http://www.acru.ukzn.ac.za/~hirax

COSMOLOGY WITH HIRAX

COMBINING 21-CM AND LARGE-SCALE STRUCTURE SURVEYS

Moumita Aich

(collaboration with Warren Naidoo and Kavilan Moodley)

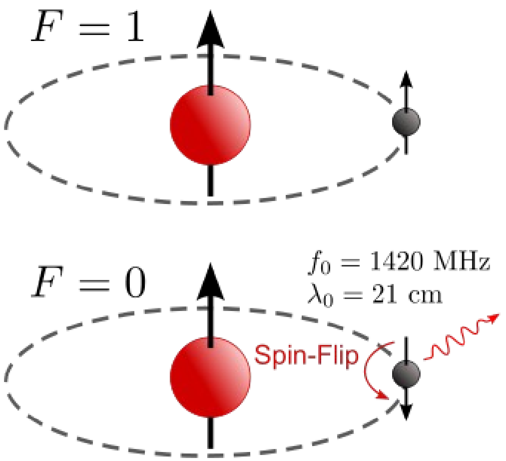
University of KwaZulu-Natal, Durban, South Africa

Cosmology – The Next Decade

ICTS, Bengaluru

25 January 2019

21 cm line as cosmological probe



- 21 cm (1.4 GHz) line becoming powerful cosmology probe
- Hydrogen abundant, not much confusion from other lines
- A "forbidden" transition, ~10 Myr lifetime of excited state => observed frequency gives good measurement of redshift of emission

$$1+z = \frac{1420}{\nu_{obs}\,(\text{in MHz})}$$

- Can use 21 cm line to study history of matter and growth of structure in universe

Baryon acoustic oscillations: CMB and galaxies

Imprints left by the baryon-photon plasma oscillations prior to decoupling

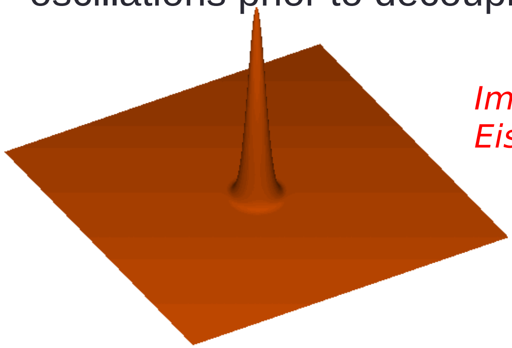
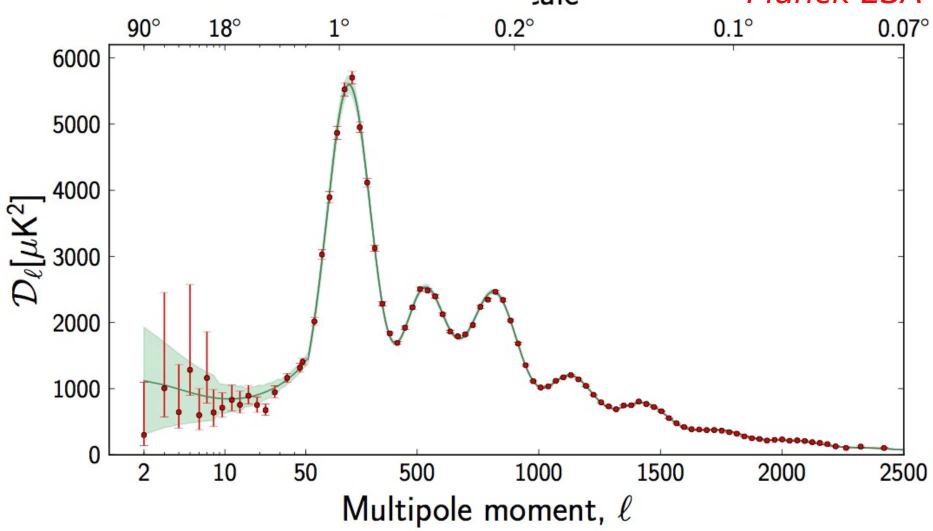


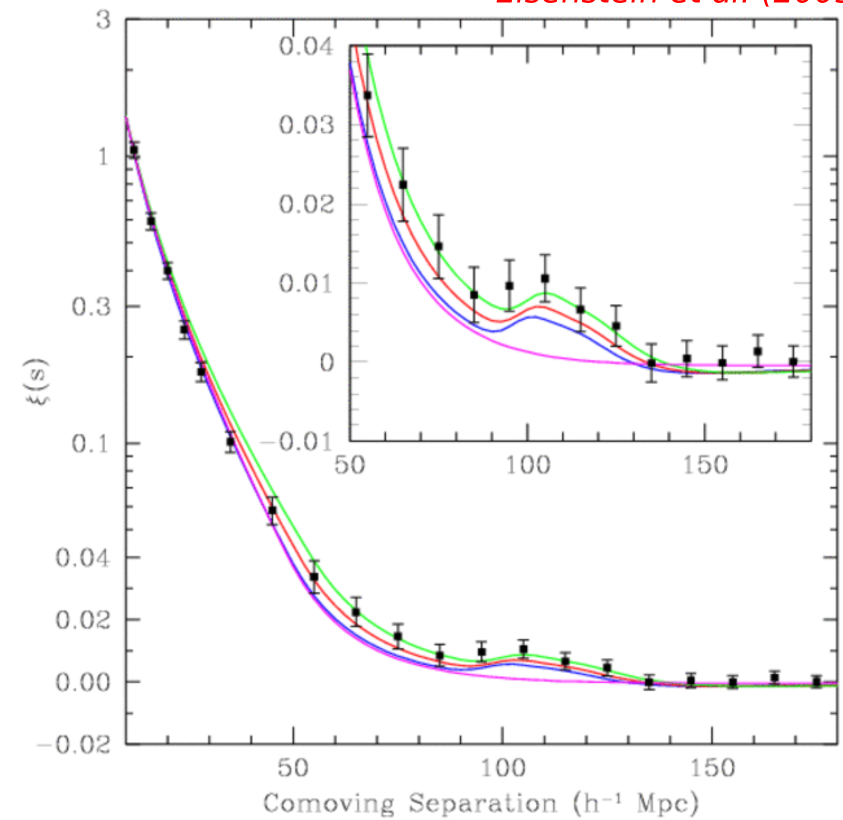
Image : Daniel Eisenstein

Planck ESA



Effects on dark matter and visible matter (galaxies) during structure formation after decoupling

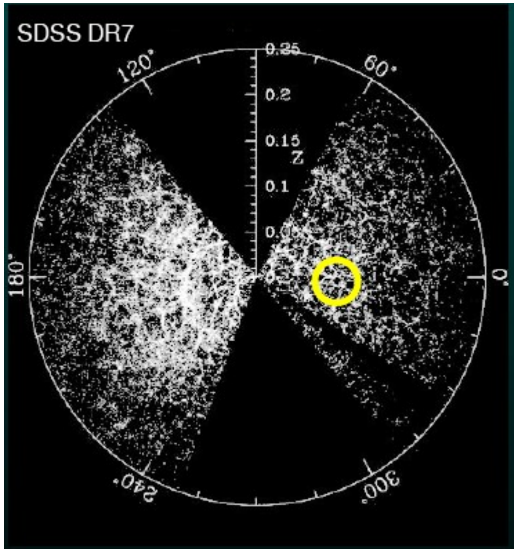
Eisenstein et al. (2005)

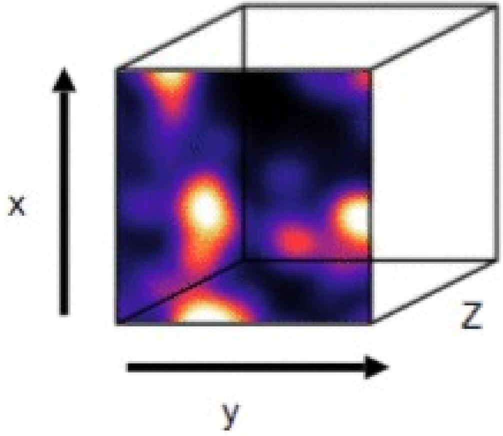


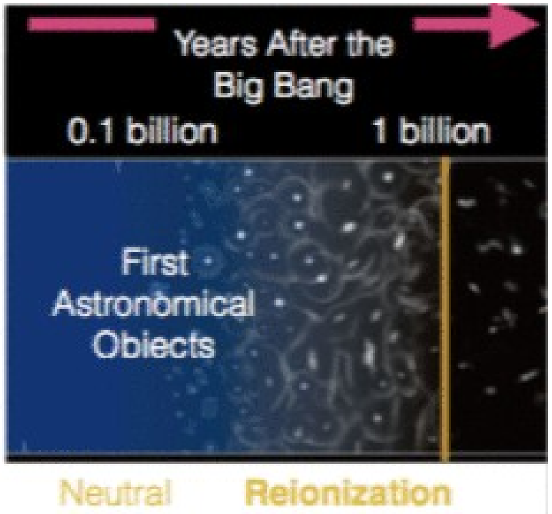
- BAO scale provides a **standard ruler*;*** same comoving length scale is observed over many epochs
- Observed angular scale over different redshifts provides geometric measure of expansion history: At late times, particularly useful for **dark energy constraints (0.8 < z < 2.5)**

BAOs with 21 cm intensity mapping

- Large volumes (large sky, large z range) required for precision cosmology
- 150 Mpc scale ~ degree scale, large spectroscopic survey
- Counting individual galaxies is hard, and getting to high redshifts is challenging
- Hydrogen 21 cm line can be used. Very faint per galaxy.
- Instead, stack up signal from many galaxies with low resolution survey - **HI intensity mapping** to measure matter distribution & obtain redshift information.





