BAO Cosmology with the Hydrogen Intensity and Real-time Analysis eXperiment

SKACH Spring Meeting 2024 - 11.06.24

Devin Crichton - ETH Zürich

HI Intensity Mapping Tomography

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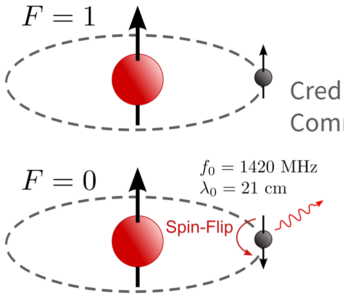
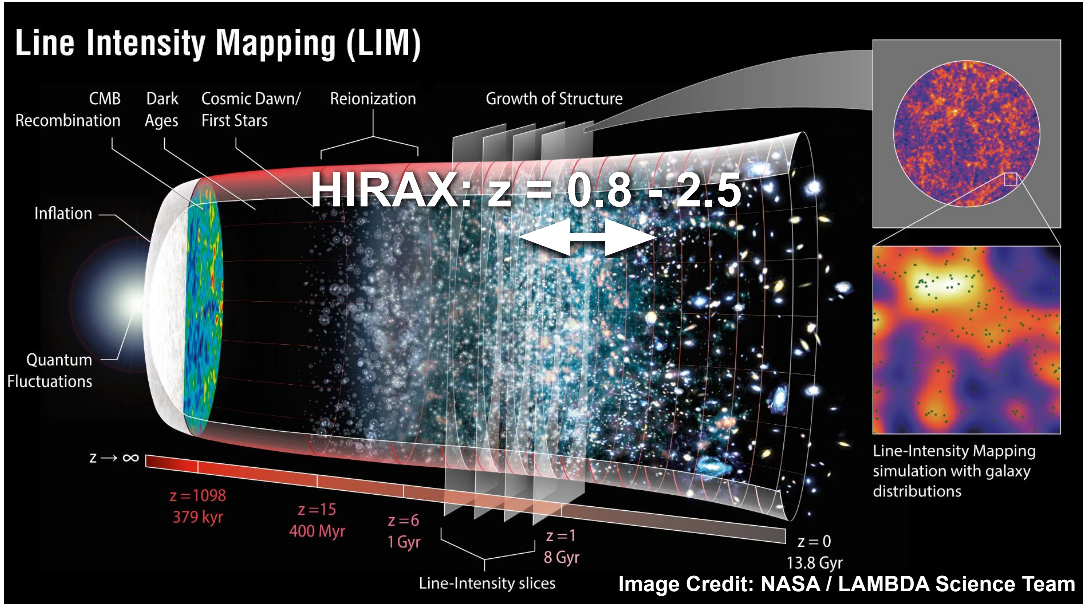


Credit: Wikimedia Commons

- Hyperfine Hydrogen transition line at 1420.4 MHz
- Probe cosmic dawn and epoch of reionisation at low frequencies and large scale structure at high frequencies
- Low angular resolution, high spectral resolution

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

- Post-reionisation IM
  - ν > 200-300 MHz
  - HI emission acts as biased tracer of large scale structure
  - Large volumes on linear-quasilinear scales



Baryon Acoustic Oscillation Cosmology

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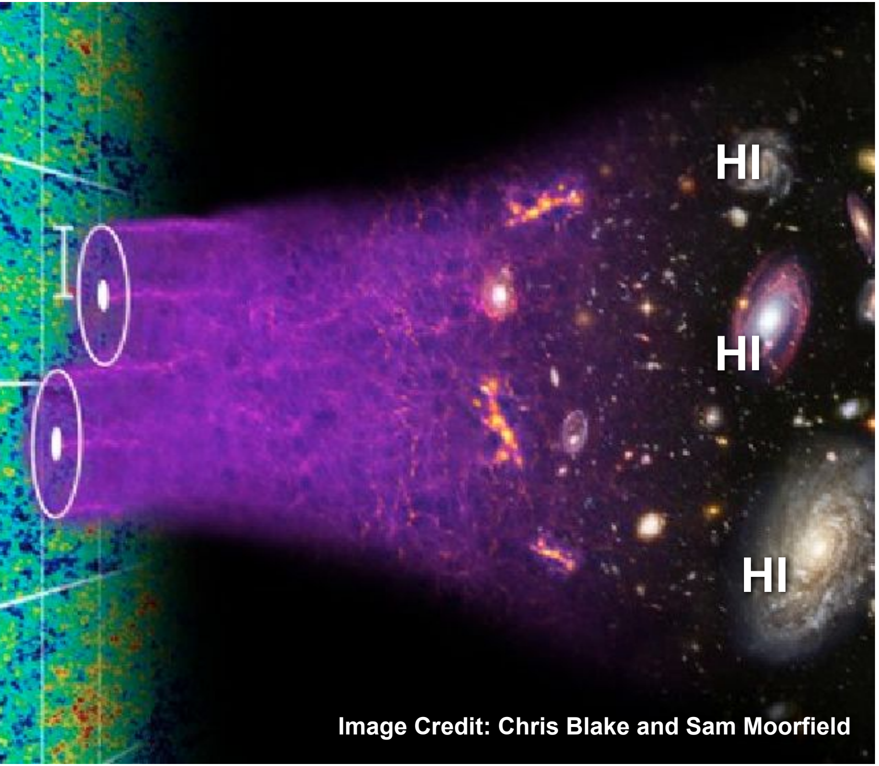
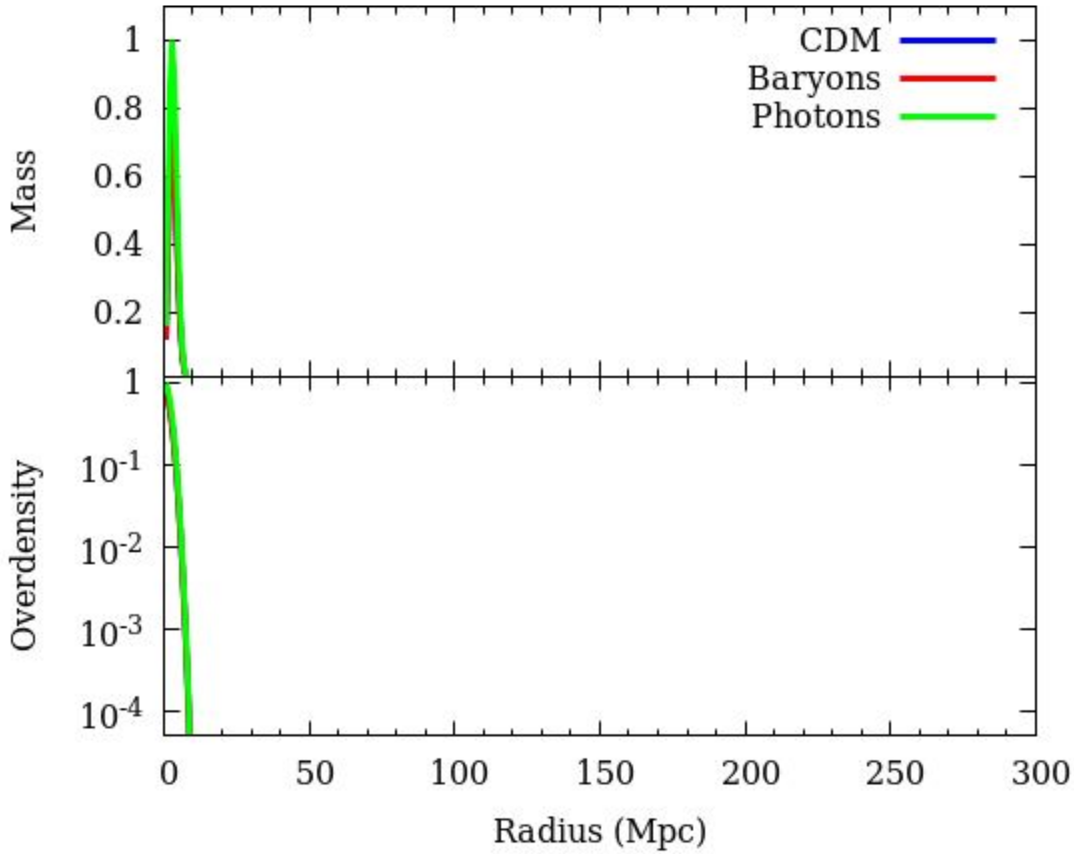
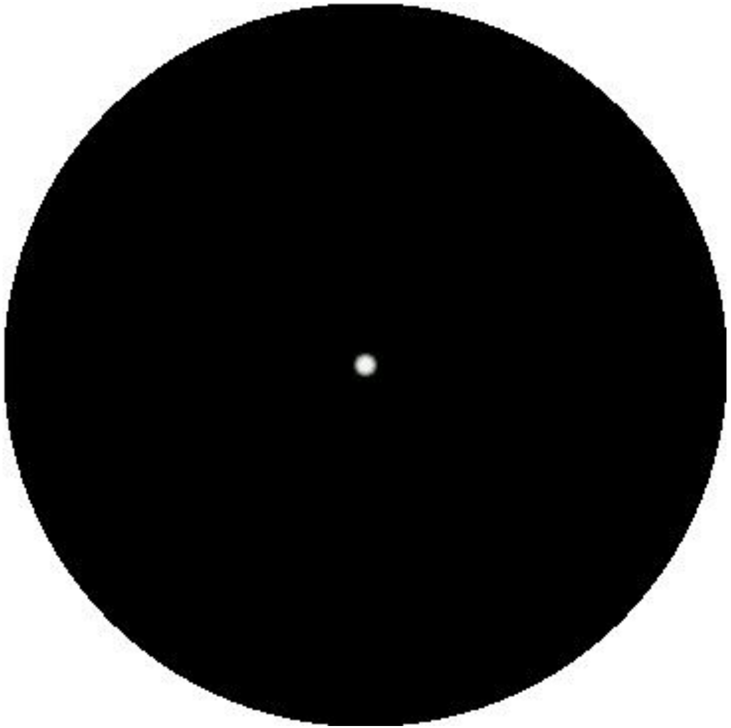


- Characteristic scale imparted on statistical distribution of matter in early universe
  - ~150 Mpc comoving 1.5-3° (HI @ 400-800MHz)
- Post-reionisation HI located in dense regions within galaxies, tracing matter.
- Tomographic measurements provide ***standard ruler*** observable of universe's geometry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

