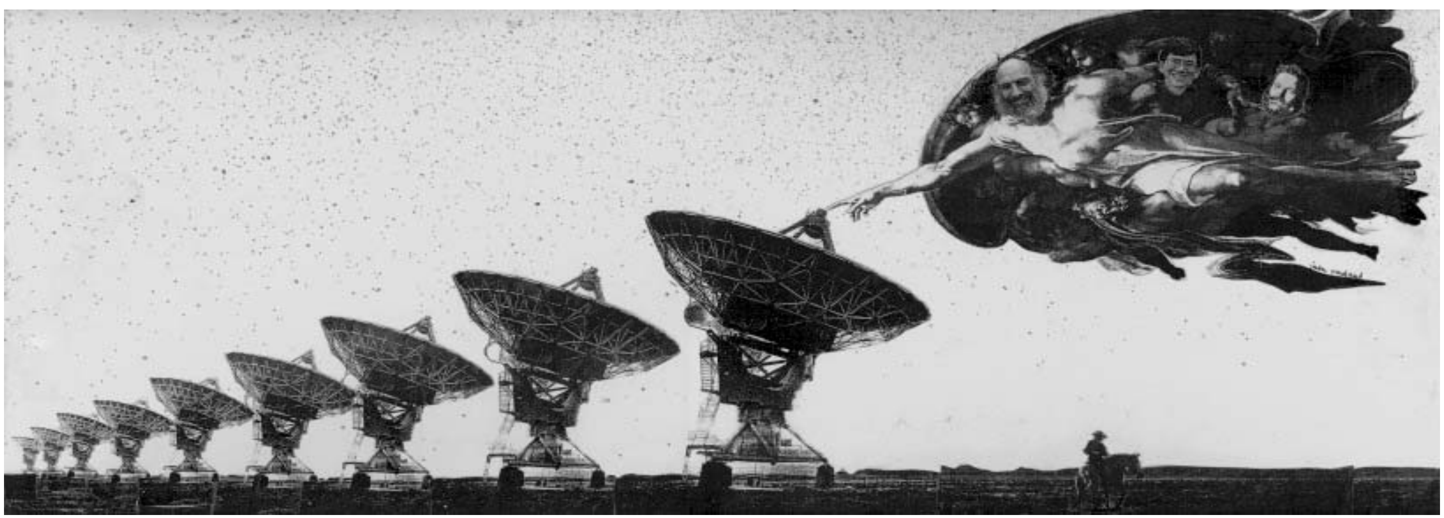
Cosmology with Large Radio Continuum Surveys

Mário Santos
UWC, SKA SA

SPARCS, Kruger, July 2015

Continuum?

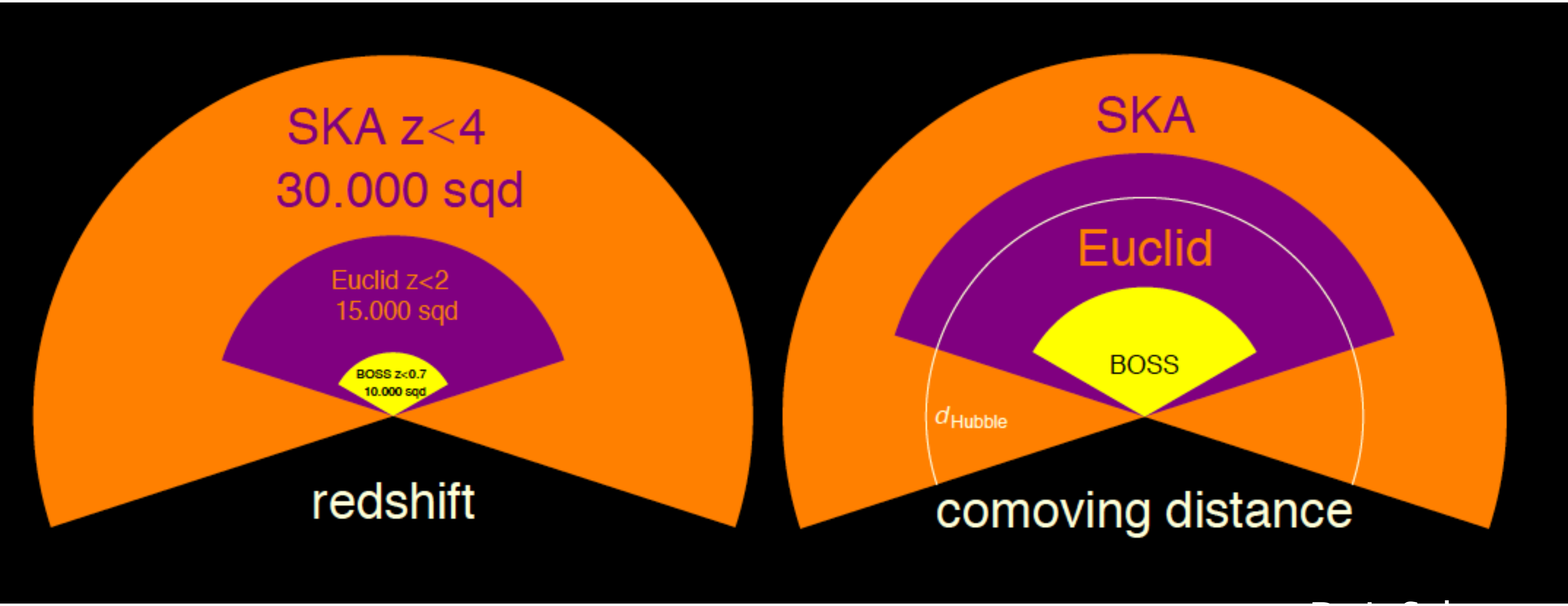
- Advantage: Strong signal – large number of galaxies; high-z tail
- Disadvantage: no redshift information
- Example: The VLA FIRST Survey (1994 – …)
  - 10,000 deg^2; 0.15 mJy; 9x10^5 galaxies
  - 128x2 MHz channels – averaged over 256 MHz



