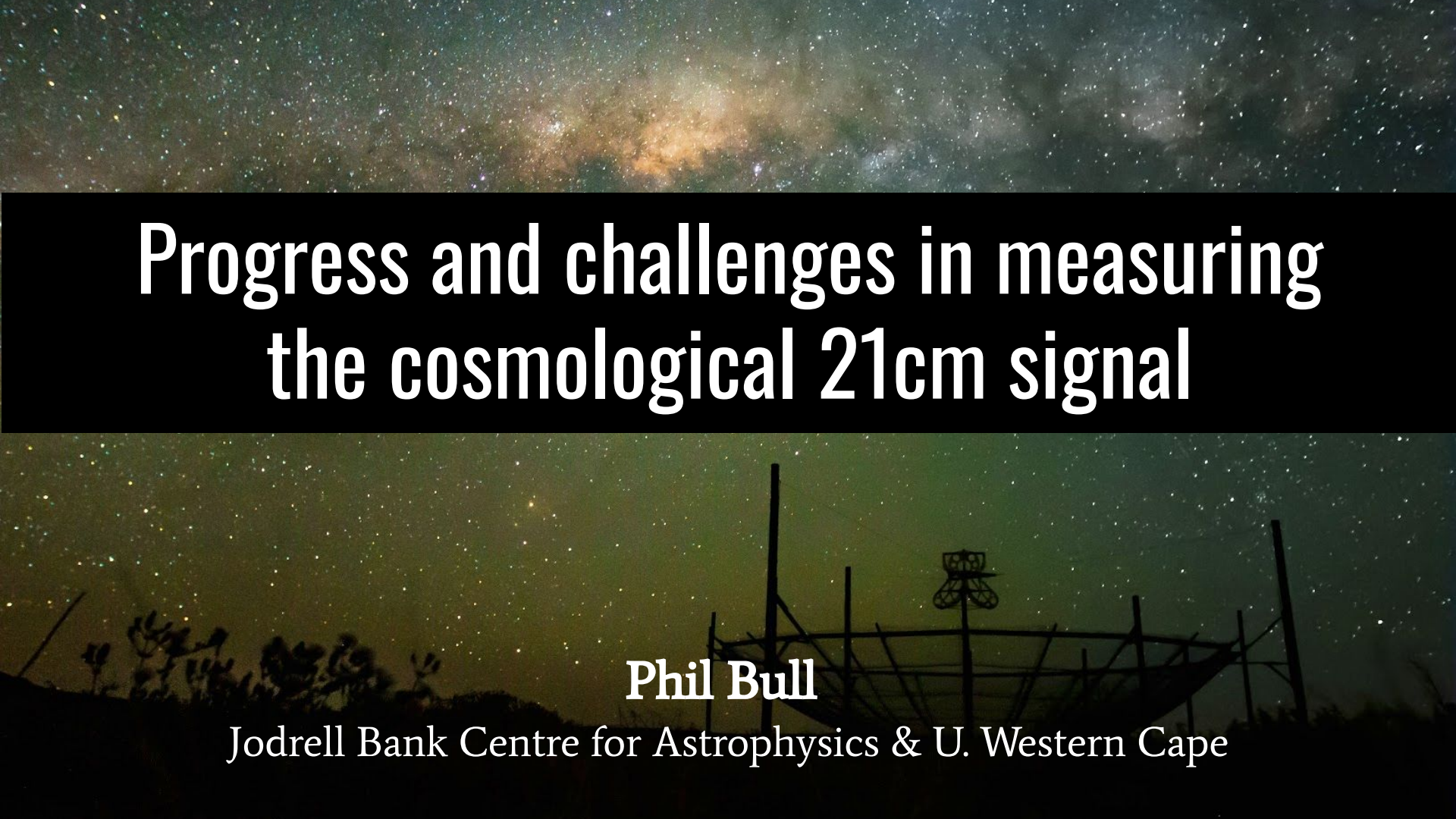

# Progress and challenges in measuring the cosmological 21cm signal

**Phil Bull**

Jodrell Bank Centre for Astrophysics & U. Western Cape

# Overview

Motivation

Observational approaches

Latest results

The future

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 948764)


European Research Council
Established by the European Commission

# Motivation

*Neutral hydrogen (HI) is ubiquitous in the post-recombination Universe*

- The IGM is mostly neutral from z ~ 1090 until z ~ 6 – 10 (reionisation)
- After reionisation, dense self-shielded clumps of HI persist in galaxies, where they provide the “fuel” for star formation

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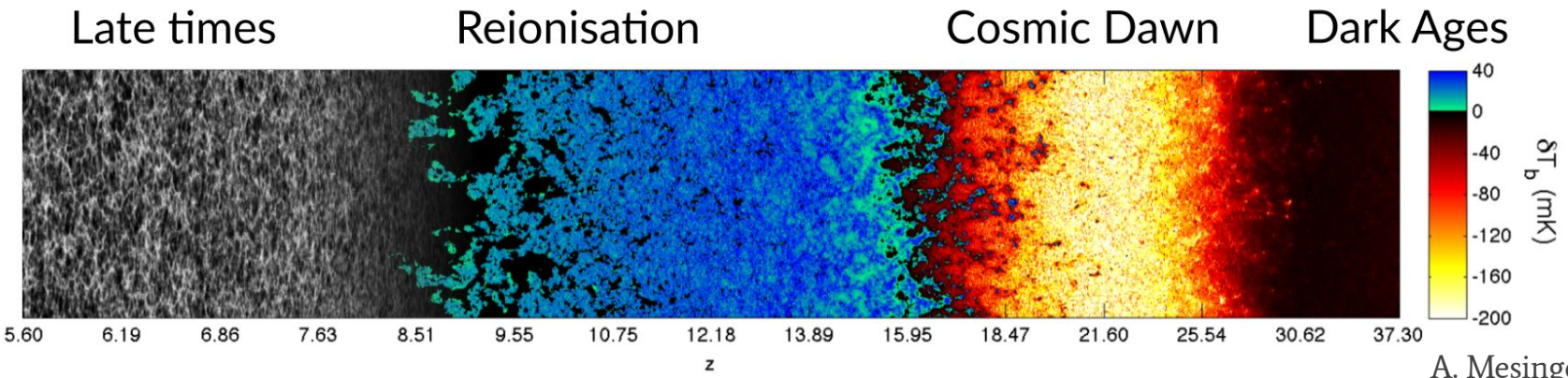
- **Redshifted 21cm emission** from HI traces the IGM or galaxy distribution
  → Continuous tracer of large-scale structure from z ≈ 200 to today

