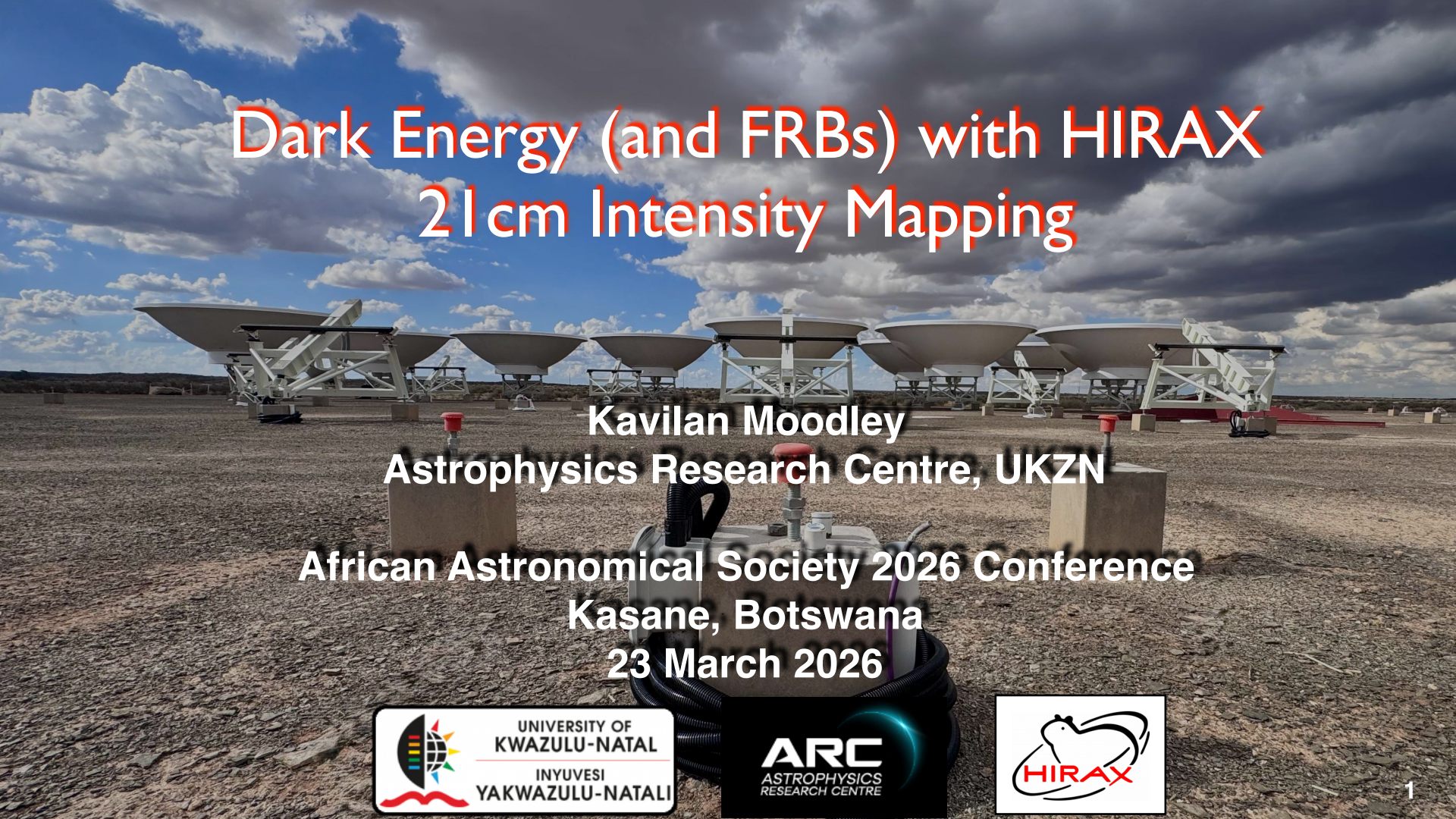


Dark Energy (and FRBs) with HIRAX
21cm Intensity Mapping

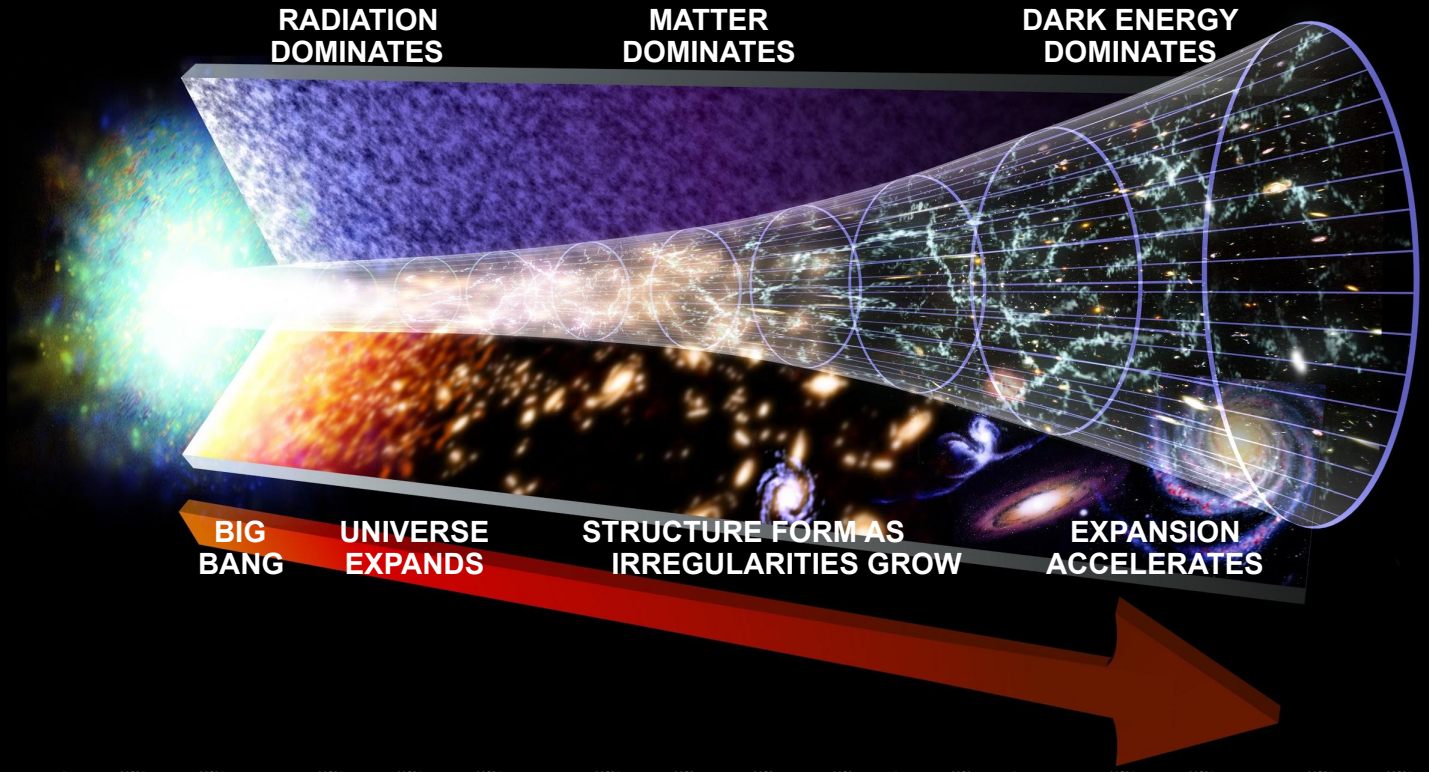
Kavilan Moodley
Astrophysics Research Centre, UKZN

