Cosmology : theory

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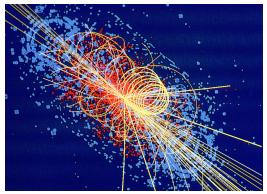
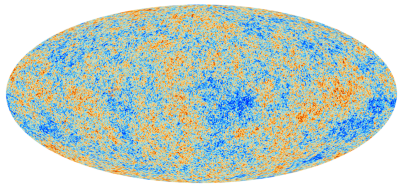
EPS HEP, Vienna 28 July 2015

From the point of view of cosmology,
two compelling events in recent years:

2012: discovery of the Higgs particle at LHC



2013: release of Planck data

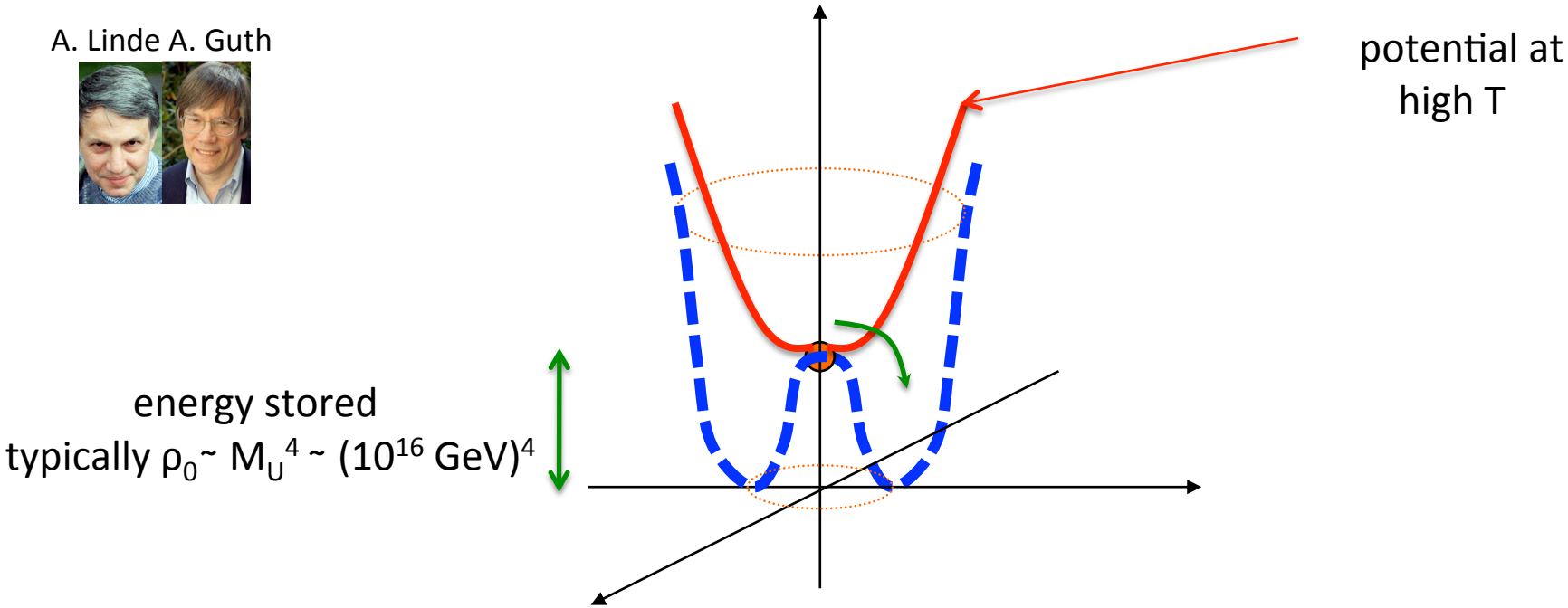


Why? In the early 1980s, the high energy community developed a model of the Primordial Universe based on the Standard Model and its extensions (in particular Grand Unification)

This Model led to a common framework for explaining:

- the matter-antimatter asymmetry through fundamental interactions
- the flatness, horizon (and monopole) problems through the scenario of inflation

A. Linde A. Guth



Einstein eqns : $T_{\mu\nu} \sim \rho_0\, g_{\mu\nu} \implies H^2 = 8\pi G_N \rho_0 /3 = \mathrm{cst}\ H_{vac}^2 \implies$ de Sitter solution $a(t) \sim \exp(H_{vac} t)$

This Model led to a common framework for explaining:

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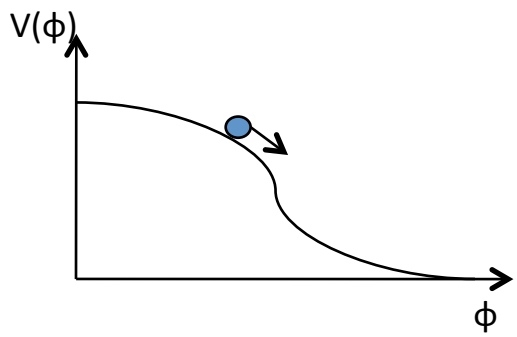
- the rotation curves of galaxies, and more recent manifestations of dark matter

- more recently, the acceleration of the expansion of the Universe, through a new component, dark energy

In all this, « fundamental » scalar fields play a central role.

Why?



