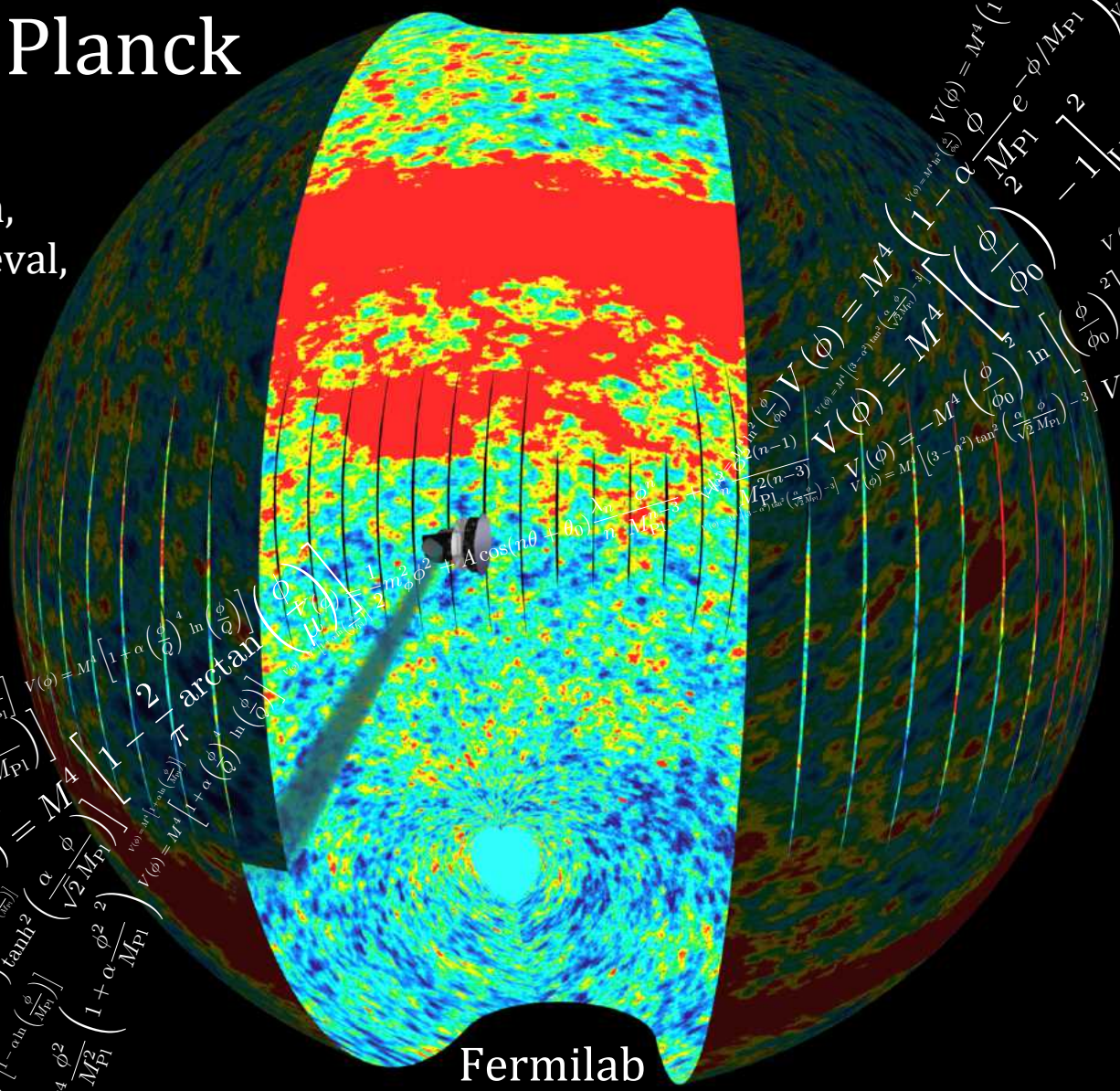
Inflationary Models after Planck

Jérôme Martin,
Christophe Ringeval,
VV



Fermilab

IAP, France

Vincent Vennin

November 22, 2013

Outline

- Introduction: Inflation in a nutshell
- Which class of models is favored after Planck? Single Field Slow-Roll Models!
- Computing the observable predictions of single field slow-roll models. Which accuracy do we need after Planck?
- Model Comparison: **What is the Best Model of Inflation?** Encyclopaedia Inflationaris and the ASPIC project
- Conclusions & Summary

Cosmological Inflation

Cosmological Inflation

- Is a high energy phase of accelerated expansion in the early Universe $\ddot{a} > 0$

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2\left(t\right)\mathrm{d}\vec{x}^2$$

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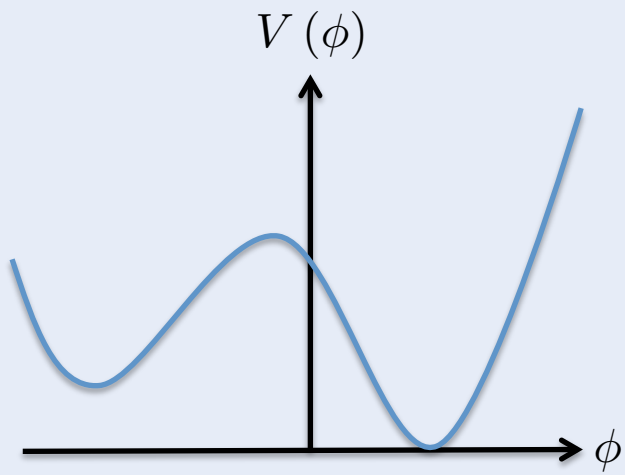
$$\Rightarrow \begin{cases} \rho = \frac{1}{2}\left(\dot{\phi}\right)^2 + V(\phi) \\ p = \frac{1}{2}\left(\dot{\phi}\right)^2 - V(\phi) \end{cases}$$



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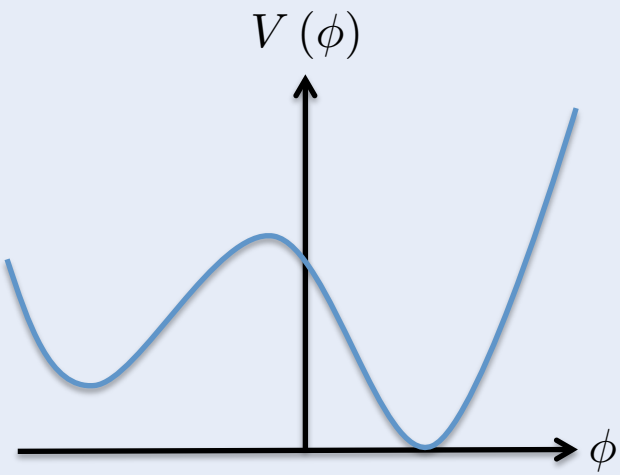
$$\ddot{a}/a = -\frac{1}{6M_{\mathrm{P}}^2}(\rho + 3p) \quad \Longrightarrow \quad V(\phi) \gg \dot{\phi}^2$$



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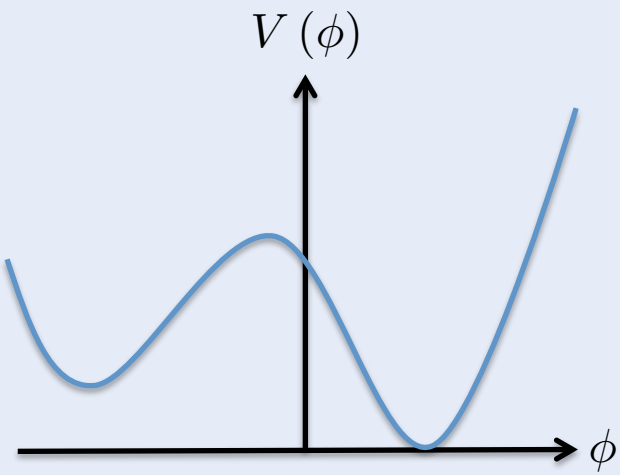

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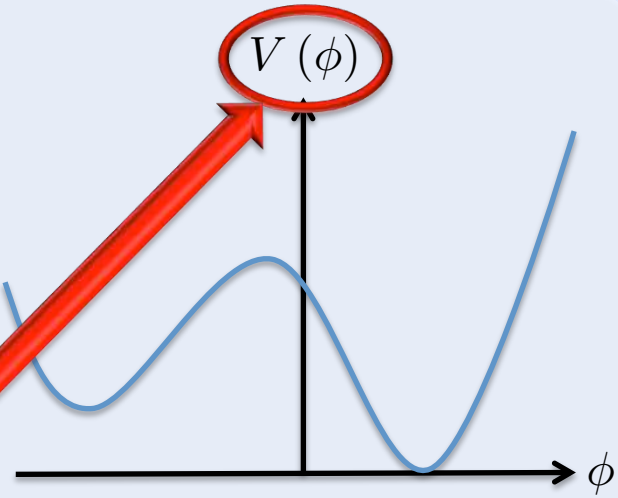

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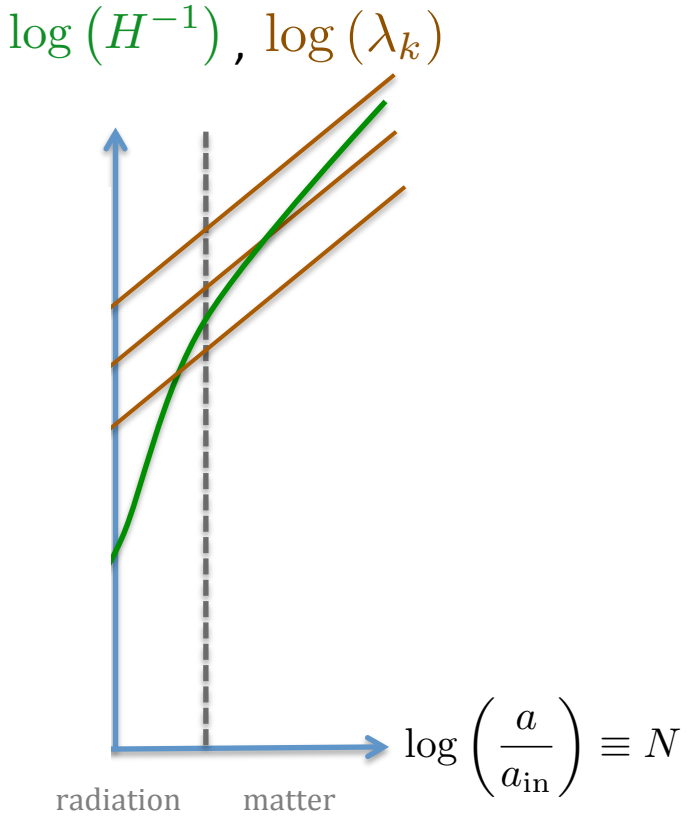
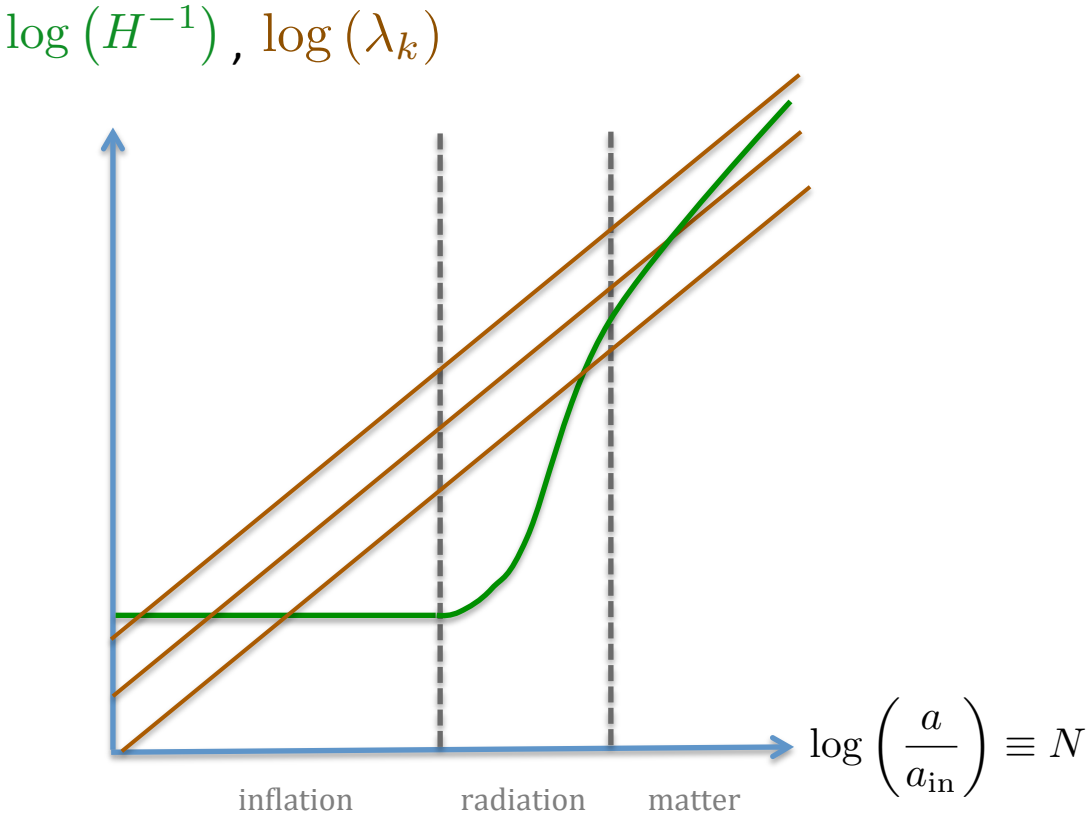
Cosmological Inflation

Solves the Horizon Problem



Cosmological Inflation

Quantized fluctuations evolved over an expanding background



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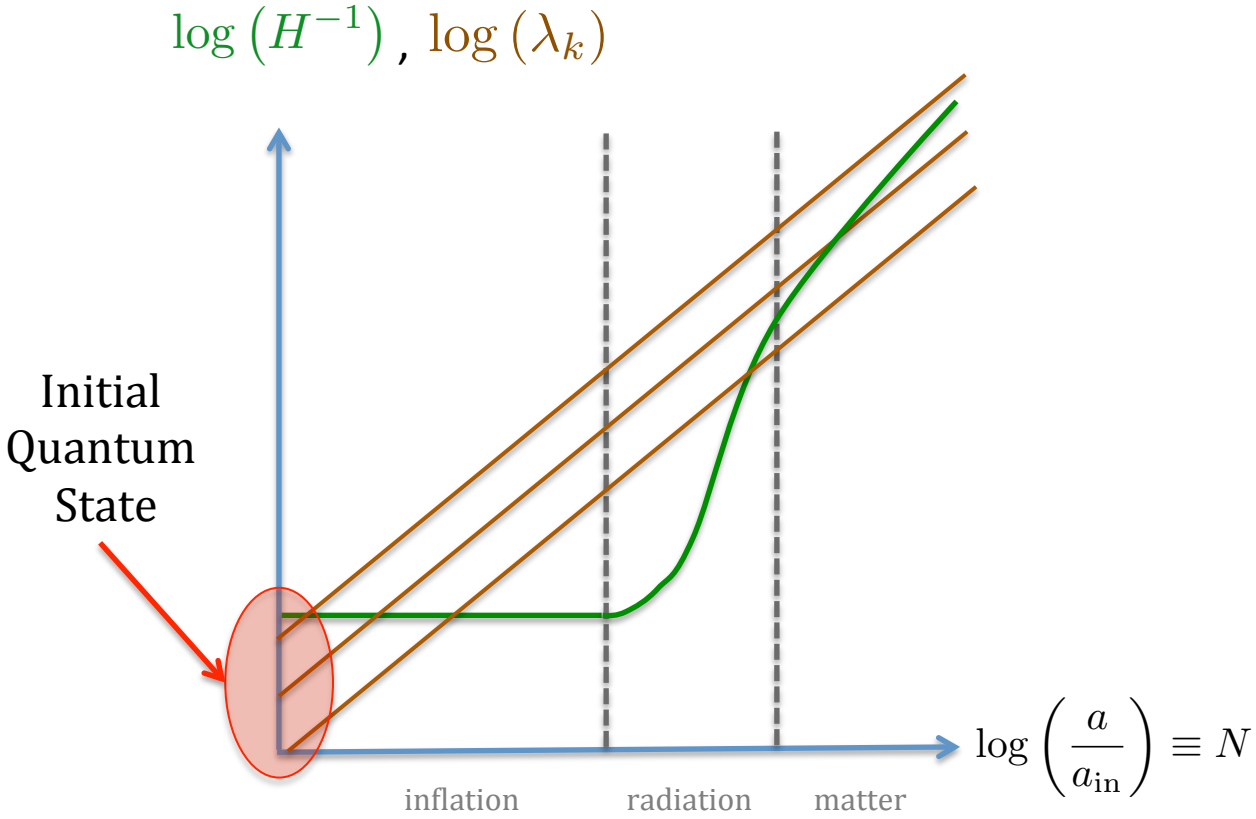

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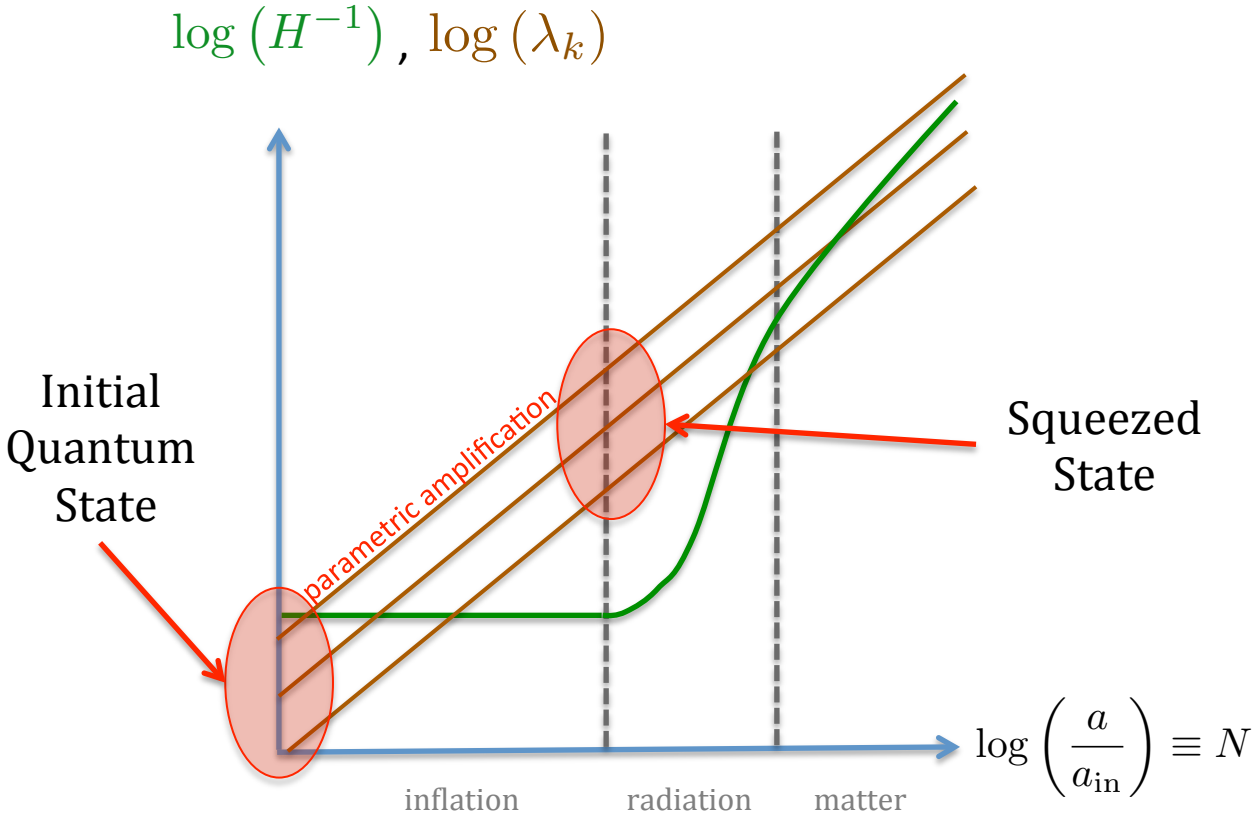

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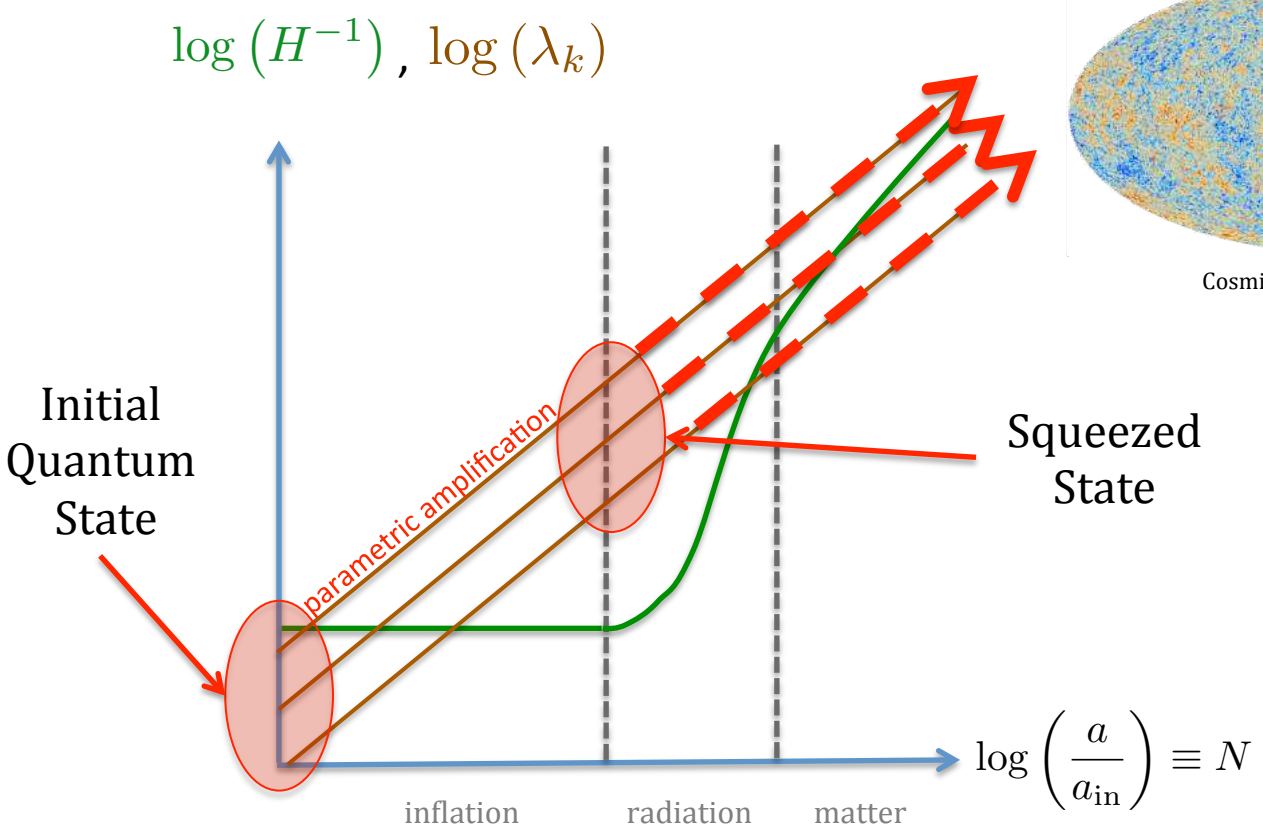
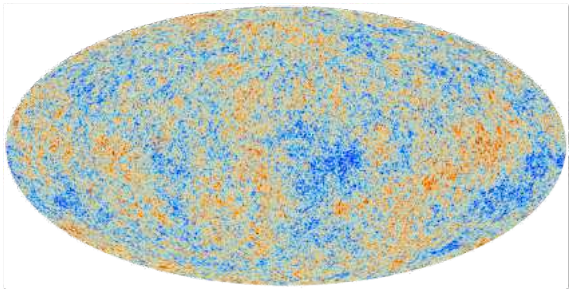
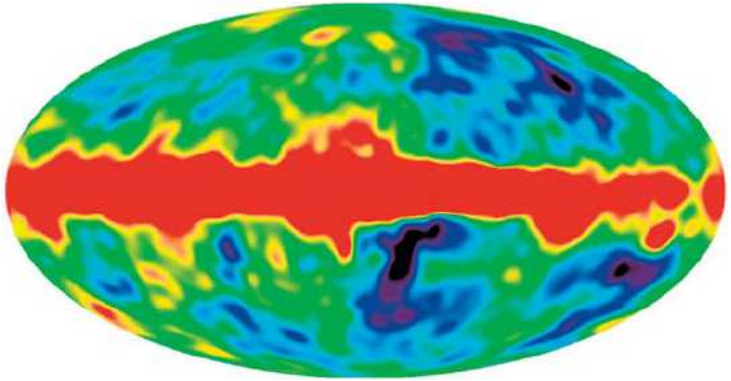


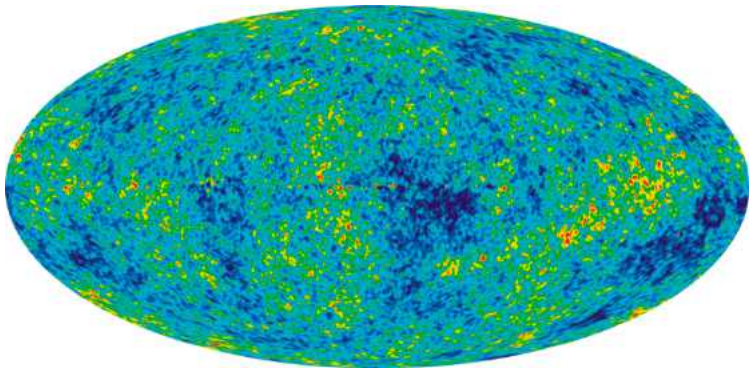


Cosmic Microwave Background

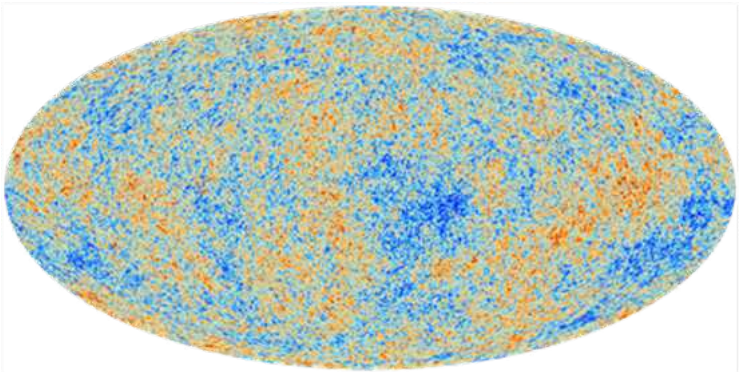
Increased Accuracy Observations



COBE (1992)



WMAP (2003)



Planck (2013)

Increased Accuracy Observations

	n_S ($\pm1\sigma$)	r (95%CL)	α_S ($\pm1\sigma$)	f_{nl}^{local} ($\pm1\sigma$)	$\mathcal{I}/\mathcal{R}$ (95%CL)
COBE 2	1.21 ± 0.57				
COBE 4	1.20 ± 0.3				
WMAP 1	1.20 ± 0.11	<0.81	-0.077 ± 0.05	40 ± 49	<32%
WMAP 3	0.984 ± 0.029	<0.65	-0.055 ± 0.03	30 ± 42	
WMAP 5	0.960 ± 0.013	<0.43	-0.037 ± 0.028	51 ± 30	<16%
WMAP 7	0.968 ± 0.012	<0.36	-0.034 ± 0.026	32 ± 21	<13%
WMAP 9	0.972 ± 0.0013	<0.13	-0.019 ± 0.025	37.2 ± 19.9	<15%
Planck 2013	0.9603 ± 0.007	<0.11	-0.013 ± 0.009	2.7 ± 5.8	<3.6%

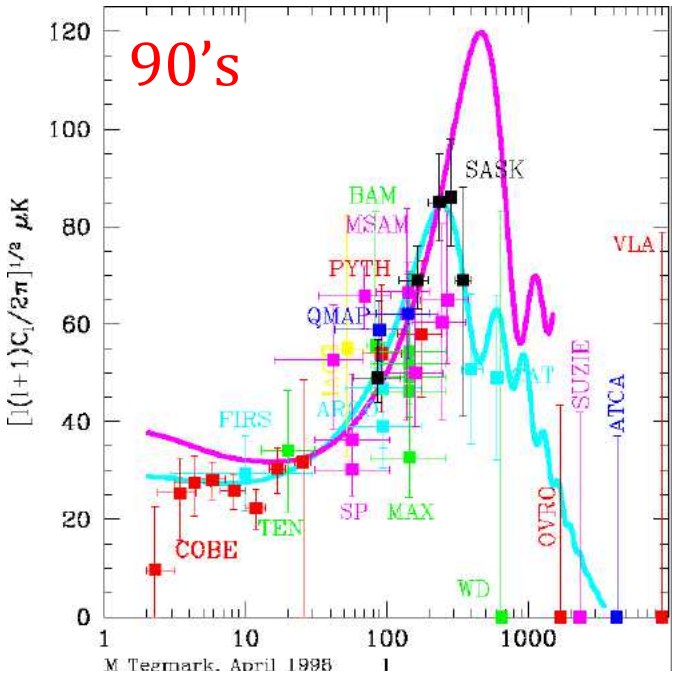
Flat universe with adiabatic, Gaussian
and almost scale invariant fluctuations

Observables / Physical Models	Regular Single Field	Single Field with Features	Single Field Non-canonical K-term	Multiple Field	...
scalar power spectrum $n_S \sim 1$ $\alpha_S \sim 0$	✓	DANGER	✓	✓	...
entropic & adiabatic perturbations $\mathcal{I} \ll \mathcal{R}$	✓	✓	✓	DANGER	...
gravity waves $r < 1$	✓	✓	✓	✓	...
non gaussianities $f_{\rm nl}^{\rm local} \lesssim 1$	✓	DANGER	DANGER	DANGER	...

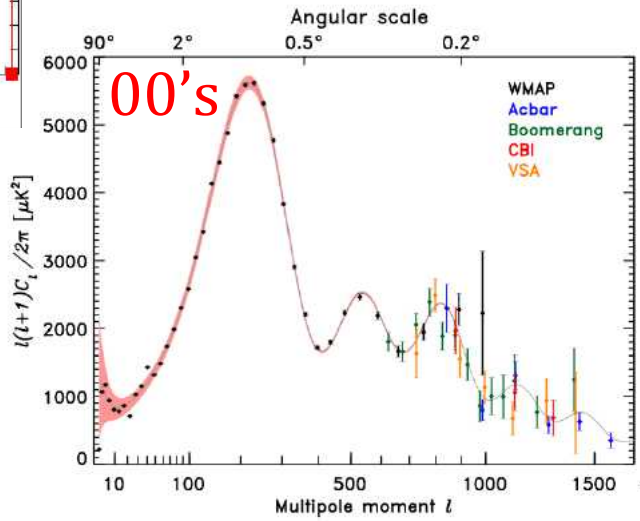
GOAL

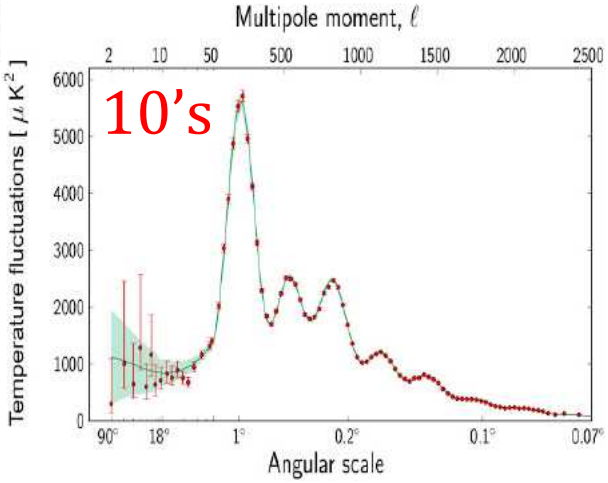
Find the correct single field scenario
from the measurement of the two point correlation function
(the fluctuations are Gaussian)

What is the shape of the potential??



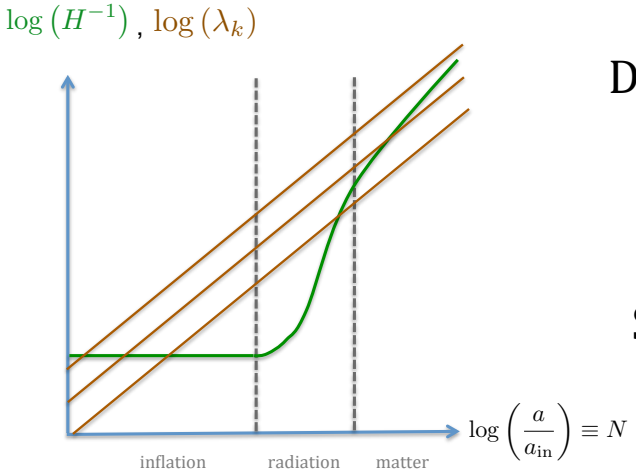
From COBE to Planck ...





