Dark Energy with HIRAX

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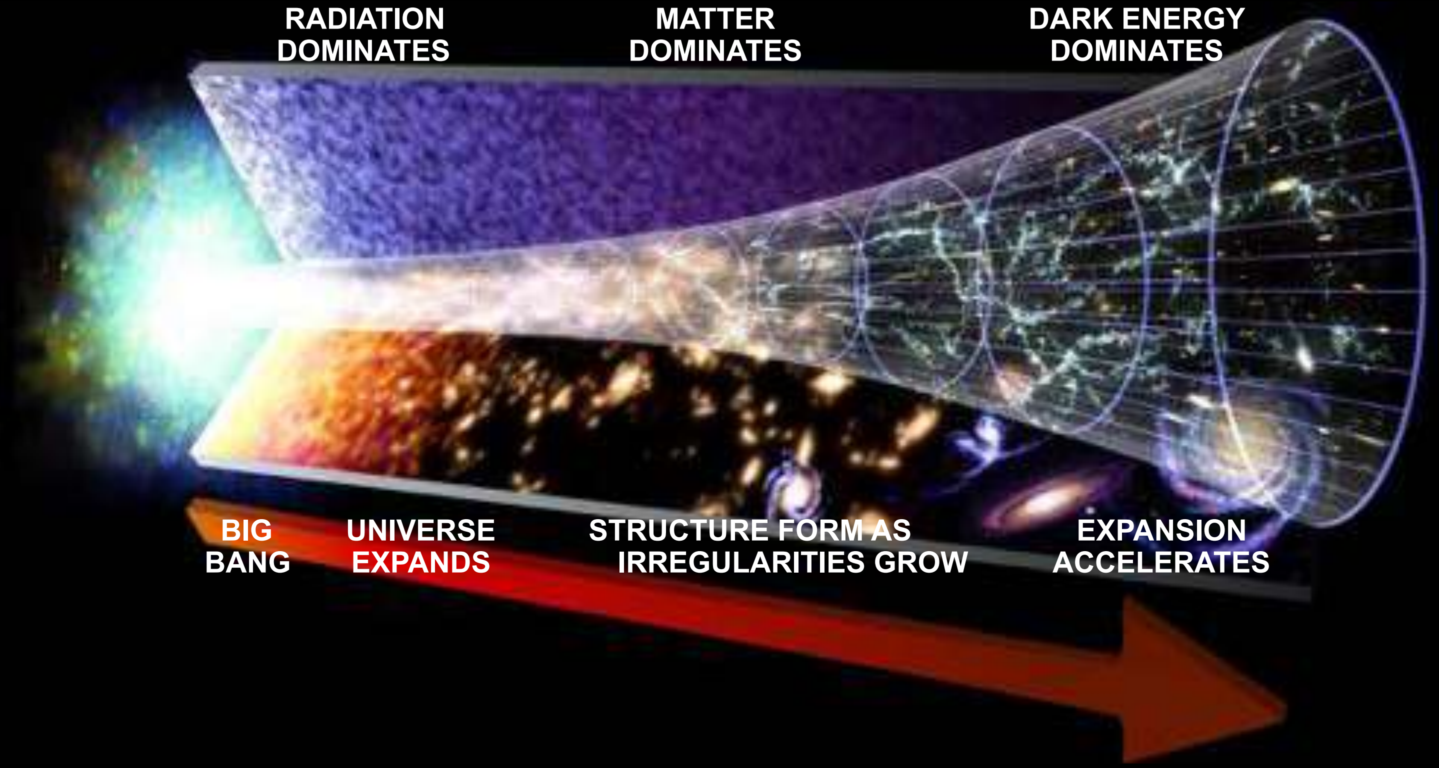
UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

