News from the CMB

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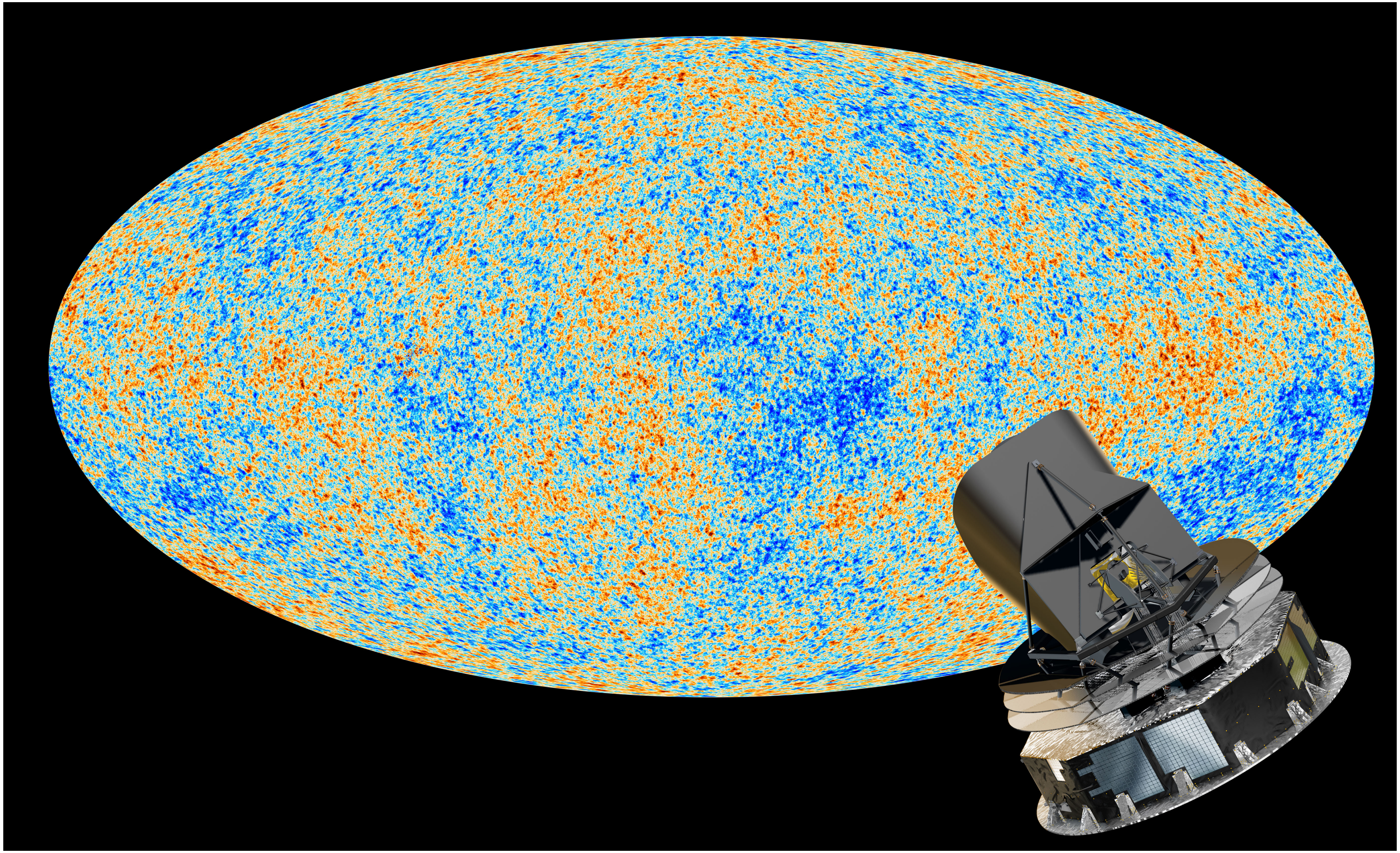
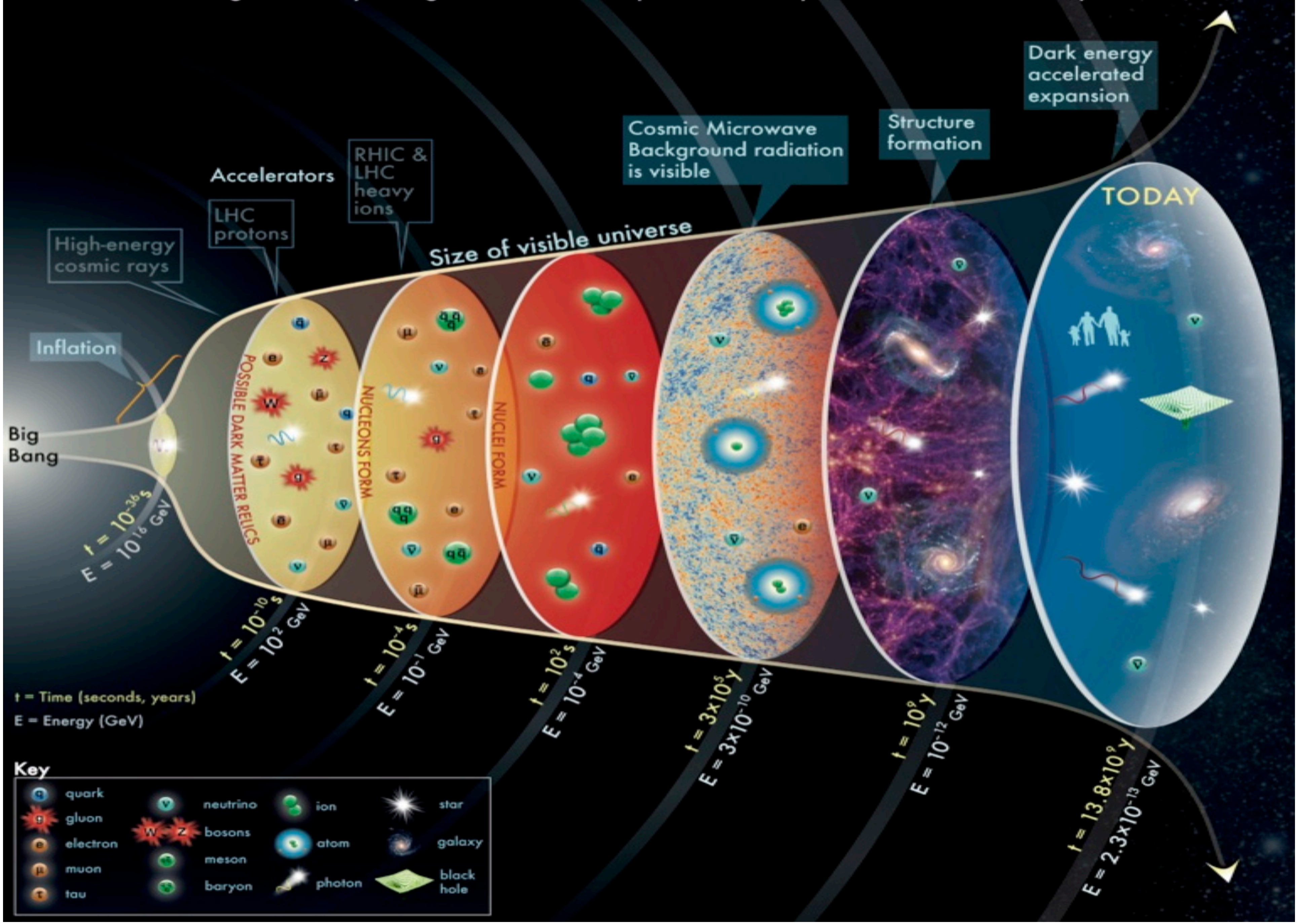
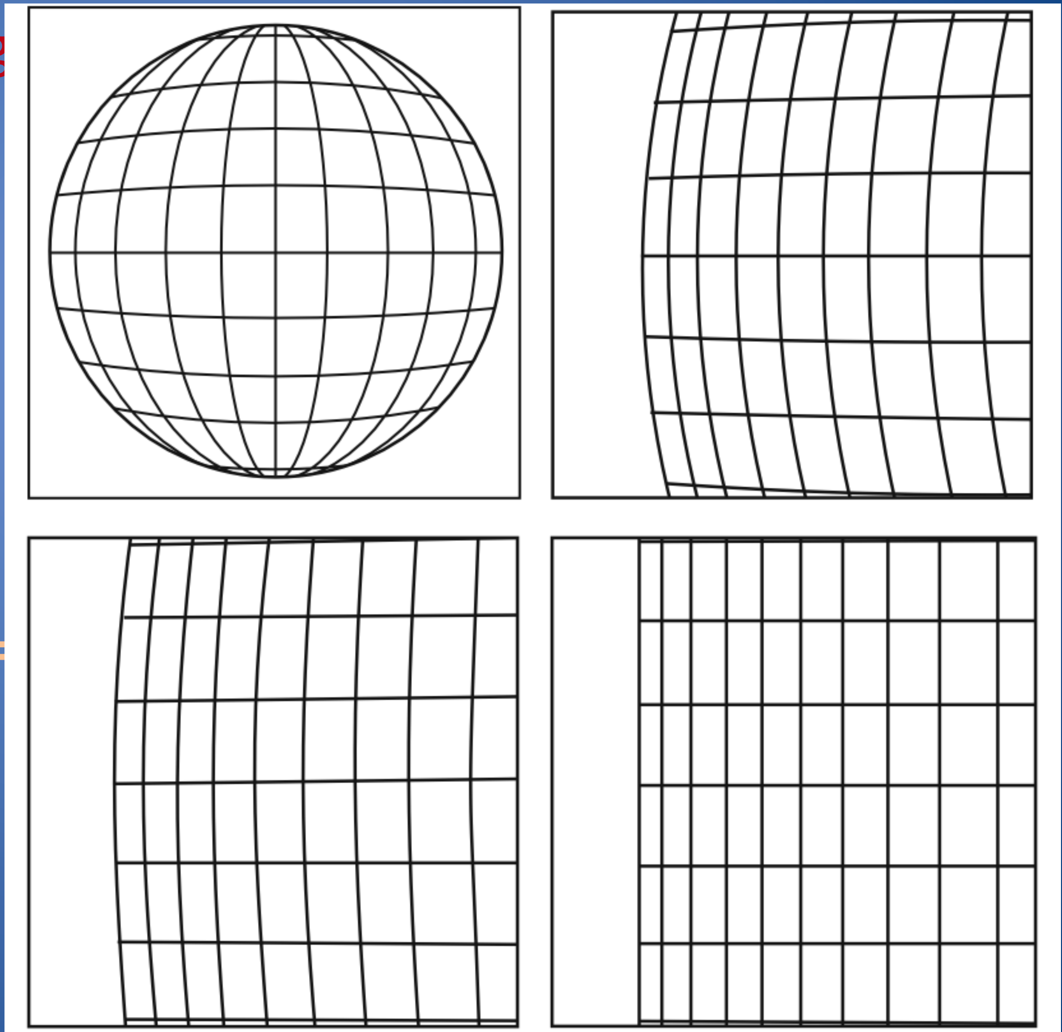


Ancient light from sources billions of light-years away, such as galaxies and the cosmic background radiation, show us events occurring billions of years ago. These events map out the history of the universe and even predict its fate.



Inflation makes the universe flat, homogeneous and isotropic

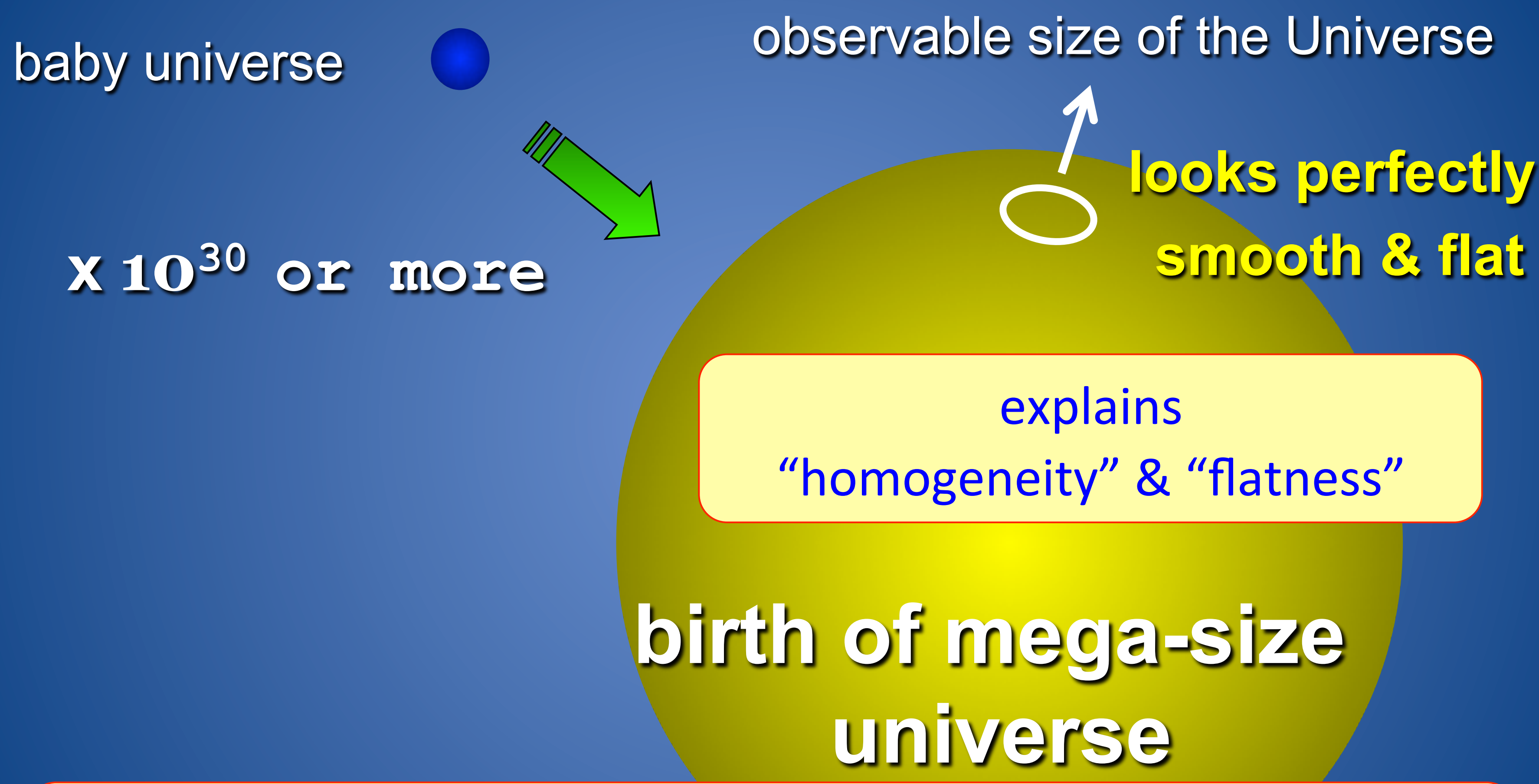
The new-born universe experienced rapid accelerating (inflation) expansion.



In this simple model the universe typically grows >10^{30} times during inflation.
(N ~ 50 – 60 or more)

Now we can see just a tiny part of the universe of size ct = 10^{10} light yrs. That is why the universe looks flat, homogeneous, and isotropic.

