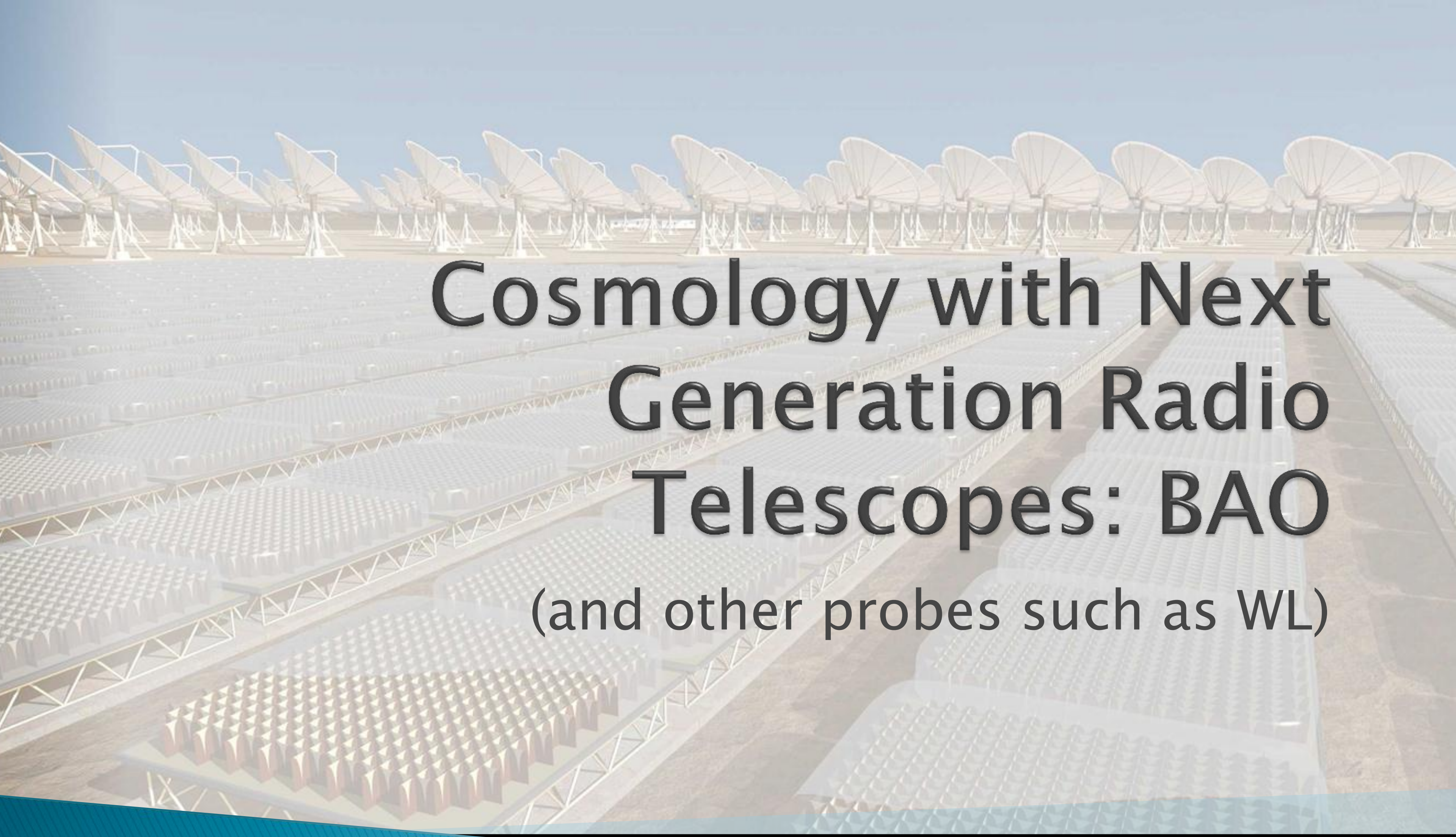


Cosmology with Next Generation Radio Telescopes: BAO

(and other probes such as WL)

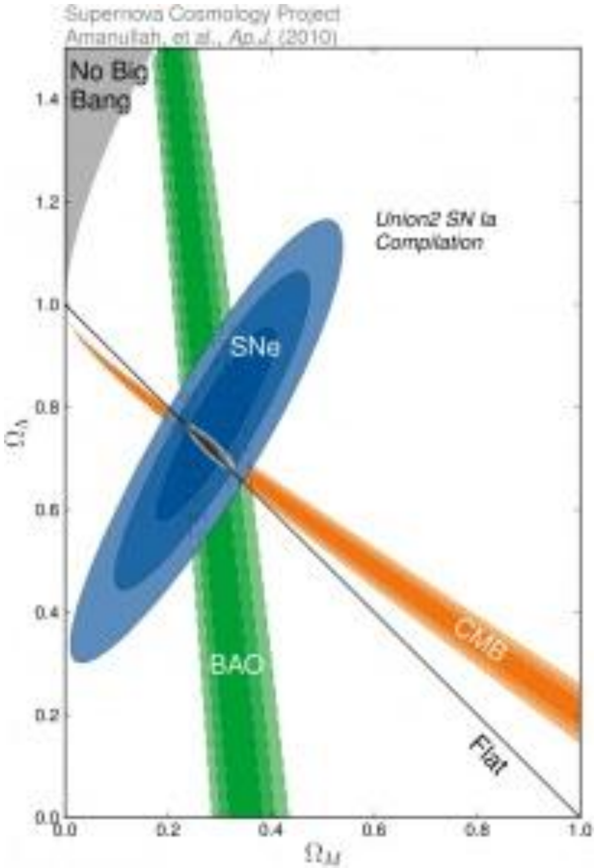
Mário Santos – Instituto Superior Técnico / CENTRA

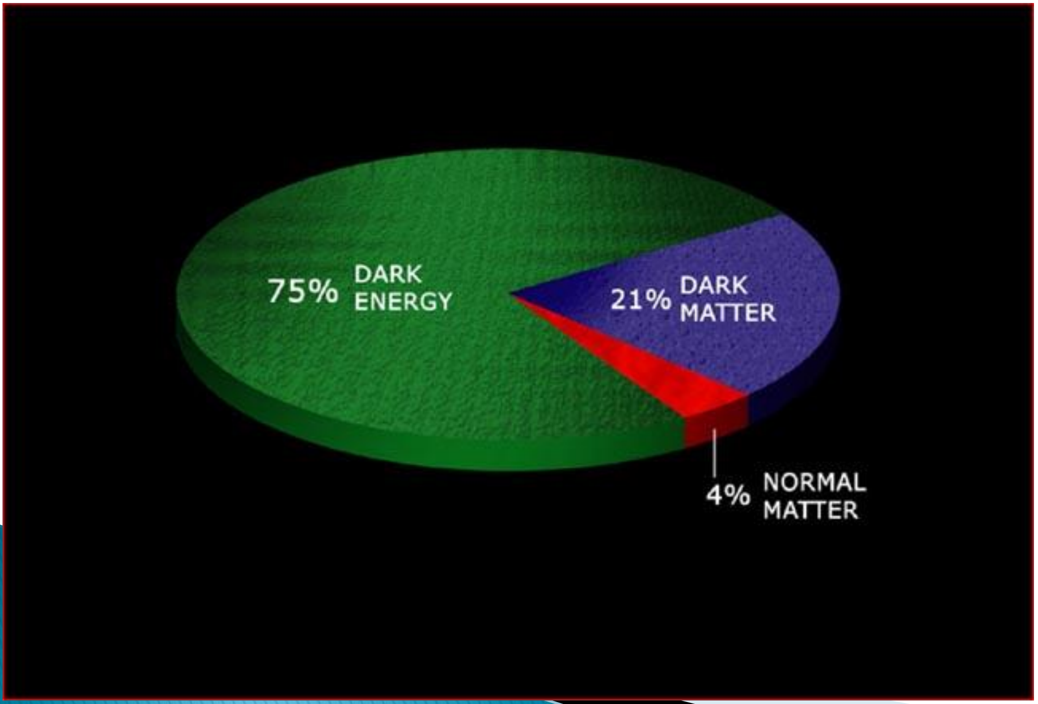
AAVP – ASTRON – Dec 2011

What do we want to probe?

Gold is gold...

Accelerated expansion is now official: 2011 nobel prize!
But **WHAT IS THE REASON??**


Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)



What do we want to probe?

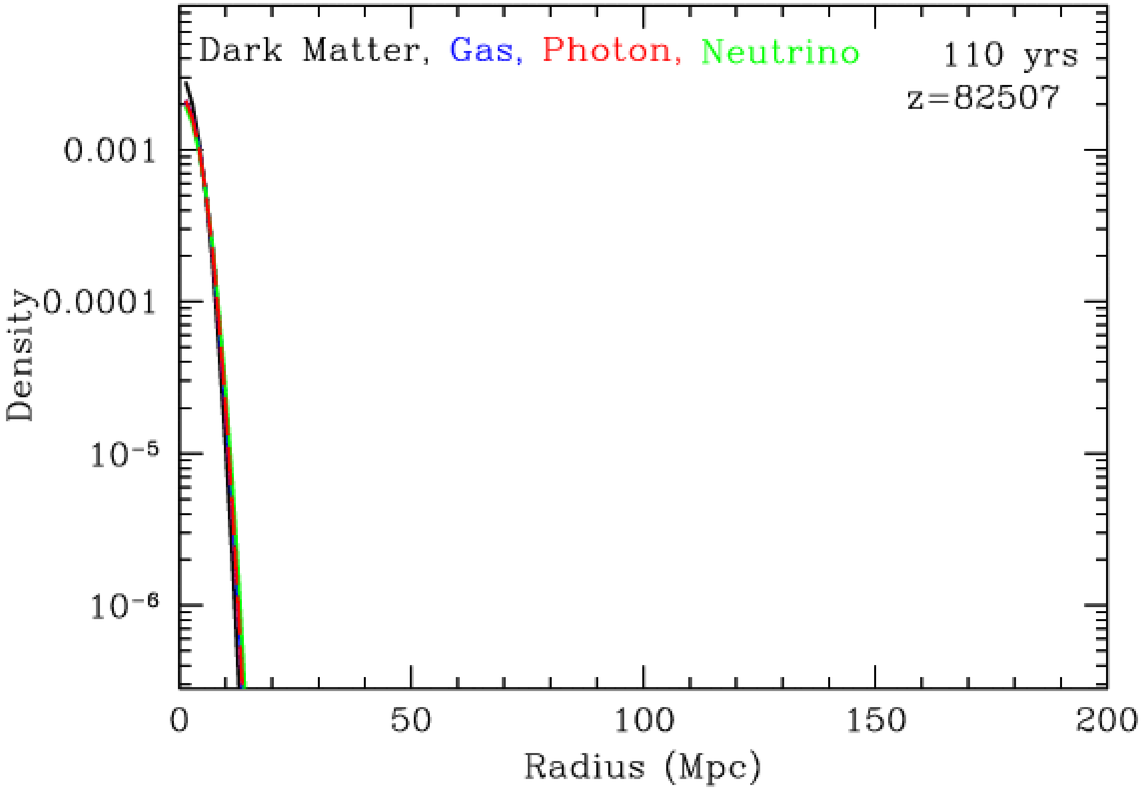
- Nature of Dark Energy (Cosmological Constant, Dynamical dark energy, Modified Gravity)
- Inflation (spectral index, primordial non-Gaussianity)
- Neutrino mass
- …