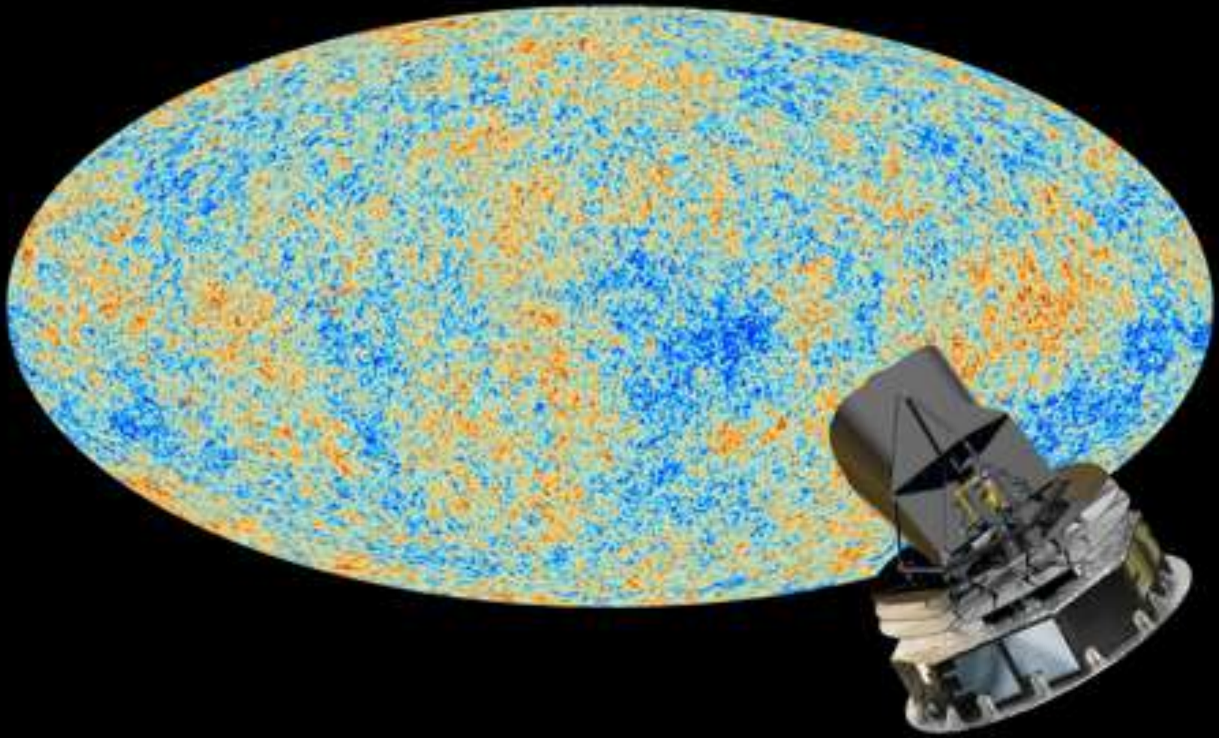
HIRAX

ARC ASTROPHYSICS RESEARCH CENTRE

Cosmic History



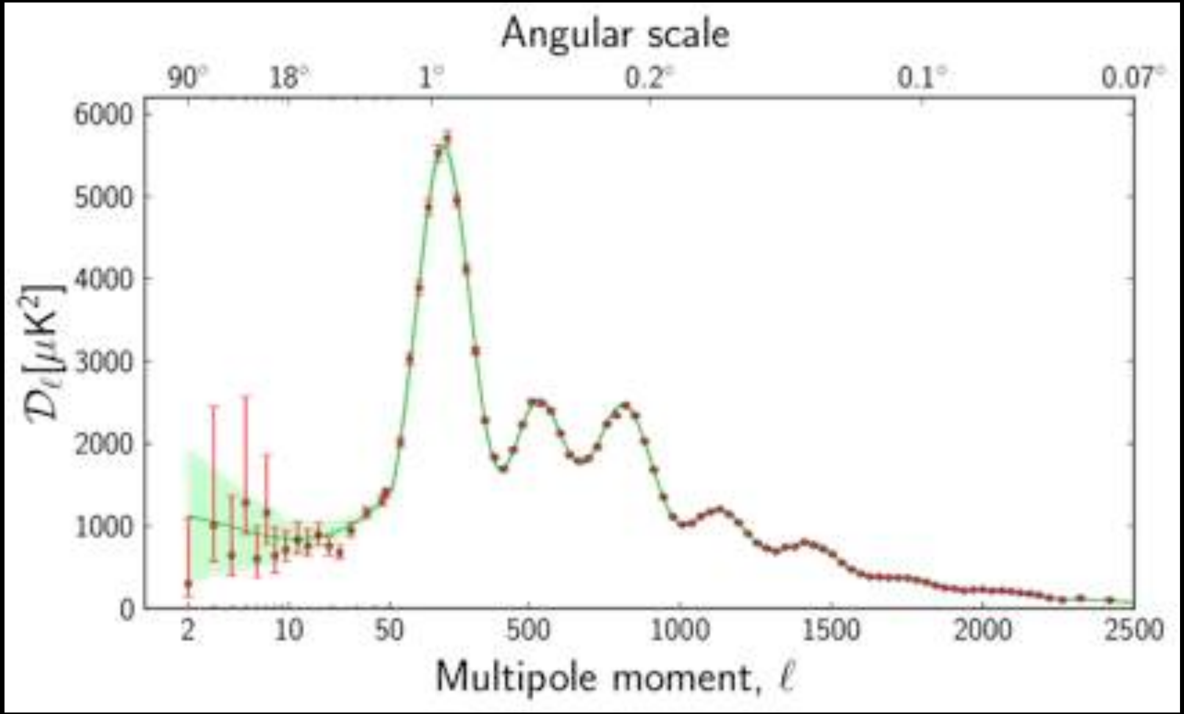
CMB Anisotropies



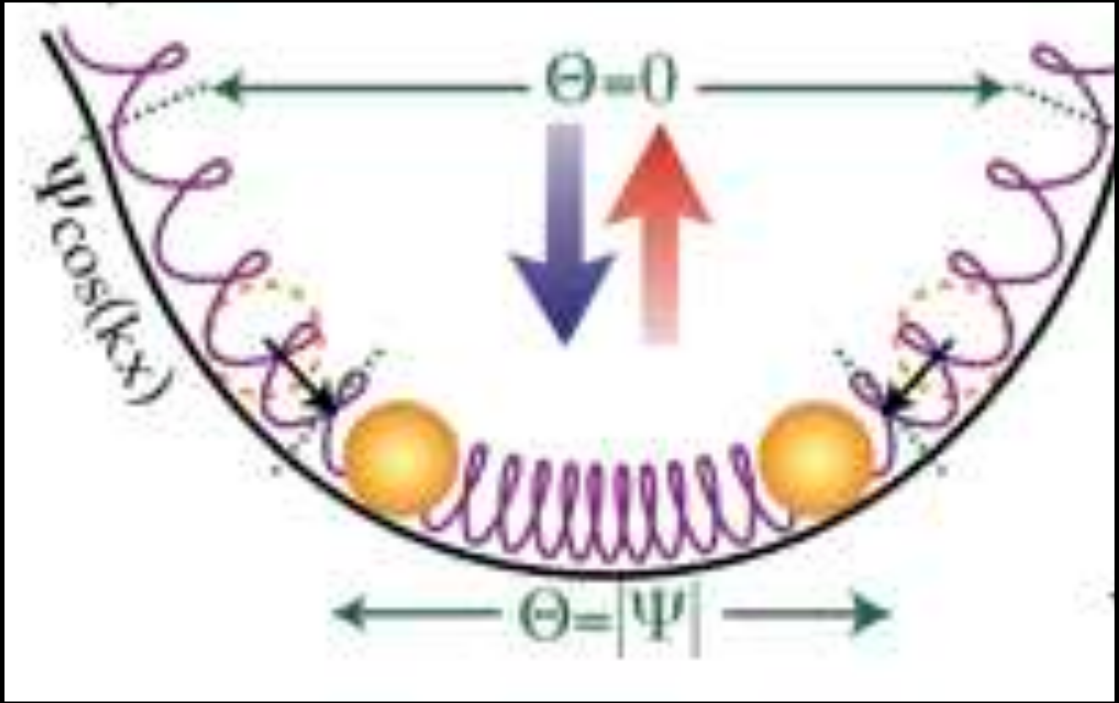
PLANCK

Credit: NASA

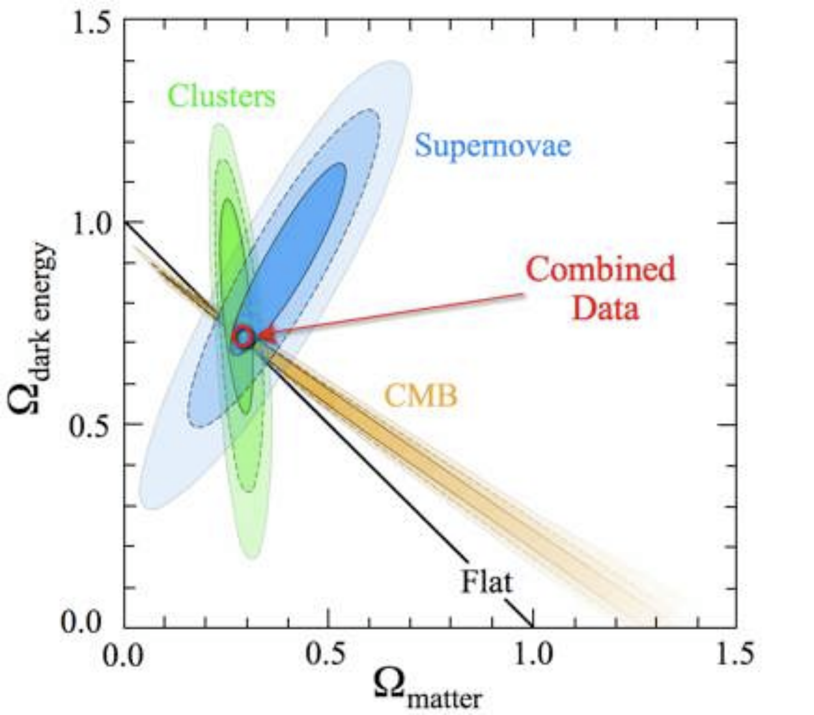
CMB Spectrum



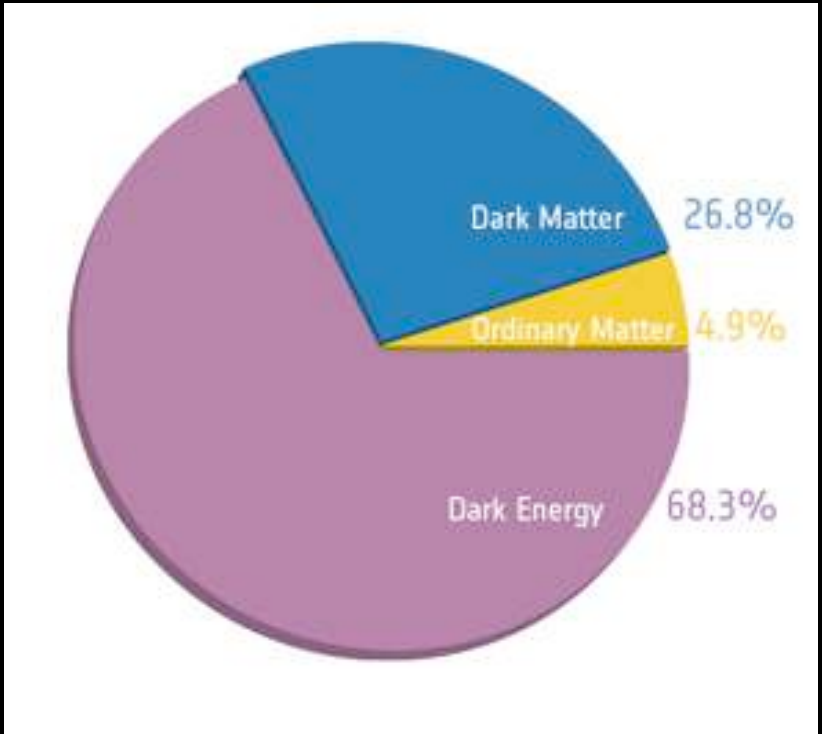
Acoustic Oscillations



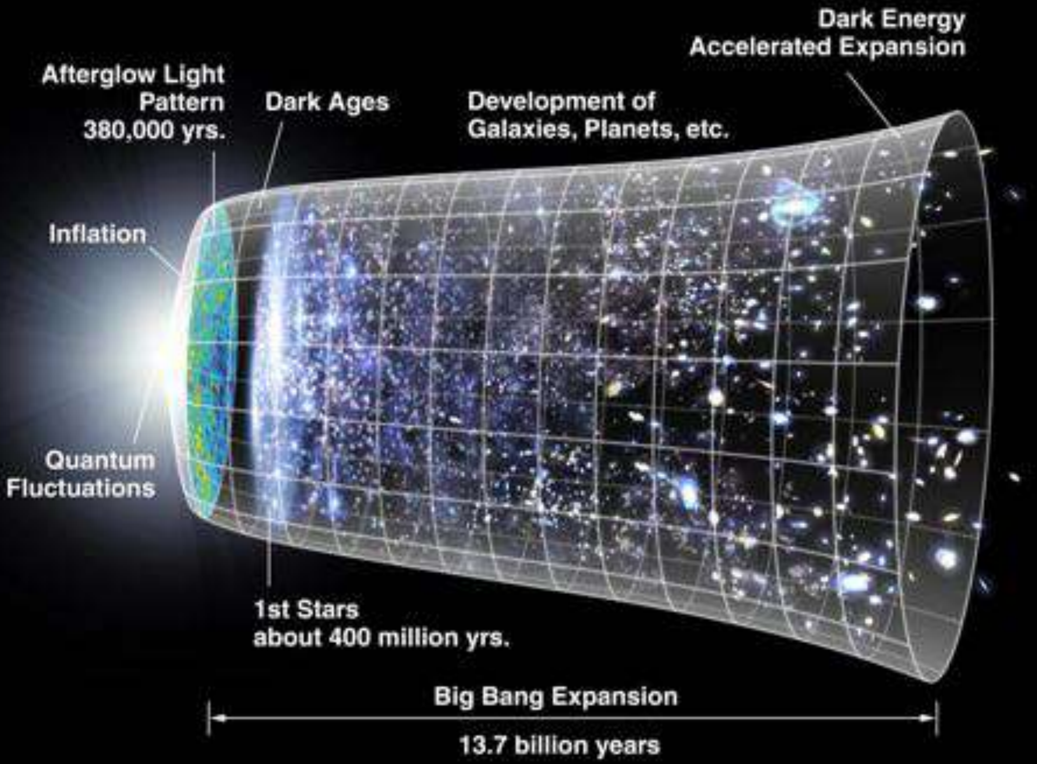
Cosmic Concordance



Cosmic Composition



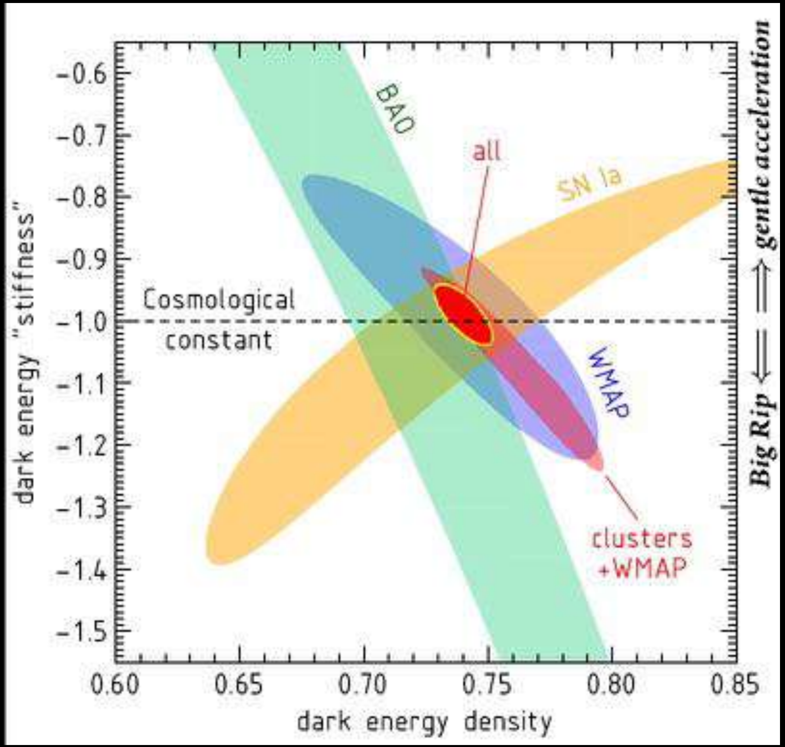
What is the Dark Energy?



Credit: NASA

Dark Energy Key Probes

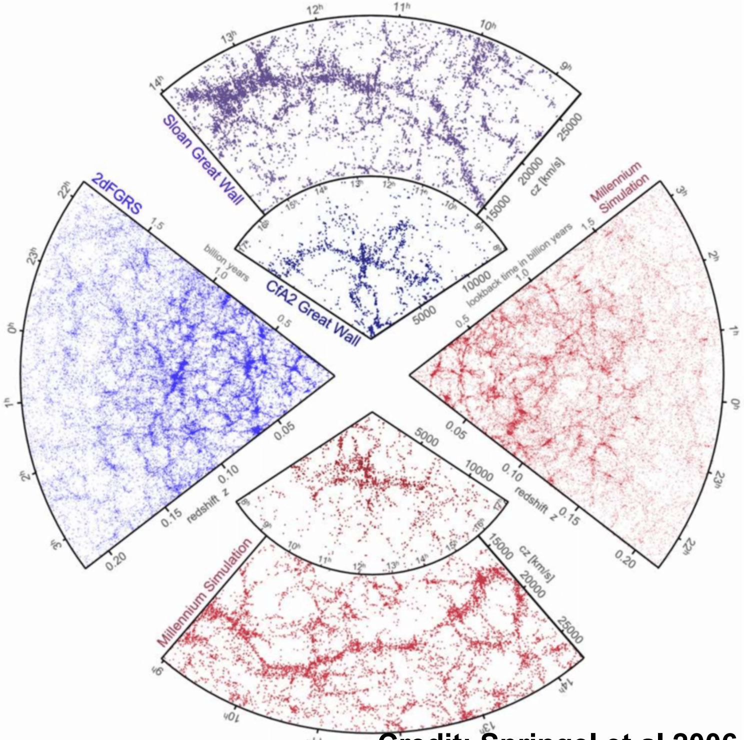
- Type 1a supernovae: measure luminosity distance $D_L(z)$
- Cosmic lensing: measure growth factor $G(z)$ in combination with angular diameter distance $D_A(z)$
- Galaxy clusters: measure growth factor $G(z)$ and comoving volume $dV(z) \sim D_A^2(z)/H(z)$
- **Baryon acoustic oscillations**: measure angular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



Vikhlinin et al 2009

Baryon Acoustic Oscillations

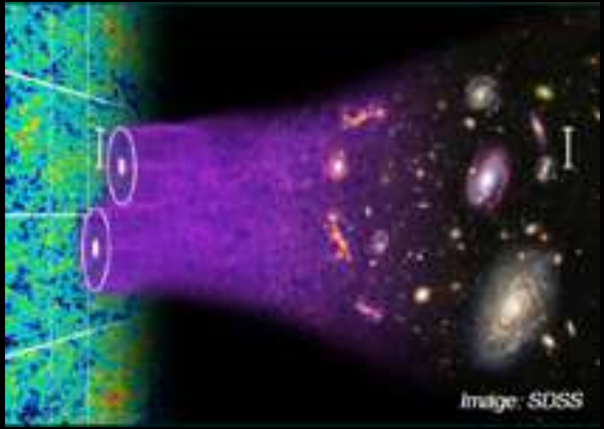
Galaxies trace Matter Distribution



Credit: Springel et al 2006

Credit: NASA

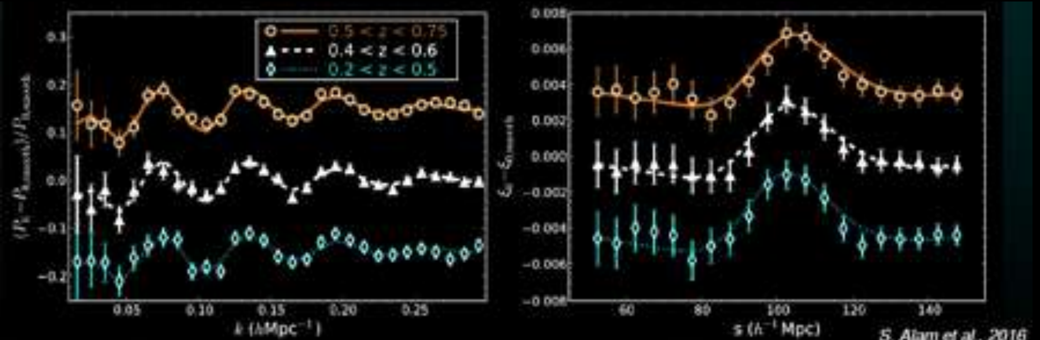
Dark Energy with BAOs



- Galaxy positions trace acoustic waves from the early universe: sound horizon sets characteristic 150 Mpc scale