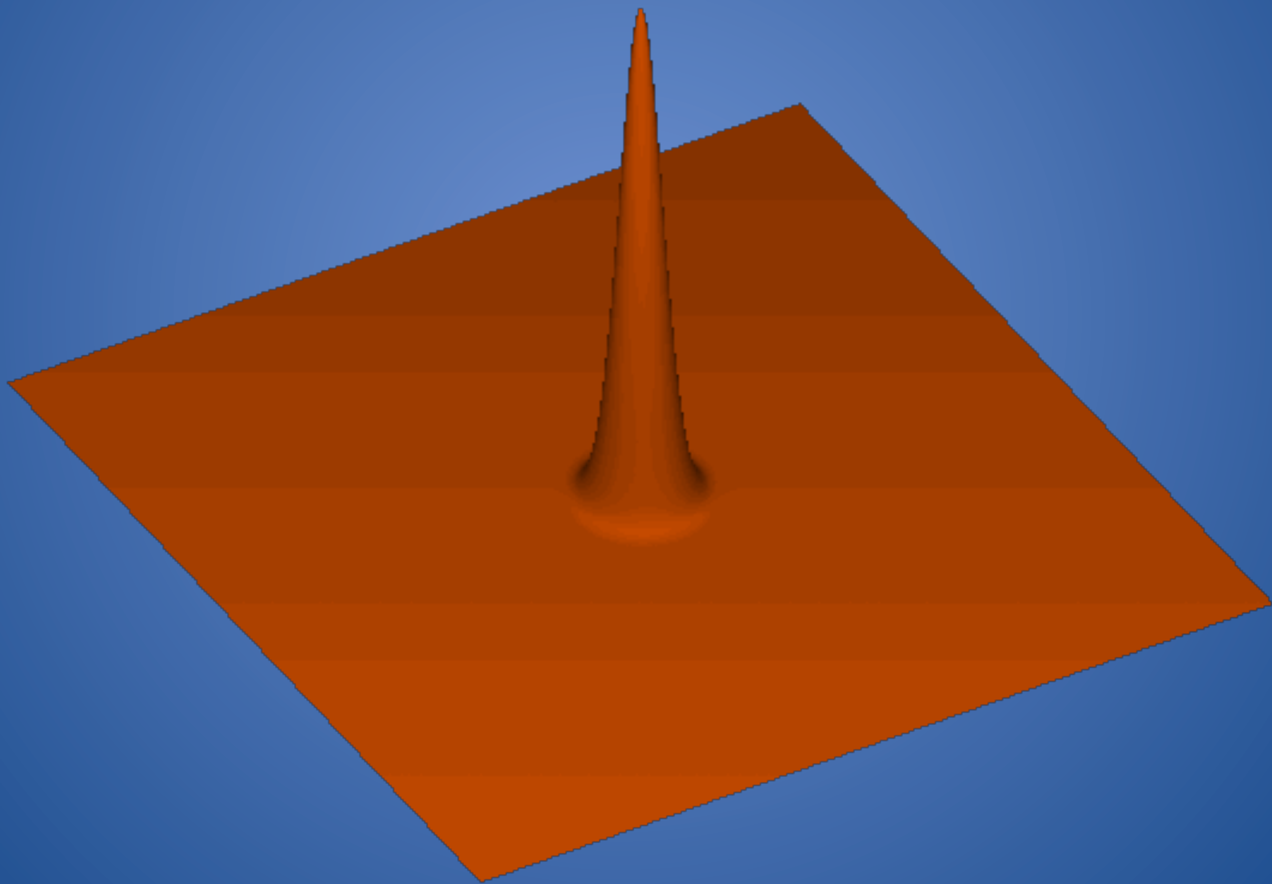
Cosmic Inflation



quantum vacuum fluctuations are also stretched to mega scales and they become seeds for formation of stars and galaxies

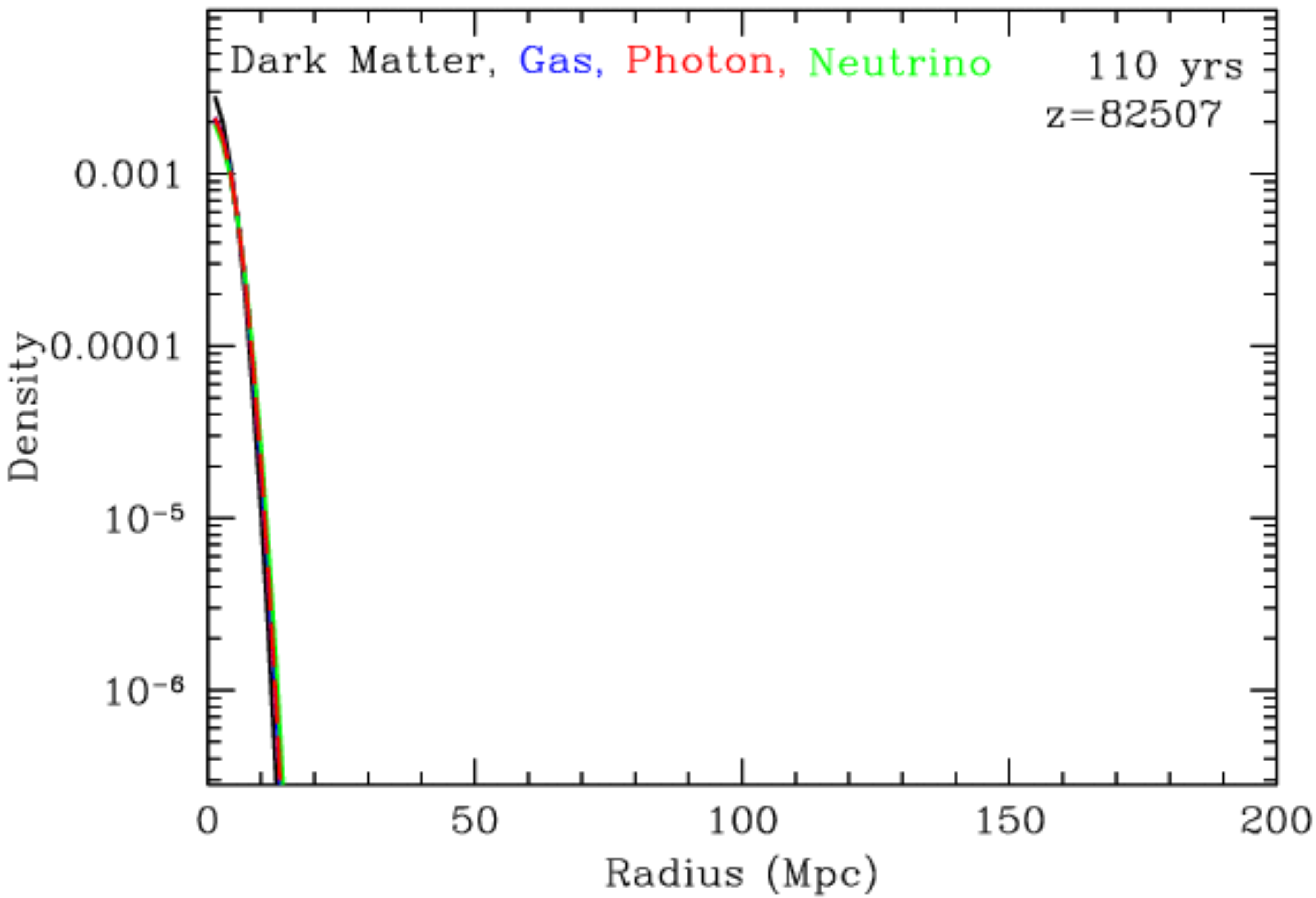
Evolution of single over dense lump

e.g. a quantum fluctuation after Inflation in comoving coordinates

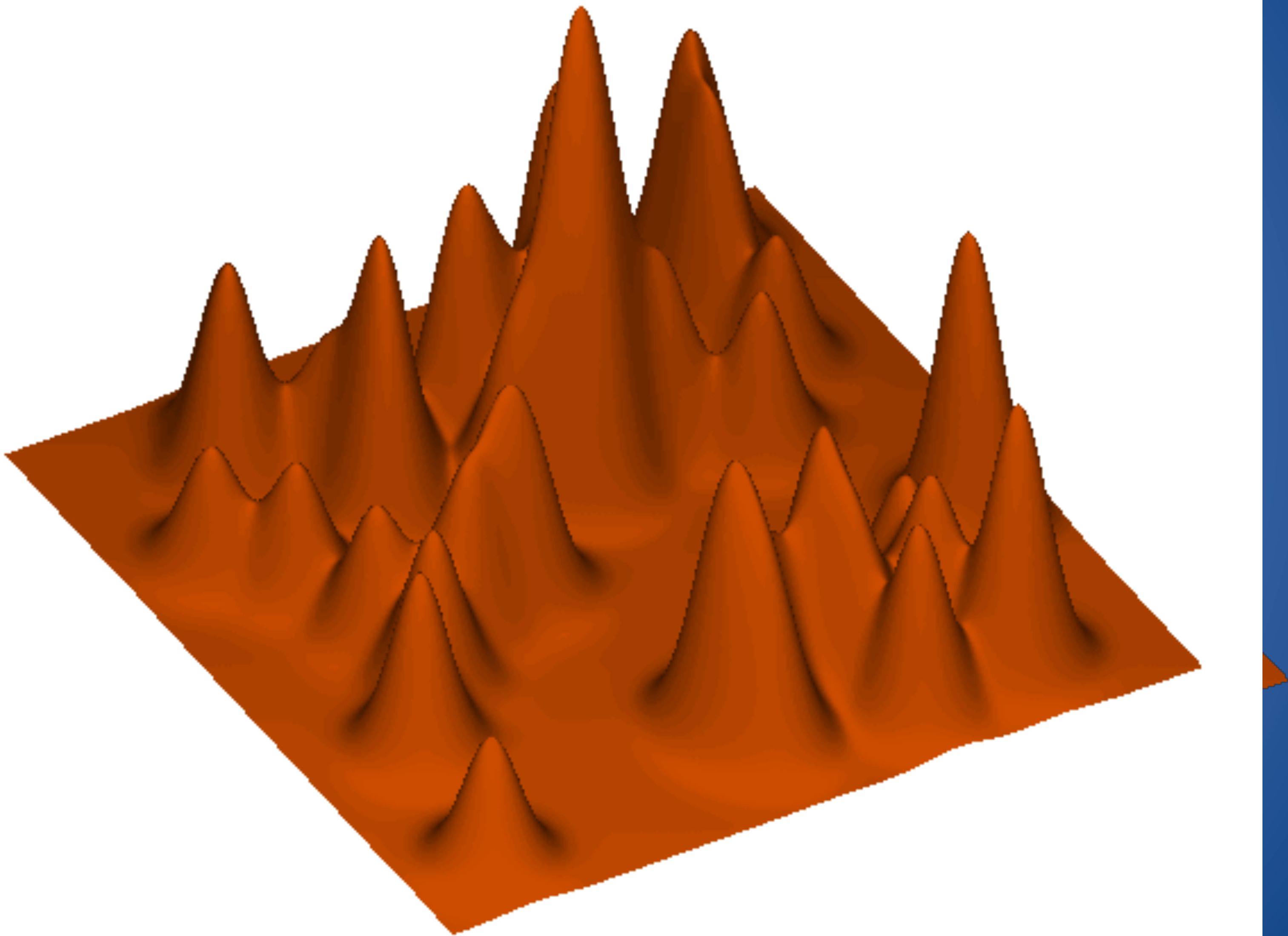


Daniel Eisenstein 2006

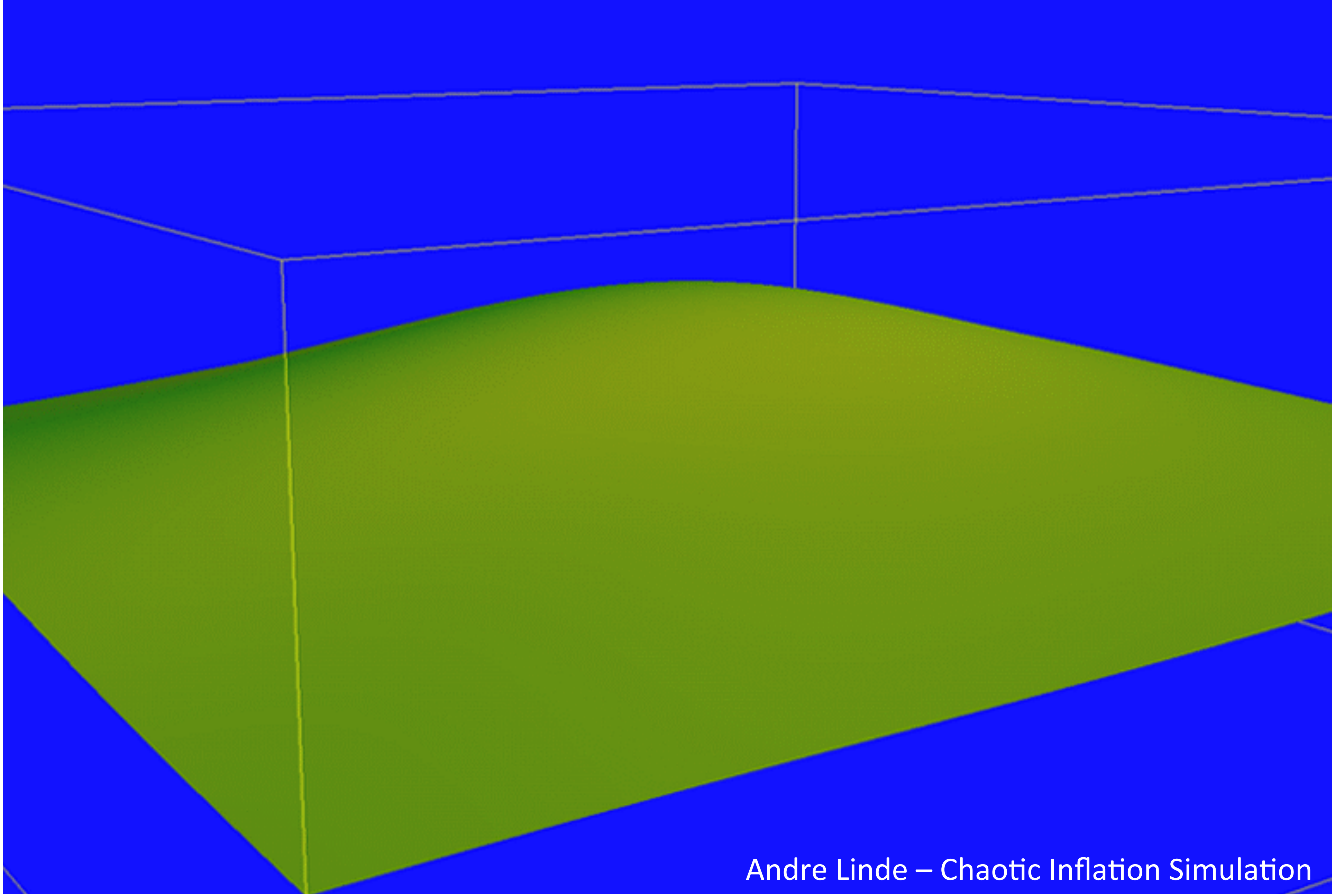
Evolution of Lumps Components



Many Random Perturbations

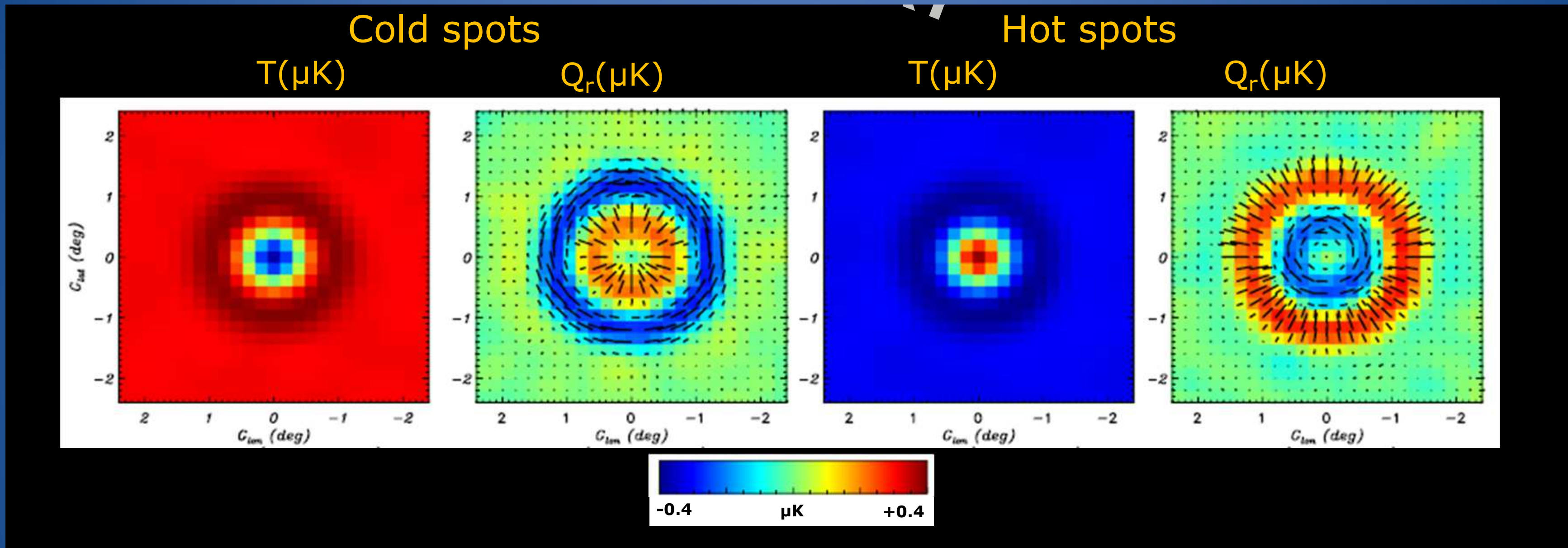


Generation of Quantum Fluctuations



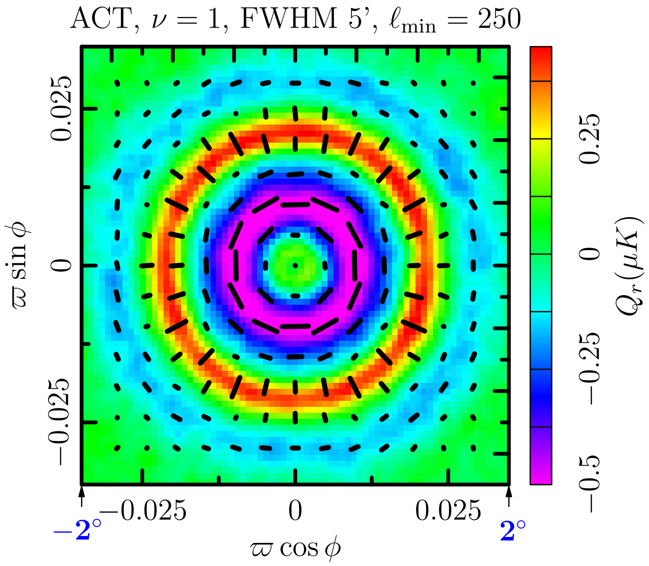
Andre Linde – Chaotic Inflation Simulation