Scalar fields easily provide a diffuse background

$\rho_\phi = \dot{\phi}^2/2 + V(\phi)$ energy density

$p_\phi = \dot{\phi}^2/2 + V(\phi)$ pressure

Speed of sound $c_s^2 = (\delta p / \delta \rho)_{adiabatic}$

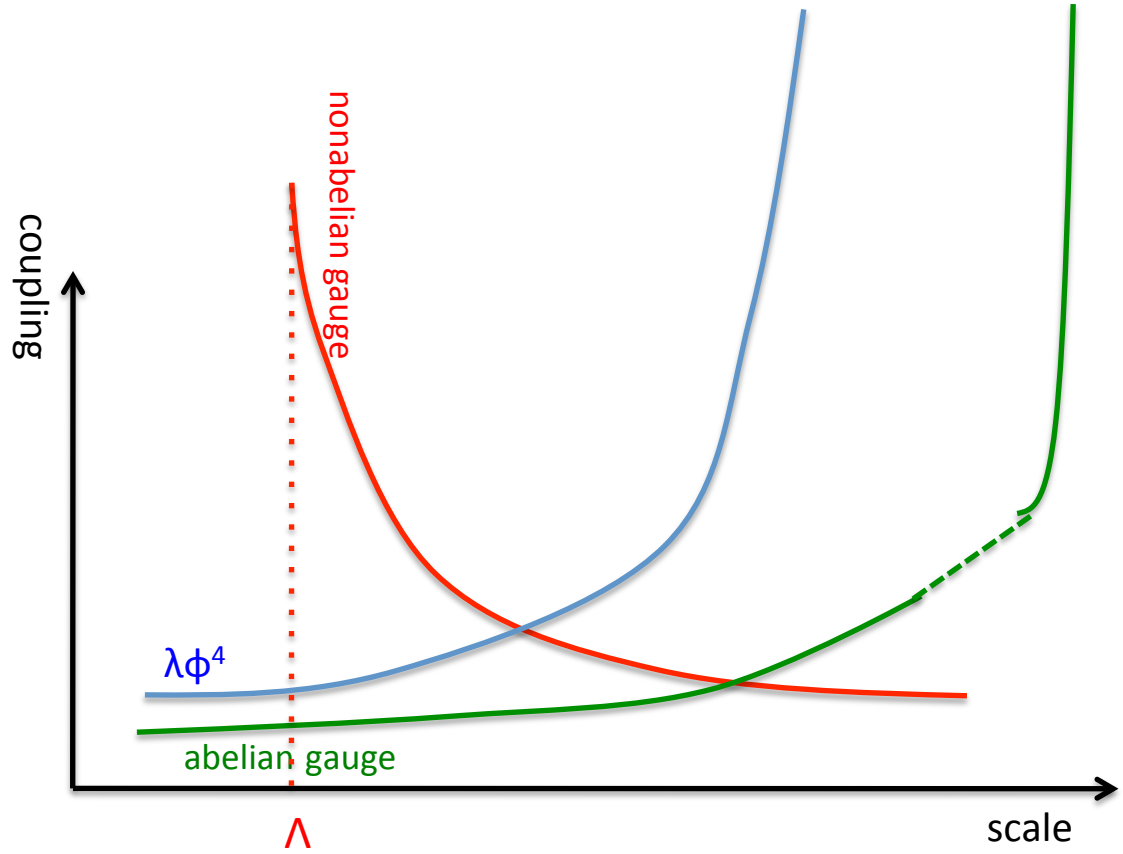
In most models, $c_s^2 \sim 1$, i.e. the pressure of the scalar field resists gravitational clustering :

Unless in specific cases, scalar fields tend not to cluster.

Hence the discovery of the Higgs has provided the first « fundamental » scalar field.

If there is one, why not many?

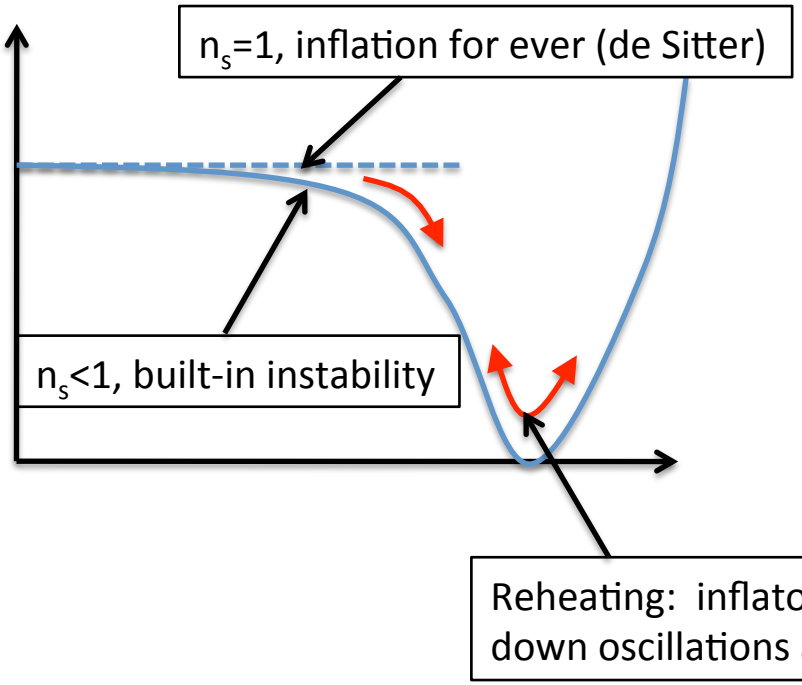
Indeed, triviality argument

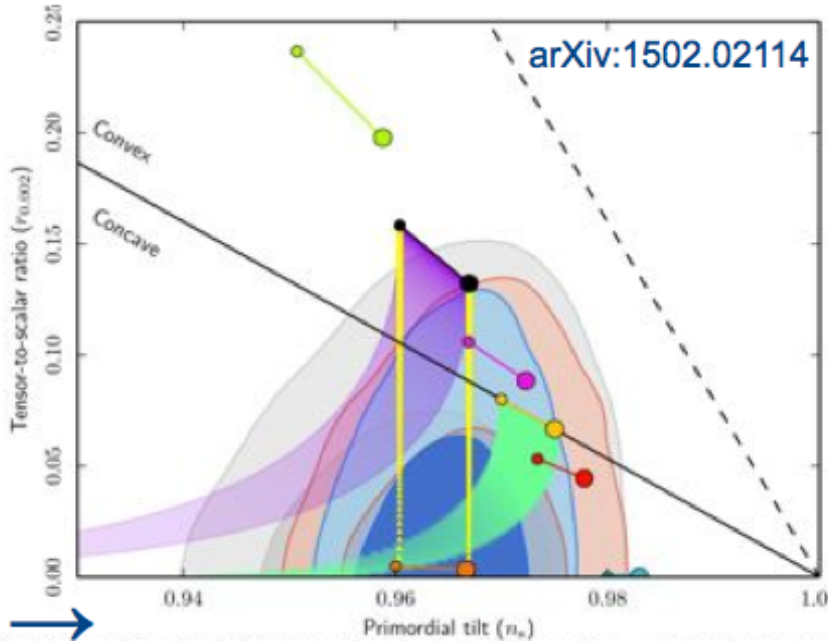


Planck results: what comforted the inflation paradigm?

Pre-Planck: spacetime is spatially flat $\Omega = 1$ or $\rho = \rho_c$

Planck: $n_s = 0.968 \pm 0.006$





Basic questions which cosmology may have to address:

- What is the exact mechanism for inflation? Is eternal inflation a valid option?

- How to explain the matter-antimatter asymmetry?