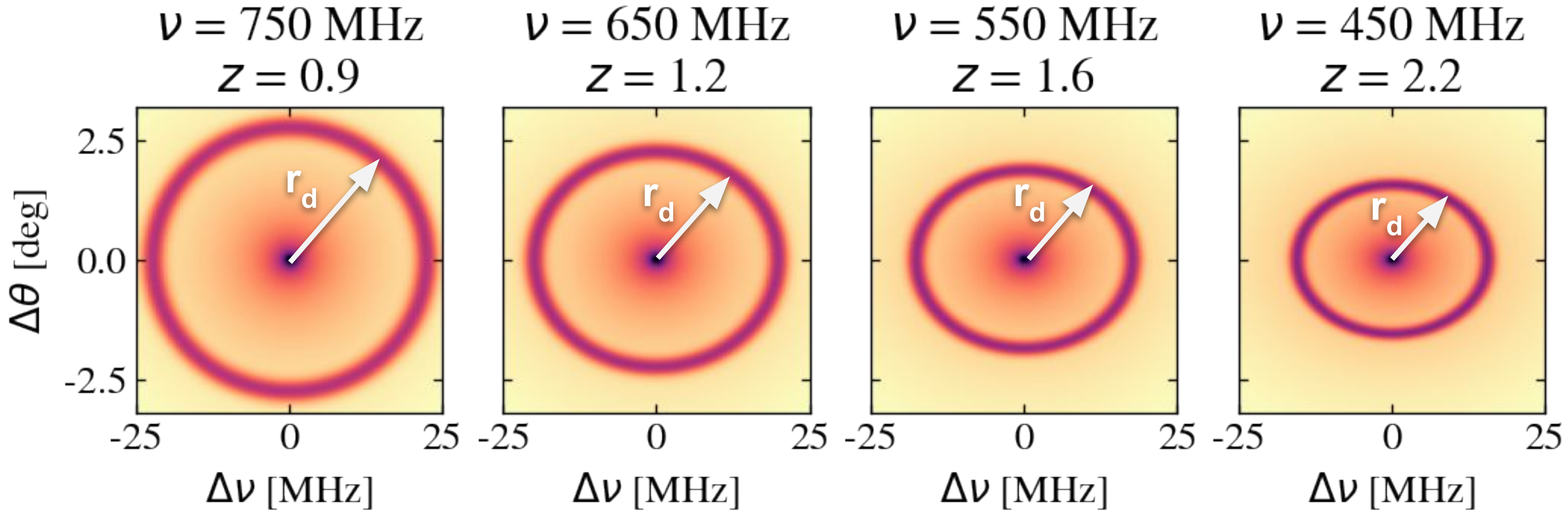
Baryon Acoustic Oscillation Cosmology





Animation Credit: Adam Hincks

BAO Cosmology with Interferometers



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

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

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

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

$$\Omega_m, \Omega_k, \Omega_\Lambda, w_0, w_a \ldots$$

BAO Cosmology with Interferometers

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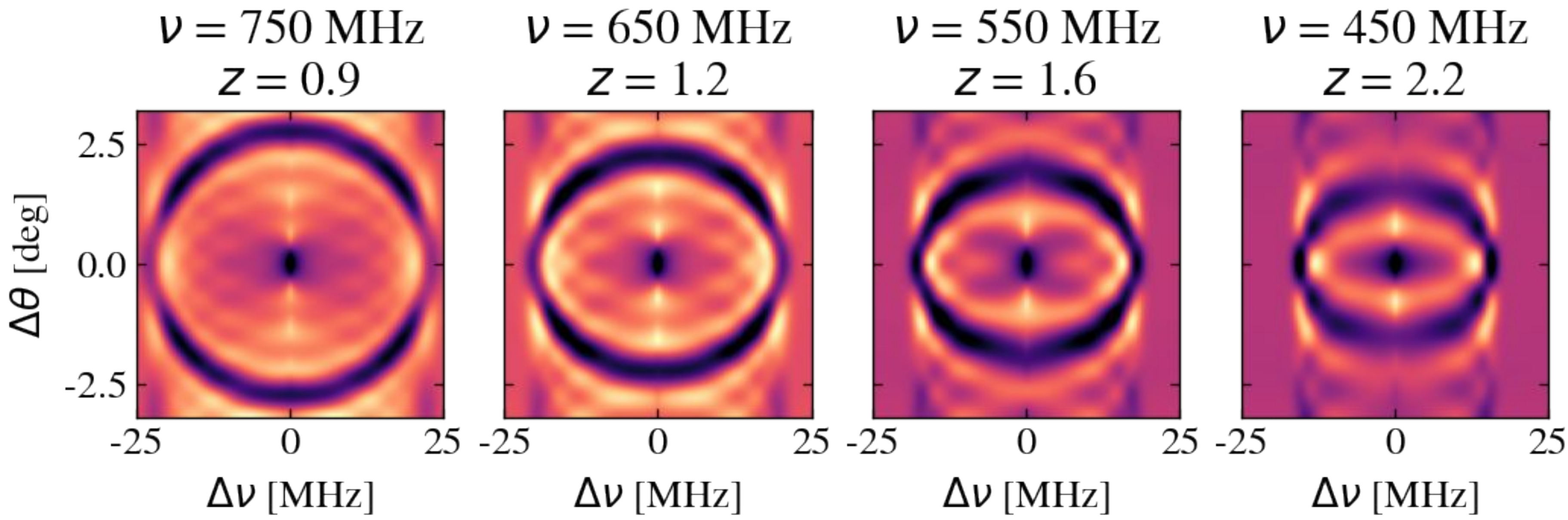
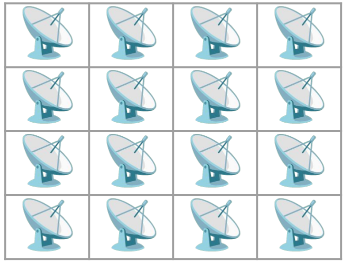


$$\theta_{\text{res.}} = (1+z)\frac{21\ \text{cm}}{|\vec{b}|}$$

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



BAO Cosmology with Interferometers

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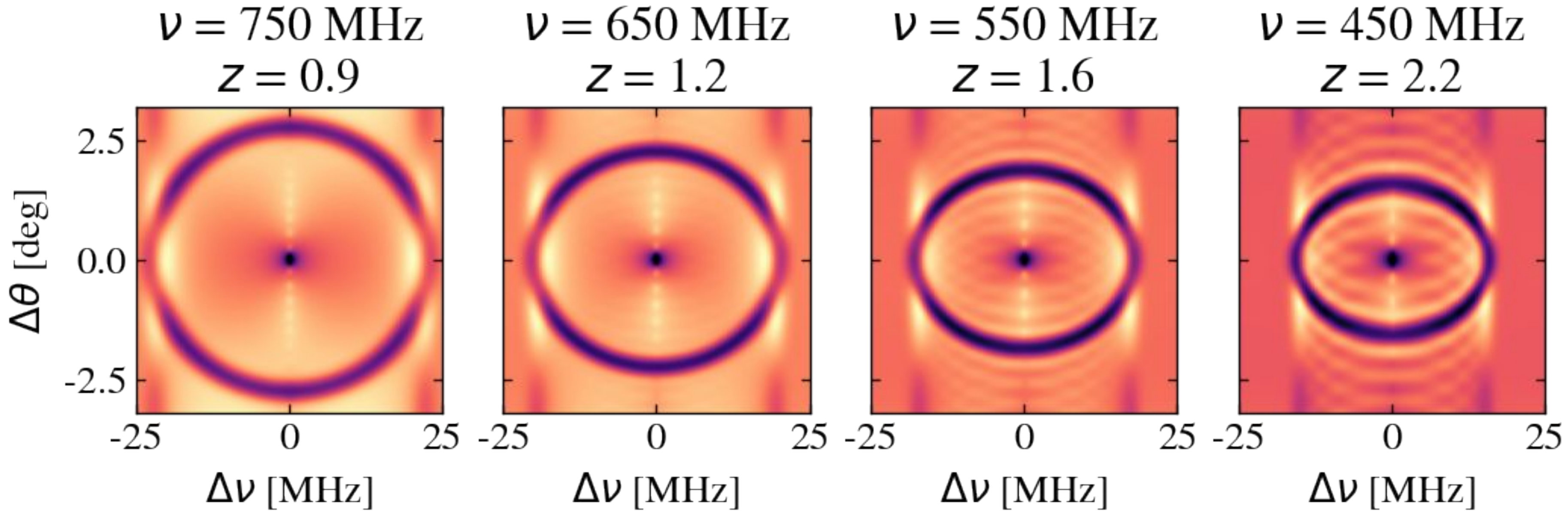

$$\theta_{\mathrm{res.}} = (1+z)\frac{21\ \mathrm{cm}}{|\vec{b}|}$$

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

BAO Cosmology with Interferometers

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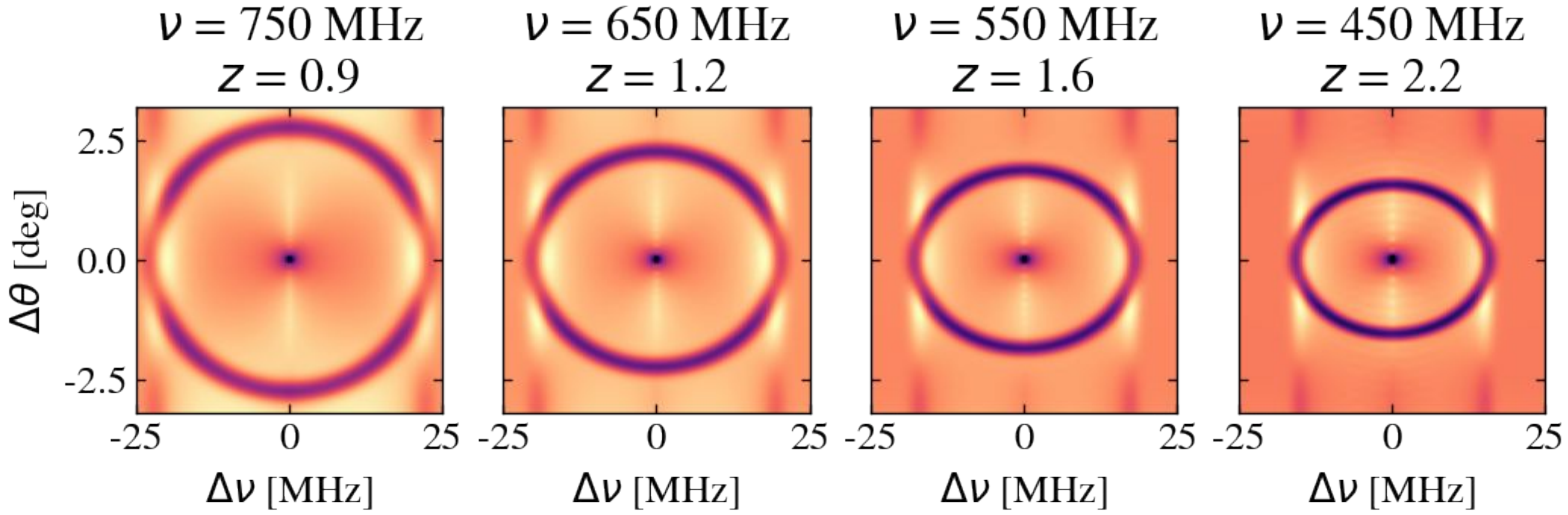

