Title: Measuring ultra-large scales with the Square Kilometre Array

Date: Dec 02, 2014 11:00 AM

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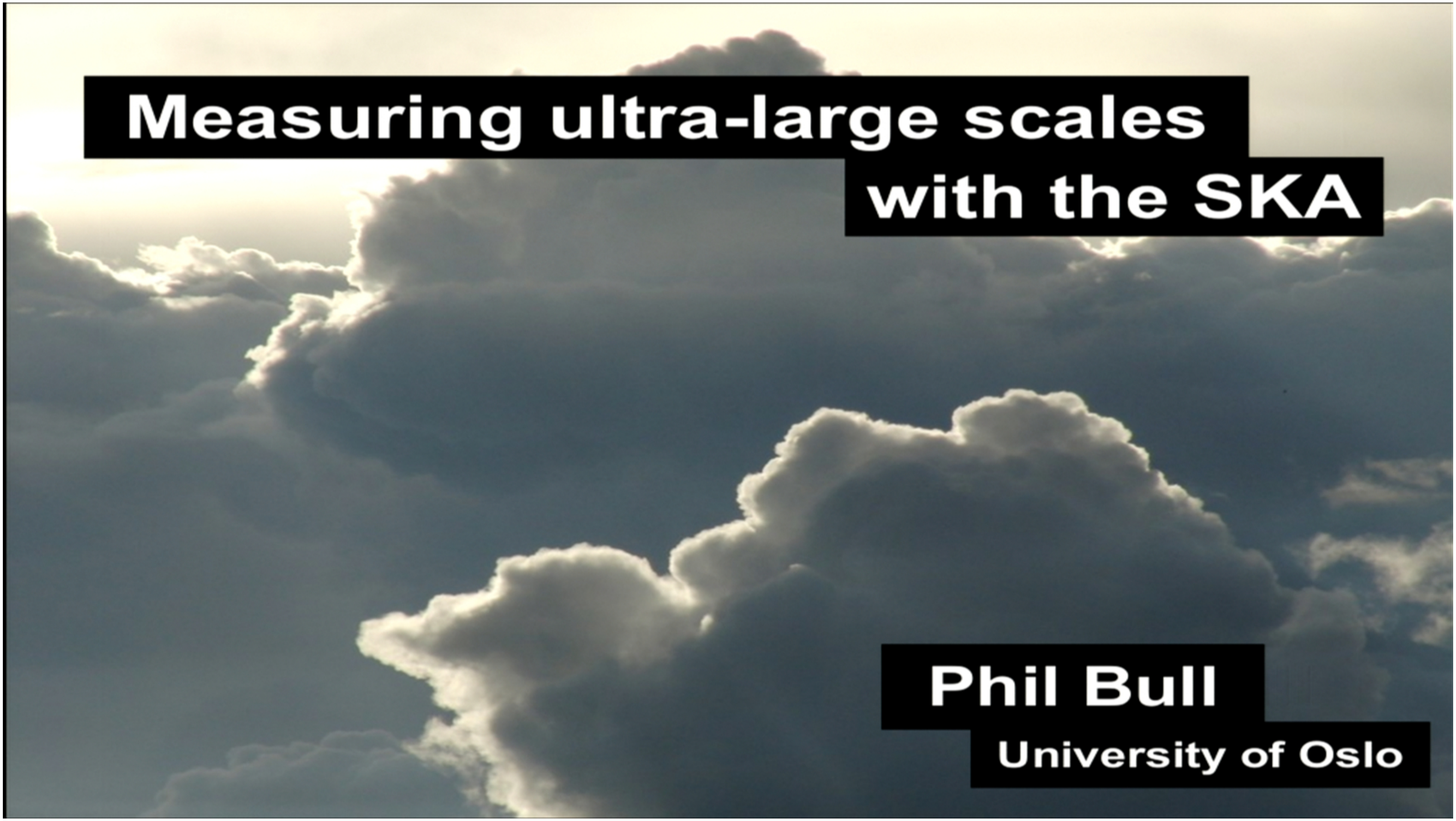
Abstract: <p>Forthcoming 21cm intensity mapping surveys on the Square Kilometre Array (SKA) will be capable of probing unprecedentedly large volumes of the Universe. This will make it possible to detect effects beyond the matter-radiation equality peak in the power spectrum, including primordial non-Gaussianity, GR corrections, and possible signatures of modified gravity. I give an overview of the proposed SKA intensity mapping surveys, the science that they will be able to do, and some of the challenges that they face.</p>


Measuring ultra-large scales
with the SKA
Phil Bull
University of Oslo

Outline

1) Cosmology with the Square Kilometre Array

2) Physics on ultra-large scales

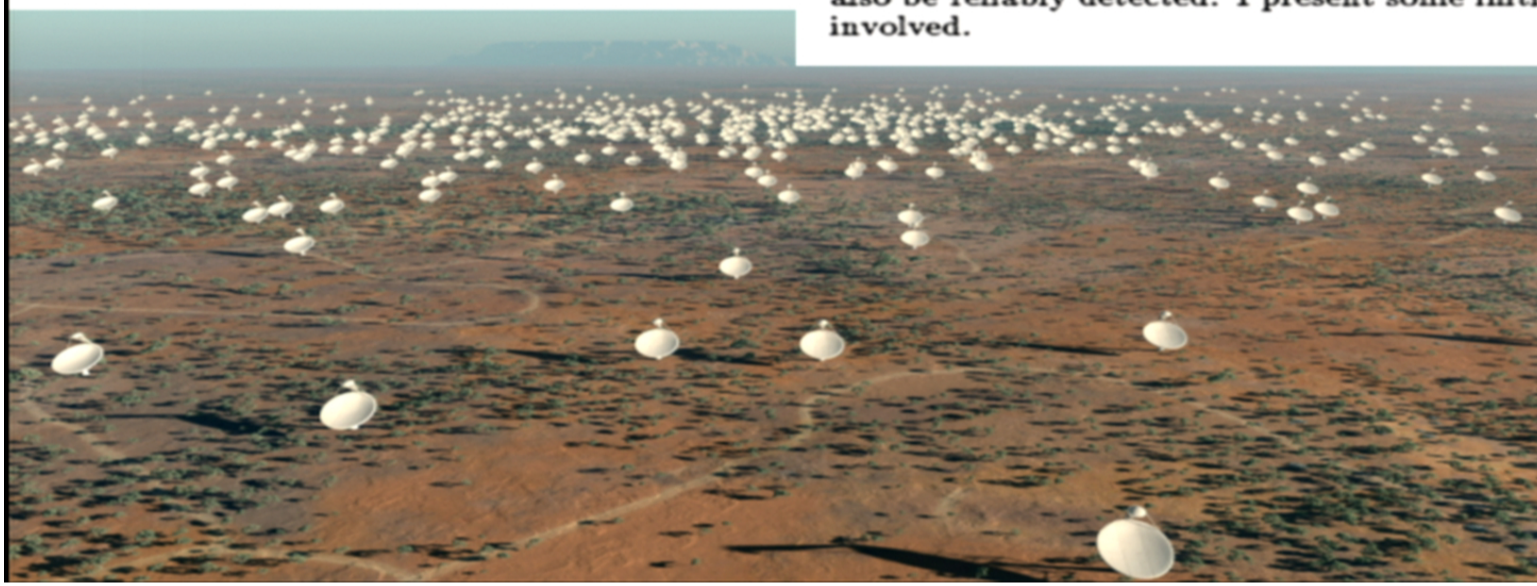
3) Practicalities of measuring ultra-large scales

Square Kilometre Array

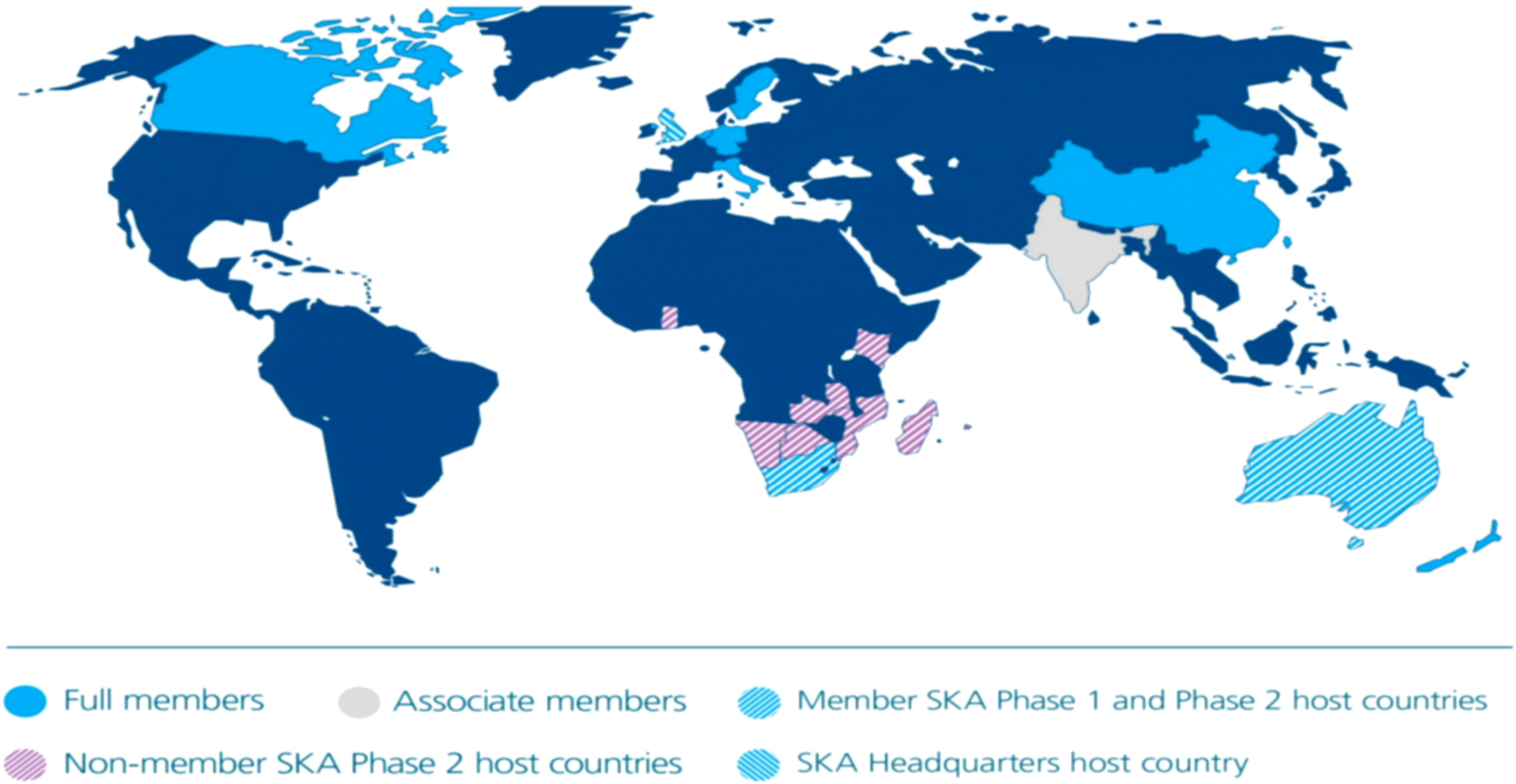
THE HYDROGEN ARRAY **(1991)**

P.N. WILKINSON
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK11 9DL, United Kingdom

ABSTRACT The time is ripe for planning an array with a collecting area of 1 km^2 (14 times larger than Arecibo and 75 times larger than the VLA). In view of its major astronomical target I have dubbed this concept 'The Hydrogen Array', although 1μJy continuum sources will also be reliably detected. I present some initial thoughts about the issues involved.