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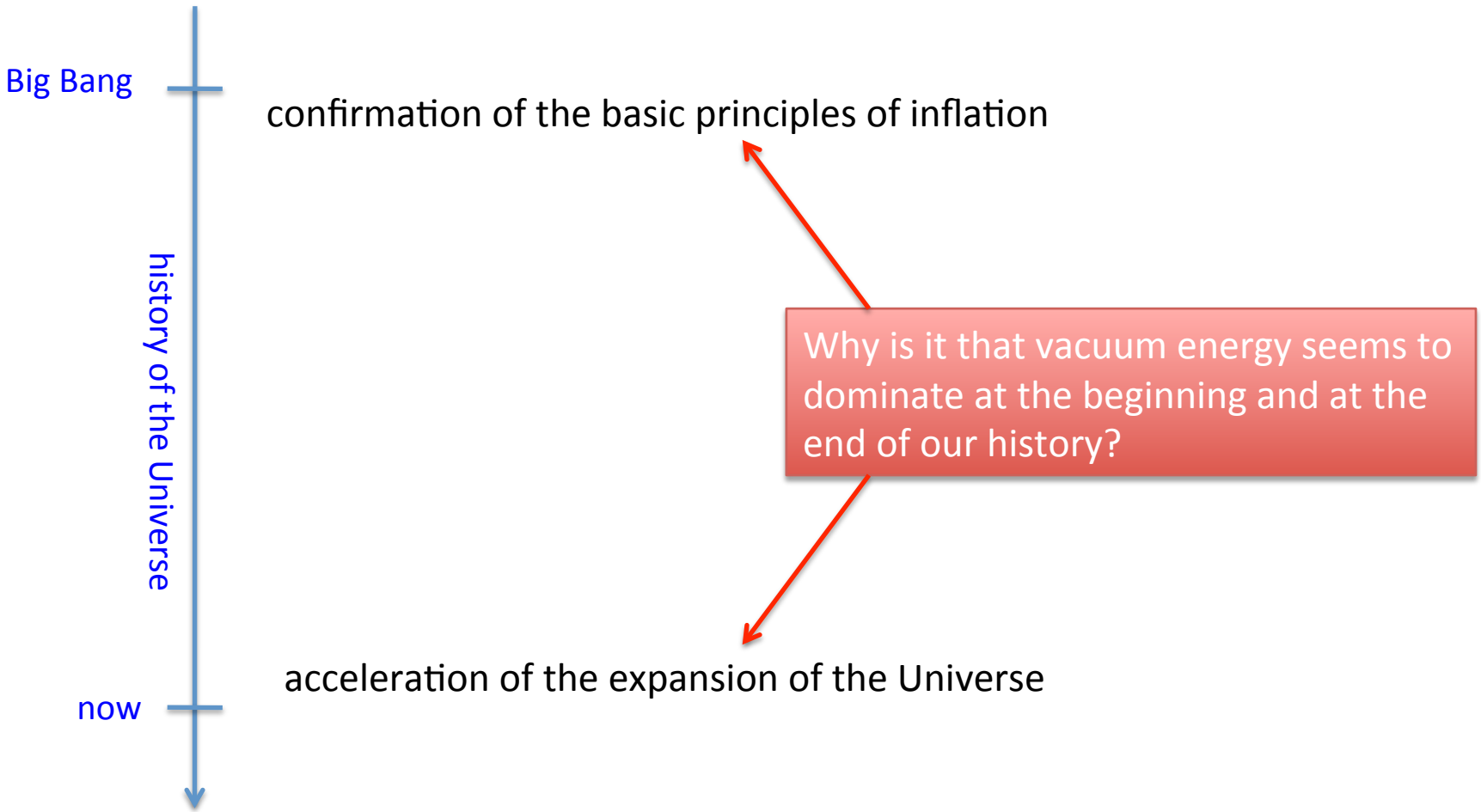
- Why is the Higgs mass stable under radiative corrections?
- Why is the Higgs mass so close to the instability frontier?

Potential clues for future theories:



Potential clues for future theories:

Big Bang

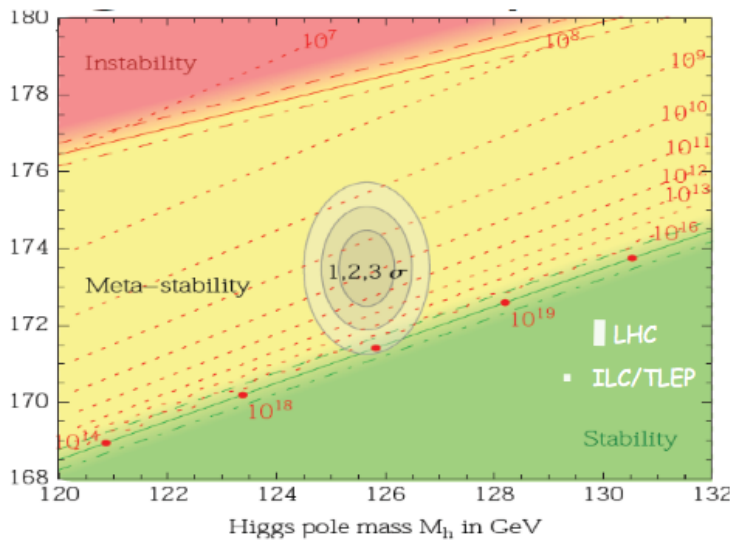
history of the Universe

now

confirmation of the basic principles of inflation

Higgs close to instability?

Does it mean anything?



acceleration of the expansion of the Universe

Regarding inflation and/or dark energy, we have an infinite range of possibilities but, on the other hand, no sign of new physics.

$\Longrightarrow$ a trend in the theory studies of the last two years has been to follow the road of minimality

Rely on the Higgs (+ possibly the QCD axion field) to address the issues

Higgs inflation

Higgs h of the original SM cannot be the inflaton

Condition to avoid quantum gravity regime during slowroll: quartic coupling $\lambda \ll 10^{-2}$

(whereas $\lambda \sim 10^{-1}$)

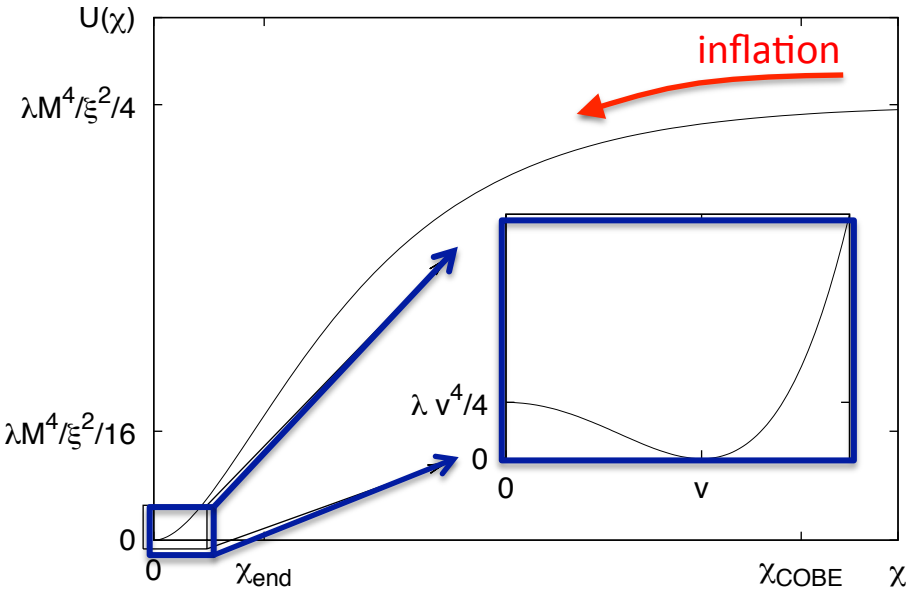
Need to couple it to spacetime curvature R

$$S = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2}\left(1 + \xi \frac{h^2}{M_P^2}\right) R + \frac{1}{2}\partial^\mu h\, \partial_\mu h - \frac{\lambda}{4}(h^2 - v^2)^2 \right\}$$

Berzukov, Shaposhnikov
0710.3755 [hep-th]...

$$S = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R - \frac{1}{2}\left[g^{\mu\nu} - \frac{w^2}{M_P^2}(R^{\mu\nu} - R\, g^{\mu\nu}/2)\right] \partial_\mu h\, \partial_\nu h - \frac{\lambda}{4}(h^2 - v^2)^2 \right\}$$

Germani, Kehagias
1003.2635 [hep-ph]...

