Measuring ultra-large scales with radio telescopes

Phil Bull

University of Oslo

Outline

1) Next-generation radio telescopes

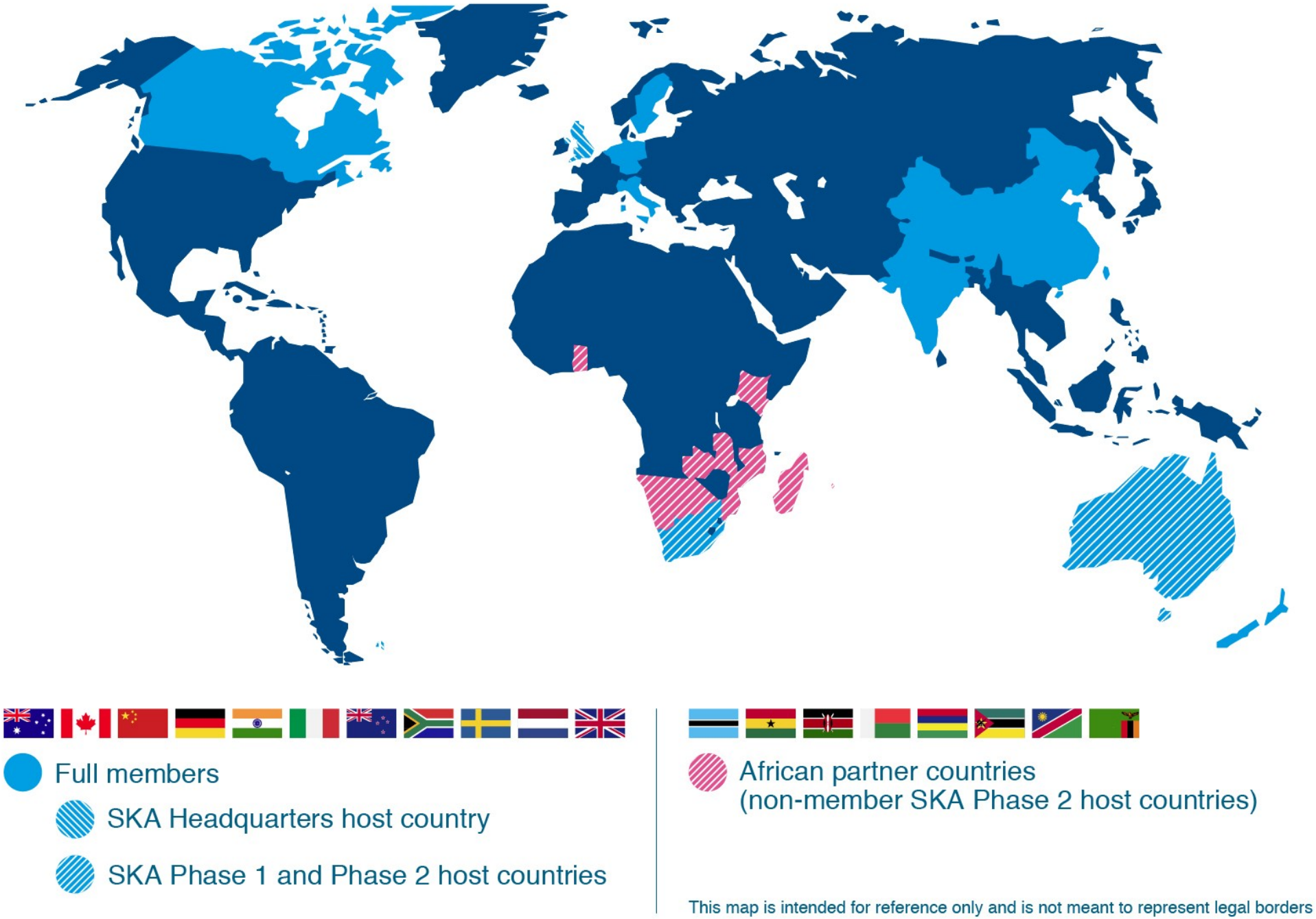
2) Cosmology with radio surveys

3) Physics on ultra-large scales

4) Practicalities of measuring ultra-large scales

SPDO / Swinburne

Square Kilometre Array

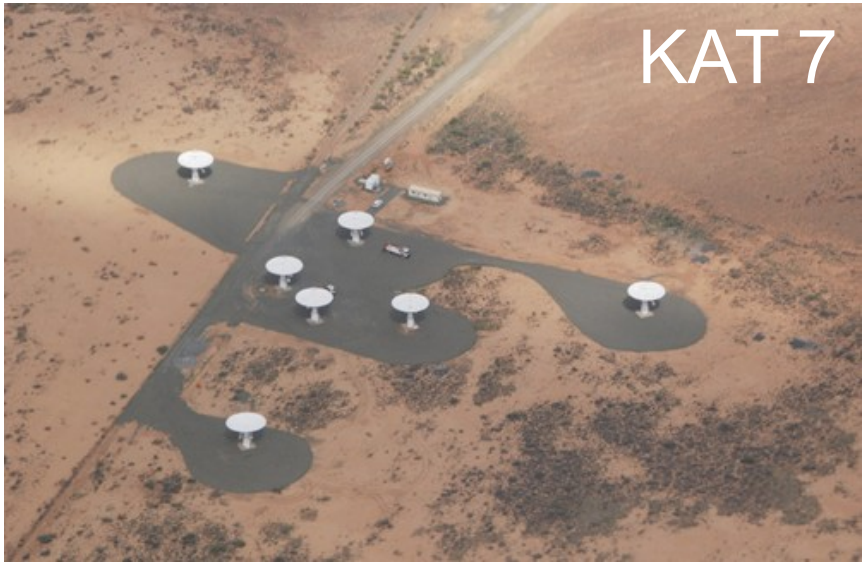


KAT 7

7 x 12m dishes

S. African site

Already producing results (2014)



MeerKAT

64 x 13.5m dishes

Choice of two bands for HI

S. African site (due 2017)

ASKAP

36 x 12m dishes

36-element multi-pixel feeds

W. Australia (completed 2012)

Low-freq. aperture array

Very cheap, large field of view

Electronic beam forming

SKA1-LOW (2020)

Dish arrays

~96-250 steerable dishes

Interferometer with dense core

Baselines from 20m – 100km+

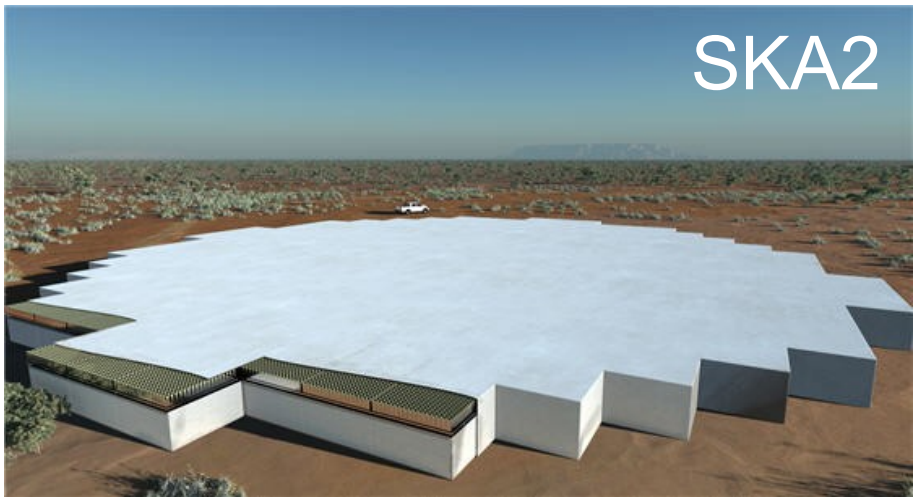
SKA1-MID, SKA1-SUR (2020)

Mid-freq. aperture array

Cheap, large field of view

Electronic beam forming

SKA Phase 2 (2025)



CHIME

Five 20 x 80m cylinders

GPU correlation (1280x recv.)

Site in British Columbia

Pathfinder up and running (2013)

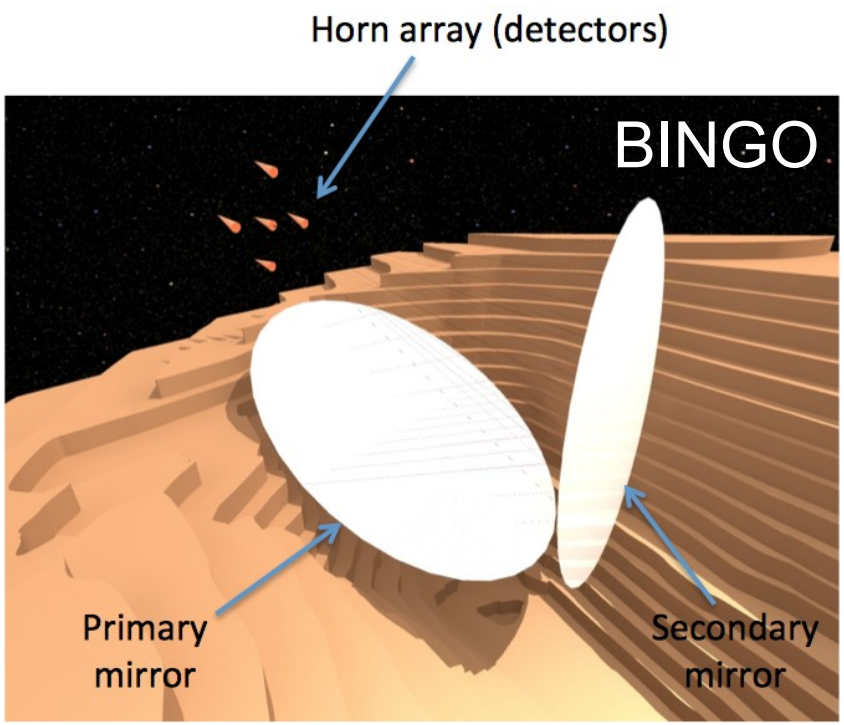
K. Vanderlinde

BINGO

~40m dual reflector system

50x autocorrelation receivers

UK-based, site in Uruguay/Brazil



Others

FAST (China)

HIRAX (S. Africa)

LOFAR (Netherlands)

TIANLAI (China)

The future of radio cosmology

Big surveys...

- Large instantaneous field of view (e.g. multiple beams)
- Large collecting area (many dishes/aperture array tiles)
- Many, many low-noise receivers
- Wide instantaneous bandwidth (100's of MHz)

The future of radio cosmology

Big surveys...

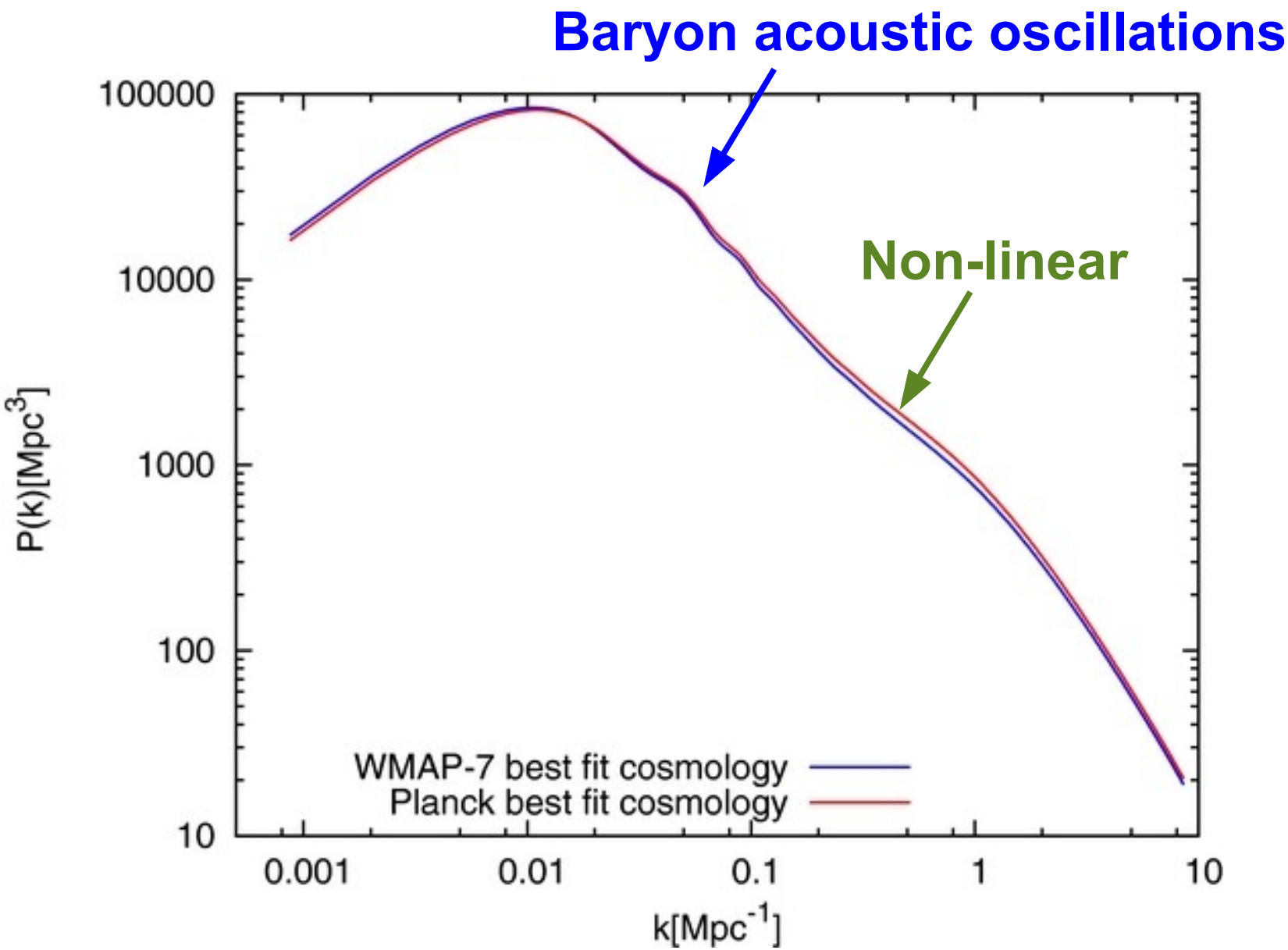
- Large instantaneous field of view (e.g. multiple beams)
- Large collecting area (many dishes/aperture array tiles)
- Many, many low-noise receivers
- Wide instantaneous bandwidth (100's of MHz)

...and big problems

- Need very (read:impossibly) high performance computing:
  - High sample rates, narrow channels → very high data rates
  - Massive cross-correlation
  - On-the-fly calibration (can't store all the data)
- Frequency-dependent beams, gigantic foregrounds, polarisation leakage...

