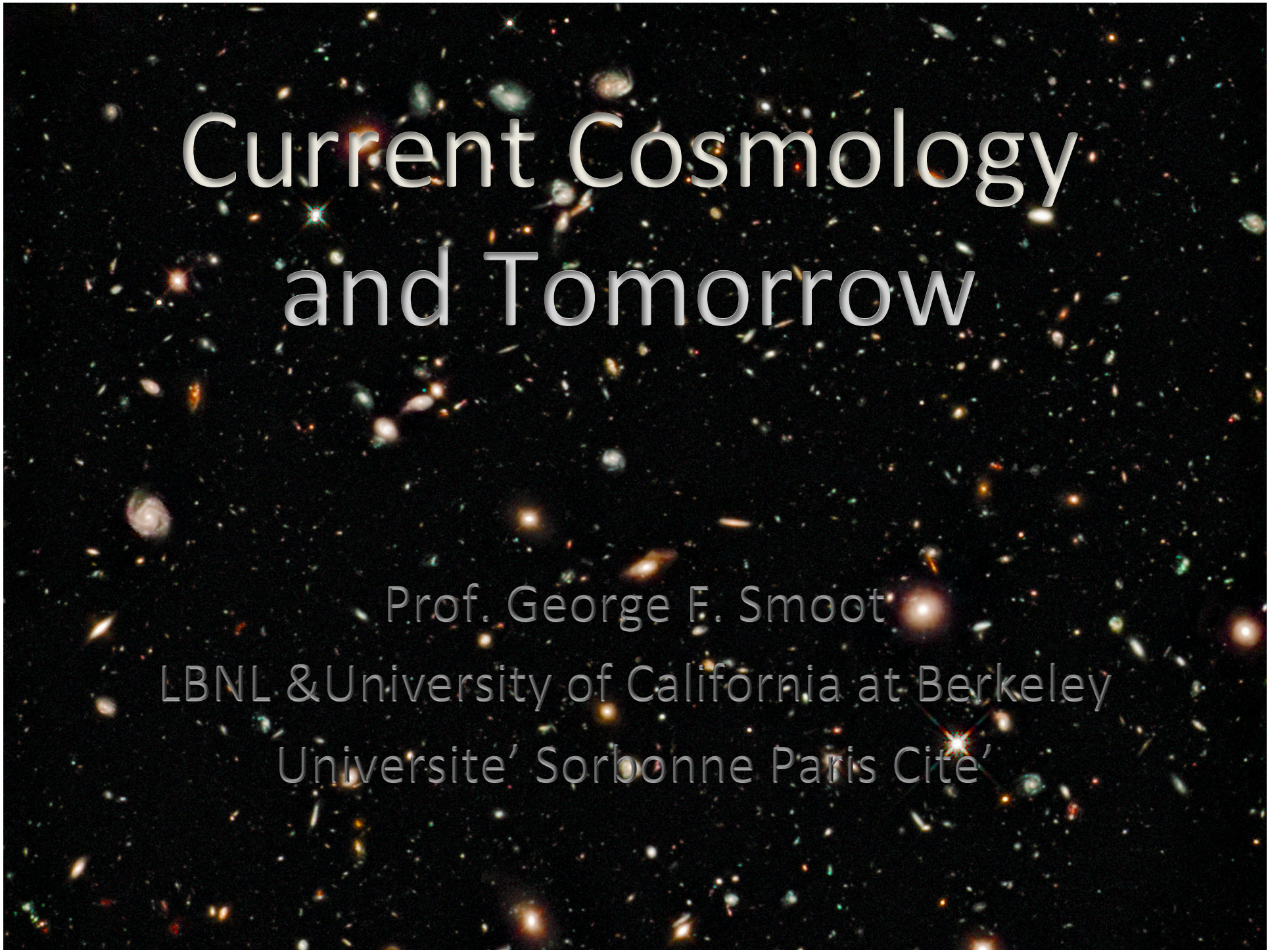
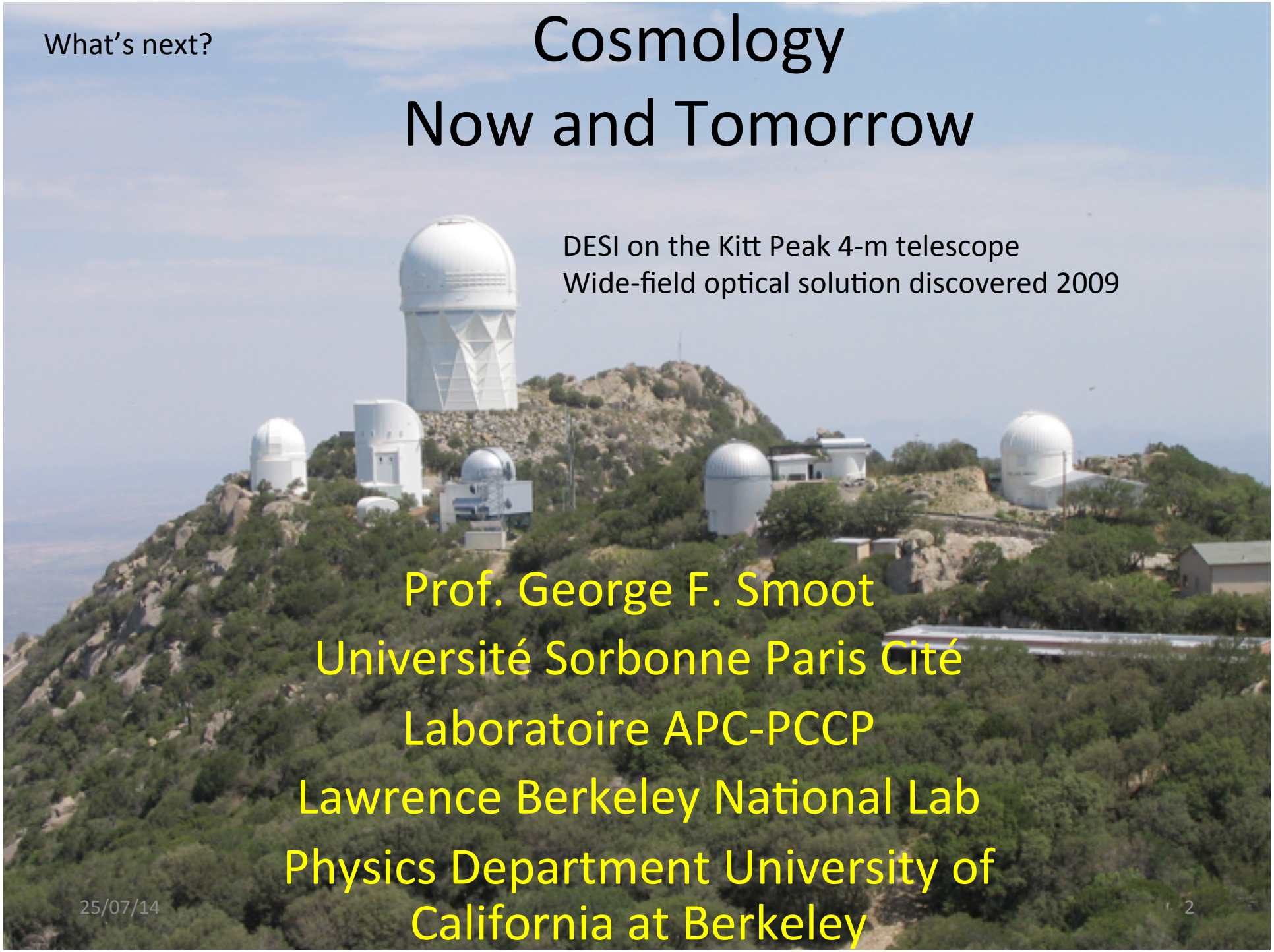


Current Cosmology and Tomorrow

Prof. George F. Smoot
LBNL &University of California at Berkeley
Universite' Sorbonne Paris Cite'

What's next?

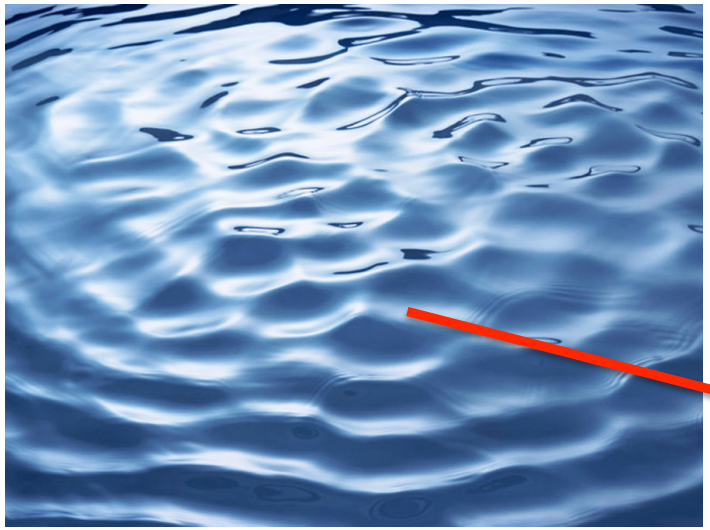
Cosmology Now and Tomorrow



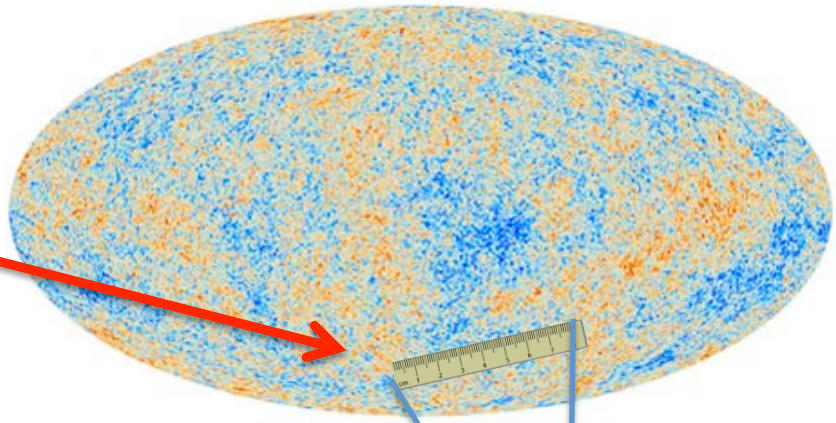
DESI on the Kitt Peak 4-m telescope
Wide-field optical solution discovered 2009

Prof. George F. Smoot
Université Sorbonne Paris Cité
Laboratoire APC-PCCP
Lawrence Berkeley National Lab
Physics Department University of California at Berkeley

Tiny Ripples in Early Universe

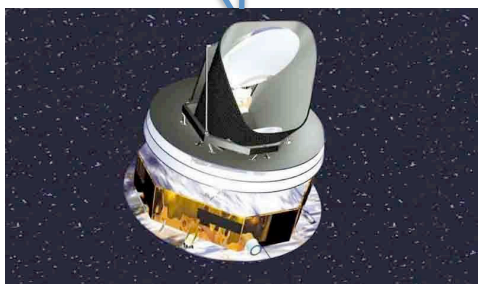


Cosmic Microwave Background



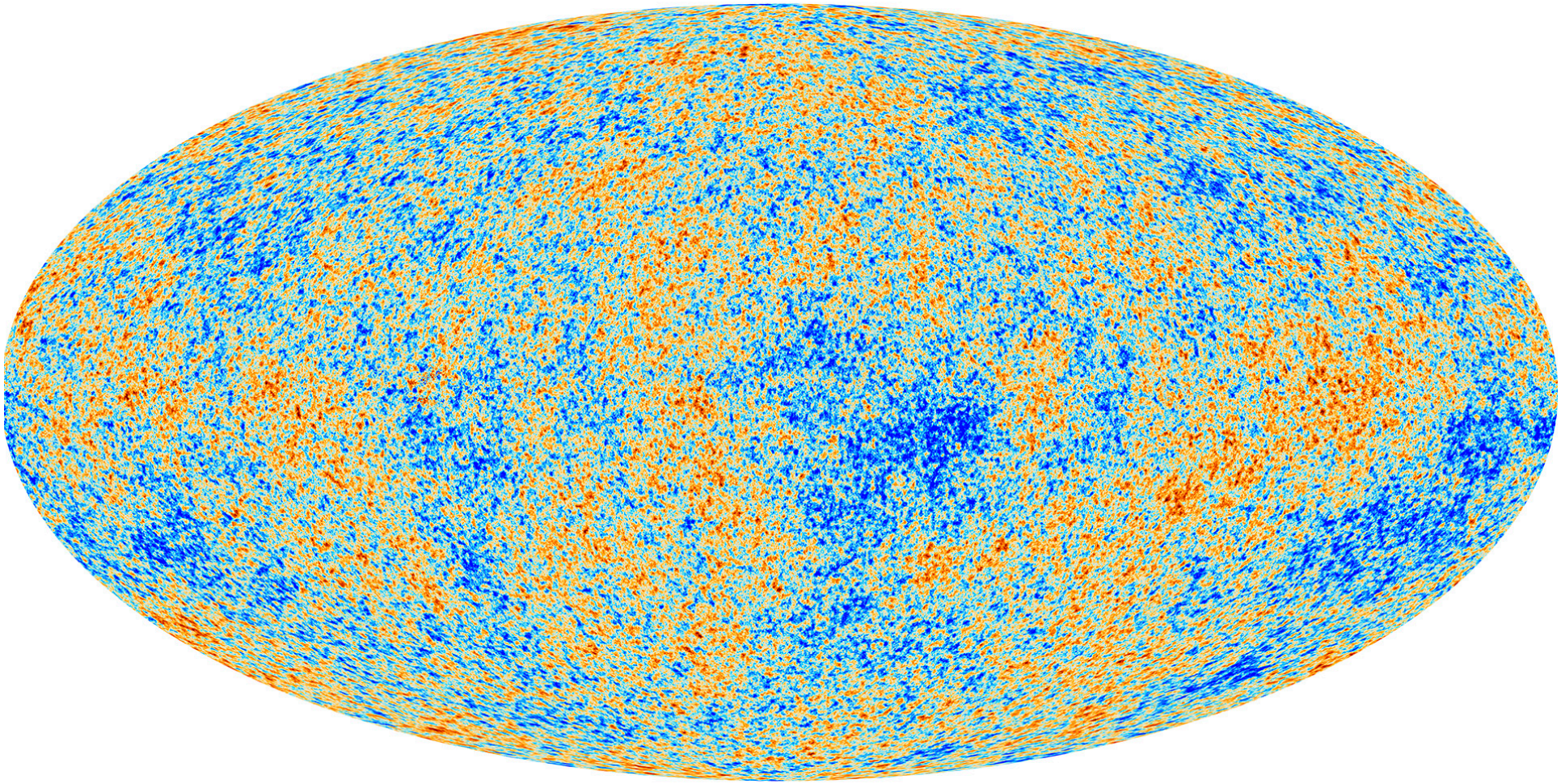
Ripples in early universe imprint standard ruler in cosmic microwave background

