# CMB, gravitational waves and inflation in the Universe

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Inflation as a self consistent model
of the very early universe

# Inflation in the early Universe

- Inflation (Brout et al. 1978; Starobinski 1980; Kazanas 1980; Sato 1981; Guth 1981; Linde 1982, Albrecht & Steinhardt 1982; etc. ...) is an epoch of accelerated expansion in the early Universe ( ~ $10^{-34}$ s after the "Big Bang") which allows to solve two inconsistencies of the standard Big Bang model.
  - ***horizon****: why is the Universe so homogeneous and isotropic on average?*
  - ***flatness****: why is the Universe spatial curvature so small even ~ 14 billion years after the Big Bang?)*
- Inflation is based upon the idea that the **vacuum energy** of a scalar quantum field, dubbed the "inflaton", dominates over other forms of energy, hence giving rise to a quasi-exponential (de Sitter) expansion, with scale-factor

$$a(t) \approx \exp(Ht)$$

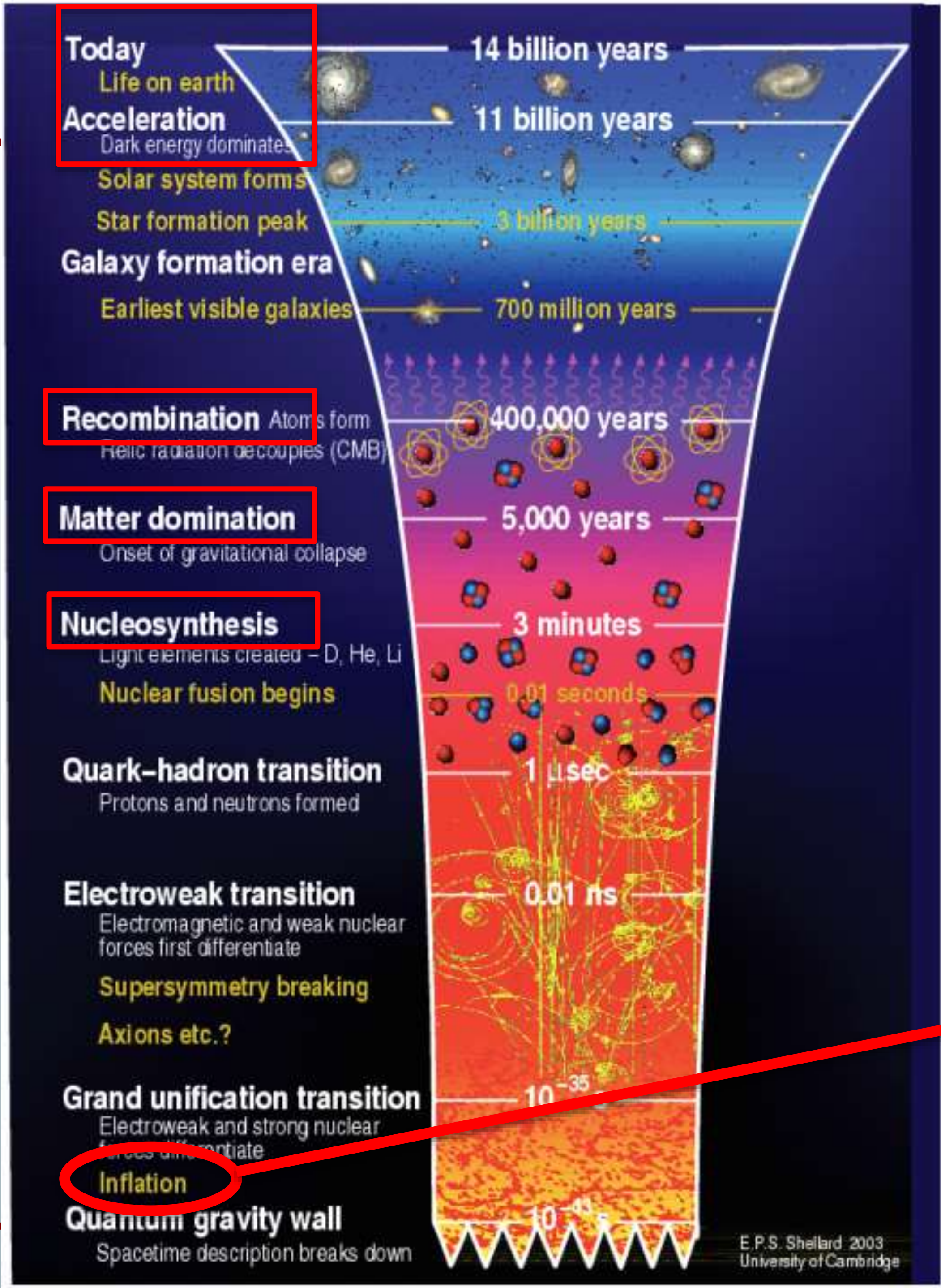
# Inflation in the Universe

Alan Guth


Andrei Linde

- "The theory of cosmic inflation, proposed and developed by Alan Guth, Andrei Linde and Alexei Starobinsky, has revolutionized our thinking about the universe. This theory extends our physical description of the cosmos to the earliest times, when the universe was only a tiny fraction of a second old. According to this theory, very soon after our universe came into existence it underwent a short-lived phase of exponential expansion. During this brief period the universe expanded by a huge factor – hence the name inflation. The consequences of this episode were momentous for the evolution of the cosmos. Without inflation, the Big Bang theory – a great achievement of 20th century science – is incomplete. ..."

Alexei Starobinsky




**We are here**

$Z_{rec}$~1100

$Z_{eq}$~3500

T~1 MeV

**We seek information about very early times and very high energies E~$10^{16}$ GeV**

***... did we get it?***

# Inflation predictions

✓ <u>Cosmological aspects</u>

- *Critical density Universe*
- *Almost scale-invariant and nearly Gaussian, adiabatic density fluctuations*
- *Almost scale-invariant stochastic background of relic gravitational waves*

✓ <u>Particle physics aspects</u>

- *Nature of the inflaton*
- *Inflation energy scale*

Inflation is the generator of

cosmological perturbations that give rise to

CMB anisotropies and LSS formation

# Inflation predictions

- Quantum vacuum oscillations of the inflaton (or other scalar fields) give rise to classical fluctuations in the energy density, which provide the seeds for **Cosmic Microwave Background (CMB)** radiation temperature anisotropies and polarization, as well as for the formation of **Large Scale Structures (LSS)** in the present Universe.

- All the matter and radiation which we see today must have been generated after inflation (during "reheating"), since all previous forms of matter and radiation have been tremendously diluted by the accelerated expansion ("Cosmic no-hair conjecture").

Inflation is the generator of a stochastic background of gravitational waves that we could detect either directly or indirectly, thanks to the temperature anisotropies and B-mode polarization that they induce on the CMB

# Gravity-wave background from inflation

- As originally noticed by Starobinski (1979) an early period of quasi-de Sitter evolution leaves its imprint in terms of a low-amplitude **stochastic background of gravitational waves** (also: Grishchuck 1975, Rubakov et al. 1982, Fabbri & Pollock 1982, Abbott & Wise 1984; Lucchin & Matarrese 1985; ...) which originated from quantum vacuum fluctuations of (linearized) spin-2 gravitational perturbations (**gravitons**), left the horizon during inflation (remaining frozen and unobservable) and rentered the horizon recently, becoming potentially observable as classical tensor perturbations of space-time.
- The detection of this primordial gravitational-wave background would represent the "**smoking gun**" proof of the validity of the inflation paradigm, otherwise hard to "falsify".
- Other crucial imprints of inflation: existence of perturbations with a super-horizon seed (***detected!***), specific non-Gaussian signatures of primordial perturbations (***strongly constrained by Planck, which supports the simplest inflation models***).

# Inflation and the Inflaton

$$\mathcal{L}_\phi[\phi, g_{\mu\nu}] = \frac{1}{2} g^{\mu\nu} \phi_{,\mu} \phi_{,\nu} - V(\phi)$$

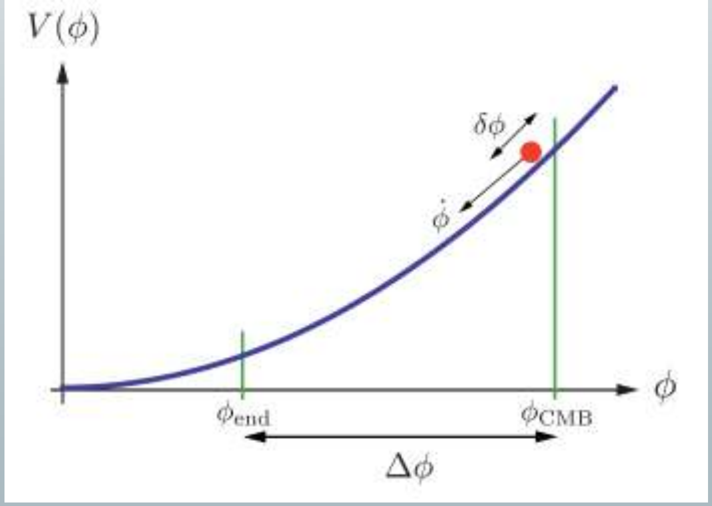
***Standard kinetic term***

***Inflaton potential:*** describes the self-interactions of the inflaton field and its interactions with the rest of the world

Think the inflaton mean field as a particle moving under a force induced by the potential V