African Astronomical Society 2026 Conference
Kasane, Botswana
23 March 2026

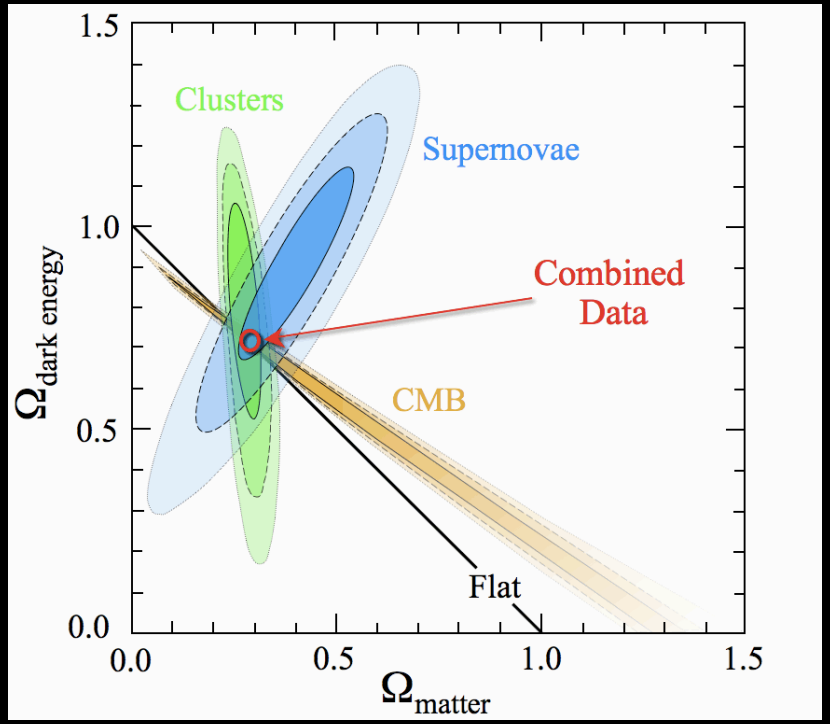
Overview

- Dark energy with baryon acoustic oscillations (BAOs)
- Measuring BAOs via 21cm intensity mapping
- The HIRAX telescope
- HIRAX BAO cosmology forecasts
- Fast radio burst detection and localisation with HIRAX

