CMB constraints for particle physics

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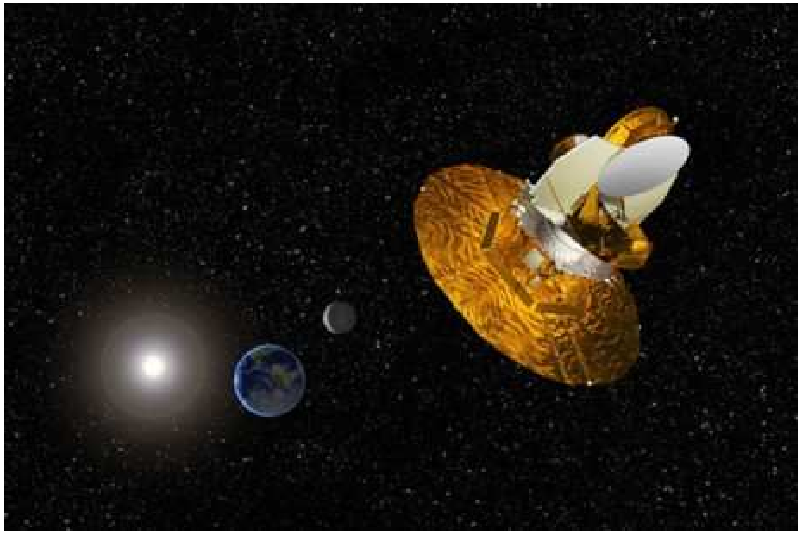
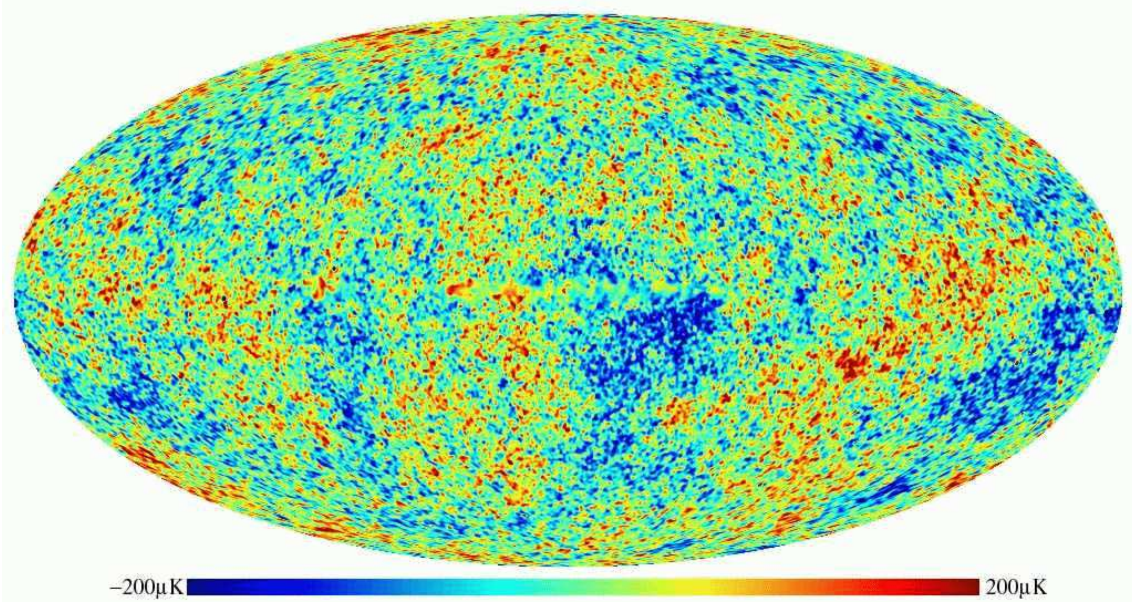
Plan

CMB physics summarized

- CMB anisotropies with a good satellite: WMAP (and soon PLANCK)