$$\theta_{\text{res.}} = (1+z)\frac{21\ \text{cm}}{|\vec{b}|}$$

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

Motivation for Compact Redundant Arrays

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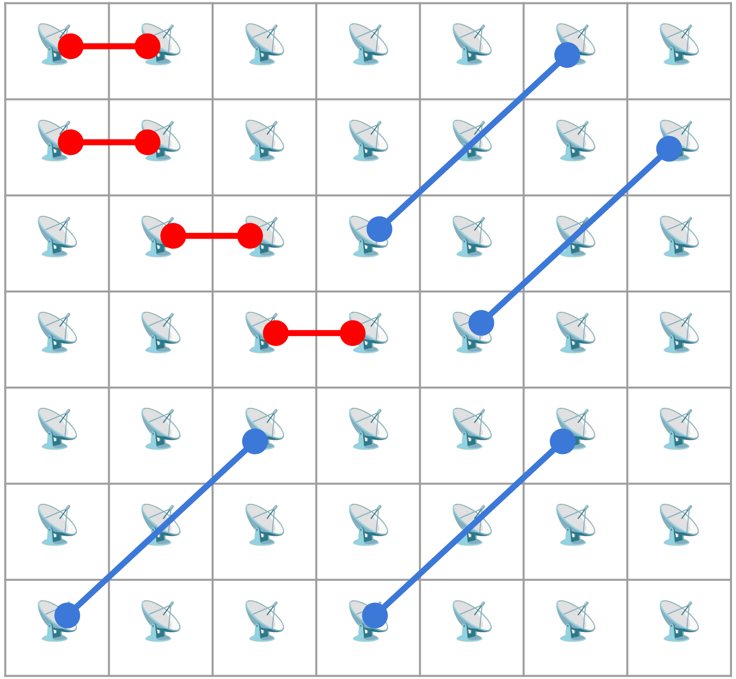
- Compact
  - ***Accessing large, cosmological angular scales***
  - Most weight on short baselines
  - Potential for cross-talk, reflections and impact from array-level effects
- Redundant array
  - **Enhanced sensitivity on sky Fourier modes on interest**
  - Large N with many repeated baselines
 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



Systematics / Chromaticity and Foregrounds

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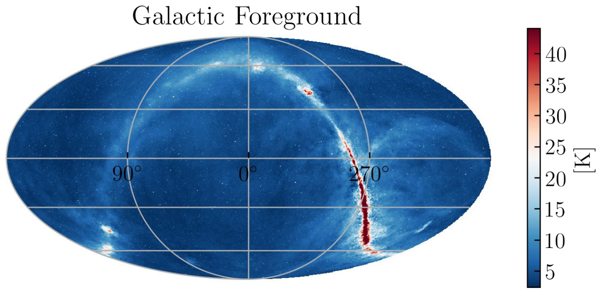
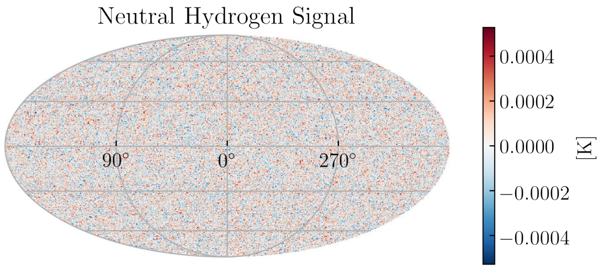
- Foregrounds are the primary challenge for 21cm cosmology
    - Galactic signal brighter by many orders of magnitude
- Signal and Foregrounds have different, *on-sky* properties
    - Galactic emission is:
        - Polarised
        - Strongly correlated over wide frequency bands
        - Structured 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
- **Tight requirements on telescope design**
- **Instrument simulation and characterisation is critical**





HIRAX Overview

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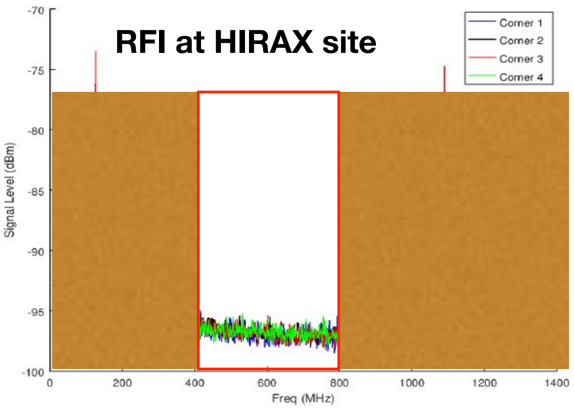
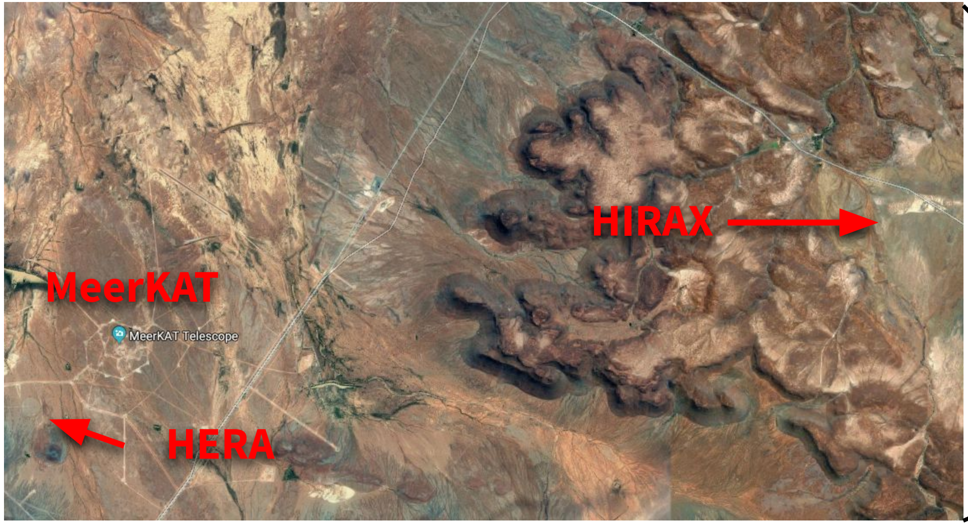
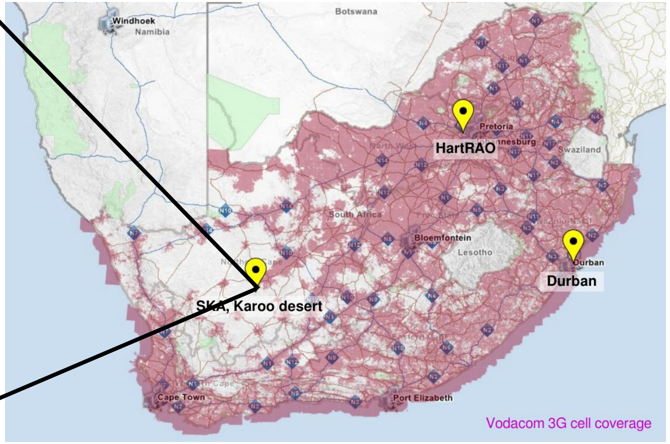
- Guest instrument on SARAO managed Karoo site
- Low RFI site - protected by government regulations
- Close to road for access, power and external network connection and SARAO infrastructure







HIRAX BAO Cosmology

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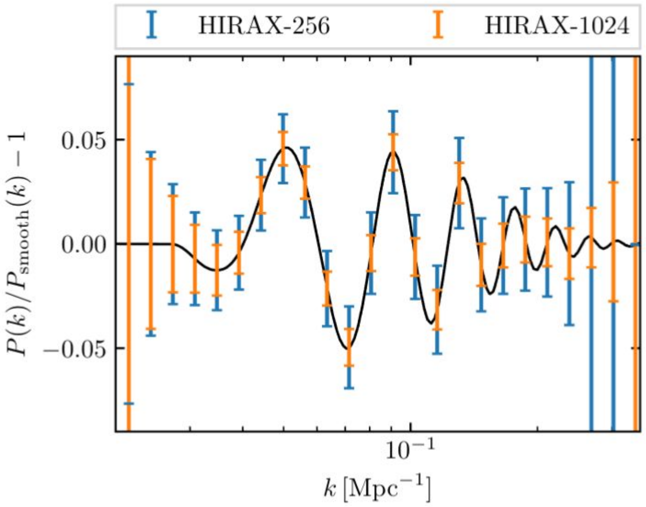
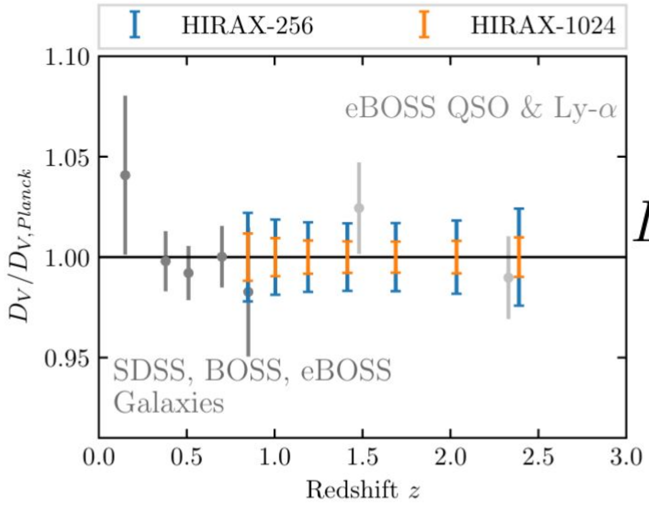
Parameter	Value
Number of dishes	256
Dish diameter	6 m
Dish focal ratio	~~0.23~~ 0.21
Collecting area	7200 m^2
Frequency range	400–800 MHz
Frequency resolution	1024 channels, 390 kHz
Field of view	5°–10°
Resolution	0.2°–0.4°
Target system temperature	50 K