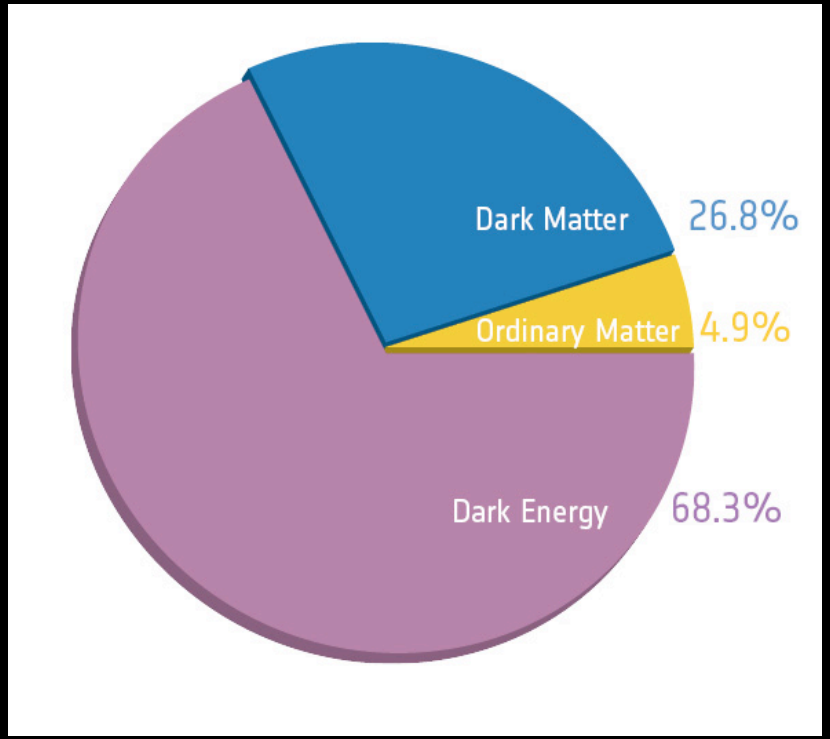
Cosmic History

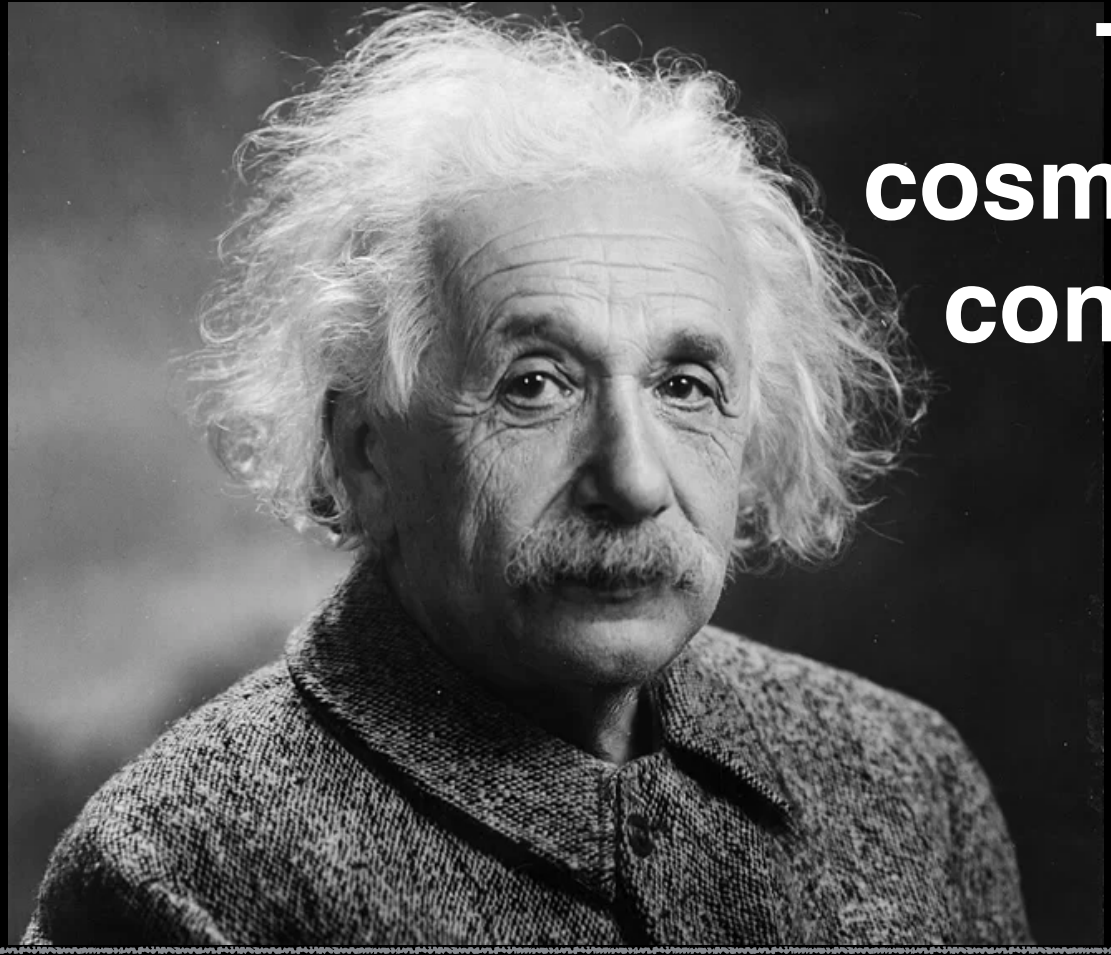


Cosmic Concordance



Cosmic Composition



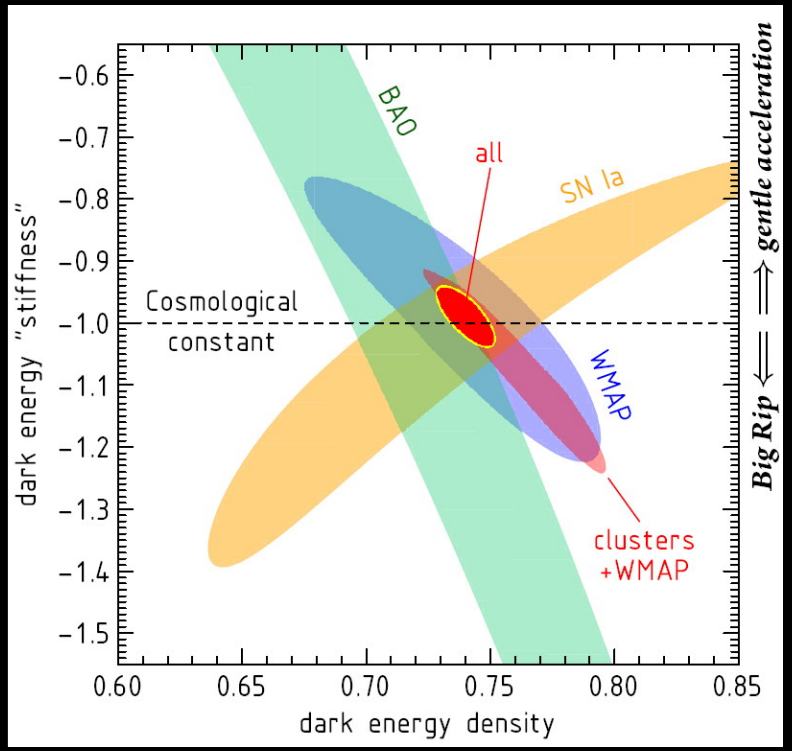


The cosmological constant?

Dark Energy Key Probes

- Type 1a supernovae: measure luminosity distance $D_L(z)$
- Cosmic lensing: measure growth factor G(z) in combination with angular diameter distance $D_A(z)$
- Galaxy clusters: measure growth factor G(z) and comoving volume $dV(z) \sim D_A^2(z)/H(z)$
- **Baryon acoustic oscillations**: measure angular diameter distance $D_A(z)$ and Hubble parameter H(z)

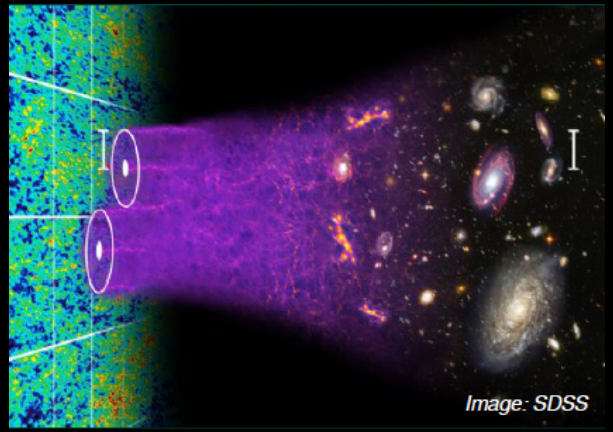
Vikhlinin et al 2009

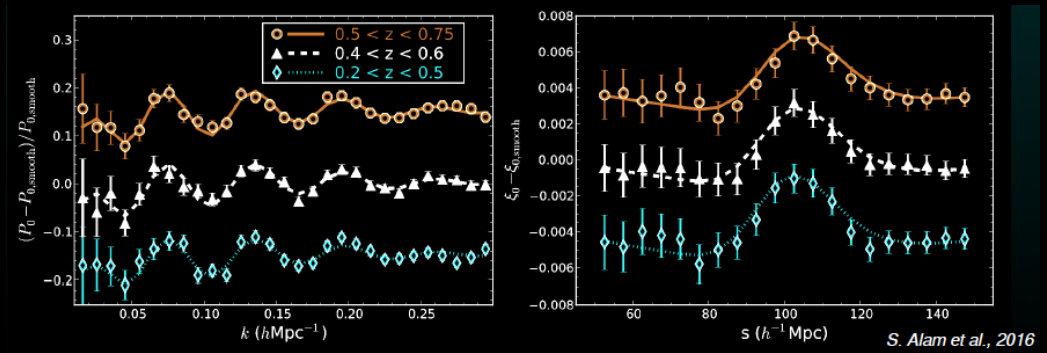


Baryon Acoustic Oscillations

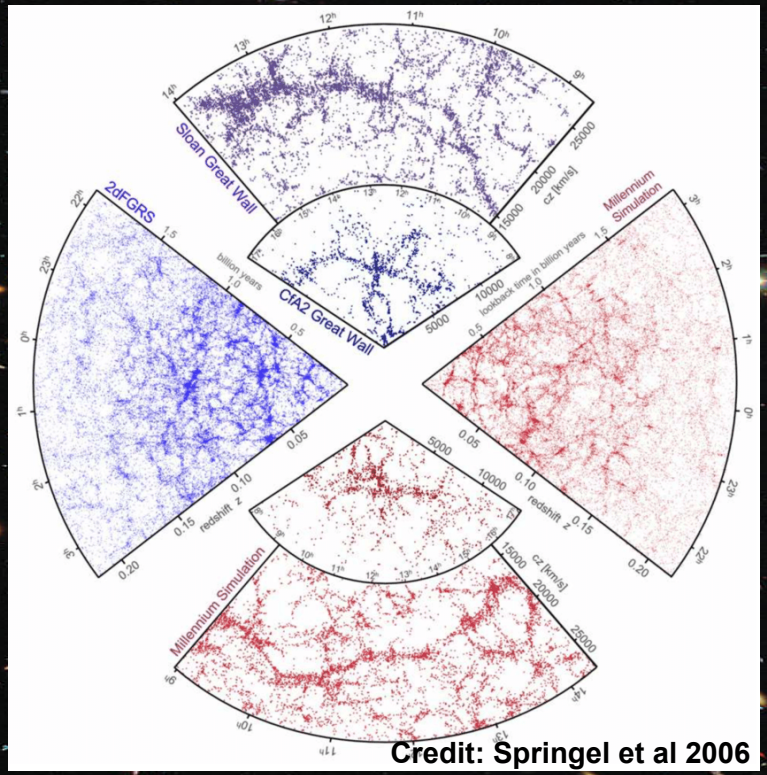
Dark Energy with BAOs

- Galaxy positions trace acoustic waves from the early universe: sound horizon sets characteristic 150 Mpc scale - standard ruler
- Measure galaxy positions -> see ripples in the power spectrum, peak in the correlation function
- DR12 release from SDSS-III shown below, redshift range 0.2 < z < 0.75