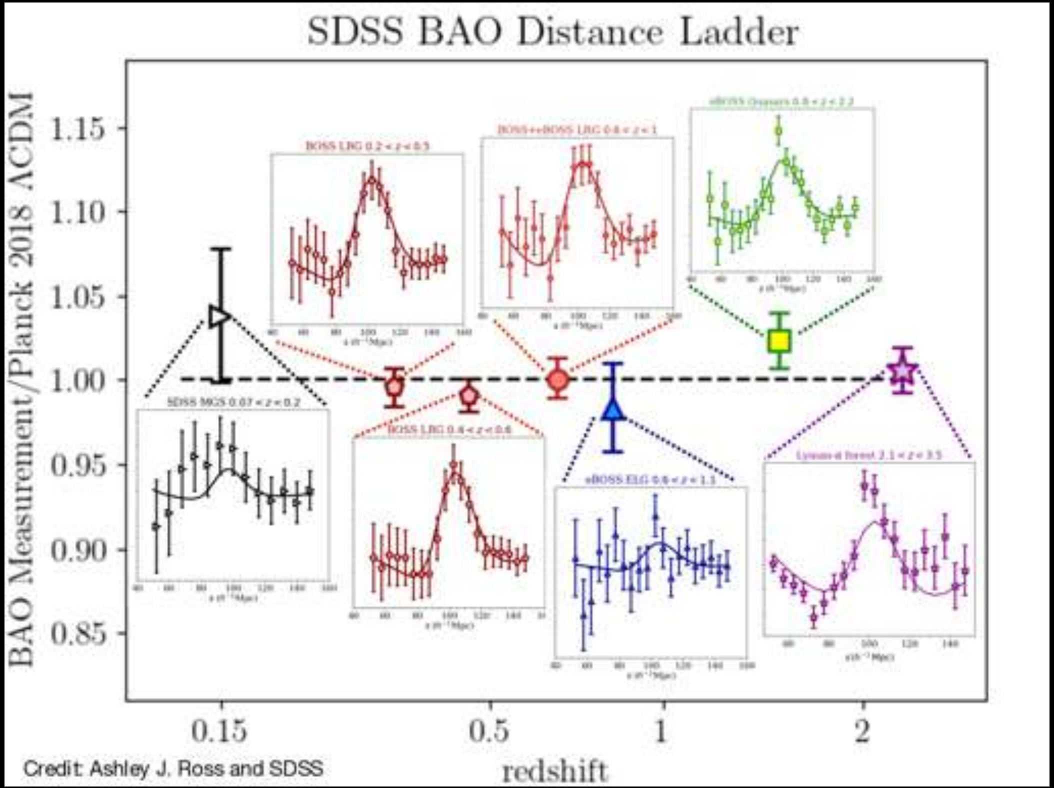
- Measure galaxy positions -> see ripples in the power spectrum, peak in the correlation function

- DR12 release from SDSS-III shown below, redshift range 0.2 < z < 0.75



S. Alam et al., 2016

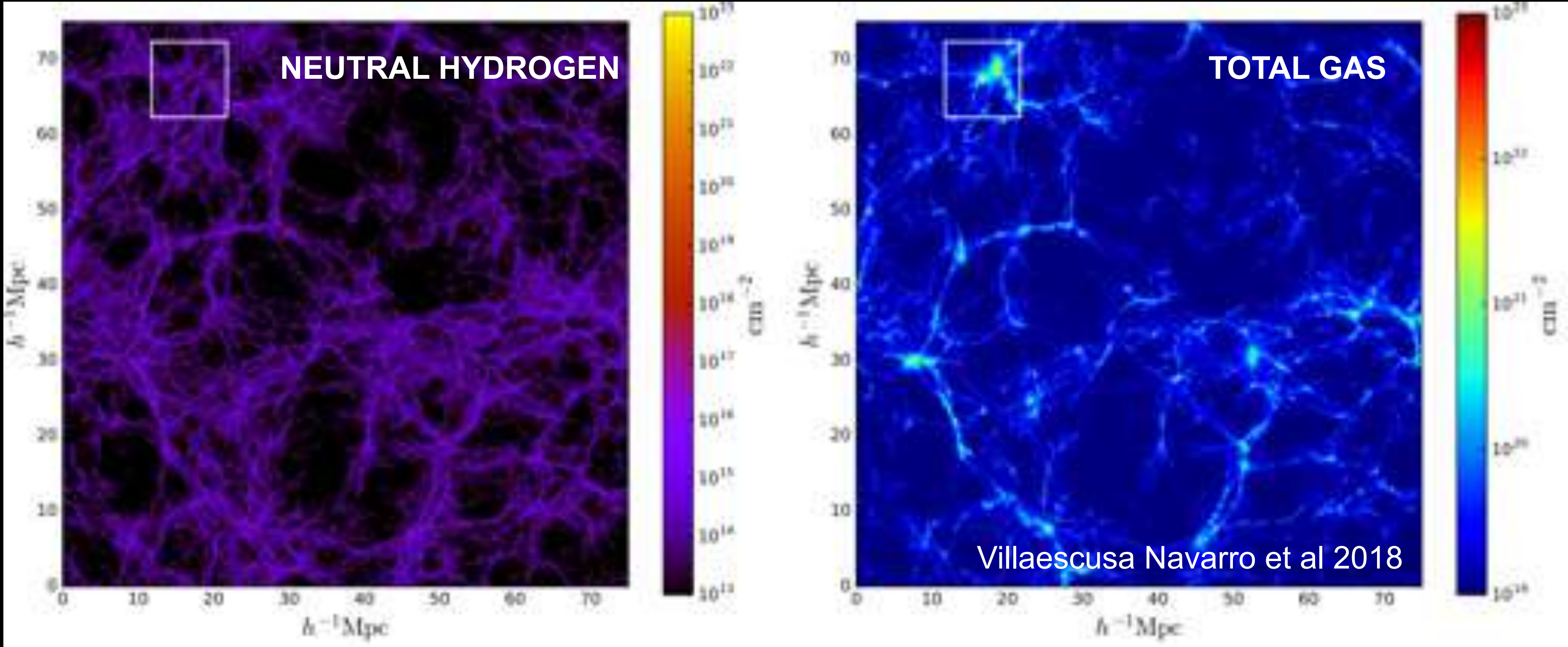
BAO Distance Ladder Measurements



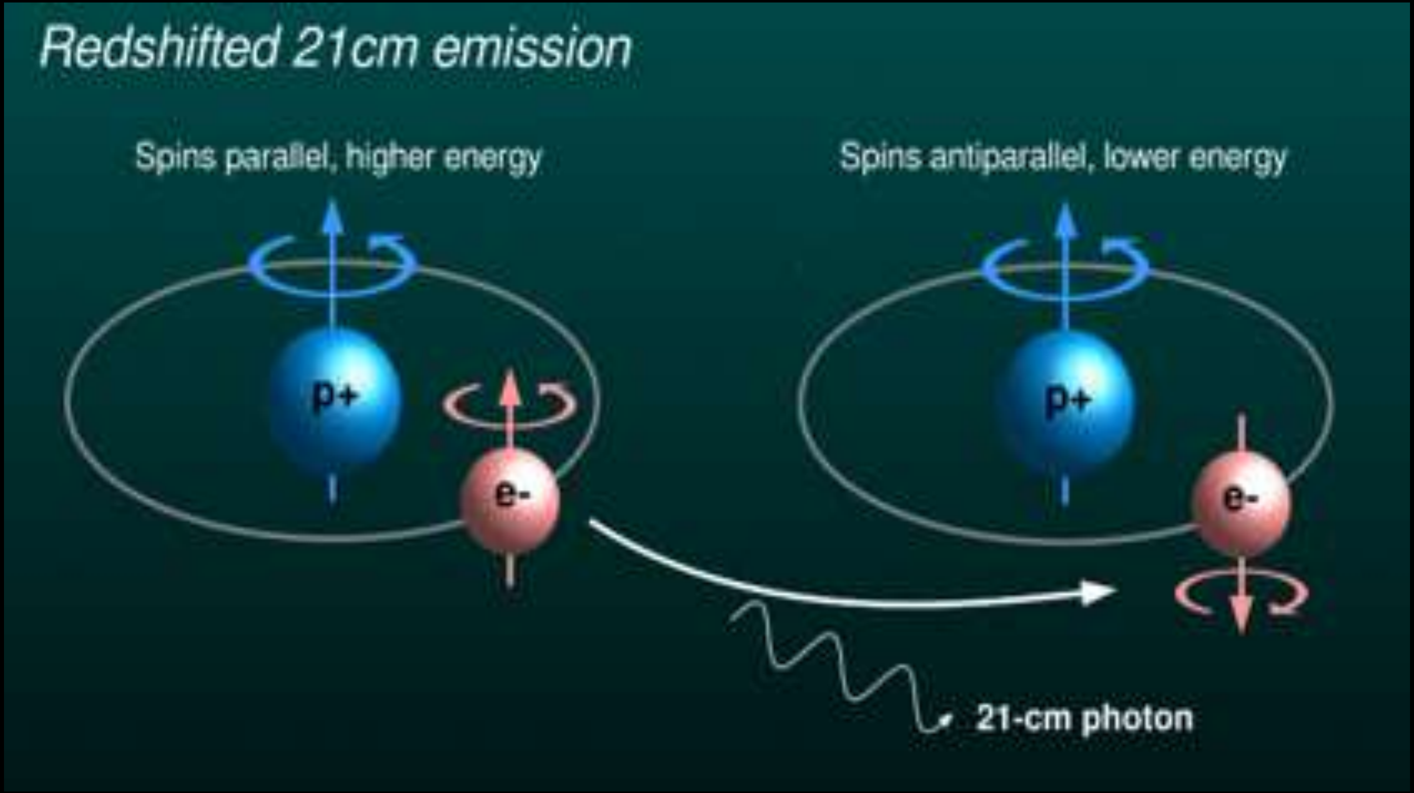
Recent eBOSS results:

Distance scale measurements at few percent level from tracers at different redshifts

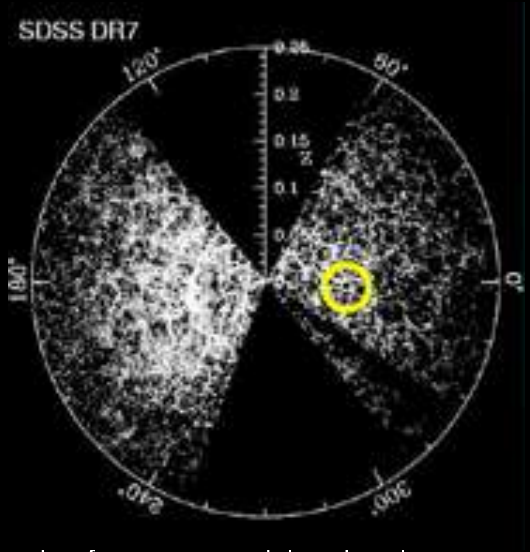
Hydrogen in Galaxies Traces Matter Distribution

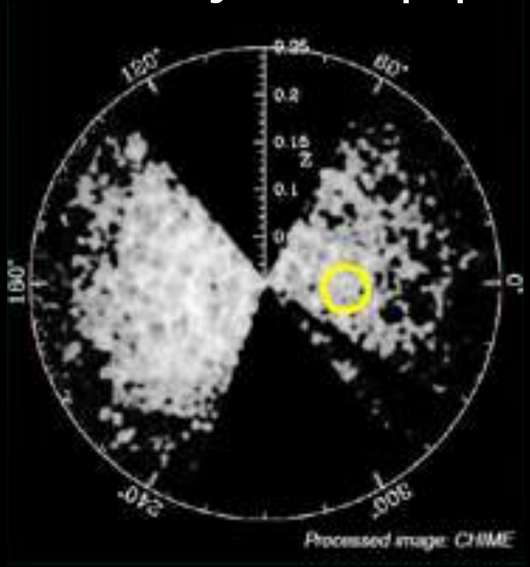


Track Hydrogen with the 21cm Line



BAOs with 21cm Intensity Mapping





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

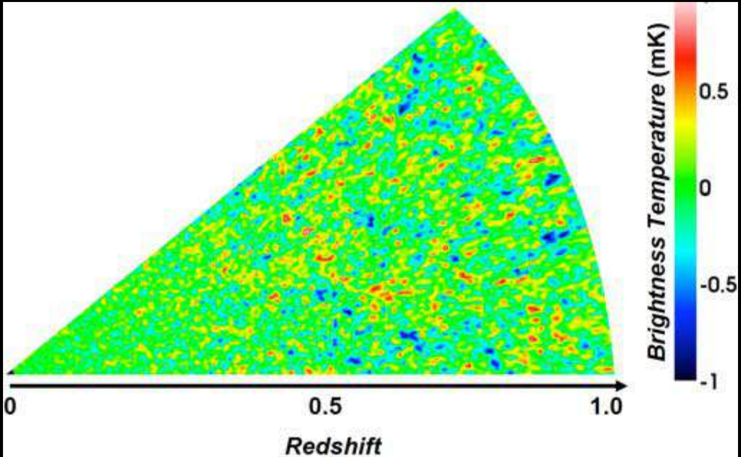
Require large volumes (large sky area and z range)

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.

