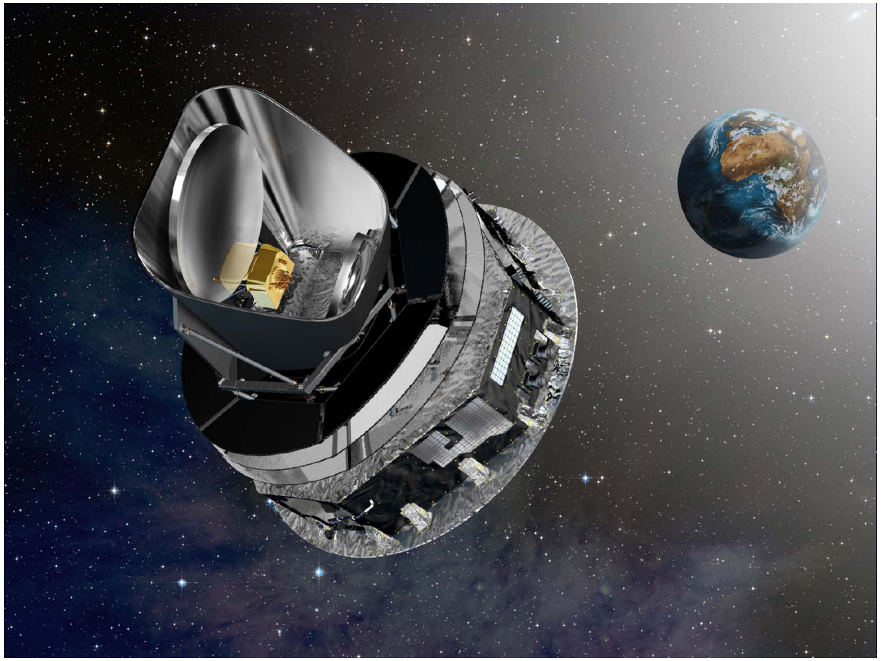
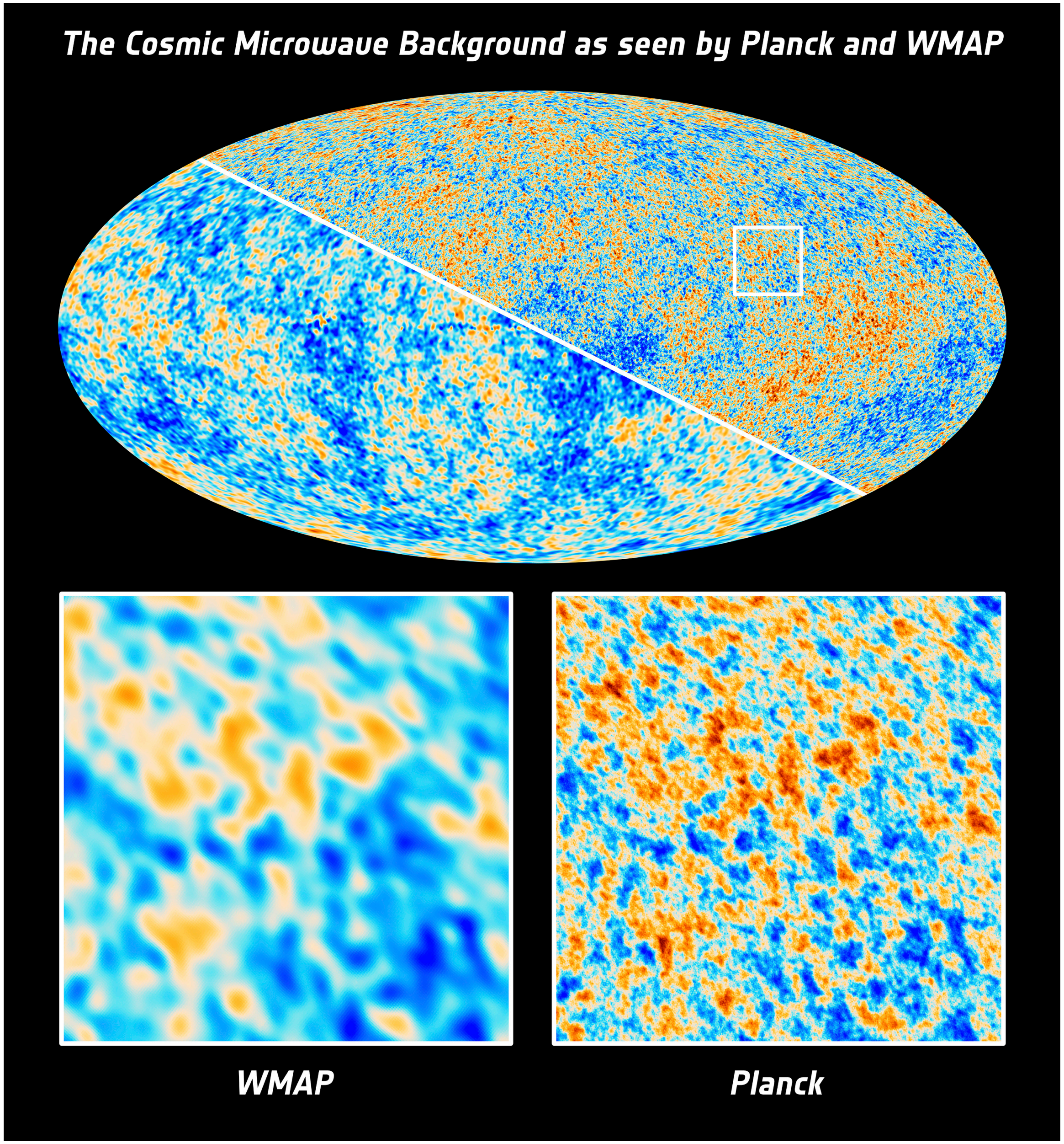


Cosmology in Planck era

String Winter School, CERN, 03-05.02.2014
J. Lesgourgues (EPFL, CERN, LAPTh)


The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

CMB physics and Planck results

1. The standard cosmological model

    1.1. Background

    1.2. Thermodynamics

    1.3. Perturbations

    Bibliography: TASI lectures on Cosmological Perturbations, JL, arXiv:1302.4640

2. Basic Planck results and implications for standard model

3. Inflation

4. Beyond the standard model

1. Standard cosmological model

1.2. Background

- FLRW metric: homogeneous but not static

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)\right]$$

- Origin irrelevant, normalisation of *a* irrelevant

- 2 physical quantitites:

$$R_c = \frac{a}{\sqrt{K}} \qquad\qquad H = \frac{\dot{a}}{a}, \qquad R_H = \frac{c}{H}$$

- Einstein:

$$G_{\mu\nu} = 8\pi G \ \ T_{\mu\nu}$$

- Friedmann

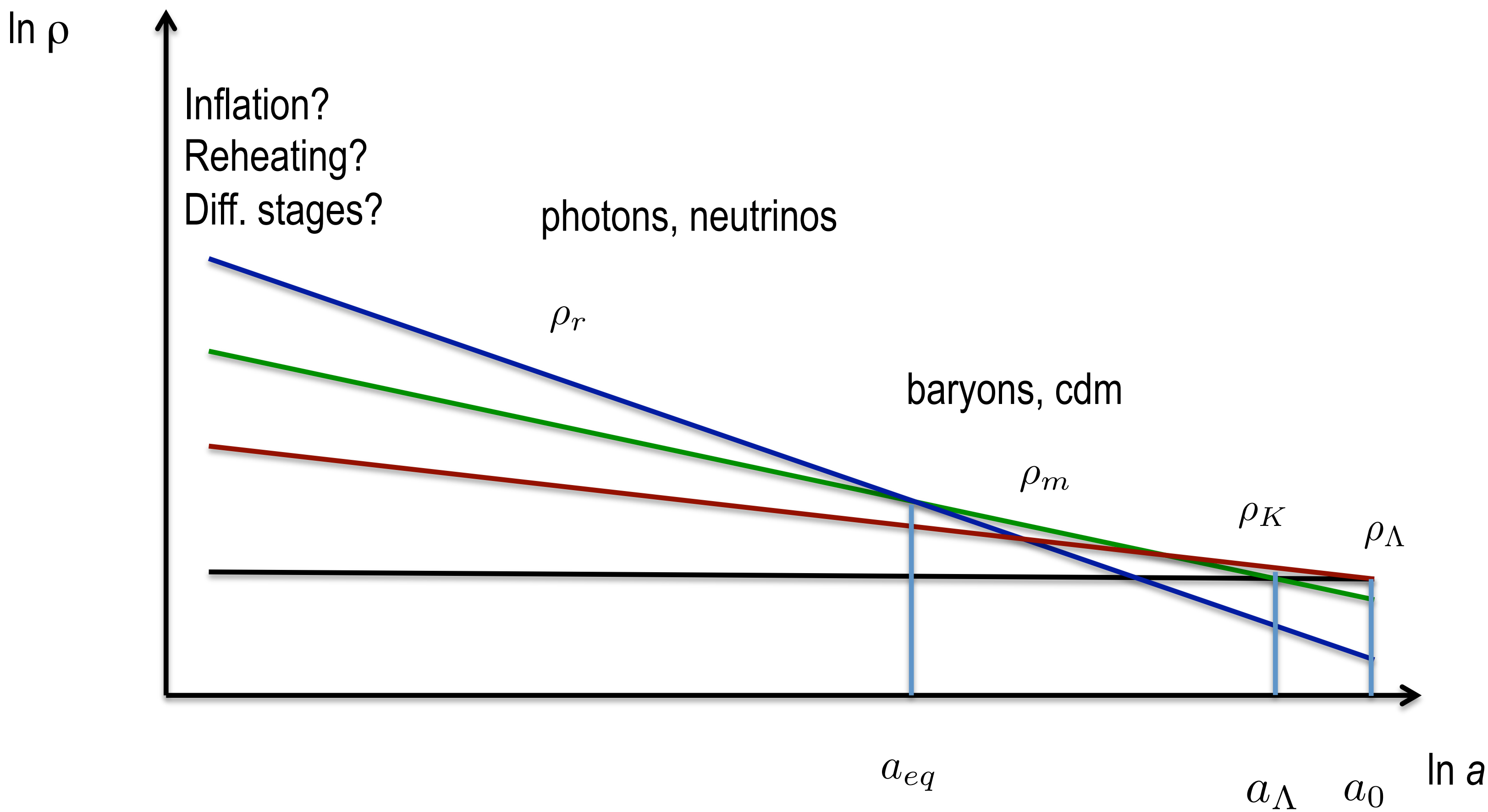
$$3\left[\frac{1}{R_c^2} + \frac{1}{R_H^2}\right] = 8\pi G \ \rho$$

$$3H^2 = 8\pi G \ \rho - \frac{3K}{a^2}$$

- Conservation of energy

$$\dot{\rho} = -3\frac{\dot{a}}{a}(\rho + p)$$

- Relevant densities:



- Distances depend on expansion; e.g. d_A :
  - Euclidian: $$\lambda = d_A \theta$$
  - FLRW: $$d_a = \frac{\lambda}{\theta} = a(t_e) \int_{t_e}^{t_0} \frac{dt}{a(t)}$$
- Time labelled by:

$$a, \quad t, \quad \tau \quad \left(d\tau = \frac{dt}{a} = \pm dr \right), \qquad z = \frac{a_0}{a} - 1$$

1.2. Thermodynamics:

- After BBN: baryonic matter = H^+, He^{++} (25% of mass)

- Neutral atoms cannot form (photo-dissociation)

- Then $He^{++} + e^- \rightarrow He^+$

  $He^+ + e^- \rightarrow He$

  $H^+ + e^- \rightarrow H$ z~1080 (recombination)

- Reionisation at z~10 (star formation)

- High energy: g ←Thomson→ e^- ←Coulomb→ b

  Tightly coupled fluid

- Γ < H when n_e drops during recombination: decoupling = recombination (CMB emission)

- Γ < H even after reionisation (dilution of free electrons): only 7% of CMB photons re-scatter

1.3. Linear perturbations

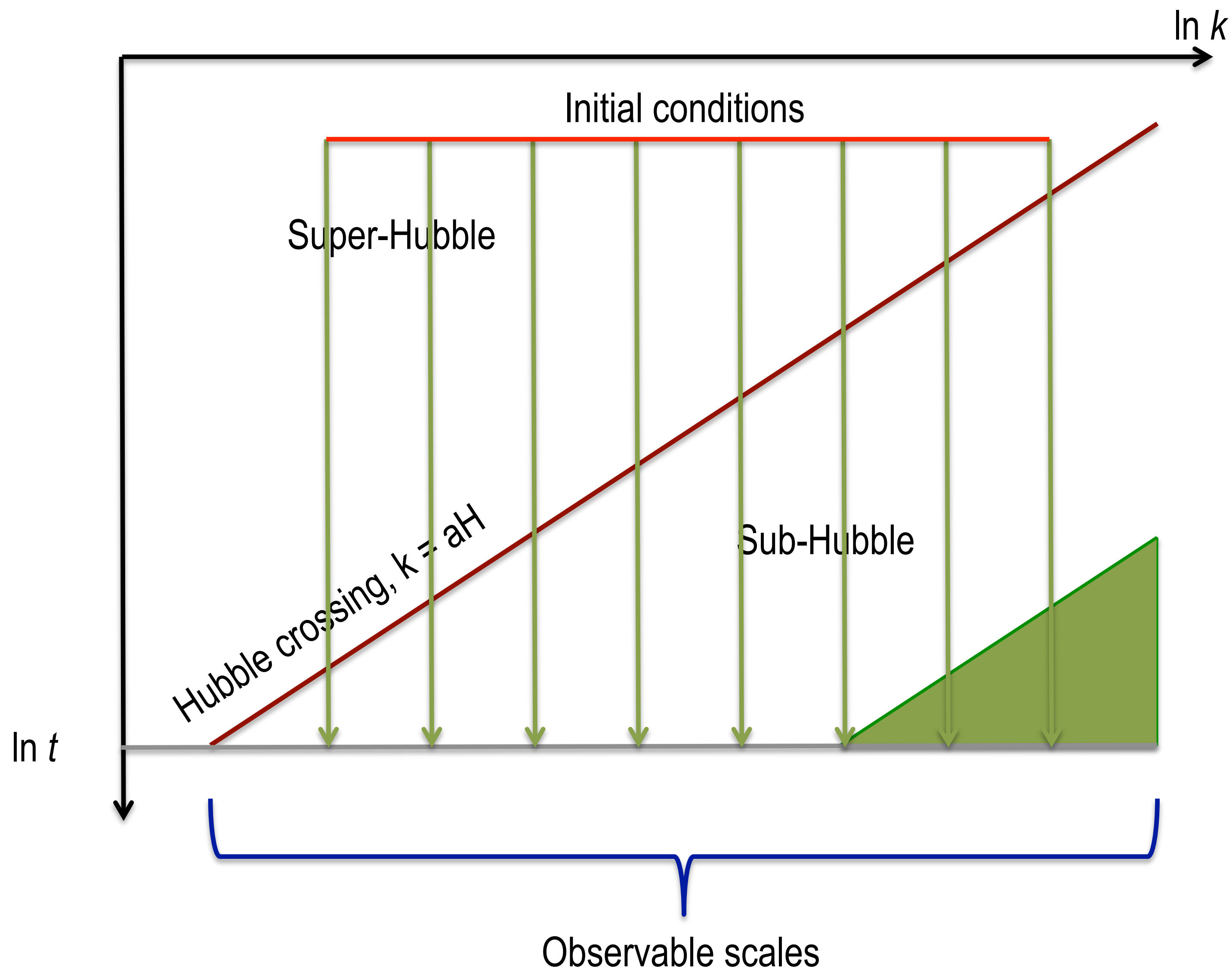
- Comoving Fourier wavelength $\frac{2\pi}{k}$, physical $\frac{2\pi a(t)}{k}$

- Radius of universe ~ O(R_H) : all observables modes sub-Hubble

- Decelerated expansion, modes cross from outside to inside Hubble radius:

$$\frac{\lambda}{R_H} = \frac{2\pi a}{k}\frac{\dot{a}}{a} = \frac{2\pi}{k}\dot{a}$$

- Modes all outside Hubble radius in the past



ln *k*
Initial conditions
Super-Hubble
Hubble crossing, k = aH
Sub-Hubble
ln *t*
Observable scales

- Metric expansion: $g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$

- Gauge freedom (time slicing), Newtonian gauge:

$$ds^2 = -(1+2\psi)dt^2 + (1-2\phi)a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)\right]$$

- Matter perturbations: $T_{\mu\nu} = \bar{T}_{\mu\nu} + \delta T_{\mu\nu}$

- Scalar/vector/tensors under spatial rotations

- Einstein + Boltzmann for each species (b, cdm, γ, ν, …)

$$D_\tau f(t, \vec{x}, \vec{p}) = 0$$ *or interaction term*

- tightly coupled baryon-photon fluid with $\Theta = \frac{\delta T}{T}$

$$\Theta'' + \frac{R'}{1+R}\Theta' + k^2 c_s^2 \Theta = -\frac{k^2}{3}\psi + \frac{R'}{1+R}\phi' + \phi''$$