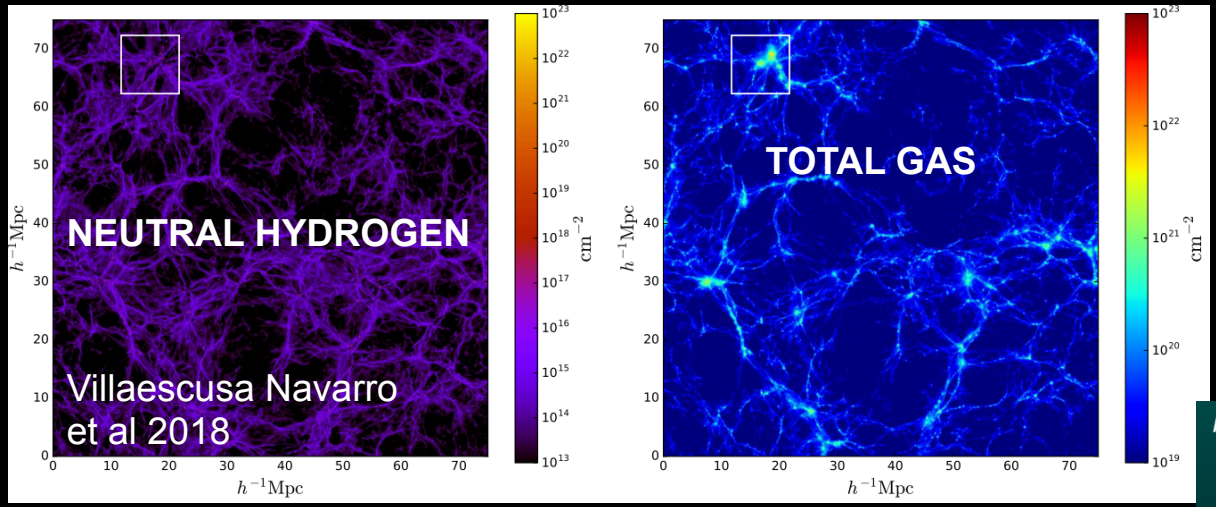
Galaxies trace Matter Distribution



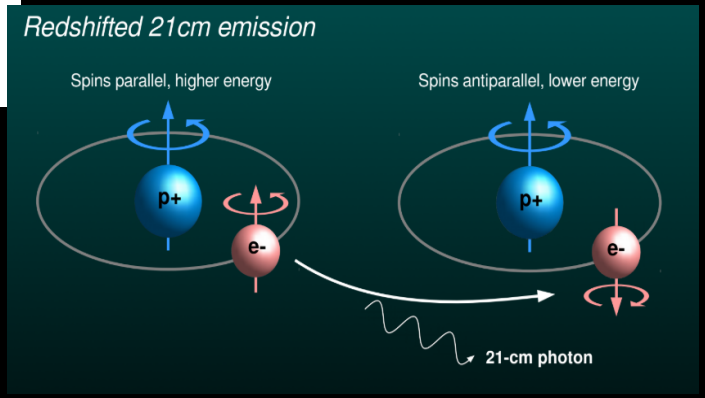
Credit: Springel et al 2006

Credit: NASA

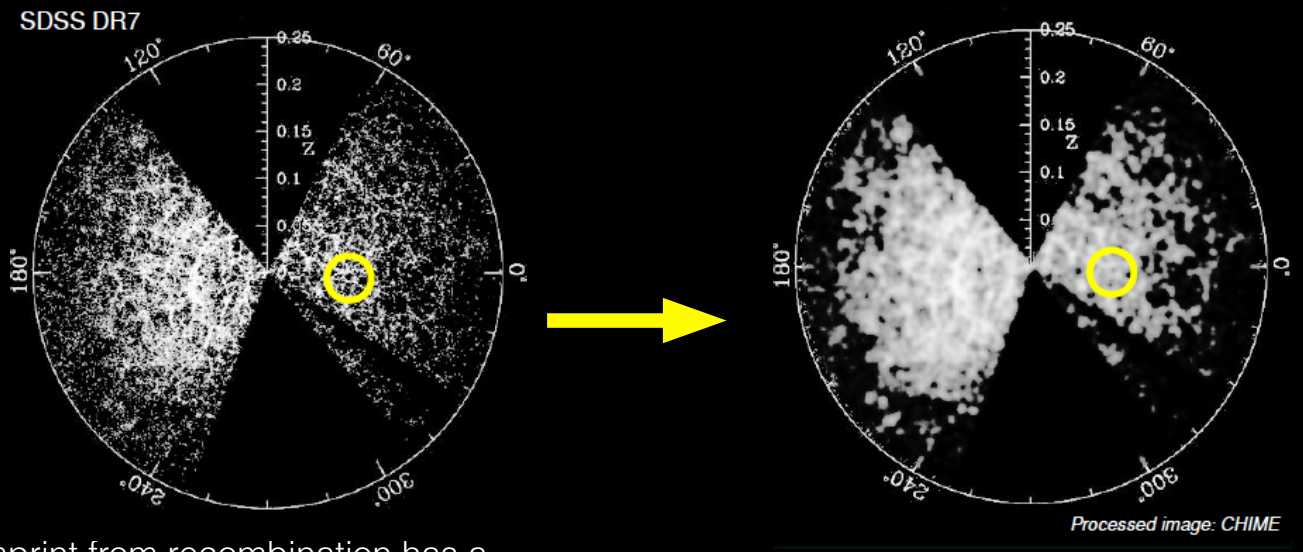
Hydrogen in Galaxies Traces Matter Distribution



Track Hydrogen via the 21cm Line



BAOs with 21cm Intensity Mapping



Sound wave imprint from recombination has a characteristic 150 Mpc scale (1 degree) - large

Require large volumes (large sky area and z range)

Counting individual galaxies & getting to high redshift is challenging

Throw away spatial resolution: use HI intensity mapping to measure matter distribution AND obtain redshift information.

Use the BAO peak as a standard ruler for charting the expansion history.

Designing a 21cm Intensity Mapping Dark Energy Telescope

- Maximise sensitivity on scales of interest -> Use compact array geometry
- Redshift range: 0.8 < z < 2.5 to capture dark energy domination at z ~ 1 and sufficient volume -> Required frequencies: 400 - 800 MHz
- BAO 150 Mpc angular scale: 3 - 1.3 degrees at 0.8 < z < 2.5 -> Required interferometer baseline lengths: 15 - 60 metres
- BAO scale along line of sight: 20 - 12 MHz at 0.8 < z < 2.5 -> Required frequency resolution: 100 channels, more for foregrounds and higher order peaks
- BAO signal level: ~ 0.1 mK -> Low system temperature, large collecting area (lots of elements)

The **H**ydrogen **I**ntensity mapping and **R**eal time **A**nalysis e**X**periment (HIRAX)

Frequency Range	400–800 MHz
Frequency Resolution	390 kHz, 1024 channels
Dish size	6 m diameter, f/D=0.25→**0.21**
Interferometric layout	32×32 square grid, 7 m spacing
Field of View	15 deg^2–56 deg^2
Resolution	∼5'–10'
Beam Crossing Time	17–32 minutes
System Temperature	50 K

Newburgh et al (1607.02059)

- A compact array of 1024 six metre dishes operating at 400-800 MHz
- Scalable array built in stages: 2, 8, 128 (funded), 256 to retire key risks at each stage, then expand to 1024 dishes and operate full array for 4 years
- Dishes stationary but can tilt for more sky area, fabrication in South Africa
- Back-end: overlap with CHIME - channelize with FPGA ICE boards, correlation with GPUs

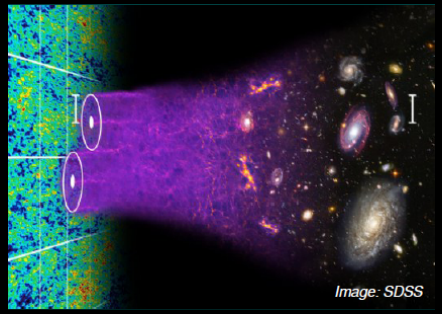
Collaboration and Funding

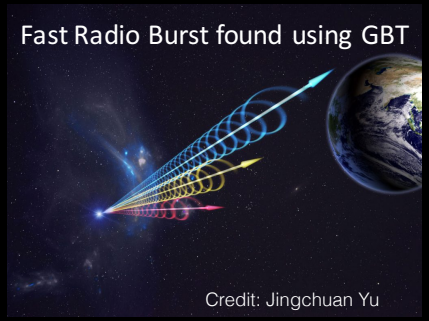
https://hirax.ukzn.ac.za/

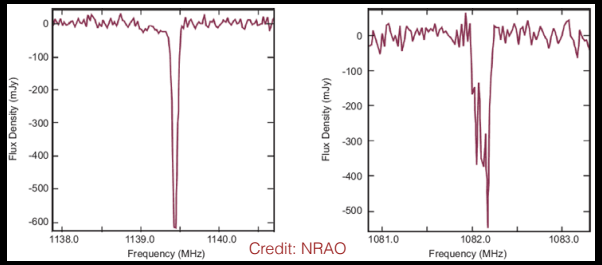
- UKZN and South African NRF flagship funding secured for site infrastructure and pathfinder array. SARAO providing site, power and data.
- Swiss SNF funding secured for 512 channel X-engine (GPU correlator) and Science Data Processing system. McGill funding for F-engine up to 512 channels (ICE boards).
- NRF strategic research equipment (SRE) funding secured to expand pathfinder array.
- First phase with additional funding from the Simons Foundation to build up to 128 dishes.

