Testing standard cosmology with the SKA and other galaxy surveys

RESPICE PROSPICE
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Daejeon, April 2017

Ultra-large volume galaxy surveys – the next frontier

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

LSST

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Ultra-large volume galaxy surveys – the next frontier

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

SKA – new potential and new challenges:

- potential to cover the largest volumes
- challenge of new imaging techniques, new systematics

Ultra-large volume galaxy surveys – the next frontier

Combining radio and optical/IR can deliver more than either separately.

Next-generation 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
  - 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 2017.

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

SKA PHASE 2

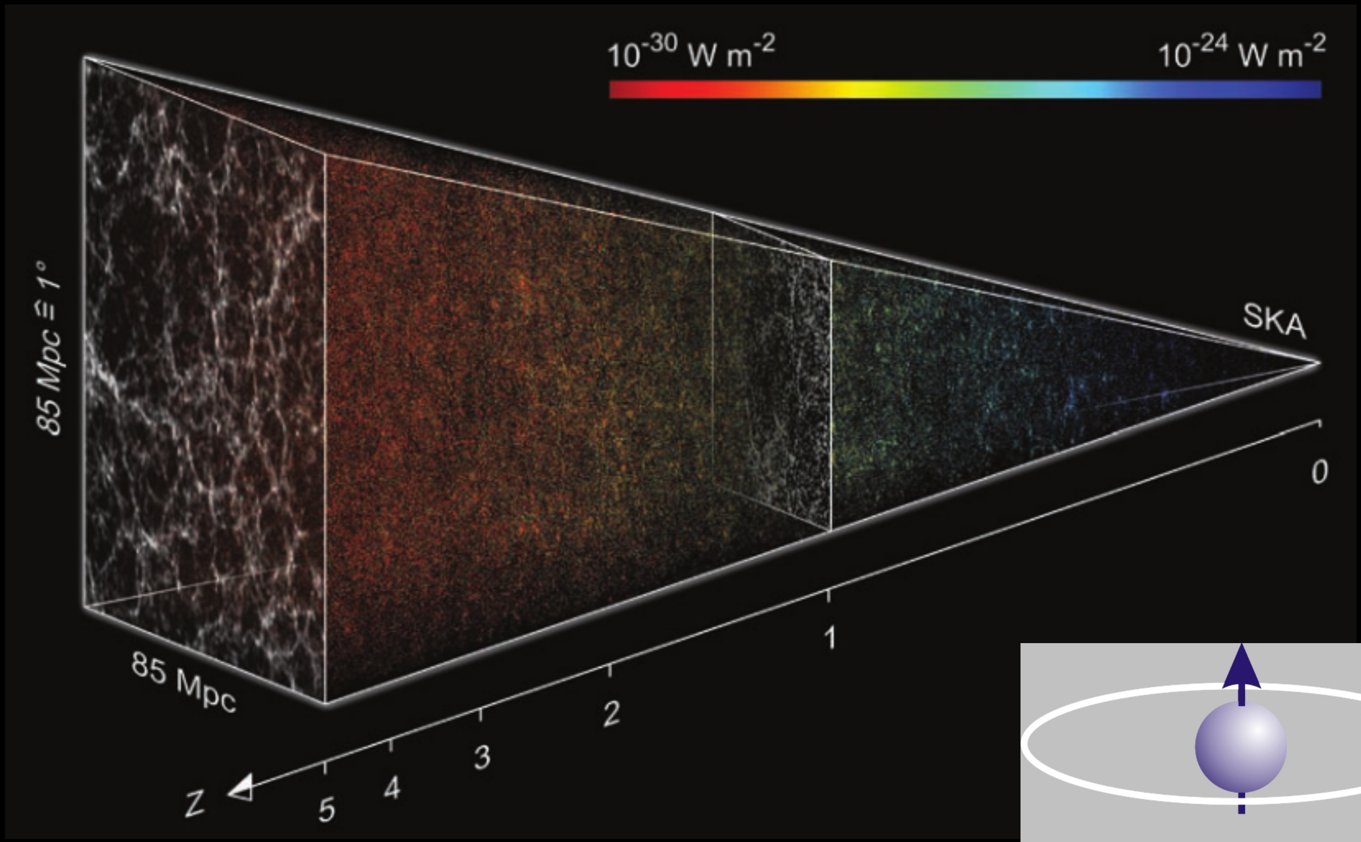
~ 10 X SKA1
~ 2025 -

MeerKAT array – in progress (32 dishes now)

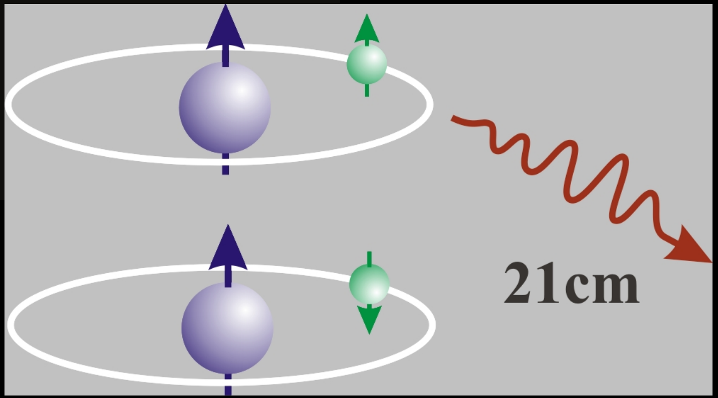
- 64 x 13.5m dishes
- Build complete 2017, full operations 2018
- To be absorbed into SKA1 2024 (?)
- Proposed cosmology survey MeerKLASS (Santos et al)