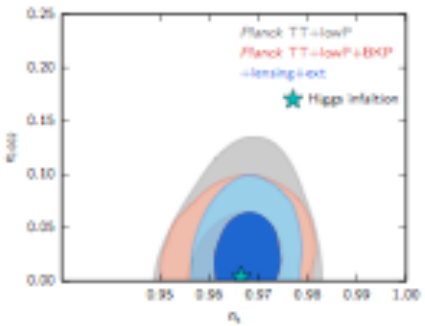


Bezrukov, Shaposhnikov

Mathematical trick:
conformal transformation on the metric

$$g_{\mu\nu} \to \hat{g}_{\mu\nu} = \sqrt{1 + \frac{\xi\phi^2}{M_P^2}}\, g_{\mu\nu},$$

$$V(\phi) \to \hat{V}(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2$$



For large ξ Higgs inflation

spectral index	$n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2}$	$\simeq 0.97$
tensor/scalar ratio	$r \simeq \frac{192}{(4N+3)^2}$	$\simeq 0.0033$

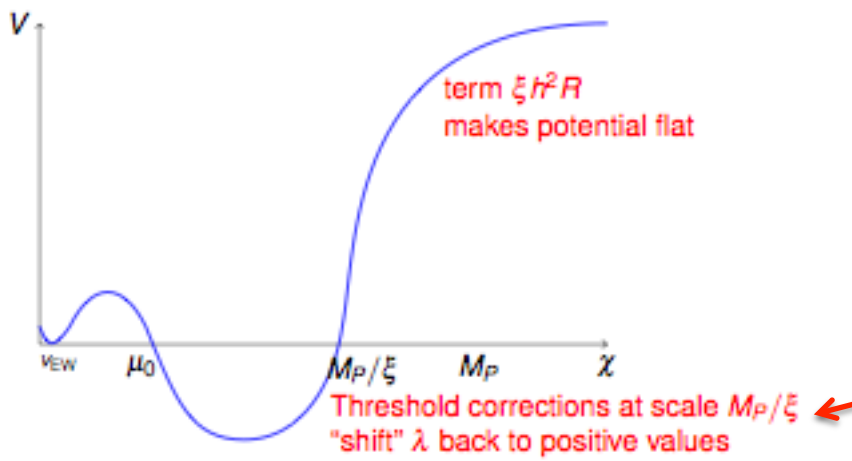
$\delta T/T \sim 10^{-5} \quad \Rightarrow \quad \xi/\sqrt{\lambda} \sim 47000$

Note: problem with unitarity at scale M_P/ξ; app. shift symmetry helps at scale $\gg M_P/\xi$ (inflation)

Burgess, Lee, Trott 0902.4465,1002.2730
George, Mooij, Postma, 1310.2157

Bezrukov, Magnin, Shaposhnikov, Sibiryakov 1008.5157
Ferrara, Kallosh, Linde, Marrani, Van Proeyen 1008.2942

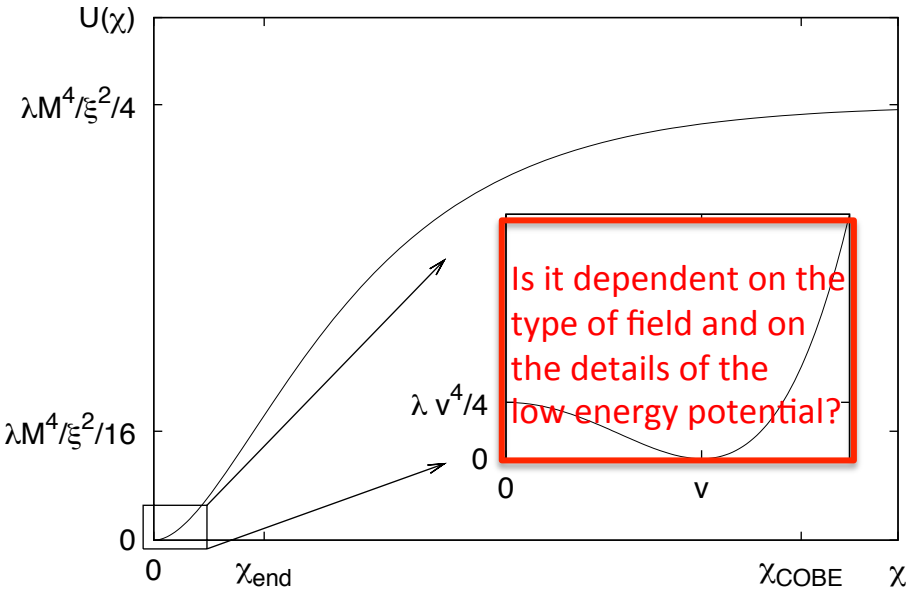
What happens if the Higgs field is in the instability region?



requires to know how to compute in this region

In the general case, this might require Higgs-inflaton coupling :

Metastable SM vacuum	inflaton = Higgs	inflaton & Higgs independent	inflaton & Higgs interacting
Large r	No	No	Yes Model dep.
Small r	Yes (threshold corr.)	Yes $r < 10^{-9}$	Yes Model dep.
Planck scale corections	Scale inv.	Restricted	Model dep.



