Inflation after Planck

Jerome Martin

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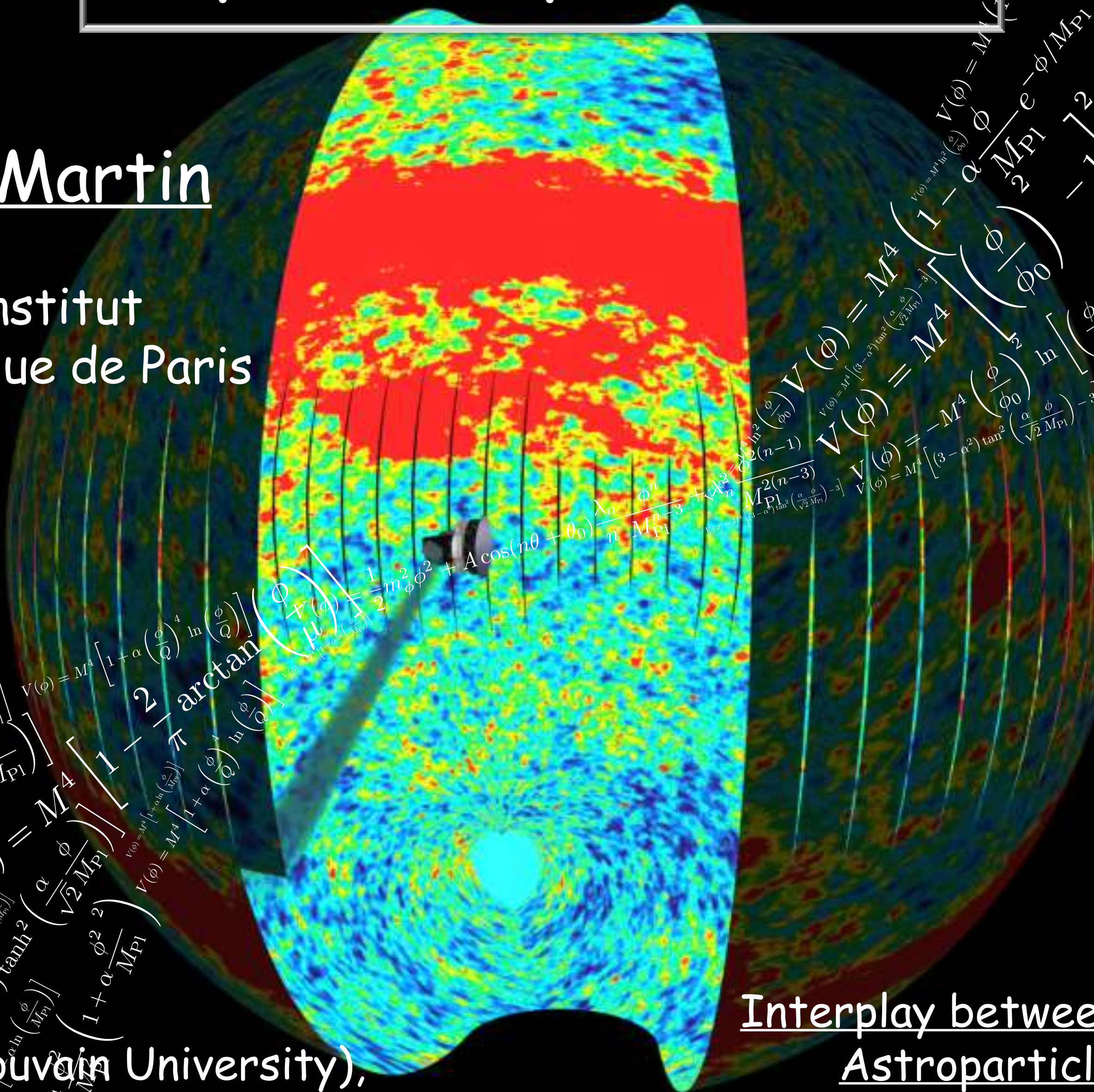

Collaborators:

- C. Ringeval (Louvain University),
- R. Trotta (Imperial College, London)
- V. Vennin (Portsmouth University)

Interplay between Particle and Astroparticle Physics

LAL-Orsay

September 05-09, 2016

Outline

- Which class of inflationary scenarios after Planck 2013 & 2015?

- What is the best model of inflation? Model comparison.

- Constraints on reheating (aka end of inflation).

- The next generation of CMB experiments and inflation.

- Conclusions.

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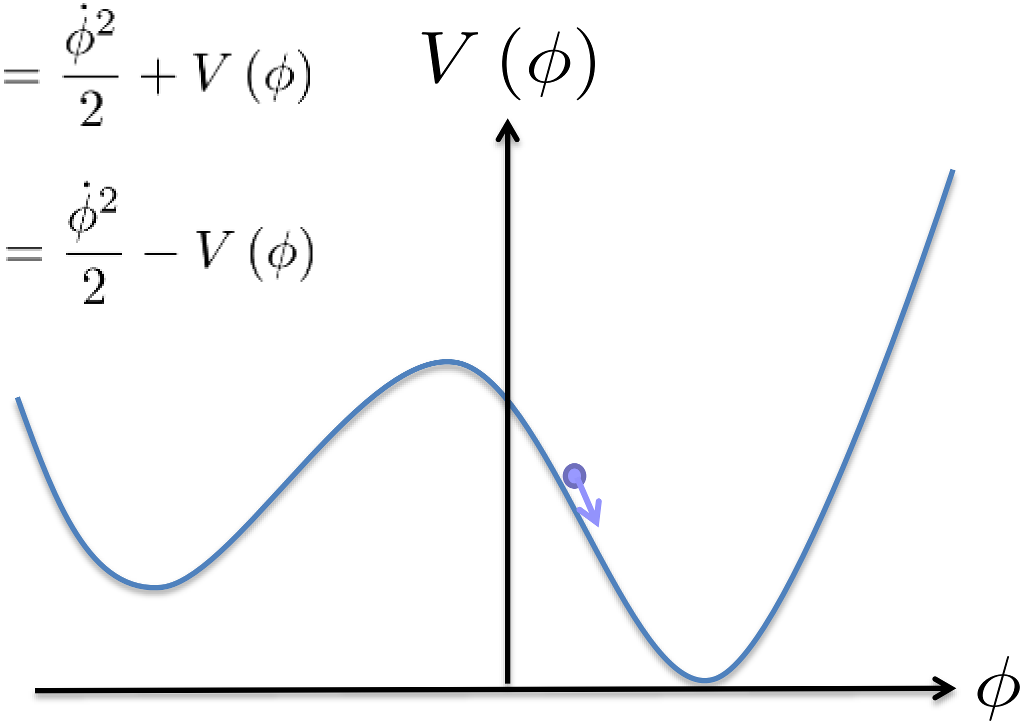
Inflation in brief

Inflation is a phase of accelerated expansion taking place in the very early Universe. It solves the puzzles of the standard model of cosmology.

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

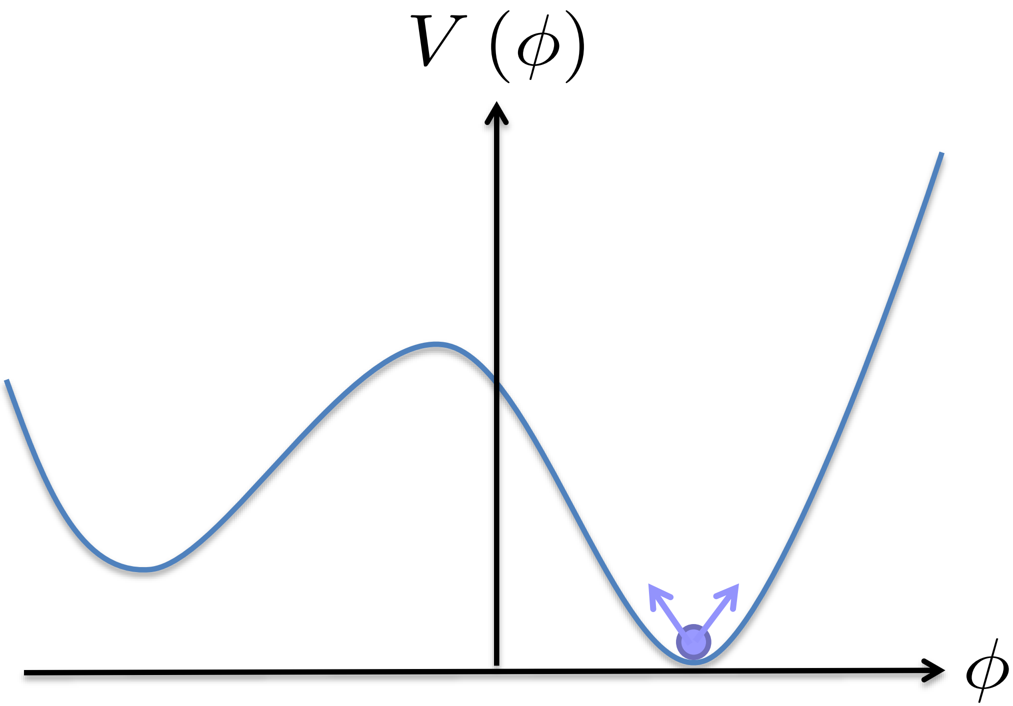
$$p = \frac{\dot{\phi}^2}{2} - V(\phi)$$



Inflation is (usually) realized with one (or many) scalar field(s)

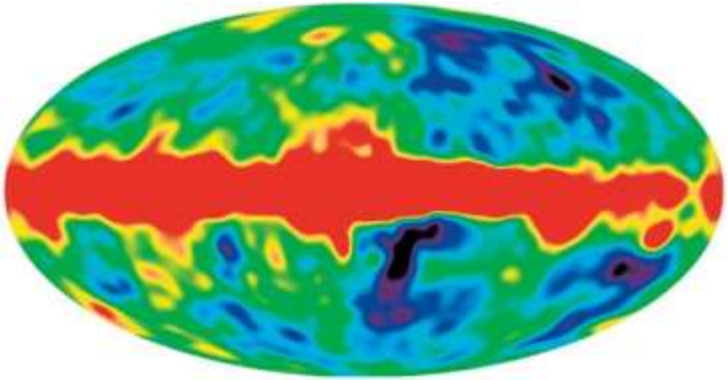
If the scalar field moves slowly (the potential is flat), then pressure is negative which, in the context of GR, means accelerated expansion and, hence, inflation takes place.

Inflation (usually) stops when the field reaches the bottom of the potential

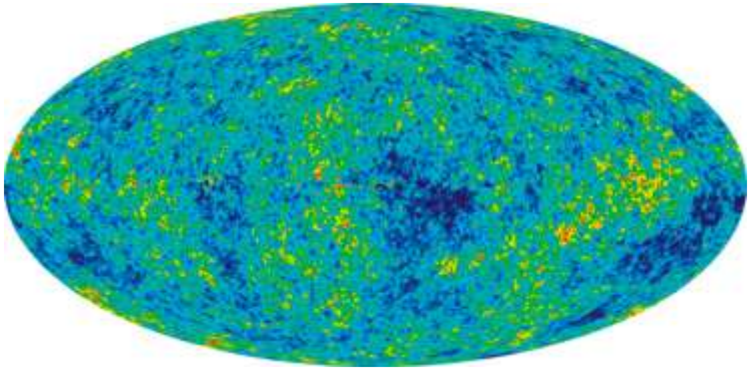


The field oscillates, decays and the decay products thermalize …Then the radiation dominated era starts …

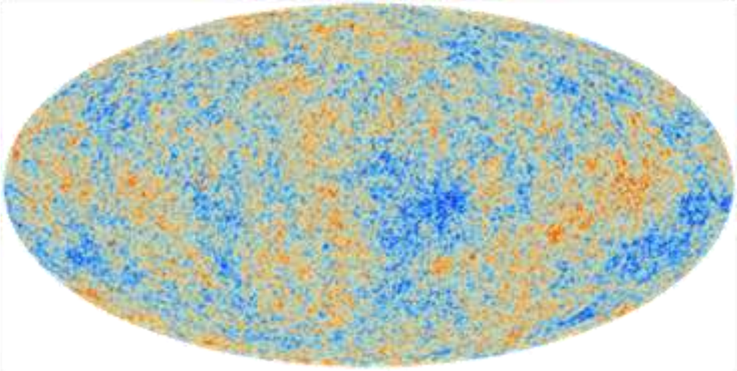
Planck: third CMB experiment generation



COBE (1992)

