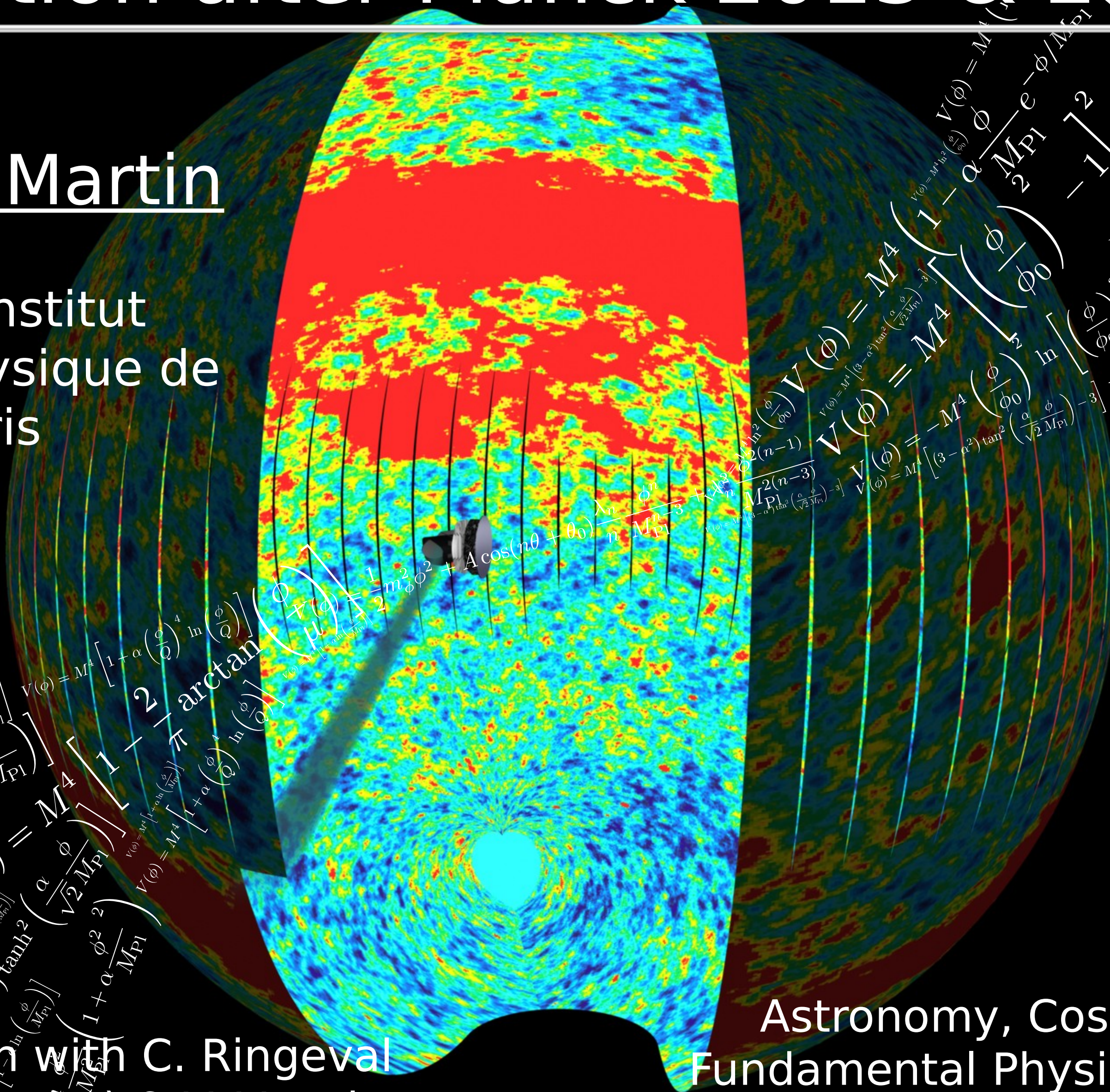
Inflation after Planck 2013 & 2015



Jerome Martin

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In collaboration with C. Ringeval (Louvain University) & V. Vennin (Portsmouth University)

Astronomy, Cosmology & Fundamental Physics with GWs,
Chennai Mathematical Institute
March 2/4, 2015

Outline

- Inflation in brief
- The Planck CMB data and their implications for inflation
- Constraints on Vanilla models
- Model comparison: what is the best model of inflation?
- First constraints on the reheating epoch

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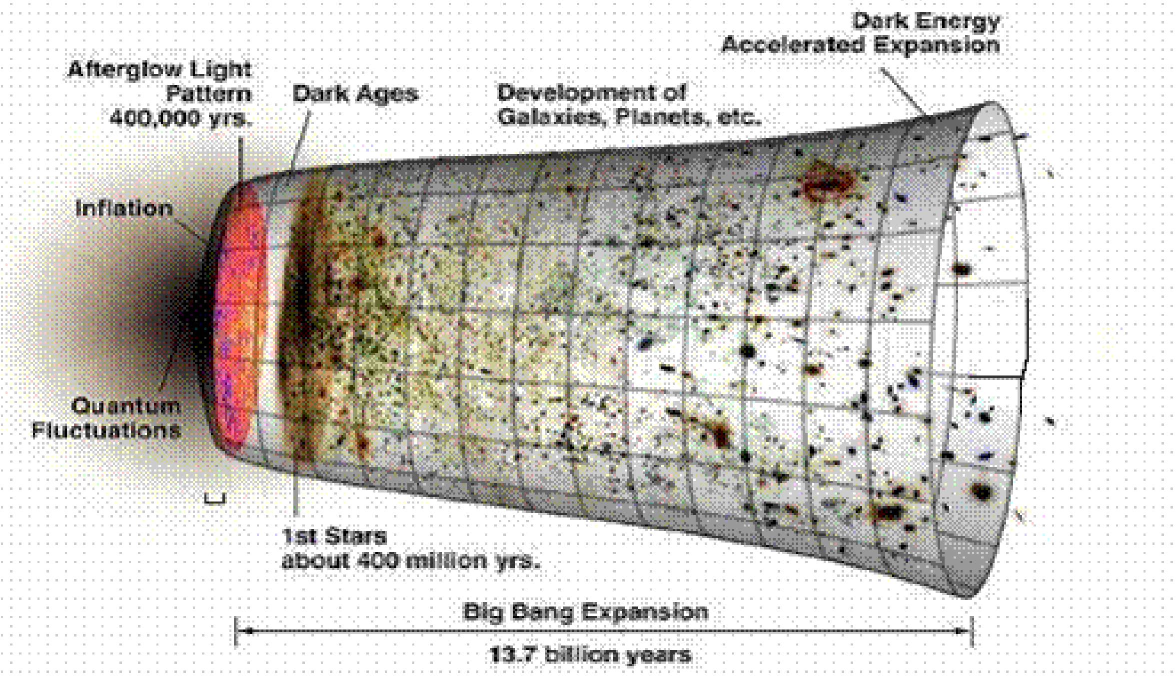

Inflation does not replace the Hot Big Bang model. It is a new ingredient which completes the standard model. It takes place before the Hot Big Bang phase

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$$\boxed{\frac{\ddot{a}}{a} = -\frac{1}{6M_{\mathrm{Pl}}^2}\left(\rho + 3p\right)}$$

In GR, any form of energy weighs including pressure

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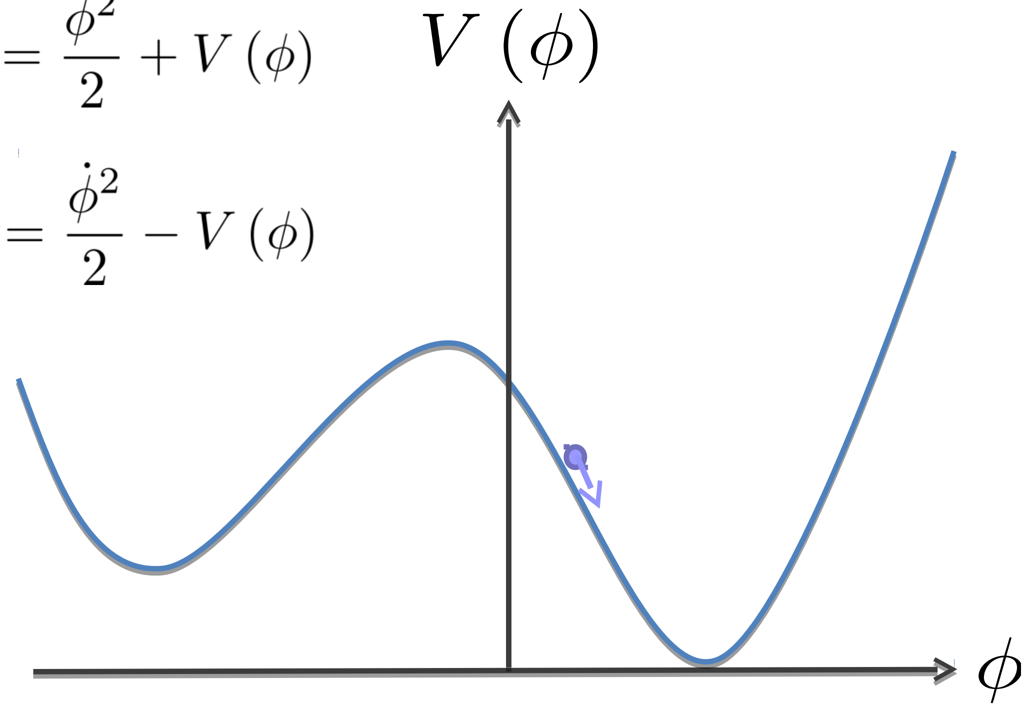
$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi)$$

$$p = \frac{\dot{\phi}^2}{2} - V(\phi)$$



If the scalar field moves slowly (the potential is flat), then pressure is negative

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- Inflation is also a phase of exponential expansion during which the Hubble radius is almost constant

Inflation is an exponential expansion

$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi)$$

$$p = \frac{\dot{\phi}^2}{2} - V(\phi)$$

$$\Downarrow$$

$$p \simeq -\rho$$

$$\Downarrow$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -3H(\rho + p) \simeq 0$$

$$\Downarrow$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_{\mathrm{Pl}}^2} \simeq \mathrm{Constant}$$

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$$a(t) \sim \mathrm{e}^{Ht}$$

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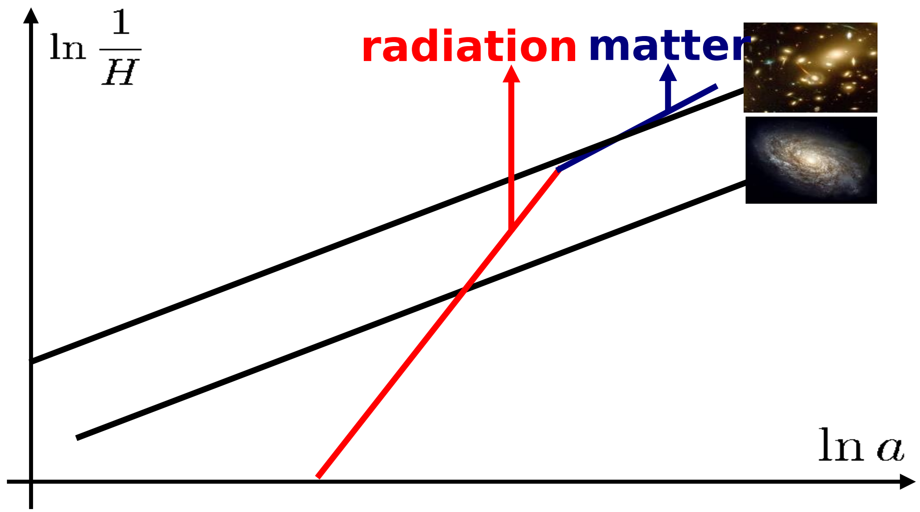

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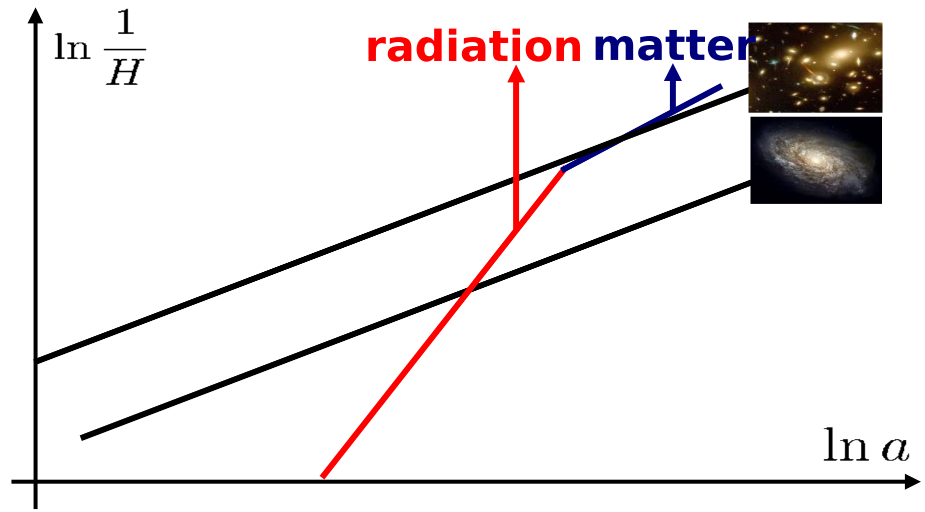

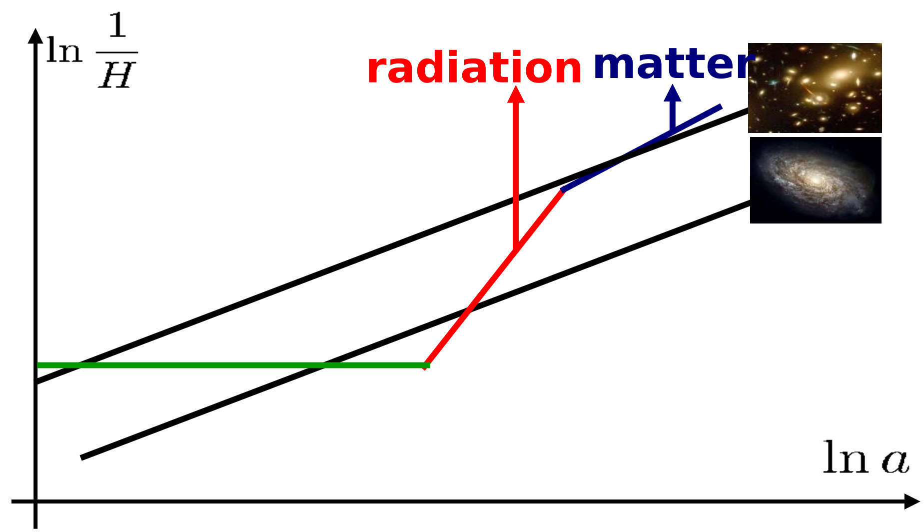

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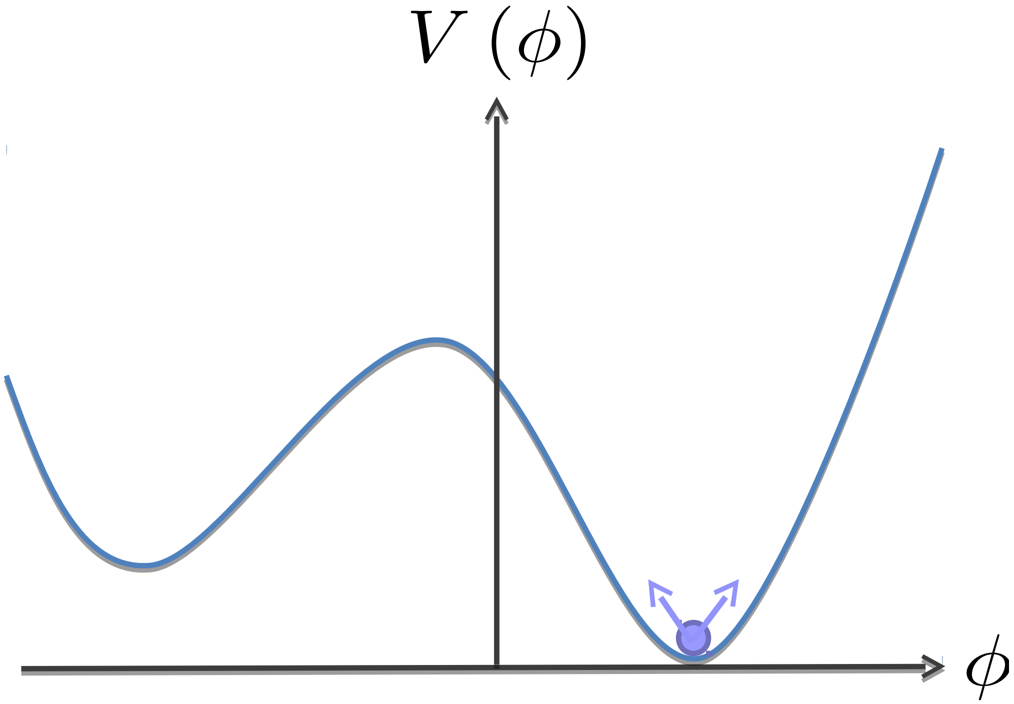

The field oscillates, decays and the decay products thermalize …
Then the radiation dominated era starts …