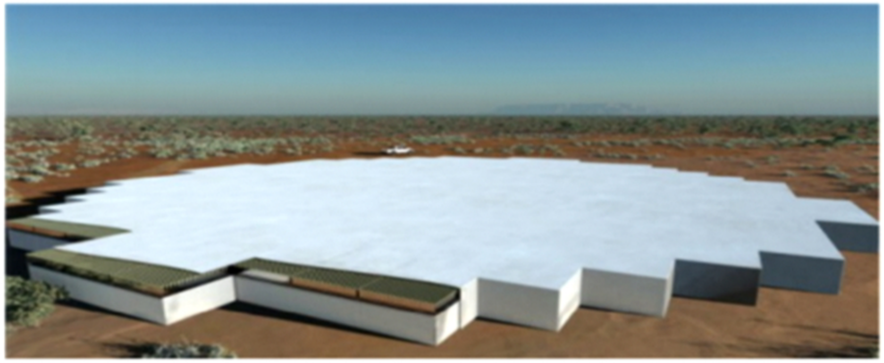


J. Bowler

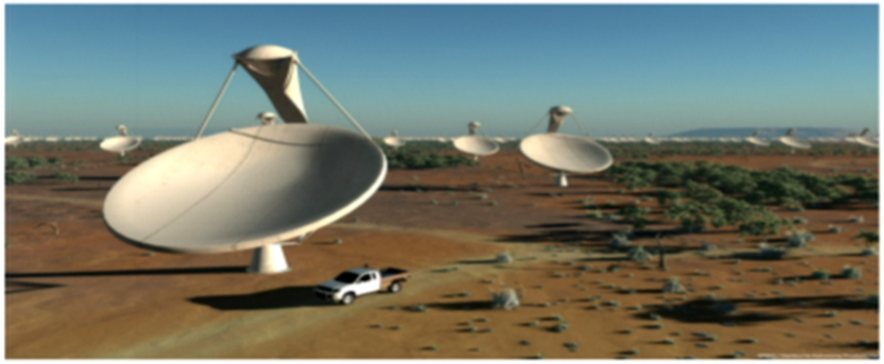

Full members
Associate members
Member SKA Phase 1 and Phase 2 host countries
Non-member SKA Phase 2 host countries
SKA Headquarters host country

Low-freq. aperture array
Very cheap, large field of view
Electronic beam forming
SKA1-LOW (2020)

Mid-freq. aperture array
Cheap, large field of view
Electronic beam forming
SKA Phase 2 (2025)



Dish arrays
~96-250 steerable dishes
Interferometer with dense core
Baselines from 20m – 100km
SKA1-MID, SKA1-SUR (2020)



KAT 7
7 x 12m dishes
S. African site
Already producing results

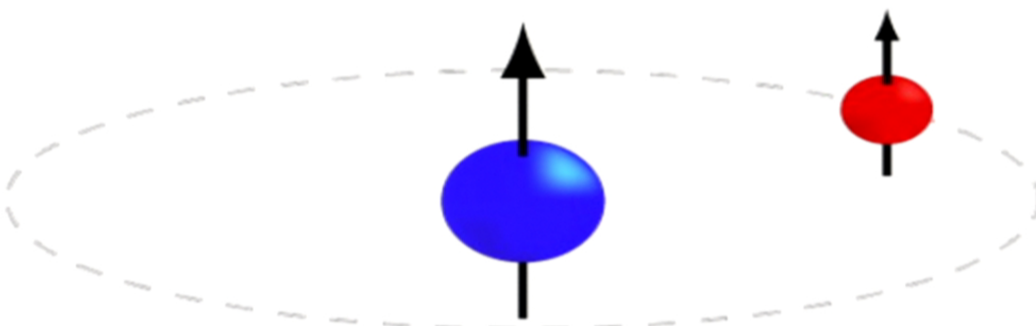
MeerKAT
64 x 13.5m dishes
Choice of two bands for HI
S. African site (due 2017)

ASKAP
36 x 12m dishes
36-element PAFs
W. Australia (completed 2012)

Neutral Hydrogen

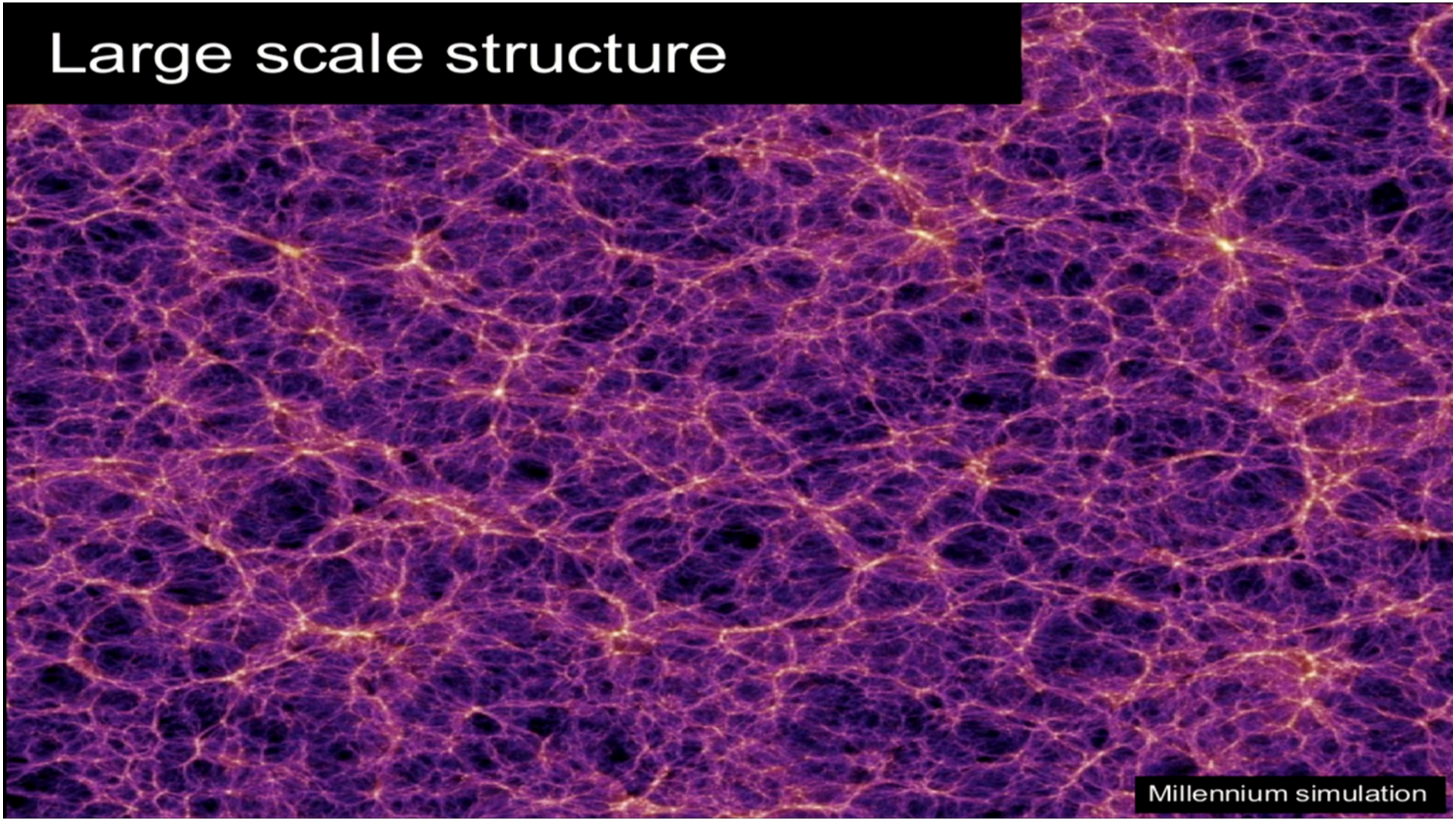
- Hyperfine splitting due to proton/electron spin alignment
- Extremely forbidden (rate: once per 10 million years)

  $\longrightarrow$ Very narrow line at “1420.40575177 MHz”
- But the Universe contains huge amounts of HI



Wikipedia

Large scale structure



Big questions

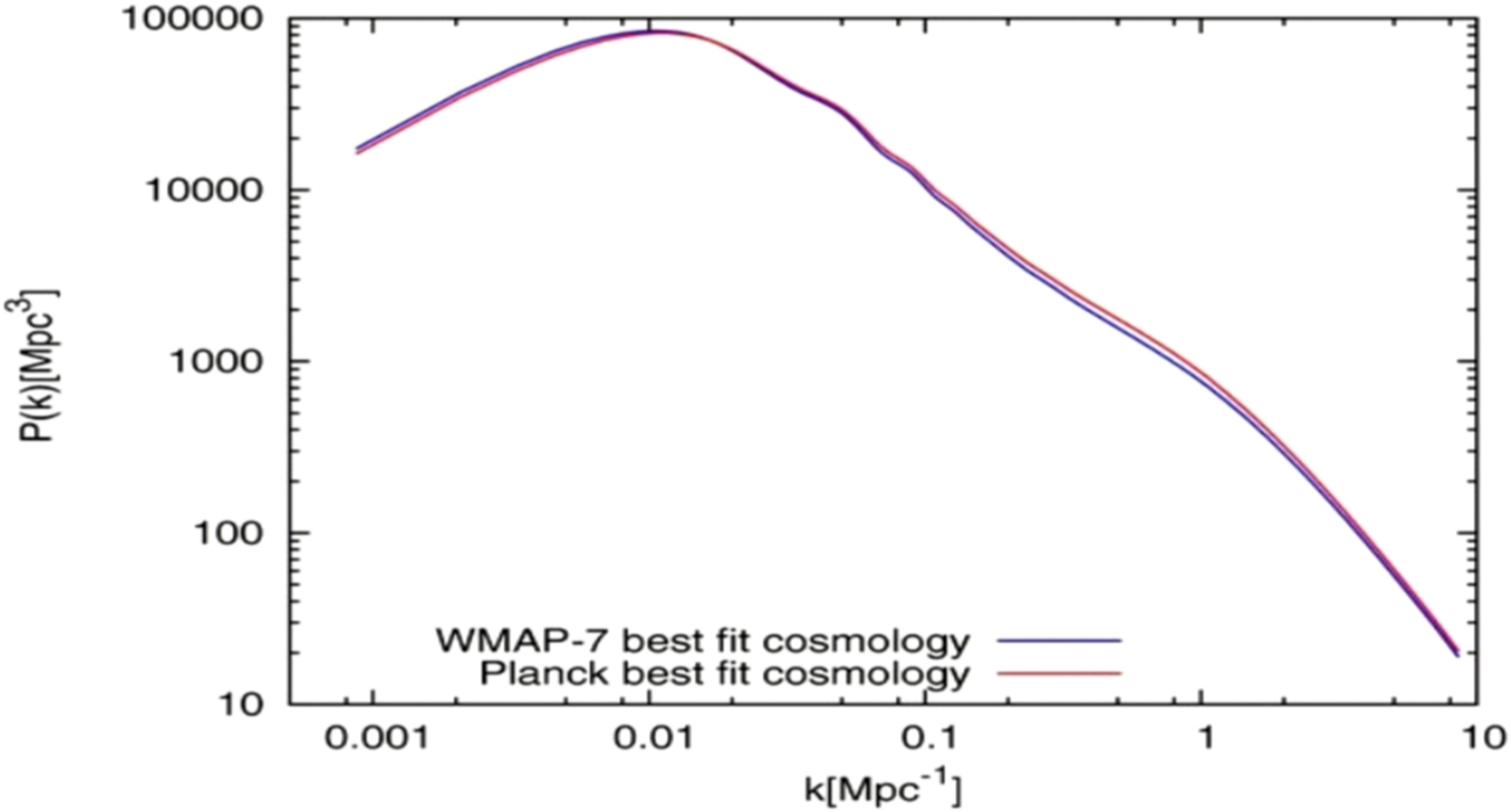
Cosmic acceleration

- Does dark energy evolve with time?
- If so, what is its equation of state?
- Is GR the correct theory of gravity, or are there modifications?