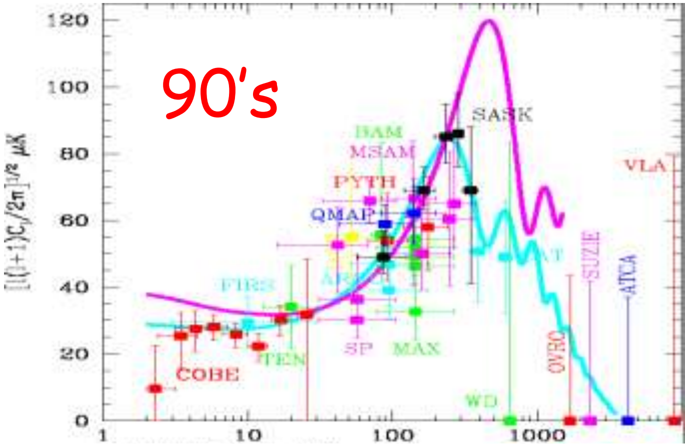


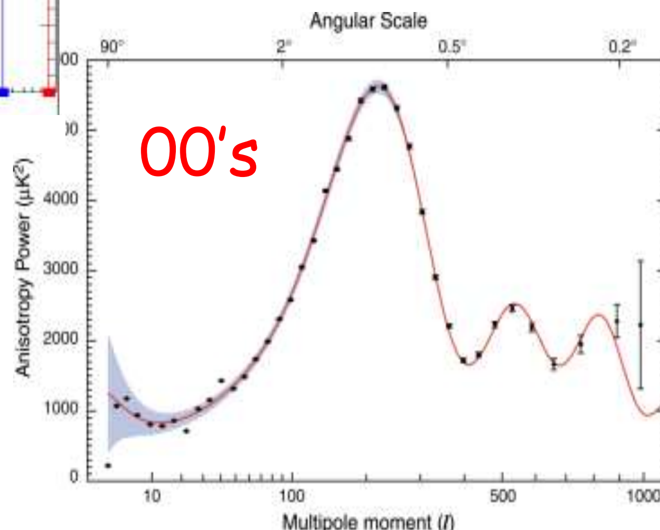
WMAP (2003)

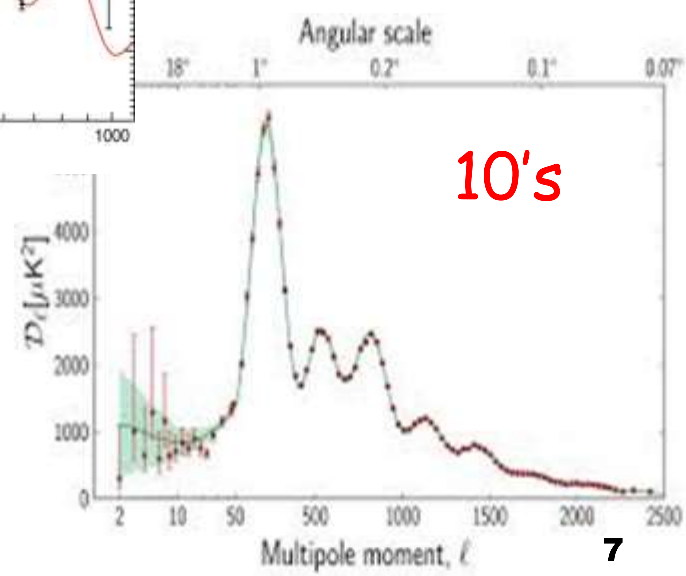


Planck (2013 & 2015)

From COBE to Planck …

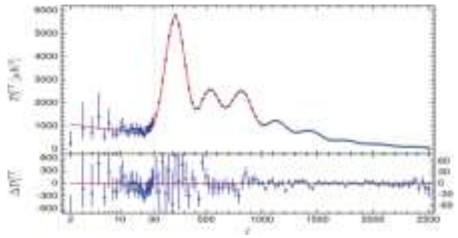






Planck Measurements

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



- Phase coherence

- Adiabatic perturbations $\alpha^{(2,2500)}_{\mathcal{R}\mathcal{R}} \in [0.985, 0.999]$

- Gaussian perturbations

$$f_{\rm NL}^{\rm loc} = 0.8 \pm 5$$
$$f_{\rm NL}^{\rm eq} = -4 \pm 43$$

- Almost scale invariant power spectrum $n_{\rm S} = 0.9645 \pm 0.0049$

- Background of quantum gravitational waves $r = T/S < 0.07$

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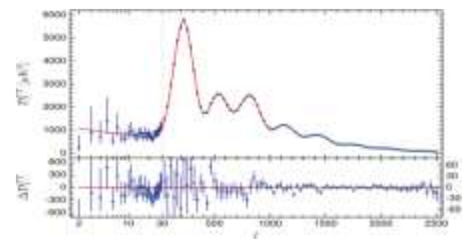

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Single field slow-roll models, with minimal kinetic terms, are preferred

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The performance of an inflationary model can be described by two numbers

- the Bayesian evidence (integral of the likelihood over prior space)

$$p\left(\mathcal{M}_i|\mathcal{D}\right) = \mathcal{E}\left(\mathcal{D}|\mathcal{M}_i\right)\pi\left(\mathcal{M}_i\right)$$

- the effective number of unconstrained parameters (aka Bayesian complexity)

$$N^{\mathrm{uc}} = N - \mathcal{C} = N - \left[\langle -2\ln\mathcal{L}(\theta)\rangle + 2\ln\mathcal{L}(\theta^{\mathrm{ML}})\right]$$

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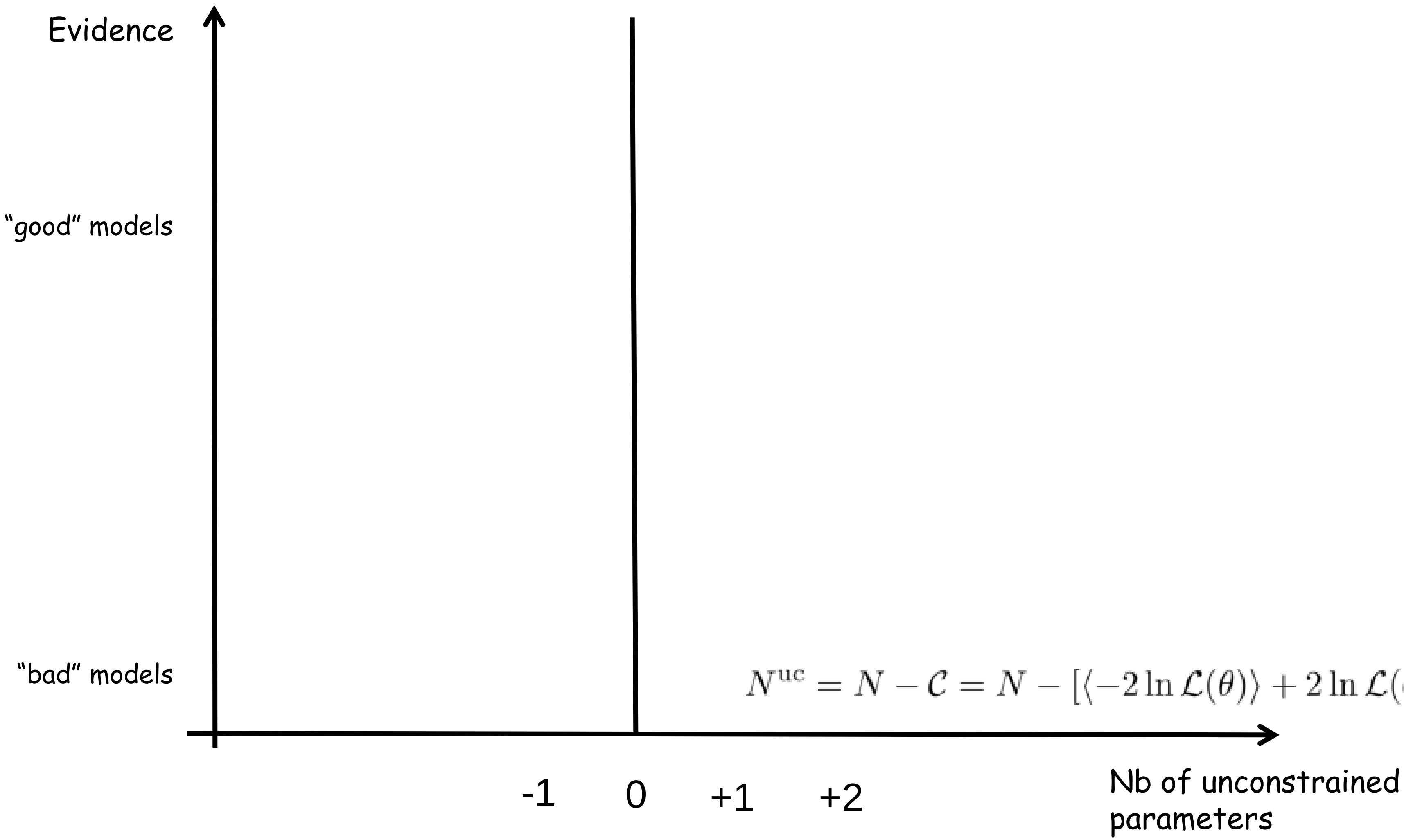

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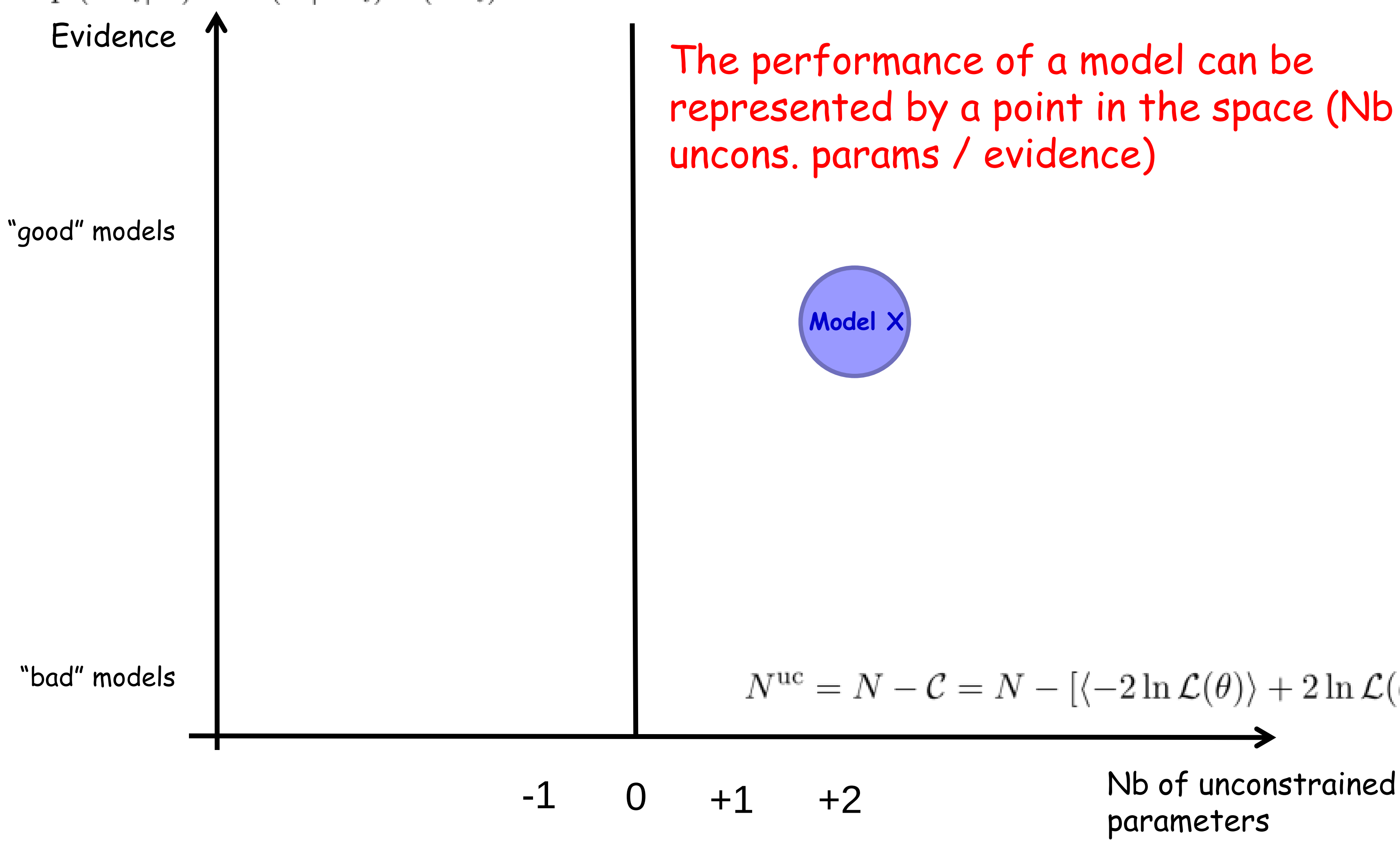
The performance of a model can be represented by a point in the space (Nb of uncons. params / evidence)