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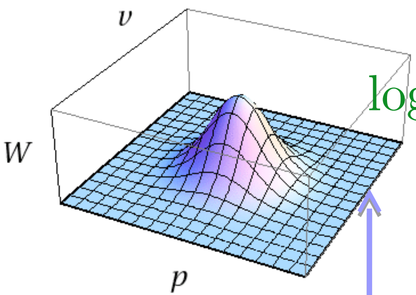
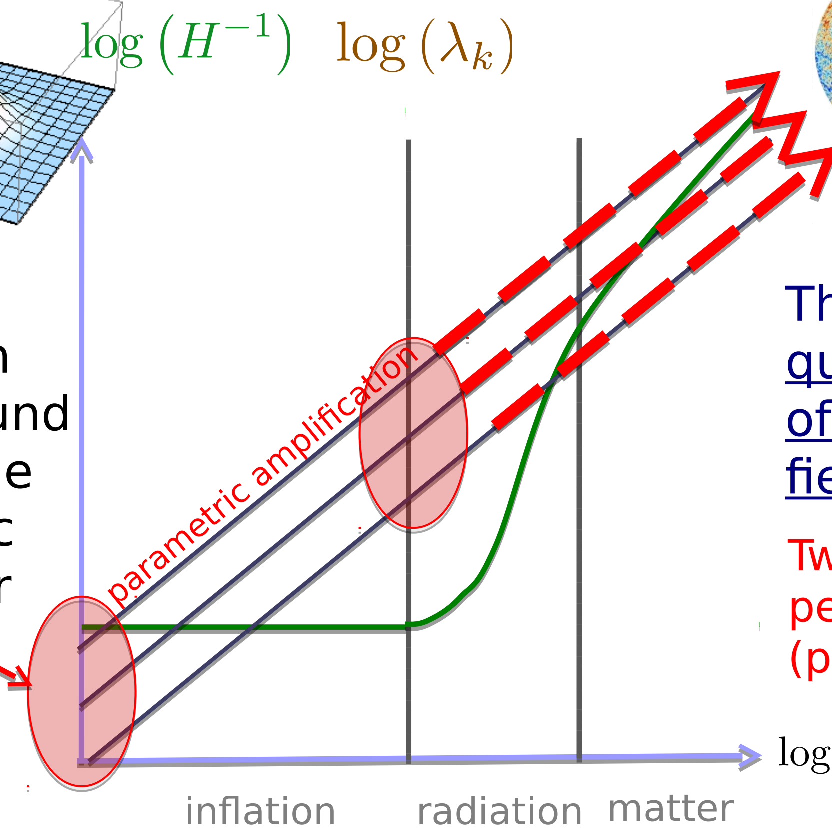
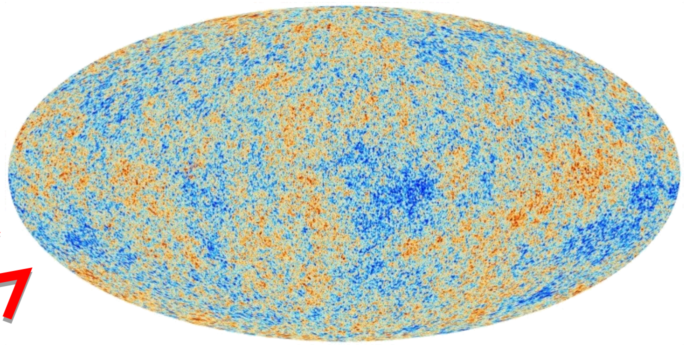
- The large scale structure and the CMB anisotropy originate from the vacuum fluctuations stretched on cosmological scales

Quantum fluctuations as seeds of CMB anisotropy and large scale structures



Initial quantum state: ground state of the harmonic oscillator





The mechanism rests on the quantum gravitational nature of the inflaton and gravitational fields

Two types of fluctuations: density perturbations +tensor perturbations (primordial gravity waves)

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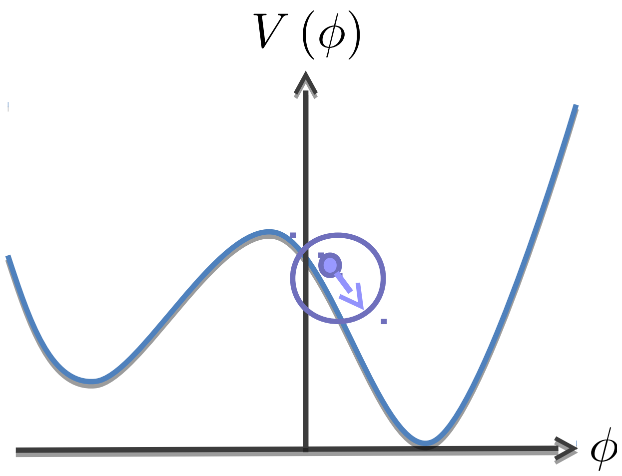
- The large scale structure and the CMB anisotropy originate from the vacuum fluctuations stretched on cosmological scales
- The properties of the fluctuations can be characterized by the correlation function: 2-point functions (power spectrum), 3-point function (bispectrum) etc …

Parametrizing single field slow-roll inflation

- The slow-roll phase is described in terms of slow-roll parameters

$$\epsilon_1 \simeq \frac{1}{2M_{\mathrm{Pl}}^2}\left(\frac{V_\phi}{V}\right)^2$$

$$\epsilon_2 \simeq \frac{2}{M_{\mathrm{Pl}}^2}\left[\left(\frac{V_\phi}{V}\right)^2 - \frac{V_{\phi\phi}}{V}\right]$$



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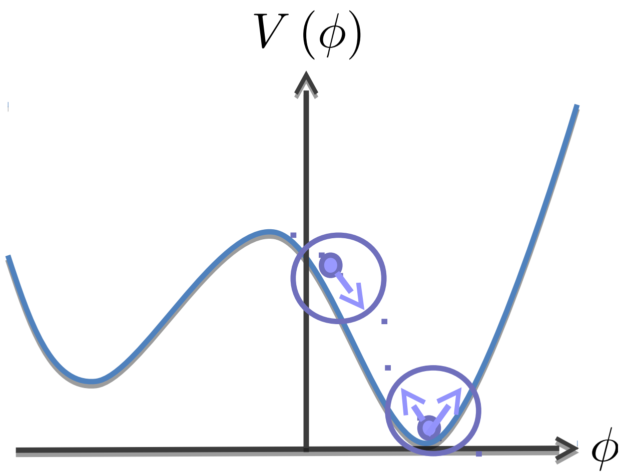

- The reheating phase depends on all the couplings between the inflaton and the other fields (scalar, fermions, gauge bosons)

- It can be parametrized by the the reheating temperature and the mean equation of state during reheating.

$$T_{\mathrm{reh}} = \left(g_* \frac{30}{\pi^2}\rho_{\mathrm{reh}}\right)^{1/4}$$

$$\bar{w}_{\mathrm{reh}} = \frac{1}{\Delta N}\int_{N_{\mathrm{T}}}^{N_{\mathrm{reh}}} w_{\mathrm{reh}}(n)\mathrm{d}n$$

In fact, the CMB only depends on a specific combination, the <u>Reheating parameter</u>

$$\ln R_{\mathrm{rad}} = \frac{1-3\bar{w}_{\mathrm{reh}}}{12+12\bar{w}_{\mathrm{reh}}}\ln\left(\frac{\rho_{\mathrm{reh}}}{\rho_{\mathrm{end}}}\right)$$

Calculating the two-point correlations: slow-roll parameters

- The correlation functions depend on the slow-roll parameters evaluated at the time at which the pivot scale crossed out the Hubble radius during inflation

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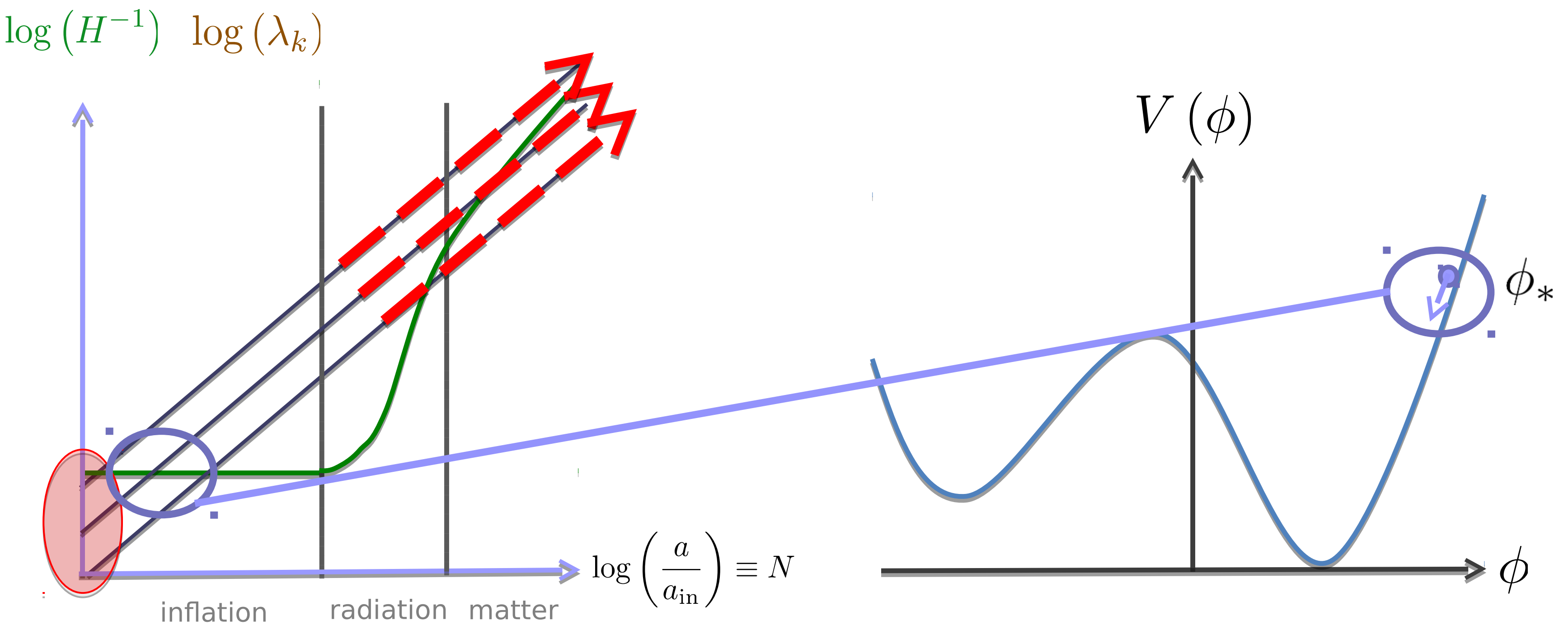

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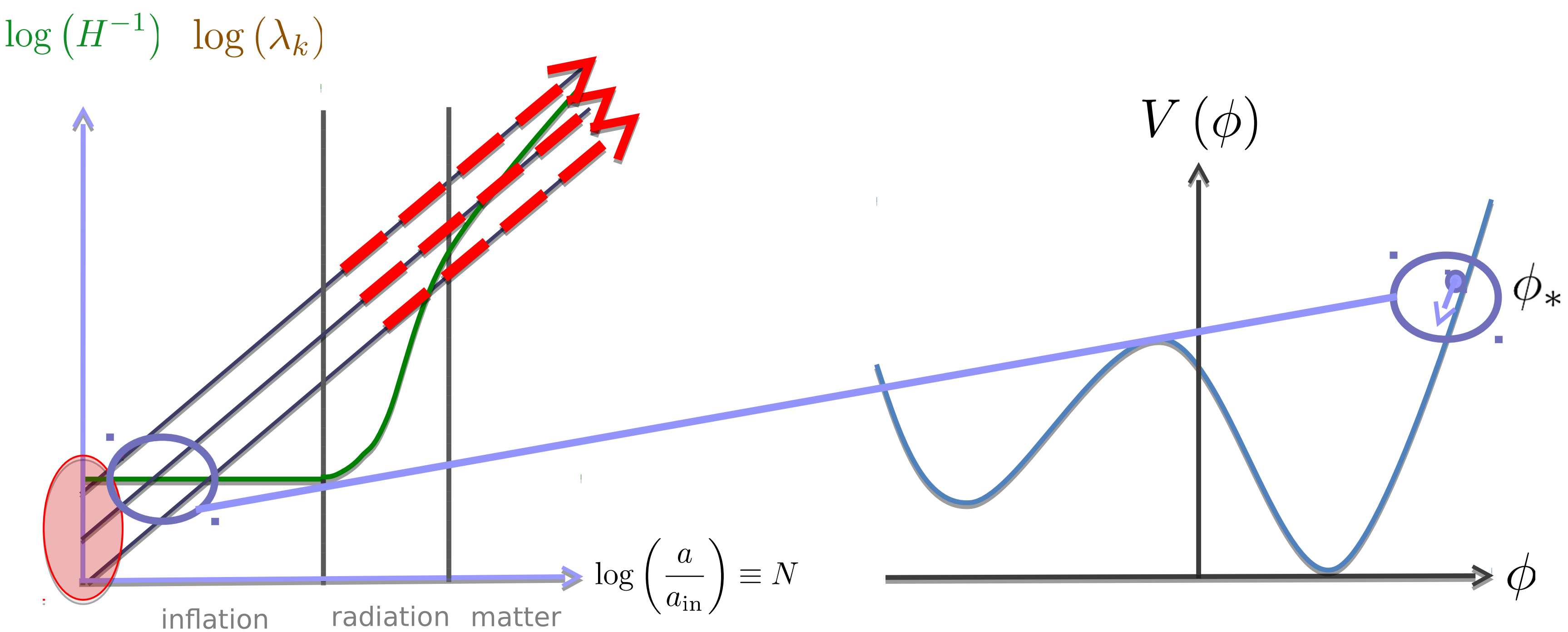
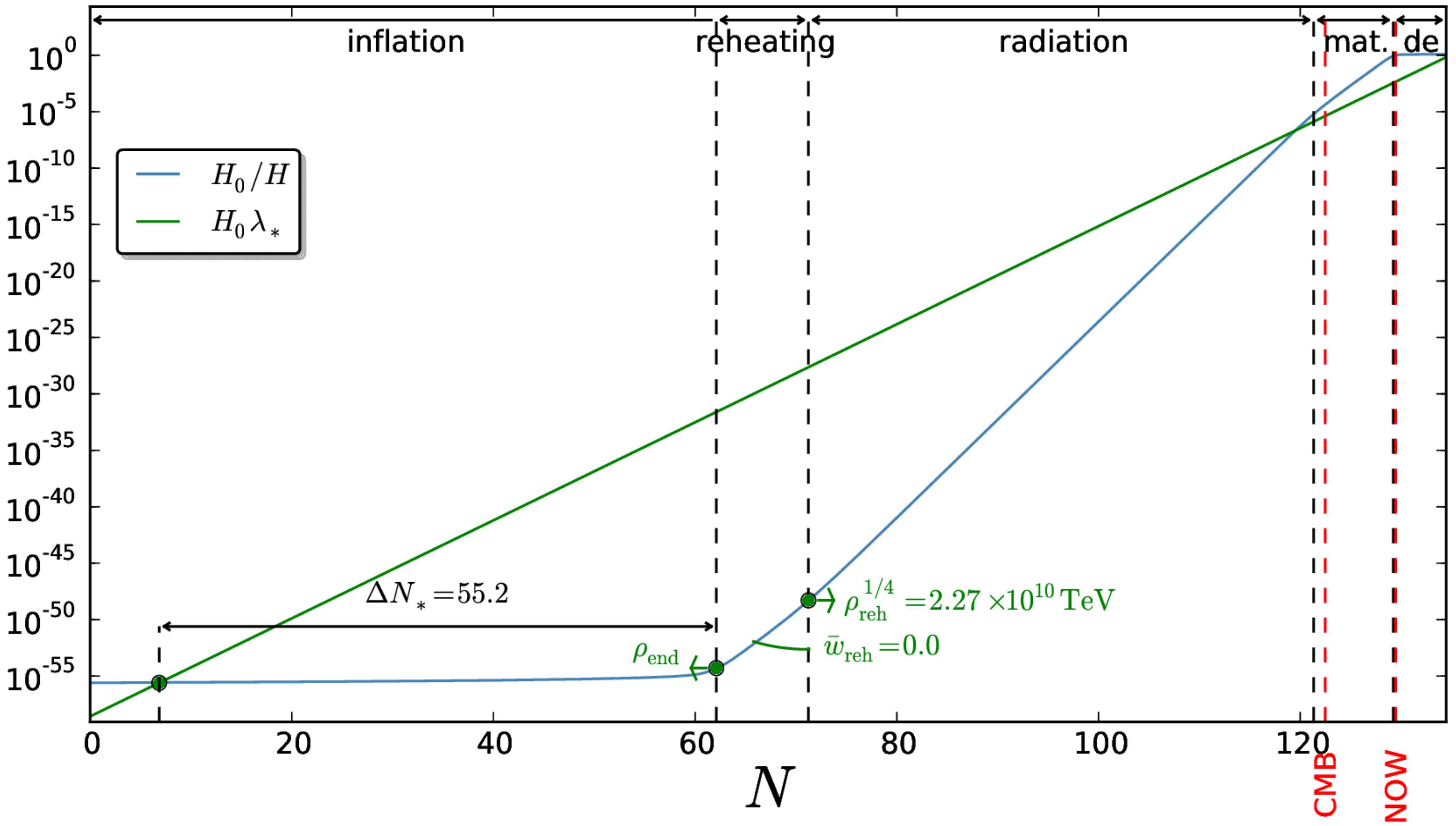


- The relevant quantities are $\epsilon_{1*}=\epsilon_1(\phi_*)$ and $\epsilon_{2*}=\epsilon_2(\phi_*)$ and the reheating dependence enters here since ϕ_* depends on the reheating parameter

Reheating



inflation
reheating
radiation
mat.
de
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
10^{-45}
10^{-50}
10^{-55}
H_0/H
$H_0\lambda_*$
$\Delta N_* = 55.2$
$\rho_{\rm end}$
$\rho_{\rm reh}^{1/4} = 2.27 \times 10^{10}\,\mathrm{TeV}$
$\bar{w}_{\rm reh} = 0.0$
0
20
40
60
80
100
120
N
CMB
NOW

Inflationary predictions: the two-point correlation function

$$\mathcal{P}_\zeta = \frac{H^2}{\pi\epsilon_{1*}m_{\rm Pl}^2}\left[1-2\left(C+1\right)\epsilon_{1*}-C\epsilon_{2*}-\left(2\epsilon_{1*}+\epsilon_{2*}\right)\ln\left(\frac{k}{k_{\rm P}}\right)\right]$$

$$\mathcal{P}_h = \frac{16H^2}{\pi m_{\rm Pl}^2}\left[1-2\left(C+1\right)\epsilon_{1*}-2\epsilon_{1*}\ln\left(\frac{k}{k_{\rm P}}\right)\right]$$