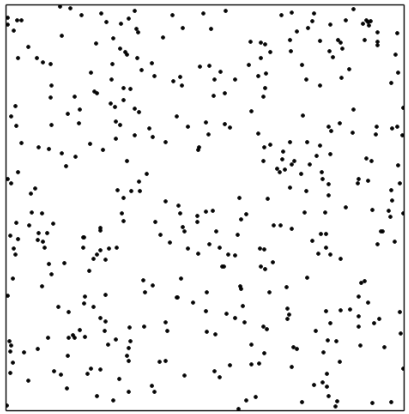


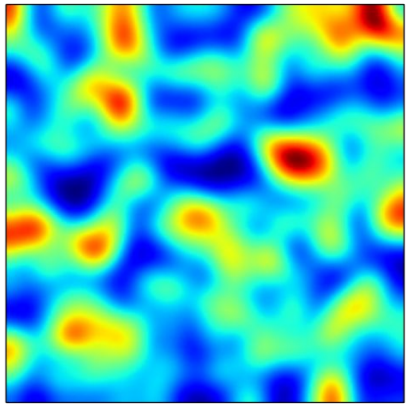

A. Mesinger

# Motivation

*Can we make a 3D map of the cosmos from z = 0 to (almost) the Big Bang?*

- Observing individual galaxy spectra (for 3D coordinates) is time consuming, especially at z > 2; and no galaxies above z > 10 or so!
- If we only care about the large-scale structure, resolving individual galaxies is inefficient. Why not just collect (emission line) photons into coarse voxels that are ~Mpc across?





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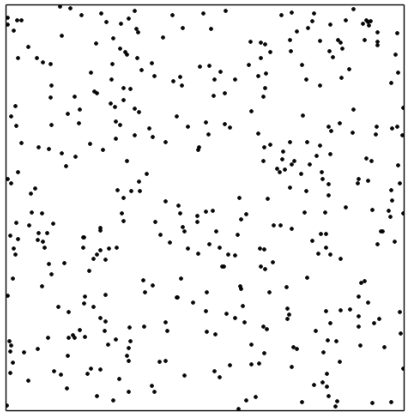
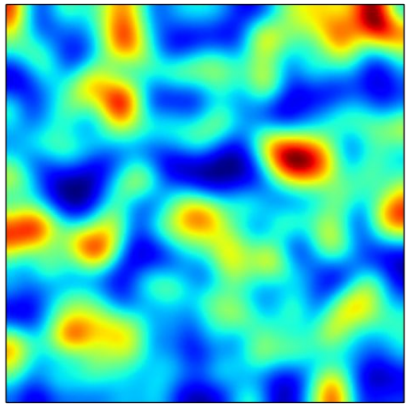




This is **line intensity mapping (LIM)**

- Recover 3D map of tracer on cosmological scales directly
- Lower resolution + no detection threshold = faster survey speed
- Access much higher redshifts (total emission, not single objects)

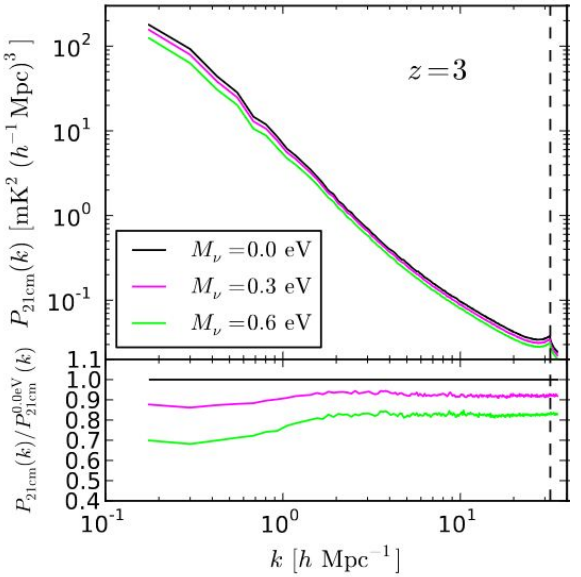
# Applications of 21cm surveys

- Usual large-scale structure observables (BAO, RSD etc.)
- Can cover large survey areas/high z; recover ultra-large scales
- Weak lensing (like having “spectroscopic” CMB lensing)
- **HI distribution sensitive to low-mass halo abundance**
- Unique probe of IGM at reionisation and Cosmic Dawn
- Massive number of linear modes in Dark Ages

**Example: Massive neutrinos (and WDM) suppress low-mass halo abundance**

Redistribute HI across mass range; impacts all scales

Villaescusa-Navarro, **PB**, Viel (2015)