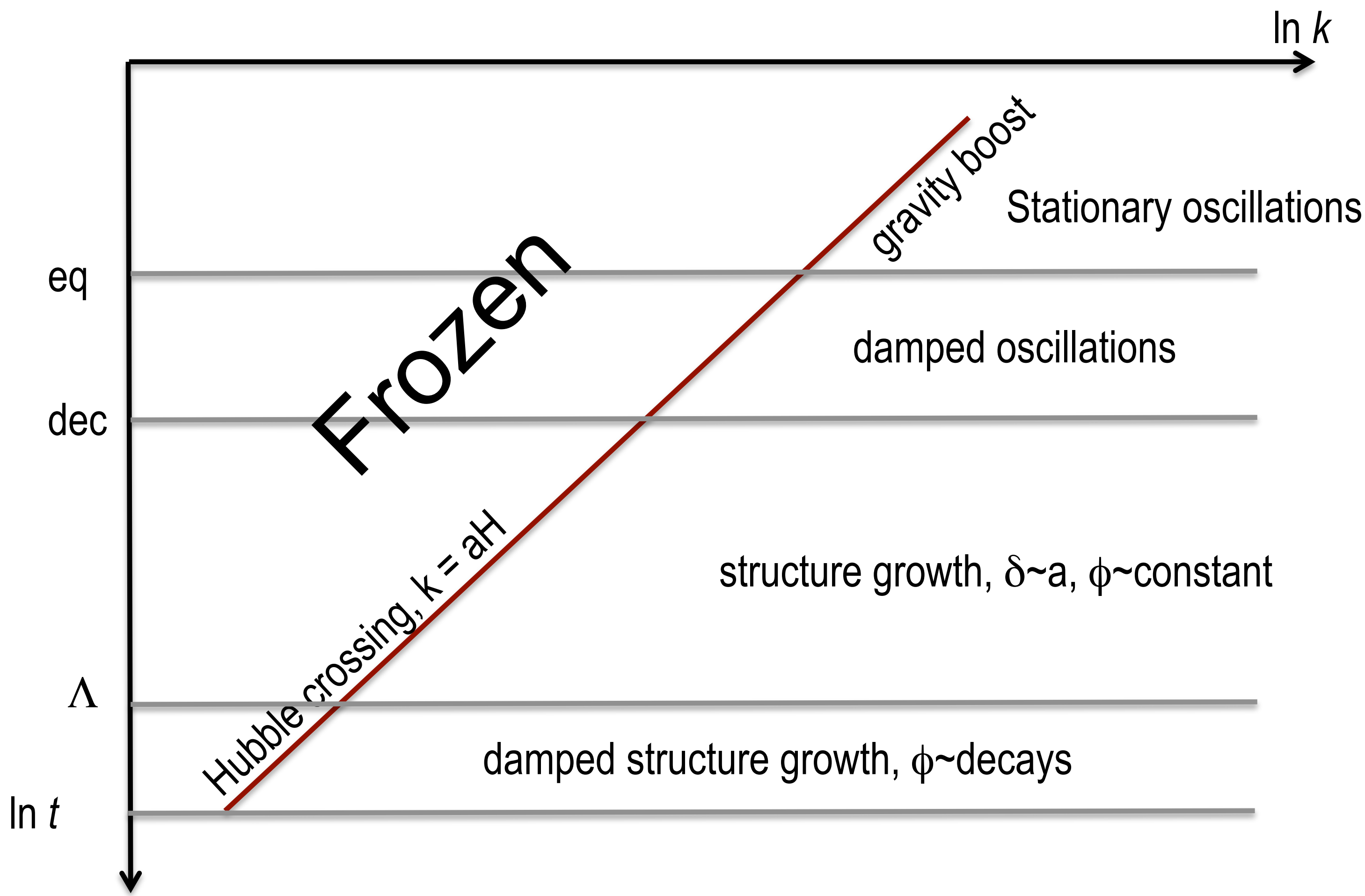
Baryon	Pressure	Newtonian	Dilation
damping	(acoust. waves)	force	effect

$$R = \frac{4\rho_b}{3\rho_\gamma} \qquad c_s^2 = \frac{\delta p_\gamma + \delta p_b}{\delta \rho_\gamma + \delta \rho_b} = \frac{1}{3(1+R)}$$

- Acoustic oscillations because system places initially out of equilibrium:

Super-H : $\delta_\gamma = -2\phi$ Equilibrium : $\langle \delta_\gamma \rangle = -(1+R)\phi$

- in summary:



ln k
gravity boost
Stationary oscillations
eq
Frozen
damped oscillations
dec
Hubble crossing, $k = aH$
structure growth, δ~a, ϕ~constant
Λ
damped structure growth, ϕ~decays
ln t

- CMB spectrum in Sachs-Wolfe approximation:
  - assume instantaneous decoupling, then free-streaming without interactions
  - then $\frac{\delta T}{T}$ conserved along each line-of-sight
  - Sachs-Wolfe : $\left.\frac{\delta T}{T}\right|_{obs} = \left.\frac{\delta T}{T}\right|_{dec} + \psi$
  - Relation between $\left\langle \left| \frac{\delta T}{T}(t_{dec}) \right|^2 \right\rangle$ versus k

    $\left\langle \left| \frac{\delta T}{T}(t_0) \right|^2 \right\rangle$ versus l , also called C_l

(using $\lambda = d_A \theta$)

- Correction from Doppler

- Correction from diffusion damping (Silk damping)

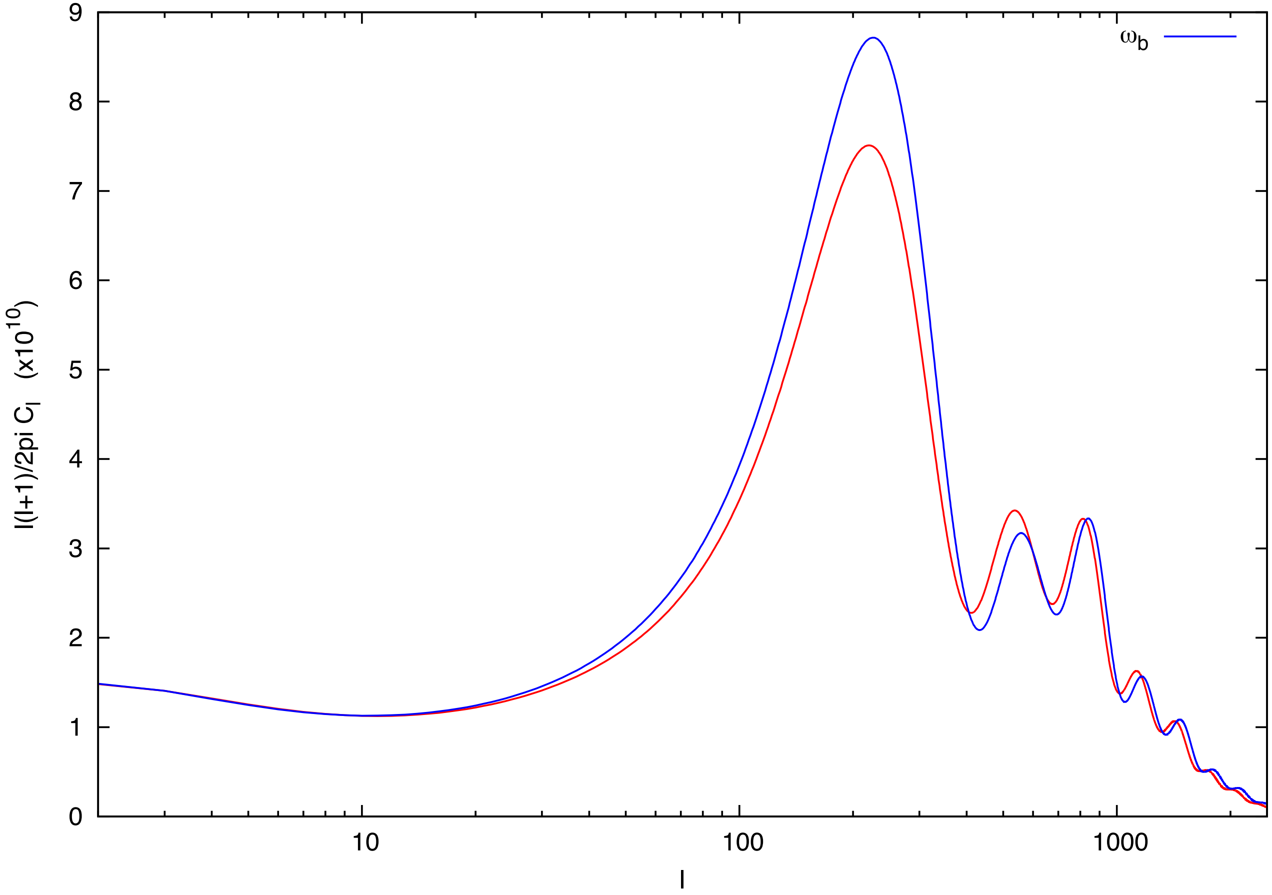
- Correction from reionisation

- Correction from gravitational effects along line-of-sight (Integrated Sachs-Wolfe effect)

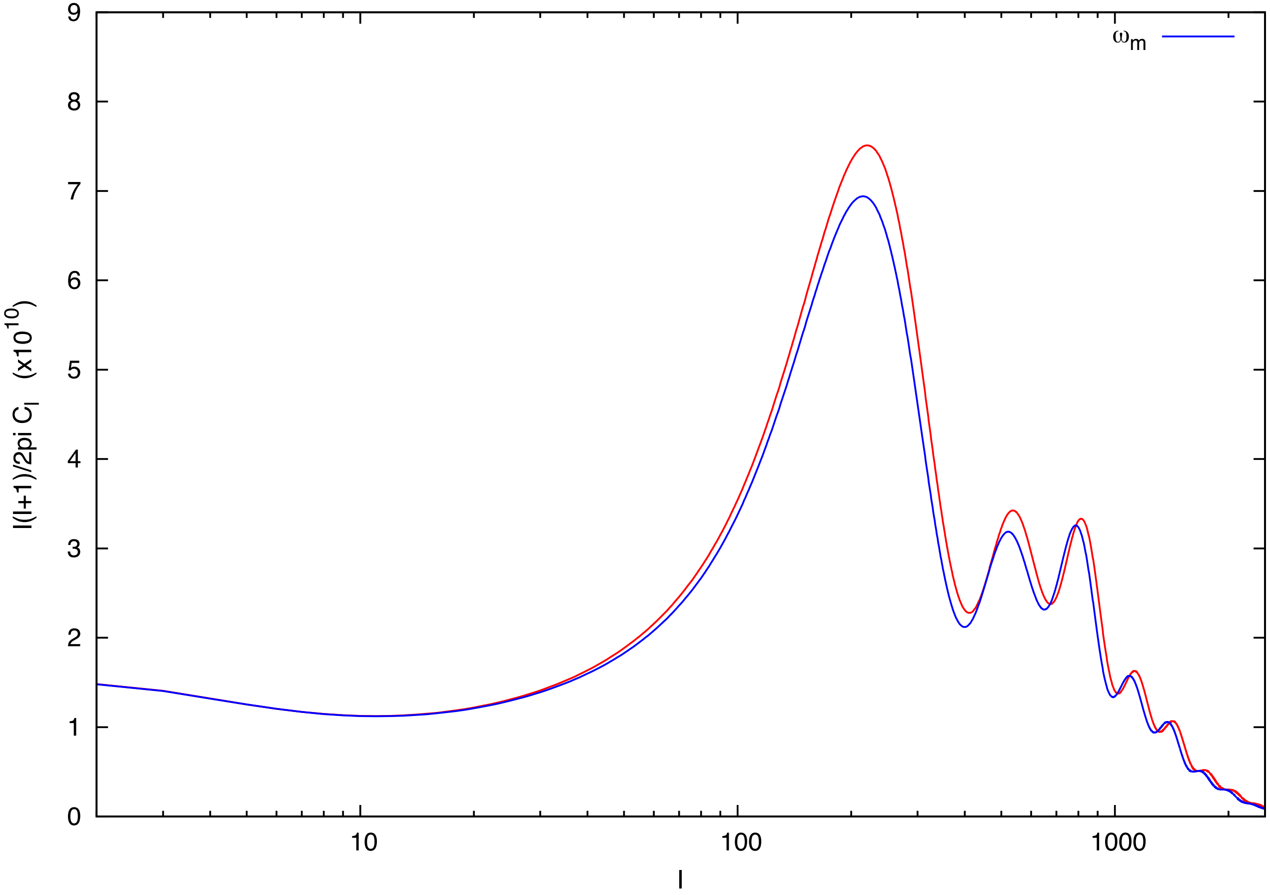
… hence lots of intricated effects… but they are not degenerate at list in the standard cosmological model with 6 parameters:

