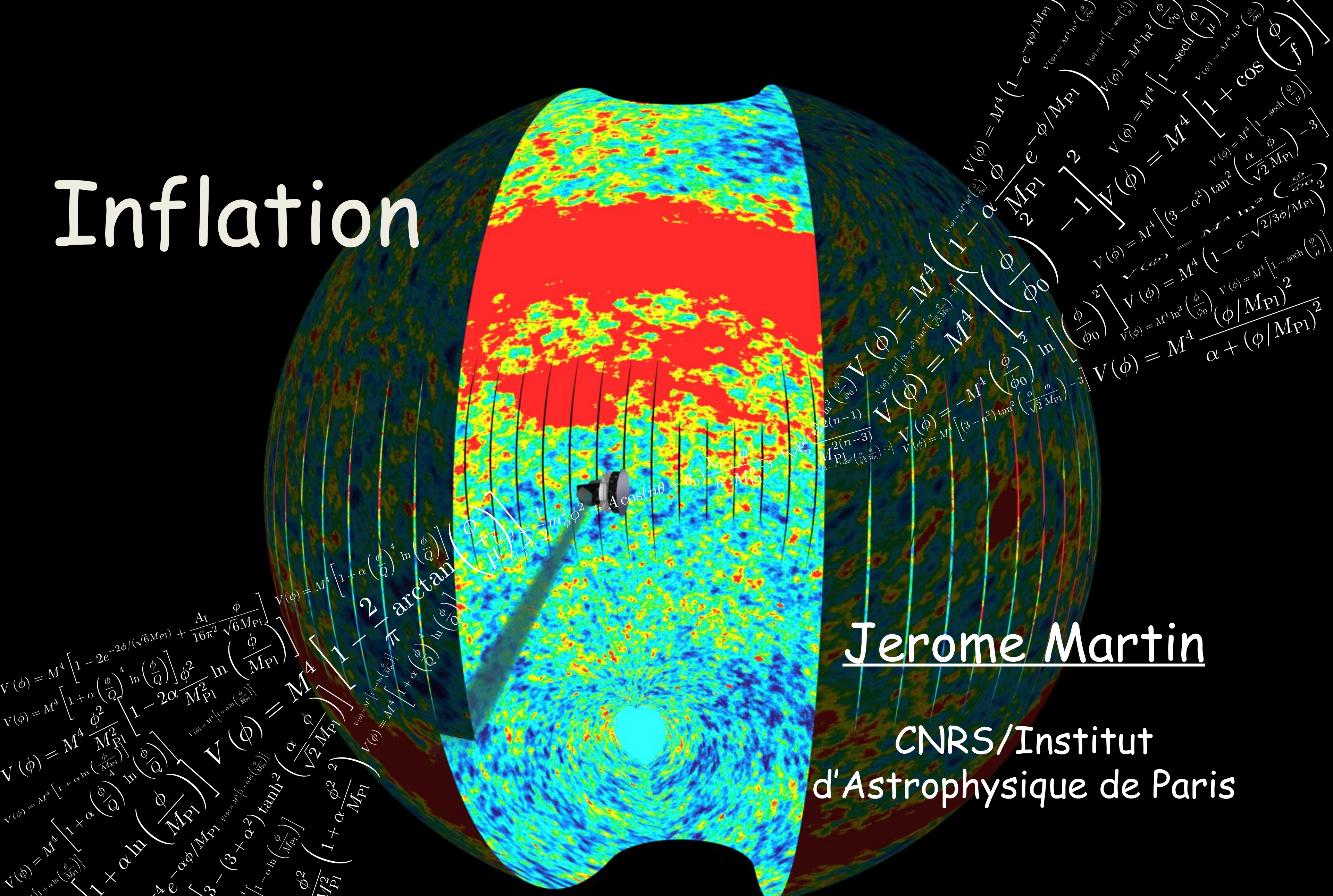
Inflation



Jerome Martin

CNRS/Institut d'Astrophysique de Paris

"Towards a next space probe for CMB observations and cosmic origins explorer", CERN, May 17-20

Outline

- The observational status of inflation after Planck (in brief)

- Going beyond Planck: what can we learn about inflation?

- Conclusions

Outline

- The observational status of inflation after Planck (in brief)
- Going beyond Planck: what can we learn about inflation?
- Conclusions

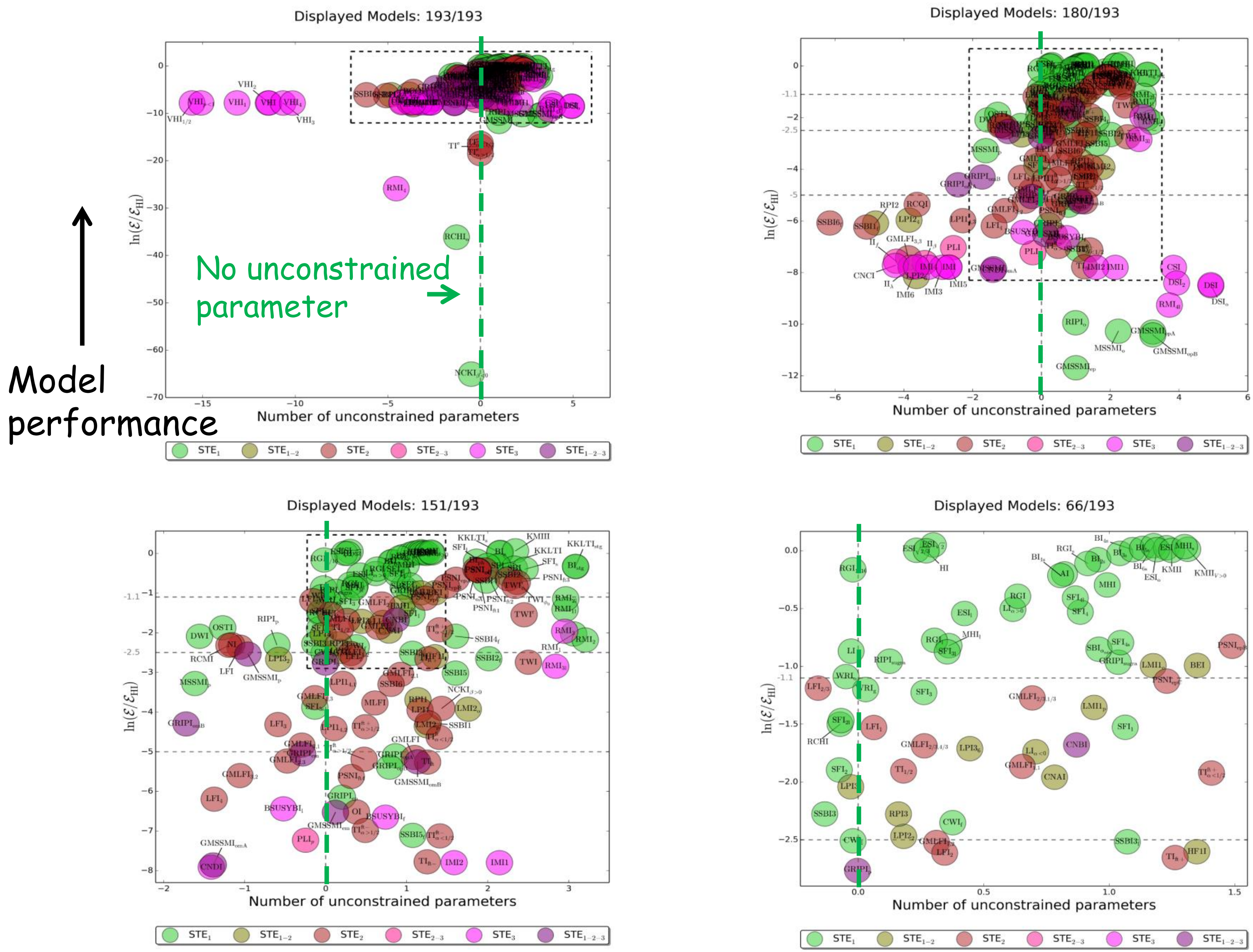
Planck legacy

- Physics in the early Universe is non trivial ("dynamical") since deviation from scale invariance has been detected.
- Everything is consistent with inflation.
- Inflation seems to be realized in a vanilla fashion.

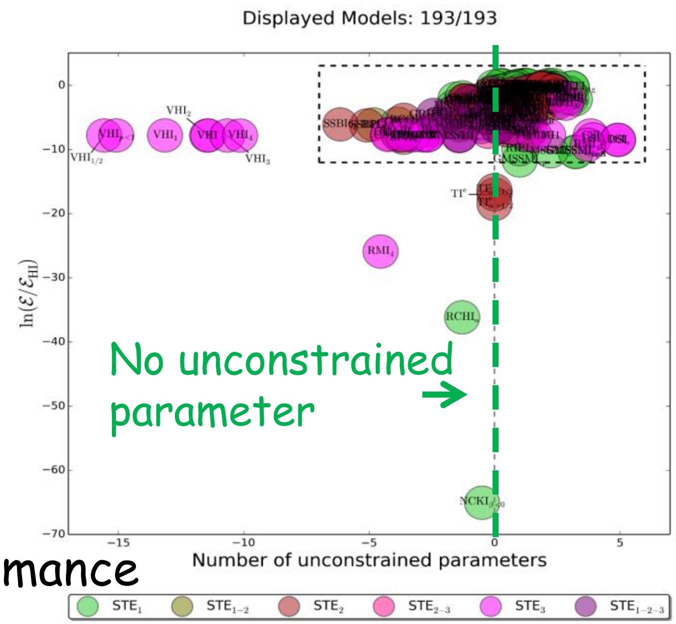
The simplest models of inflation make seven key predictions:

- Universe spatially flat $\Omega_{\mathcal{K}} = -0.040^{+0.038}_{-0.041}$
- Phase coherence Doppler peaks
- Adiabatic perturbations $\alpha^{(2,2500)}_{\mathcal{R}\mathcal{R}} \in [0.985, 0.999]$
- Almost Gaussian perturbations $f^{\mathrm{loc}}_{\mathrm{NL}} = 0.8 \pm 5$, $f^{\mathrm{eq}}_{\mathrm{NL}} = -4 \pm 43$
- Almost scale invariant power spectrum $n_{\mathrm{S}} = 0.9645 \pm 0.0049$
- Background of quantum gravitational waves ???
- Consistency check $n_{\mathrm{T}} = -\frac{r}{8}$???

