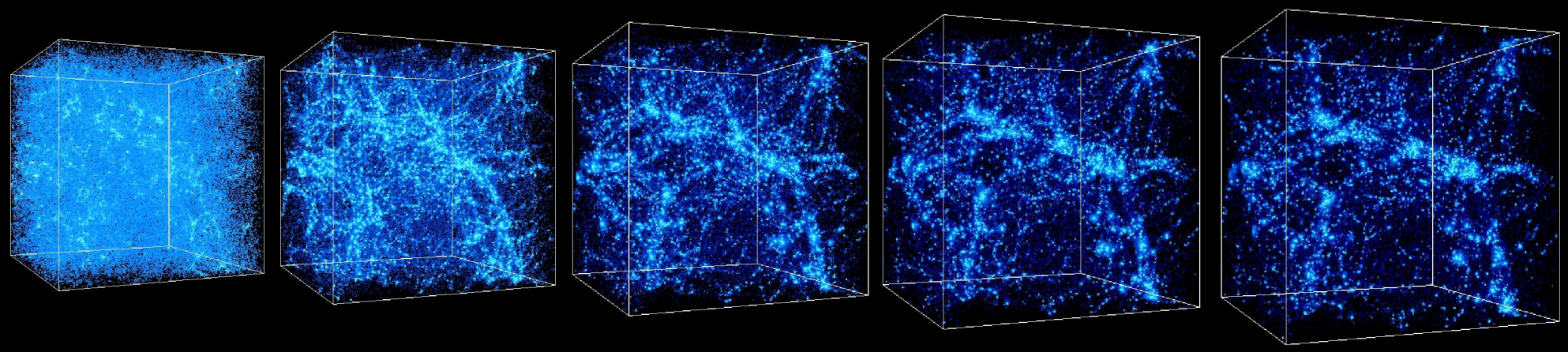
Cosmology with SKA1



Matt Jarvis
University of Oxford & University of the Western Cape

(on behalf of the Cosmology SWG)

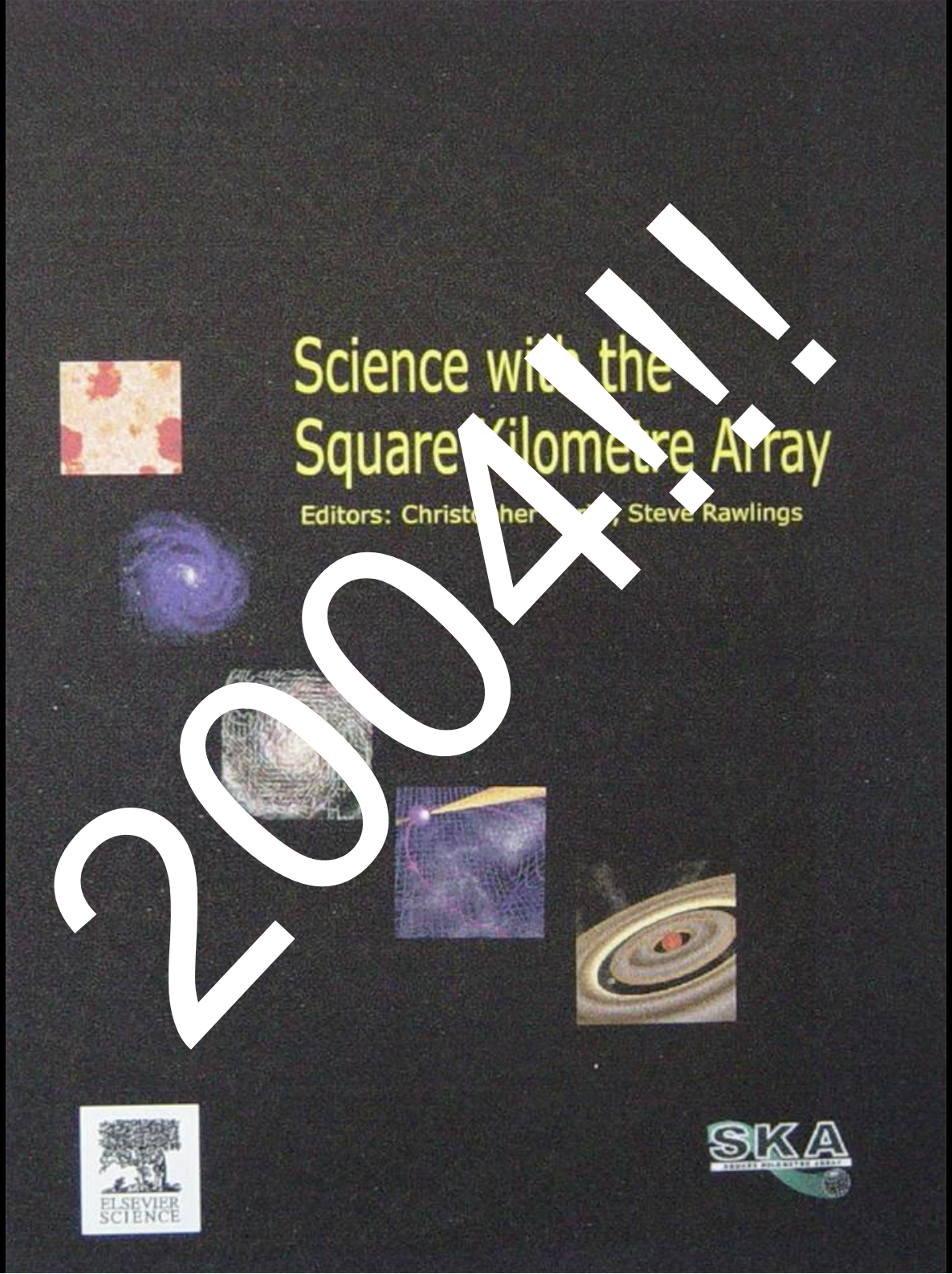
Roy Maartens, Tzu-Ching Chang, David Bacon, Filipe Abdalla, Mario Santos, Stefano Camera, Michael Brown, Pedro Ferreira, Chris Blake, Saleem Zaroubi, Jean-Luc Starck, Ue-Li Pen, Xuelie Chen, Jonathan Pritchard, Steve Furlanetto, Susumi Inoue, Keitaro Takahashi, Simn Prunet, T. R. Choudhury, Asatha Cooray, Dominik Schwarz, Hans-Rainer Kloecker

Science with the Square Kilometre Array

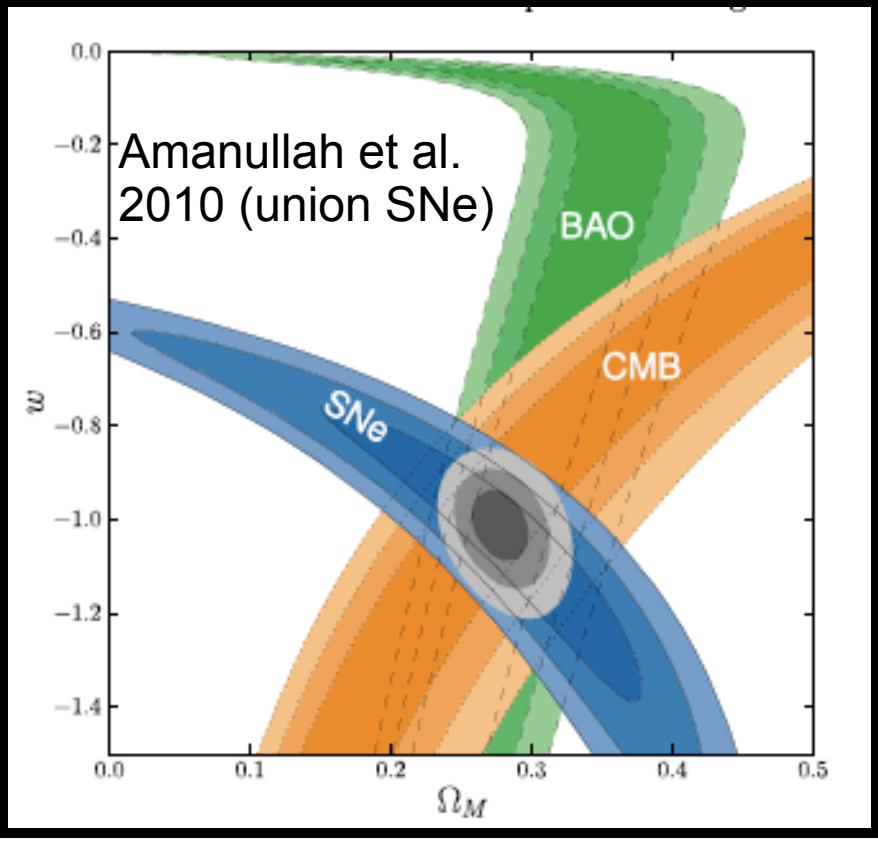
Editors: Christopher Carilli, Steve Rawlings

