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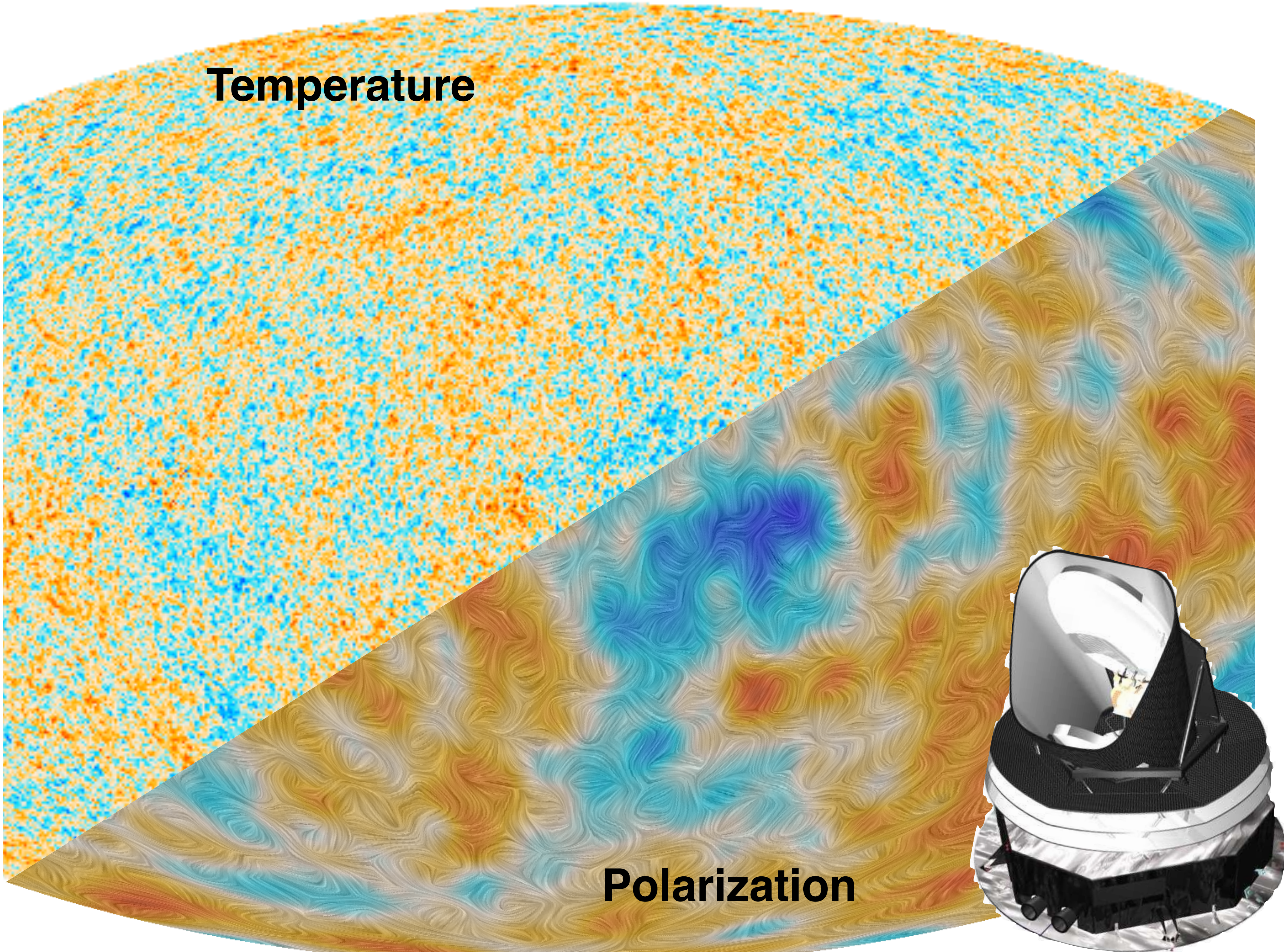
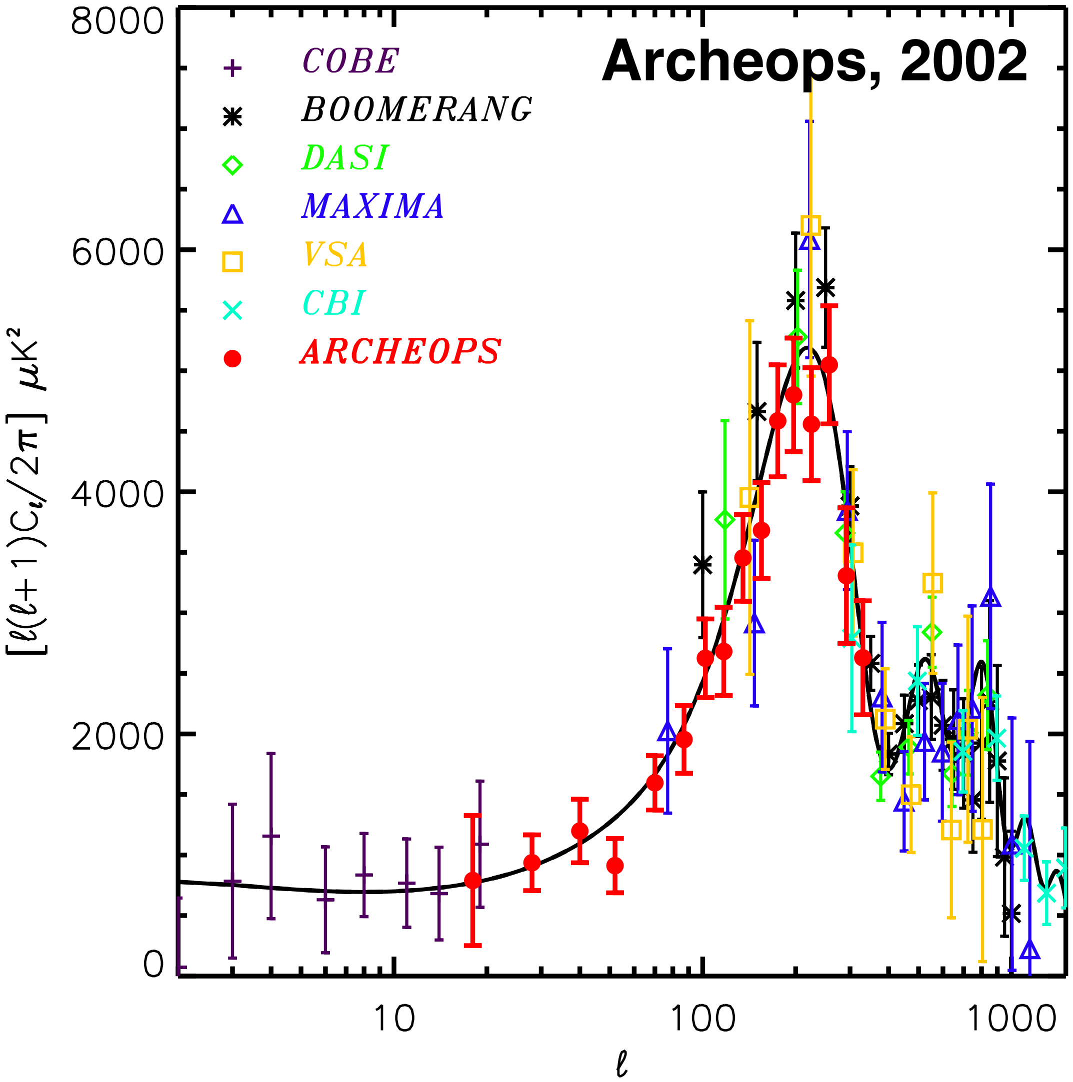
PROGRAMME NATIONAL DE COSMOLOGIE ET GALAXIES