Going beyond the Hiiggs field…

No!

$$S = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2}\left(1 + \xi \frac{h^2}{M_P^2}\right) R + \frac{1}{2}\partial^\mu h\, \partial_\mu h - \frac{\lambda}{4}(h^2 - v^2)^2 \right\}$$

generalize

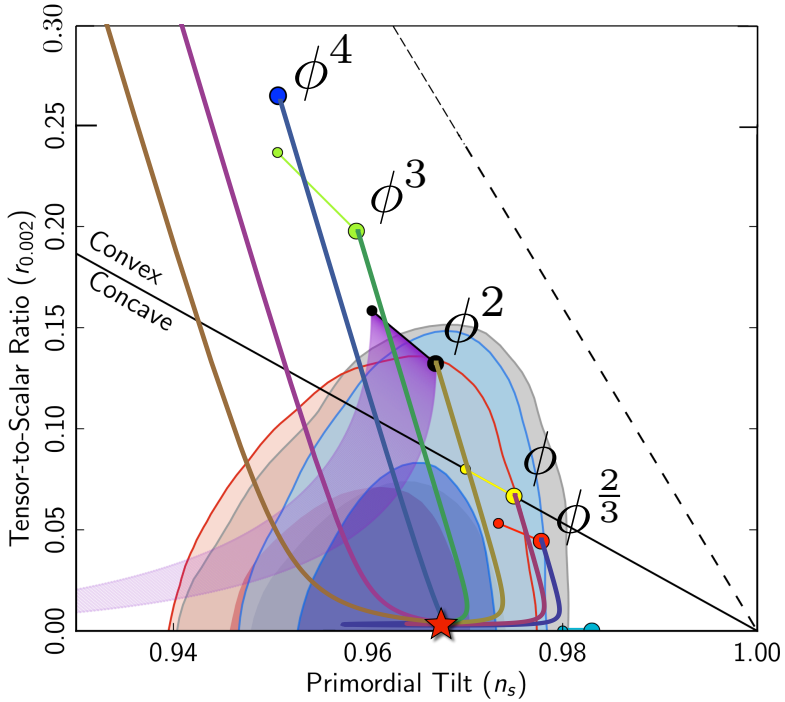
$$S = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2}\left(1 + \xi f(\phi)\right) R + \frac{1}{2}\partial^\mu h\, \partial_\mu h - \lambda f(\phi)^2 \right\}$$

In the limit ξ large, one obtains the predictions of Higgs inflation

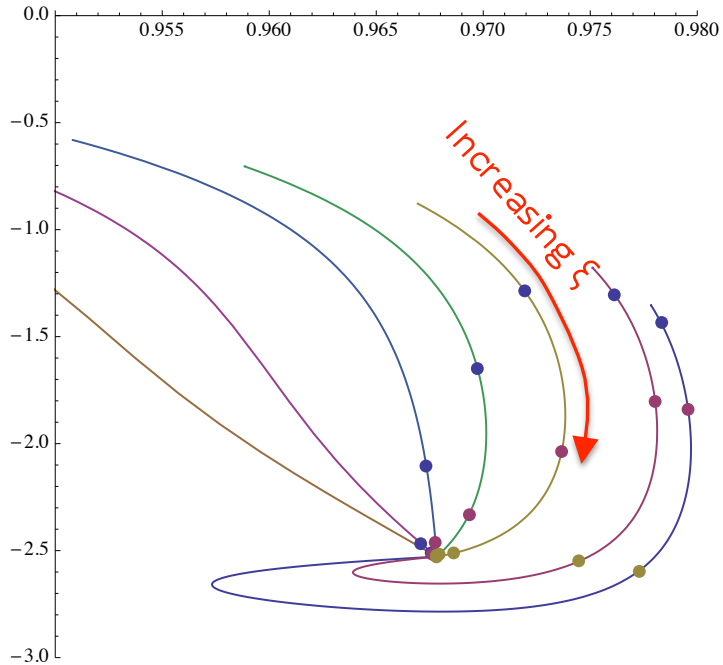
Kallosh, Linde, Roest 1310.3950

Kallosh, Linde, Roest 1310.3950

α-attractors



log scale



Fine tuning and naturalness

We have to understand two severe fine tuning problems:

$$M_P^4/\Lambda \sim 10^{120}$$

$$M_P/m \sim 10^{16}$$ m Higgs mass

see A. Wulzer talk

<u>Dirac large number hypothesis (1937)</u>

Large mass scale ratios are a consequence of the age of the Universe, i.e. are the result of the cosmological evolution.

Dirac concluded that $G \propto 1/t$ which is not observed.

But could we apply similar arguments to fine tuning ratios?

Abbott 1985, Dvali and Vilenkin hep-th/0404043, Dvali hep-th/0410286

The rel(axion)

D. Kaplan, this conference

Graham, Kaplan, Rajendran 1504.0755

Simplest model: SM + QCD axion ϕ

$\Lambda^4 \sim f_\pi m_\pi^2 \propto (\lambda_u + \lambda_d) \langle h \rangle$

large mass scale M

V(gϕ)

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + \boxed{gM^2\phi + g^2\phi^2 + \cdots} + \Lambda^4 \cos\frac{\phi}{f}$$

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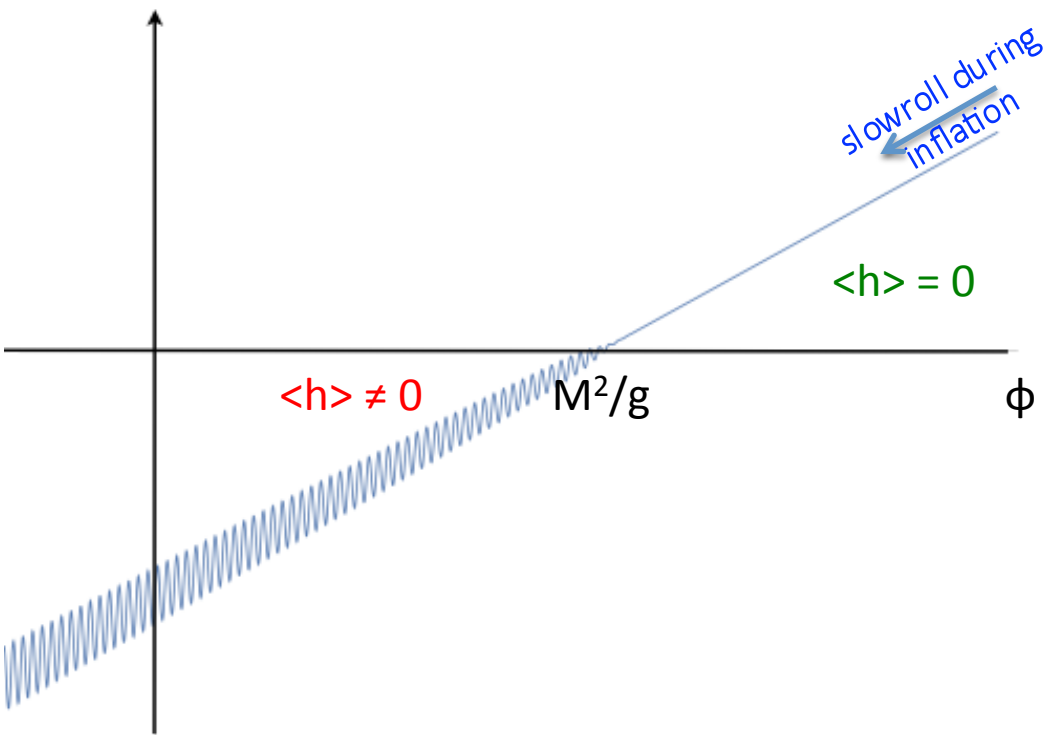


In the limit $g \to 0$,
shift symmetry: $\phi \to \phi + 2\pi f$
(from continuous symmetry
(in the absence of strong interactions)
$\phi \to \phi + cst$
g naturally small

Bound on cutoff...