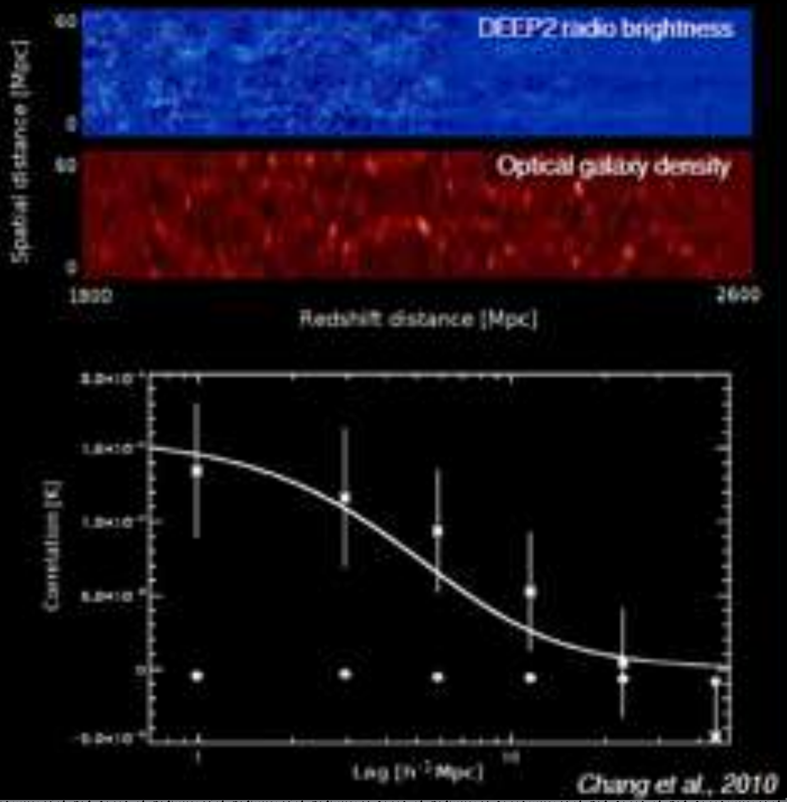
Use the BAO peak as a standard ruler for charting the expansion history.

Challenges for 21cm Intensity Detection



- Signal is weak - need lots of collecting area and sensitive receivers
- Large volume is required to reduce cosmic variance since BAO scale is large - need to cover large sky area and redshift range
- Precise calibration is required - need a very stable instrument
- Foregrounds (galactic and extragalactic) are significantly larger than the 21cm signal - need an extremely well characterised instrument to limit foreground leakage

21cm Intensity Signal Correlated with Galaxies

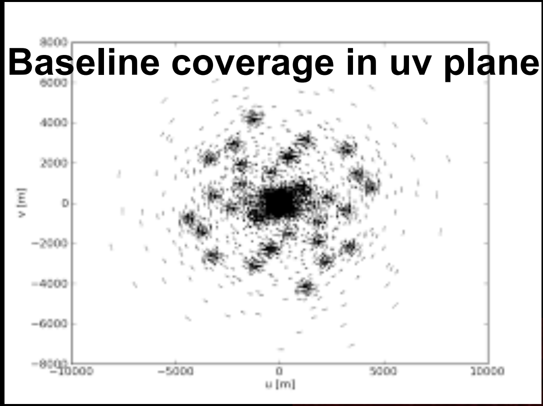


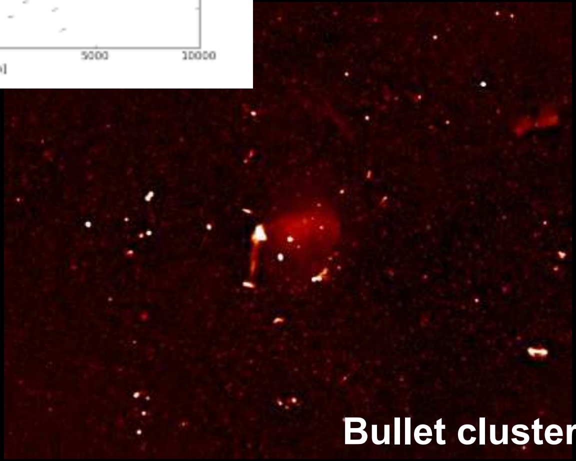
21cm intensity detected in cross-correlation

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 $z \sim 1$ 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)

Traditional Radio Interferometers





- Long baselines for resolution
- Layout optimised to sample uv plane: better imaging
- Trace structure on small to intermediate scales

The Hydrogen Intensity mapping and Real time Analysis eXperiment (HIRAX)

Frequency Range	400–800 MHz
Frequency Resolution	390 kHz, 1024 channels
Dish size	6 m diameter, f/D=0.25
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)

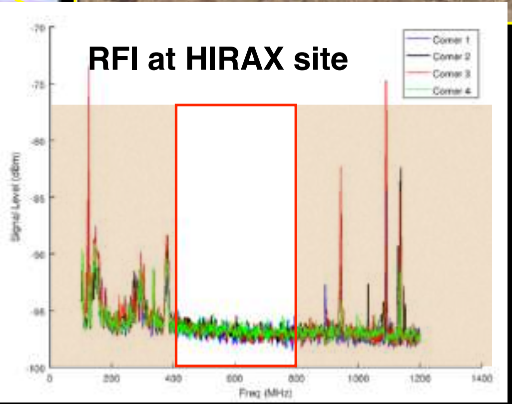
- A compact array of 1024 six metre dishes operating at 400-800 MHz
- Scalable array built in stages: 128 (2021, funded), 256 (2022, funded) then 1024 elements - Operate full array for 4 years
- Dishes stationary but can tilt for more sky area, fabrication in South Africa
- Back-end: overlap with CHIME - 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). McGill funding for F-engine (ICE boards).
- NRF strategic research equipment (SRE) funding secured to expand pathfinder array.
- Sufficient budget to build 256 dishes.

Location, Location, Location …



Government Gazette

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Vol. 516 Cape Town 17 June 2008 No. 31157

THE PRESIDENCY

No. 666 17 June 2008

It is hereby notified that the President has assented to the following Act, which is hereby published for general information:–

No. 21 of 2007: Astronomy Geographic Advantage Act, 2007.

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

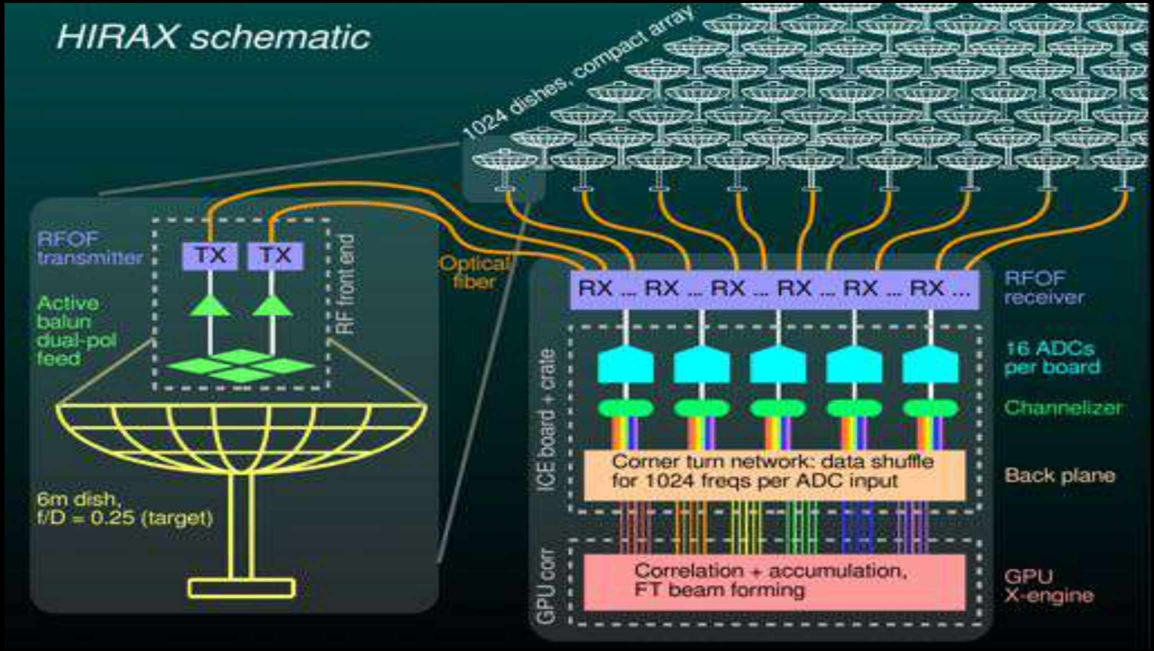
Other HIRAXers

Rock hyrax (dassie)
resident in the Karoo

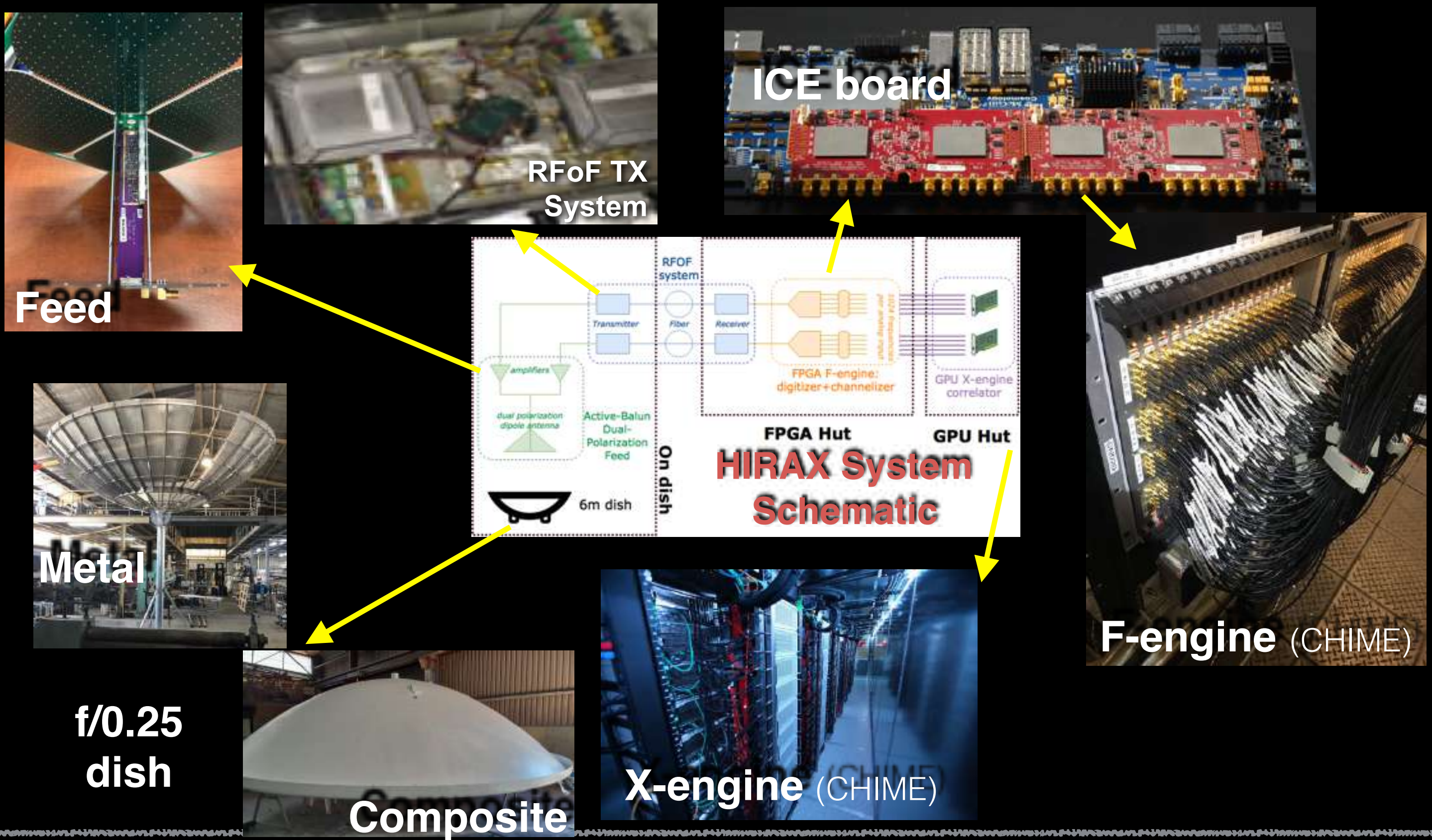
Thrash metal band

HIRAX Design Plan

- 1024 close-packed 6m dishes. Fibre-glass and metal prototypes fabrication in South Africa.
- Cloverleaf dual-pol feed, RF over fibre
- Operate between 400-800 MHz, 1000 channels
- Channelizing on FPGA ICE boards
- Correlation on GPUs



