Inflation and classical scale invariance

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based on 1410.xxxx
in collaboration with

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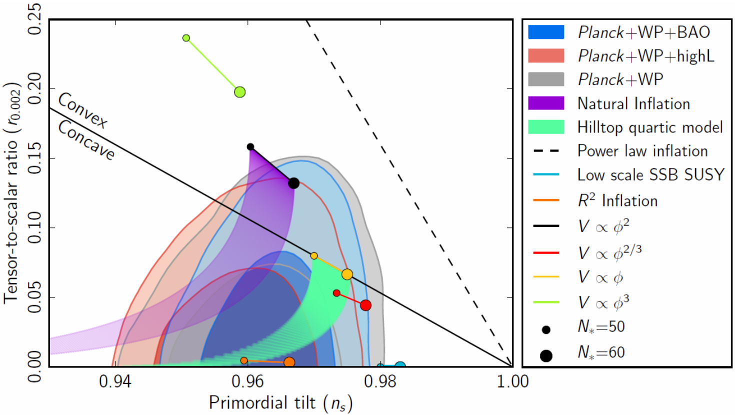
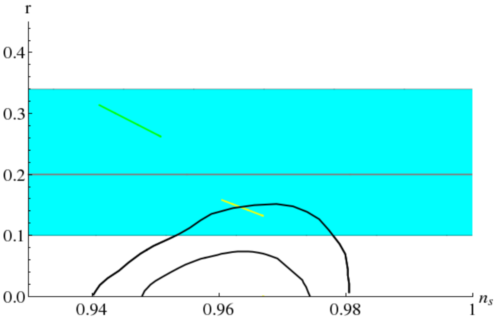
Summary

Experimental Data: 2013



$$\mathbf{r} = \frac{P_T(k)}{P_S(k)} \qquad P_S(k) = A_s \left(\frac{k}{k_*}\right)^{\mathbf{n_s}-1+\dots}$$

Experimental Data: 2014



$\mathbf{r} = \frac{P_T(k)}{P_S(k)}$ – Planck bound – $V = m^2\phi^2$

$P_S(k) \sim k^{\mathbf{n_s}-1}$ BICEP2 2σ region – $V = \lambda\phi^4$

Experimental Data and Analysis: 2014

Reactions to $\mathbf{r} = \mathbf{0.2}^{+\mathbf{0.07}}_{-\mathbf{0.05}}$ (BICEP2 Coll., Phys. Rev. Lett. **112** (2014) 241101)

- initially: many many papers trying to explain/predict BICEP2 signal
- later: all the signal could be just dust (or not)
  - M. J. Mortonson and U. Seljak, arXiv:1405.5857
  - R. Flauger, J. C. Hill and D. N. Spergel, JCAP **1408** (2014) 039

$\Rightarrow$ we need more data from Planck

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a. W. N. Colley and J. R. Gott, arXiv:1409.4491
The main uncertainty seems to be the amplitude of the dust signal in the BICEP2 map. The previous studies have considered the power spectrum of the B-modes. But this leaves out the other information in the maps. Looking at the power spectrum alone is unsufficient.
Therefore they designed a study which does not depend on the amplitude of the dust signal at all (fore more details check the article).

$r = 0.11 \pm 0.04$ (based on **preliminary** public Planck dust data)

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- Planck collaboration **official** dust data (arXiv:1409.5738)

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  $\Rightarrow$ we need more data from Planck

a. W. N. Colley and J. R. Gott, arXiv:1409.4491
   $r = 0.11 \pm 0.04$ (based on **preliminary** public Planck dust data)

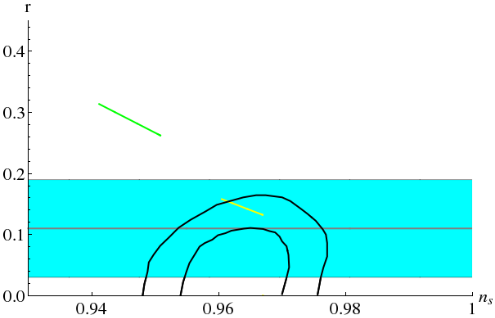
b. Planck collaboration **official** dust data (arXiv:1409.5738) analized
   - C. Cheng, Q. G. Huang and S. Wang, arXiv:1409.7025
   - L. Xu, arXiv:1409.7870

   $\Rightarrow$ the BICEP2 signal is due to dust (based on power spectrum study)

- a. has a better study but b. have used the most recent data.

