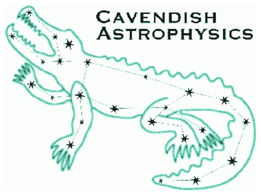
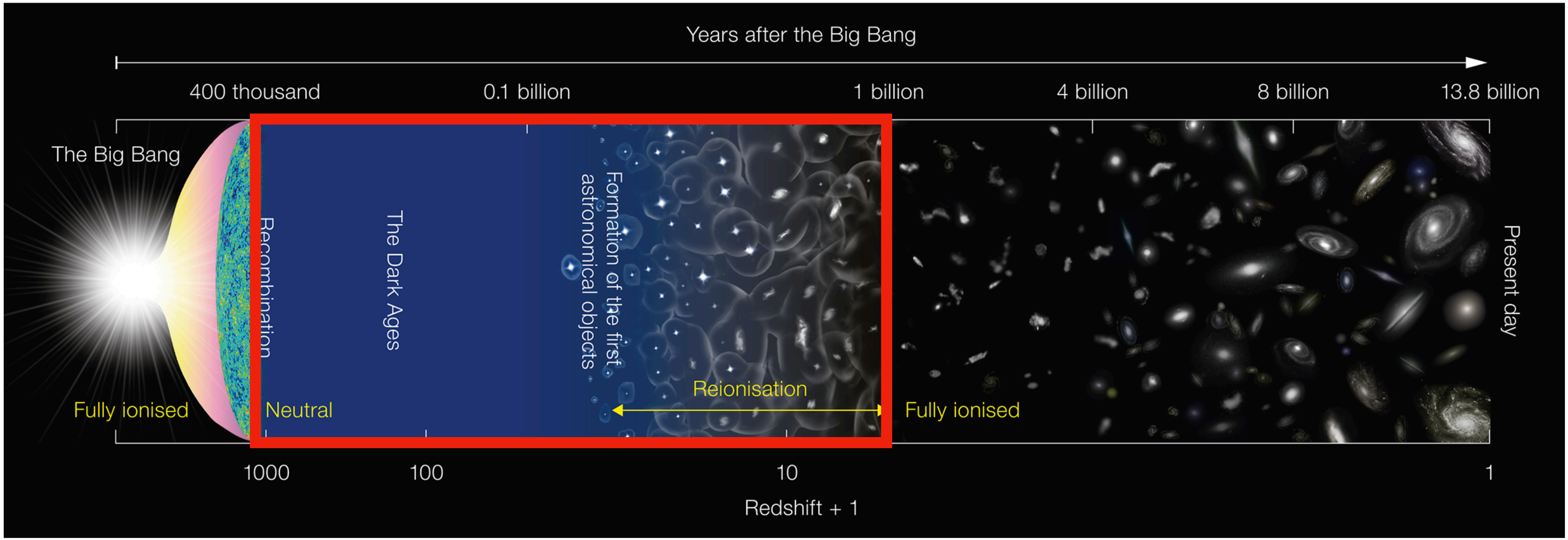
Machine Learning the Infant Universe

