Cosmology on ultra-large scales with the SKA and other galaxy surveys

UNIVERSITY of the WESTERN CAPE

SKA AFRICA
SQUARE KILOMETRE ARRAY

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9th Aegean Summer School 2017

ICG Portsmouth

Ultra-large volume galaxy surveys – the next frontier

The next generation of surveys will map the matter distribution in ultra-large volumes:

These surveys will advance ‘precision cosmology’. But they will also:

- Lead to *new and unexpected discoveries.*
- Facilitate *improved and new tests* of the foundations of the standard model of cosmology:
    - GR
    - the Cosmological Principle
    - (non-)Gaussianity of primordial fluctuations

The SKA

SKA PHASE 1

Build ~ 2019-2024

SKA1-MID:

~200 dishes, ~15 m – in South Africa.

MeerKAT Pathfinder – 64 dishes 2018.

SKA1-LOW:

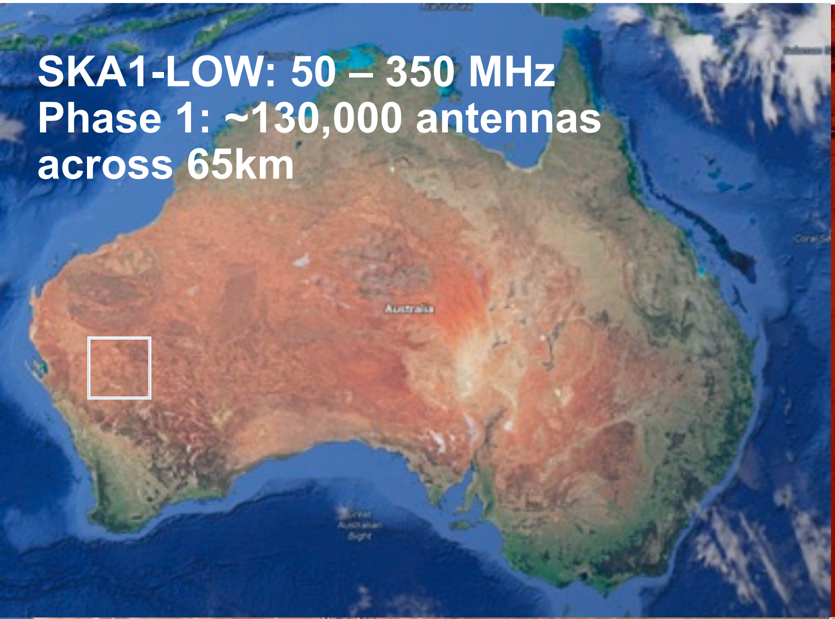
~130,000 dipole antennas – in Australia.

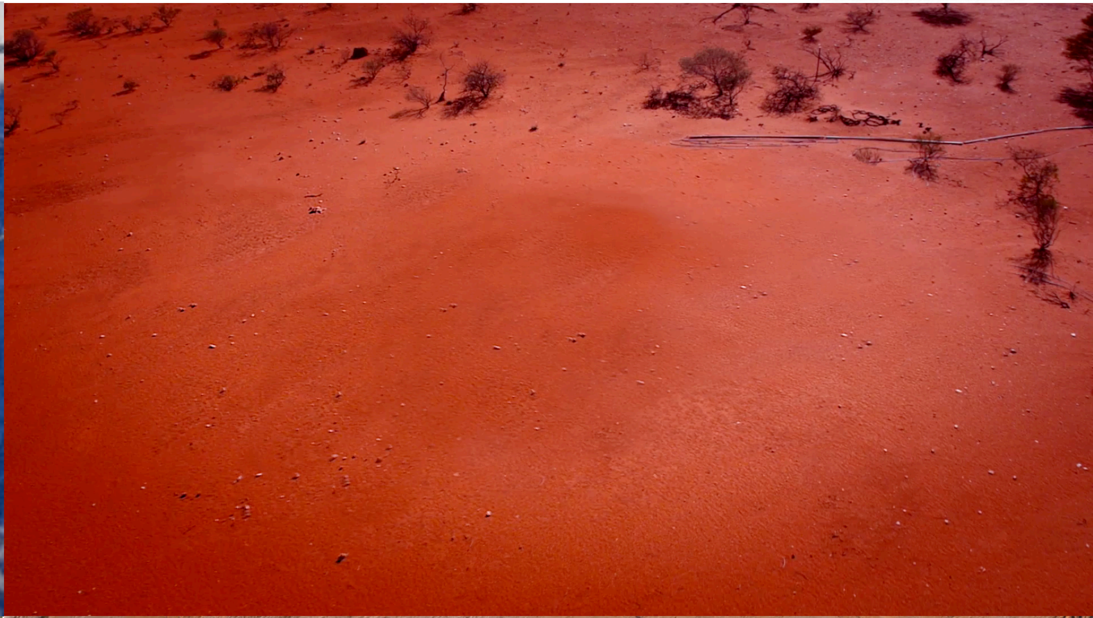
SKA PHASE 2

~ 10 X SKA1

~ 2025 -

SKA1-LOW: 50 – 350 MHz
Phase 1: ~130,000 antennas across 65km

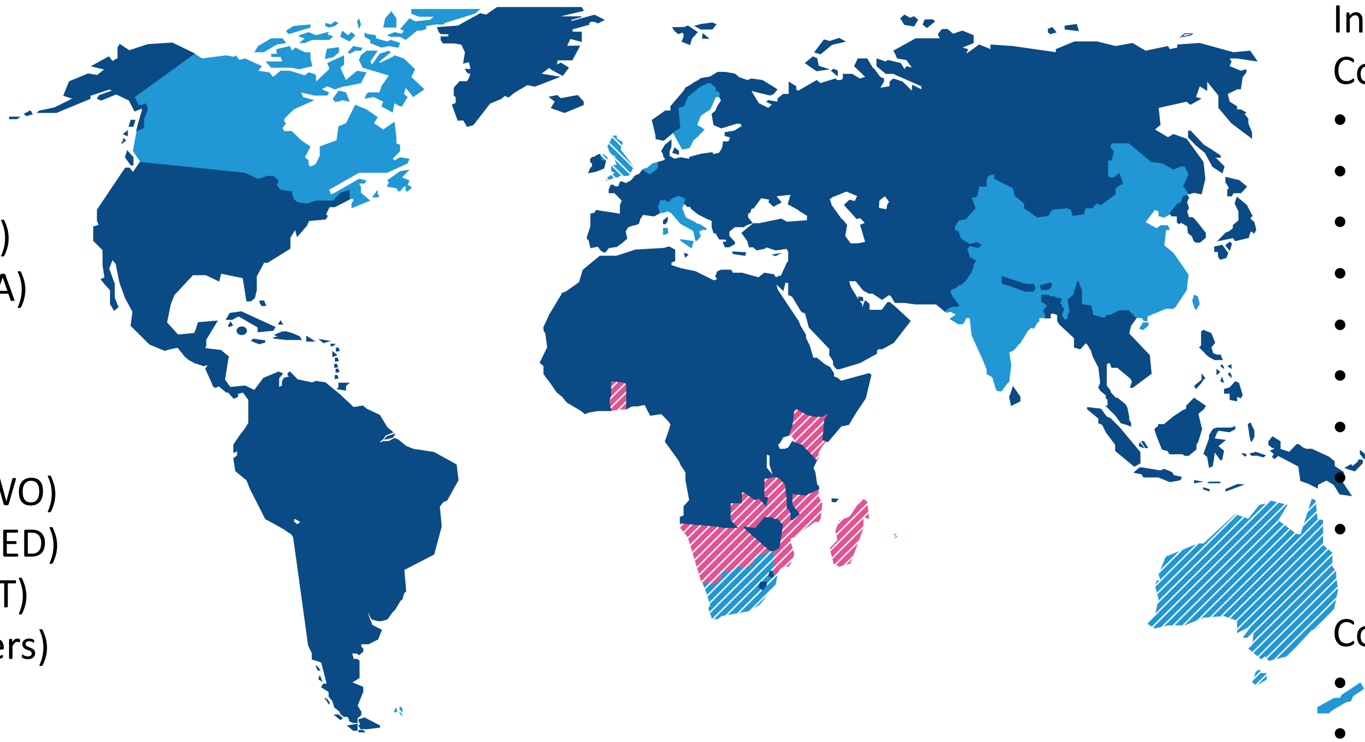




SKA1-Mid: 350 MHz – 24 GHz
Phase 1: ~200 15-m dishes across 150 km

SKA Organisation: 10 countries, more to join

Australia (DoI&S)
Canada (NRC-HIA)
China (MOST)
India (DAE)
Italy (INAF)
Netherlands (NWO)
New Zealand (MED)
South Africa (DST)
Sweden (Chalmers)
UK (STFC)



Interested Countries:

- France
- Germany
- Japan
- Korea
- Malta
- Portugal
- Spain
- Switzerland
- USA

Contacts:

- Mexico
- Brazil
- Ireland
- Russia

Full members

SKA Headquarters host country

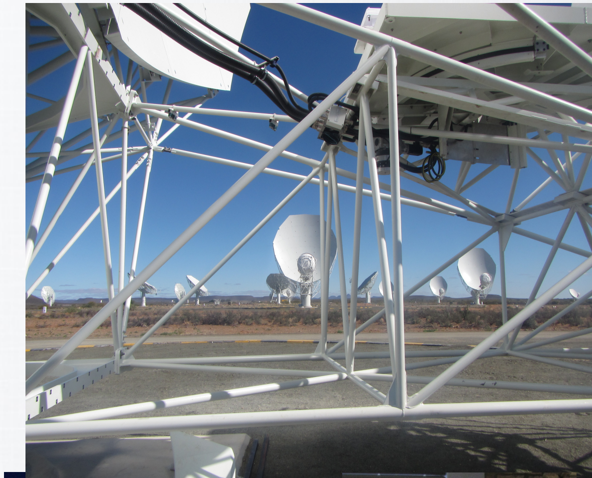
SKA Phase 1 and Phase 2 host countries

African partner countries (non-member SKA Phase 2 host countries)

