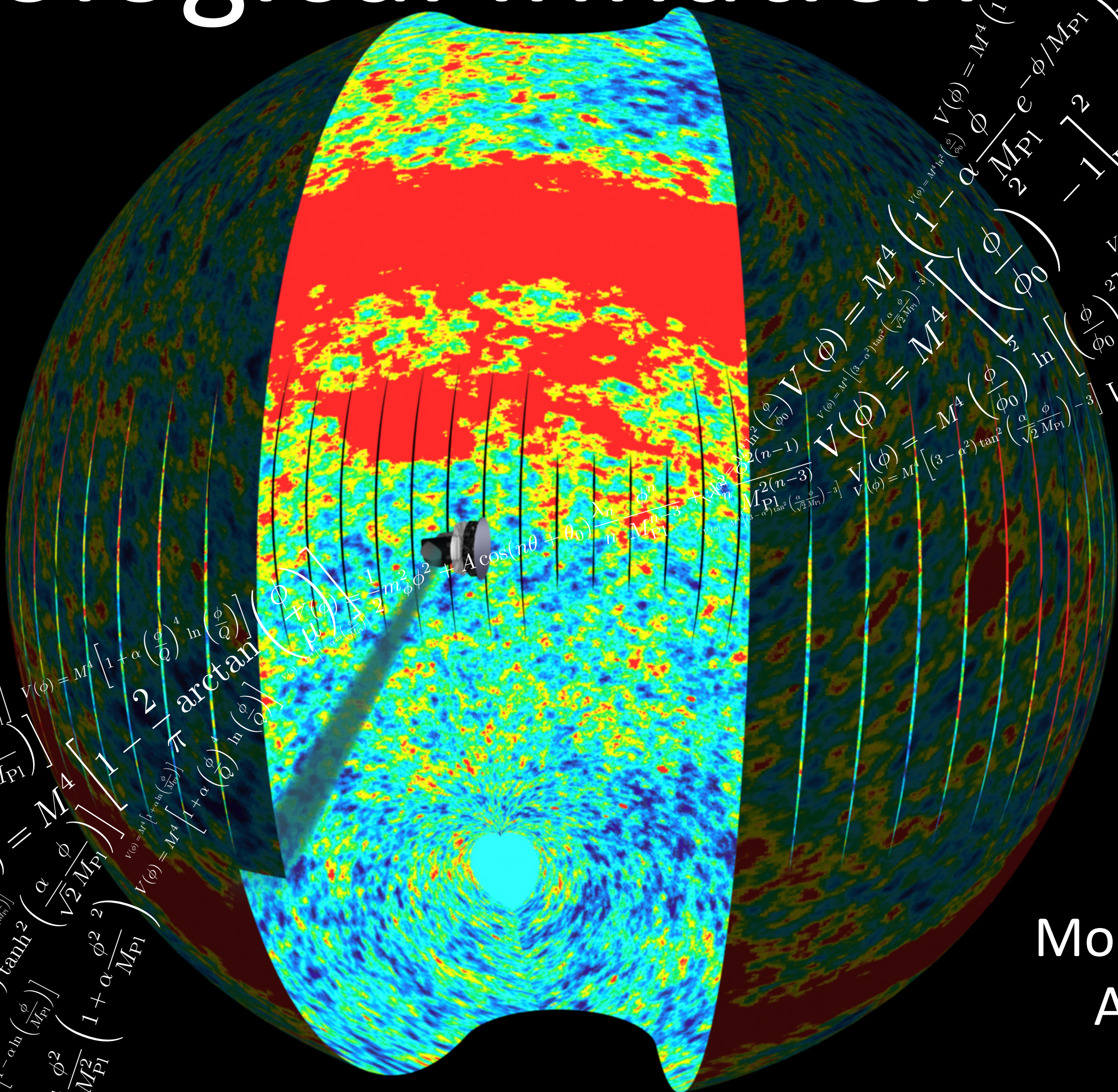
Cosmological Inflation

to the test



Montpellier L2C
April 7th 2016

Vincent Vennin, ICG Portsmouth

Outline

- Inflation: Where do we Stand?
- Bayesian Model Comparison for Single-Field Models
- Including (and constraining) Reheating
- Adding a Light Scalar Field

Collaborators:
Jérôme Martin (IAP), Christophe Ringeval (Louvain U. CP3), and Roberto Trotta (Imp.Coll)
David Wands (ICG), Kazuya Koyama (ICG)

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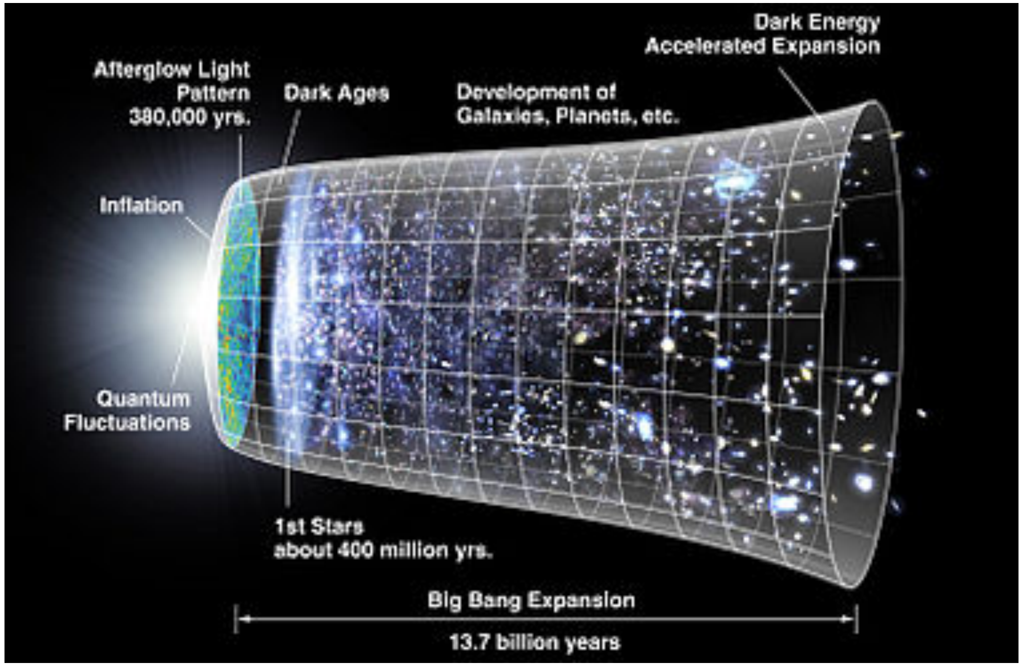

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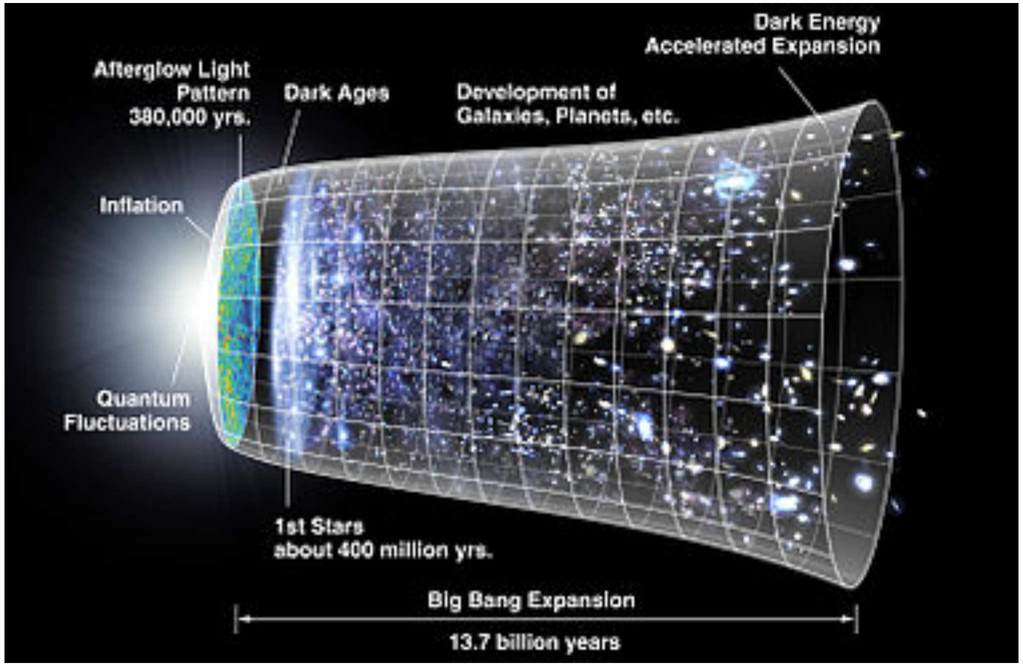

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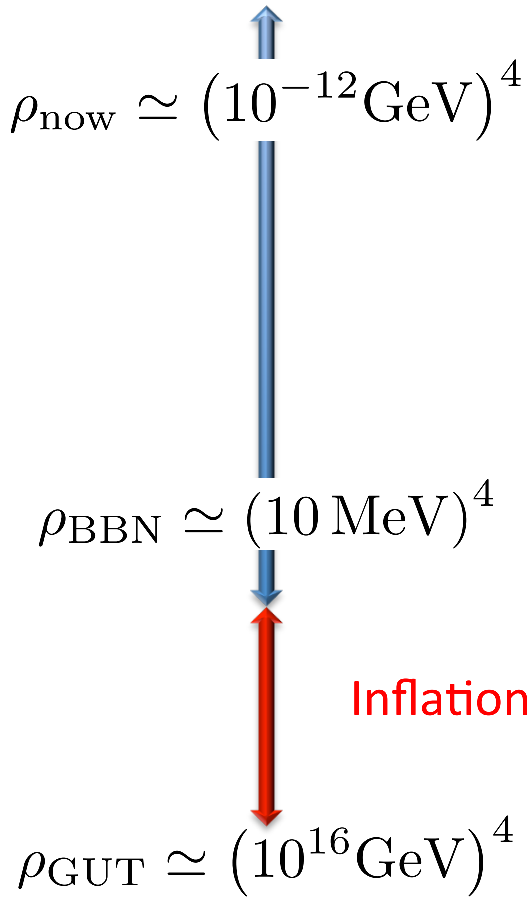

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- Combined with QM, accounts for the production of cosmological perturbations whose features depend on the underlying inflationary model.

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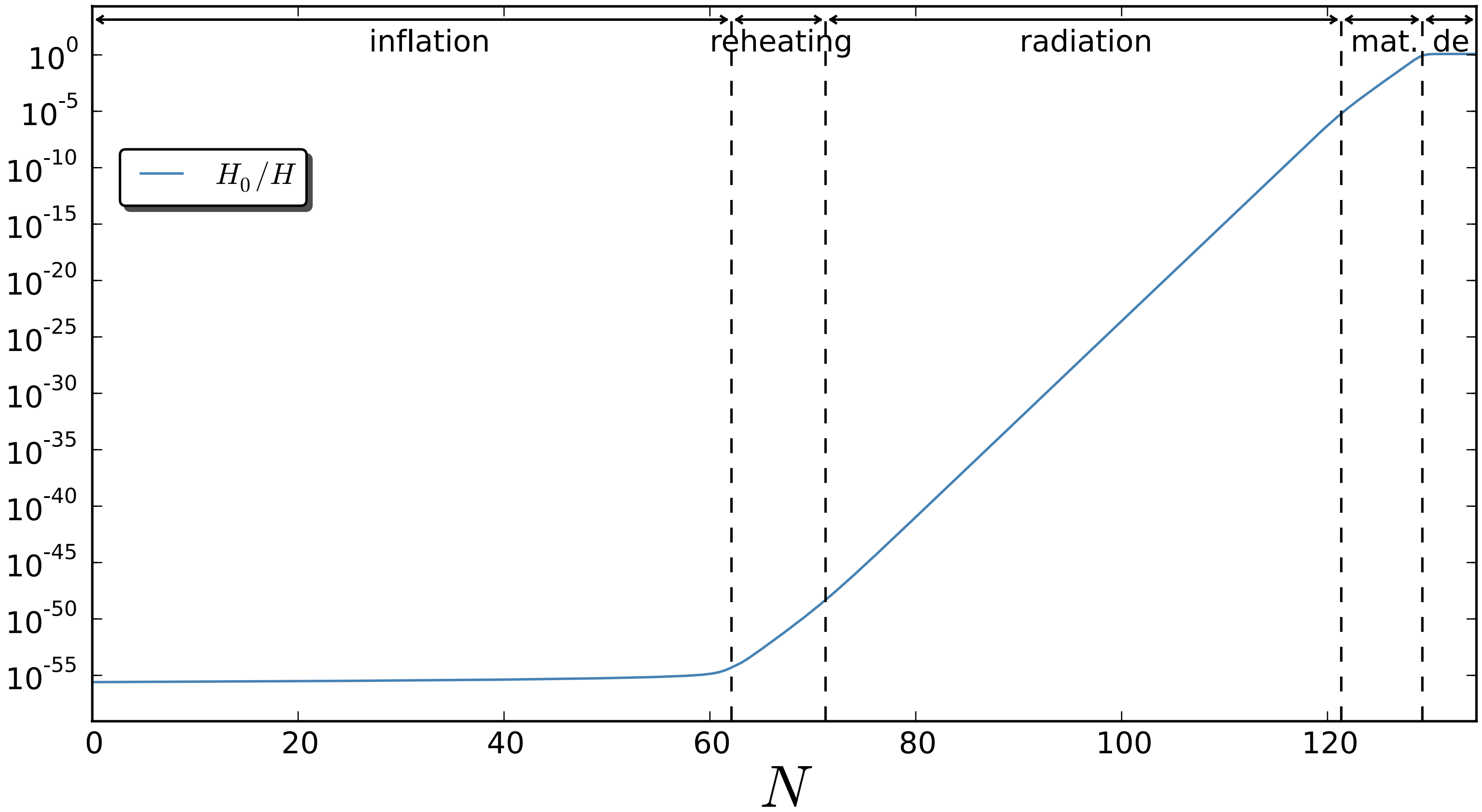

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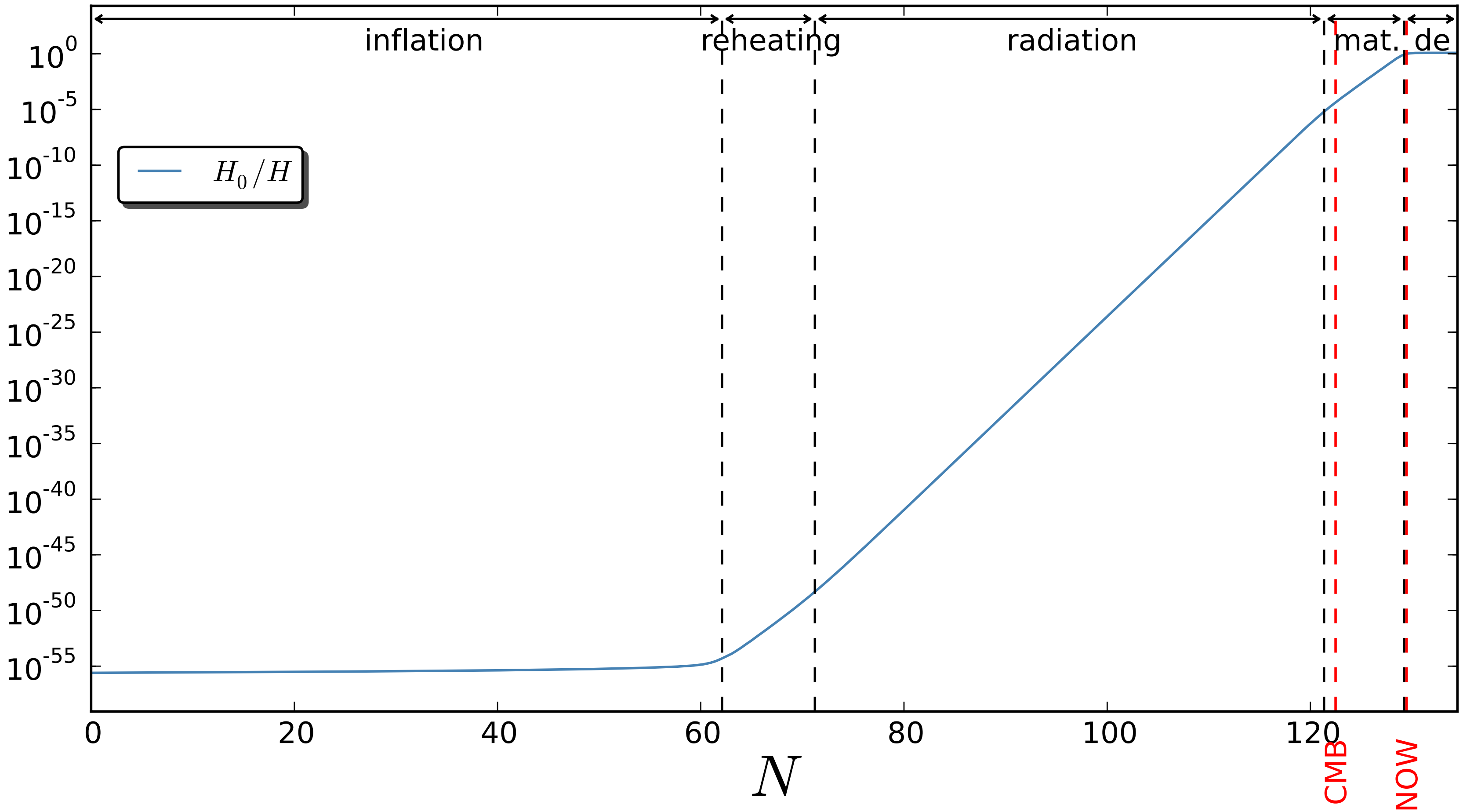

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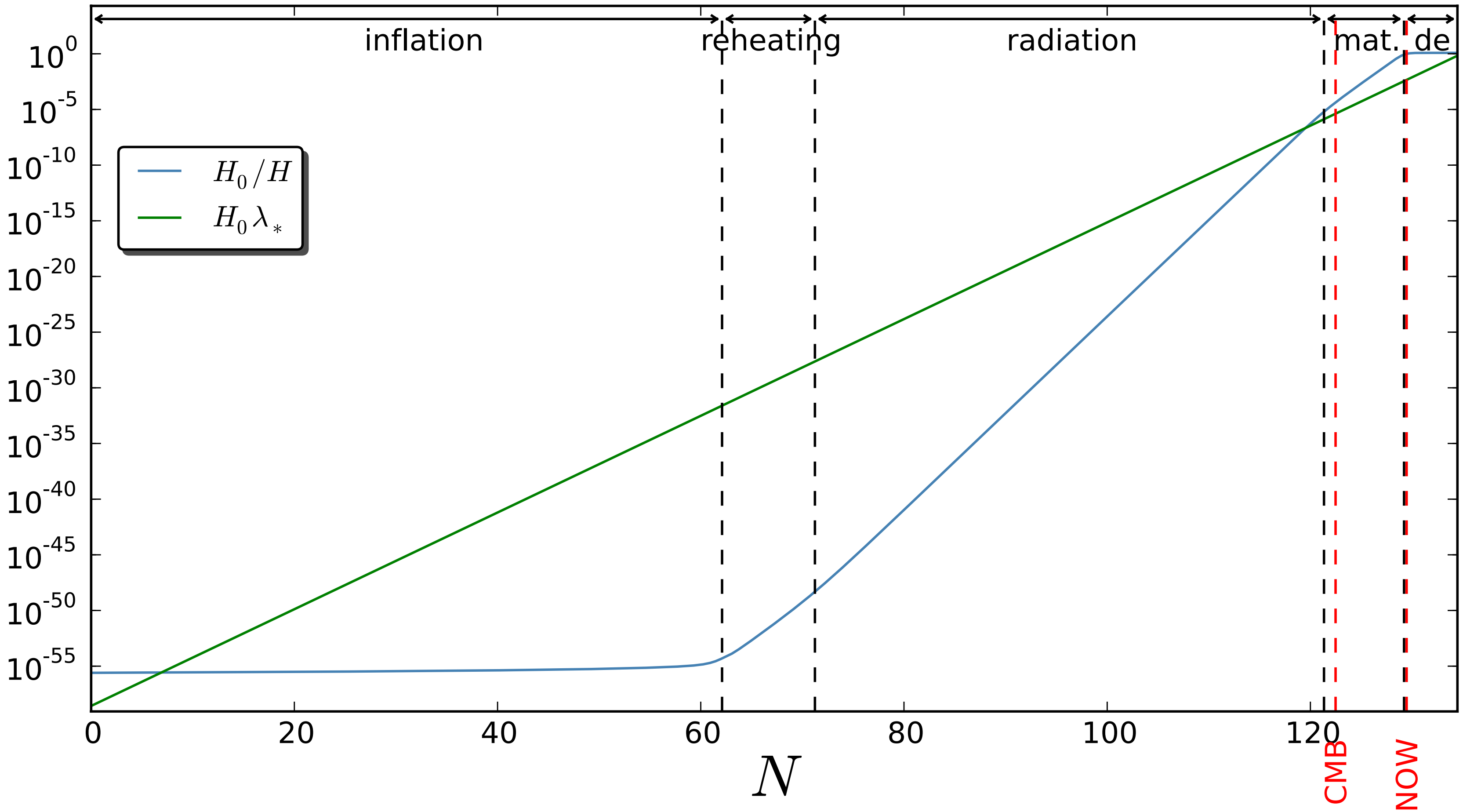

Inflationary Predictions

Coherent, Gaussian, almost scale invariant, adiabatic perturbations

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- **Standard Scalar Field**
- **Non Minimal Coupling**
- Potential with Features
- Multi-Field Inflation
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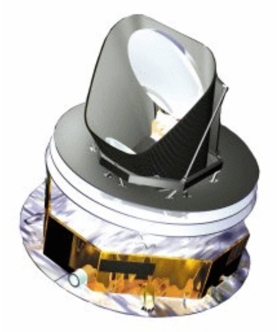
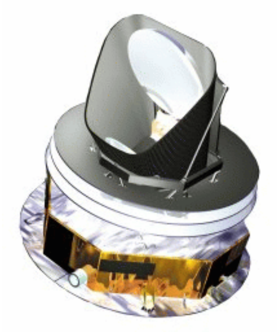


Planck Results in brief

Released March 2013, Updated February 2015

Planck +…



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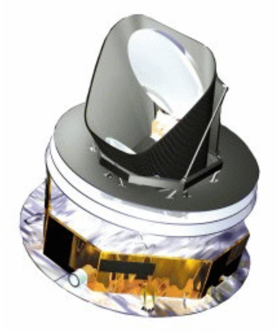

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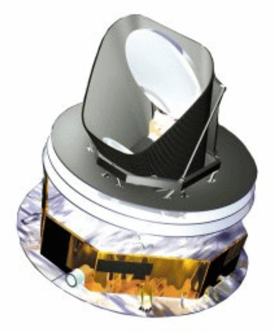

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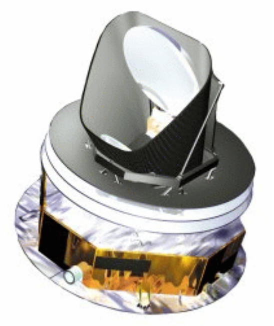

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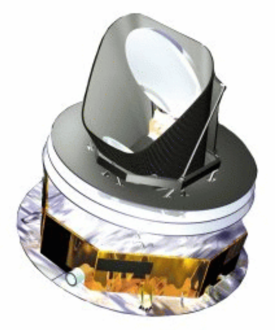