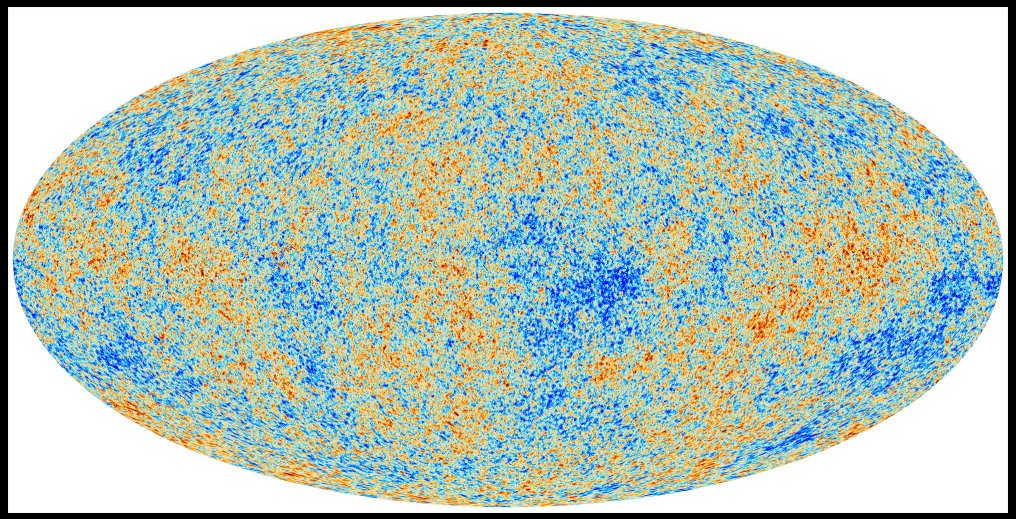
ELSEVIER SCIENCE

SKA

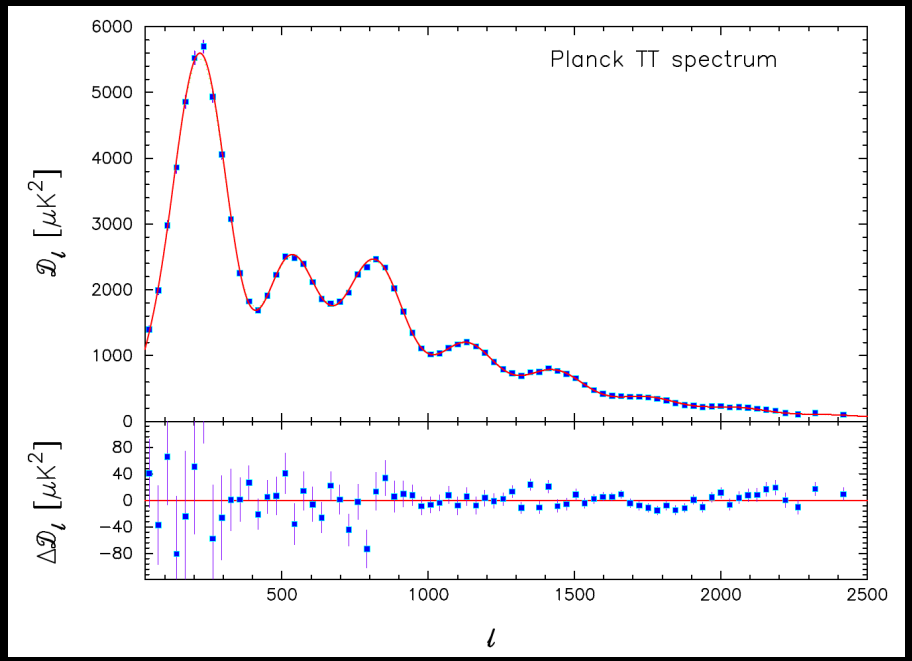

Science with the
Square Kilometre Array
Editors: Christopher Carilli, Steve Rawlings
ELSEVIER
SCIENCE
SKA

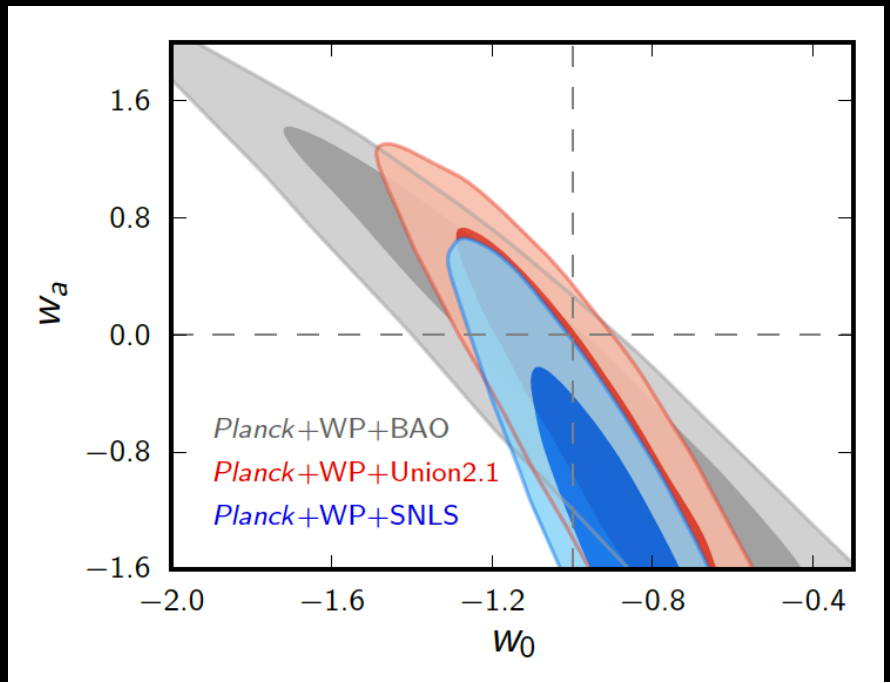
2004!!!





Planck collaboration (2013) paper XVI





The baseline design is NOT a good machine for most/any ground-breaking cosmological science

However, with small(ish) adjustments it could be a world leading instrument for cosmology

Statistics might not well be the most important thing when we come to future surveys such as Euclid/SKA/LSST...

- Filipe Abdalla (Euclid-SKA meeting Sep 2013)

There's nothing quite as useless as a radio source

- Jim Condon (SPARCS - Sep 2013)

The 2nd quote is not quite true for cosmology

Key Questions…

- What is the Equation of state of Dark Energy?
  - Cosmological constant or evolving scalar field
- Does General Relativity break down on cosmological scales?
- What kind of inflation?
  - Non-Gaussianity from non-vanilla inflation
- The nature of Dark Matter
- Neutrino mass

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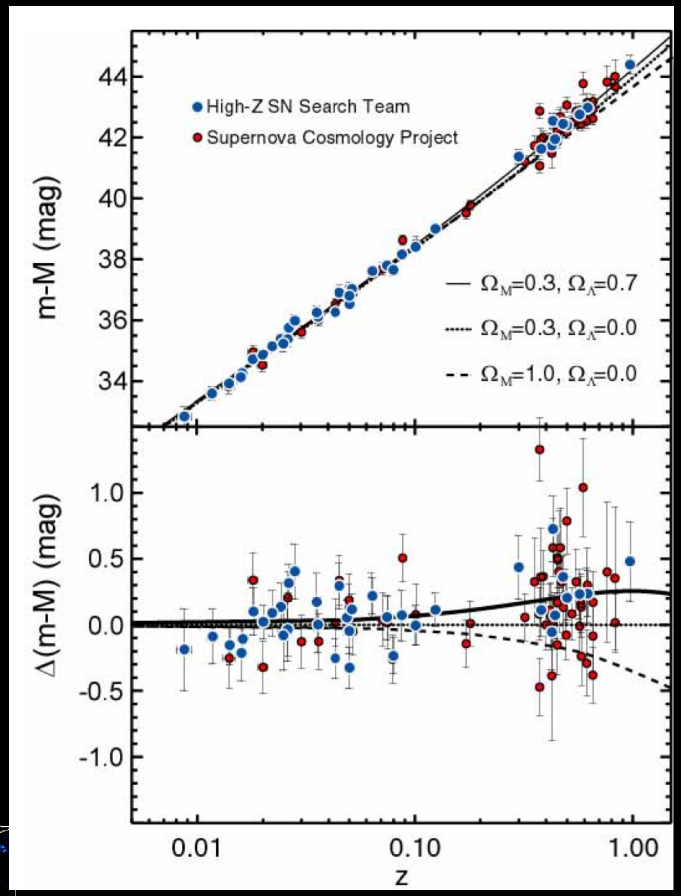
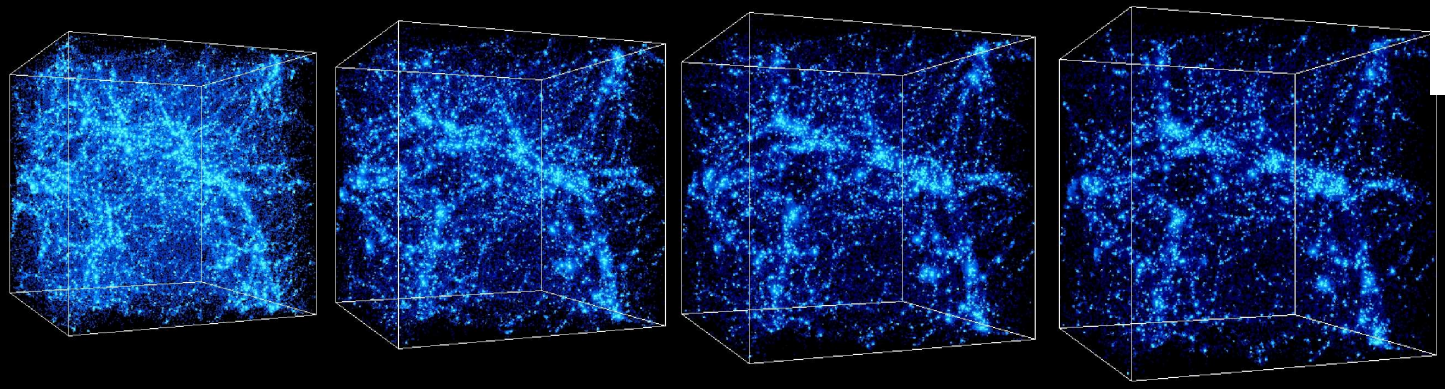
How do we answer these questions?

- Need to measure the expansion history (geometrical measurements)
- Need to measure the growth of structure (trace where the mass is as a function of redshift)
- Obviously these are linked!





How do we answer these questions?

