The role of HI & Continuum radio surveys in cosmology

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UWC ASTROPHYSICS

SKA AFRICA
SQUARE KILOMETRE ARRAY

Big questions in Cosmology

- Why is the expansion of the Universe accelerating? Dark energy? Modified gravity?
- What is the nature of the primordial Universe? Inflation? Is the primordial spectrum of perturbations non-Gaussian?
- Does the General Theory of Relativity really applies to cosmological scales, or does it needs modification?
- Is the Universe really isotropic and homogeneous? Is the Universe really flat?

What can we use in the radio?

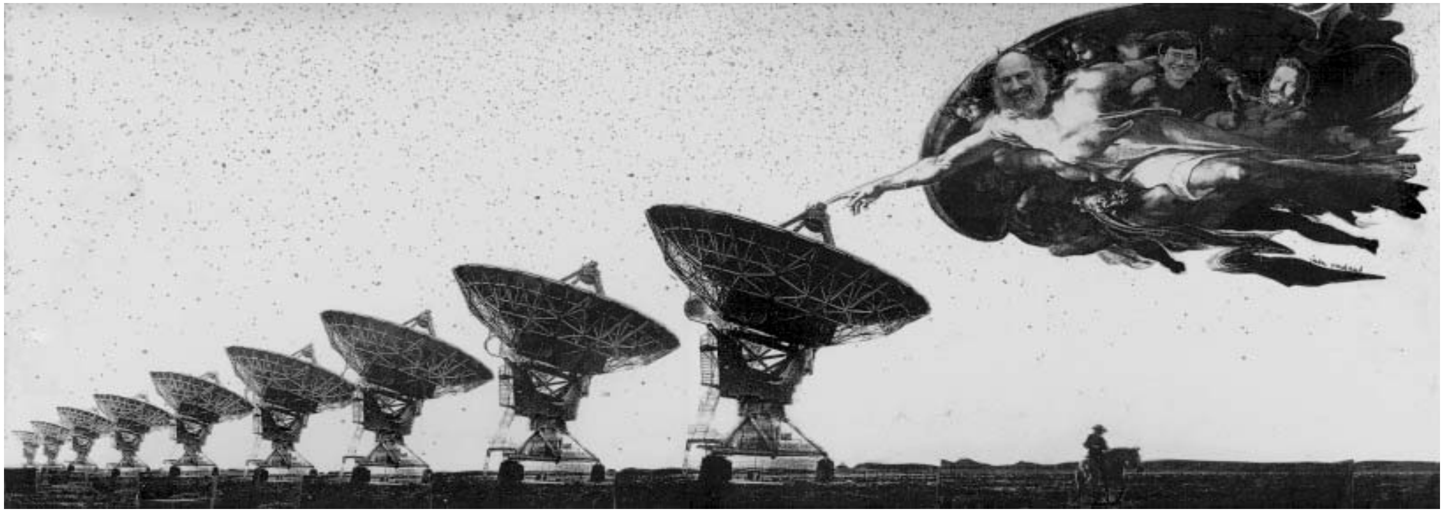
- Continuum radio galaxy survey
- HI galaxy survey
- HI intensity mapping survey

I: Cosmology with galaxy continuum surveys

Mario Santos, UWC, Bologna 2015

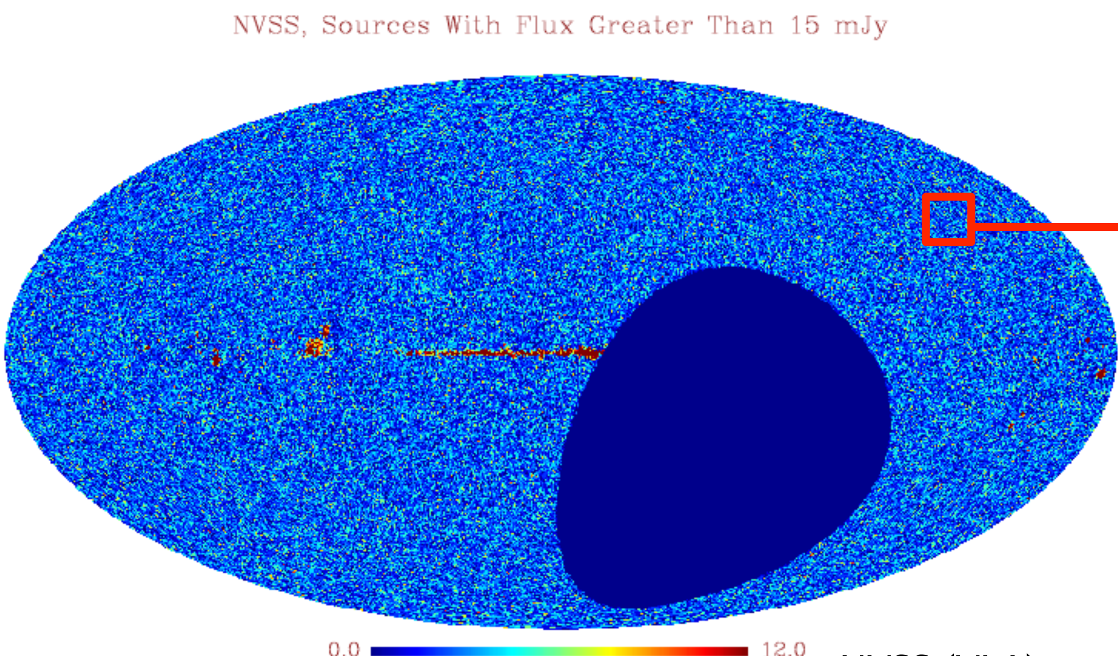
Continuum?

- Advantage: Strong signal – large number of galaxies
- Disadvantage: no redshift information
- Example: The VLA FIRST Survey (1994 – …)
    - 10,000 deg^2; 0.15 mJy; $9x10^5$ galaxies
    - 128x2 MHz channels – averaged over 256 MHz



Basic probe: galaxy number counts

- Count the number of galaxies in each pixel
- Look at the fluctuations in the number – take the 2-point correlation function – should trace the dark matter



$$\frac{\delta n}{\bar{n}} = b\delta_m + \delta_p$$

Galaxy bias

Poisson fluctuations

Galaxy number fluctuations

Matter density fluctuations

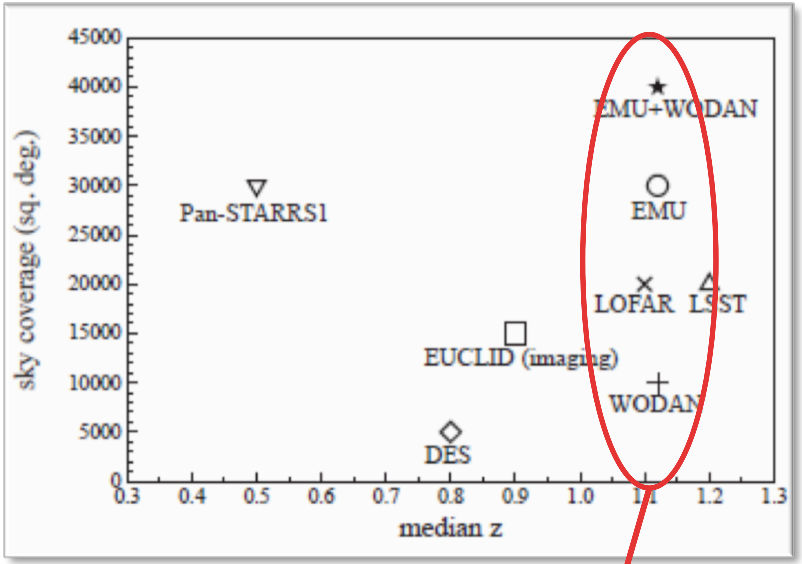
NVSS (VLA) continuum survey
Each point represents a galaxy

Example: Cosmology with SKA Pathfinders

- Use large radio continuum surveys: EMU, WODAN, LOFAR, MeerKAT?
- No redshift information – success due to large number of sources, sky area and median redshift ~ 1

Survey	Frequency	N_{gal}
LOFAR MS^3 10σ	150 MHz	1.0×10^6
LOFAR MS^3 5σ	150 MHz	2.0×10^6
LOFAR Tier1 10σ	120 MHz	6.5×10^6
LOFAR Tier1 5σ	120 MHz	1.5×10^7
EMU 10σ	1400 MHz	2.2×10^7
EMU 5σ	1400 MHz	5.4×10^7
WODAN 10σ	1400 MHz	7.3×10^6
WODAN 5σ	1400 MHz	1.8×10^6

Needs updating!