- The amplitude is controlled by H
- For the scalar modes, the amplitude also depends on ε_1

C~ -0.7

The power spectra are scale-invariant plus <u>logarithmic corrections the amplitude of which depend</u> on the sr parameters, ie on the <u>microphysics of inflation</u>

Consistency relation:

$$r = \frac{T}{S} \equiv \frac{\mathcal{P}_h}{\mathcal{P}_\zeta} = 16\epsilon_{1*} = -8n_{\rm T}$$

Gravitational waves are subdominant

The spectral indices are given by

$$n_{\rm S}-1 \equiv \frac{{\rm d}\ln\mathcal{P}_\zeta}{{\rm d}\ln k}\,, \quad n_{\rm T} \equiv \frac{{\rm d}\ln\mathcal{P}_h}{{\rm d}\ln k}$$

$$n_{\rm S} = -2\epsilon_{1*}-\epsilon_{2*} \quad n_{\rm T} = -2\epsilon_{1*}$$

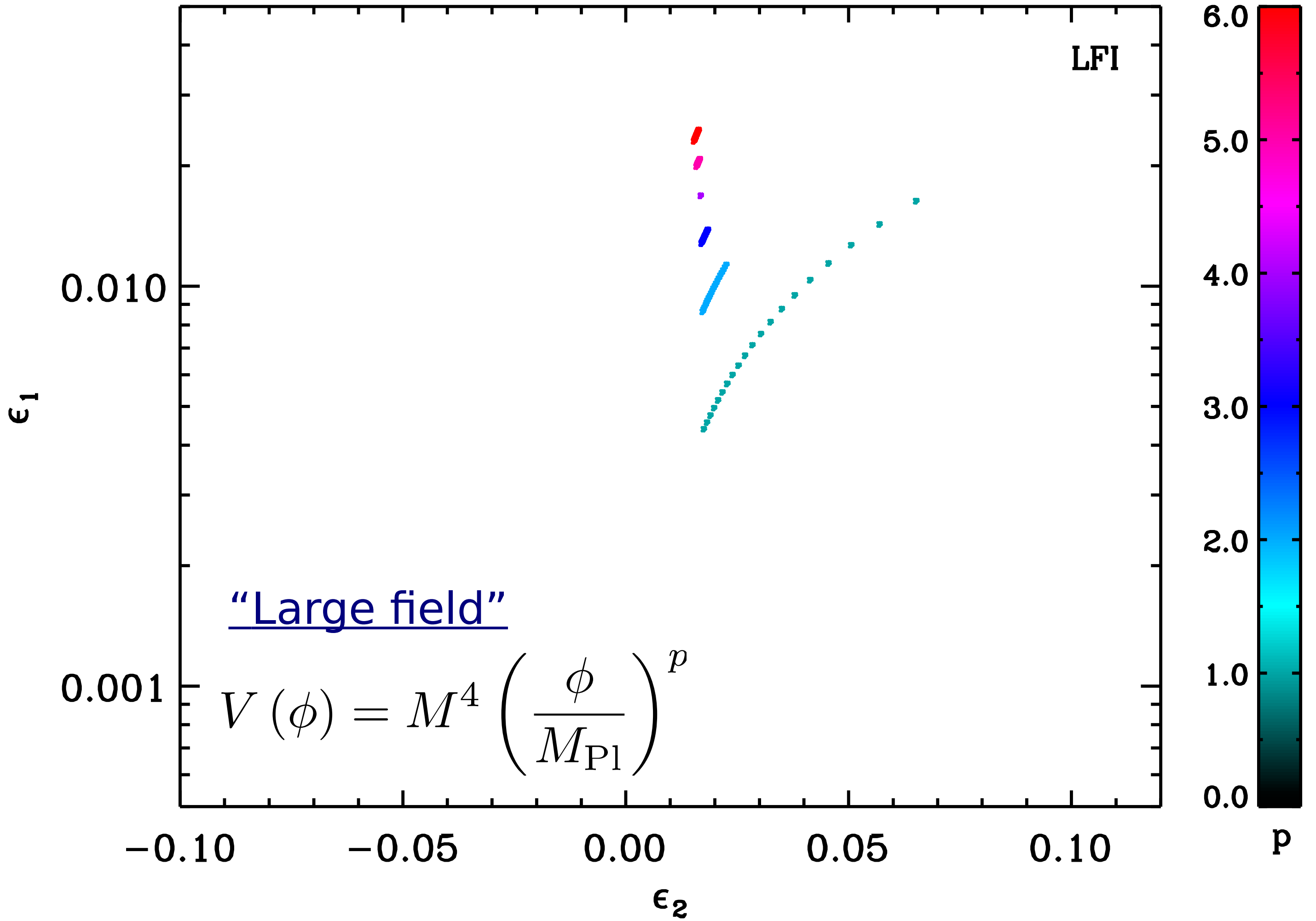
The running, i.e. the scale dependence of the spectral indices, of dp and gw are

$$\alpha_{\rm S} \equiv \frac{{\rm d}^2\ln\mathcal{P}_\zeta}{{\rm d}\left(\ln k\right)^2} \qquad \alpha_{\rm T} \equiv \frac{{\rm d}^2\ln\mathcal{P}_h}{{\rm d}\left(\ln k\right)^2}$$

$$\alpha_{\rm S} = -2\epsilon_{1*}\epsilon_{2*}-\epsilon_{2*}\epsilon_{3*}$$

$$\alpha_{\rm T} = -2\epsilon_{1*}\epsilon_{2*}$$

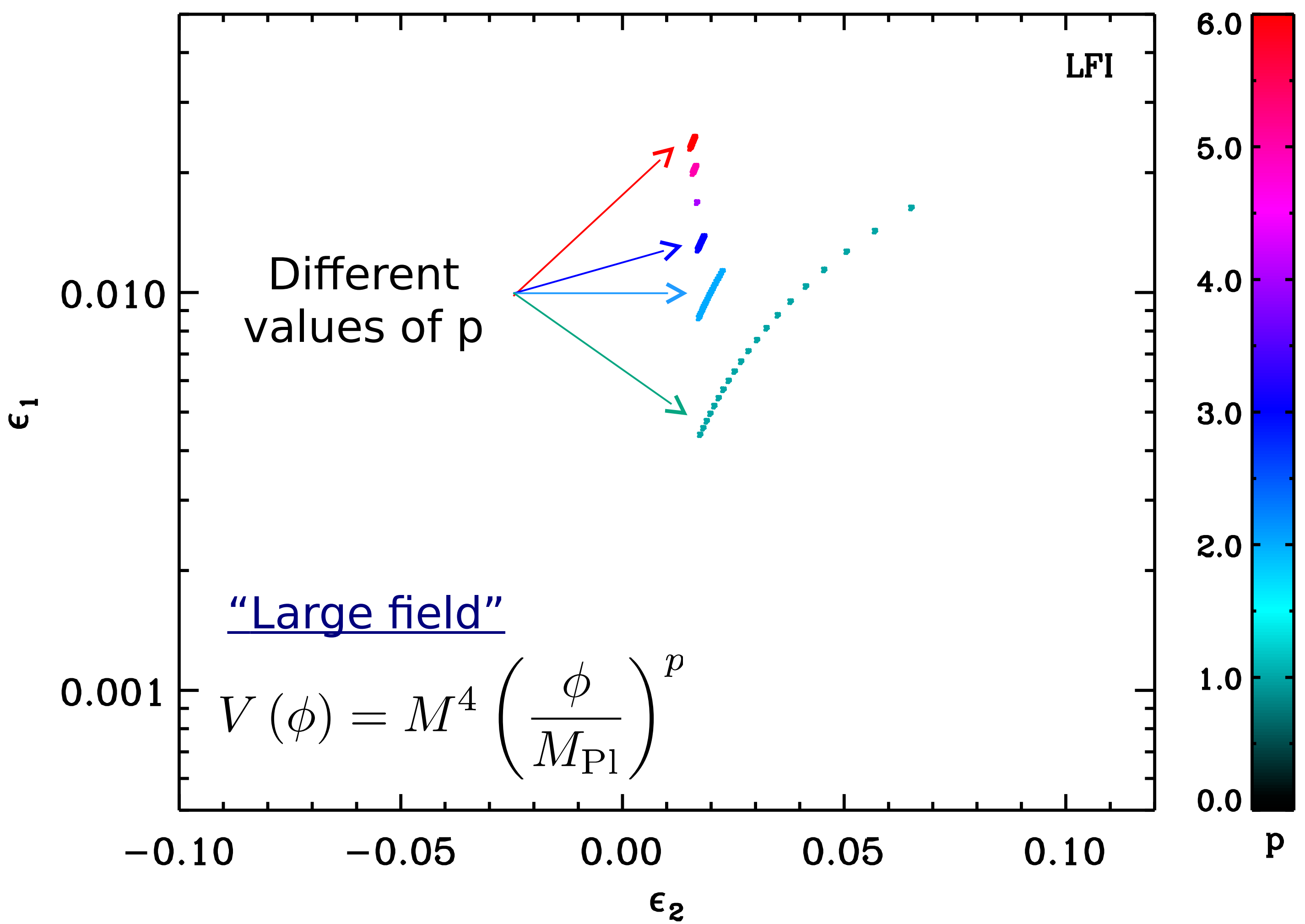
Predictions in the slow-roll space: one example



"Large field"

$$V(\phi) = M^4 \left(\frac{\phi}{M_{\rm Pl}}\right)^p$$

Predictions in the slow-roll space



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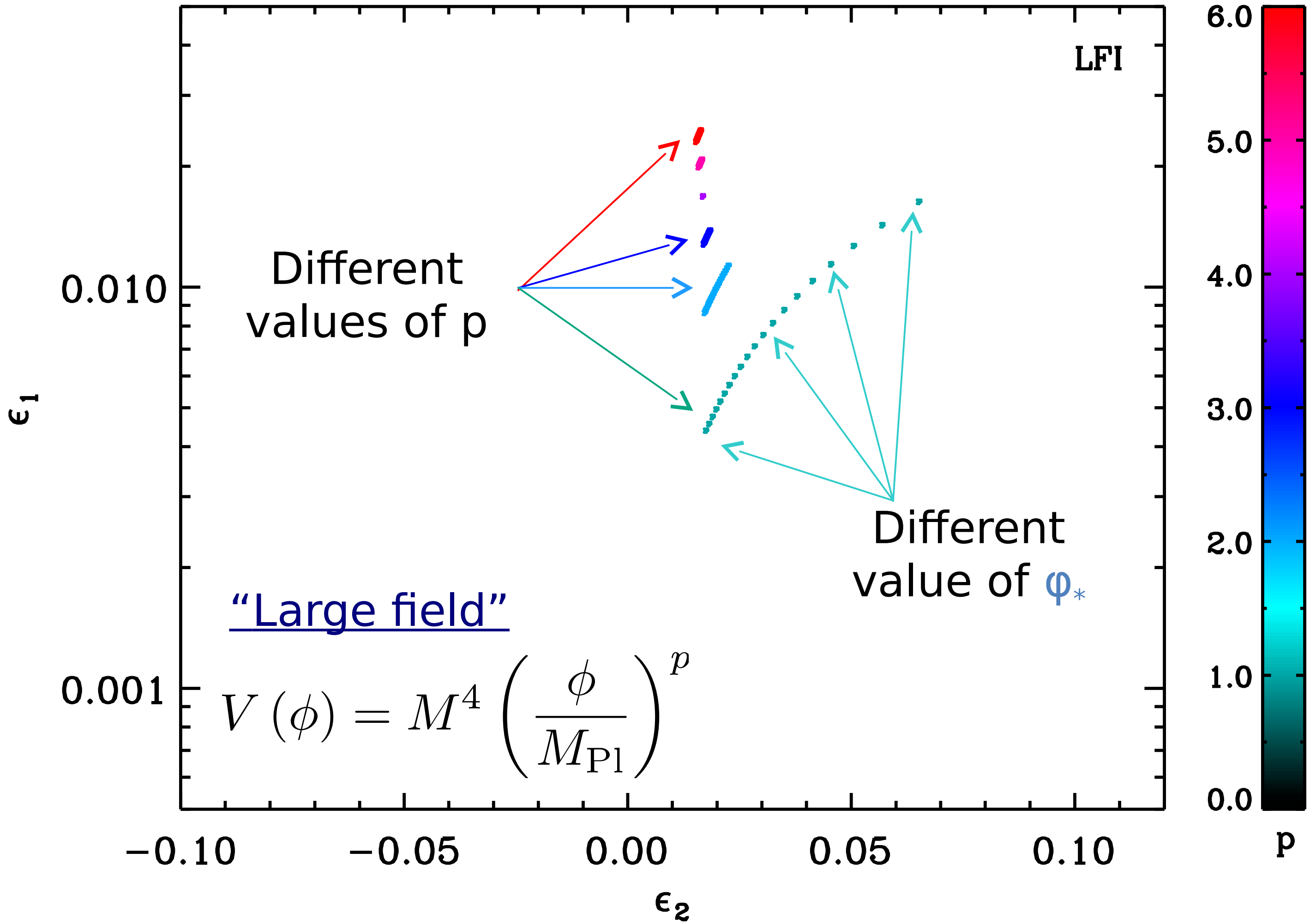

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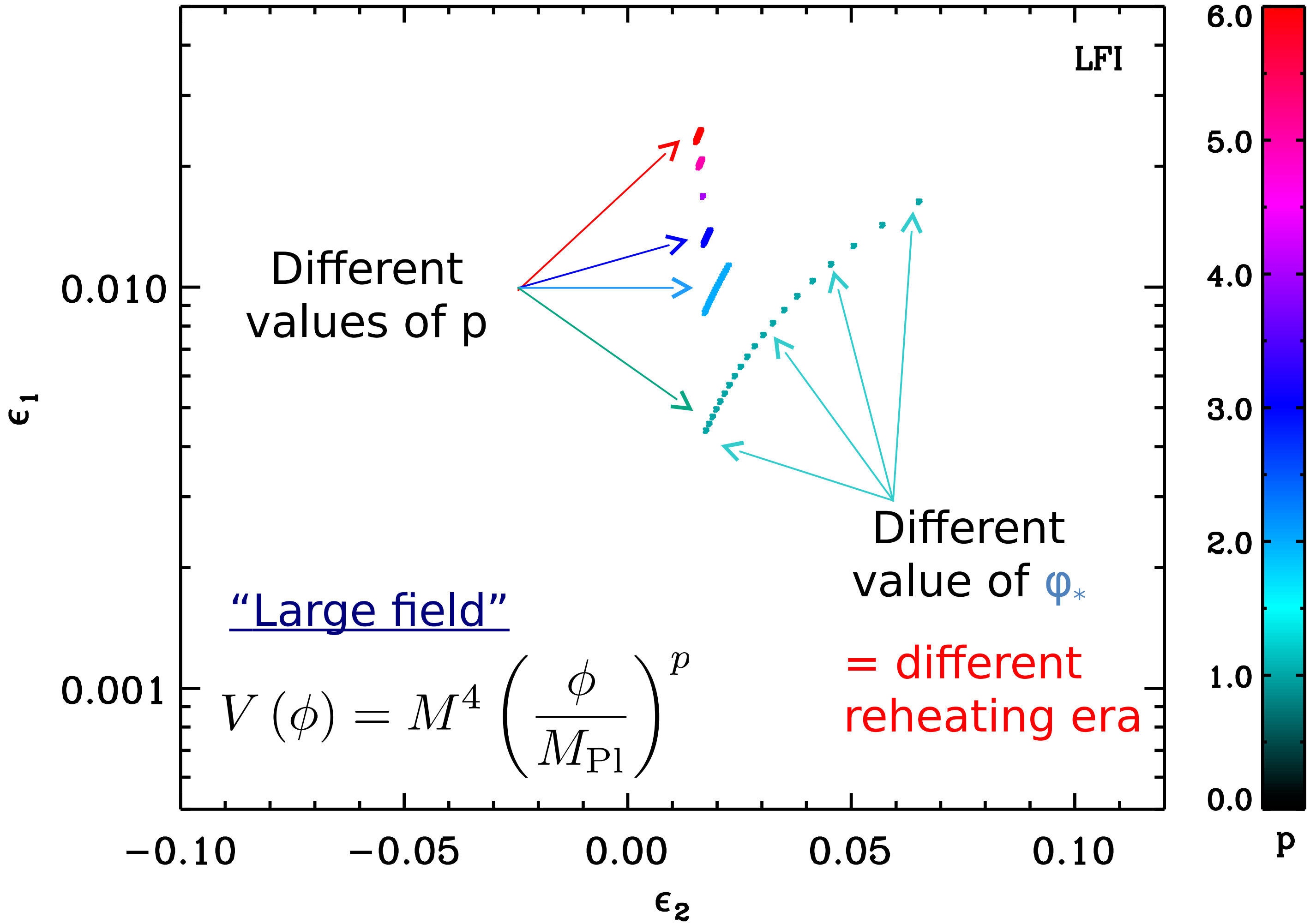
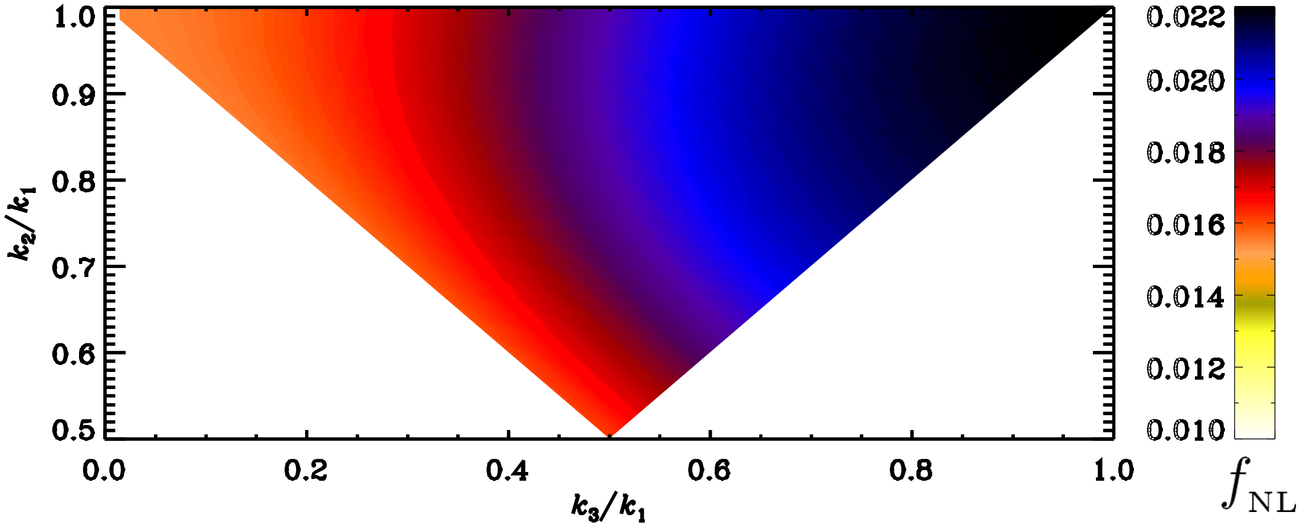


Three-point correlation function for vanilla models

$$\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle = -\frac{3}{10}f_{\mathrm{NL}}\left(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3\right)\frac{(2\pi)^{5/2}}{k_1^3k_2^3k_3^3}\delta\left(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3\right)\left[k_1^3\mathcal{P}_\zeta\left(k_2\right)\mathcal{P}_\zeta\left(k_3\right)+2\text{ permutations}\right]$$



f_{NL} is of the order of the slow-roll parameters and hence unobservable with the current technology ...