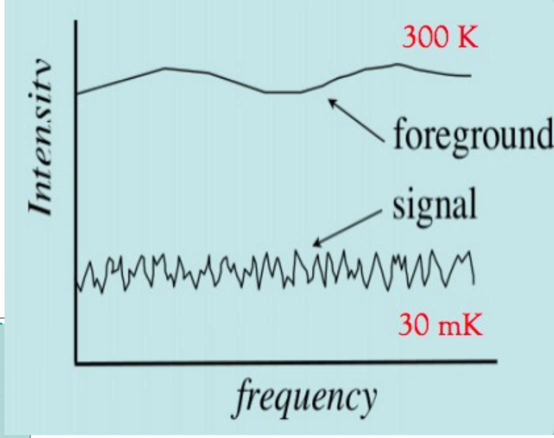


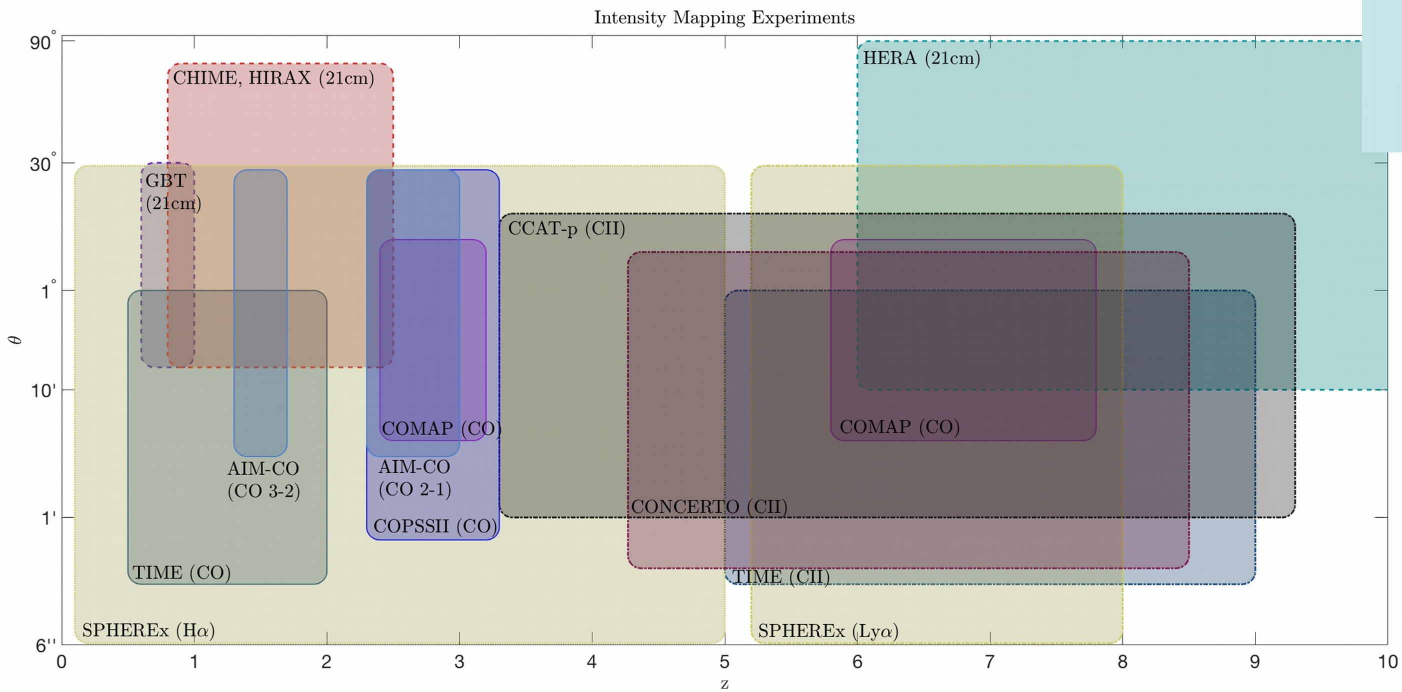
HI intensity mapping

- 21cm emission is treated like a diffuse source, measure the collective emission from a large region, without spatially resolving down to galaxy scales. 3D map of the HI density.

- Use spectral lines as tracers of structure over cosmological volume, retain high frequency resolution thus redshift information

- Foregrounds can be removed by filtering in frequency structure than the foregrounds)





- Single dish experiments: GBT, BINGO, FAST

- Radio interferometers: CHIME, HIRAX, HERA

Line-Intensity Mapping: 2017 Status Report - E. Kovetz

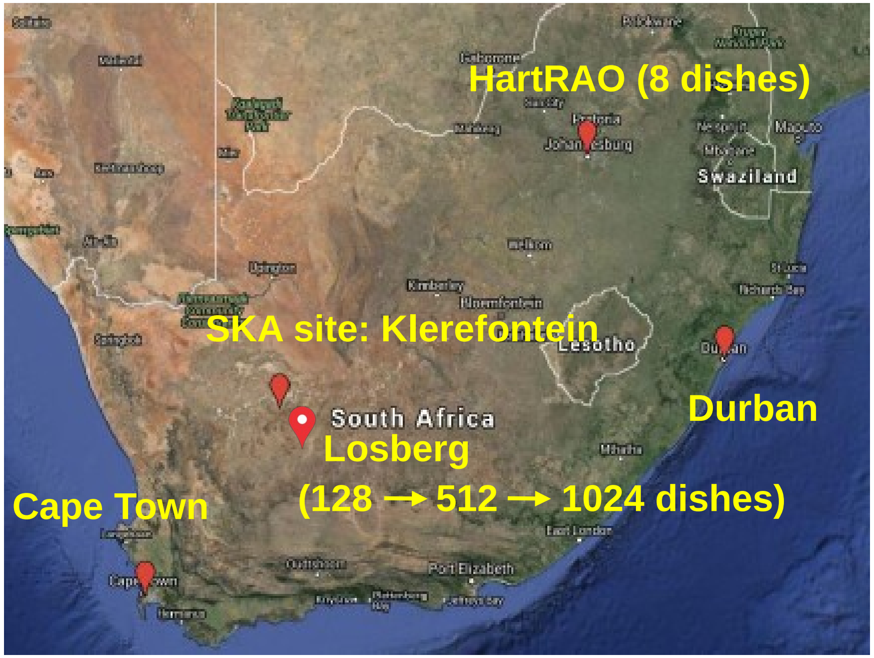
The Hydrogen Intensity and Real-time Analysis eXperiment

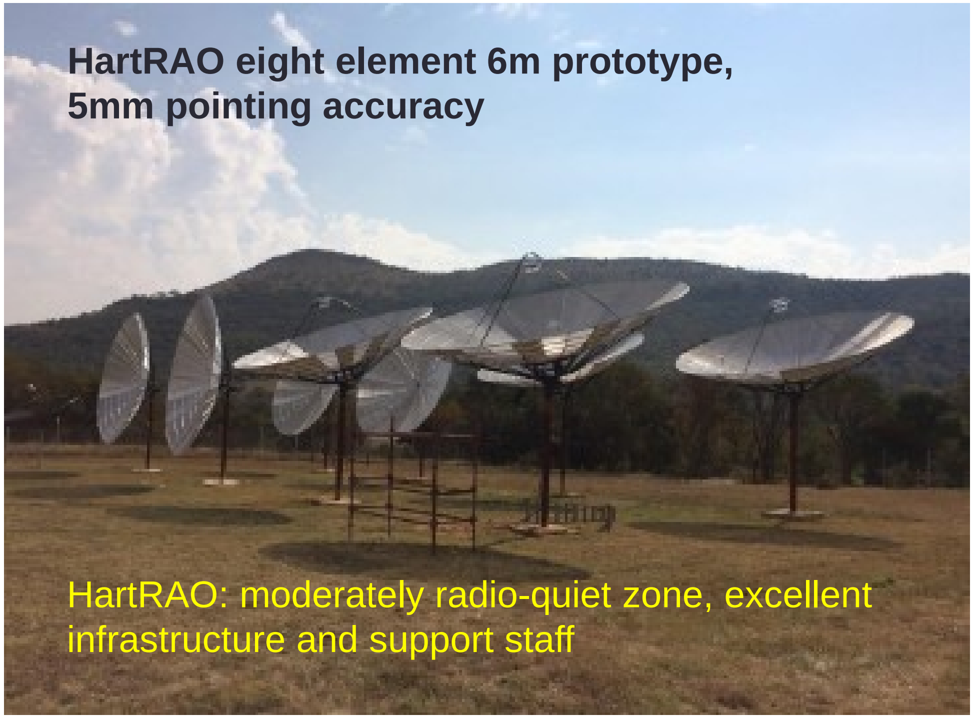
Rock hyrax/dassie

- 1024 closely packed 6 m stationary dishes (can be manually tilted)
- Survey area ~ 15,000 deg^2, daily sensitivity 12 Jy, repoint every 150 days, 4 years for full survey
- **Measure BAOs to characterize dark energy**
- Radio transients + pulsar searches ***(talk by Jon Sievers)***
- Neutral hydrogen absorbers, diffuse polarization of Galaxy