Cosmology with radio surveys

Matter power spectrum



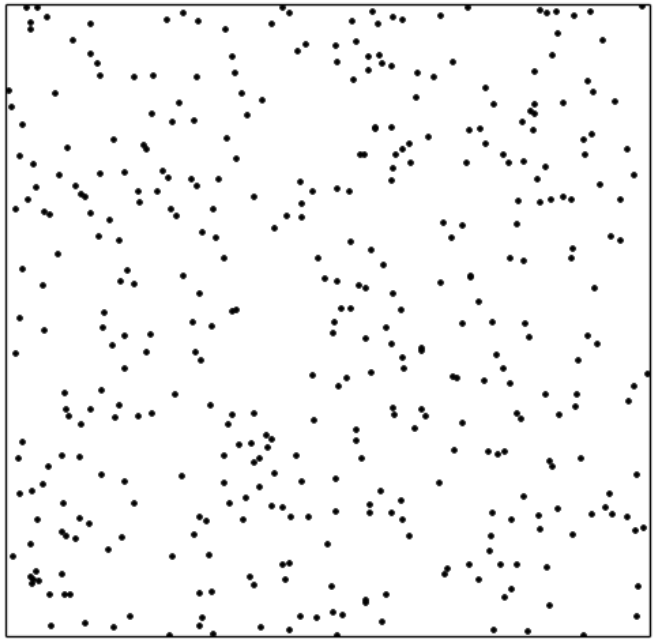
K. Heitmann et al. (2014)

LSS with radio surveys

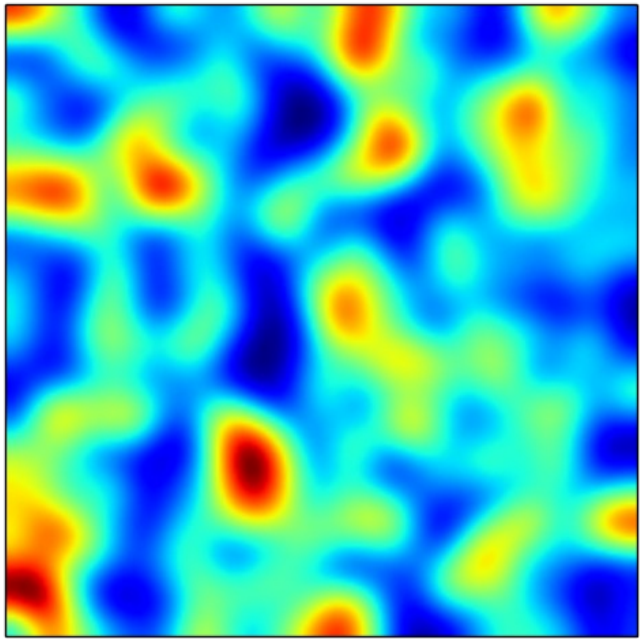
Neutral hydrogen is an excellent tracer of large-scale structure

- HI is ubiquitous in the Universe
- Very narrow emission line at 21cm → get redshifts

Galaxy counts + redshifts



HI brightness fluctuations



Galaxy redshift surveys

Large FOV, many intermediate baselines → high survey speed

BOSS (2014)	~ 1.5 million galaxies
	8,500 sq. deg. ($z < 0.7$)
SKA 1 (~2022)	~ 5 million galaxies
	5,000 sq. deg. ($z < 0.4$)

Galaxy redshift surveys

Large FOV, many intermediate baselines → high survey speed

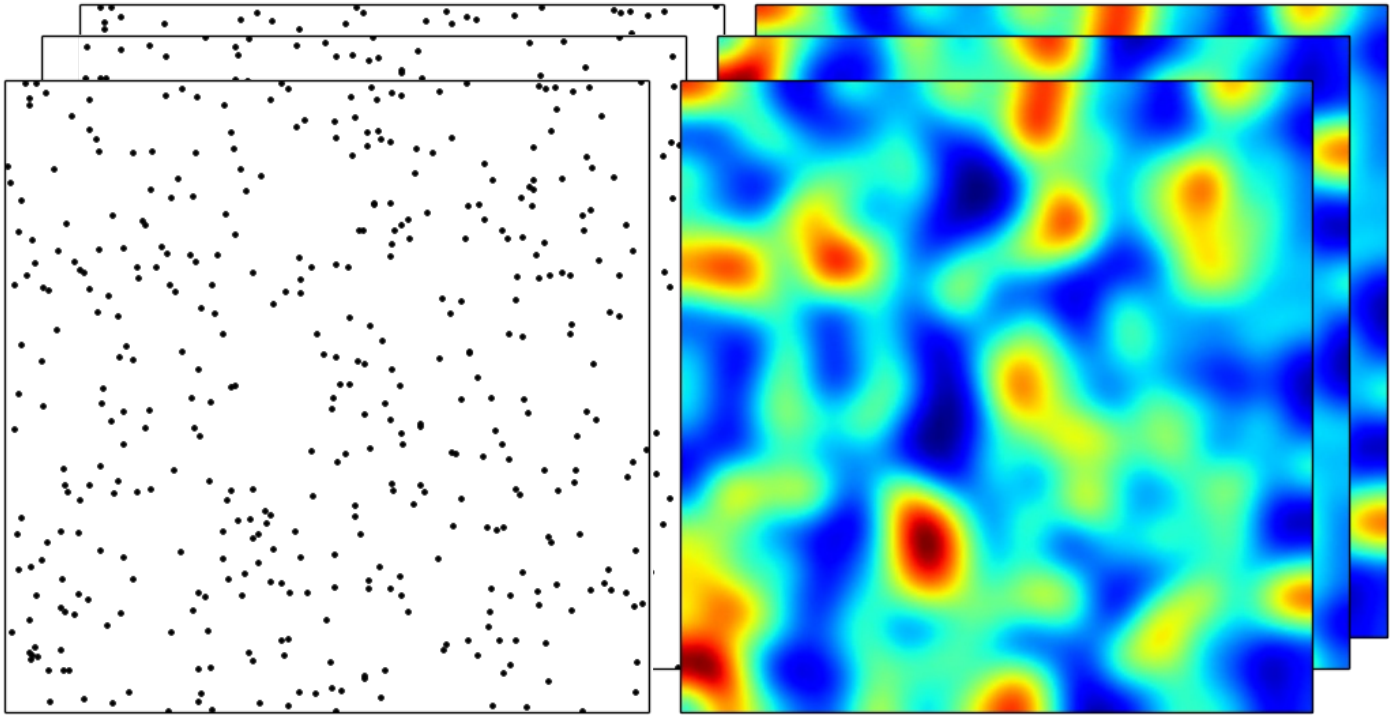
BOSS (2014)	~ 1.5 million galaxies 8,500 sq. deg. ($z < 0.7$)
SKA 1 (~2022)	~ 5 million galaxies 5,000 sq. deg. ($z < 0.4$)
Euclid (~2025)	~ 60 million galaxies 15,000 sq. deg. ($0.7 < z < 2.0$)
SKA 2 (~2027)	**~ 1 billion galaxies** 30,000 sq. deg. ($0.2 < z < 1.7$)

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

→ **Map out emission integrated over many galaxies**



Why intensity mapping?

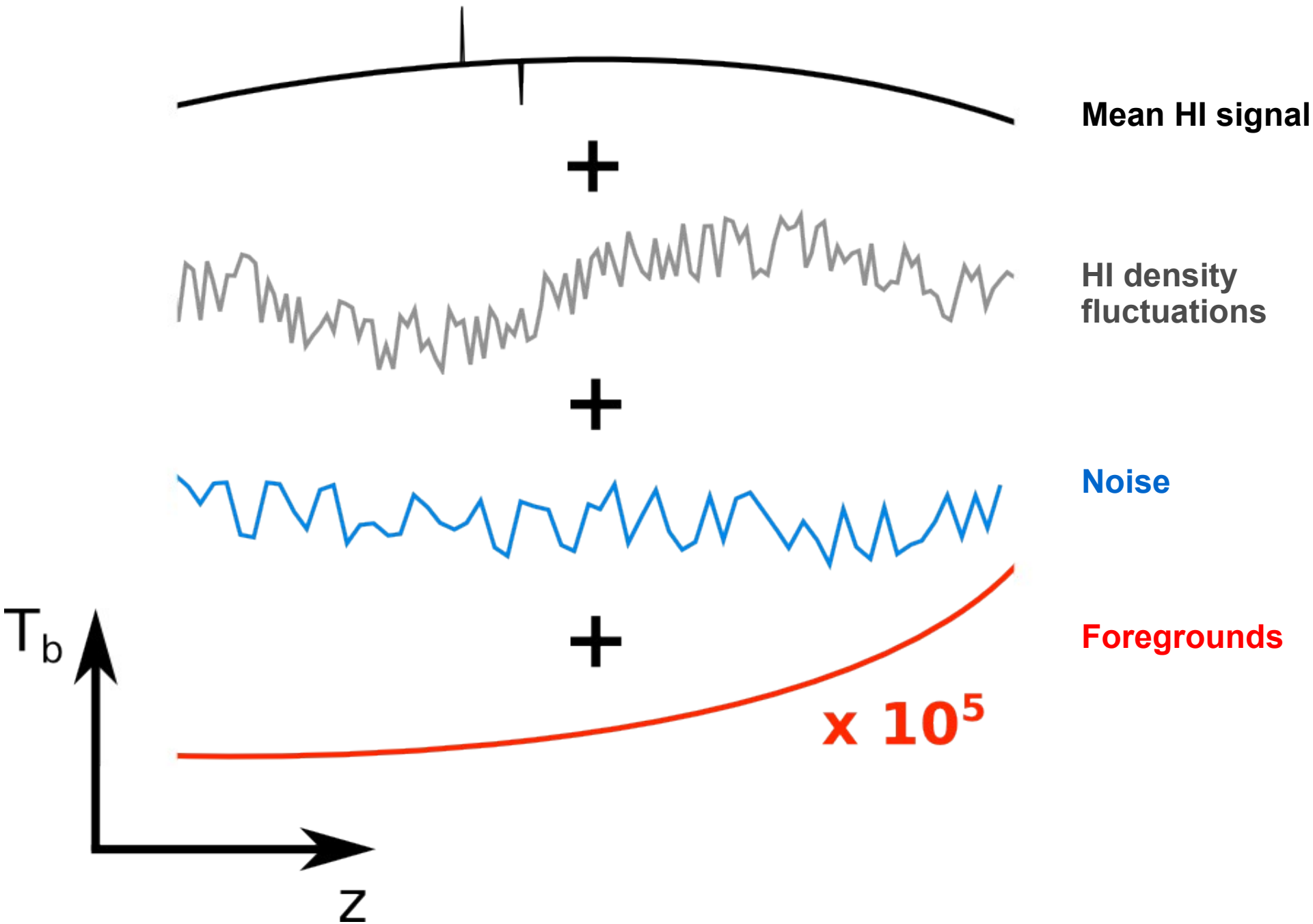
Why detect individual galaxies?

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

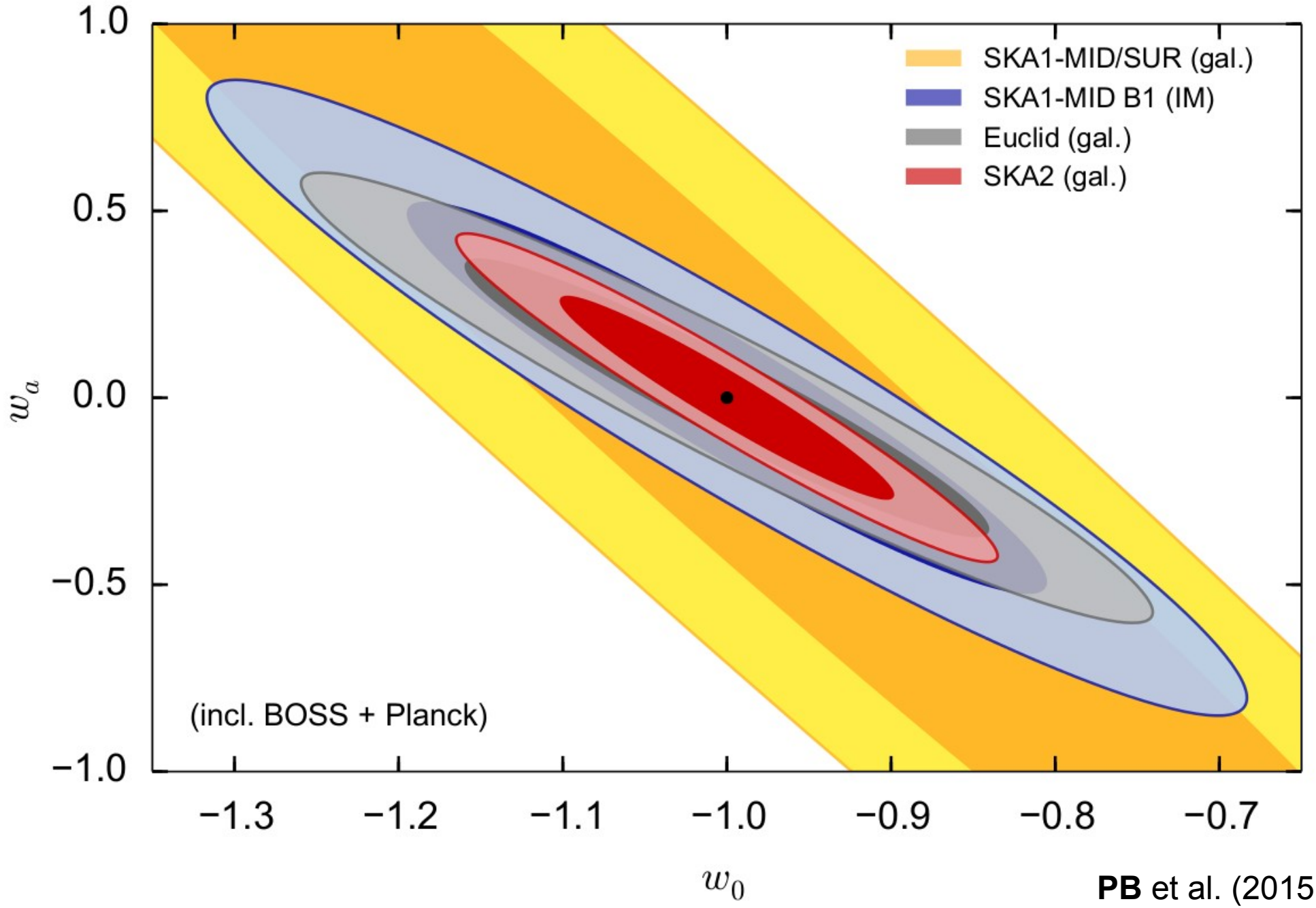
→ **Map out emission integrated over many galaxies**