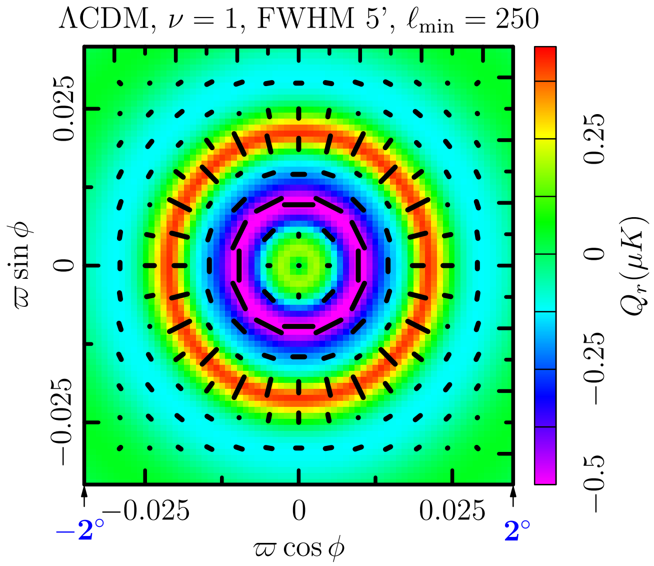
Stack Cold Spots / Hot Spots



We observe the temperature and polarization patterns predicted for baryon acoustic oscillations
Very direct test of the hypothesis and adiabatic nature of perturbations
Data from Planck satellite

Stacks for Atacama Cosmology Telescope & Sims

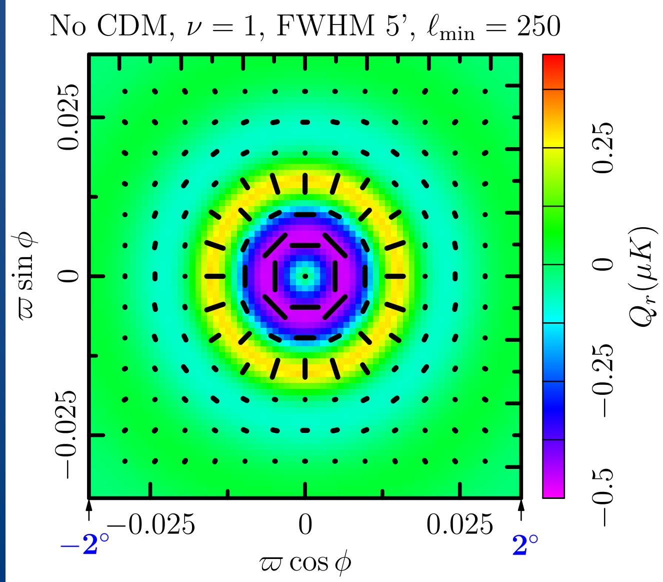


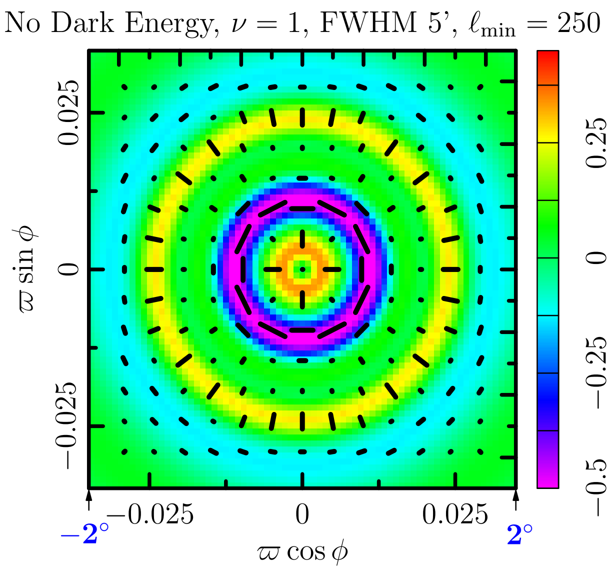


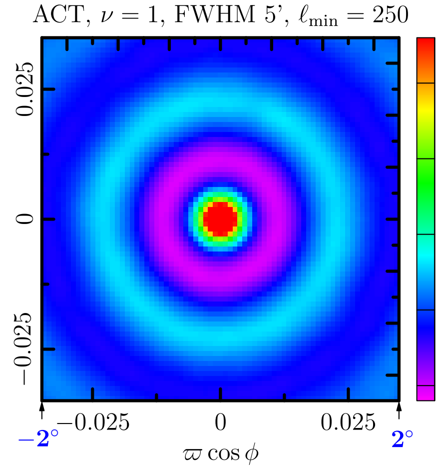
Stacking rotated polarization on field points (ACTpol data)

complementary view to 2D power spectrum,

you select the points to stack on



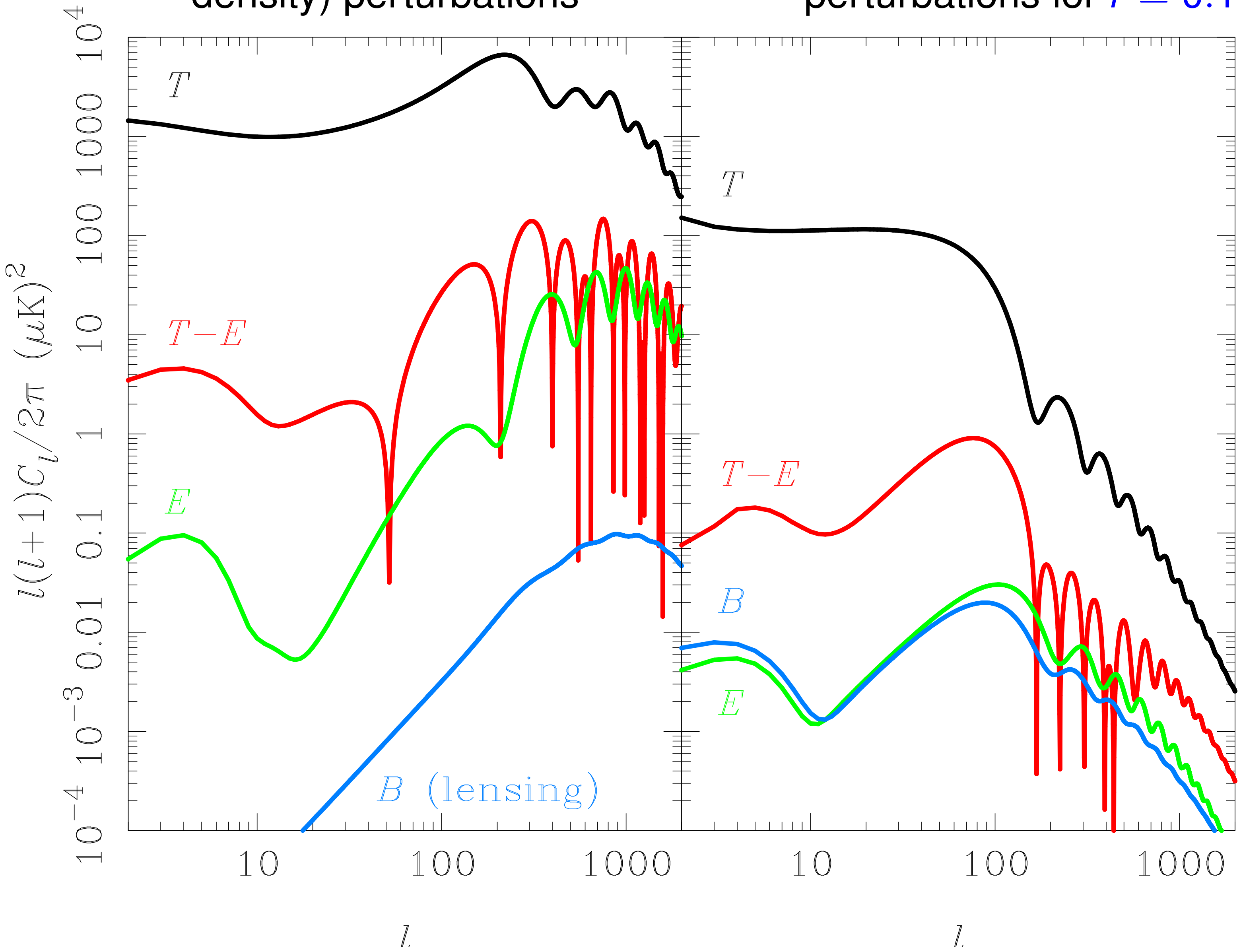




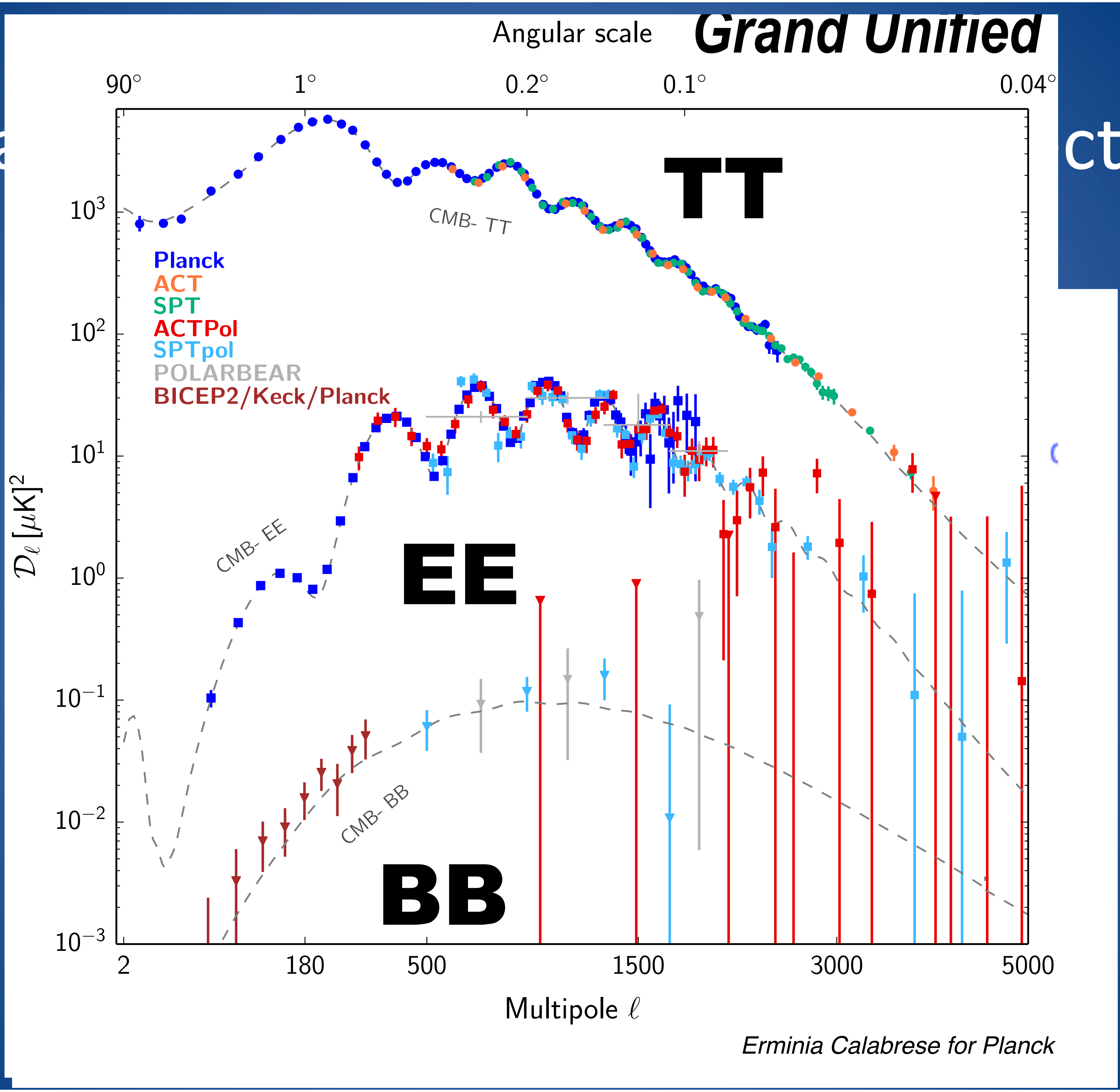
CMB Power spectra (Two parts separately)

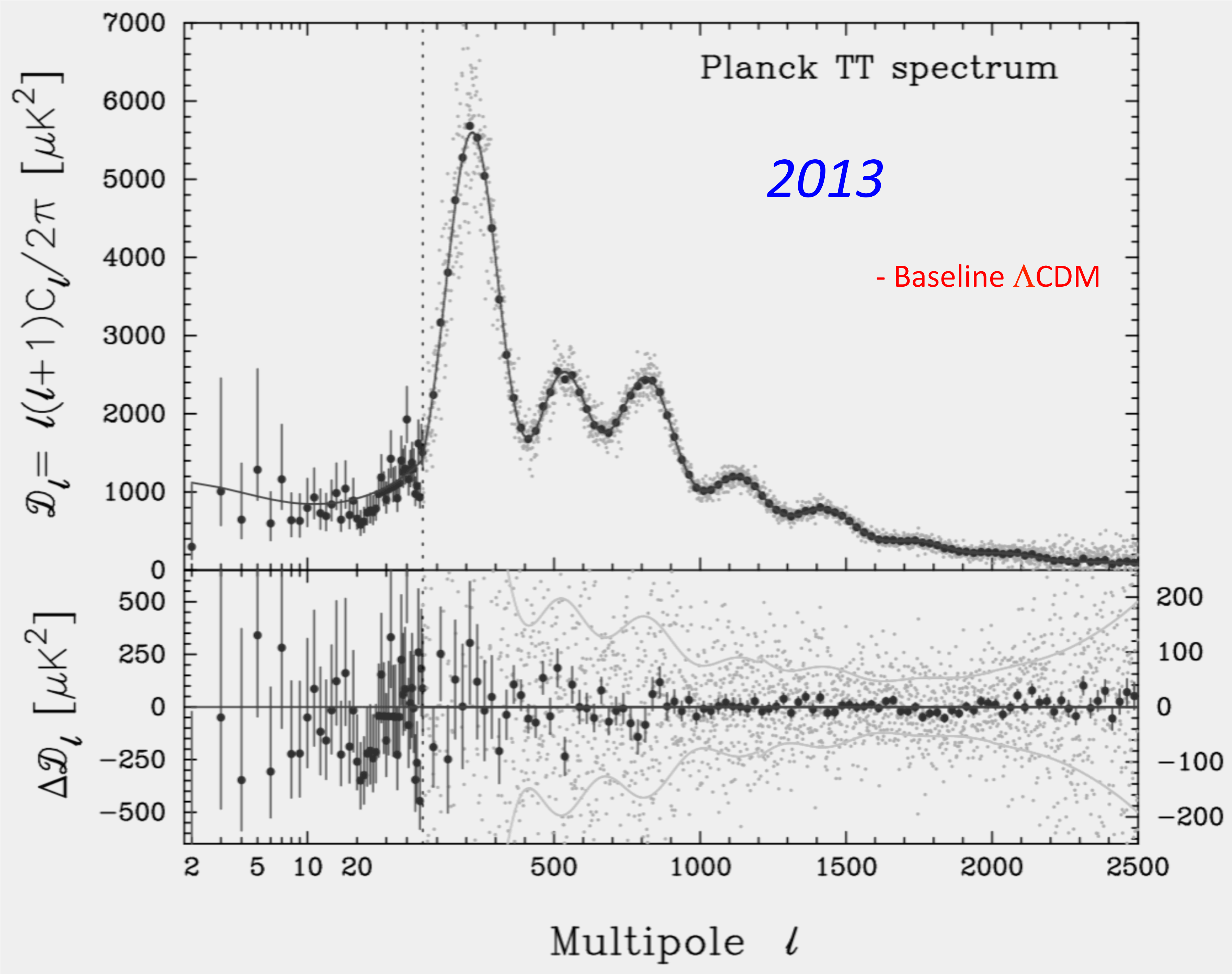
Scalar (matter and radiation density) perturbations