SKA1 – MID after "re-baselining"

- Construction by ~ 2020
- Total ~ 197 dishes
  - 133 new – 15 m diameter
  - 64 from MeerKAT – 13.5 m
- Single pixel feeds (might replace MeerKAT feeds)
- 0.35 – 14 GHz…
- Note: also possible to do a continuum survey with SKA1-LOW…

Large volumes with the SKA



- SKA1 should detect ~ 5×10^8 galaxies over ~ 25,000 deg^2 (10,000 hours – 5 μJy flux cut)

SKA1 science cases for Cosmology with continuum surveys

- Probe the initial conditions and the global features of the Universe through non-Gaussianity and the dipole in the matter distribution using high precision measurements of the angular correlation functions.
  - Continuum survey of 30,000 square degrees at few microJy sensitivity and few arcsecond resolution.
  - SKA1 will give the first answer to the key question – does the matter dipole agree with the CMB dipole? – with precision ~100x better than NVSS.
  - Precision on non-Gaussianity ~3x better than Planck and independent of HI IM approach.
- Map the dark Universe with a completely new kind of weak lensing survey in the radio.
  - Measuring galaxy shapes in a Continuum survey of 5000 deg^2; achieving 0.5 arcsec resolution or better, and 5 galaxies per square arcmin or more.
  - Competitive with DES but probing higher redshifts – and SKA/DES cross-correlation could be a game changer in overcoming the systematic floor that either survey reaches on its own.

SKA1 top science cases for cosmology

High Priority Science Objective	SWG	Science Objective	SKA1 Component	Band	Mode	Frequency			Sensitivity		
						Range Low - High	Resolution Initial:Cal:Final	Spectral Dynamic Range (I_max/ I_min)	RMS Noise Min:Max @ Beam @ Bandwidth	Brightness Dynamic Range (I_max/ I_min)	Polarisation Dynamic Range (I_max/ P_min)
32	Cosmology	**Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.**	**SKA1-MID**	**SPF1**	**Auto-correlations**	**350 - 1050 MHz**	10:300 kHz	**45 dB**	3.3 mJy/Beam @ 1.7 deg Line	40 dB	**40 dB**
33	Cosmology	**Angular correlation functions to probe non-Gaussianity and the matter dipole.**	**SKA1-MID**	**SPF2**	**Imaging**	1000 - 1700 MHz	10:1000 kHz	30 dB	7 μJy/Beam @ 2 arcsec Cont	45 dB	30 dB

High Priority Science Objective	SWG	Observing Area					Integration						
		Total Area	Area of Single Pointing/ Beam	Angular Resolution Min:Max	Targets/ Beams	Tracking	Total	Per Pointing	Dump Rate / Temporal Resolution	Epochs	Cadence Min:Max	# Sessions per Interval	Time per Session
32	Cosmology	30000 deg2	1.4 deg2	1.7 deg	21500 Pointings	Drift	10000 hr	2.2 hr @ 190 Dishes	0.15 s			1250	8 hr
33	Cosmology	31000 deg2	0.38 deg2	2 arcsec	81600 Pointings	Sidereal	10000 hr	7.4 mn	0.15 s			1250	8 hr
37 + 38	Continuum	1000 deg2	0.38 deg2	0.5:1 arcsec	2600 Pointings	Sidereal	10000 hr	3.8 hr	0.15 s			1250	8 hr
		7.8 deg2	0.38 deg2	0.5:1 arcsec	21 Pointings	Sidereal	2000 hr	95 hr	0.15 s			250	8 hr
		0.38 deg2	0.38 deg2	0.5:1 arcsec	1 Pointings	Sidereal	2000 hr	2000 hr	0.15 s			250	8 hr
		0.5 deg2	30 arcmin2	0.05:1 arcsec	61 Pointings	Sidereal	1000 hr	16.4 hr	0.15 s			125	8 hr
		30 arcmin2	30 arcmin2	0.05:1 arcsec	1 Pointing	Sidereal	1000 hr	1000 hr	0.15 s			125	8 hr

