Early Universe physics after Planck and Bicep2

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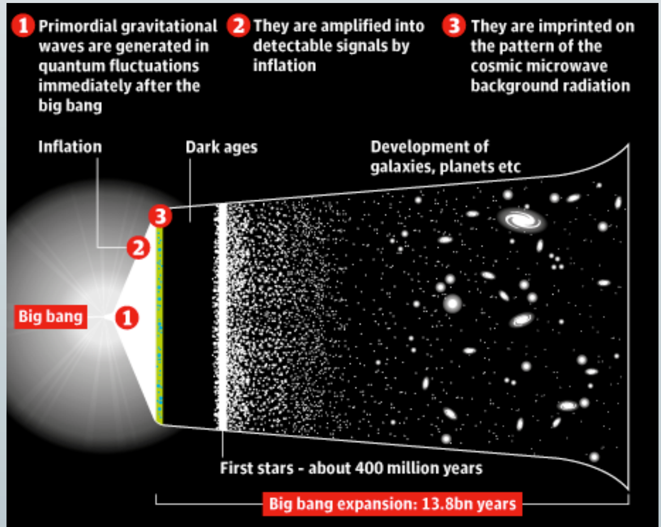
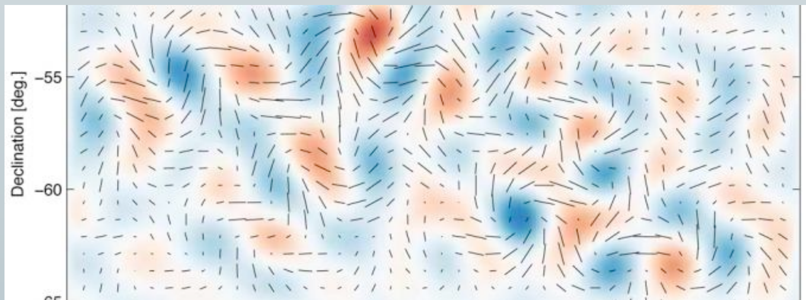
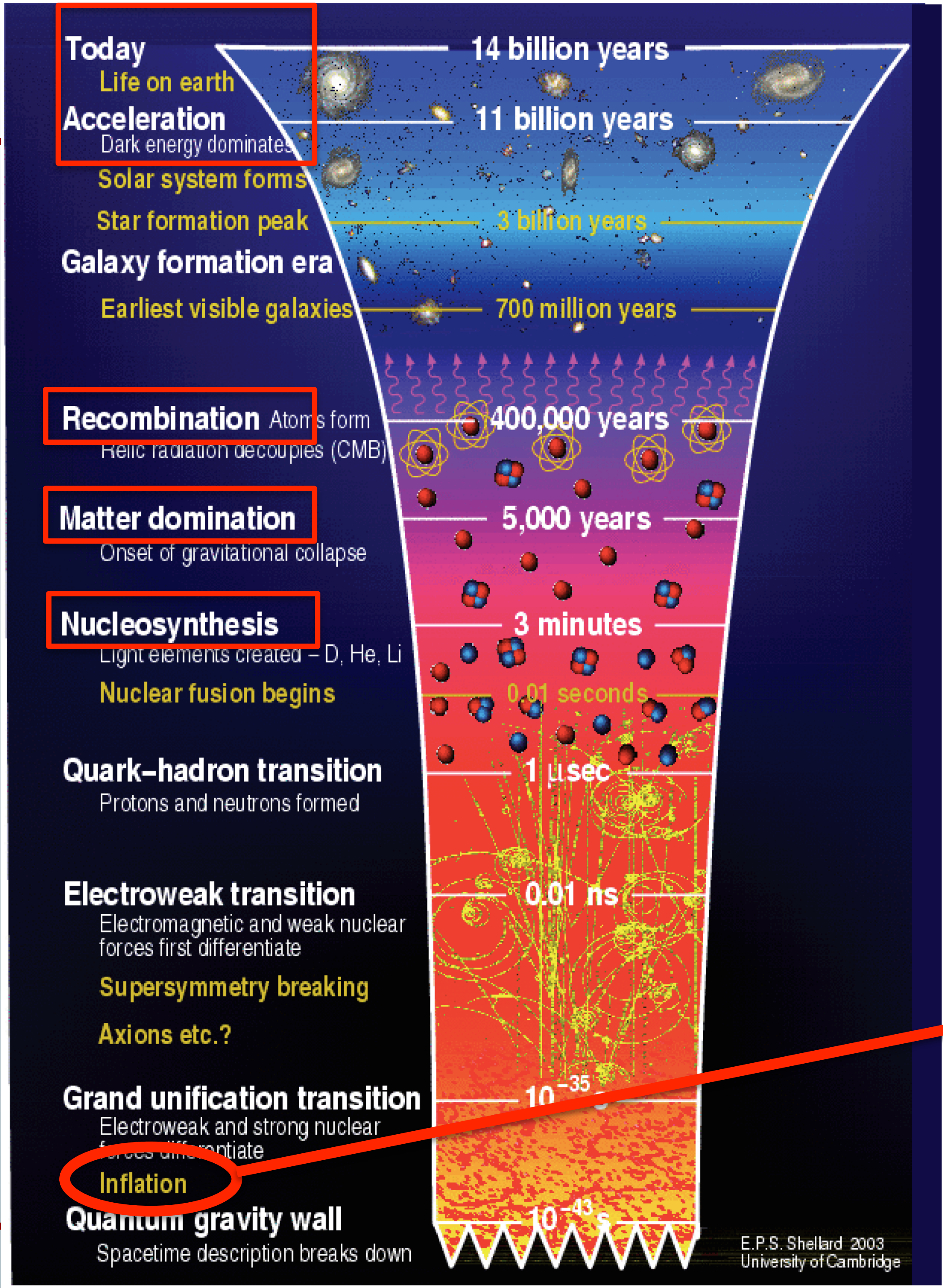
“a major discovery ...(?)”

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.







→ **We are here**

Z_{rec}~1100

Z_{eq}~3500

T~1 MeV

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

... and we got it!

Inflation in the early Universe

- Inflation 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 (Brout et al. 1978; Starobinski 1980; Kazanas 1980; Sato 1981; Guth 1981; Linde 1982, Albrecht & Steinhardt 1982; etc. ...) 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

$$\mathbf{a(t) \approx \exp(Ht)}$$

The rise and fall ... of the comoving Hubble horizon

(late-time dark energy dominance neglected for simplicity)

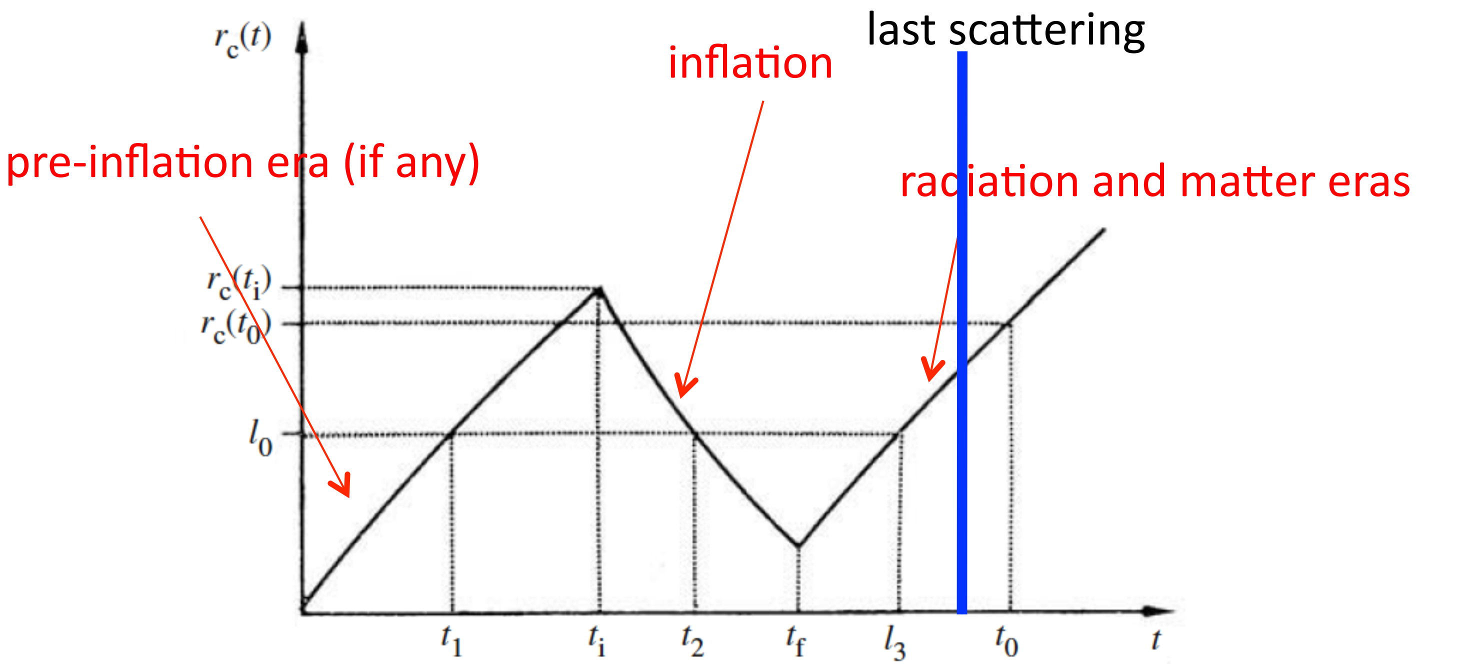


Figure 7.4 Evolution of the comoving cosmological horizon $r_c(t)$ in a universe characterised by a phase with an accelerated expansion (inflation) from t_i to t_f. The scale l_0 enters the horizon at t_1, leaves at t_2 and re-enters at t_3. In a model without inflation the horizon scale would never decrease so scales entering at t_0 could never have been in causal contact before. The horizon problem is resolved if $r_c(t_0) \leqslant r_c(t_i)$.

credits: Coles & Lucchin 2002

Inflation predictions

✓ Cosmological aspects

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

✓ Particle physics aspects

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

Inflation predictions

- Quantum vacuum oscillations of the inflaton (or other scalar fields, such as the "curvaton") 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").

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.