Main probes

- Galaxy number density: clustering / 2-point correlation function (including BAO and Redshift Space Distortions)
- Weak Lensing (shear and magnification)
- Intensity mapping
- Test both the geometry of the Universe and the growth of structure

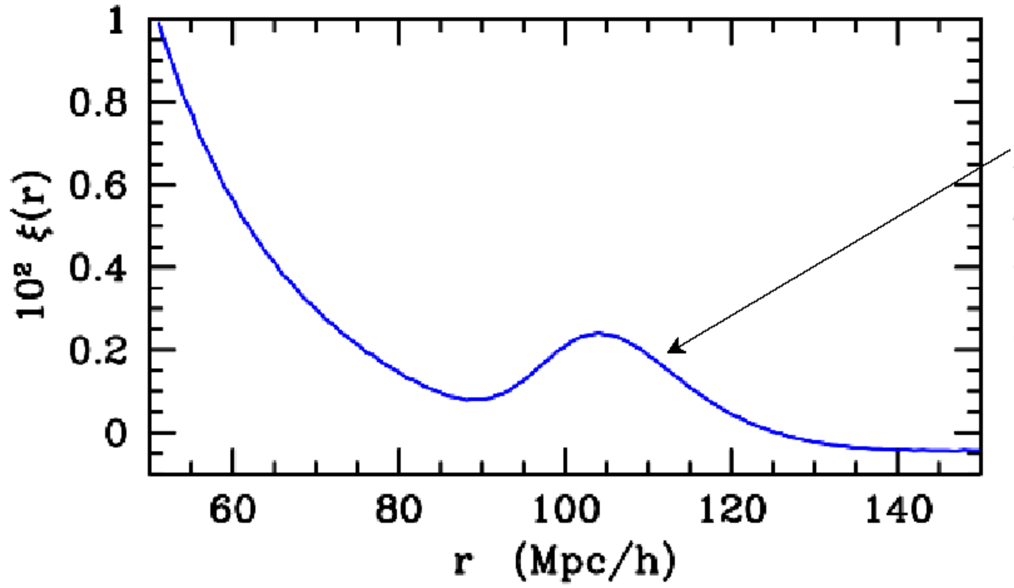
Baryon Acoustic Oscillations (BAO 101)

- Baryon-photon fluid in the early Universe
- Start with single perturbation
- Pressure drives fluid outward close to speed of light
- After decoupling photons diffuse
- Baryons remain overdense in a shell ~ 100 Mpc in radius (sound horizon)
- Baryons and DM reach equilibrium density

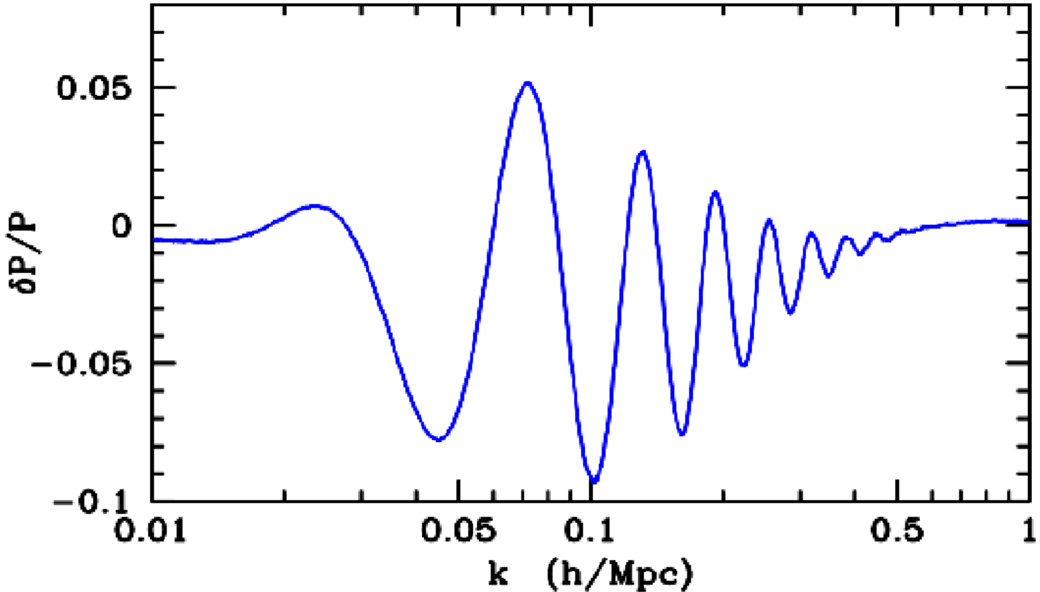


Martin White

BAO 101 – standard ruler



Acoustic feature at ~100 Mpc/*h* with width ~10 Mpc/*h* (Silk scale)



- Characteristic scale: L ~ 150 Mpc (determined from CMB)
- Measured in correlation function or power spectrum:

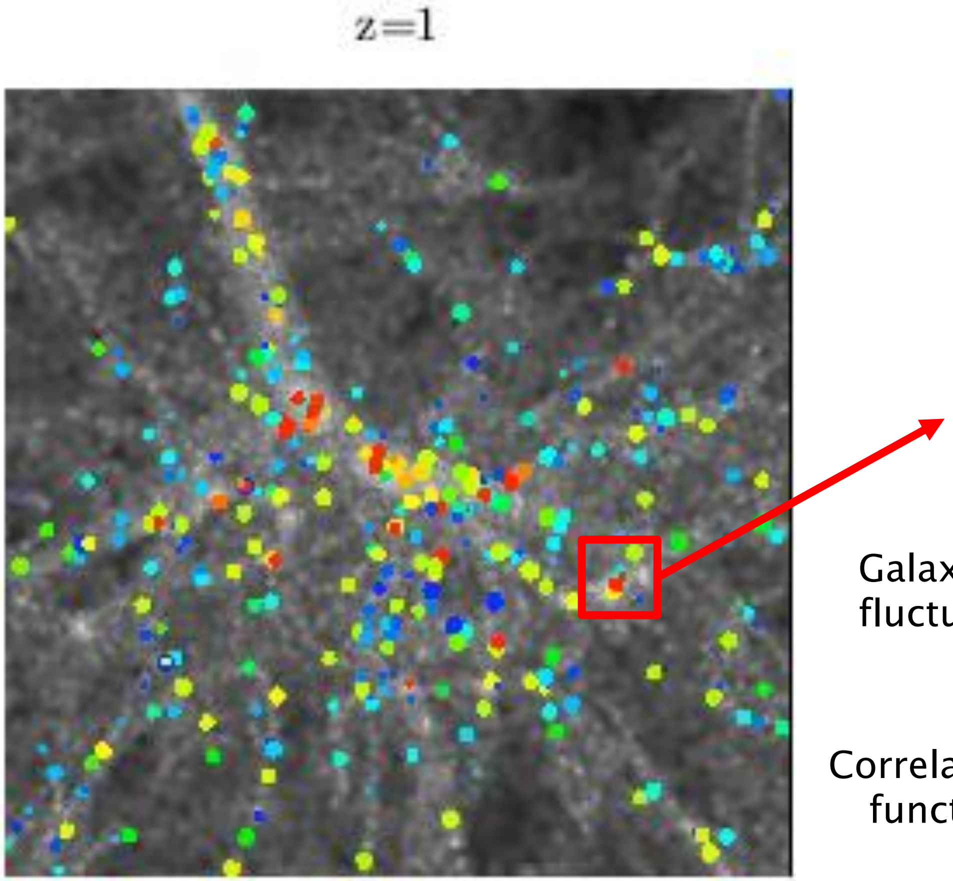
Compare to model (with DE)

