Intensity Mapping Systematics for HIRAX

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Swiss SKA Days @ Lugano
03.10.2022

HI Intensity Mapping

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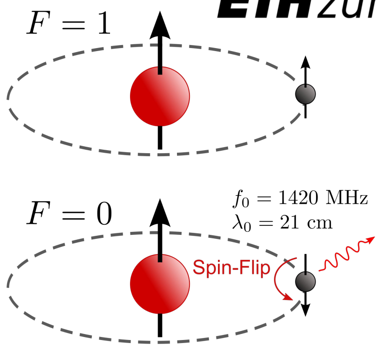
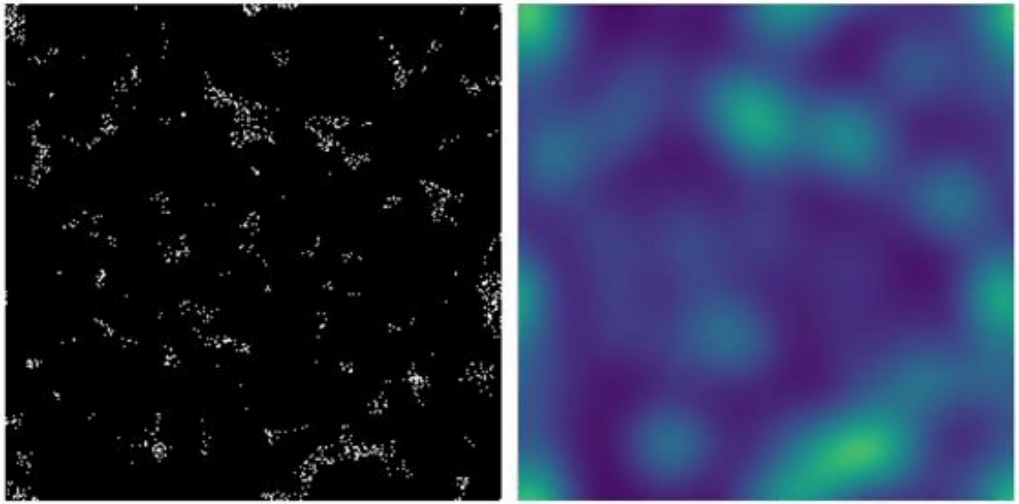


Credit: Wikimedia Commons

- Hyperfine Hydrogen transition line at 1420.4 MHz
- Efficiently and tomographically map cosmological volumes
  - Generally low angular resolution but redshift information cheap
  - Probe epoch of reionisation at low frequencies and large scale structure at high frequencies.
- Post-reionisation IM
  - ν > 200-300MHz
  - Biased tracer of large scale structure
  - Cosmological constraints from HI power spectrum
  - Large volumes achievable



