COSMOLOGY WITH THE SKA

Roy Maartens

3 March 2016

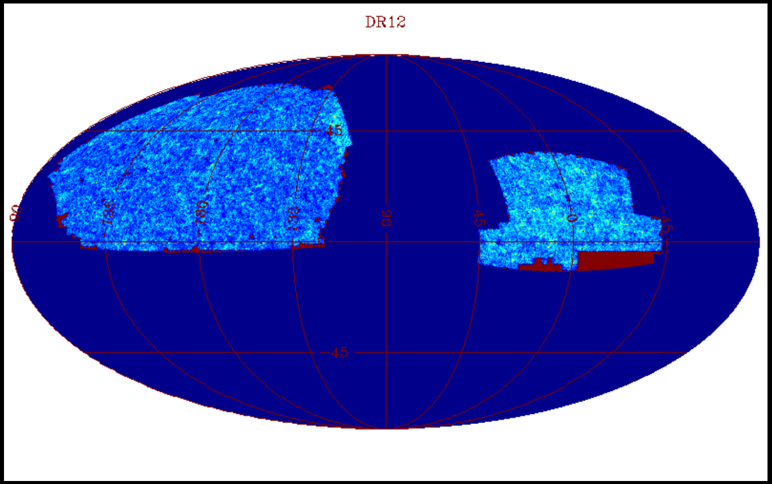
RESPICE PROSPICE
UNIVERSITY of the WESTERN CAPE

SKA AFRICA
SQUARE KILOMETRE ARRAY

SKA
SQUARE KILOMETRE ARRAY

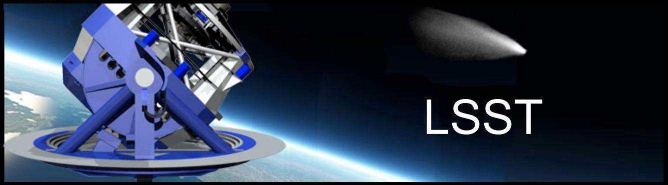
HUGE GALAXY SURVEYS – THE NEXT FRONTIER

State-of-the-art galaxy surveys today (BOSS, DES)



BOSS sky coverage

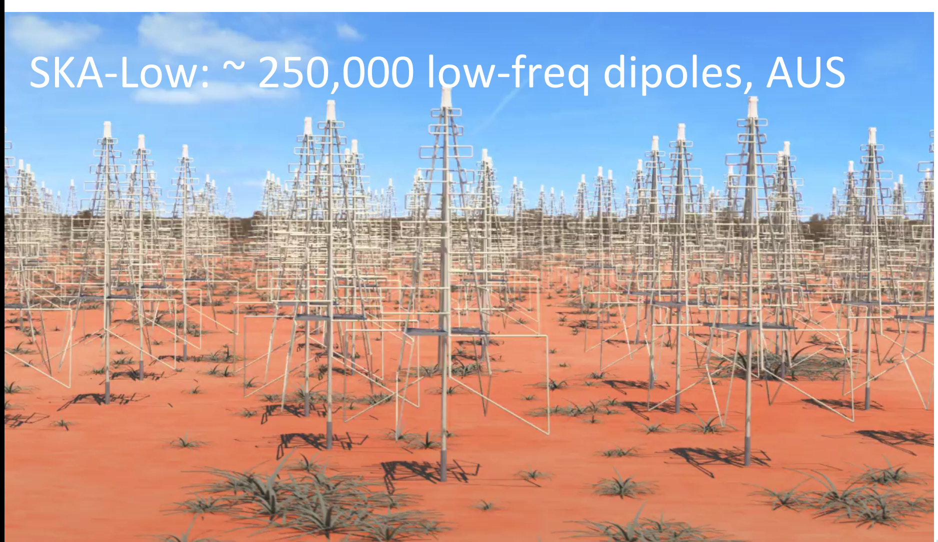
The next generation of surveys – SKA, Euclid, LSST, … – will deliver much greater volume and thus precision.



SKA Phase 1 Before rebaselining

2 sites (South Africa, Australia);
3 telescopes; one Observatory
Frequency range SKA1: 50 MHz – 3 GHz

Cost-cap: €650M
Construction: 2017 – 2023
Early science: 2020
Phase 2 SKA: 2023 - 2030



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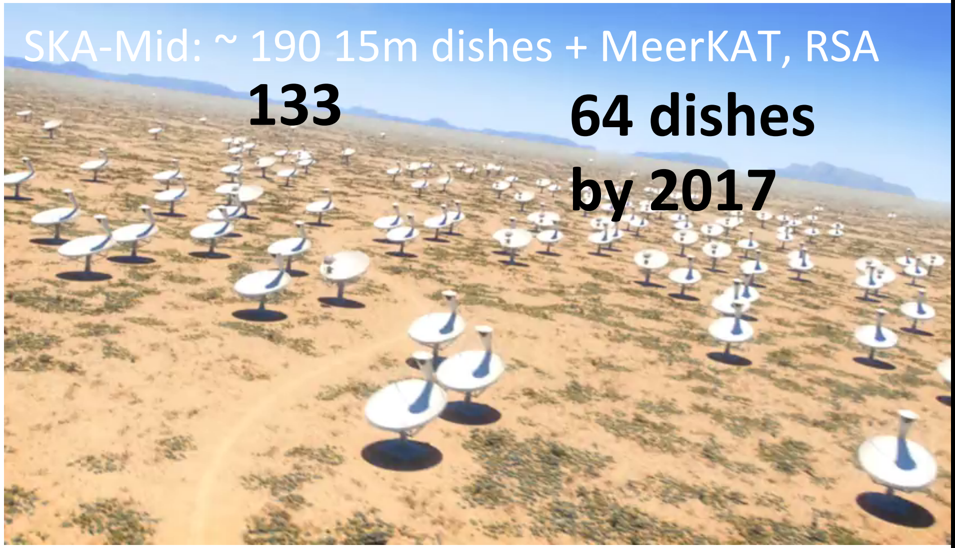
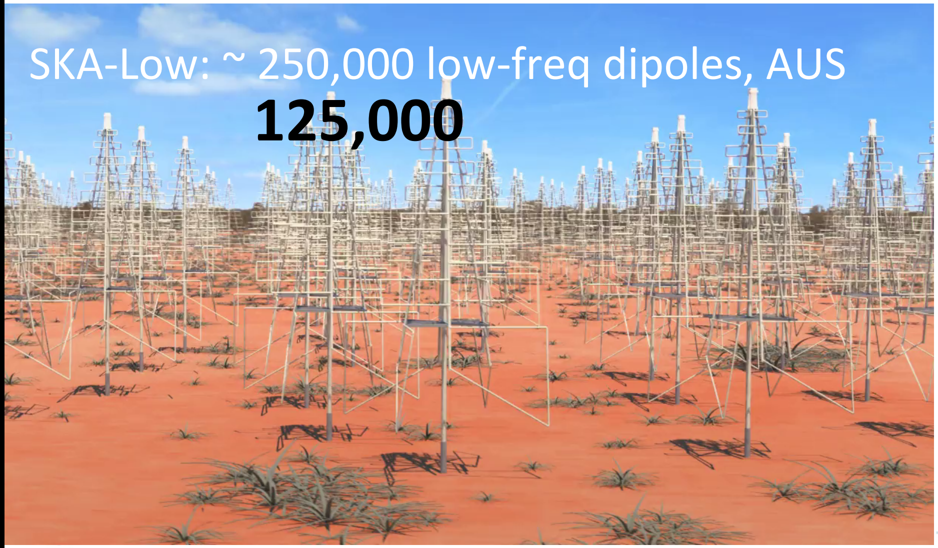
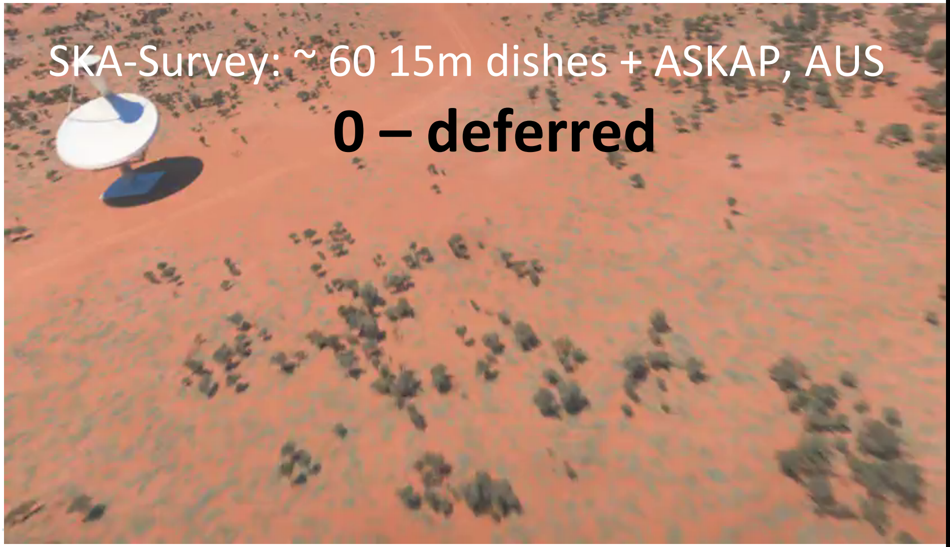
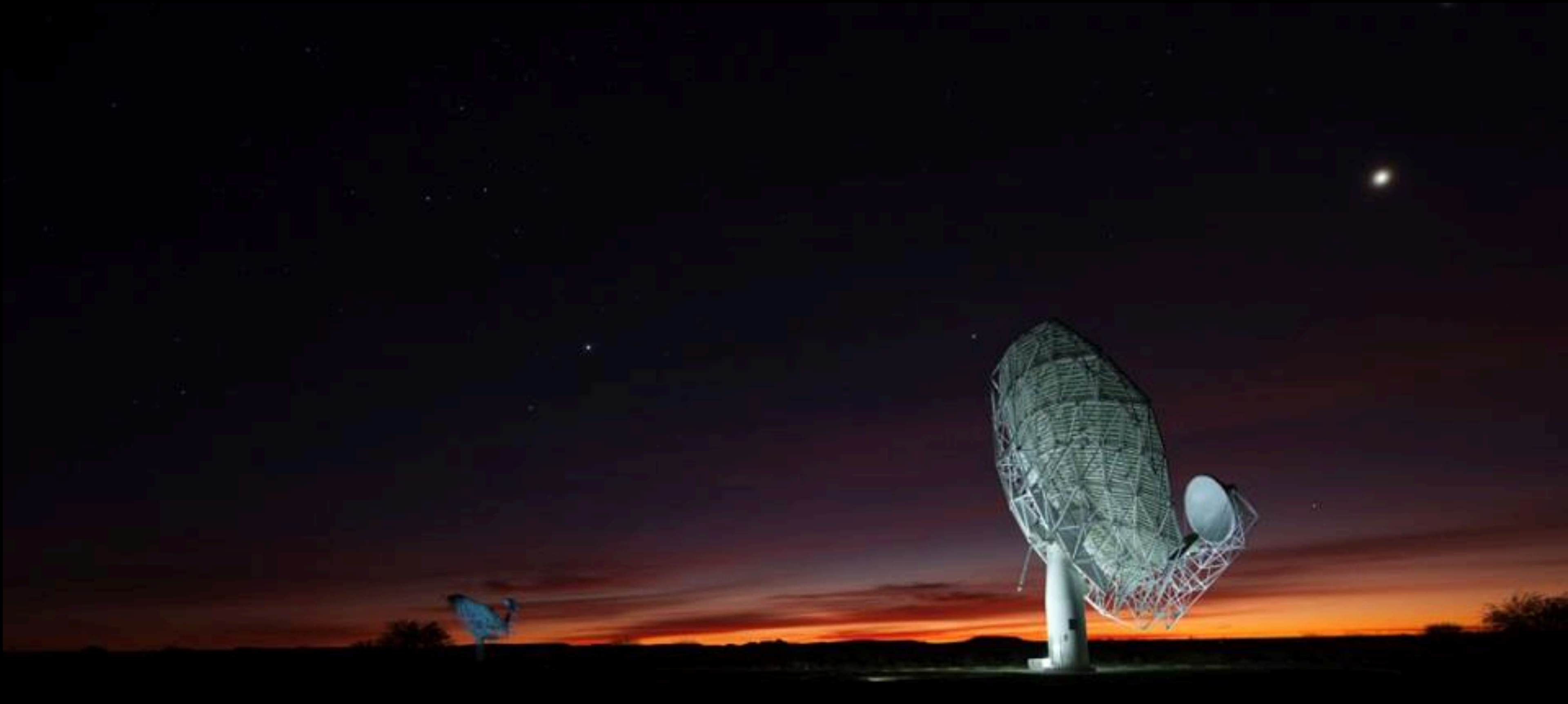