21cm intensity maps

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

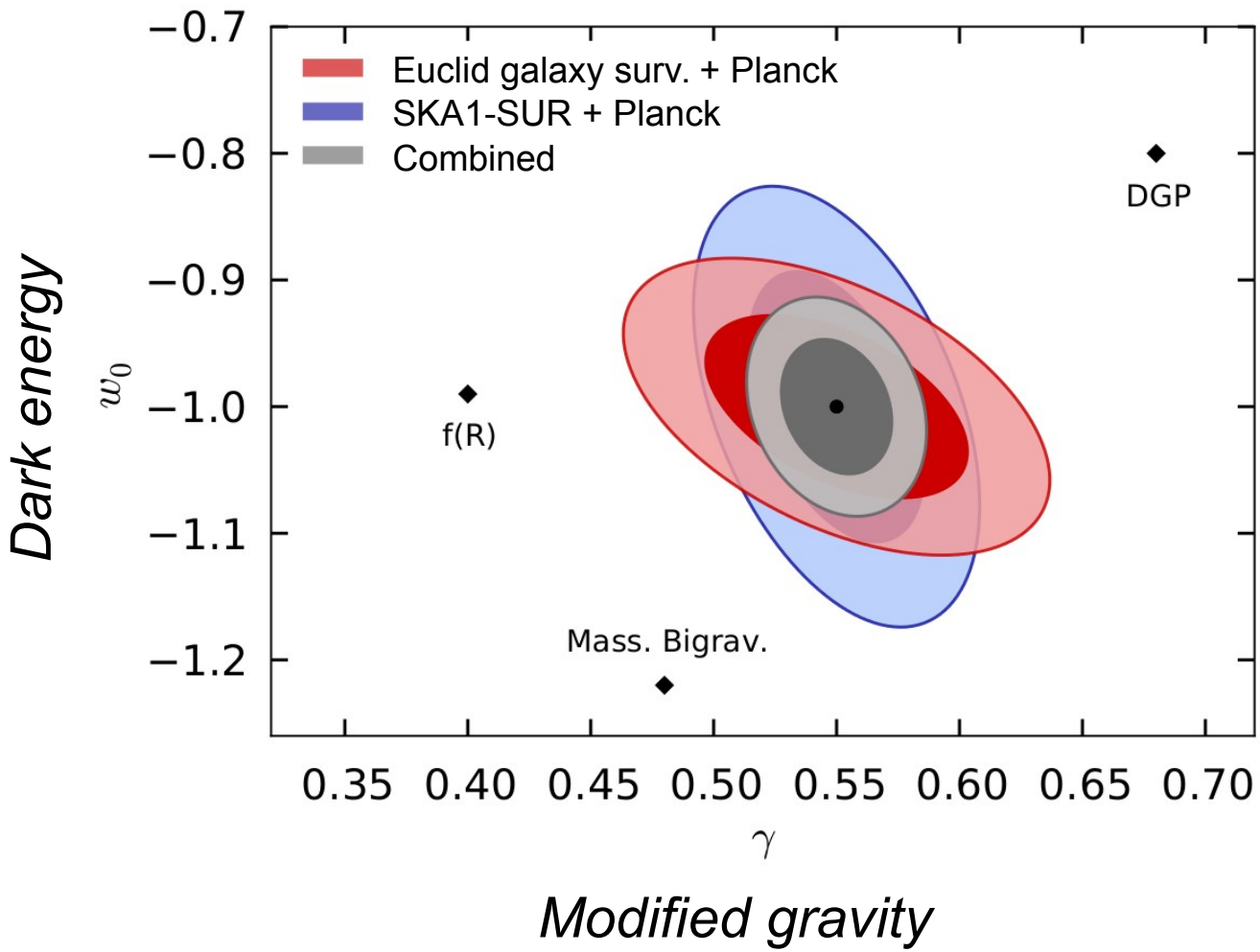

Mean HI signal
+
HI density fluctuations
+
Noise
+
Foregrounds
x 10^5
T_b
z

Dark Energy



PB et al. (2015)

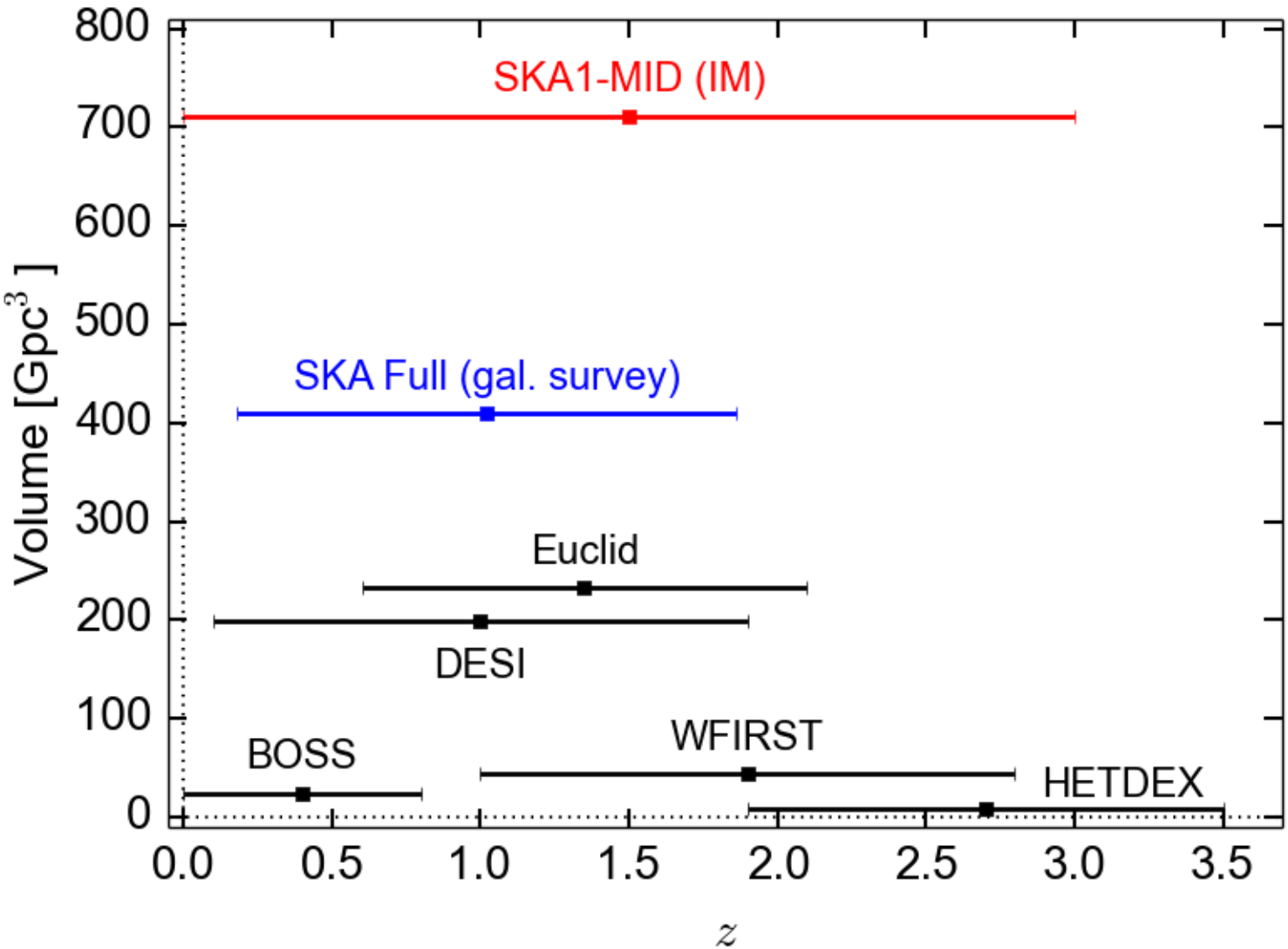
Modified gravity



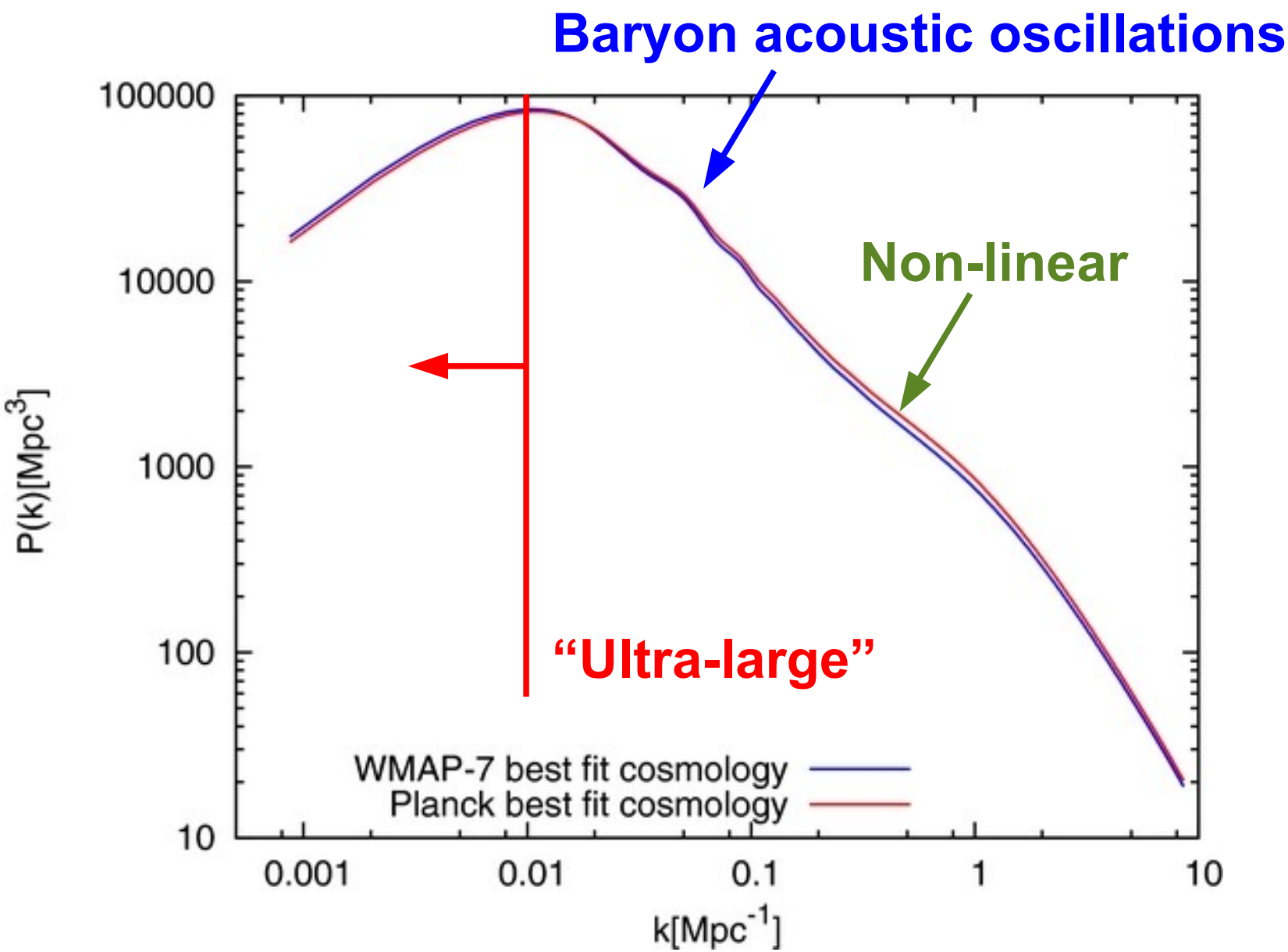
PB, Ferreira, Patel & Santos (2014)

Ultra-Large Scales

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

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
- **Surprises?**

Guinness World Records

Large-scale corrections

GR corrections become important at ultra-large scales

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

Large-scale corrections

GR corrections become important at ultra-large scales

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

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

Bonvin & Durrer (2011)

Hall, Bonvin, Challinor (2013)

Large-scale corrections

GR corrections become important at ultra-large scales

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

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

Bonvin & Durrer (2011)

Hall, Bonvin, Challinor (2013)