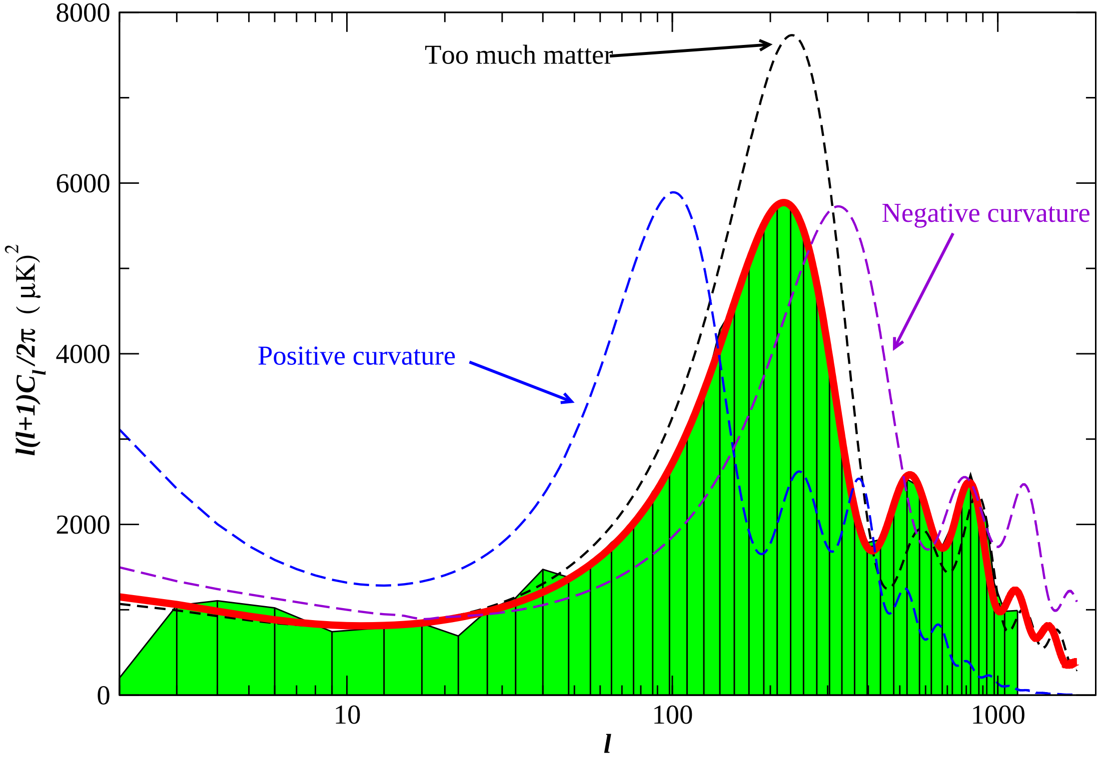




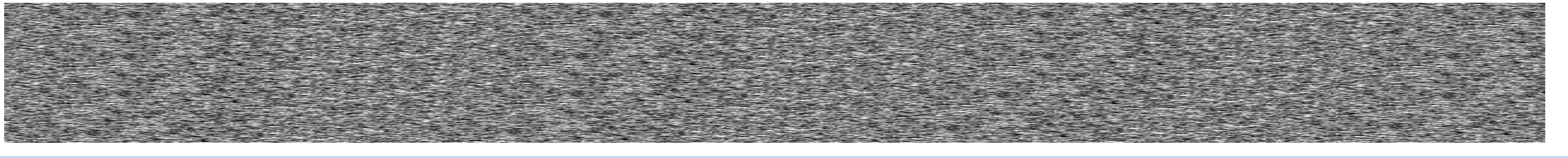
- Snapshot of the universe when it became transparent
  - The fluctuations trace the plasma acoustic oscillations
  - Sound speed depends on the matter/radiation content
  - Observed angular size depends on the universe geometry

CMB angular power spectrum

- Strongly depends on the universe constituents



- Needs a primordial white noise!



ΛCDM cosmological model

- Homogeneous + isotropic background: Friedmann–Lemaître model

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\frac{\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j}{\left(1+\frac{1}{4}K\delta_{kl}x^kx^l\right)^2}, \quad H(t) = \frac{\mathrm{d}\ln a}{\mathrm{d}t}$$

  - Contains

$$\rho_{\mathrm{mat}} = (\Omega_{\mathrm{dm}} + \Omega_{\mathrm{b}})\frac{\rho_{\mathrm{c}}}{a^3}, \quad \rho_{\mathrm{rad}} = \Omega_{\mathrm{rad}}\frac{\rho_{\mathrm{c}}}{a^4}, \quad \rho_{\mathrm{c}} = 3\kappa^{-2}{H_0}^2$$

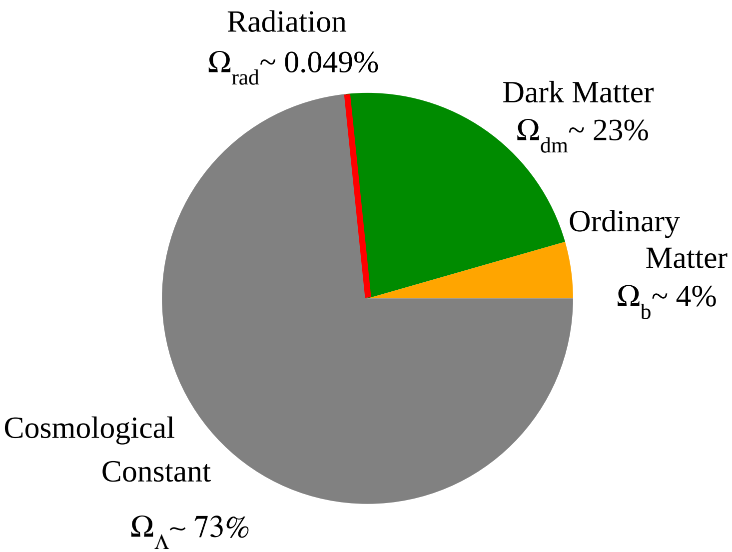
  - Gravitation

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa^2 T_{\mu\nu},$$

- + linear perturbations (origin of CMB and galaxies)
  - No extra evolution parameters but *a priori* unknown IC
  - Statistical isotropy + adiabaticity