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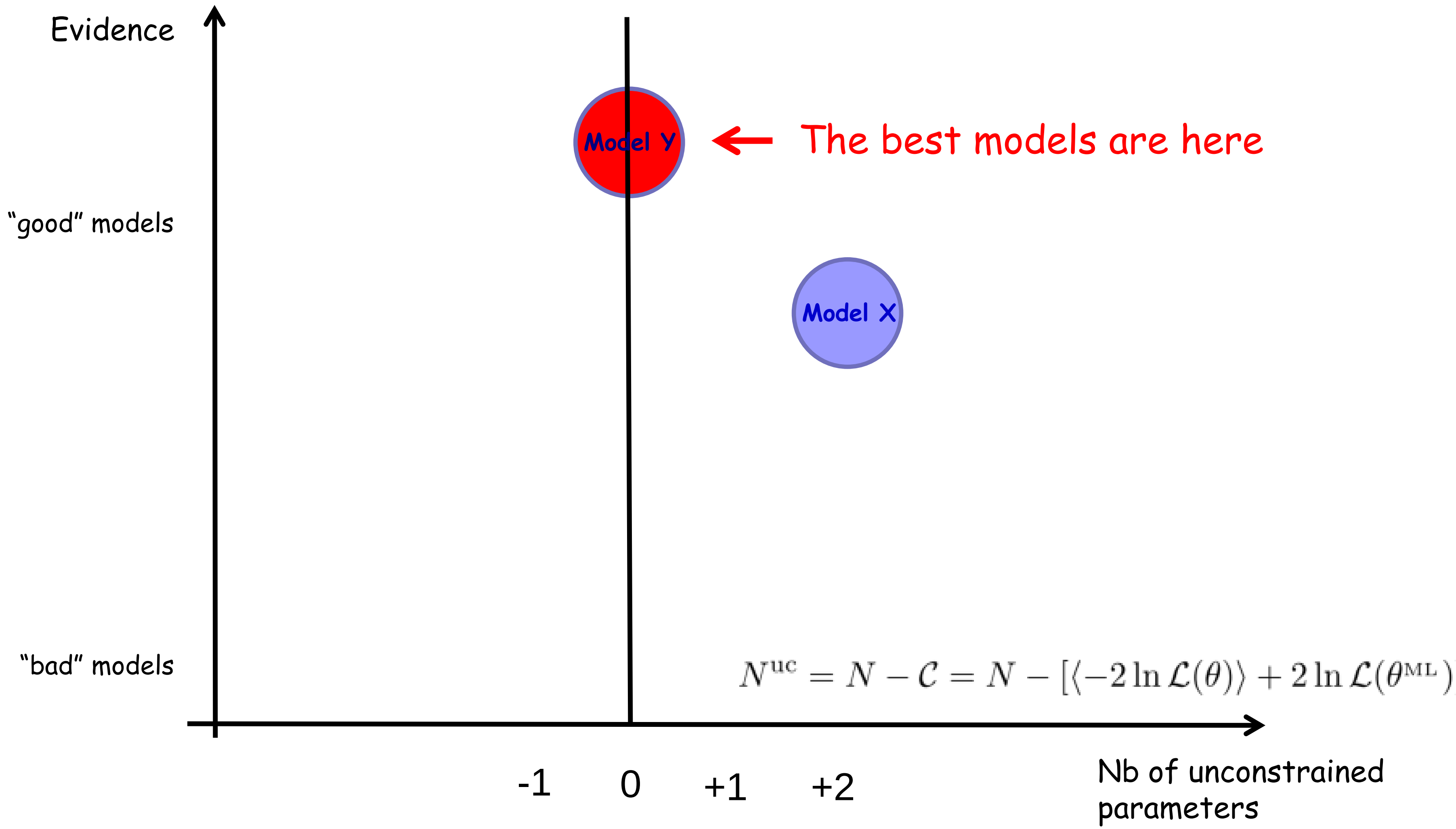

Encyclopedia Inflationaris

- We have carried out a survey of all (single field slwo-roll) models invented since 1979

- This complete survey includes

  ≈ 74 potentials

  ≈ 200 scenarios

  ≈ 700 slow roll formulas

  ≈ 365 pages

  ≈ 30 000 lines of code

arXiv:1303.3787

Encyclopædia Inflationaris

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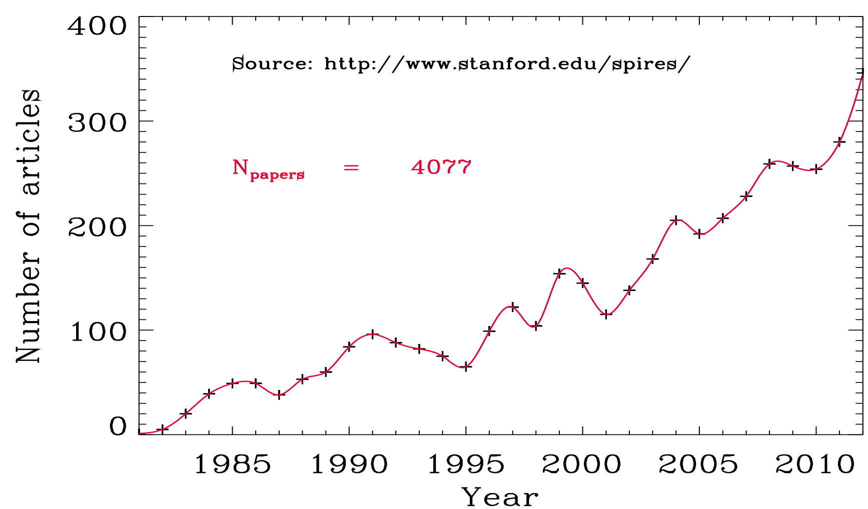
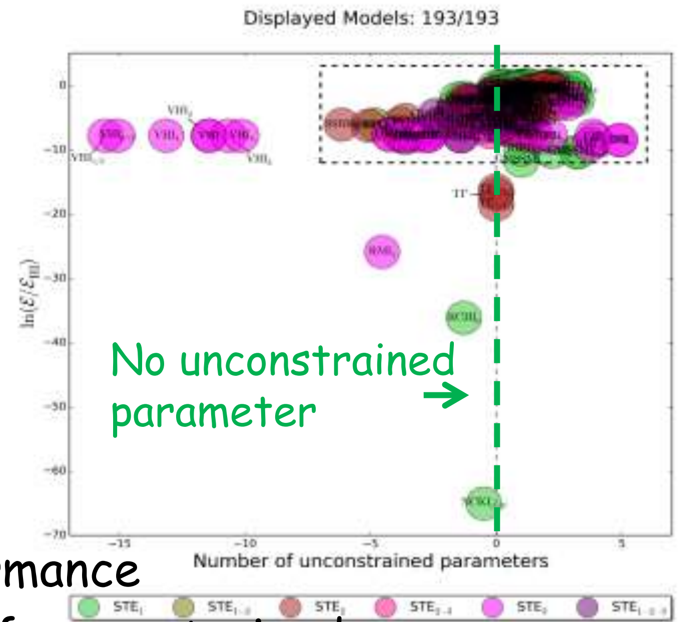
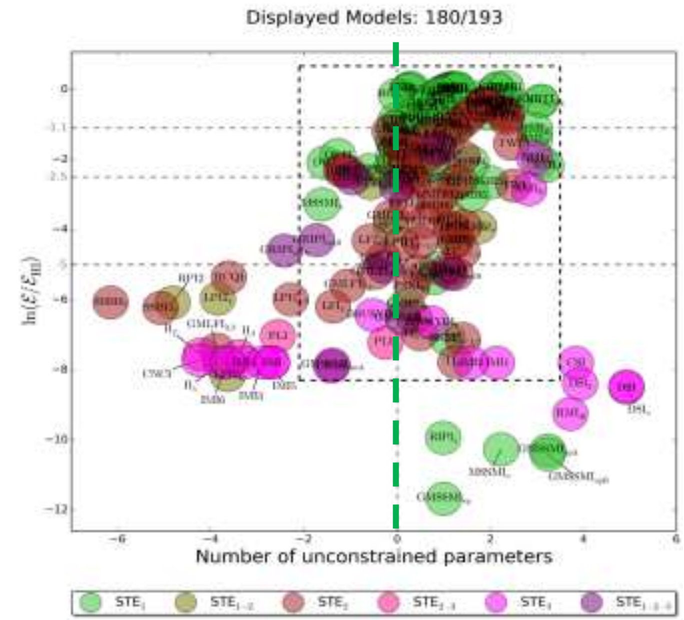
Keywords: Cosmic Inflation, Slow-Roll, Reheating, Cosmic Microwave Background, Aspic



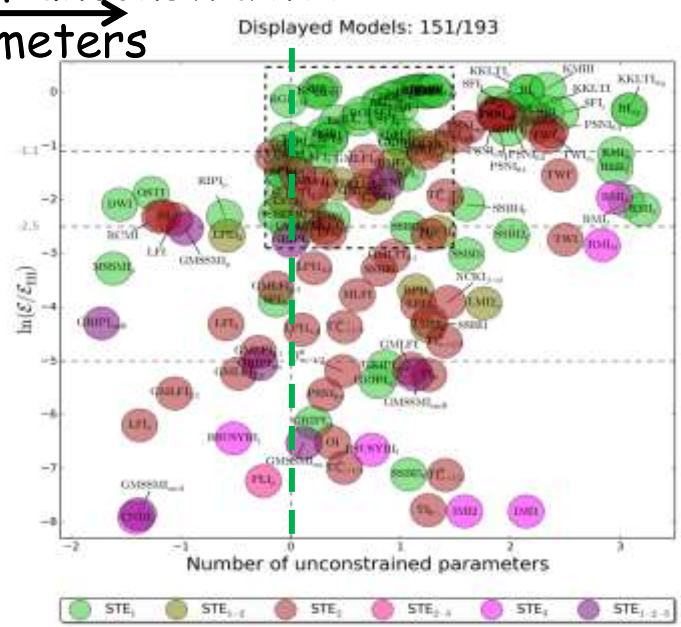
Inflation in the evidence-Number of unconstrained parameter space