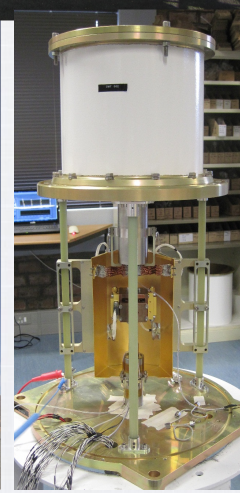
This map is intended for reference only and is not meant to represent legal borders

MeerKAT array – in progress (>32 dishes now)

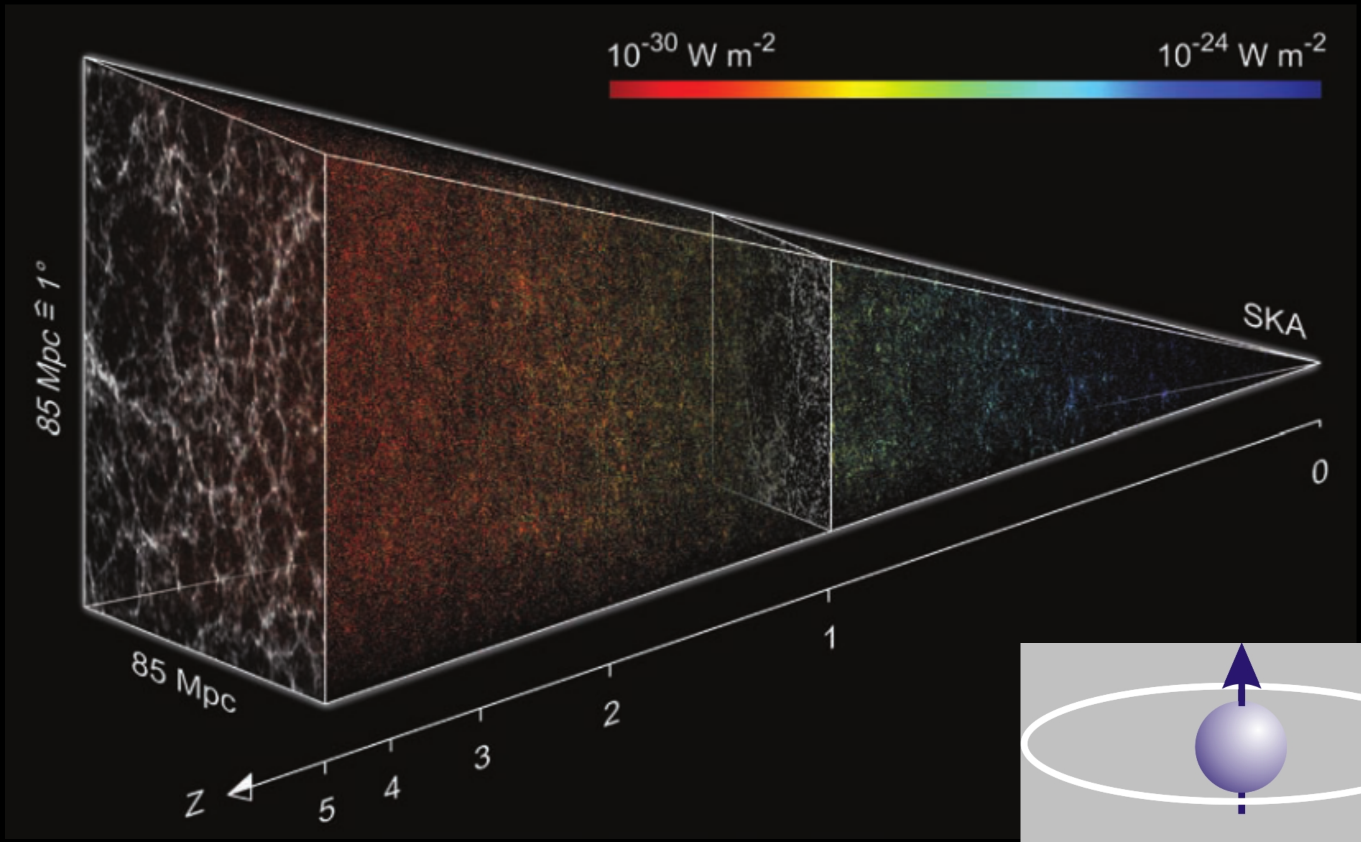
- 64 x 13.5m dishes
- Full operations April 2018
- To be absorbed into SKA1 2024 (?)
- Proposed cosmology survey MeerKLASS (Santos, RM et al)

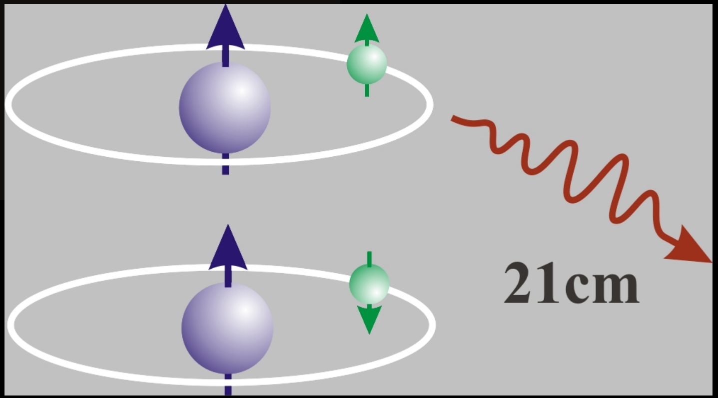

2014/06/06




3D map of galaxies will be based on detecting the radio waves emitted by hydrogen atoms in galaxies – automatically get the redshift.



$$1 + z = \frac{\lambda}{21\,\mathrm{cm}}$$



SKA spectroscopic surveys 1

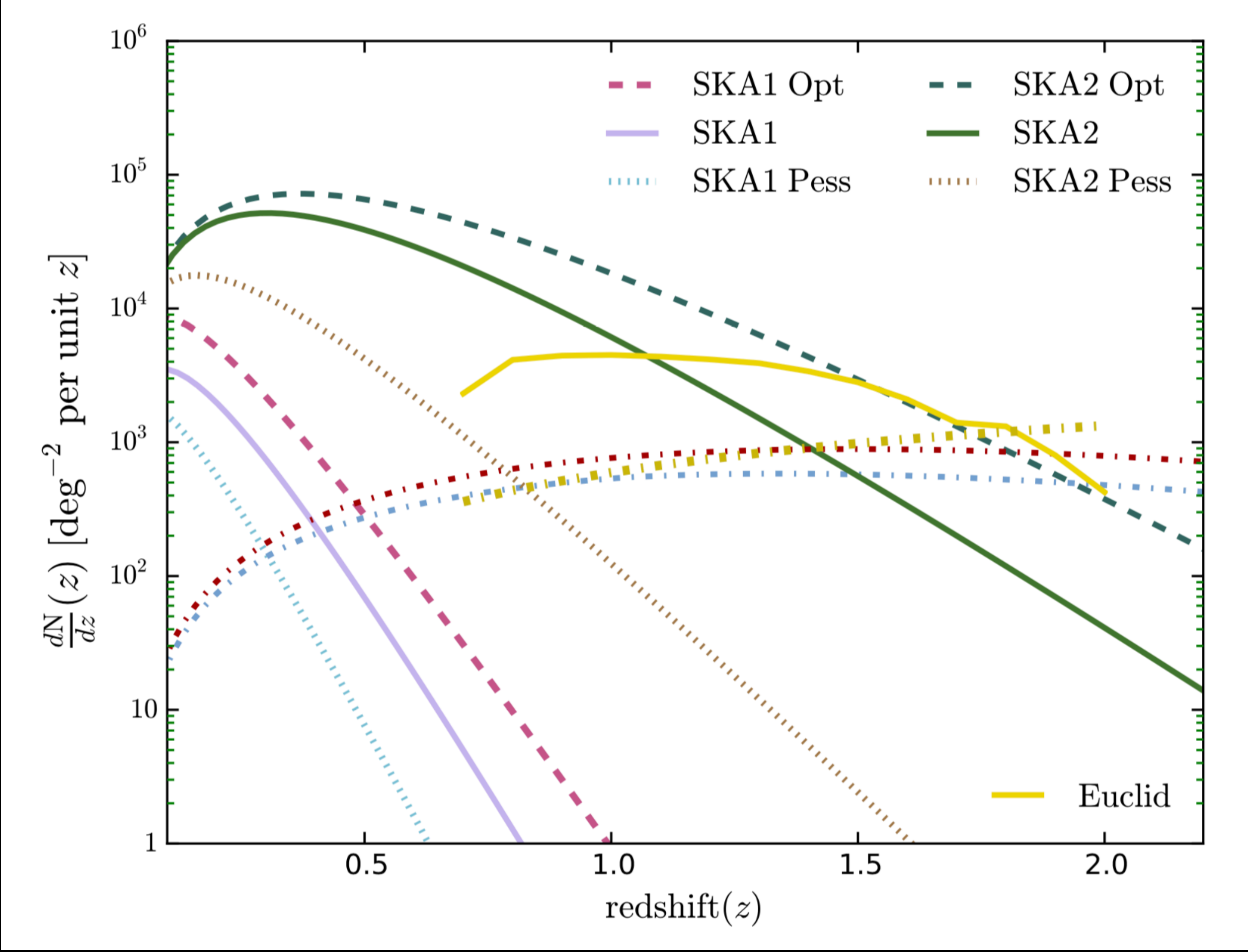
HI galaxy redshift surveys

- 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 could be a game-changer.