$$d_A(z) = L/(\Delta\theta(1+z))$$

measured

$$H(z) = c\Delta z/L$$

BAO using Galaxy number density



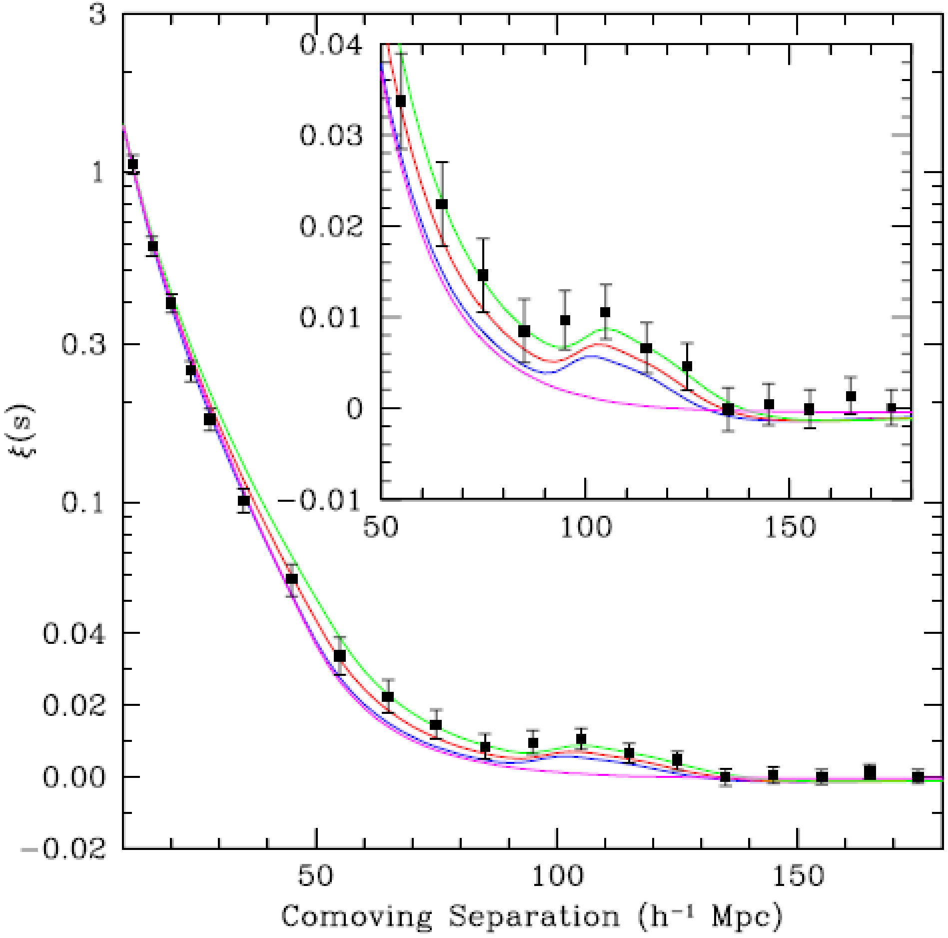
$$\underset{\underset{\text{Galaxy number fluctuations}}{\downarrow}}{\frac{\delta n}{n}} = \overset{\overset{\text{Galaxy bias}}{\downarrow}}{b()}\,\underset{\underset{\text{Matter density fluctuations}}{\downarrow}}{\delta_m} + \overset{\overset{\text{Poisson fluctuations}}{\downarrow}}{\delta_p}$$

Correlation function: $\xi_G = b()^2\xi_m + \frac{1}{nV}$

- Detect galaxies (~ 10 sigma threshold)
- Use 2-point correlation in 2d (angular) and 3d (with z)
- Need large number in each pixel to beat down Poisson fluctuations

BAO 101: measurements

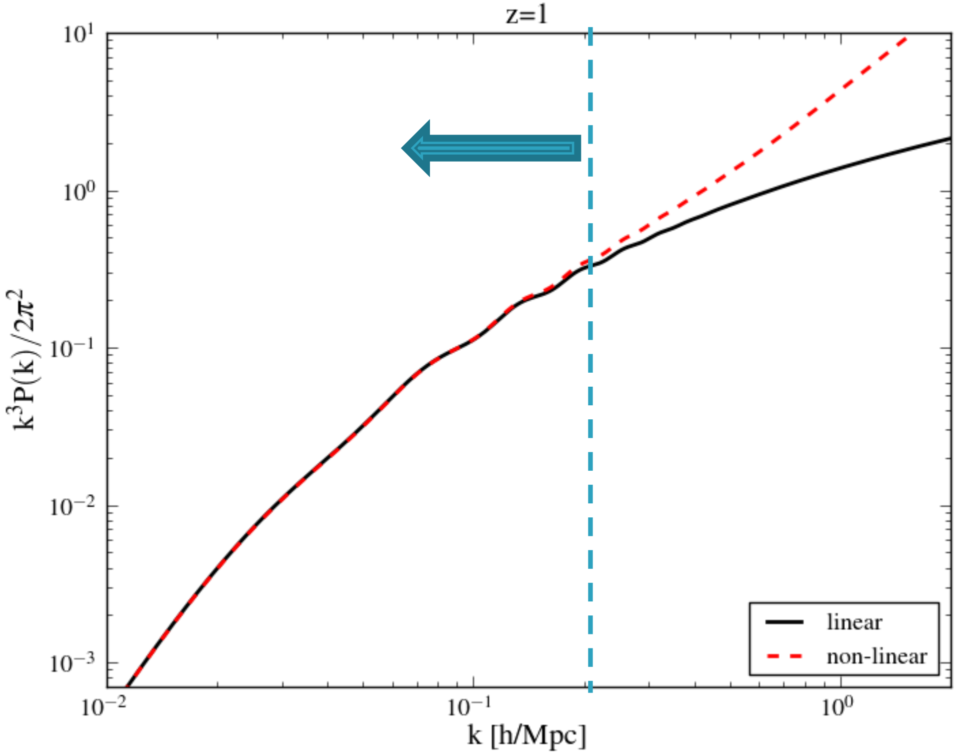
- Galaxies form in dark matter overdensities
- 1% enhancement at the acoustic scale
- Can be seen in galaxy correlation function
- Position of the "bump" is independent of galaxy bias! (assuming it is constant on those scales)



SDSS: Eisenstein et al. 2005

BAO observations wish list

Dark matter power spectrum



- Scales of interest (z=1):
  - Min. BAO scale ~ 15.7 Mpc/h
  - k_{max} ~ 0.2 h/Mpc
  - Angular resol ~ 22.8 arcmin
  - dz ~ 0.009
  - Freq. resol ~ 3.14 MHz

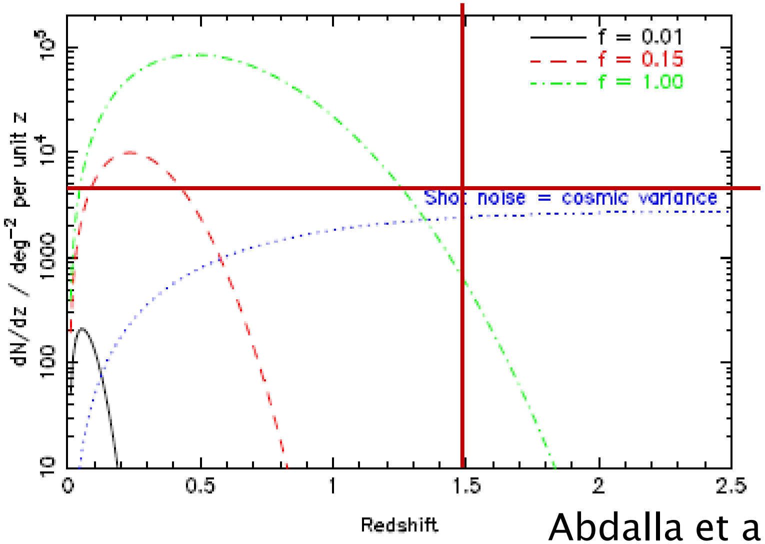
  - Max. BAO scale ~ 628 Mpc/h
  - k_{min} ~ 0.01 h/Mpc
  - Maximum angular scale ~ 15 deg
  - dz ~ 0.35
  - BW ~ 123 MHz

  - Survey area ~ 20000 deg^2
  - $0.5 < z < 1.5$ (2.0?)
  - 550 MHz $< \nu <$ 950 MHz
  - Full Bandwidth ~ 500 MHz

BAO: design issues (threshold experiments)

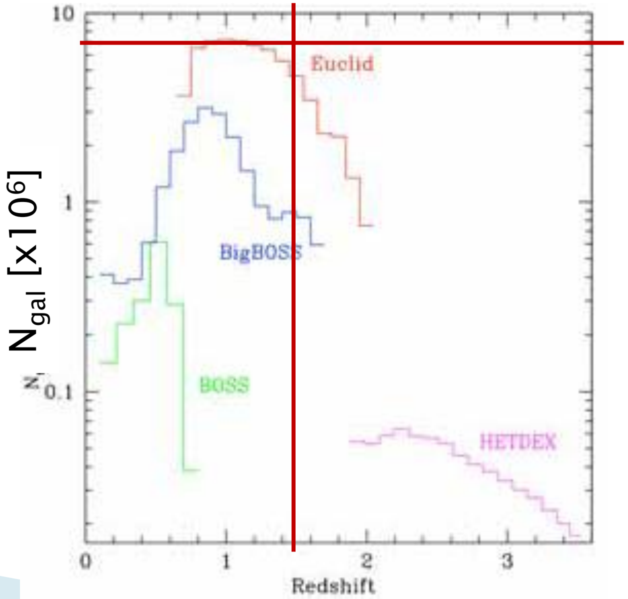
- Galaxy surveys:
  - High sensitivity to beat shot noise ($n \times P(k) \sim 1$)
  - Large survey volume to probe BAO scales and reduce cosmic variance

- Full SKA HI survey:
  - $f=1$ ($f=[10^6\ m^2/A_{eff}][50\ K/T_{sys}]$)
  - FoV ~ 10 deg^2
  - 10σ detection
  - Full BW
  - 1 year
  - Survey area: 20,000 deg^2
  - ~ 10^9 HI galaxies



