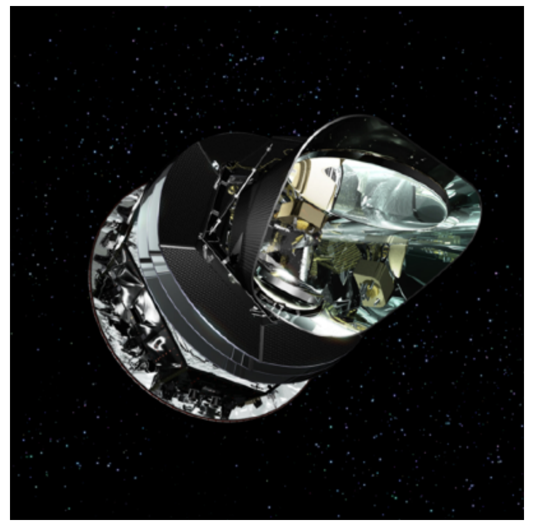
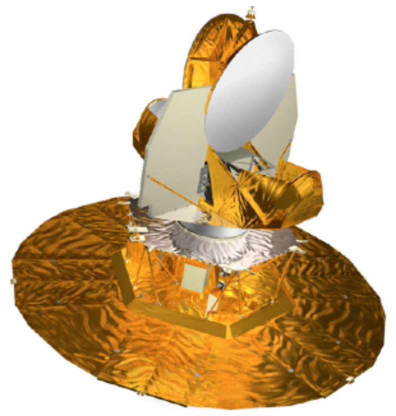
# Machine Learning the Infant Universe

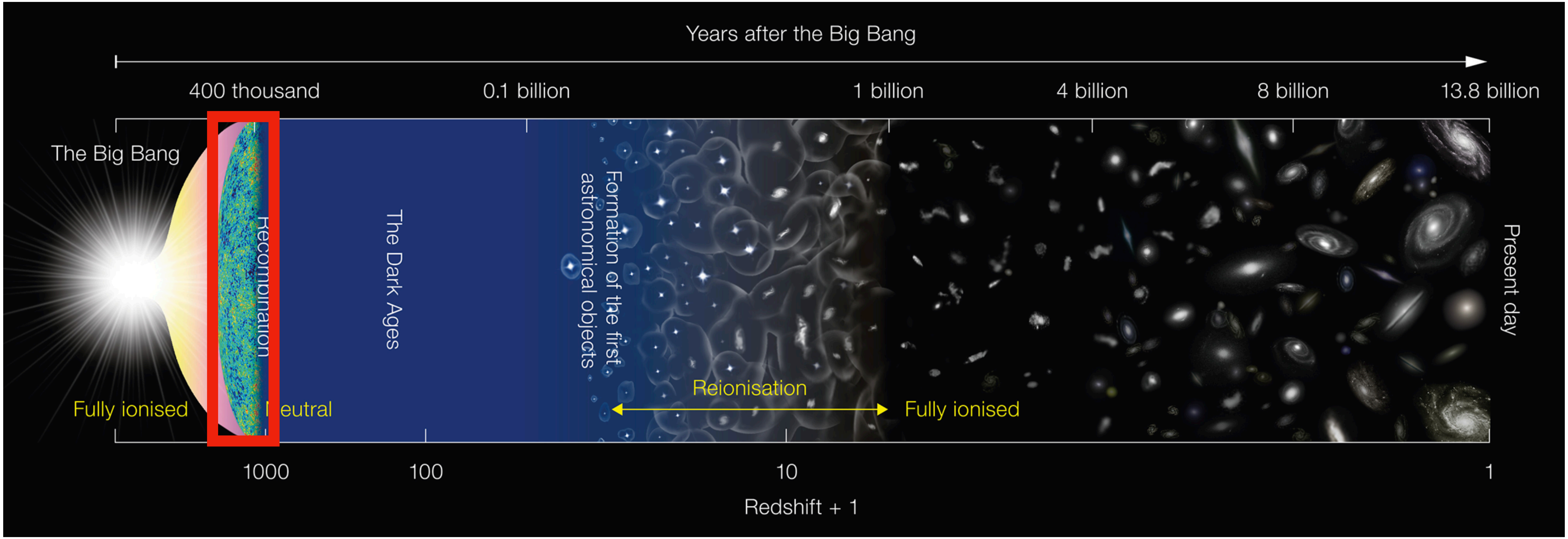
Harry T. J. Bevins
Kavli Fellow

# The Infant Universe and 21-cm Cosmology

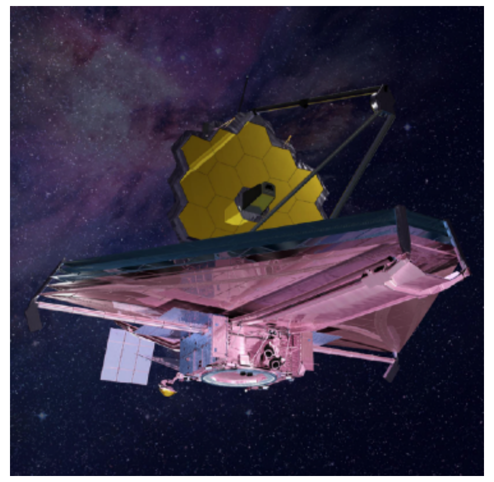
# A brief history of the universe

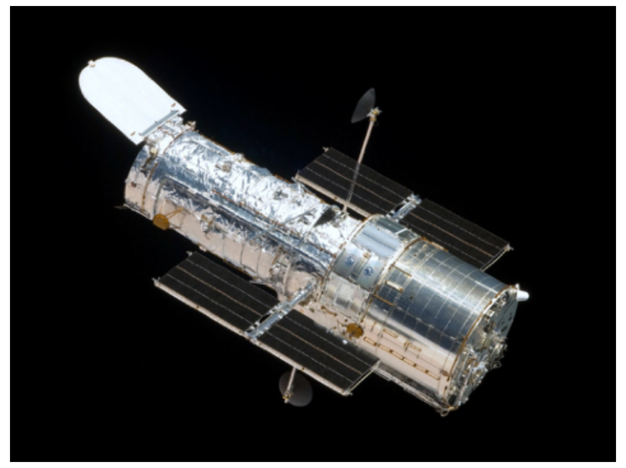


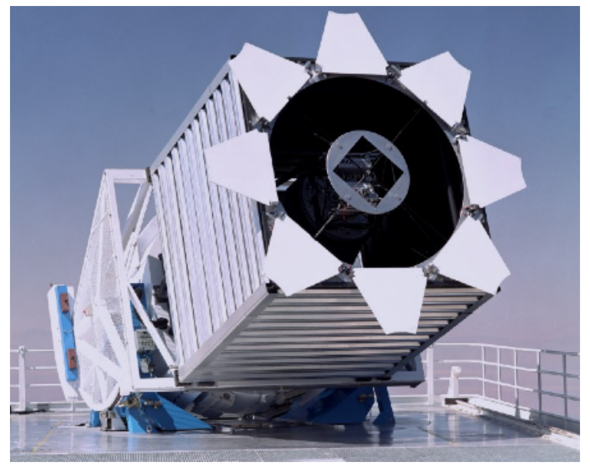


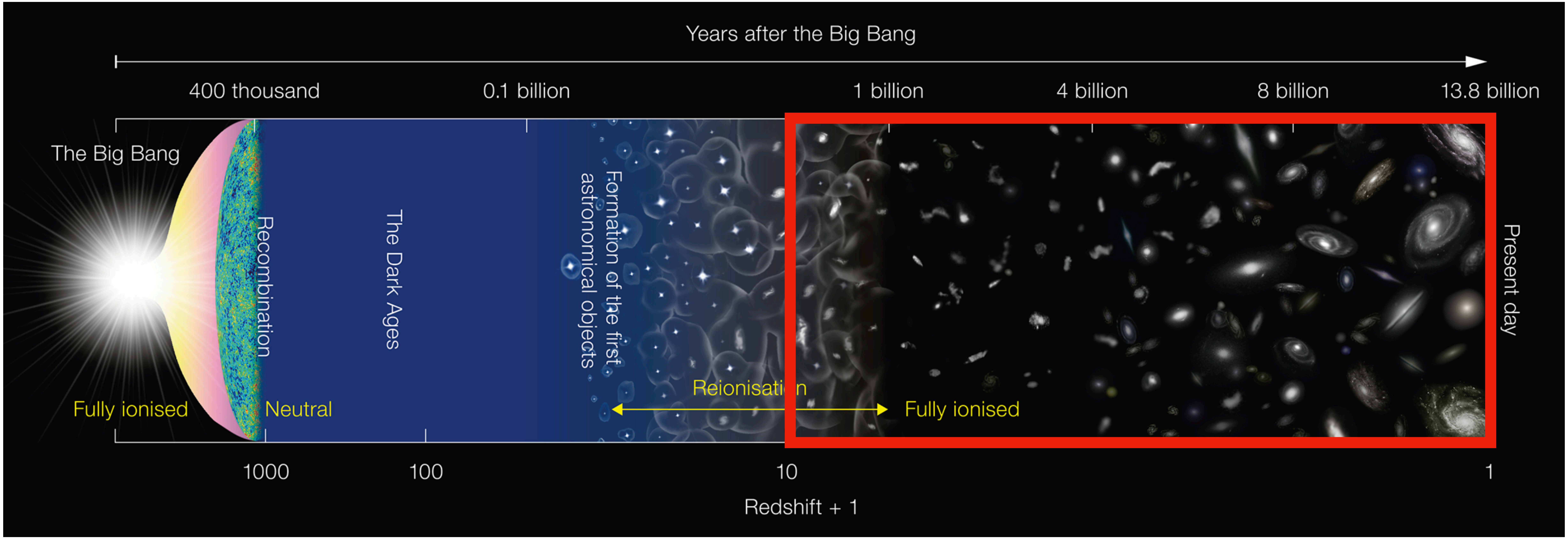


# A brief history of the universe





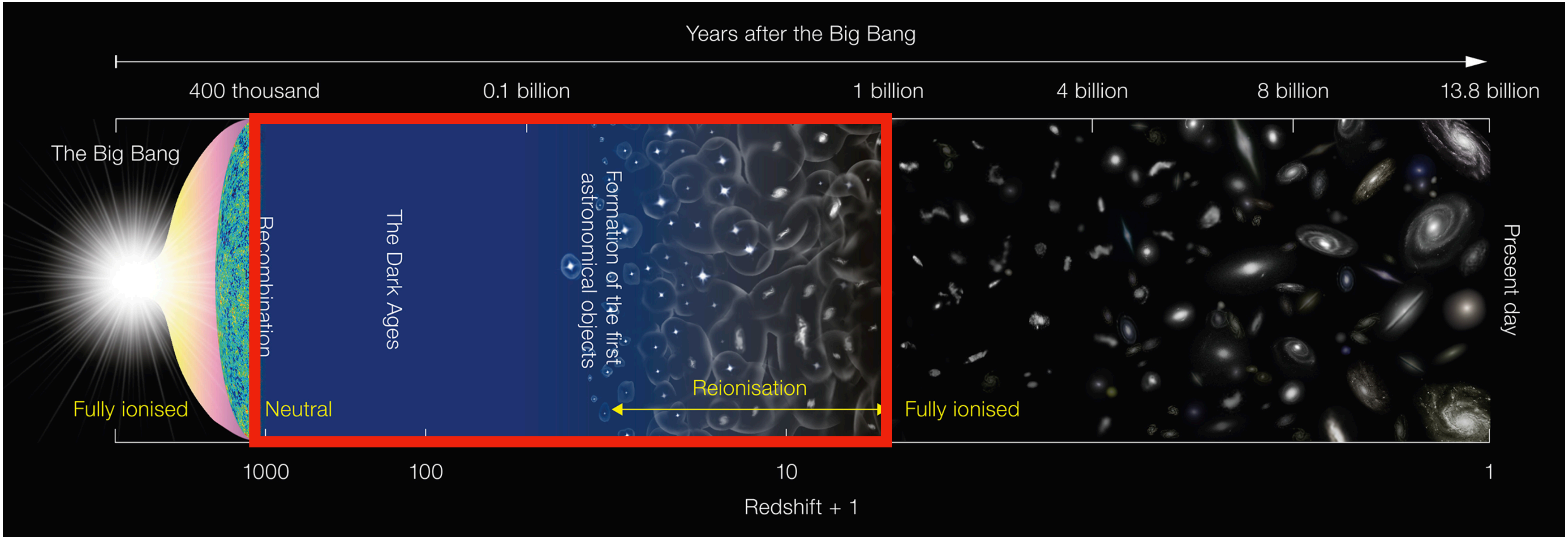




# A brief history of the universe





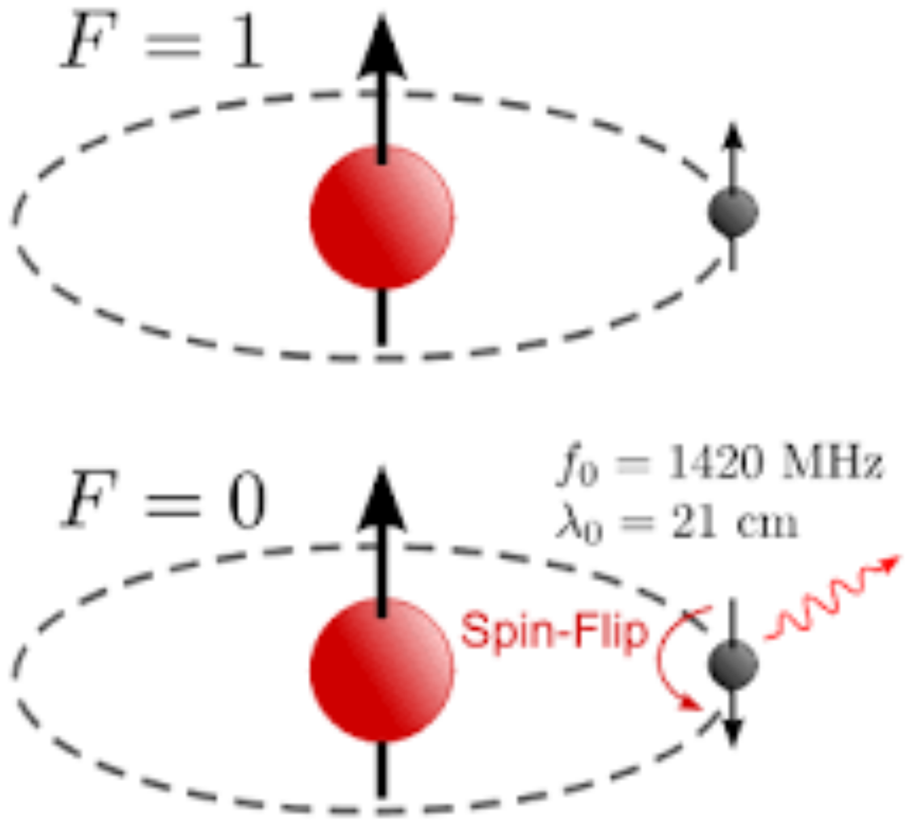


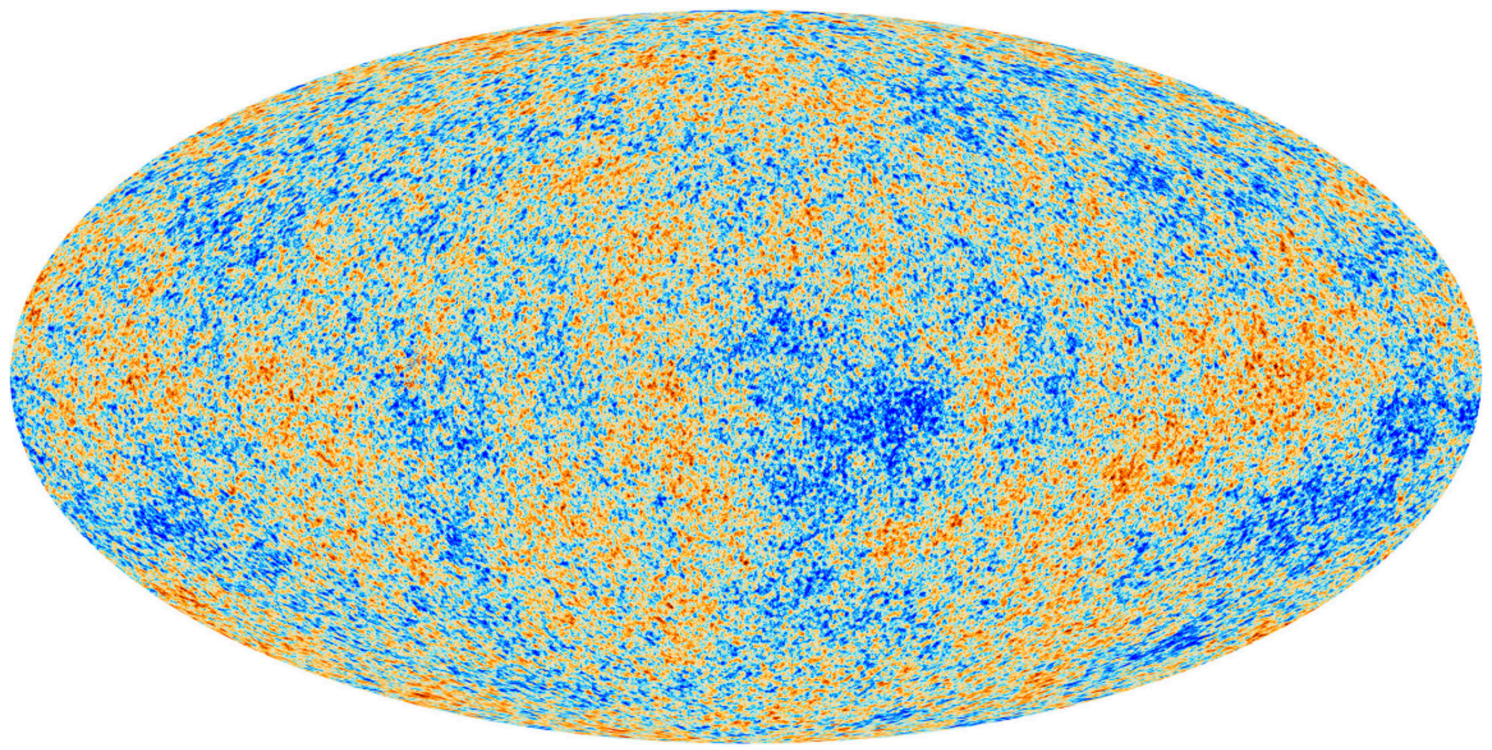
# 21-cm Cosmology

- Spin-flip transition in neutral hydrogen
- Define the spin temperature $T_s$
- Measure relative to the radio background $T_{\text{CMB}}$

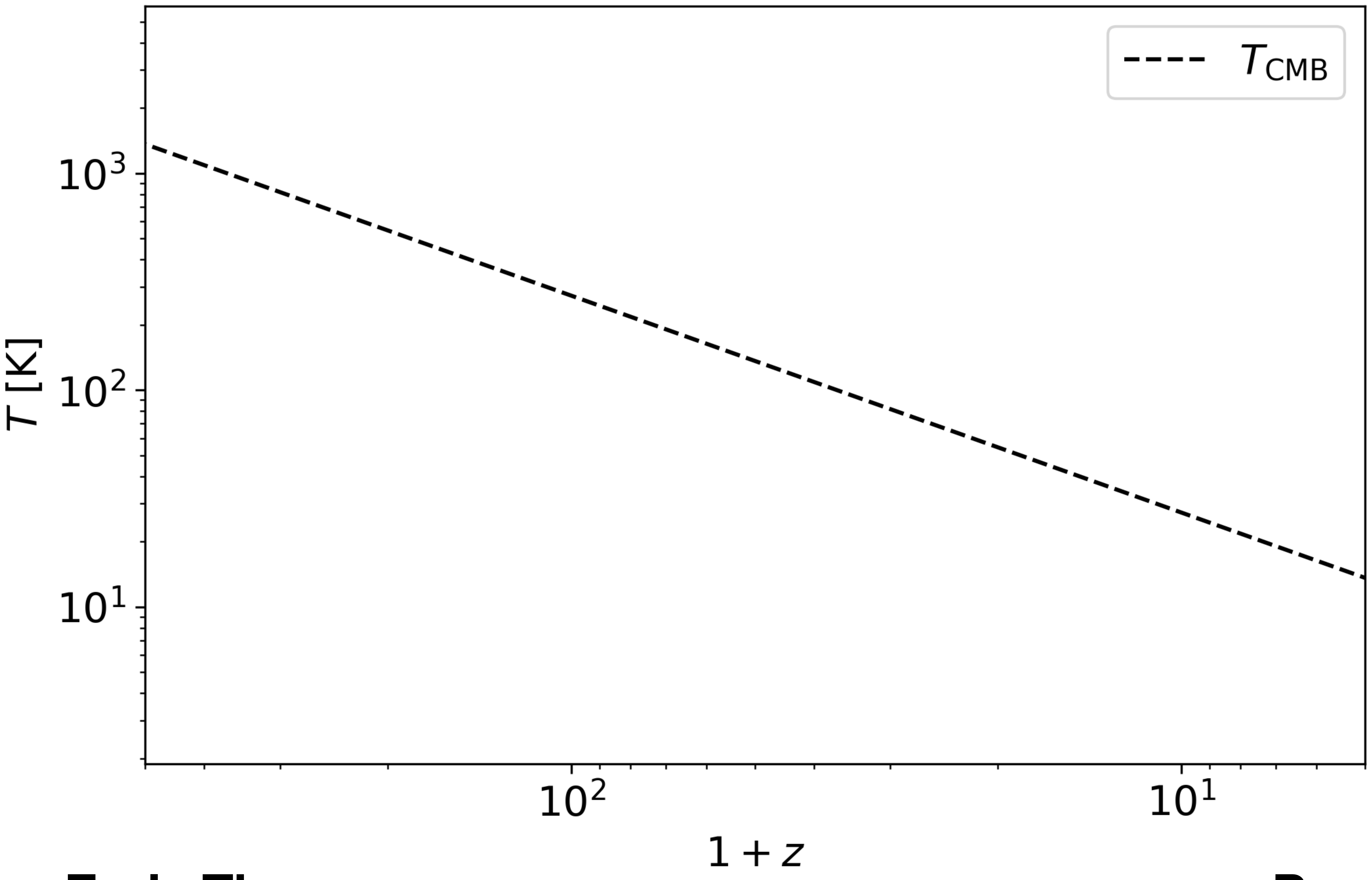
$$T_{21} = \frac{T_s - T_{\text{CMB}}}{1+z}\left(1 - e^{-\tau_{21}}\right)$$

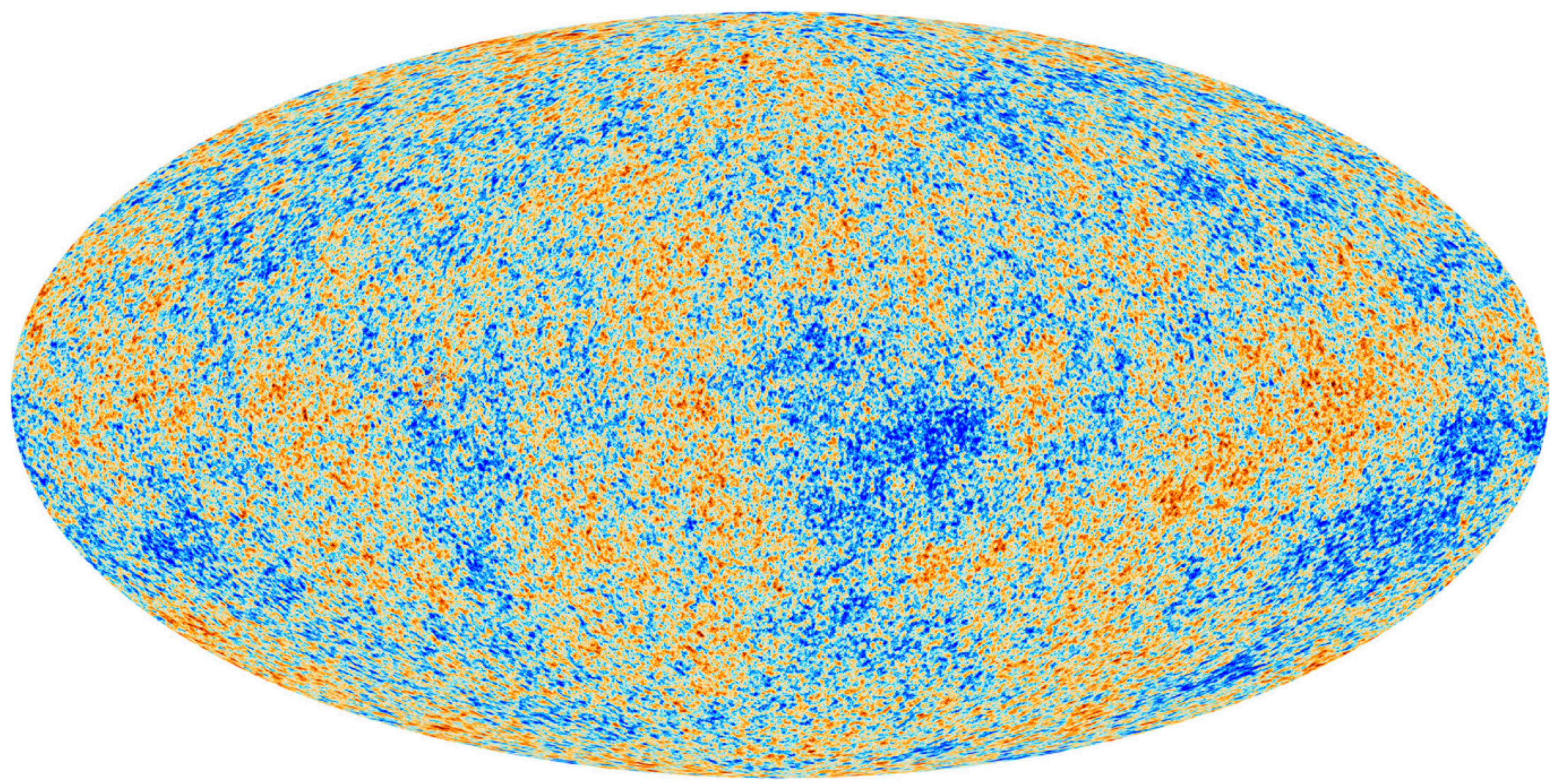
- To understand the importance of the spin temperature we look at the thermal history of the universe