$$\{\omega_b,\ \omega_{cdm},\ h,\ A_s,\ n_s, z_{reio}\}$$

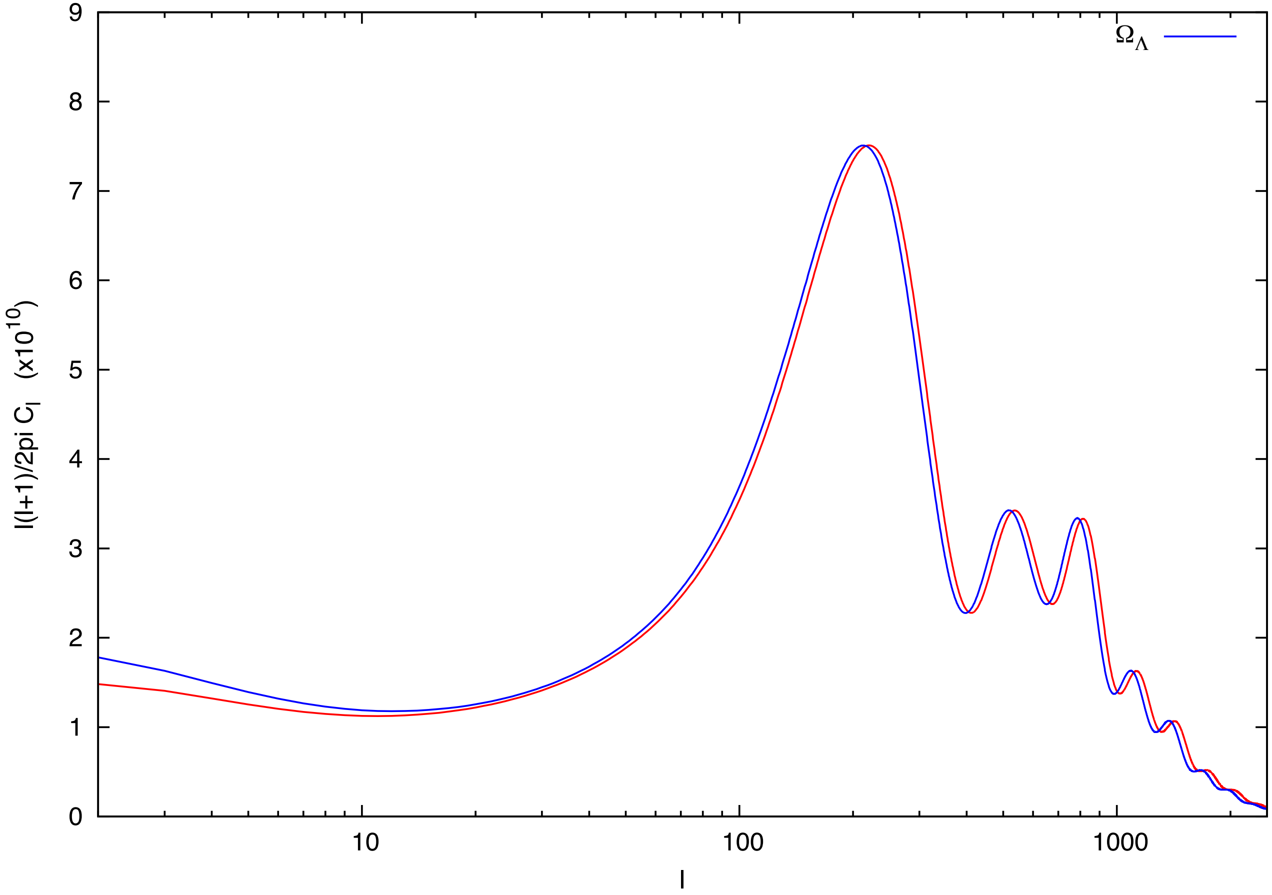
Effect of increasing ω_b



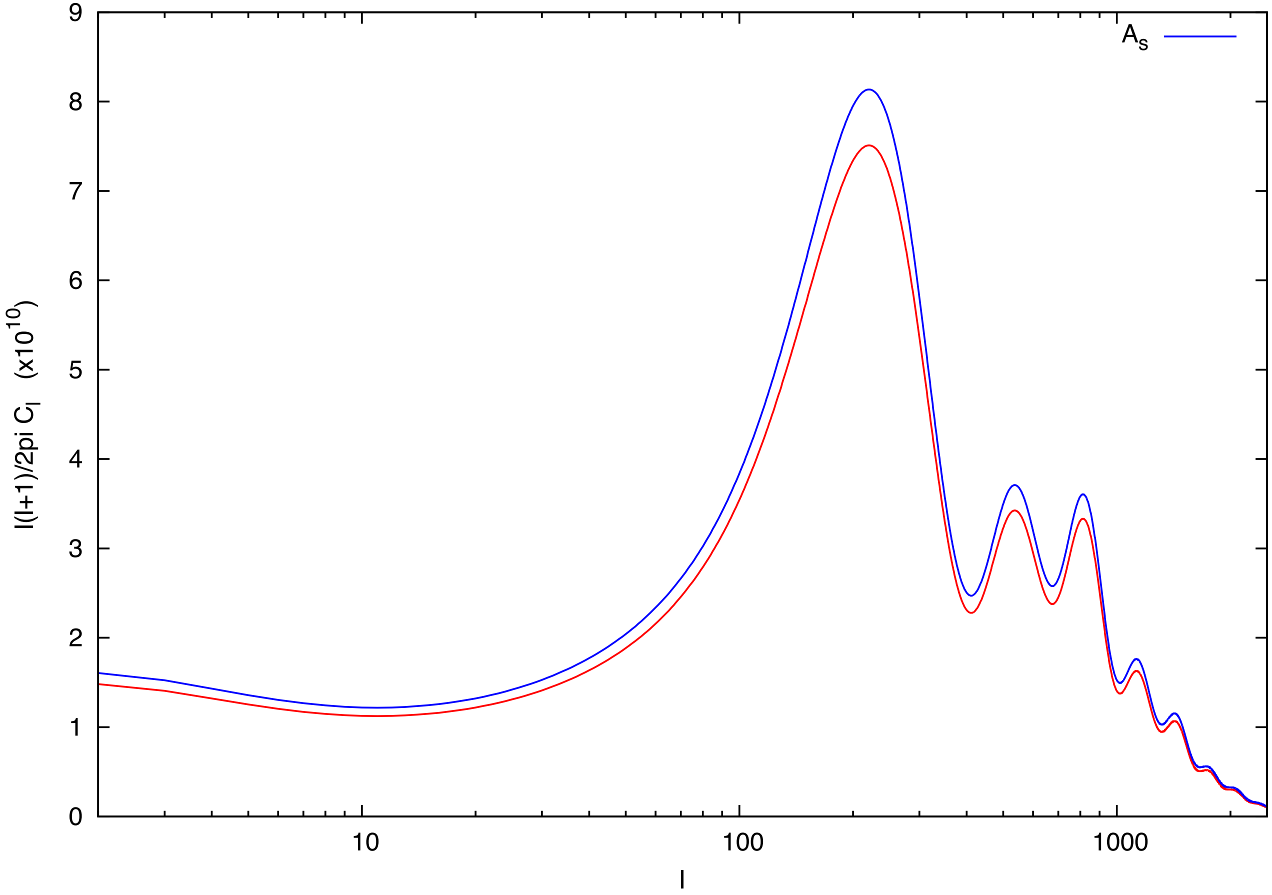
Effect of increasing ω_m



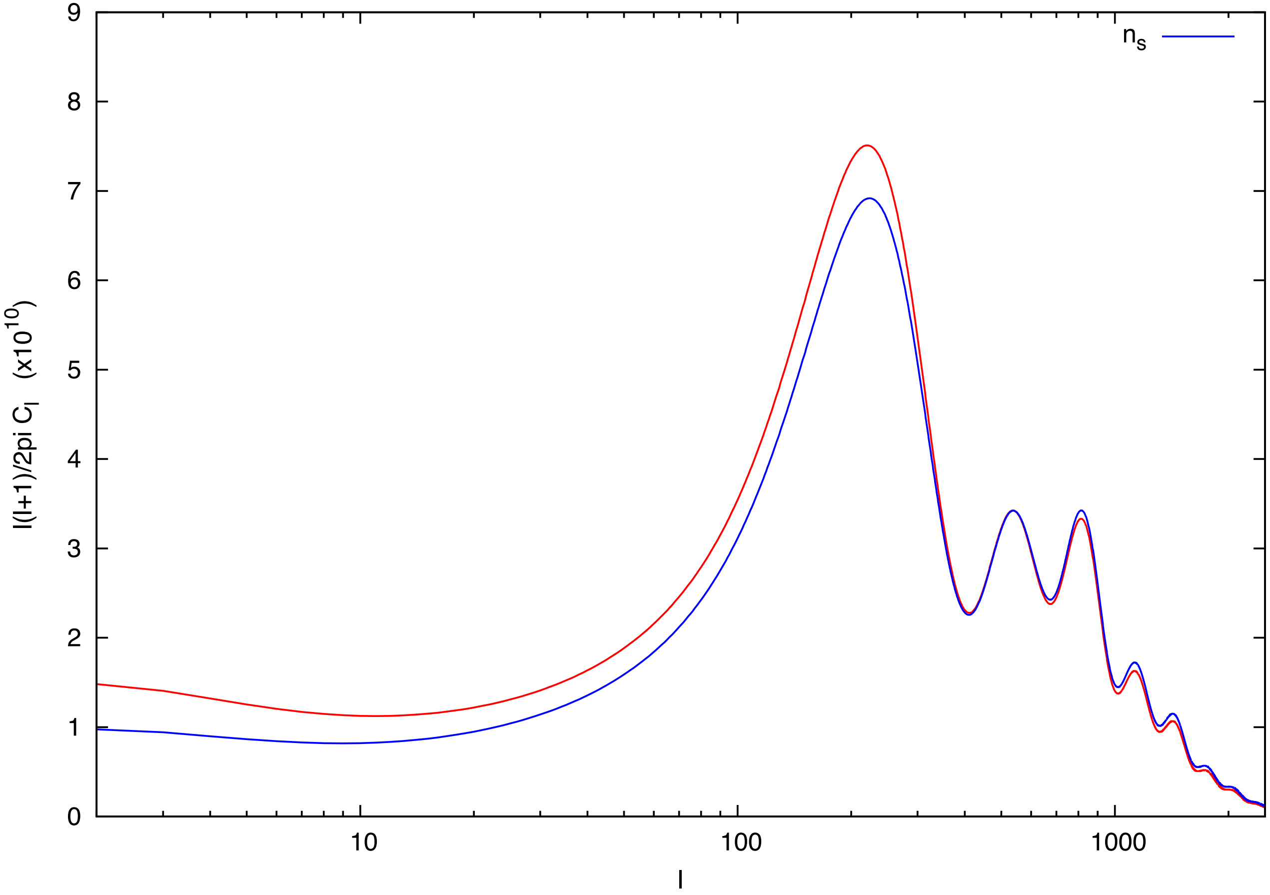
Effect of increasing Ω_Λ



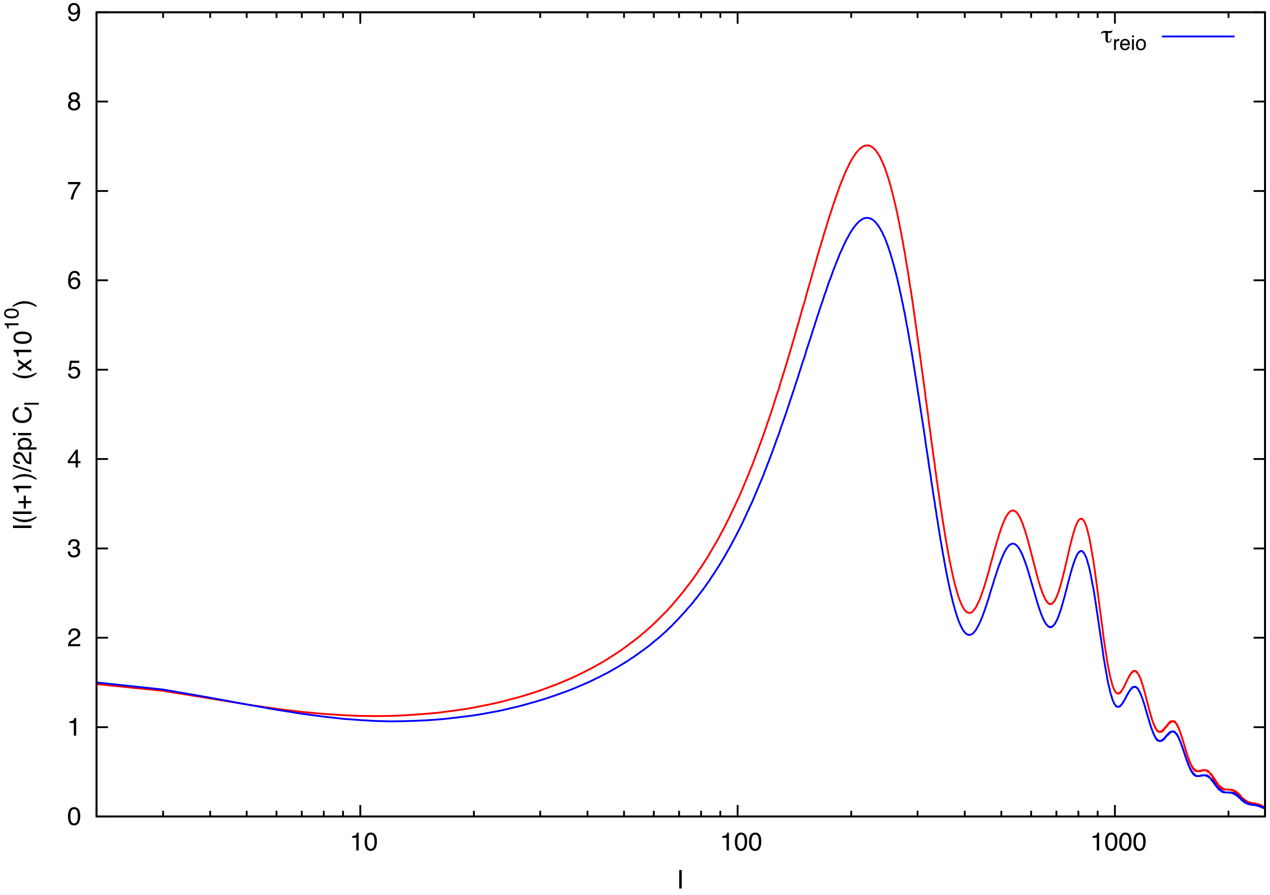
Effect of increasing A_s



Effect of increasing n_s



Effect of increasing τ_{reio}



2. Planck basic results

2.1. observation of temperature anisotropies

- Launched by ESA and placed in L2 orbit in 2009. Full scan every 6 month.
- 75 detectors cover 9 frequency channels

Frequency (GHz)

2. Planck basic results

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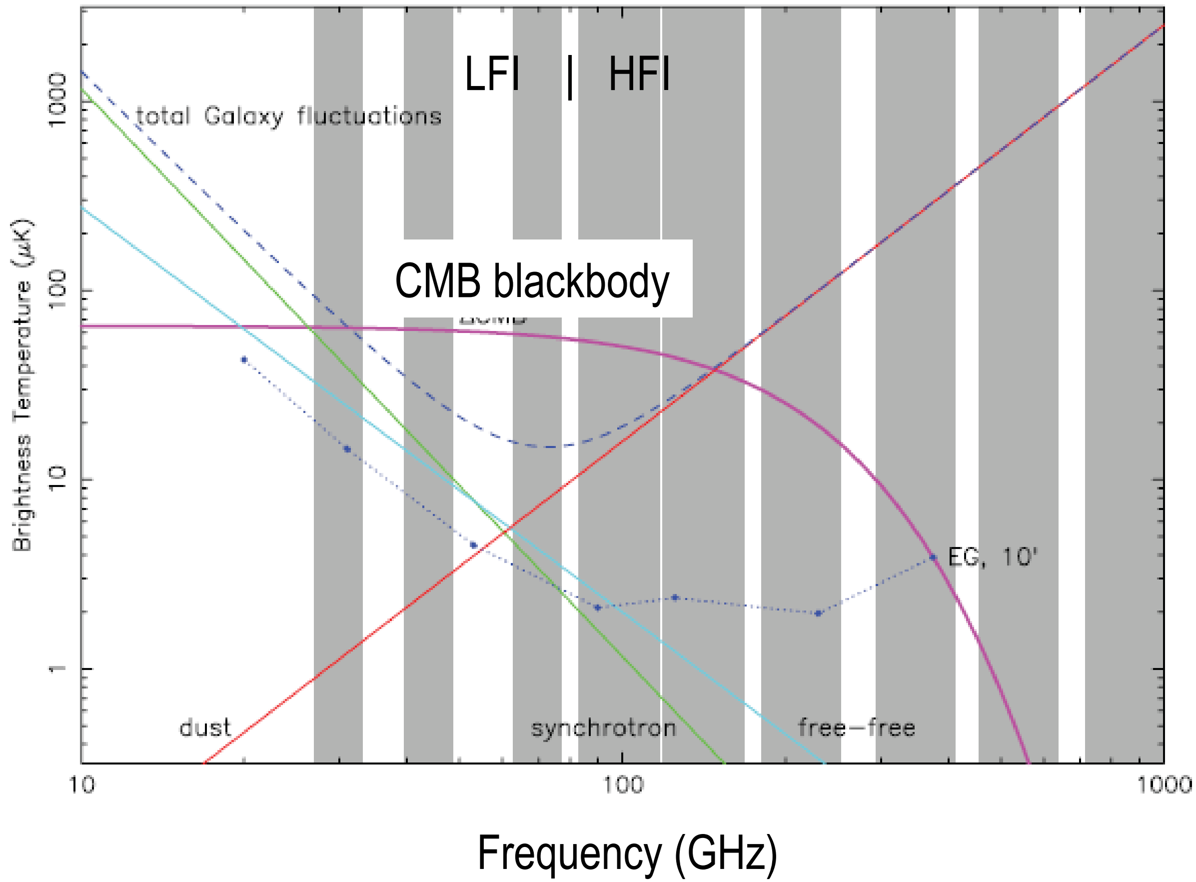
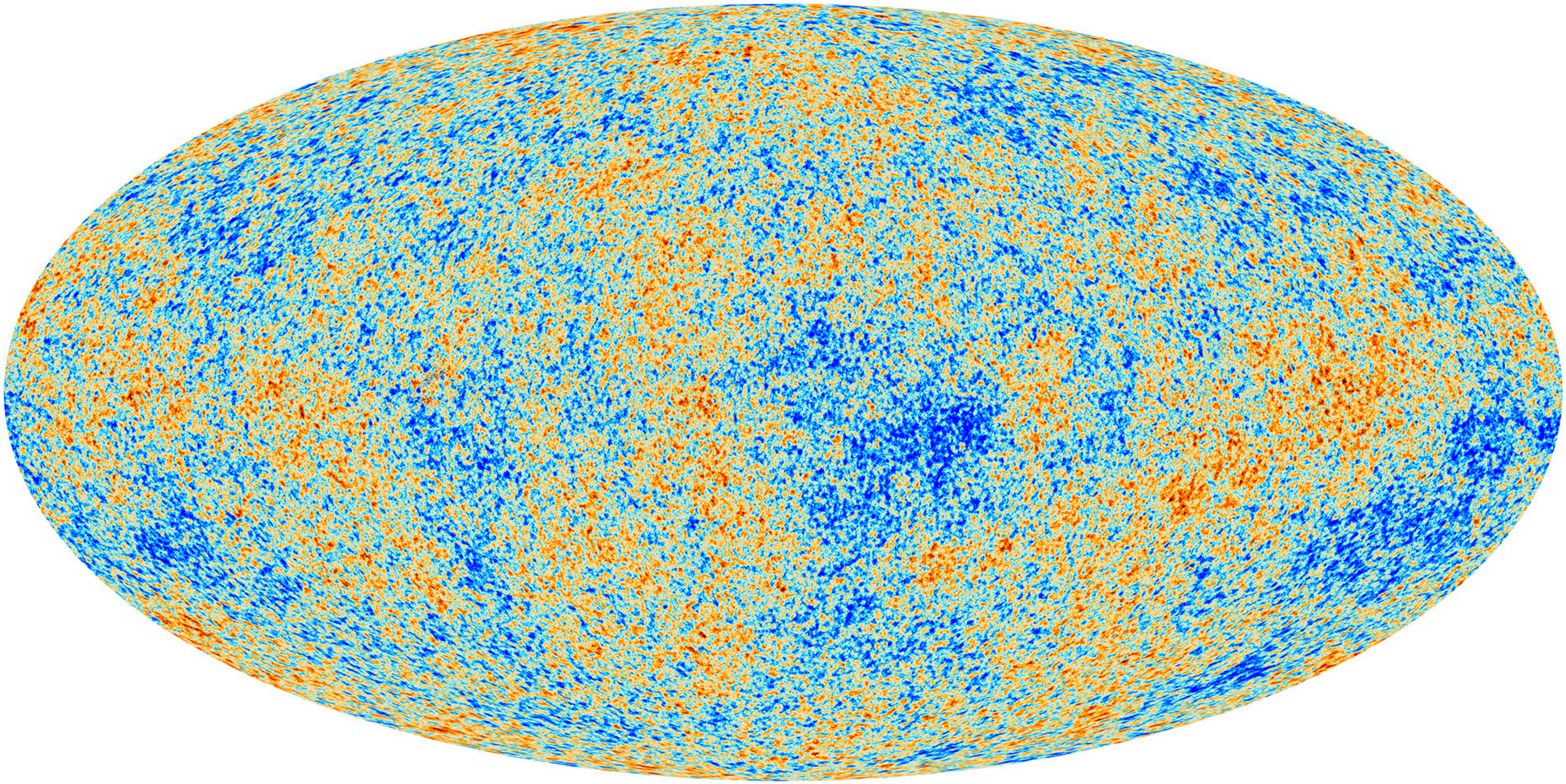
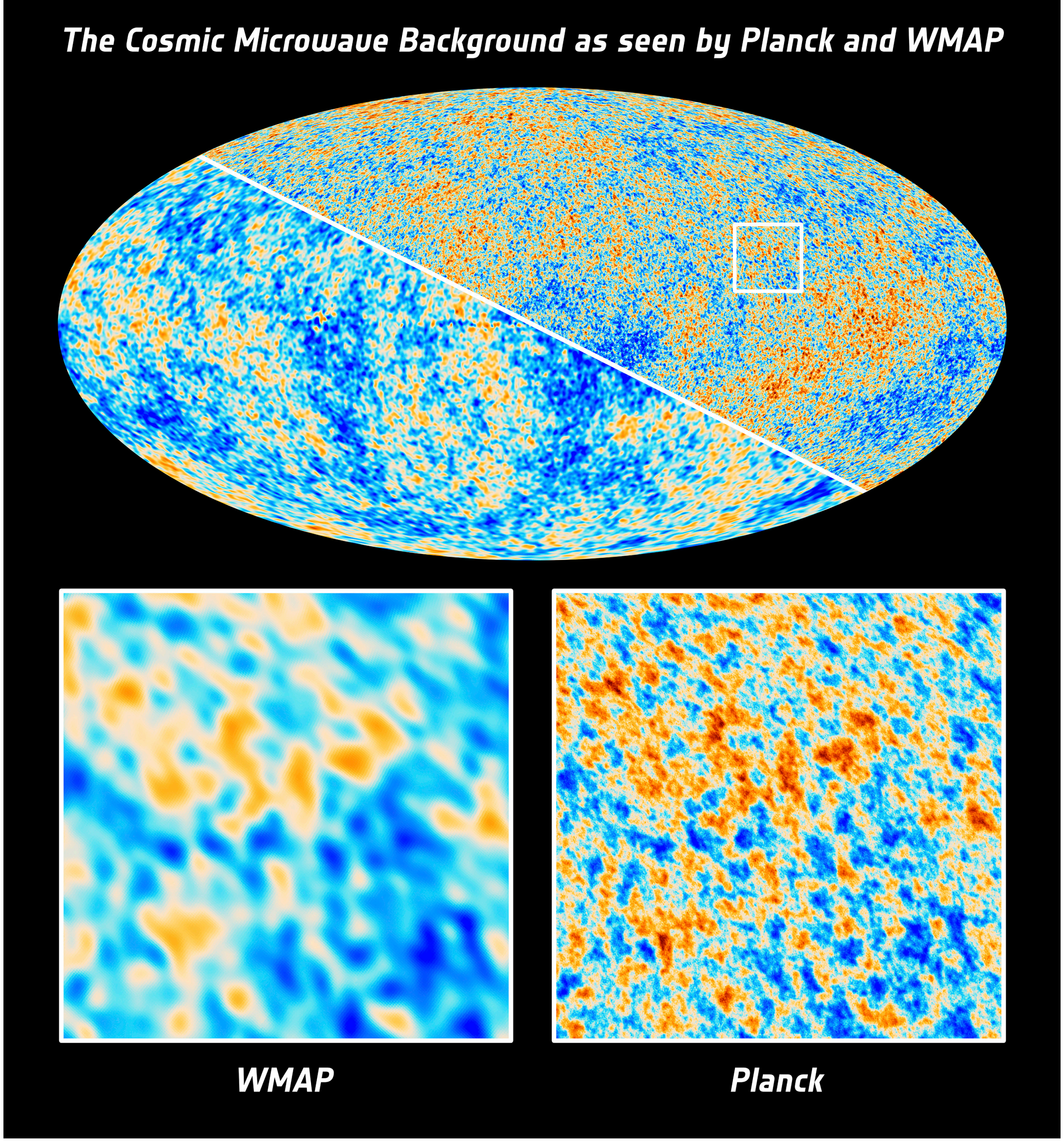
detectors:






The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

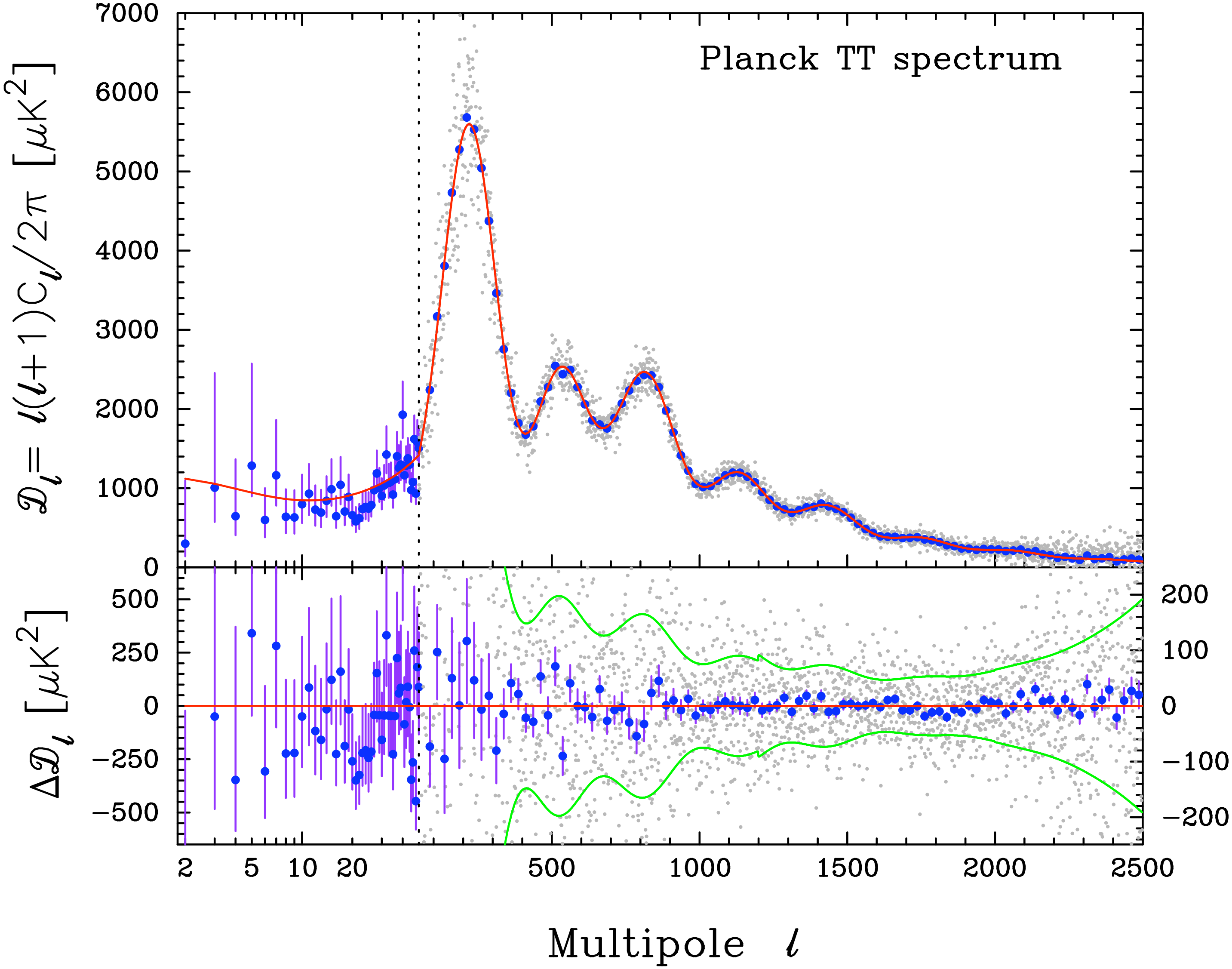
- Expansion of temperature map in spherical harmonic:

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{lm} a_{lm} Y_{lm}(\theta, \phi)$$

- Temperature spectrum in multipole space:

$$C_l^{th} = \langle a_{lm} a_{lm}^* \rangle$$

$$C_l^{obs} = \sum_{m=-l}^{l} \frac{a_{lm}^2}{2l+1}$$



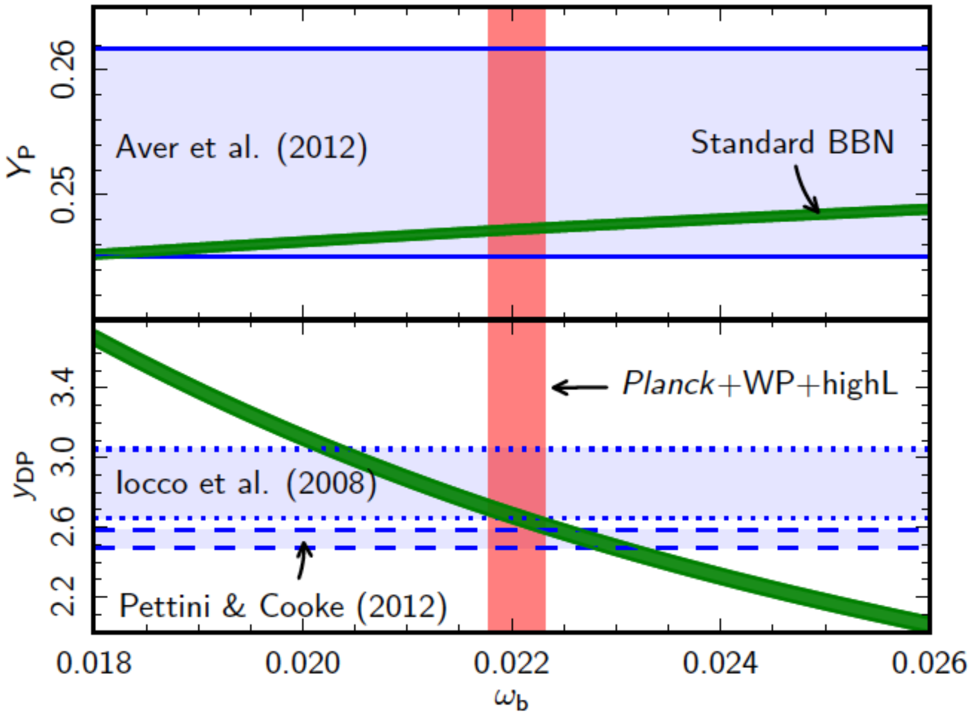
Planck TT spectrum
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

2.2. Implications for ΛCDM

	Planck	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072
Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020
σ_8	0.8344	0.834 ± 0.027
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$
H_0	67.11	67.4 ± 1.4

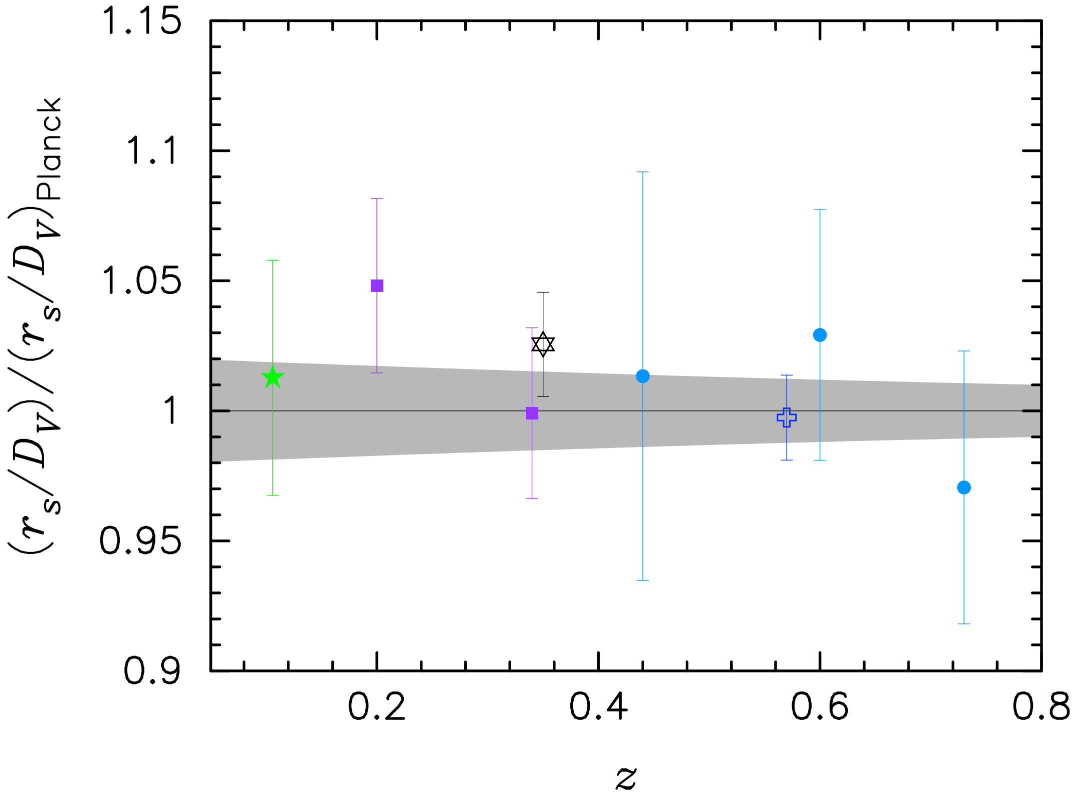
Mesure directly $\theta_* = \frac{\pi}{l} = \frac{d_s(t_{dec})}{d_A(t_{dec})} = \frac{\int_{t_i}^{t_{dec}} c_s \frac{dt}{a}}{\int_{t_{dec}}^{t_0} \frac{dt}{a}}$ and indirectly Ω_Λ, H_0