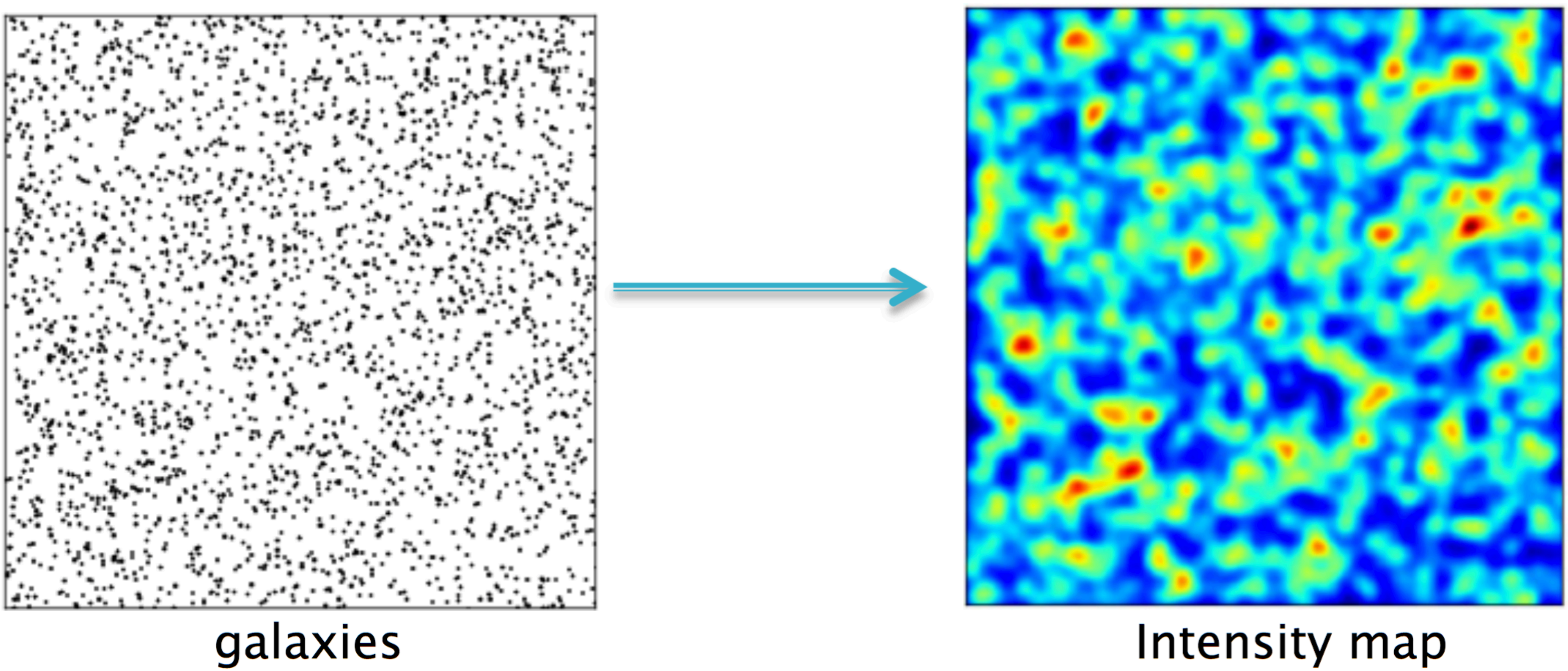
Yahya, RM et al 2015



SKA spectroscopic surveys 2

HI intensity mapping surveys (integrated emission – like CMB)

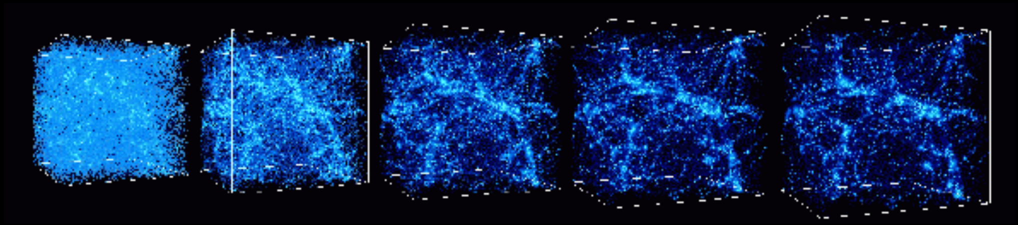
SKA1 – up to 25000 deg^2 , $z<3$



I. Testing GR via the growth rate

Growth rate of large-scale structure:

- insensitive to (non-exotic) models of dark energy,
- sensitive to the theory of gravity.

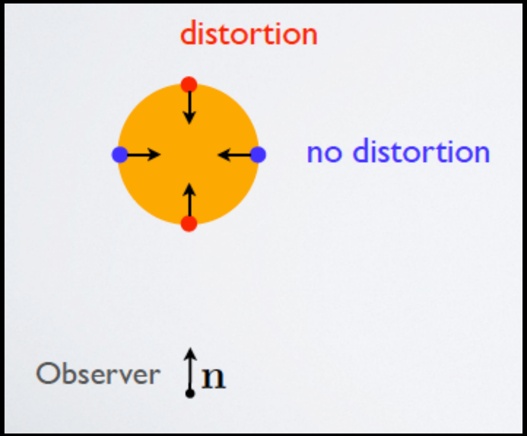


δ_m

Growth rate $$f = \frac{\mathrm{d}\ln\delta_m}{\mathrm{d}\ln a}$$

Redshift space distortions measure the growth rate:

$$\delta_g^{\mathrm{obs}} = \delta_g - \frac{(1+z)}{H}\frac{\partial}{\partial r}(\mathbf{n}\cdot\mathbf{v})$$
$$= (b + f\mu^2)\delta_m, \quad \mu = \mathbf{n}\cdot\hat{\mathbf{k}}$$

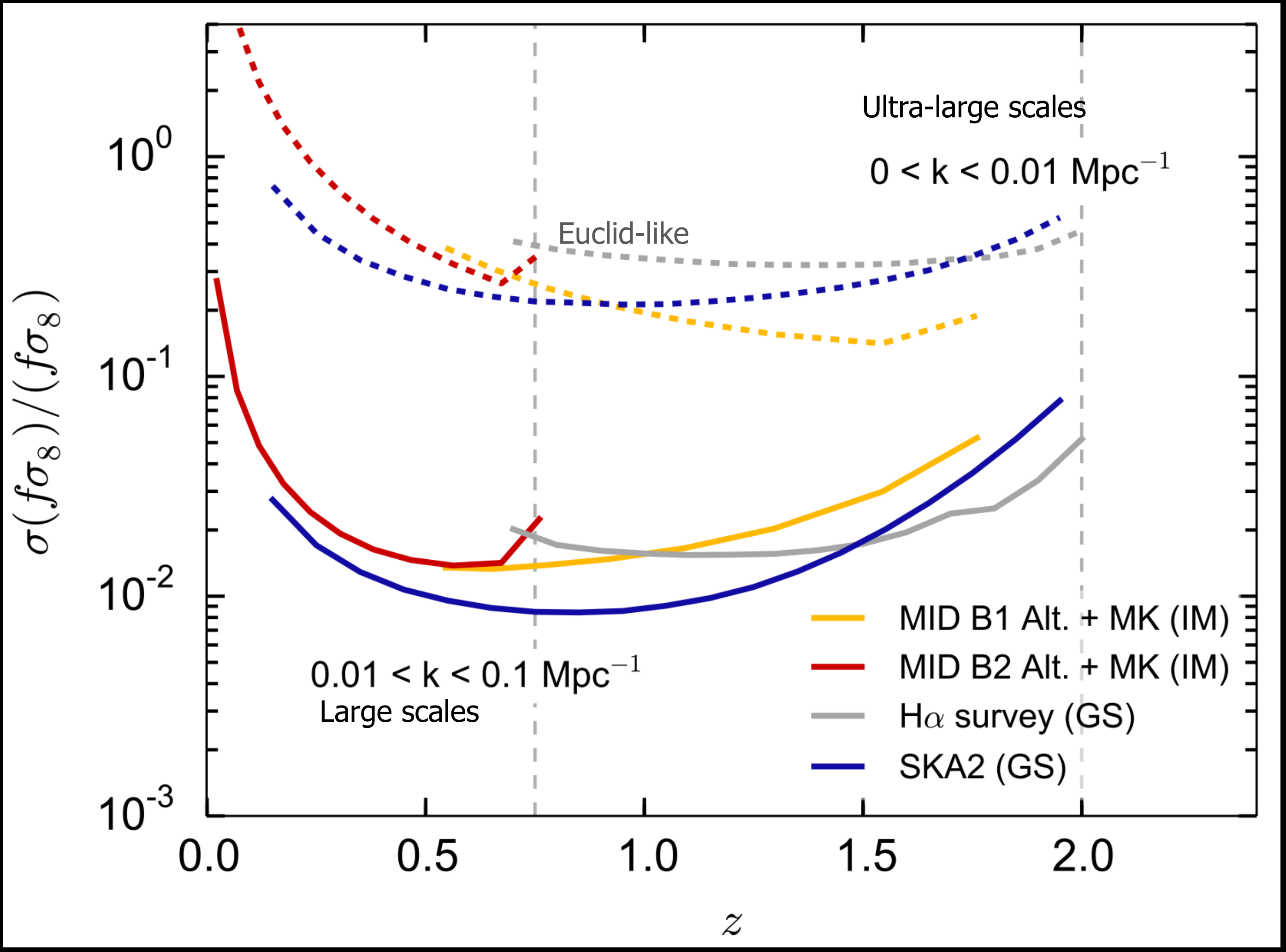


Constraining f via RSD with SKA spectroscopic surveys

SKA2 galaxy survey gives the best constraint –
but in Phase 1, HI intensity mapping can be very competitive:

Allows us to map huge volumes *before* SKA2
- with spectro-z
- but foregrounds are a problem

Errors on the growth rate from RSD: at large and ultra-large scales.