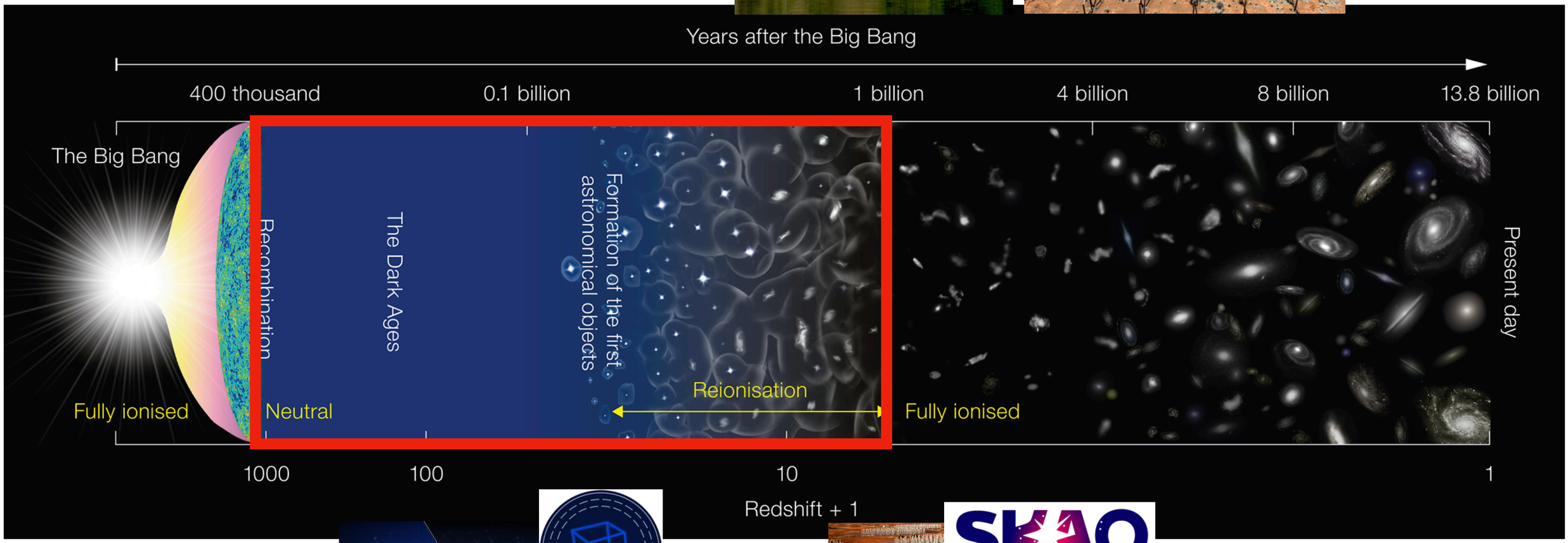
Harry Bevins
Kavli Junior Fellow K32

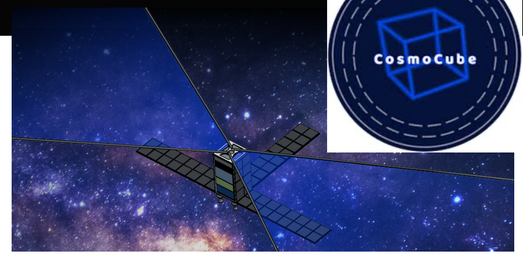


The Infant Universe



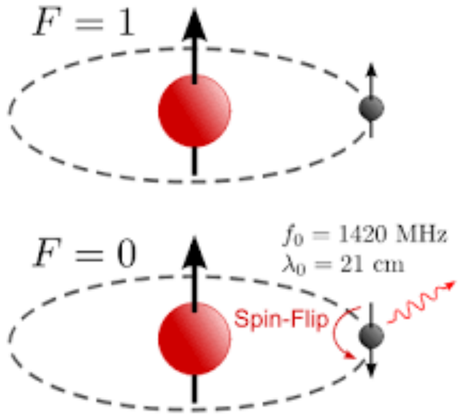
The Infant Universe

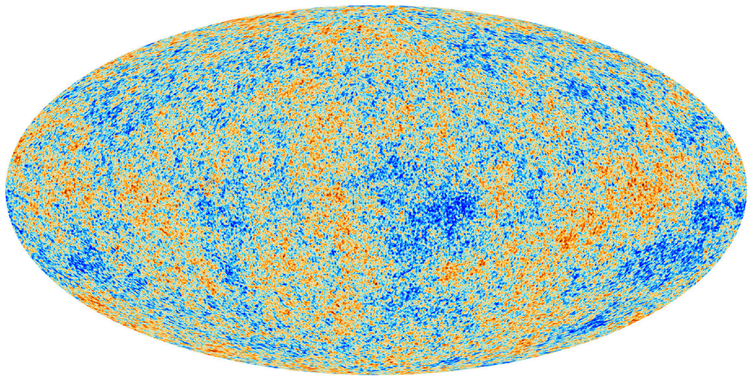




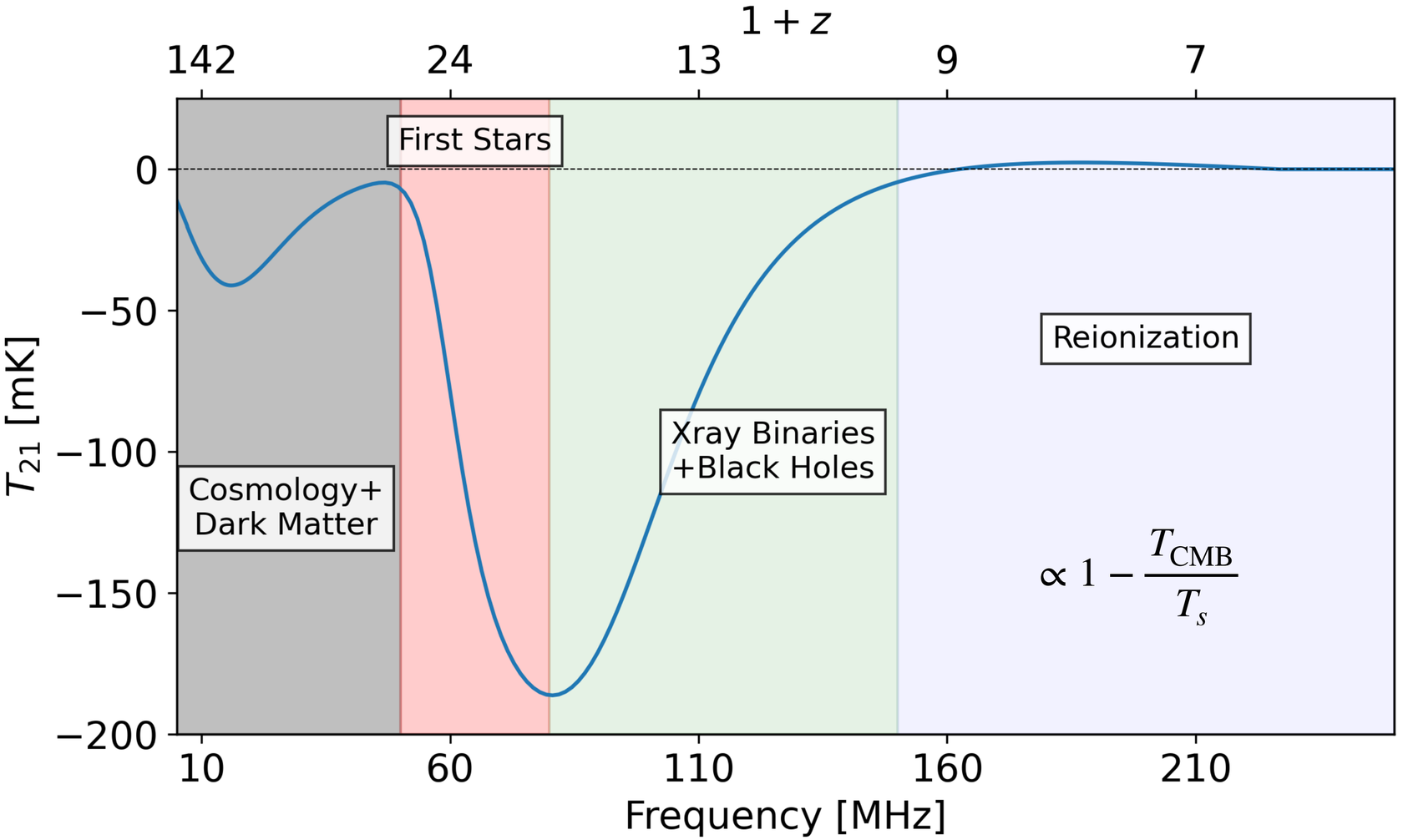