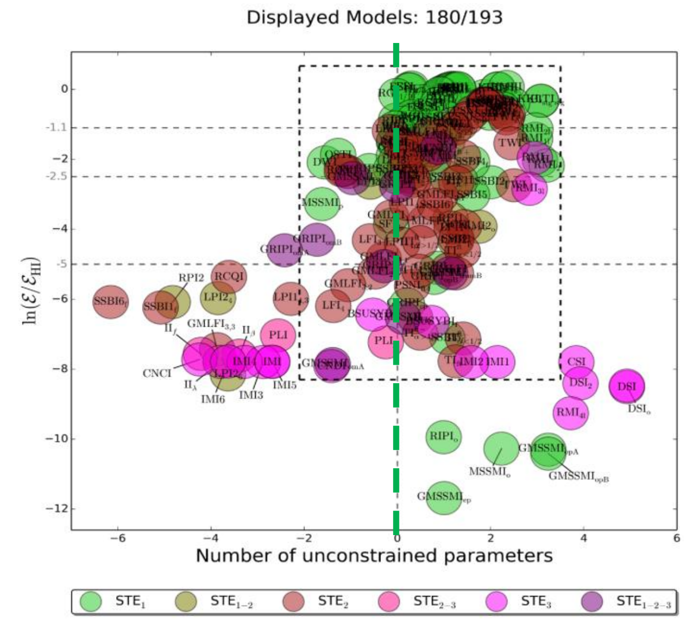
Inflation in the evidence-Number of unconstrained parameter space

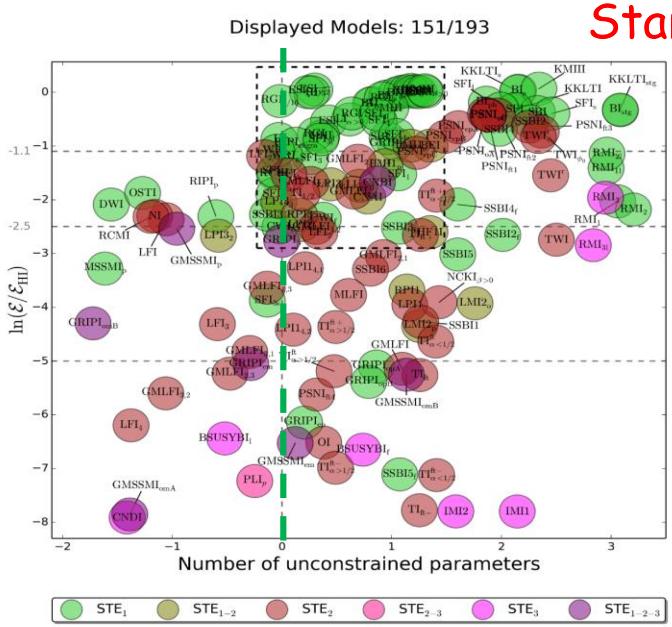


Inflation in the evidence-Number of unconstrained parameter plane

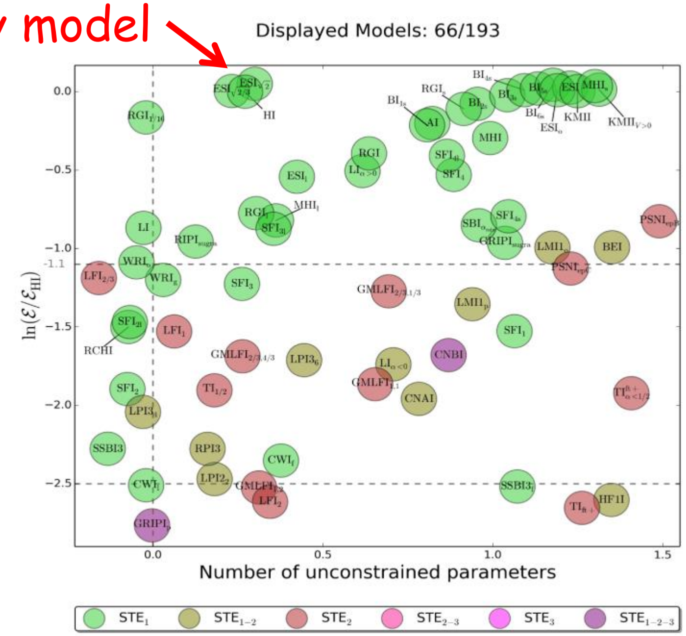


Model performance

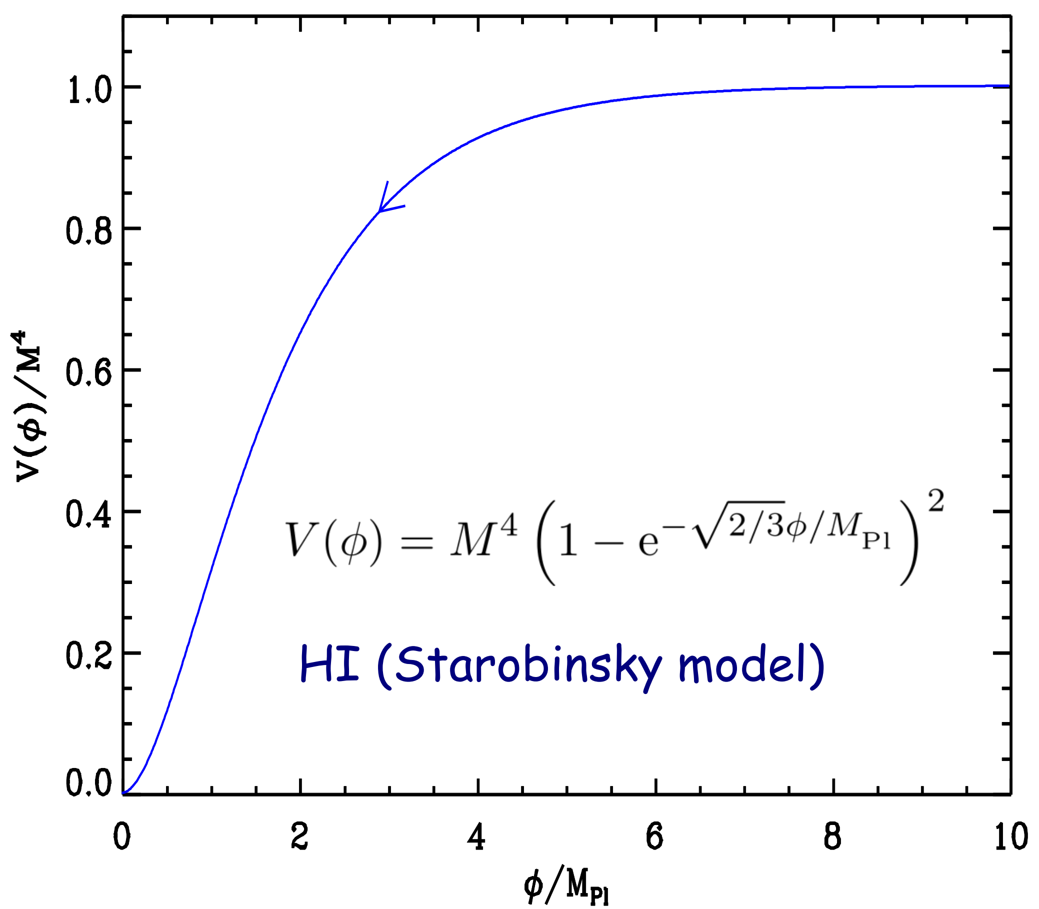




Starobinsky model



Plateau inflationary models are the winners!



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

The reheating parameter

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

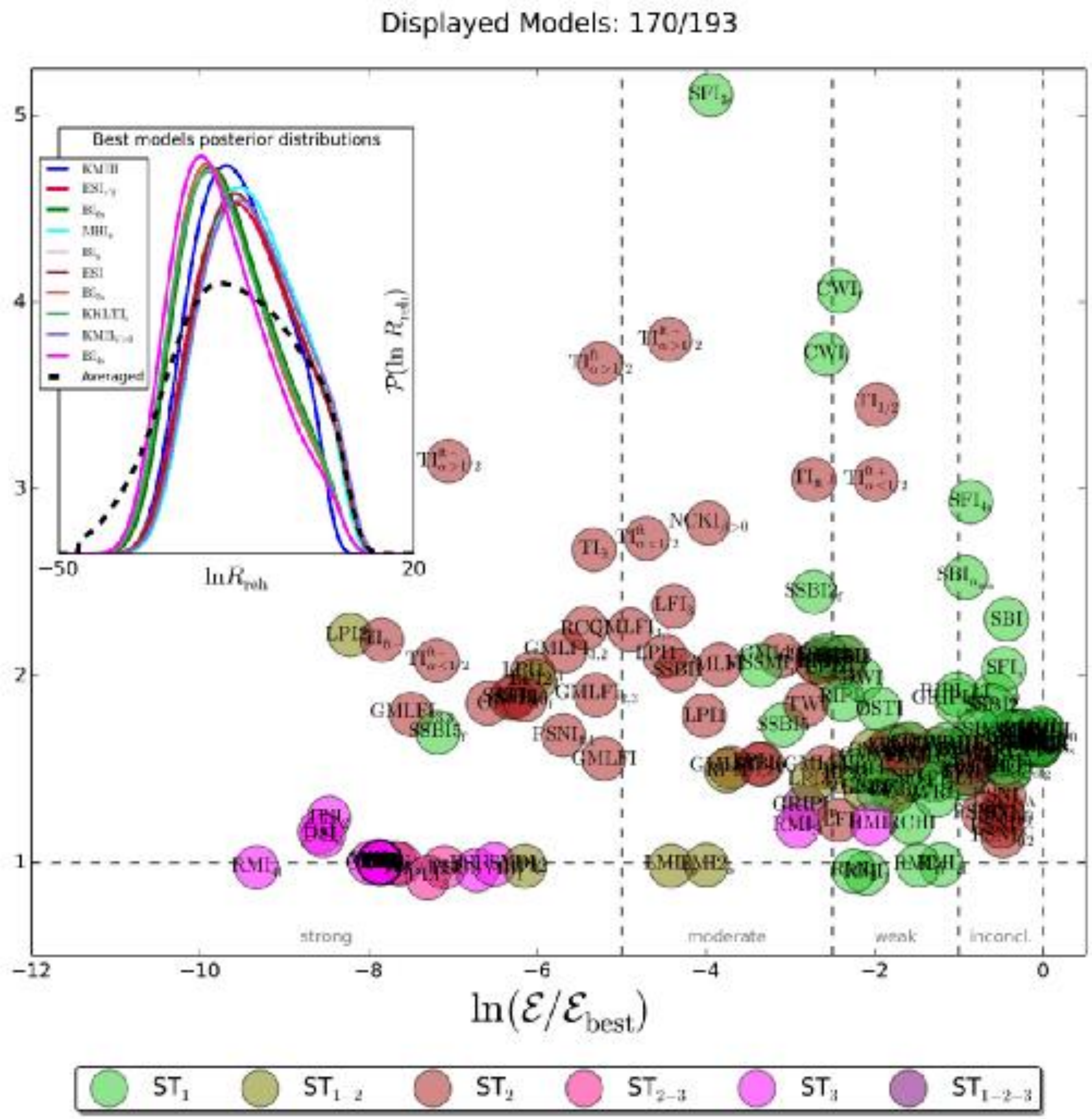
$$\ln R_{\rm rad} = \frac{1-3\bar{w}_{\rm reh}}{12+12\bar{w}_{\rm reh}} \ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right)$$

