Cosmology and new physics from large-scale structure of the universe

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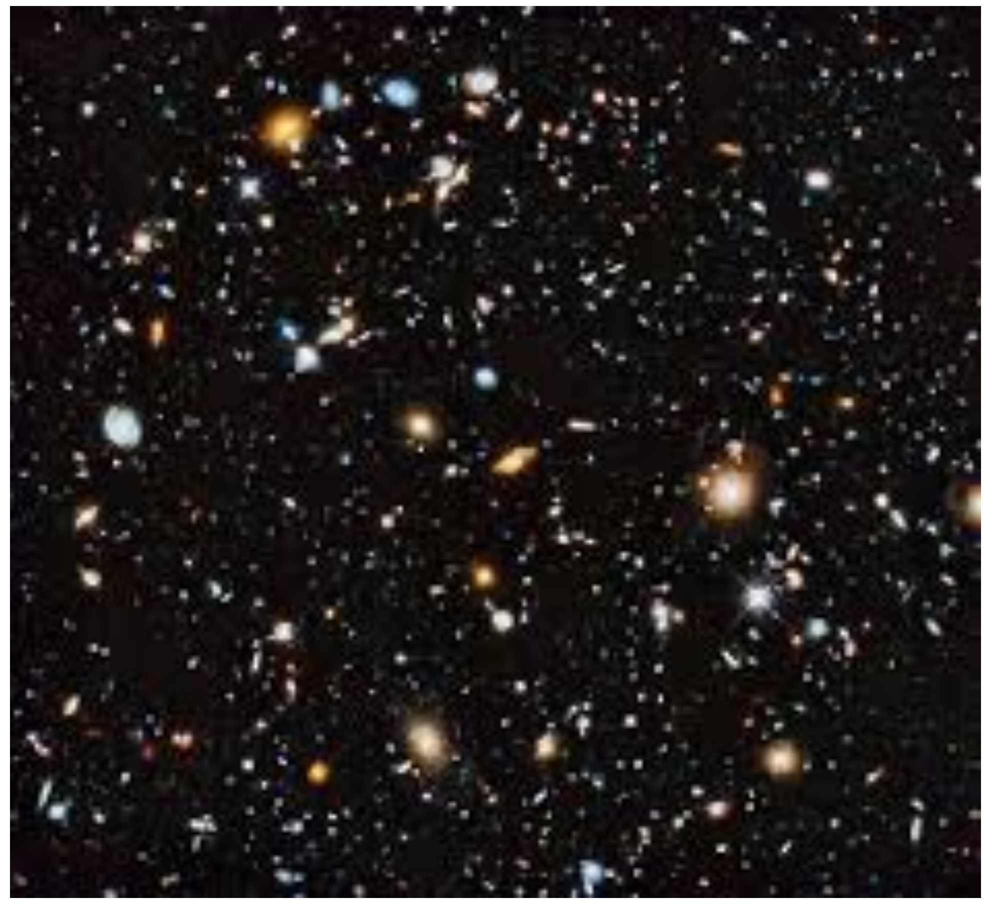
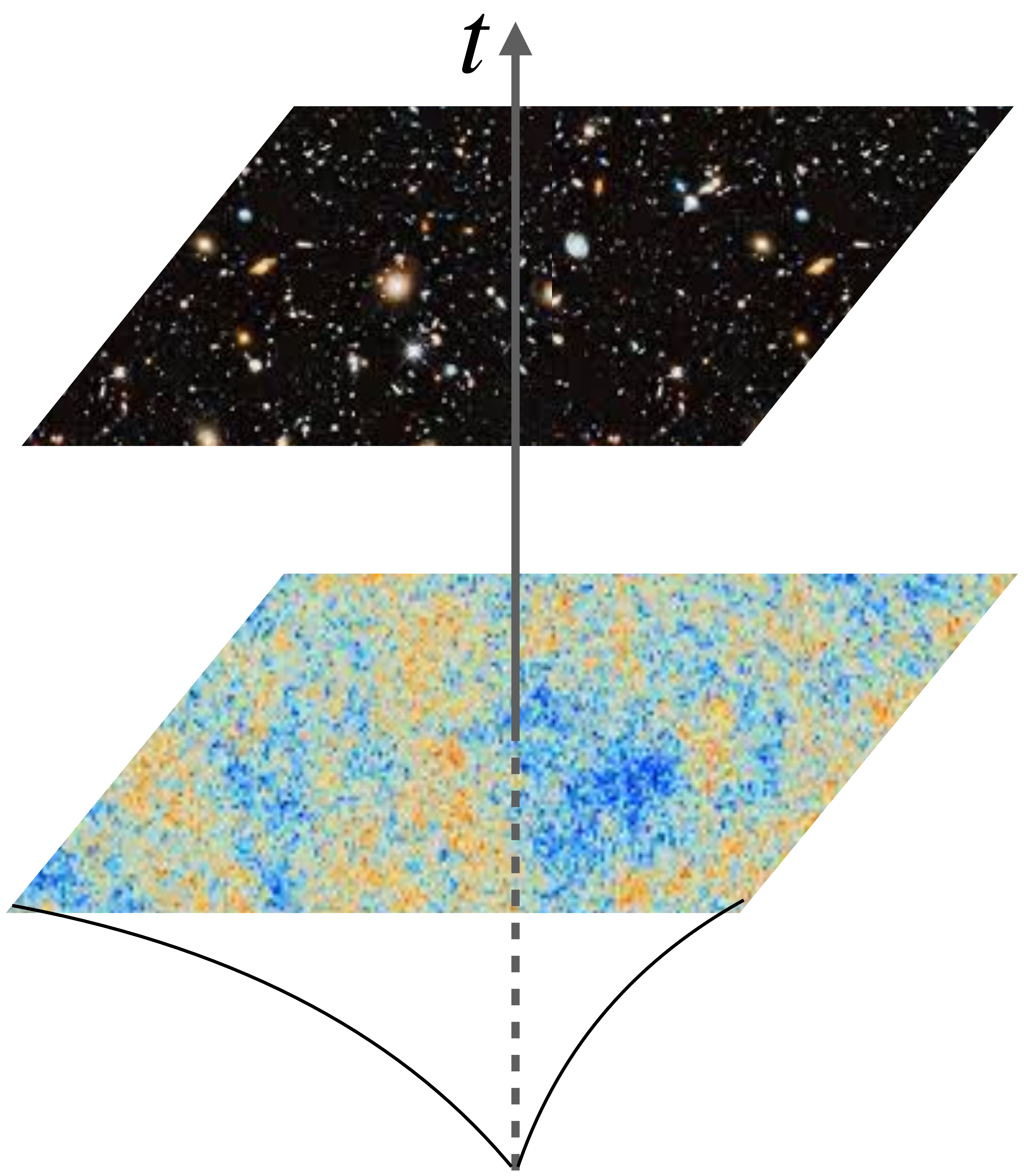


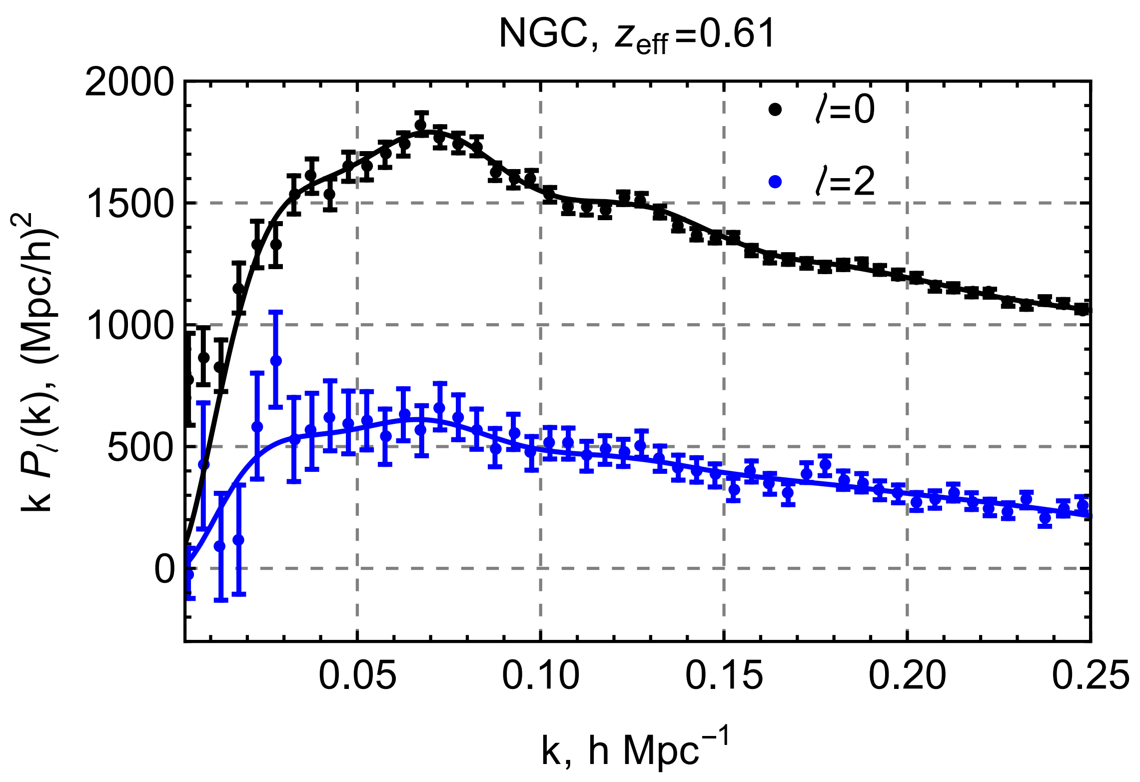
	base $\nu\Lambda$CDM	
Parameter	FS	FS+BAO
ω_{cdm}	$0.1265^{+0.01}_{-0.01}$	$0.1259^{+0.009}_{-0.0093}$
n_s	$0.8791^{+0.081}_{-0.076}$	$0.9003^{+0.076}_{-0.071}$
H_0	$68.55^{+1.5}_{-1.5}$	$68.55^{+1.1}_{-1.1}$
σ_8	$0.7285^{+0.055}_{-0.053}$	$0.7492^{+0.053}_{-0.052}$
Ω_m	$0.3203^{+0.018}_{-0.019}$	$0.3189^{+0.015}_{-0.015}$

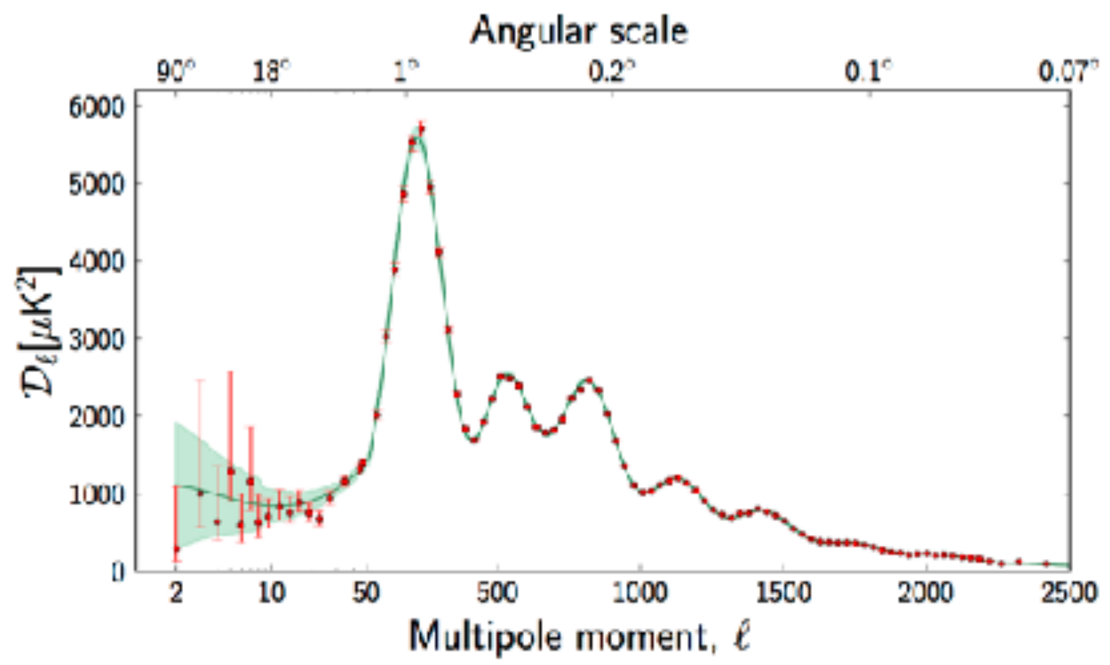


$$\delta_g = \frac{\rho_g - \bar{\rho}_g}{\bar{\rho}_g}$$

$$\delta_T = \frac{T - \bar{T}}{\bar{T}}$$

Initial conditions
(inflation)





Fluctuations are not random!