Experimental Data and Analysis: 2014

However a.(■) and b.(−) are compatible results.



It is too soon for taking final conclusion.
Hopefully Gert will give soon a seminar on this topic... $\ddot{\smile}$

Recipe for studying inflation

$$S = \int d^4x\sqrt{-g}\left(\frac{M_P^2}{2}R + \mathcal{L}_\phi\right) \qquad \mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

1. Compute the slow roll parameters

$$\begin{aligned}\epsilon(\phi) &= \frac{M_{\rm P}^2}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2\\ \eta(\phi) &= M_{\rm P}^2\frac{V''(\phi)}{V(\phi)}\end{aligned}$$

   Inflation takes place when $\epsilon,\ \eta \ll 1$

2. Compute the field value at the end of inflation ϕ_e from

$$\epsilon(\phi_e) = 1$$

Recipe for studying inflation

3. Compute ϕ^*, N e-folds before the end of inflation,

$$N = \frac{1}{M_{\mathrm{P}}} \int_{\phi_e}^{\phi^*} \frac{d\phi'}{\sqrt{2\epsilon\left(\phi'\right)}}$$

4. Compute r and n_S at $N = [50, 60]$ by

$$\begin{aligned} r &= 16\epsilon\left(\phi^*\right) \\ n_s &= 1 - 6\epsilon\left(\phi^*\right) + 2\eta\left(\phi^*\right) \end{aligned}$$

5. From the scalar amplitude measurement: $A_s^2 = \frac{V(\phi^*)}{24\pi^2 M_P^4 \epsilon(\phi^*)} \approx 2.45 \times 10^{-9}$ fix the overall normalization of V:

$$V(\phi^*) \simeq \left(1.94 \times 10^{16}\ \mathrm{GeV}\right)^4 \frac{r}{0.12}$$

Classical scale invariance

- I do not want to discuss why to choose classical scale invariance, its meaning, pros and cons
- Let us just threat it as a possible configuration of the parameters space
- We consider a configuration in which the classical Lagrangian has all the dimensionful parameters set to be zero
- Therefore mass terms must be generated at quantum level

Dimensional transmutation

Tree level: $V_\phi = \frac{1}{4}\lambda_\phi \phi^4 \quad \Rightarrow \quad V_\phi^{\text{min}} : \langle\phi\rangle = v_\phi = 0 \ \& \ m_\phi^2 = 0$

RGE : $\beta_{\lambda_\phi} = \frac{d\lambda_\phi}{d\ln\mu}$

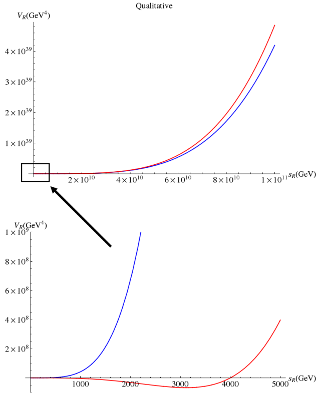
$\Rightarrow$ if: $\beta_{\lambda_\phi} \sim$ const. (at least in some region) and > 0

$$\Rightarrow \int_{\lambda_{\phi_0}}^{\lambda_\phi} d\lambda_\phi \simeq \beta_{\lambda_\phi} \int_{\ln\mu_0}^{\ln\mu} d\,(\ln\mu)$$

$$\Rightarrow \quad \lambda_\phi \simeq \lambda_{\phi_0} + \beta_{\lambda_\phi} \ln\frac{\mu}{\mu_0}$$

$$\Rightarrow \quad \text{fixing } \lambda_{\phi_0} = 0$$

$$\Rightarrow \quad \boxed{\lambda_\phi \simeq \beta_{\lambda_\phi} \ln\frac{\mu}{\mu_0}} \rightarrow \begin{cases} \lambda_\phi(\mu > \mu_0) > 0 \\ \lambda_\phi(\mu < \mu_0) < 0 \end{cases}$$