SKA AFRICA
SQUARE KILOMETRE ARRAY

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

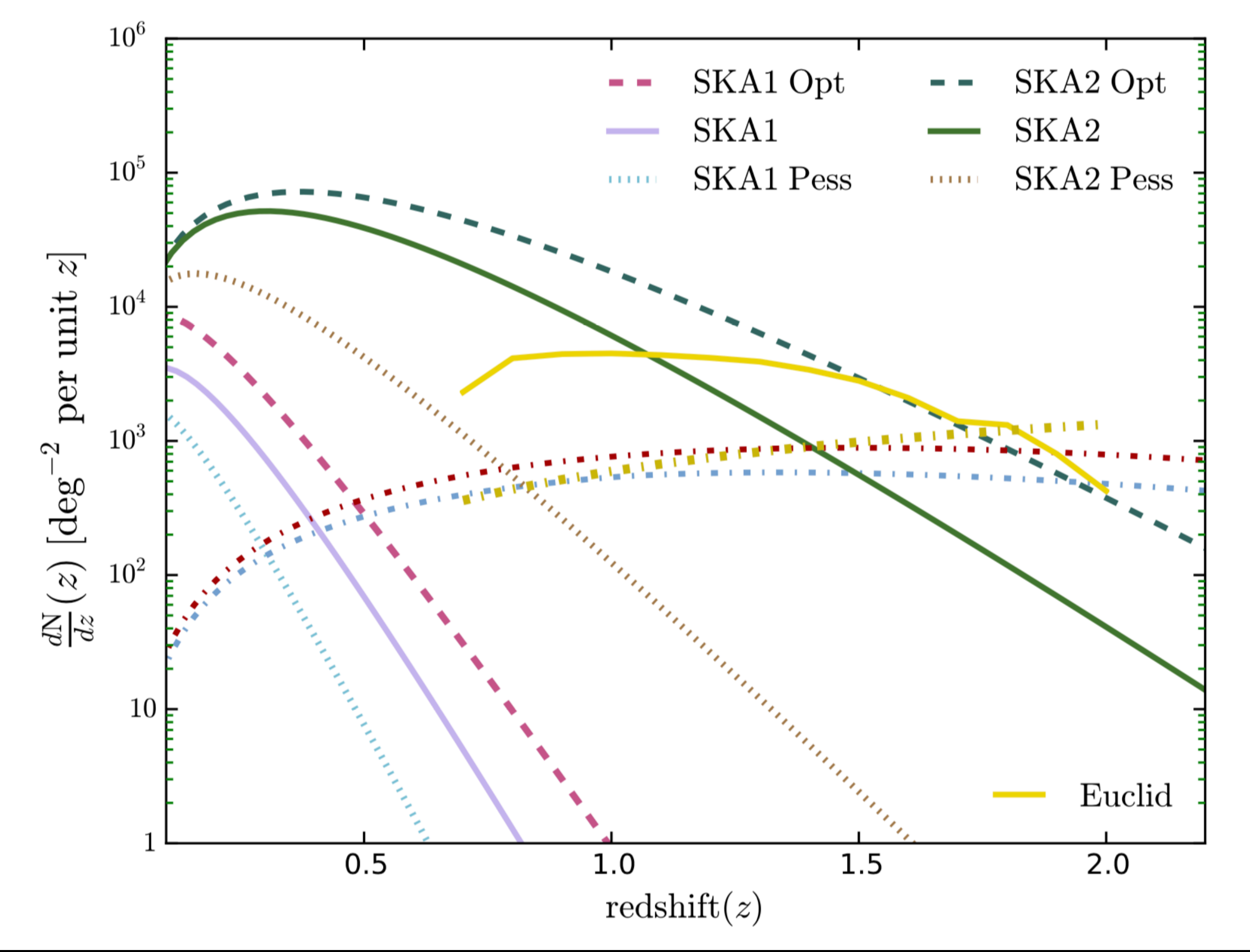
HI galaxy redshift surveys

- 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.