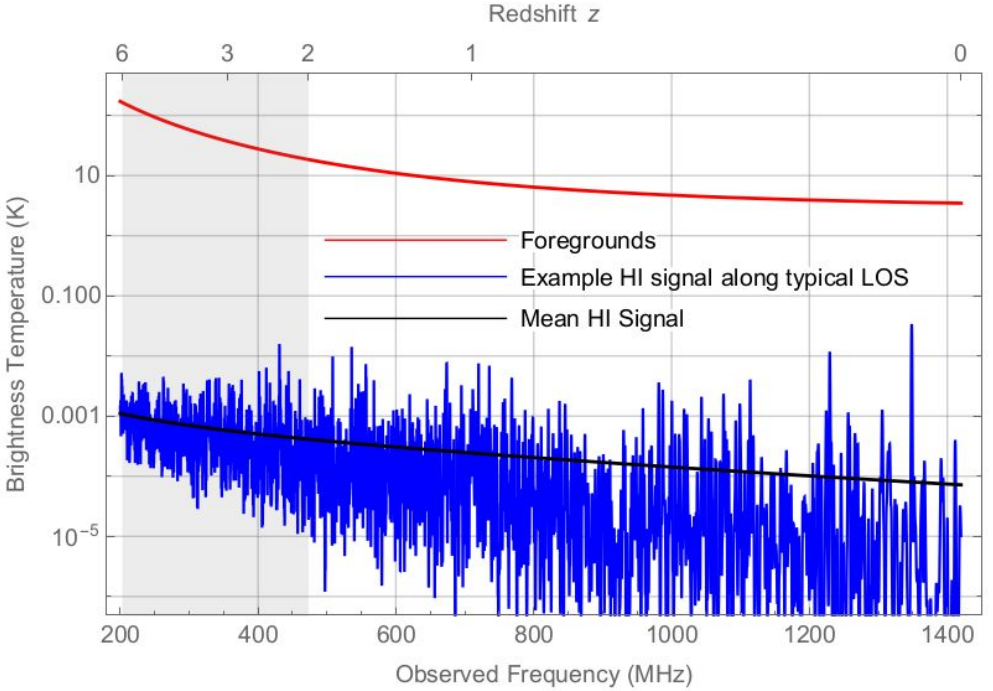


# Components of the observed signal

We measure **brightness temperature** vs frequency and angle (pixel or baseline)

**Components:**

- 21cm mean + fluctuations (~1 mK)
- Galactic + extragalactic foreground emission ($10^1 - 10^4$ K)
- Thermal noise
- Leakage terms (e.g. polarisation)
- Modulation due to beam
- Modulation due to calibration errors
- Interference

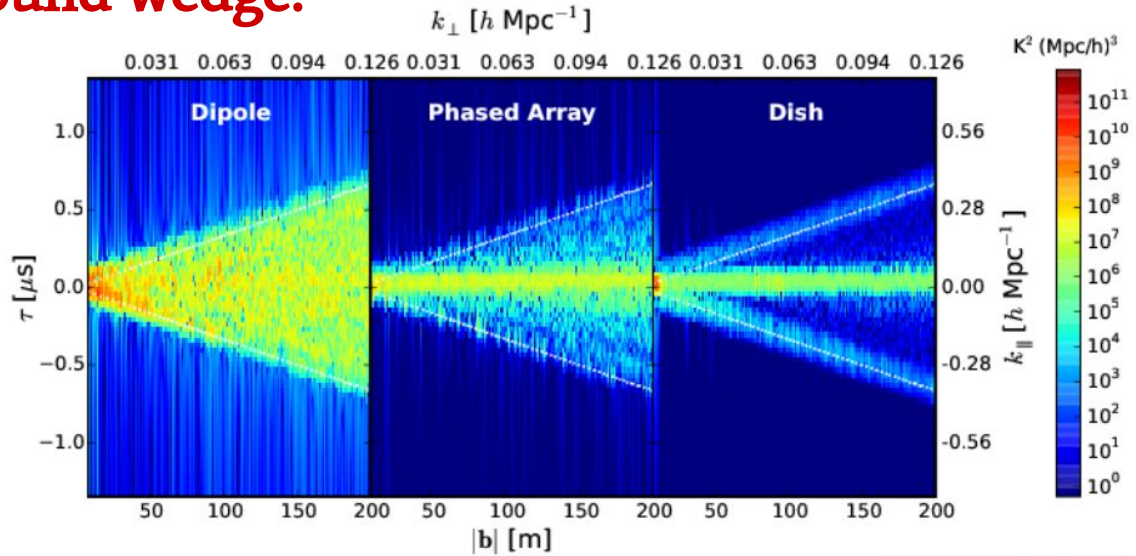



Cosmic Visions (2018)

# Foreground contamination

1. Foregrounds are intrinsically smooth in frequency (localised to low $k_{//}$ modes)
2. Beam sidelobes have lots of angular structure that depends on frequency
3. Modulation by frequency-dependent beam scatters FG power to higher $k_{//}$
4. Modulation is more extreme for longer baselines (higher $k_{\perp}$)

**Foreground wedge:**

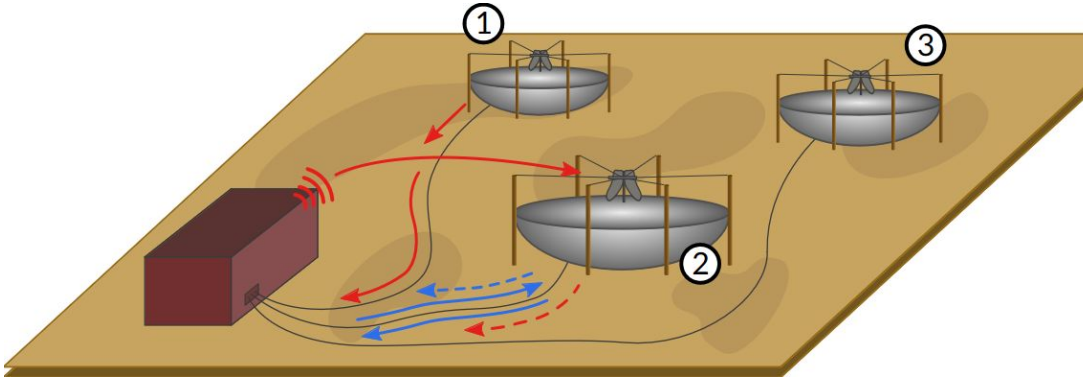



Thyagarajan et al. 2015

# Systematics

Wide variety of instrument-specific systematic effects, e.g.

