Observational Cosmology

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COST CA18108 Second Training School

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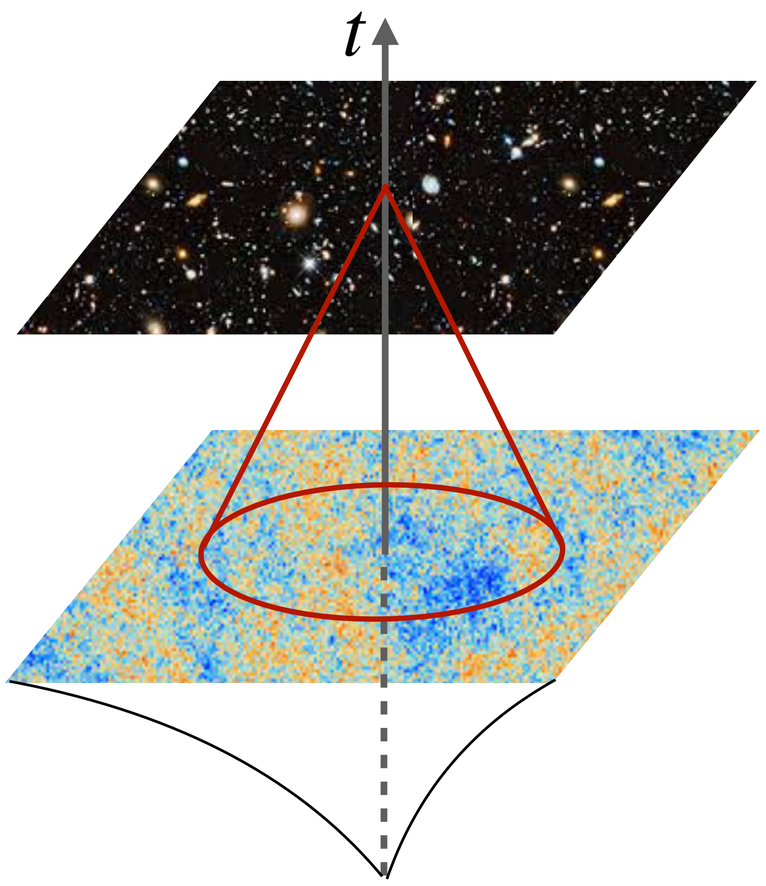
Profound impact of cosmology on HEP



Initial conditions
(inflation)

Matter-antimatter asymmetry
Dark matter
Dark energy
Inflation

Particle physics, string theory…

What are we hoping for?

Energy scale of inflation

Precise measurements of dark energy

Ultralight axion-like particles

Higher mass/spin particles in PNG

…

Goals for these lectures

The most important observations in cosmology (CMB & LSS)

Observables

Angular power spectra (CMB) and galaxy/matter power spectra (LSS)

Comparison of data and theory

Estimating S/N for cosmological signals

CMB angular power spectrum

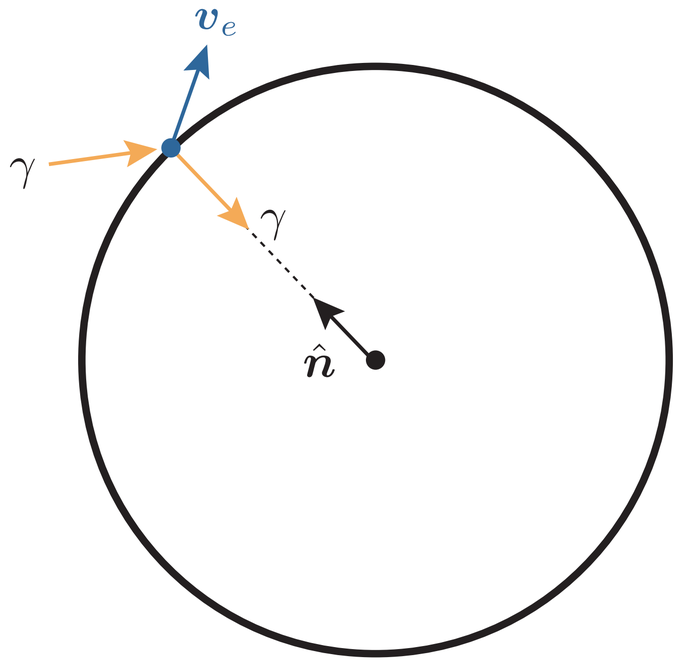
$$\frac{\delta T}{\bar{T}}(\hat{\boldsymbol{n}}) = \left(\frac{1}{4}\delta_\gamma + \Psi + \hat{\boldsymbol{n}}\cdot\boldsymbol{v}_e\right)_* + \int_{\eta_*}^{\eta_0} \mathrm{d}\eta\,(\Psi' + \Phi')$$

density fluct.

Sachs-Wolfe

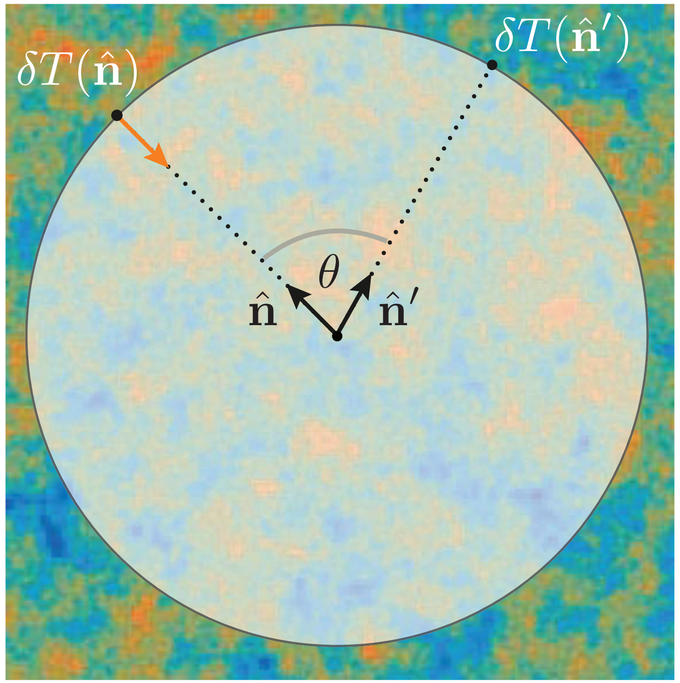
Dopler

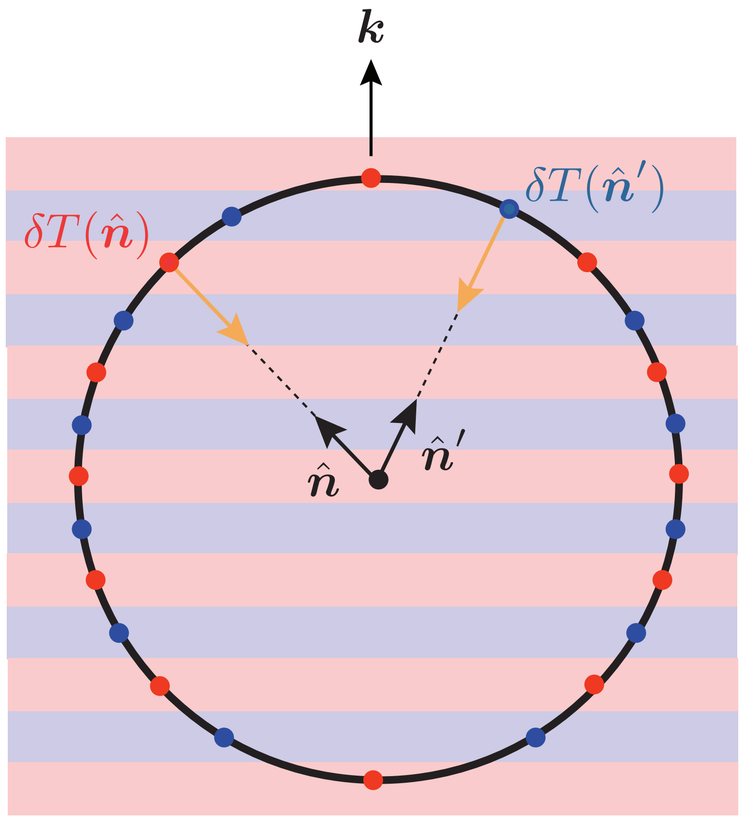
Integrated Sachs-Wolfe



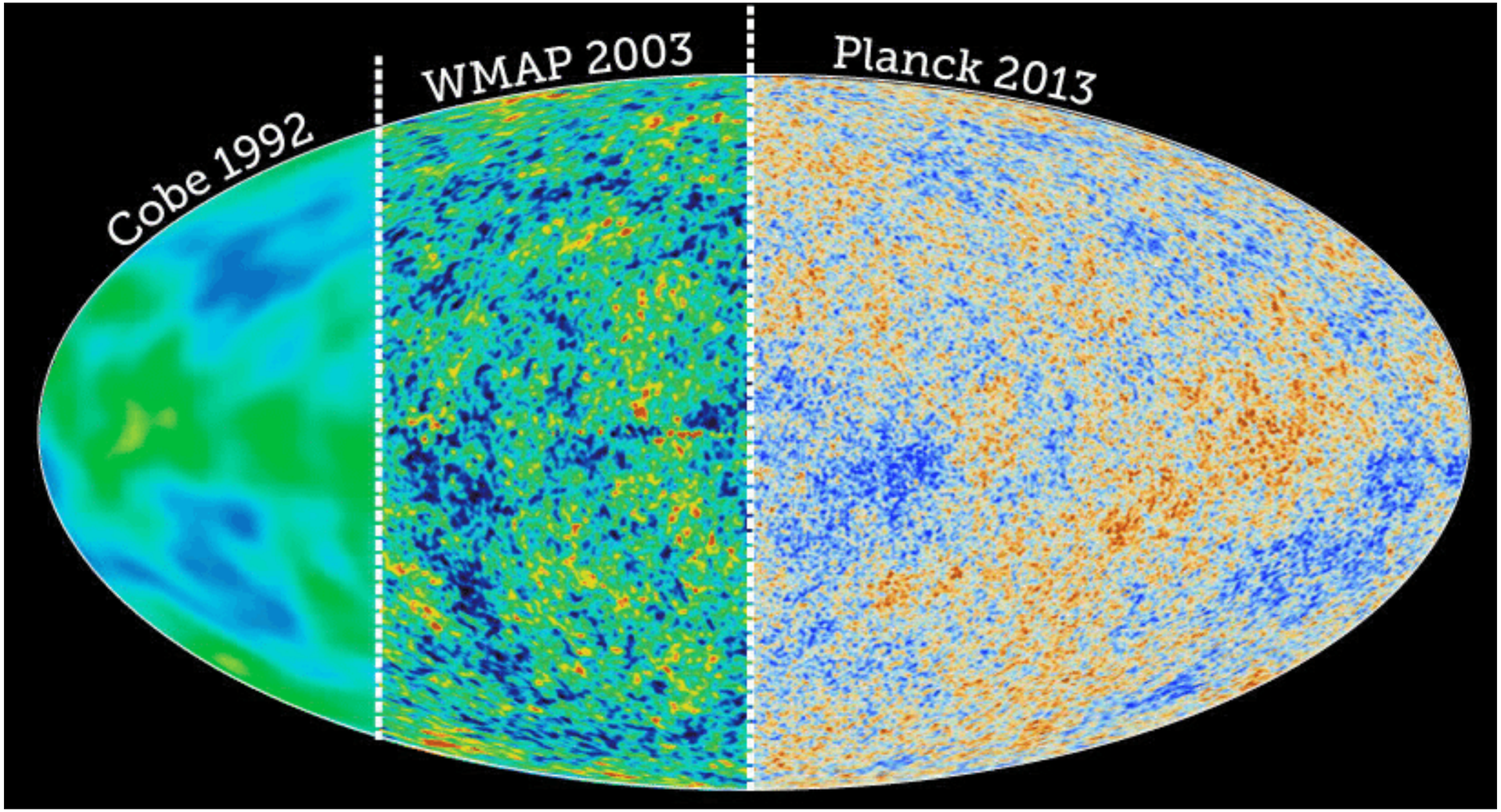
CMB angular power spectrum

There is a simple geometrical connection between the Fourier modes in k-space and the angular power spectrum