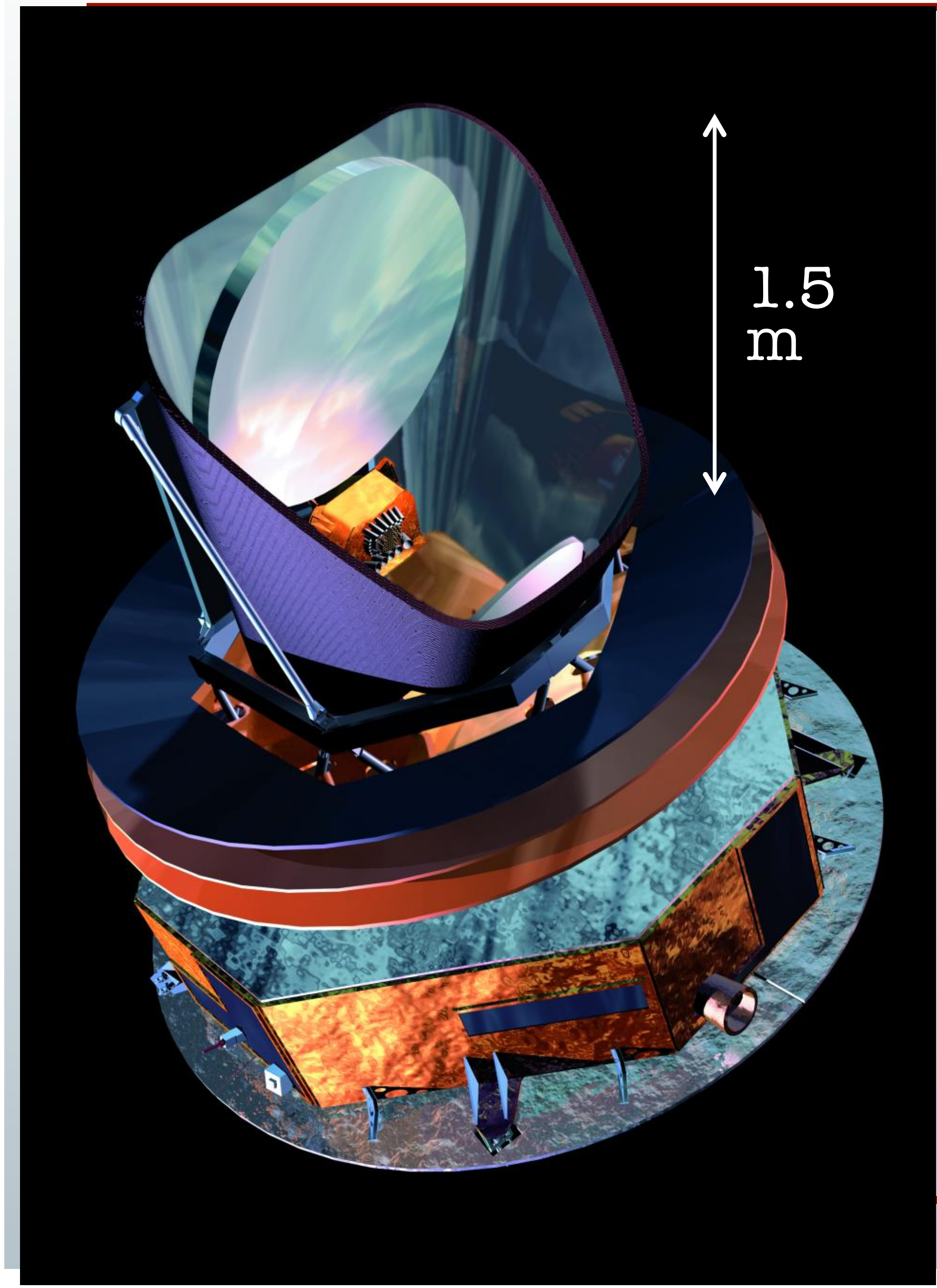
The *Planck* satellite

- 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 ~25 and ~1000 GHz, which scan the sky simultaneously and continuously with an angular resolution varying between ~30 arcminutes at the lowest frequencies and ~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 twice per year, with a combination of sensitivity, angular resolution, and frequency coverage never before achieved.

Planck satellite

- Planck is equipped with a passive cooling system that brings its temperature down to about -230°C by radiating heat into space. Three active coolers bring the temperature down further to an amazing low temperature of -273.05°C, only 0.1°C above absolute zero - the coldest temperature theoretically possible in our Universe.
- Such low temperatures are necessary for Planck's detectors to study the Cosmic Microwave Background (CMB), the first light released by the universe only 380000 years after the Big Bang, by measuring its temperature across the sky.
- The detectors will look for variations in the temperature of the CMB that are about a million times smaller than one degree – this is comparable to measuring from Earth the heat produced by a rabbit sitting on the Moon. This is why the detectors must be cooled to temperatures close to absolute zero (–273.15°C, or zero Kelvin, 0K).
- Cost: 5 cents/european/yr (700 M€), 400-650 scientists. Selected by ESA in 1996 as 3rd Medium size mission. 2 tons, 4.2m diameter, 36000 l of ^{4}He, 12000 l of ^{3}He

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 €

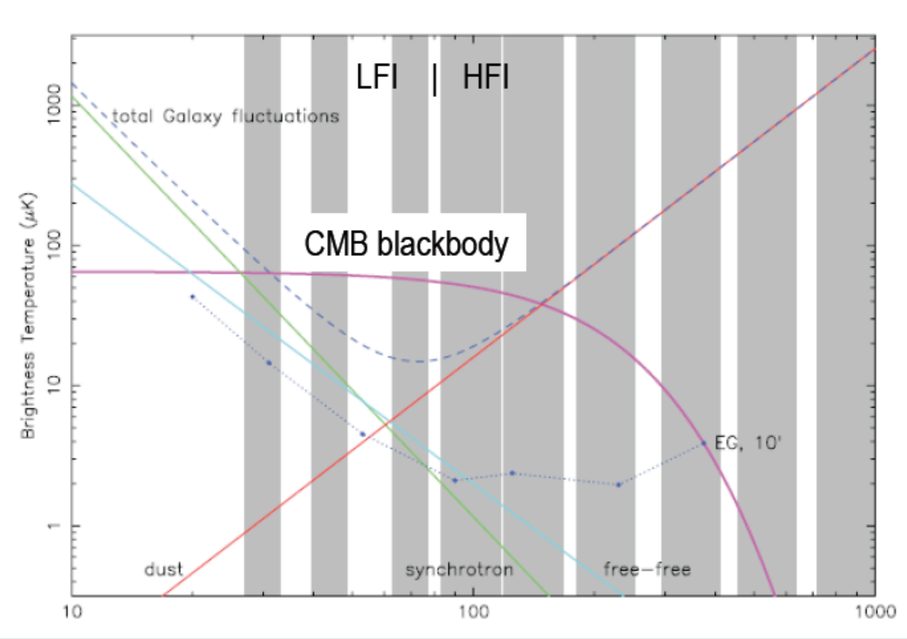
50'000 Electronic components
36'000 l ^4He
12'000 l ^3He

20 yrs between project & results

2 instruments & consortia
16 countries
~ 400 researchers

Planck

- Launched and placed in L2 orbit in 2009. Full scan every 6 month.
- 75 detectors covering 9 frequency channels, grouped as "LFI" (HEM transistors) and "HFI" (bolometers).
- Planck strengths: large and redundant sky coverage, number of channels & detectors, low detector noise (25 x better than WMAP). Resolution intermediate between WMAP (3 x better) and ACT, SPT.
- HFI requires complex cryogenic cooling at 0.1K (with ^{3}He+^{4}He). Designed for > 2 scans, achieved 5. Turned off in Jan 2012 (due to ^{3}He level).
- LFI requires cooling at 20K with ^{4}He only and proceeds until autumn 2013 (8 scans). Turned off a few days ago.
- The March 21 2013 release is restricted to the "nominal mission" (15 months, > 2 scans).



Scientific target of *Planck*

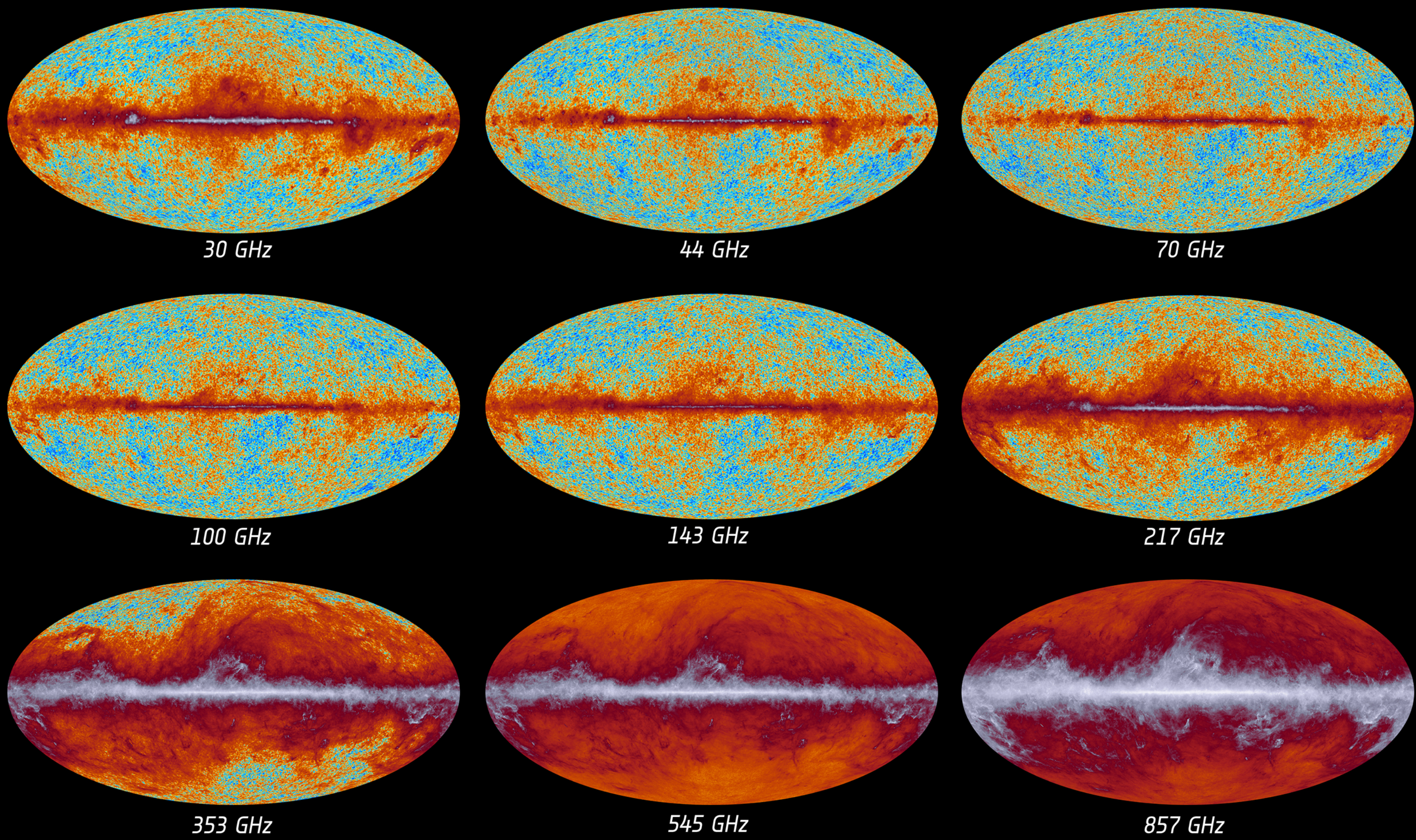
- The main objective of *Planck* is to measure the spatial anisotropies of the temperature of the Cosmic Microwave Background (CMB), with an accuracy set by fundamental astrophysical limits. Its level of performance was designed to enable *Planck* to extract essentially all the cosmological information 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, ...).