- To measure the expansion history
  - *Type Ia Sne*
  - *Baryon Acoustic Oscillations*
  - *Gravitational Lensing*
- To find departures from GR on cosmological scales, need to measure the influence of gravity on these scales
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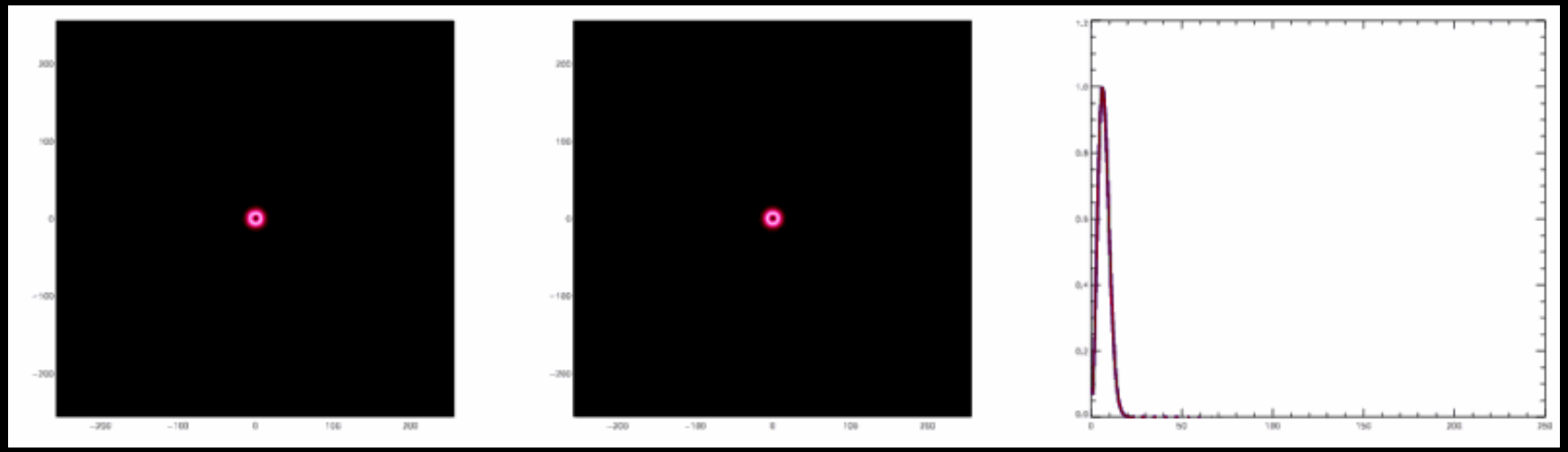
What can we do with spectral line surveys?

Baryon Acoustic Oscillations (BAO)

- Oscillations of coupled baryons & photons in early universe
- *Outward* photon pressure vs. *Inward* gravitational attraction
- Preferred distance scale frozen at decoupling
- Cosmological "standard ruler" (~100 h^{-1} Mpc)

Test: Autocorrelation function and/or power spectrum



Baryons | Photons | Density vs. Radius (Baryons, Photons)

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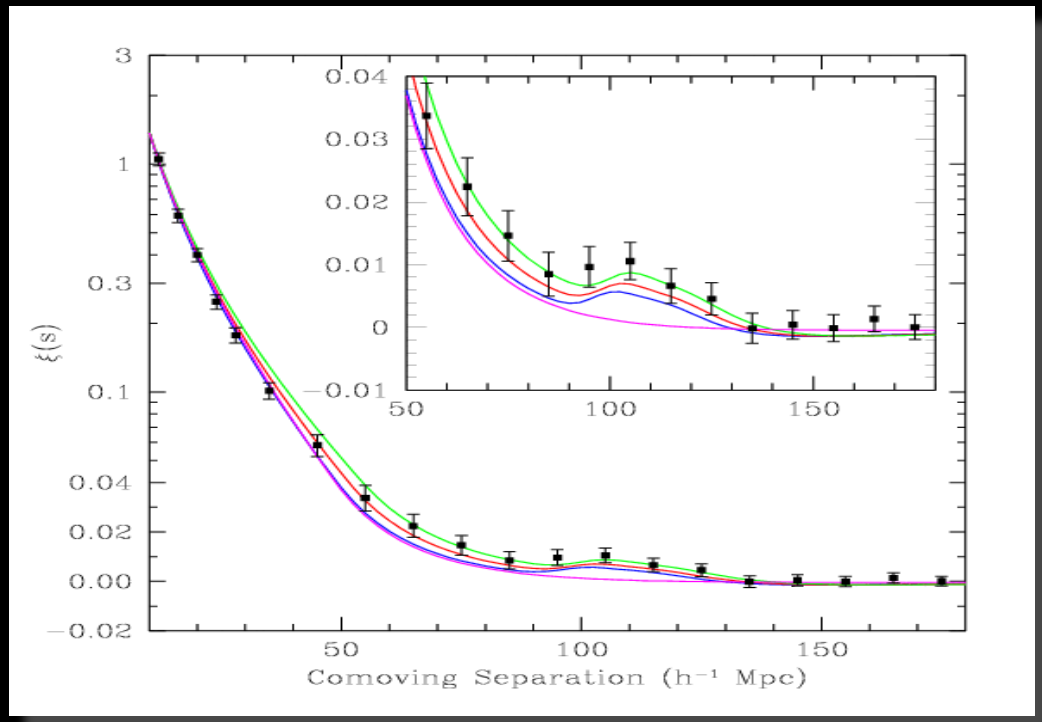

- Original cosmology science case for the SKA
- "The Billion Galaxy Redshift Survey" (Abdalla & Rawlings 200*)
- Phase 1 restricted to "proof of concept" type science at low-z
- The first non-optical detection of BAO

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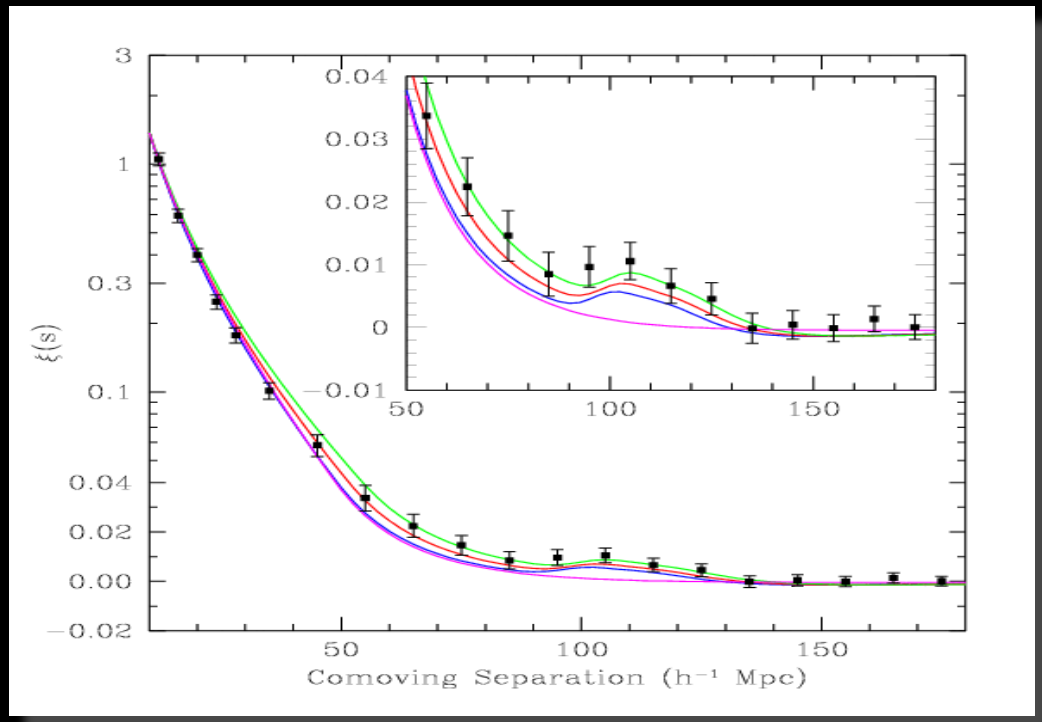


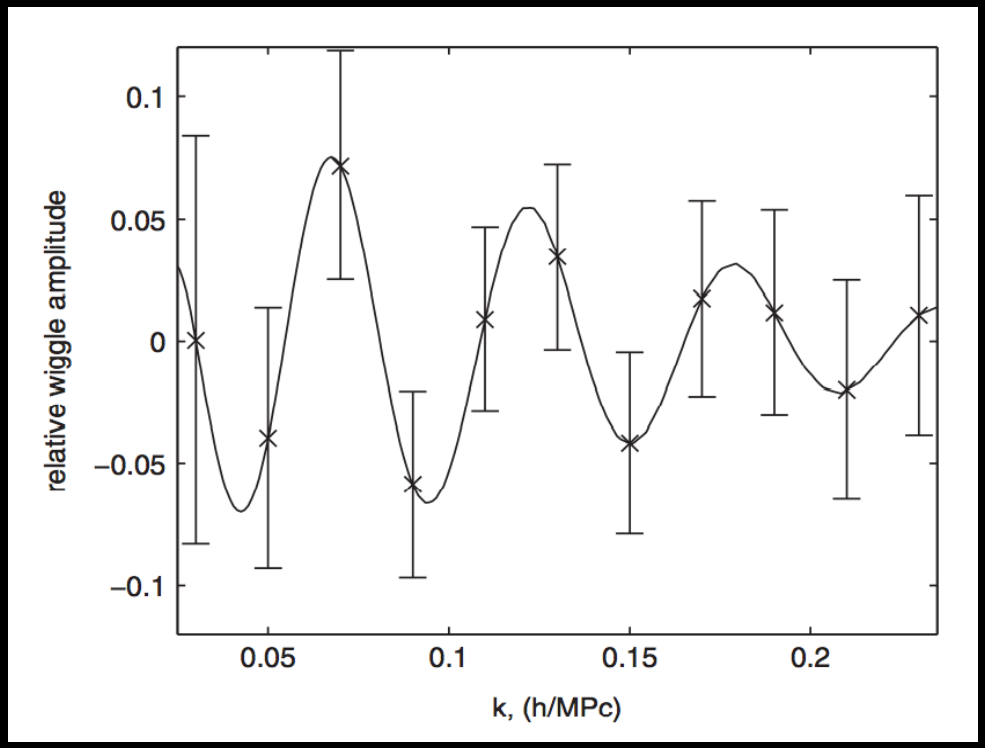
- However BAO is a large-scale effect, therefore no real need to resolve individual galaxies
- Could do with Intensity Mapping…