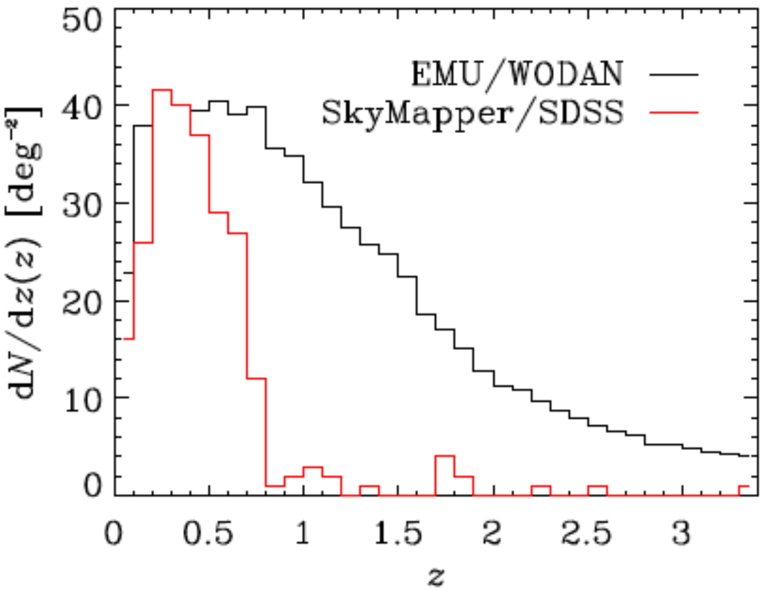


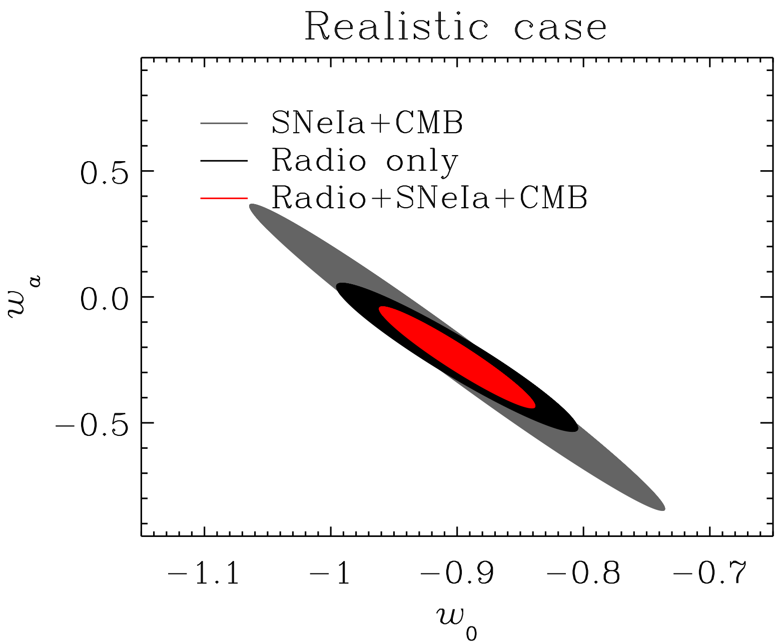
Most of radio-galaxies at high-z

- SKA1 should detect ~ 20 times more galaxies ~ 5×10^8

Constraints on dark energy with SKA pathfinders…

- Cross correlate with low z (< 0.8) photometric survey to split radio galaxies into low-z and high-z bins

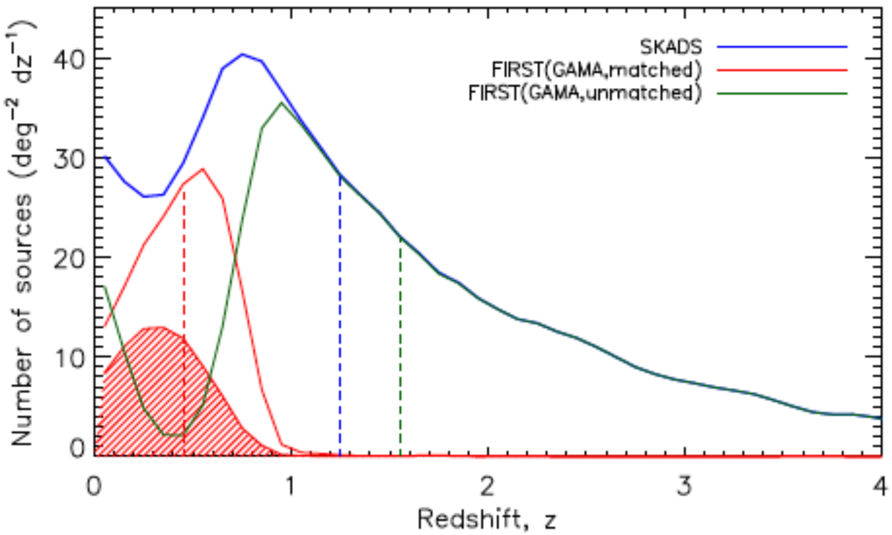




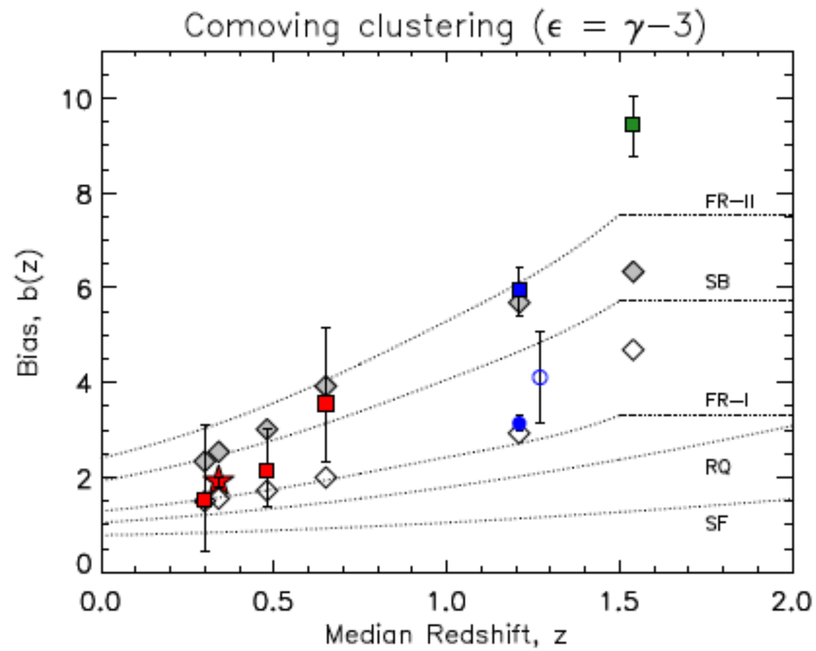
Camera, Santos, et al., MNRAS 2012

Galaxy bias?

- Crucial to have accurate (<10%) measurements of *n(z)*b(z)* for cosmology (up to a constant amplitude at least)
- Need deep radio continuum surveys matched to other data for redshifts



n(z)

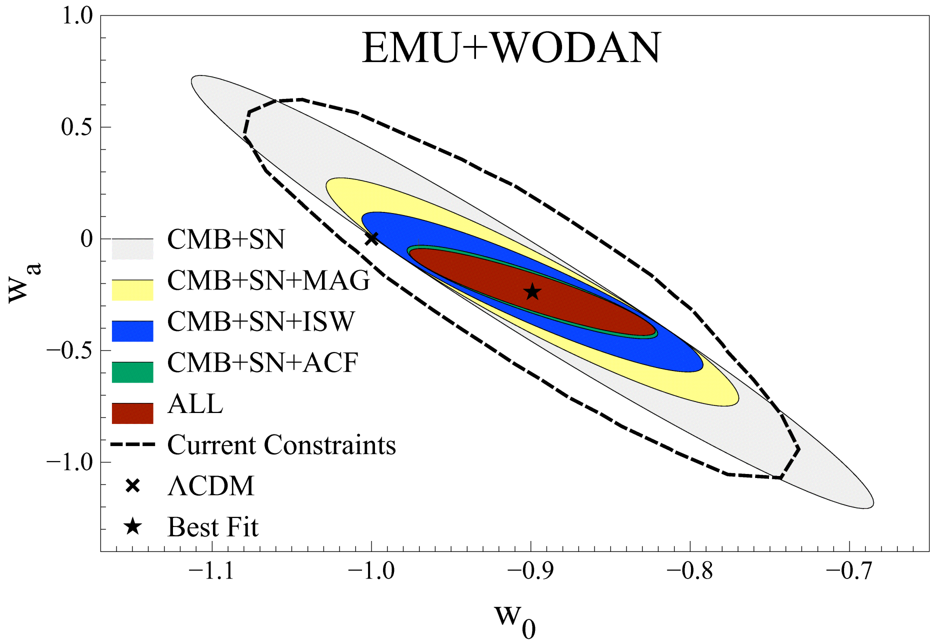


b(z)