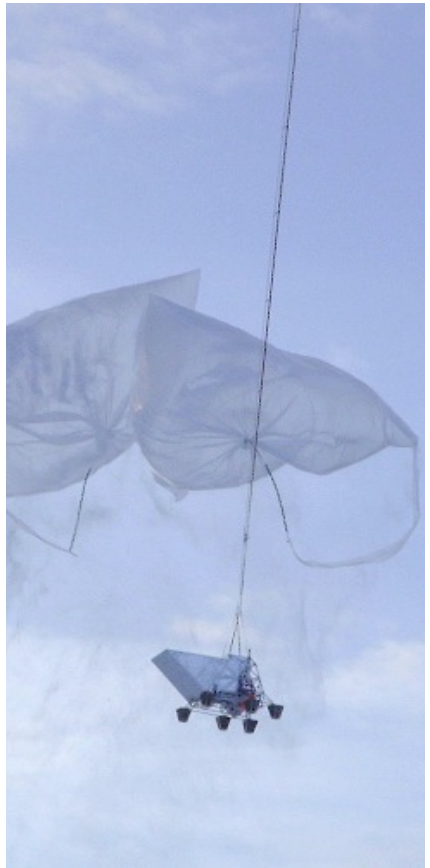
Le modèle cosmologique avec et après Planck et questions ouvertes

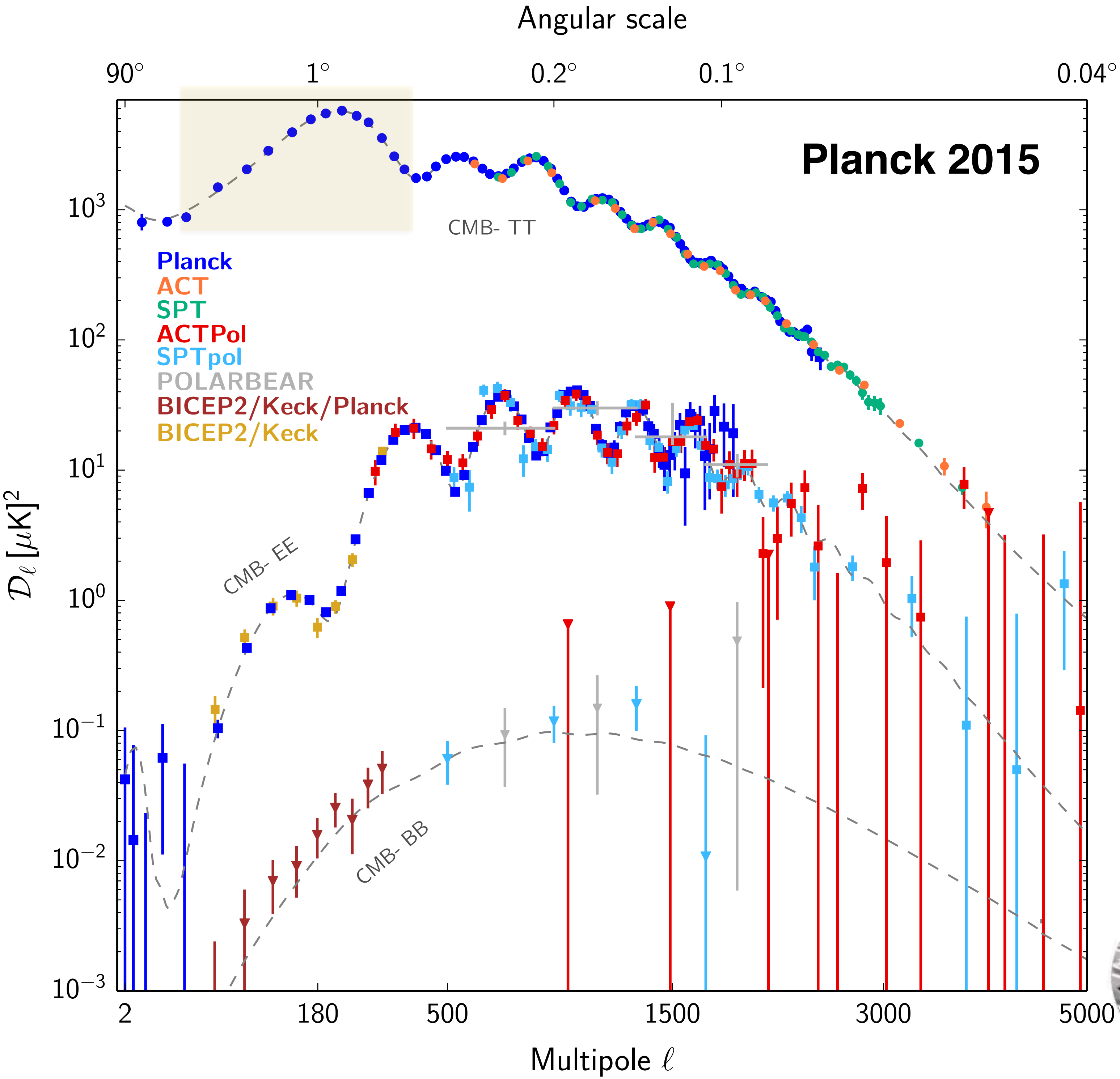
Avec les contributions de J. Martin, S. Renaux-Petel, S. Clesse, C. Caprini