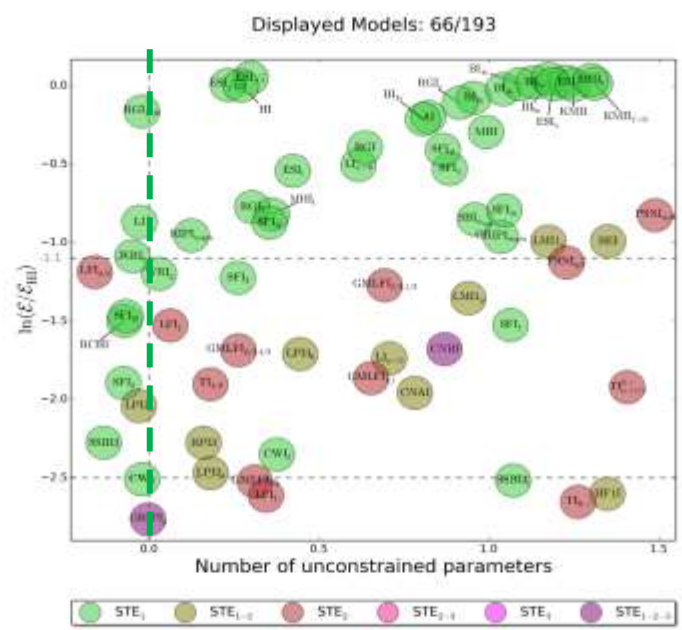




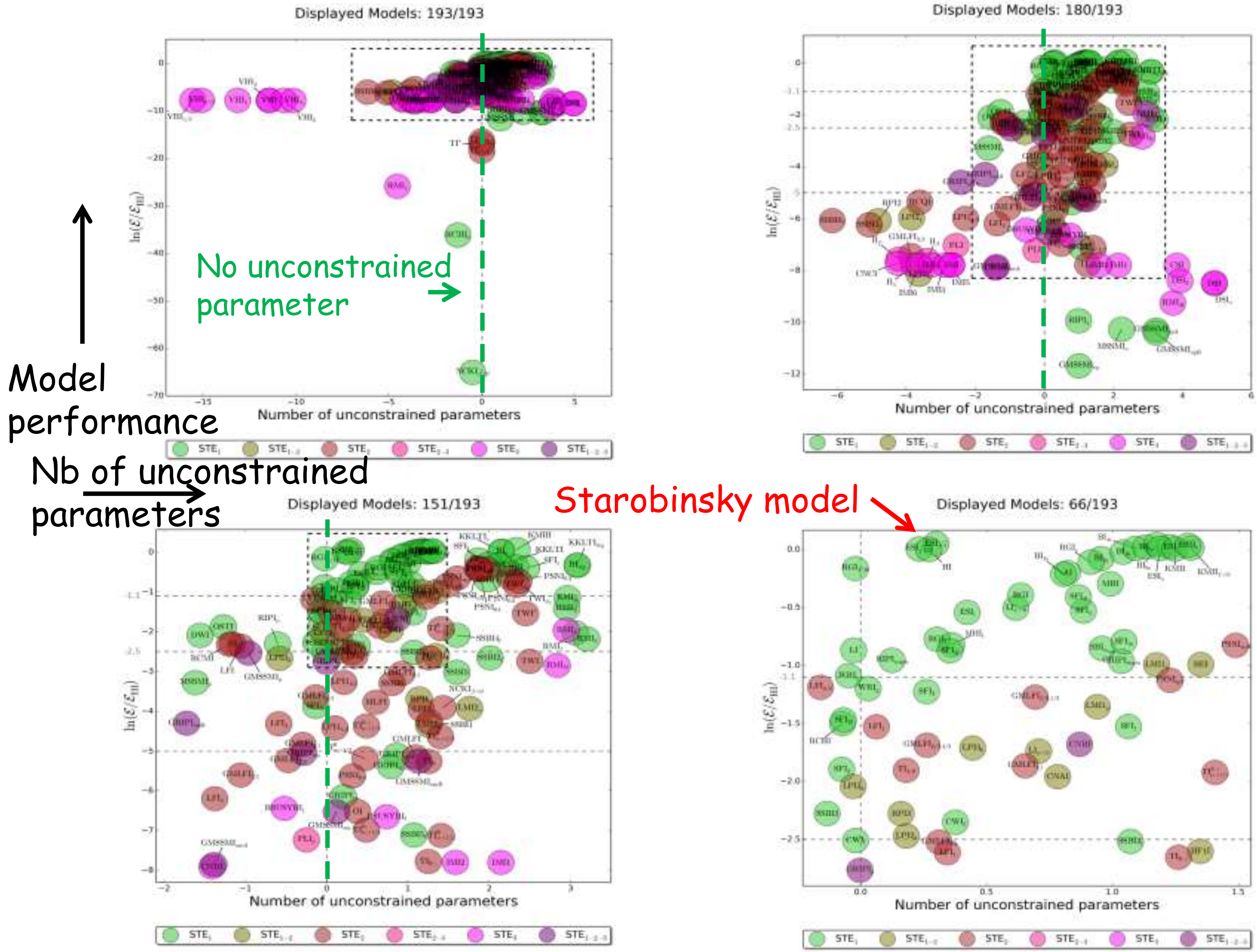
Model performance

Nb of unconstrained parameters

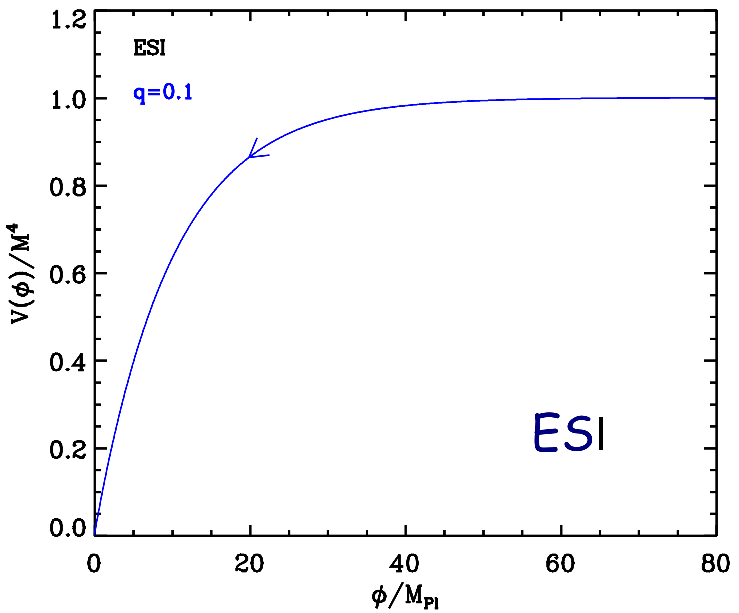


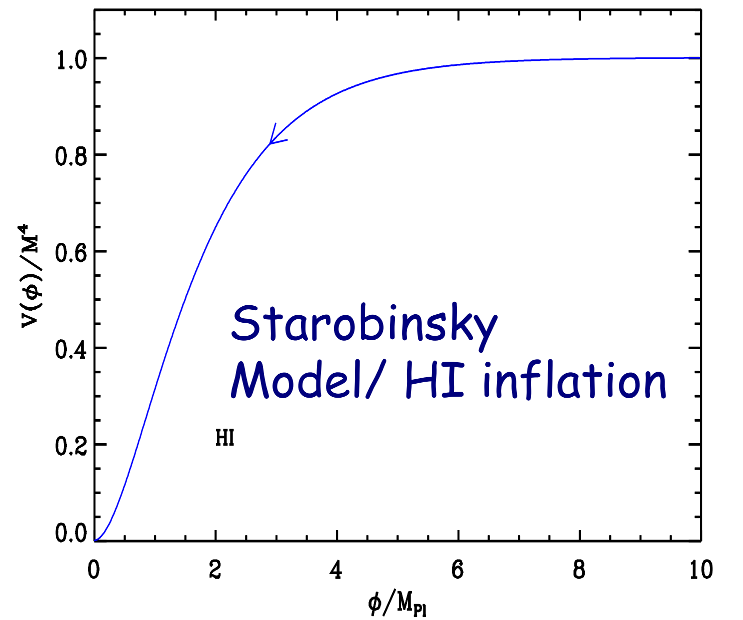


Inflation in the evidence-Number of unconstrained parameter plane



Plateau inflationary models are the winners!





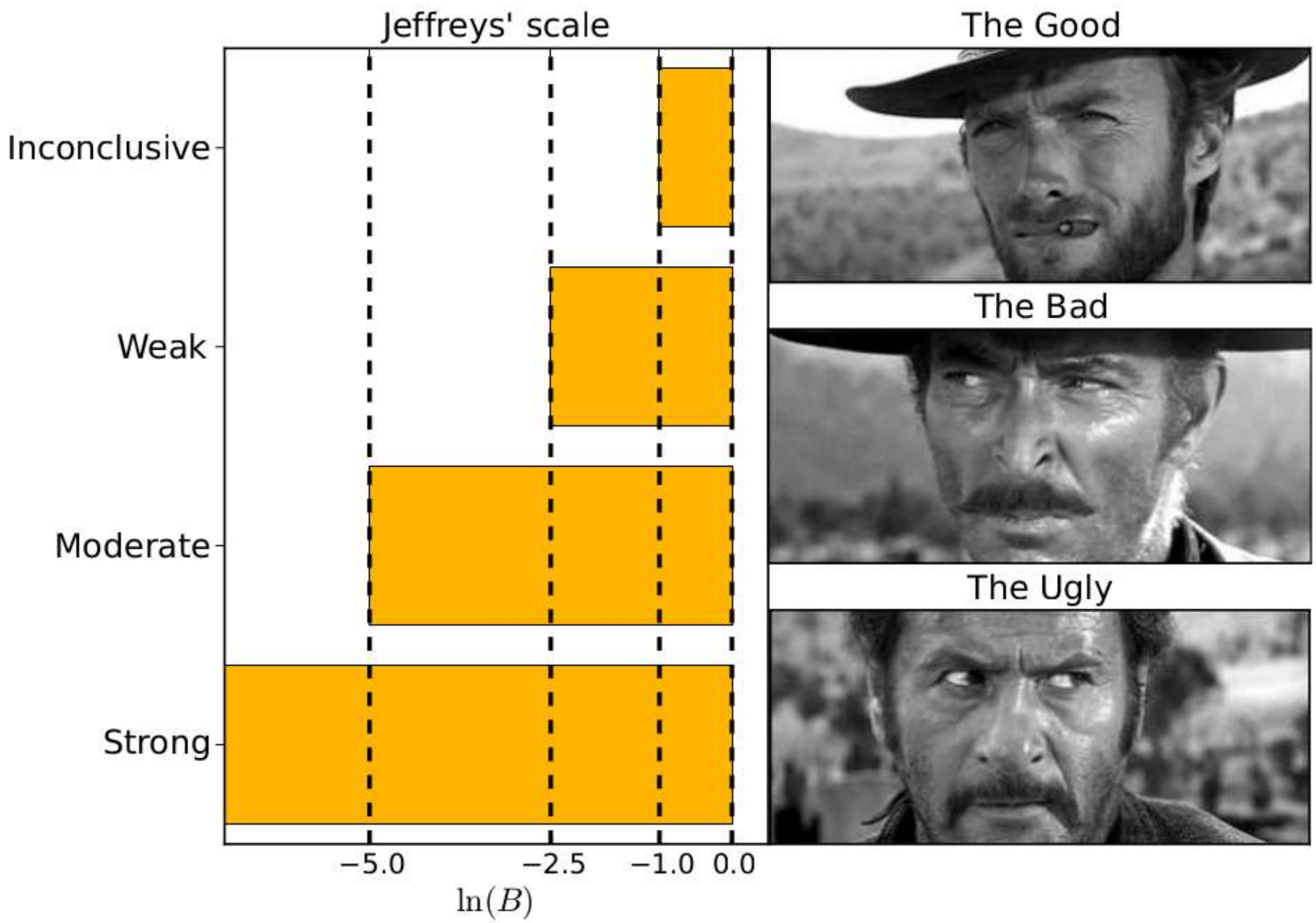
$$V(\phi) = M^4\left(1 - \mathrm{e}^{-q\phi/M_{\mathrm{Pl}}}\right)$$

$$V(\phi) = M^4\left(1 - \mathrm{e}^{-\sqrt{2/3}\phi/M_{\mathrm{Pl}}}\right)^2$$

J. Martin, C. Ringeval and V. Vennin, Phys. Dark Univ. 5-6 (2014) 75, arXiv:1303.3787

J. Martin, C. Ringeval, R. Trotta and V. Vennin, JCAP 1403 (2014) 039, arXiv1312.3529

$$B_{i-\mathrm{best}} = \frac{\mathcal{E}(D|\mathcal{M}_i)}{\mathcal{E}(D|\mathrm{best})} < 1$$



Constraining power of Planck

The distribution of models over the Jeffreys' scale gives a measure of the constraining power of an experiment

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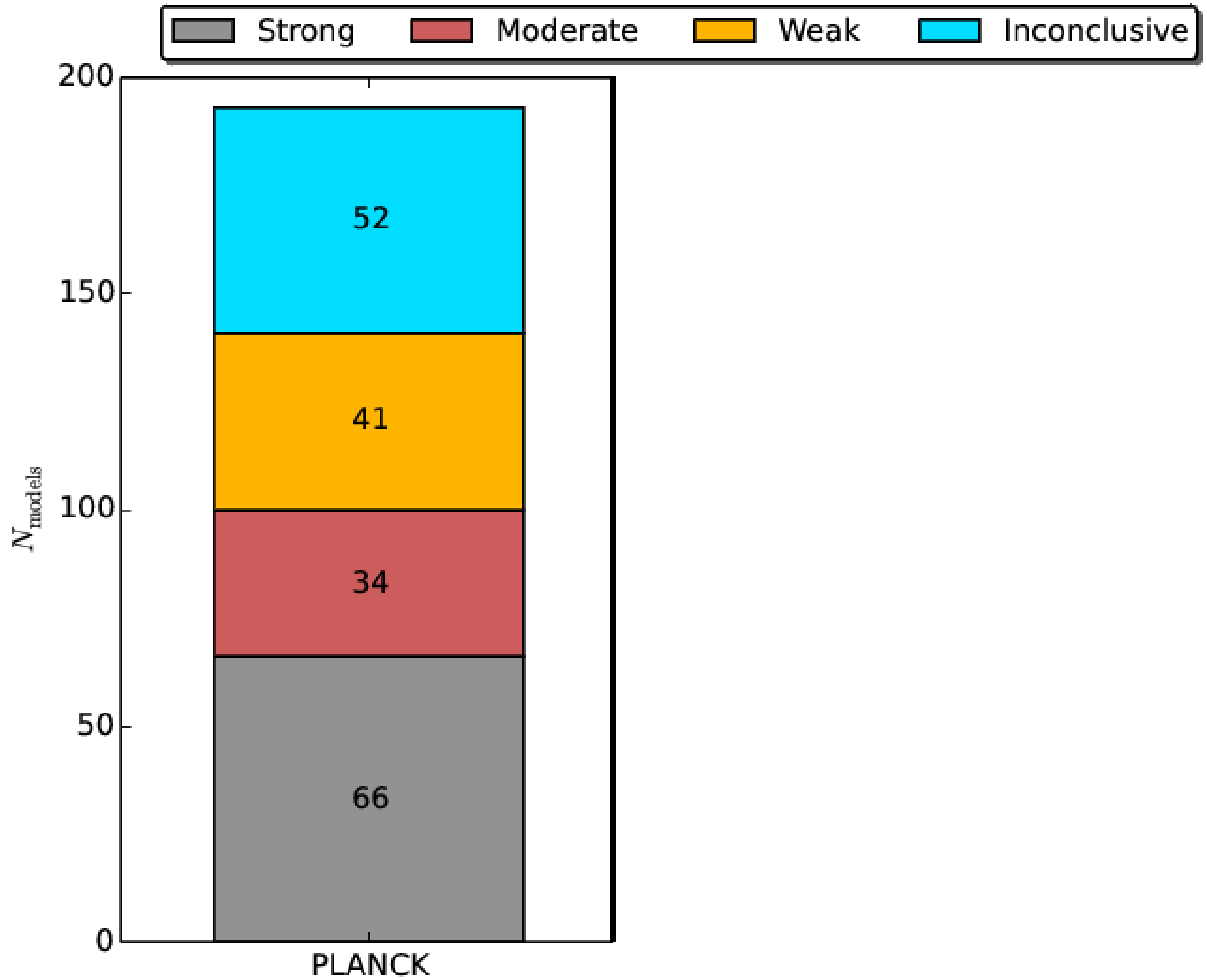