Frequency range	400 – 800 MHz (0.8 < z < 2.5)
Frequency resolution	390 kHz, 1024 channels
Dish size	6 m diameter
Interferometric layout	32x32 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

HIRAX: Location and status





HIRAX

http://www.acru.ukzn.ac.za/~hirax

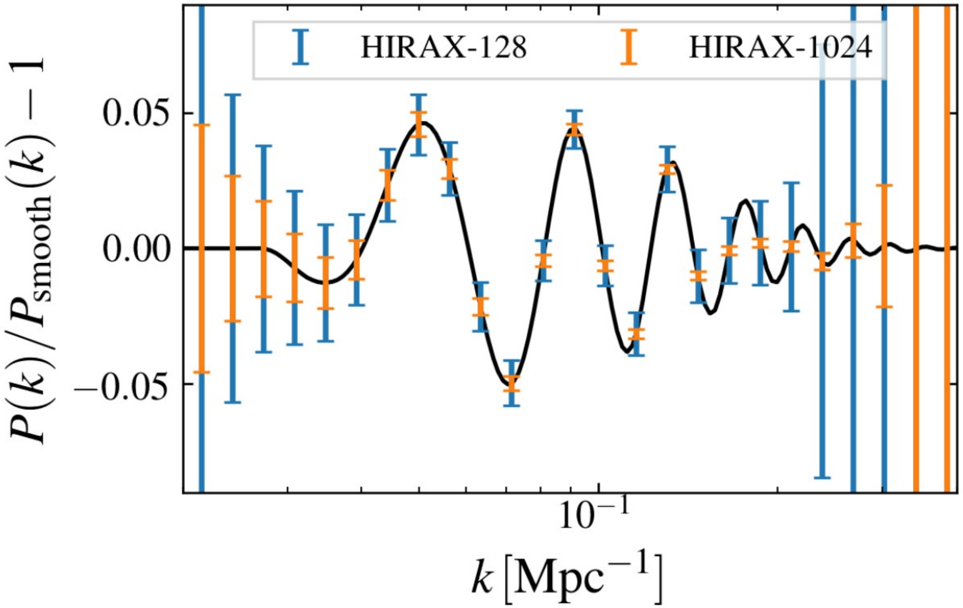
Complementarity with the Canadian Hydrogen Intensity Mapping Experiment (CHIME)

	CHIME	HIRAX
Site	DRAO, Canada	South Africa (lower RFI, no snow)
Telescope	Cylinder array	Dish array (easier to baffle)
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

Optical surveys in the south, esp. LSST: cross-correlate for foreground mitigation and other science. More pulsars in the south.

BAO cosmology with HIRAX

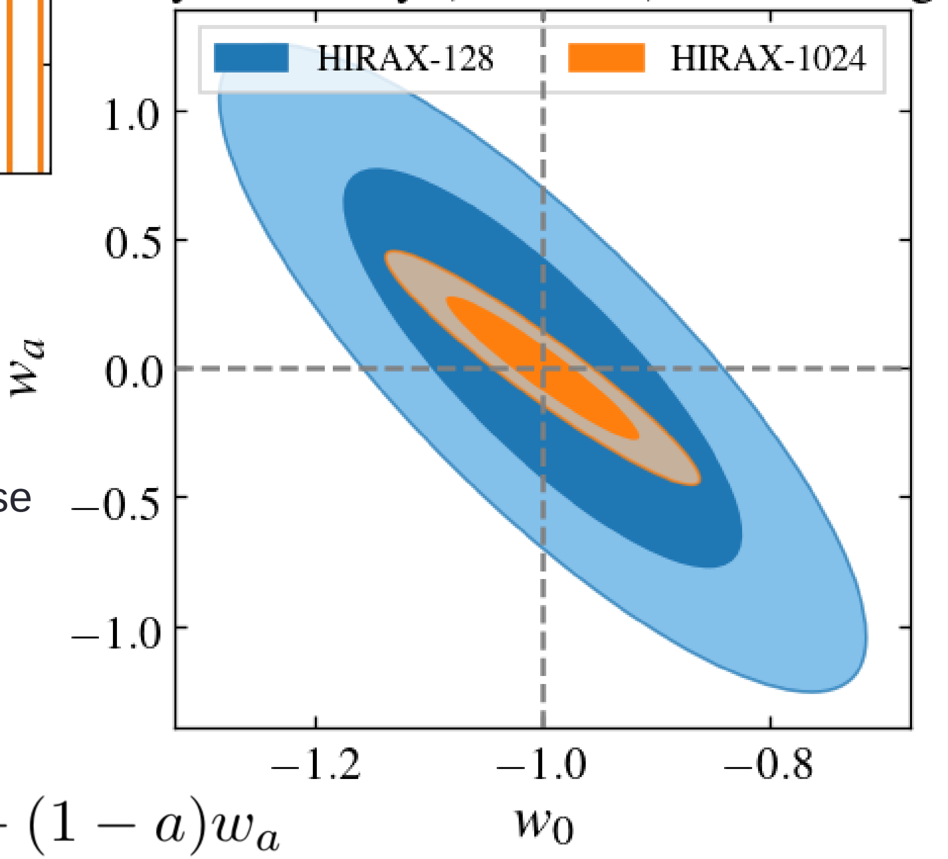
*Preliminary, naive noise



$$P(k) = \left[1 + Af_{\rm bao}(k)\right]P_{\rm smooth}(k)$$

Planck 2015 Prior

4 year survey (50% eff.); 15,000 deg^2



Dark energy task force Figure of Merit (inverse area of w_0, w_a contours) comparable to e.g. CHIME, ~300

Analysis: Devin Crichton

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

Analysis & Sims Pipeline: m-mode method

For cosmology and map-making, use m-mode analysis *(Shaw et al. arXiv: 1302.0327, 1401.2095)*

- Linearizes a drift-scan interferometer wrt harmonic (l, m) coefficients of the sky; for each m-mode:

$$\boldsymbol{v} = \mathbf{B}\,\boldsymbol{a} + \boldsymbol{n}.$$

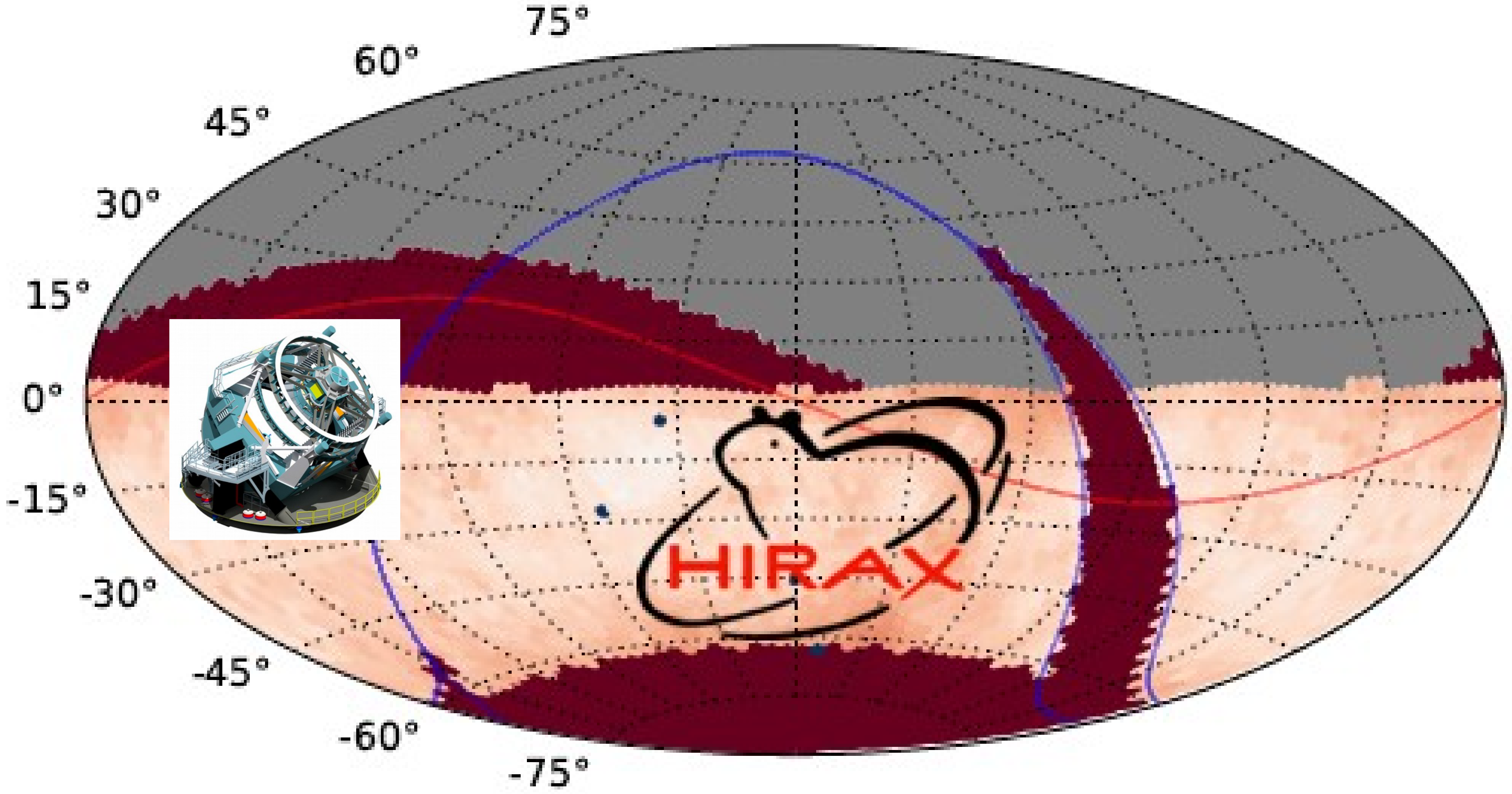
Data	Instrument and sky rotation	Sky
$(\boldsymbol{v}_m)_{(\alpha\nu)}$	$(\mathbf{B}_m)_{(\alpha\nu)(l\nu')}$	$(\boldsymbol{a}_m)_{(l\nu)}$

- Relates m-modes, the Fourier components of visibilities as a function of time/R.A. to spherical harmonic coefficients ; bypasses UV plane for full sky treatment, ideal for wide-field, transit instruments

- For HIRAX $(\mathbf{B}_m)_{(\alpha\nu)(l\nu')} \longrightarrow$ (2 x $N_{baselines}$ x N_{bands}) x (~2000 x N_{bands}) matrix.
  - In practice, bands can be split into sub-bands that are analysed separately
  - Each m-mode has an independent mapping, can parallelize simply across m-modes
  - Matrix can be decomposed using e.g. SVD and less significant mappings can be discarded.
  - Allows for natural filtering of foregrounds by conservatively down-weighting foreground dominated modes using Karhunen–Loève (KL) filter.

