The geometrical destabilization of inflation

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YITP, Kyoto University, Gravity and Cosmology 2018
13th February

European Research Council
Established by the European Commission

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 758792)

Outline

1. *Inflation*
2. *General mechanism of the geometrical destabilization*
3. *Minimal realization and fate of the instability*
4. *Premature end of inflation*

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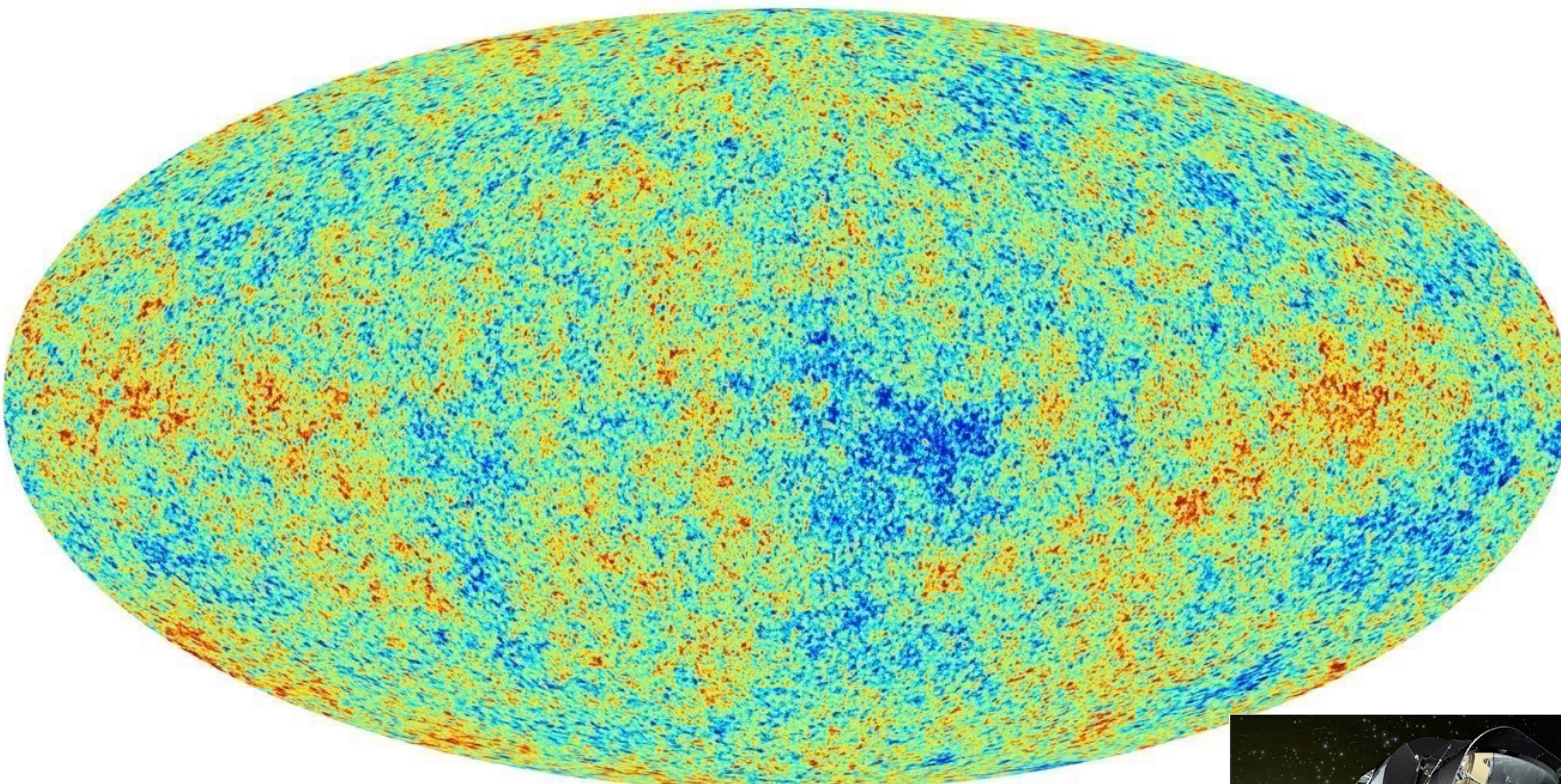
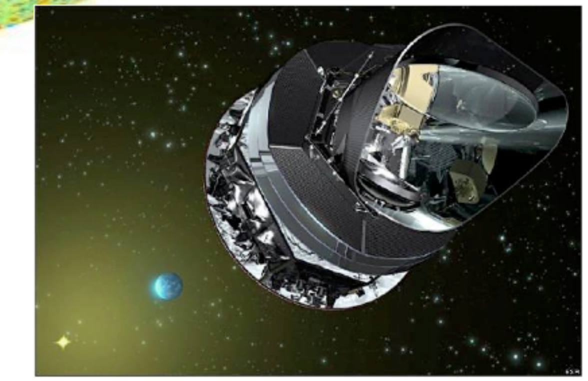
Inflation: a phenomenological success

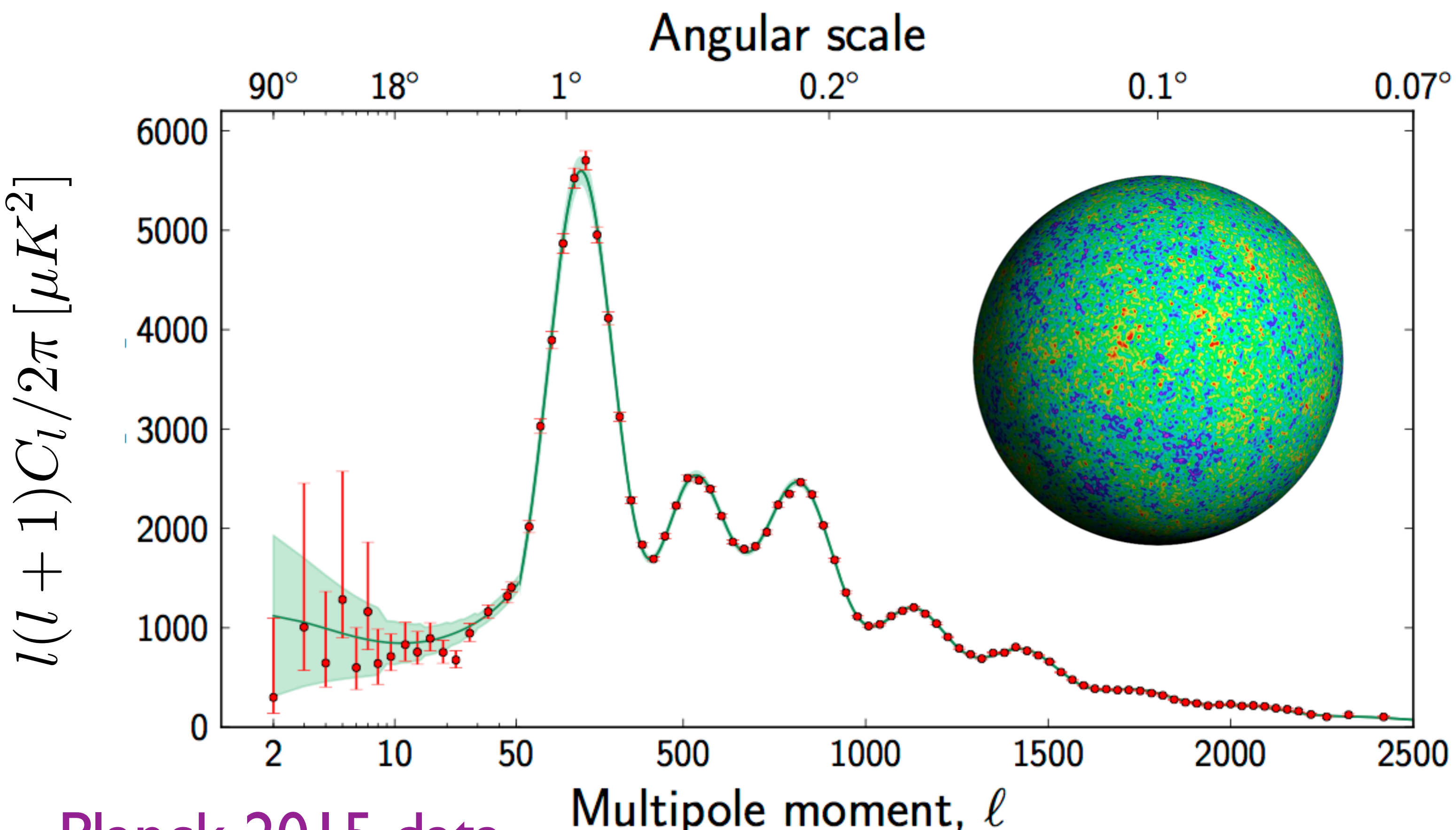


Planck all sky map, 2015

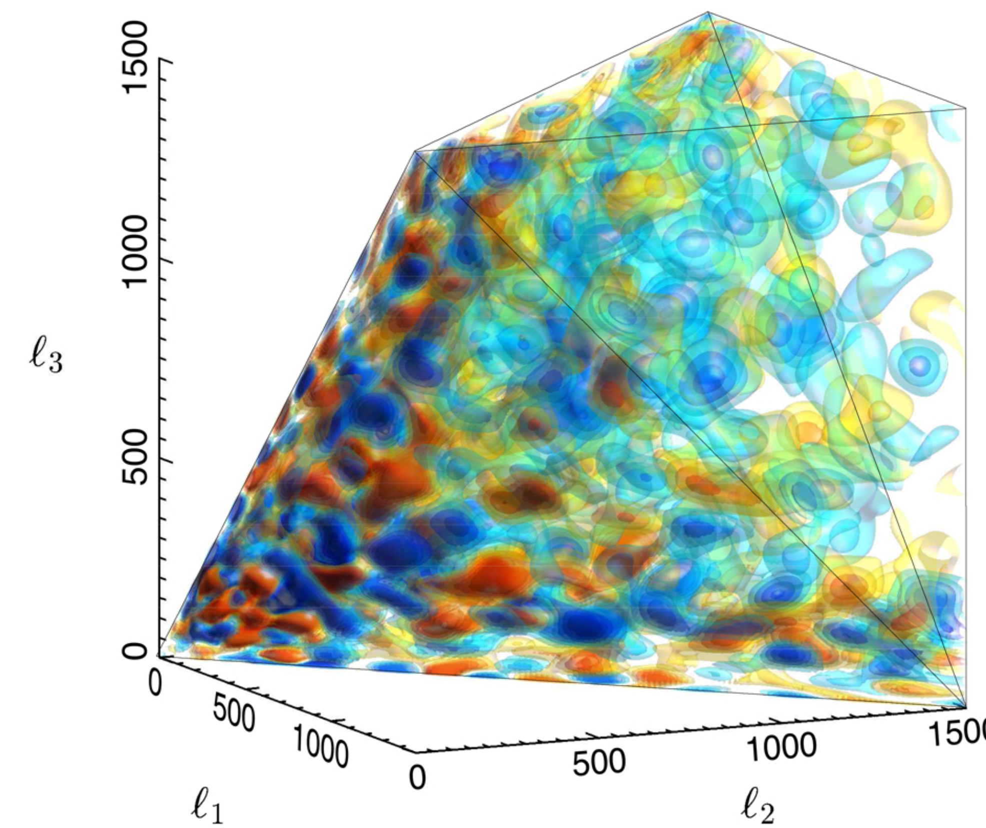


Inflation: a phenomenological success

Primordial fluctuations are adiabatic, super horizon at recombination, almost scale-invariant, Gaussian.