- 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



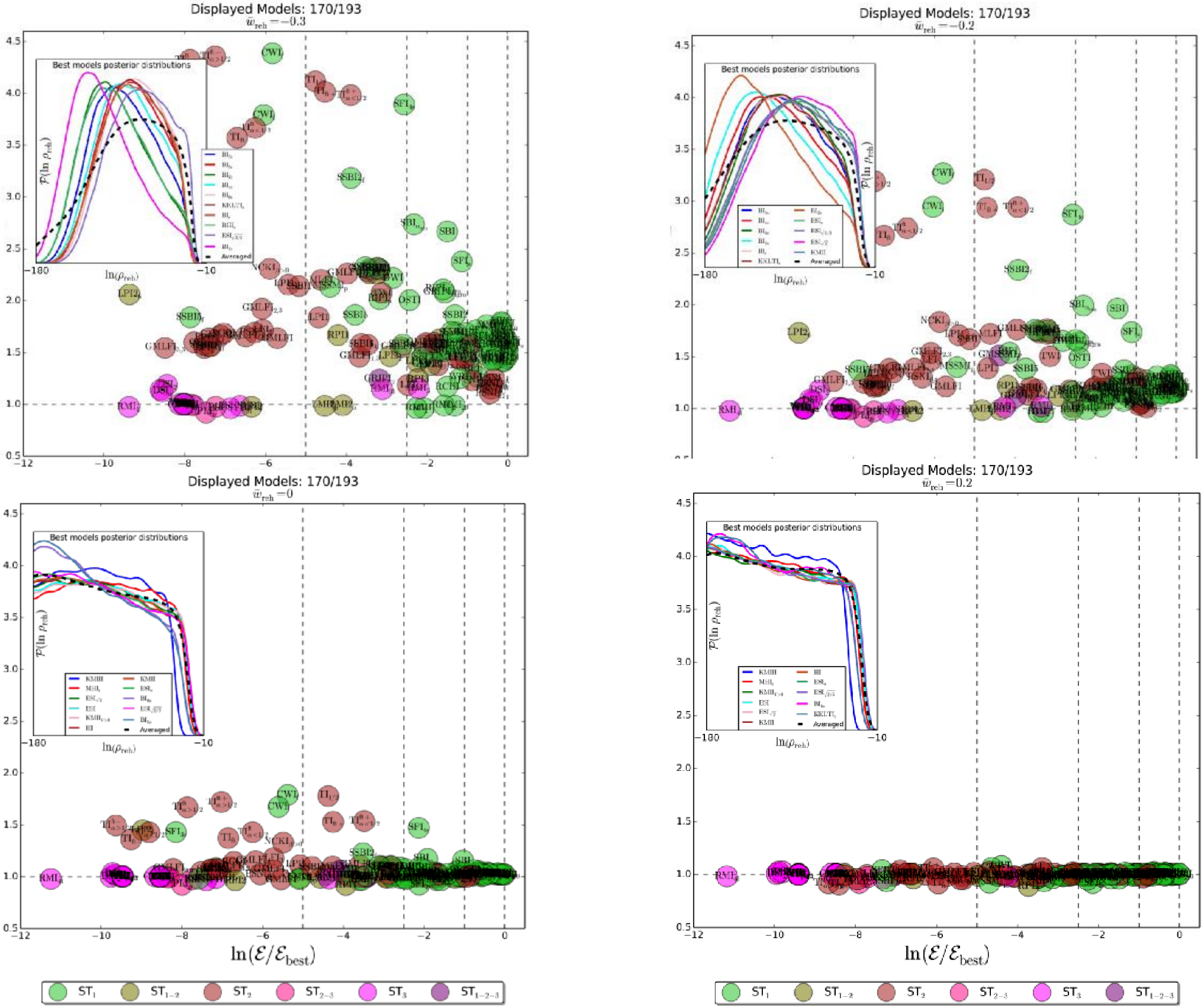
Constraints on reheating

No constraint on reheating

Model performance

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

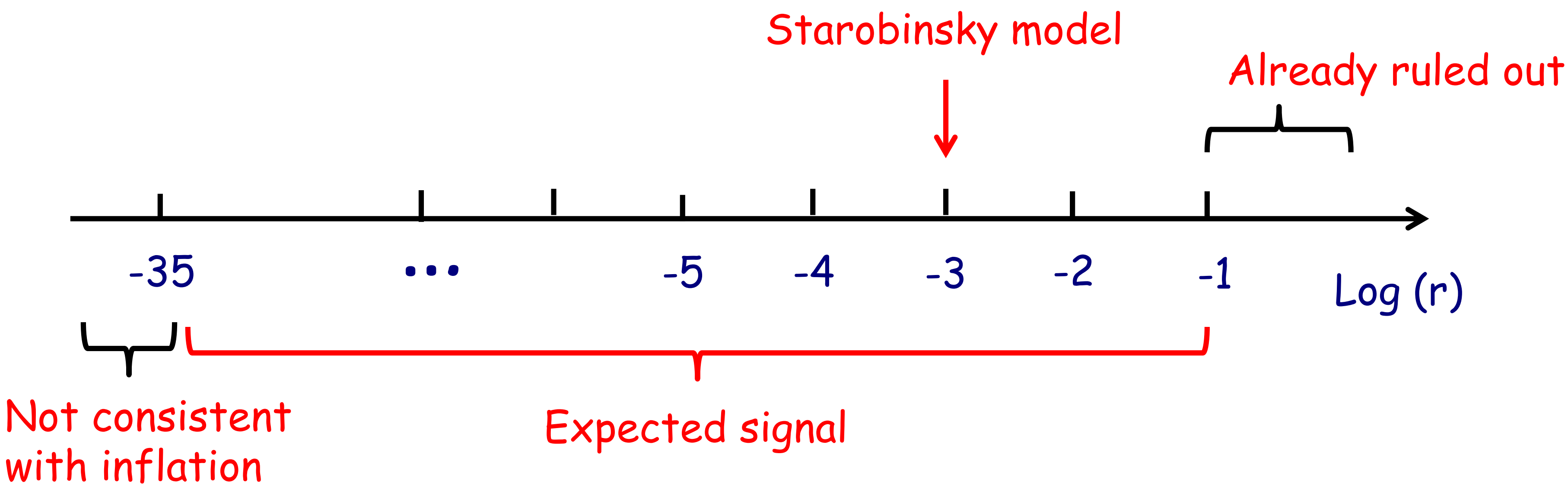
Planck2013 constraints on reheating



Outline

- The observational status of inflation after Planck (in brief)
- Going beyond Planck: what can we learn about inflation?
- Conclusions

- Searching for B-polarization is like searching for SUSY, we do not know where to find the signal but if we find it, it has drastic consequences … in practice, it seems feasible ($r > 10^{-3}$)



- By contrat, searching for NG is like searching for the Higgs, we know where to find the signal and if we do not find it, it has drastic consequences … But, in practice, not realistic (at least for the moment!)

Detection of tensors modes

- Check the remaining key prediction of inflation
- Final proof of vanilla inflation: consistency check (but needs n_T)
- Energy scale of inflation
- Measurement of the first derivative of the potential
- Field excursion
- Greatly improve model selection
- Greatly improve constraints on reheating

Model selection and reheating constraints

Fiducial Model	$V(\phi)/M^4$	Parameters	n_S	r
$\mathrm{LFI_{fid}}$	$(\phi/M_{\mathrm{Pl}})^2$		0.961	1.52×10^{-1}
$\mathrm{DWI_{fid}}$	$[(\phi/\phi_0)-1]^2$	$\phi_0=25M_{\mathrm{pl}}$	0.962	8.45×10^{-2}
$\mathrm{HI_{fid}}$	$[1-\exp(-\sqrt{2/3}\,\phi/M_{\mathrm{pl}})]^2$		0.961	4.12×10^{-3}
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$\mathrm{MHIf_{id}}$	$1-\mathrm{sech}(\phi/\mu)$	$\mu=0.01M_{\mathrm{pl}}$	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, $w_{reh}=0$, $P_*=2.203 \times 10^{-9}$.

