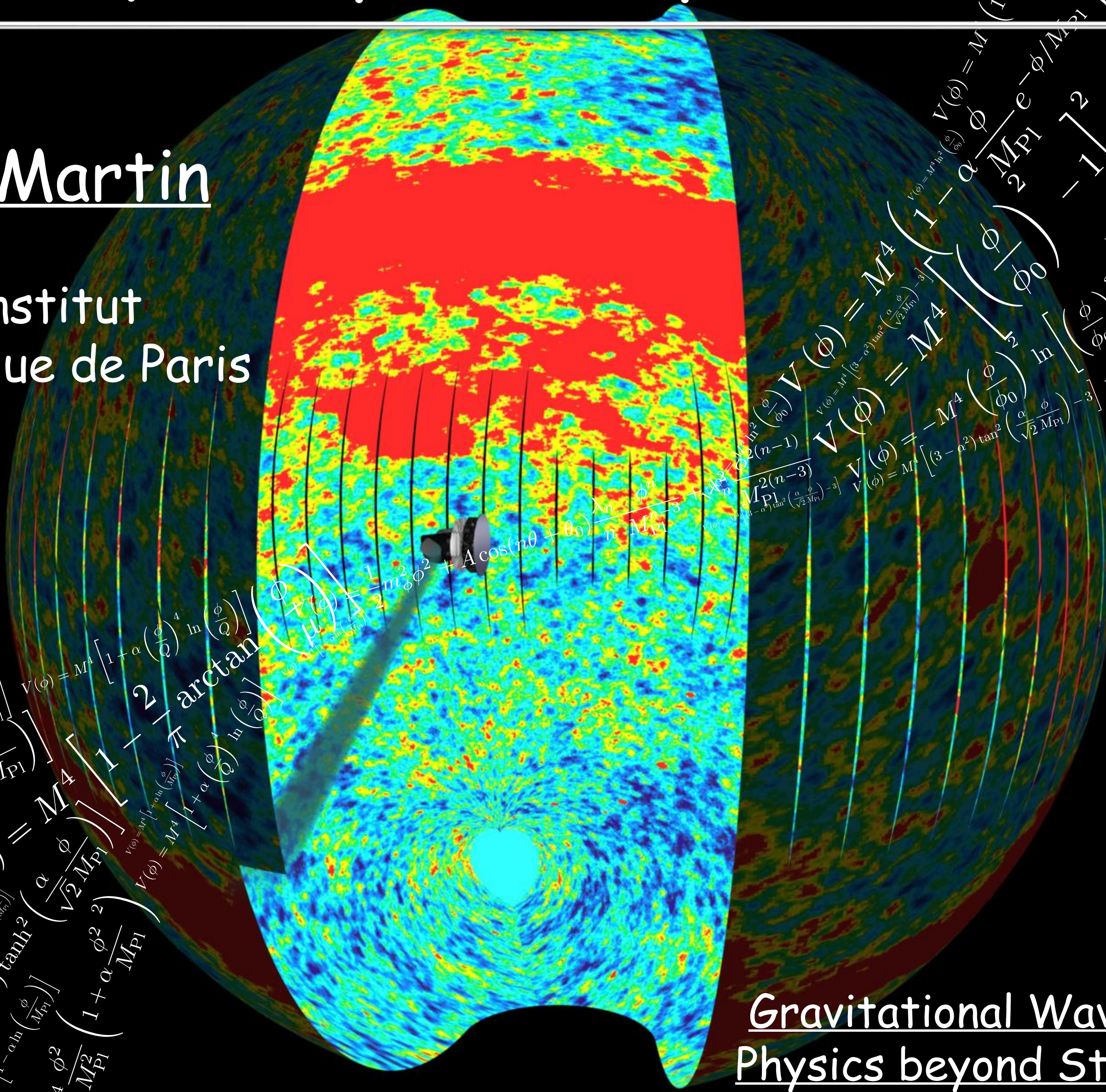
Cosmic Inflation after Planck

Jerome Martin

CNRS/Institut d'Astrophysique de Paris



Gravitational Waves Probes of Physics beyond Standard Model

12-16 July 2021

Outline

- Observational status of inflation after Planck 2013 & 2015 & 2018

- Assessing the theoretical status of inflation after Planck

- Going beyond the present state of the art … GW & PBHs from "vanilla" inflationary models

- Conclusions.

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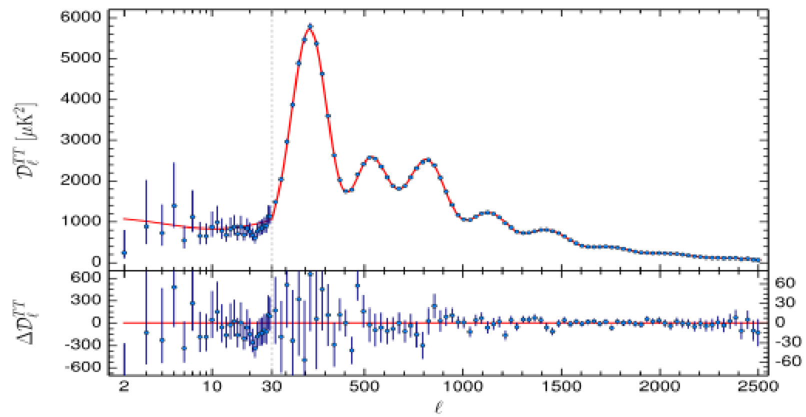
- Universe spatially flat $\Omega_{\mathcal{K}} = -0.011^{+0.013}_{-0.012}$

- Phase coherence



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

- Gaussian perturbations $f^{\rm loc}_{\rm NL} = 0.8 \pm 5$

- Almost scale invariant power spectrum $n_{\rm S} = 0.9649 \pm 0.0042$

- Background of quantum gravitational waves $r < 0.056$

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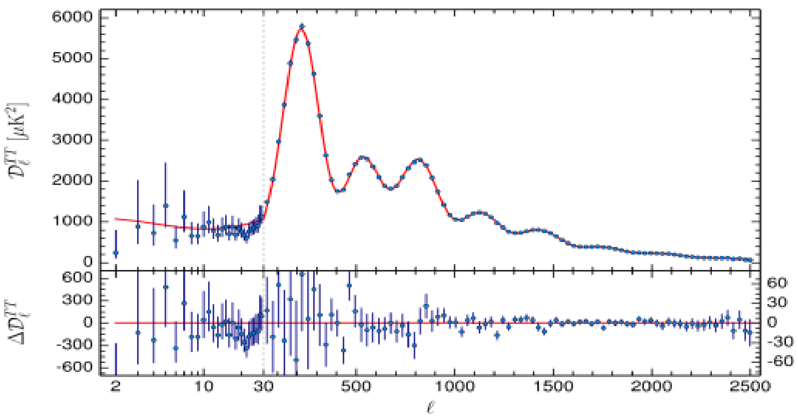

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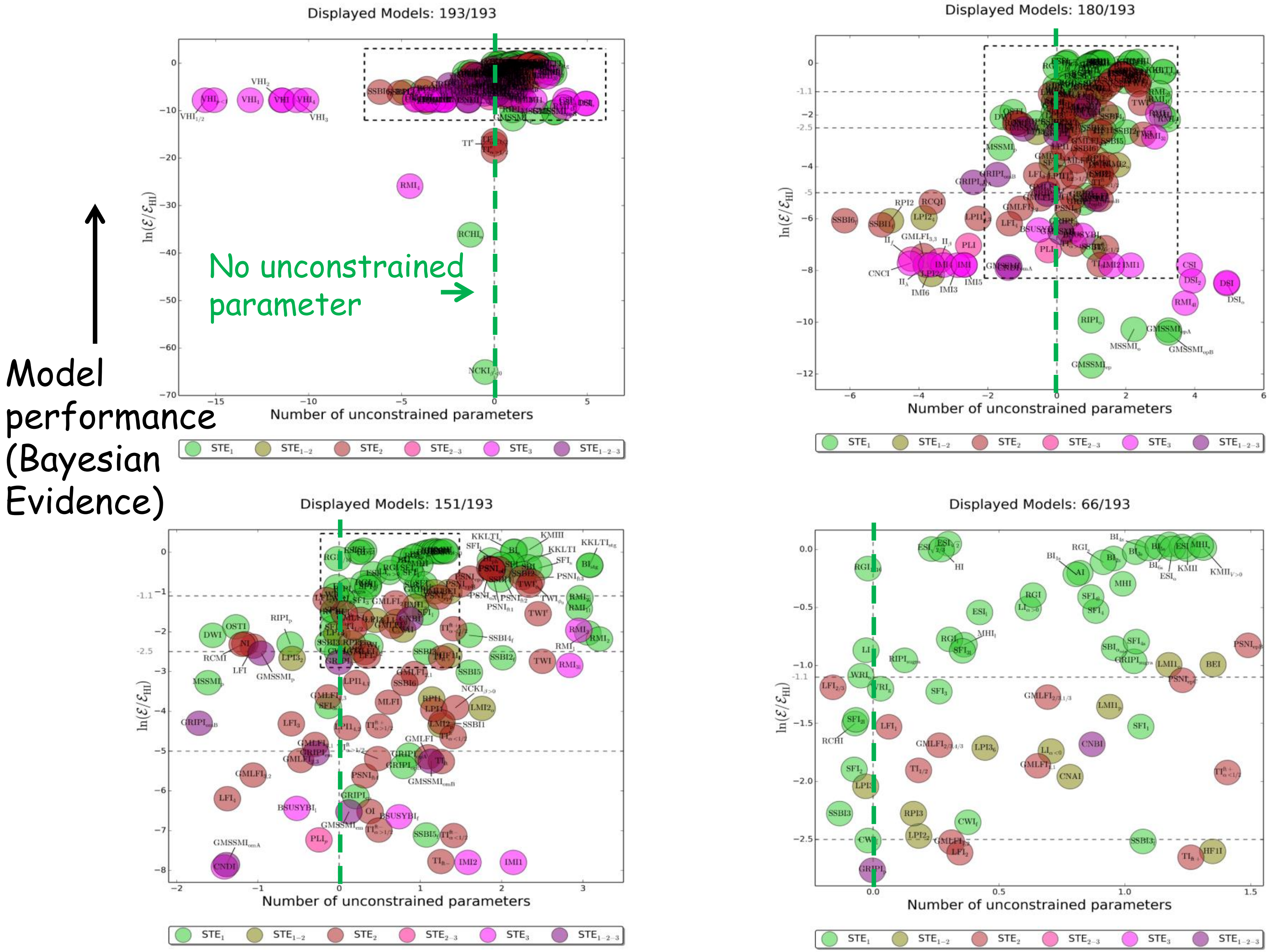
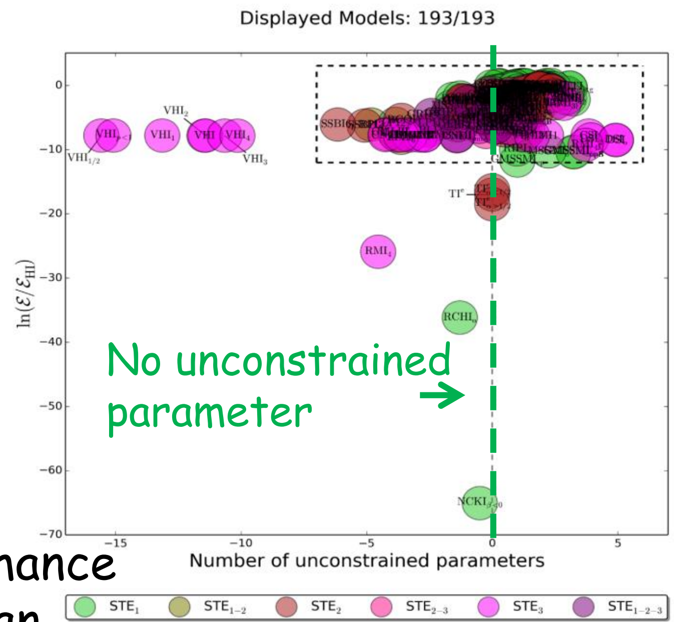
Single field slow-roll models, with minimal kinetic terms, are preferred

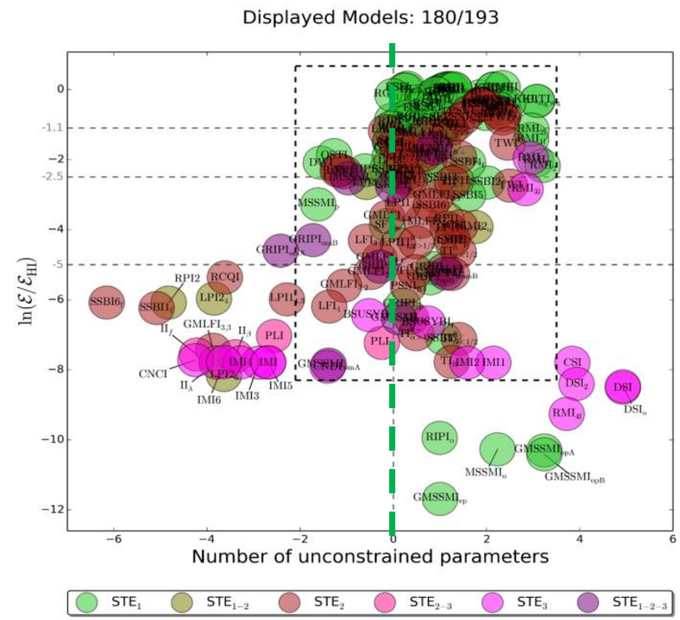
Which models?



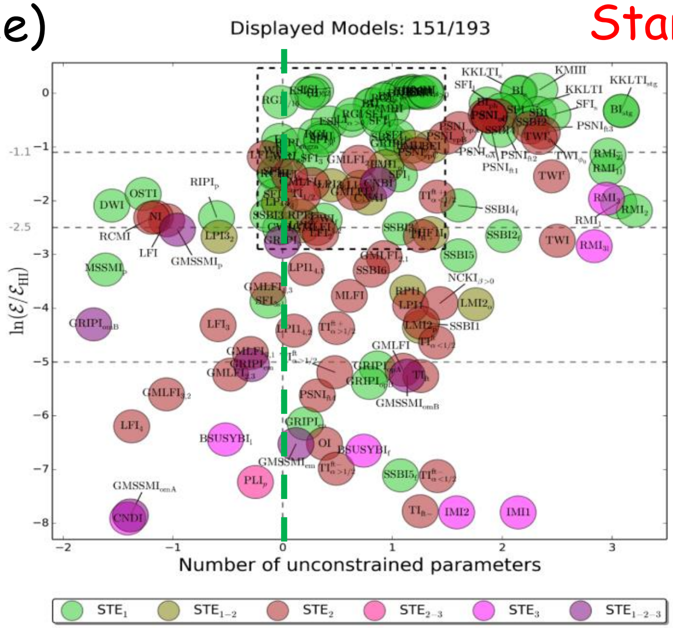
Which models?