Cosmology is science about density fluctuations, their origin and evolution

nearly Gaussian initial conditions at 10^{-4} level

~0.1% upper bound on isocurvature fluctuations

positions and relative amplitudes of the BAO peaks

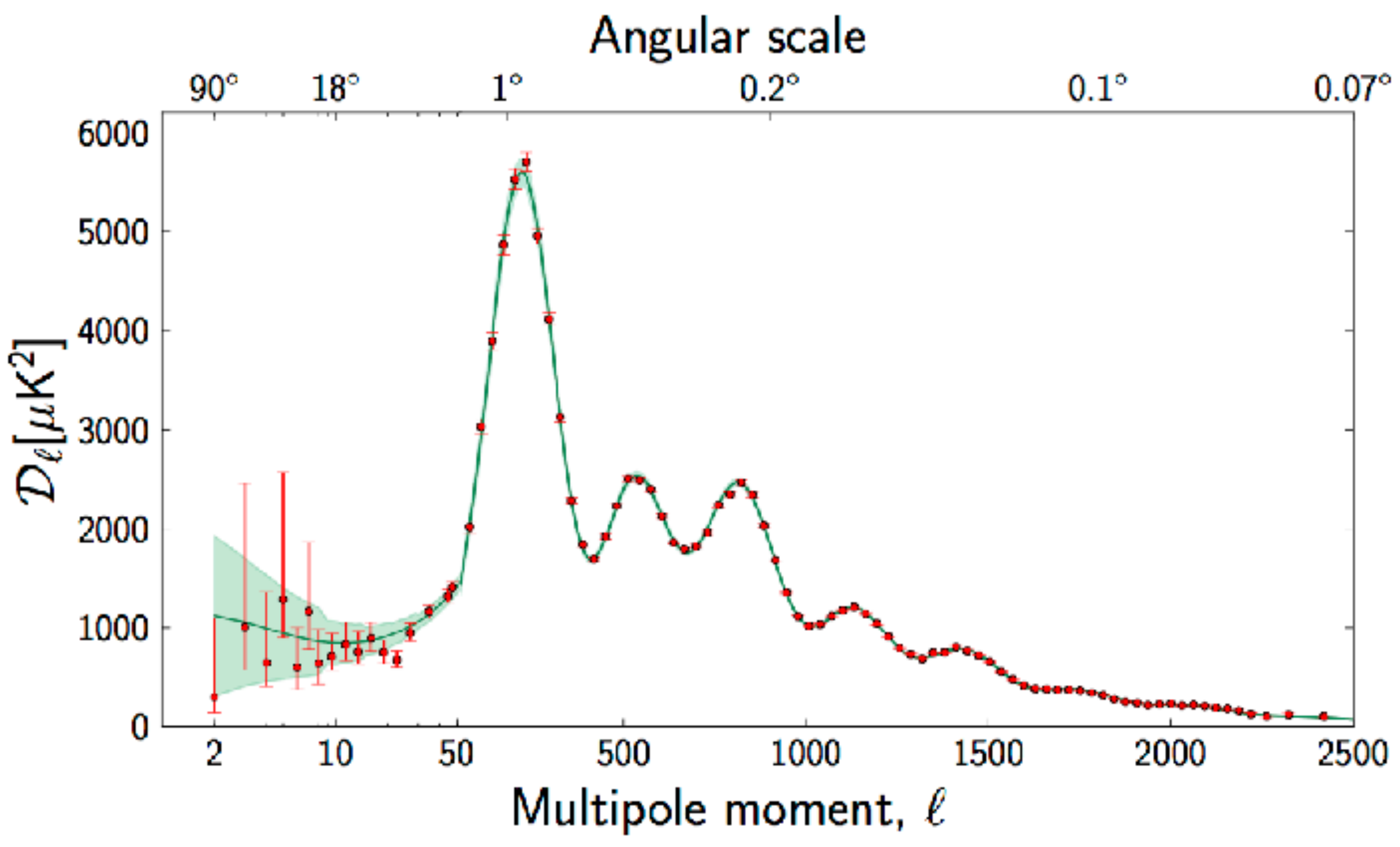
negative spectral index or primordial curvature perturbations