$$\langle X^*(\boldsymbol{k},t_{\mathrm{ini}})X(\boldsymbol{k}',t_{\mathrm{ini}})\rangle = (2\pi)^3 P_X(k)\delta(\boldsymbol{k}-\boldsymbol{k}'), \quad 4\pi k^3 P(k) = A_{\mathrm{S}}\, k^{n_{\mathrm{S}}-1}$$

- Fits of background + perturbations
  - CMB anisotropies in the Standard Model (SM) of particle physics



  - Gaussian perturbations
  - No evidence for non-adiabaticity
  - Accelerating flat universe today

$$\Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2} \simeq 0.73$$

$$\Omega_K \equiv \frac{-K}{H_0^2} = 0 \pm 0.01$$

- Almost scale invariant primordial power spectra

$$n_S - 1 \simeq -0.036 \pm 0.013$$

BSM in a ΛCDM universe

- Dark sector
  - $\Omega_{\mathrm{dm}} \neq 0$: dark matter $\Leftrightarrow P = 0$ + non-interacting with baryons

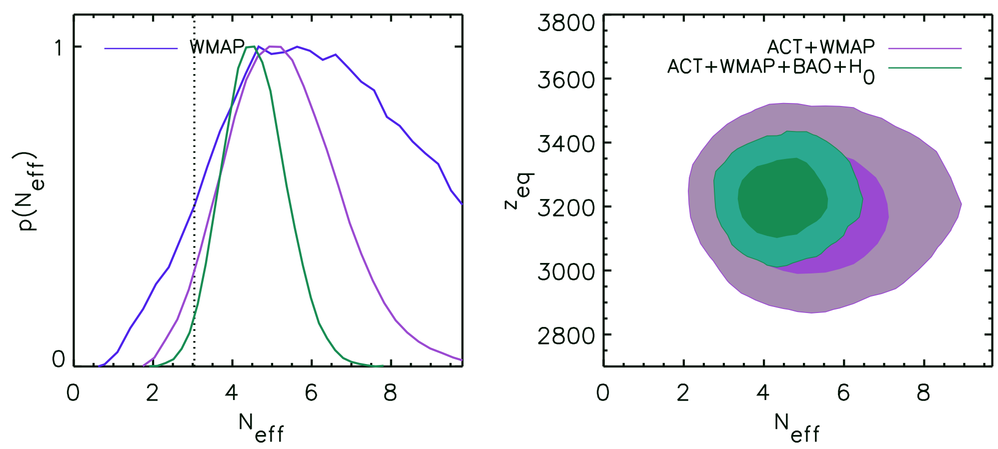
    It is not necessarily a WIMP, neither a particle!
  - $\Omega_\Lambda \neq 0$
    - No new physics in ΛCDM cosmology: this is the second GR fundamental constant
    - if dark energy one has to include linear fluctuations and fit again CMB (previous slide does not apply anymore)
- Deccelerating issues (flatness is unstable and horizon problems) + Gaussianity + almost scale invariant primordial noise + adiabaticity
  - Primordial inflation explains all this
  - Not possible with the SM Higgs (see however [Bezrukov 08])

Testing the Standard Model?

- Cosmology is assumed to be ΛCDM + SM tested/modified
- CMB constrains how much radiation/matter gravitates (eV physics)
  - Assuming 3 species, neutrinos mass from WMAP7

$$\sum m_i < 1.3\,\mathrm{eV} \quad (95\%)$$

  - ρ_{rad} is bounded so is N_{eff} (assuming $m = 0$)



- CMB can also bounds rotation of polarization (parity violation)...

High energy physics with CMB

- Assuming SM + ΛCDM only at $T < \mathrm{GeV}$
- We still measure eV physics and late time universe geometry with CMB $\Rightarrow$ new physics is not directly visible
- High energy effects visible through
  - IC for the linear perturbations: $P(k)$
  - Unexpected low energy remnants; as WIMP dark matter
- Two examples
  - Primordial inflation: accelerated expansion at early times
    - Existence of HE scalar field(s)
  - Topological defects: phases transitions from SSBM
    - Cosmic strings