Intensity Mapping

- “Intensity Mapping” (instead of HI associated with galaxies, interested in HI associated with large-scale structure)
- measure the collective HI emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.
- Measurement of spatially diffused spectral line, in the confusion-limited regime, but redshift information is retained.
- Brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D
- Low-angular resolution redshift surveys: LSS science, economical

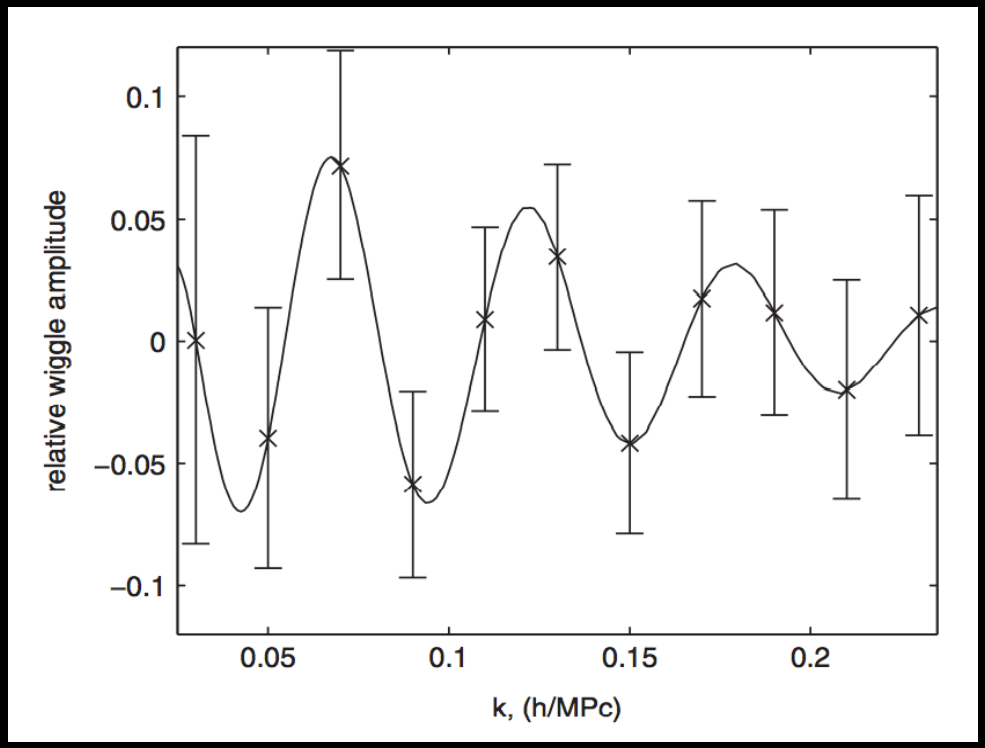
see e.g. Wyithe & Loeb 2008, Chang et al 2008

Intensity Mapping



- Signal is on large scales (150 comoving Mpc)
- Signals are weak - ~100uK (z)
- Need high surface-brightness sensitivity in the core, similar to EoR requirements

Intensity Mapping



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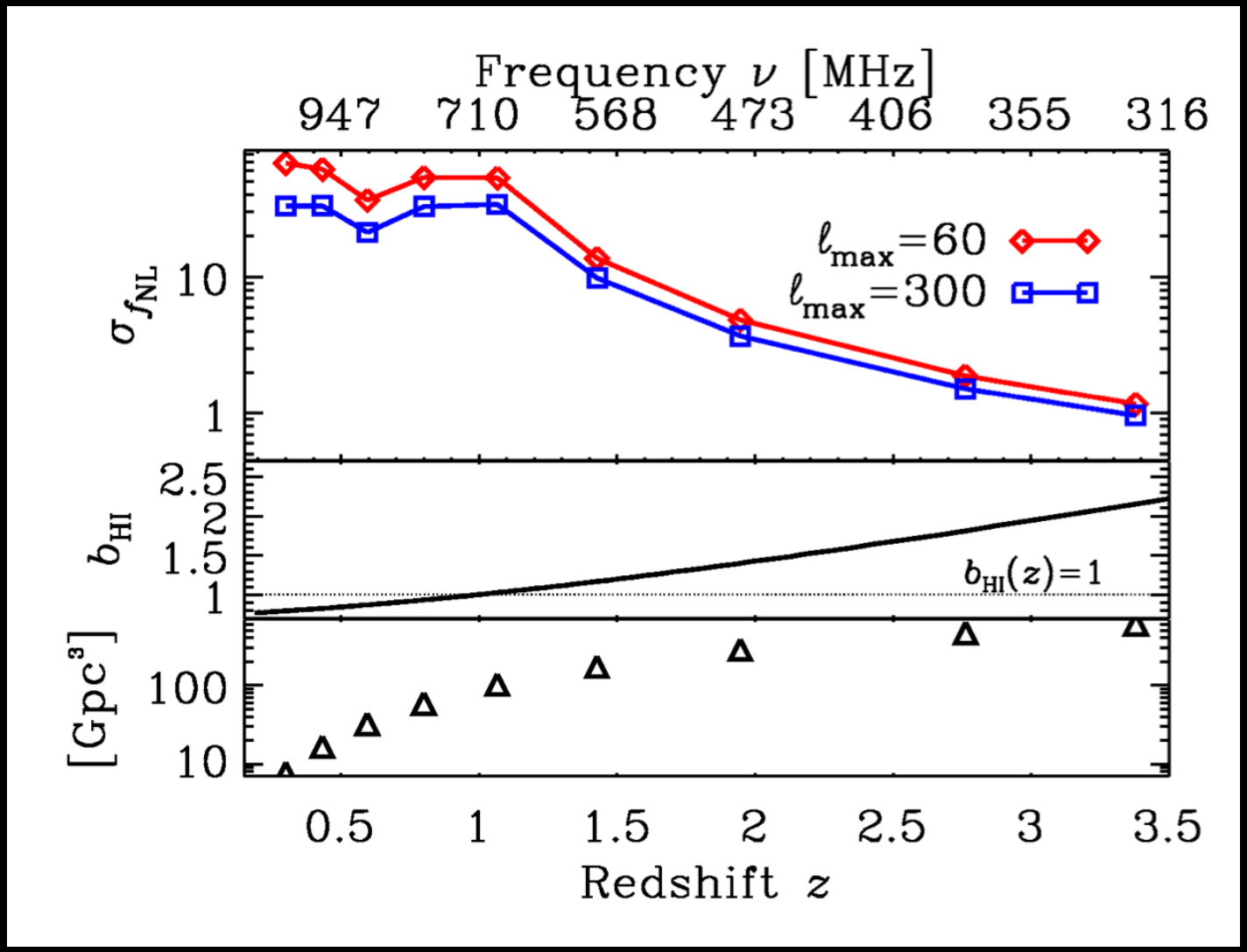
- Need to subtract foregrounds to high accuracy (better than 0.1%)
- Requires high degree of polarization purity (polarized foregrounds don't leak into I
- No bandpass structures that can mimic HI signal (>MHz scales)
- Large instantaneous field of view (similar to EoR)

Intensity Mapping



Use the 250 SKA-MID dishes as single dishes!

30,000sq.deg survey

Error on BAO distance scales proportionallt to the (core filling factor)$^{-1}$

SKA1-MID f~0.03 (<400m)

SKA1-SUR f~0.003 (<400m)

NOT IDEAL!

Cosmology SWG, 2013

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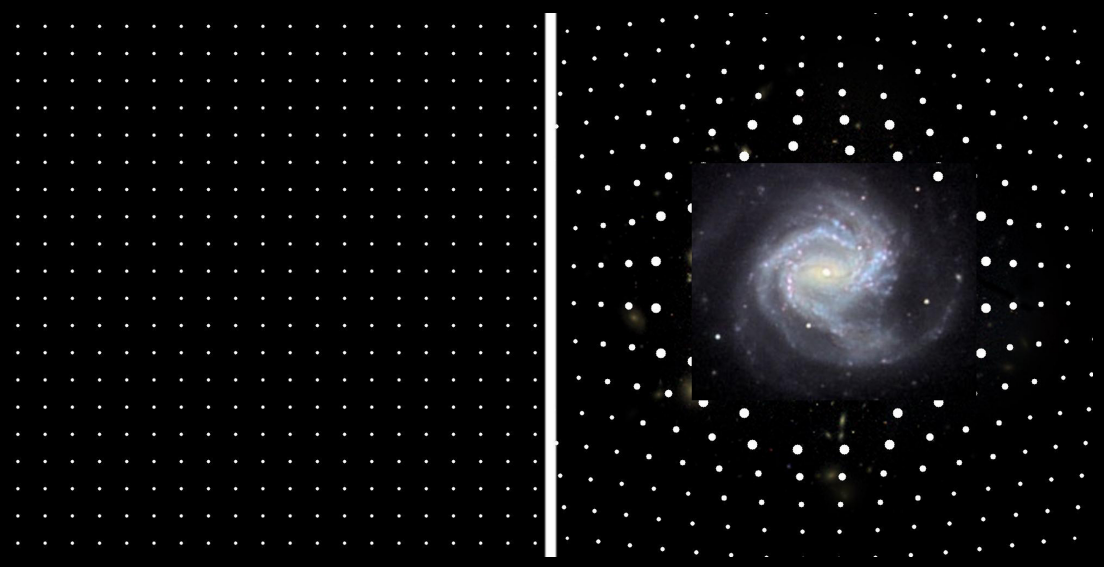
What can we do with continuum surveys?