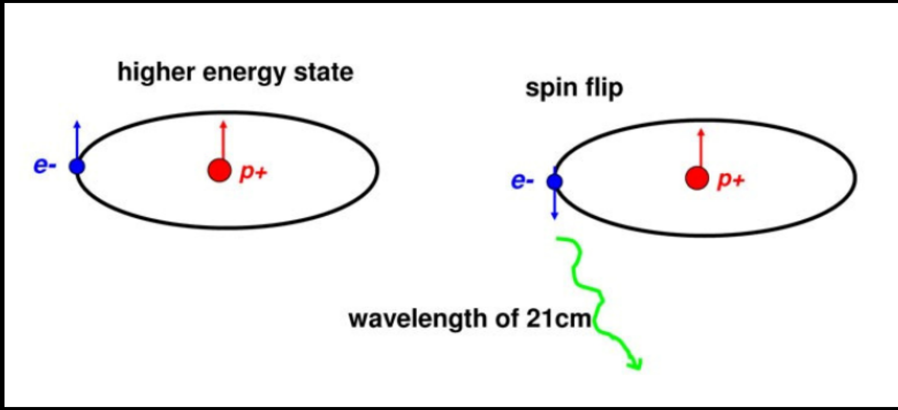


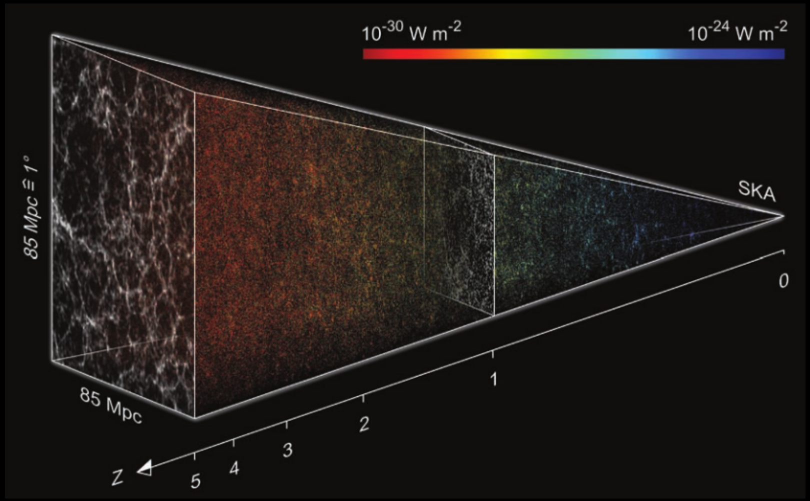
2 of the 64 MeerKAT dishes

COSMOLOGICAL SURVEYS IN THE RADIO

HI GALAXY REDSHIFT SURVEY

- Neutral Hydrogen emits 21cm/ 1420 MHz in restframe
- Individual HI galaxies detected, very accurate redshifts
- The radio analogue of an optical spectroscopic survey
- No foregrounds, no stellar contamination
- But – this needs very high sensitivity

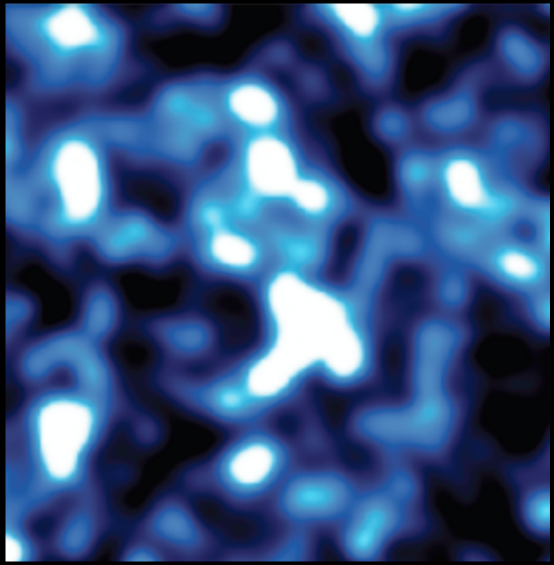


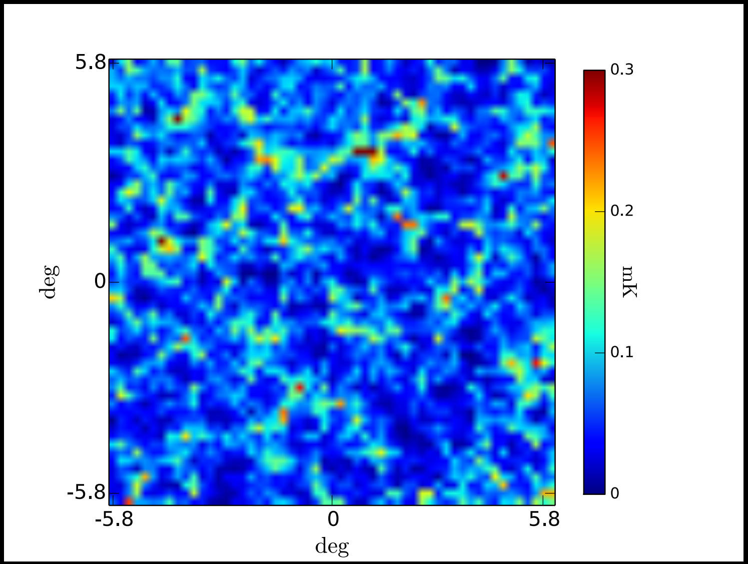


COSMOLOGICAL SURVEYS IN THE RADIO

HI INTENSITY MAPPING SURVEY

- Individual HI galaxies not detected, only integrated HI emission
- Perfectly good for large-scale cosmology (BAO, RSD, PNG)
- Very narrow redshift bins possible
- Like the CMB – but at many redshifts
- Mainly via single-dish auto-correlations
- Major problem of foreground removal (worsens as *z* increases)
- Also used in Epoch of Reionization experiments

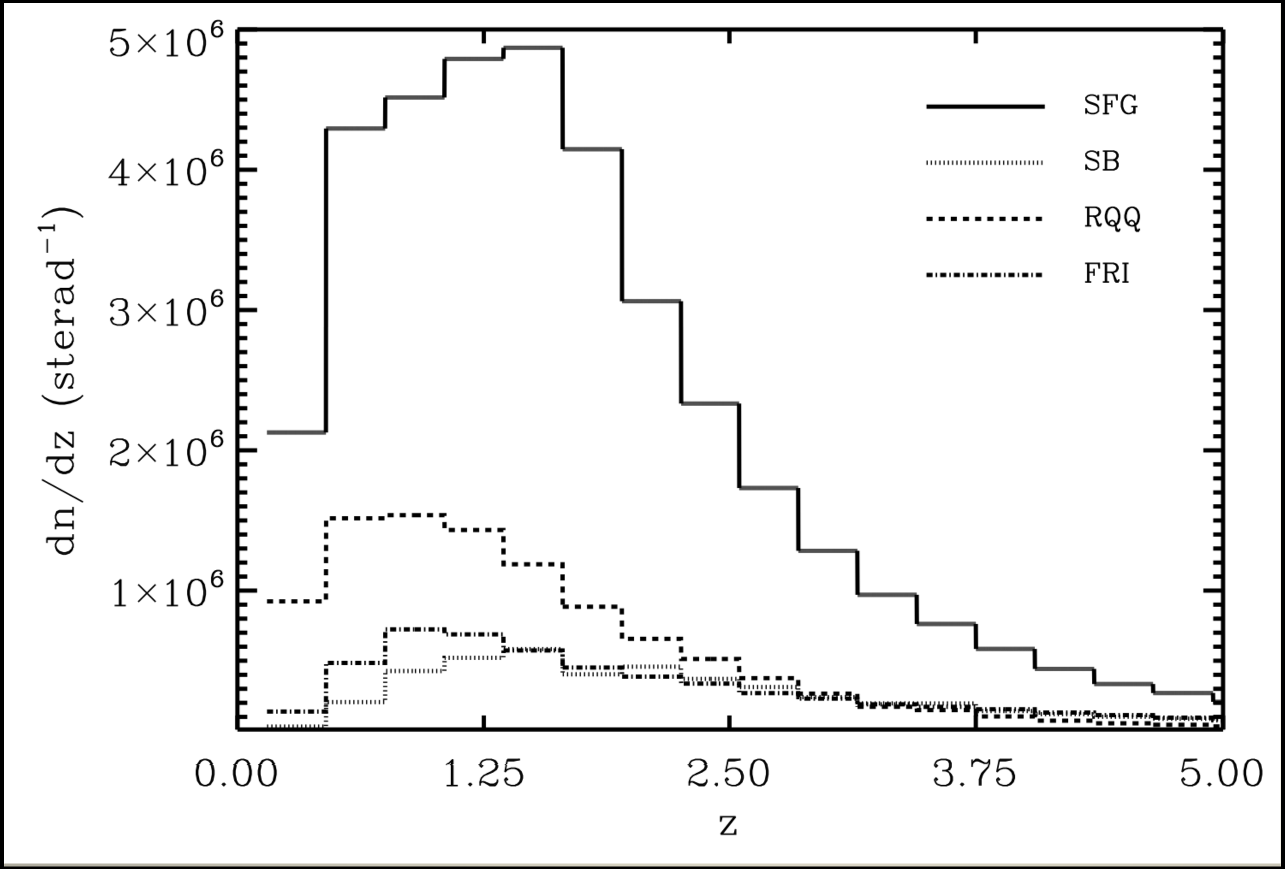




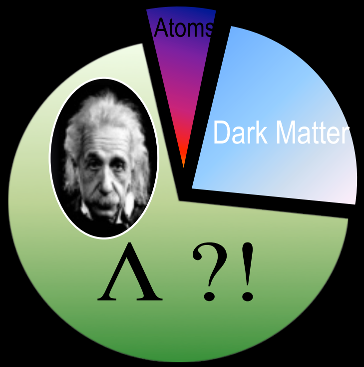
COSMOLOGICAL SURVEYS IN THE RADIO

RADIO CONTINUUM SURVEY

- Total radio emission from galaxies (mainly synchrotron)
- No redshift information – but can get some, using HI or optical data
- Many galaxies at high redshift



SOME OF THE BIG QUESTIONS



- Is Dark Energy not the vacuum energy Λ – but a dynamical field?

$$w \equiv \frac{p_{\rm de}}{\rho_{\rm de}} = w_0 + (1-a)w_a$$

- Is there no DE? Is acceleration driven by modified gravity? i.e. – does GR fail on the largest cosmological scales?
- Is the primordial spectrum of perturbations non-Gaussian? What does it tell us about Inflation?
- Is the large-scale structure of matter isotropic like the CMB?