θ



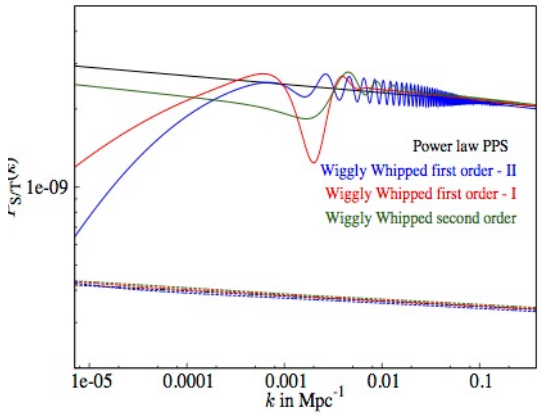
COBE, WMAP, Planck,
ACT, SPT, PolarBear

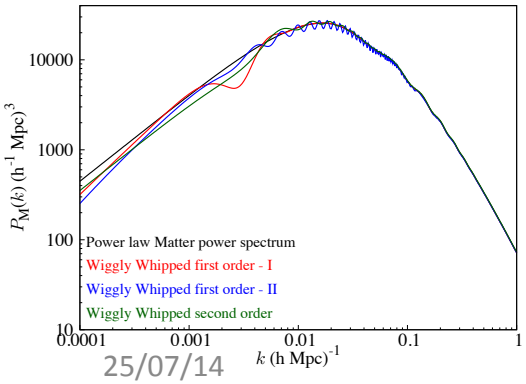
Planck full sky CMB map

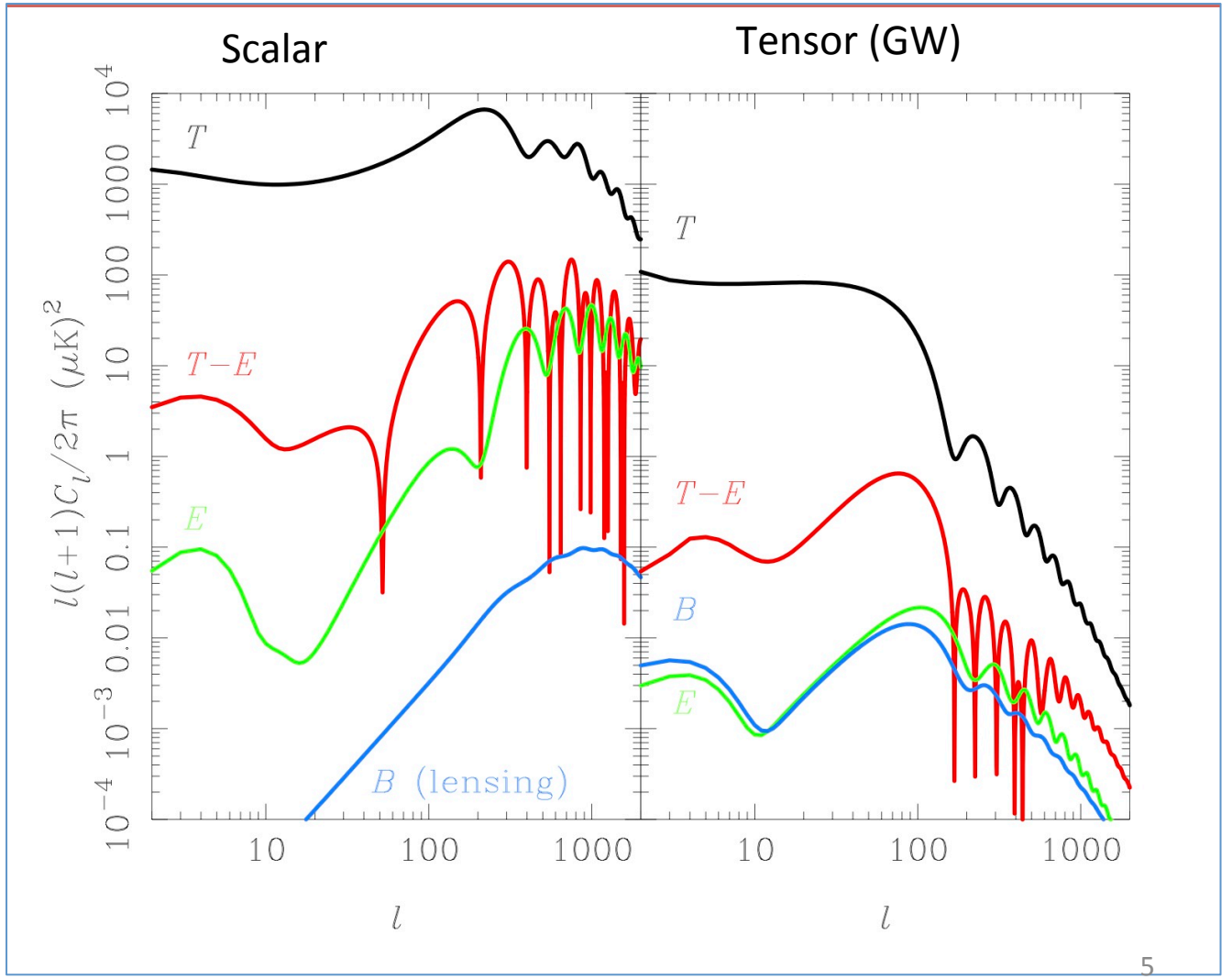


Inflation -> primordial fluctuations -> CMB Anisotropy Power Spectra 6-param

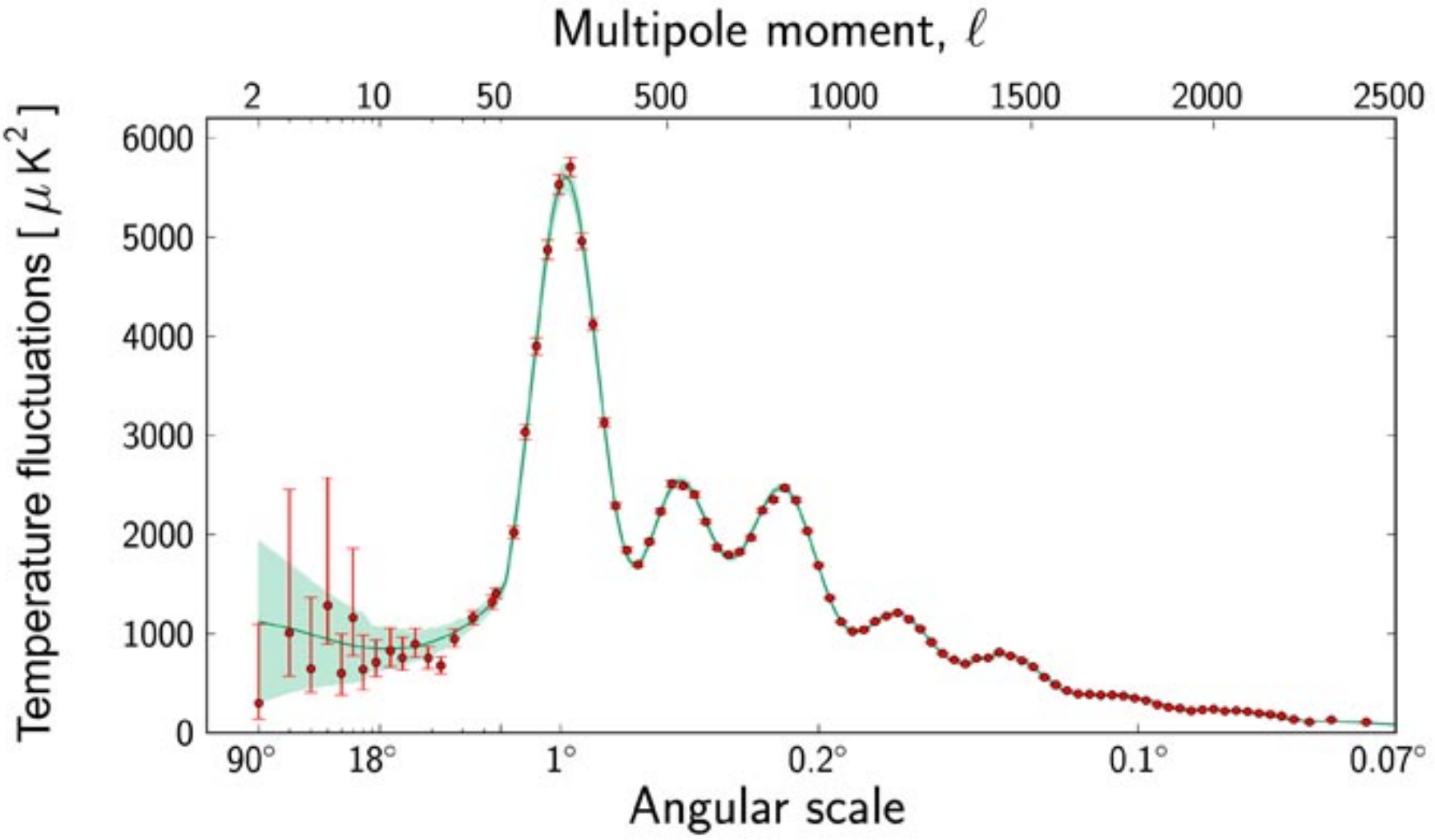
T = TT power
TE = T x E
E = EE
B = BB



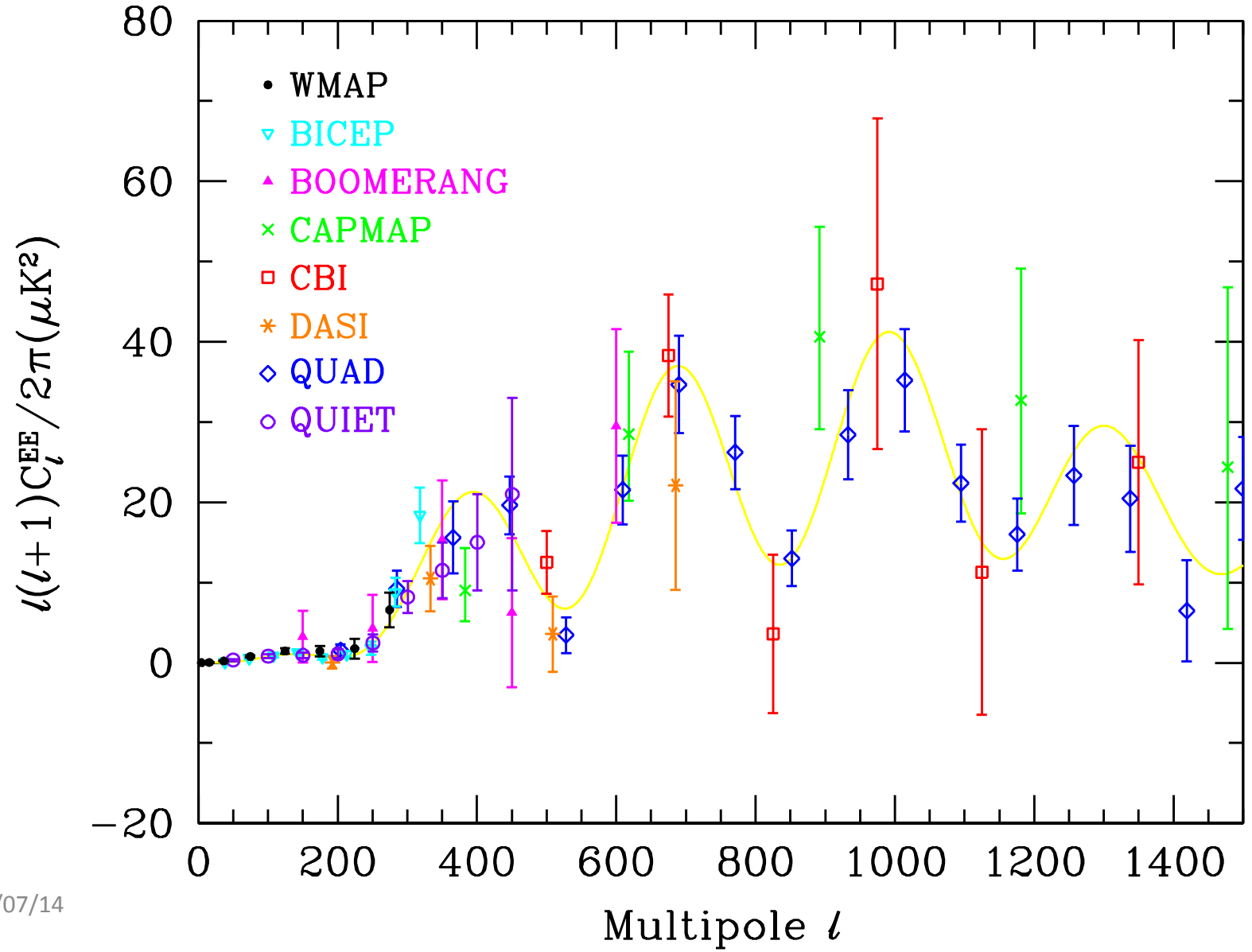




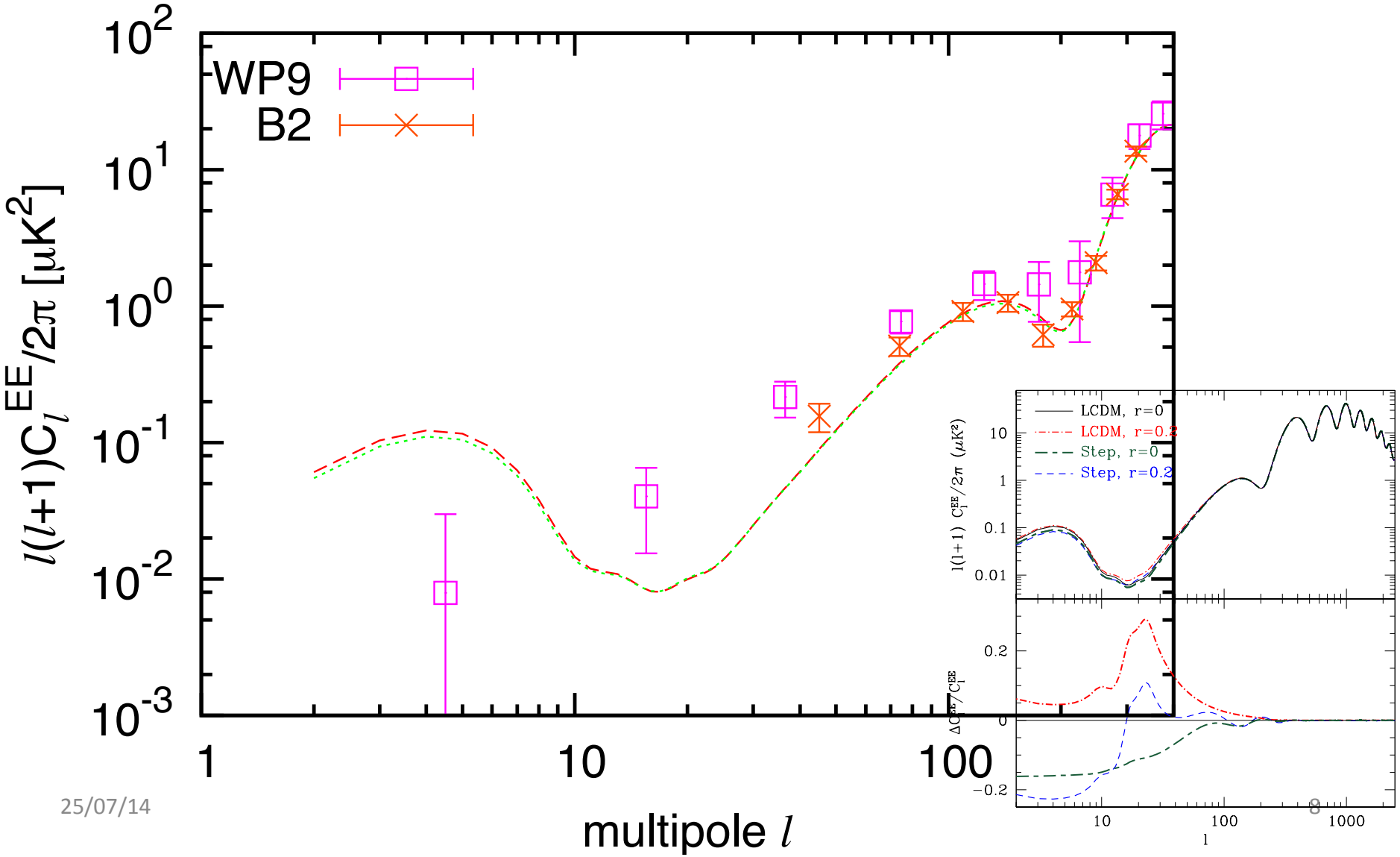
Power spectrum angular scale