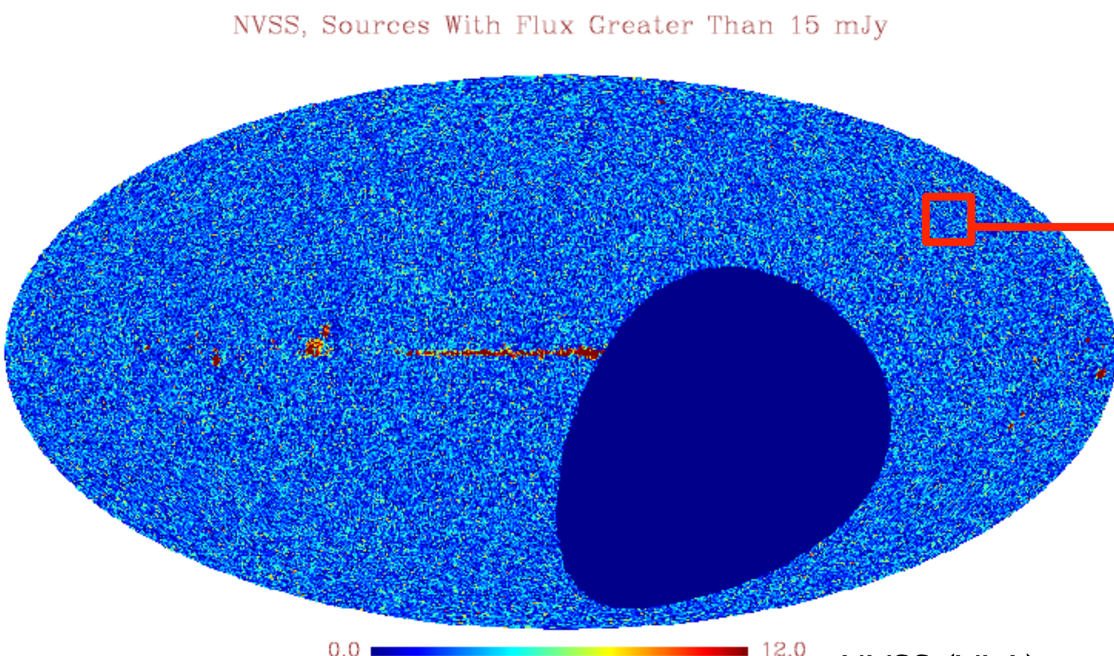
Note: need sub-arcsec resolution to separate galaxy populations

SKA1-MID large continuum survey?

- ~25,000 deg^2
- Band?
  - Band 1 baseline design: 350 – 1050 MHz
  - Band 2 baseline design: 950 – 1760 MHz
  - Band 1 option: 450 – 825 MHz ("octave" receivers)
  - Band 2 option: 795-1470 MHz ("octave" receivers)
- Resolution? Need ~ 0.5 arcsec resolution for morphological classification of sources and weak lensing
- ~ flux sensitivity ~ 1 uJy rms (~ 5×10^8 galaxies)
- Observing mode? ("point and observe" or take data while scanning?)

Basic probe: galaxy number density

- 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



Galaxy bias

Poisson fluctuations

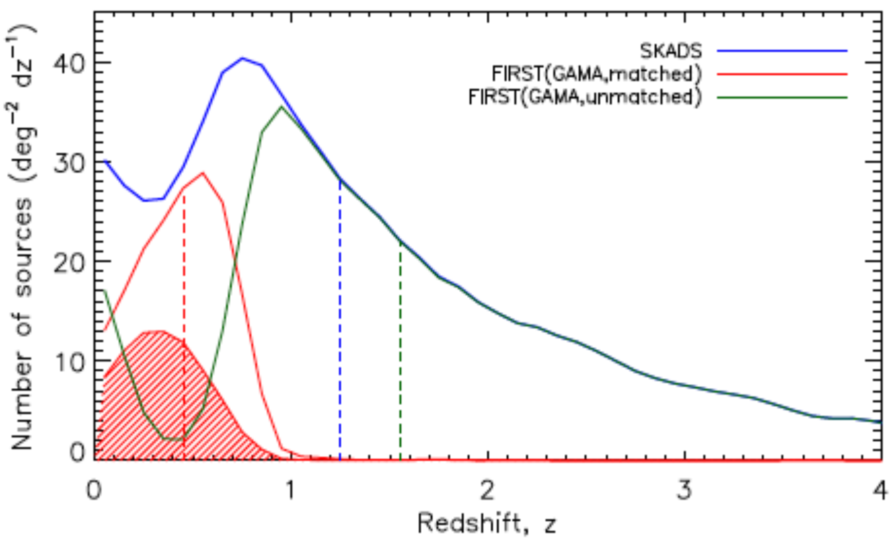
$$\underbrace{\frac{\delta n}{\bar{n}}}_{\text{Galaxy number fluctuations}} = b\delta_m + \delta_p$$