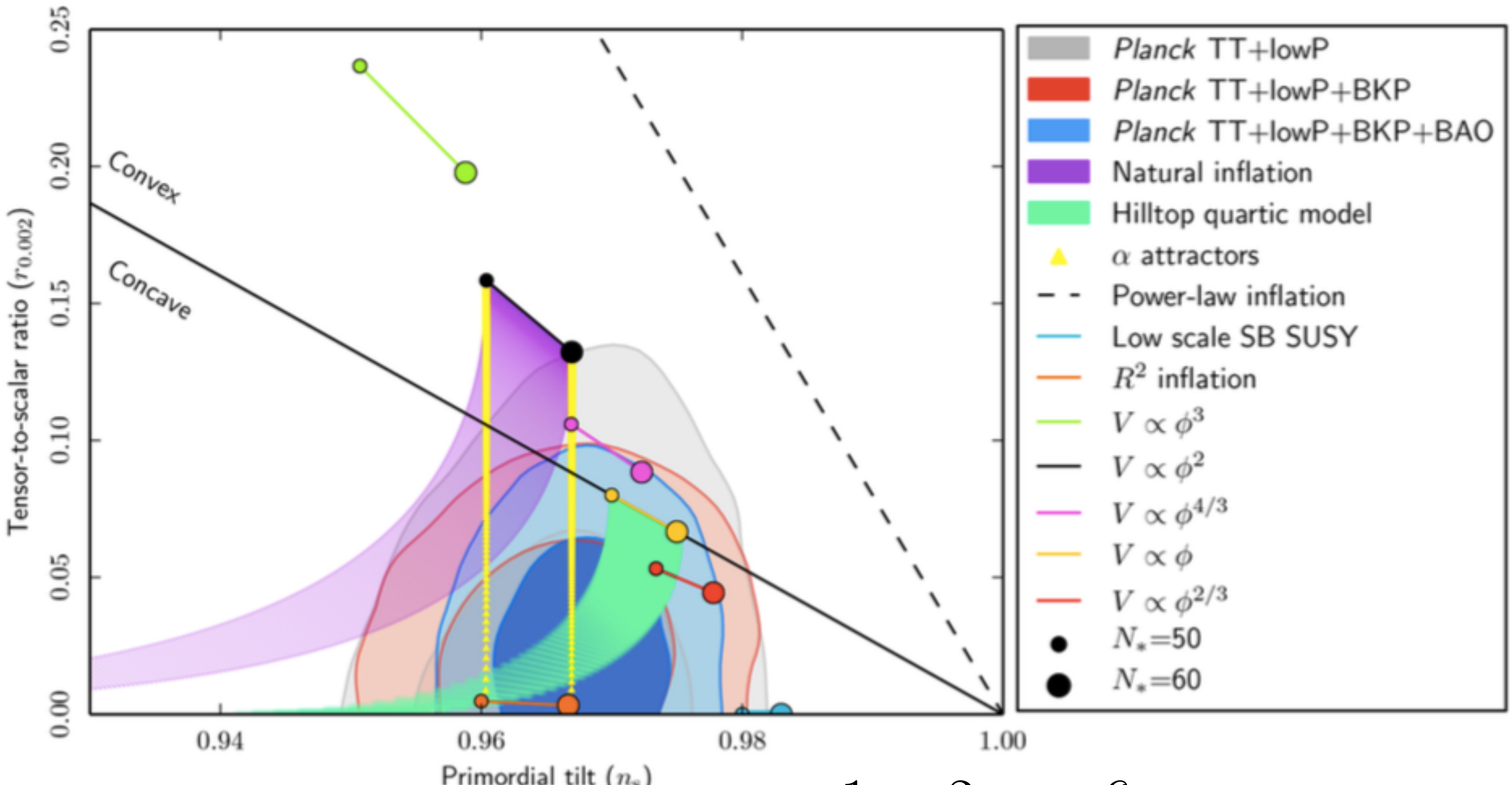
Planck 2015 data



The simplest models, single-field slow-roll, economically explain all current data

The Planck ns-r plane

$$r = 16\epsilon_\star$$



$$n_s - 1 = 2\eta_\star - 6\epsilon_\star$$

Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

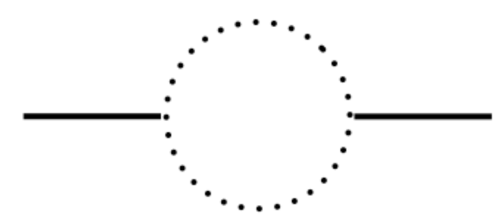
Beyond toy-models?

- So far, merely phenomenological description.
- Inflation is sensitive to the physics at the Planck scale

\- eta-problem

Why is the inflaton so light? $\eta \approx \frac{m_\phi^2}{H^2} \ll 1$

like the Higgs
hierarchy problem



$m_\phi^2 \sim \Lambda_{\rm uv}^2 \gg H^2$

\- multiple (heavy) fields in ultraviolet completions of slow-roll single-field inflation do not decouple

\- Inflation is not in general predictive without reheating

UV-sensitivity of inflation

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V_0(\phi) + \sum_\delta \frac{\mathcal{O}_\delta(\phi)}{\Lambda^{\delta-4}}$$

Slow-roll action

Corrections to the low-energy effective action

Unless symmetry forbids it, presence of terms of the form

$$\Delta V = cV_0(\phi)\frac{\phi^2}{\Lambda^2}$$

$$\boxed{\Delta m_\phi^2 \sim c\frac{V_0}{\Lambda^2} \sim c\,H^2\left(\frac{M_P}{\Lambda}\right)^2}$$

Wilson coefficient

$c \sim \mathcal{O}(1)$

+

$\Lambda \lesssim M_P$

$\Delta\eta \gtrsim 1$

Sensitivity of inflation to Planck-suppressed operators

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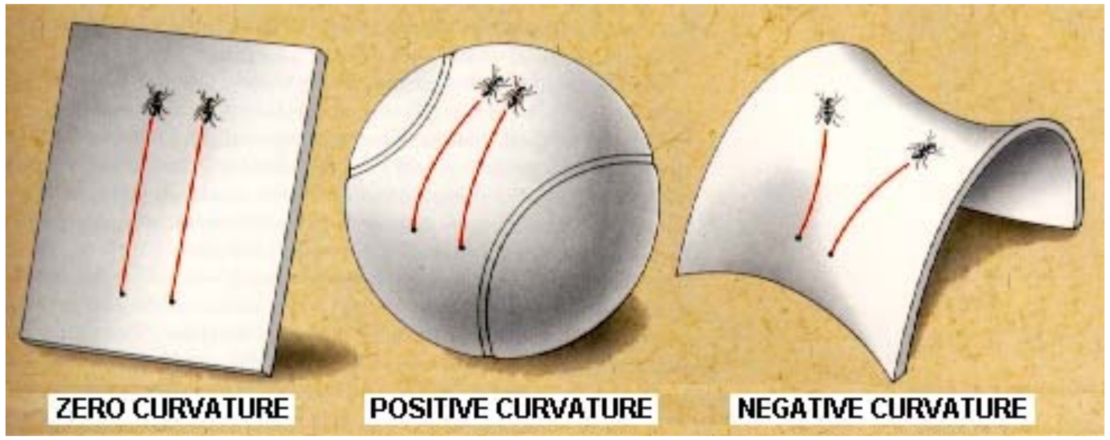
Basic idea

Realistic inflationary models have fields which live in an internal space with curved geometry.

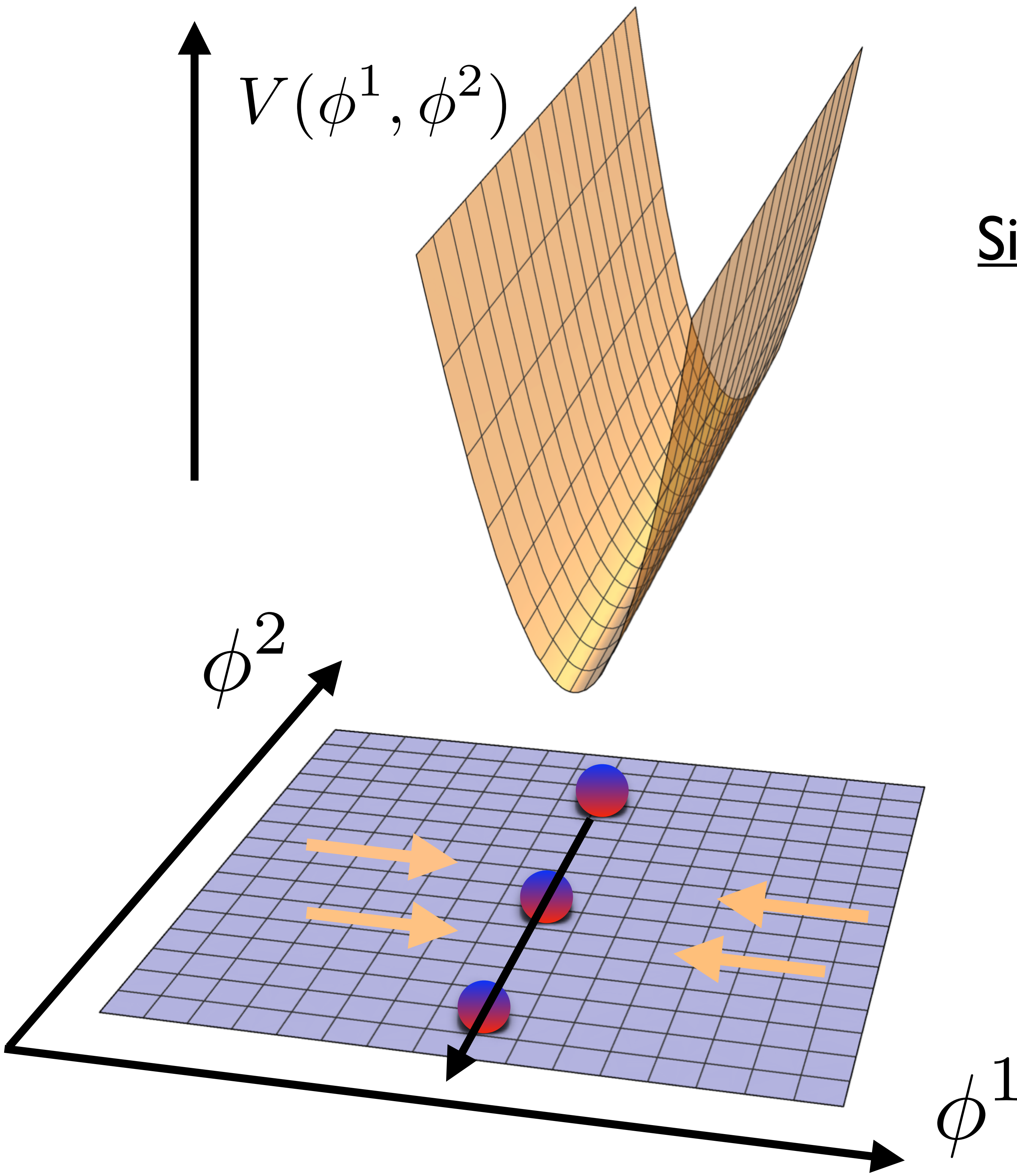
Initially neighboring geodesics tend to fall away from each other in the presence of negative curvature.