Incompatible with limit on neutron dipole moment

- QCD axion

$$M < 3 \times 10^8 \text{ GeV}$$

- Variations: i) drop the slope

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + \kappa\sigma^2\phi + gM^2\phi + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

inflaton - drops at end of inflation

$$\boxed{M < 1000 \text{ TeV} \left(\frac{\theta}{10^{-10}}\right)^{\frac{1}{4}}}$$

ii) Use a different strong group and couple ϕ to $G'^{\mu\nu}\tilde{G}'_{\mu\nu}$.

Thus interesting class of modelswhich require further investigation:

- the g parameter is very small (e.g. 10^{-31} GeV): this is natural in a technical senses but why?

- the model requires a long inflation period; connection ϕ field $\leftrightarrow$ inflaton

- reheating

- can the ϕ field provide dark matter

see also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant 1506.09217

Back to general models of inflation:

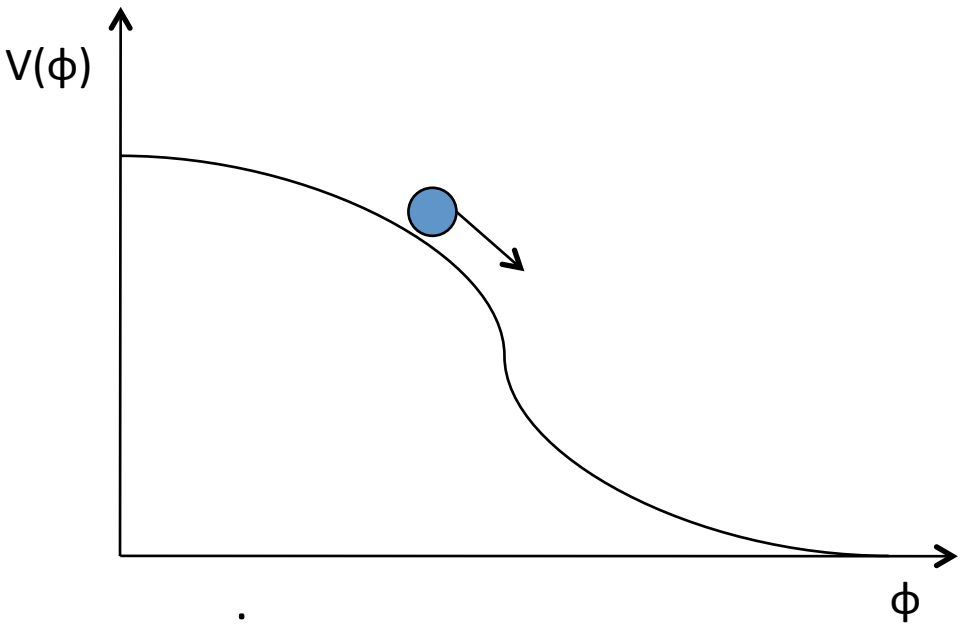
- how to use cosmological data to identify the dynamics of inflation?
- can we understand why different models give the same predictions?

Indeed, and this might be due to a very fundamental reasons

In fact, one may identify characteristic classes of models (in a sense very similar to the characteristic classes of critical phenomena in condensed matter physics)

In an inflation scenario, one first have to solve the classical equation of motion of the inflaton field in its potential.

Suppose that we are in an expanding Universe with cosmic scale factor a(t)



Hubble parameter $H(t) \equiv \dot{a}(t)/a(t)$

$\dot{} \equiv d/dt$

Equation of evolution of the field ϕ

$$\boxed{\ddot{\phi} + 3 H \dot{\phi} = - dV/d\phi}$$

$\rho_\phi = \dot{\phi}^2 /2 + V(\phi)$ energy density

$p_\phi = \dot{\phi}^2 /2 - V(\phi)$ pressure

There is a simple way of extracting a first integral of motion

Bond and Salopek, 1990

Write $H(t) = \dot{a}/a(t) \equiv -W(\phi)/2$

Then [...] the equation of motion becomes simply

$$\boxed{\dot{\phi} = W_\phi}$$

$$\boxed{V(\phi) = 3W^2/4 - W_\phi{}^2/2}$$

$W(\phi)$ superpotential

But $$\frac{d\phi}{d\ln a} = \frac{d\phi}{dt}\frac{dt}{d\ln a} = \frac{\dot{\phi}}{H} = \frac{1}{H}\frac{dW}{d\phi} = -2\frac{W_\phi}{W}$$

W_ϕ $dW/d\phi$

evolution of ϕ

$$\frac{d\phi}{d\ln a} = -2\,\frac{W_\phi}{W}$$

evolution of ϕ

$$\frac{d\phi}{d\ln a} = -2\,\frac{W_\phi}{W} \equiv \beta(\phi)$$

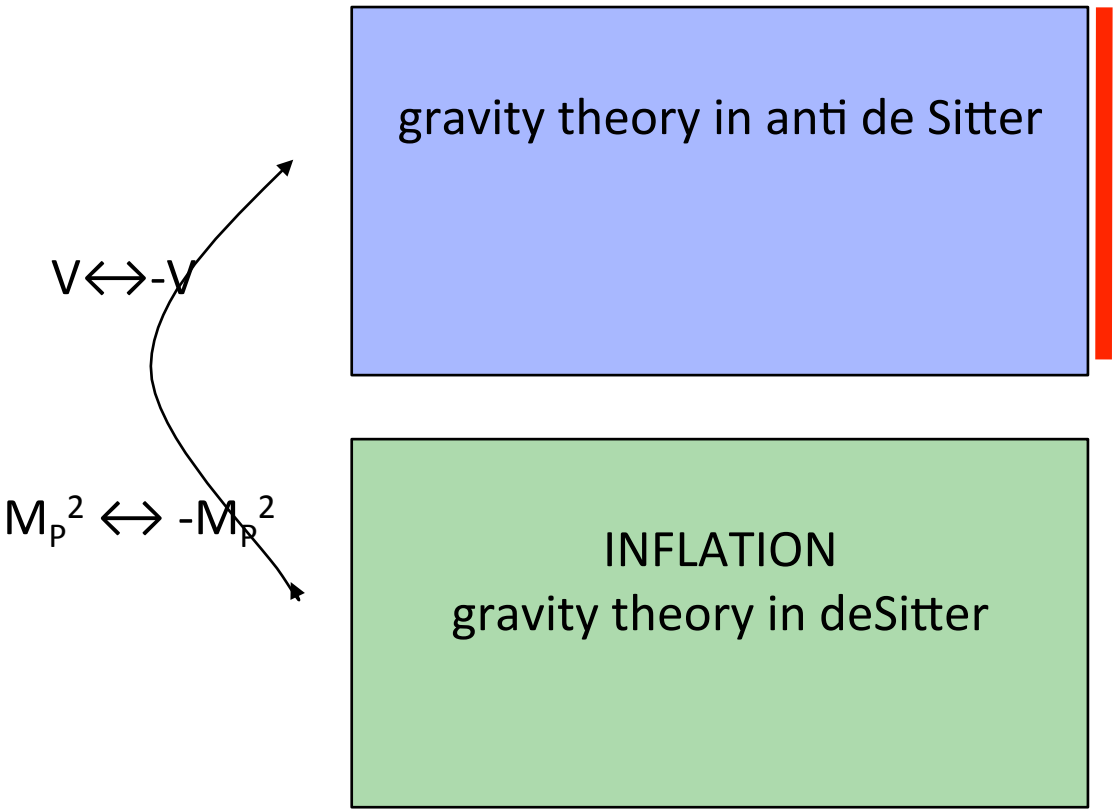
renormalisation group equation
in QFT or statistical physics