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





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

Dynamical Dark Energy

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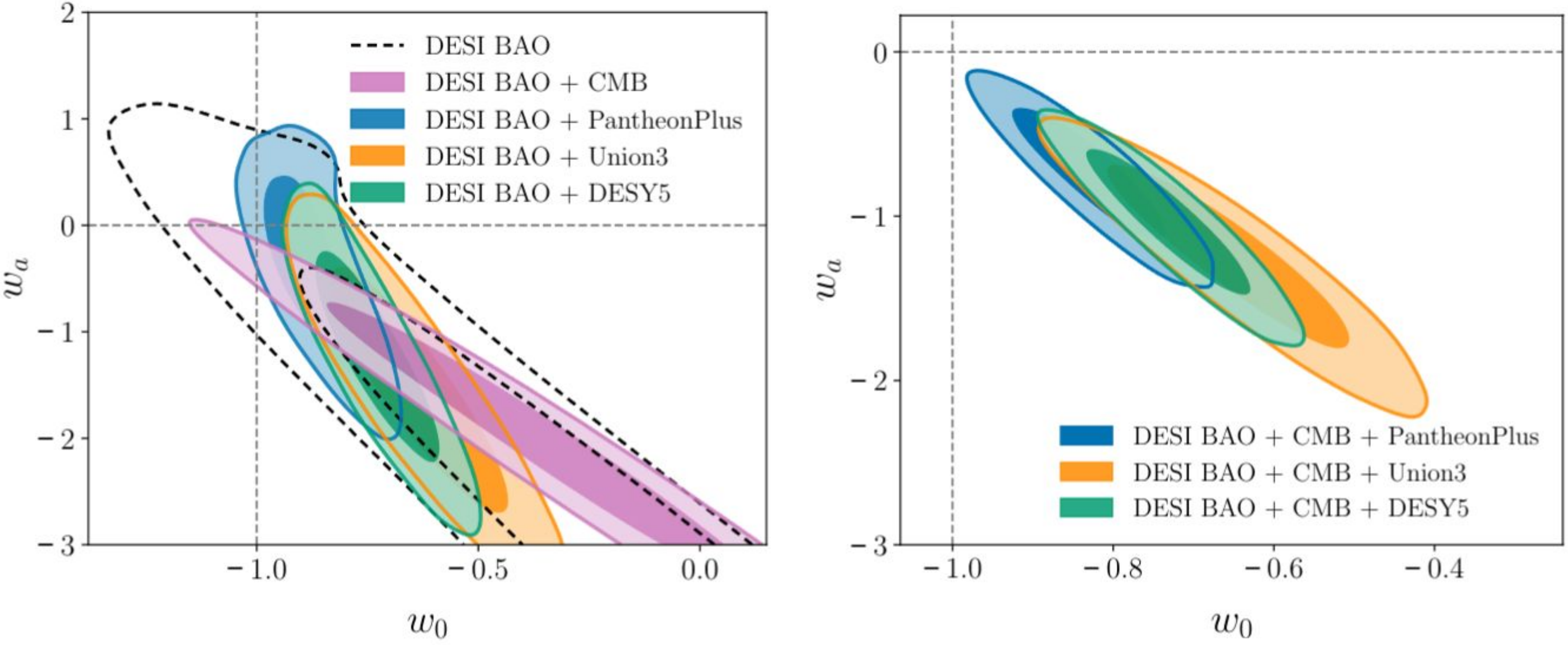

$$p = w\rho \qquad w(a) = w_0 + (1-a)w_a$$

DESI Collaboration 2024

HIRAX Dynamical Dark Energy

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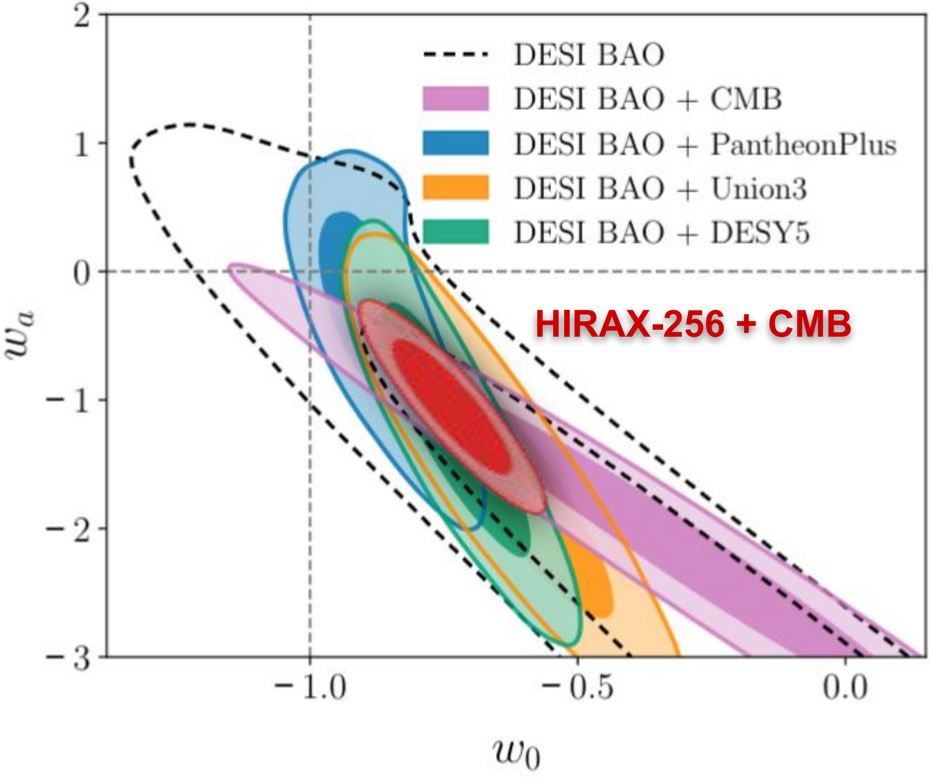

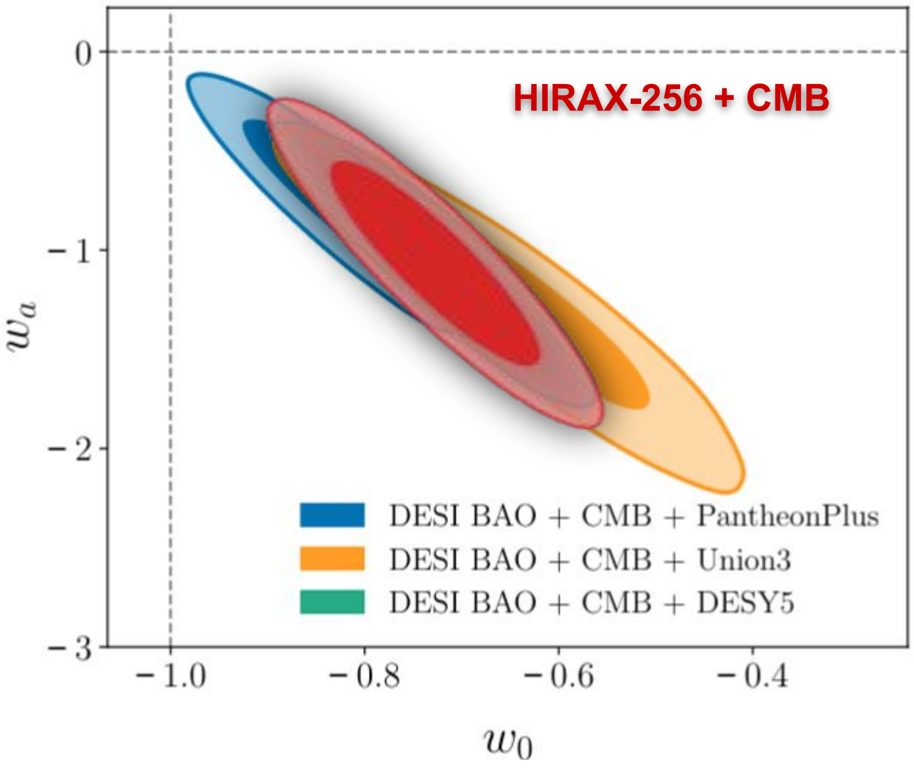

$$p = w\rho \qquad w(a) = w_0 + (1 - a)w_a$$

*Only Illustrative

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HIRAX Dynamical Dark Energy

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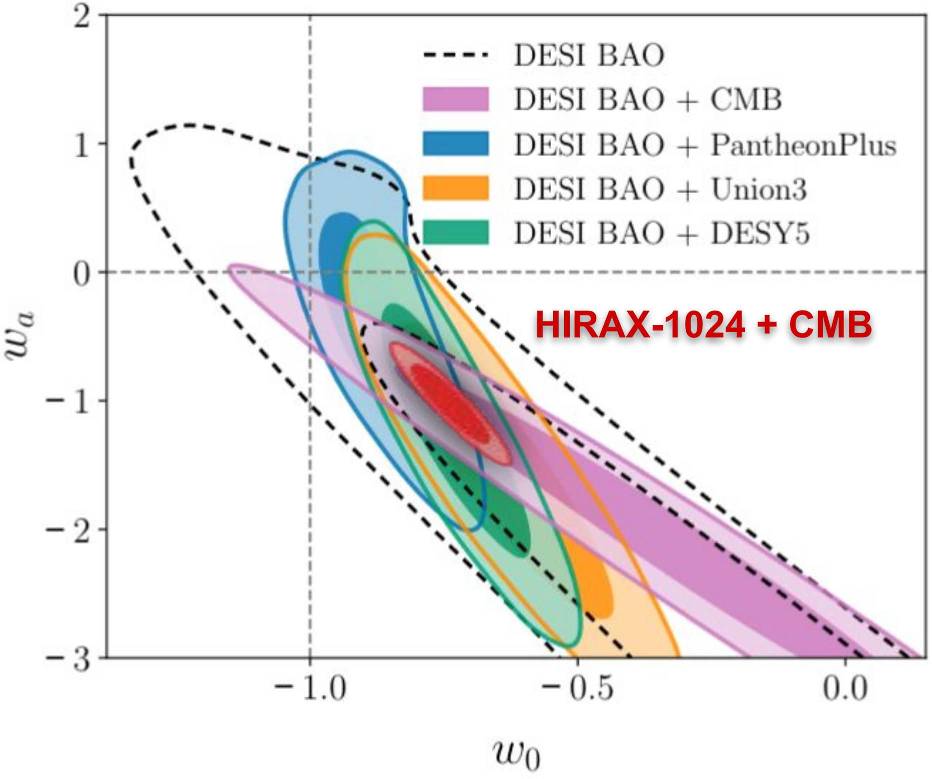