Euclid

Abdalla et al, 2010

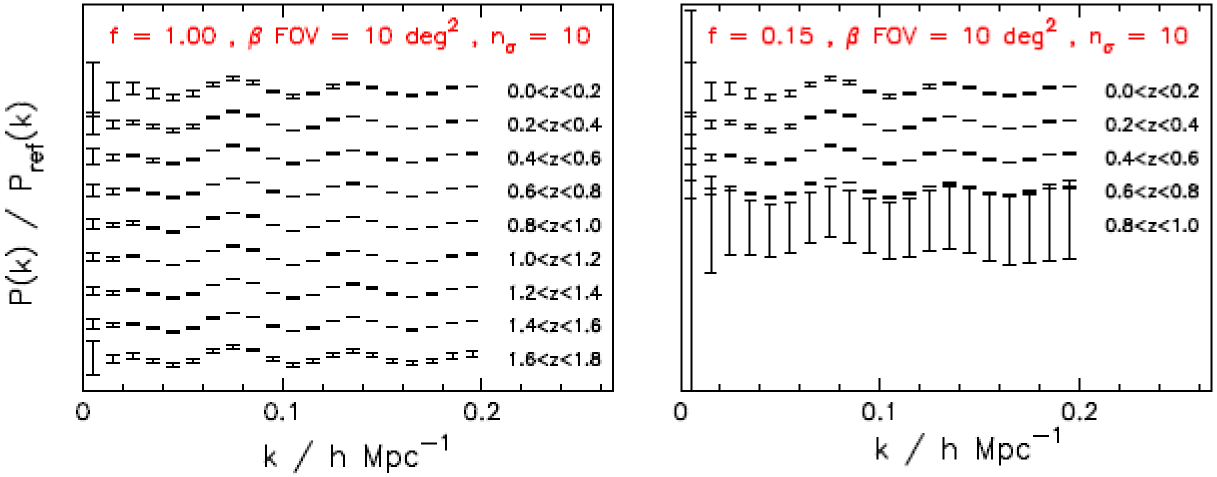


~ 4600 galaxies/deg^{-2} per unit z

~ 50 million galaxies (from Euclid Study Report)

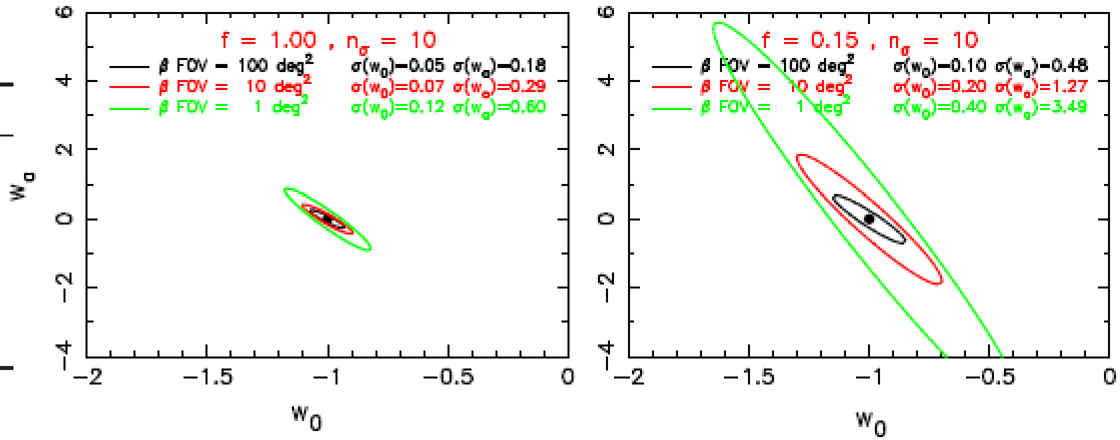
BAO: constraints from SKA HI survey

- Measuring the BAO wiggles



- Constraints from **full power** spectrum measurement (includes redshift-space distortions) + Planck

Parameter	$f = 0.15$ SKA (1)	$f = 0.15$ SKA (2)	$f = 1$ SKA
Ω_b	0.00024	0.00044	0.00016
Ω_c	0.0016	0.0021	0.00086
w	0.010	0.022	0.0062
n_s	0.0024	0.0028	0.0021
σ_8	0.0026	0.010	0.0013
h	0.0019	0.0035	0.0010
τ	0.0042	0.0041	0.0036



- Dark energy constraints (BAO only)

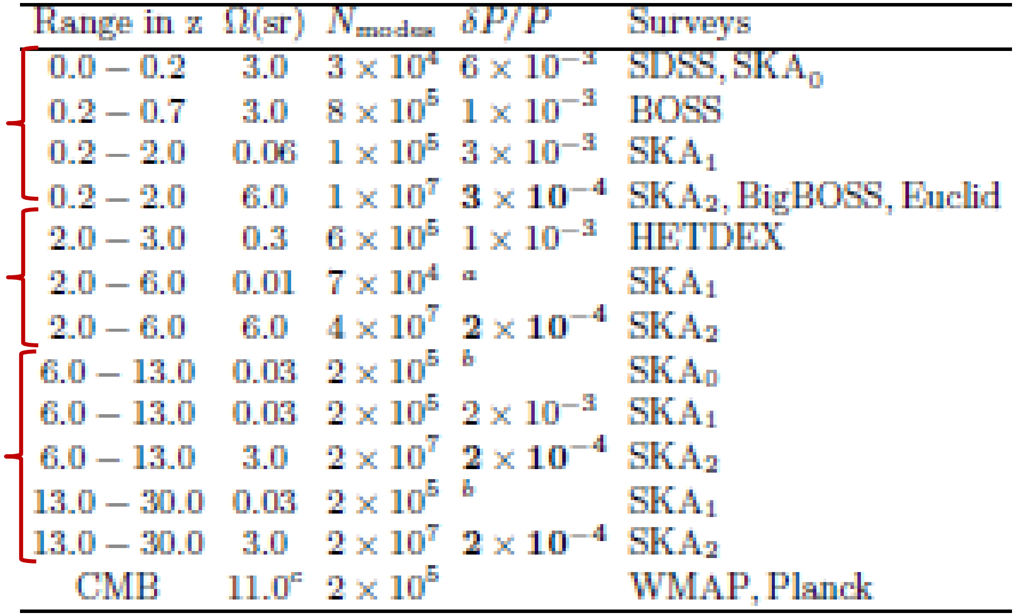
Abdalla, et al, 2010

Measuring the matter density field

Dark Energy
Modified gravity

Curvature, non-Gaussianity, etc

EoR, Dark ages, but also cosmology…

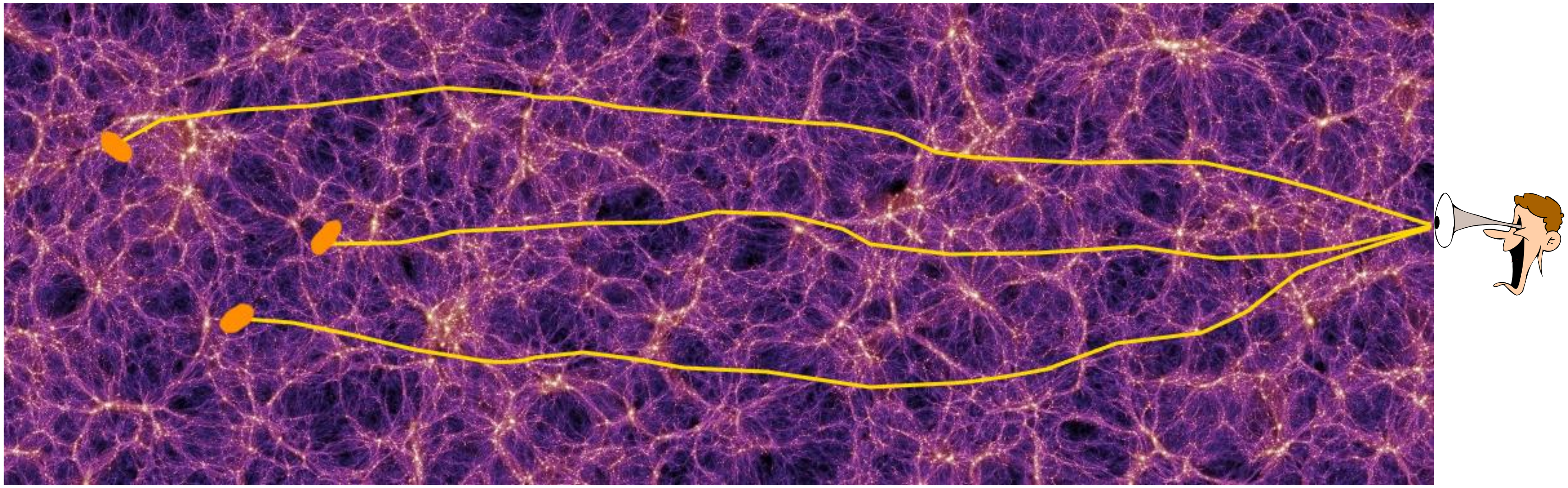


Range in z	Ω(sr)	N_{modes}	$\delta P/P$	Surveys
$0.0-0.2$	3.0	3×10^4	6×10^{-3}	SDSS, SKA$_0$
$0.2-0.7$	3.0	8×10^5	1×10^{-3}	BOSS
$0.2-2.0$	0.06	1×10^5	3×10^{-3}	SKA$_1$
$0.2-2.0$	6.0	1×10^7	$\mathbf{3\times10^{-4}}$	SKA$_2$, BigBOSS, Euclid
$2.0-3.0$	0.3	6×10^5	1×10^{-3}	HETDEX
$2.0-6.0$	0.01	7×10^4	^{a}	SKA$_1$
$2.0-6.0$	6.0	4×10^7	$\mathbf{2\times10^{-4}}$	SKA$_2$
$6.0-13.0$	0.03	2×10^5	^{b}	SKA$_0$
$6.0-13.0$	0.03	2×10^5	2×10^{-3}	SKA$_1$
$6.0-13.0$	3.0	2×10^7	$\mathbf{2\times10^{-4}}$	SKA$_2$
$13.0-30.0$	0.03	2×10^5	^{b}	SKA$_1$
$13.0-30.0$	3.0	2×10^7	$\mathbf{2\times10^{-4}}$	SKA$_2$
CMB	11.0^c	2×10^5		WMAP, Planck