One loop: $V_{\text{R,1loop}} \simeq \frac{1}{4}\beta_{\lambda_\phi} \ln\frac{|\phi|}{\phi_0}\phi^4 \quad \Rightarrow \quad v_\phi \simeq \frac{\phi_0}{e^{1/4}} \ \& \ m_\phi^2 = \frac{\beta_{\lambda_\phi}\phi_0^2}{\sqrt{e}} \qquad (\phi_0 \leftrightarrow \mu_0)$

Coleman-Weinberg inflation

- Already the first papers on inflation considered CW inflation:
  Linde, Phys. Lett. B108 (1982) 389-393, Phys. Lett. B114 (1982) 431; Albrecht and Steinhardt, Phys. Rev. Lett. 48 (1982) 1220-1223; Ellis et al., Nucl. Phys. B221 (1983) 524, Phys. Lett. B120 (1983) 331.
- This idea has been (is being) extensively studied in the context of
  - GUT:
    Langbeine et al, Mod.Phys.Lett. A11 (1996) 631-646; Gonzalez-Diaz, Phys.Lett. B176 (1986) 29-32; Yokoyama, Phys.Rev. D59 (1999) 107303; Rehman et al., Phys.Rev. D78 (2008) 123516.
  - $U(1)_{B-L}$:
    Barenboim et al., Phys.Lett. B730 (2014) 81-88; N. Okada and Q. Shafi, 1311.0921.
  - $SU(N)$:
    Elizalde et al., 1408.1285.
- They all suppose new gauge groups beyond the SM: NO NEED FOR IT!
- It can occur just due to running of some scalar quartic coupling, to negative values at some energy scale due to couplings to other scalar fields, generating non-trivial physical potentials.

Lagrangian

$$S = \int d^4x\sqrt{-g}\left[f(\phi)R + \mathcal{L}_{\text{matter}}\right] \qquad f(\phi) = \frac{\xi_\phi}{2}\phi^2$$

$$\mathcal{L}_{\text{matter}} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta + \mathcal{L}_Y - V$$

$$\mathcal{L}_Y = y_\phi\phi\bar{N}^c N + y_\eta\eta\bar{N}^c N$$

$$V = \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_{\phi\eta}}{4}\eta^2\phi^2 + \frac{\lambda_\eta}{4}\eta^4$$

- Full classical scale invariance $\rightarrow M_P$ dynamically
- The running of λ_ϕ allows $v_\phi \neq 0 \Rightarrow \phi = v_\phi + \varphi$

$$\Rightarrow \quad f(\phi) \rightarrow f(\varphi + v_\phi) = \xi_\phi\left(\varphi + v_\phi\right)^2/2 \quad \Rightarrow \quad \boxed{M_P^2 = \xi_\phi v_\phi^2}$$

- inflaton: ϕ
- N not needed for CW inflation itself, but for our particular case

From the Jordan frame to the Einstein frame

- Conformal transformation:

$$g_{\mu\nu} \to \Omega(\phi)^2 g_{\mu\nu}$$
$$\Omega(\phi)^2 = \frac{2}{M_P^2} f(\phi)$$

- The scalar potential in the Einstein frame is given by

$$U = \frac{V(\phi)}{\Omega(\phi)^4} = \frac{\lambda_\phi(\phi)\phi^4}{4\Omega(\phi)^4}$$

- Canonically normalised field χ

$$\frac{d\chi}{d\phi} = M_P \sqrt{\frac{f(\phi) + 3f(\phi)'^2}{2f(\phi)^2}}$$

Scalar potential $U(\phi)$

- Since we live in the minimum with non-zero Planck scale: $\phi = \varphi + v_\phi$. Moreover during inflation $\eta = 0 \rightarrow$ back to this point later.

$$\left.\begin{aligned} V(\varphi) &= \lambda_\phi \left(\varphi + v_\phi\right)^4 \\ f(\varphi) &= \tfrac{1}{2}(\varphi + v_\phi)^2 \end{aligned}\right\} \Rightarrow \boxed{U = \frac{1}{4}\lambda_\phi \frac{M_P^4}{\xi_\phi^2}}$$