Lindsay et al., MNRAS 2014

Combining with other probes

- ISW (Integrated Sachs-Wolfe) – Correlation with the CMB
- Cosmic Magnification – Correlation with galaxy surveys at lower redshifts (use optical galaxies as foregrounds)
- Improve constraints on dark energy equation of state (w_0, w_a)



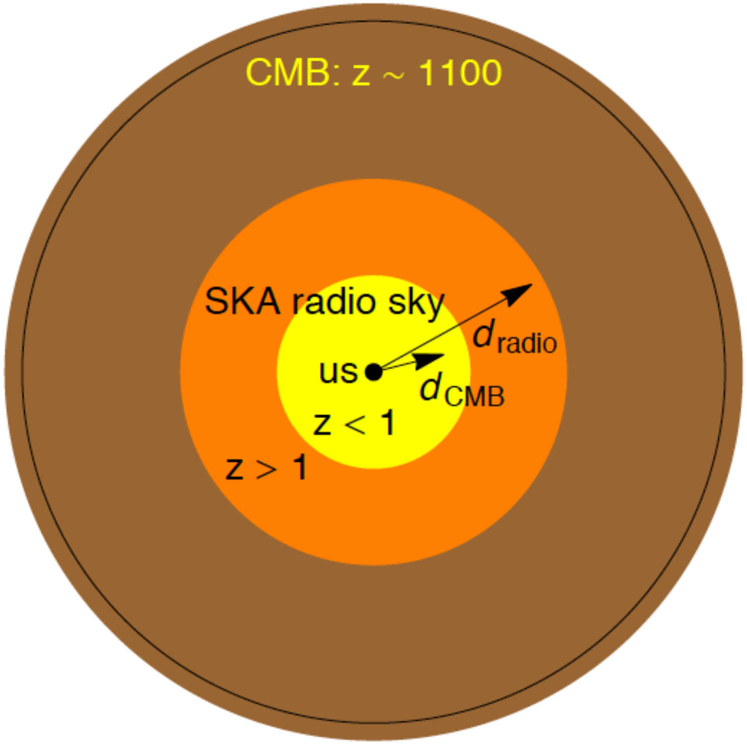
Raccanelli et al, MNRAS 2012

Cosmology with SKA1 – MID continuum

- Survey ~ 25,000 deg^2
- Frequency ~ 1 GHz
- Resolution? Need ~ 0.5 arcsec resolution for morphological classification of sources
- flux sensitivity ~ 1 uJy rms (~10,000 hours)
- ~ $5x10^8$ galaxies, mostly star-forming

SKA1 and large scales: testing the Cosmological Principle using galaxy counts

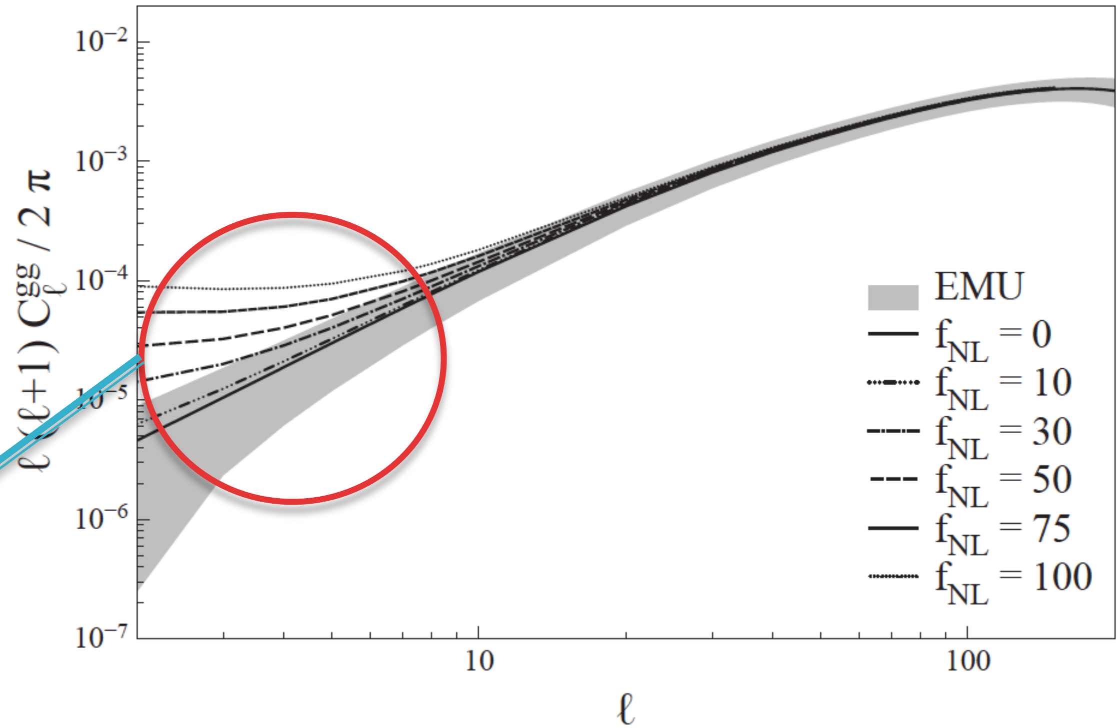
- Tests of isotropy (CMB anomalies?)
- Test if the cosmological dipole (with radio-galaxies) is the same as the CMB one
- Reach a few degrees precision with SKA1



D. J. Schwarz, et al., PoS(AASKA15), SKA chapters, 2015

SKA1 and the nature of primordial fluctuations

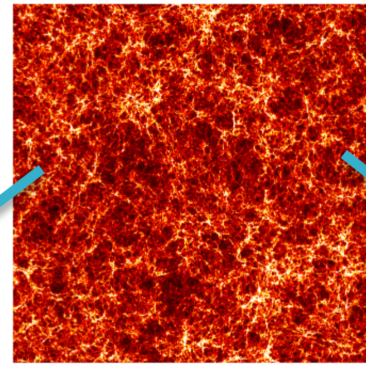
- Are they Gaussian?
  - $f_{NL}=0$ – yes
  - $f_{NL}\neq 0$ – No
- Look for clustering effect on large scales – bias



Hard to measure due to cosmic variance
But we're only interested on the bias of the galaxies…

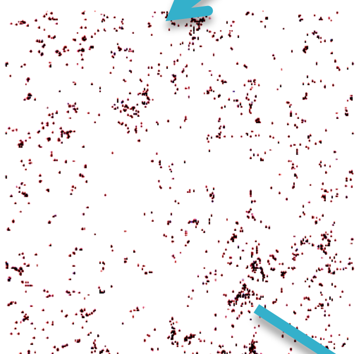
Beating cosmic variance on large scales

- The multi-tracer technique: look at the ratio of bias for 2 tracers!



1 realization of
dark matter field
(our Universe)

Galaxy
survey 1
(Dark
matter halo
of mass M_1)



$\delta_1 \sim b_1\delta_m$

Galaxy
survey 2
(Dark
matter halo
of mass M_2)