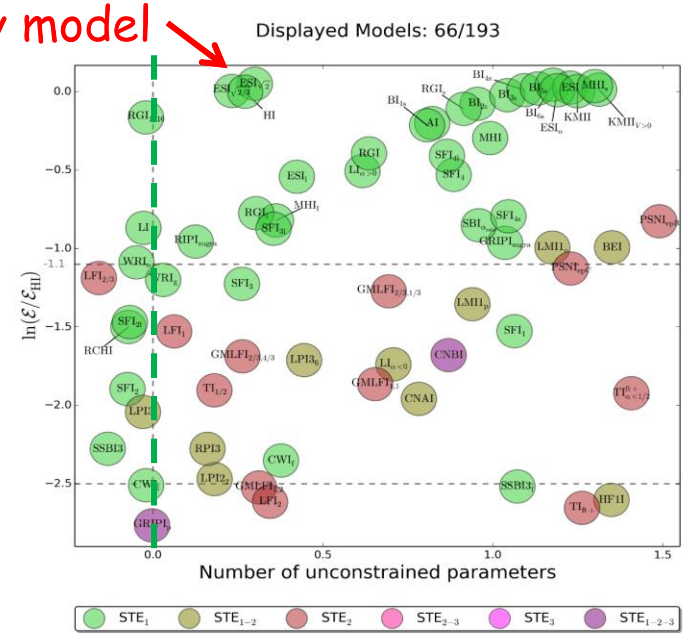
Model performance (Bayesian Evidence)



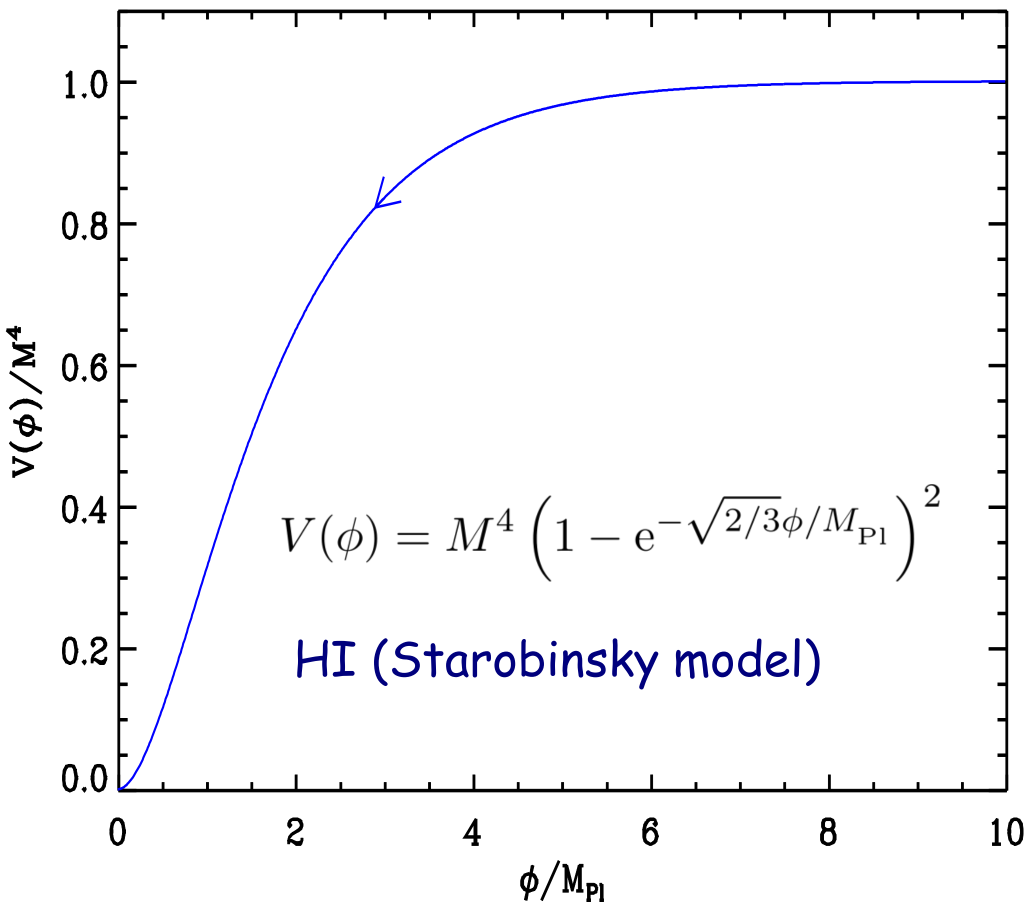


Starobinsky model





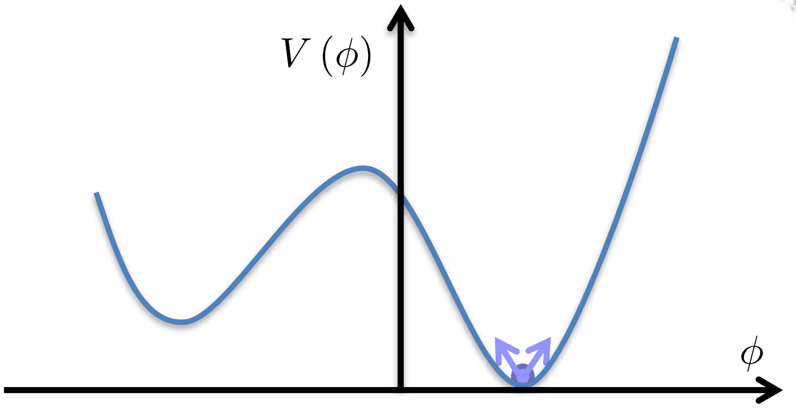
Plateau inflationary models are the winners! … examplified by the Starobinsky model

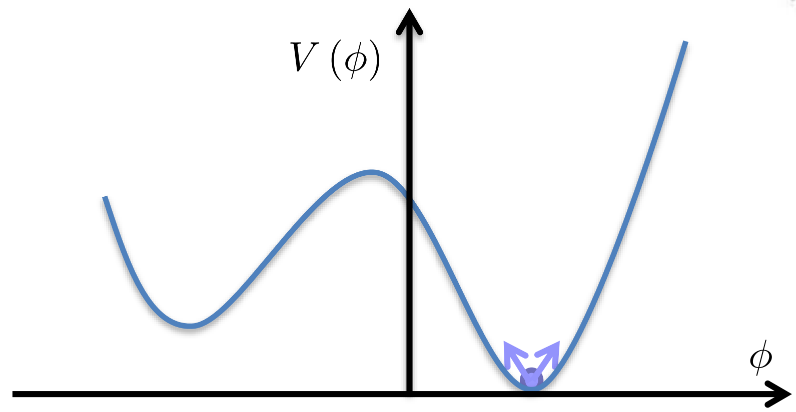


J. Martin, C. Ringeval and V. Vennin, Phys. Dark Univ. 5-6 (2014) 75, arXiv:1303.3787

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

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





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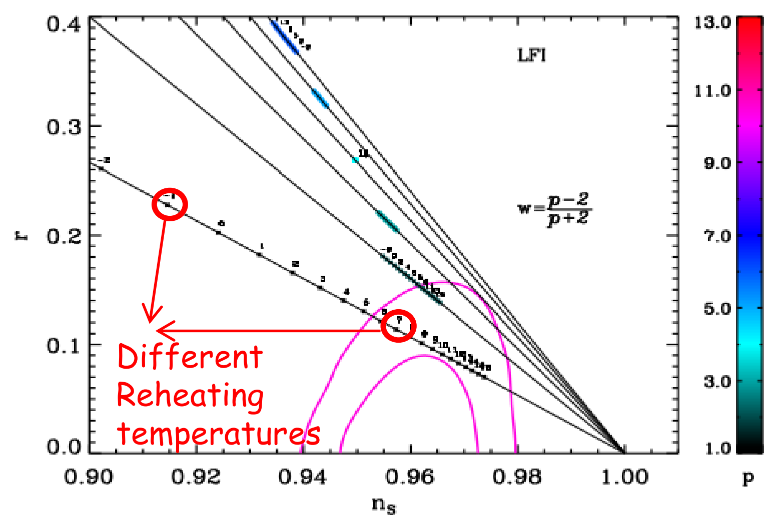

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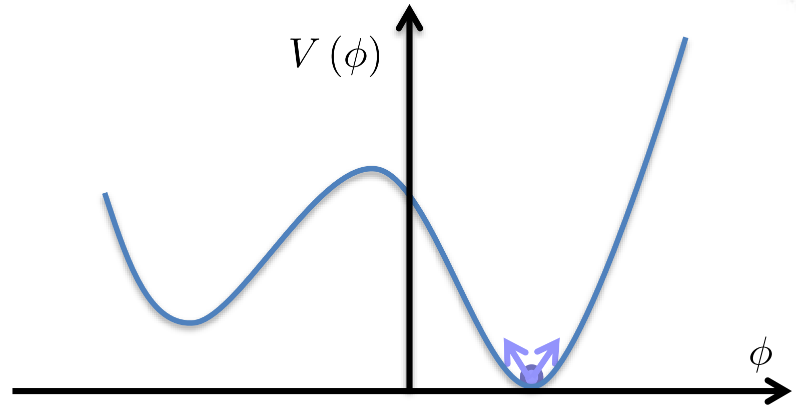

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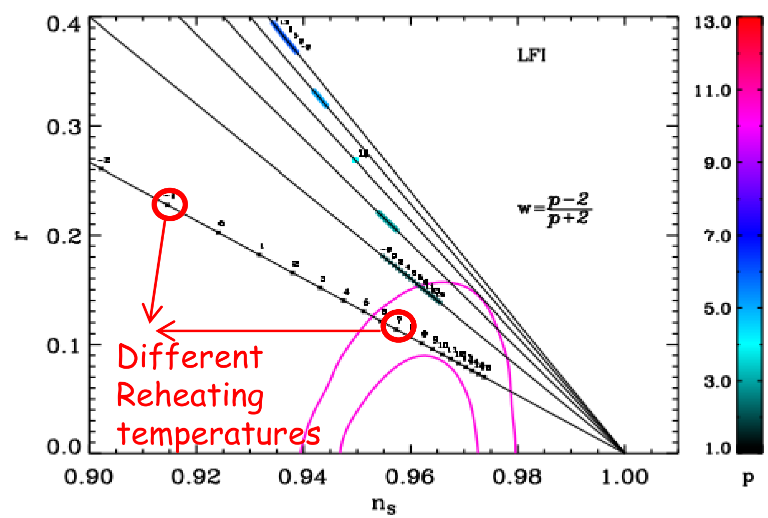
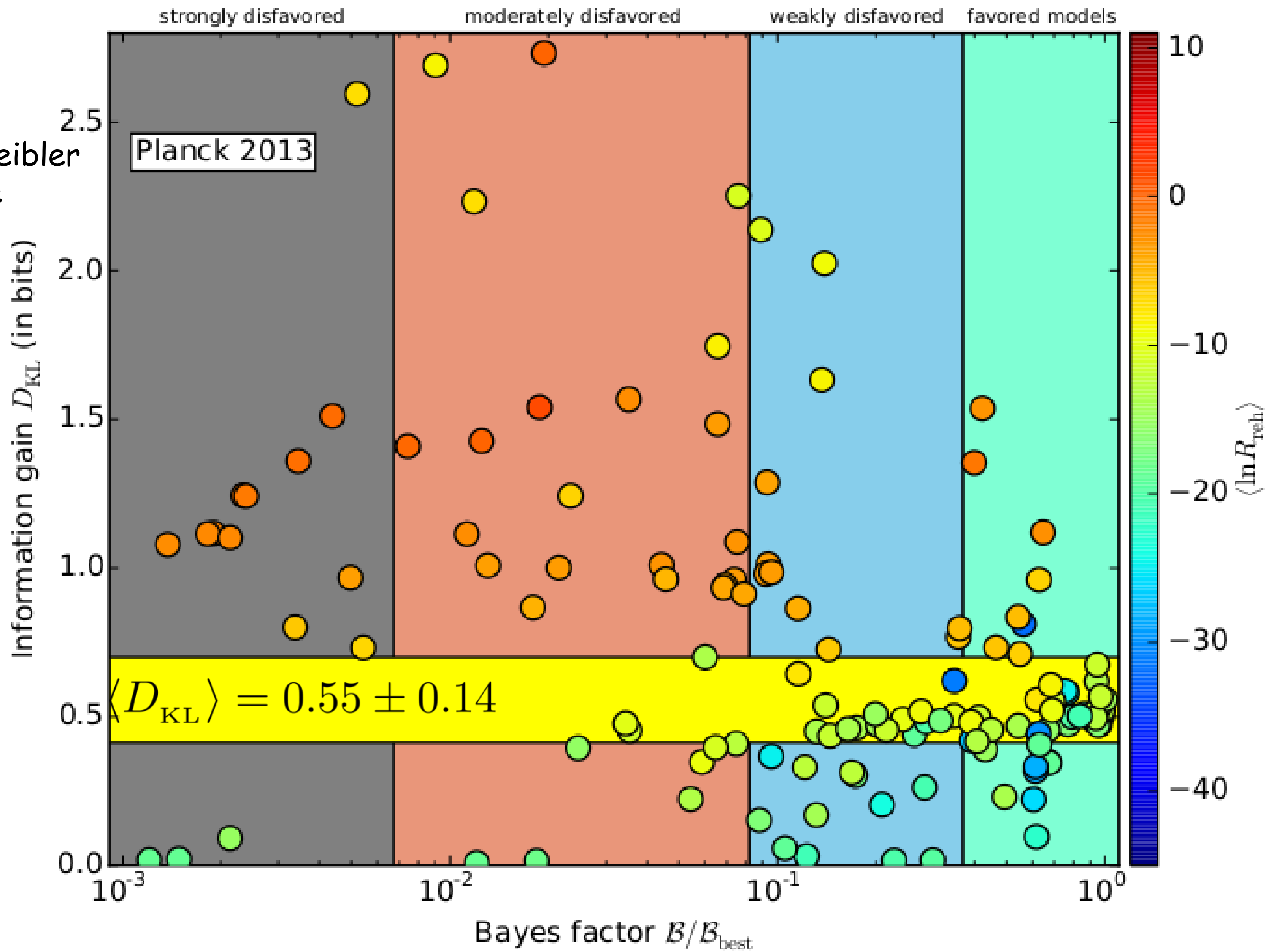


- Reheating can be very complicated (as the process of re-ionization) but, as long as the CMB is concerned, only the reheating parameter is important