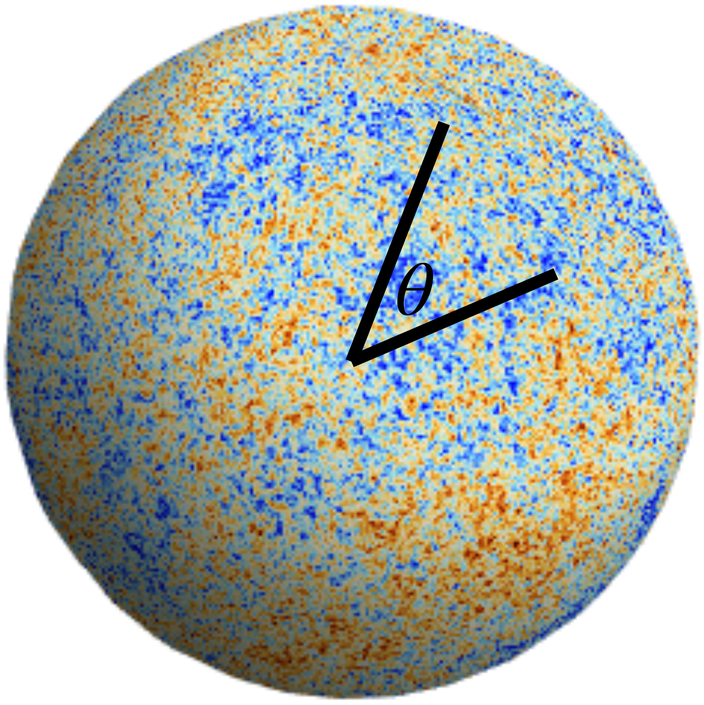




CMB angular power spectrum



CMB angular power spectrum

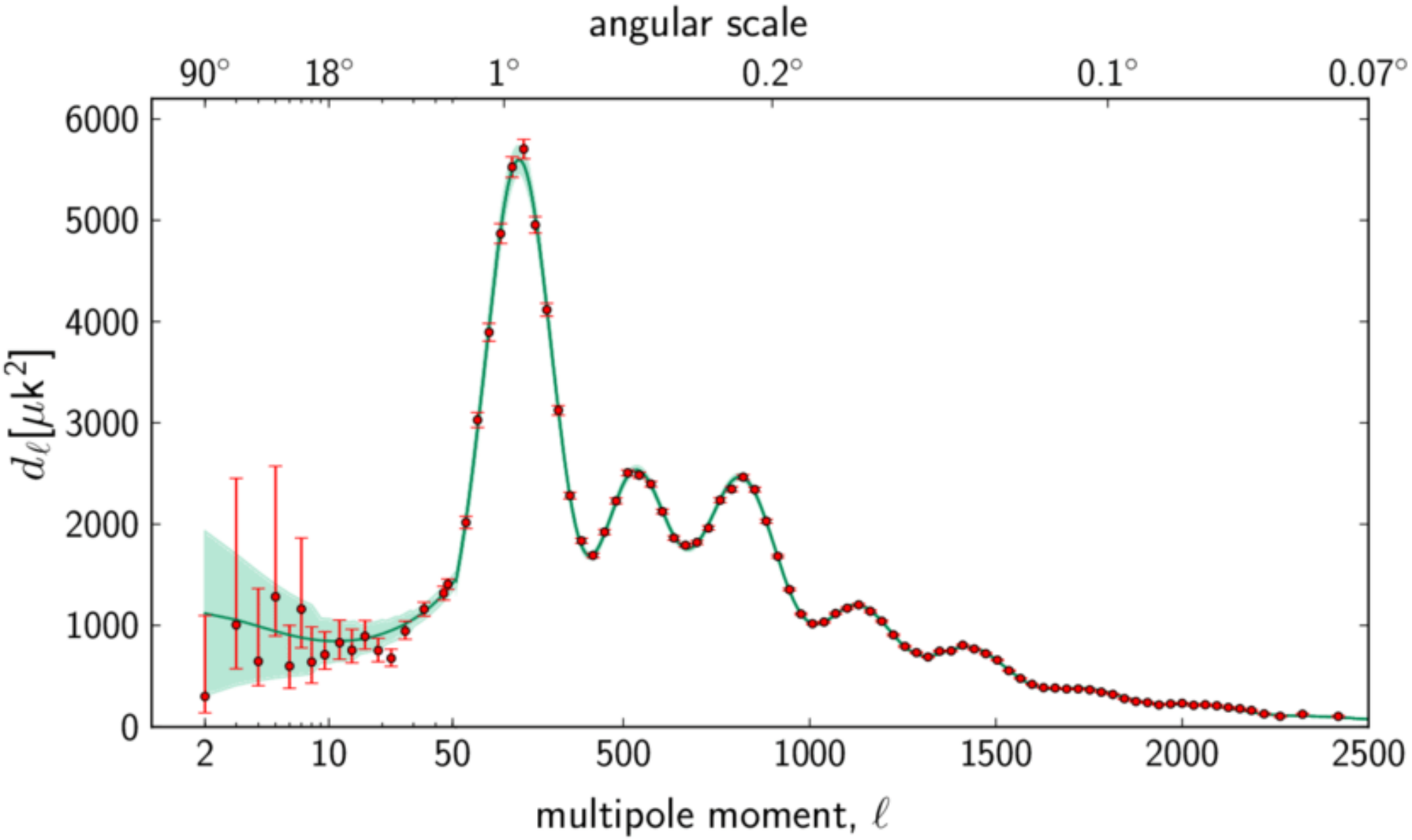


Measure the temperature fluctuations

Estimate the 2-point correlation function

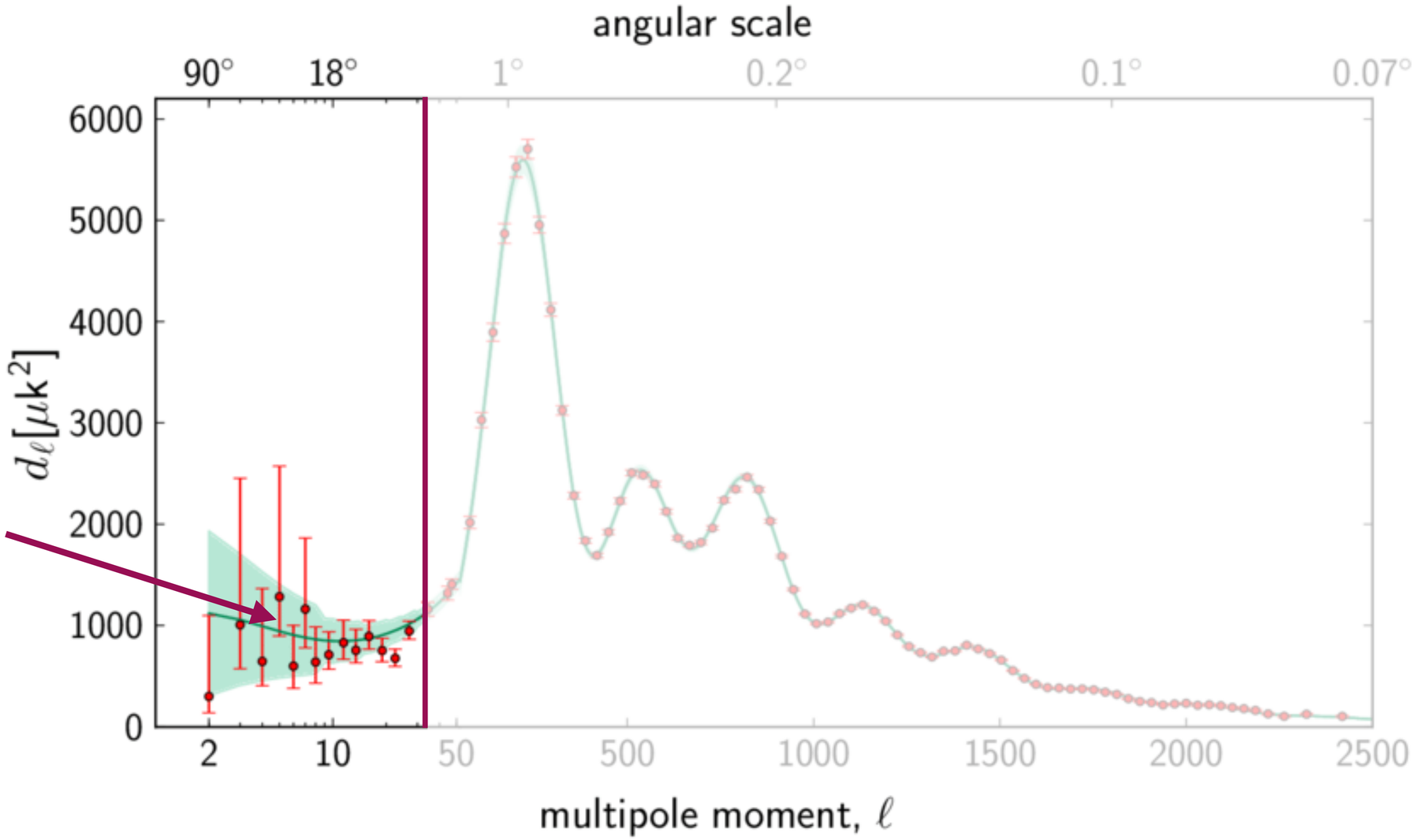
Alternatively, estimate the power spectrum