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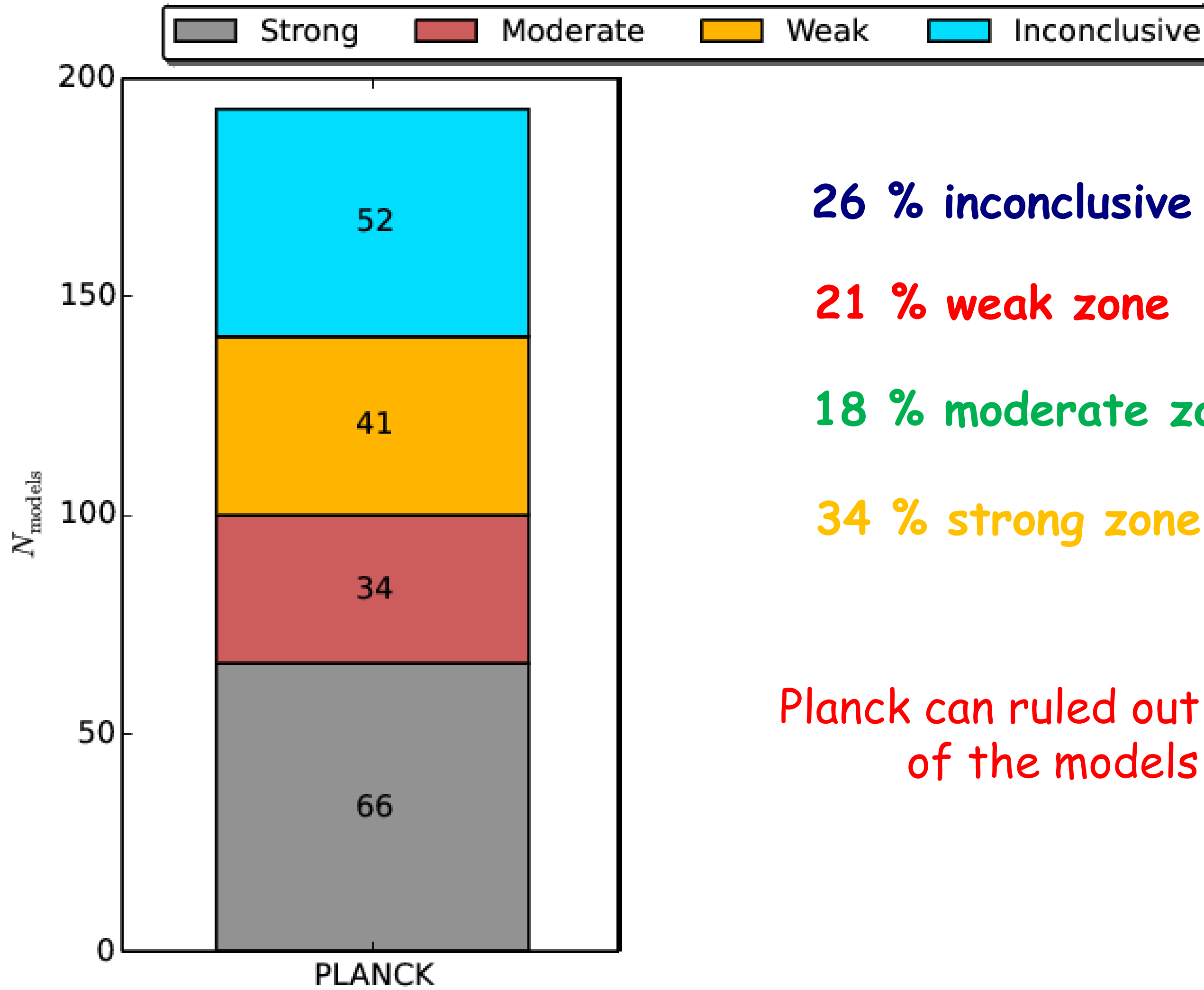

26 % inconclusive zone

21 % weak zone

18 % moderate zone

34 % strong zone

Planck can ruled out ~ 1/3 of the models

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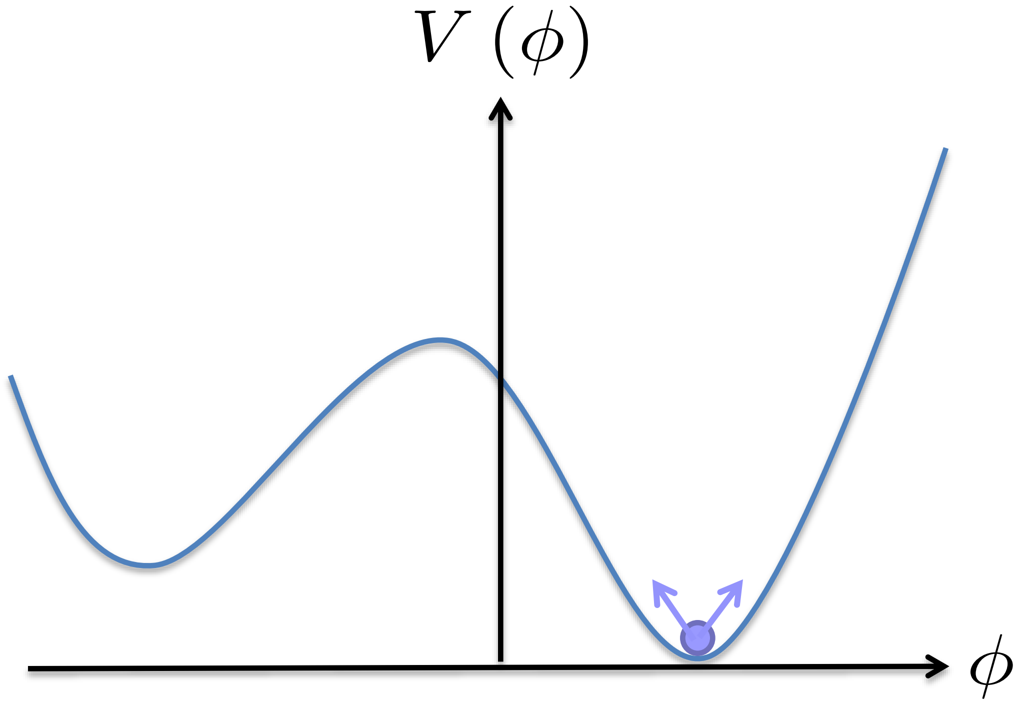
Inflation (usually) stops when the field reaches the bottom of the potential



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

The reheating parameter

- The reheating phase can parameterized by ρ_{reh} and $\overline{w}_{\mathrm{reh}}$.
  In fact, the CMB only depends on a specific combination, the Reheating parameter

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

- The reheating parameter is like the optical depth for reionization: at the atomic level, reionization is a very complicated phenomenon but, as long as the CMB is concerned, only one parameter matter. Reheating can be very complicated but as long the CMB is concerned, only the reheating parameter is important.

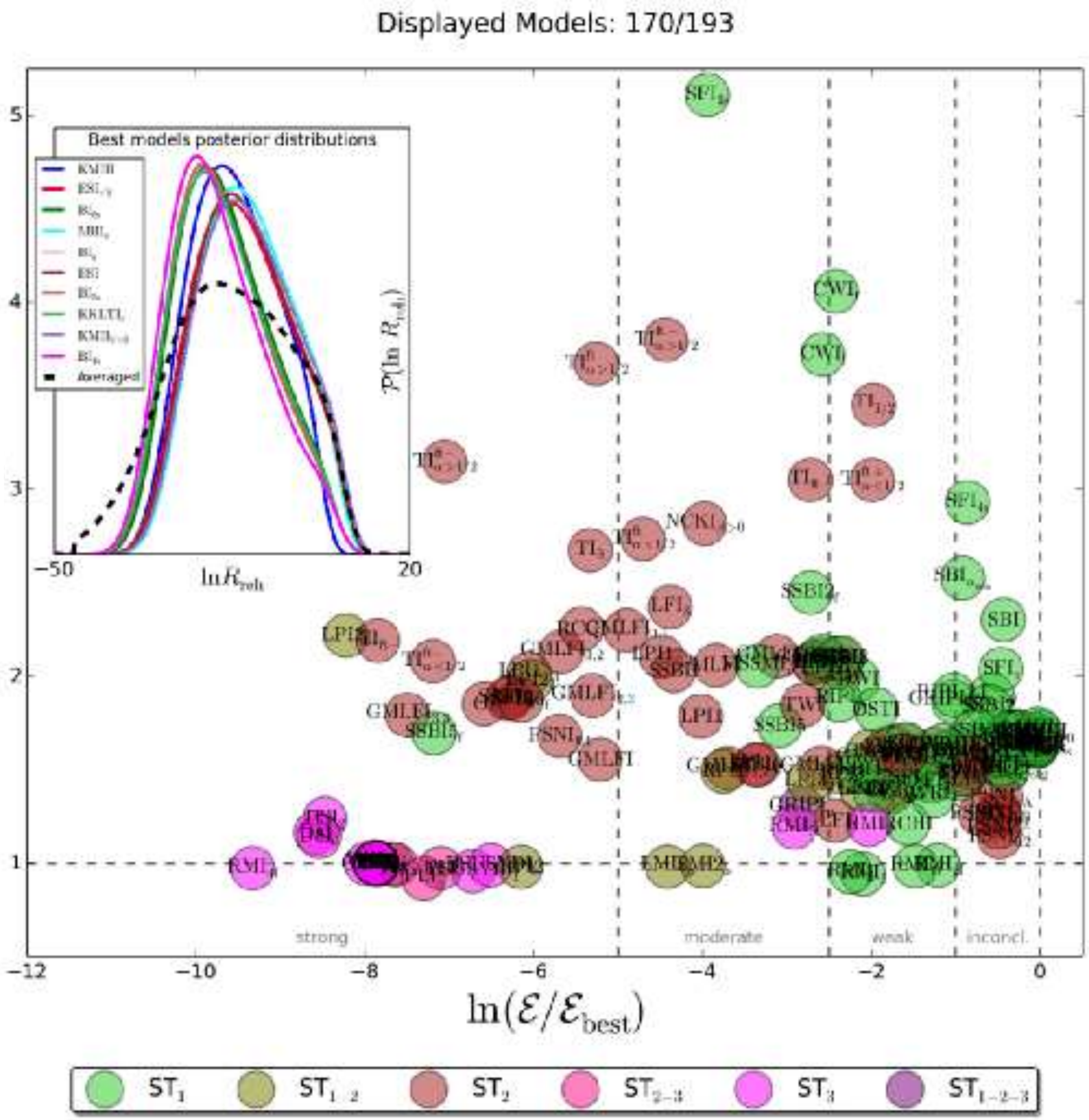
- So the constraints on the reheating era are expressed as constraints on the reheating parameter (posterior distribution).