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

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

Kullback-Leibler divergence



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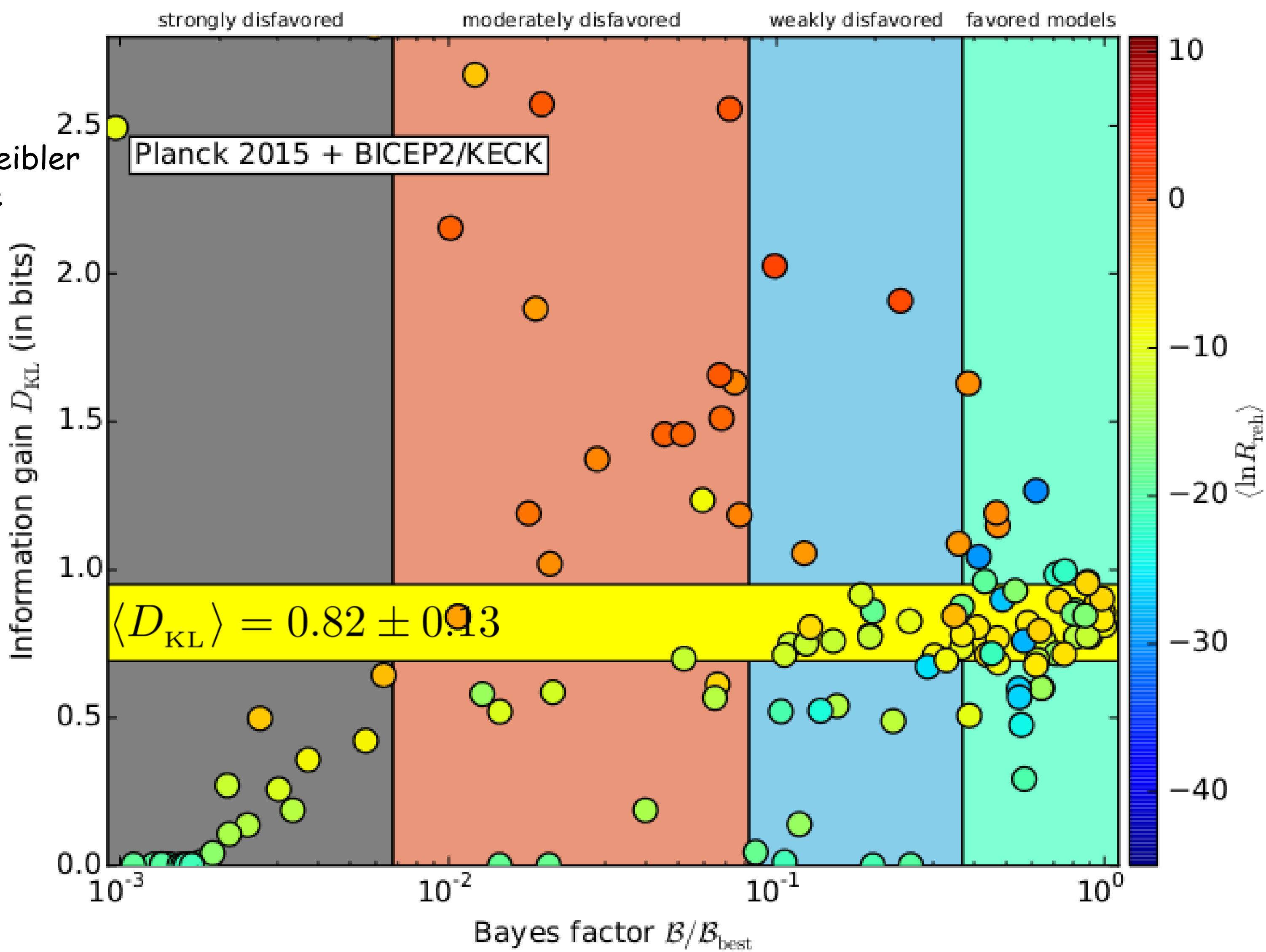

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Assessing inflation

- Inflationary mechanism (accelerated expansion) rests on GR which is a very well-tested theory …

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- More precisely, it rests on the fundamental principle that, in GR, every form of energy weighs including pressure

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

Also at play in:
- dark energy
- Neutron stars
- BBN

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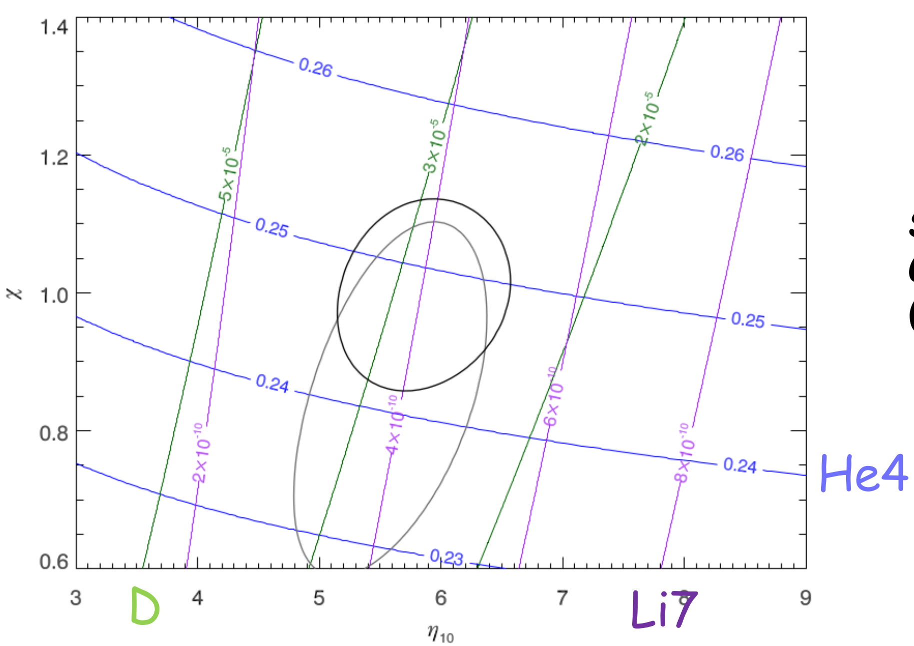


S. Rappaport, J. Schwab, S. Burles, and G. Steigman, Phys. Rev. D77, 023515 (2008), arXiv:0710.5300

This is similar to the Schwinger effect: interaction of a quantum field with a classical source

J. Martin, Lect. Notes Phys. 738 (2008), 195
arXiv:0704.3540

Schwinger effect

- Electron and positron fields
- Classical electric field
- Amplitude of the effect controlled by E

Inflationary cosmological perturbations

- Inhomogeneous gravity field
- Background gravitational field: scale factor
- Amplitude controlled by the Hubble parameter H

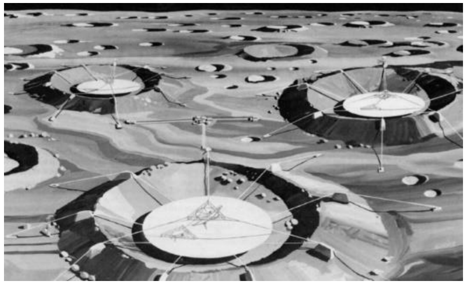
See also dynamical Schwinger effect, dynamical Casimir effect etc …

Theoretical open issues

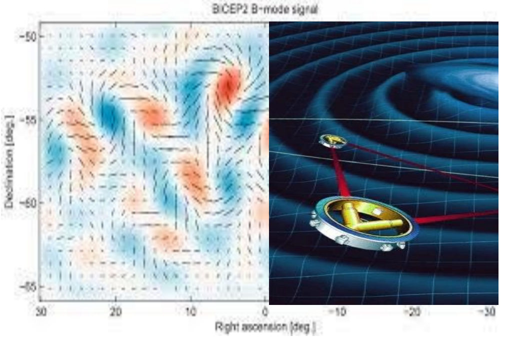
- Model building & physical nature of the inflaton field:
    - Has inflation some connections with the Higgs?
    - Extensions to the standard model contains mainy degrees of freedom … how a single field description emerges from that?
    - Can we observe the effect of these extra degrees of freedom (multi-field inflation, gauge fields, inflationary magnetogenesis, PBHs etc …)
- How does inflation end?
    - Reheating/preheating/thermalization, PBHs …
- Inflationary mechanism for structure formation
    - Quantum-to-classical transition of inflationary perturbations: inflation is the only known system that uses GR and QM and where high-accuracy data are available

Observational tools

- Non-Gaussianity



- Gravitational Waves



- PBHs

Remark: these probes can be used to study inflation beyond simple models but they can also be useful (although challenging) to further test the vanilla scenarios.

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Other key predictions of vanilla inflation

1- the presence of a "quantum" GW background from inflation

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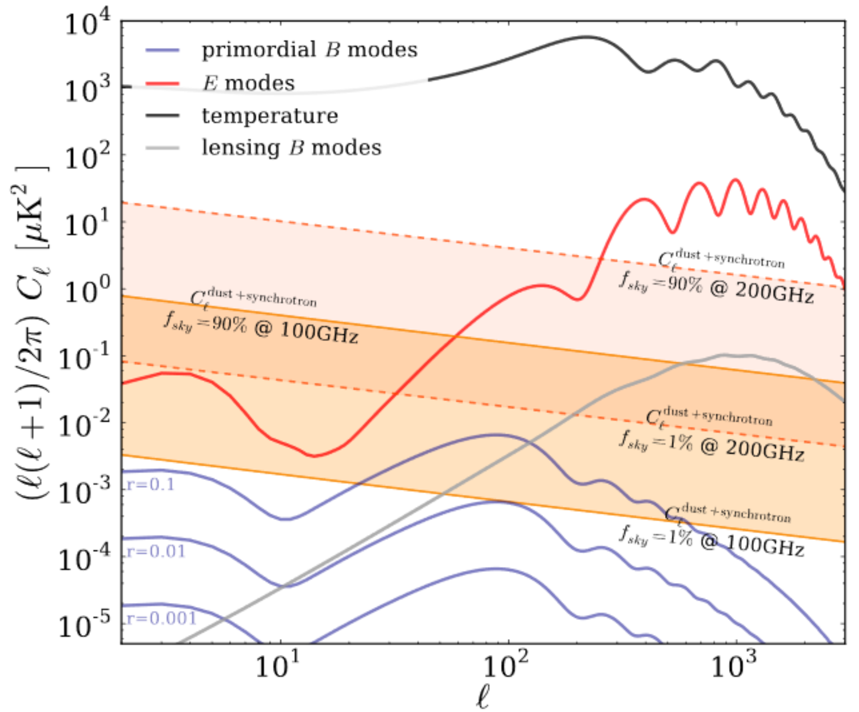
- On large scales can be revealed through CMB B modes



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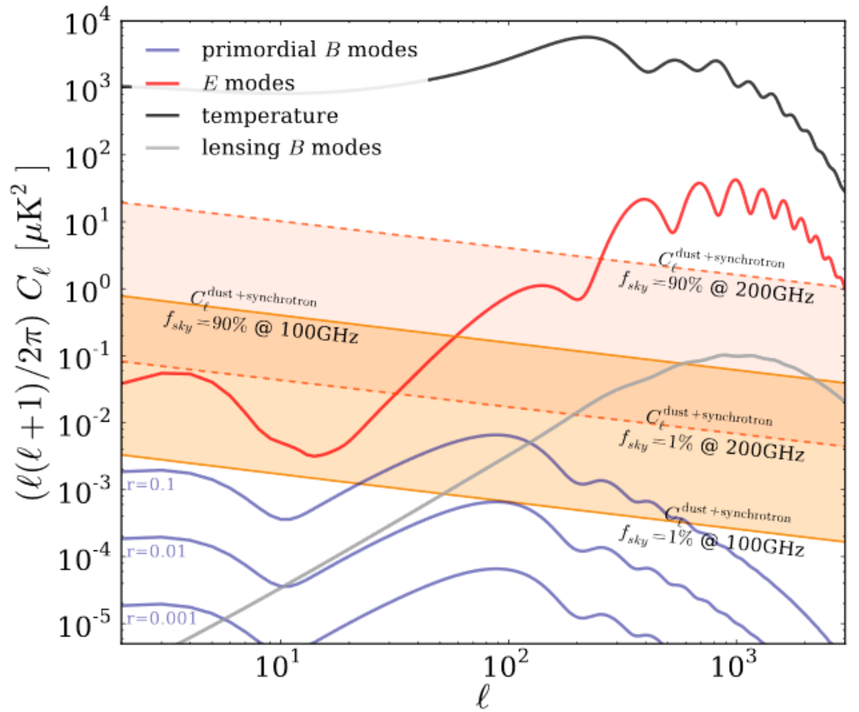

- Next generation of CMB mission with a target: r ~ 10^{-4} [Starobinsky model, r ~ (2-4) x10^{-3} , Planckian excursion r~ 10^{-3}]

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- Next generation of CMB mission with a target: $r \sim 10^{-4}$ [Starobinsky model, $r \sim (2\text{-}4) \times 10^{-3}$, Planckian excursion $r \sim 10^{-3}$]

- What can be learned from a detection ?

- ❑ Energy scale of inflation
- ❑ Final proof of vanilla inflation: consistency check (but needs n_T) $n_{\rm T} = -r/8$
- ❑ Measurement of the first derivative of the potential
- ❑ Field excursion
- ❑ Greatly improve model selection
- ❑ Greatly improve constraints on reheating

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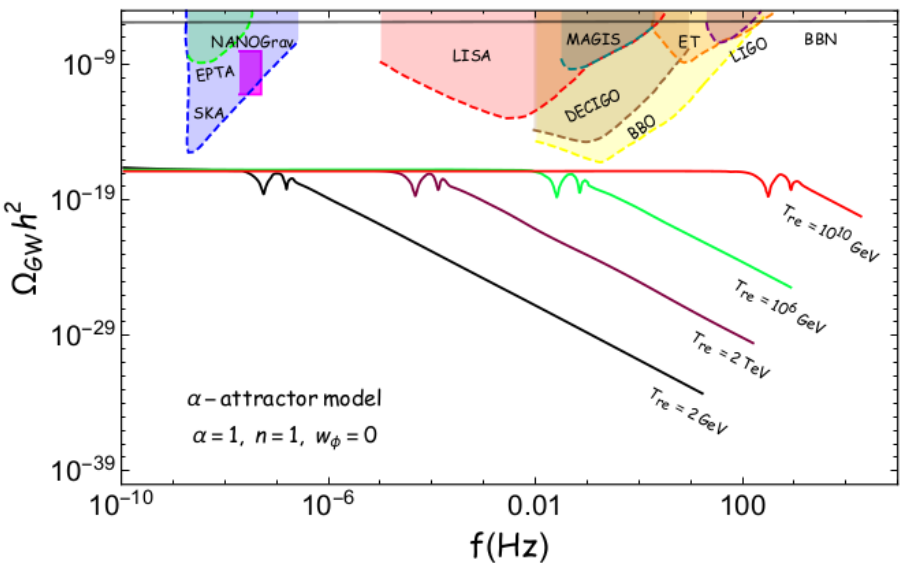

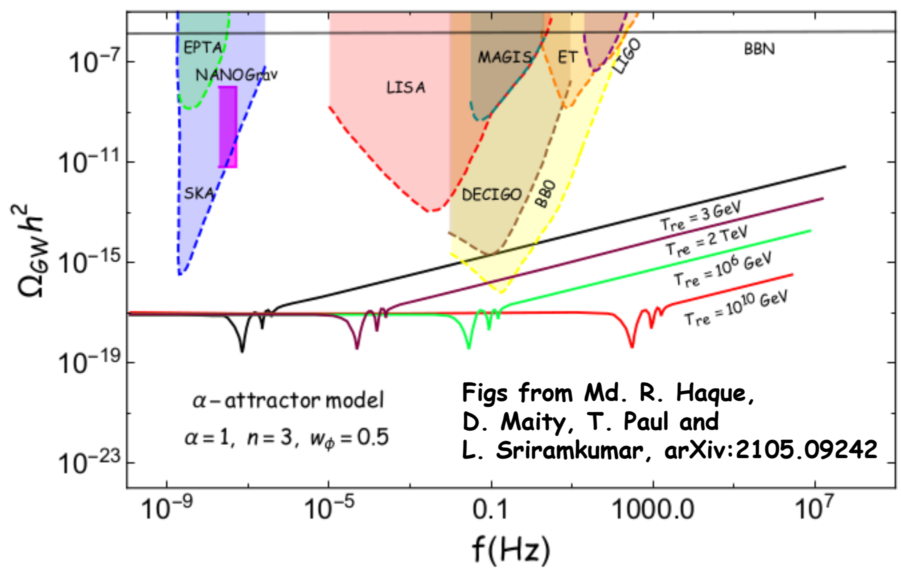

Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, arXiv:2105.09242

K. Nakayama, S. Saito, Y. Suwa J. Yokoyama, arXiv:0804.1827

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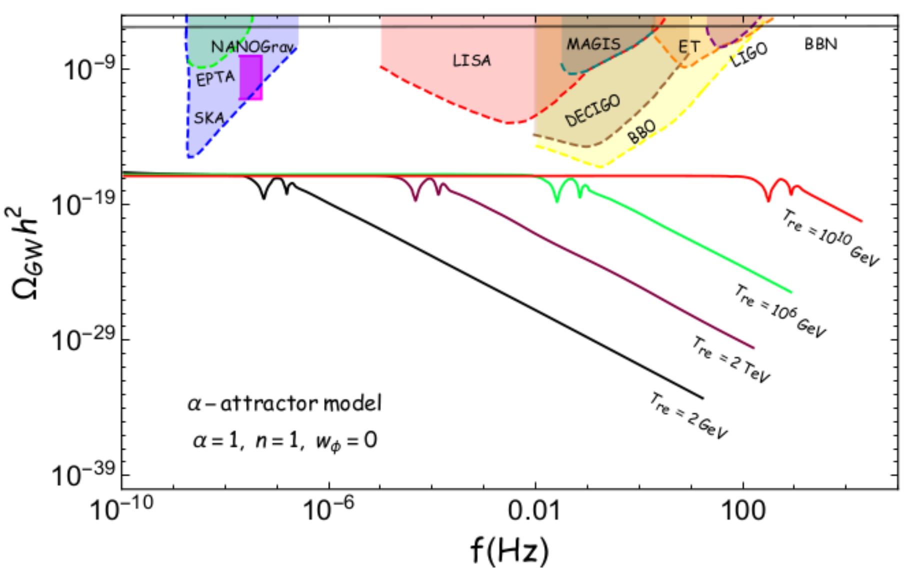