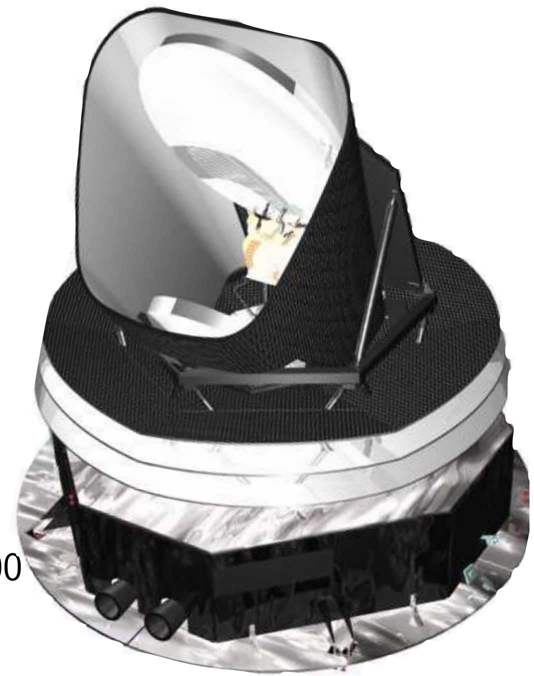

Temperature
Polarization



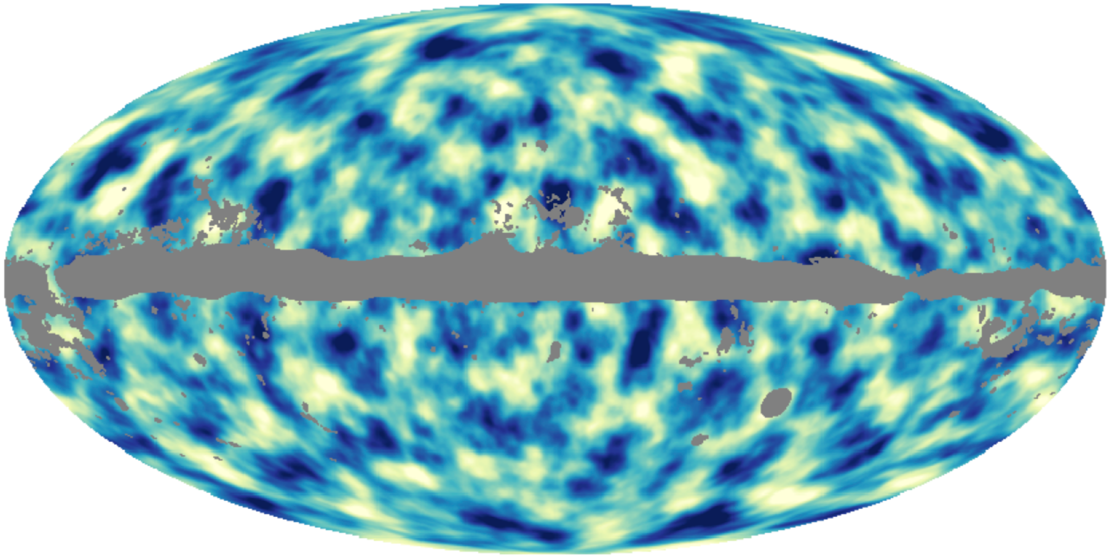
Une petite perspective historique :
Archeops 2002