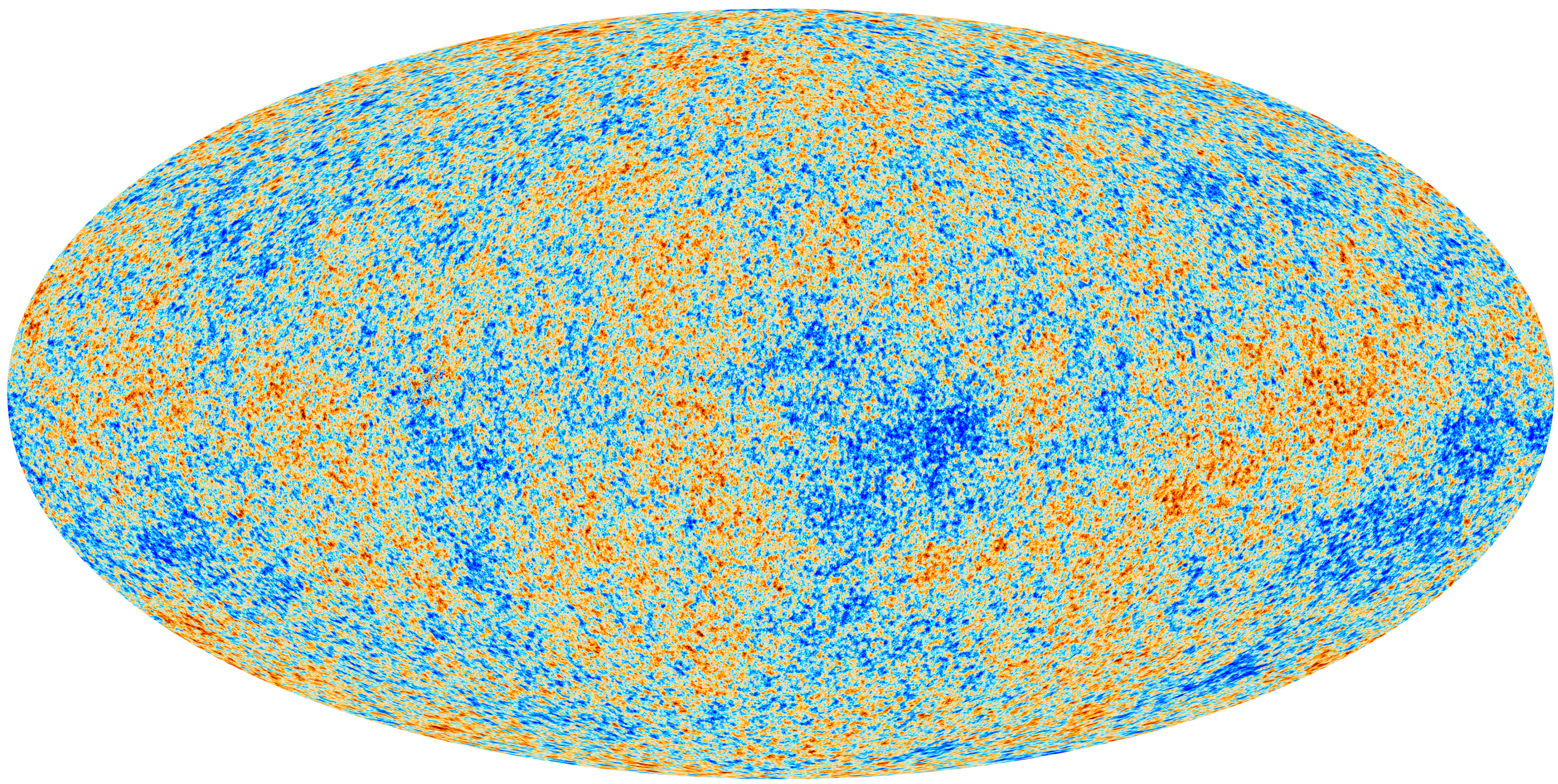
The sky as seen by Planck

planck

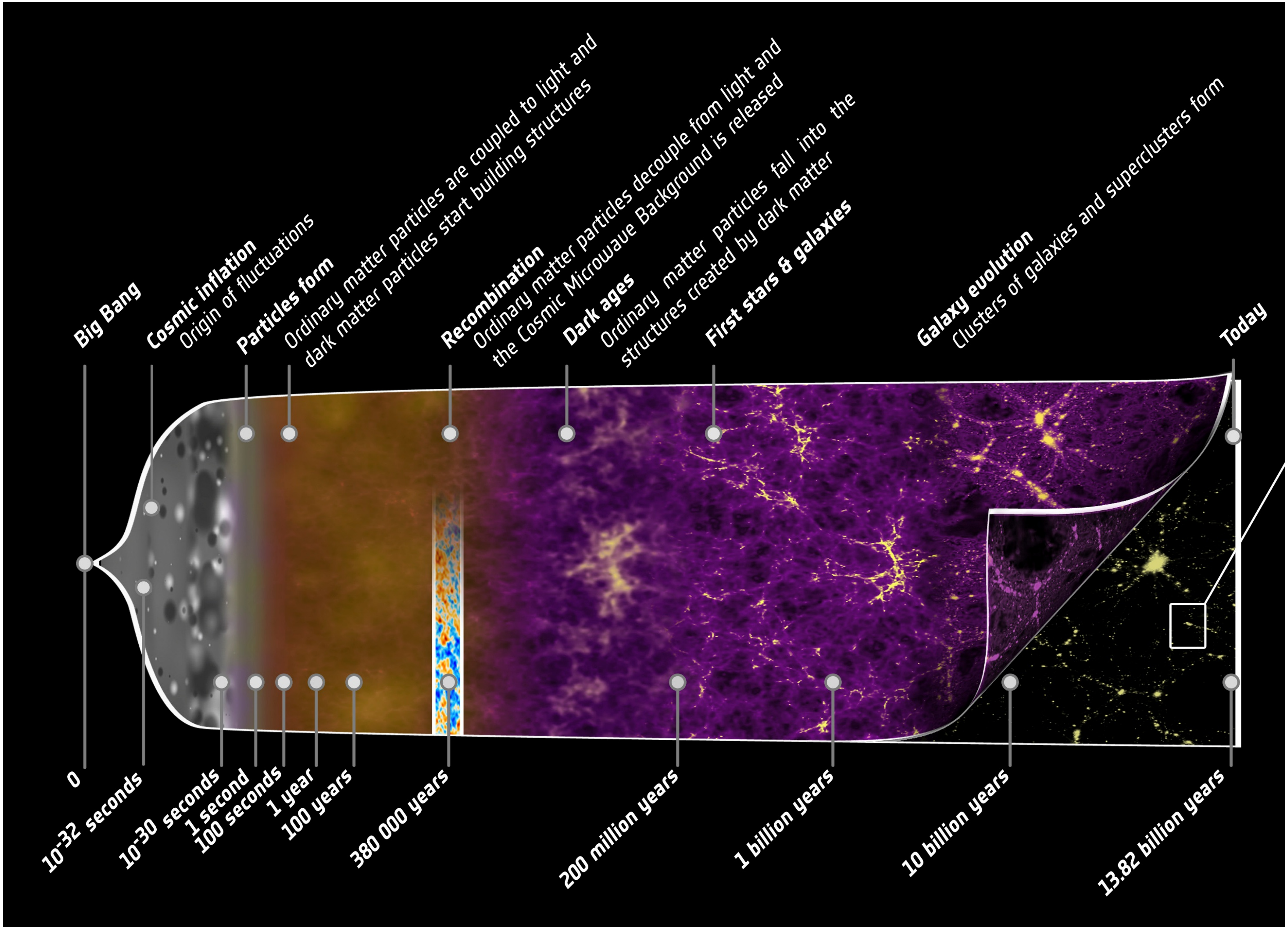
esa



The CMB @ *Planck* resolution

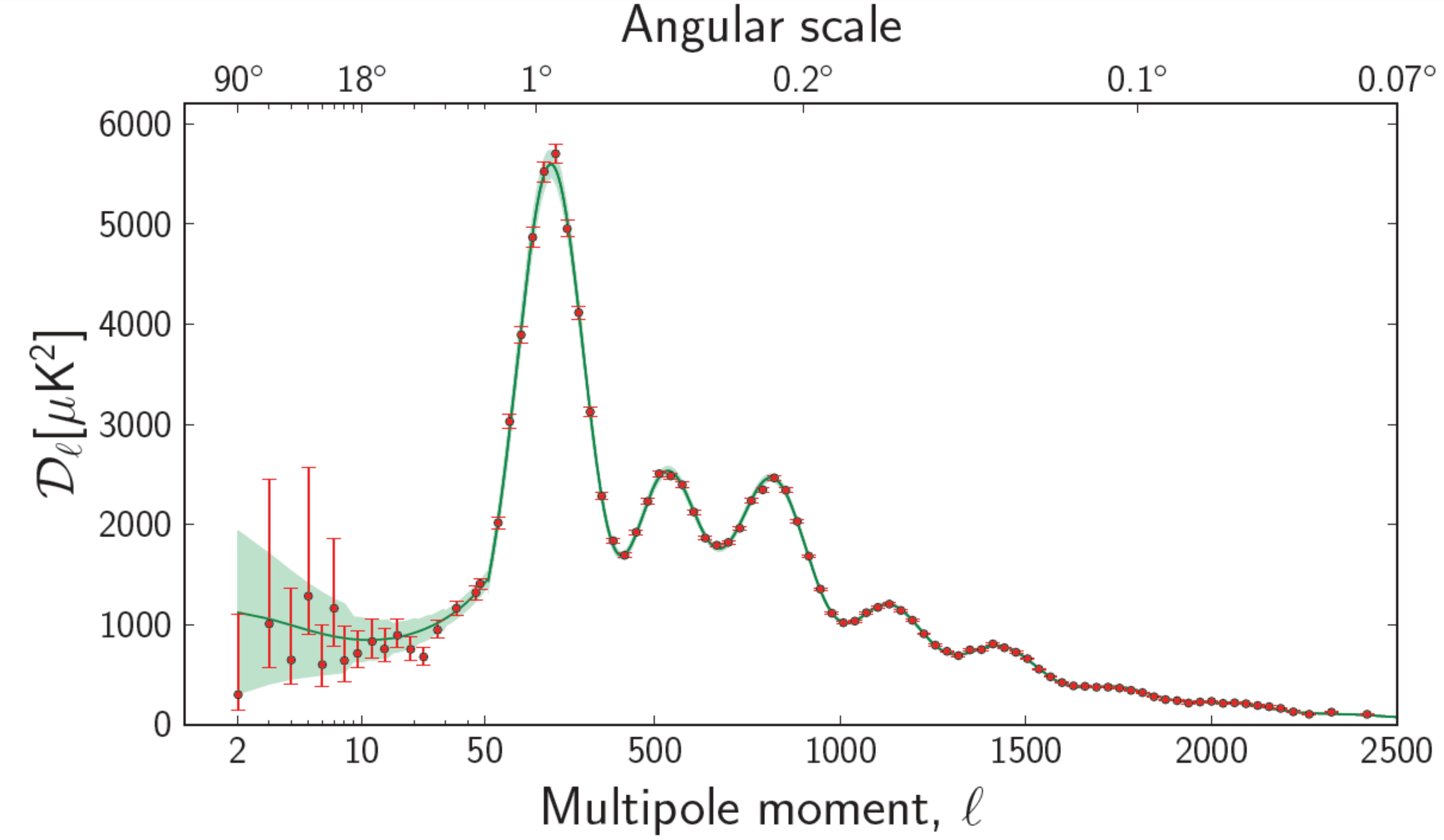


The SMICA CMB map (with 3 % of the sky replaced by a constrained Gaussian realization).



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

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.

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* (see also Grishchuck 1975, Rubakov et al. 1982, Fabbri & Pollock 1982, Abbott & Wise 1984) which originated from quantum vacuum fluctuations of (linearized) spin-2 gravitational perturbations ("gravitons"), left the horizon during inflation (hence remaining frozen and unobservable) and rentered the horizon recently, hence becoming potentially observable as classical tensor perturbations of space-time.

- The detection of these primordial gravitational waves represents the "smoking gun" proof of the validity of the inflationary theory, otherwise very hard to "falsify"; other crucial specific imprints being: the existence of perturbations with a super-horizon seed (***detected!***), specific non-Gaussian signatures of primordial perturbations (***strongly constrained by Planck, which strongly supports the simplest inflation models***).

Inflation and the Inflaton

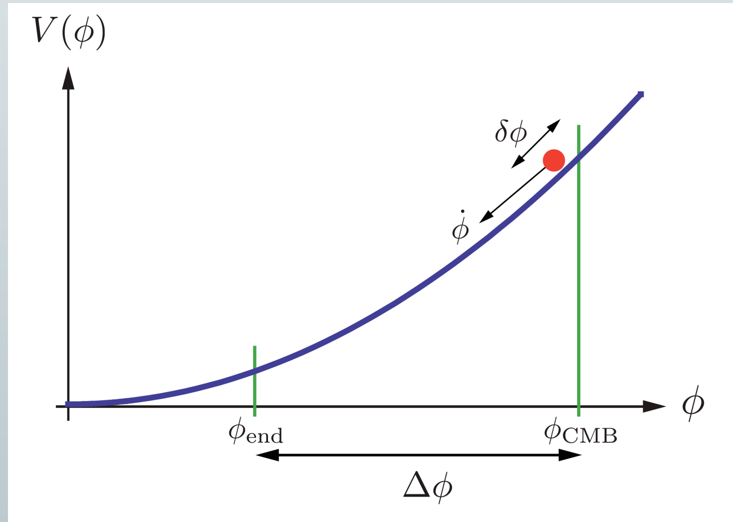
$$\mathcal{L}_\phi[\phi, g_{\mu\nu}] = \frac{1}{2} g^{\mu\nu} \phi_{,\mu} \phi_{,\nu} - V(\phi)$$

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



Slow-roll Inflation

$$\begin{cases} H^2 \simeq \dfrac{8\pi G}{3} V(\phi) \\ \dot{\phi} \simeq -\dfrac{V_{,\phi}}{3H} \end{cases} \longrightarrow$$

$$V(\phi) \gg \frac{1}{2}\dot{\phi}^2 \Rightarrow \frac{(V_{,\phi})^2}{V} \ll H^2$$

AND

$$\ddot{\phi} << 3H\dot{\phi} \Rightarrow V_{,\phi\phi} \ll H^2$$

So the slow-roll conditions, as expected, means that the inflaton potential is very flat

It is then customary to parametrize inflationary models (i.e. the form of the inflaton potential) in a sort of model-independent way by introducing the slow-roll parameters

$$\epsilon = -\frac{\dot{H}}{H^2} = 4\pi G \frac{\dot{\phi}^2}{H^2} \simeq \frac{1}{16\pi G}\left(\frac{V_{,\phi}}{V}\right)^2 \ll 1$$: the Hubble rate changes slowly

$$\eta = \frac{1}{3}\frac{V_{,\phi\phi}}{H^2} = \frac{1}{8\pi G}\left(\frac{V_{,\phi\phi}}{V}\right) \ll 1$$: attractor solution