scale-invariant TT power spectrum for $\ell < 10$

TE correlation on scales larger than 1°

smearing of the acoustic peaks produced by weak lensing

excess correlation in the 2pf of galaxy density fluctuations at ~100 Mpc/h



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

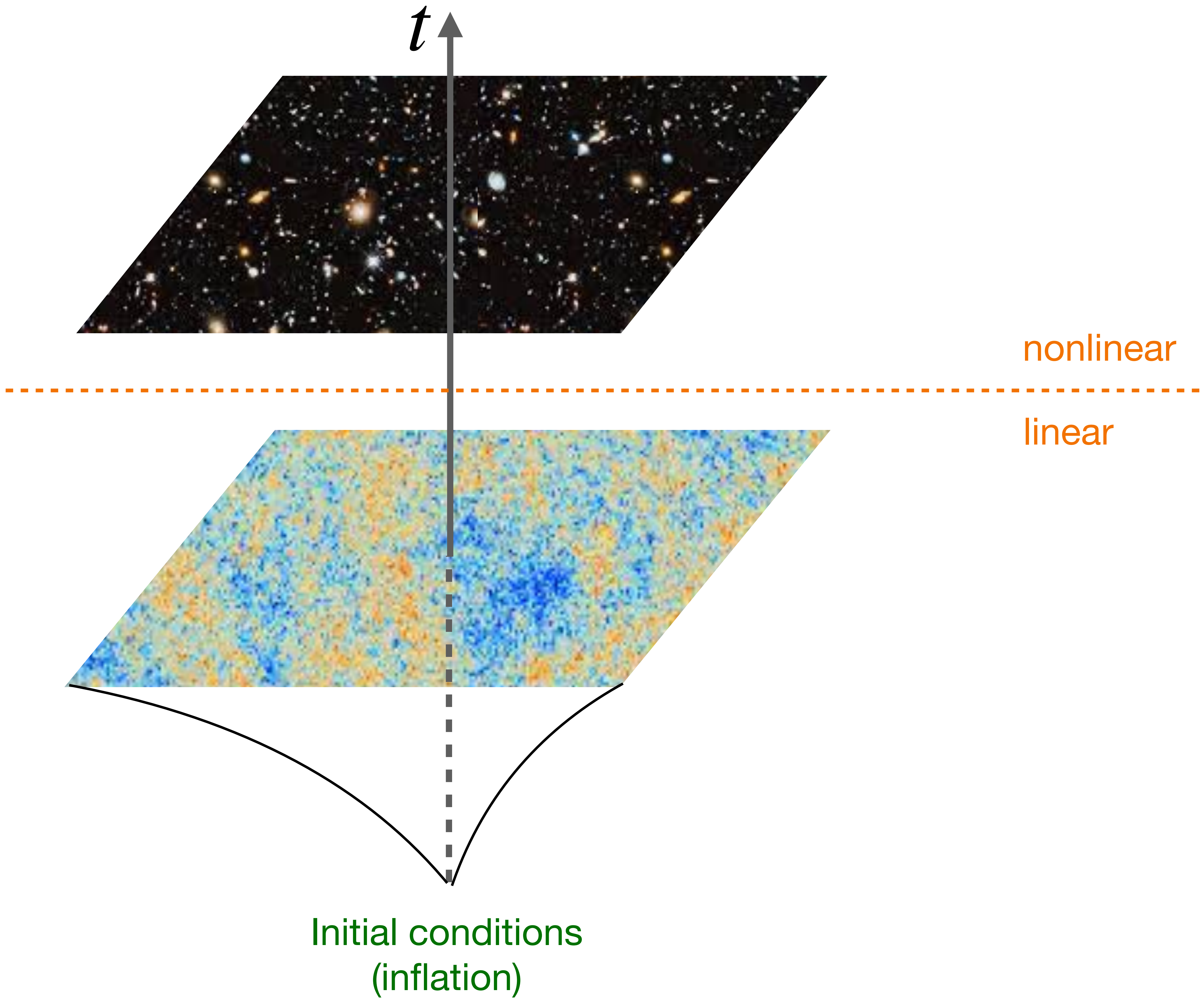
relative amplitudes
of the BAO peaks

$$\omega_i \equiv \Omega_i h^2$$
$$\omega_b, \omega_{cdm}$$

ΛCDM

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

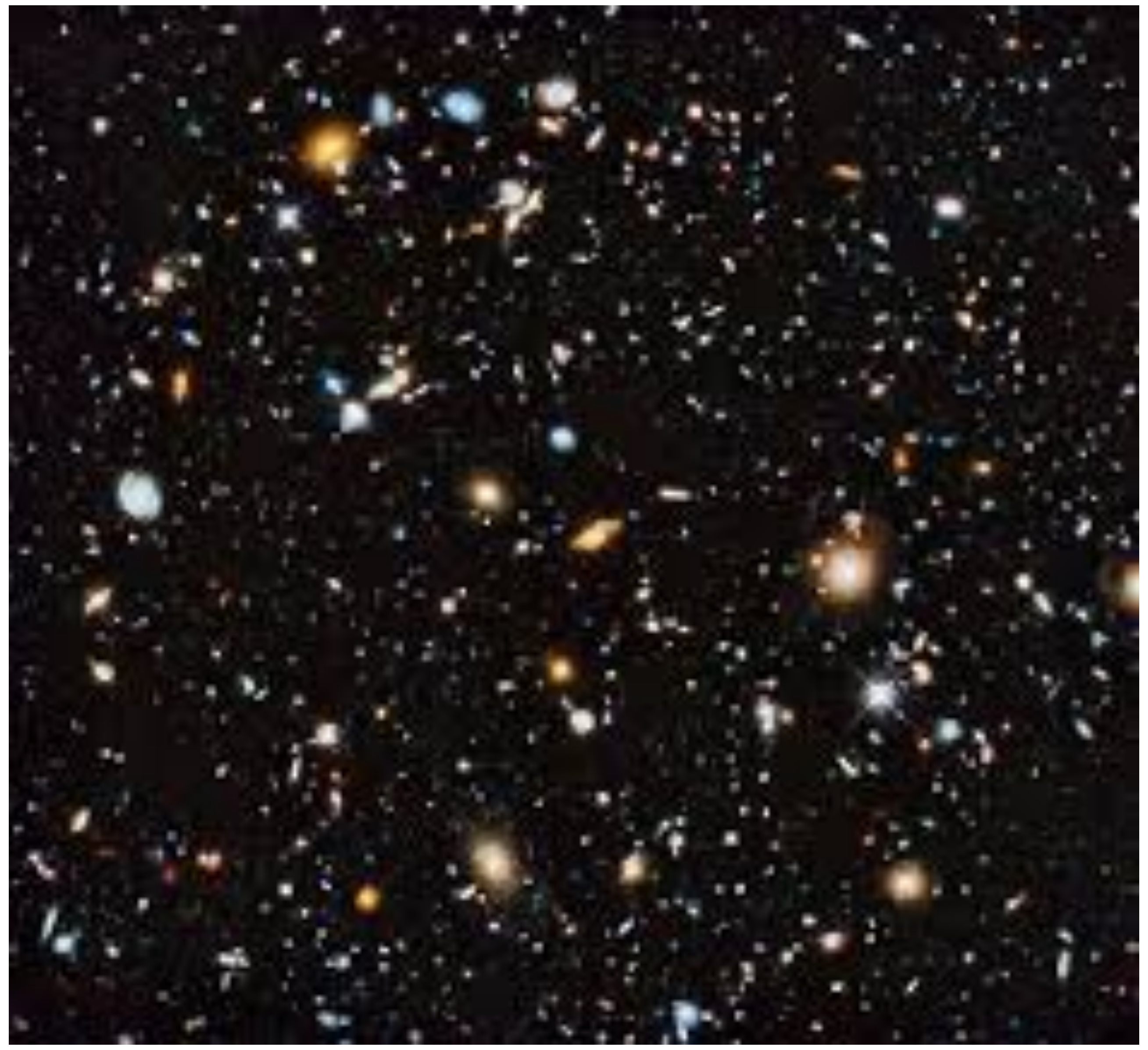
H_0 from positions of the BAO peaks

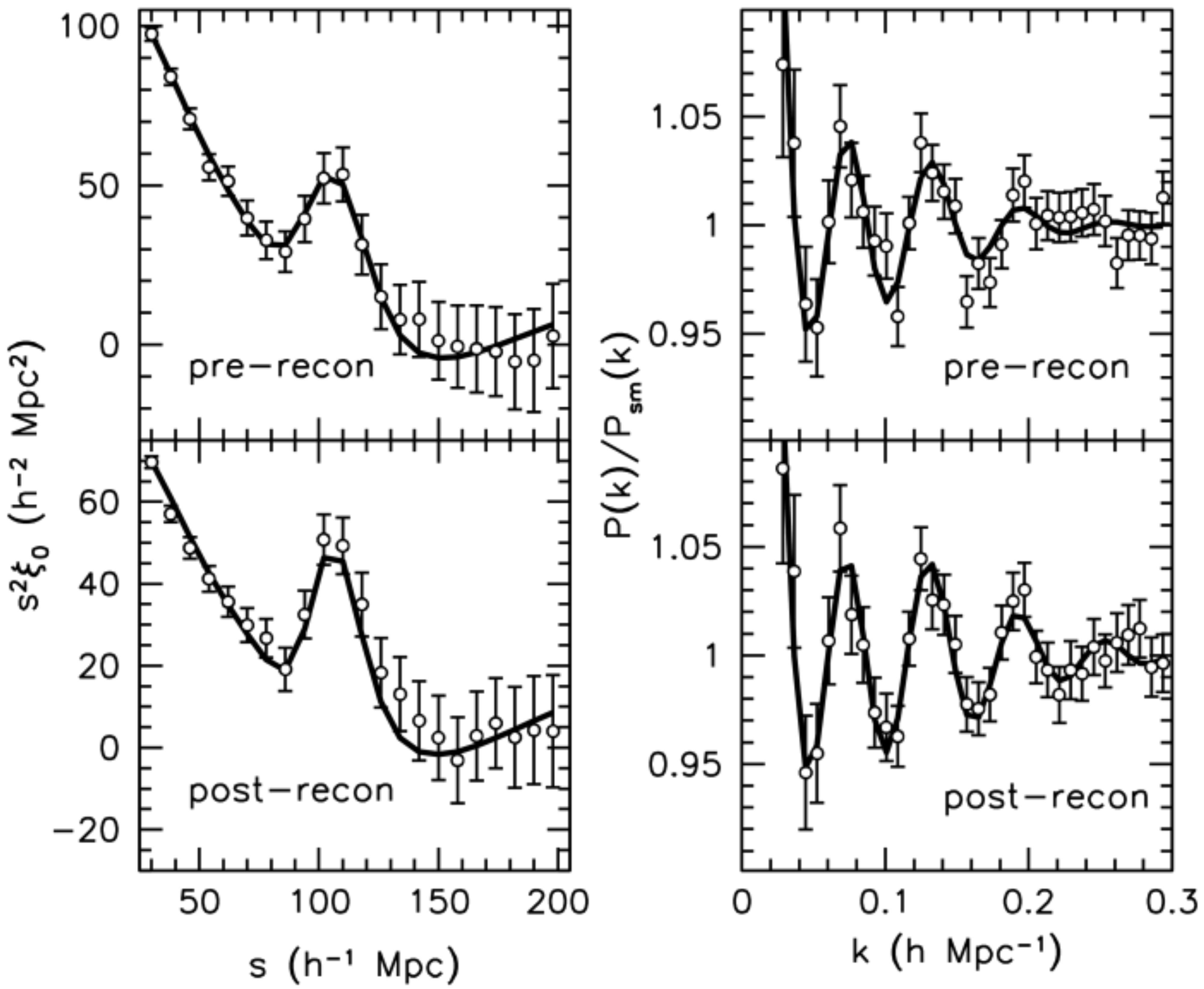


?