One needs a general calculation of the two-point correlation function for single field inflation

Slow-Roll Approximation



During inflation, H is almost constant

$$\epsilon_0 = \frac{H_{\rm in}}{H} \simeq \text{constant}$$

Slow-Roll hierarchy: $$\epsilon_{n+1} = \frac{1}{\epsilon_n}\frac{\mathrm{d}\epsilon_n}{\mathrm{d}N}$$

Friedmann equation: $3M_{\rm Pl}^2 H^2 = V + \dot{\phi}^2/2$

Klein Gordon equation: $\cancel{\ddot{\phi}} + 3H\dot{\phi} + V_\phi = 0$

$$\Longrightarrow \epsilon_1 = 3\frac{\dot{\phi}^2/\left(2V\right)}{1+\dot{\phi}^2/\left(2V\right)} \ll 1$$

$$\Rightarrow \dot{\phi}^2/V \ll 1$$ « slow roll »

$$\epsilon_1 \simeq \frac{1}{2M_{\rm Pl}^2}\left(\frac{V_\phi}{V}\right)^2 \qquad \epsilon_2 \simeq \frac{2}{M_{\rm Pl}^2}\left[\left(\frac{V_\phi}{V}\right)^2 - \frac{V_{\phi\phi}}{V}\right] \qquad \epsilon_3 \simeq \text{etc...}$$

Scalar Power Spectrum

Cosmological Fluctuations:

- are combined gauge invariant perturbations of the metric and of the inflaton field v
- are the seeds of temperature anisotropies in the CMB $v \propto \frac{\delta T}{T}$
- Follow a parametric amplifying equation of motion

$$v_{\boldsymbol{k}}'' + \left[k^2 - \frac{\left(a\sqrt{\epsilon_1}\right)''}{a\sqrt{\epsilon_1}}\right] v_{\boldsymbol{k}} = 0$$

Power Spectrum:

$$P_v(k) = \frac{k^3}{2\pi^2}\left\langle \hat{v}_k^2 \right\rangle$$

$$= \frac{a^2 H^2}{8\pi^2 M_{\rm Pl}^2 \epsilon_{1\diamond}}\left[1 - \left(2\epsilon_{1\diamond} + \epsilon_{2\diamond} + \cdots\right)\ln\frac{k}{k_\diamond} + \left(2\epsilon_{1\diamond}^2 + \epsilon_{1\diamond}\epsilon_{2\diamond} + \frac{\epsilon_{2\diamond}^2}{2} - \frac{\epsilon_{2\diamond}\epsilon_{3\diamond}}{2} + \cdots\right)\ln^2\frac{k}{k_\diamond} + \cdots\right]$$

Spectral index $n_{\rm S} = \left.\frac{{\rm d}\ln P}{{\rm d}\ln k}\right|_{k_*}$

$n_{\rm S}^{\rm Planck} \sim 0.96$

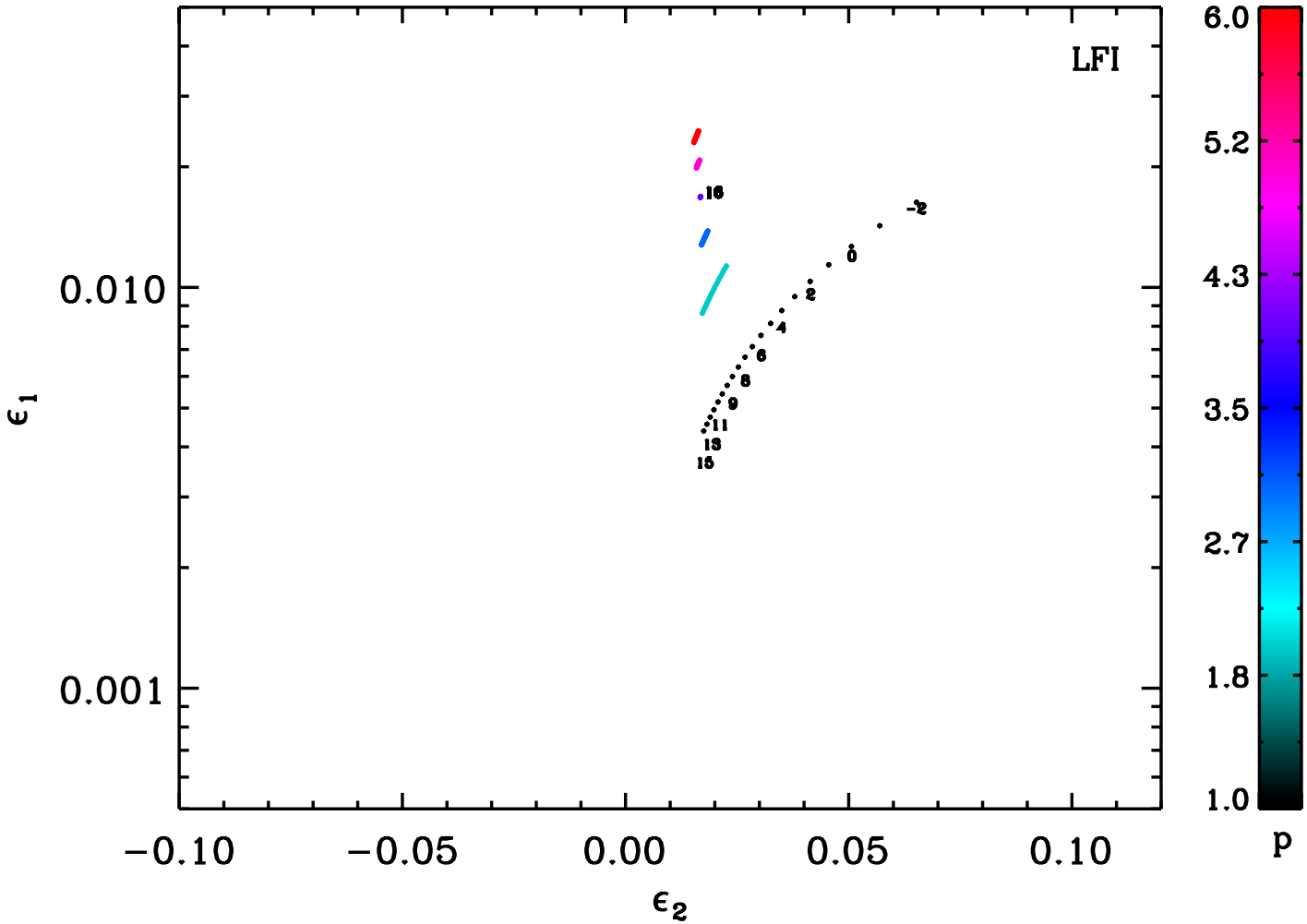
Gravity waves:

$$r = \frac{P_h(k_*)}{P_v(k_*)} = 16\epsilon_{1*} + \cdots$$

Confronting Models with Data

An example: « large field inflation »

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



The calculation of the inflationary predictions involves three steps:

1 – Expressing the power spectrum in terms of the slow-roll parameters

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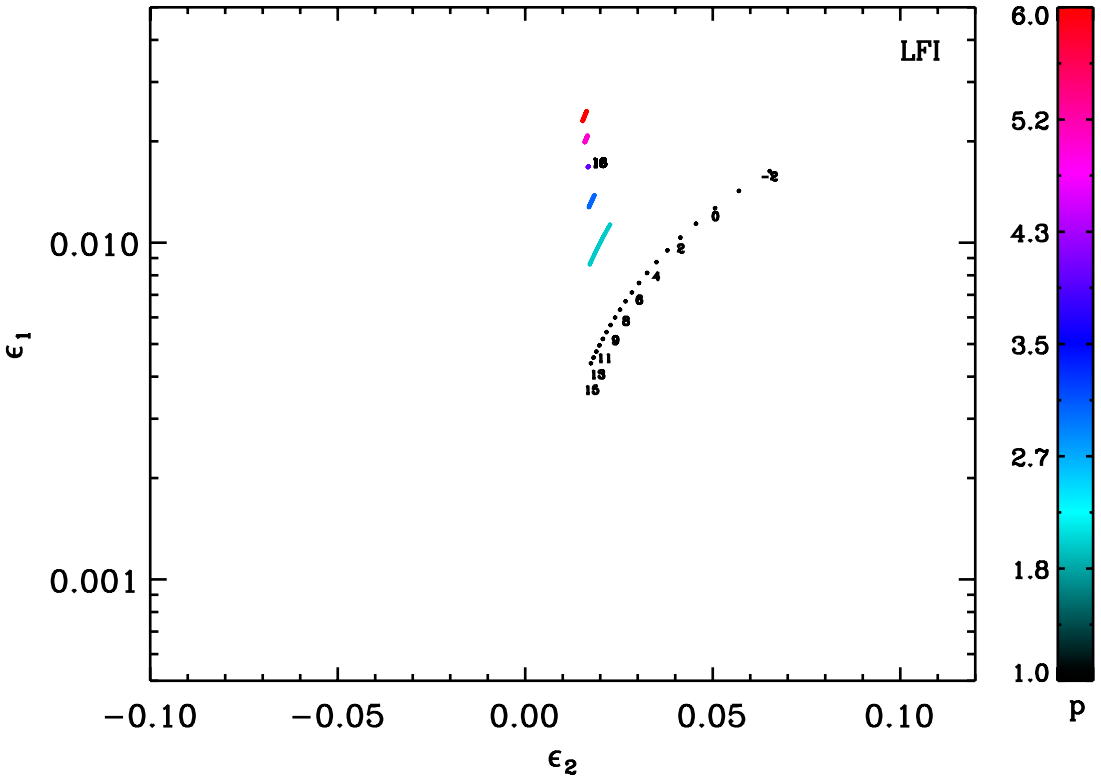
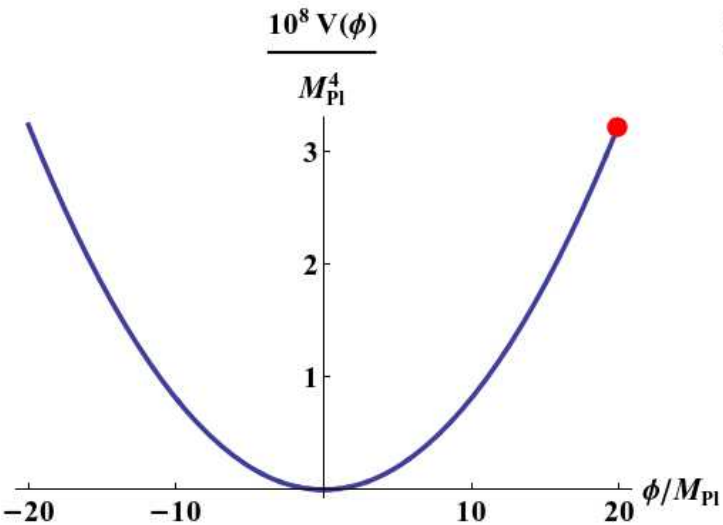
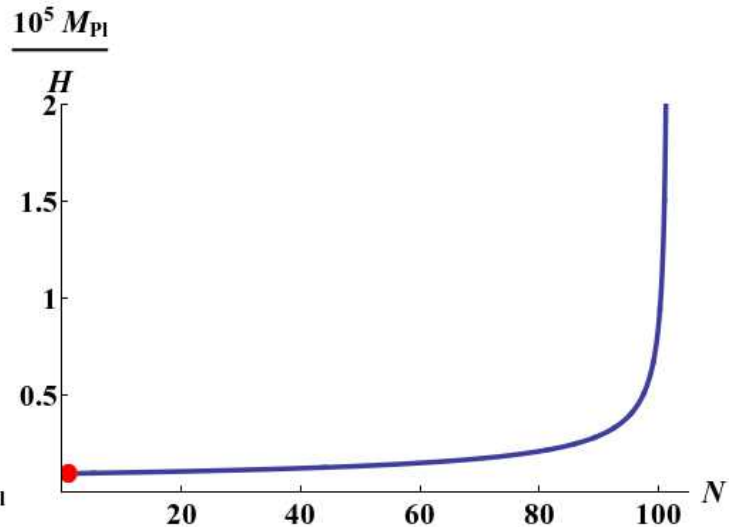
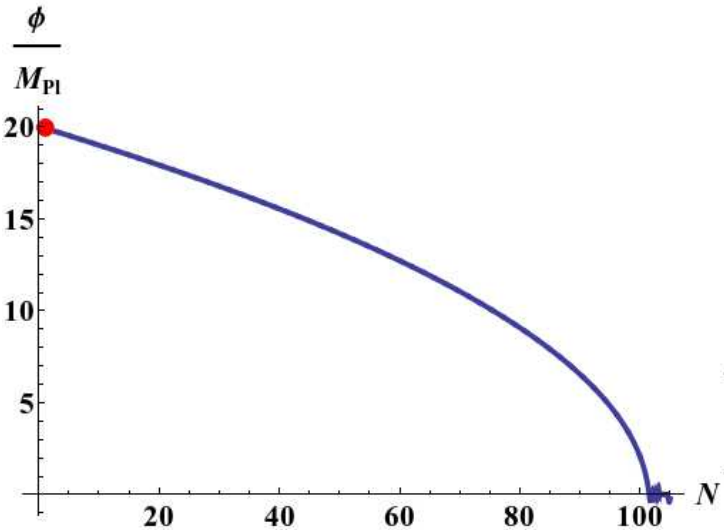


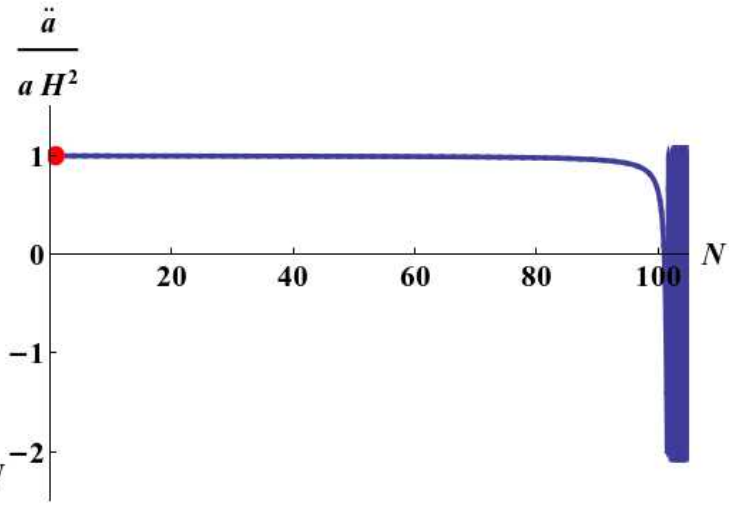
Inflationary Dynamics





An example: « large field inflation » $V(\phi) = \frac{m^2}{2}\phi^2$





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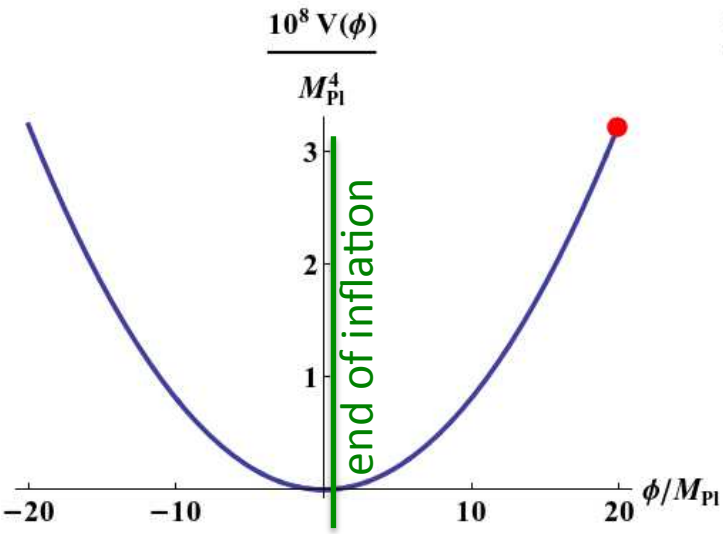

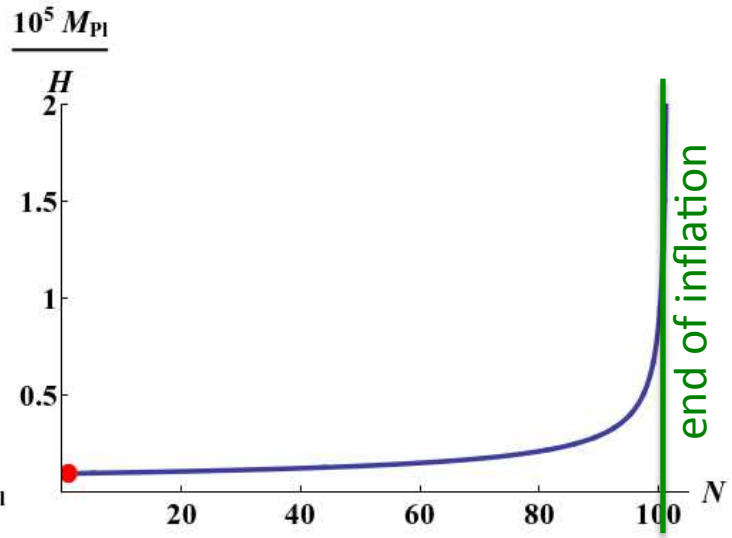

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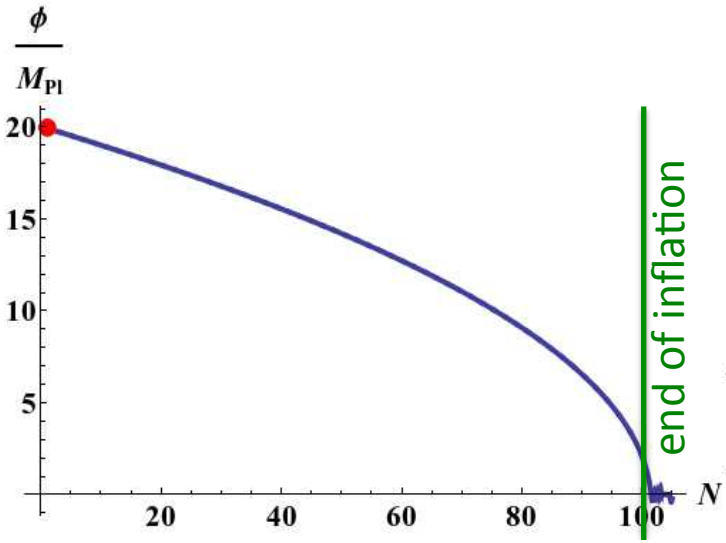

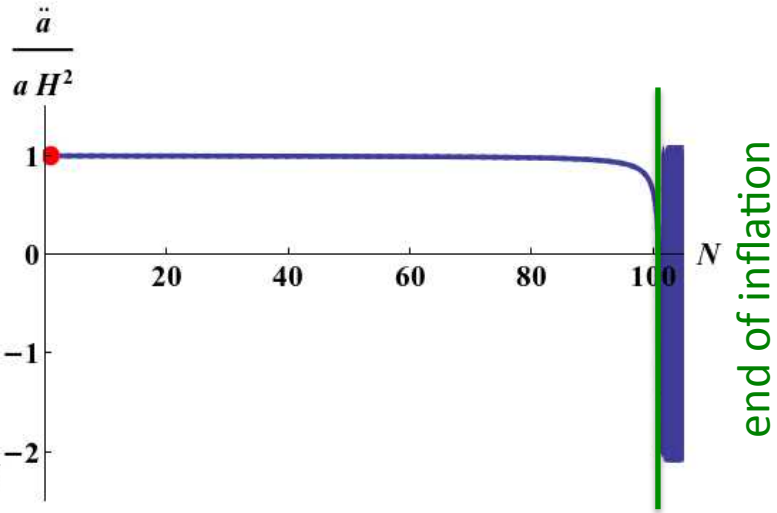

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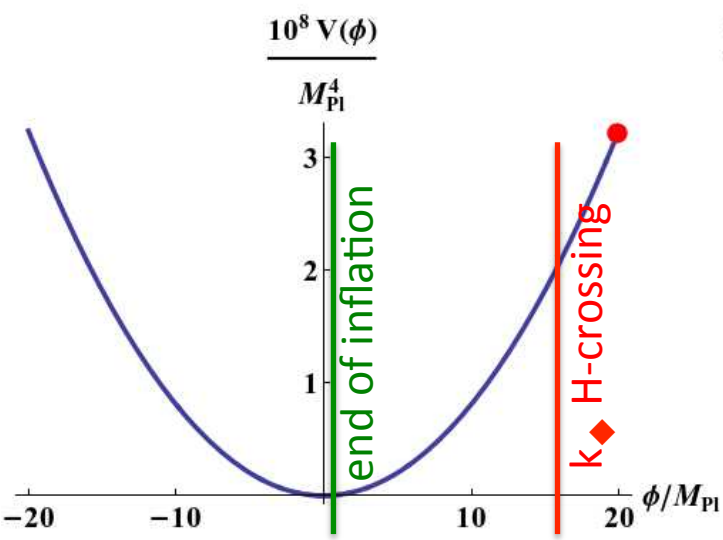

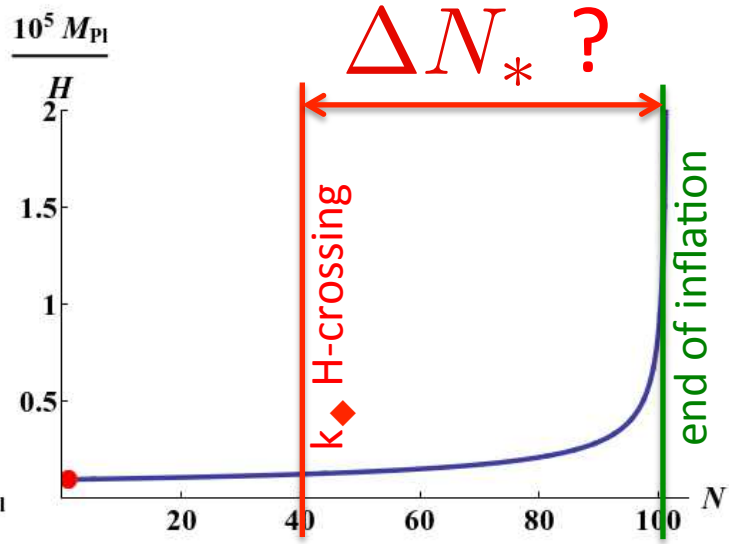

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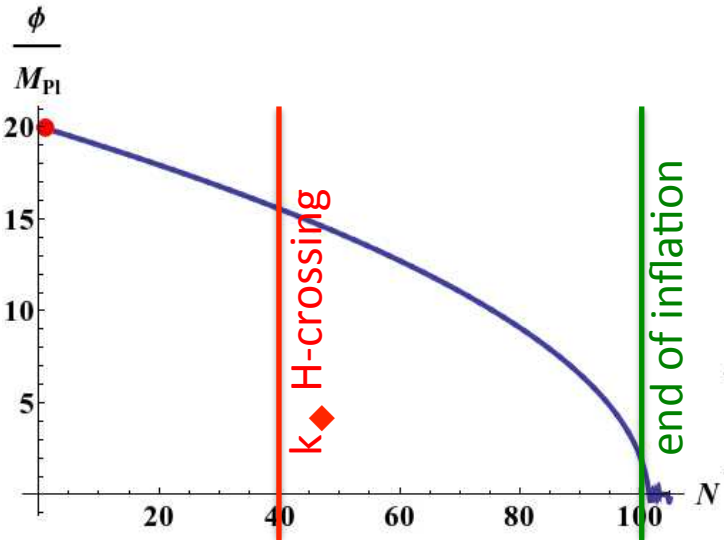

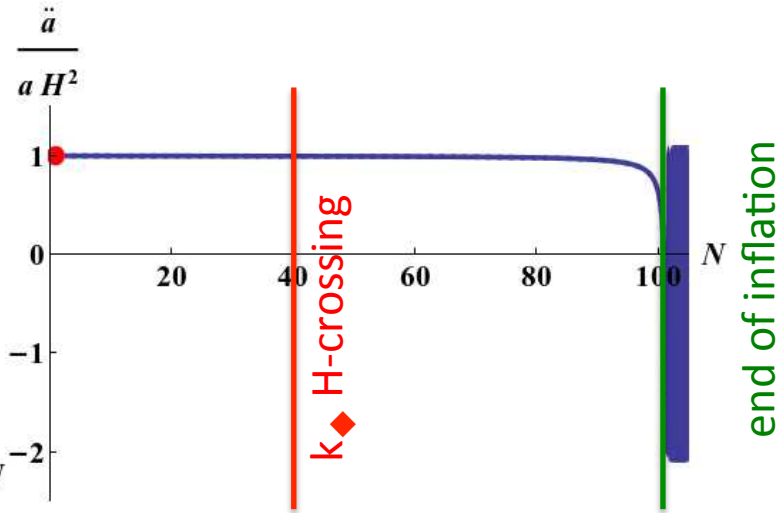

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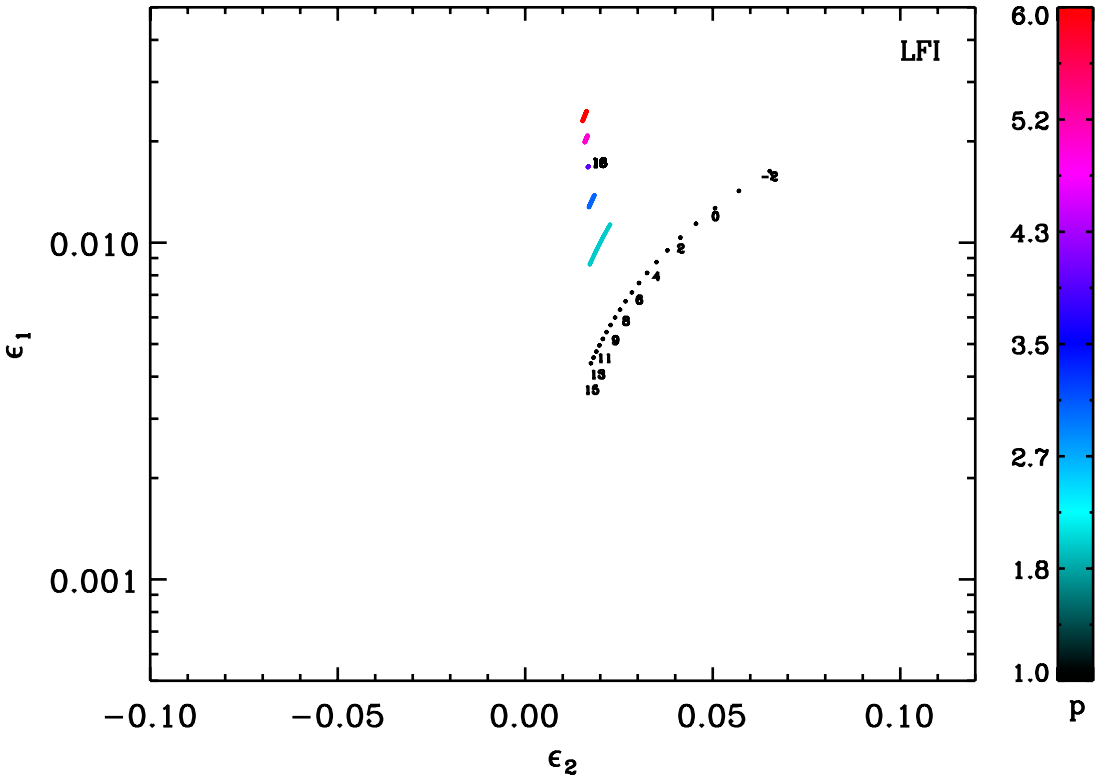
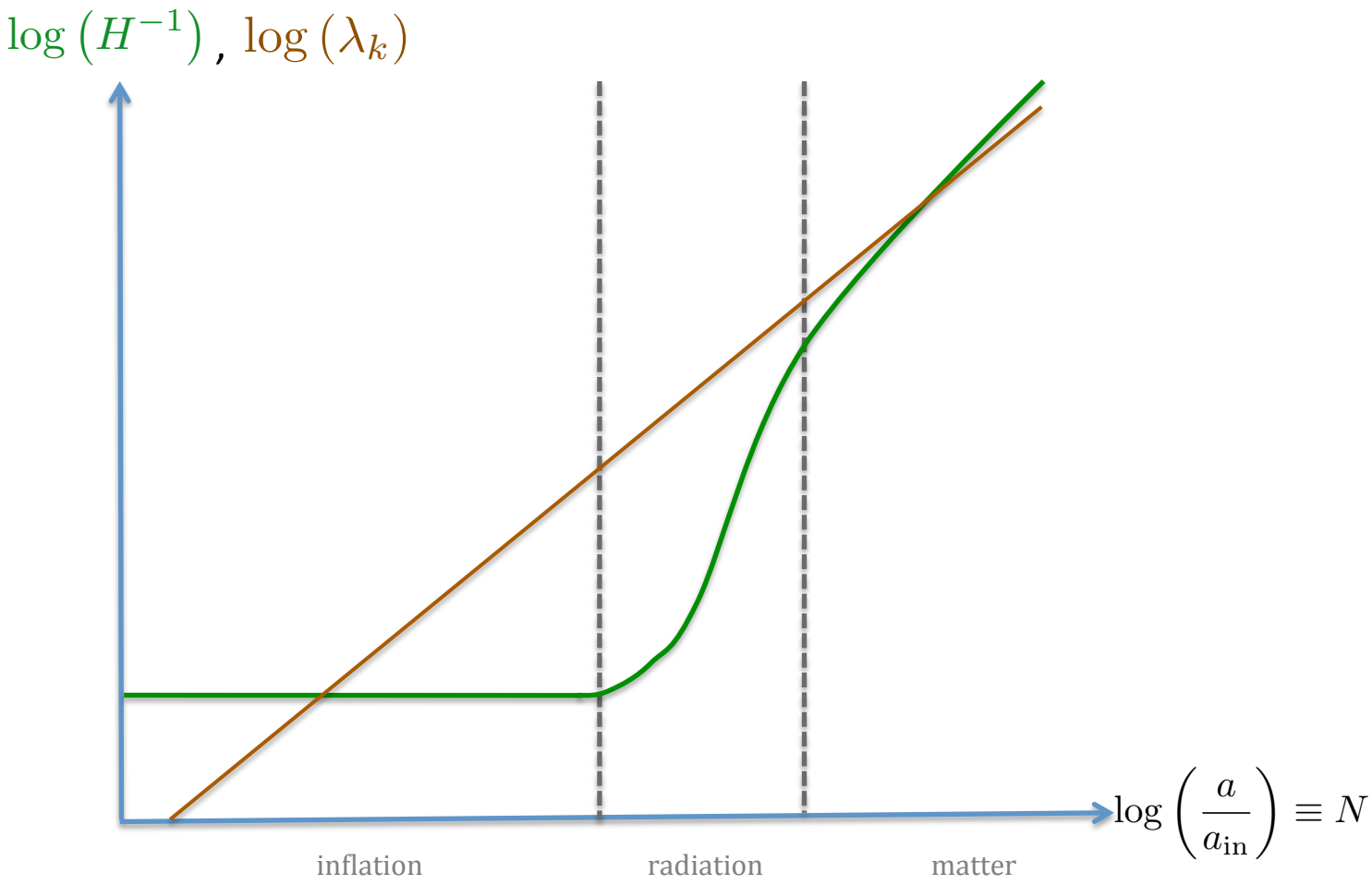
This step requires:

- The slow-roll trajectory
- The time at which inflation end
- The number of e-folds between Hubble crossing of the pivot scale and the end of inflation



ΔN_* fixed by the thermal subsequent history



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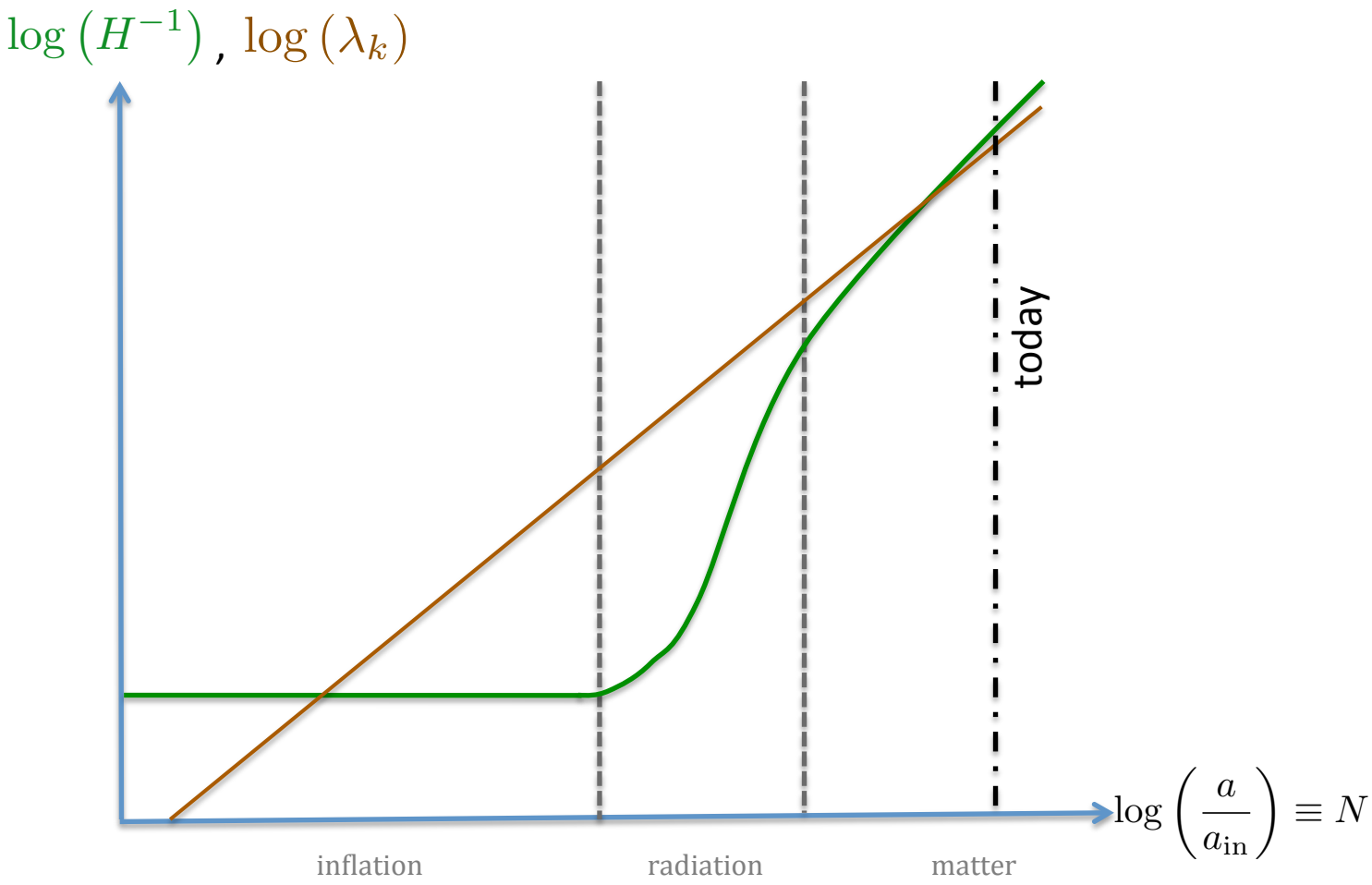

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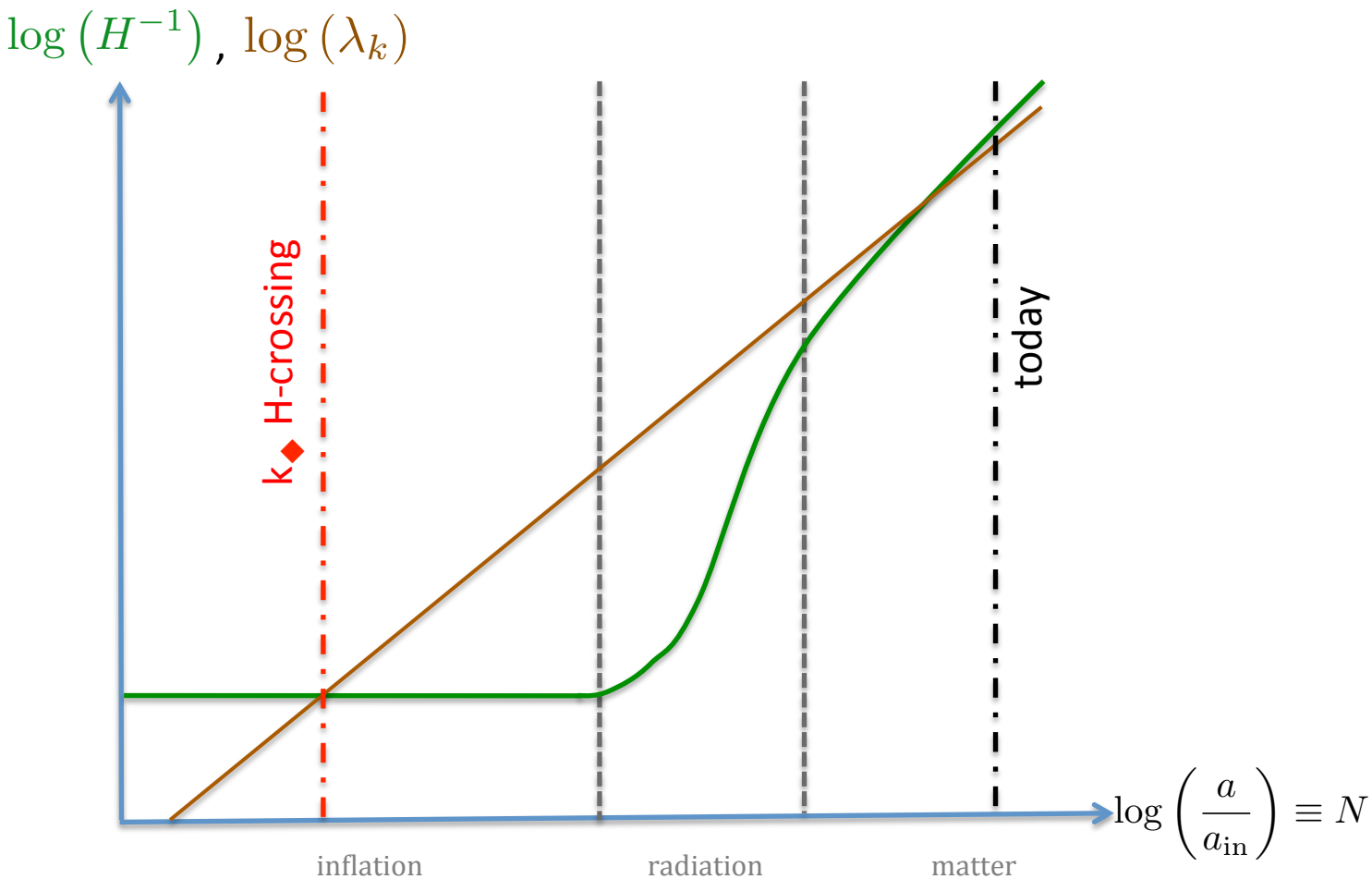