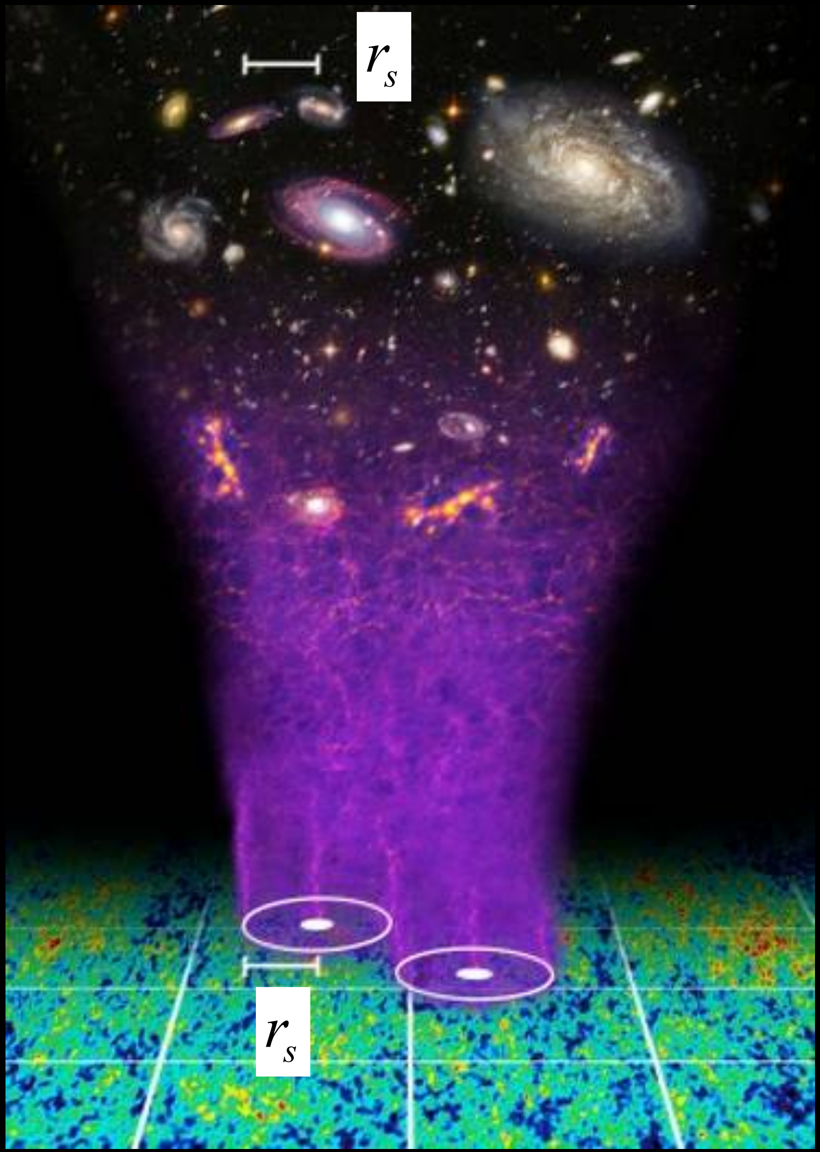
Probes that we use to answer these questions:

BAO + redshift space distortions + angular power spectra

BAO – a fossil record in the galaxy distribution

galaxy formation

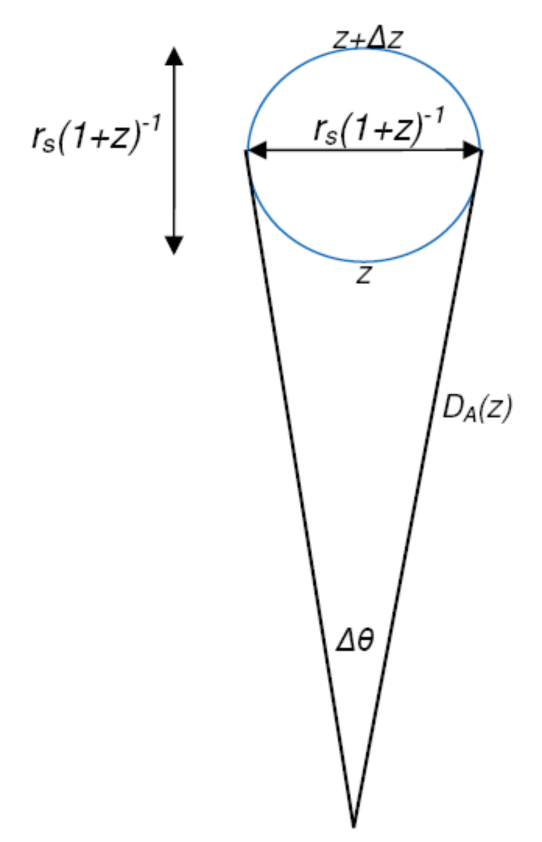
z < 30



decoupling

z = 1100

BAO – a powerful probe of $H(z)$ and $D_A(z)$

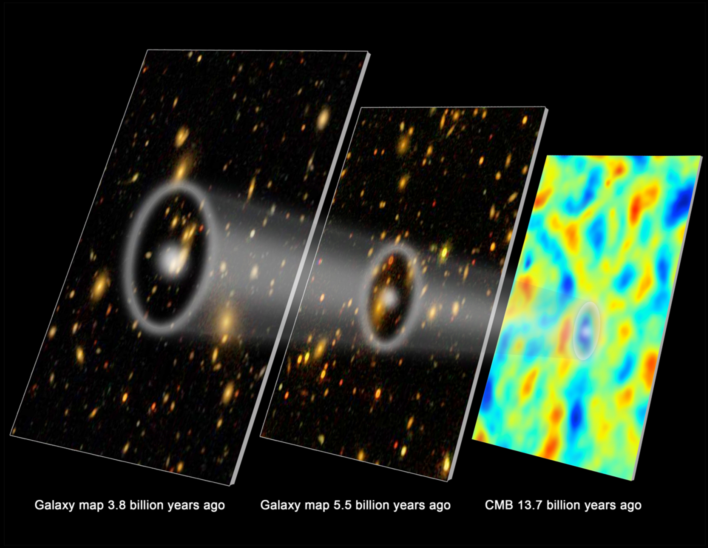


$$\frac{r_s}{1+z} = D_A(z)\Delta\theta(z) \qquad r_s \approx 100h^{-1}\ \mathrm{Mpc}$$

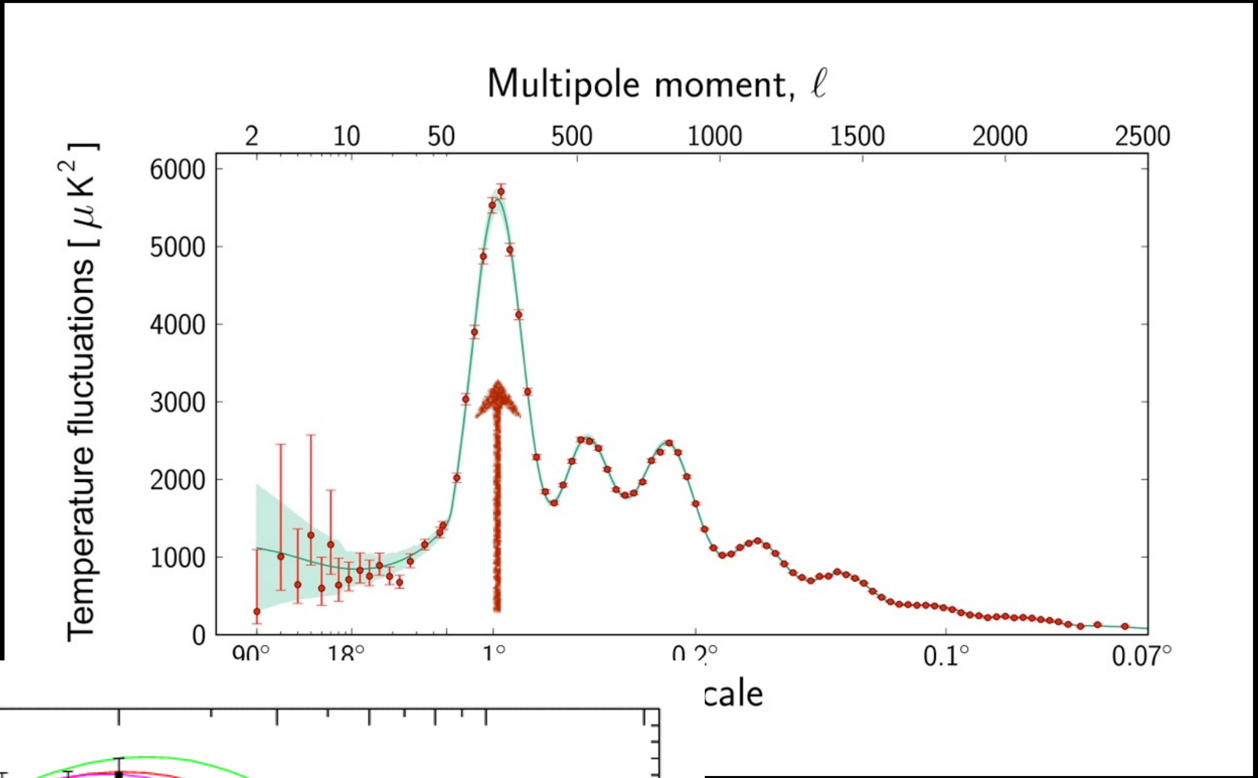
$$\frac{r_s}{1+z} = \frac{\Delta z}{(1+z)H(z)}$$

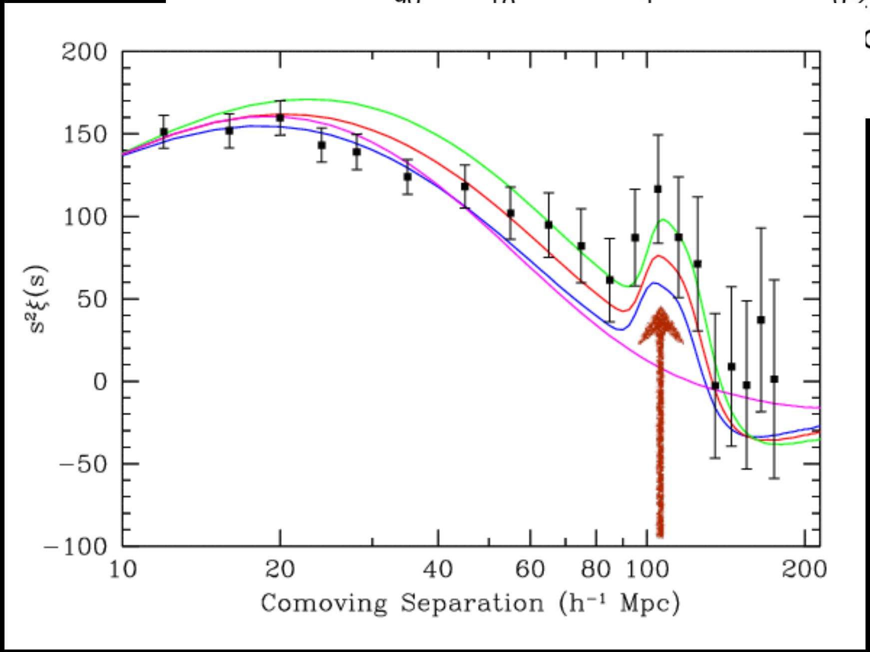
Measure $\Delta\theta(z)$ and Δz

Deduce $D_A(z)$ and $H(z)$



CMB





Galaxy correlations

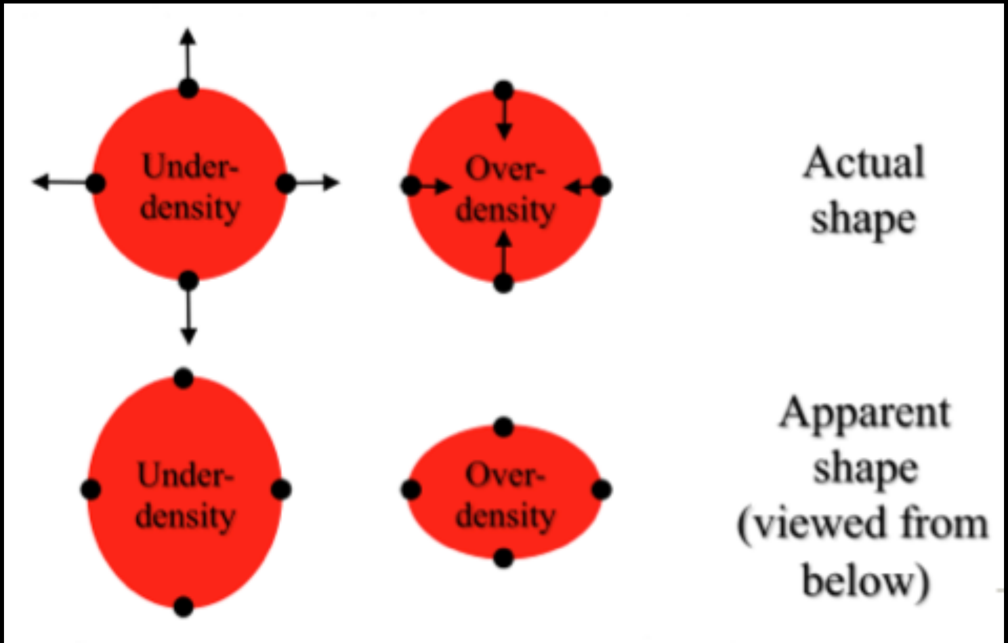
Redshift space distortions

The average motion of galaxies relative to us is given by the Hubble expansion.