CMBFAST
CAMB
CLASS

MCMC on industrial scales

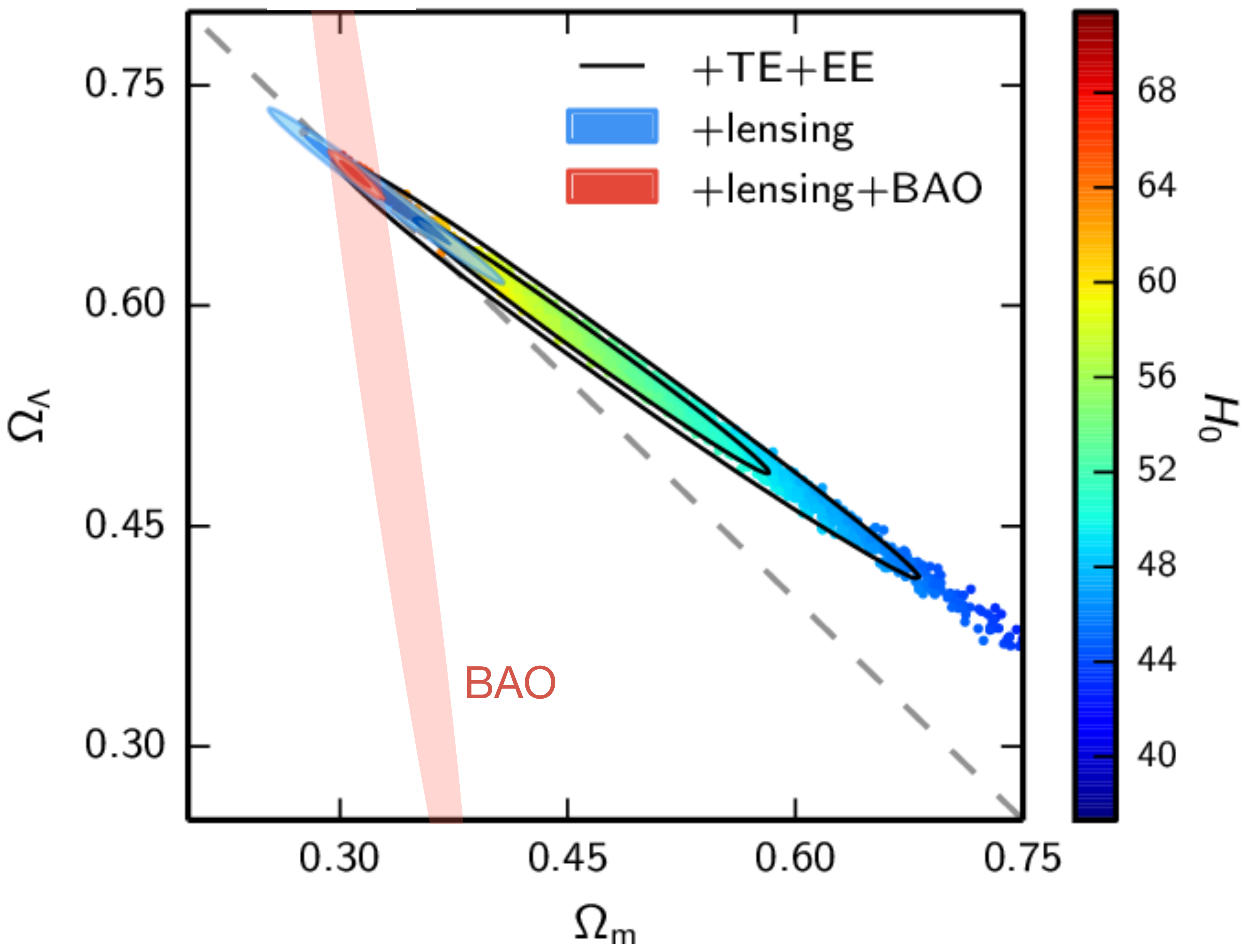




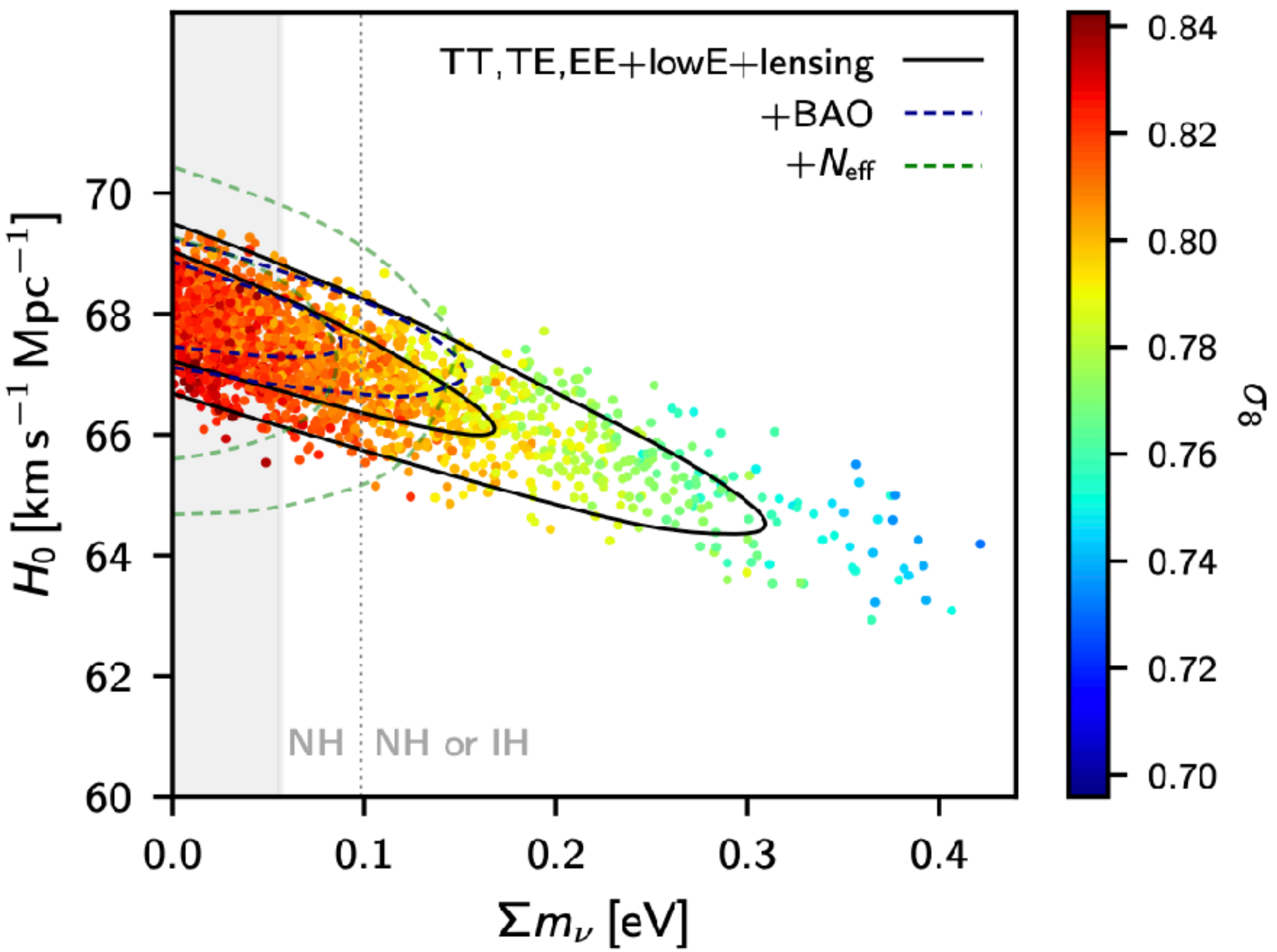
easy to model and easy to measure!

CMB → $\omega_{\rm b}, \omega_{\rm cdm}$ —ΛCDM→ H_0 from position of the BAO peak

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



+TE+EE
+lensing
+lensing+BAO
BAO
0.75
0.60
0.45
0.30
0.30
0.45
0.60
0.75
Ω_Λ
Ω_m
68
64
60
56
52
48
44
40
H_0



TT,TE,EE+lowE+lensing
+BAO
+N_{eff}
NH
NH or IH
70
68
66
64
62
60
0.0
0.1
0.2
0.3
0.4
H_0 [km s^{-1} Mpc^{-1}]
Σm_ν [eV]
0.84
0.82
0.80
0.78
0.76
0.74
0.72
0.70
σ_8

Standard LSS analyses, like BAO or $f\sigma_8$, always assume cosmology (ω_m) from the CMB

We want cosmology from LSS as much independent of the CMB as possible

— we want to make sure that the two are consistent *before* we combine them

— at some point, LSS will be the leading probe of cosmology

Examples of new physics we can constrain

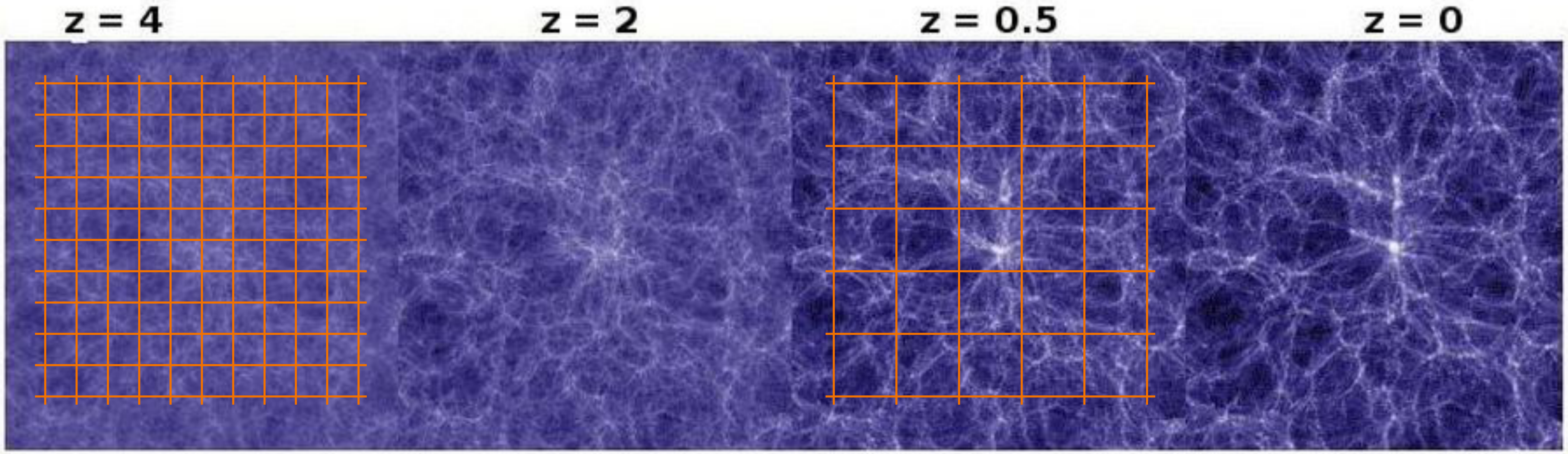
$\sum m_\nu$, $f_{\rm NL}$, DE, DM interactions, early universe physics, EDE, dark sector phase transitions, N_{eff} , etc.

The resolution with which we can predict clustering maps is very important

information ~ N_{pix} ~ $(l_{\text{max}}/l_{\text{min}})^D$

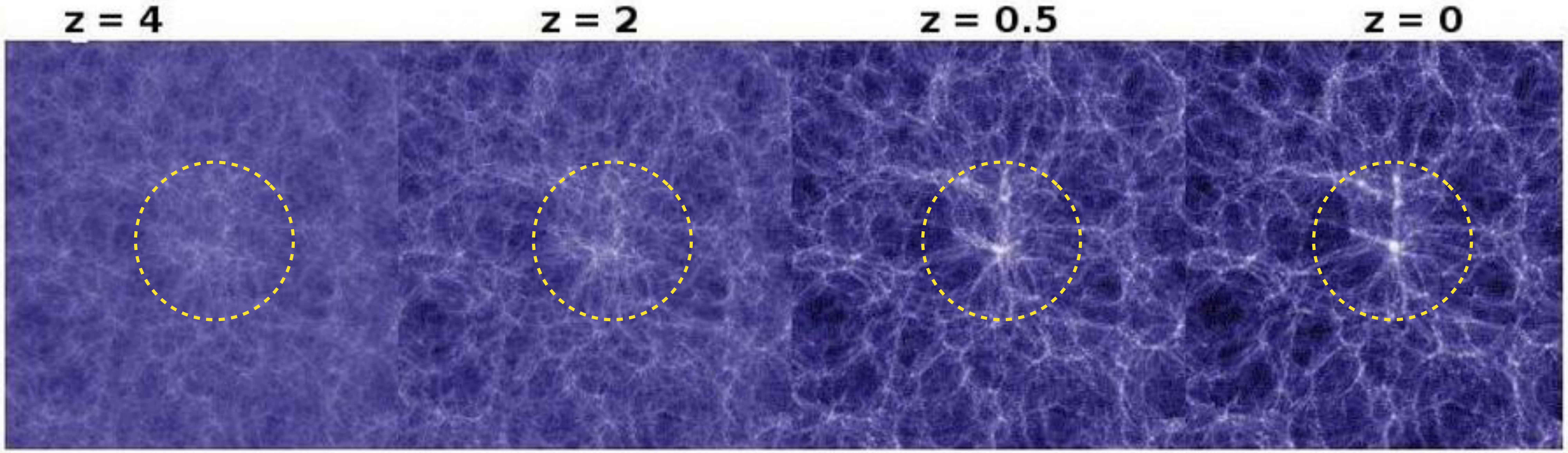
encoded in CV error bars — S/N ~ N_{pix} ~ Vk^3_{max}

2x res → 8x information



Variance of the density field $-$ $\sigma_R^2 \approx \int_0^{1/R} k^2 dk\, P(k)$

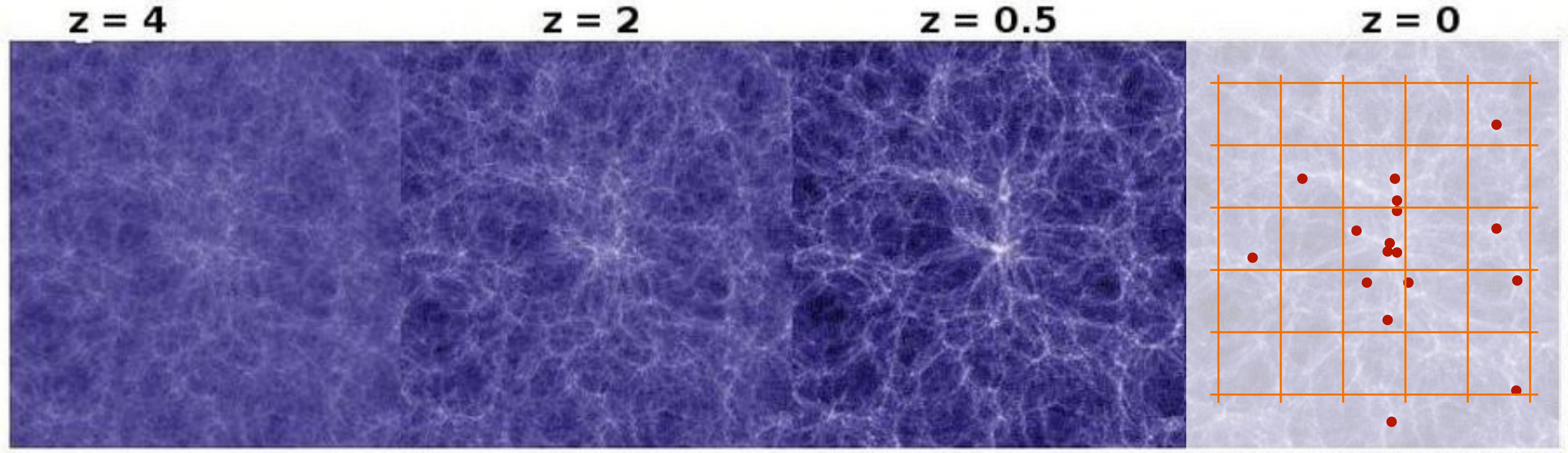
Fluctuations are small when $\sigma_R^2 < 1$ $-$ at $z = 0.5$, this happens for R ~ few Mpc/h