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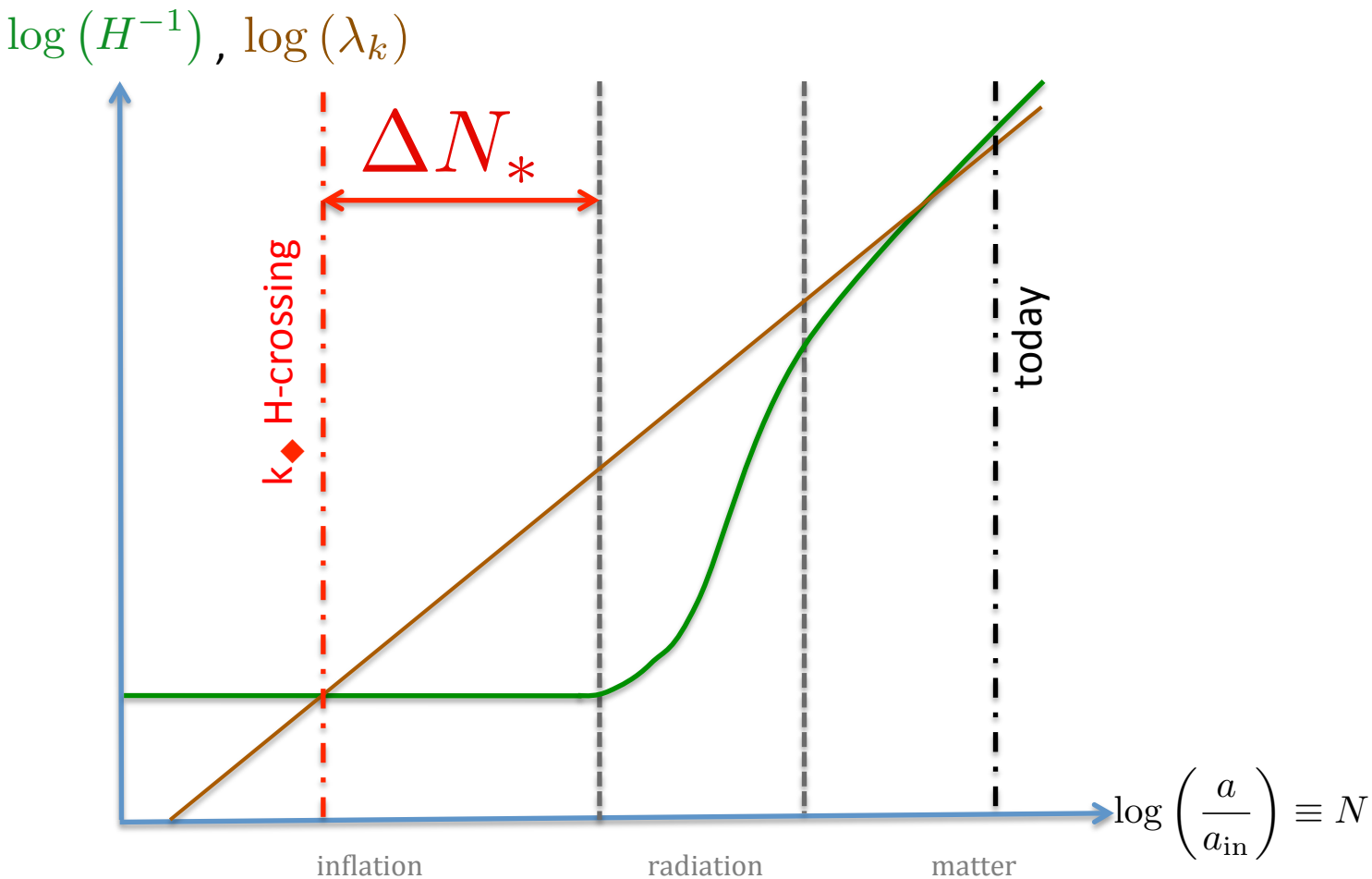

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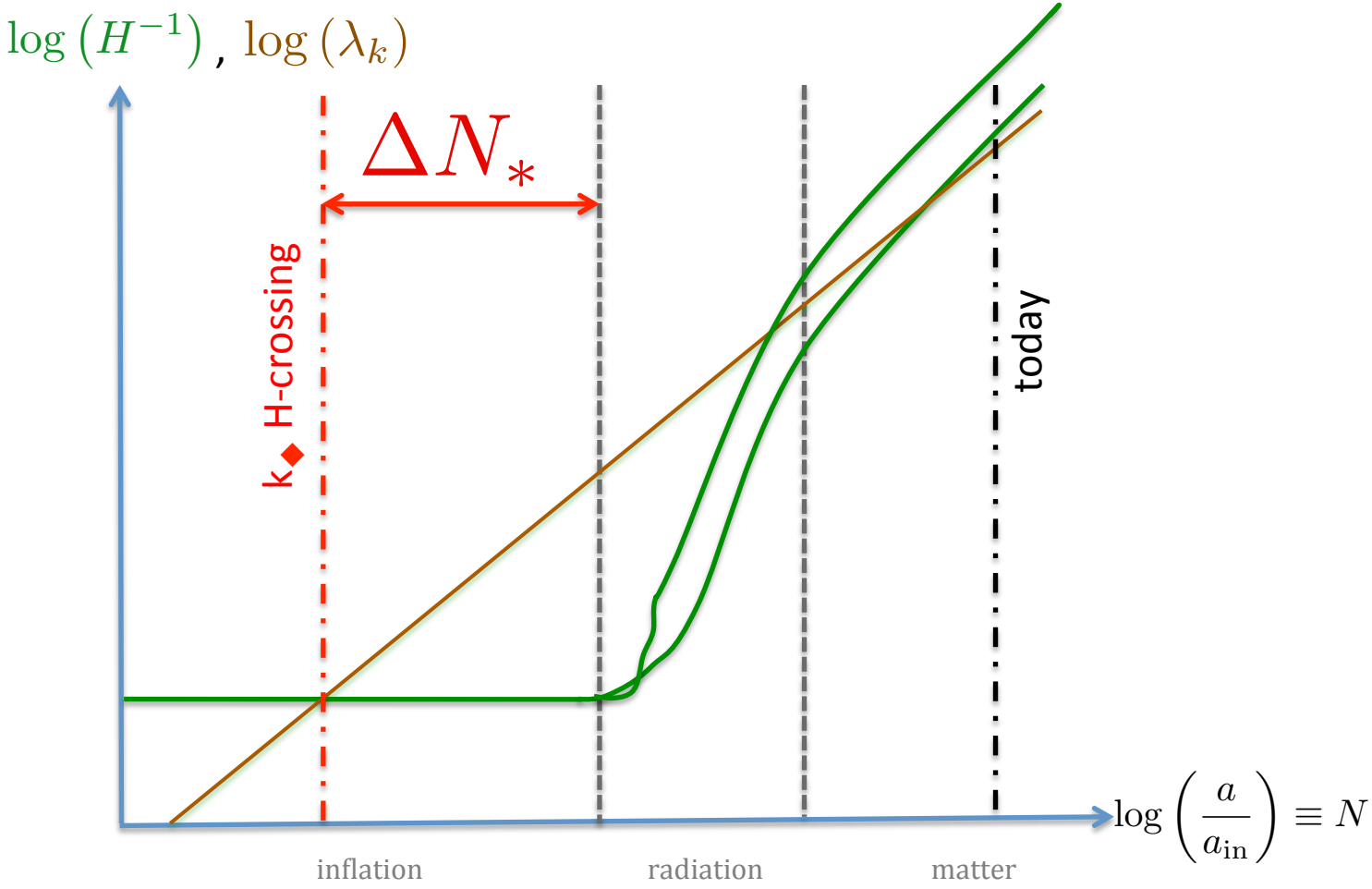
changing reheating history…



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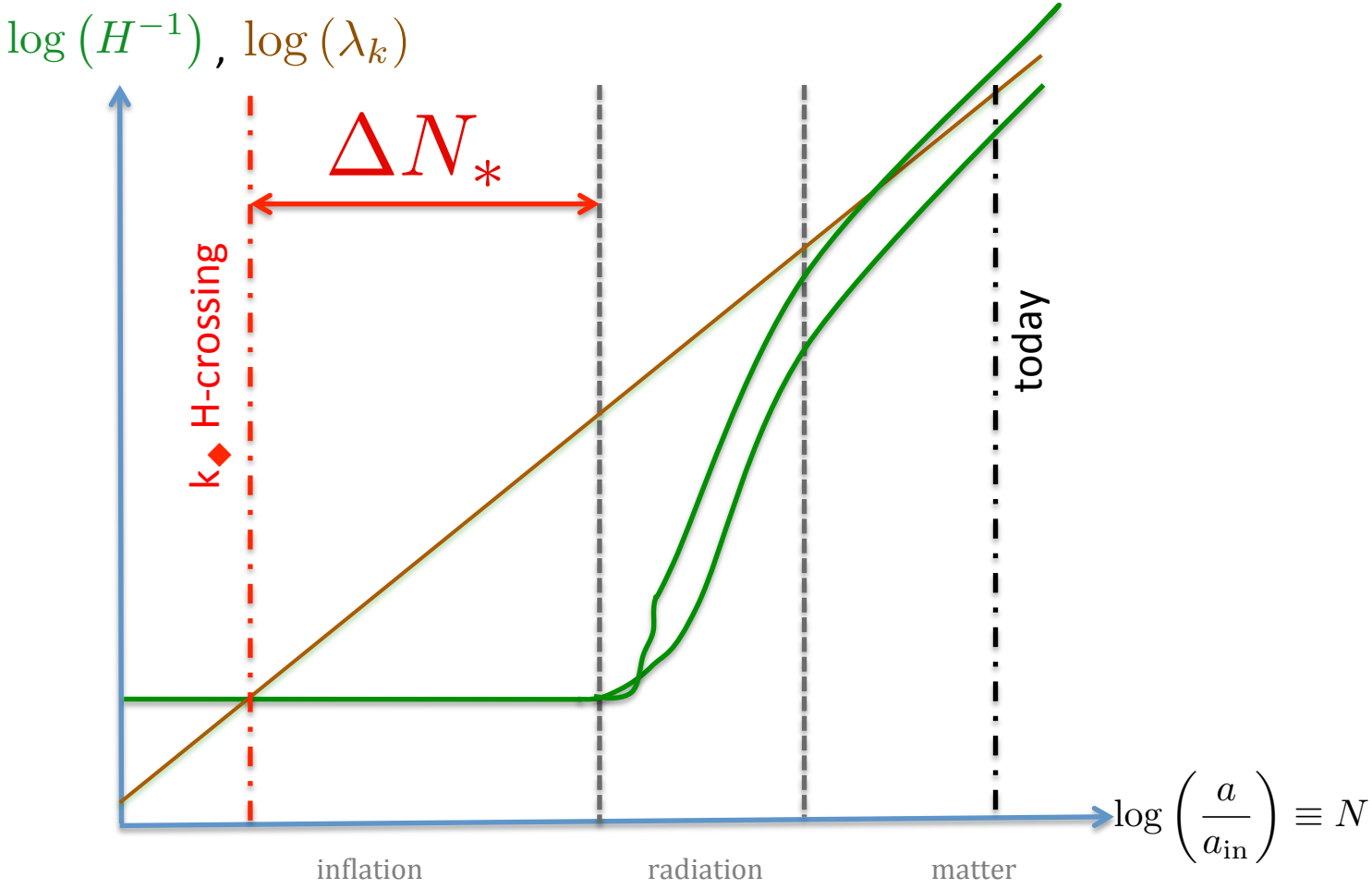

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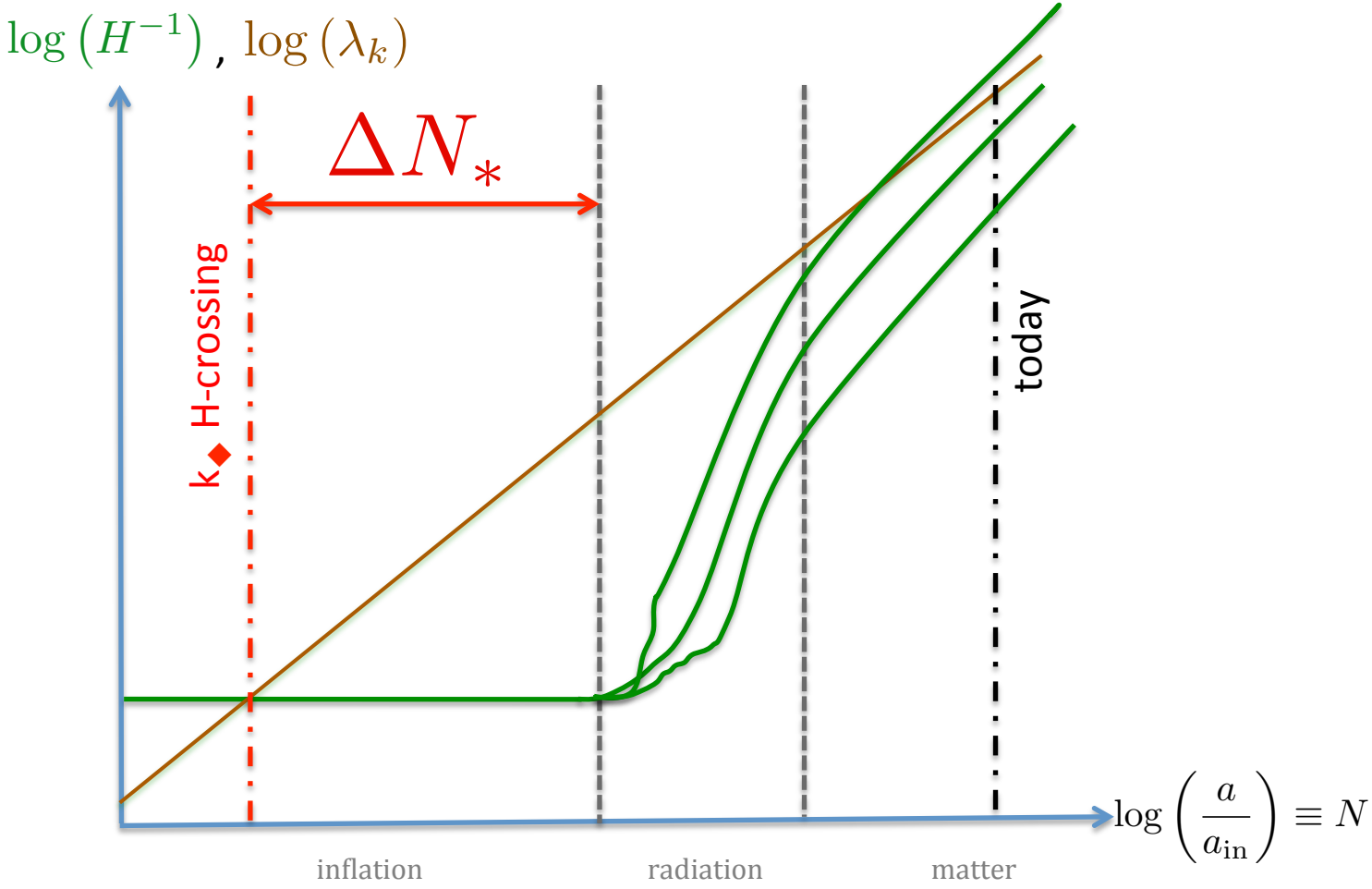
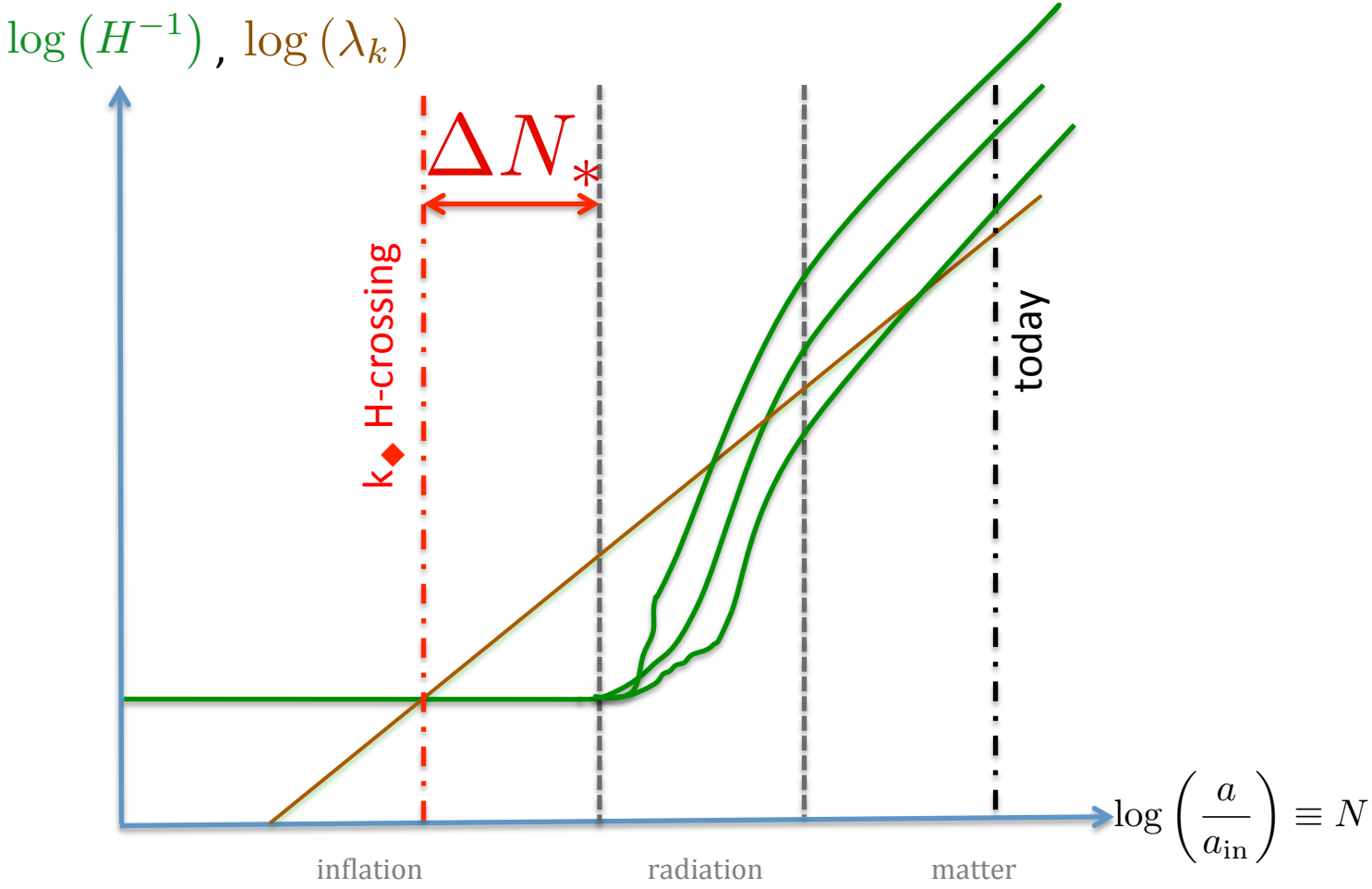


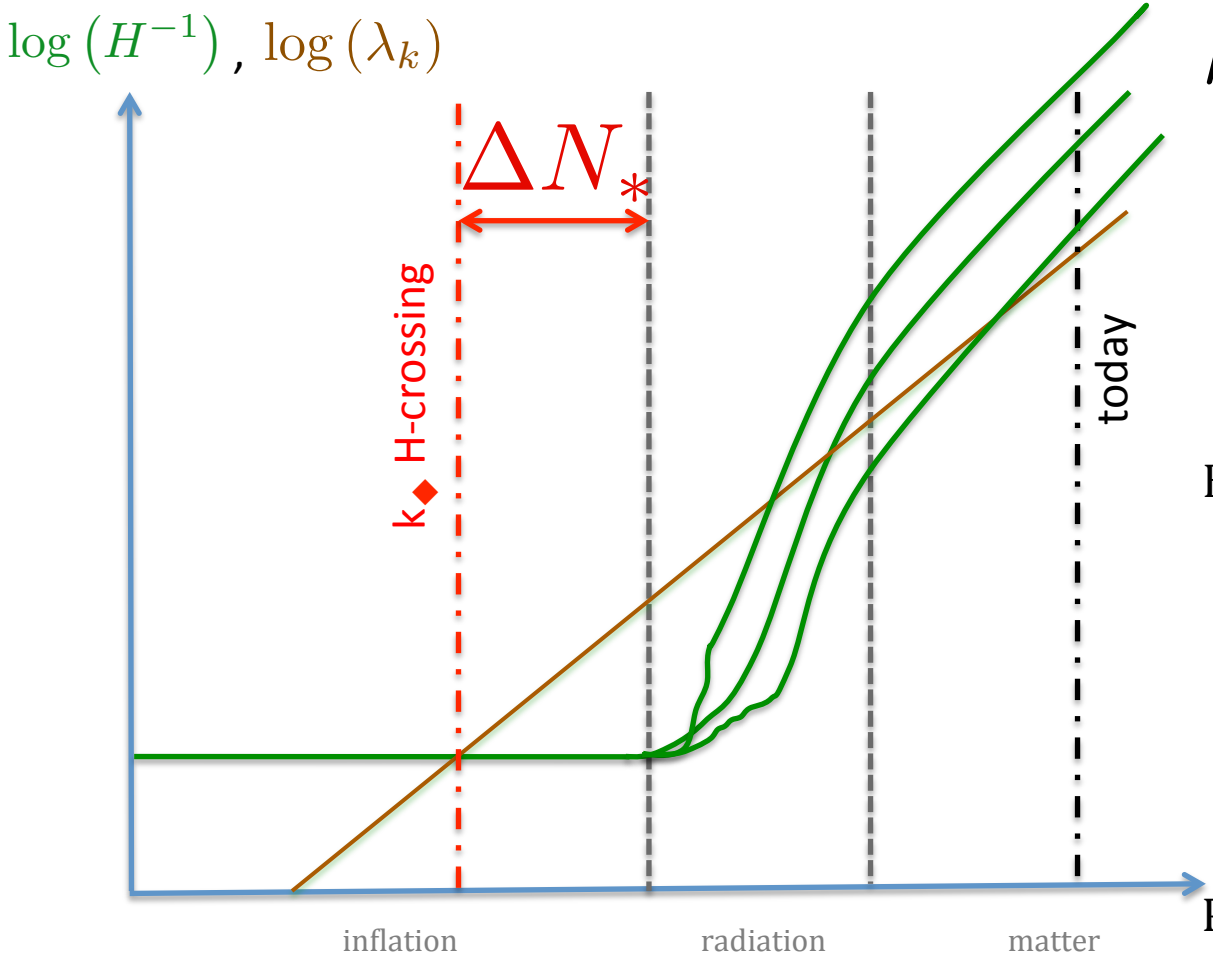
ΔN_* fixed by the thermal subsequent history

changing reheating history…



ΔN_* fixed by the thermal subsequent history

$$\Delta N_* \left(\bar{\rho}_{\rm reh}, \bar{w}_{\rm reh}\right)$$



$$\rho_{\rm nuc} < \bar{\rho}_{\rm reh} < \rho_{\rm end}$$

ΔN_*

restrains ΔN_* in some range

Example: $V = M^4\left(1 - \phi^3/\mu^3\right)$

$$\mu = 0.001 M_{\rm Pl}\,, \quad \bar{w}_{\rm reh} = -0.3$$

$$17.2 < \Delta N_* < 46.0$$

$\Delta N_* = 60$?

Planck coll [1303.5082] prior:

$$\Delta N_* \in [20, 90]$$

The calculation of the inflationary predictions involves three steps:

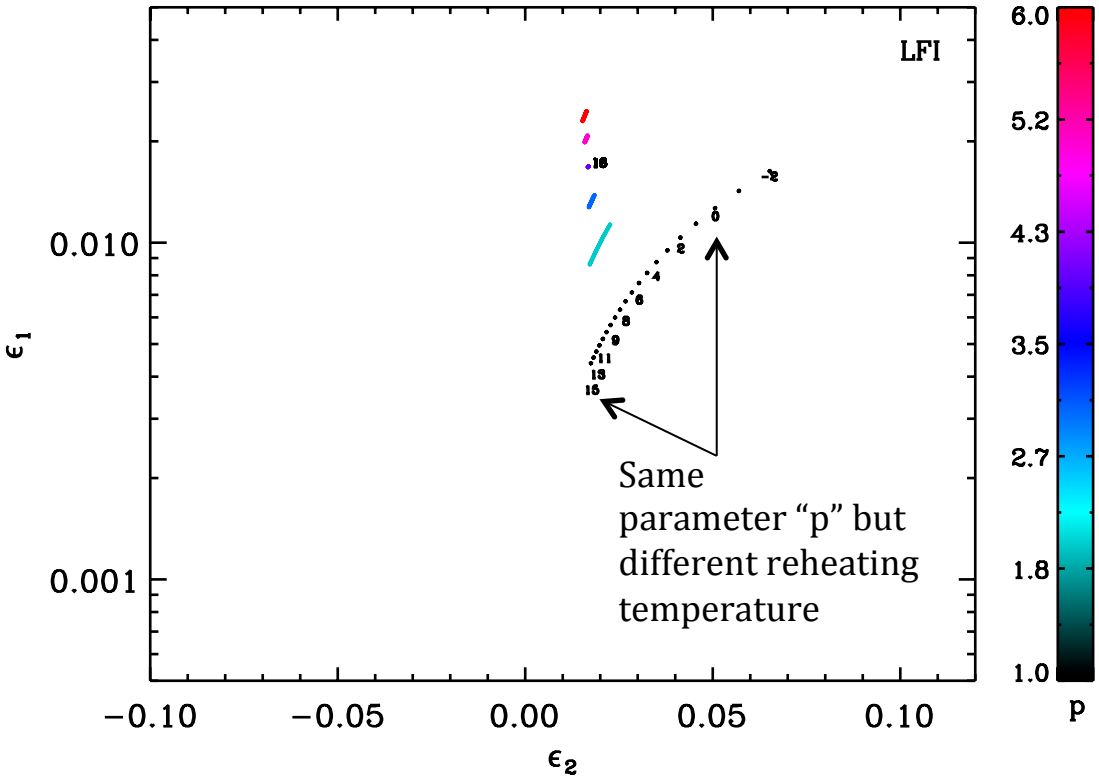
1 – Expressing the power spectrum in terms of the slow-roll parameters

2 – Expressing the slow-roll parameters in term of V, V', V'', ...

3 – Determine the value $\phi_\blacklozenge$ where to evaluate V, V', V'', ...

This step requires:

- The slow-roll trajectory
- The time at which inflation end
- The number of e-folds between Hubble crossing of the pivot scale and the end of inflation



The predictions depend on what happens during reheating

The calculation of the inflationary predictions involves two steps:

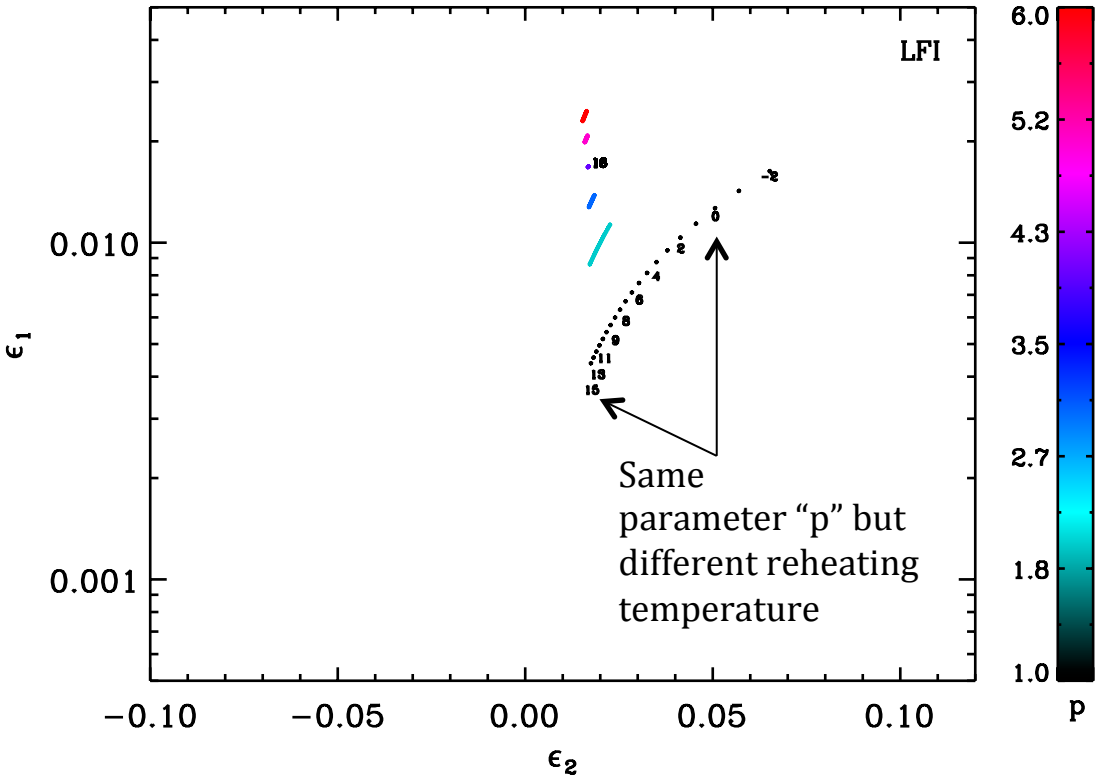
1 - Expressing the power spectrum in terms of the slow-roll parameters

2 – Expressing the slow-roll parameters in term of the parameters characterizing the potential; this step requires

- The slow-roll trajectory

- An accurate estimation of the time at which slow-roll breaks down

- The post-inflationary history (reheating temperature, equation of state)

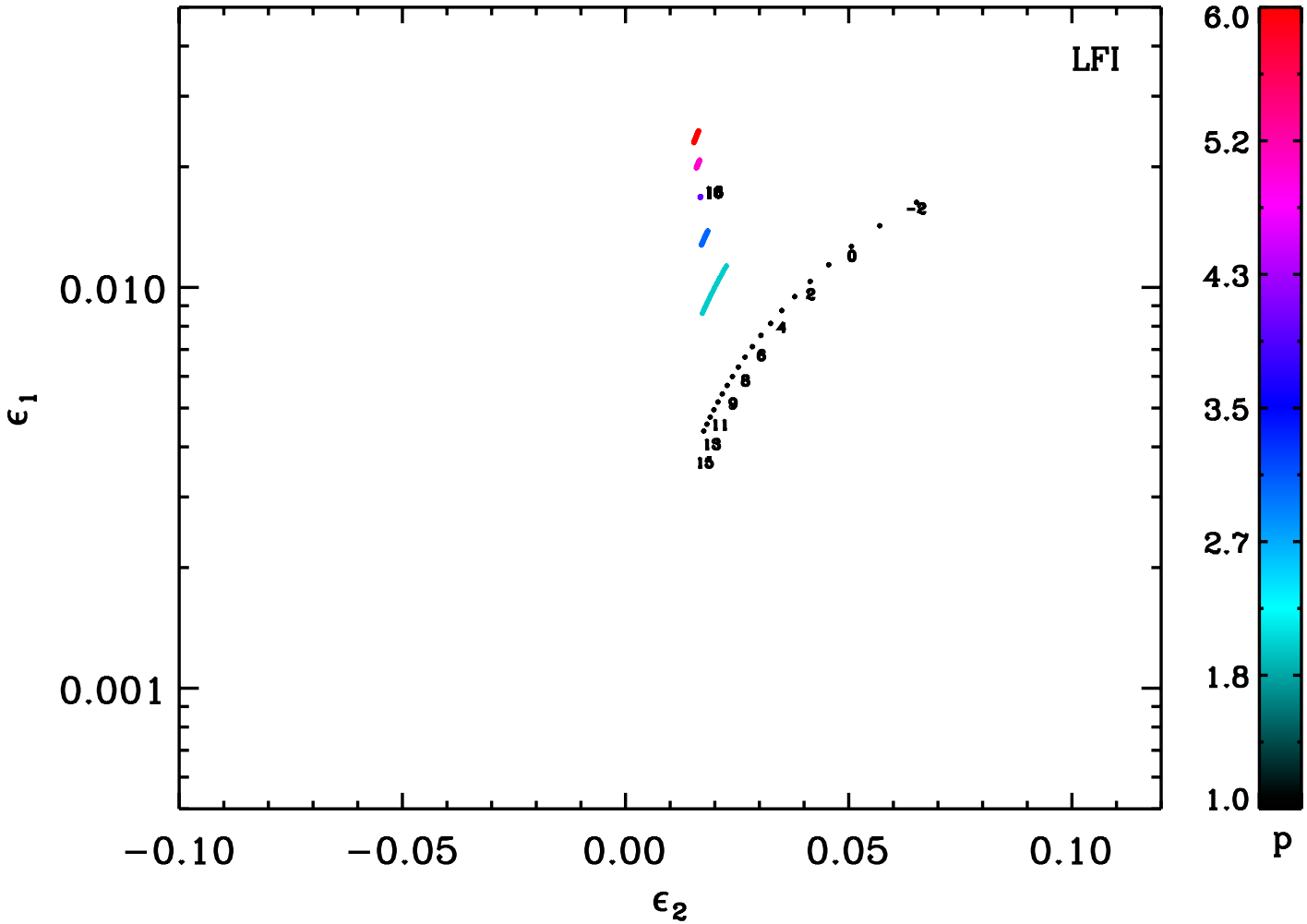


The predictions depend on what happens during reheating

Confronting Models with Data

An example: « large field inflation »