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

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

Consequences of a B-modes detection

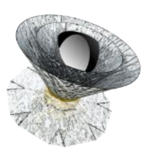
Message 4: Significant improvement of model comparison

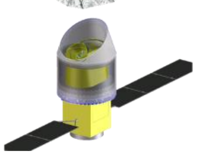
We have simulated data and data analysis for two missions: PRISM & LiteBIRD

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)

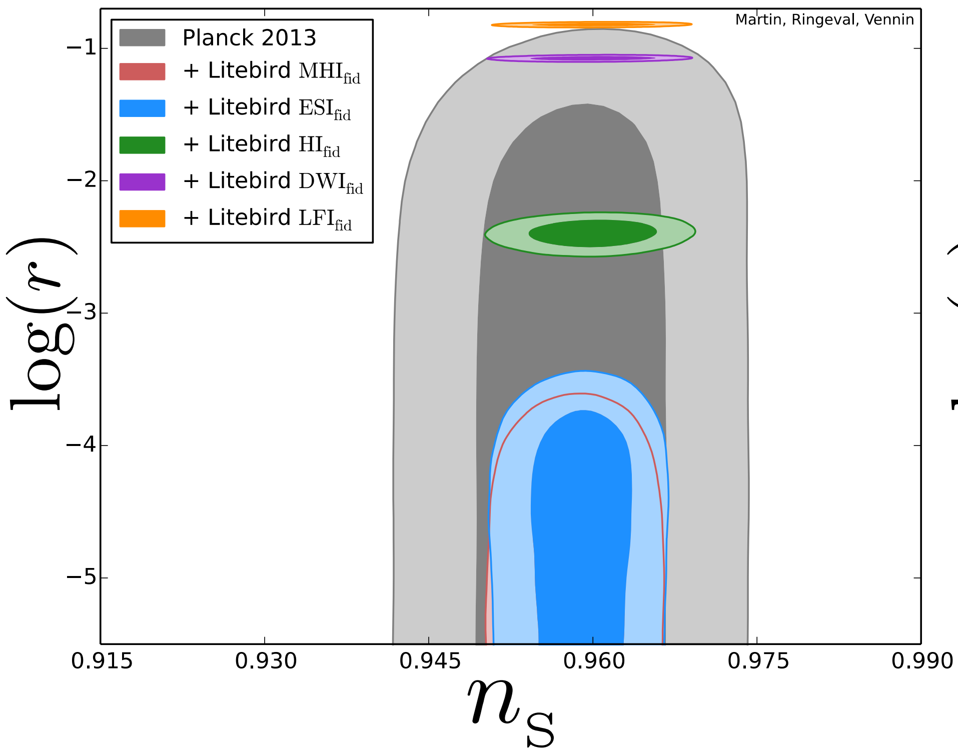
Should obviously be updated for Core++

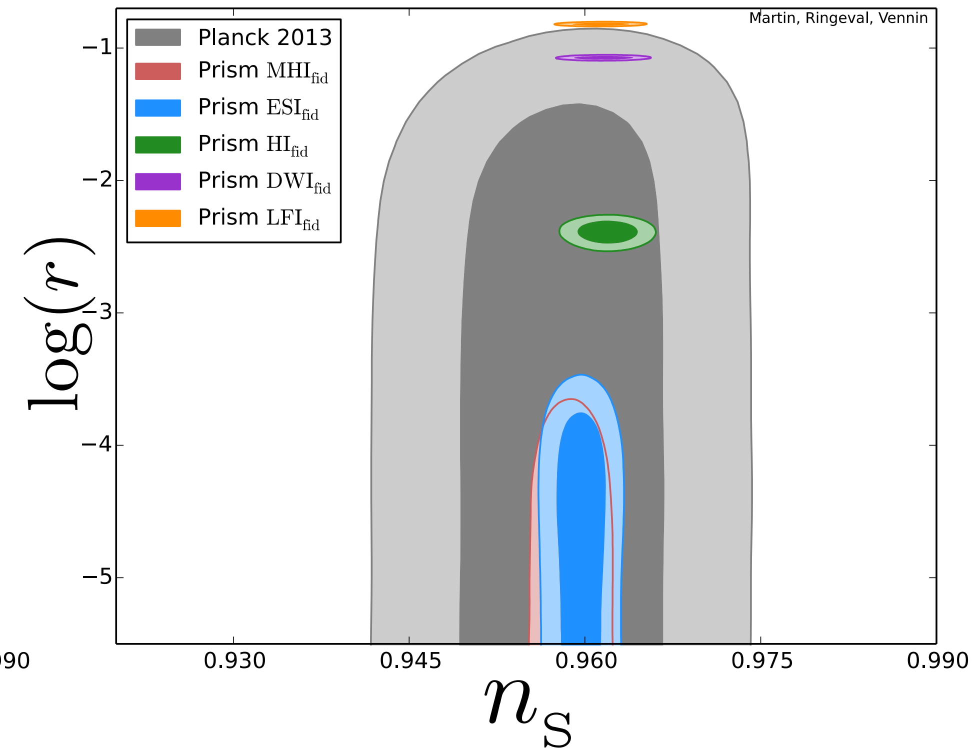


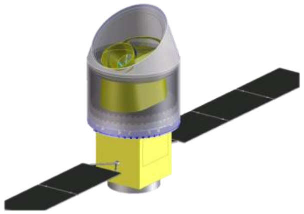


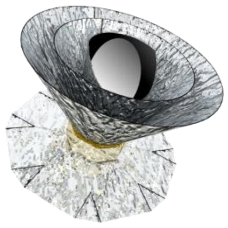
Satellite	C^T_{noise}	C^E_{noise}	C^B_{noise}	θ_{fwhm}	f_{sky}
PRISM	5×10^{-7} μK^2	$2C^T_{noise}$	$2C^T_{noise}$	3.2’	0.7
LiteBIRD	7×10^{-7} μK^2	$2C^T_{noise}$	$2C^T_{noise}$	38.5’	0.7