Initial conditions

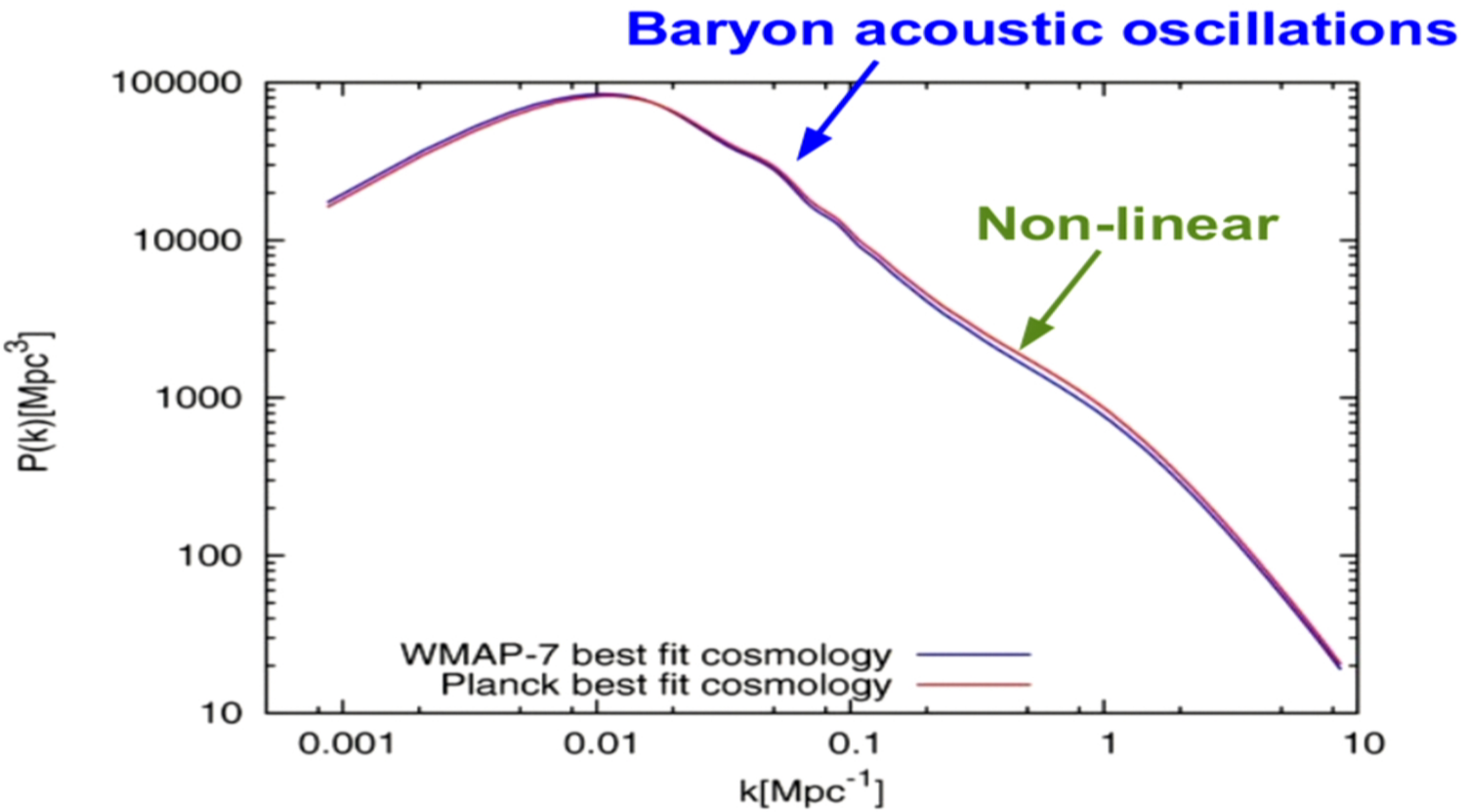
- Are the basic predictions of inflation borne out?
- What is its energy scale?
- What was the inflationary potential? How many fields?

Matter power spectrum



K. Heitmann et al. (2014)

Matter power spectrum



K. Heitmann et al. (2014)

SKA galaxy redshift survey

Good redshift resolution → small bandwidth → higher noise

$$\sigma_{rms} \propto \frac{T_{\rm sys}}{\sqrt{\delta\nu\, t_{\rm obs}}}$$

BOSS (2014)	~ 1.5 million galaxies 10,000 sq. deg. ($z < 0.7$)
SKA 1 (~2022)	~ 5 million galaxies 5,000 sq. deg. ($z < 0.4$)

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Euclid (~2025)	~ 60 million galaxies 15,000 sq. deg. (0.7 < z < 2.0)
Full SKA (~2027)	**~ 1 billion galaxies** 30,000 sq. deg. (0.2 < z < 1.7)

Intensity mapping

Why detect individual galaxies?

- Often only want to keep larger scales
- High SNR detection wastes a lot of photons
- Spectroscopic redshifts take a long time

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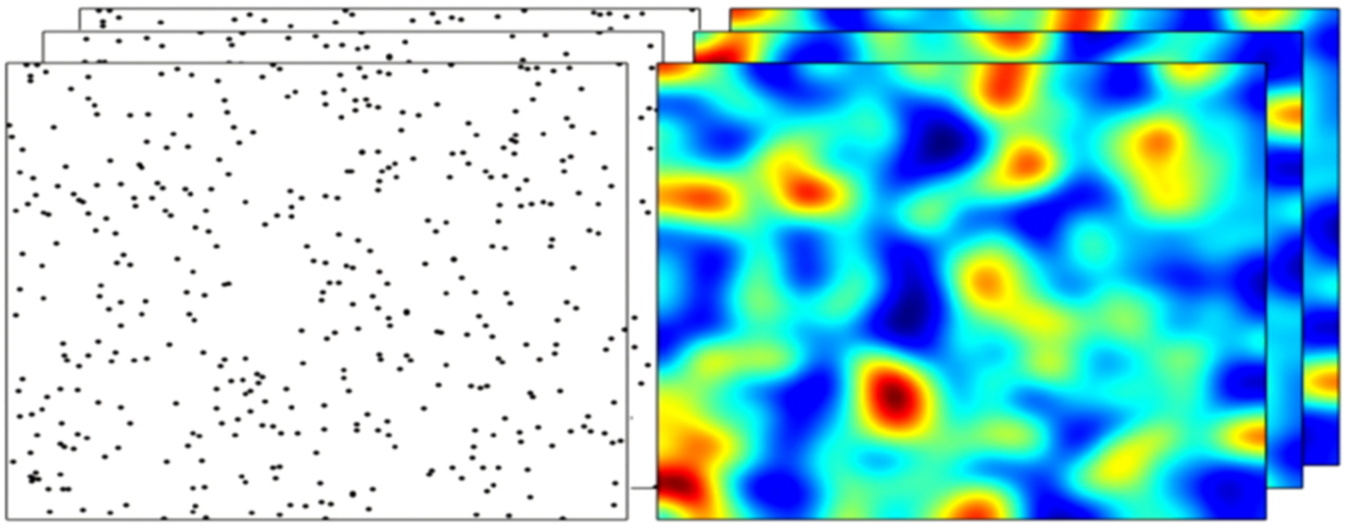
$\rightarrow$ **Map out emission integrated over many galaxies**



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21cm intensity maps

- Low-resolution still preserves large-scales (c.f. CMB)
- Integrated emission is easier to detect / no thresholding
- Detecting an emission line $\rightarrow$ get redshifts for free

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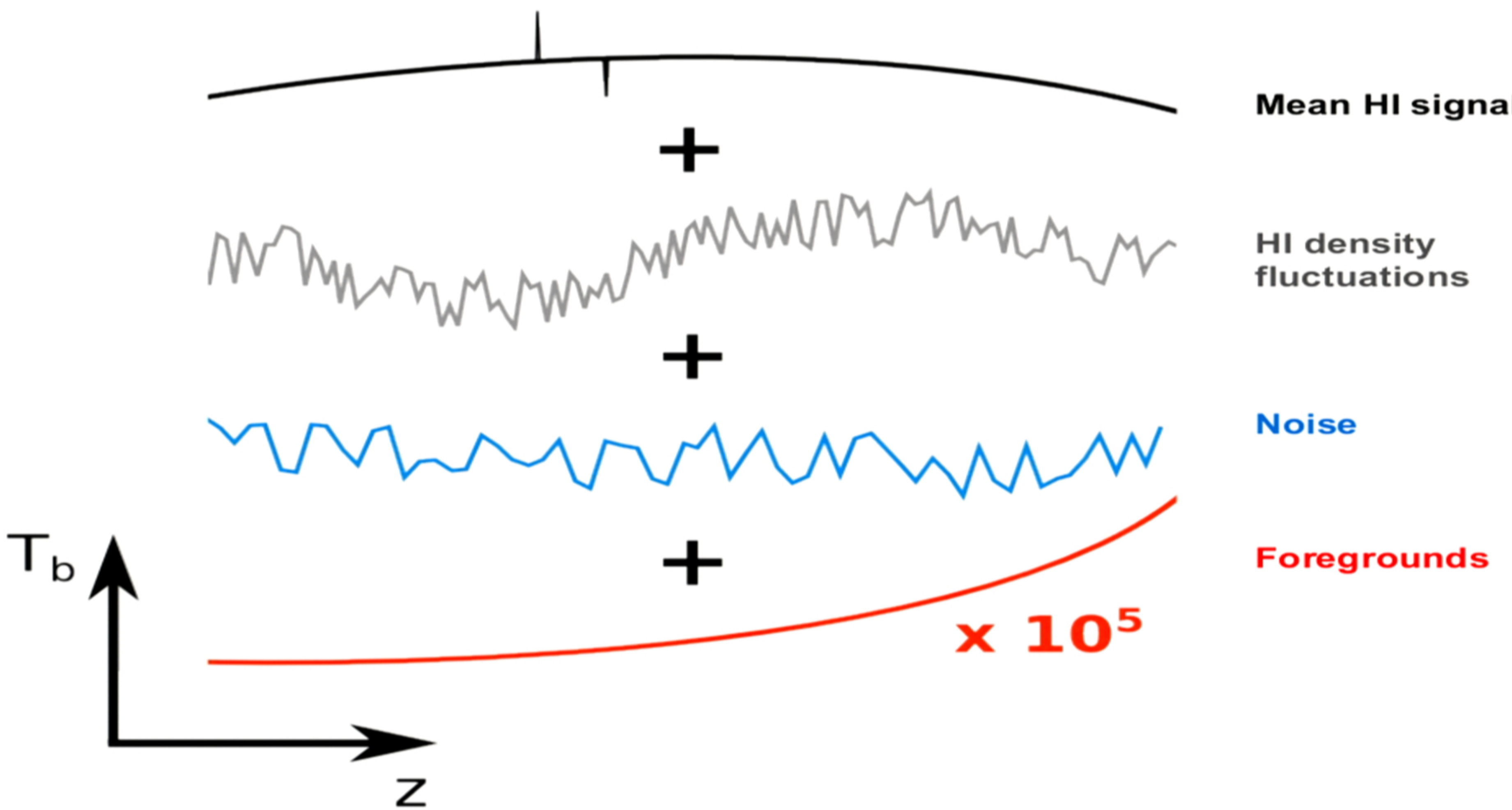
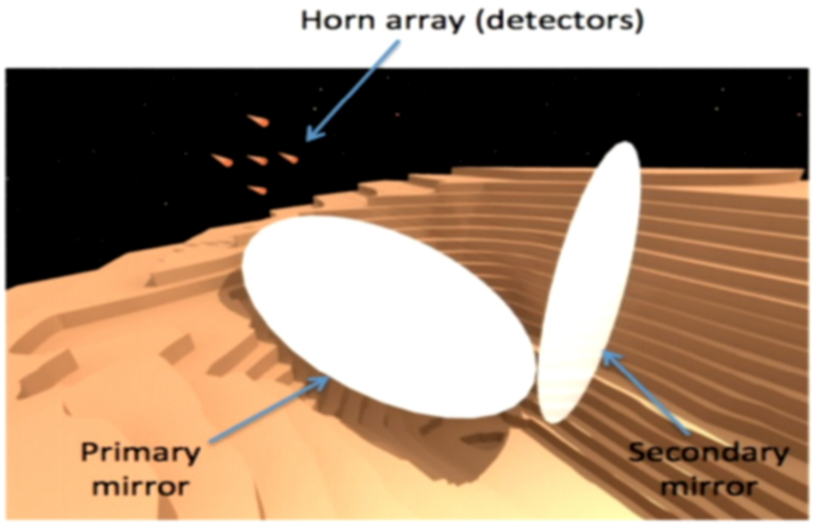

Mean HI signal
+
HI density fluctuations
+
Noise
+
Foregrounds
x 10^5
T_b
z

Detecting the BAOs

It's still early days for intensity mapping!