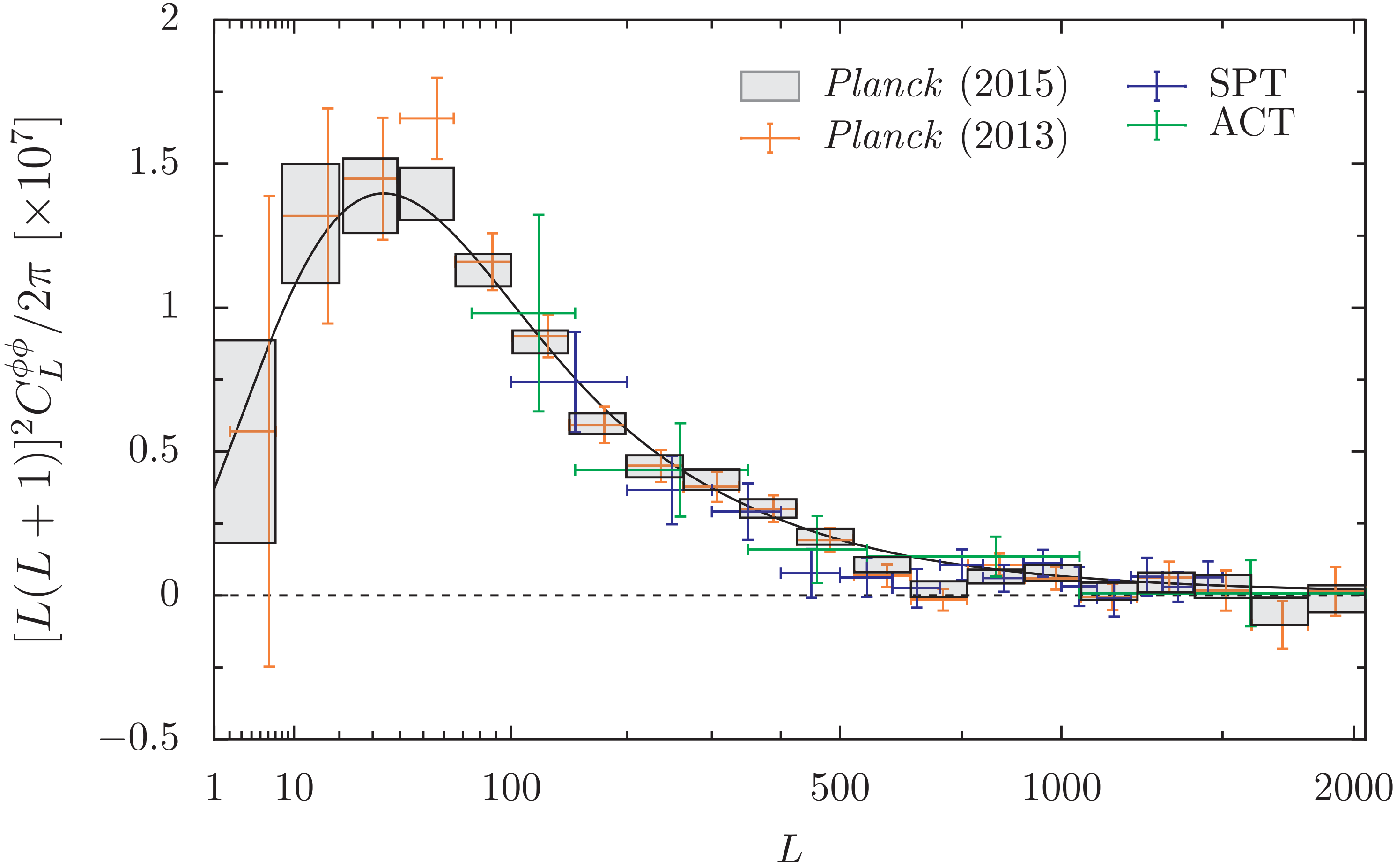


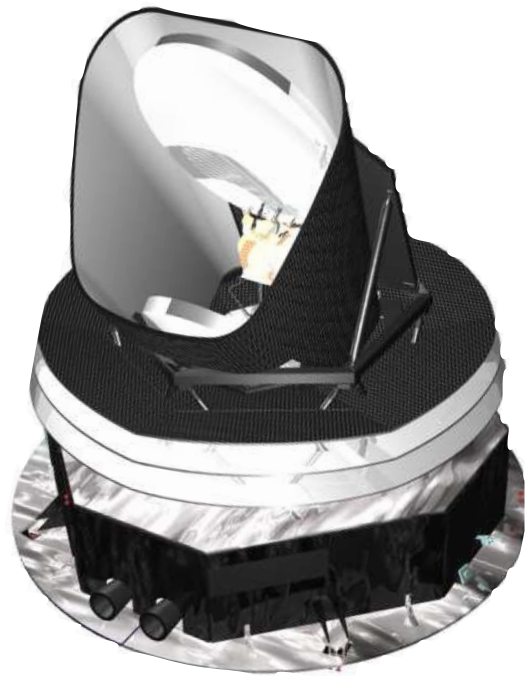

Angular scale
90°
1°
0.2°
0.1°
0.04°
Planck 2015
CMB- TT
CMB- EE
CMB- BB
Planck
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck/Planck
BICEP2/Keck
$\mathcal{D}_\ell$ [μK]^2
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
2
180
500
1500
3000
5000
Multipole ℓ



First measure of full sky CMB lensing





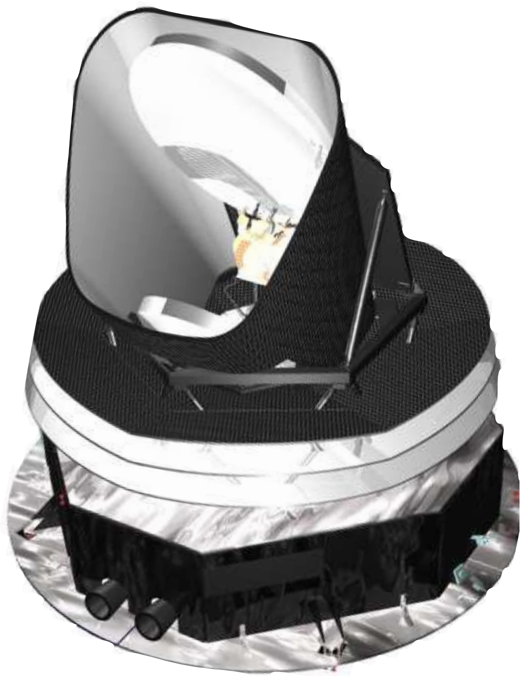


The early Universe physics and the origin of the Large-Scale structure of the Universe after Planck

➡ 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

$$\Omega_{\mathcal{K}} = -0.040^{+0.038}_{-0.041}$$

✓ Phase coherence of Doppler peaks/ adiabatic modes

$$\alpha^{(2,2500)}_{\mathcal{RR}} \in [0.985, 0.999]$$

✓ Almost Gaussian perturbations

$$f_{\mathrm{NL}}^{\mathrm{loc}} = 0.8 \pm 5$$

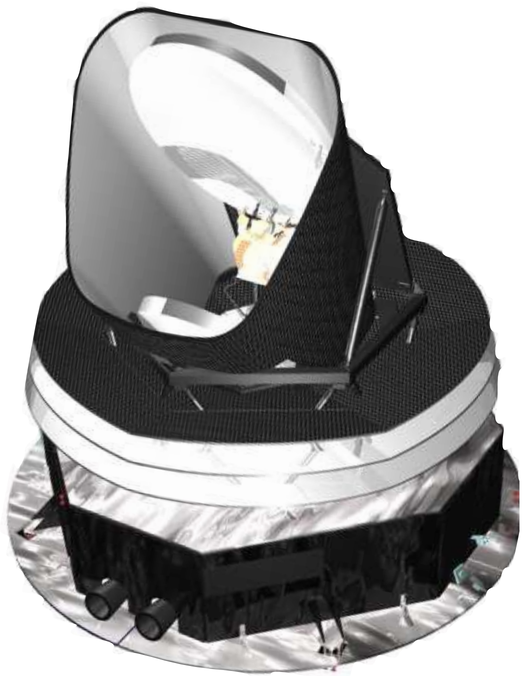
$$f_{\mathrm{NL}}^{\mathrm{eq}} = -4 \pm 43$$