Cosmic inflation

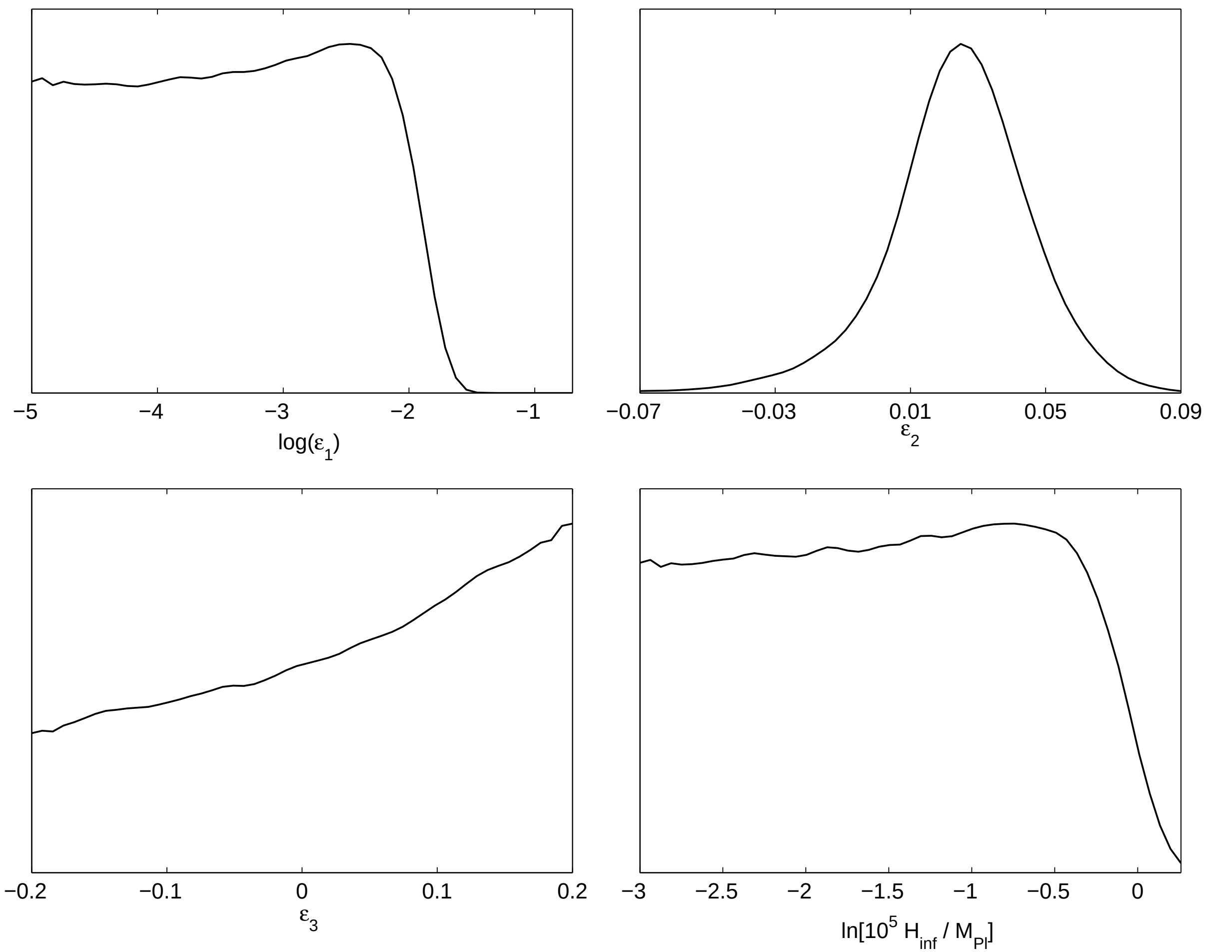
- Accelerated expansion naturally triggered by scalar fields ϕ when $V(\phi) \gg \nabla\phi$
  - Solves the flatness/horizon issues (and monopoles)
- Linear perturbations of quantum mechanical origin $\{\delta\phi, \delta\zeta\}$
  - IC completely determined + primordial gravitational waves

$$A_\mathrm{S} = \frac{\kappa^2 H_\mathrm{inf}^2}{8\pi^2 \epsilon_{1*}}, \quad n_\mathrm{S} = 1 - 2\epsilon_{1*} - \left.\frac{\mathrm{d}\ln\epsilon_1}{\mathrm{d}N}\right|_* \lesssim 1, \quad r = 16\epsilon_{1*}$$

  - Quantum origin explains observed Gaussianity
  - A scalar field decaying into cosmological fluids yields adiabaticity
  - Constant branching ratios: $\delta n_\mathrm{dm}/n_\mathrm{dm} = \delta n_\gamma/n_\gamma = \delta n_\mathrm{b}/n_\mathrm{b}$
- Inflationary paradigm
  - V and ϕ unknown, but constrained: $\epsilon_1 \propto (-V'/V)^2$