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



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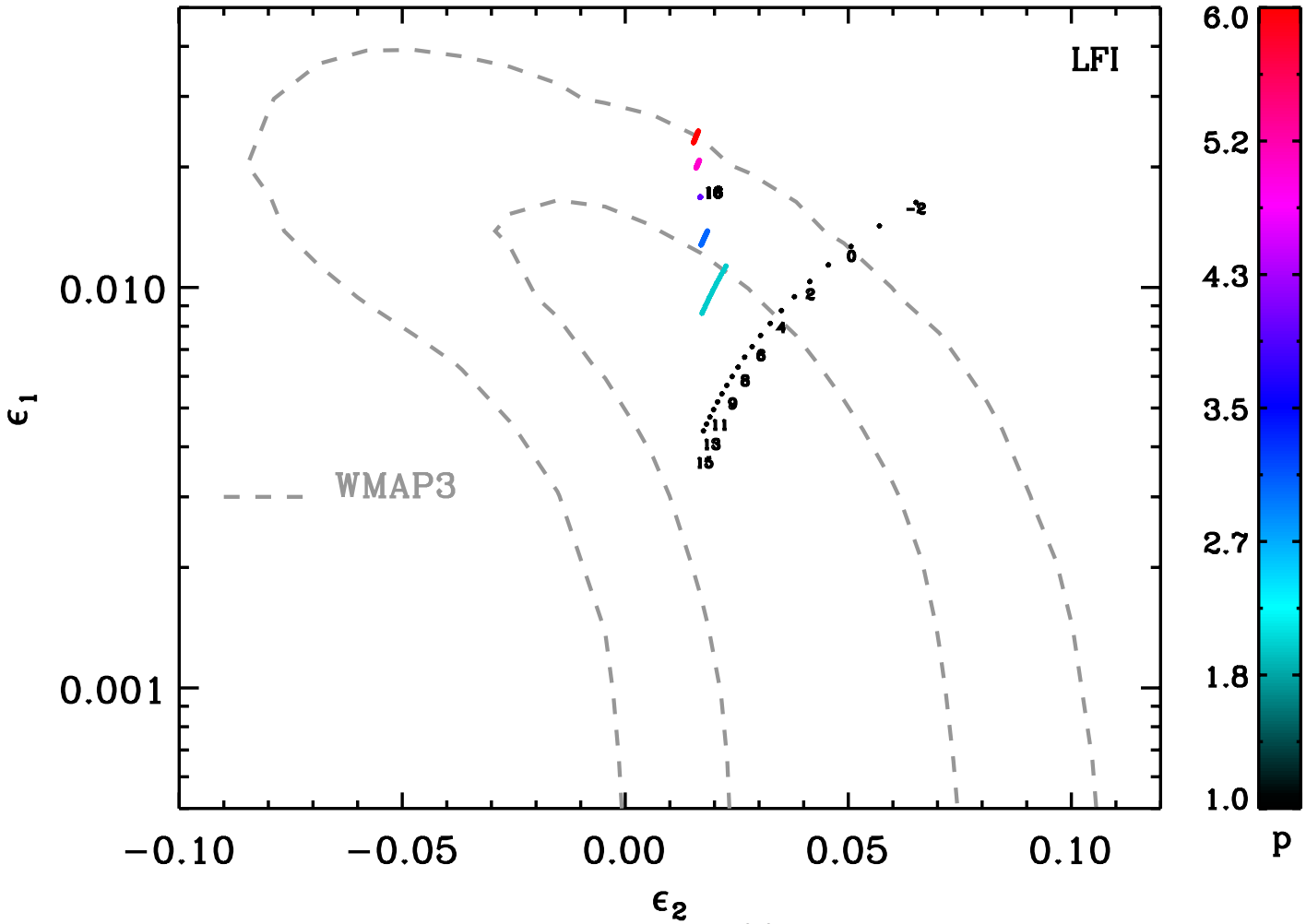

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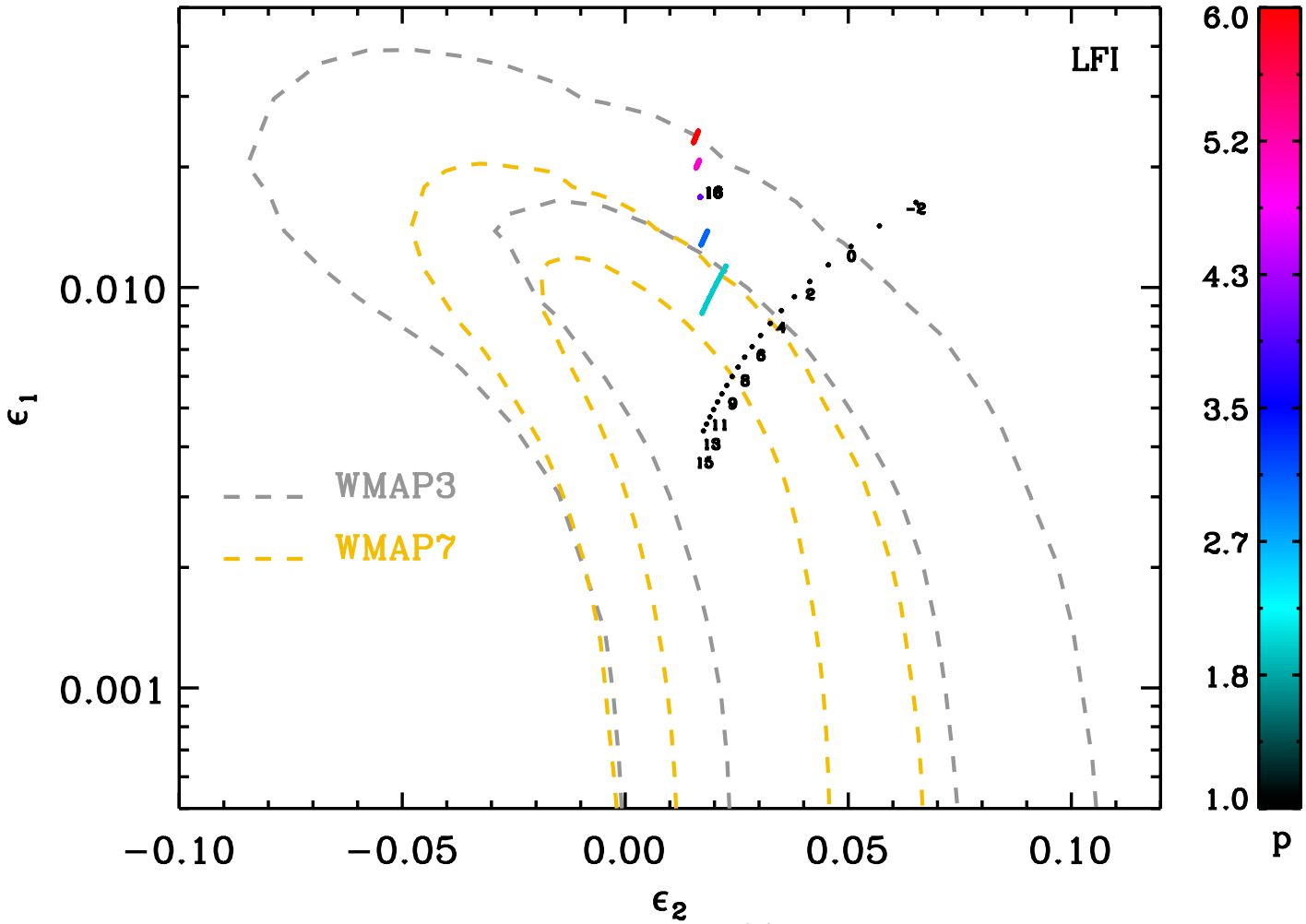

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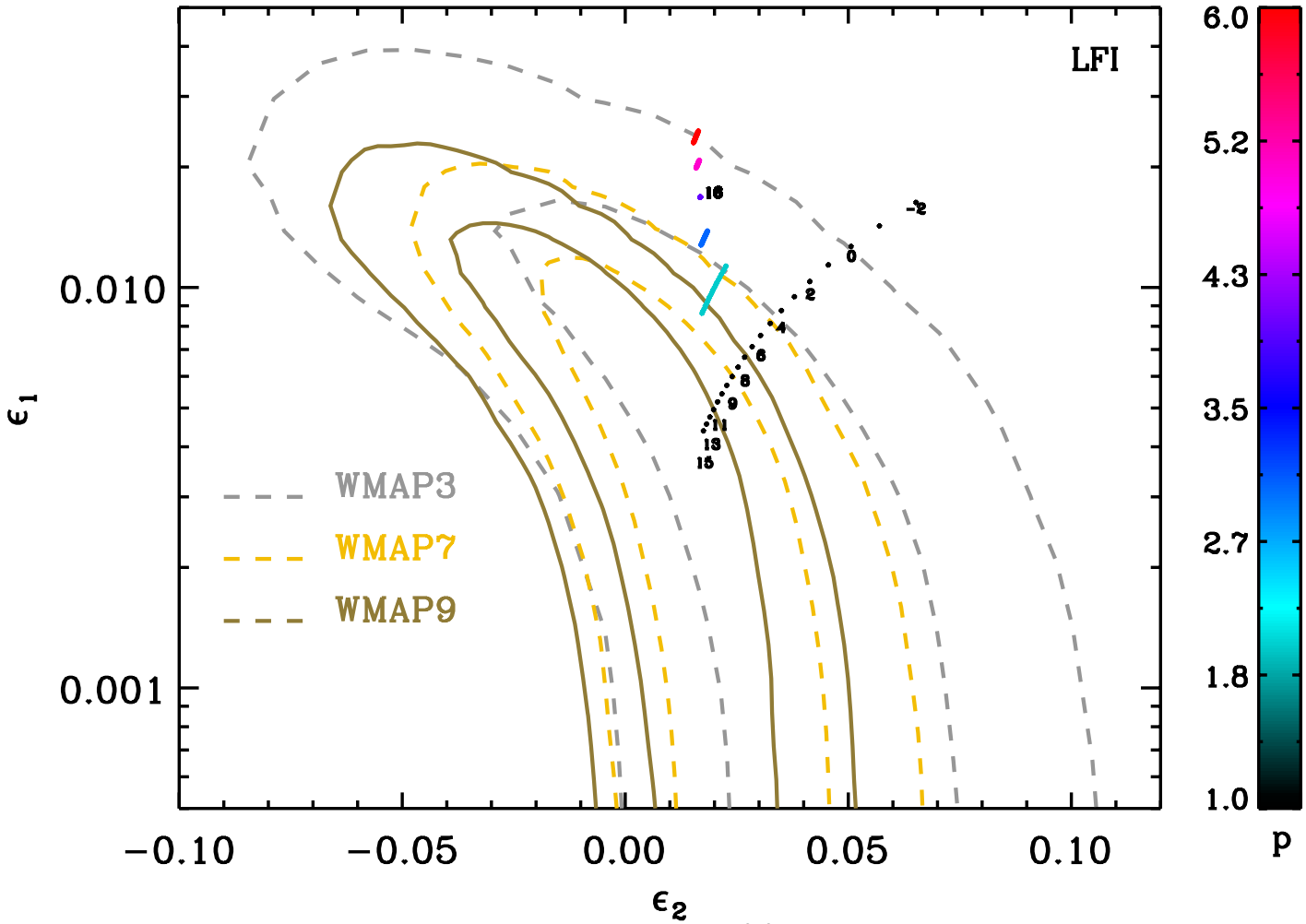

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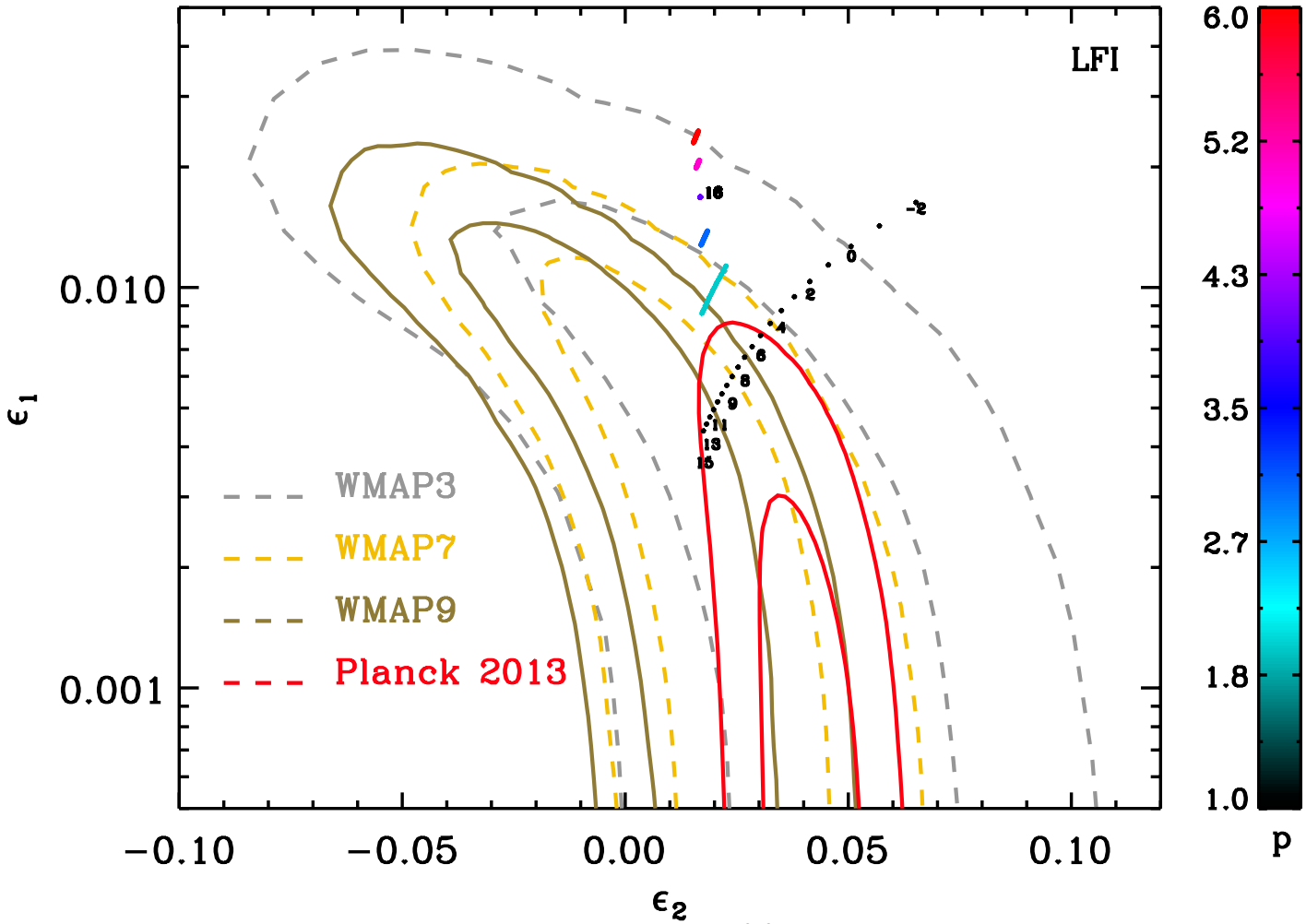
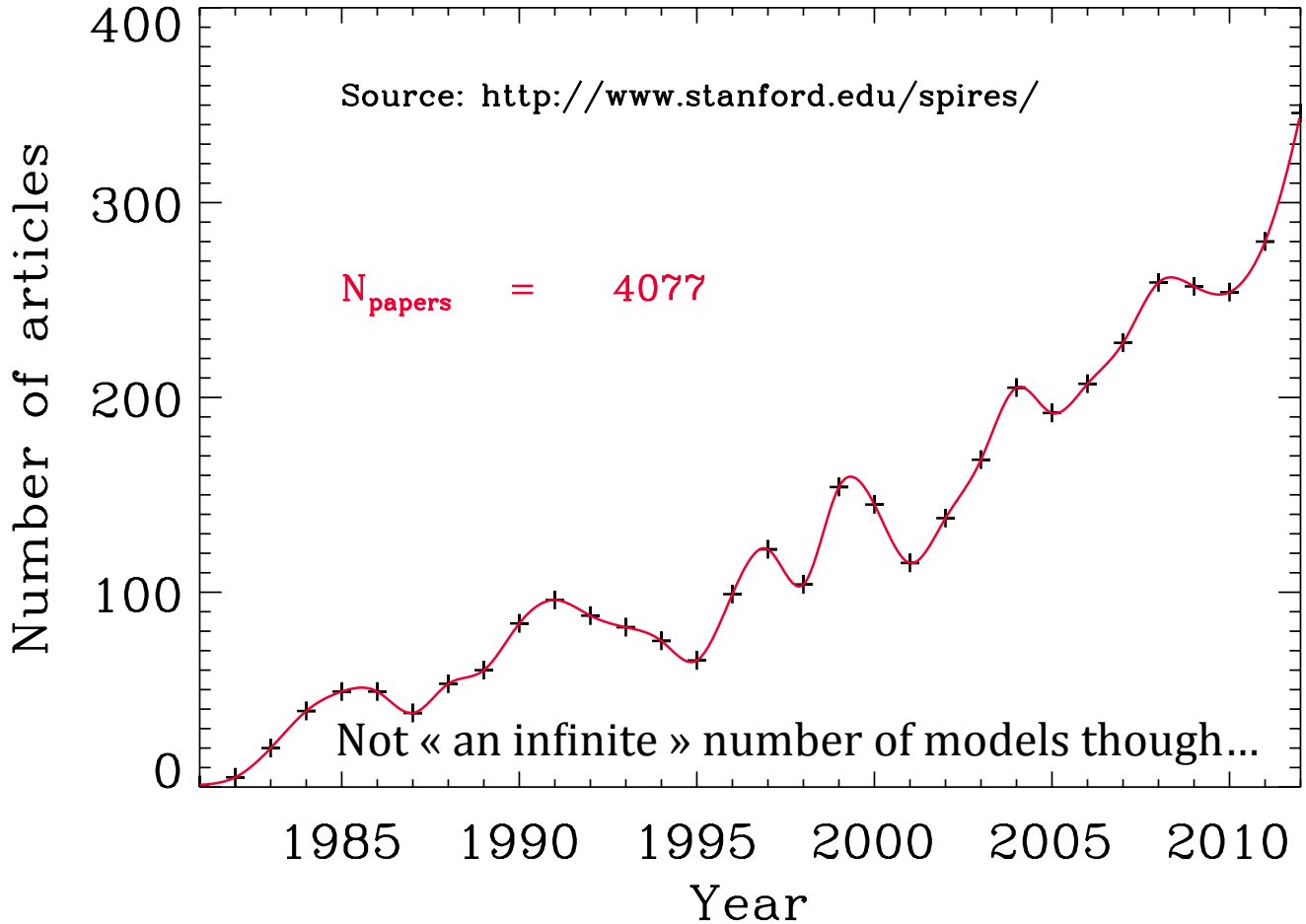


Repeat the analysis for all single field, canonical k, model?

Which models? How many of them?



Not « an infinite » number of models though…

Proliferation of inflationary models[1]

5-dimensional assisted inflation
anisotropic brane inflation
anomaly-induced inflation
assisted inflation
assisted chaotic inflation
boundary inflation
brane inflation
brane-assisted inflation
brane gas inflation
brane-antibrane inflation
braneworld inflation
Brans-Dicke chaotic inflation
Brans-Dicke inflation
bulky brane inflation
chaotic hybrid inflation
chaotic inflation
chaotic new inflation
D-brane inflation
D-term inflation
dilaton-driven inflation
dilaton-driven brane inflation
double inflation
double D-term inflation
dual inflation
dynamical inflation
dynamical SUSY inflation
eternal inflation
extended inflation
extended open inflation
extended warm inflation
extra dimensional inflation
F-term inflation
F-term hybrid inflation
false vacuum inflation
false vacuum chaotic inflation
fast-roll inflation
first order inflation
gauged inflation
generalised inflation
generalized assisted inflation
generalized slow-roll inflation
gravity driven inflation
Hagedorn inflation
higher-curvature inflation
hybrid inflation
hyperextended inflation
induced gravity inflation
induced gravity open inflation
intermediate inflation
inverted hybrid inflation
isocurvature inflation
K inflation
kinetic inflation
lambda inflation
large field inflation
late D-term inflation
late-time mild inflation
low-scale inflation
low-scale supergravity inflation
M-theory inflation
mass inflation
massive chaotic inflation
moduli inflation
multi-scalar inflation
multiple inflation
multiple-field slow-roll inflation
multiple-stage inflation
natural inflation
natural Chaotic inflation
natural double inflation
natural supergravity inflation
new inflation
next-to-minimal supersymmetric hybrid inflation
non-commutative inflation
non-slow-roll inflation
nonminimal chaotic inflation
old inflation
open hybrid inflation
open inflation
oscillating inflation
polynomial chaotic inflation
polynomial hybrid inflation
power-law inflation
pre-Big-Bang inflation
primary inflation
primordial inflation
quasi-open inflation
quintessential inflation
R-invariant topological inflation
rapid asymmetric inflation
running inflation
scalar-tensor gravity inflation
scalar-tensor stochastic inflation
Seiberg-Witten inflation
single-bubble open inflation
spinodal inflation
stable starobinsky-type inflation
steady-state eternal inflation
steep inflation
stochastic inflation
string-forming open inflation
successful D-term inflation
supergravity inflation
supernatural inflation
superstring inflation
supersymmetric hybrid inflation
supersymmetric inflation
supersymmetric topological inflation
supersymmetric new inflation
synergistic warm inflation
TeV-scale hybrid inflation

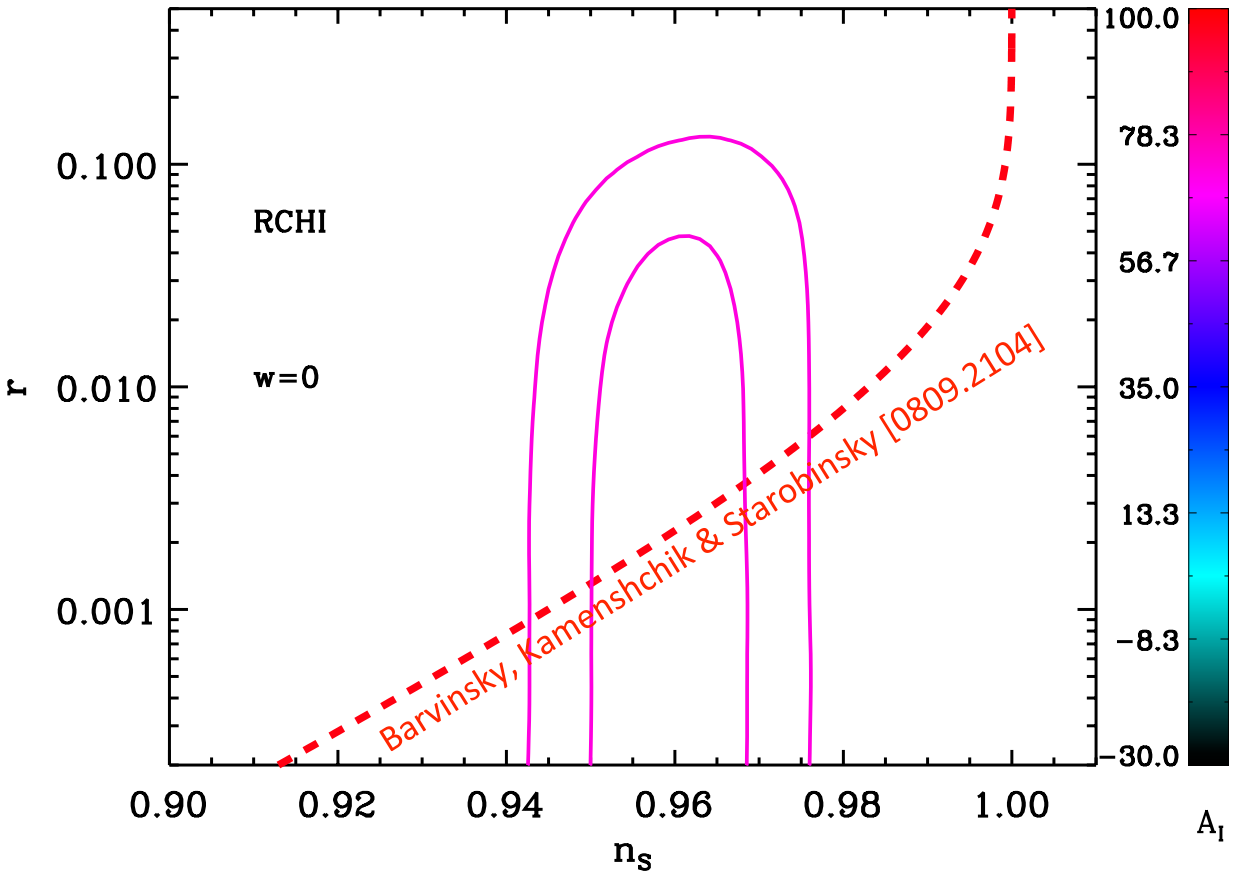
A partial list of ever-increasing number of inflationary models!

[1] From E. P. S. Shellard, *The future of cosmology: Observational and computational prospects*, in *The Future of Theoretical Physics and Cosmology*, Eds. G. W. Gibbons, E. P. S. Shellard and S. J. Rankin (Cambridge University Press, Cambridge, England, 2003).

Need for exact Formulas

Example: Radiatively Corrected Higgs Inflation

$$V = M^4 \left[1 - 2e^{-2\phi/(\sqrt{6}M_{\rm Pl})} + \frac{A_{\rm I}}{16\pi^2} \frac{\phi}{\sqrt{6}M_{\rm Pl}} \right]$$



$V \sim M^4$ in

- Inflationary Dynamics
- $\Phi_{\rm end}$
- $\Delta N_* = 60$

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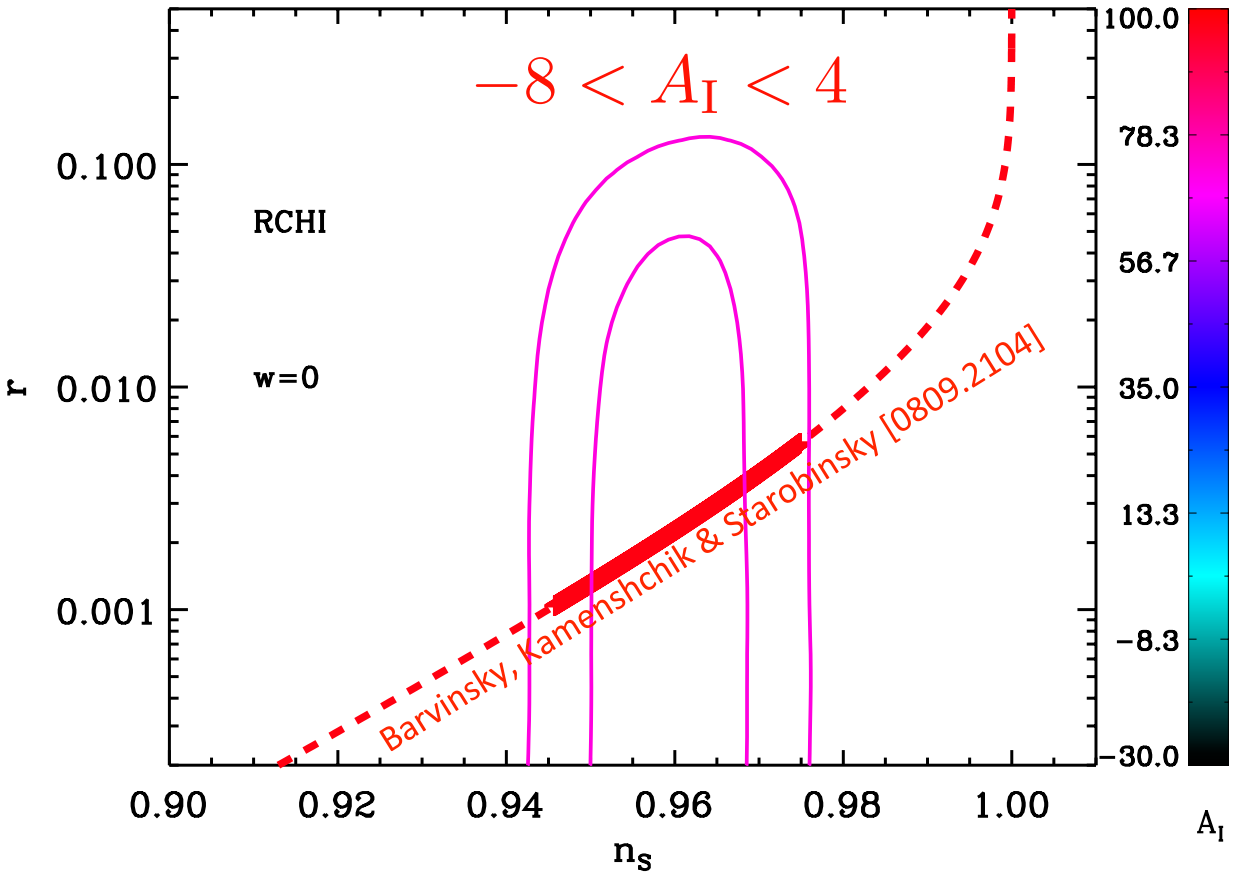

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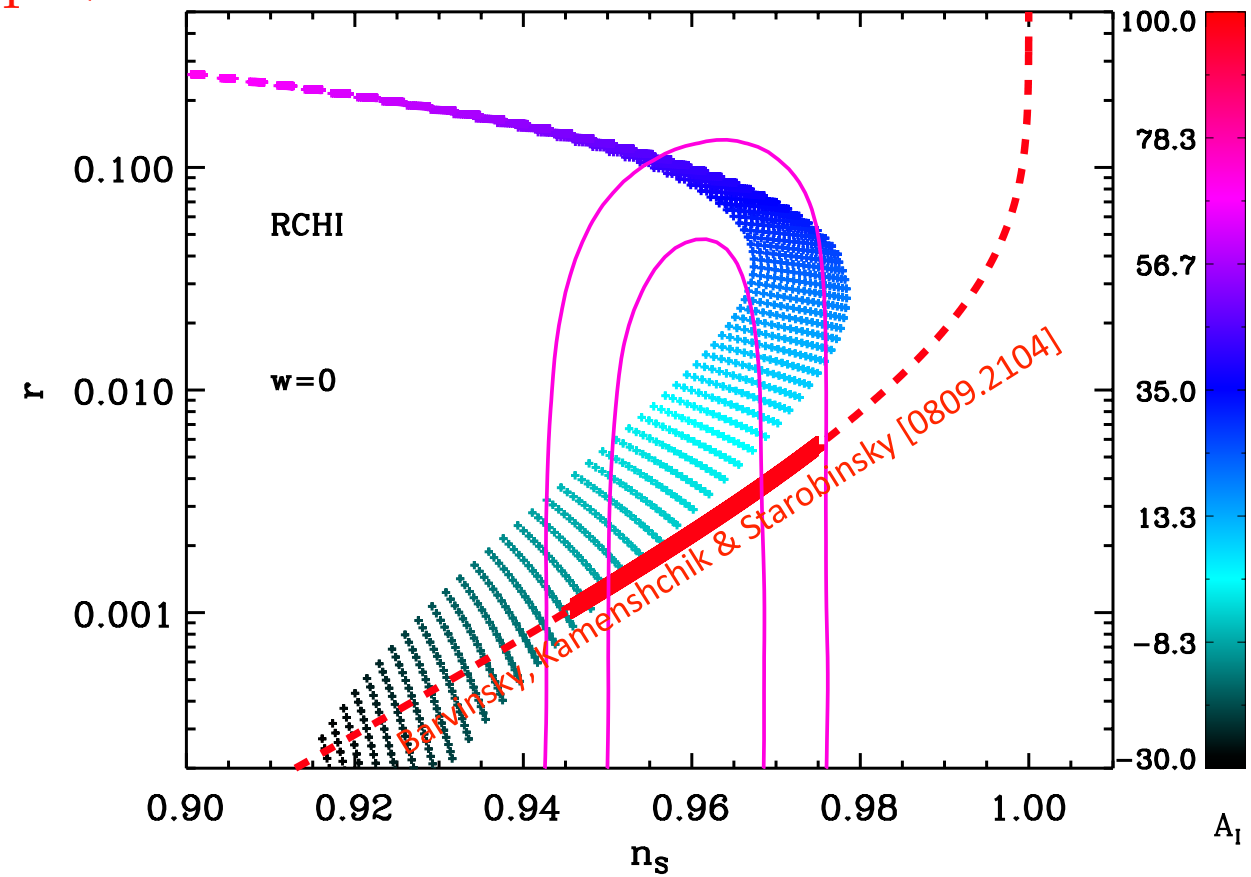
$-8 < A_{\rm I} < 4$



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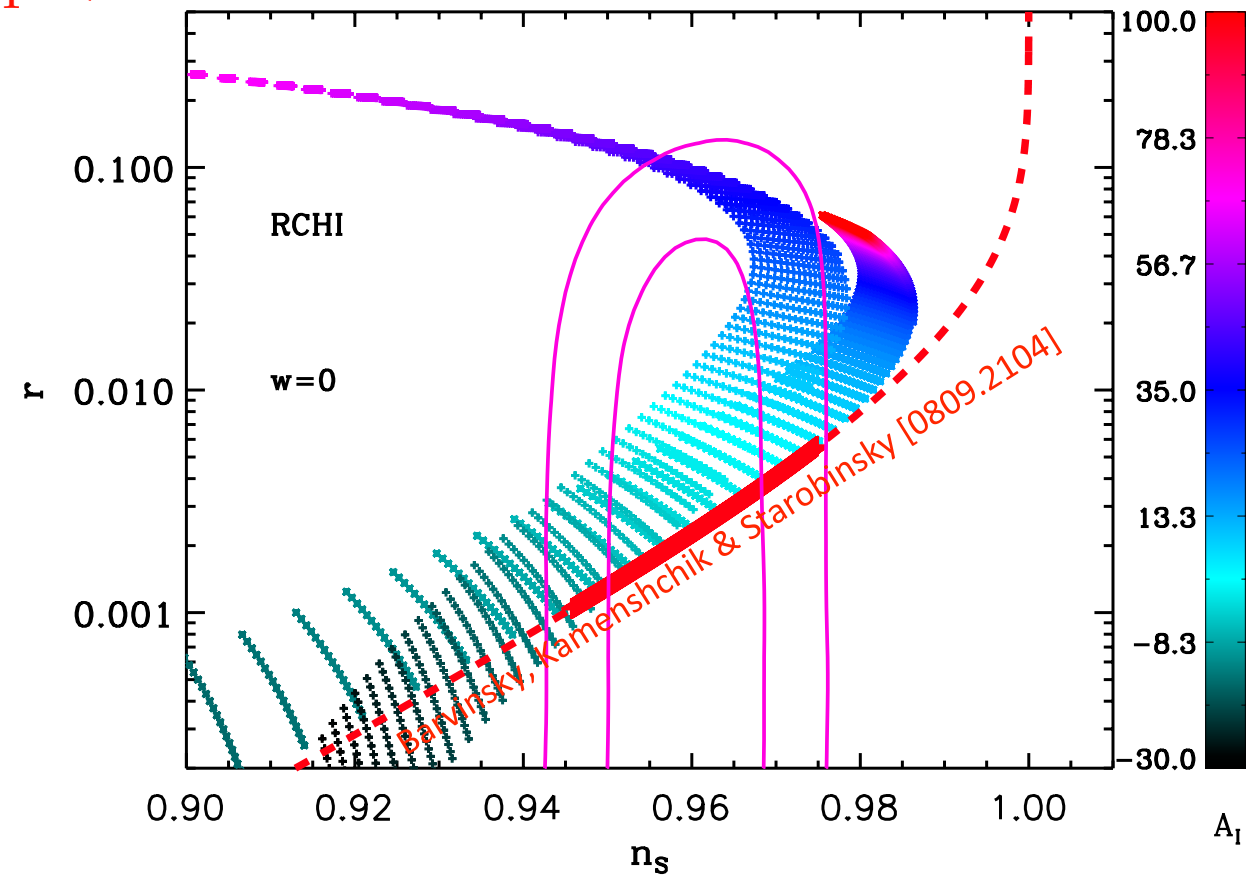
Particle Physics:

$$-48 < A_{\rm I} < -20$$

$$-8 < A_{\rm I} < 4$$



$V \sim M^4$ in

- ~~Inflationary Dynamics~~
- ~~$\Phi_{\rm end}$~~
- ~~$\Delta N_* = 60$~~

[1303.3787]

Encyclopædia Inflationaris

Jérôme Martin,[a] **Christophe Ringeval**[b] **and Vincent Vennin**[a]

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[b]Centre for Cosmology, Particle Physics and Phenomenology, Institute of Mathematics and Physics, Louvain University, 2 Chemin du Cyclotron, 1348 Louvain-la-Neuve (Belgium)

E-mail: jmartin@iap.fr, christophe.ringeval@uclouvain.be, vennin@iap.fr

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

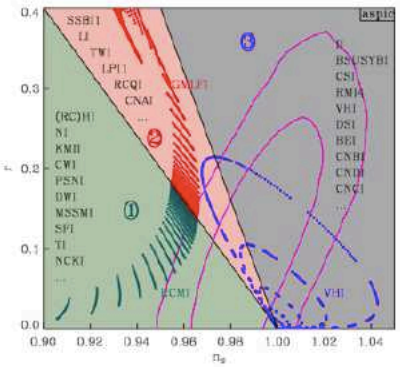
≈ 75 models

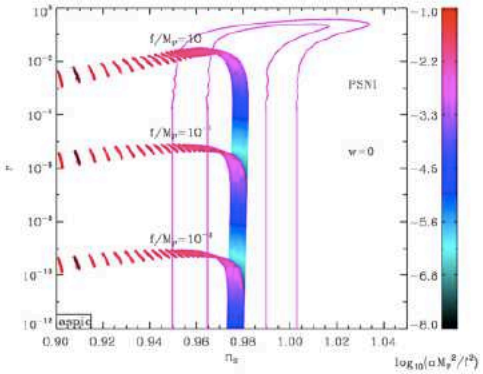
≈ 700 slow roll formulas

≈ 370 pages

theory.physics.unige.ch/~ringeval/aspic.html

Accurate Slow-roll Predictions for Inflationary Cosmology





Reheating consistent slow-roll predictions for a subset of inflationary models supported by **aspic** (left). The right panel features the Pseudo Natural Inflation (PSNI) predictions. The annotated values show the logarithmic energy scale, log(Ereh/GeV), at which a matter dominated reheating ends (arXiv:1303.3787).