Current E-mode PS Observations

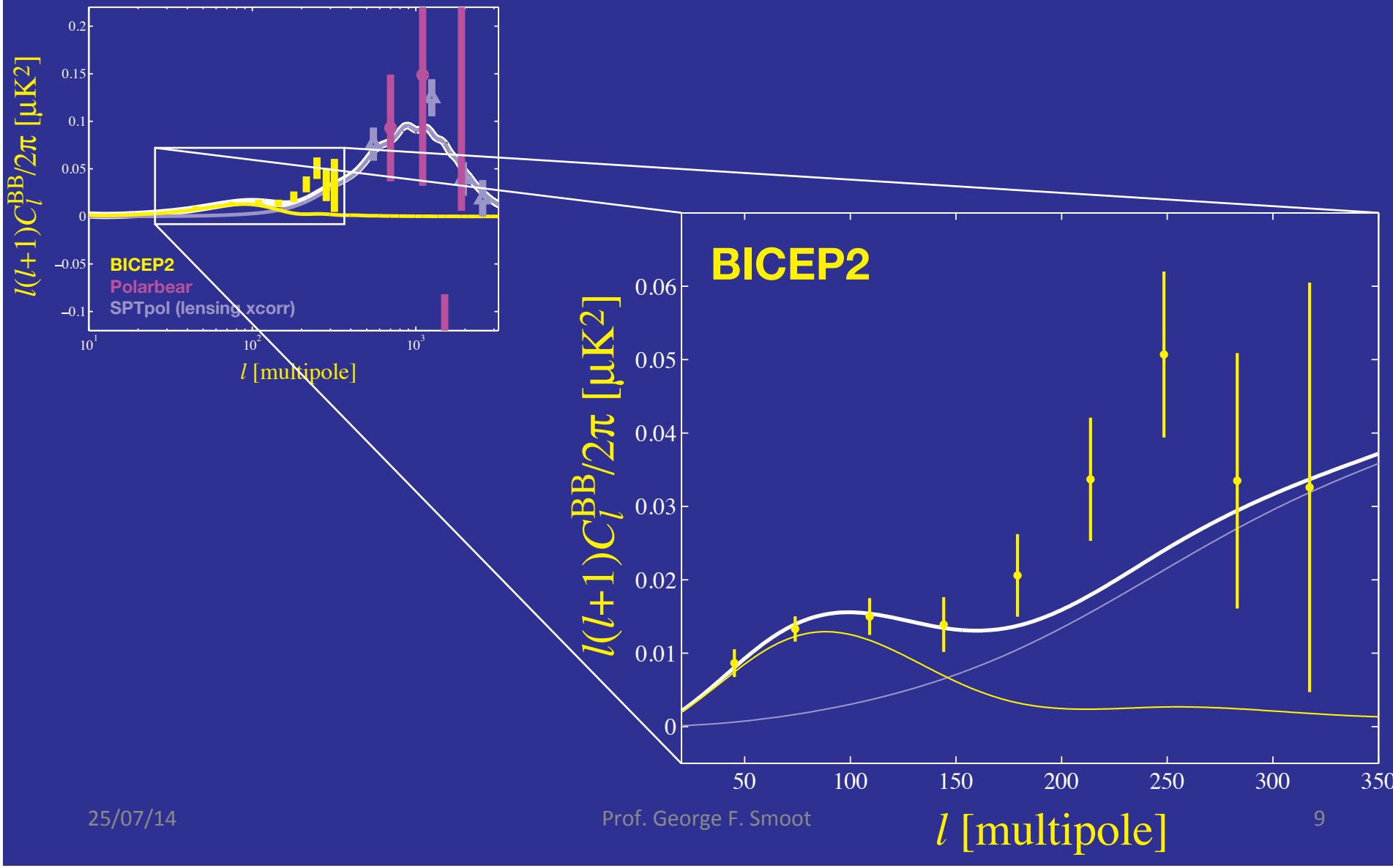


Close up in the relevant region
looking for the EE bump for the TT depression

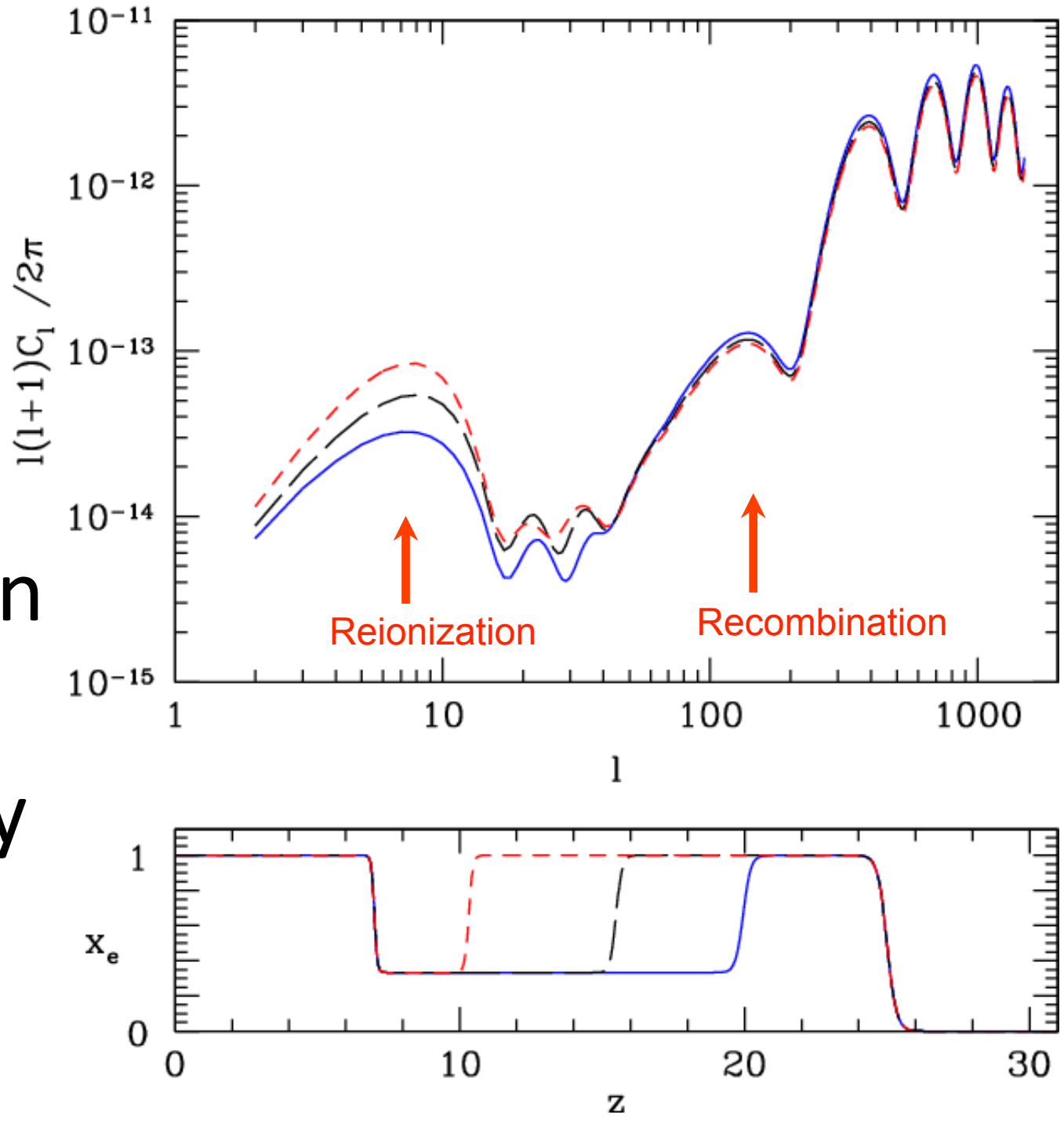


Epoch of B-modes

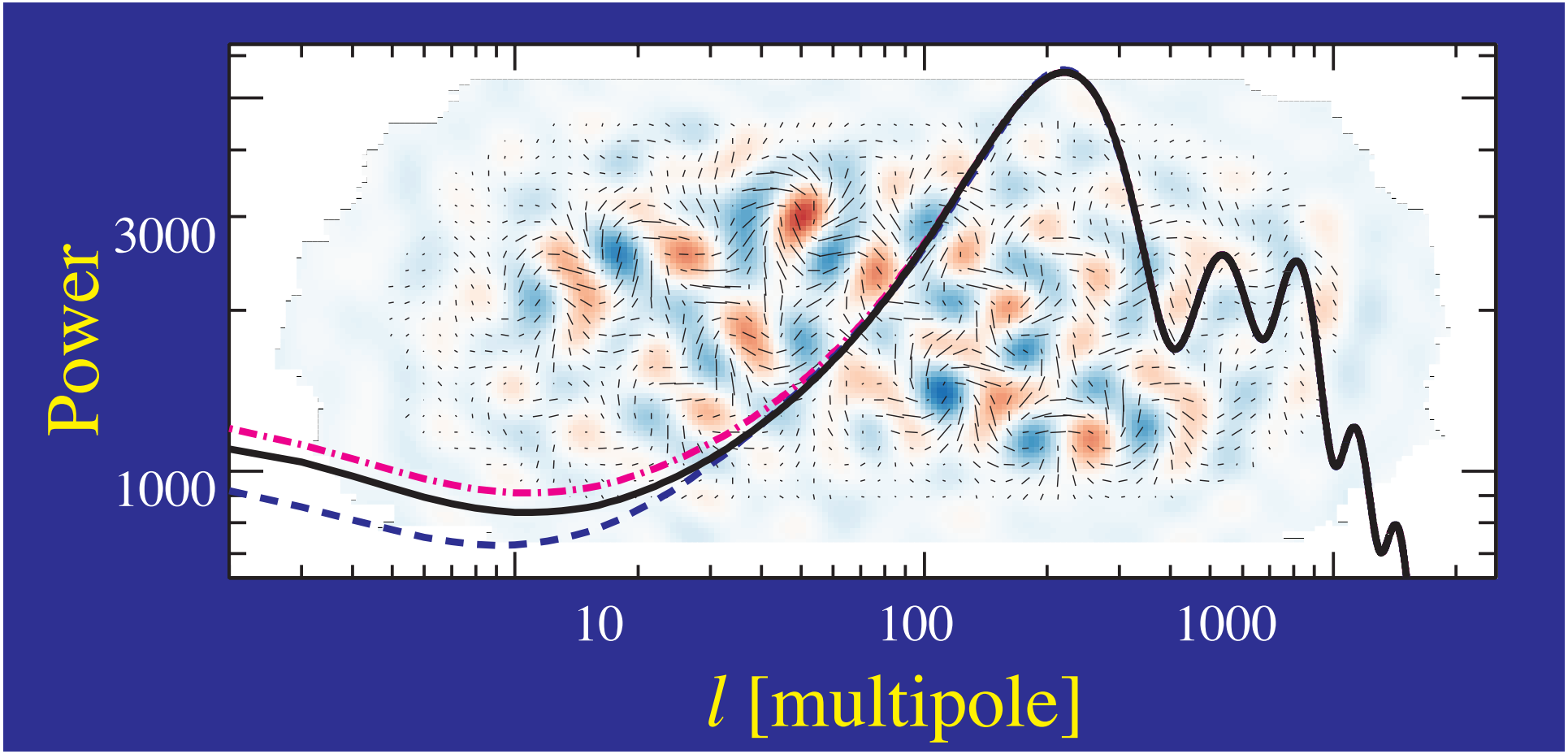
- Gravitational lensing B-modes (SPTPol, Polarbear...) detected
- Gravitational wave B-modes (BICEP2) measured



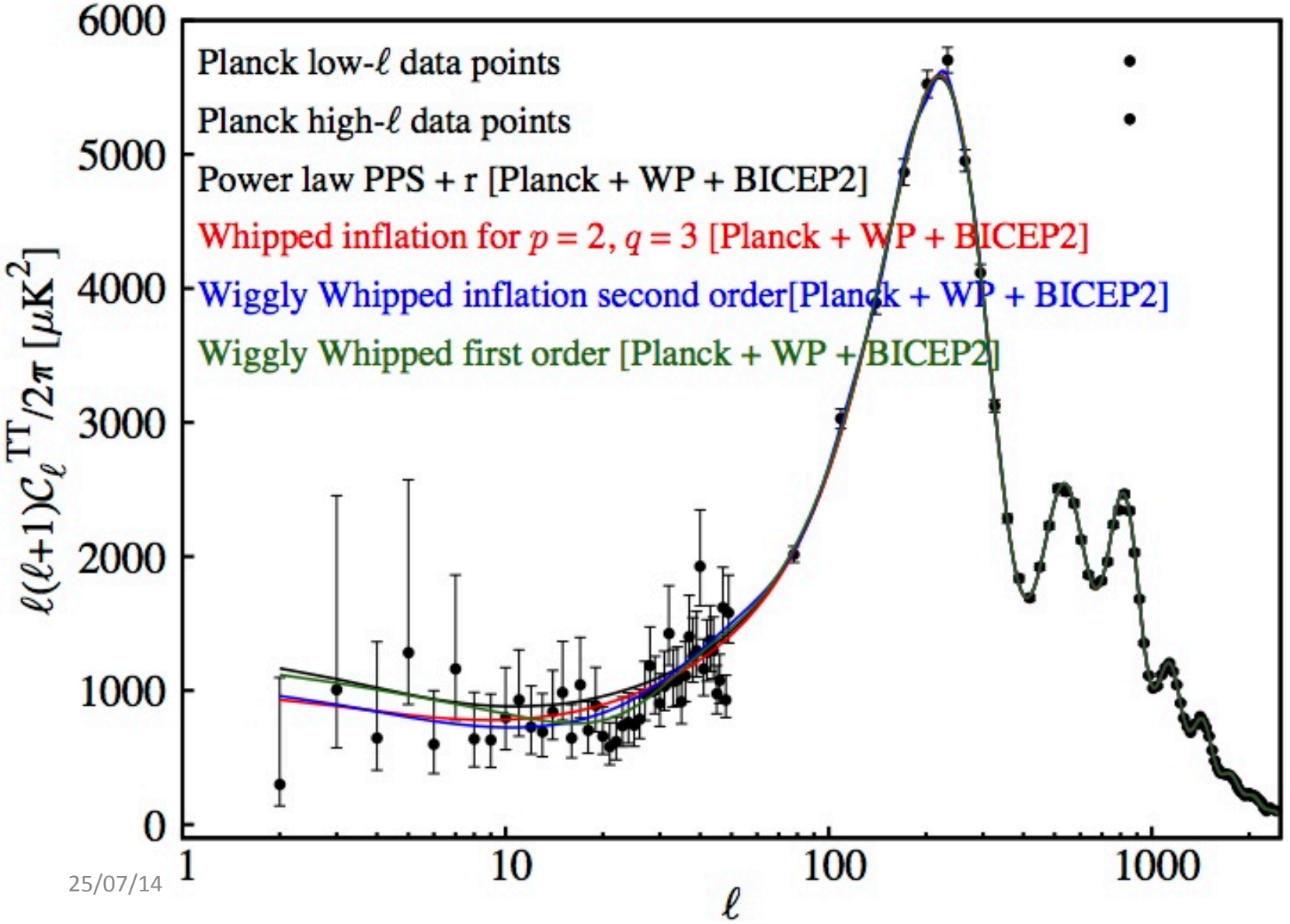
But the Effect of Reionization uncertianty