WMAP7 constraints on slow-roll inflation

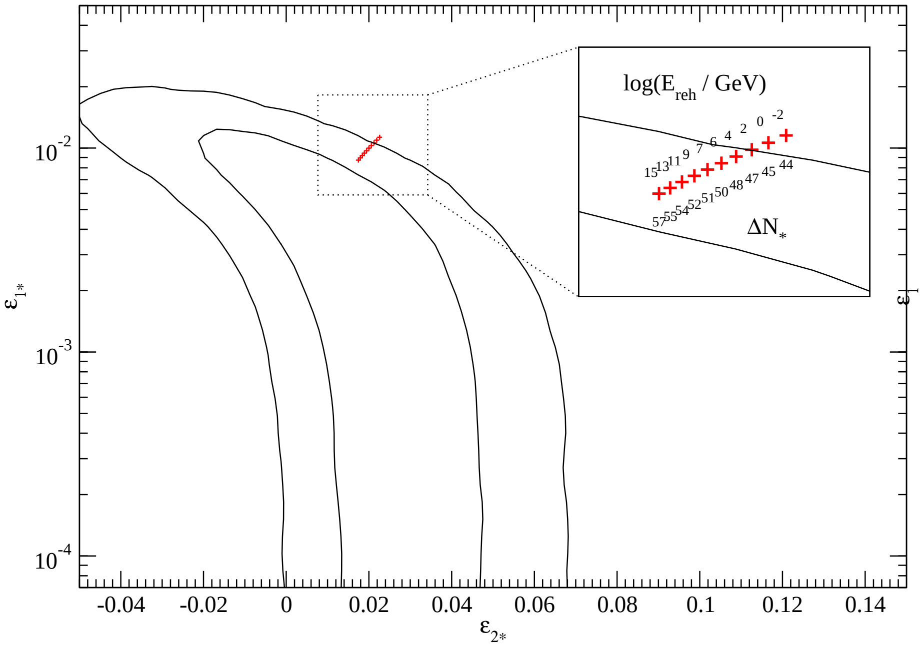
- Bayesian analysis from slow-roll $P(k)$