$$\frac{dg}{d\ln\mu} = \beta(g)$$

field ϕ ⟷ gauge coupling g

cosmic scale factor a ⟷ renormalisation scale μ

Where does this come from? Understandable in the context of AdS/CFT



conformally invariant QFT
(typically gauge theory w/ $\beta(g)=0$)

McFadden, Skenderis E. Kiritsis 1307.5873

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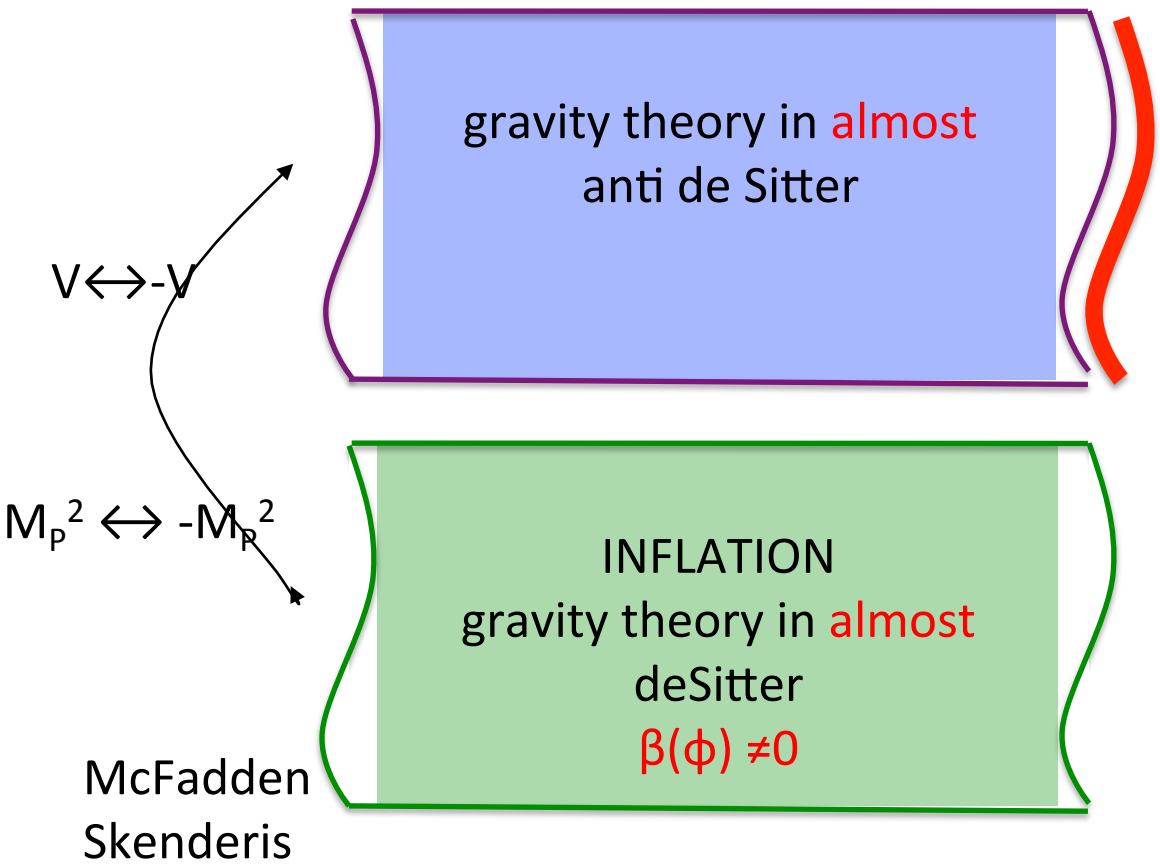

conformally invariant QFT
(typically gauge theory)
+ operators β(g)≠0

McFadden, Skenderis E. Kiritsis 1307.5873

evolution of ϕ

$$\frac{d\phi}{d\ln a} = -2\,\frac{W_\phi}{W} \equiv \beta(\phi)$$

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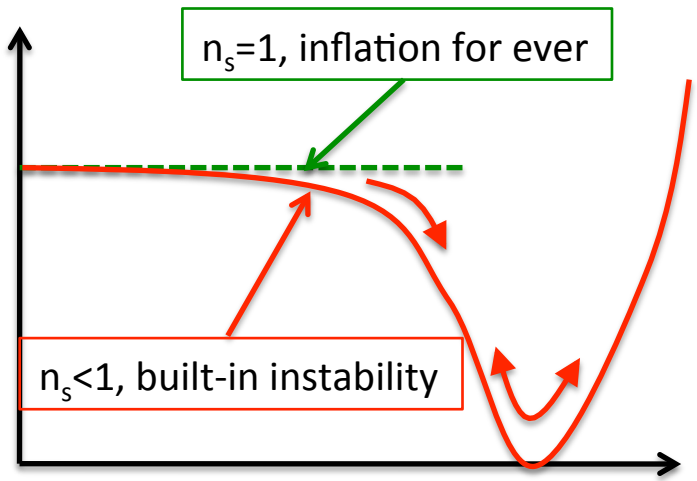
Note: $\beta(\phi) = [\,3(p_\phi+\rho_\phi)/\rho_\phi]^{1/2}$

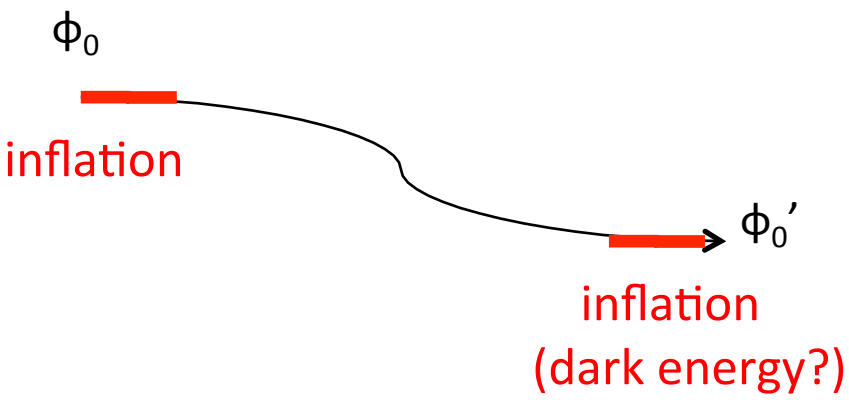
Vacuum energy: $p = -\rho \Rightarrow \beta = 0$ fixed point