2.3. Consistency with other experiments



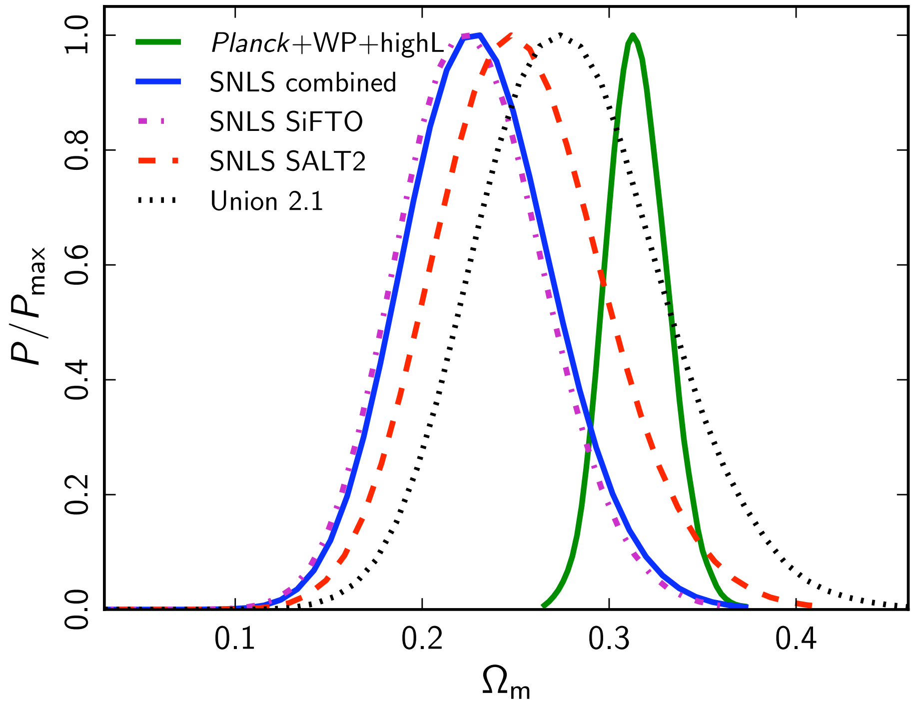
BBN

2.3. Consistency with other experiments



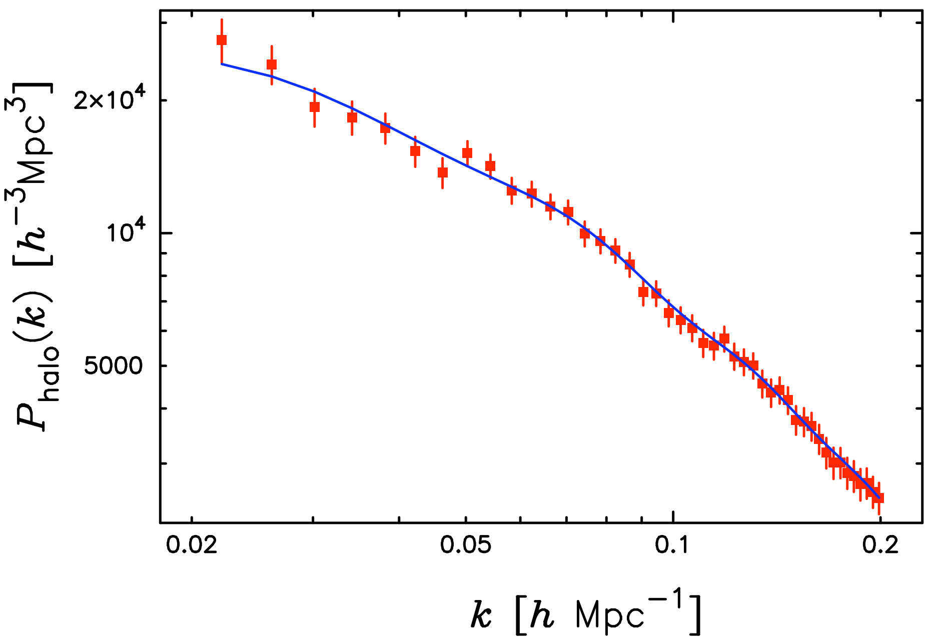
BAO

2.3. Consistency with other experiments



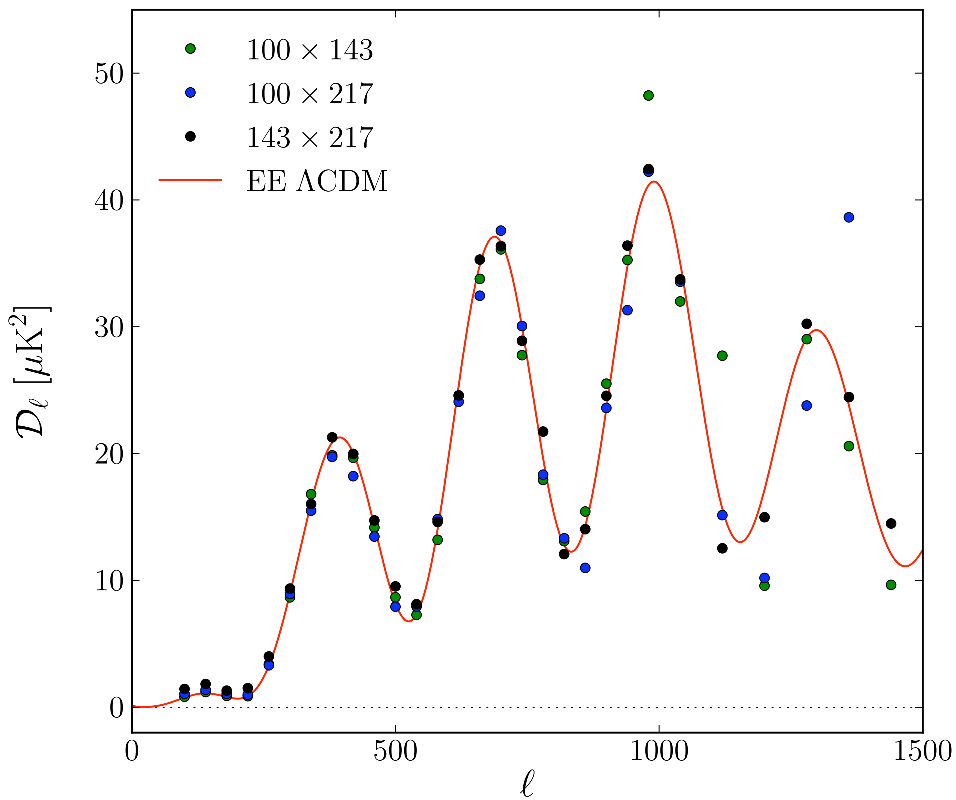
SNIa

2.3. Consistency with other experiments



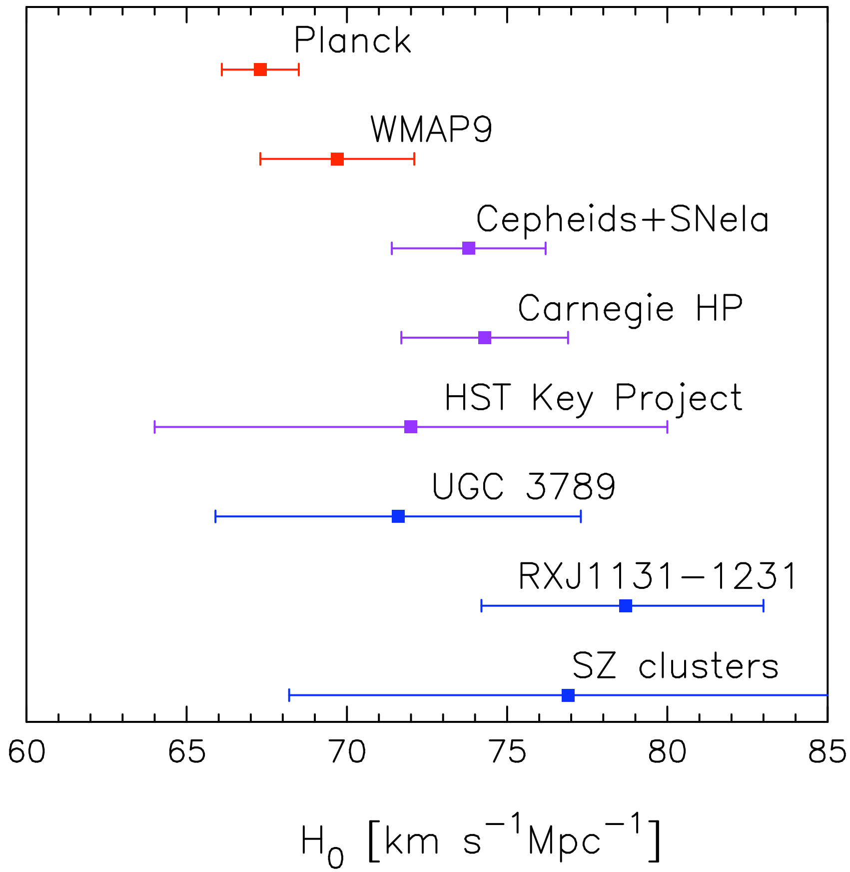
Galaxy correlation function

2.3. Consistency with other data



Preliminary polarisation spectrum

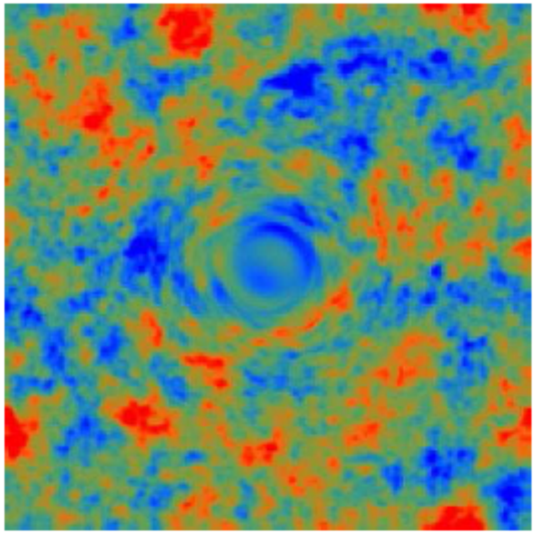
2.3. Consistency with other data



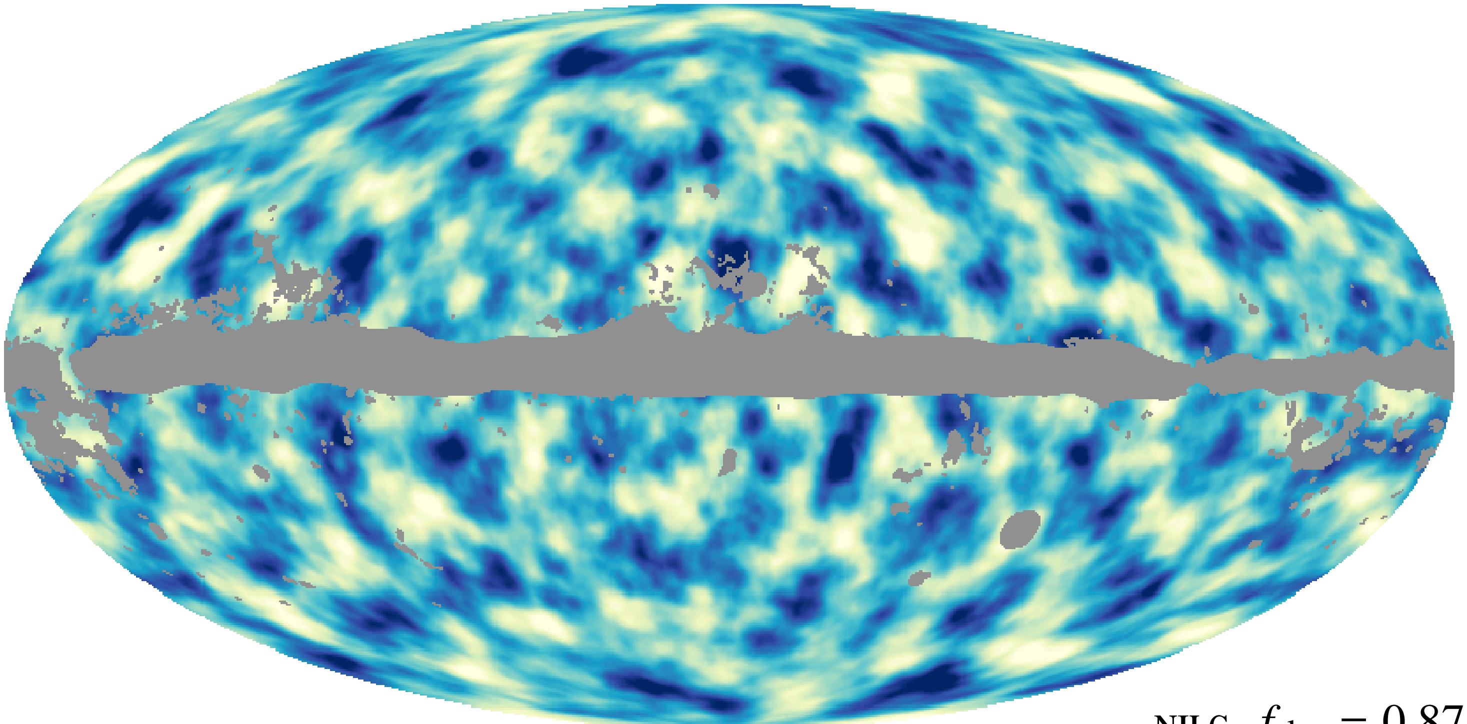
Direct measurement of H_0

2.3. Consistency with other data

- exaggerated effect of a huge cluster:
- In fact, only 2'-3' deflections, coherent over large scales: invisible by eye
- Lensing potential = projected gravitational field (with some kernel: sensitive to structures at z~1-3)
- Induces non-gaussianity with very specific correlations. Can be extracted with specific "quadratic estimator" (= 4-point correlations)
- Proposed by Hu & Okamoto (2001)
  First success in 2012 (SPT-ACT)



Lensing potential map:



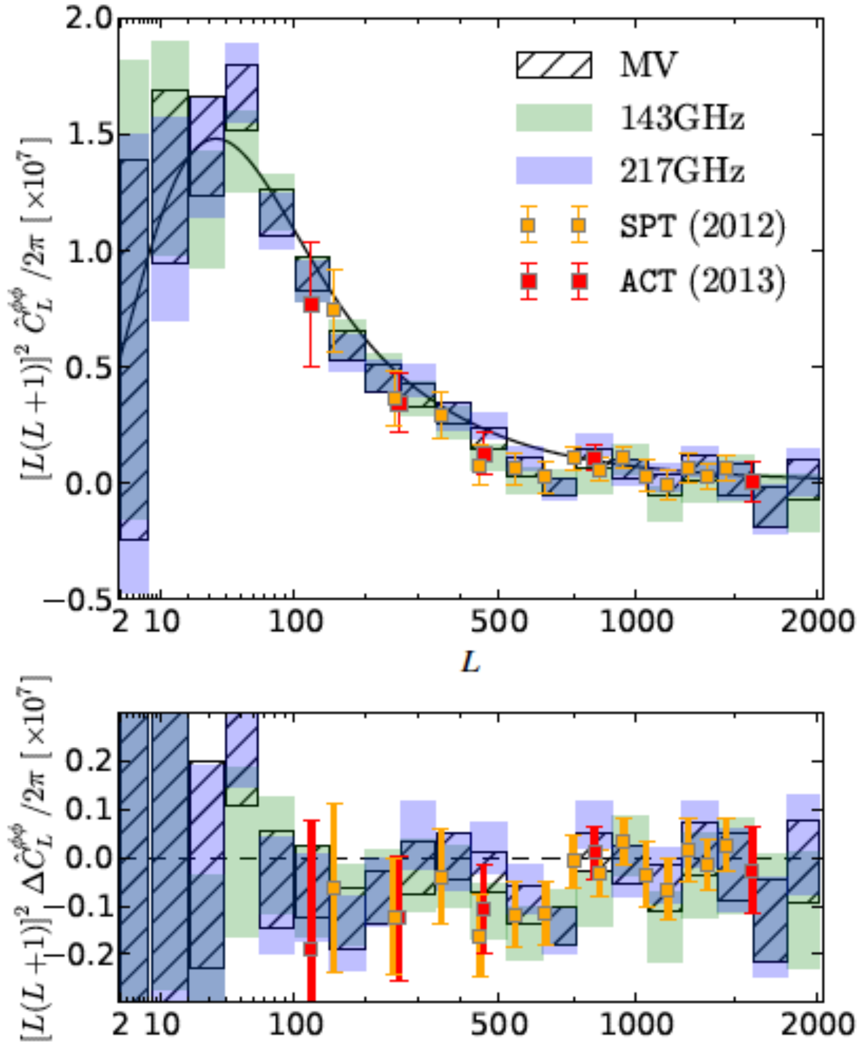
NILC, $f_{\rm sky} = 0.87$

Low signal-to-noise, but correlates at high level with different tracers of LSS (20 sigma with NVSS quasars, 10 sigma with SDSS LRG, 42 sigma with Planck's CIB)

2.3. Consistency with other data

- Lensing power spectrum consistent with ΛCDM

- Helps removing degeneracies and measuring extended model parameters with Planck alone



3. Inflation

3.1. Causality

3.2. Flatness

3.3. Slow-roll

3.4. Generation of perturbations

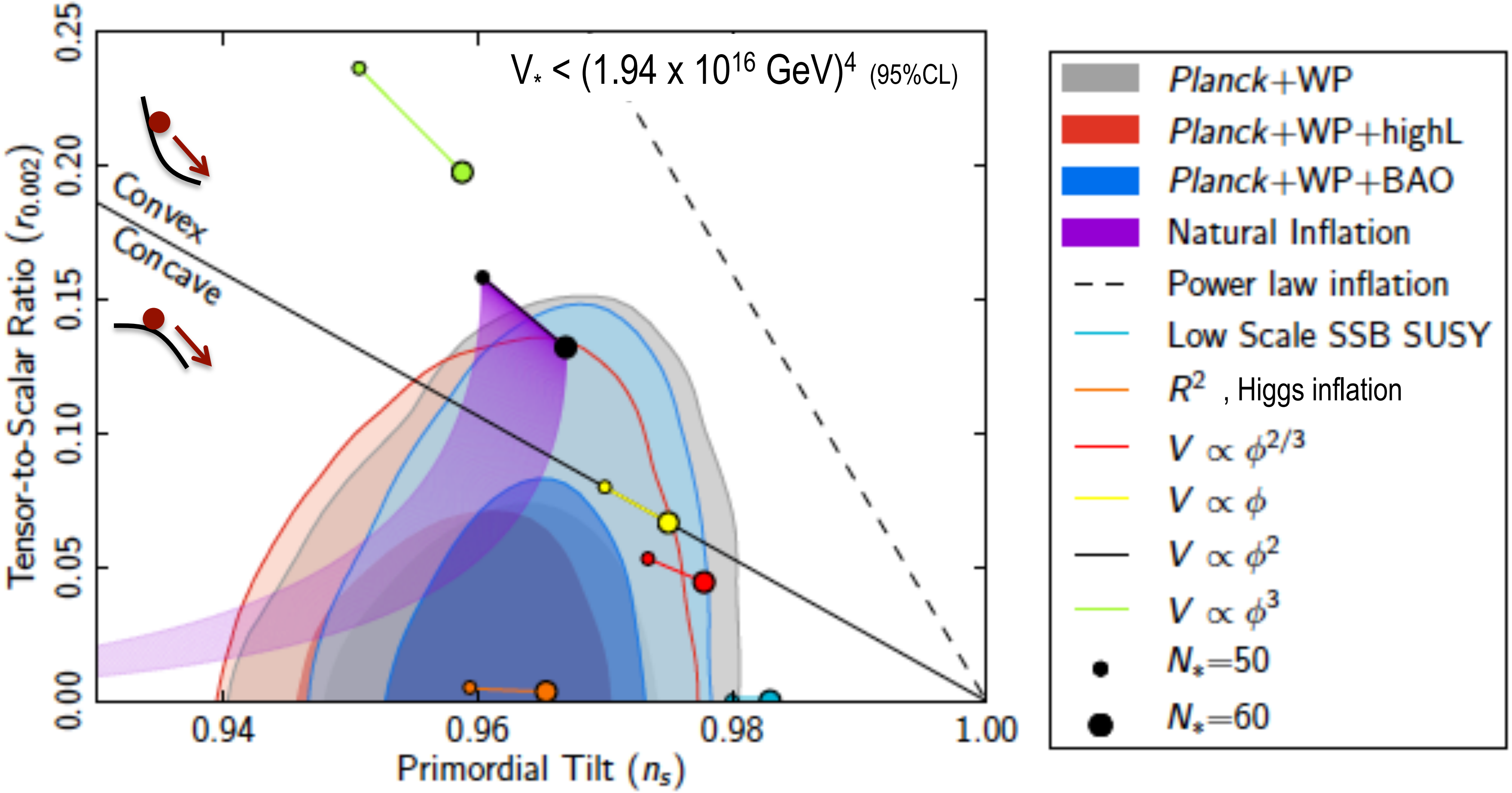
3.5. Summary of predictions of simple inflationary model

- nearly flat universe
- super-Hubble correlations + coherent oscillations
- Gaussian statistics
- adiabatic initial conditions
- nearly scale-invariant primordial spectrum
- gravitational wave background

Can alternative theories predict theses?