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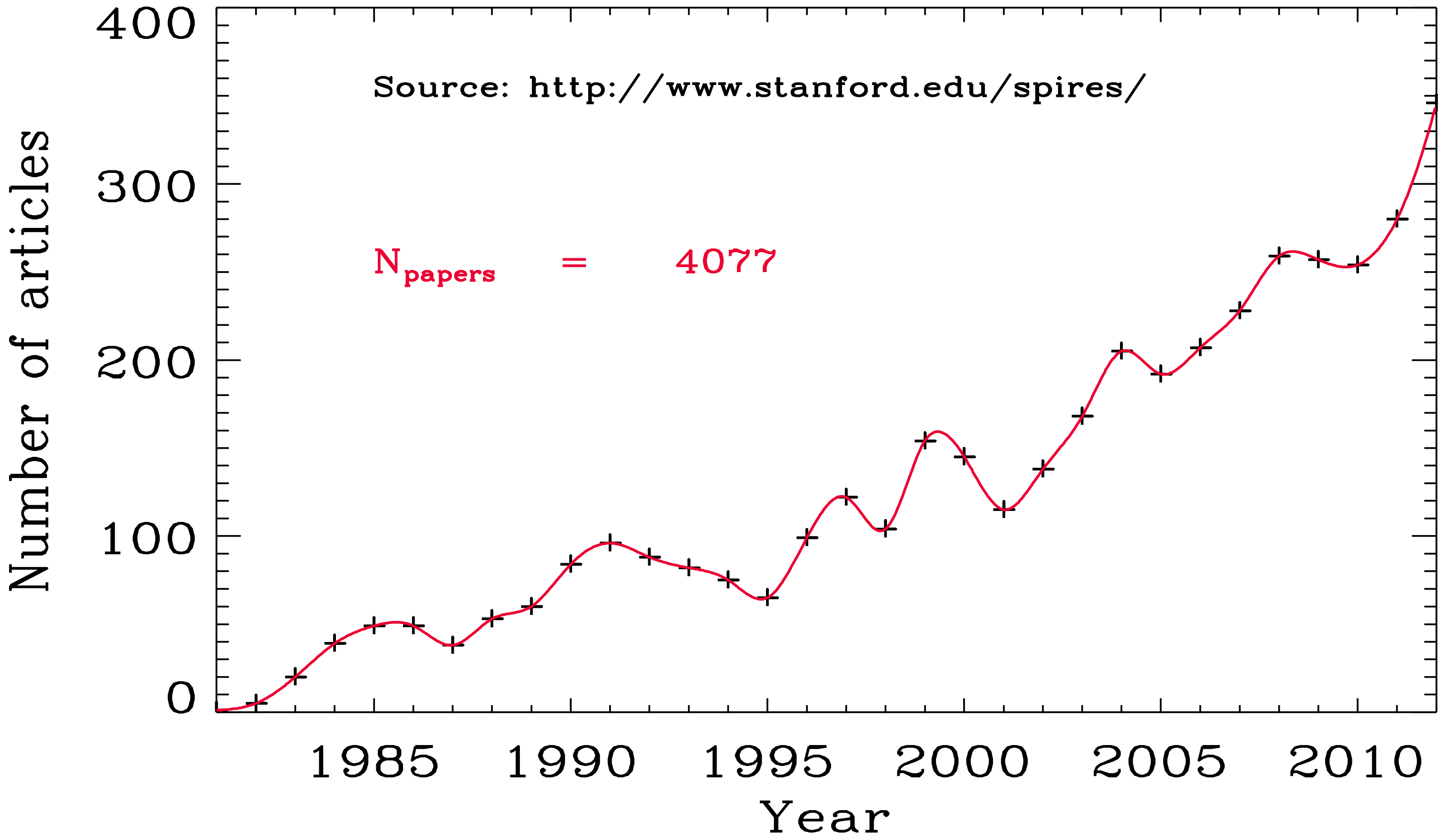

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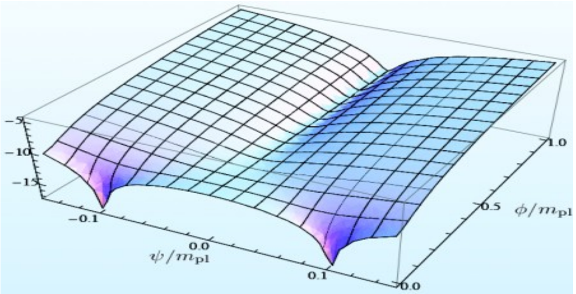

Multiple field inflation

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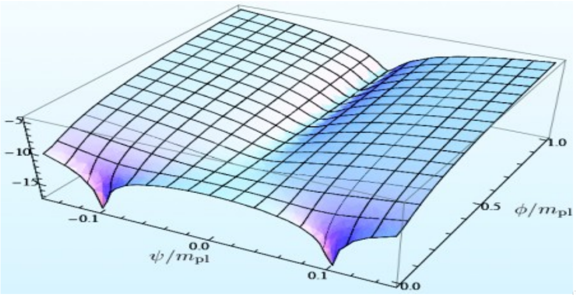

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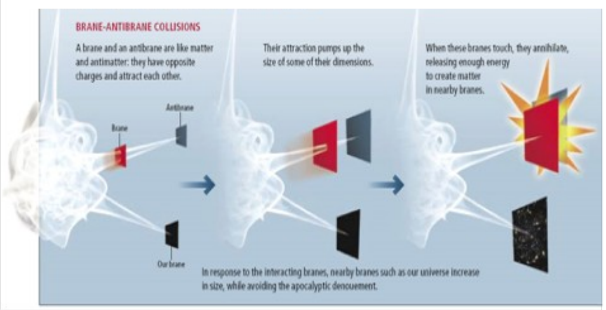

Inflation with non-minimal kinetic term

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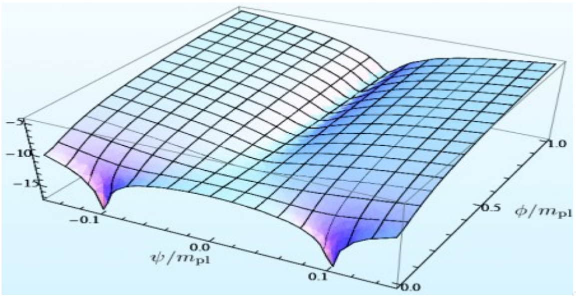

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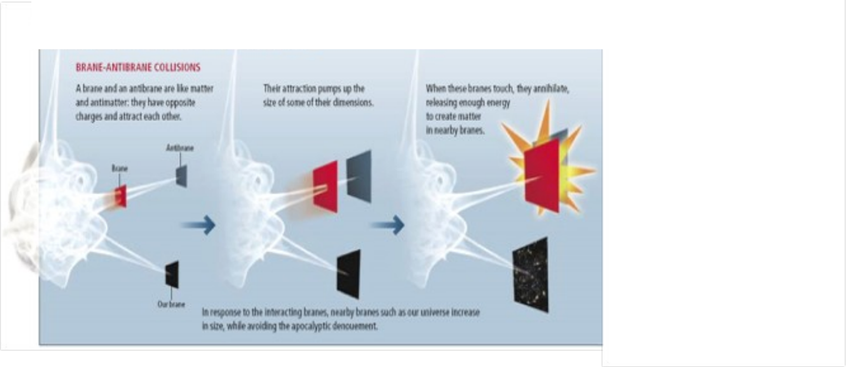

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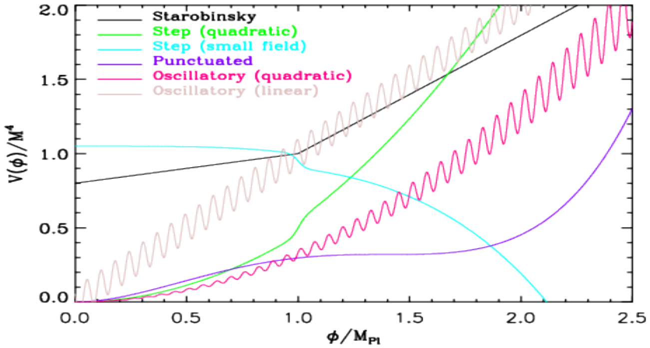

Inflation with features

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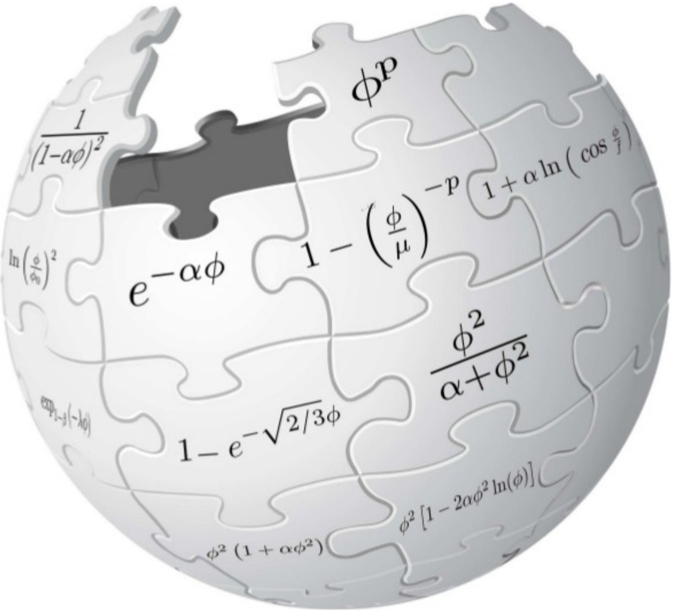

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- All these models were recently compared to Planck data in "Encyclopedia Inflationaris" (JM, C. Ringeval & V. Vennin, arXiv:1303.3787)

- But different models make different predictions so we can distinguish among them. Non-vanilla models typically predict non-adiabatic perturbation or non-Gaussianities.

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- First constraints on the reheating epoch

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$$\Omega_{\mathcal{K}} = -0.058^{+0.046}_{-0.026}$$

$$\alpha^{(2,2500)}_{\mathcal{RR}} \in [0.98, 1.07]$$

$$f_{\rm NL}^{\rm loc} = 2.7 \pm 5.8$$

$$f_{\rm NL}^{\rm eq} = -42 \pm 75$$

$$f_{\rm NL}^{\rm ortho} = -25 \pm 39$$

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- We can focus on single field models, not because they are the simplest ones but because they are favored by Planck (Giannantonio & Komatsu 20

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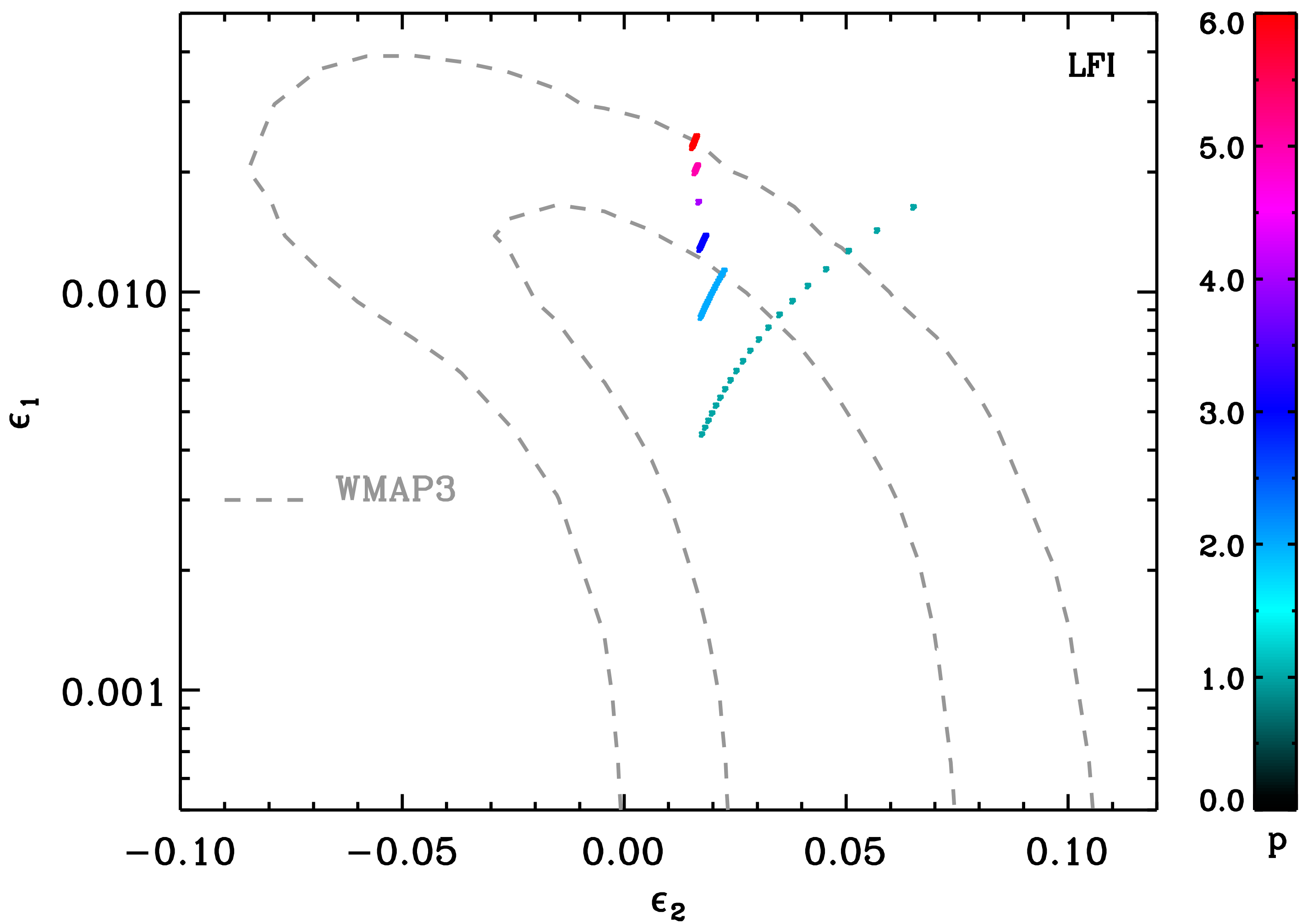
CMB constraints in the slow-roll plane



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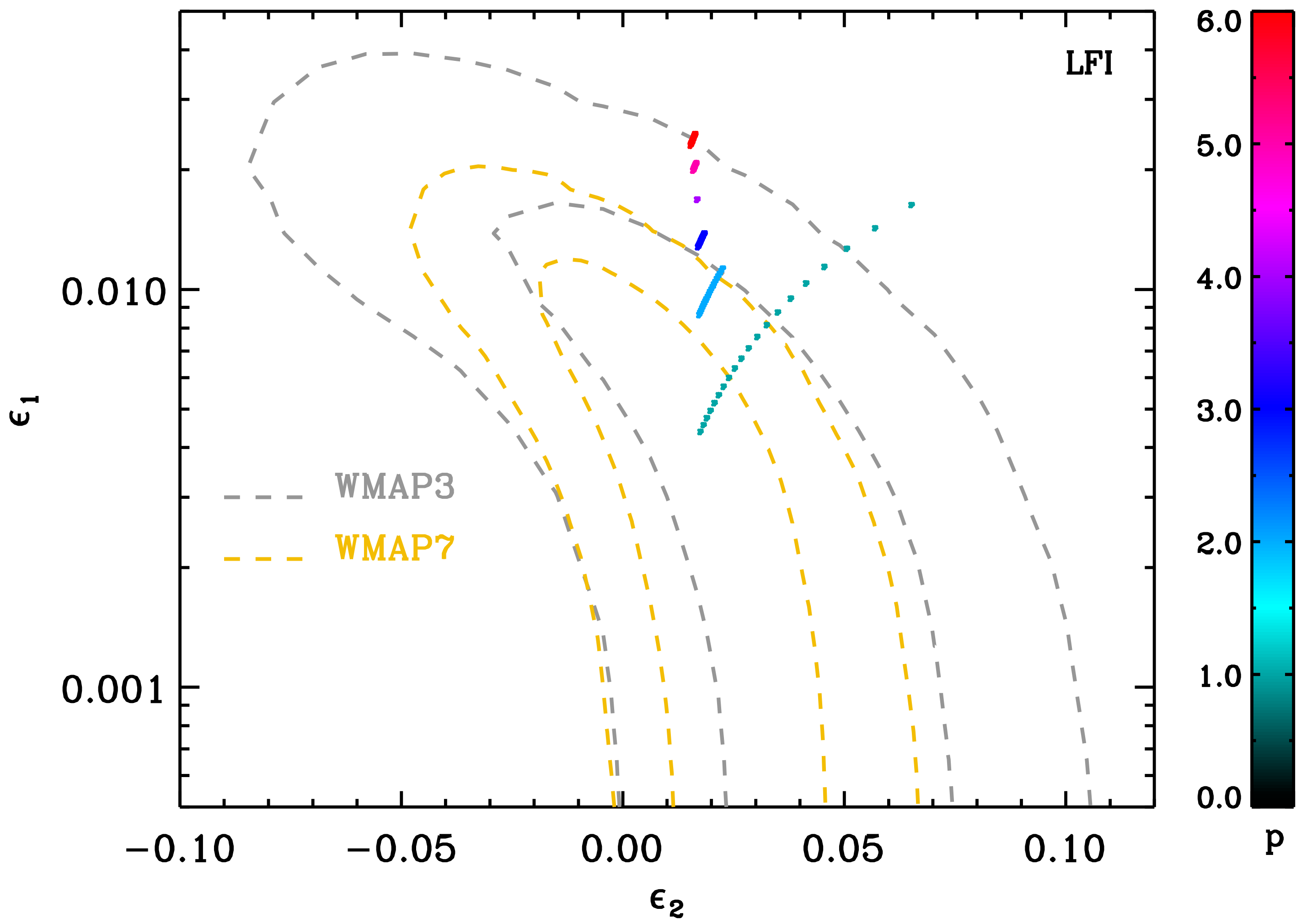