CMB angular power spectrum

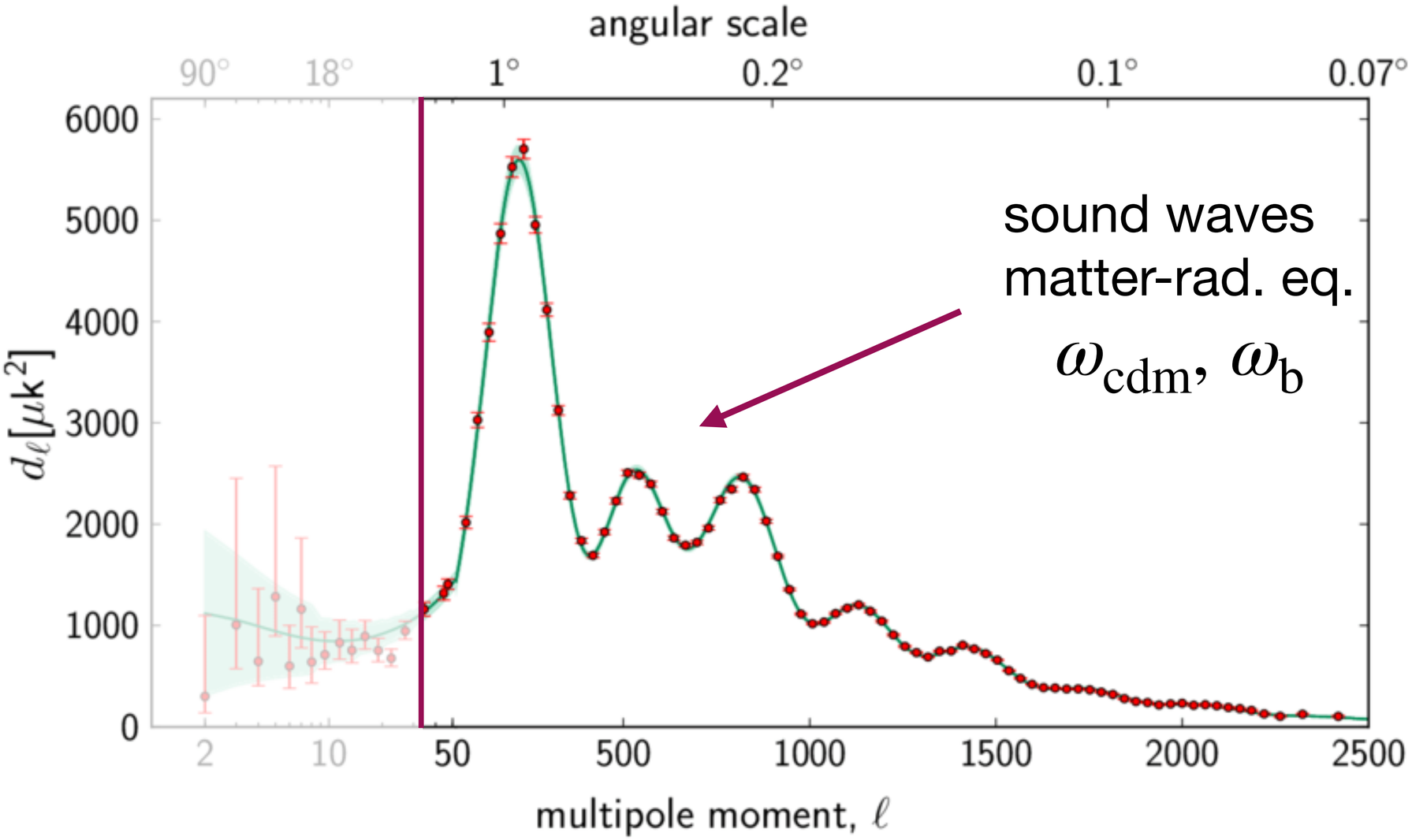


CMB angular power spectrum

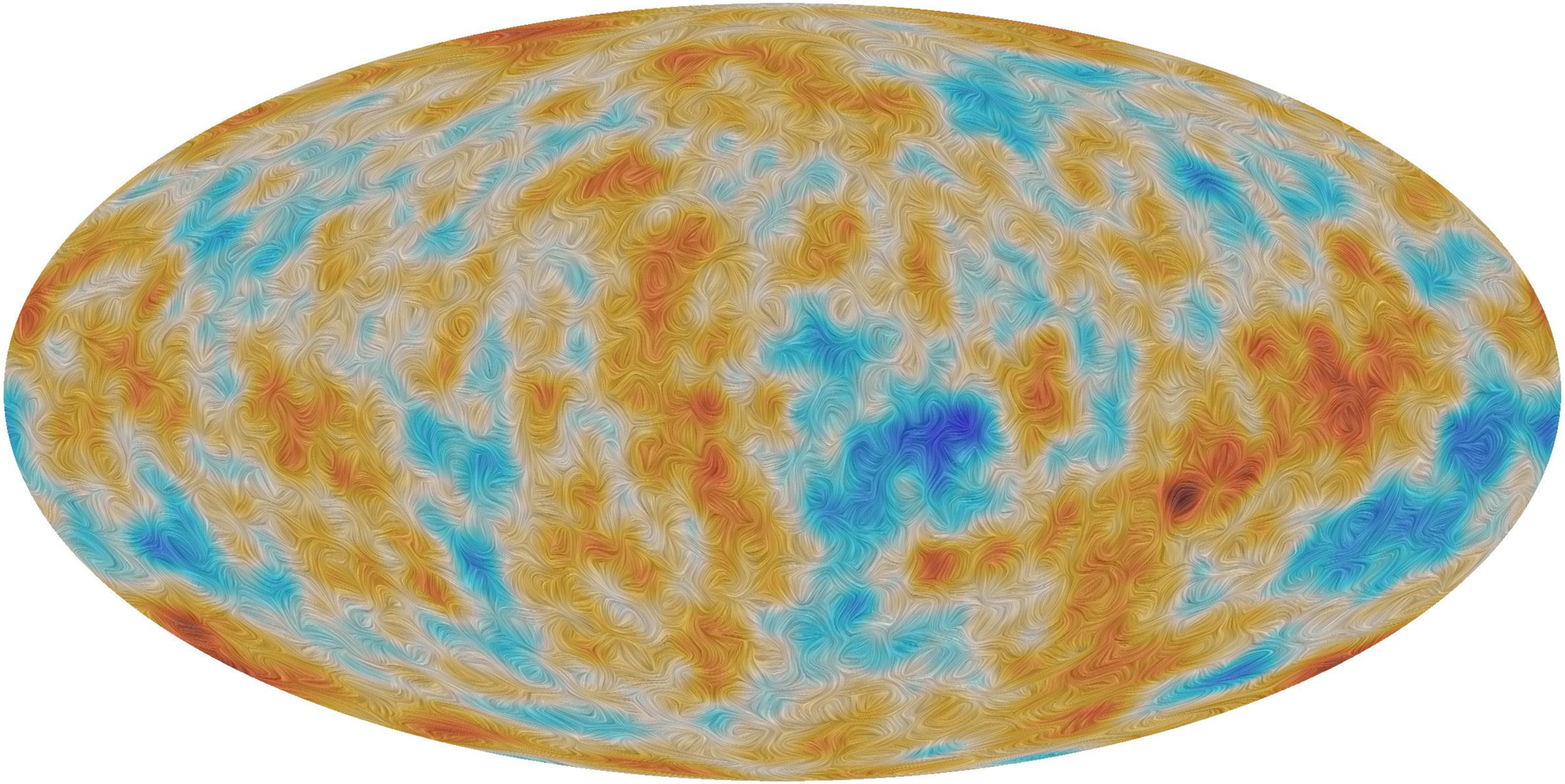
scale-invariant
power spectrum



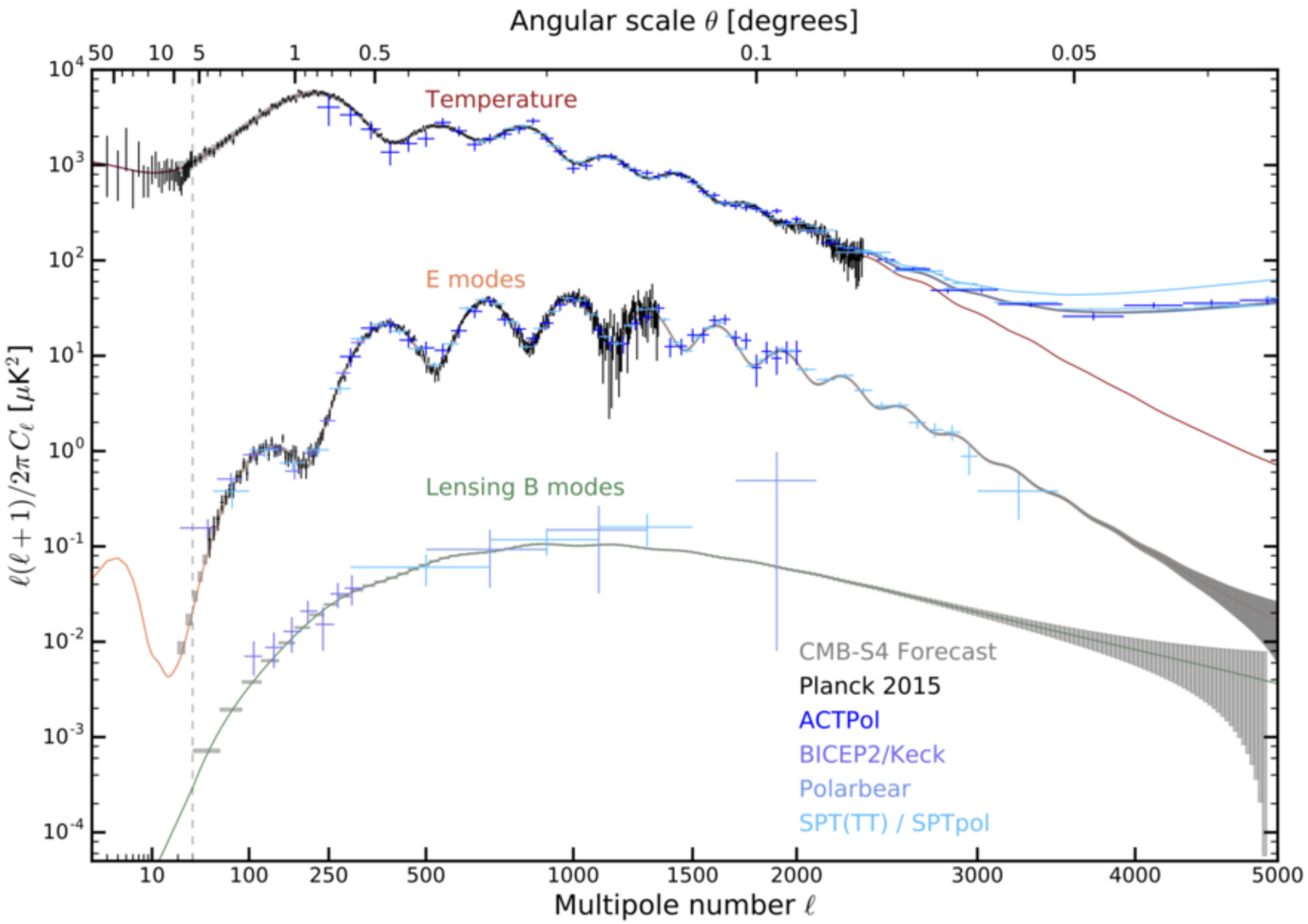
CMB angular power spectrum

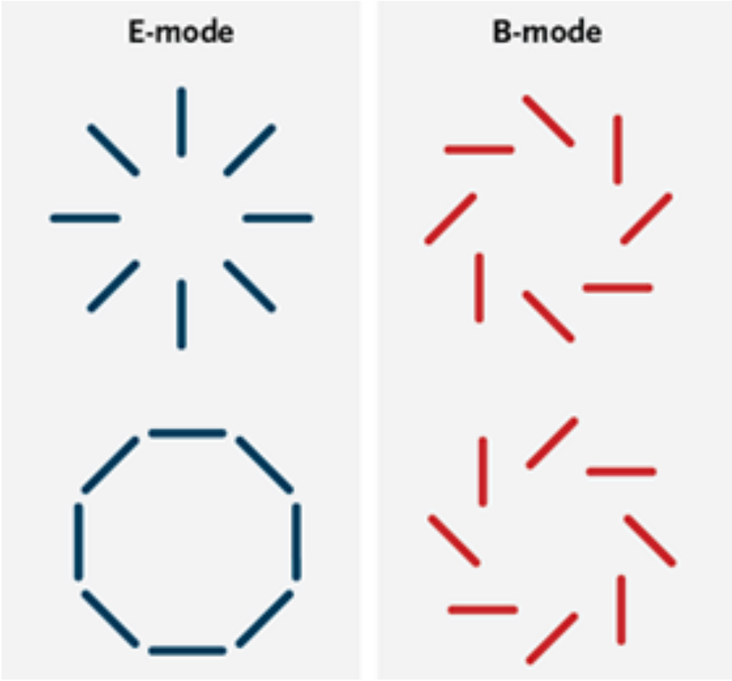


CMB angular power spectrum



CMB angular power spectrum

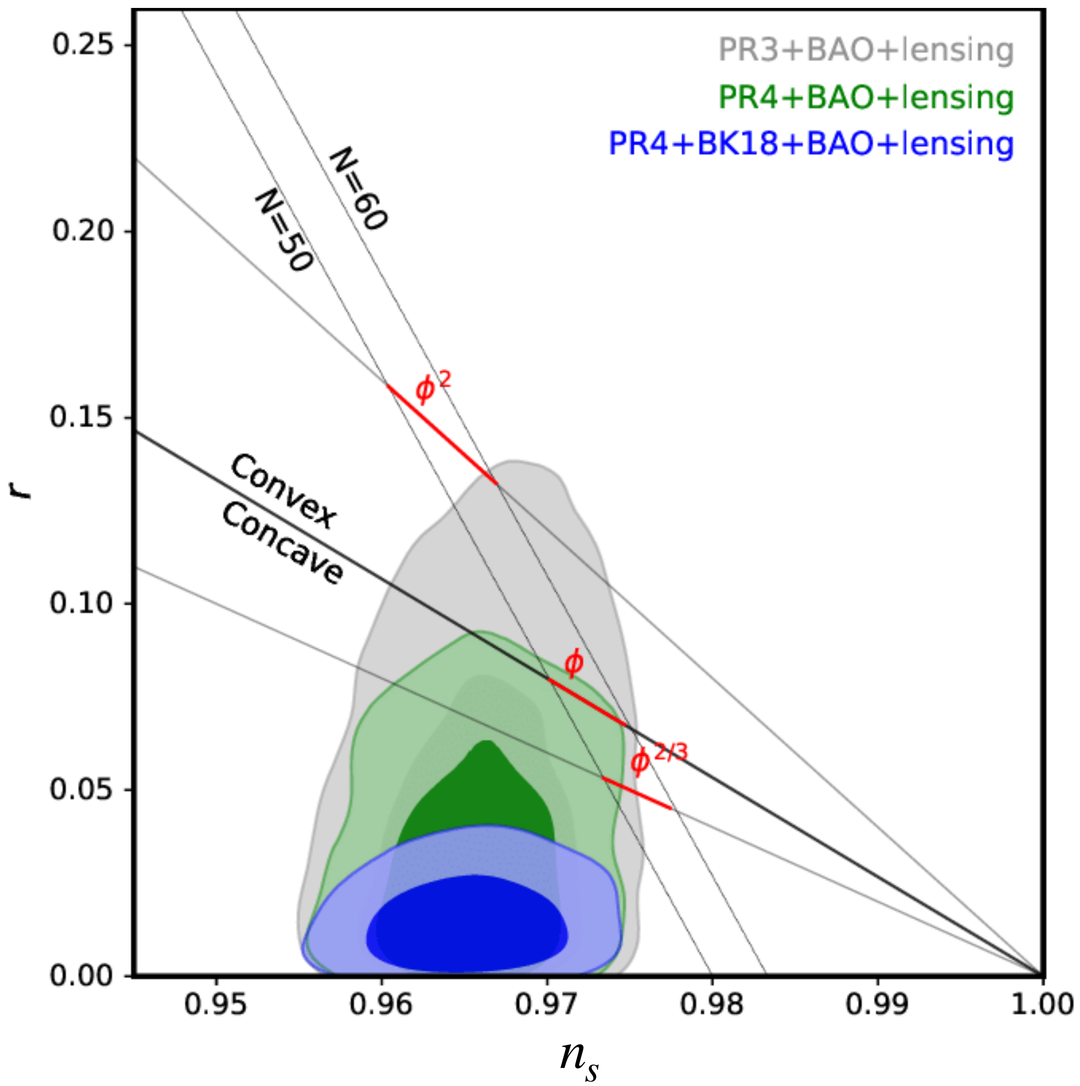




CMB angular power spectrum

Parameter	TT+lowP+lensing 68% limits	TT,TE,EE+lowP+lensing+ext 68% limits