The (n_S,r) space

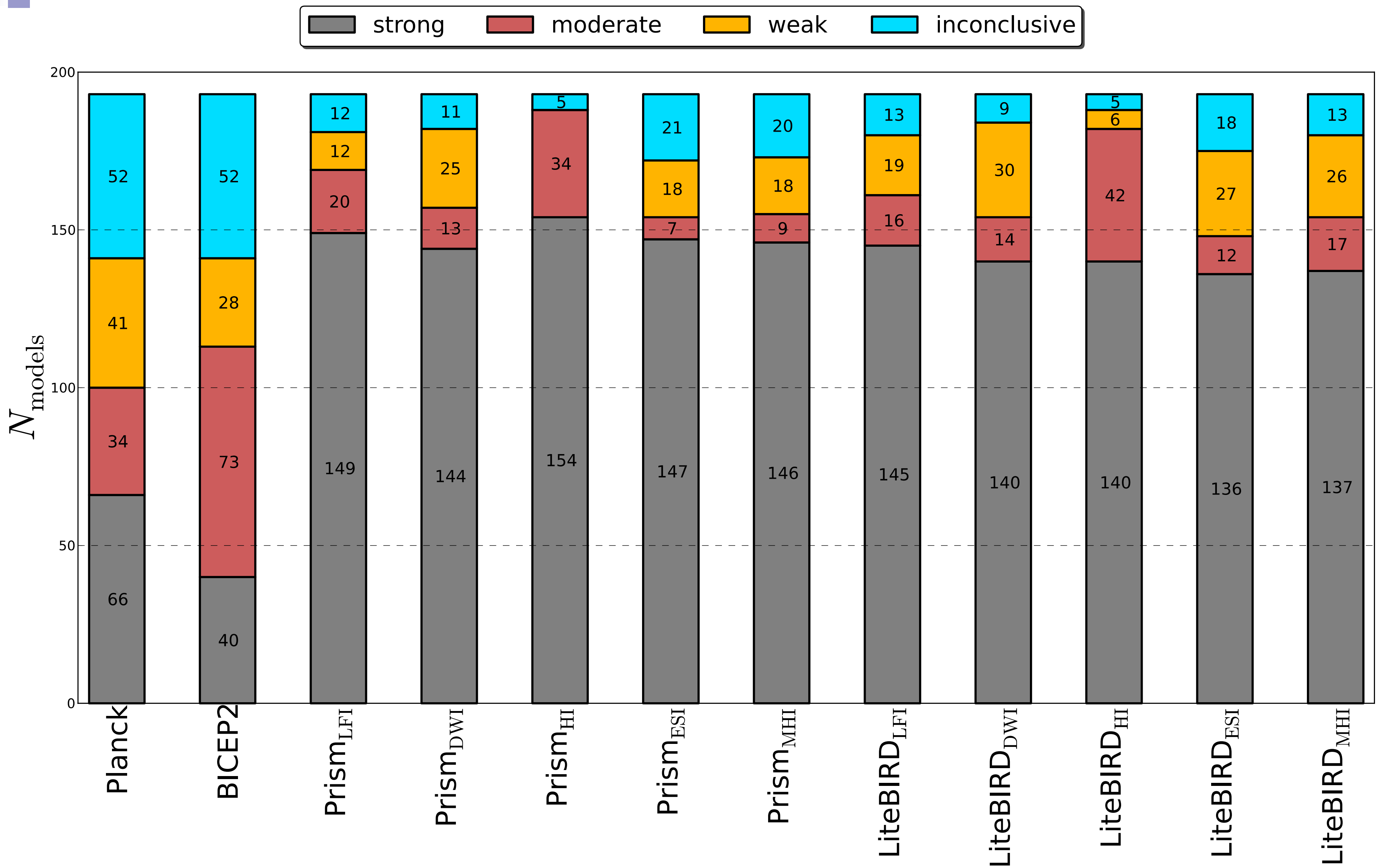








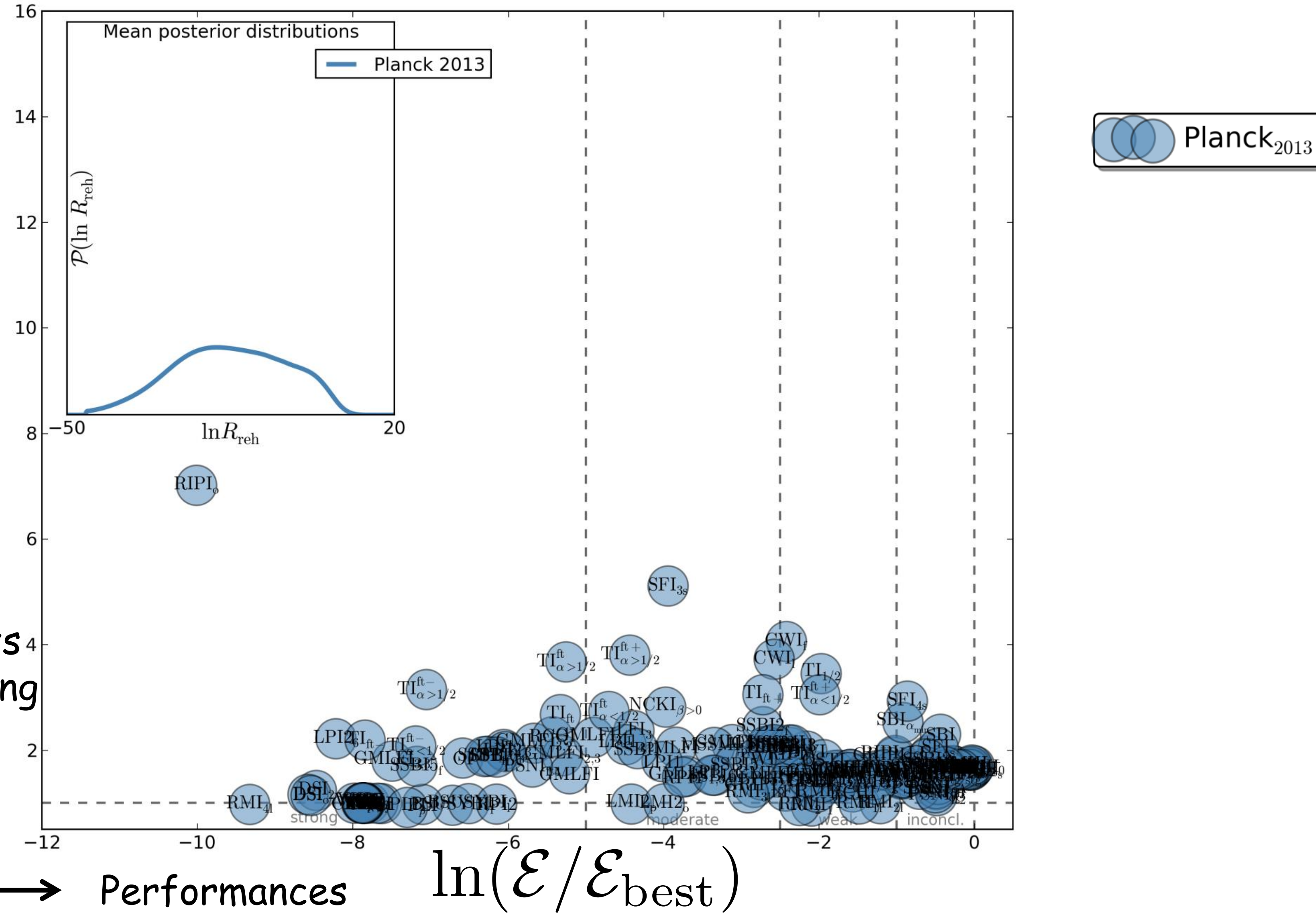
Going beyond Planck



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

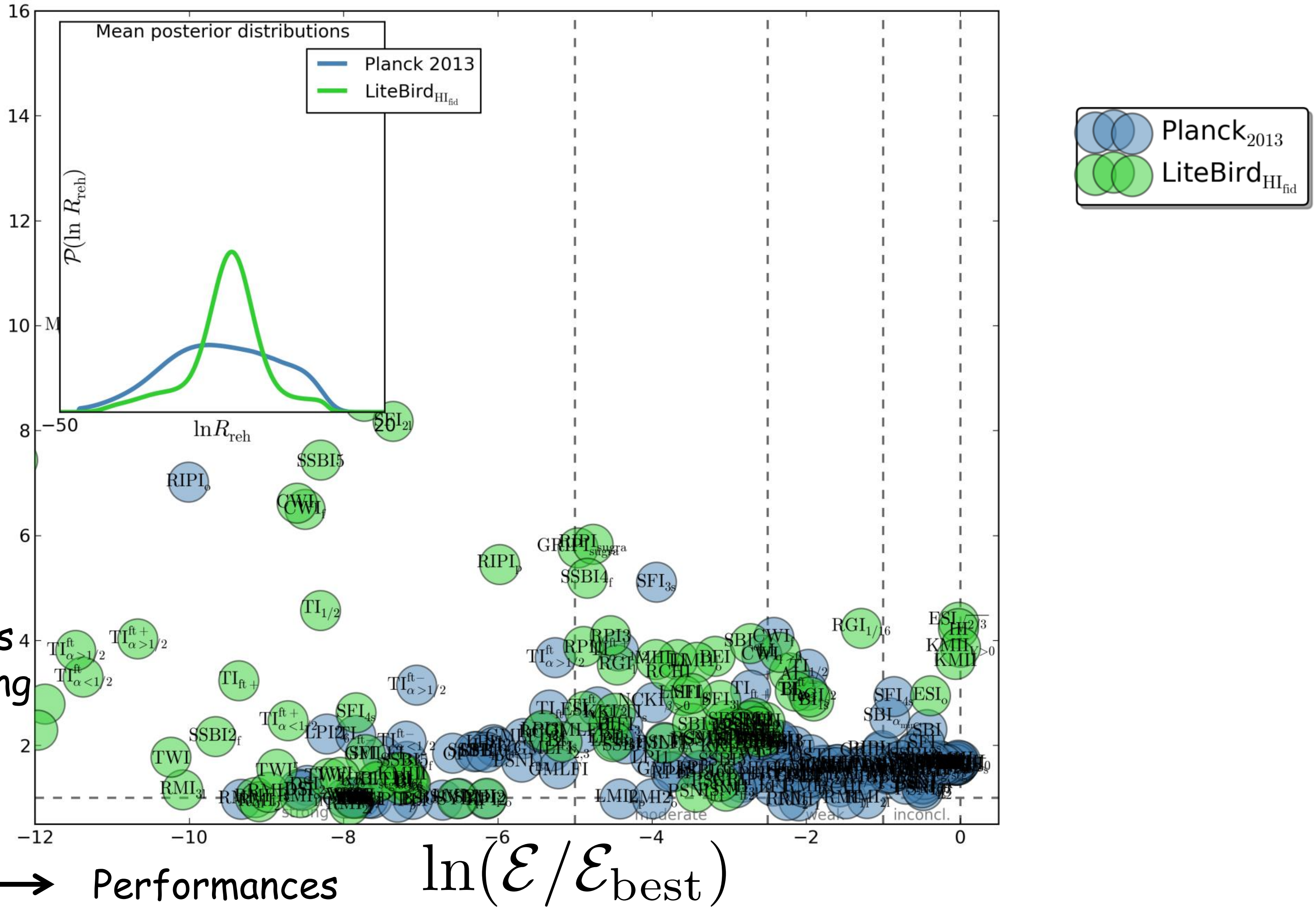
Reheating



Constraints on reheating

Performances

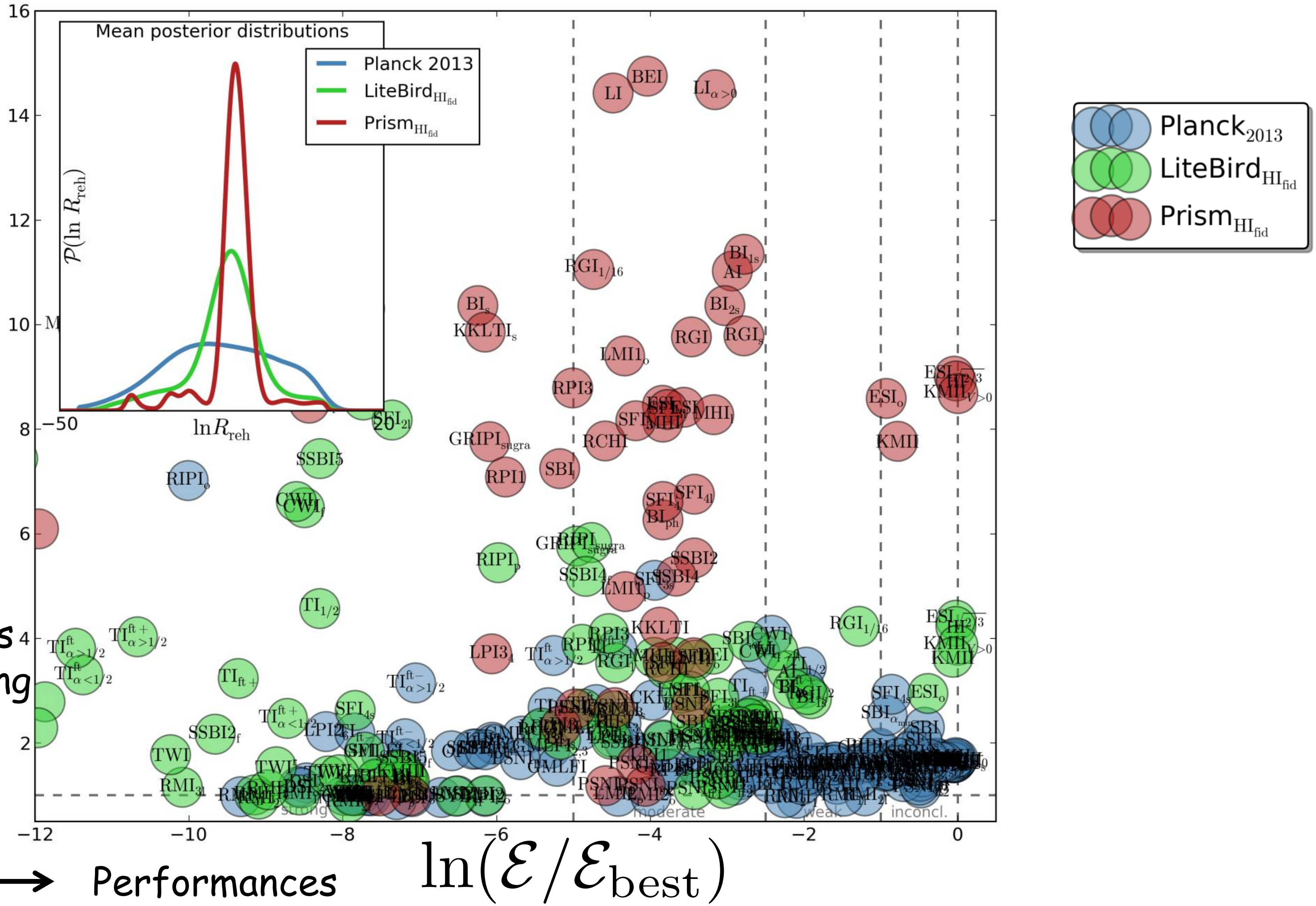
Reheating



Constraints on reheating

Performances

Reheating



Constraints on reheating

Performances

Outline

- The observational status of inflation after Planck (in brief)
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List of hot topics presently discussed in the "inflation community"

1) Are we sure it is inflation?

List of hot topics presently discussed in the "inflation community"

1) Are we sure it is inflation?

No, but it looks very likely. A smoking gun would be to verify the consistency checks

$$n_{\mathrm{T}} = -\frac{r}{8} \simeq -0.025\left(\frac{r}{0.2}\right)$$

$$\alpha_{\mathrm{T}} = \frac{r}{8}\left[\frac{r}{8} + (n_{\mathrm{S}} - 1)\right] \simeq 0.0016$$

List of hot topics presently discussed in the "inflation community"

1) Are we sure it is inflation?