HIRAX Overview

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

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

Science Goals - BAO Cosmology

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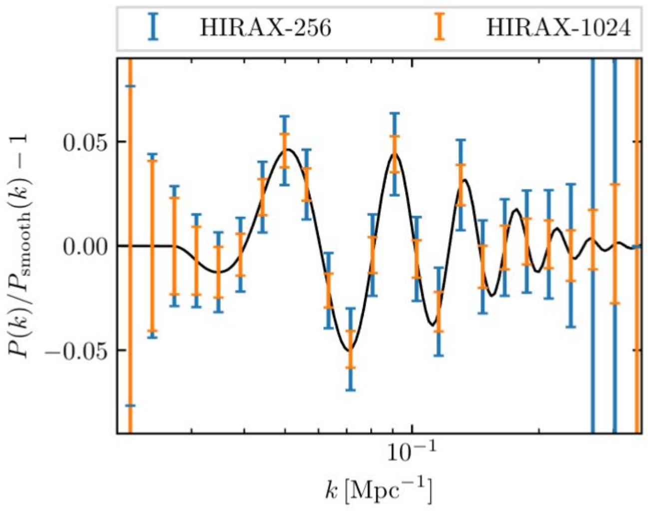
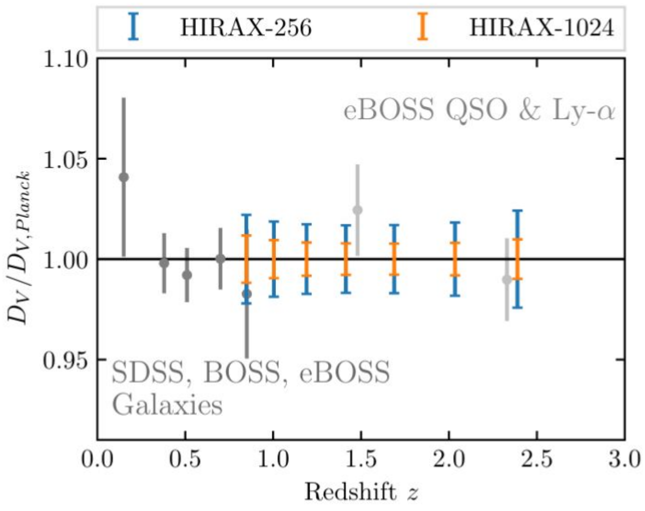
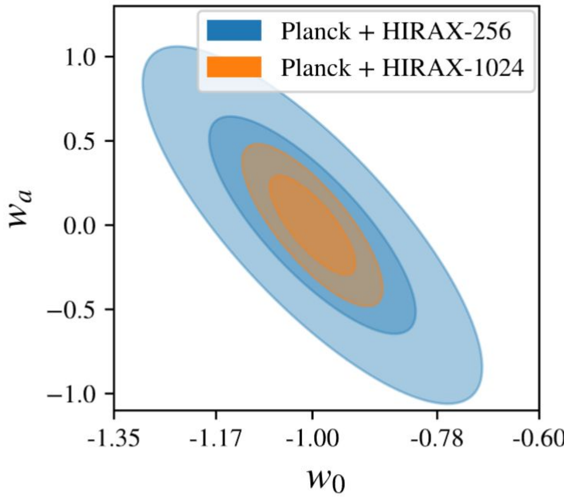
Parameter	Value
Number of dishes	256
Dish diameter	6 m
Dish focal ratio	0.23
Collecting area	7200 m^2
Frequency range	400–800 MHz
Frequency resolution	1024 channels, 390 kHz
Field of view	5°–10°
Resolution	0.2°–0.4°
Target system temperature	50 K

- Survey has statistical power to significantly constrain parameters, even at 256 element stage .
- Requires careful control of systematics
- More detailed, beyond Fisher, forecasting analysis in preparation (Viraj Nistane)







HI Power Spectrum

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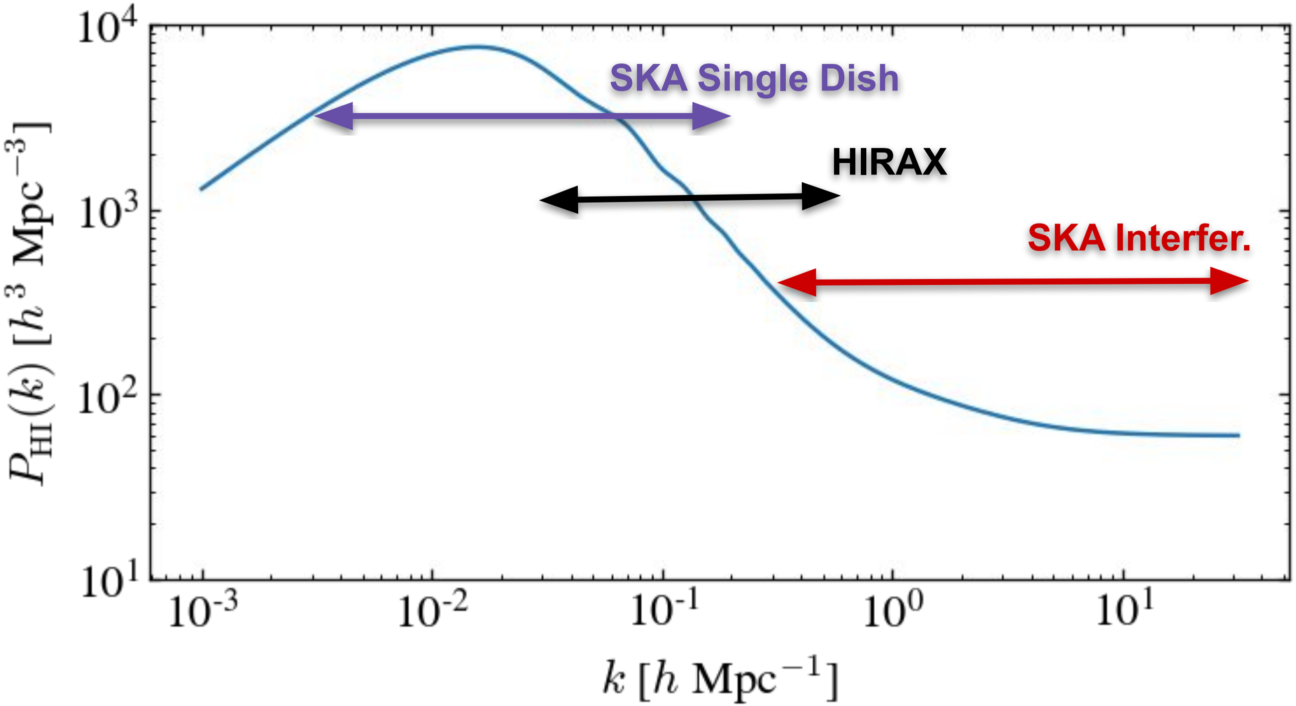