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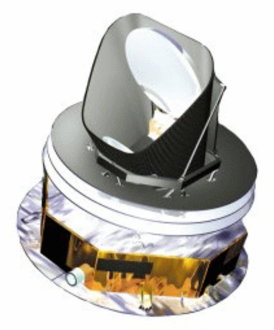
$$f_{\mathrm{NL}}^{\mathrm{loc}} = 0.8 \pm 5 \qquad f_{\mathrm{NL}}^{\mathrm{eq}} = -16 \pm 70 \qquad f_{\mathrm{NL}}^{\mathrm{orth}} = -34 \pm 33$$



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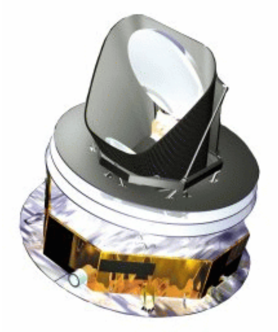

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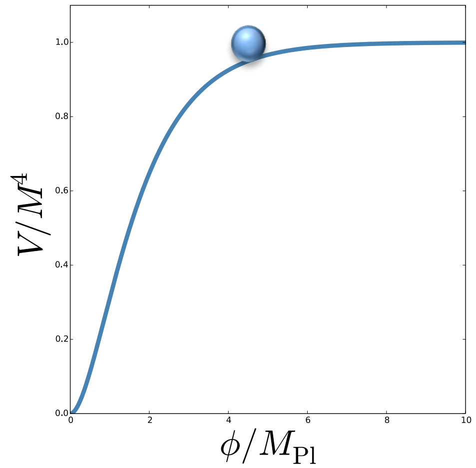
•Consequences for Inflationary Models in Particular …

Inflationary Observables

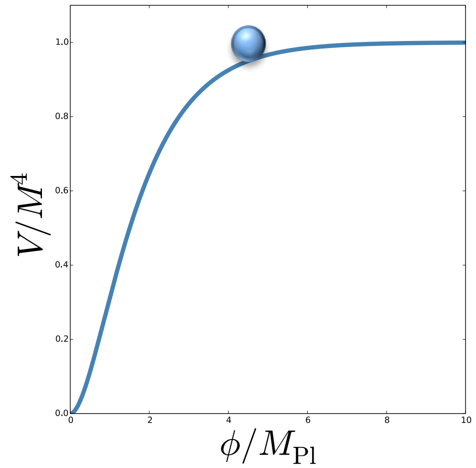
of single-field slow-roll models



Inflationary Observables

of single-field slow-roll models

- **The slow-roll approximation** Sasaki, Nambu & Nakao (1988)
Liddle, Pearsons & Barrow (1994)



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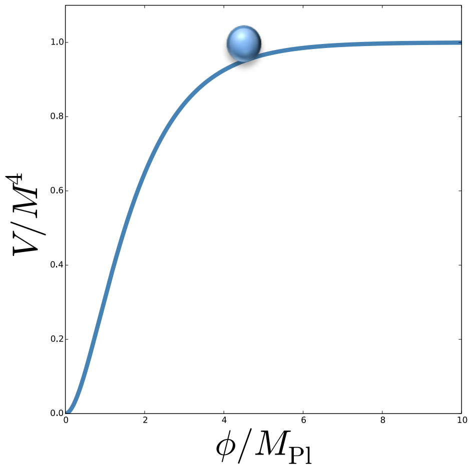

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During inflation, H is almost constant

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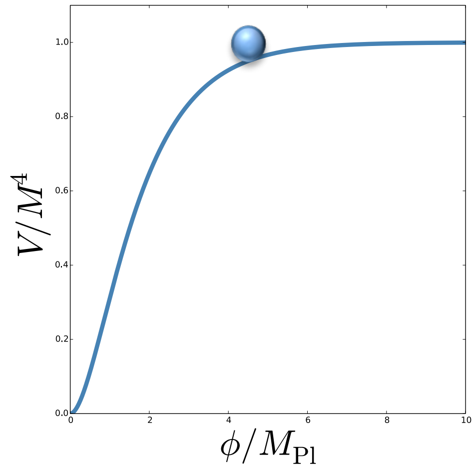

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$$\epsilon_{n+1} = \frac{1}{\epsilon_n}\frac{\mathrm{d}\epsilon_n}{\mathrm{d}N}$$

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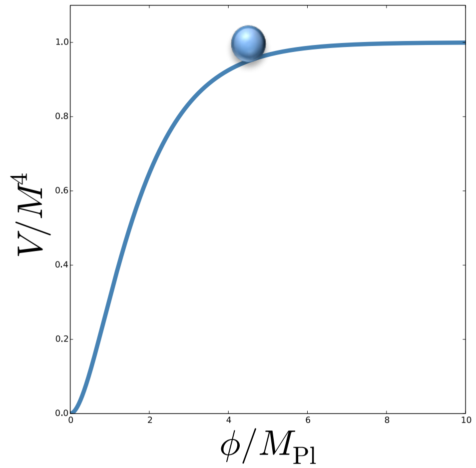

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Inflationary Observables

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of single-field slow-roll models

$$\mathcal{P}_\zeta = \frac{H_*^2}{8\pi^2 M_{\mathrm{Pl}}^2 \epsilon_{1*}} \left[1 - 2\left(C+1\right)\epsilon_{1*} - C\epsilon_{2*} - \left(2\epsilon_{1*} + \epsilon_{2*}\right)\ln\left(\frac{k}{k_*}\right)\right]$$

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$$f_{\rm NL}^{\rm loc} = \frac{5}{12}\left(2\epsilon_{1*} + \epsilon_{2*}\right)$$

Maldacena (2002)

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$$r \equiv \frac{\mathcal{P}_h(k_*)}{\mathcal{P}_\zeta(k_*)} \simeq 16\epsilon_{1*}$$

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$$n_{\rm S} \simeq 0.96$$

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Targeted Measurements

r → energy scale of inflation

$$\frac{H_*^2}{M_{\rm Pl}^2} \simeq \frac{\pi^2}{2} r\mathcal{P}_\zeta\left(k_*\right)$$

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$n_{\rm T}$ → consistency relation

$$n_{\rm T} \simeq -r/8$$

Model Predictions

Described in terms of ϵ_{i*}

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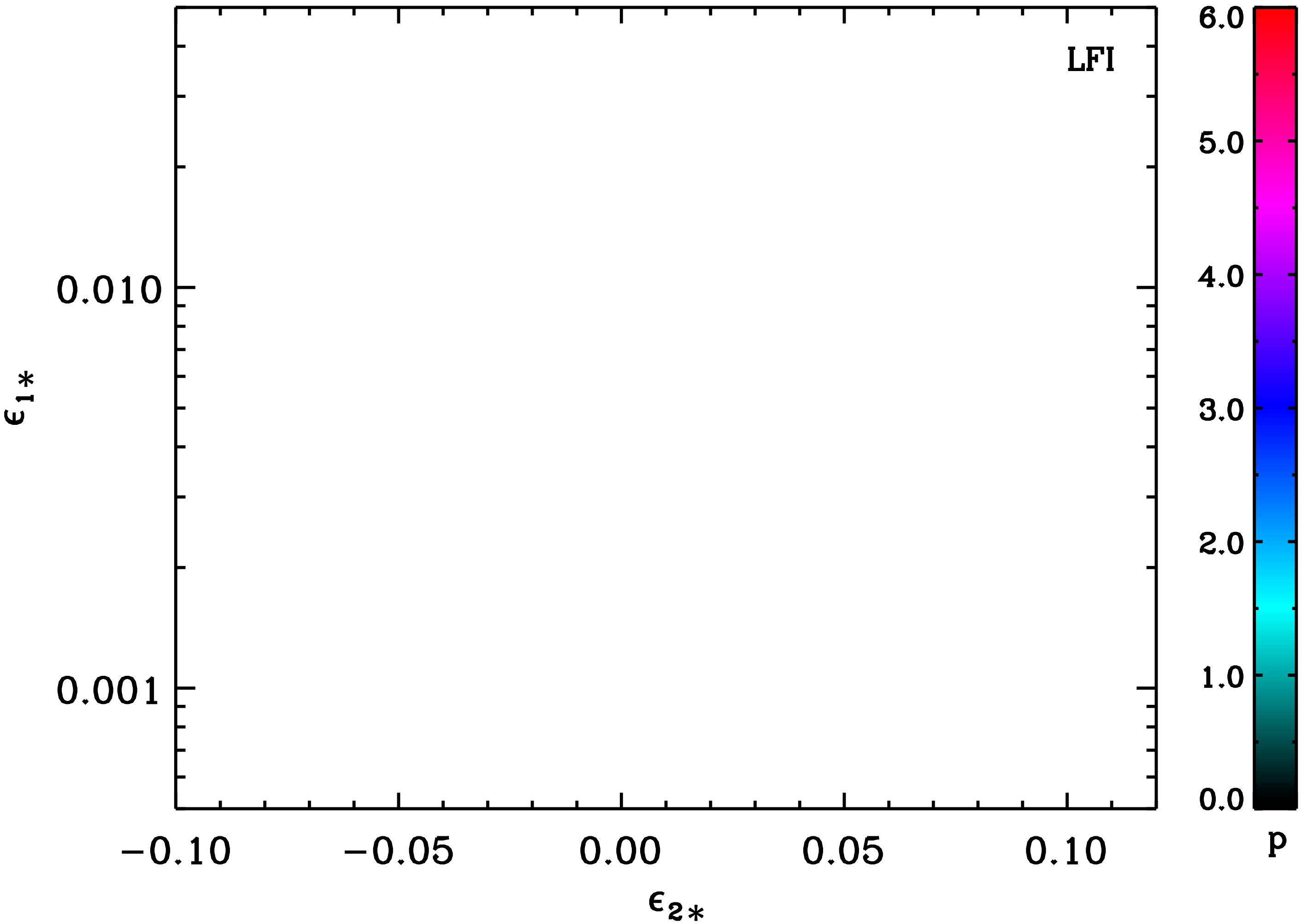
Described in terms of ϵ_{i*}

An example: « large field inflation » $$V(\phi) = M^4 \left(\frac{\phi}{M_{\mathrm{Pl}}}\right)^p$$

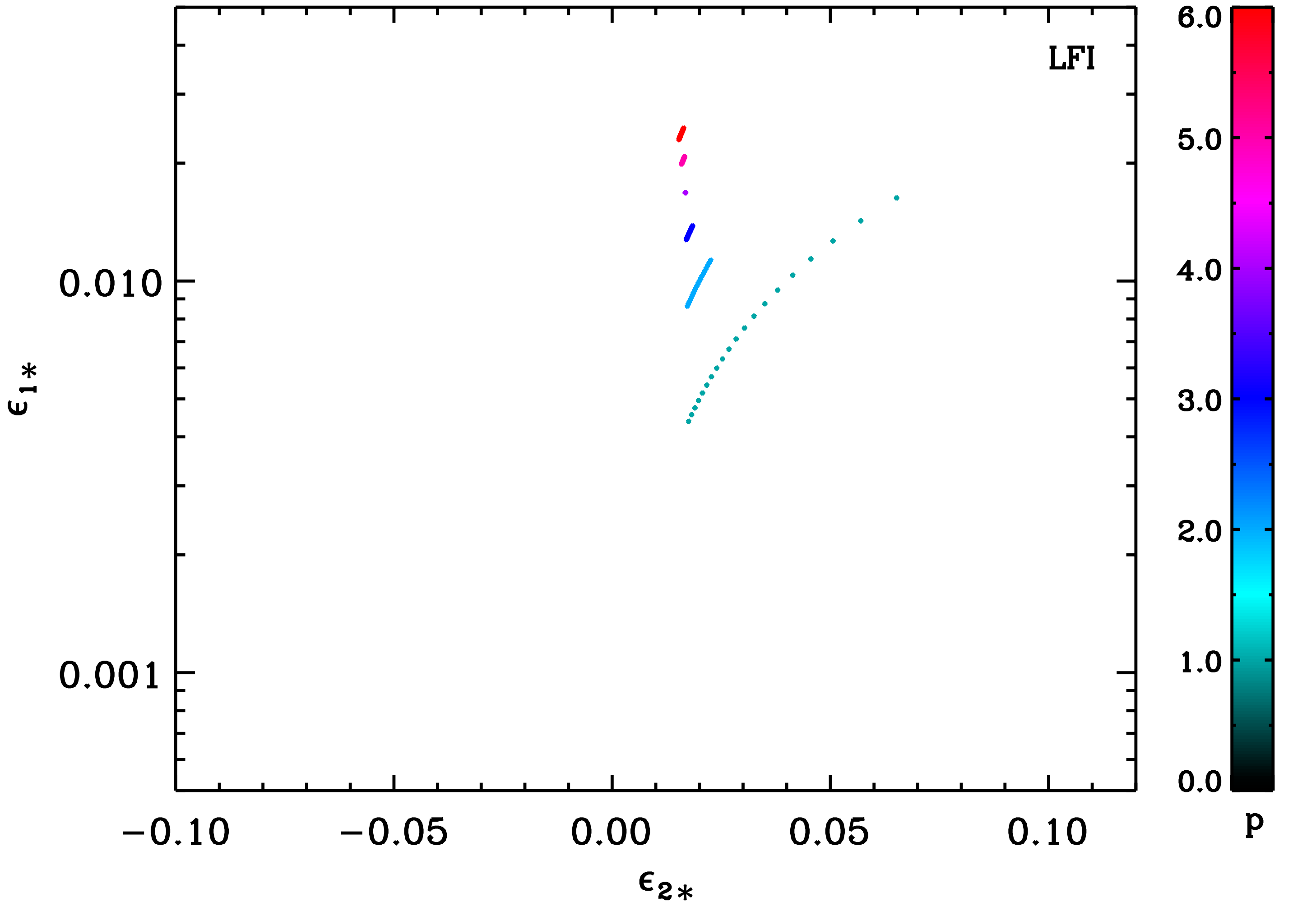


Model Predictions

Described in terms of ϵ_{i*}

An example: « large field inflation »

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



Model Predictions

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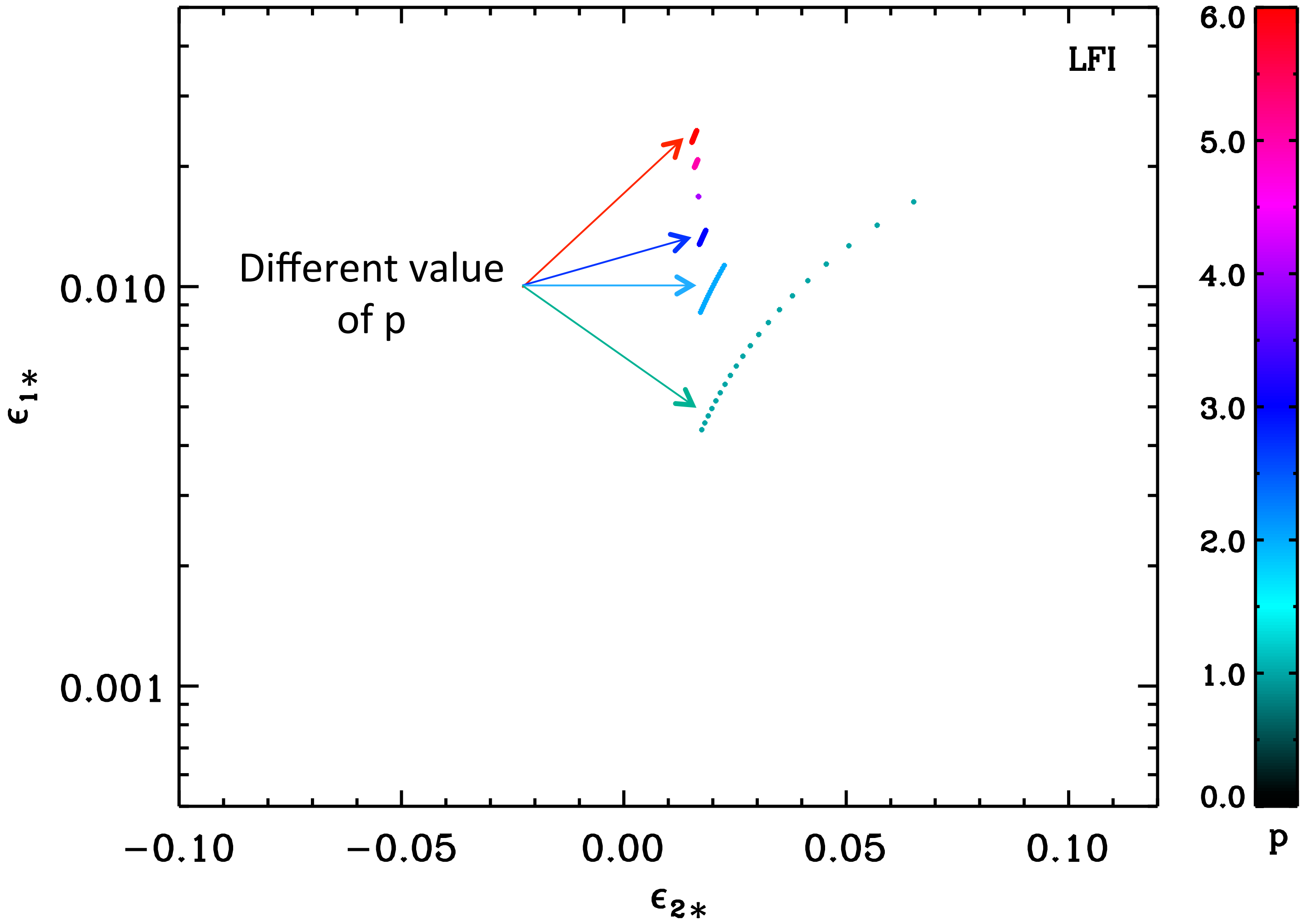
An example: « large field inflation » $$V\left(\phi\right) = M^4 \left(\frac{\phi}{M_{\rm Pl}}\right)^p$$



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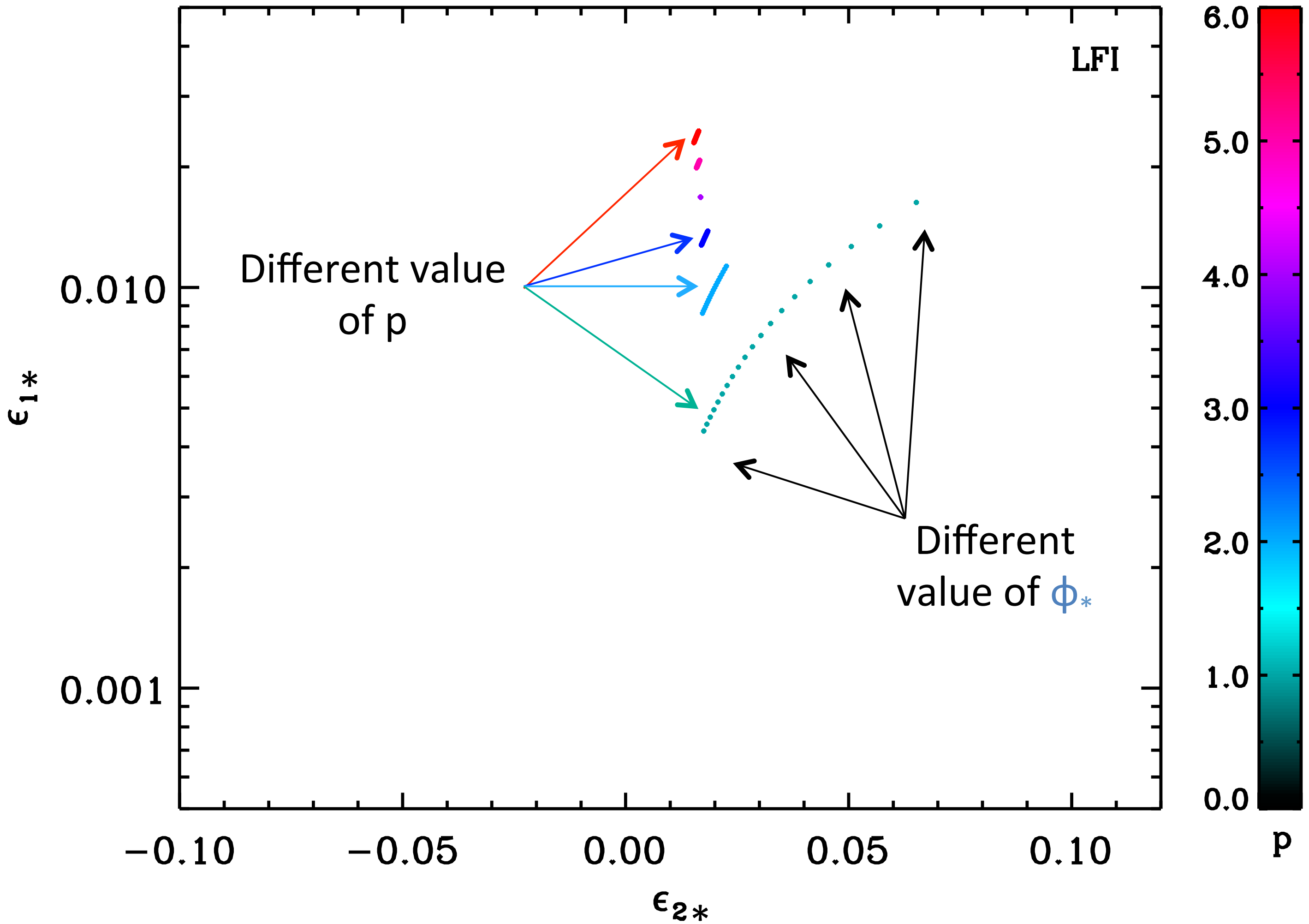

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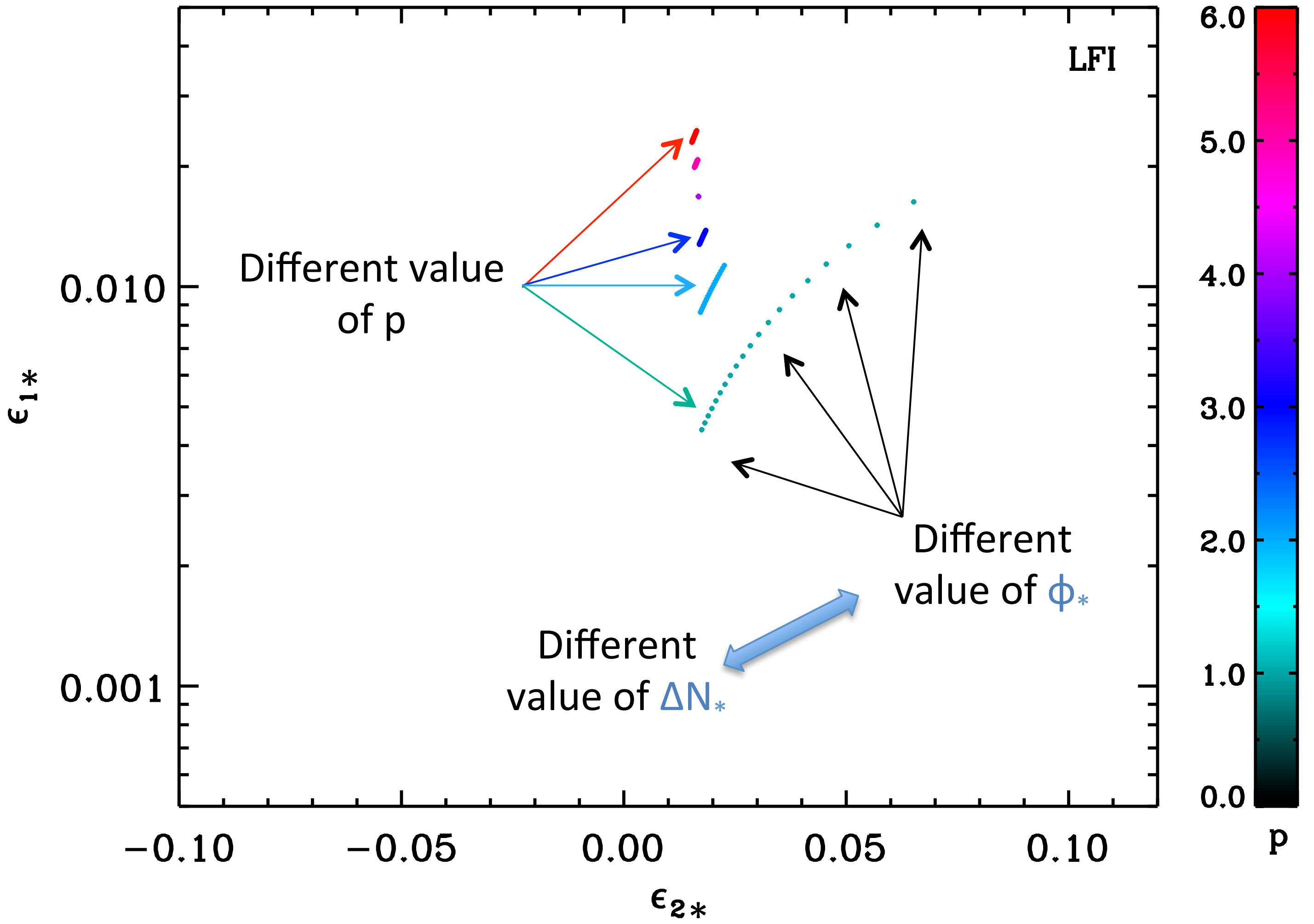

