A model-independent fit to Planck and BICEP2 data

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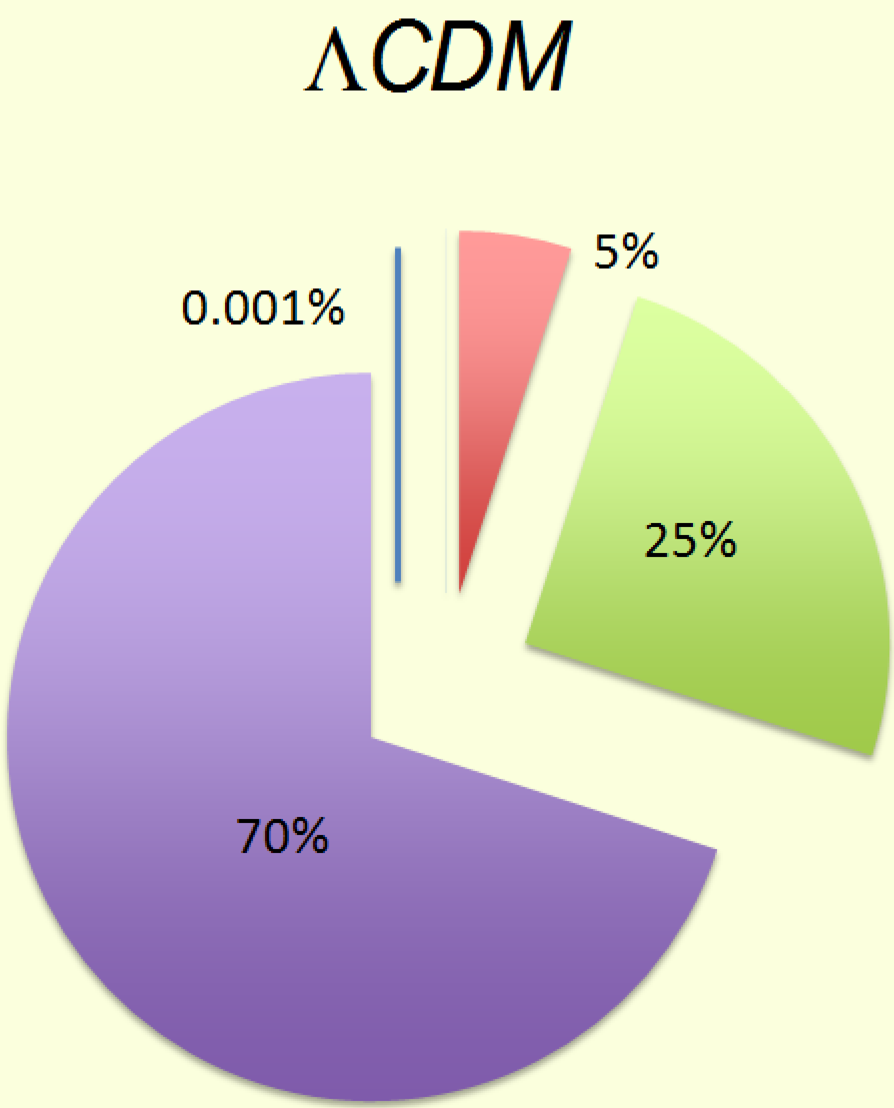
Outline

- The standard cosmological model
- Inflation
- BICEP2 and Planck data
- An alternative parameterization
- Method
- Results
- Conclusions

What is the universe made of?



- Radiation $a \propto t^{1/2}$
- Baryonic matter $a \propto t^{2/3}$
- Dark matter $a \propto t^{2/3}$
- Dark energy $a \propto t^{2/3(1+\omega)}$