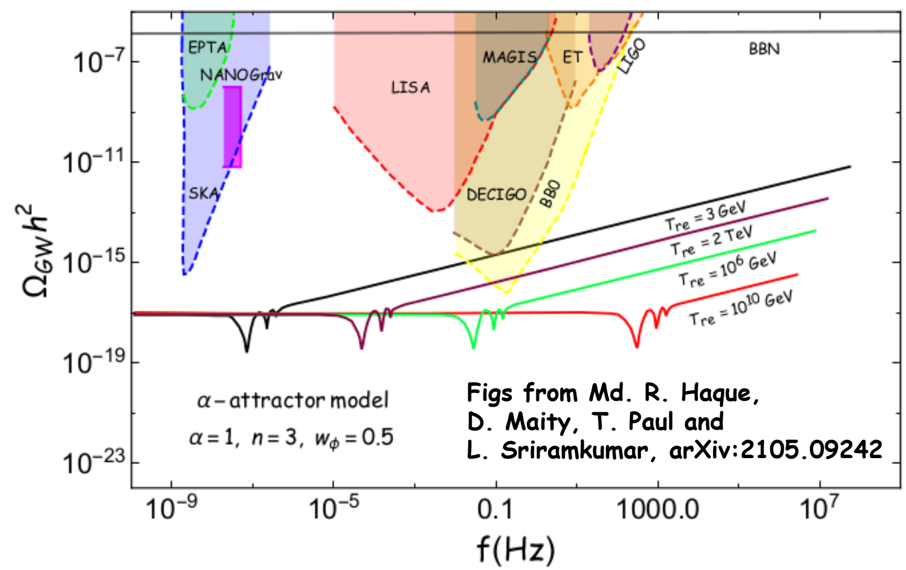

Figs from Md. R. Haque, D. Maity, T. Paul and L. Sriramkumar, arXiv:2105.09242

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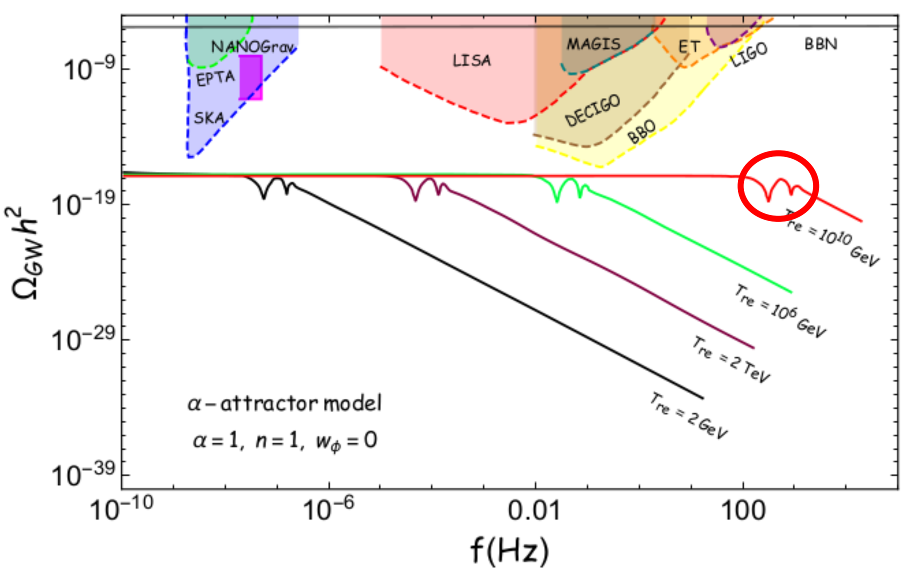

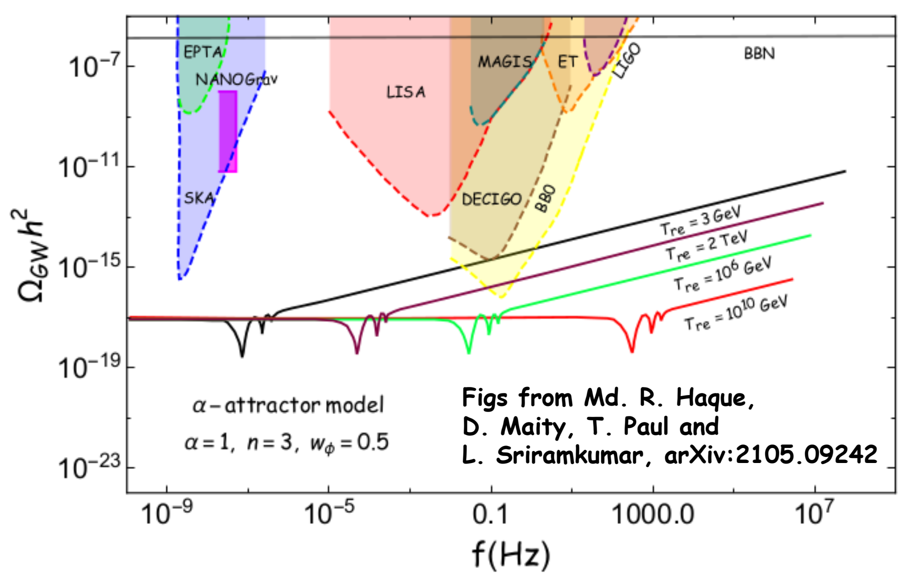

- What can be learned from a detection ?

❑ Reheating temperature

1- the presence of a "quantum" GW background from inflation

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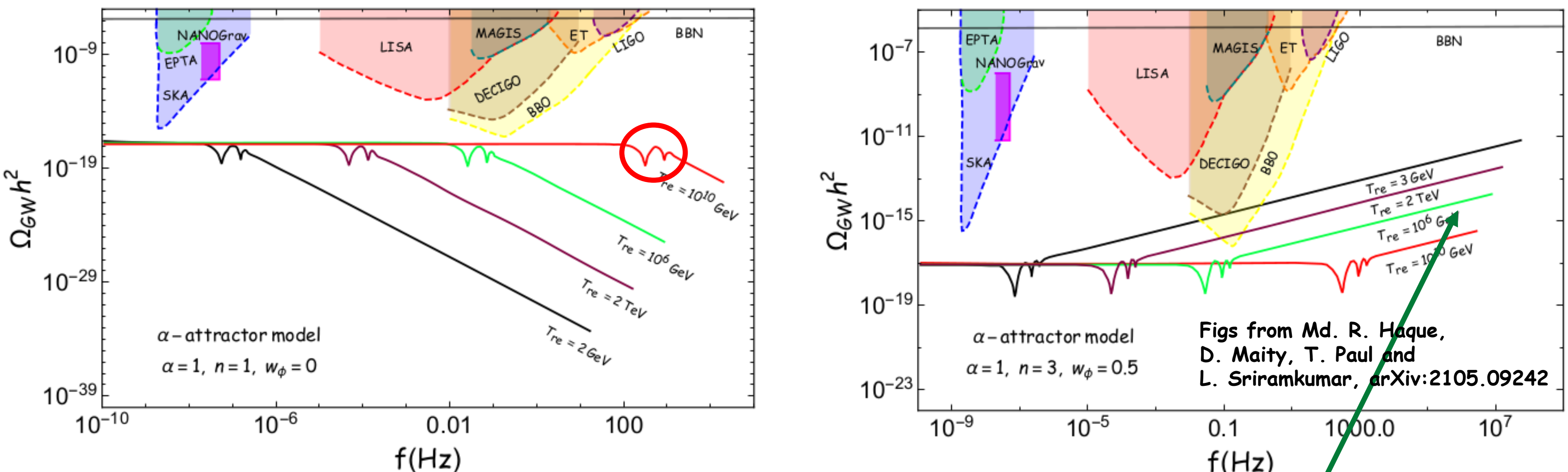

- What can be learned from a detection ?

- ❑ Reheating temperature
- ❑ Equation of state during reheating

$$n_{\rm GW} = -2\frac{1-3w_\phi}{1+3w_\phi}$$

2- the presence of a GW background from background preheating

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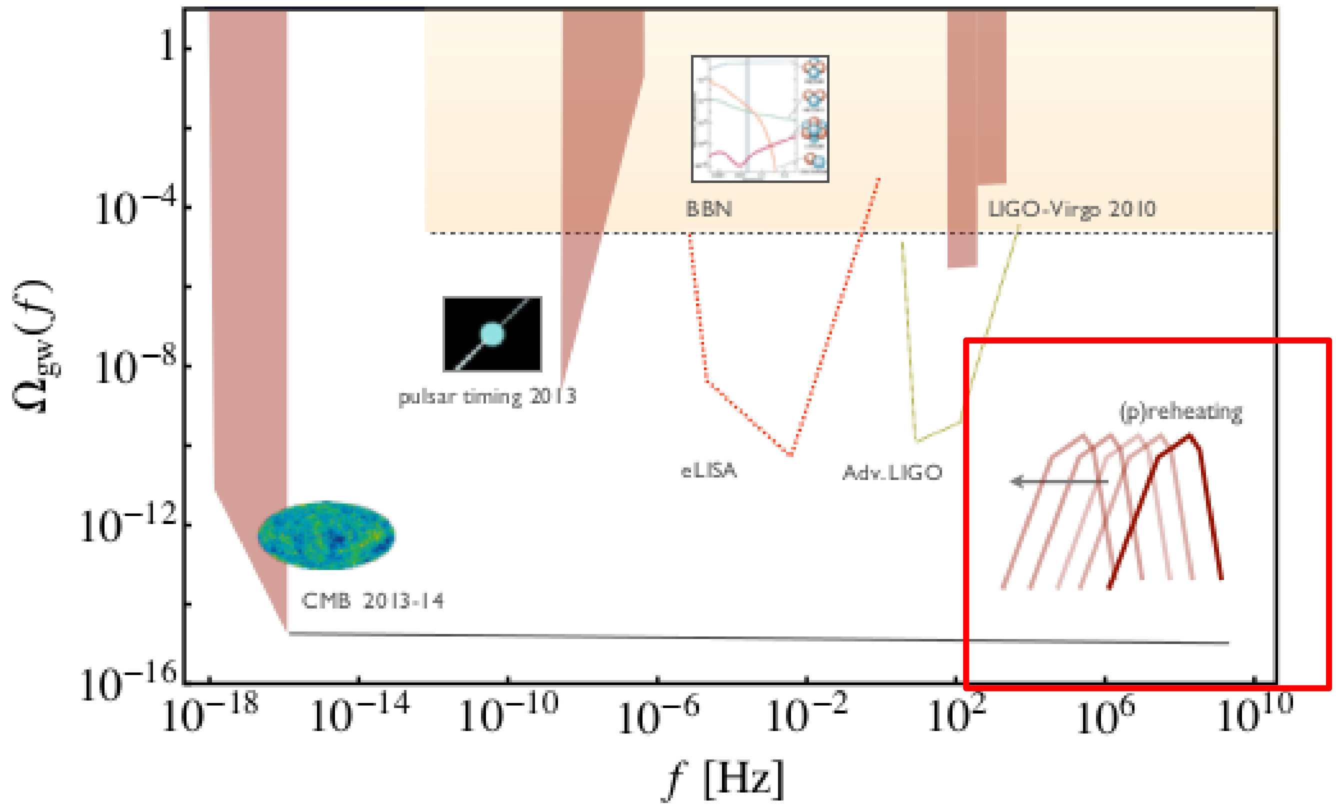

J.F. Dufaux, arXiv:1209.4024

D. Figueroa & F. Torrenti, arXiv:1707.04533

3- GW and ultra-lights PBHs from metric preheating

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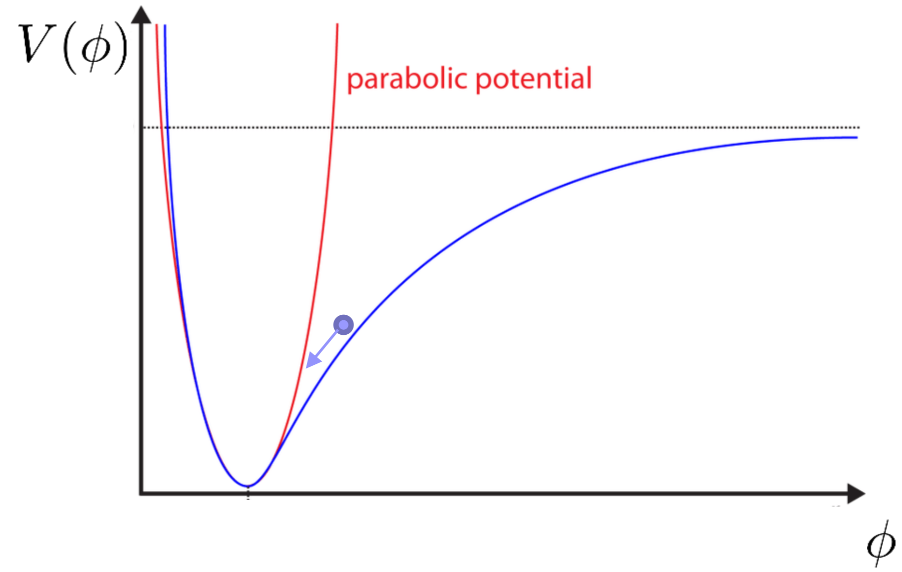
$$V(\phi) = \frac{1}{2}m^2\phi^2 + \cdots$$



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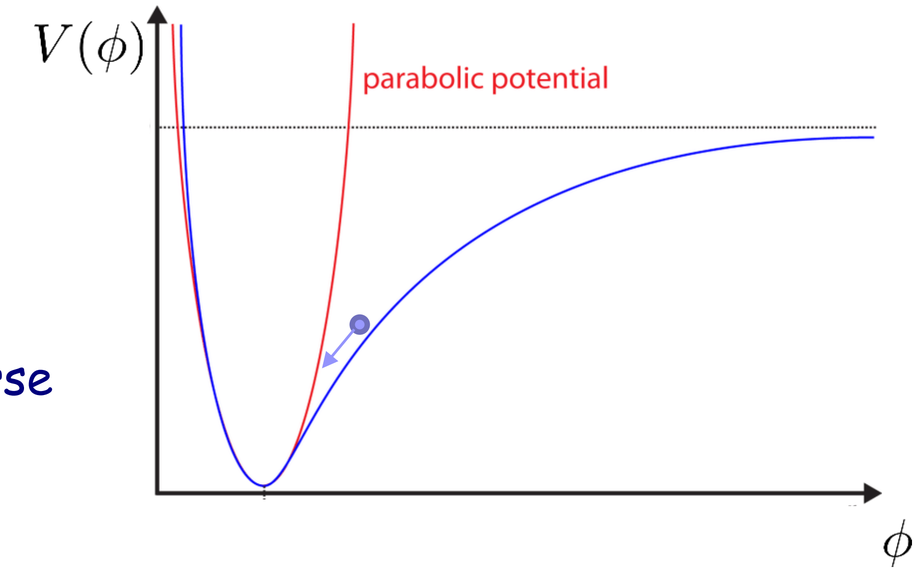