- Slow-roll parameters

$$\epsilon = \frac{M_P^2}{2}\left(\frac{U'}{U}\frac{1}{d\chi/d\varphi}\right)^2$$

$$\eta = \frac{M_P^2}{U}\frac{d^2U}{d\chi^2} = \frac{M_P^2}{U}\left[U''\left(\frac{d\chi}{d\varphi}\right) - U'\left(\frac{d\chi}{d\varphi}\right)'\right] \Big/ \left(\frac{d\chi}{d\varphi}\right)^3$$

- $N = \dfrac{1}{\sqrt{2}M_P}\displaystyle\int_{\varphi_{\text{end}}}^{\varphi^*}\frac{d\varphi}{\sqrt{\epsilon}}$ where $d\varphi = \dfrac{d\chi}{d\chi/d\varphi}$

- now we can apply the recipe given before

Multiple Point Criticality Principle

A generic full classical scale invariant theory implies:

- $V \sim \lambda_{ijkl}\phi_i\phi_j\phi_k\phi_l$
- $\Lambda = 0$

Therefore problems at the minimum:

$$a.\ v_i = 0 \Rightarrow \begin{cases} V(v_i) = 0 \rightarrow \text{ OK: avoid eternal inflation} \\ M_P = 0 \rightarrow \text{ unphysical!} \end{cases}$$

$$b.\ v_i \neq 0 \Rightarrow \begin{cases} V(v_i) \neq 0 \rightarrow \text{ bad: eternal inflation} \\ M_P \neq 0 \rightarrow \text{ physical} \end{cases}$$

Unless we also impose MPCP so that in addition to the trivial solution $v_i = 0$ we also get

$$v_i \neq 0 \Rightarrow \begin{cases} V(v_i) = 0 \rightarrow \text{ OK: avoid eternal inflation} \\ M_P \neq 0 \rightarrow \text{ physical!} \end{cases}$$

Multiple Point Criticality Principle

- Old concept. Used for predicting the Higgs mass from boundary conditions at the Planck scale: $\lambda_H(M_P) = \beta_{\lambda_H}(M_P) = 0$
  C. D. Froggatt, H. B. Nielsen, Phys.Lett. B368 (1996)
- Same idea already applied for Higgs inflation: Haba et al. 1406.0158 (tuning of top mass, scalar singlet and right handed neutrino couplings)
- MPCP is general feature for all full classical scale invariant models of inflation.

MPCP and $U(\phi)$

- full classical scale invariance $\rightarrow U(v_\phi) \sim 0$
- induce the minimum in U via a minimum in λ_ϕ.

$$U = \frac{1}{4}\lambda_\phi \frac{M_P^4}{\xi_\phi^2}$$

Therefore we need to impose:

i. $\lambda_\phi(v_\phi) = 0 \rightarrow$ ensure a small vacuum energy after inflation (condition on the RGE of λ_ϕ)

ii. $\lambda'_\phi(v_\phi) = 0 \rightarrow$ minimum of $\lambda \Rightarrow$ minimum of U (condition on the RGE of $\lambda_{\phi\eta}$ and y_ϕ: N contribution crucial!)

RGEs

From R. N. Lerner, J. McDonald, Phys.Rev.D80:123507, 2009

In can be shown that the commutation relation for an arbitrary scalar ϕ

$$\begin{aligned}\pi &= \frac{\partial L}{\partial \dot{\phi}} = \sqrt{-\tilde{g}} \left(\frac{d\chi}{d\phi}\right)^2 \eta_\mu \tilde{g}^{\mu\nu} \tilde{\partial}_\nu \phi \\ [\phi(\vec{x}), \pi(\vec{y})] &\equiv \Omega^2 \left(\frac{d\chi}{d\phi}\right)^2 \sqrt{-g}\ \left[\phi, \dot{\phi}\right] = i\,\hbar \delta^3(\vec{x} - \vec{y})\end{aligned}$$

This implies that the scalar propagator will be suppressed by a factor $c(\phi) = \frac{1}{\Omega^2 \left(\frac{d\chi}{d\phi}\right)^2}$. In our case

$$c_\varphi = \frac{1 + \frac{\xi_\phi \varphi^2}{M_p^2}}{1 + (6\xi_\phi + 1)\frac{\xi_\phi \varphi^2}{M_p^2}}$$

When calculating the RG equations or Coleman-Weinberg potential, one suppression factor is inserted for each φ propagator in a loop.