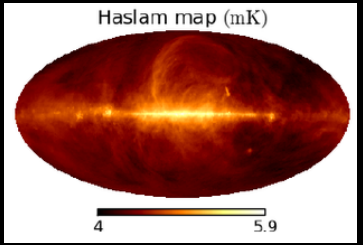
HIRAX Science Goals

- **Measure BAOs with 21cm intensity mapping: characterise dark energy**
- Cross-correlation with other cosmological surveys
- Radio transient searches, slow and fast
  - **Fast radio bursts (FRBs)**
- Pulsar searches: 15 uJy/scan - search in each of 10-20 beams, galactic centre searches
- Neutral hydrogen absorbers: upres frequency in beam-formed data (FFTs on GPUs)
- Diffuse galactic polarization



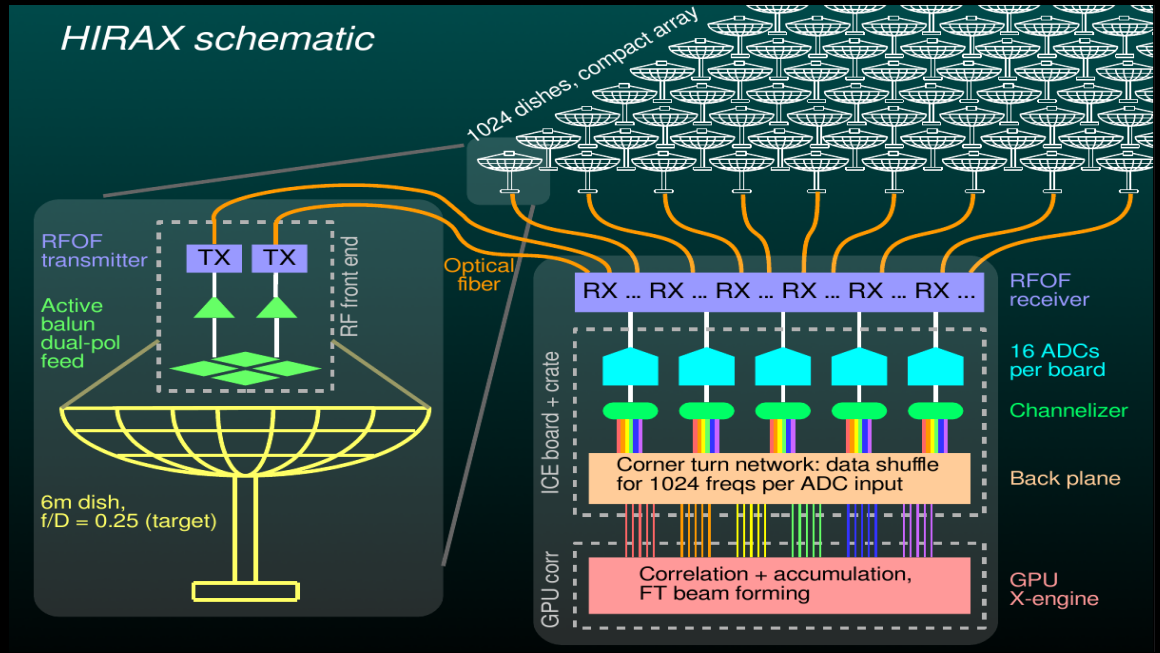




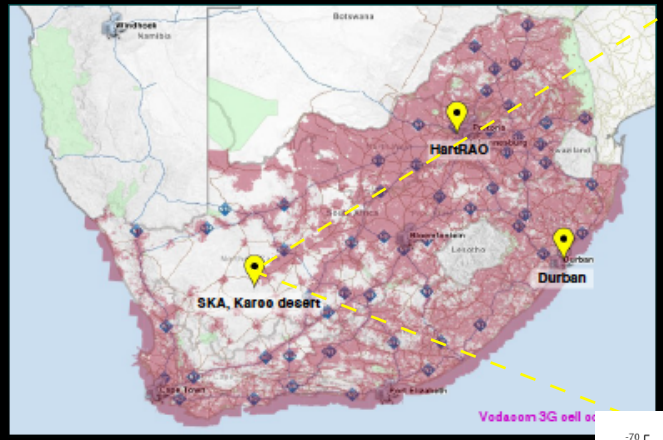


HIRAX Design Plan

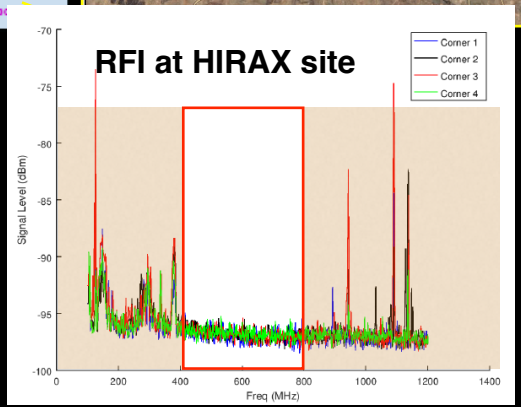
- Goal of 1024 close-packed 6m dishes. Fibre-glass fabrication in South Africa by AFF, design from NRC (Canada).
- Cloverleaf dual-pol feed, RF over fibre
- Operate between 400-800 MHz, 1000 channels
- Channelizing on FPGA ICE boards
- Correlation on GPUs

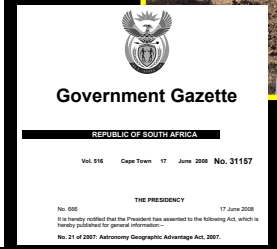


Location, Location, Location …



- SKA South Africa Karoo site, MoA in place
- Existing infrastructure (roads, power, data)
- Low levels of RFI - site protected
- Access to southern skies





HIRAX Progress

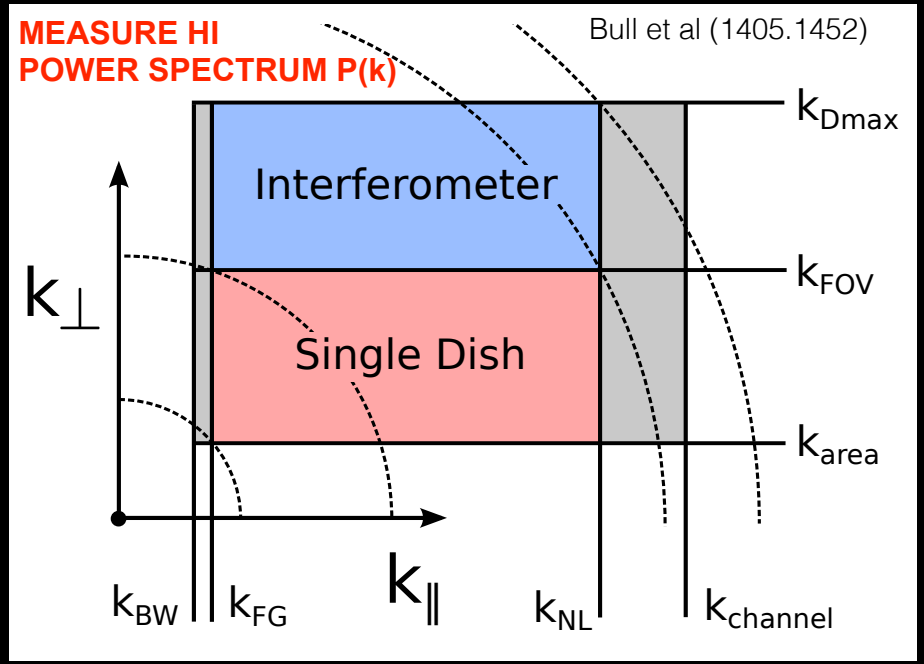
- Site: Civil, foundations, and electrical work completed. Fibre to be installed by May. Containers installed and RFI shielding verified; Cooling system by April.
- Dishes: 19 TMAs installed at the main site, producing 8 per month.
- Signal Chain: Developed and qualified new feed. Deploying two element array at main site.
- Back-end Hardware: X-engine (correlator) installed in container. F-engine (digitiser, channeliser) currently being shipped. Commissioning back-ends by June.

