Testing standard cosmology with the SKA (and other galaxy surveys)

RESPICE PROSPICE
UNIVERSITY of the WESTERN CAPE

Roy Maartens

Vancouver, January 2017

ICG Portsmouth

Huge galaxy surveys – the next frontier

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

SKA
SQUARE KILOMETRE ARRAY

LSST

This will allow us to test the foundations of the standard model of cosmology:

- test GR
- test the Copernican Principle
- test Gaussian fluctuations from inflation

The SKA

SKA PHASE 1

Build ~ 2018-2024

SKA1-MID:
200 dishes, ~15 m – in South Africa.
MeerKAT Pathfinder – 64 dishes 2017.

SKA1-LOW:
130,000 dipole antennas – in Australia.

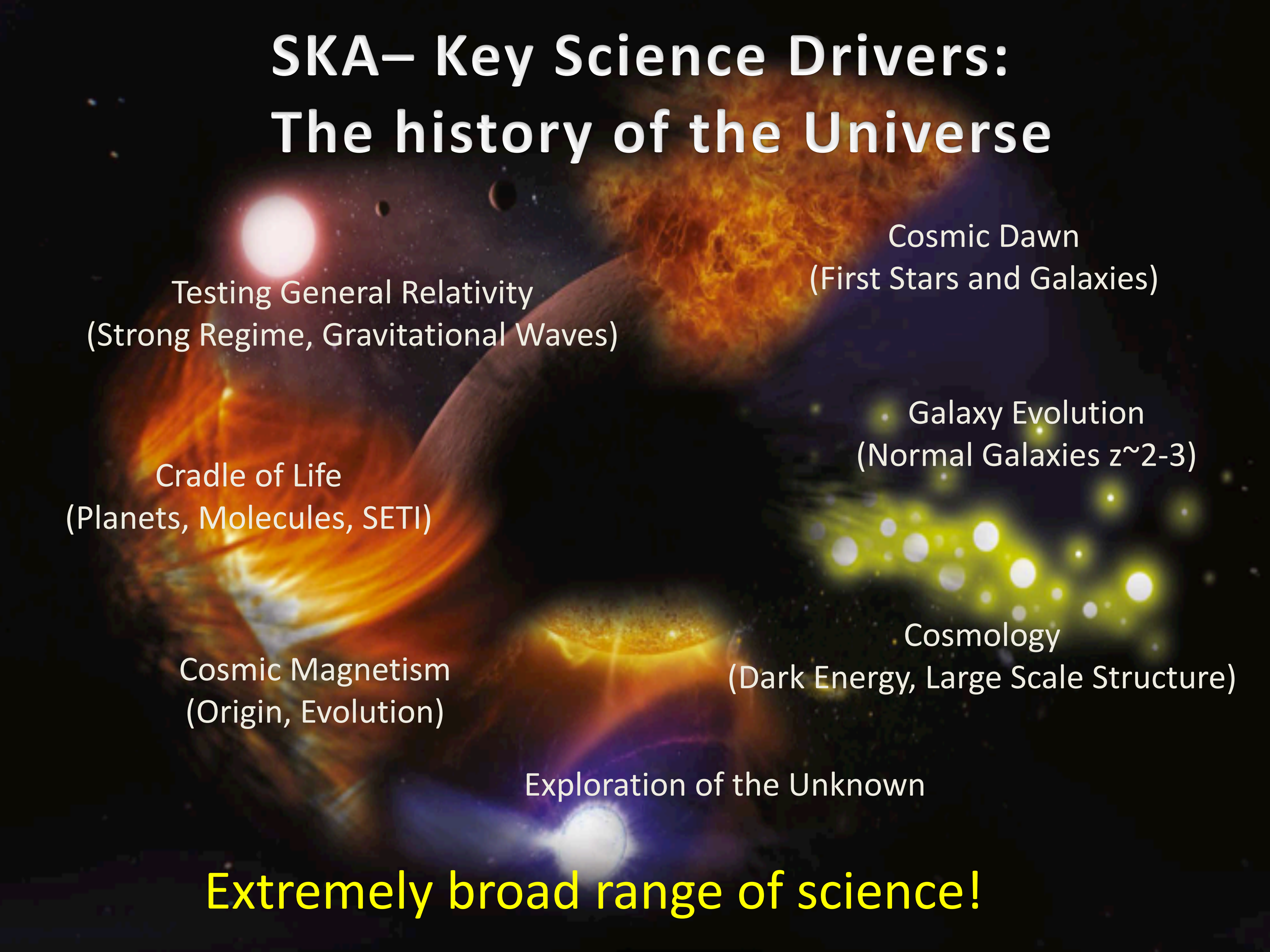
SKA PHASE 2

~ 10 X SKA1