Ex. (Piran & Williams 1985):

$$V(\phi) = \frac{m^2}{2} \phi^2$$



# Observational predictions of inflation

- **Primordial density (scalar) perturbations**

$$\mathcal{P}_\zeta(k) = \frac{16}{9}\frac{V^2}{M_{\rm Pl}^4\dot{\phi}^2}\left(\frac{k}{k_0}\right)^{n-1}$$

***amplitude***

***spectral index:*** $n-1 = 2\eta - 6\epsilon$
***(or ``tilt'')***

$$\epsilon = \frac{M_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \ll 1; \;\; \eta = \frac{M_{\rm Pl}^2}{8\pi}\left(\frac{V''}{V}\right) \ll 1$$

- **Primordial (tensor) gravitational waves**

$$\mathcal{P}_{\rm T}(k) = \frac{128}{3}\frac{V}{M_{\rm Pl}^4}\left(\frac{k}{k_0}\right)^{n_{\rm T}}$$

Tensor spectral index: $n_{\rm T} = -2\epsilon$

- **Tensor-to-scalar ratio**

$$r = \frac{\mathcal{P}_{\rm T}}{\mathcal{P}_\zeta} = 16\epsilon$$

- **Consistency relation** (valid for *all* single field slow-roll inflation, easily generalizable to non-canonical kinetic term)

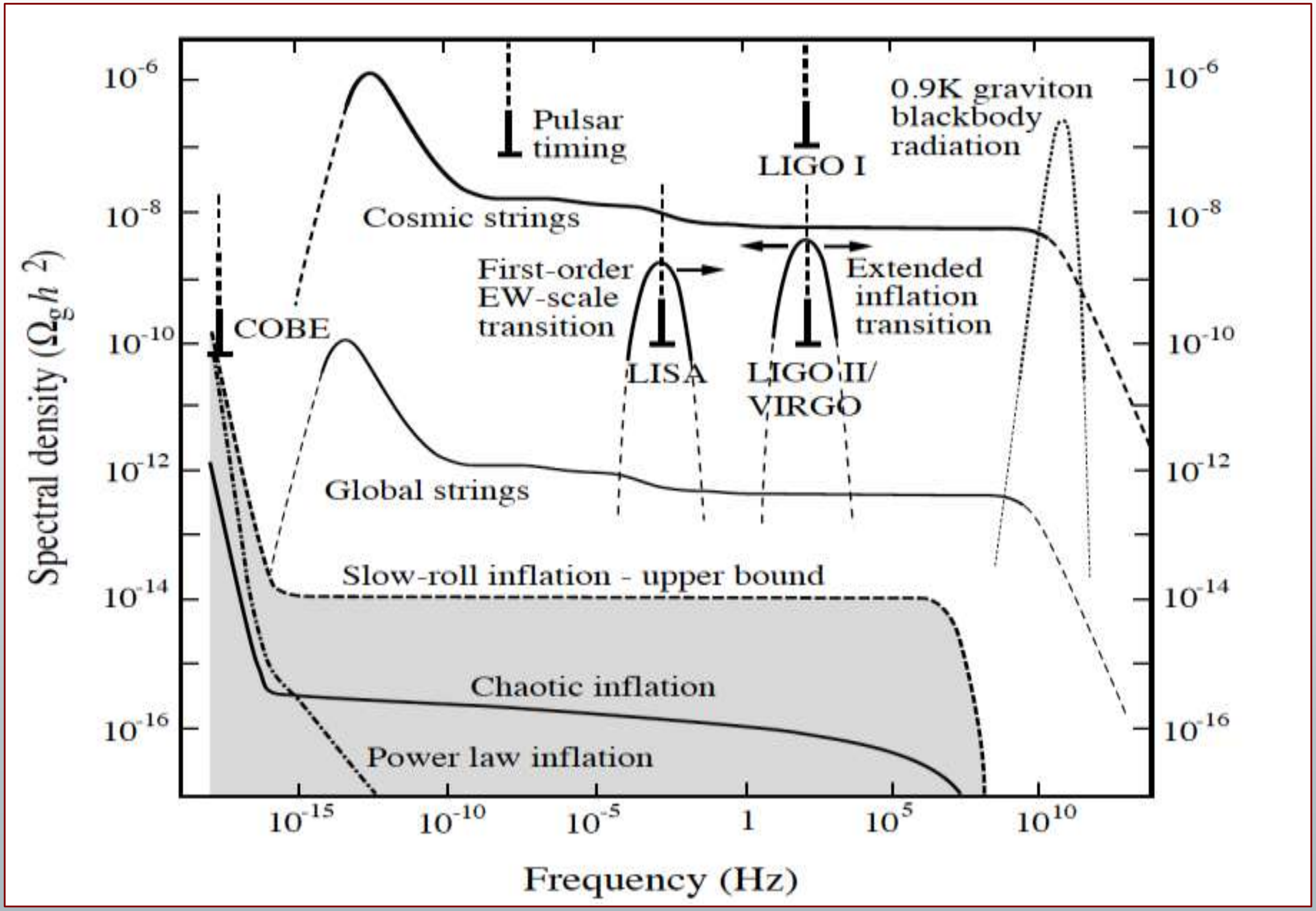
$$r = -8n_T$$

# The search for primordial GW

- The primordial GW amplitude is maximal at horizon reentering → *search for primordial GW background effects on CMB temperature and polarization*
- CMB temperature anisotropy mixes scalar and tensor modes (→ indirect upper bound; e.g. *Planck 2013*)
- Tensor modes (*and vector modes, if present*) induce a specific polarization type ("**B-mode**") which cannot be induced by scalar perturbations (which produce "**E-mode**" only)
- However, a cosmological foreground B-mode is non-linearly induced by conversion of E-modes into B-modes, owing to gravitational lensing from LSS (***recently detected***) → accurate "delensing" required & GWs detectable only if their amplitude is above a certain level

# The search for primordial GW

Note: this is an “historical” plot, used for illustration purposes only!



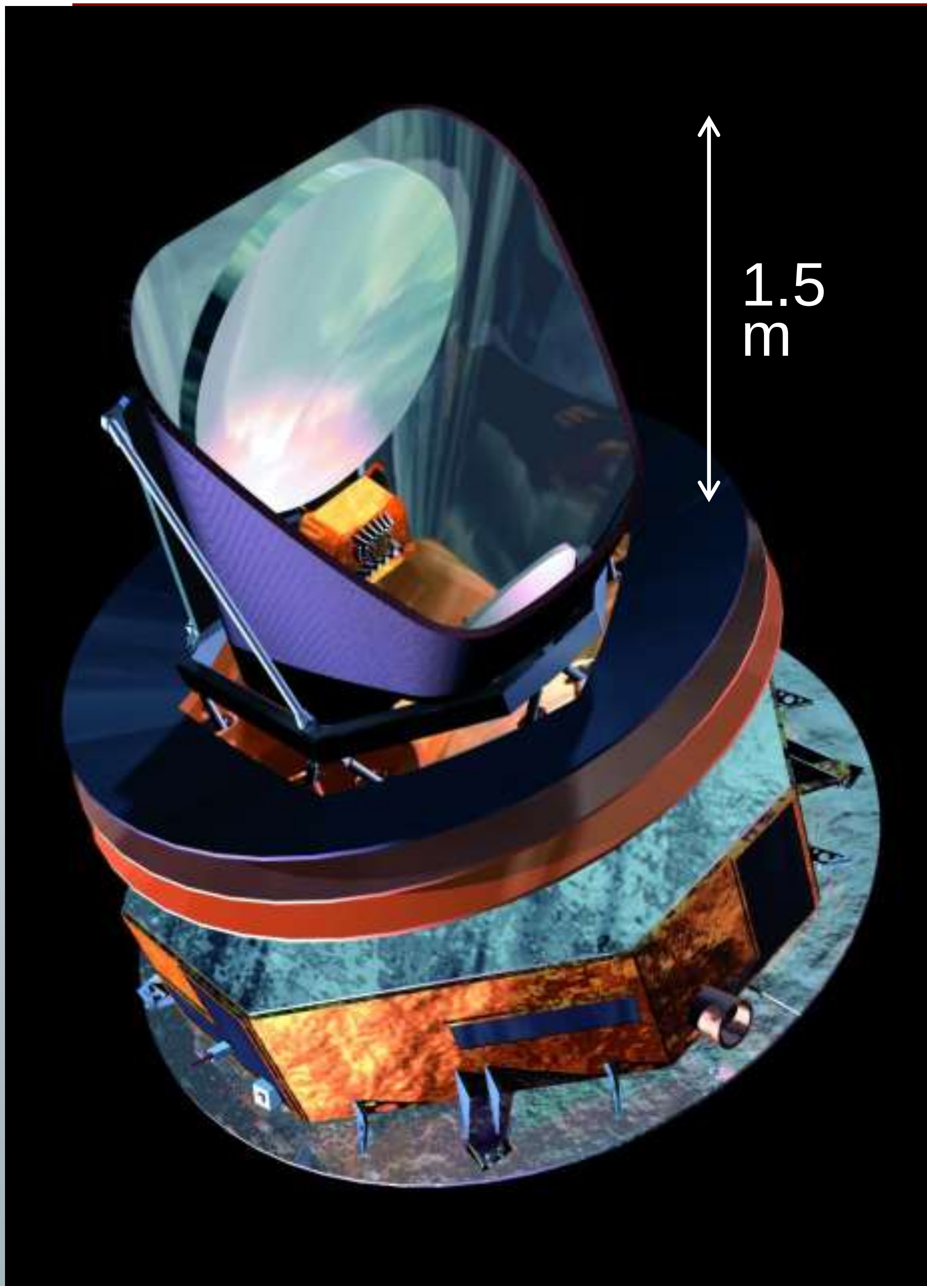

*Battye & Shellard 1996*

Inflation model predictions have already been confirmed by several observations!