Model Predictions

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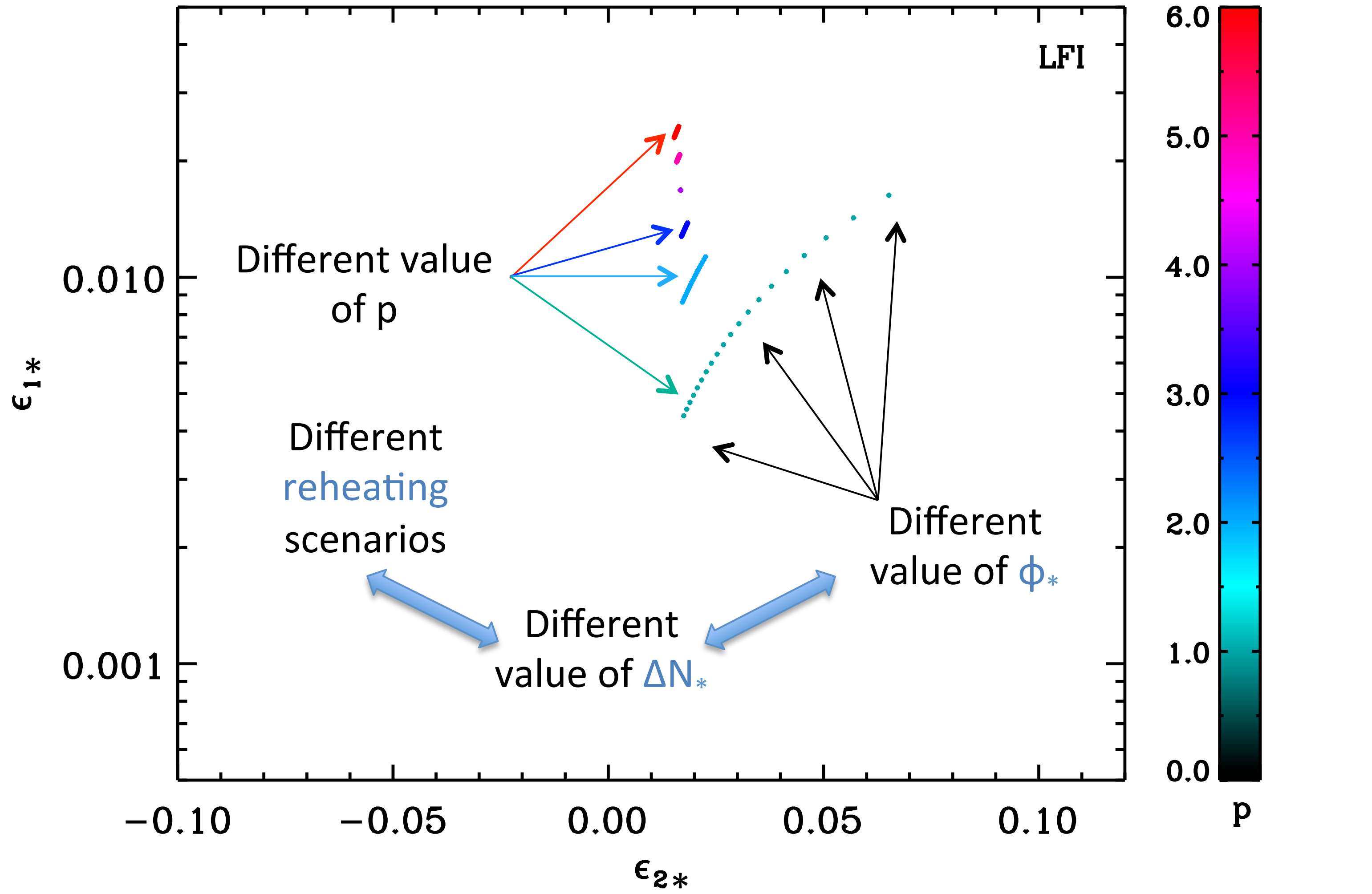
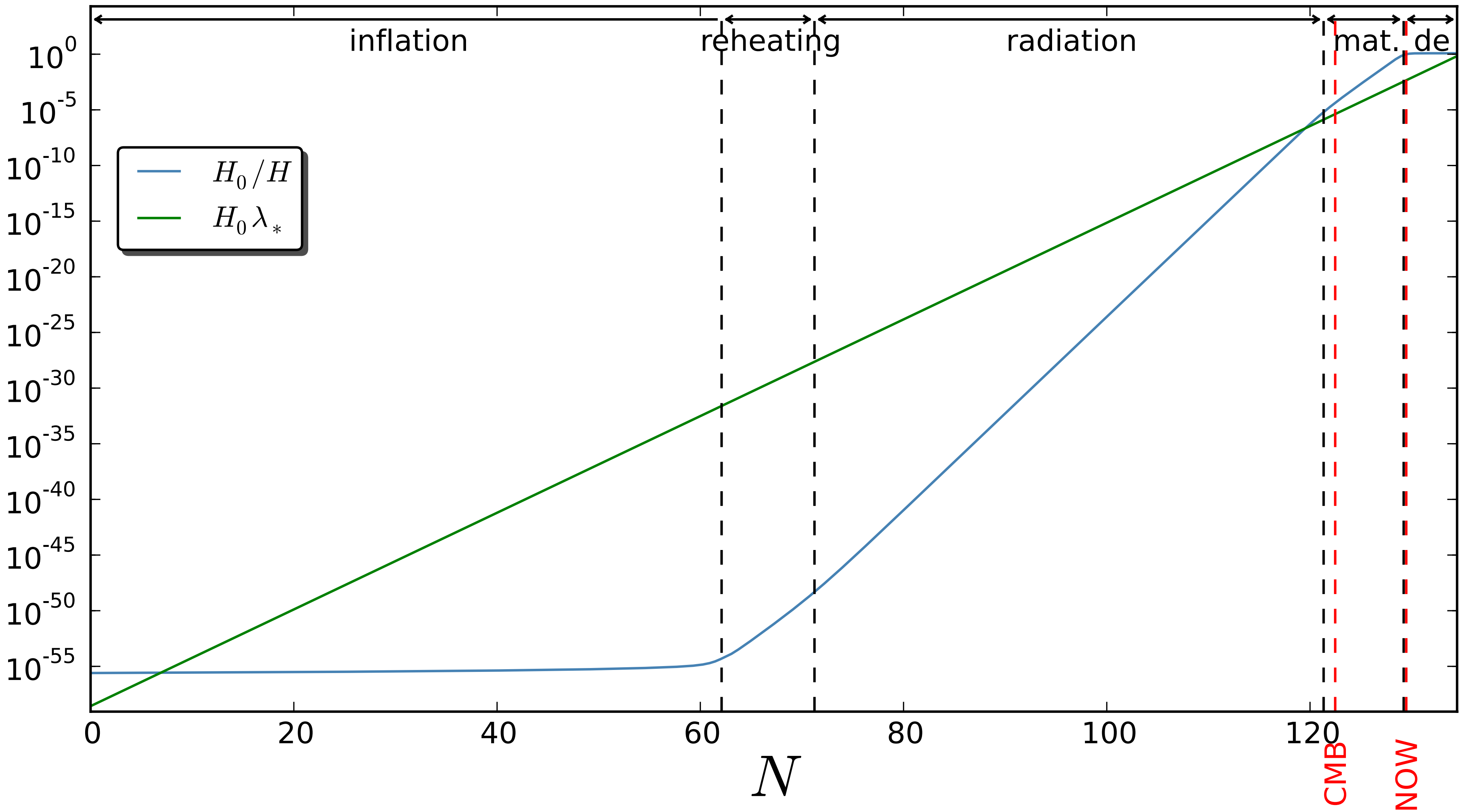


Role of Reheating

Martin & Ringeval (2010)
Easther & Peiris (2011)

A technical aspect



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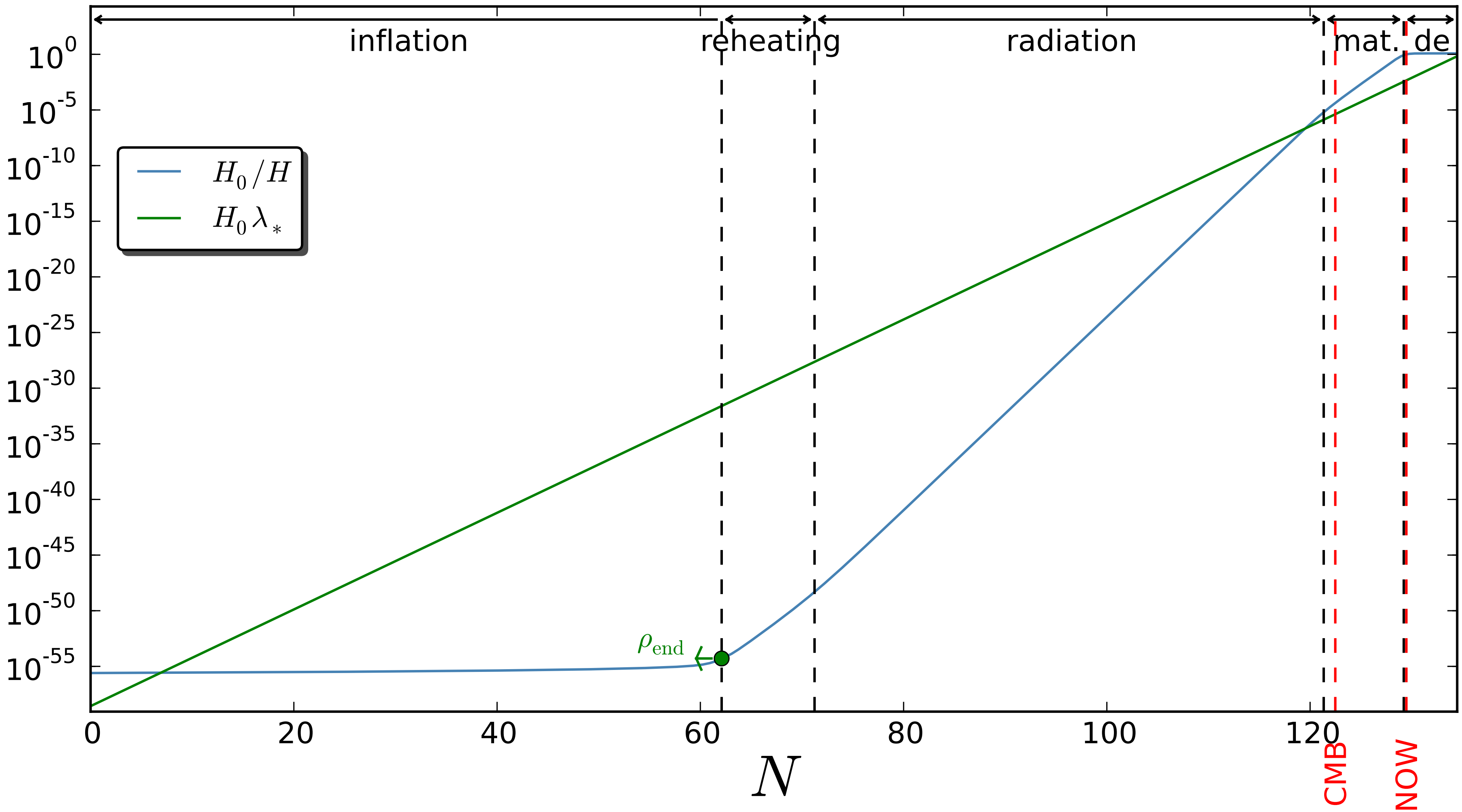

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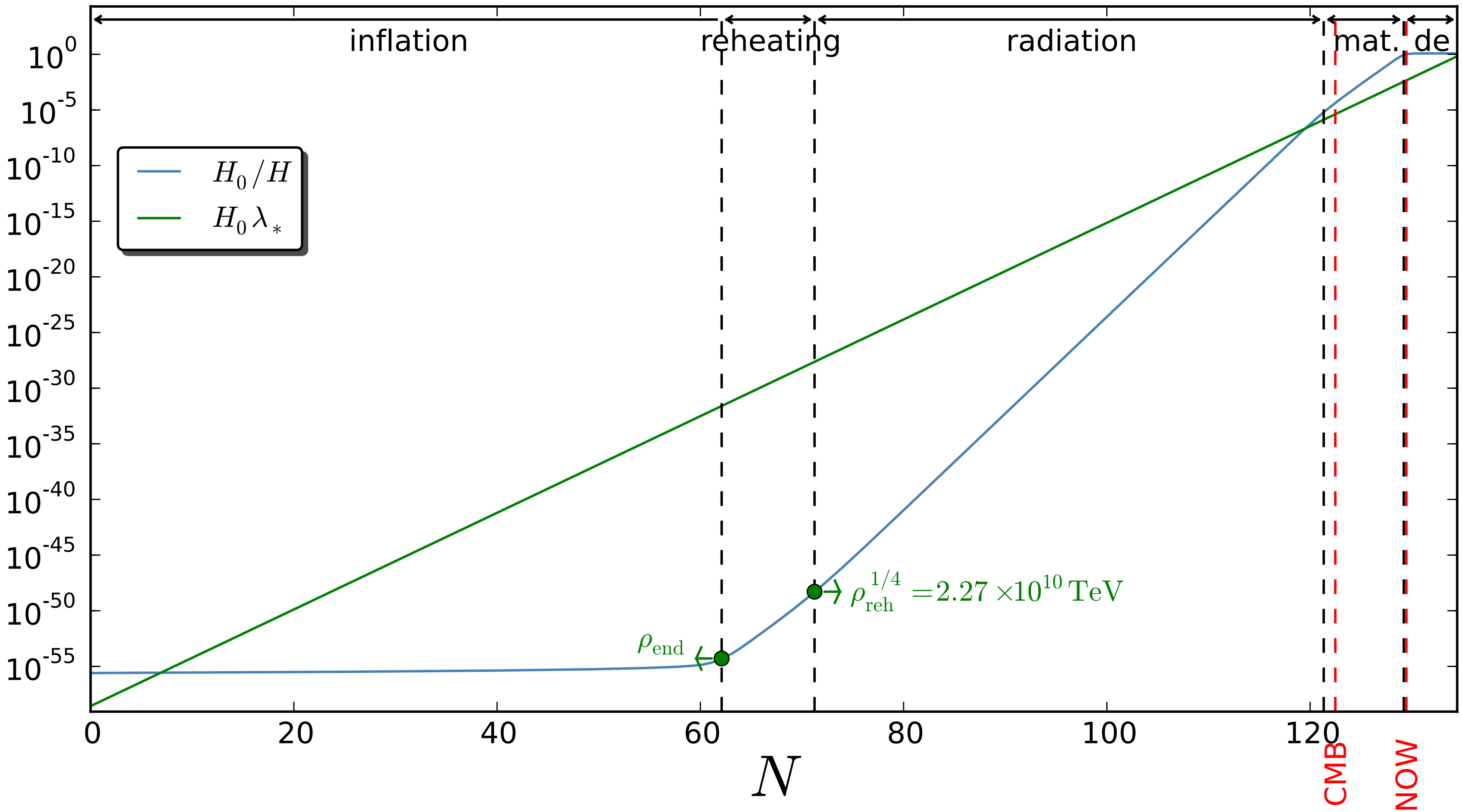

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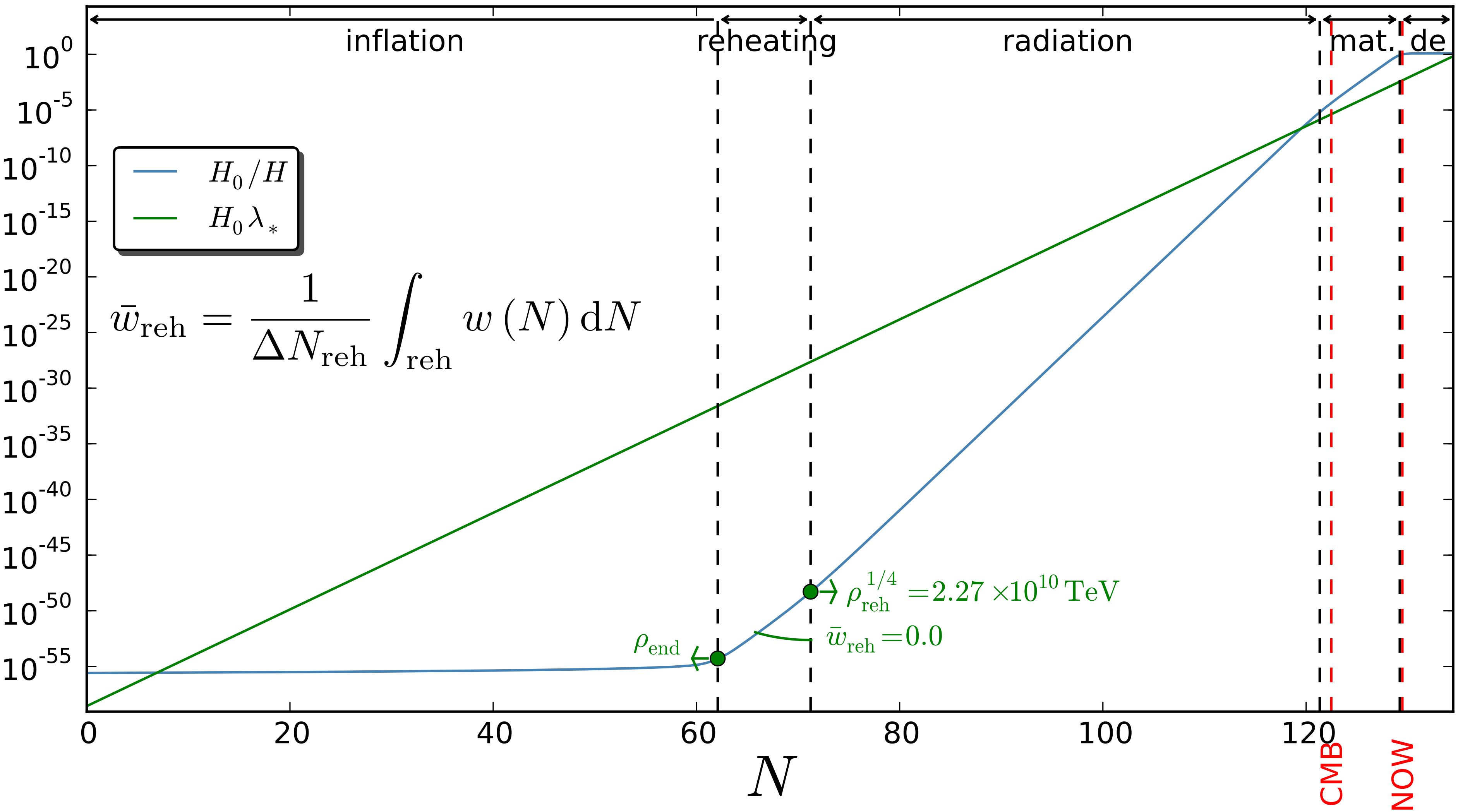