~ 2025 -

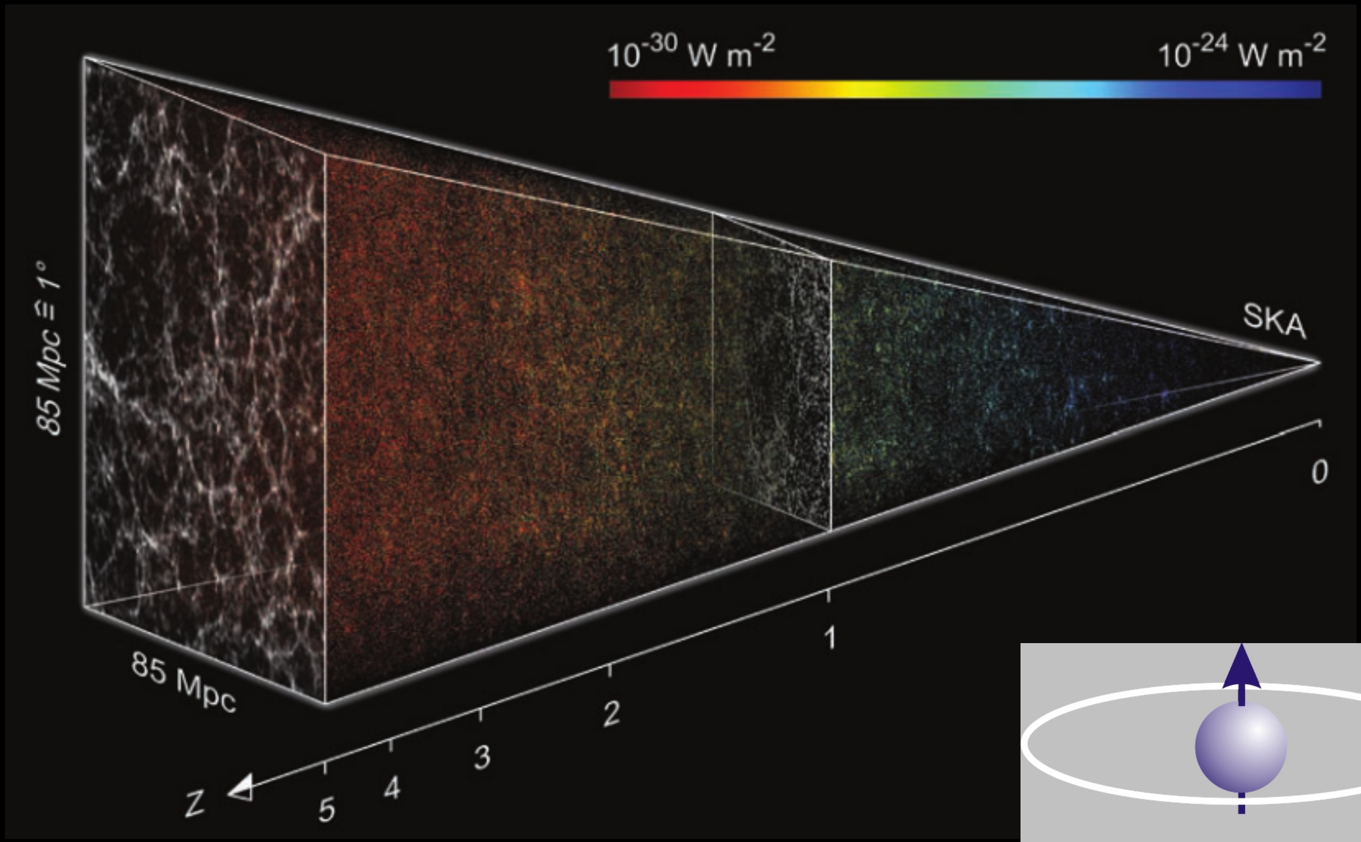
MeerKAT array – in progress (32 dishes now)

- 64 x 13.5m dishes
- Build complete 2017, full operations 2018
- To be absorbed into SKA1 2024 (?)
- Proposed cosmology survey MeerKLASS (Santos et al)

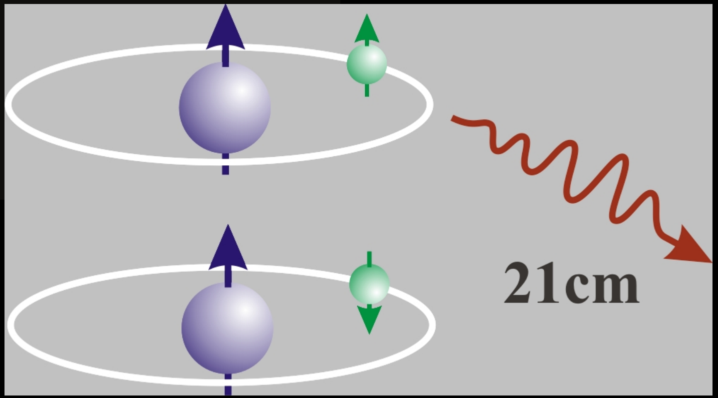
SKA AFRICA
SQUARE KILOMETRE ARRAY


SKA– Key Science Drivers:
The history of the Universe
Cosmic Dawn
(First Stars and Galaxies)
Testing General Relativity
(Strong Regime, Gravitational Waves)
Galaxy Evolution
(Normal Galaxies z~2-3)
Cradle of Life
(Planets, Molecules, SETI)
Cosmology
(Dark Energy, Large Scale Structure)
Cosmic Magnetism
(Origin, Evolution)
Exploration of the Unknown
Extremely broad range of science!