# The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

*Planck* is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

# *Planck* mission




3rd CMB space mission - 1st ESA in collaboration with European, US and Canadian scientific community

Mass 2˙000 kg
Power 1˙600 W
Size 4.2 × 4.2 m
Cost 600×$10^6$ €

50˙000 Electronic components
36˙000 l $^4He$
12˙000 l $^3He$

20 yrs between project & results

2 instruments & consortia
16 countries
~ 400 researchers

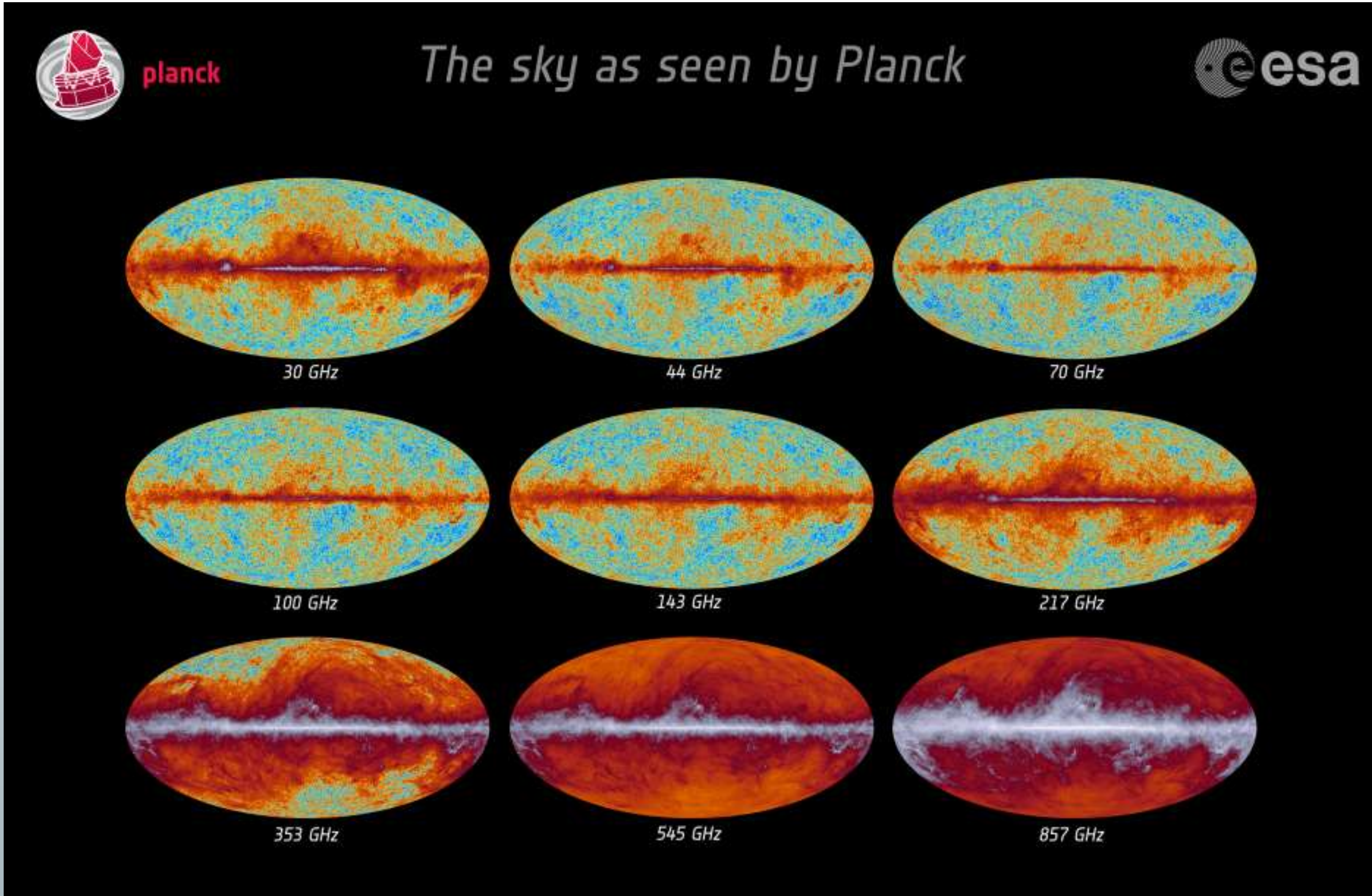
# CMB observations: the *Planck* satellite

- The *Planck* satellite was launched on 14 May 2009 (from Kourou, French Guiana) by Ariane 5 (together with the Herschel satellite), reached its final orbit around the second Lagrange point L2 of the Sun-Earth system after 2 months, and has been scanning the sky stably and continuously since 12 August 2009. *Planck* carries a scientific payload consisting of an array of 74 detectors sensitive to a range of frequencies between $\sim$25 and $\sim$1000 GHz, which scan the sky simultaneously and continuously with an angular resolution varying between $\sim$30 arcminutes at the lowest frequencies and $\sim$5’ at the highest. The array is arranged into two instruments. The detectors of the **Low Frequency Instrument** (**LFI**) are radiometers, covering three bands (centred at 30, 44, and 70 GHz). The detectors of the **High Frequency Instrument** (**HFI**) are bolometers, covering six bands (centred at 100, 143, 217, 353, 545 and 857 GHz). The design of *Planck* allows it to image the whole sky <u>twice per year</u>, with a combination of sensitivity, angular resolution, and frequency coverage never before achieved.

# Scientific target of *Planck*

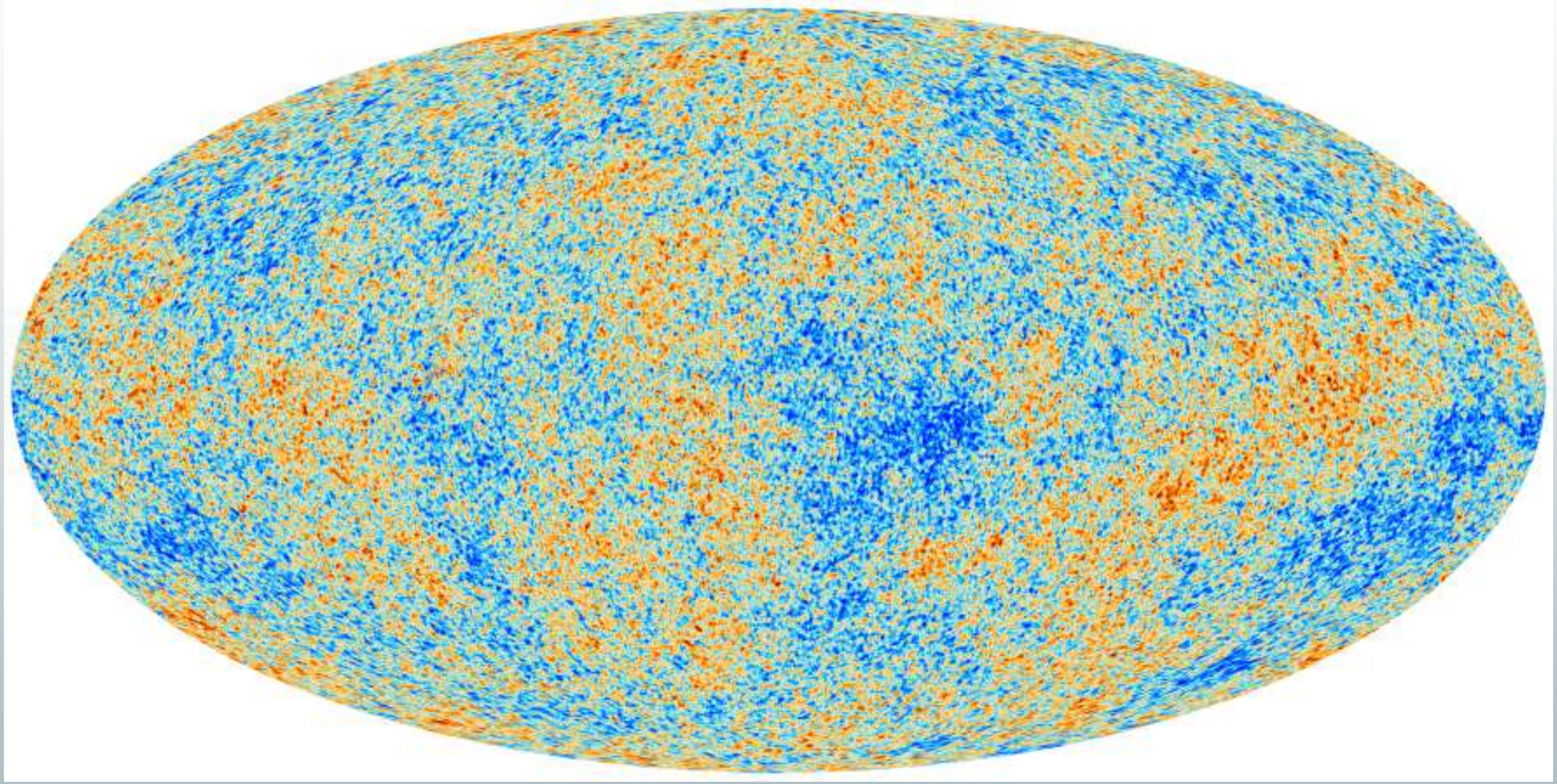
- The main objective of *Planck* is to measure the spatial anisotropies of the temperature of the CMB, with accuracy set by fundamental astrophysical limits. Its level of performance was designed to enable *Planck* to extract essentially all the cosmological information embedded in the CMB temperature anisotropies. *Planck* was also designed to measure, to high accuracy, the polarization of the CMB anisotropies, which encodes not only a wealth of cosmological information, but also provides a unique probe of the early history of the Universe during the time when the first stars and galaxies formed. Finally, the Planck sky surveys produce a wealth of information on the properties of extragalactic sources and on the dust and gas in our own galaxy.