J. Martin and C. Ringeval, Phys. Rev. D82 (2010) 023511, arXiv:1004.5525

J. Martin, C. Ringeval and V. Vennin, Phys. Rev. Lett. 114 (2015) 8, 081303, arXiv:1410.7958

Planck 2013 constraints on reheating

Constraints on reheating ↑

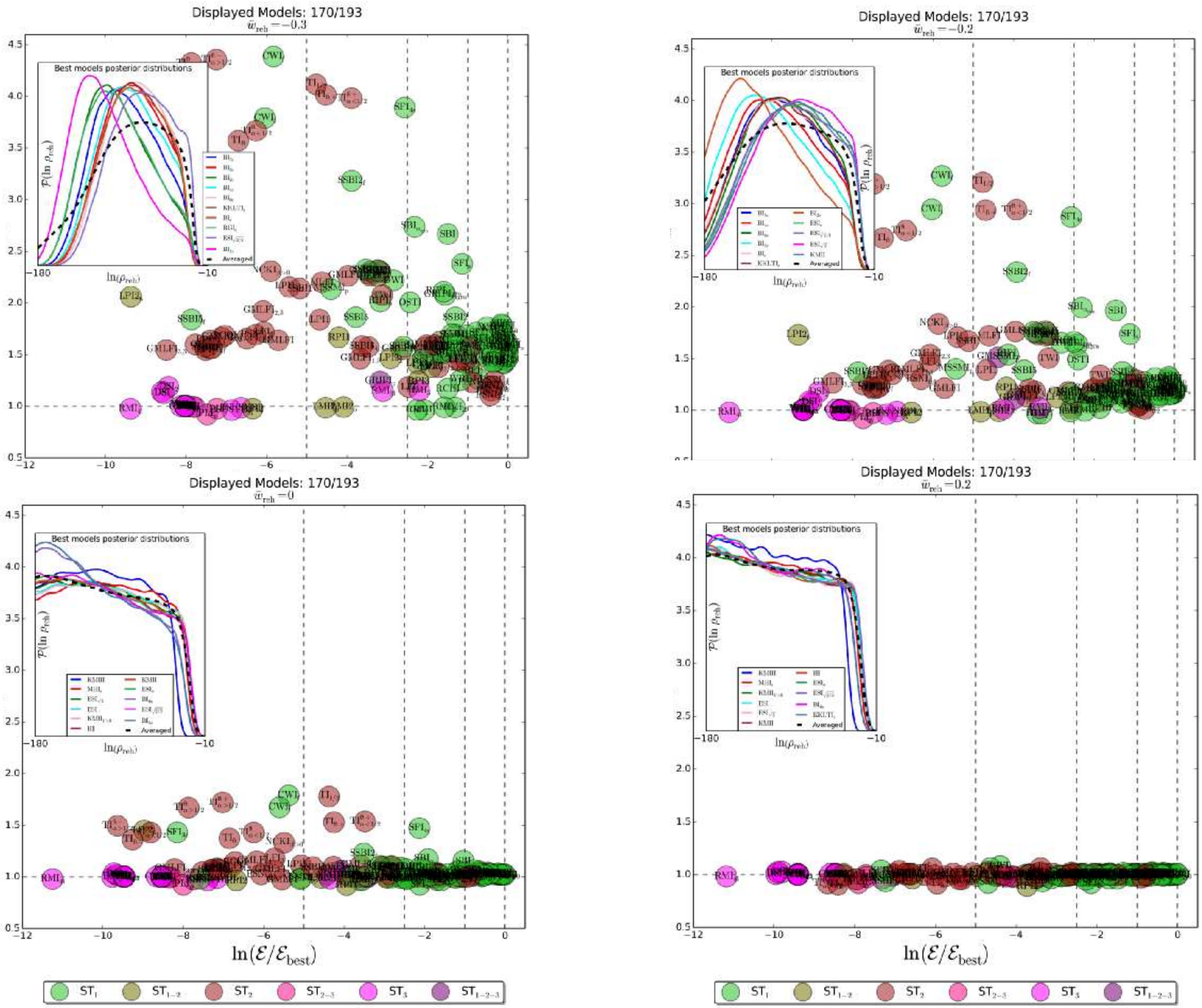


No constraint on reheating

→ Model performance

J. Martin, C. Ringeval and V. Vennin, Phys. Rev. Lett. 114 (2015) 8, 081303, arXiv:1410.7958

Planck2013 constraints on reheating



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The future

- Tensor modes is the only inflationary prediction not yet checked …

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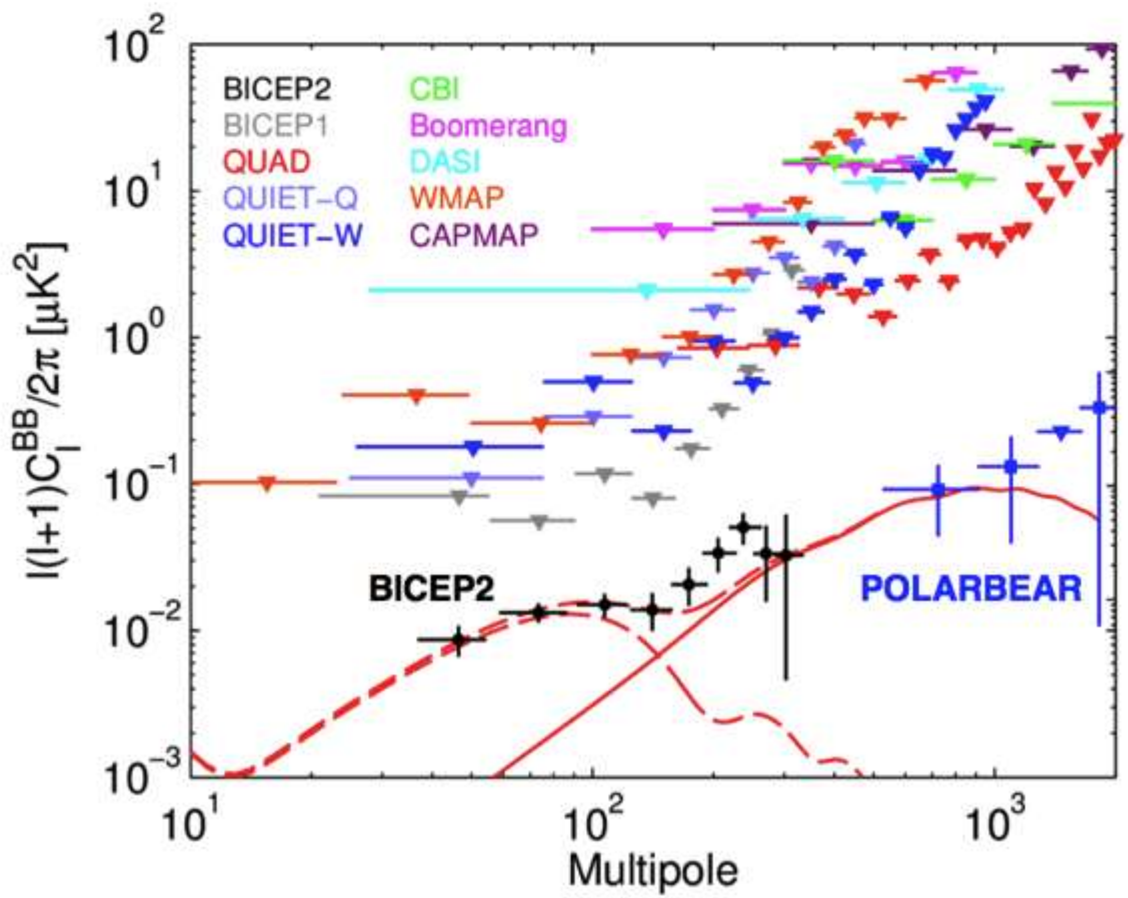
- This can be done by measuring CMB B-mode polarization



Message 1: the energy scale of inflation

$$H \simeq 1.23 \left(\frac{r}{0.2}\right)^{1/2} 10^{14}\mathrm{GeV}$$

$$\rho^{1/4} \simeq 2.26 \left(\frac{r}{0.2}\right)^{1/4} 10^{16}\mathrm{GeV}$$

Message 2: first derivative of the potential

$$r = \frac{T}{S} = 16\epsilon_1 = \frac{8}{M_{\mathrm{Pl}}^2}\left(\frac{V_\phi}{V}\right)^2$$

Message 3: the field excursion

$$\frac{\Delta\phi}{M_{\rm Pl}} \simeq \mathcal{O}(1)\left(\frac{r}{0.2}\right)^{1/2}$$

- Also known as the Lyth bound.

- Important for model building

- Planckian excursions correspond to r>0.001

Message 4: Significant improvement of model comparison

We have simulated data and data analysis for two missions: PRISM & LiteBIRD

LiteBIRD: Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (Japan)

PRISM: the Polarized Radiation Imaging and Spectroscopy Mission (Europe)

Should obviously be updated for Core++

Satellite	C^T_{noise}	C^E_{noise}	C^B_{noise}	θ_{fwhm}	f_{sky}
PRISM	5×10^{-7} μK^2	$2C^T_{noise}$	$2C^T_{noise}$	3.2'	0.7
LiteBIRD	7×10^{-7} μK^2	$2C^T_{noise}$	$2C^T_{noise}$	38.5'	0.7

Message 4: Significant improvement of model comparison

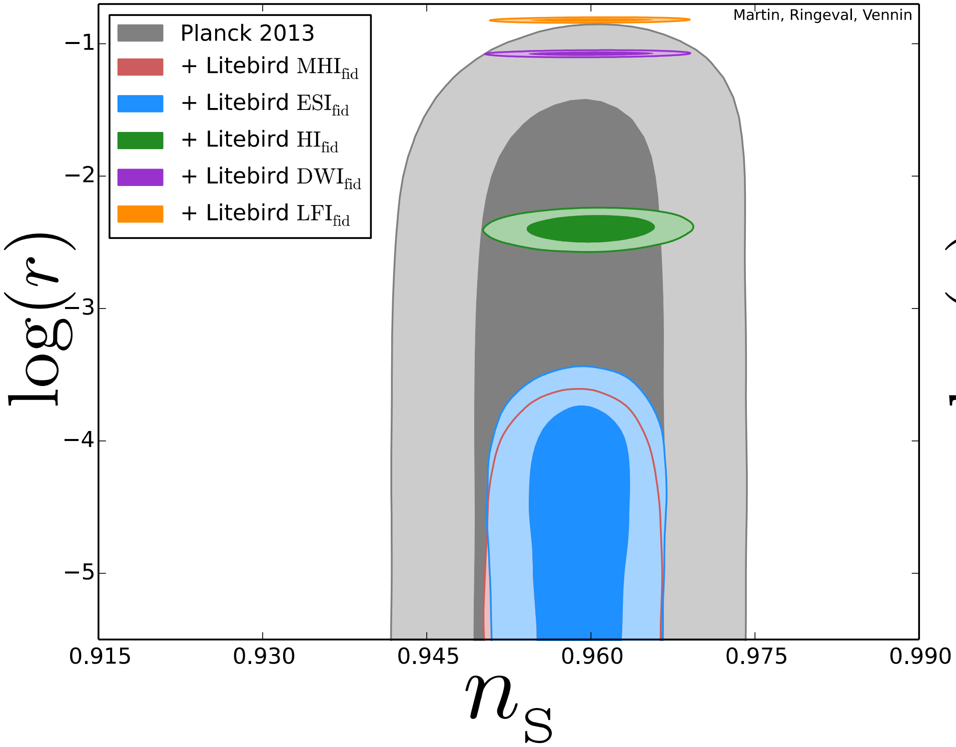
5 fiducial models from "Encyclopedia Inflationaris" predicting different values of r

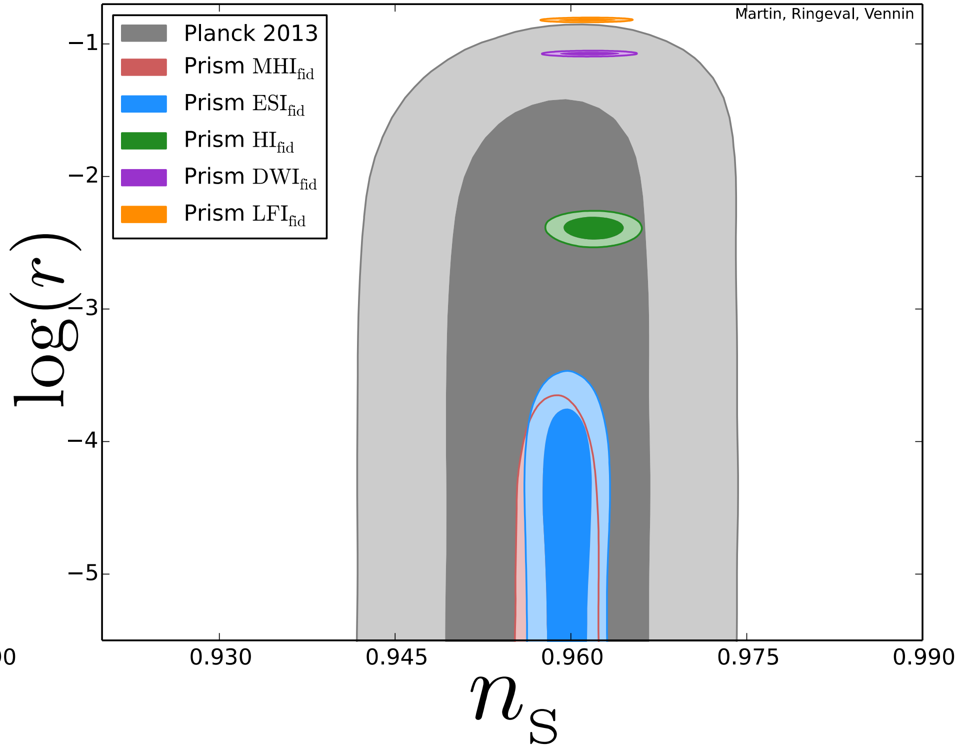
Fiducial Model	$V(\phi)/M^4$	Parameters	n_S	r
LFI_{fid}	$(\phi/M_{Pl})^2$		0.961	1.52×10^{-1}
DWI_{fid}	$[(\phi/\phi_0)-1]^2$	$\phi_0=25M_{pl}$	0.962	8.45×10^{-2}
HI_{fid}	$[1-\exp(-\sqrt{2/3}\,\phi/M_{pl})]^2$		0.961	4.12×10^{-3}
ESI_{fid}	$1-\exp(-q\phi/M_{pl})$	$q=8$	0.959	5.09×10^{-5}
$MHIf_{id}$	$1-\mathrm{sech}(\phi/\mu)$	$\mu=0.01M_{pl}$	0.958	3.40×10^{-7}

with $\Omega_b h^2=0.0223$, $\Omega_{dm}h^2=0.120$, $\Omega_\nu h^2=0.000645$, $\tau=0.0931$, $h=0.674$, $T_{reh}=10^8$ GeV, $w_{reh}=0$, $P_*=2.203 \times 10^{-9}$.

