BAO Cosmology with HI Intensity Mapping and HIRAX

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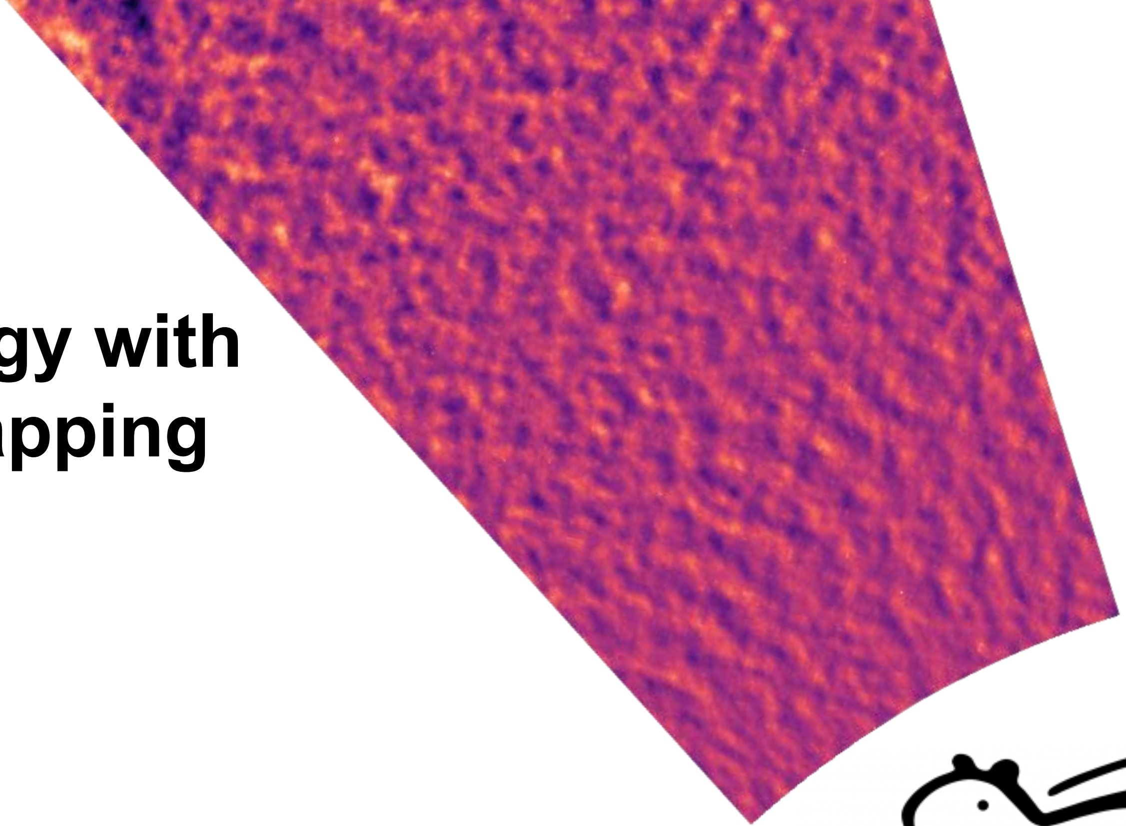
ETH Zürich
EDSU - Tools 2024



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HIRAX

HI Intensity Mapping Tomography

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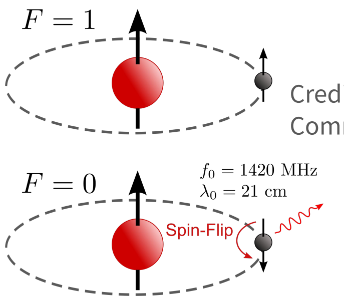
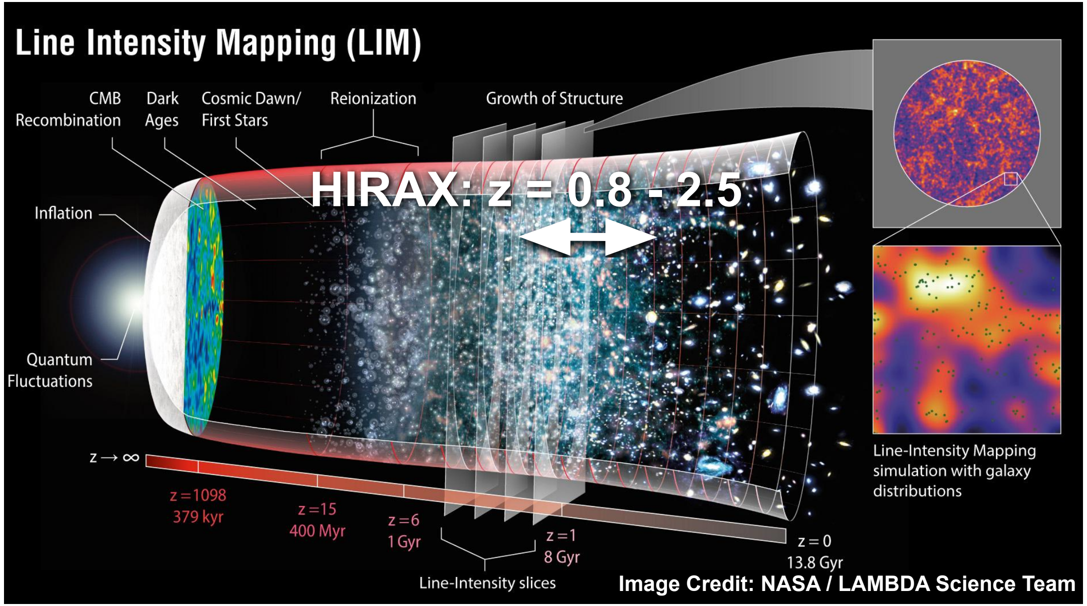
- Hyperfine Hydrogen transition line at 1420.4 MHz
- Efficiently and tomographically map cosmological volumes
  - Probe cosmic dawn and epoch of reionisation at low frequencies and large scale structure at high frequencies
  - Generally low angular resolution but redshift information cheap



Credit: Wikimedia Commons

$$\nu_{\mathrm{obs.}} = \frac{1420.4\ \mathrm{MHz}}{1+z}$$

- Post-reionisation IM
  - ν > 200-300 MHz
  - HI emission acts as biased tracer of large scale structure
  - Large volumes achievable
  - Comparable to low angular resolution spectroscopic galaxy survey



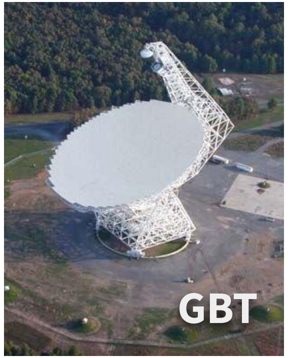
Classes of HI Intensity Mapping Experiments

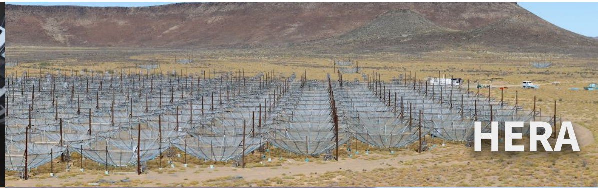
Single dish telescopes

- Scan sky with single dish or array of dishes working independently
- GBT, MeerKAT (non-inter.), SKA-MID, FAST

Interferometers

- Correlate signals across many elements - targeting angular scales of interest. E.g. BAO, EoR
- HERA, CHIME, MWA, CHORD, HIRAX, SKA-low