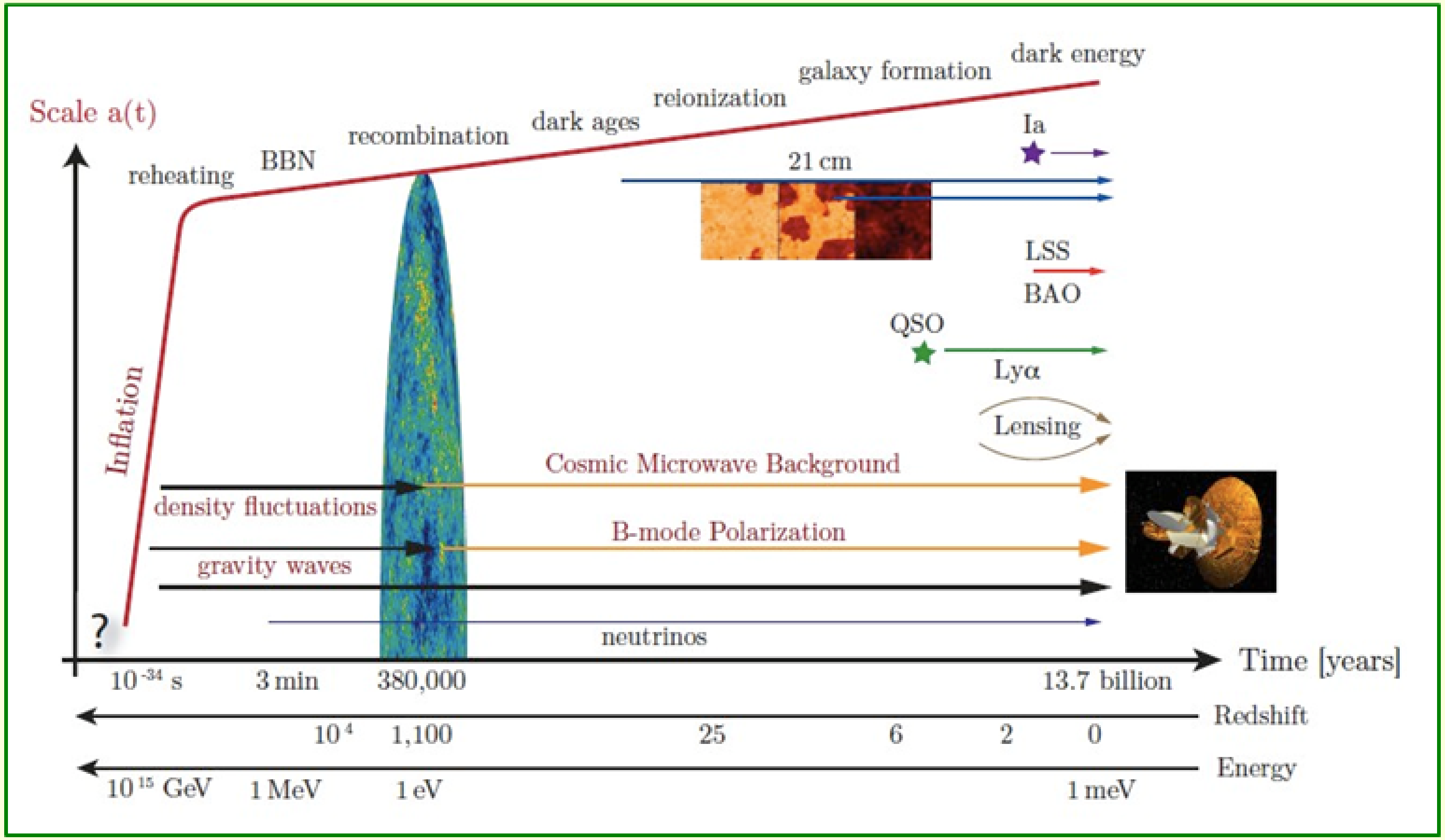
Friedmann equation:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

Fluid equation:

$$\dot{\rho} + 3H(\rho + p) = 0$$

Inflation: ä>0



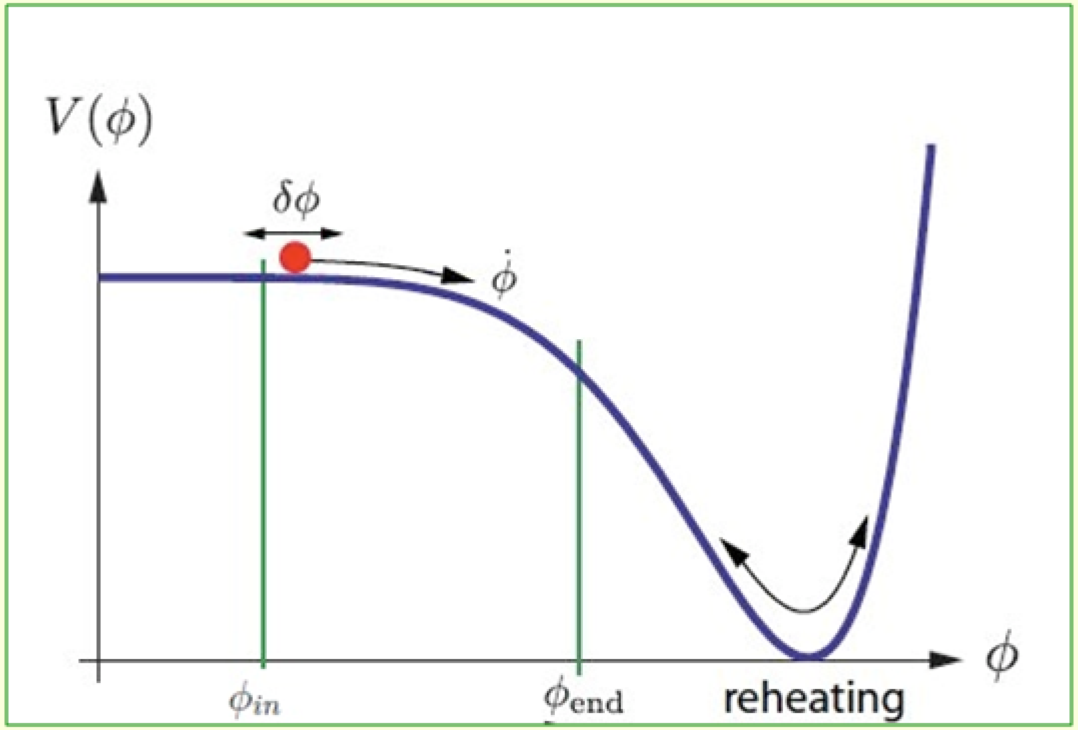
$$p = -\rho \Rightarrow a(t) = a_0 e^{Ht}$$

(Starobinsky'1980,Guth'1981, Linde'1983)

Inflation: Slow Roll parameterization

Slow Roll approximation

- Beginning:
  $\dot{\phi}^2 << V(\phi)$
- End:
  $\dot{\phi}^2 \approx V(\phi)$



Slow-roll parameters

$$\varepsilon \equiv \frac{1}{2} M_{Pl}^2 \left(\frac{V'}{V} \right)^2$$

$$\eta \equiv M_{Pl}^2 \left(\frac{V''}{V} \right)$$

Inflation: generation of perturbations

- Scalar perturbations ➔ Growth of structures
- Tensor perturbations ➔ Gravitational waves

