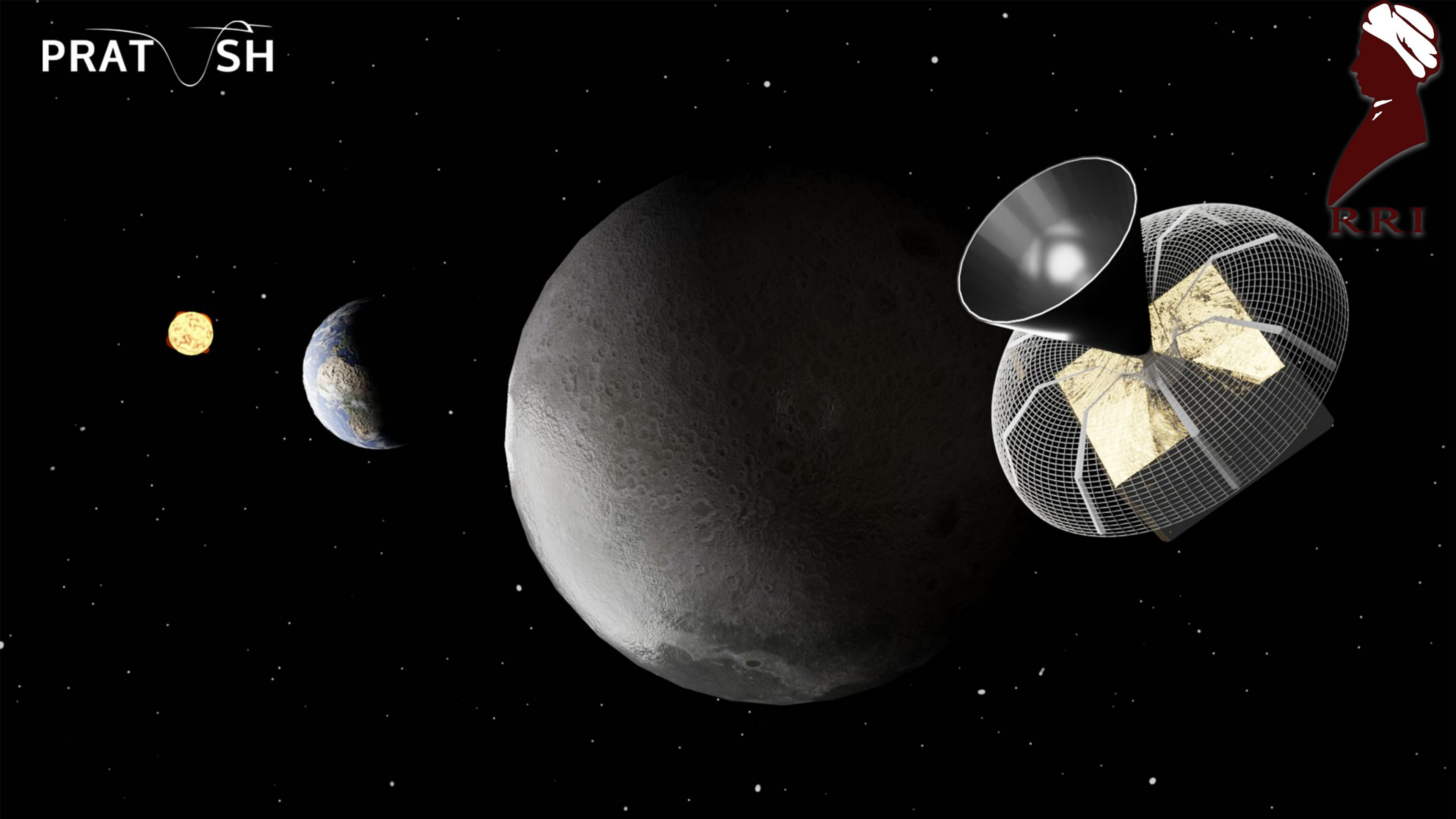



Sky Coverage: TARANG
Atacama: Ideal
TARANG: Ideal
Milky Way (|b| < 10°)
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°