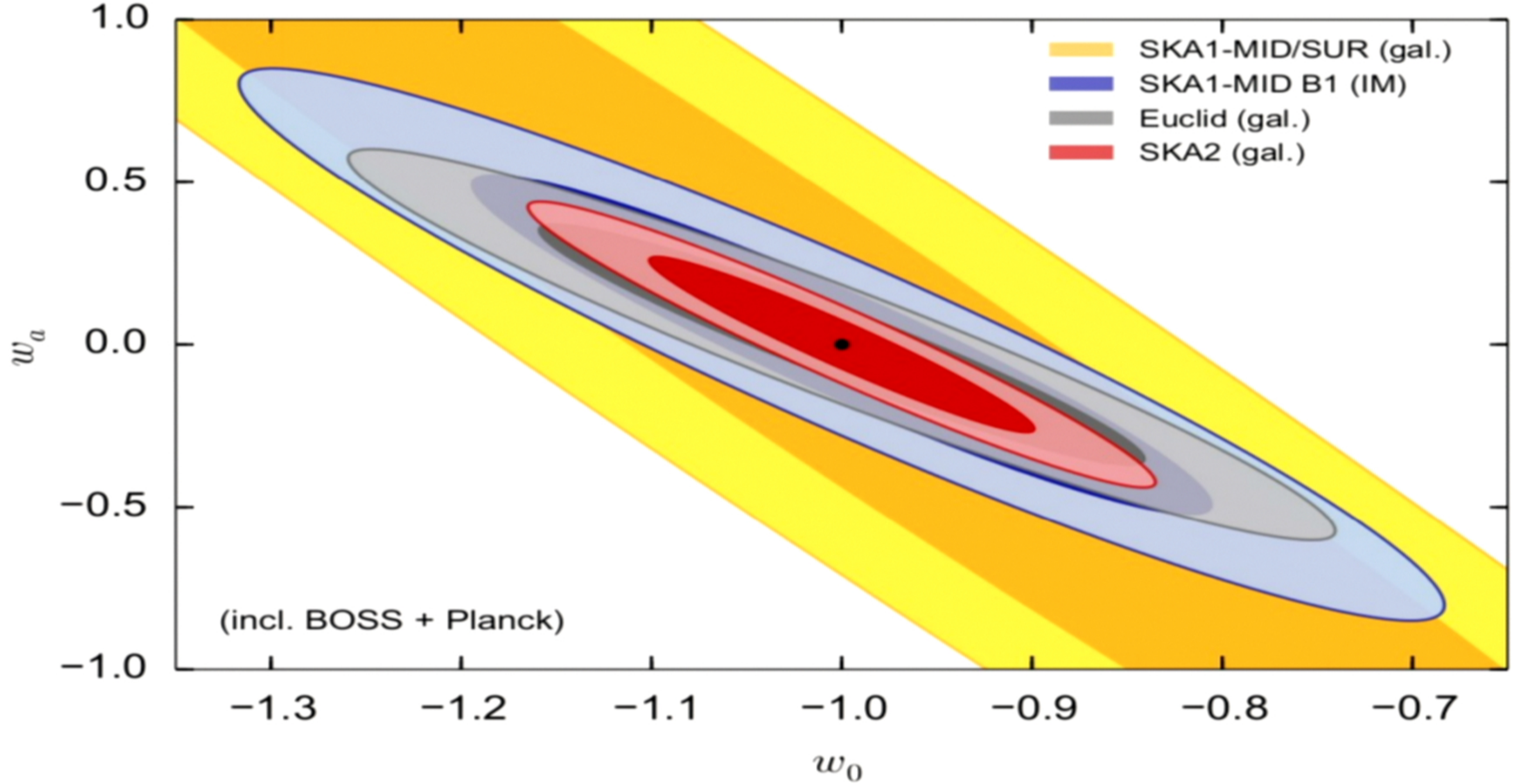
- First detection of cosmological signal with the Green Bank Telescope in 2010 (Chang et al.)
- BAO have not been detected yet!
- New experiments in Canada (CHIME), Uruguay (BINGO)

K. Vanderlinde



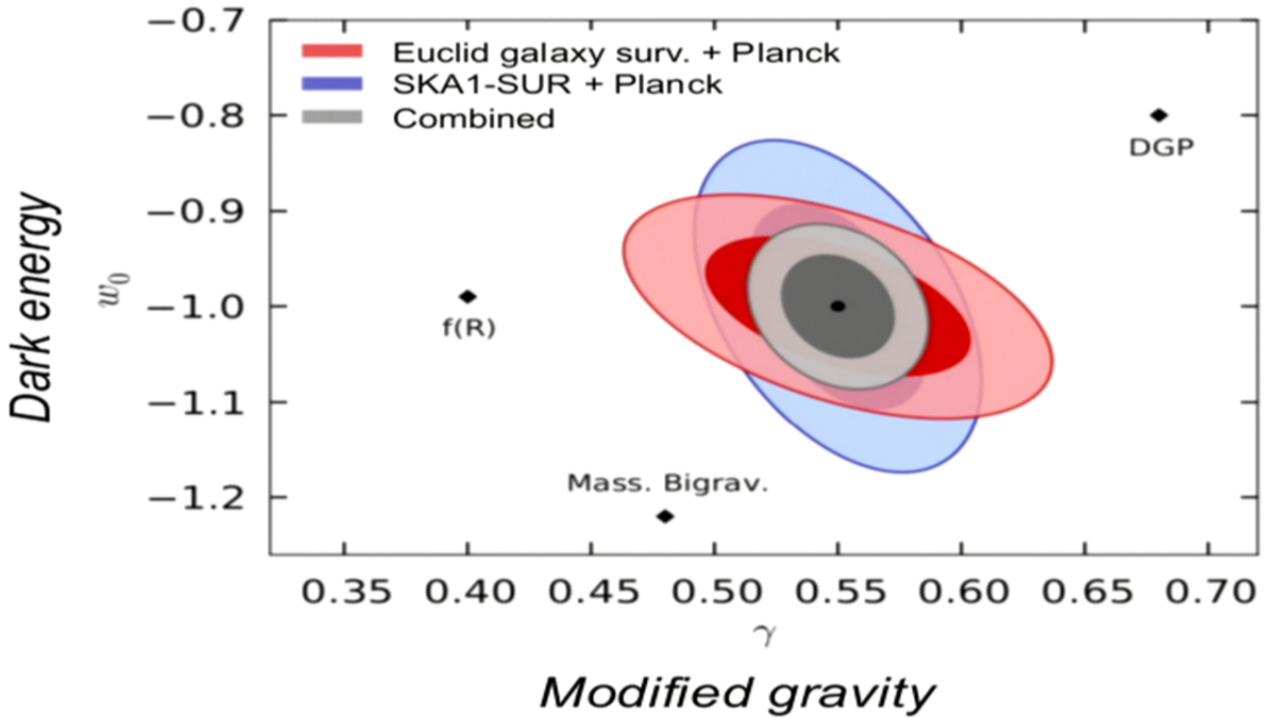
BINGO

Dark Energy



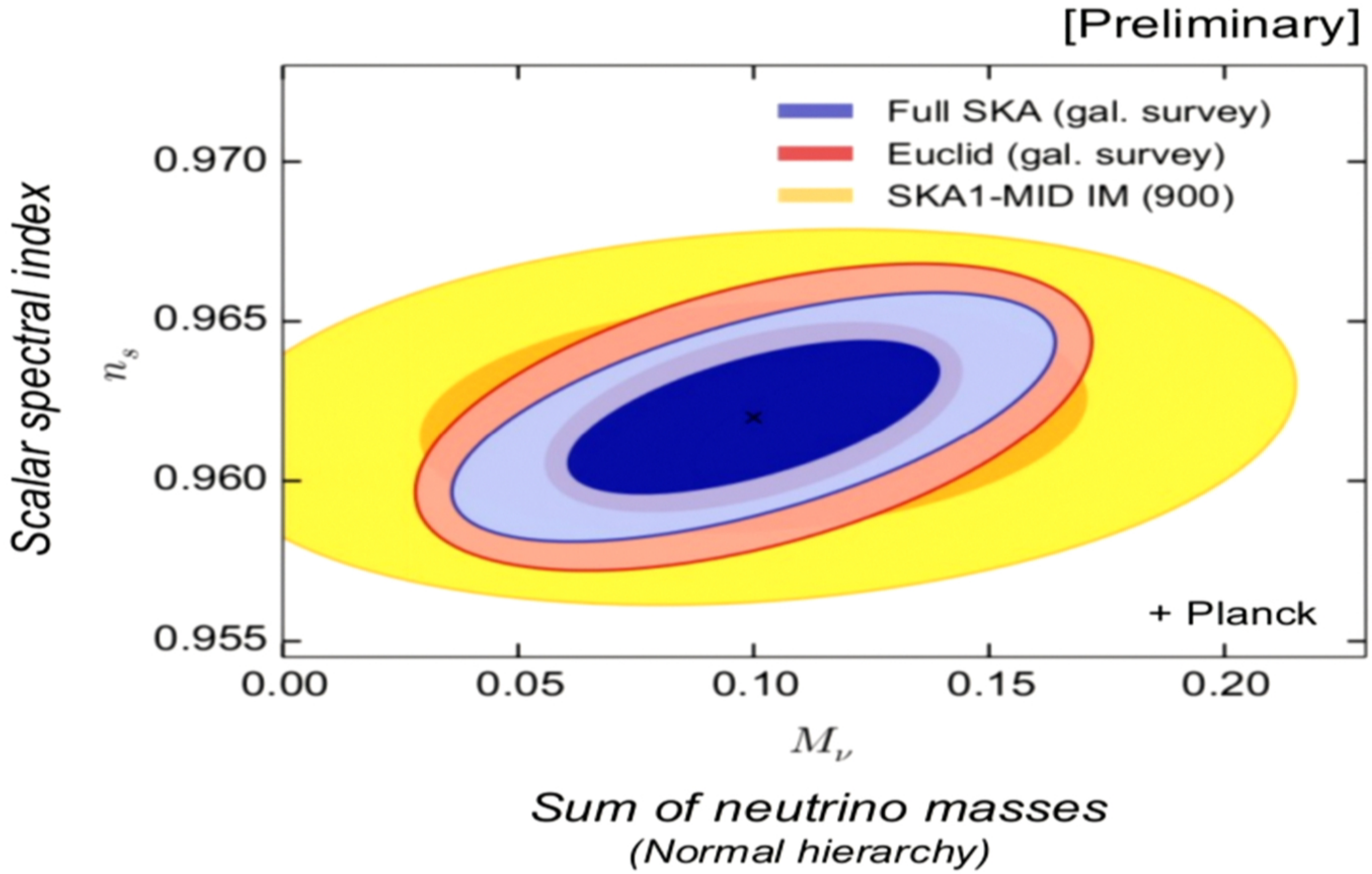
SKA1-MID/SUR (gal.)
SKA1-MID B1 (IM)
Euclid (gal.)
SKA2 (gal.)
(incl. BOSS + Planck)
1.0
0.5
0.0
−0.5
−1.0
w_a
−1.3
−1.2
−1.1
−1.0
−0.9
−0.8
−0.7
w_0