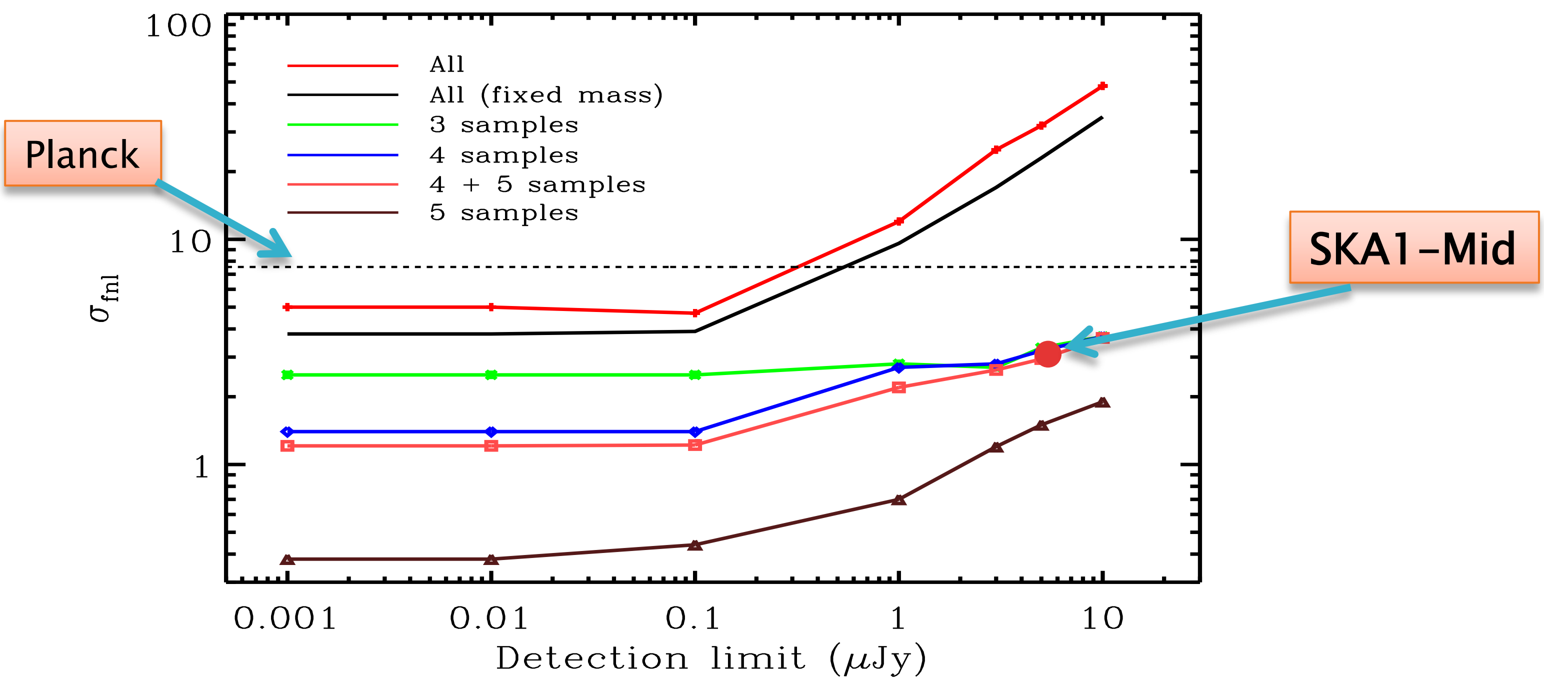
$\delta_2 \sim b_2\delta_m$

Can measure directly b1/b2 (plus
shot noise) – no cosmic variance!

Seljak, PRL 2009

Pushing the limits on primordial non-Gaussianity with multiple populations

- Separate radio galaxies into different populations (**masses**…)
- Need ~ 0.5 arcsec resolution to identify the FR galaxies – use SKA1-MID
- No need for redshift information!

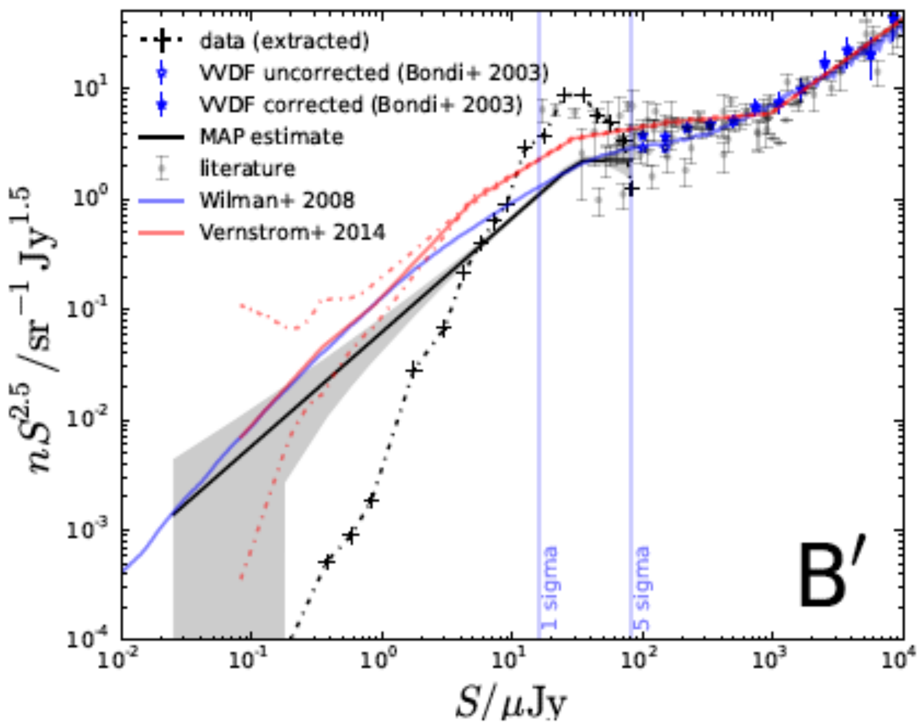


fNL ~ 3! (SKA1)

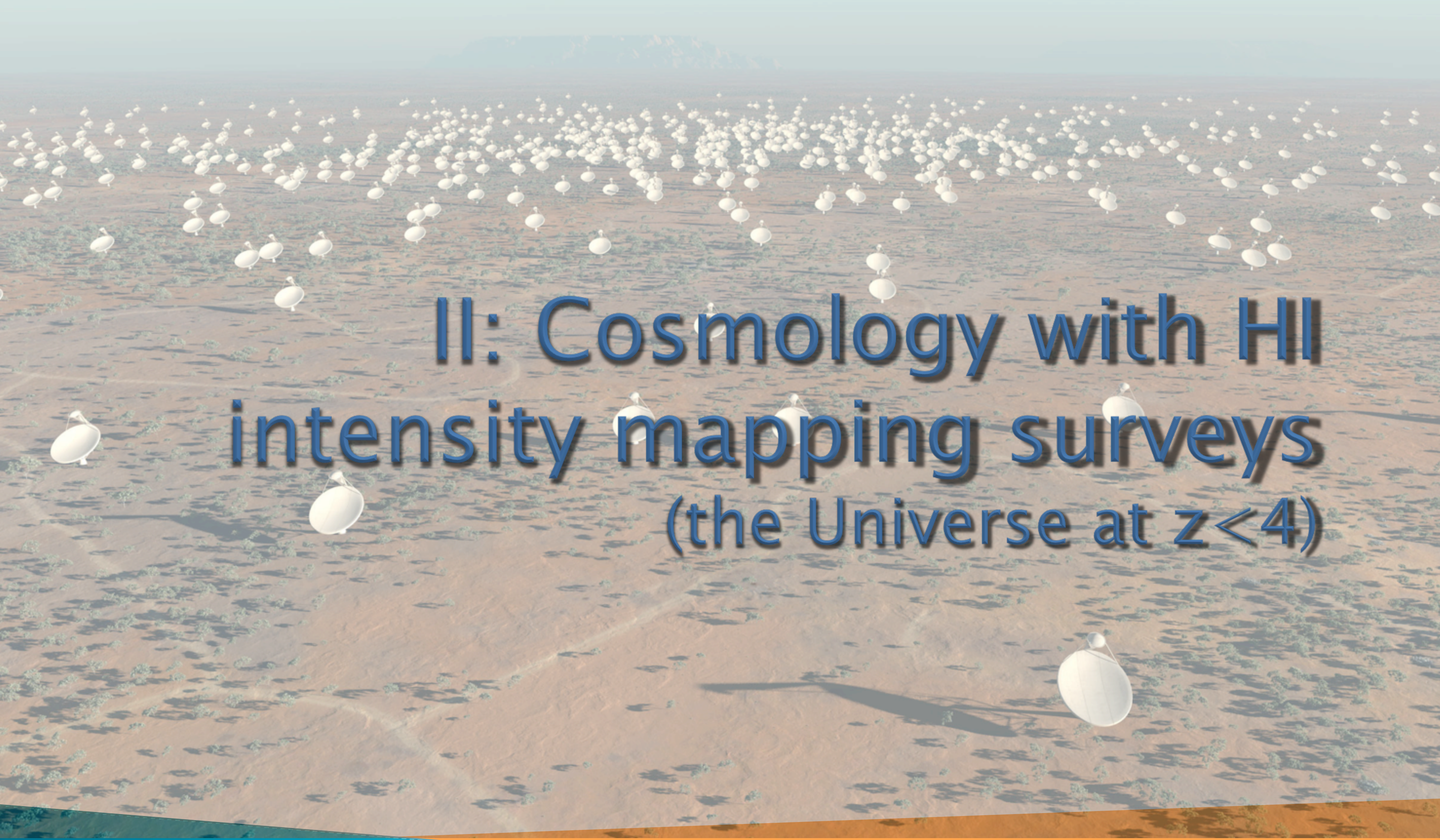
L. Ferramacho, M. Santos et al., MNRAS 2014, arXiv:1402.2290

A final word: digging below the noise…

- Give up source finding – can we use the information below the 5 or 10-sigma cut?
    - Yes, but, careful with systematics…
- Method 1: Maximum likelihood stacking – great way to study galaxy population properties…
- Method 2: use all pixels in the map – “P(D) analysis” + correlation functions…