S. Rawlings, 2011

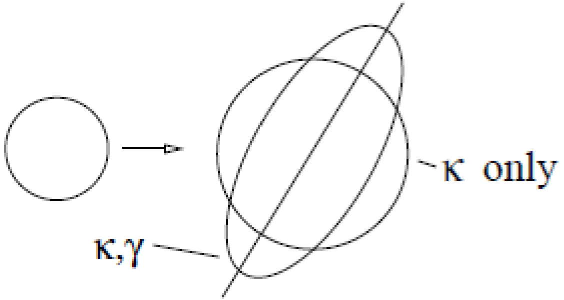
- SKA phase 1, $z < 2$: dishes with PAFs ~ 100 deg^2 survey
- SKA phase 2, $z < 2$: 250x56-m diameter AA? – billion galaxy survey
- Important to have different experiments/multi-wavelength approach to the dark energy problem (control of systematics)

Weak Gravitational Lensing



Hartlap, 2009

- Light is continuously deflected by large-scale structure
- Distortion (shear) of images of distant galaxies
- Direct measure of geometry and mass (growth of structure)
- No bias dependence!
- Great Modified Gravity probe: $\Psi + \Phi$



- Estimated from galaxies ellipticities
- 1% change in ellipticity
- Assumption: random intrinsic orientation

Weak Lensing requirements

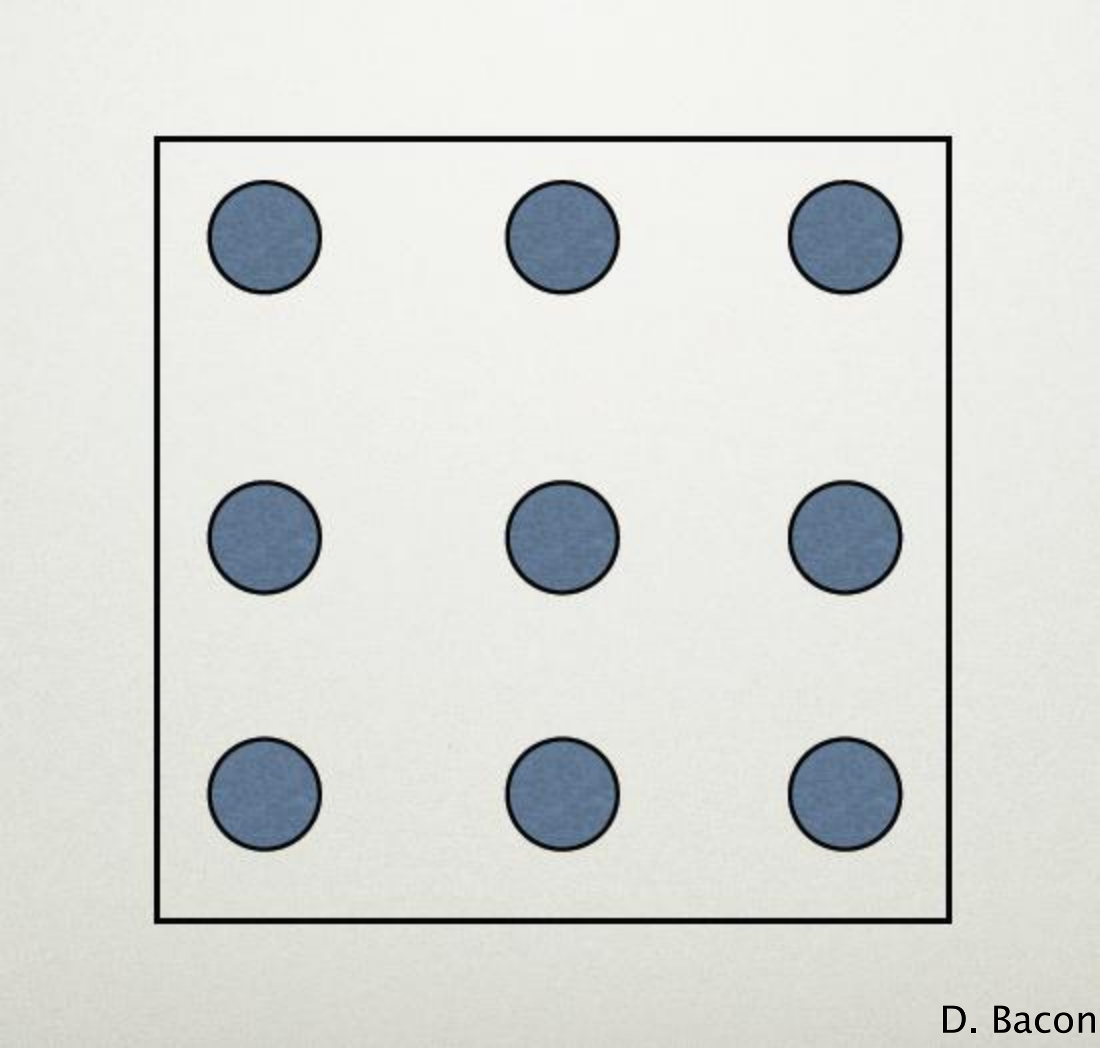
- Need very high image quality for shape measurements (good control of psf)
- Resolution ~ 0.1 arcsec
- High source density (~ 100 galaxies/arcmin^2) to reduce shot noise
- High survey area (~ 20,000 deg^2) to reduce cosmic variance (and probe large scales)
- Some redshift information (dz ~ 0.2)

Weak Lensing and SKA

- Not a design driver at the moment…
- Do continuum survey (30 nJy in 4h, Blake et al 2004)
- ~ 500 gal/arcmin^2 and shear rms ~ 0.2?
- Unknown scatter in intrinsic ellipticities…
- Tomographic WL experiment using HI survey
- 0.1 arcsec ~ 100 Km baselines
- Use dishes (with PAFs?) at ~ 1-2 GHz (~ 10 deg^2 FoV)
- Hard but worth trying!
- However…

Don’t forget Magnification!

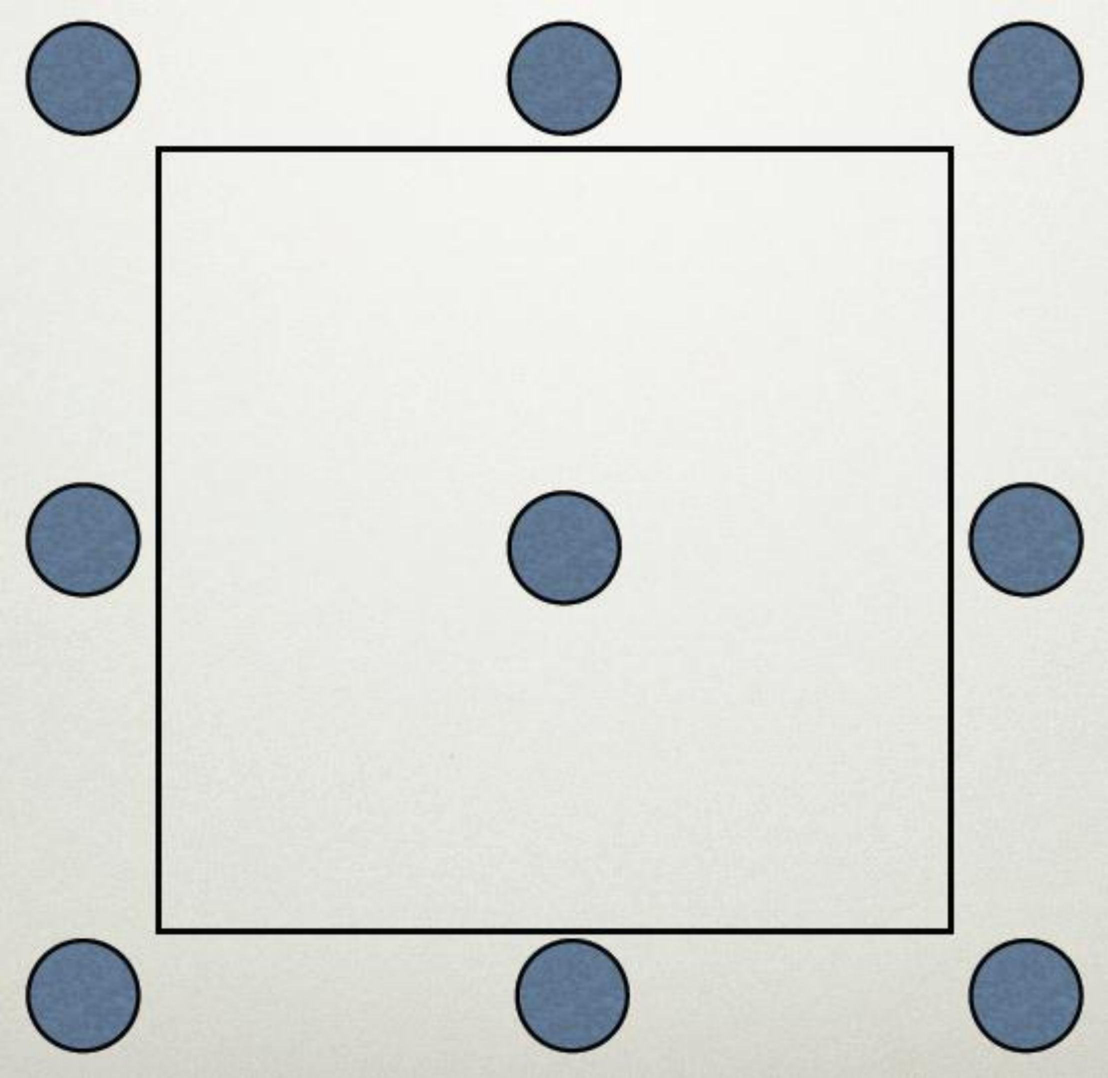
- Effect on galaxy number:



D. Bacon

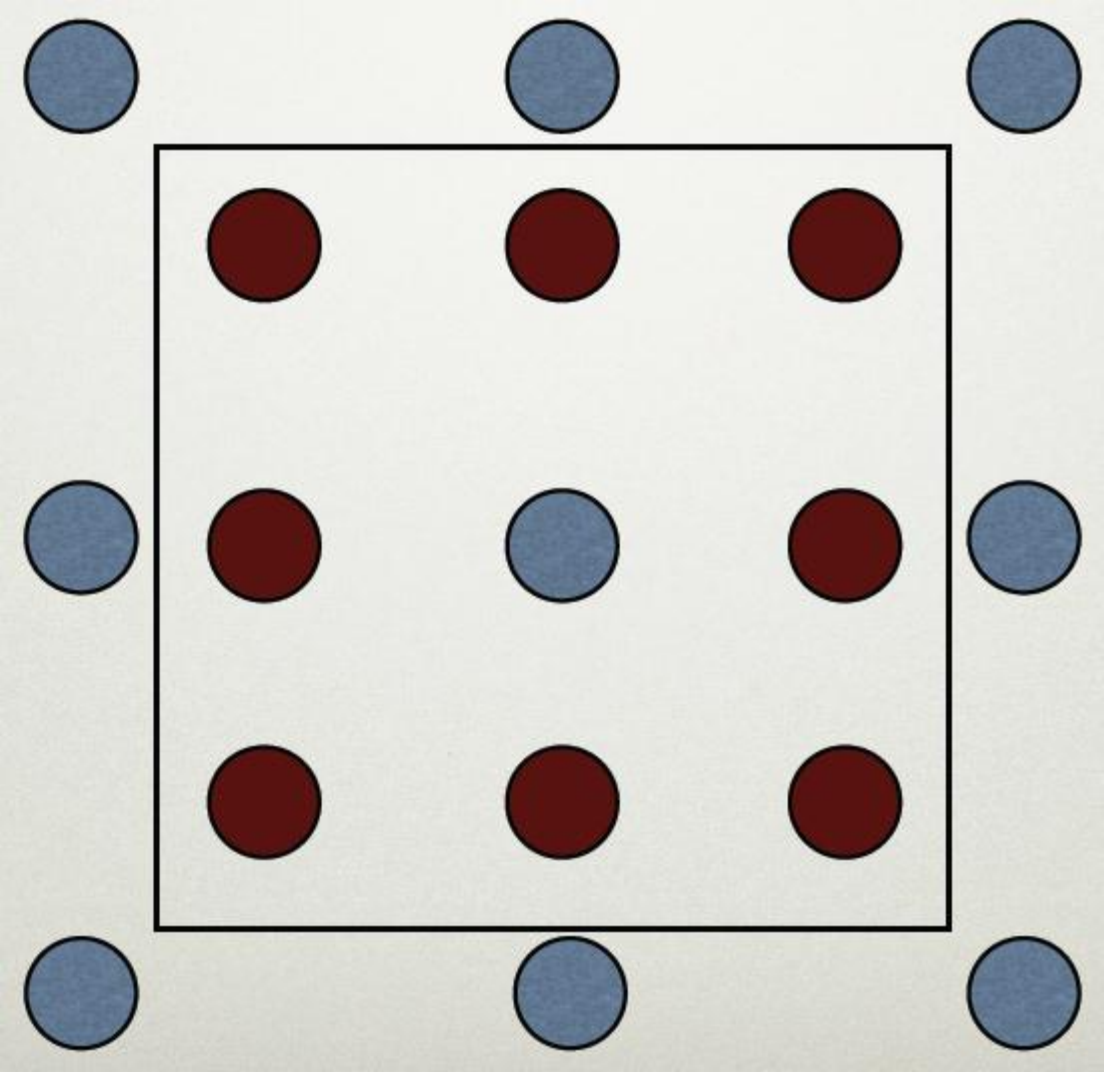
Don’t forget Magnification!

- Increase of solid angle:

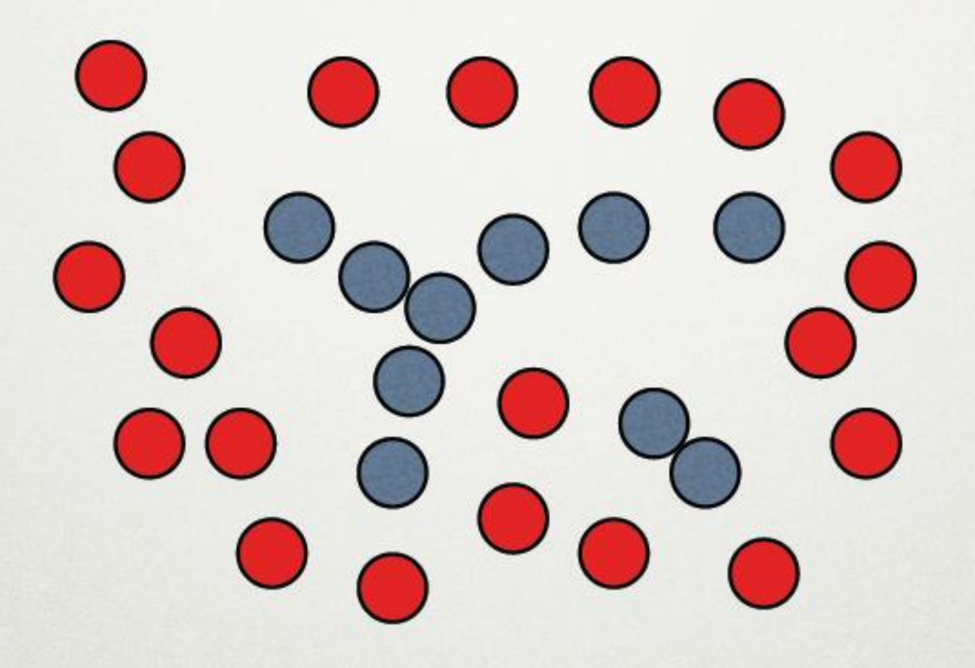


Don’t forget Magnification!

- Magnification of galaxy flux:



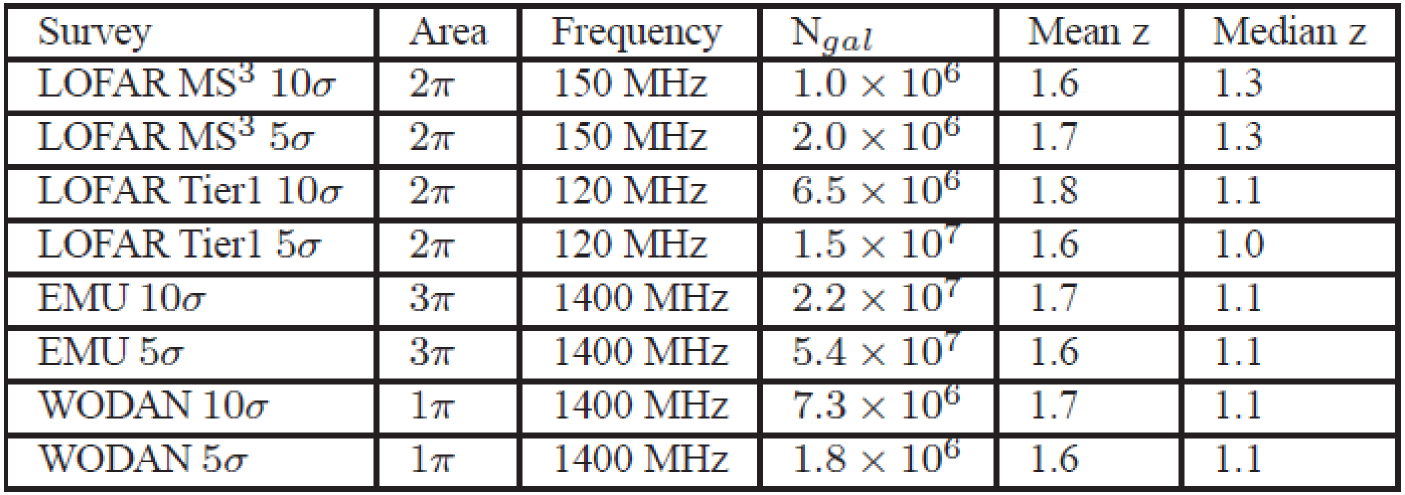
Magnification cross-correlation



- Correlate background and foreground object densities
- Effect will depend on the galaxy spectral index
- Use HI spectroscopic survey for both populations and divide into flux bins
- Work in progress (see e.g. Yang and Zhang, 2011)

Some examples: Cosmology with SKA_0

- Use large radio continuum surveys: EMU, WODAN (as well as LOFAR)
- Very little redshift information – success due to large number of sources and median redshift ~ 1



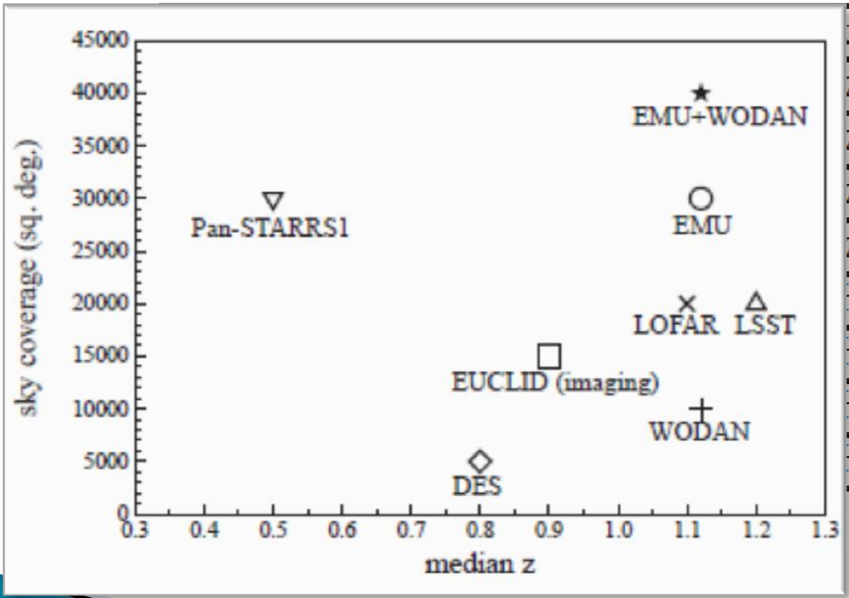
Survey	Area	Frequency	N_{gal}	Mean z	Median z
LOFAR MS^3 10σ	2π	150 MHz	1.0×10^6	1.6	1.3
LOFAR MS^3 5σ	2π	150 MHz	2.0×10^6	1.7	1.3
LOFAR Tier1 10σ	2π	120 MHz	6.5×10^6	1.8	1.1
LOFAR Tier1 5σ	2π	120 MHz	1.5×10^7	1.6	1.0
EMU 10σ	3π	1400 MHz	2.2×10^7	1.7	1.1
EMU 5σ	3π	1400 MHz	5.4×10^7	1.6	1.1
WODAN 10σ	1π	1400 MHz	7.3×10^6	1.7	1.1
WODAN 5σ	1π	1400 MHz	1.8×10^6	1.6	1.1