This effect applies during inflation,
it easily overcomes the effect of the potential,
and can destabilize inflationary trajectories.

Basic mechanism

Renaux-Petel, Turzynski, September 2016
PRL Editors' Highlight



Simplest 'realistic' models (hope):

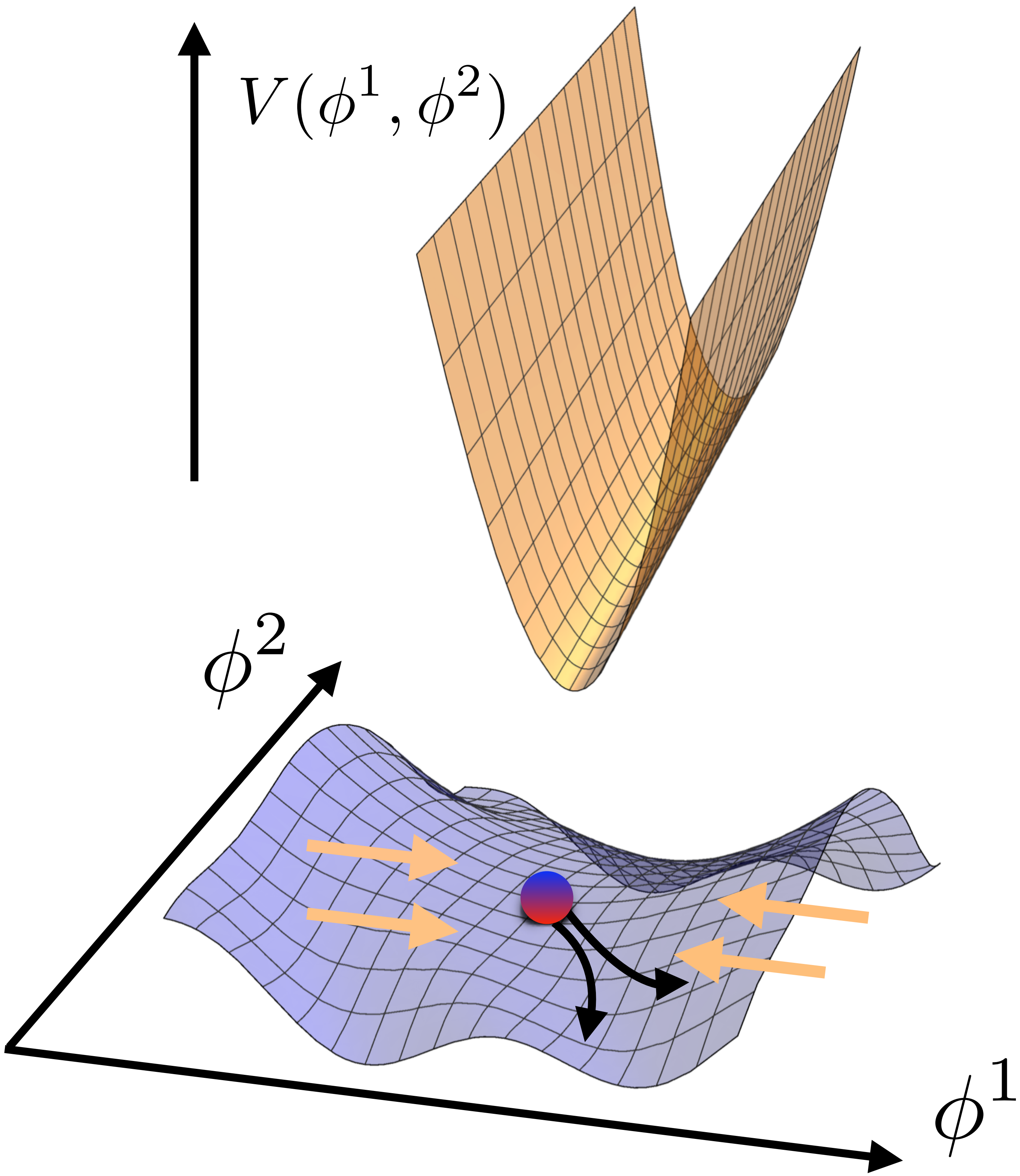
Light inflaton
+
Extra heavy fields

Effective
single-field dynamics

(valley with steep walls)

Basic mechanism

Renaux-Petel, Turzynski, September 2016
PRL Editors' Highlight



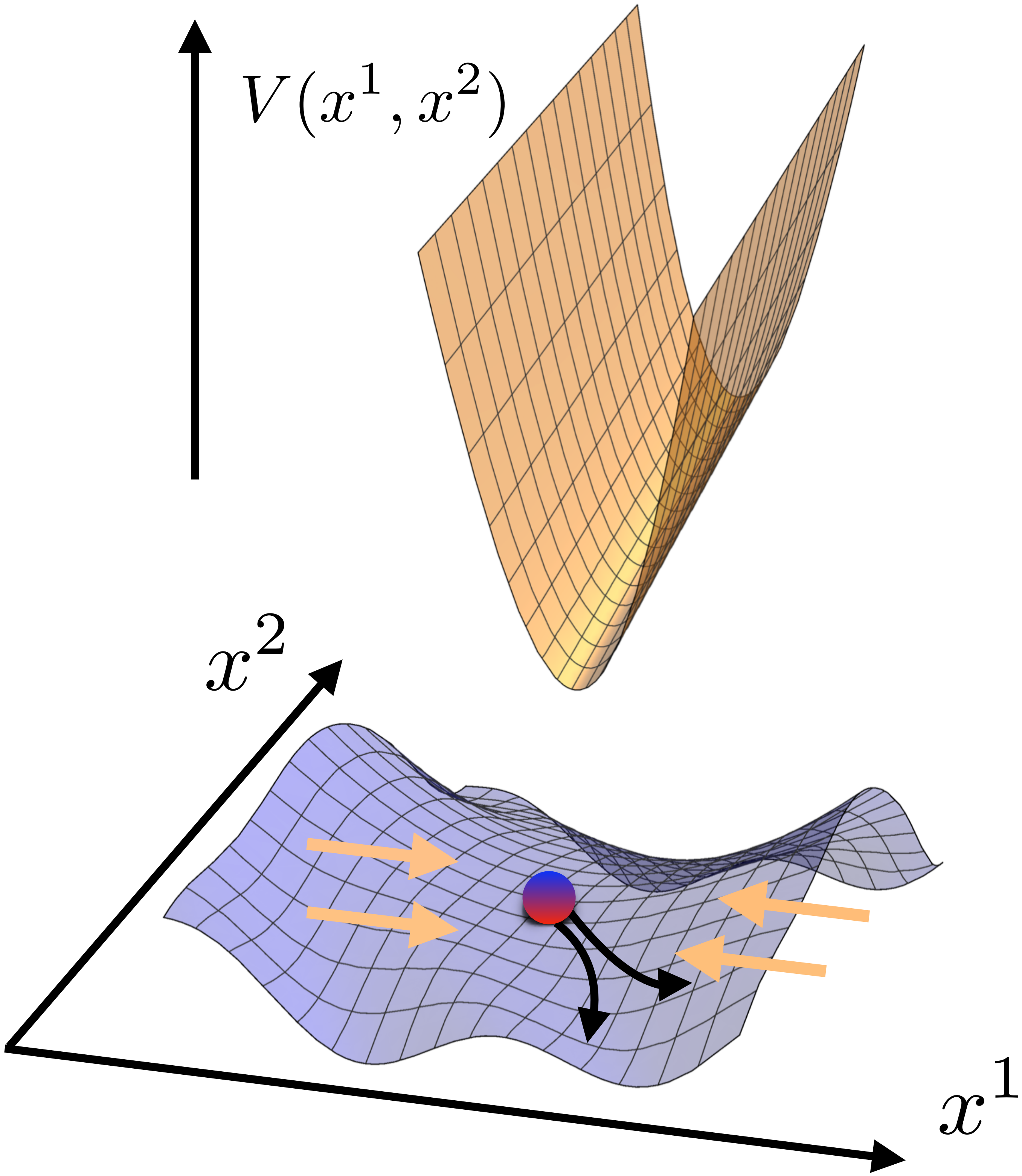
More realistic:

Light inflaton
+
Extra heavy fields
+
Curved field space

Geometrical instability

Basic mechanism

Renaux-Petel, Turzynski, September 2016
PRL Editors' Highlight



<u>Simple analogy:</u>

- Position of a charged particle

- Electric force

- Surface geometry

Geometrical instability

Multifield Lagrangian

$$S=\int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2}G_{IJ}(\phi^K)\partial_\mu\phi^I\partial^\mu\phi^J-V(\phi^I)\right)$$

1. A curved field space is generic

Top-down (e.g. supergravity), or bottom-up (EFT)

Field space curvature $\sim 1/M^2$

2. A priori, M can lie anywhere between H and Mp

Example: alpha-attractors $R^{\text{field space}}M_{\text{Pl}}^2=-\dfrac{2}{3\alpha}$

Linear perturbation theory

$$\mathcal{D}_t\mathcal{D}_t Q^I + 3H\mathcal{D}_t Q^I + \frac{k^2}{a^2}Q^I + M^I_{\ J}Q^J = 0$$