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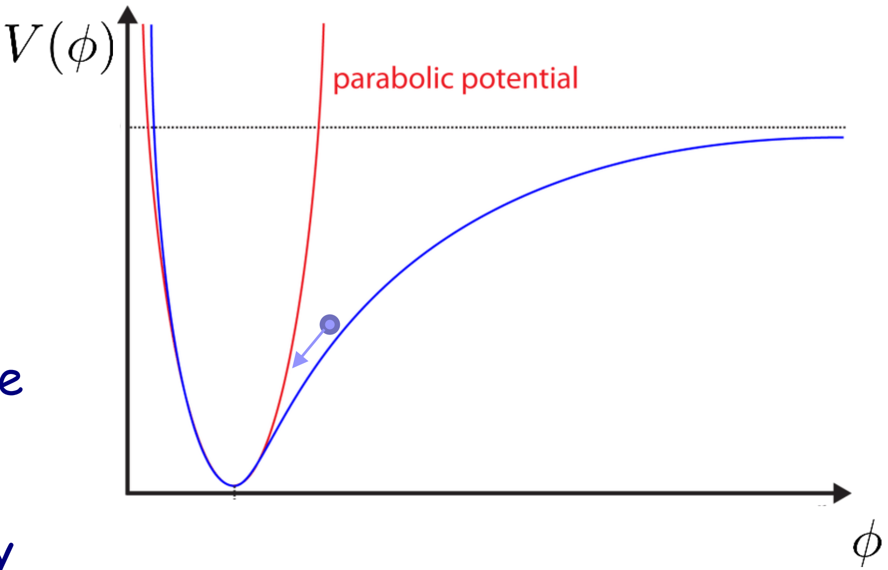

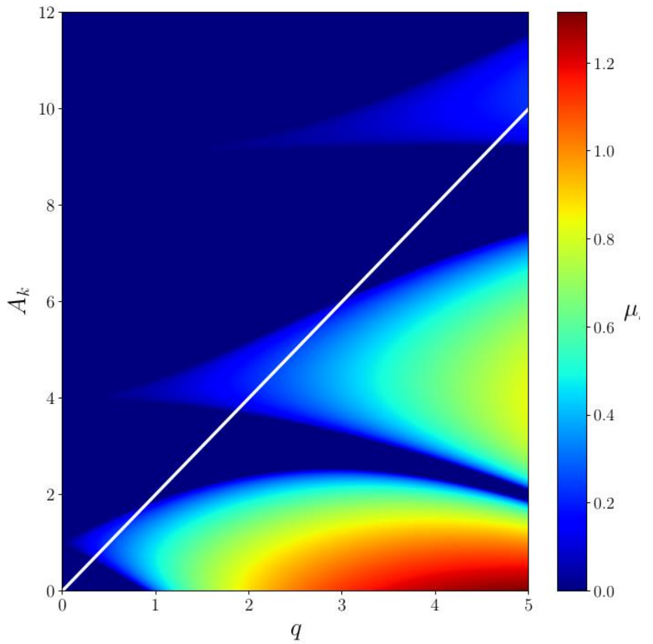

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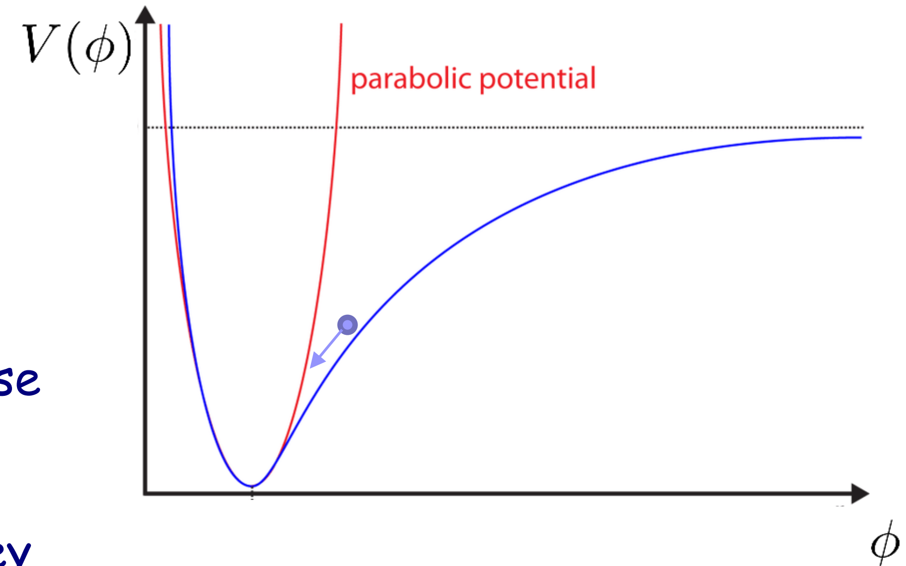
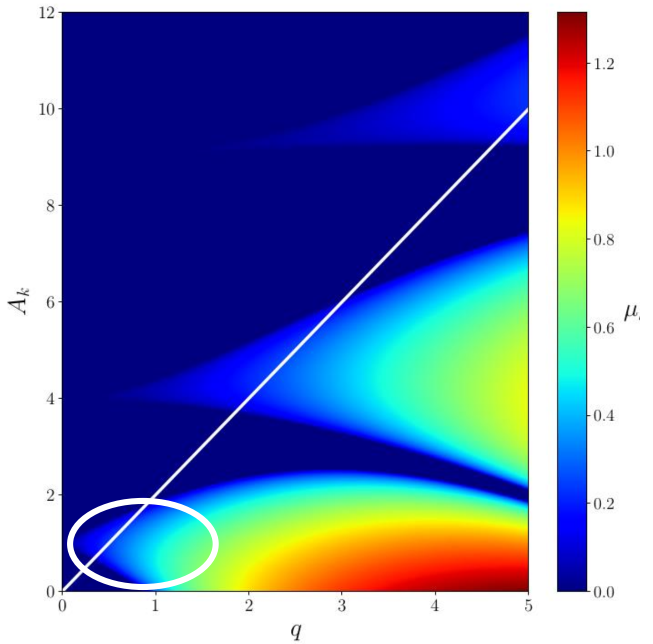
- During this phase, perturbations obey a Mathieu equation. Modes in the first instability band, ie

$$0 < \frac{k}{a} < \sqrt{3Hm}$$

undergo parametric reasonance and the density contrast grows like the scale factor, like a matter dominated Universe

K. Jedamzik, M. Lemoine, J. Martin, arXiv:1002.3039





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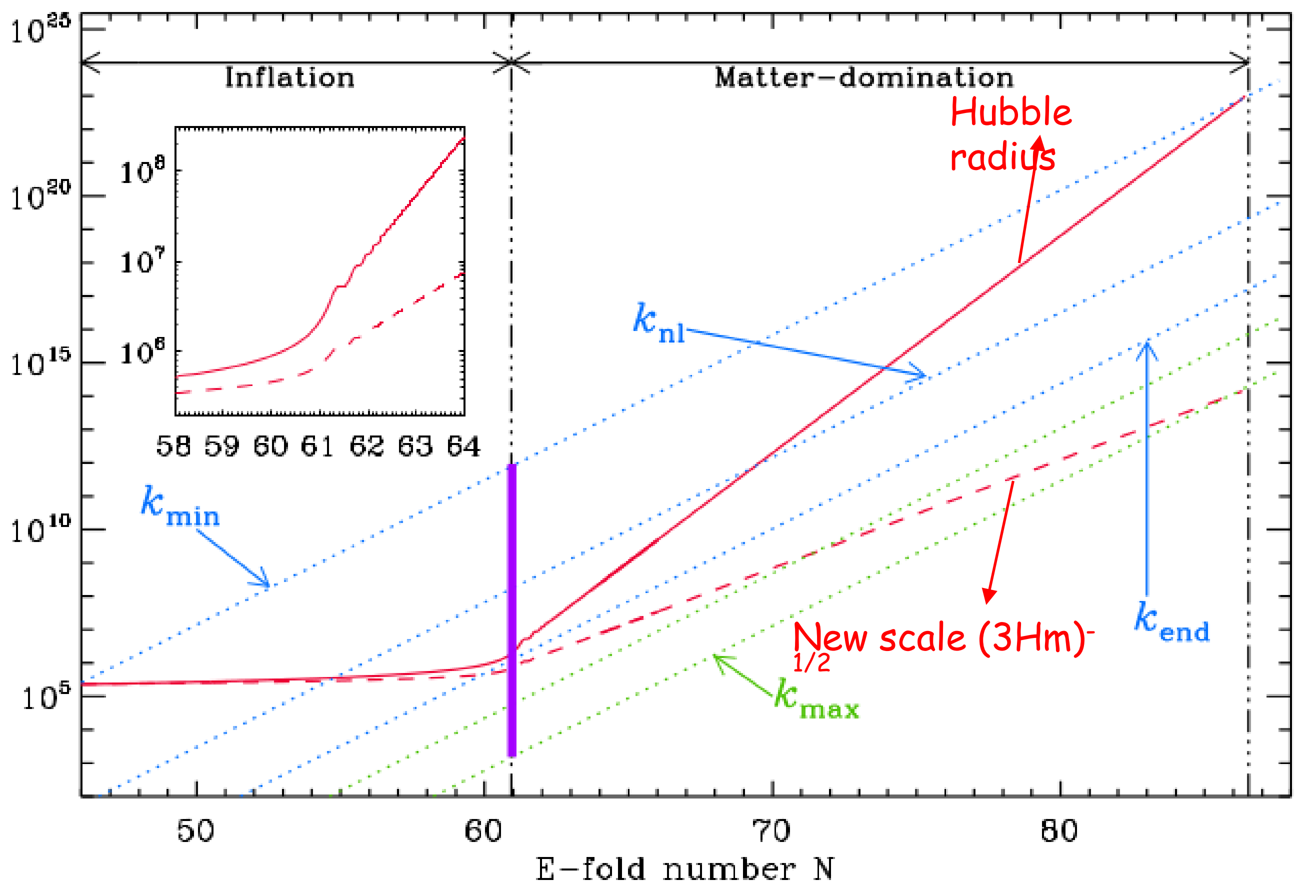

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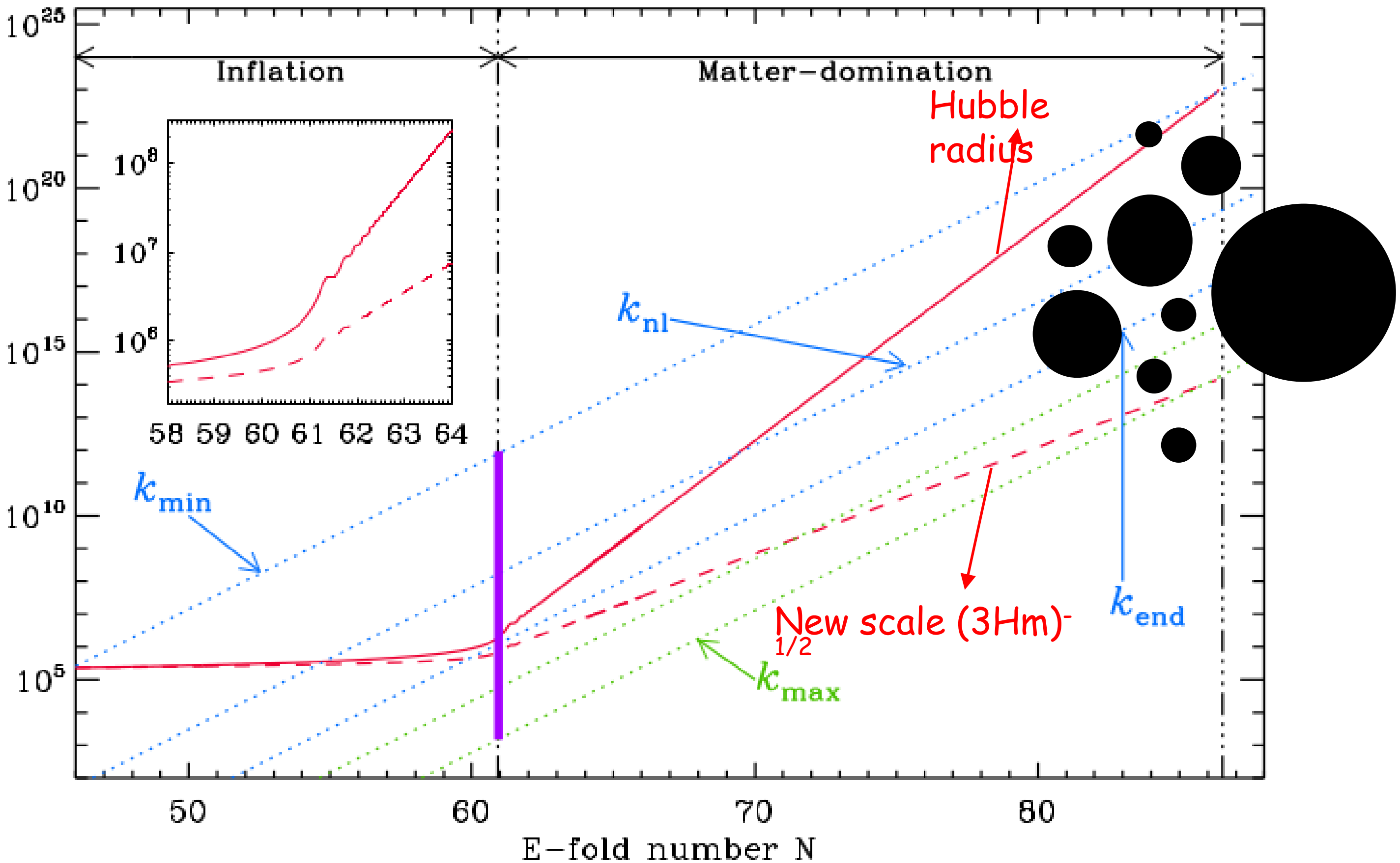

- Lead to the formation of ultra-light PBHs at the end of inflation

  J. Martin, T. Papanikolaou, V. Vennin, arXiv:1907.04236

- Remark: no need to "distord" the potential, USR, multifield etc …

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Recap

- Single field slow-roll (with canonical kinetic terms) models are solid, robust and fasifiable scenarios of the early Universe

- They have made predictions (ie not postdictions) that fit well the data

- There are still open issues, eg how to understand (single field) inflation from a high energy point of view, reheating …