n_s	0.9677 ± 0.0060	0.9667 ± 0.0040
H_0	67.81 ± 0.92	67.74 ± 0.46
Ω_Λ	0.692 ± 0.012	0.6911 ± 0.0062
Ω_m	0.308 ± 0.012	0.3089 ± 0.0062
$\Omega_b h^2$	0.02226 ± 0.00023	0.02230 ± 0.00014
$\Omega_c h^2$	0.1186 ± 0.0020	0.1188 ± 0.0010
σ_8	0.8149 ± 0.0093	0.8159 ± 0.0086
z_{re}	$8.8^{+1.7}_{-1.4}$	$8.8^{+1.2}_{-1.1}$
Age/Gyr	13.799 ± 0.038	13.799 ± 0.021

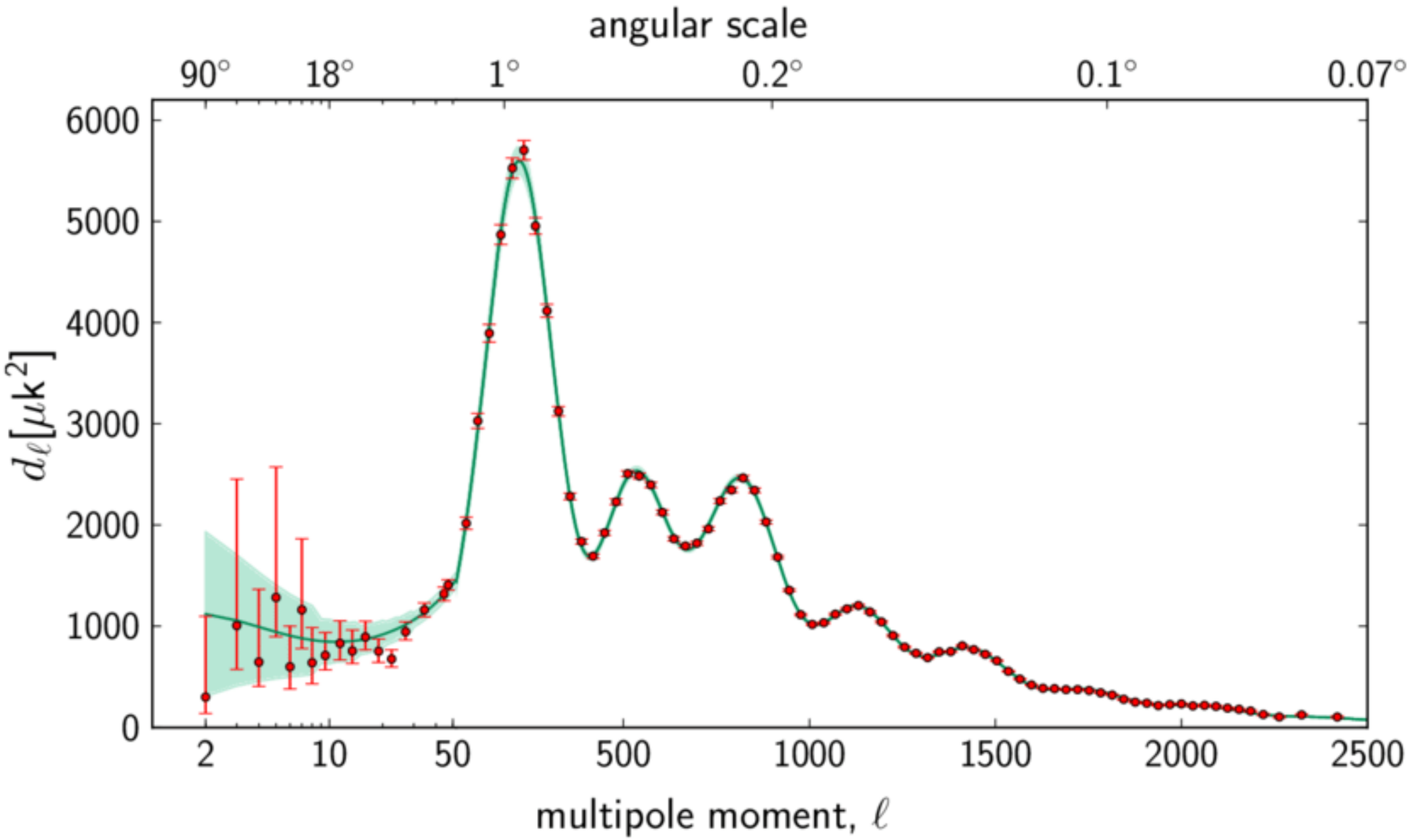
CMB angular power spectrum



Simple potentials are observationally ruled out!