Sasaki, Stewart, 95

$Q^I =$ fluctuations of field I in flat gauge

$$\mathcal{D}_t A^I = \dot{A}^I + \Gamma^I_{JK}\dot{\phi}^J A^K$$

Mass matrix:

$$M^I_{\ J} = V^I_{;J} - \mathcal{R}^I_{\ KLJ}\dot{\phi}^K\dot{\phi}^L - \frac{1}{a^3 M_{\rm Pl}^2}\mathcal{D}_t\left(\frac{a^3}{H}\dot{\phi}^I\dot{\phi}_J\right)$$

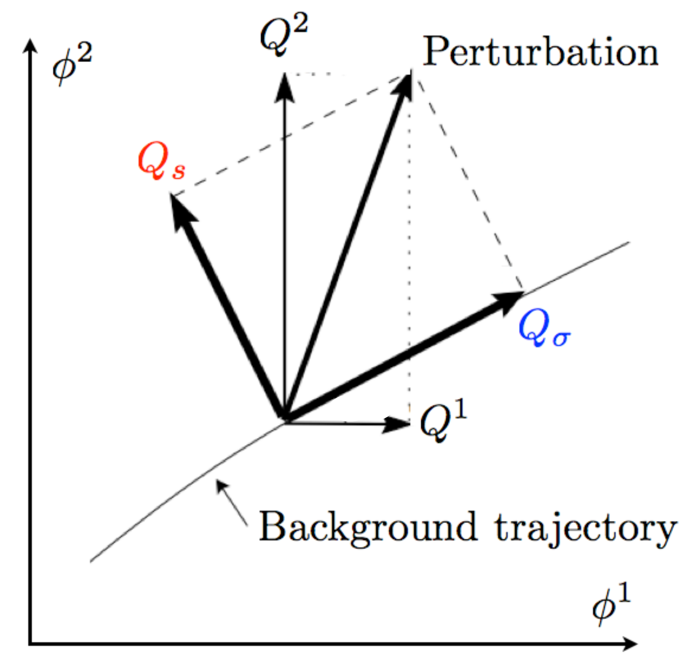
Riemann curvature tensor
of the field space metric

cf geodesic deviation equation

Two-field models (simplicity)

super-Hubble evolution
of the entropic field

$$\ddot{Q}_s + 3H\dot{Q}_s + m^2_{s(\mathrm{eff})} Q_s = 0$$



Gordon et al, 2000

Effective entropic mass squared:

$$\frac{m^2_{s(\mathrm{eff})}}{H^2} \equiv \frac{V_{;ss}}{H^2} + 3\eta_\perp^2 + \epsilon R^{\text{field space}} M^2_{\mathrm{Pl}}$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2}$$

Hessian contribution

bending contribution

'geometrical' contribution

Geometrical destabilization

$$\frac{m^2_{s(\mathrm{eff})}}{H^2} \equiv \frac{V_{;ss}}{H^2} + 3\eta_\perp^2 + \epsilon\, R^{\text{field space}} M_{\text{Pl}}^2$$

Hessian contribution

bending contribution

'geometrical' contribution

When the geometrical contribution is negative and large enough, it can **render the entropic fluctuation tachyonic, even with a large mass in the static vacuum**, with potentially dramatic observational consequences.

Geometrical destabilization

Necessary condition (2-field): $\boldsymbol{R^{\text{field space}} < 0}$

$$R^{\text{field space}} M_{\text{Pl}}^2 \sim (M_{\text{Pl}}/M)^2$$ generically $\gg 1$

→

Let us consider for instance

$$\underline{M = \mathcal{O}(10^{-2}, 10^{-3}) M_{\text{Pl}}}$$

(string scale, KK scale, GUT scale...)

Even for $\dfrac{V_{;ss}}{H^2} \sim 100$

The effective mass becomes tachyonic when:
$\epsilon \to \epsilon_c = 10^{-4} \quad \text{or} \quad 10^{-2}$

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Minimal realization

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2\left(1 + 2\frac{\chi^2}{M^2}\right) - V(\phi) - \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m_h^2\chi^2$$

- Slow-roll model of inflation, with inflaton ϕ
- Heavy field χ with $m_h^2 \gg H^2$
- Simple dimension 6 operator suppressed by a **mass scale of new physics** $M \gg H$

Minimal realization

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2\left(1 + 2\frac{\chi^2}{M^2}\right) - V(\phi) - \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m_h^2\chi^2$$

• Generally expected from the effective theory point of view (respect approximate shift-symmetry of inflaton)

• Terms linear in chi absent for consistency (or Z2 symmetry), and higher-orders in chi suppressed near the inflationary valley

• Does correspond to lots of models in the literature, in which it is sometimes said : «chi is stabilized by a large mass» so let us put chi=0 (consistently with the equations of motion)

Minimal realization

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2\left(1 + 2\frac{\chi^2}{M^2}\right) - V(\phi) - \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m_h^2\chi^2$$

- Apparently benign high-energy correction (small correction to the kinetic term) but ...

$$R^{\text{field space}} \simeq -\frac{4}{M^2} \quad \text{for} \quad \chi \ll M$$

$$\frac{m^2_{s(\text{eff})}}{H^2} = \frac{m_h^2}{H^2} - 4\,\epsilon(t)\left(\frac{M_{\text{Pl}}}{M}\right)^2 \quad \text{along} \quad \chi = 0$$

- The inflationary trajectory becomes unstable after $\epsilon \longrightarrow \epsilon_c$

Similarity with the eta-problem

$$\mathcal{L}_{\text{eff}}[\phi^I] = \mathcal{L}_l[\phi^I] + \sum_i c_i \frac{\mathcal{O}_i[\phi^I, \partial\phi^I, \ldots]}{\Lambda^{\delta_i - 4}}$$

Slow-roll action

Corrections to the low-energy effective action

Unless symmetry forbids it, presence of terms of the form

$$\boxed{\Delta\mathcal{L} = c(\partial\phi)^2 \frac{\chi^2}{\Lambda^2}}$$

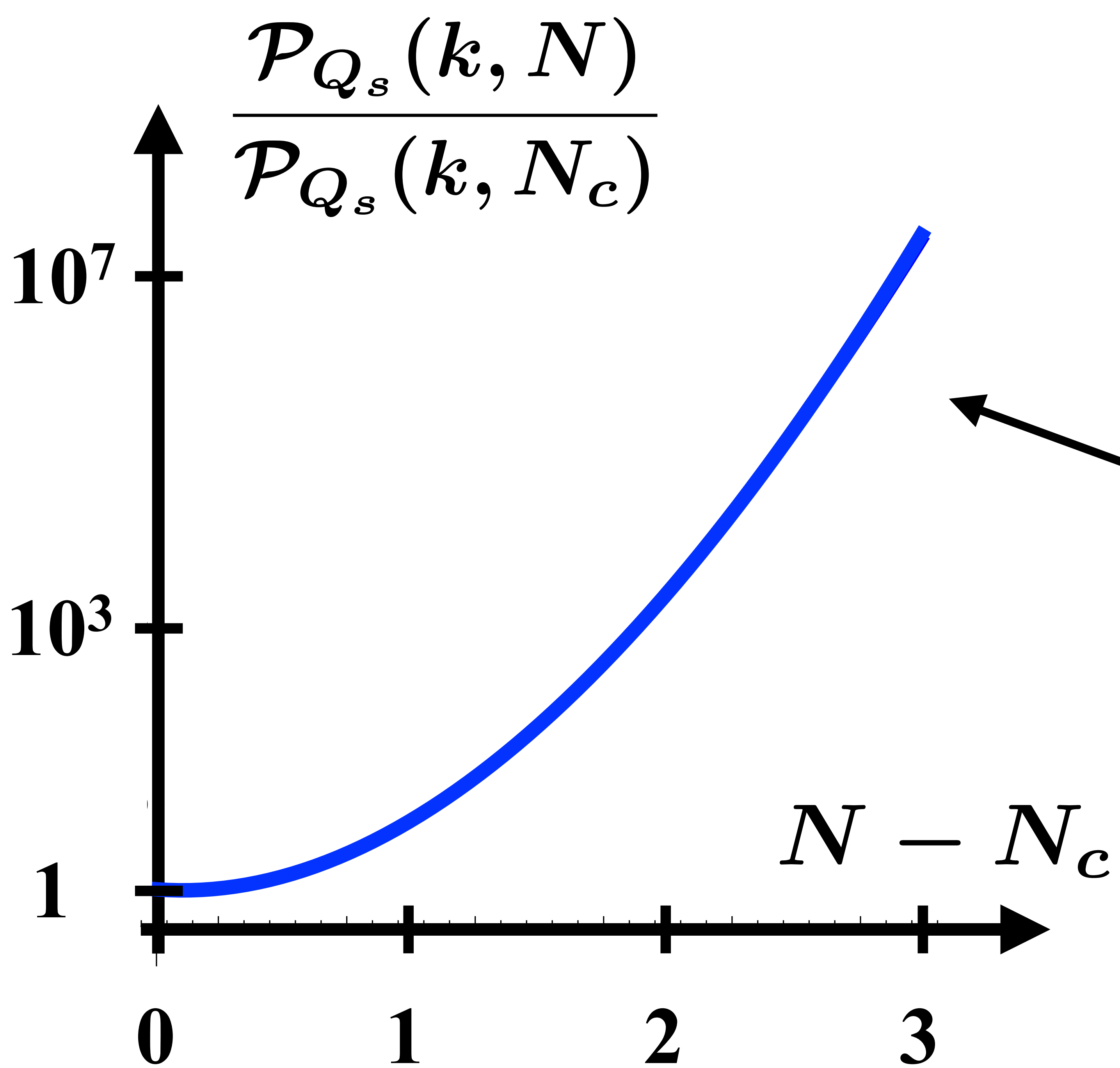
$$\Rightarrow \quad \Delta m_\chi^2 \sim c\frac{(\partial\phi)^2}{\Lambda^2} \sim c\,\epsilon H^2 \left(\frac{M_P}{\Lambda}\right)^2$$

$\Lambda \ll M_P \Rightarrow \epsilon_c \ll 1$ Geometrical destabilization of inflation

$\Lambda \simeq M_P \Rightarrow \epsilon_c \sim 1$ Modified reheating

Fate of the instability?

Rapid and efficient growth of super-Hubble entropic fluctuations



Example:

Starobinsky potential

$m_h = 10H_c$

$M = 10^{-2}M_{\rm Pl}$

Numerical resolution (linear theory)

Theoretical modeling (early time):

$$\sim e^{\frac{1}{3}\frac{m_h^2}{H_c^2}\eta_c(N-N_c)^3}$$

Fate of the instability?