Over-dense regions (eg galaxy clusters) and under-dense regions (eg voids) induce additional peculiar velocities relative to the Hubble flow.

Real space

Redshift space



The Kaiser formula

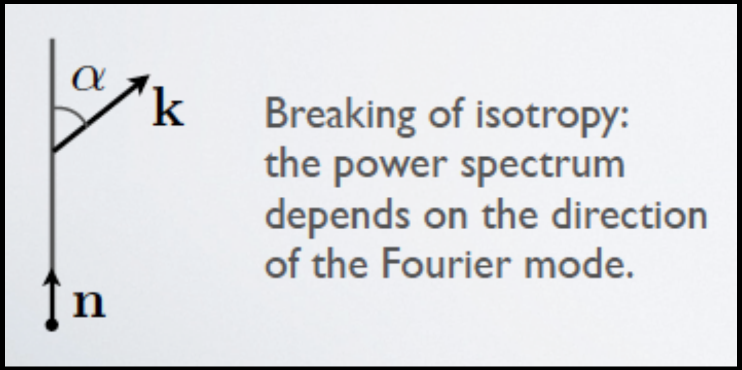
$$\delta_{g\,\mathrm{obs}} = (b + f\mu^2)\delta_m$$

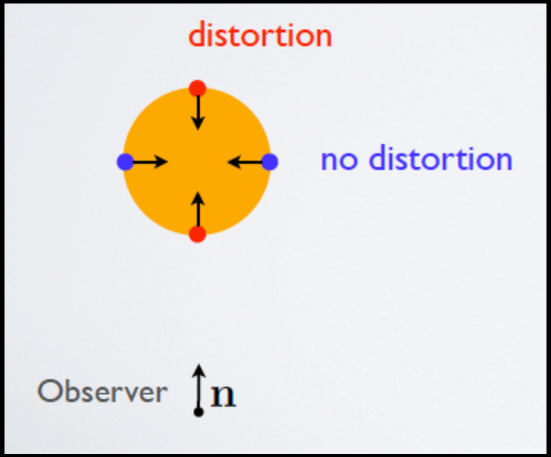
where

$$\mu = \mathbf{n} \cdot \hat{\mathbf{k}} = \frac{k_{||}}{k} = \cos\alpha \qquad f = \frac{d\ln\delta_m}{d\ln a}$$

leading to the power spectrum:

$$P_{g\,\mathrm{obs}}(\eta, k, \mu) = (b + f\mu^2)^2 P_m(\eta, k)$$





Measuring the monopole and quadrupole allow us to separately extract *b* and *f* (up to a normalization of the power spectrum).

The growth rate *f* is a good diagnostic of deviations from LCDM and also from GR.

Parametrization:

$$f(\eta, \mathbf{k}) = \left[\Omega_m(\eta)\right]^{\gamma(\eta, \mathbf{k})}$$

In LCDM, and dynamical DE where the clustering of DE is negligible,

$$\gamma \approx 0.55$$

A significant deviation from this value could indicate a breakdown of GR

SKA COSMOLOGICAL SURVEYS

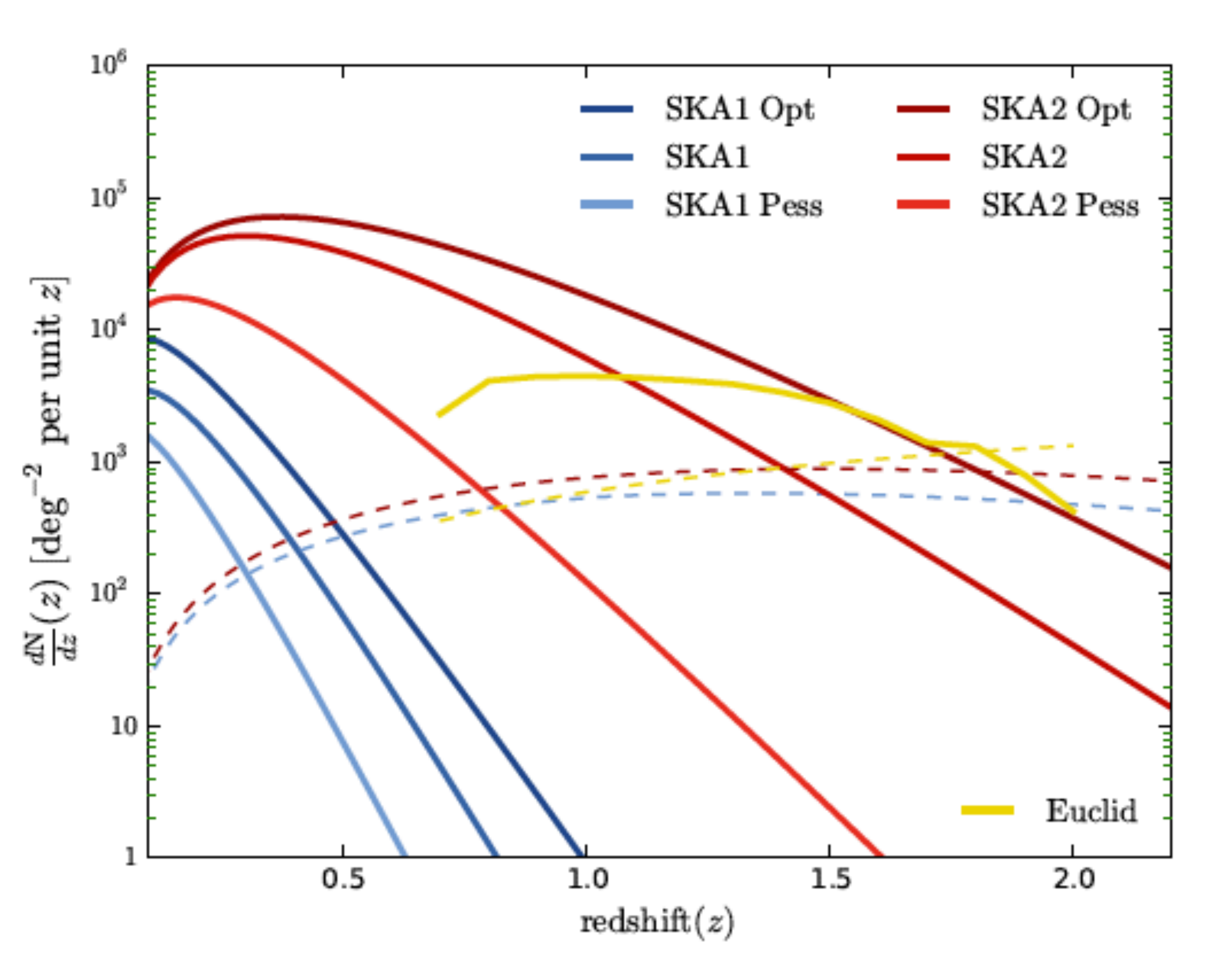
HI GALAXY REDSHIFT SURVEY

- SKA1 – 10 million galaxies, 5000 deg^2 , z<0.6
- SKA2 – 1 billion galaxies, 30000 deg^2 , z<2

SKA1 will not be a game-changer but will provide excellent complement to optical surveys

SKA2 will be a game-changer

(Yahya et al 2015)