Matter density fluctuations

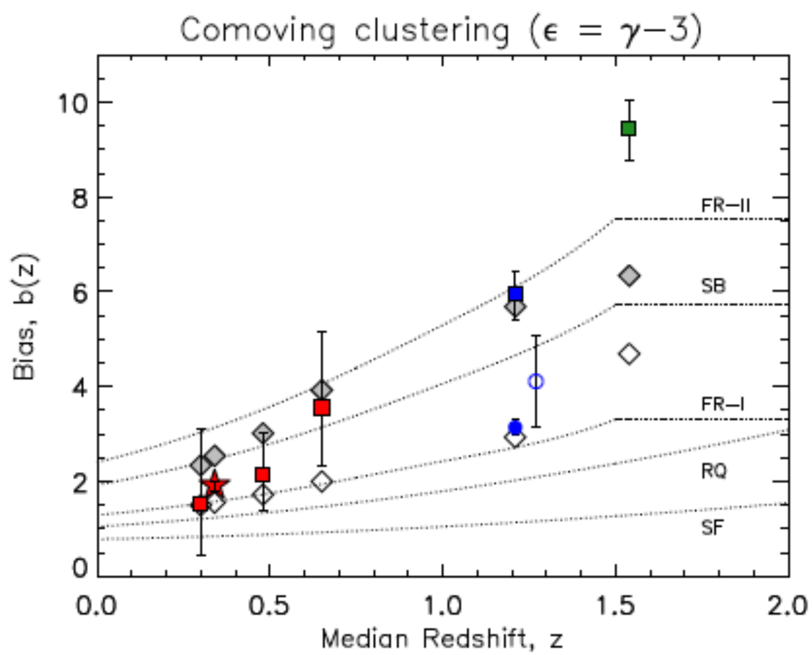
NVSS (VLA) continuum survey
Each point represents a galaxy

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)

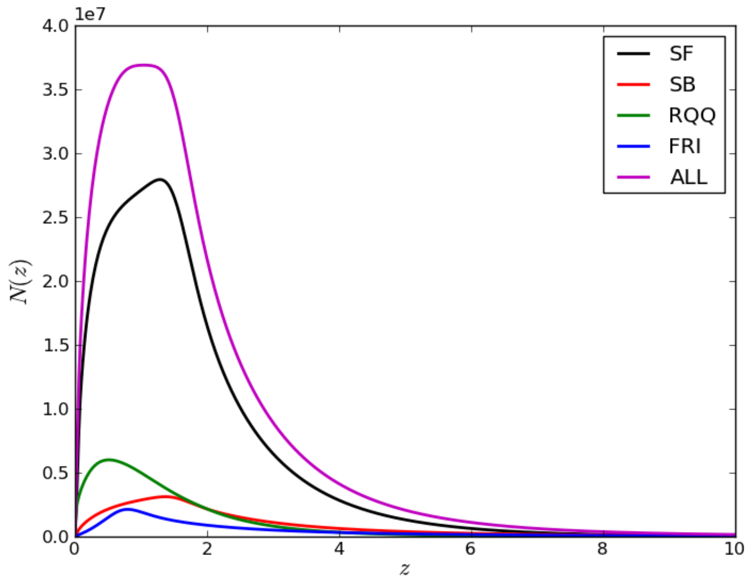


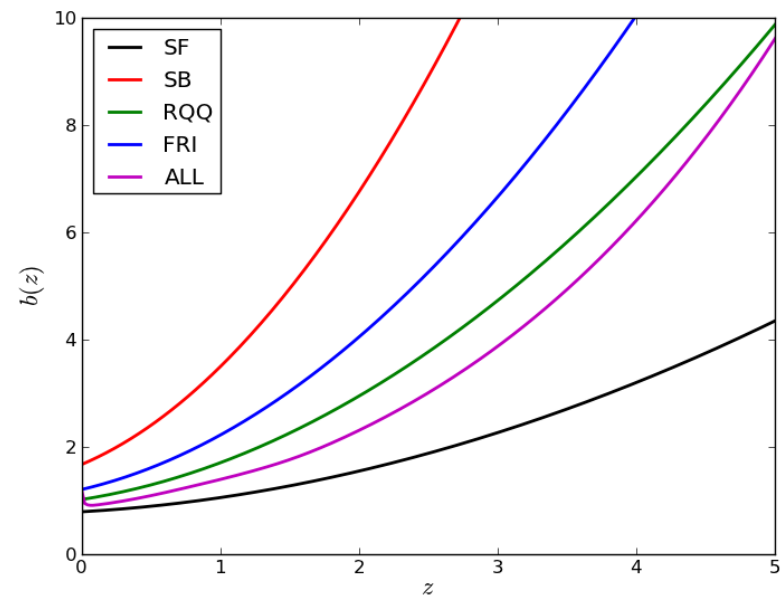
b(z)

Lindsay et al., MNRAS 2014

New and quick method to get dn/dz and bias…

- For most purposes, we only need galaxy number density distributions and bias.
- See Alonso et al., arXiv: 1505.07596: http://intensitymapping.physics.ox.ac.uk/Codes/ULS/continuum