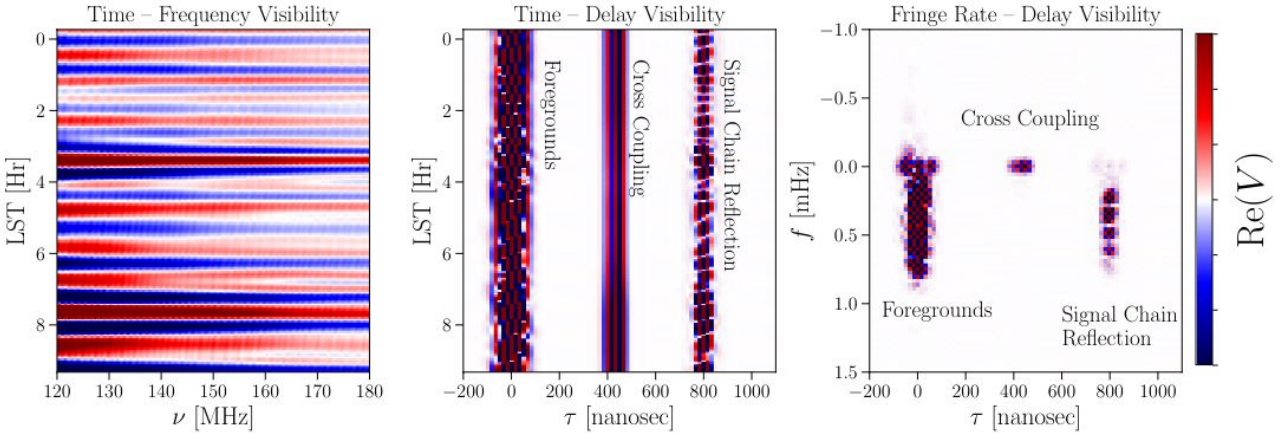
- Reflections in the signal chain
- Mutual coupling/cross-talk
- Polarisation leakage
- Calibration errors




Murphy+ [2312.03697]

**Options:**

– Improve hardware?
– Remove with software?
– Avoid/isolate modes?

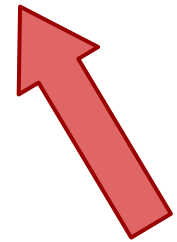



Kern+ (2019)

# Experiment design: Where are all the intensity maps?

*Generations of difficult lessons!*

- **`1st Gen:`** Use existing multi-purpose facilities and try your best!
  *Apply for time on suitable facilities like GBT, LOFAR*
- **`2nd Gen:`** Purpose-built arrays designed for high sensitivity
  *Build lots of (cheap-ish) receivers, try to fix problems as they arise*
- **`3rd Gen:`** Purpose-built arrays with systematics-mitigating features
  *More careful hardware design to suppress the worst 2nd Gen. issues*



We are here

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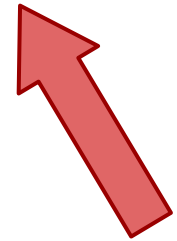
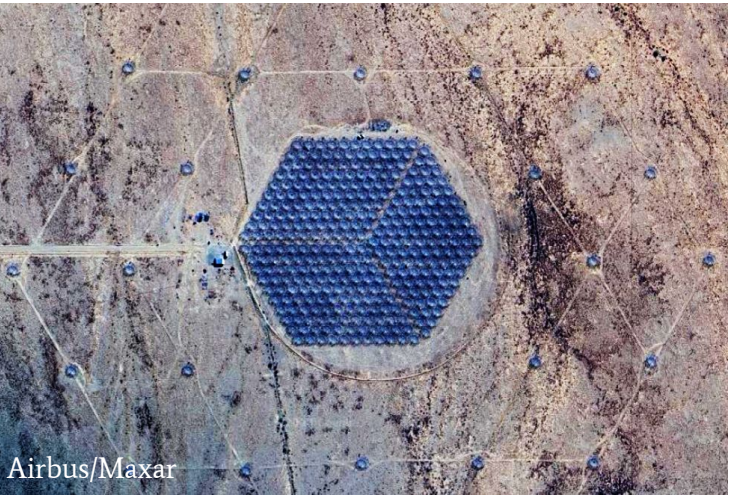
- **3rd Gen:** Purpose-built arrays with systematics-mitigating features
  *More careful hardware design to suppress the worst 2nd Gen. issues*
- **4th Gen:** Mega-science projects **or** refined 3rd Gen. experiments
  *SKA is a (1+2+3)-Gen. experiment; others refine 3rd Gen. ideas*
- **5th Gen:** The Moonshot
  *Literally build an array on the Moon*