2) Are we sure it is vanilla inflation?

more complicated models of inflation may imply:

- ✓ Violation of the consistency check
- ✓ Presence of non-adiabatic perturbations
- ✓ Non-Gaussianities
- ✓ Super-imposed oscillations in the primordial power spectrum

Polarization is important for very early universe physics: if a new effect comes from the early universe, and is seen in temperature, it must also been seen in the polarization in a consistent way: eg features, non-adiabatic modes …

List of hot topics presently discussed in the "inflation community"

1) Are we sure it is inflation?

2) Are we sure it is vanilla inflation?

3) Who is the inflaton?

- ✓ Can we consistently embed inflation in high energy physics?
- ✓ HEP more complicated than a simple scalar field so why vanilla inflation seems to emerge from the data (so far …)?
- ✓ UV sensitivity of inflation: problem or window of opportunity?

Improved model selection will play a crucial role

See S. Clesse and V. Vennin talks where more up to date (and accurate) results are presented (in particular using new version of Encyclopedia Inflationaris and of the public library of models ASPIC)

List of hot topics presently discussed in the "inflation community"

1) Are we sure it is inflation?

2) Are we sure it is vanilla inflation?

3) Who is the inflaton?

4) How did inflation come to an end?

For the moment, the constraints are dominated by rather exotic reheating scenarios. This will no longer be the case in the future, see Vincent Vennin's talk

List of hot topics presently discussed in the "inflation community"

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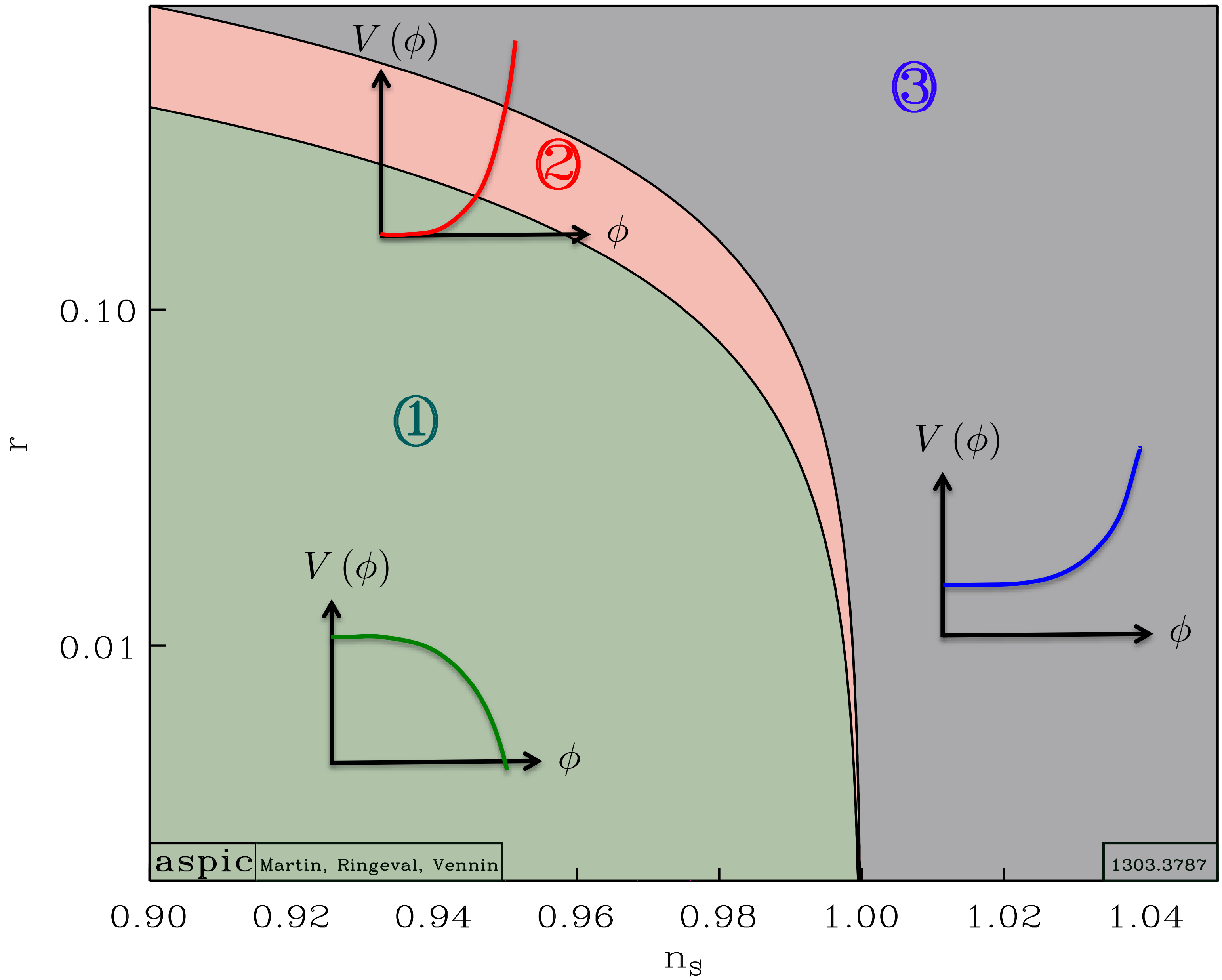
For the moment, the constraints are dominated by rather exotic reheating scenarios. This will no longer be the case in the future, see Vincent Vennin's talk

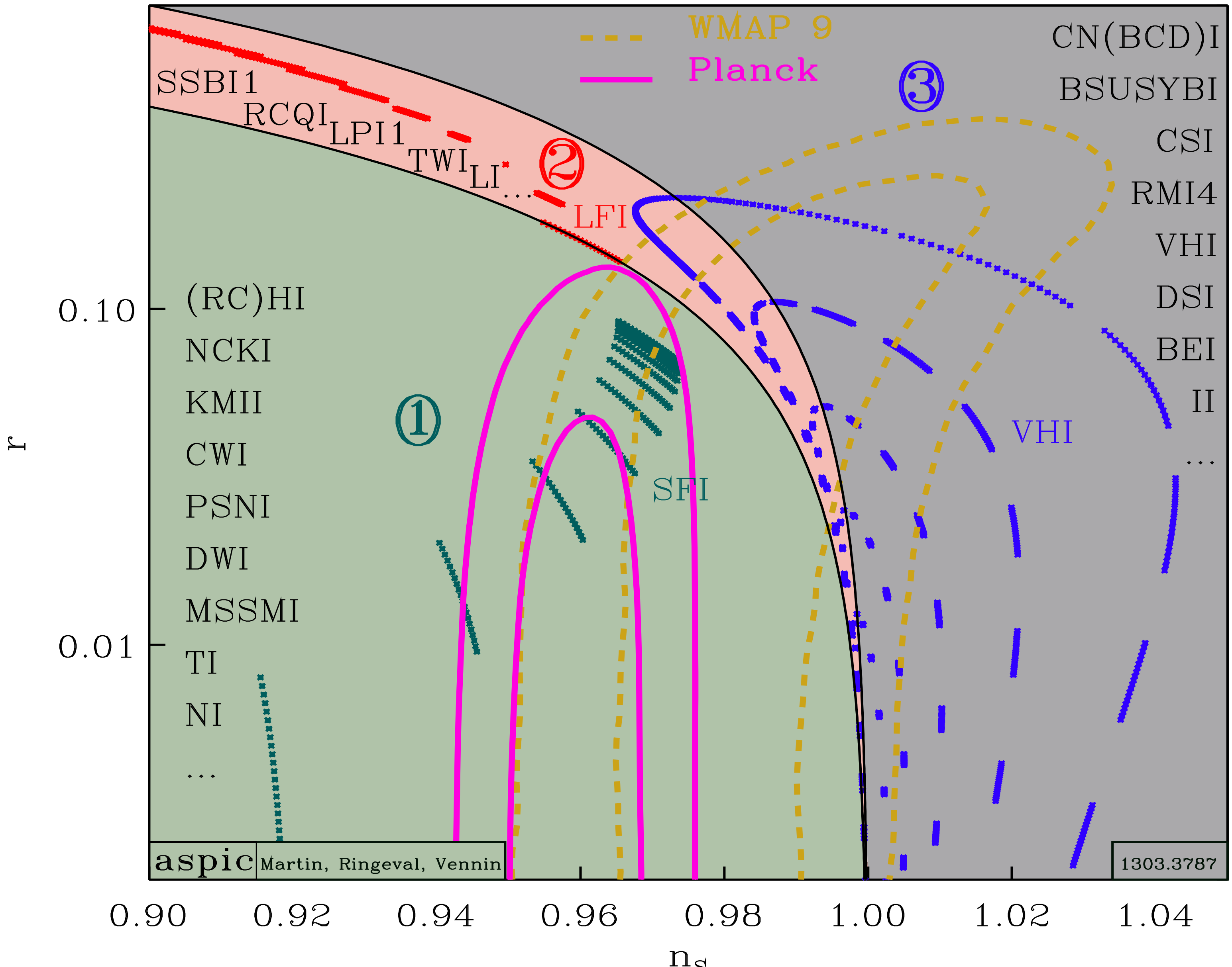
Thank you!