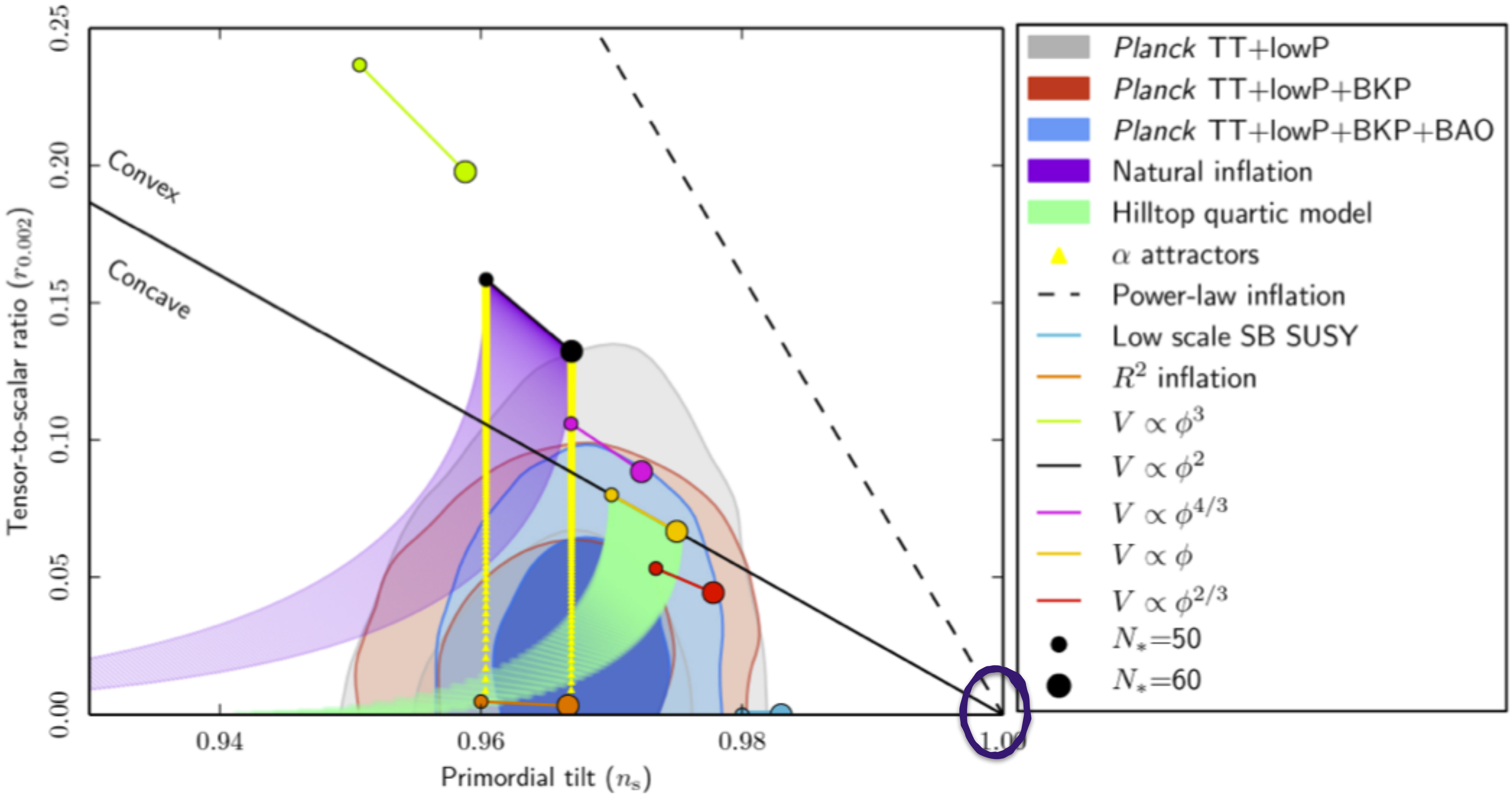
✓ Almost scale invariant power spectrum

$$n_{\mathrm{S}} = 0.9645 \pm 0.0049$$

- 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.

Beyond Planck: the « key »questions

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

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

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

$$n_s(k) - 1 = \frac{\mathrm{d}\log \mathrm{P}_\zeta(\mathrm{k})}{\mathrm{d}\log \mathrm{k}}$$