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



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



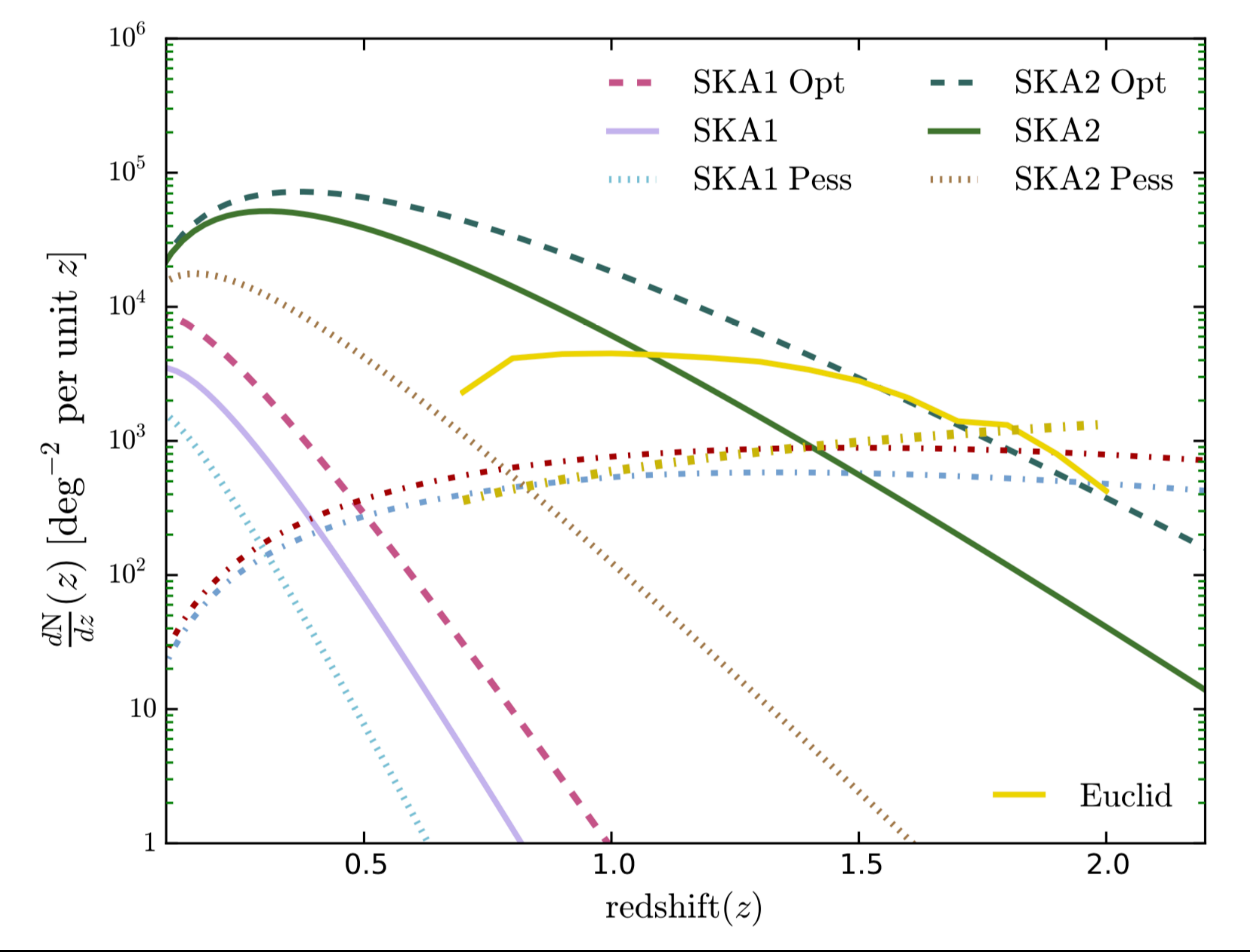
SKA spectroscopic surveys 1

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 et al 2015

SKA spectroscopic surveys 2

HI intensity mapping surveys (integrated emission – like CMB)

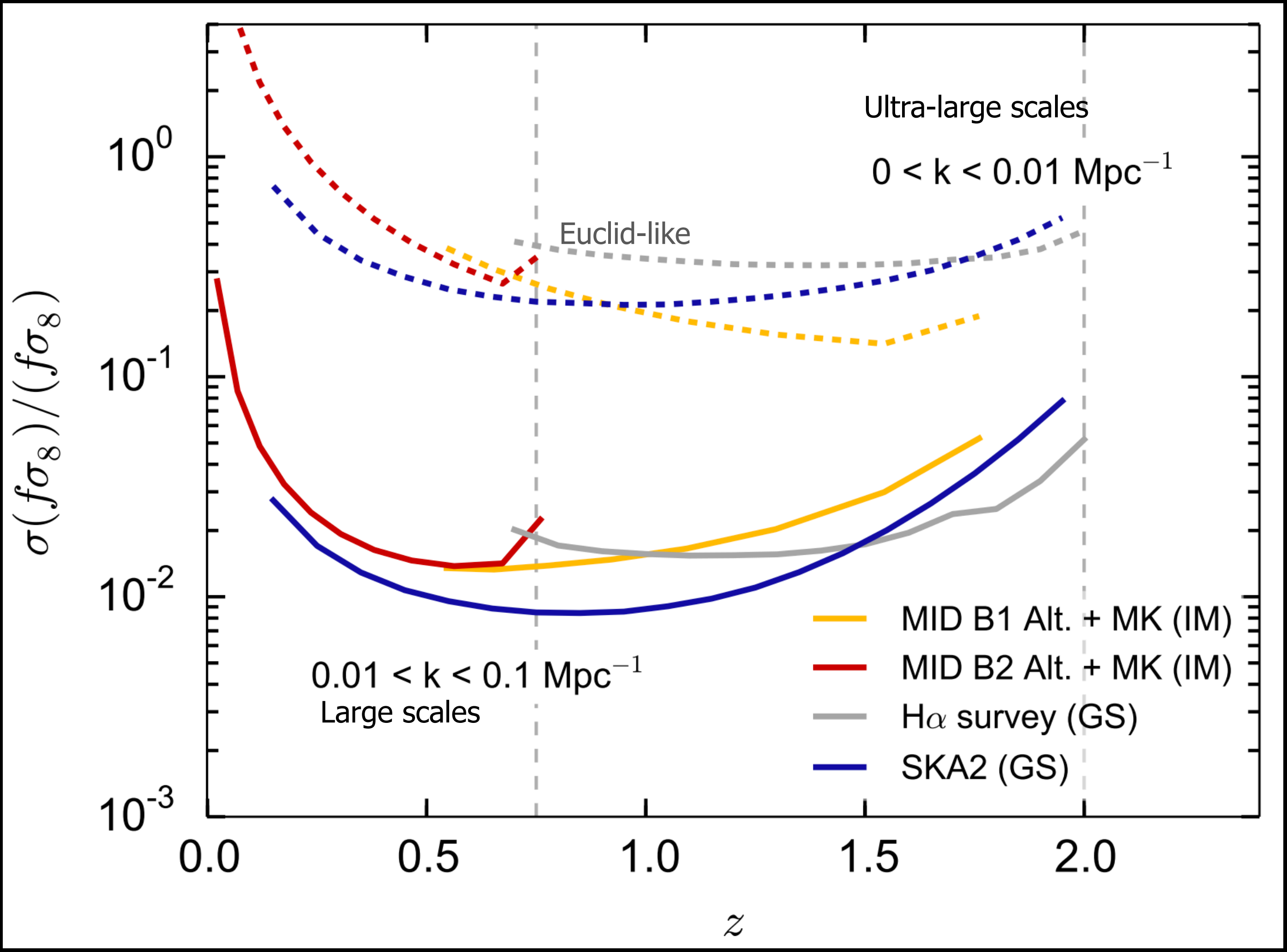
SKA1 – up to 25000 deg^2 , z<3

Don't need sensitivity – can get huge volume in SKA1

Growth rate from RSD: errors at large and ultra-large scales.

$$f = \frac{d \ln \delta_m}{d \ln a}$$

Bull 2015



Testing GR via the growth rate

Growth rate *f* of large-scale structure is insensitive to (non-exotic) models of dark energy, but is sensitive to the theory of gravity. (Ferreira's talk)

A simple way to parametrize this is as follows:

Background evolution

$$p_X(a) = w_0 \rho_X(a)$$

Growth rate

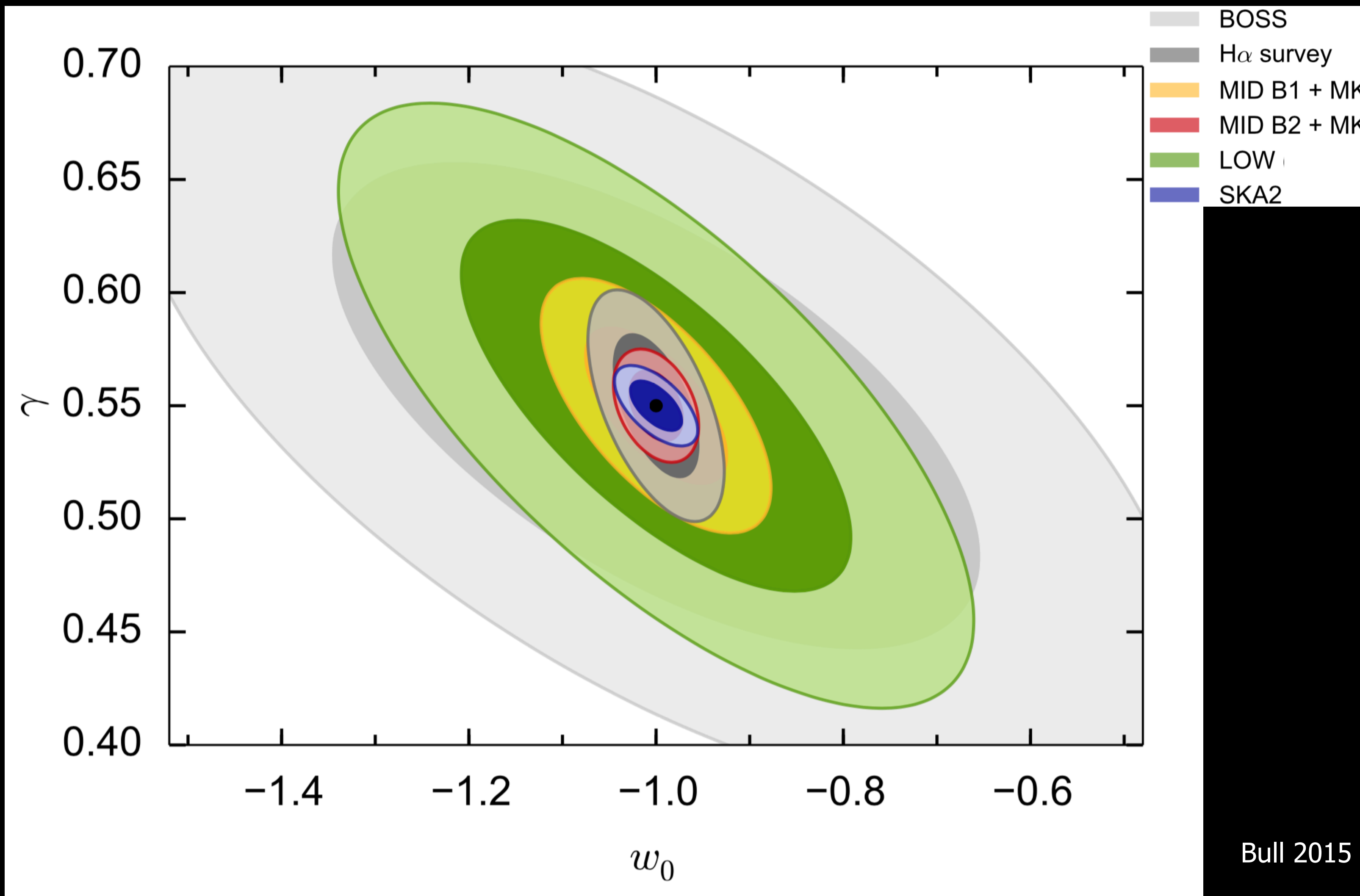
$$f(a) = [\Omega_m(a)]^\gamma$$

The standard model has

$$w_0 = -1, \qquad \gamma = 0.55$$

Testing GR via the growth rate

Forecast constraints on w_0 and γ :

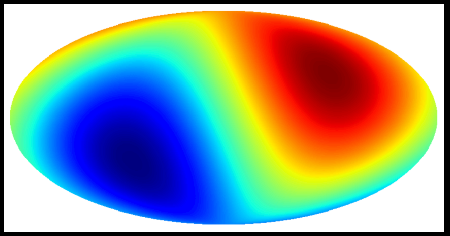


Bull 2015

Testing the CP 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.

LSS kinematic dipole gives higher number counts/ luminosity in the motion direction, less behind:

$$1 + \tilde{z} = (1+z)\big[1 + \mathbf{n}\cdot\mathbf{v}_0\big], \quad d\tilde{\Omega}_0 = d\Omega_0\big[1 - 2\mathbf{n}\cdot\mathbf{v}_0\big]$$

$$\Rightarrow \quad \tilde{N}(\tilde{z}, \tilde{\mathbf{n}}) = N(z, \mathbf{n})\big[1 + 3\mathbf{n}\cdot\mathbf{v}_0\big]$$

To measure the LSS dipole, free of Local Group contamination, we need:

near-full 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.

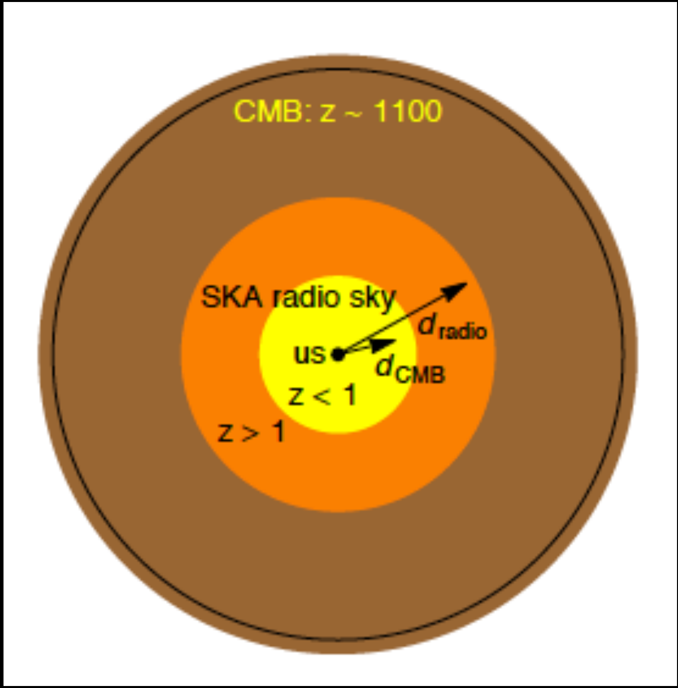
There is an SKA survey that is well-suited to this:
a radio continuum survey (detects total radio emission, but no redshifts)

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

Forecast to detect the LSS dipole direction:

- within ~5^o (SKA1)
- within ~1^o (SKA2)

(Schwarz et al 2015)



Testing primordial Gaussianity

Primordial quantum fluctuations are generated during inflation –
Gaussian for simple inflation models (standard model)
non-Gaussian for other models

Constraining primordial non-Gaussianity (PNG) is a powerful way to probe inflation and rule out 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:*

$$\sigma(f_{\rm NL}) = 6.5$$

Future CMB experiments will not be able to improve significantly on this constraint:
only LSS can push the errors down towards 1 and below.