Primordial gravitational waves

GWs are tensor perturbations of the metric. Restricting ourselves to a flat FRW background (and disregarding scalar and vector modes)

$$ds^2=a^2(\tau)[- d\tau^2 + (\delta_{ij} + h_{ij}(\underline{x},\tau))\, dx^i\, dx^j]$$

where h_{ij} are tensor modes which have the following properties

$h_{ij} = h_{ji}$ (symmetric)

$h^i_{\ i} = 0$ (traceless)

$h^i_{\ j|i} = 0$ (transverse)

and satisfy the equation of motion

$$h''_{ij} + 2\frac{a'}{a} h'_{ij} - \nabla^2 h_{ij} = 0$$

$' = d/d\tau$

Primordial gravitational waves

GWs have only (9→6-1-3=) 2 independent degrees of freedom, corresponding to the 2 polarization states of the graviton

$$h_{ij}(\vec{x},\tau) = \int \frac{d^3k}{(2\pi)^3} e^{i\vec{k}\bullet\vec{x}} \varphi(\vec{x},\tau)\varepsilon_{ij}(\vec{k})$$

$$\varphi'' + 2\frac{a'}{a}\varphi' + k^2\varphi = 0$$

polarization tensor

free massless, *minimally coupled* scalar field

dynamical behaviour:

k « aH (outside the horizon) **φ ≈ const + decaying mode**

k » aH (inside the horizon**)** **$\varphi \approx e^{\pm ik\tau}/a$** gravitational waves: freely stream, experiencing redshift and dilution, just like free photons)

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

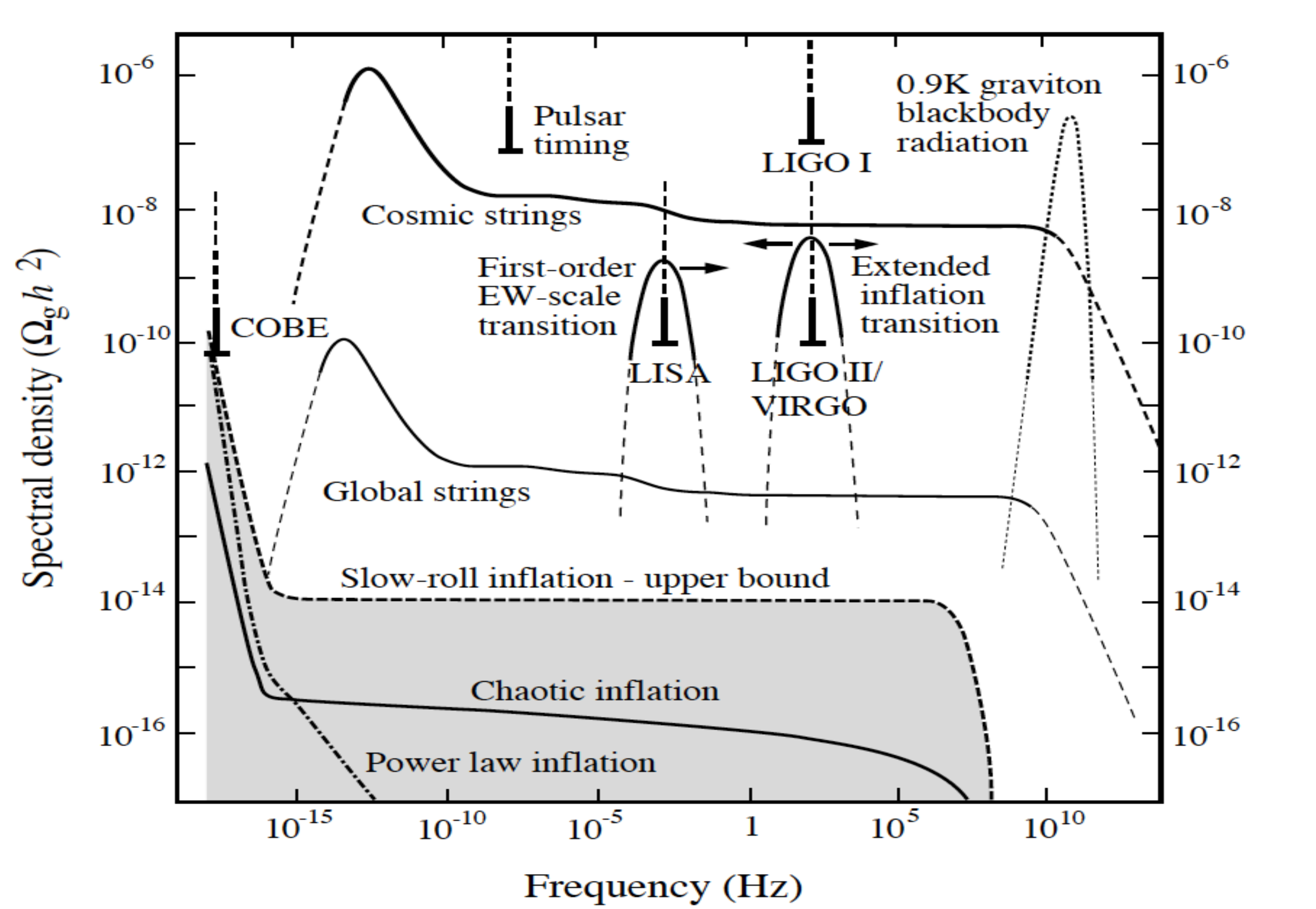
- **Tensor-to-scalar perturbation ratio**

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

- **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

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

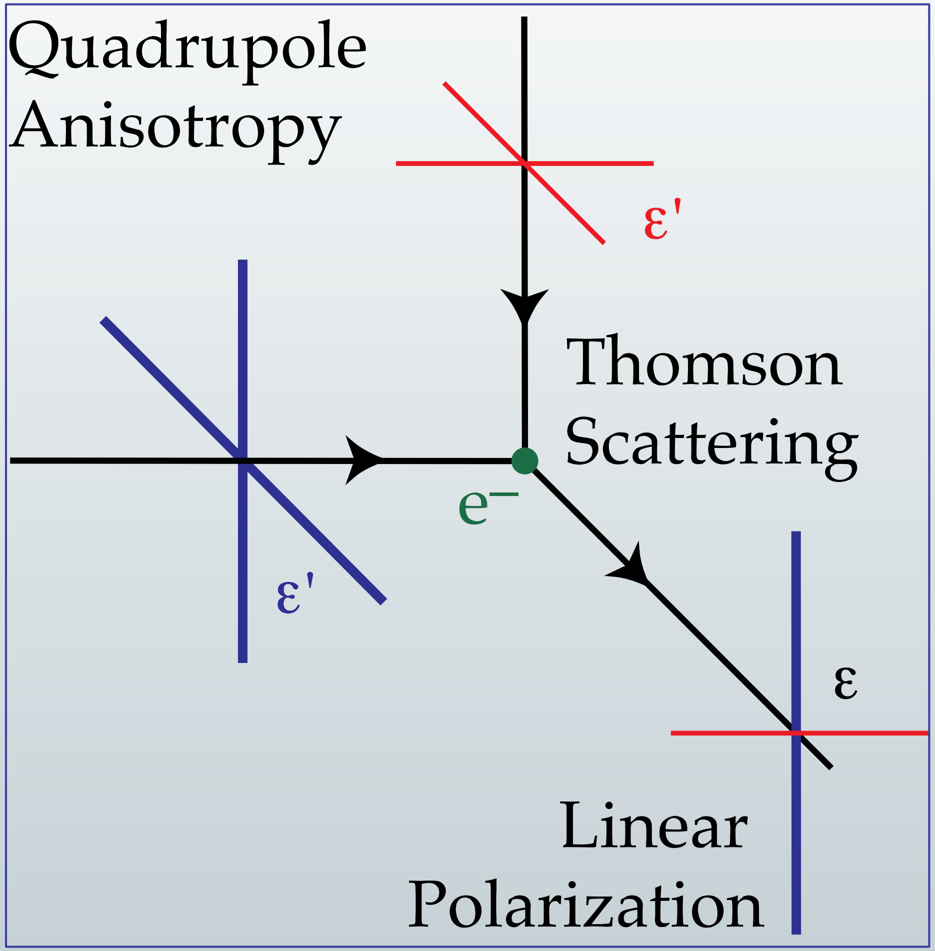


Battye & Shellard 1996

The search for primordial GW

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

CMB polarization



$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi}\left|\hat{\varepsilon}' \cdot \hat{\varepsilon}\right|$$

- Thomson scattering generates linear polarized radiation if the intensity of the incident radiation presents a quadrupole moment

- An incident quadrupole can arise from

  1. Anisotropies in the density of photons surrounding the electron (scalar perturbations)
  2. **A quadrupolar stretching of space due to a passing gravitational wave**

Assume we observed polarization in the CMB. Can we tell whether the source is a scalar or a tensor?

E, B polarization modes

- A vector can always be decomposed into a curl-free (electric) and a divergenceless (magnetic) component.

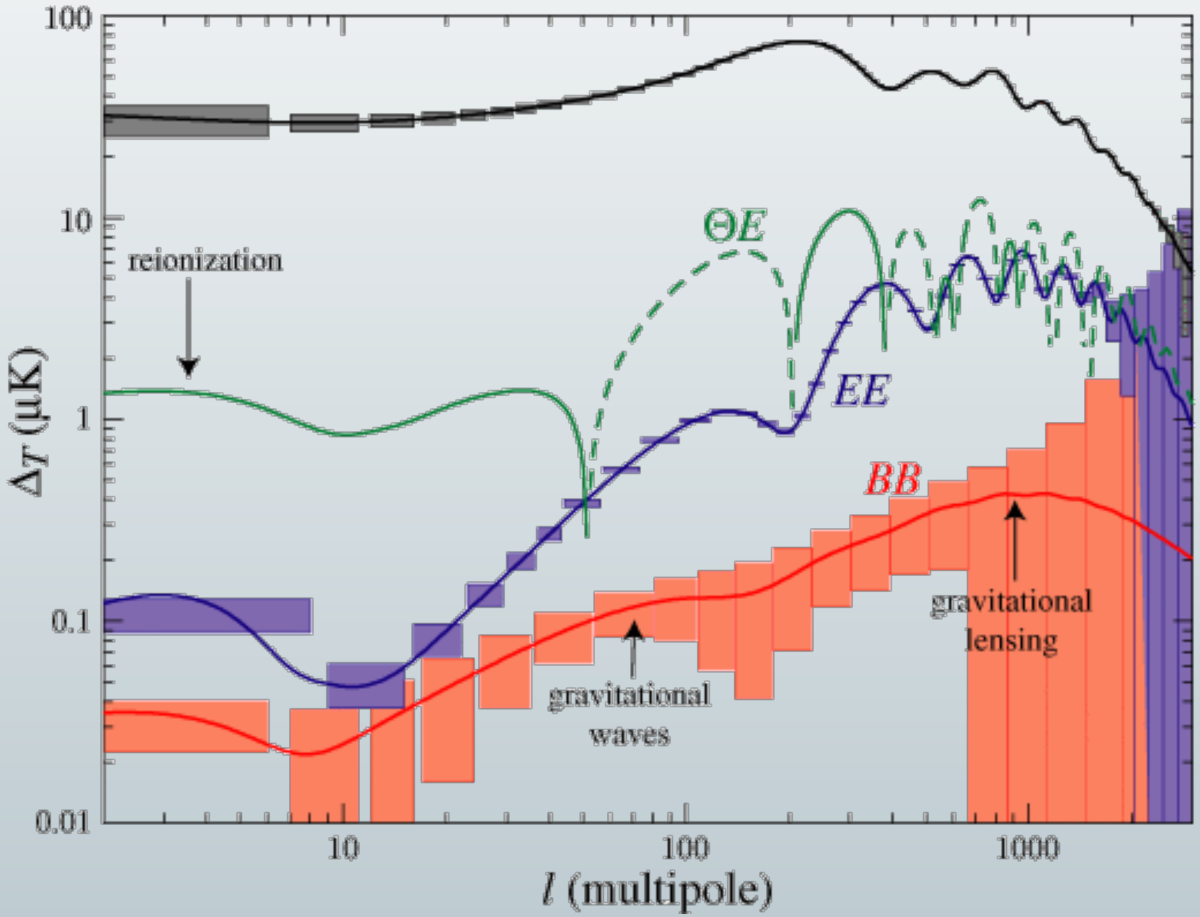
$$\vec{v} = \vec{\nabla}\phi + \vec{\nabla} \times \vec{A}$$