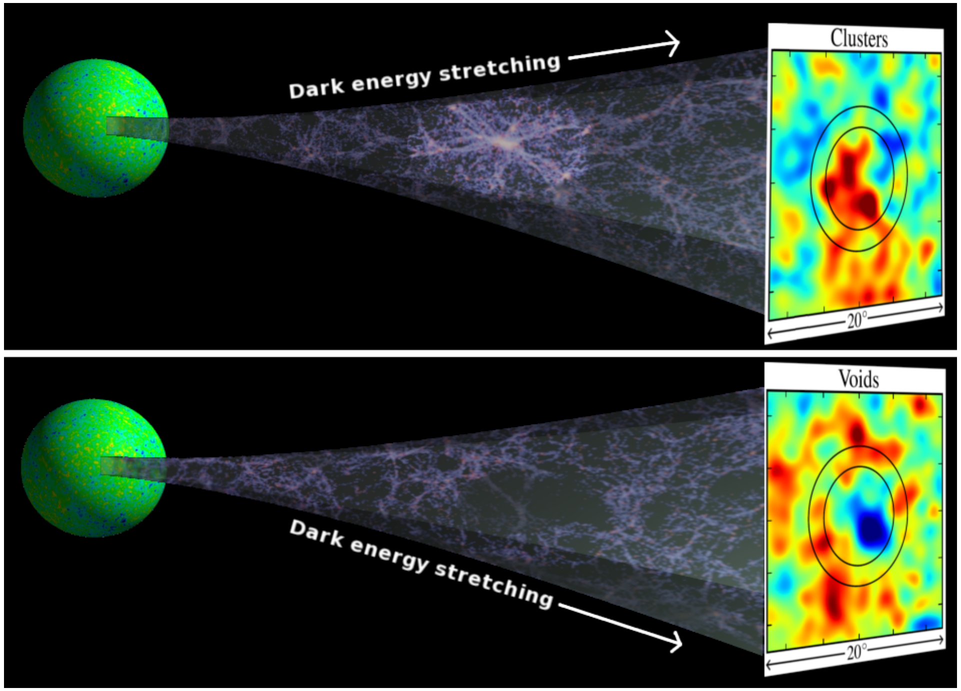




- Can easily change cosmology, luminosity function parameters, etc
- Runs in Python!
- Calculates GR bias corrections for ultra-large scales

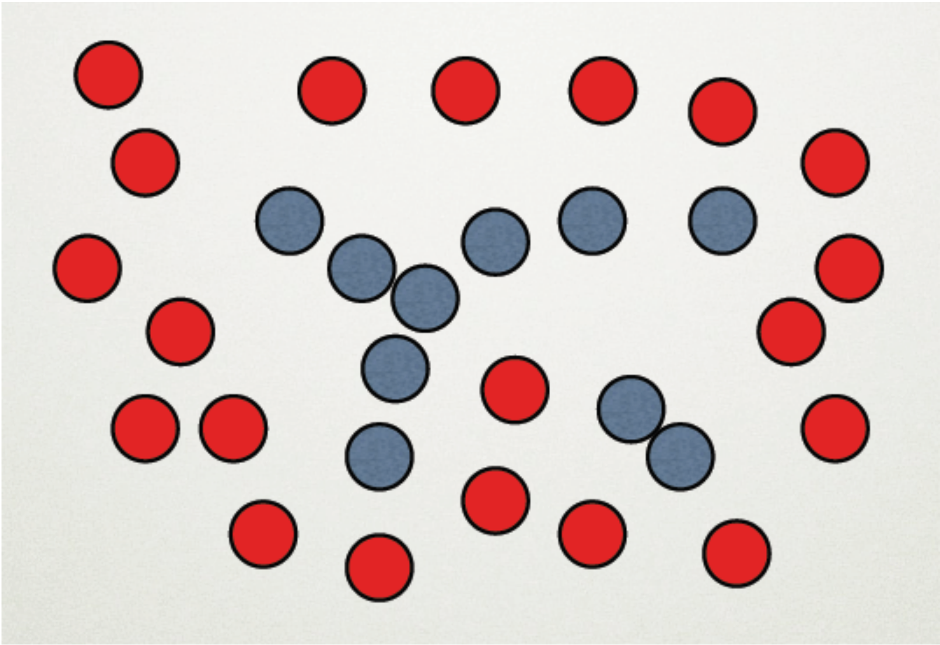
Other probes: ISW

- Correlation between galaxies and the CMB – Integrated Sachs-Wolfe (ISW)



As the CMB goes through over-densities and under-densities it gets hotter or colder because of density evolution due to dark energy