Baryon Acoustic Oscillation Cosmology

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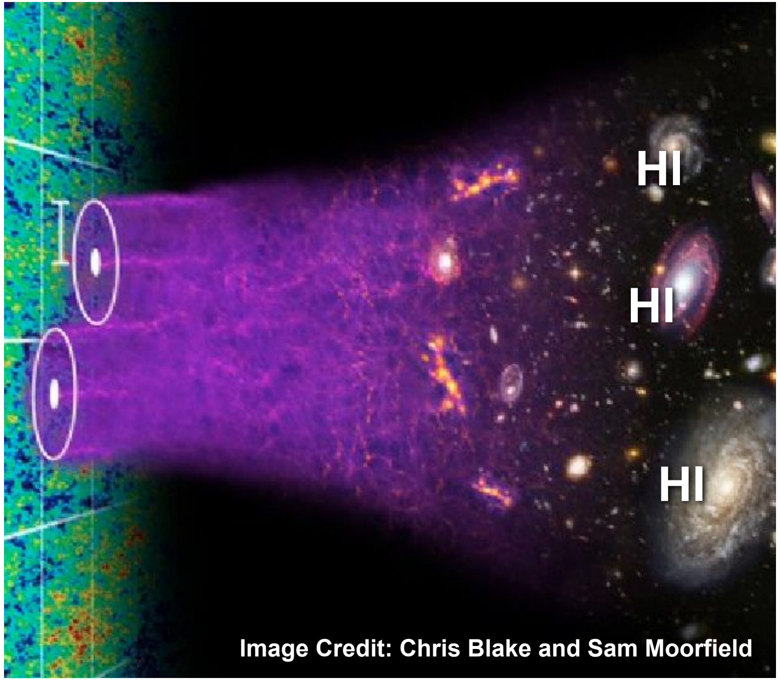

- Characteristic scale imparted on statistical distribution of matter in early universe
  - ~150 Mpc comoving 1.5-3° (HI @ 400-800MHz)
- Post-reionisation HI located in dense regions within galaxies, tracing matter.
- BAO scale statistically detectable in sky distribution of HI emission
- Tomographic measurements provide ***standard ruler*** observable of universe's geometry over cosmic time
- Constrains cosmological parameters related to geometric expansion, e.g. dynamical dark energy

BAO Cosmology with Interferometers

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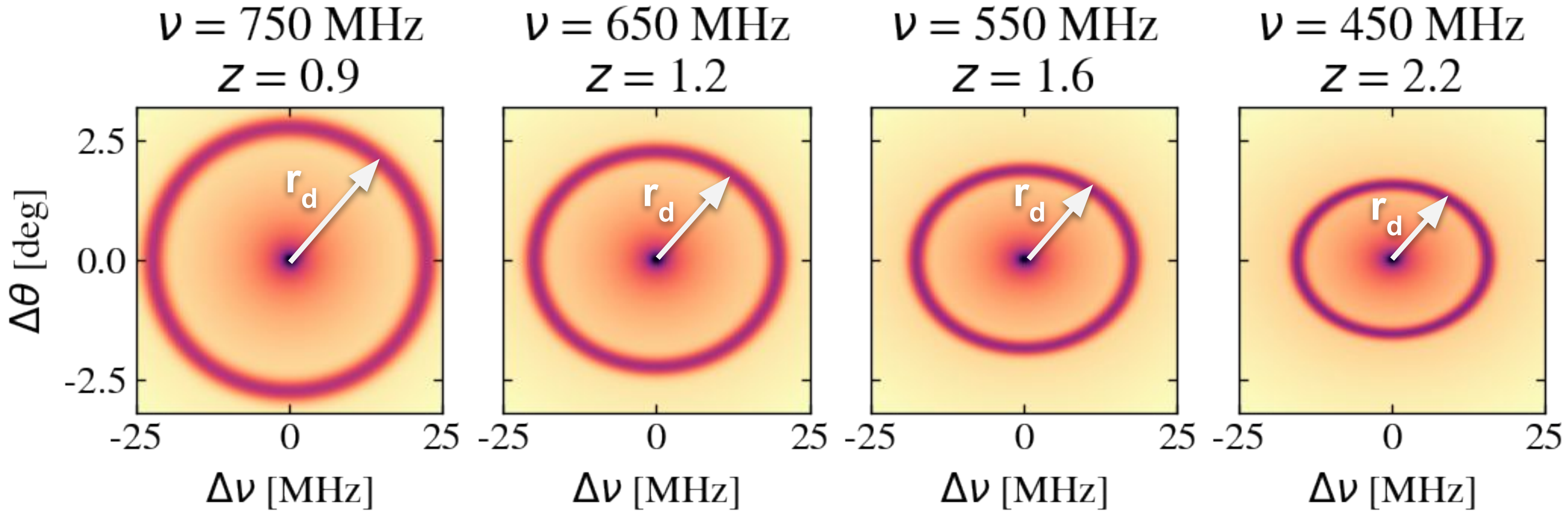

$$\Delta\nu_{\mathrm{obs.}} \propto \frac{H(z)}{(1+z)^2} r_{\mathrm{d}}$$

$$\theta_{\mathrm{obs.}} = \frac{r_{\mathrm{d}}}{D_{\mathrm{M}}(z)}$$

$$D_{\mathrm{M}}(z) \overset{\mathrm{flat}}{\propto} \int_0^z \frac{dz'}{H(z')}$$