- P=(Q,U) does not transform as a vector but as a trace-free symmetric 2x2 tensor. A decomposition similar to the vector case still exists but it involves *second* (covariant) derivatives of two scalar fields called the E and B mode, in analogy with the vector case

- The usefulness of the E-B decomposition of CMB polarization will be clear shortly. As an anticipation: **scalar (density) perturbations can generate only an E-mode, while tensor (GW) perturbations source both E and B modes.**

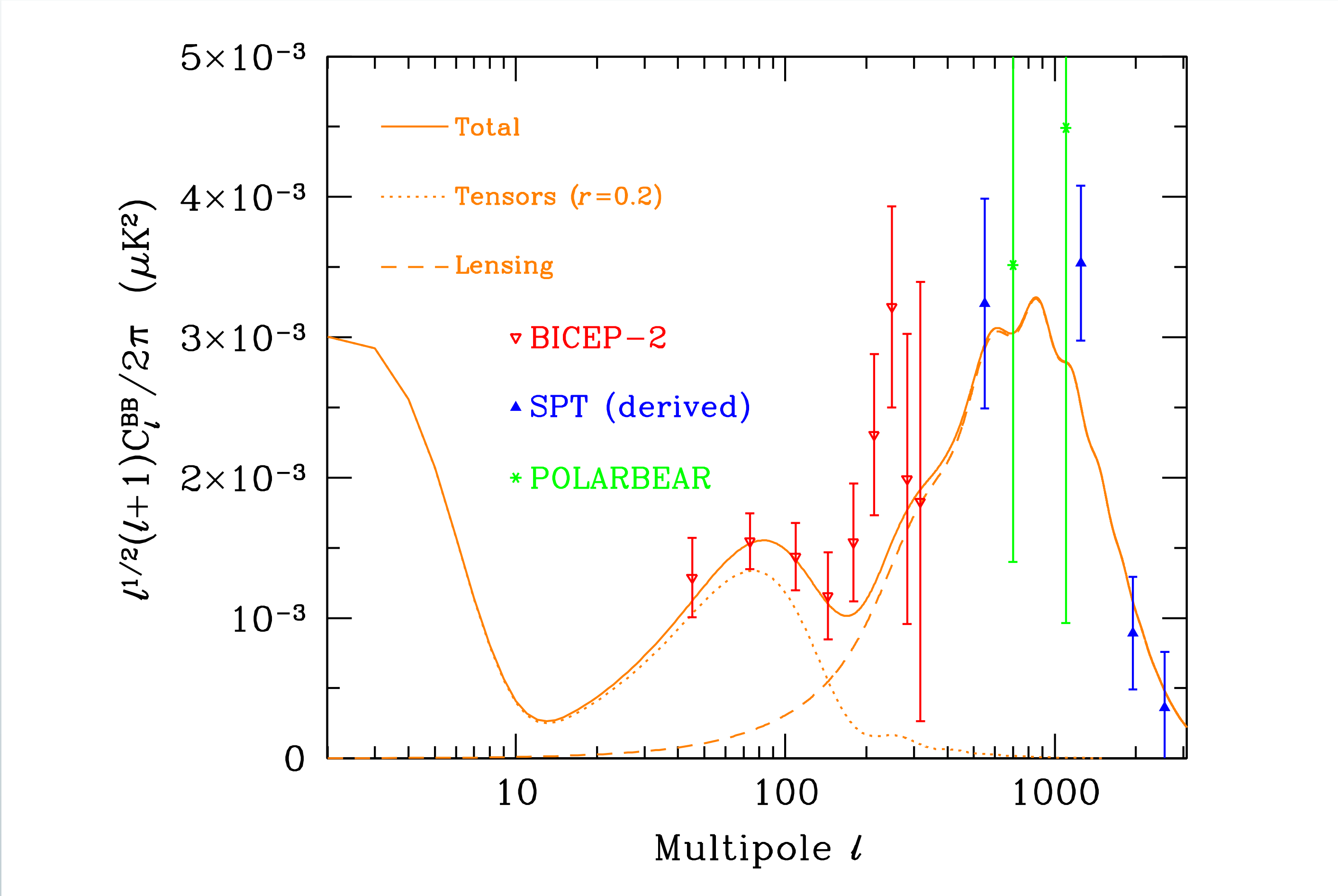
Power spectra

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



ℓ defines the wave angular frequency, corresponding to an angular scale $\vartheta \sim \dfrac{\pi}{\ell}$

BICEP2 vs. other observations



BICEP-2: $r = 0.2^{+0.07}_{-0.05}$ - r=0 excluded at the 5.9 σ level

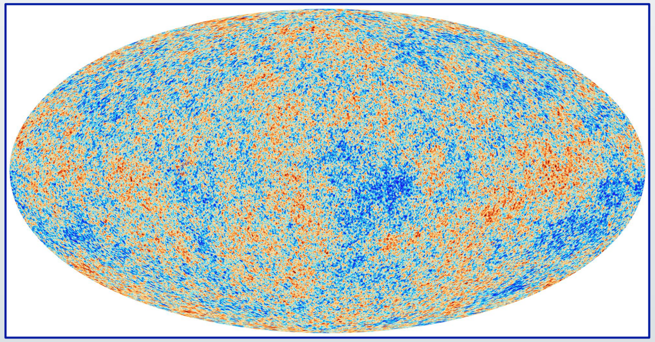
Comparison with *Planck*

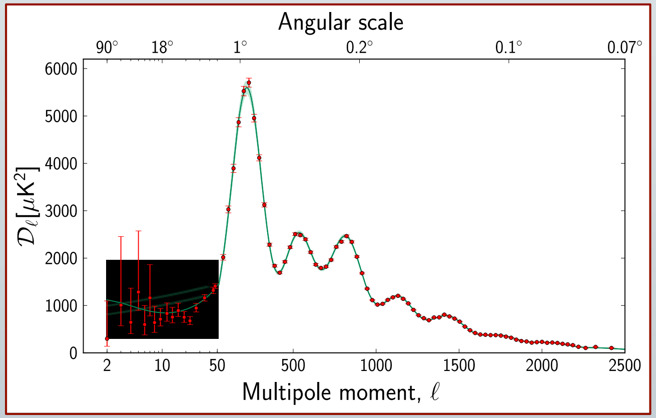
Tensor perturbations provide a contribution to the TT power spectrum. *Planck* could use this to set a constraint on r (in good agreement, and improving on previous WMAP constraint).

Foreground subtraction using DDM2 model (353 Ghz *Planck*-based) yields

$$r = 0.2^{+0.07}_{-0.05}$$ Bicep2 (BB) $$r = 0.16^{+0.06}_{-0.05}$$

$$r < 0.11 \ (95\% \ c.l.)$$ *Planck* (TT)





- There is some tension between the two measurements. It can be alleviated allowing a running of the scalar spectral index. However the required level of running is not easy to realize in an inflationary context.

- Note however that dust subraction already brings r from BICEP2 down to r=0.16. The preliminary plot from Keck array also shows that high-l outliers disappear. That might bring r down further

Future prospects

- The primordial B-mode detection by Bicep2 looks robust
- Additional and more accurate measurements from the ground will come from Keck array and Bicep3.
- *Planck* can play a crucial role in confirming the discovery:
  - *Full sky* measurements → low-l reionization BB spectrum bump is accessible
  - *Multi-frequency* measurements. Accurate characterization of B-mode dust emission

Observational predictions

- Primordial density (scalar) perturbations

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amplitude

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

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

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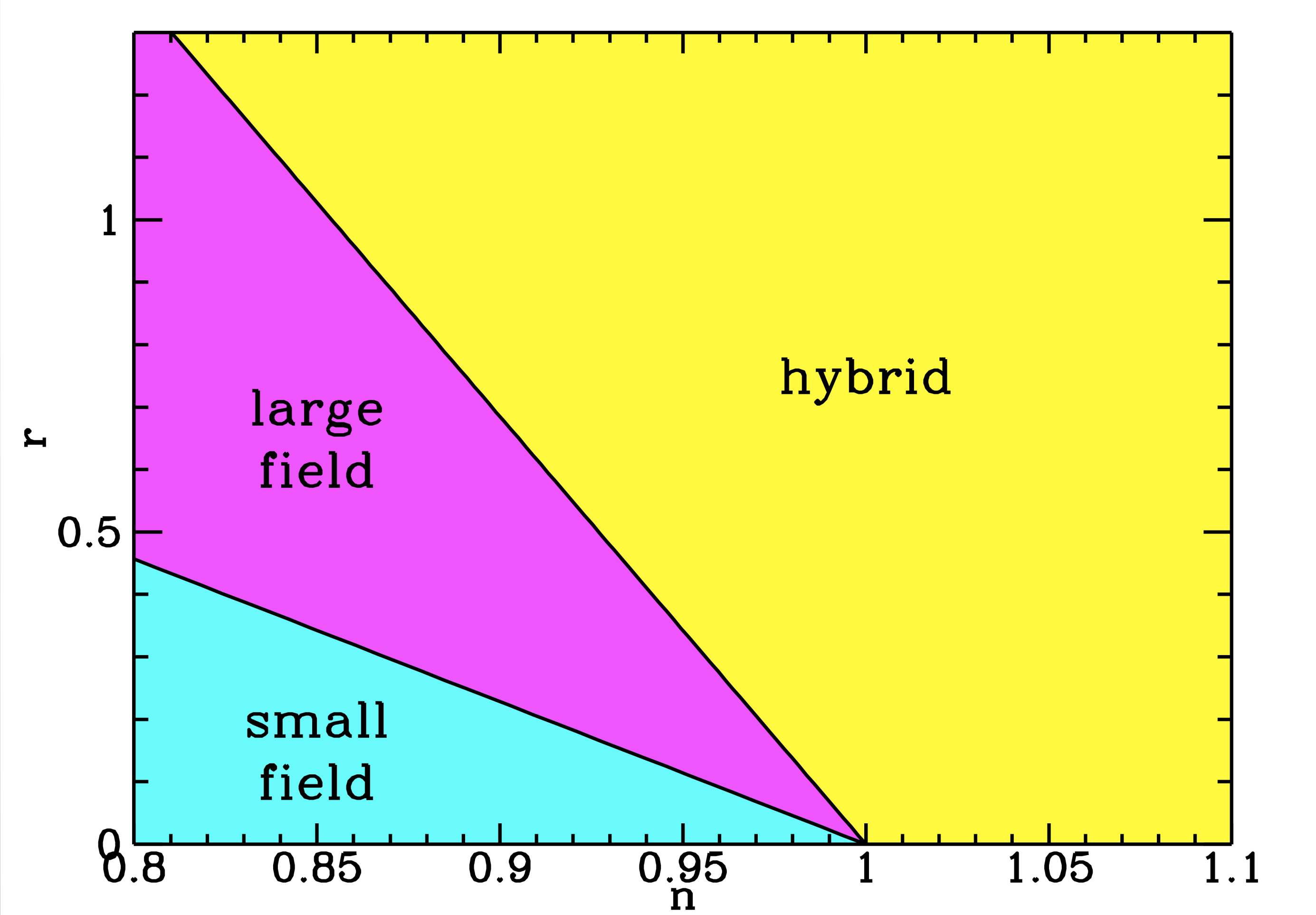
- Consistency relation (valid for *all* single field models of slow-roll inflation):

$$r = -8n_T$$

Classifying inflationary models



e.g., Kinney et al.
astro-ph/0007375

Two simple but very important examples

``Large field'' models

$$V(\phi) \propto \phi^{\alpha}$$

typical of ``caothic inflation scenario''
(Linde `83)