- Backreaction of fluctuations on background trajectory?
Non-perturbative phenomenon

- Similar to hybrid inflation (but different kinetic origin and kinetic effects).

- Tachyonic preheating, possible production of primordial black holes, inflating topological defects …

Challenging! Work in progress

Fate of the instability?

Inhomogeneities dominate

↓

Premature end of inflation

↓

- Universal bound on curvature scale

RP, Turzynski, 1510.01281, PRL

- Modified ranking of inflationary models

1706.01835 JCAP
RP, Turzynski, Vennin

OR

Inhomogeneities are shut off

↓

Second phase of inflation

↓

RP, Turzynski, 1510.01281

Works to appear

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A universal bound on the field space curvature

- With an abrupt end of inflation, let us simply write that the extra field had a positive mass at Hubble exit for the pivot scale:

$$\frac{m_h^2}{H_\star^2} > 4\epsilon_\star \left(\frac{M_P}{M}\right)^2 \qquad + \qquad A_s = \frac{1}{8\pi^2\epsilon_\star}\left(\frac{H_\star}{M_P}\right)^2$$

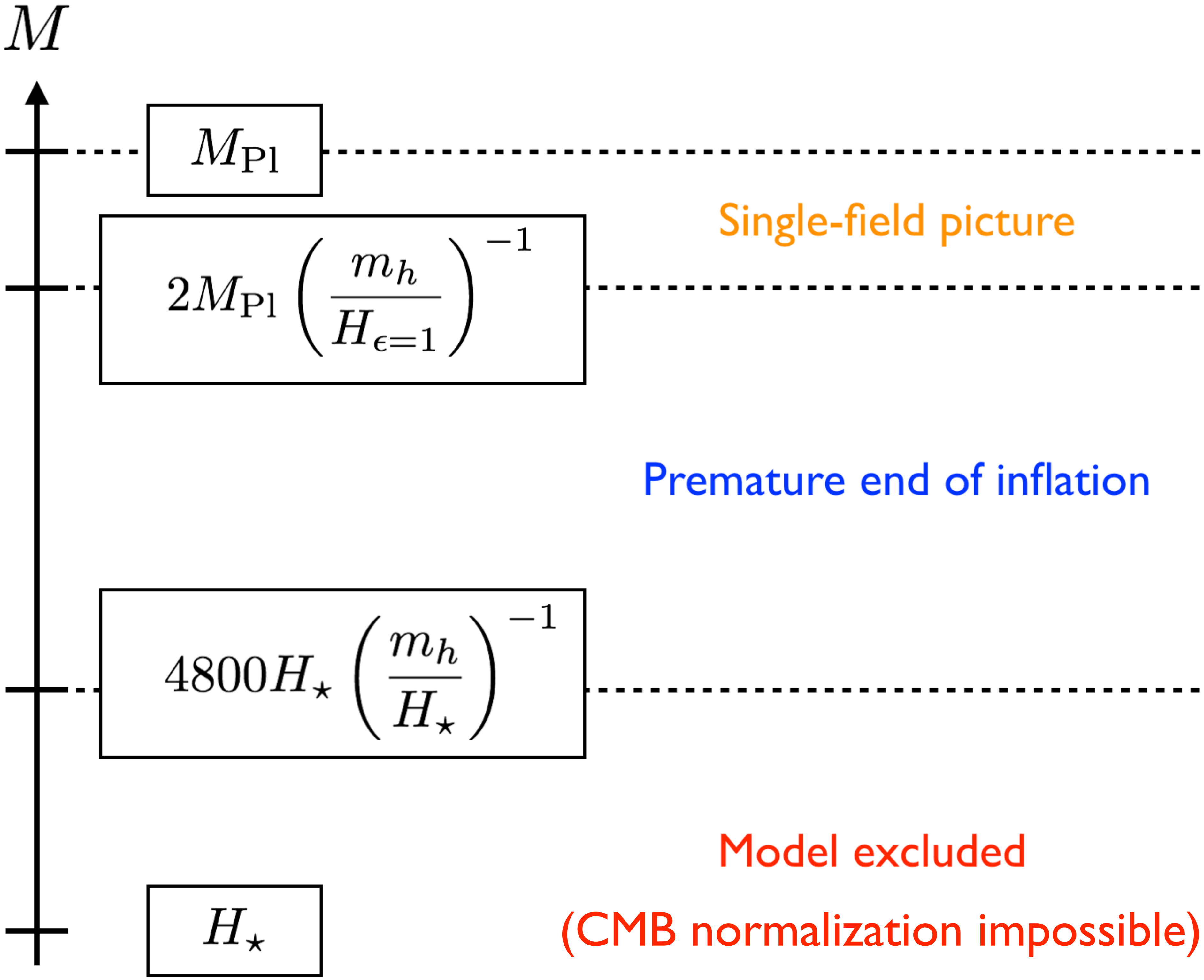
$m^2_{s(\mathrm{eff})\star} > 0$ *CMB normalization*

$$\Rightarrow \quad \boxed{\frac{M}{H_\star} > \frac{1}{\sqrt{2\pi^2 A_s}}\frac{1}{\left(\frac{m_h}{H_\star}\right)} \simeq 5500\frac{1}{\left(\frac{m_h}{H_\star}\right)}}$$

extends to any (2-)field model and any dynamics

- Models with a lower value of the curvature scale generate a universe with more structure than ours, so they are excluded!

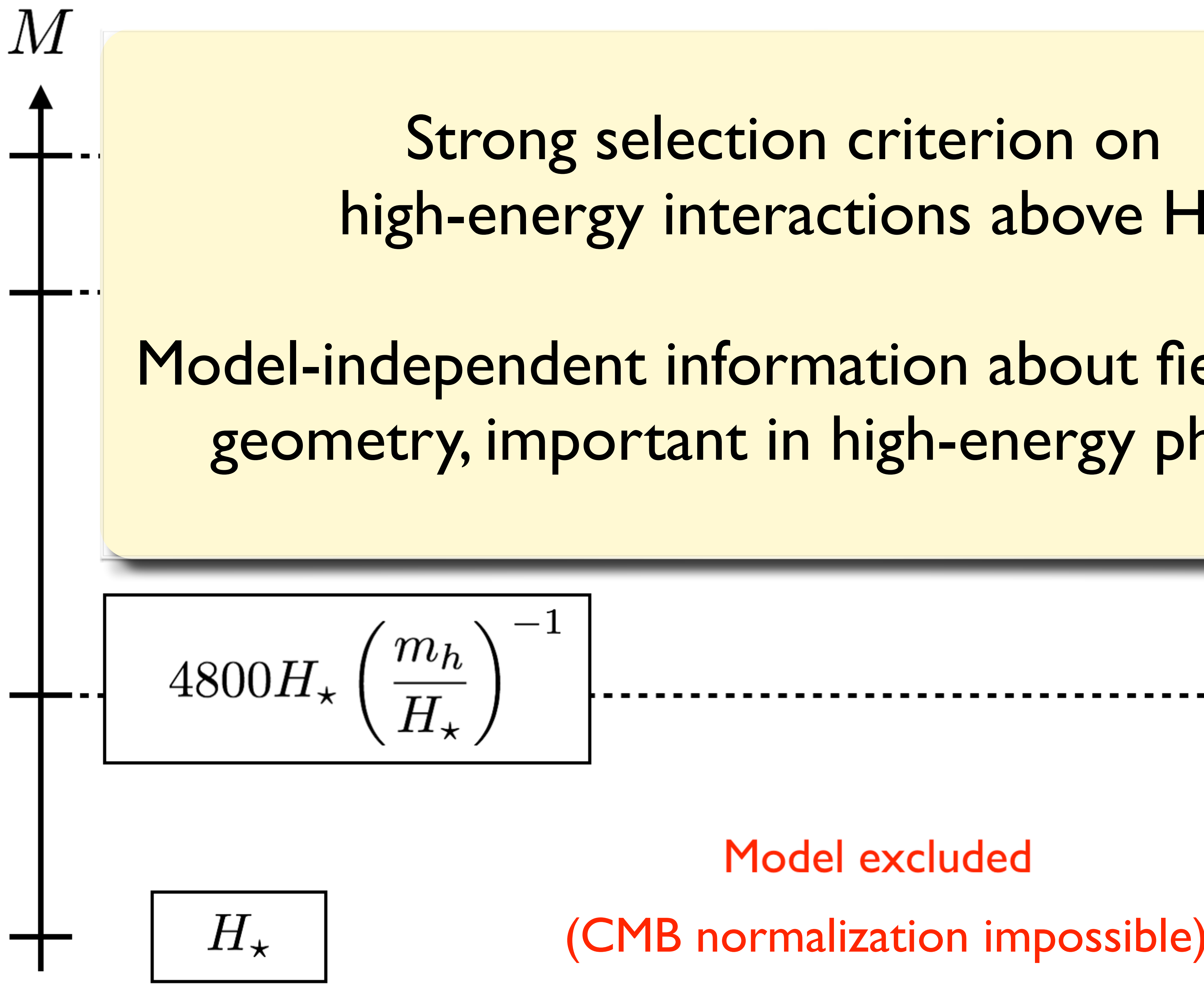
(Non)-decoupling and the field space curvature scale