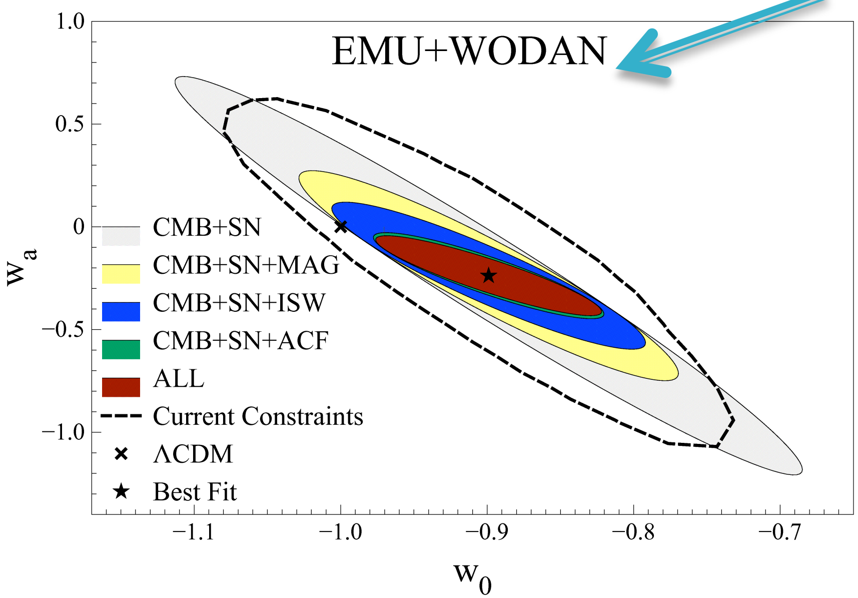
Other probes: Cosmic Magnification



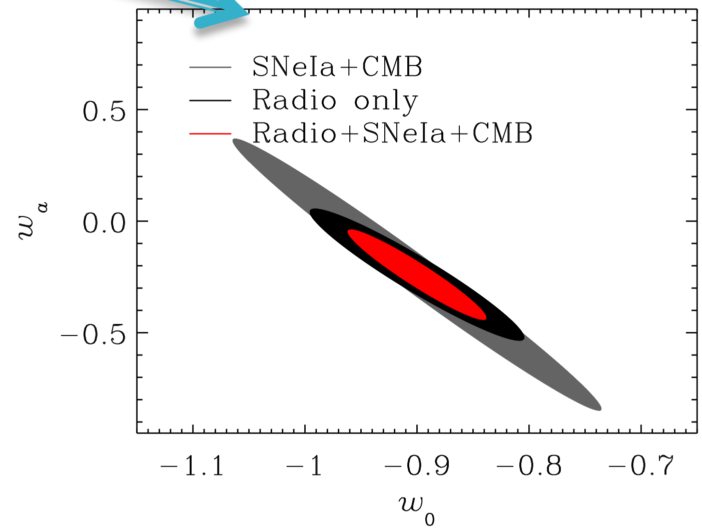
- Dark matter will act as a lens of background galaxies:
  - Increase flux
  - Increase solid angle
- Foreground galaxies trace dark matter
- Expected correlation between background and foreground galaxies

Combining probes: Constraints on dark energy using continuum surveys

With SKA pathfinders



Raccanelli et al, MNRAS 2012



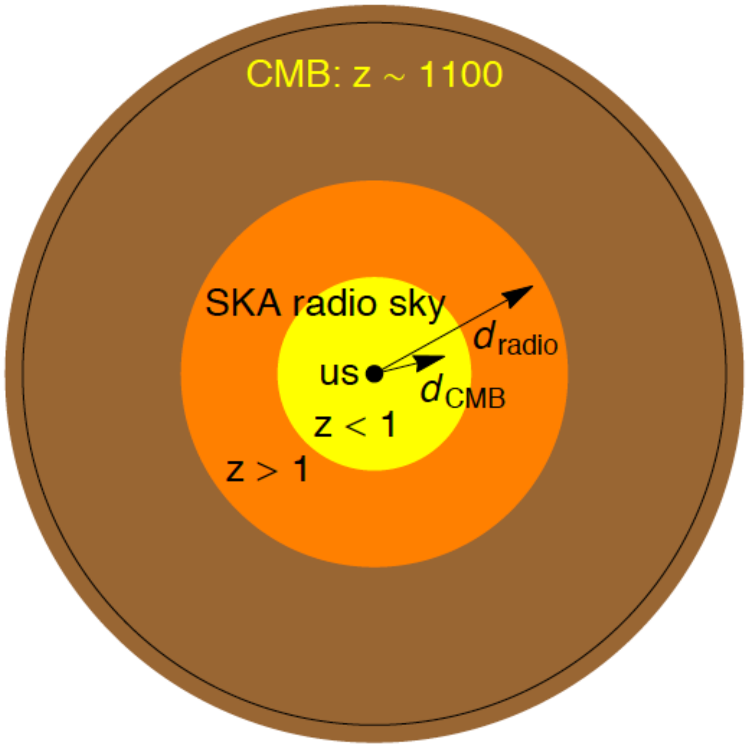
Camera, Santos, et al., MNRAS 2012

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

  - SKA1 should detect ~ 20 times more galaxies than pathfinders…

VERY Large scales?: testing the Cosmological Principle using galaxy counts

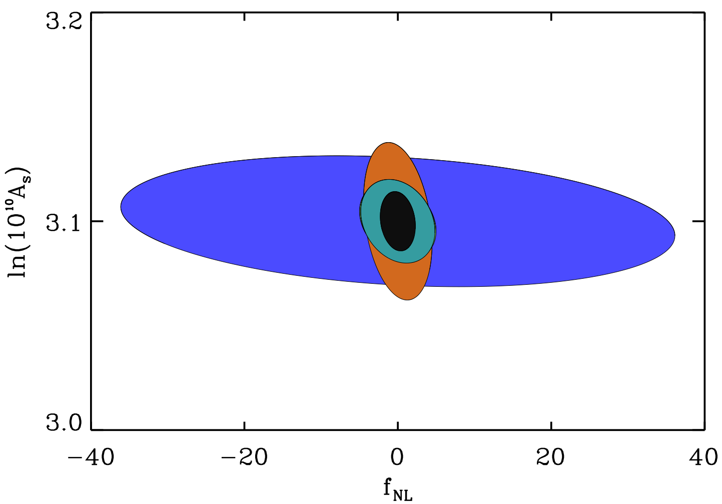
- Tests of isotropy (CMB anomalies?)
- Test if the cosmological dipole (with radio-galaxies) is the same as the CMB one
- Reach a few degrees precision with SKA1