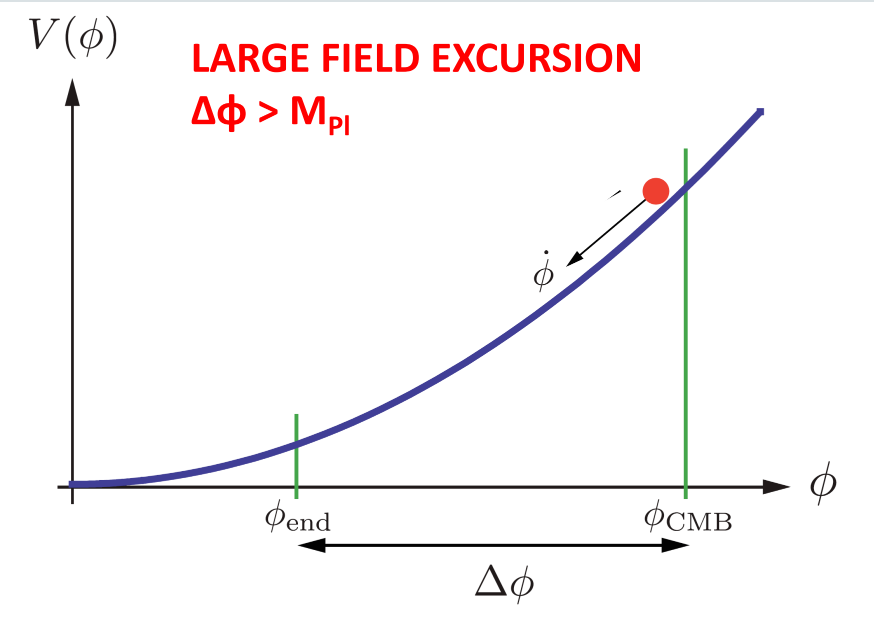
$$V(\phi) \propto \exp[\phi/\mu]$$

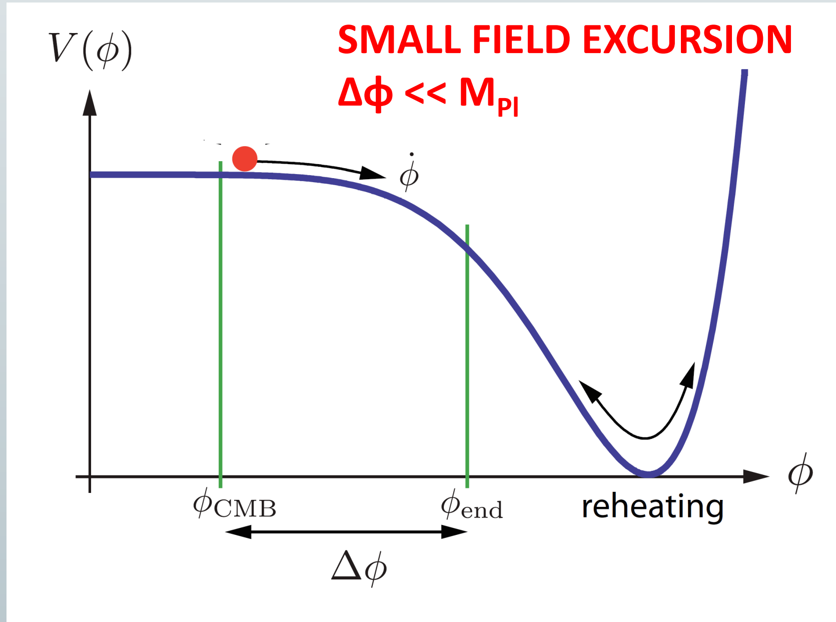
``power law inflation'' (Lucchin, Matarrese'85)

``Small field'' models

$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{\mu}\right)^p\right] \qquad \phi < \mu < M_{\rm Pl}$$

from spontaneous symmetry breaking or Goldstone, axion models (Linde; Albrecht, Steinhardt `82; Freese et al '90)





Inflaton dynamics and the level of gravity waves

"Large field'' models can produce a high level of gravity waves (r>0.01)
"Small field'' models produce a low level of gravity waves (r<0.01)

$$\frac{\Delta\phi}{m_{\rm Pl}} \simeq \left(\frac{N}{30}\right) \times \left(\frac{r}{0.01}\right)^{1/2}$$

$30 \leq N \leq 60$.

So the bigger the field excursion during inflation the bigger the amplitude of gravity waves

Planck constraints on inflation

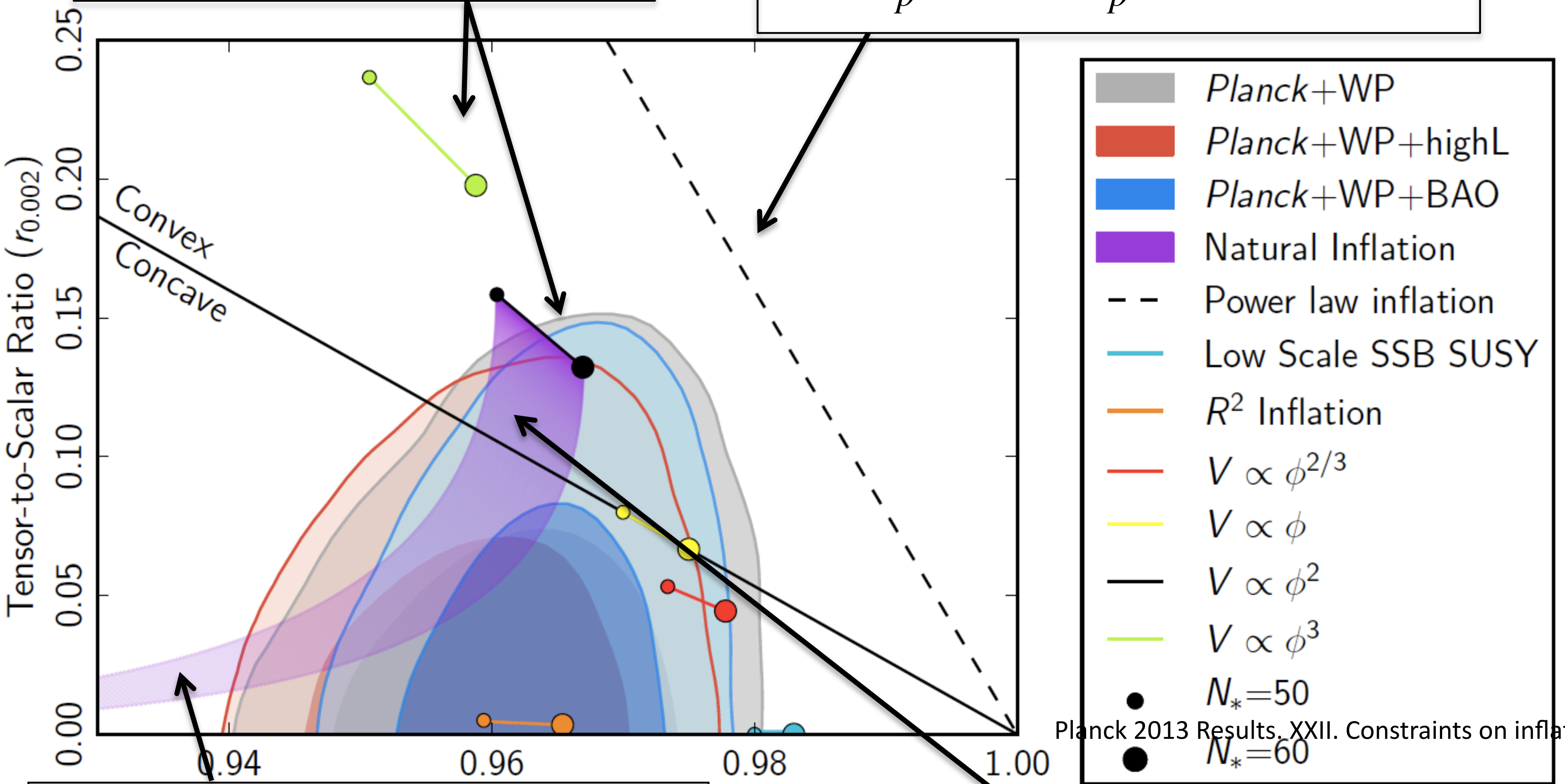
Large field models $V(\phi) \propto \phi^{\alpha}$

$$r = \frac{4\alpha}{N} \qquad 1-n = \frac{\alpha+2}{2N}$$

Exponential models

$$V(\phi) \propto \exp[-\sqrt{2/p}\ \phi / M_{Pl}] \rightarrow a(t) \propto t^{p}$$

$$r = \frac{16}{p} \qquad 1-n = \frac{2}{p}$$



Planck 2013 Results, XXII. Constraints on inflation

Small field models $V(\phi) \propto 1-(\phi/\mu)^{p}$, $p \geq 3$

$$r \sim 0 \quad 1-n = \frac{2}{N}\frac{(p-1)}{(p-2)}$$

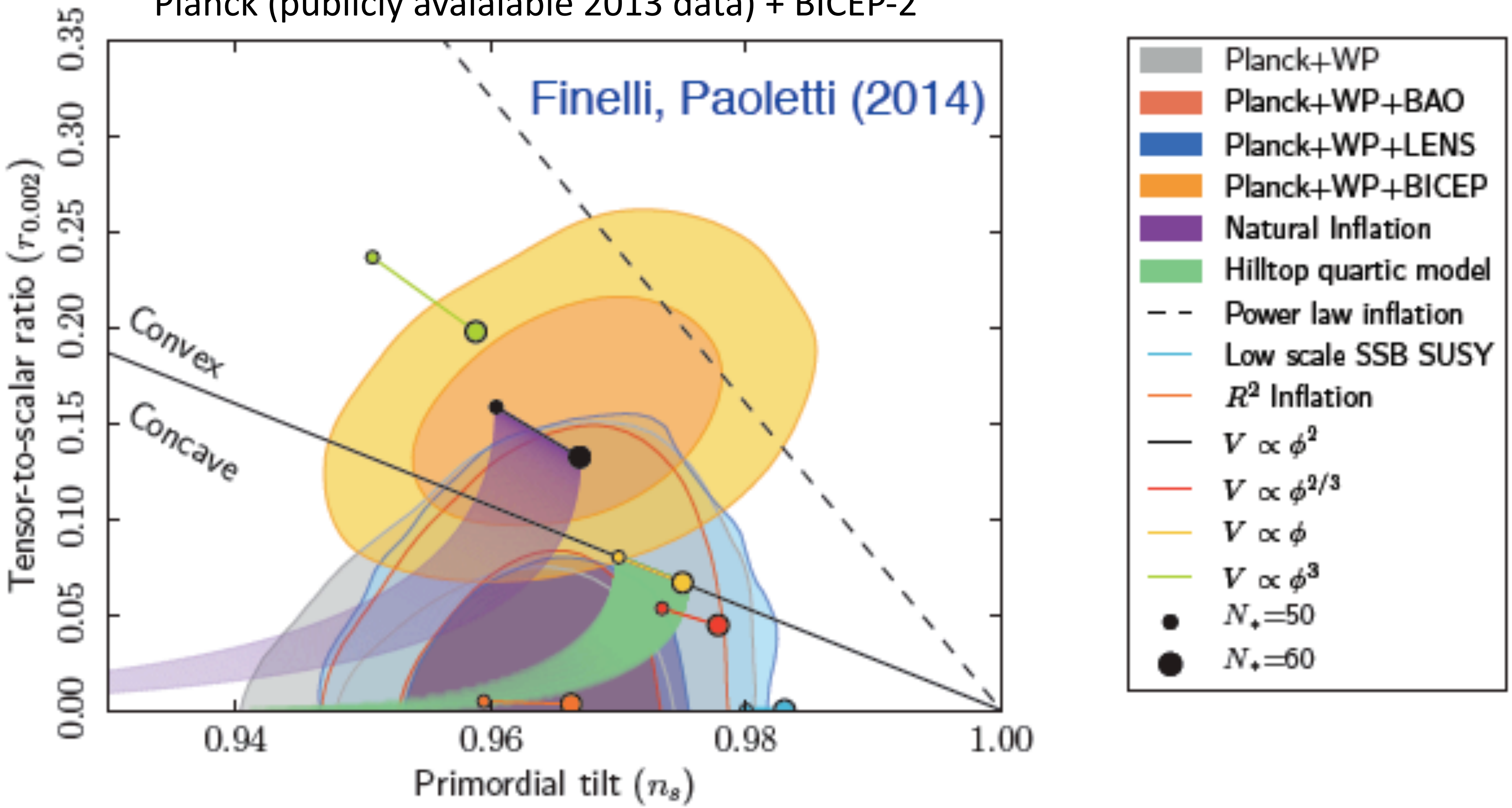
for example p = 3 out of 95% *CL*

Natural inflation $V(\phi) \propto 1+\cos(\phi/f)$

consistent for $f \geq 5M_{Pl}$

After BICEP-2 ... consequences for inflation models

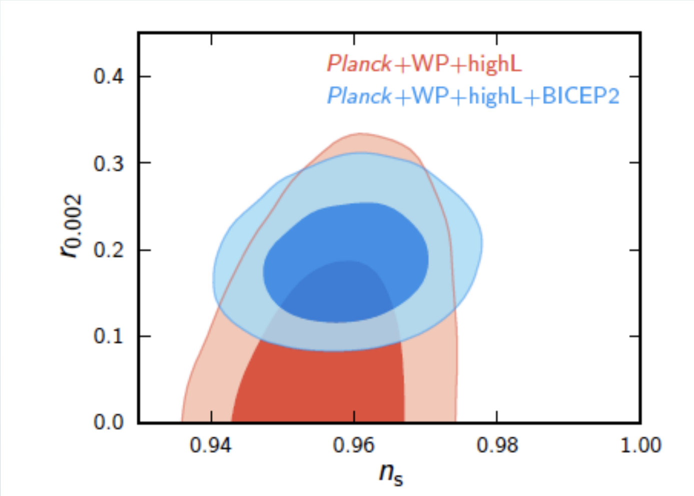
Planck (publicly avaialable 2013 data) + BICEP-2



Is there a tension between *Planck* and BICEP-2?