How does PNG affect the galaxy distribution?

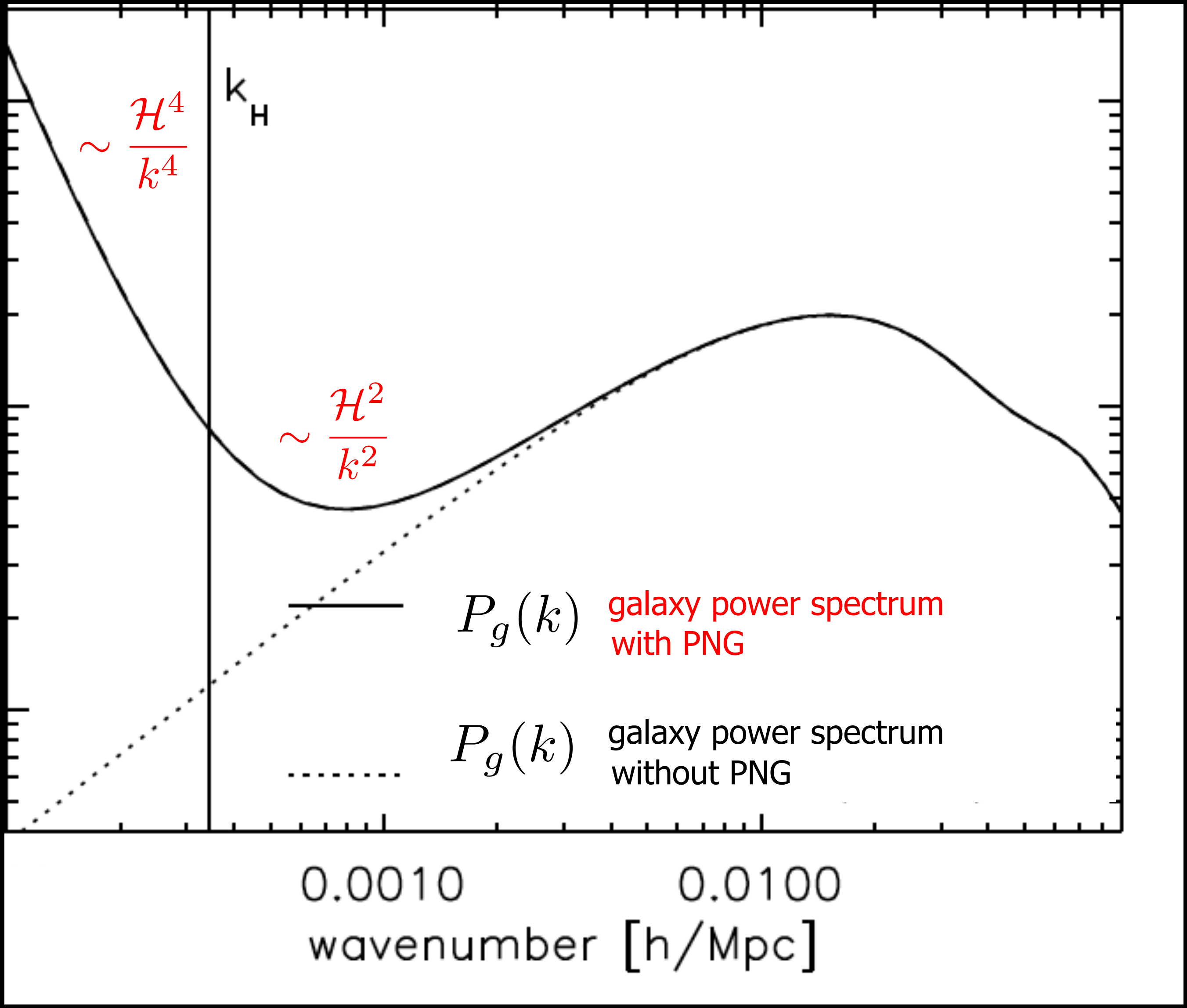
It modifies the bias of galaxies:

$$\delta_g(z,k) = b(z)\delta_m(z,k)$$

$$b(z) \to b(z) + \Delta b(z,k), \quad \Delta b \propto f_{\rm NL}\frac{\mathcal{H}^2}{k^2}$$