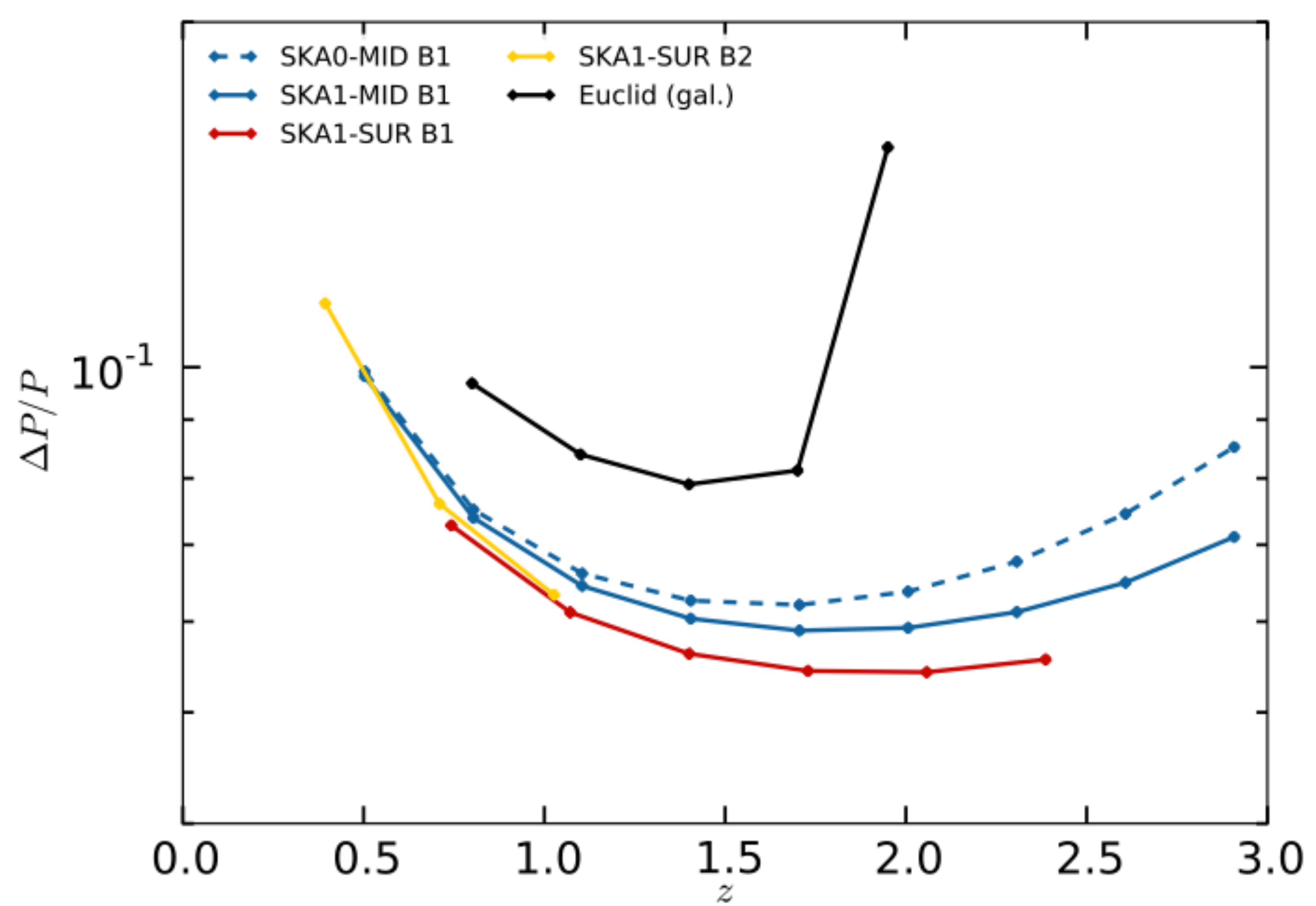
SKA COSMOLOGICAL SURVEYS

HI INTENSITY MAPPING SURVEY
SKA1 – 30000 deg^2 , z<3

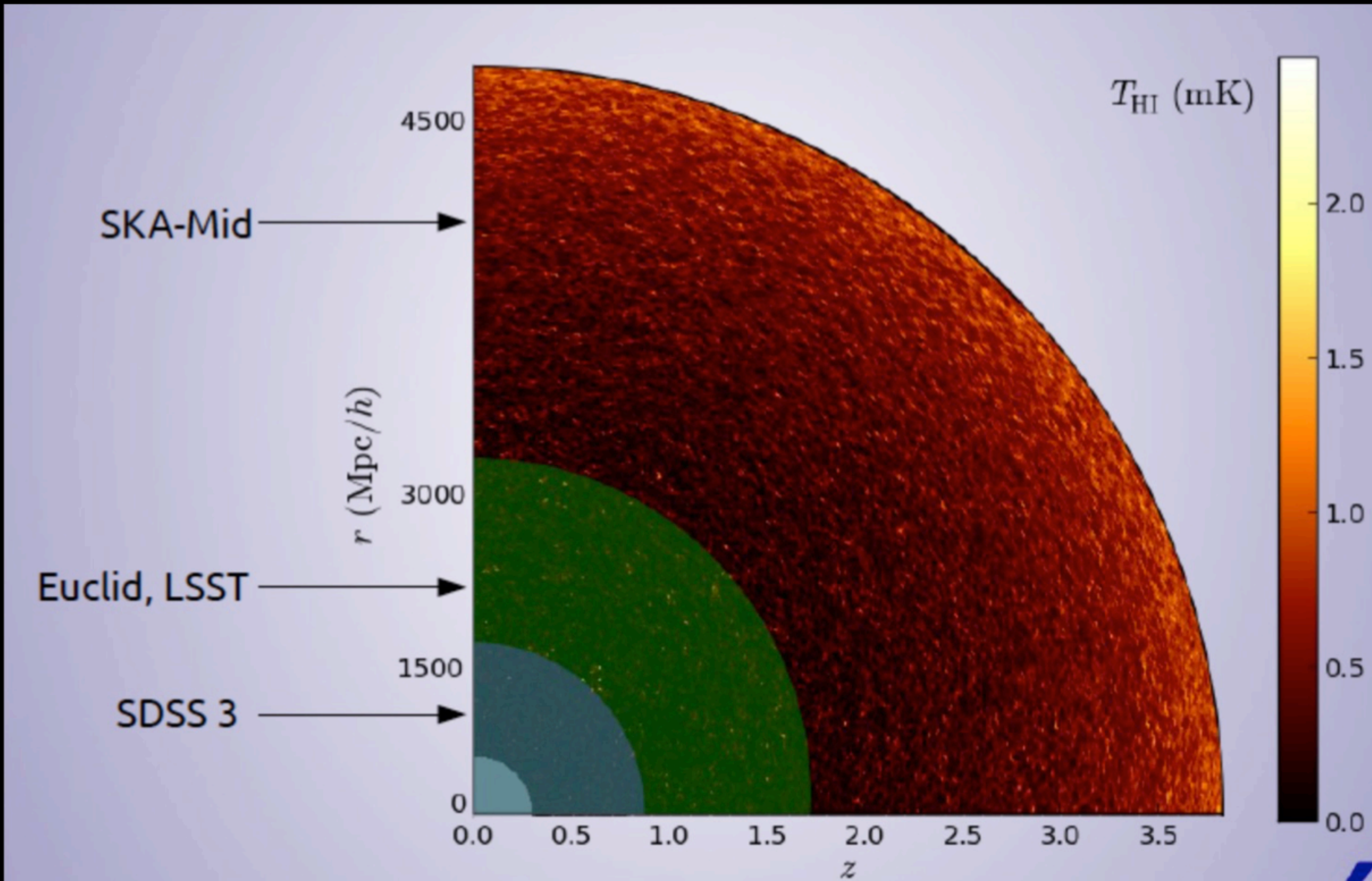
Wide area and deep redshift – can measure very large scales with game-changing precision.

Error over signal on P(k) at k~0.01/Mpc – beyond turnover scale

(Bull et al 2015)

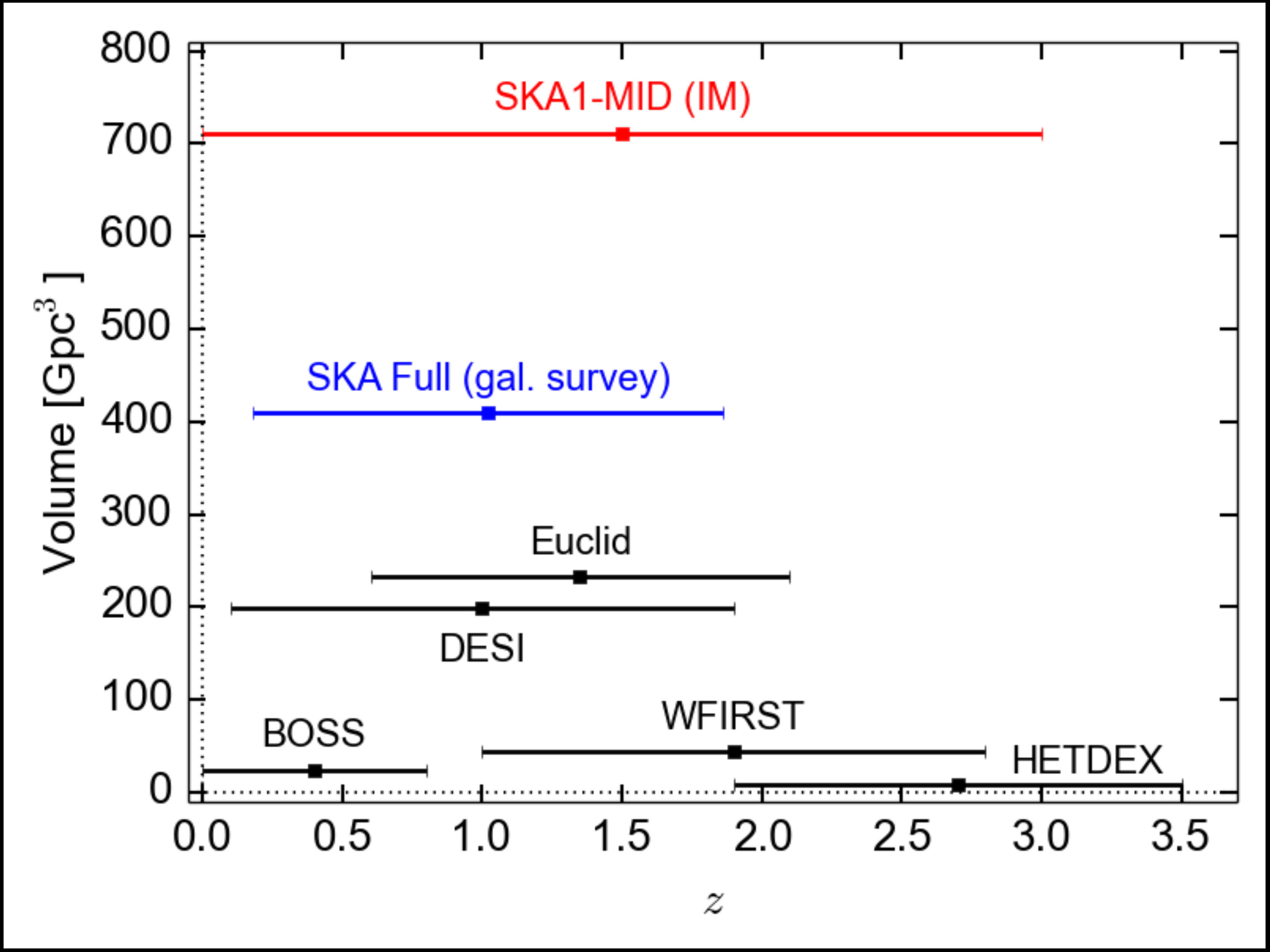


Huge volume of SKA1 intensity mapping



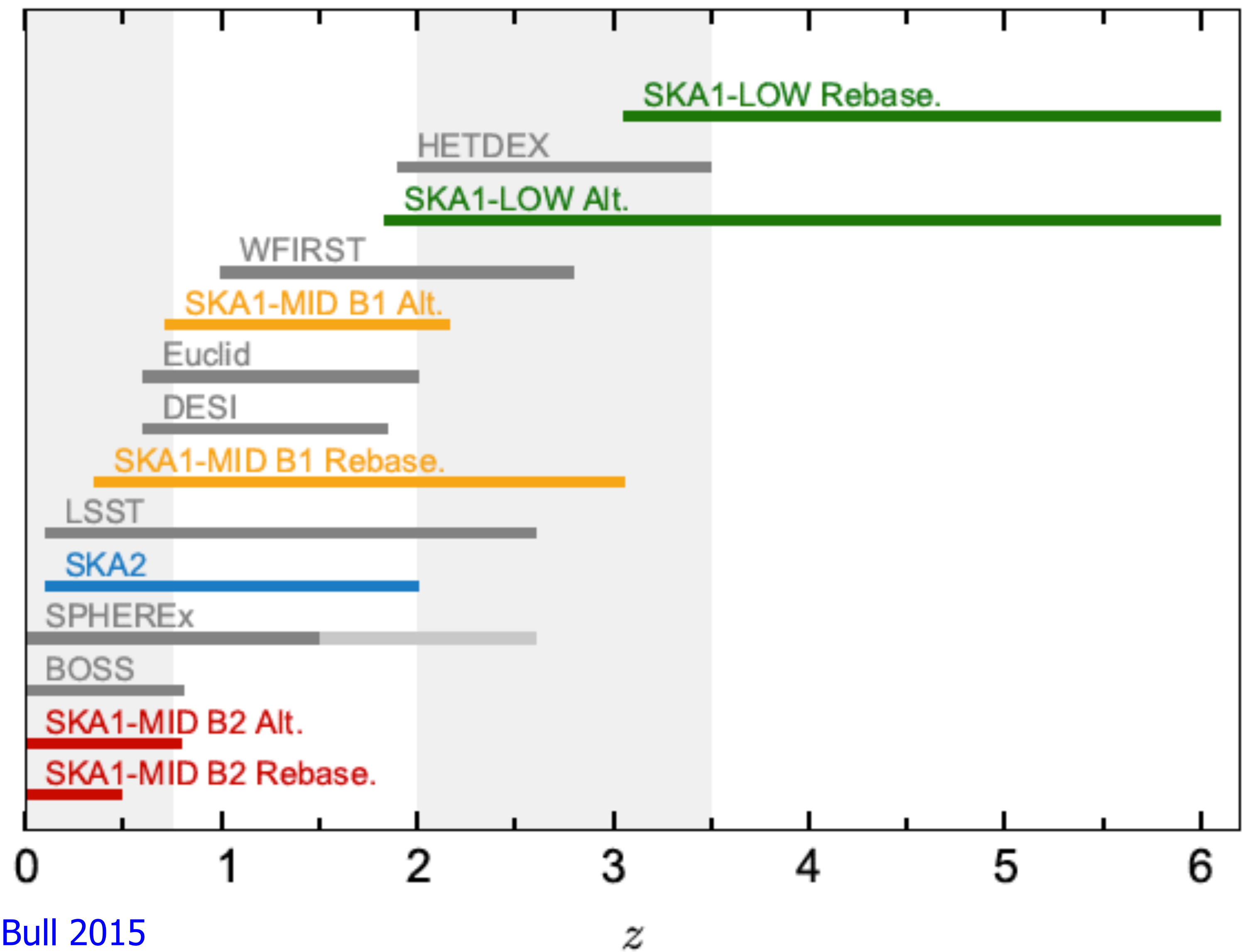
Alonso 2015

Volume of different surveys



(Maartens et al 2014)