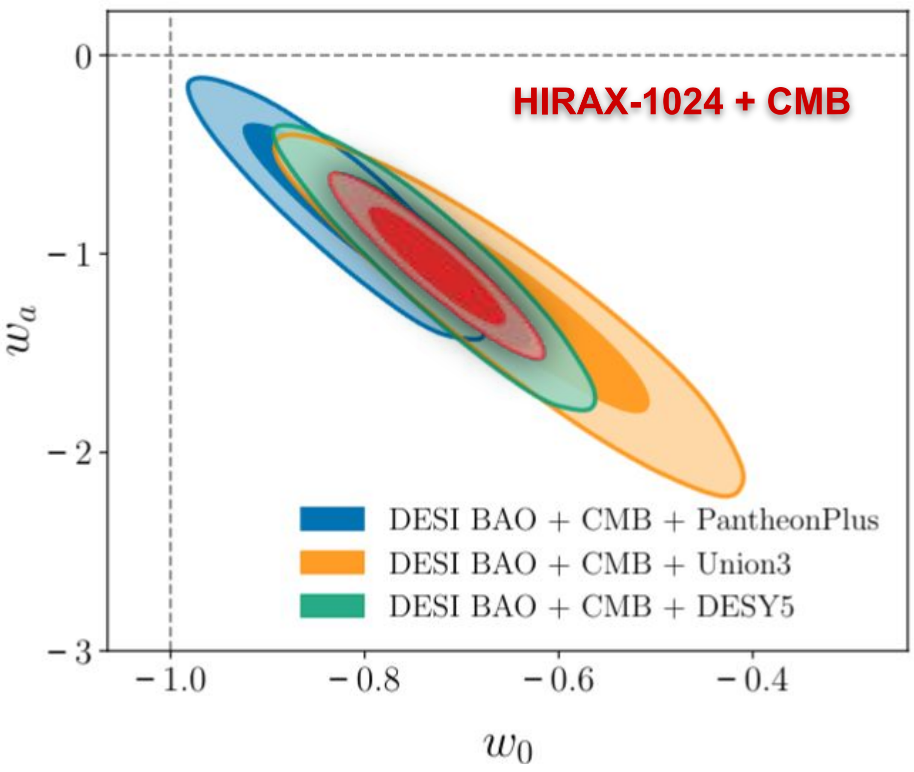

$$p = w\rho \qquad w(a) = w_0 + (1-a)w_a$$

*Only Illustrative

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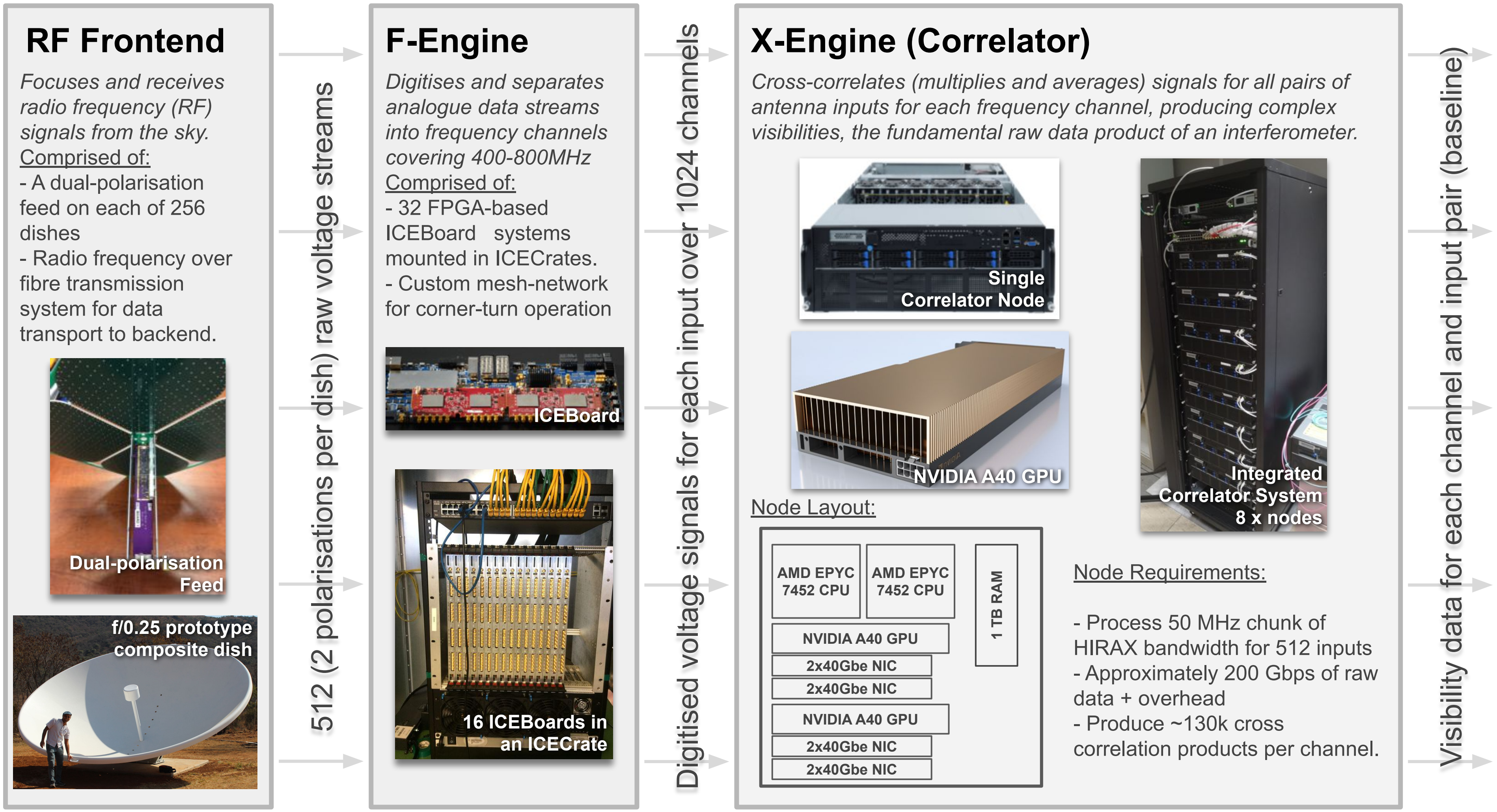
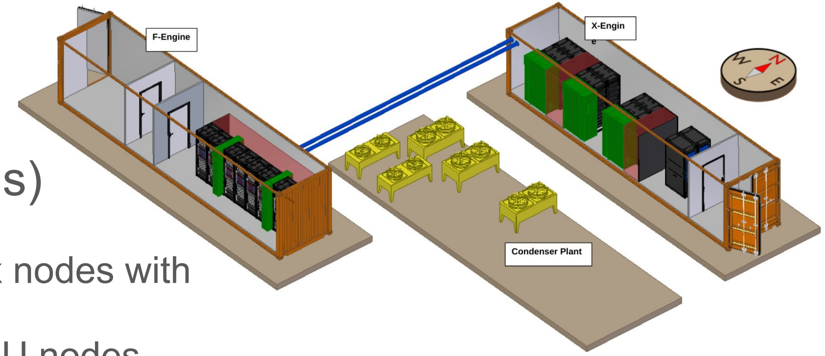
HIRAX Hardware and Status


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.
Dual-polarisation Feed
f/0.25 prototype composite dish
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
ICEBoard
16 ICEBoards in an ICECrate
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.
Single Correlator Node
NVIDIA A40 GPU
Integrated Correlator System 8 x nodes
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.
Visibility data for each channel and input pair (baseline)

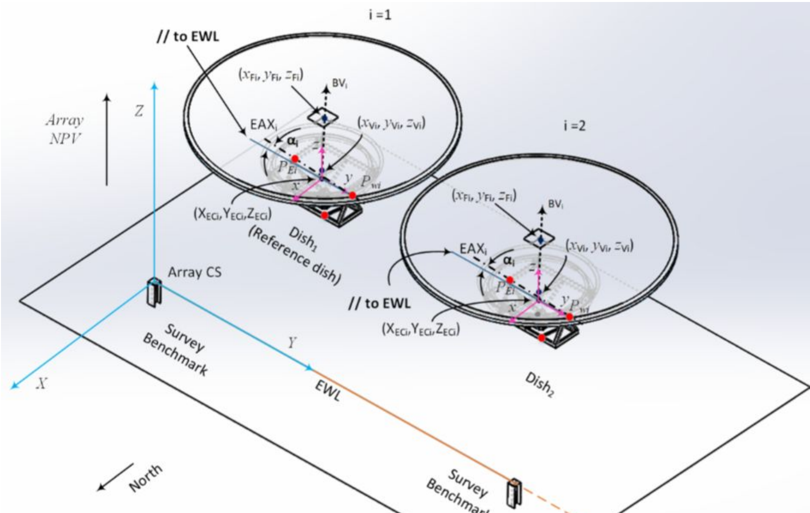
Heterogenous Data Processing Backend



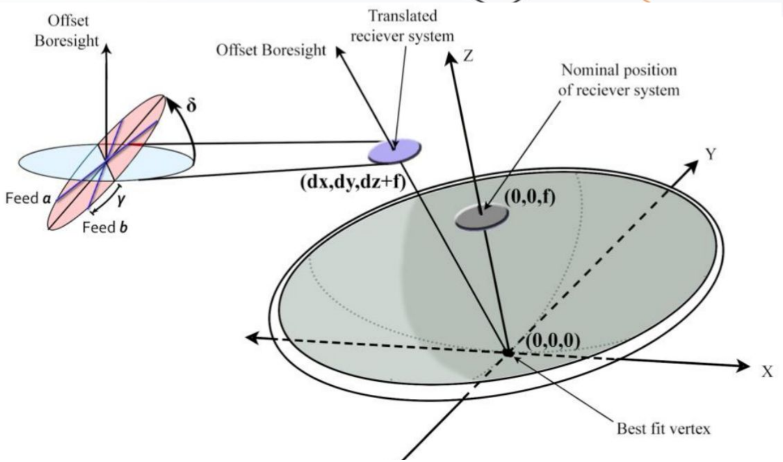
- On-site for real-time analysis and compression
- Beam-forming backends (nominal specifications)
  - FRB: O(100s) Beams @ 32k channels, 1ms sampling
    - GPU based incoherent dedispersion search, 5 x nodes with Nvidia A40s, 1TB RAM
  - Pulsar Search/Timing: ~6 full baseband beams 3 x GPU nodes
    - Coherent dedispersion for timing
    - Incoherent dedispersion at 1us, up to 16k channels for search
  - Blind HI Abs. Search: ~ FRB Beams @ 128k channels, accumulating ~30s.
- On-site analysis machines
  - On-site cosmology reduction/analysis / intake / storage
    - On-site calibration/visibility stacking for cosmological analysis
    - Daily pipeline tasks, data quality metric, housekeeping TOD-DBs

HIRAX Calibration Challenges

- Dishes fixed per elevation pointing
  - **Calibration options limited, pointing etc. needs external verification/measurement**
    - Rely on 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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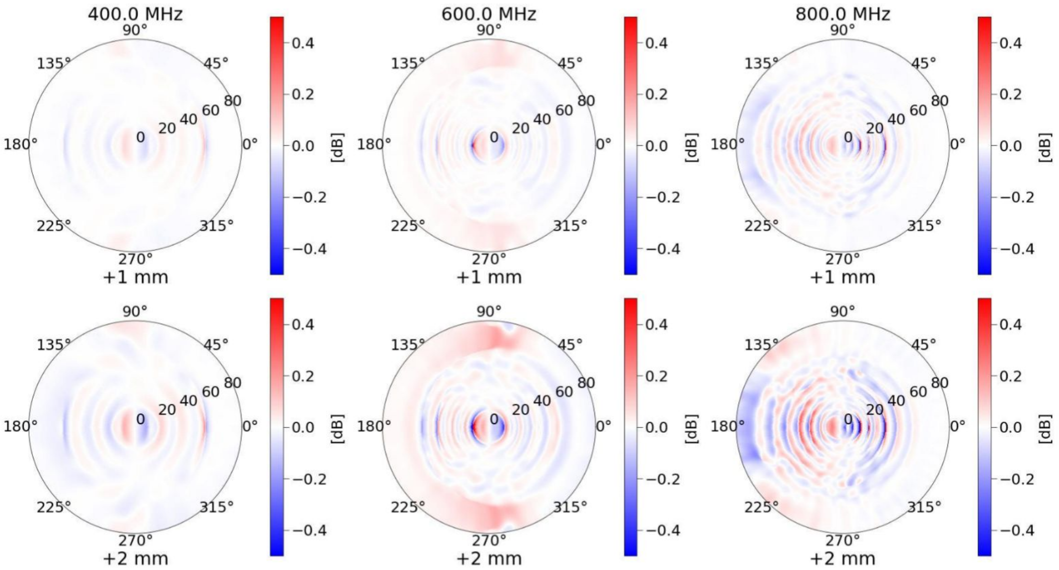
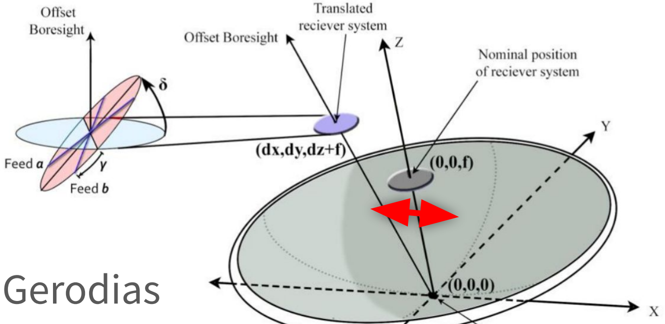