- Primordial non-gaussianity
- Modified gravity theories

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

- Non-linear dynamics
- HI content of galaxies

HIRAX-256 Correlator

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HIRAX-256 correlator built and being tested at ETHZ

- RFI measurements at CERN RF chamber.
- Performance testing with `kotekan`

Approximate Performance (For 200 Gbps/node)

HIRAX-256:

~54 TeraOp/s/node (N=512, 50 MHz, **U=13%**)

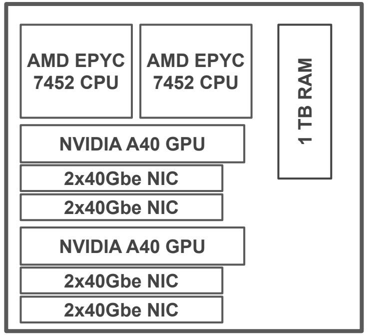
HIRAX-1024:

~211 TeraOp/s/node (N=2048, 12.5 MHz, **U=29%**)

Lots of headroom for beamforming and other real-time analysis. Utilization likely to decrease.

Upcoming `kotekan` HIRAX-256 correlator papers

Thierry Viant, Andre Renard, Keith Vanderlinde and others



Systematics / Chromaticity and Foregrounds

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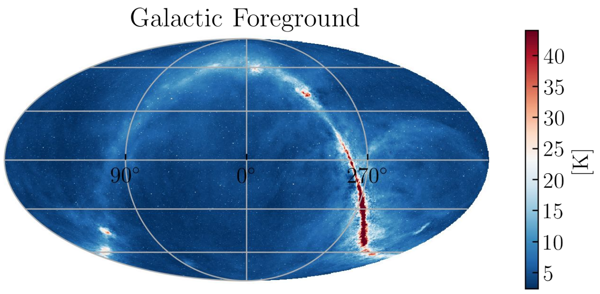
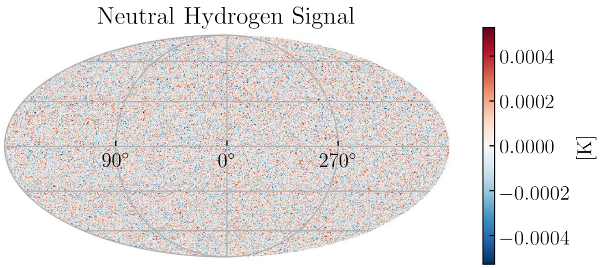
- Foregrounds are the primary challenge for 21cm cosmology
    - Galactic signal brighter by many orders of magnitude
- Signal and Foregrounds have different, *on-sky* properties
    - Galactic emission is:
        - Polarised
        - Strongly correlated over wide frequency bands
        - Structured 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
- **Instument Simulation is critical!**