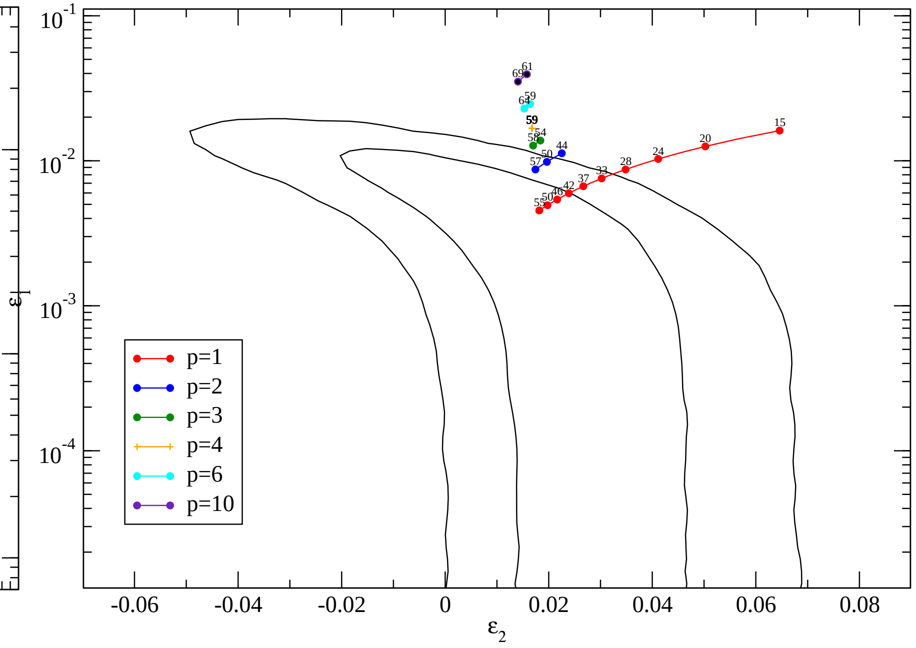


Assuming an inflationary potential

- CMB can now be used to infer the reheating energy scale
- Large field models

$V(\phi) \propto \phi^2$ $\quad\quad$ $V(\phi) \propto \phi^p$

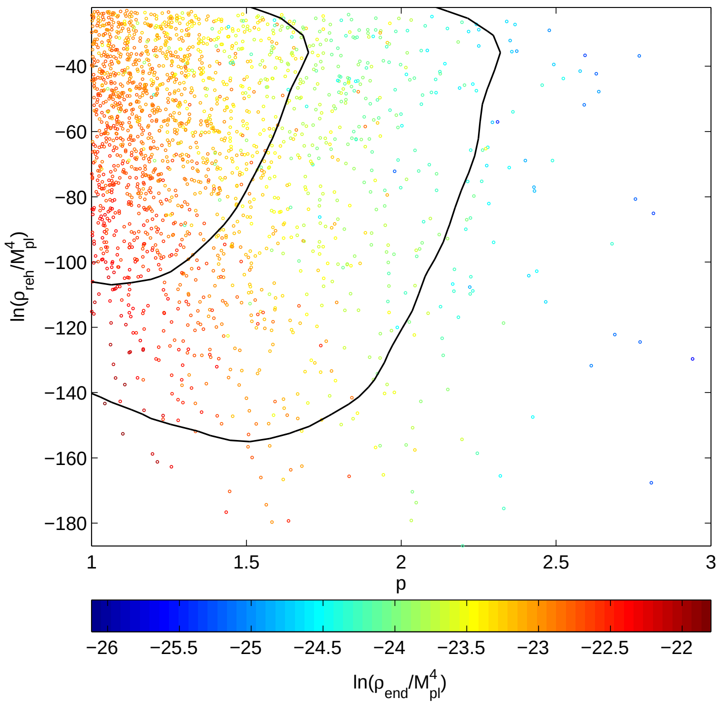


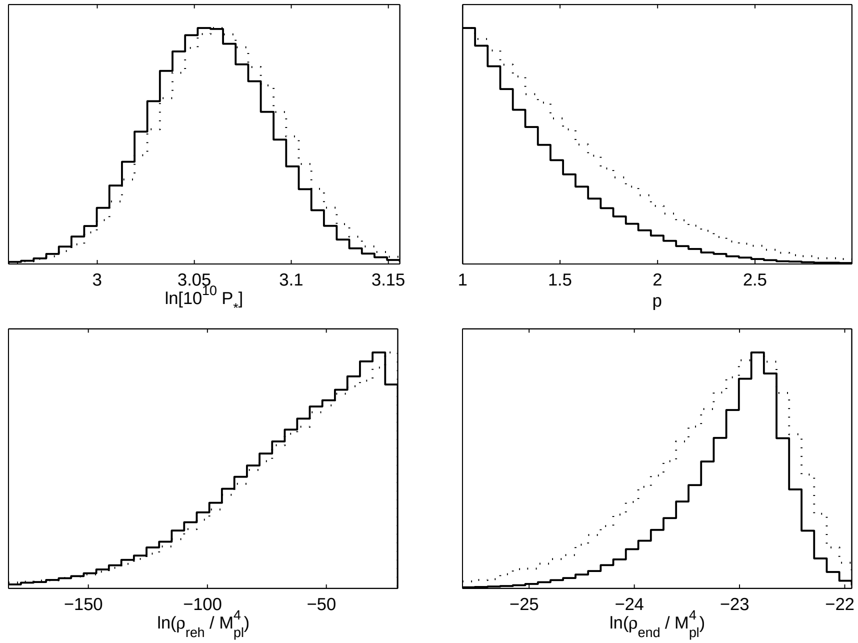


- A more consistent data analysis needs the exact $P(k)$ in $V(\phi) = M^4\phi^p$ + marginalisation

Large field reheating with WMAP7

- Bayesian marginalisation over cosmological parameters





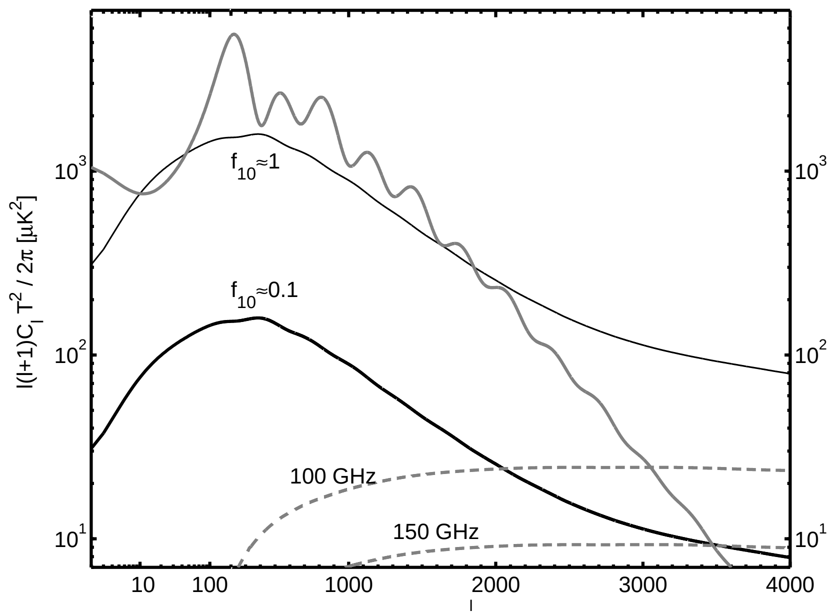
- Two-sigma confidence intervals

$$p < 2.2, \quad \rho_{\mathrm{reh}}^{1/4} > 17.3\,\mathrm{TeV}, \quad 4.4\times10^{15}\,\mathrm{GeV} < \rho_{\mathrm{end}}^{1/4} < 1.2\times10^{16}\,\mathrm{GeV}$$