Power Spectra

$$P_\Psi(k) = A_S k^{n_s-1}$$

$$P_h(k) = A_T k^{n_T}$$

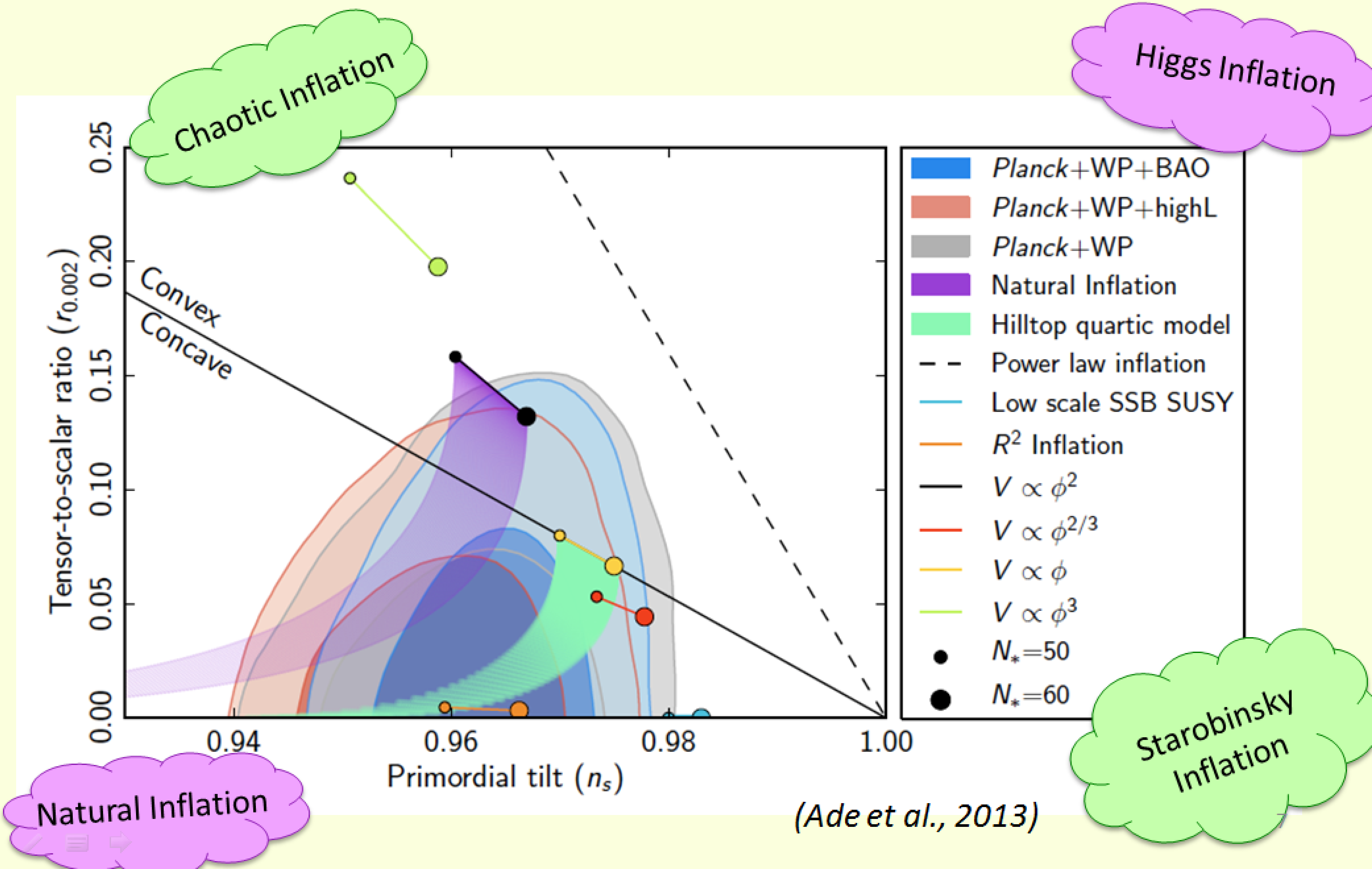
Tensor-to-scalar ratio:

$$n_S = 1 + 2\eta - 6\varepsilon$$

$$r \equiv \frac{P_h}{P_\psi} = 16\varepsilon = -8n_T$$

Inflation consistency

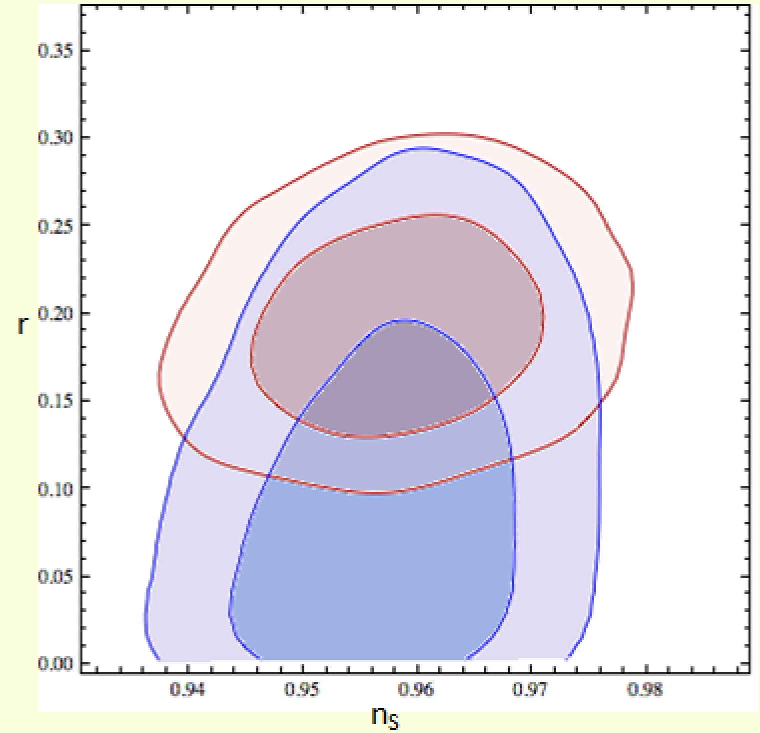
Some models and predictions



(Ade et al., 2013)

BICEP2 and Planck data

BICEP2	Planck
Polarimeter at South Pole	Satellite
Small patches of the sky	All the Sky
$30 < \ell < 150$	$2 < \ell < 2400$
$r = 0.20^{+0.07}_{-0.05}$	$r < 0.11 (95\% CL)$