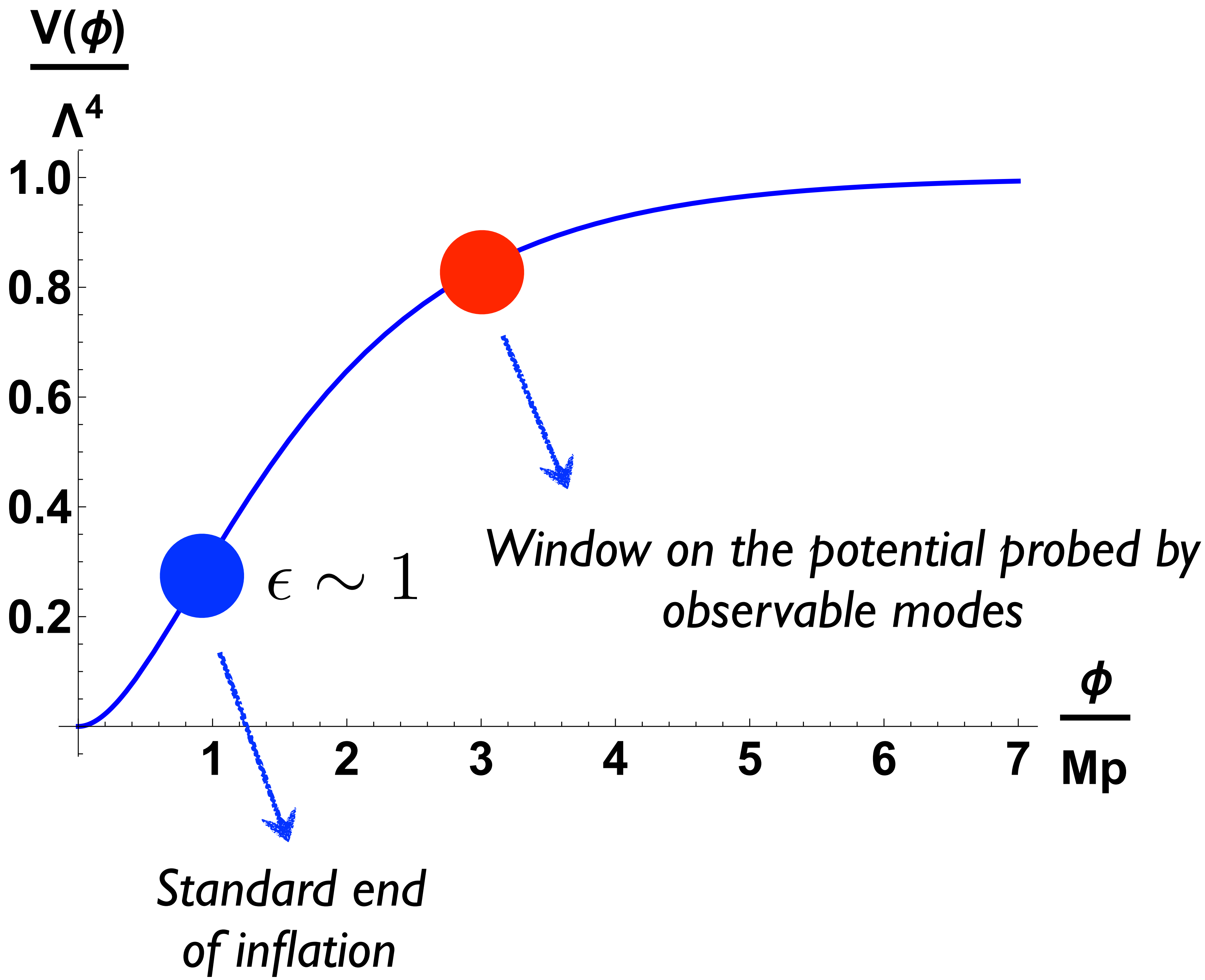
(Non)-decoupling and the field space curvature scale

Strong selection criterion on
high-energy interactions above H!

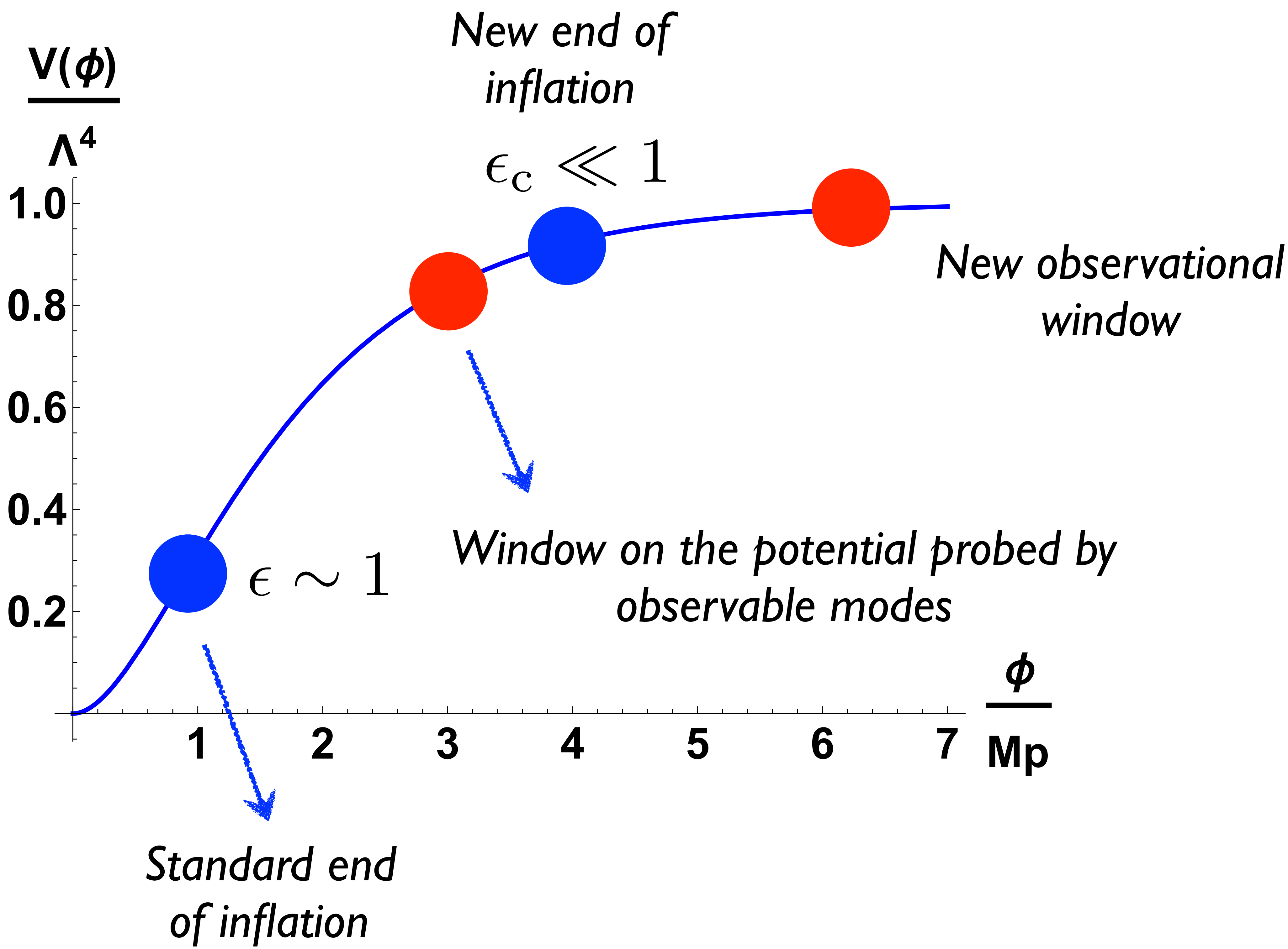
Model-independent information about field space
geometry, important in high-energy physics!