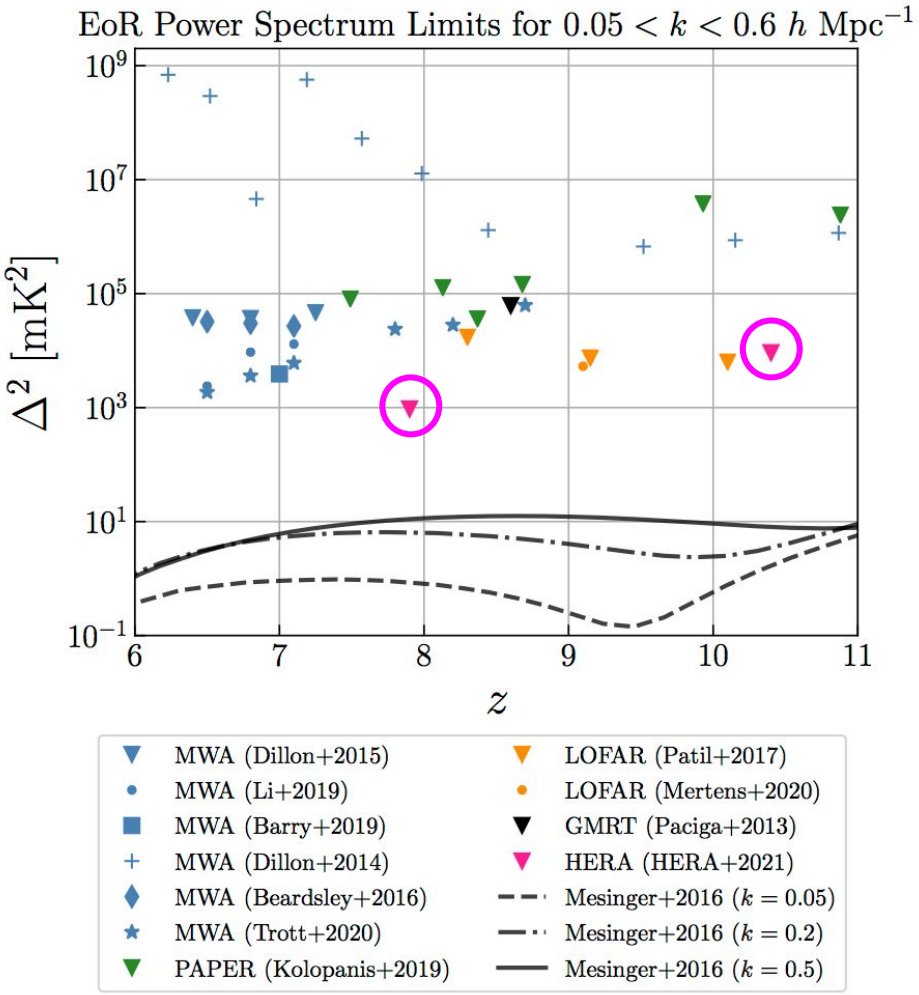


We are here

# HERA upper limits

- Redundant hex array in South Africa
- Current best upper limits on EoR 21cm power spectrum from 40 antennas, 94 nights (2017-18 season)
- Now analysing multiple seasons with more (+ upgraded antennas)



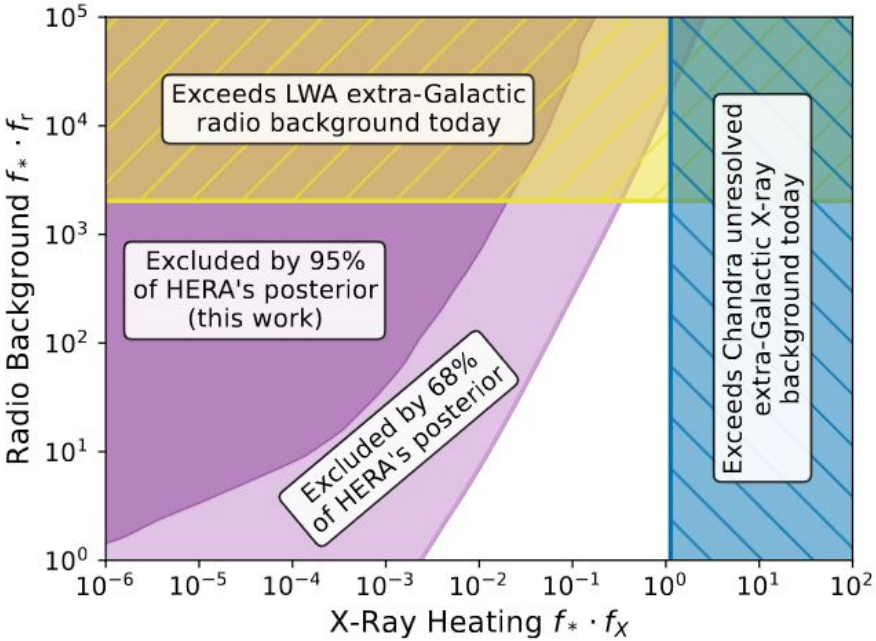

HERA Collab. (2022)

# HERA upper limits

What can you do with upper limits that are >100x larger than the expected signal level?

- IGM must have been heated above adiabatic cooling limit by z = 10.4 at the latest (rules out ‘cold reionisation’)

HERA Collab. (2023)



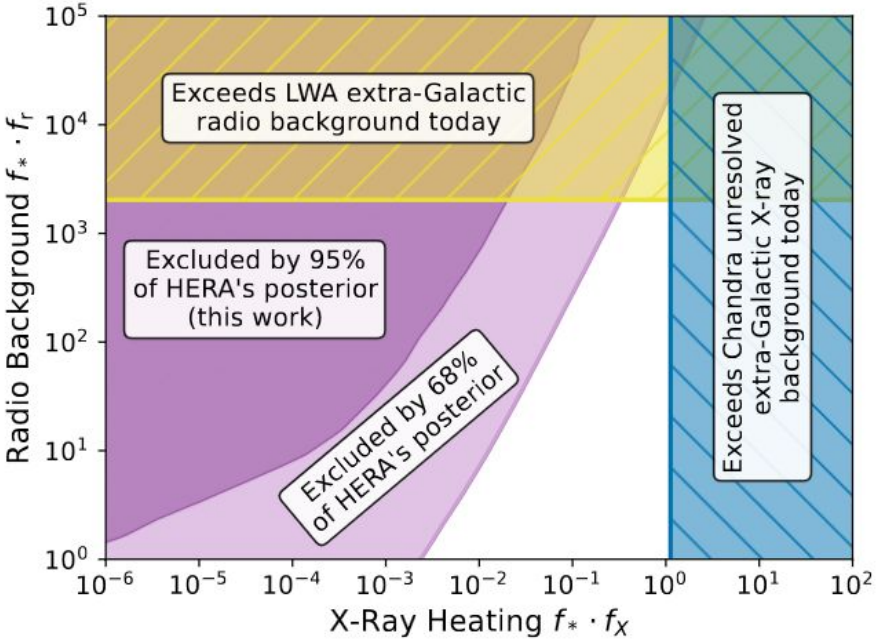
# HERA upper limits

What can you do with upper limits that are >100x larger than the expected signal level?