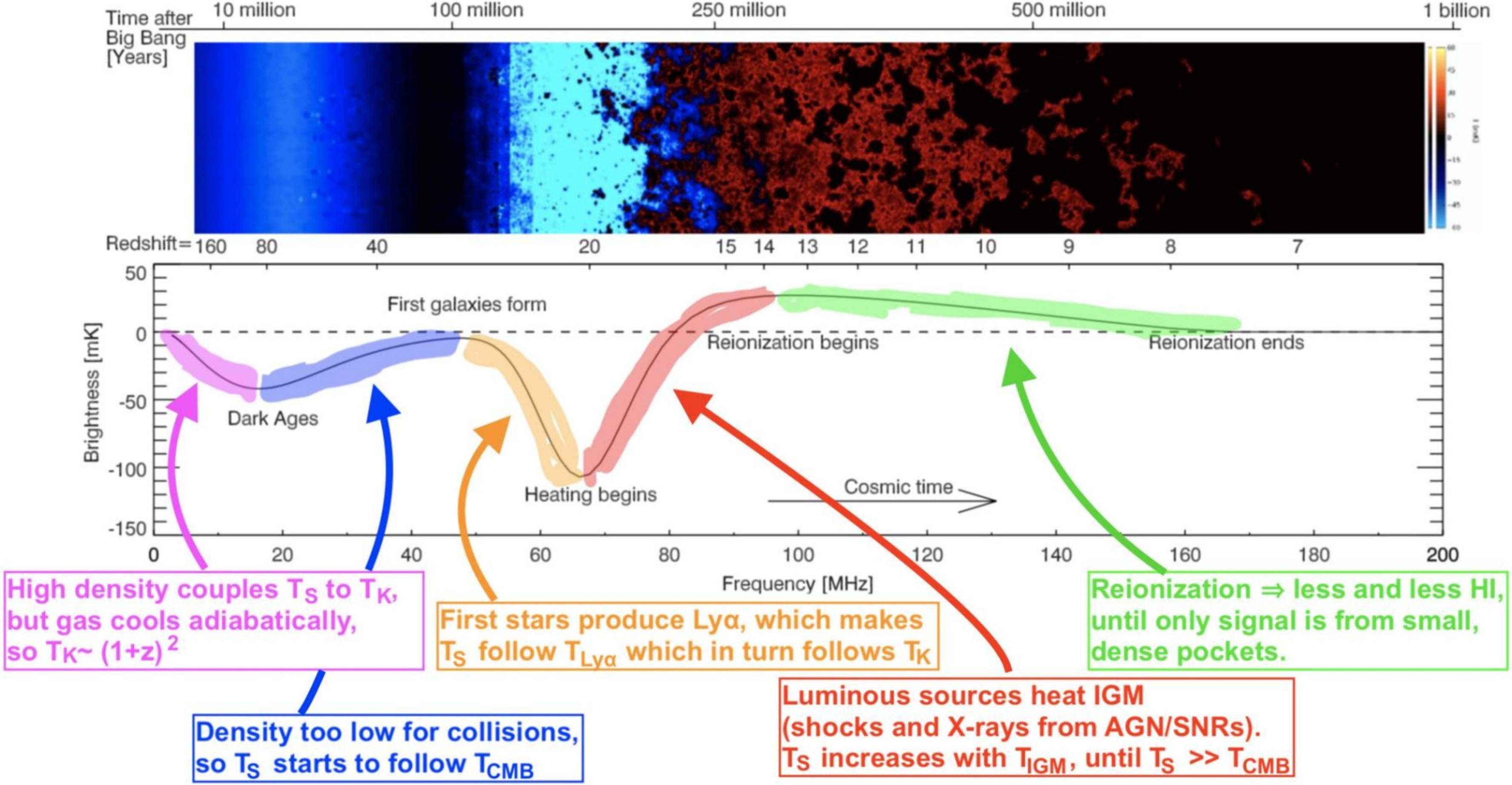

TARANG
Thermal And Relic Anisotropies from the Northern Globe
India-led CMB survey
Proposed site: Norbu La Top, Ladakh, India | 5300 m
Large Aperture Telescope (LAT)
6 m diameter
Small Aperture Telescope (SAT)
50 cm aperture
Fourier Transform Spectrometer (FTS)
Cryogenic interferometer
Scale comparison
LAT
6 m diameter
SAT
50 cm aperture
FTS
Cryogenic interferometer
Key science
Primordial B-modes
CMB Spectral Distortions (μ, y)
Foregrounds & Fundamental Physics
Artist impression

LOOKING FORWARD TO PARTICIPATION FROM THE INTERNATIONAL CMB COMMUNITY!