Zwart et al., MNRAS 2015, VLA + VIDEO data



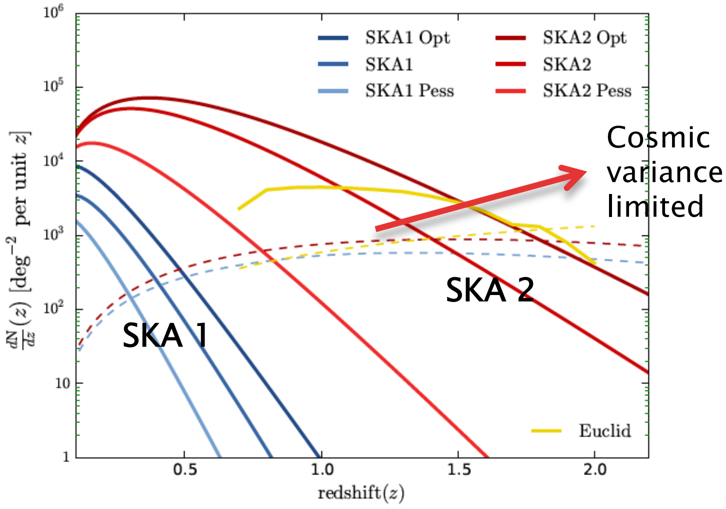
II: Cosmology with HI intensity mapping surveys

(the Universe at z<4)

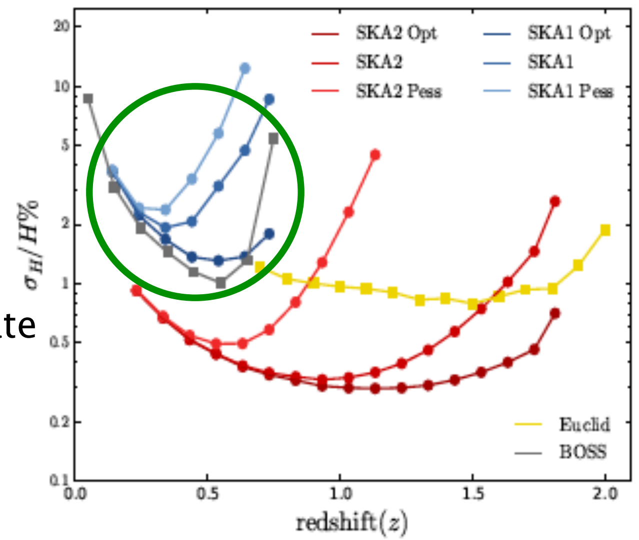
Mario Santos, UWC, Bologna 2015

Cosmology with a HI galaxy survey?

- First cosmological survey with HI galaxies using SKA1-MID (10^7 galaxies!) ~ 5,000 deg^2
- **Not competitive with optical…**
- Interesting for redshift space distortions
- Will provide a large catalogue of HI redshifts
- Will prepare for the key project in SKA2
- Might be done commensally with other surveys



Hubble rate

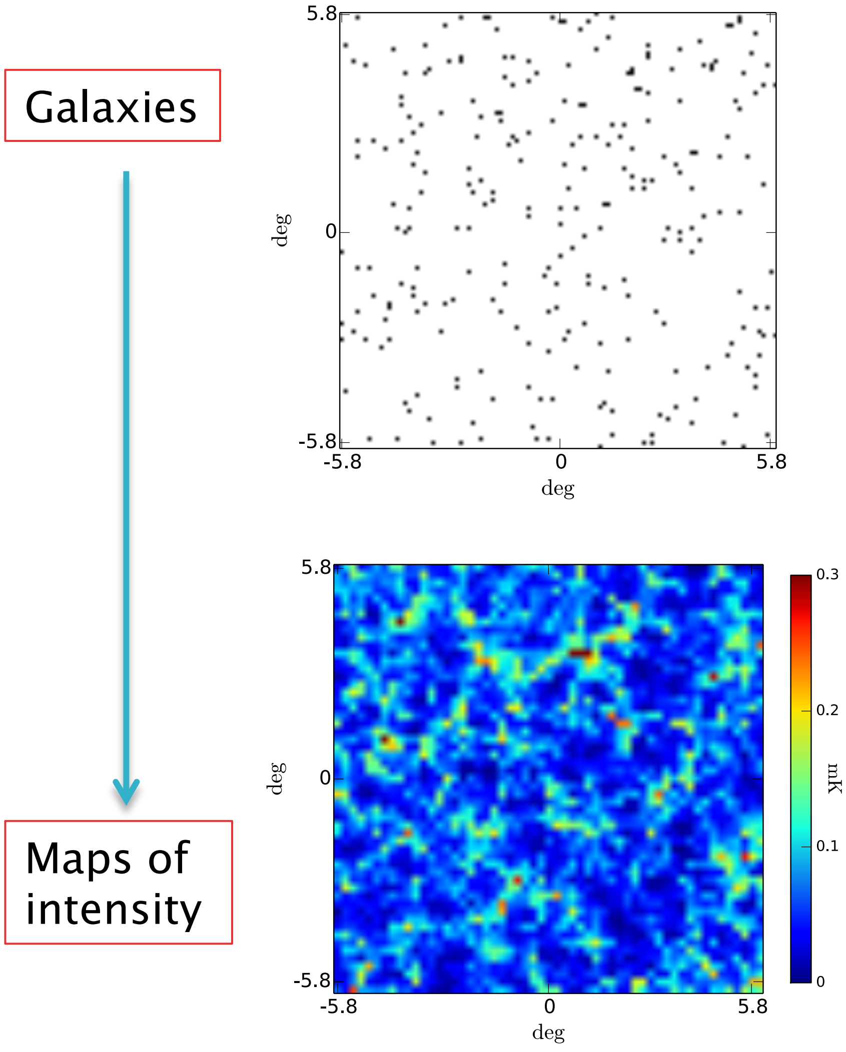


See Santos et al., PoS(AASKA14)017
Yahya et al., MNRAS, http://arxiv.org/abs/1412.4700

Do we need to "see" the galaxies?

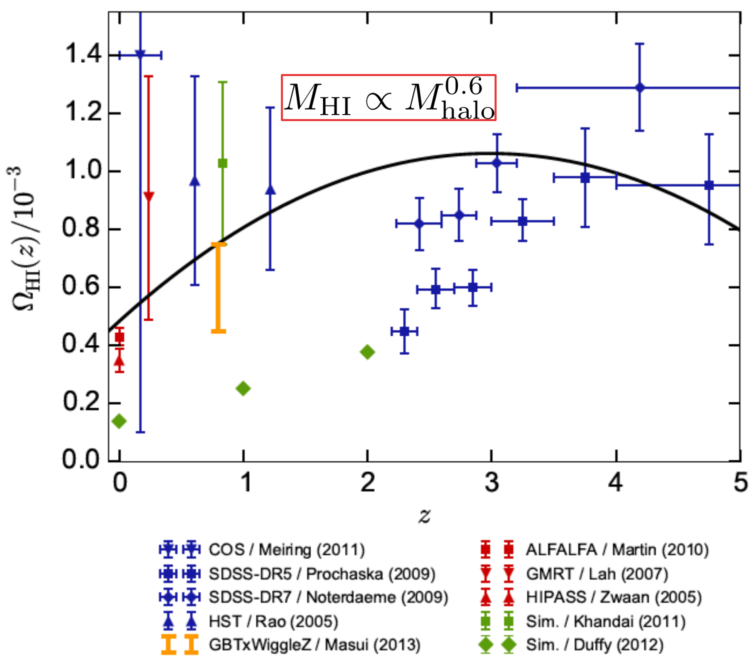
- Detecting HI galaxies is extremely expensive…
- Scales of interest are well beyond galaxy scales
- Give up detecting galaxies
- Look instead at the integrated **line** emission from many galaxies in one big pixel – intensity mapping
- Just like the CMB but with 3d information (tomography)

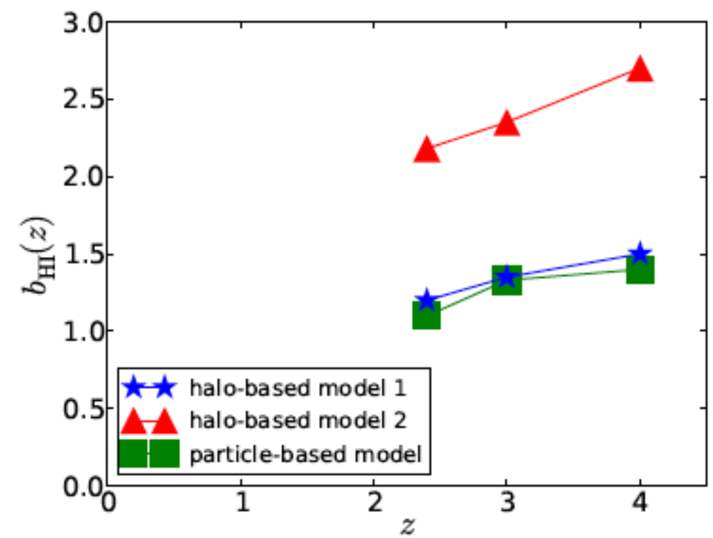
z ~ 0.6, 1 MHz slice



The HI signal

- Our signal is a sum over many galaxies (one "pixel" of (1 deg)^{2}x(5 MHz) ~ 10^5 Mpc^3 contains ~ 10^4 HI galaxies at z~1!
- Assume HI mass function to calculate the HI density
- Power spectrum depends on the product of total temperature (HI density) and bias…