Interesting target $r \sim 10^{-3}$

CMB angular power spectrum

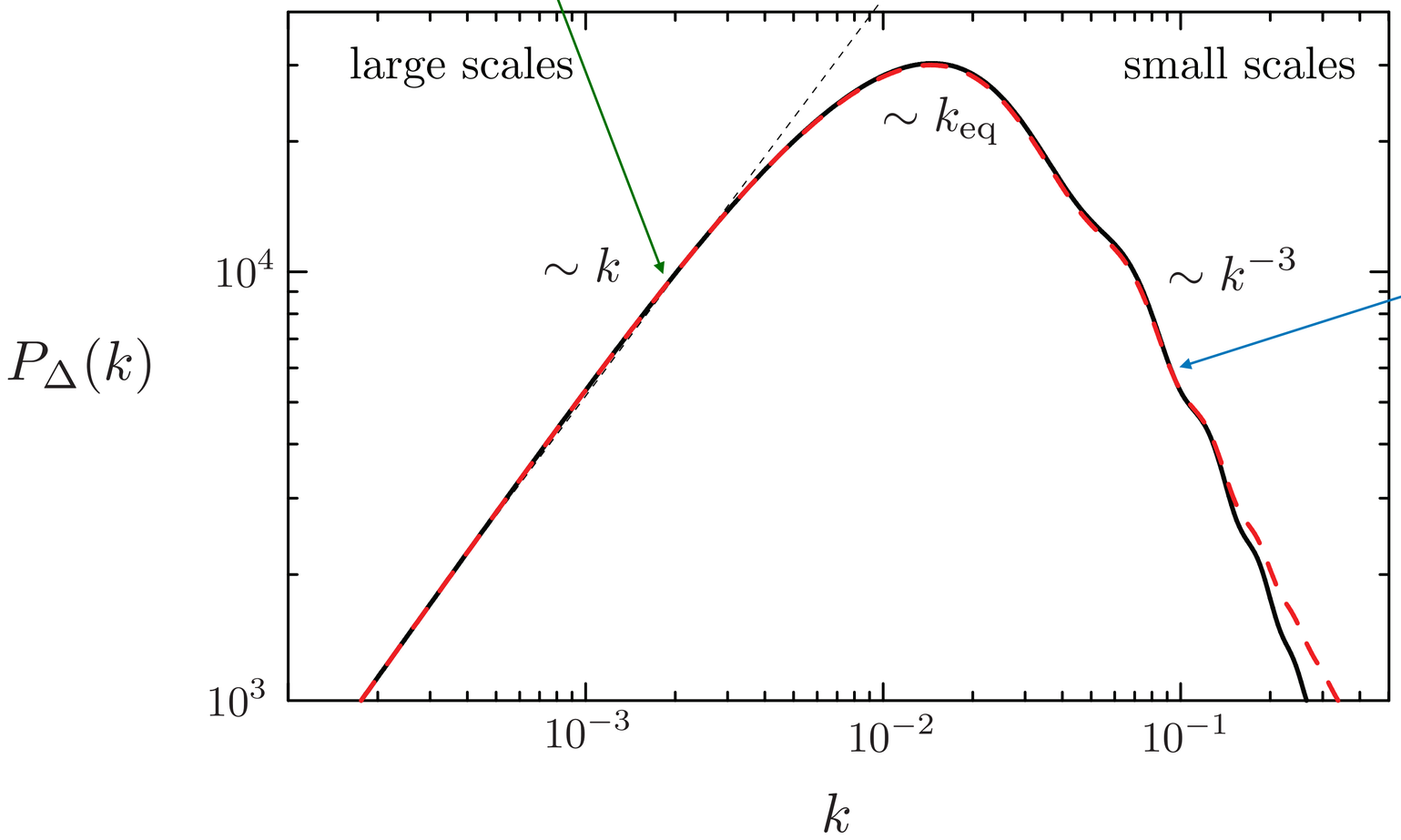


Linear matter power spectrum

these wavenumbers
are smaller than H_eq

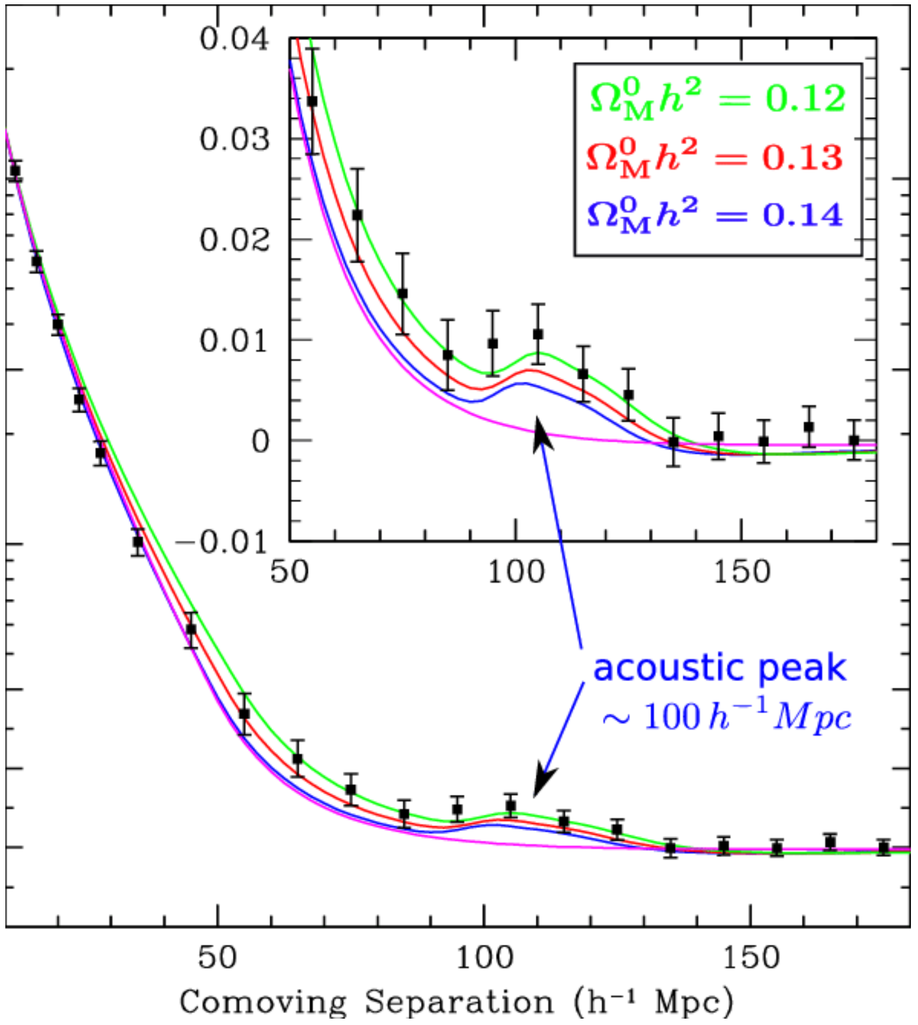
Ak^{α}

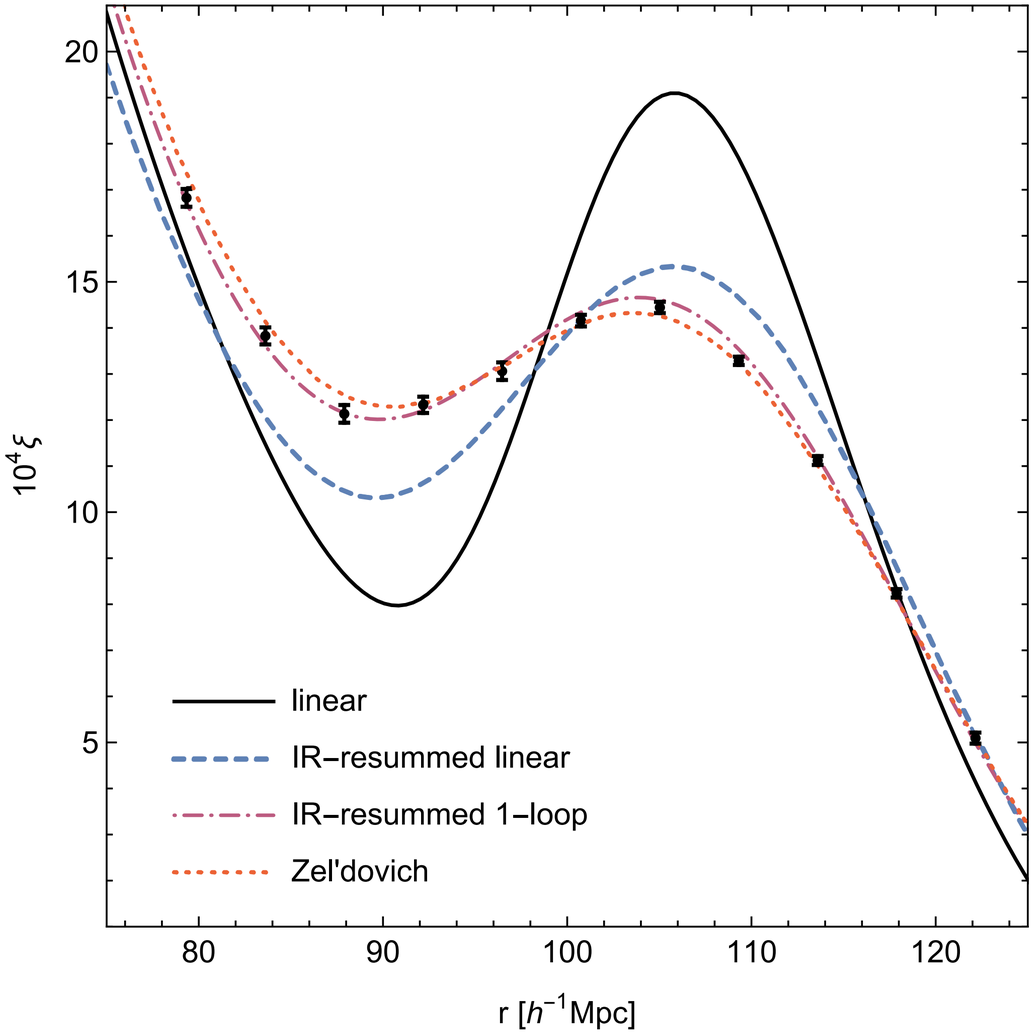
$\alpha \sim 1$



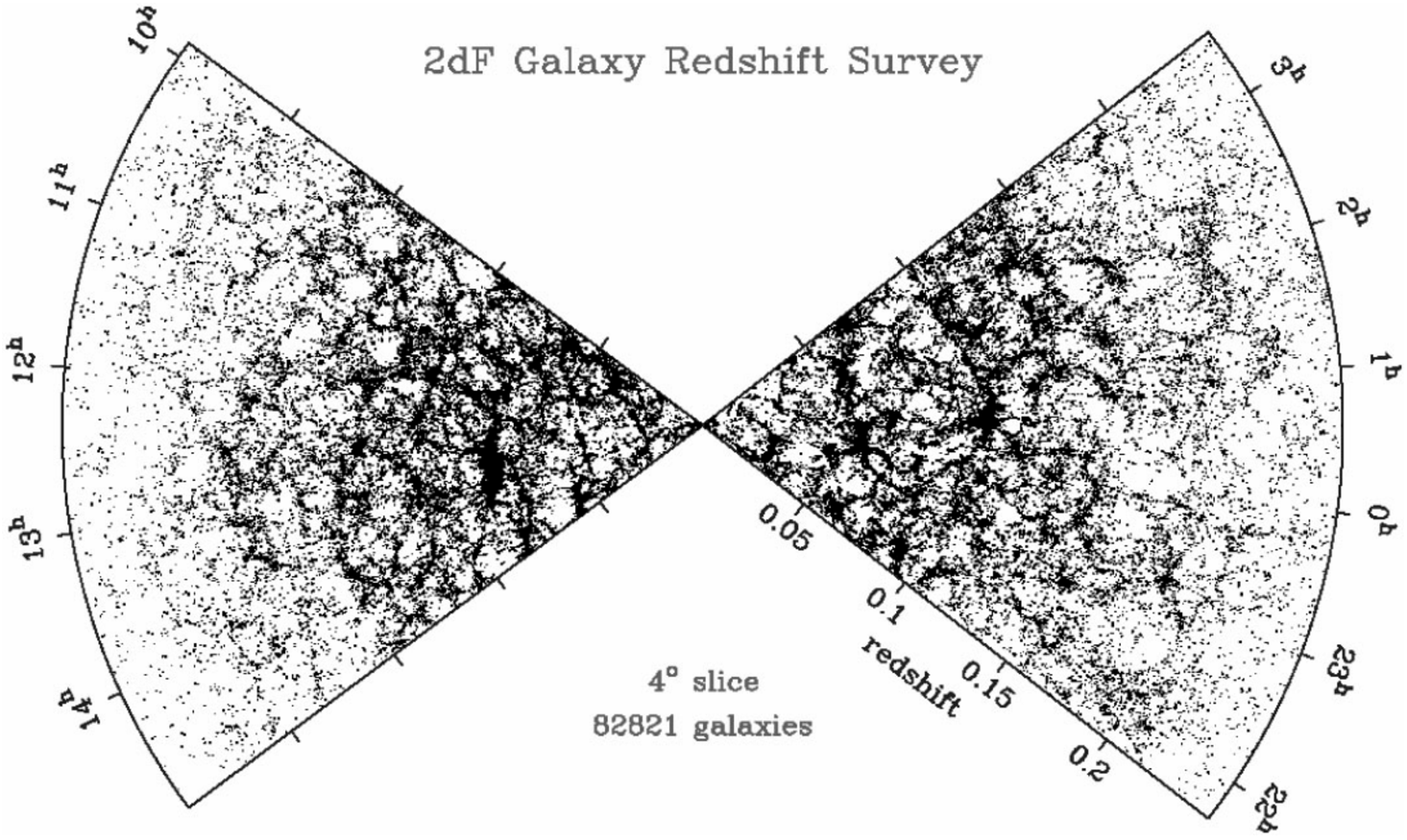
Baryon acoustic
oscillation wiggles

Linear matter correlation function

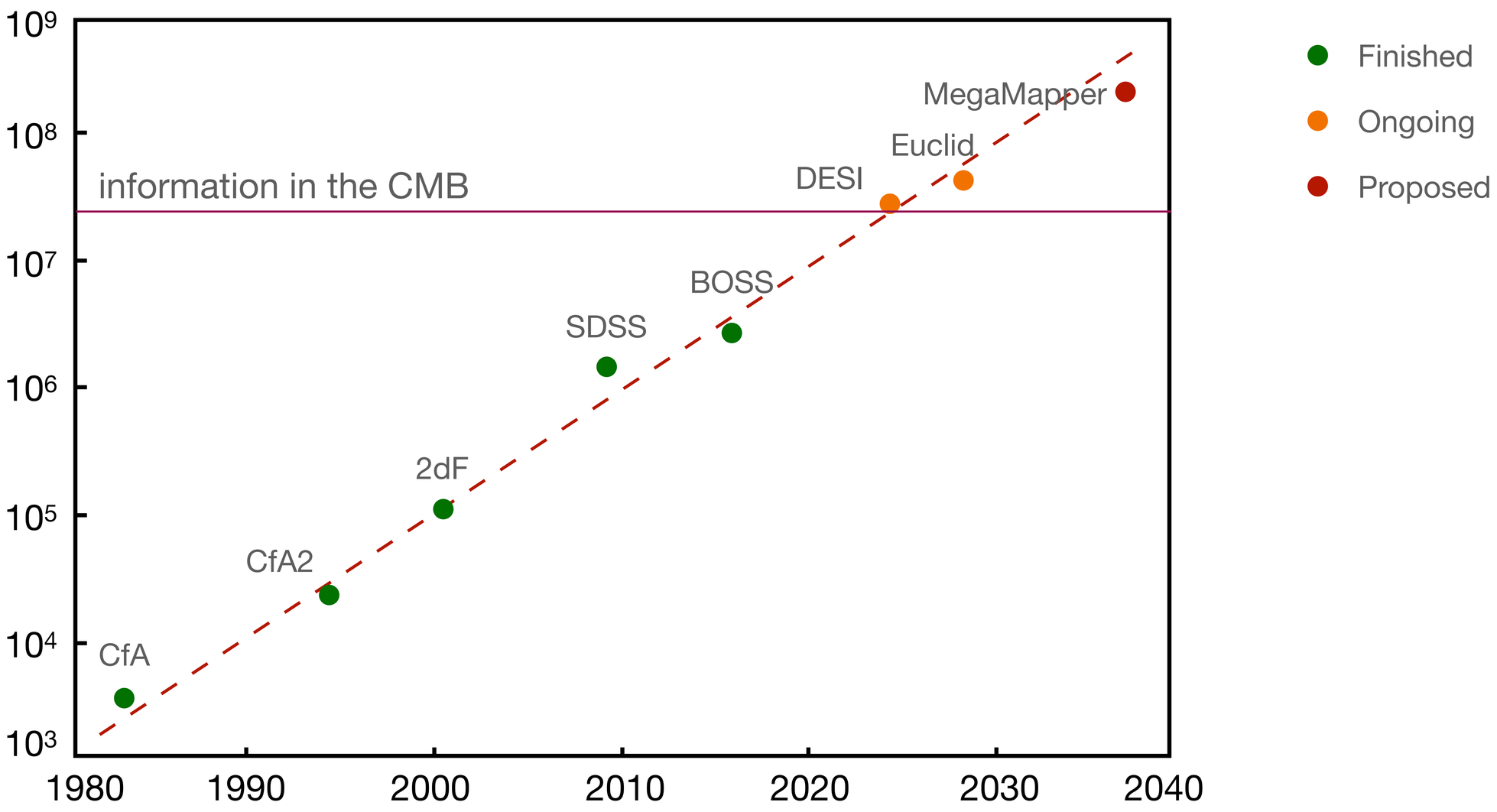




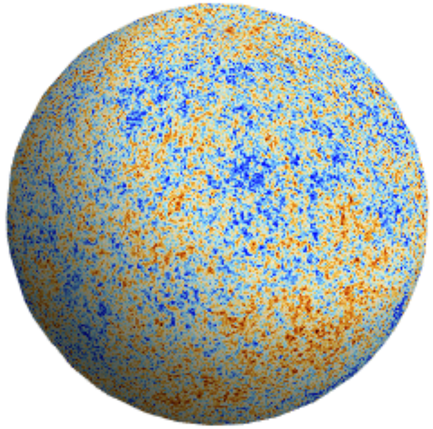
What do we actually measure?