Requirements set with simulations

- 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

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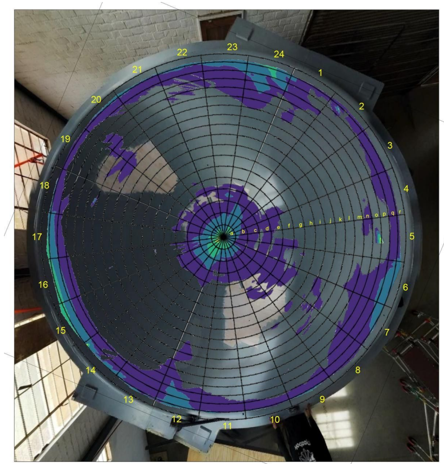
- Many components e.g. correlator and on-site compute in final stages of testing
- Dish factory established at site, site development plan in late stages
- First non-monolithic reflectors for outriggers under QA
- Significant activity in developing dish construction tooling with Advanced Fiber Form, 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



Conclusions

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- 21cm intensity mapping provides access to large cosmological volumes over mostly linear scales
- BAO can be targeted with dedicated, compact interferometers.
- HIRAX has the statistical power for a compelling cosmological survey - BAO focused
- 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!

Backup Slides

State of Late-time Cosmological HI Observations

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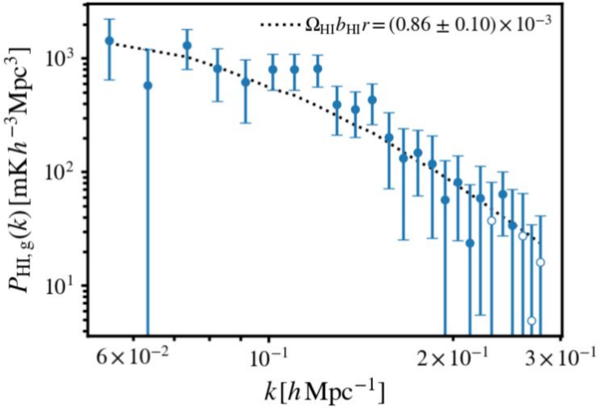
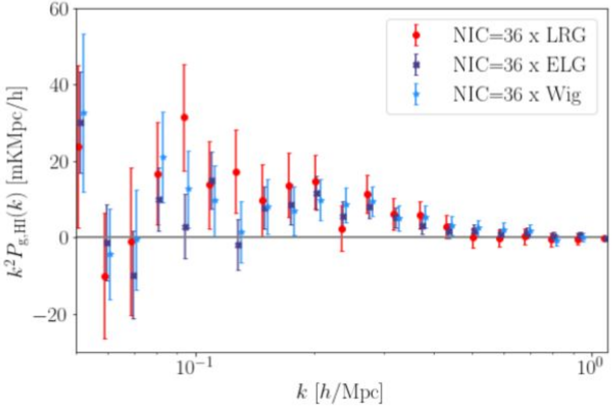
Multiple measurements in cross-correlations with spectroscopic surveys

- 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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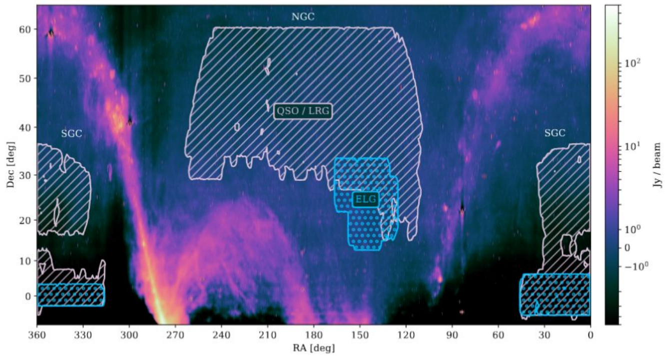
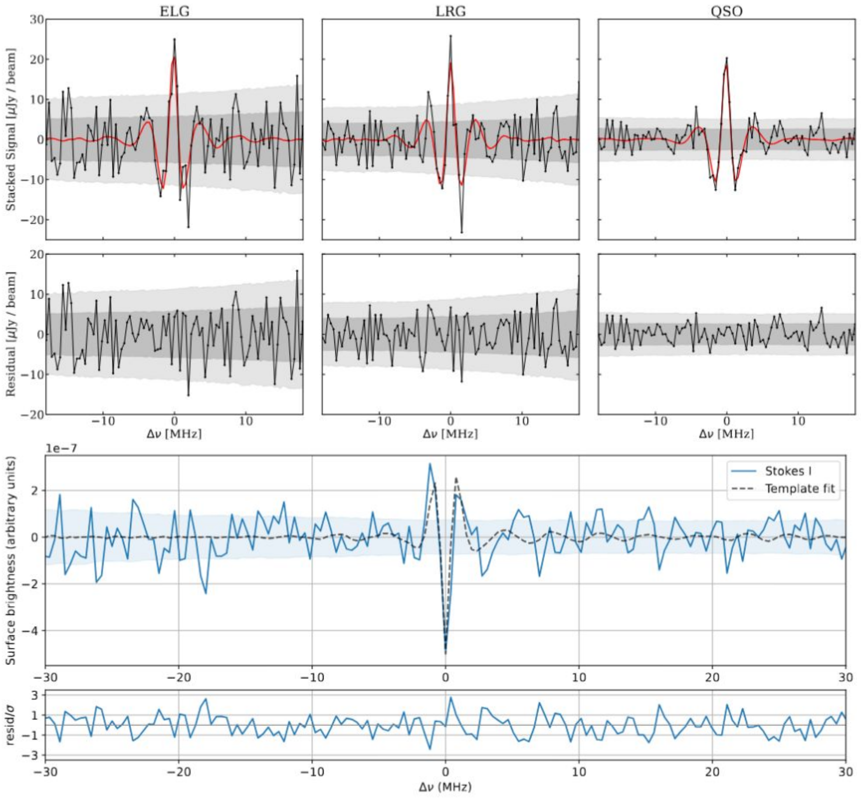
CHIME x eBOSS

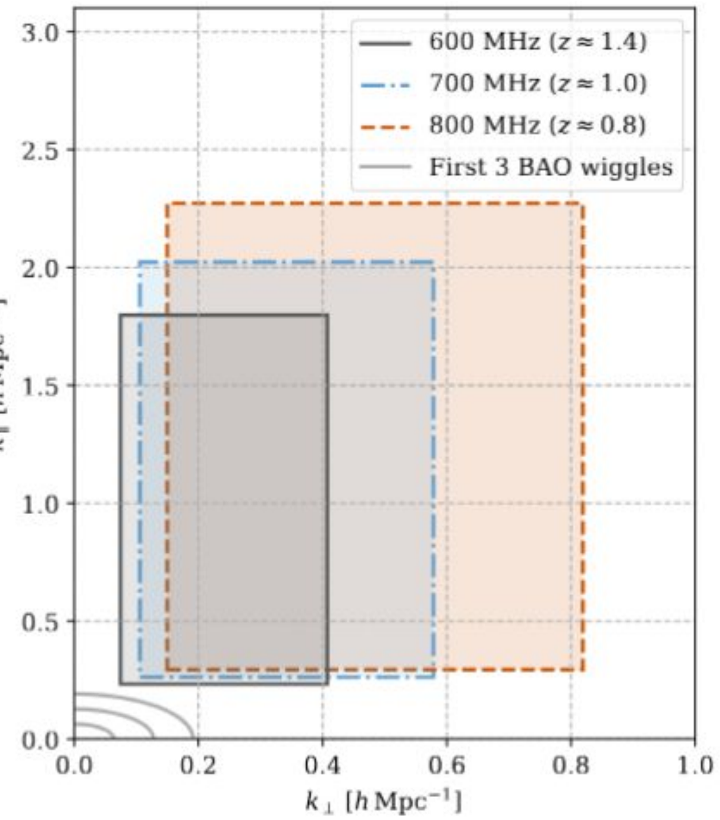
- Spectral stacking of spectropic tracers
- Strong detections out to high redshift
- Anti-correlation with Lyman-ɑ absorbers recently detected