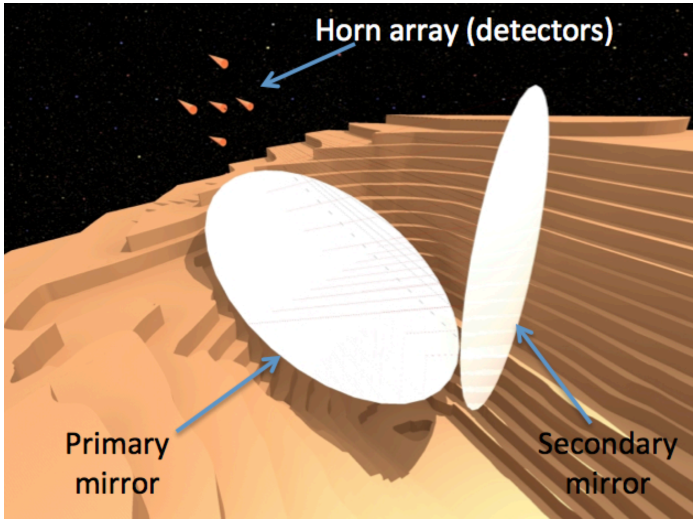
Simulations from Villaescusa-Navarro et al. (2014)

Bull et al., ApJ, 2015

Experiments: dish surveys

- Angular scales > λ/D_{dish}
- Each pointing gives you 1 pixel on the sky
- Brightness sensitivity does not depend on dish size
- Good to scan large areas of the sky

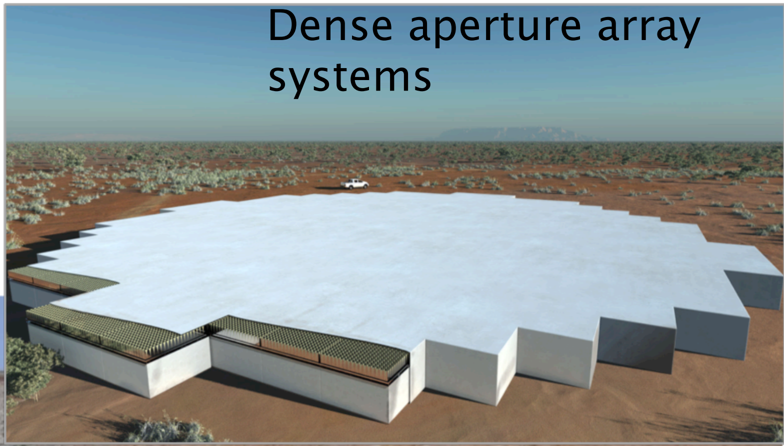
- **GBT** (Chang et al.)
- **Parkes**



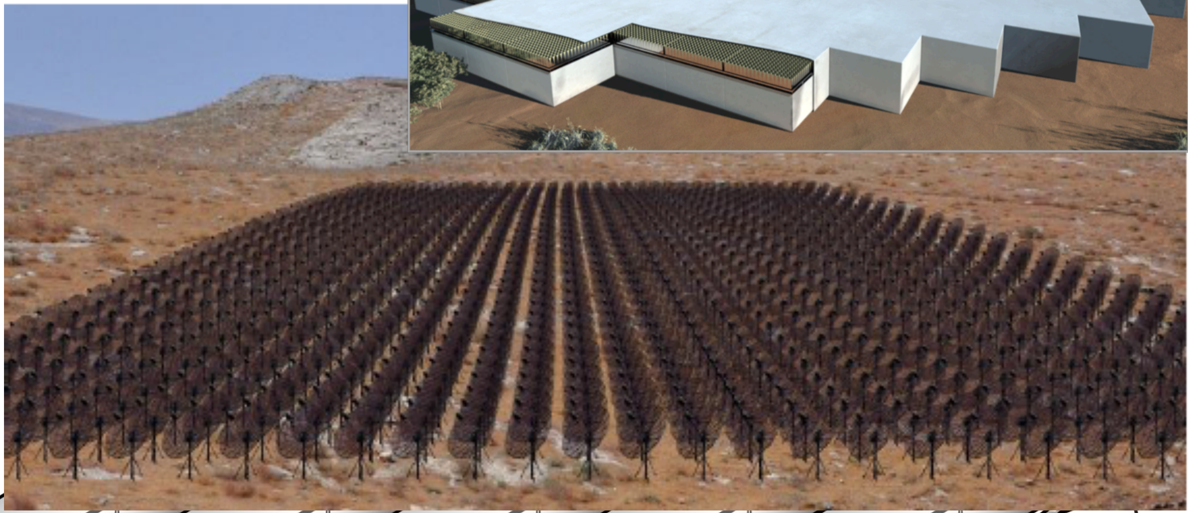
BINGO (Battye, et al., http://arxiv.org/abs/1209.1041)

Experiments: interferometers

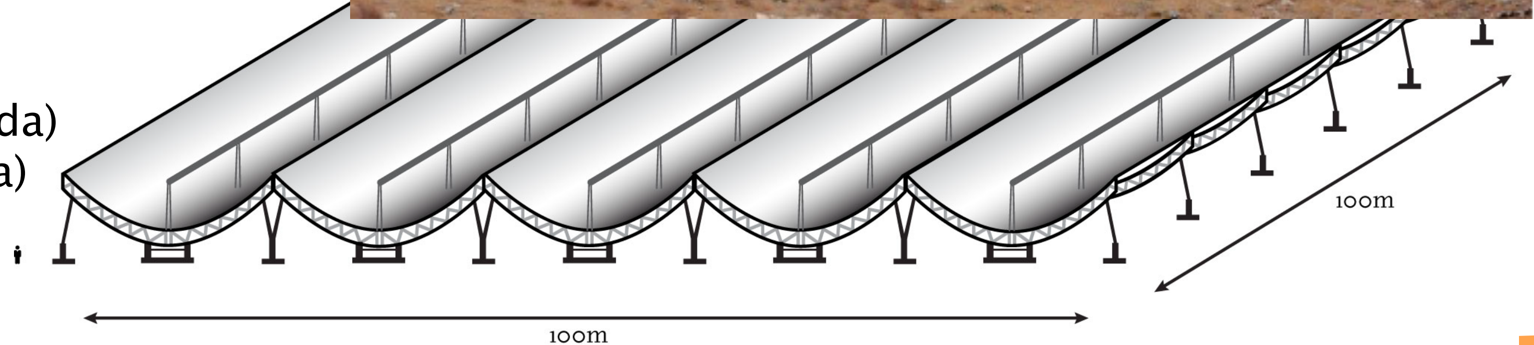
- λ/b_{max} < angular scales < λ/b_{min}
- Provide higher resolution
- Hard to do “full sky” surveys…



HIRAX (South Africa)
~ 1000, 5 m dishes
400 – 800 MHz (0.8 < z < 2.5)

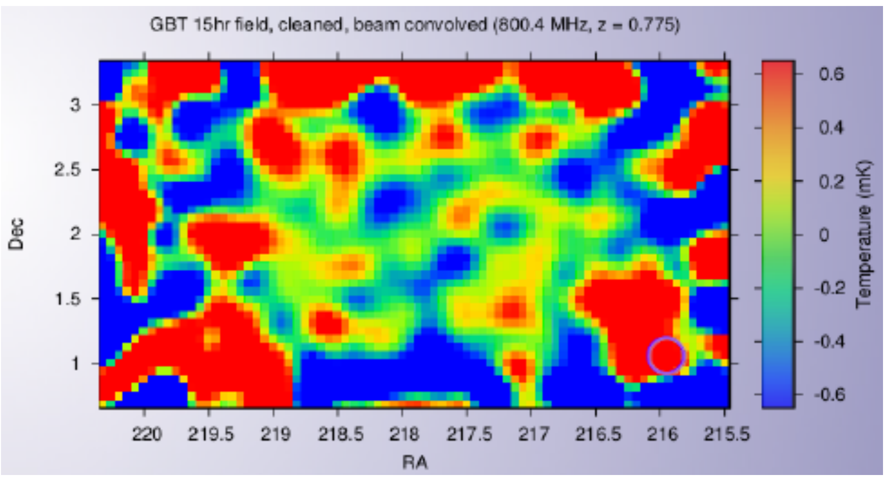


- CHIME (Canada)
- Tianlai (China)