Constraining specific models for r and ns

However models can be found everywhere…

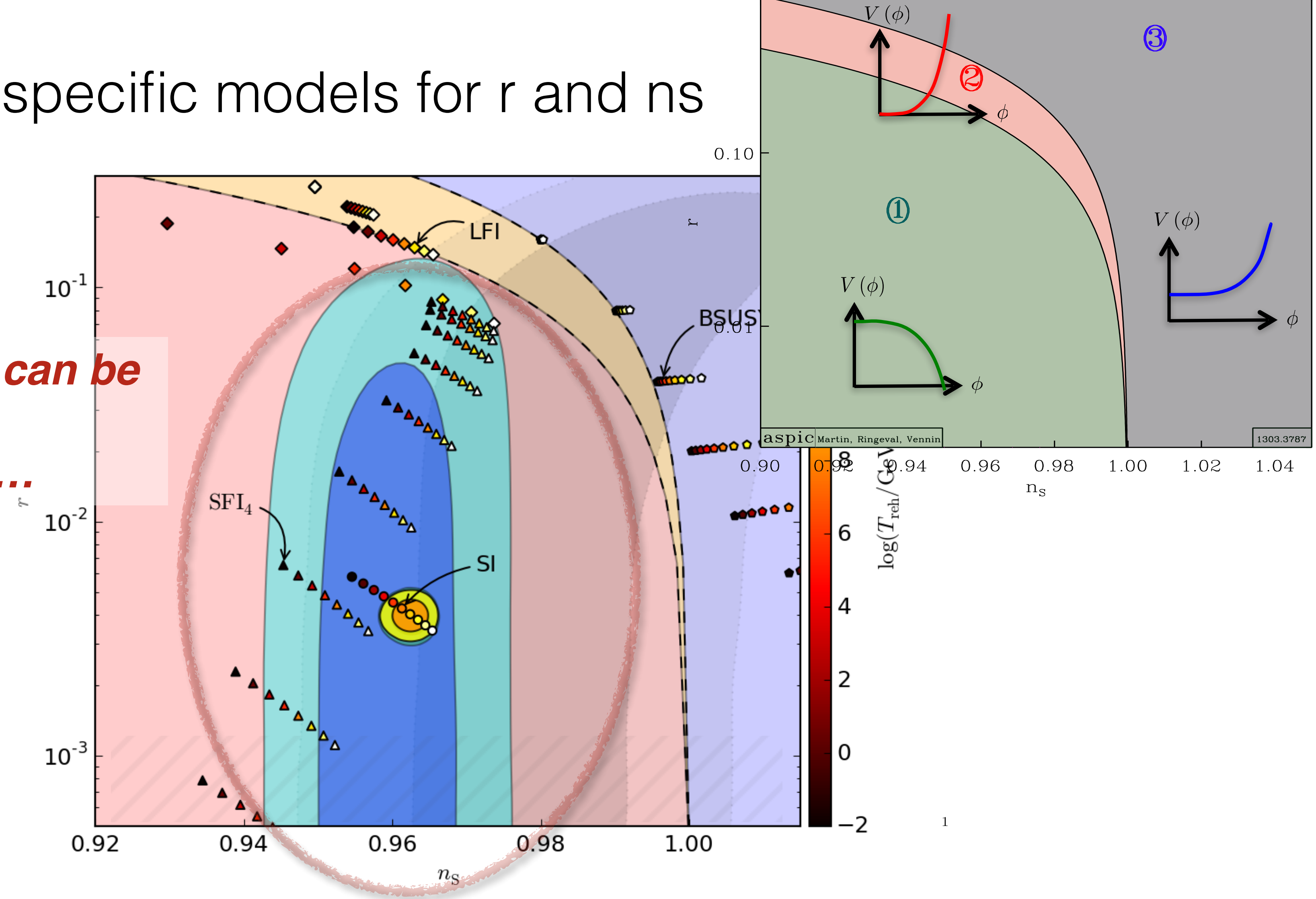


Figure 2: **Existing and expected constraints on n_S and r.** The orange and yellow contours show the 68% and 95% confidence regions expected from the baseline configuration of *COrE+*. The possibility to improve the error bars by delensing is not included in this forecast. The fiducial model is the 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 distorsions: a new window ?

$$\mu(z) = 1.4 \int_z^{z_{\rm dC}} {\rm d}z' \, \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'} e^{-\tau_{\rm dC}(z')}$$

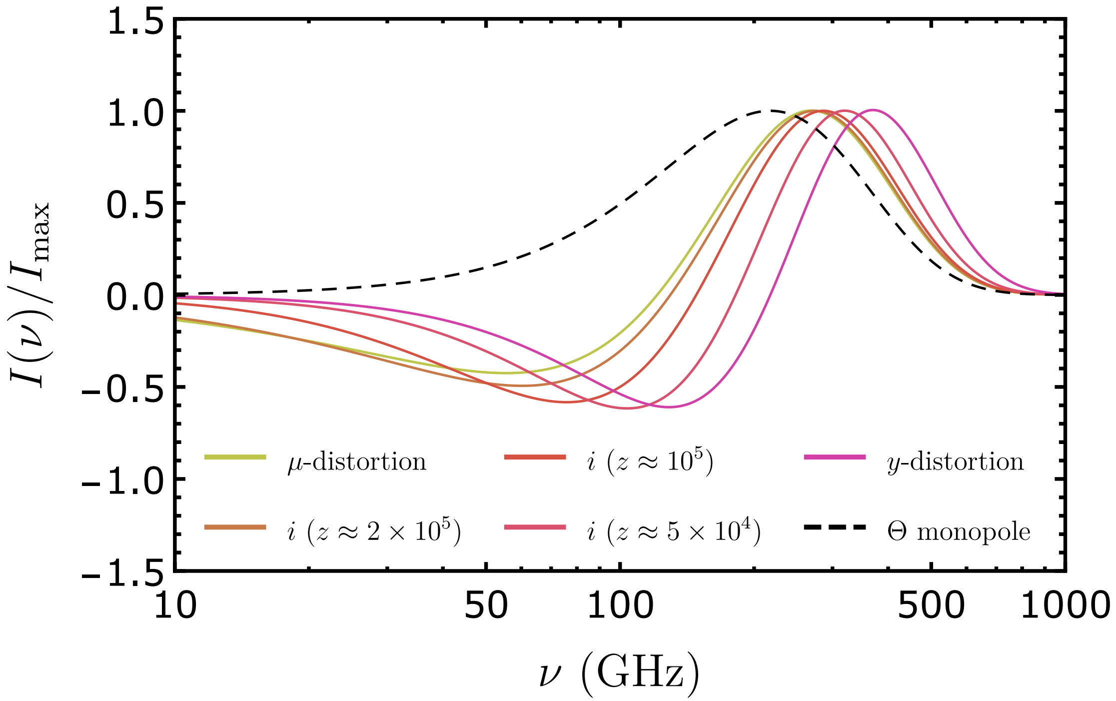
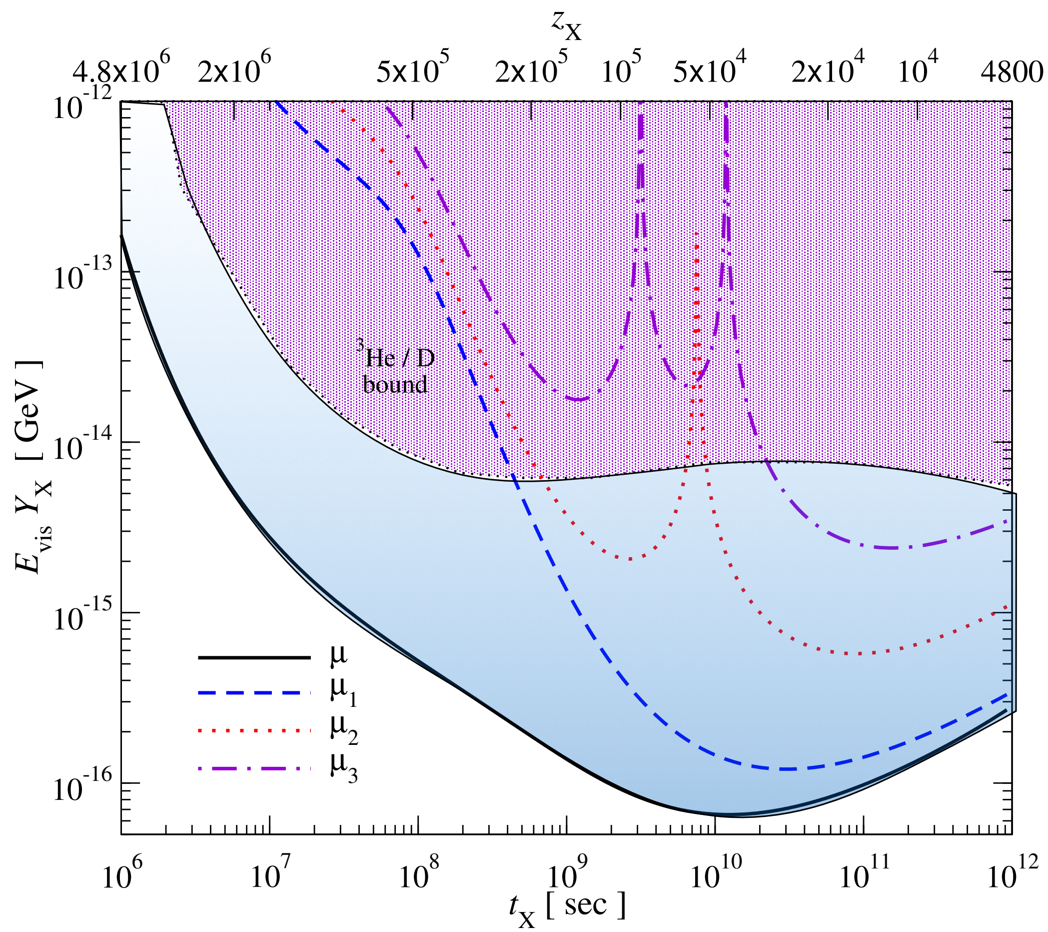