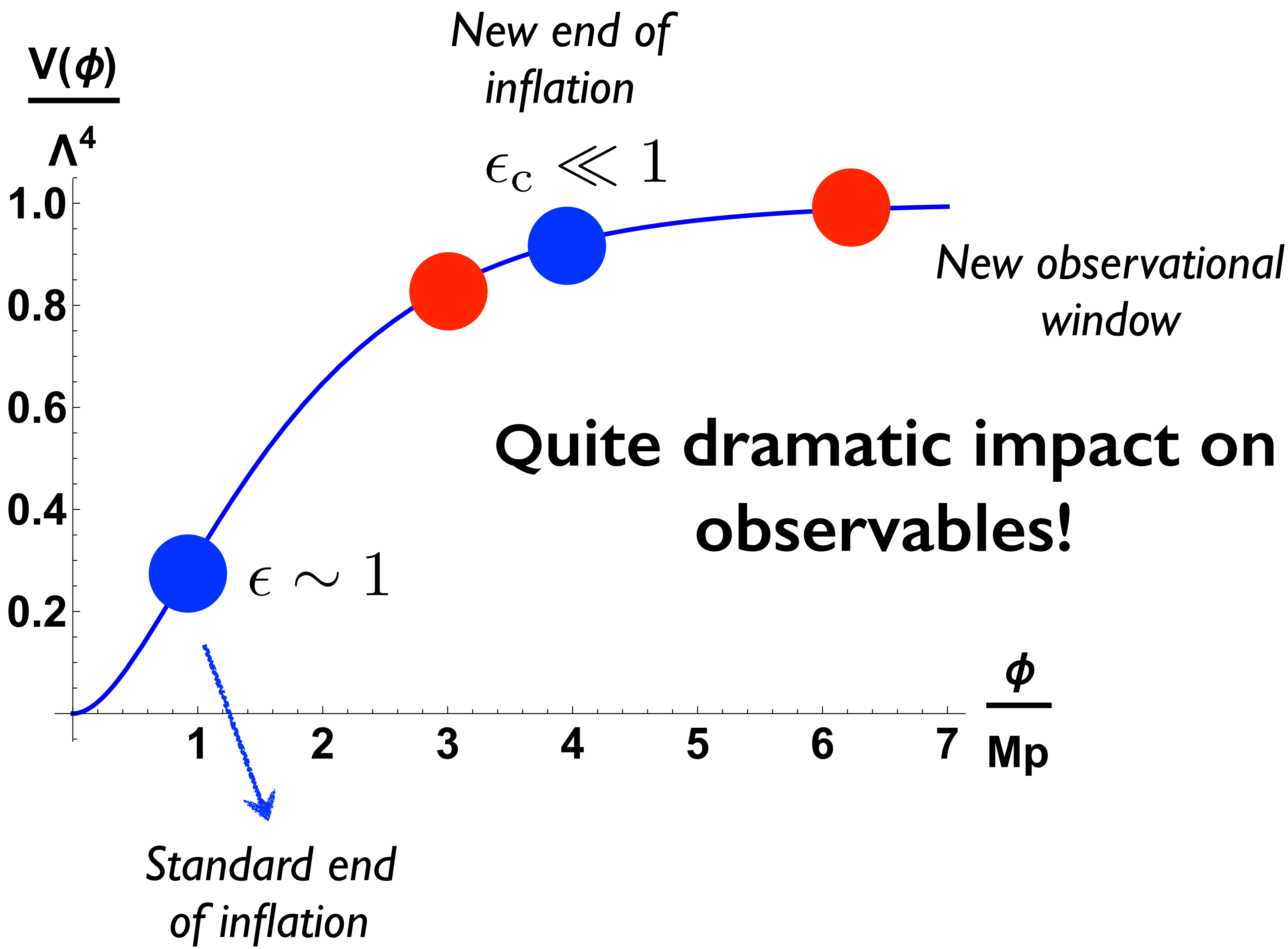
Premature end of inflation



Premature end of inflation

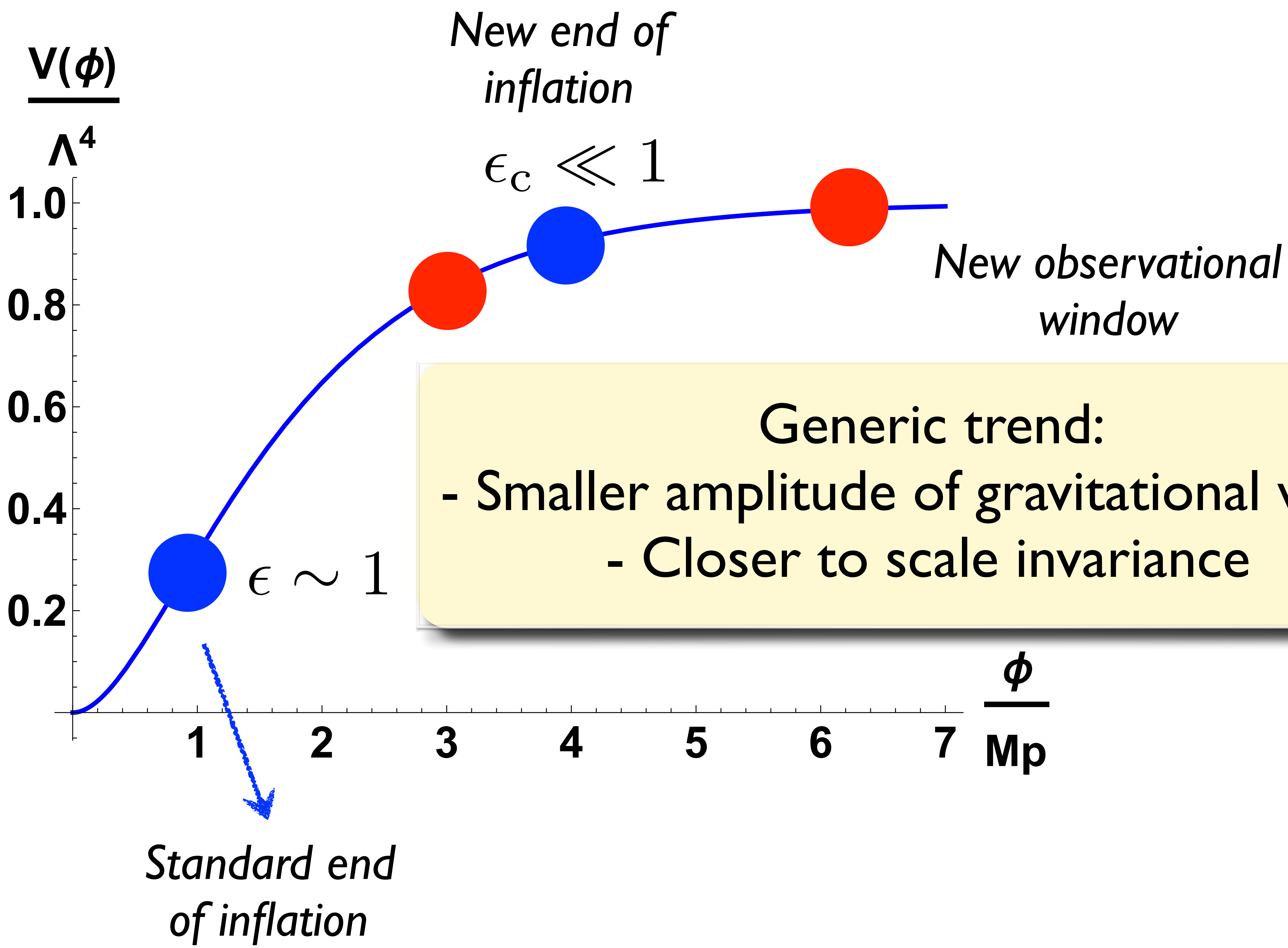


Premature end of inflation



Quite dramatic impact on observables!

Premature end of inflation



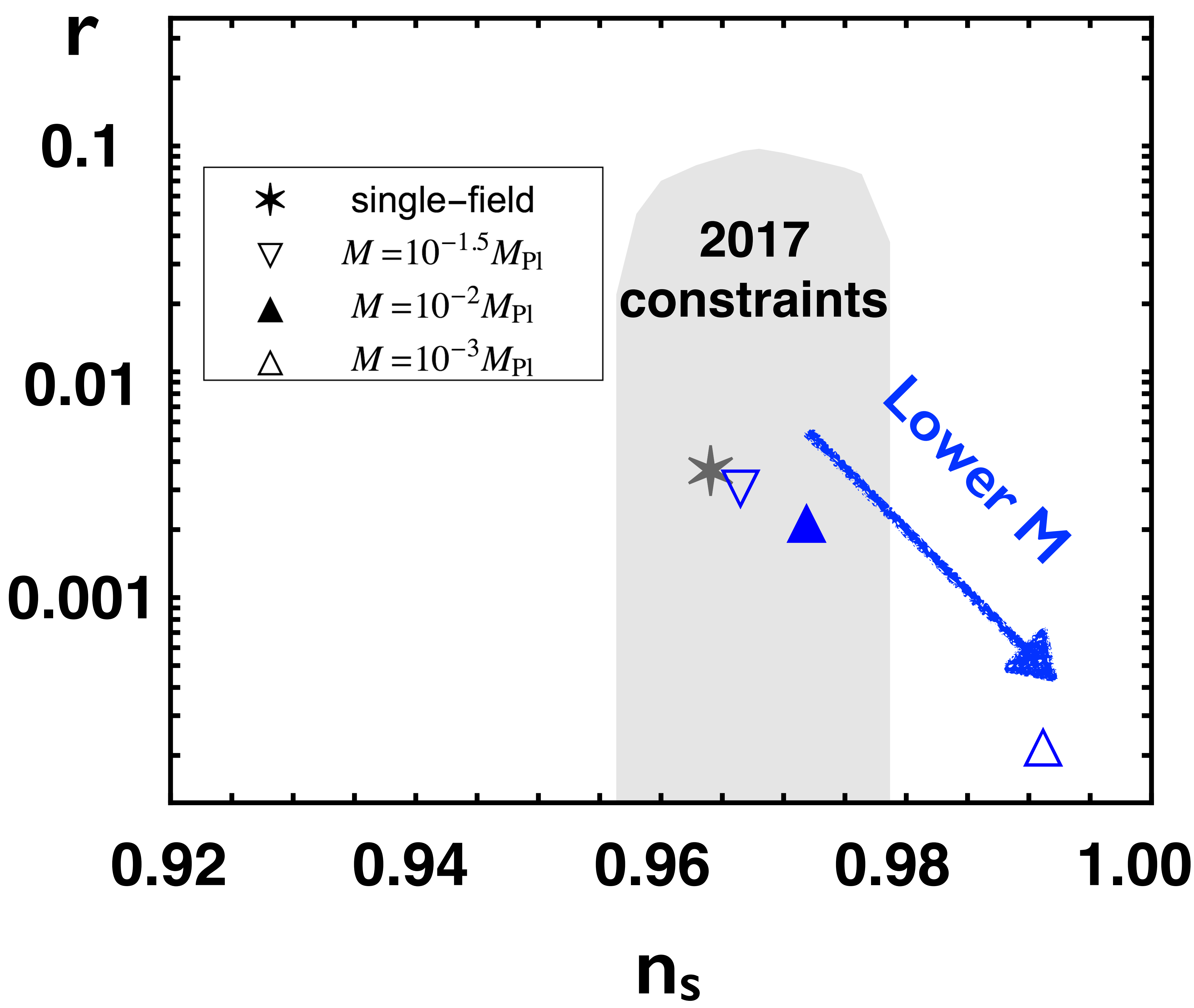
Generic trend:
- Smaller amplitude of gravitational waves
- Closer to scale invariance

Observational predictions

Example:

Starobinsky potential

$m_h = 10 H_c$



Geometrical destabilization, premature end of inflation and Bayesian model selection

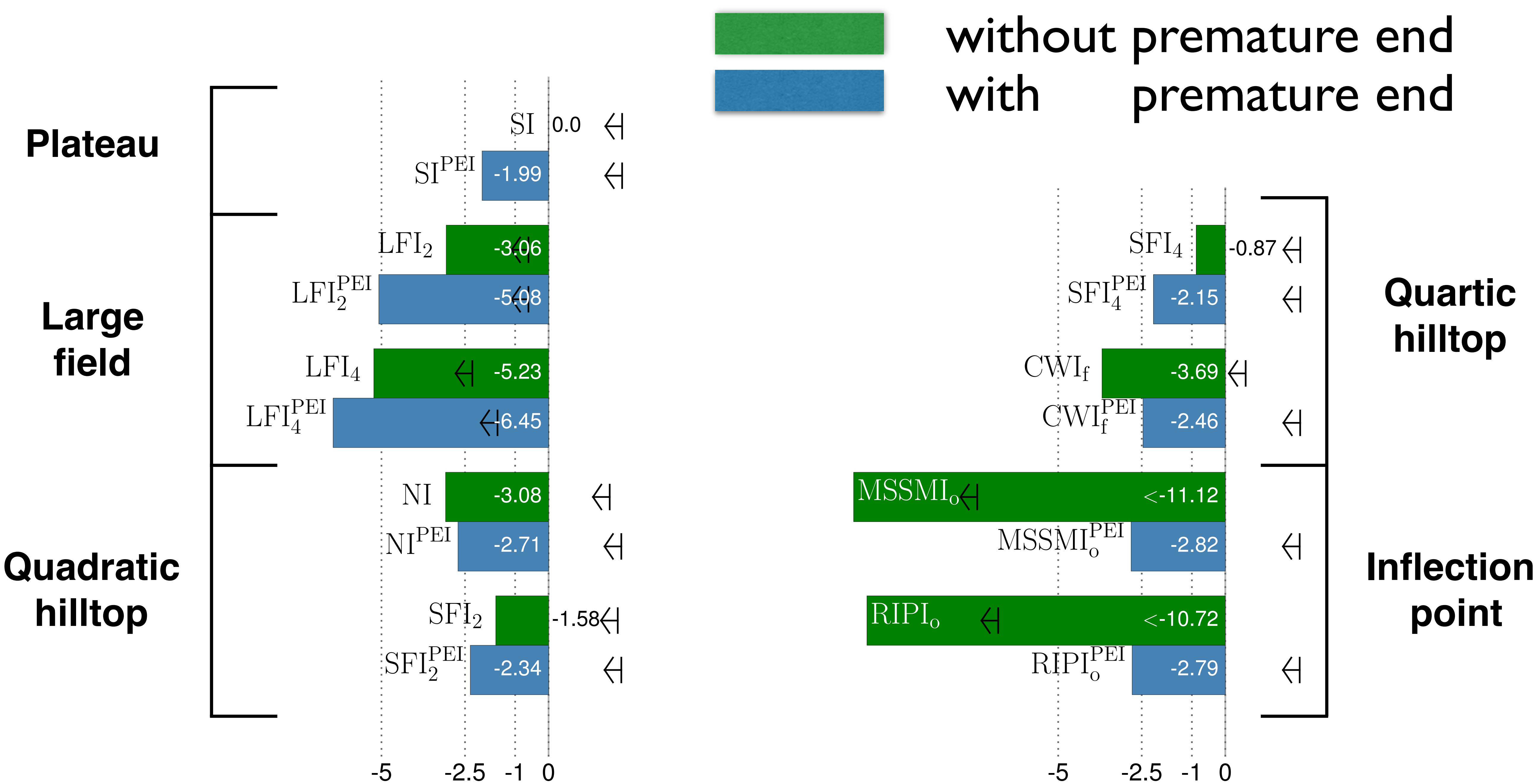
arXiv:1706.01835 RP, Turzynski, Vennin, JCAP