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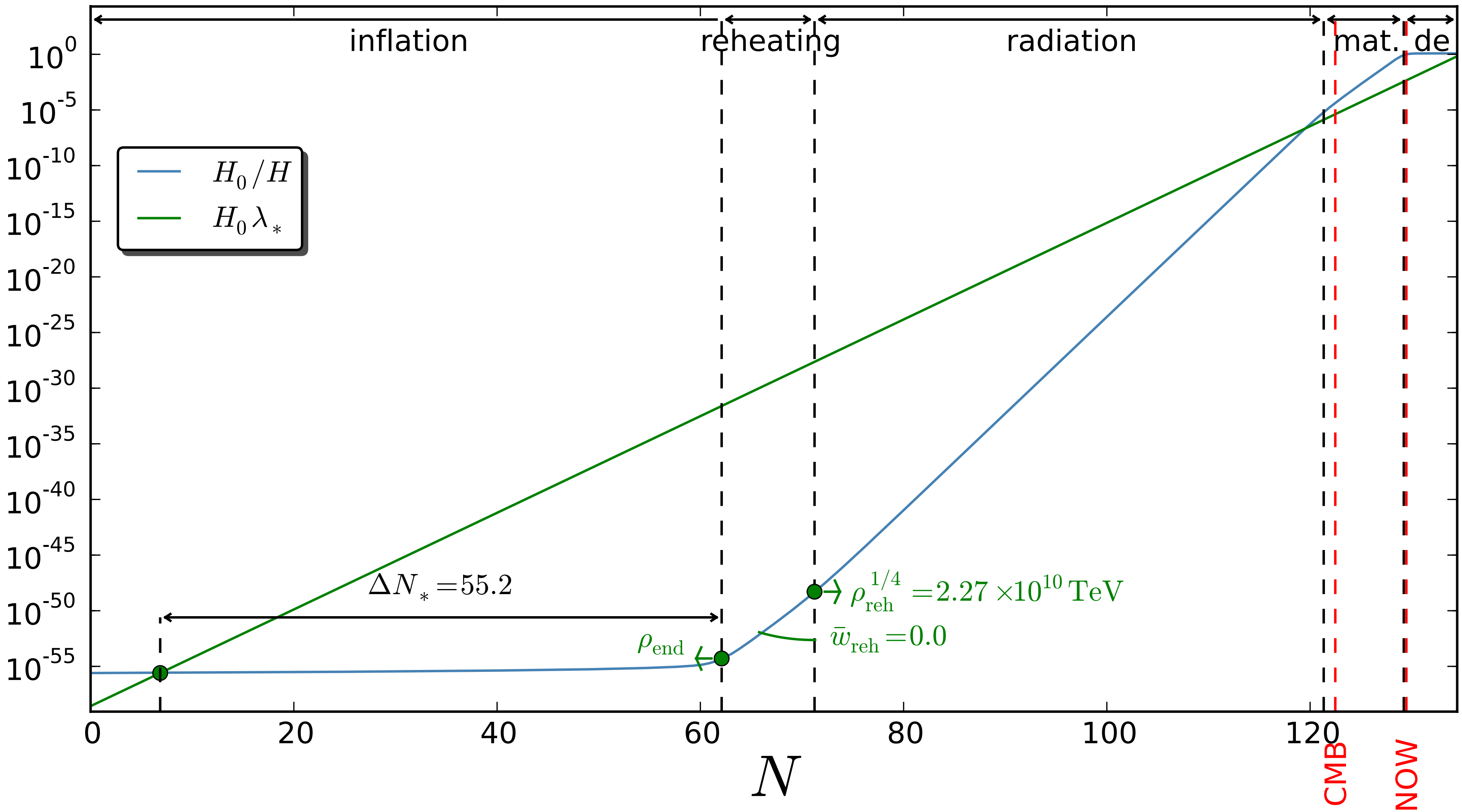
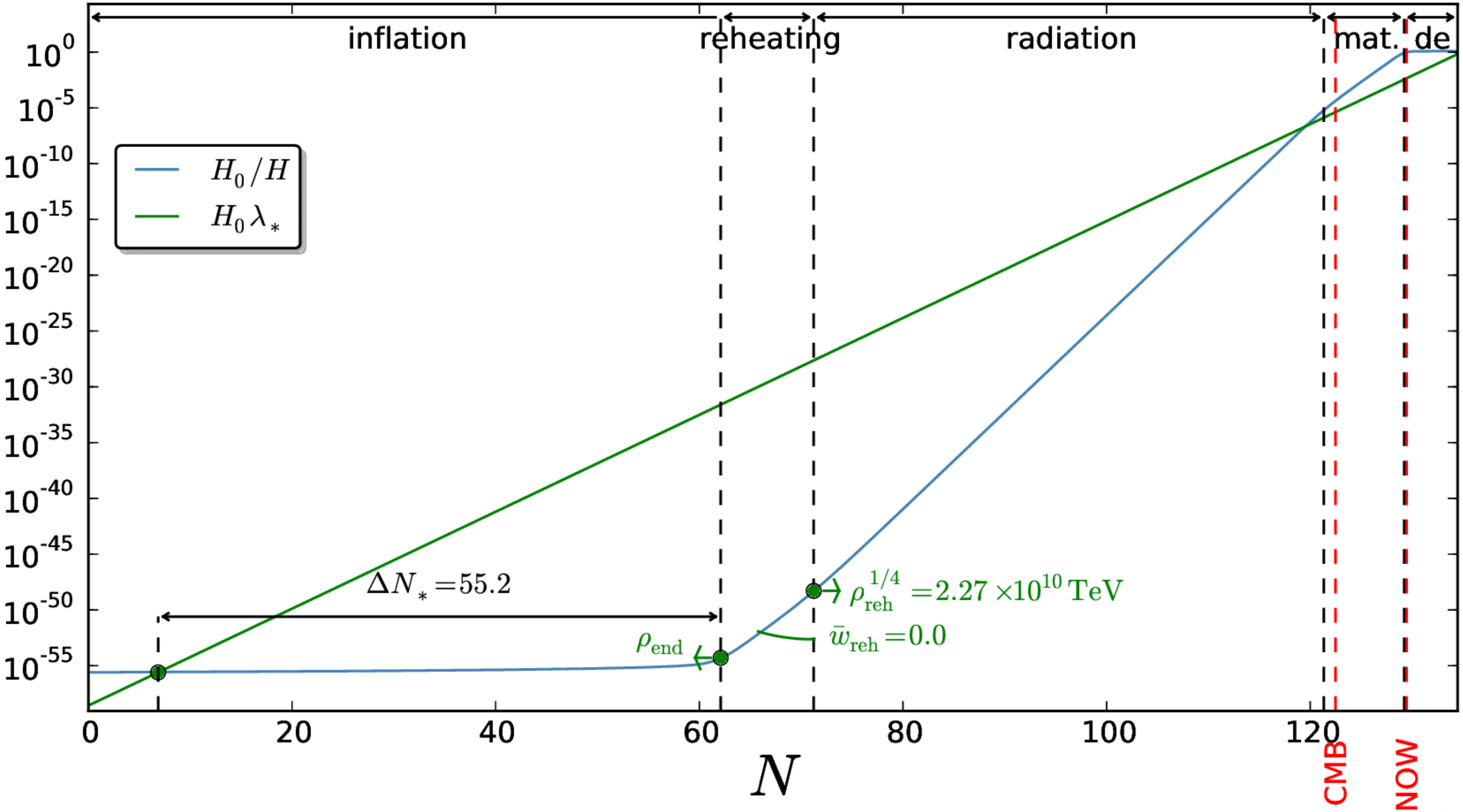


Role of Reheating

Martin & Ringeval (2010)
Easther & Peiris (2011)

A technical aspect

$\rho_{\rm BBN} < \rho_{\rm reh} < \rho_{\rm end}$

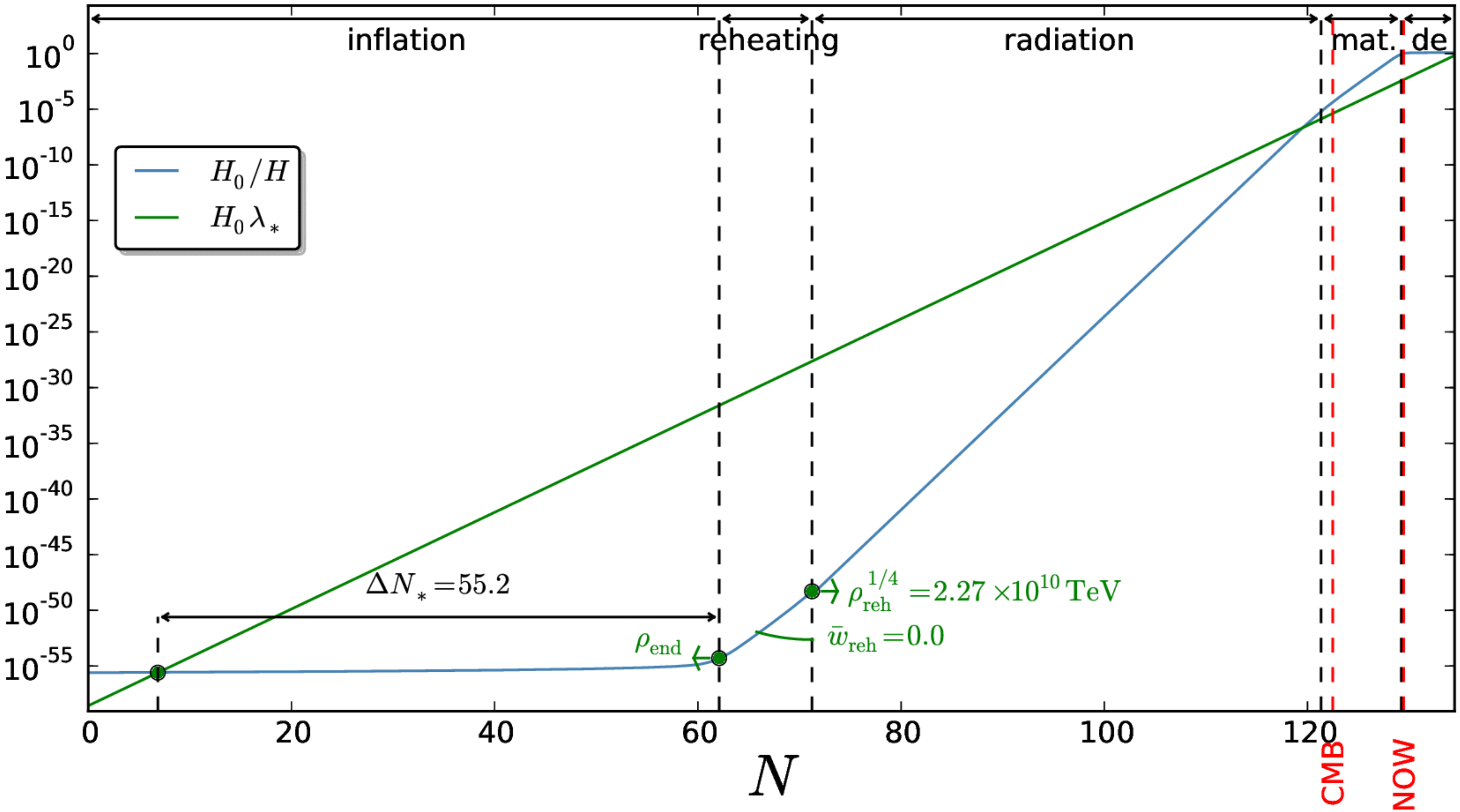


Role of Reheating

Martin & Ringeval (2010)
Easther & Peiris (2011)

A technical aspect

$$-1/3 < \bar{w}_{\rm reh} < 1$$



Role of Reheating

Martin & Ringeval (2010)
Easther & Peiris (2011)

$$\Delta N_* = \frac{1-3\bar{w}_{\rm reh}}{12\,(1+\bar{w}_{\rm reh})} \ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right) + \frac{1}{4}\ln\left(\frac{\rho_*}{3M_{\rm Pl}^4}\frac{\rho_*}{\rho_{\rm end}}\right) - \ln\left(\frac{k_*/a_{\rm now}}{\rho_{\gamma,{\rm now}}^{1/4}}\right)$$

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- depends on reheating parameters

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- depends on reheating parameters
- depends on V parameters
  (model dependent)

Role of Reheating

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- depends on reheating parameters
- depends on V parameters
- accurately measured

Role of Reheating

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Easther & Peiris (2011)

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- depends on reheating parameters
- depends on V parameters
- accurately measured
- implicit equation
  (requires numerical solving)

Role of Reheating

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In practice:

Role of Reheating

Martin & Ringeval (2010)
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In practice:
- $\rho_{\rm BBN} < \rho_{\rm reh} < \rho_{\rm end}$

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In practice:
- $\rho_{\rm BBN} < \rho_{\rm reh} < \rho_{\rm end}$
- $-1/3 < \bar{w}_{\rm reh} < 1$

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not inflation

dominant energy condition

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In practice:

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not inflation — dominant energy condition

- ρ_γ set to measured value, $k_*/a_{\rm now}$ chosen to pivot scale

Role of Reheating

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In practice:

- $\rho_{\rm BBN} < \rho_{\rm reh} < \rho_{\rm end}$
- $-1/3 < \bar{w}_{\rm reh} < 1$

not inflation — dominant energy condition

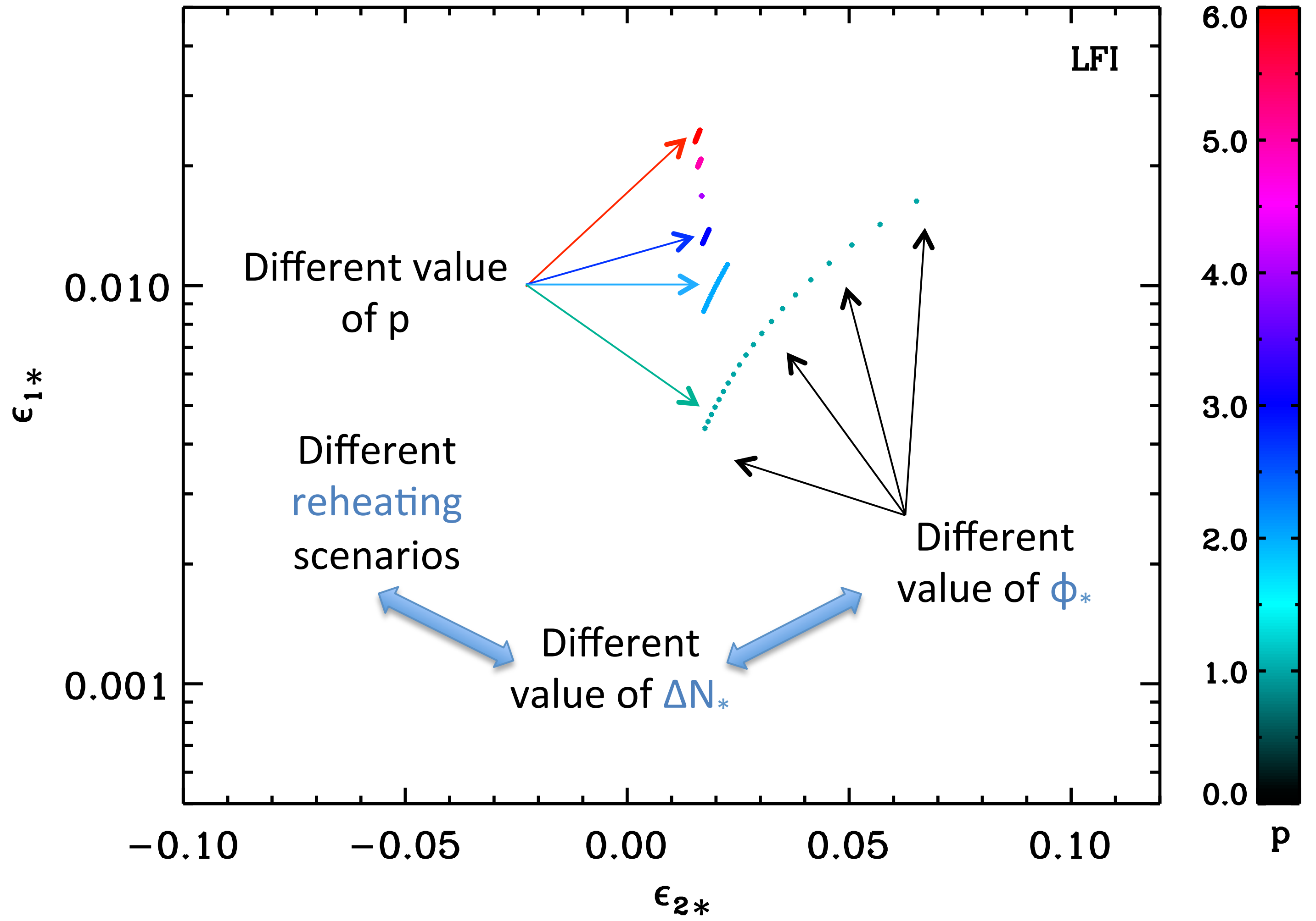
Yields a model dependent range of admitted values for ΔN_*

- ρ_γ set to measured value, $k_*/a_{\rm now}$ chosen to pivot scale

Model Predictions

Described in terms of ϵ_{i*}

An example: « large field inflation » $$V(\phi) = M^4 \left(\frac{\phi}{M_{\rm Pl}}\right)^p$$



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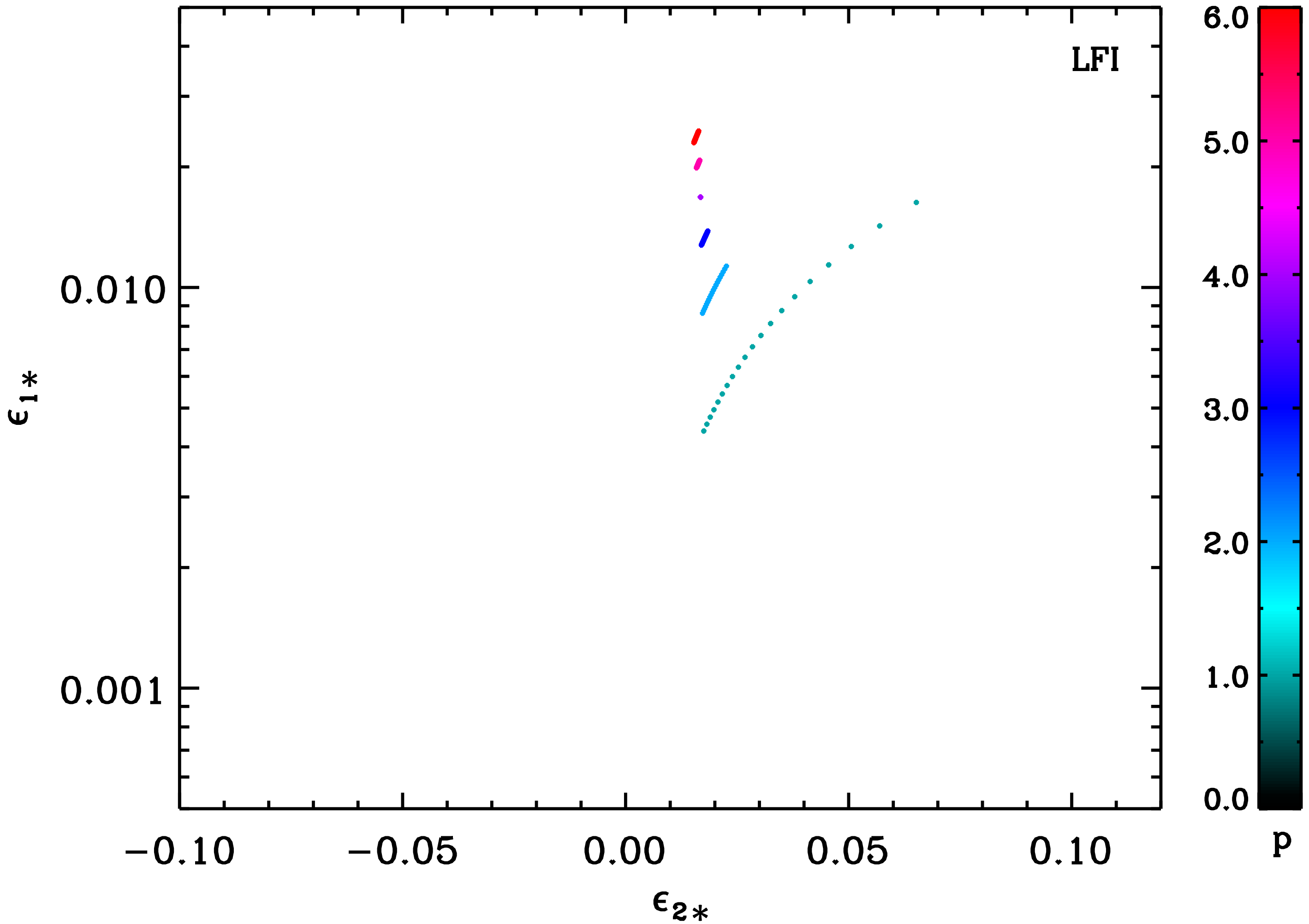

Model Predictions and Observations

Martin, Ringeval, V.V (2013)

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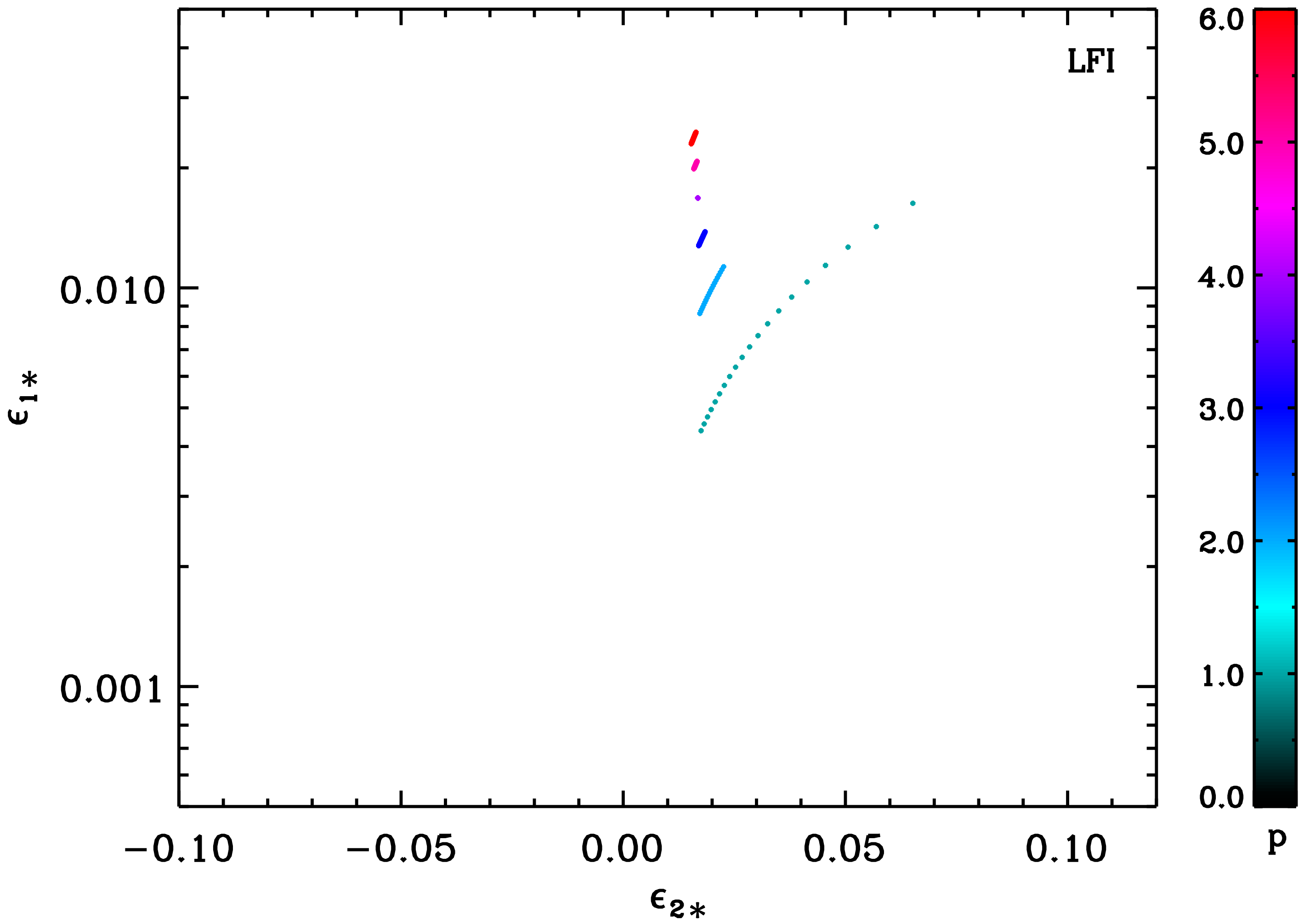

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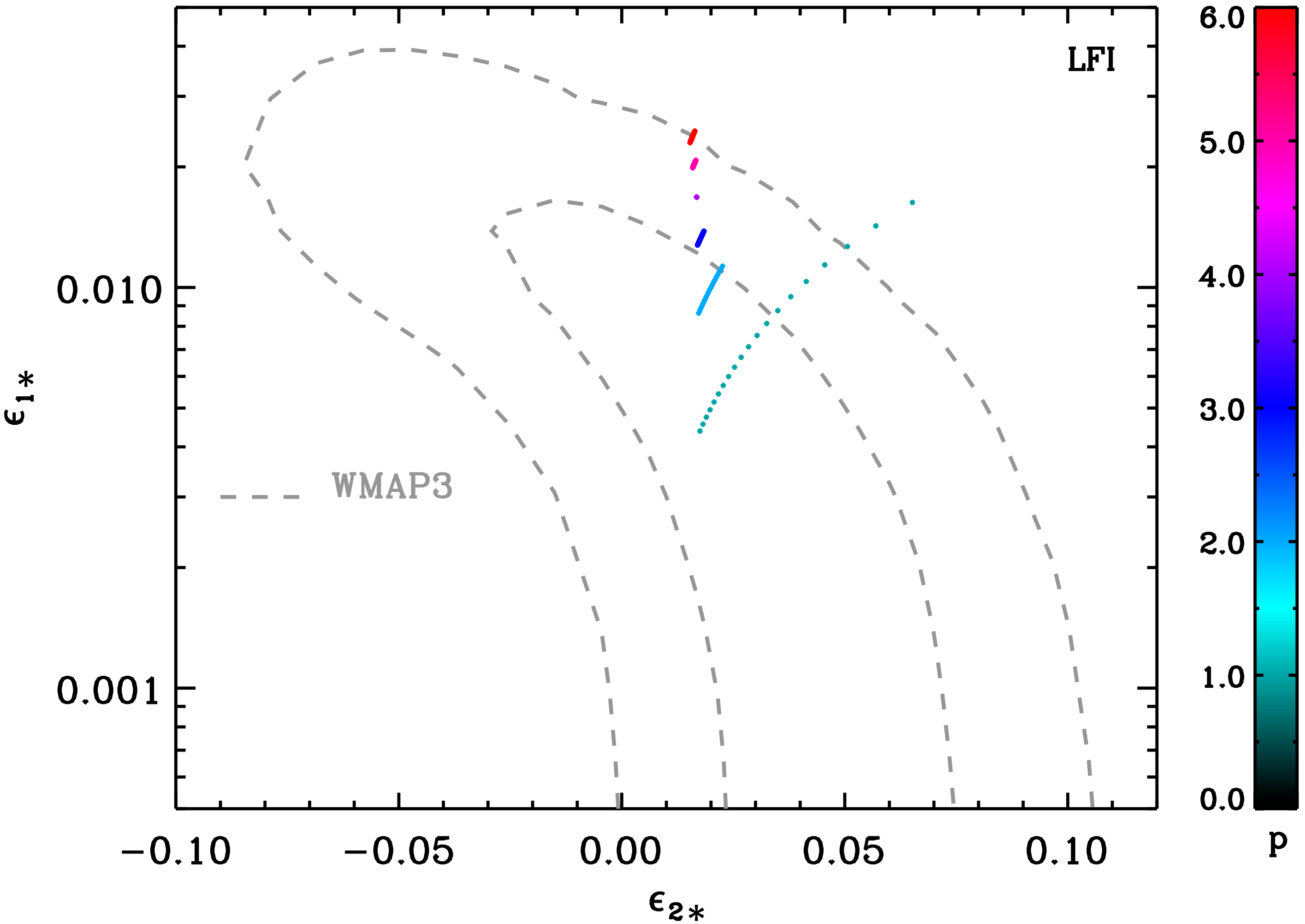