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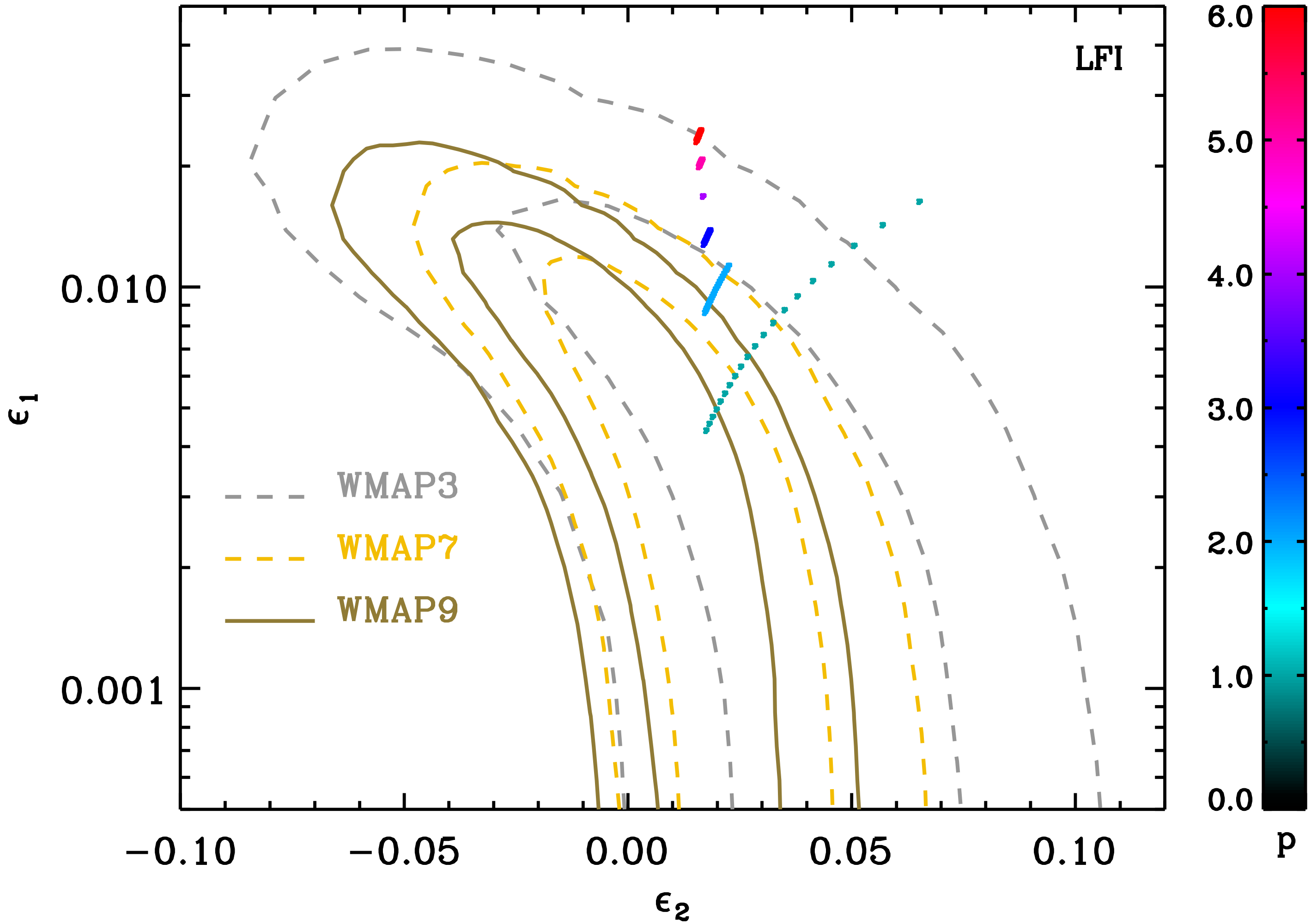

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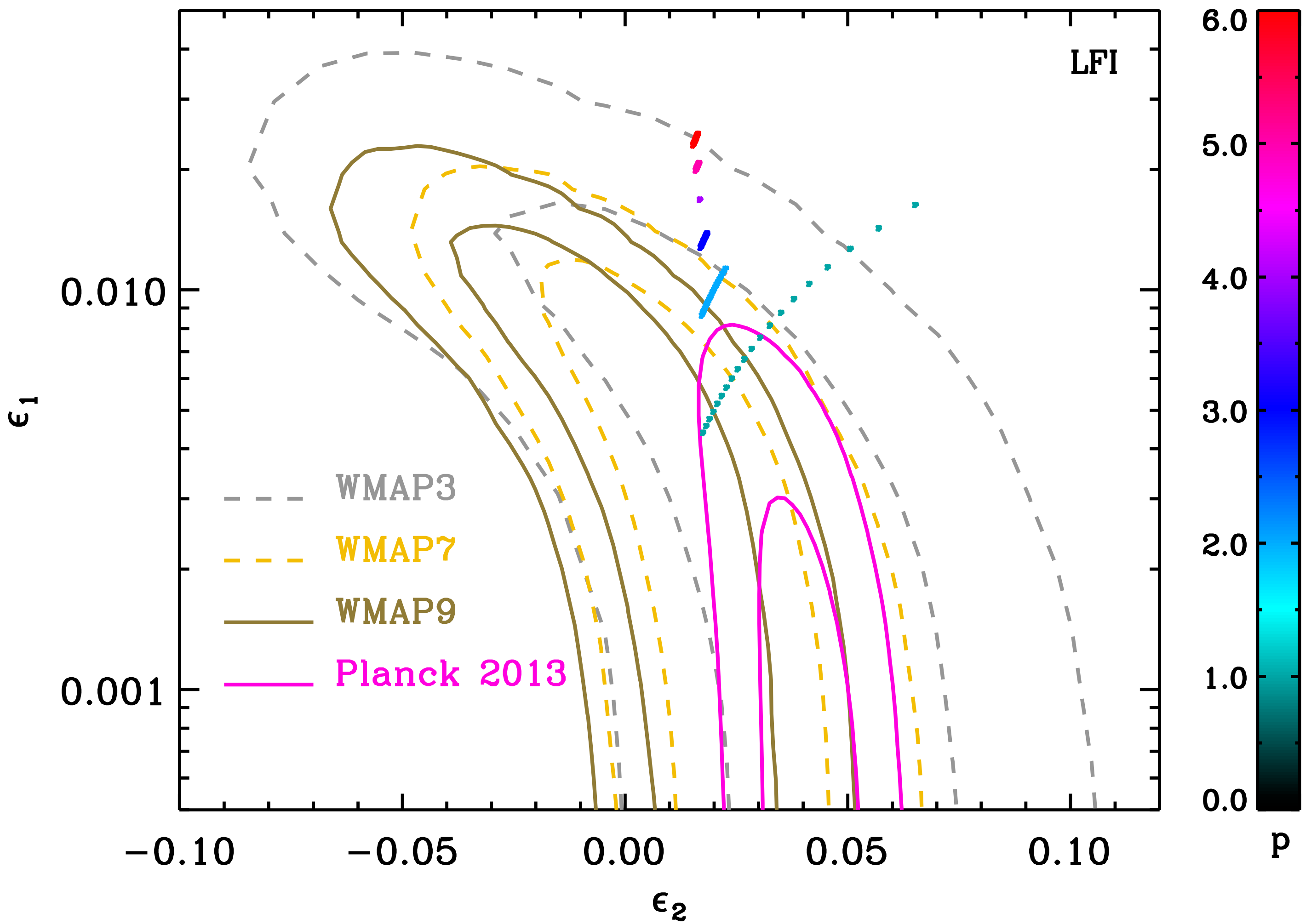
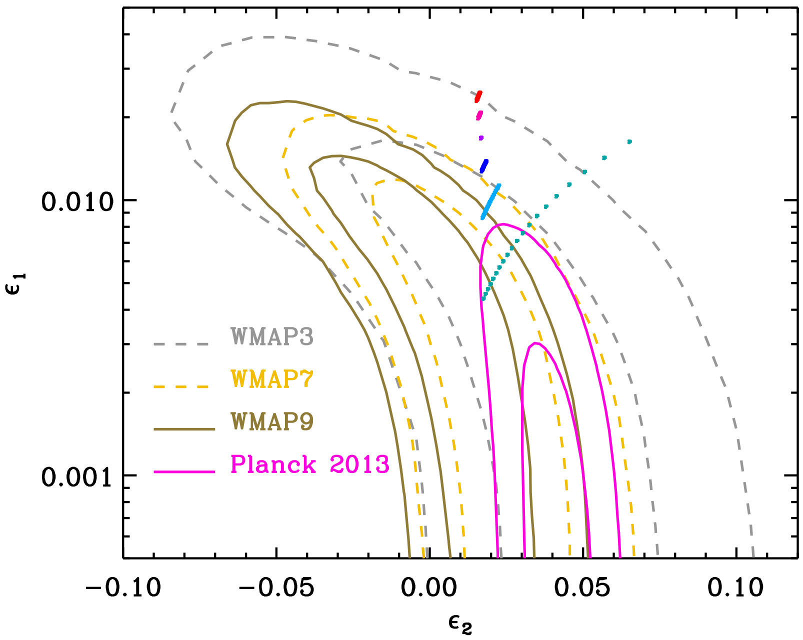


- Planck 2015 constraints on the slow-roll parameters

$$\epsilon_{1*} < 0.0068$$

$$\epsilon_{2*} = 0.029^{+0.008}_{-0.007}$$



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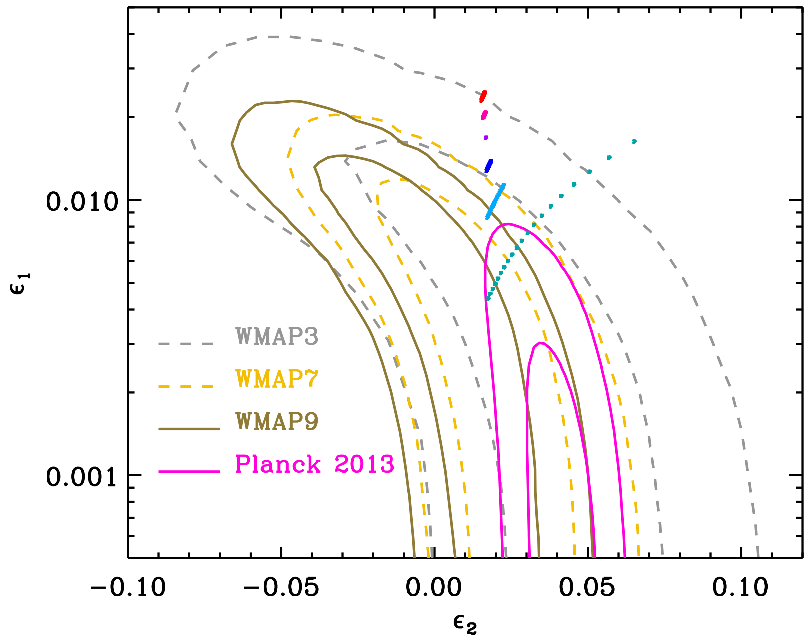

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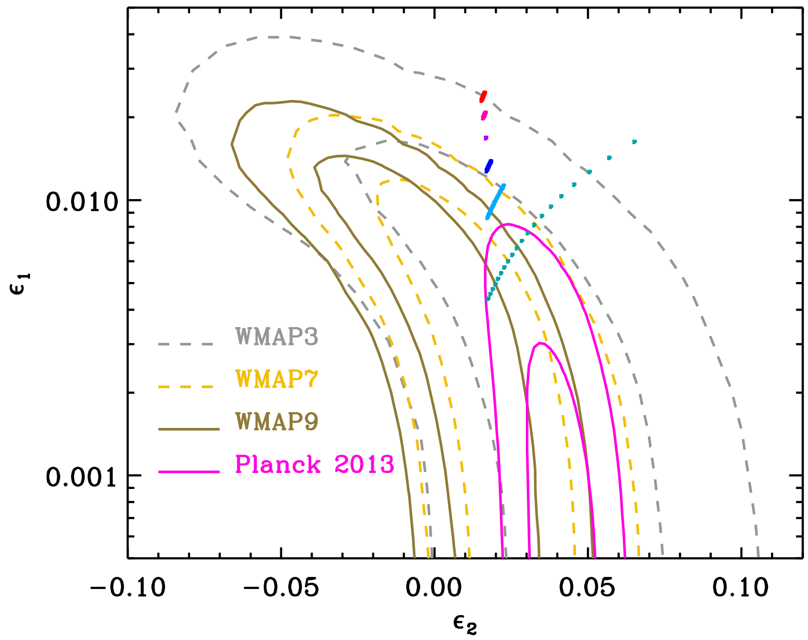

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- Planck 2015 constraints on the energy scale of inflation

$$H_*^2 \sim \mathcal{P}_\zeta \epsilon_{1*} \quad \Rightarrow \quad \rho_*^{1/4} < 2.2 \times 10^{16}\,\mathrm{GeV}$$

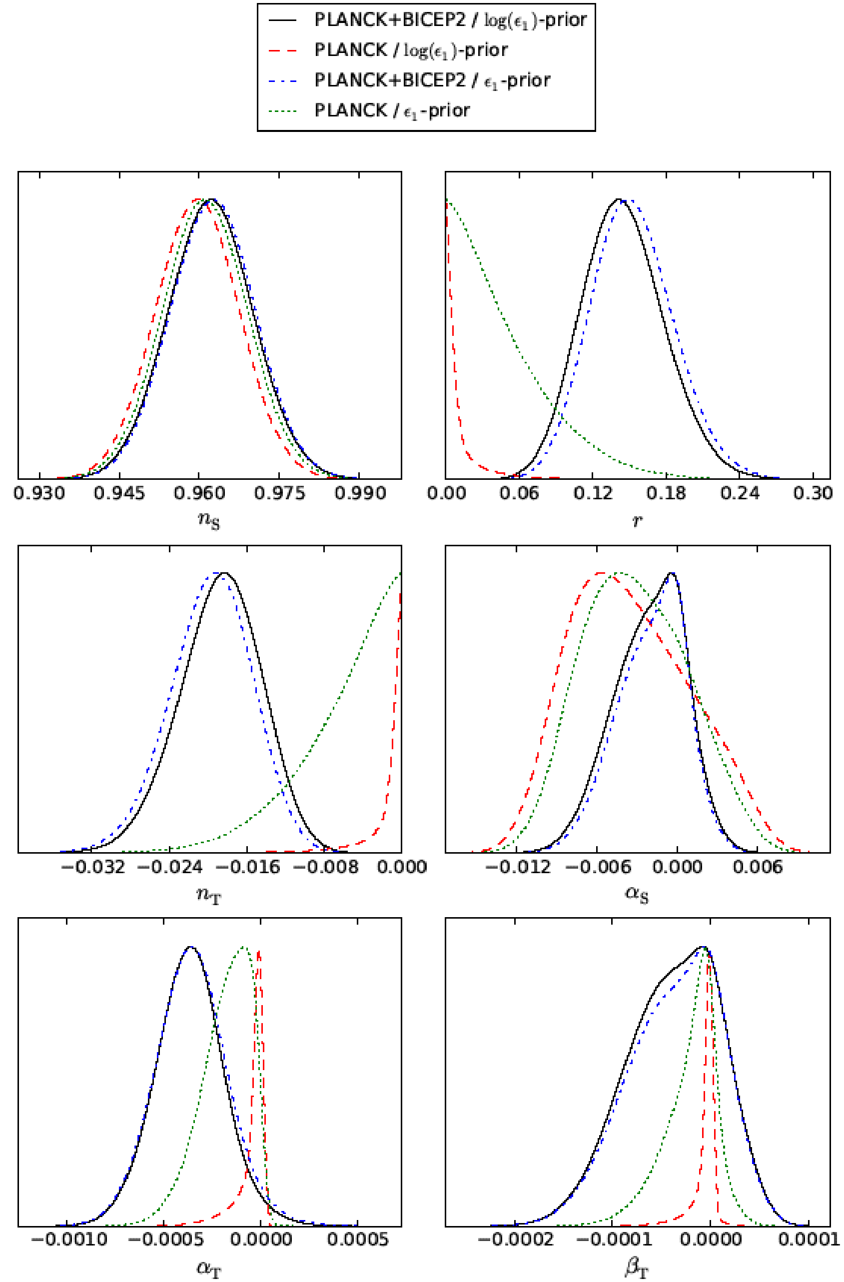
$$H_* < 1.2 \times 10^{14}\,\mathrm{GeV}$$