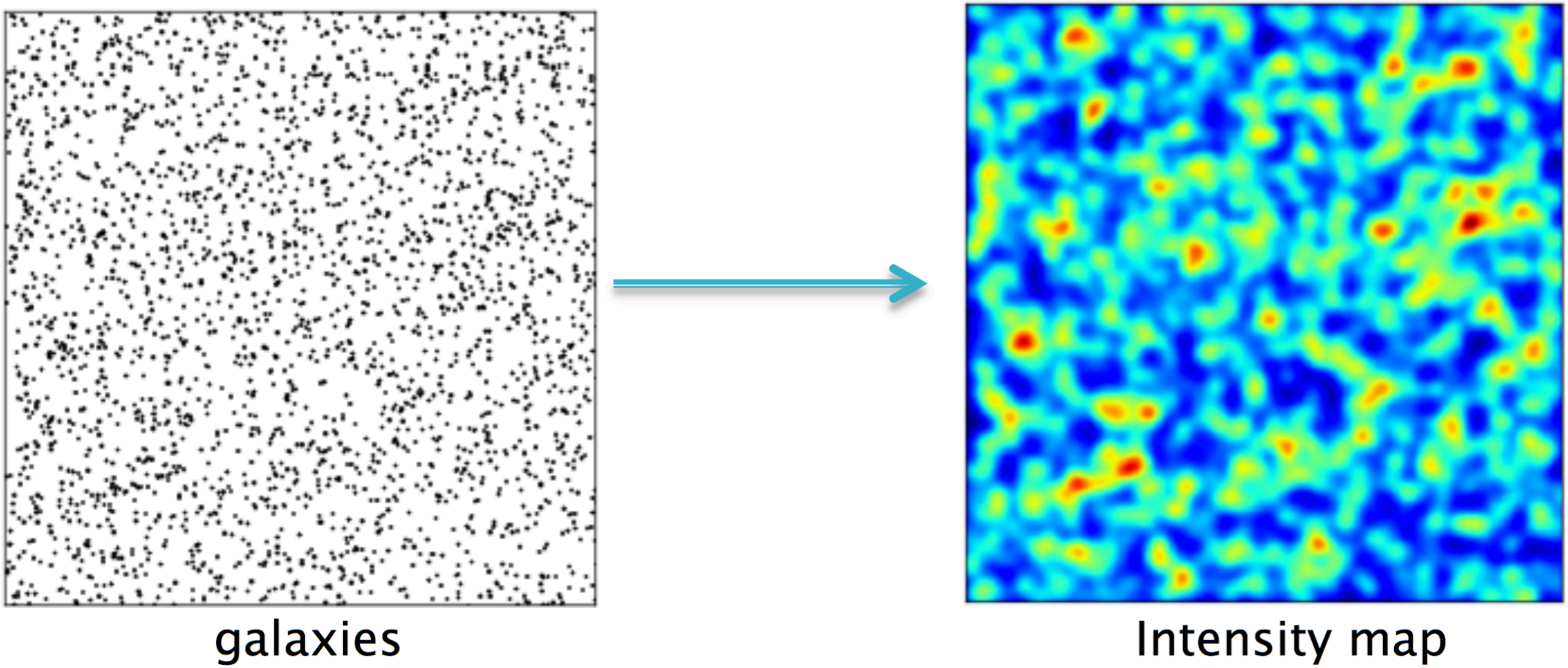
Yahya et al 2015



SKA spectroscopic surveys 2

HI intensity mapping surveys (integrated emission – like CMB)

SKA1 – up to 25000 deg^2 , $z<3$



SKA spectroscopic surveys 2

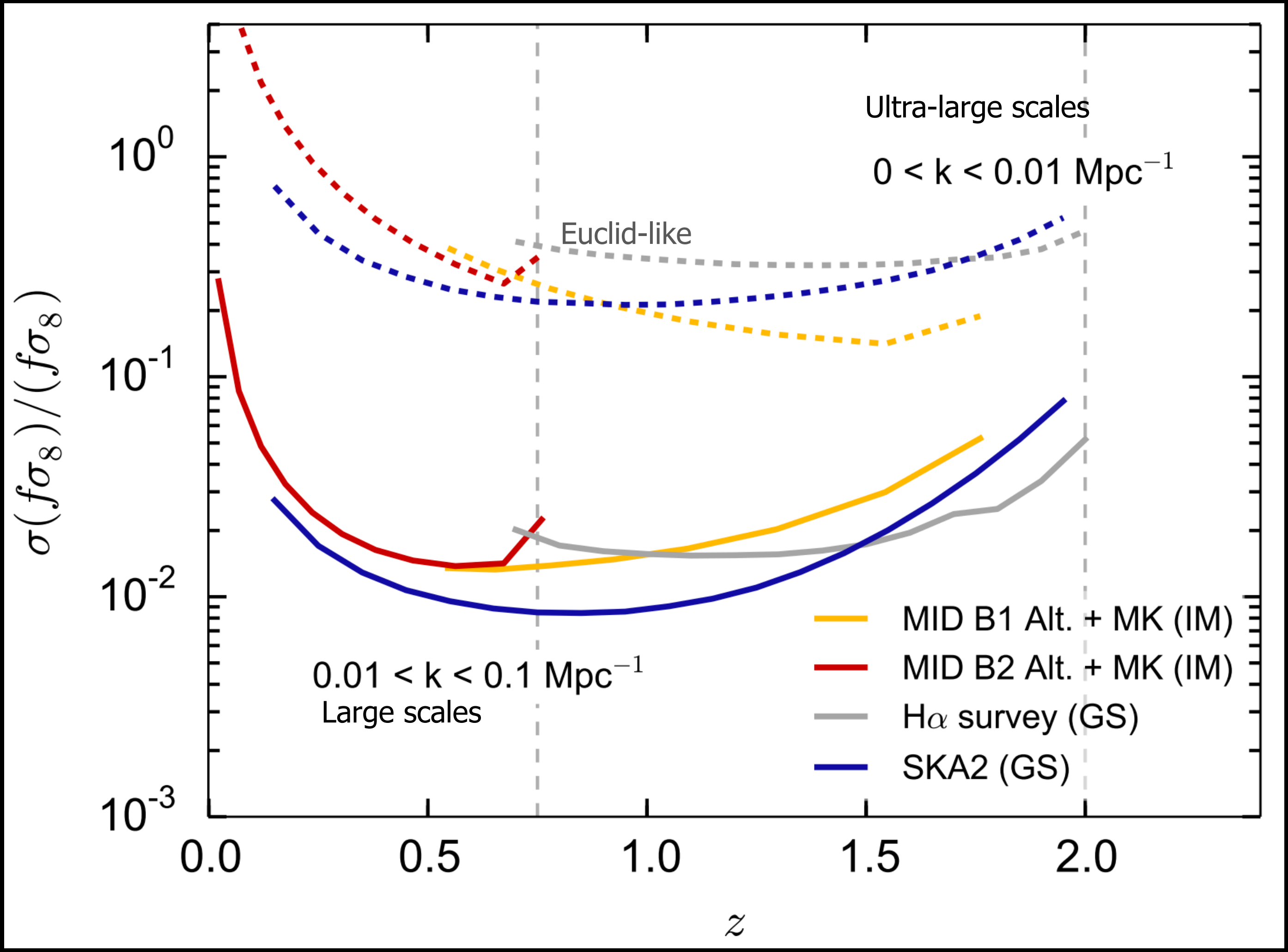
HI intensity mapping surveys (integrated emission – like CMB)

SKA1 – up to 25000 deg^2 , $z<3$

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. →

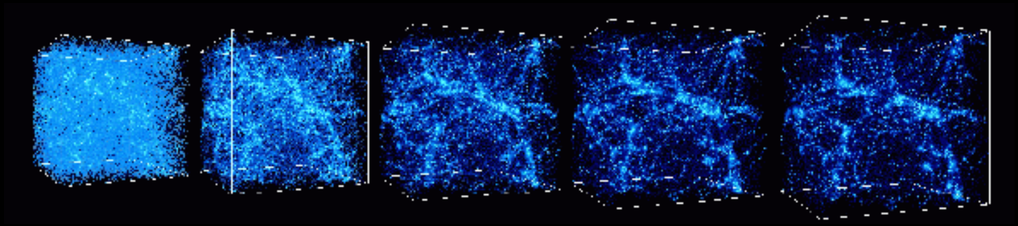


Bull 2015

Testing GR via the growth rate

Growth rate *f* of large-scale structure:

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



A simplified way to parametrize this:

Background evolution $p_X = w_0 \rho_X$

Growth rate

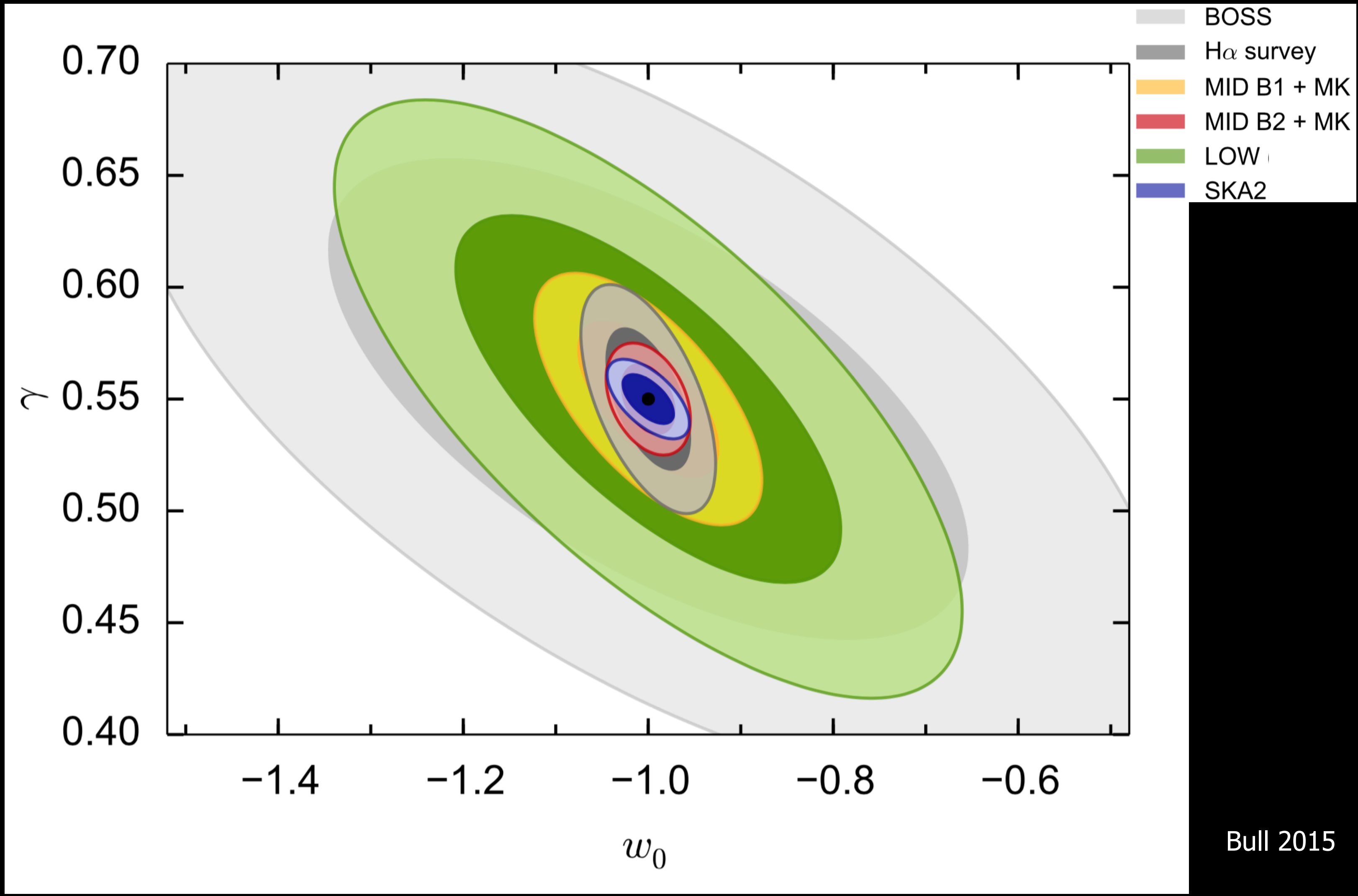
$$f \equiv \frac{d \ln \delta_m}{d \ln a} = \Omega_m^\gamma$$

The standard model has

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

Testing GR via the growth rate

Forecast constraints on w_0 and γ – SKA1 could be very effective:

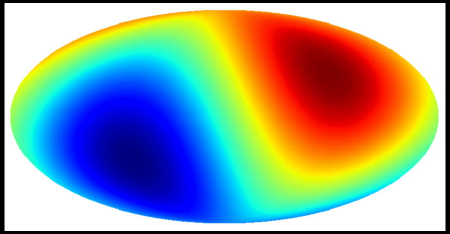


Bull 2015

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/ luminosity in the motion direction, less behind

The boosted observer measures redshifts and solid angles as:

$$1+\tilde{z} = (1+z)\left[1-\mathbf{n}\cdot\mathbf{v_0}\right]$$
$$d\tilde{\Omega}_o = \left(1+2\mathbf{n}\cdot\mathbf{v}_0\right)d\Omega_o$$

Total number of particles is conserved:

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

Then the number per redshift per solid angle is

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

To measure the LSS dipole, 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.