Upcoming HIRAX Schedule

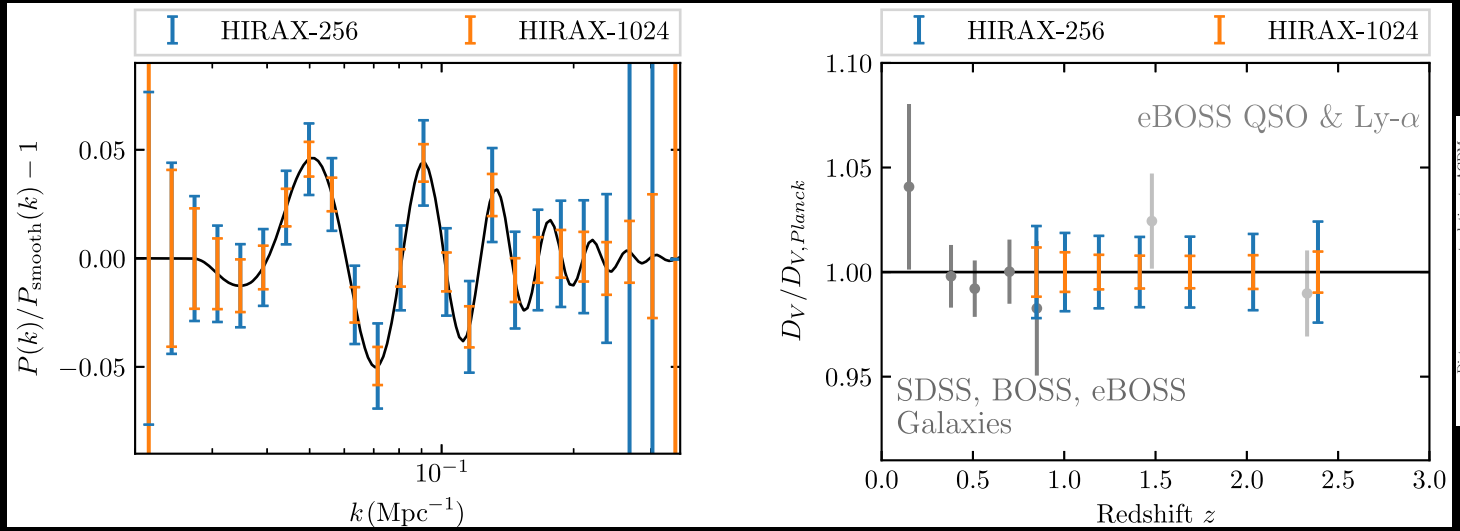
- Site:
  - Develop HIRAX Karoo Swartfontein main site (Q2 2026)
- Instrument (staged to mitigate risks):
  - Prototyping on 2-element array at Swartfontein site (Q2 2026): **qualify signal chain, verify dish precision, measure telescope beams**
  - Commission 8-element prototype at Swartfontein site (Q3 2026): **verify RF performance and stability, preliminary study of redundancy & chromaticity**
  - Commission 32-element prototype at Swartfontein site (Q4 2026-Q1 2027): **verify RF performance and stability, detailed study of redundancy & chromaticity**
  - Commission 128-element pathfinder array at Swartfontein site (Q2-3 2027): **verify redundant calibration approach, constrain chromaticity**

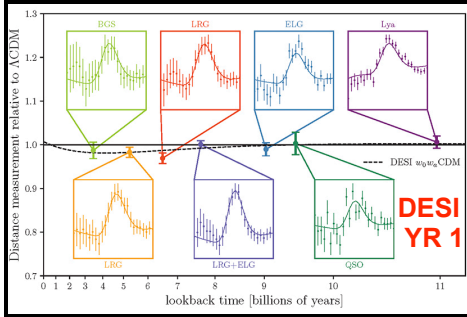
Cosmology with HIRAX

- Wide redshift coverage: z ~ 0.8 - 2.5
- Survey area: ~15,000 deg^2
- Angular coverage: ℓ ~ 40 - 2000 gives k_{perp} ~ [10^{-2}, 1] h Mpc^{-1} at z~1 ; limited by primary beam and maximum baseline.
- Frequency coverage: y ~ 20 - 20000 gives k_{par} ~ [10^{-3}, 1] h Mpc^{-1} ; limited by foregrounds and nonlinearities.
- Sensitivity: 15 uJy/beam daily,1 uJy/beam full survey



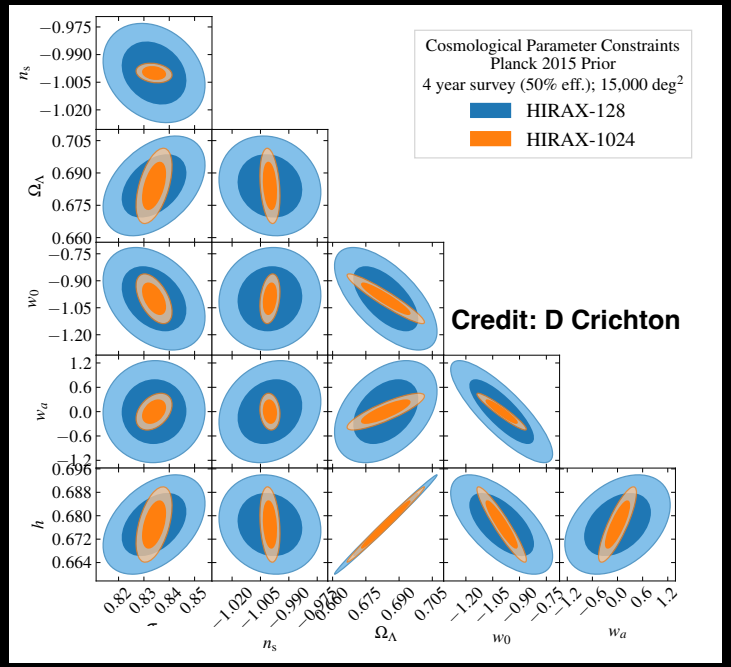
HIRAX BAO & Distance Scale Forecasts





- HIRAX will make a precise measurement of the matter power spectrum in the BAO regime in a number of redshift bins from z = 0.775 to 2.55
- Convert power spectrum BAO constraints into constraints on D_V in each redshift bin => constrain the BAO scale at the percent level out to high redshift with HIRAX-1024

HIRAX Cosmology Forecasts



Crichton et al 2109.13755

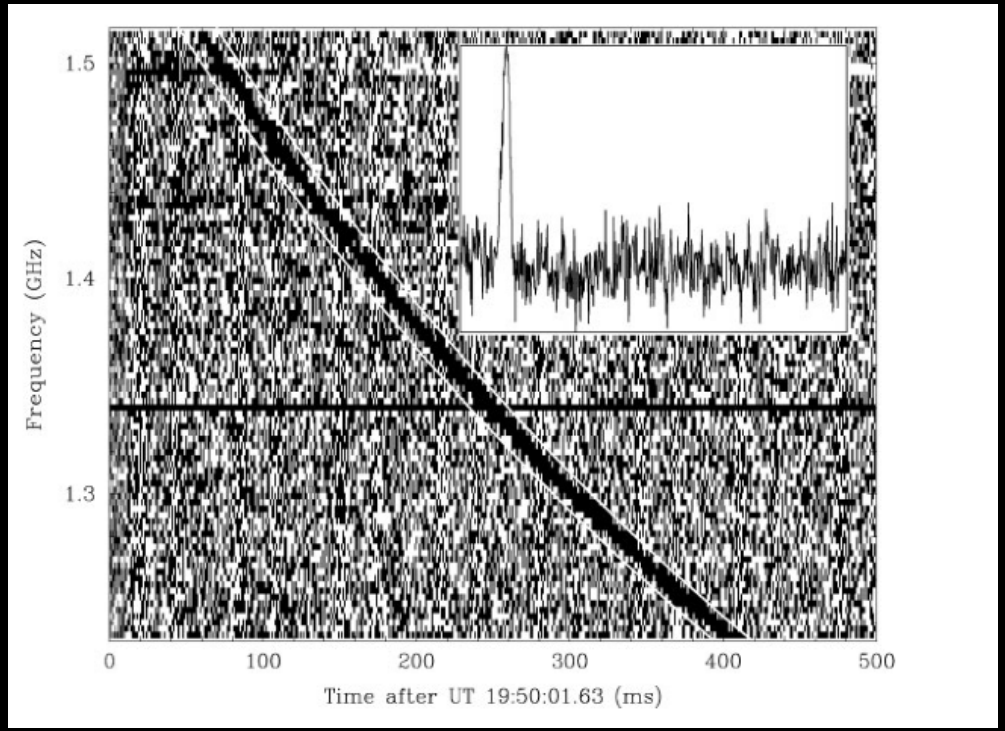
HIRAX-256 + *Planck*	σ_8	Ω_Λ	w_0	w_a
ΛCDM	0.0044	0.0039	-	-
wCDM	0.0047	0.0042	0.0739	-
w_0w_aCDM	0.0053	0.0043	0.1223	0.4332
HIRAX-1024 + *Planck*				
ΛCDM	0.0027	0.0034	-	-
wCDM	0.0028	0.0036	0.0316	-
w_0w_aCDM	0.0038	0.0037	0.0506	0.1965
eBOSS + *Planck* + SNe Ia + Lens.				
ΛCDM	0.0056	0.0047	-	-
wCDM	0.0092	0.0066	0.027	-
w_0w_aCDM	0.0093	0.0069	0.073	0.5200