- IGM must have been heated above adiabatic cooling limit by z = 10.4 at the latest (rules out 'cold reionisation')
- If HMXBs are the main heating source, they must be low-metallicity ones
- Radio backgrounds seen by ARCADE2 and LWA must come from z < 8 (most high-z models excluded)*

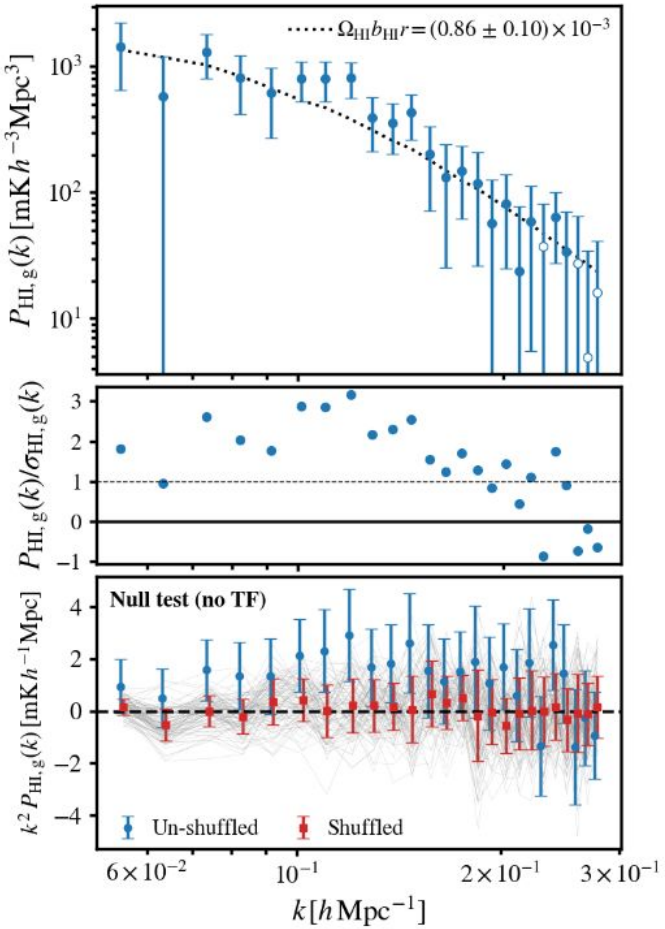
** Unless soft photon heating is important*

HERA Collab. (2023)



# MeerKAT cross-correlation detection

- **Multi-dish autocorrelation approach:** Use 64x MeerKAT dishes independently (also for SKA)
- The MeerKAT system turns out to perform *extremely well*; more stable than expected!




Cunnington, Li+ (2023)

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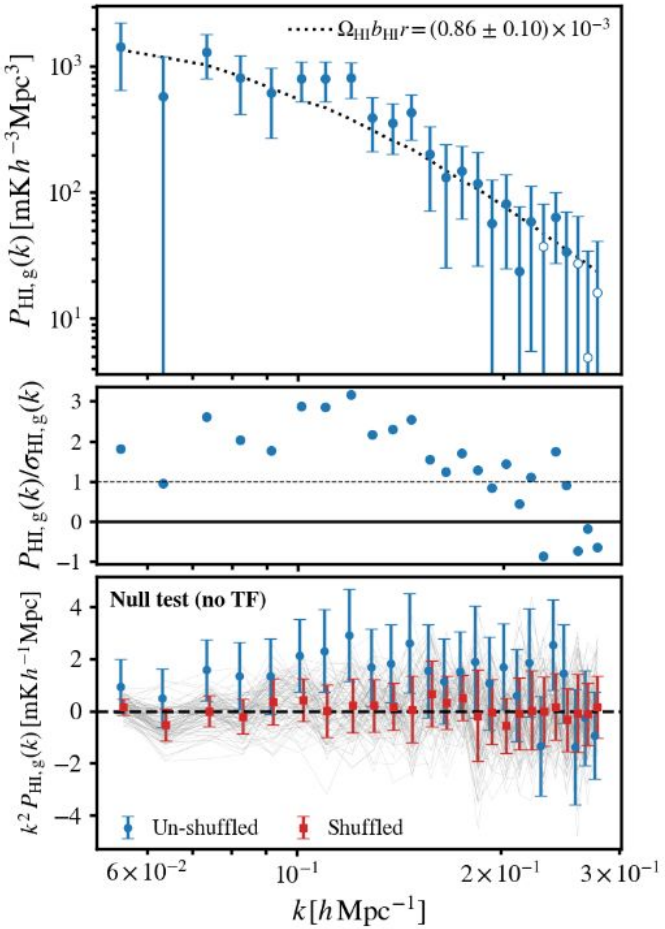
- The MeerKAT system turns out to perform *extremely well*; more stable than expected!
- With only 10.5 hours of data, we get a nice 7.7$\sigma$ cross-correlation detection with WiggleZ at z = 0.40 – 0.46
- **Transfer function:** Need to correct for signal loss due to foreground filtering (Cunnington+ 2023); we remove N = 30 FG modes!