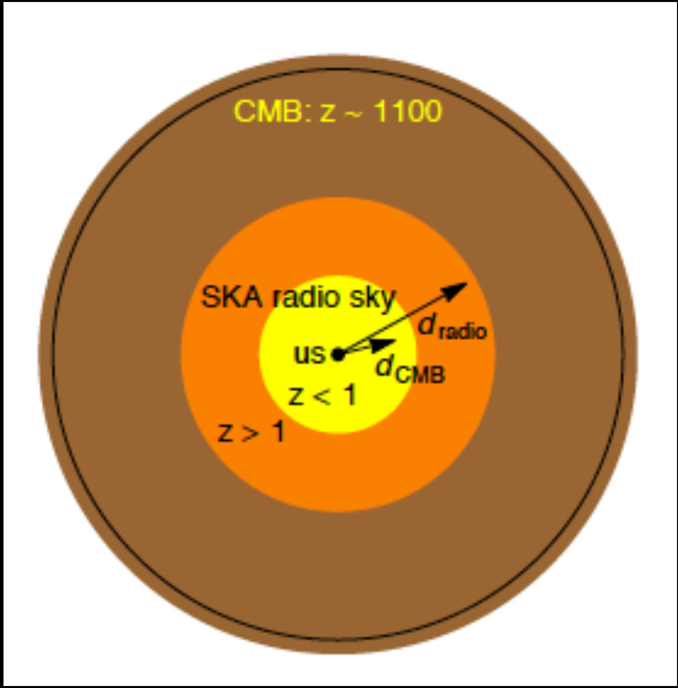
There is an SKA survey that is well-suited to this:
a radio continuum survey (detects total radio emission, but no redshifts)

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 (as in standard LCDM)
  * non-Gaussian for other models

Constraining primordial non-Gaussianity (PNG) is a powerful probe of inflation and 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:*

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

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

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

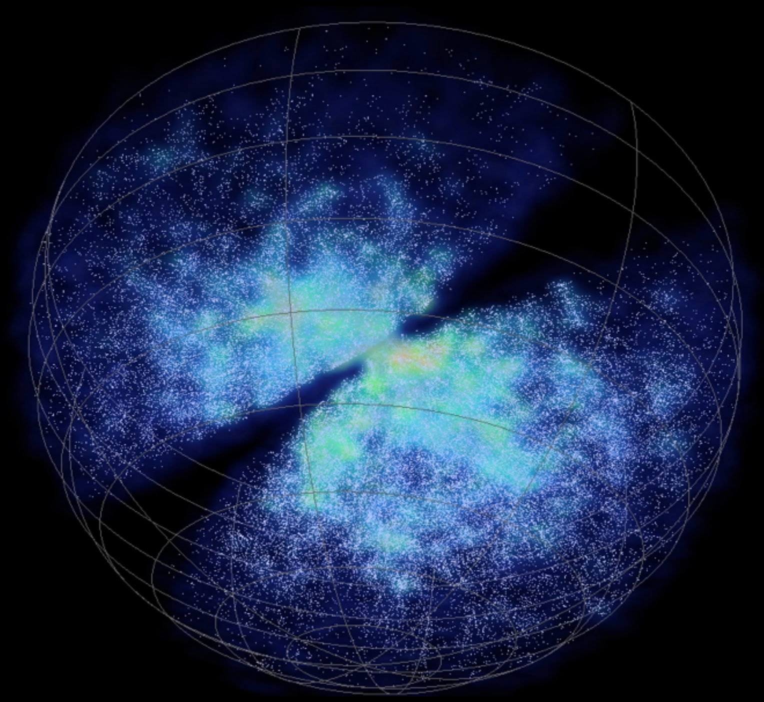
How does PNG affect the galaxy distribution?