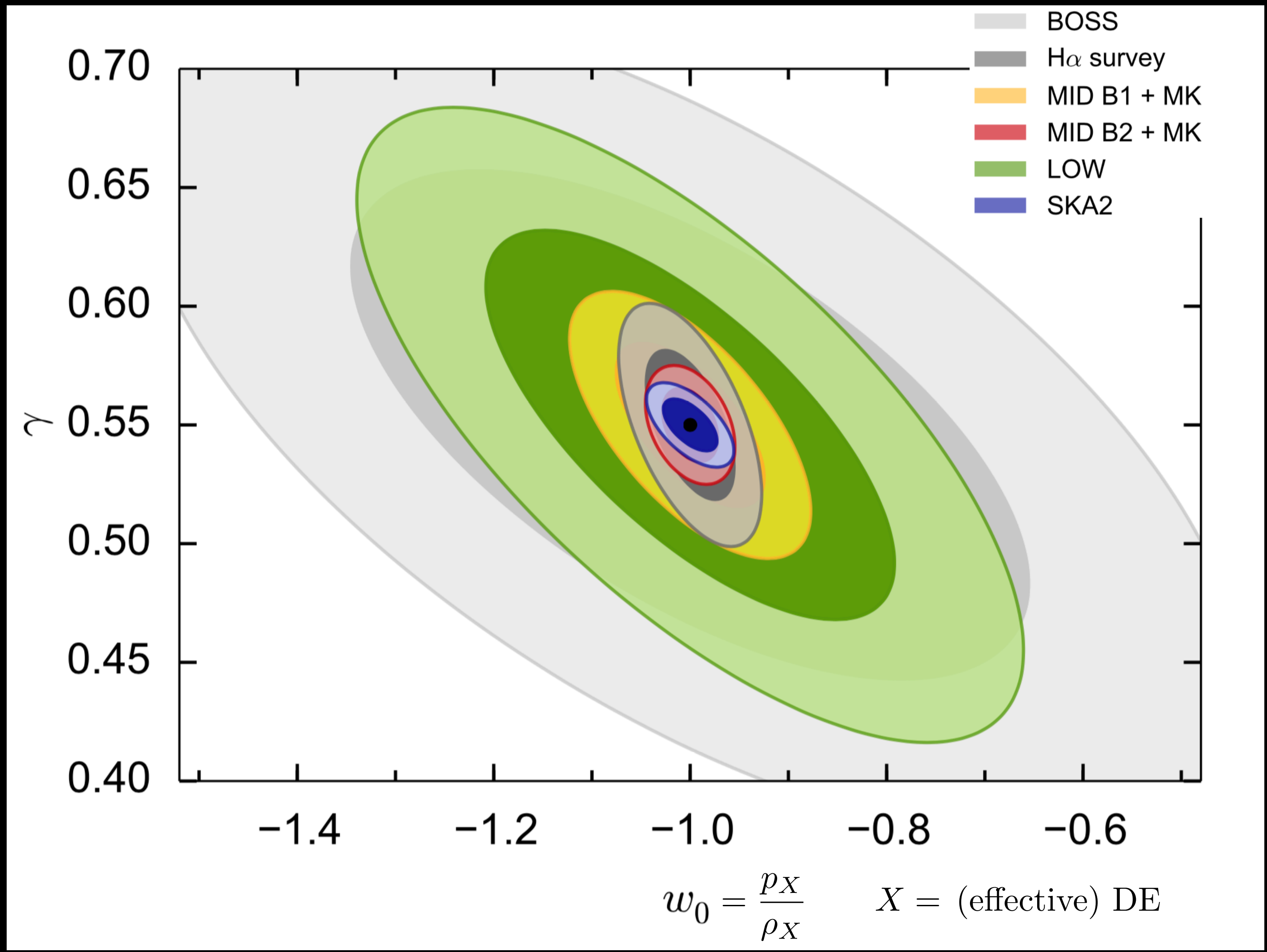


Bull 2015

Forecasts for testing GR via the growth rate

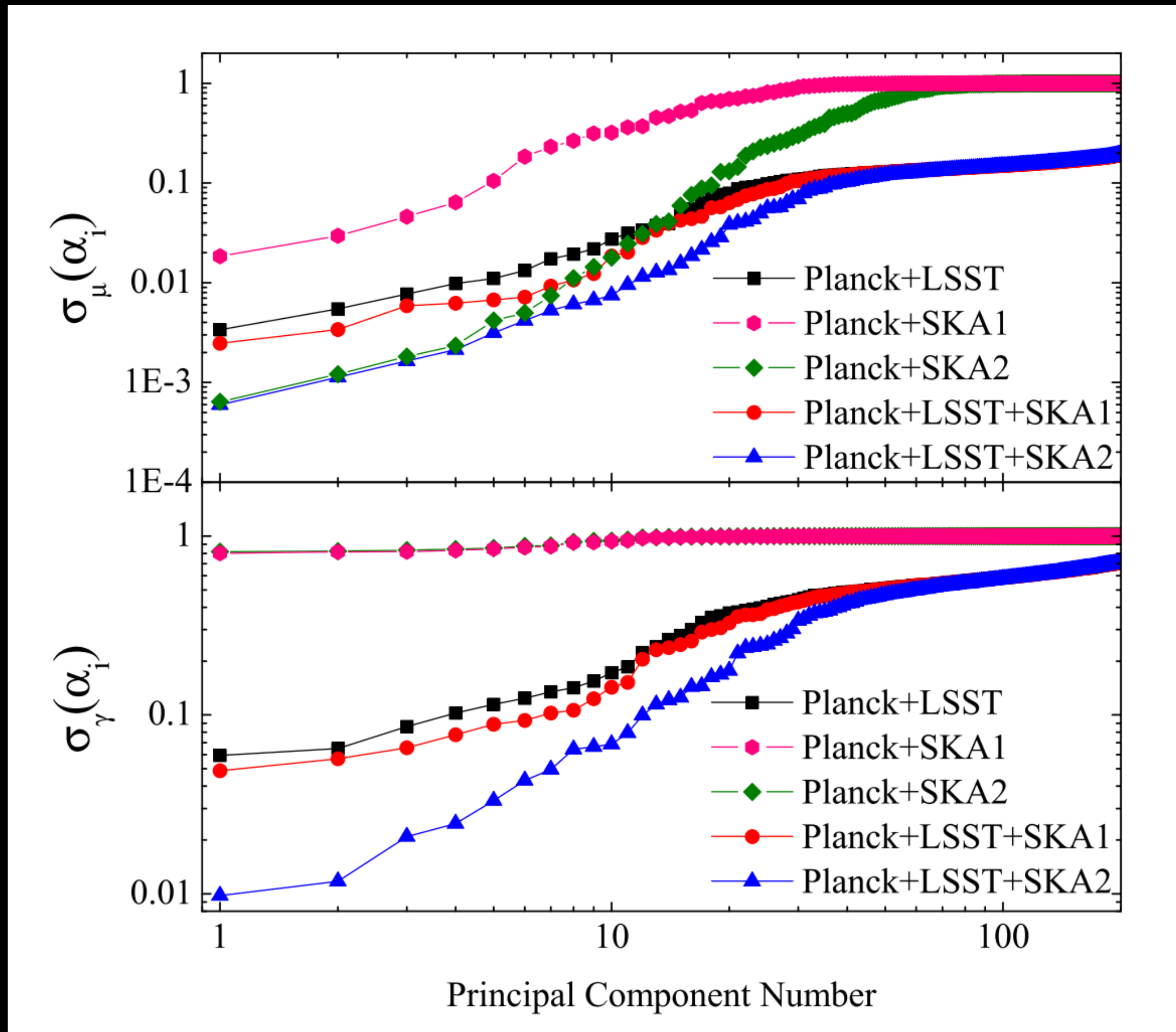
Use f to test gravity: $f(a) = \left[\Omega_m(a)\right]^\gamma, \qquad \gamma \approx 0.55$ (standard model)

We will need to combine with other tests to really constrain MG



Bull 2015

Example of using 2 surveys to constrain the strength of gravity:



$$\frac{G_{\rm eff}}{G}$$

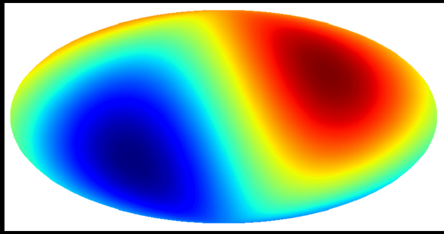
$$\frac{\Psi}{\Phi}$$

Zhao et al 2015

II. Testing the Cosmological Principle via the cosmic dipole

We are moving relative to the CMB rest-frame.
This generates a kinematic dipole in the CMB temperature – hotter in the motion direction, cooler behind:

$$\tilde{T}(\tilde{\mathbf{n}}) = T(\mathbf{n})\big[1 + \mathbf{n}\cdot\mathbf{v}_0\big], \qquad v_0 \approx 10^{-3}$$



In standard cosmology:

large-scale structure (LSS) rest-frame = CMB rest-frame.