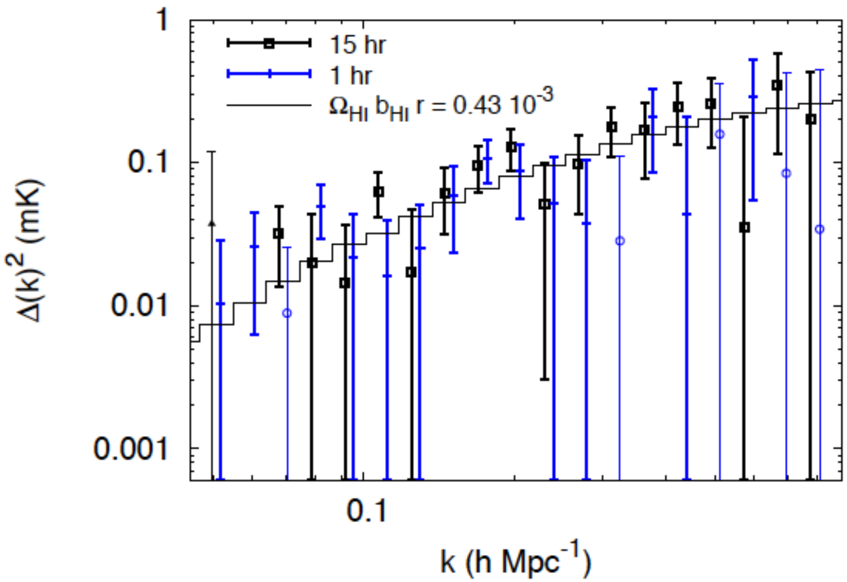
Current measurements…

- GBT: HI map at z~0.8 (noise/ systematics dominated)



Masui, et al., ApJ 2012,
Chang et al., Nature 2010

- Detection: GBT cross-correlation with Wigglez



GBT (Switzer et al., 2013): Ω_{Hi}bias $\sim 0.6\times 10^{-3}$ at z~0.8

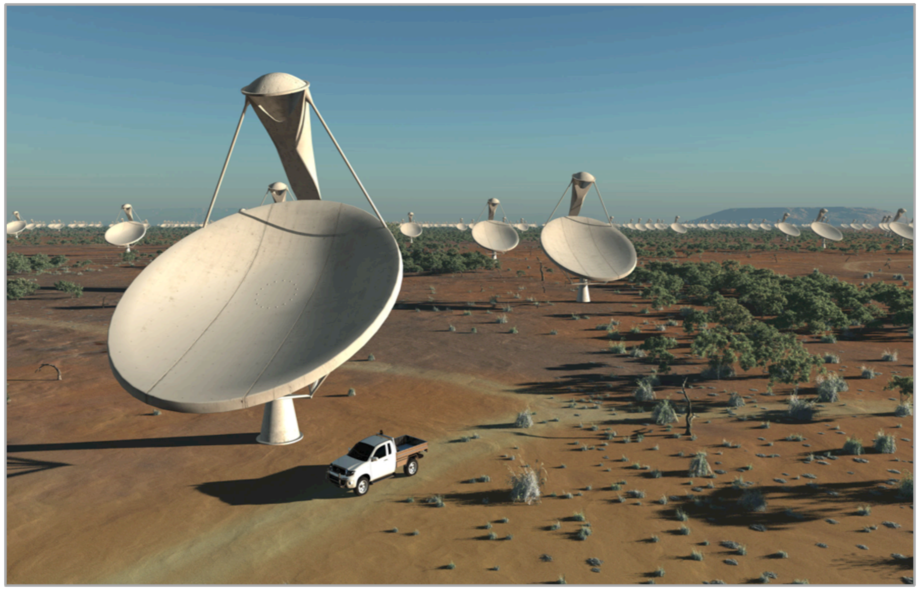
Crucial to have more detections, even if at low z…

Stay tuned for MeerKAT 8/16!

SKA1 as an intensity mapping "machine"

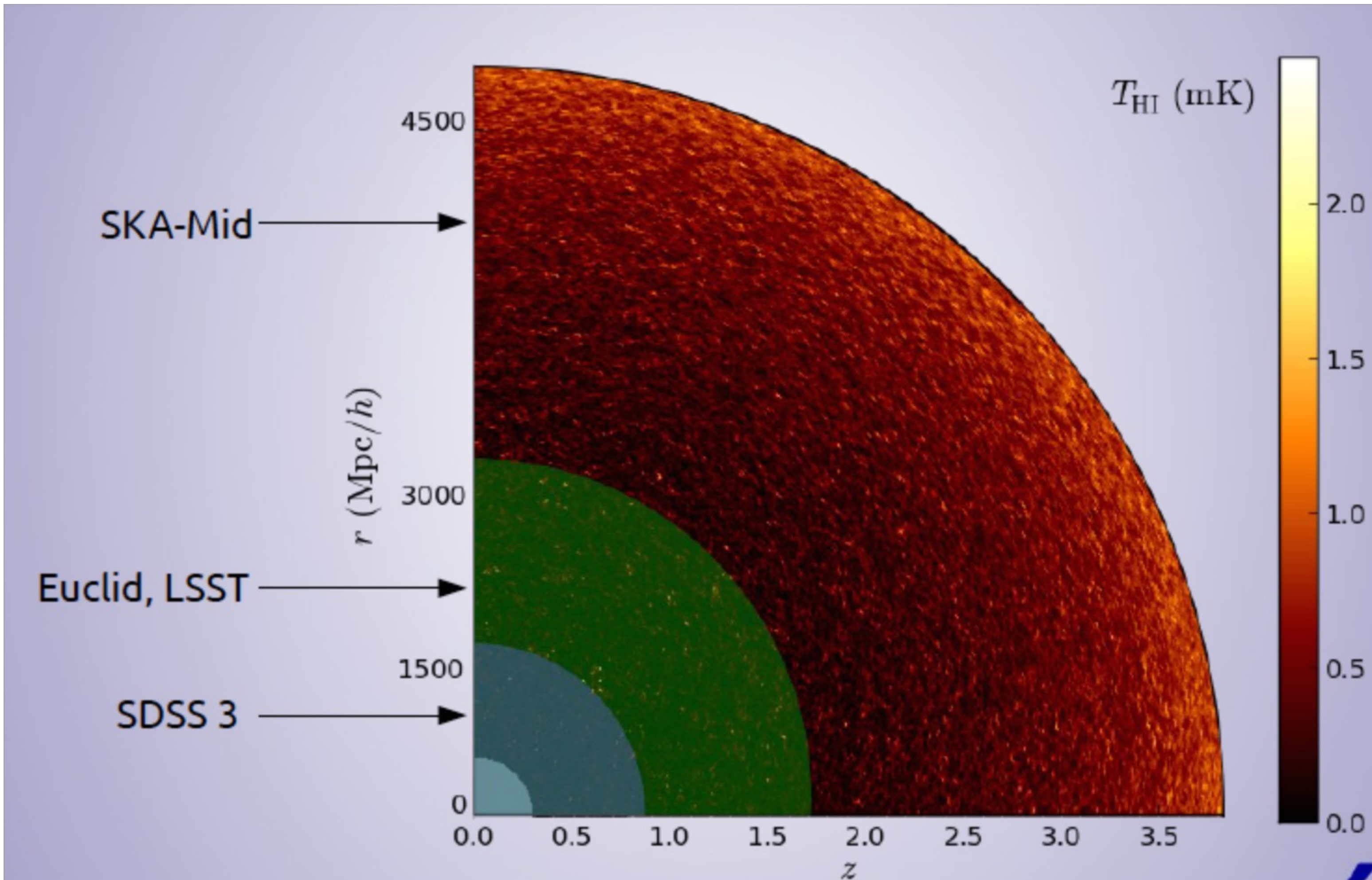
- Interferometer: baselines not small enough to probe BAO scales and above
- Main idea: use each dish in "single observation mode"
- Save interferometer data for imaging/calibration
- Approved SKA1 "Engineering Change Proposal" to provide calibrated auto-correlations

MeerKAT -> SKA1-MID
(~200 dishes by 2023)



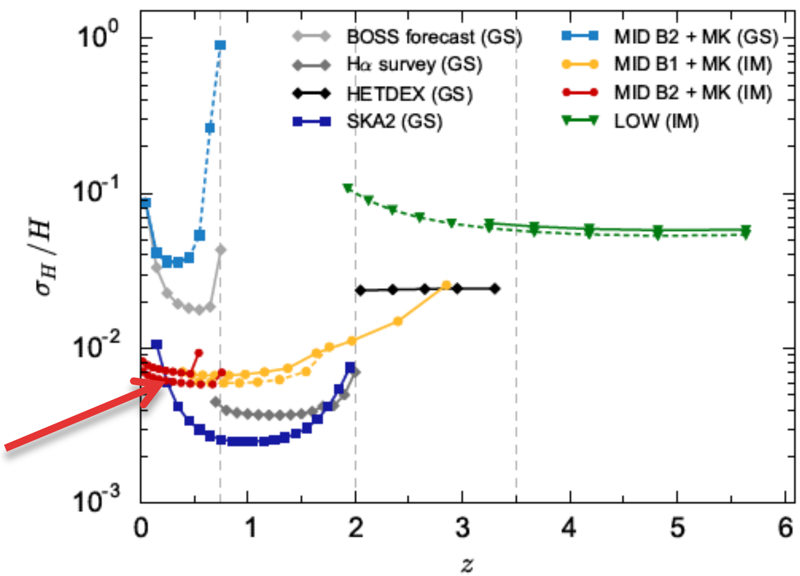
SKA1-MID: Cosmology with HI IM

- Competitive with large redshift surveys for "precision cosmology"
- Huge available volume/low resolution – ideal for large scale tests