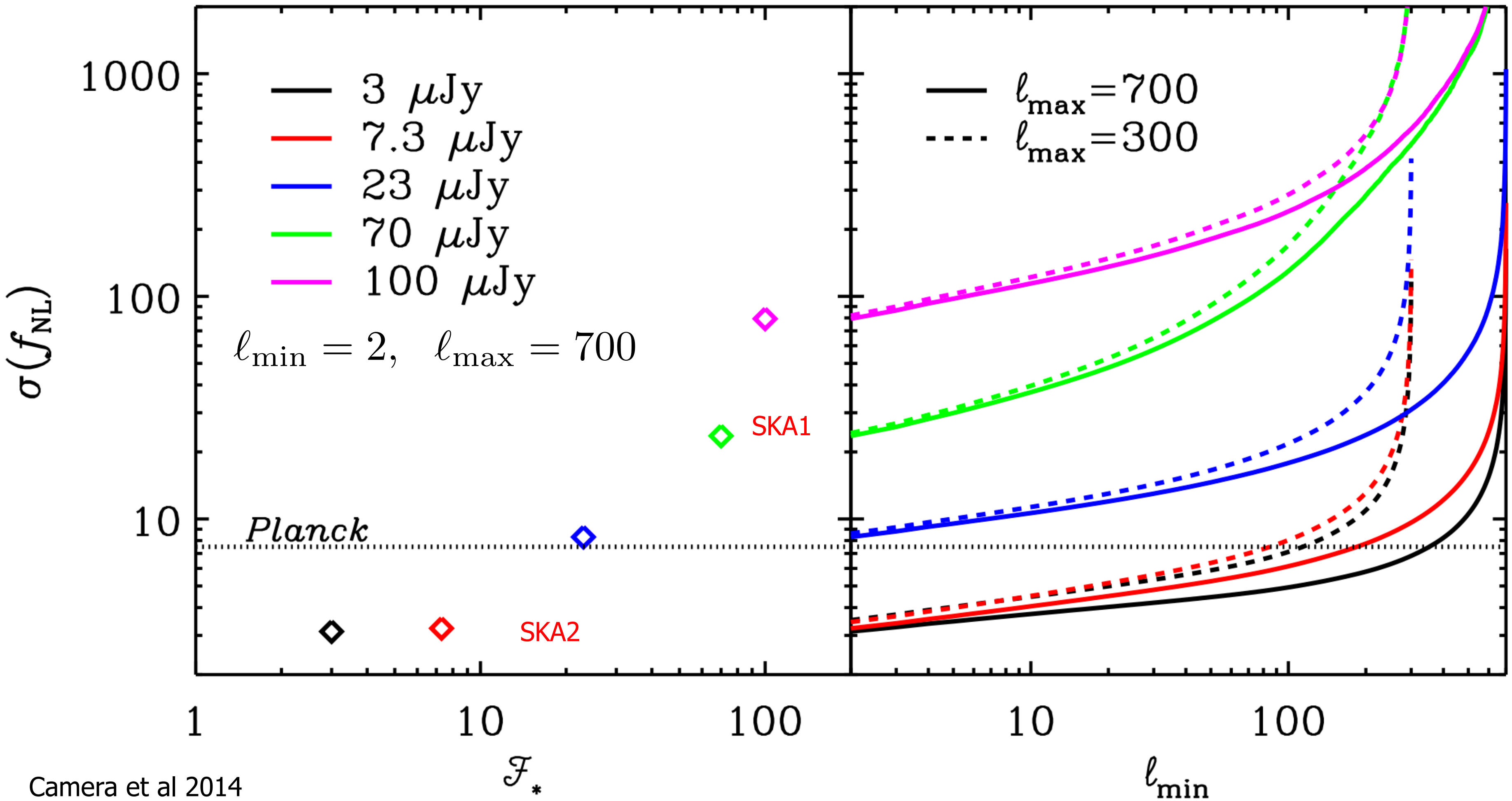
Galaxy surveys can probe the primordial Universe!

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



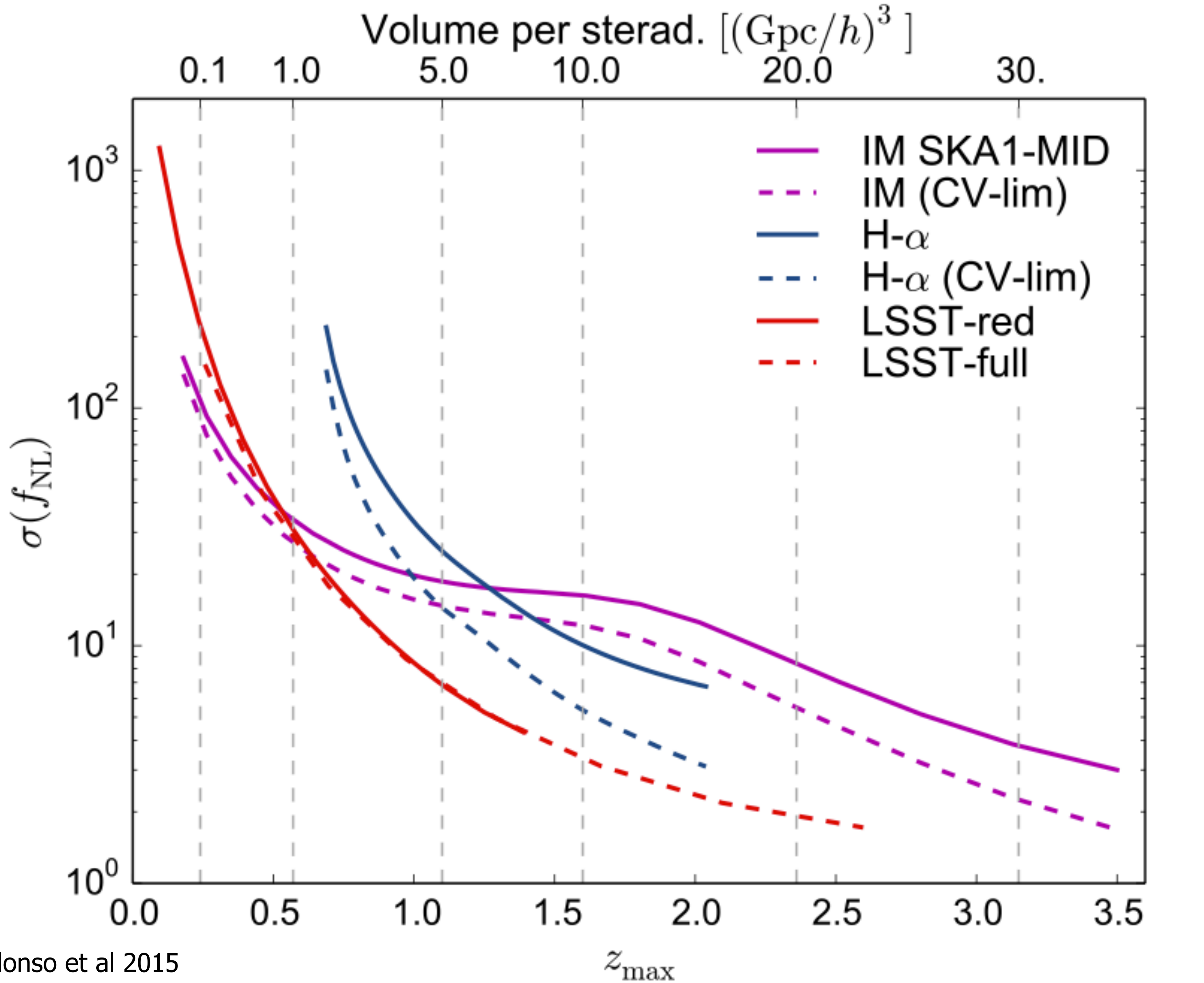
Local PNG thus boosts the clustering of galaxies on ultra-large scales. Surveys with ultra-large volumes are better at constraining PNG.

SKA2 HI galaxy redshift survey is probably the best:



Camera et al 2014

Comparing with other (earlier) next-generation surveys:



Alonso et al 2015

How to push the PNG error below 1?