- Blue: 68% and 95% CL regions of Planck
- Red:68% and 95% CL regions of BICEP2

(Ade et al. Planck coll'2013, Ade et al. BICEP2 coll'2014)

An alternative parameterization: Mukhanov parameterization

$$\frac{p}{\rho}+1=\frac{\beta}{(1+N_e)^{\alpha}}$$

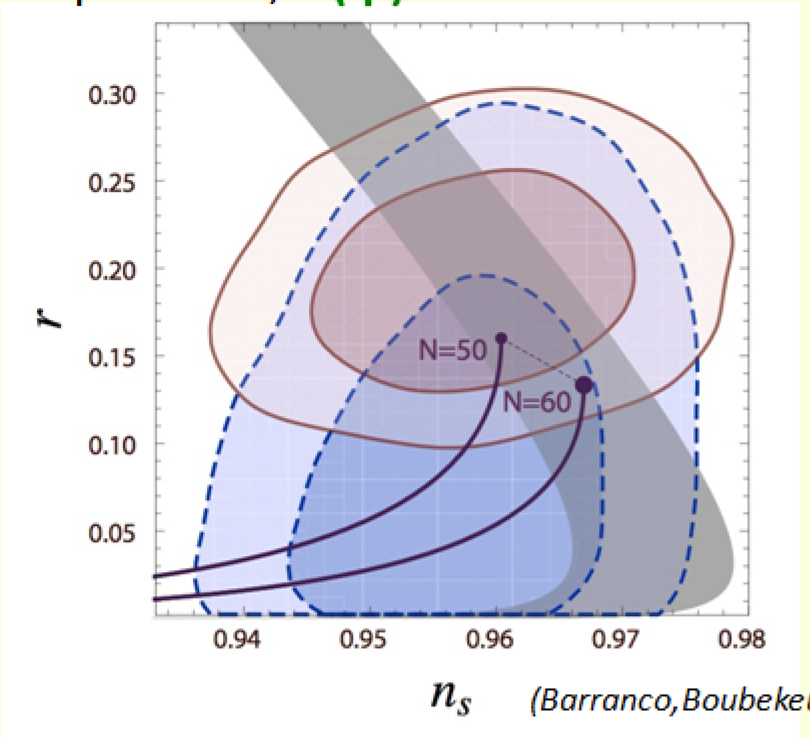
(Mukhanov'2013)