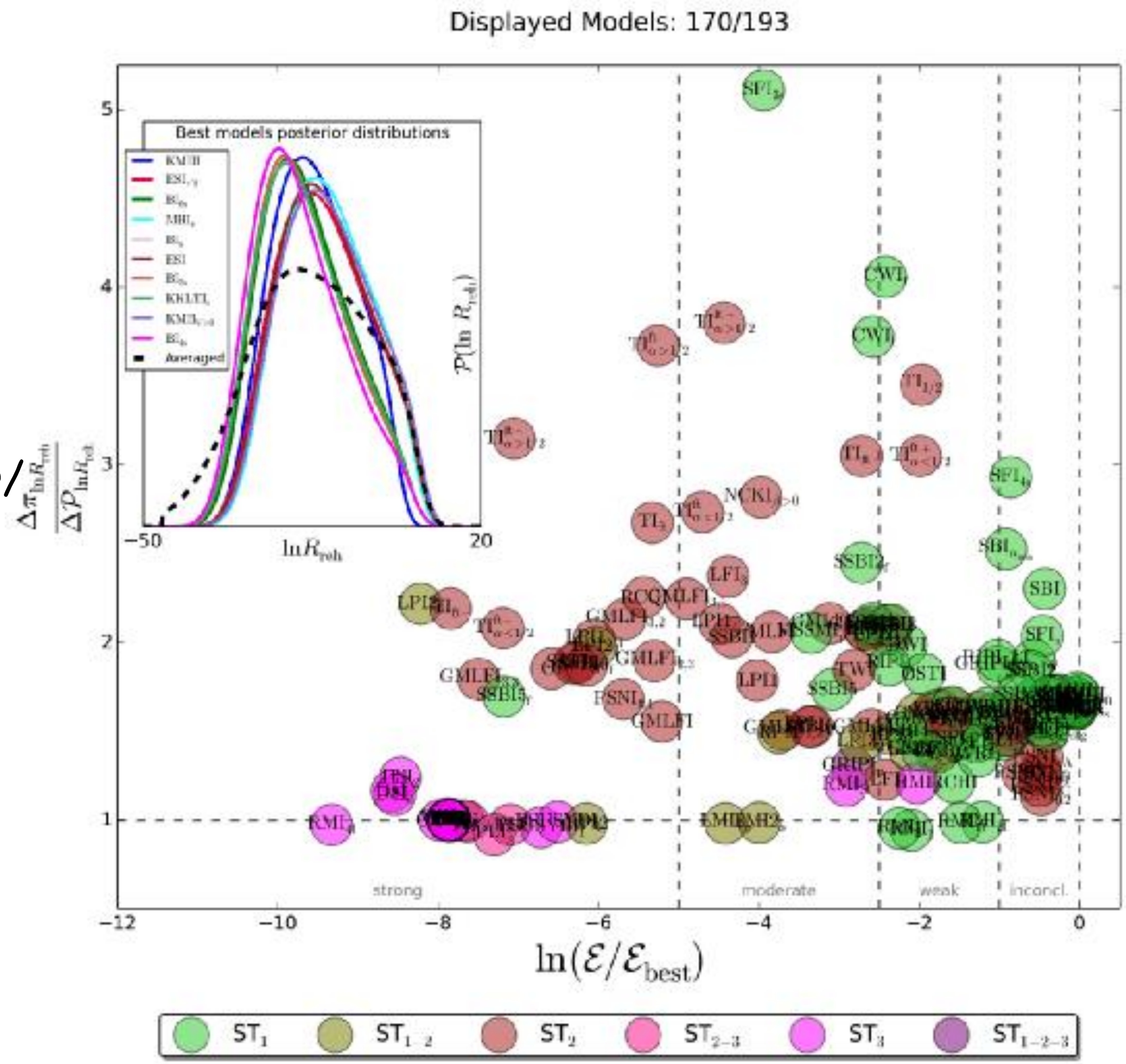
- There are still predictions that have not been verified, GW and PBHs

- Recently, many new interesting mechanisms for non-minimal inflation have been studied (multi-field inflation, inflation and gauge fields etc …)

- To see to which realizations of inflation we deal with, GW, PBHs and NG are keys

Planck 2013 constraints on reheating

Constraints on reheating (width of prior/ width of posterior>1)

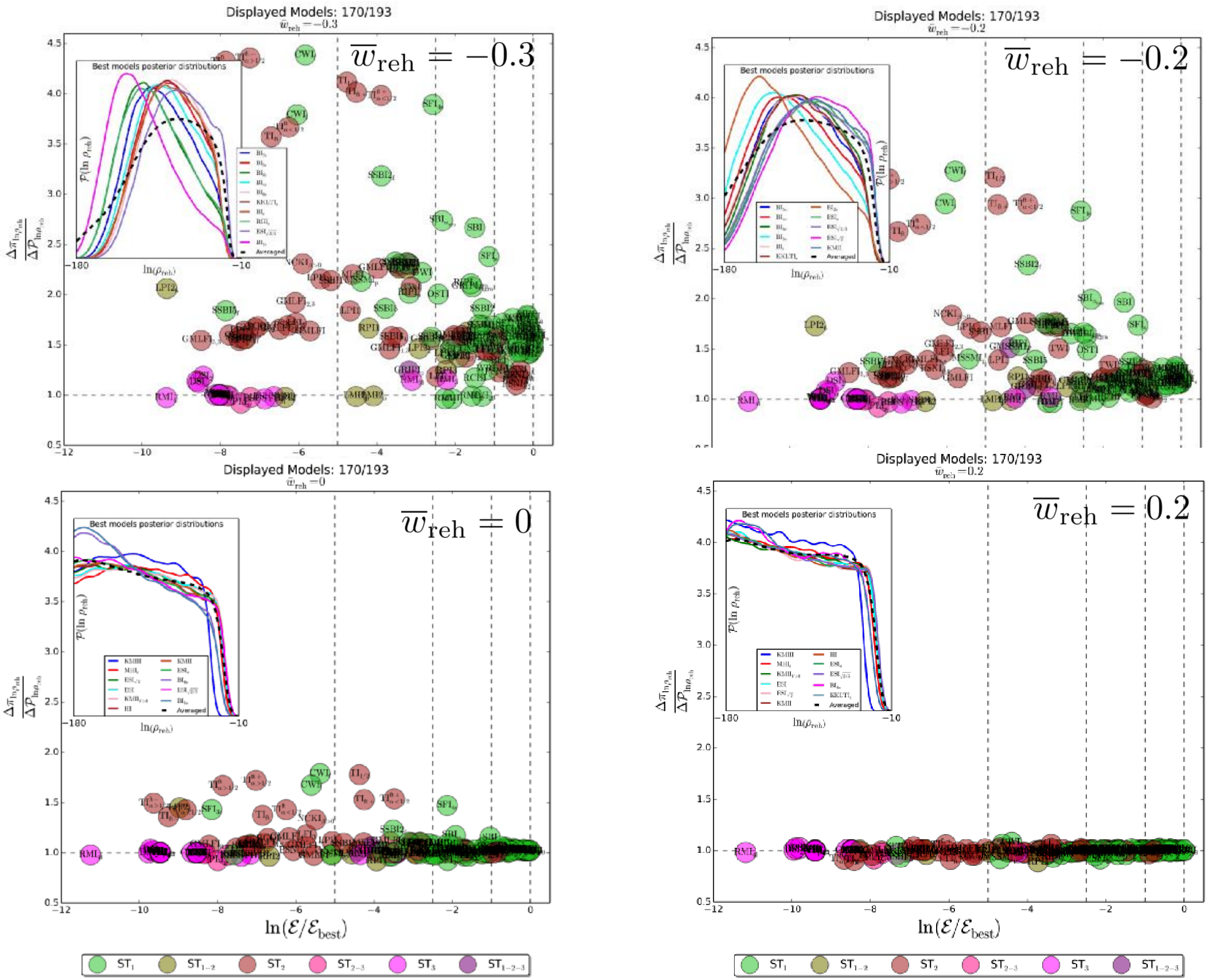


No constraint on reheating

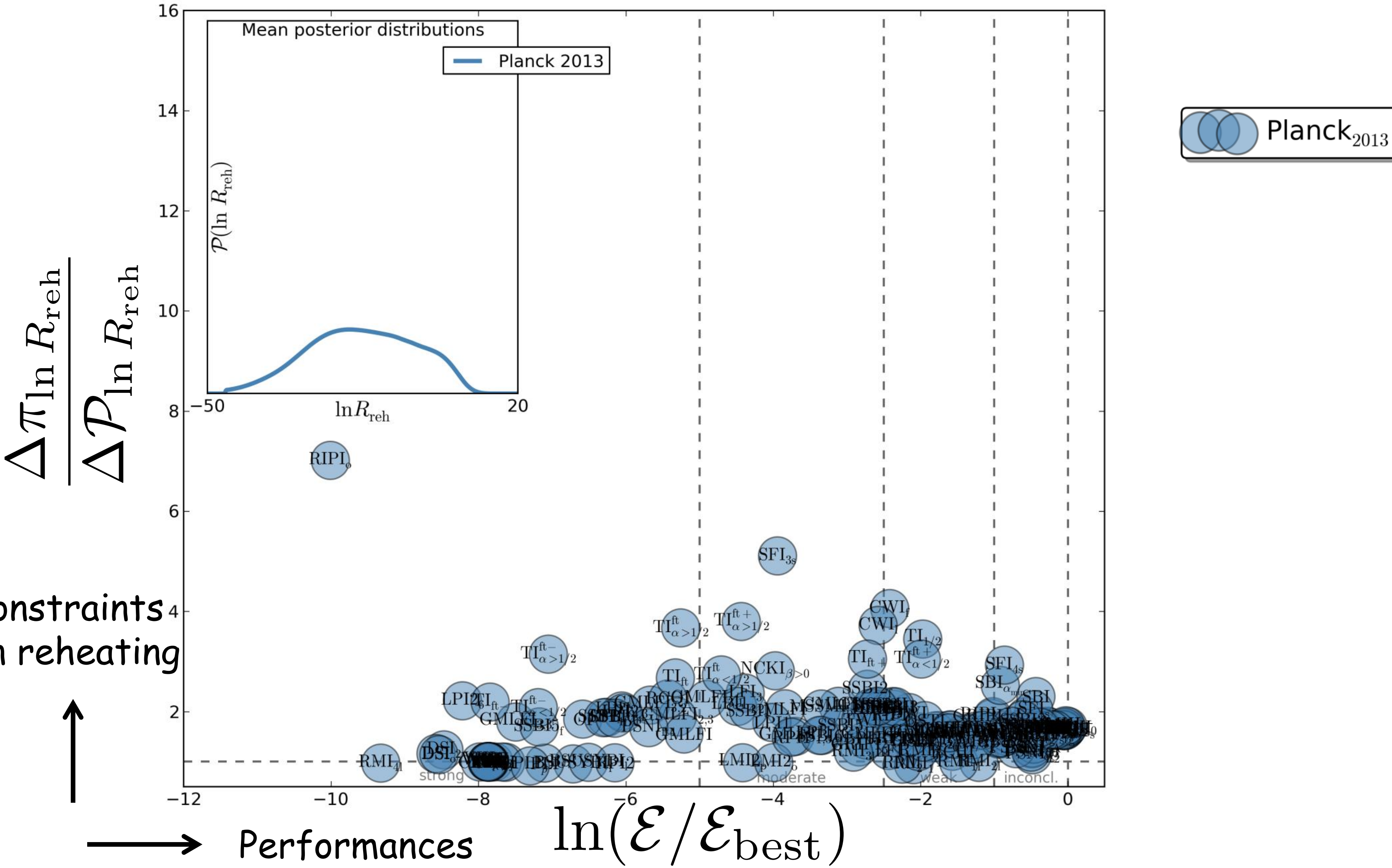
Model performance (Bayesian evidence)

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

Planck2013 constraints on reheating



Message 6: Significant improvement of the constraints of reheating



Constraints on reheating

Performances

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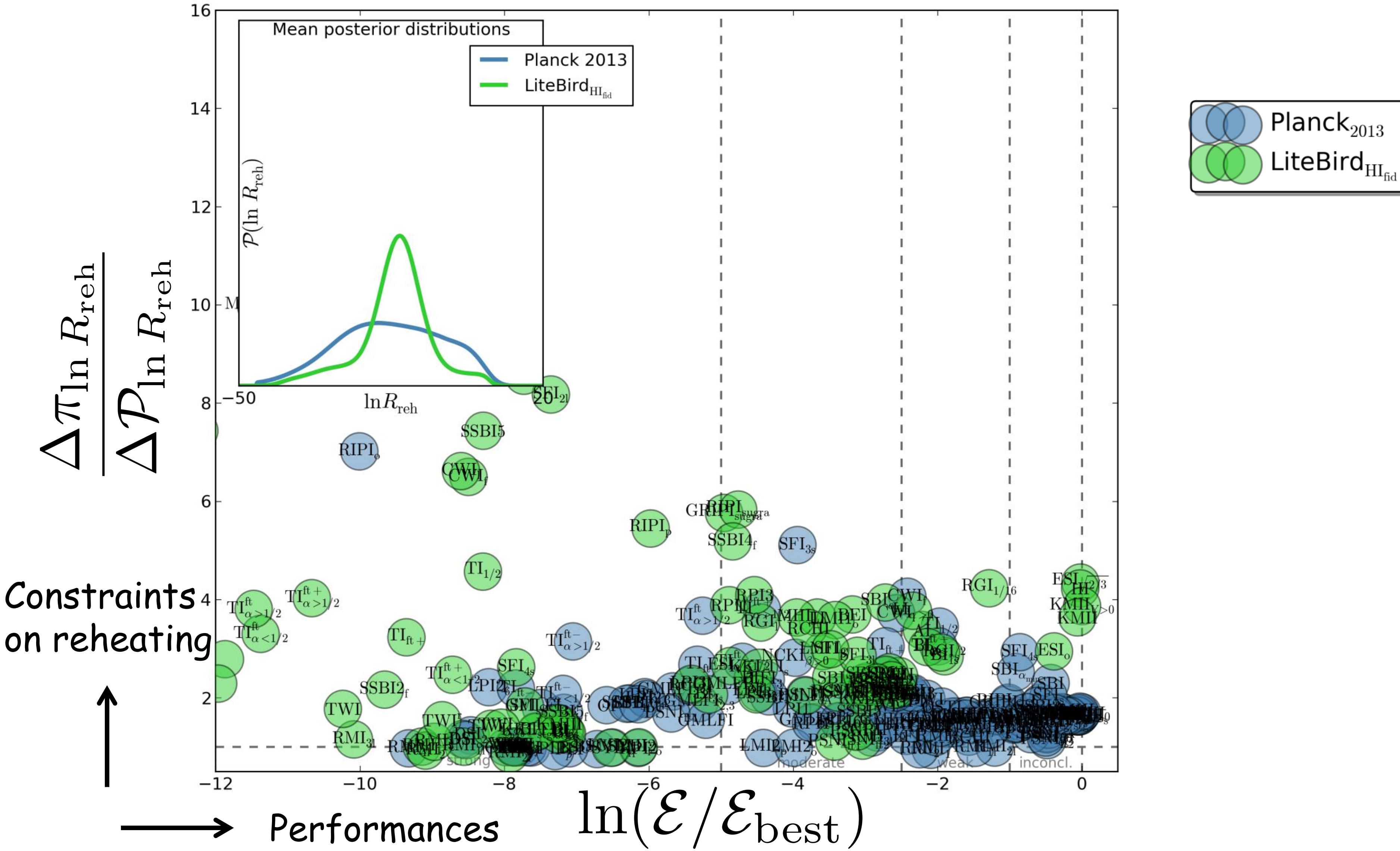