- *Planck* is able to measure anisotropies on intermediate and small angular scales over the whole sky much more accurately than previous experiments (COBE, Boomerang, Maxima, WMAP, ...).



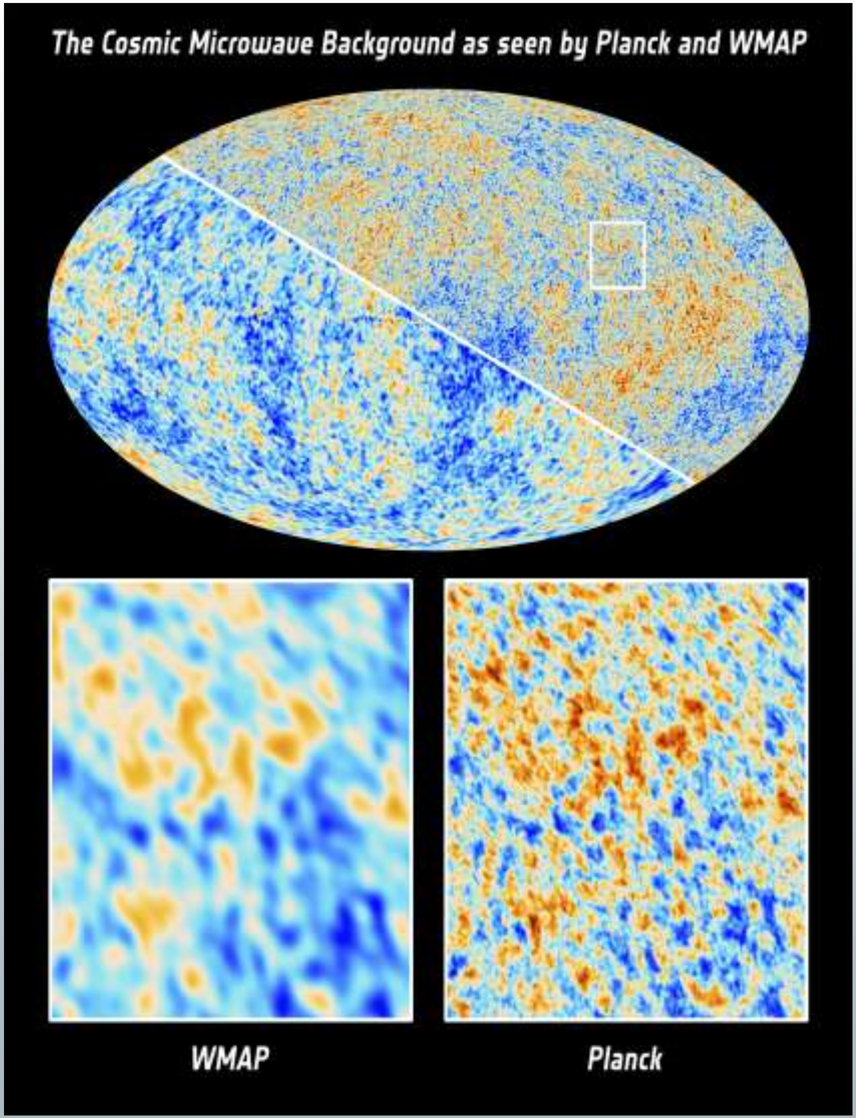
planck
The sky as seen by Planck
esa
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

# The CMB @ *Planck* resolution



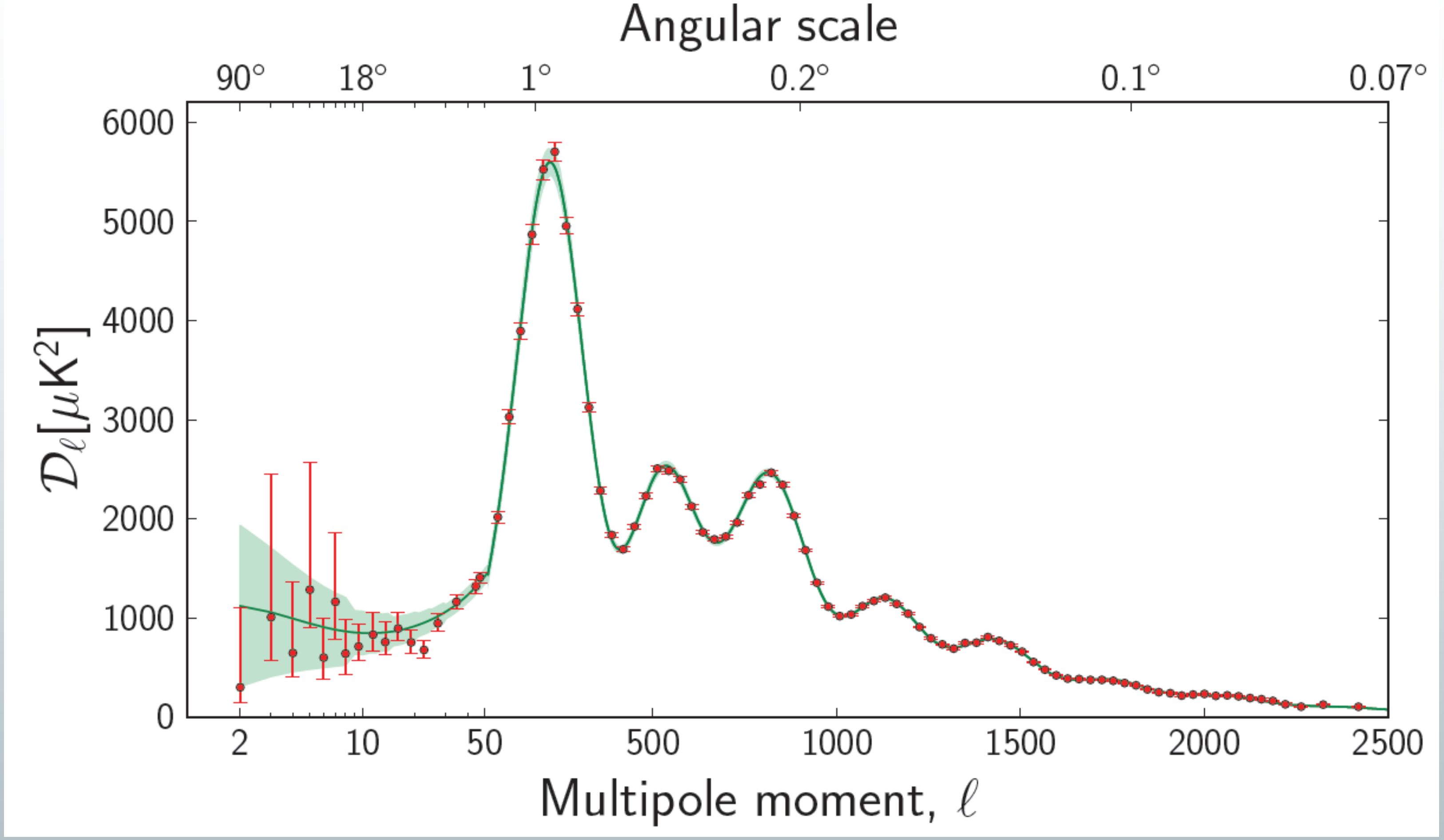
The SMICA CMB map (with 3 % of the sky replaced by a constrained Gaussian realization