$$n_S-1=-3\frac{\beta}{(N_*+1)^{\alpha}}-\frac{\alpha}{N_*+1}$$

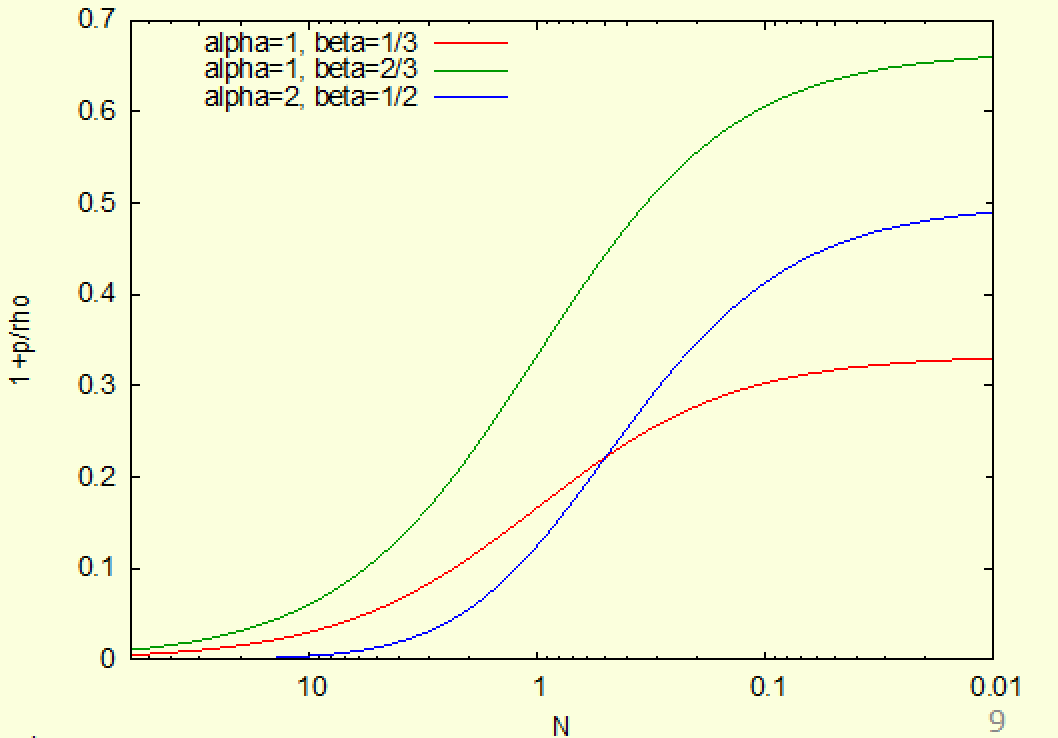
$$r=\frac{24\beta}{(N_*+1)^{\alpha}}$$

α: 0 → 2.5
β: 0 → 1

We can relate the phenomenological parameters, **α** and **β**, to the inflation potential, **V(ϕ)**



(Barranco,Boubekeur,Mena'2014)



Method, cosmological parameters and cosmological data

Cosmological Parameters

Parameter	Prior
$\Omega_b h^2$	$0.005 \rightarrow 0.1$
$\Omega_c h^2$	$0.001 \rightarrow 0.99$
Θ_S	$0.5 \rightarrow 10$
τ	$0.01 \rightarrow 0.8$
$\ln(10^{10} A_S)$	$2.7 \rightarrow 4$
α	$0 \rightarrow 2.5$
β	$0 \rightarrow 1$

Cosmological Data

- Planck CMB temperature data
- 9-year WMAP polarization data
- 3-year BICEP2 polarization data

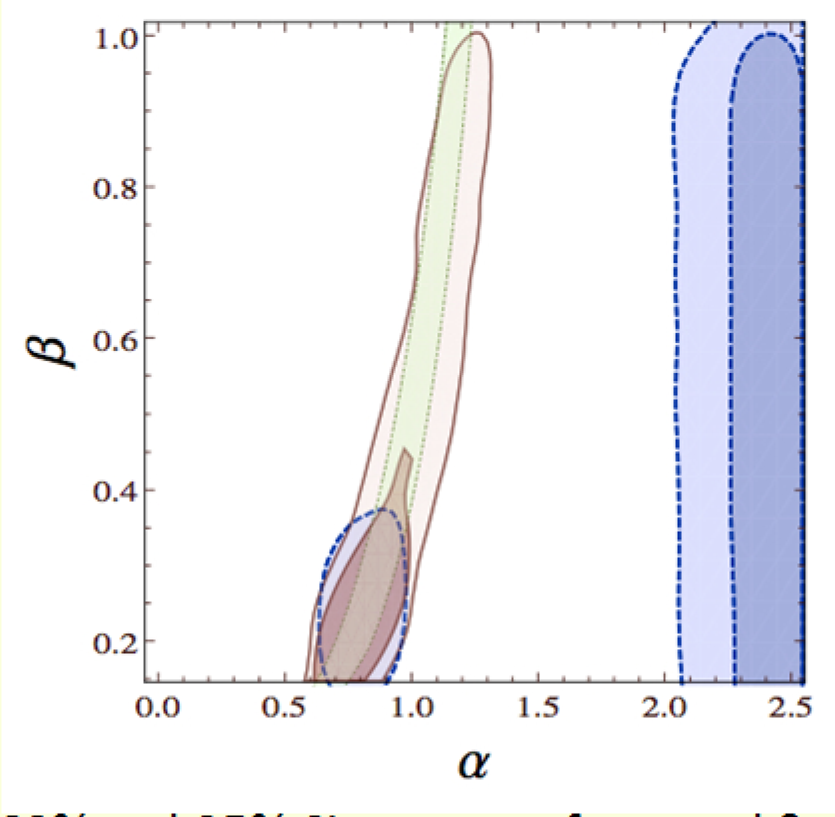
(Ade et al. Planck Coll.'2013,
Spergel et al. WMAP Coll.'2003
Ade et al. BICEP2 Coll'2014)

Method

- Numerical calculations: camb Boltzmann code *(camb: Lewis,Challinor,Lasenby'2000)*
- Derivation of distributions for the cosmological parameters: Monte Carlo Markov Chain analyses using cosmomc code which implements the Metropolis-Hasting algorithm *(cosmomc: Lewis, Bridle'2002)*