Planck 2013 (and 2015) constraints

One can derive constraints on power-law parameters

$$n_{\mathrm{S}} = -2\epsilon_{1*} - \epsilon_{2*}$$

$$r = \frac{T}{S} \equiv \frac{\mathcal{P}_h}{\mathcal{P}_\zeta} = 16\epsilon_{1*} = -8n_{\mathrm{T}}$$

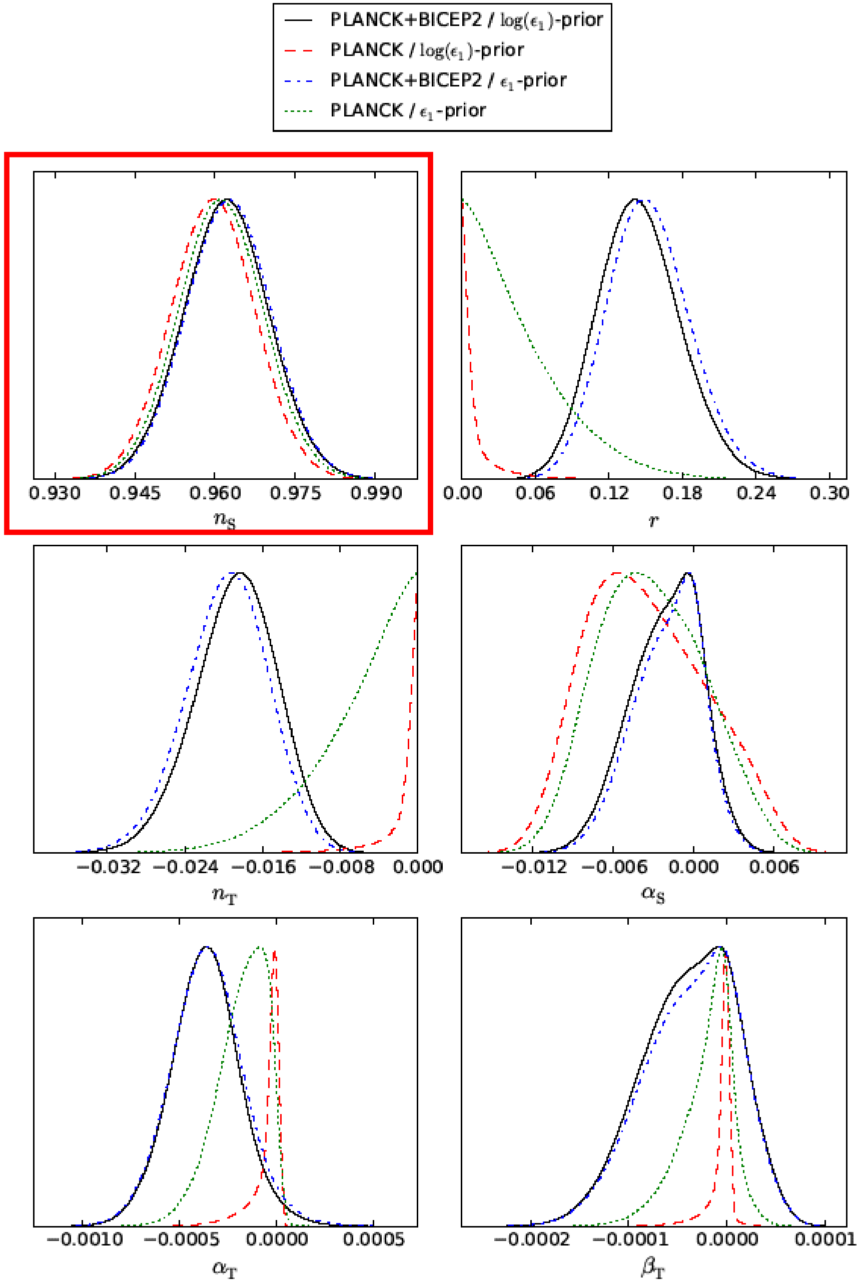


Planck 2013 (and 2015) constraints

- Deviation from exact scale invariance detected at a significant level and robust

Planck 2013 $n_S = 0.9603 \pm 0.0073$

Planck 2015 $n_S = 0.9645 \pm 0.0049$



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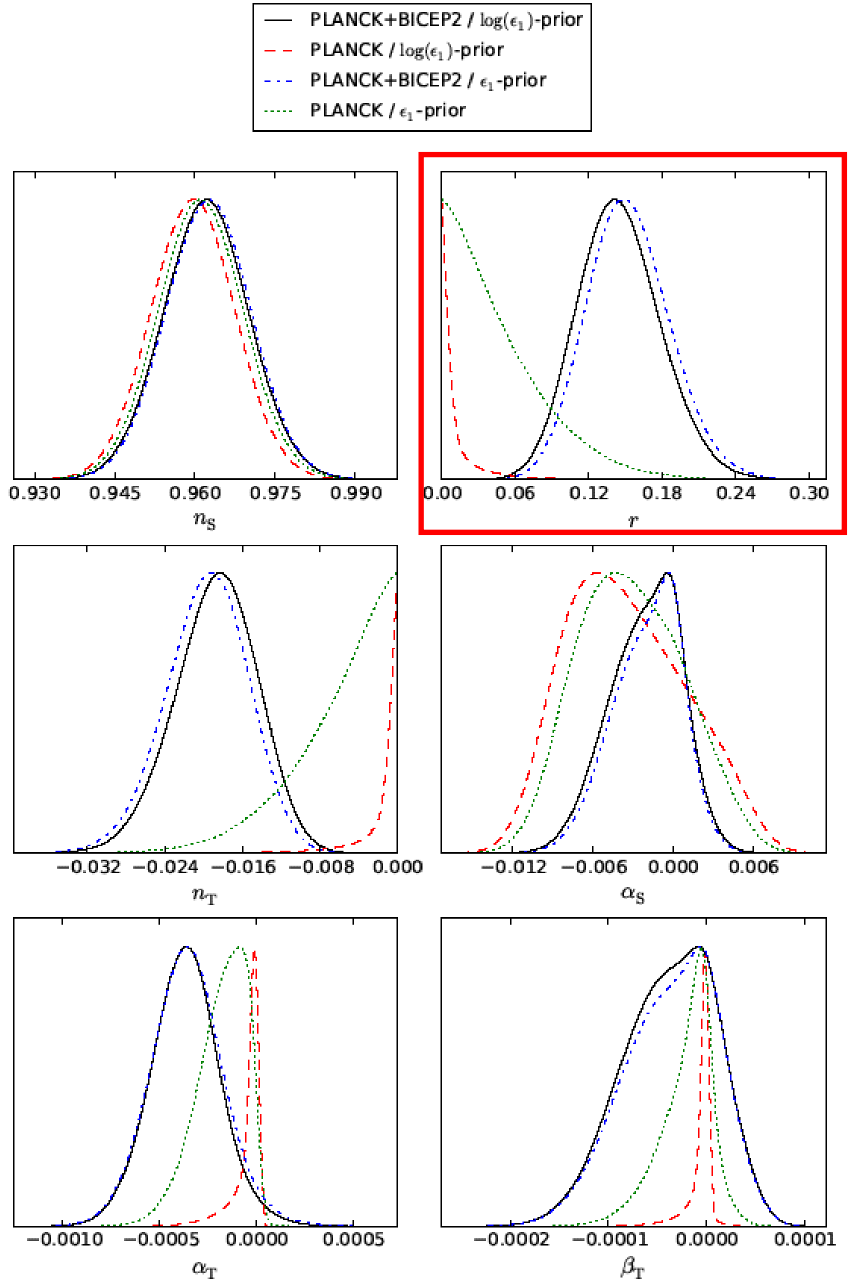

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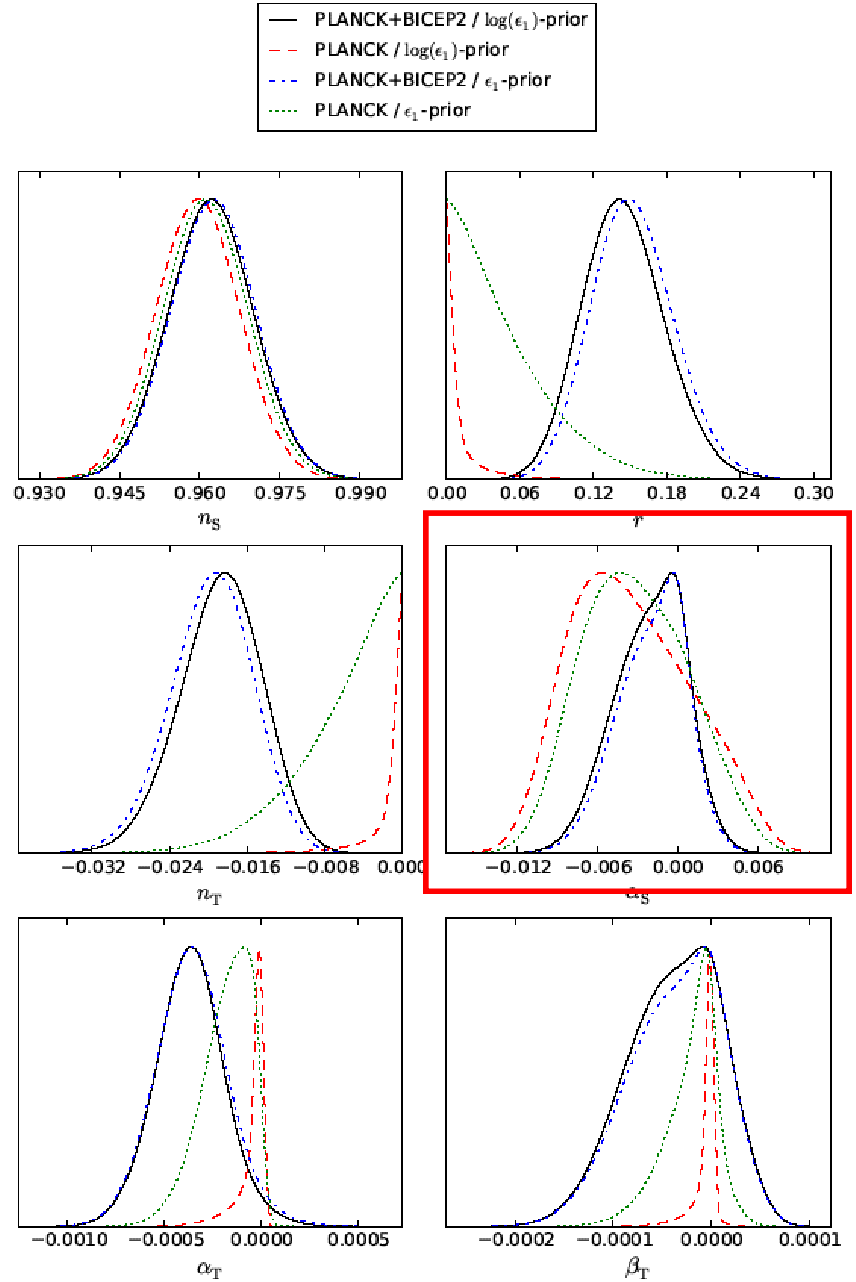
$$\frac{\mathrm{d}n_\mathrm{S}}{\mathrm{d}\ln k} = -0.0134 \pm 0.009$$



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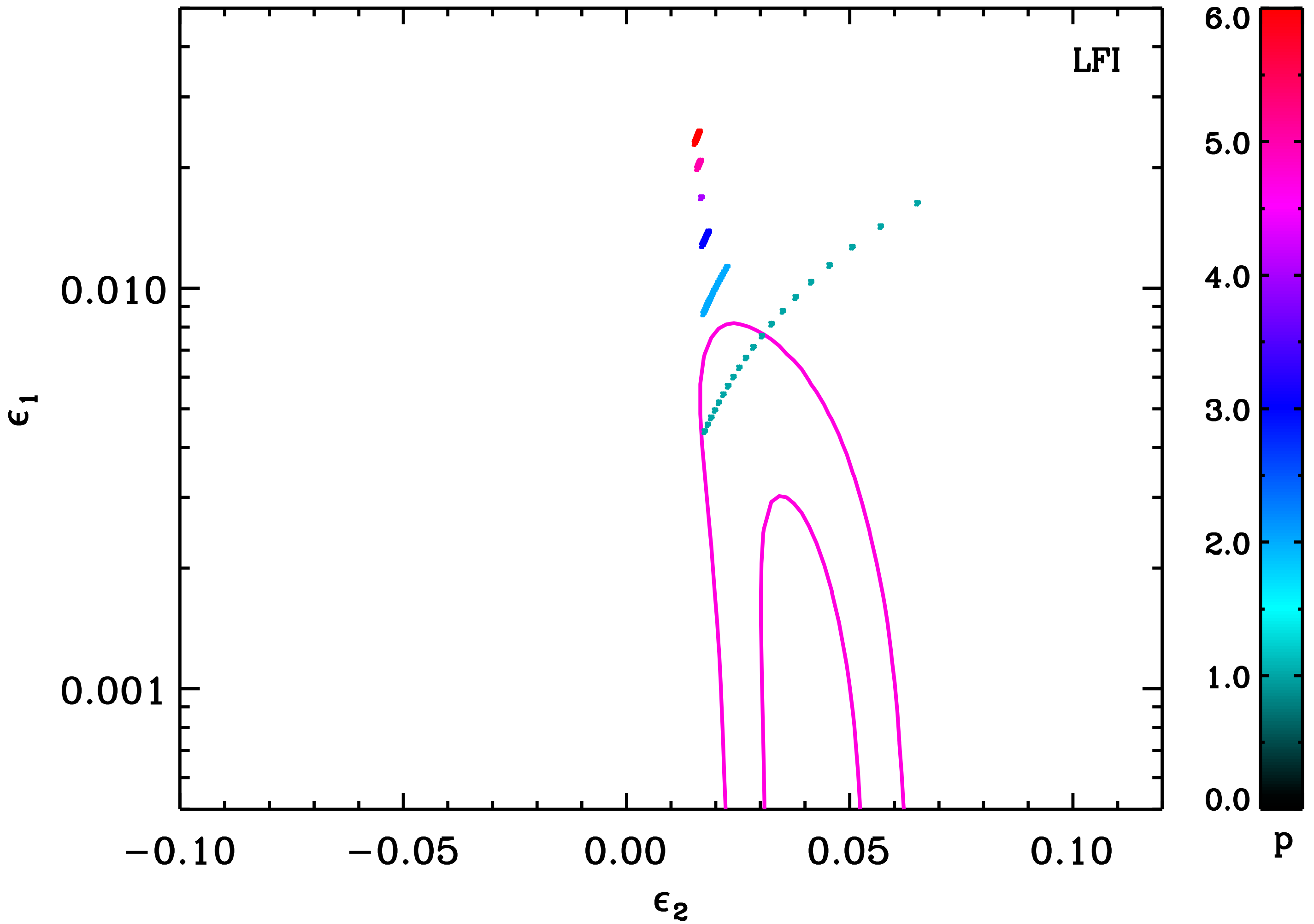
What is the best model of inflation?