$$r_{\mathrm{d}} \approx 150\ \mathrm{Mpc}$$

$$\Omega_m, \Omega_k, \Omega_\Lambda, w_0, w_{\mathrm{a}} \ldots$$

BAO Cosmology with Interferometers

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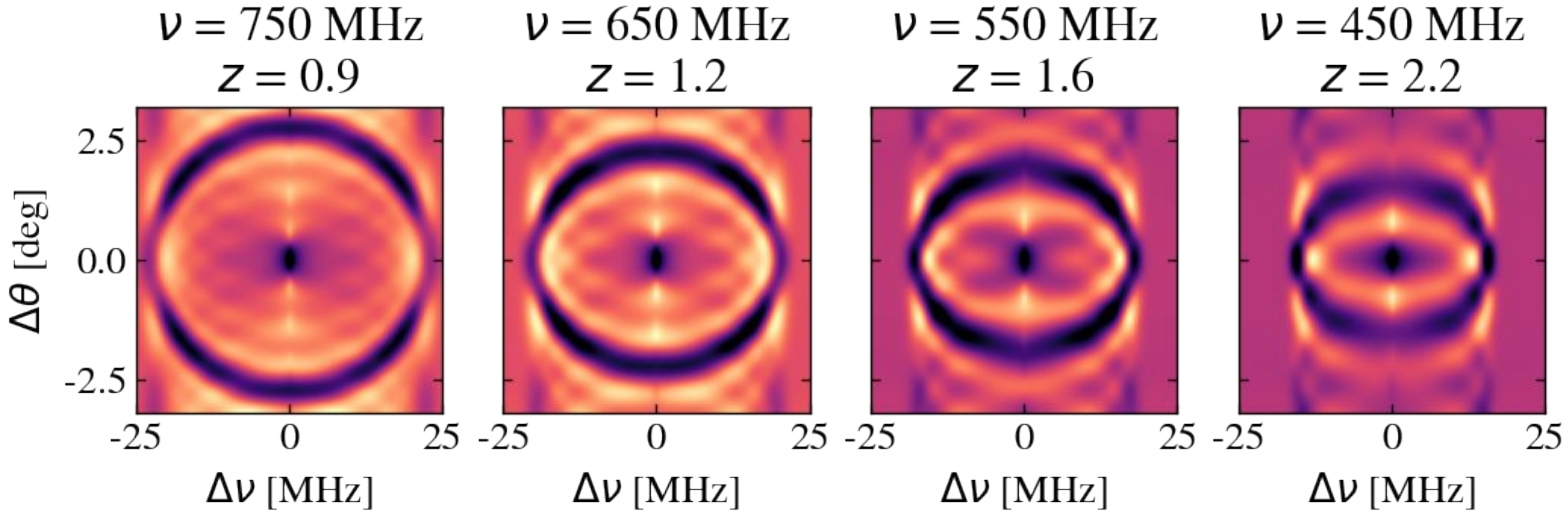
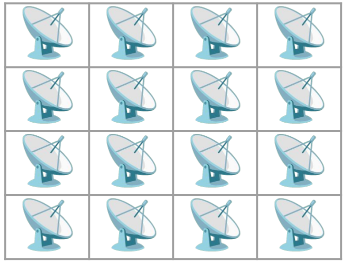
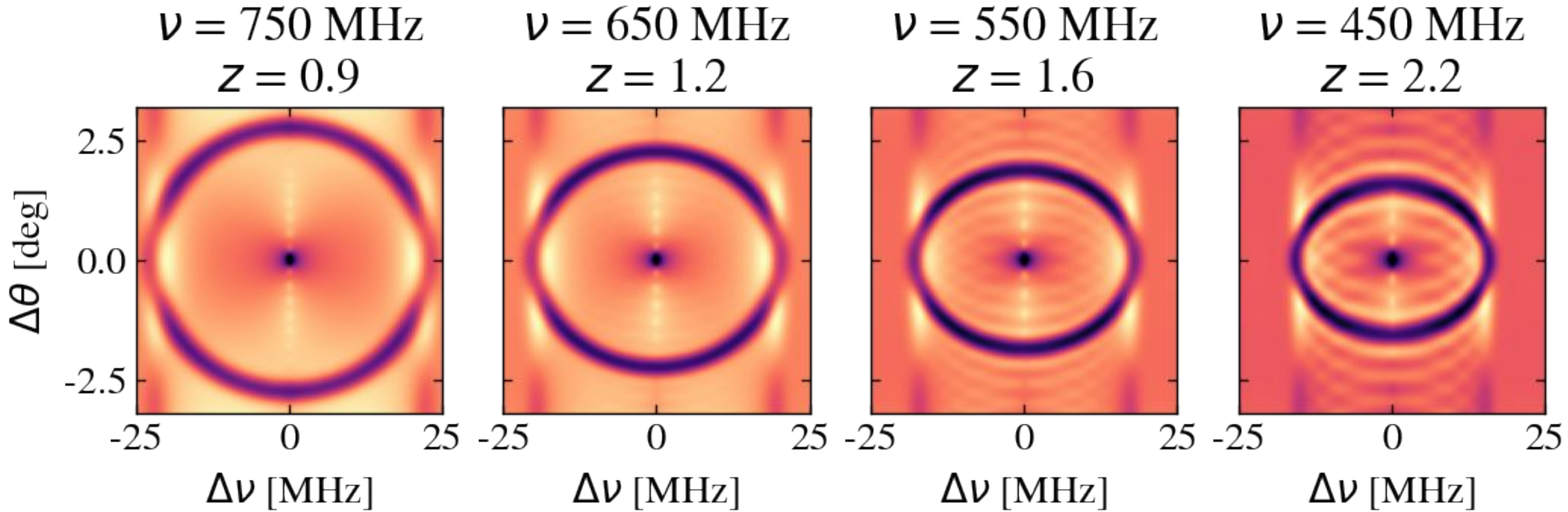


$$\theta_{\text{res.}} = (1+z)\frac{21\text{ cm}}{|\vec{b}|}$$

4x4 Array
Spacing:
6.5 m EW, 8.5m NS



BAO Cosmology with Interferometers



$$\theta_{\text{res.}} = (1+z)\frac{21\ \text{cm}}{|\vec{b}|}$$

8x8 Array
Spacing:
6.5 m EW, 8.5m NS

BAO Cosmology with Interferometers

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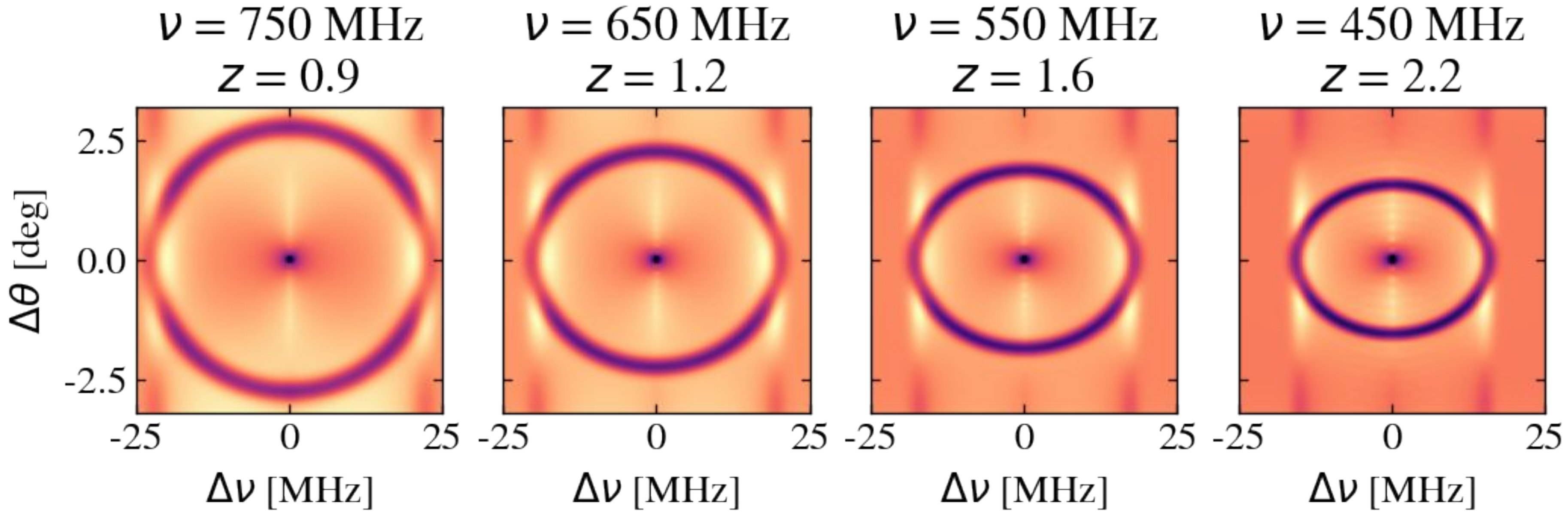

$$\theta_{\text{res.}} = (1+z)\frac{21\ \text{cm}}{|\vec{b}|}$$

16x16 Array
Spacing:
6.5 m EW, 8.5m NS

Motivation for Compact Redundant Arrays

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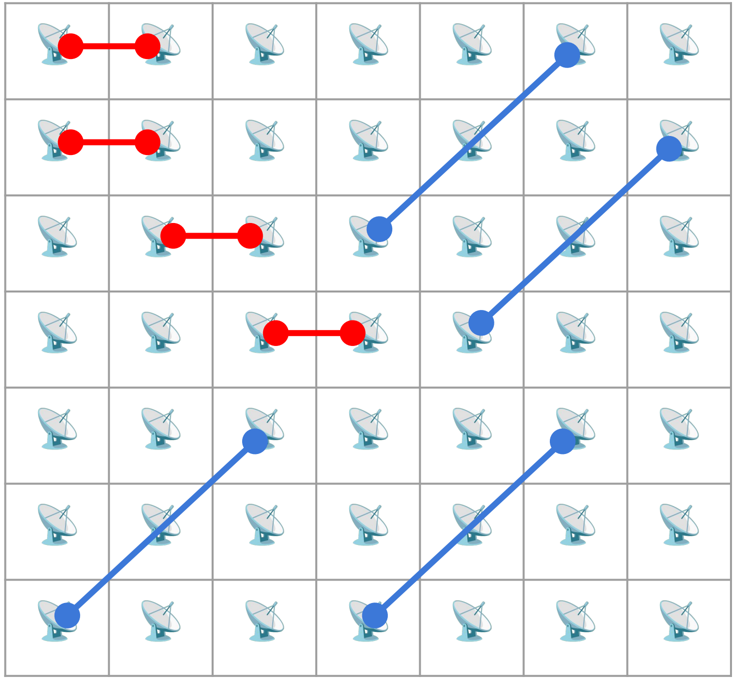
- Compact
  - Most weight on short baselines
  - ***Targeting large, cosmological angular scales***
  - Potential for cross-talk, reflections and impact from array-level effects
- Redundant array
  - Large N with many repeated baselines
  - **Enhanced sensitivity on sky Fourier modes on interest**
  - Internal, redundant, calibration
  - Large grating lobes leads to poor imaging capability
- E.g HIRAX, CHIME, CHORD, HERA, MWA