Cosmic Magnification

Background sources (high-z) lensed by massive foreground (low-z) sources:

- Background area appears stretched
  → *decreased surface density*

- Fainter background sources appear brighter
  → *increased surface density*

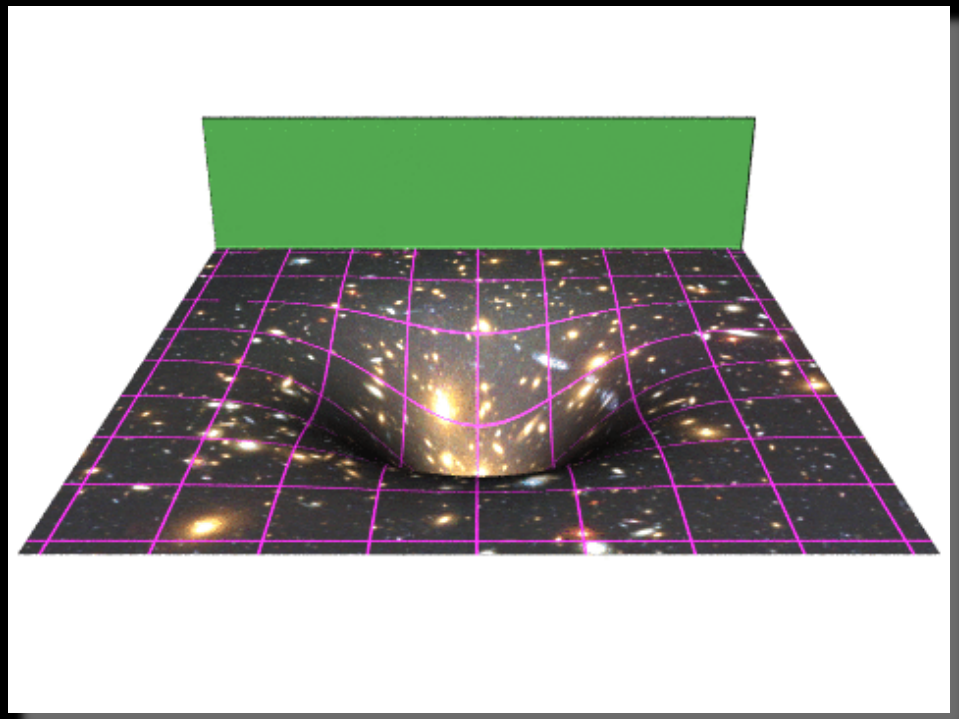


Joerg Colberg, Ryan Scranton, Robert Lupton, SDSS

Test: Cross-correlation of foreground and background objects

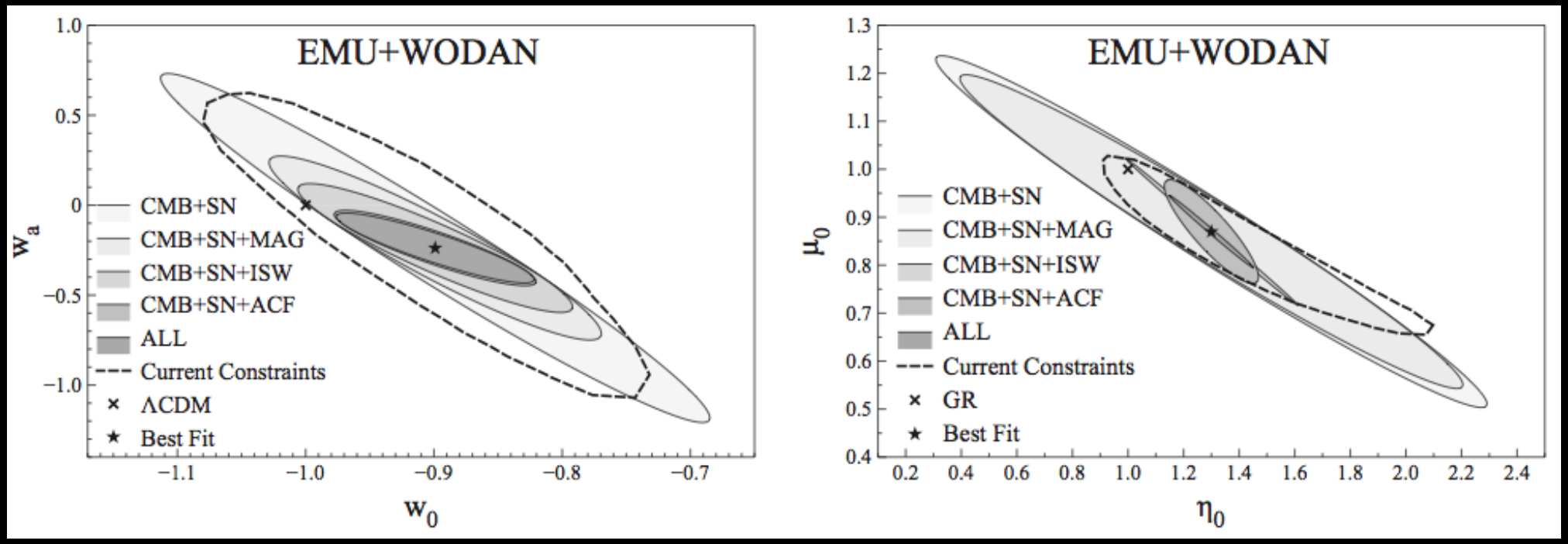
Integrated Sachs-Wolfe (ISW) effect

- CMB photons gain energy entering a deep gravitational potential well
- Universe undergoes accelerated expansion
- Photons lose less energy upon exit



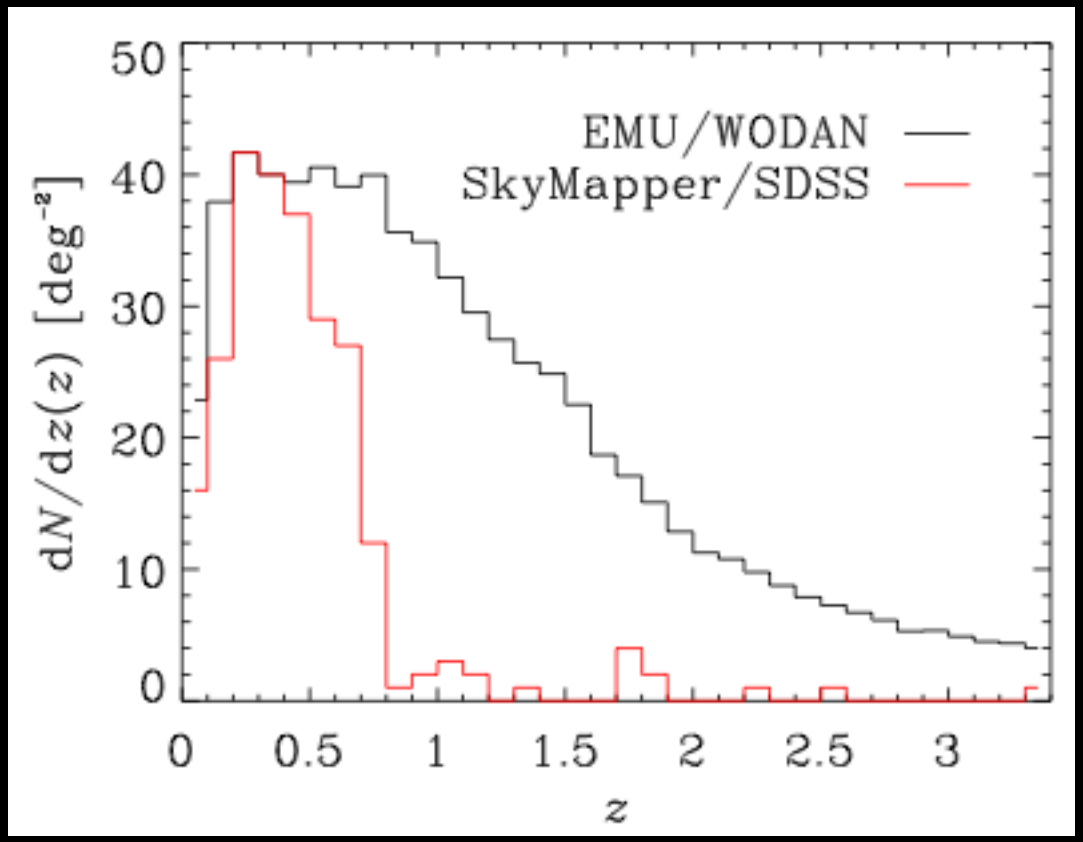
Test: Cross-correlation of large structures with CMB

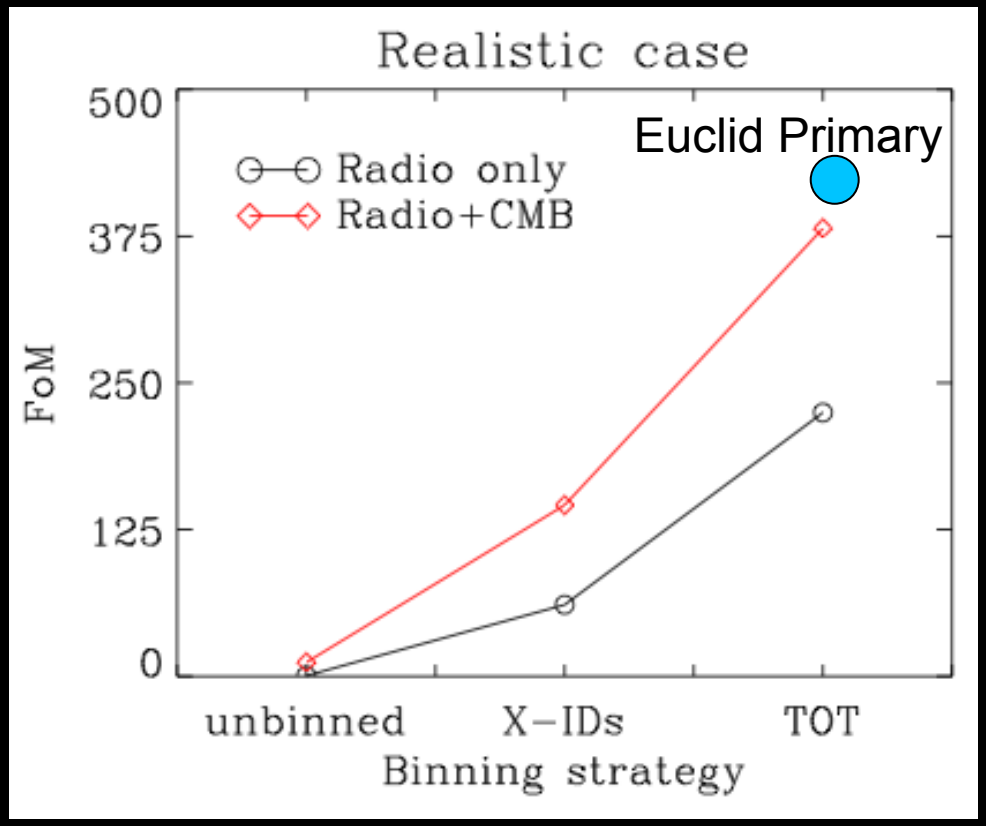
Dark Energy & Modified Gravity



Raccanelli et al. 2012

With redshifts





Camera et al. 2012

- With minimal photo-zs for radio sources at z<1 ish you get much improved constraints on the evolution of DE.
- ~5 years earlier than Euclid

Weak Gravitational Lensing

- Measurement of the distortion in galaxy shapes due to the dark matter distribution along the line of sight allows the reconstruction of the density field.