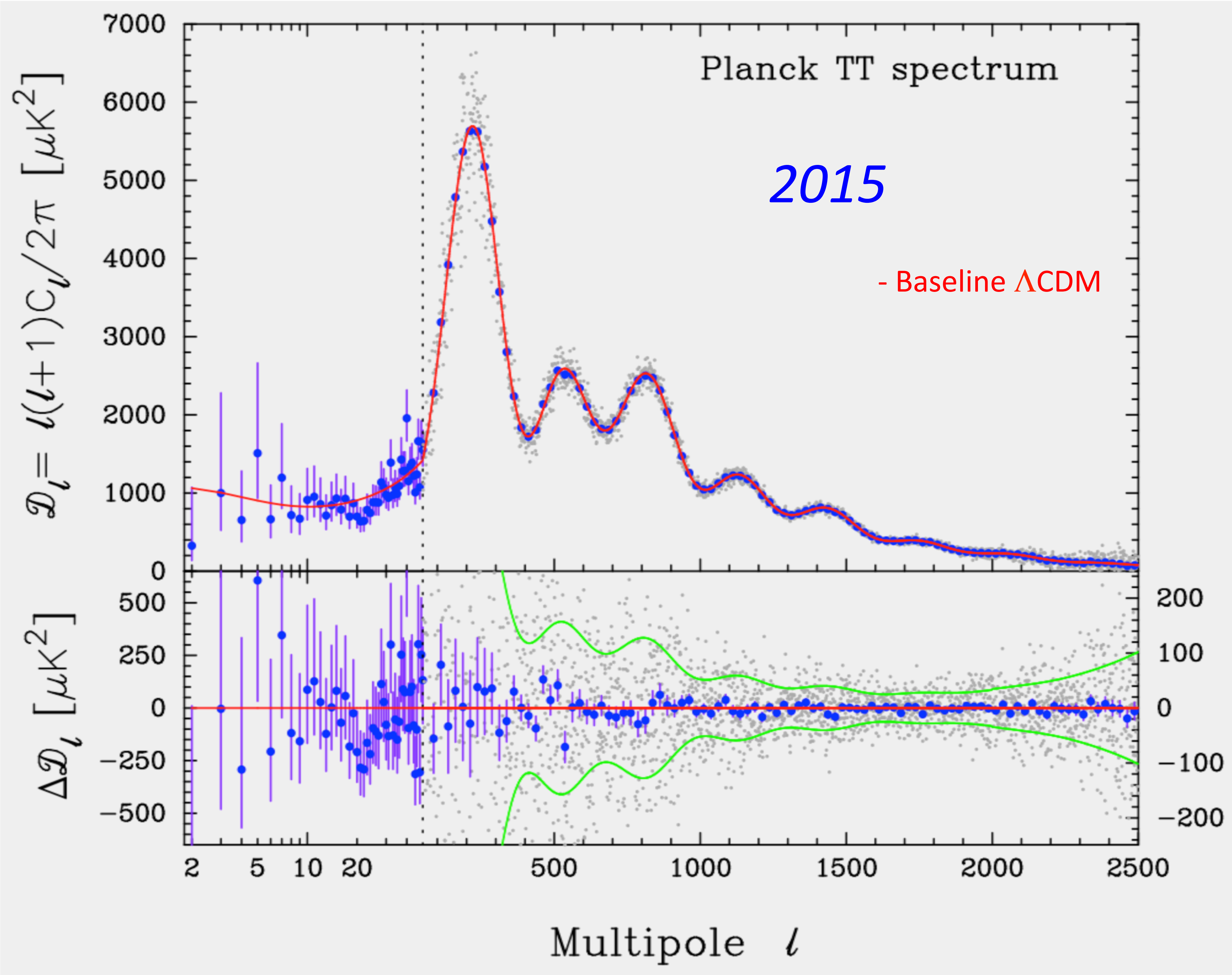
Tensor (gravity wave) perturbations for $r = 0.1$



Gra ctra


Angular scale
Grand Unified
90°
1°
0.2°
0.1°
0.04°
TT
EE
BB
CMB- TT
CMB- EE
CMB- BB
Planck
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck/Planck
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$\mathcal{D}_\ell\ [\mu K]^2$
2
180
500
1500
3000
5000
Multipole ℓ
Erminia Calabrese for Planck

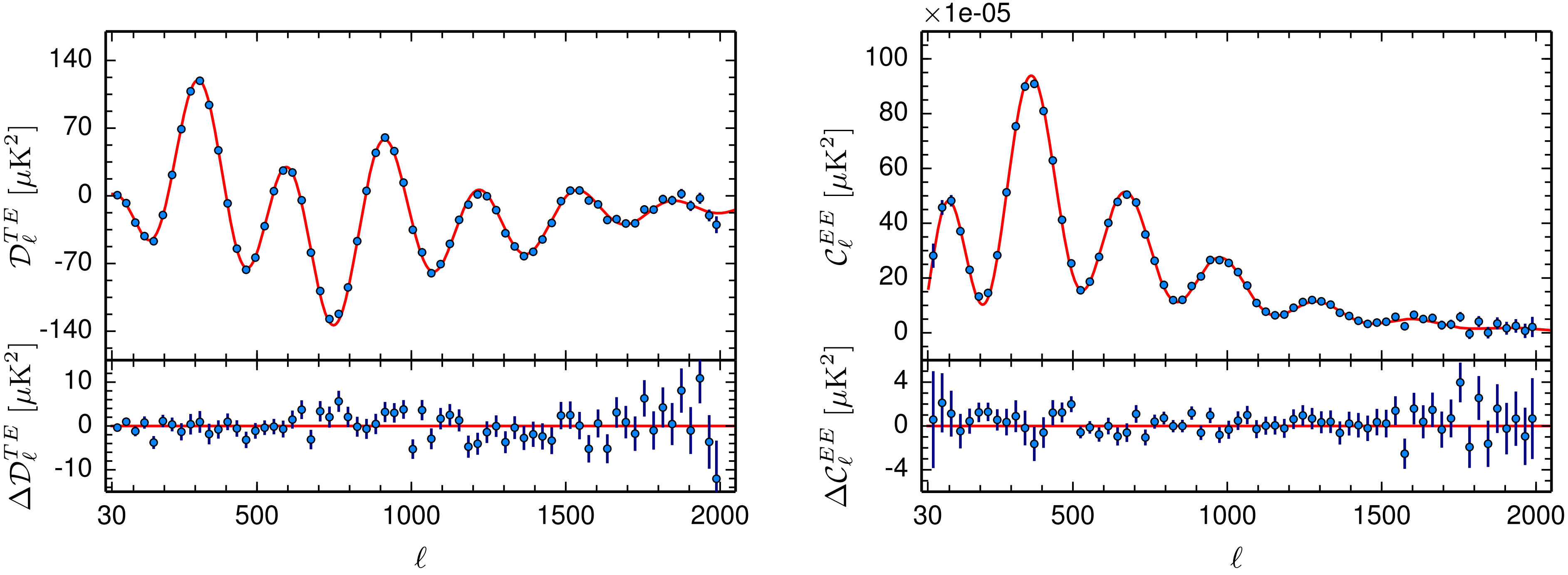

Planck TT spectrum
2013
- Baseline ΛCDM
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500



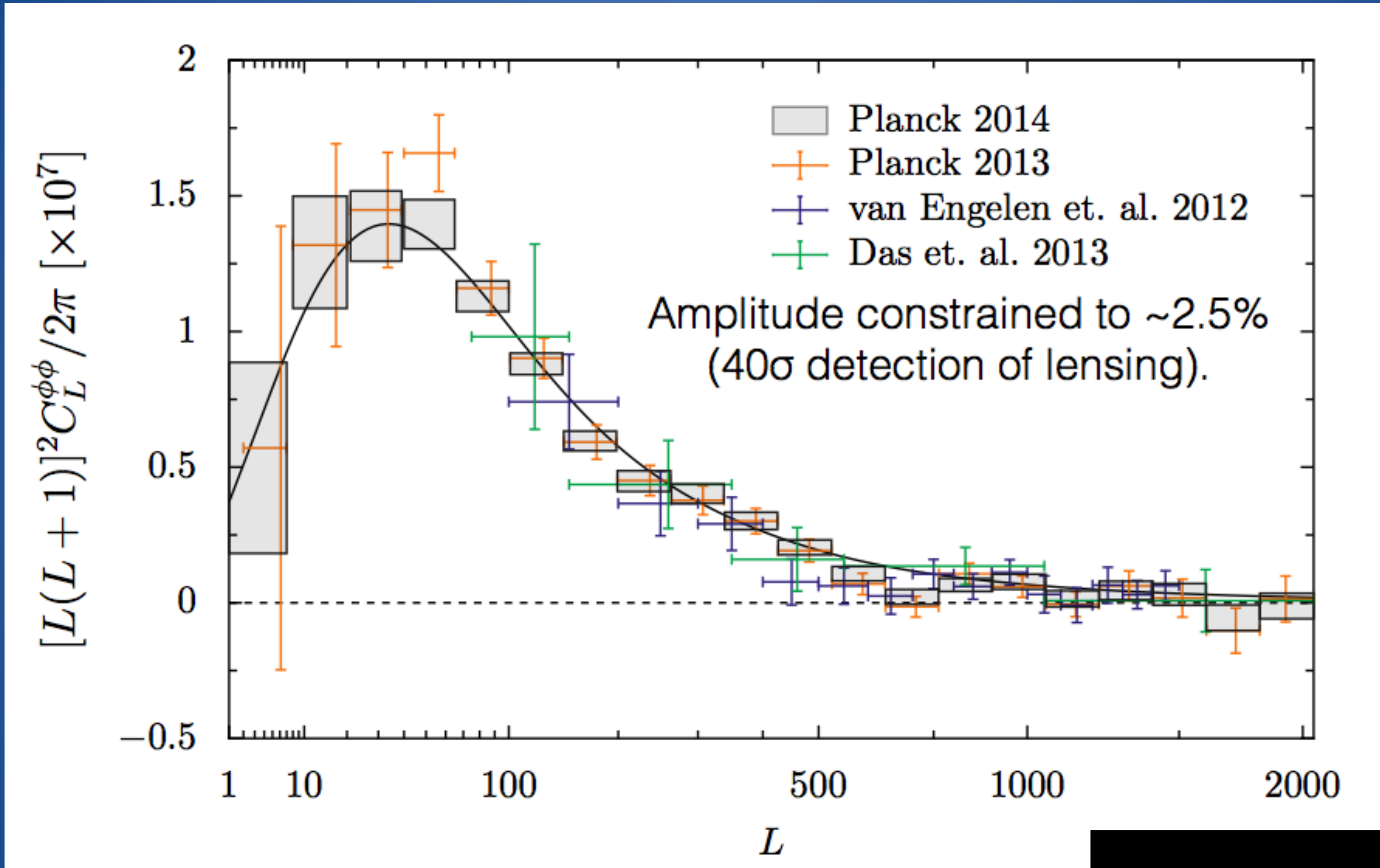
Planck TT spectrum
2015
- Baseline ΛCDM
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

… and beautiful polarization spectra

TE *EE*

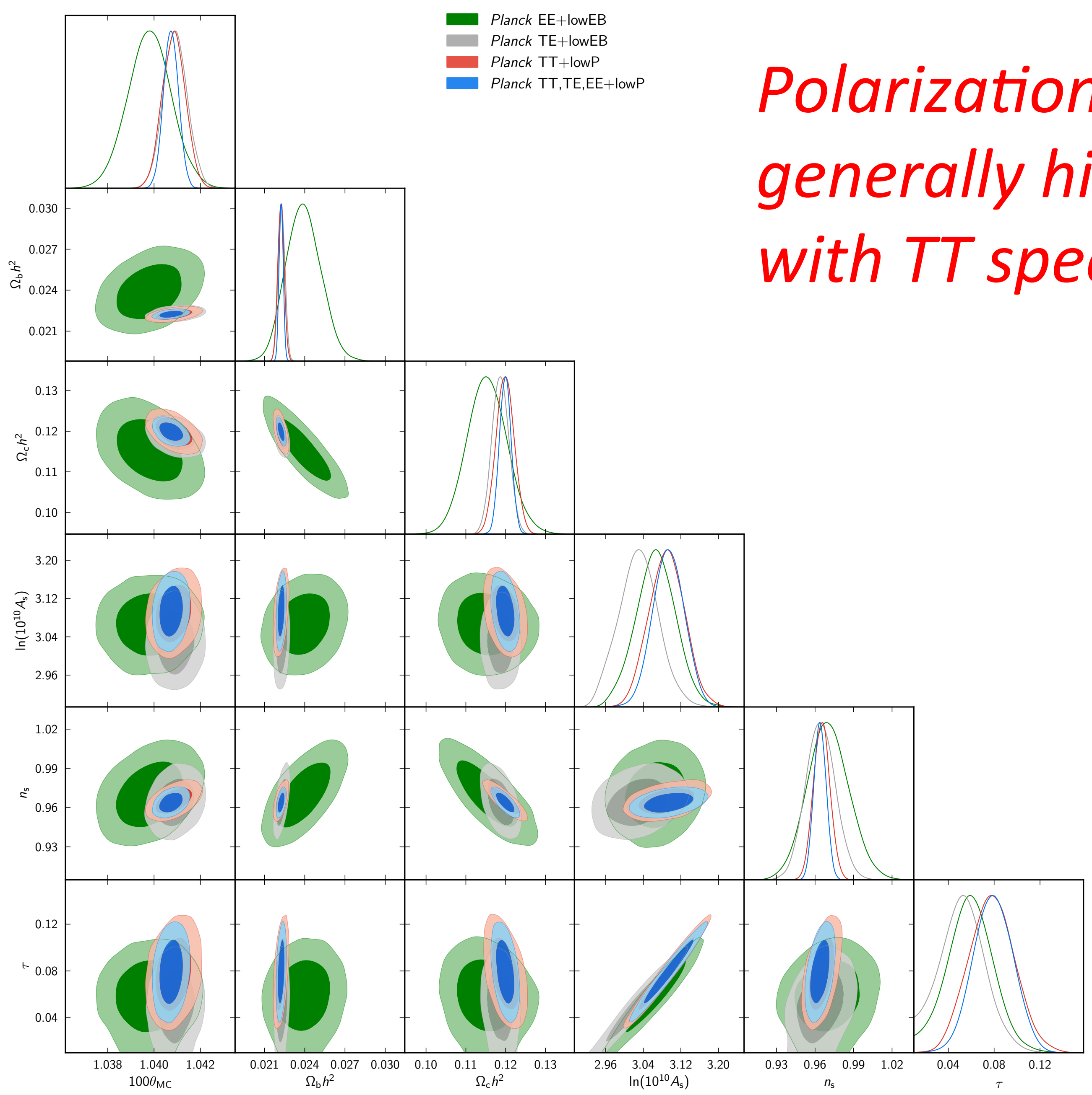


… and beautiful lensing spectra



[redacted]