BAO Cosmology with Interferometers

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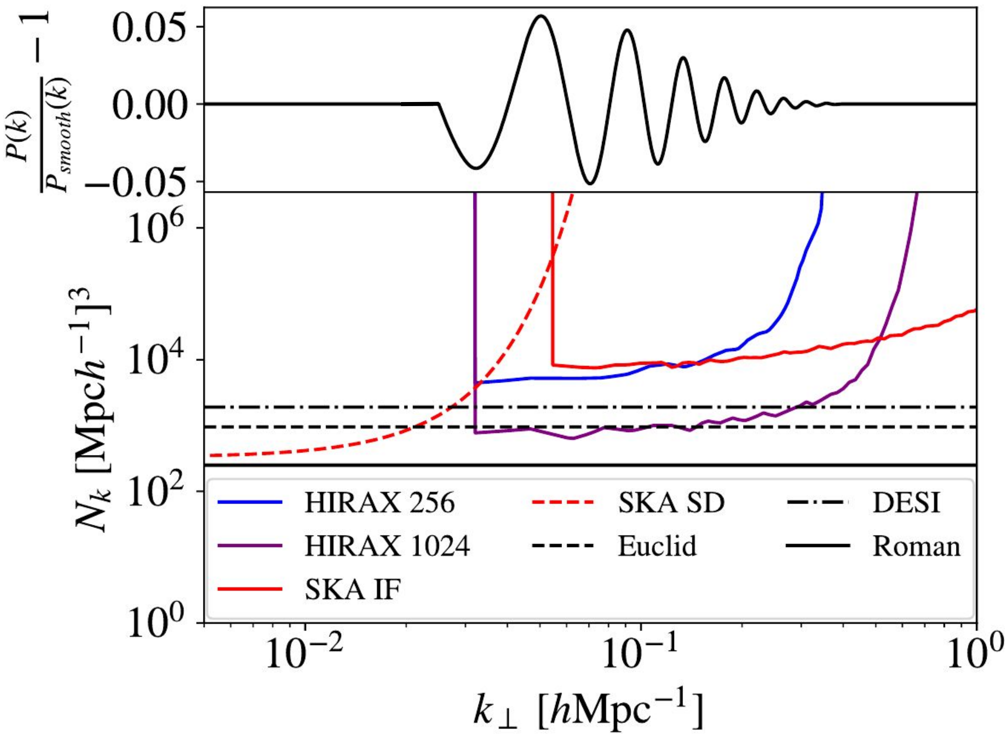

- Sensitivity in power spectrum space over finite domain
- Can be targeted on modes of interest with interferometers
  - BAO feature for HIRAX
- Comparable to spectroscopic surveys over most sensitive region

Systematics / Chromaticity and Foregrounds

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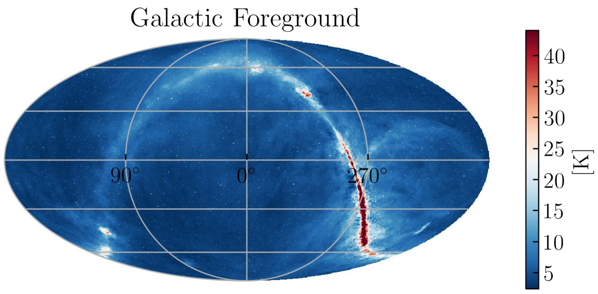
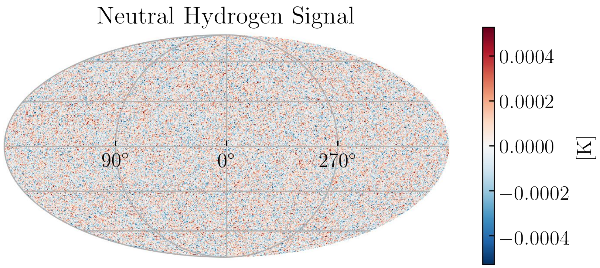
- Foregrounds are the primary challenge for 21cm cosmology
  - Galactic signal brighter by many orders of magnitude
- Signal and Foregrounds have different, *on-sky* properties
  - Galactic emission is:
    - Polarised
    - Strongly correlated over wide frequency bands
    - Structured on the sky in ~known way
  - In principle, there are not many mixed *on-sky* degrees of freedom
- Mode-mixing inherent in measurement is a major issue
  - Instrument has chromatic response *fundamentally* as well as arising from *systematics*
  - With perfect knowledge of the instrument, this can be accounted for, however the large contrast in signal strengths can make small reconstruction residuals a big problem
- **Instrument simulation and characterisation is critical!**





Foreground Wedge

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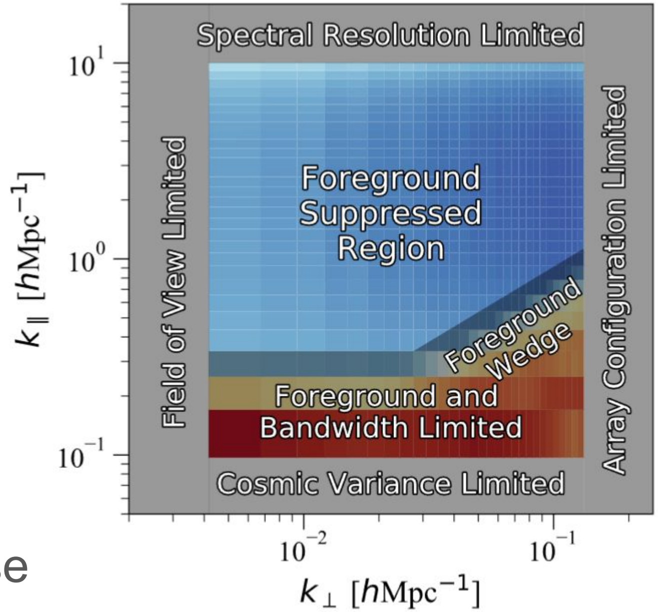
- Chromatic response of wide-field interferometer
- Details of where the wedge is limited depend on the instrument and, in particular, spectral wide-field response
- Many ways for foregrounds to leak out of the wedge
    - Miscalibration
    - Systematic reflections and correlations
    - etc.



Liu & Shaw 2020

$$\mathcal{V}_{i-j}(\nu) = \int d\Omega\, \underbrace{A_i A_j^*(\hat{n}, \nu)}_{\text{Primary Beams}} T(\hat{n}, \nu) \underbrace{\exp\left[2\pi i \frac{\nu}{c} \vec{b} \cdot \hat{n}\right]}_{\text{Baseline Term}}$$

As $\vec{b} \cdot \hat{n}$ increases towards horizon, instrument response become increasingly chromatic, scaling with baseline length.