Modified gravity

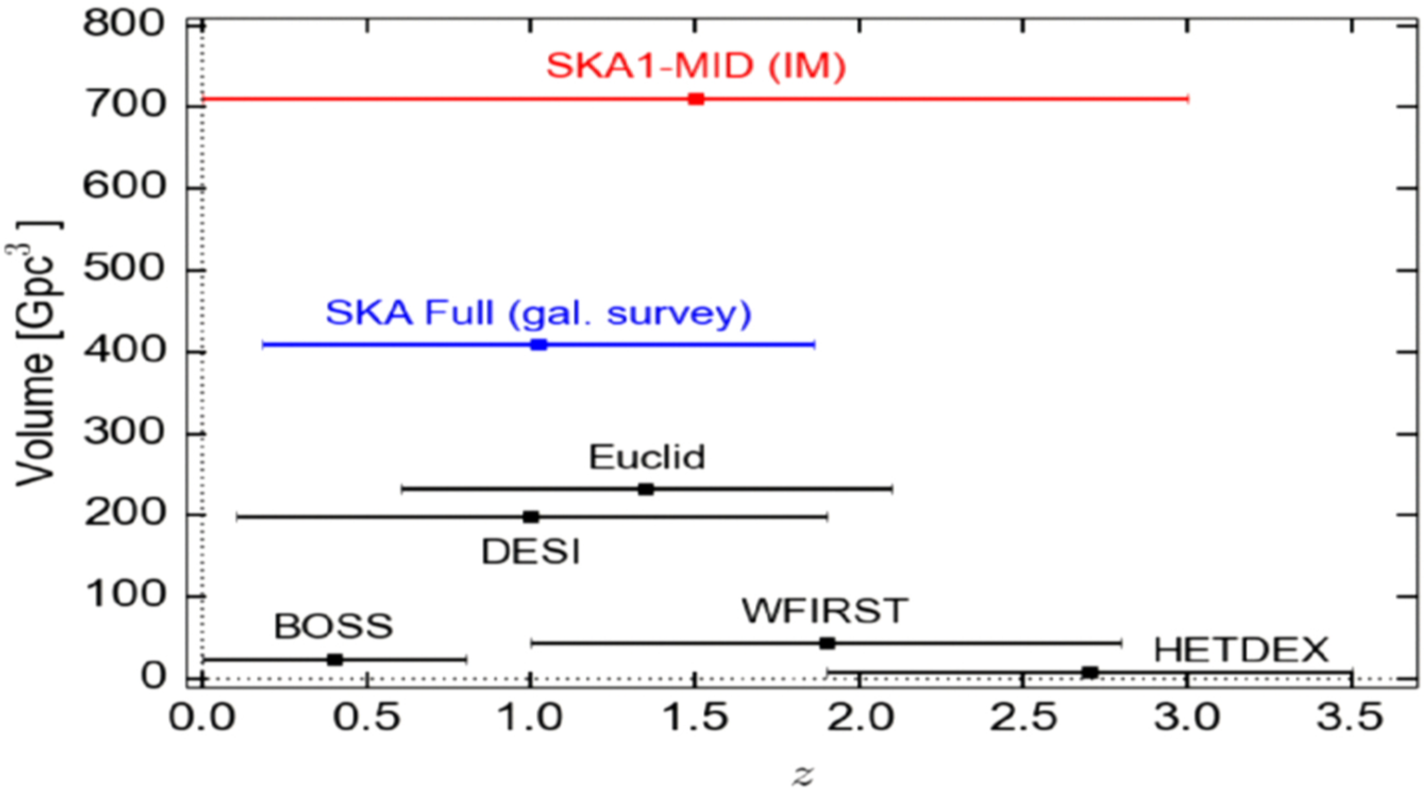


PB, Ferreira, Patel & Santos (2014)

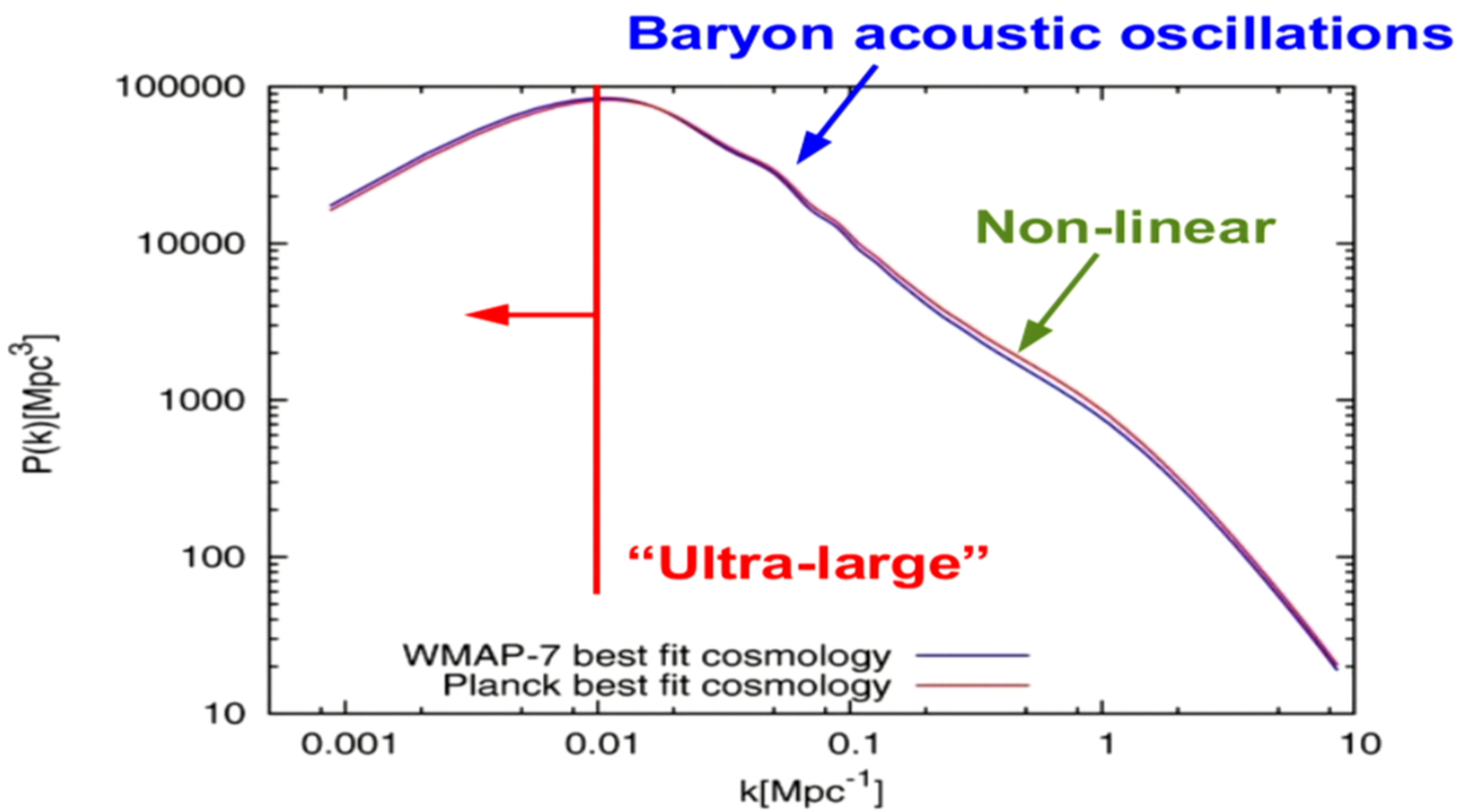
Neutrinos


[Preliminary]
Full SKA (gal. survey)
Euclid (gal. survey)
SKA1-MID IM (900)
+ Planck
0.970
0.965
0.960
0.955
0.00
0.05
0.10
0.15
0.20
Scalar spectral index
n_s
M_ν
Sum of neutrino masses
(Normal hierarchy)

Survey volumes



Matter power spectrum



K. Heitmann et al. (2014)

Why ultra-large?

- **New physical regime**: Newtonian approx. breaks down, other effects become important
- **Pristine**: Unaffected by messy non-linear effects
- **Connection to the primordial**: Signatures of inflation can appear / causality matters

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- **Surprises?**

Guinness World Records

Large-scale corrections

GR corrections become important at ultra-large scales

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$$\begin{aligned}\Delta(\mathbf{n}, z) \;=\; & D_g + \Phi + \Psi + \frac{1}{\mathcal{H}}\left[\dot{\Phi} + \partial_r(\mathbf{V}\cdot\mathbf{n})\right] \\ & + \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r_S\mathcal{H}}\right)\left(\Psi + \mathbf{V}\cdot\mathbf{n} + \int_0^{r_S} d\lambda(\dot{\Phi} + \dot{\Psi})\right) \\ & + \frac{1}{r_S}\int_0^{r_S} d\lambda\left[2 - \frac{r_S - r}{r}\Delta_\Omega\right](\Phi + \Psi).\end{aligned}$$

Bonvin & Durrer (2011)

Relativistic effects

GR corrections become important at ultra-large scales

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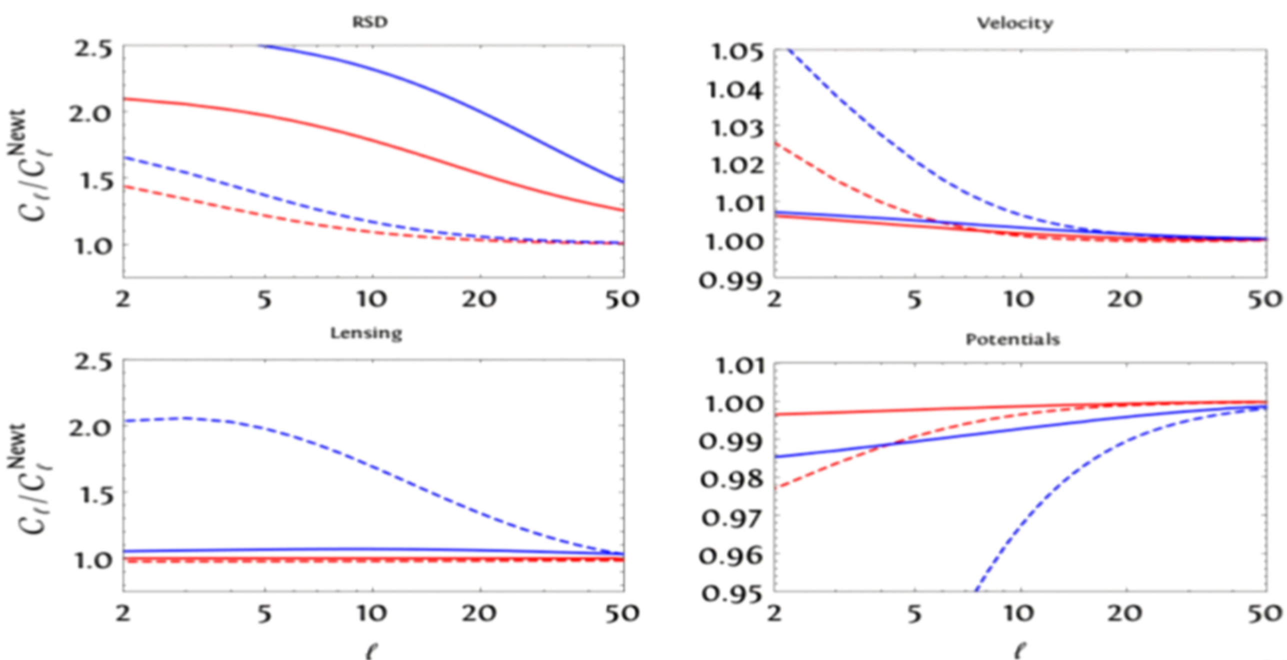
- Non-Newtonian effects are large (lensing, Doppler...)



Red: z ~ 0.5
Blue: z ~ 2.0

Solid: Narrow bin
Dashed: Wide bin

SKA Cosmology SWG

Relativistic effects

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Can see causally-disconnected regions at late times

- Distances too large for light to have traversed since the Big Bang
- Consistency test for homogeneity / spatial variations of fundamental constants

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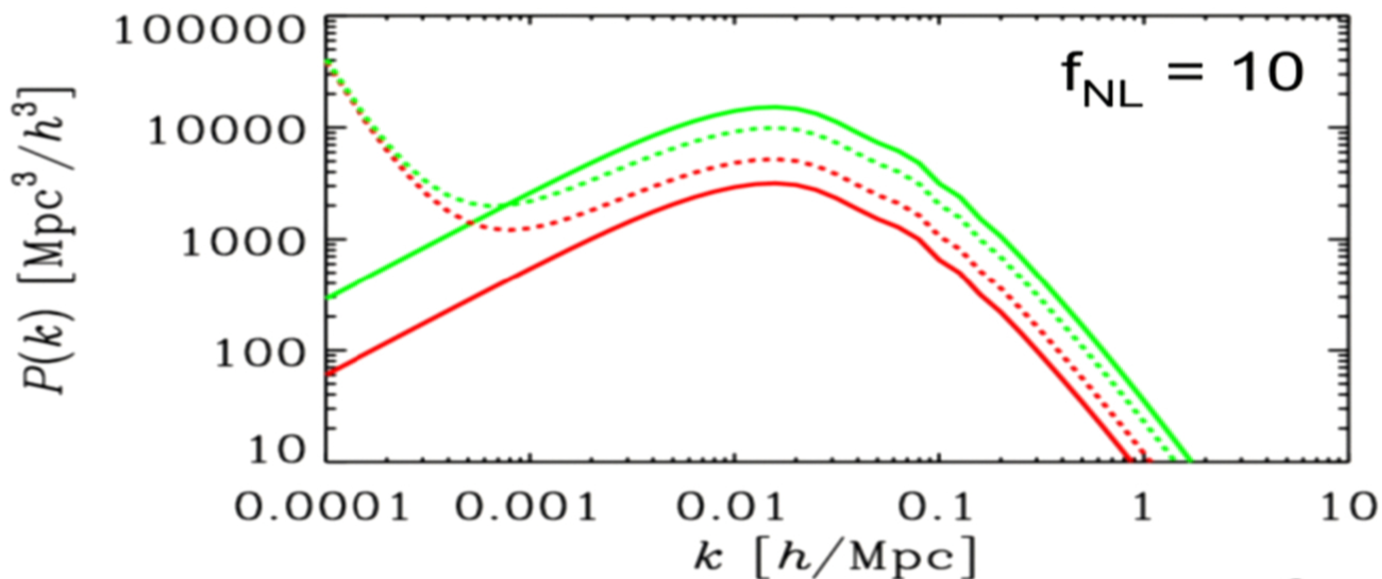
Scale-dependence of growth of structure