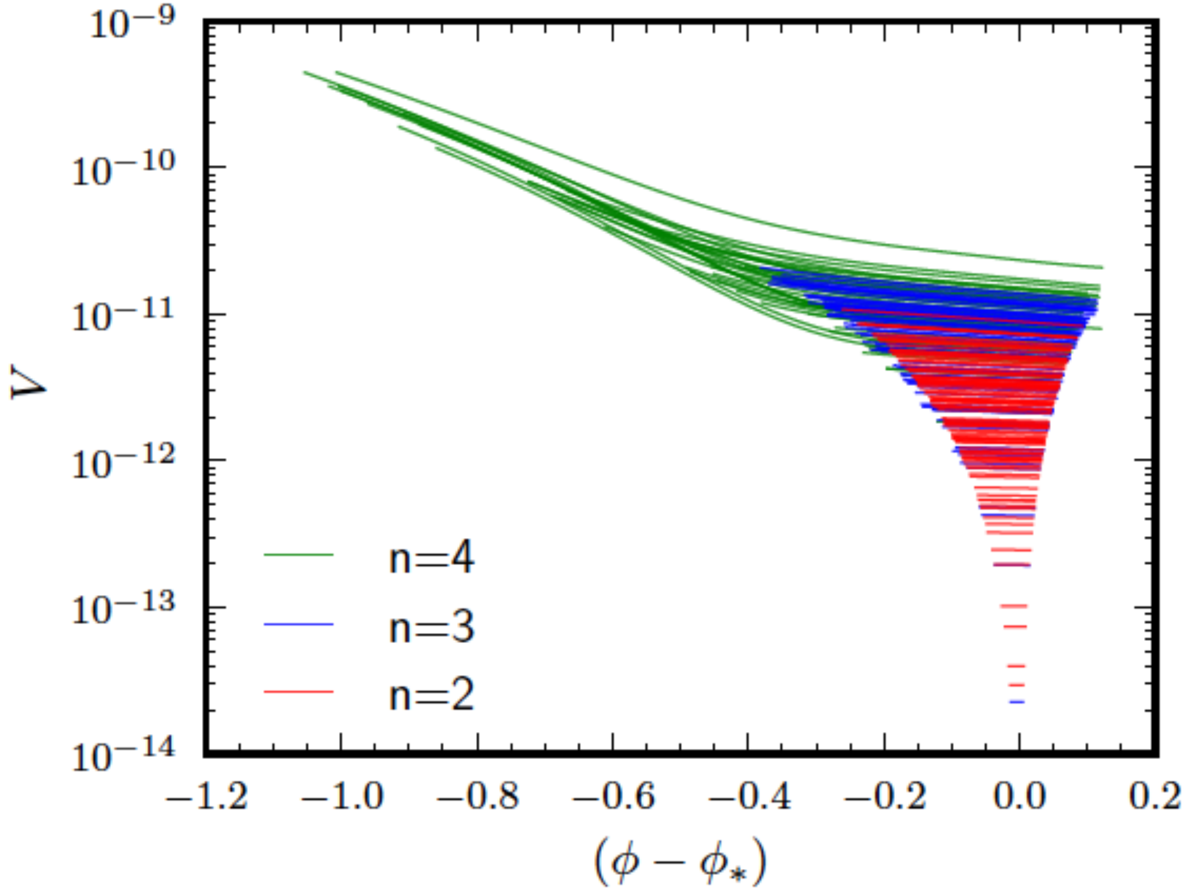
3.5. Planck constraints on inflationary phase space

Tensors, spectral index and inflation



- Also OK: Hill-top with p=2 or p≥4; also disfavored: inverse power-law

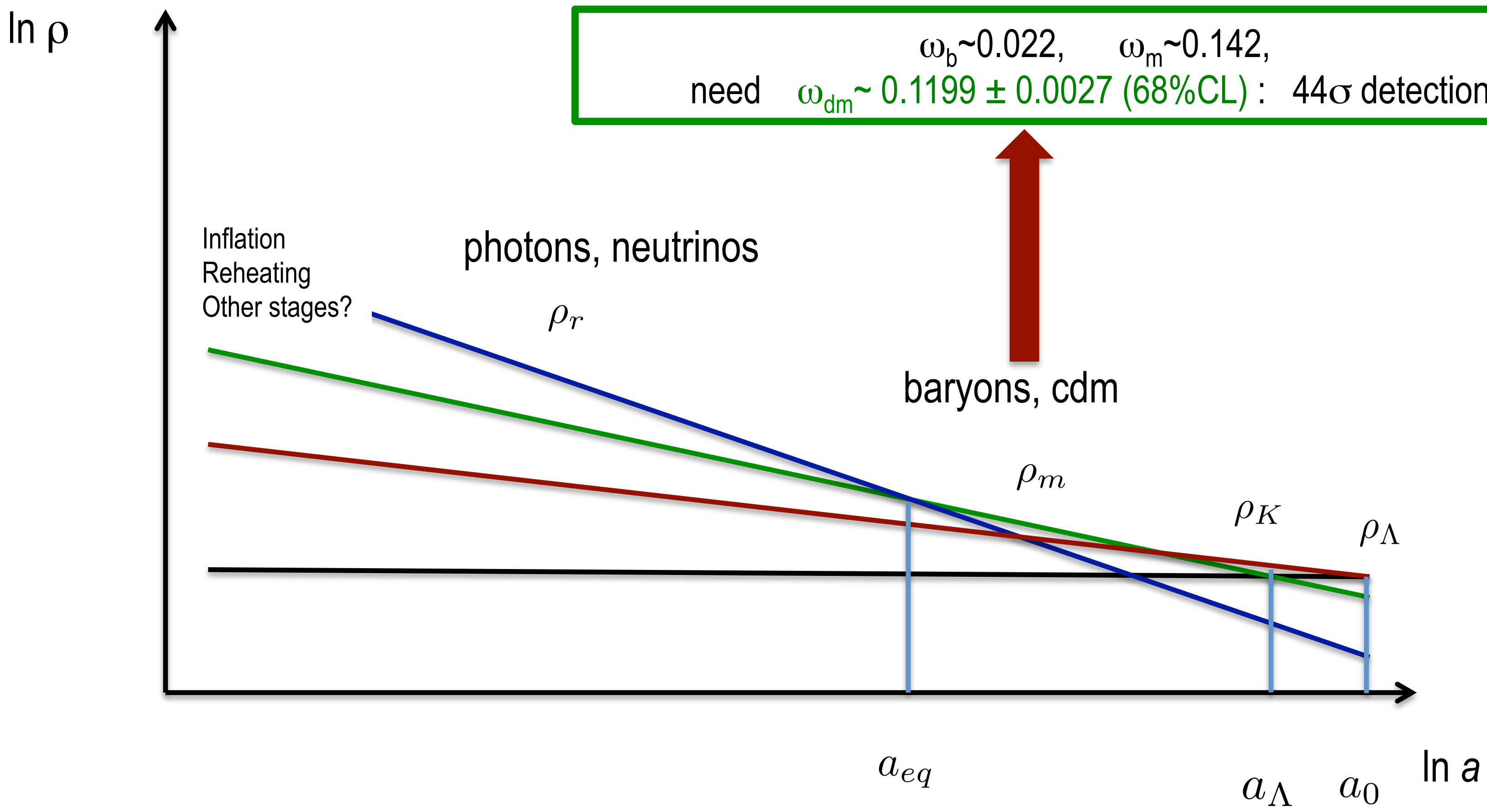
Inflation potential reconstruction



"observable window" of the inflaton potential, assuming that it can be Taylor-expanded inside this region at order n = 2, 3, 4 (units of true m_P)

4. Beyond minimal ΛCDM

- Relevant densities:



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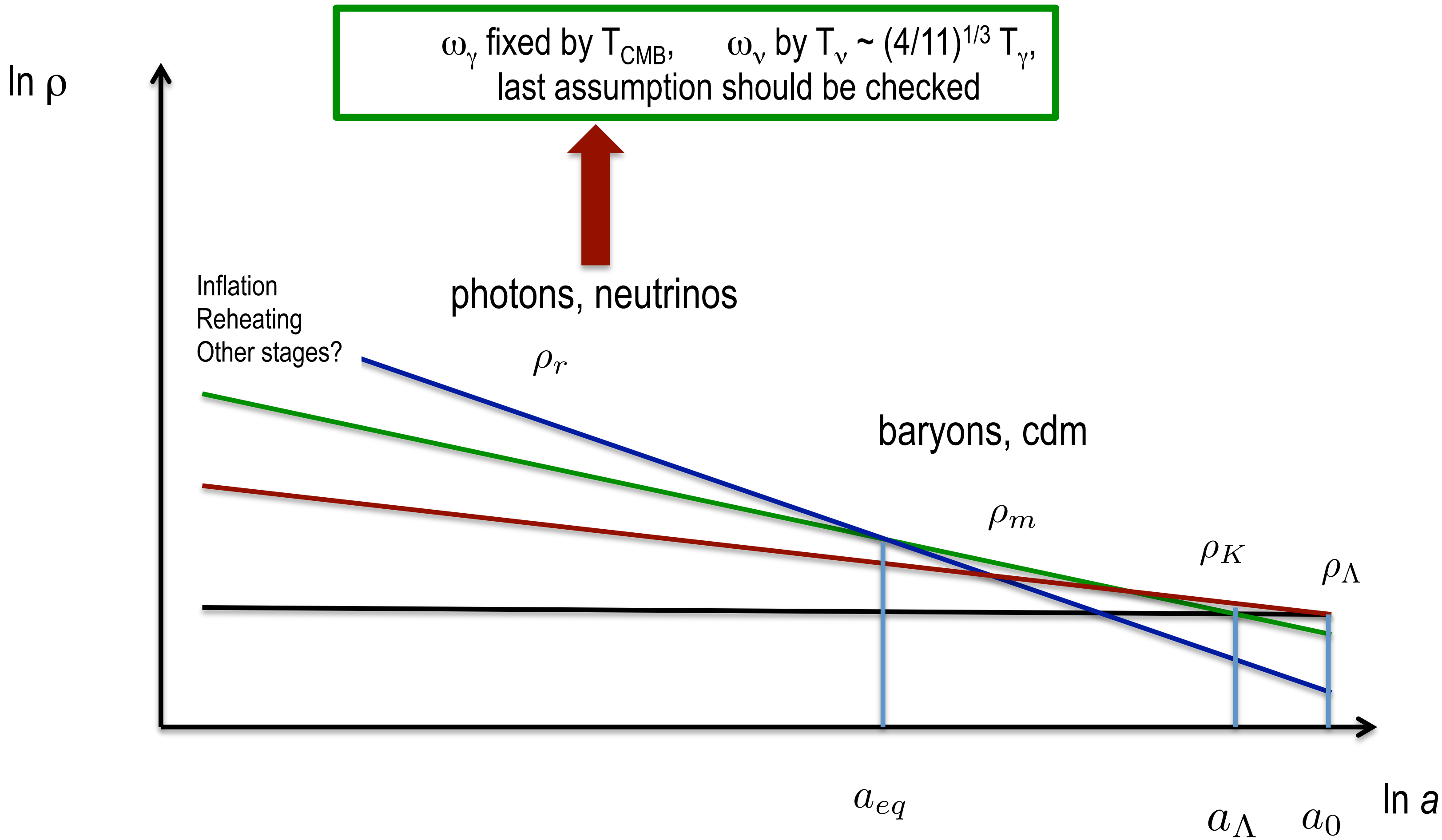

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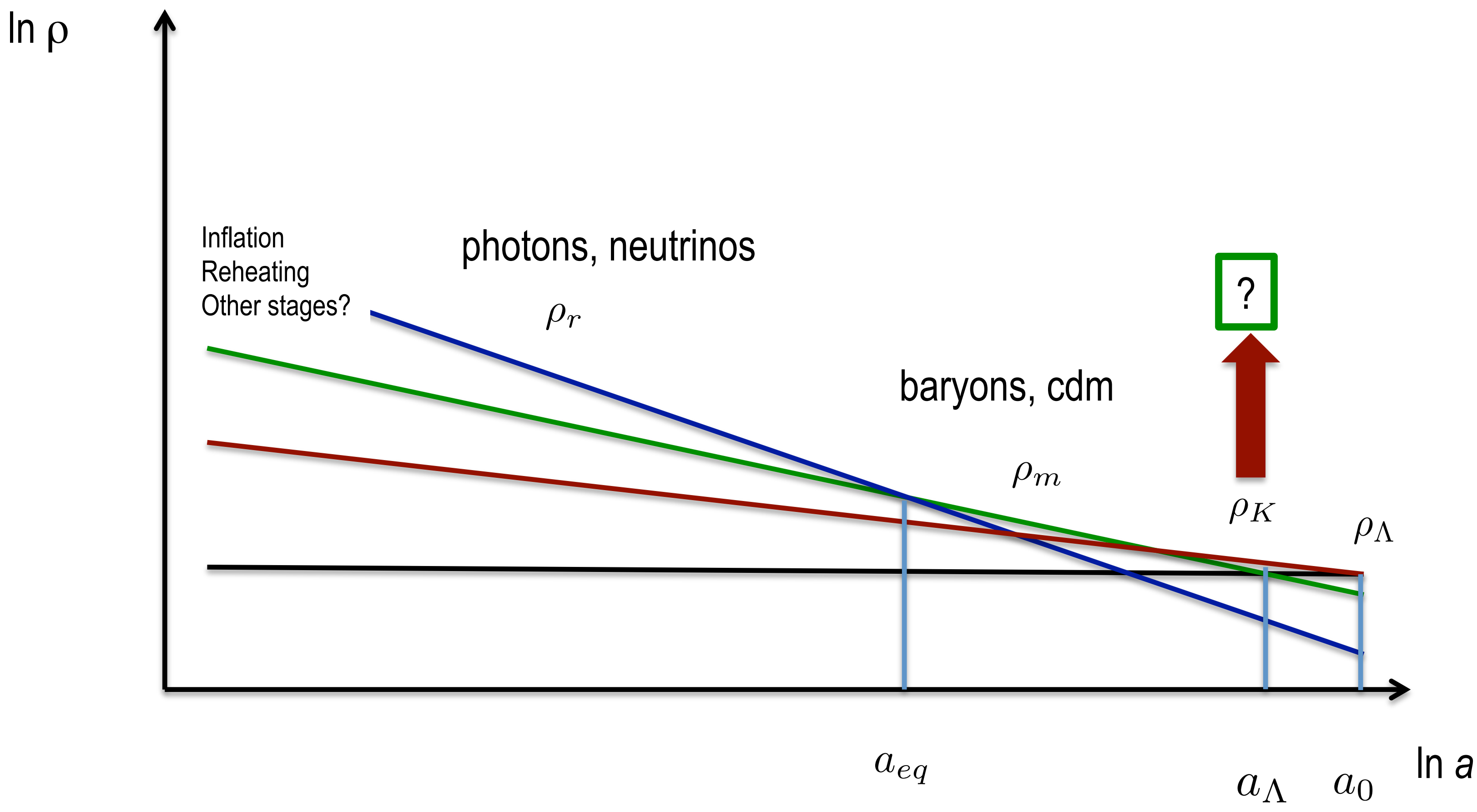

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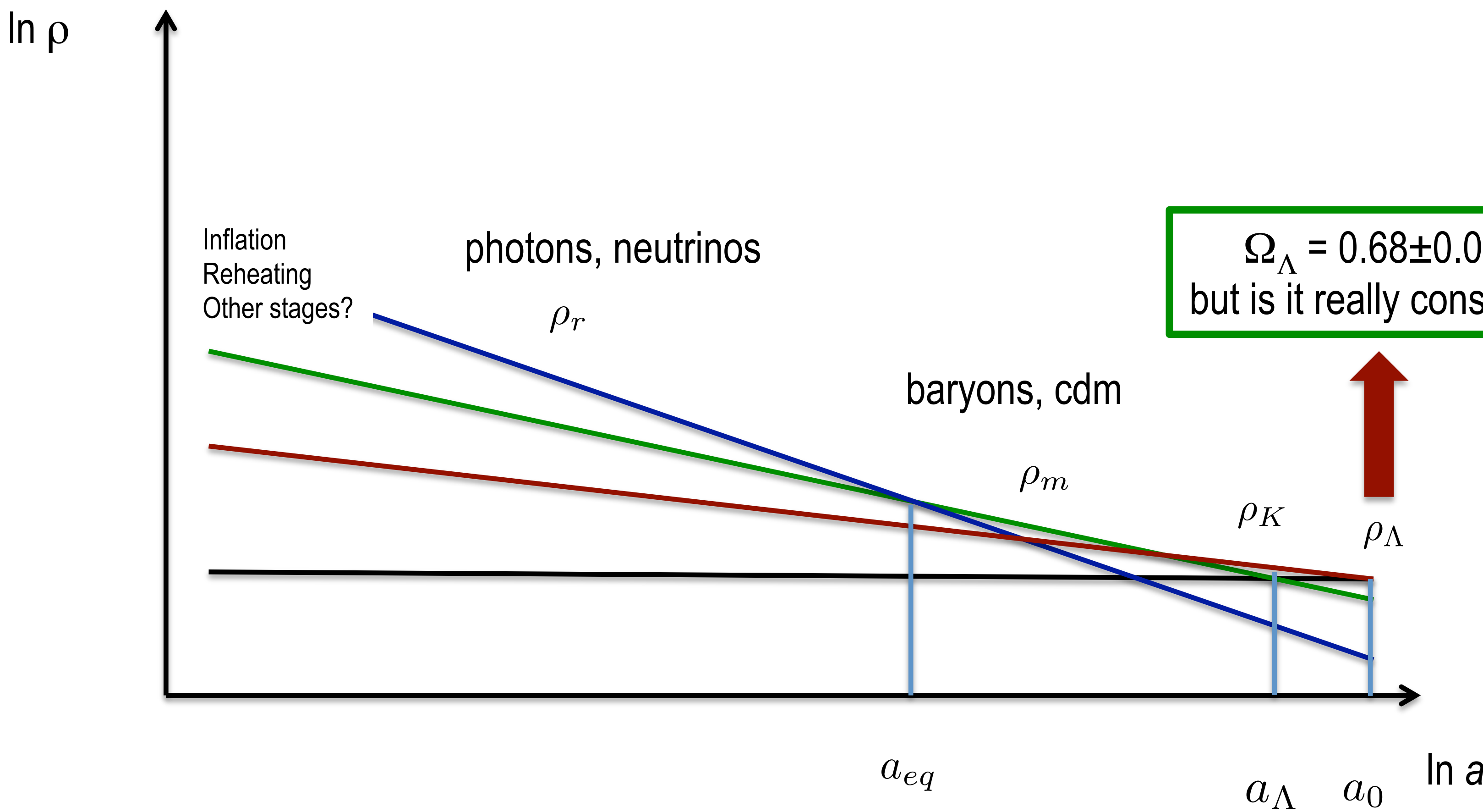


Relativistic d.o.f. (N_{eff})

$$\rho_{\rm R} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \rho_\gamma$$

- CMB alone (Planck+WP+HighL)

  $N_{eff} = 3.36 \pm 0.66$ (95%CL)