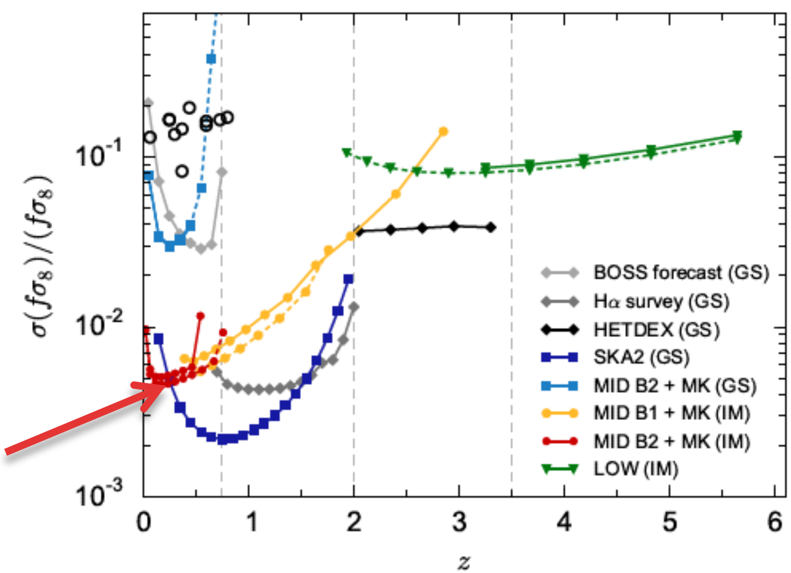


High precision cosmology with SKA1-MID HI intensity mapping survey

Hubble rate



Growth rate

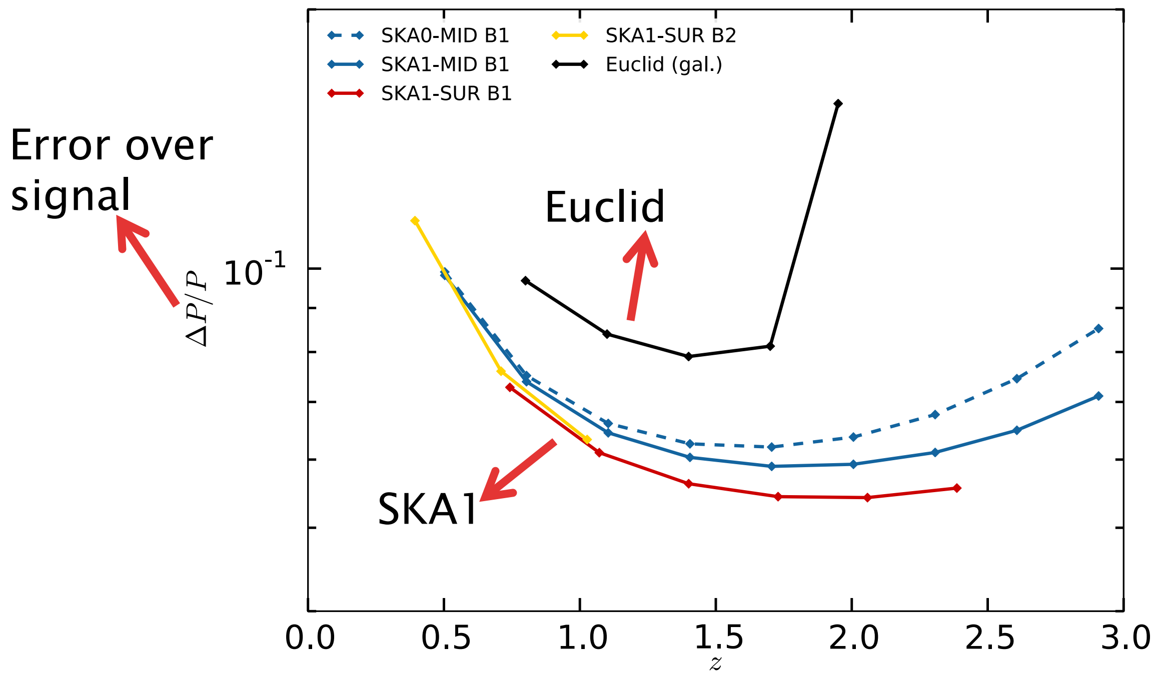


P. Bull, arXiv:1509.07562, 2015

- Use SKA1-MID band 2 (z < 0.8)
- Low z measurements will be unmatched and surpass contemporary spectroscopic galaxy surveys such as DESI and Euclid in terms of constraints on modified gravity parameters

Probing very large scales with a SKA1 HI intensity mapping survey

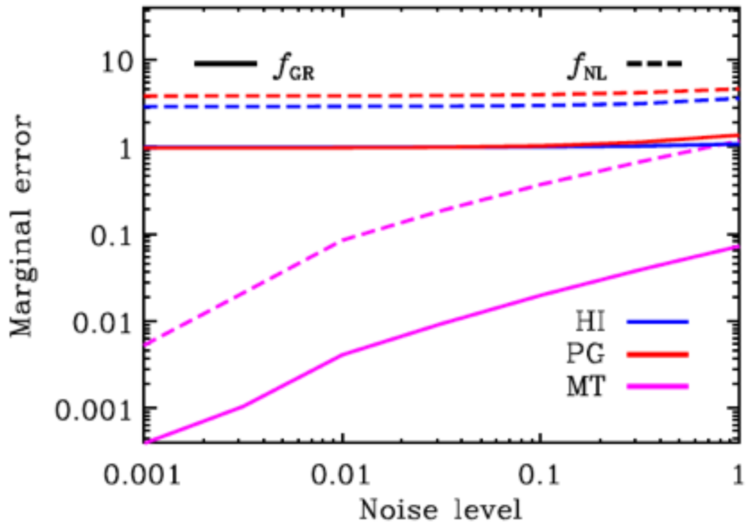
- Use band 1 ~ $0.5 < z < 3.0$
- ~ 20,000 deg^2
- Probe HI signal across large redshift range
- Probe homogeneity and primordial fluctuations (f_{NL} constraints > 1)

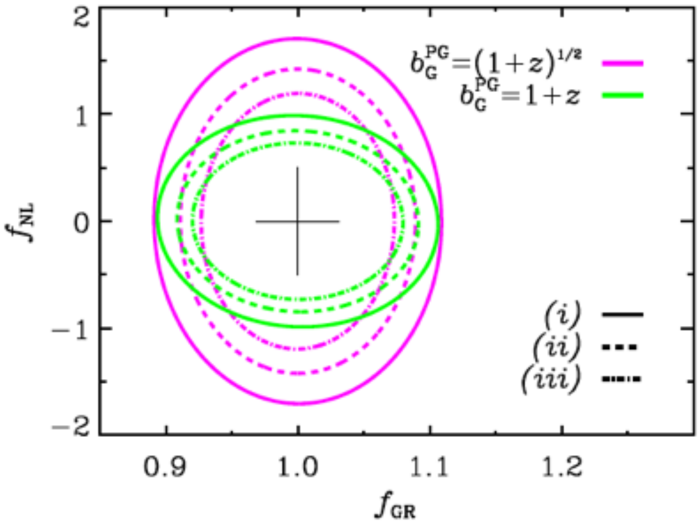


k ~ 10^{-2} Mpc^{-1} (past the equality peak)

Camera, Santos, Ferreira and Ferramacho, PRL, 2013

The breakthrough: SKA1-MID HI intensity mapping and the multi-tracer technique





Fonseca et al., ApJ Letters, 2015
Alonso et al., PRD, 2015

- Combining a HI intensity mapping survey using SKA1-MID with Euclid or LSST will detect fNL < 1 as well as GR corrections!
- A powerful test of GR on large scales!
- A nice way to “fight” systematics

Conclusions…

1. The combination of several probes available with radio telescopes will provide unprecedented constraints on cosmological parameters and a handle on systematics
2. Large continuum survey will probe the isotropy of the Universe and the cosmic dipole (as well as "standard" cosmology!)
3. HI intensity mapping in particular opens up a new possibility for SKA1 (as a total power array)
4. Competitive constraints on DE and GR modified theories with HI IM at $z < 0.8$
5. But real strength is in probing very large scales: cross-correlate with Euclid/LSST at $z < 2$ to probe the nature of primordial fluctuations and deviations from General Relativity