If the tension is real → various ways to reconcile the two observations. However, beware of different notation (!!). *When the two experiments are compared using the same notation, the tension reduces to less than 1 sigma!*

Negative *running of the spectral index*



$$\frac{dn_s}{d\ln k} \sim -2\%$$

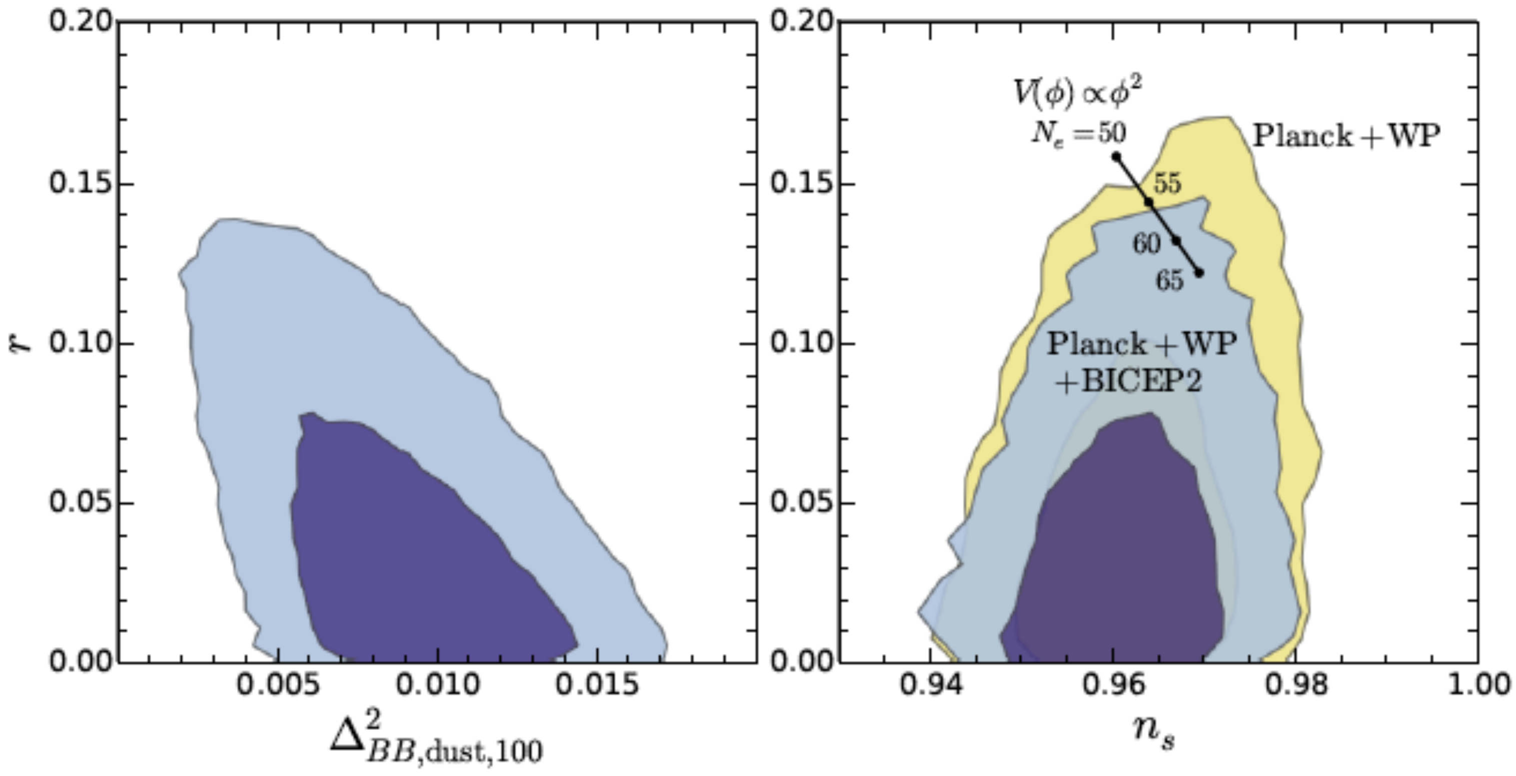
BUT THIS WOULD RULE OUT ALL SIMPLEST MODELS OF INFLATION

(they typically predict running O(10^{-3})).

- Blue tilt of GW (Giusarma et al. 2014; Smith et al. 2014; Hu et al. 2014)
- (step) Feature in the inflaton potential, e.g. Miranda et al. *arXiV:1403.5231*
- etc. ...

First attempts to account for dust

Mortonson & Seljak 2014



Left: Joint constraints (68% and 95% c.l.) on r and the amplitude of the dust polarization spectrum at l = 100 from Planck+W +BICEP2, assuming a flat prior on the dust amplitude. Right: Constraints from the same combination of data in the r–n_s plane (blue contours), compared with constraints from Planck+WP alone (yellow contours). The 95% c.l. contour of Planck+WP can be seen extending to larger values of r than the contours that include BICEP2. The plotted line shows the relation between ns and r predicted by inflation models with ϕ^2 potentials and the number of e-folds varying from 50 to 65.

See also Flauger et al. 2014

Problems with BICEP-2 ?

- Flauger, Hill & Spergel 2014: <<Bicep2 has reported the detection of a degree-scale B-mode polarization pattern in the CMB and has interpreted the measurement as evidence for primordial gravitational waves. Motivated by the profound importance of the discovery of gravitational waves from the early Universe, we examine to what extent a combination of Galactic foregrounds and lensed E-modes could be responsible for the signal. We reanalyze the Bicep2 results and show that the 100 150 GHz and 150 150 GHz data are consistent with a cosmology with r = 0:2 and negligible foregrounds, but also with a cosmology with r = 0 and a signicant dust polarization signal. ... >>

Consequences for high energy physics

- Inflation is probing the GUT scale!
  Tremendously high-energy scales never achievable in laboratories

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

- Inflation is providing a clear 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 *strongly* reduces the number of inflationary models that agree with data

- Low-energy scale inflation models are strongly 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≈0.0034 → RULED OUT *(some fairly contrived variants still alive)*

- R^2 inflation (Starobinsky '80) *(connected to Higgs inflation by a Weyl rescaling)*

  Prediction: r≈0.0034 → RULED OUT

... many more inflation models ruled out by BICEP2 results (if confirmed)

Consequences for inflationary models

- A simple quadratic potential $V(\phi) = \frac{m^2}{2}\phi^2$ (Linde '82) perfectly sits within 1σ-regions

- ``Natural'' inflation (Freese et al. 90):
  flat potential arises naturally as result of a shift symmetry

$$V(\phi) = V_0 \left[1 - \cos\left(\frac{\phi}{\mu}\right)\right]$$

  consistent with data

Sensitivity of Inflation to fundamental physics?

The question is: "is the excursion of the field $\Delta\varphi > M_{PL}$ a problem for inflation models?"

Not necessarily. Rather, it could be an opportunity to probe high-energy physics and the physics behind inflation.

Rely on some symmetry criterion: e.g. approximate shift-symmetry → flatness of inflaton potential

Interpreting the energy scale ...

- "The inflationary energy density ($\rho^{1/4}$ = 1.5 x 10^{16} GeV) is the same as the GUT scale M_G. That must be a coincidence, though, because M_G represents the *vev* of the GUT Higgs fields and not the height of their potential. The height of their potential will be some coupling constant $\lambda << 1$ times M_G^4. The energy scale of GUT inflation models, which generate the inflationary energy density from the GUT Higgs fields, is therefore too low to generate the observed r."

David Lyth, 28/03/2014

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''):

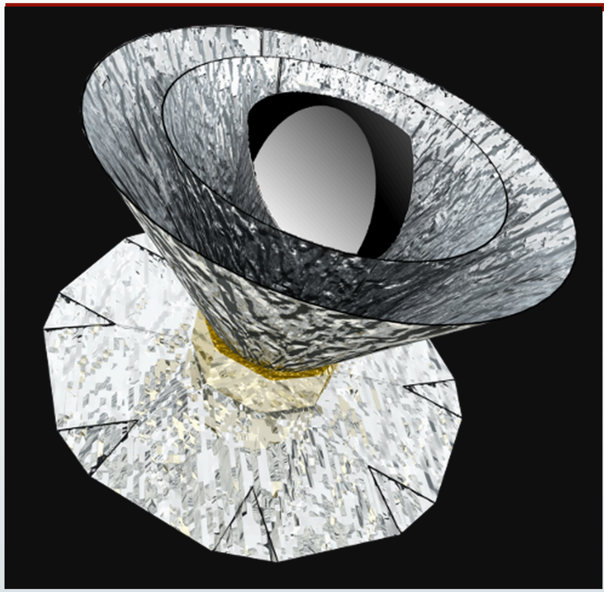
$$r = -8n_T$$

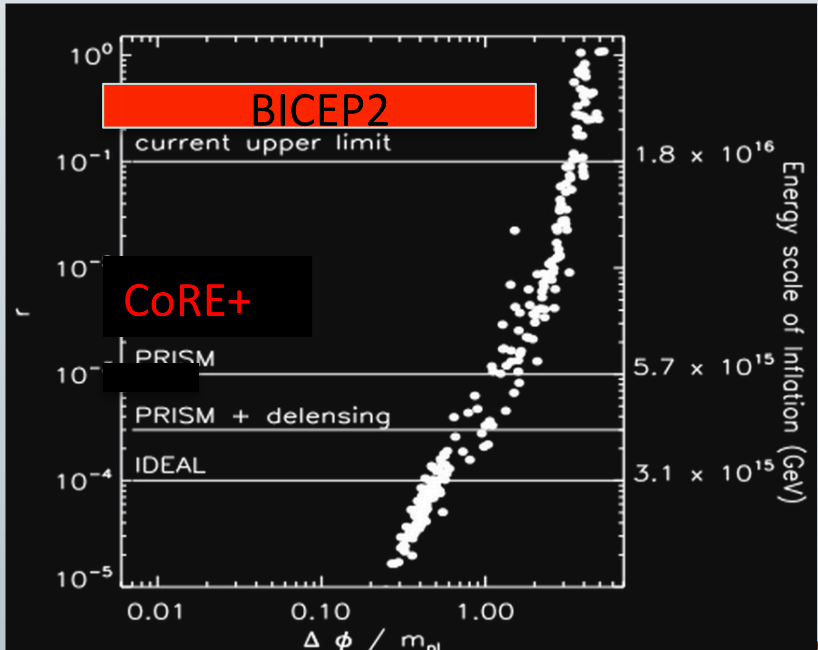
generalized to inflaton w. non-canonical kinetic term
$r = -8c_s n_T$ with $c_S > 0.02$ (Planck 2013)

- Try to measure higher-order correlators of the tensor perturbations, like the 3-point function of tensors <hhh> → graviton interactions (upper bounds obtainable by *Planck* 2014)

- Try to constrain deviation from GR at very high-energies
  → Implications for GW detectors?