HIRAX Instrument



HIRAX Complementarity with CHIME

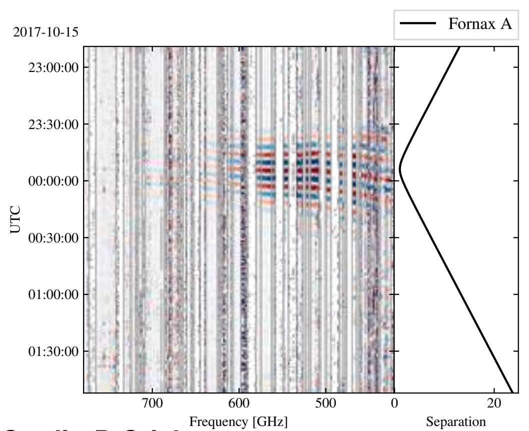
- HIRAX dishes || CHIME cylinders - different systematics, larger collecting area
- Lower RFI at SKA SA Karoo site
- CHIME sees whole (accessible) sky each day || HIRAX can integrate deep on narrow strips
- HIRAX observes southern sky
  - optical surveys: cross-correlation science and foreground mitigation
  - more pulsars in south

	CHIME	HIRAX
Site	DRAO, Canada	Karoo (lower RFI, no snow)
Telescope	Cylinder array	Dish array (different systematics)
Field of view	100° NS, 1°–2° EW	5° – 10° deg
Beam size	0.23° – 0.53°	0.1° – 0.2°
Collecting area	8000 m^2	28,000 m^2
Sky coverage	North	South

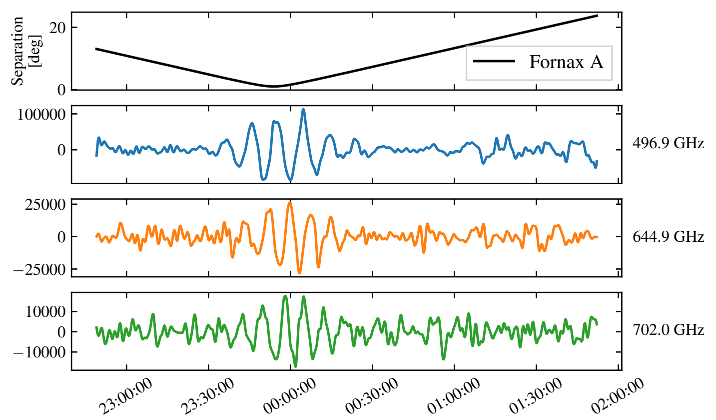
HartRAO Prototype Array

- 8-element prototype at Hartebeeshoek Radio Observatory informing design, analysis and systematics
- Eight “off-the-shelf” f/0.38 dishes fully instrumented with fully functional scaled-down digital backend with single ICE board and GPU correlator
- Metal and fibreglass f/0.25 dishes installed and being tested
- Field-testing RFoF system
- Complementary prototyping efforts at DRAO and Green Bank

HartRAO Prototype Data



Credit: D Crichton



Credit: D Crichton

- Currently characterising instrumental properties from the data
- We see fringes. Can fit basic beam and gain models.
- Poor RFI environment at HartRAO limits high-precision characterisation
- RF characterisation on DRAO 3m f/D=0.25 dishes, Green Bank 6m f/D=0.38 dishes; Shift to (low RFI) Karoo qualification array site with selected 6m dishes

Upcoming Schedule

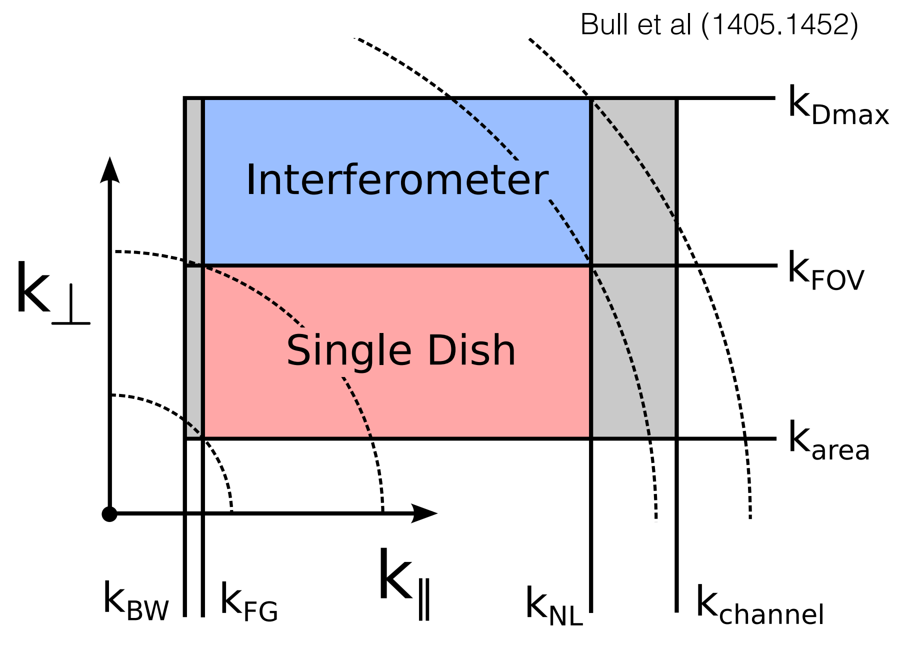
- Inform instrument design + layout through cosmology/electromagnetic simulations in 2020
- HartRAO programme in 2020/2021*
  - Test f/0.25 fibreglass and metal dishes
  - Finalise dish requirements and go out on tender
  - Test RFoF and feeds on f/0.25 dishes
  - Develop holography/drone beam calibration system

- Develop HIRAX Karoo main site by Q2 2021*
- 2-element qualification dishes at HIRAX Karoo Klerefontein site by Q2 2021*
- 8-element prototype at HIRAX Karoo Swartfontein site by Q3 2021*
- 128-element pathfinder at HIRAX Karoo Swartfontein site by Q1 2022*

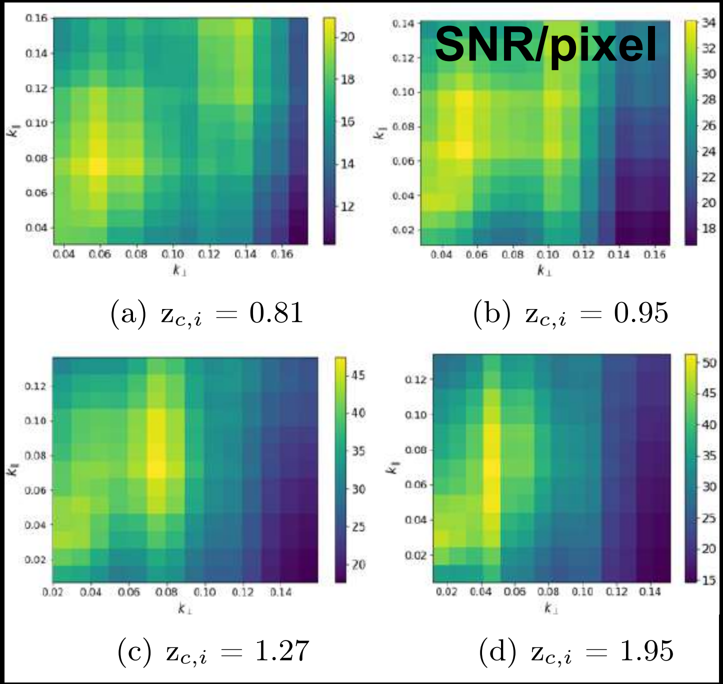
* subject to COVID-19 restrictions

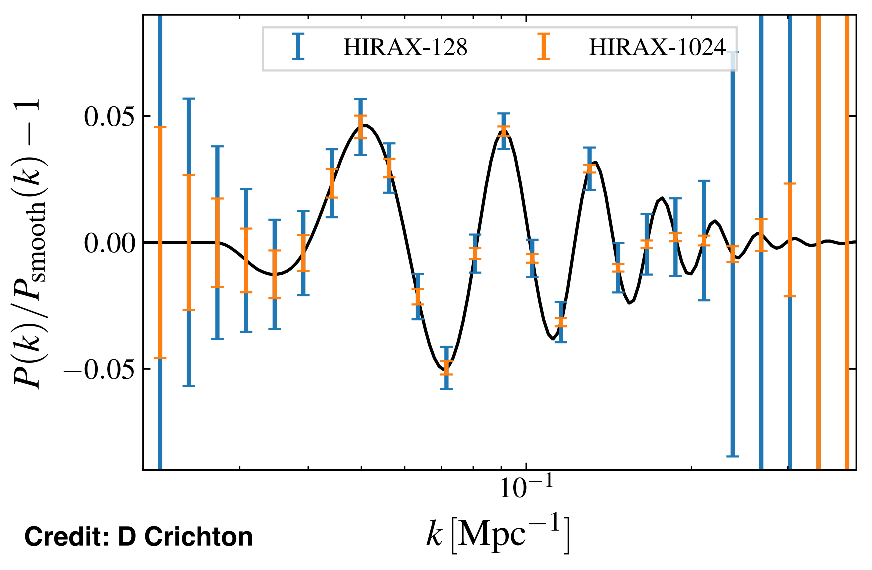
HIRAX 21cm Intensity Mapping Survey

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



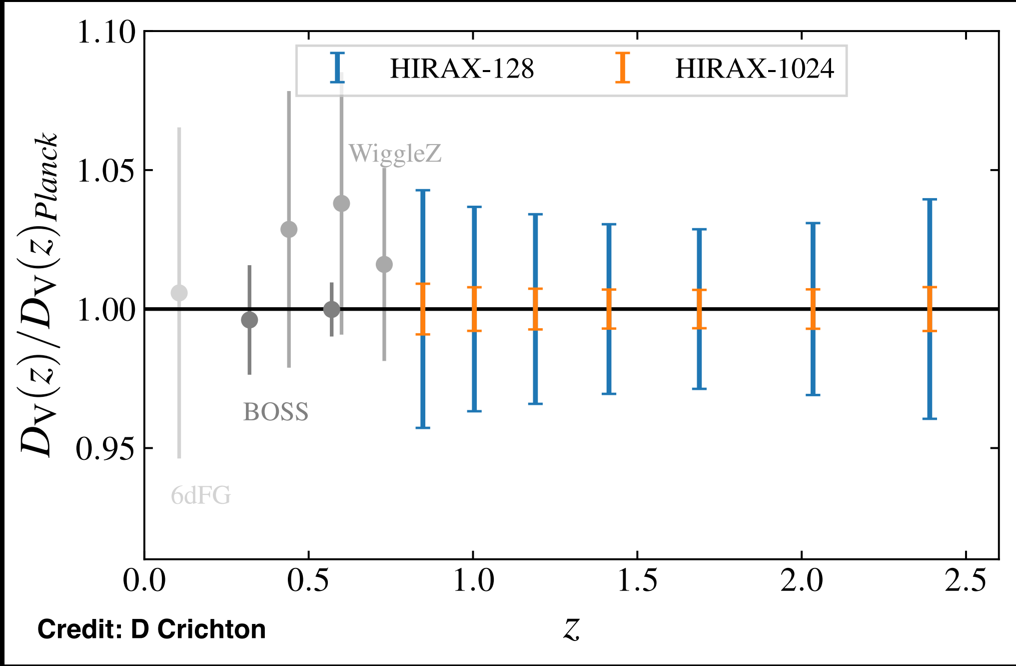
BAO Forecasts with HIRAX

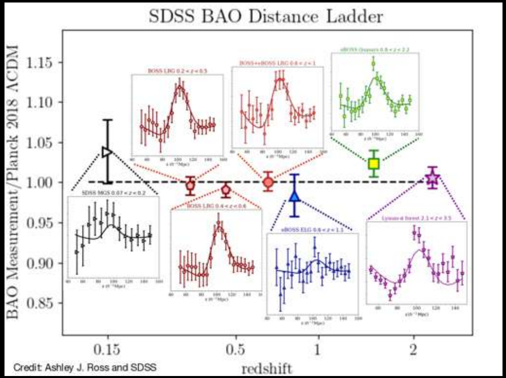




- HIRAX will make a precise measurement of the matter power spectrum in the BAO regime in a number of redshift bins from z = 0.775 to 2.55.