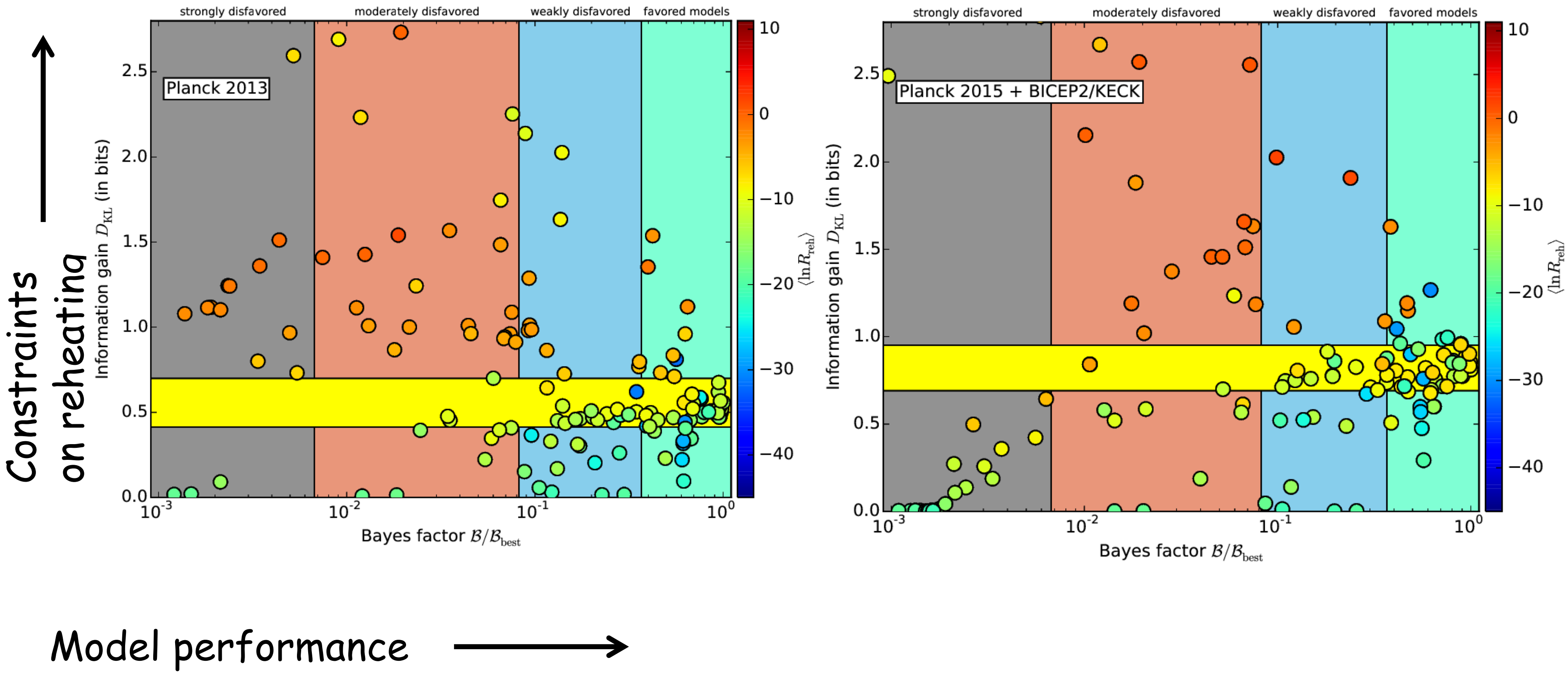
Back-up slides

Inflationary categories



Planck likes category 1





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

Message 1: the energy scale of inflation

Before a B-mode detection

$$\mathcal{P}_h \simeq \left(\frac{H}{m_{\rm Pl}}\right)^2 < \mathcal{O}(1)\left(\frac{\delta T}{T}\right)^2 \simeq 10^{-10} \rightarrow$$

Upper bound on the energy scale of inflation ~ less than the GUT scale

Message 1: the energy scale of inflation

Before a B-mode detection

$$\mathcal{P}_h \simeq \left(\frac{H}{m_{\rm Pl}}\right)^2 < \mathcal{O}(1)\left(\frac{\delta T}{T}\right)^2 \simeq 10^{-10}$$

→ Upper bound on the energy scale of inflation ~ less than the GUT scale

After (for example at the BICEP2 level)

J. Martin, C. Ringeval, R. Trotta and V. Vennin, Phys. Rev. D90 (2014) 6, 063501arXiv:1405.7272

$$\mathcal{P}_h \simeq \left(\frac{H}{m_{\rm Pl}}\right)^2 \simeq 0.2\left(\frac{\delta T}{T}\right)^2 \simeq 0.2\times 10^{-10}$$

→ Energy scale of inflation measured to be ~ the GUT scale

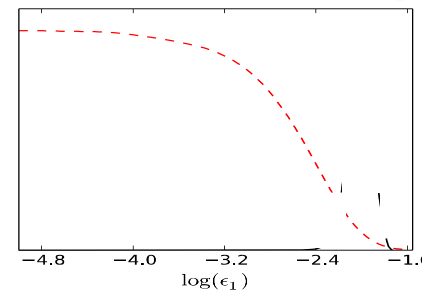
$$\boxed{\begin{aligned} H &\simeq 1.23\left(\frac{r}{0.2}\right)^{1/2} 10^{14}\,\mathrm{GeV} \\ \rho^{1/4} &\simeq 2.26\left(\frac{r}{0.2}\right)^{1/4} 10^{16}\,\mathrm{GeV}\end{aligned}}$$

Message 2: first derivative of the potential

Before a B-mode detection

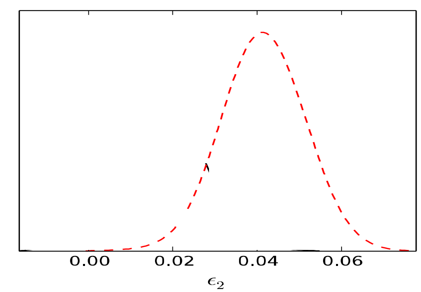
$$r=\frac{T}{S}=16\epsilon_1=\frac{8}{M_{\mathrm{Pl}}^2}\left(\frac{V_\phi}{V}\right)^2<\mathcal{O}(1)$$

→ Upper bound on the value of the first derivative



$$n_{\mathrm{S}}-1=-2\epsilon_1-\epsilon_2\simeq 0.96$$

→ Second sr parameter measured!

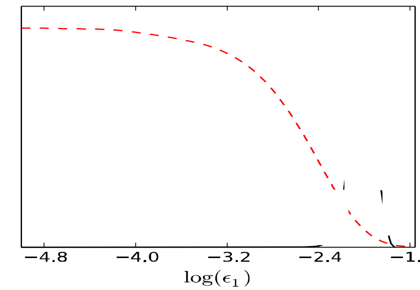


Message 2: first derivative of the potential

Before BICEP2

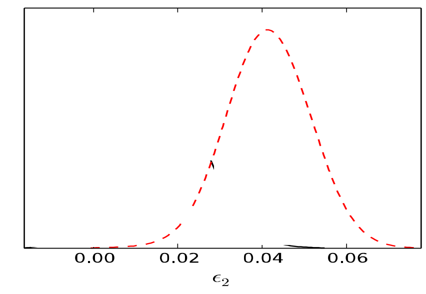
$$r = \frac{T}{S} = 16\epsilon_1 = \frac{8}{M_{\mathrm{Pl}}^2}\left(\frac{V_\phi}{V}\right)^2 < \mathcal{O}(1)$$

→ Upper bound on the value of the first derivative



$$n_{\mathrm{S}} - 1 = -2\epsilon_1 - \epsilon_2 \simeq 0.96$$

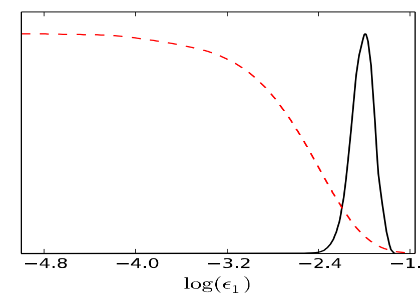
→ Second derivative measured!



After (for example at the BICEP2 level)

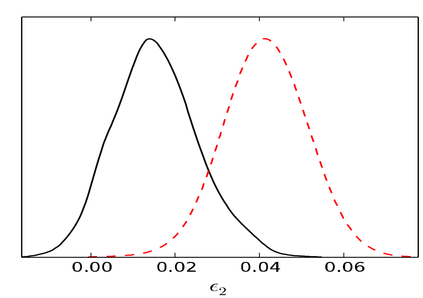
$$r = \frac{T}{S} = 16\epsilon_1 = \frac{8}{M_{\mathrm{Pl}}^2}\left(\frac{V_\phi}{V}\right)^2 = 0.2$$

→ First derivative measured!



