Le modèle cosmologique avec et après Planck et questions ouvertes

Avec les contributions de J. Martin, S. Renaux-Petel, S. Clesse, C. Caprini
Correspondence to
from the early mission to Trapani

The spectacular results of Boomerang and Maxima have
provided a first constraint on the geometry of the
Universe (Lineweaver
Netterfield
Hanany
and using the Archeops and Cobe data only, we find
and from the other experiments. Moreover, the data from
reionization, respectively. The predictions of inflationa
tistic peak, are in agreement with the results from Archeops
spectrum at large angular scales followed by a first acous-
tics with other cosmological measurements (such as
3. Model grid and likelihood method

Une petite perspective historique :
Archeops 2002
Figure 2: Top CMB angular power spectra determinations as of mid-2015 (Modified from Planck Collaboration et al. (2015g) thanks to E. Calabrese). This corresponds to the determination (with $S/N > 1$) of 114,000 modes measured with TT, 96,000 with EE (60,000 with TE, not shown), and tens of modes in BB (and weak constraints on TB and EB).

Bottom Lensing potential power spectrum measurement from Planck (Planck Collaboration et al. 2015f), as well as earlier measurements. The goal for the future is now to measure the million polarisation modes which are still unknown.
INTRODUCTION

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French roadmap for CMB science 30/06/2016

First measure of full sky CMB lensing
The early Universe physics and the origin of the Large-Scale structure of the Universe after Planck

- Everything is consistent with inflation, that is with the fact that the LSS emerged out of early metric perturbations.

- Physics in the early Universe is non trivial ("dynamical") since deviation from scale invariance has been unambiguously detected.

- Inflation seems to be realized in its simplest incarnation (single slow roll field) although a large fractions of the models are disfavored.
The simplest models of inflation make several key predictions:

✓ Universe spatially flat
✓ Phase coherence of Doppler peaks/adiabatic modes
✓ Almost Gaussian perturbations
✓ Almost scale invariant power spectrum

- Background of quantum gravitational waves: only upper limit on $r$
- Consistency check between $n_T$ and $r$: not feasible (in foreseeable future)
The Planck 2015 data constraints are shown with the red and blue contours. Steeper models with $V \sim \phi^3$ or $V \sim \phi^2$ appear ruled out, whereas $R^2$, à la Starobinsky, inflation looks quite attractive.
Questions that we would like to be ideally addressed by next generations of CMB missions comprise,

- Find a way to validate the general paradigm, i.e. to show that metric fluctuations have been generated from quantum field fluctuations of scalar and tensorial degrees of freedom; determine the energy scale of inflaton; better characterize its potential - its shape and the various degrees of freedom at play - during the inflationary phase;

- Explore the thermal history of the universe from the end of inflation to recombination to better characterize inflationary models, explore the stability of dark matter, find exotic phenomena;

- Assess the matter/energy content of universe with better precision (a still missing part is the mass of the neutrinos).
1. What is to be learnt from $r$?

$r$ determines the absolute value energy density during inflation

$$V^{1/4} \approx 10^{16} \text{ GeV} \left( \frac{r_*}{0.01} \right)^{1/4}$$

$r < 0.07$ (Planck 2015+Bicep2) with a potential factor 2 improvement expected with better control of the systematics

- no theoretical useful lower bound for $r$
- a weak upper bound to avoid large excursions of inflaton vev value

$$\frac{\Delta \phi}{M_{pl}} = N_e \left( \frac{r}{8} \right)^{1/2}$$

* A value of $r$ below the 0.001 range would put effective models on a safe ground.

- complementary to the scalar spectral index for constraining models

$$n_s(k) - 1 = \frac{d \log P_\zeta(k)}{d \log k}$$
Figure 2: Existing and expected constraints on $n_S$ and $r$. The orange and yellow contours show the 68% and 95% confidence regions expected from the baseline configuration of $COrE+$. The possibility to improve the error bars by delensing is not included in this forecast. The fiducial model is the Starobinsky $R^2$ model [7]. The blue and cyan contours show the Planck 2013 constraints, while the gray contours show the WMAP 9-year constraints. The symbols show predictions of a few other well known inflationary models. The violet, yellow, and red regions show vacuum-dominated convex potentials ($V'' > 0$), convex potentials vanishing at their minimum, and concave potentials ($V'' < 0$; hilltop or plateau inflation), respectively.
2. spectral distortions: a new window?

\[ \mu(z) = 1.4 \int_{z}^{z_{dC}} \frac{d(Q/\rho_{\gamma})}{dz'} e^{-\tau_{dC}(z')} \]

**FIG. 8.** This plot shows the spectral shapes (normalized at the maximum) \(I(\nu)\) for \(\mu-, y-\) and \(t\)-type distortions, together with the spectra for \(i\)-type distortions at redshifts \(z = \mathcal{O}(2 \times 10^5), z = \mathcal{O}(1 \times 10^5)\) and \(z = \mathcal{O}(5 \times 10^4)\). We see that for increasing redshift, the maximum, minimum and zero of the occupation numbers are moved towards lower frequencies.
Spectral distortions from annihilating particles

For such processes the distortion has a fixed shape (but neither of ν- or of μ types) and only the overall amplitude changes, depending on the annihilation efficiency, $f_{\text{ann}}$.