Issue: TT Power Spectrum with r=0.2, Best fit, needed



Fitting CMB with GUT S Inflation

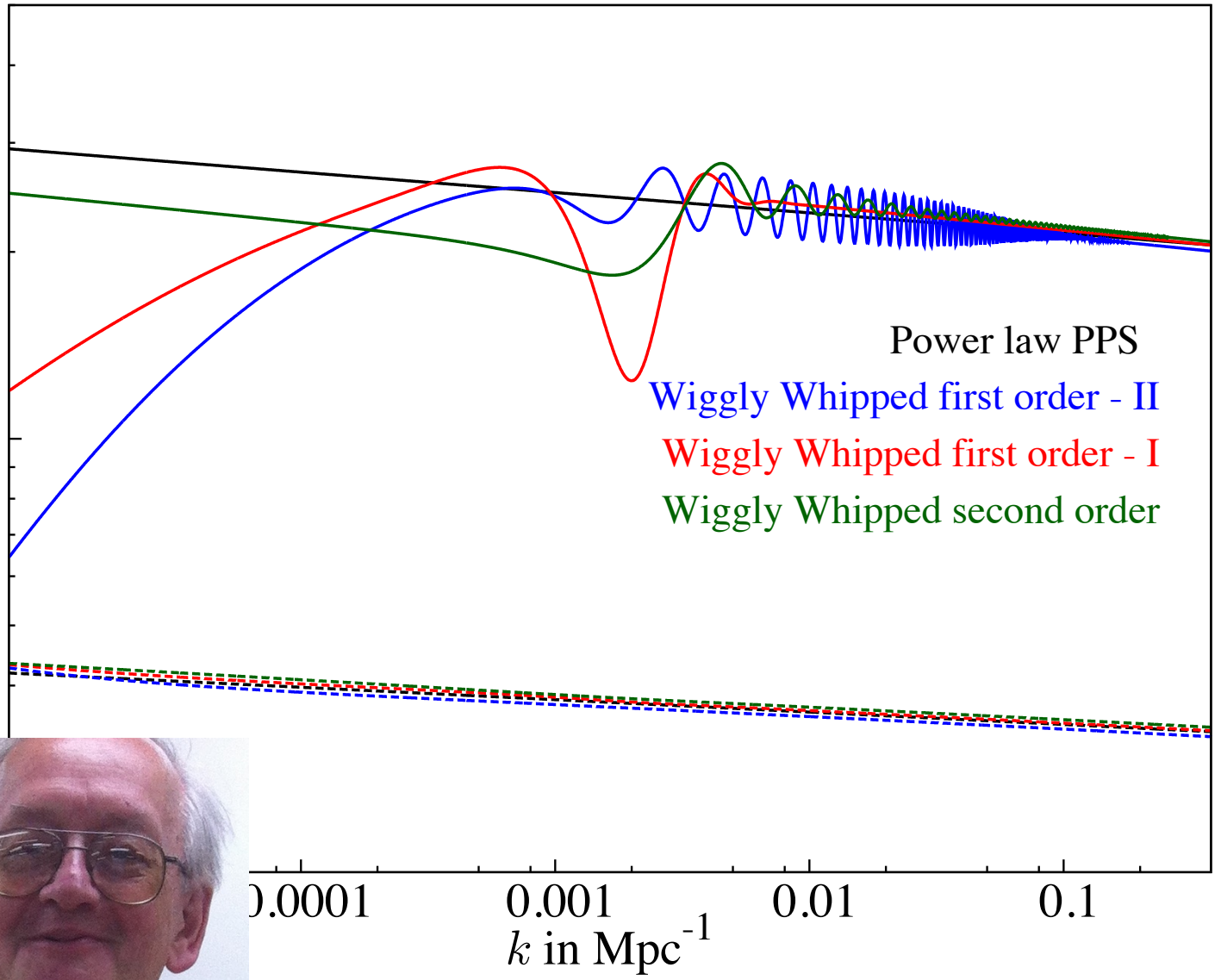


Wiggly Whipped Primordial Power Spectra

Dhiraj Hazra

Arman Shaffieloo

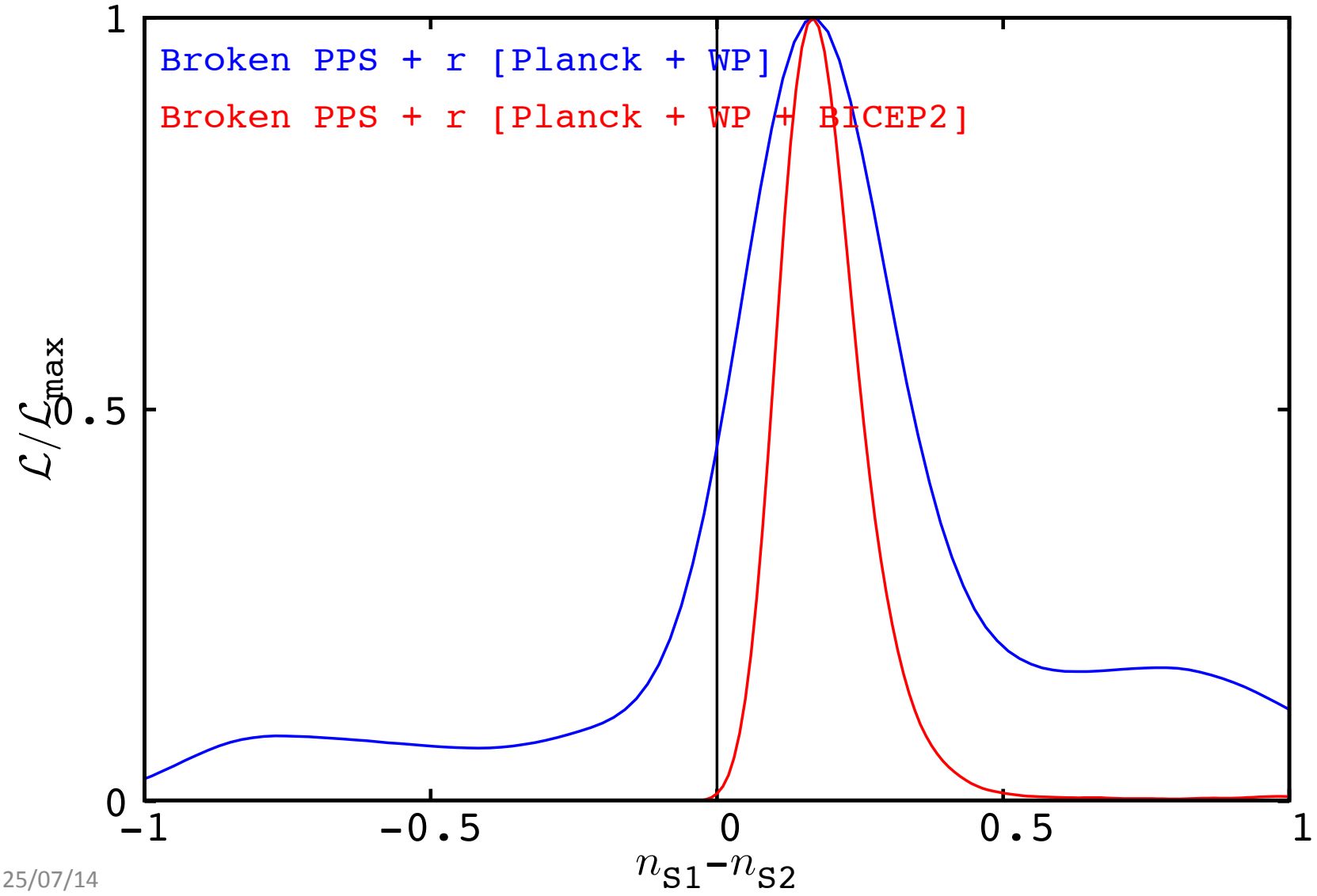
Alexei Starobinsky



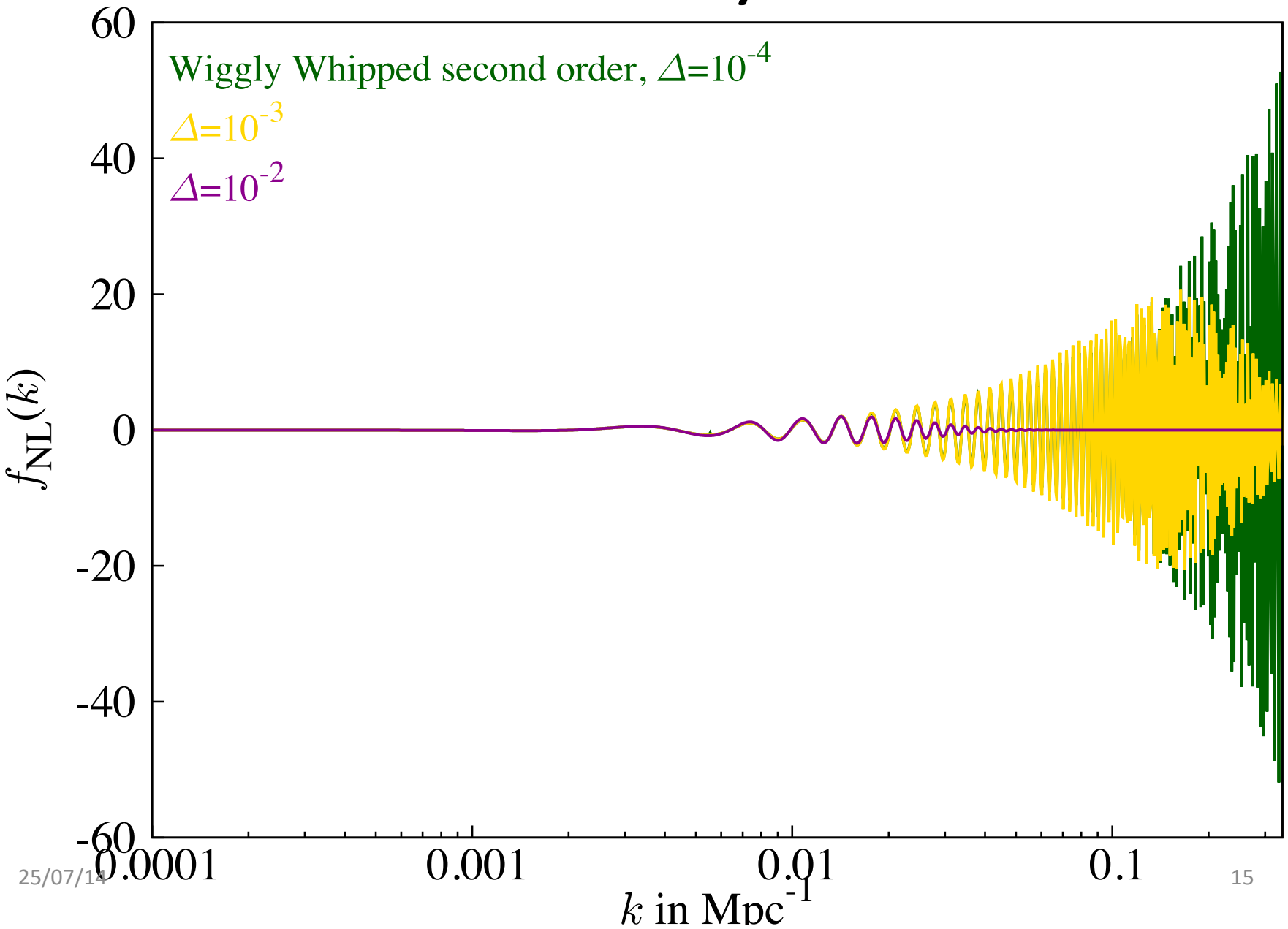
Hazra, Shaffieloo, Smoot, & Starobinsky 2014

arXiv:1405.2012

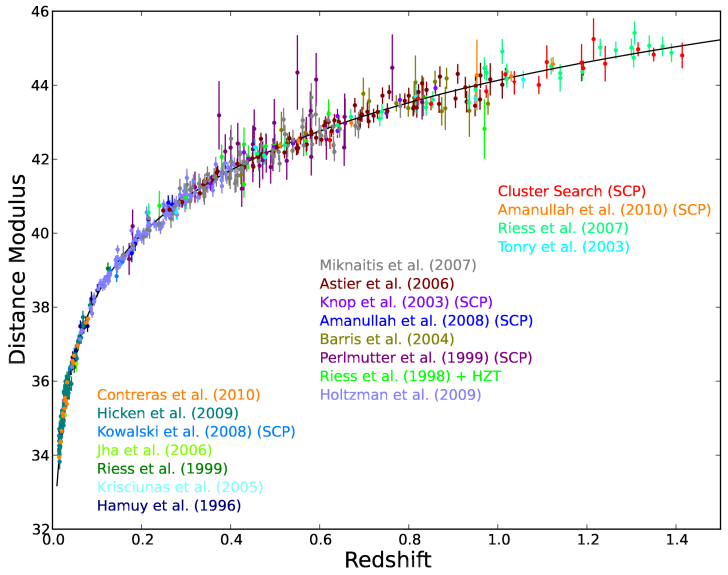
Evidence of low-ell deficit fitted by broken power law; 1403 1.7786

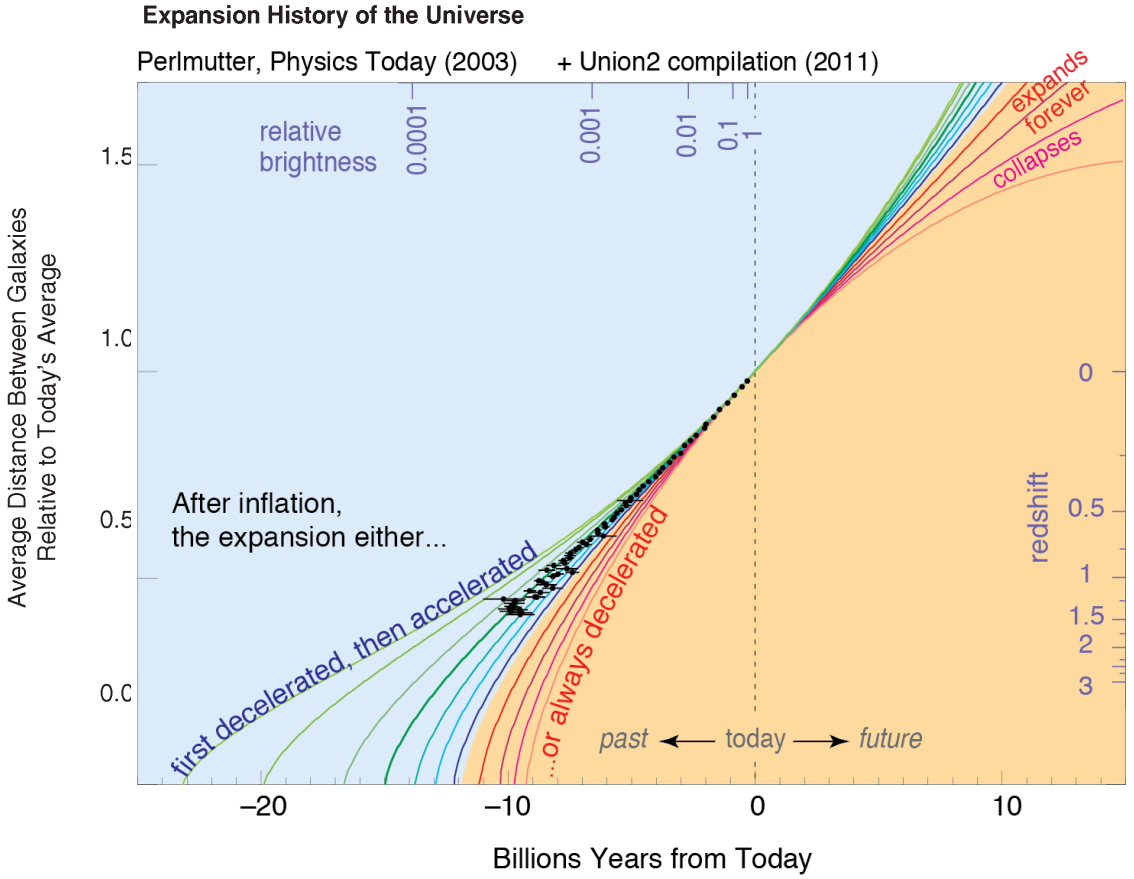


Non Gaussianity WW2nd



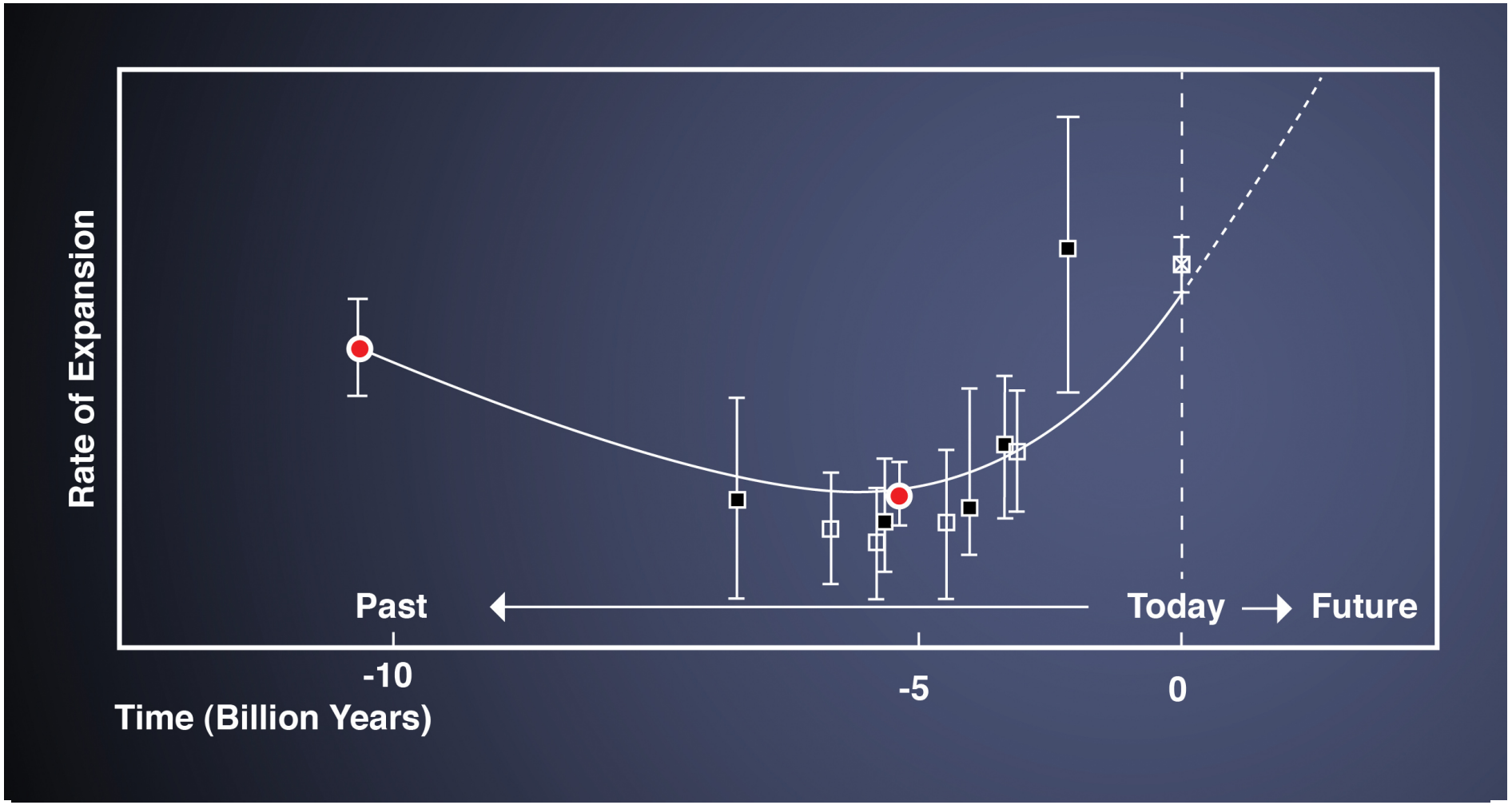
Evidence for Dark Energy





Expansion Rate vs. Time

recent BOSS results in red



CREDIT: Zosia Rostomian, LBNL, and Nic Ross, BOSS Lyman-alpha team, LBNL Baryon Acoustic Oscillations in the Ly-α forest of BOSS quasars, Submitted to *Astronomy & Astrophysics*, arXiv:1211.2616.

Dark Energy: Dynamical Field vs. Cosmological Constant

DE eq. of state: $p = w\rho, \quad w = w_0 + w_a(1-a).$

$w_0 = -1.04^{+0.72}_{-0.69}, \; w_a < 1.32$ (95%; Planck+WP+BAO)

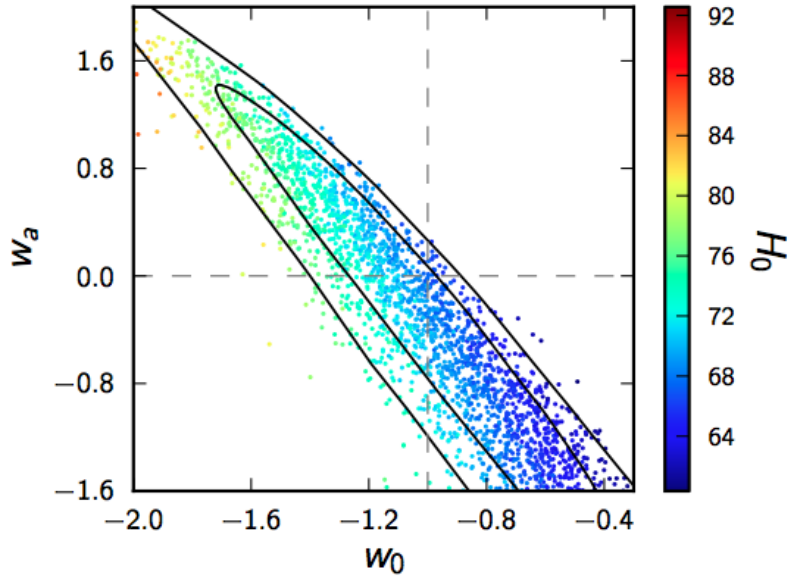


Fig. 35. 2D marginalized posterior distribution for w_0 and w_a for *Planck*+WP+BAO data. The contours are 68% and 95%, and the samples are colour-coded according to the value of H_0. Independent flat priors of $-3 < w_0 < -0.3$ and $-2 < w_a < 2$ are assumed. Dashed grey lines show the cosmological constant solution $w_0 = -1$ and $w_a = 0$.