TT, TE, EE, EB, TB spectra



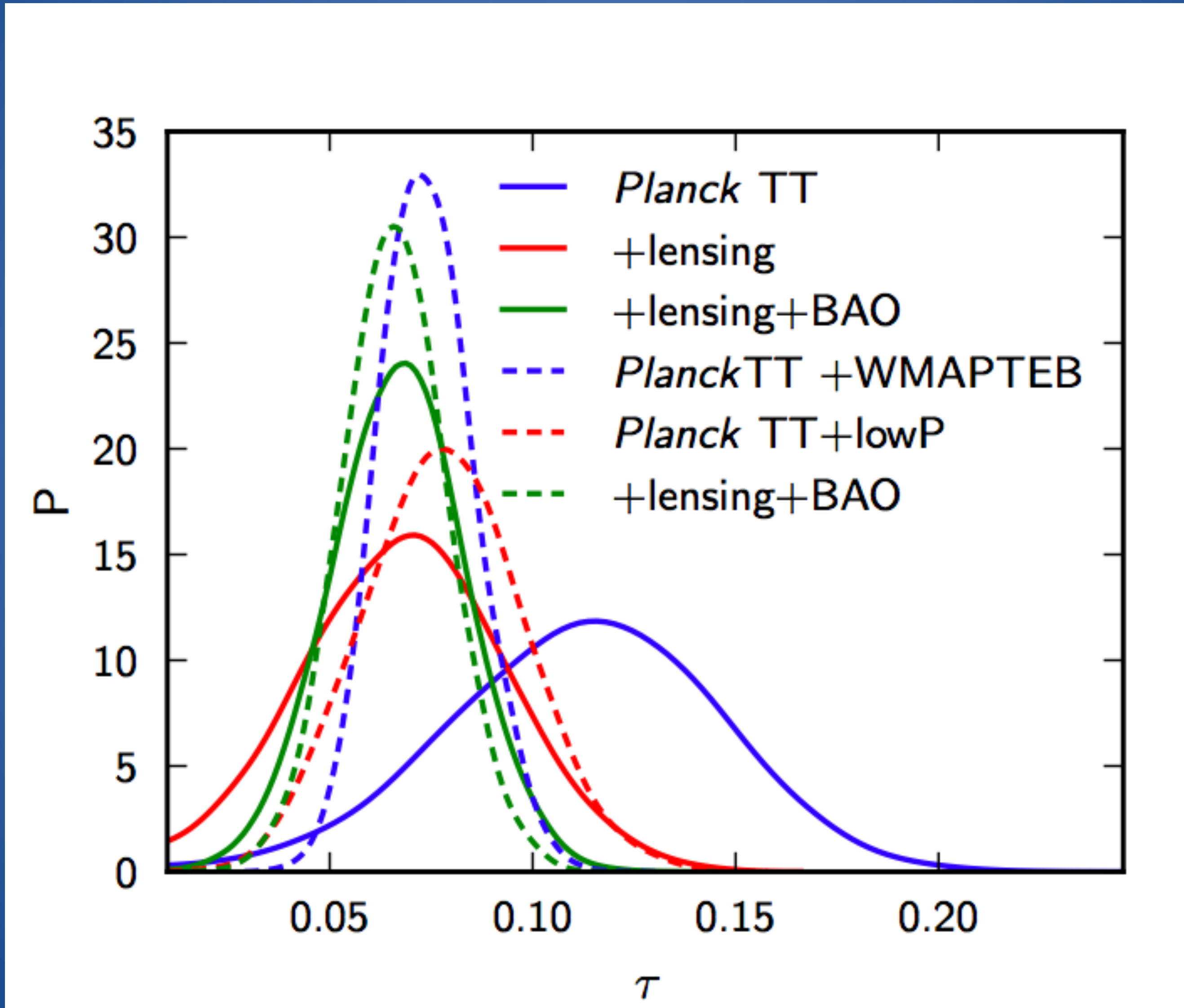
Polarization spectra are generally highly consistent with TT spectra.

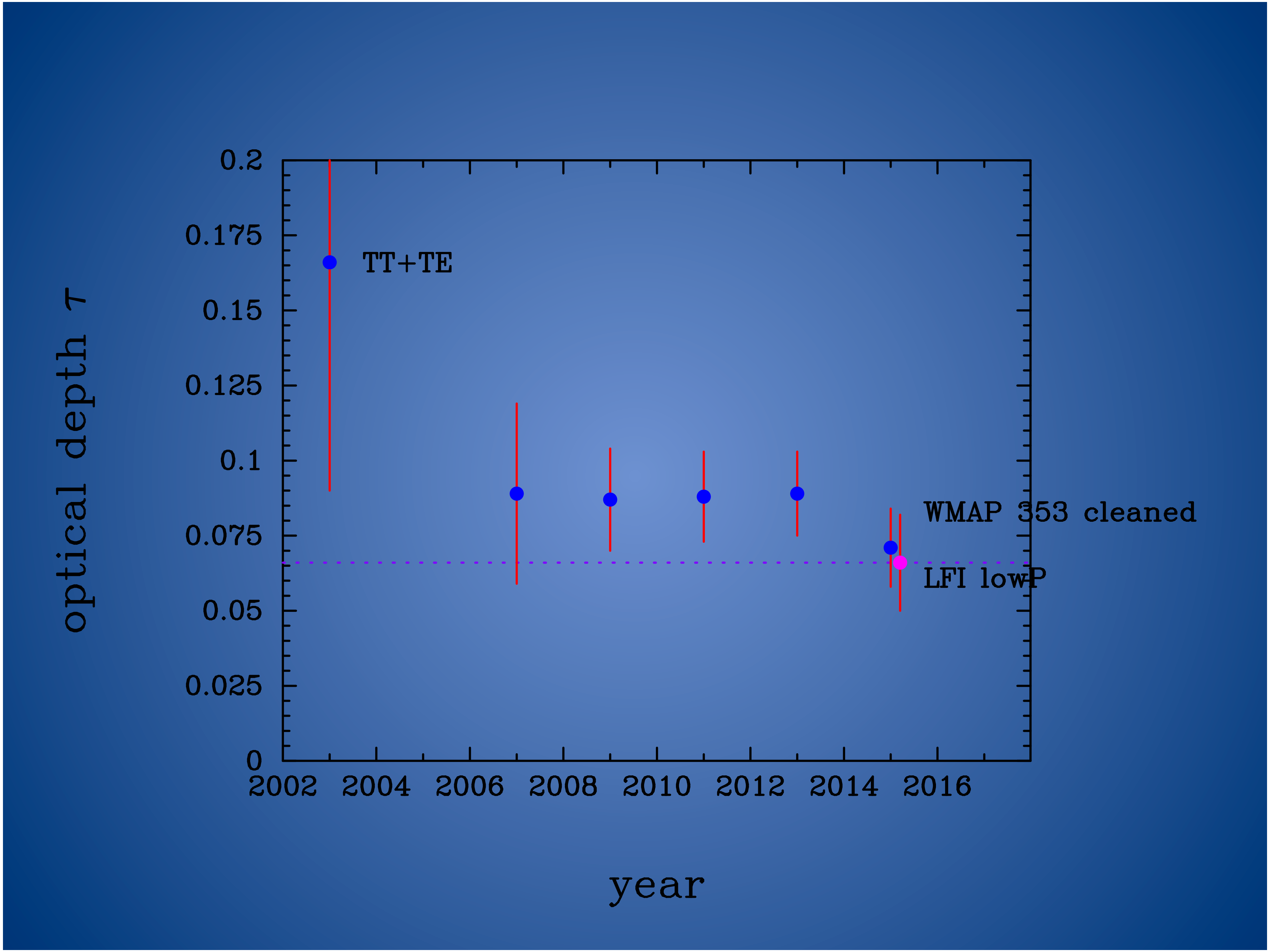
BASE ΛCDM MODEL

Parameter	TT	TT,TE,EE
$\Omega_b h^2$	0.02222±0.00023	0.02224±0.00015
$\Omega_c h^2$	0.1199±0.0022	0.1199±0.0014
$100\theta_*$	1.04086±0.00048	1.04073±0.00032
τ	0.078±0.019	0.079±0.017
n_s	0.9652±0.0062	0.9639±0.0047
H_0	67.3±1.0	67.23±0.64
Ω_m	0.316±0.014	0.316±0.009
σ_8	0.830±0.015	0.831±0.013
z_{re}	9.9±1.9	10.7±1.7

…but warning: there are still low level systematics in the polarization spectra

Constraints on reionization optical depth τ





optical depth τ
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
2002
2004
2006
2008
2010
2012
2014
2016
year
TT+TE
WMAP 353 cleaned
LFI lowP

Planck 2013:

- good agreement with Planck lensing
- consistent with BAO
- ~2σ tension with Ia SNe
- ~2.5σ tension with H_0
- tension with measures of σ_8 including:
  - weak lensing
  - cluster counts
  - redshift space distortions

2015 illuminates some of these

Non-Gaussianity

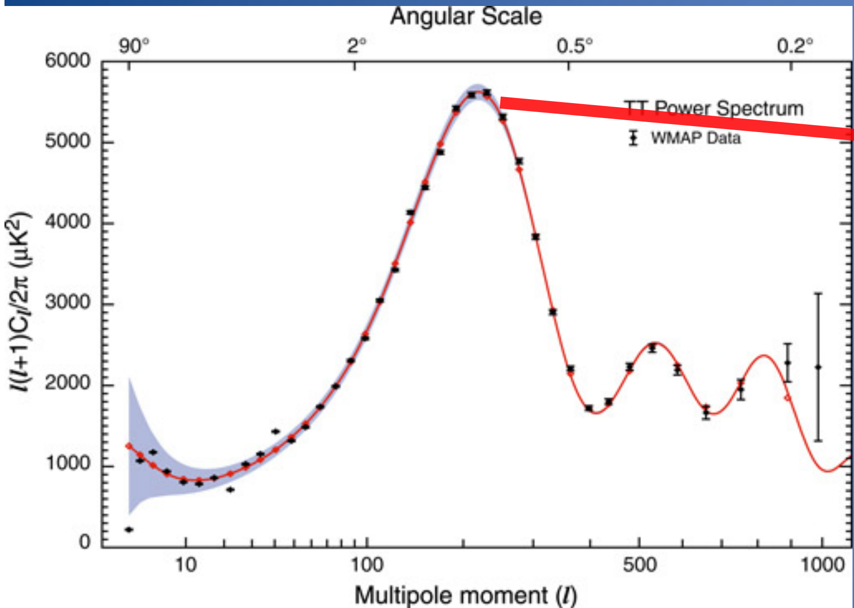
Temperature	Temperature+polarization
$f_{NL}^{local} = 2.5 \pm 5.7$	$f_{NL}^{local} = 0.8 \pm 5.0$
$f_{NL}^{equil} = -16 \pm 70$	$f_{NL}^{equil} = -4 \pm 43$
$f_{NL}^{ortho} = -34 \pm 33$	$f_{NL}^{orthol} = -26 \pm 21$

$$g_{NL}^{local} = (-9.0 \pm 7.7) \times 10^4$$

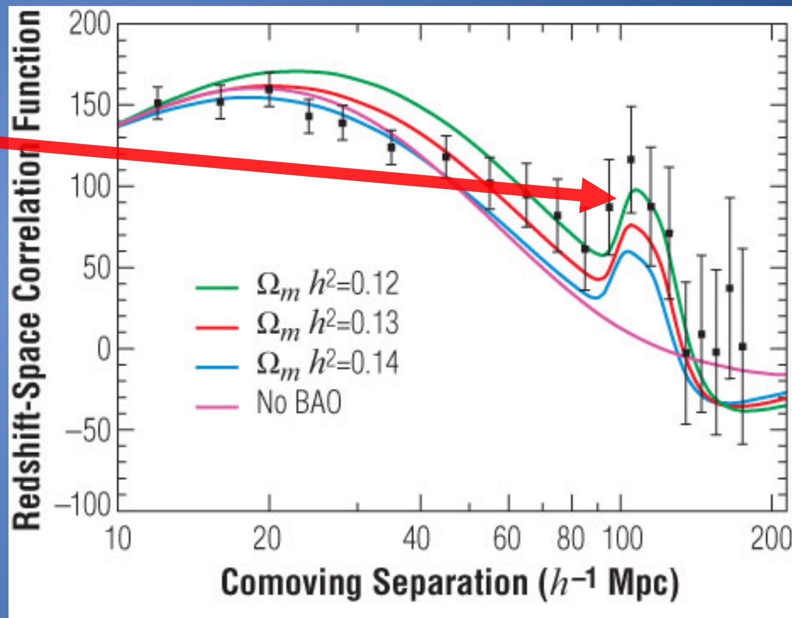
2nd Dark Energy Tool: Acoustic Oscillations

Fluctuations on all scales, but there is a characteristic scale.

CMB (WMAP 2003): Photon+Baryon



SDSS (2005): Baryons

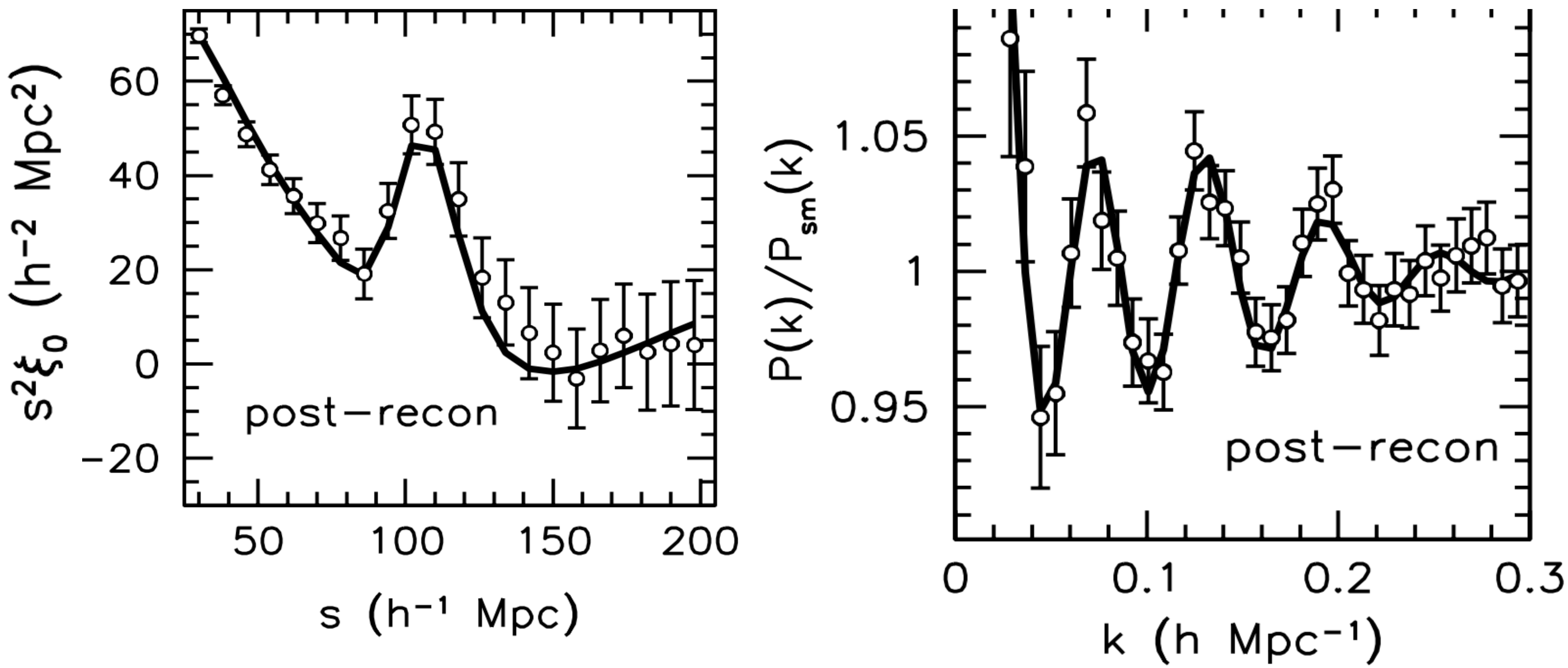


Eisentein et al. 2005

- Smallest systematic errors (DETF), simple physics
- Angles easier to measure than fluxes and source shapes
- Gives two independent measures, H(z) and D(z), from radial and transverse correlation function
- Can usefully measure w(z) to z~2