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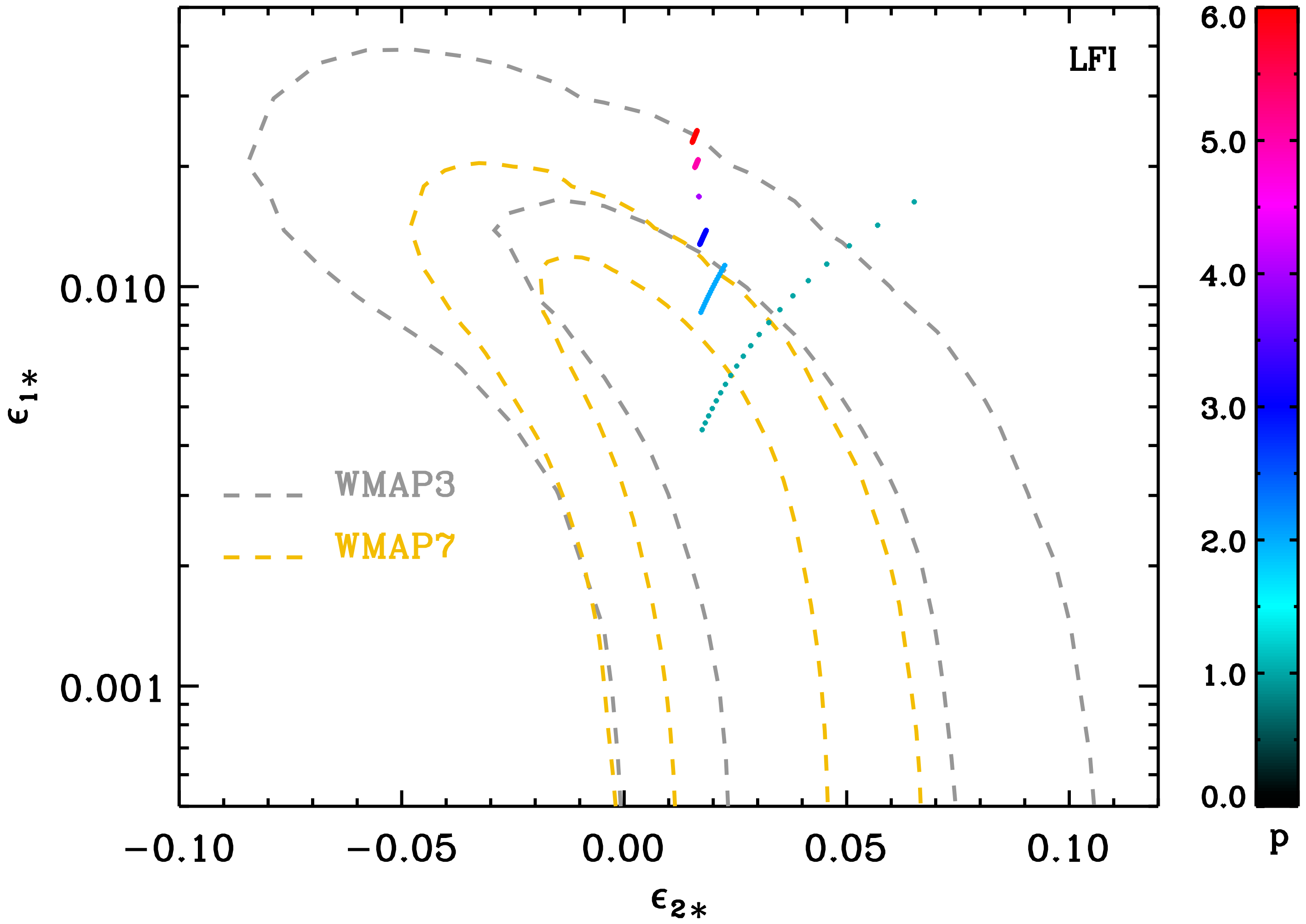

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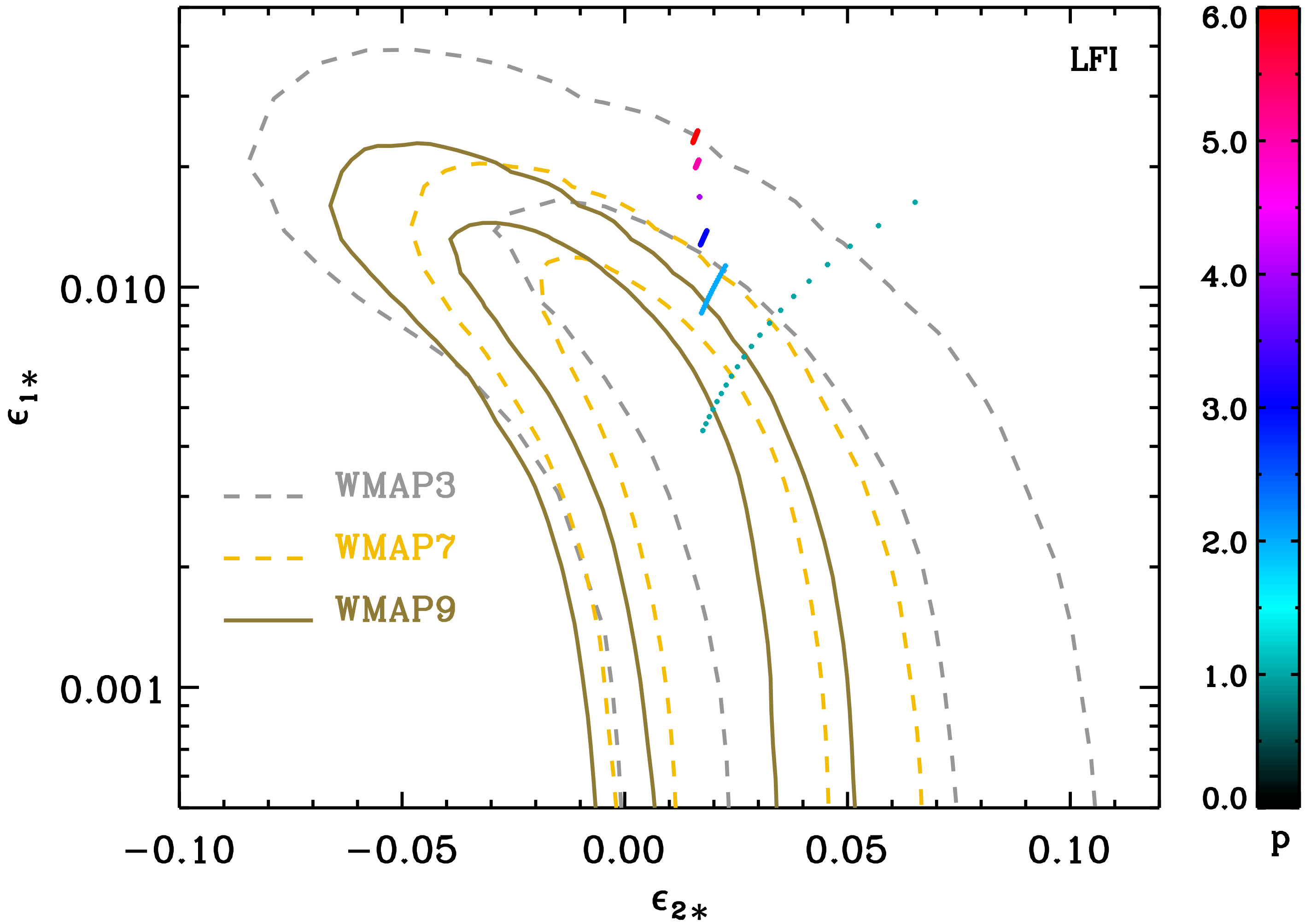

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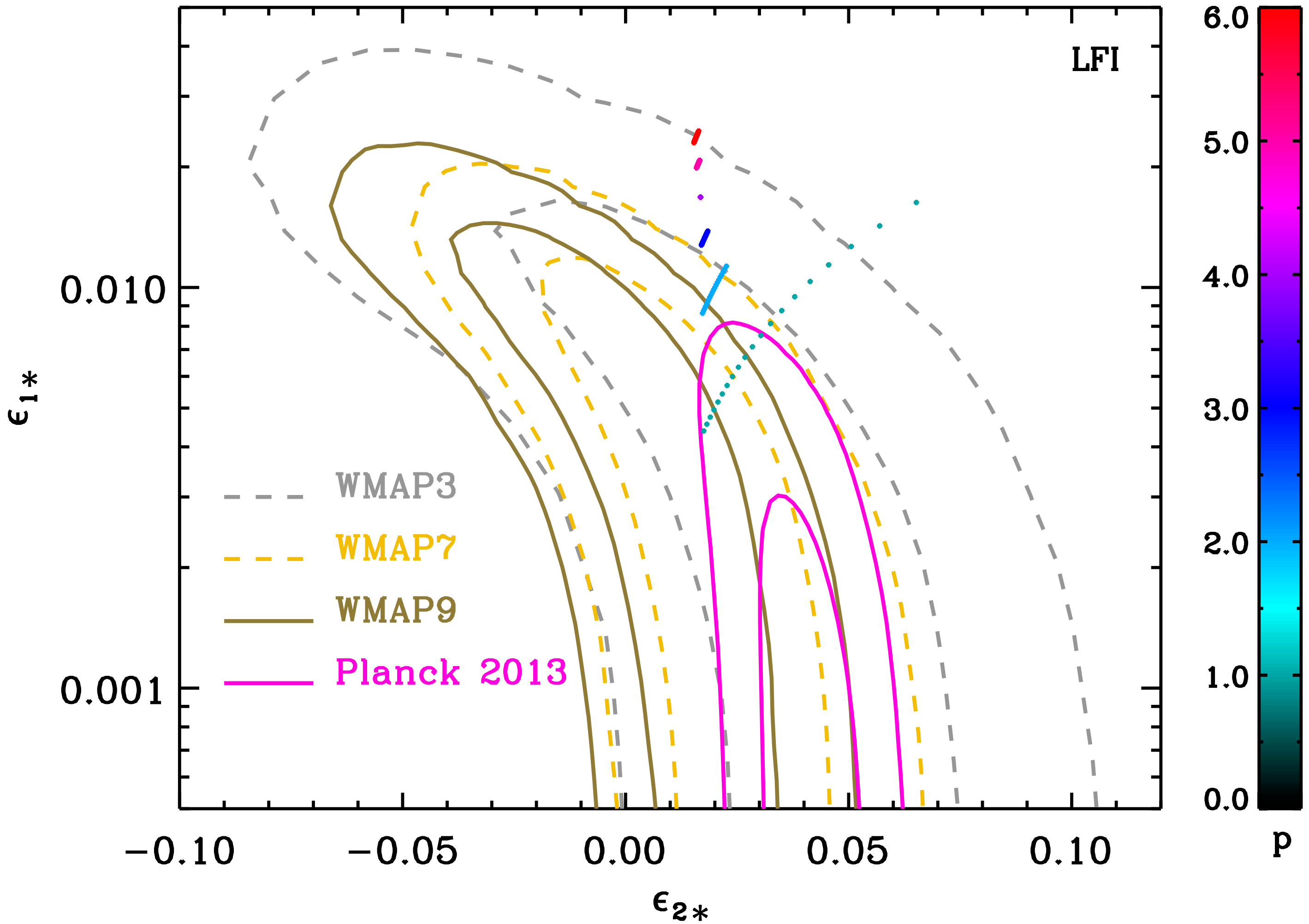

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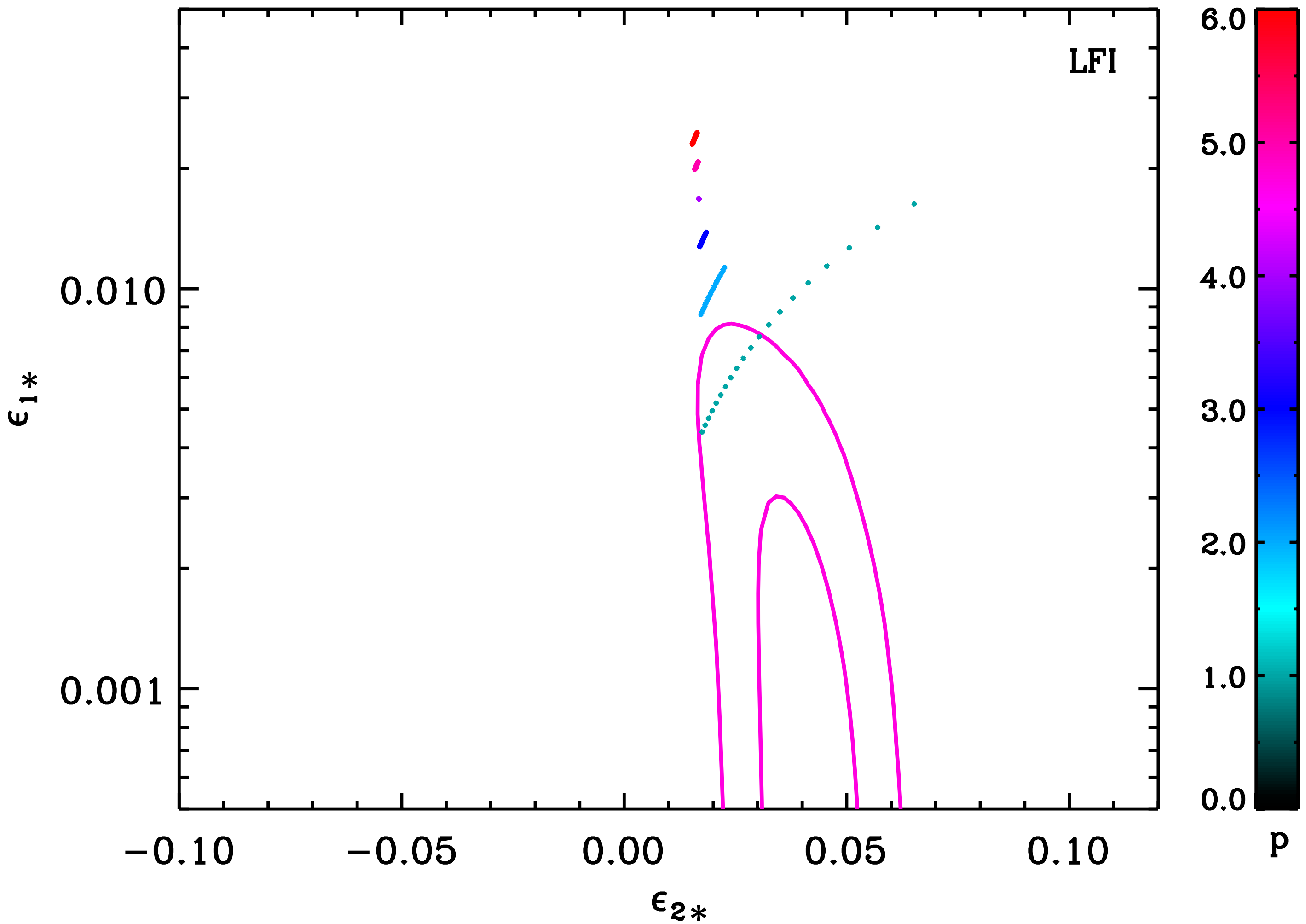


Bayesian Approach

to model comparison

Bayesian Approach

to model comparison

Bayesian evidence: Integral of the likelihood over parameter prior

Bayesian Approach

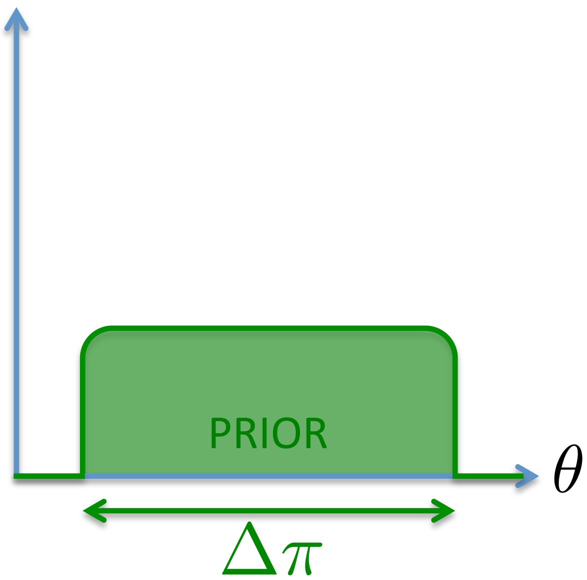
to model comparison

Bayesian evidence: Integral of the likelihood over parameter prior

Bayesian Approach

to model comparison

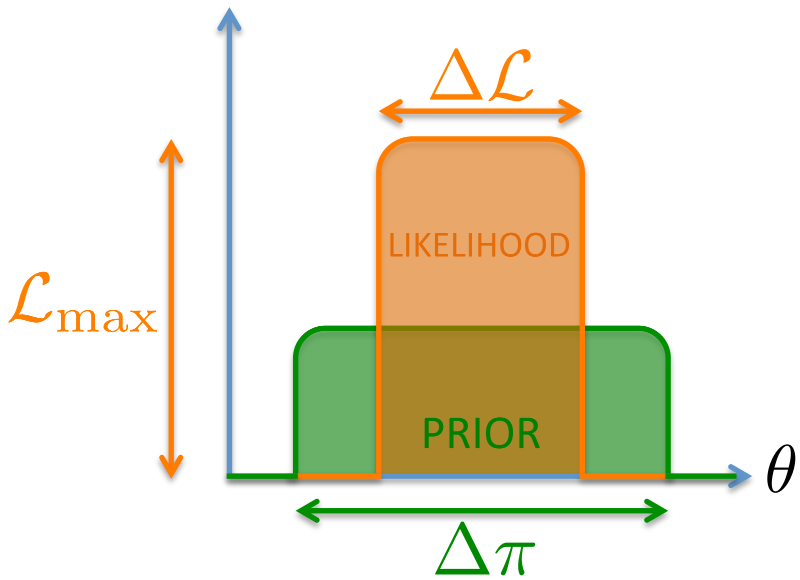
Bayesian evidence: Integral of the likelihood over parameter prior



Bayesian Approach

to model comparison

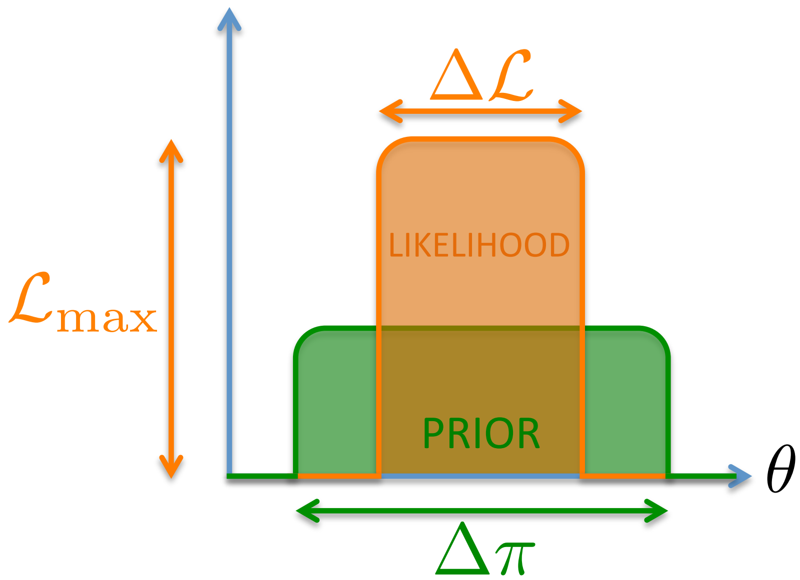
Bayesian evidence: Integral of the likelihood over parameter prior



Bayesian Approach

to model comparison

Bayesian evidence: Integral of the likelihood over parameter prior

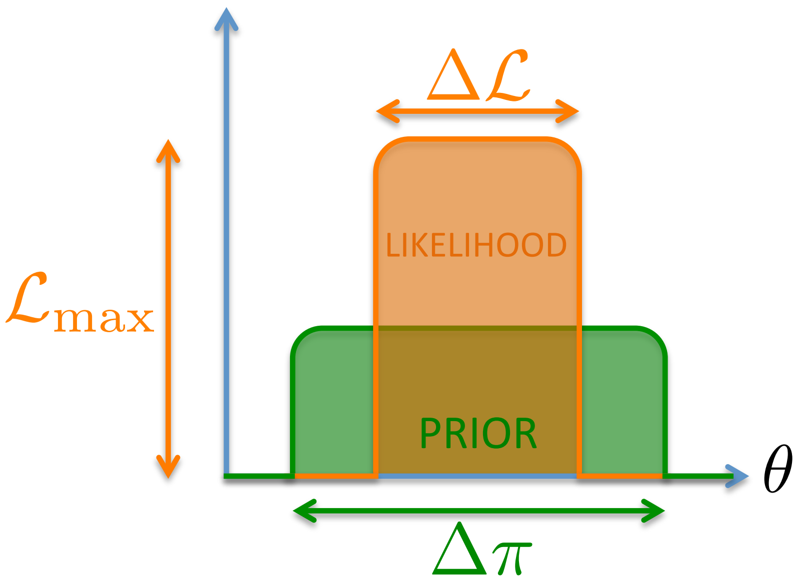


$$\mathcal{E}\left(\mathcal{M}\right) = \mathcal{L}_{\max}\,\frac{\Delta\mathcal{L}}{\Delta\pi}$$