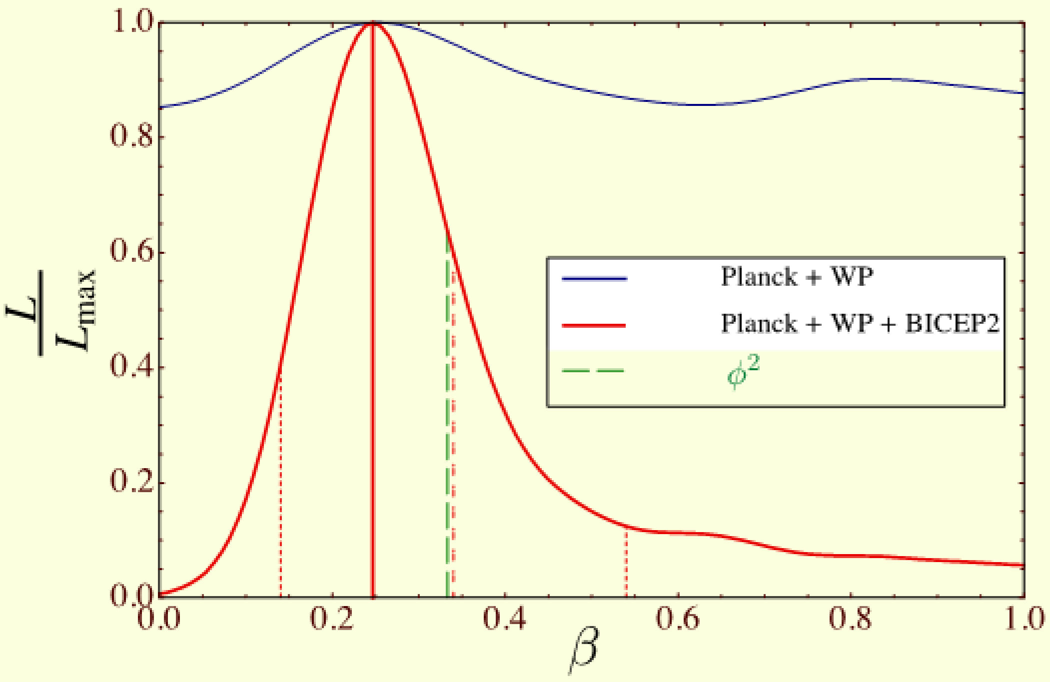
Results

(α,β) plane



68% and 95% CL contours for α and β:

- Blue: Plank + WP
- Red: BICEP2 + Planck + WP
- Green: limits from the 1σ preferred values for n_S (Planck) and r (BICEP2)