HIRAX Distance Scale Forecasts

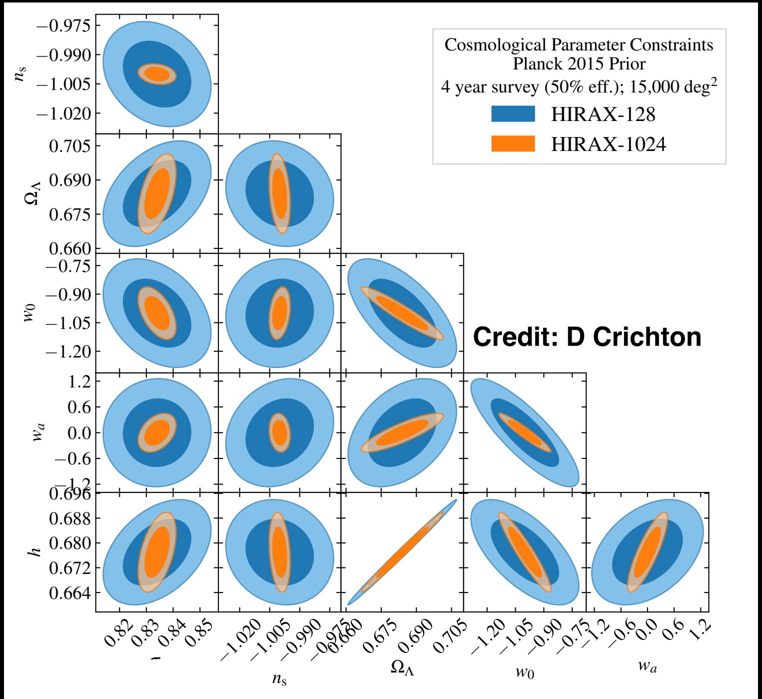




eBOSS 2020

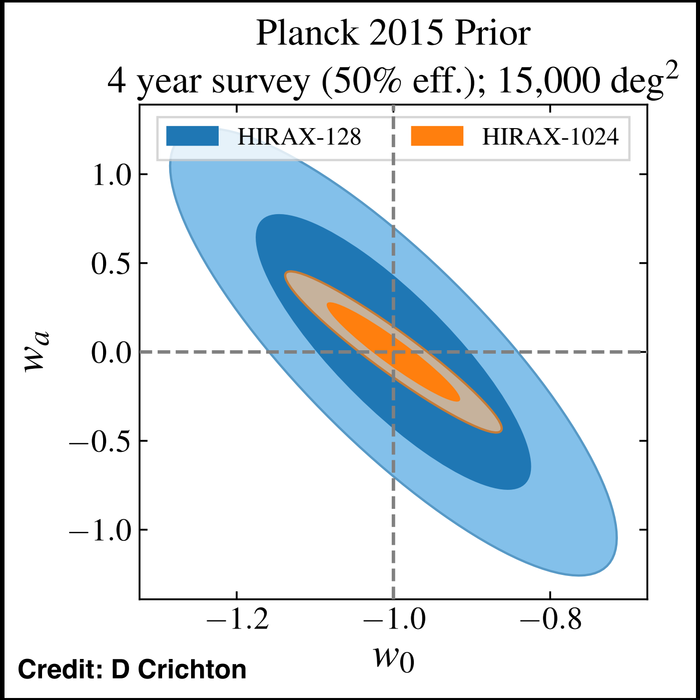
- Convert power spectrum BAO constraints into constraints on D_V in each redshift bin -> constrain the BAO scale at the percent level out to high redshift with HIRAX-1024

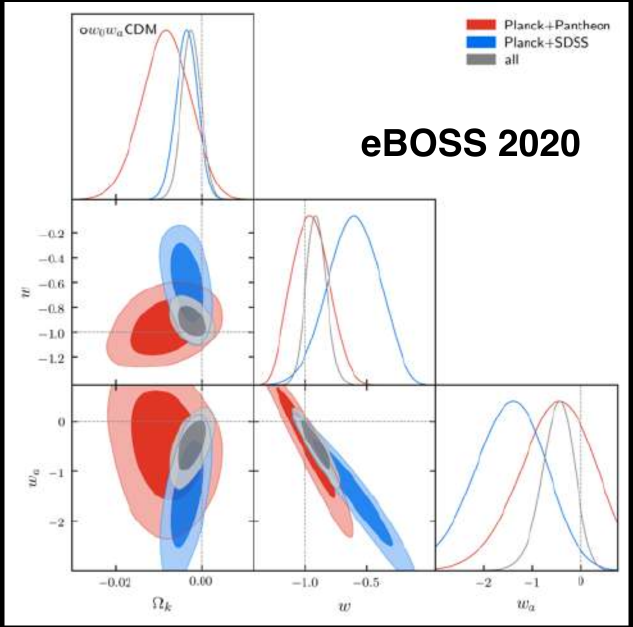
HIRAX Cosmological Parameter Forecasts



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

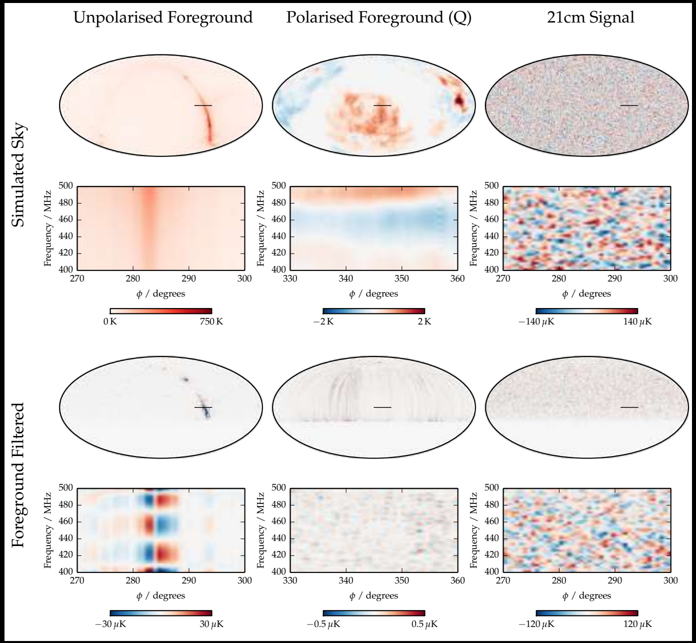
HIRAX Dark Energy Constraints

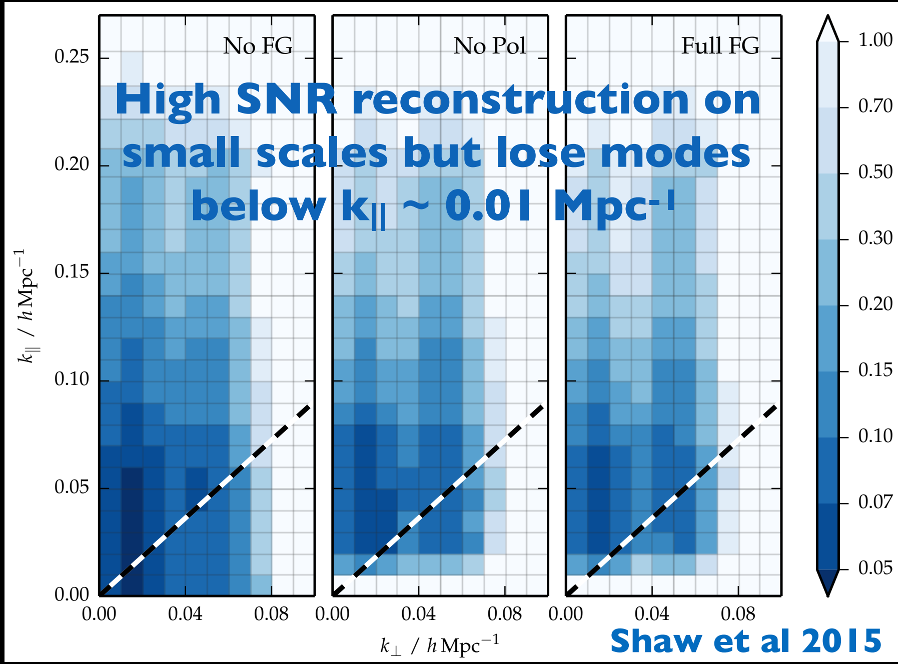




- HIRAX-1024 FoM ~ 300 approaching DETF Stage IV class galaxy surveys ~400

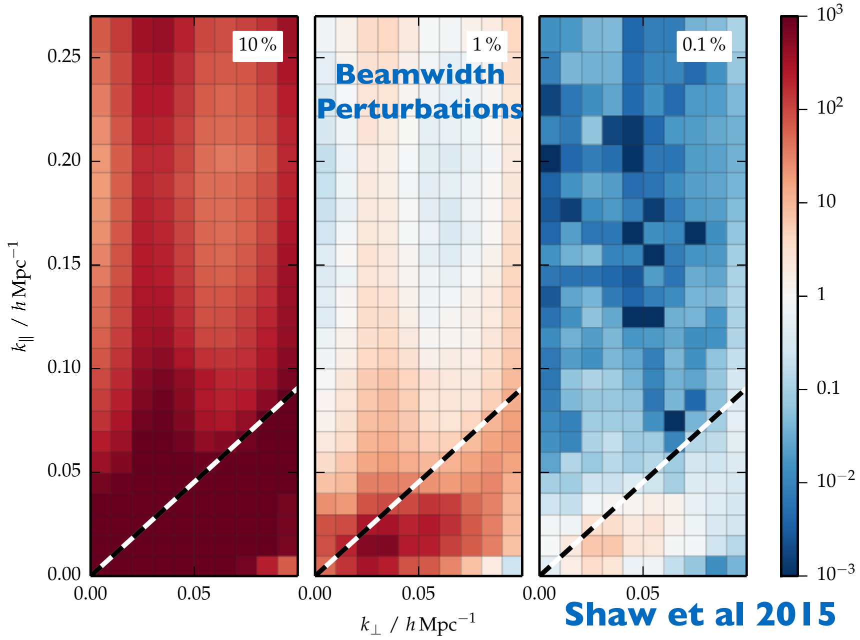
Foregrounds Challenge





- Galactic signal is several orders of magnitude larger than the 21cm intensity mapping signal
- Filter foregrounds by using spectral smoothness of foreground intensity spectrum (polarisation is more complicated)

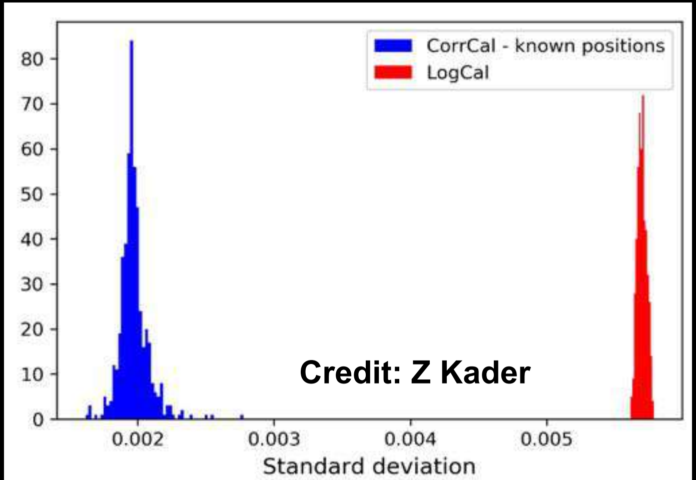
Foregrounds Challenge



Foreground wedge builds up

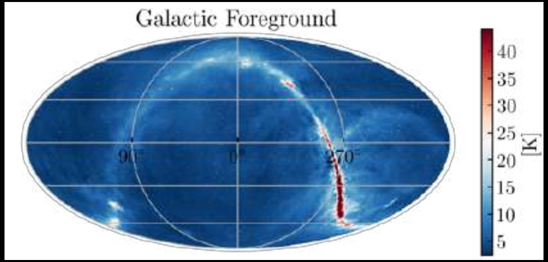
- $v = (B_{instr} + \delta B_{instr})(a_{fg} + \delta a_{fg} + a_{21}) =$ $B_{instr}\, a_{fg}$ (**filter**) + $B_{instr}\, \delta a_{fg}$ (**leakage**) + $\delta B_{instr}\, a_{fg}$ (**leakage**) + $B_{instr}\, a_{21}$ (**signal**) + higher order terms
- Precise foreground modelling and characterisation is required
- Precise knowledge of the instrument is vital - need to characterise beams, pointing, delay, gain, bandpass, cross-polarisation etc.