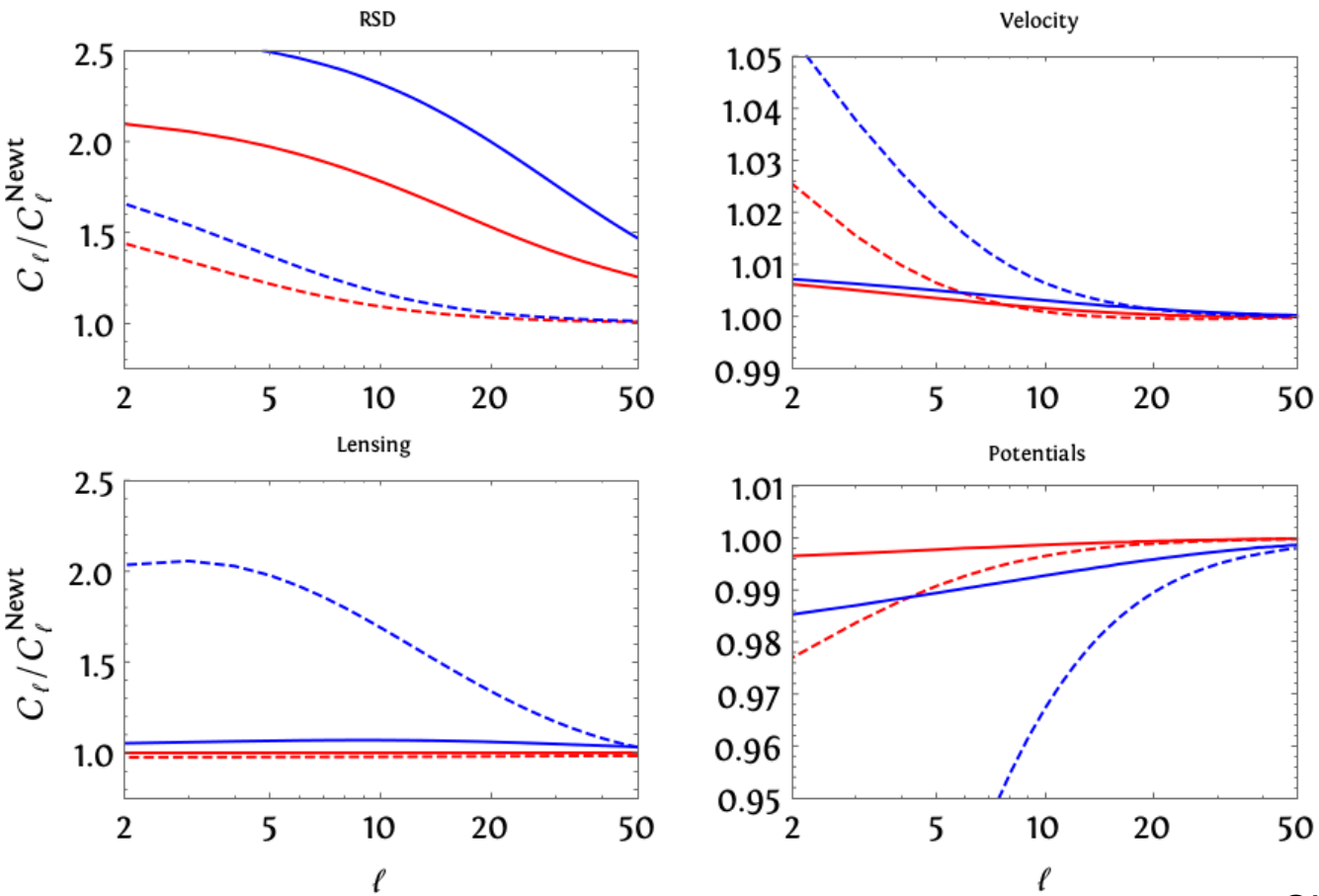
Intensity mapping: luminosity distance perturbation cancels

$$\Delta_{T_b}(z, \hat{\mathbf{n}}) = \Delta(z, \hat{\mathbf{n}}) - 2\frac{\delta d_L(z, \hat{\mathbf{n}})}{\bar{d}_L(z)}$$

Relativistic effects

GR corrections become important at ultra-large scales

- Newtonian approximation breaks down
- Non-Newtonian effects can be large (lensing, Doppler...)



Red: z ~ 0.5
Blue: z ~ 2.0

Solid: Narrow bin
Dashed: Wide bin

SKA Cosmology SWG

Relativistic effects

GR corrections become important at ultra-large scales

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

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

Relativistic effects

GR corrections become important at ultra-large scales

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

Can see causally-disconnected regions at late times

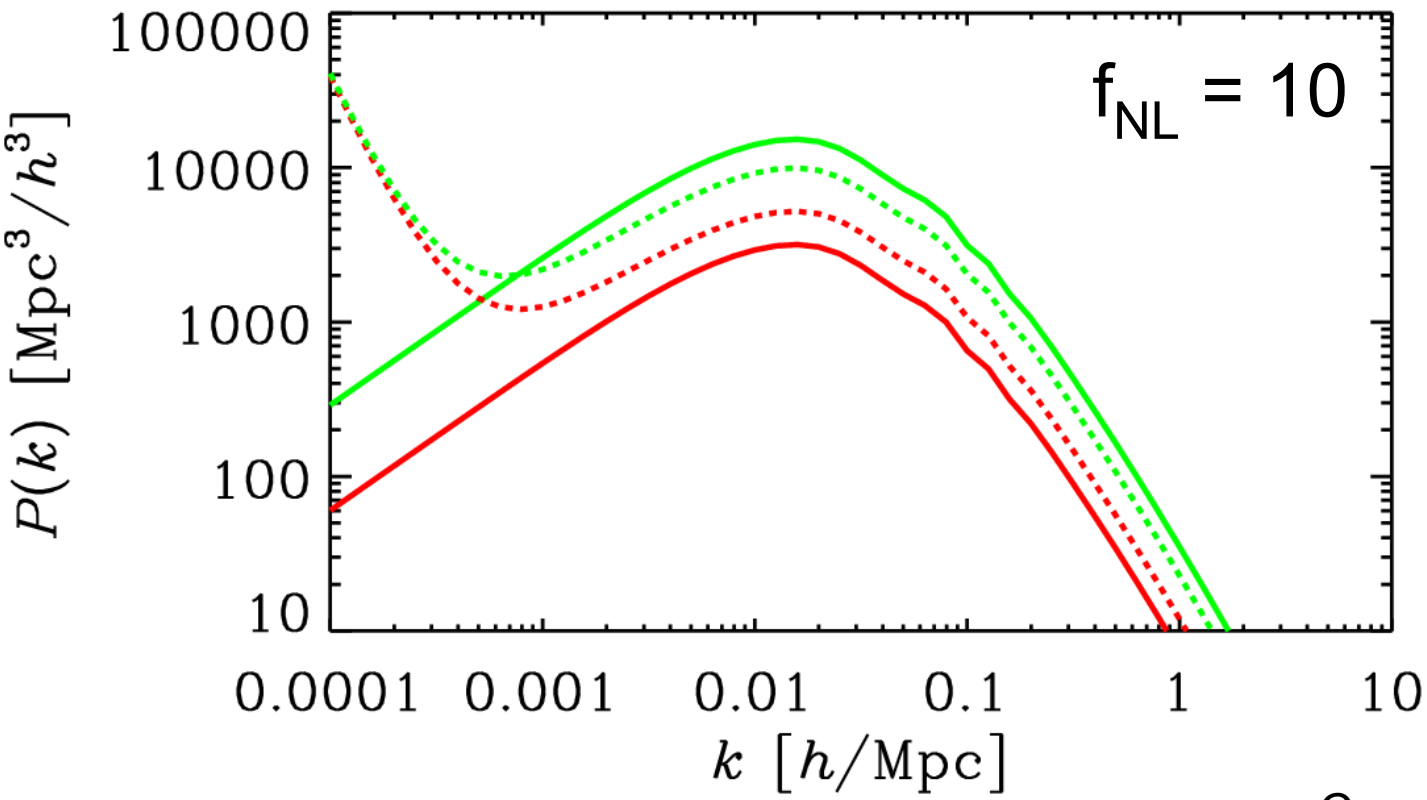
- Distances too large for light to have traversed since the Big Bang
- Consistency test for homogeneity / spatial variations of fundamental constants

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

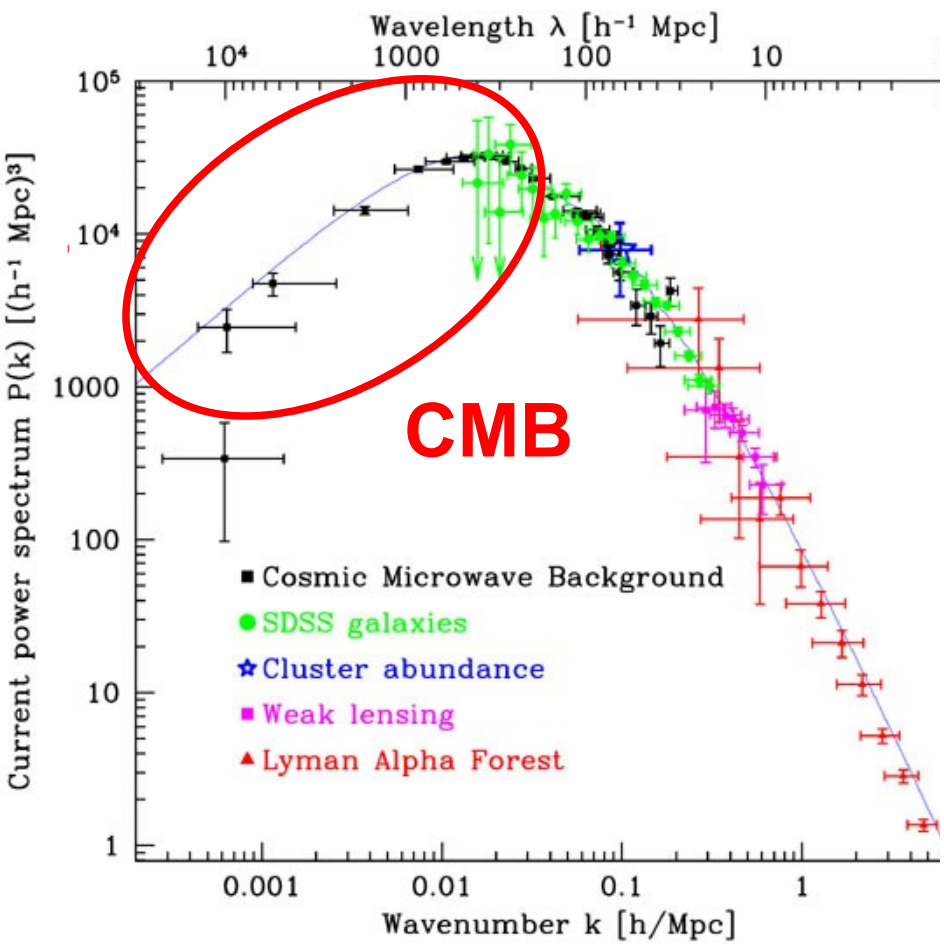
- Non-Gaussianity enhances clustering at ULS
- SKA should be able to measure $\sigma(f_{NL}) < 1$



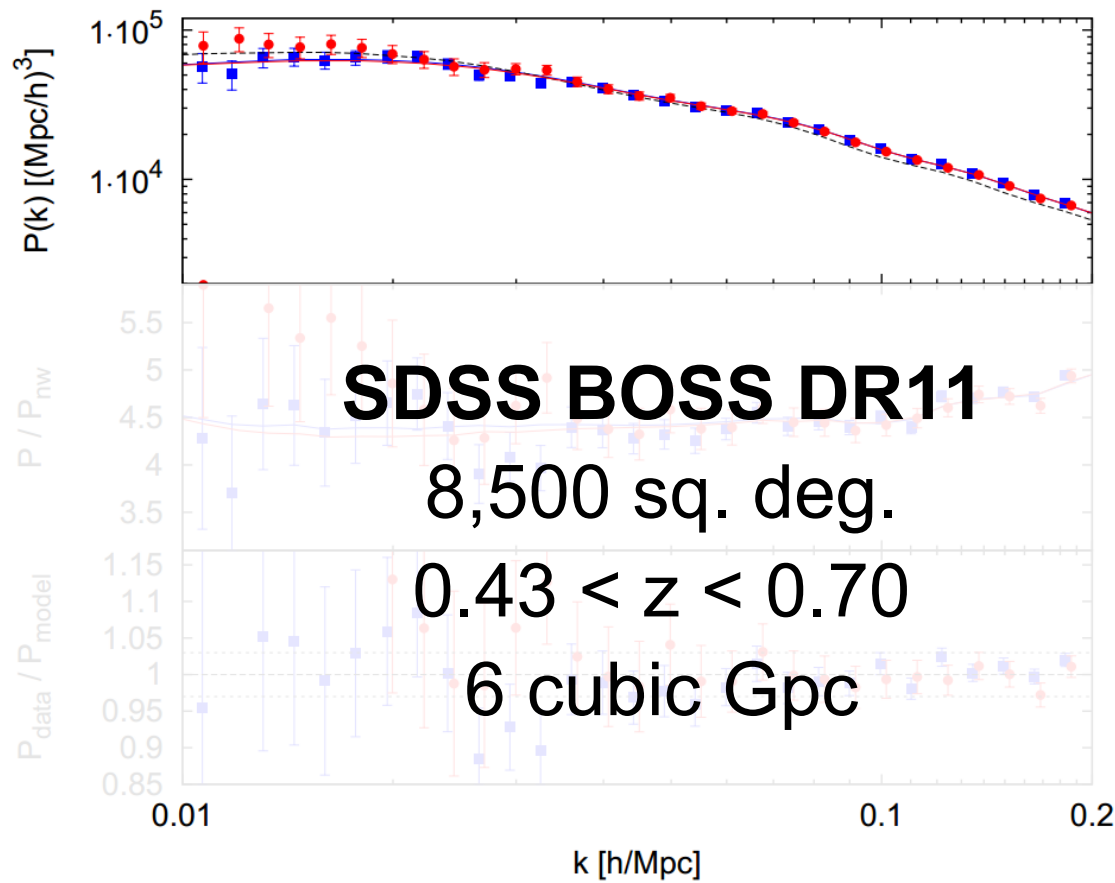
Camera et al. (2013)

Existing constraints

- Haven't ULS been measured already?