21-cm Cosmology

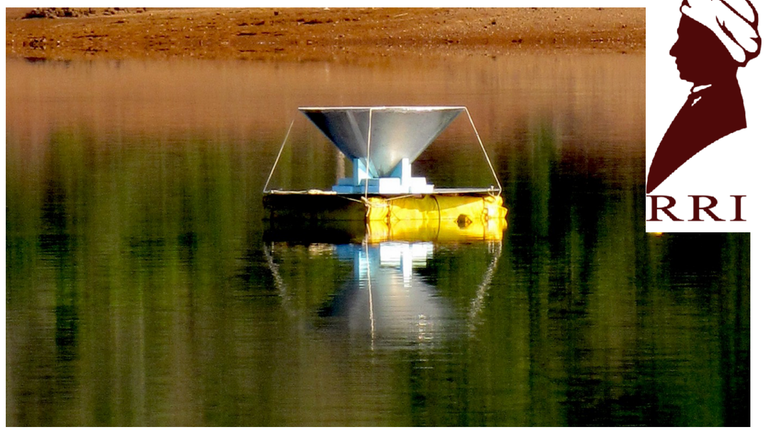
- Spin-flip transition in neutral hydrogen
- Define the spin temperature $T_s \rightarrow$ number of atoms in each spin state
- T_s driven by different processes at different times
- Trace its evolution relative to the CMB temperature