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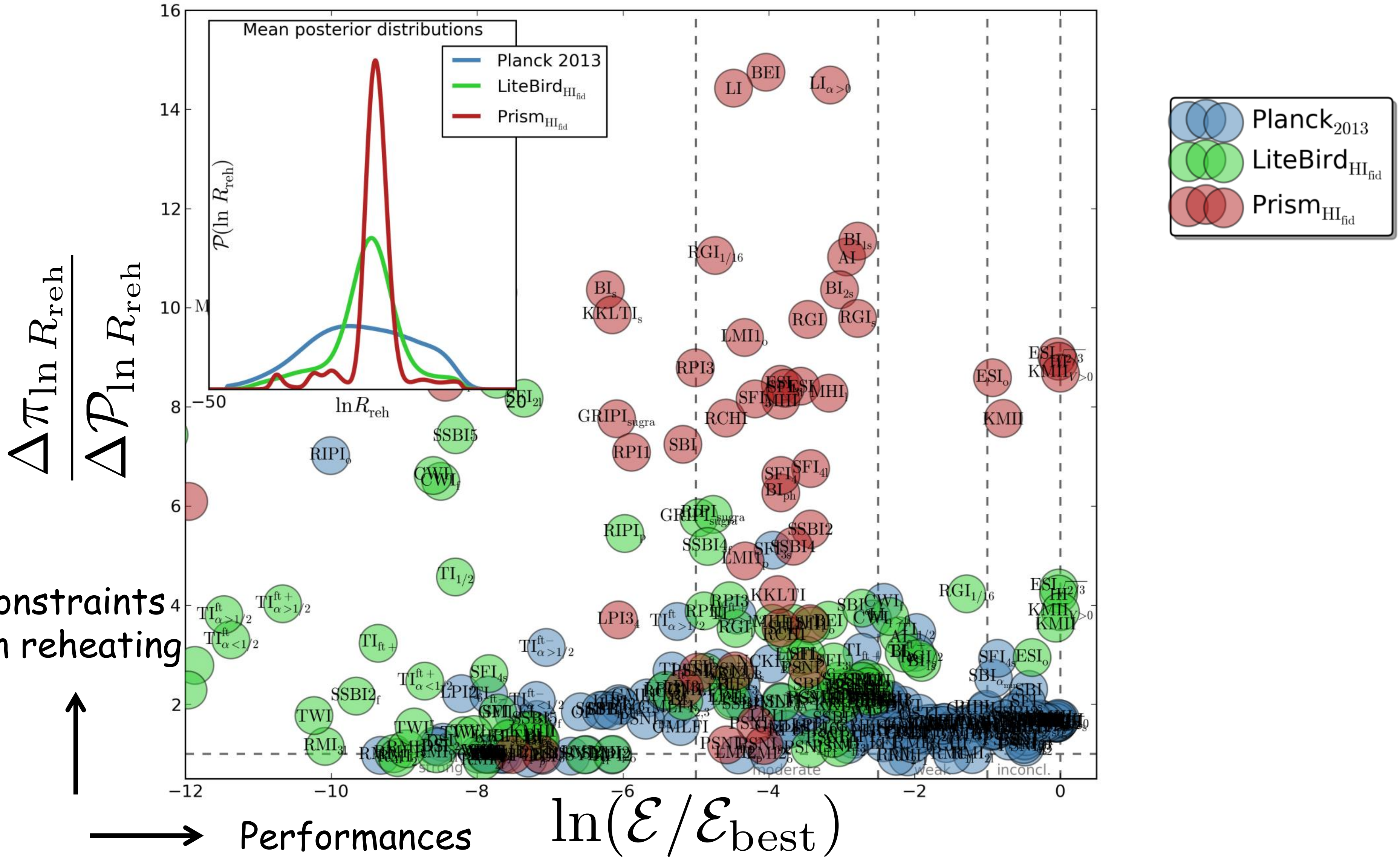

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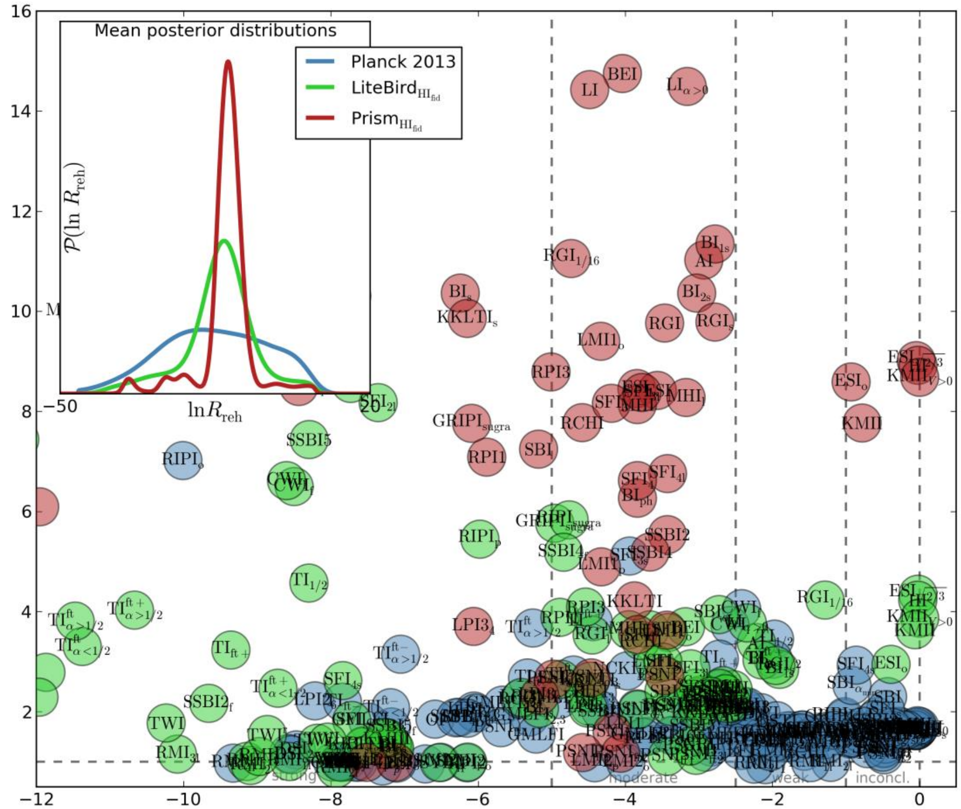


J. Martin, C. Ringeval and V. Vennin, Phys. Rev. Lett. 114 (2015) 8, 081303, arXiv:1410.7958

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

Planck 2013

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

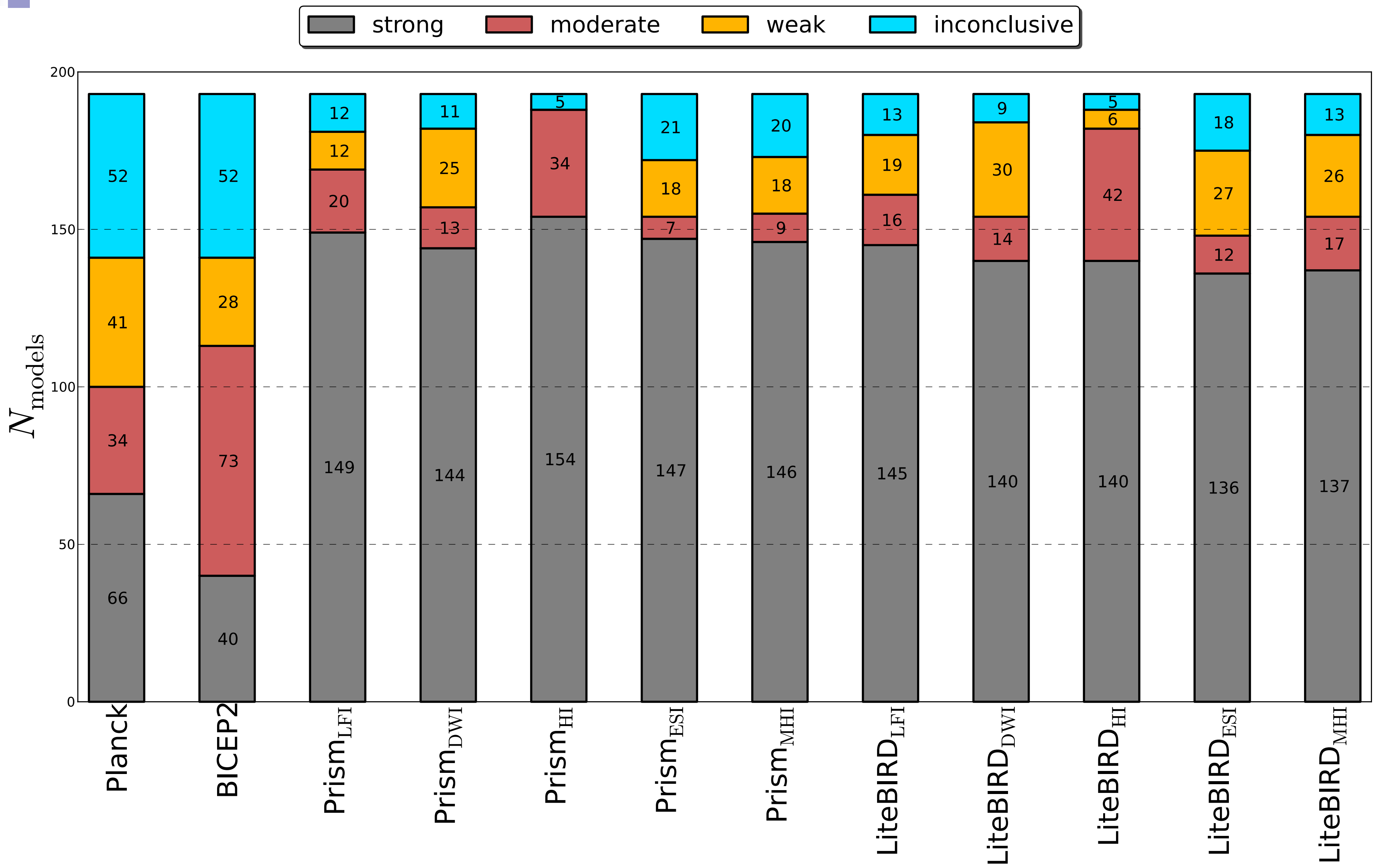
LiteBIRD HI

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

Prism HI

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

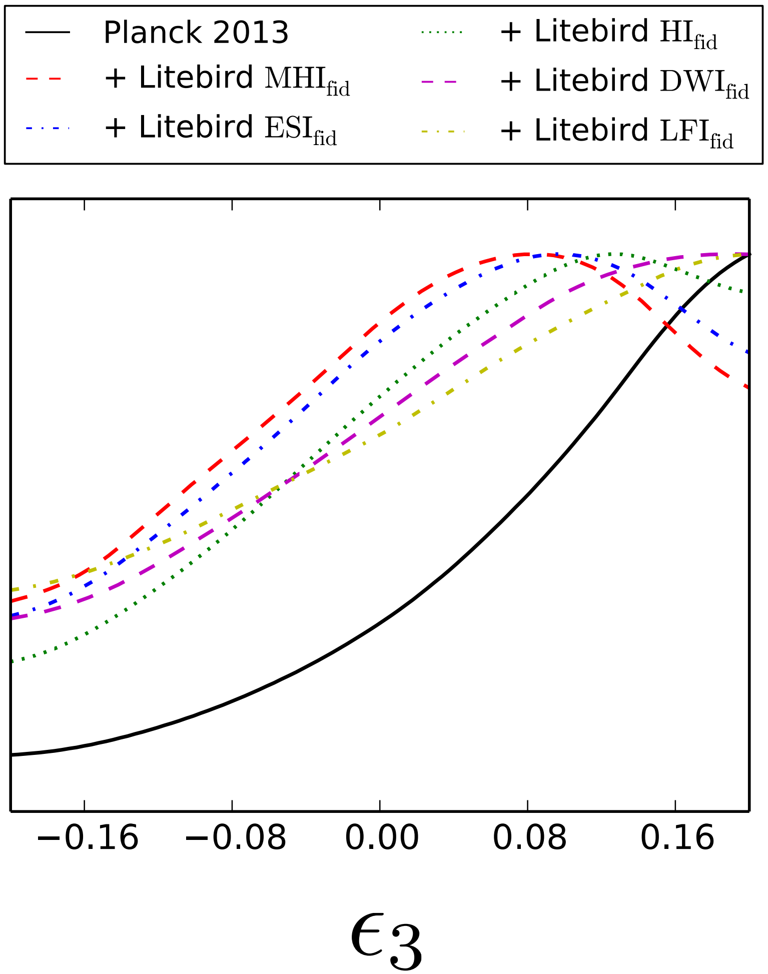
Consequences of a B-modes detection

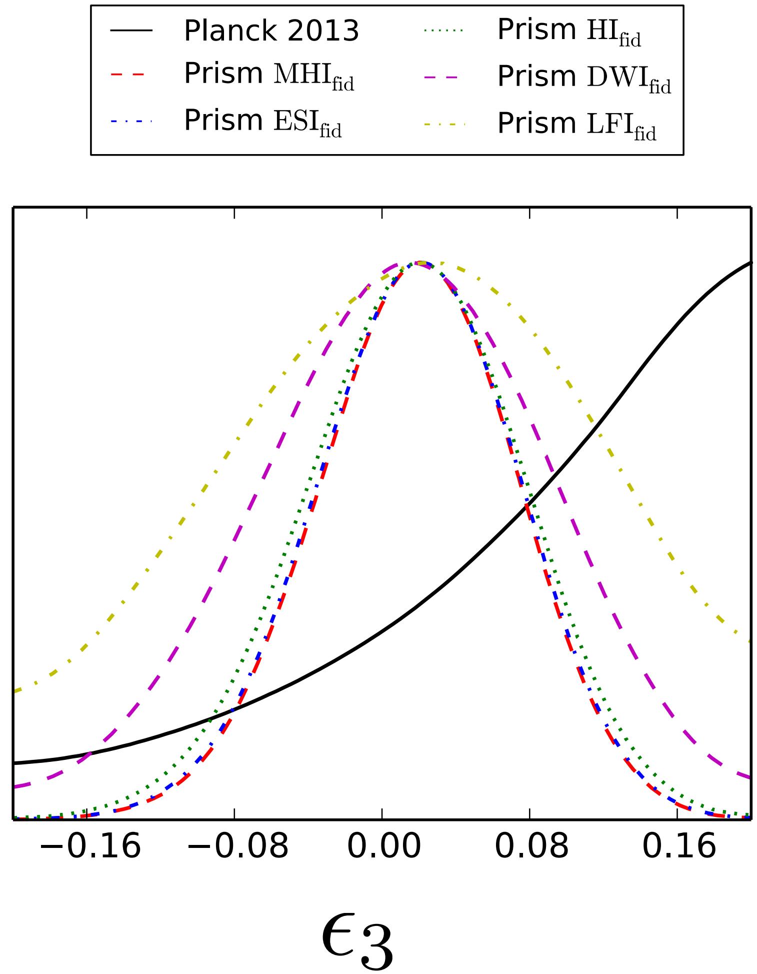


Planck: 1/3 of the models excluded; PRISM & LiteBIRD > 4/5

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

What is the best model of inflation?

- Even in the class of the simplest models, it remains hundreds of scenarios!

- In order to evaluate the performance of a model, one can compare its predictions to the data in the parameter space (n_{S}, r)

- But how can we compare the performance of models with each other?