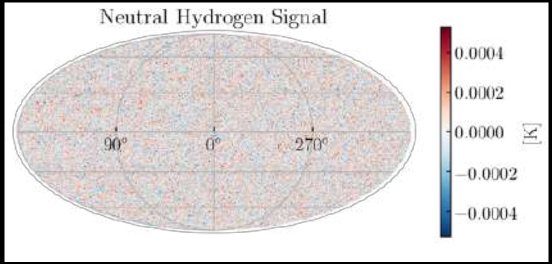
Instrument Characterisation is a Major Challenge

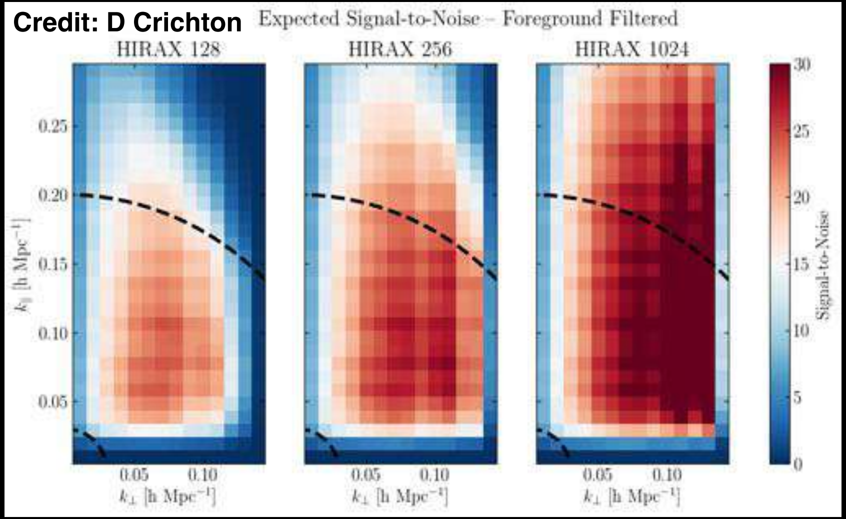


- Instrument Calibration: Beam calibration using holography + drone calibrator mapping: mapping tests will start with HartRAO prototype, characterise using full electromagnetic simulations
- Analysis: Quasi-redundant calibration for non-idealities in HIRAX array (Sievers,1701.01860)
- Design Simulations: Determine tolerances on telescope parameters to limit instrumental leakage

Simulations for Instrument Design







- End-to-end cosmology simulations pipeline that incorporates beams from full EM simulations
- Simulations used to set requirements for upcoming dish tender -> control errors in beam shape, pointing and geometric delay that result in non-redundancies
- Fisher matrix approach with 21cm/foreground/instrument parameters -> determine instrument tolerances that will mitigate foreground leakage and preserve dark energy FoM

Simulations for Instrument Design

Simulated Instrument $(\mathbf{B}_m)_{(\alpha\nu)(l\nu')}$ x Simulated Sky $(\boldsymbol{a}_m)_{(l\nu)}$ → Simulated Data $(\boldsymbol{v}_m)_{(\alpha\nu)}$

Include systematics

Add solved for or unsolved for systematics to recovery pipeline and evaluate relative quality of results

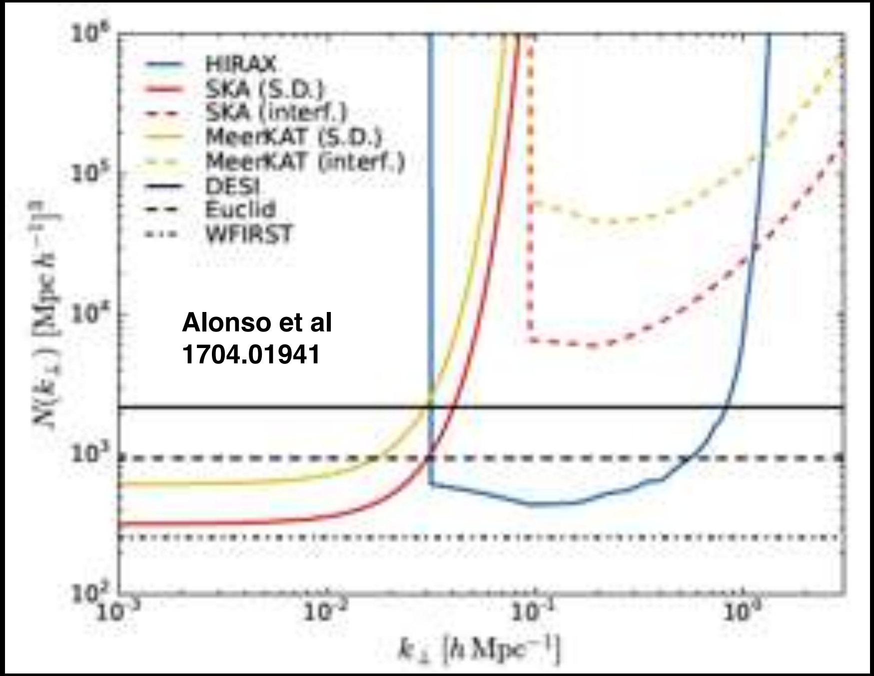
Inverse Instrument $(\mathbf{B}_m)_{(\alpha\nu)(l\nu')}$ x Simulated Data + Noise $(\boldsymbol{v}_m)_{(\alpha\nu)} + \boldsymbol{n}$ → Recovered Sky $(\boldsymbol{a}_m)_{(l\nu)}$

Include **known** systematics

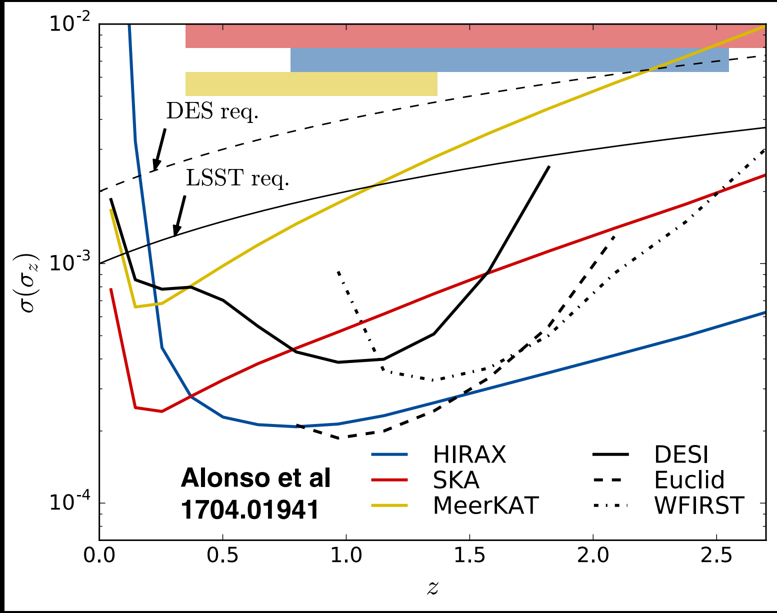
Include calibration solution

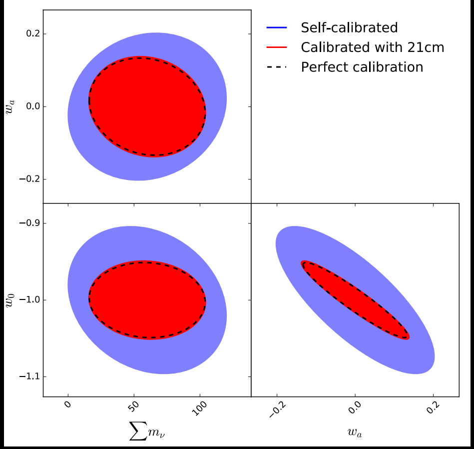
HIRAX Cross-Correlation Cosmology

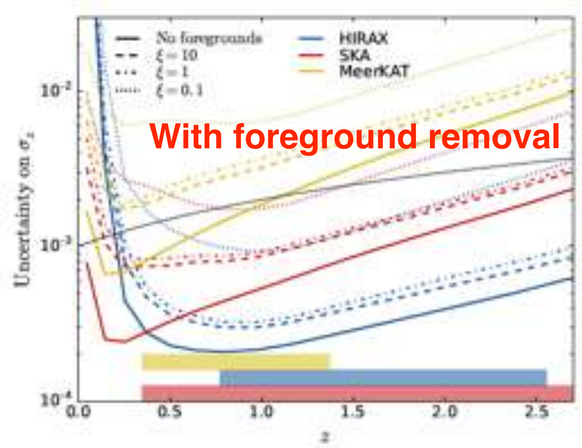
- HIRAX intensity mapping survey will have good redshift overlap with other large-area cosmological surveys, primarily in the southern sky
  - ✦ Photometric: DES, LSST
  - ✦ Spectroscopic: DESI, Euclid and W-FIRST
  - ✦ CMB: ACT, SPT, Simons Observatory
- HIRAX has excellent noise over cosmologically interesting scales, complementary to MeerKAT and SKA
- Cross-correlations ideal for testing systematics and joint science



LSST Photo-z Calibration







- Cross-correlation with the LSST photometric survey can provide photo-z calibration via the clustering redshifts method and improve dark energy parameter constraints from cosmic shear and galaxy clustering.

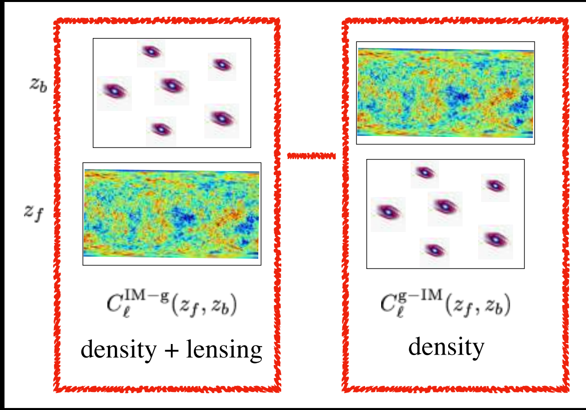
Galaxy-21cm Magnification Bias Estimator

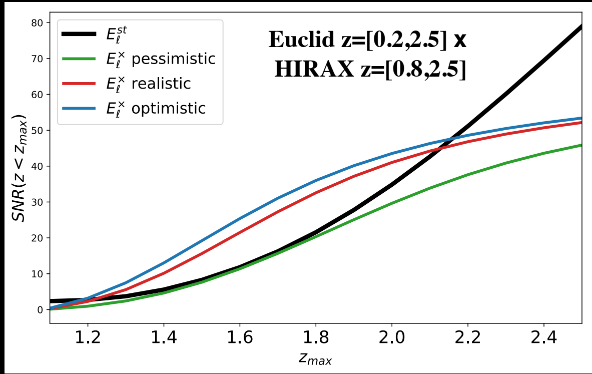
Contamination: reduced by a factor proportional to bias difference

$$
\begin{aligned}
E^{\times} &= C_\ell^{g\text{-HI}}(z_b, z_f) - C_\ell^{\text{HI-}g}(z_b, z_f) \\
&= \left[b_g(z_b) b_{\text{HI}}(z_f) - b_{\text{HI}}(z_b) b_g(z_f)\right] C_\ell^{\delta\delta}(z_b, z_f) \\
&+ \frac{1}{2} b_{\text{HI}}(z_f)(2 - 5s(z_b)) C_\ell^{\phi\delta}(z_b, z_f) \\
&- \frac{1}{2} b_{\text{HI}}(z_b)(2 - 5s(z_f)) C_\ell^{\delta\phi}(z_b, z_f)
\end{aligned}
$$

Jalilvand et al 1907.00071

Lensing terms





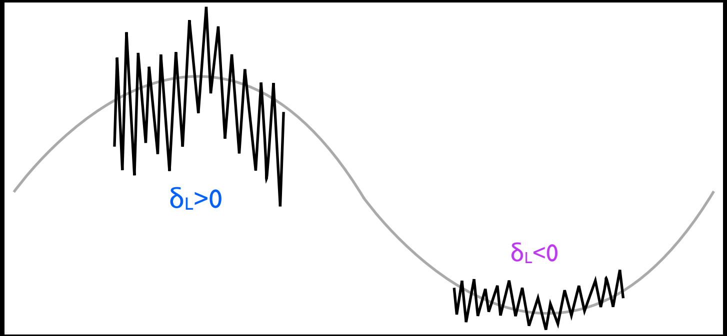
- SNR improvement of E^x over E^{st} by a factor of ~2 over z = 1.2 - 2.0.