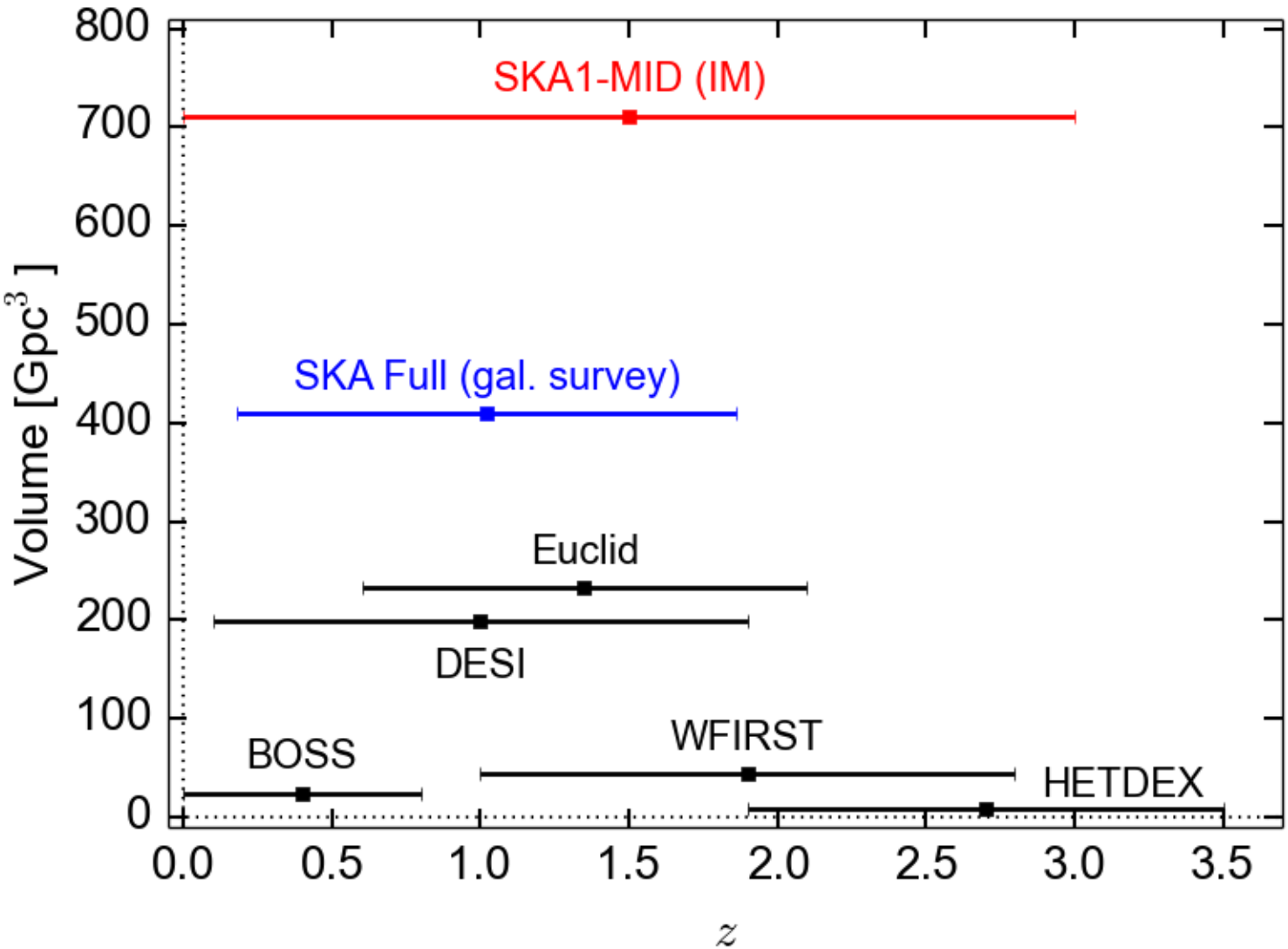


Freedman & Turner (2003)



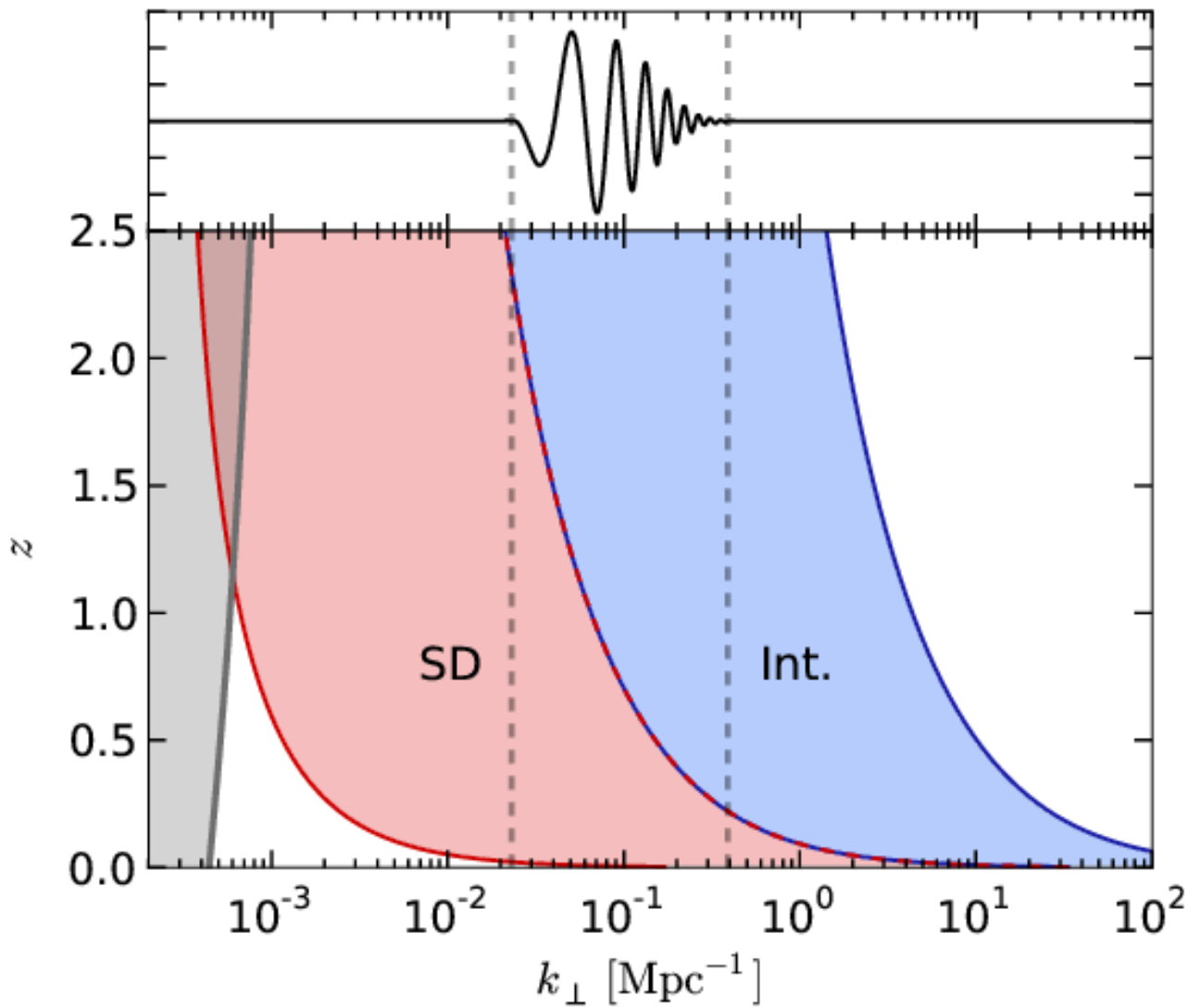
H. Gil-Marin et al. (2014)

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

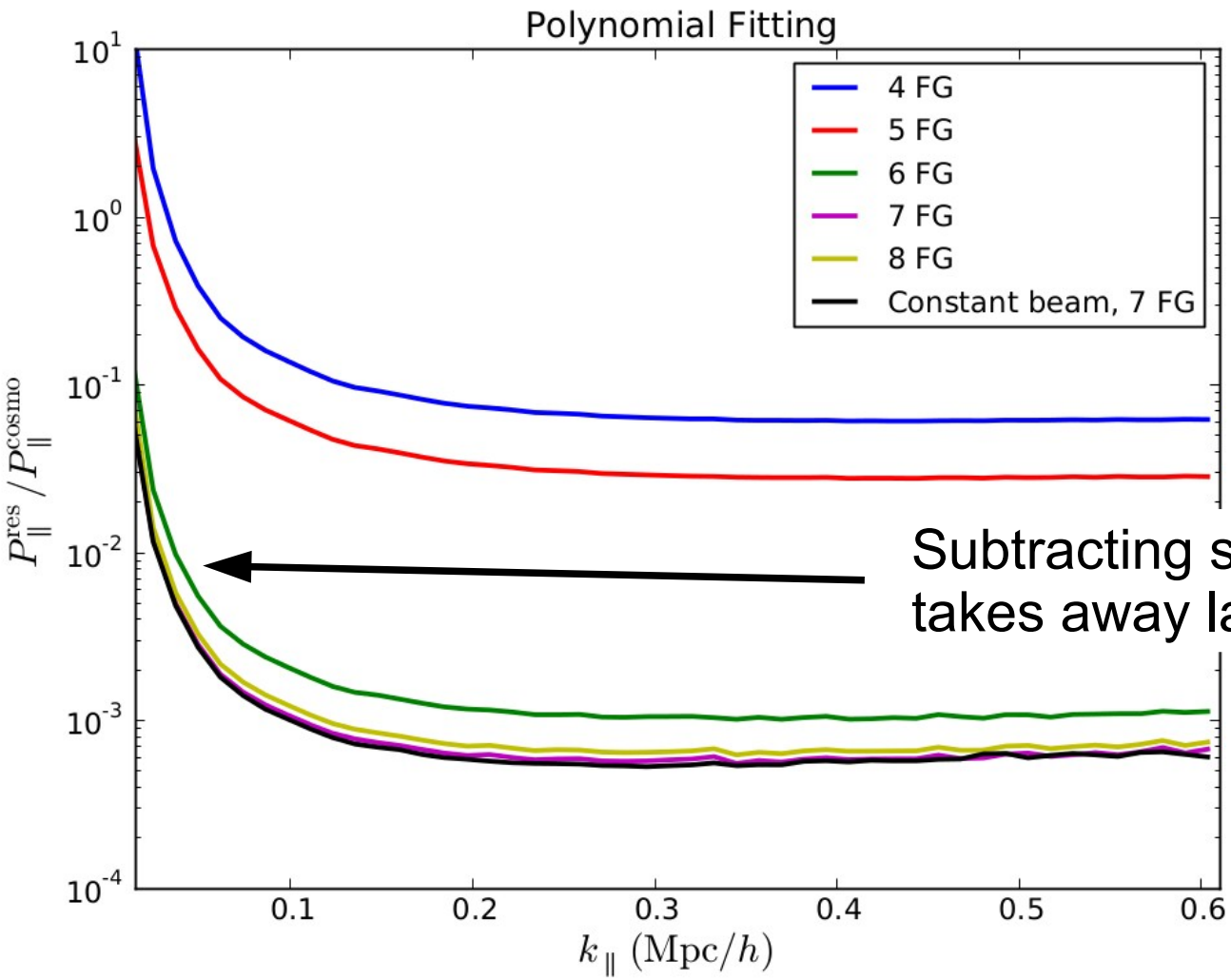
✗ Need very careful calibration

Practicalities

Foreground contamination

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

But: spectrally smooth, so subtraction is possible



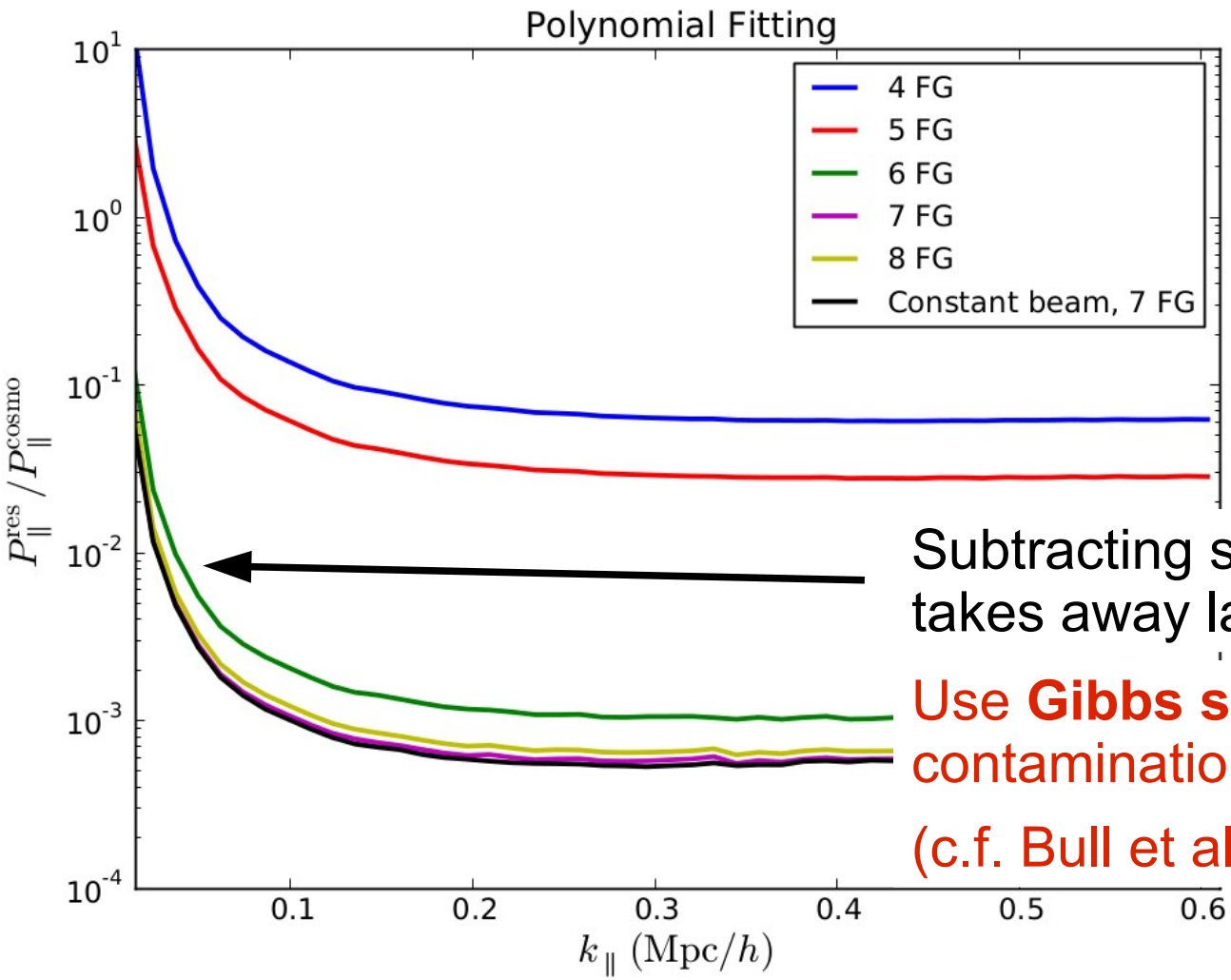
Subtracting smooth functions also takes away large-scale modes