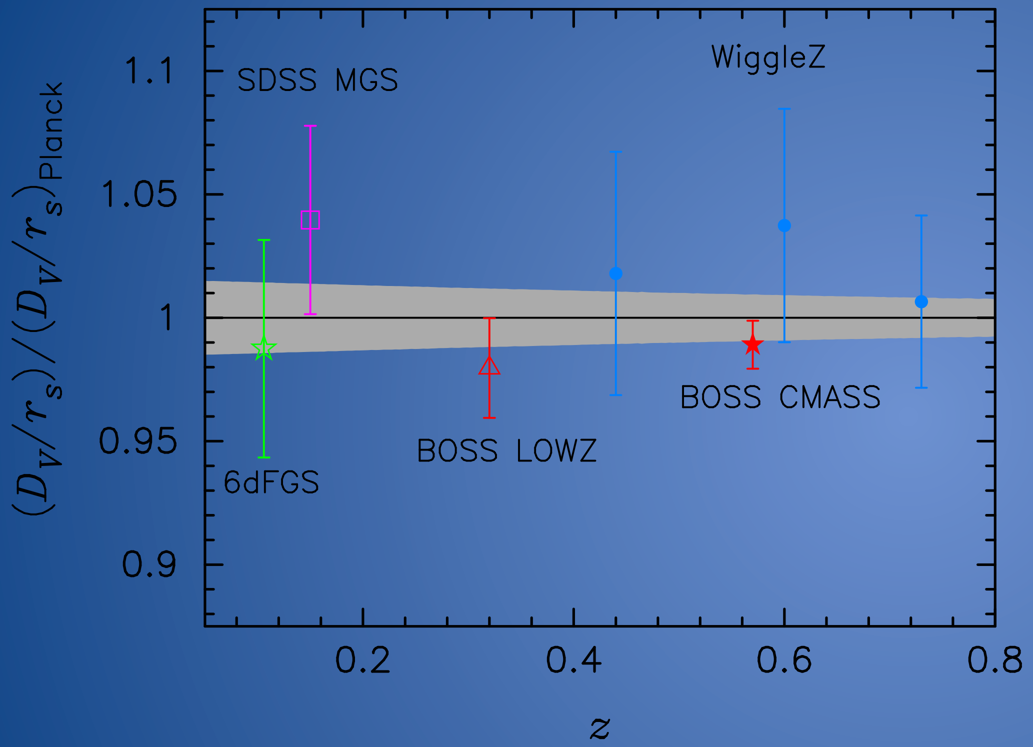
Baryon Acoustic Oscillations (BAO) 2014

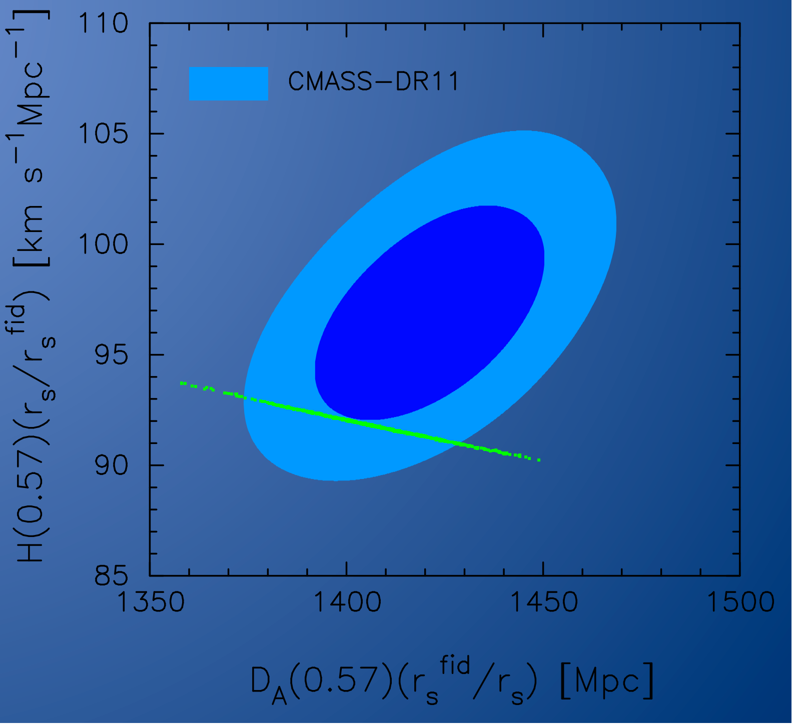
2014, 1%



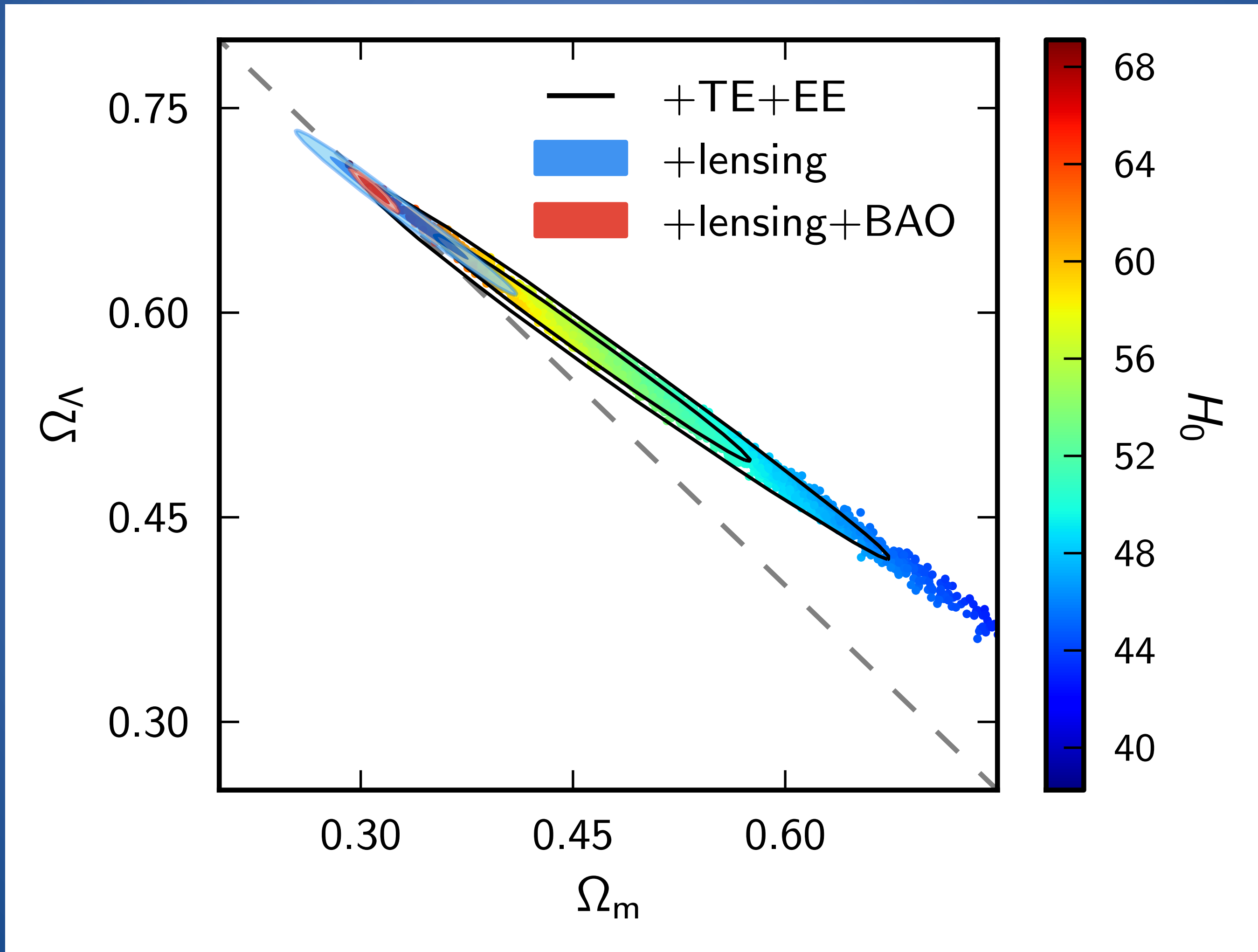
BOSS CMASS

Baryon Acoustic Oscillations (BAO)

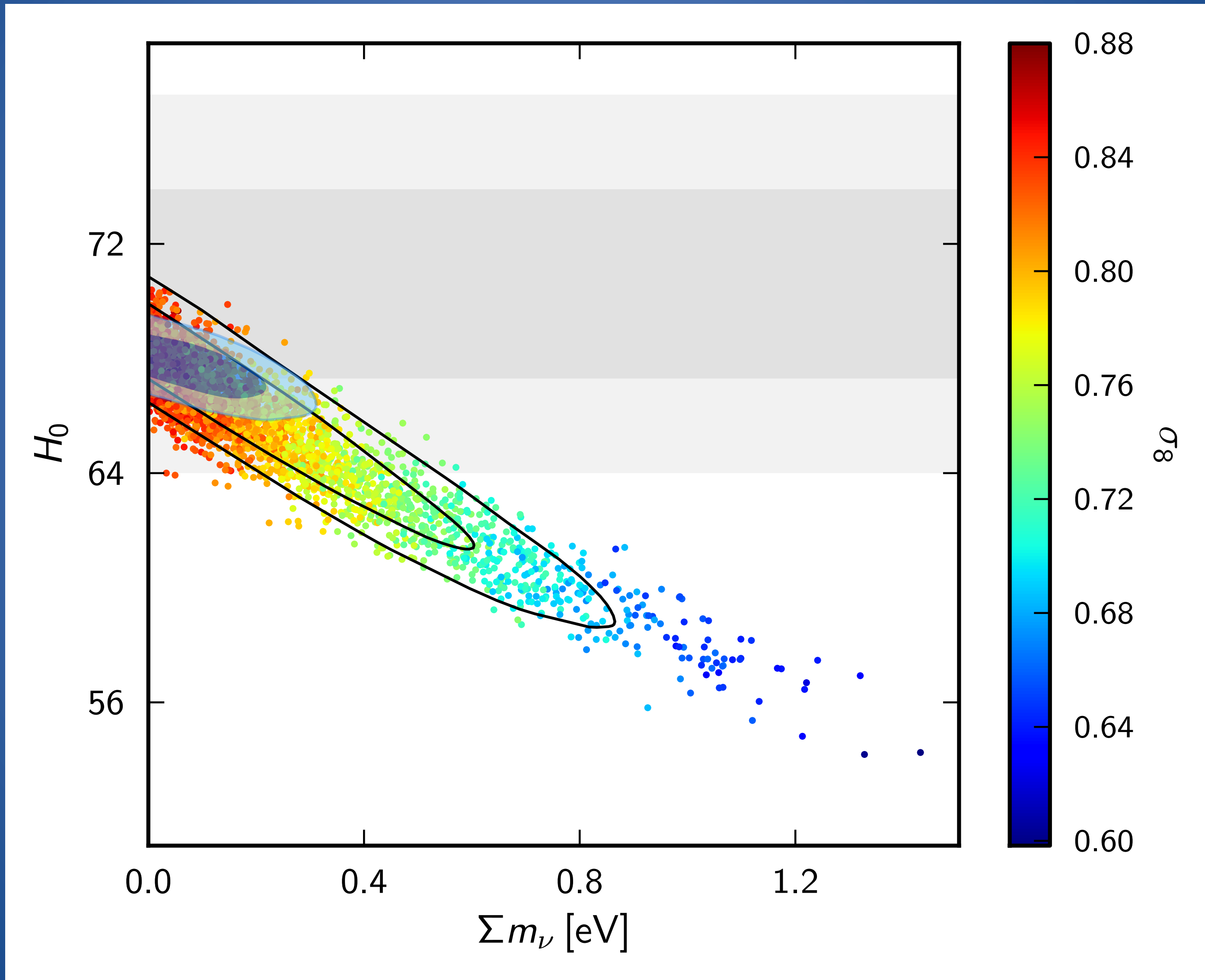




.... leading to remarkable constraints on spatial curvature $\Omega_k = 1 - \Omega_m - \Omega_\Lambda = 0.000 \pm 0.005$ (95%)



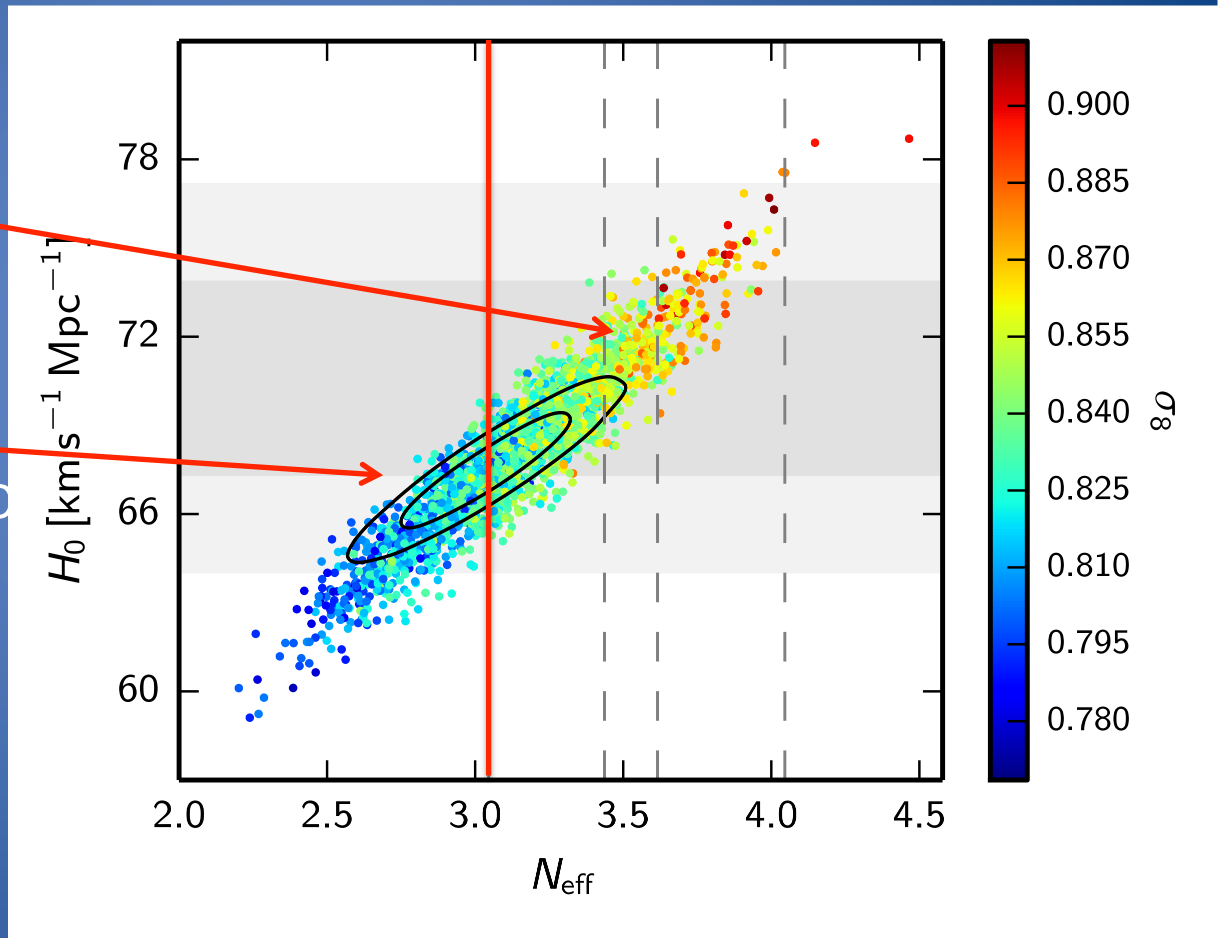
.... and to neutrino masses $\Sigma m_\nu < 0.21$ eV (95%)



.... and to relativisic species

N_{eff}=3.13±0.32
(Planck TT+lowP)

N_{eff}=3.04±0.18
(Planck TT+TE+EE+lowP +BAO



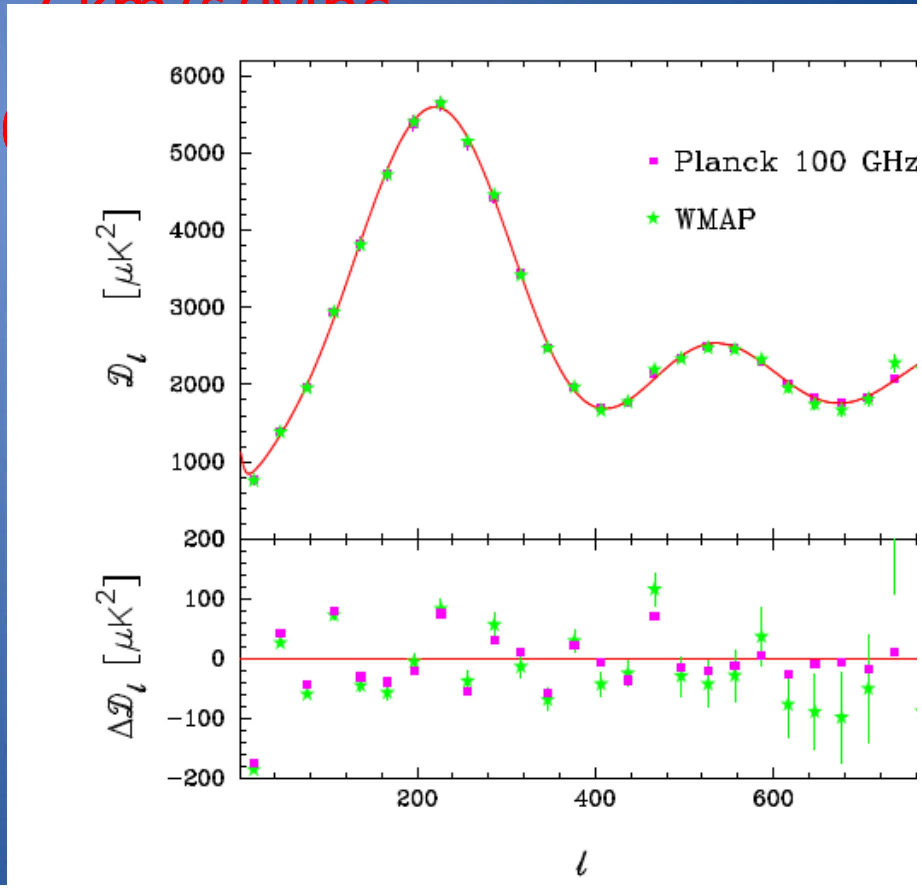
An aside on H_0:

WMAP9 H_0= 69.7± 2.2 km/s/Mpc

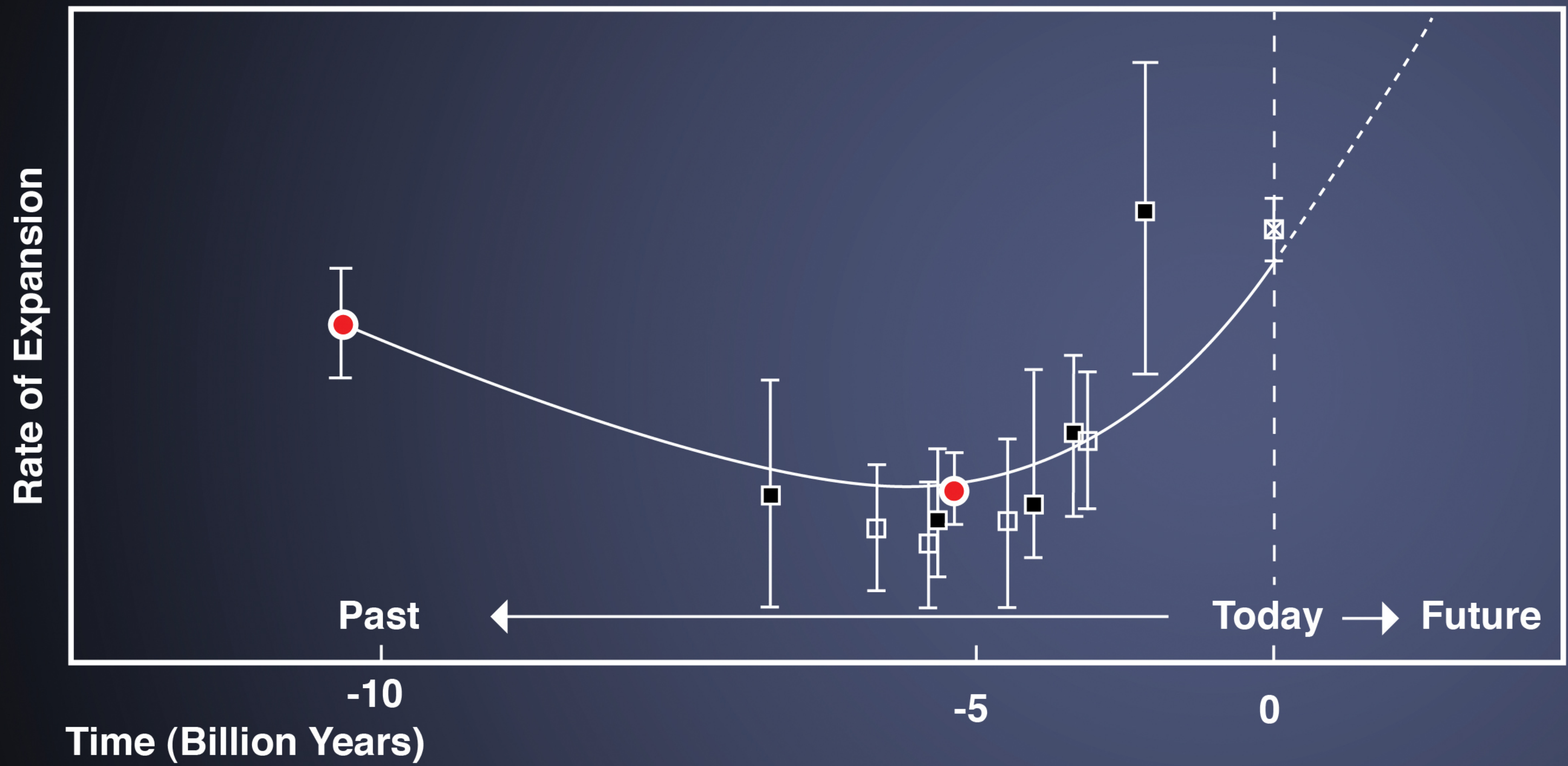
Planck TT H_0= 67.3± 1.0 km/s/Mpc

WMAP9+BAO H_0= 68.0± 0.7 km/s/Mpc

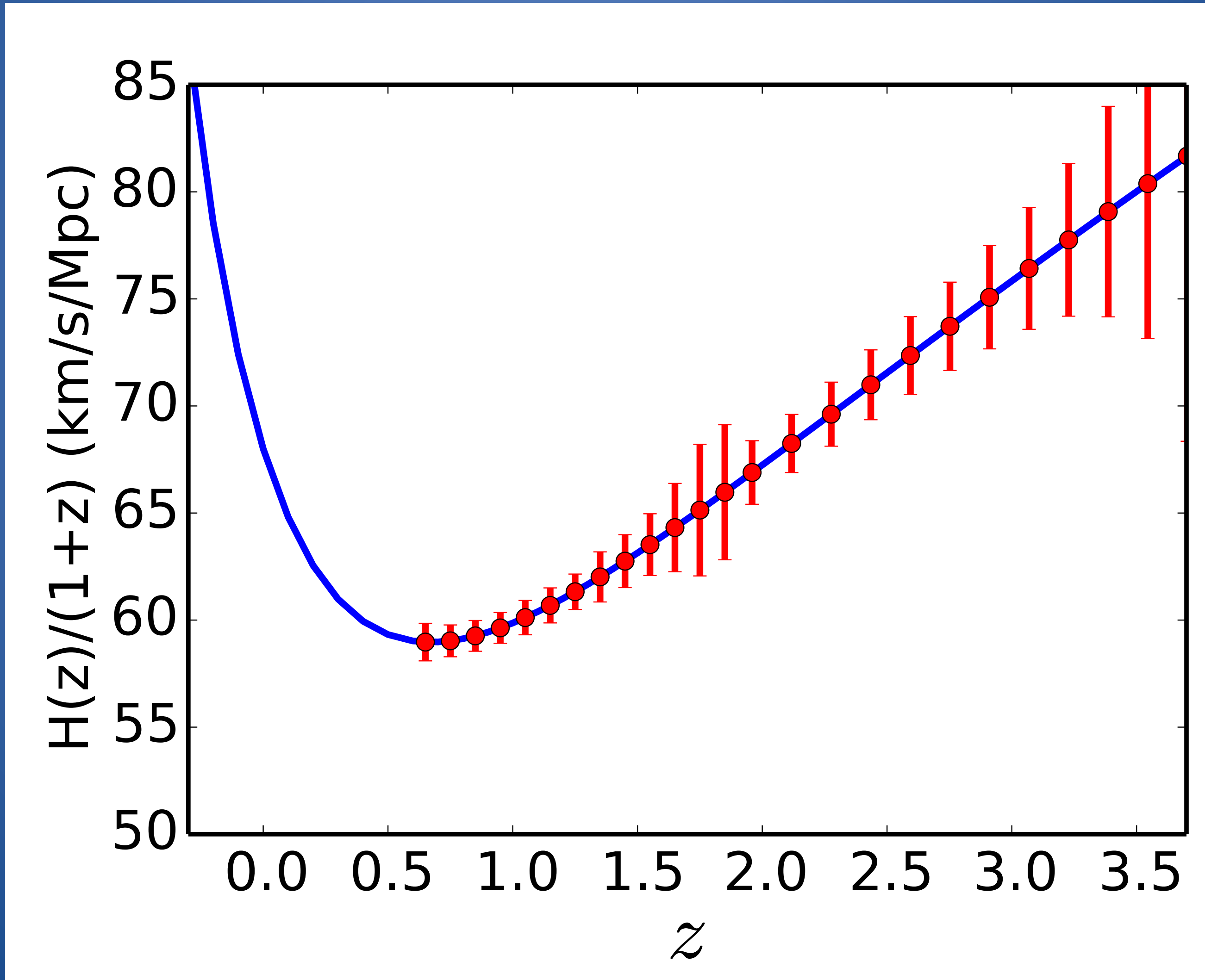
Planck TT+BAO H_0= 67.6±



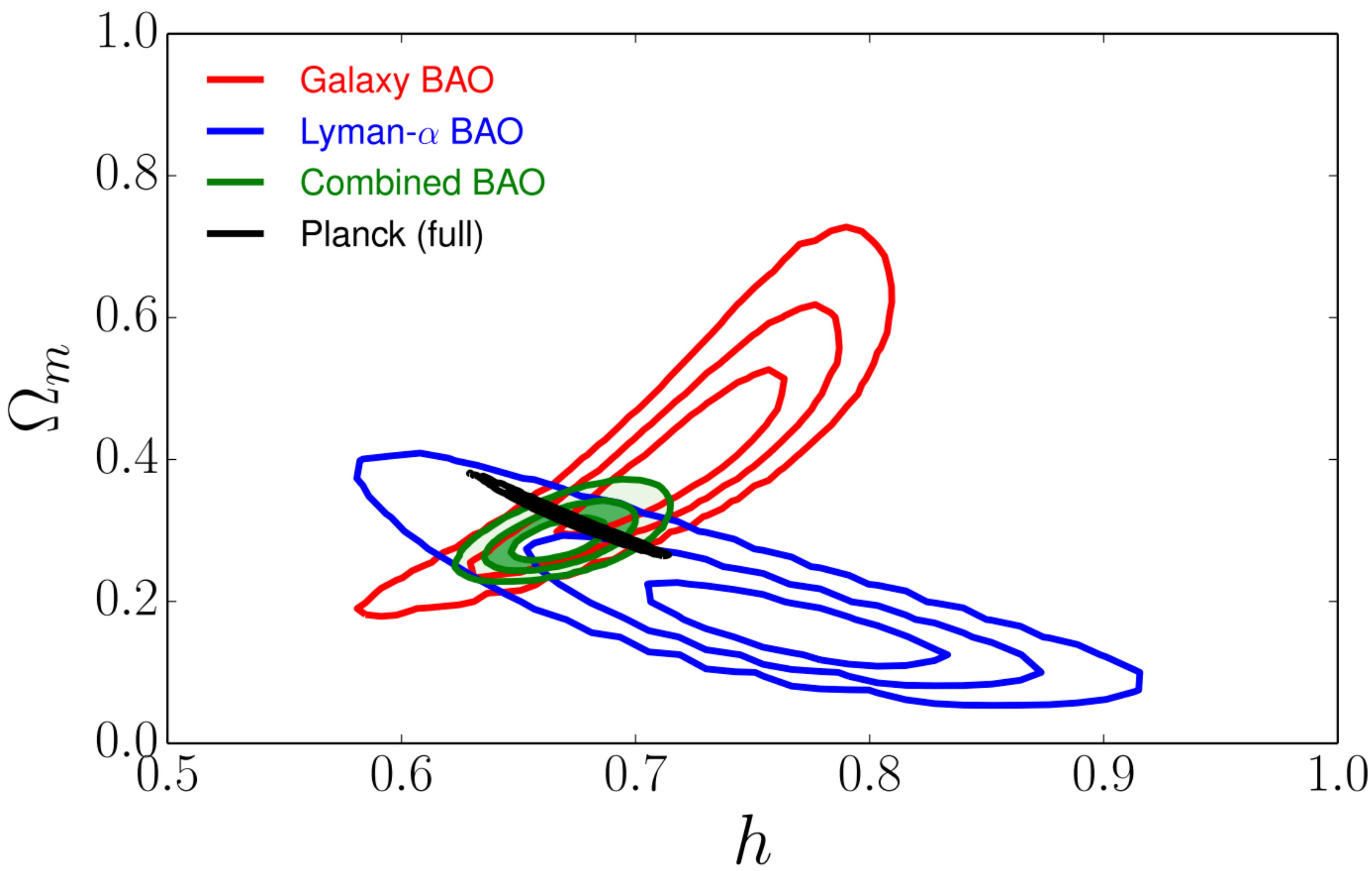
Expansion Rate H of Universe vs time measured via BAO Observations



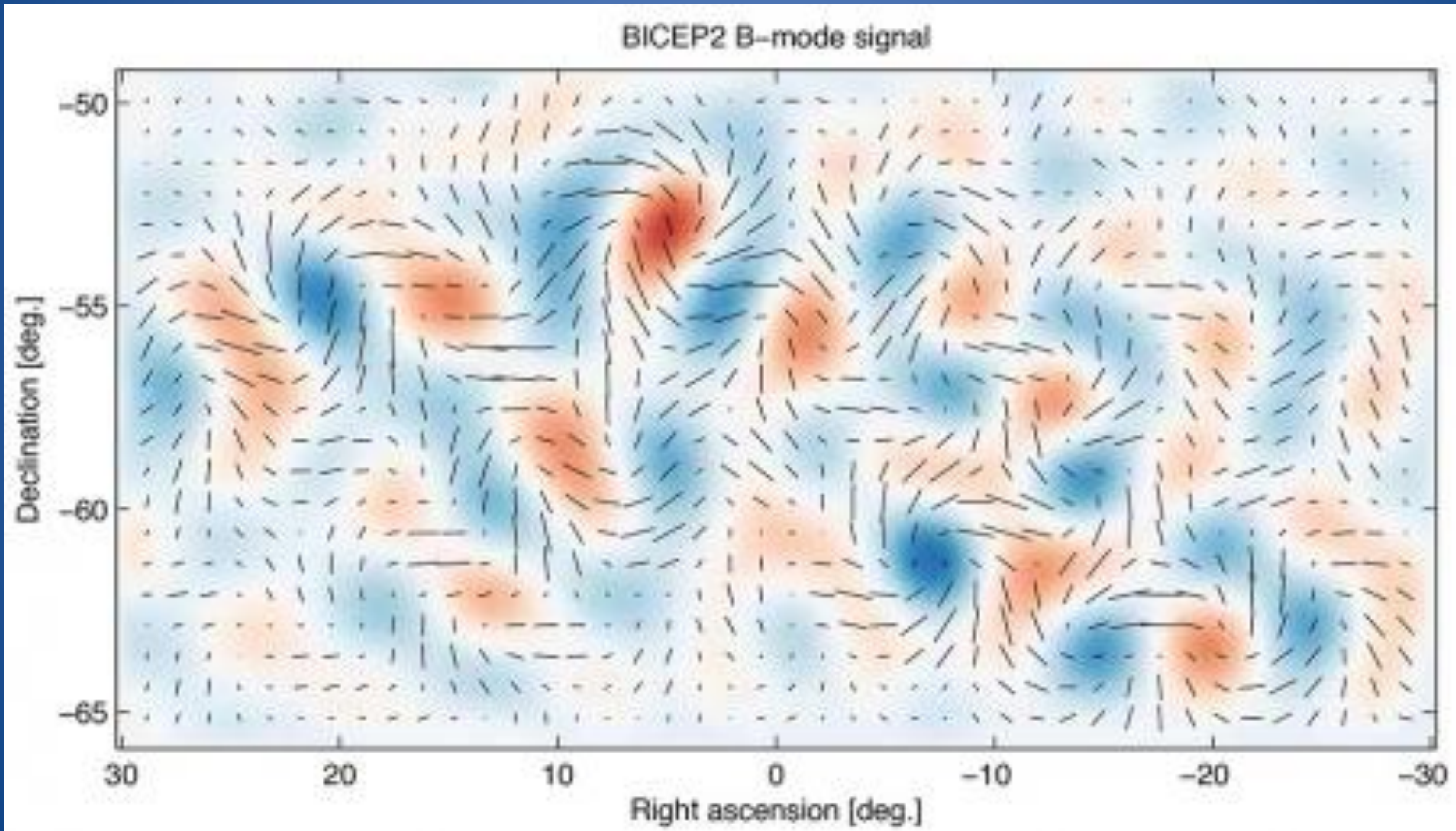
Soon to be Observations of Expansion Rate vs Redshift *z*