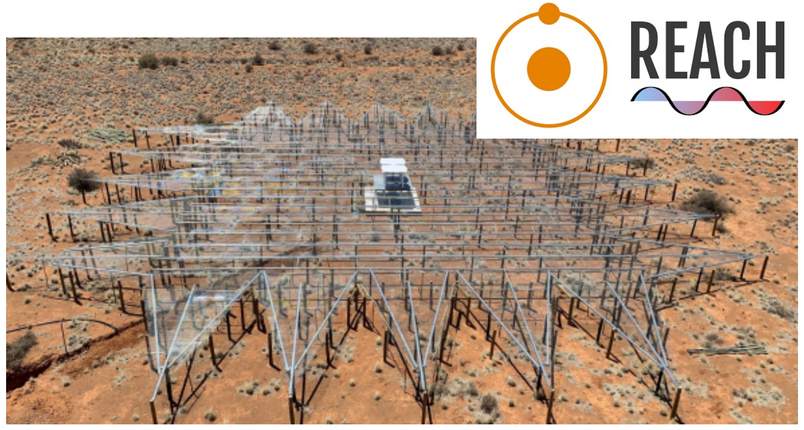




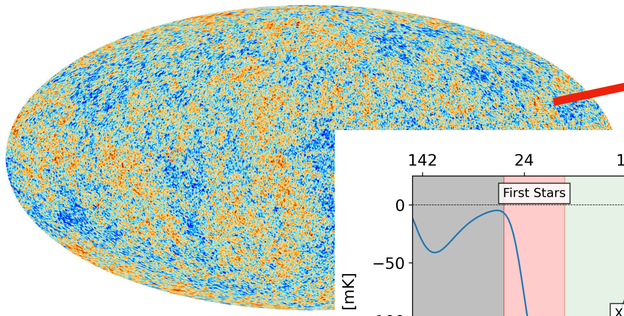
Sky Averaged 21-cm Signal



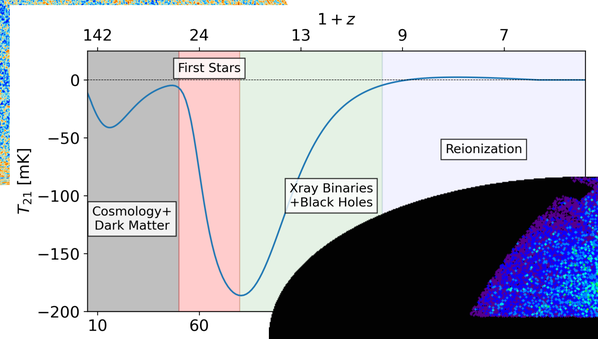


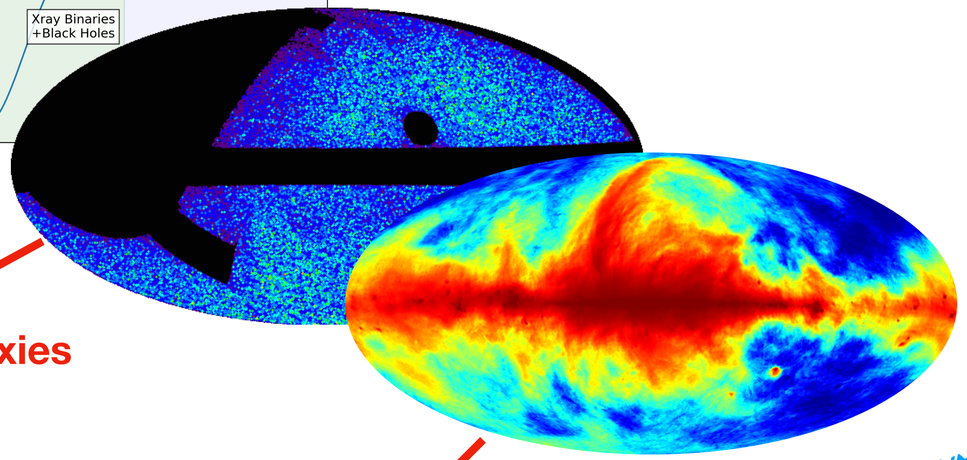


The issue…



The Cosmic Microwave Background





Foreground galaxies

Our own Galaxy

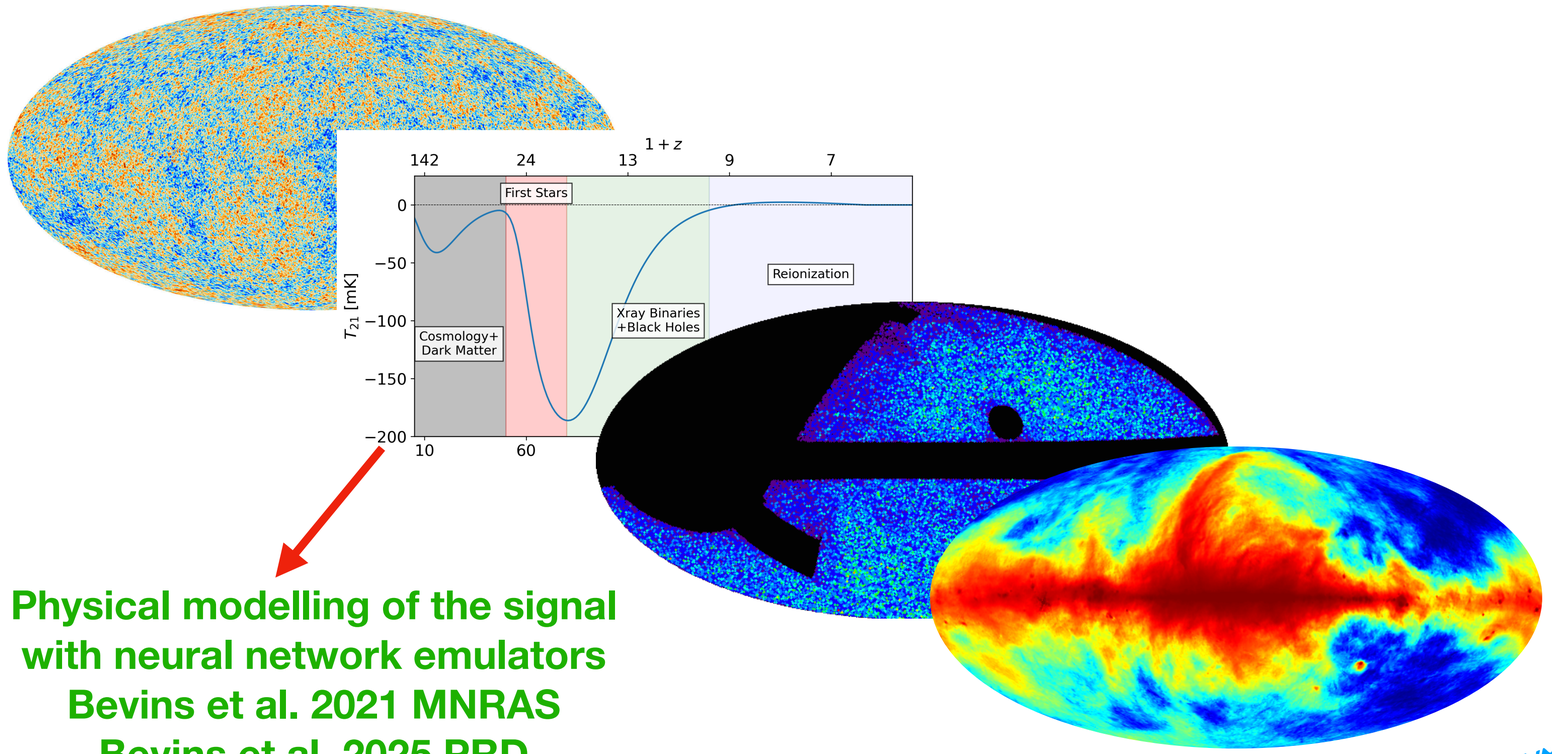
The atmosphere