State of Late-time Cosmological HI Observations

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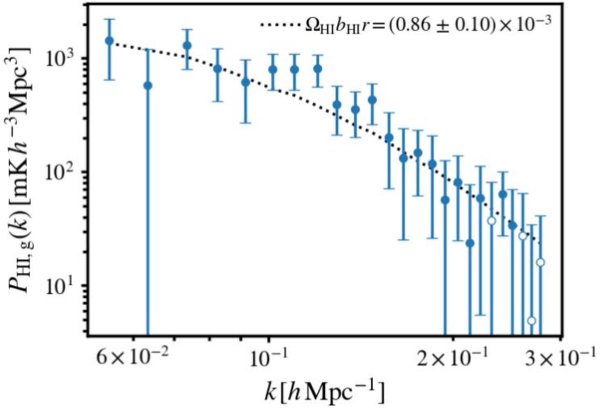
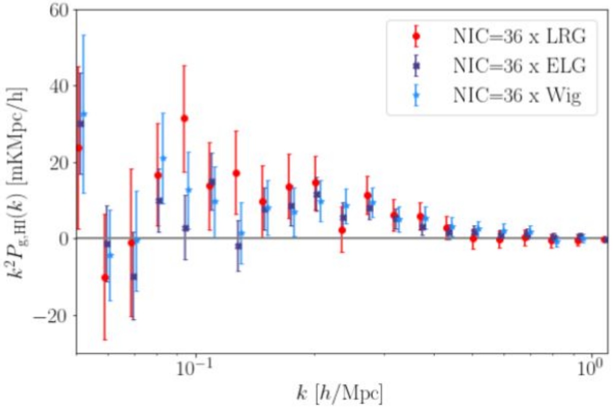
Multiple measurements in cross-correlations with spectroscopic surveys

- Green Bank Telescope x WiggleZ / BOSS
- MeerKAT Single Dish x WiggleZ
- Significant signal loss from foreground cleaning but strong detections





Wolz et al. 2022

Cunnington et al. 2022

State of Late-time Cosmological HI Observations

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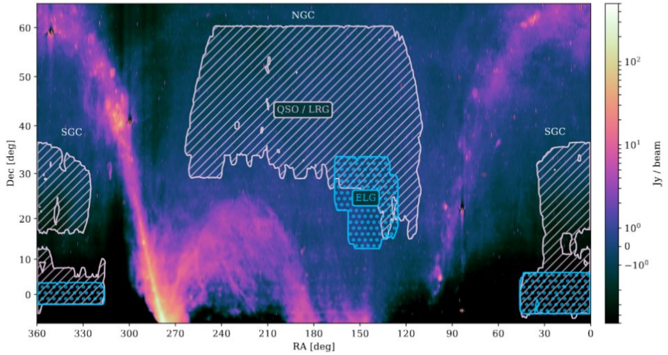
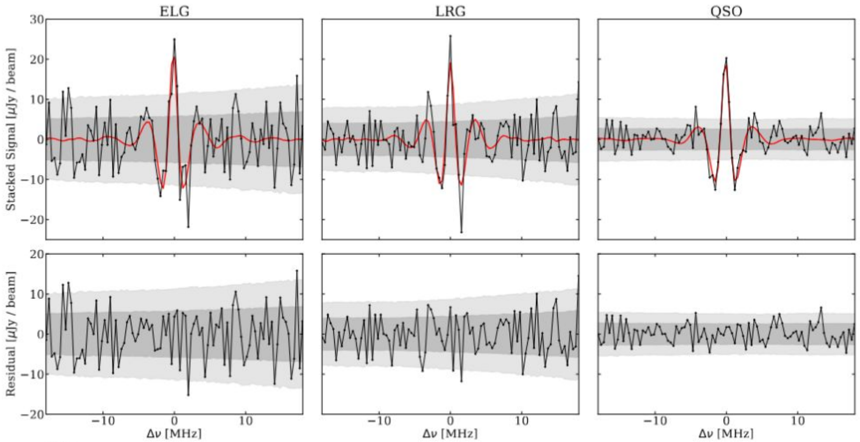
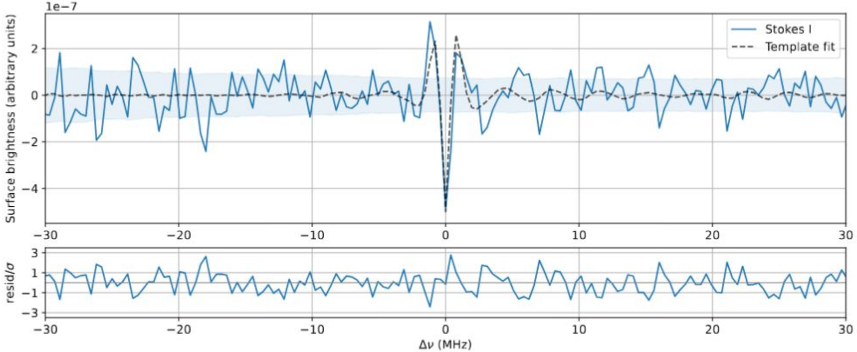
CHIME x eBOSS

- Spectral stacking of spectropic tracers
- Strong detections out to high redshift
- Anti-correlation with Lyman-α absorbers recently detected







CHIME Collaboration 2022 & 2023

State of Late-time Cosmological HI Observations

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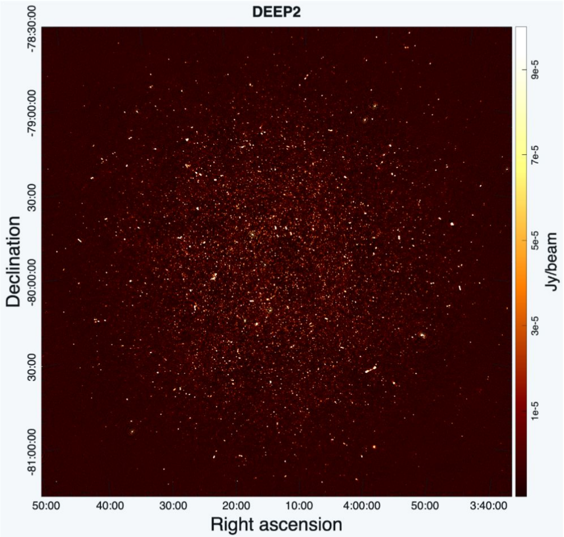
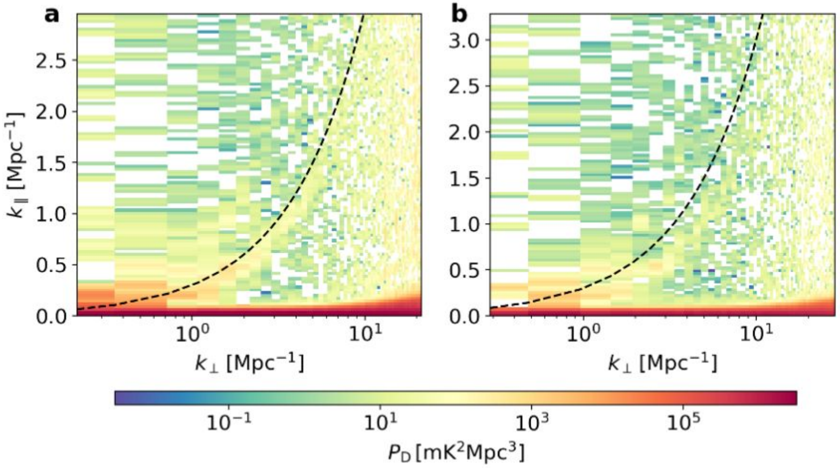
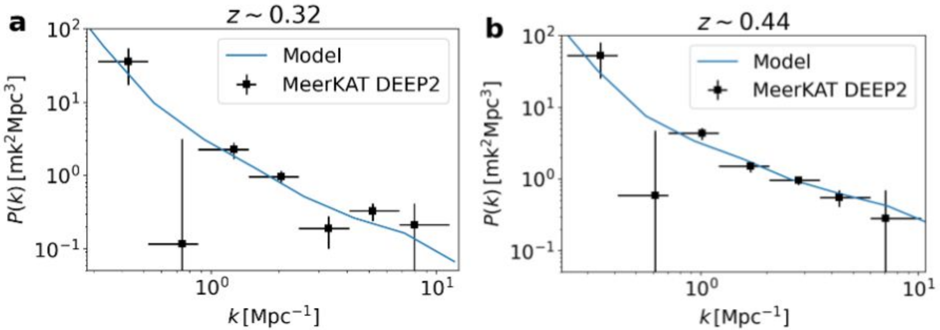
First detection in auto-spectrum