- Combining the continuum measurement with redshift allows lensing tomography, which measures a combination of geometry and the growth of structure

- Key to success
  - source density (40 sources/arcmin^2 with Euclid)
  - Shape measurement of distant galaxies (~1arcsec in size)
  - **resolution required ~0.5”**

- Why do this in the radio when you only get 5 sources arcmin for a 1.4GHz sensitivity of 0.5uJy rms per total flux – or **0.35uJy/beam!**

Weak Gravitational Lensing

- Radio Interferometers have a determinable and stable PSF
- You can “pick” the important spatial modes as a default
- Radio spectra are smooth and vary little across a galaxy
  - (cf optical imaging which have stellar absorption/emission features along with bulge and disk components of different colours)
  - Colour dependent shape biases can be much better controlled in the radio (frequency information available)
- Polarization can be used to measure the intrinsic orientation (Brown & Battye 2011a,b)

The combination of optical and radio surveys if greater than the sum of the parts!

How do we answer these questions?

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Large volume surveys really help with all of these!

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  - *Integrated Sachs-Wolfe* ✔
  - Neutrino mass
  - Non-Gaussianity

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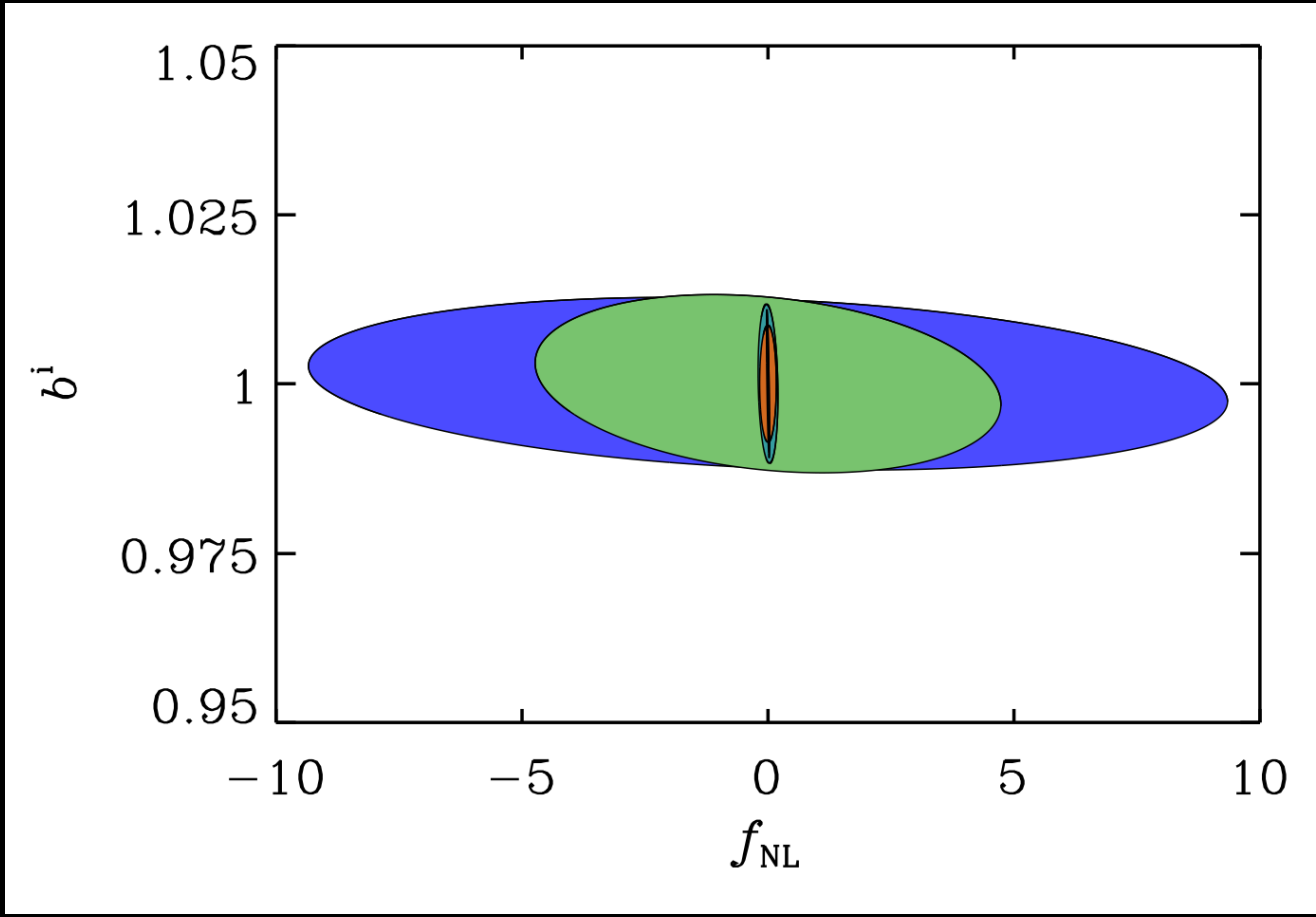
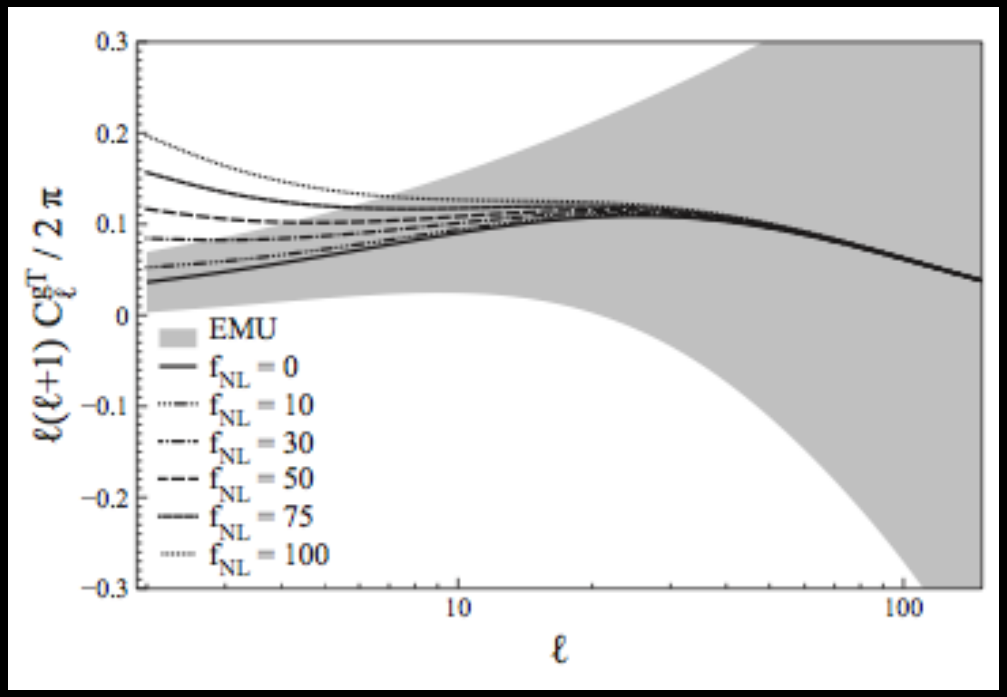
Non-Gaussianity with Continuum