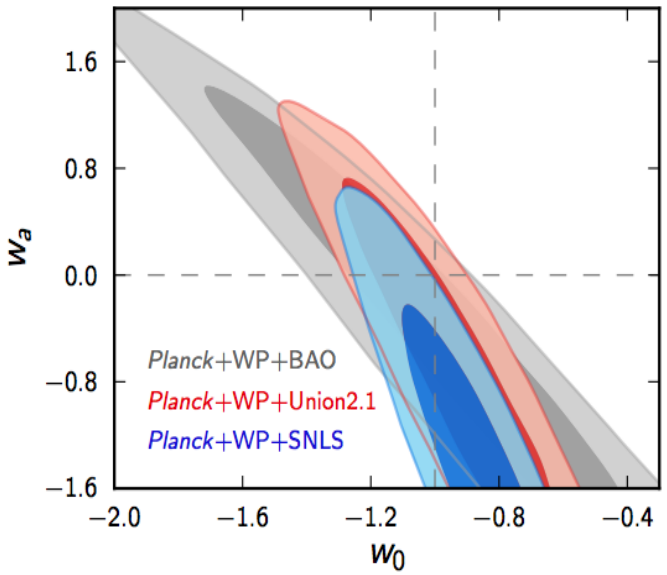
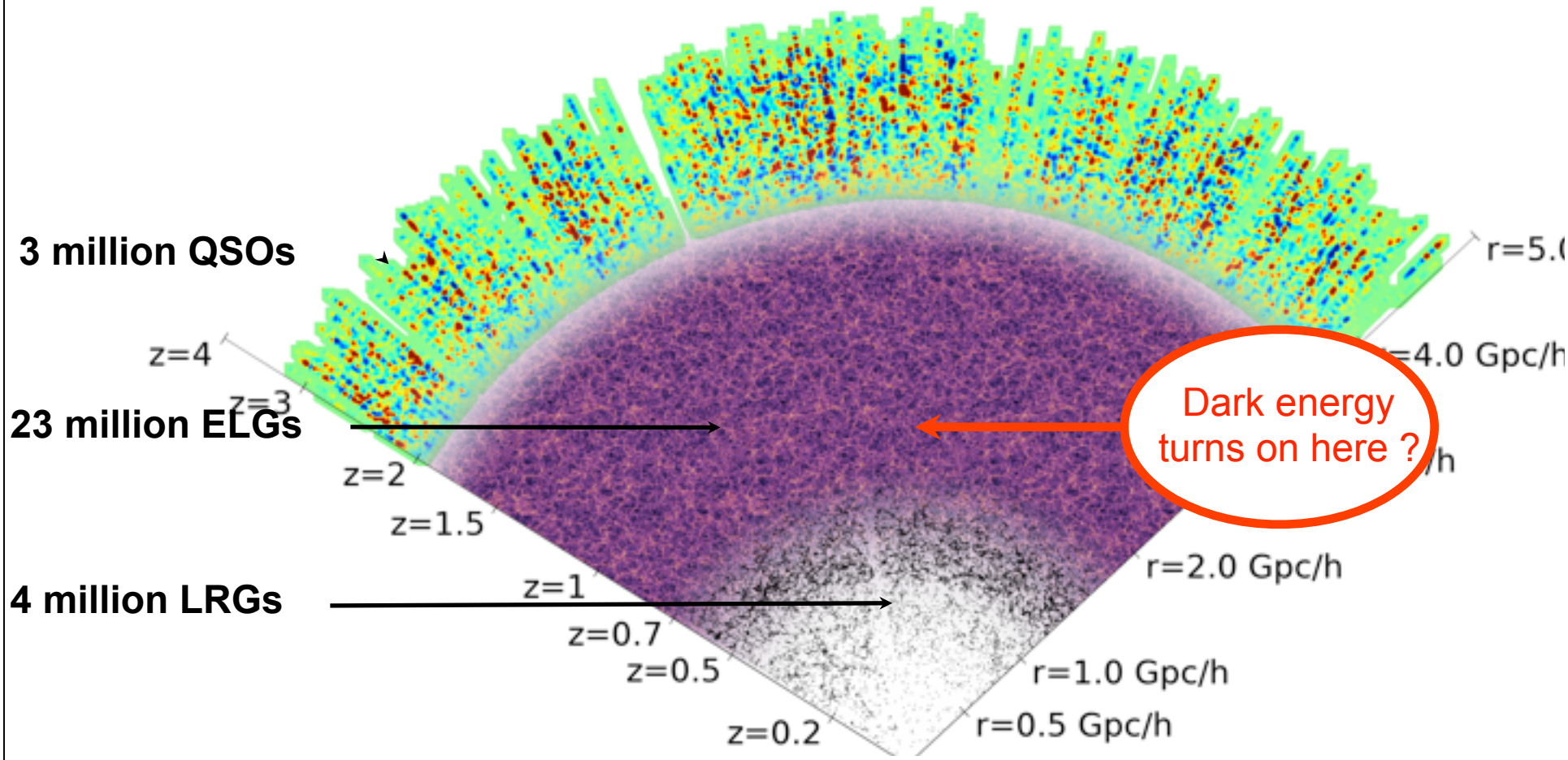


Fig. 36. 2D marginalized posterior distributions for w_0 and w_a, for the data combinations *Planck*+WP+BAO (grey), *Planck*+WP+Union2.1 (red) and *Planck*+WP+SNLS (blue). The contours are 68% and 95%, and dashed grey lines show the cosmological constant solution.

Volume of redshift surveys

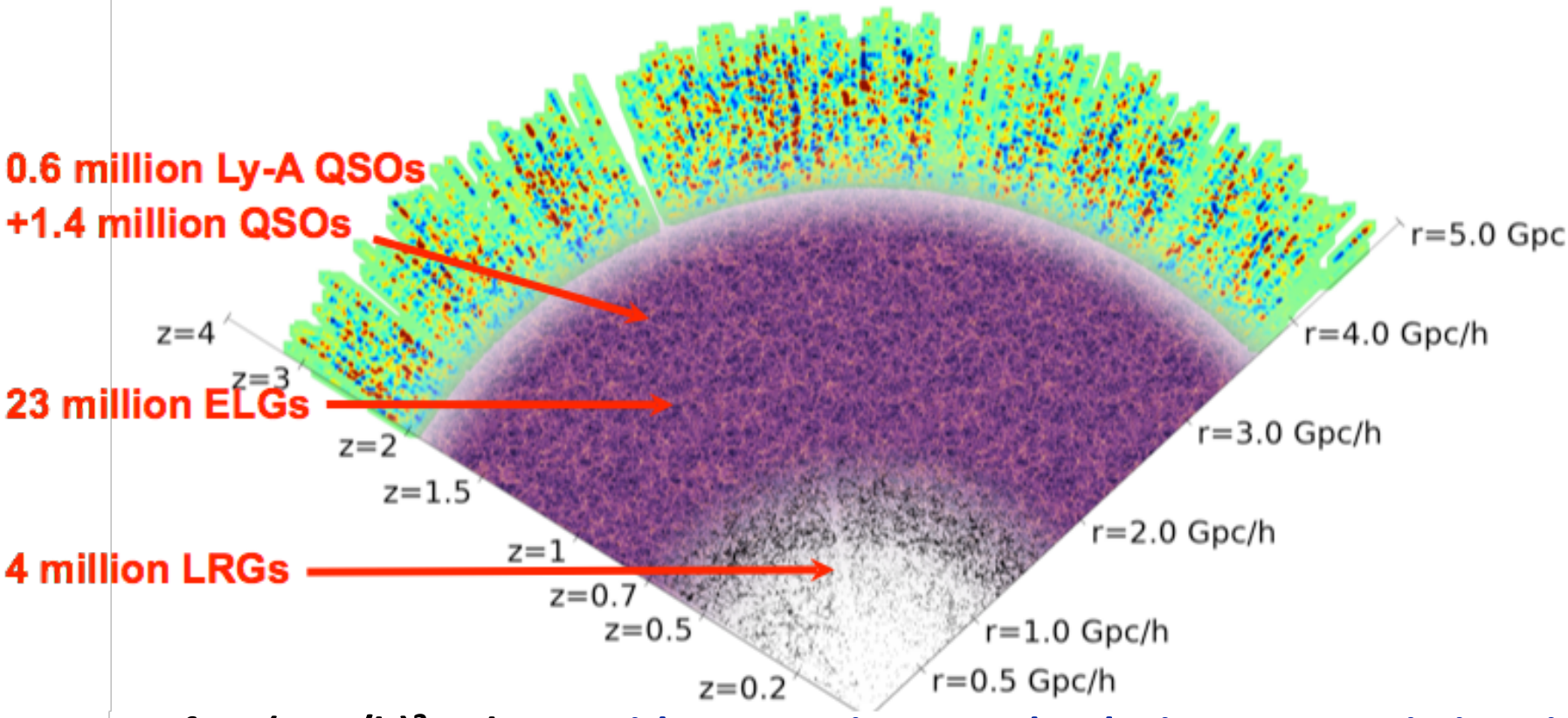
These are the <u>easiest</u> 30 million objects to observe



What is DESI ?

Four target classes spanning redshifts z=0 → 3.5

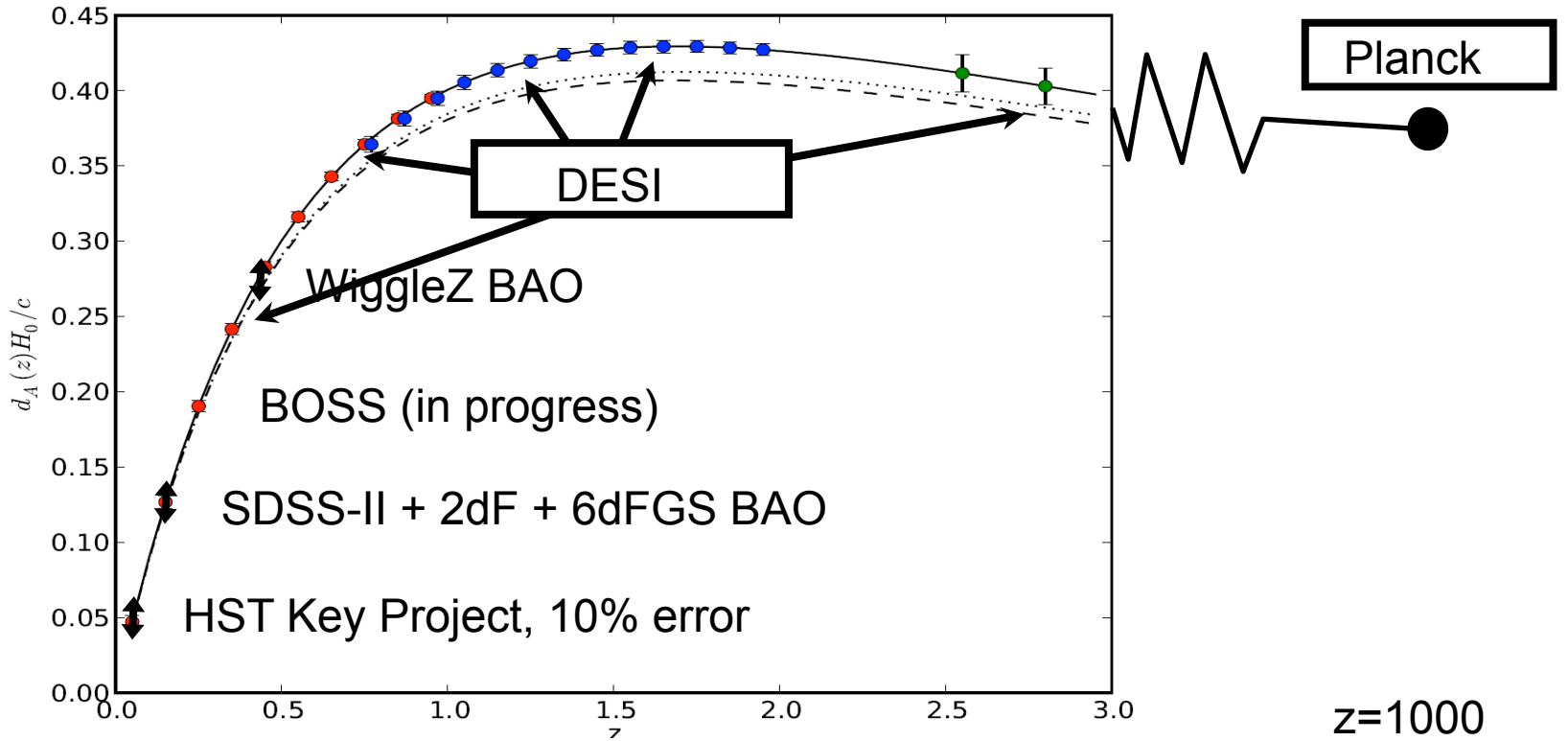
Includes all the massive black holes in the Universe (LRGs + QSOs)



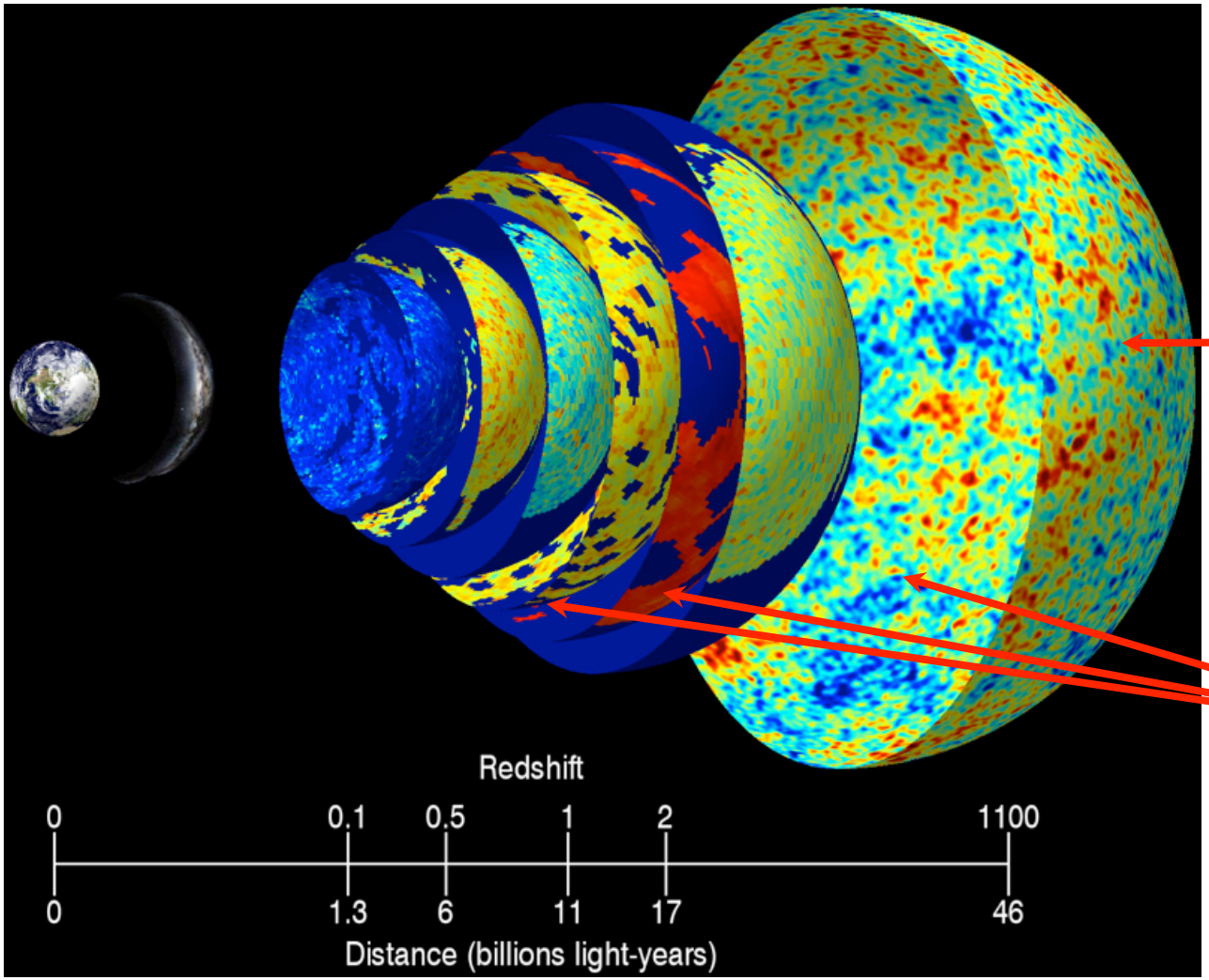
3D map of 50 (Gpc/h)^3 volume with 4M Luminous Red Galaxies, 23 M Emission Line Galaxies, 2M Quasars Tomographic surveys of density/velocity field.