Bayesian Approach

to model comparison

Bayesian evidence: Integral of the likelihood over parameter prior



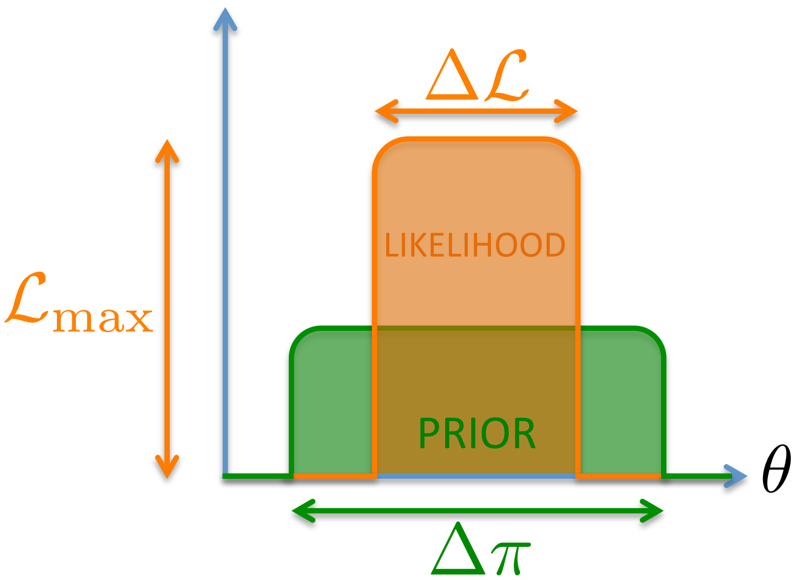
$$\mathcal{E}\left(\mathcal{M}\right) = \mathcal{L}_{\max} \frac{\Delta\mathcal{L}}{\Delta\pi}$$

Compromise between quality of fit and simplicity

Bayesian Approach

to model comparison

Bayesian evidence: Integral of the likelihood over parameter prior



$$\mathcal{E}\left(\mathcal{M}\right) = \mathcal{L}_{\max}\,\frac{\Delta\mathcal{L}}{\Delta\pi}$$

Compromise between quality of fit and simplicity

For a set of models $\{\mathcal{M}_j\}$,

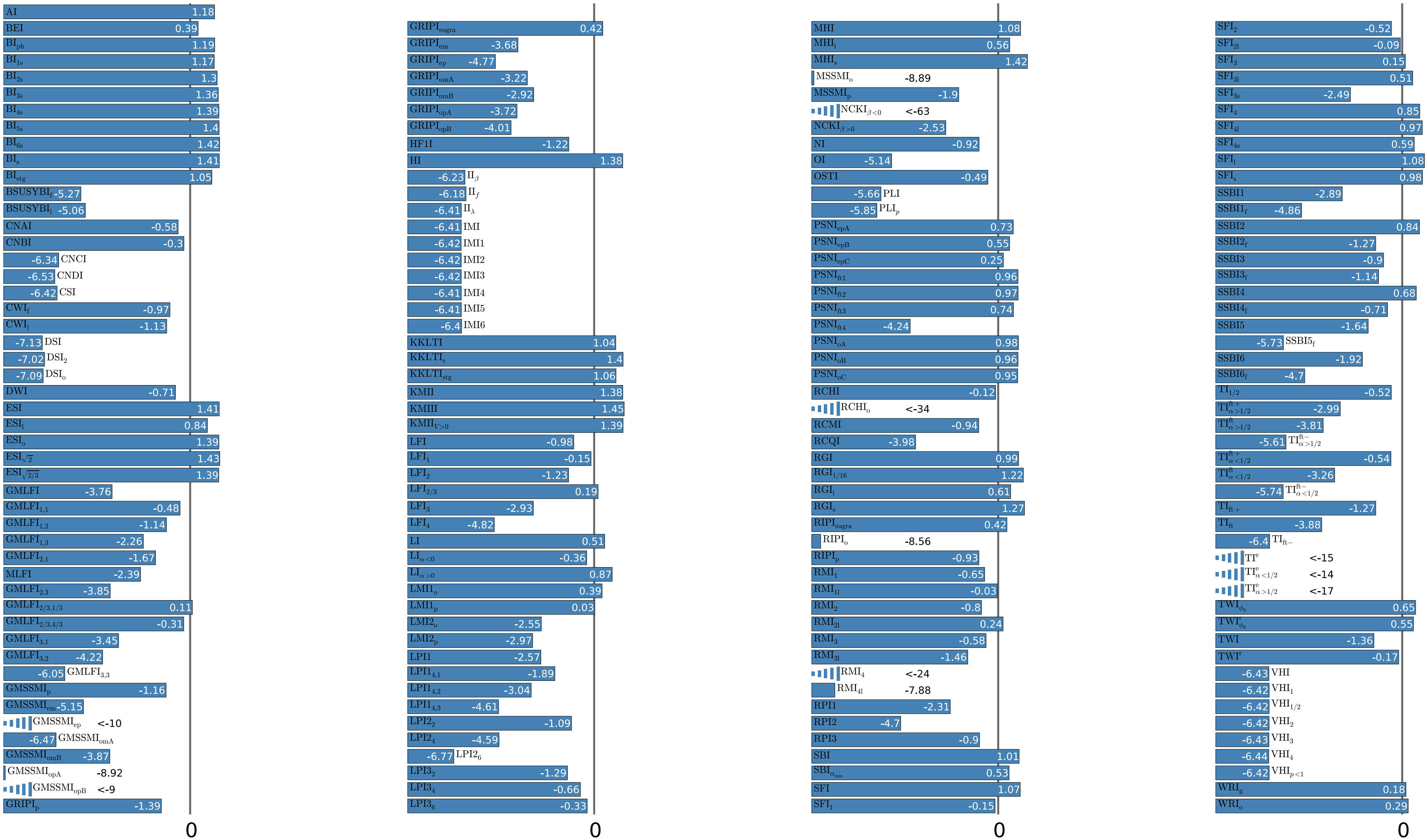
the posterior-to-prior ratio $N_{\mathrm{models}}\mathcal{E}\left(\mathcal{M}_i\right) / \sum \mathcal{E}\left(\mathcal{M}_j\right)$

represents the degree by which the data have modified our a priori relative belief

in a given model $\mathcal{M}_i$.

Posterior-to-Prior Ratio computed with Planck

Martin, Ringeval, V.V (2014)



Bayesian evidences computed with Planck

Martin, Ringeval, V.V (2014)

Summary of the results

Bayesian evidences computed with Planck

Martin, Ringeval, V.V (2014)

Summary of the results

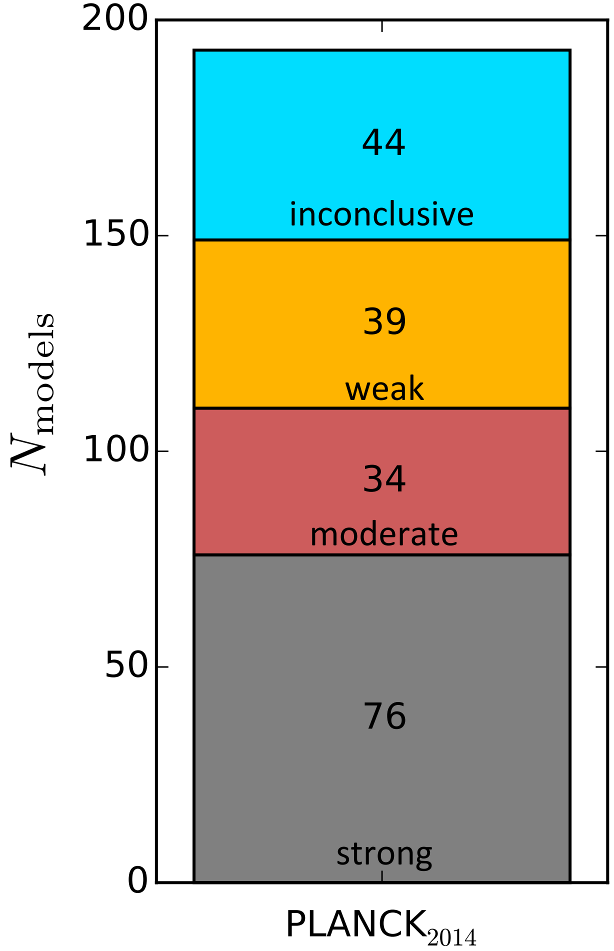
- One third of the models are "ruled out"

Bayesian evidences computed with Planck

Martin, Ringeval, V.V (2014)

Summary of the results

- One third of the models are "ruled out" according to the Jeffreys scale



Bayesian evidences computed with Planck

Martin, Ringeval, V.V (2014)

Summary of the results

- One third of the models are "ruled out"
- Planck favors "Plateau Inflation"

Bayesian evidences computed with Planck

Martin, Ringeval, V.V (2014)

Summary of the results

- One third of the models are "ruled out"
- Planck favors "Plateau Inflation"
- Some models are killed by "fine-tuning"

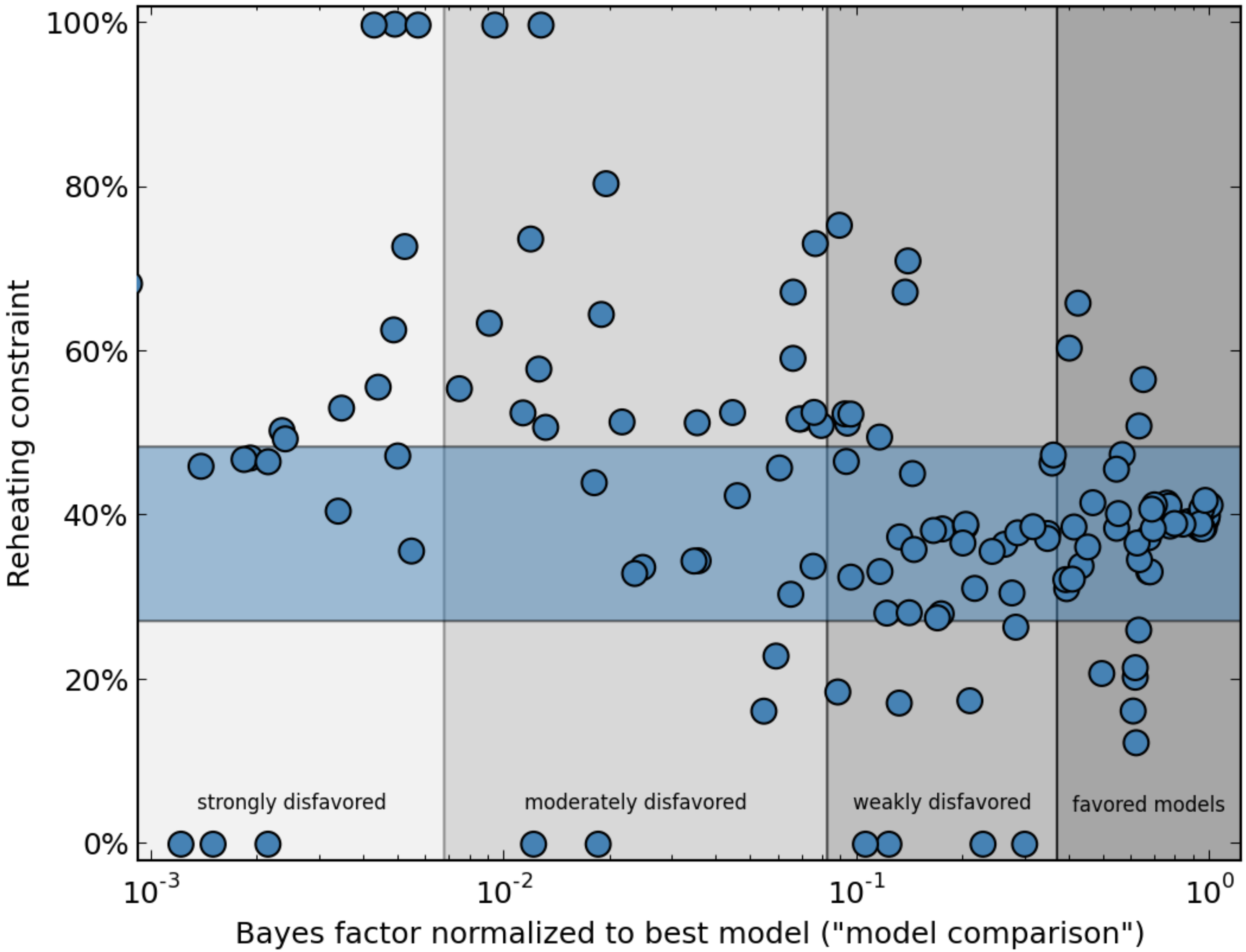
Constraints on Reheating

Martin, Ringeval, V.V (2014)

$$\ln R_{\rm reh} = \frac{1 - 3\bar{w}_{\rm reh}}{12\,(1 + \bar{w}_{\rm reh})} \ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right) + \ln\left(\frac{\rho_{\rm end}^{1/4}}{M_{_{\rm Pl}}}\right)$$

Constraints on Reheating

Martin, Ringeval, V.V (2014)



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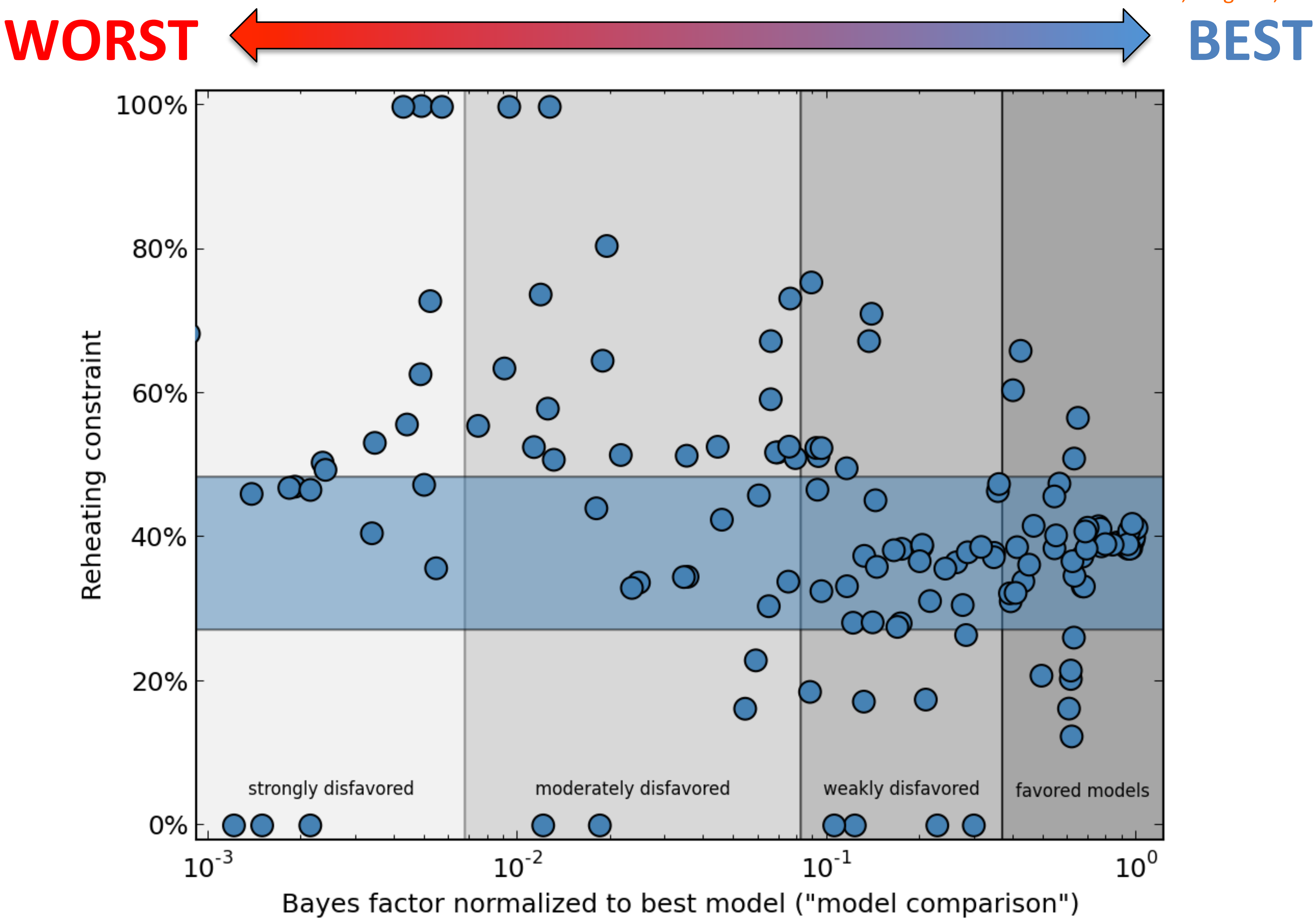

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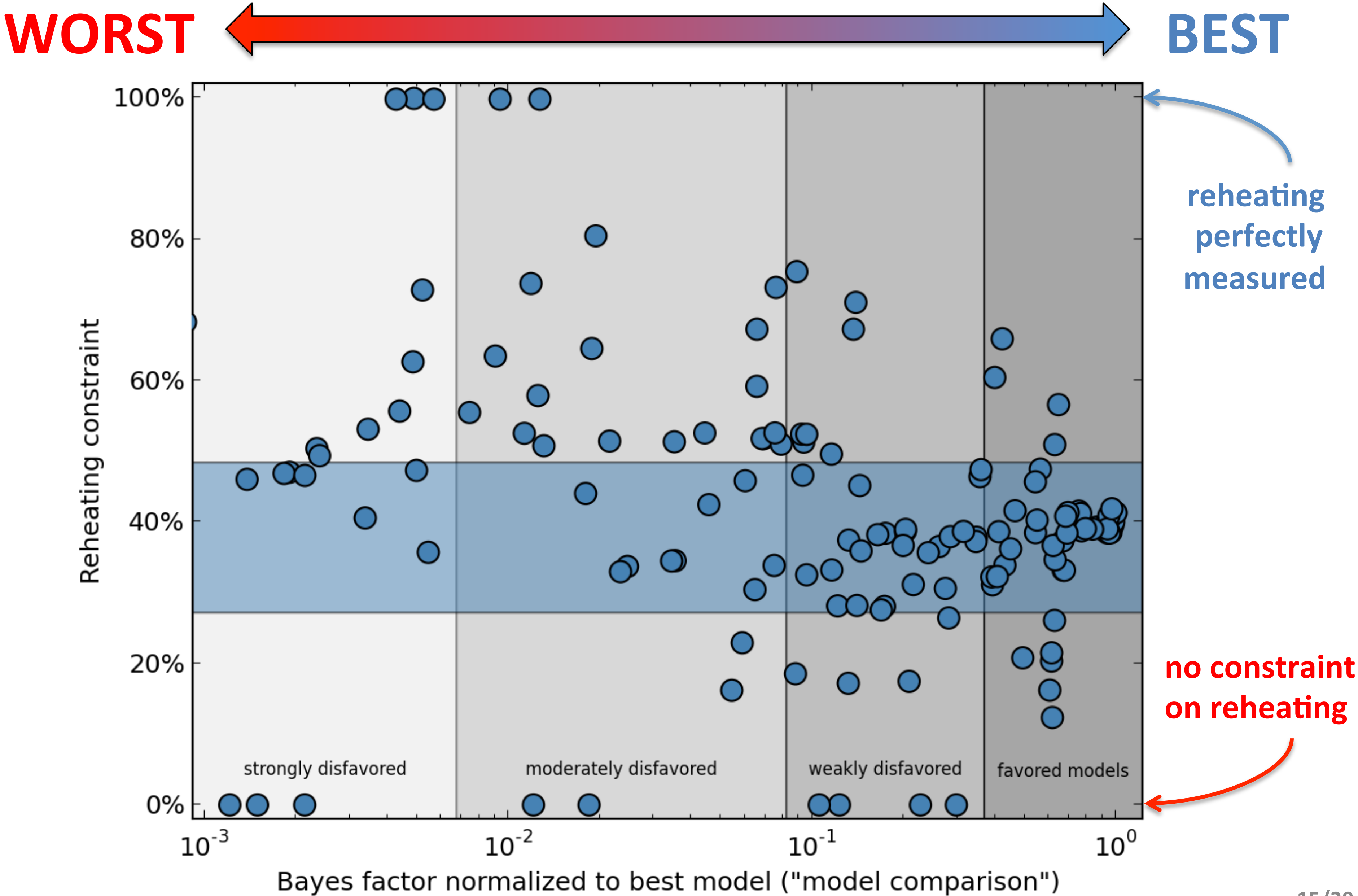
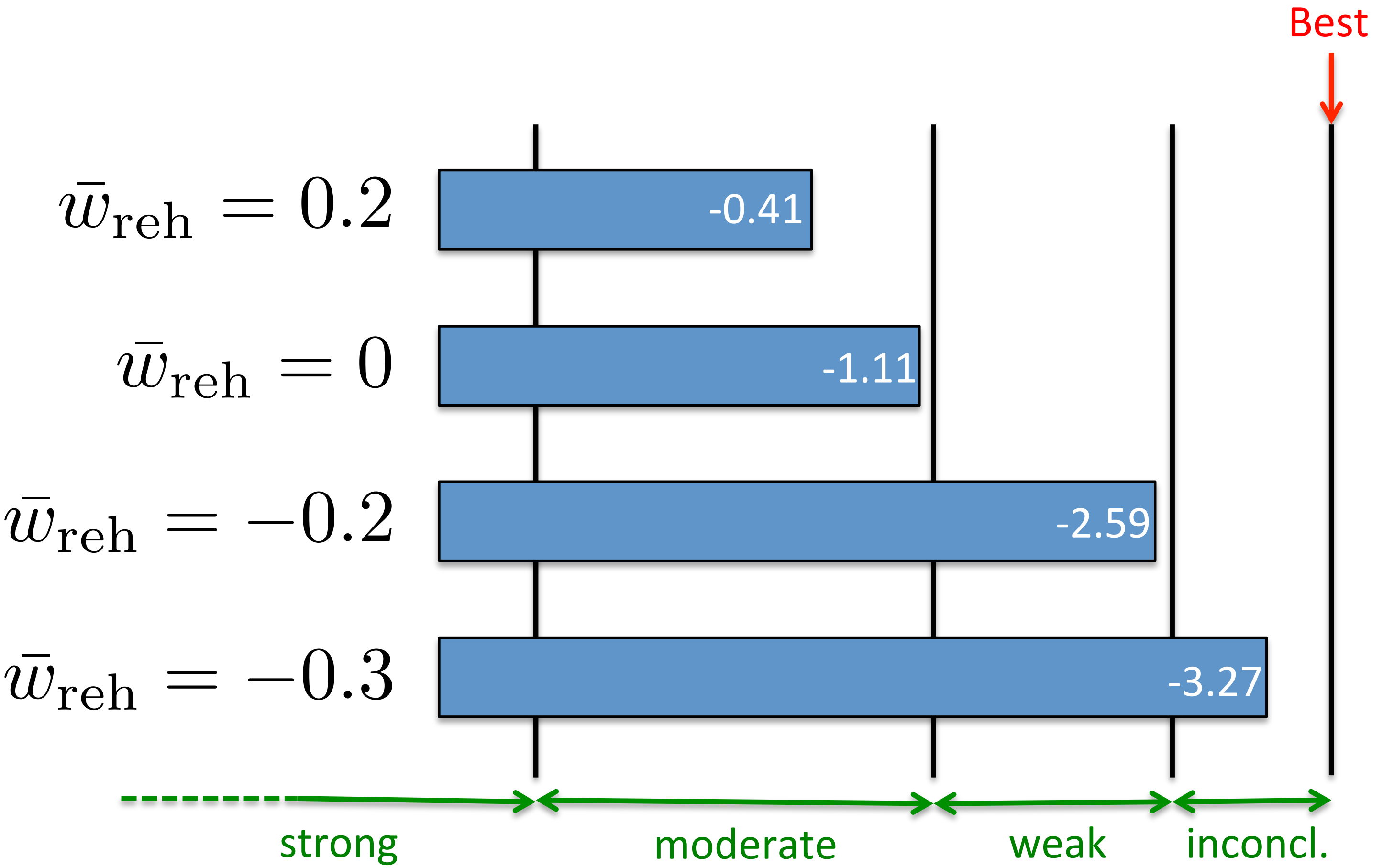


Reheating does Matters!