# *Planck* CMB temperature maps




*Planck* (ESA) vs *WMAP* (NASA): 5 times higher angular resolution

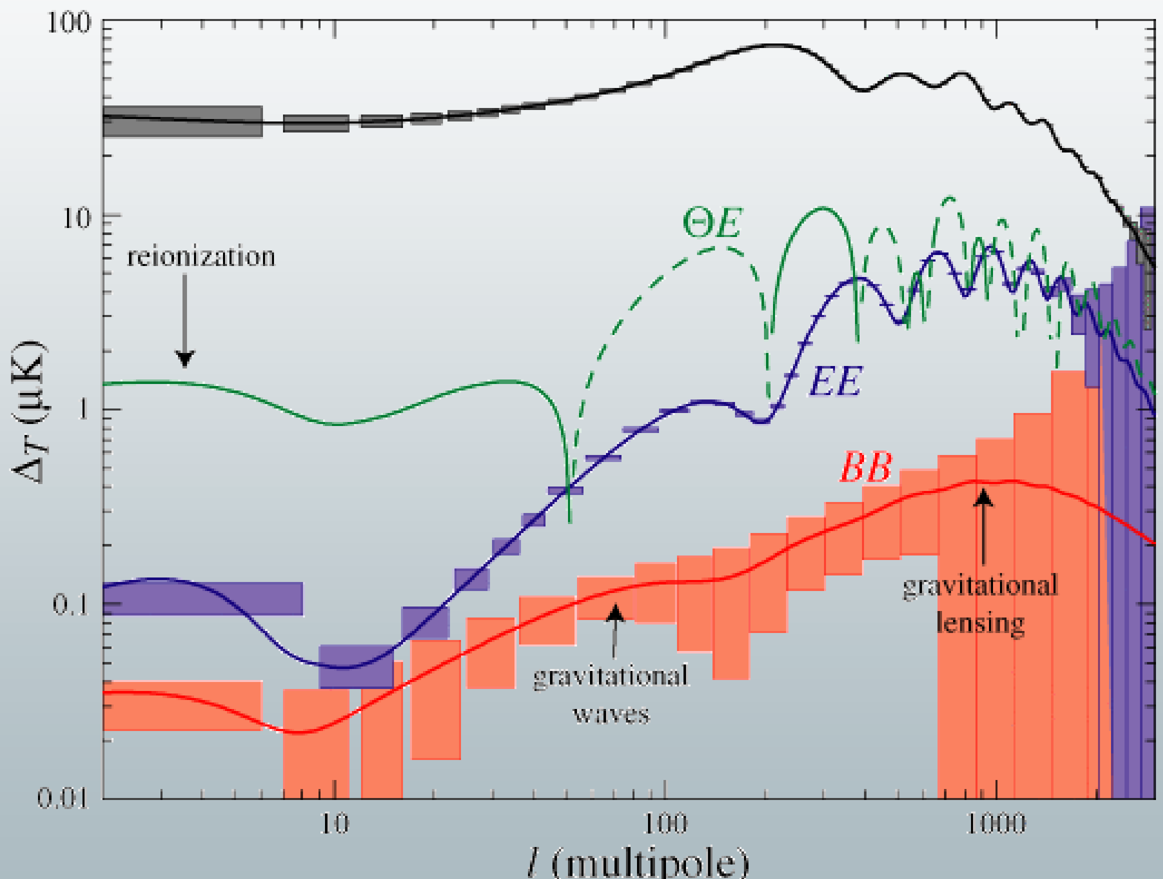
# The *Planck* angular power-spectrum




The temperature angular power spectrum ($l(l + 1)C_l/2\pi$) of the primary CMB from Planck, showing a precise measurement of 7 acoustic peaks, well fit by a simple 6-parameter ΛCDM model [Planck+WP+highL]. The shaded area around the best-fit curve represents cosmic variance, including sky cut. The error bars on individual points also include cosmic variance. The horizontal axis is logarithmic up to $l = 50$, and linear beyond. The measured spectrum here is the same as the previous figure, rebinned to show better the low-l region.

# CMB angular power spectra

If **T, E, B** are Gaussian scalar fields on the sphere → they are entirely defined by their **angular power spectrum**.




model predictions

$\ell$ defines the wave angular frequency, corresponding to an angular scale $J \sim \frac{p}{\ell}$

# Theoretical background

ingredients

- General relativity, simple QED, assumption of homogeneous and isotropic Friedmann-Lemaître universe with at least photons, electrons, baryons, neutrinos, CDM, $\Lambda$
- Primordial fluctuations induce temperature fluctuations in photon-baryon
- Acoustic waves due to photon pressure, modulated by baryon inertia and gravitational interactions
- Photon-electron decoupling: diffusion processes inducing fluctuation damping and photon polarization

- Primary anisotropies: temperature 2-point function at decoupling features correlation length (real space), peak series (multipole space)
- Secondary anisotropies:
  - Light deflection by gravitational lenses
  - Gravitational redshifting by structures along line of sight
  - Rescattering in reionized universe at low redshift

# Cosmological parameters

Hubble constant $H_0$ (= 100 h km $s^{-1}$ $Mpc^{-1}$) = 67.3 ± 1.2 km $s^{-1}$ $Mpc^{-1}$

Cold Dark Matter density today $\omega_c = \Omega_c h^2 = 0.1199 \pm 0.0027$

Baryon density today $\omega_b = \Omega_b h^2 = 0.02205 \pm 0.00028$

Dark Energy density $\Omega_\Lambda = 0.686 \pm 0.020$

Optical depth $\tau = 0.089 \pm 0.032$

Reionization redshift $z_{re} \approx 11 \pm 3$

Age of the Universe $t_0 = 13.796 \pm 0.058$ Gyr

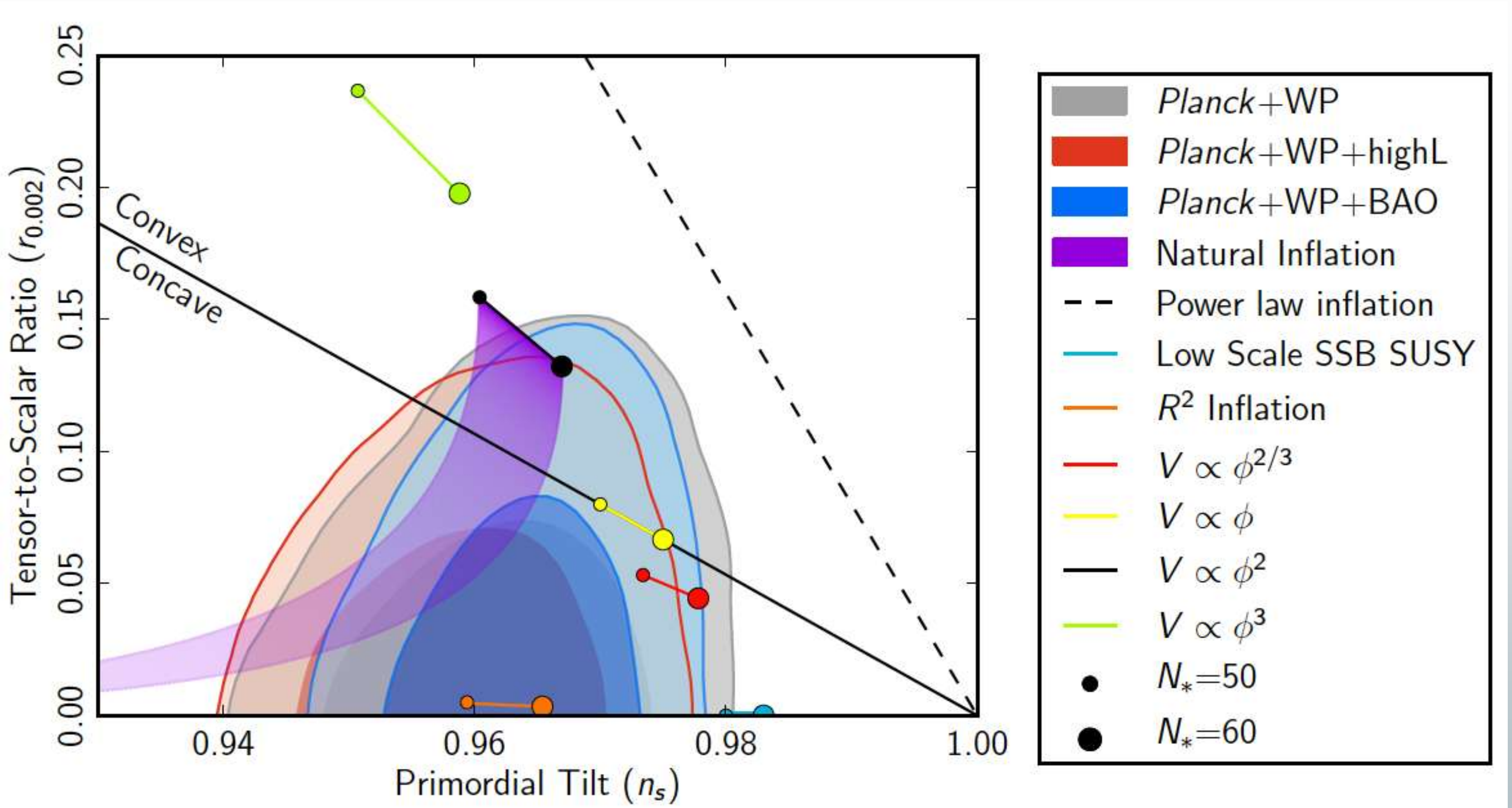
*Planck* finds that the Universe is consistent with spatial flatness to percent level precision

# The Universe, as observed by *Planck*

- *Planck* fully confirms the “standard” Λ-CDM model of Cosmology, which relies on the idea that ~ 95 % of the present energy of the Universe is provided by 2 dark components: Dark Matter (attractive) and Dark Energy (repulsive) in the form of a cosmological constant, whose origin is probably to be ascribed to quantum oscillations of the vacuum state.