$$n_{\mathrm{S}} - 1 = -2\epsilon_1 - \epsilon_2 \simeq 0.96$$

→ Second derivative measured but different value



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

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

Fiducial Model	$V(\phi)/M^4$	Parameters	n_S	r
$\mathrm{LFI}_{\mathrm{fid}}$	$(\phi/M_{\mathrm{Pl}})^2$		0.961	1.52×10^{-1}
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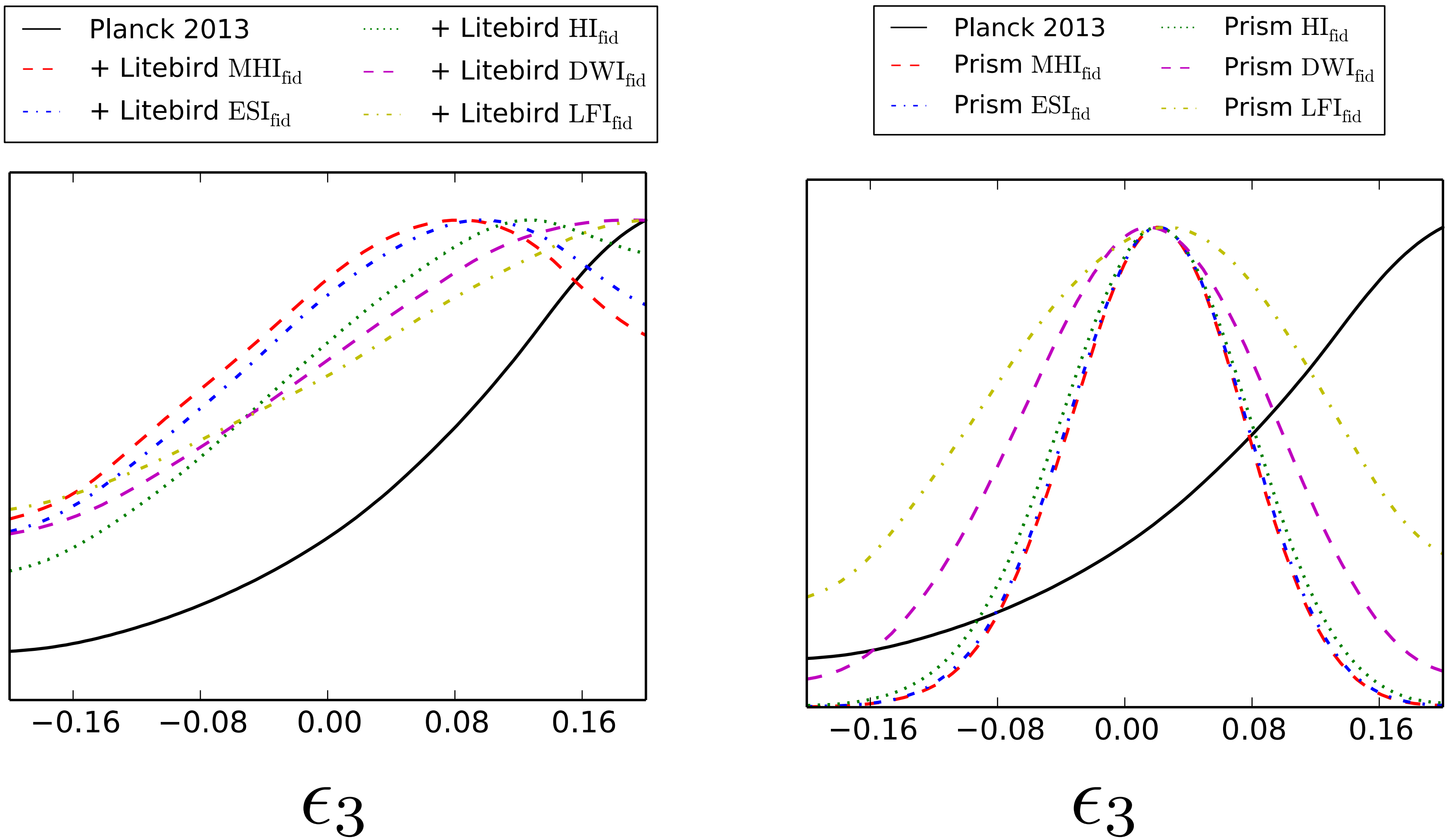
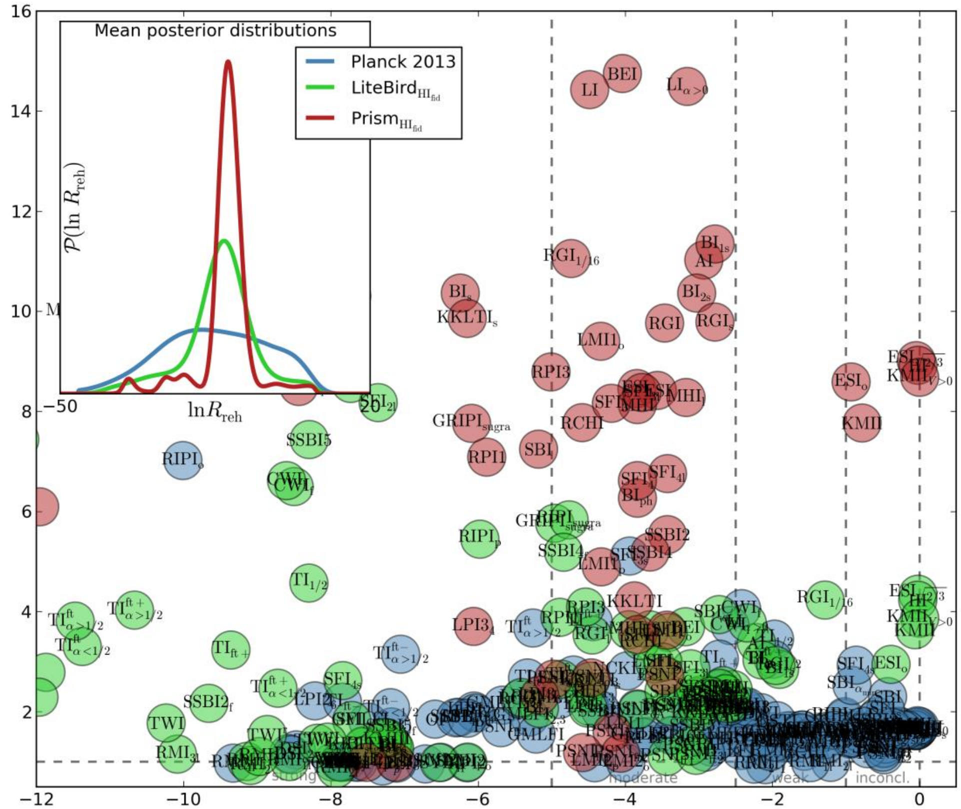
J. Martin, C. Ringeval and V. Vennin, JCAP 1410 (2014) 10, 038, arXiv:1407.4034

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



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

Message 6: Significant improvement of the constraints of reheating



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

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

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

Beyond slow-roll: examples

- In general, more complicated models of inflation may imply:

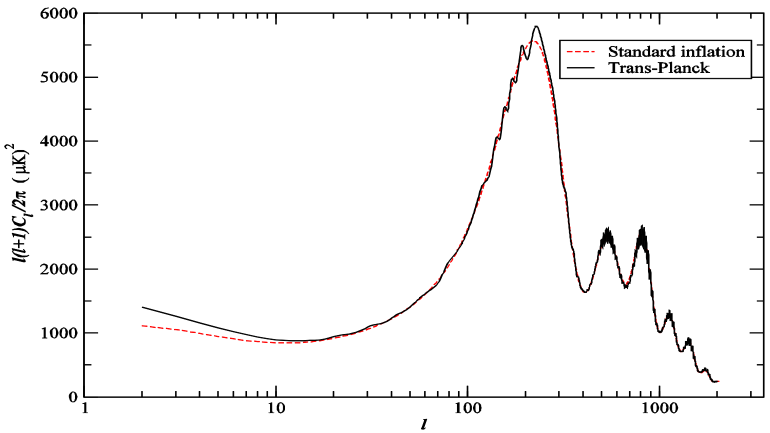
  ✓ Violation of the consistency check

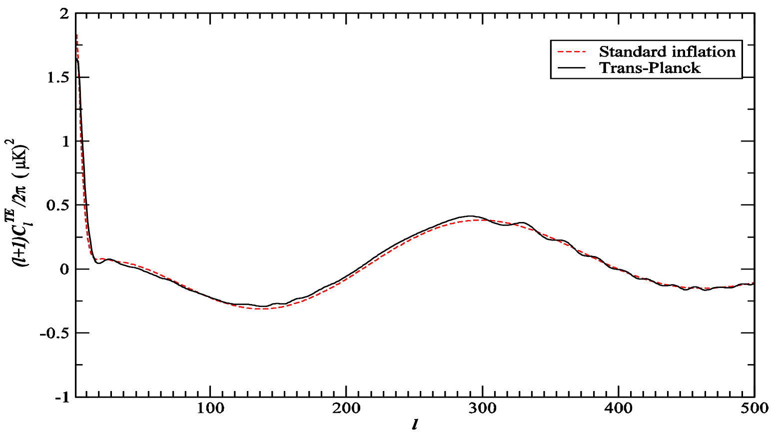
  - K-inflation $r = -8 n_{\mathrm{T}} c_{\mathrm{S}}\,, \quad c_{\mathrm{S}} < 1$
  - Multiple field inflation $r = -8 n_{\mathrm{T}} \sin^2 \Theta$

Polarization can obviously helps … if r not too small

- In general, more complicated models of inflation may imply:

  ✓ Super-imposed oscillations in the primordial power spectrum





Super imposed oscillations due to trans-Planckian corrections

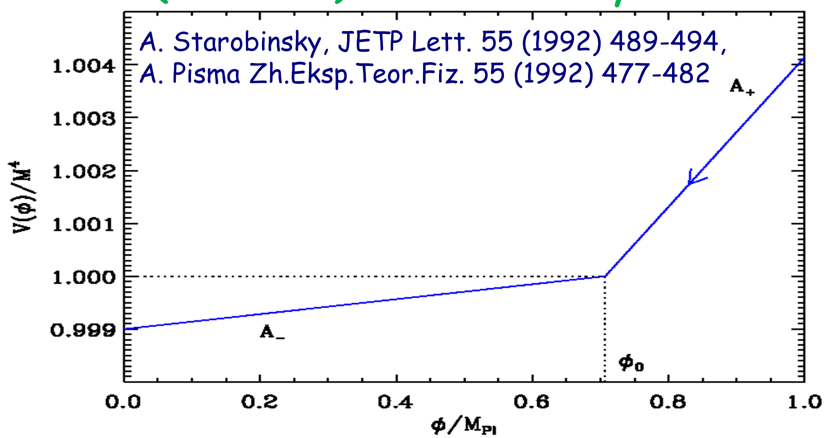
J. Martin and R. Brandenberger, Phys. Rev. D (2001) 123501, hep-th/0005209

J. Martin and C. Ringeval, Phys. Rev. D69 (2004) 083515, astro-ph/0310382

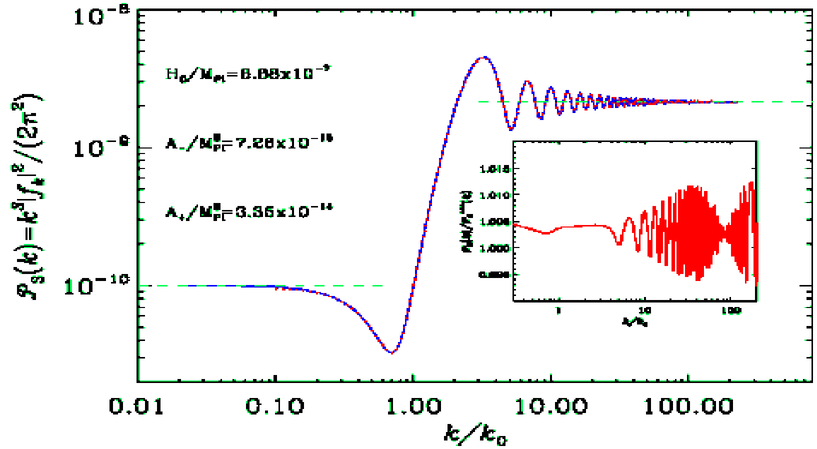
- In general, more complicated models of inflation may imply:

  - ✓ Super-imposed oscillations in the primordial power spectrum

(Second) Starobinsky model



J. Martin and L. Sriramkumar, JCAP 1201 (2012) 008, arXiv:1109.5838



If of primordial origin, the superimposed oscillations should be seen in temperature and polarization in a consistent way: polarization is therefore a smoking gun which guarantees that non-minimal features are indeed of primordial origin

- Non-Gaussianity

Searching for NG is like searching for the Higgs, we know where to find the signal and if we do not find it, it has drastic consequences … But, in practice, not realistic (at least for the moment!)