• Different classes of inflationary models are affected differently by a premature end of inflation (hilltop, inflection points, plateau, large-field…)

• Effects is degenerate with theoretical uncertainties about reheating

• Need for a full Bayesian analysis, consistently scanning over M >> H and reheating parameters

Reassessing the status of inflationary models

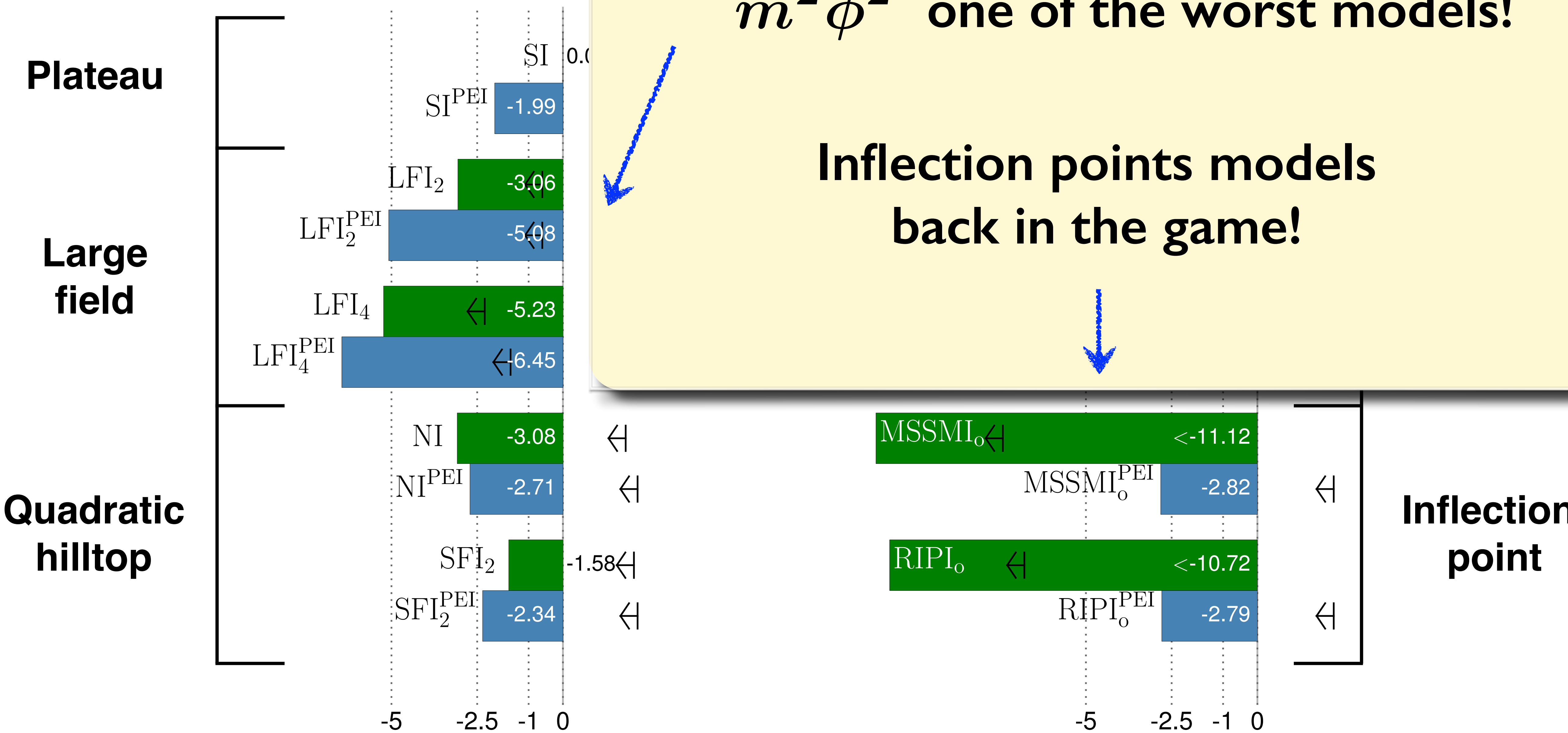


Bayesian evidences $\ln(\mathcal{E}/\mathcal{E}_{SI})$

Reassessing the status of inflationary models

$m^2\phi^2$ one of the worst models!

Inflection points models back in the game!



Bayesian evidences $\ln(\mathcal{E}/\mathcal{E}_{SI})$

Perspectives and generalizations

- Study of concrete models in the literature

- Similar discussion in N-field models, with (N-1) threats of tachyonic instabilities, and the Ricci scalar replaced by relevant sectional curvatures

- Even more dramatic impact on models with masses of order the Hubble parameter (typical in susy)

- Links with constraints on primordial non-Gaussianities

- Constraints on the internal geometry of HEP models, including string compactifications, rare!

Summary

In generic inflationary models in high-energy physics, there is the threat of an instability, so far overlooked, that:

- can prematurely end inflation (new mechanism)
- dramatically impacts observables
- modifies the interpretation of observations in terms of fundamental physics (and hence the observational status of models)
- constrain HEP in a unique manner

Conclusion

- The geometrical destabilization can qualitatively change our vision of inflation (e.g. landscapes 'with trivial field space geometry for simplicity' may not capture the correct physics)

- As important as the eta problem

- Exciting perspectives: new theoretical developments needed

September 3rd to December 14th, 2018

Organized by:

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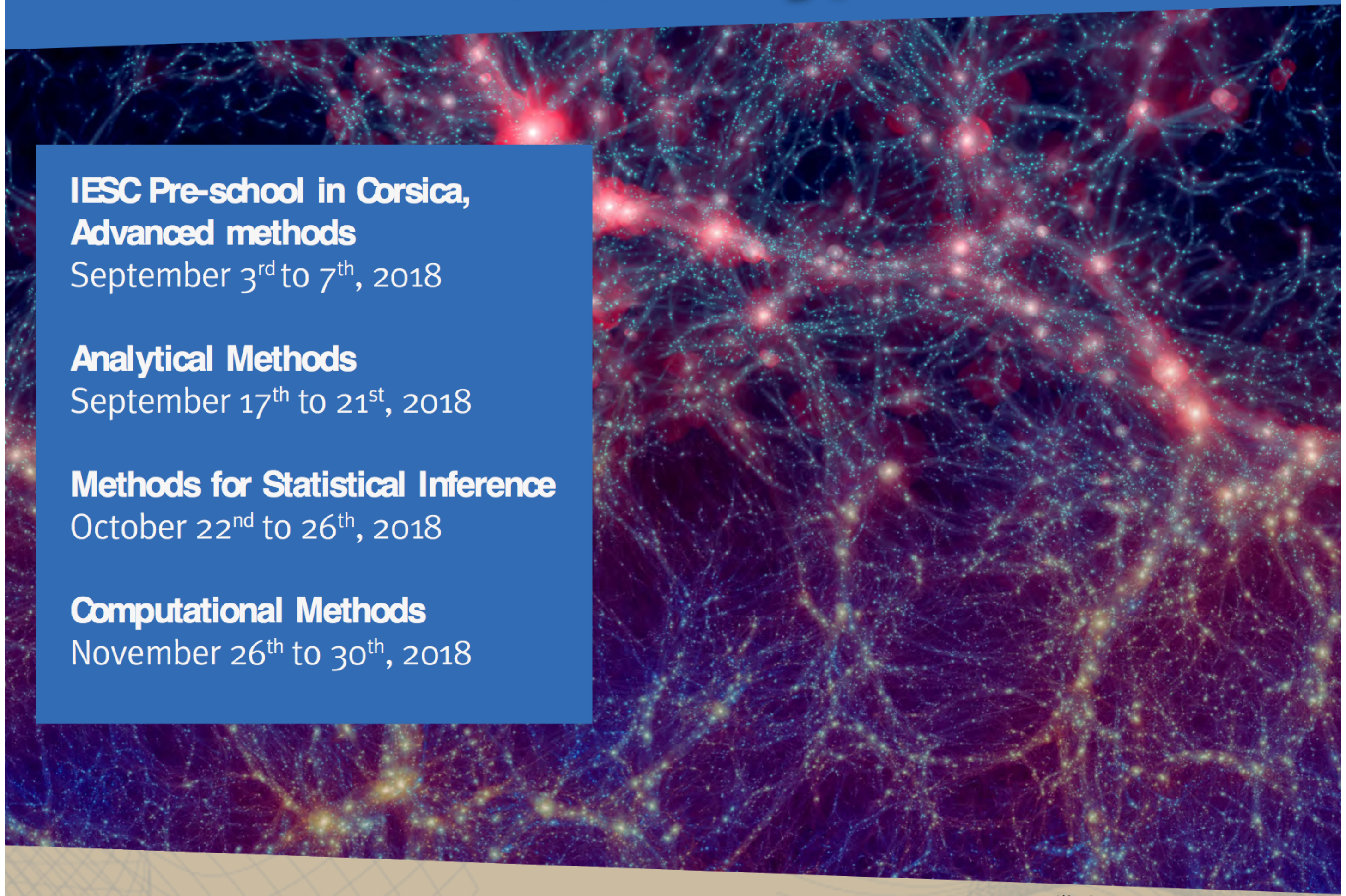
Analytics, Inference, and Computation in Cosmology



IESC Pre-school in Corsica, Advanced methods
September 3rd to 7th, 2018

Analytical Methods
September 17th to 21st, 2018

Methods for Statistical Inference
October 22nd to 26th, 2018

Computational Methods
November 26th to 30th, 2018

©Y. Dubois & S. Colombi (Horizon-AGN simulation)

Programme coordinated by the Centre Emile Borel at IHP
Participation of Postdocs and Ph. D Students is strongly encouraged
Scientific programme on: **http://ilp.upmc.fr/CosmoMath18**

Registration is free however mandatory on: **www.ihp.fr**
Deadline for financial support: **March 15th, 2018**
Contact: CosmoMath18@ihp.fr

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