Inputs from Devin Crichton

Cross-correlations of HIRAX & Large Synoptic Survey Telescope (LSST)



Case for radio-optical cross-correlations

- **1st detections of the 21cm IM** signal, GBT x WiggleZ - *Chang et al 2010, Masui et al 2013*

$$P_{\mathrm{HI,g}}(k,z) = \bar{T}(z) b_{\mathrm{HI}} b_g P(k,z)$$

$$\Omega_{\mathrm{HI}} b_{\mathrm{HI}} r = [0.43 \pm 0.07(stat.) \pm 0.04(sys.)] \times 10^{-3}$$

- **Complementary physical constraints, cross-confirmation of results** and **mutual support**
  - LSST is able to provide photometric redshifts for HI continuum survey
  - HIRAX HI redshifts can calibrate LSST photo-z, using cross-correlation
- **Removal of systematics** by cross-correlation - *Morales 2006, Brown & Battye 2011*
- Cross-correlation of 21cm IM surveys with galaxy surveys can help us understand
  - how hydrogen is distributed in galaxies (e.g. Wolz et al 2017), and
  - the correlation between hydrogen and tracer galaxies (e.g. Pourtsidou et al 2015, 2016).
  - Cross-correlation with photometric surveys e.g. LSST can provide photo-z calibration (Alonso et al 2017).

HI auto-correlations

Bull et. al. 2015

RSD

$$\delta T_{21}(\vec{k}; z_c) = \bar{T}(z_c)[b_{HI} + f\mu_k^2]\delta_m(\vec{k})$$

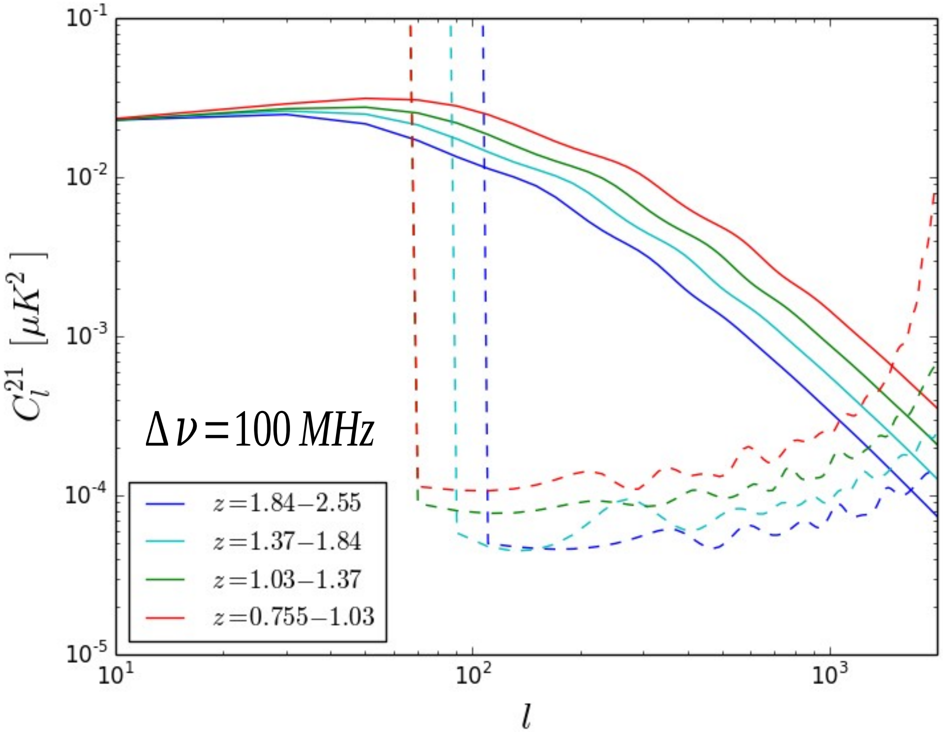
HI bias = $a_0 + a_1 z + a_2 z^2$

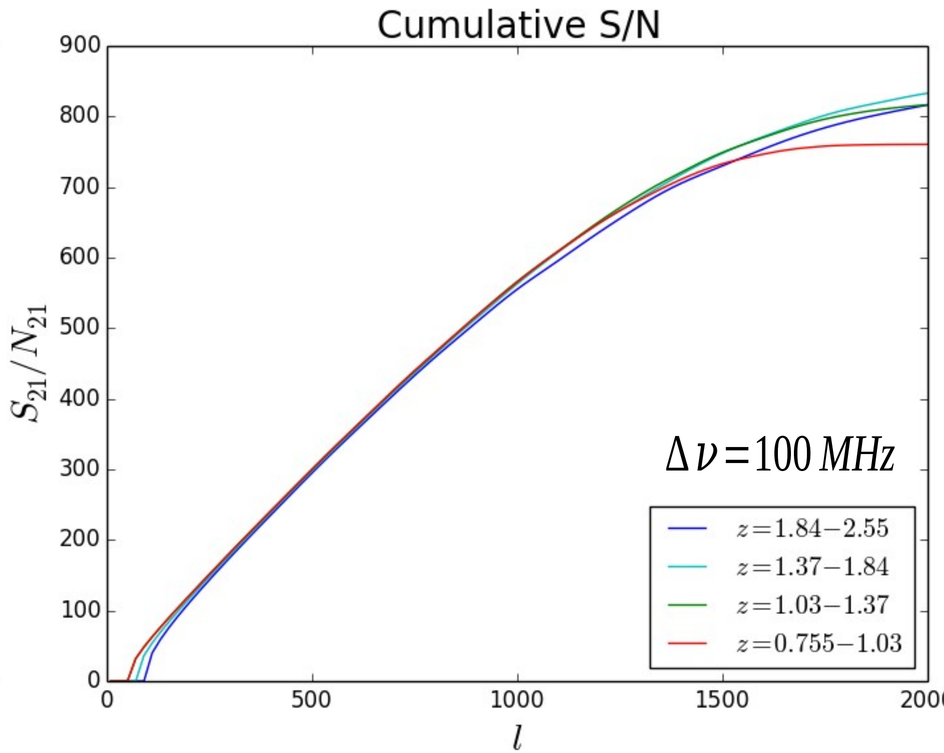
$$P_{21}(\vec{k}; z_c) = \left(\bar{T}(z_c)[b_{HI} + f\mu_k^2]D(z_c)\right)^2 P_m(\vec{k}, z = 0)$$

$$P_N(\vec{k}; z_c) = \chi_{\parallel}^2(z_c) r_\nu \frac{T_{sys}^2 \lambda^4}{A_e^2 \nu_{21} n(u = l/2\pi)}$$

baseline density

$$\left(\frac{S}{N}\right)^2 = 1/2V_{bin} \int \frac{d^3k}{(2\pi)^3} \left[\frac{P_{21}^S(k)}{P_{21}^S(k) + P_N(k)}\right]^2$$