Coupling of the telescope to the sky

The environment around the telescope

Amplification of signals

Machine learning as a solution!



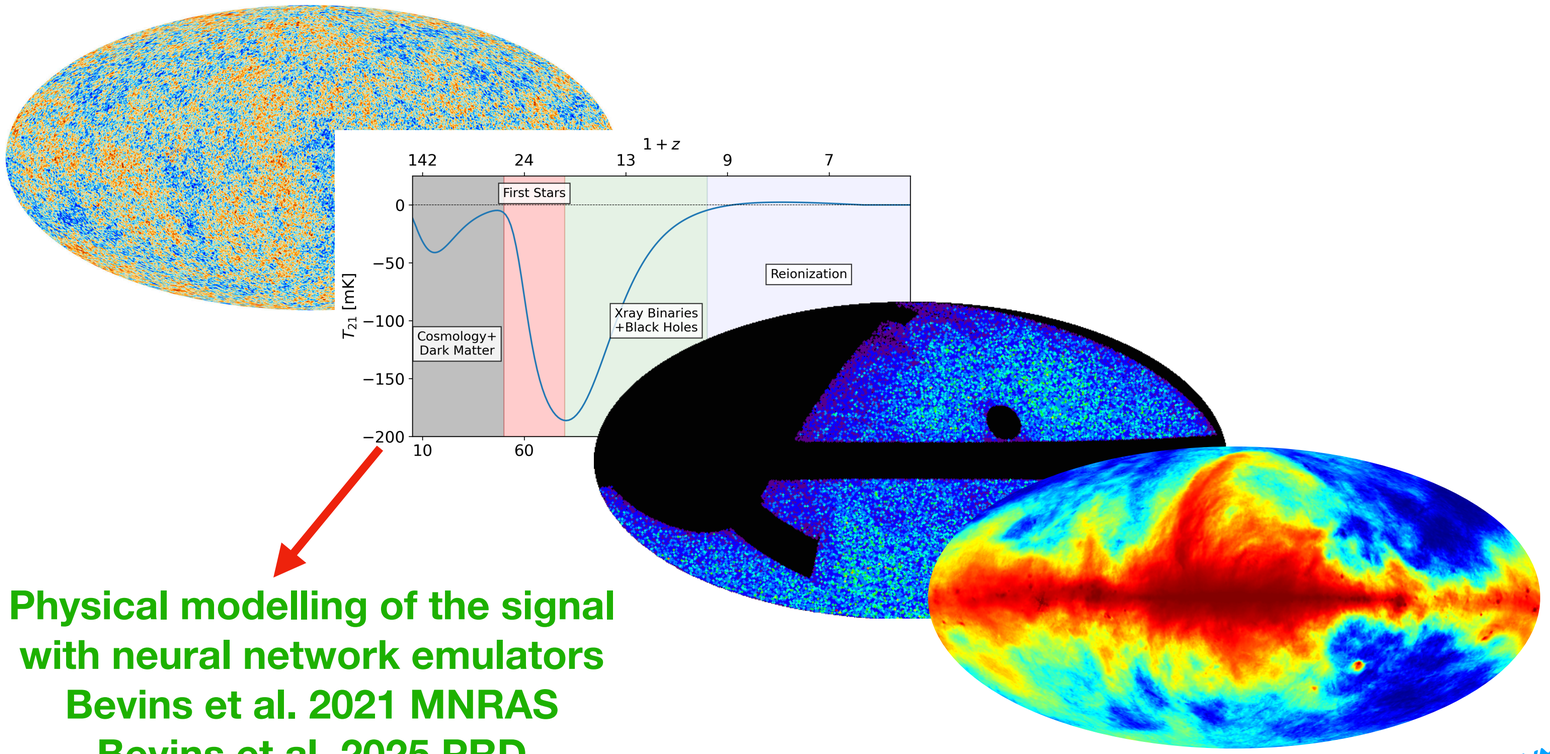
Physical modelling of the signal with neural network emulators
Bevins et al. 2021 MNRAS
Bevins et al. 2025 PRD

Coupling of the telescope to the sky
Currently working on!