- Deep 96hr MeerKAT L-band data
- Very well calibrated, ~10^{-5}
- Signal primarily from small, non-cosmological scales







Paul et al. 2023

HIRAX

Hydrogen Intensity and Real-time Analysis eXperiment

HIRAX Overview

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HIRAX

- **H**ydrogen **I**ntensity and **R**eal-time **A**nalysis e**X**periment
- Radio interferometer with a compact, redundant layout
- To be co-located with the SKA-MID in the Karoo
- Funded up to 256 element deployment.
- 6m diameter dishes instrumented to operate between 400–800 MHz.
    - Plans to extend to 1024.
- Intensity mapping survey of ~⅓ of the sky over 4 years
- Primary Science Goals:
    - Observationally probe the evolution of dark energy
    - Survey the transient radio sky

Overview of HIRAX-256 Crichton et al.
https://arxiv.org/abs/2109.13755

HIRAX Site

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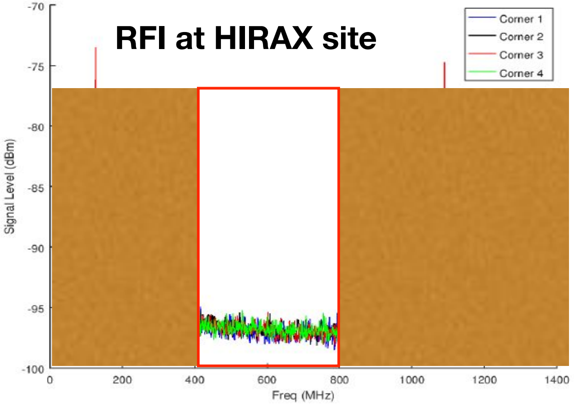
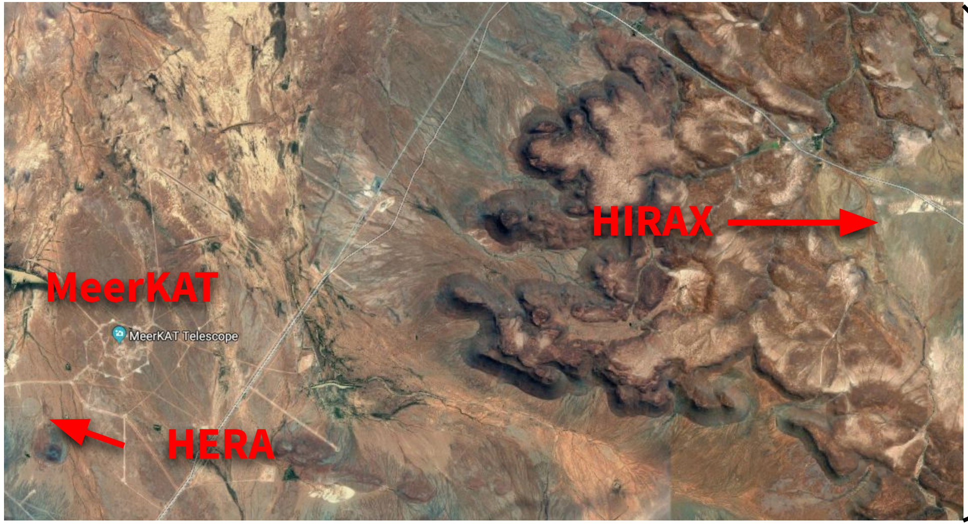
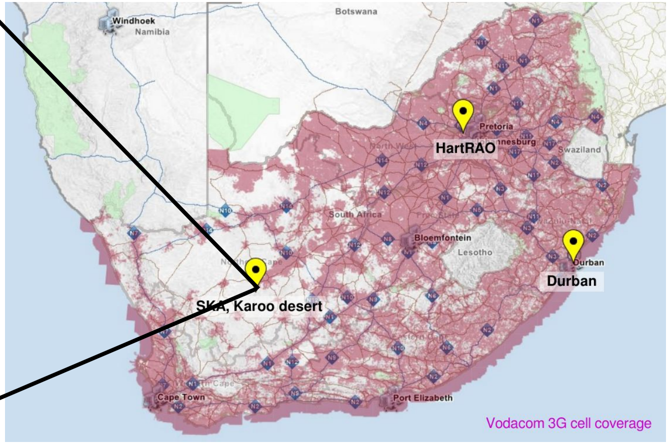
- Guest instrument on SARAO managed Karoo site
- Low RFI site - protected by government regulations
- Close to road for access, power and external network connection and SARAO infrastructure



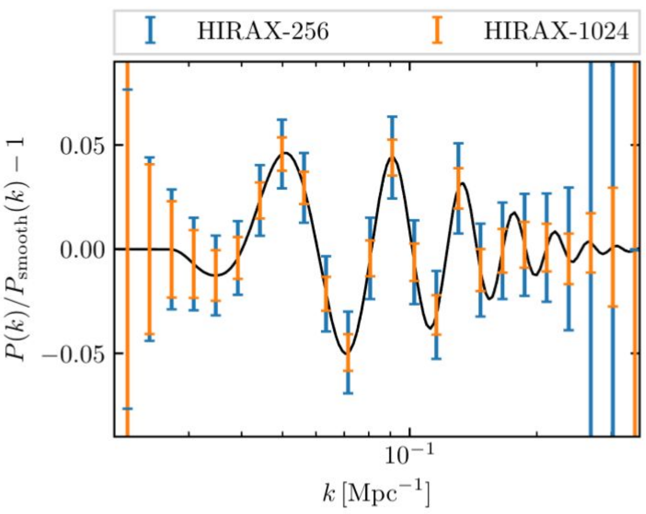


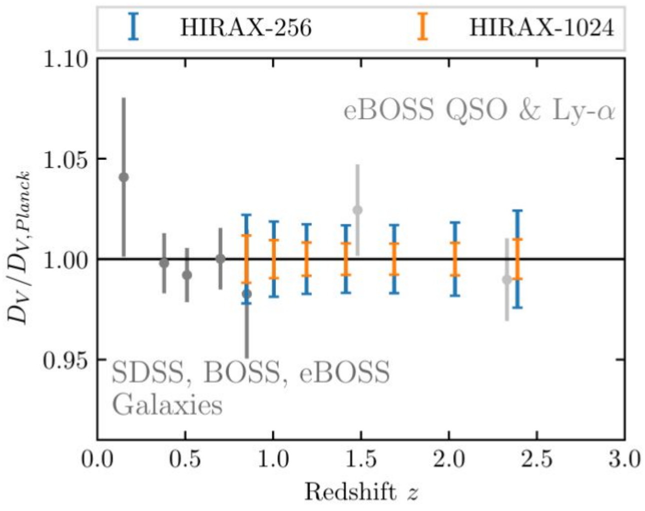


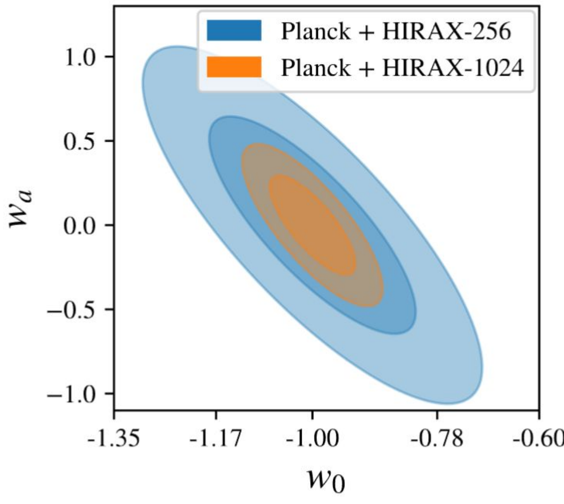
HIRAX BAO Cosmology

Parameter	Value
Number of dishes	256
Dish diameter	6 m
Dish focal ratio	~~0.23~~ **0.21**
Collecting area	7200 m^2
Frequency range	400–800 MHz
Frequency resolution	1024 channels, 390 kHz
Field of view	5°–10°
Resolution	0.2°–0.4°
Target system temperature	50 K