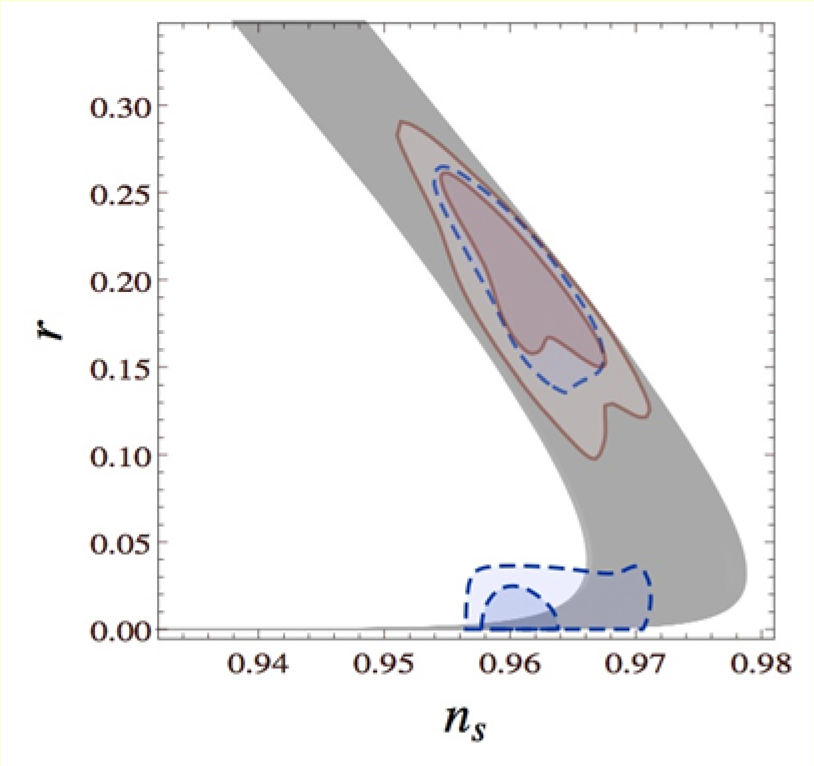


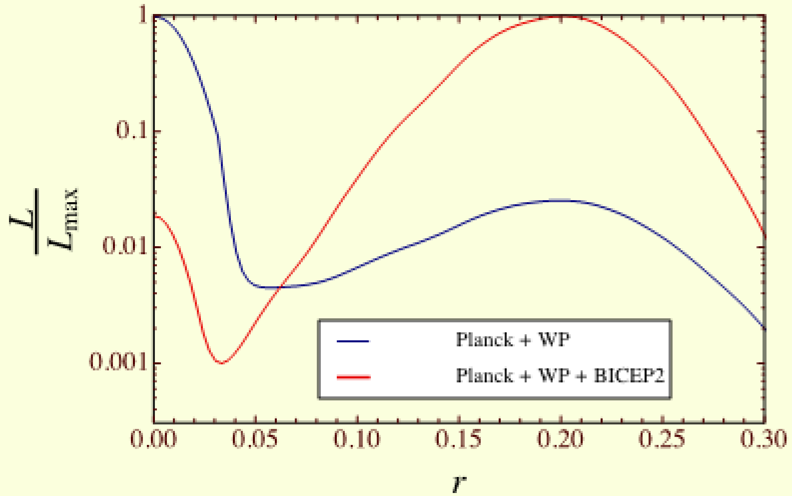
One-dimensional probability density for the β parameter:

- Red vertical: best-fit (±1σ) of β
- Green vertical: quadratic chaotic scenario (β=1/3)

Results

(n_s,r) plane





Derived posterior likelihood for r

68% and 95% CL contours for n_S and r:

- Blue: Plank + WP
- Red: BICEP2 + Planck + WP
- Grey: region covered by the parameterization for 50<N*<60

Parameter	Planck+WP	Planck+WP+BICEP2
$\Omega_b h^2$	0.0209 ± 0.0002	0.0209 ± 0.0002
$\Omega_c h^2$	0.1165 ± 0.0018	0.1167 ± 0.0020
θ	1.0409 ± 0.00055	1.0408 ± 0.00055
τ	0.086 ± 0.015	0.078 ± 0.013
$\log[10^{10} A_s]$	3.063 ± 0.031	3.047 ± 0.026
α	2.24 ± 0.43	0.88 ± 0.17
β	0.50 ± 0.28	0.34 ± 0.20
n_s *(derived)*	0.961 ± 0.002	0.961 ± 0.003
r *(derived)*	< 0.18	0.195 ± 0.037

Conclusions

- Standard Cosmological Model presents some **unsolved questions**
- **Inflation** gives a **solution** to some of them
  - **Prediction** of all models: generation of **gravitational waves**, parameterized by the tensor-to-scalar ratio, r
  - Recent measurements: $r < 0.11 (95\% CL)$ (Planck), $r = 0.20^{+0.07}_{-0.05}$ (BICEP2)
- **Alternative** parameterization
  - Describes inflation by an **effective EOS** in terms of α and β
  - **Captures** almost all inflationary **models**
  - Usual parameters, n_S and r, are easily derived
- **MCMC analyses**
  - Planck + WP
    - $\alpha = 2.24 \pm 0.43$ ($n_S \approx 0.96$)
    - Starobinsky and Higgs inflation
  - Planck + WP + BICEP2
    - $\beta \approx 1/3$, $\alpha \approx 1$
    - Chaotic inflation

BICEP2 data: foregrounds

CAUTION

Dust

BICEP2 assumed 5%

New Planck map: 8-10%

Discrepancy (can be) due to

- Old maps not corrected for CIB
- DDM2 lacks of degree-scale angular variations of the polarization direction

(Mortonson, Seljak'2014)

Weak lensing can induce *B*-modes from *E*-polarization

Observed signal **compatible** with:

- r=0.2 and negligible foregrouds

or

- r=0 and significant dust polarization

(Flauger, Hill, Spergel'2014)

We will assume that the BICEP2 signal is primordial...

Algoritmo de Metropolis-Hastings