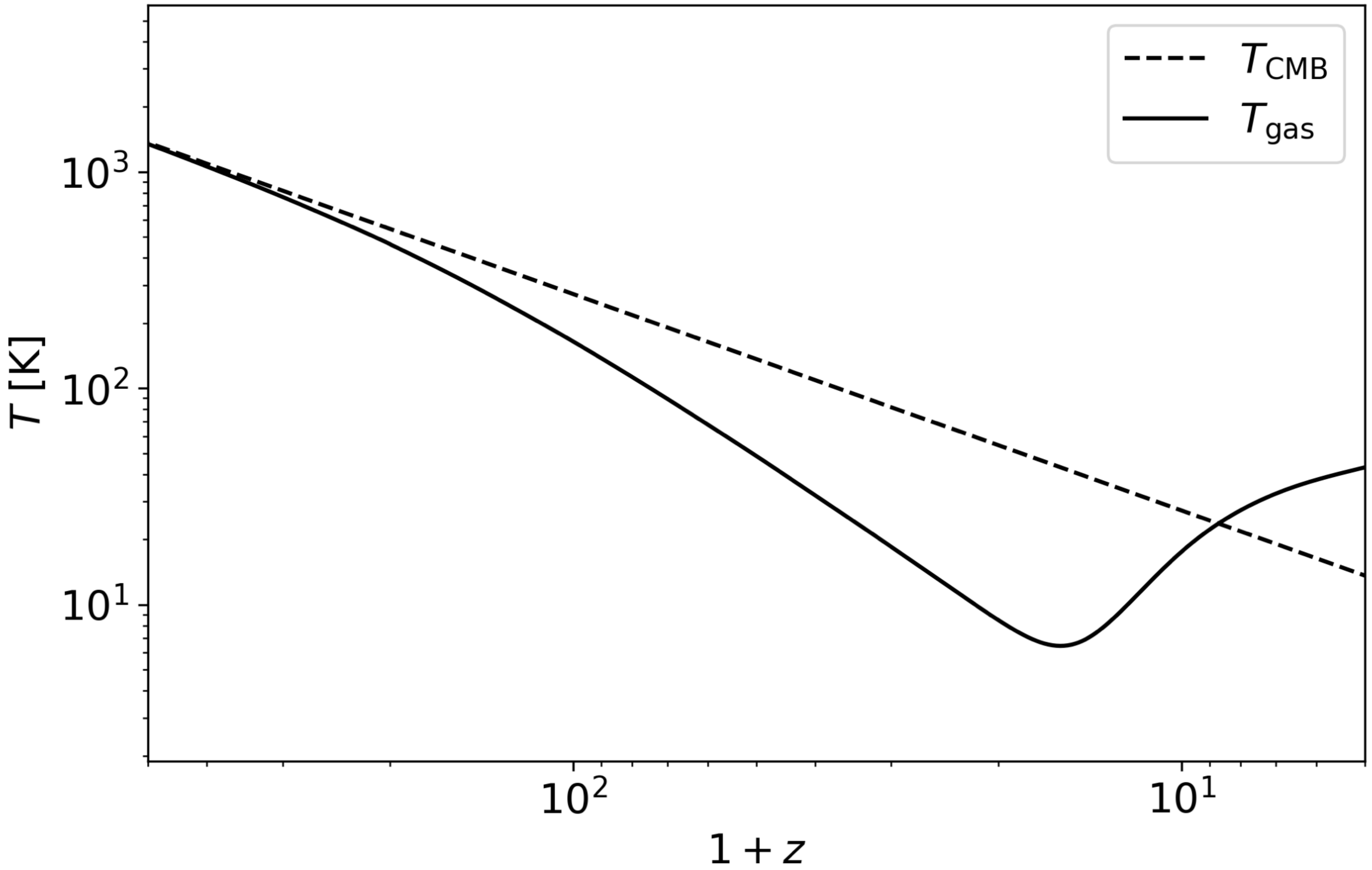
# 21-cm Cosmology



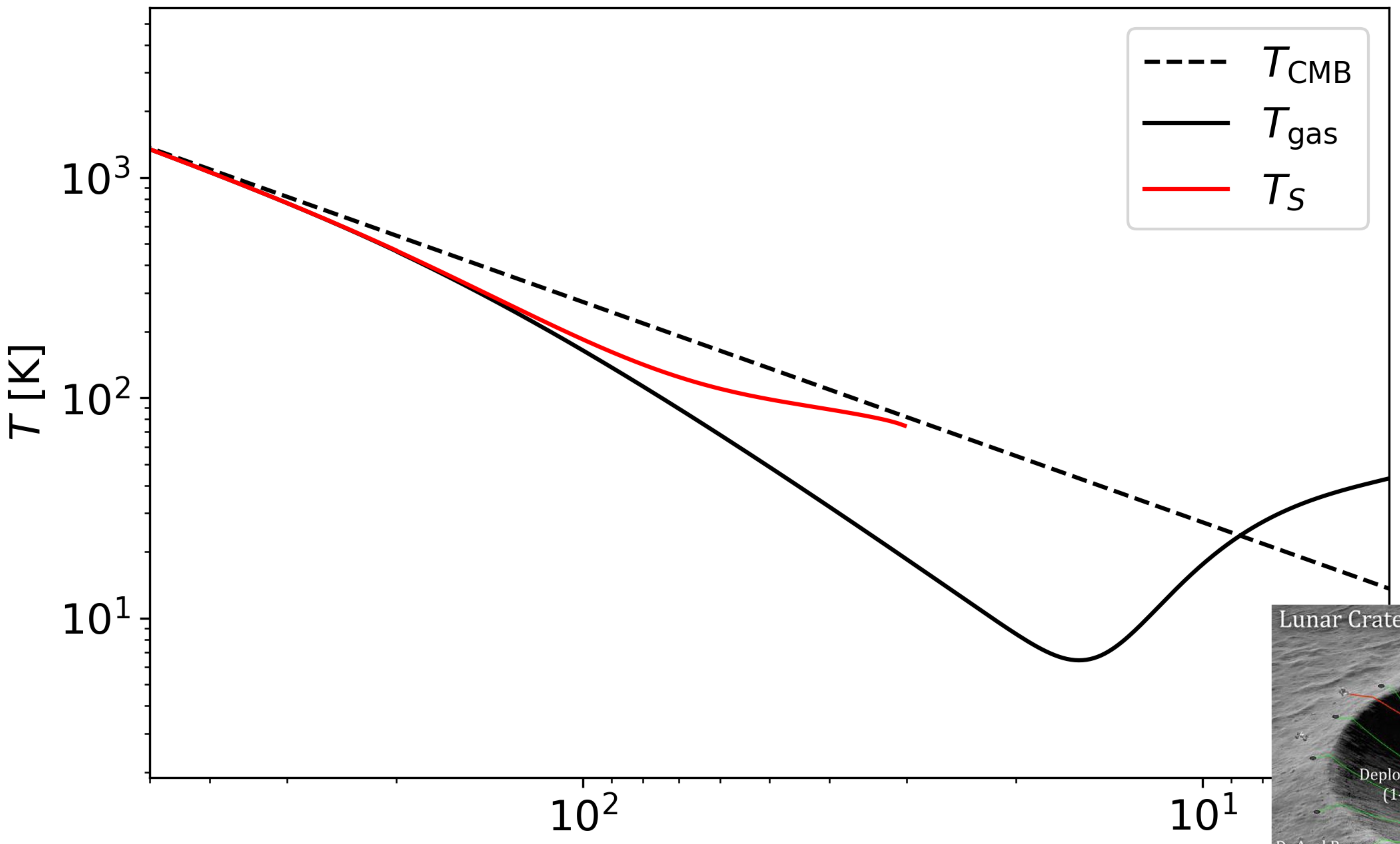
**Early Times** **Present**

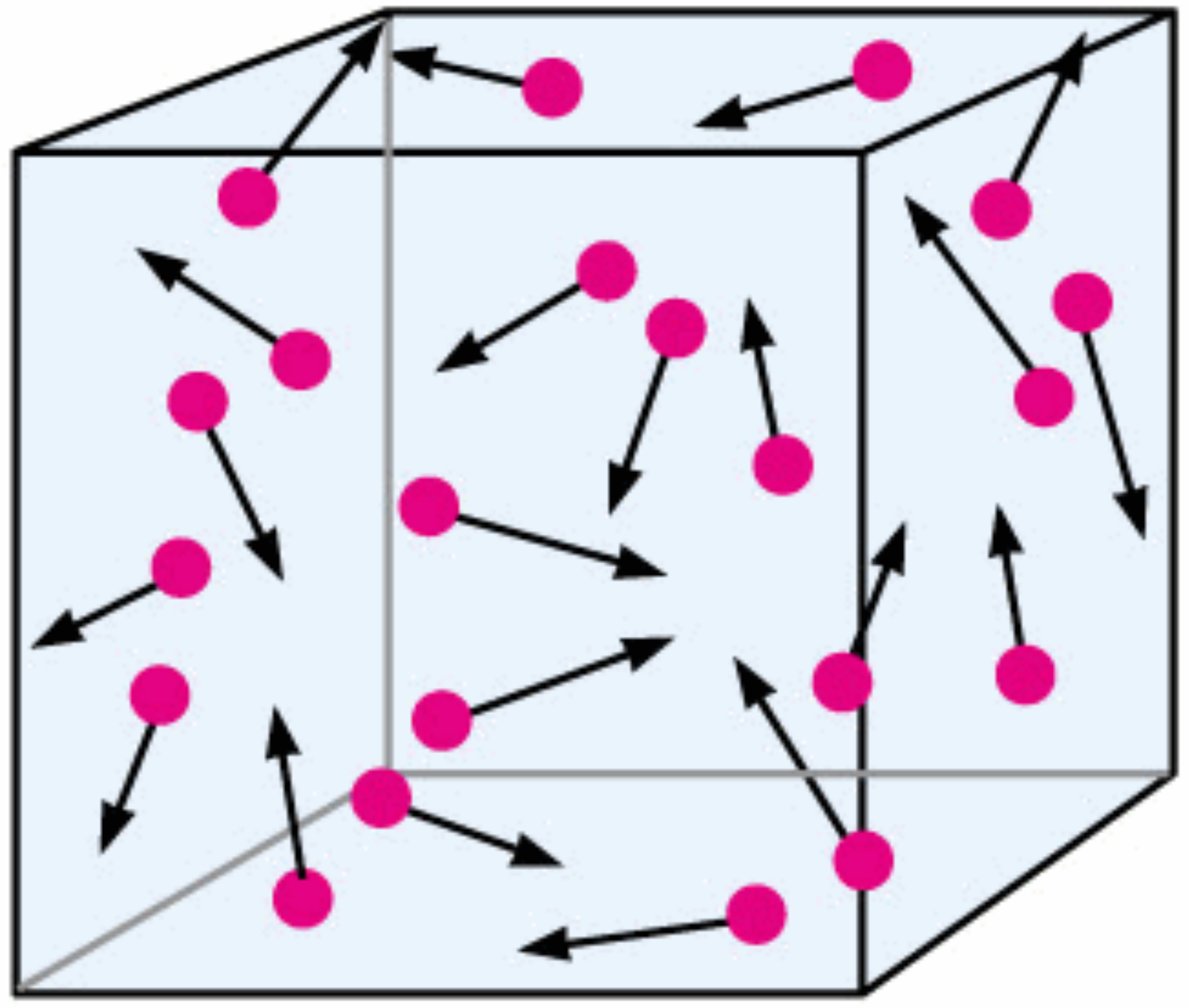
# 21-cm Cosmology



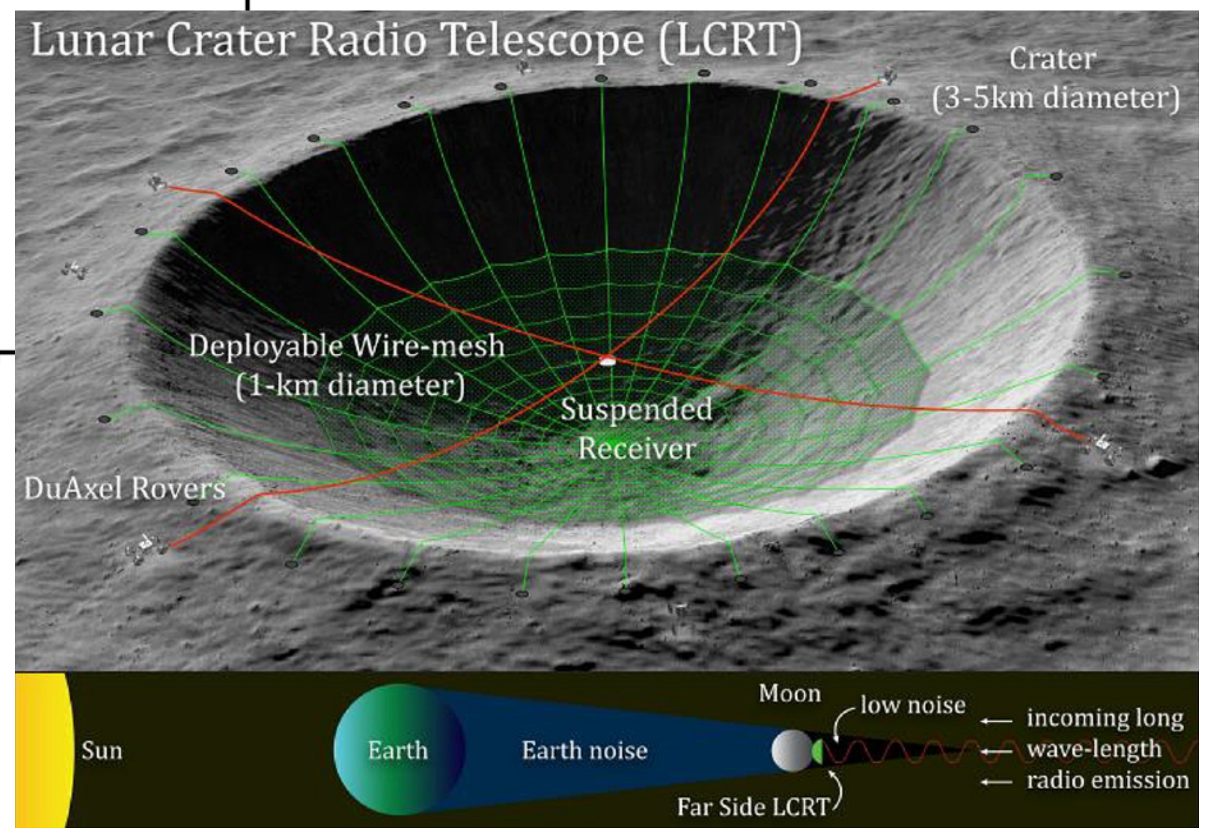

**Early Times** **Present**

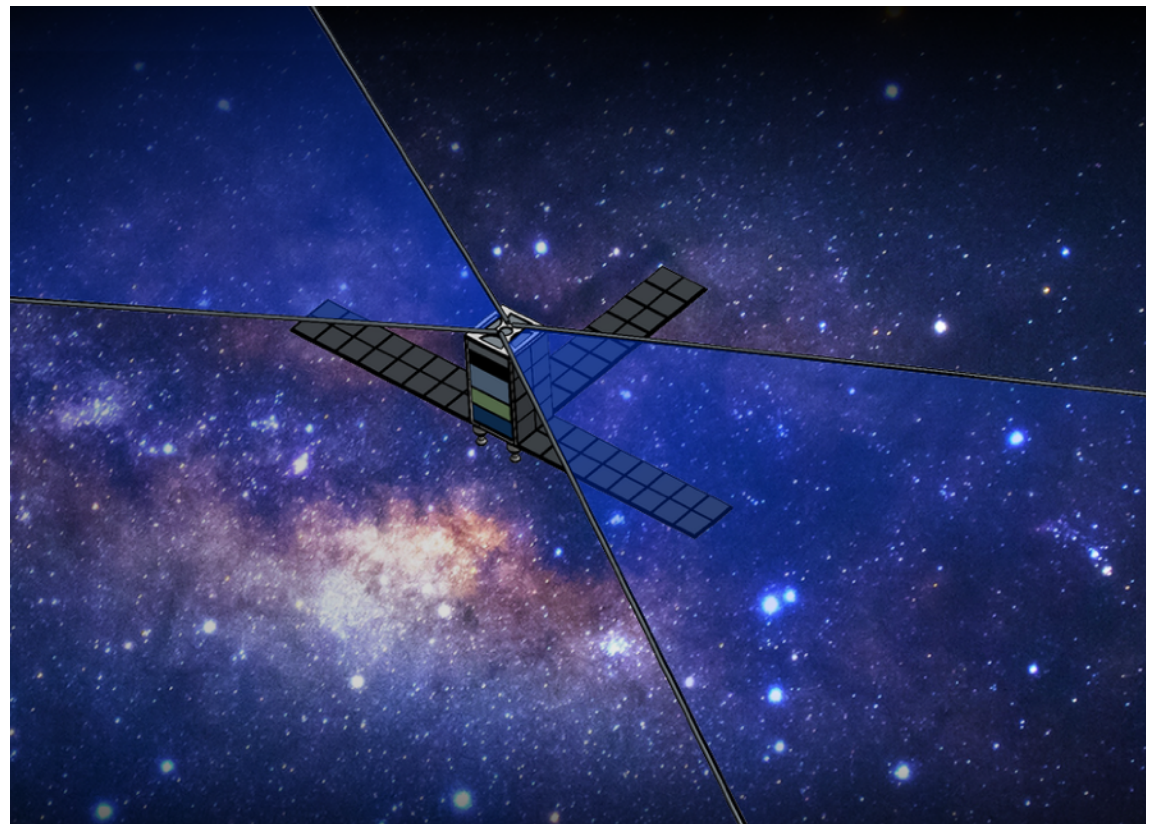
# Dark Ages ($z \lesssim 30; t \lesssim 0.5$ Gyr)



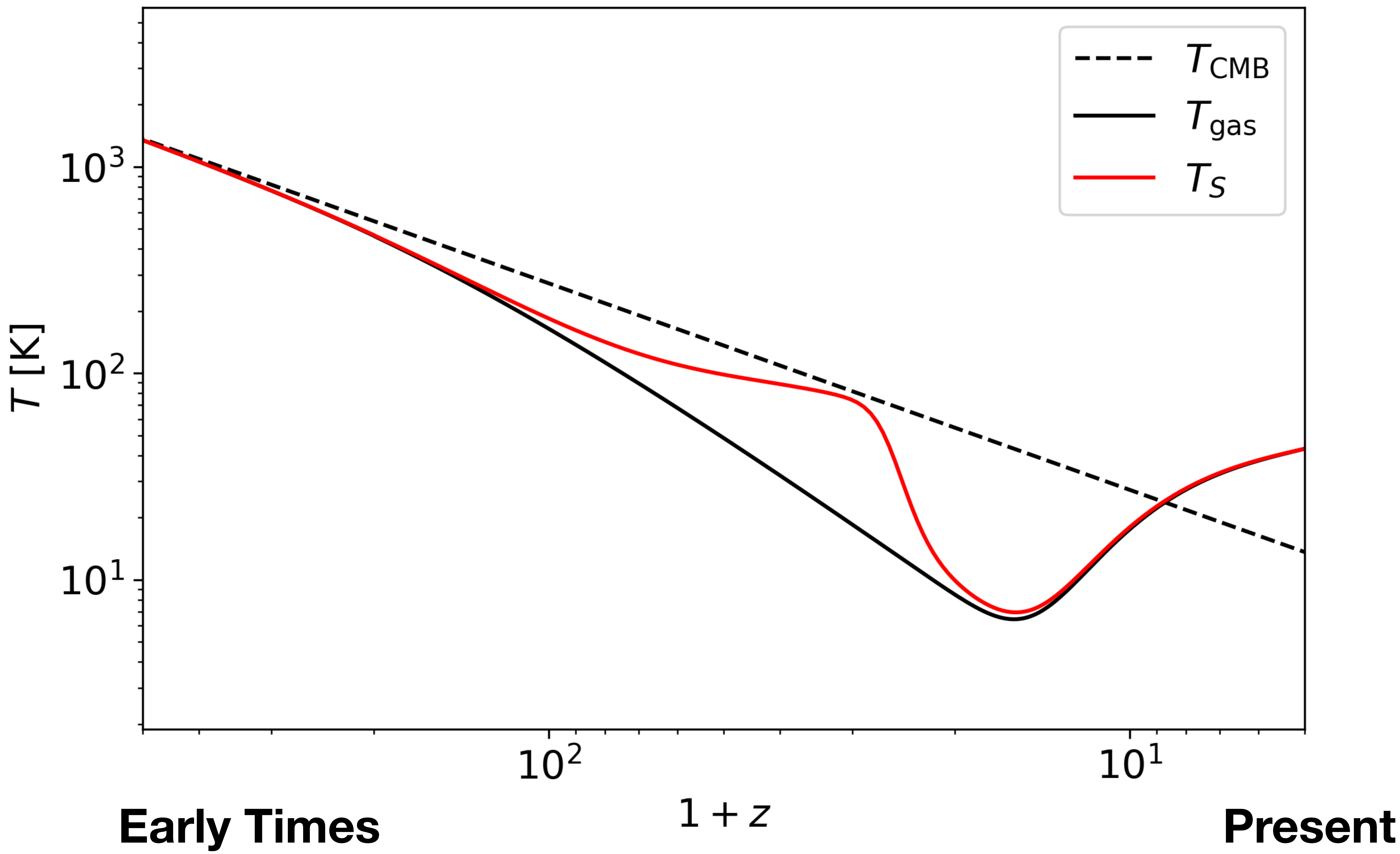
**Early Times**

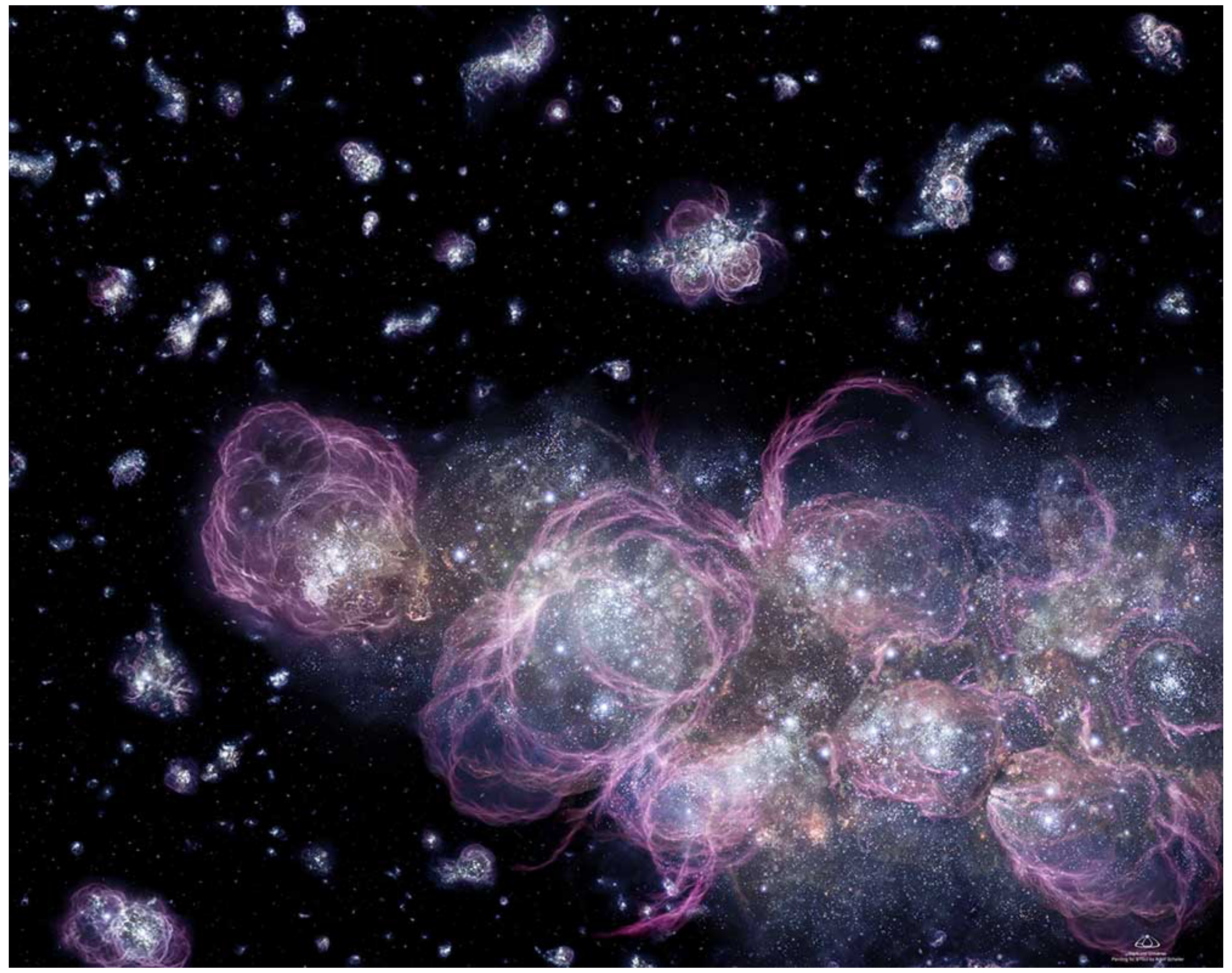


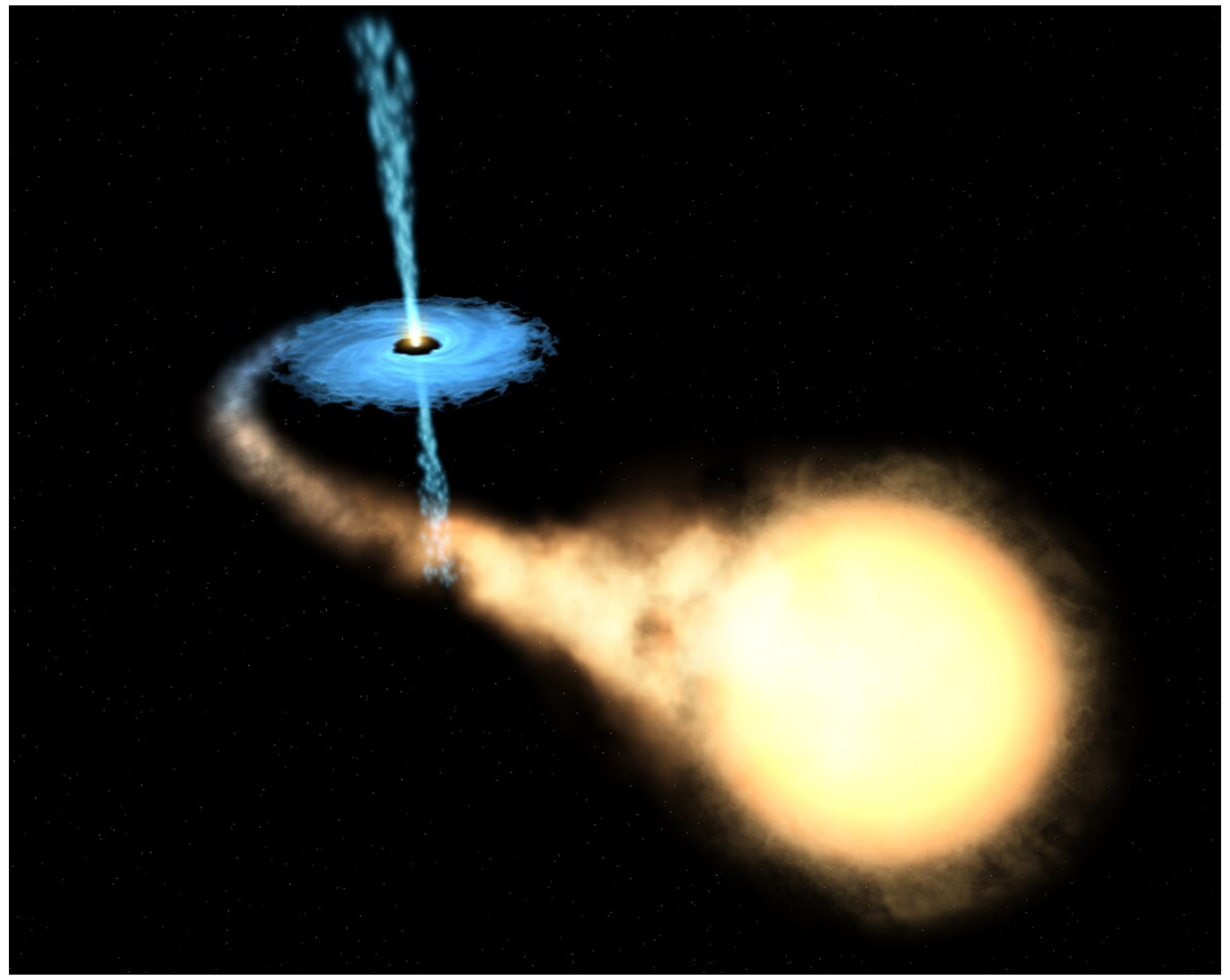



# Cosmic Dawn and Reionisation

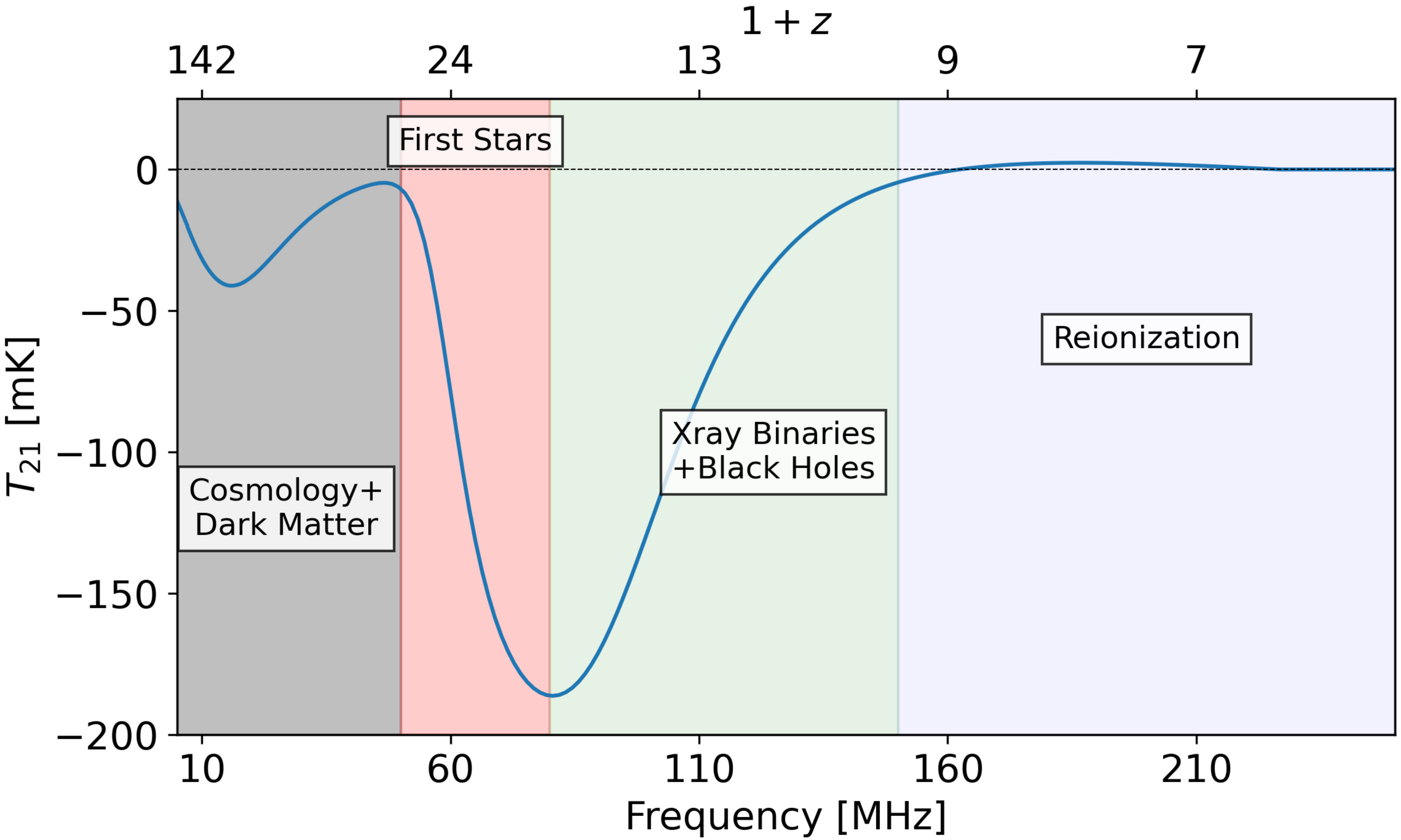
$(30 \lesssim z \lesssim 5; t = 0.5 - 12.5 \text{ Gyr})$