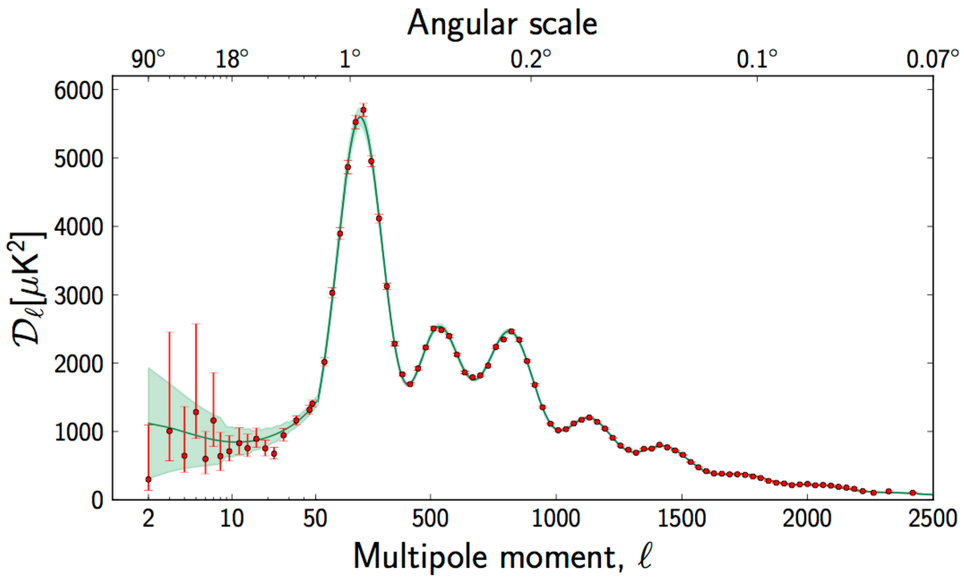


Size of galaxy samples as a function of time



Isn't the CMB good enough?





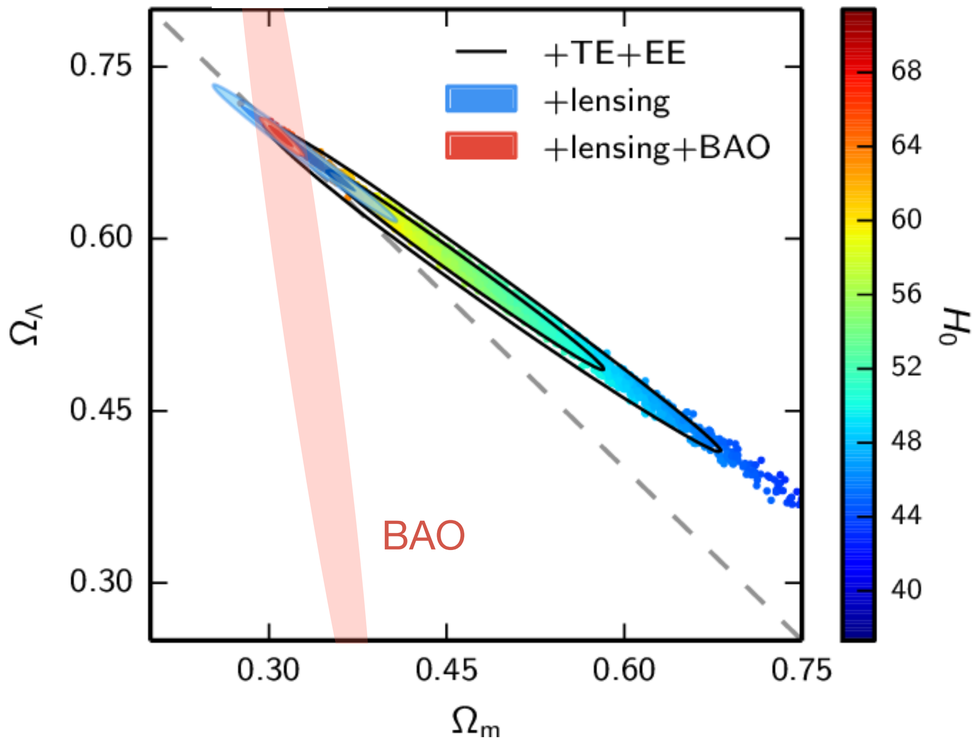
Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54

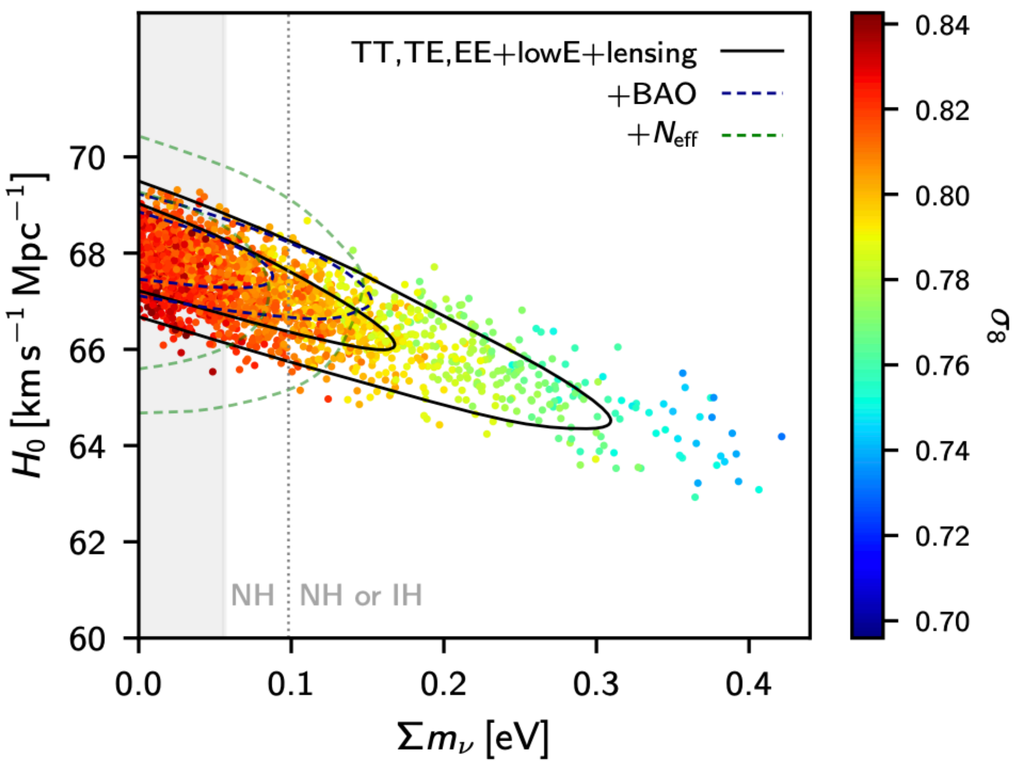
$$r_s(\omega_{\rm cdm}, \omega_{\rm b}) \xrightarrow{\Lambda\text{CDM}} H_0$$

$$D_A(z) = \frac{1}{1+z}\int_0^z \frac{dz'}{H(z')}$$

1) Approaching the limit, given by the number of pixels: $N_{\rm pix.} \approx \ell^2_{\rm max.} \sim 10^7$