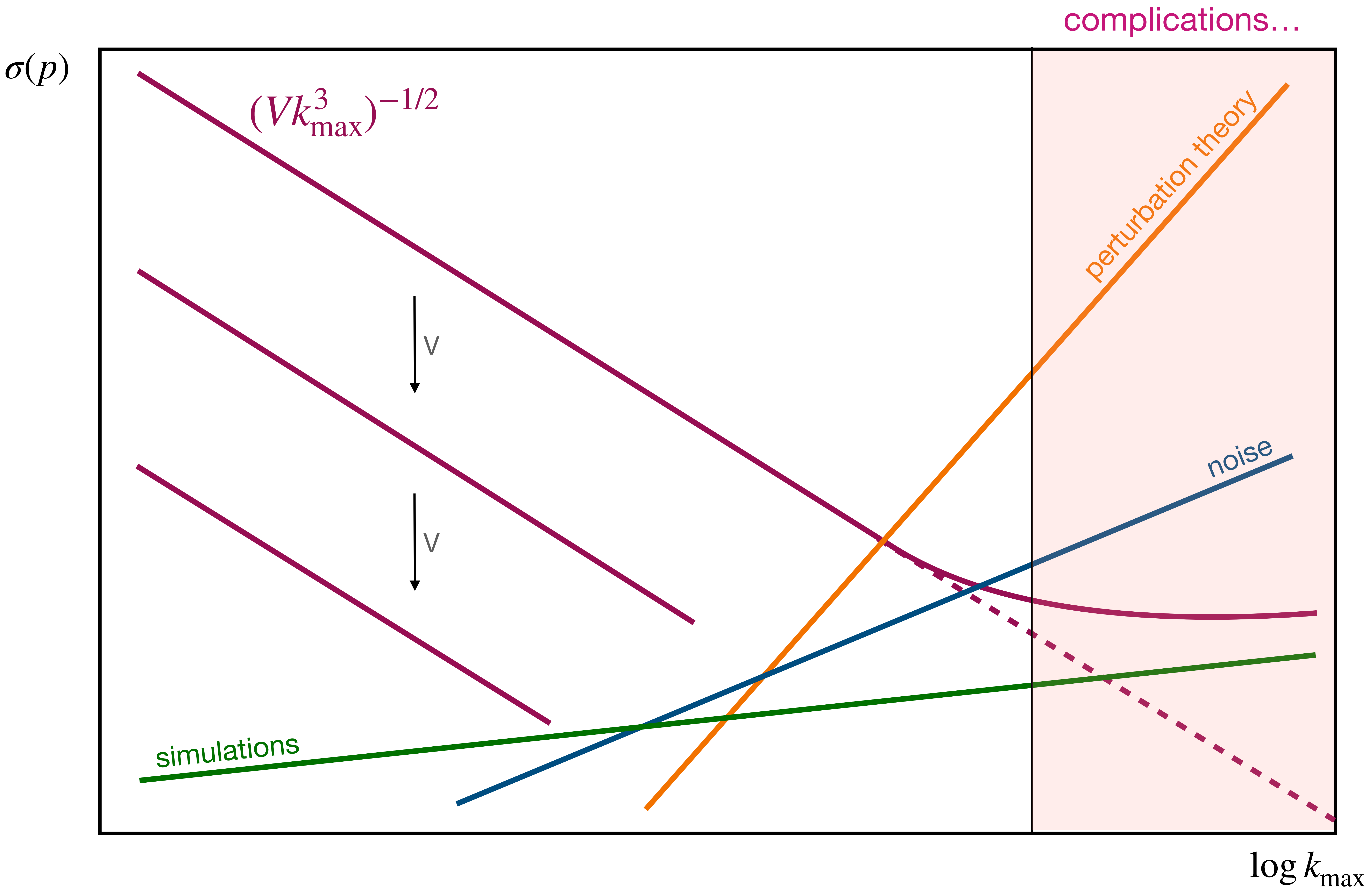
No need to be perfect at small scales — the ultimate resolution set by the number of galaxies

Information saturates when $P(k)\bar{n} \sim 1$

typical separation is ~10 Mpc/h



Fundamental plot of observational cosmology



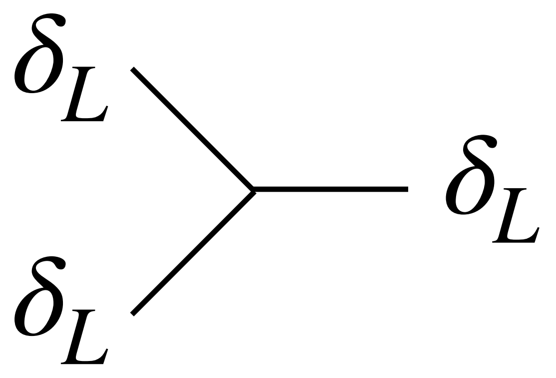
In the era of large volume surveys
we need more precision/accuracy on *large* scales

This is a perfect setup for perturbation theory

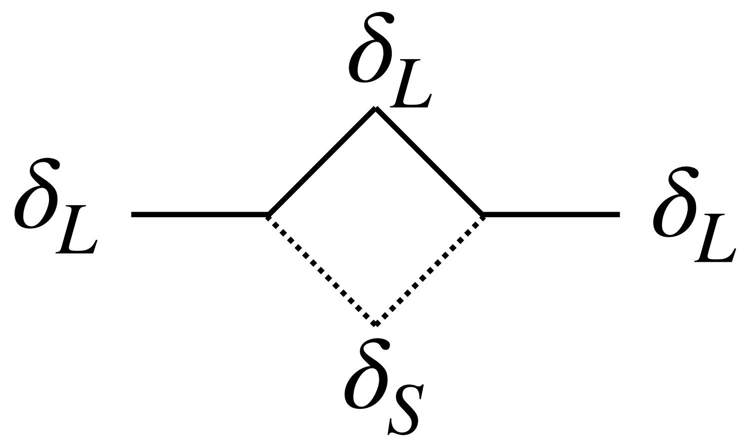
(large volume means higher redshifts where the fundamental plot of observational cosmology looks even better for PT)

Key ingredients for perturbative description of galaxy clustering

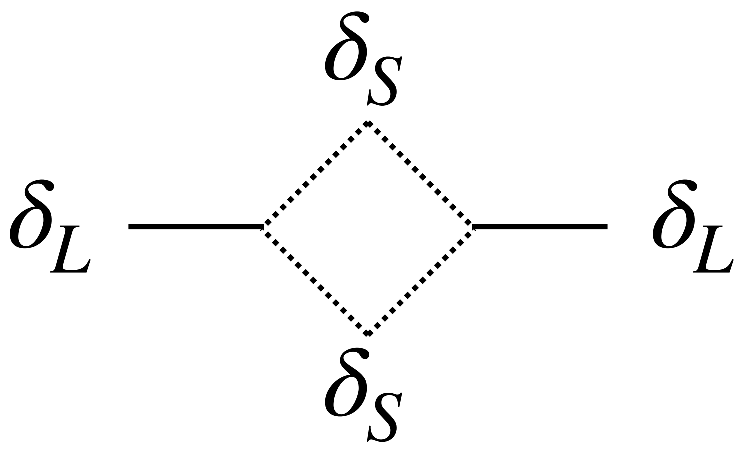
Fluctuations are small on large scales — perturbation theory



long-long interactions dictated by gravitational dynamics and symmetries



$\sim R^2 k^2 P_{\rm lin}(k)$



$\sim R^4 k^4$

Effects of short modes fixed by symmetries: EFT of LSS

Baumann, Nicolis, Senatore, Zaldarriaga (2010)

The rules for long-distance physics do not depend on small-scale details!

similar to hydrodynamics

Key ingredients for perturbative description of galaxy clustering

— gravitational nonlinearities: growth of fluctuations, tides etc.

— large bulk flows: have to be treated nonperturbatively, IR resummation

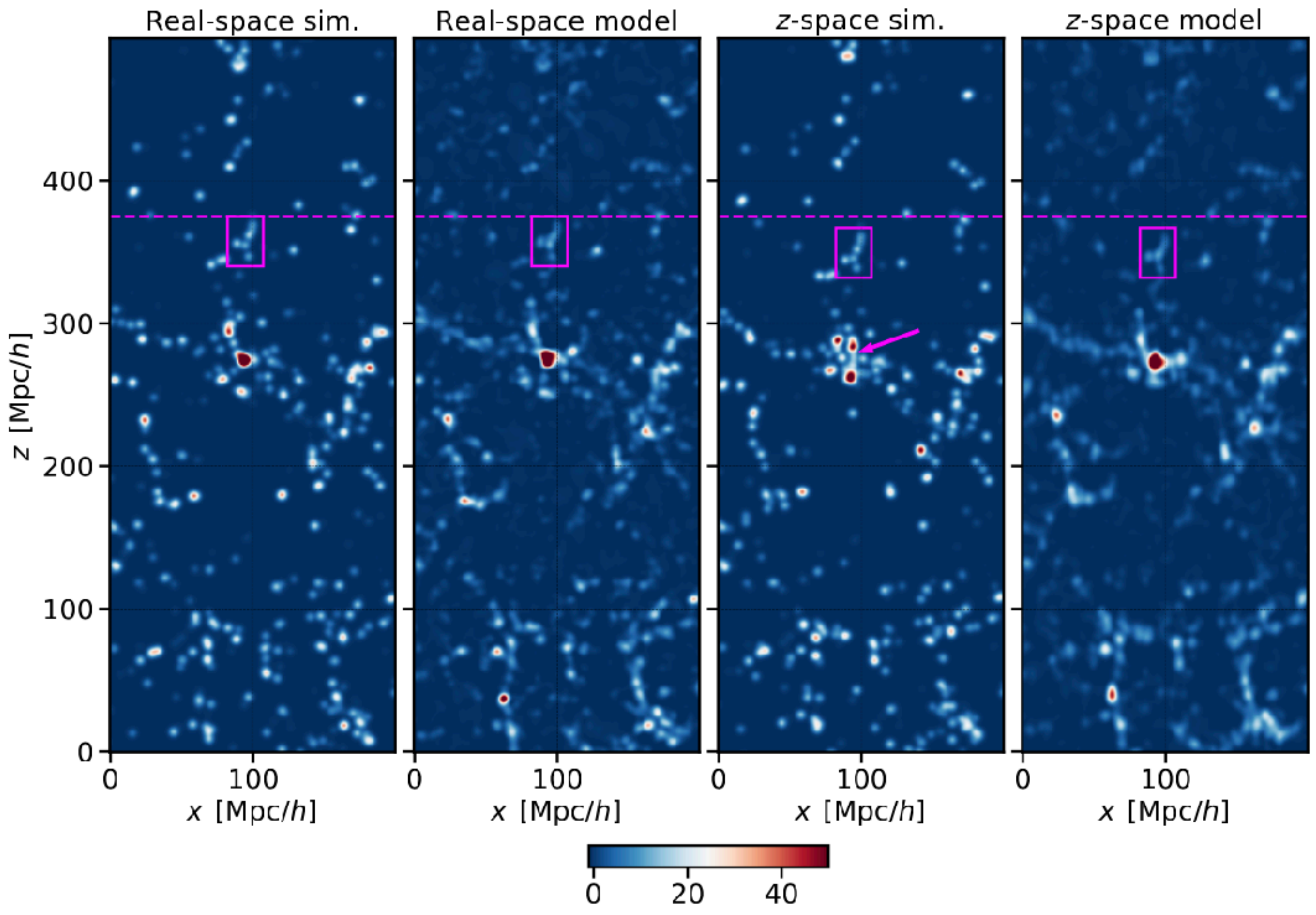
— nonlinearities for biased tracers: no mass and momentum conservation

— redshift space distortions: velocities and UV/IR mixing along the line of sight

— small scales impact: effective field theory approach, counter terms etc.