Redshift reach of spectroscopic SKA and optical/IR

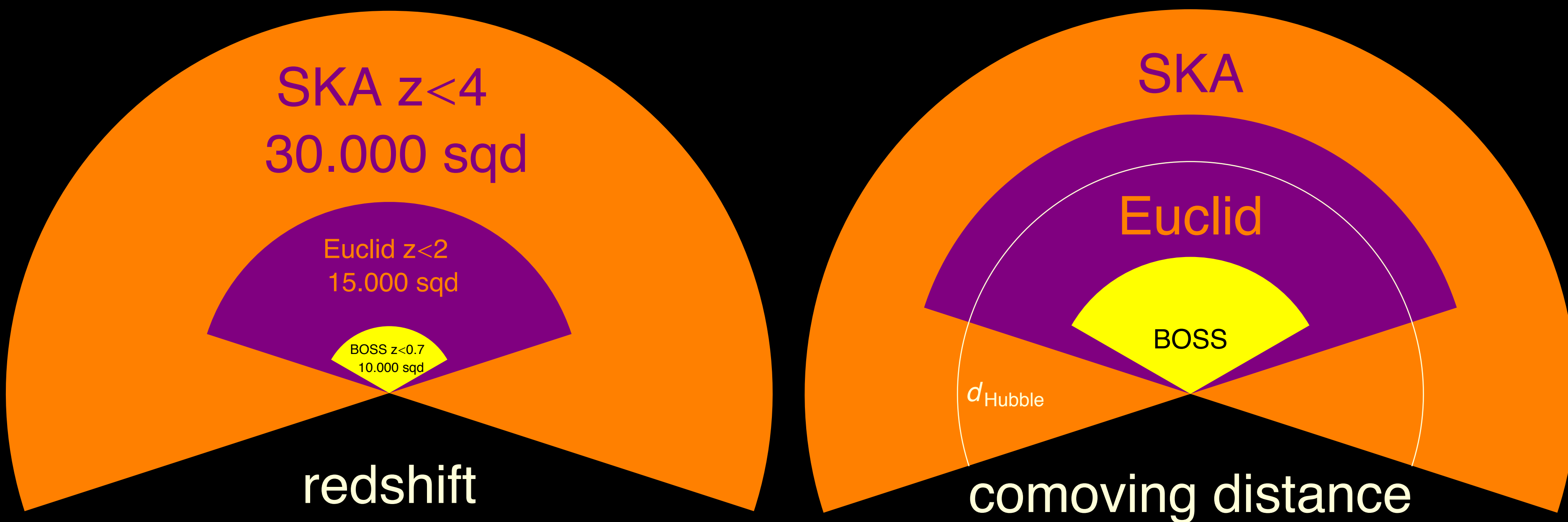


Bull 2015

SKA COSMOLOGICAL SURVEYS

CONTINUUM SURVEY

- SKA1 – 100 million galaxies, 30000 deg^2
- SKA2 – 2 billion galaxies, 30000 deg^2

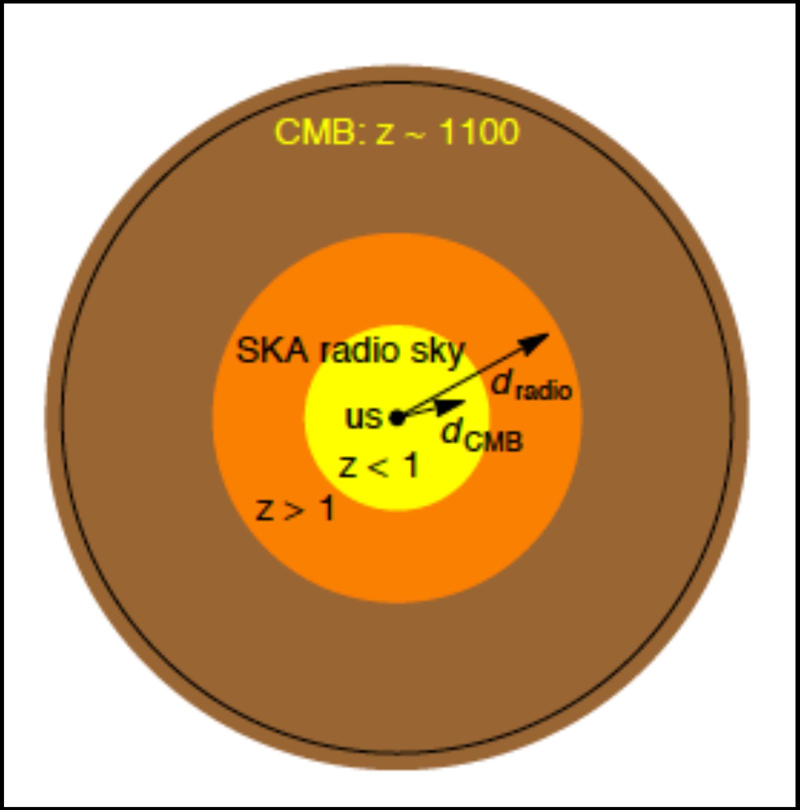


Consistency between galaxies & CMB

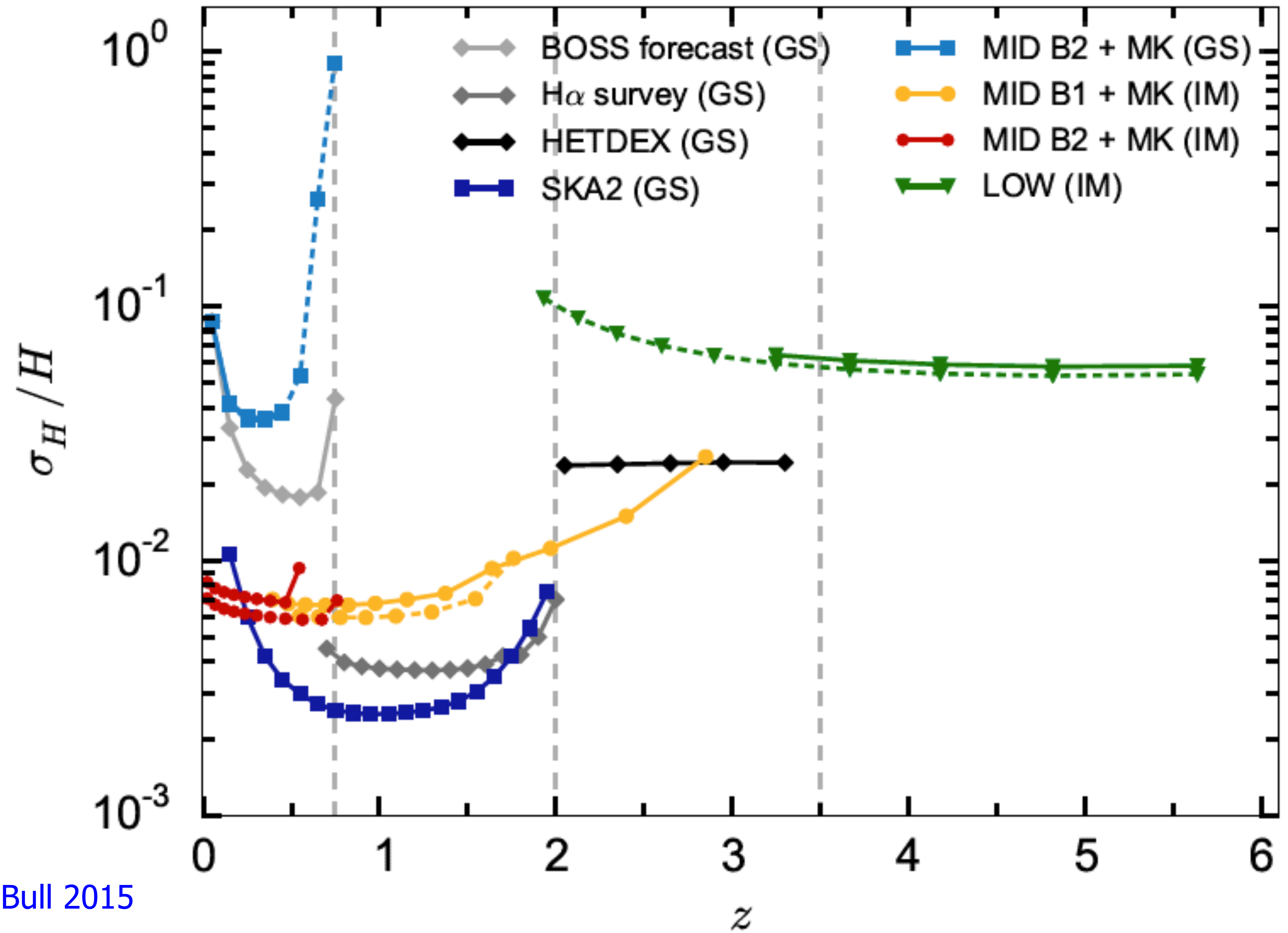
In standard cosmology, the dipole of the matter distribution should agree with the dipole of the CMB.

NVSS all-sky radio survey shows consistency in direction (within very large error bars) but not amplitude.

SKA angular correlation function (100's millions galaxies) will be able to detect dipole within ~5º (Phase 1) and ~1º (Phase 2).