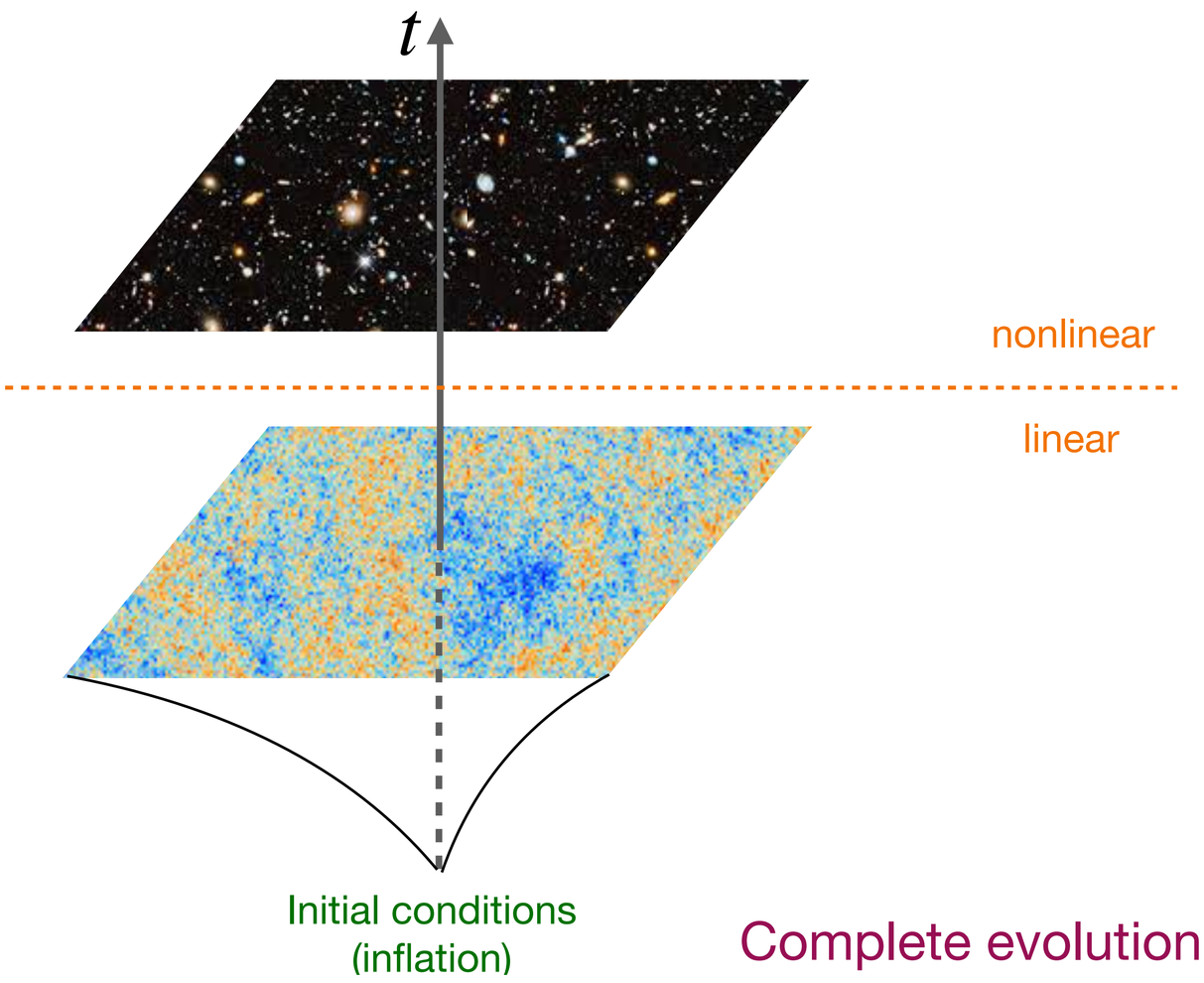
Isn’t the CMB good enough?





2) Degeneracies in the CMB have to be broken by the external data

A dawn of new era in cosmology



CLASS-PT Chudaykin, Ivanov, Philcox, MS (2019)

PyBird D'Amico, Senatore, Zhang (2019)

velocileptors Chen, Vlah, Castorina, White (2020)

MCMC made possible

CMBFAST
CAMB
CLASS

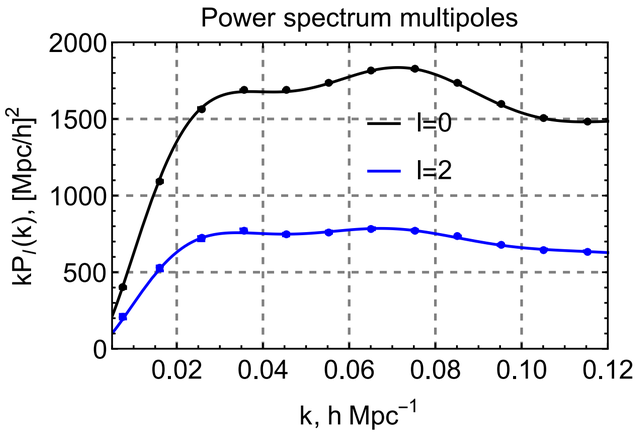
MCMC done routinely

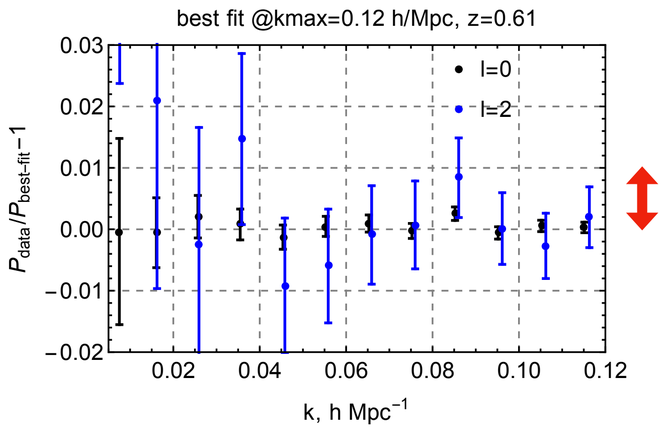
Complete evolution of the vacuum state from inflation to redshift zero

How well does PT work?

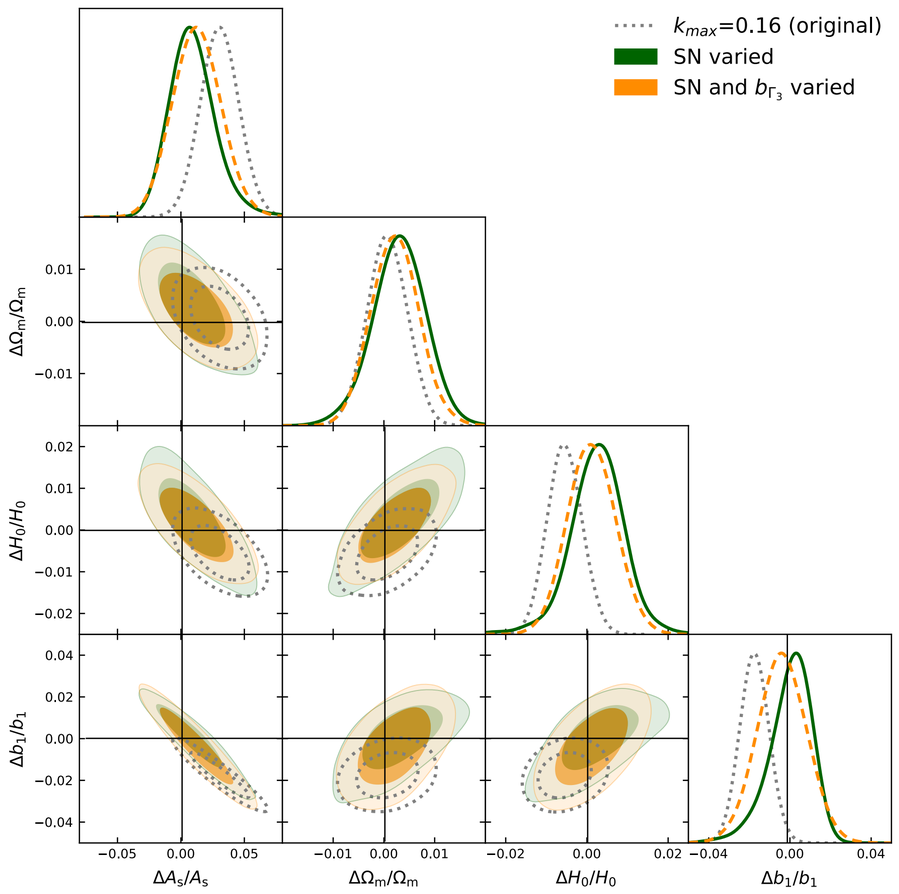
Nishimichi et al. (2020)