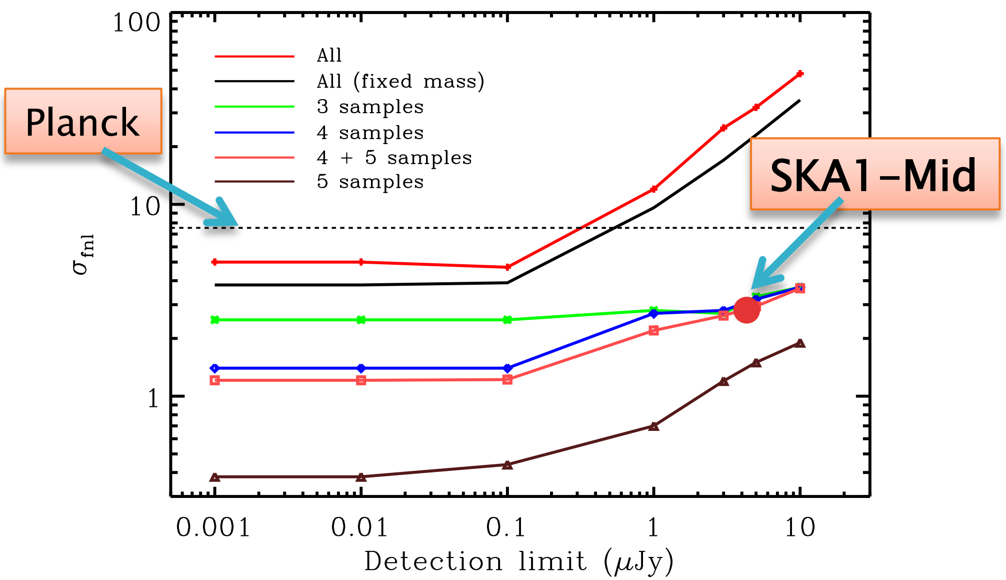


D. J. Schwarz, et al., PoS(AASKA15), SKA chapters, 2015

Pushing the limits on primordial non-Gaussianity with multiple populations

- Look at clustering of galaxies
- 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!



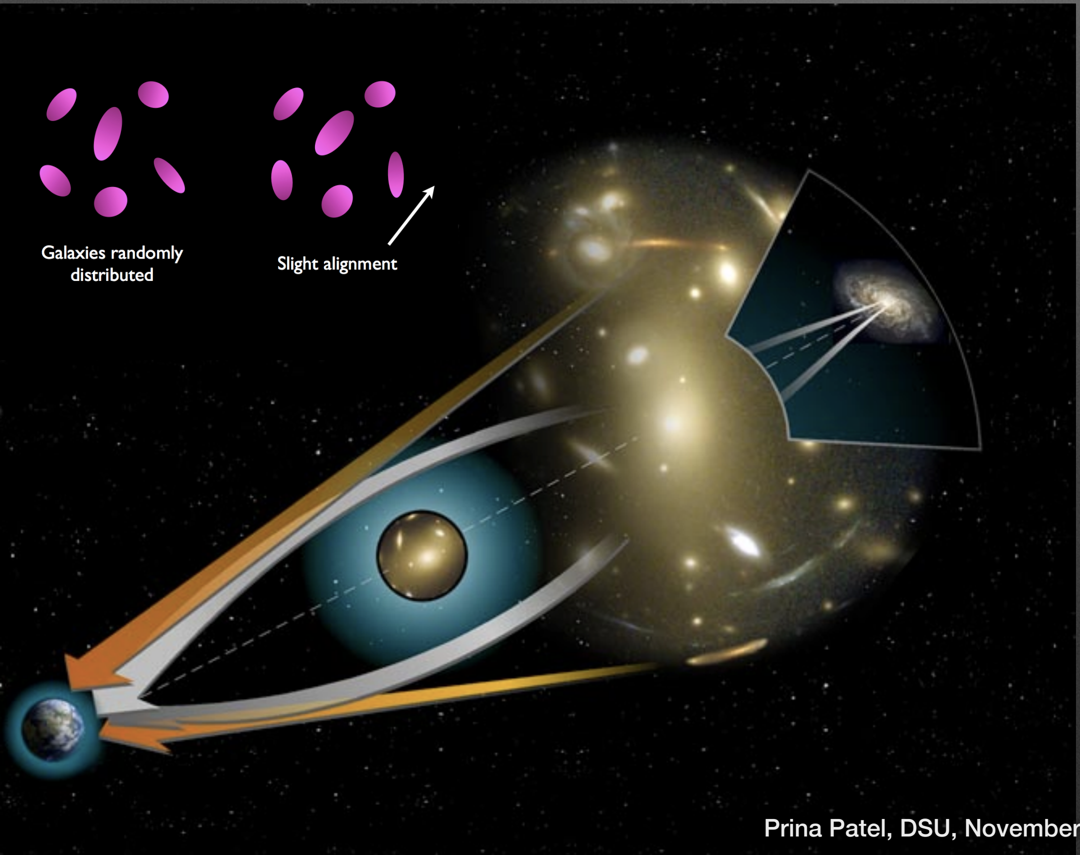


- Blue: everything combined
- Light blue: FRI, FRII, RQQ and (SFG+SB)

fNL ~ 2.9! (SKA1)
L. Ferramacho, M. Santos et al., MNRAS 2014, arXiv:1402.2290

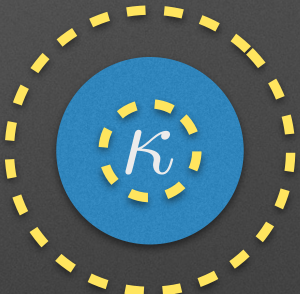
Weak Gravitational Lensing

Intervening matter (mostly dark) bends light from distant sources and causes the source shapes to appear distorted.