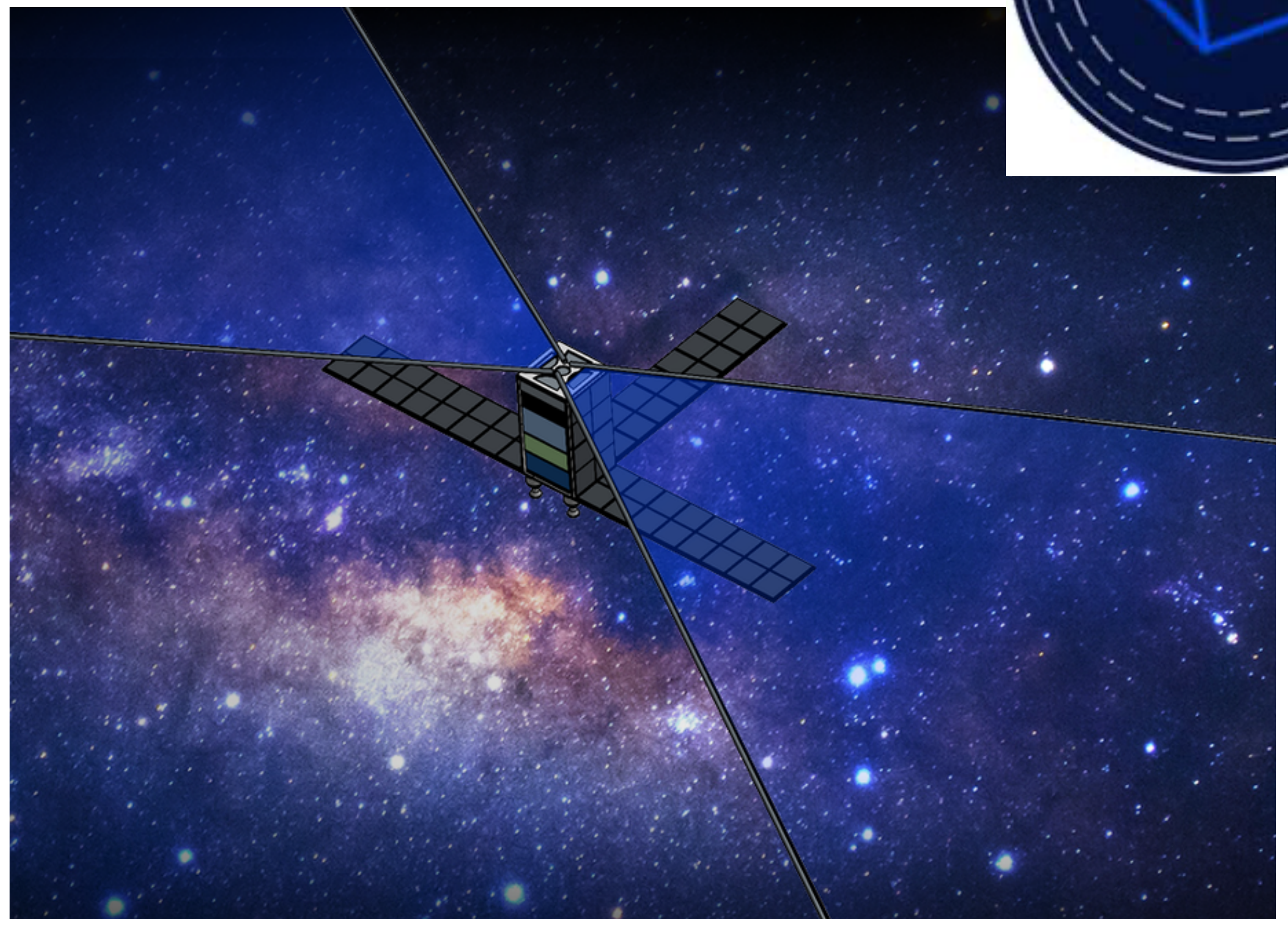


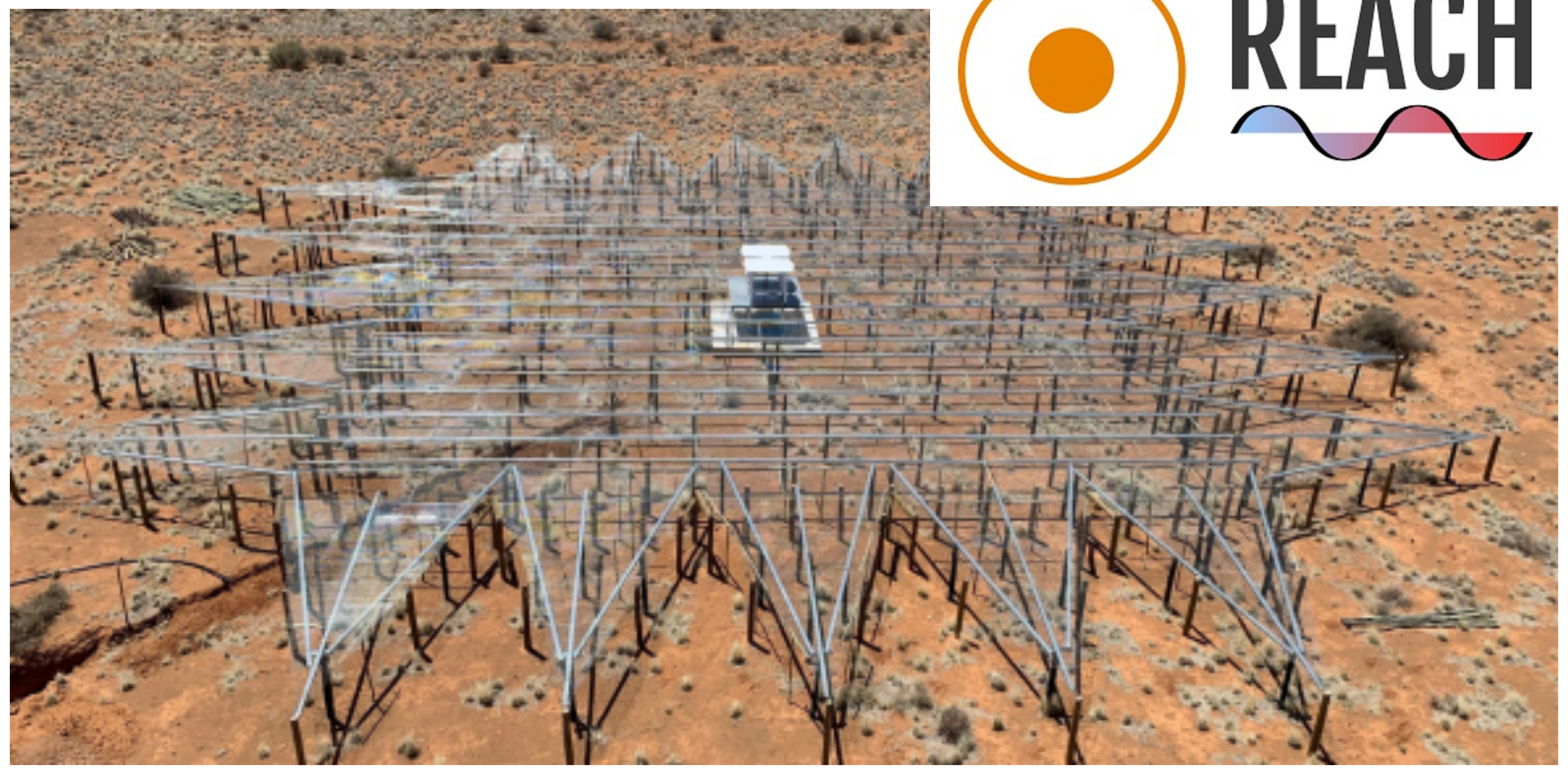





# Sky Averaged 21-cm Signal

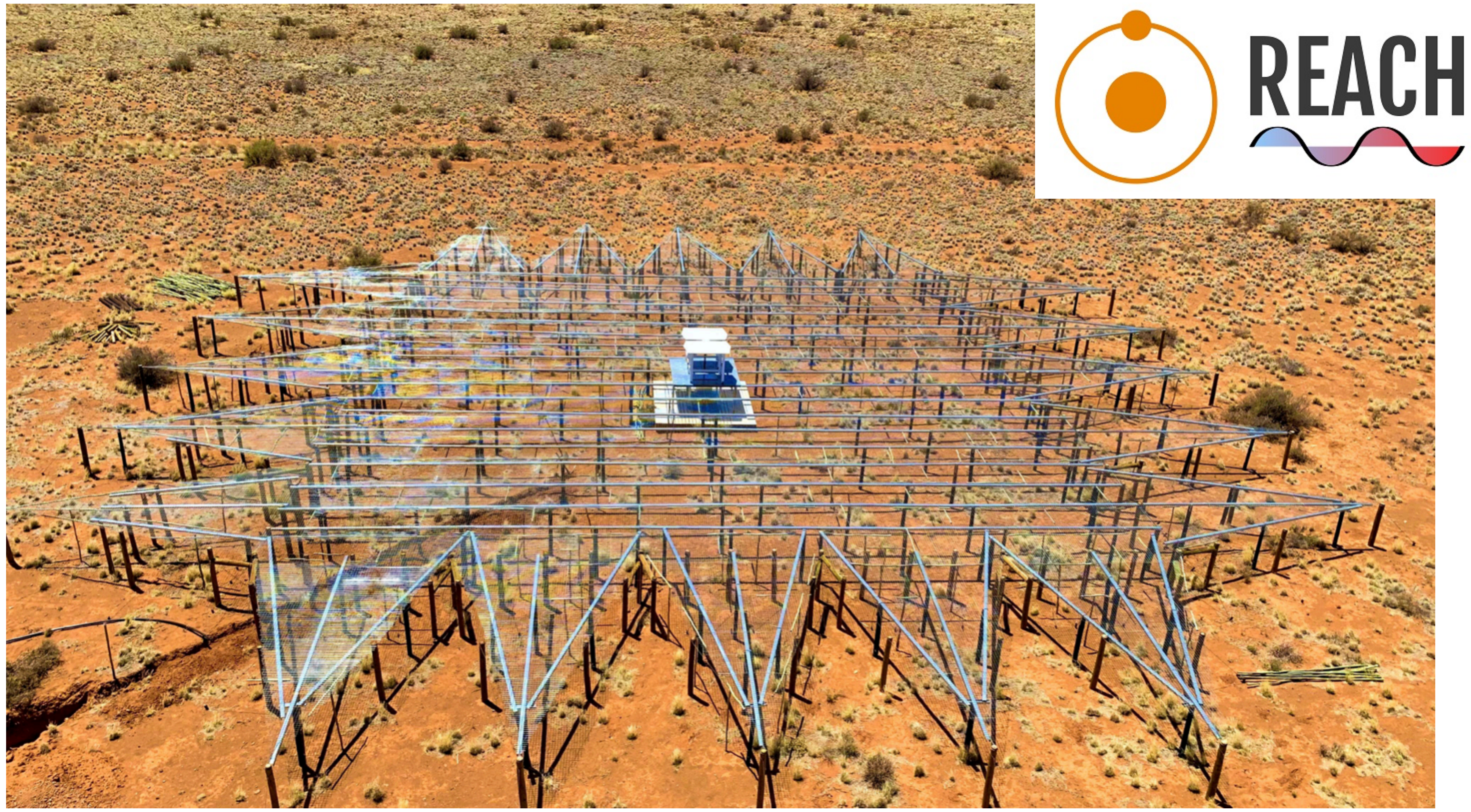




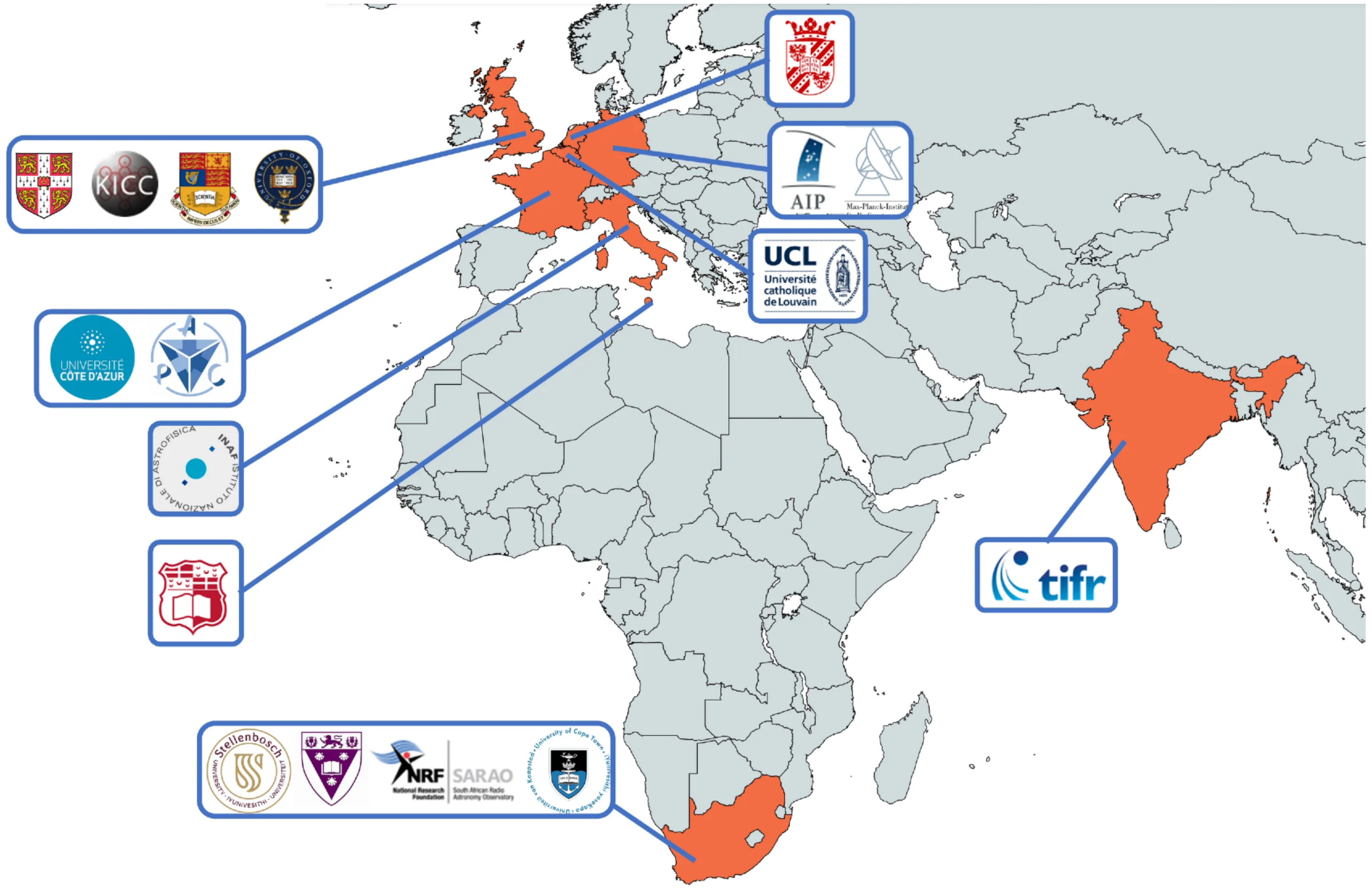
# REACH

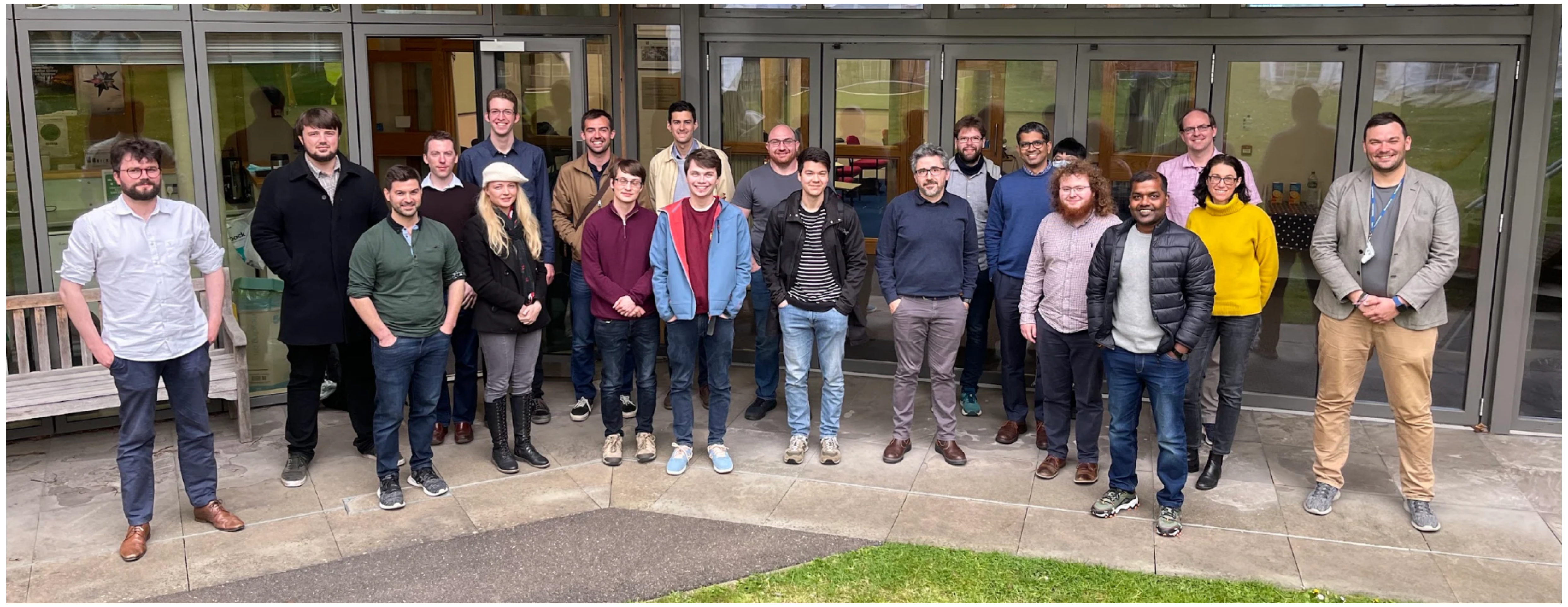
- REACH is sky-averaged 21-cm experiment based in the Karoo in South Africa
- Focused on 50-200 MHz
- Goal is to forward model the observations and instrument
- Currently operating a dipole antenna and developing additional instruments



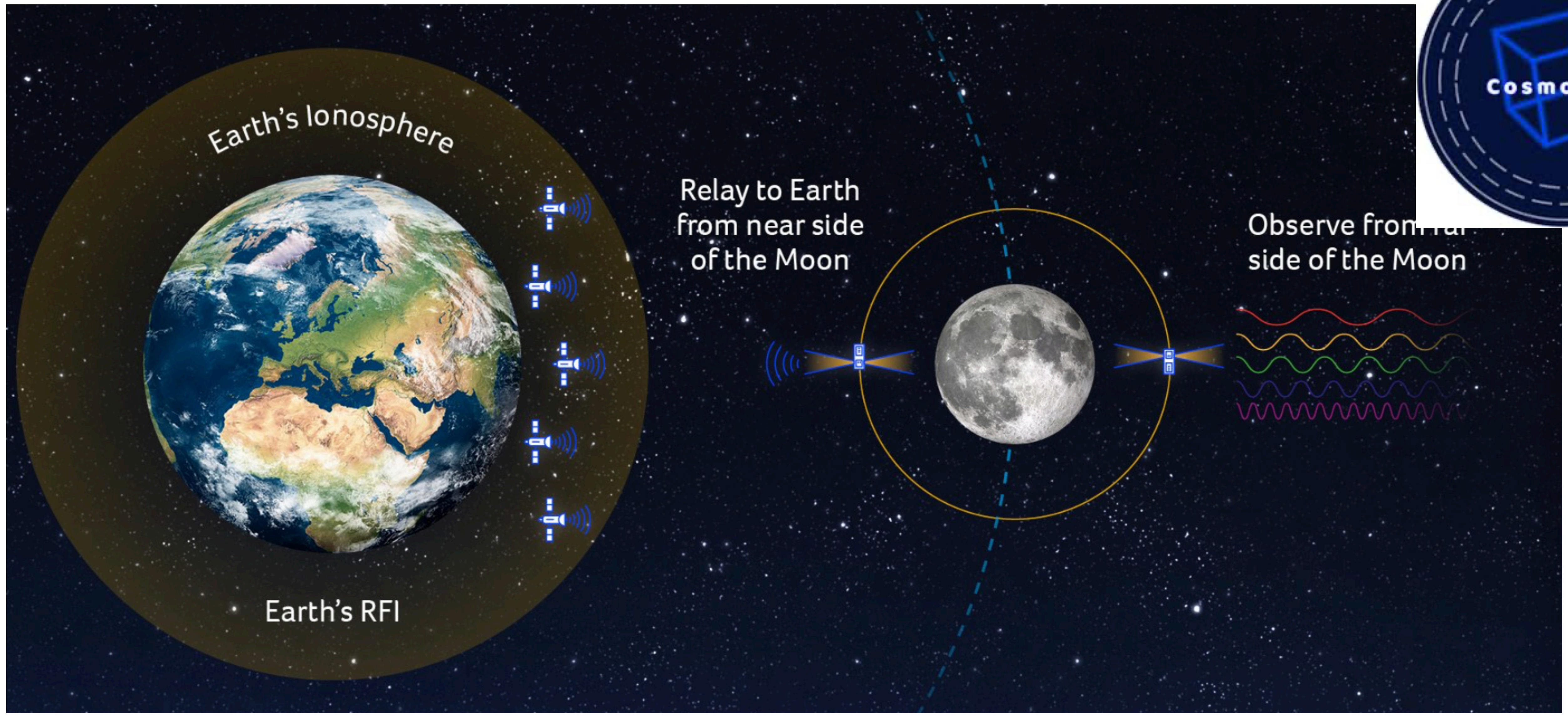
# REACH

- Currently have 40 members from across Europe, India and South Africa
- Led by Cambridge
- The REACH Collaboration, Nature Astronomy, 2022 (2210.07409)
- Collecting data since 2023

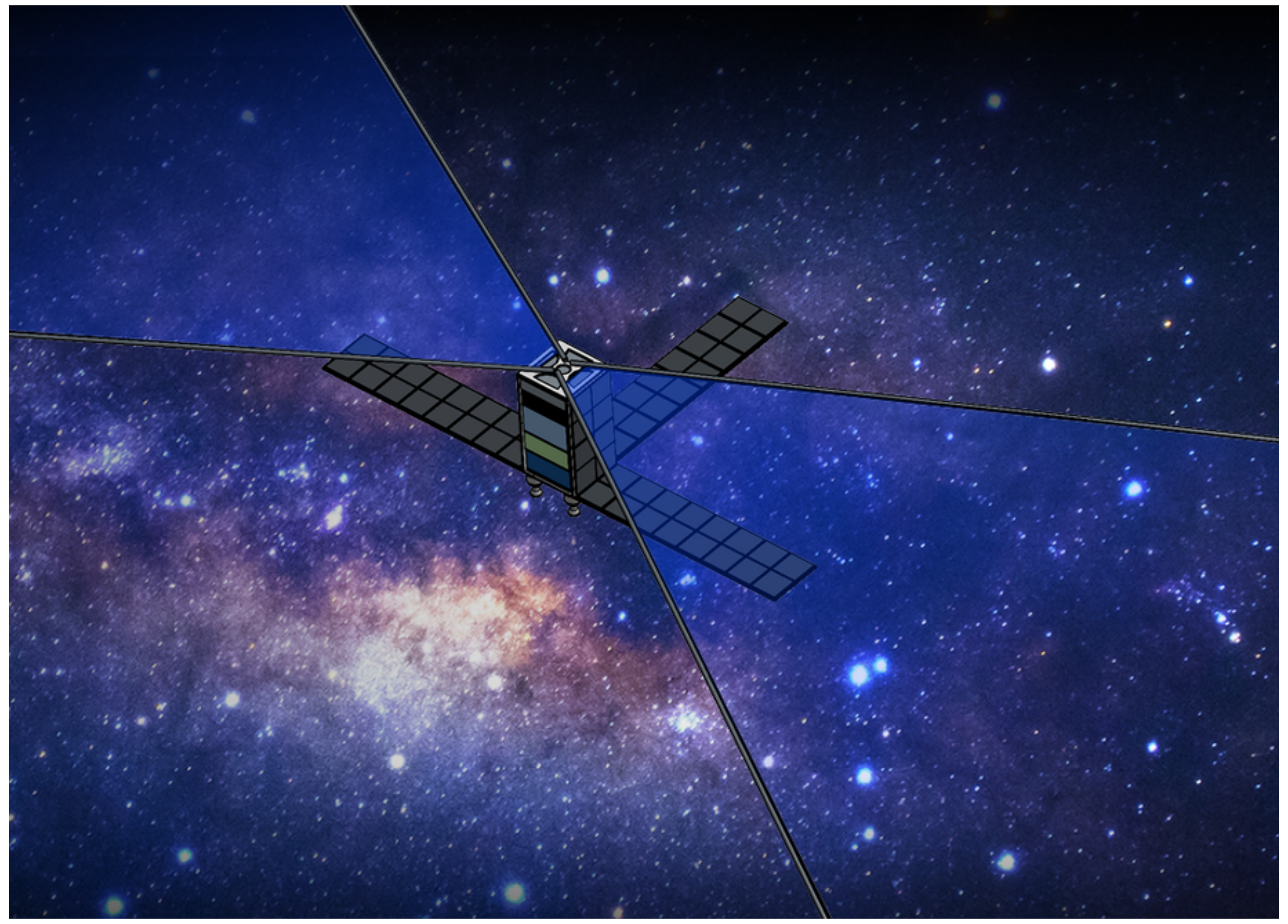


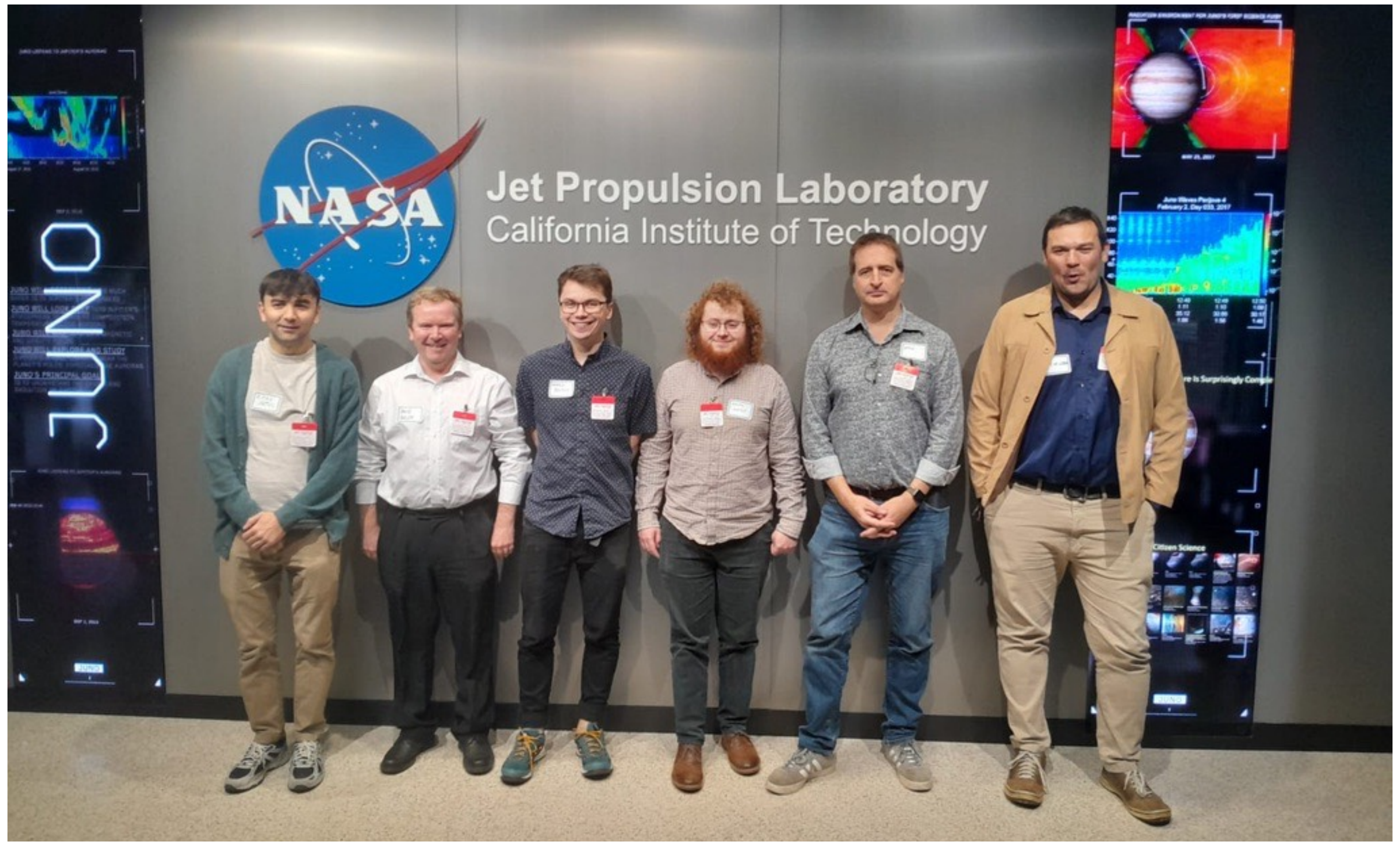
# CosmoCube



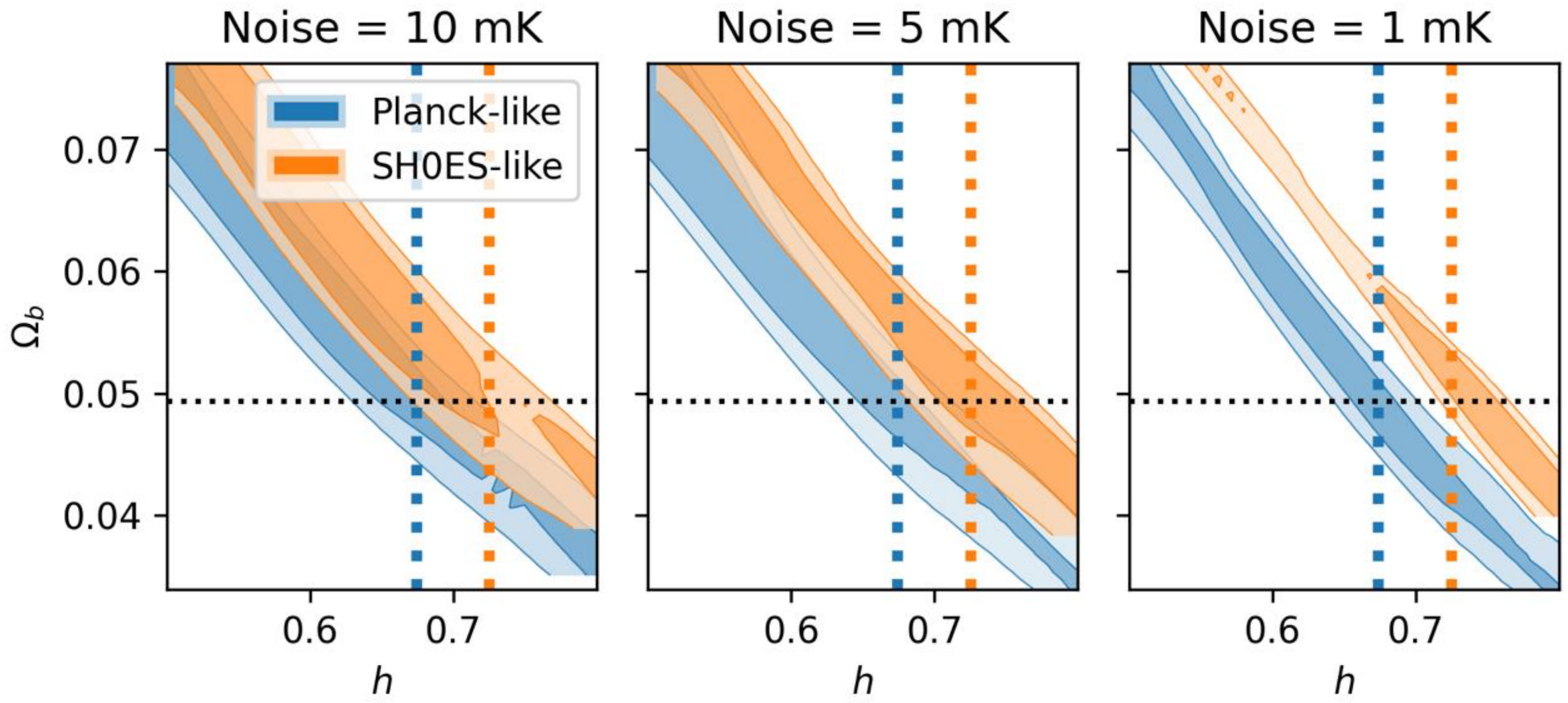

- CosmoCube aims to detect the dark ages 21-cm signal from the far side of the moon using a CubeSat
- Initial development funded by UKSA
- EoI for ESA Mini-Fast ( $\lesssim 50$ €M; $\leq 5$ yr to launch)
- Lower frequencies than REACH around 5-100 MHz



# CosmoCube



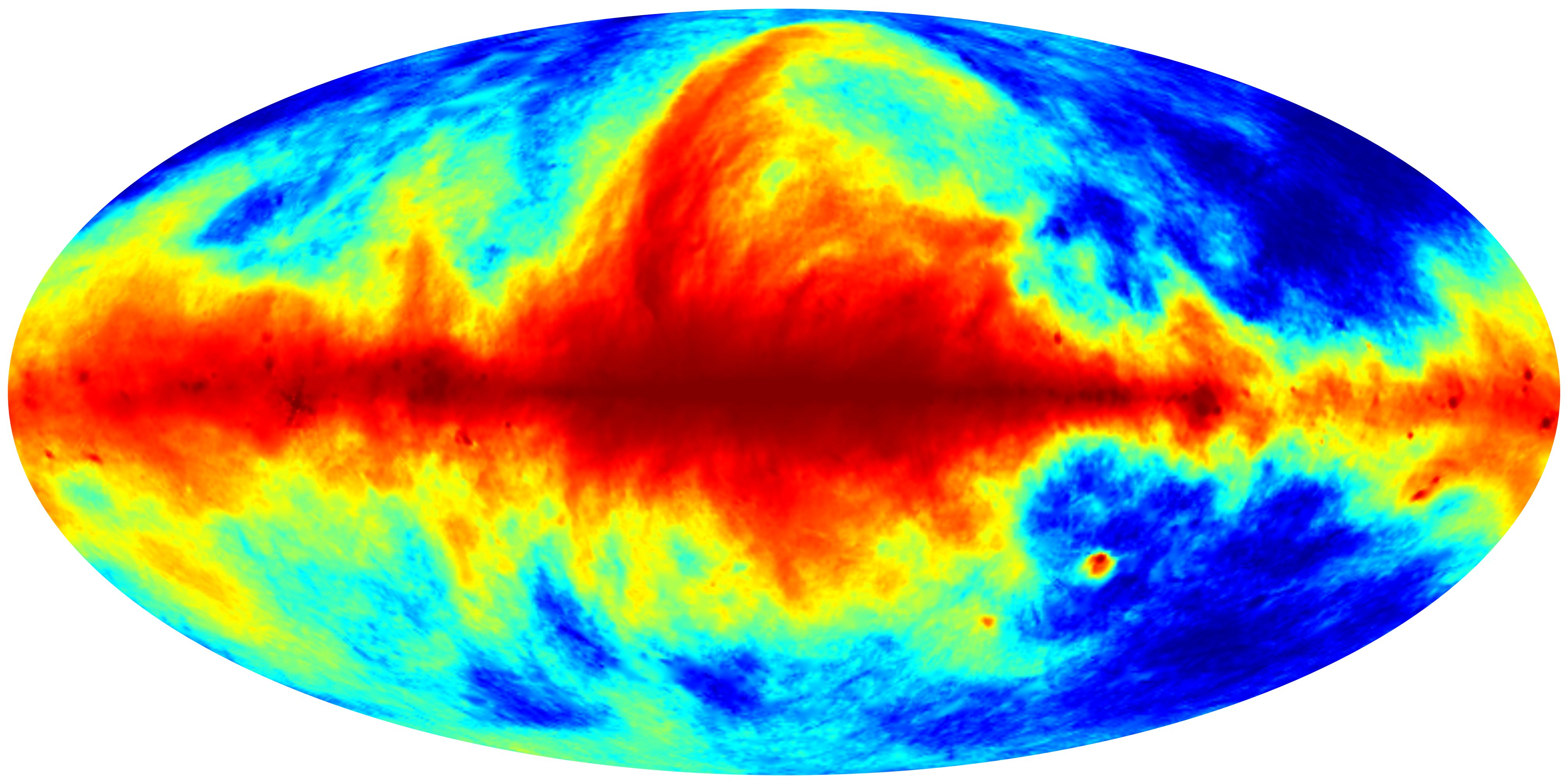

- Led by Cambridge, Portsmouth and RAL
- Collaborating with Surrey Satellite Technology Ltd, University of Malta, JPL, ASU and Embry-Riddle
- Mission paper submitted to Nature Astronomy
- Artuc and de Lera Acedo 2024, 2406.10096
- Zhu et al. RASTI 2025, 2510.06558

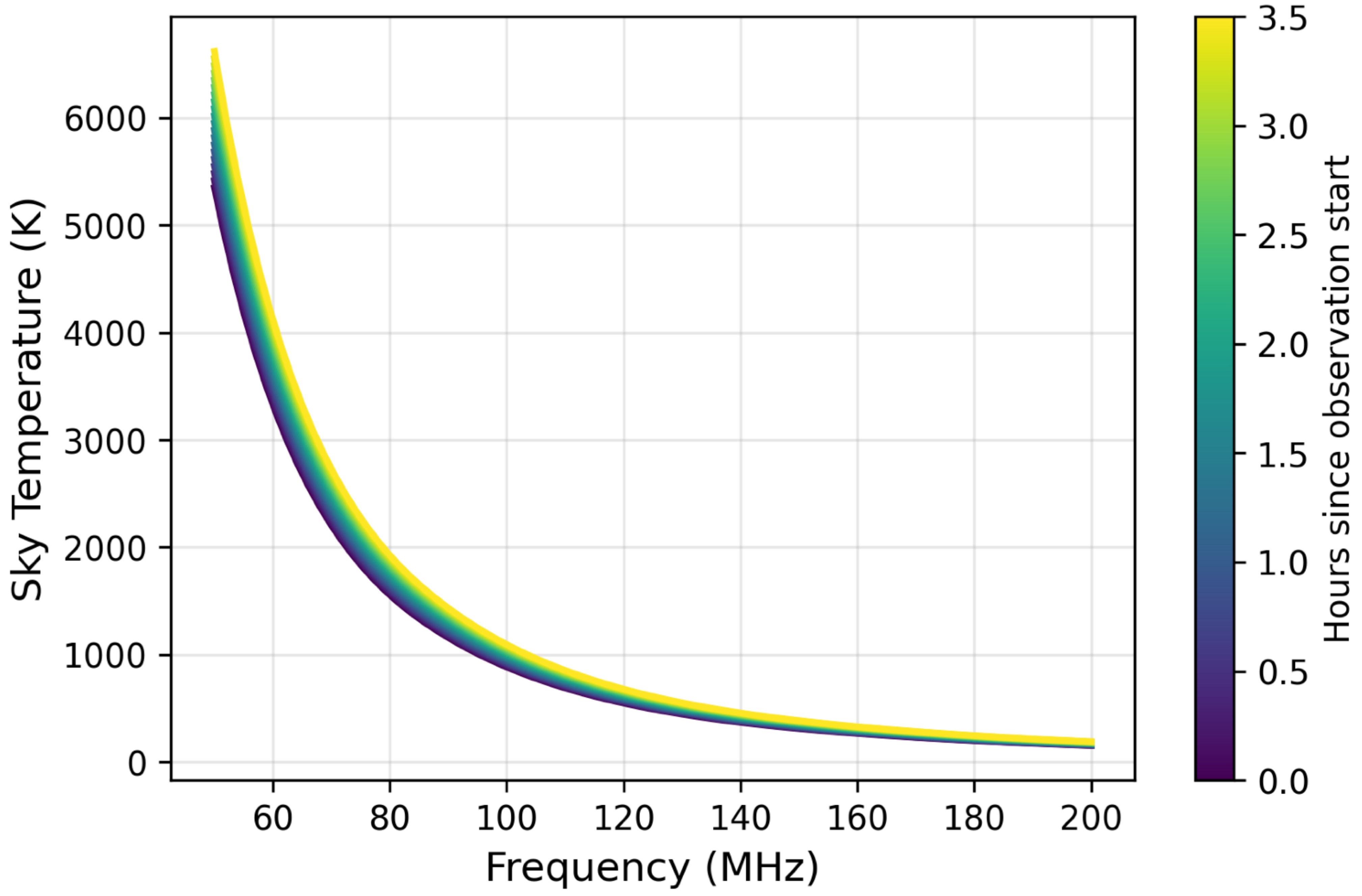


# Challenges and (some) solutions

# Many challenges faced by the field…

- While our instruments are sensitive to the 21-cm signal they are also sensitive to many other things!
- Foregrounds are 5 orders of magnitude brighter than the signal
- Predominantly synchrotron emission
- REACH Pipeline (Anstey et al. MNRAS 2025, 2010.09644)
- B-GSM (Carter et al. MNRAS 2025, 2501.01417)