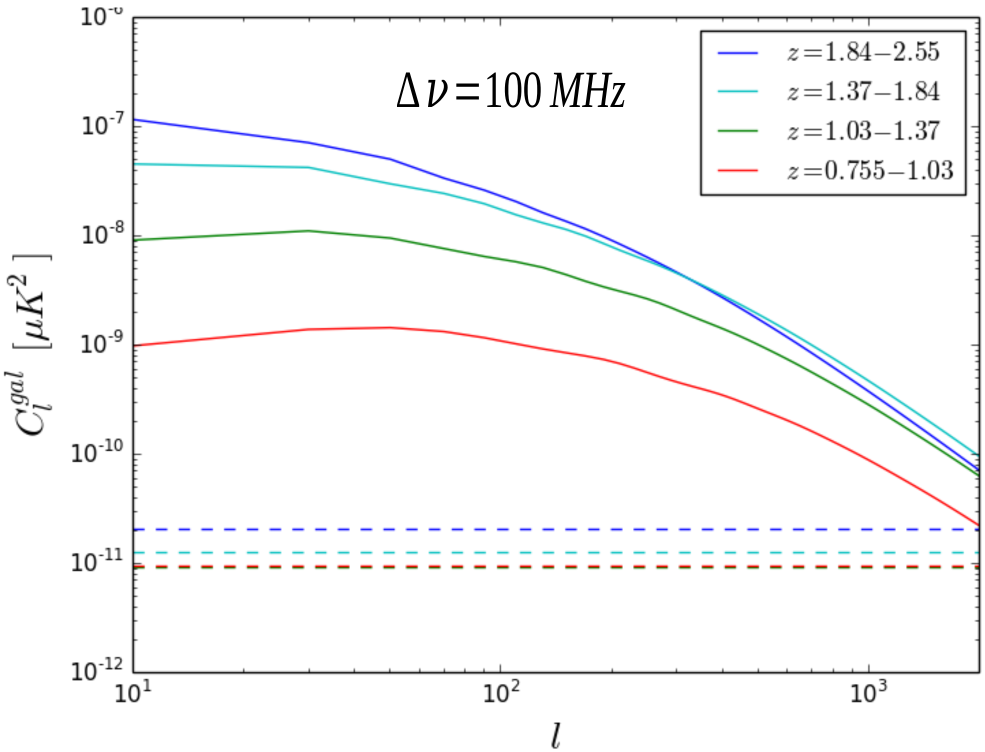


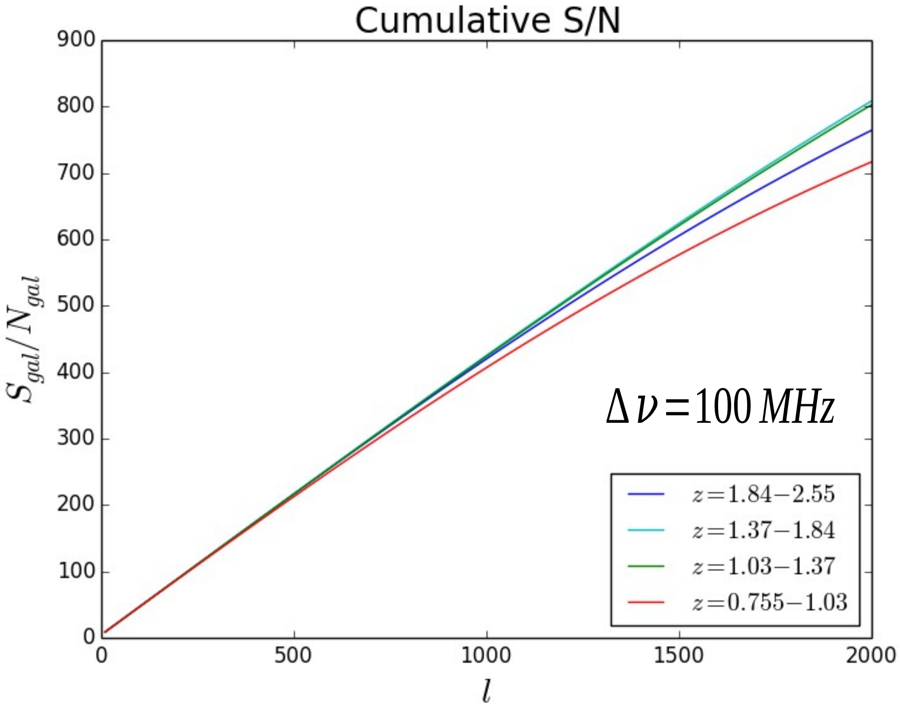


Galaxy auto-correlations

$$P_{gal}(\vec{k}, z_c) = [W_{gal}(\chi_{\parallel}(z_c))D(\chi_{\parallel}(z_c))]^2 P_m(\vec{k}, z = 0)$$

$$P_N^{Shot} = \frac{1}{\bar{n}} = \frac{1}{N_g/V_{sur}}$$





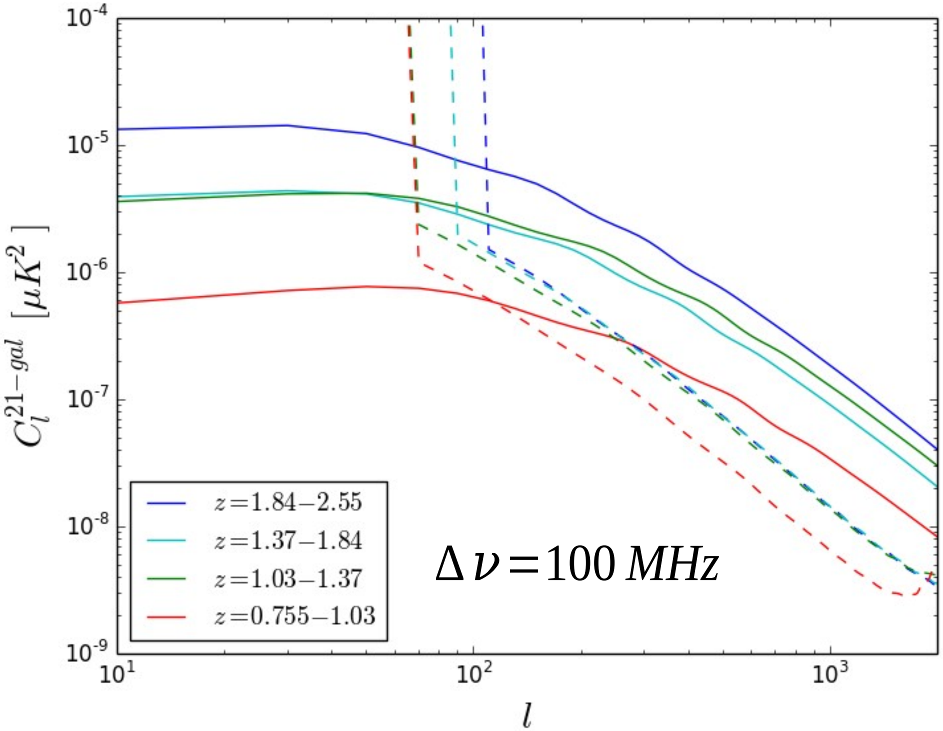
HI-galaxy cross power spectrum

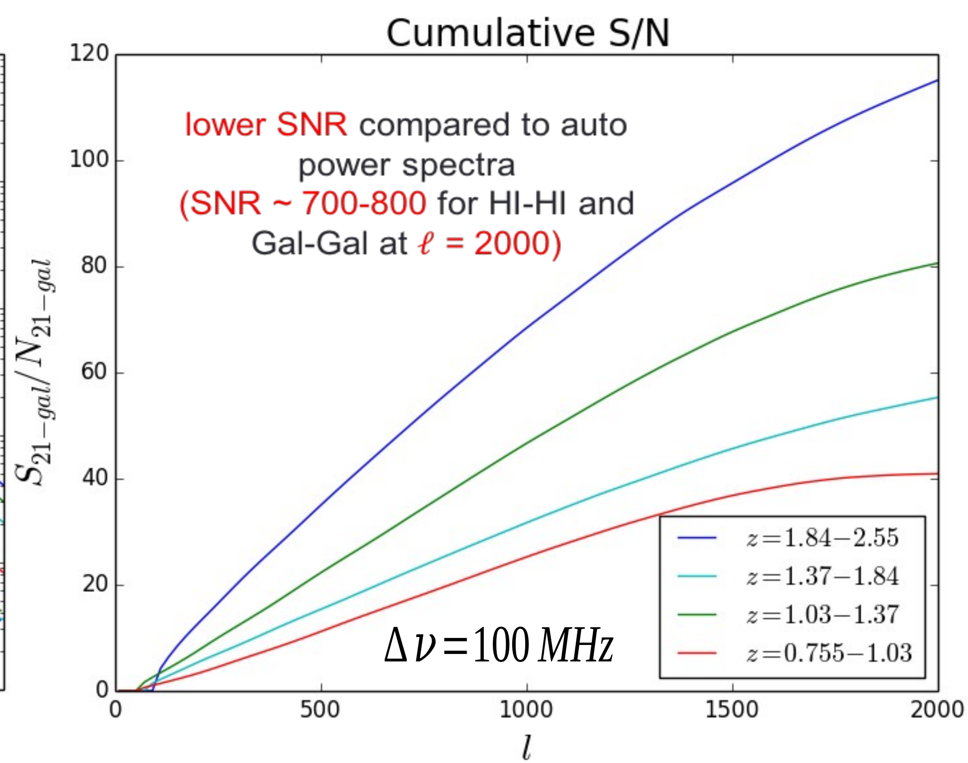
$$P_{21-gal}(\vec{k}; z_c) = r_{21-gal}\bar{T}(z_c)[b_{HI} + f\mu_k^2] D(z_c)^2 W_{gal}(z_c) P_m(\vec{k}; z = 0).$$

$$\delta P_{21-gal} = \sqrt{2\frac{(2\pi)^3}{V_{sur}}\frac{1}{4\pi k^2 \Delta k}}\sqrt{P_{21-gal}^2 + P_{21}^{Tot} P_{gal}^{Tot}}$$