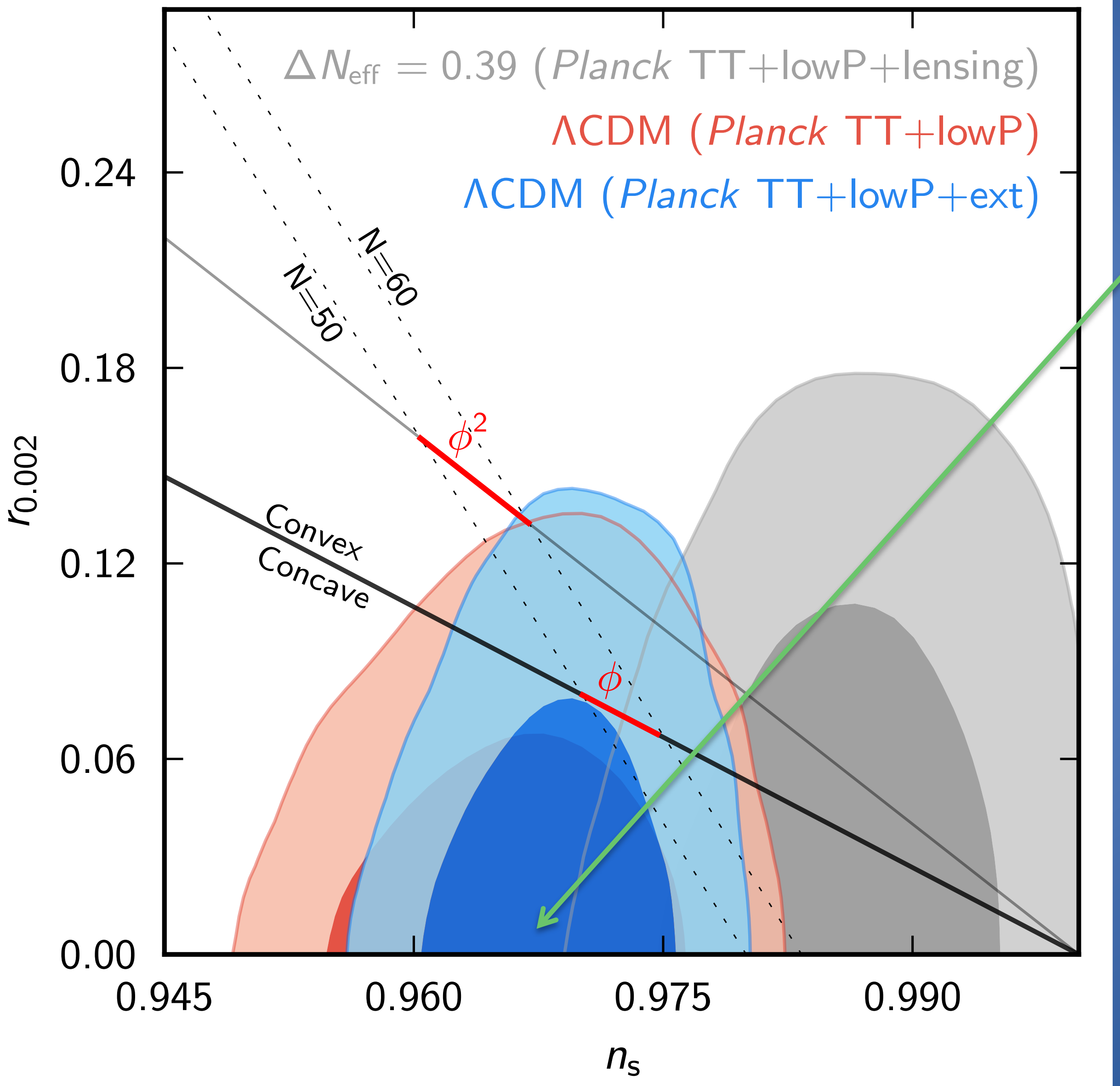


More Degrees of Freedom Shown



Planck and BICEP





Starobinsky (R^2) inflation

$n_s \approx 1 - 2/N \approx 0.967$

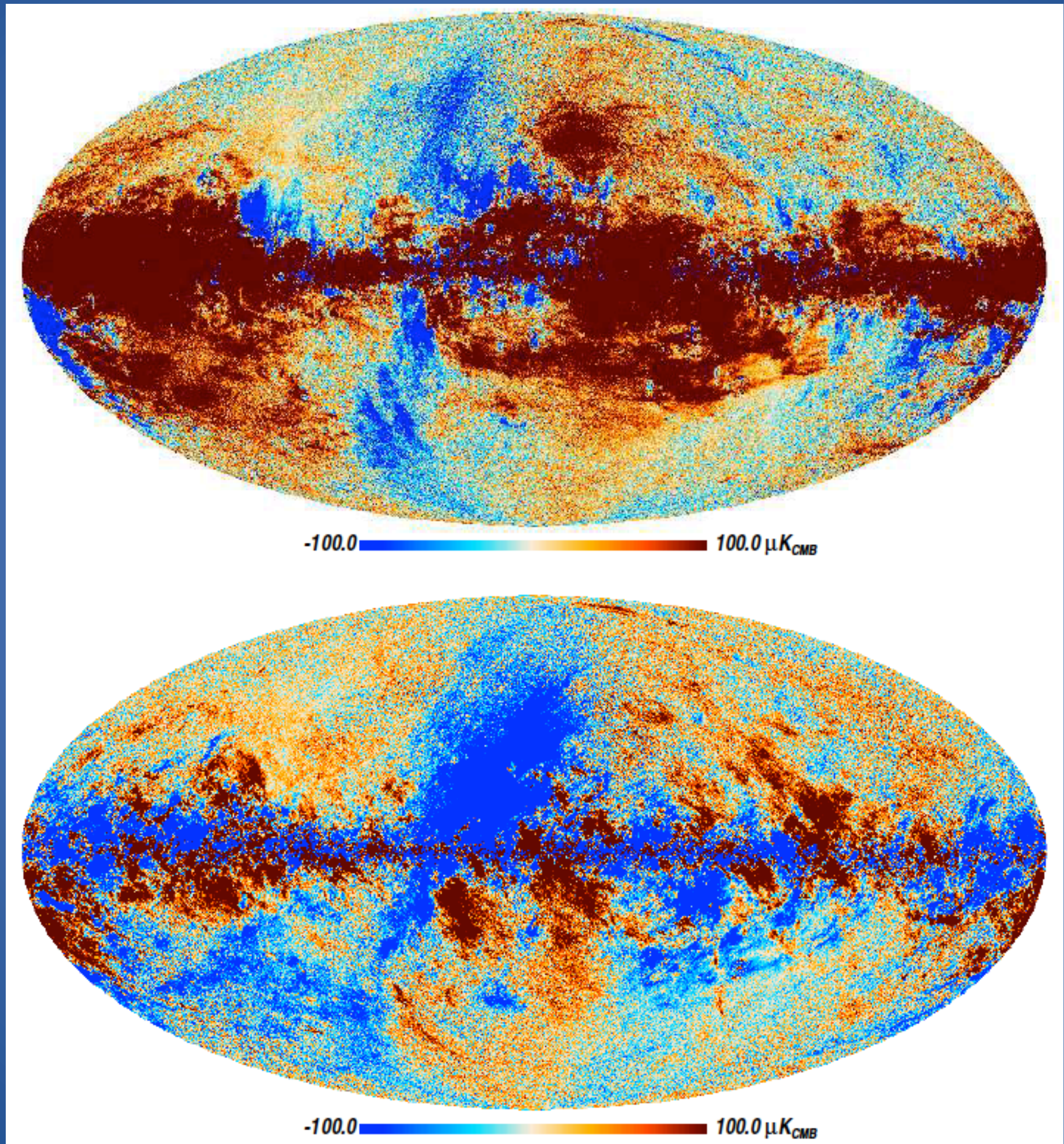
$r \approx 12/N^2 \approx 0.0033$

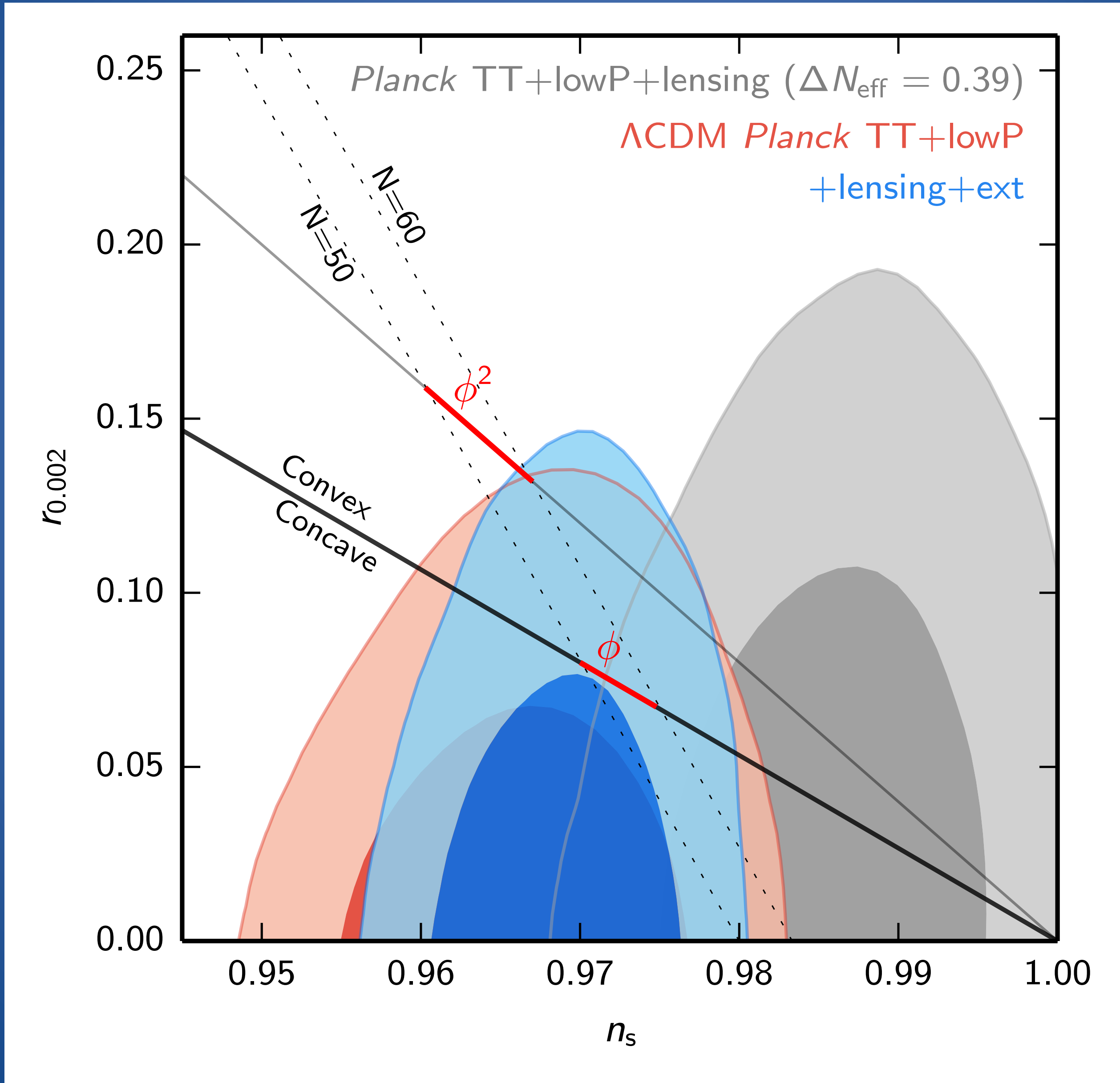
$dn_s/d\ln k \approx -2/N^2 \approx -0.0006$

…… but, there is plenty of room at the top

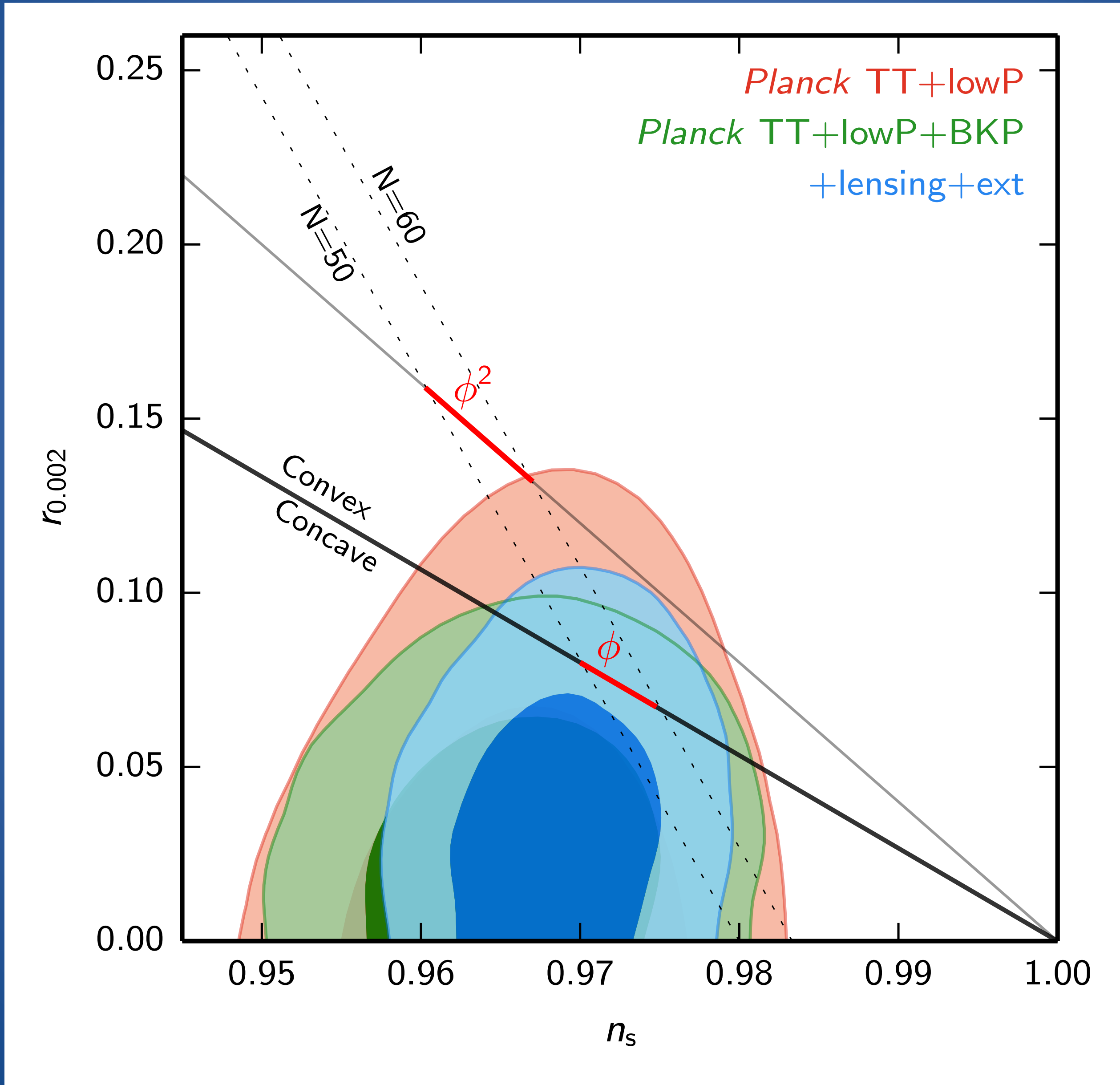
(and to the side!)

Planck 353 GHz full sky maps in polarization





Planck TT+lowP+lensing (ΔN_eff = 0.39)
ΛCDM Planck TT+lowP
+lensing+ext
N=60
N=50
ϕ^2
ϕ
Convex
Concave
0.25
0.20
0.15
0.10
0.05
0.00
r_0.002
0.95
0.96
0.97
0.98
0.99
1.00
n_s


Planck TT+lowP
Planck TT+lowP+BKP
+lensing+ext
N=60
N=50
ϕ^2
ϕ
Convex
Concave
0.25
0.20
0.15
0.10
0.05
0.00
0.95
0.96
0.97
0.98
0.99
1.00
$r_{0.002}$
n_s

Conclusions

- For 2015, as in 2013, base ΛCDM continues to be a good fit to the CMB data, *including polarization*.
- No convincing evidence for any simple extensions (e.g. in the neutrino sector).
- Scalar spectral index $n_s = 0.968 \pm 0.006$
- Constraints on r (95%) .

  $r<0.11$ Planck $r<0.09$ Planck+BKP
- Inflation $V(\phi) \propto \phi^2$ excluded at high significance.
- Scalar fluctuations consistent with pure adiabatic modes with a featureless tilted spectrum.
- No detection of non-Gaussianity.
- DE equation of state $w=-1.006 \pm 0.045$.