See Raccanelli et al, 2011

Some examples: Cosmology with SKA_0

- Use large radio continuum surveys: EMU, WODAN (as well as LOFAR)
- Very little redshift information – success due to large number of sources / sky area and mean redshift ~ 1

ASTRON



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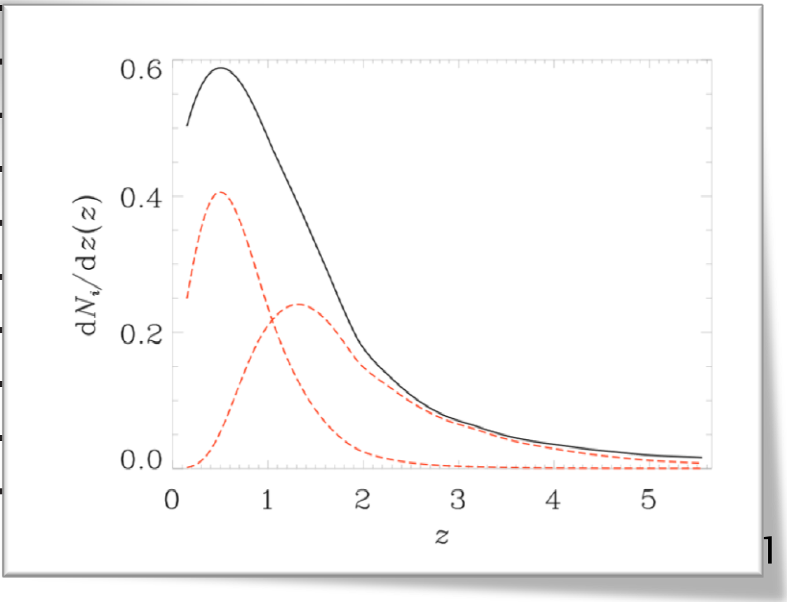
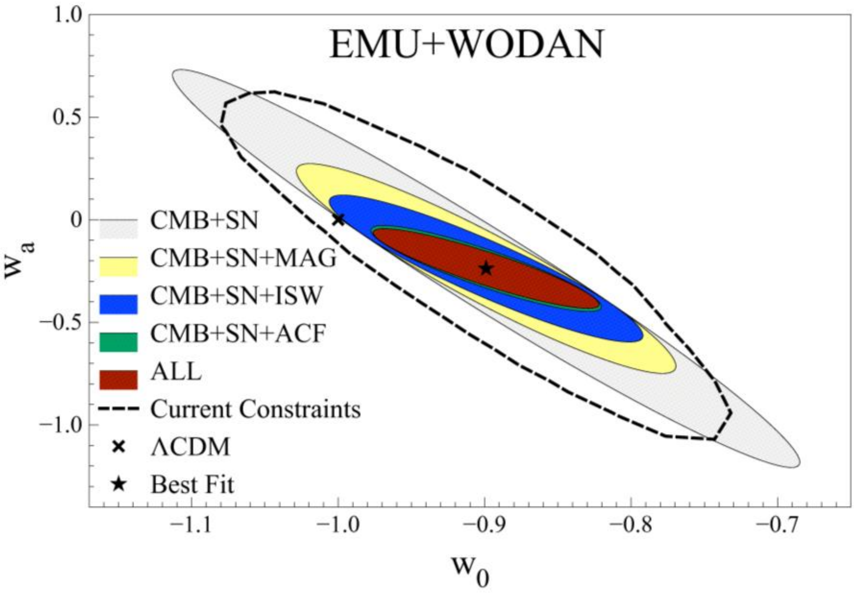
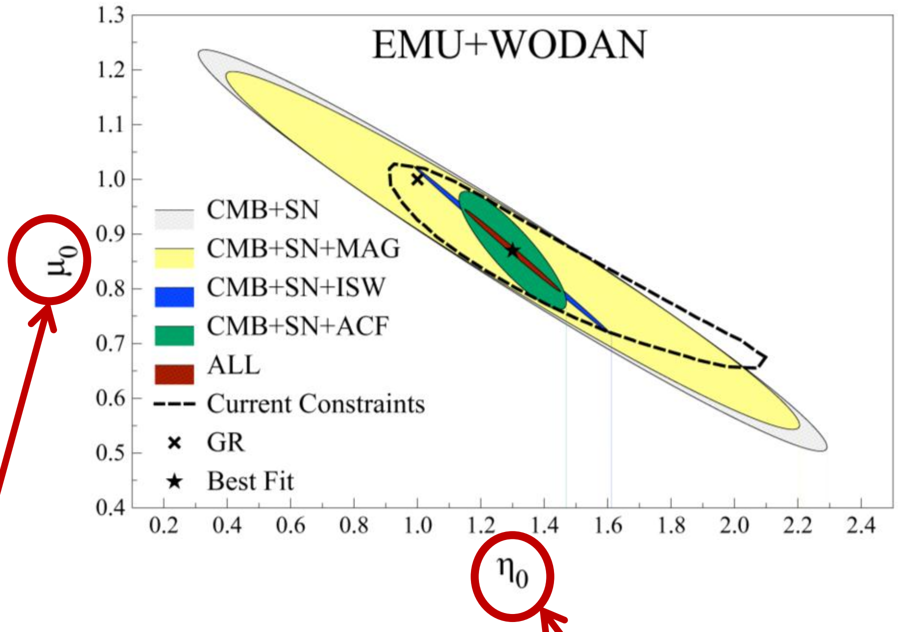


Possible improvement with “statistical” redshift information (Camera et al, in preparation)

The power of combining datasets

- Use: source power spectrum + integrated Sachs-Wolfe effect (ISW – correlation between density and CMB) + Cosmic Magnification (Dark Energy Survey galaxies as foreground)





Raccanelli et al, 2011

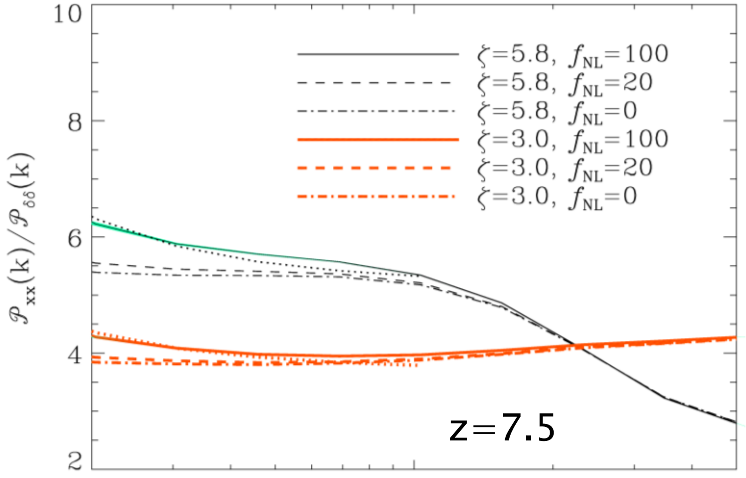
Modification to Poisson equation

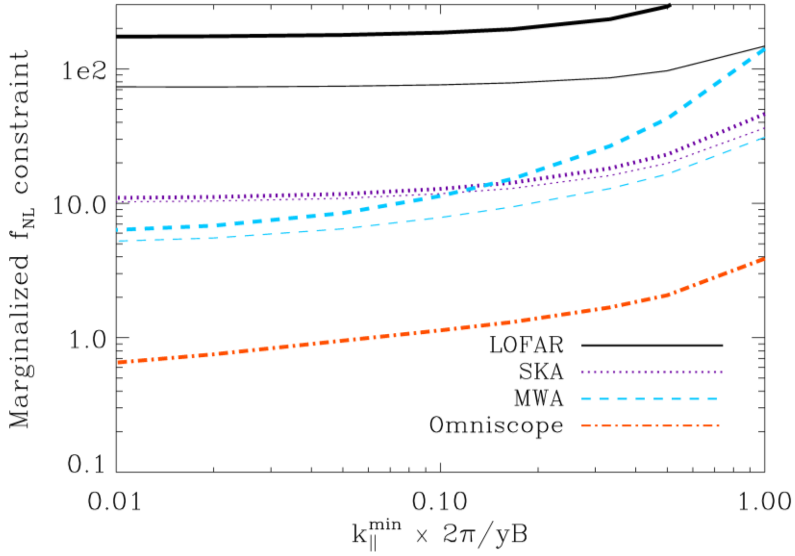
Rate of space and time potentials

Cosmology with SKA$_0$ – yes, even at z > 6

- Look at large scales ($k < 0.15$/Mpc)
- Telescopes need large FoV and bandwidth to probe small k modes
- $\sigma(f_{NL})$=[**200, 6, 10, 0.6**] for [LOFAR, MWA, SKA, Omniscope/FFTT]
- Current constraints: WMAP – $\sigma(f_{NL})$~30; Planck: $\sigma(f_{NL})$~8
- Analysis independent of Reionization model
- First generation experiments can be competitive with Planck!