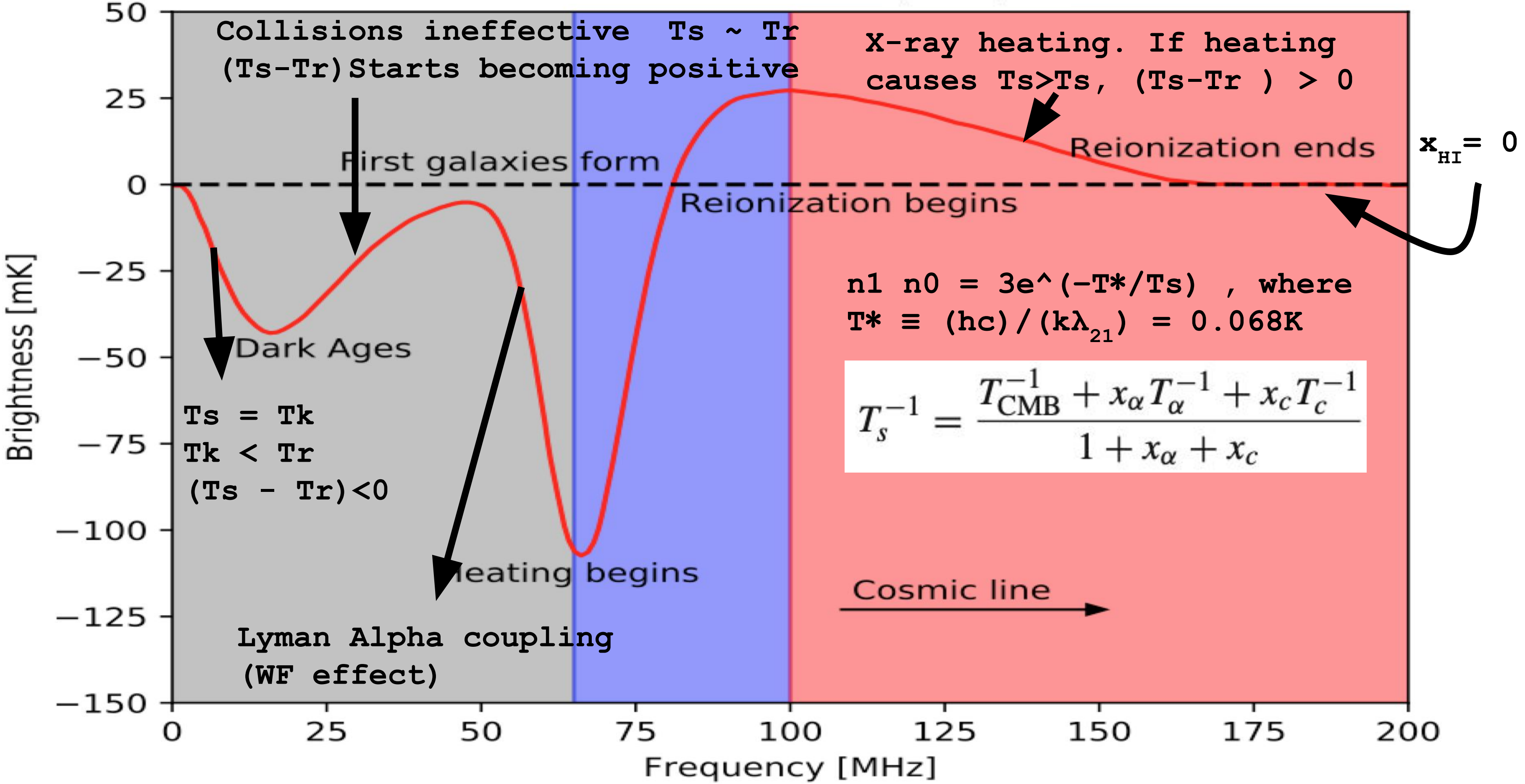
Artist impression


PRATUSH
RRI

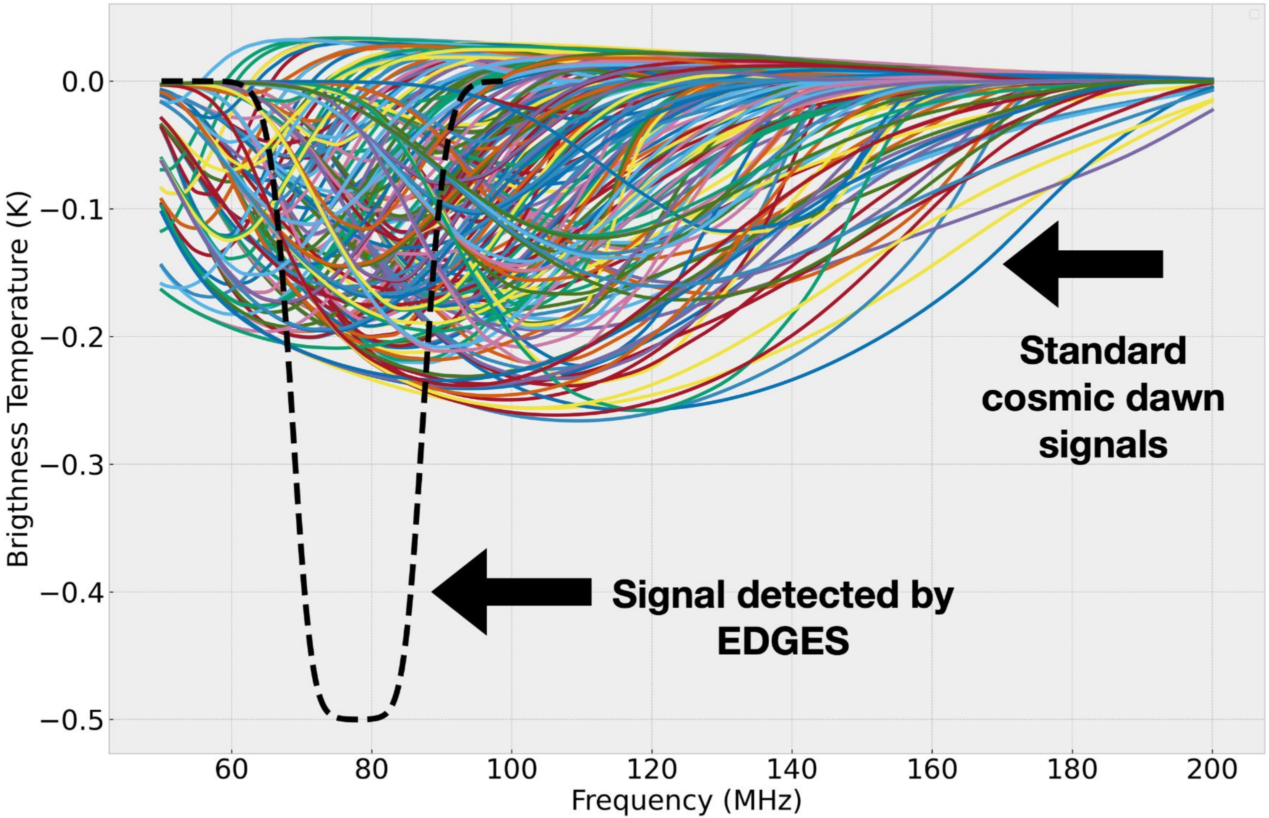
21-cm cosmology as a global radio signal



$$\delta T_b^{\mathrm{obs}}(\nu) \approx 27 x_{\mathrm{HI}} \left(\frac{\Omega_b h^2}{0.022}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{\frac{1}{2}}\left(\frac{T_s - T_R}{T_s}\right)\mathrm{mK}.$$