➢ Vanilla models are preferred but this leaves us with many different models (~ 200 models) … for each of them, one can establish their predictions and compare to the Planck data



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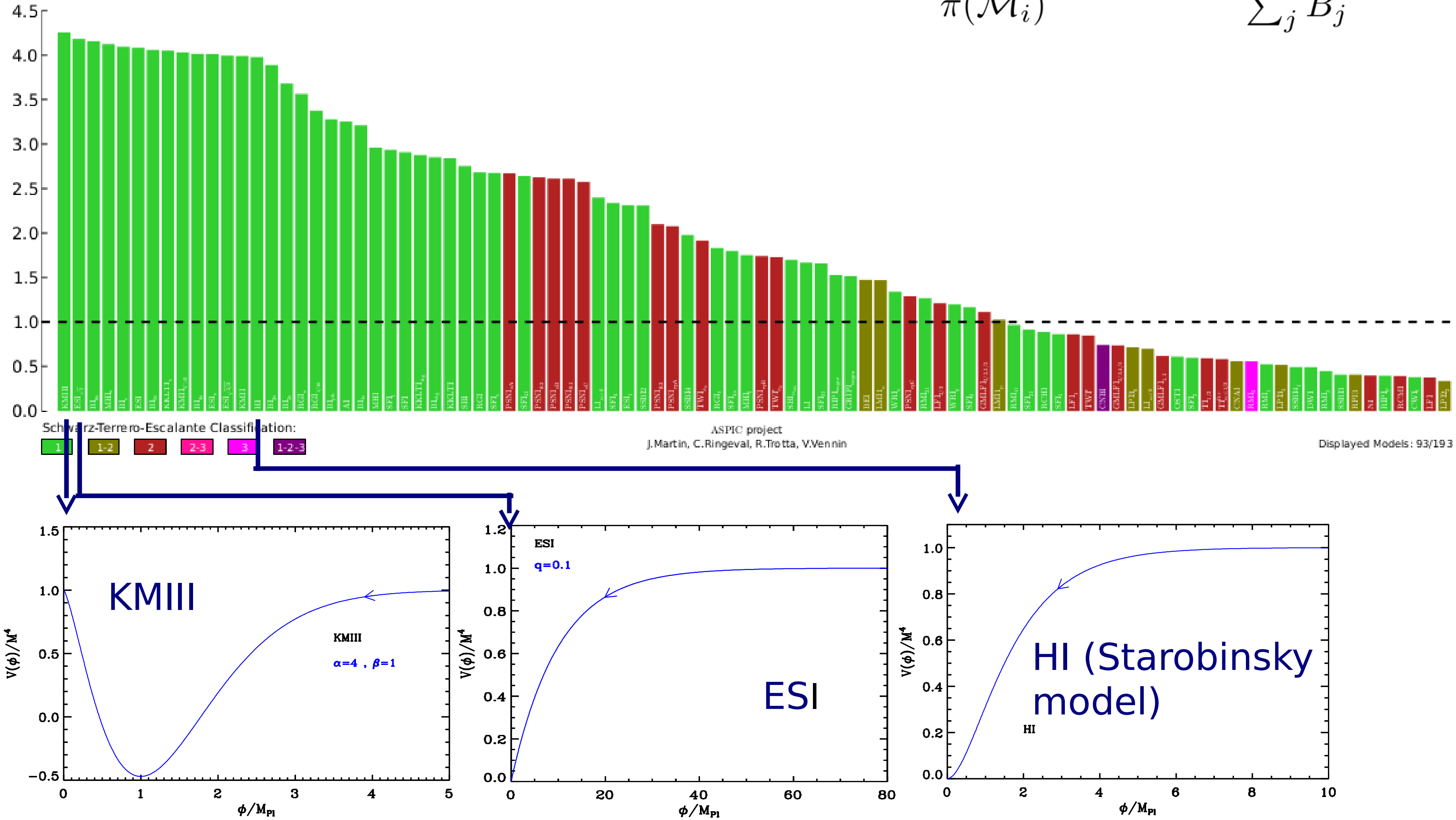
- This is a highly non-trivial computing problem … needs to set a pipeline of numerical codes: CAMB, CosmoMC, Multinest …

Planck: and the winners are …

posterior-to-prior ratio of inflationary models $\dfrac{p(\mathcal{M}_i|D)}{\pi(\mathcal{M}_i)} = N_{\text{models}} \dfrac{B_i}{\sum_j B_j}$



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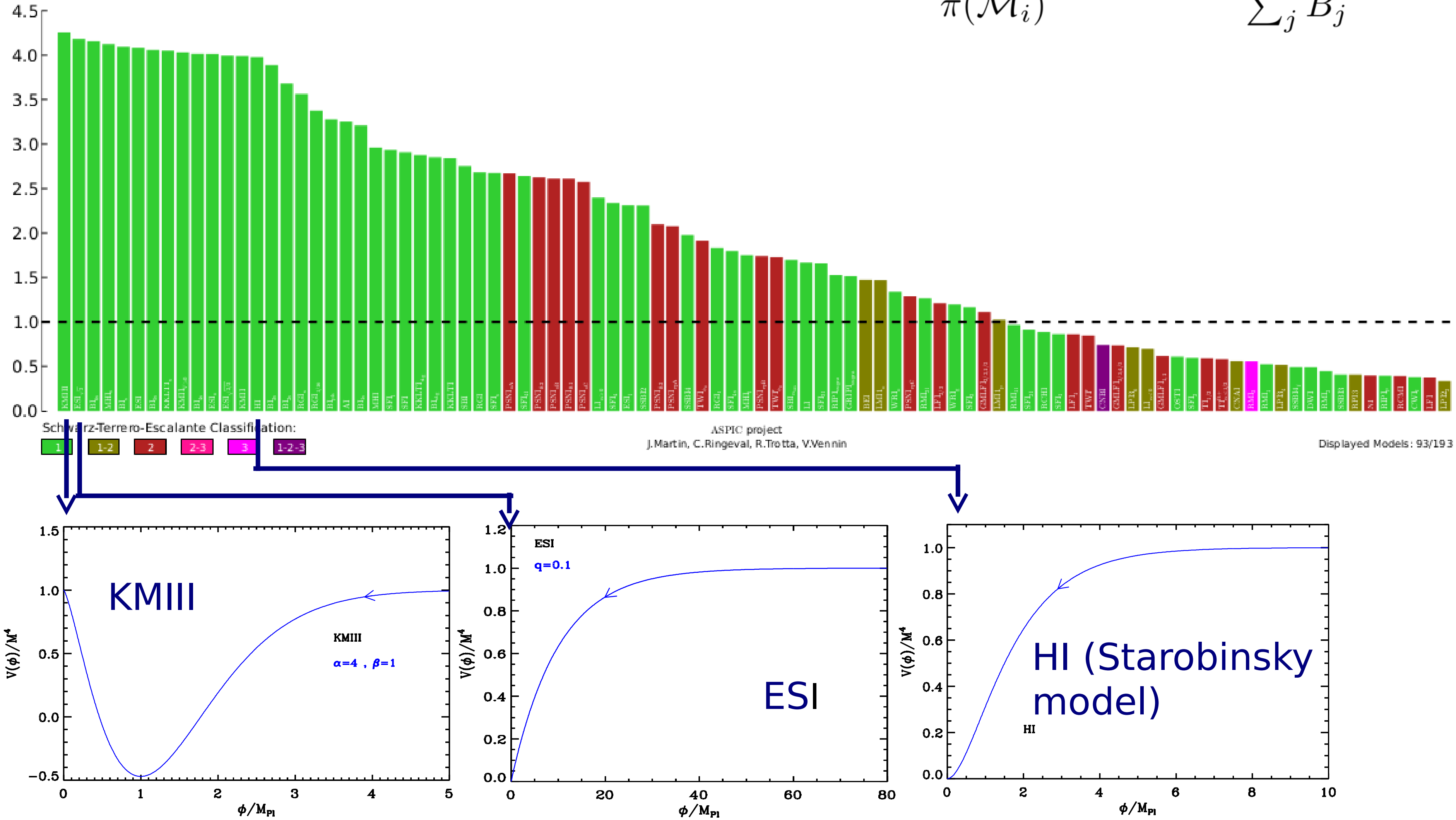

Plateau inflation are the winners!

Inflation in the evidence-Number of unconstrained parameter plane

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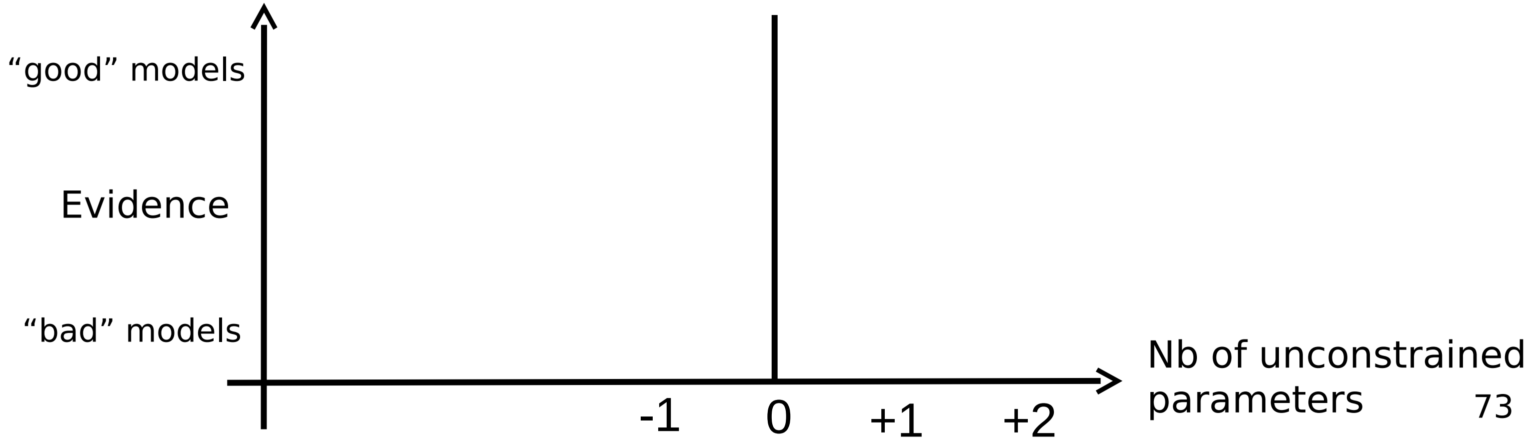

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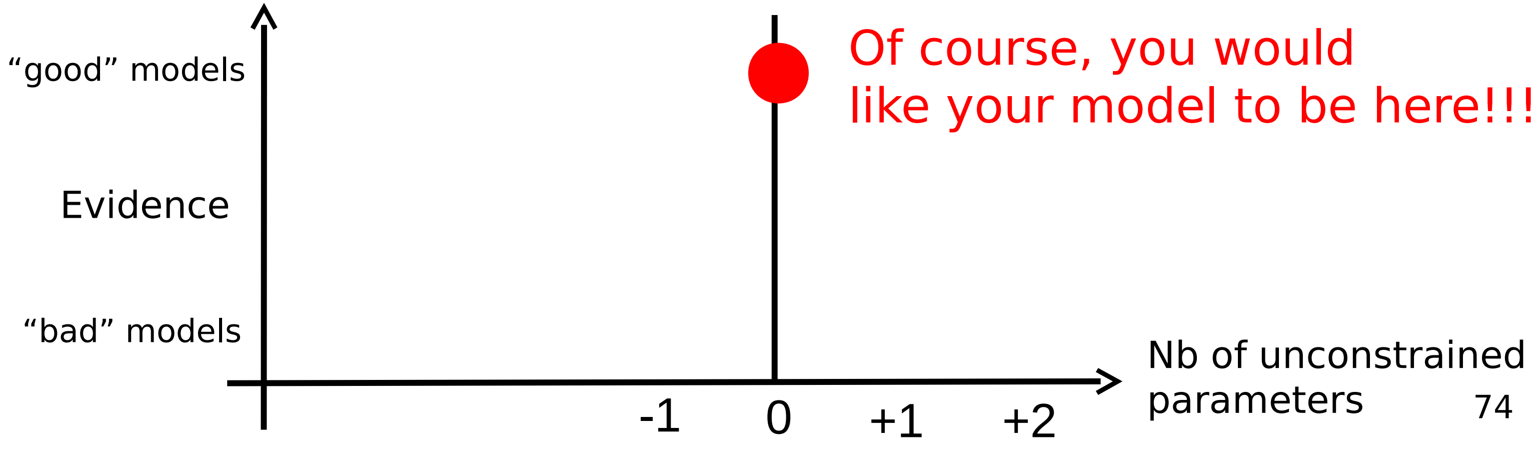

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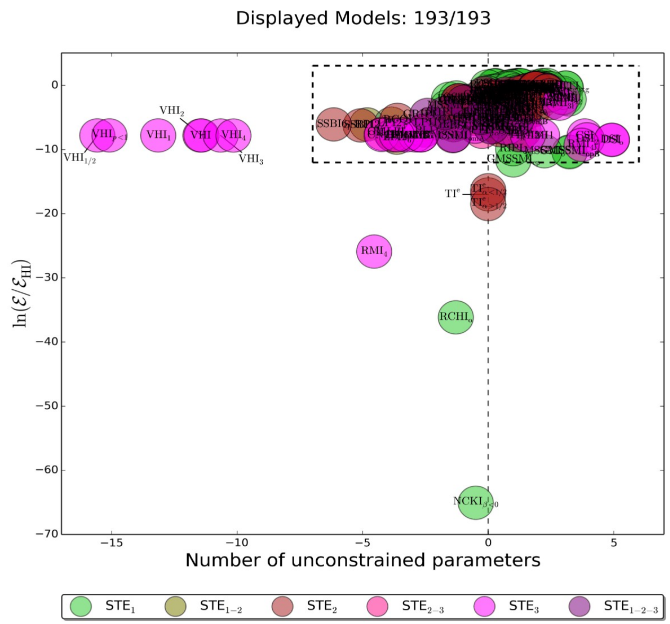
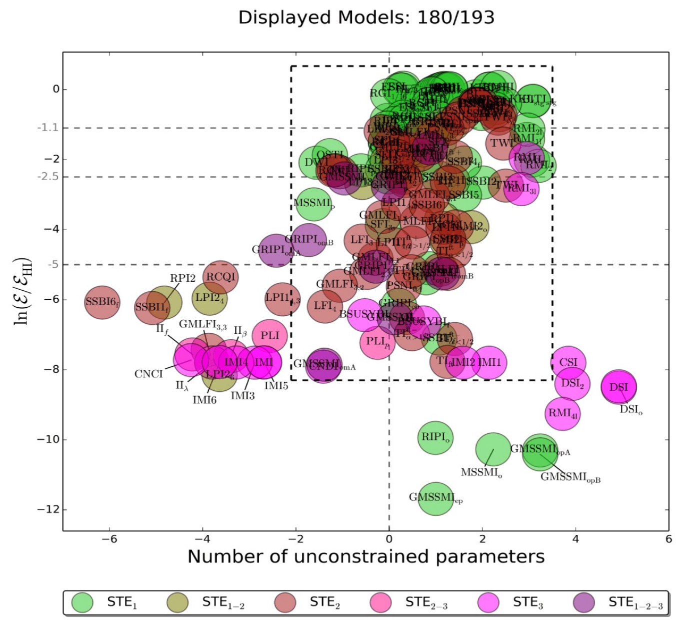
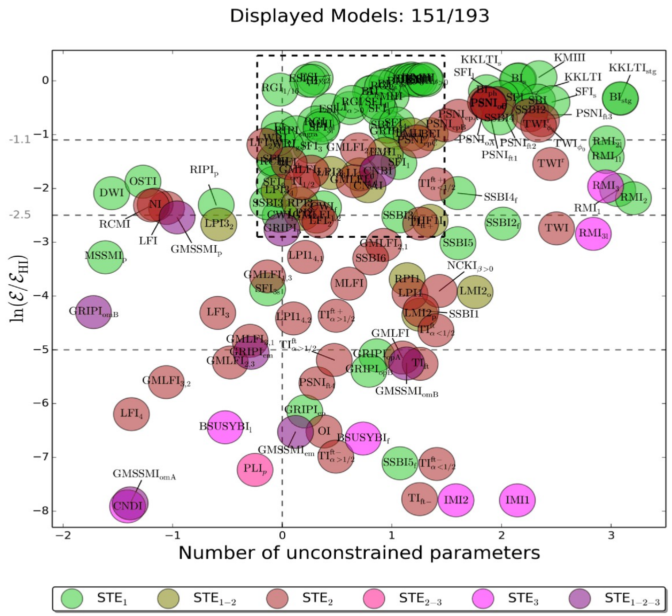
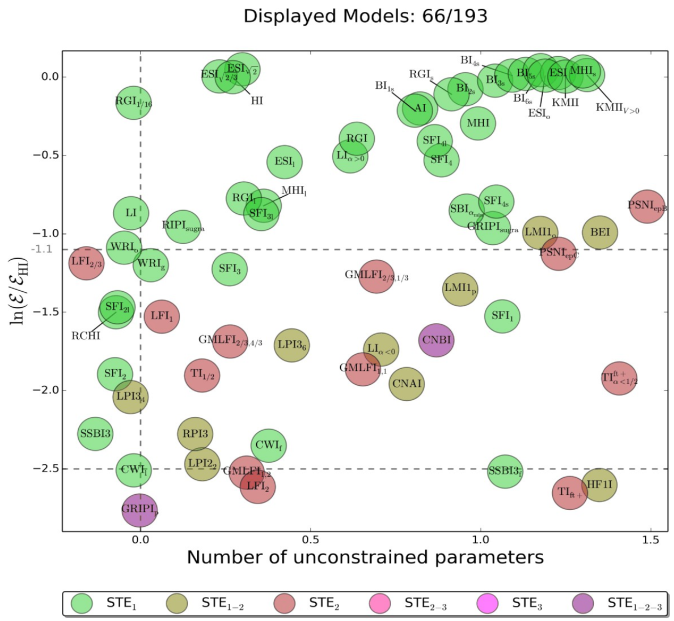
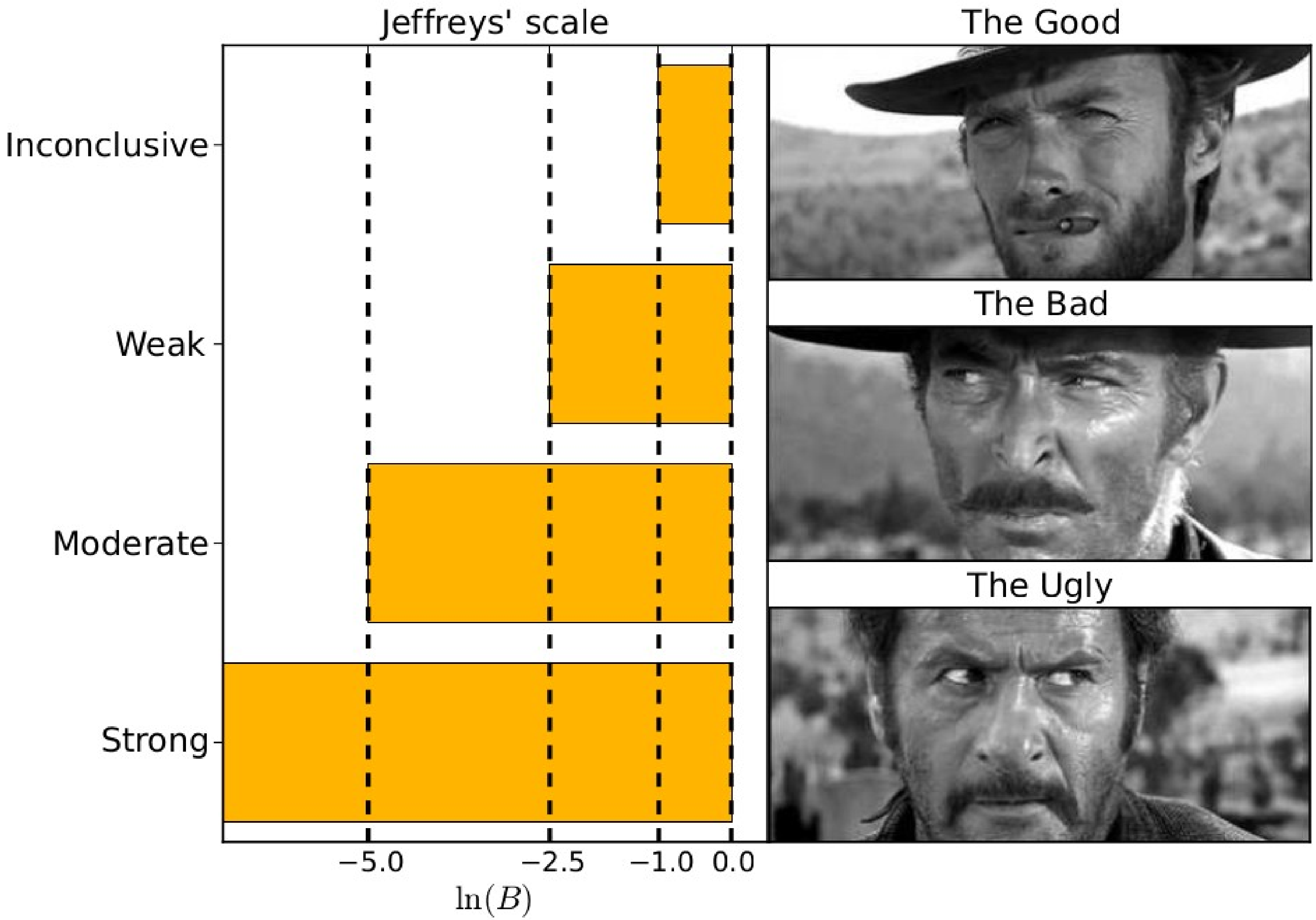