Aspic is a collection of fast modern fortran routines for computing various observable quantities used in Cosmology from definite single field inflationary models. It is distributed as a scientific library and aims at providing an efficient, extendable and accurate way of comparing theoretical inflationary predictions with cosmological data. **Aspic** currently supports 64 models of inflation, and more to come!

By observable quantities, we currently refer to as the Hubble flow functions, up to second order in the slow-roll approximation, which are in direct correspondence with the spectral index, the tensor-to-scalar ratio and the running of the primordial power spectrum. The **aspic** library also provides the field potential, its first and second derivatives, the energy density at the end of inflation, the energy density at the end of reheating, and the field value (or e-fold value) at which the pivot scale crossed the Hubble radius during inflation. All these quantities are computed in a way which is consistent with the existence of a reheating phase.

The code is released as a GNU software which compiles itself into both a static and shared library. As the list of inflationary models is always increasing, you are encouraged to add support for any model that would not yet be implemented.

Please, check the MAN file for a complete documentation a

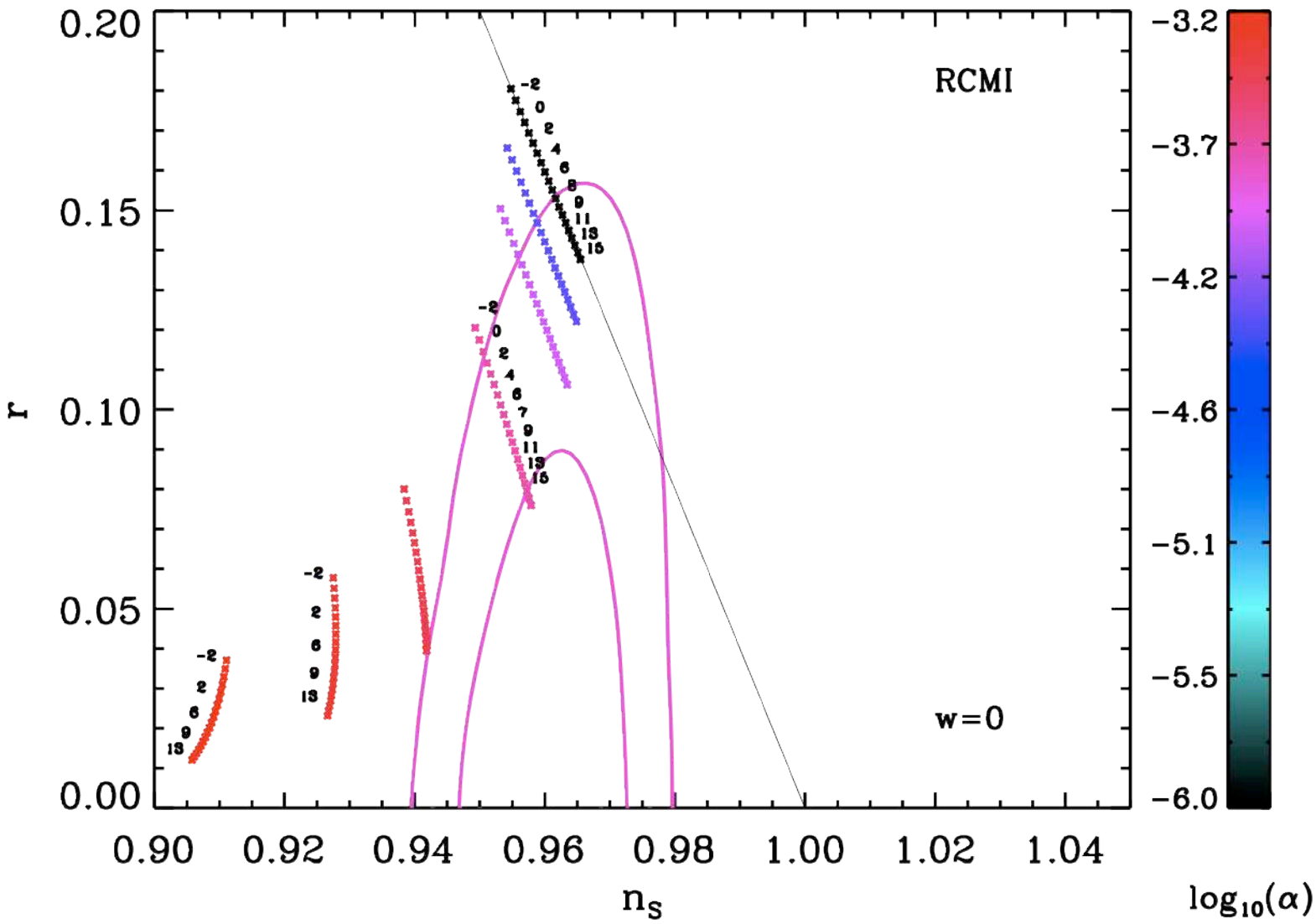
download the source file.

For details, please read the original paper arXiv:1303.3787

For an exact integration of any inflationary models, without assuming slow-roll, checkout the **fieldinf** code and library.

Last modif 03/2013

A few examples



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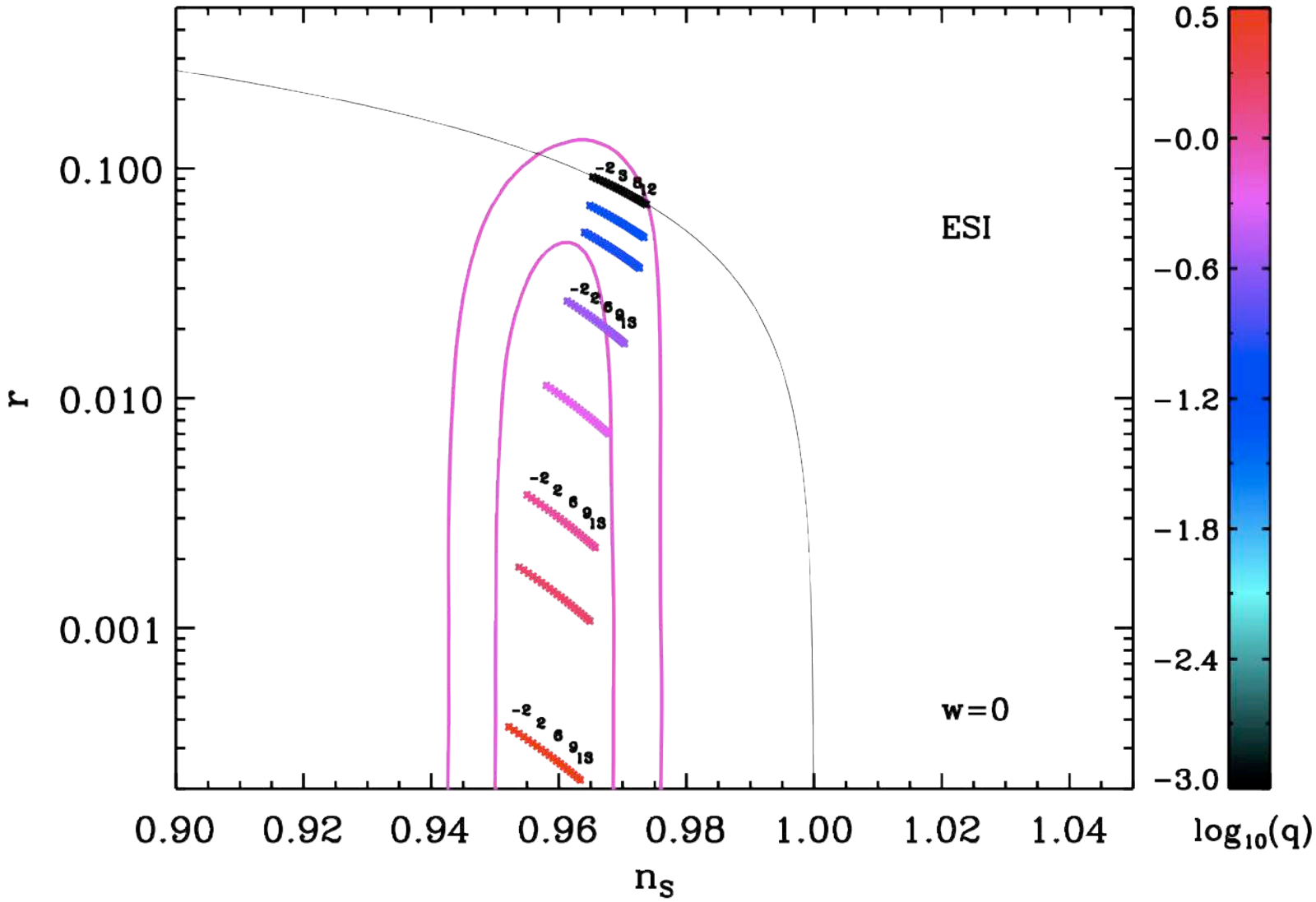

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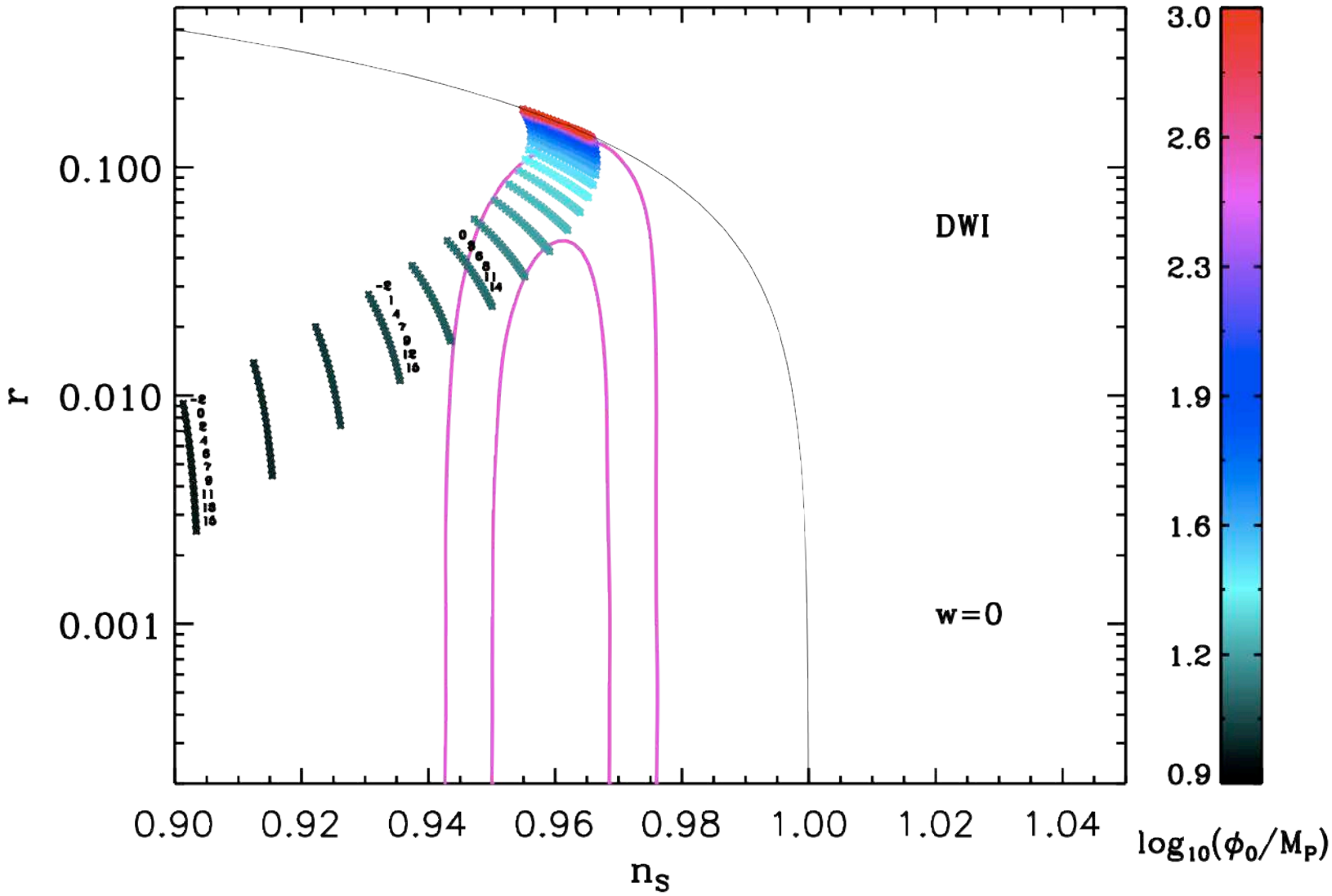

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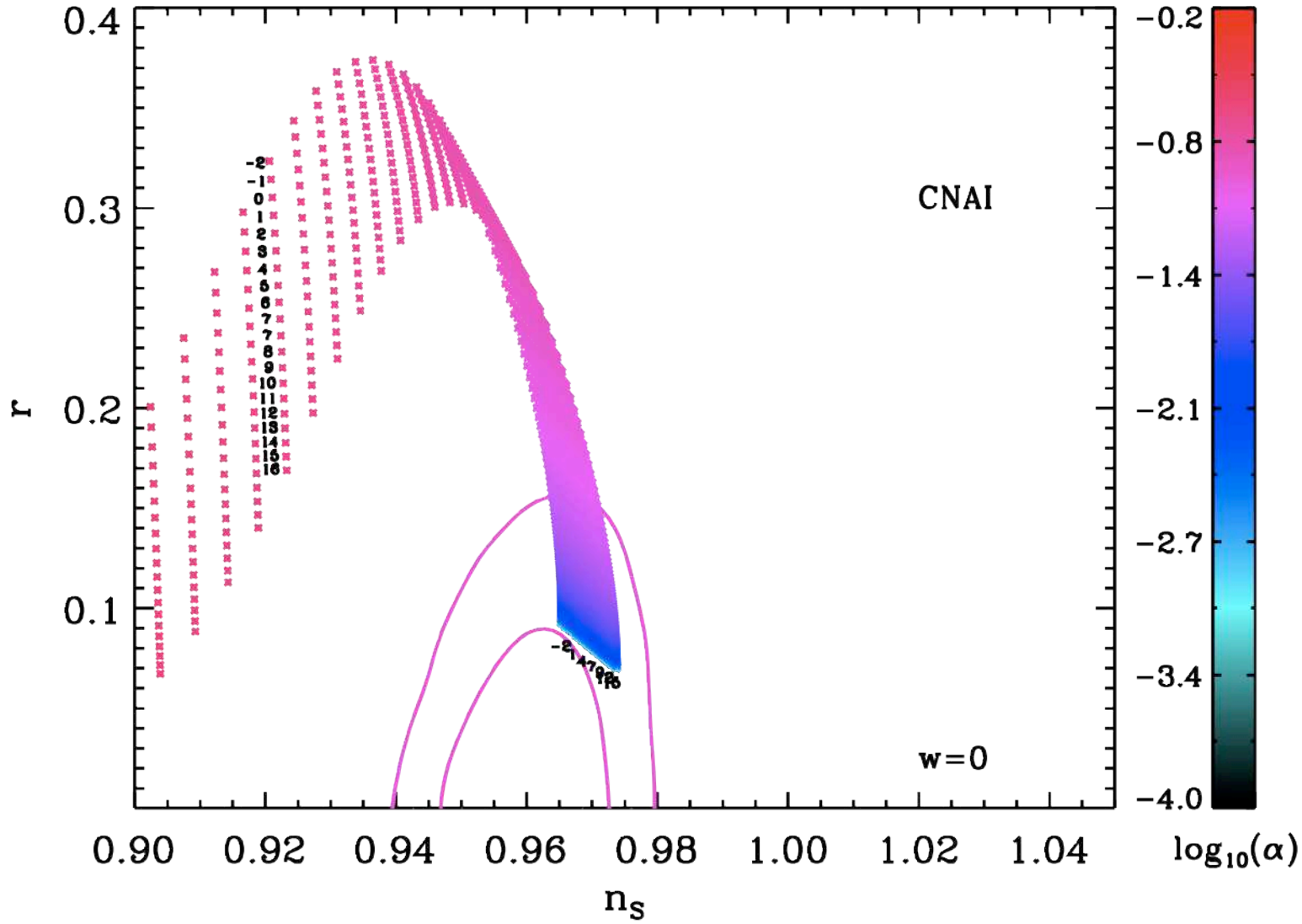

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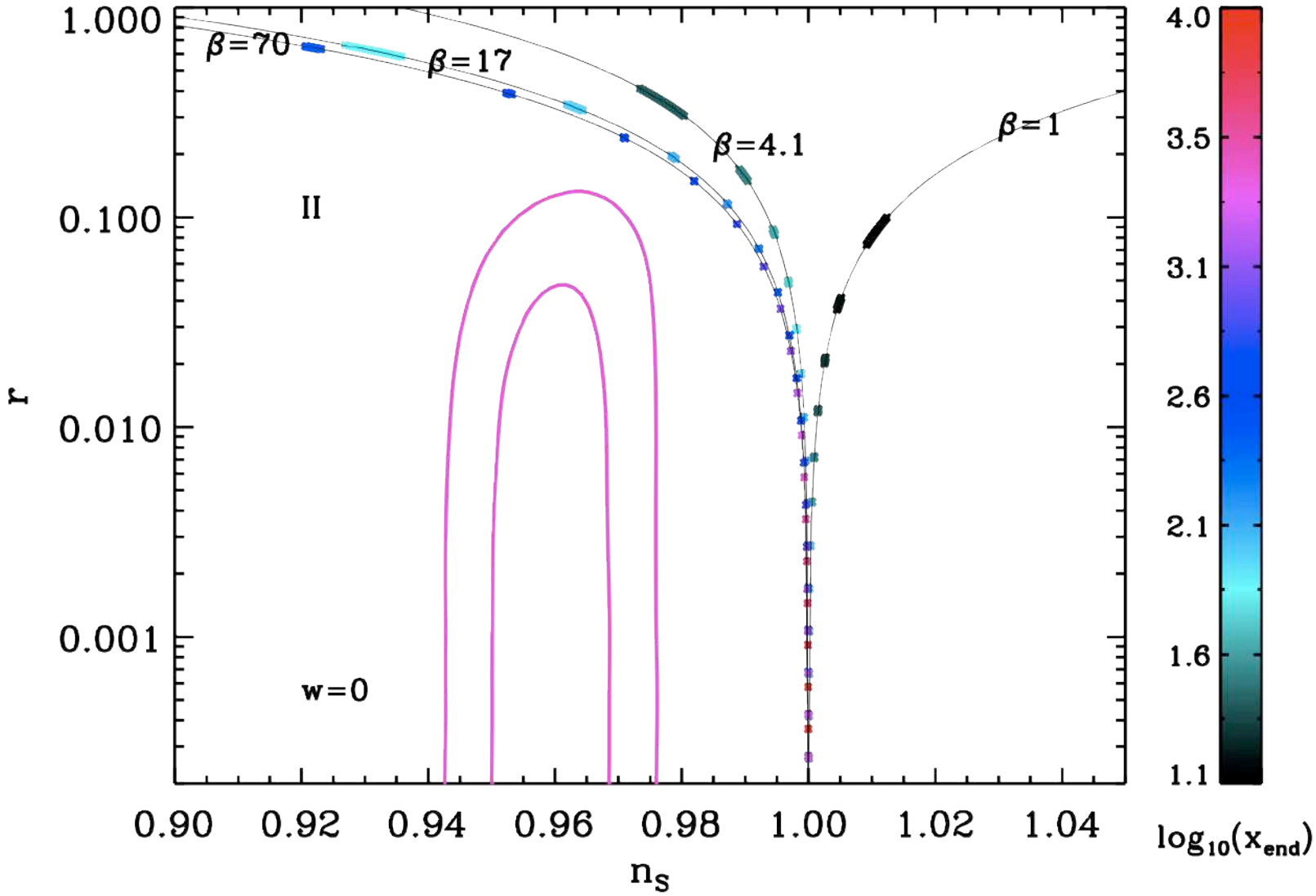

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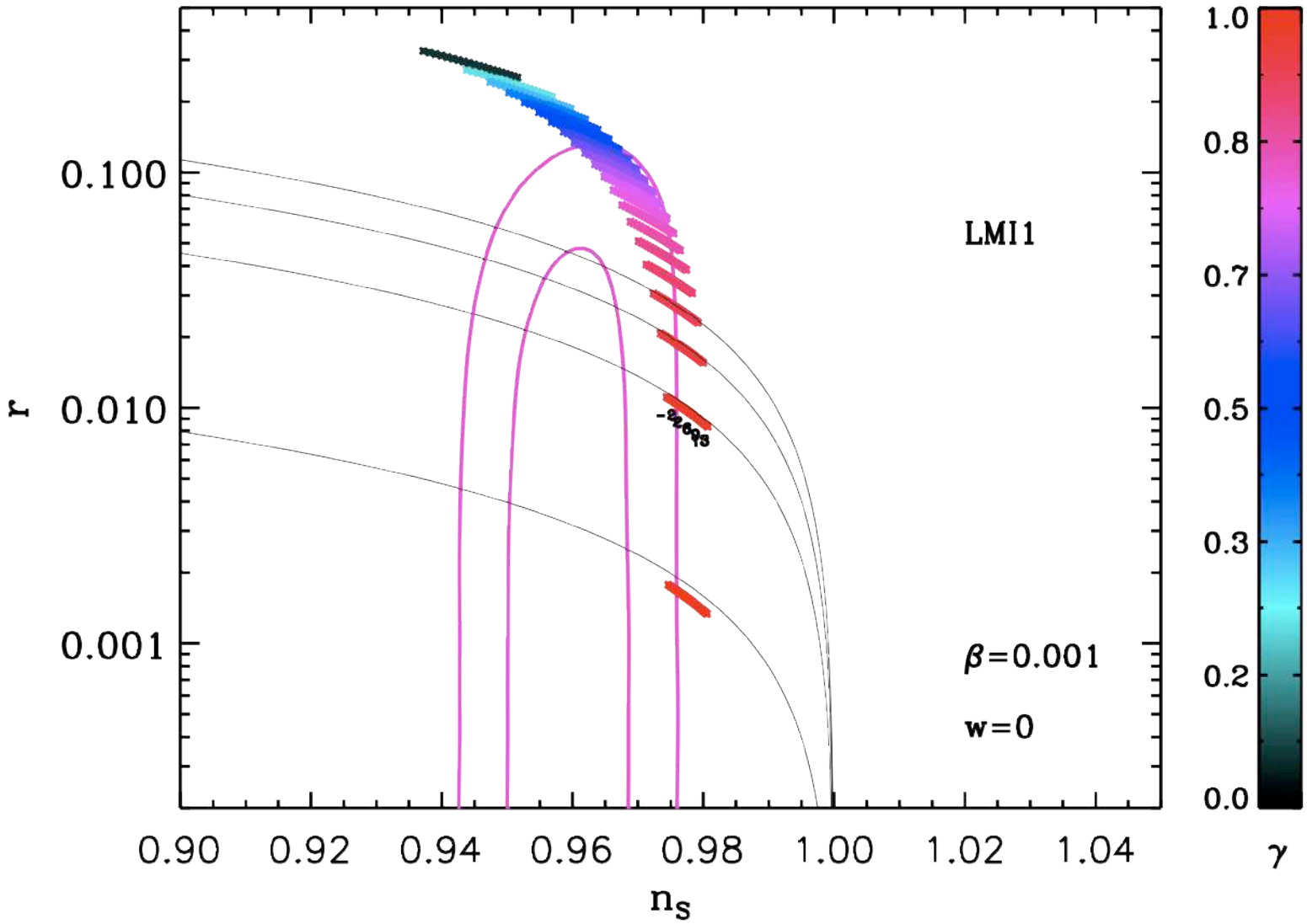

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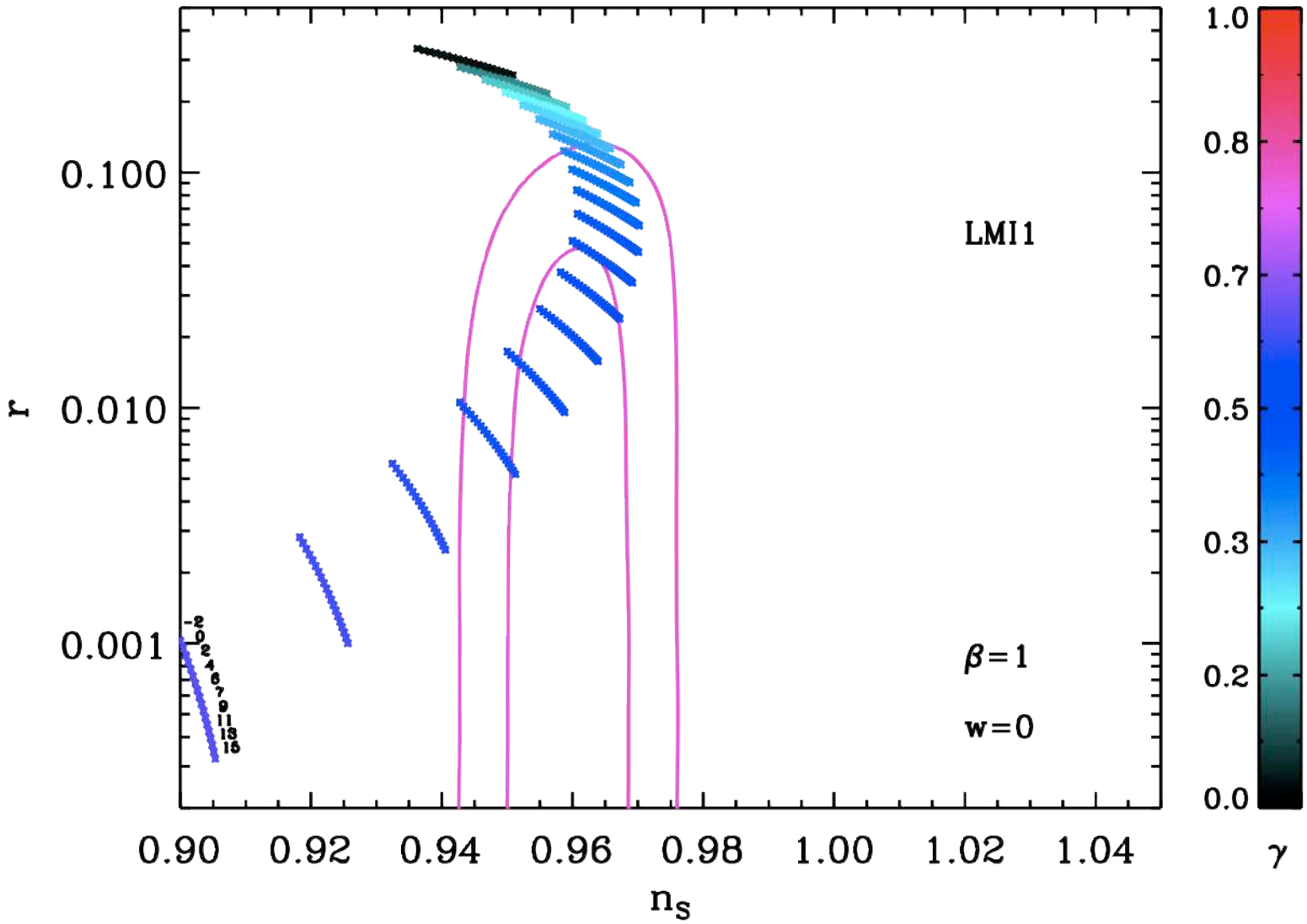

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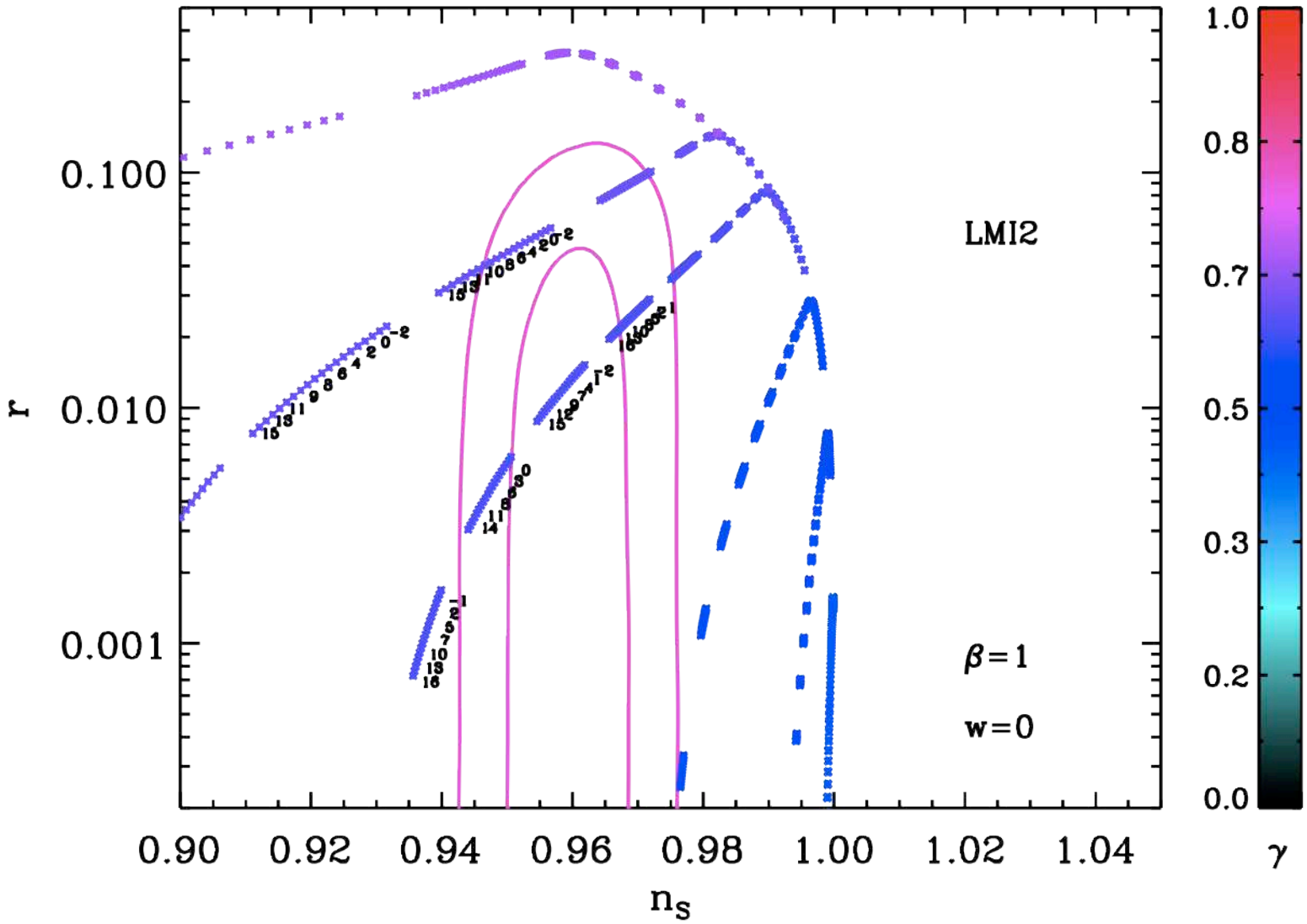