For local PNG, the bias of galaxies is modified as

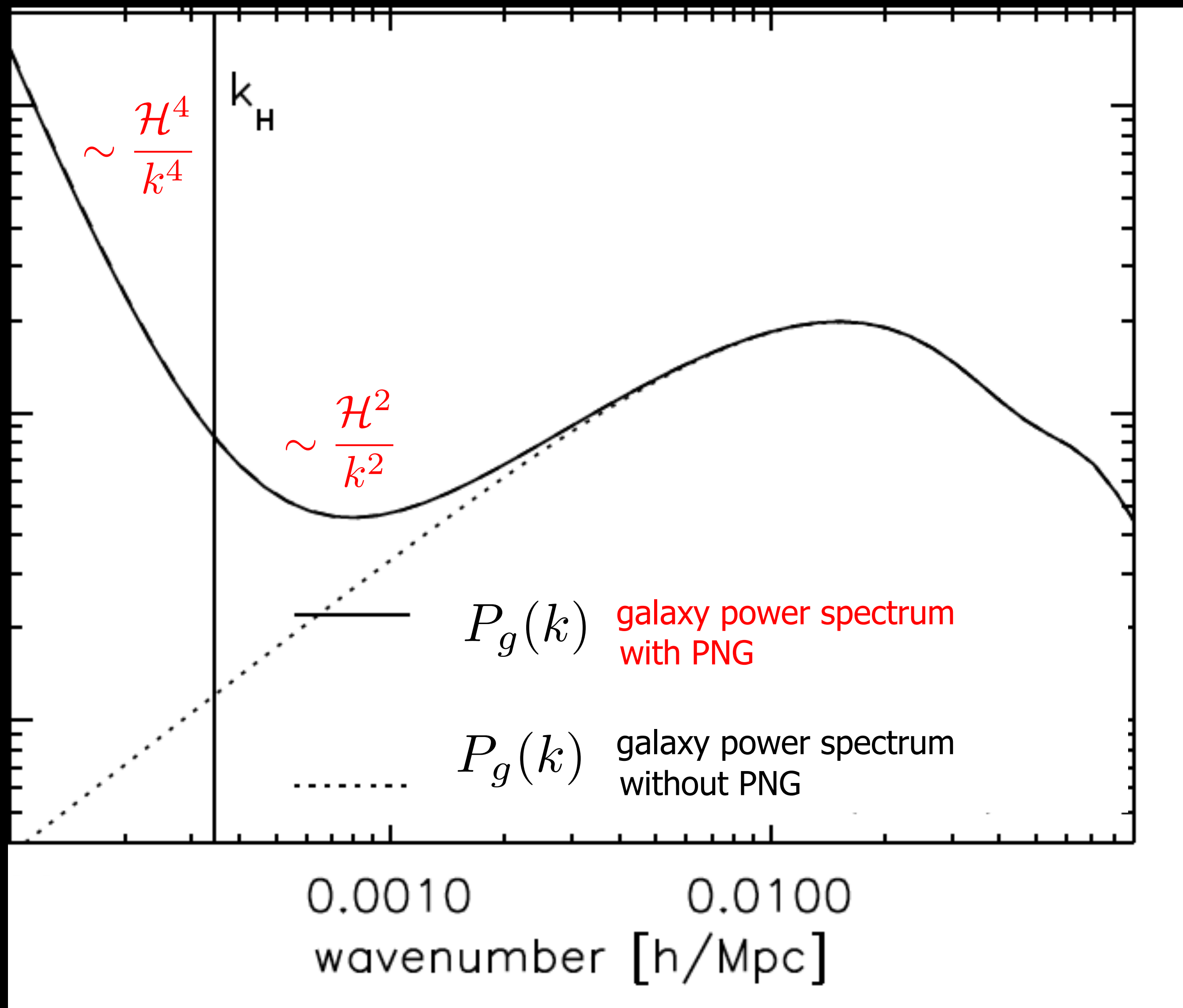
$$\delta_g(z,k) = b(z)\delta_m(z,k)$$

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

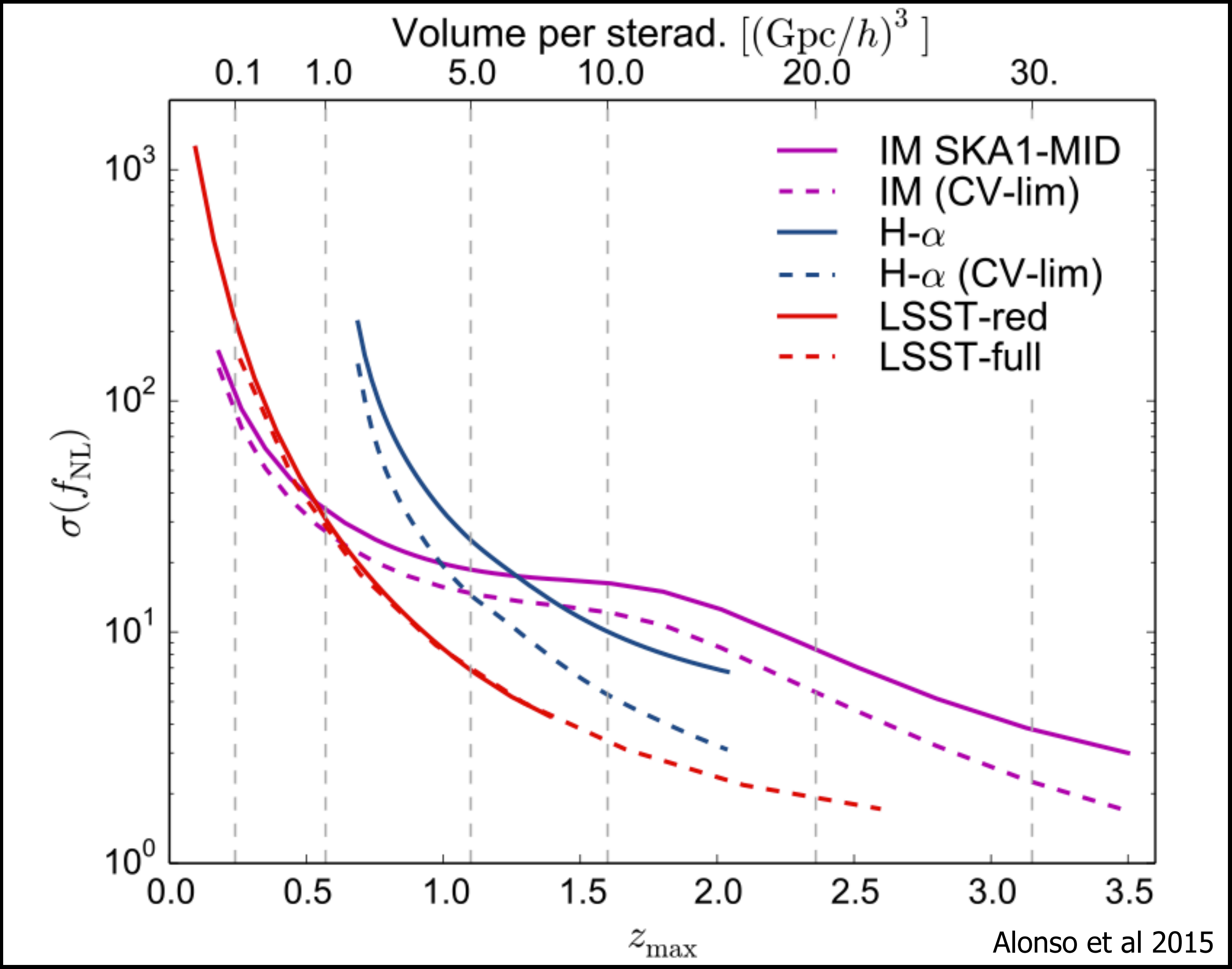
Galaxy surveys on ultra-large scales can probe the primordial Universe!



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



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



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.