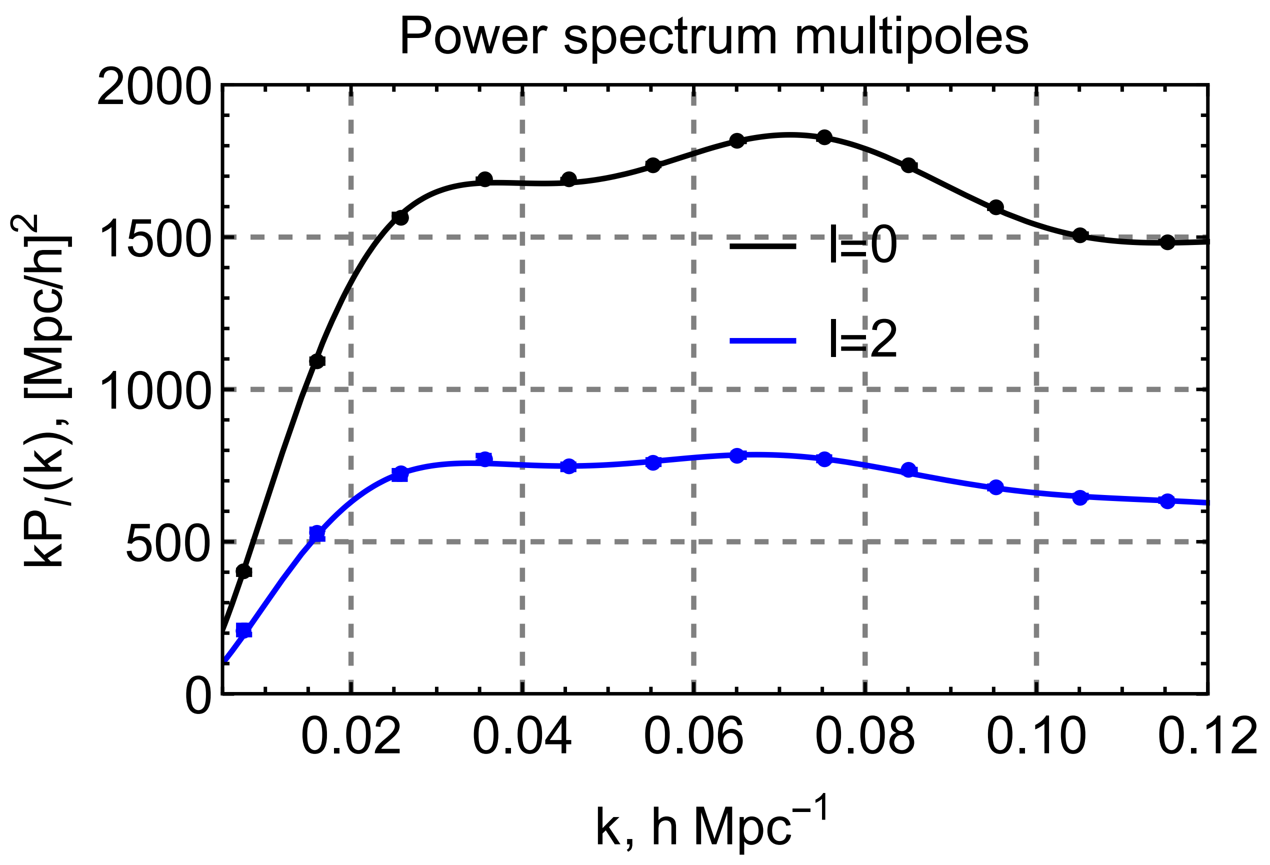
How well does it work?

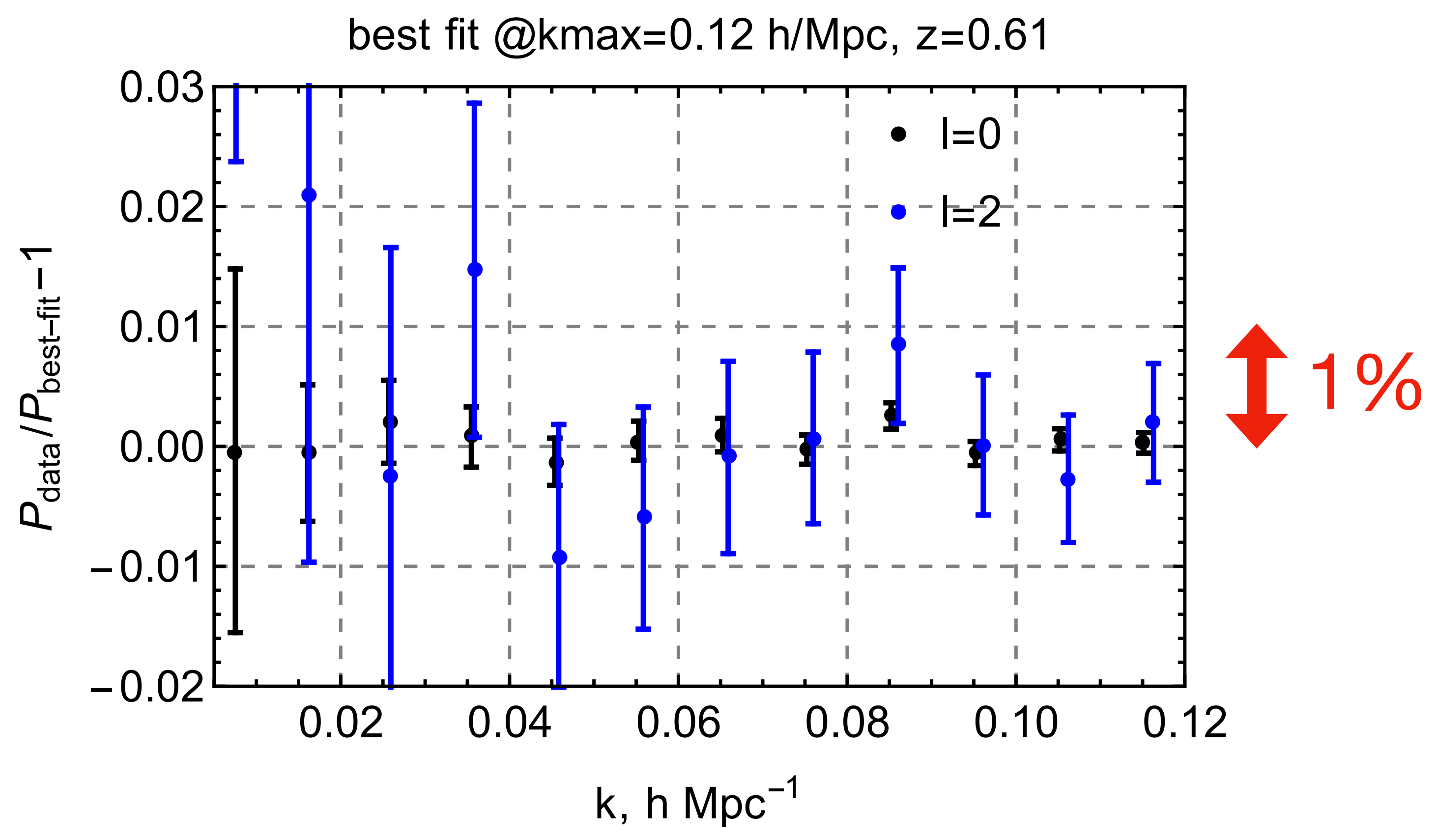
field level comparisons, no cosmic variance prize to pay

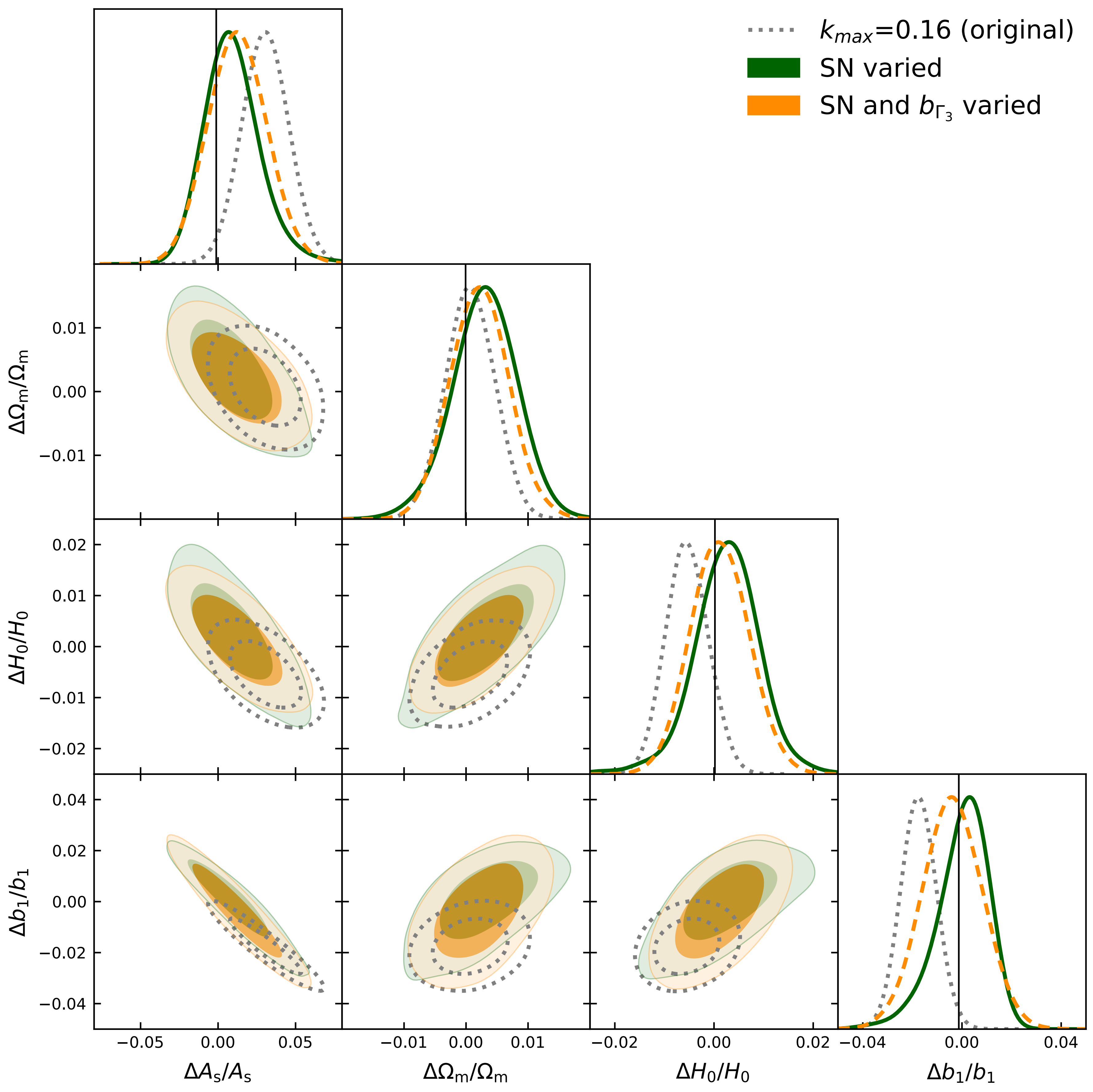


How well does it work?