Therefore the LSS dipole should be aligned with the CMB dipole – a critical test of the standard model.

Large-scale structure kinematic dipole:

higher number counts in the motion direction, lower behind.

The boosted observer measures redshifts and solid angles as:

$$1+\tilde{z} = (1+z)\big(1-\mathbf{n}\cdot\mathbf{v}_0\big)$$

$$d\tilde{\Omega}_o = \big(1-2\mathbf{n}\cdot\mathbf{v}_0\big)d\Omega_o$$

Total number of particles is conserved:

$$d\mathcal{N} = \tilde{N}\,d\tilde{z}\,d\tilde{\Omega}_o = N\,dz\,d\Omega_o$$

Then the number per redshift per solid angle is

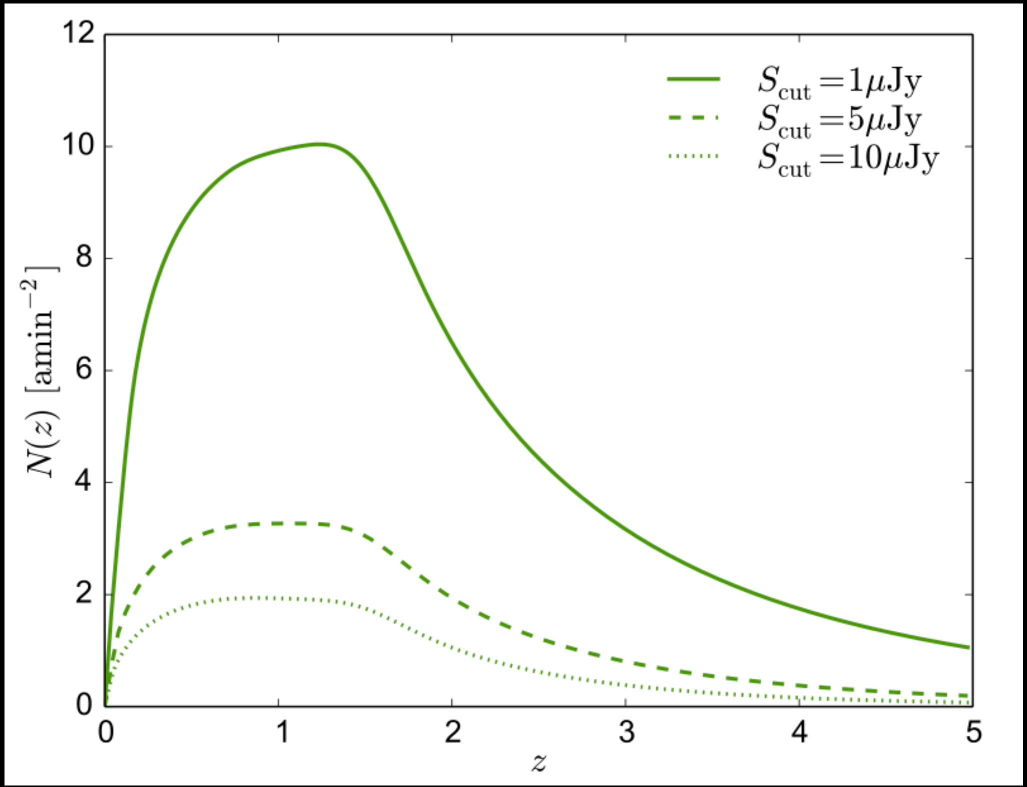
$$\tilde{N}(\tilde{z},\tilde{\mathbf{n}}) = N(z,\mathbf{n})\big[1+3\mathbf{n}\cdot\mathbf{v}_o\big]$$

To measure the LSS dipole, we need:

very large sky coverage + high number density + high z

It is easier to measure the dipole by counting numbers in opposite patches of the sky without regard to redshift – i.e. using the 2D angular correlations.

There is an SKA survey that is well-suited to this:
a radio continuum survey (detects total radio emission, but no redshifts).

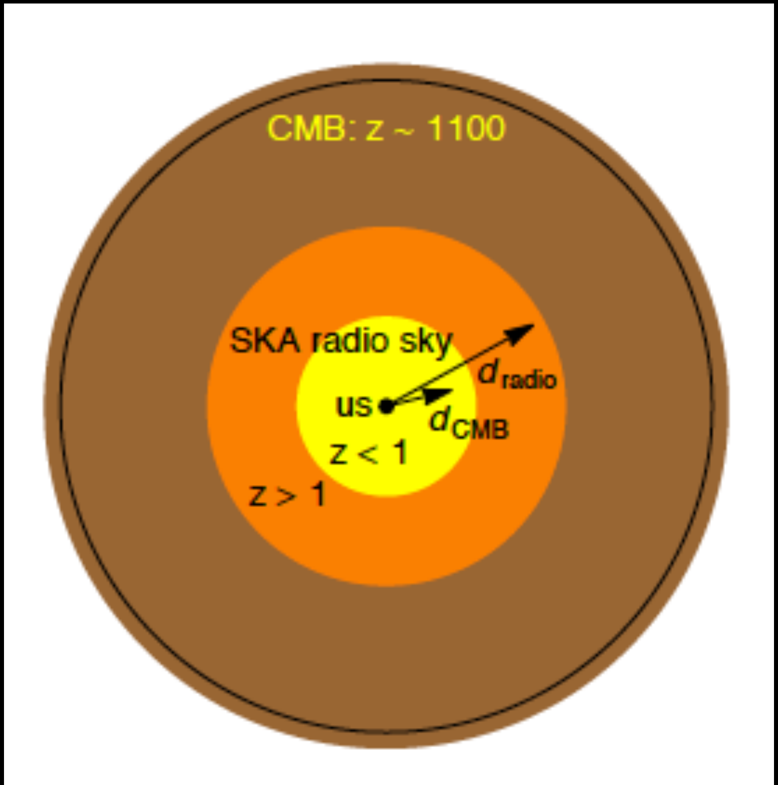


SKA continuum survey:

SKA1 – 100 million galaxies, 30000 deg^2, $z<4$
SKA2 – 2 billion galaxies, 30000 deg^2, $z<5$

Forecast to detect the LSS dipole direction:

- within ~5° (SKA1)
- within ~1° (SKA2)



Schwarz, RM et al 2015

III. Testing primordial Gaussianity

Primordial quantum fluctuations are generated during inflation –
* Gaussian for simple inflation models (as in standard LCDM)
* non-Gaussian for many other models

Constraining primordial non-Gaussianity (PNG) is a powerful probe of inflation – can rule out some inflationary models.

PNG is 'frozen' on ultra-large scales during the expansion of the Universe – and affects the CMB and LSS.

State-of-the-art constraint from *Planck:*

$$\sigma(f_{\rm NL}) = 5$$

Future CMB experiments will not be able to improve significantly on this constraint:

only LSS can push the errors down to 1 and below.

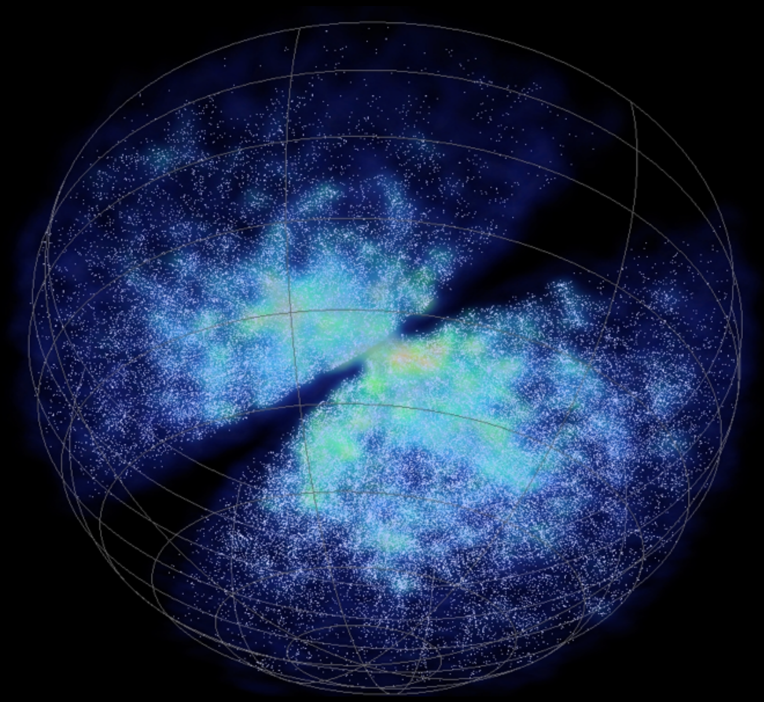
How does PNG affect the galaxy distribution?