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

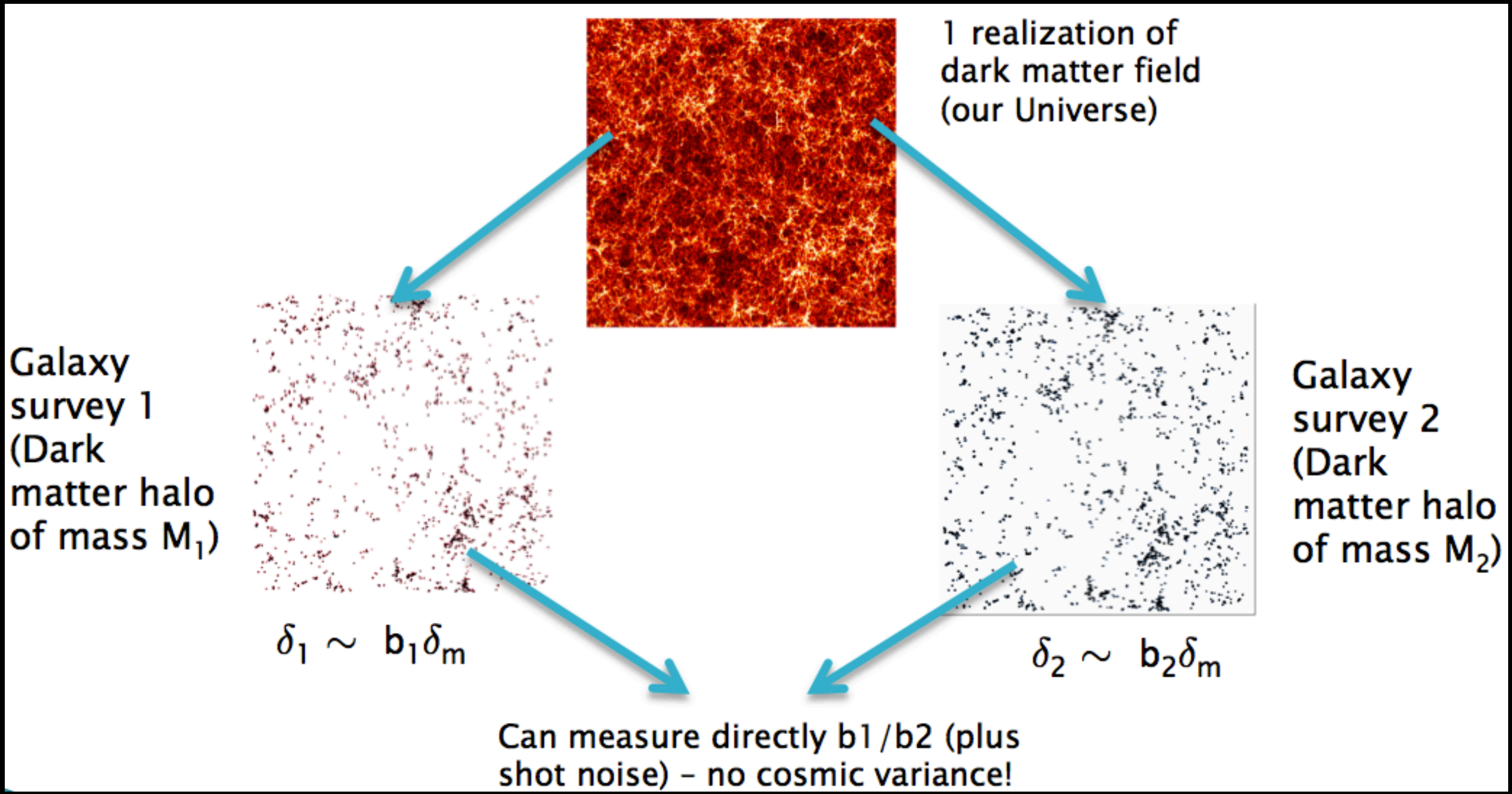
Even the biggest and best future galaxy surveys – Euclid, LSST and SKA – will be unable to achieve

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

on their own, using single tracers of the DM distribution.

(Yoo et al 2013; Alonso et al 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

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

(Alonso & Ferreira 2015; Fonseca et al 2015)