model/dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_K$	w or w_0	w_a
DESI+CMB	$0.344^{+0.032}_{-0.027}$	$64.7^{+2.2}_{-3.3}$	—	$-0.45^{+0.34}_{-0.21}$	$-1.79^{+0.48}_{-1.0}$
DESI+CMB+Panth.	0.3085 ± 0.0068	68.03 ± 0.72	—	-0.827 ± 0.063	$-0.75^{+0.29}_{-0.25}$
DESI+CMB+Union3	0.3230 ± 0.0095	66.53 ± 0.94	—	-0.65 ± 0.10	$-1.27^{+0.40}_{-0.34}$
DESI+CMB+DESY5	0.3160 ± 0.0065	67.24 ± 0.66	—	-0.727 ± 0.067	$-1.05^{+0.31}_{-0.27}$

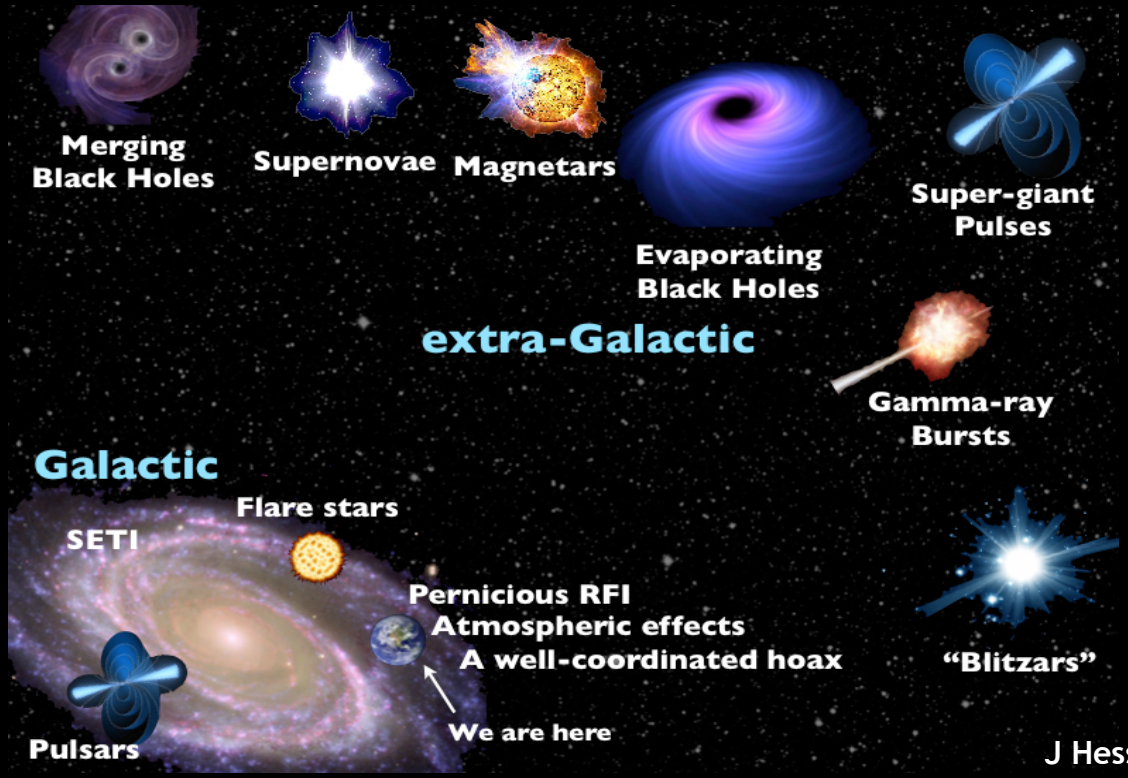
- HIRAX measurements of D_V will provide tight constraints on cosmological parameters in combination with CMB data

Fast Radio Bursts

FRBs are mysterious short duration (millisecond), bright (~Jy) radio bursts discovered a decade ago, and remain unexplained.

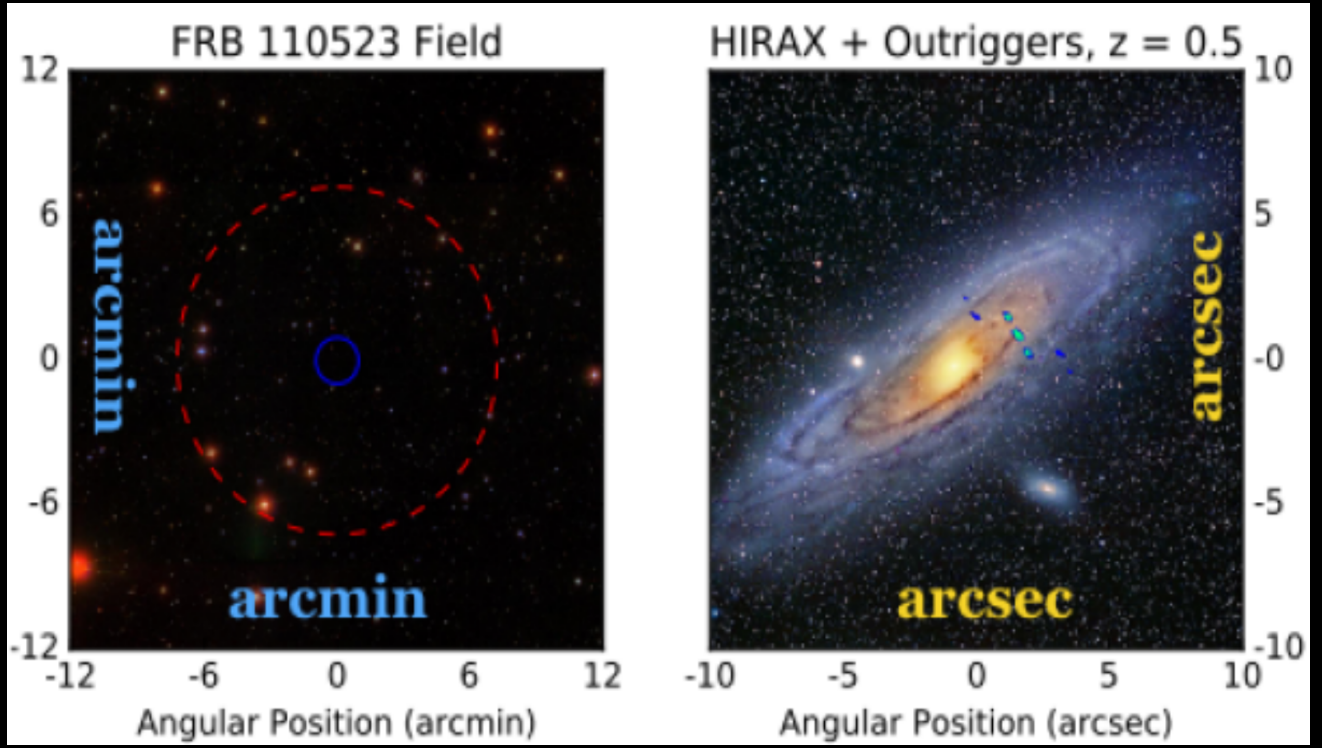


FRB Models


Merging Black Holes
Supernovae
Magnetars
Evaporating Black Holes
Super-giant Pulses
extra-Galactic
Gamma-ray Bursts
Galactic
Flare stars
SETI
Pernicious RFI
Atmospheric effects
A well-coordinated hoax
"Blitzars"
We are here
Pulsars
J Hessels