DESI distance-redshift relation (predicted for 2022)

- *BAO geometric probe with 0.3-1% precision from z=0.5 -> 3*
- *35 measurements with 1% precision*



CMB is 2-d BAO is 3-d



BAO standard ruler from Planck

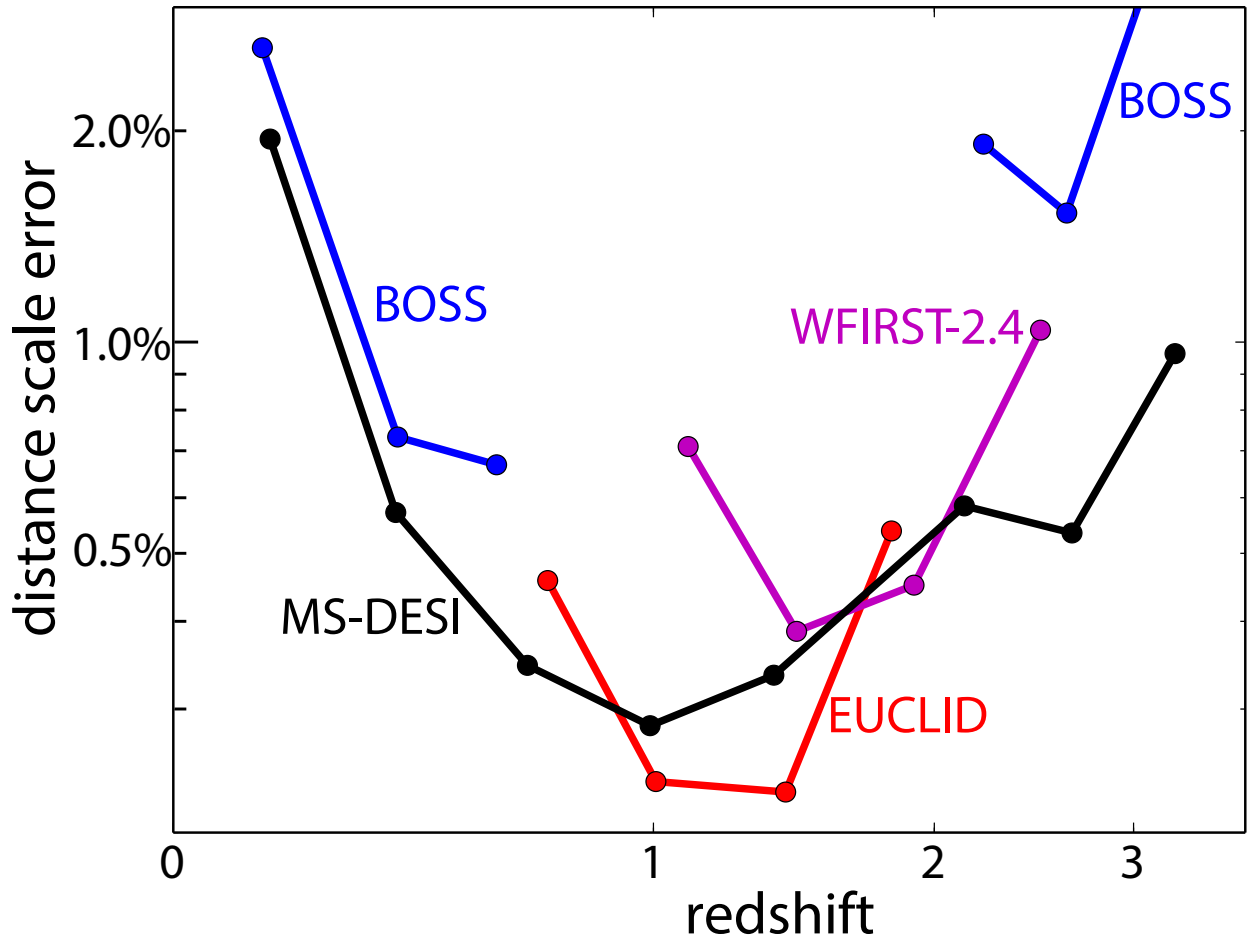
$\theta_s = 0.596724 \pm 0.00038$ deg

BAO standard ruler from BOSS & DESI

From 2D to 3D – CMB anisotropies to tomographic surveys of density/velocity field.

Data, Data, Data – CMB maps l^2~10M modes; BOSS maps k^3V~0.4M modes; DESI 15M modes

DESI Achieves Space-Based Precision

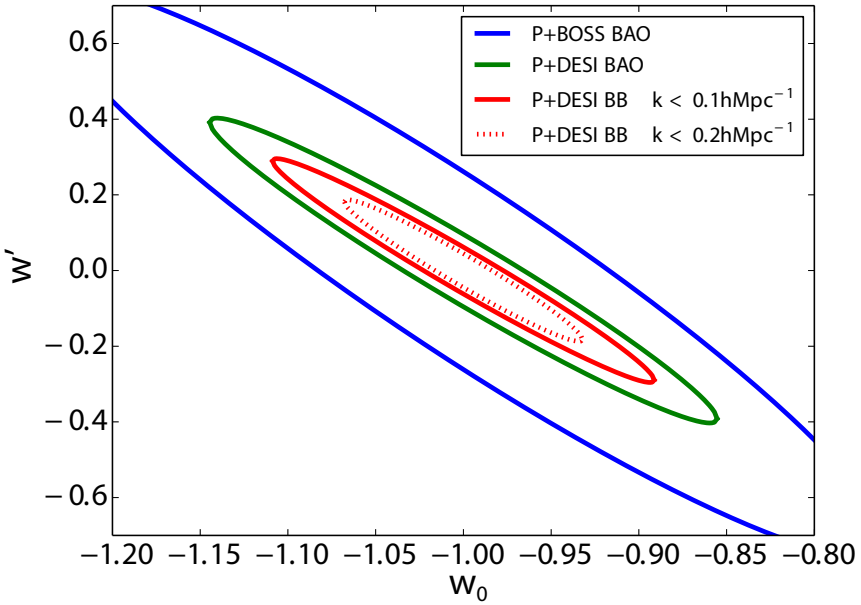


Characterizing Dark Energy Precision

$$w(a) = w_0 + (1-a)w_a$$

Dark Energy Task Force Figure of Merit:

$\propto 1/$ Area of $w_0 - w_a$ error ellipse



DESI: Not just BAO

Power spectrum is Fourier transform of two-point correlation function.

Power spectrum tests:

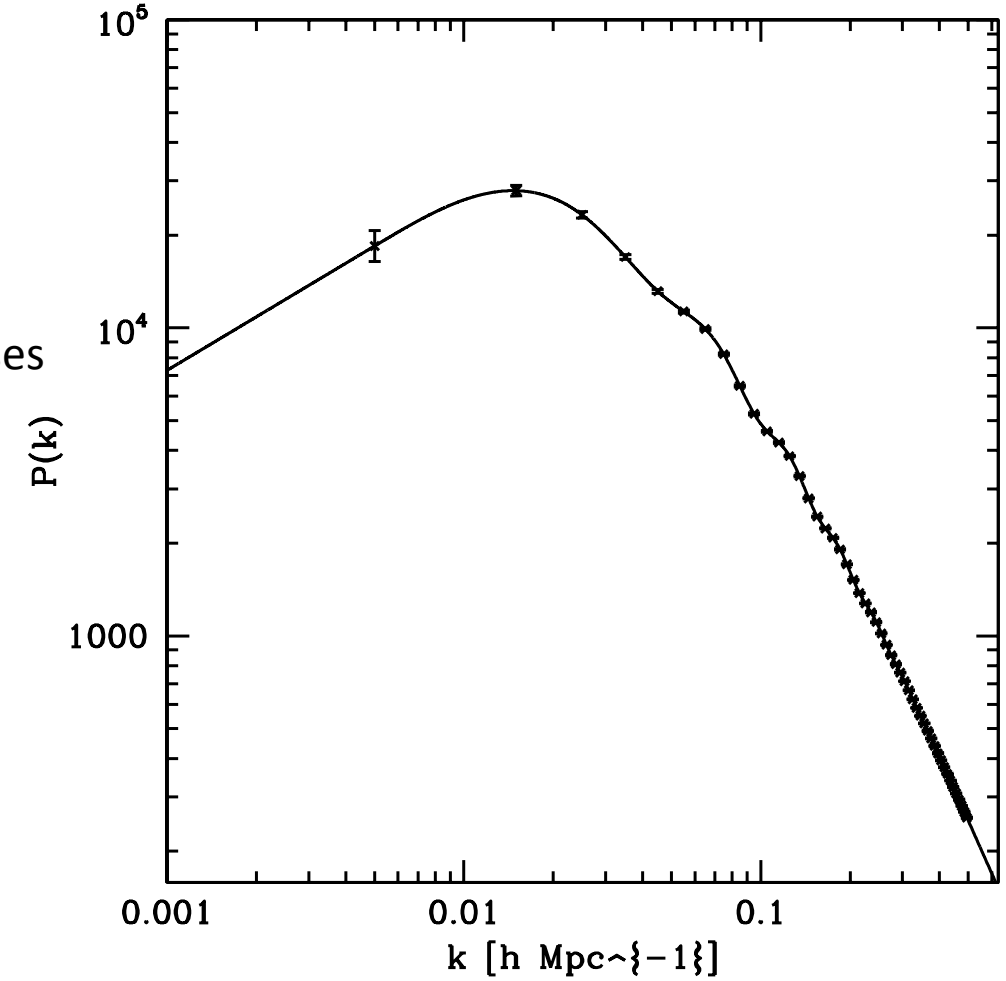
- General Relativity
- Inflation
- Number of neutrinos
- Sum of the neutrino masses