- BAO scales targeted with HIRAX array layout and frequency range - standard ruler for geom. constraints
- Forecasted high significance P(k) measurement
- (More detailed simulation based, forecasting analysis in preparation - Viraj Nistane)







HIRAX Dynamical Dark Energy

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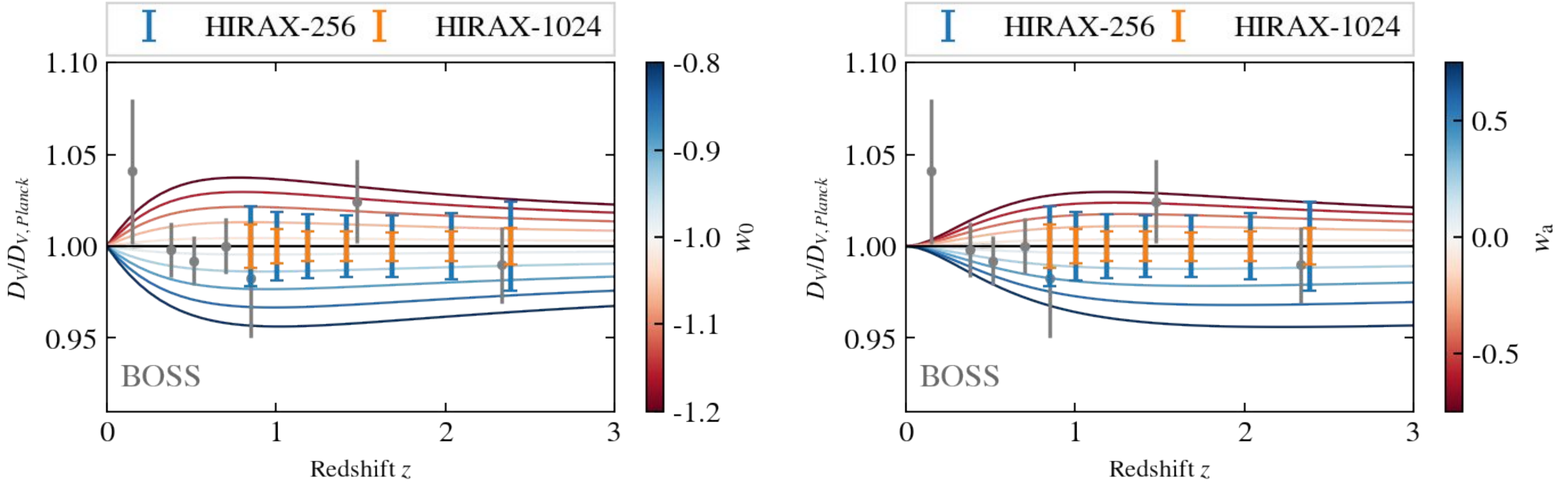

$$D_V(z) = \left[cz D_M^2(z)/H(z)\right]^{1/3}$$

$$w(a) = w_0 + (1-a)w_a$$

Transient and Additional Science Goals

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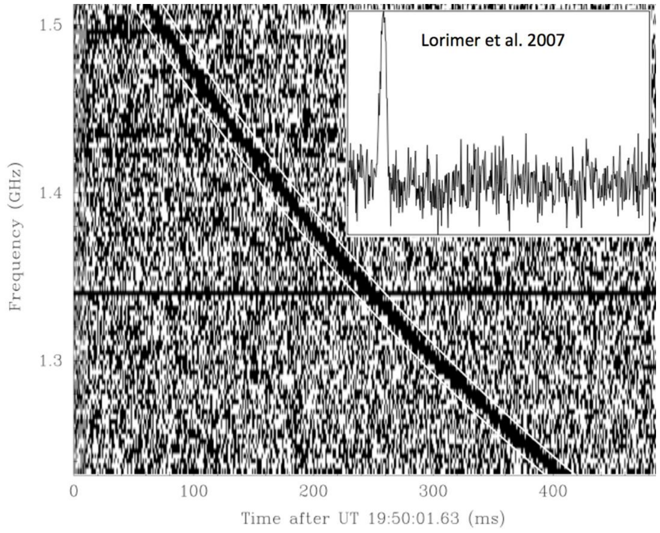
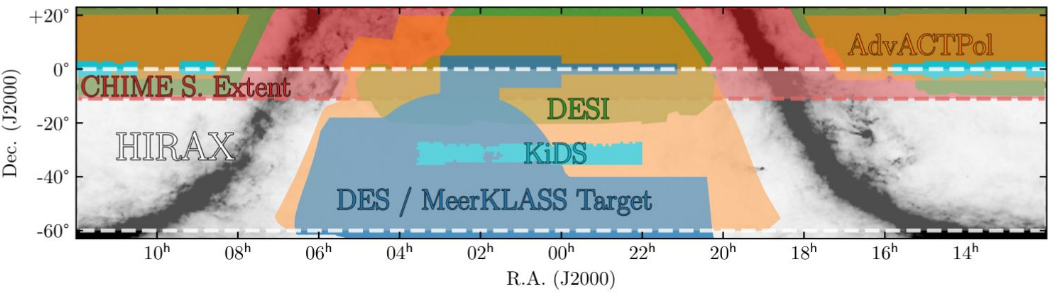


Real-time analysis of beamformed data

- **Fast Radio Burst Search**
  - Fast dedispersion algorithms over range of dispersion measures
  - Localisation with outriggers (e.g. BIUST Botswana)
- **Pulsar timing and search**
  - Timing and pulse profiles of known pulsars with coherent dedispersion
  - Incoherent search with high frequency and time sampling
- **HI Absorbers**
  - Blind and targeted absorption line search by long time integration on highly upchanneled beams



Cross-correlations with overlapping surveys

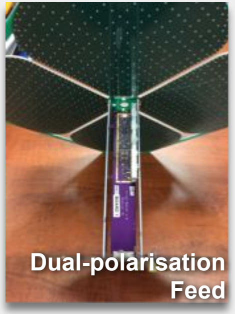
- DES, Rubin LSST, HSC, KiDS, DESI
- Euclid, Roman
- Ground based CMB (Lensing), ACT, SPT.

RF Frontend

Focuses and receives radio frequency (RF) signals from the sky.

Comprised of:

- A dual-polarisation feed on each of 256 dishes
- Radio frequency over fibre transmission system for data transport to backend.



→ 512 (2 polarisations per dish) raw voltage streams →

F-Engine

Digitises and separates analogue data streams into frequency channels covering 400-800MHz

Comprised of:

- 32 FPGA-based ICEBoard systems mounted in ICECrates.
- Custom mesh-network for corner-turn operation

→ Digitised voltage signals for each input over 1024 channels →

X-Engine (Correlator)

Cross-correlates (multiplies and averages) signals for all pairs of antenna inputs for each frequency channel, producing complex visibilities, the fundamental raw data product of an interferometer.