For local PNG, the large-scale bias of galaxies is modified as follows:

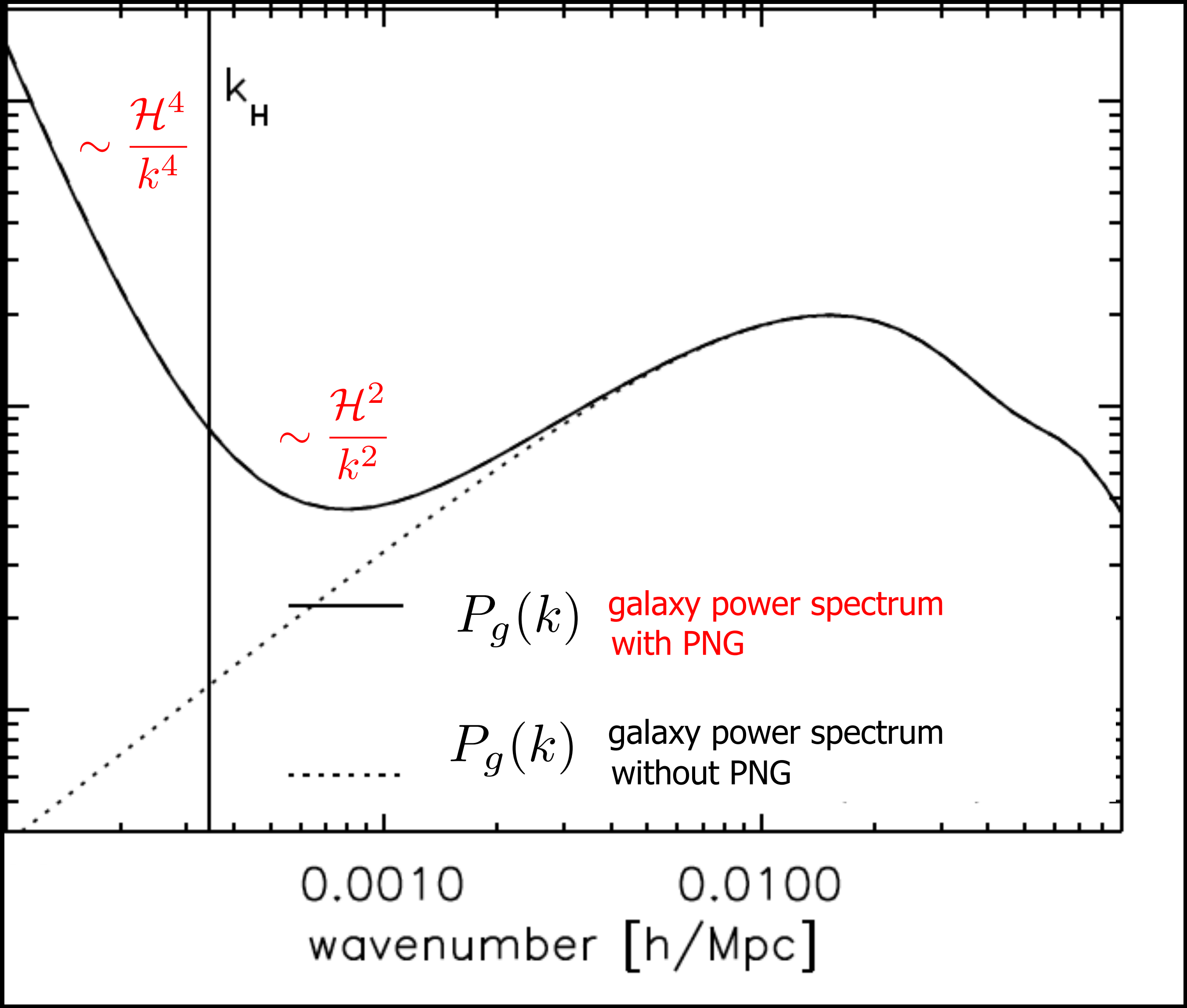
$$\delta_g(z,k) = b(z)\delta_m(z,k) \qquad \text{(synchronous gauge)}$$

$$b(z) \to b(z) + \Delta b(z,k), \quad \Delta b \propto f_{\rm NL}\frac{\mathcal{H}^2}{k^2} \qquad \text{for } k \lesssim k_{\rm eq}$$

Galaxy surveys on ultra-large scales can probe the primordial Universe!

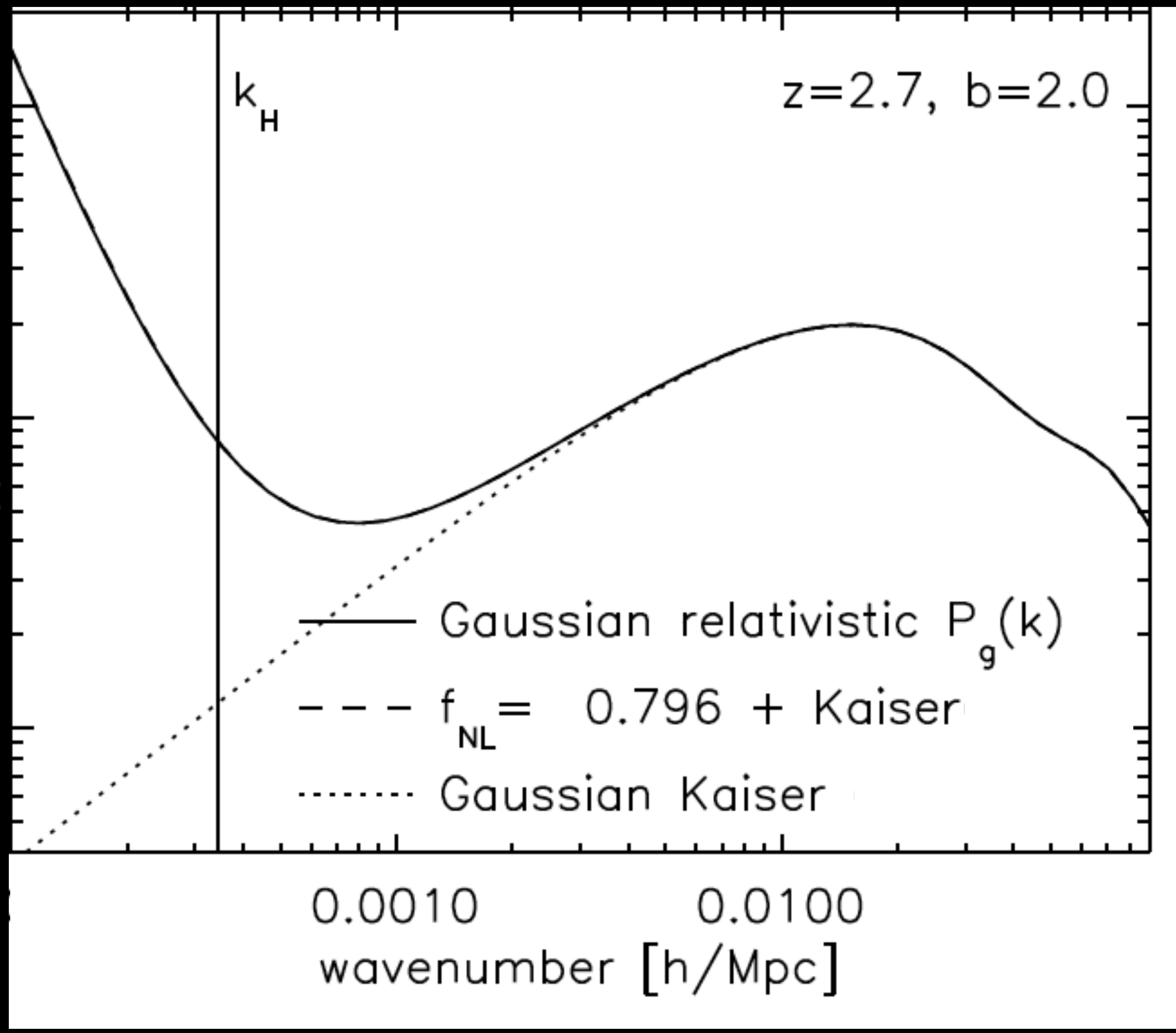


$$P_g(k) = \left[b + \alpha f_{\rm NL}\frac{\mathcal{H}^2}{k^2}\right]^2 P_m(k)$$