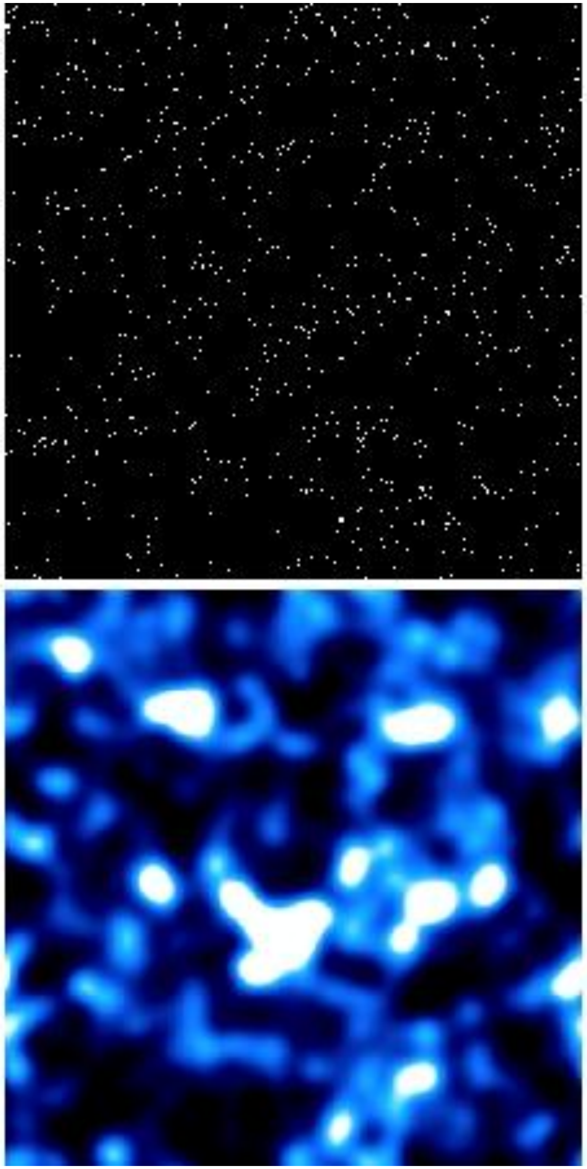
S. Joudaki et al, PRL, 2011





Cosmology with SKA$_0$: HI Intensity mapping

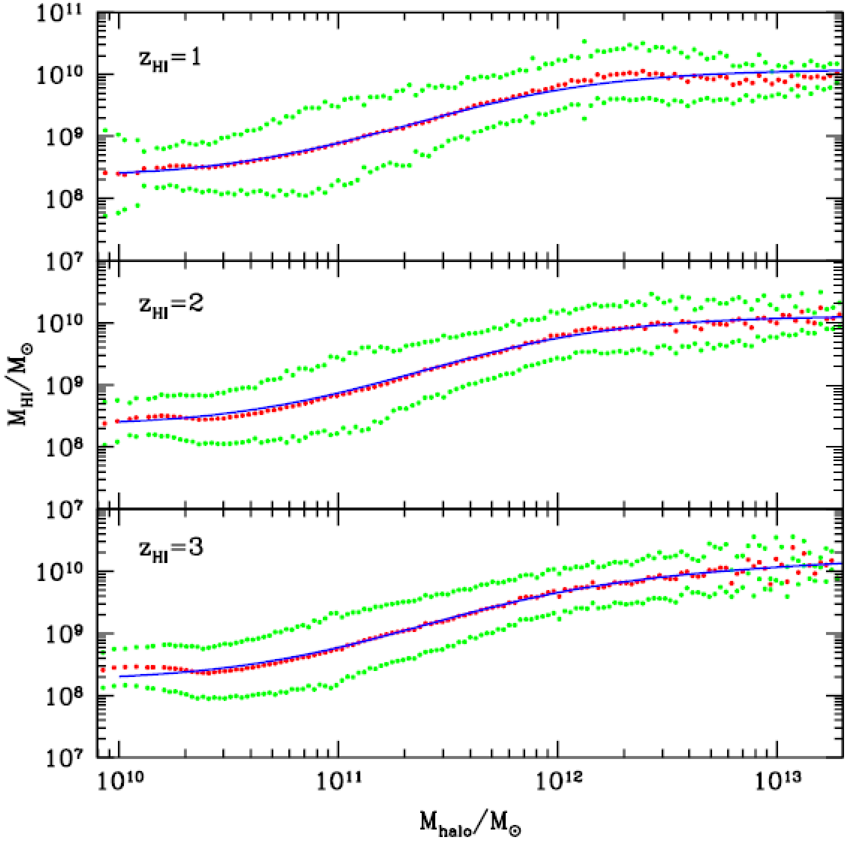
- Measure integrated flux in each pixel at a given frequency
- Non-threshold experiment
- Just like the CMB (and EoR)
- Great for BAO!



A. Lidz

HI intensity: expected signal

- Assume: $M_{HI}(M_{halo})$ at z
- Remember: large pixels! (low resolution)
- ~ (481, 573, 544) μK at z=(1,2,3)
- $\Omega_{HI} \sim 10^{-3}$
- Consistent with Chang et al. measurements, etc
- Bias ~ 1 at z=1

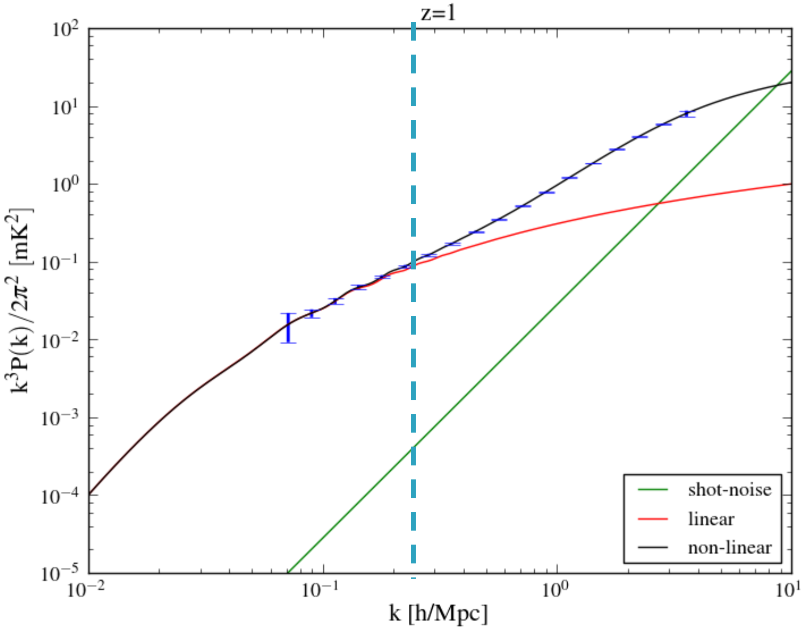


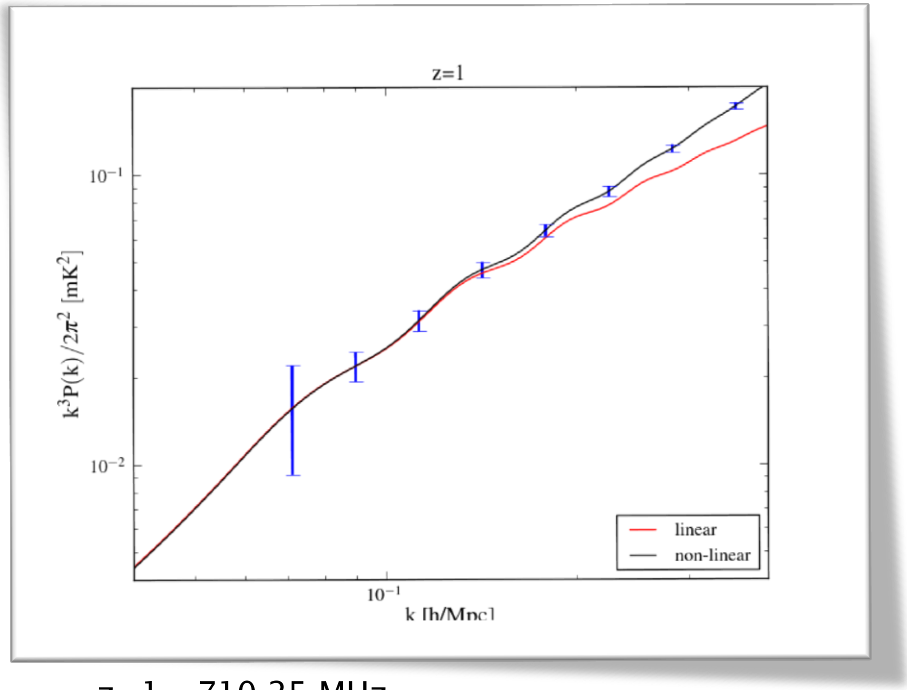
Using Obreschkow et al., 2010 + Millennium Simulation

Gong et al, 2011

EMMA BAO constraints

- Assume:
  - A=2000 m^2
  - 14 stations
  - Tsys~45K
  - FoV=78 deg^2
  - time=2000 hours
  - Maximum baseline=300m
  - Minimum baseline=10m ?
  - Frequency resolution=0.3 MHz





z=1 – 710.25 MHz
dz ~ 0.2 (0.3 MHz)
Note: with 500 MHz BW can measure 7 bins in one go!

Conclusions…

- Radio Telescopes provide brave new world for Cosmology
- Radio Galaxy surveys ~ 700 MHz give competitive dark energy constraints with future surveys
- Multi-wavelength / cross-correlation surveys crucial for future precision cosmology (systematics…)
- Already very interesting results with current pathfinders
- HI intensity mapping opens a novel window for Cosmology (the race is on!)
- Requirements: large FoV and reasonable collecting area at ~ 700 MHz
- We still have to sort out problem with foregrounds and calibration, but if you can do it for the EoR…

Thank you!