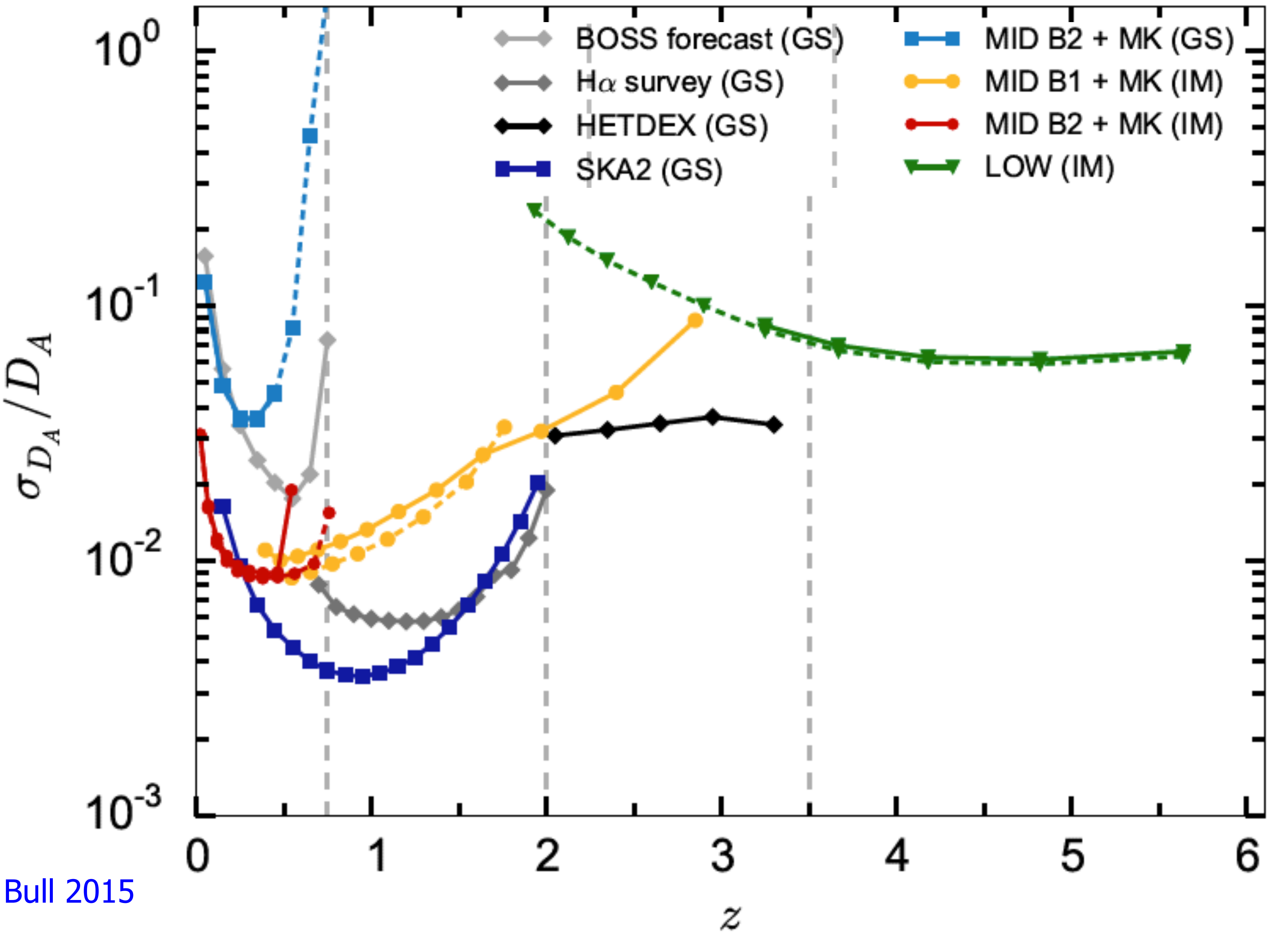


BAO precision – radial



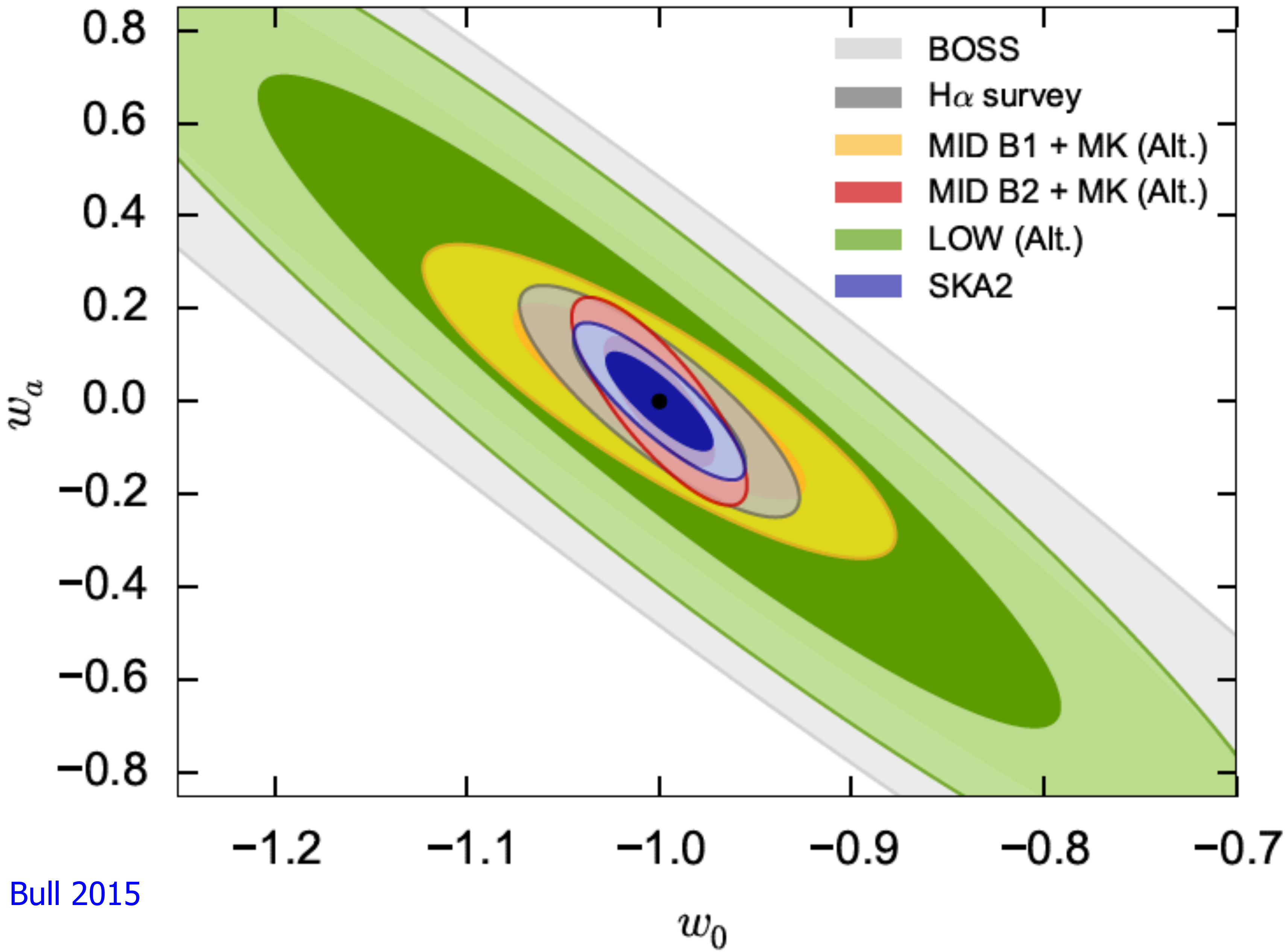
Bull 2015

BAO precision – transverse



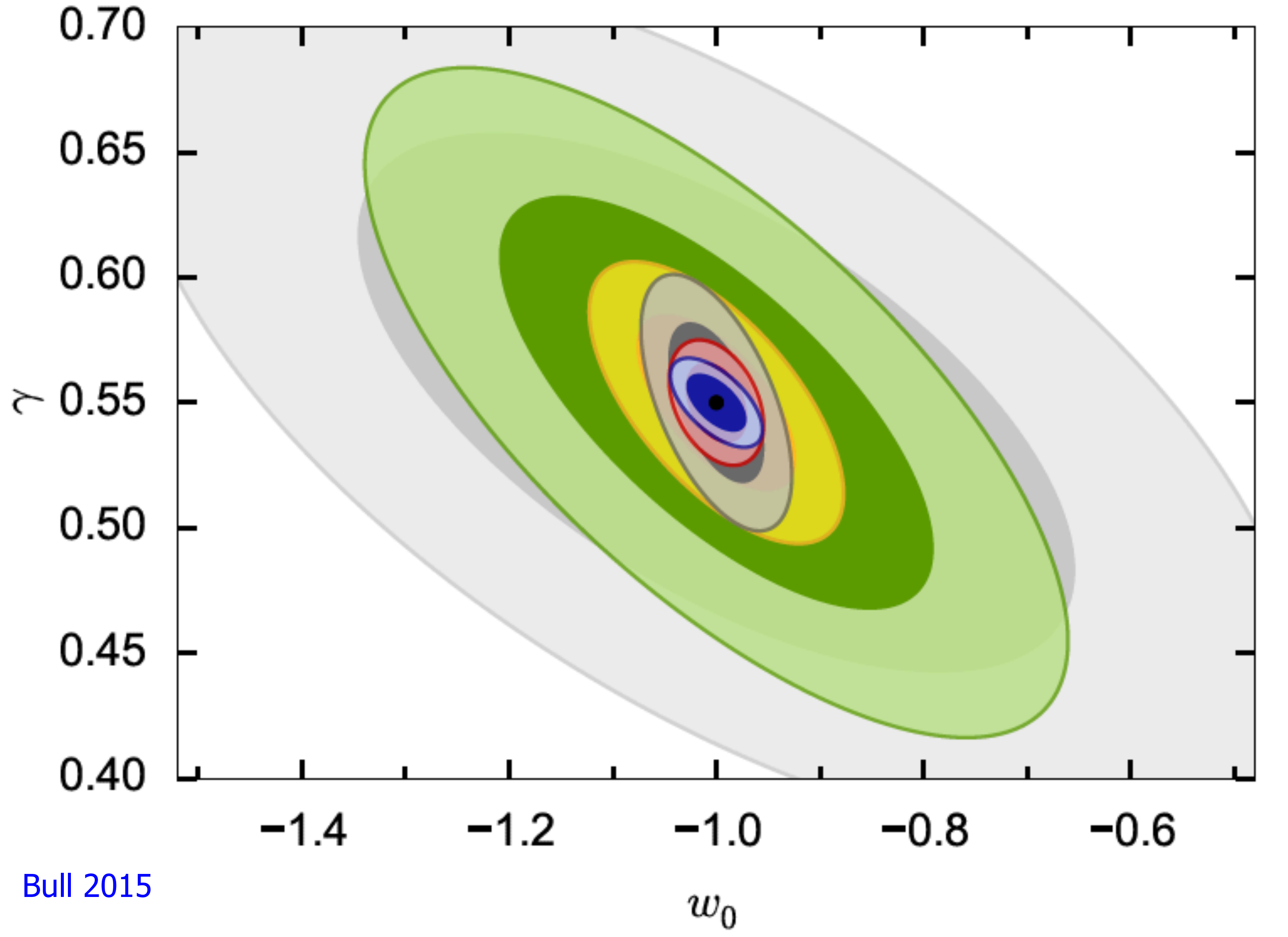
Bull 2015

Probing Dark Energy using RSD



Bull 2015

Testing General Relativity using RSD



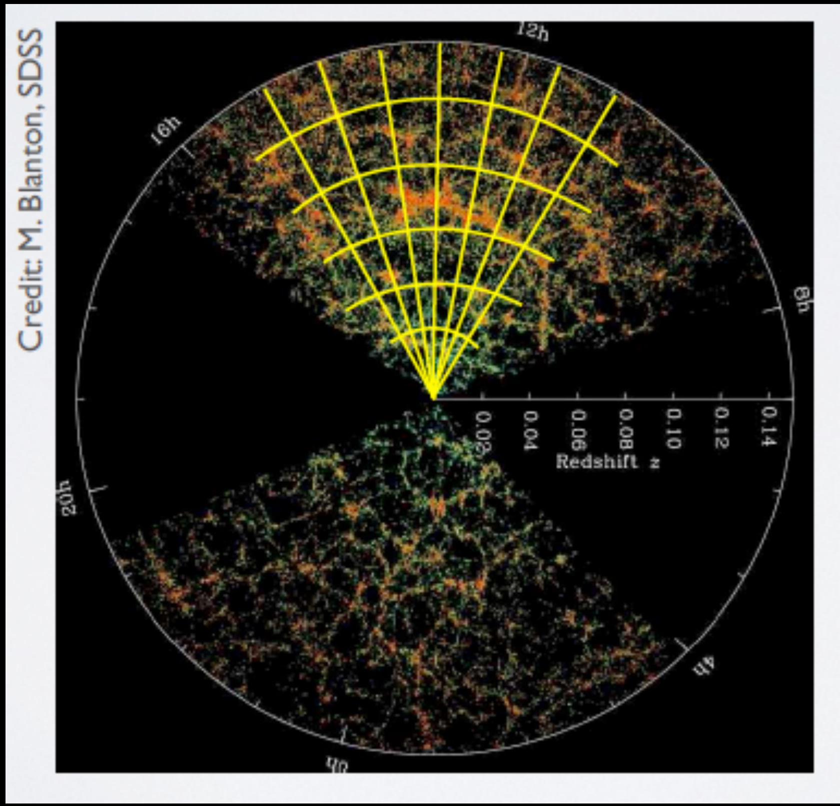
Bull 2015

Observed galaxy counts on the largest scales

We count the number of galaxies per pixel:

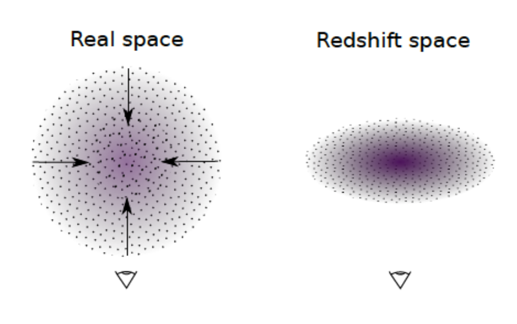
Angular position $\mathbf{n}$ Redshift z

$$N\left(\mathbf{n}, z\right) d\Omega_{\mathbf{n}} dz$$



How do we describe the count fluctuations theoretically?