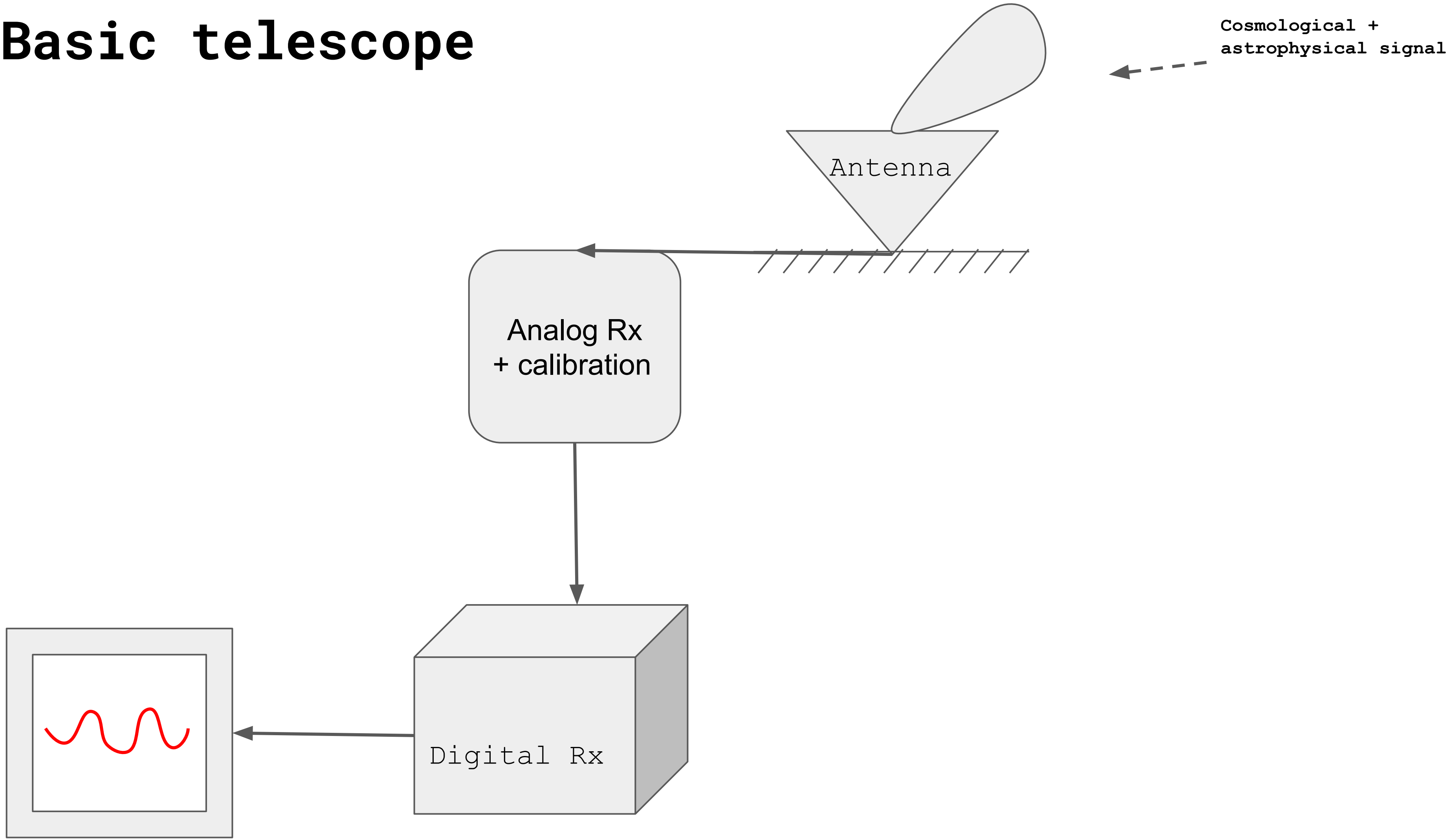


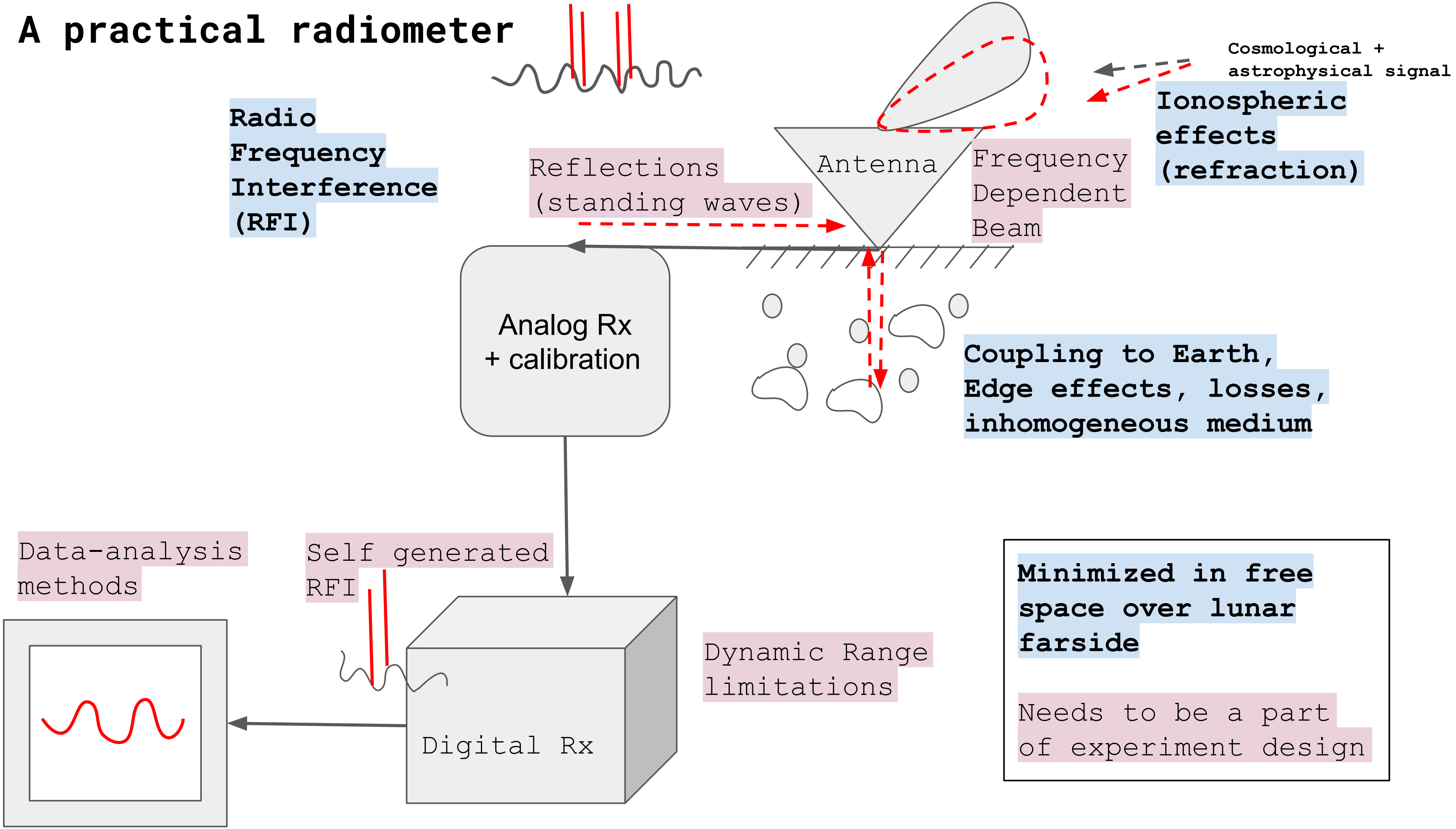
Big open question in Standard Cosmology – when, how, what nature of first stars?