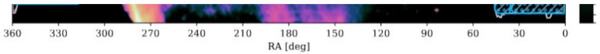


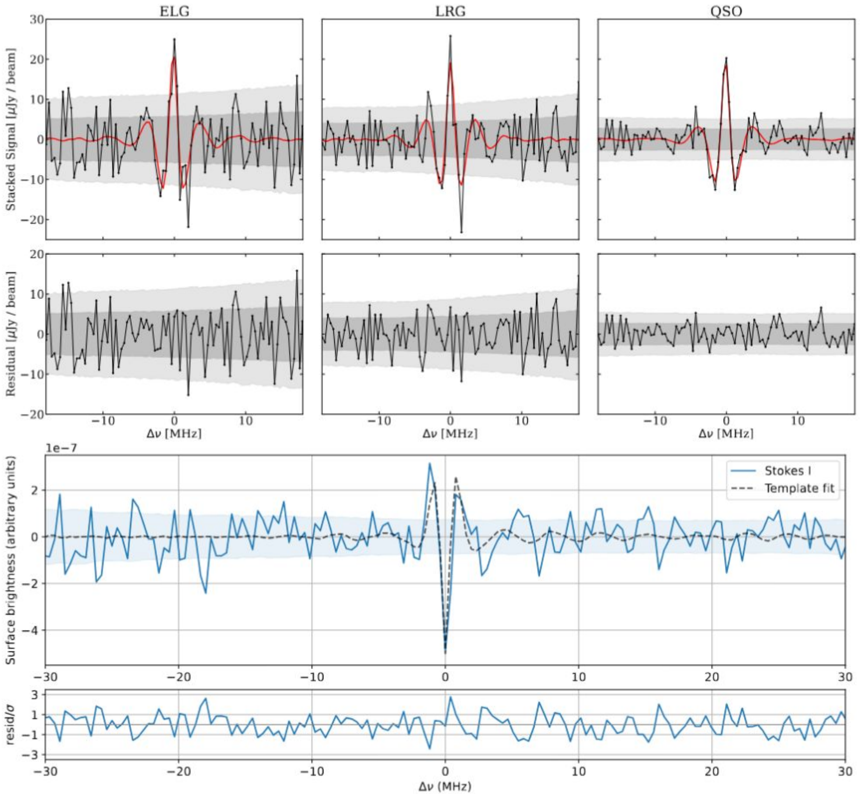


CHIME Collaboration 2022 & 2023

State of Late-time Cosmological HI Observations







CHIME Collaboration 2022 & 2023

State of Late-time Cosmological HI Observations

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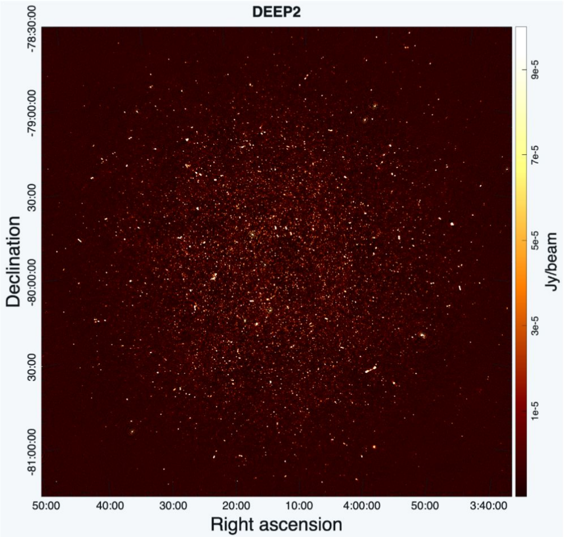
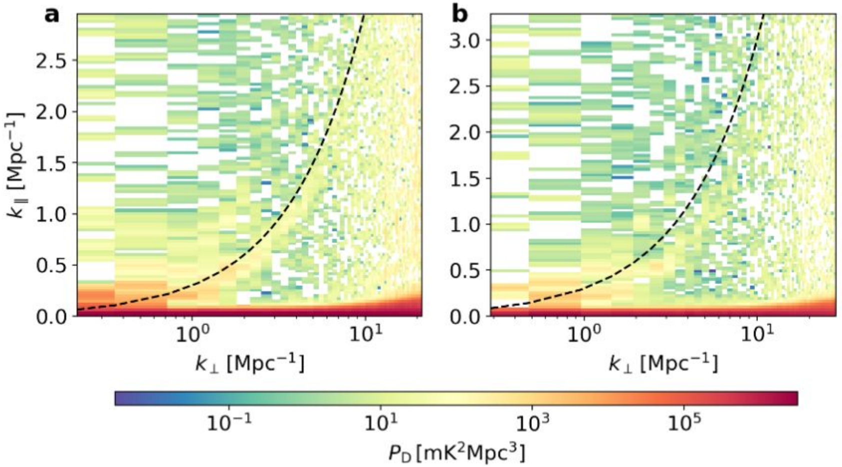
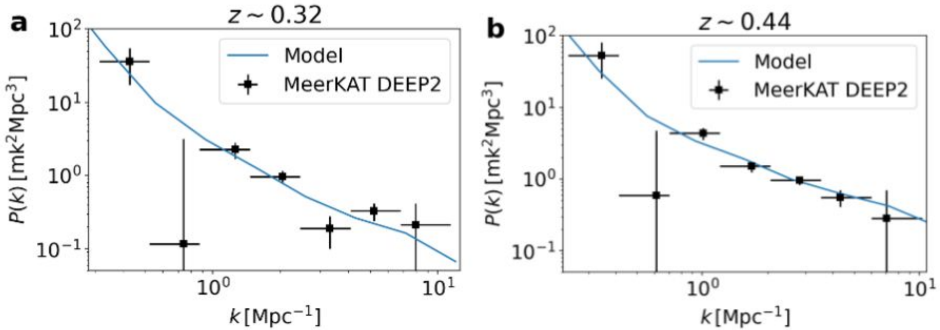
First detection in auto-spectrum

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







Paul et al. 2023

HIRAX Dynamical Dark Energy

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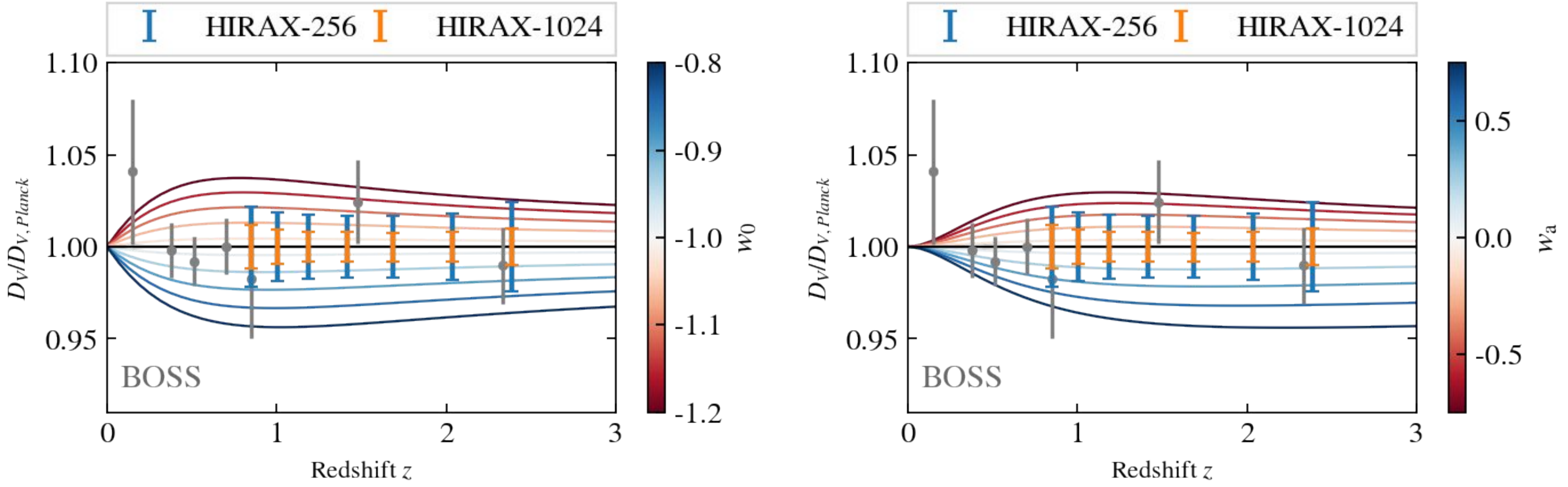

$$D_V(z) = \left[czD_M^2(z)/H(z)\right]^{1/3}$$

$$p = w\rho$$

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

HIRAX Dynamical Dark Energy

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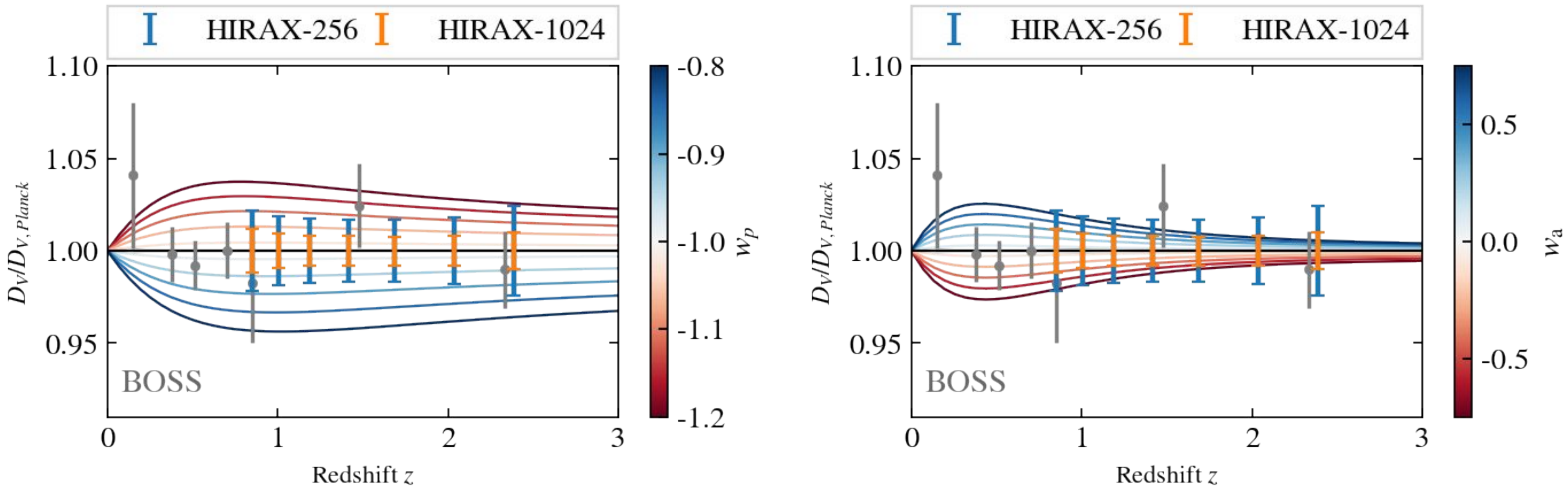

$$D_V(z) = \left[czD_{\mathrm{M}}^2(z)/H(z)\right]^{1/3}$$

$$p = w\rho$$

$$w(a) = w_p + (a_p - a)w_a$$

$$z_p = 0.5$$

BAO Cosmology with Interferometers

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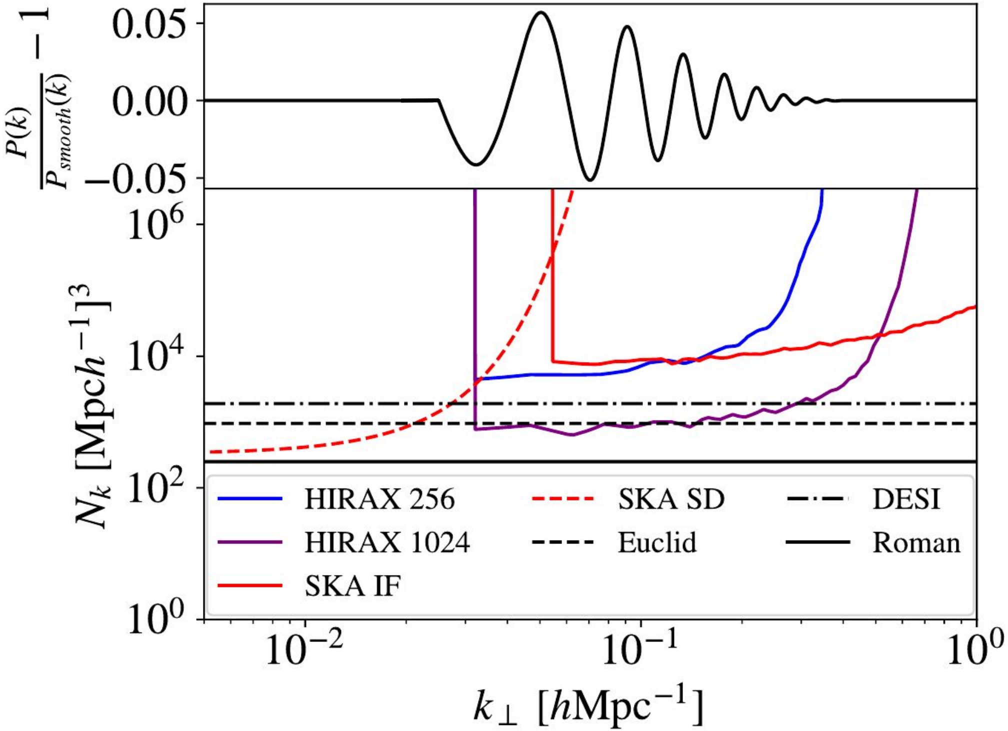