If we can separate radio sources that trace difference mass DM haloes…

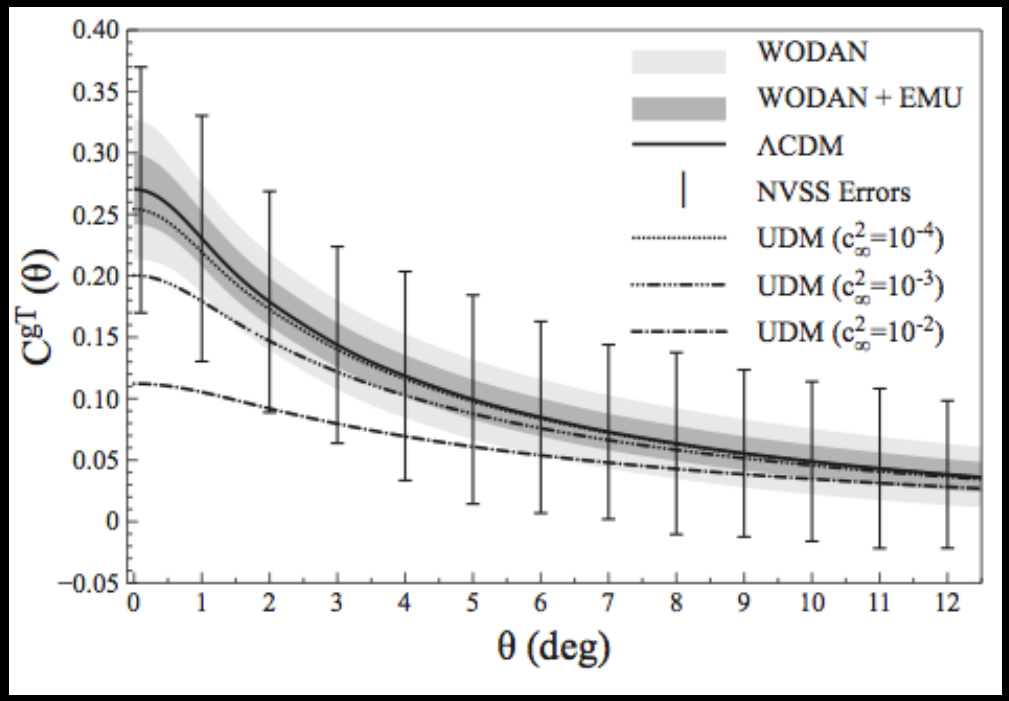


Ferramacho, Santos, Jarvis et al. in prep

Cross-correlation with CMB



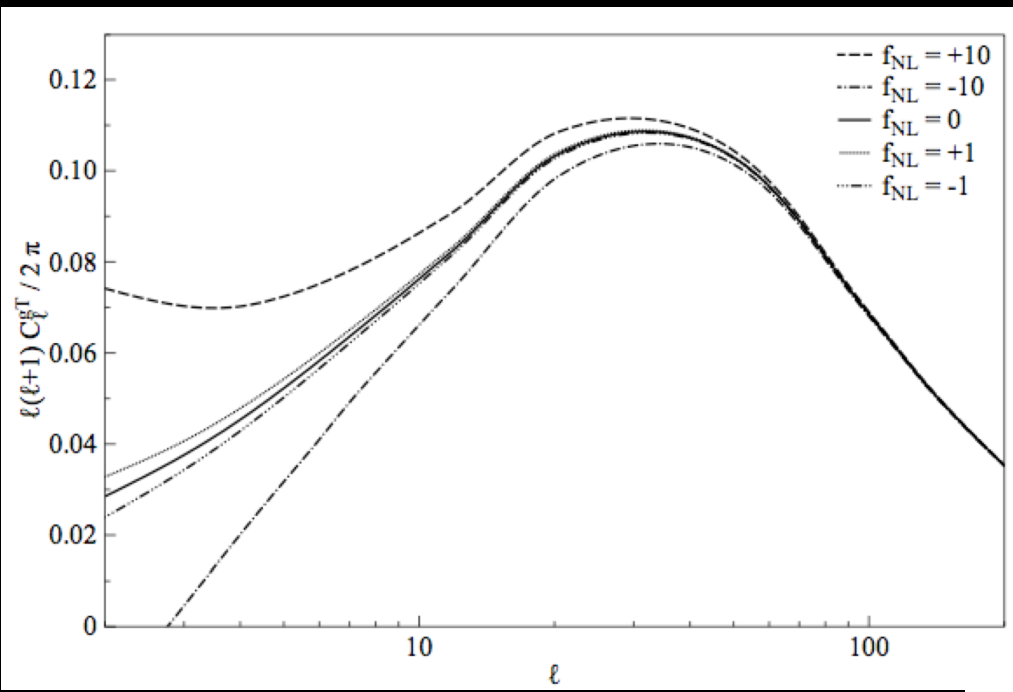
Non-Gaussianity



ISW

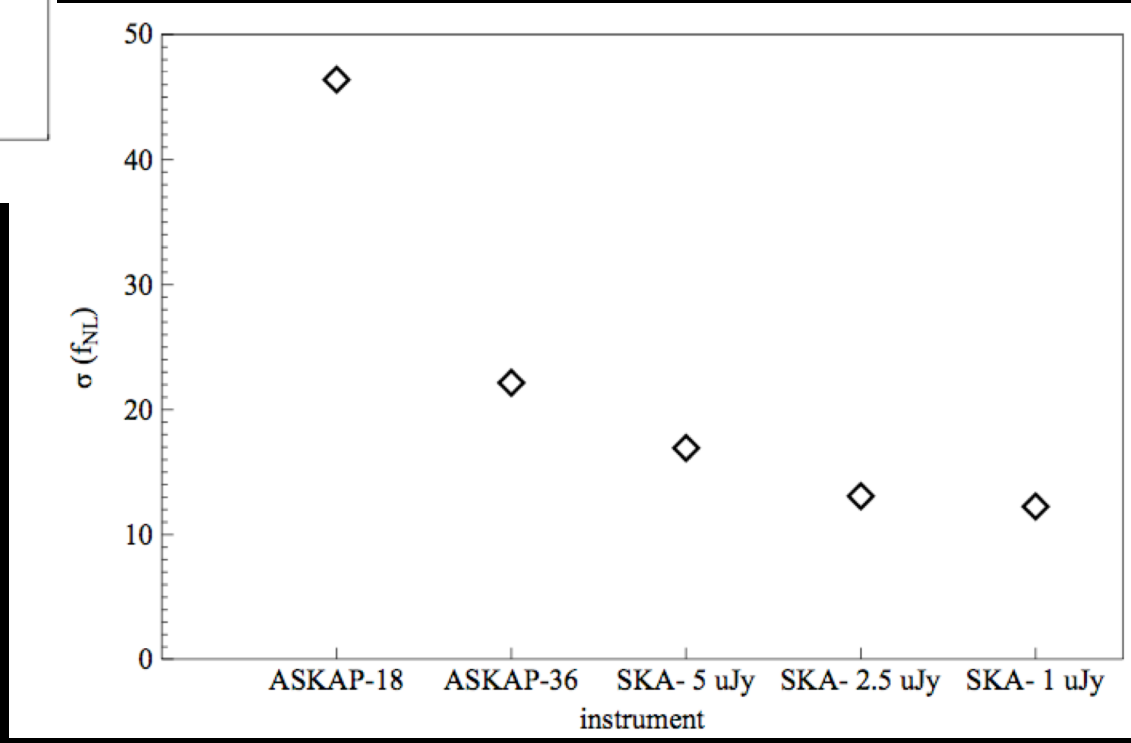
Raccanelli et al. 2012

Moving to the SKA...



f_{NL} from ISW

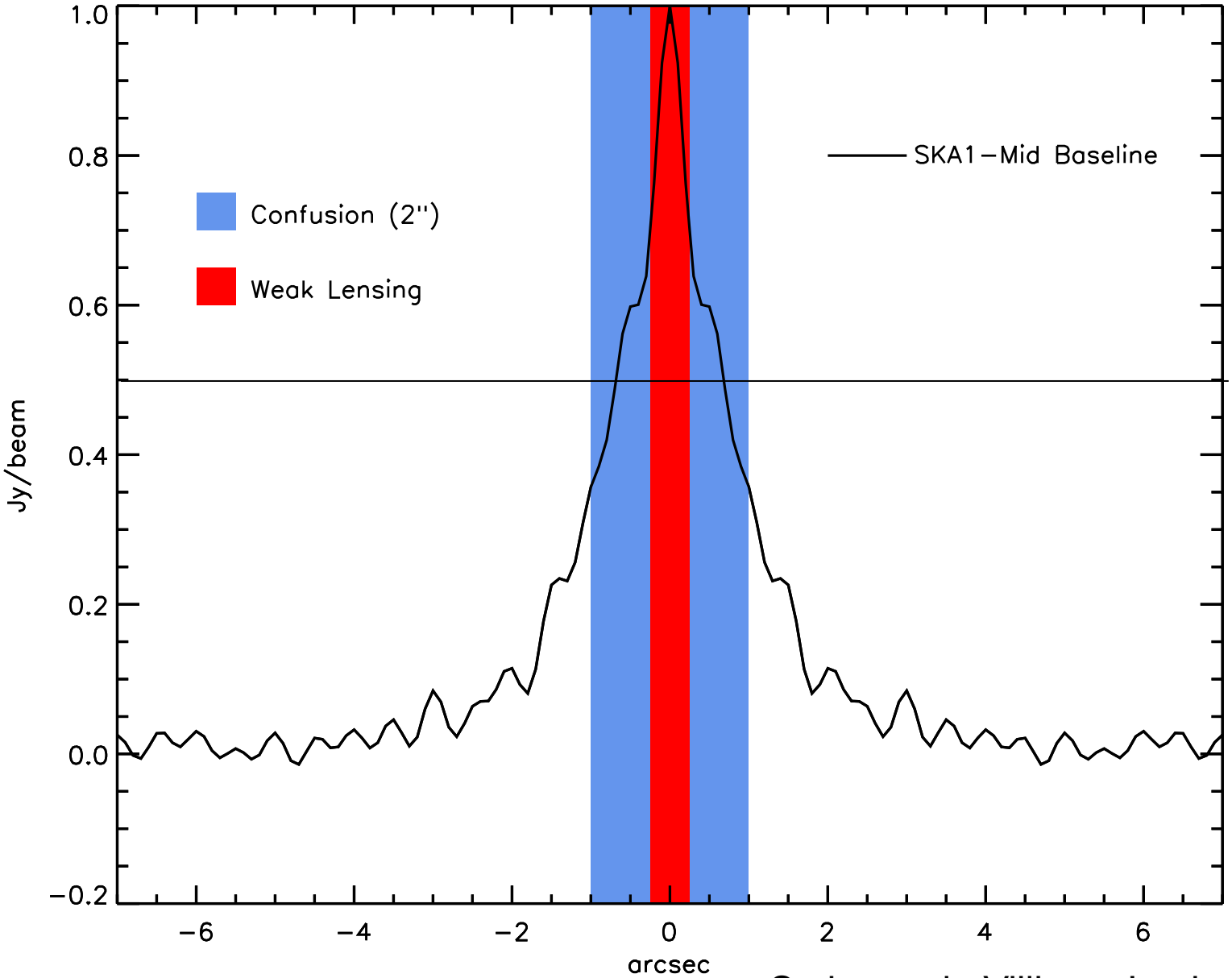
Raccanelli et al. in prep.



Moving to the SKA…

- Weak lensing requirements in the radio…
  - Source density of ~5 /arcmin^2 (frequency independent)
  - Resolution (synthesised beam) of ~0.5”
    - Sensitivity needed is ~0.35uJy/beam at 1.4GHz
      - (scale as freq^-0.8 for required depth at other frequencies)
  - Area required to probe the large-scale power that you are sensitive to with 5 sources / arcmin^2 is ~5000 sq.deg
  - Less area would still help control systematics of other facilities
- Strong lensing
  - Weak lensing survey could find many of the expected strong lenses
  - With 0.5” resolution at 1GHz, we would get <0.2” resolution at 3GHz – good enough for studying the lens systems

Continuum Surveys & Weak lensing with SKA-1



Smirnov, de Villiers, Jarvis et al. in prep.