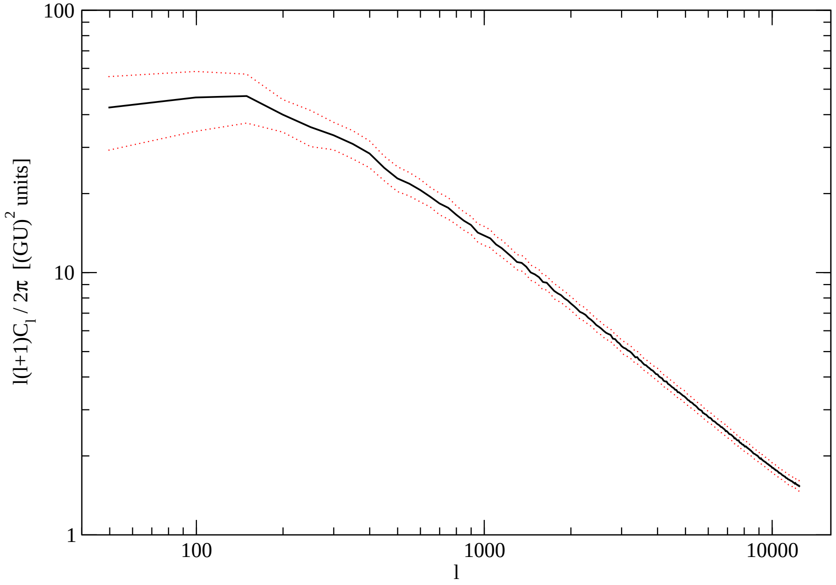
- Not fantastic, but will improve with PLANCK!

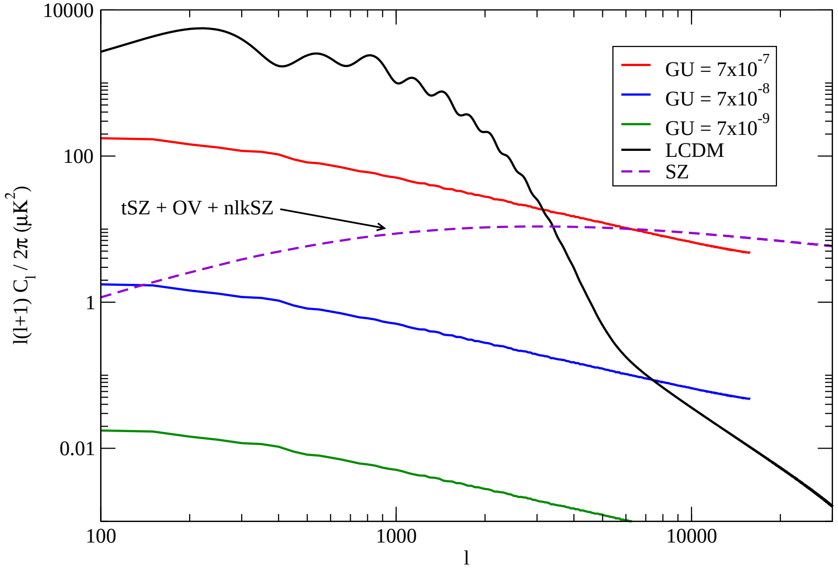
Cosmic strings

- Line-like vacuum energy
  - Topological defects formed during phase transitions $\mathcal{G} \to \mathcal{H}$ with $\pi_1(\mathcal{G}/\mathcal{H}) \neq 1$
  - In brane inflation, can be superstrings
- One parameter only U: the energy density per unit length (SSB scale)
- Should still be present today: at most 10% in WMAP [Bevis 10]