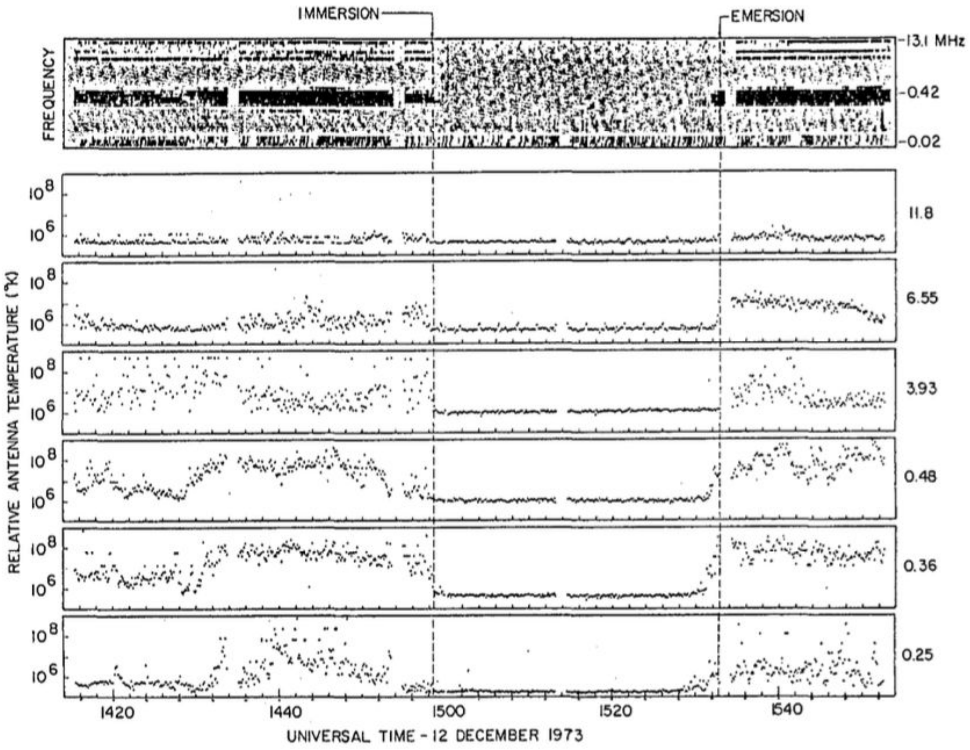
Singh,.. MSR Nature Astronomy 6.5 (2022): 607-617.

Basic telescope

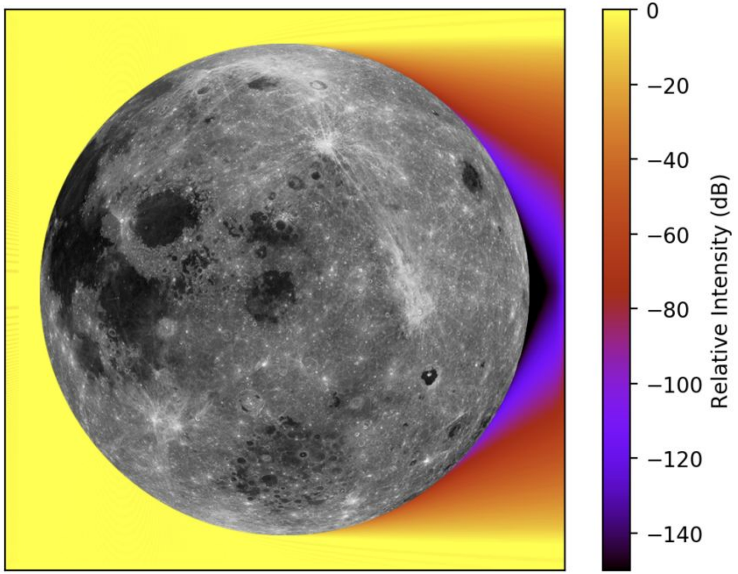



A practical radiometer
Radio Frequency Interference (RFI)
Reflections (standing waves)
Antenna
Frequency Dependent Beam
Cosmological + astrophysical signal
Ionospheric effects (refraction)
Analog Rx + calibration
Coupling to Earth, Edge effects, losses, inhomogeneous medium
Data-analysis methods
Self generated RFI
Digital Rx
Dynamic Range limitations
Minimized in free space over lunar farside
Needs to be a part of experiment design

Lunar orbit RFI measurement / simulation



Alexander, J. K, et al. *Astronomy and Astrophysics, vol. 40, no. 4, May 1975, p. 365-371.* 40 (1975): 365-371.