The environment around the telescope
Normalising flows to handle varying soil conditions
Pattison, Cavillot, Bevins et al 2025 MNRAS

Amplification of signals
Machine Learning Calibration
Leeney, Bevins et al. 2025
Scientific Reports

Machine learning as a solution!



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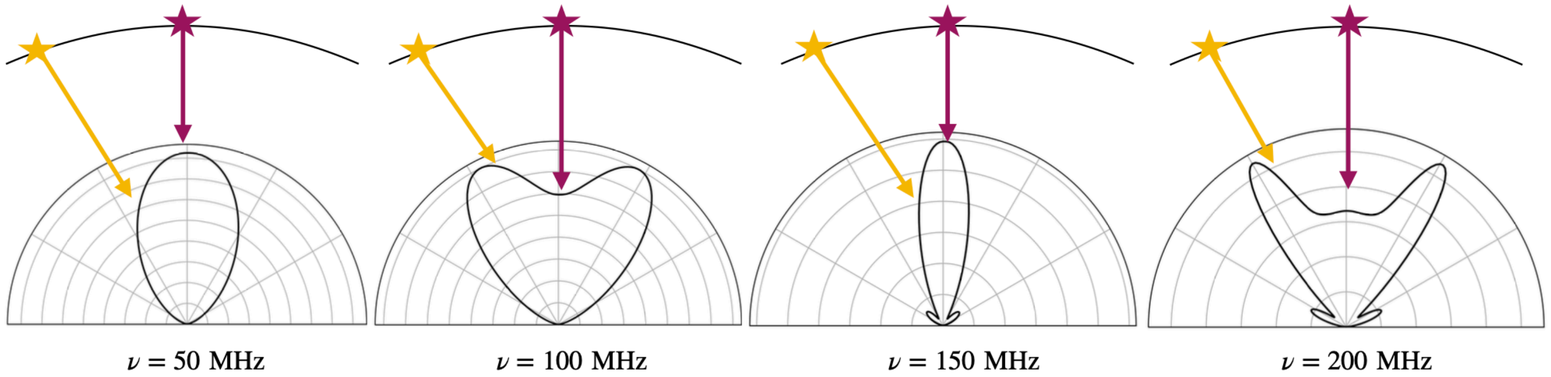
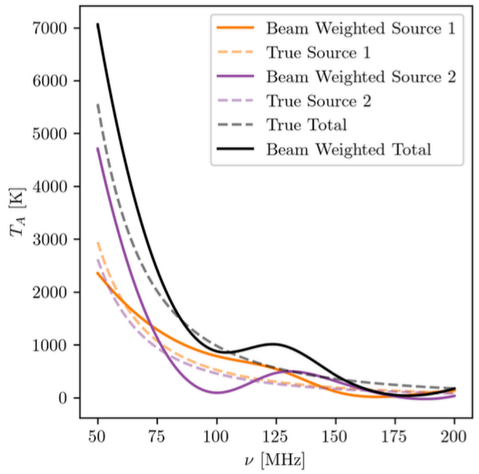
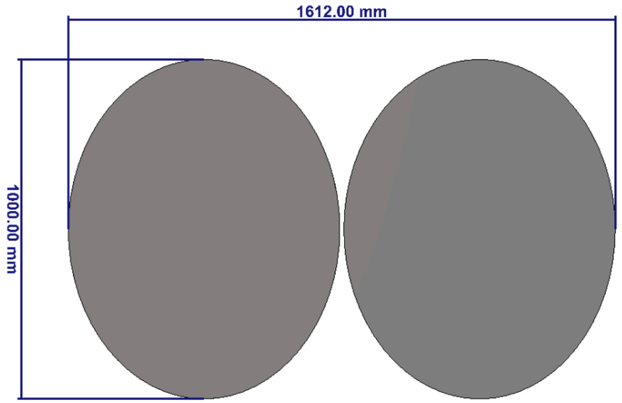
Modelling the REACH Beam pattern