- Sensitivity in power spectrum space over finite domain
- Can be targeted on modes of interest with interferometers
  - BAO feature for HIRAX
- Comparable to spectroscopic surveys over most sensitive region

Cosmology from the HI Power Spectrum

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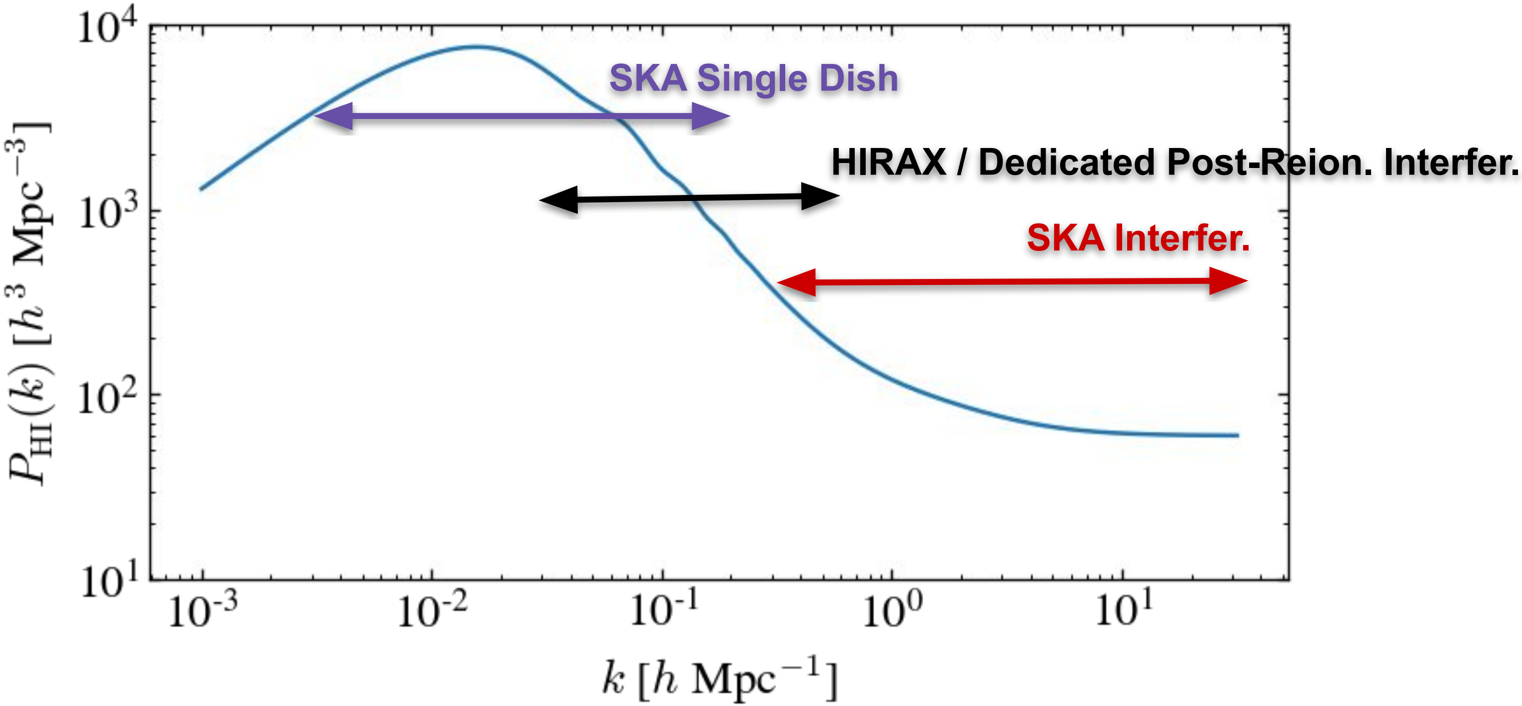
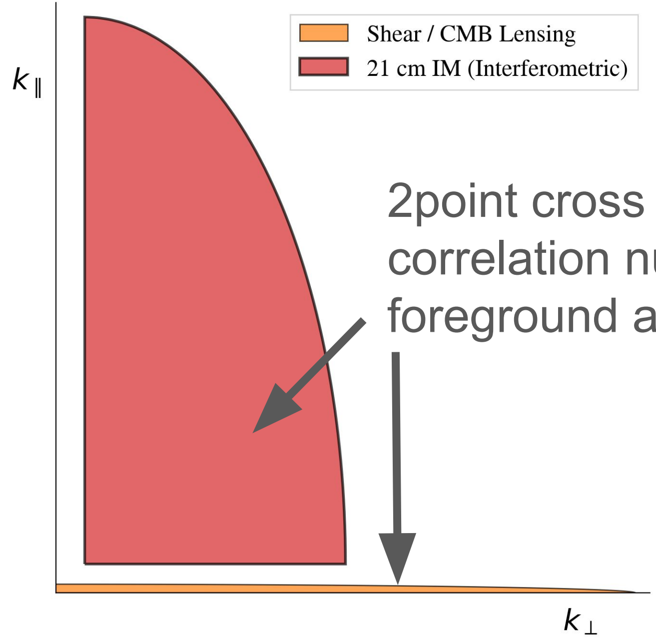


- Primordial non-gaussianity
- Modified gravity theories

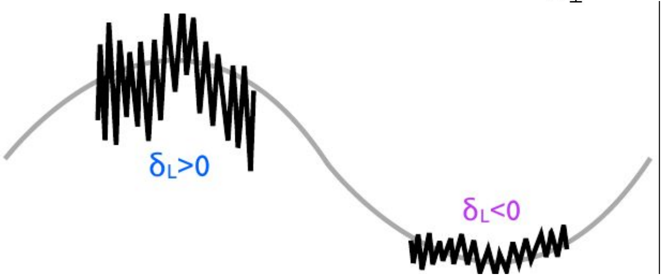
- Growth of structure
- Geometric Constraints
  - Expansion rate
  - Dark energy

- Nonlinear dynamics
- HI content of galaxies

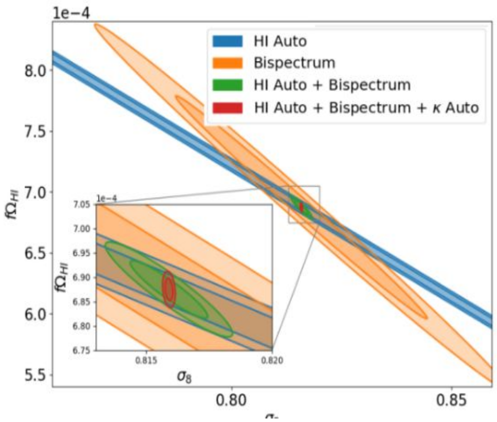
Higher order cross-correlations

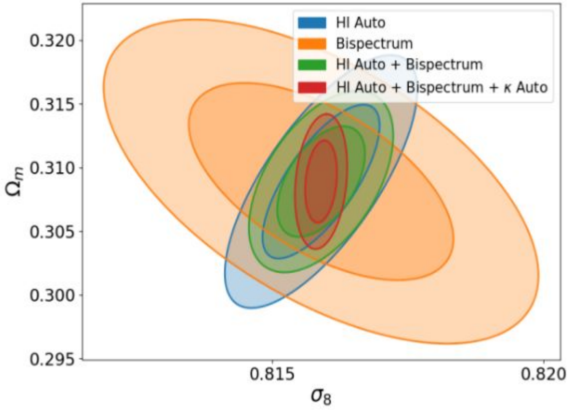


2point cross correlation nulled by foreground avoidance

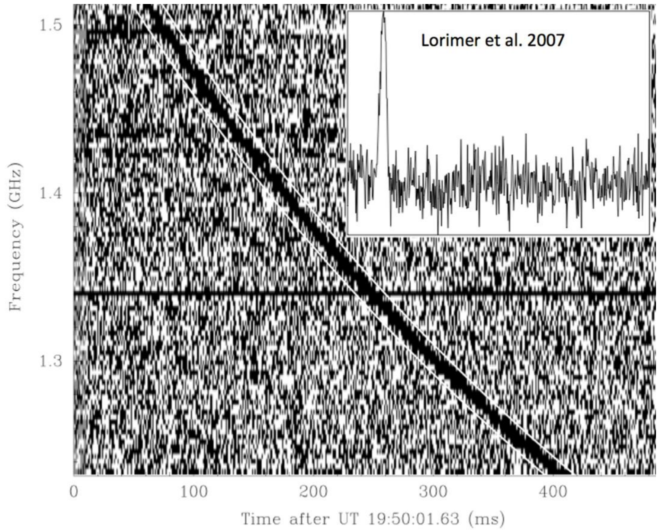


- CMB-21cm Cross Bispectrum: Low-k lensing modes cross with two high-k 21 cm modes.
- Forecast signal to noise promising using upcoming ground based lensing maps
- Detection strong enough to provide cosmological constraints - different degeneracy axis
- Moodley, Naidoo et al. arXiv: 2311.05904



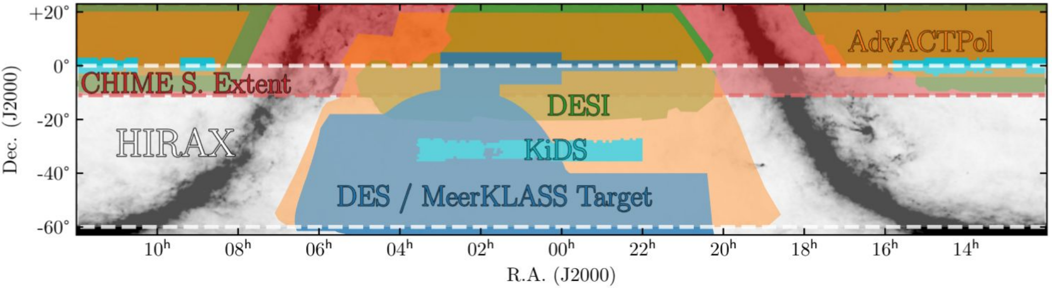


Transient and Additional Science Goals



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.