- The performance of a model can be described by its Bayesian evidence which is the integral of the likelihood over prior space

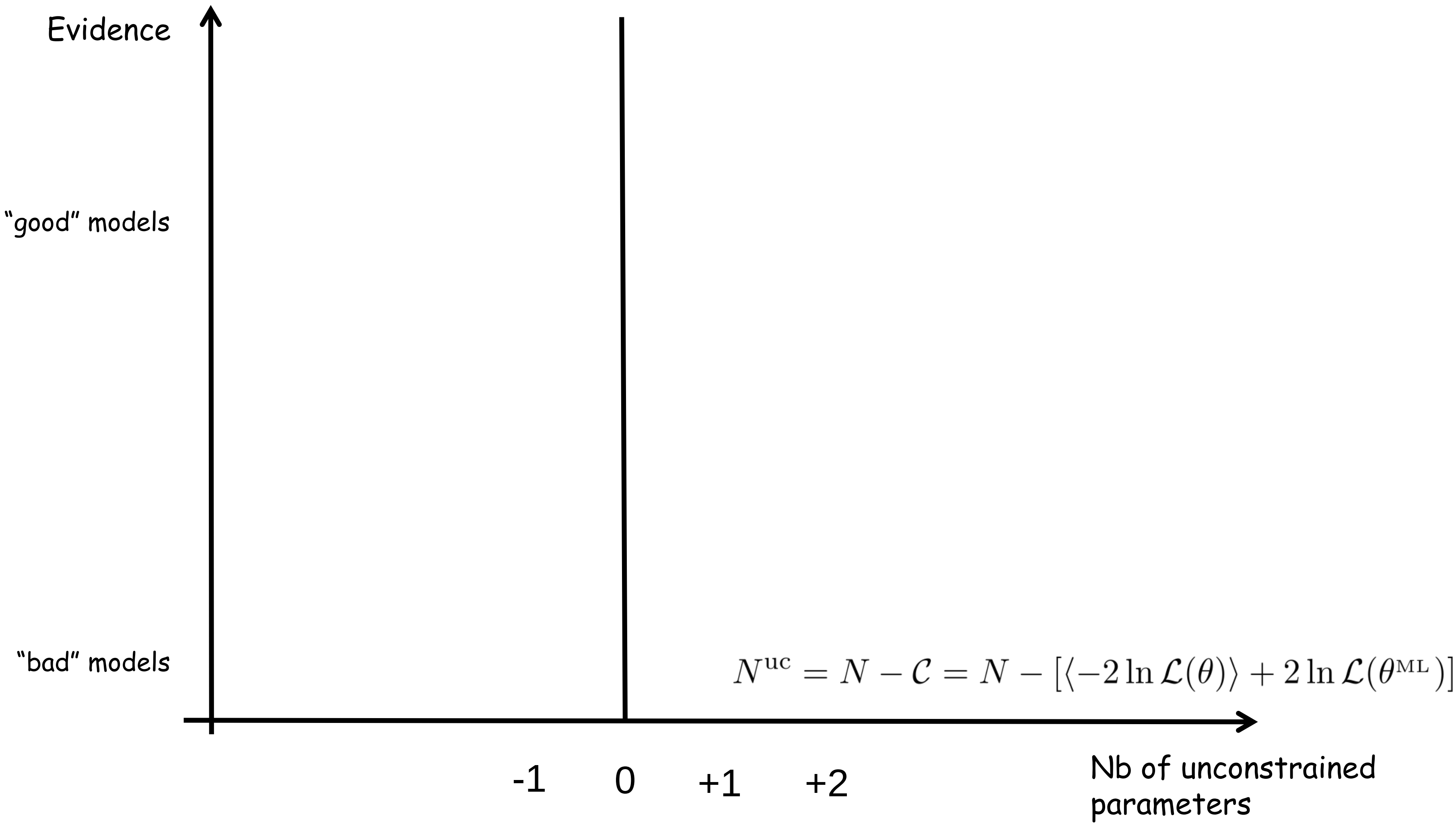
$$p\left(\mathcal{M}_i|\mathcal{D}\right) = \mathcal{E}\left(\mathcal{D}|\mathcal{M}_i\right)\pi\left(\mathcal{M}_i\right)$$

- Another number is needed in order to describe the performance of a model: the effective number of unconstrained parameters or Bayesian complexity

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

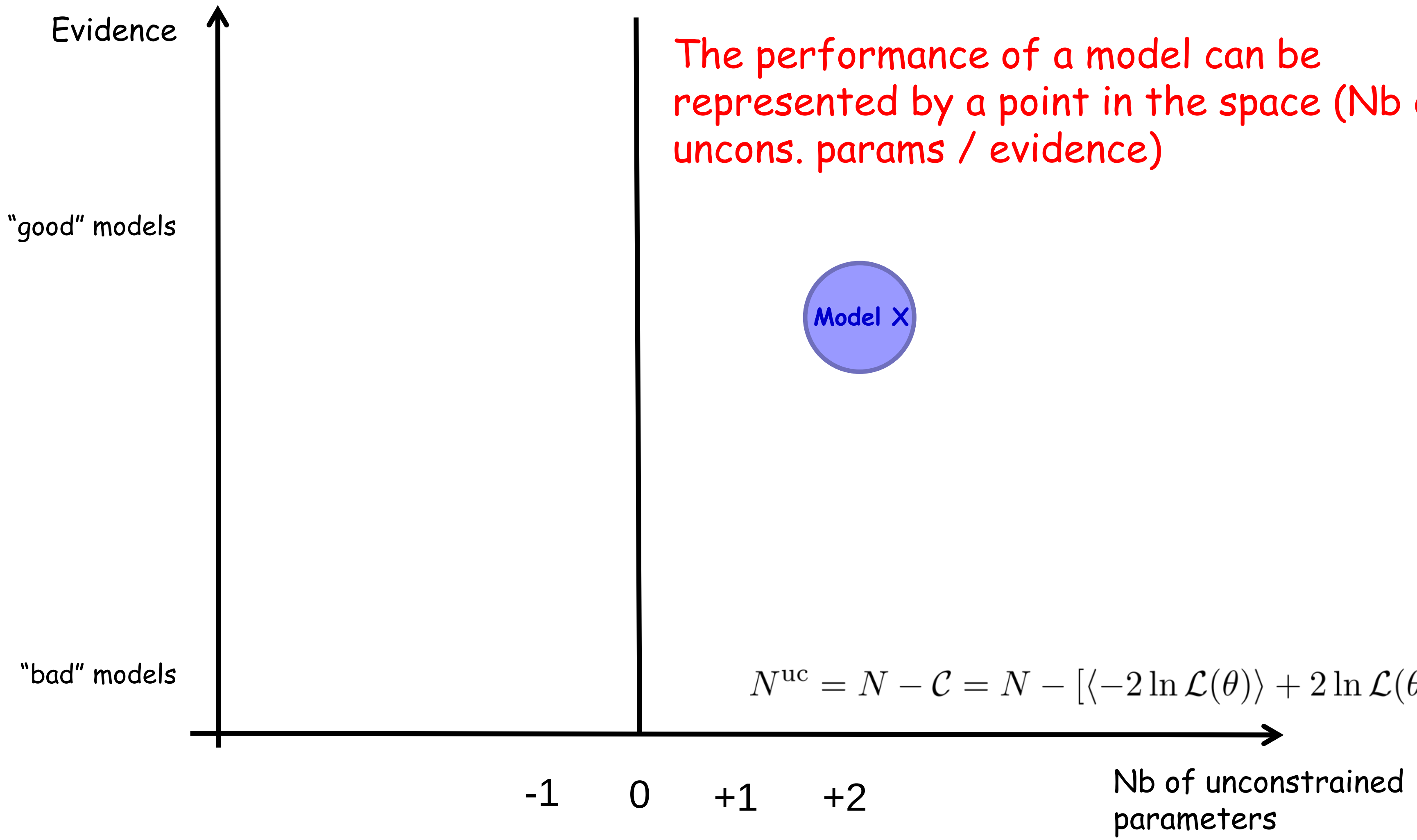
The performance of a model can be represented in the space (complexity,evidence)

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



The performance of a model can be represented in the space (complexity,evidence)

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

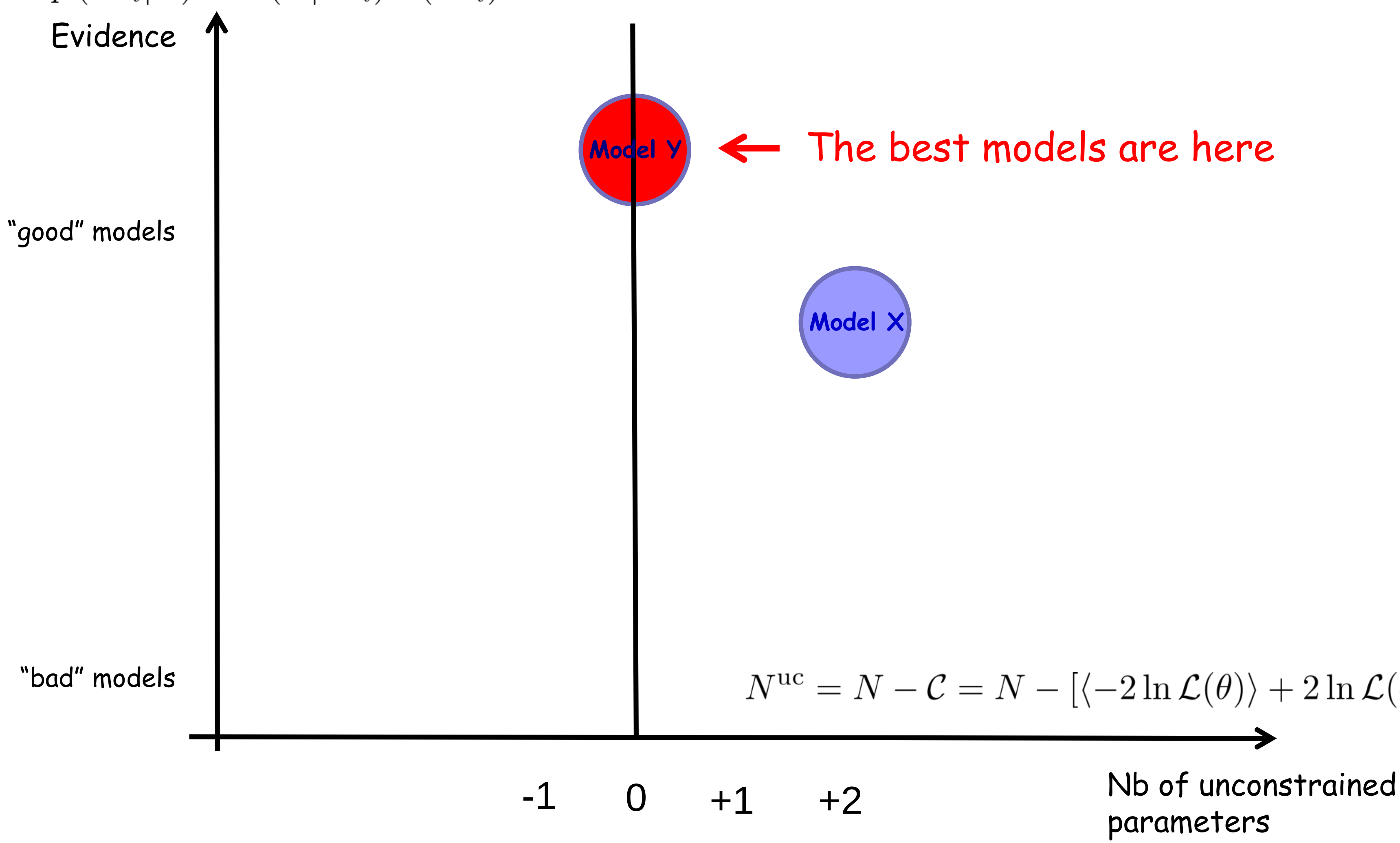


The performance of a model can be represented by a point in the space (Nb of uncons. params / evidence)

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

The performance of a model can be represented in the space (complexity,evidence)

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



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

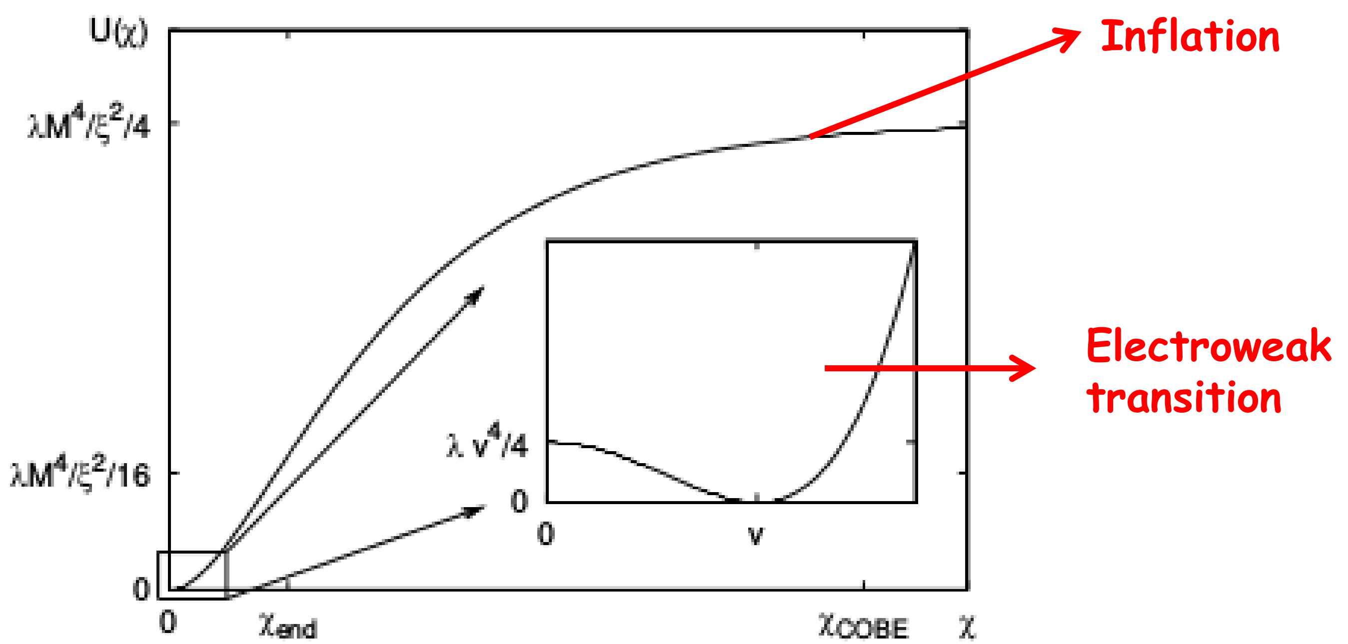
Can the inflaton field be the Higgs boson?

$$\mathcal{L}_{\rm tot} = \mathcal{L}_{\rm SM} - \frac{M_{\rm Pl}^2}{2} R - \xi H^\dagger H R$$

↑ Standard model of particle physics

↑ Gravity

↑ Non-minimal coupling



Constraints on reheating temperature: examples

Small field inflation

$$\rho_{\rm reh}^{1/4} > 400\,\mathrm{TeV} \qquad \overline{w}_{\rm reh} = -0.3$$

$$\rho_{\rm reh}^{1/4} > 90\,\mathrm{TeV} \qquad \overline{w}_{\rm reh} = -0.2$$

Loop inflation

$$\rho_{\rm reh}^{1/4} < 1.8 \times 10^{7}\,\mathrm{TeV} \qquad \overline{w}_{\rm reh} = -0.3$$

$$\rho_{\rm reh}^{1/4} < 6.5 \times 10^{7}\,\mathrm{TeV} \qquad \overline{w}_{\rm reh} = -0.2$$

$$\rho_{\rm reh}^{1/4} < 4 \times 10^{10}\,\mathrm{TeV} \qquad \overline{w}_{\rm reh} = 0$$