- Modified gravity theories predict scale-dependent growth on large scales (e.g. T. Baker et al., arXiv:1409.8284)

Non-Gaussianity

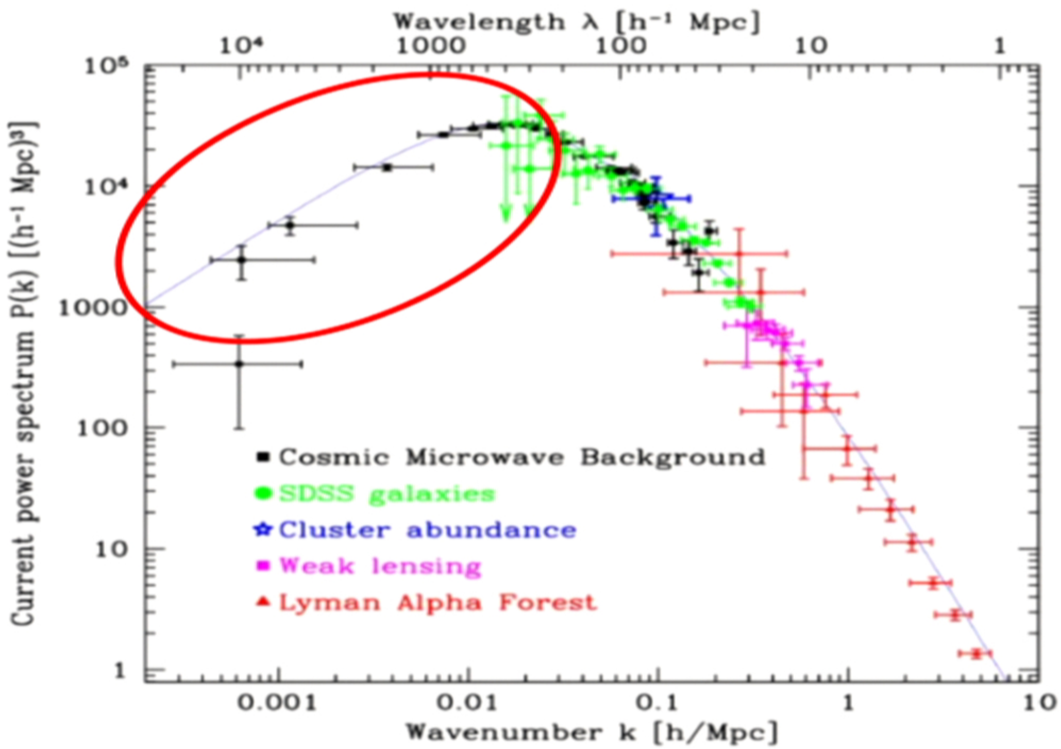
- Non-Gaussianity enhances clustering at ULS
- SKA should be able to measure $\sigma(f_{NL}) < 1$



Camera et al. (2013)

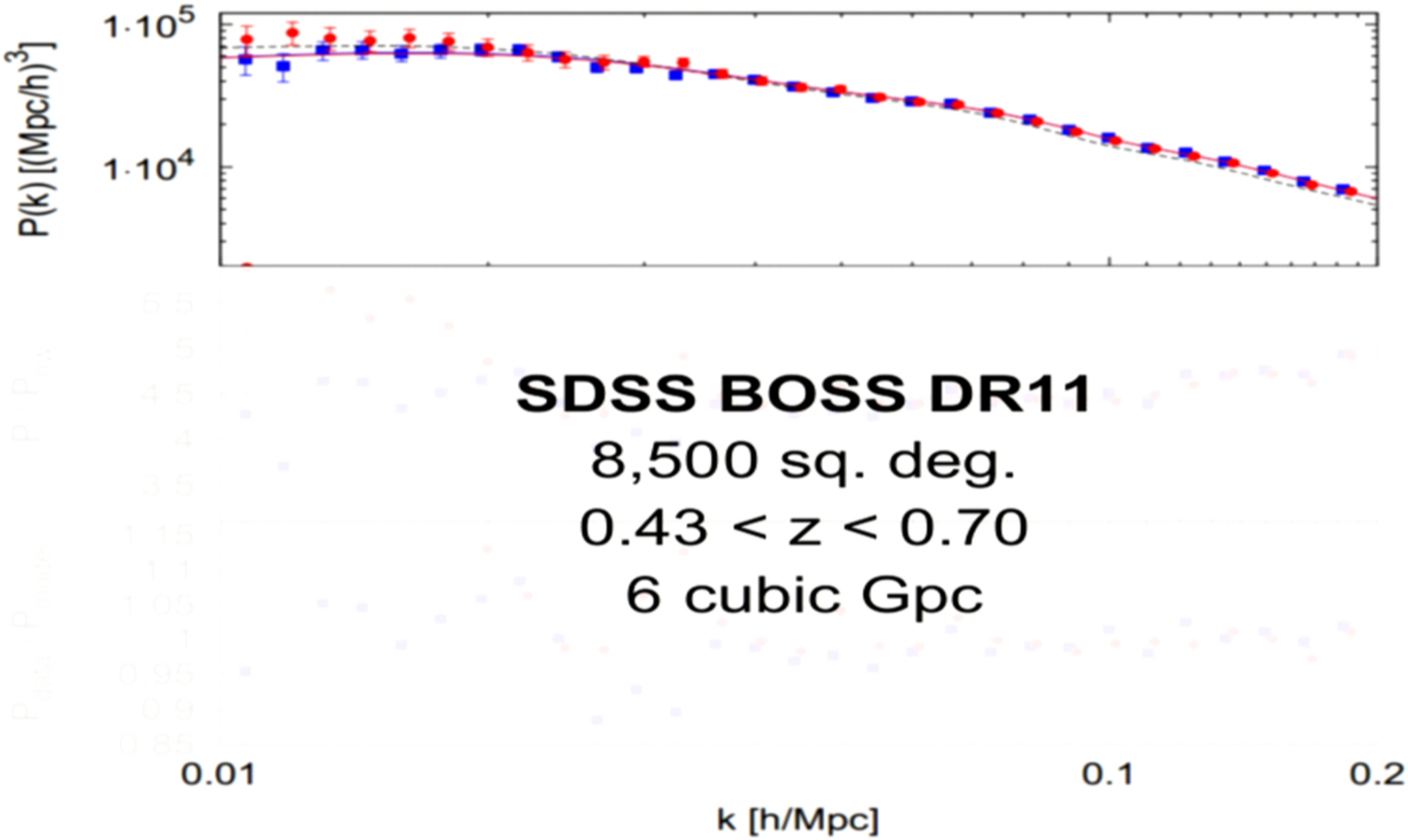
Existing constraints

- Haven't ULS been measured already?



Freedman & Turner (2003)

Existing constraints



SDSS BOSS DR11

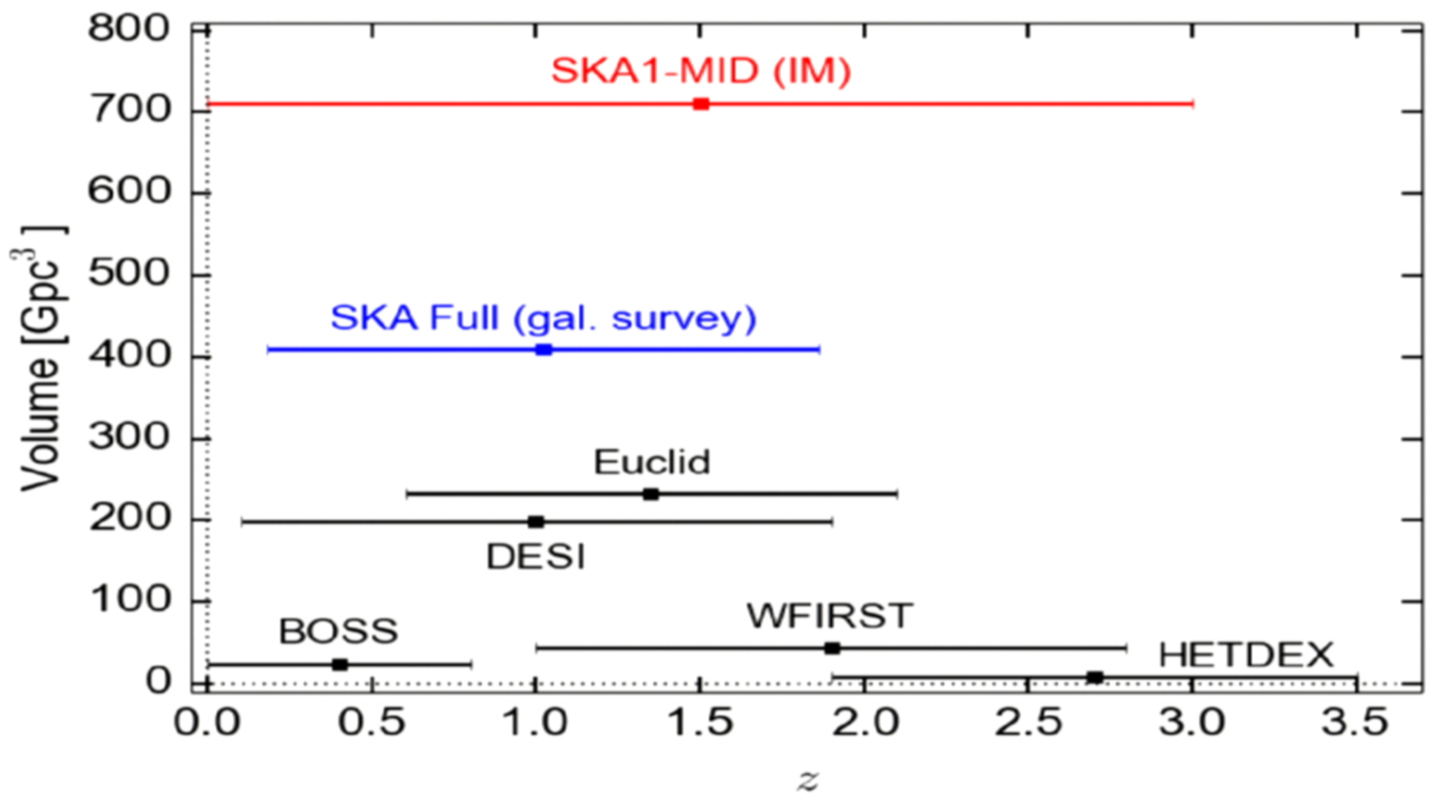
8,500 sq. deg.