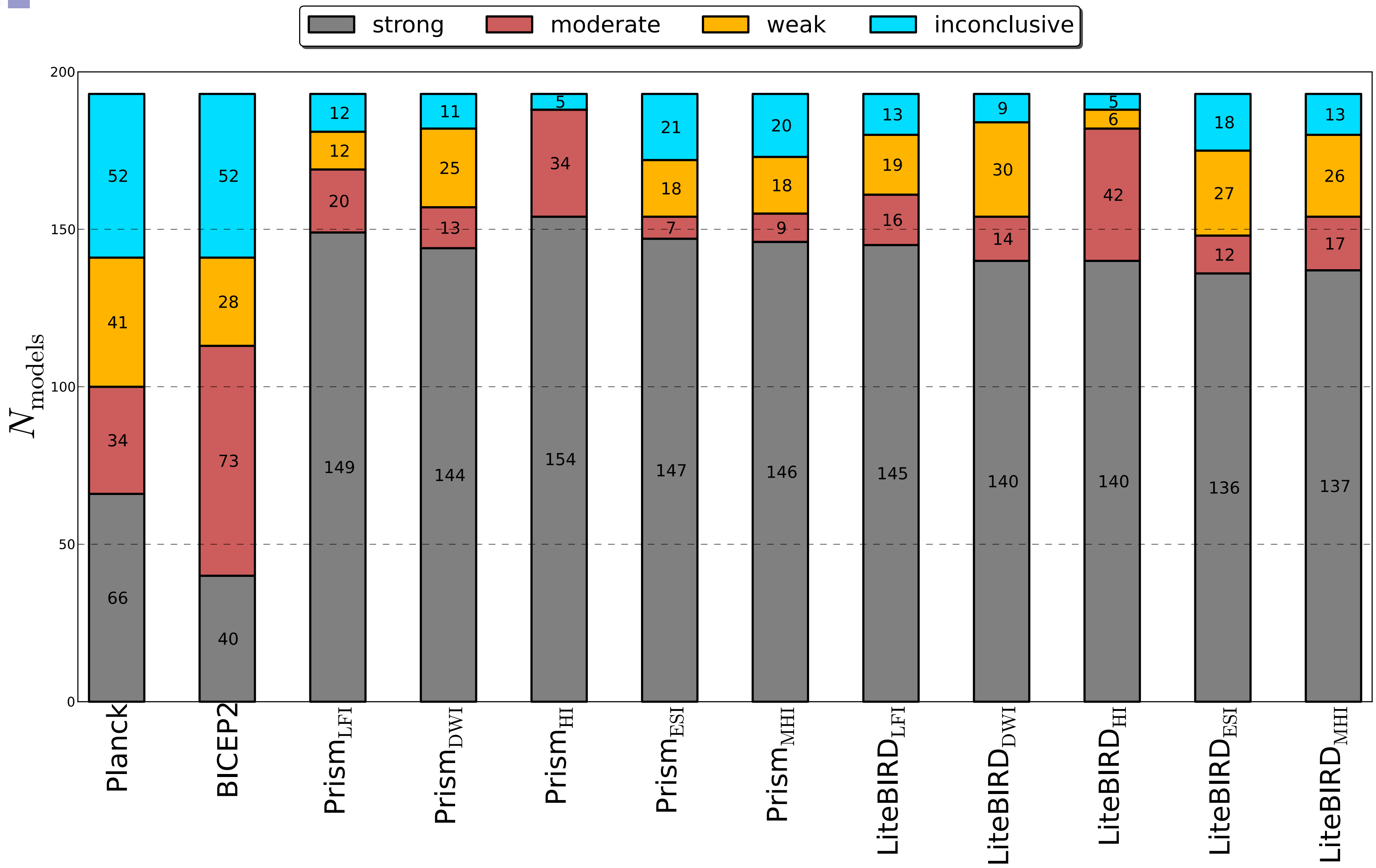
J. Martin, C. Ringeval and V. Vennin, JCAP 1410 (2014) 10, 038, arXiv:1407.4034

Message 4: Significant improvement of model comparison





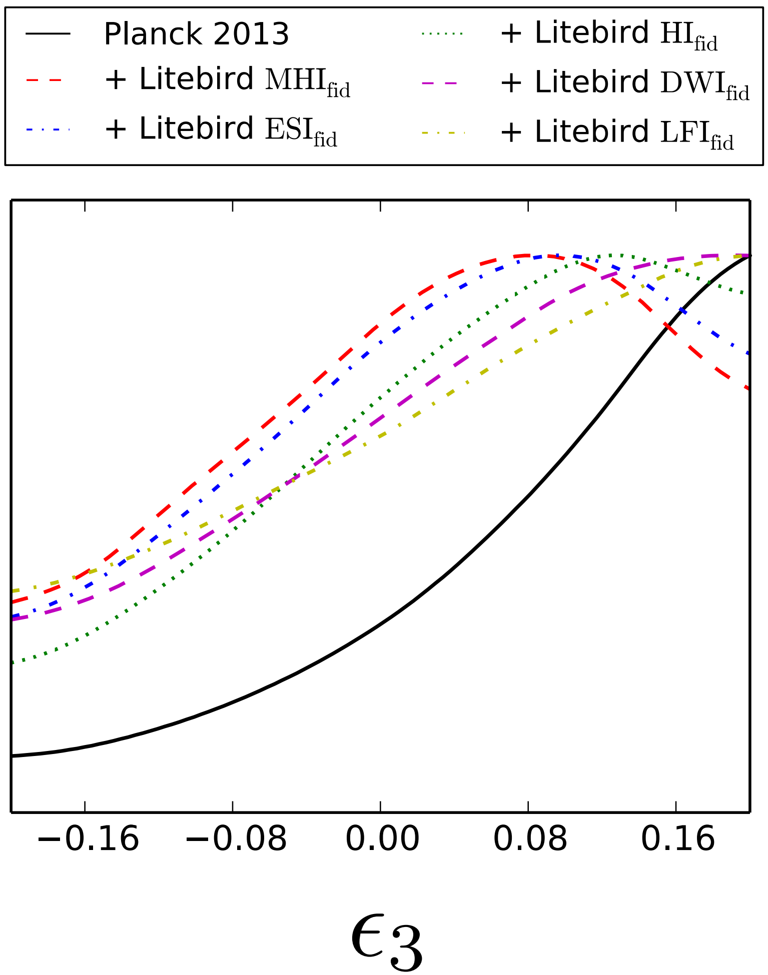
Consequences of a B-modes detection

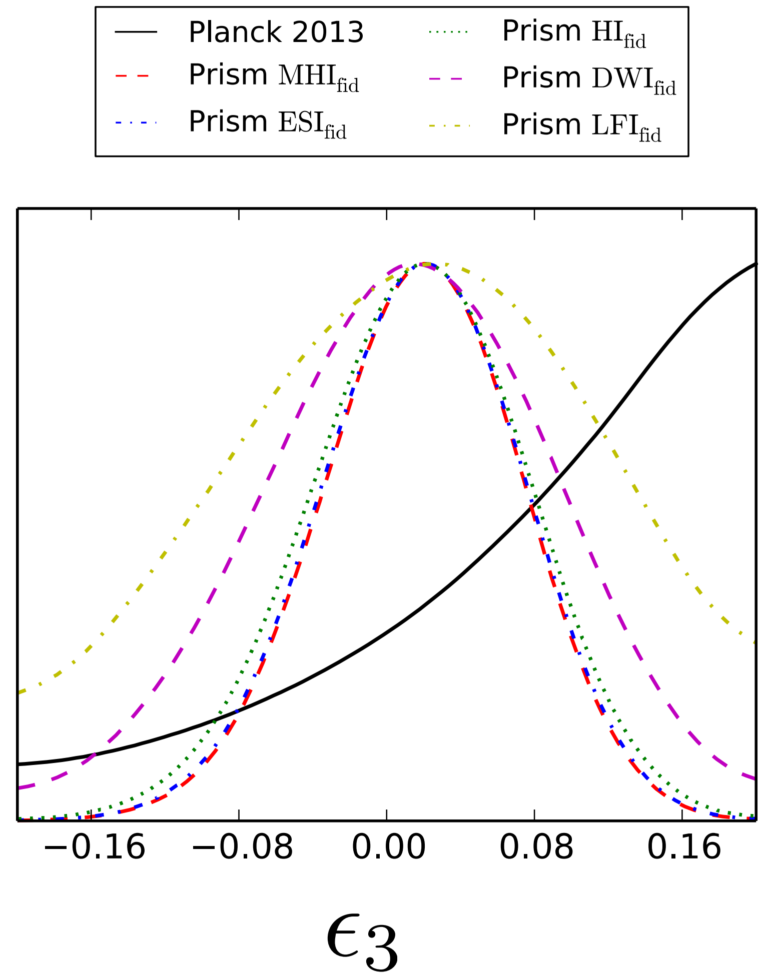


Planck: 1/3 of the models excluded; PRISM & LiteBIRD > 4/5

J. Martin, C. Ringeval and V. Vennin, JCAP 1410 (2014) 10, 038, arXiv:1407.4034

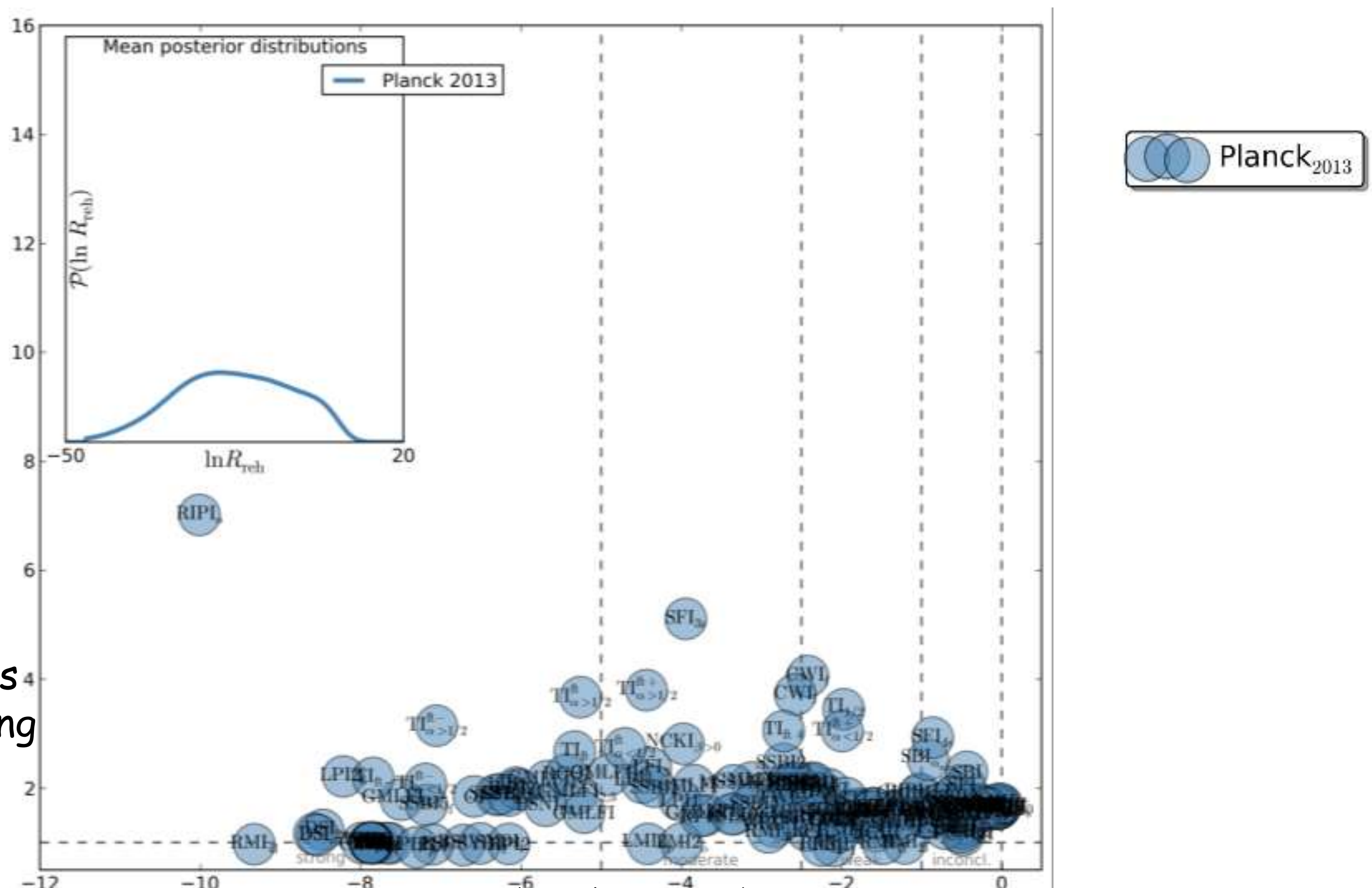
Message 5: Prism can detect the slow-roll running …