RGEs II

At one-loop level, the β-functions for the scalar coupling and the non-minimal coupling of ϕ are given by

$$
\begin{aligned}
16\pi^2\beta_{\lambda_\phi} &= 18c_\varphi^2\lambda_\phi^2 + \frac{1}{2}\lambda_{\phi\eta}^2 + 16c_\varphi\lambda_\phi y_\phi^2 - 64y_\phi^4 \\
16\pi^2\beta_{\lambda_\eta} &= 18\lambda_\eta^2 + \frac{1}{2}c_\varphi^2\lambda_{\phi\eta}^2 + 16\lambda_\eta y_\eta^2 - 64y_\eta^4 \\
16\pi^2\beta_{\lambda_{\phi\eta}} &= 4c_\varphi\lambda_{\phi\eta}^2 + 6\lambda_{\phi\eta}(c_\varphi^2\lambda_\phi + \lambda_\eta) + 8\lambda_{\phi\eta}(c_\varphi y_\phi^2 + y_\eta^2) - 384y_\phi^2 y_\eta^2 \\
16\pi^2\beta_{y_\phi} &= 16y_\phi(c_\varphi y_\phi^2 + y_\eta^2), \\
16\pi^2\beta_{y_\eta} &= 16y_\eta(c_\varphi y_\phi^2 + y_\eta^2) \\
16\pi^2\beta_{\xi_\phi} &= 6c_\varphi\left(\xi_\phi + \frac{1}{6}\right)\lambda_\phi
\end{aligned}
$$

For numerical purposes

- neglect λ_ϕ in the RGEs
- $\xi_\phi \in [0, 0.0115] \to c_\varphi \simeq 1$

RGEs II

At one-loop level, the β-functions for the scalar coupling and the non-minimal coupling of ϕ are given by

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\begin{aligned}
16\pi^2\beta_{\lambda_\phi} &= \frac{1}{2}\lambda_{\phi\eta}^2 - 64y_\phi^4 \\
16\pi^2\beta_{\lambda_\eta} &= 18\lambda_\eta^2 + \frac{1}{2}\lambda_{\phi\eta}^2 + 16\lambda_\eta y_\eta^2 - 64y_\eta^4 \\
16\pi^2\beta_{\lambda_{\phi\eta}} &= 4\lambda_{\phi\eta}^2 + 6\lambda_{\phi\eta}\lambda_\eta + 8\lambda_{\phi\eta}(y_\phi^2 + y_\eta^2) - 384y_\phi^2 y_\eta^2 \\
16\pi^2\beta_{y_\phi} &= 16y_\phi(y_\phi^2 + y_\eta^2), \\
16\pi^2\beta_{y_\eta} &= 16y_\eta(y_\phi^2 + y_\eta^2) \\
16\pi^2\beta_{\xi_\phi} &= 0
\end{aligned}
$$

For numerical purposes

- neglect λ_ϕ in the RGEs $\Rightarrow \xi_\phi \sim$ constant
- $\xi_\phi \in [0, 0.0115] \to c_\varphi \simeq 1$

Minimum condition

- The β-functions are logarithmic derivatives of couplings: $\beta_{\lambda_i} = \mu \frac{d\lambda_i}{d\mu}$.

- Using $\mu = \phi$:

$$\lambda'_\phi(v_\phi) = \frac{\beta_{\lambda_\phi}(v_\phi)}{\phi} = 0 \quad \Rightarrow \quad \beta_{\lambda_\phi}(v_\phi) = 0 \quad \Rightarrow \boxed{\frac{1}{2}\lambda^2_{\phi\eta} - 64 y^4_\phi \simeq 0}$$