Blind analysis, very large volume, realistic galaxies



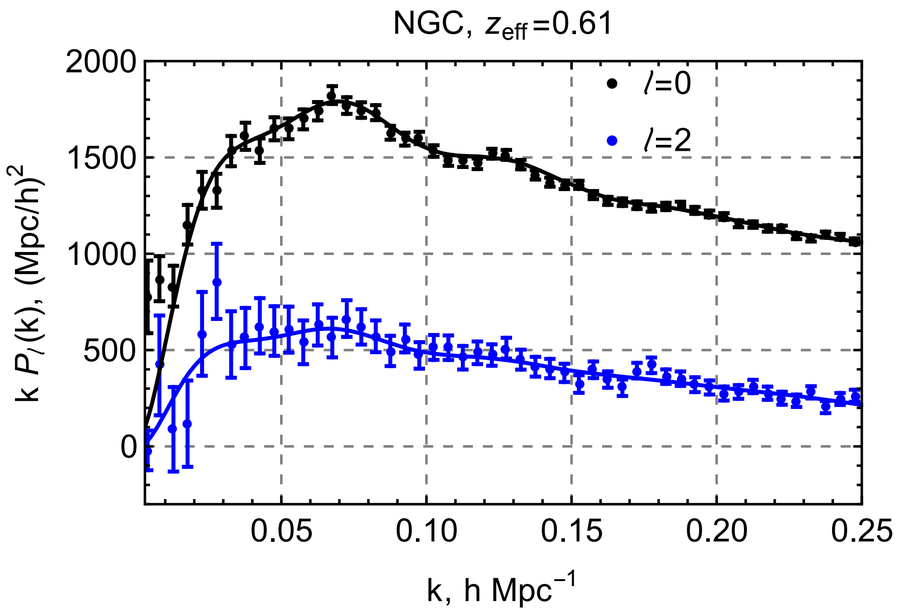


1%



Application to BOSS data

Galaxy map



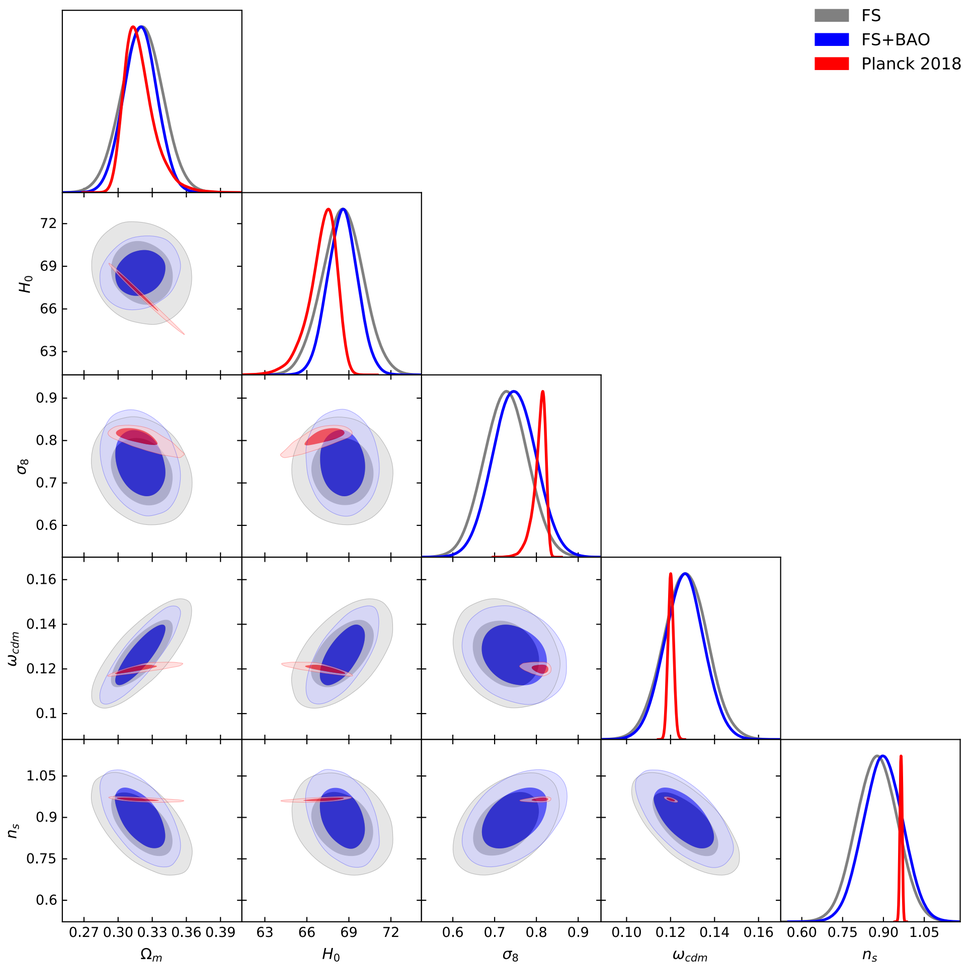
Full-shape analysis

Similar to CMB, directly measures “shape” parameters

all cosmological parameters
no CMB input needed

Different from the standard
fixed-shape analysis!

Application to BOSS data



Ivanov, MS, Zaldarriaga (2019)

d'Amico, Gleyzes, Kokron, Markovic, Senatore, Zhang, Beutler, Gil Marin (2019)

Philcox, Ivanov, MS, Zaldarriaga (2020)

Here we use the BBN prior on ω_b

$$H_0 = 68.6 \pm 1.1 \text{ km/s/Mpc}$$

$$H_0 = 67.8 \pm 0.7 \text{ km/s/Mpc}$$ (fixing the tilt)

1) Datasets are consistent

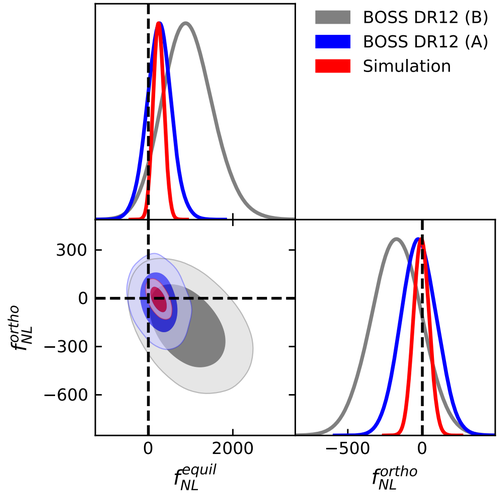
2) BOSS H0 and Ω_m comparable to Planck

Application to BOSS data

Cabass, Ivanov, Philcox, MS, Zaldarriaga (2022)

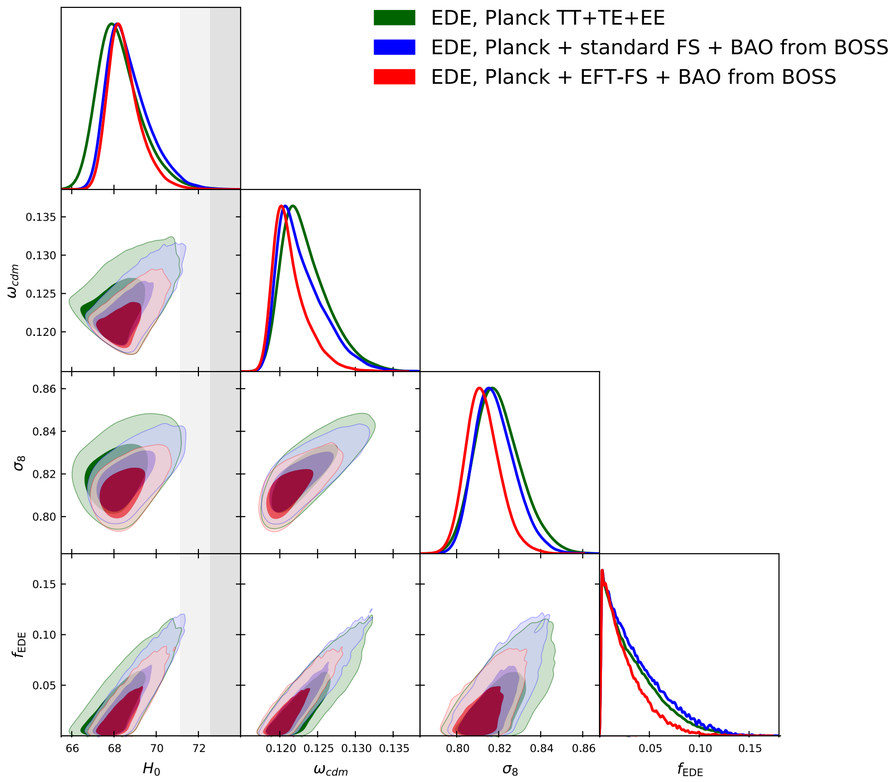
D'Amico, Lewandowski, Senatore, Zhang (2022)

PNG in single-field inflation



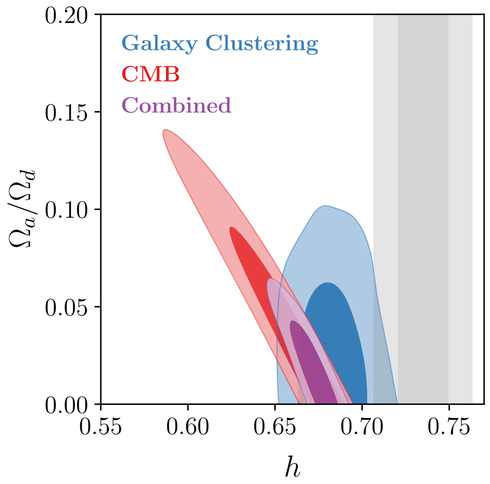
Ivanov et al. (2020)

Early dark energy



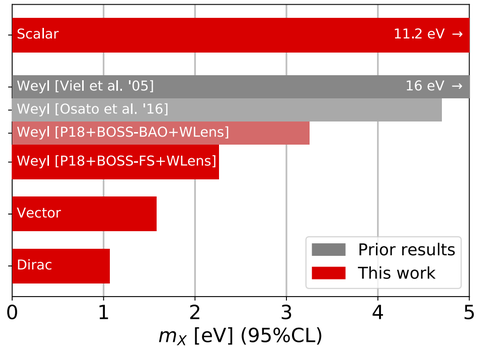
Laguë, Bond, Hložek, Rogers, Marsh, Grin (2021)

Ultralight axions



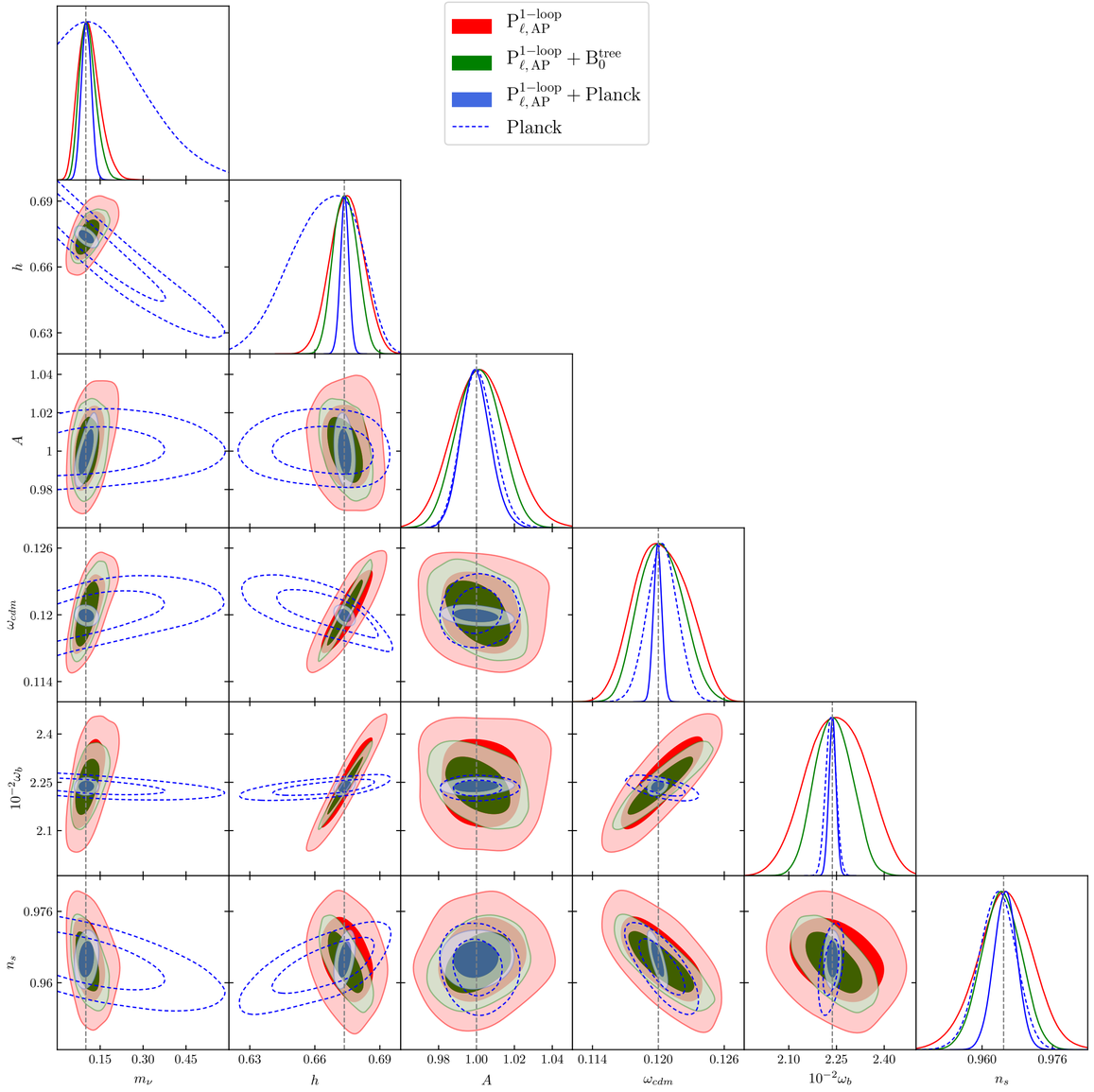
Xu, Muñoz, Dvorkin (2021)

Light (but Massive) Relices — LiMRs



Forecast for a Euclid/DESI-like survey

Chudaykin, Ivanov (2019)



1) Euclid/DESI ~ Planck

2) much better in combination