We need the correct bias definition (in synchronous gauge) plus RSD:



$$\delta_{\rm obs} = b\Delta_m - \frac{1}{\mathcal{H}}\partial_\chi(\mathbf{n}\cdot\mathbf{v}_m)$$

There are additional terms from redshift perturbations and volume perturbations. Start with lensing:

Distant galaxies are magnified by intervening matter. The number density of lensed galaxies is related to the unlensed number density by

$$n_g = \frac{\bar{n}_g}{\mu} \approx \bar{n}_g(1-2\kappa)$$

where we neglect magnification bias and the lensing convergence is

$$\kappa = -\frac{1}{2}\nabla_n^2 \int_{\eta_o}^{\eta} d\tilde{\eta}\, \frac{(\tilde{\eta}-\eta)}{(\eta_o-\eta)(\eta_o-\tilde{\eta})}(\Phi+\Psi).$$

This leads to a lensing contribution to the number counts:

$$\delta_{\rm obs} = b\Delta_m - \frac{1}{\mathcal{H}}\partial_\chi(\mathbf{n}\cdot\mathbf{v}_m) - 2\kappa$$

- RSD allow us to effectively measure peculiar velocities
- Lensing convergence allows us to effectively measure the lensing potential from number counts
  (Alonso et al 2015, Montanari & Durrer 2015)

This offers a possible new way to measure the lensing potential – without the need to measure shapes or sizes or magnitudes of galaxies.

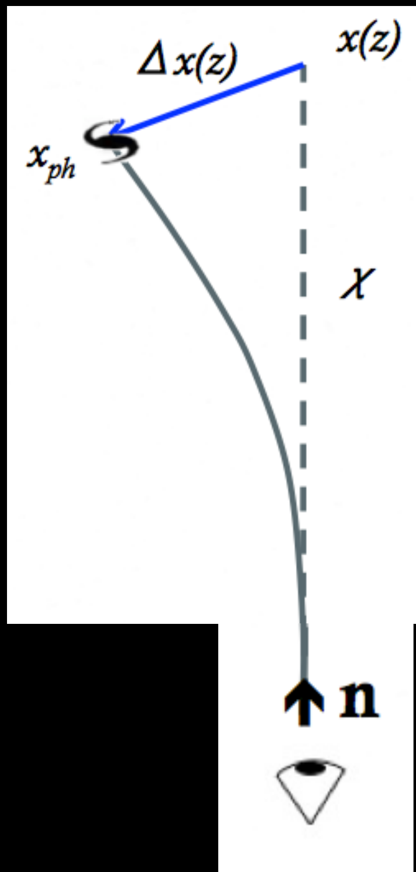
What other contributions are there to $\delta_{\rm obs}$?

Gravitational redshift?

Thinking of the CMB – what about Sachs-Wolfe and ISW effects? And time-delay?

These (and some other terms) are all present – but they are only non-negligible on horizon scales.

We need to consider the full perturbed lightray equation, including the perturbation of the direction vector.



$$(\delta\theta,\ \delta\varphi) = (\theta_S - \theta_O,\ \varphi_S - \varphi_O)$$

$$\frac{\delta z}{1+\bar{z}} = \boldsymbol{n}\cdot\boldsymbol{v} - \Phi - \int^{\eta_o} d\eta(\Phi' + \Psi')$$

These effects have been computed:

Yoo, Fitzpatrick, Zaldarriaga 2009; Yoo 2010; Bonvin, Durrer 2011; Challinor, Lewis 2011

Notation change: $\delta_{\rm obs} \to \Delta, \quad \Delta_m \to D, \quad \chi \to r,$

density

redshift-space distortion

lensing

Doppler

gravitational redshift

$$\Delta(z,\mathbf{n}) = b\cdot D - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$
$$- \int_0^r dr' \frac{r-r'}{rr'}\Delta_\Omega(\Phi+\Psi)$$
$$+ \left(1 - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - \frac{2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n} + \frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n} + \frac{1}{\mathcal{H}}\partial_r\Psi$$
$$\left.\begin{array}{l} + \Psi - 2\Phi + \frac{1}{\mathcal{H}}\dot{\Phi} - 3\frac{\mathcal{H}}{k}V + \frac{2}{r}\int_0^r dr'(\Phi+\Psi) \\ + \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}}\right)\left[\Psi + \int_0^r dr'(\dot{\Phi}+\dot{\Psi})\right] \end{array}\right] \to \text{potential}$$

$$ds^2 = -a^2\left[(1+2\Psi)d\eta^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\right]$$

(Bonvin 2014)

standard expression

$$\Delta(z,\mathbf{n}) = b\cdot D - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$

lensing: important at high z

$$- \int_0^r dr' \frac{r-r'}{rr'}\Delta_\Omega(\Phi+\Psi)$$

relativistic contributions: important at large scale

$$+ \left(1 - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - \frac{2}{r\mathcal{H}}\right)\mathbf{V}\cdot\mathbf{n} + \frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\mathbf{n} + \frac{1}{\mathcal{H}}\partial_r\Psi \qquad \frac{\mathcal{H}}{k}D$$

$$+ \Psi - 2\Phi + \frac{1}{\mathcal{H}}\dot{\Phi} - 3\frac{\mathcal{H}}{k}V + \frac{2}{r}\int_0^r dr'(\Phi+\Psi)$$

$$+ \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}}\right)\left[\Psi + \int_0^r dr'(\dot{\Phi}+\dot{\Psi})\right] \qquad \left(\frac{\mathcal{H}}{k}\right)^2 D$$

New information in the observed overdensity.

Relativistic terms grow on very large scales – but there is cosmic variance

Primordial non-Gaussianity in the galaxy distribution

- Primordial quantum fluctuations generated during Inflation – may be non-Gaussian.
- Primordial non-Gaussianity is 'frozen' on large scales during the expansion of the Universe.
- The effect of PNG of local type is to modify the bias of galaxies relative to the underlying total matter distribution:

$$\Delta_{\mathrm{g}} = b\Delta_{\mathrm{m}} \text{ where } \quad b \rightarrow b + \Delta b, \;\; \Delta b \propto f_{\mathrm{NL}} k^{-2}$$

Local PNG thus boosts the clustering of galaxies on very large scales.
The same problem of cosmic variance.
And – degeneracy between GR effects and PNG

Cosmic variance limits our ability to

- Measure the horizon-scale GR effects
- Measure PNG at the level $\sigma(f_{NL}) < 1$

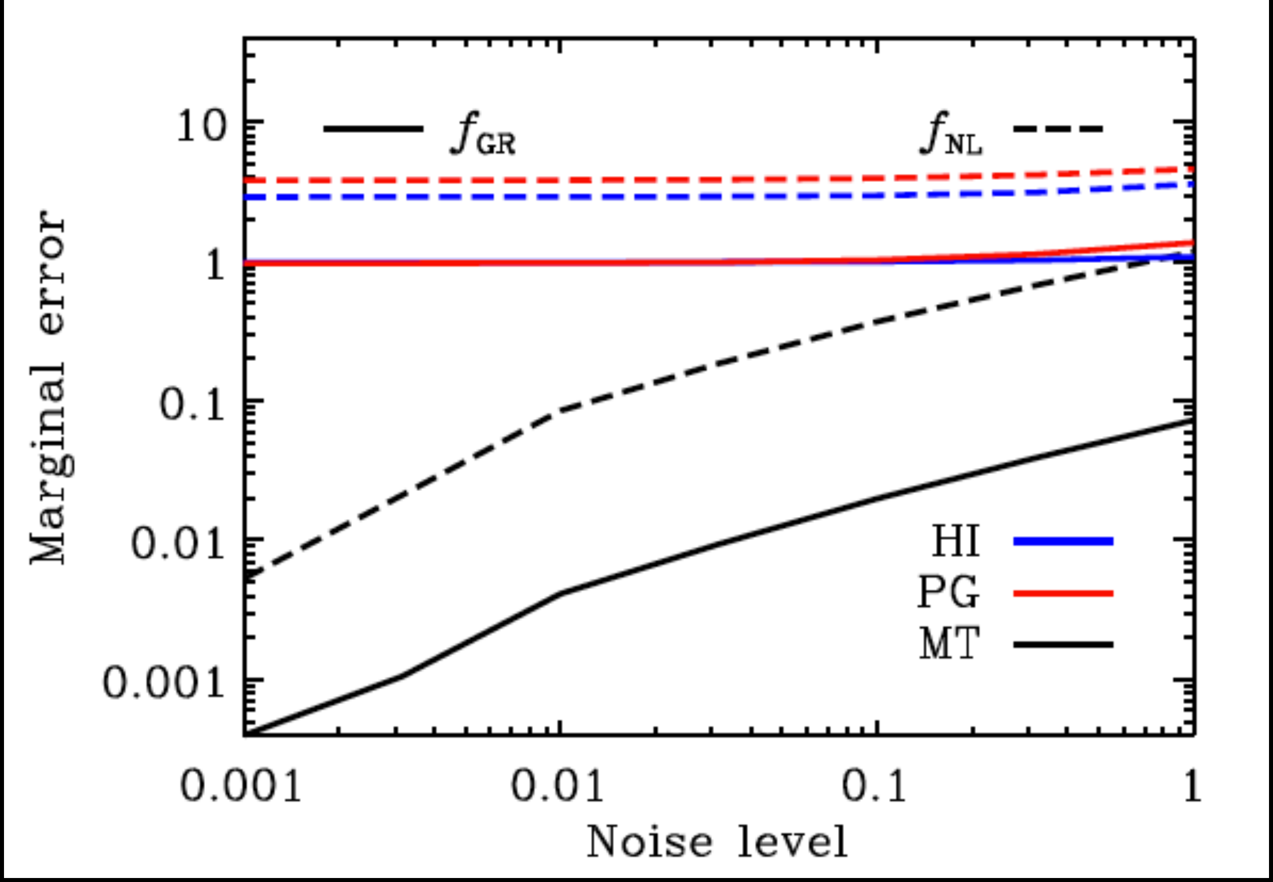
Even the biggest and best future galaxy surveys – Euclid and SKA – will be unable to measure these effects *on their own.*

(Yoo et al 2013, Alonso et al 2015, Raccanelli et al 2015)

However, with the multi-tracer method – i.e. using 2 different tracers of the matter stochastic DM distribution – we can detect the horizon-scale GR terms at high confidence, and achieve $\sigma(f_{NL}) < 1$

(Alonso & Ferreira 2015, Fonseca et al 2015)

Multi-tracer method – using SKA1 HI intensity mapping + Euclid photometric survey



- New information from the galaxy distribution on horizon scales
- Probe PNG well beyond the CMB precision – new tests of inflation

THE HEADLINE MESSAGE

SKA1

- HI intensity mapping survey:
  precise BAO, RSD up to z~3
  excellent constraints on DE and modified gravity
  probe the largest scales ever – non-Gaussianity, modified gravity
- HI galaxy redshift survey:
  precise RSD at z<0.5
- Continuum survey:
  test isotropy of the universe
  good constraints on non-Gaussianity

SKA2

- HI redshift survey ('billion galaxy survey') will be the state of the art
- Radio lensing competitive with optical lensing surveys

SYNERGY

- Radio gives different systematics to optical/ IR – and the combination is stronger than each separately