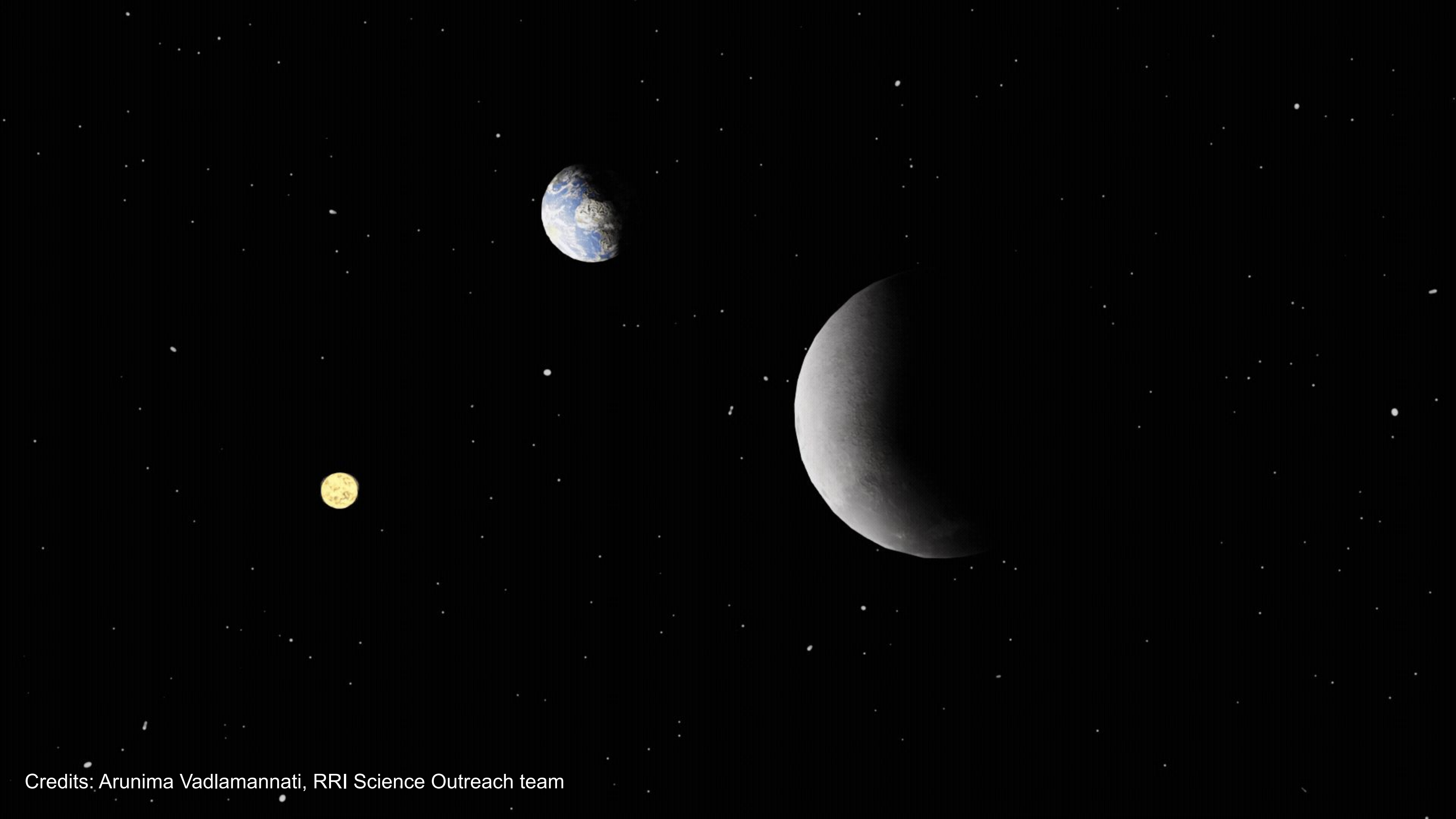


Finite Difference Time Domain (FDTD) model of radio propagation behind the moon at 30 kHz

Bassett, Neil, et al. *Advances in Space Research* 66.6 (2020): 1265-1275.

WHAT IS PRATUSH? प्रत्यूष ⇔ Dawn, Sun

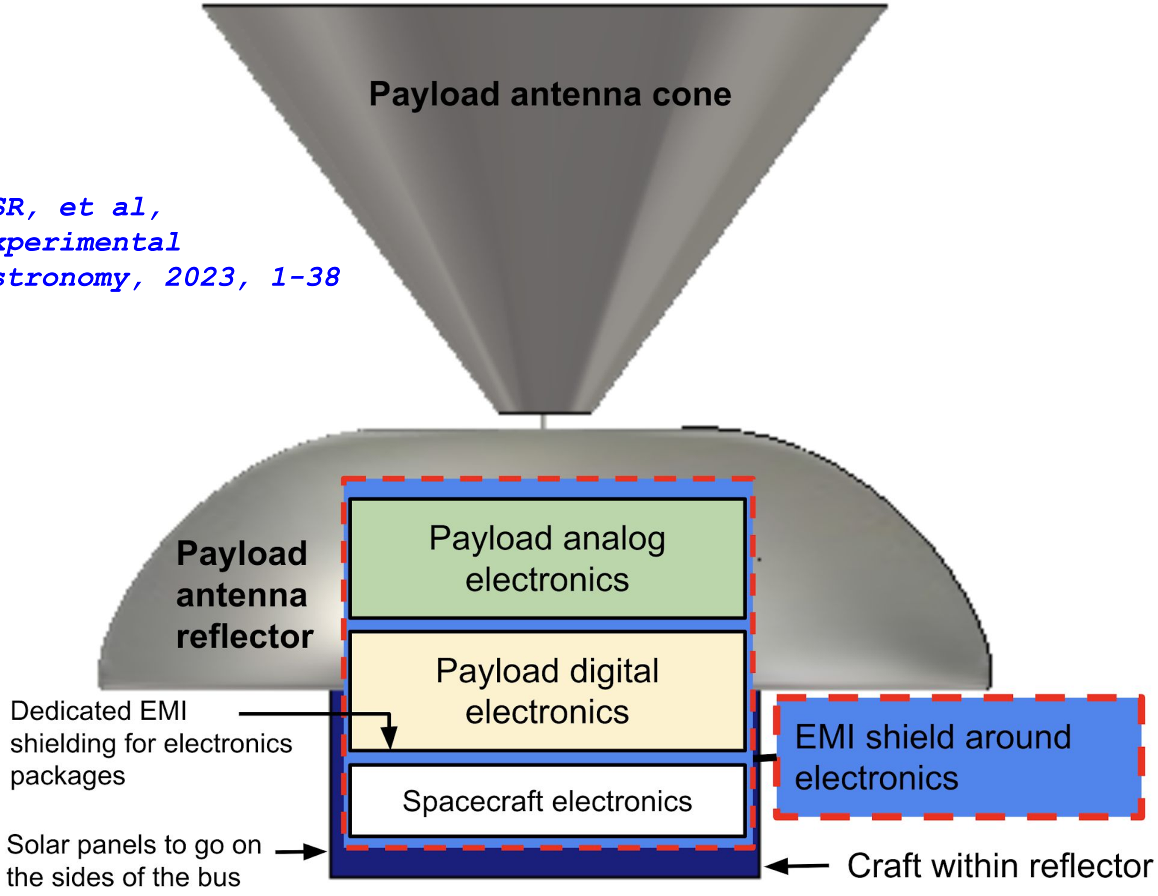
- ★ **PRATUSH: Probing ReionizATion of the Universe using Signal from Hydrogen**
  - 40 - 200 MHz (CD and EoR)
  - Baseline design 55 - 110 MHz (CD)
  - Lunar orbiter custom designed for the primary science goal of detecting the signal from CD/EoR
- ★ **Funded for pre-project studies by the Indian Space Research Organisation (ISRO) since 2019**
- ★ **Laboratory model is ready - undergoing subsystem testing. Will be followed by system level testing.**
- ★ **Expected to fly as a dedicated craft**
- ★ **Dedicated craft flying as a Lunar Orbiter**
- ★ **Precursor - PRATUSH-0 will be an RFI survey instrument**