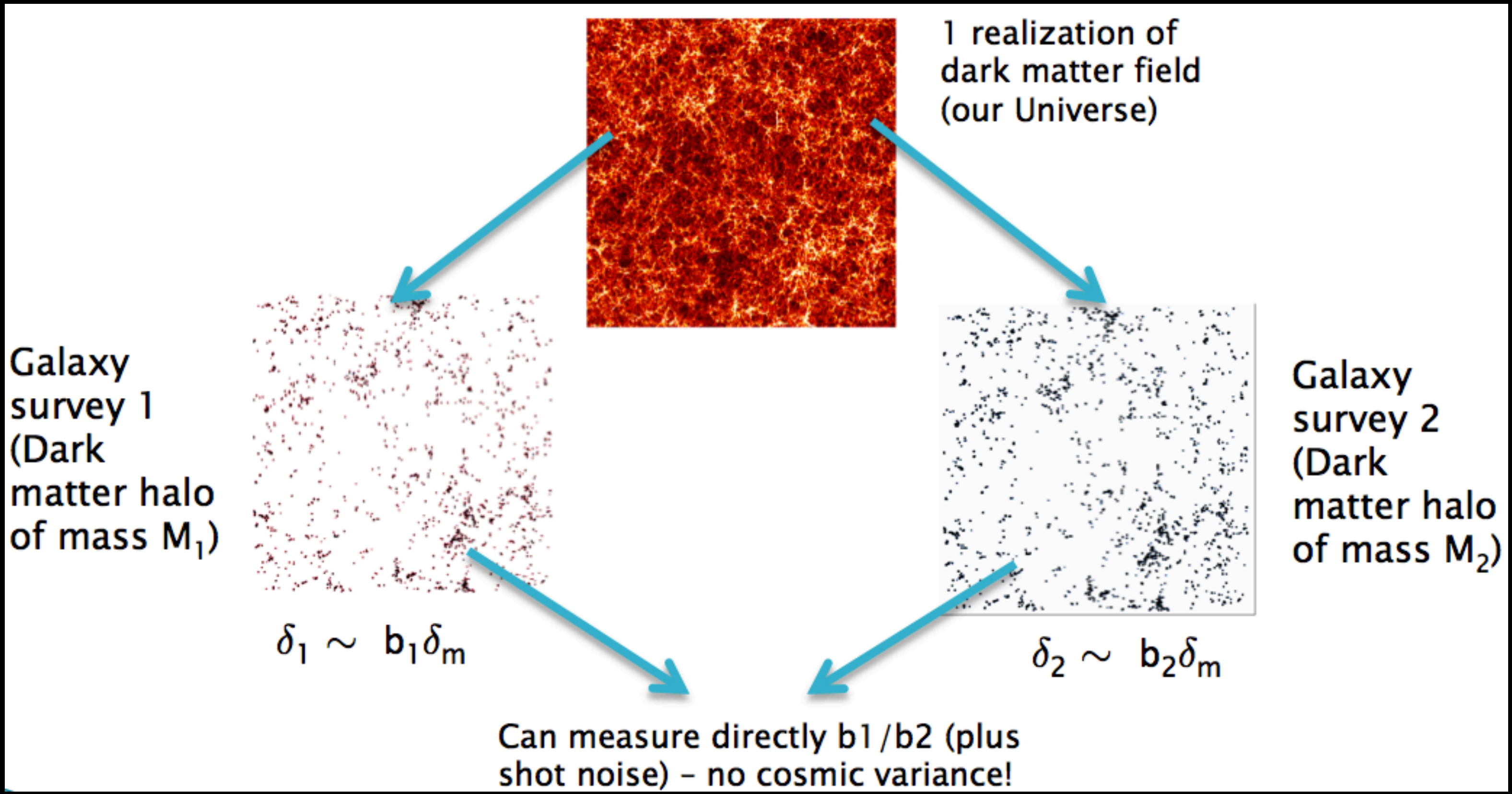
Even the biggest and best future galaxy surveys – Euclid, LSST and SKA – will be unable to achieve