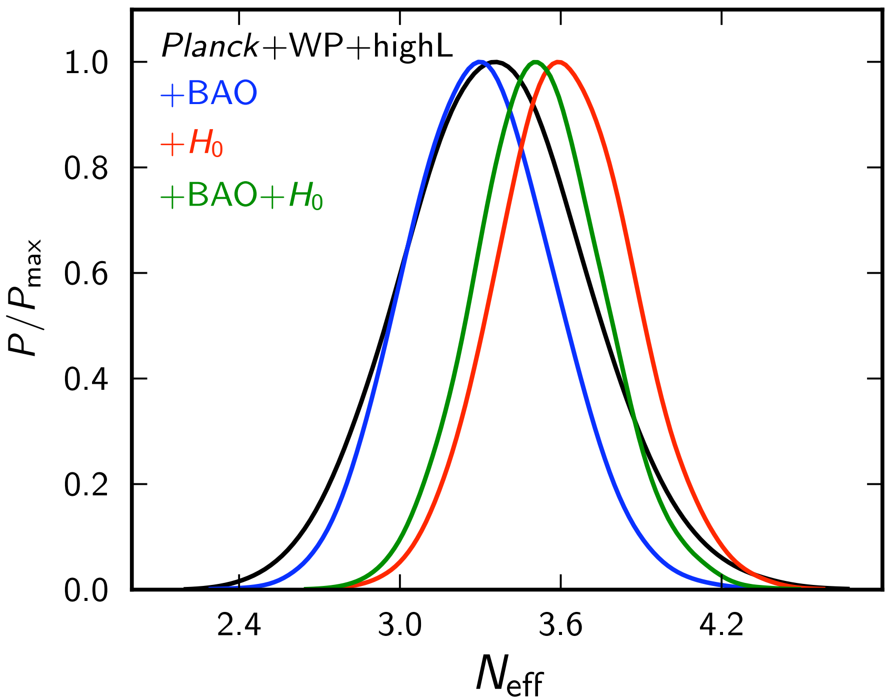
- With lensing and BAO:

  $N_{eff} = 3.30 \pm 0.52$ (95%CL)

- With H_0 and BAO:

  $N_{eff} = 3.53 \pm 0.46$ (95%CL)

  $\Delta\chi^2 = -3.6 = -3.3 + 2.0 - 2.8 + 0.4$



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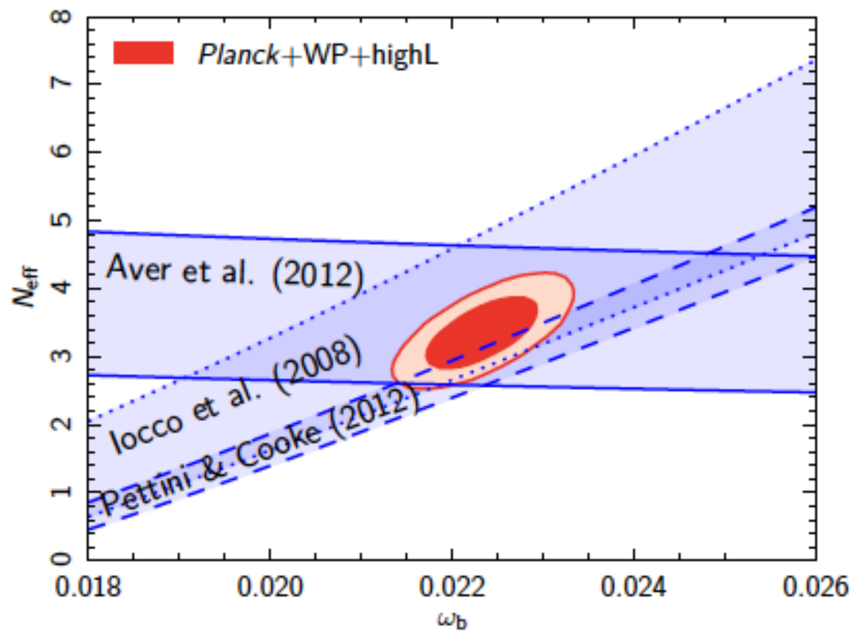
  $\Delta\chi^2 = -3.6 = -3.3 + 2.0 - 2.8 + 0.4$



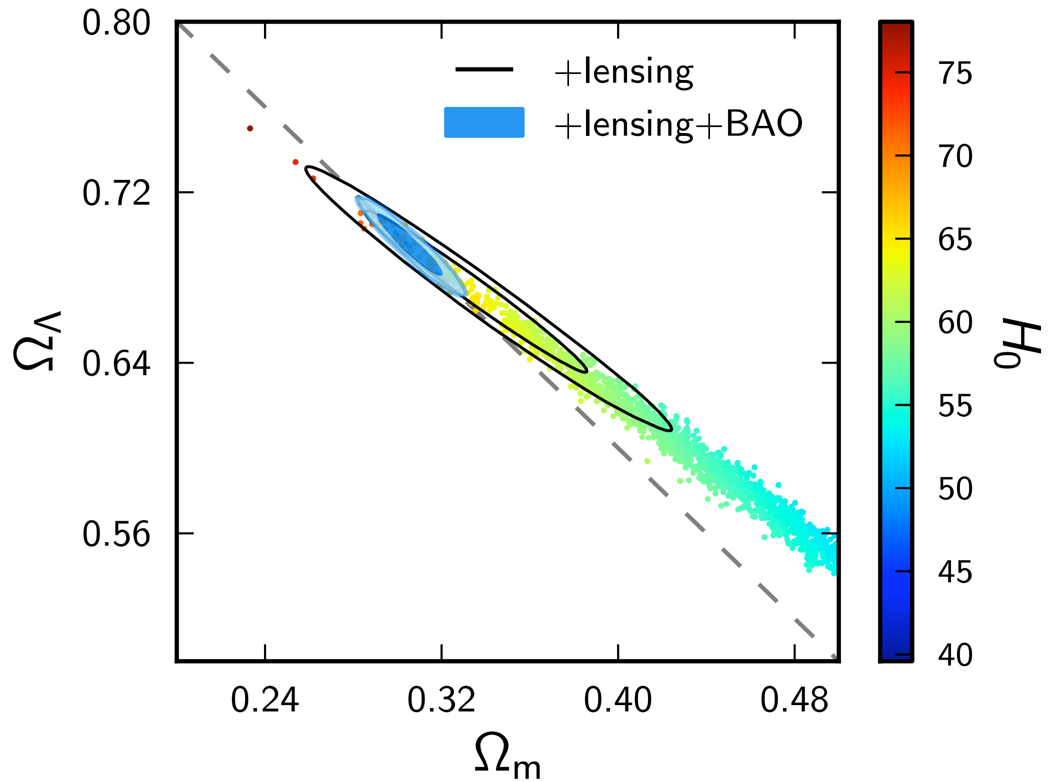
Curvature

CMB alone (Planck+WP+HighL), despite geometrical degeneracy:

$100\Omega_k = -4.2 \pm 4.5$ (95%CL)

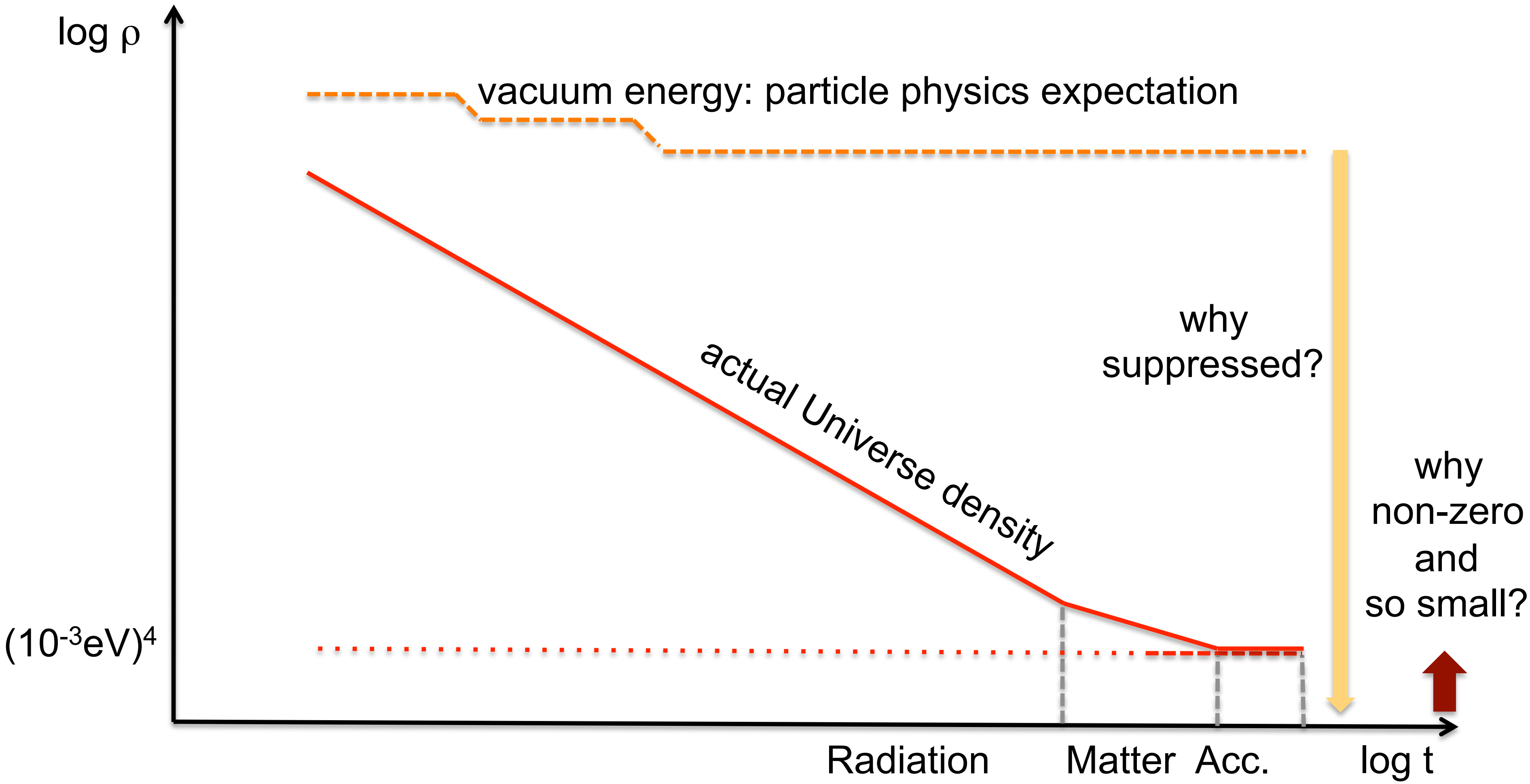
With lensing and BAO:

$100\Omega_k = -0.10 \pm 0.63$ (95%CL)



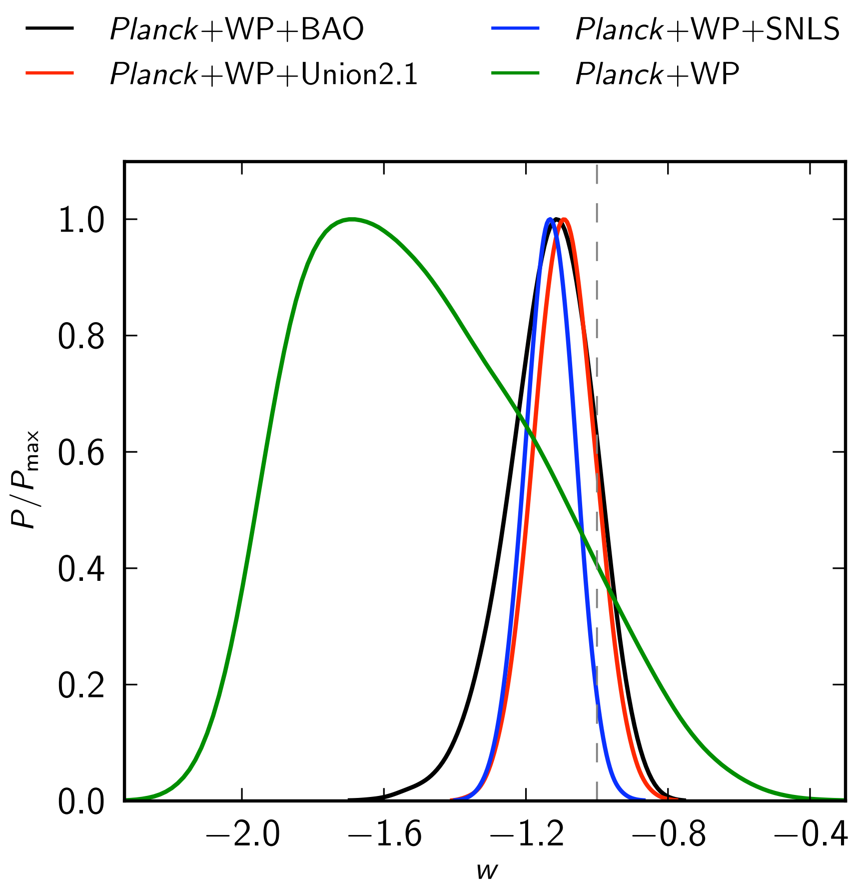
Dark Energy

- $\rho \sim m_P^4 \sim (10^{28}\mathrm{eV})^4$ or m_{susy}^4 or $m_{EW}^4 \sim (10^{11}\mathrm{eV})^4$ from radiative corrections to vacuum energy
- $\Delta\rho \sim m_{EW}^4 \sim (10^{11}\mathrm{eV})^4$ or $m_{QCD}^4 \sim (10^8\mathrm{eV})^4$ variations of vacuum energy during phase transitions



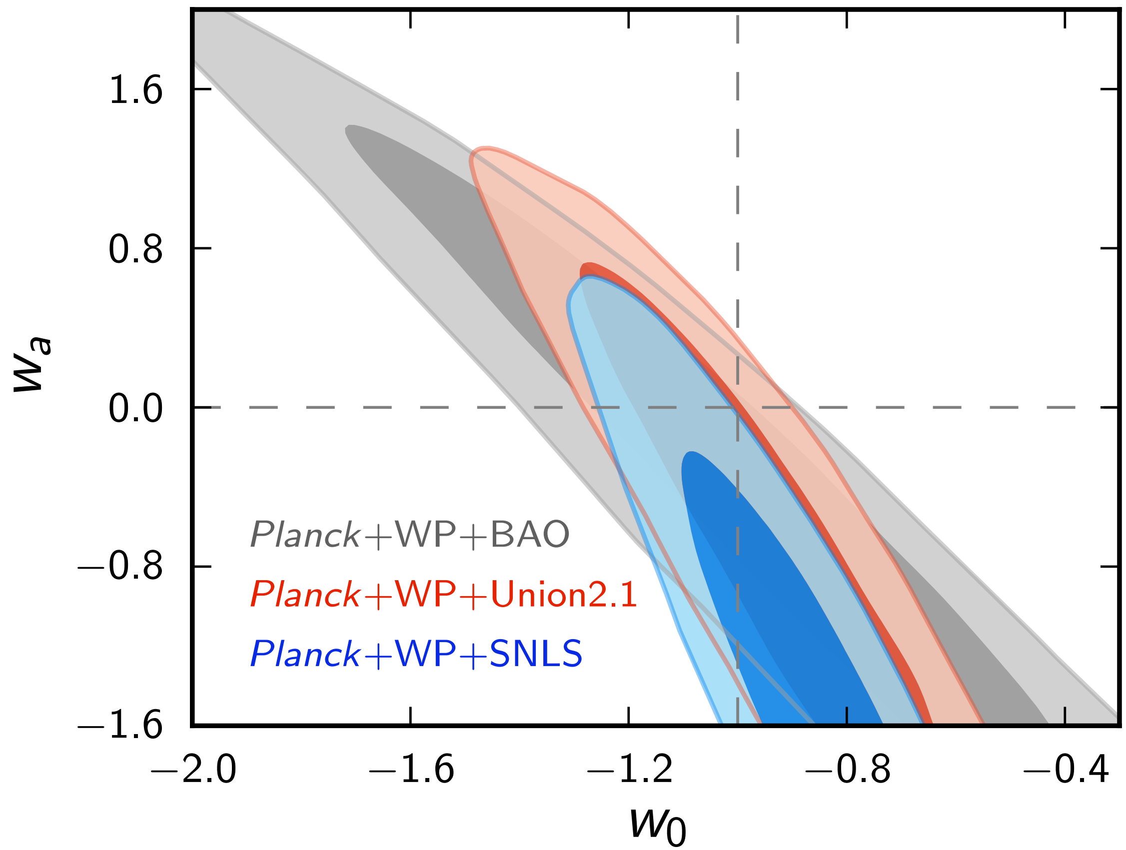
Dark Energy

- constant w:



Dark Energy

- varying w(a) (linear):



Neutrino mass

- Neutrino oscillation experiments: $\Sigma m_\nu > 0.06$ eV

- CMB alone (Planck+WP+HighL):

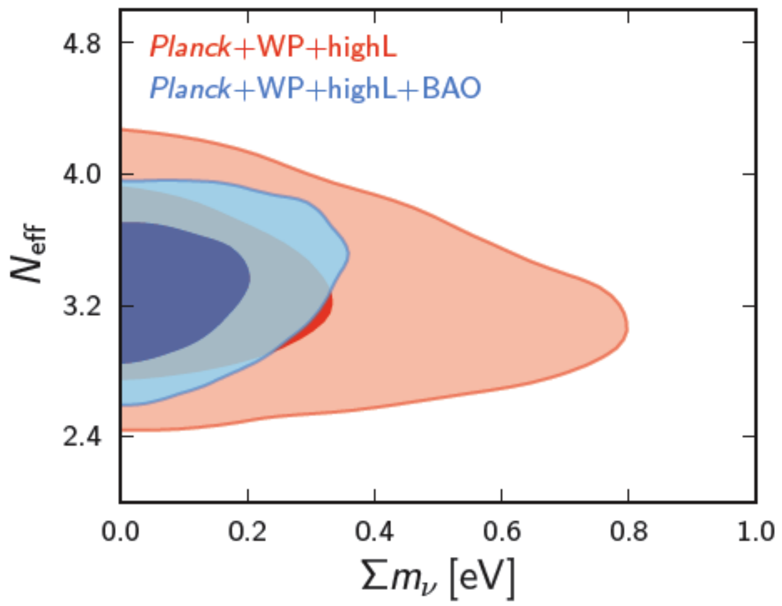
  $\Sigma m_\nu < 0.66$eV (95%CL)