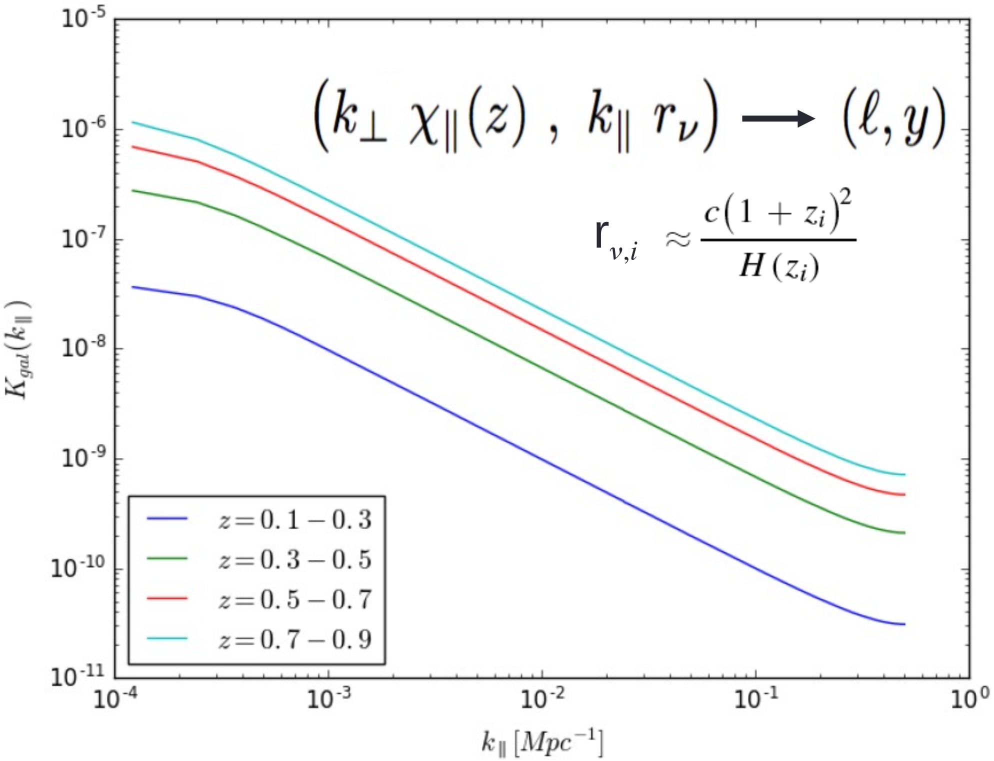
$$P_{gal}^{Tot} = P_{gal} + N_{gal}.$$

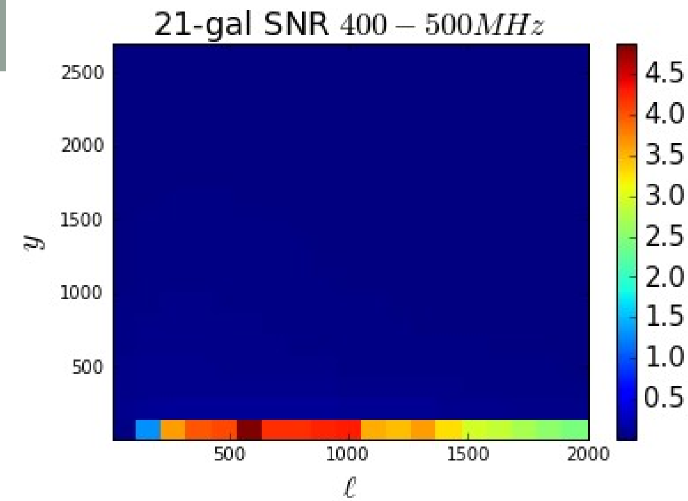
$$P_{21}^{Tot} = P_{21} + N_{21}$$

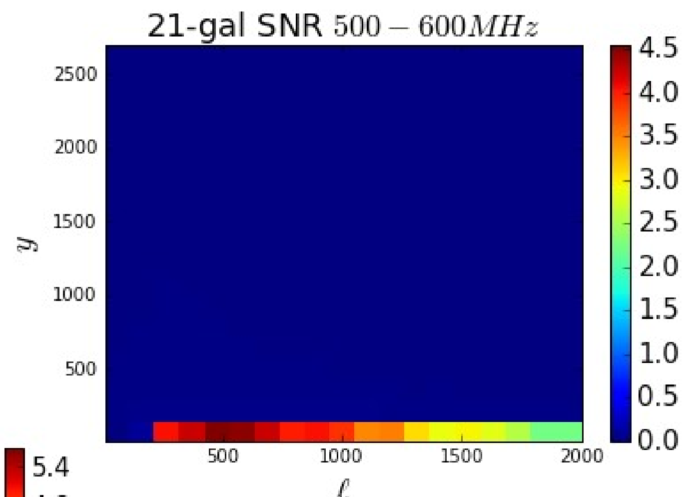


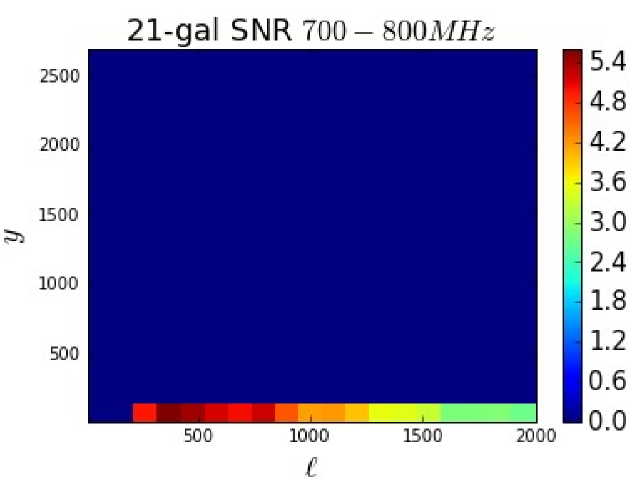


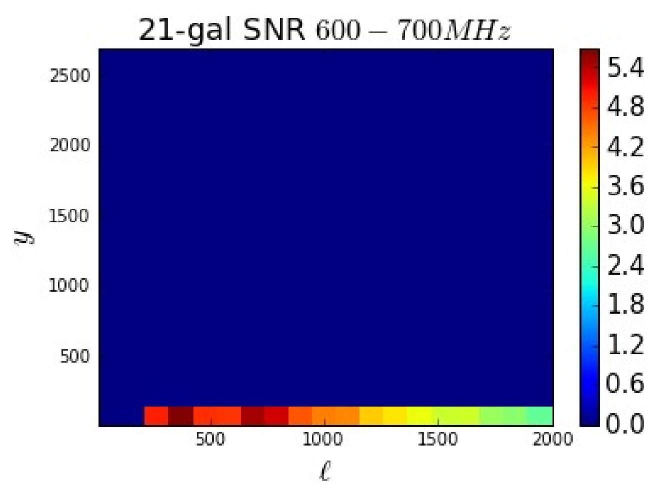
Galaxy kernel in Fourier space





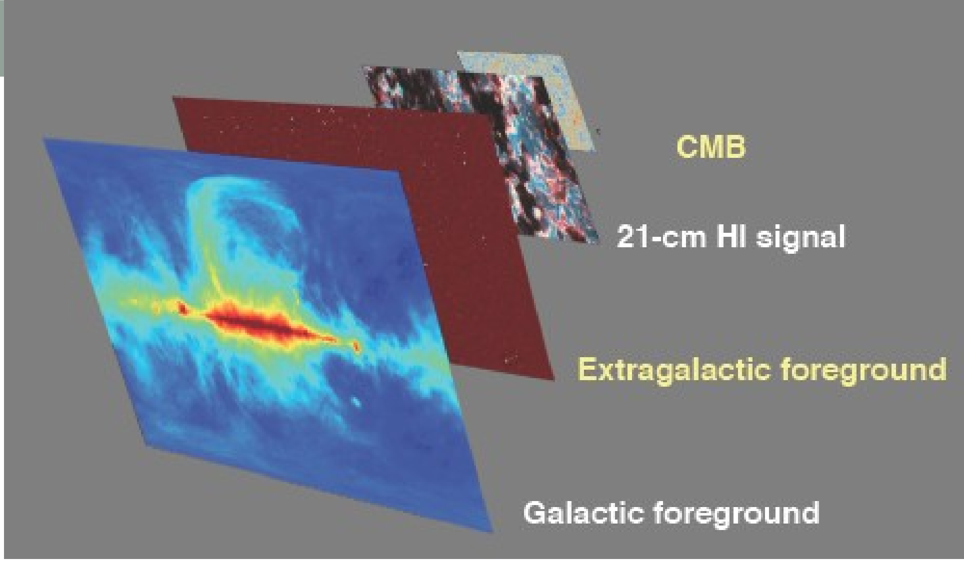






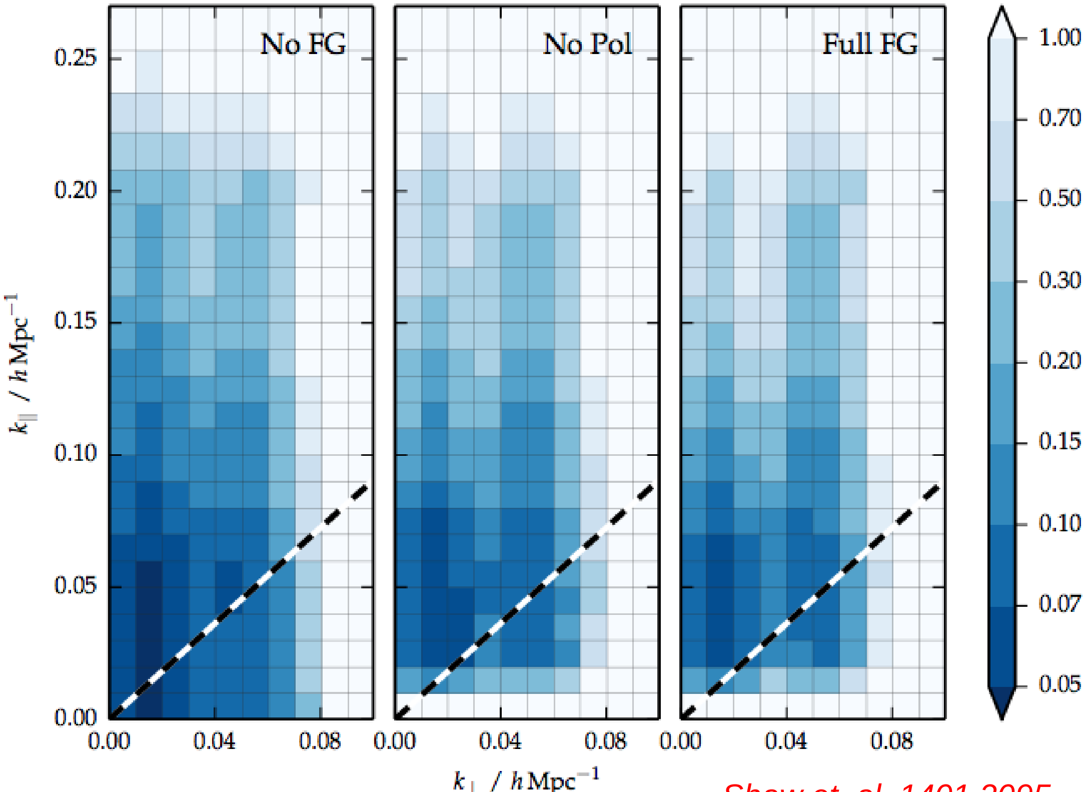
Cross-correlation SNR drops sharply with y as seen in the plots since the galaxy kernel in $k_{parallel}$ space drops quickly

Challenges from foregrounds