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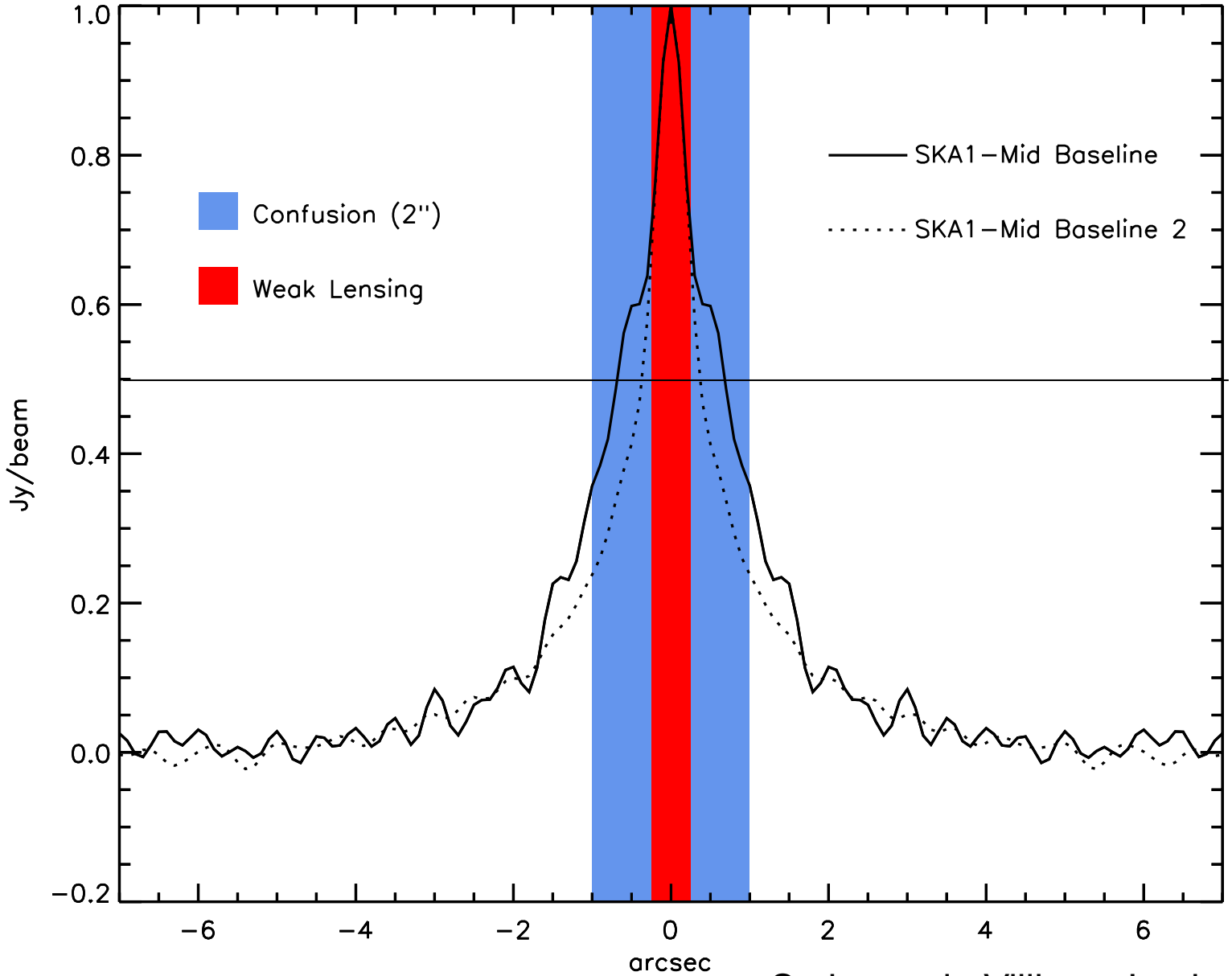

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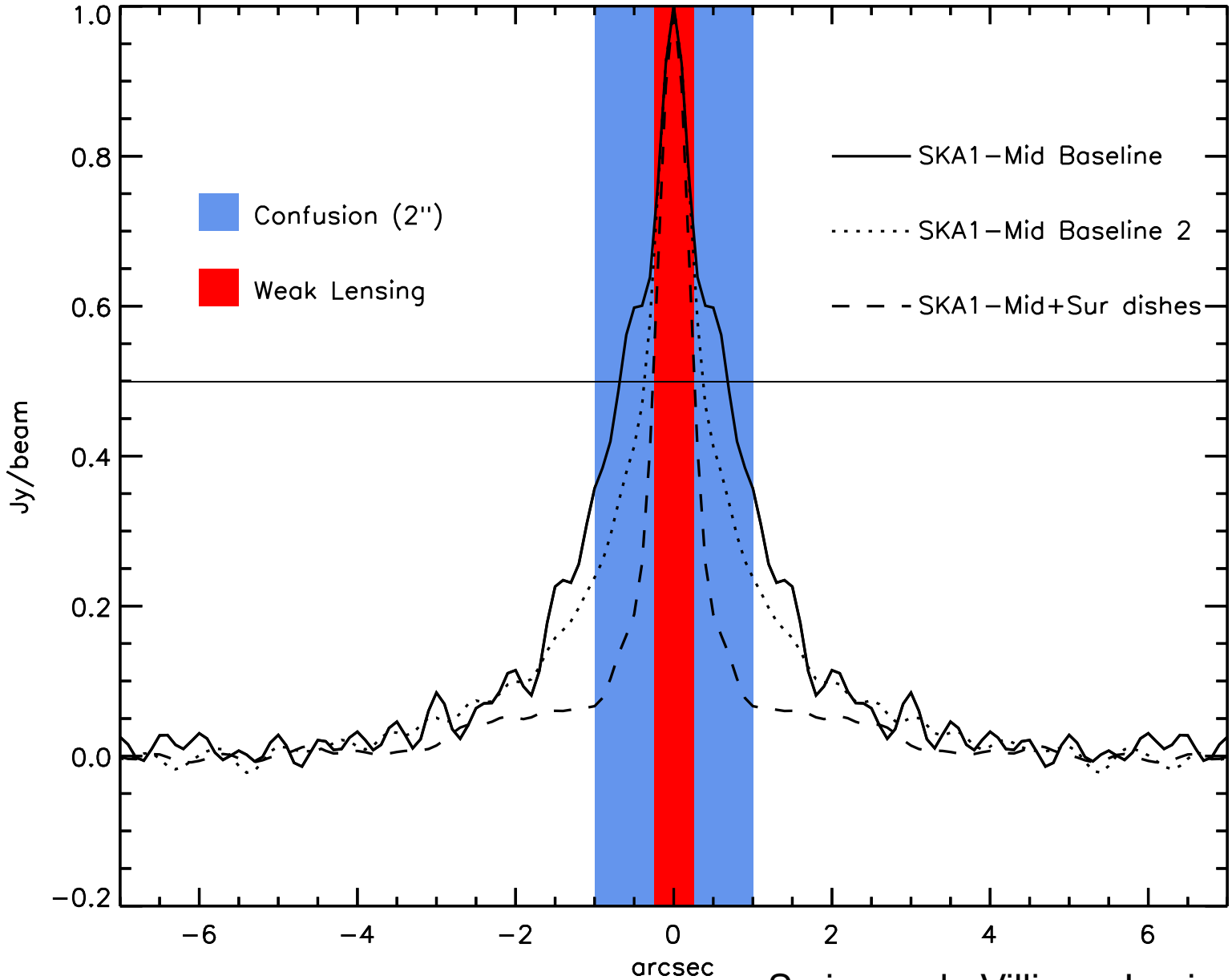

Smirnov, de Villiers, Jarvis et al. in prep.

You can do way more ground-breaking science with a 300 dishes distributed on sensible baselines than you can with a separate SKA-MID + SKA-SUR

Summary – Spectral Line

- HI cosmology with Intensity Mapping should be high-priority for SKA1
  - Compact configuration at all frequencies (SKA-Low too sparse at high-freq)

- SKA-Low is too sparse at >200MHz for Intensity Mapping at z>3

- SKA-Mid may be good enough with a denser core
  - 50 antennae within 100m radius would result in a filling factor f of ~0.3,
  - 25 antennae within 50m radius will have a f of ~0.6
  - Other possibility to gain a "single disk" experiment with a projected filled core
  - Extending frequency coverage to as low as possible would be advantageous (no need for > 800MHz for IM)
  - 250-single dish experiment also worth pursuing

  - More work on feasibility and competitiveness is still required

- Low-redshift BAO and Redshift Space Distortions will still be useful
  - provide confirmation of results from optical/nearIR surveys
  - reduce systematics
  - overcome cosmic variance with multiple tracers of the density field

  - Multi-bias tracer
    - HI less biased tracer of the density field – Good for low-z Redshift Space Distortions (growth of structure)
    - less prone to finger of God effect

Summary - Continuum

- Radio continuum surveys have potential to do cosmology

- Three tests that need area can be done well with 2 arcsec, 1uJy/beam all-sky survey
  - ISW
  - Power Spectrum
  - Cosmic Magnification bias

    - all need very high-precision calibration over 3pi sr (~1%)

Just about possible with baseline design with weighting -> more time needed

But…

- If SKA1 can combine resolution (0.5”) and sensitivity(0.35uJy/beam) then weak lensing surveys are within reach.
  - Unique and groundbreaking science for SKA1
  - Very complementary to optical/nearIR surveys
  - Key to accounting for systematics at different wavelengths
  - Polarization – would like large ~1GHz bandwidth

- With this resolution can also utilise multiple tracers to overcome cosmic variance
  - Distinguish FRII,FRI,RQQ, SFGs – possibly leading to tight(est) constraints on f_{NL}

We can do cutting-edge cosmology with SKA1!

So we should make sure that this science case
(that dominates the science agenda of most astronomy-rich nations)
does NOT get built OUT of the SKA