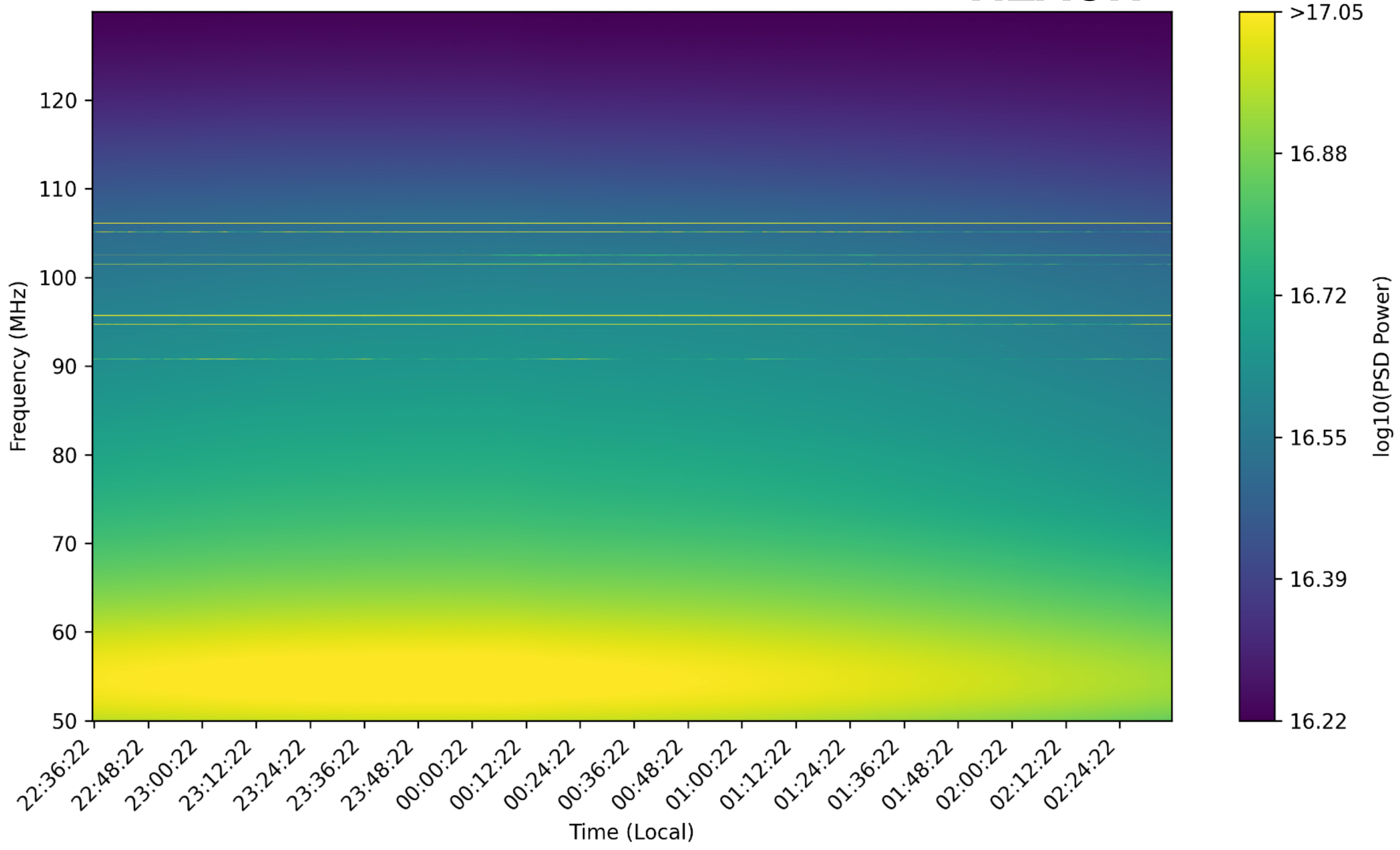


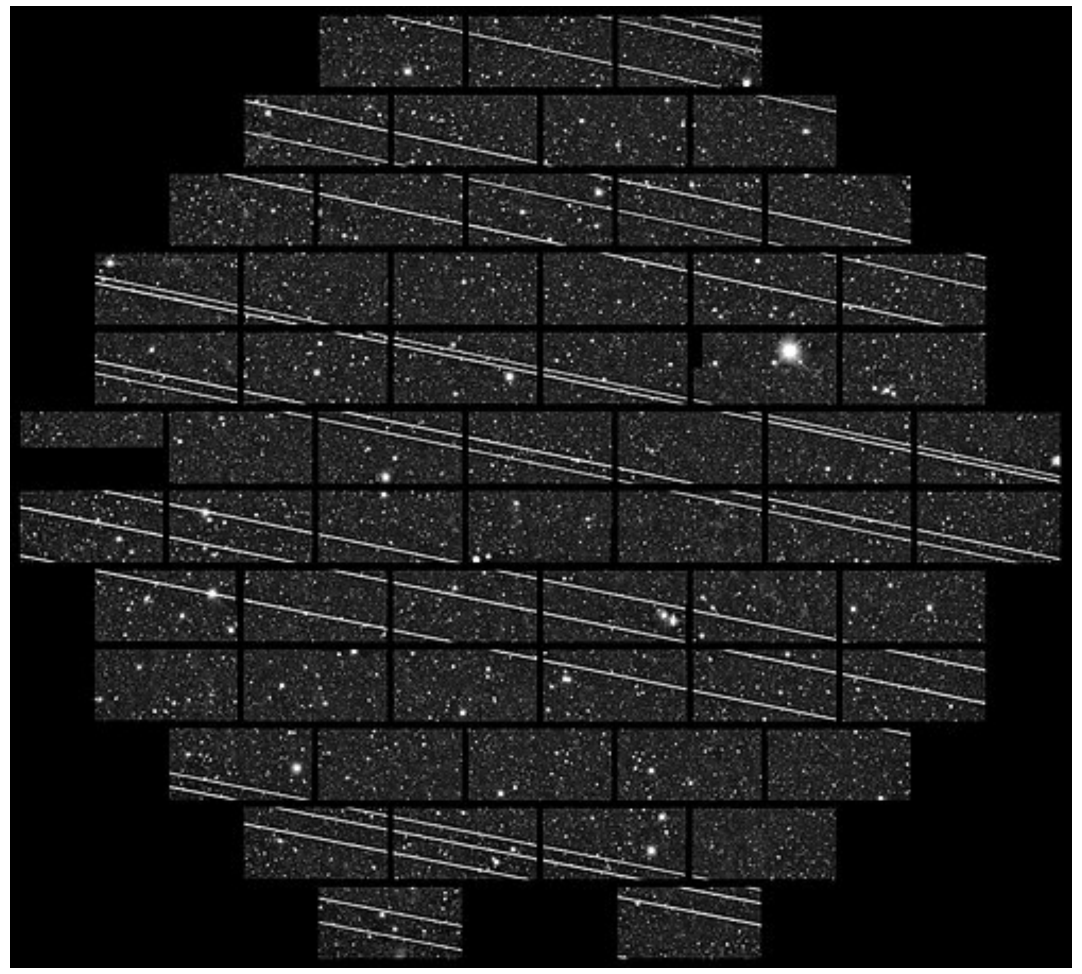


# Radio Frequency Interference

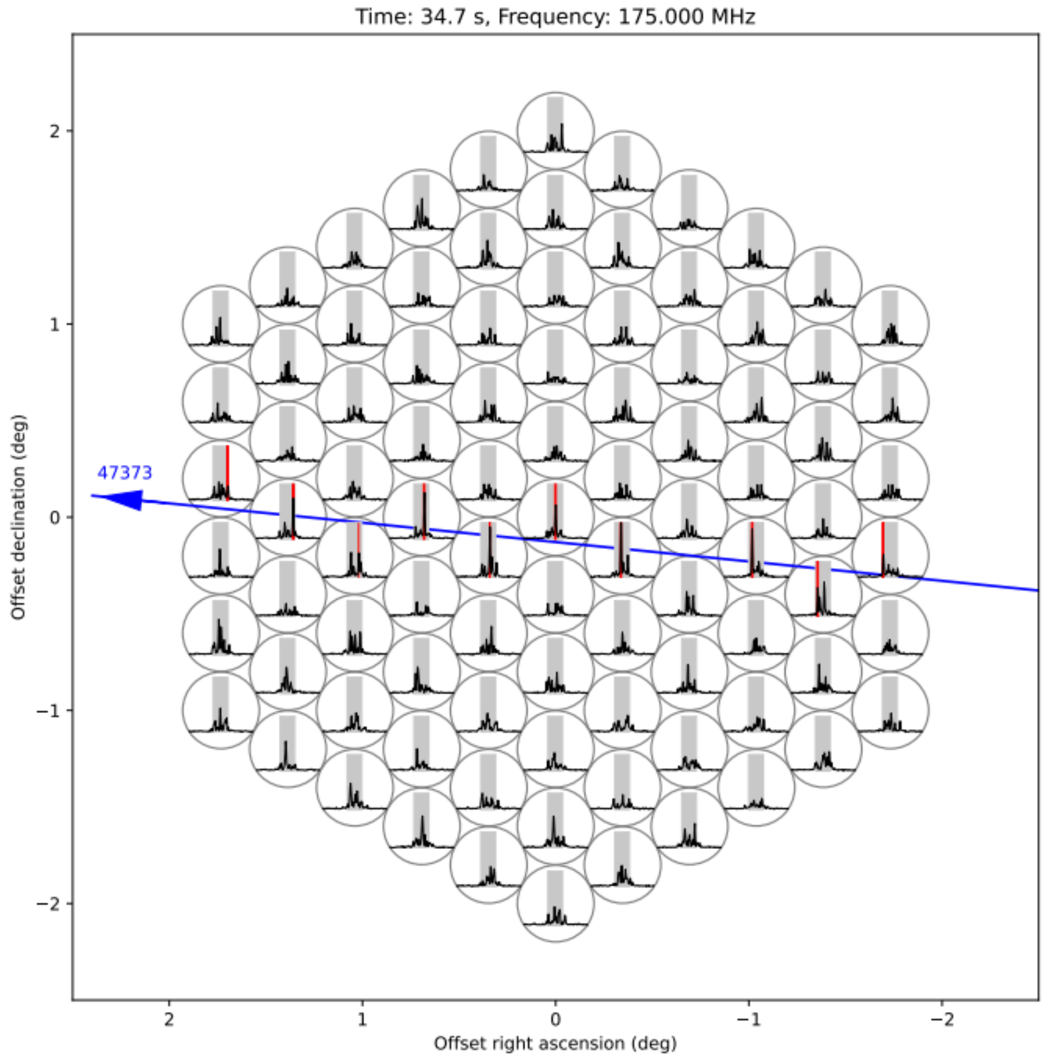
- FM transmits at 88 - 108 MHz and is very bright!
- Also sensitive to aeroplanes, satellites, walkie talkies…
- Bayesian RFI flagger (Leeney et al. 2211.15448)
- LOFAR (Di Vruno et al. A&A 2023, 2307.02316)
- AstroTrack (Rajpoot et al., in prep.; incl. HB)

**REACH**



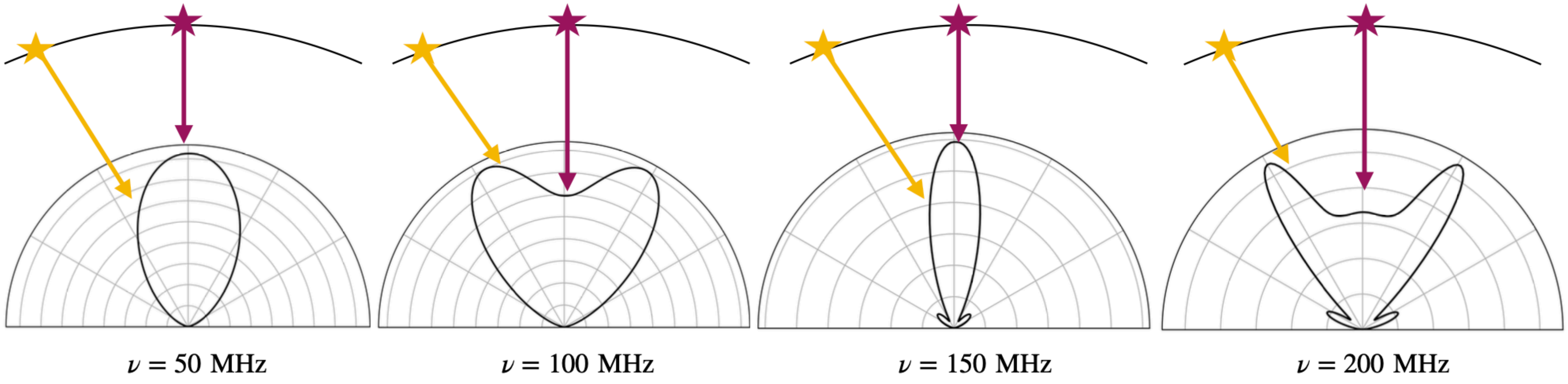
**Blanco 4m Telescope**




**LOFAR core**

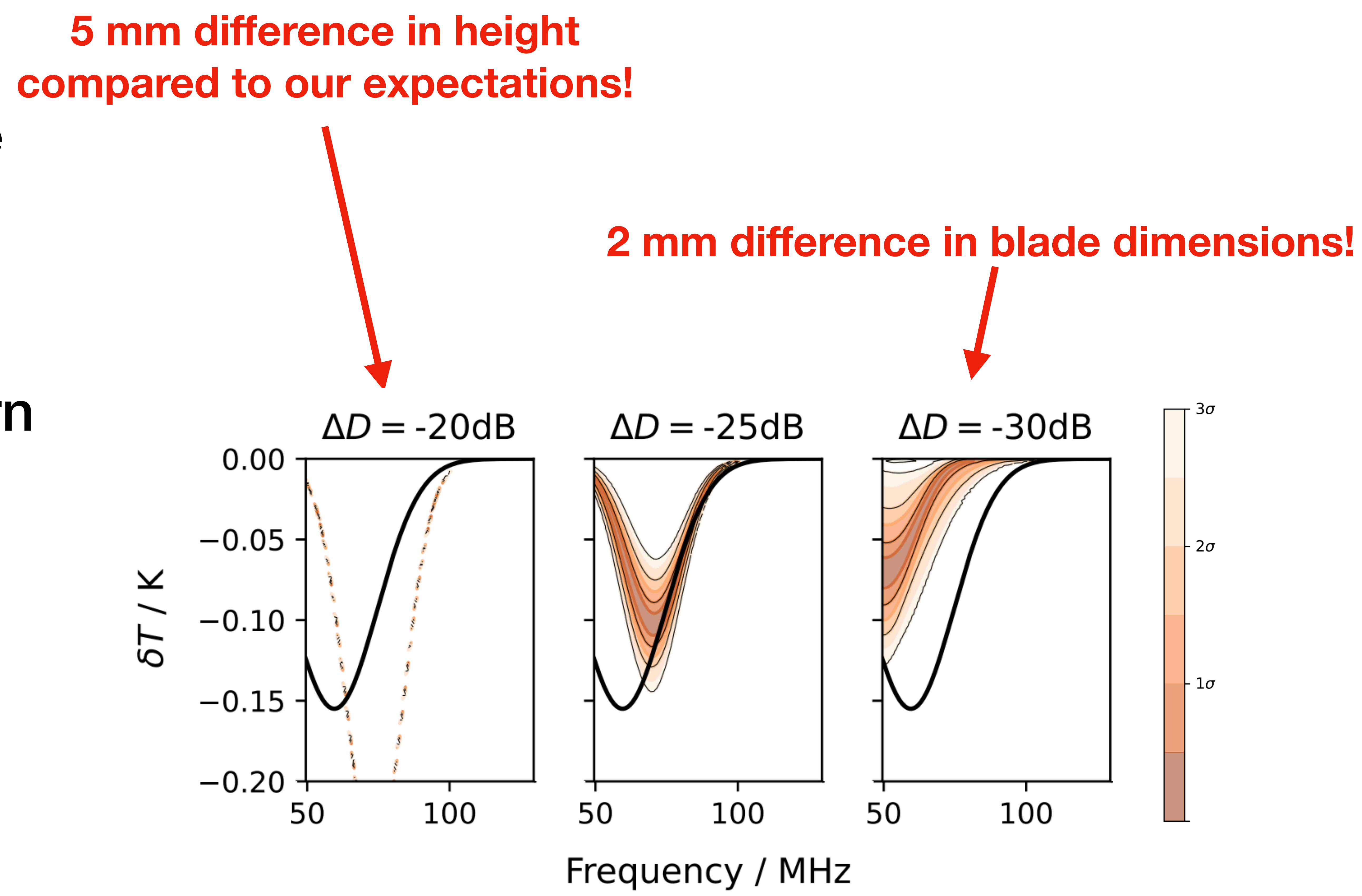
# Beam

- Taking a an all sky measurement with a very wide beam antenna
- Response of our antenna varies with spatial coordinates and frequency
- Rely on Electromagnetic simulations and assume absolute knowledge of the beam in the REACH analysis pipelines

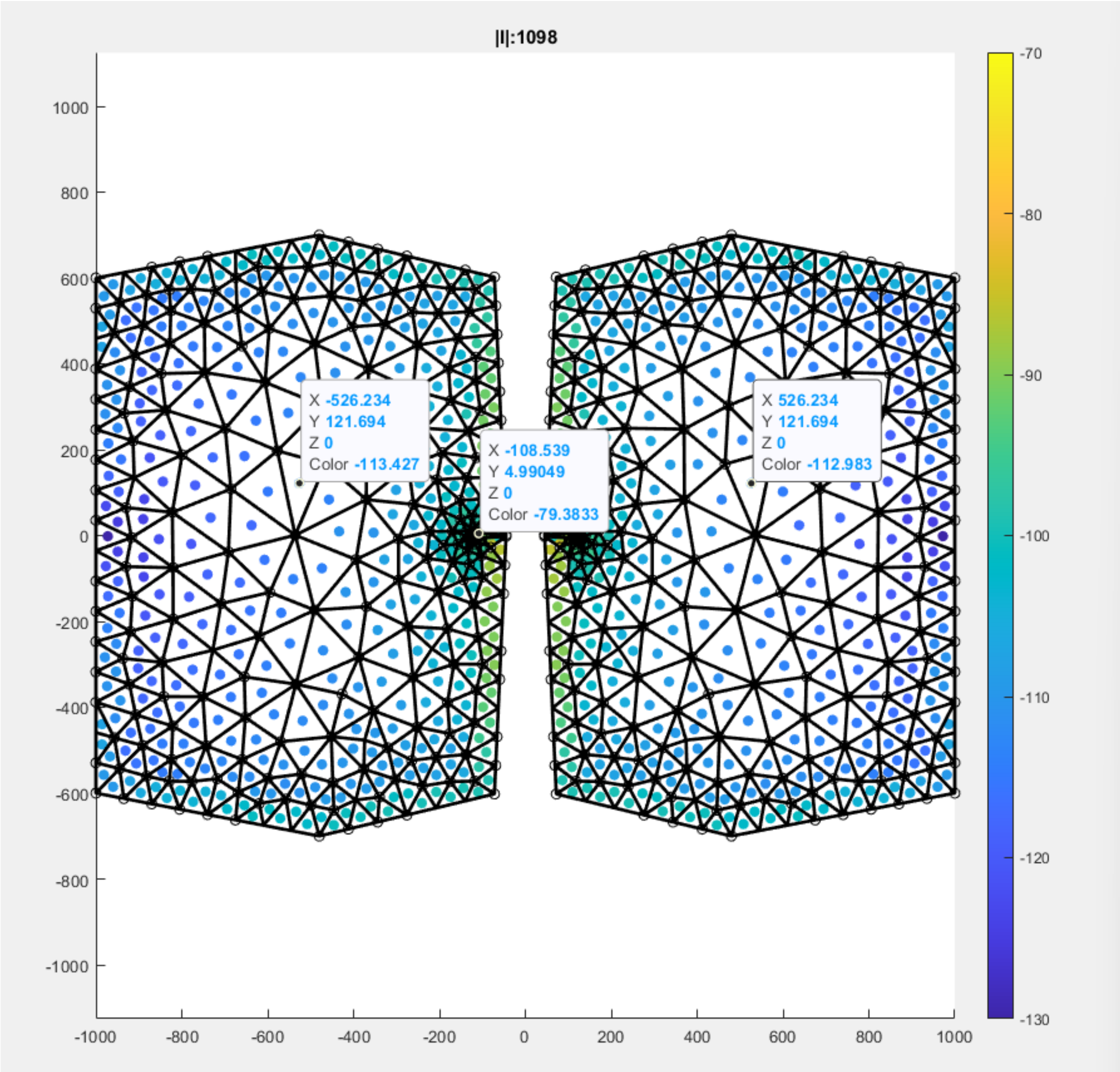


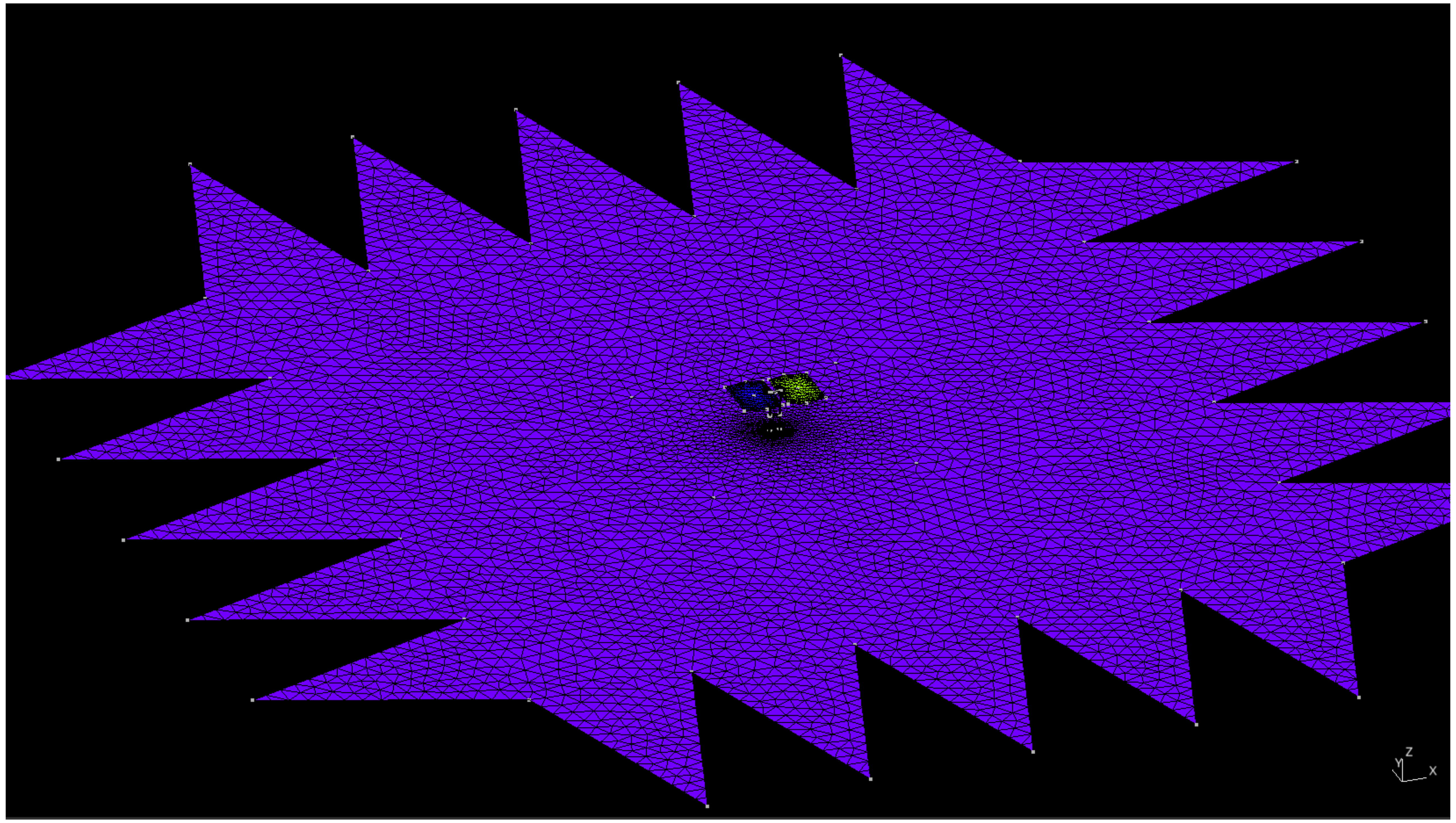
# Emulating the REACH Beam

- Really want to be able to physically model the beam pattern in our analysis pipeline
- DiRAC RAC17 application to build neural network emulators of the REACH beam pattern (3.22 Million CPU hrs)
- Using a Method of Moments solver for the beam pattern



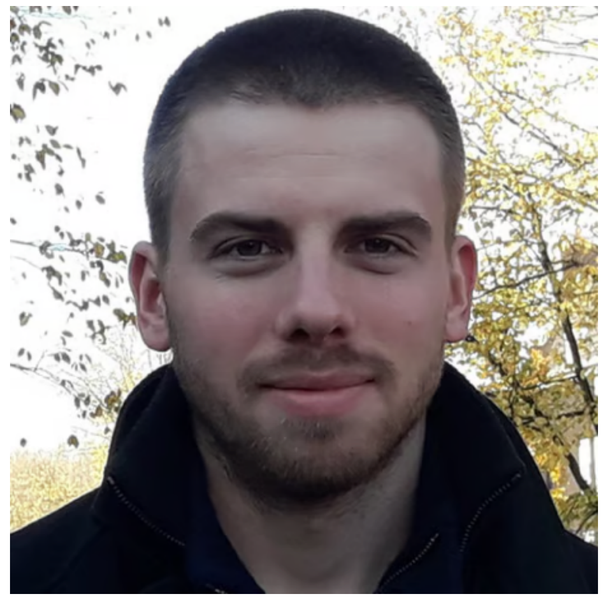
# Emulating the REACH Beam



Credit: Jean Cavillot

# Emulating the REACH Beam



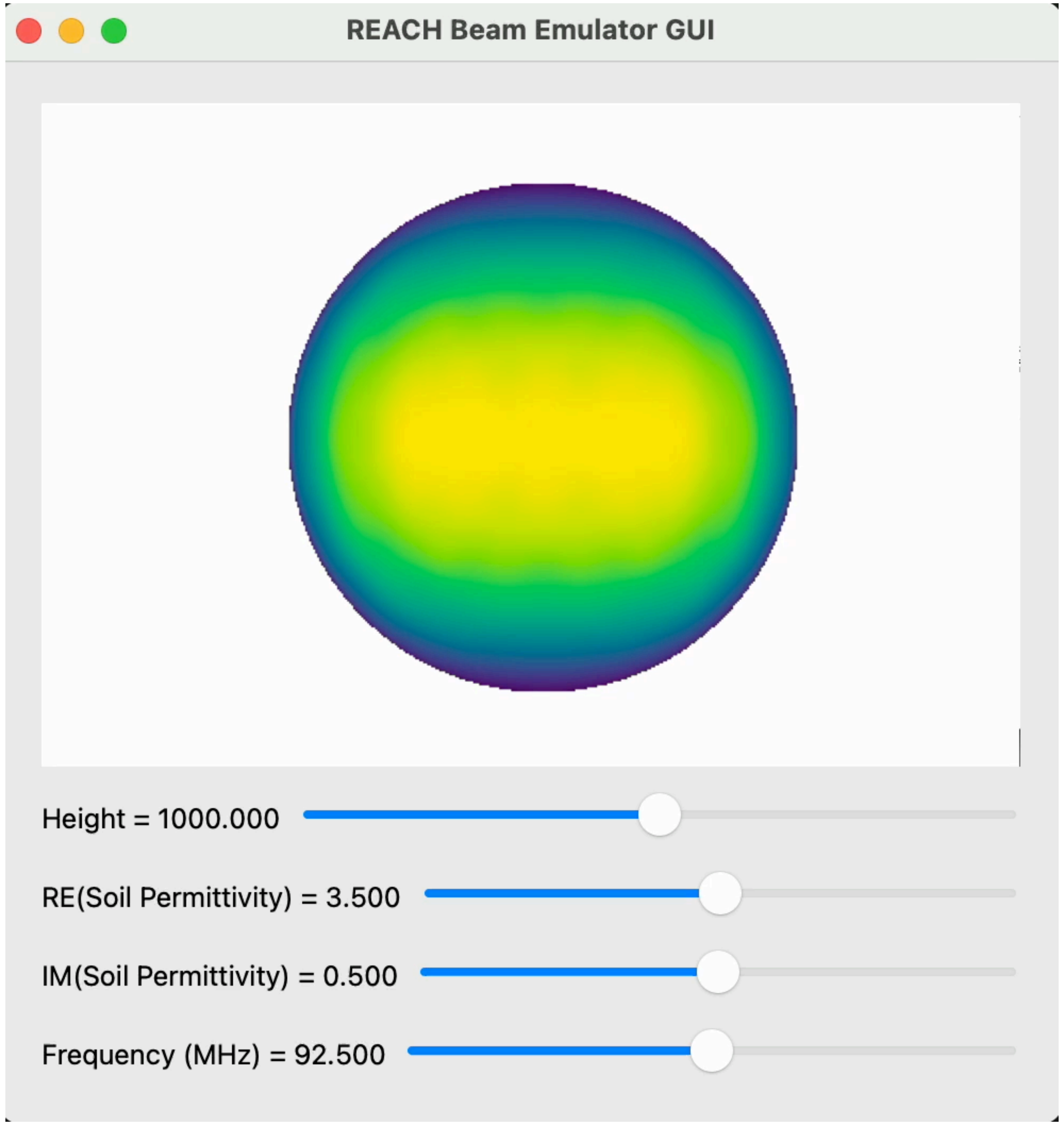
- Train neural network emulators to approximate our simulations

- Vary the height of the antenna above the ground plane and the properties of the soil

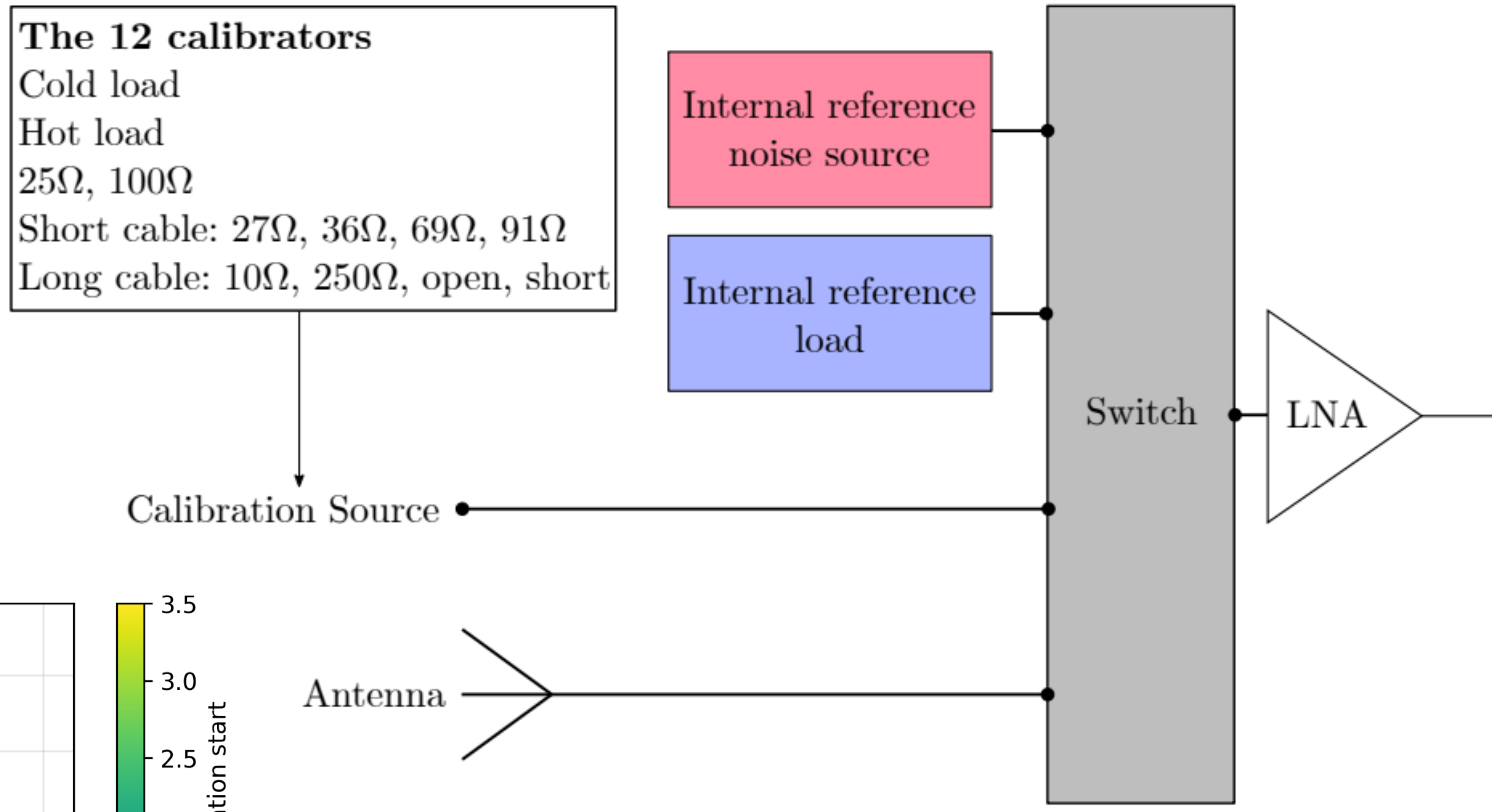
- We can emulate to around $-20$ dB accuracy (around 1 %)

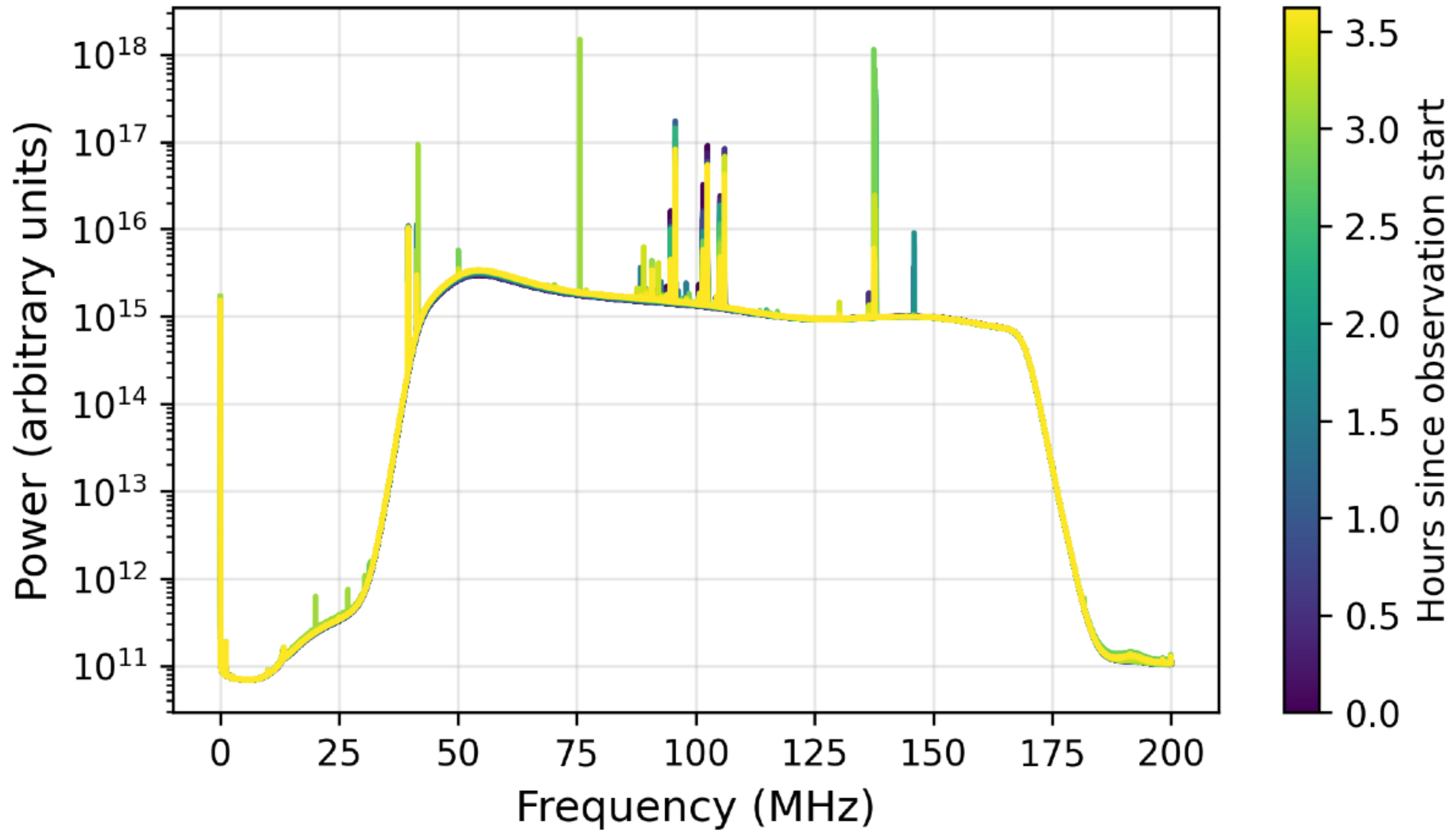
- We think we need to get it to around $\lesssim -30$ dB

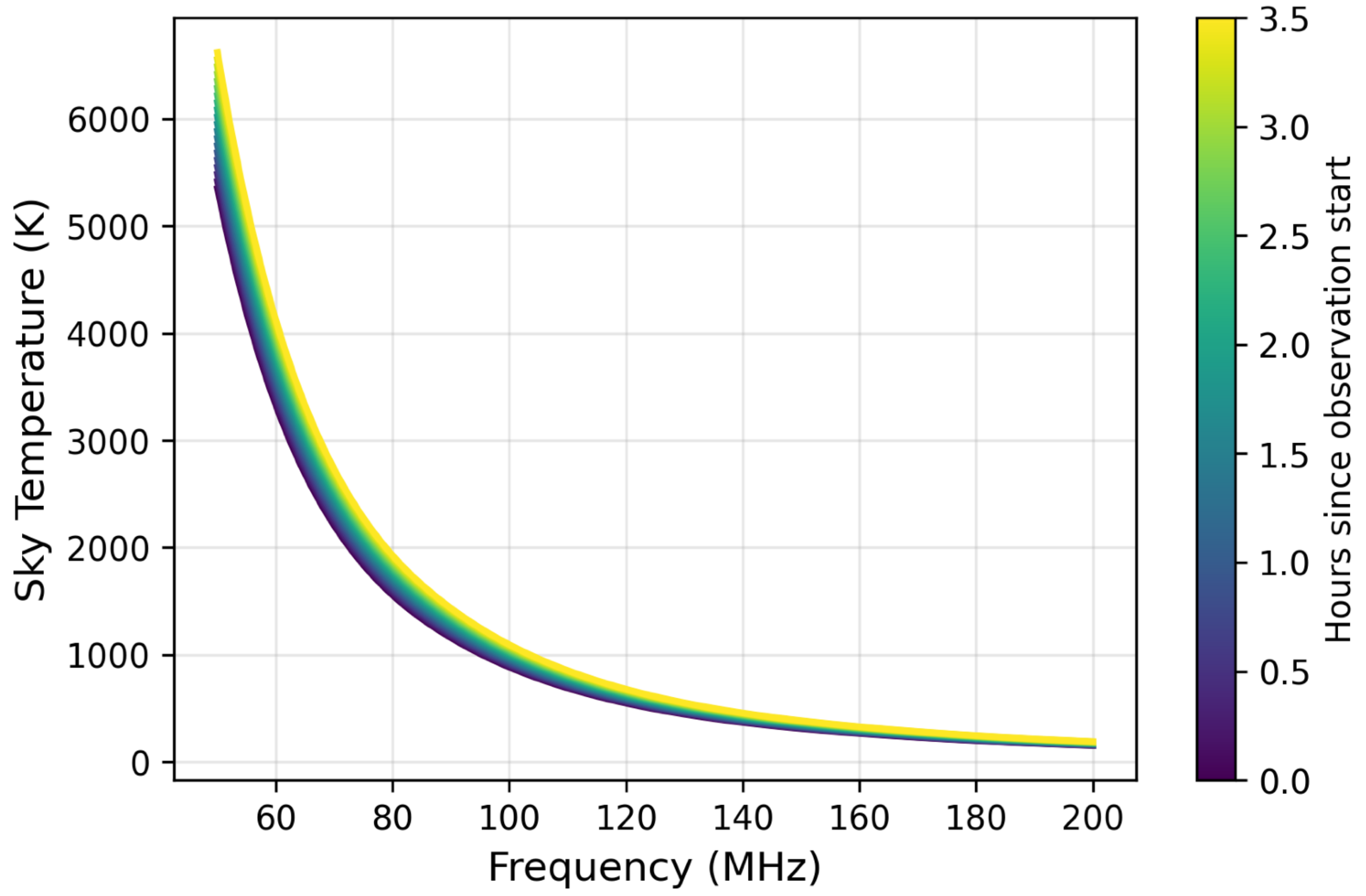
- Around about 0.5 Million CPU hours in this figure!