- With BAO:

  $\Sigma m_\nu < 0.23$eV (95%CL)

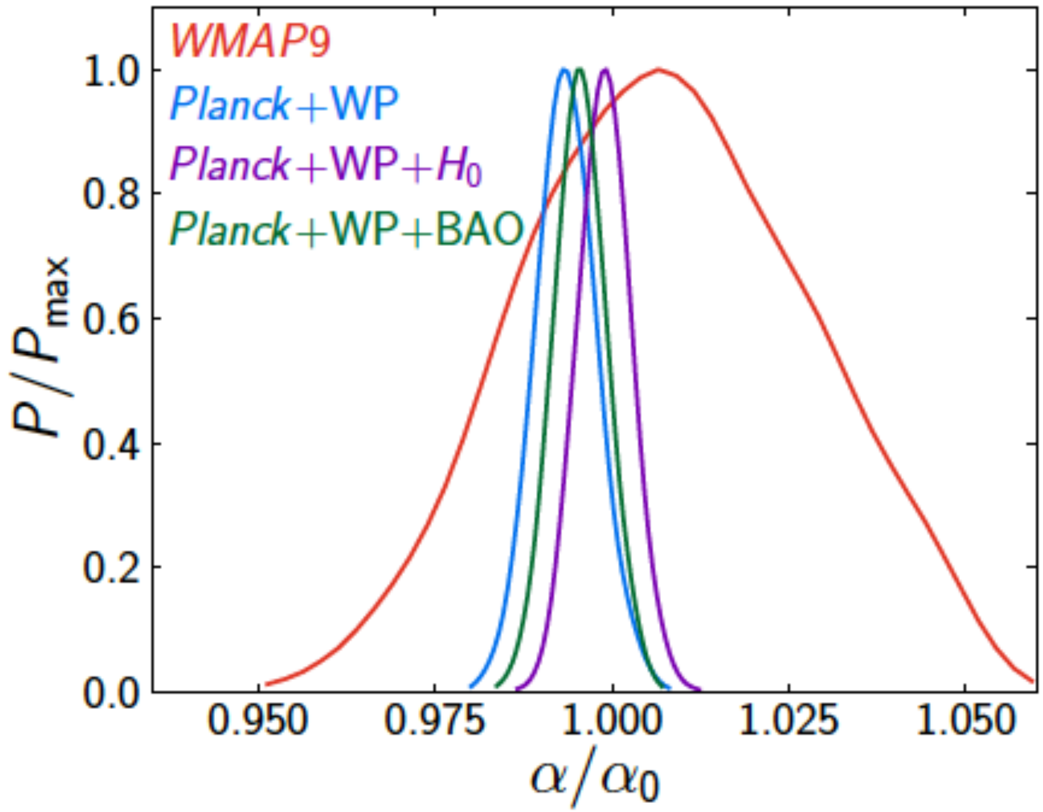
- With lensing:

  $\Sigma m_\nu < 0.85$eV (95%CL)



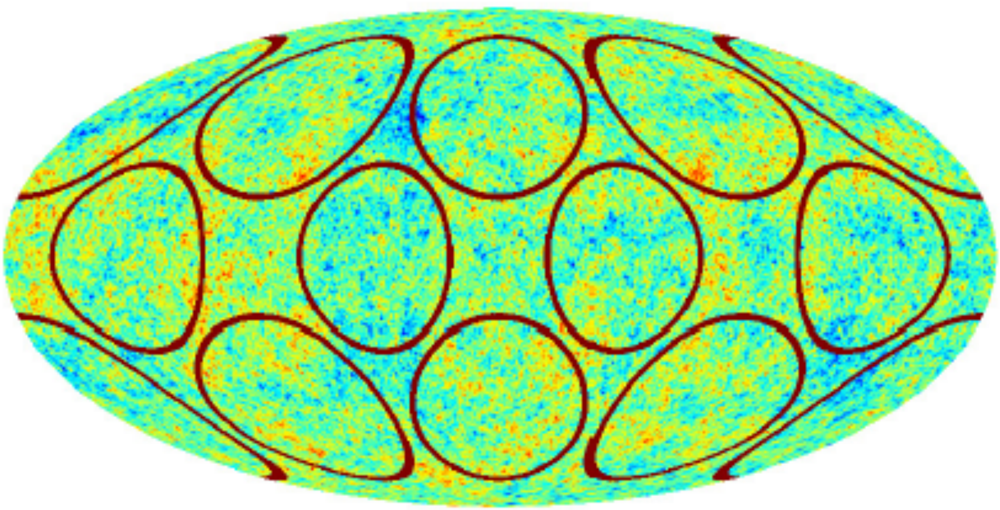
Variations of fine-structure constant

All experiments (atomic clocks, geological radioactivity, BBN, etc.) consistent with no variations, excepted quasar absorption lines
(Webb et al. 2001, Murphy et al. 2003)



Topology

- Search for matching circles
- Search for specific patterns for flat spaces with cubic toroidal (T3), equal-sided chimney (T2) and slab (T1) topologies, three multi-connected spaces of constant positive curvature (dodecahedral, truncated cube and octahedral) and two compact negative-curvature spaces
- Search for Bianchi VII_h cosmology

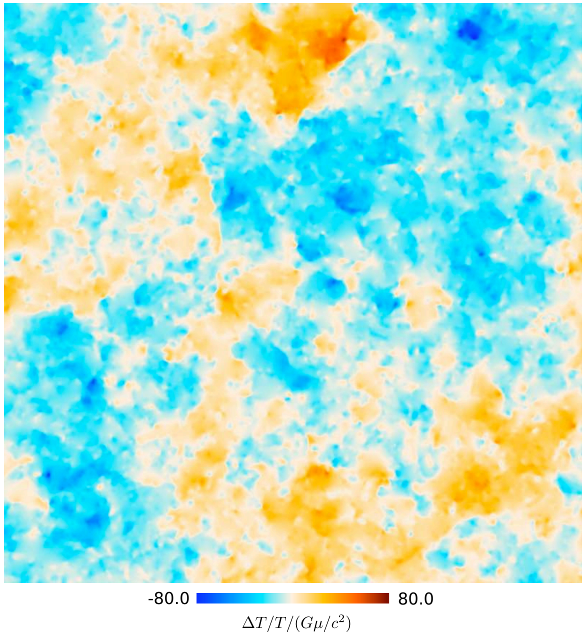


simulated maps with matching circles at 24^o

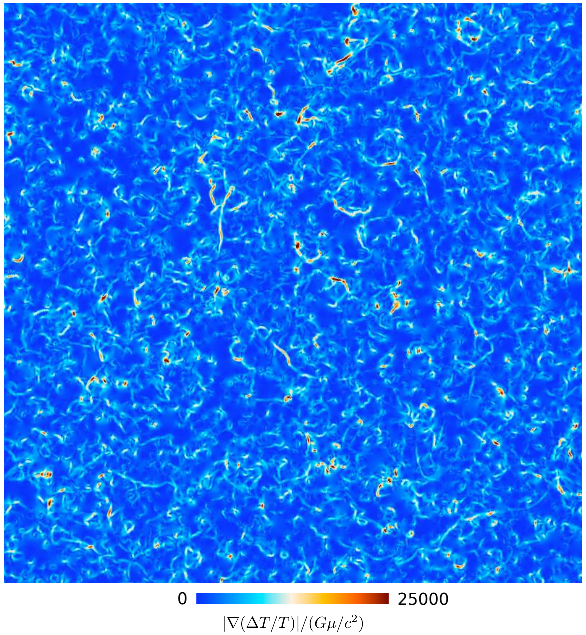
Defects

- Simulation of CMB distorted by cosmic strings:

temperature:

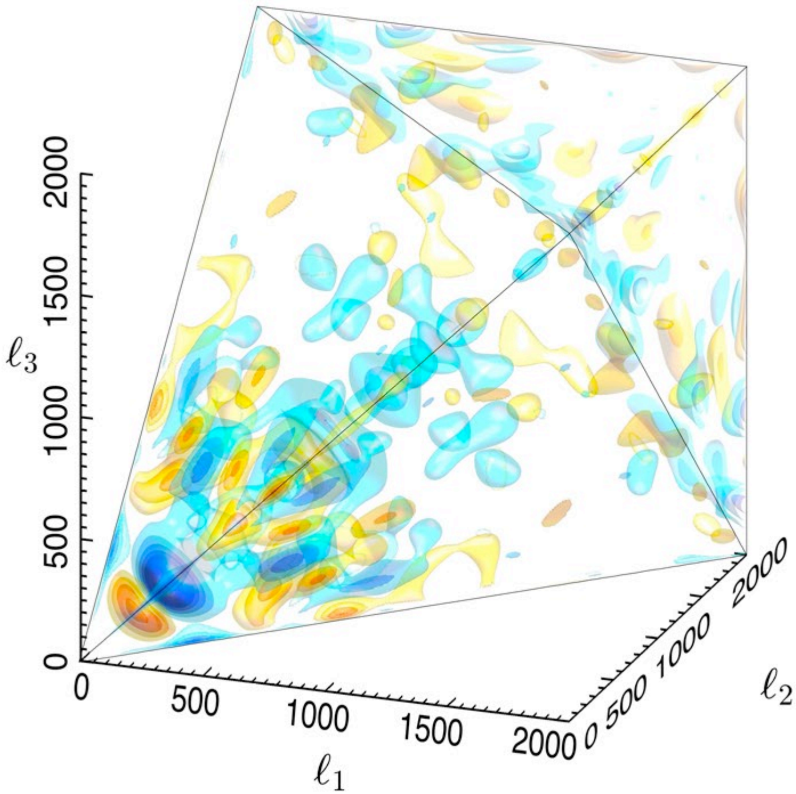


spherical gradient:



Search through power spectrum distortions and specific types of non-gaussianity: no evidence ($G\mu/c^2 < 10^{-7}$)

Primordial non-gaussianity



Temperature bispectrum
(after foreground cleaning)

- Amplitude of specific bispectrum shapes: *(WMAP9)*
  - $f_{NL}^{local} = 2.7 \pm 5.8$ (68%CL) *37 ± 20*
  - $f_{NL}^{equi} = -42 \pm 75$ (68%CL) *51 ± 136*
  - $f_{NL}^{ortho} = -25 \pm 39$ (68%CL) *-245 ± 100*
- For trispectrum:
  - $\tau_{NL}^{local} < 2500$ (95%CL)
- Compatible with very small NG level predicted by canonical single-field inflationary models

Other investigated extensions

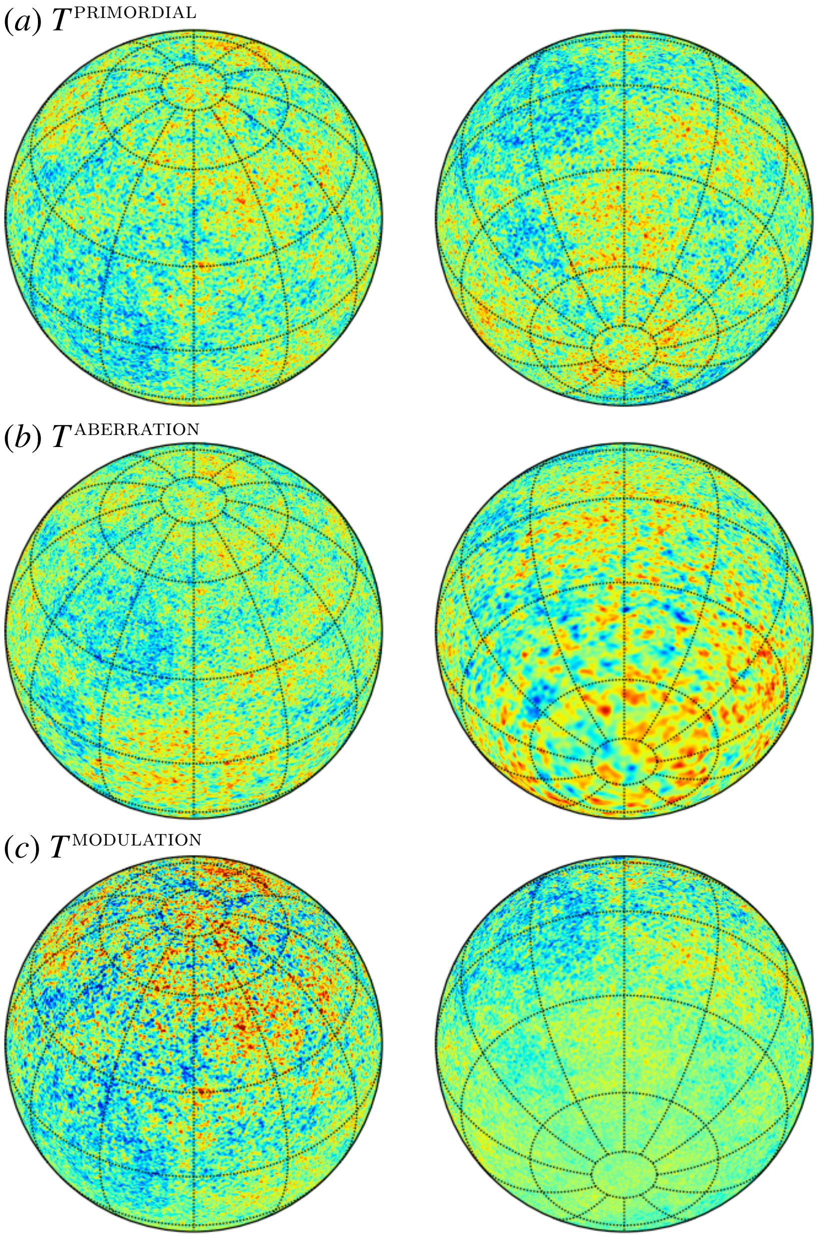
- Light sterile neutrino (thermal or non-thermal, m < 10 eV)
- DM annihilation (smooth background)
- Running of the primordial spectral index
- Features in the primodial spectrum
  - Binning method
  - Parametric search
- Primordial magnetic fields (neglect Faraday; non-helical case; vectors and scalars)
- Isocurvature modes
  - General correlated CDM, neutrino density/velocity
  - Axion-like (CDM, uncorrelated)
  - Curvaton-like (CDM, maximally correlated)

CMB Dipole

- Newtonian gravity: motion of observer gives dipole from Doppler effect
- GR: Doppler *boost* affects all multipoles at 10^{-5} level. Aberration (similar to coherent lensing) and modulation.
- First detection based on tripsectrum:

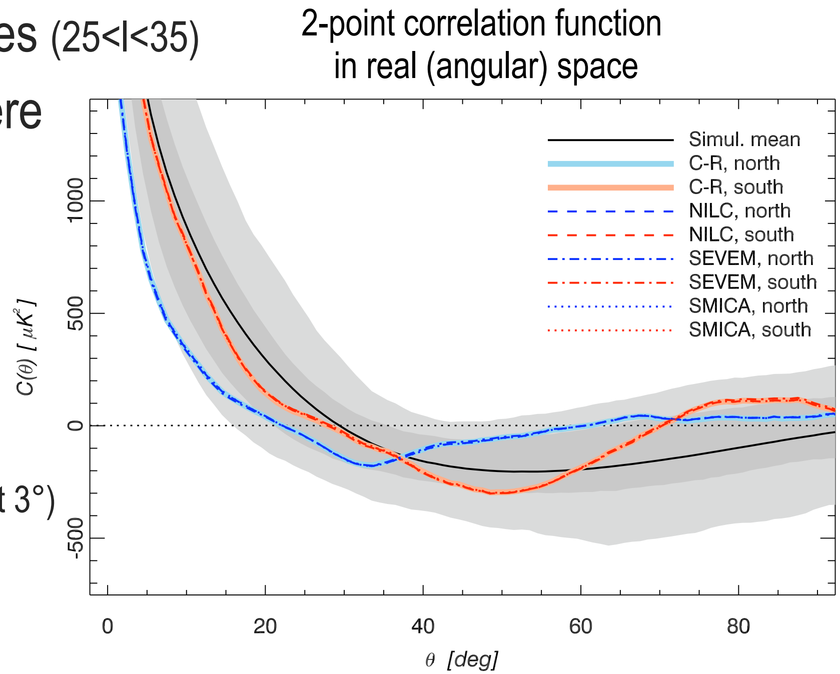
$$v = 384\ \mathrm{km.s^{-1}} \pm 78\ \mathrm{km.s^{-1}}\ (\mathrm{stat}) \pm 115\ \mathrm{km.s^{-1}} (\mathrm{sys})$$

- Compatible with observed dipole: 369 km.s^{-1}
- No evidence for anomalous primordial dipole



Large-scale anomalies

- Confirmation of lack of power on large scales (25<l<35)
- Less variance in northern ecliptic hemisphere (0.1% chance) up to l~1500
- [Even multipoles supressed till l~25]
- Cold spot (0.3% chance)
- Low quadrupole
- Quadrupole-octopole alignement (9° to 13°, not 3°)



Galactic foregrounds? Solar emission? Local universe?

Primordial fluctuations? Topology? Magnetic fields?

- More details on the theory in:
  - ``TASI lectures on Cosmological Perturbations'', JL, arXiv:1302.4640

- More details on observational constraints in the 1st Planck release papers, in particular:
  - Planck 2013 results. XVI. Cosmological parameters, arXiv:1303.5076
  - Planck 2013 results. XXII. Constraints on inflation, arXiv:1303.5082
  - Planck 2013 results. XXIII. Isotropy and statistics of the CMB, arXiv:1303.5083
  - Planck 2013 Results. XXIV. Constraints on primordial non-Gaussianity, arXiv:1303.5084
  - Planck 2013 results. XXV. Searches for cosmic strings and other topological defects, arXiv:1303.5085
  - Planck 2013 results. XXVI. Background geometry and topology of the Universe, arXiv:1303.5086