**Much more MeerKAT data on the way – BAO next?**

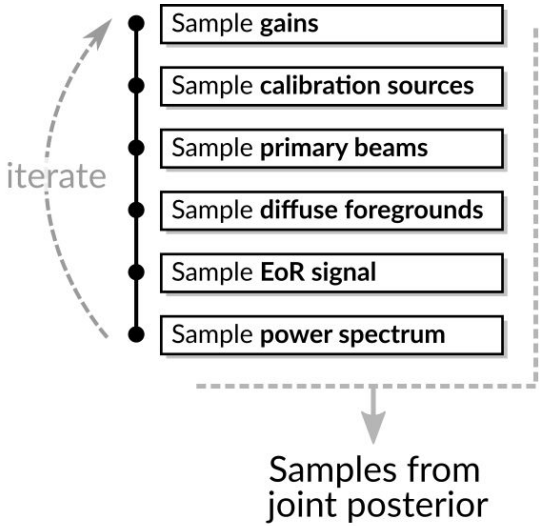



Cunnington, Li+ (2023)

# Hydra: A Bayesian pipeline for 21cm analysis

*Draw samples from a complete model of sky + instrument*

- Data model is complex, uncertain and has high dynamic range
- Use **Gibbs sampling** to decompose gigantic posterior distribution into tractable chunks (then iterate)
- Can handle $10^5 - 10^6$ sky + instrument parameters!



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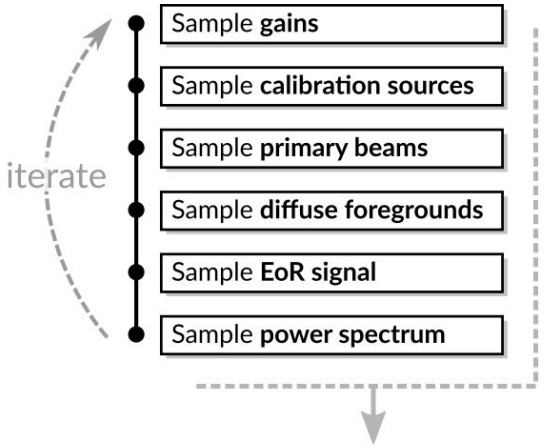
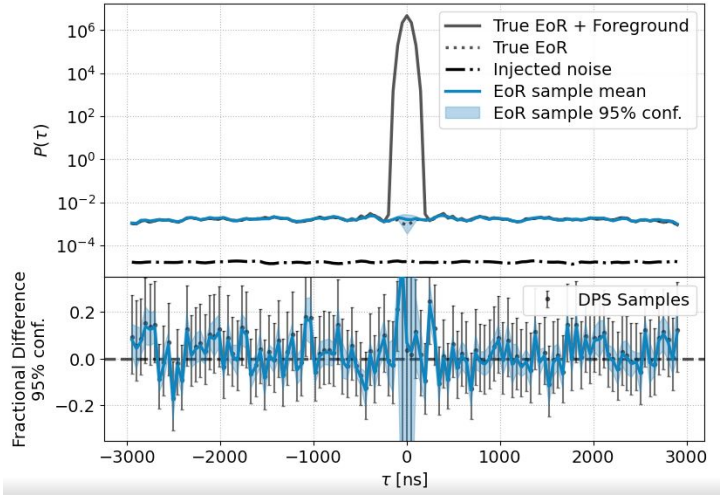
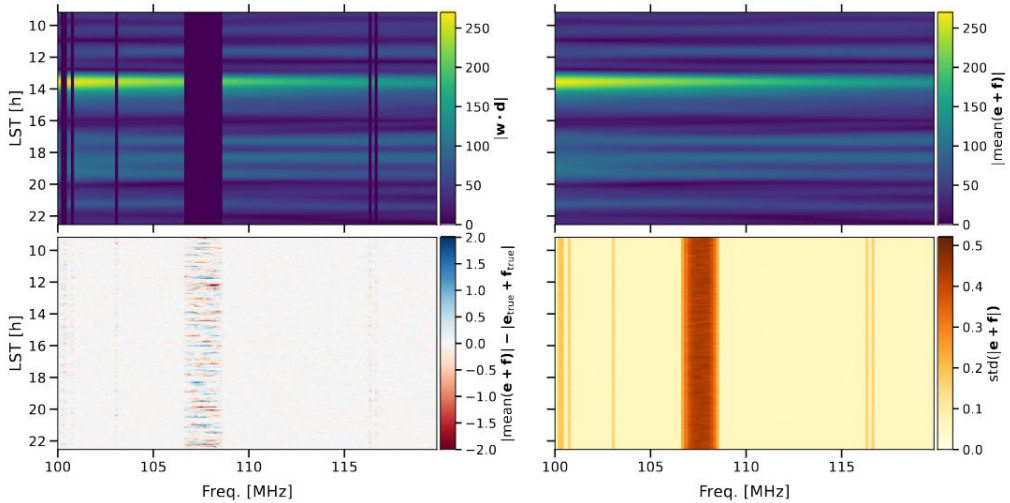



Burba, PB, Wilensky+ [2403.13767]



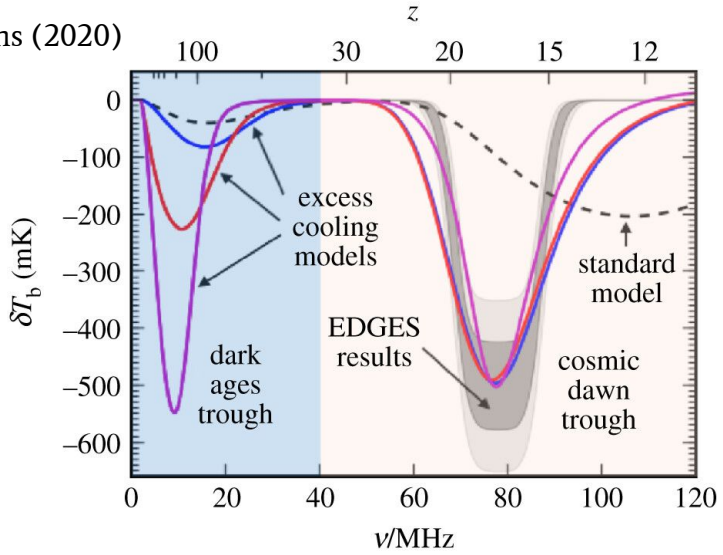

Kennedy, PB, Wilensky+ (2023)