- However this only ensures that $\phi = v_\phi$ is a stationary point. To make it a minimum, we need to impose $\lambda''_\phi(v_\phi) > 0$

$$\lambda''_\phi = \frac{d}{d\mu}\left(\frac{\beta_{\lambda_\phi}}{\mu}\right) = \frac{1}{\mu}\frac{d\beta_{\lambda_\phi}}{d\mu} - \frac{\beta_{\lambda_\phi}}{\mu^2}$$

$$\lambda''_\phi(v_\phi) = \frac{\beta'_{\lambda_\phi}(v_\phi)}{v_\phi} \Rightarrow \dots$$

$$\boxed{\xi_\phi \lambda_{\phi\eta}\left[12\lambda_\eta + (8 - 3\sqrt{2})\lambda_{\phi\eta} - 48(1+\sqrt{2})y^2_\eta\right] > 0}$$

More on the parameters

- $\xi_\phi \in [0, 0.0115] \Rightarrow v_\phi > M_P$
  $\Rightarrow$ we need to assume that quantum gravity is weakly coupled and subdominant

- $0 \leq \lambda_\eta < \frac{2}{3}\pi$ for perturbativity and in order to avoid a VEV for η (DM?).
  λ_η fixed by the constraint on $U(\varphi^*)$.

- $y_\eta = 0$. We wanted η to be a superheavy DM candidate (WIMPZILLA). Unluckily it is too heavy even for a WIMPZILLA. Negligible relic density. (the case $y_\eta \neq 0$ is under study)

- $\lambda_{\phi\eta}$, y_ϕ are fixed via the boundary condition $\lambda_\phi(v_\phi) = \beta_{\lambda_\phi}(v_\phi) = 0$

- $\eta = 0$ during inflation

More on $U(\phi)$

- Einstein frame potential: $U = \frac{1}{4}\lambda_\phi \frac{M_\mathrm{P}^4}{\xi_\phi^2}$
- $m_\phi^2 = U''(v_\phi) = \frac{1}{8}\frac{\lambda_\phi''(v_\phi) M_\mathrm{P}^4}{\xi_\phi^2}$
- $m_\eta^2 = \frac{1}{2}\lambda_{\phi\eta} v_\phi^2 = \frac{1}{2}\lambda_{\phi\eta}\frac{M_\mathrm{P}^2}{\xi_\phi}$
- The slow-roll parameters

$$\epsilon = \frac{\left(\lambda_\phi'\right)^2}{\lambda_\phi^2}\frac{(M_\mathrm{P} + \sqrt{\xi_\phi}\varphi)^2}{2(1+6\xi_\phi)\varphi^2}$$

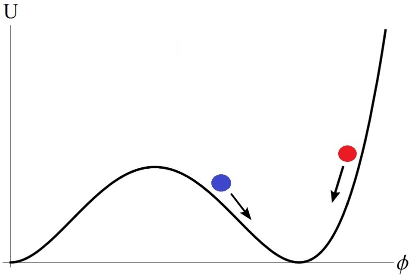
$$\eta = \frac{\xi_\phi(v_\phi + \varphi)[\lambda_\phi' + (v_\phi + \varphi)\lambda_\phi'']}{\lambda_\phi(1+6\xi_\phi)}$$

Shape of potential

$$S = \int d^4x \sqrt{-g}\left[f(\phi)R + \mathcal{L}_{\text{matter}}\right]$$

$$f(\phi) = \frac{\xi_\phi}{2}\phi^2$$

$$\mathcal{L}_{\text{matter}} = \text{ same as before}$$



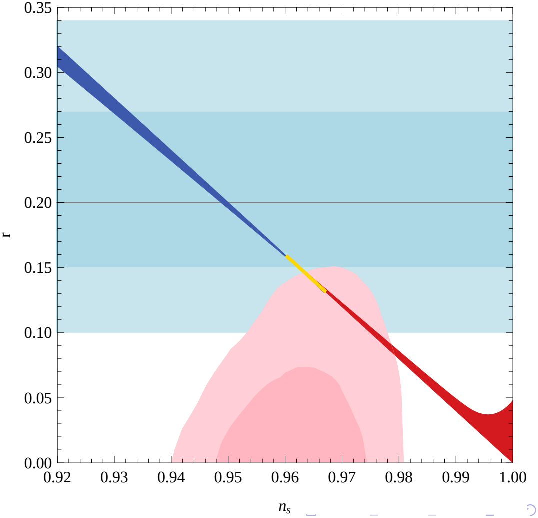
- Such a shape allows for two different, generic types of inflation:
  i. Small-field inflation, when ϕ rolls forward down to v_ϕ: ●
  ii. Large-field (chaotic) inflation, when ϕ rolls back down to v_ϕ: ●