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

This suggests using a radio survey and an optical/IR survey, such as

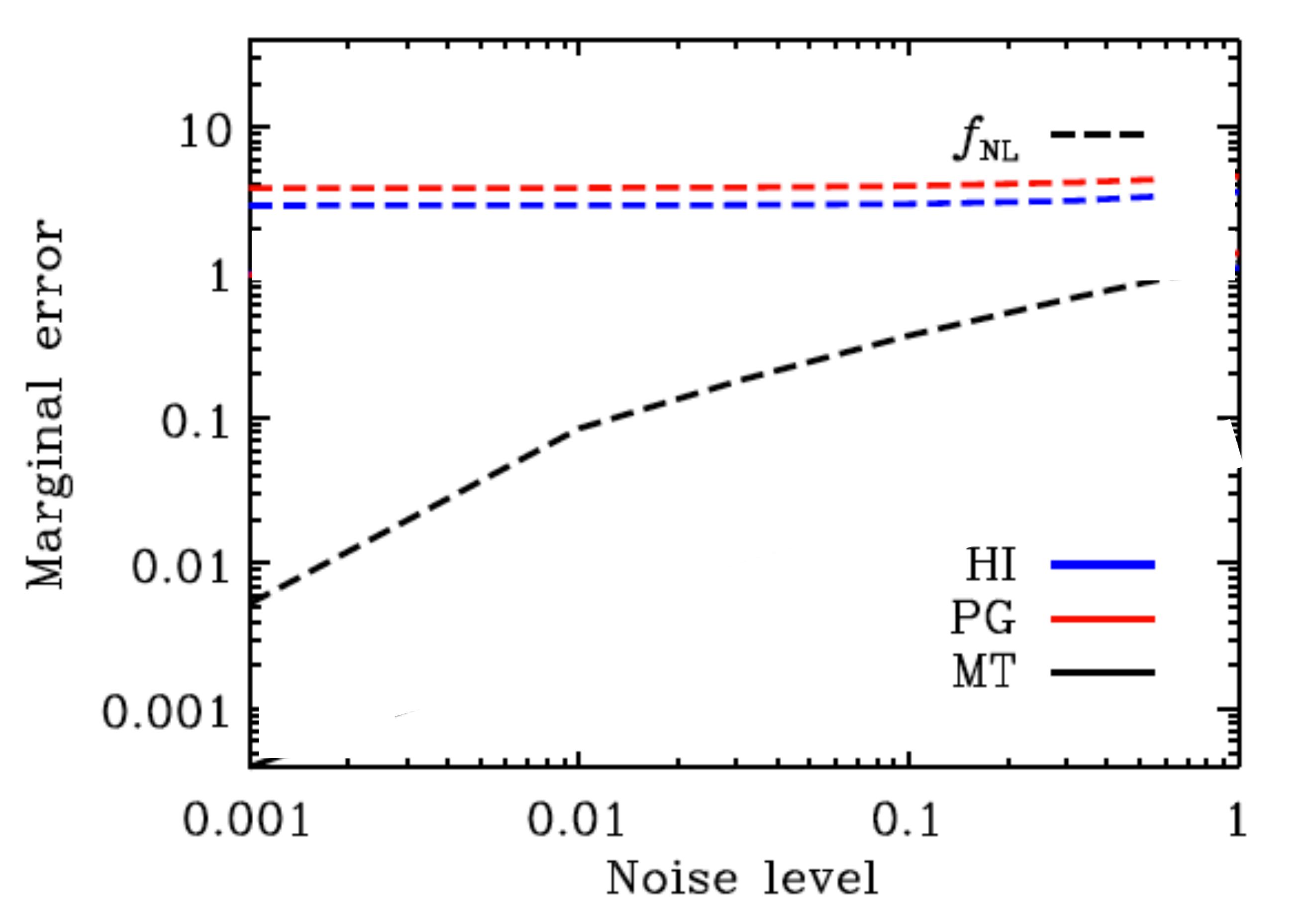
SKA1 intensity map X LSST photo-z

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).



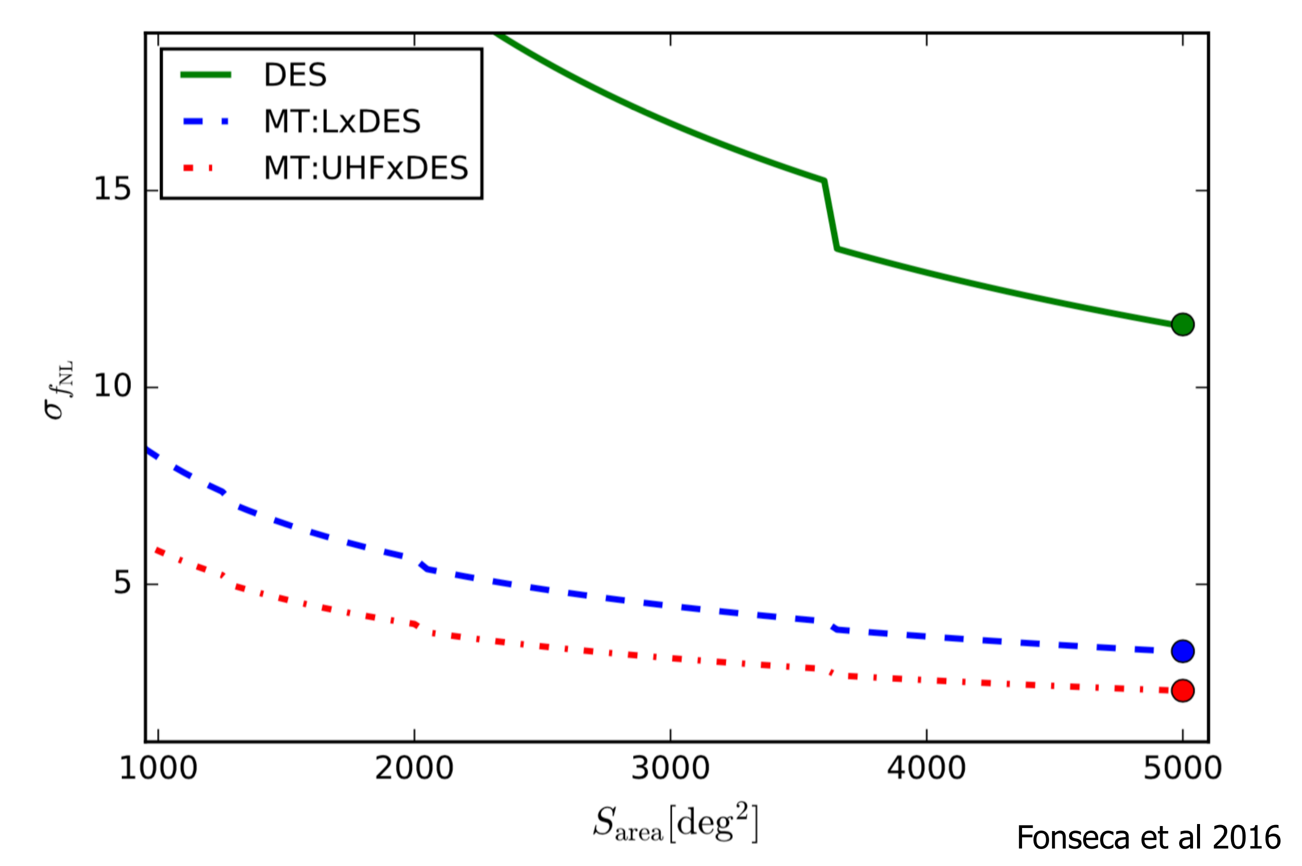
Fonseca et al 2015

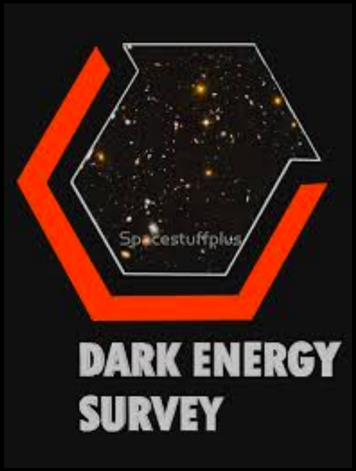
Experiment type	Tracers	$\sigma(f_{\rm NL})$
Photometric survey (LSST)	LSST, red-only	4.53 (4.54)
	LSST, blue-only	1.71 (1.72)
	LSST, red $\times$ blue	1.62 (1.63)
	DES, red $\times$ blue	7.18 (7.20)
Radio (SKA1-MID)	IM-only	3.00 (3.01)
	IM$\times$Cont., 1 sample	0.86 (0.89)
	IM$\times$Cont., 2 samples	0.69 (0.71)
	Continuum-only, 2 samples	1.91 (1.97)
Synergy (SKA1-MID$\times$LSST)	IM$\times$all	0.41 (0.41)
	IM$\times$red$\times$blue	0.40 (0.40)

Alonso & Ferreira 2015

We can probe PNG well beyond the CMB precision
– much more powerful tests of inflation.

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!