J. Martin, C. Ringeval and V. Vennin, JCAP 1410 (2014) 10, 038, arXiv:1407.4034

Reheating

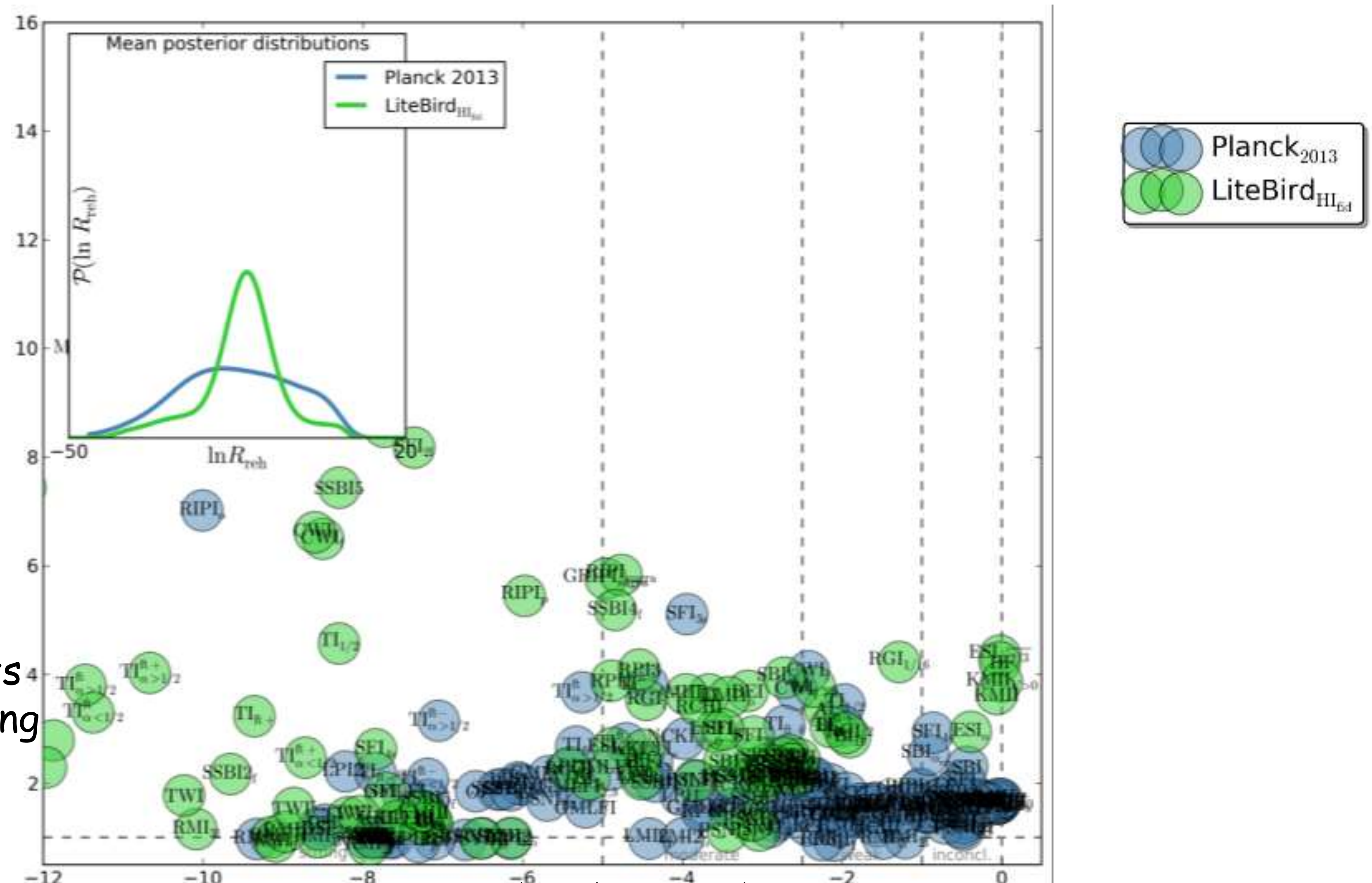


Constraints on reheating ↑

→ Performances

$$\ln(\mathcal{E}/\mathcal{E}_{\rm best})$$

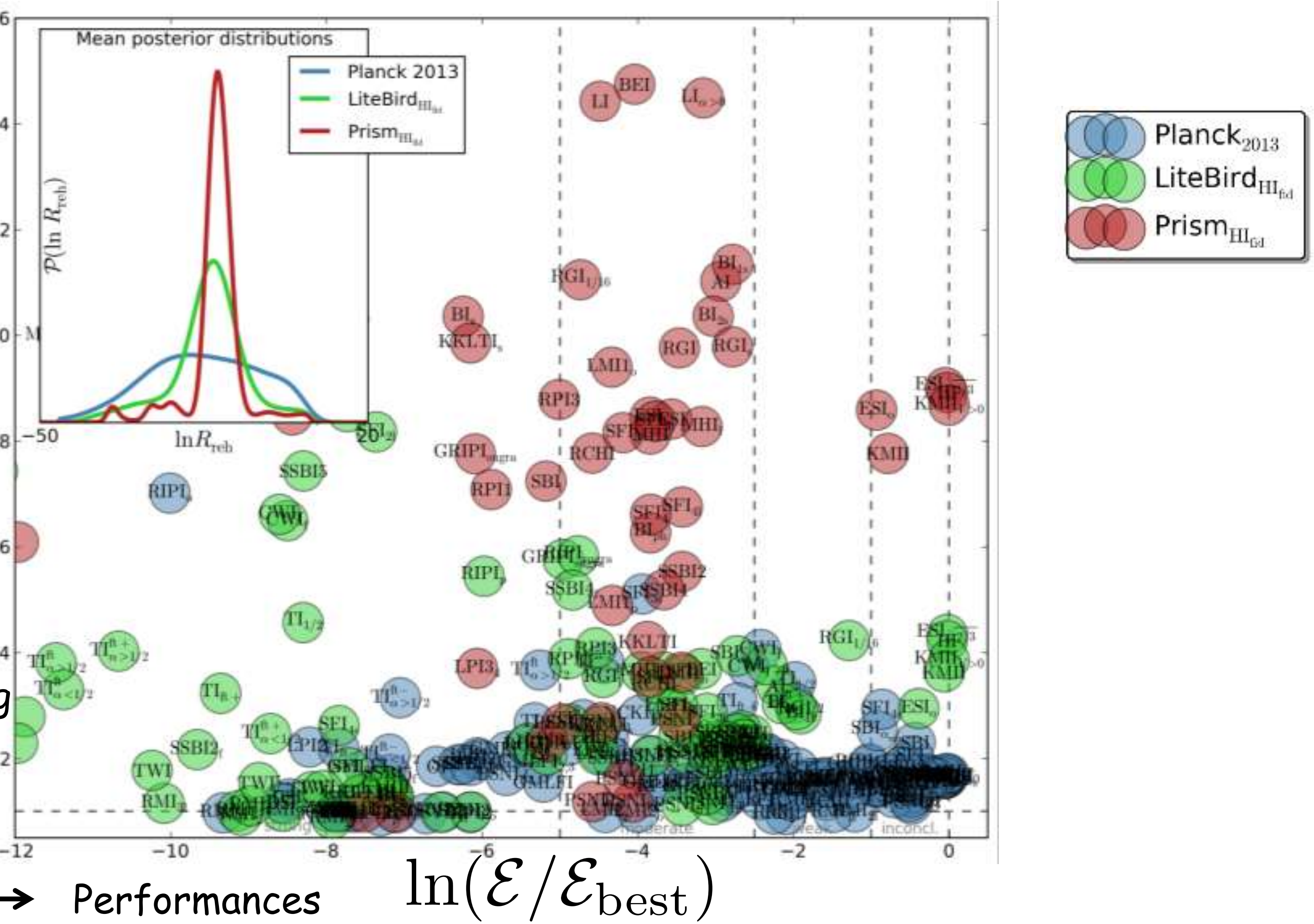
Reheating



Constraints on reheating

Performances $\ln(\mathcal{E}/\mathcal{E}_{\rm best})$

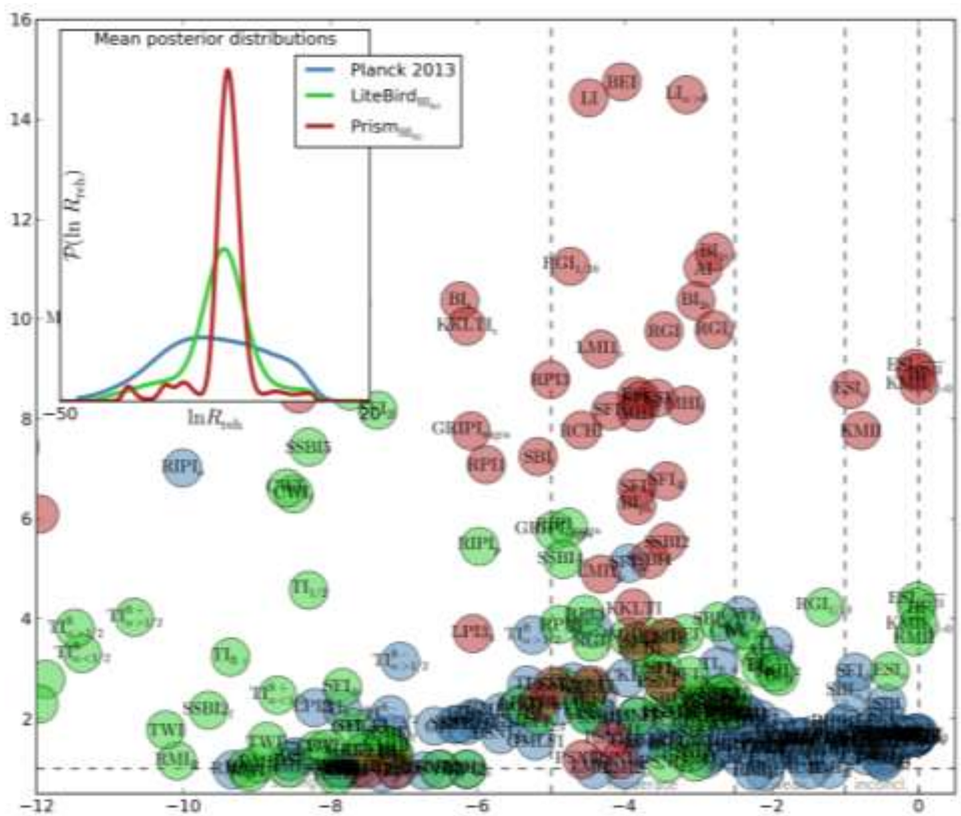
Reheating



Constraints on reheating

Performances

Message 6: Significant improvement of the constraints of reheating



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J. Martin, C. Ringeval and V. Vennin, JCAP 1410 (2014) 10, 038, arXiv:1407.4034

Planck 2013

$$\left\langle \frac{\Delta \pi_{\ln R_{\mathrm{reh}}}}{\Delta \mathcal{P}_{\ln R_{\mathrm{reh}}}} \right\rangle \simeq 40\%$$

LiteBIRD HI

$$\left\langle \frac{\Delta \pi_{\ln R_{\mathrm{reh}}}}{\Delta \mathcal{P}_{\ln R_{\mathrm{reh}}}} \right\rangle \simeq 73\%$$

Prism HI

$$\left\langle \frac{\Delta \pi_{\ln R_{\mathrm{reh}}}}{\Delta \mathcal{P}_{\ln R_{\mathrm{reh}}}} \right\rangle \simeq 88\%$$

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Recap

- Planck 2013: single field inflation are preferred. More complicated models (multiple field scenarios, non-minimal kinetic term scenario etc …) should all have a "bad" Bayesian evidence …

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

- KMIII, ESI, Starobinsky model, ie plateau inflation … are the winners

- Reheating is now constrained, average reduction of the prior to posterior width of about 40%. But this is mainly driven by "exotic" equations of state.

- The inflationary gravitational waves background remains to be detected

- Fourth generation of CMB experiments aims at detecting B-modes. This can significantly improve our knowledge of inflation