- *Planck* yields the strongest constraints so far on the physics of Inflation

# *Planck* constraints on inflation models

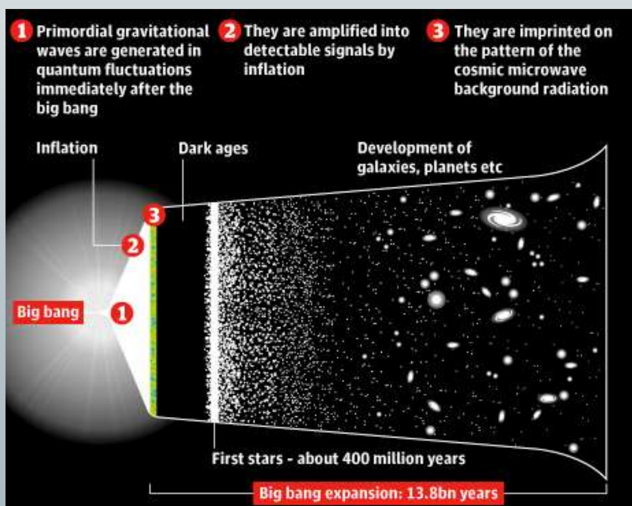


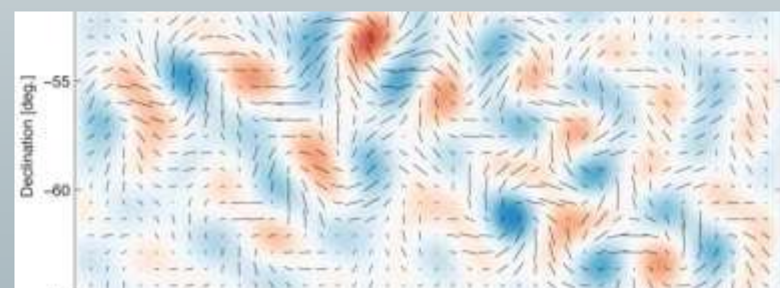

Marginalized joint 68% and 95% CL regions for $n_s$ and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Have primordial (i.e. inflationary)
gravitational waves been detected?

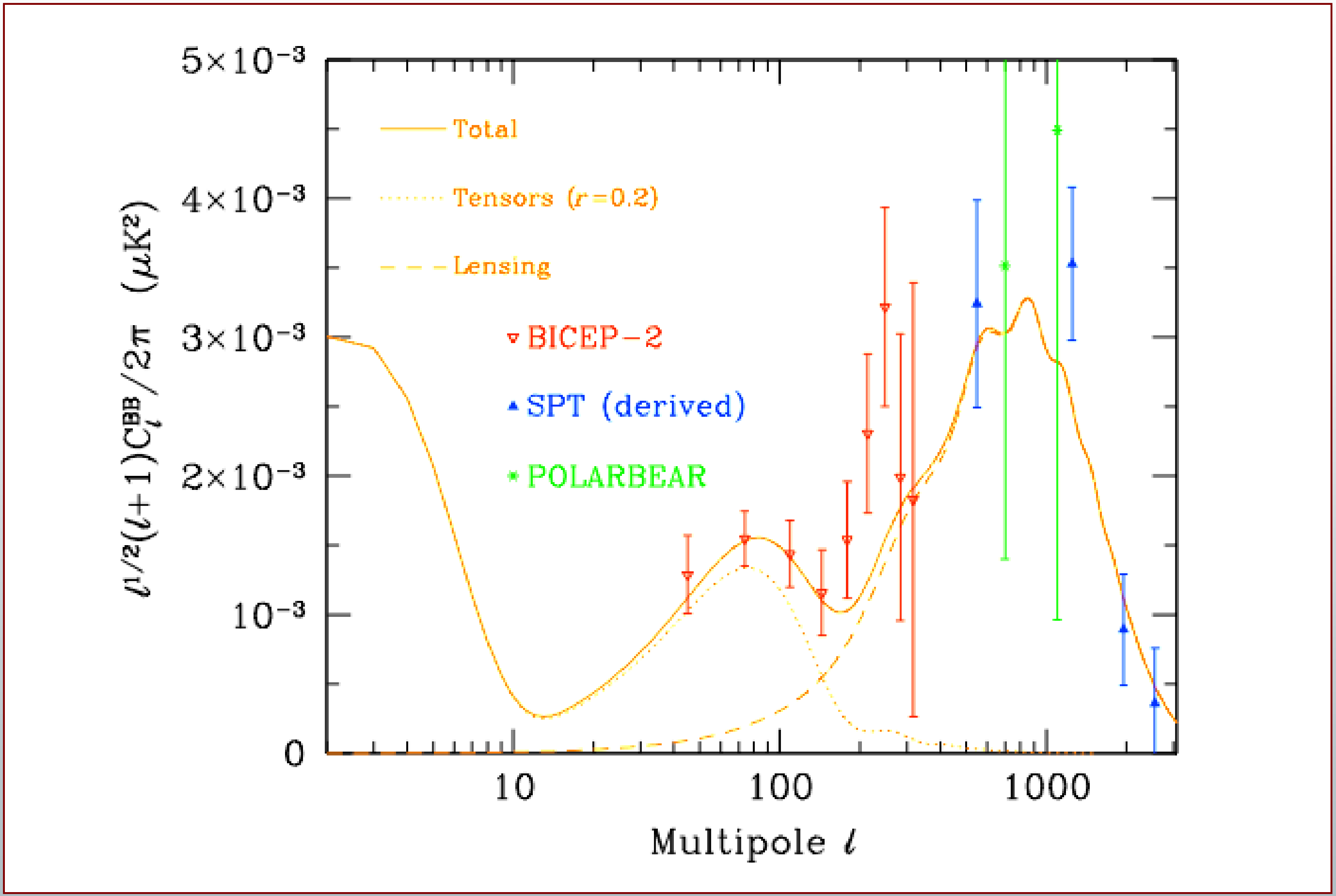
# BICEP2 observation of CMB B-mode polarization

**17 March 2014 press conference at Harvard-Smithsonian CfA:** A team of US scientists detected telltale signs of gravitational waves using the Bicep2 telescope at the south pole. Primordial gravitational wave discovery heralds 'whole new era' in physics. “Gravitational waves could help unite general relativity and quantum mechanics ...”.The detection also provides the first direct evidence for a long-held hypothesis called *inflation*. This states that a fraction of a second after the big bang, the universe was driven to expand hugely



# BICEP2 vs. other observations




BICEP2: $r = 0.2^{+0.07}_{-0.05}$ r=0 excluded at the 5.9 σ level

# *Planck* analysis of polarized dust

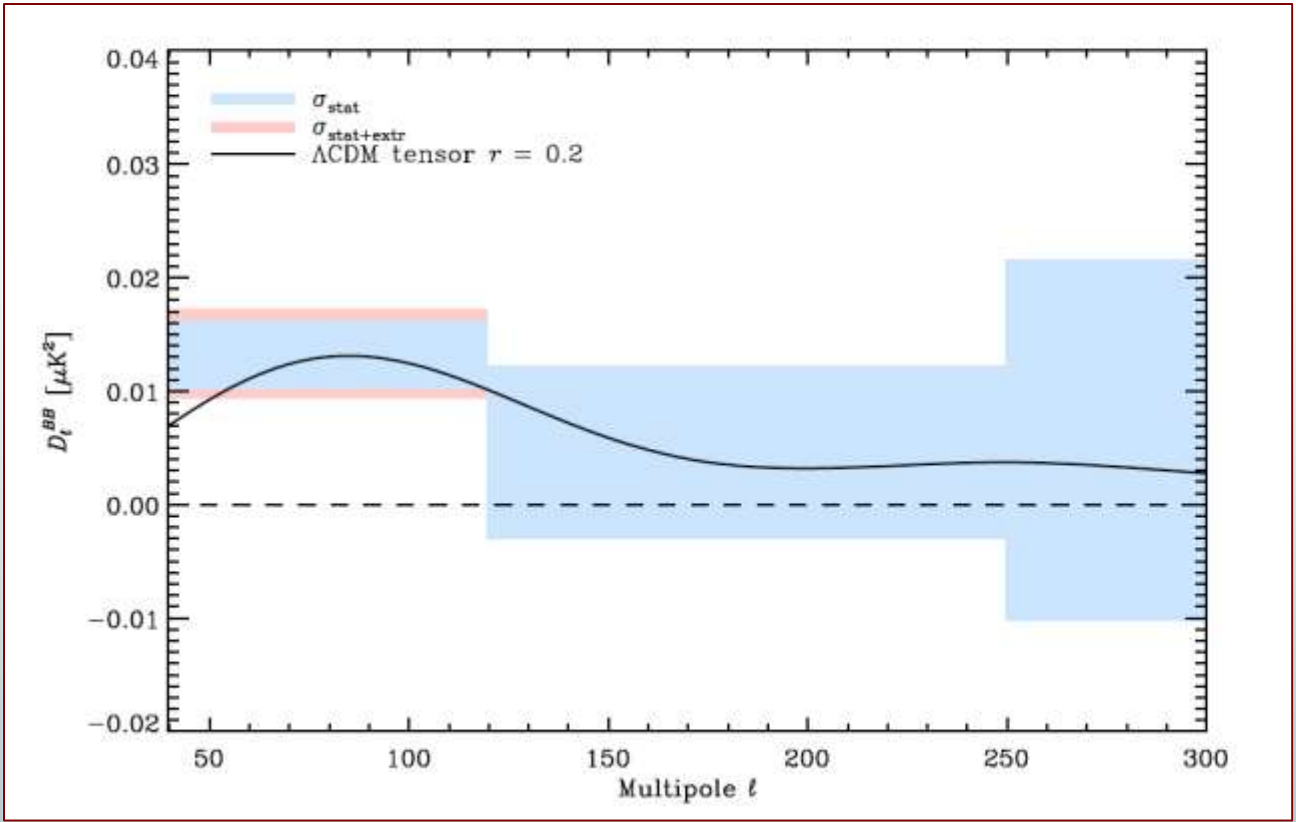
- ***Planck* intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitude, *Planck* collabor. arXiv:1409.5738**
- The polarized thermal emission from diffuse Galactic dust is the main foreground present in measurements of the polarization of the CMB at frequencies above 100 GHz. We exploit *Planck* polarization data from 100 to 353 GHz to measure the polarized dust angular power spectra $C^{EE}$ and $C^{BB}$ over the multipole range 40 < l < 600, well away from the Galactic plane.
- Even in the faintest dust-emitting regions there are **no "clean" windows** in the sky where primordial *B*-mode polarization measurements could be made without subtraction of foreground emission. Extrapolation of the *Planck* 353 GHz data to 150 GHz gives a dust polarization power in the BICEP 2 field

$$\mathbf{D^{BB} \equiv l\,(l + 1)C^{BB}/(2\pi)\ of\ 1.32 \times 10^{-2}\ \mu K^2_{CMB}}$$

for 40 < l < 120, with statistical uncertainty $\pm\, 0.29 \times 10^{-2}\ \mu K^2_{CMB}$ additional uncertainty $(+0.28, -0.24) \times 10^{-2}\ \mu K^2_{CMB}$ from the extrapolation.