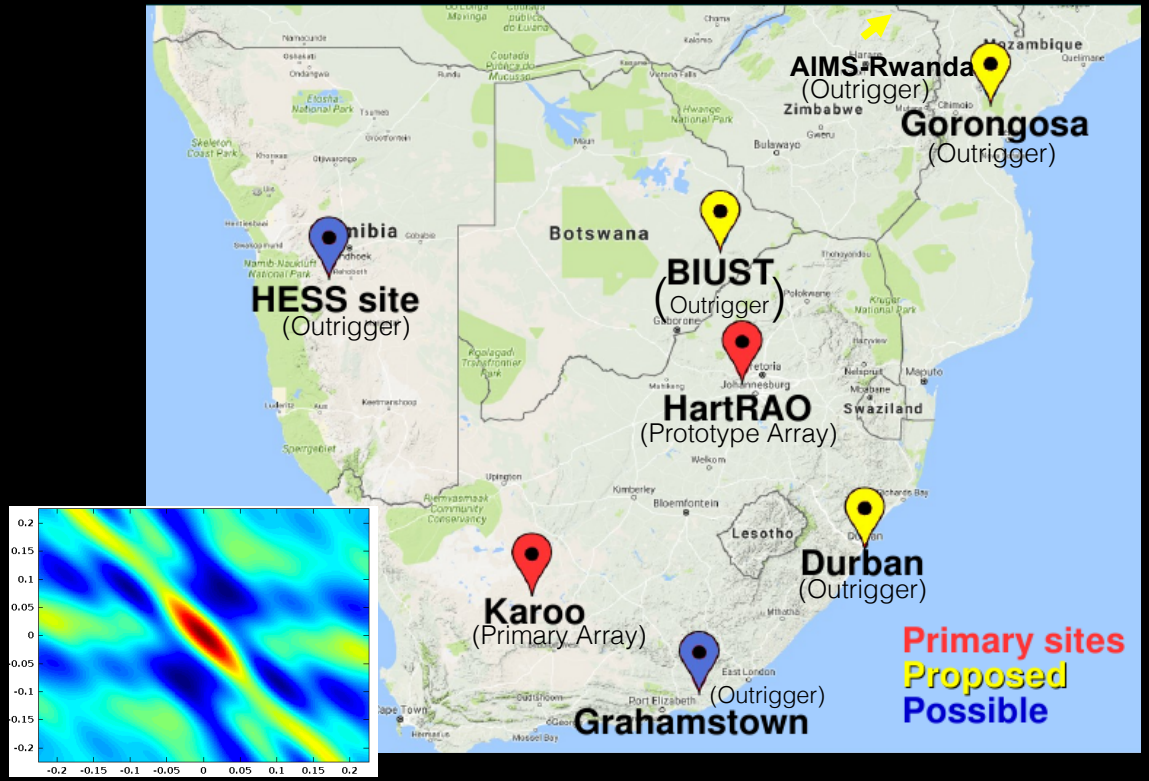
Localising FRBs with Outrigger Arrays

- Localising FRBS will allow us to determine where they originate and shed insight into their nature
- If standard objects then very useful for cosmology!



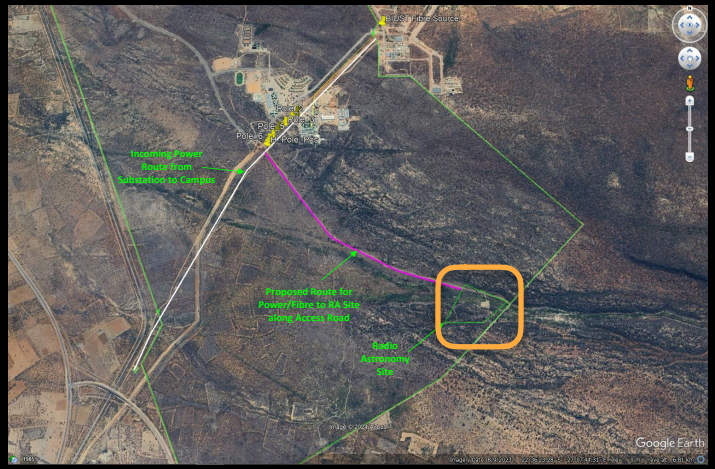
Localising FRBs with HIRAX Outriggers

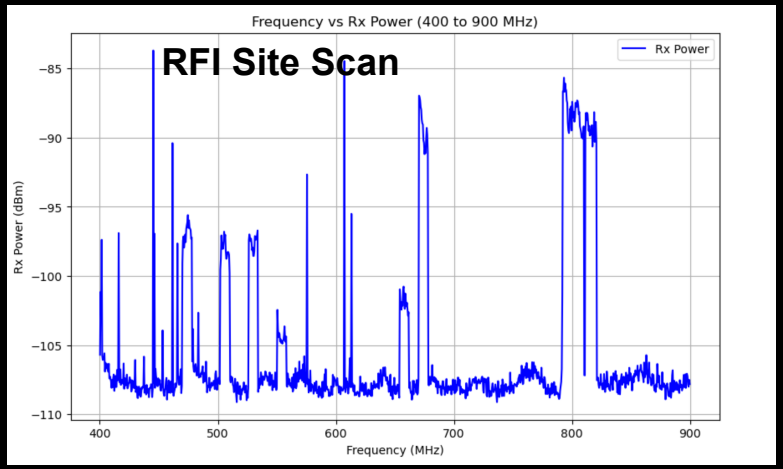
- Main site hosting the full array on the Swartfontein farm at the SKA Karoo site.
- Outrigger arrays in African partner countries provide very long baselines for FRB sub-arcsec localisation



BIUST HIRAX Outrigger Array

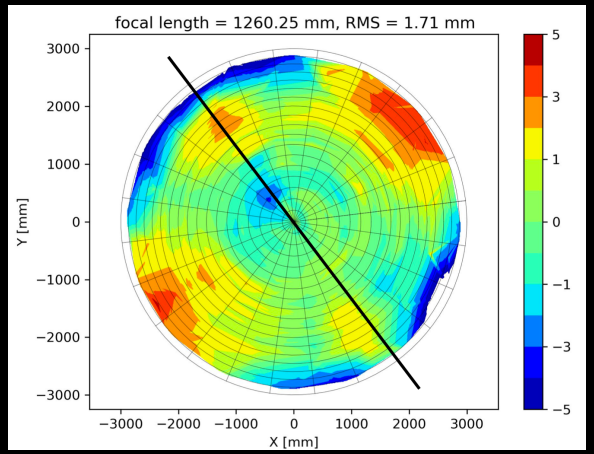
- Formal MoA being signed between UKZN, BIUST, AFF and McGill
- Hardware funding from DSTI/SARAO; Site infrastructure funding from Botswana government
- Site infrastructure: Requirements are set and at design stage; Expect site construction to be completed in 2026





BIUST HIRAX Outrigger Array

- Already built 16 split dishes (32 halves) for HIRAX BIUST outrigger with dish partners AFF and NRC
- Assembled 1 split dish in Cape Town and 2 at Klerefontein site - well within spec (of 10mm)
- Continuing with design and build of (manual) 16 az-el mounts and assembly heights
- Same feeds and receiver as main array and similar but smaller back-end



Thank you!