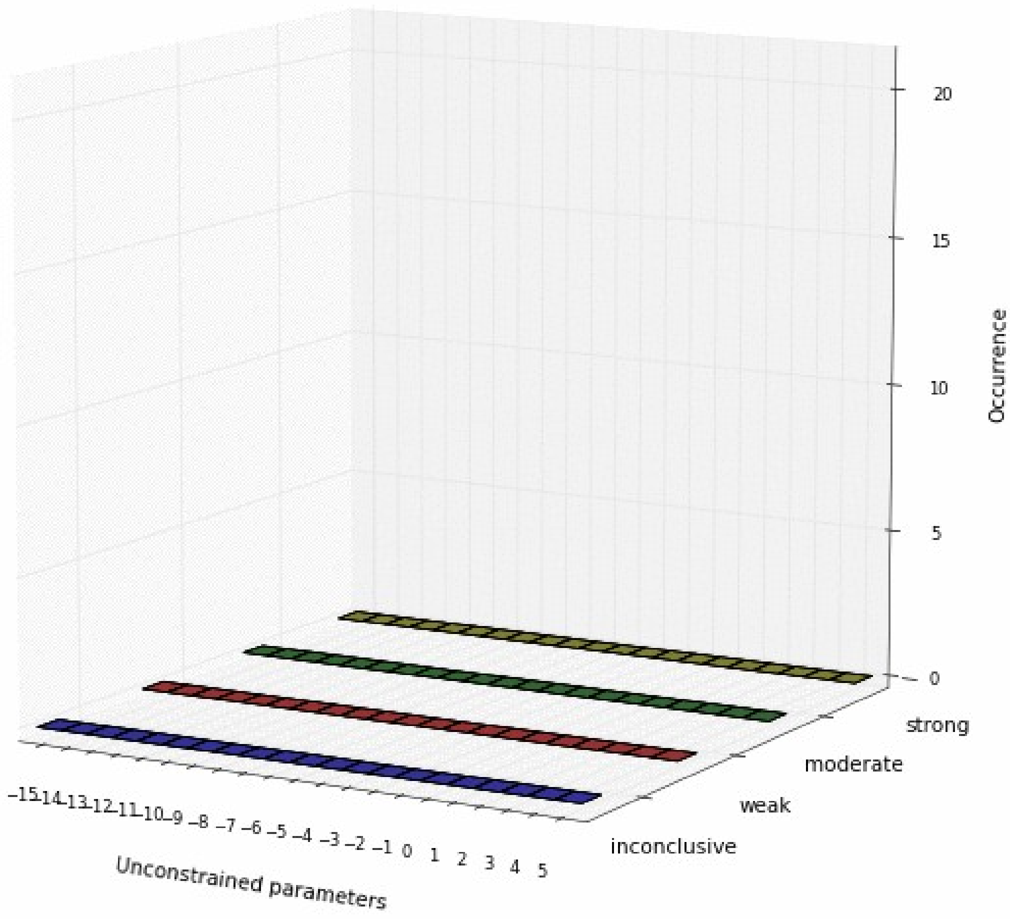


The Jeffreys' scale



NB: Here, the reference is the best model!!

Statistics



Summary

26 % inconclusive zone

21 % weak zone

18 % moderate zone

34 % strong zone

15 different potentials in the inconclusive zone

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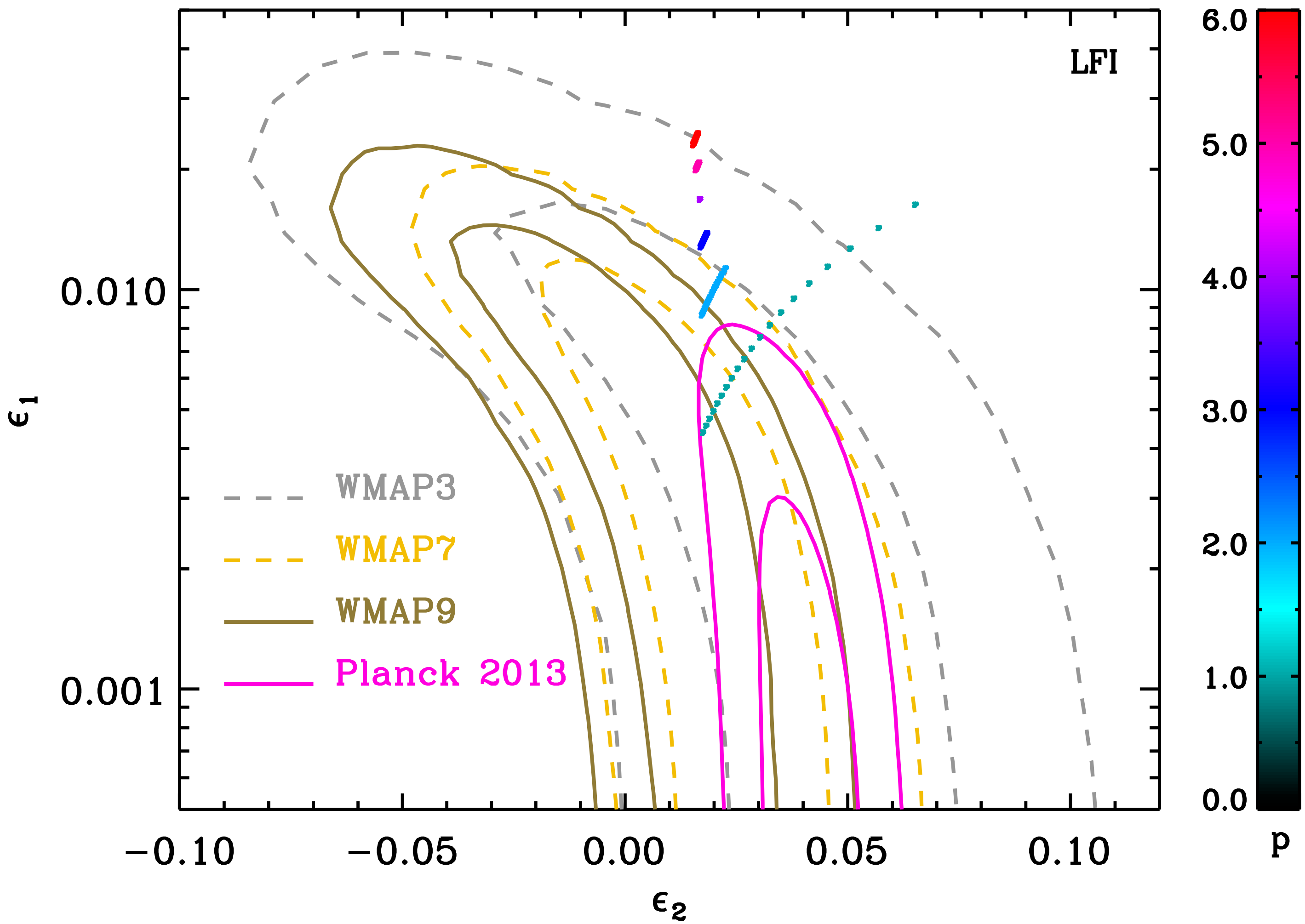

Planck 2013 constraints on reheating

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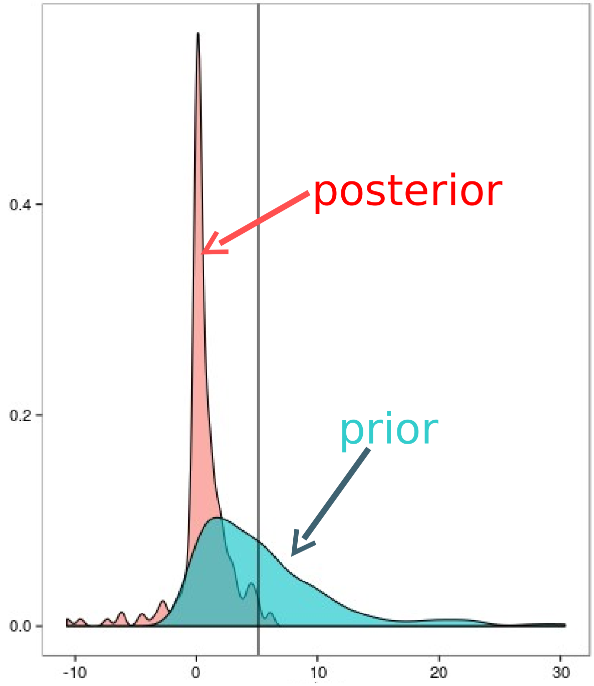
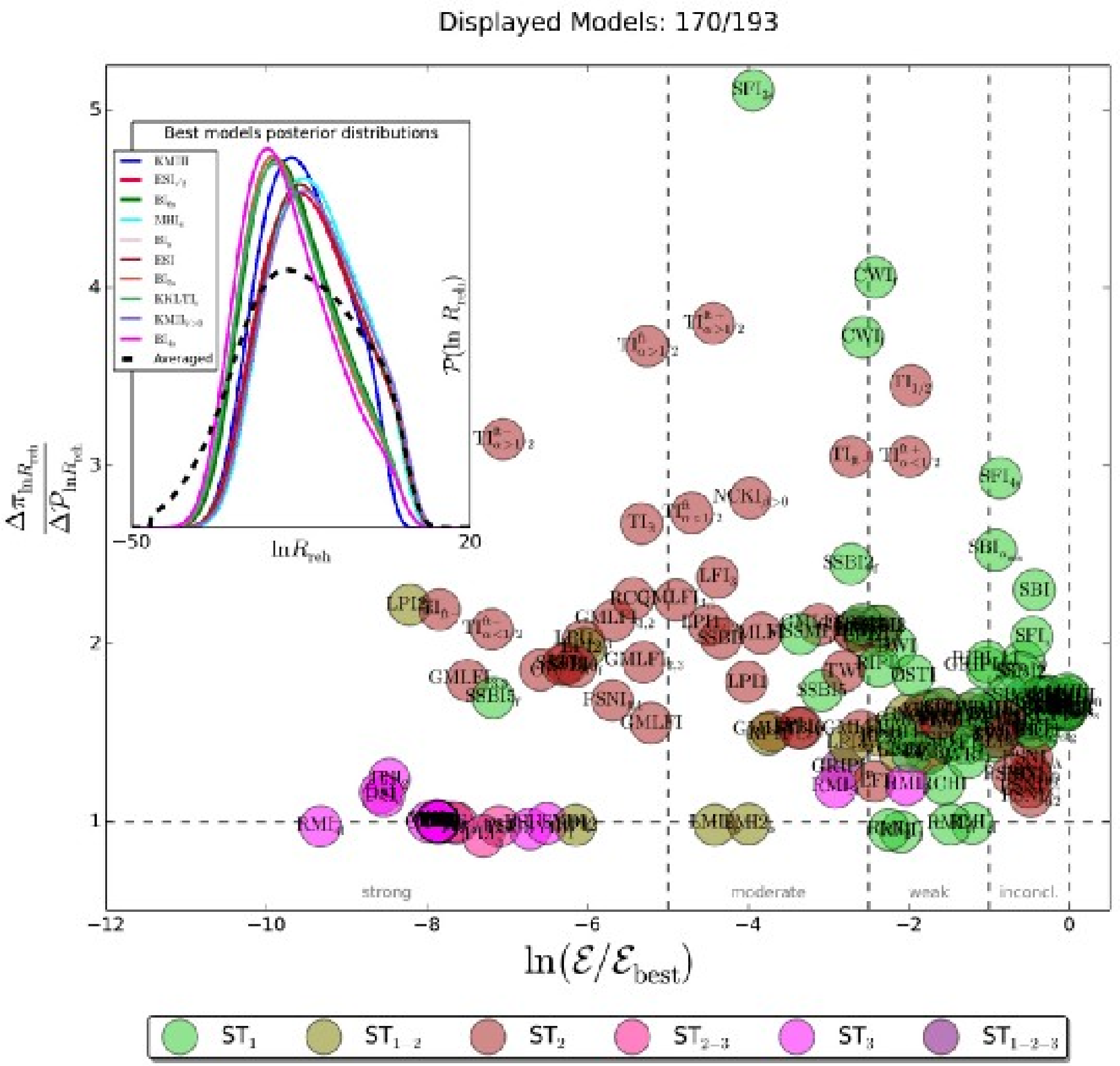
- Reheating is contrained if the posterior has a width smaller than that of the prior



Constrain on reheating
= width of prior/width of posterior>

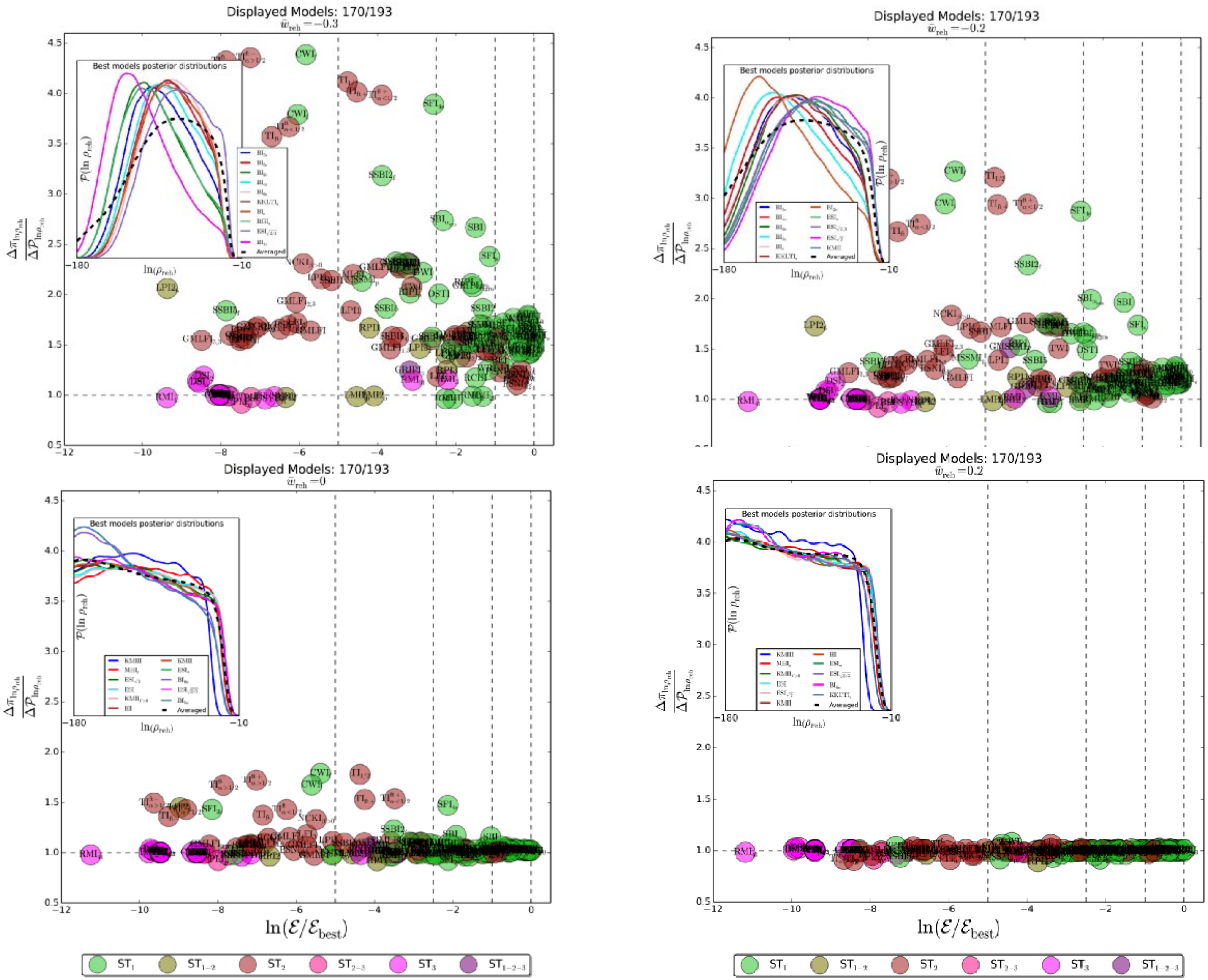


Constraints on reheating

No constraint on reheating

Model performance

Planck2013 constraints on reheating



Recap

- Planck 2013: single field inflation with a plateau-like potential. More complicated models (multiple field scenarios, non-minimal kinetic term scenario etc …) should all have a “bad” Bayesian evidence …

- This could change if non standard features are found (NG etc …)

- Planck2013: 1/3 of the models are now ruled out

- KMIII, ESI, Starobinsky model, … are the winners

- Reheating is now constrained, average reduction of the prior to posterior width of about 40%

- Future CMB experiments such as COrE+: can ruled out 3/4 of the models and provide very good constraints on the reheatin epoch.

Gravitational Waves Production (III)