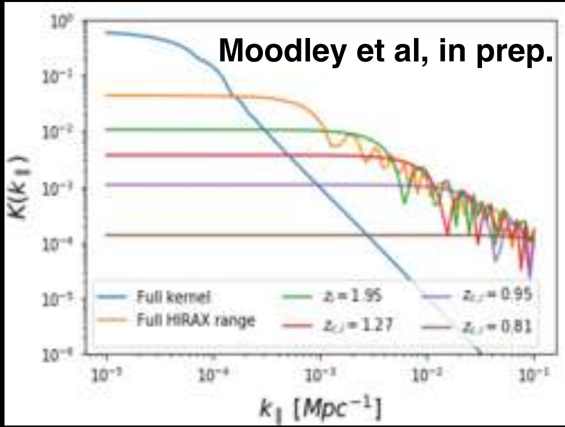
21cm Correlation with CMB Lensing

- Direct 21cm-CMB lensing correlation vanishes because of loss of low k_{par} 21cm modes in foreground subtraction

- Construct a bispectrum estimator that uses two copies of the 21cm intensity field and one copy of the CMB lensing field.

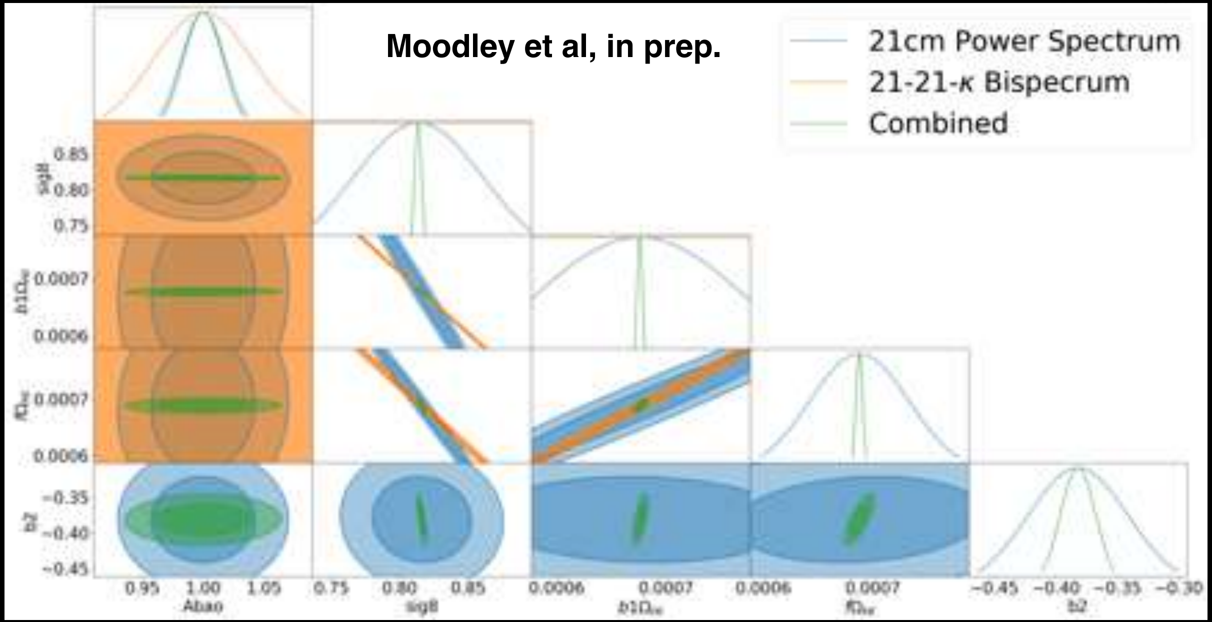
- Estimator relies on modulation of small-scale 21cm modes by large-scale (super-sample) modes to recover the line-of-sight long wavelength modes that are required for correlation with CMB lensing.





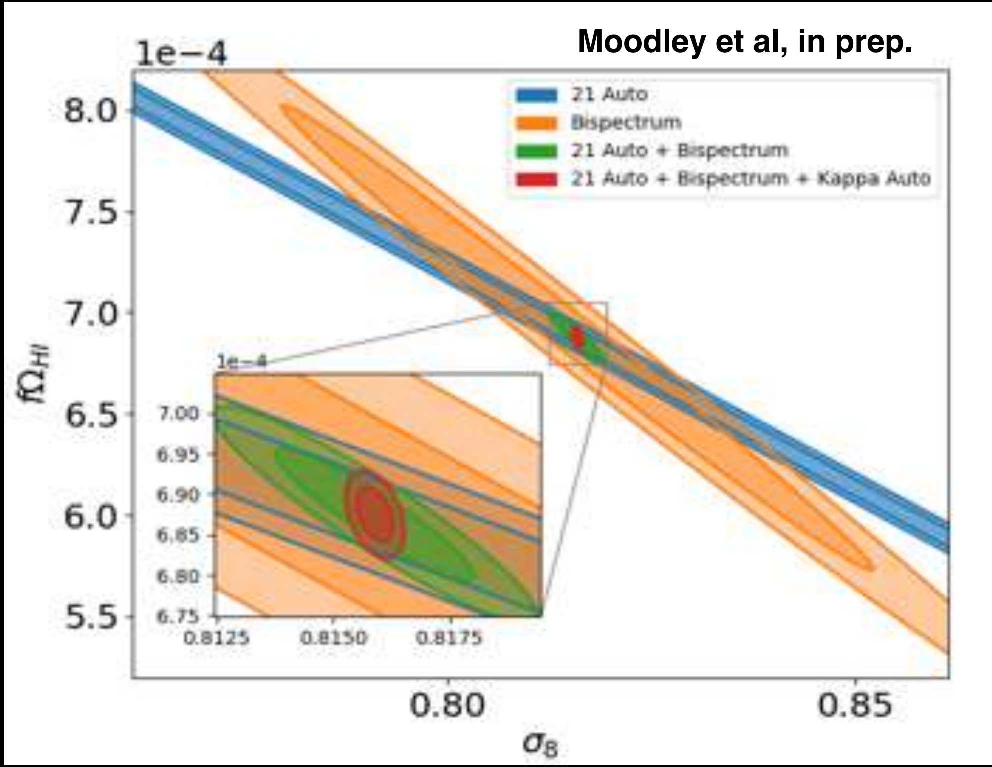
21cm Correlation with CMB Lensing

- **Provide tight constraints on HI bias parameters**
- Independently constrain growth function and clustering amplitude
- Improve dark energy constraints



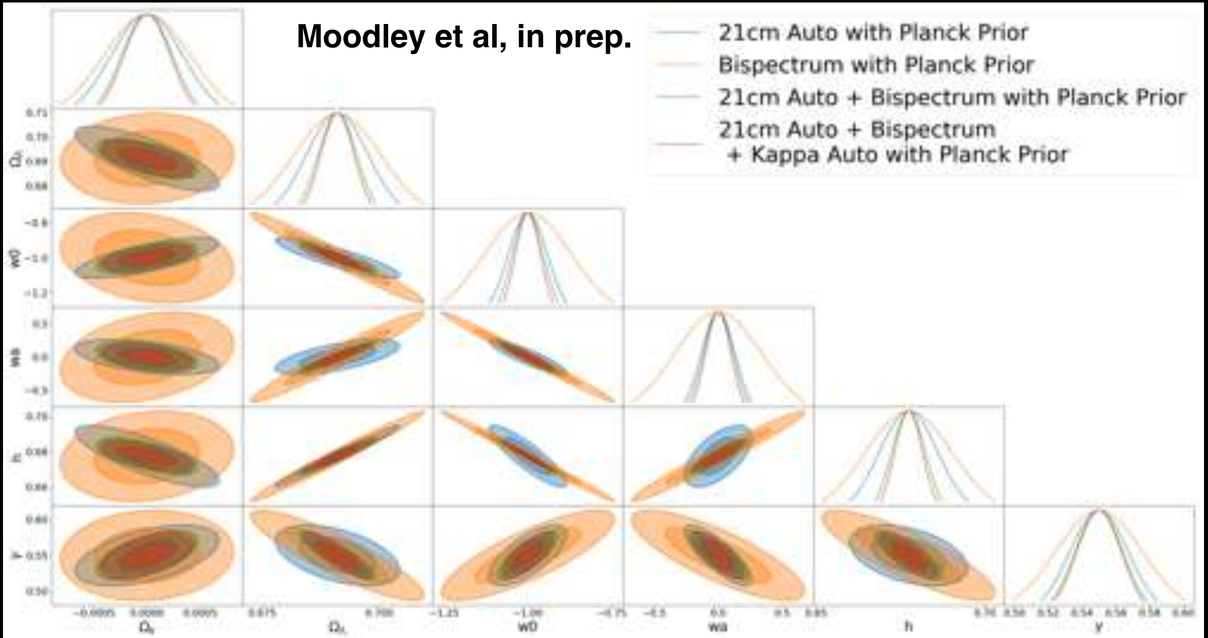
21cm Correlation with CMB Lensing

- Provide tight constraints on HI bias parameters
- **Independently constrain growth function and clustering amplitude**
- Improve dark energy constraints



21cm Correlation with CMB Lensing

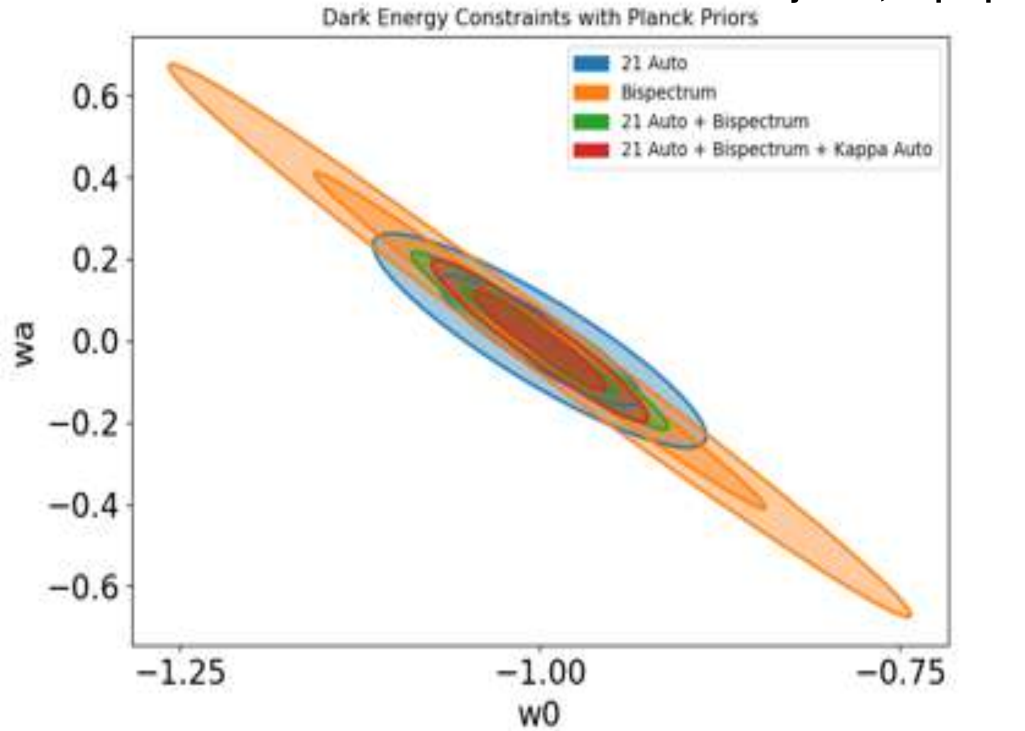
- Provide tight constraints on HI bias parameters
- Independently constrain growth function and clustering amplitude
- **Improve cosmological constraints**



21cm Correlation with CMB Lensing

- Provide tight constraints on HI bias parameters
- Independently constrain growth function and clustering amplitude
- **Improve dark energy constraints**

Moodley et al, in prep.



Thank you!