- **This level is the same magnitude as reported by BICEP2 over this l range, which calls for assessment of polarized dust signal. Present uncertainties are large; they will be reduced through an ongoing, joint analysis of the *Planck* and BICEP2 data sets.**

# *Planck* analysis of polarized dust




*Planck* 353 GHz $D^{BB}$ angular power spectrum extrapolated to 150 GHz (box centres). The shaded boxes represent the 1 sigma uncertainties: blue for the statistical uncertainties from noise; and red adding in quadrature the uncertainty from extrapolation to 150 GHz. The *Planck* 2013 best-fit CDM $D_{BB}$ CMB model based on temperature anisotropies, with a tensor amplitude fixed at r = 0.2, is overplotted as a black line.

# *Planck* – BICEP joint analysis: ongoing

- How much is the BICEP2 interpretation affected? This is not yet clear and will be the outcome of a detailed joint analysis of BICEP2 and *Planck* data being carried out by the two teams jointly.

- **Note**: the sensitivity of *Planck* in a small field such as the BICEP2 field is low. However, the actual strength of *Planck* is in its all-sky survey capability and its wide frequency coverage.

- Independently of the *Planck*–BICEP2 joint work, ***Planck* will set its own limit on the amplitude of primordial gravitational waves** over the whole sky.

# Consequences for high energy physics

- *For values of r ≈$10^{-1}$*, inflation probes the GUT scale, i.e. high-energy scales never achievable in laboratories

$$\boxed{V^{1/4} = 1.94 \times 10^{16} \left(\frac{r}{0.12}\right)^{1/4} \mathrm{GeV}}$$

- The many observational confirmations of inflation predictions (may) provide evidence of physics beyond the Standard Model of particle physics

- *Who* is the inflaton??
  Now this question has become more and more pressing (most probably it is not the Higgs field!!).

# Consequences for inflationary models

BICEP2 resukts (if confirmed **even as an order of magnitude!**) *strongly* reduce the number of inflationary models that agree with data

- Low-energy scale inflation models: **RULED OUT**

- Higgs-inflation (Bezrukov & Shaponiskov 2008) tries to identify the Higgs of the SM with the inflaton (needs non-minimal coupling with gravity)
  Prediction: $r \approx 0.0034 \rightarrow$ **RULED OUT** *(some fairly contrived variants still alive)*

- $R^2$ inflation (Starobinsky ’80) *(connected to Higgs inflation by a Weyl rescaling*
  Prediction: $r \approx 0.0034 \rightarrow$ **RULED OUT**

- ... many more inflation models ruled out by BICEP2 results, if confirmed

# The future: a new era of gravity-wave based cosmology

- Measure the tensor spectral index

$$\mathcal{P}_{\mathrm{T}}(k) = \frac{128}{3}\frac{V}{M_{\mathrm{Pl}}^4}\left(\frac{k}{k_0}\right)^{n_{\mathrm{T}}}$$

Tensor spectral index: $n_{\mathrm{T}} = -2\epsilon$

- Test the consistency relation (``*the holy grail of inflation*''):

$$r = -8n_T$$

generalized to inflaton w. non-canonical kinetic term as r = - 8$c_s n_T$ with $c_S$ > 0.02 (*Planck* 2013)

- Constrain higher-order correlators of tensor perturbations, e.g. 3-point function <hhh> → graviton interactions (upper bounds obtainable by *Planck* 2014)

- Constrain deviation from GR at very high-energies → Implications for GW detectors?

## Inflation as the generator of a tiny level of non-Gaussianity in cosmological perturbations

# Simple-minded NG model

Many primordial (inflationary) models of non-Gaussianity can be represented in configuration space by the simple formula (Salopek & Bond 1990; Gangui et al. 1994; Verde et al. 1999; Komatsu & Spergel 2001)

$$\Phi = \phi_L + f_{NL} * (\phi_L^2 - \langle\phi_L^2\rangle) + g_{NL} * (\phi_L^3 - \langle\phi_L^2\rangle \phi_L) + \ldots$$

where $\Phi$ is the large-scale gravitational potential (more precisely $\Phi = 3/5\ \zeta$ on superhorizon scales, where $\zeta$ is the gauge-invariant comovign curvature perturbation), $\phi_L$ its linear Gaussian contribution and $f_{NL}$ the dimensionless <u>*non-linearity parameter*</u> (or more generally *non-linearity function*). The percent of non-Gaussianity in CMB data implied by this model is

$$\text{NG \%} \sim 10^{-5}\ |f_{NL}|$$

< $10^{-4}$ from CMB & LSS

$$\sim 10^{-10}\ |g_{NL}|$$

< $10^{-4}$ from CMB & LSS

# Non-Gaussianity: probes the physics of the Early Universe

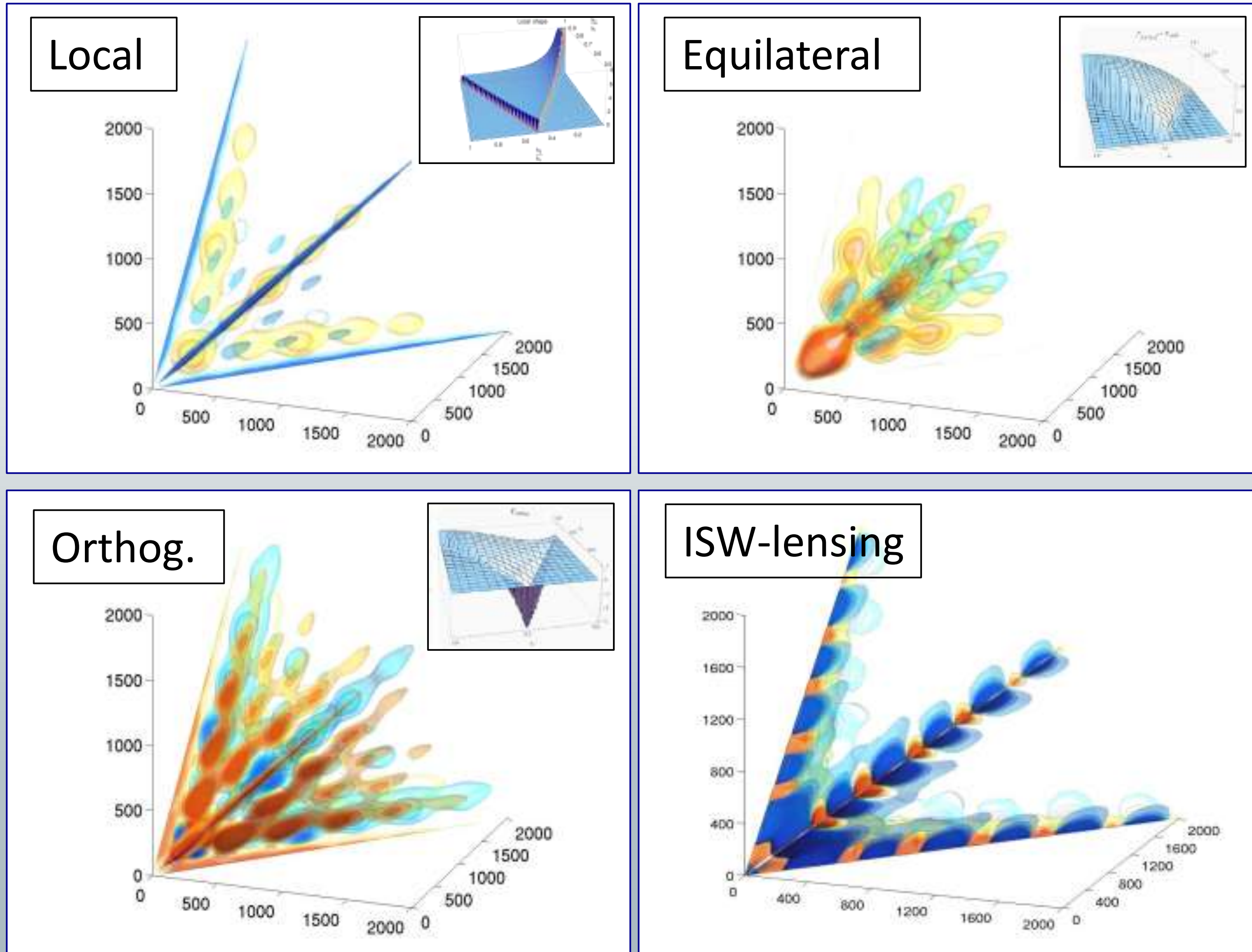
- The NG amplitude and shape measures deviations from standard inflation, perturbation generating processes after inflation, initial state before inflation, ...