Astrophysical foregrounds

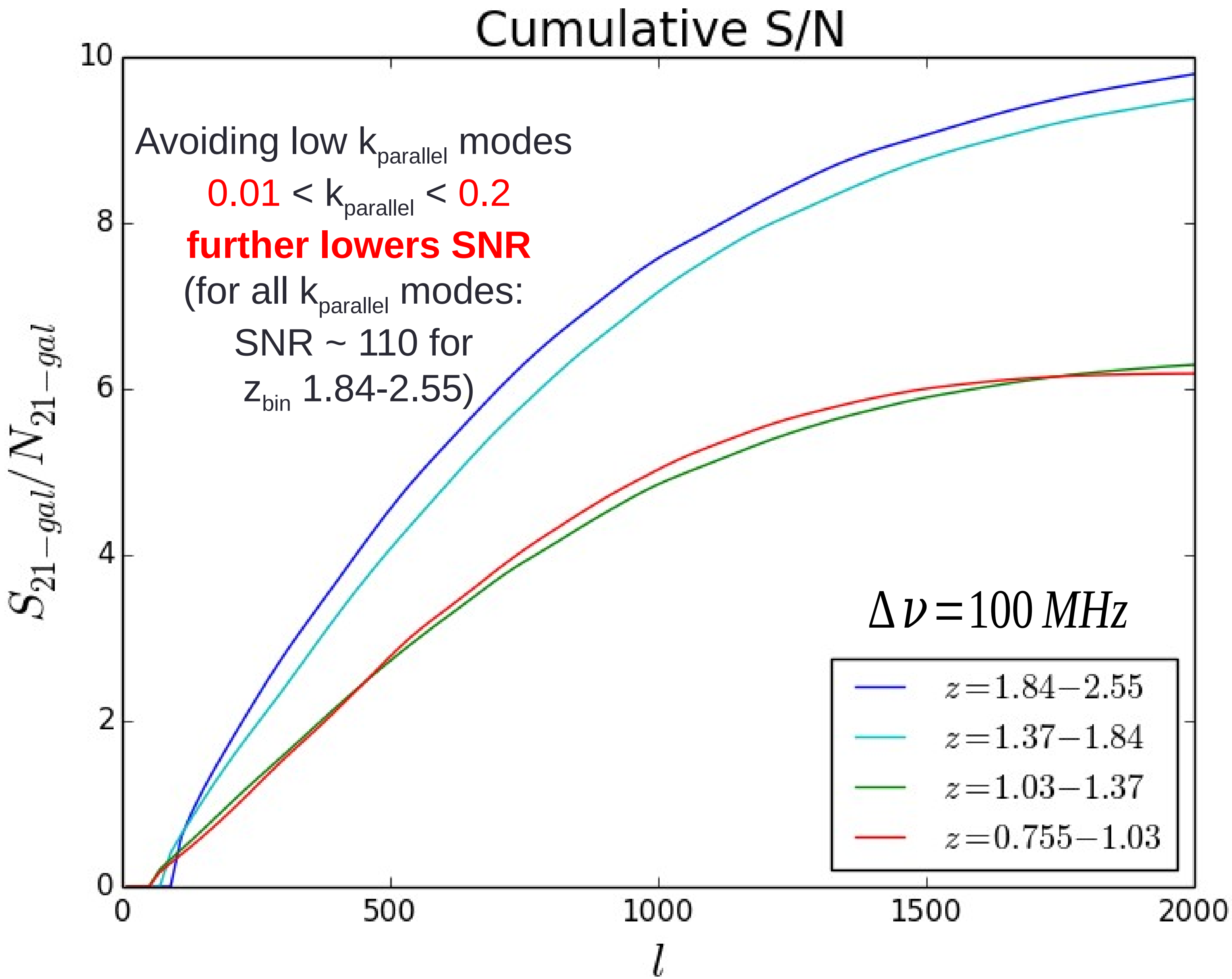
4-5 orders of magnitude
brighter than the 21-cm signal



Shaw et. al. 1401.2095

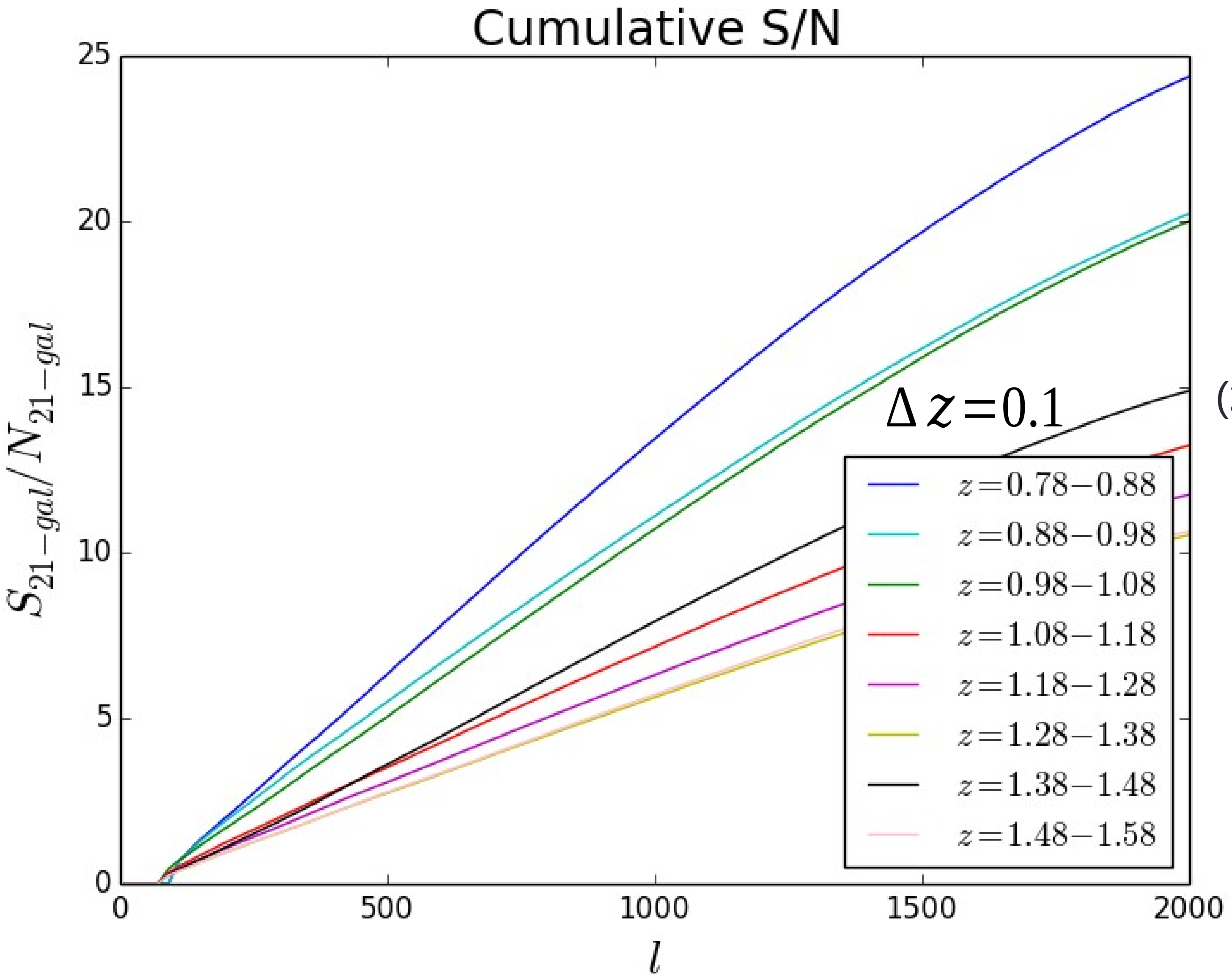
- Foregrounds contaminate the large scale frequency modes (small $k_{parallel}$)
- Removal relies on fact that smooth spectrum foregrounds are limited to region below k-space "wedge", while line emissions have power that extends beyond wedge.
- Dominant effect of foreground removal is that we become insensitive to power at low $k_{parallel}$
- **Avoid $k_{parallel}$ < 0.01 Mpc^{-1}**