What Next? CoRE+ → an opportunity





- The *ultimate* CMB polarization mission
- A "Cosmic Origins" explorer will be submitted to ESA in response to a M4 call for proposal (next Fall?)
- Timeframe: late 2020s
- At least 30 times more sensitive than Planck
- Wide frequency coverage (e.g. 50 - 800 GHz) to leverage out foreground contamination
- Near total control of systematics – no suborbital probe can achieve this
- If Bicep2 result will hold to scrutiny, you will need a CoRE+ mission to squeeze inflation science out of tensor modes
- If Bicep2 results will not hold, the lesson learnt will call even more strongly for a satellite mission, the only chance to squeeze r to $O(10^{-3})$ and measure tensor spectral index n_T to high accuracy, hence being able falsify inflationary tensor consistency relation

Non-Gaussian 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.
- We should aim at "reconstructing" the inflationary action, starting from measurements of a few observables (like n_S, r, n_T, f_{NL}, g_{NL}, etc. …), just like in the nineties we were aiming at a reconstruction of the inflationary potential (see revival of this industry after Bicep2 ...).

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)

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

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

$$\text{NG \%} \sim 10^{-5}\ |f_{NL}| \quad \leftarrow \quad < 10^{-4} \text{ from CMB \& LSS}$$

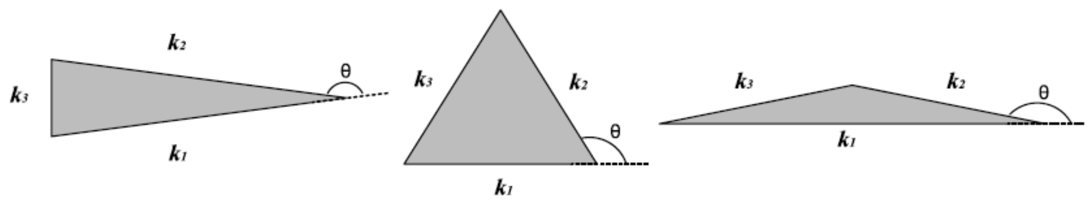
$$\sim 10^{-10}\ |g_{NL}| \quad \leftarrow \quad < 10^{-4} \text{ from CMB \& LSS}$$

"non-Gaussian = non-dog"
(Ya.B. Zel'dovich)

.. and the NG shape information

... there are more shapes of non-Gaussianity (from inflation) than ... stars in the sky

bispectrum shapes



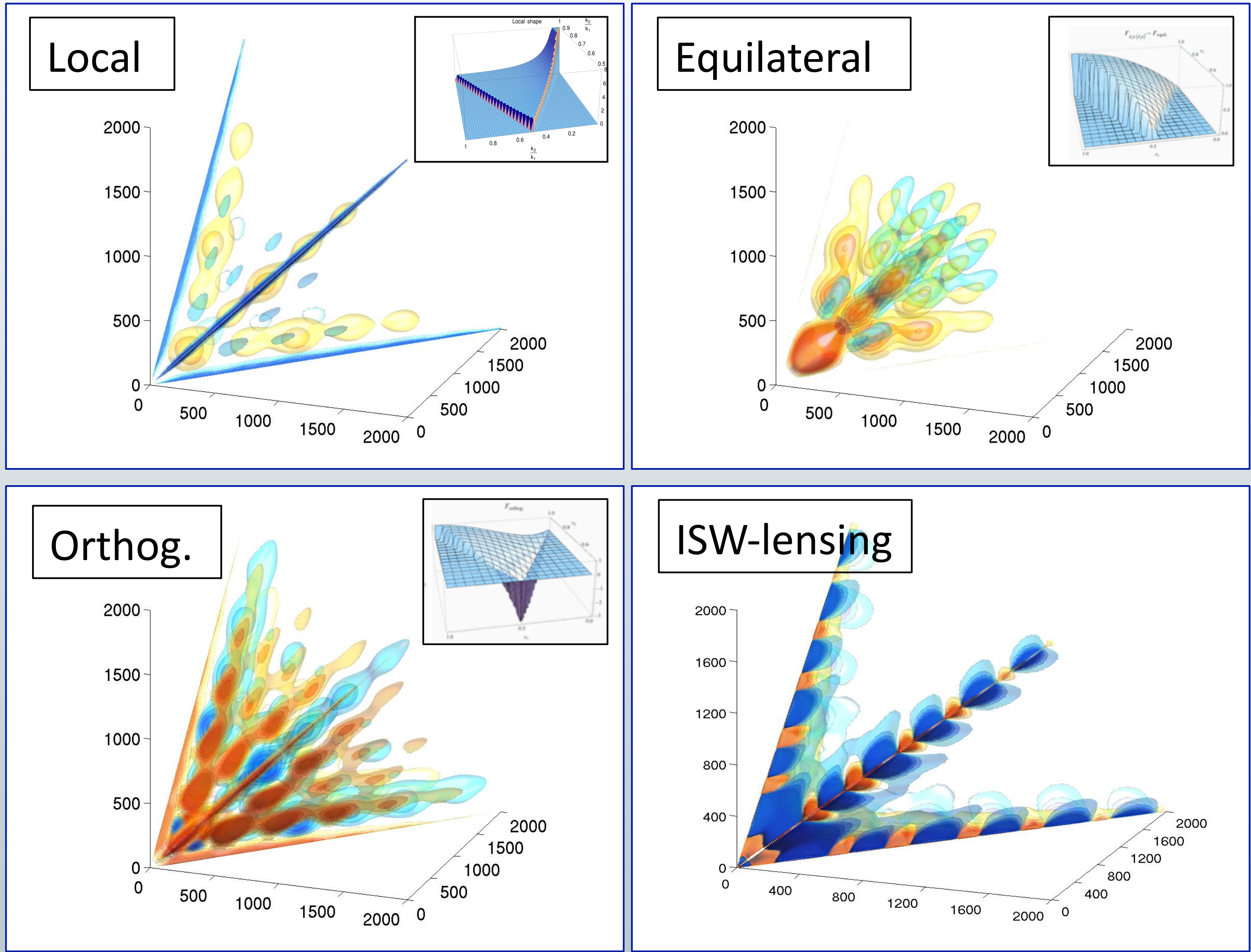
(1) Squeezed (2) Equilateral (3) Folded

+ many more

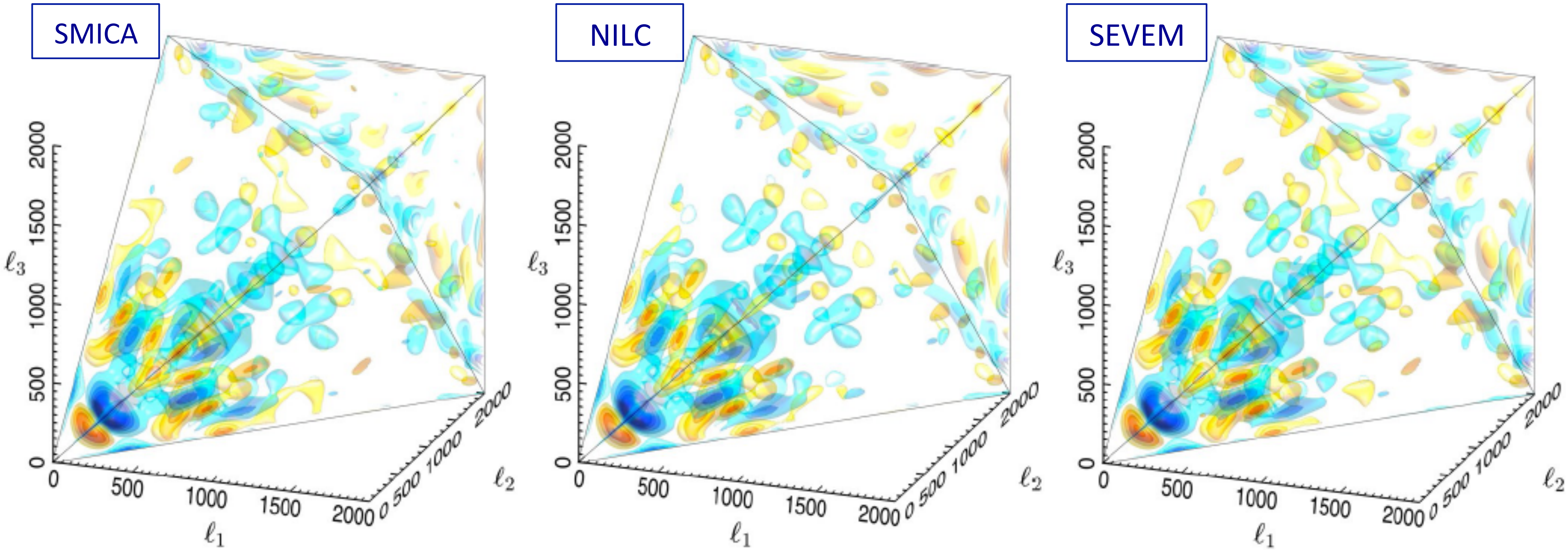
Bispectrum shapes (... a few of them)

- **local** shape: Multi-field models, Curvaton, Ekpyrotic/cyclic, etc. ...
- **equilateral** shape: Non-canonical kinetic term, DBI, K-inflation, Higher-derivative terms, Ghost, EFT approach
- **orthogonal** shape: Distinguishes between variants of non-canonical kinetic term, higher-derivative interactions, Galilean inflation
- **flat** shape: non-Bunch-Davies initial state and higher-derivative interactions, models where a Galilean symmetry is imposed. The flat shape can be written in terms of equilateral and orthogonal.

Bispectrum shapes



The *Planck* modal bispectrum



Full 3D CMB bispectrum recovered from the *Planck* foreground-cleaned maps, including SMICA, NILC and SEVEM, using hybrid Fourier mode coefficients, These are plotted in three-dimensions with multipole coordinates (l_1,l_2,l_3) on the tetrahedral domain out to l_{max} = 2000. Several density contours are plotted with red positive and blue negative. The bispectra extracted from the different foreground-separated maps are almost indistinguishable

Fundamental shapes (KSW)

- Results for the f_{NL} parameters of the primordial local, equilateral, and orthogonal shapes, determined by the KSW estimator from the SMICA foreground-cleaned map. Both independent single-shape results and results marginalized over the point-source bispectrum and with the ISW-lensing bias subtracted are reported; error bars are 68% CL.

	Independent KSW	**ISW-lensing subtracted** KSW
SMICA		
Local	9.8 ± 5.8	**2.7 ± 5.8**
Equilateral	-37 ± 75	**-42 ± 75**
Orthogonal	-46 ± 39	**-25 ± 39**

- Union Mask U73 (73% sky coverage) used throughout. Diffusive inpainting pre-filtering procedure applied.

Standard inflation vs. NG

Standard inflation i.e.

- *single scalar field*
- *canonical kinetic term*
- *slow-roll dynamics*
- *Bunch-Davies initiual vacuum state*
- *standard Einstein gravity*

predicts $O(10^{-2})$ primordial NG signal

→ no (presently) detectable primordial NG

Planck results

- We have detected the Integrated-Sachs-Wolfe-lensing bispectrum at the level expected in the ΛCDM scenario and the Poissonian point-source bispectrum contribution.
- We have derived constraints on early-Universe scenarios that generate primordial NG, including general single-field models of inflation, excited initial states (non-Bunch-Davies vacua), and directionally-dependent vector models.
- We have provided an initial survey of scale-dependent feature and resonance models. These results bound both general single-field and multi-field model parameter ranges, such as the speed of sound, $c_s \geq 0.02$ (95% CL), in an effective field theory parametrization ($c_s \geq 0.07$ *for DBI inflation*), and the curvaton decay fraction $r_D \geq 0.15$ (95% CL).
- We have constrained the amplitude of the four-point function in the local model $\tau_{NL} < 2800$ (95% CL), using an estimator introduced by Hanson & Lewis 2009, which is based on large-scale modulation of small-scale power.

Planck results

- 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.*
- *Analyzing the statistics of fields in cosmology proved an incredibly powerful tool to test fundamental physics at the highest achievable physical scales (10^{16} GeV?)*

Conclusions

- BICEP-2 claimed having observed the imprints on CMB polarization of gravitational waves originated by quantum vacuum oscillations (→ gravitons) in the very early Universe
- If confirmed it provides strong support for inflation theory
- Energy scale of inflation (GUT scale) determined
- Probe of physics at 10^{13} times the energy scale of LHC → evidence for physics beyond the SM
- Together with *Planck* limits on primordial NG these results suggest that standard single-field slow-roll inflation is favoured
- Far reaching consequences for detailed models of inflation (hints for UV completion?)
- This observation calls for confirmation by independent observations, such as *Planck* CMB polarization data analysis can soon (!) provide.