- Inflation models which would yield the same predictions for scalar spectral index and tensor-to-scalar ratio might be distuinguishable in terms of NG features.

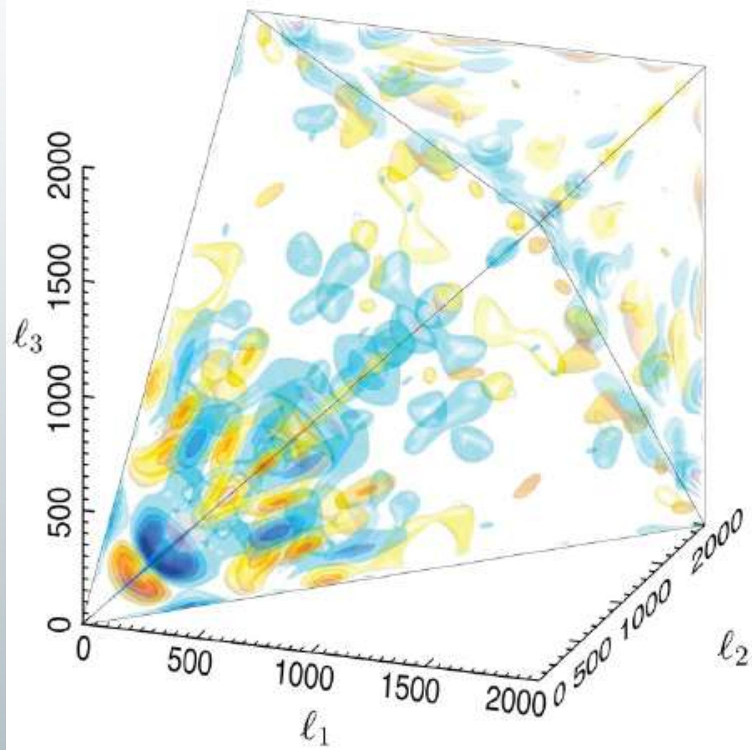
- *Mild non-Gaussianity allows to constrain deviations from GR at the highest achievable energy scales (Bartolo, Cannone, Jimenez, Matarrese & Verde 2014, PRL, in press).*

*new!*

# Bispectrum shapes



# *Planck* constraints on primordial NG

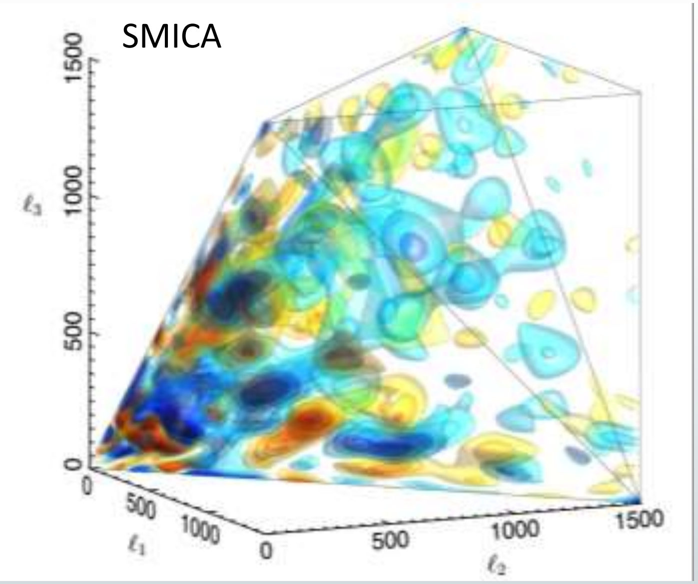



Temperature bispectrum
(after foreground cleaning)

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

# ISW-lensing bispectrum from *Planck*

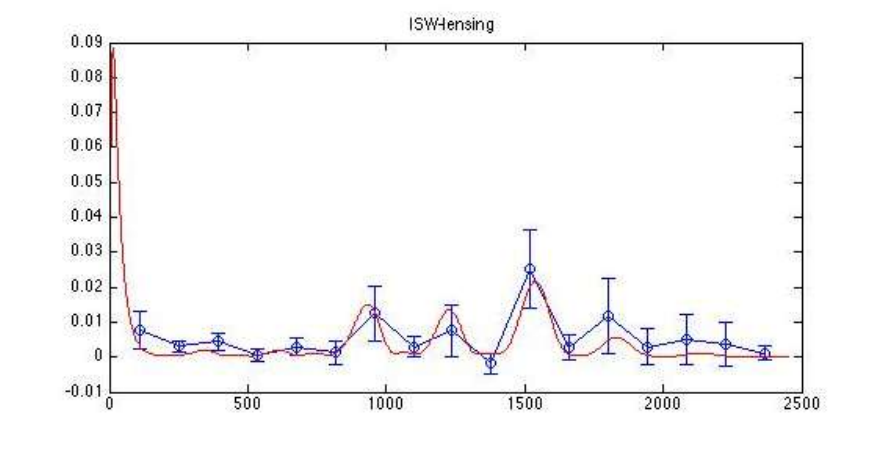
The coupling between weak lensing and Integrated Sachs-Wolfe (ISW) effects is the leading contamination to local NG. We have detected the ISW lensing bispectrum with a significance of 2.6 σ




| | SMICA | NILC | SEVEM | C-R |
|---|---|---|---|---|
| KSW . . . . . | 0.81 ± 0.31 | 0.85 ± 0.32 | 0.68 ± 0.32 | 0.75 ± 0.32 |
| Binned . . . . | 0.91 ± 0.37 | 1.03 ± 0.37 | 0.83 ± 0.39 | 0.80 ± 0.40 |
| Modal . . . . | 0.77 ± 0.37 | 0.93 ± 0.37 | 0.60 ± 0.37 | 0.68 ± 0.39 |

Results for the amplitude of the ISW-lensing bispectrum from the SMICA, NILC, SEVEM, and C-R foreground-cleaned maps, for the KSW, binned, and modal (polynomial) estimators; error bars are 68% CL.

Skew-$C_l$ detection of ISW-lensing signal




| | SMICA | NILC | SEVEM | C-R |
|---|---|---|---|---|
| Local . . . . . . . . . . . . . . . . | 7.1 | 7.0 | 7.1 | 6.0 |
| Equilateral . . . . . . . . . . . . | 0.4 | 0.5 | 0.4 | 1.4 |
| Orthogonal . . . . . . . . . . . . | −22 | −21 | −21 | −19 |

The bias in the three primordial fNL parameters due to the ISW-lensing signal for the 4 component-separation methods.

# *Planck* results on NG

- The **simplest** inflation models (*single-field slow-roll, standard kinetic term, BD initial vacuum state*) are favoured by *Planck* data

- Multi-field models are not ruled out but also not detected

- Ekpyrotic/cyclic models (*the only alternative to inflation!*) are either ruled out or under severe pressure

- *Taken together, these constraints represent the highest precision tests to date of physical mechanisms for the origin of cosmic structure*

# Prospects for improving NG constraints

- *Planck* full mission intensity data + E-mode polarization will improve accuracy by about 30% (*Planck* collaboration 2014, in preparation).
- LSS constraints (from halo bias and possibly halo bispectrum) will allow to pin down NG constraints to $\Delta f_{NL}^{local} \approx 1$ (Carbone, Verde & Matarrese 2008; Hamaus, Seljak & Desjacques 2011; Giannantonio et al. 2012; ...)
- CMB spectral distortions have the potentiality to achieve accuracy of $\Delta f_{NL}^{local} \approx 10^{-2}$ (Pajer & Zaldarriaga 2012; Ganc & Komatsu 2012; ...)
- Using 21 cm background data is also very promising (Cooray 2007; Pillepich, Porciani & Matarrese 2007; Joudaki et al. 2011; ...)

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- Achieving $\Delta f_{NL}^{local} \approx 1$ would allow to probe GR (Verde & Matarrese 2009; Bruni, Hidalgo, Meures & Wands 2014) and modifications of gravity at the inflation energy scale (Bartolo, Cannone, Jimenez, Matarrese & Verde 2014).
- Reaching a sensitivity of $\Delta f_{NL}^{local} \approx 10^{-2}$ would allow to probe the very idea of inflation + GR during inflation (Gangui, Lucchin, Matarrese & Mollerach 1995; Acquaviva, Bartolo, Matarrese & Riotto 2002; Maldacena 2002). *This would represent another important smoking gun proof of inflation!*

# Conclusions

- CMB temperature and polarization anisotropy data fully confirm the predictions of inflation (existence of fluctuations beyond the horizon at last scattering, slight tilt of scalar spectral index, ...).
- BICEP2 claimed observation of the imprints on CMB polarization of the gravitational wave stochastic background originated by quantum vacuum oscillations (gravitons) in the very early Universe; however, *Planck* observation of polarized dust shows that dust contamination is higher than assumed → the BICEP2 interpretation of the B-mode detection as of primordial origin is questionable!
- *Planck* limits on primordial NG suggest that standard single-field slow-roll inflation is favoured over alternative models of the early Universe. More accurate limits will come soon with *Planck* 2014 release.
- These observations call for higher sensitivity observations of CMB polarization via space missions (e.g. COrE proposal), to understand the physics at the highest energy scales, that *only Cosmology can probe*!