FIG. 8. This plot shows the spectral shapes (normalized at the maximum) $I(\nu)$ for μ-, y- and t-type distortions, together with the spectra for i-type distortions at redshifts $z = \mathcal{O}(2 \times 10^5)$, $z = \mathcal{O}(1 \times 10^5)$ and $z = \mathcal{O}(5 \times 10^4)$. We see that for increasing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

Spectral distorsions from annihilating particles

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



large new discovery window

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 σ-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

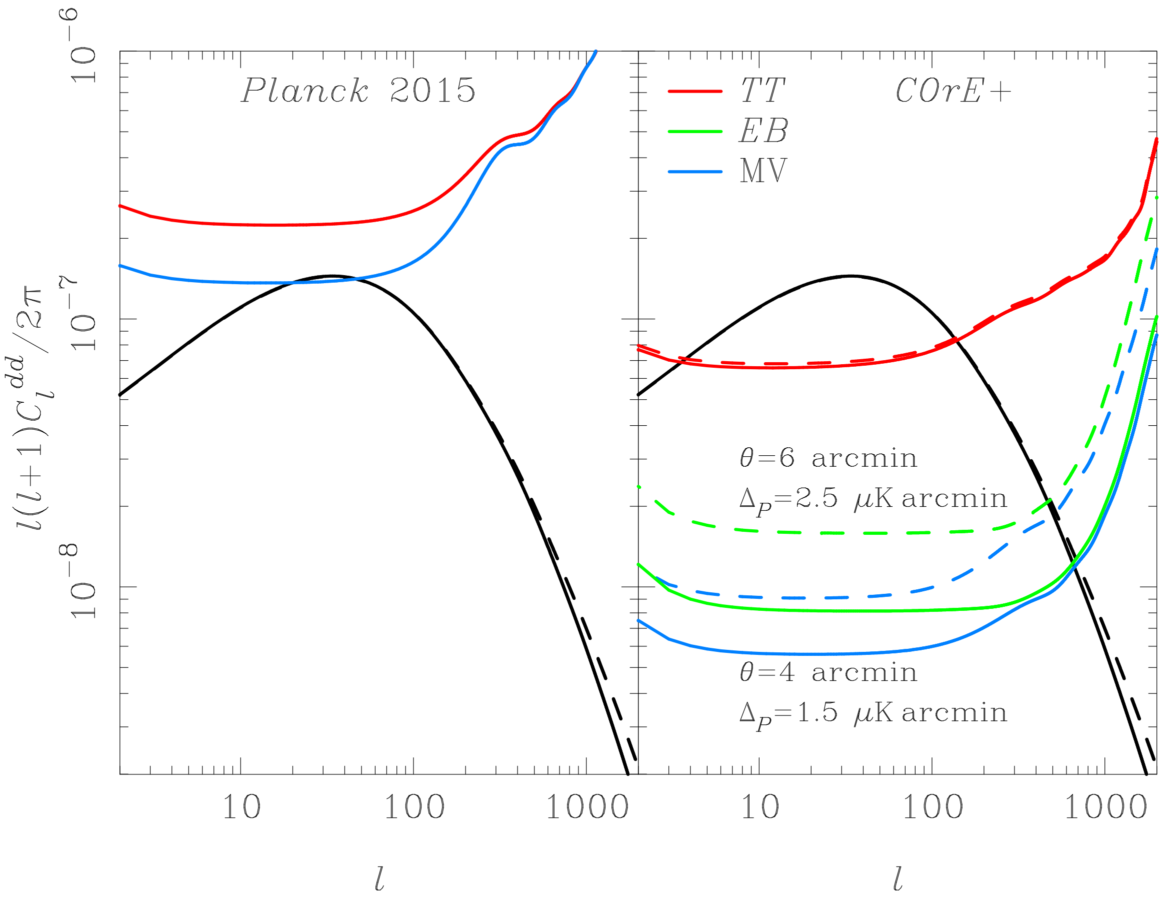


FIGURE 5. The signal to noise ratio for the determination of the lensing potential power spectra. The Core+ concept allows to dramatically extend the range of modes for which it can be accurately measured.

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 distorsions of the CMB;
- A capacity of getting the better precision on the fundamental cosmological parameters such as
  - values of ns 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 ;

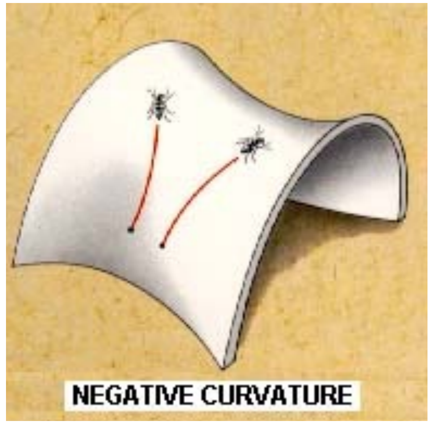
- Stability of dark matter/baryogenesis/(sterile) neutrinos/axion mass/… from spectral distortions ?