# 21cm global signal

- Sky-averaged temperature as a function of frequency
- Probes dominant heating/cooling mechanisms vs redshift
- EDGES detected an anomalously deep absorption trough at z ~ 17
  - New physics? Radio background?
- Difficult systematics involved
  - We are building a horn antenna at Jodrell Bank to follow up EDGES

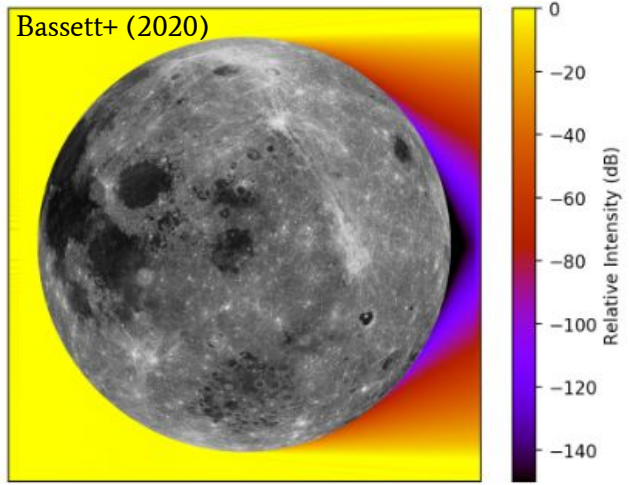
Burns (2020)

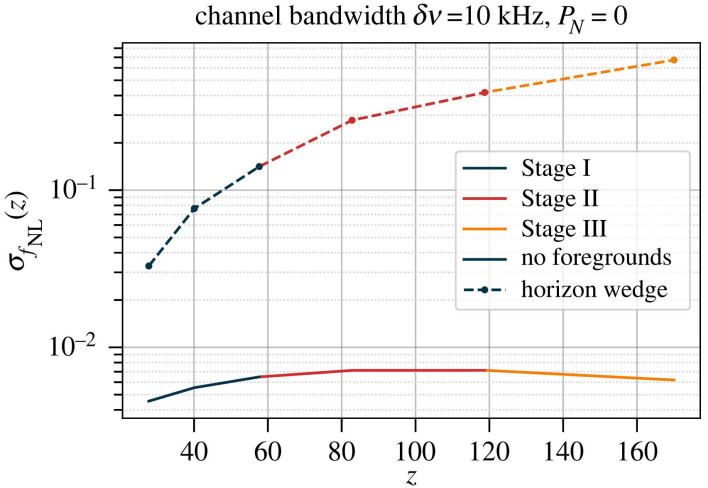



# To the Moon?

- Need Dark Ages to better constrain inflation
- Dark Ages science needs high sensitivity and low frequencies (< 30 MHz)
- Need to go into space to avoid ionosphere – lunar far side also shielded from terrestrial RFI
- Currently strong international interest in lunar
  - Opportunity and funding for scientific missions
  - But: Risk of degradation of RFI environment

**Seems futuristic, but the best chance to do this might be... now?**




PB, Guandalin, Addis (2024)

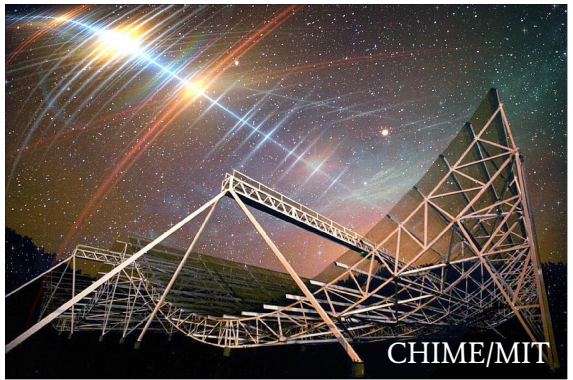
# Summary

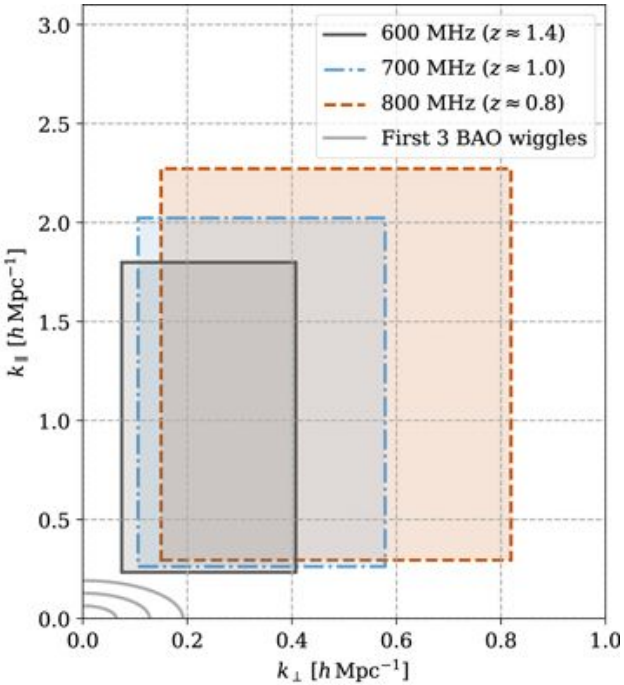
- 21cm surveys are difficult but promise to do lots of interesting things
- We *have* to figure out how to do them if we ever want to access the Dark Ages
- We might need to invest more heavily (space mission-style) to get best results
- In the meantime, good progress with HERA, and keep a close eye on MeerKAT

# Other experiments

- **CHIME**
  Detection at z = 0.78 – 1.43 by stacking on galaxy locations (CHIME Collab. 2022)
  Severe cuts needed; can't reach BAO wiggles
  (beam modelling + removal of intra-cylinder baselines)

- **21cm global signal experiments**
  Not intensity mapping per se, but important
  EDGES sees an anomalous absorption feature at
  z ~ 17; SARAS3 does not see this


CHIME Collab. (2022)