very large volume simulations, realistic galaxies, blind analysis



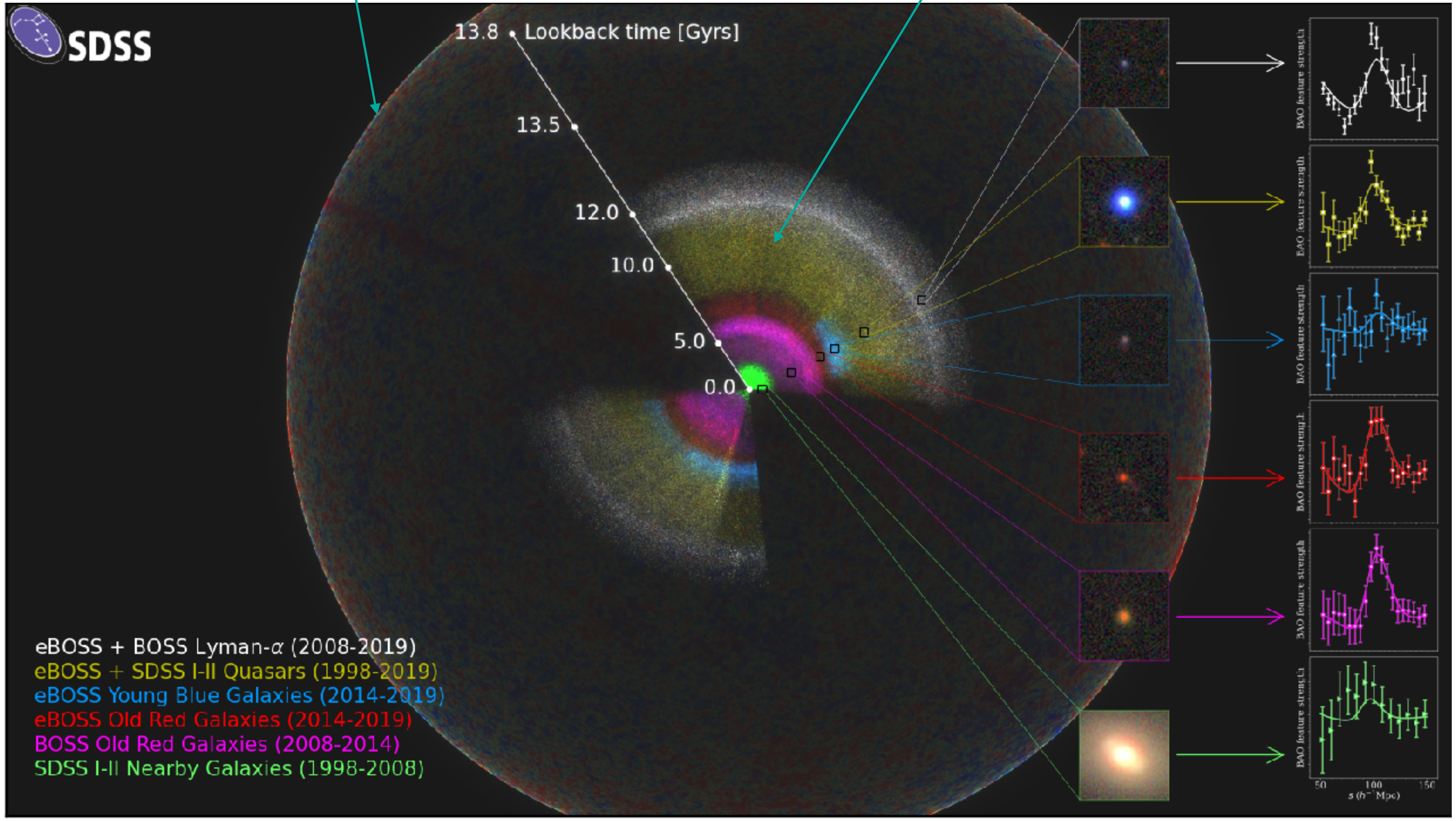




BOSS data reanalysis

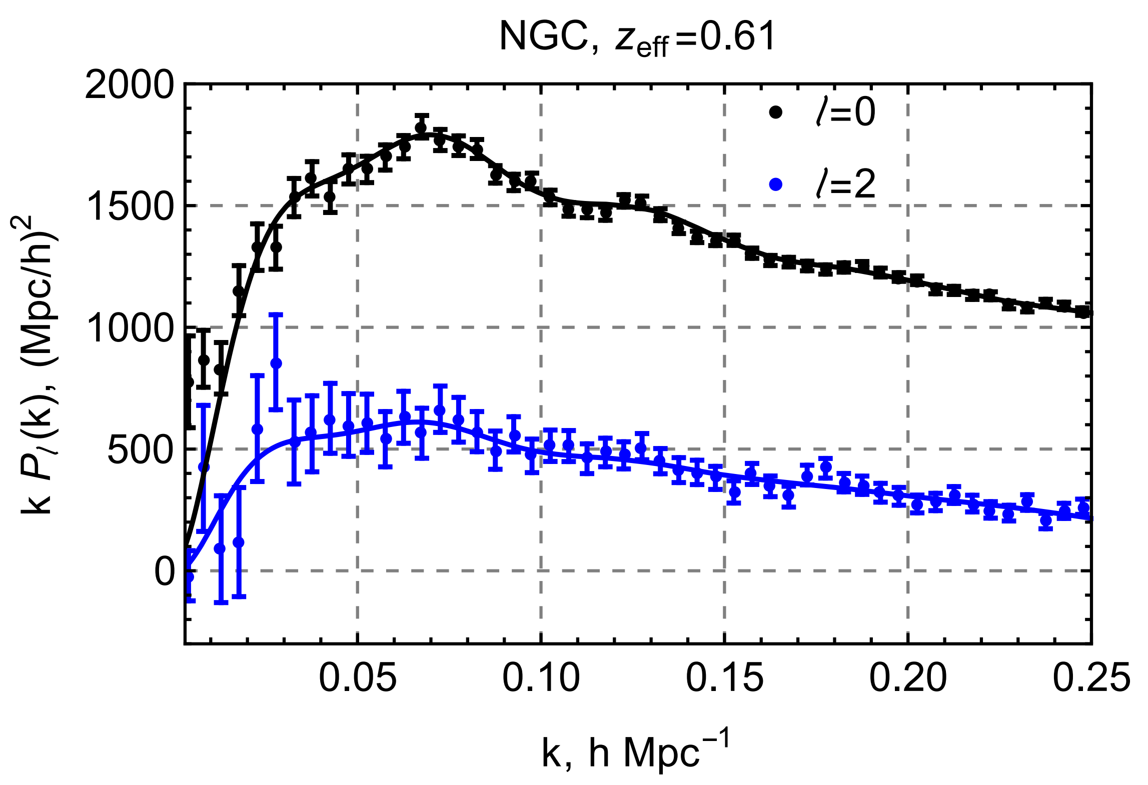
$N_{\rm pix} \sim 10^7$

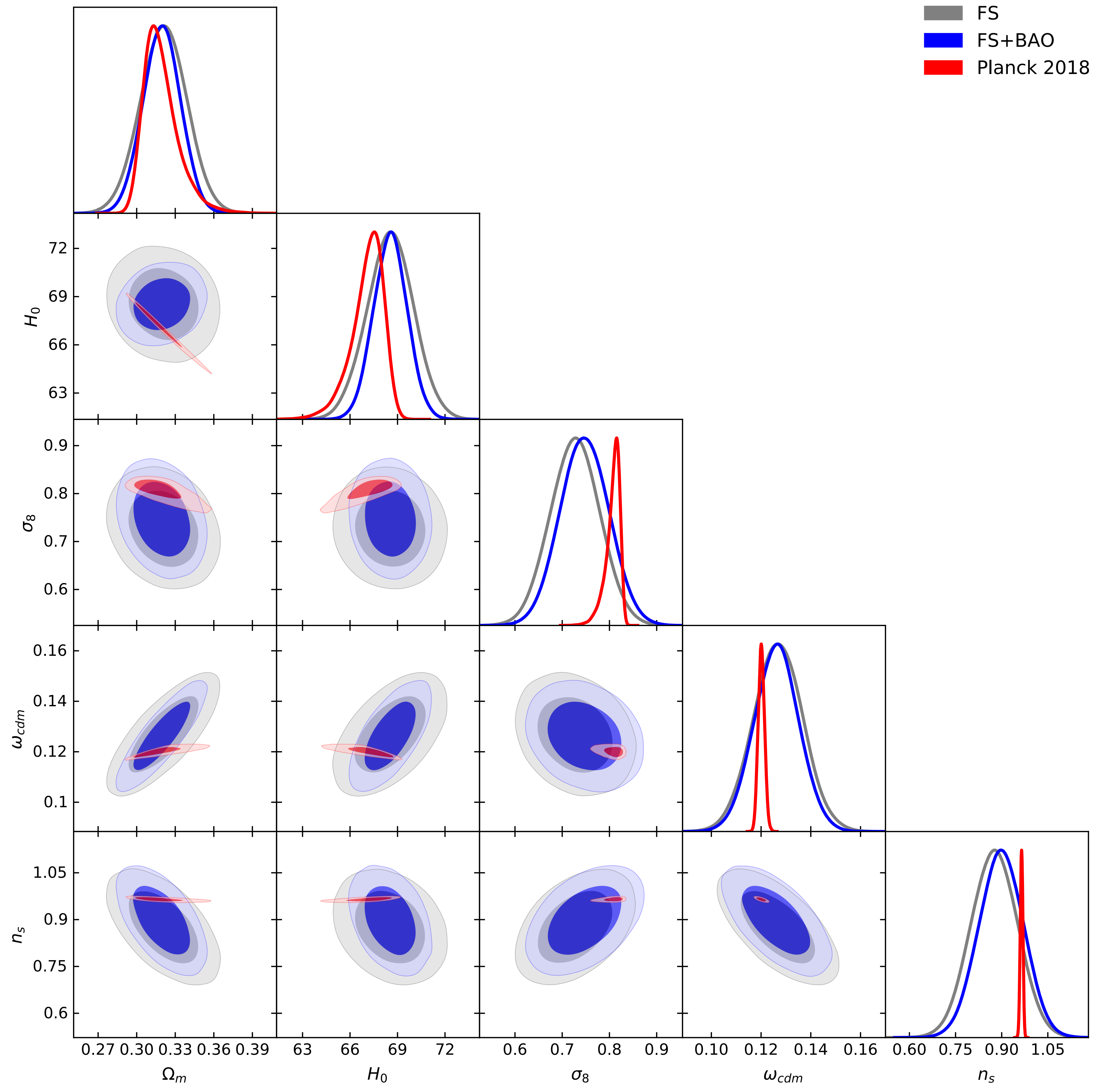
$N_{\rm pix} \sim 10^{10}$



BOSS data reanalysis

No CMB input, just BBN





FS + BAO reconstruction

$$H_0 = (68.5 \pm 1.1)\ \mathrm{km/s/Mpc}$$

The first measurement of cosmological parameters from LSS only!