# Calibrating REACH

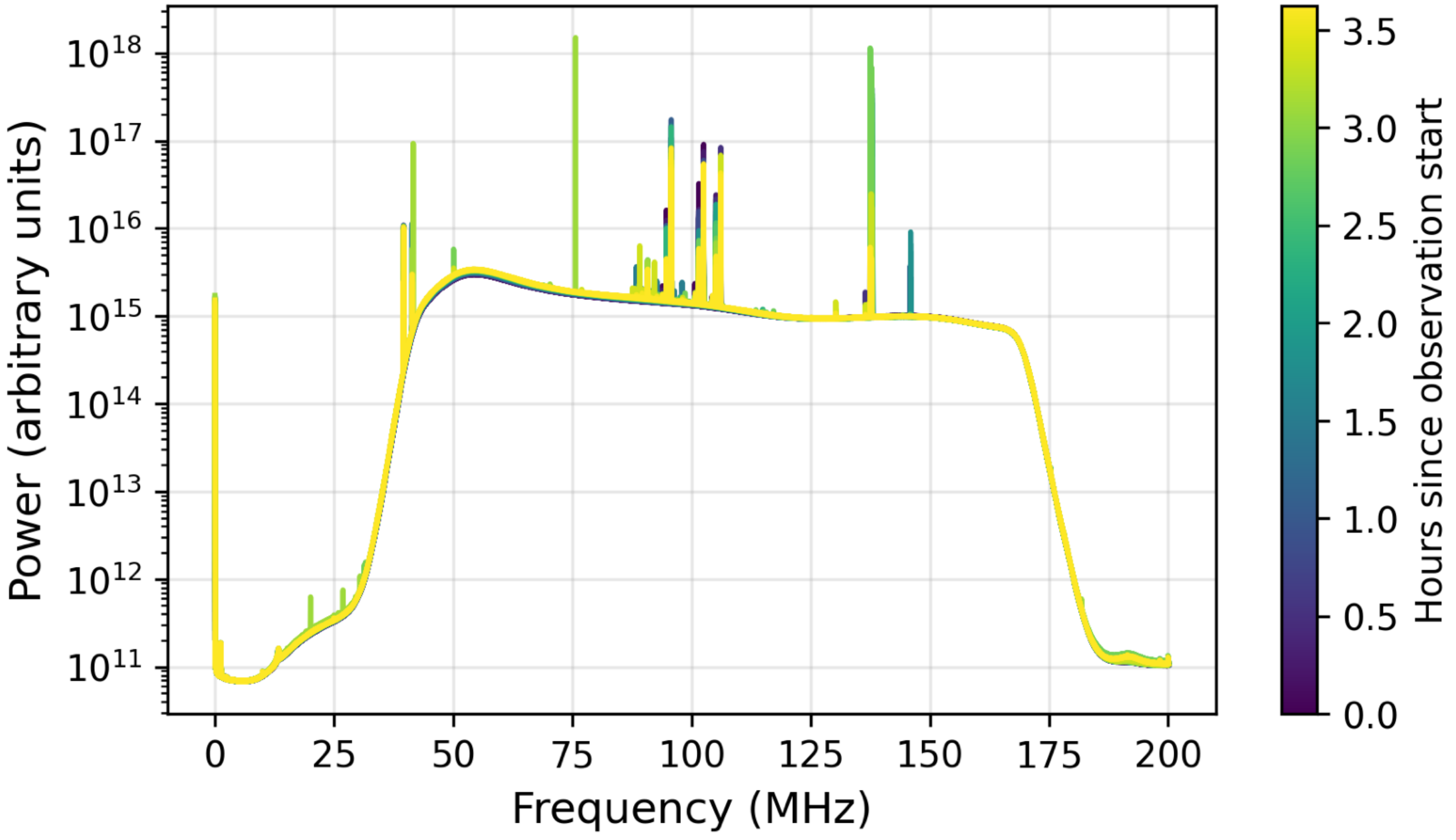


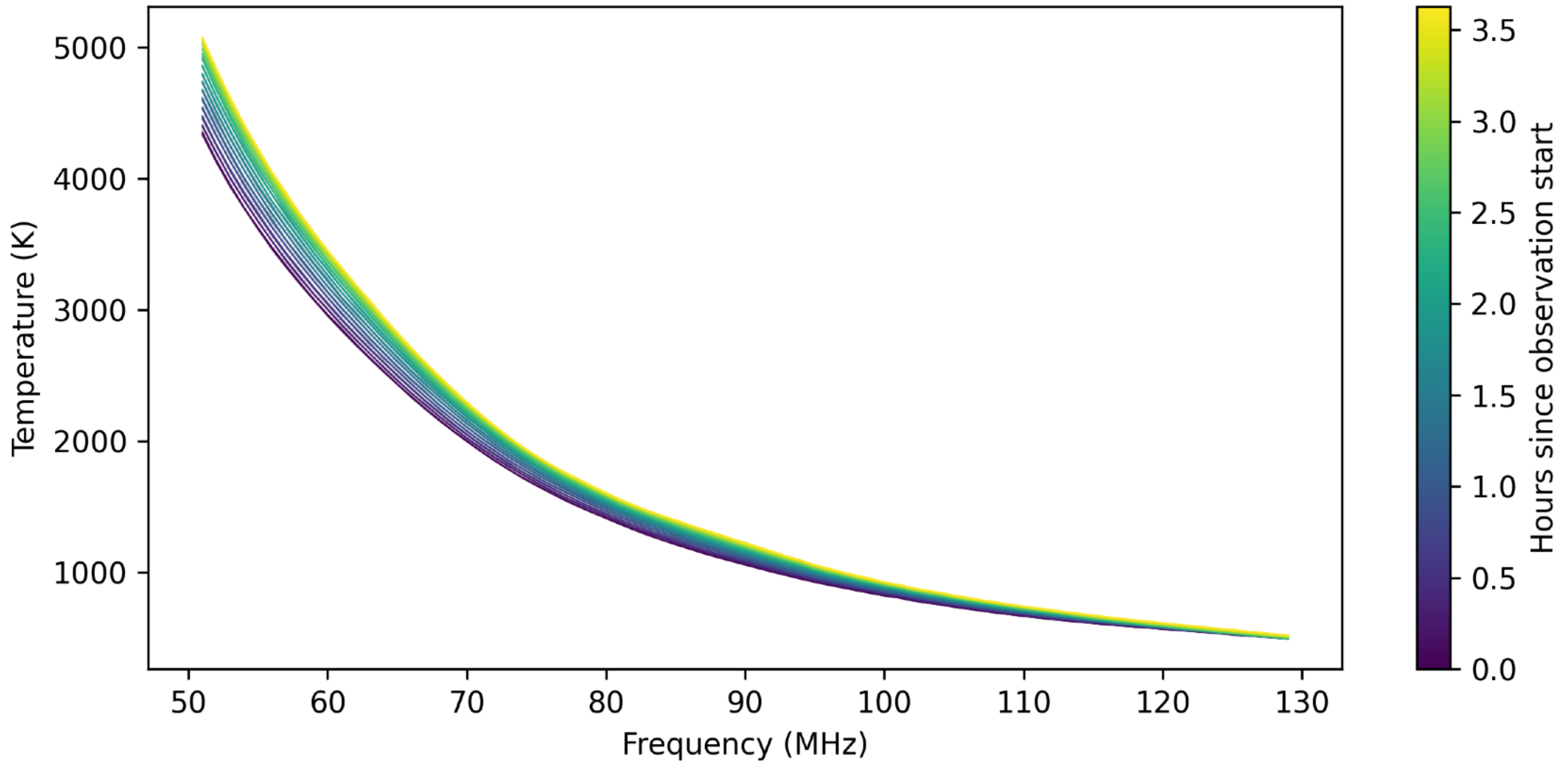



# Calibrating REACH

- Based around the dickie switching algorithm but extended to account for impedance mismatches between different sources
- Least squares and conjugate prior based solvers
- Roque et al. MNRAS 2020, (2011.14052), Roque et al. Exp. Astron. 2023, (2307.00099), Kirkham et al. MNRAS 2025, (2509.13010)

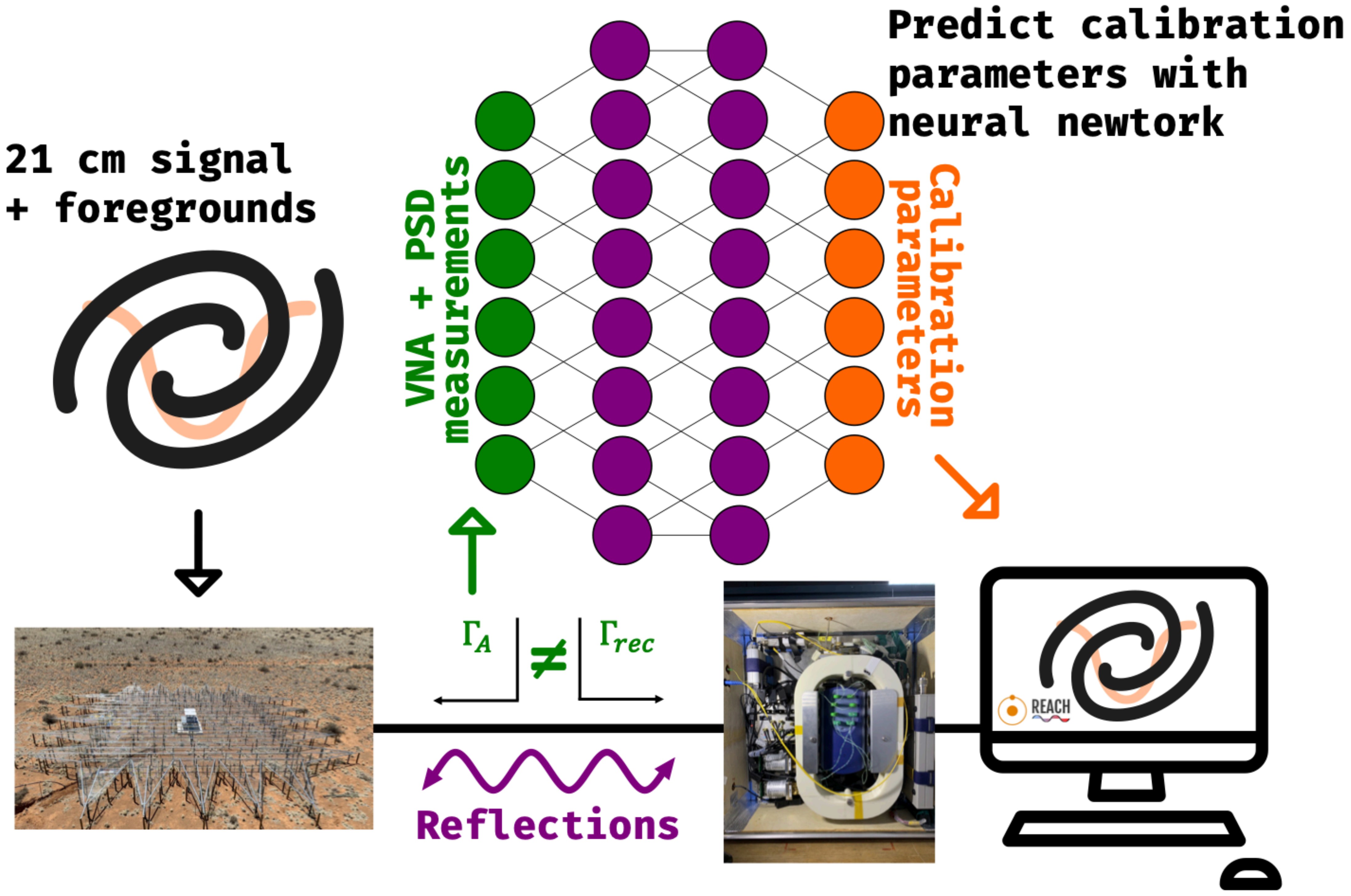



**Solve for the LNA**



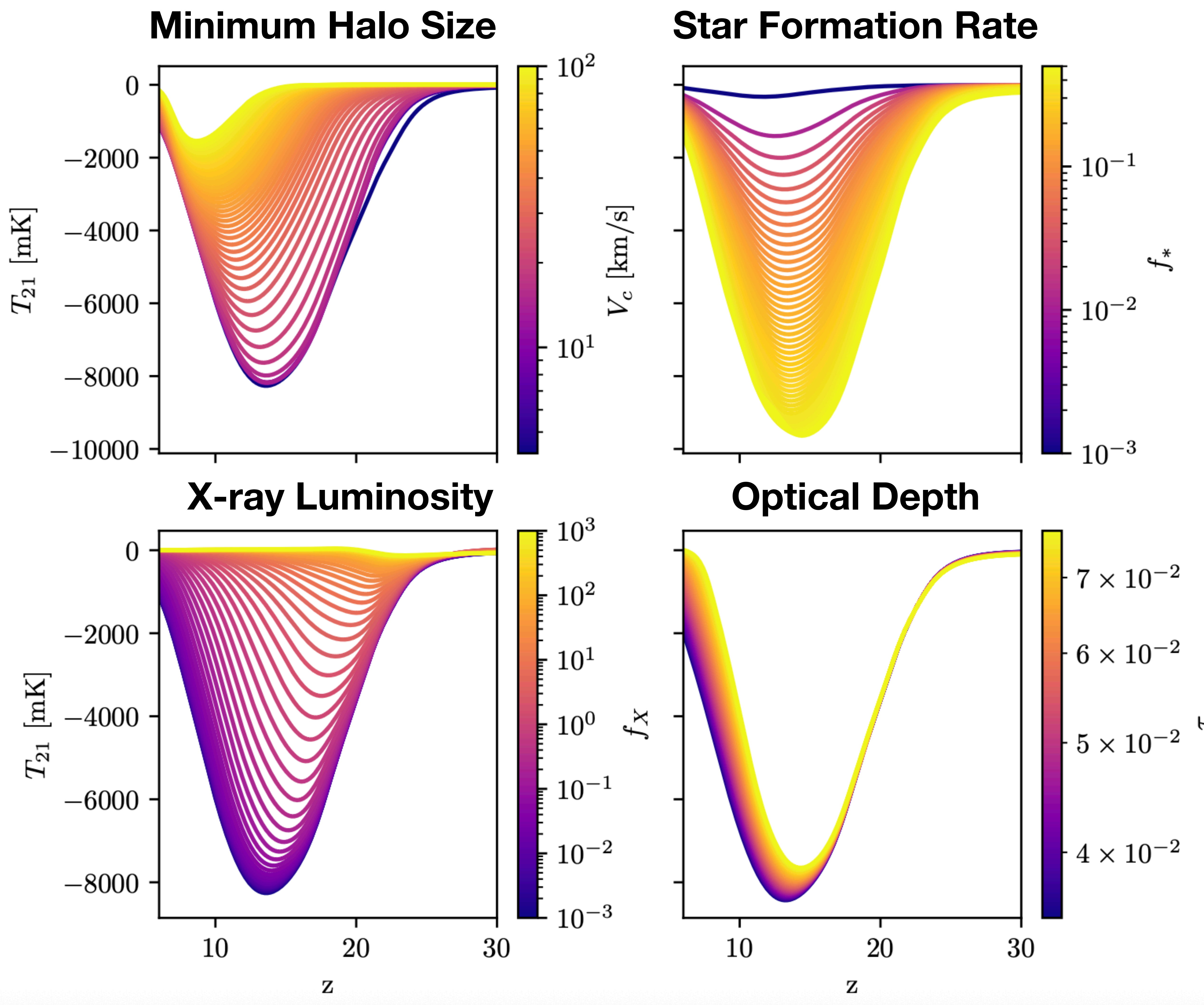
# Calibrating REACH with Machine Learning

- Developed a novel approach using machine learning to calibrate of REACH
- Observations of internal references as training data to learn the properties of the system
- Compliments more traditional approaches
- In principle this approach can capture higher order effects that are not described by the alternative analytic methods
- Leeney, Bevins et al. Scientific Reports 2025 2504.16791



# Modelling the signal

- Complex dependence on astrophysics…
- Semi-numerical simulations offer an efficient way to model the signal with a good level of detail
- However inference usually means running 100,000s to millions of calls to your signal model
- Semi-numerical simulations are too computationally expensive



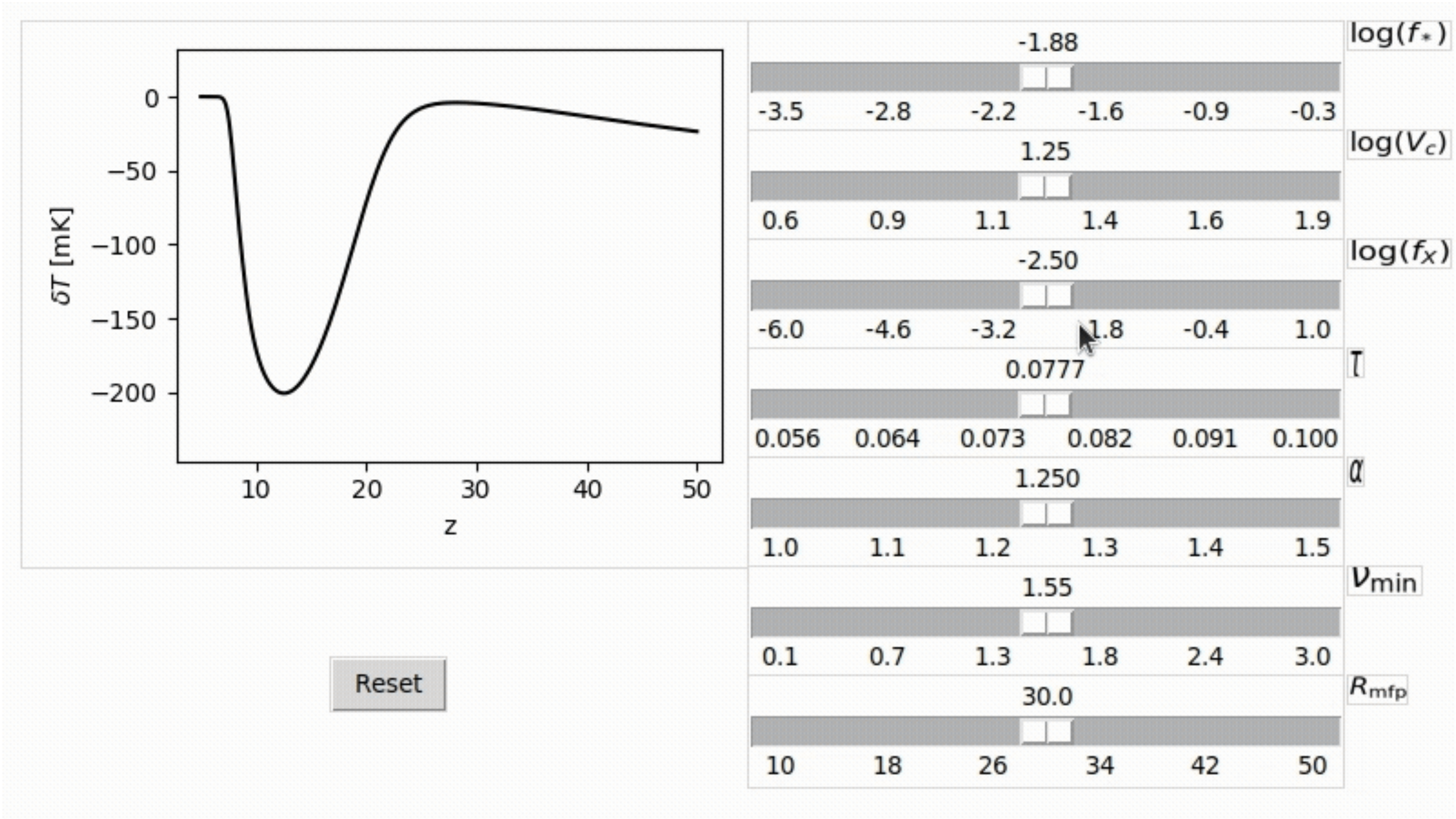
# Emulating the 21-cm signal

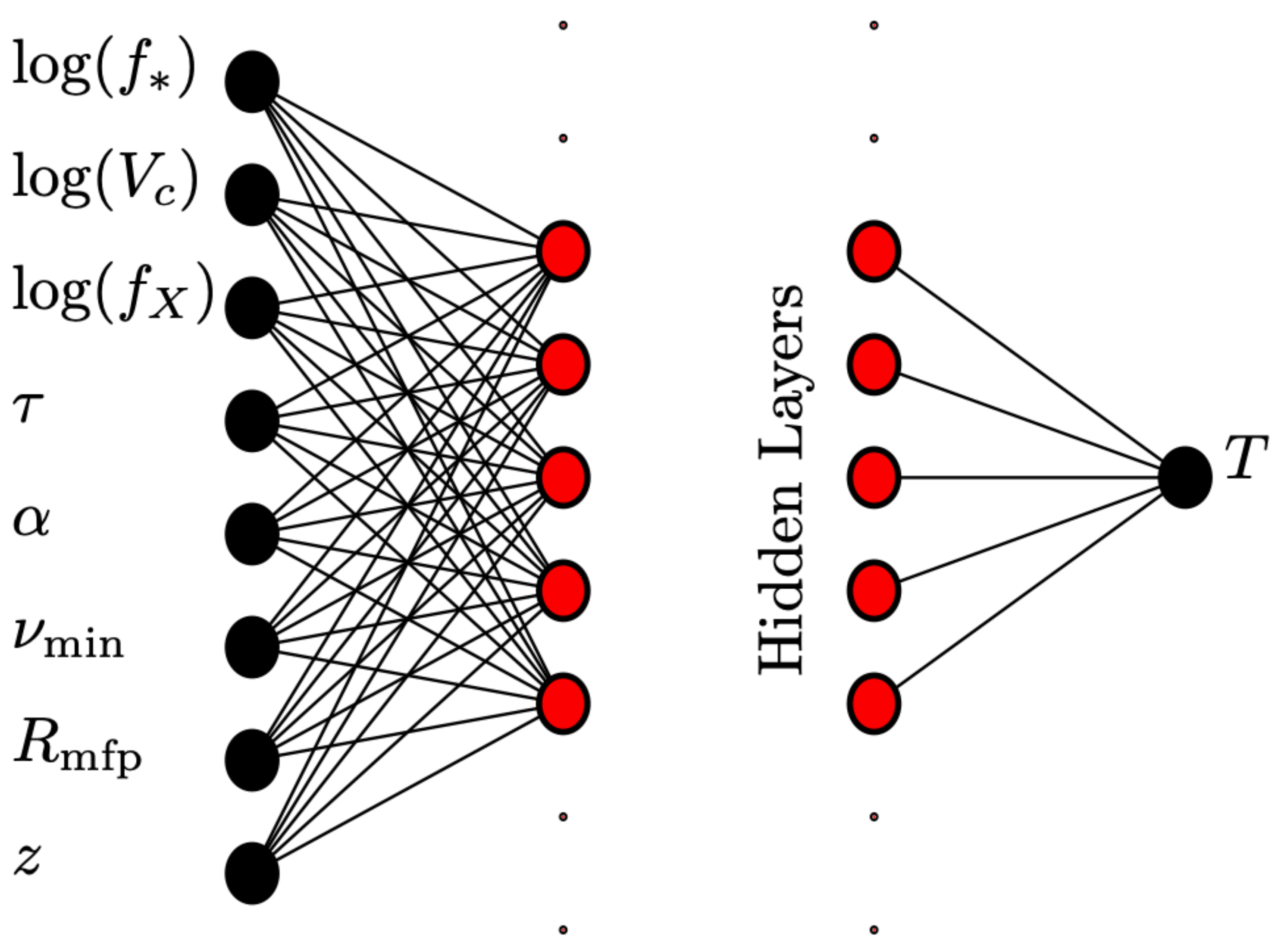
- Emulate the 21-cm signal e.g. ***globalemu*** (Bevins et al. MNRAS 2021,  2104.04336)

- $102\times$ faster than the state of the art emulators and $2\times$ as accurate

- Adapted for power spectrum with HERA (The HERA Col. ApJ 2023)

- 21cmGEM (Cohen et al. MNRAS 2019, 1910.06274), 21cmEMU (Breitman et al. MNRAS 2023, 2309.05697), 21cmKAN (Dorigo Jones et al. 2025, 2508.11752)…



# Understanding the limitations of emulators

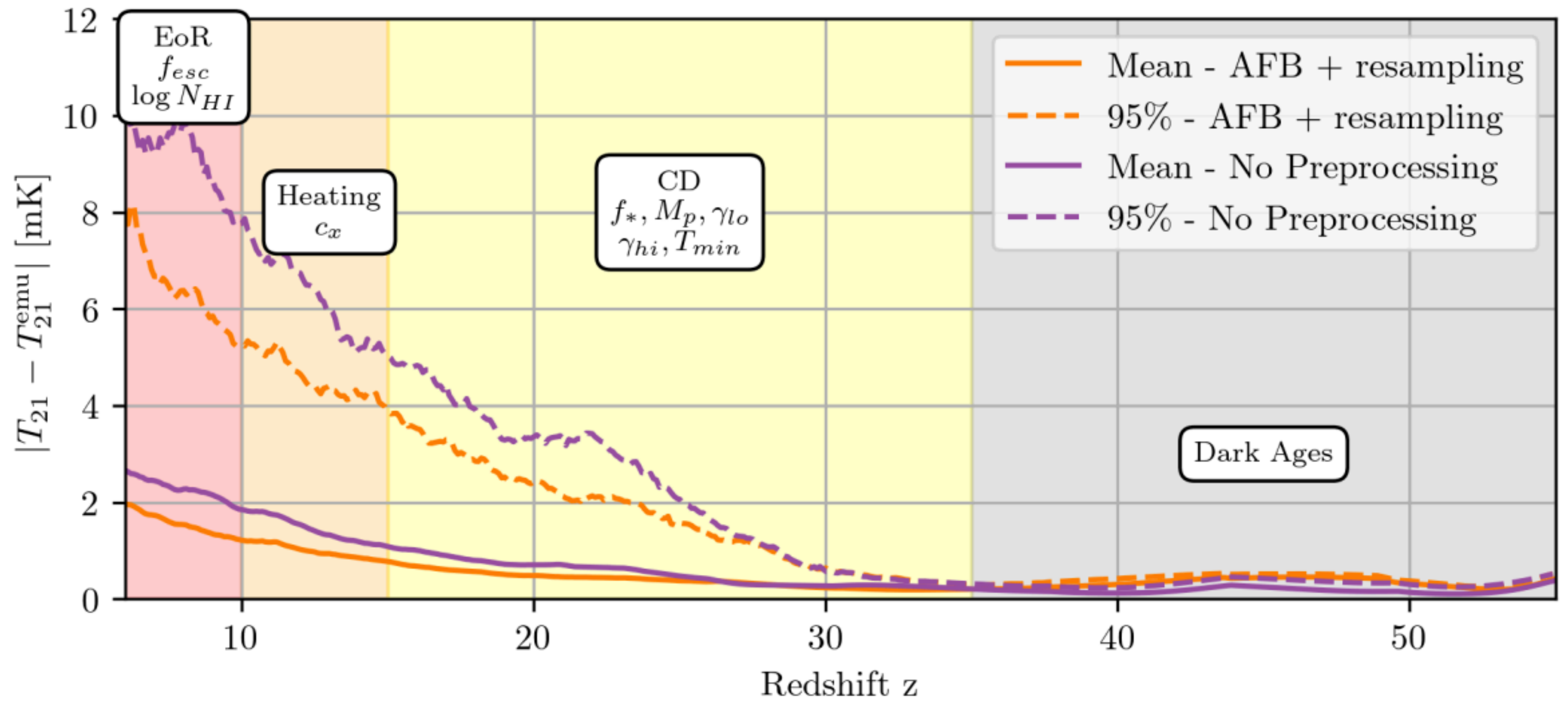
- Ideally we would use the semi-numerical simulation in our analysis