$$n_s : \pm 0.0022$$

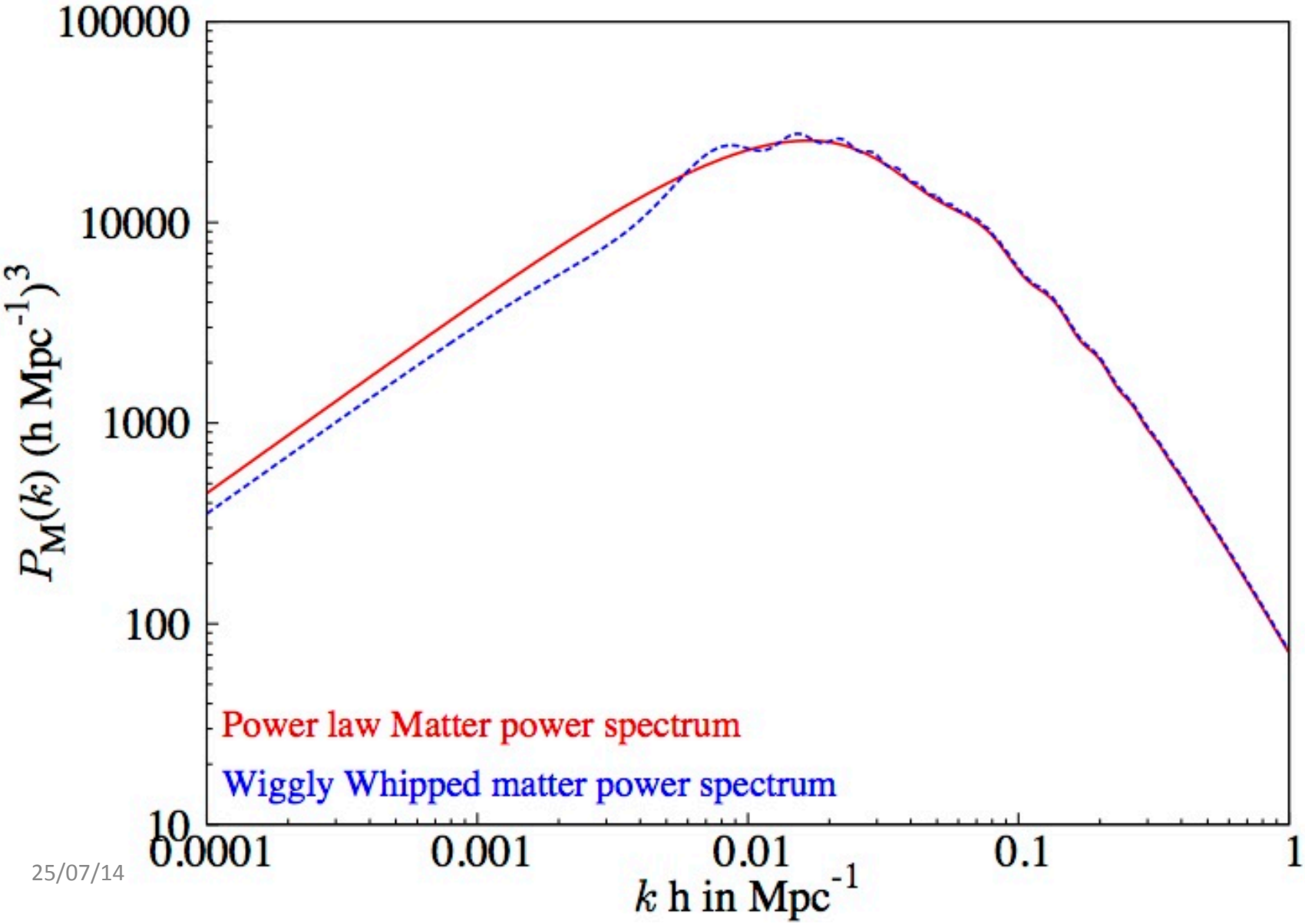
$$\alpha_s : \pm 0.0024$$

$$\Sigma m_\nu : \pm 0.024\,\mathrm{eV}$$

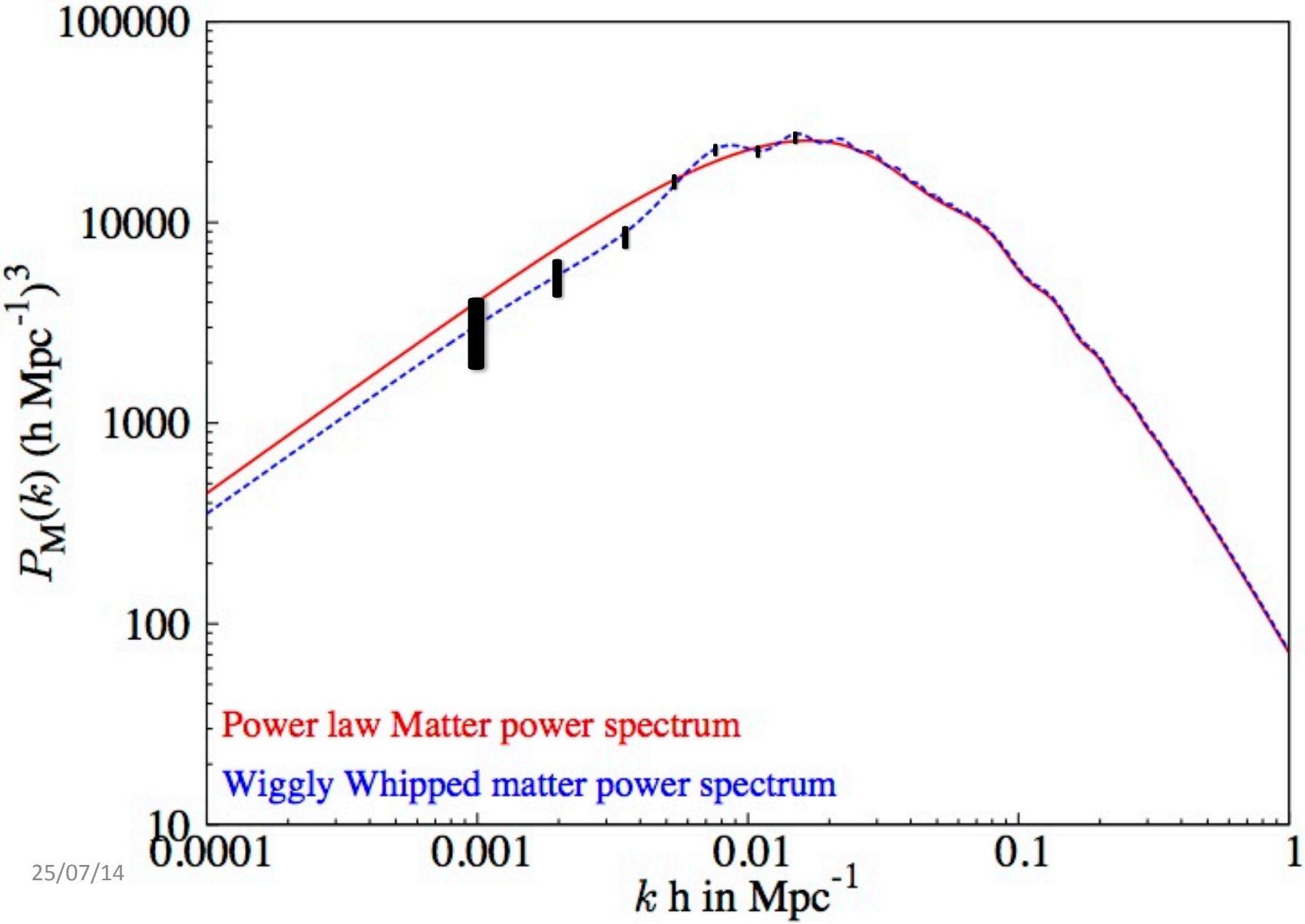
$$\Sigma \mathrm{N}_\nu : \pm 0.056$$



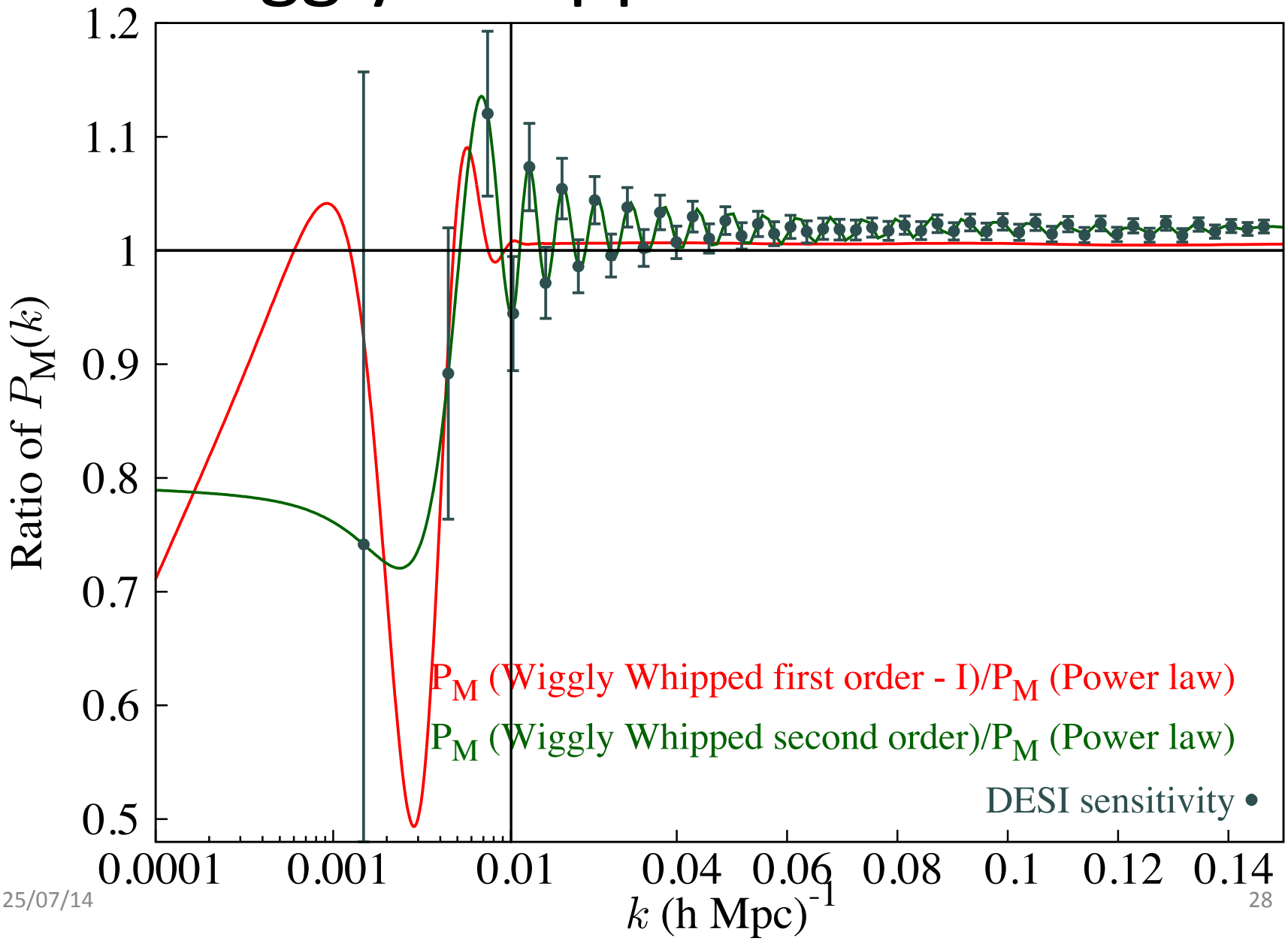
GUT-Scale Inflation



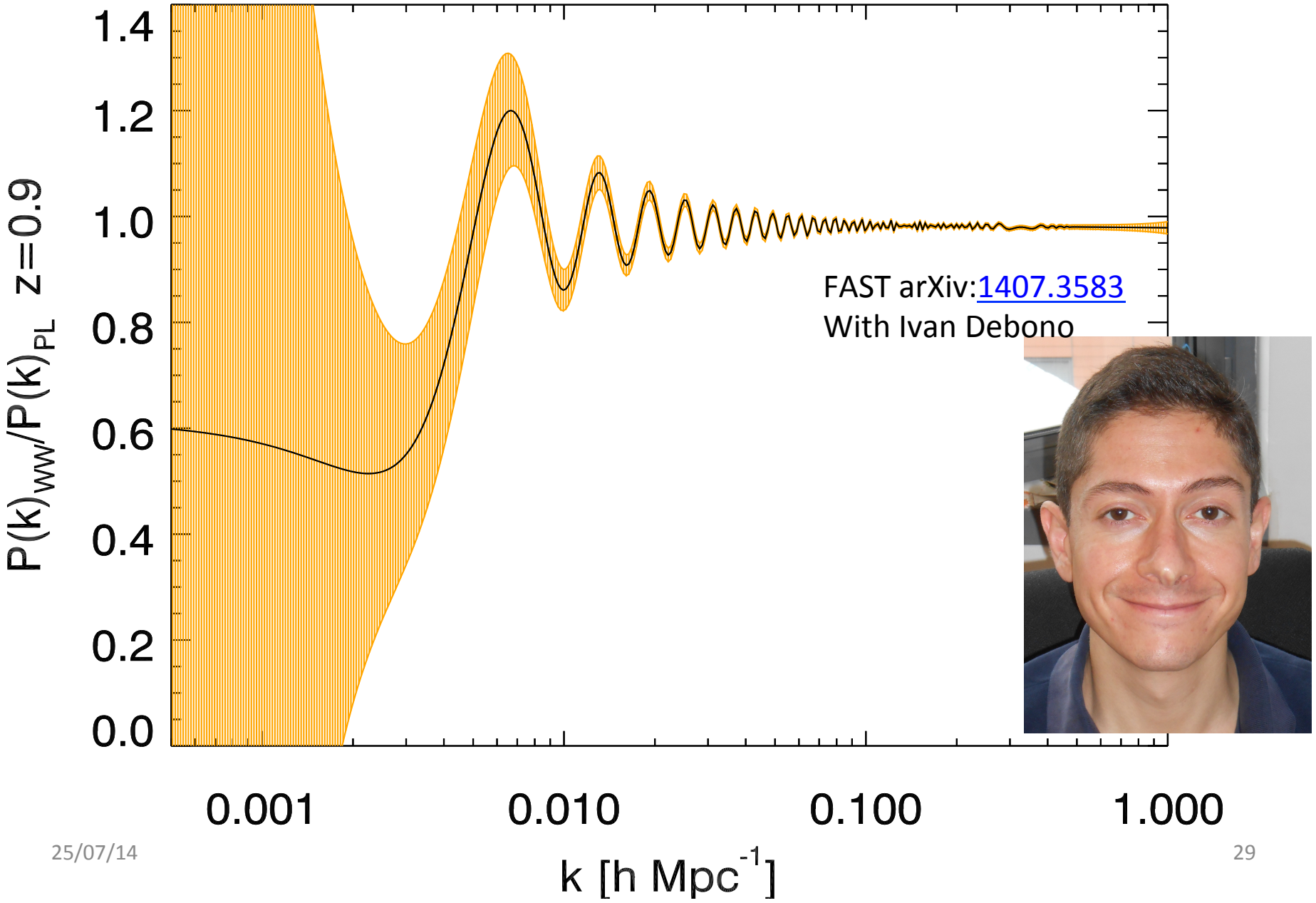
GUT-Scale Inflation



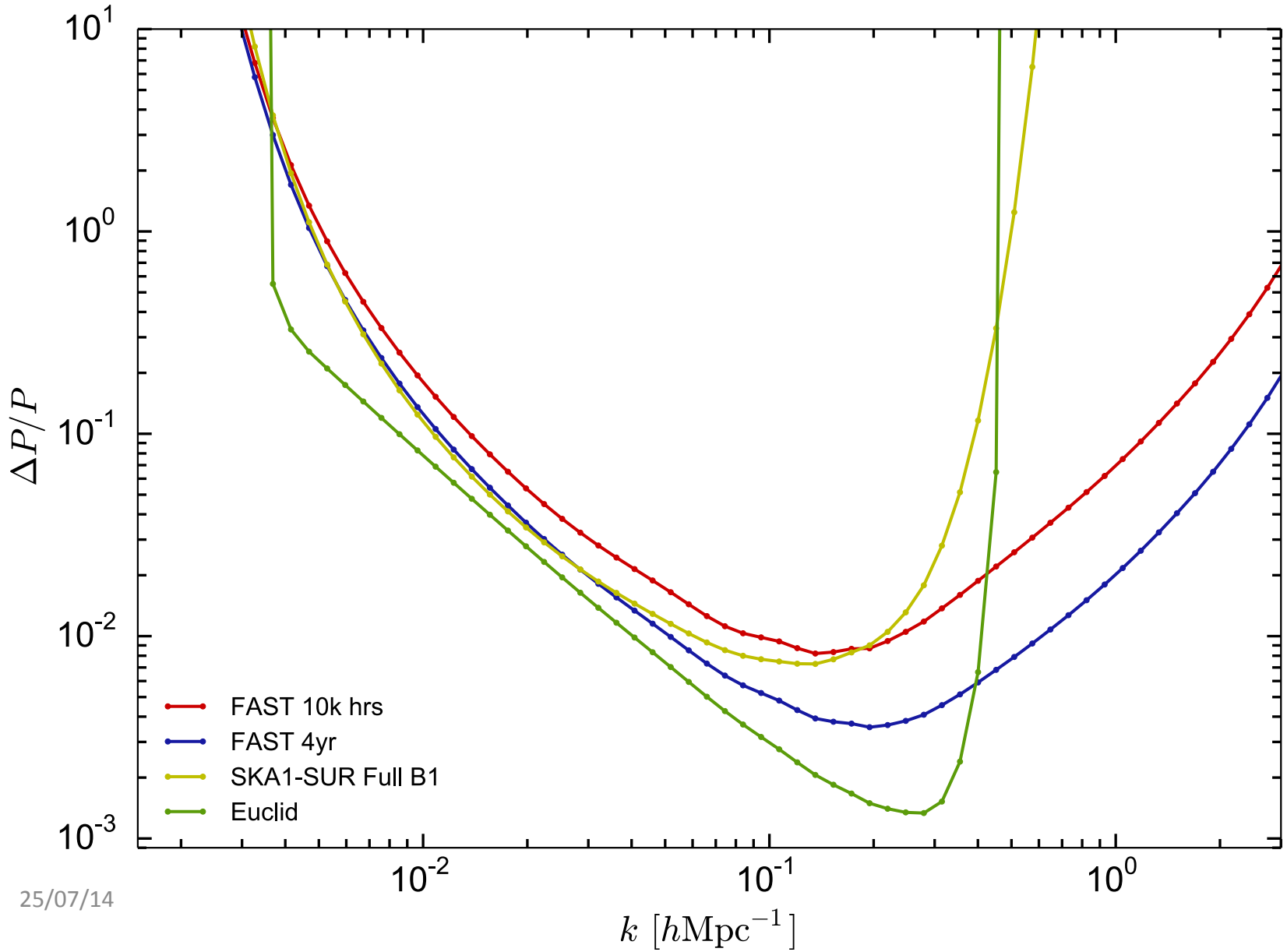
Wiggly Whipped 2nd Order



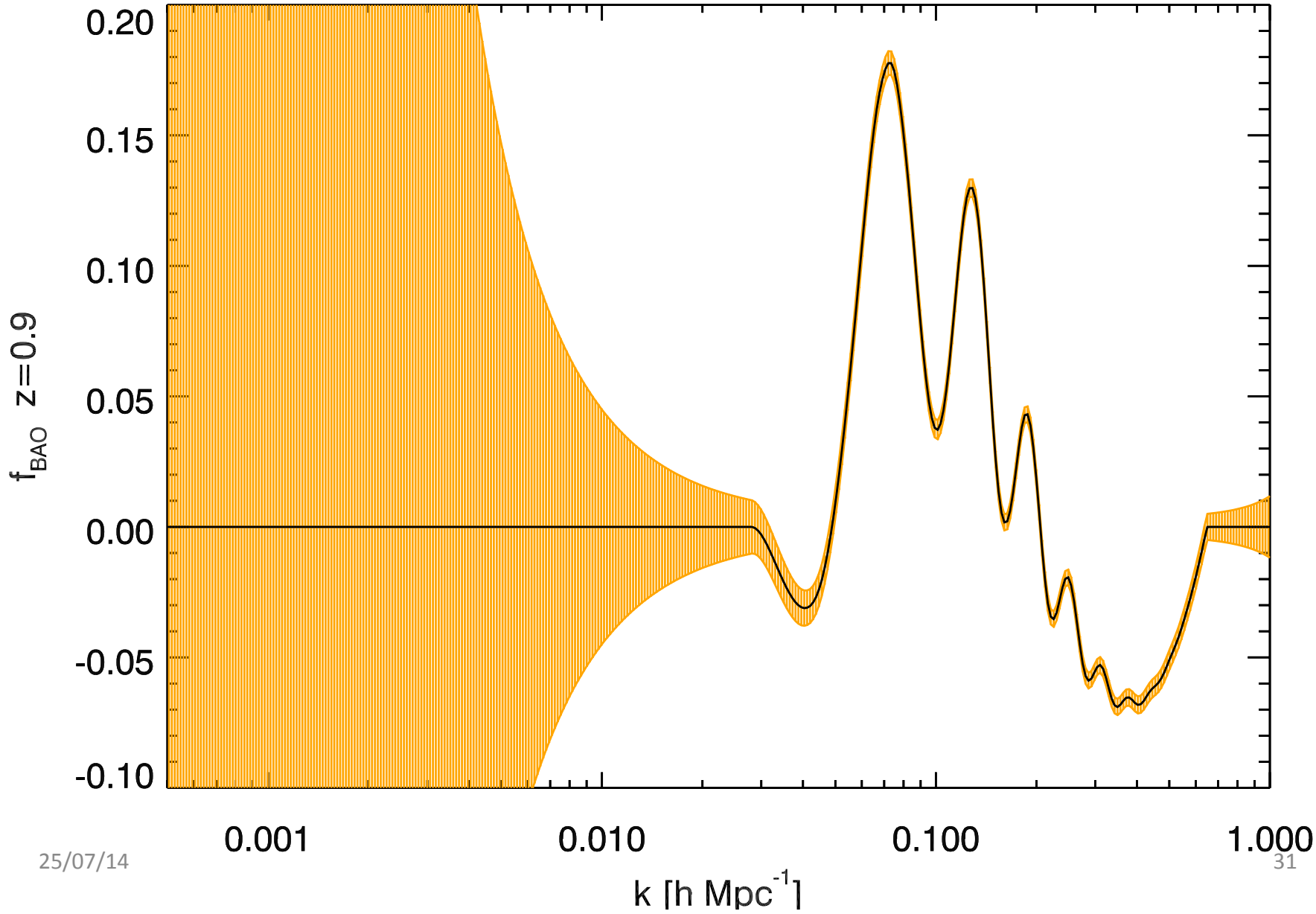
21-cm Intensity Mapping



Comparison of SKA, FAST, Euclid/DETF-IV



Baryon Acoustic Oscillation (BAO) Obs



FAST: Five-Hundred-meter Aperture Spherical Telescope; Guizhou

Inflation

- Look at power spectrum
- Look for three-point correlations (CMB)
- Look a “scale dependence” of bias

$$P(k) = P(k_0)(k/k_0)^{n_S(k_0)+\frac{1}{2}\alpha_S \ln(k/k_0)}$$

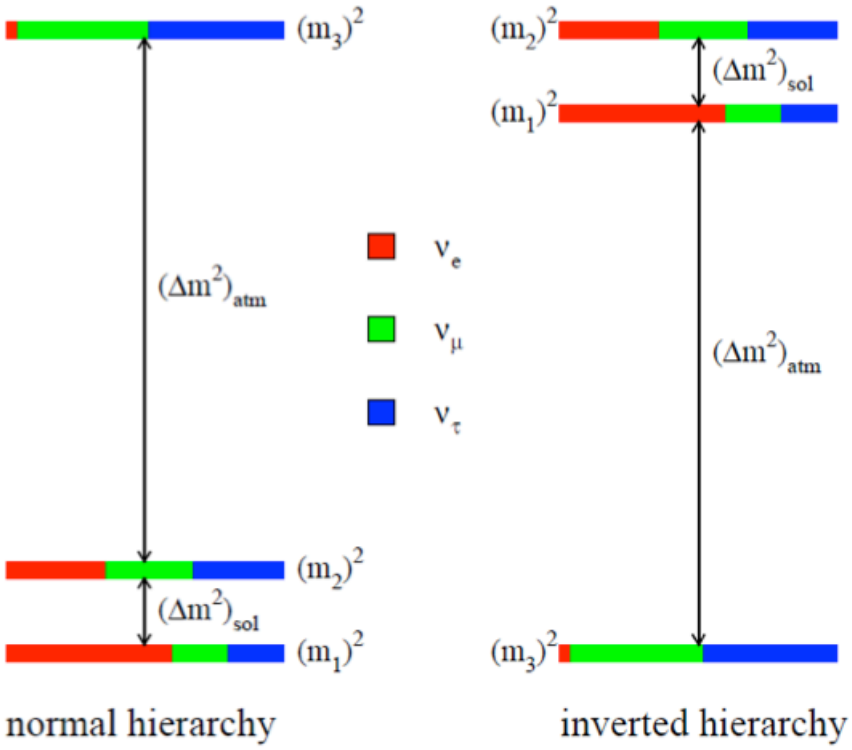
Data	σ_{n_s}	σ_{α_s}
Gal ($k_{\max} = 0.1$ h^{-1}Mpc)	0.0024 (1.6)	0.0051 (1.1)
Gal ($k_{\max} = 0.2$ h^{-1}Mpc)	0.0022 (1.7)	0.0040 (1.3)
Ly-α forest	0.0029 (1.3)	0.0027 (2.0)
Ly-α forest + Gal ($k_{\max} = 0.2$)	0.0019 (2.0)	0.0020 (2.7)