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

Foreground contamination

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

But: spectrally smooth, so subtraction is possible



Subtracting smooth functions also takes away large-scale modes

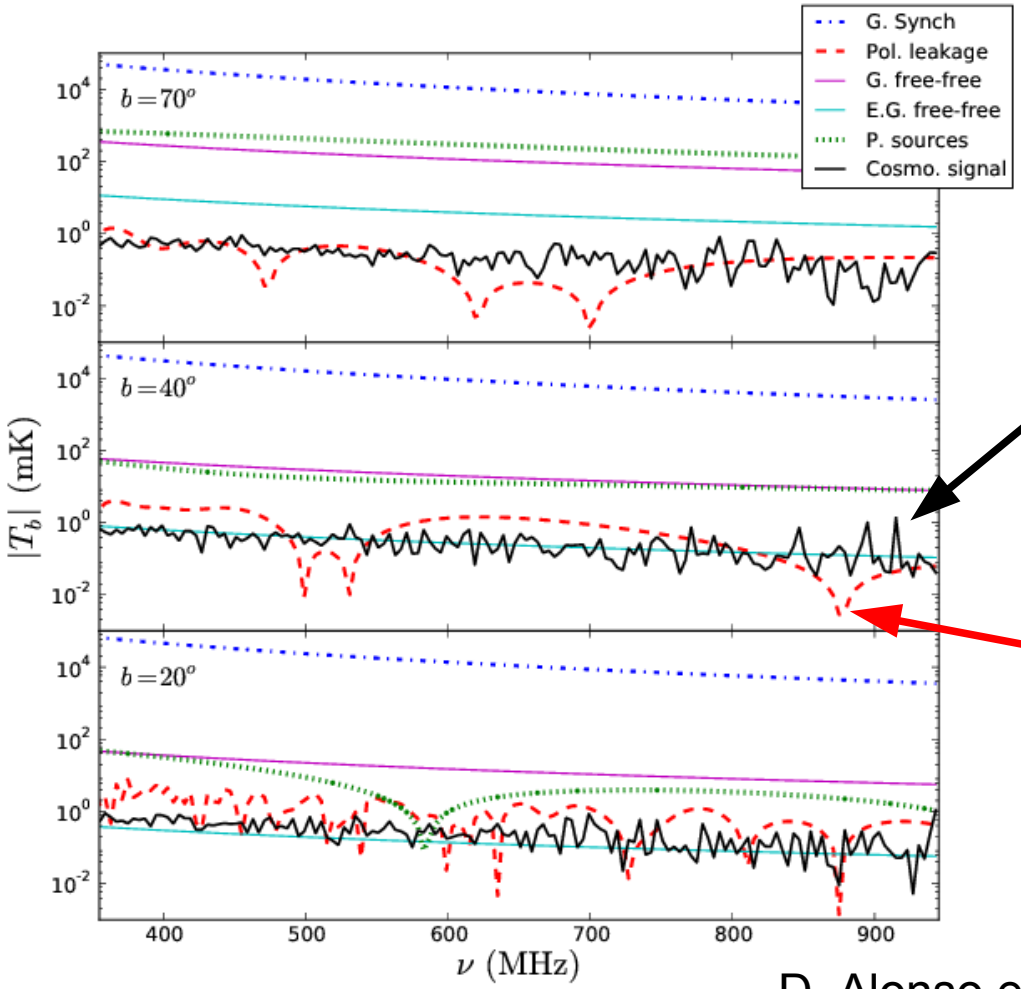
Use **Gibbs sampling** to separate contamination at large scales?

(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



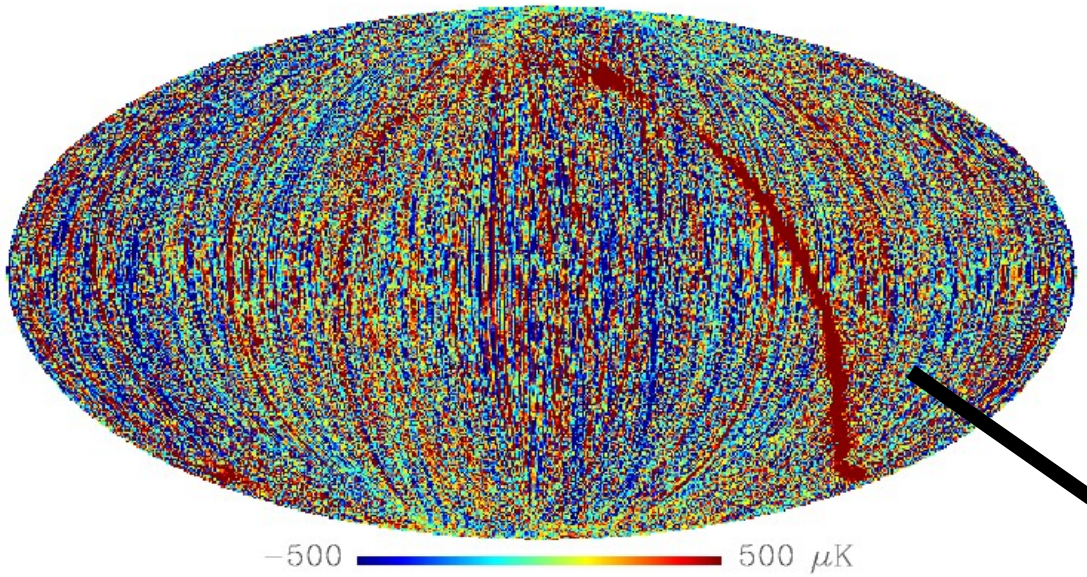
Cosmological signal

Polarisation leakage

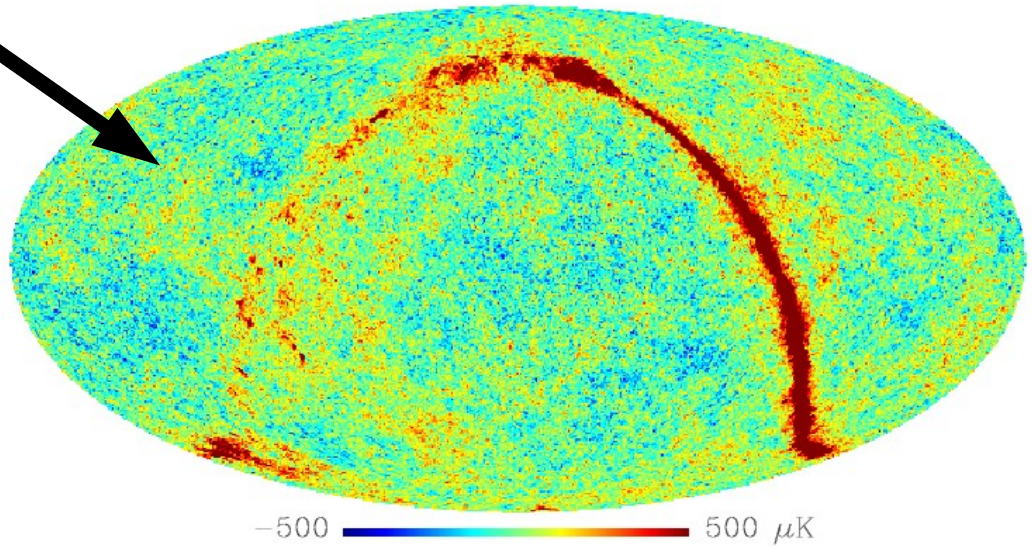
D. Alonso et al. (2014)

Autocorrelation

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



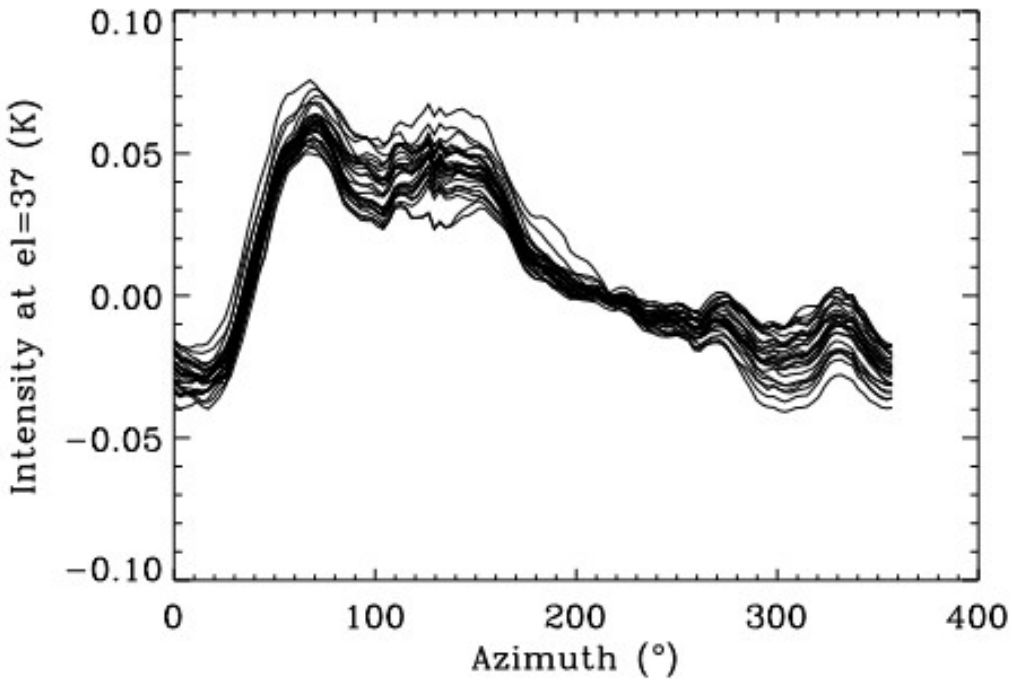
(Well-known problem in CMB experiments)



E. Keihanen et al. (2010)

Ground pickup / spillover

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



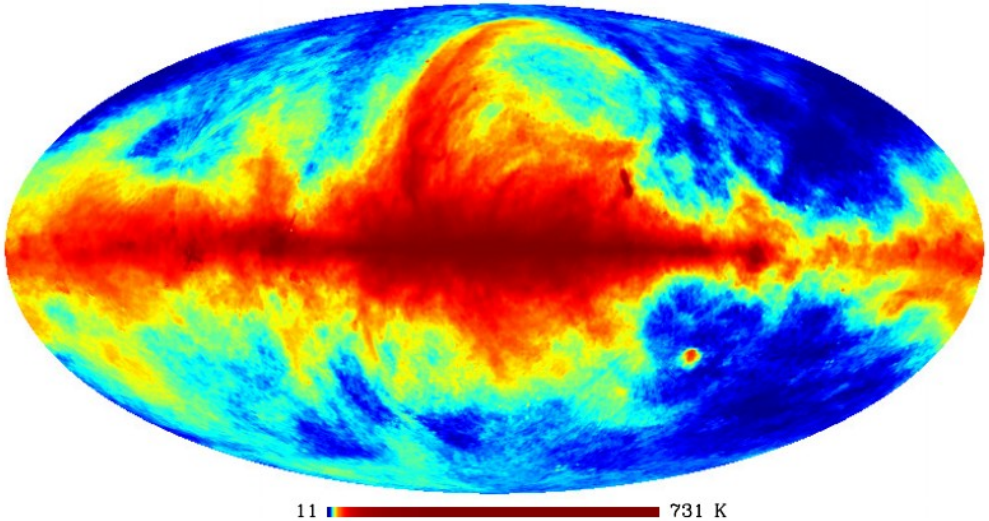
C-BASS
(5 GHz)