Figure 6: Constraints on the yield parameter as a function of the particle lifetime for decaying particles. What is computed is the required value of $Y_X$ for which a 1 $\sigma$-detection of the corresponding variable is possible with PIXIE. The violet shaded area is excluded by measurements of the primordial 3 He/D abundance ratio (1 $\sigma$ level, adapted from Kawasaki et al. 2005). From Chluba & Jeong (2014).
3. lensing measurements, towards a precise determination of the mass of the neutrinos

![Diagram showing the signal to noise ratio for the determination of the lensing potential power spectra.](image)

**Figure 5.** The signal to noise ratio for the determination of the lensing potential power spectra. The Core+ concept allows to dramatically extend the range of modes for which it can be accurately measured.

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a dramatic improvement compared to Planck
On the phenomenology side, next generations of CMB missions can provide

- A genuine chance to determine the absolute energy scale of inflation with the detection of $r$;
- A unique discovery potential with the exploration of the spectral distortions of the CMB;
- A capacity of getting the better precision on the fundamental cosmological parameters such as
  - values of $n_s$ and its running (from polarization E-mode power spectrum)
  - mass of the neutrinos from lensing reconstruction
On the theory side

- Identification of the most relevant models of inflation with the current datasets and futures surveys with novel constraints on $r$ and spectral distortions but also one may need to revisit calculations in complex settings (Higgs inflation, geometrical destabilization, etc.);

- the end of inflation and importance of the (p)reating mechanisms; limitations of the current constraints based on global parameterized shape of the inflaton potential, gravitational wave production of the end of inflation;

- Stability of dark matter/baryogenesis/(sterile) neutrinos/axion mass/… from spectral distortions?

- Gravitational lensing effects and complementarity with LSST/Euclid type missions (impact of the existence of an extra source plane on data analysis and parameter constraints);
Generic models in high-energy physics have several fields, which live in an internal space with curved geometry.

Initially neighboring geodesic tend to fall away from each other in the presence of negative curvature (very common).

This effect applies during inflation, and easily overcomes the effect of the potential, destabilizing inflationary trajectories.

Generic trend of prematurely ending inflation:

- smaller amplitude of GWs
- closer to scale invariance

Destabilization of inflation despite steep walls from the potential

Observational status of models are reshuffled

**The geometrical destabilization of inflation**

Renaux-Petel and Turzynski, PRL 2016
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A multi-messenger approach and model construction: generation of gravitational waves

![Graph of gravitational wave energy density vs. temperature and frequency]

- **Indirect**: Theoretical upper limit
- **LIGO/Virgo**: Upper limit from direct detection
- **aLIGO**: Advanced LIGO sensitivity
- **PTA**: Pulsar Timing Array sensitivity
- **CMB**: Cosmological Microwave Background

The graph shows the energy density of gravitational waves ($\Omega_{gw}(f)$) as a function of frequency ($f$) and temperature ($T$) in the low-frequency regime. The curves represent different constraints and sensitivities from various experiments, highlighting the range of possible gravitational wave backgrounds that can be detected or ruled out.
Ondes gravitationnelles : une sonde unique sur l’univers primordial, \( T_{\text{reh}} \geq T > T_{\text{BBN}} \)

C. Caprini, APC

- La détection d’un *fond stochastique d’Ondes Gravitationnelles* nous permettrait de :
  - sonder des modèles d’inflation non-standard: *tester l’index spectral du fond d’OG* 10-20 ordres de grandeurs au delà des échelles du CMB (PTA, LISA, LIGO)
  - *tester les interactions et le potentiel de l’inflaton* (reheating) (LIGO?)
  - *tester la présence de brisures de symétrie fondamentales (défauts topologiques)* (PTA, LISA, LIGO)
  - *tester des possibles solutions au problème de la hiérarchie* (LISA), transitions de phase de premier ordre liées à la présence de dimensions supplémentaires
  - *tester des modèles au delà du modèle standard et la baryogénèse* (LISA), transition de phase électrofaible de première ordre
  - *tester la QCDPT à nombre baryonique différent de zéro* (PTA), transition de phase QCD de première ordre
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Conclusions / perspectives

CMB is (still) our best chance to explore the physics of the early universe
- constraints on \( r \);
- enormous discovery potential with spectral distortions;
Other probes such as GW can be complementary to such observations

French theory community is active on
- first principle calculations (S. Renaux-Petel, J. Martin, )
- model constructions with GW (Caprini, …)
- alternatives to standard picture (Peter, Rovelli)
- strong connexion with Dark Energy theory community (Martin, Brax, Vernizzi, Deffayet, Esposito-Farèse, Blanchet, Charmousis, Polarski, etc.)