- 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) ;

The geometrical destabilization of inflation

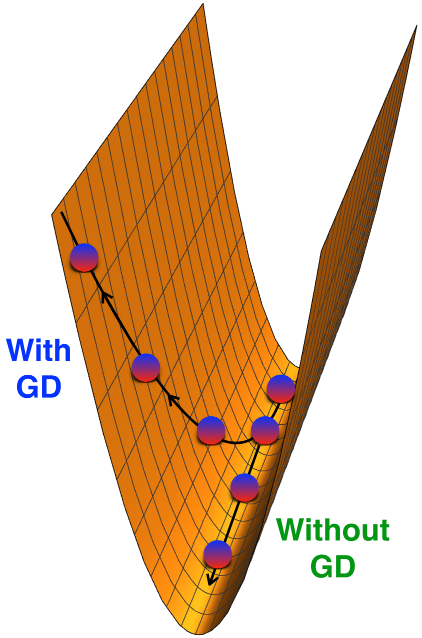
Renaux-Petel and Turzynski, PRL 2016

Generic models in high-energy physics have several fields, which live in an internal space with curved geometry.



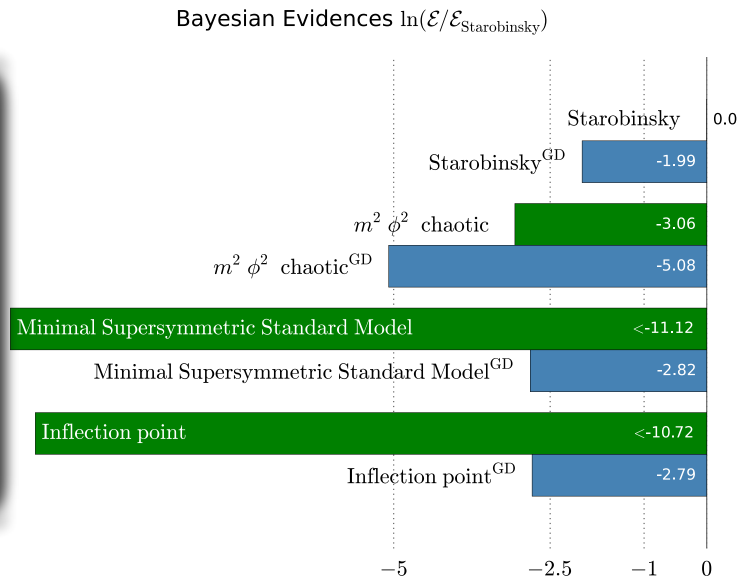
Initially neighboring geodesic tend to fall away from each other in the presence of negative curvature (very common)

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

On the theory side

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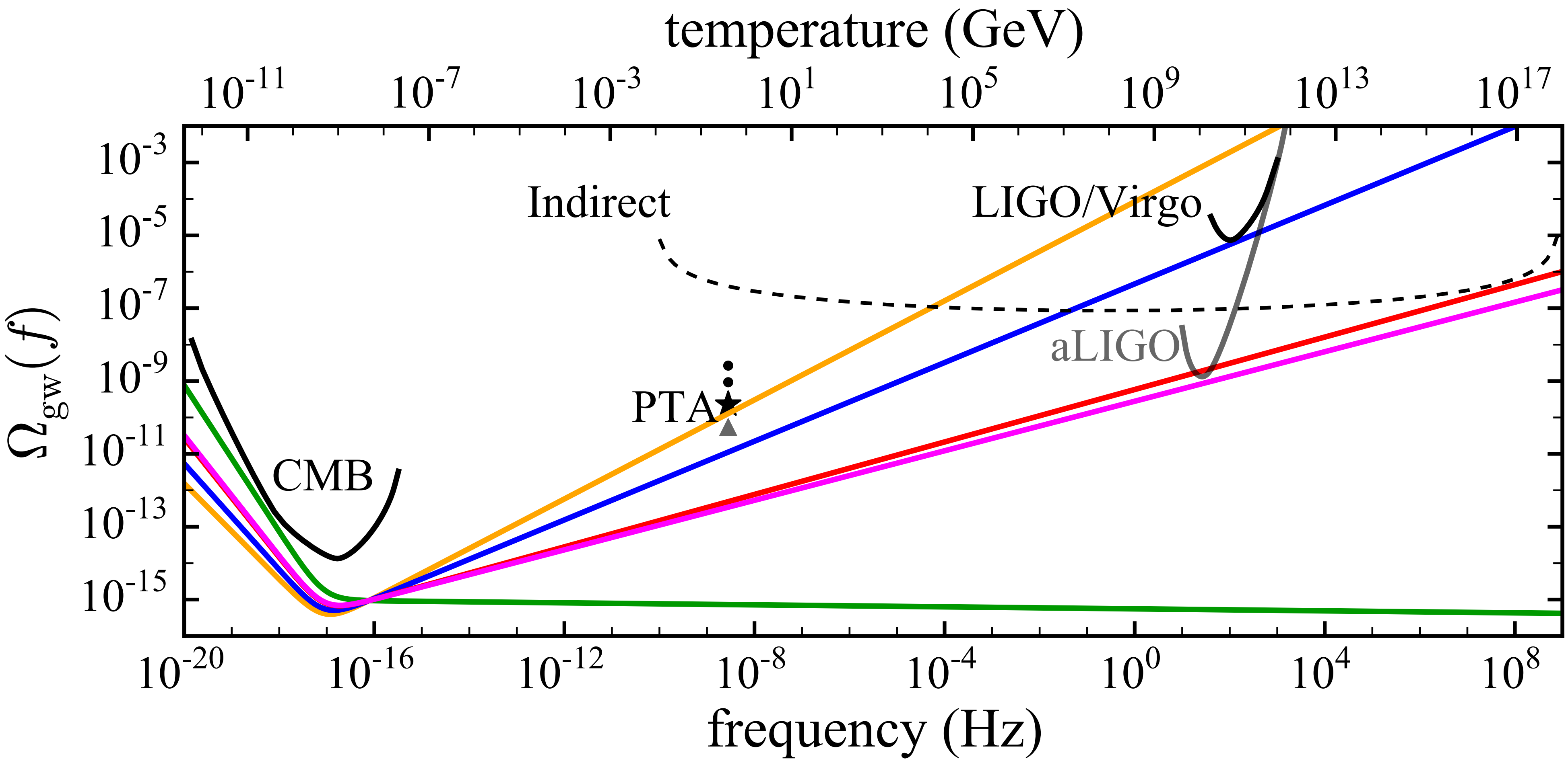
A multi-messenger approach and model construction : generation of gravitational waves



Ondes gravitationnelles : une sondes unique sur l'univers primordial, $T_{\rm reh} \geq T > T_{\rm BBN}$

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 éléctrofaible de première ordre
  - *tester la QCDPT à nombre baryonique différent de zéro* (PTA), transition de phase QCD de première ordre

On the theory side

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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 distorsions ;

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.)**