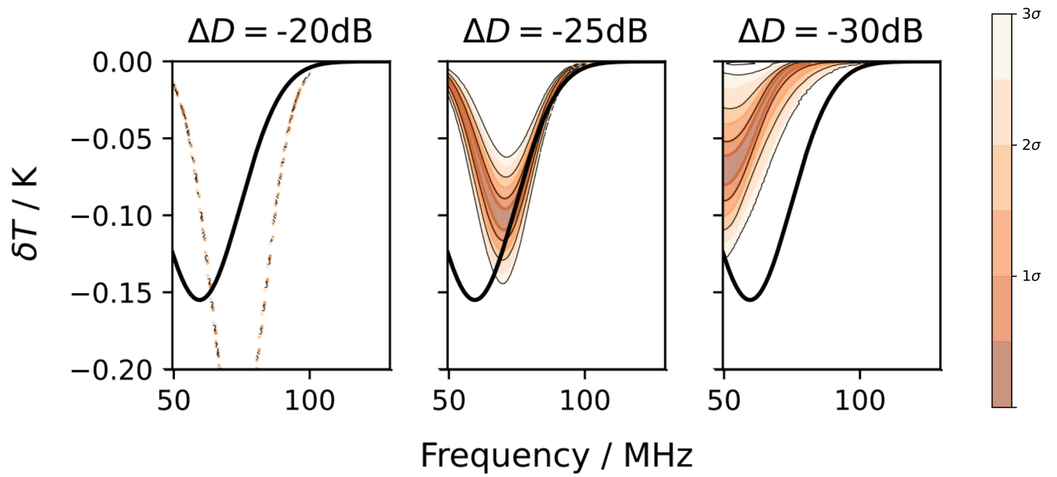


Modelling the REACH Beam pattern

- Assume absolute knowledge of the beam in the REACH analysis pipelines
- EM modelling takes hours per parameter set
- But small differences can prevent detections!

5 mm difference in height compared to our expectations!

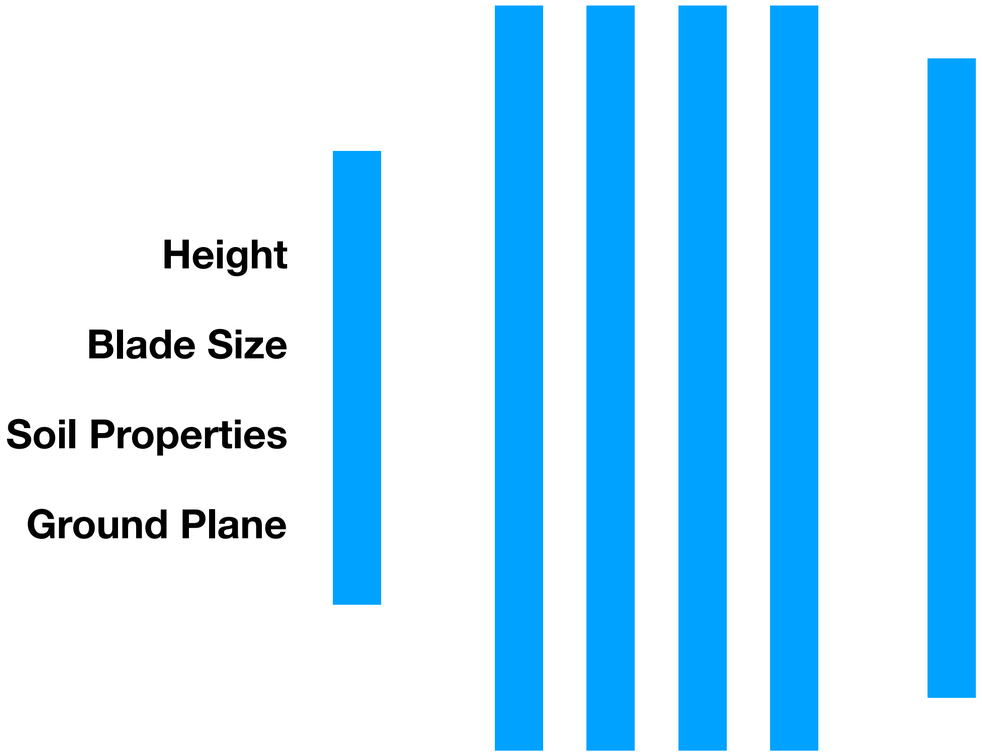
2 mm difference in blade dimensions!