Martin, Ringeval, V.V (2014)

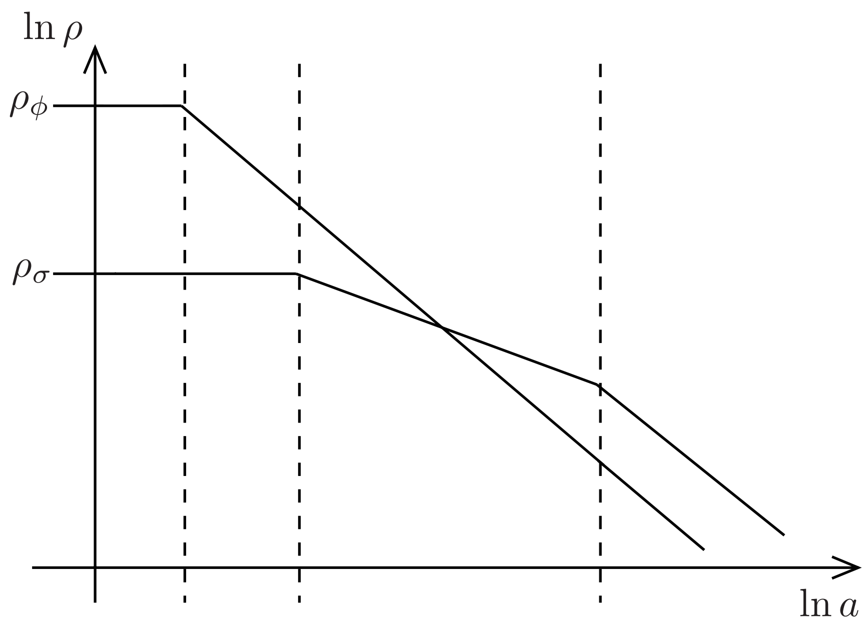
Example : $\mathrm{LI}_{\alpha>0}$ $$V(\phi) = M^4\left[1+\alpha\ln\left(\frac{\phi}{M_{\mathrm{Pl}}}\right)\right]$$



Adding a Light Scalar Field

Curvaton Scenarios

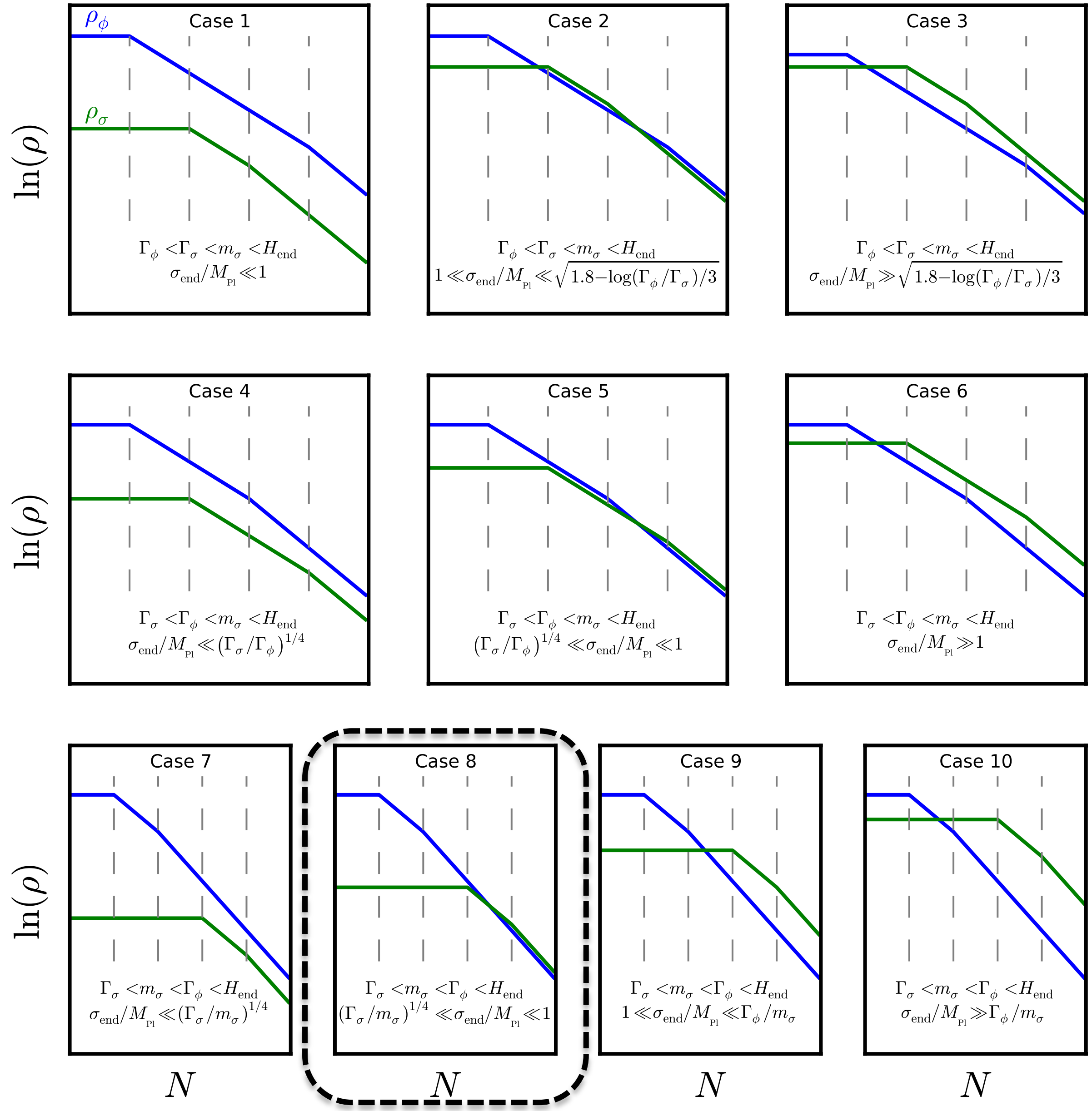
Linde and Mukhanov, 1997
Enqvist and Sloth, 2001
Lyth and Wands, 2001
Moroi and Takahashi, 2001
Langlois and Vernizzi, 2004



$$\zeta = \zeta_\phi + \zeta_\sigma \quad \Longleftrightarrow \quad \bar{w}_{\rm reh}\left(m_\sigma, \sigma_{\rm end}, \Gamma_\phi, \Gamma_\sigma\right)$$

Adding a Light Scalar Field

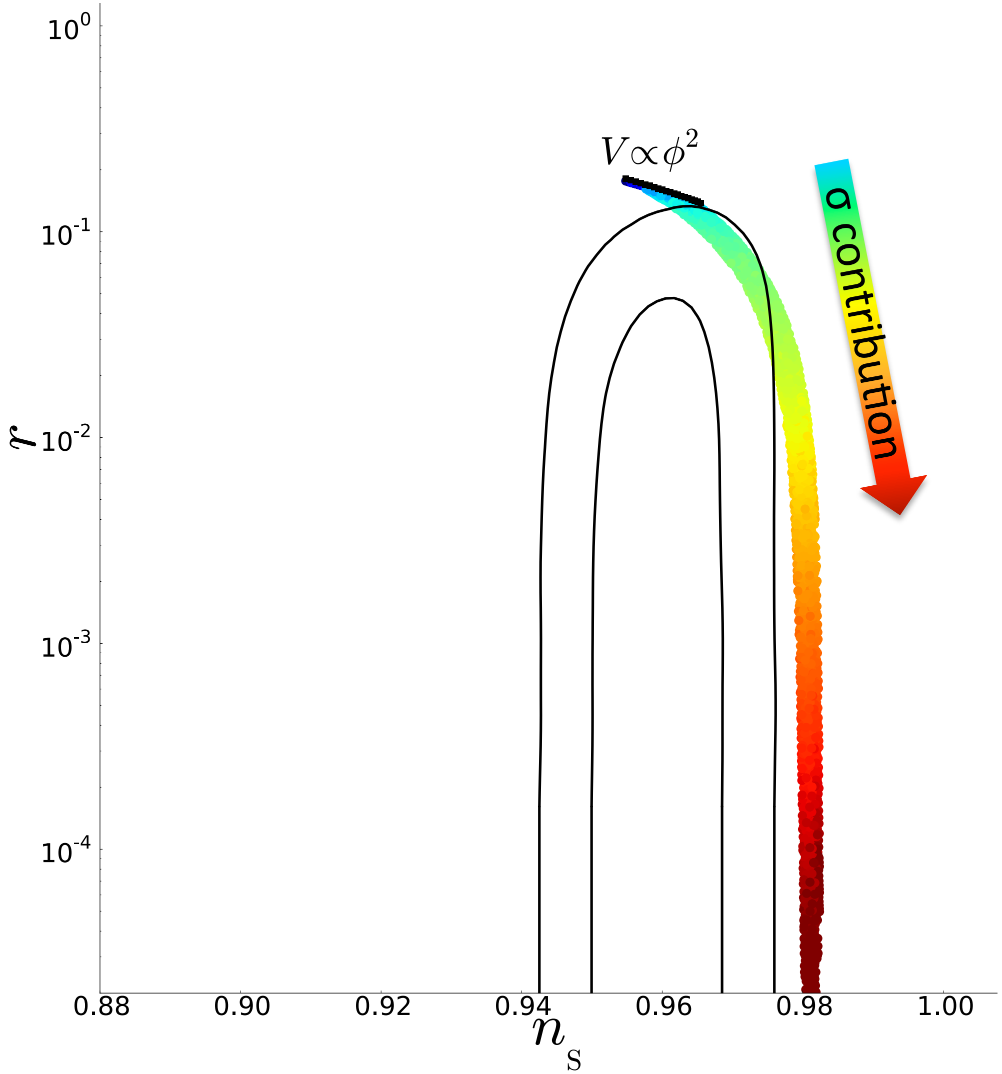
V.V, Koyama and Wands (2015)



Adding a Light Scalar Field

V.V, Koyama and Wands (2015)

CASE # 5



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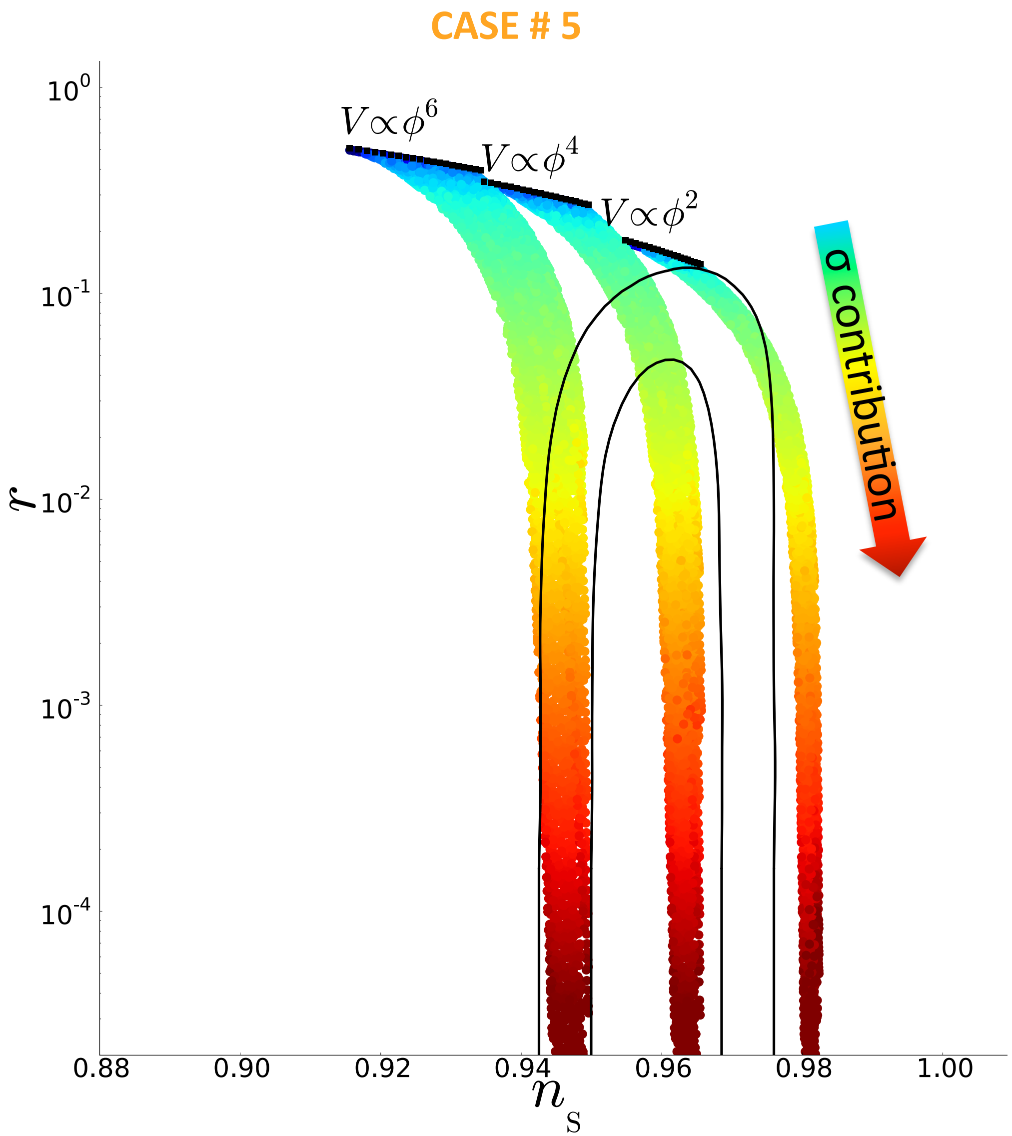
V.V, Koyama and Wands (2015)



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V.V, Koyama and Wands (2015)

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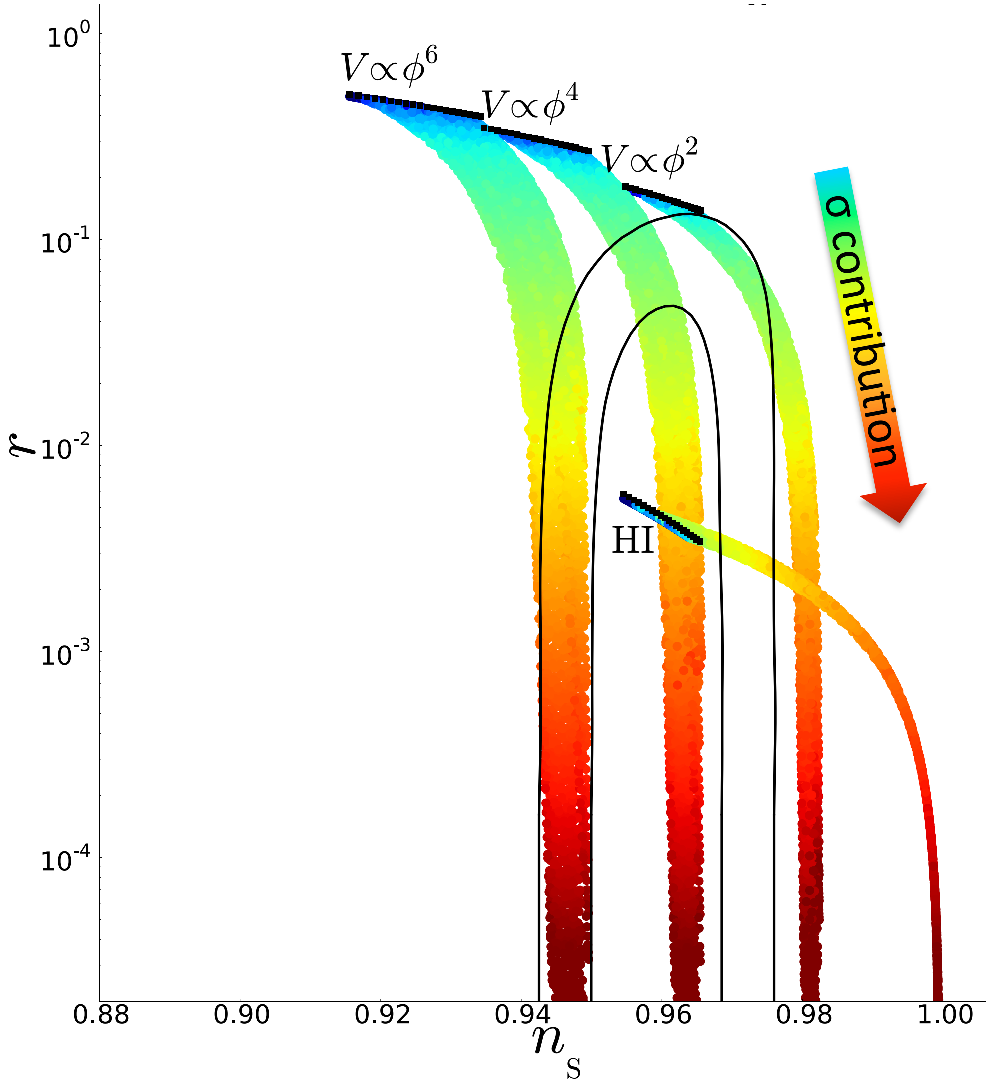
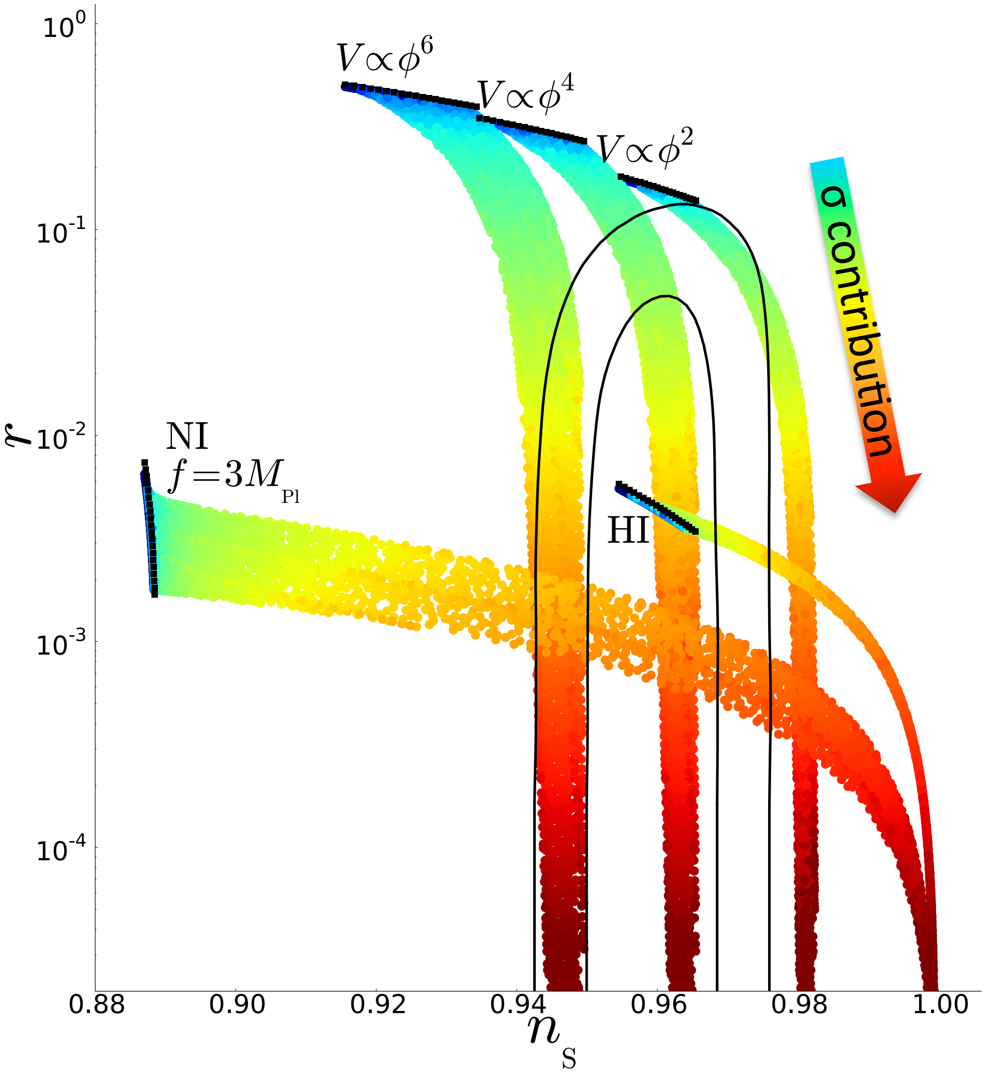


Adding a Light Scalar Field

V.V, Koyama and Wands (2015)

CASE # 5



Adding a Light Scalar Field

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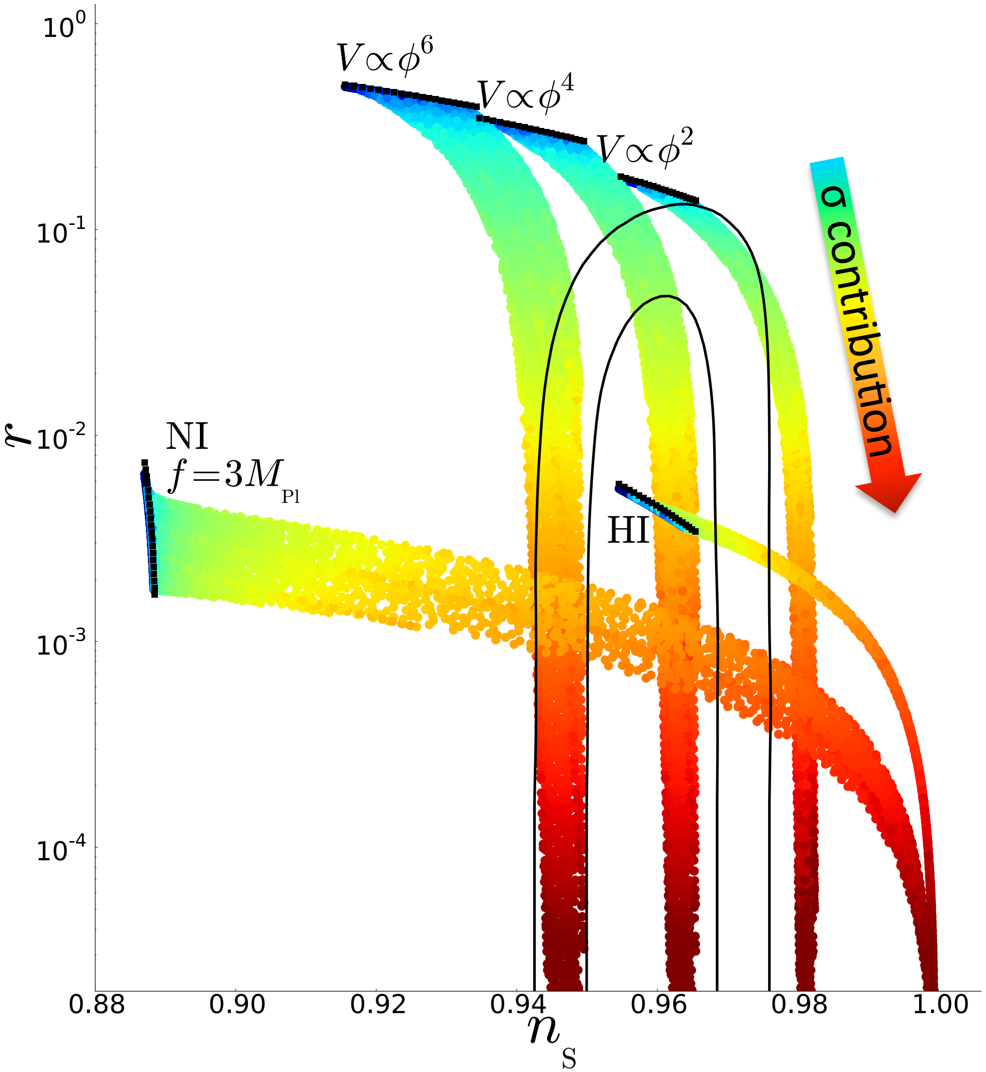
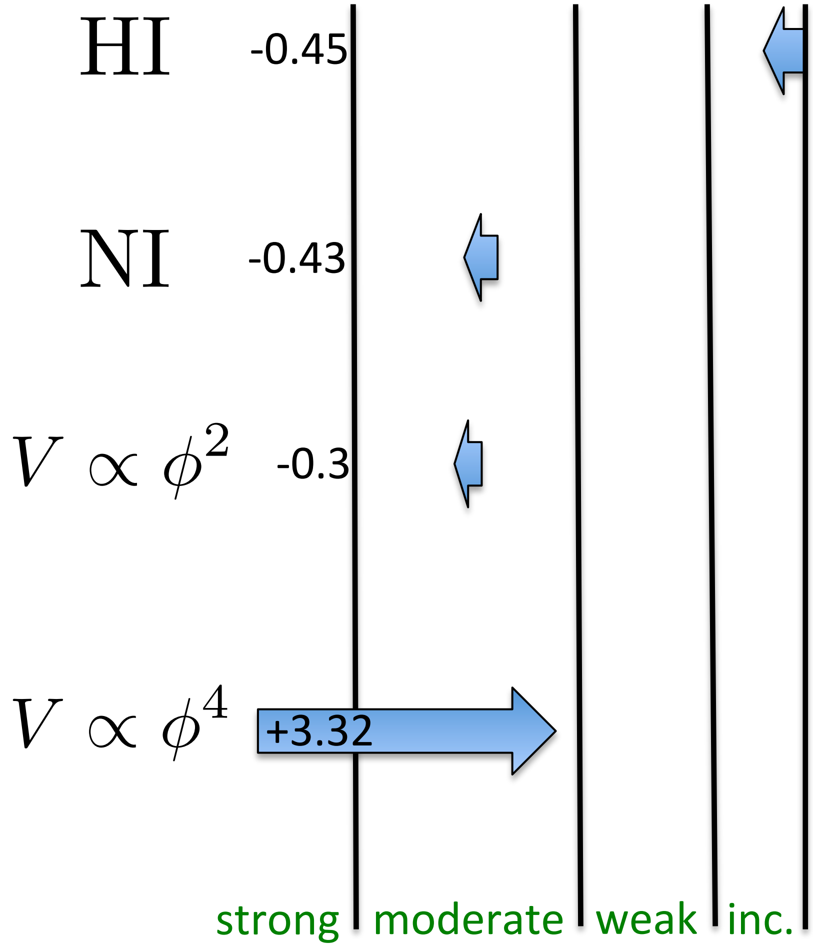