Systematics Focus - Cross-talk

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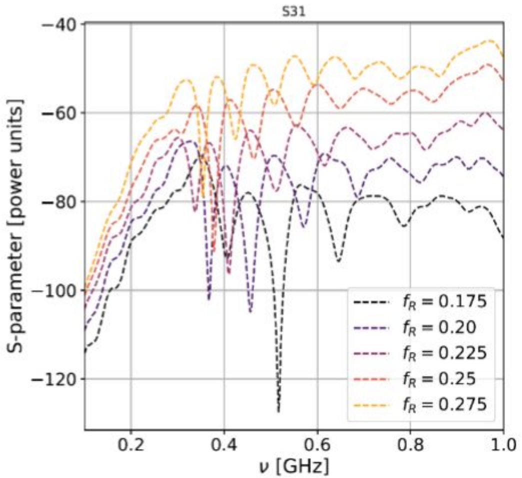
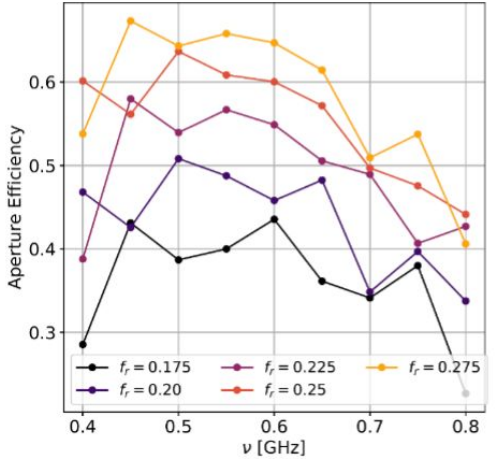
Dish design has been optimised for low cross-talk

- Deep, f/0.21 dishes currently planned
- Reduced systematic coupling effects as cost of aperture efficiency

Exploring full simulations of array-level coupling effects on redundancy

- Fast method-of-moments solver (QG)
- Incorporating array position dependent effects in simulations
- Effect of repointing on coupling to be evaluated





Aaron Ewall-Wice, Quentin Gueuning

Systematics Focus - Dish Surface and Assembly

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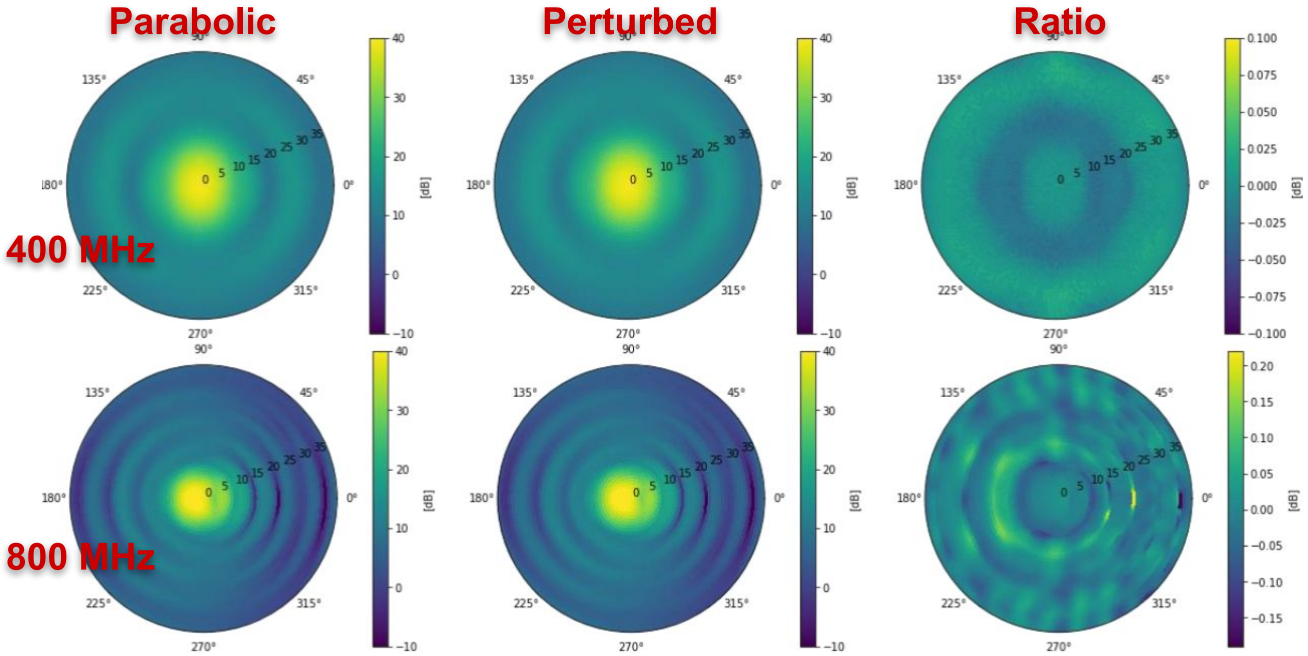
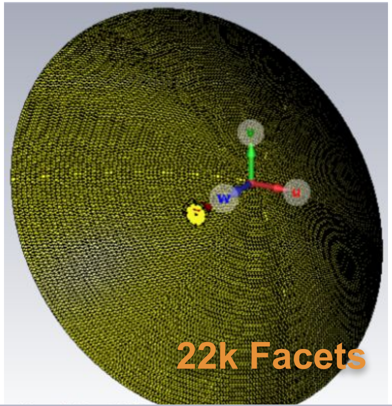
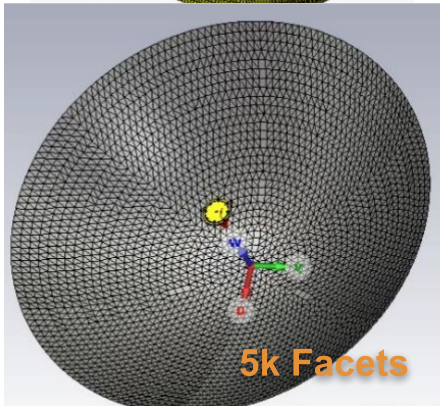
- Perturbing faceted model of dish surface
  - Random and coherent distortions
- Exploring asymmetries from feed design and mount