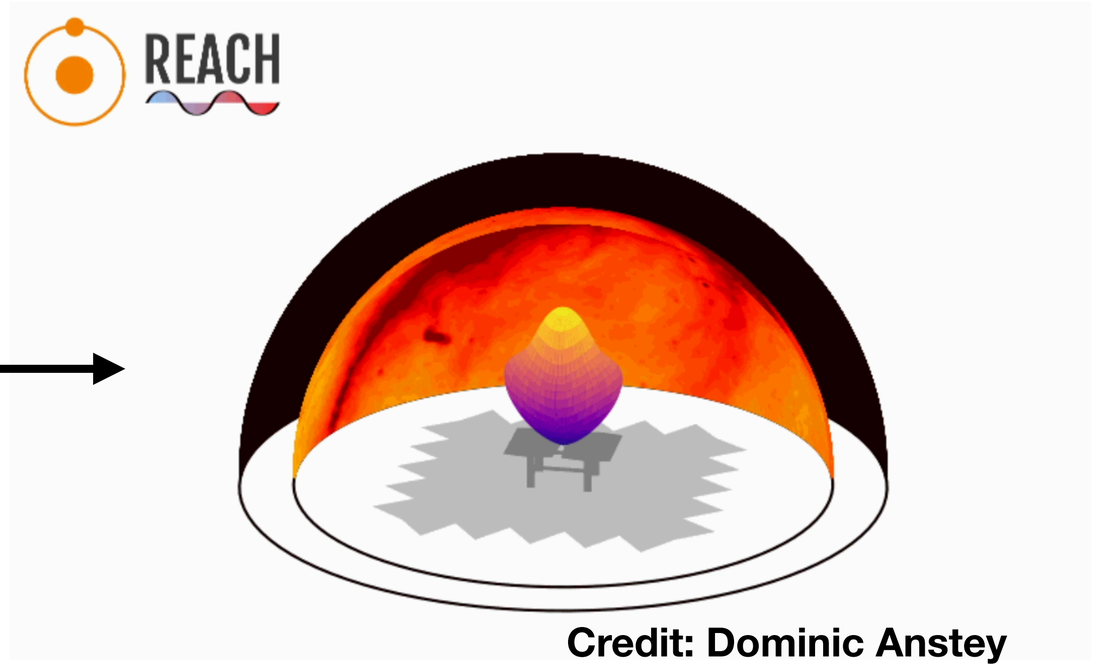


Cumner et al. 2023

Modelling the REACH Beam pattern

- Solution is to try and emulate the beam as a function of physical parameters
  - Physical dimensions of the antenna
  - Properties of the environment

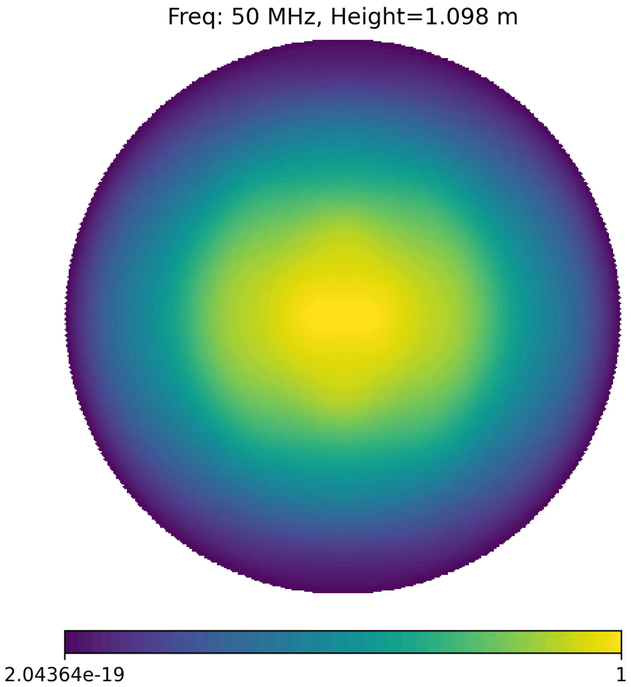


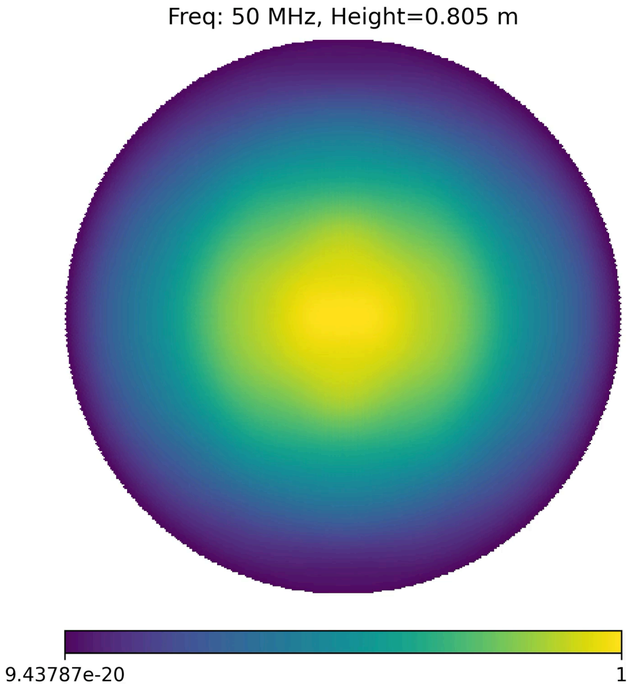


Credit: Dominic Anstey

Modelling the REACH Beam pattern

- DiRAC grant for 3.2 Million CPU hours to build training data with a Method of Moments code with Jean Cavillot, John Cumner and Dominic Anstey





Conclusions

- Machine learning helps us tackle the complex challenges faced by 21-cm Cosmology
  - Signal modelling
  - Calibration
  - Varying environmental factors
  - Experiment design

- Currently investigating applications of ML in instrument modelling tasks
  - Including the REACH beam
  - And SKA stations!

- Based in K32 and happy to chat all things ML, data analysis, 21-cm cosmology and running!