Effect of foregrounds on cross-power spectrum



Effect of foregrounds

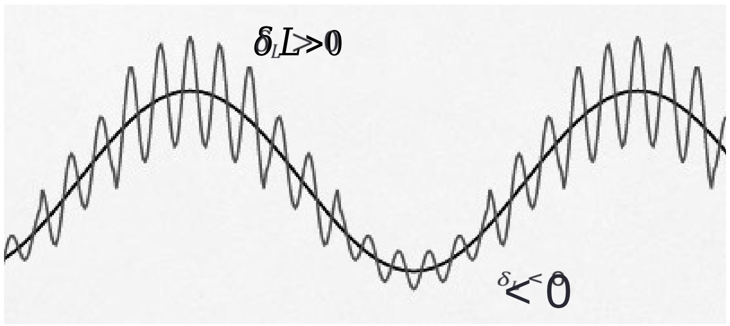
Choosing an optimum redshift bin (here $\Delta z = 0.1$) SNR can be slightly improved



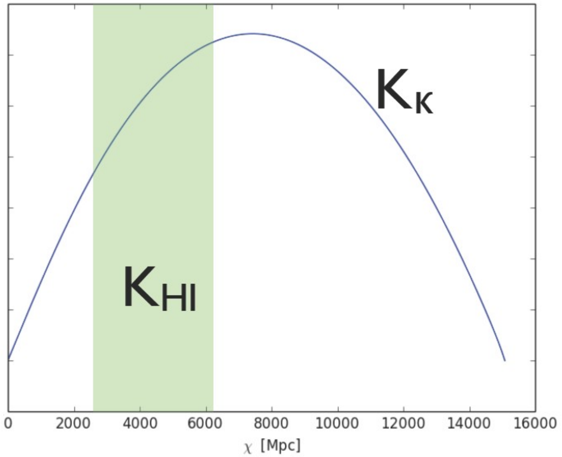
Instead of using power spectrum (2-point correlation function) use bispectrum (3-point correlation function)

Higher order correlations: bispectrum

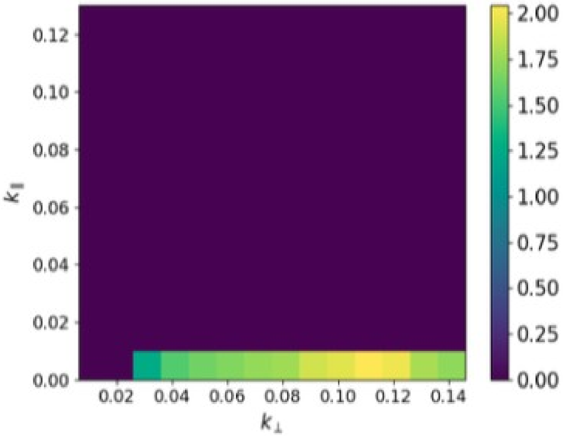
- Construct a bispectrum estimator <δ_g δT_{21} δT_{21}> - relies on modulation of two small-scale 21cm modes coupled by a long-wavelength large-scale mode; recover the line-of-sight matter modes on large scales that are required for correlation
- Relies on good spectral resolution (> 1000 channels) of upcoming 21cm IM surveys.



Density fluctuations are higher in regions with a higher background over-density

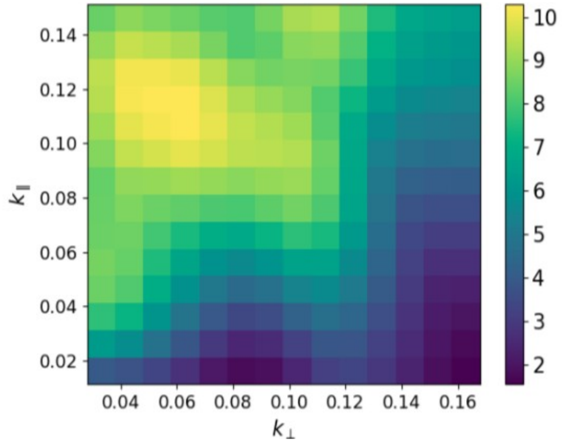


Good redshift overlap between **CMB lensing** and **21cm IM**



HI-κ SNR

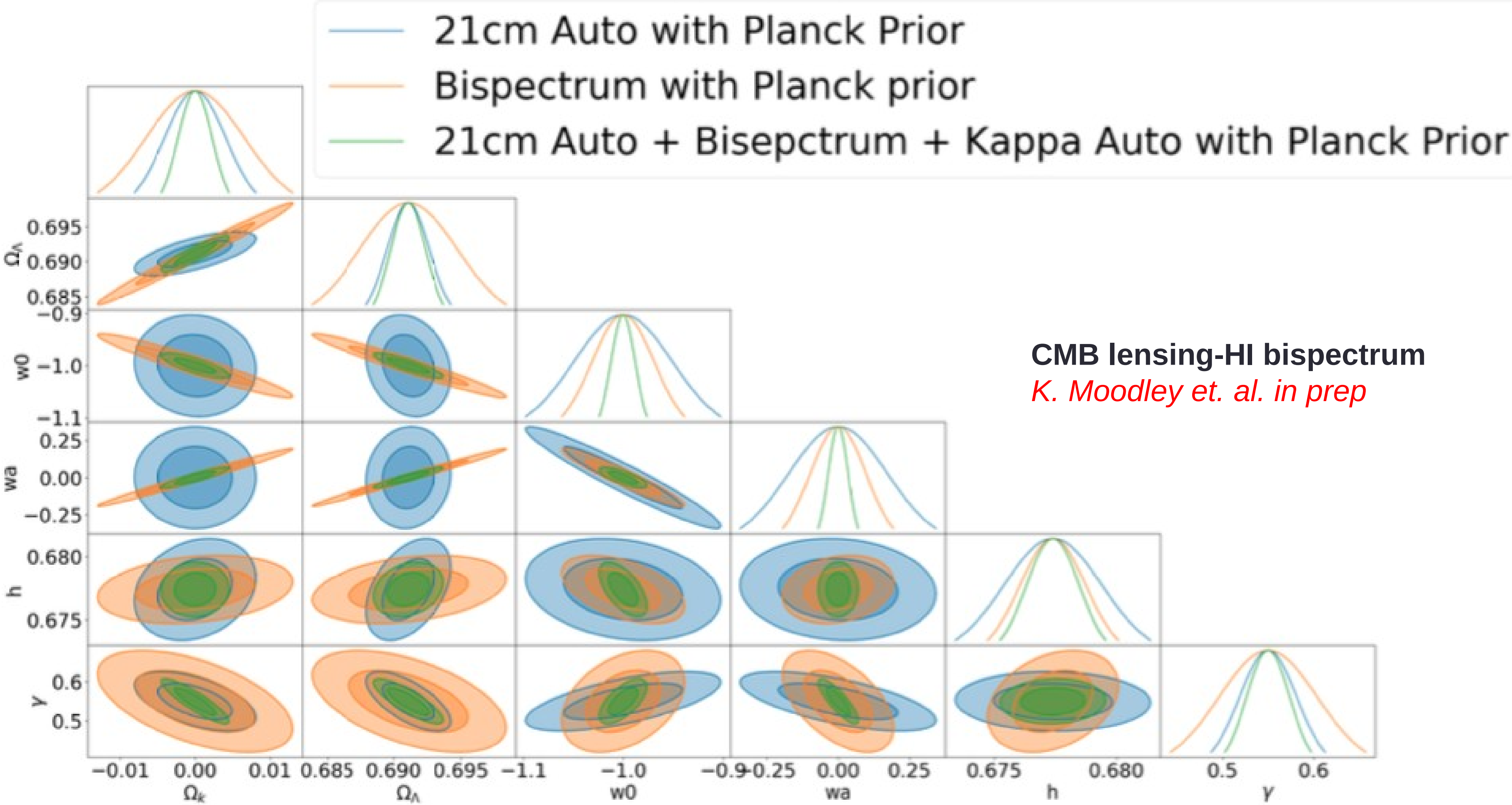
HI-HI-κ SNR



CMB lensing-HI bispectrum

K. Moodley et. al. in prep

Higher order correlations: bispectrum (HI-HI-κ)



CMB lensing-HI bispectrum
K. Moodley et. al. in prep

Work in progress - galaxy-HI bispectrum

Status and summary

- Intensity mapping cross-correlation with LSS - robust way to test cosmological parameters
- Cross-power spectrum – loss of SNR due to sharp drop in galaxy kernel in $k_{parallel}$ space
- Challenges with foregrounds, avoiding low $k_{parallel}$ modes, further loss of SNR in cross-power spectra
- Optimum choice of redshift bin-width – slight improvement in SNR
- Use bispectrum to recover large modes which are lost in foreground removal
- HIRAX approved by National Research Foundation (NRF), funded through 128-elements
- Next stage: Build out to 128-elements in Karoo beginning in 2019

Thanks!