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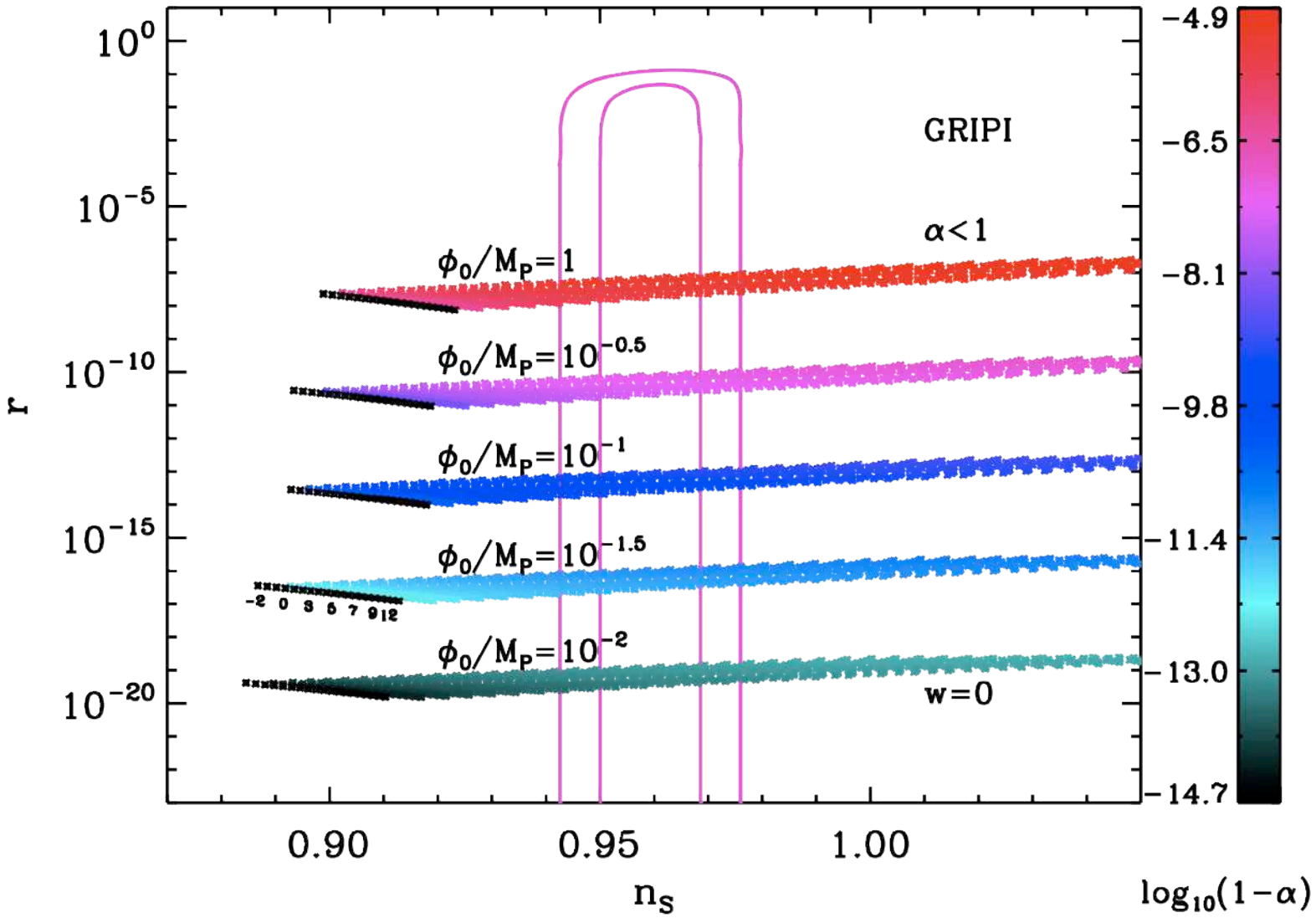

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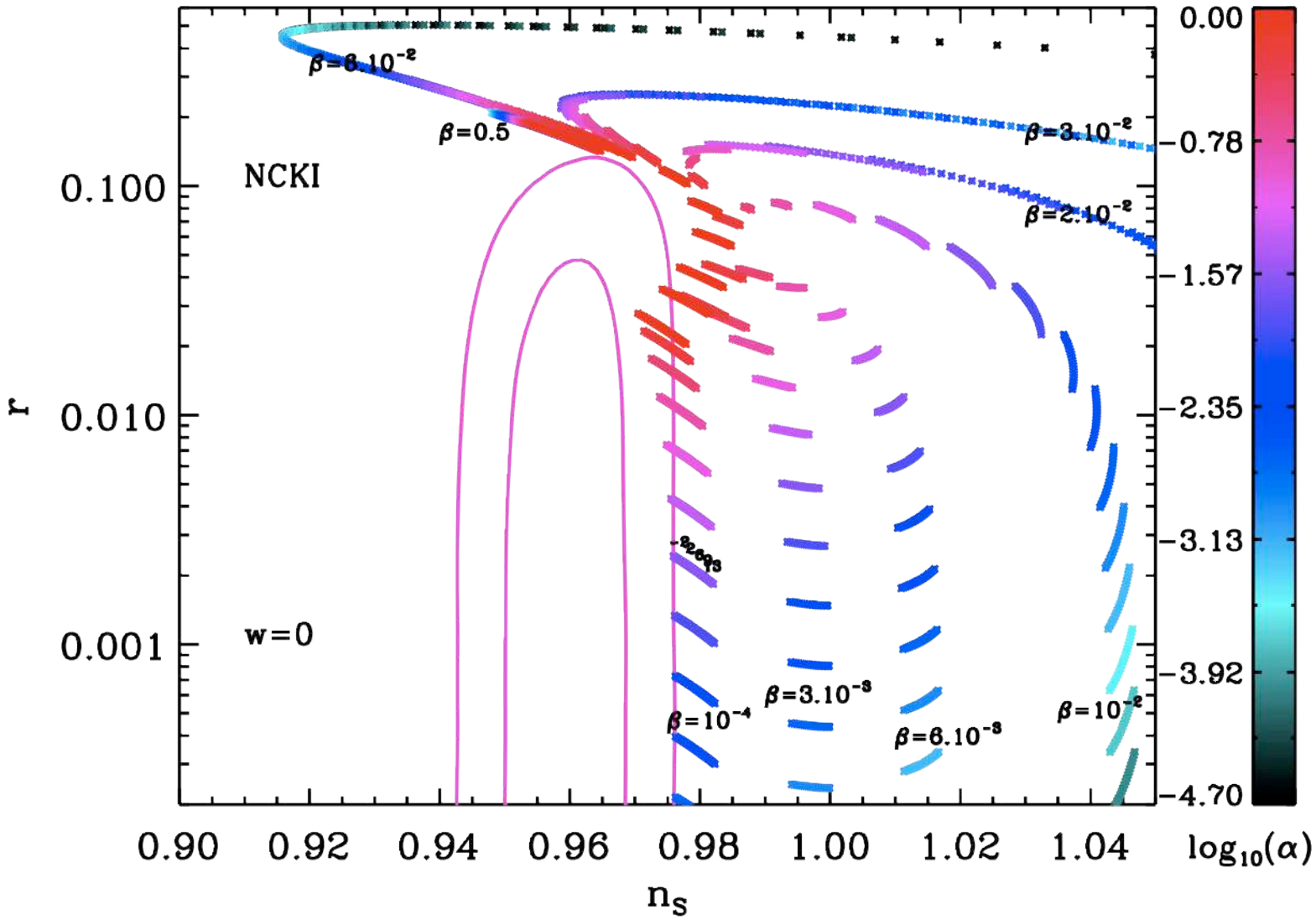

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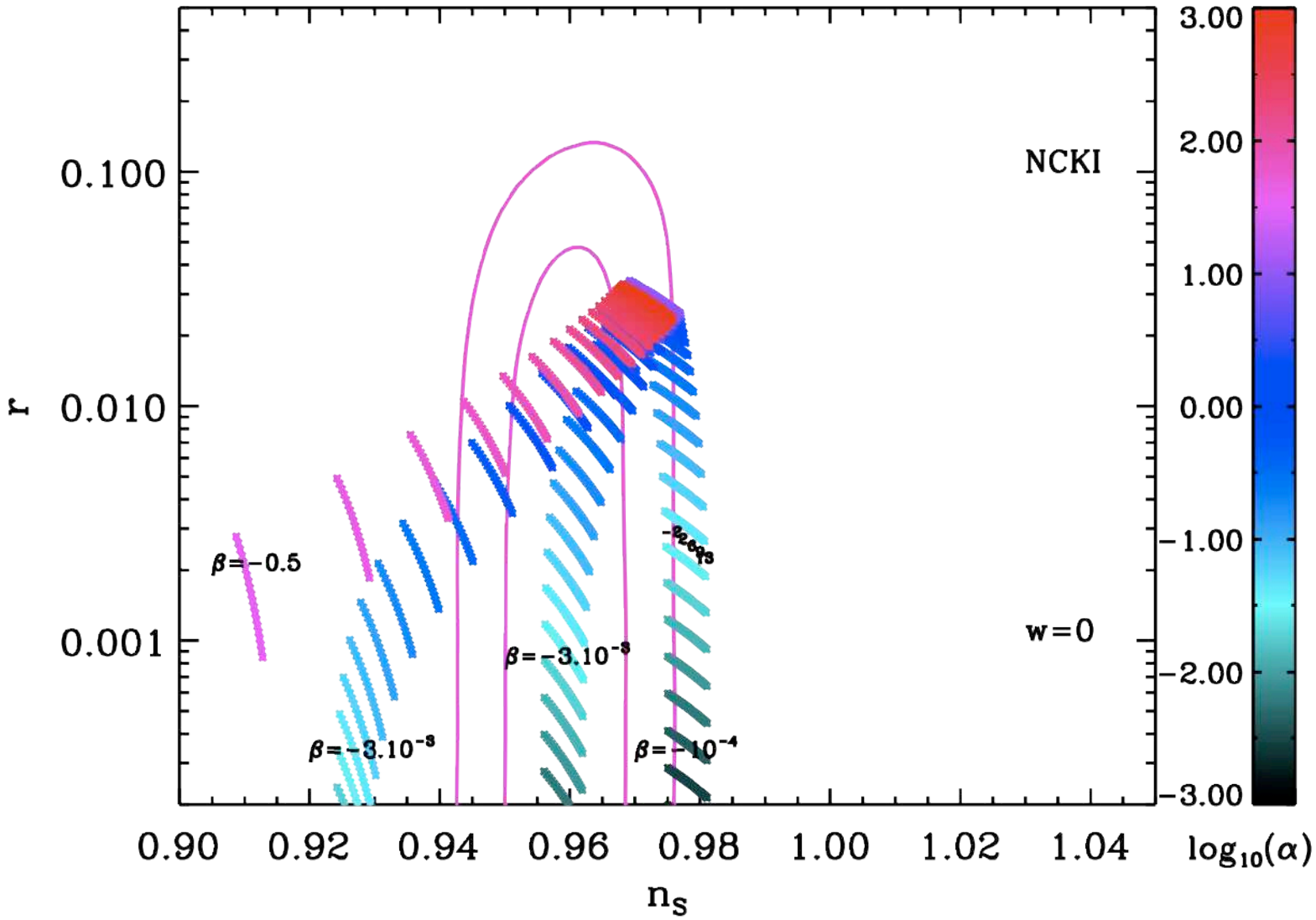

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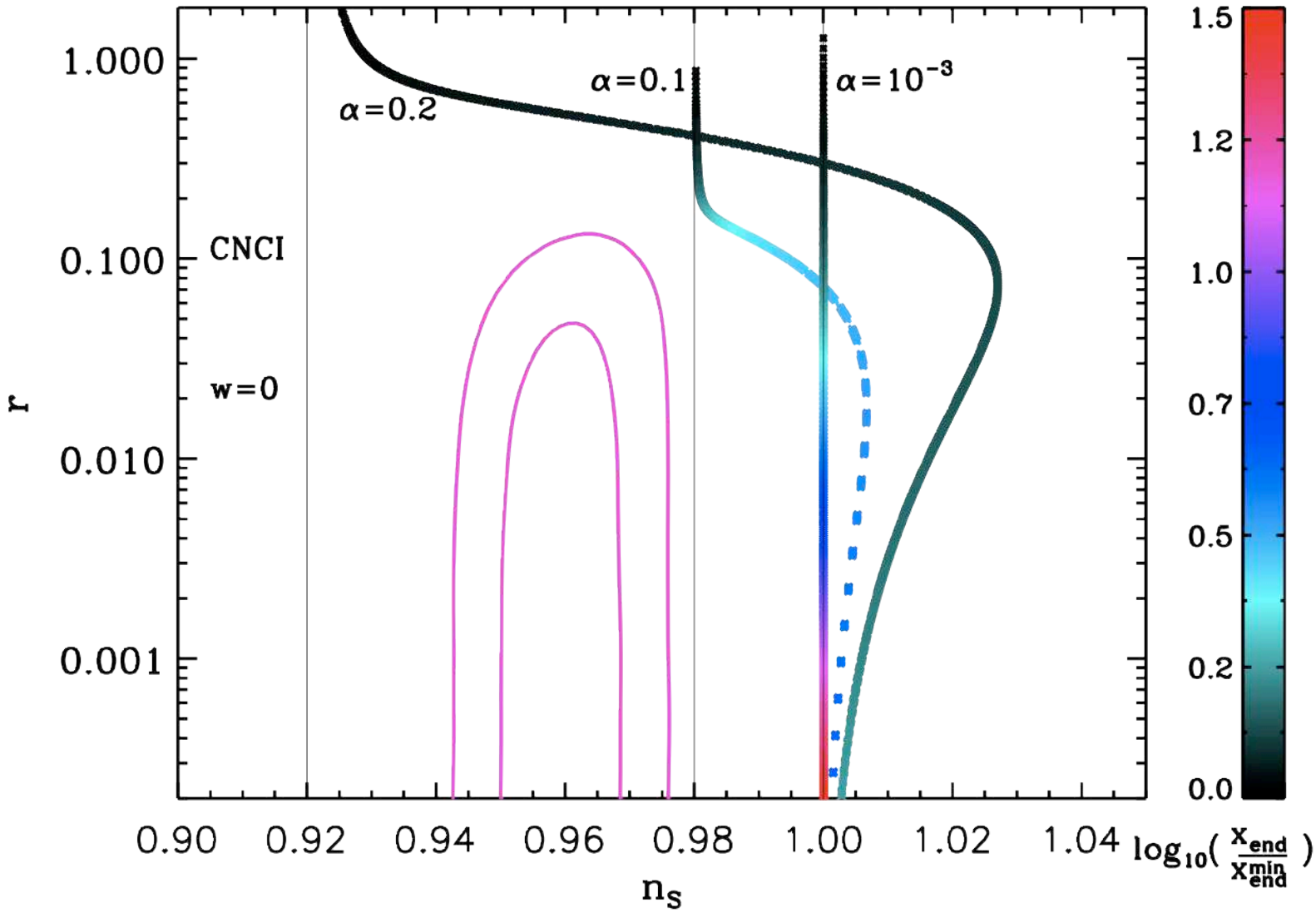

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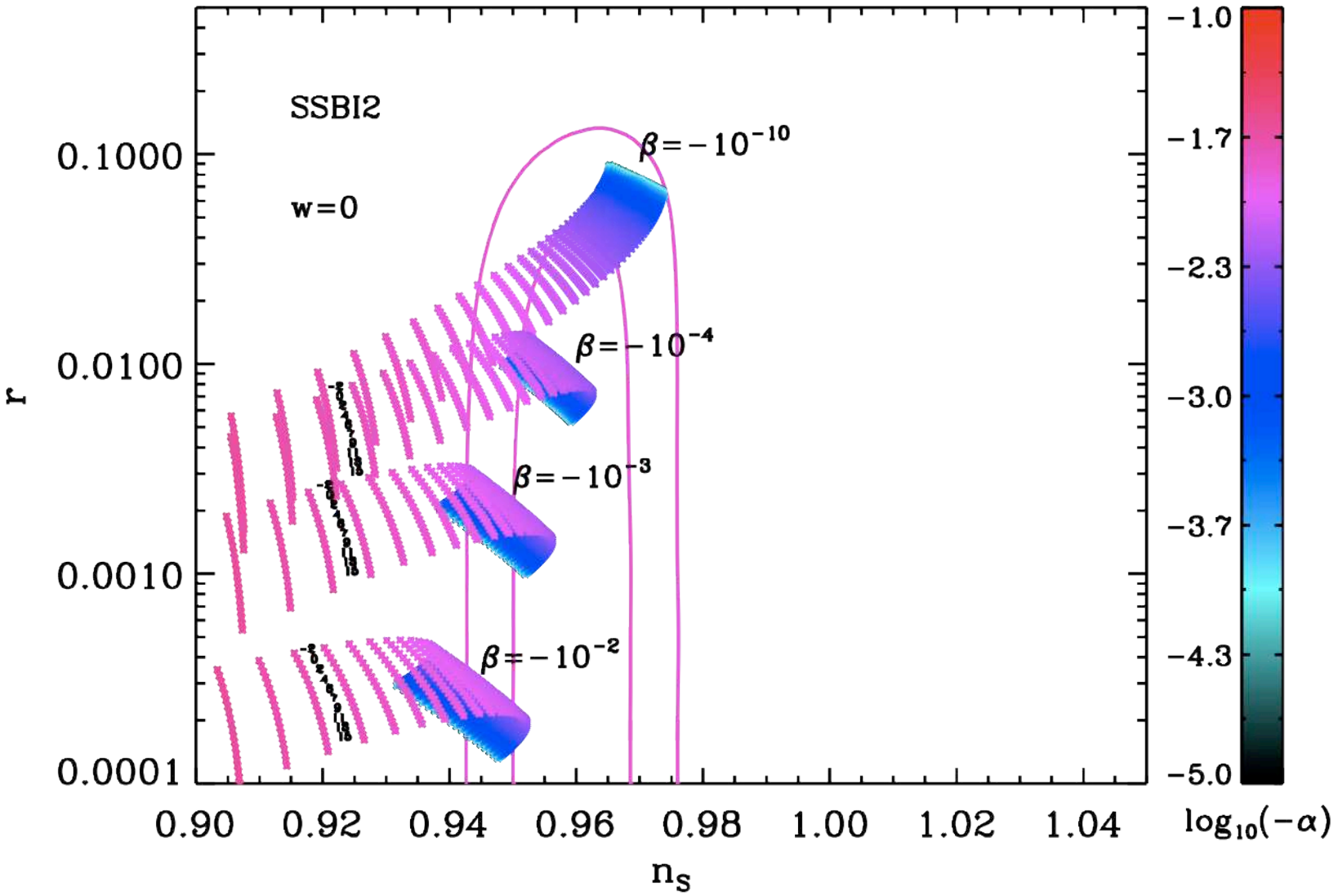

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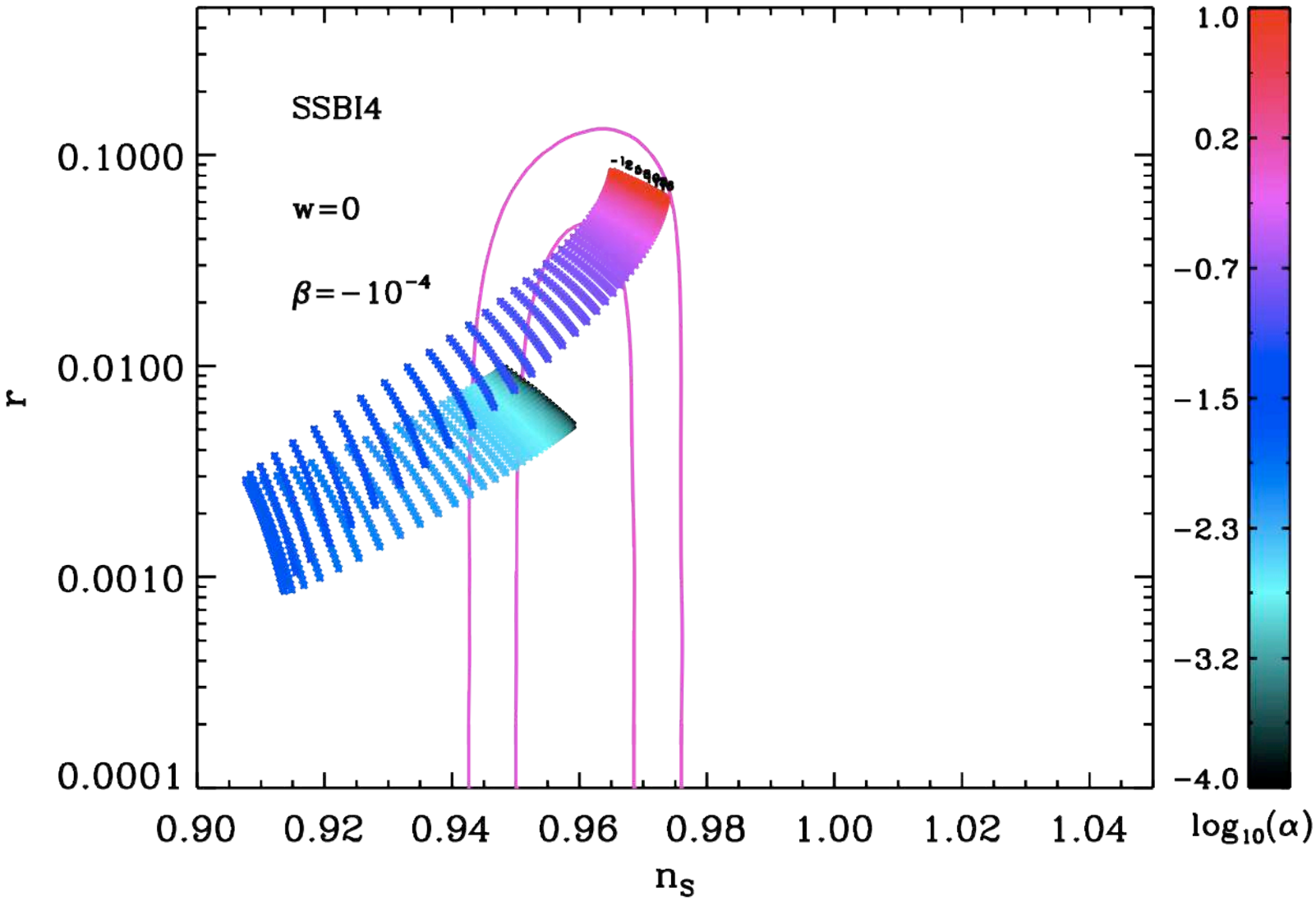

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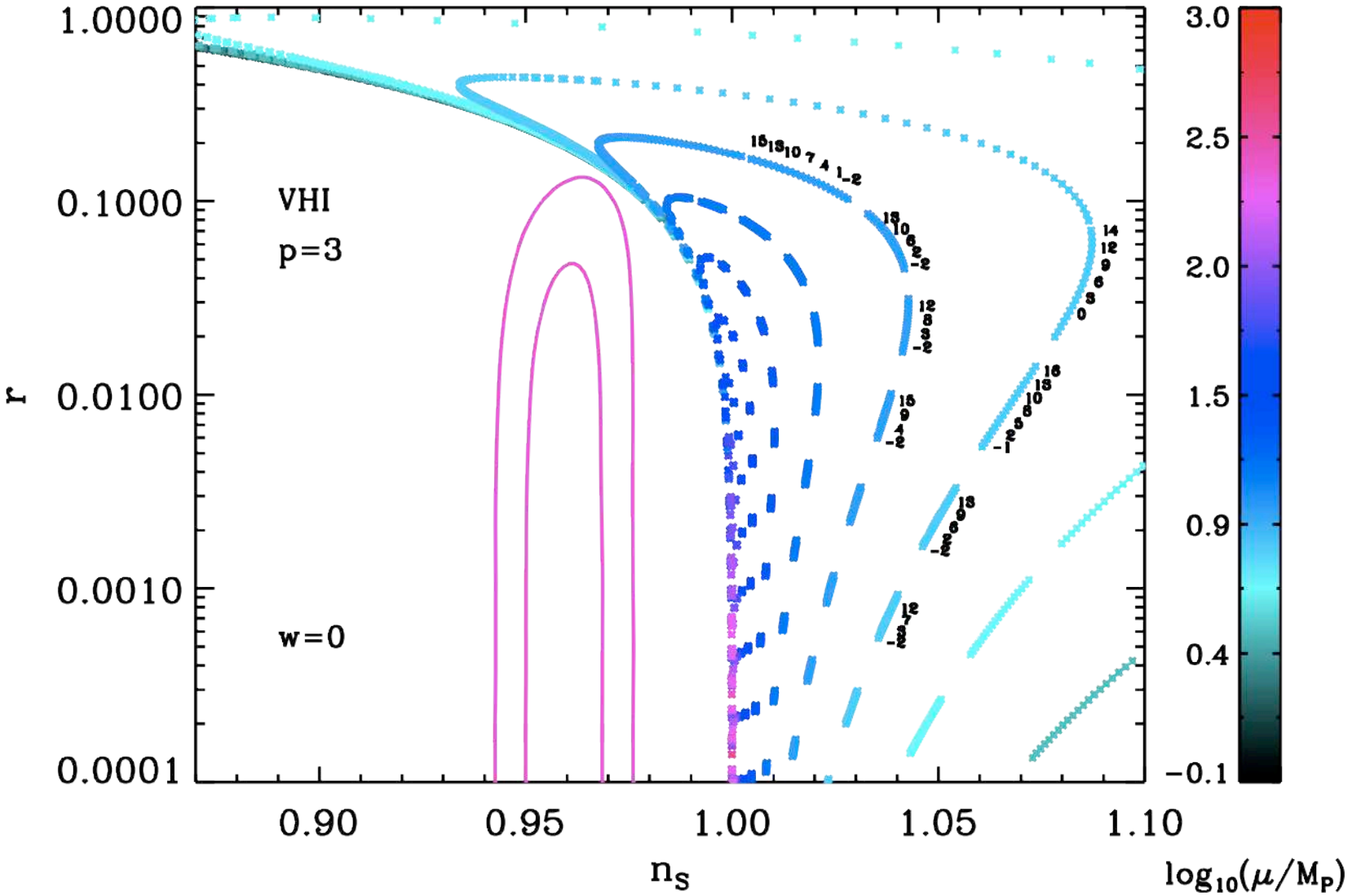

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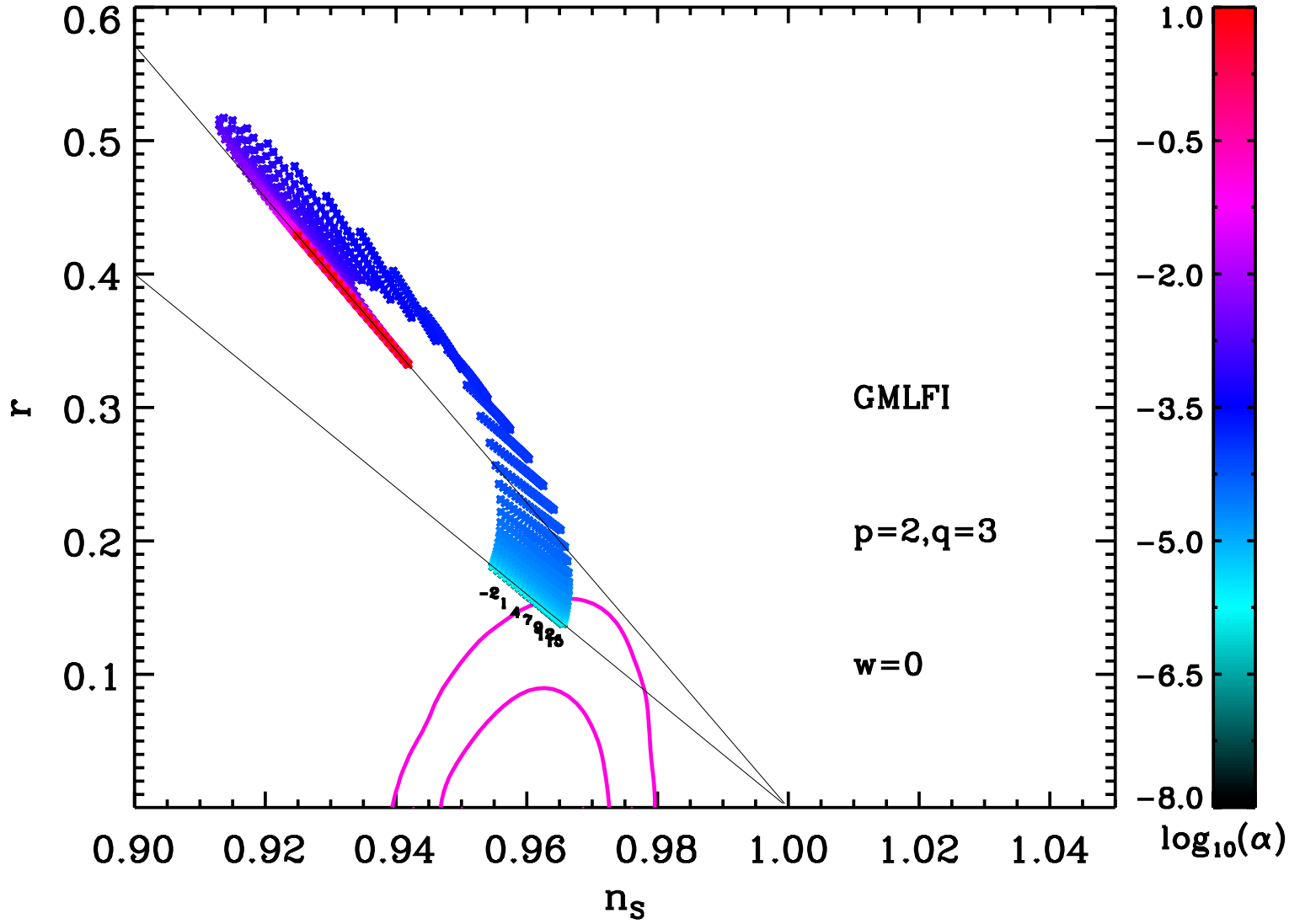
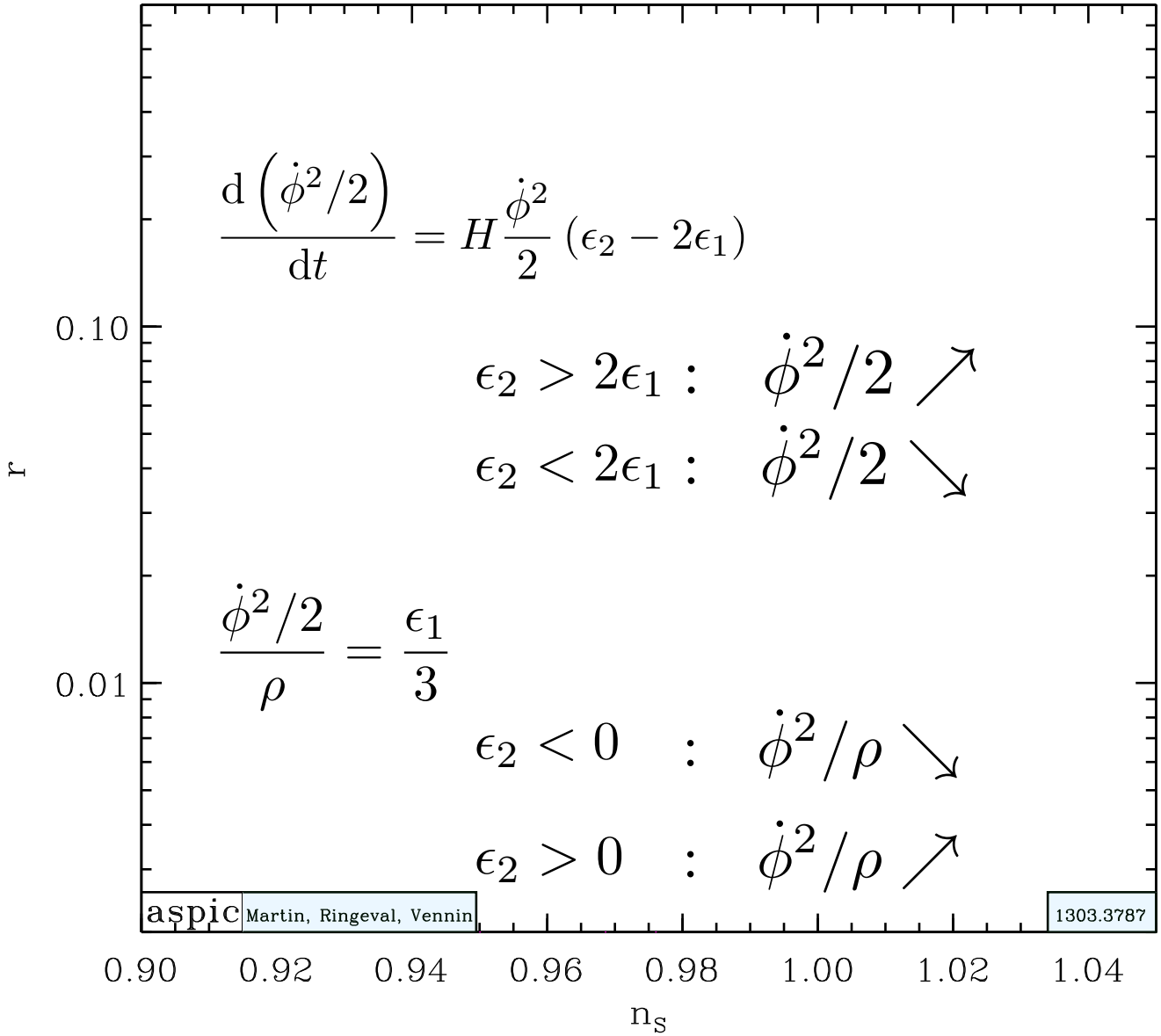


Typological Classification



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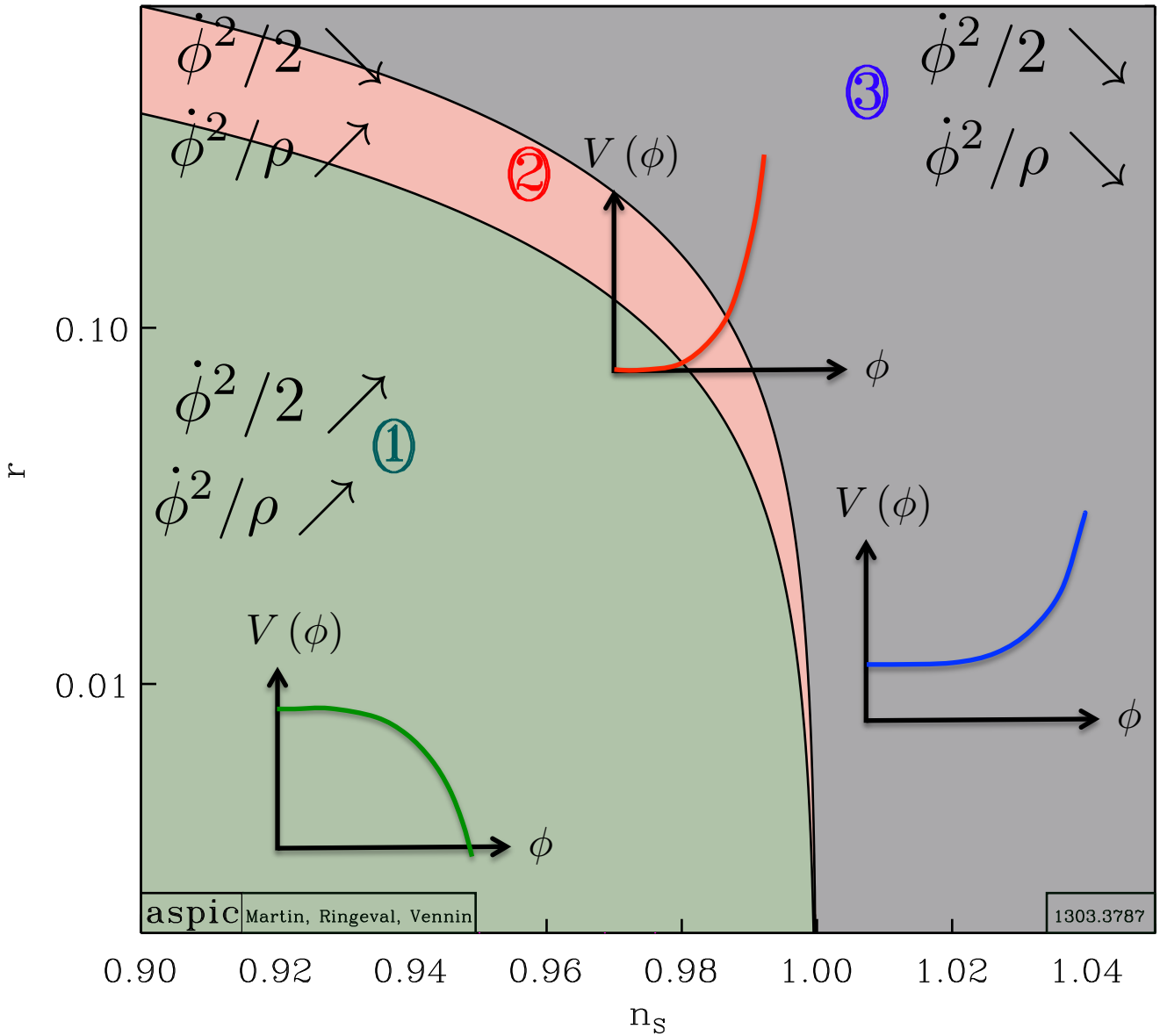