0.43 < z < 0.70

6 cubic Gpc

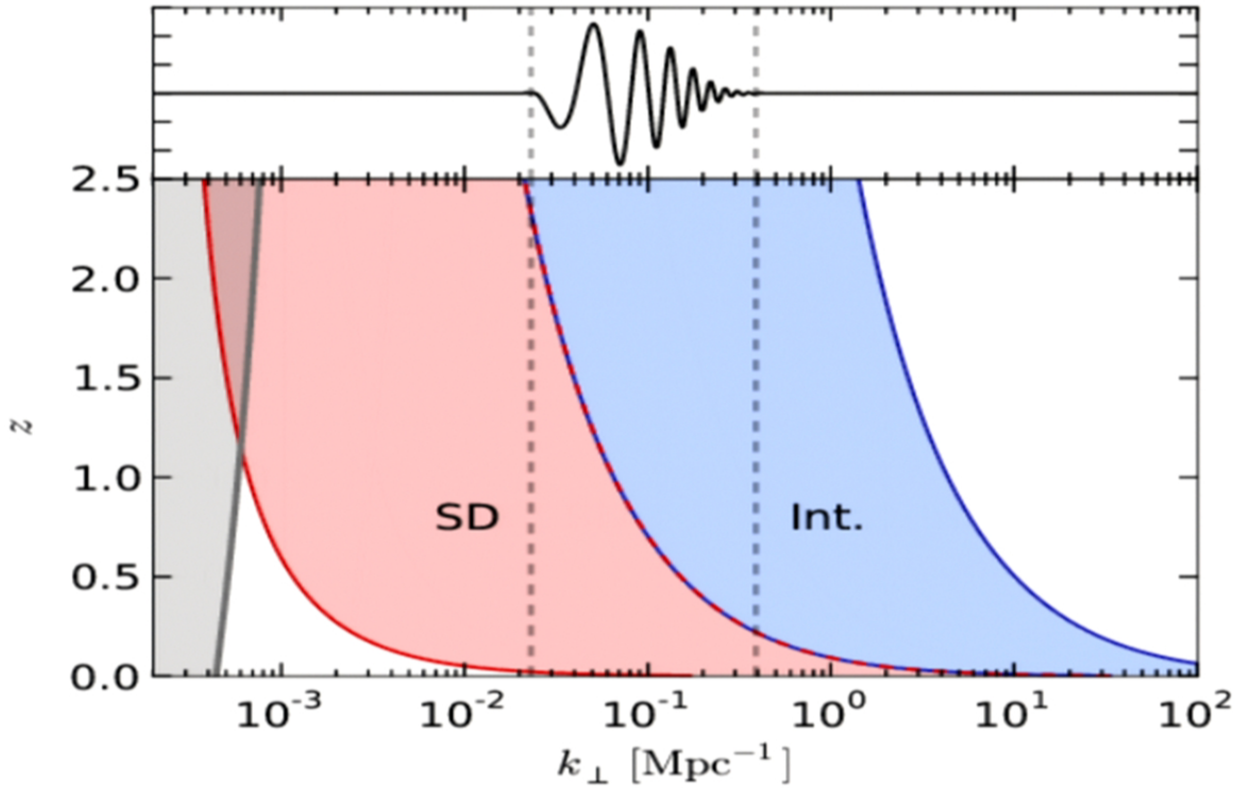
H. Gil-Marin et al. (2014)

Survey volumes



Accessing ULS with SKA-IM

15m dishes, 25,000 sq. deg survey



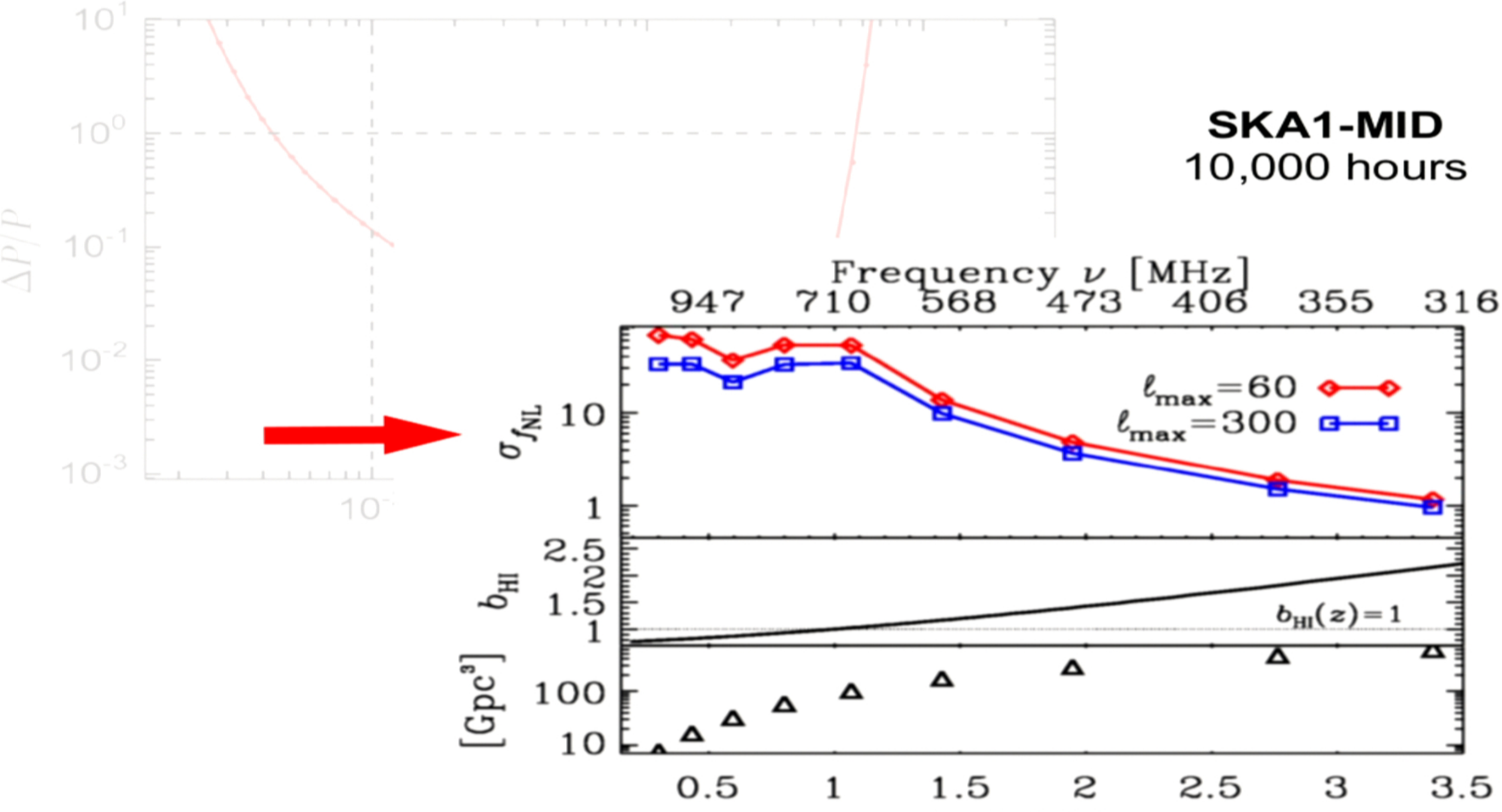
Interferometer vs. dish survey

SKA **dish survey** much more sensitive to BAO at lower redshift / ULS at higher redshift

- ✔ Good for high-precision dark energy measurements
- ✔ Easier to process images – no missing baselines
- ✔ Can access extremely large scales → new physics

- ✗ Difficult systematics; correlated noise causes striping
- ✗ Need very careful calibration

SKA1-MID
10,000 hours

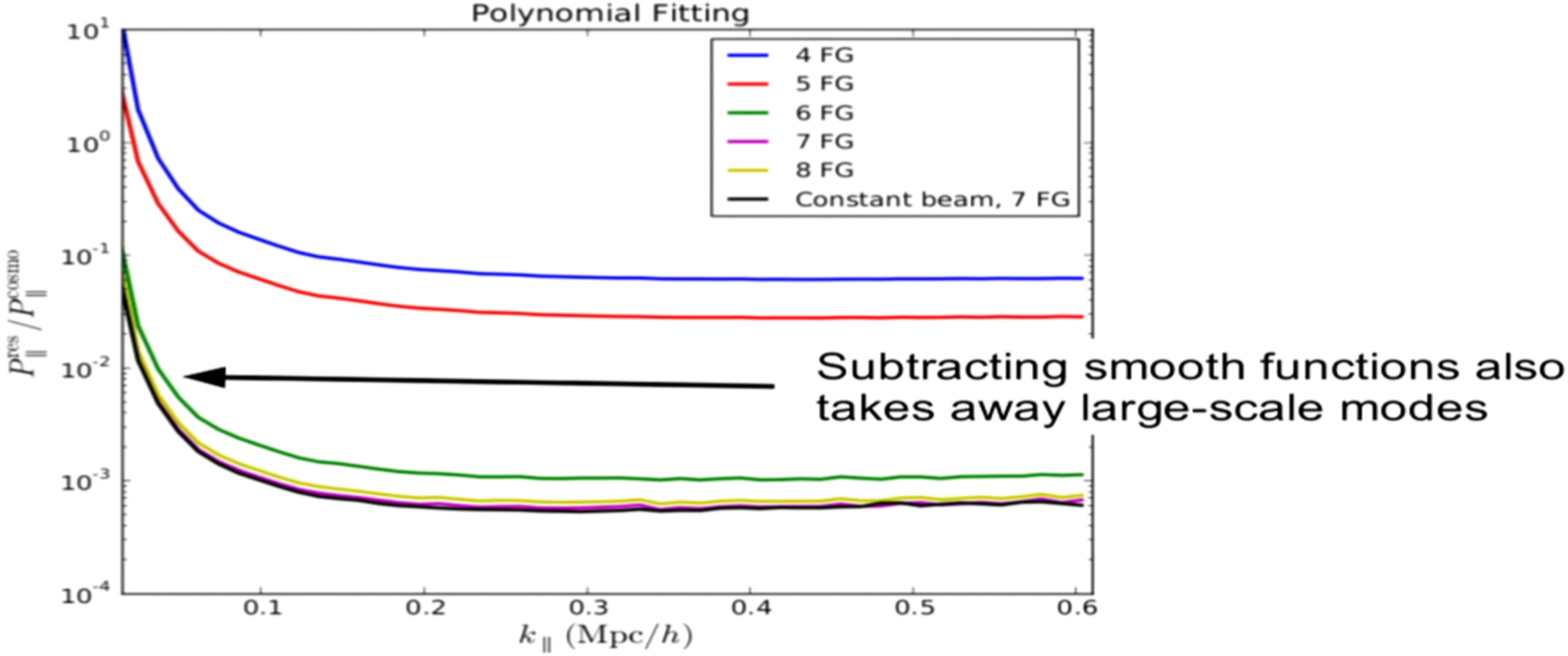


Camera et al. (2014)

Foreground contamination

Total foreground is ~10^5 times larger than cosmo signal

But: spectrally smooth, so subtraction is possible



Alonso, **PB**, Ferreira, Santos, arXiv:1409.8667

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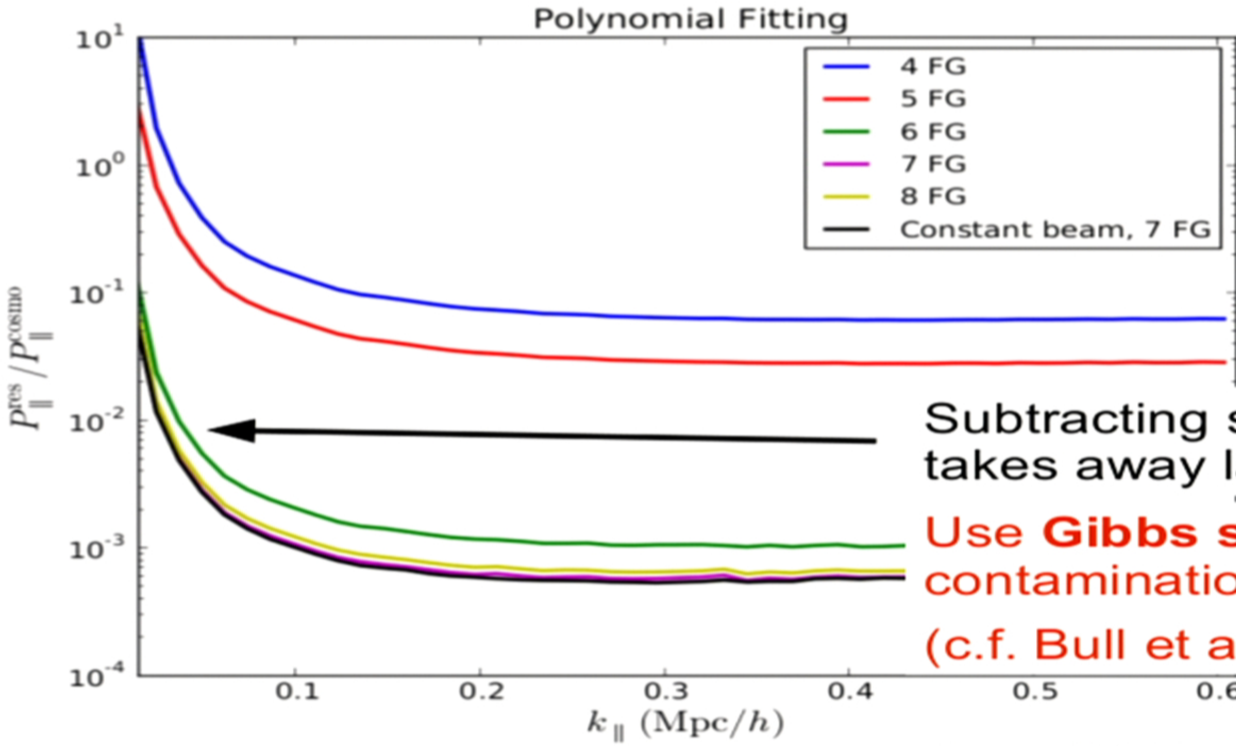