Planck:
n_S=0.9614 ±0.0063
a_S=-0.015±0.017

Measuring the sum of neutrino masses

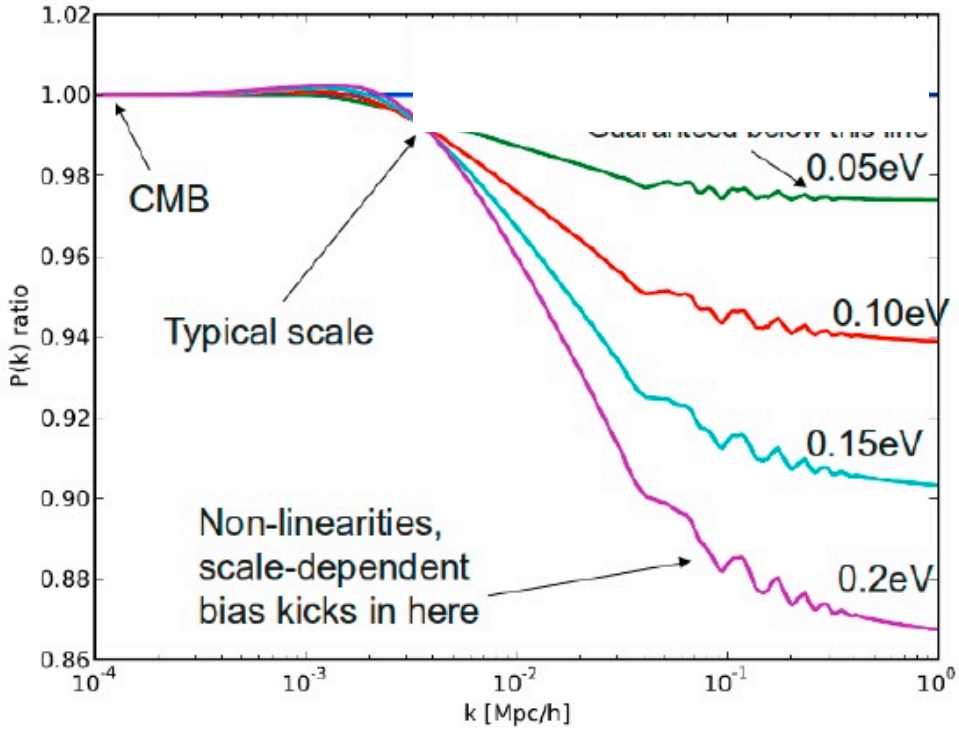
$$\Delta m^2_{32} = 2.32 \times 10^{-3}\,\mathrm{eV}^2$$
$$\Delta m^2_{21} = 7.50 \times 10^{-5}\,\mathrm{eV}^2$$

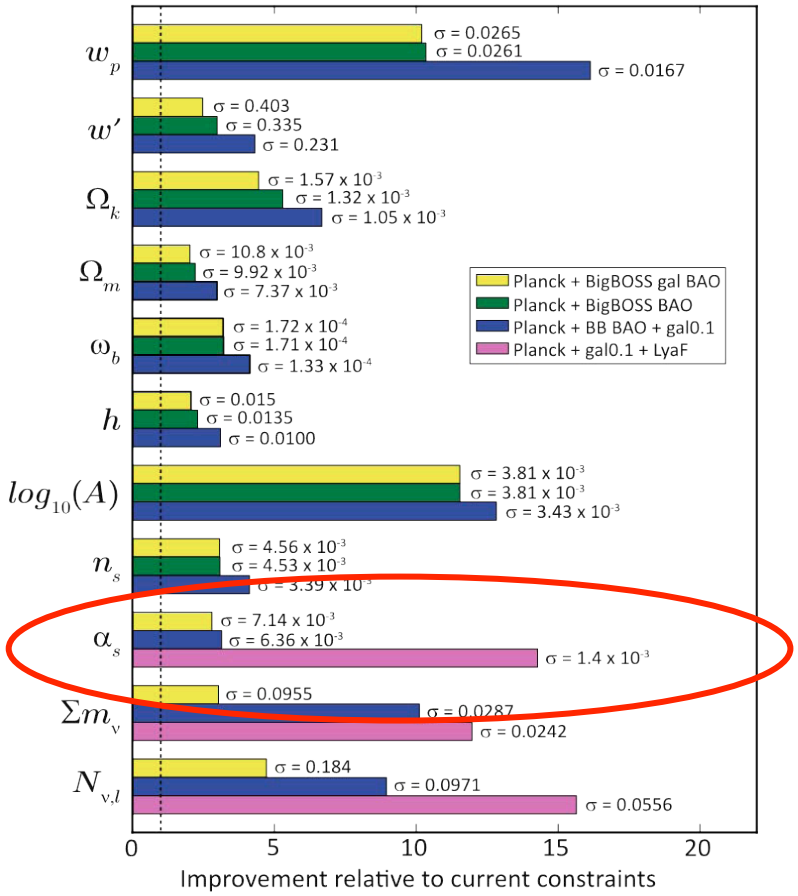
Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.350	0.18
Planck+DESI BAO	0.090	0.18
Gal ($k_{\mathrm{max}} = 0.1$)	0.024	0.13
Gal ($k_{\mathrm{max}} = 0.2$)	0.017	0.084
Ly-α forest	0.039	0.11
Ly-α forest + Gal ($k_{\mathrm{max}} = 0.2$)	0.017	0.063



Fundamental and Primordial Physics

Massive neutrinos free stream, damping the matter power on small scales. Long lever arm in *k* determines Σm_ν to 0.02 eV.



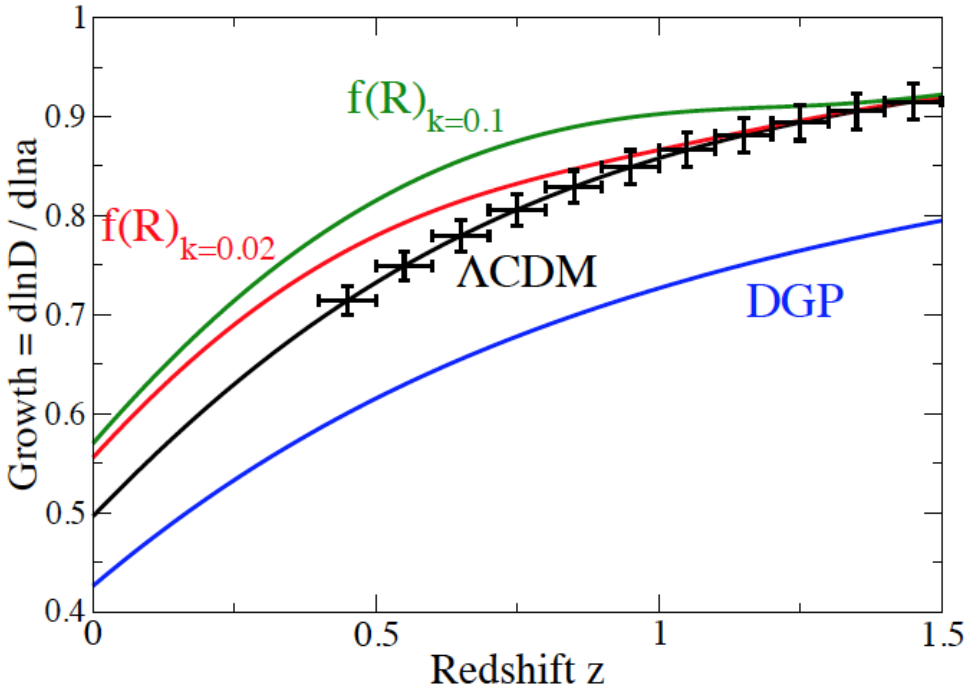


Long range in *k* tests running of primordial spectrum. Large scales test non-Gaussianity. Both are probes of inflation.

Testing General Relativity

- The growth function D(a) is determined by the matter density and General Relativity.

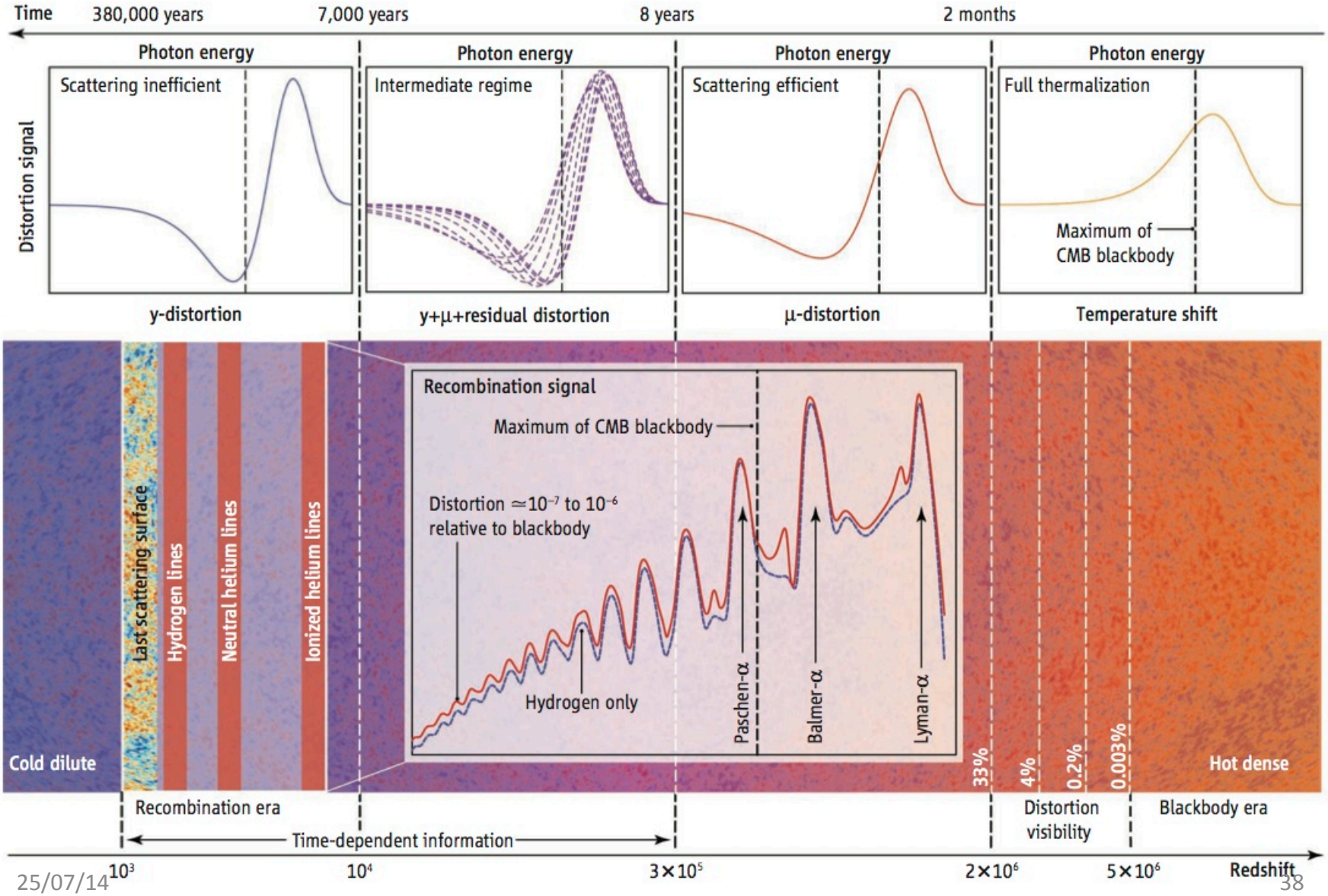
In practice, we measure $f\sigma_{8,}$ where σ_8 sets the scale for P(k).
There will be 2% measurements of $f\sigma_8$ at many values of z.



Next Bigger Steps for Cosmology

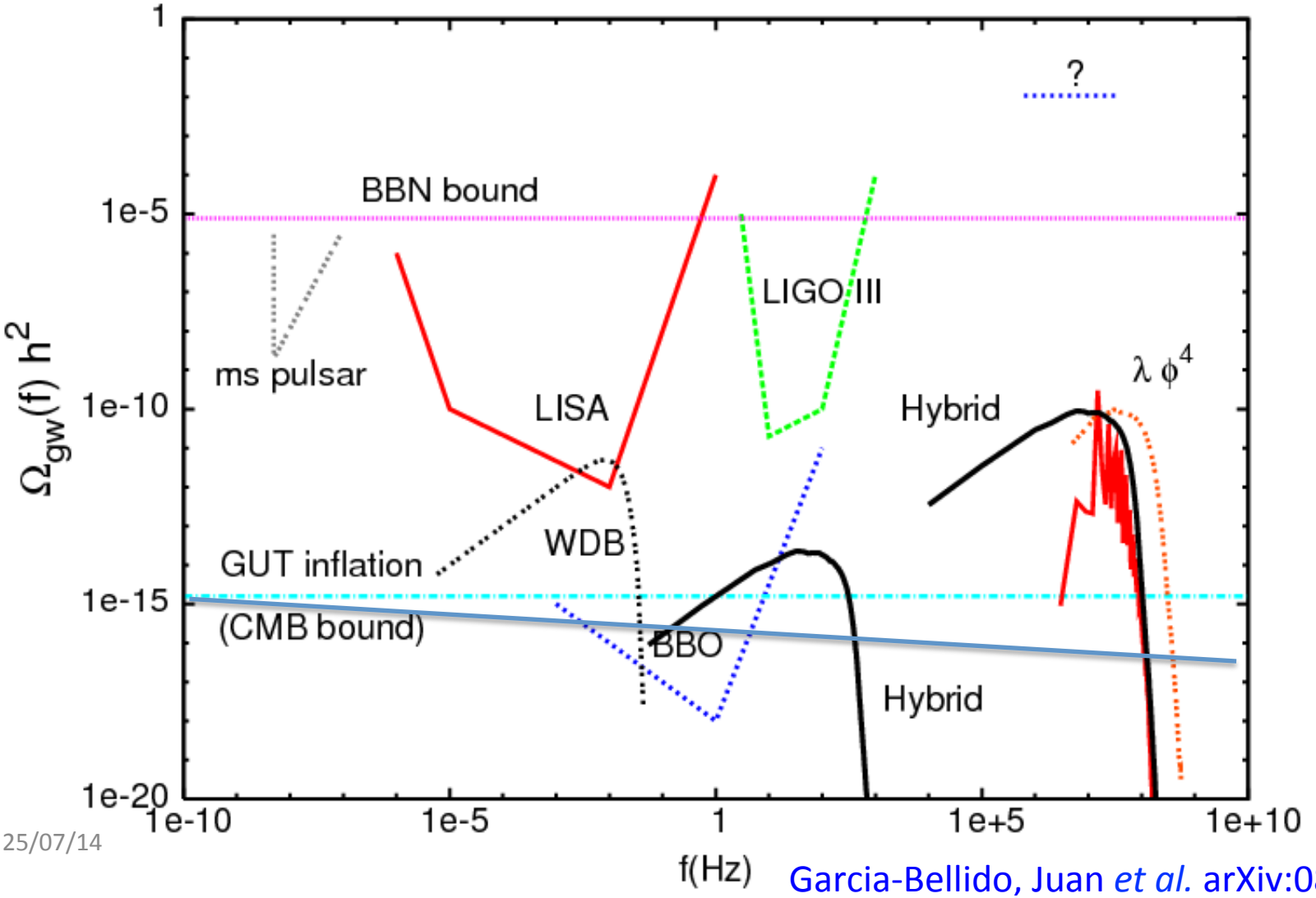
- Euclid Mission
- LSST
- Larger Scale: Large Scale Structure Surveys
- More direct ties and joint fits with HEP
- CMB
  - Is anisotropy phase peaking and winding down
  - Back to CMB spectral distortions?
    - Window on physics
    - Test of energy released in symmetry breaking transitions
- BBO ?

CMB Spectral Distortions



Silk and Chubla Science 2014

Prediction for Gravitational Waves



Garcia-Bellido, Juan *et al.* arXiv:0801.4109

Conclusions

- These are bright days for cosmology
- There are also plenty of new projects one can envision and do over the next two decades
- CMB discovered 50 years ago
- CMB anisotropies 23 years ago
- Accelerating Universe 15 years ago
- Due for another big one – Is it BICEP2 detection of gravitational waves signature?