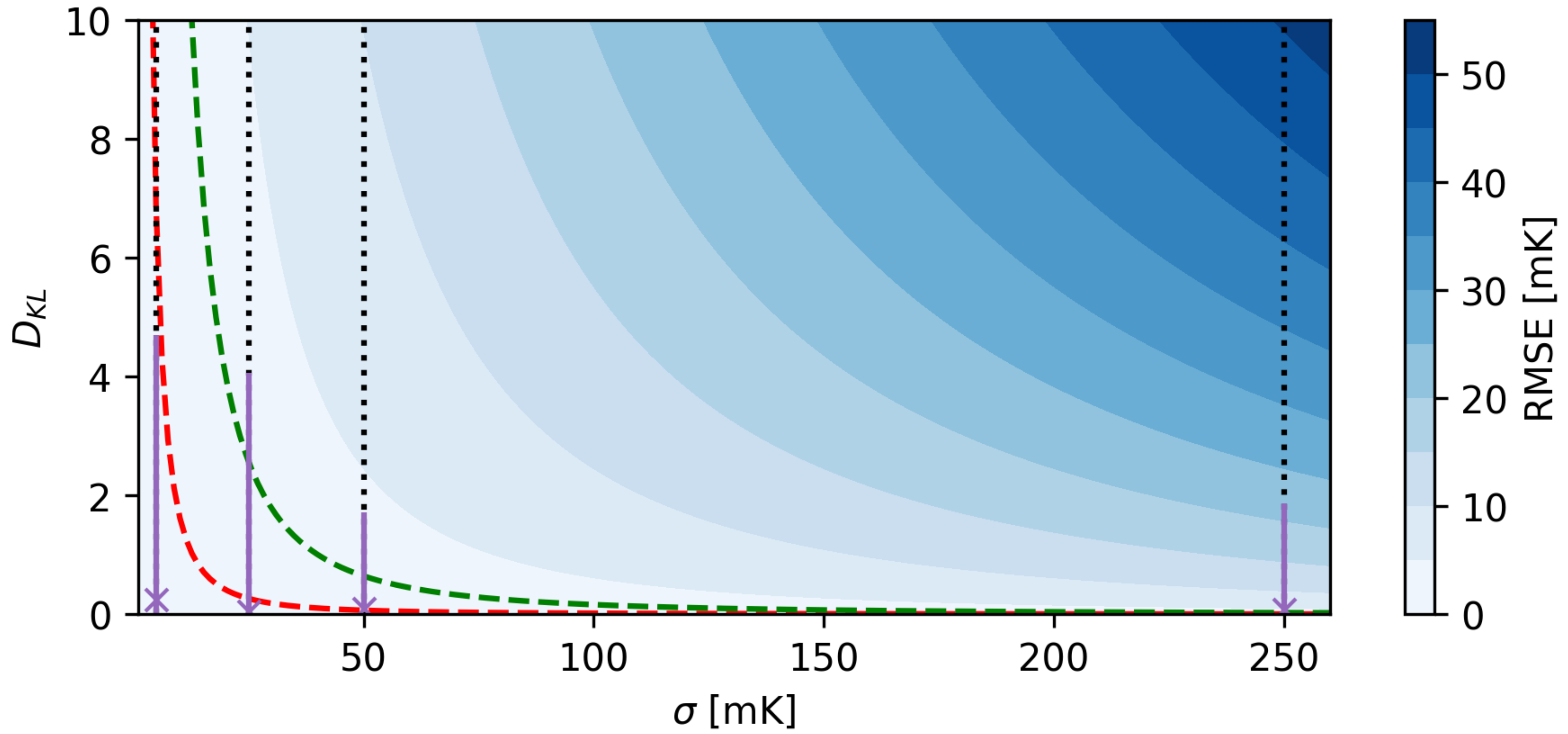
$$P_\epsilon(\theta | D, M_\epsilon) \neq P(\theta | D, M)$$

- We measure errors in our emulator in the functional space e.g. $\epsilon \propto |T_{true} - T_{pred}|$

- Bevins et al. MNRAS 2025, 2503.13263

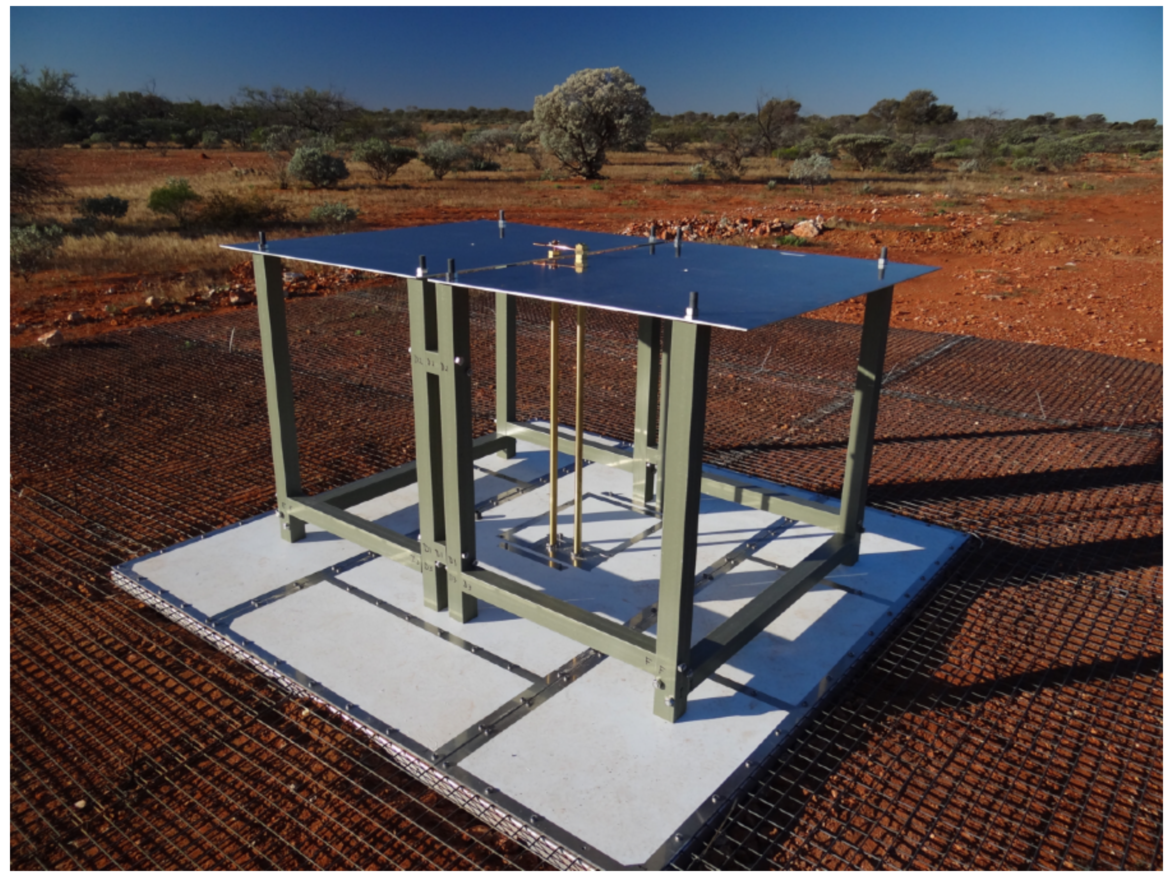
$$D_{\mathrm{KL}}(P || P_\epsilon) = \frac{N}{2}\left(\frac{\epsilon}{\sigma}\right)^2$$



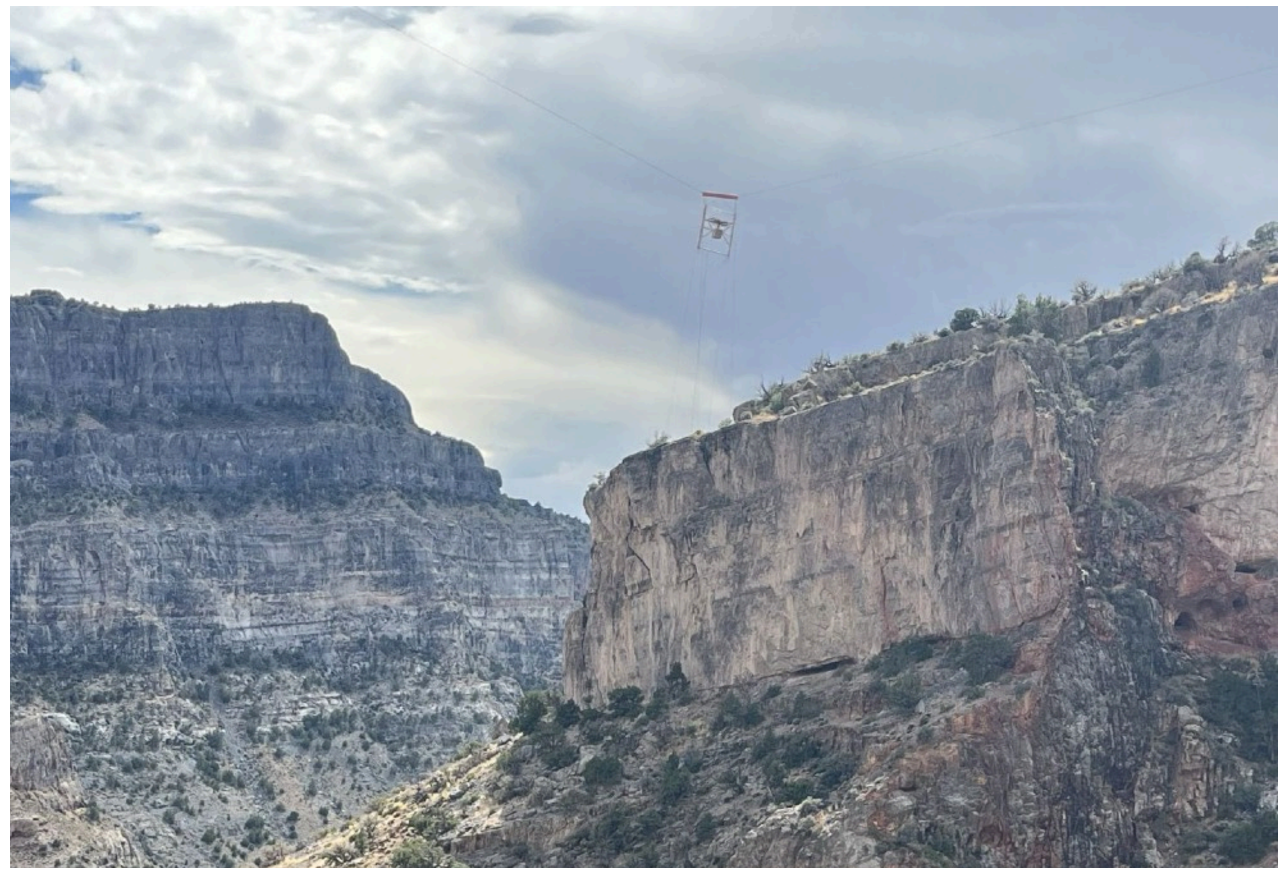



# Current State of Observations

# Lots of different approaches to 21-cm Cosmology

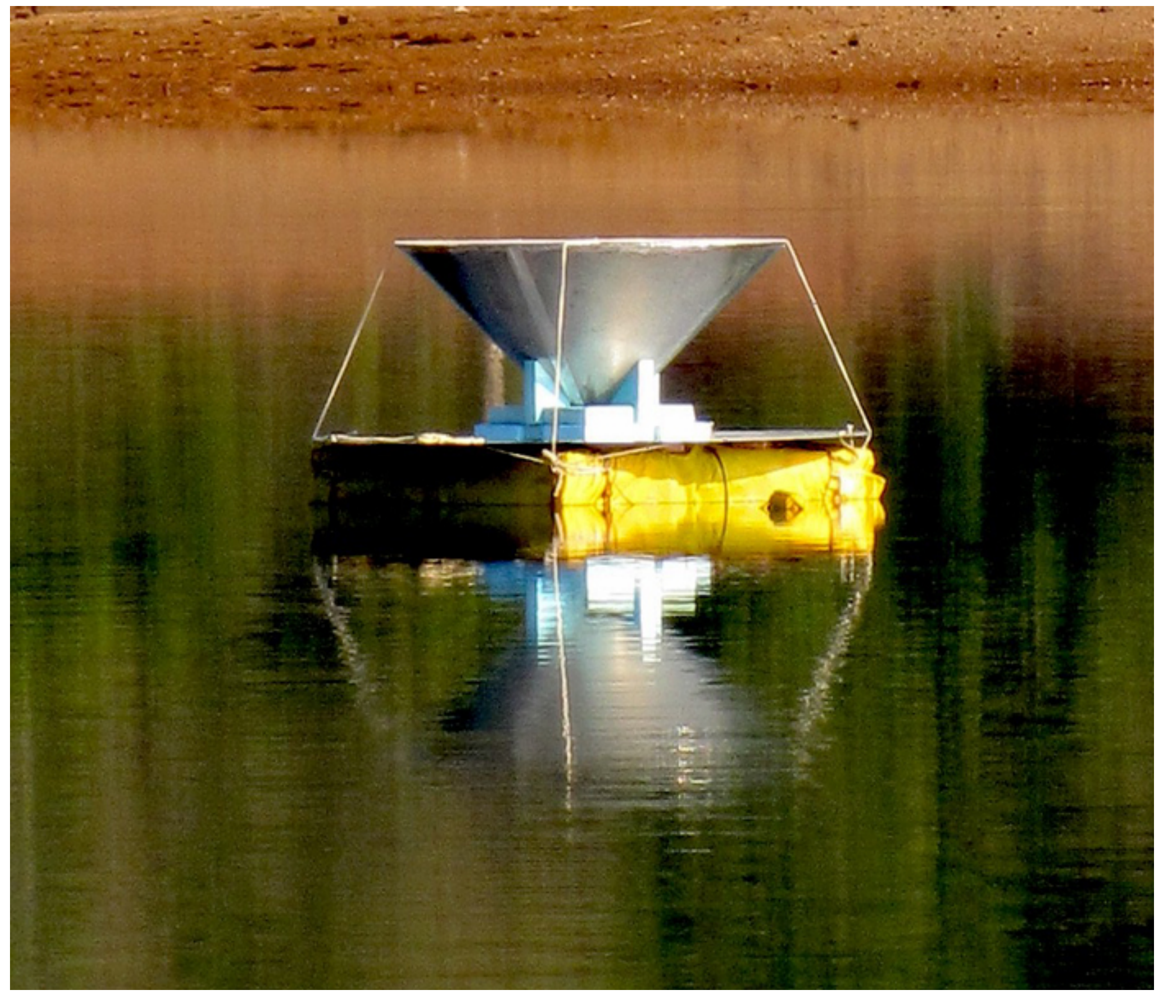


EDGES



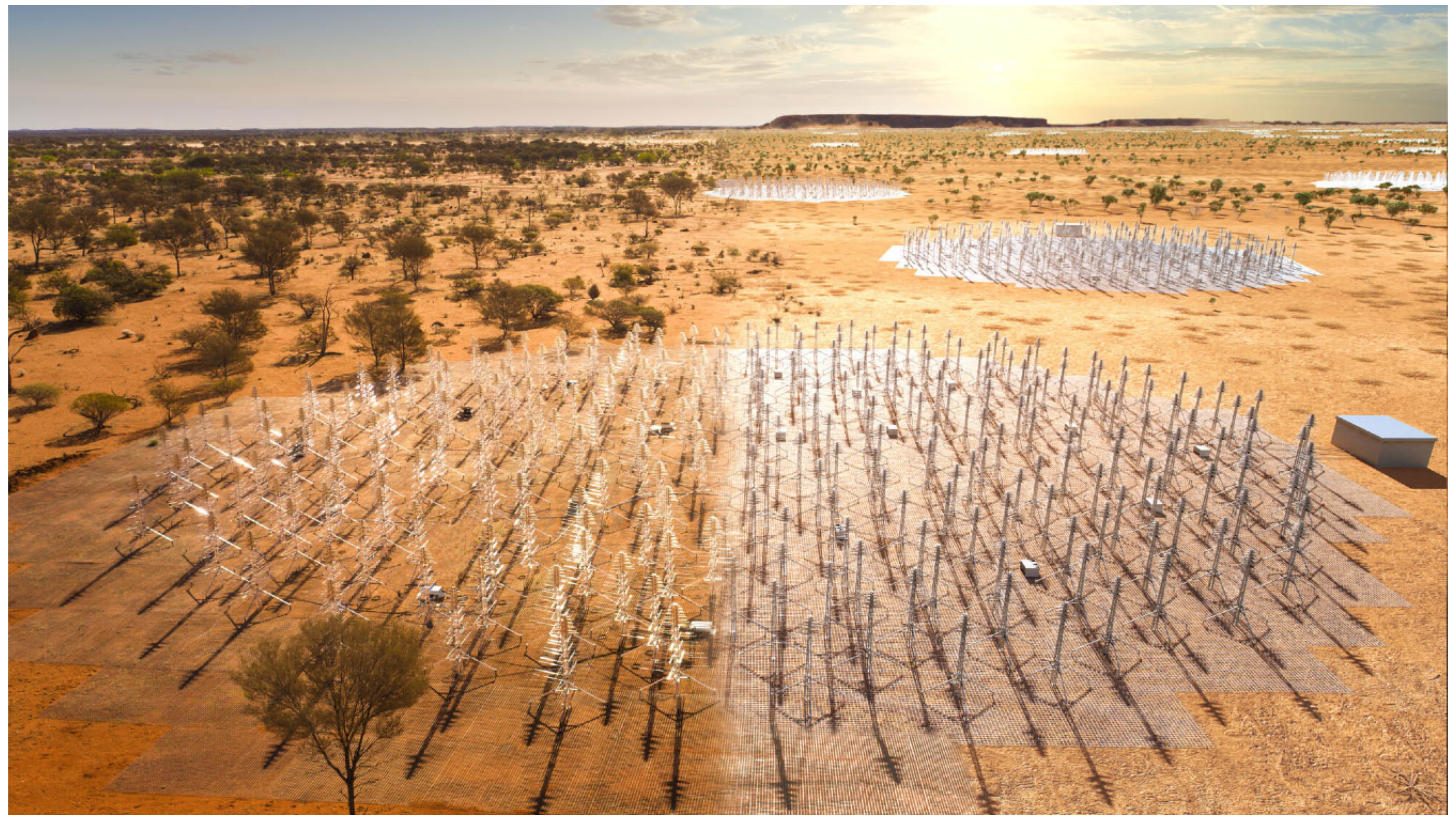
EIGSEP

HERA



SARAS

RHINO

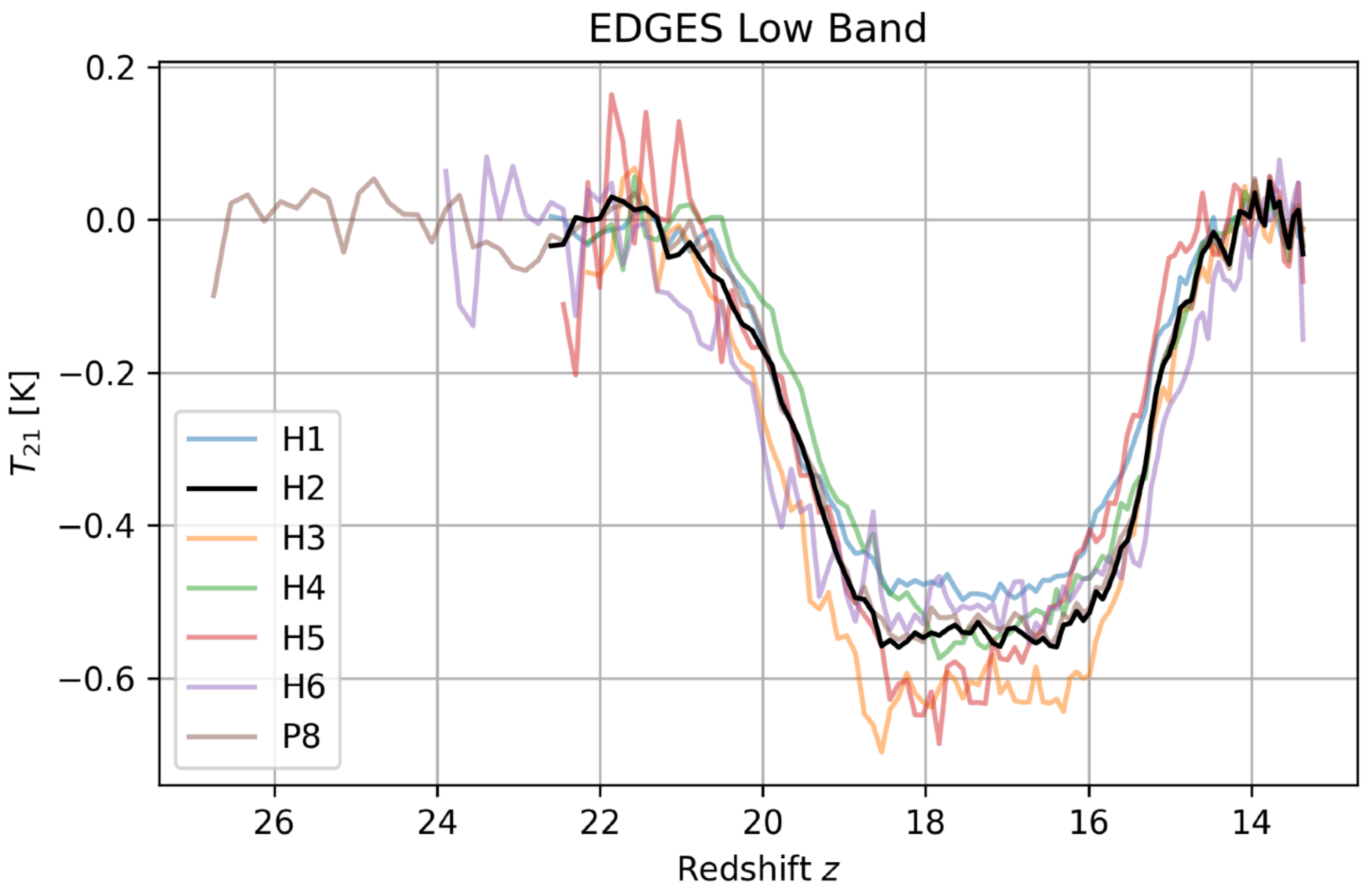


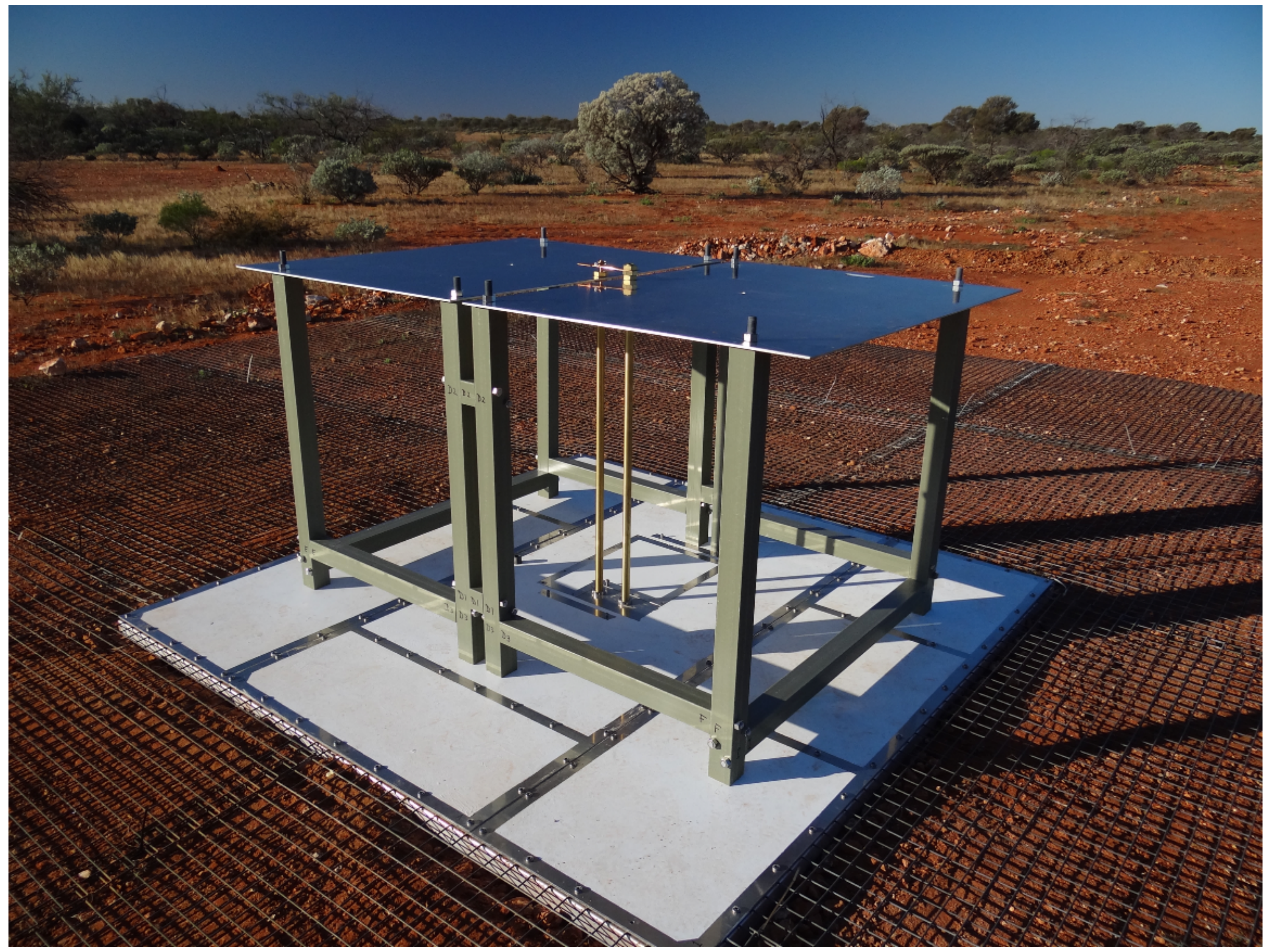
SKA Low

**…and many more!**

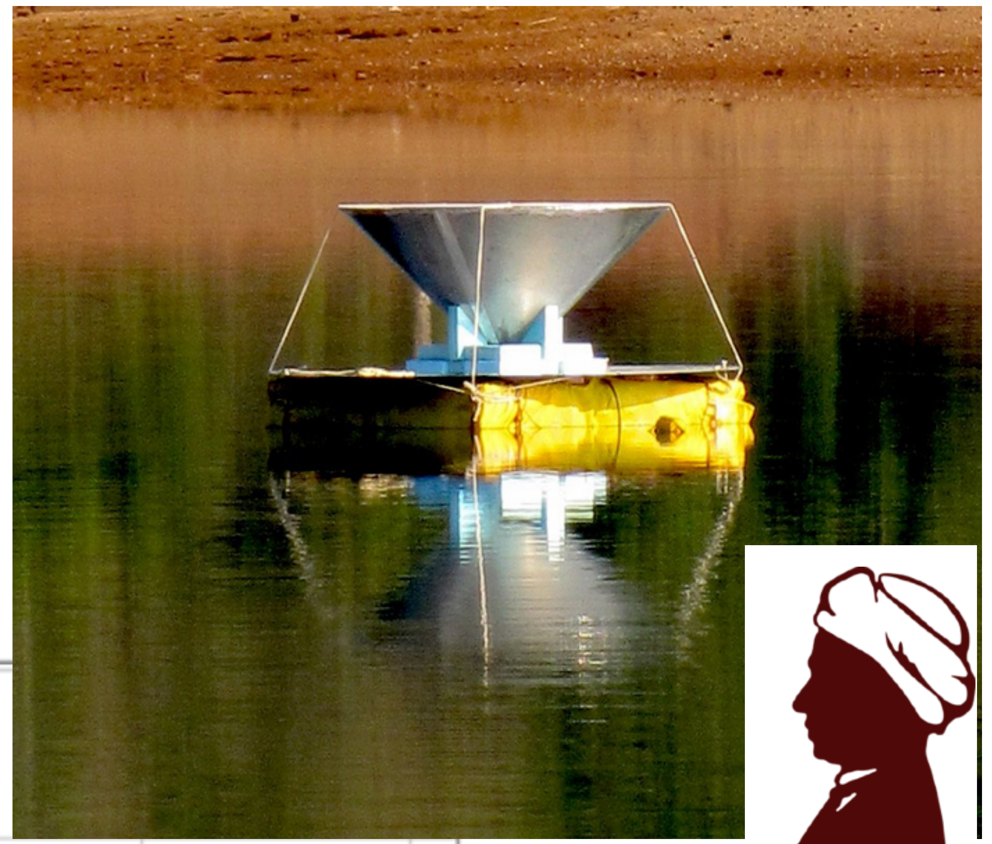
# EDGES

- EDGES low band instrument (Bowman et al. 2018)
- Uncertainty about cosmological nature of the signal if real
- Signal is much deeper than expected and the shape is hard to explain
- Excess radio background above the CMB (e.g. Reis et al. 2020)
- Cooling of the gas via dark matter-baryon interactions (e.g. Driskell et al. 2022)
- Systematics and no 21-cm signal (Bevins et al. MNRAS 2021, 2007.14970)

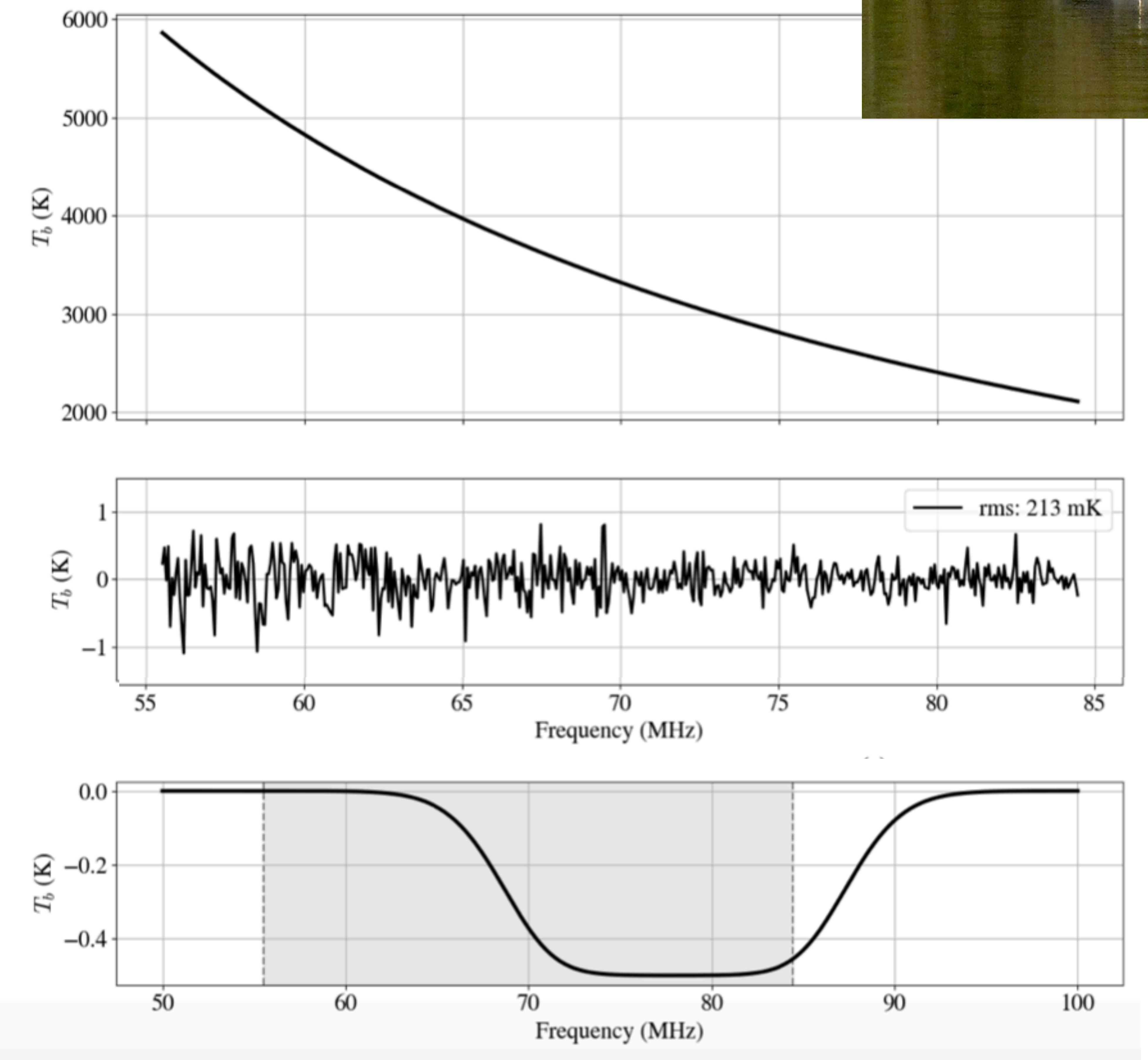


# SARAS3



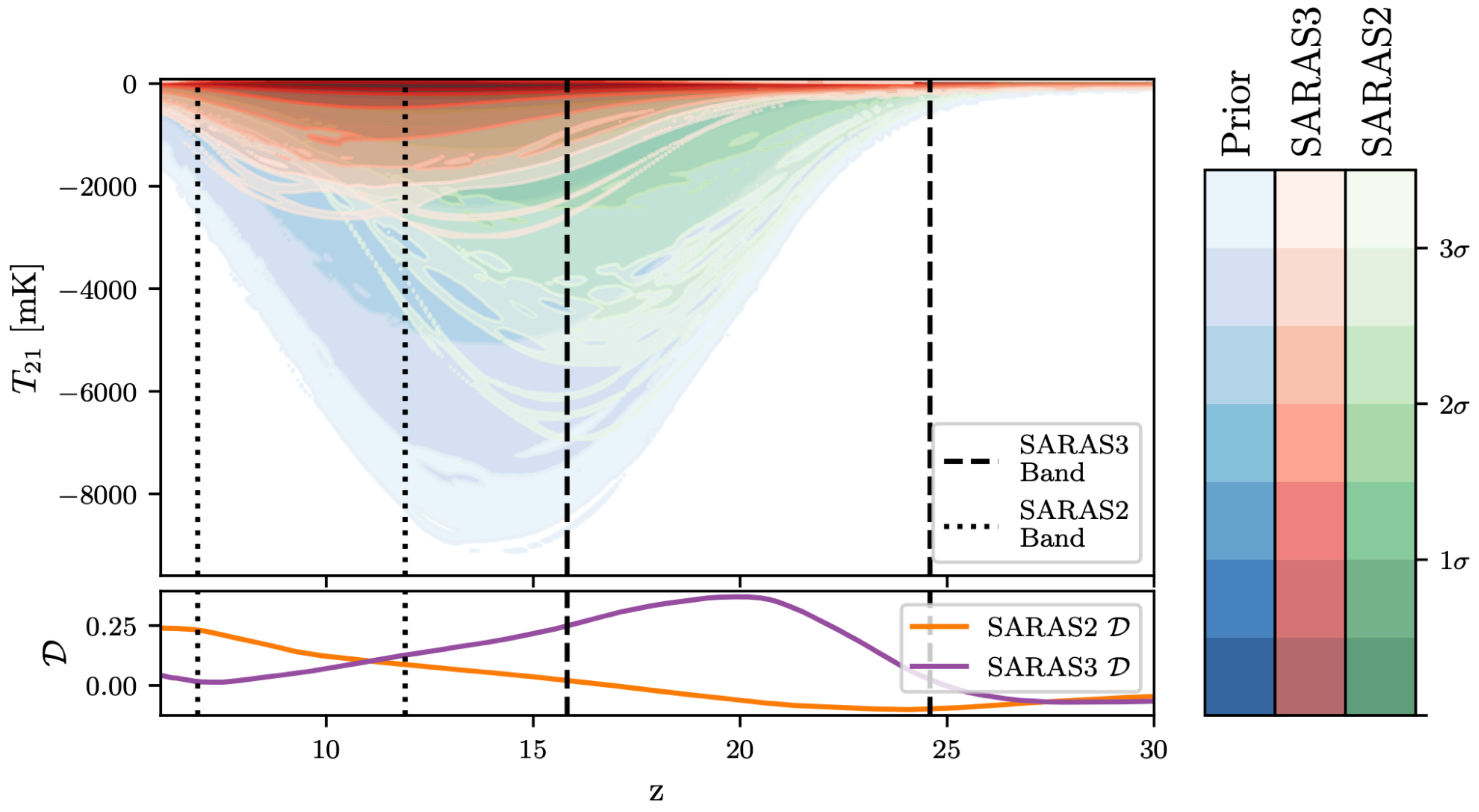
- SARAS3 recently disputed the EDGES detection at 95% confidence (Singh et al. 2021)
- Very different to the EDGES instrument
- No evidence for the EDGES signal in their data
- Use the data as an upper limit on the magnitude of the 21-cm signal after removing a model for the foregrounds