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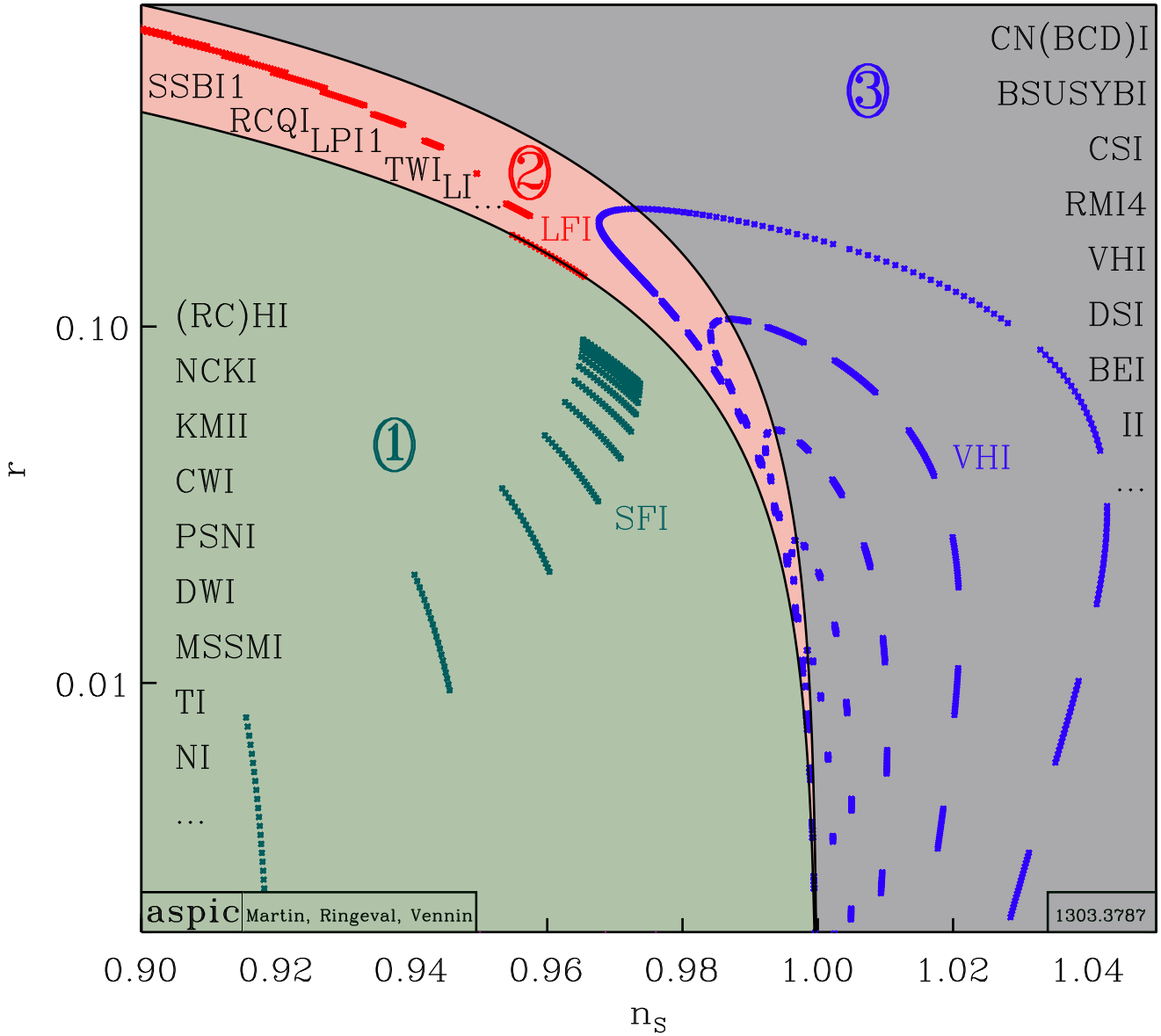

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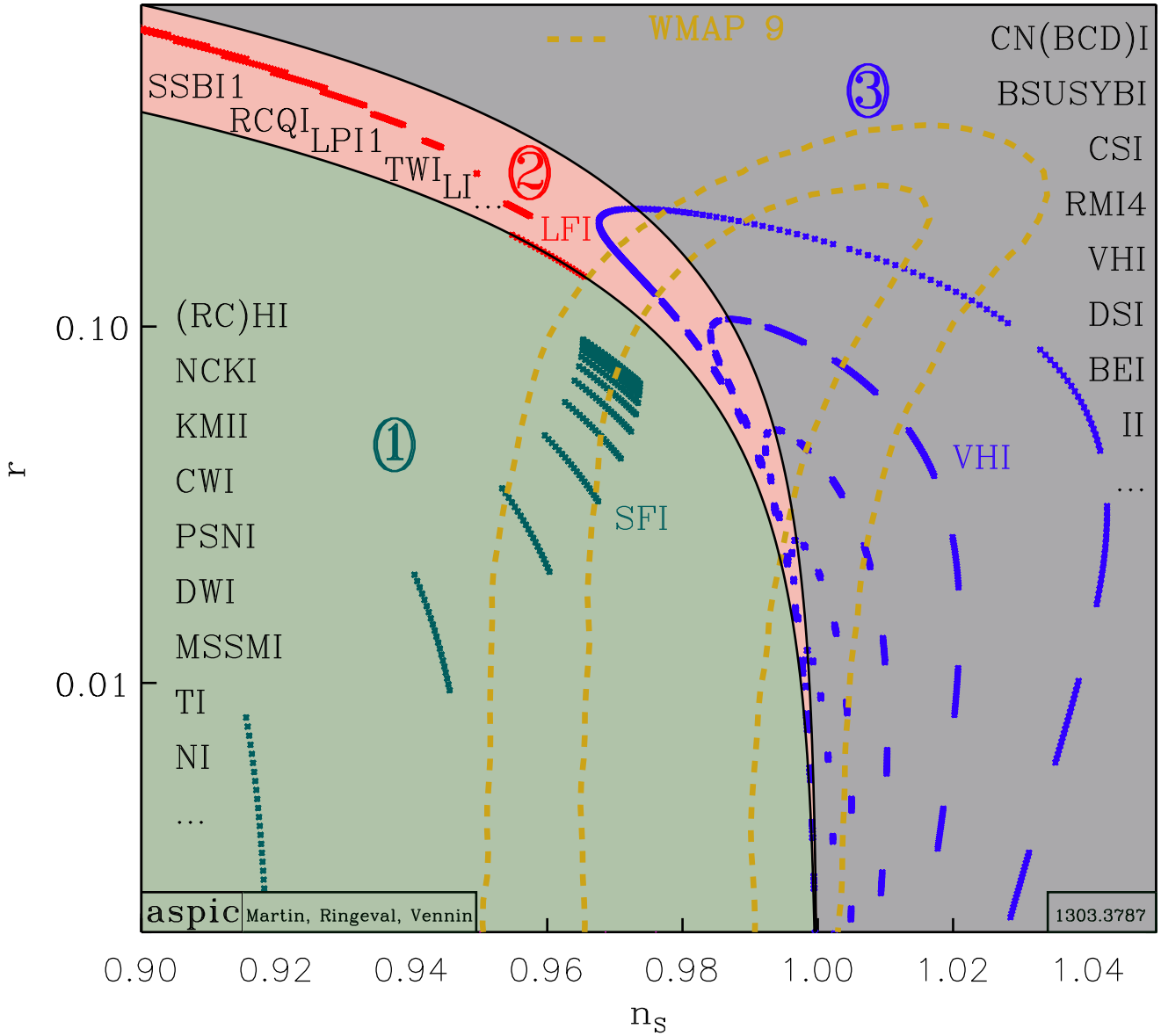

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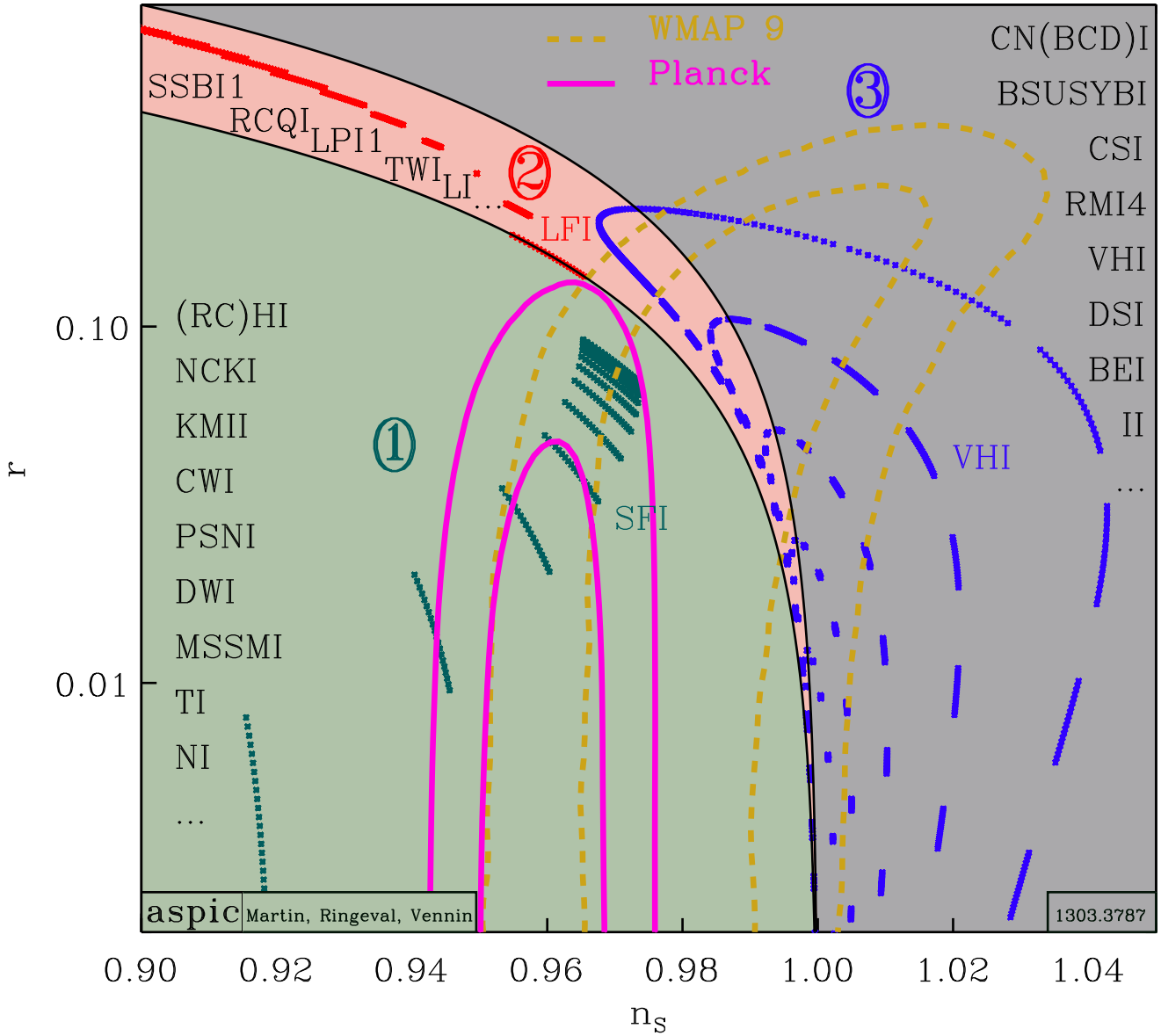

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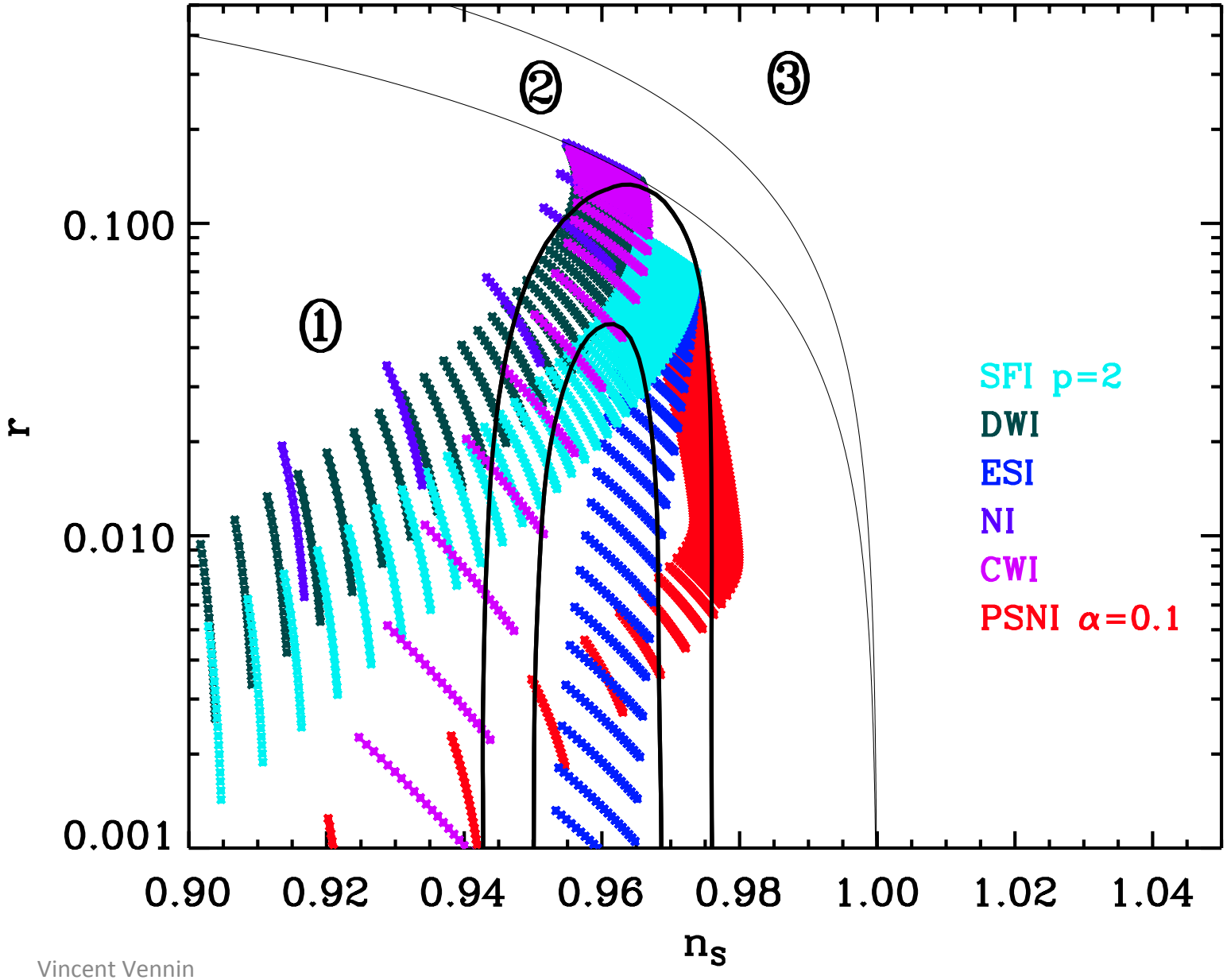
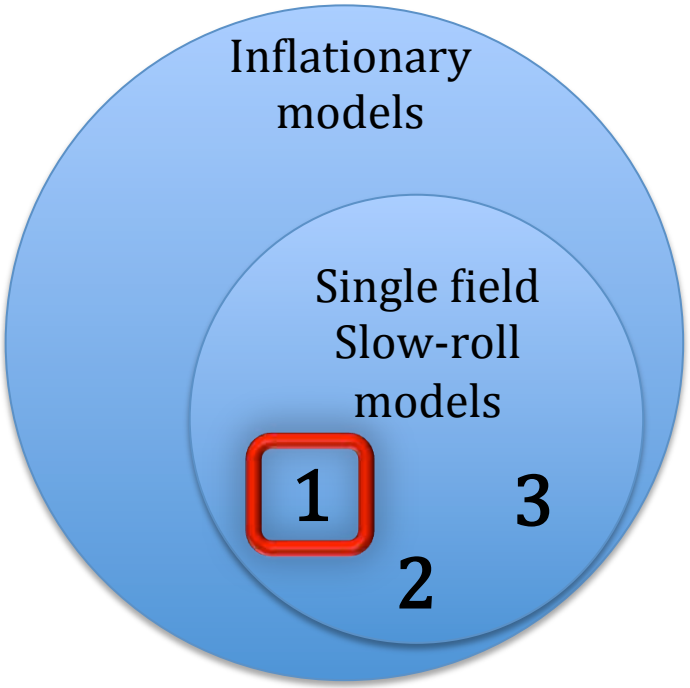


Where do we stand?



- Single field slow-roll models is the favored class of models given the Planck data and the data prefers category 1.

- But this still leaves us with hundreds of scenarios and this does not tell us what is **THE best model** among those scenarios?

- In order to define the best model, we need to:
  - Define « model A is better than model B » → Bayesian Evidence
  - Apply this definition to the complete slow-roll landscape, ie we have to scan all single field slow-roll models, one by one
  - Establish a complete ranking of all these models: model comparison program

Bayesian Approach

Model Comparison: Compute Bayesian Evidence

« Probability of a model »

Integral of the likelihood over parameter prior

Probability of model i

$$\frac{\mathcal{E}\left(\mathcal{M}_i\right)}{\mathcal{E}\left(\mathcal{M}_j\right)} = \mathcal{B}_{ij}$$

Bayes Factor

Probability of model j

$\mathcal{B}_{ij} > 1$ Model i is better than model j

$\mathcal{B}_{ij} < 1$ Model j is better than model i

Bayesian Approach

Model Comparison: Compute Bayesian Evidence

« Probability of a model »

Integral of the likelihood over parameter prior

Probability of model i

$$\frac{\mathcal{E}\left(\mathcal{M}_i\right)}{\mathcal{E}\left(\mathrm{HI}\right)} = \mathcal{B}_i$$

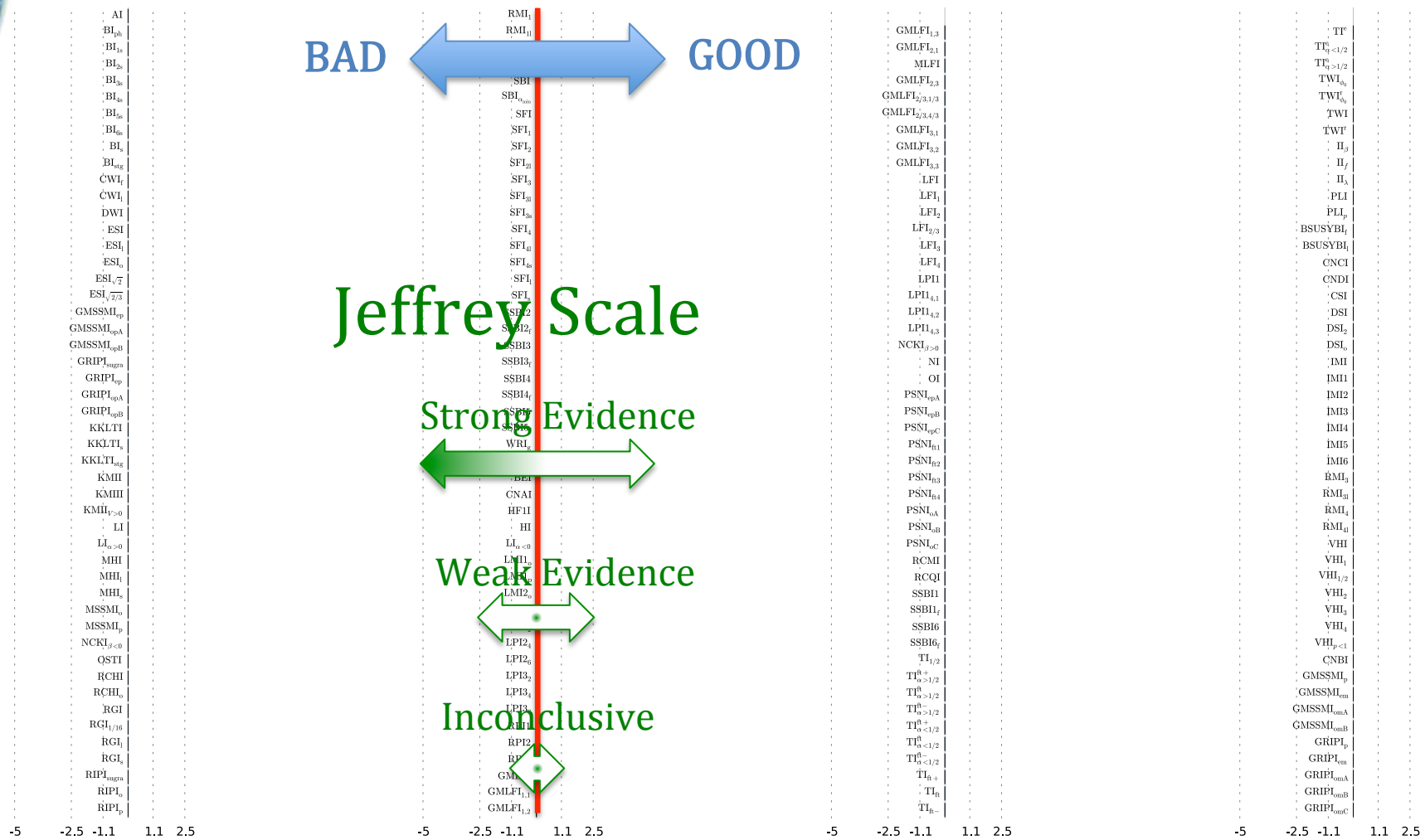
Bayes Factor

Probability of reference model = Starobinsky model

$\mathcal{B}_i > 1$ Model i is better than HI

$\mathcal{B}_i < 1$ HI is better than model i

Bayesian Evidences $\ln(\mathcal{E}/\mathcal{E}_{\mathrm{HI}})$

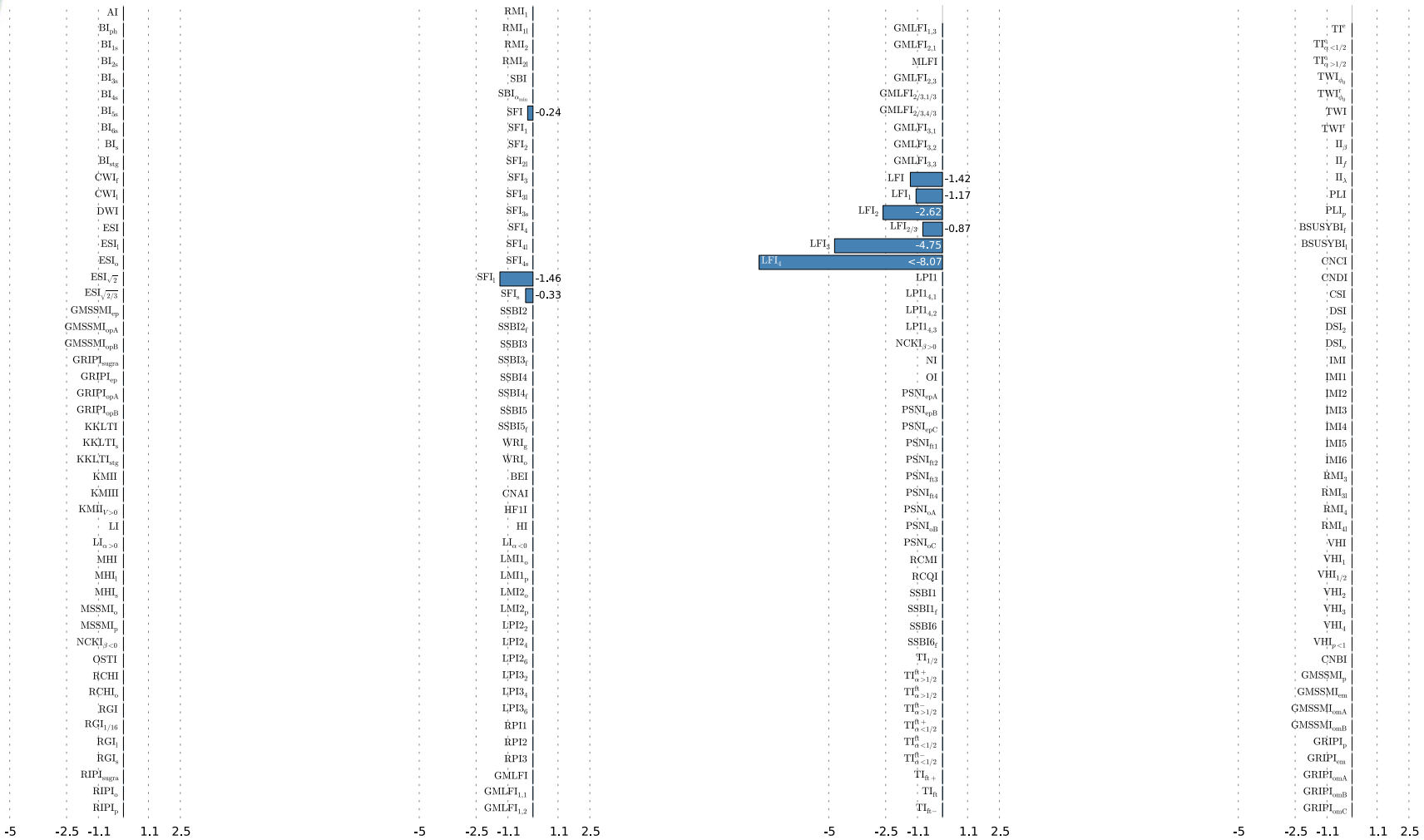


J.Martin, C.Ringeval, R.Trotta, V.Vennin
ASPIC project

Displayed Evidences: 0

Bayesian Evidences $\ln(\mathcal{E}/\mathcal{E}_{\rm HI})$

WMAP7: Martin, Ringeval & Trotta
arXiv:1009.4157

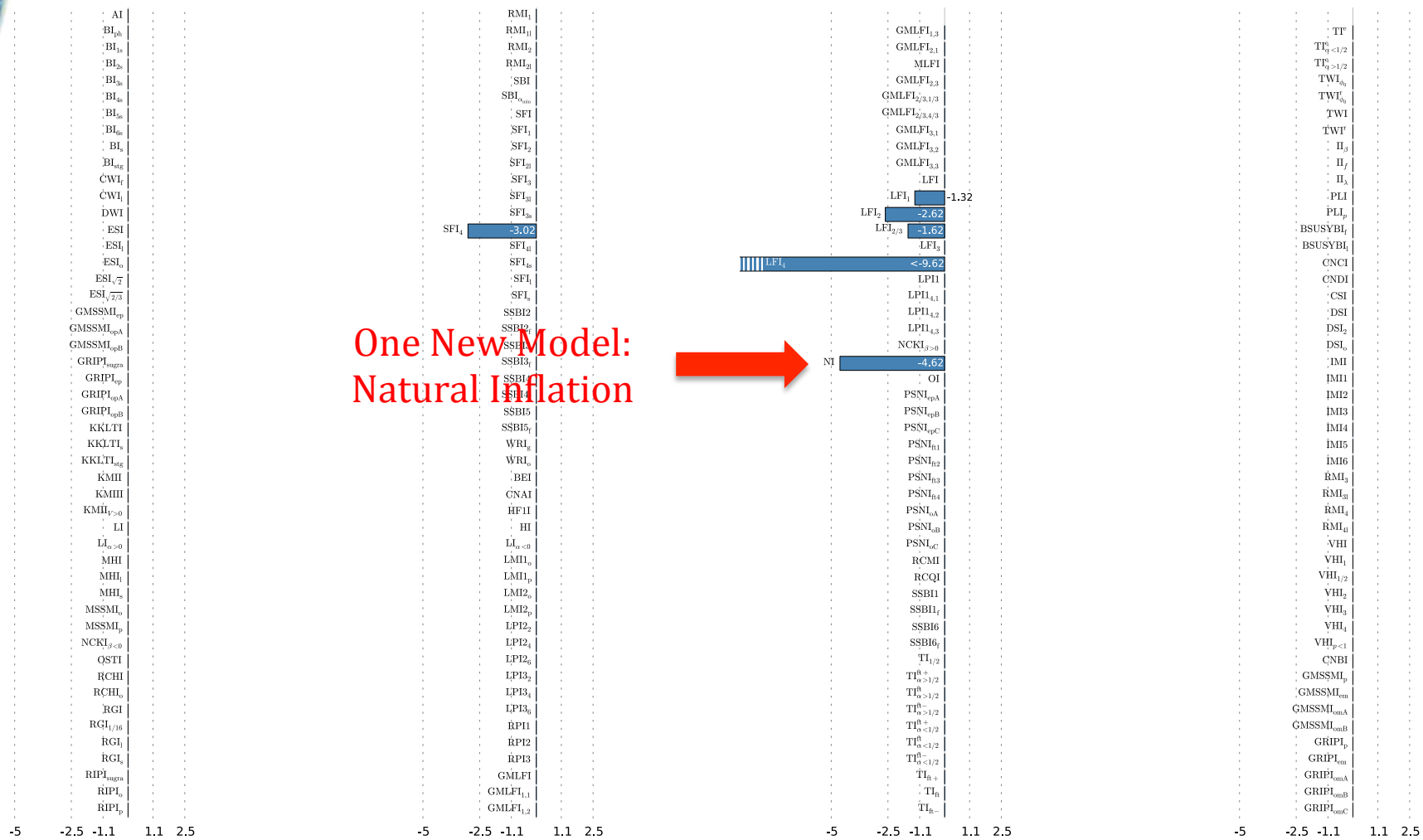


J.Martin, C.Ringeval, R.Trotta, V.Vennin
ASPIC project

Displayed Evidences: 9

Bayesian Evidences $\ln(\mathcal{E}/\mathcal{E}_{\mathrm{HI}})$

Planck collaboration
arXiv:1303.5082

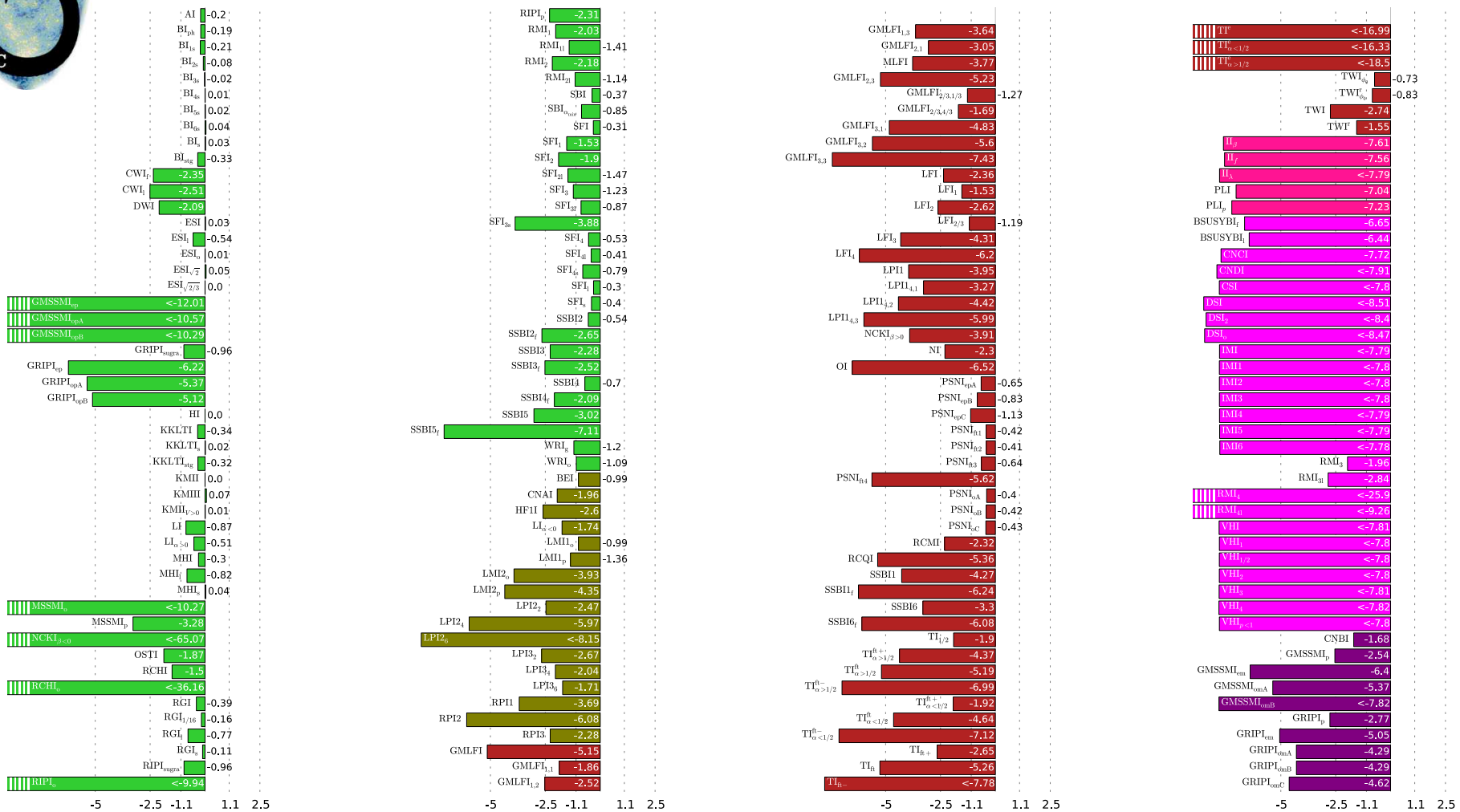


One New Model:
Natural Inflation

J.Martin, C.Ringeval, R.Trotta, V.Vennin
ASPIC project

Displayed Evidences: 5

Bayesian Evidences $\ln(\mathcal{E}/\mathcal{E}_{\rm HI})$



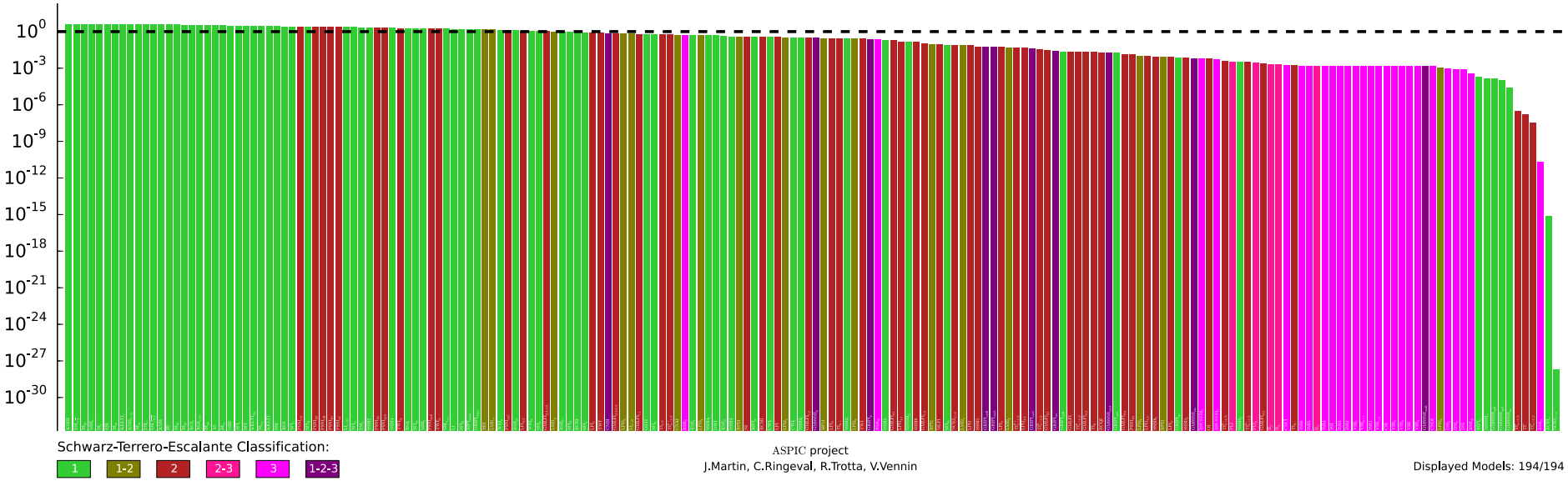
Schwarz-Terrero-Escalante Classification:

1 | 1-2 | 2 | 2-3 | 3 | 1-2-3

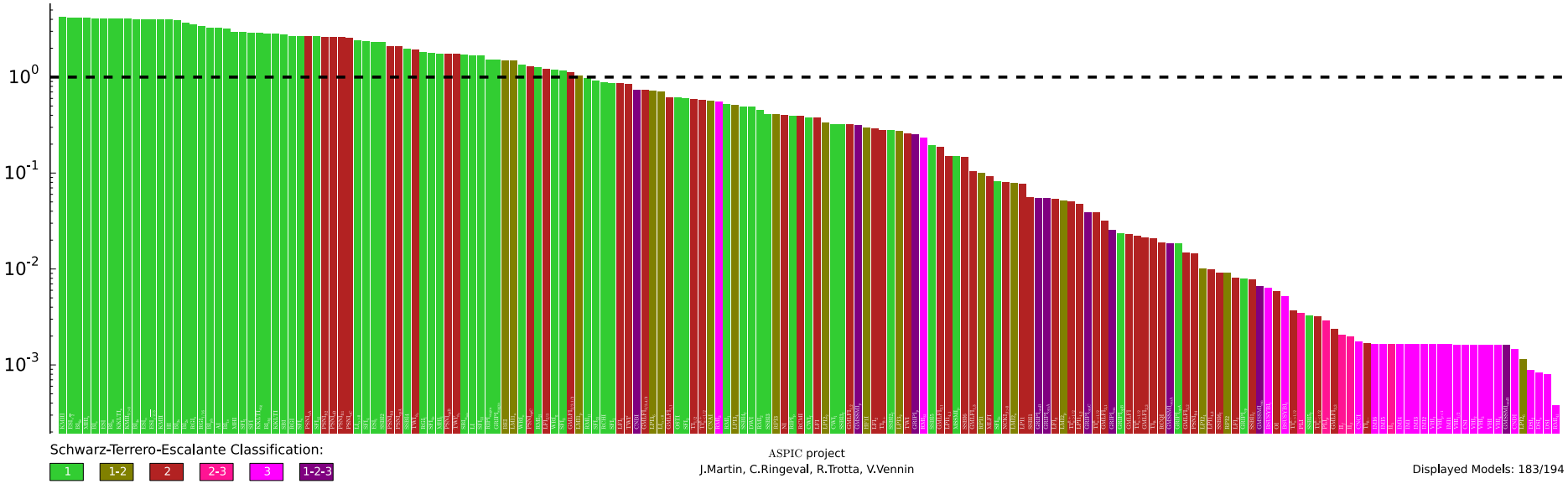
J.Martin, C.Ringeval, R.Trotta, V.Vennin
ASPIC project

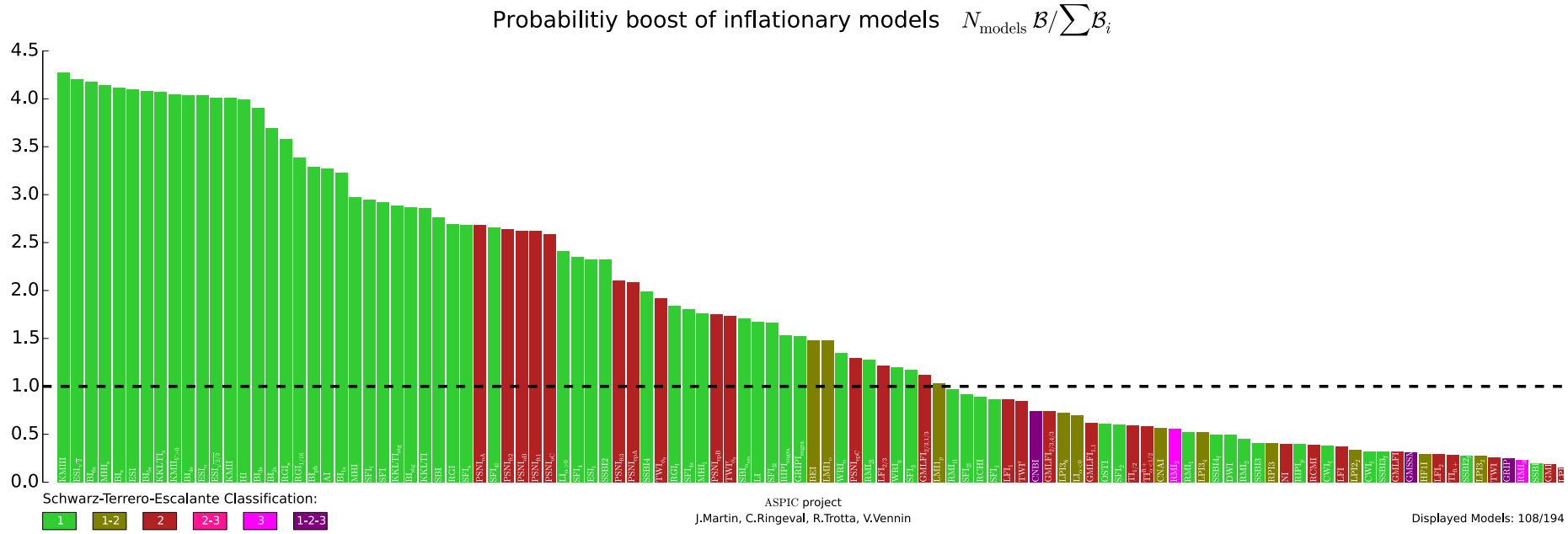
Displayed Evidences: 194

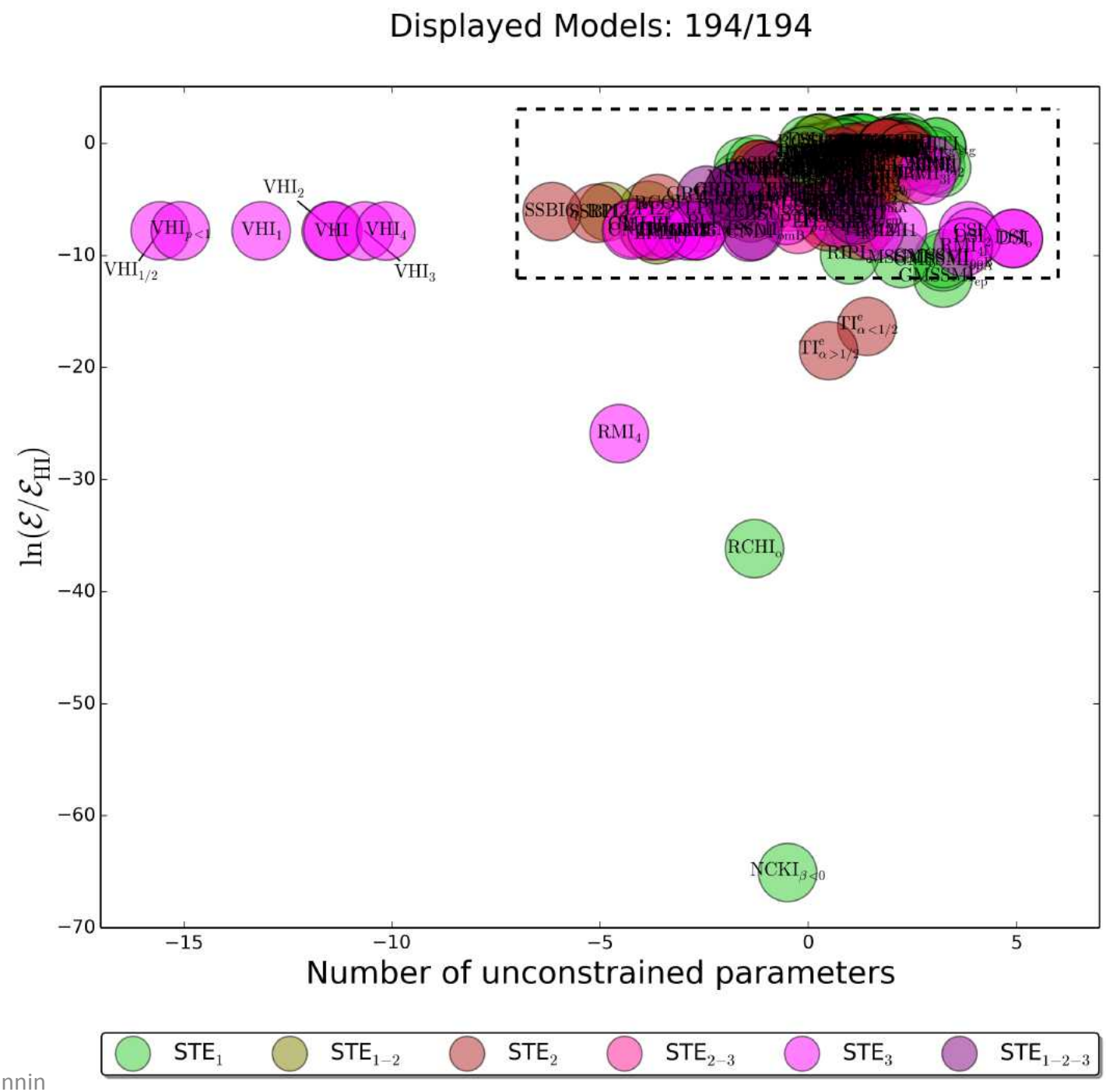
Probabilitiy boost of inflationary models $N_{\text{models}}\,\mathcal{B}/\sum\mathcal{B}_i$

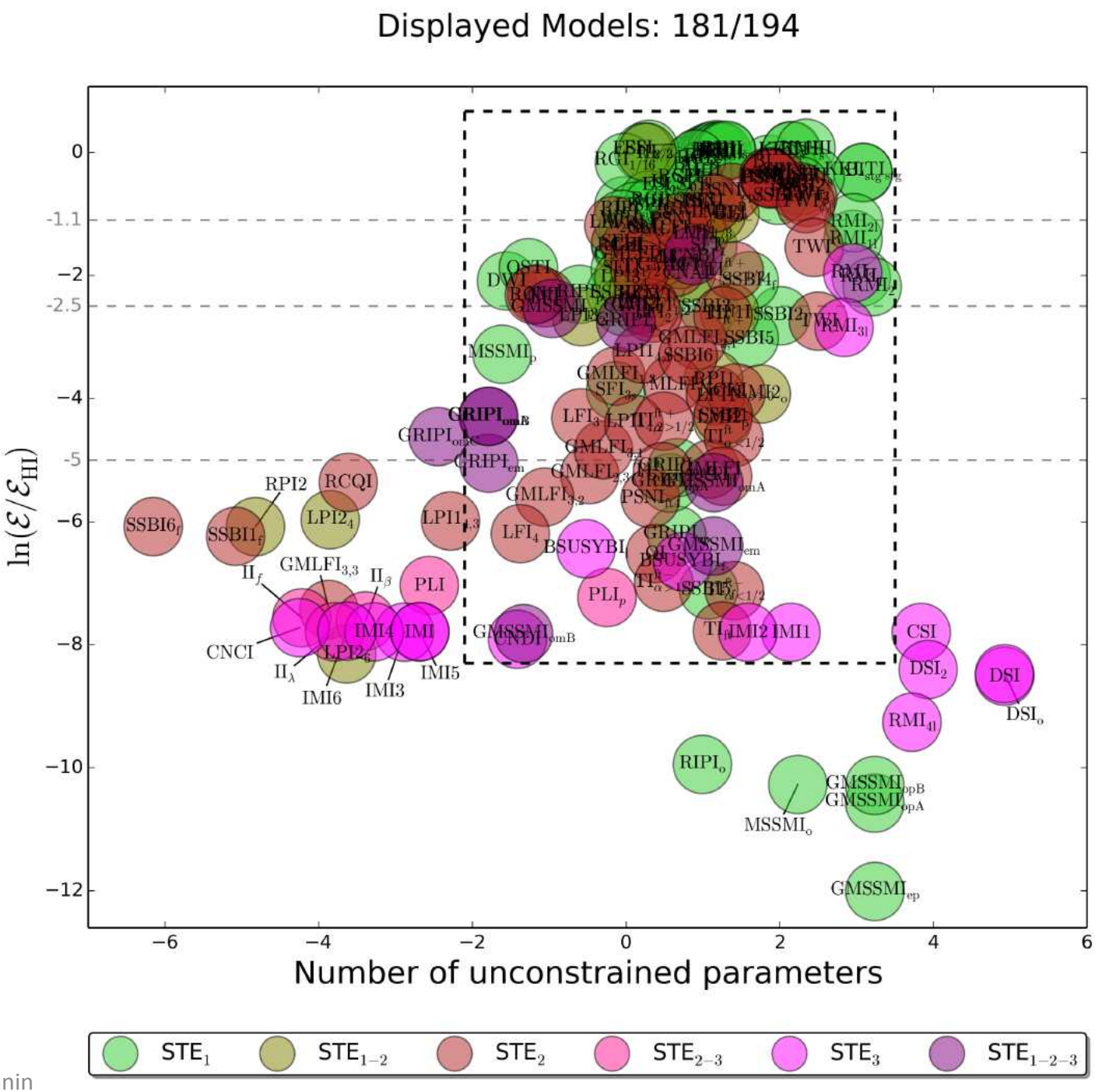


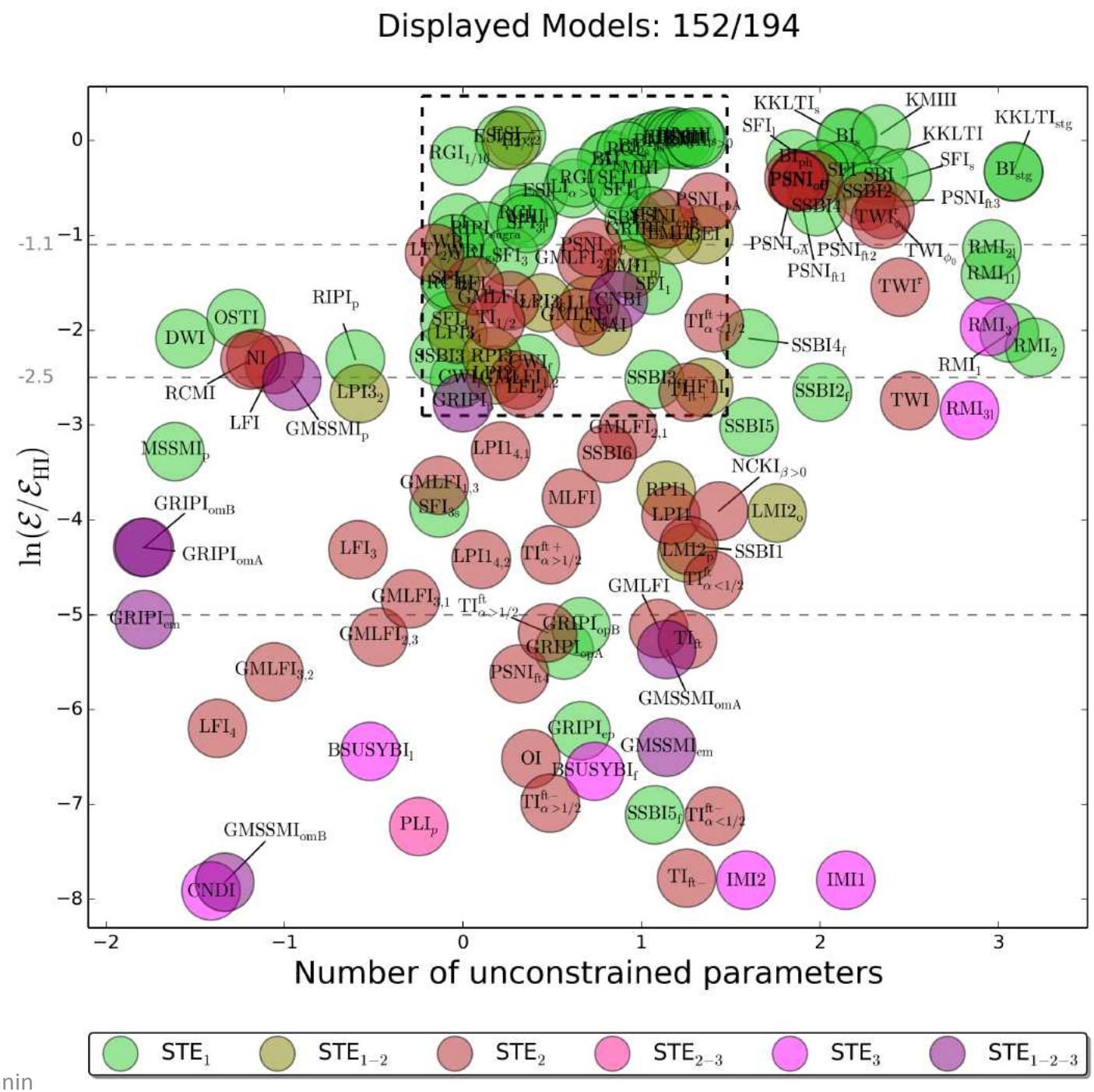
Probabilitiy boost of inflationary models $N_{\rm models}\,\mathcal{B}/\sum\mathcal{B}_i$

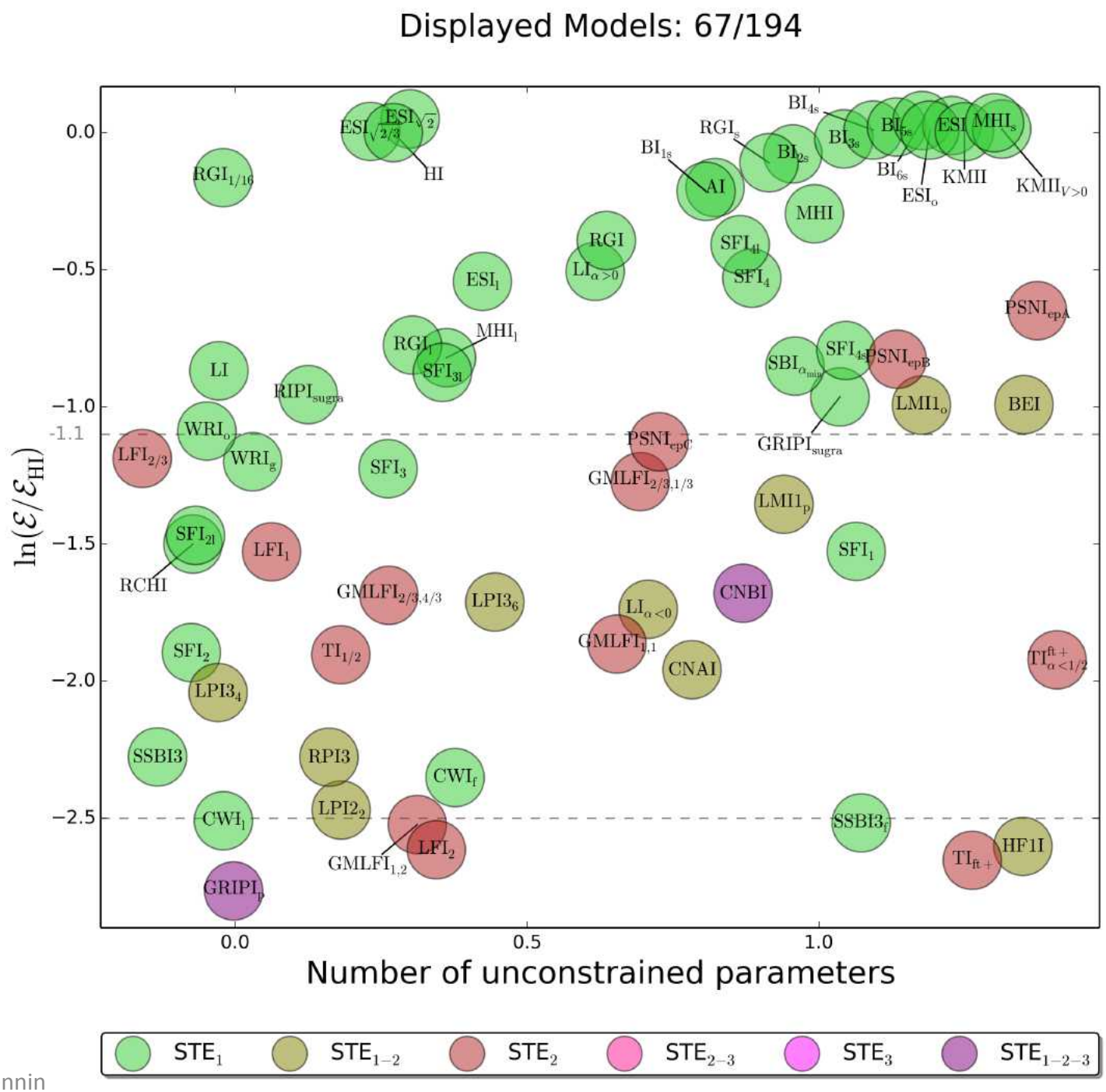



Probabilitiy boost of inflationary models $N_{\rm models}\,\mathcal{B}/\sum\mathcal{B}_i$
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Schwarz-Terrero-Escalante Classification:
1
1-2
2
2-3
3
1-2-3
ASPIC project
J.Martin, C.Ringeval, R.Trotta, V.Vennin
Displayed Models: 108/194


Displayed Models: 194/194
$\ln(\mathcal{E}/\mathcal{E}_{\rm HI})$
Number of unconstrained parameters
0
−10
−20
−30
−40
−50
−60
−70
−15
−10
−5
0
5
$\mathrm{VHI}_{1/2}$
$\mathrm{VHI}_{p<1}$
VHI_1
VHI_2
VHI
VHI_4
VHI_3
SSBI
RMI_4
RCHI_o
$\mathrm{NCKI}_{\beta<0}$
$\mathrm{TI}^e_{\alpha<1/2}$
$\mathrm{TI}^e_{\alpha>1/2}$
RIP
GMSSM
STE_1
STE_{1-2}
STE_2
STE_{2-3}
STE_3
STE_{1-2-3}


Displayed Models: 181/194
Number of unconstrained parameters
$\ln(\mathcal{E}/\mathcal{E}_{\rm HI})$
STE$_1$
STE$_{1-2}$
STE$_2$
STE$_{2-3}$
STE$_3$
STE$_{1-2-3}$


Displayed Models: 152/194
Number of unconstrained parameters
$\ln(\mathcal{E}/\mathcal{E}_{\rm HI})$
STE$_1$
STE$_{1-2}$
STE$_2$
STE$_{2-3}$
STE$_3$
STE$_{1-2-3}$


Displayed Models: 67/194
Number of unconstrained parameters
$\ln(\mathcal{E}/\mathcal{E}_{\rm HI})$
-1.1
STE$_1$
STE$_{1-2}$
STE$_2$
STE$_{2-3}$
STE$_3$
STE$_{1-2-3}$

So what are the best models ?

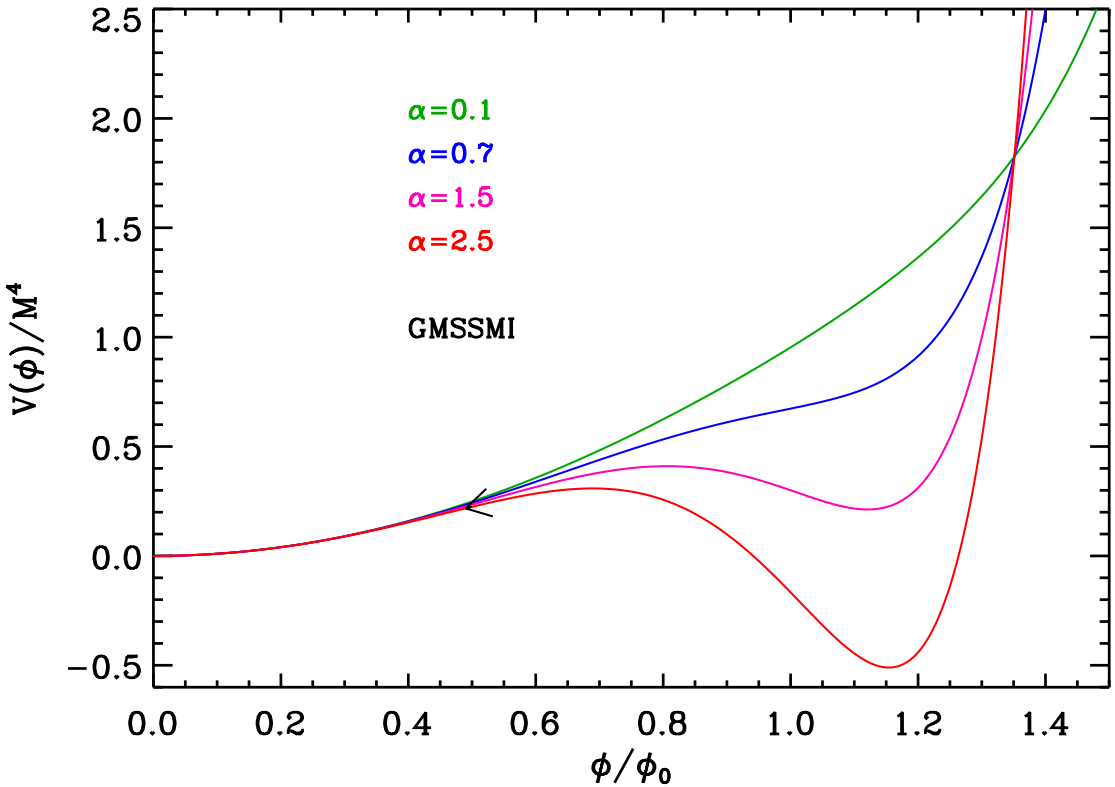
Looking for models having the best evidences together with a minimal number of unconstrained parameter narrows down the slow-roll landscape to a few inflationary scenarios:

- BI
- ESI
- HI
- KMIII
- LI
- MHI
- RGI
- SFI
- …

And there are some losers too …

For instance, inflexion point inflation (models based on the MSSM) are clearly strongly disfavored by Planck

$$V(\phi) = M^4 \left[\left(\frac{\phi}{\phi_0}\right)^2 - \frac{2}{3}\alpha \left(\frac{\phi}{\phi_0}\right)^6 + \frac{\alpha}{5}\left(\frac{\phi}{\phi_0}\right)^{10} \right]$$



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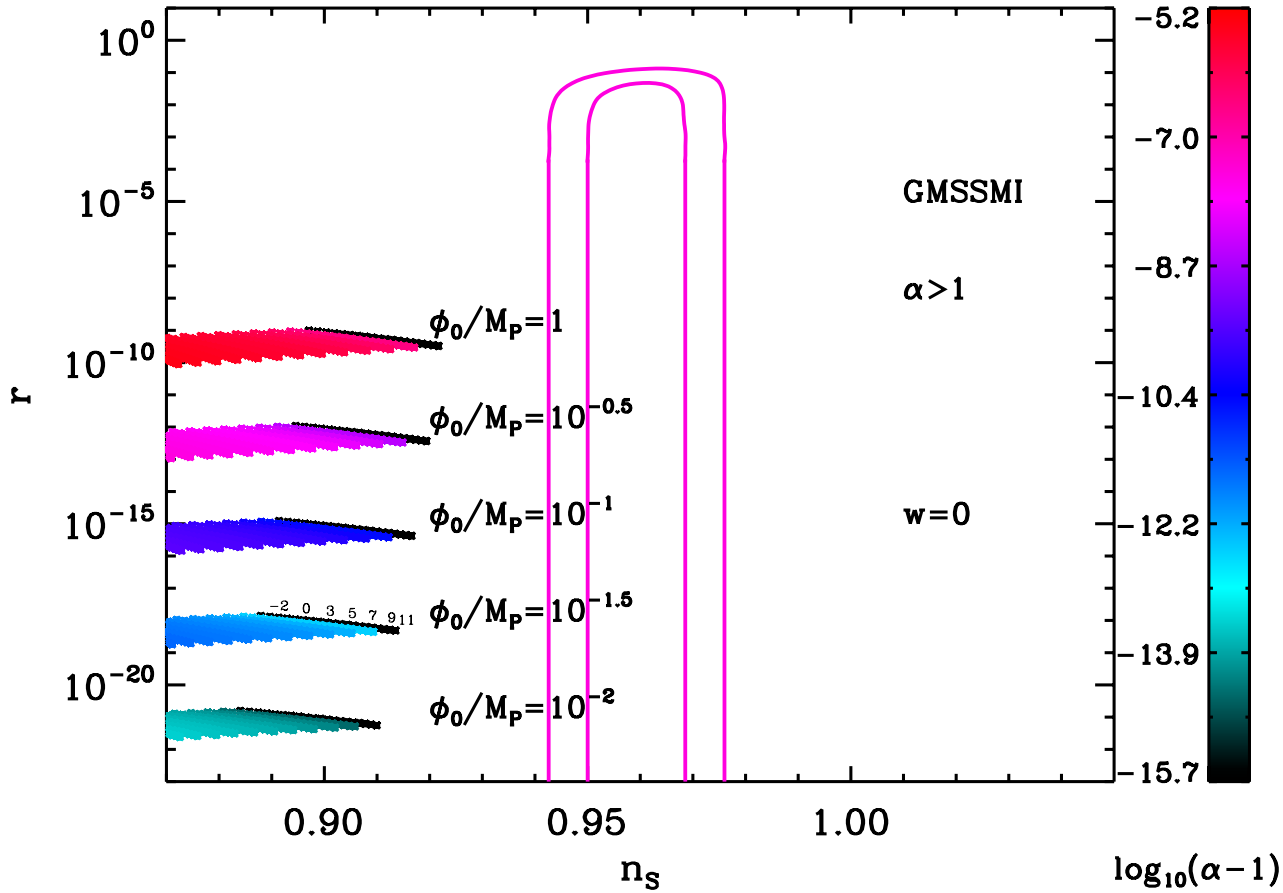


Summary

- Planck favors single field slow-roll scenarios: simplest but non trivial models

- Within this class, Planck data indicates that Plateau inflation is the correct shape of the potential (category I)

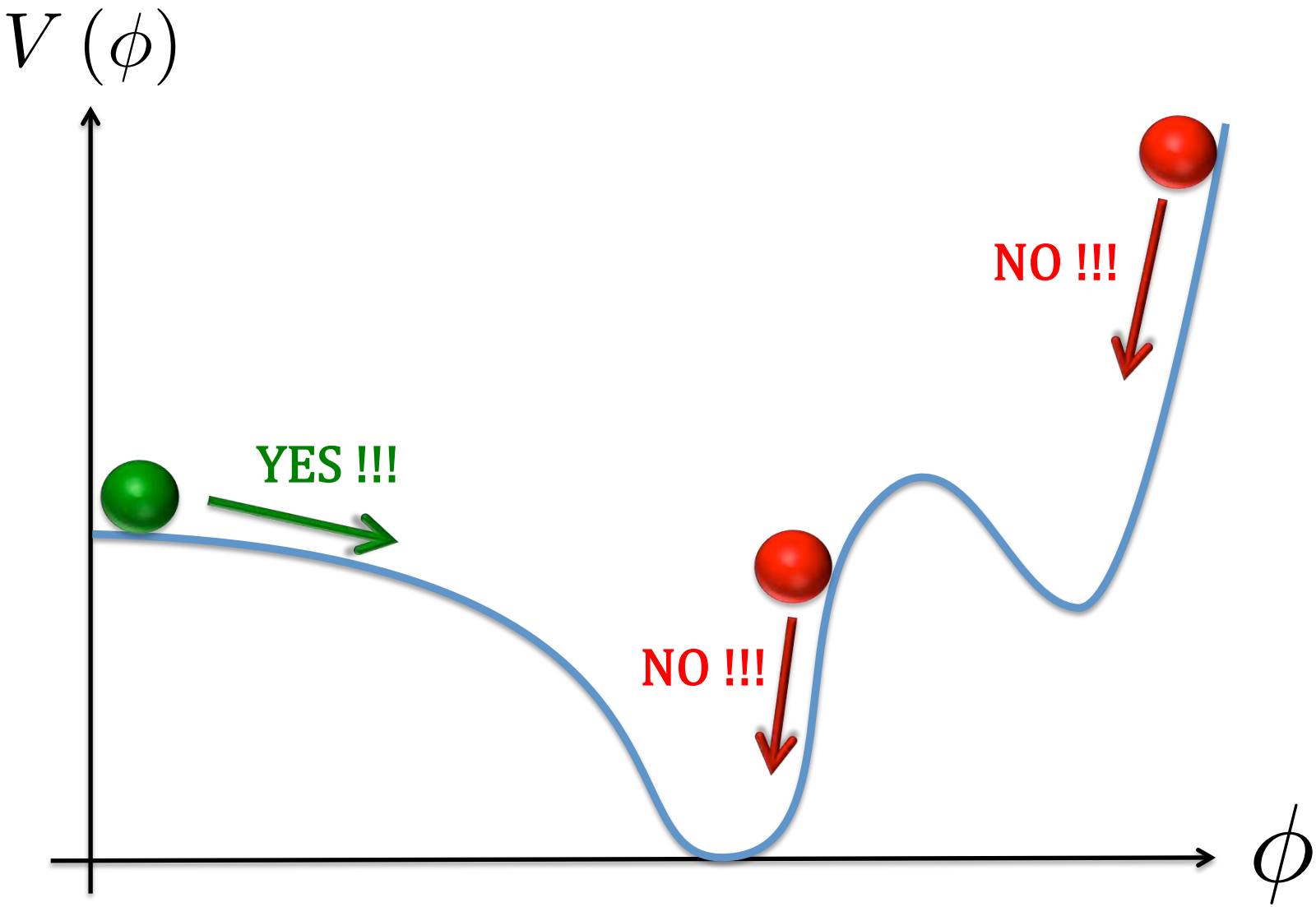
- There are a dozen of models that have a better Bayesian evidence (beyond the inconclusive level). We have come a long road … from hundreds of models, Planck has identified a dozen of favored scenarios!

- Models are clearly disfavored, ie MSSM inflation (for instance)

- More in the paper !…
  - Constraints on the reheating temperature for each model
  - Bayesian complexity
  - Evidence for categories (string models, phenomeno models etc …)

  - Update this program with Planck2014
    & polarization measurement ?

Summary of the summary



Thank you for your attention !