BOSS data reanalysis

LCDM + m_ν + N_{eff} with BBN prior

Constraints on the neutrino mass change when FS is added

Planck + BAO: $m_\nu < 0.12$ eV

Planck + FS + BAO: $m_\nu < 0.16$ eV

↑ due to somewhat lower σ_8

If we also add relativistic degrees of freedom to the fit

Planck + BAO: $N_{eff} = 2.99 \pm 0.17$

Planck + FS + BAO: $N_{eff} = 2.90 \pm 0.15$ $(H_0 = 67.0 \pm 1.0)$

↑ Interesting in the context of the H0 tension

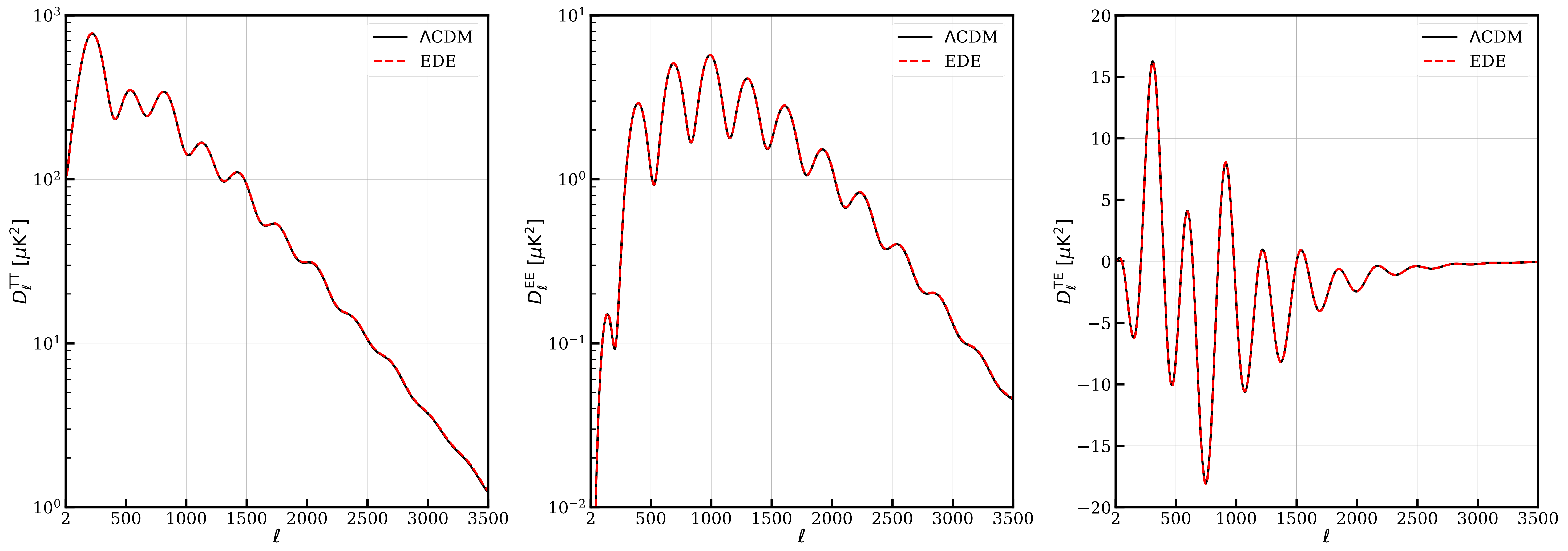
BOSS data reanalysis

EDE model tries to resolve the Hubble tension changing the early universe physics

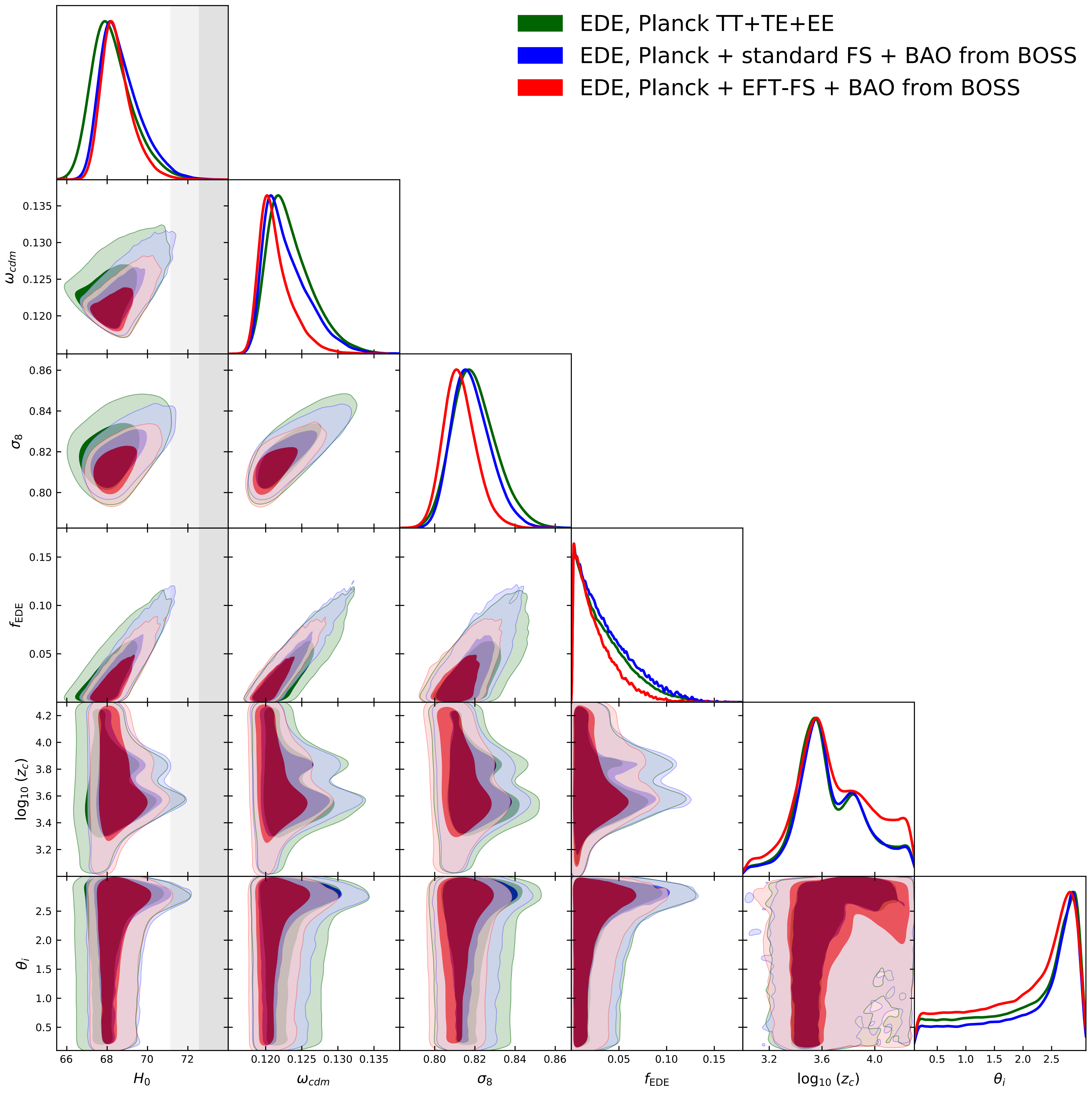
Poulin, Smith, Karwal, Kamionkowksi (2018)

O(5%) changes in the linear power spectrum are “invisible” in the CMB

How about LSS?



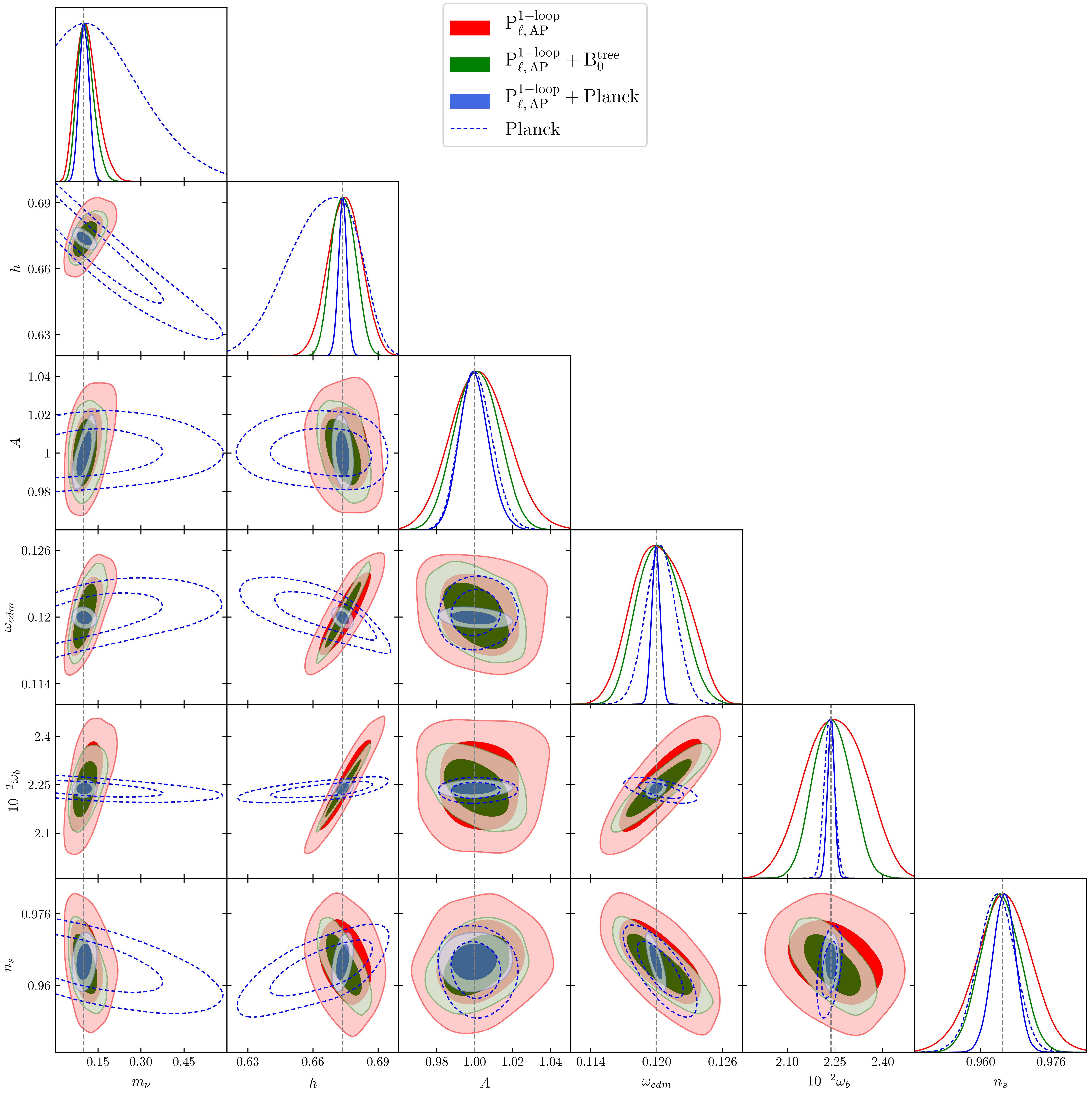
BOSS data reanalysis



Improvement compared to the standard $f\sigma_8$ + BAO analysis

An example where the FS likelihood makes some difference

Future surveys



Chudaykin, Ivanov (2019)

Euclid/DESI-like survey

Euclid/DESI ~ Planck

Conclusions

LSS surveys becoming increasingly more important

High precision on large scales — perturbation theory

The first step, one-loop power spectrum, can be now used routinely

How much more information in the higher order statistics?

Can we use simulations to put priors on nuisance parameters?

How well can we realistically do at the end of the day, can we reach $f_{\rm NL} \sim 1$?