Inflation: vicinity of a fixed point



Fixed point : zero of β

$\beta(\phi_0)=0$

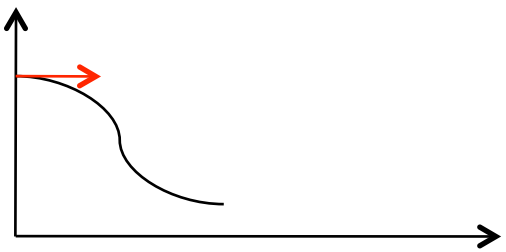


P.B., Kiritsis, Mabillard, Pietroni 1407.0820

Solutions classified into universality classes:

Class Ia: $\beta(\phi) = \beta_q (\phi-\phi_0)^q$

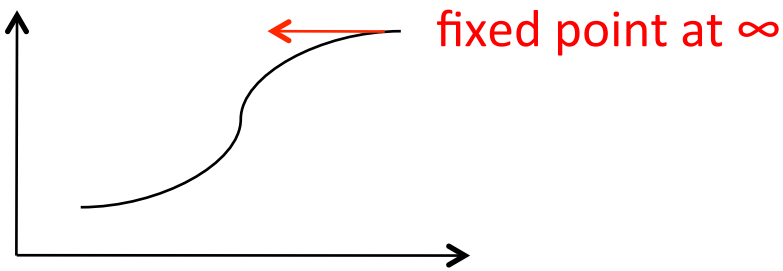
$V(\phi) \sim A[1- B(\phi-\phi_0)^{q+1}+\ldots]$



$$n_S - 1 = -6\epsilon + 2\eta \sim -\frac{2q}{q-1}\frac{1}{N} ,$$

$$r = 16\epsilon \sim \frac{8}{\beta_q^{2/(q-1)}\,[(q-1)N]^{2q/(q-1)}} .$$

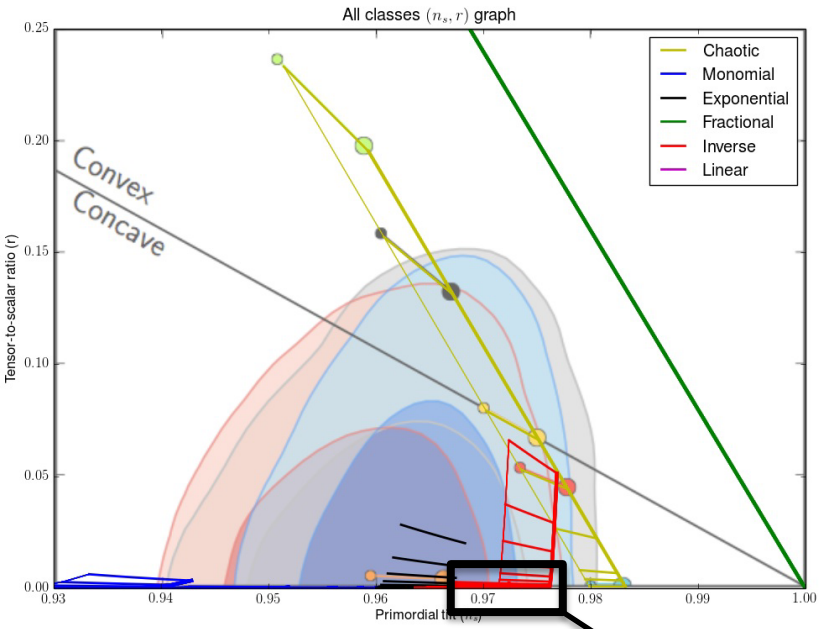
Class II: $\beta(\phi) = -\beta \exp[-\gamma\phi]$



$$n_S - 1 \sim -\frac{2}{N} ,$$

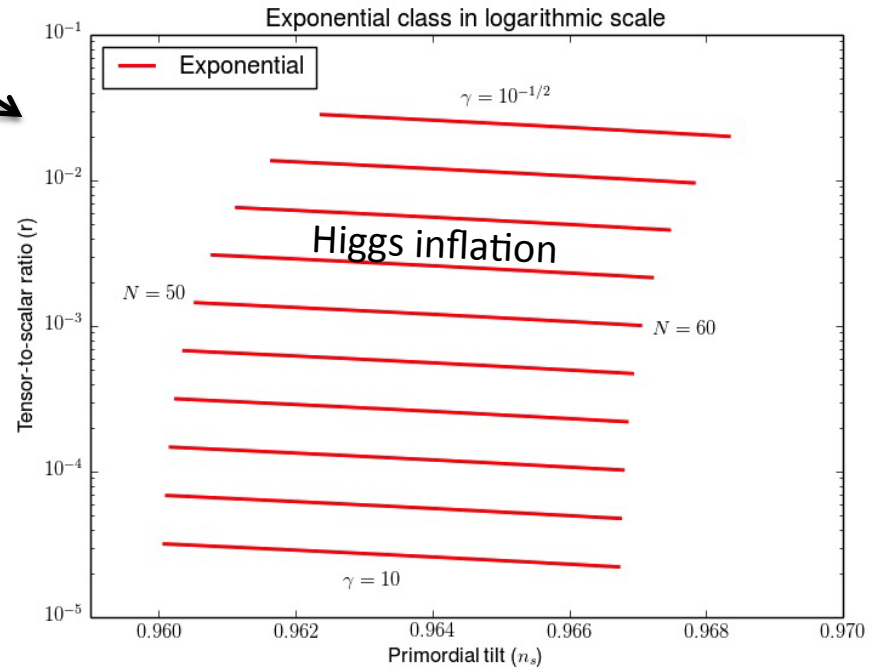
$$r \sim \frac{8}{n^2\gamma^2}\frac{1}{N^2} .$$

Ex: Higgs inflation, Starobinsky R^2 inflation



all classes

exponential class



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Conclusions

The simultaneous discovery of the Higgs and confirmation of (some of) the basic features of inflation has opened a new era in the common understanding of cosmology and particle physics.

Even to understand the basic problems faced by high energy physics today, it might be important to recall that we leave in an expanding hence dynamical Universe.

The cosmological dynamics may help us to find clues for some of the most fundamental problems that we face and maybe pave the way for a reconciliation of gravity (described by general relativity) with the quantum theory (Standard Model).