- Angular power spectrum dominates the large multipoles





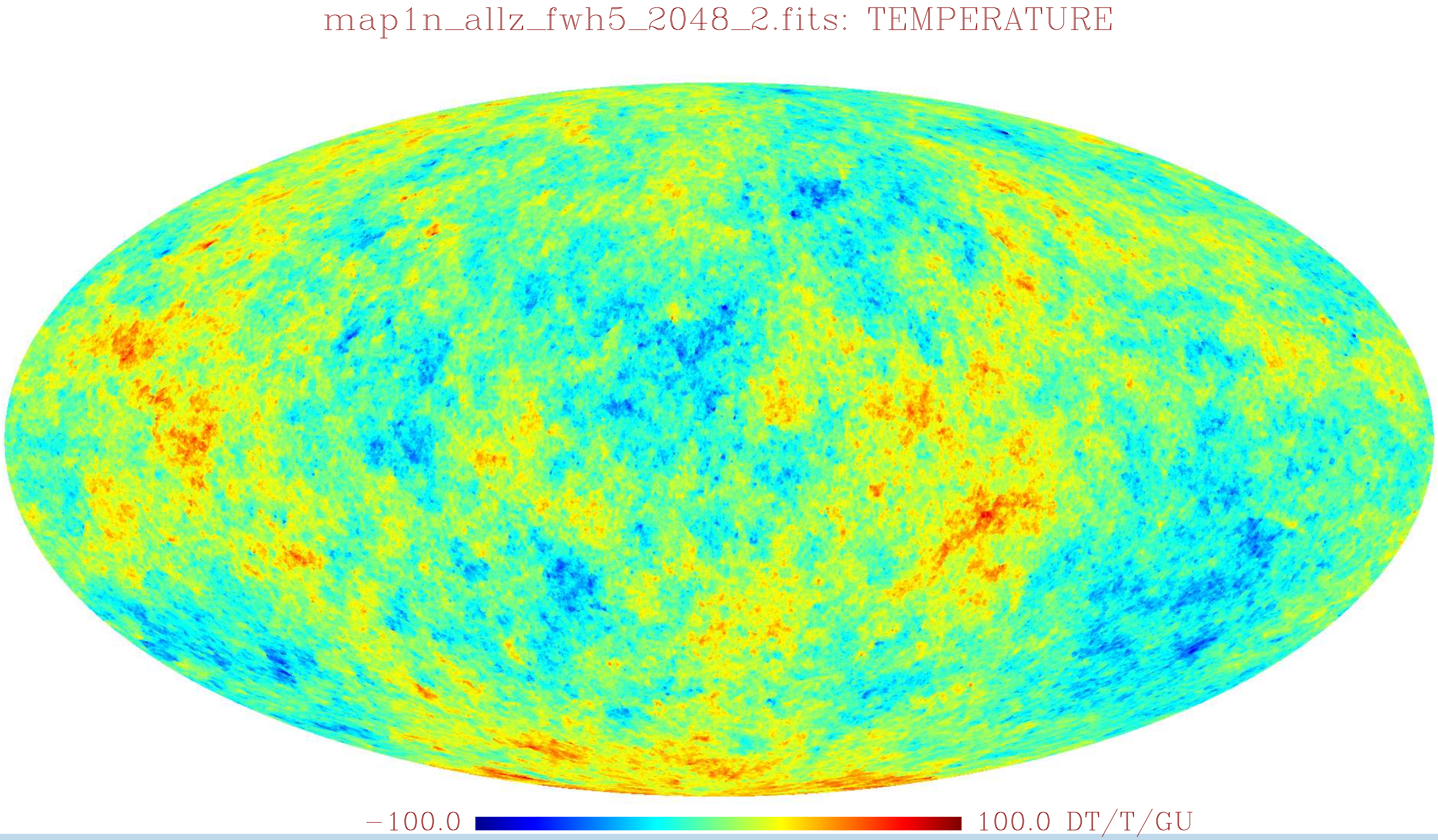
- Amplitude: $\ell(\ell+1)\,C_\ell/(2\pi) \simeq 14\,(GU)^2$

- Power law behaviour at small scales

$$\ell(\ell+1)\,C_\ell \underset{\ell \gg 1}{\propto} \ell^{-p} \quad \text{with} \quad p = 0.889^{+0.001}_{-0.090}$$

Source of Non-Gaussianities

- Analytical prediction for bi-and tri-spectrum [Hindmarsh 09a, Hindmarsh 09b, Regan 09]
- Simulated full sky map from NG string simulations (for PLANCK)



Conclusion

- CMB physics is at eV energy (recombination) + gravity. But:
  - Weights the whole universe, radiation included
  - Propagated during billion years: could have intercepted unexpected objects
  - IC $\Leftrightarrow$ primordial spectra are by nature at very high energy
- Remember that everything is degenerated!
  - Anything added calls for new data analysis with all unknown parameters free

Model [all are +SZ+LENS]	WMAP7	WMAP7+													
		WMAP7.2	BAO+ H0	BAO+ SNSALT	SNCONST	BAO+ SNCONST	BAO+ H0+ TDEL	LRG+ H0	LRG+ H0+ SNCONST	LRG+ H0+ CMB	CMB	BAO	LRG	H0	WMAP7.2+ H0
ΛCDM	●		●	◆							●	●	●	●	
ΛCDM+DELZ	●														
ΛCDM+RUN	●		●			◆					●				
ΛCDM+TENS	●		●	◆		◆					●				
ΛCDM+RUN+TENS	●		●												
ΛCDM+ISO1	●		●			◆									
ΛCDM+ISO2	●		●			◆									
ΛCDM+MNU	●	▲	●			◆		●	◆						▲
ΛCDM+YHE	●							●		●					
WCDM+MNU	●		●			●		●	●						
ΛCDM+NREL	●	▲	●					●	◆						▲
ΛCDM+NREL>3	◆		◆					◆							
OΛCDM	●		●	◆		◆									
WCDM	●	▲	◆		●	◆	●								▲
OWCDM	●		◆			●	●								