M. Irfan (Masters thesis)

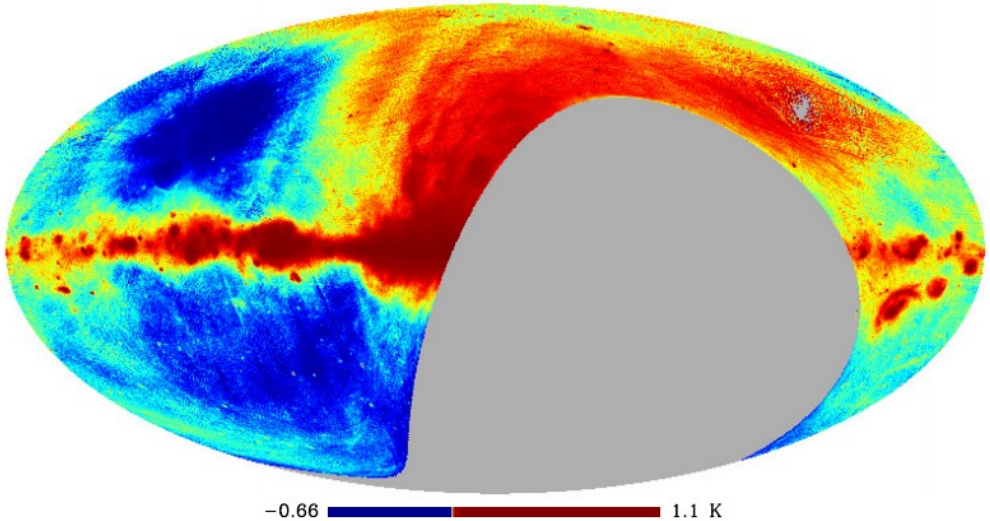
Ground pickup / spillover

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

M. Irfan (Masters thesis)



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
→ 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 IM cosmology: **PB** et al., **arXiv:1405.1452**

[Extra slides]

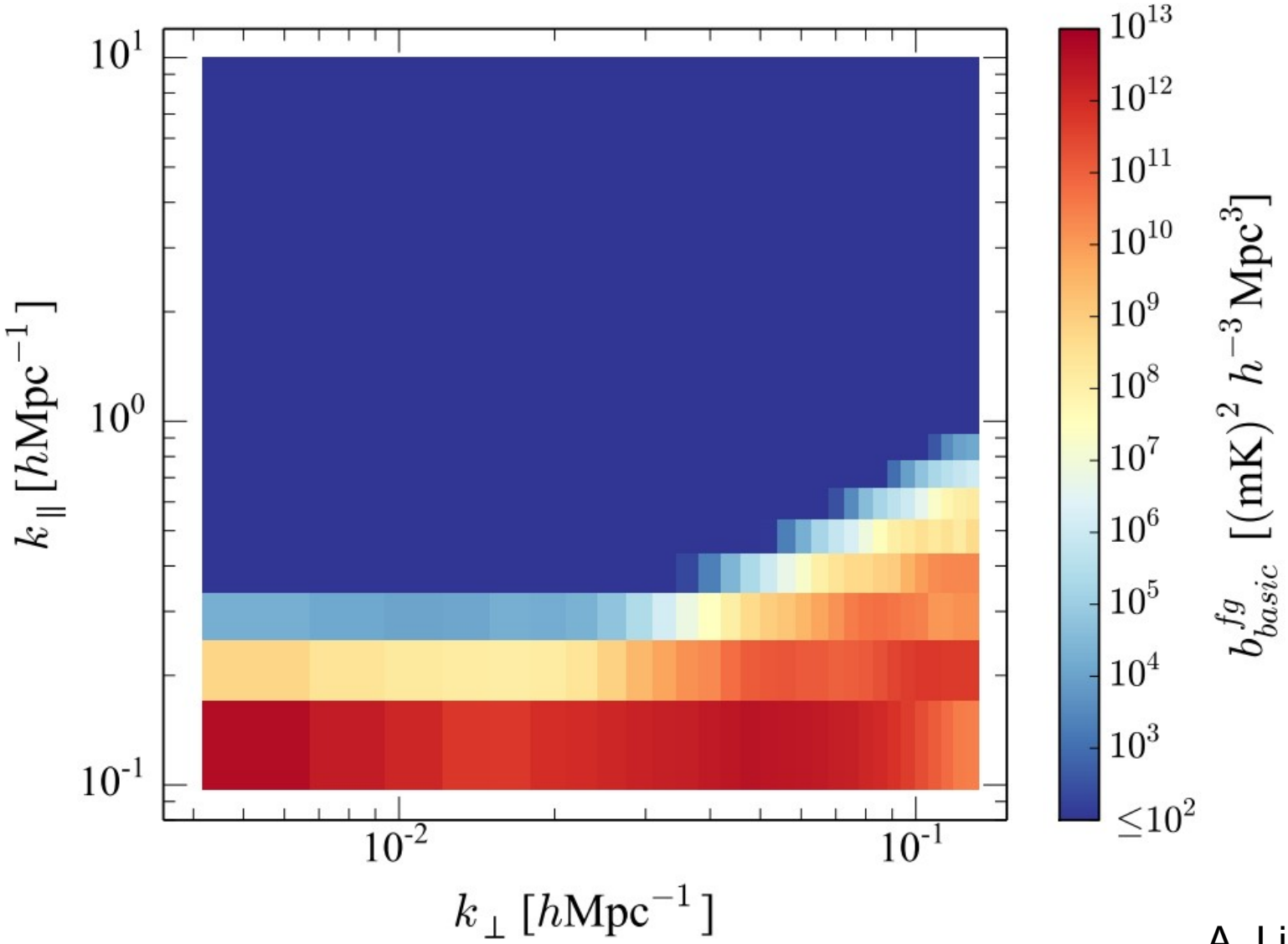
SKA Specifications

	Phase 1 MID		Phase 1 SUR		Phase 2	
	Band 1	Band 2	Band 1	Band 2	Band 1	Band 2
T_{inst} [K]	28	20	50	30	TBC	TBC
z_{min}	0.35	0.00	0.58	0.00	0.35	0.00
z_{max}	3.05	0.49	3.05	1.18	3.05	0.49
ν_{min} [MHz]	350	950	350	650	350	950
ν_{max} [MHz]	1050	1760	900	1670	1050	1760
D_{dish} [m]	15	15	12	12	15	15
$\delta\nu$ [kHz]	50	50	50	50	TBC	TBC
Ω_{sur} [10^3 deg^2]	25	25	25	25	25	25
$N_{\mathrm{dish}} \times N_{\mathrm{beam}}$	254×1	254×1	60×36	60×36	TBC	TBC

Targeting redshifted neutral hydrogen (HI)

Foreground wedge

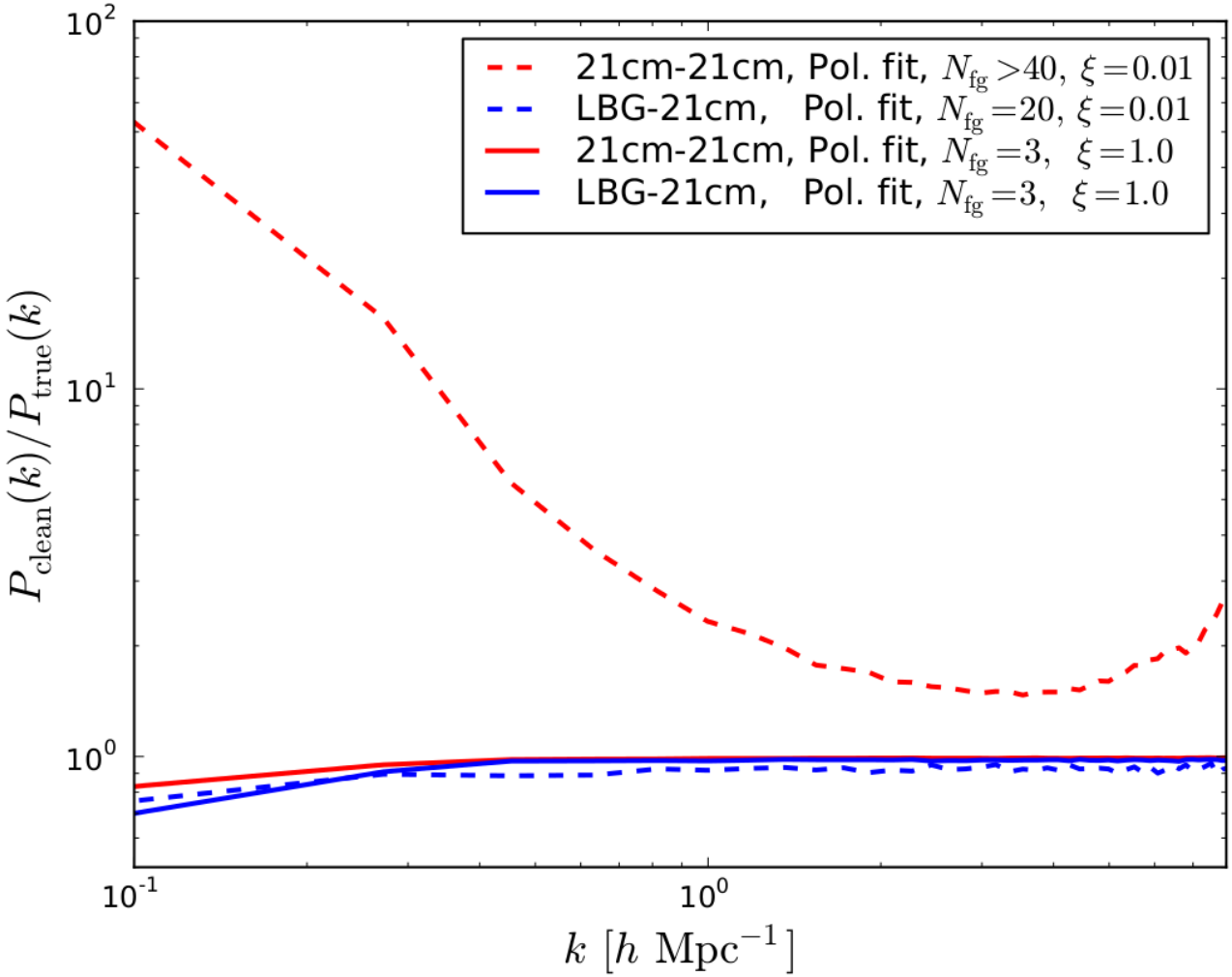
Frequency-dependent beam response couples angular and radial modes
→ foregrounds leak into small angular scales



A. Liu et al. (2014)

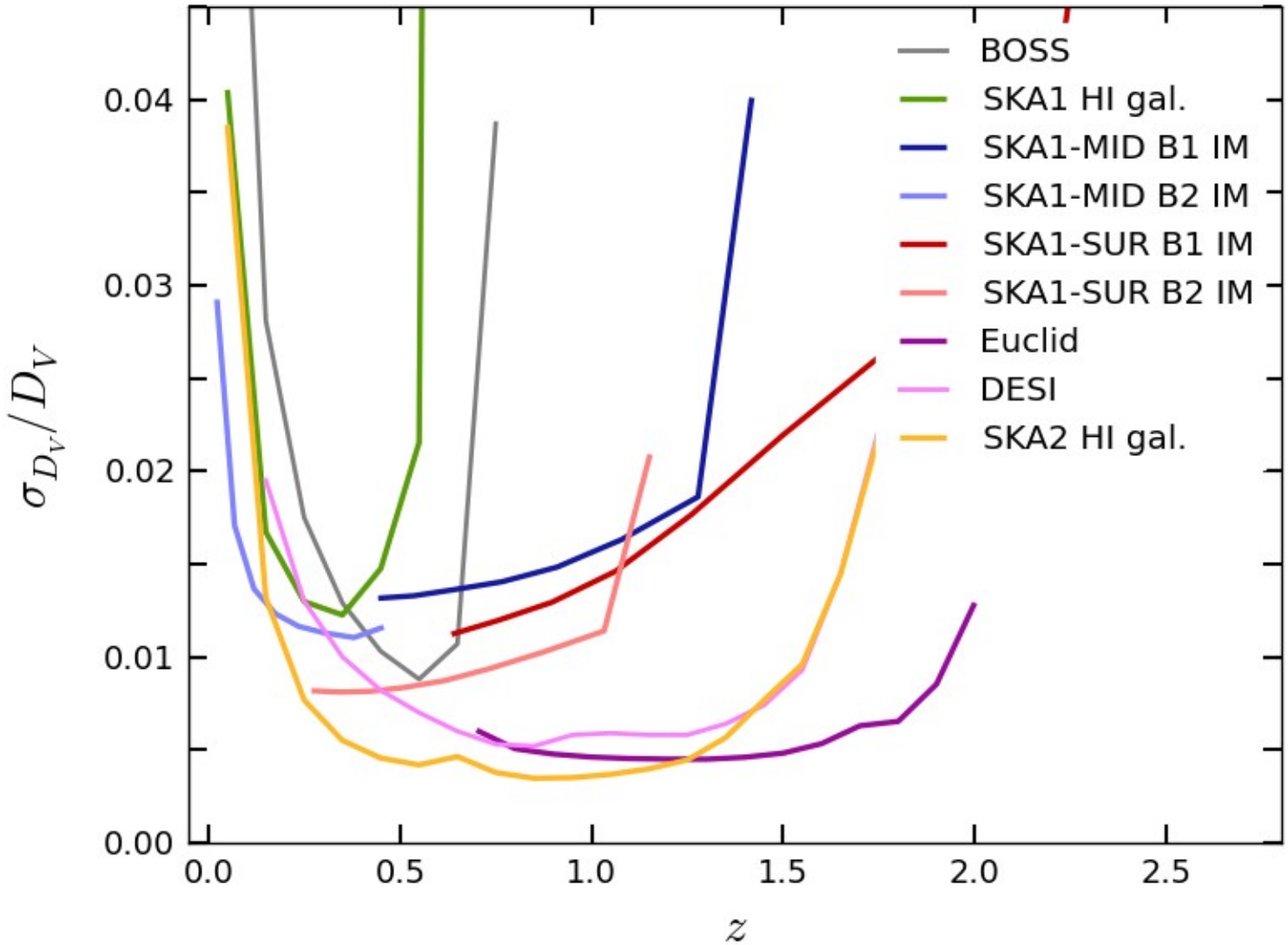
Polarisation leakage

- Check leakage with galaxy cross-correlations
  (e.g. GBT x WiggleZ, Masui et al. 2012)



F. Villaescusa-Navarro, … **PB** (2014)

Distance scale forecasts



Some data taken from Font-Ribera *et al.* (2014)