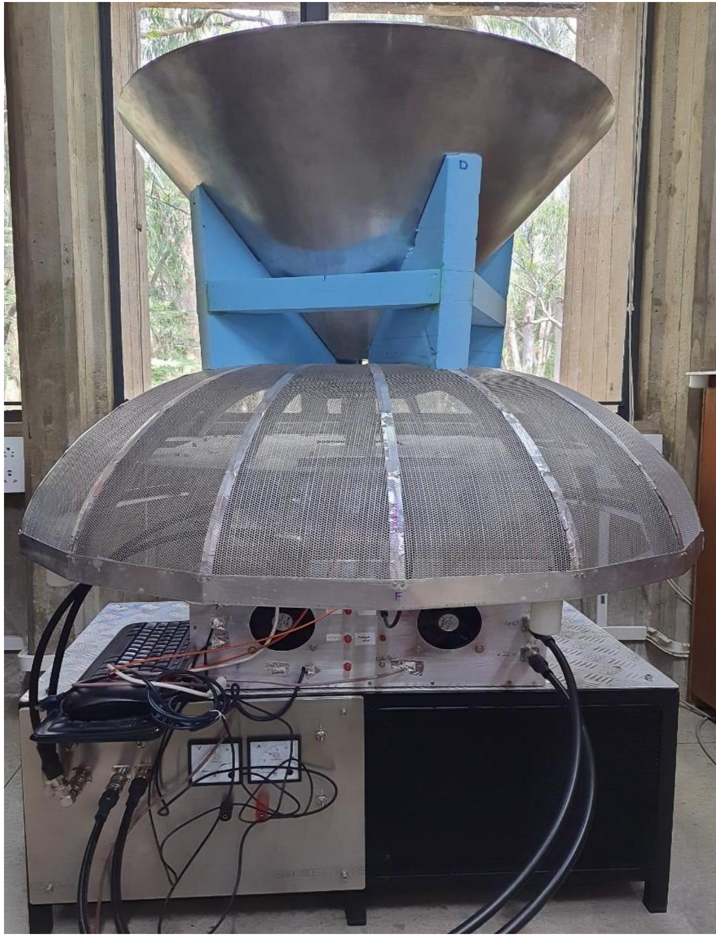


Credits: Arunima Vadlamannati, RRI Science Outreach team

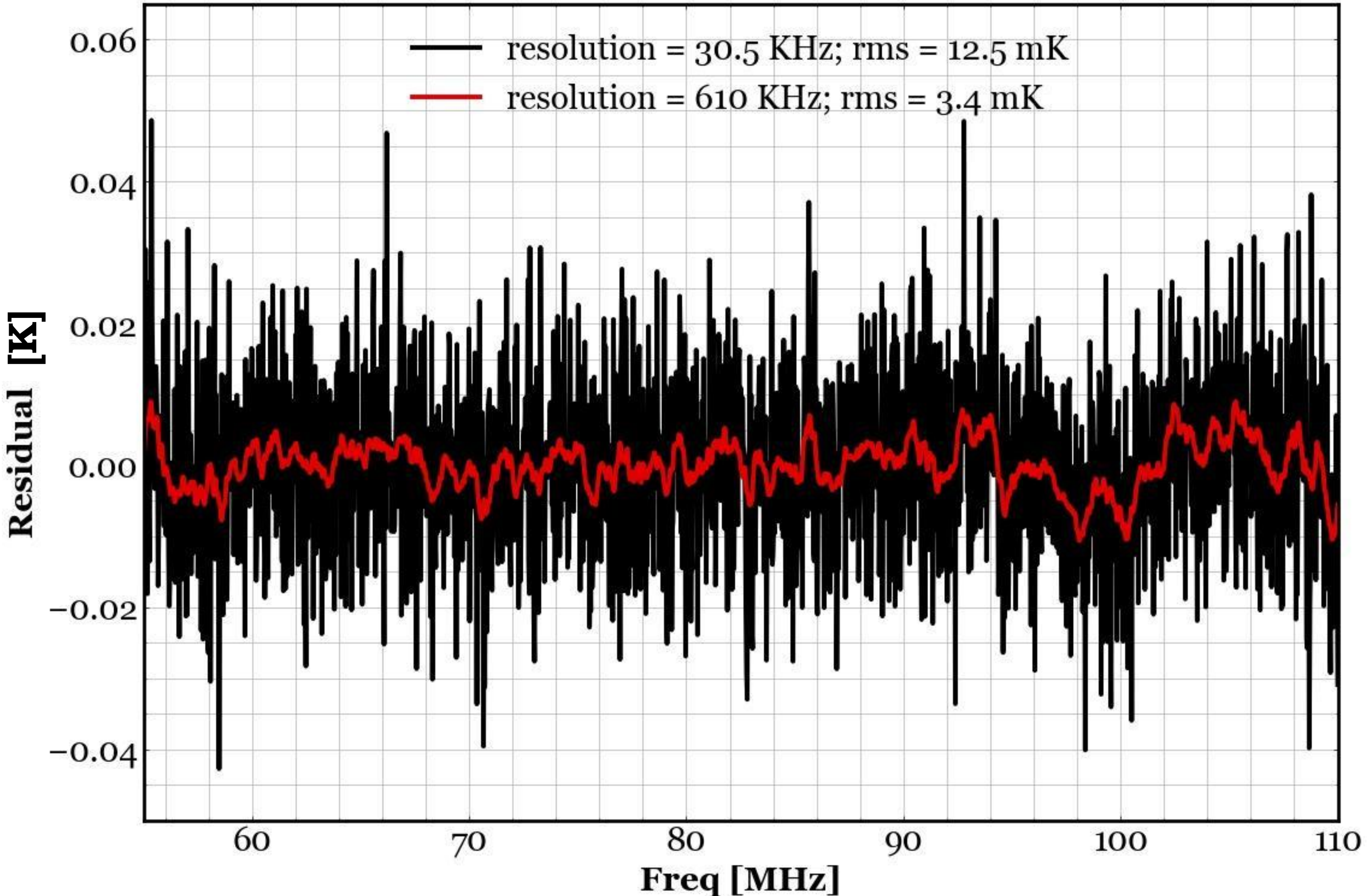
Baseline Design (55 - 110 MHz)