Benjamin Saliwanchik, Kit Gerodias, Sindhu Gaddam

Systematics Propagation to Science

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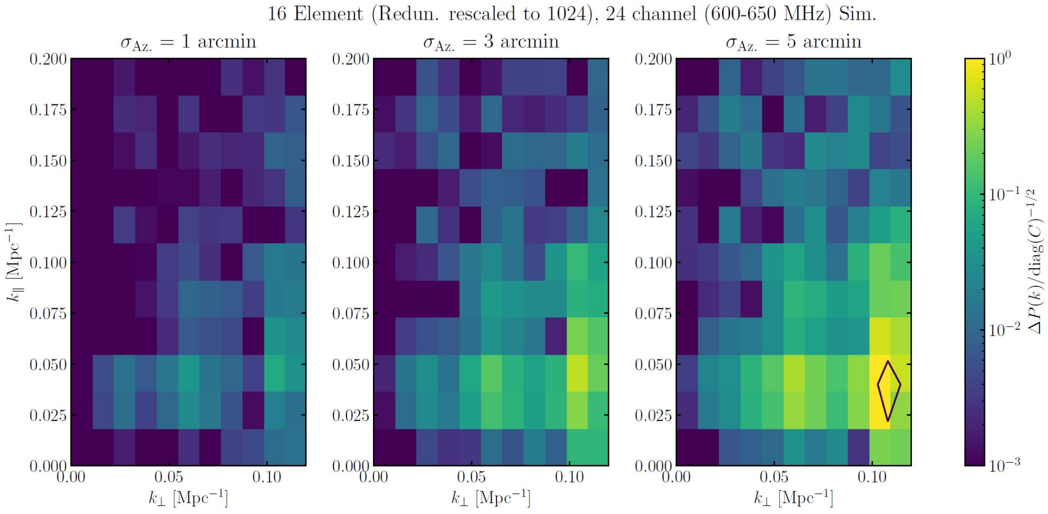
Current dish requirements set by:

- Averaging down linearised per-feed systematics over redundant baselines
- Propagating residual to power spectrum

Extending to expanded simulations with:

- No explicit linearisation
- Fast relative and abs. calibration
- Differentiable with JAX to explore propagation of systematics through pipeline



Telescope mechanical parameter	Target precision (RMS)
Receiver position relative to focus	0.5 mm
Receiver orientation relative to boresight vector	2.5′ polar and azimuthal
Dish surface deviations	1 mm
Dish vertex position relative to elevation axis	1 mm
Orthogonality of boresight vector and elevation axis	1′
Elevation axis position within the array	0.5 mm in array plane 1 mm out of array plane
Elevation axis alignment within the array	1′
Elevation pointing angle	1′

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Thanks!