Subtracting smooth functions also takes away large-scale modes

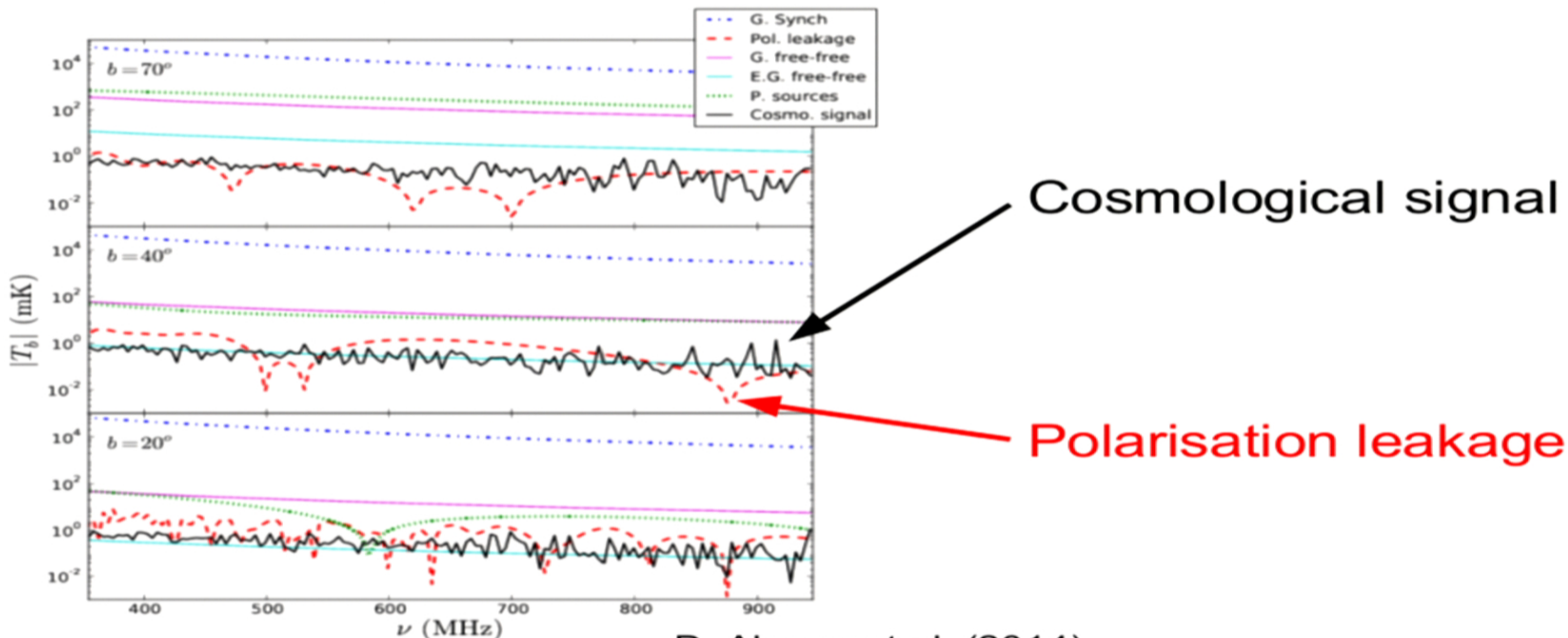
Use **Gibbs sampling** to separate contamination at large scales?

(c.f. Bull et al., arXiv:1410.2544)

Alonso, **PB**, Ferreira, Santos, arXiv:1409.8667

Polarisation leakage

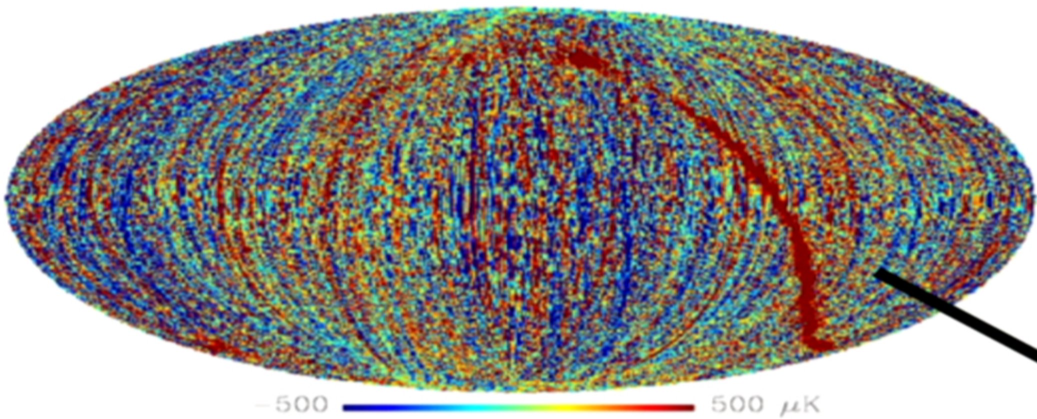
- HI signal is unpolarised, but polarised foregrounds leak into total intensity channel of receivers
- Polarised foregrounds not smooth due to Faraday rotation



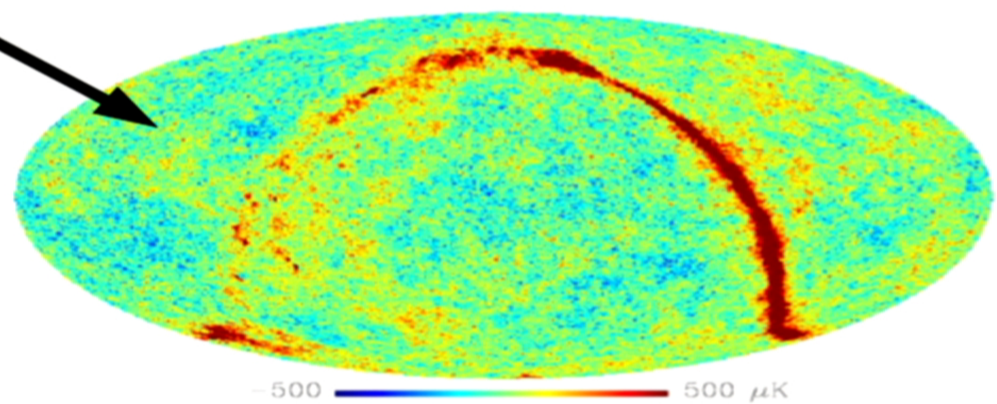
D. Alonso et al. (2014)

Autocorrelation

- Autocorrelation suffers from correlated noise → striping
- Need to scan quickly or have very stable receivers, or lose large-scale modes



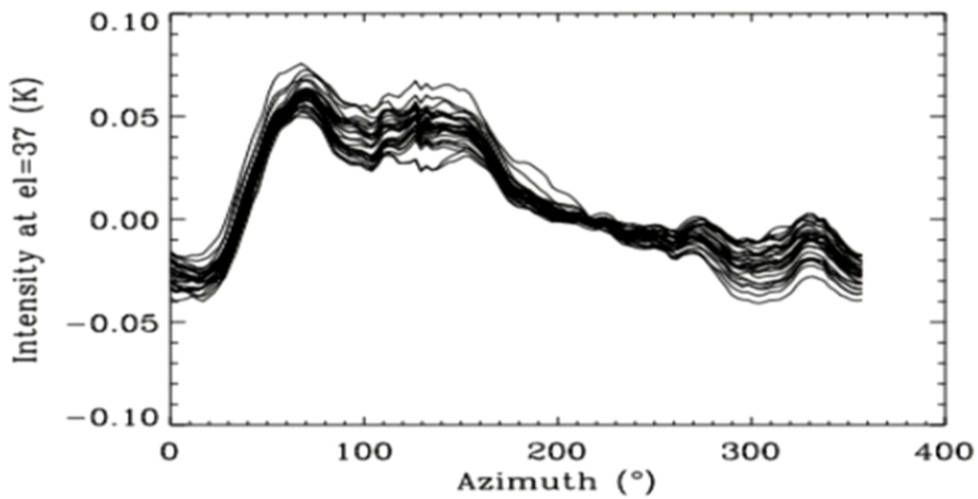
(Well-known problem in CMB experiments)



E. Keihanen et al. (2010)

Ground pickup / spillover

Autocorrelation sensitive to contamination from ground (with smooth variation in angle)



C-BASS
(5 GHz)

M. Irfan (Masters thesis)

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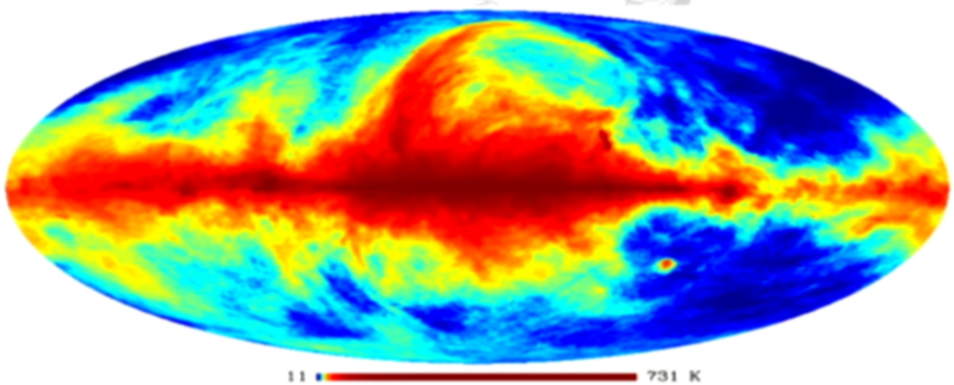
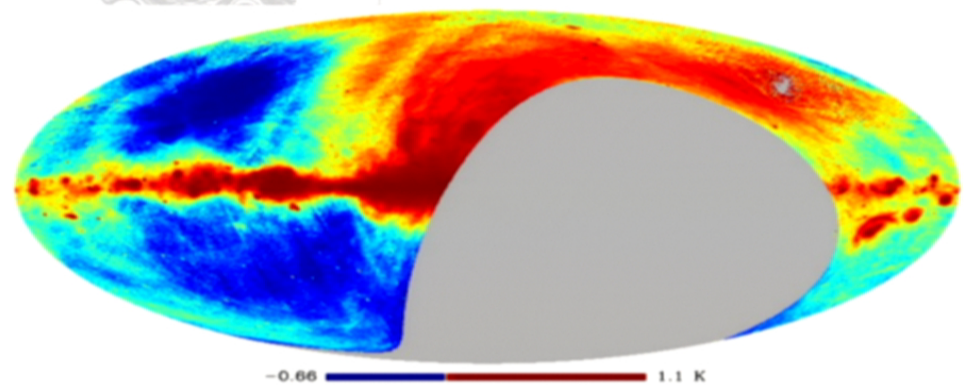


Haslam (408 MHz)



C-BASS (5 GHz)

Test surveys

- Currently analysing ~100 hour autocorrelation "test" survey on KAT7 (with R. Armstrong, M. Santos, UWC)
- BINGO will also use an autocorrelation strategy

SKA-ZA

Summary

Ultra-large scales with 21cm intensity mapping

No need to detect individual galaxies to access large scales
$\longrightarrow$ map the unresolved redshifted HI emission

✔ ULS cleanly probe fundamental physics (gravity, inflation)

✔ IM is a **very fast** way of surveying huge volumes needed

✔ SKA Phase 1 autocorrelation survey makes this possible

✗ IM is a new method; relatively **untested**

✗ Potentially difficult foregrounds/systematics

Primer on intensity mapping: **PB** et al., **arXiv:1405.1452**