Relativistic effects vs Kaiser + PNG

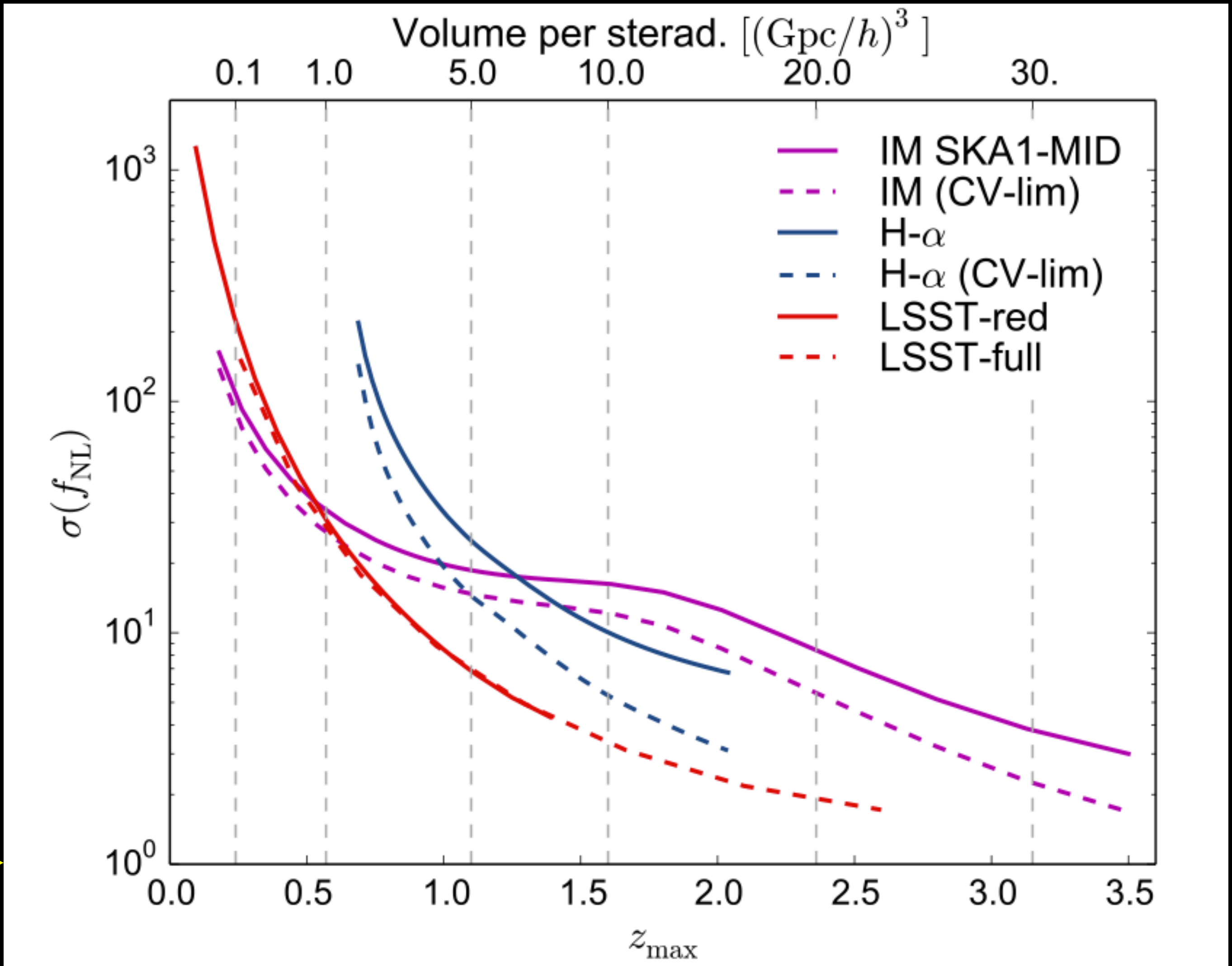
Relativistic effects are similar to PNG, with f_{NL}=O(1)



This creates an important degeneracy: relativistic effects must be incorporated for an accurate measurement of $f_{\rm NL}$

(Bruni, RM et al 2011; Camera, RM, Santos 2014)

Local PNG boosts the clustering of galaxies on ultra-large scales.
Surveys with ultra-large volumes are better at constraining PNG:



$\sigma(f_{\mathrm{NL}}) = 1$ →

Alonso, Bull, Ferreira, RM, Santos 2015

How to push the PNG error further down?

The PNG signal is strongest on ultra-large scales – but this is where *cosmic variance* degrades the constraining power.

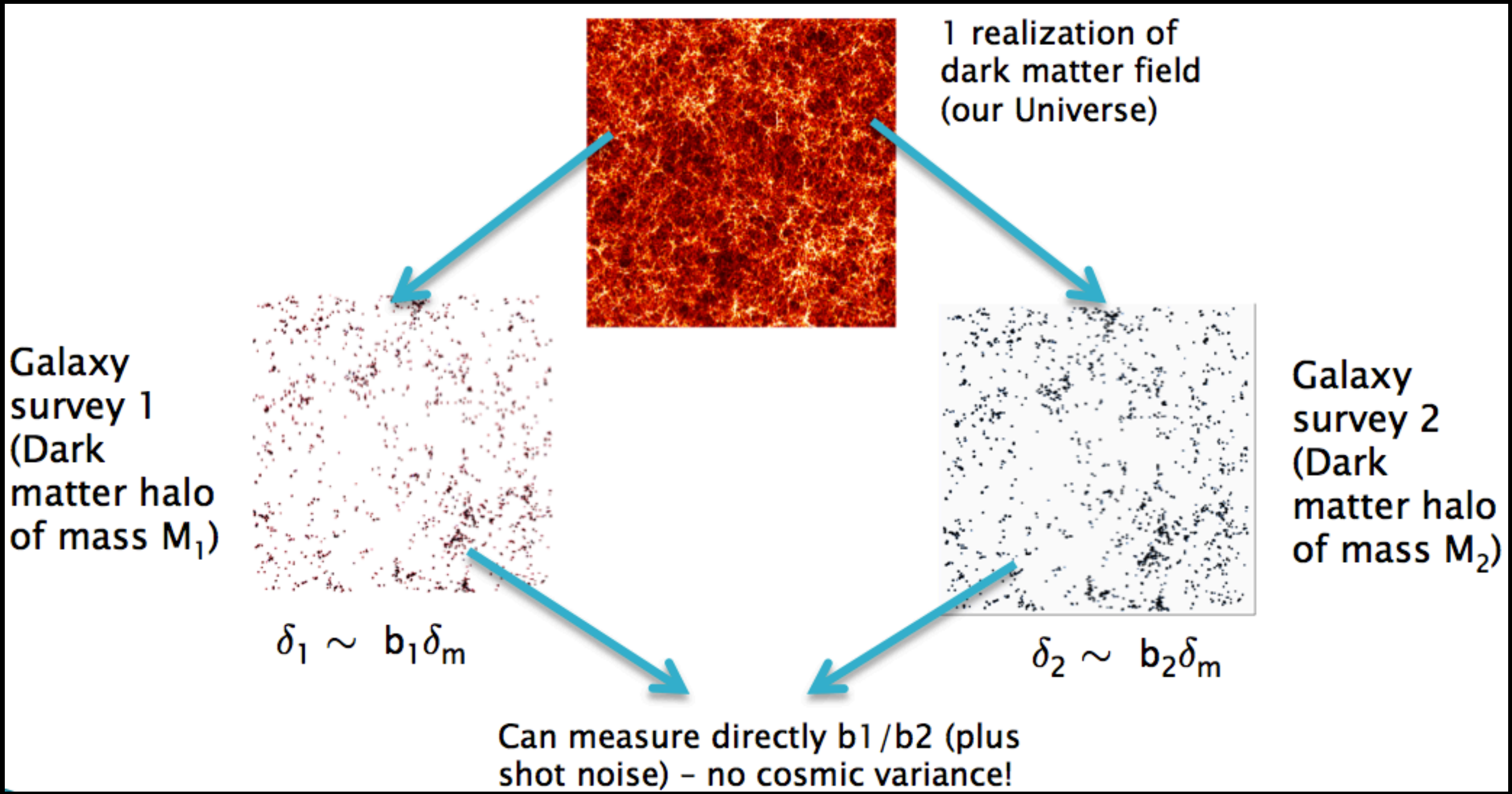
Even the biggest and best future galaxy surveys – Euclid, LSST and SKA – will be unable to achieve

$$\sigma(f_{NL}) < 1$$

using the power spectrum of single tracers of the DM distribution.

(Yoo et al 2013; Alonso, Bull, Ferreira, RM, Santos 2015; Raccanelli et al 2015)

The multi-tracer method uses 2 or more different tracers of the stochastic DM distribution to beat down cosmic variance – by combining the auto-correlations and the cross-correlations.



This allows us to achieve $\sigma(f_{NL}) < 1$ with the galaxy power spectrum.

(Alonso & Ferreira 2015; Fonseca, Camera, Santos, RM 2015)

The results improve if the tracer biases and systematics are very different.

This suggests using a radio survey and an optical/IR survey.
In particular:

intensity mapping (excellent radial resolution, no individual sources)
is 'complementary' to
photometry (poor radial resolution, very high source number density)