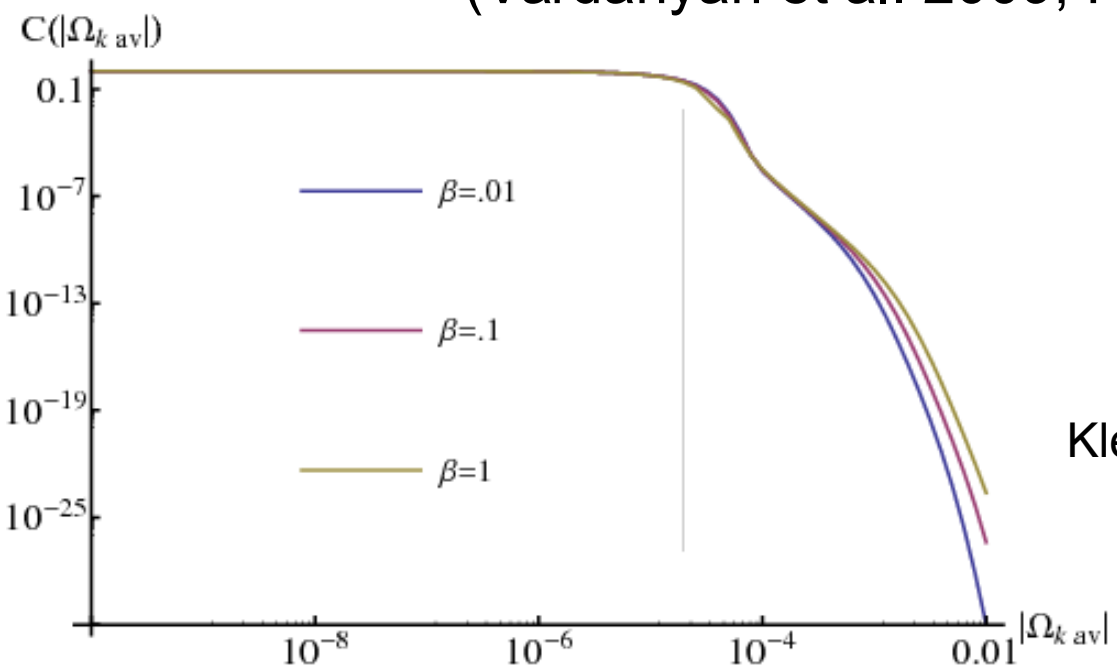
Curvature

- Curvature is a strong prediction of inflation
- Eternal inflation would be ruled-out if curvature was detected above the $|10^{-4}|$ level

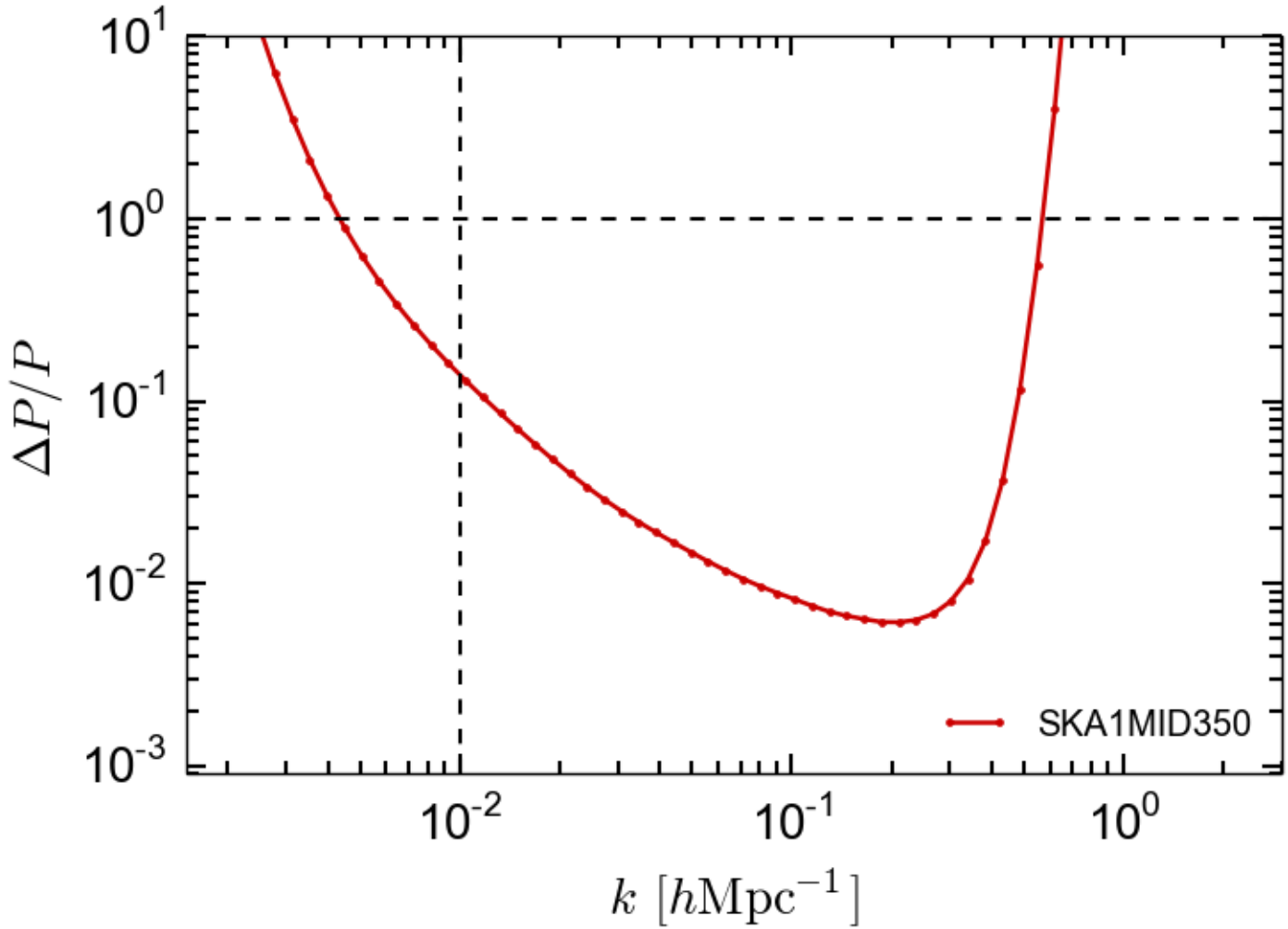
(Kleban & Schillo, Guth & Nomura)

- Fundamental limit of detectability at ~$|10^{-4}|$ too

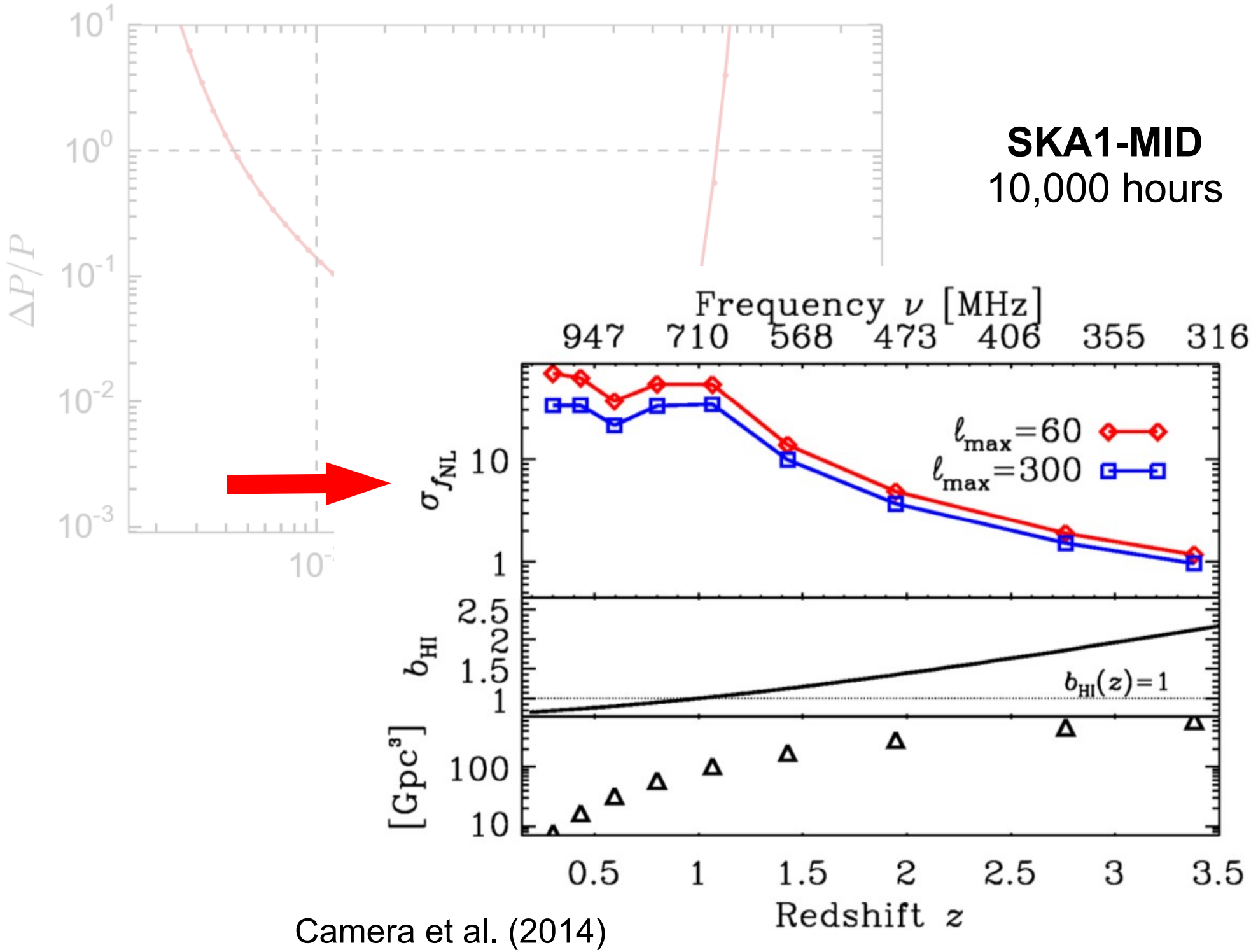
(Vardanyan et al. 2009, PB & Kamionkowski 2013)



Kleban & Schillo (2012)



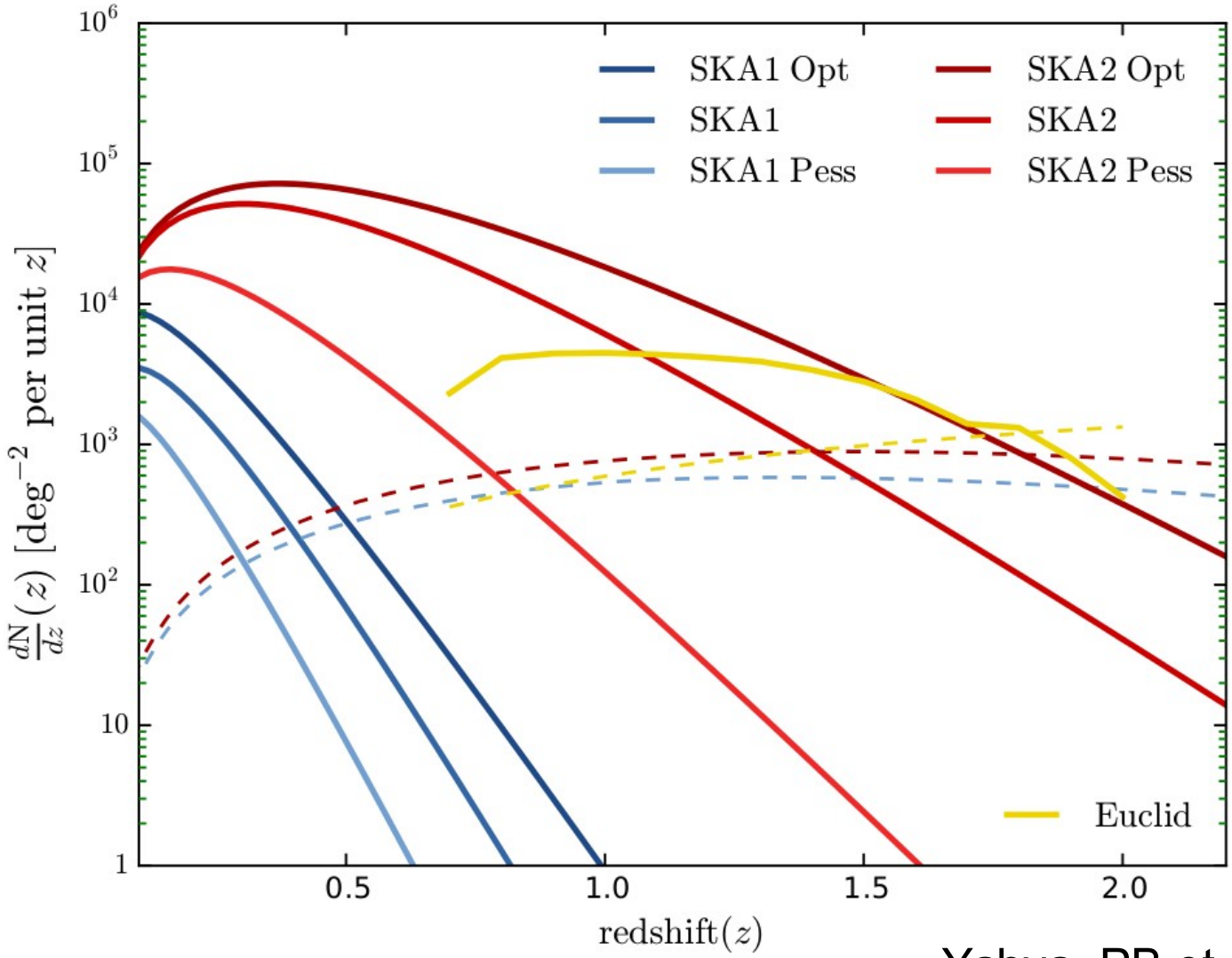
SKA1-MID
10,000 hours



Camera et al. (2014)

Galaxy redshift surveys

Large FOV, many intermediate baselines → high survey speed



Yahya, PB et al. (2014)