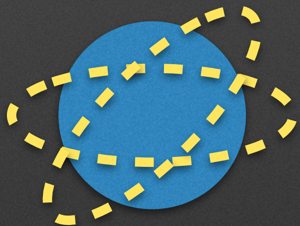


Prina Patel, DSU, November 2014.

Convergence



Shear



γ_1, γ_2

Measure lots of shapes very accurately!

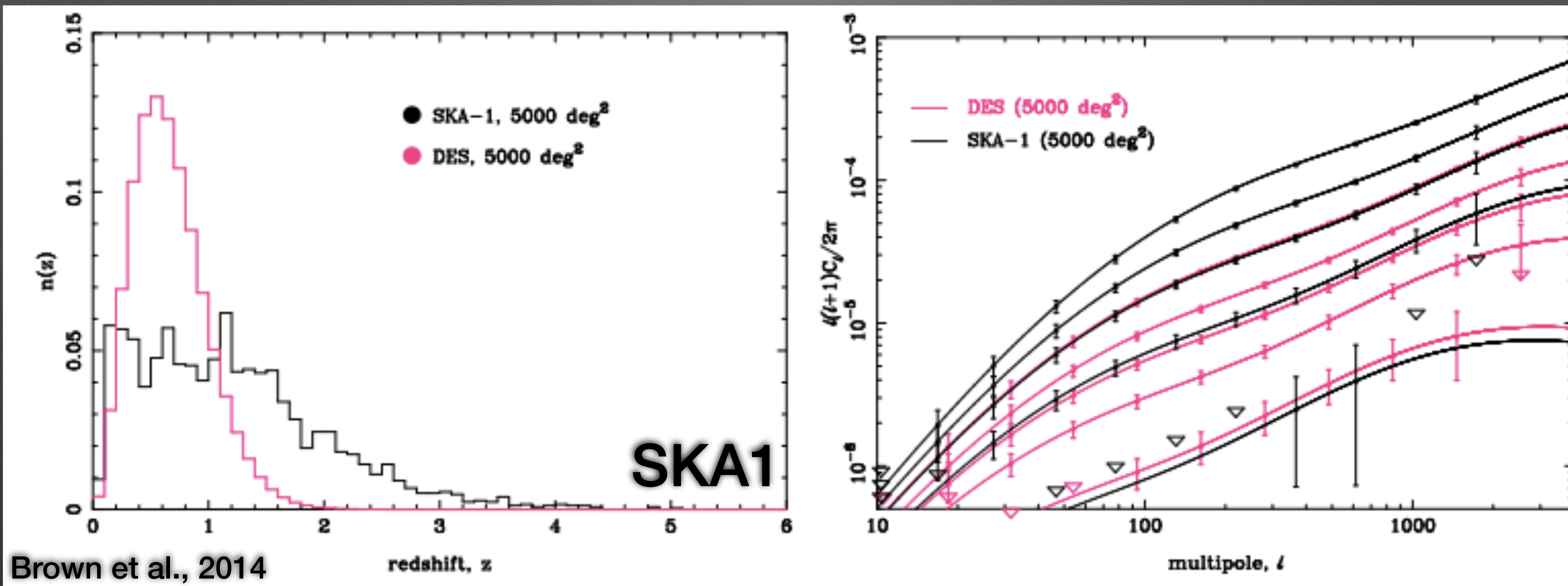
Precision weak lensing to probe accelerated expansion is key science driver for Euclid, LSST, SKA etc.

- Require exquisite control of systematics.
- Major systematics for weak lensing:
  - ⋆ Instrumental systematics (e.g. PSF anisotropies).
  - ⋆ Photometric redshift errors.
  - ⋆ Colour-gradient systematics.
  - ⋆ Intrinsic galaxy alignments.

Credit: Michael Brown

Radio survey offers unique solutions to most of these problems: stable beam, use polarization or HI rotation velocities to trace the galaxy intrinsic orientation

Radio surveys will probe higher redshifts.



Survey duration: 2 years

SKA1-Mid + Band 2 provides the most powerful survey speed at the high angular resolution required for lensing.

Conclusions…

- Continuum should be the most easily accessible survey for cosmology
- SKA1-MID continuum will provide game changing measurements in cosmology (sensitivity+resolution)
- Observables:
  - 2-point correlation functions
  - Correlations with multi-wavelength data: optical/NIR/CMB (redshifts, magnification, ISW,…)
  - Shape measurements (population type, WL)
- Questions:
  - Observing mode? (commensality with other surveys…)
  - Optimal frequency?
  - Source extraction algorithms?
  - Optimal statistics for stacking and confusion noise limited maps?