Averaging Over Cases:



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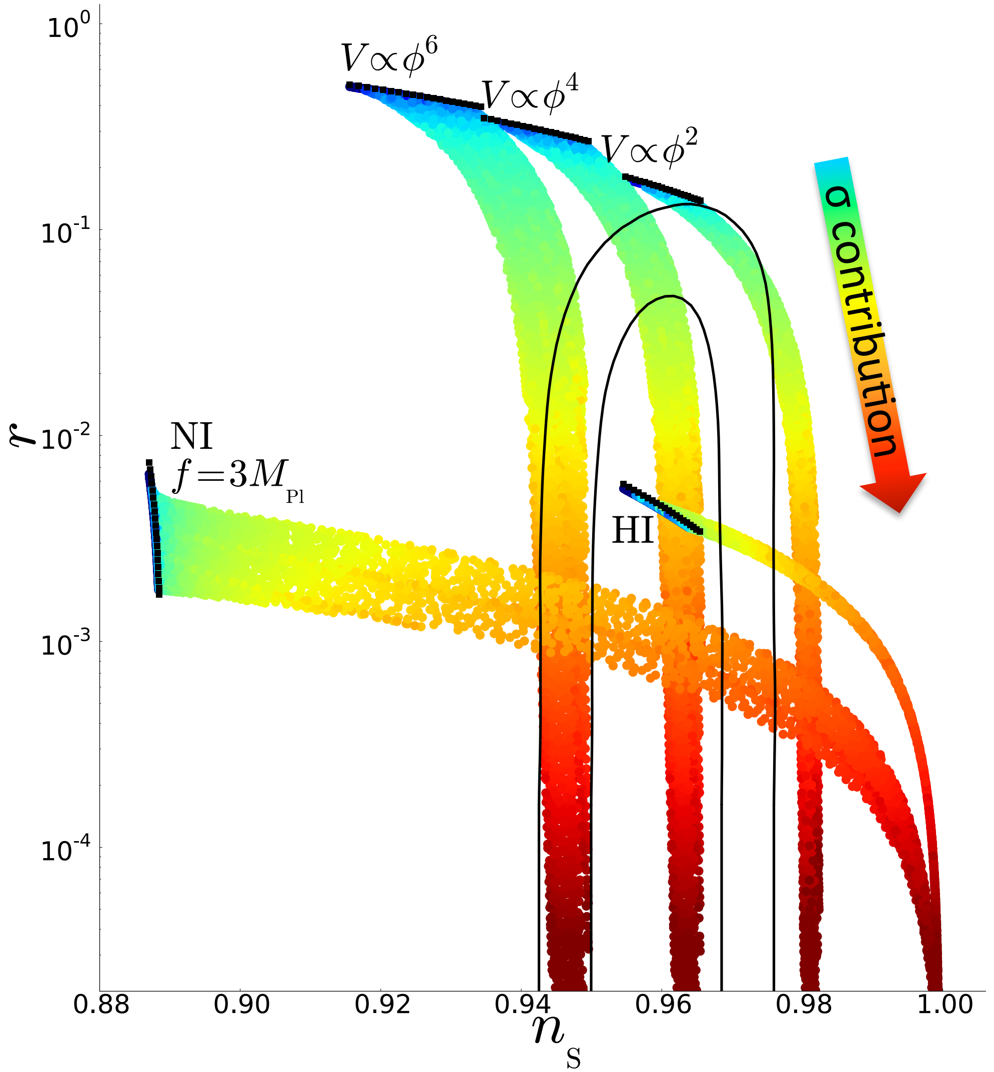

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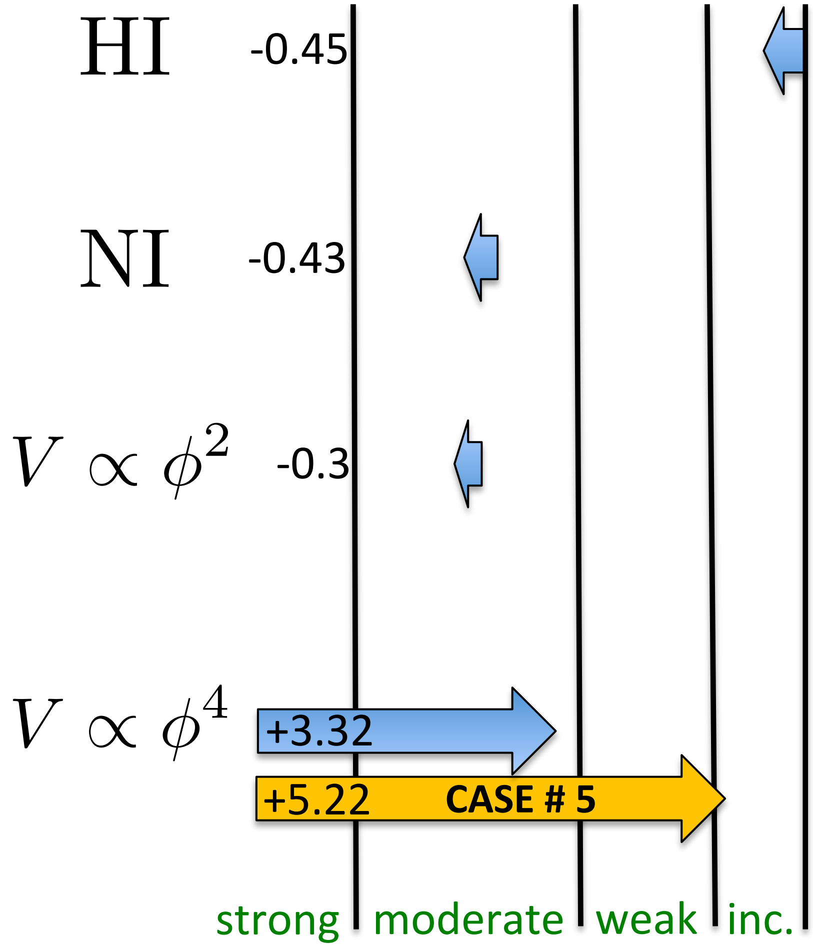

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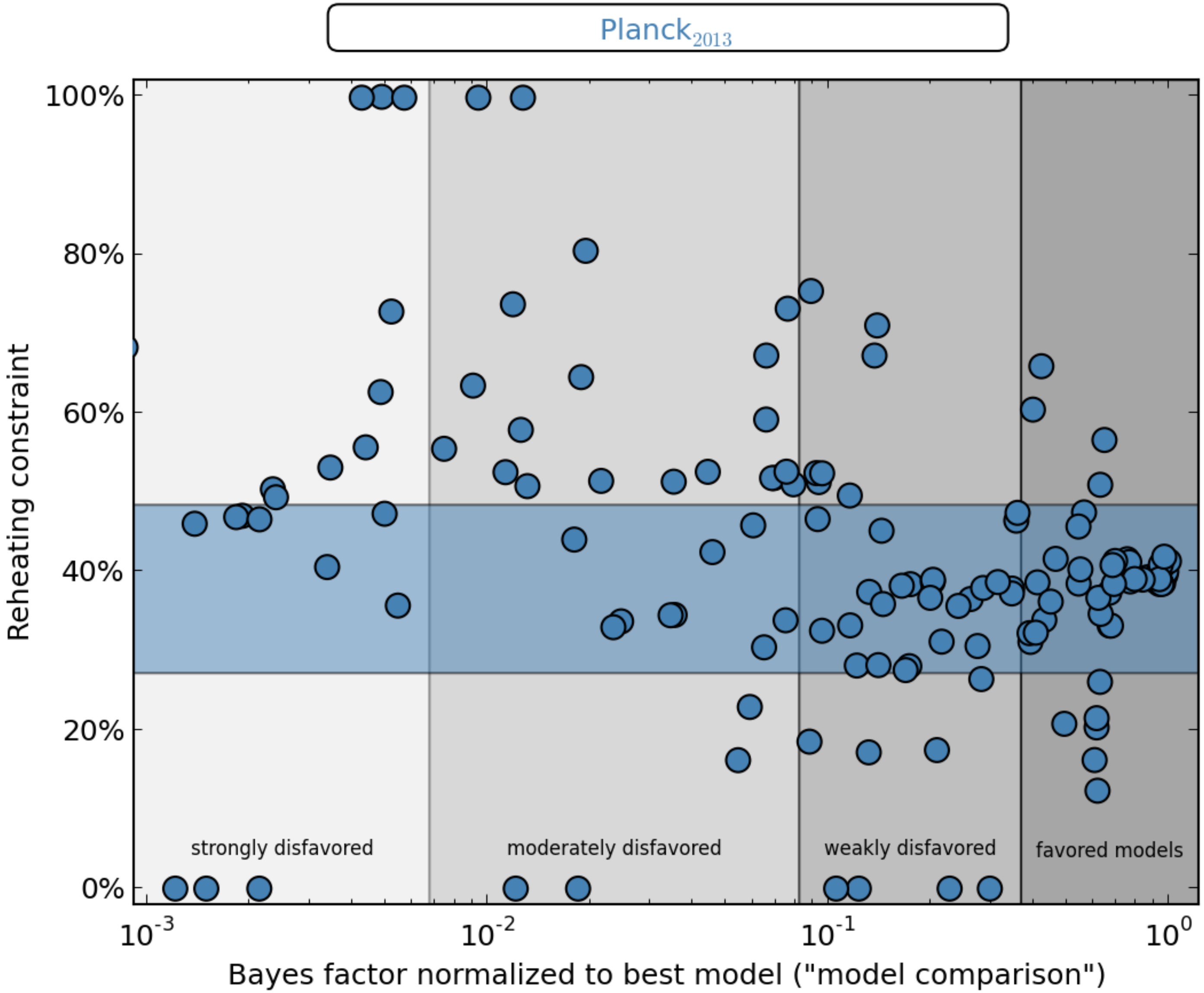
• **Prospects:** Future CMB missions?

Vennin for COrE+ proposal

Future CMB Missions



Vennin for COrE+ proposal

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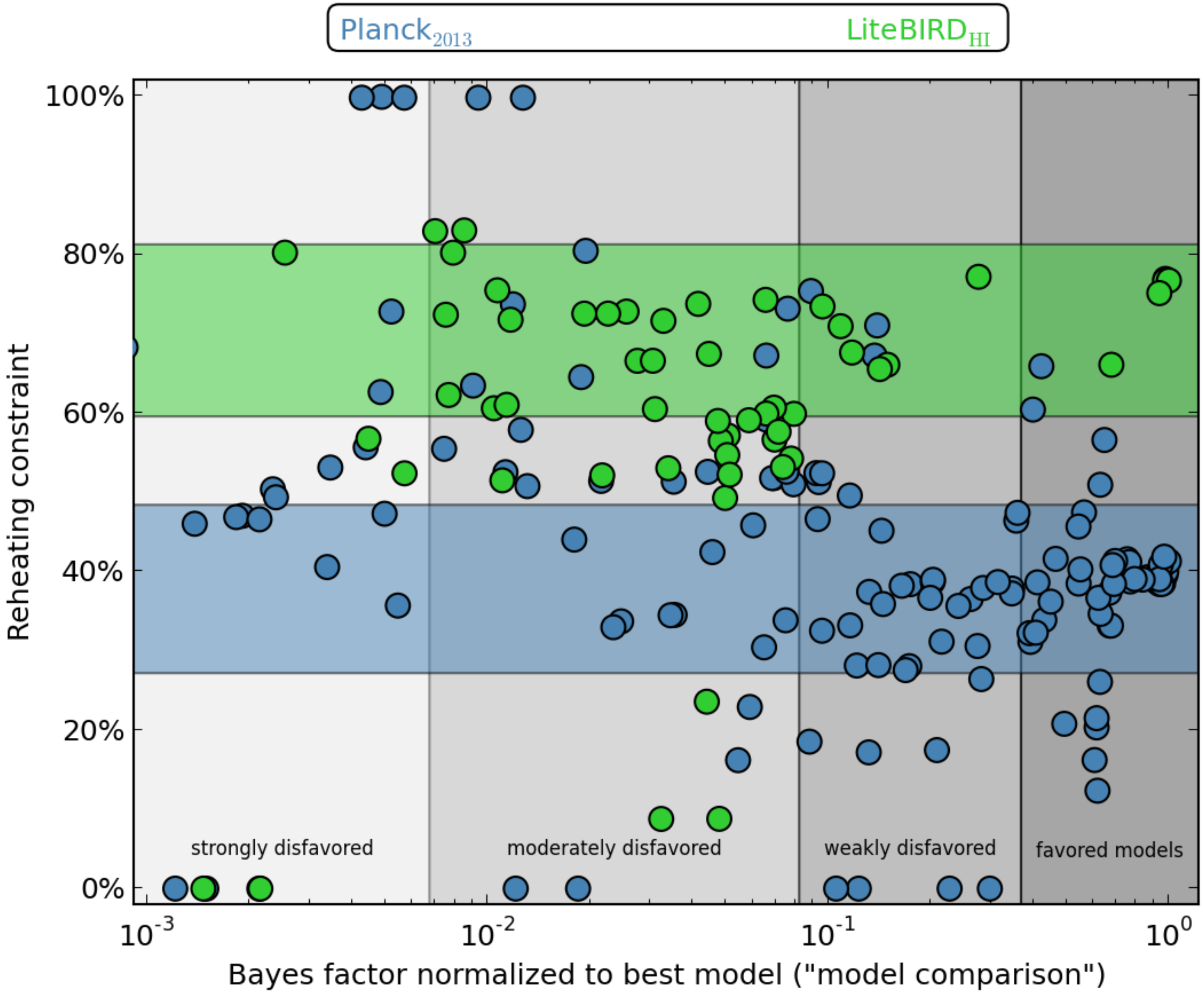

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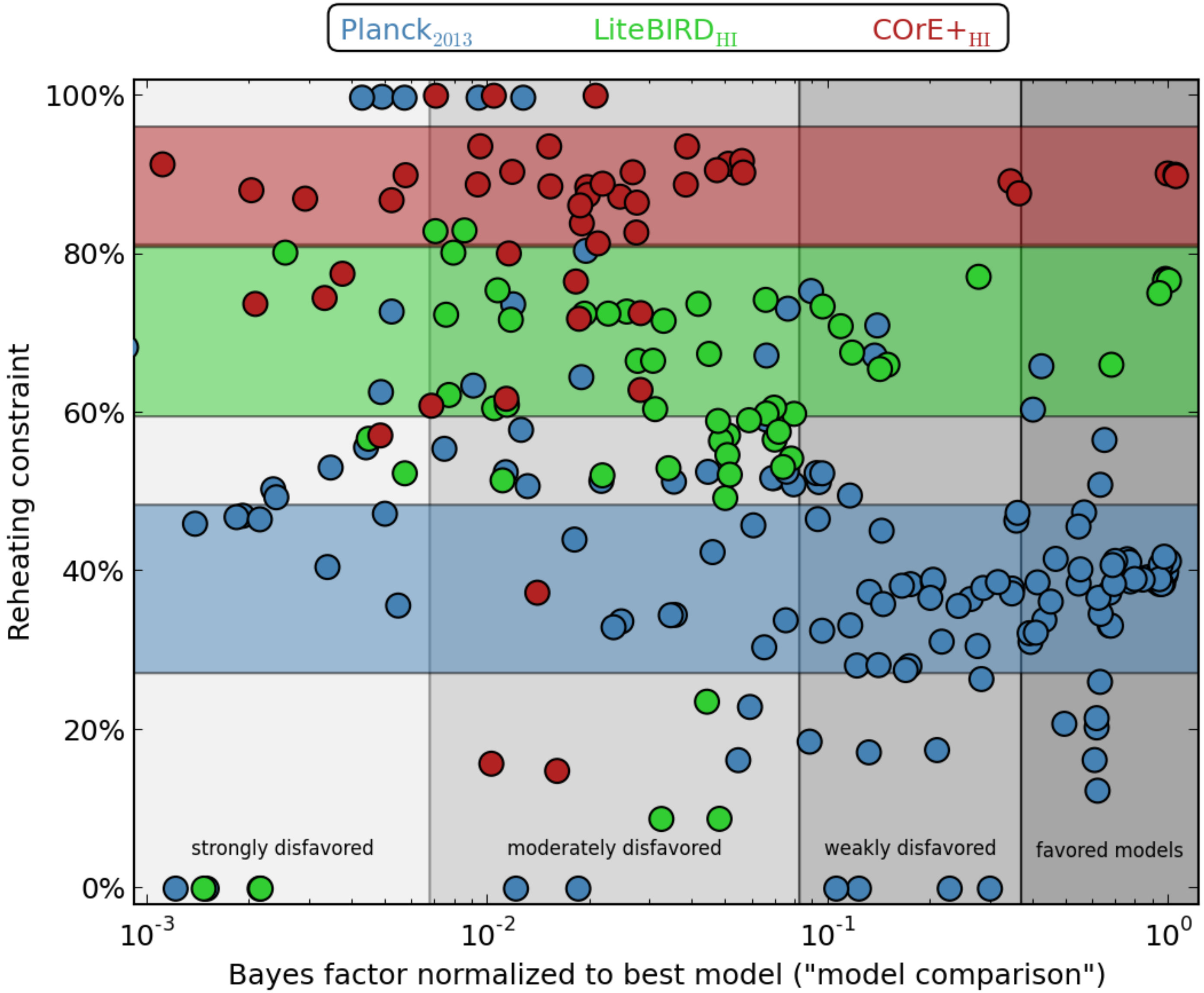
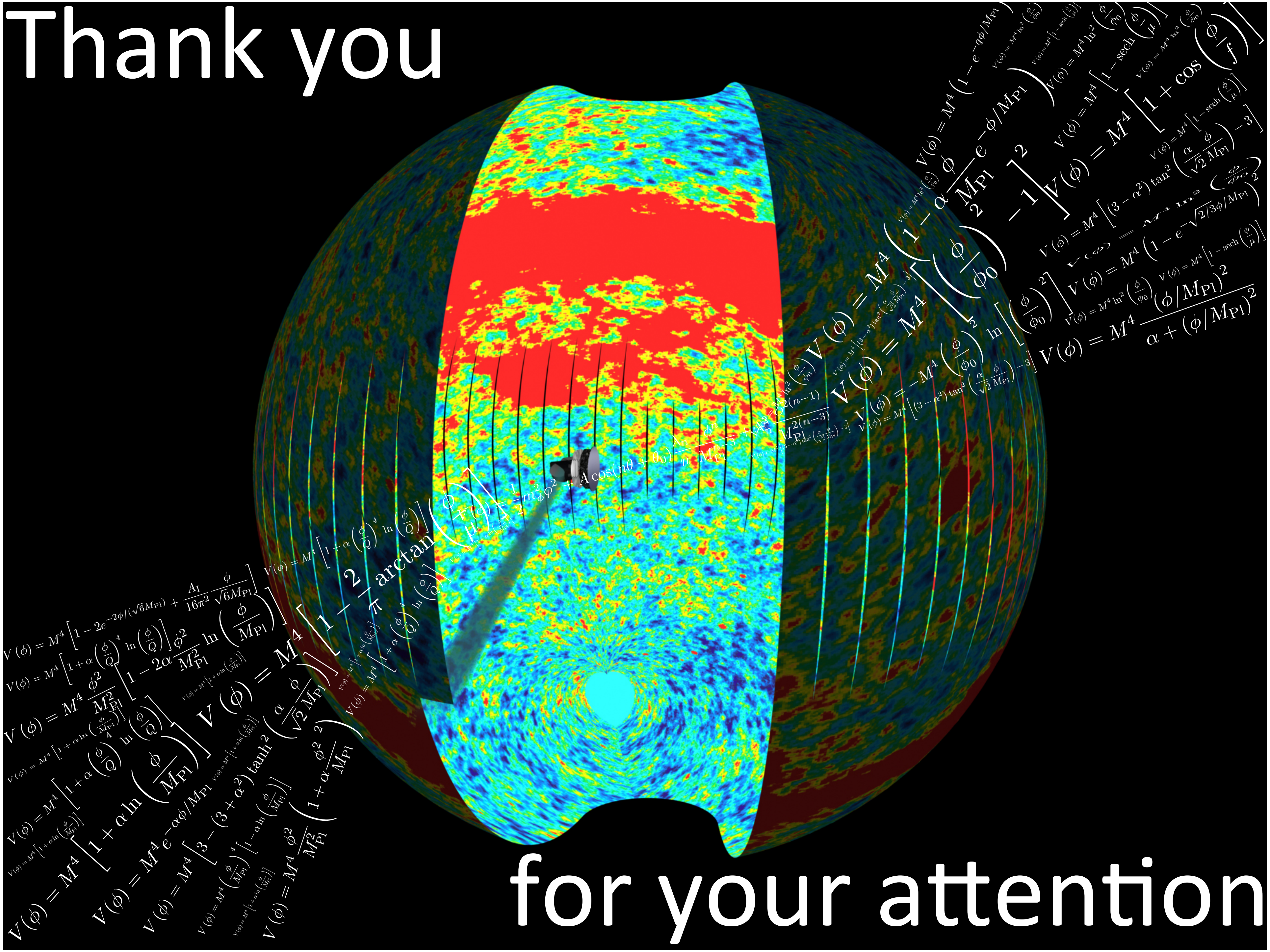


Thank you



for your attention