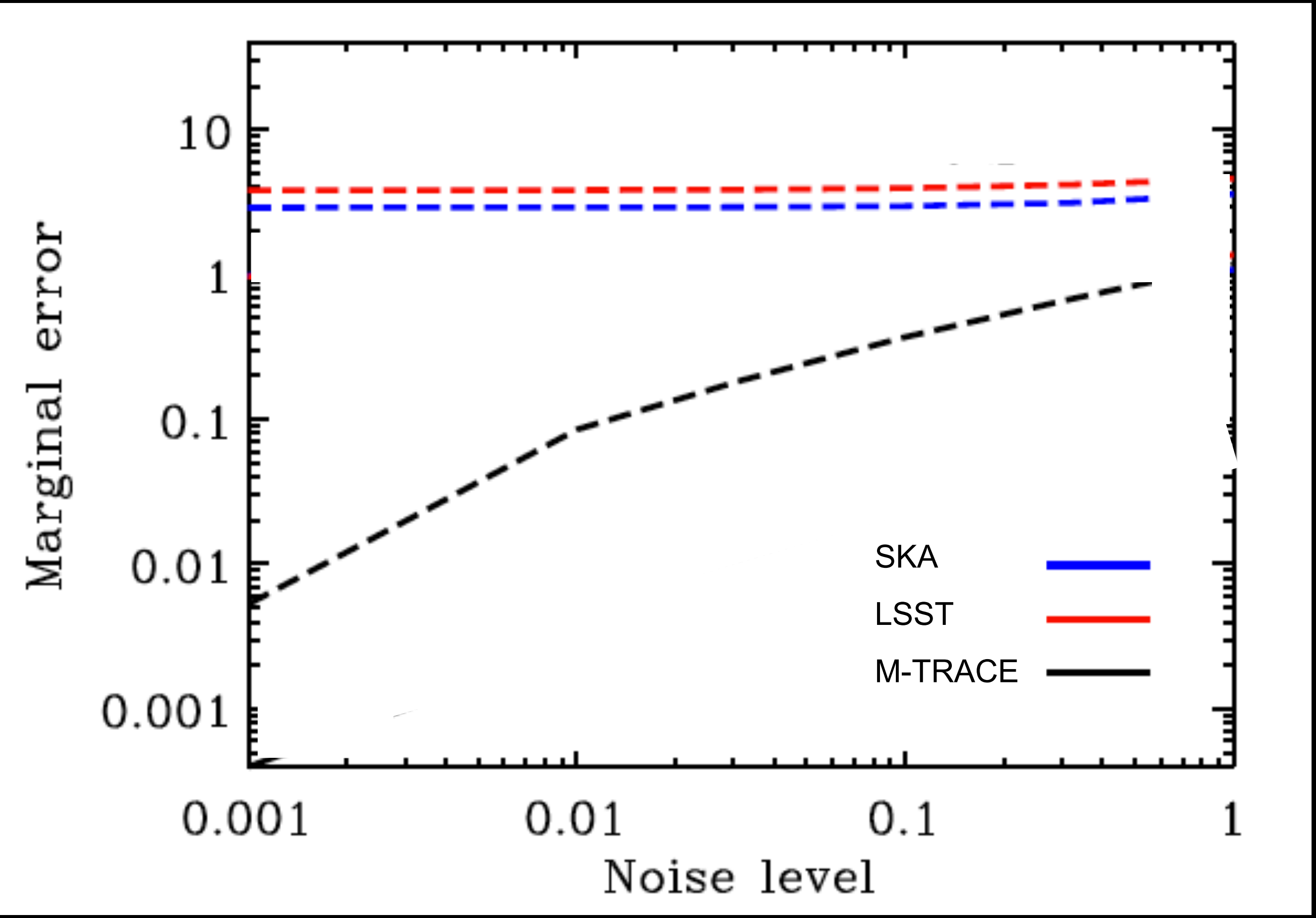
SKA1 intensity map X LSST photo-z

X

SKA1 HI intensity map X LSST photo-z

With single tracers, errors don't improve as noise reduces (red and blue).

With multi-tracer, errors reduce as noise reduces (black).



Fonseca, Camera, Santos, RM 2015

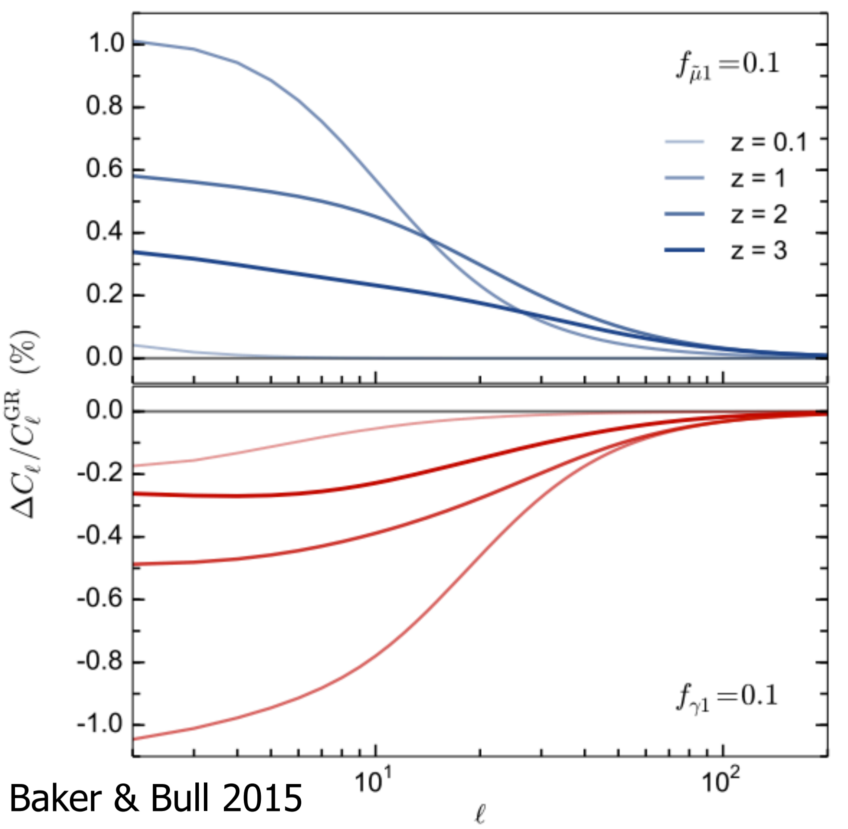
Experiment type	Tracers	$\sigma(f_{\rm NL})$
Photometric survey (LSST)	LSST, red-only	4.53
	LSST, blue-only	1.71
	LSST, red $\times$ blue	1.62
	DES, red $\times$ blue	7.18
Radio (SKA1-MID)	IM-only	3.00
	IM$\times$Cont., 1 sample	0.86
	IM$\times$Cont., 2 samples	0.69
	Continuum-only, 2 samples	1.91
Synergy (SKA1-MID$\times$LSST)	IM$\times$all	0.41
	IM$\times$red$\times$blue	0.40

Alonso & Ferreira 2015

We can probe PNG well beyond the CMB precision.

Testing modifed gravity on ultra-large scales

The same cosmic variance problem arises:



Baker & Bull 2015

With the multi-tracer, we can in principle detect deviations from GR on ultra-large scales.

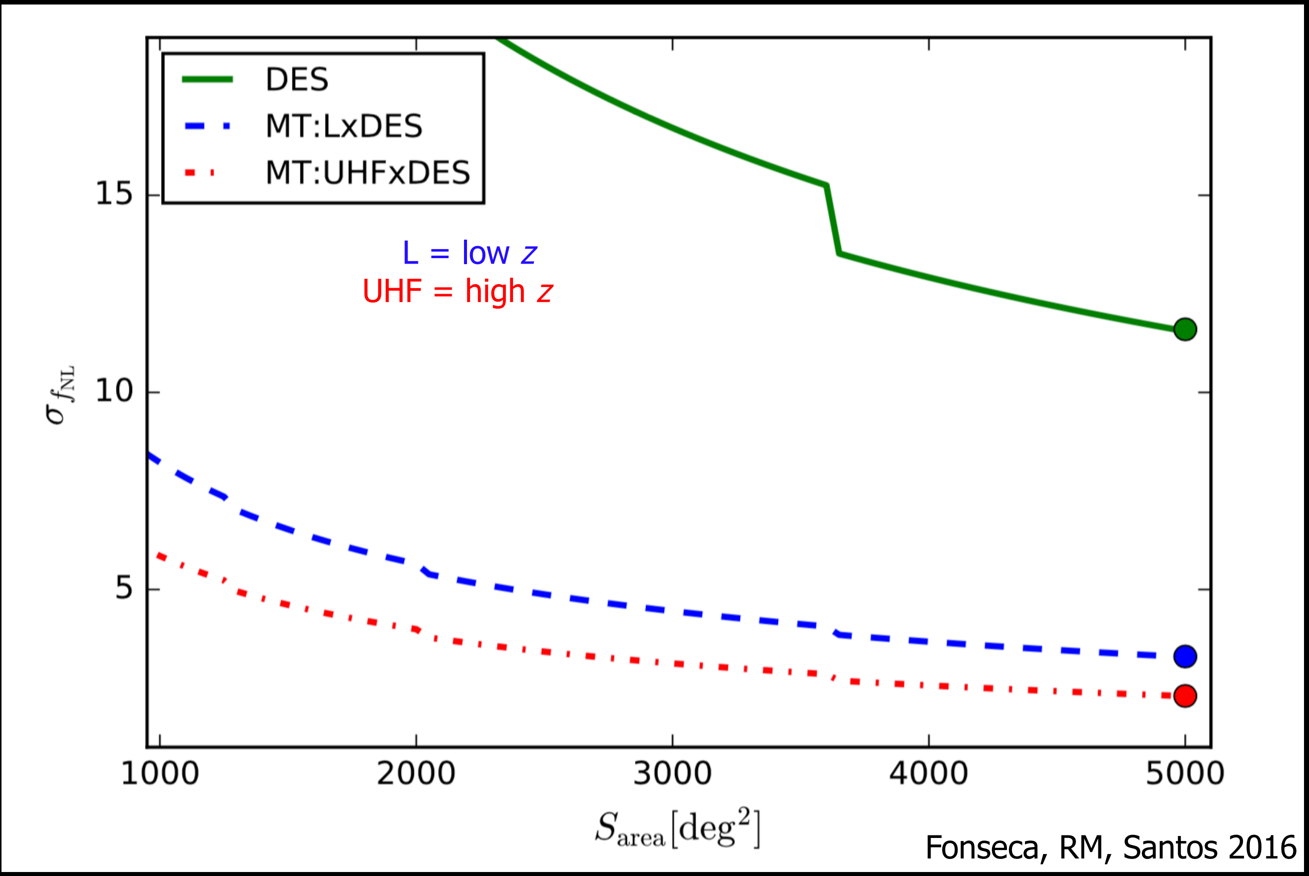
Future surveys – not competing, but combining

Multi-tracer forecasts for constraints on PNG and gravity show us the benefits of *combining* next-generation surveys.

Surveys that overlap give us additional constraining power – the multi-tracer knocks out much of the cosmic variance.

Where possible, sky areas should be chosen to maximise overlap with other surveys.

Before next-generation?
MeerKAT HI intensity map X DES photo-z



- DES on its own – better than BOSS, but behind Planck
- Multi-tracer DES X MeerKAT: beats Planck with only 2000 deg^2!

EXTRA SLIDES