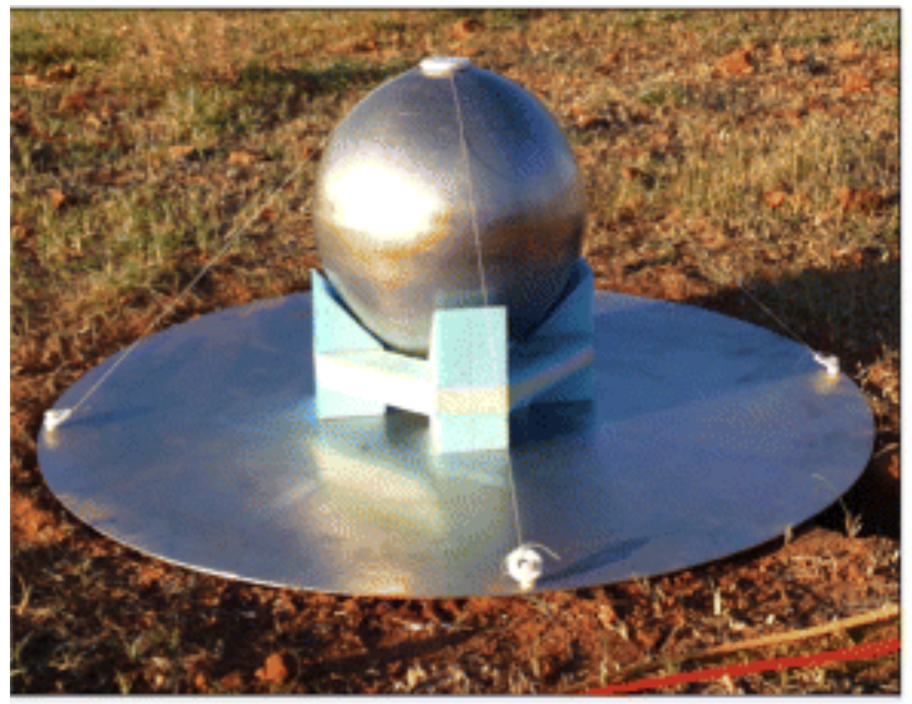


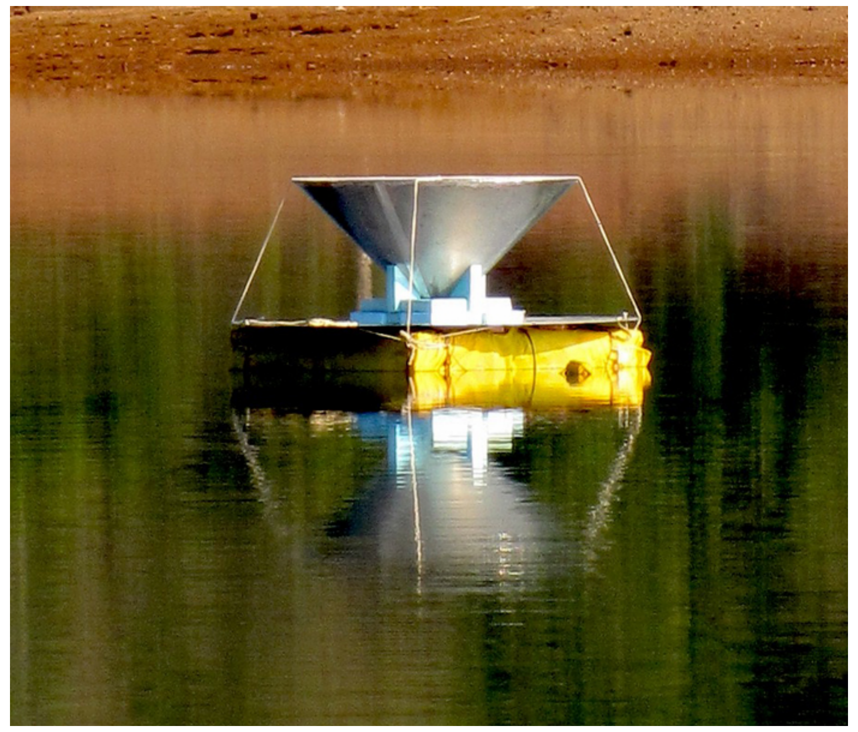

RRI

# Constraining the properties of the infant universe

- Bevins et al. MNRAS 2022, 2201.11531 - SARAS2 in a Bayesian framework
- Bevins et al. Nature Astronomy 2022, 2212.00464 - Analysed SARAS3 data
- Placed constraints on the magnitude of the 21-cm signal
- Using emulators for inference on physical signals

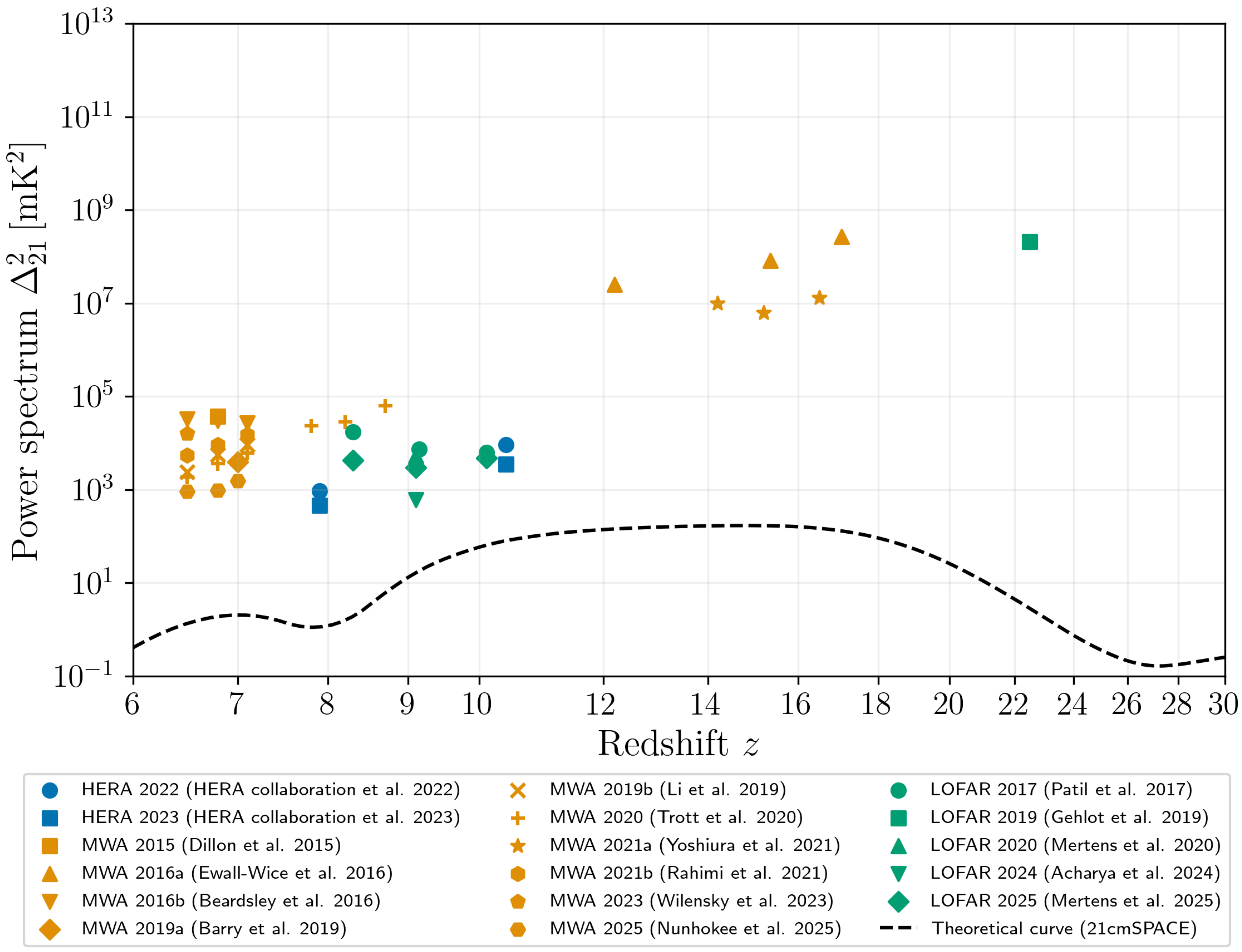




RRI

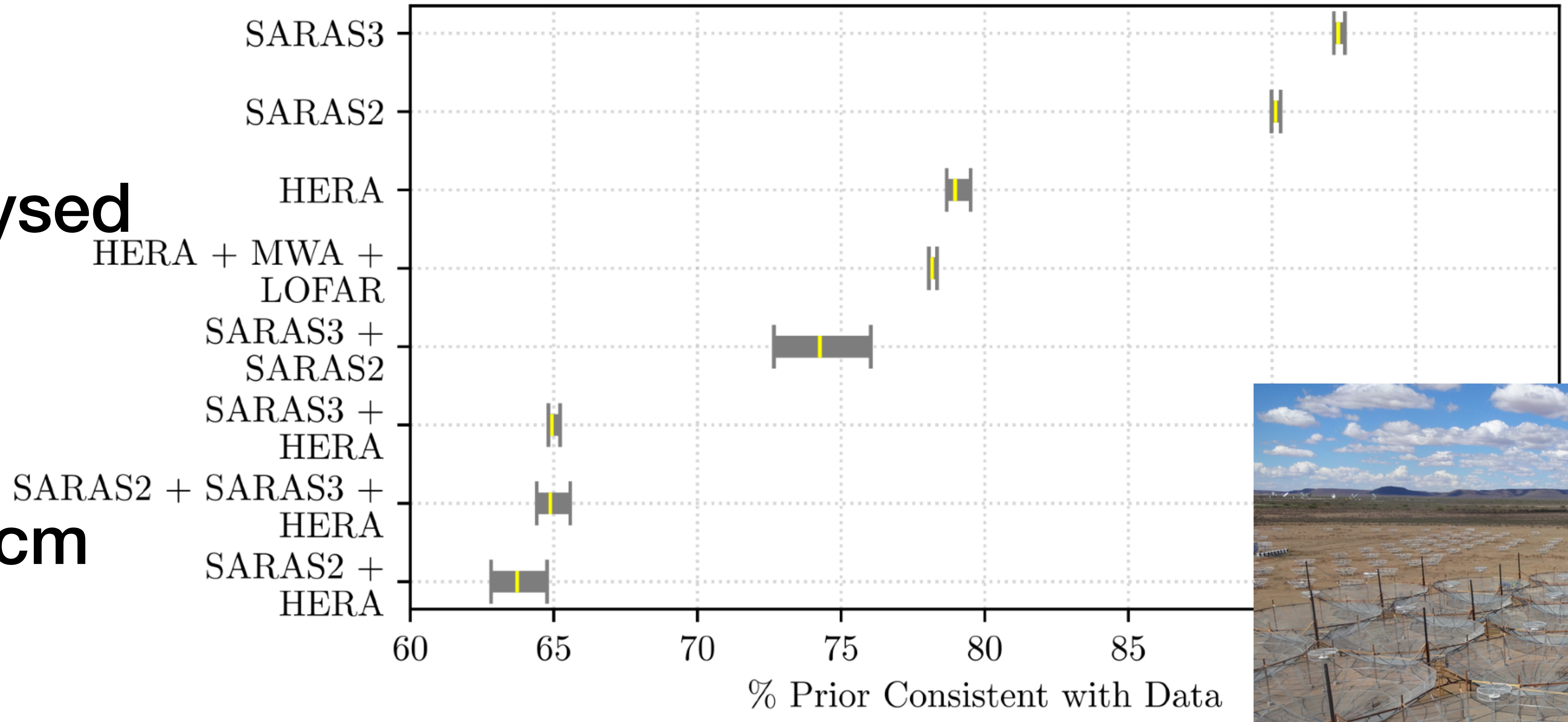
# Power Spectrum Upper Limits






# Constraining the properties of the infant universe

- Bevins et al 2024 MNRAS - jointly analysed SARAS2, SARAS3, HERA, LOFAR and MWA data
- First joint analysis of sky-averaged 21-cm experiments and power spectrum observations
- Constrained contribution of high redshift galaxies to the radio background and X-ray heating
- Used normalising flows (*margarine* Bevins et al. MNRAS 2022, 2205.12841)



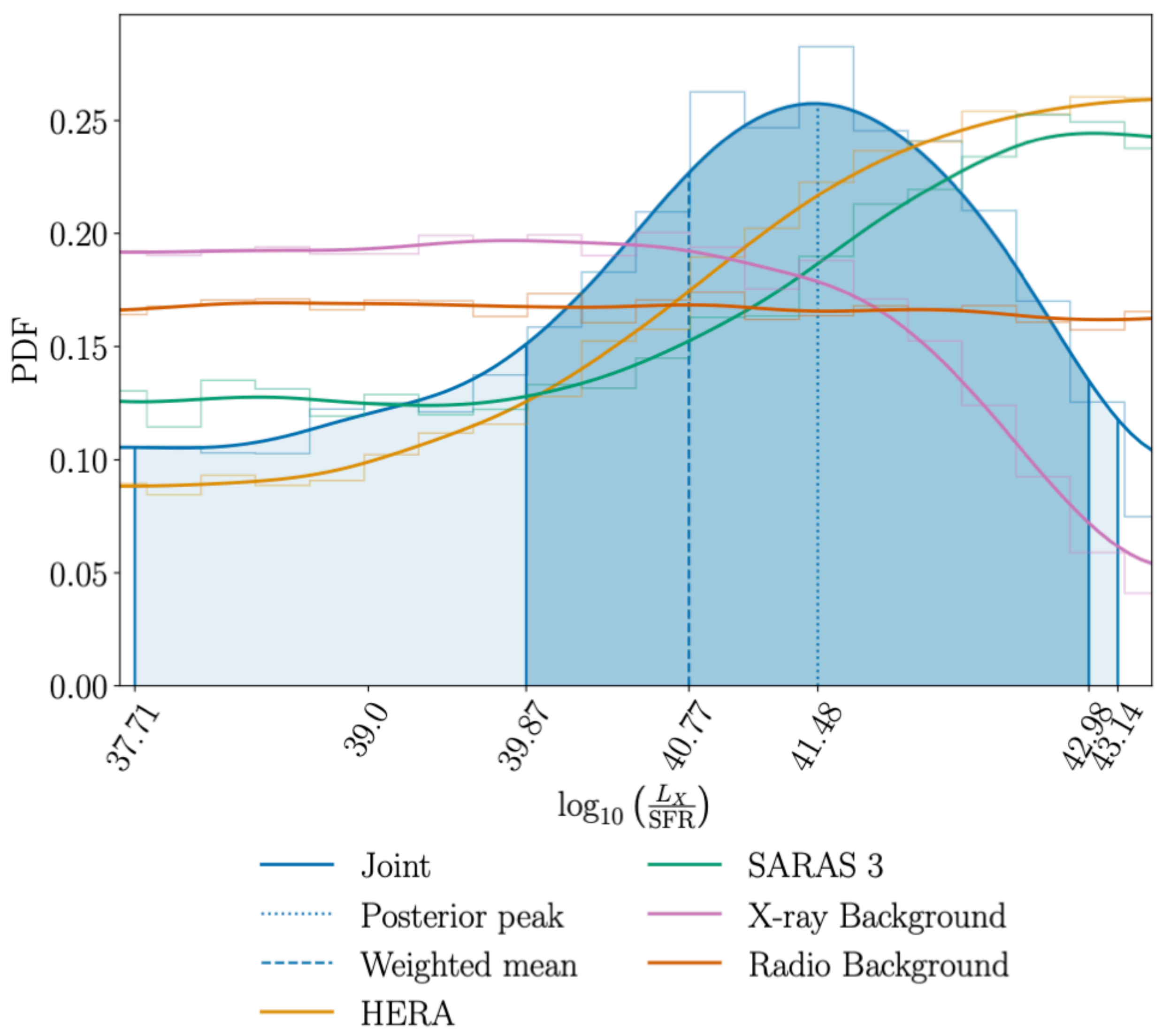

HERA

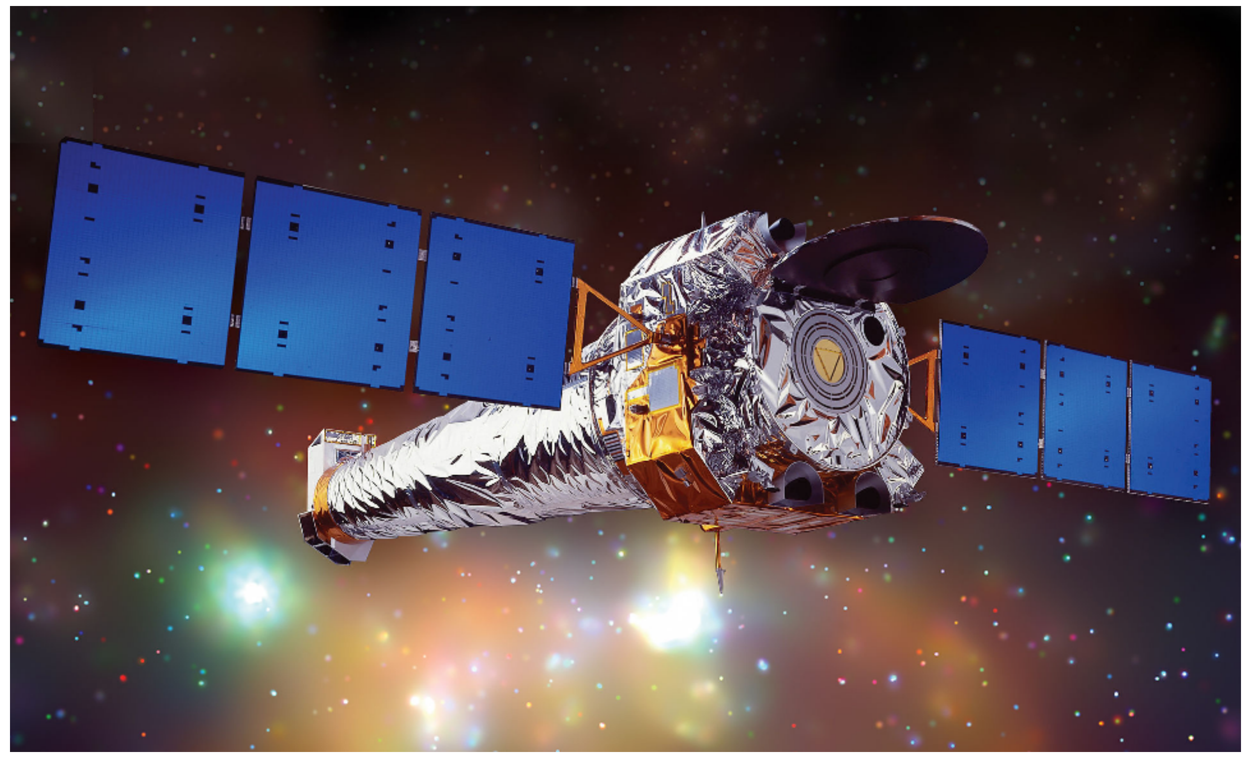
MWA
MURCHISON
WIDEFIELD
ARRAY

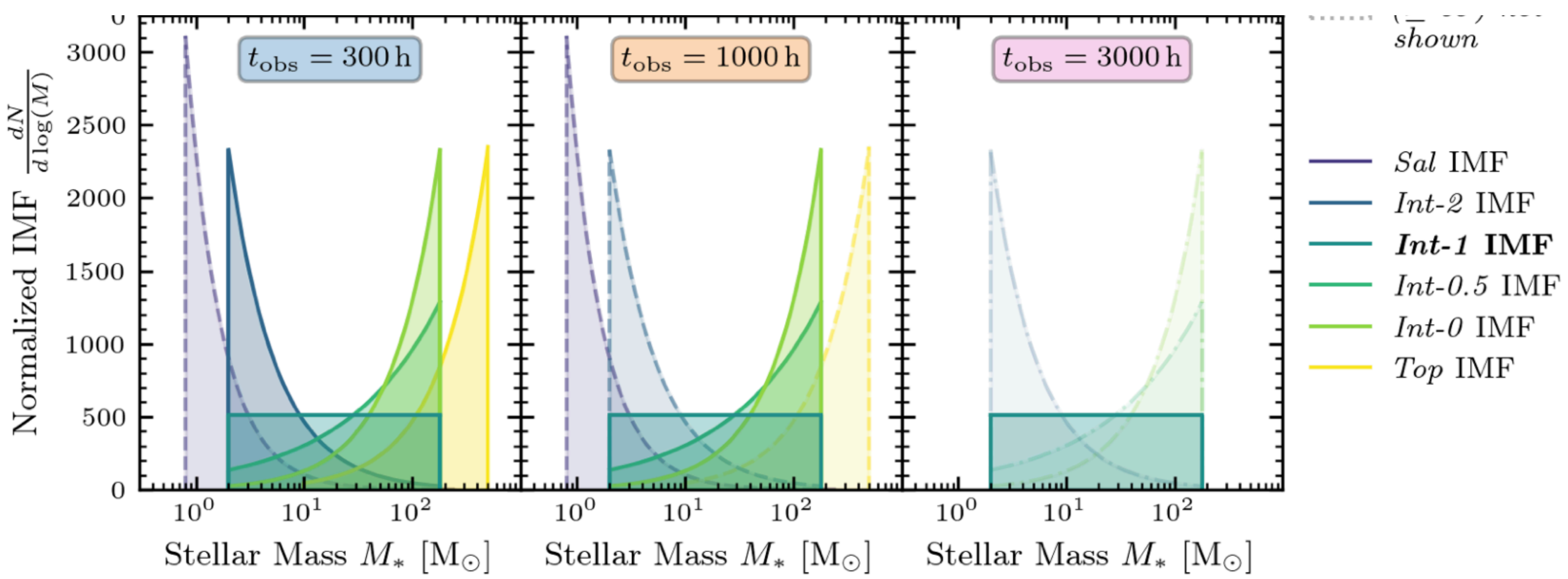
LOFAR

# Constraining the properties of the infant universe

- Pochinda, Gessey-Jones, Bevins et al. MNRAS 2024, 2312.08095 - X-ray and Radio Background observations
- Gessey-Jones, Pochinda, Bevins et al. MNRAS 2024, 2312.08828 - Cosmic strings as a source of excess radio background
- Sims, Bevins et al. MNRAS 2025 2504.09725- Lyman line and CMB observables
- Gessey-Jones, Sartorio, Bevins et al. 2025 Nature Astronomy 2025, 2502.18098 - Forecast constraints of REACH and the SKA on the Population III IMF





# Constraining the properties of the infant universe

- Dhandha et al. MNRAS 2025a 2025b incl. HB 2503.21687

- Took data from HERA and SARAS and combined it with

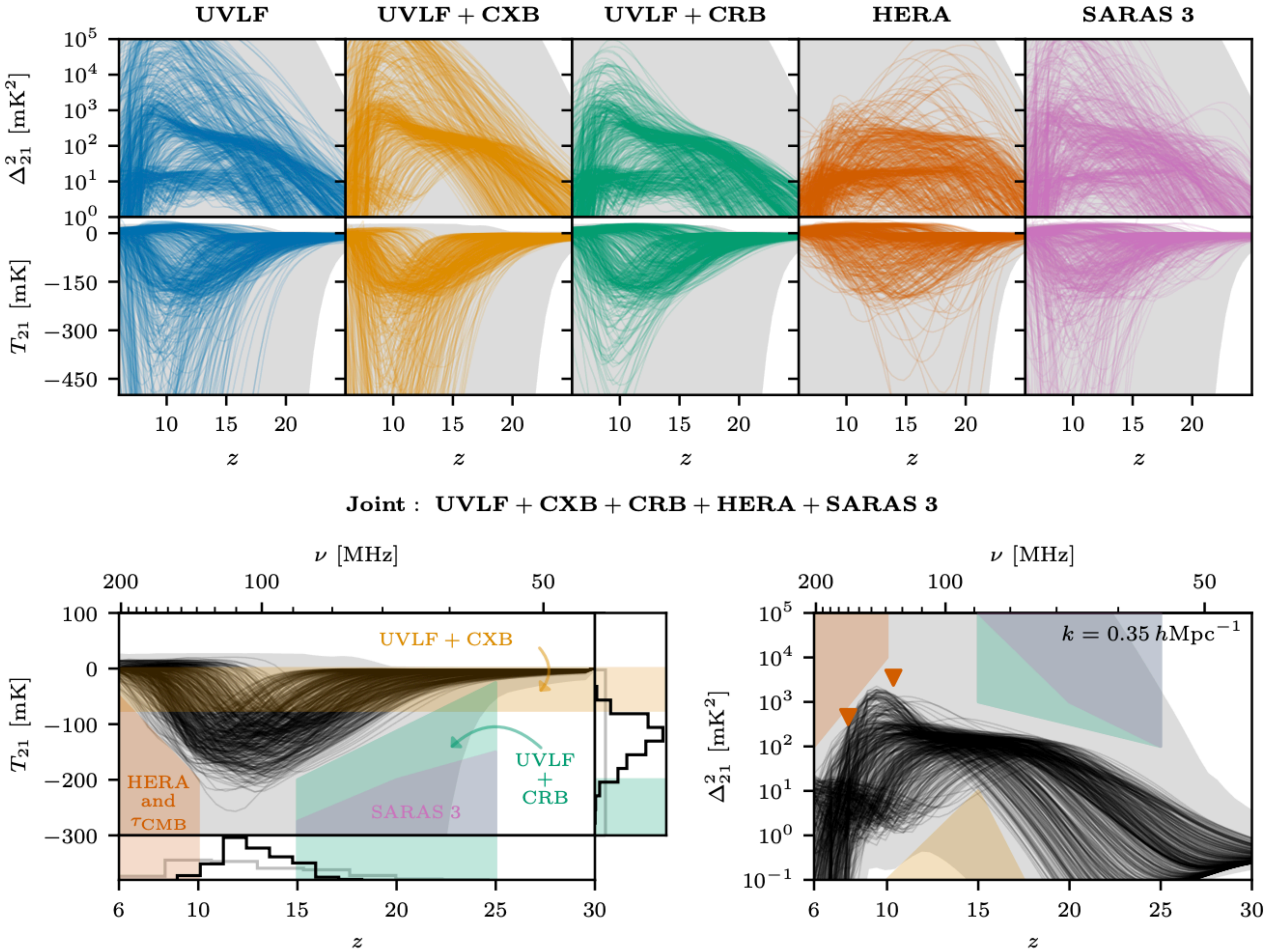
  - Measurements of the unresolved X-ray background

  - Measurements of the X-ray background

  - UV Luminosity Functions from Hubble and JWST

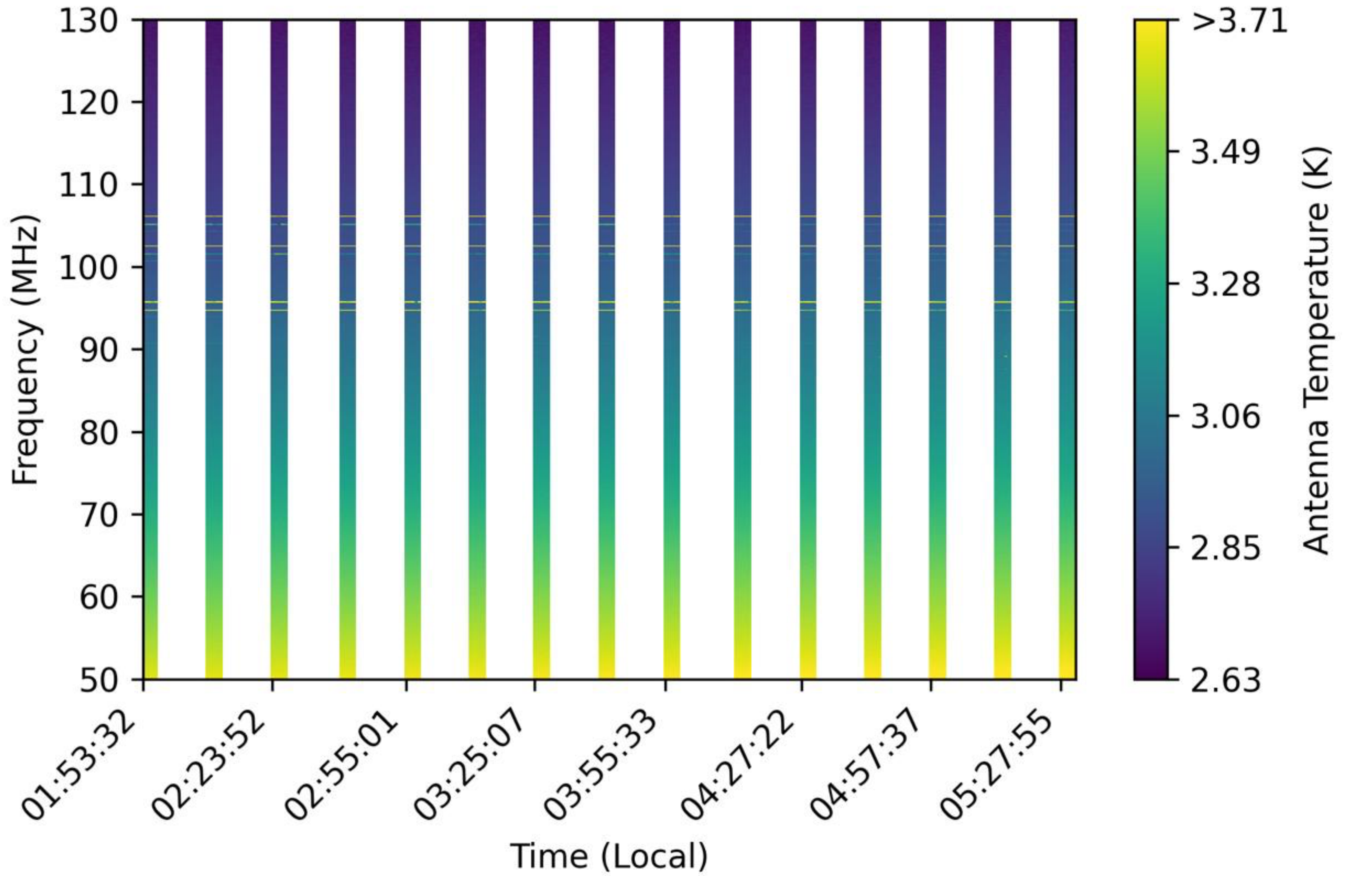
- Put limits on the magnitude of the 21-cm signal

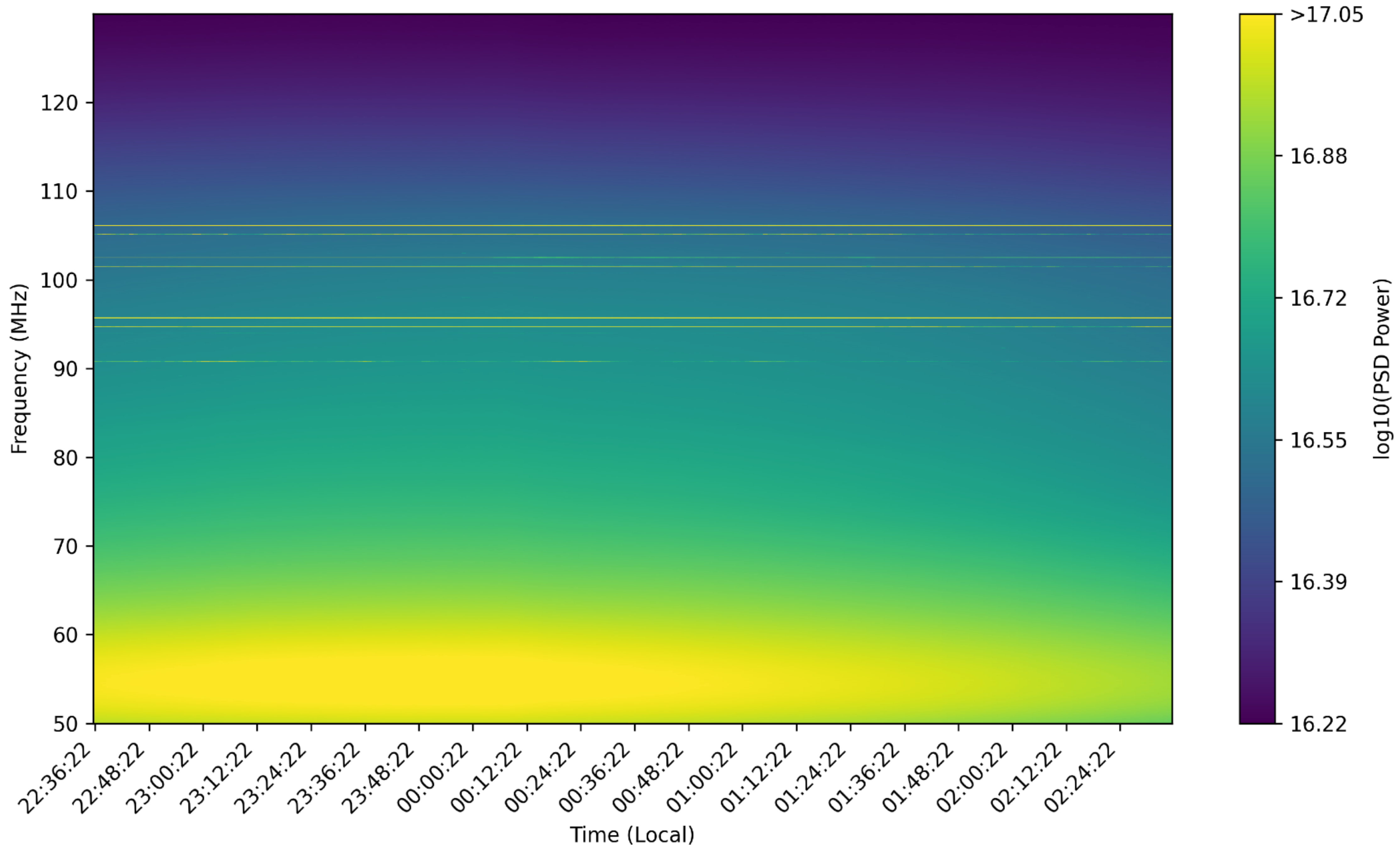
$$-201\ \mathrm{mK}\ \lesssim T_{21,\mathrm{min}} \lesssim -68\ \mathrm{mK}$$