MSR, et al, Experimental Astronomy, 2023, 1-38



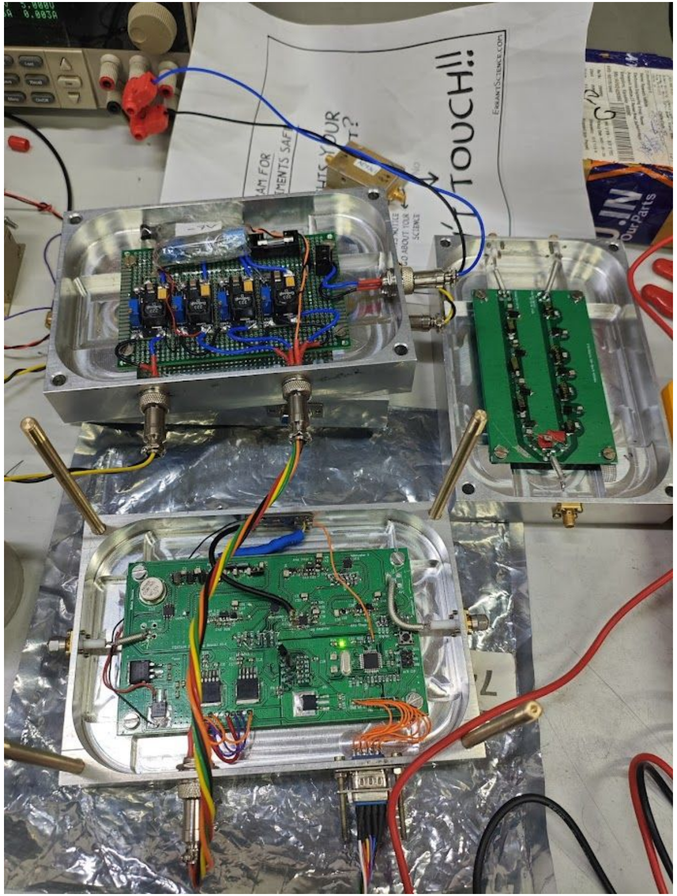


PRATUSH laboratory receiver (no antenna) has achieved $\mathcal{O}$(few mK) sensitivity in lab tests

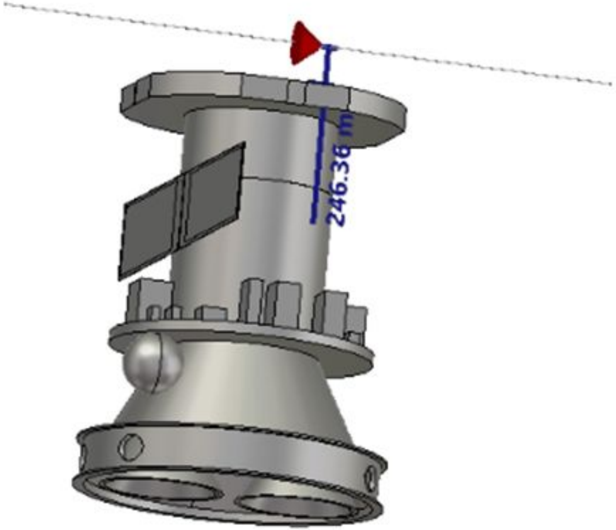


KS, Srivani, Girish BS, MSR, et al. Experimental Astronomy 60, no. 1: 1, 2025.

PRATUSH-0



Being developed as an absolute spectrum measurement and RFI survey payload for Earth / Moon



Conclusion

- APSERa : Signals from the first atoms in the Universe – 1 part per billion detection – uses 2-6 GHz window maximising sensitivity from the ground, overlap with ARCADE-2 lowest frequency for excess background studies

- PRATUSH : Signals from the first stars and galaxies in the Universe 1 part per million – operates over 55-110 MHz, and will be a lunar orbiter

- TARANG - ground based CMB observatory in India – in proposal stage, international collaboration welcome!

It's been a long time since FIRAS! The time is right for lots of exciting science from CMB spectral distortions and adjacent areas of spectrum measurement!

THANK YOU