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

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

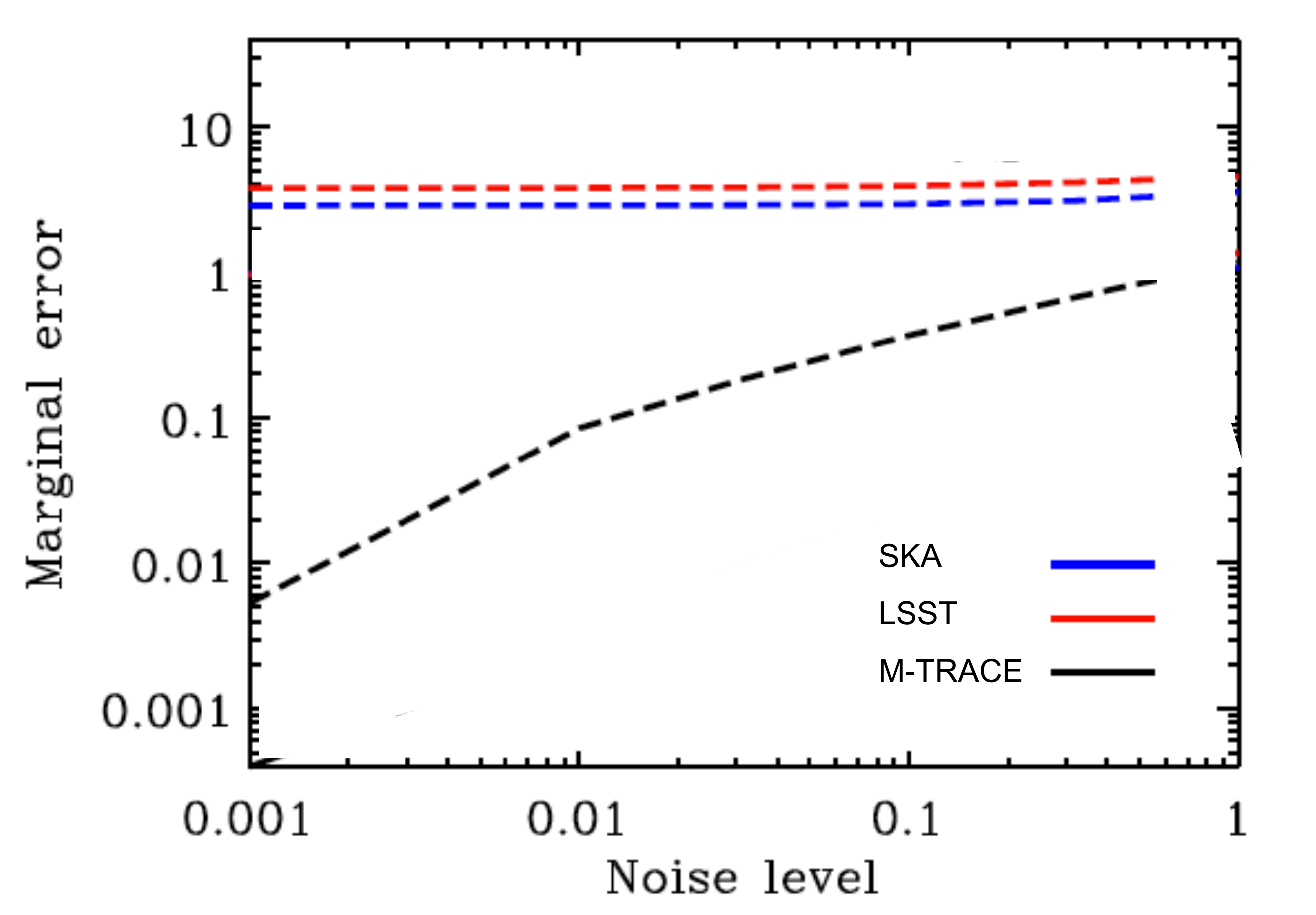
SKA1 intensity map X LSST photo-z

SKA SQUARE KILOMETRE ARRAY X LSST

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
	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.

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	IM×red×blue	0.40

Alonso & Ferreira 2015

Multi-tracing within SKA: intensity mapping X continuum surveys

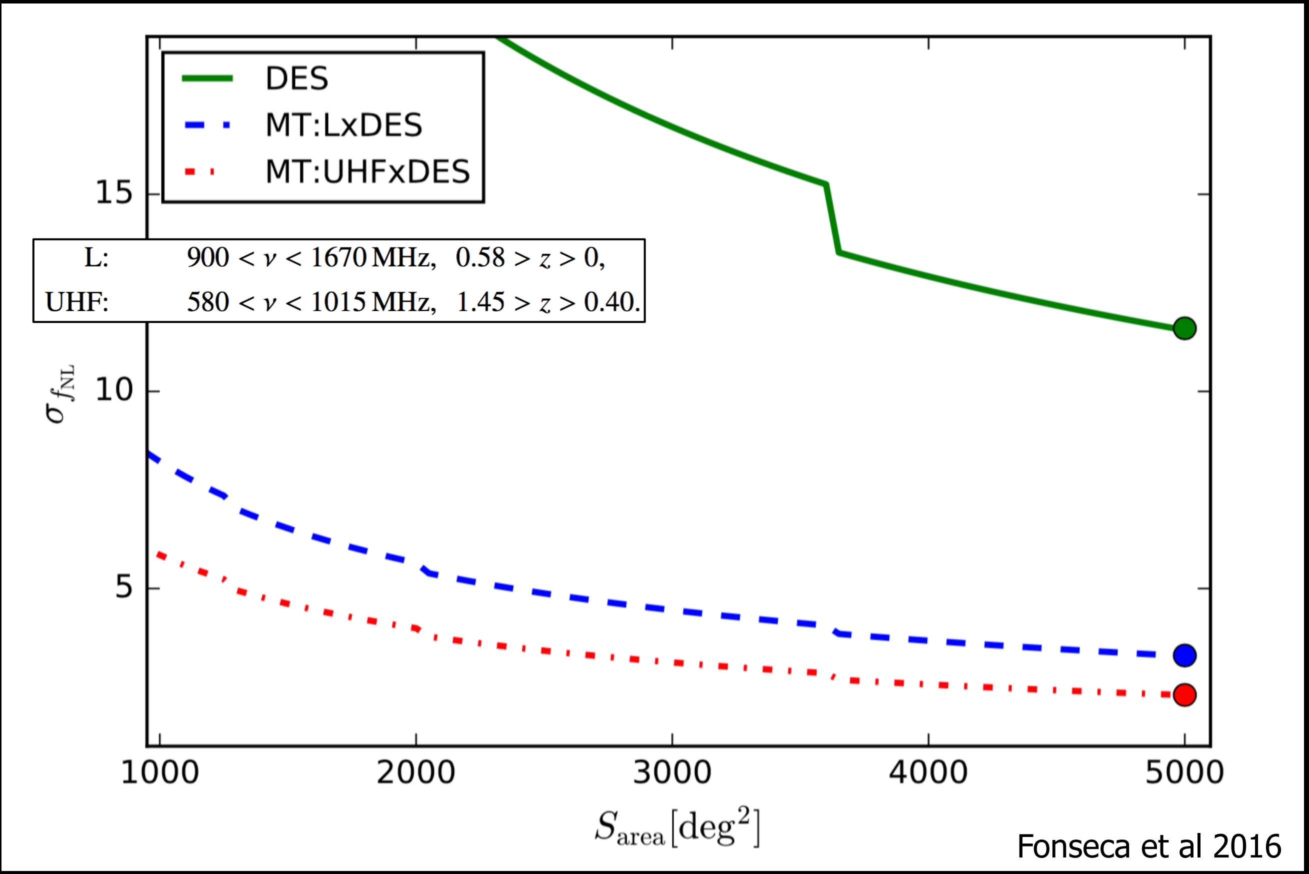
Future surveys – not competing, but combining

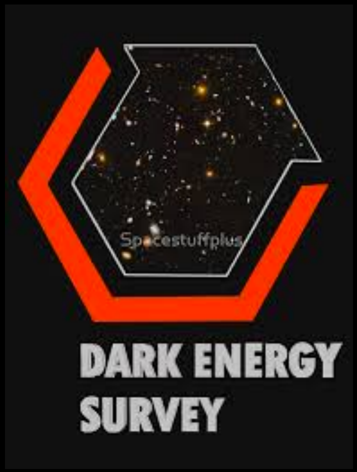
Multi-tracer forecasts for constraints on PNG show us the benefits of *combining* next-generation surveys.

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!