# REACH

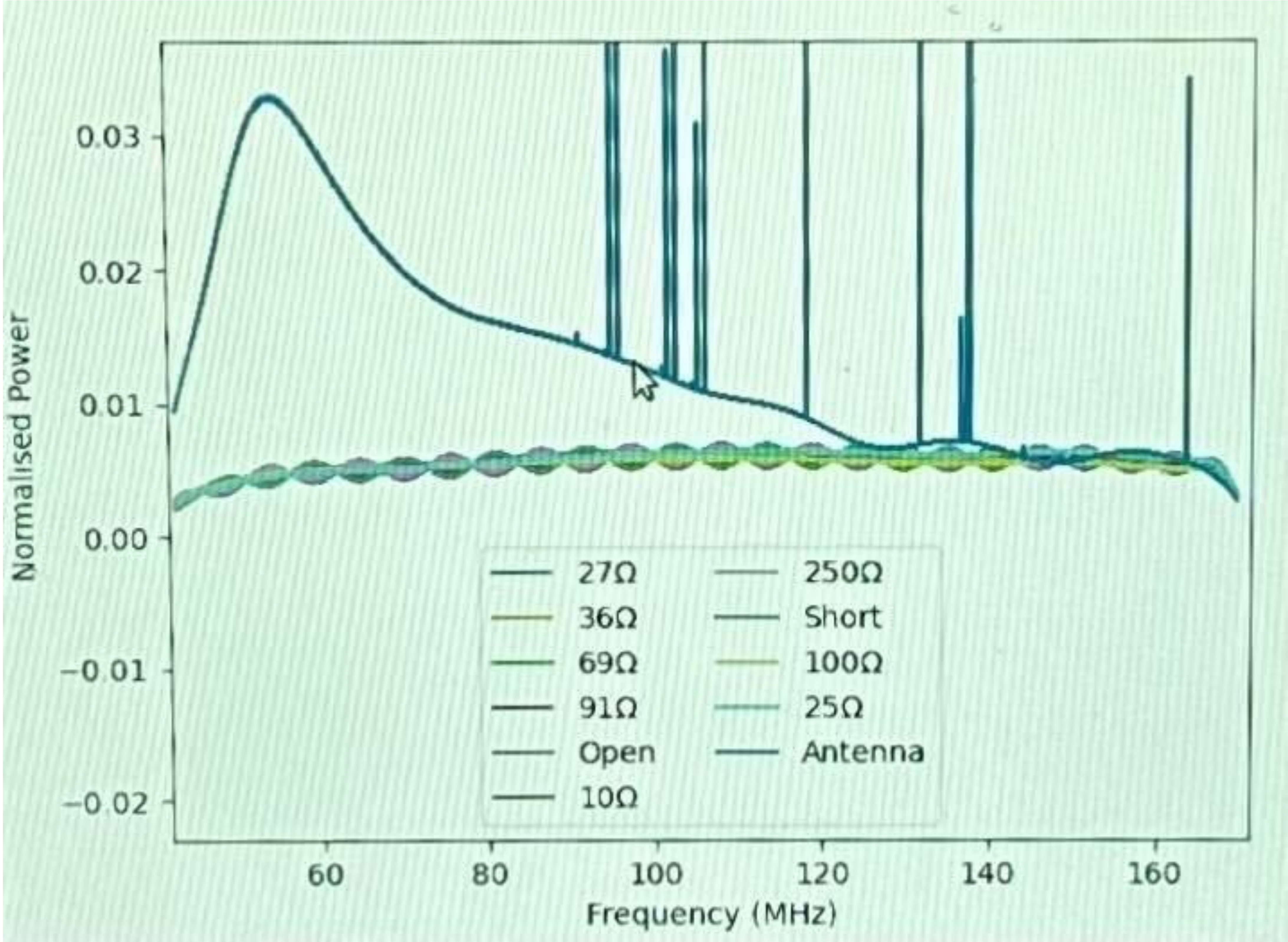
- We have roughly 310 hours of on sky data
- Most of our observations cycle through calibrators and the antenna
- This helps us keep track of any system drift
- We have a few longer observations
- Really been in a commissioning phase but we are gaining in confidence
- We have solved many many issues!

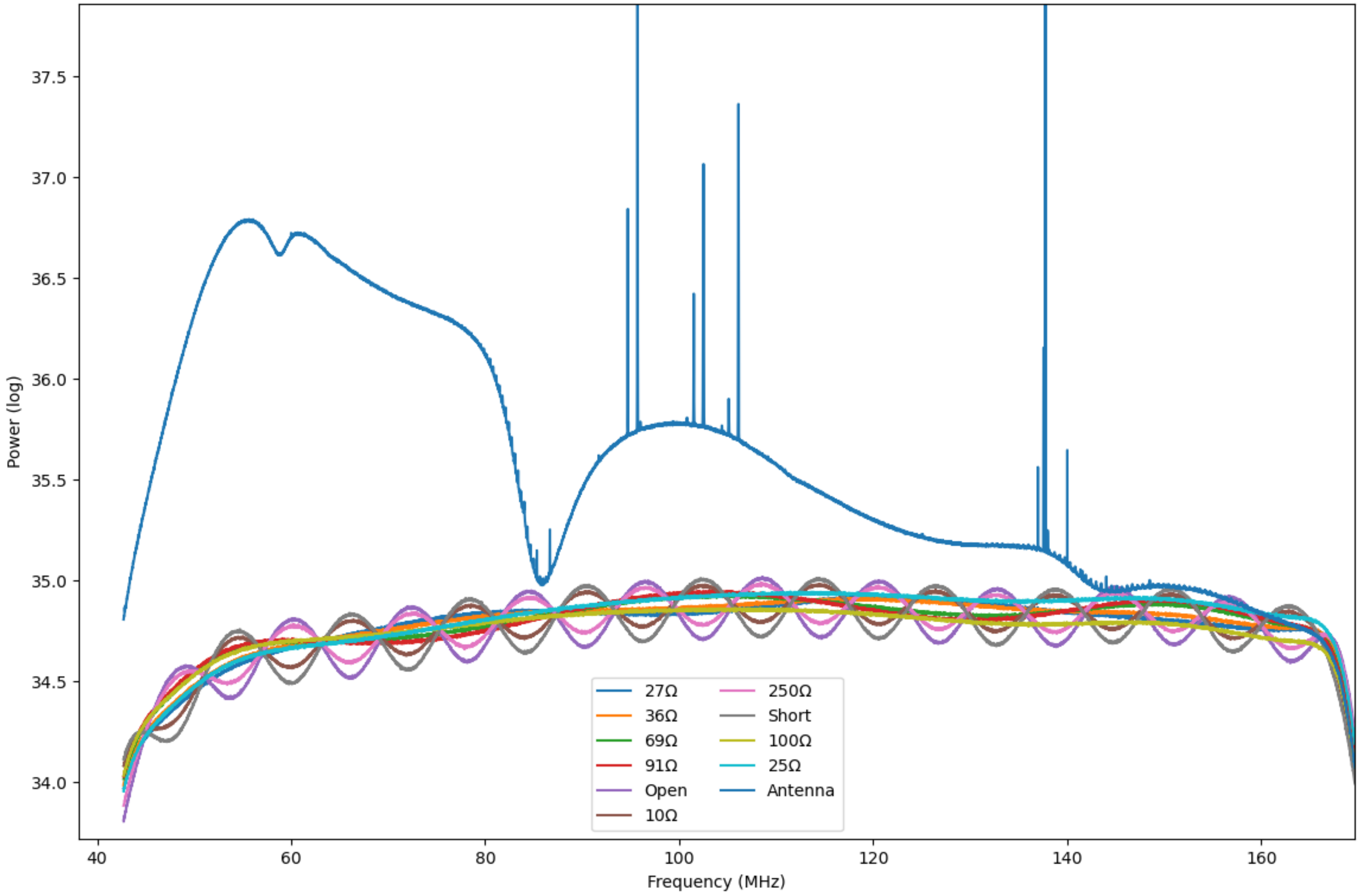


# REACH

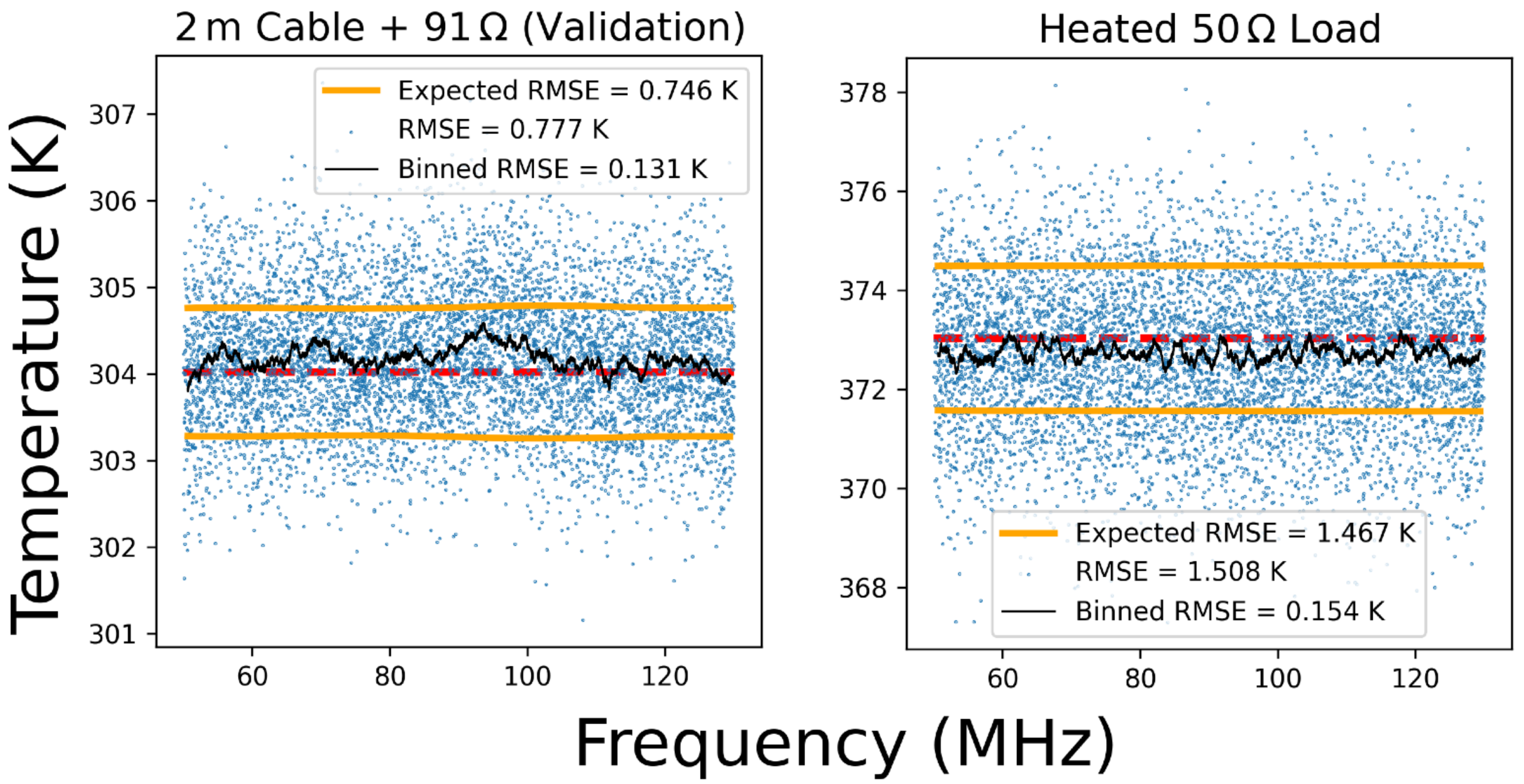
# REACH

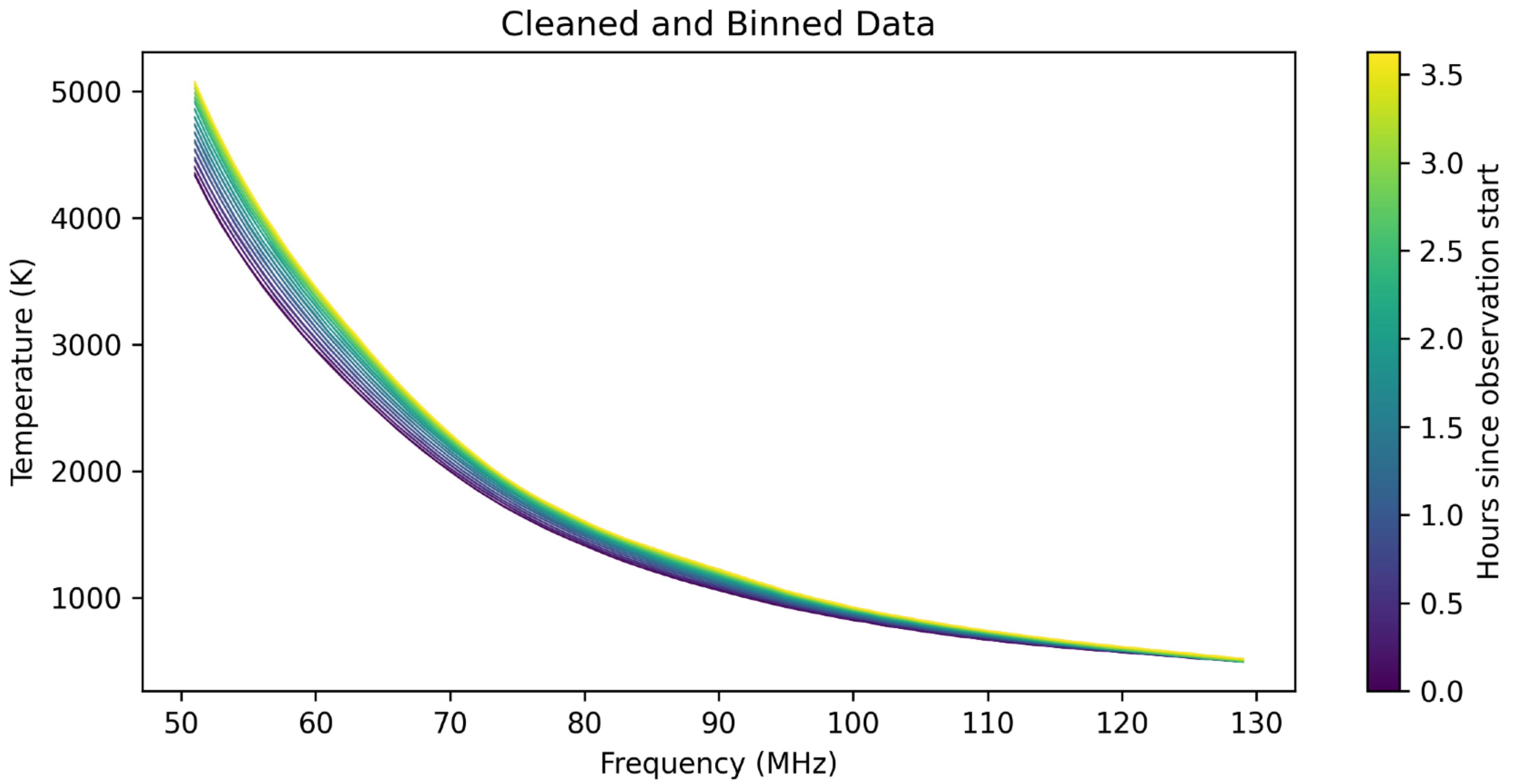

Normalised Power
0.03
0.02
0.01
0.00
−0.01
−0.02
60
80
100
120
140
160
Frequency (MHz)
27Ω
36Ω
69Ω
91Ω
Open
10Ω
250Ω
Short
100Ω
25Ω
Antenna


Power (log)
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
40
60
80
100
120
140
160
Frequency (MHz)
27Ω
36Ω
69Ω
91Ω
Open
10Ω
250Ω
Short
100Ω
25Ω
Antenna

# REACH

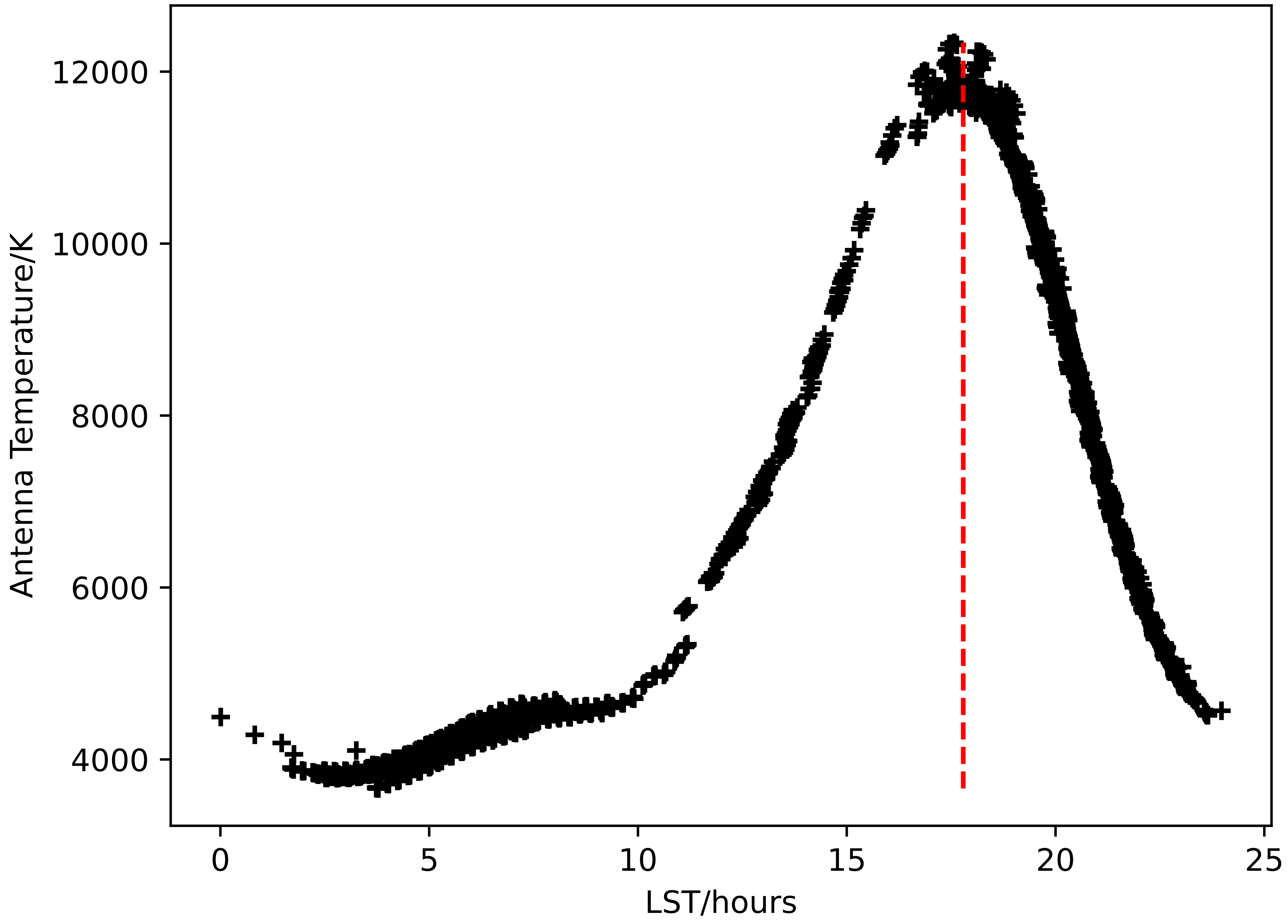
- Our calibration has improved significantly
- This is an observation from November 2024
- Approaching the expected noise level (Kirkham et al. MNRAS 2024 incl. HB, 2412.14023)
- Antenna residuals of around 10 K
- We think there are still a few systematics to deal with but we are starting to think about foreground science



# REACH - Foreground Science

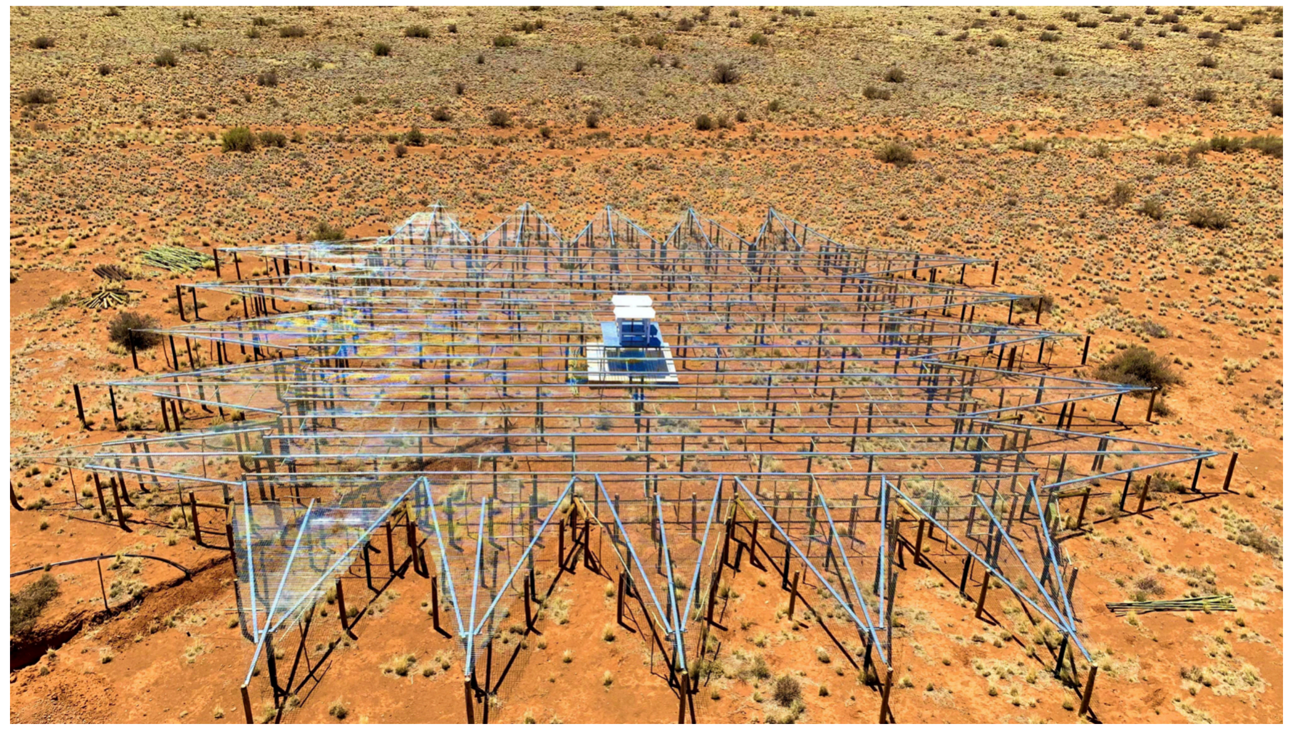
- We can collate the data we have and start to look at how the sky varies with time
- This is the antenna temperature at 50MHz over LST
- Test the calibration of all sky maps like GSM and calibrate models in the future like B-GSM
- We've also looked at the spectral index of the foreground over time
- Hoping to write these results up in the coming months

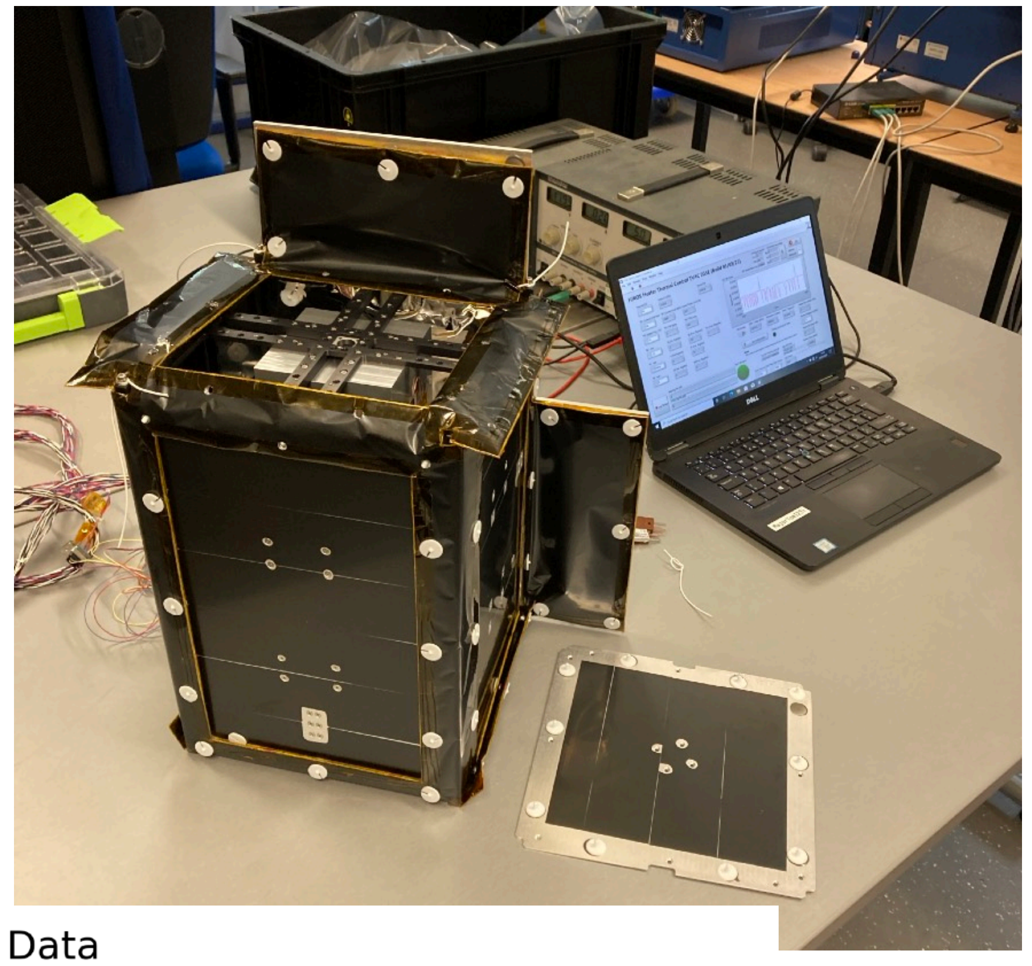


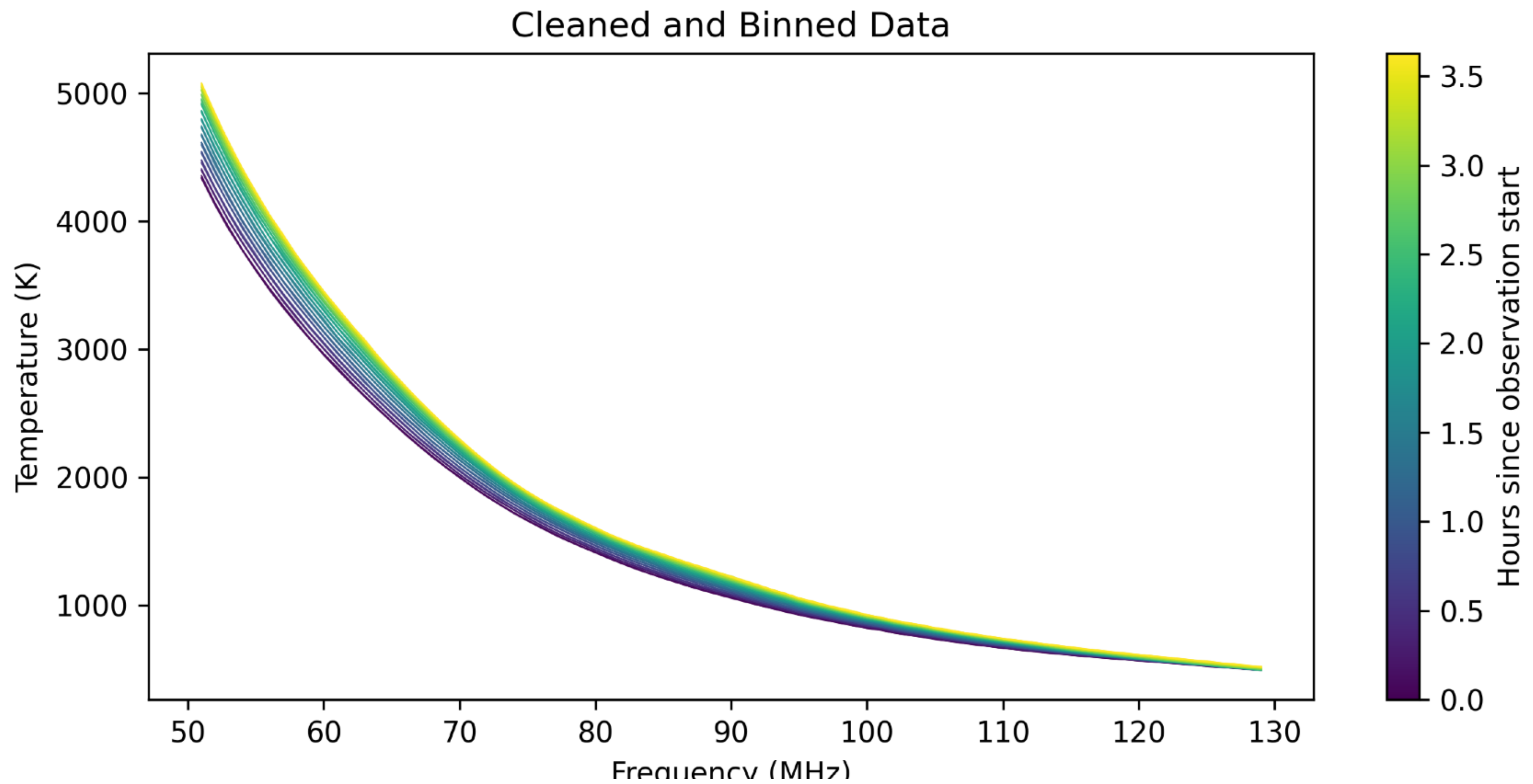
# Conclusions

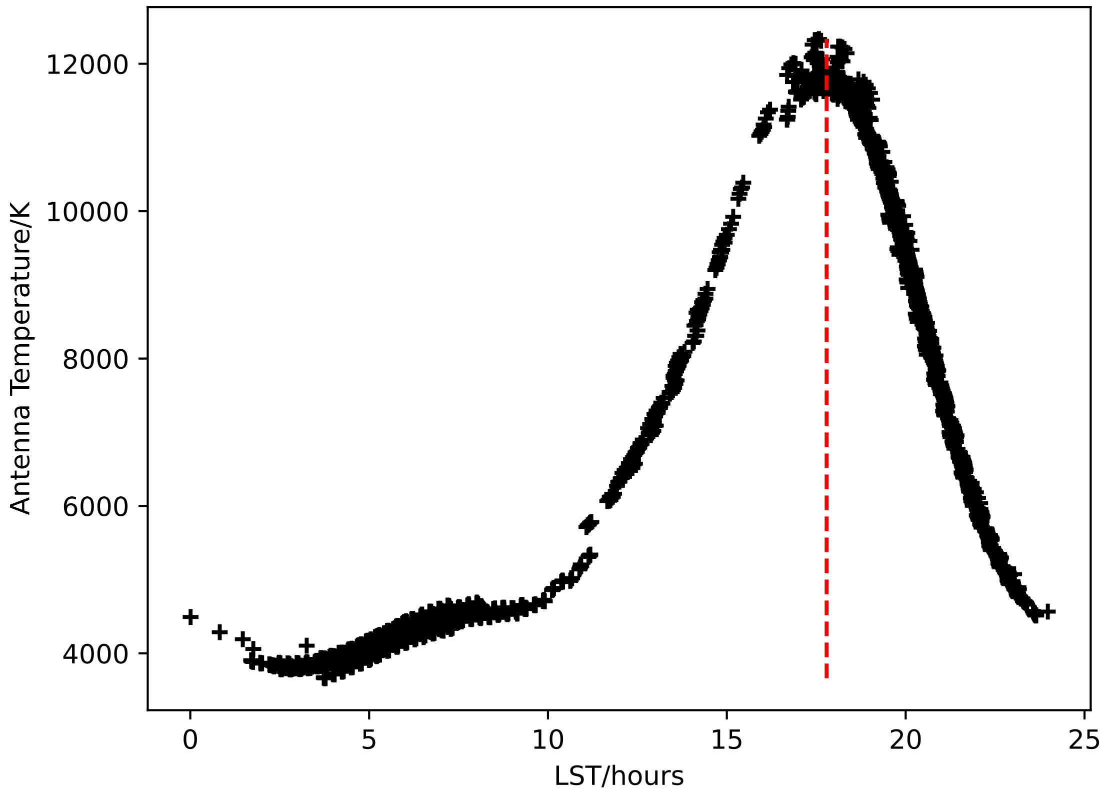
# Learning the infant universe

- 21-cm Cosmology has the potential to unlock a previously unseen epoch in the Universe's history
- Observations are challenging!
- Addressing some of those challenges with Machine Learning
- Demonstrating the power of synergetic analysis
- Exciting new data from REACH and hopefully from the lunar far side in the future!








cosmocube.net
reachtelescope.org
harrybevins.co.uk
github.com/htjb