Node Layout:

AMD EPYC 7452 CPU	AMD EPYC 7452 CPU	1 TB RAM
NVIDIA A40 GPU		
2x40Gbe NIC		
2x40Gbe NIC		
NVIDIA A40 GPU		
2x40Gbe NIC		
2x40Gbe NIC		

Node Requirements:

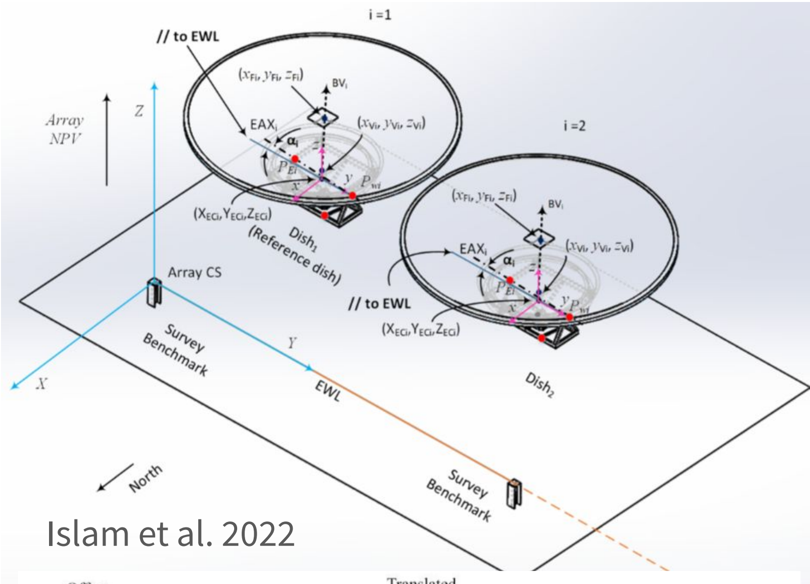
- Process 50 MHz chunk of HIRAX bandwidth for 512 inputs
- Approximately 200 Gbps of raw data + overhead
- Produce ~130k cross correlation products per channel.

irich

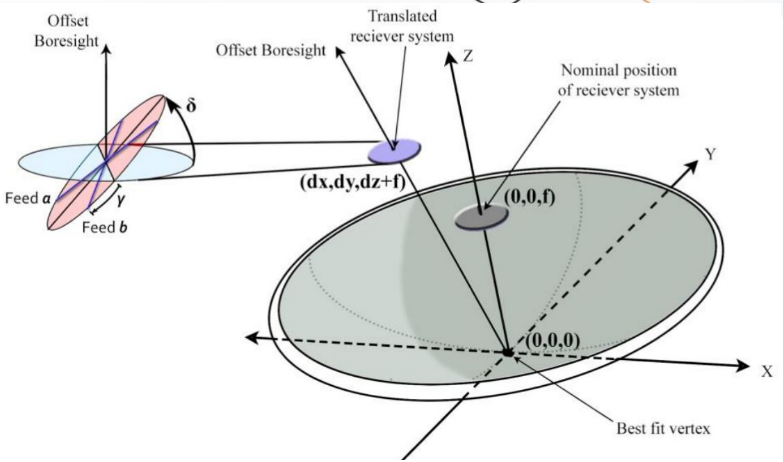
→ Visibility data for each channel and input pair (baseline) →

HIRAX Calibration Challenges

- Dishes fixed per elevation pointing
  - **Calibration options limited, pointing etc. needs external verification/measurement**
    - Informed by simulations
- Redundant interferometer
  - Calibration and on-site data compression relies on internal consistency
  - **HW Requirements on precision over accuracy**
- Consistency needs to be verified across array



Islam et al. 2022



Telescope Mechanical Assembly Requirements

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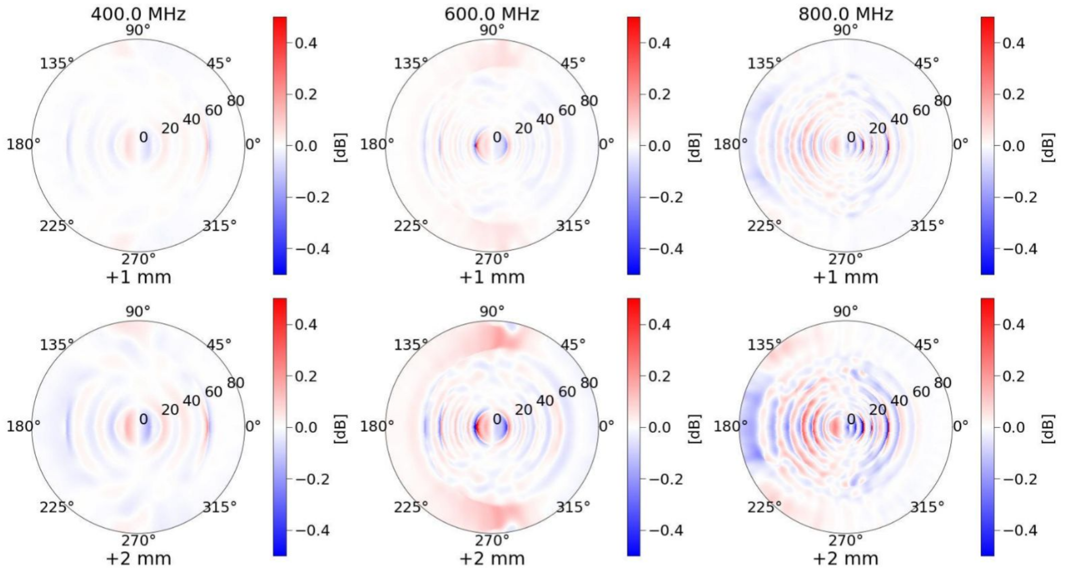
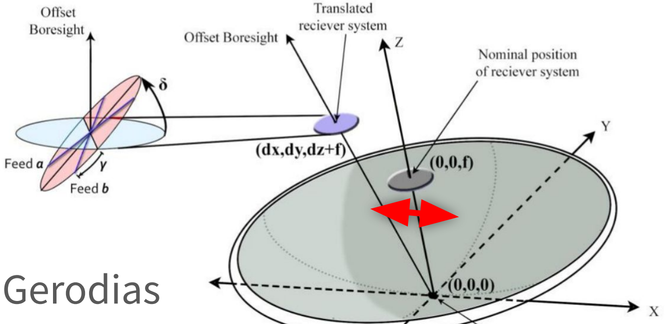


Requirements set with simulations

- λ/100 - λ/50 (< 1 mm)
  - Favour precision over accuracy
- Verified with metrology
  - Laser Tracker and Photogrammetry
  - During manufacture and operation

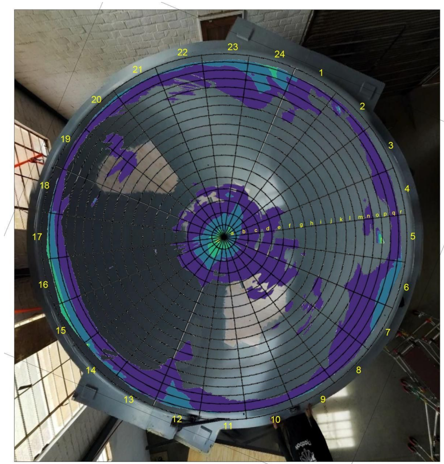


- Shifts beam centroid/effective pointing
  - Large systematic effect for physical tolerances
- Distribution of mis-pointing across the array is a large systematic concern

Beam Simulations: Kit Gerodias

HIRAX-256 Status and Timeline

- Many components e.g. correlator and on-site compute in final stages of testing
- Dish factory established at site, site development plan in late stages
- First non-monolithic reflectors for outriggers under QA
- Significant activity in developing dish construction tooling with Advanced Fiber Form, early 2023 to present, first plug at Carnarvon, moulds ~ now.
- Commission two-element qualification dishes at Klerefontein, site Q3 2024
- Dish production in full swing mid-late 2024



6m dish plug QA with laser tracker - 12.09.23

Conclusions

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- 21cm intensity mapping provides access to large cosmological volumes over mostly linear scales - can be targeted with dedicated, compact interferometers.
- HIRAX has the statistical power for a compelling cosmological survey - BAO focused
- Competitive Platform for real-time analysis with significant on-site compute
- Overcoming systematics/foregrounds challenge is difficult and requires a controlled and well-characterised instrument model.
- Static dishes cannot be easily calibrated directly, requires reconstruction and verification with system measurements.
- Many subsystems close to completion. Dishes with final design to be constructed very soon and early science data expected with array build out to follow.
- Will learn a lot for early data!

Thanks!