Results

$N \in [50, 60]$

$\xi_\phi \in [0, 0.0115]$

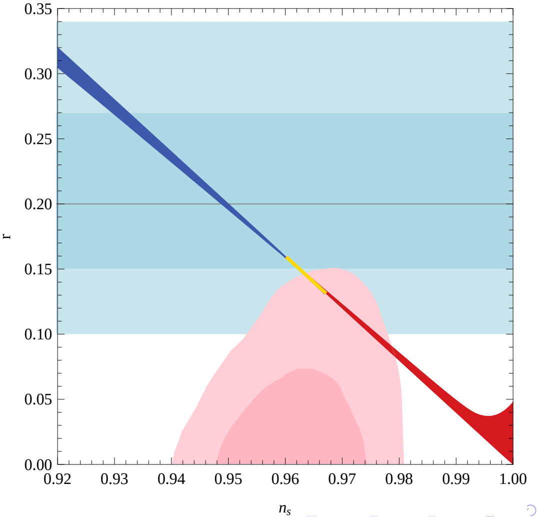
- Planck bound
- BICEP2 bound
- $V = m^2\phi^2$
- large field
- small field



Other results

In the allowed region:

- large field case favoured
- $m_\phi \sim 10^{13}$ GeV
- $\lambda_{\phi\eta} \sim 10^{-4}$
- $\xi_\phi \sim 10^{-3}$
- $m_\eta \sim M_P$
  $\rightarrow \eta = 0$ during inflation
- $T_{RH} \sim 10^{12,13}$ GeV

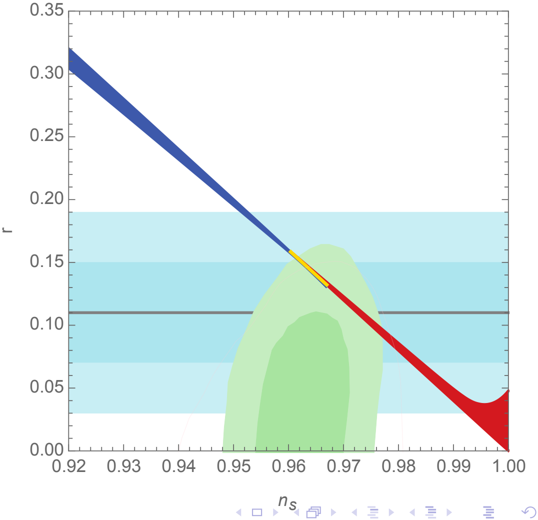


Results and new constraints

$N \in [50, 60]$

$\xi_\phi \in [0, 0.0115]$

- 1409.7870
- 1409.4491
- $V = m^2\phi^2$
- large field
- small field



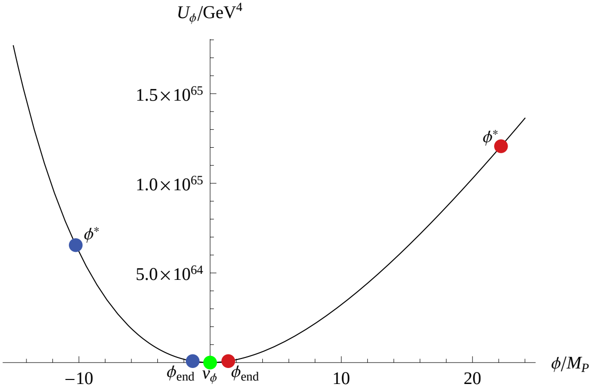
Conclusions

- We constructed a full classical scale invariant model
- MPCP is the guideline to combine full classical scale invariance and inflation
- Found region in agreement with BICEP2 & Planck
- large field case favoured
- Found region in agreement with the new data analysis
- Predictive model that can be confirmed or ruled out

Thank you!

Backup slides

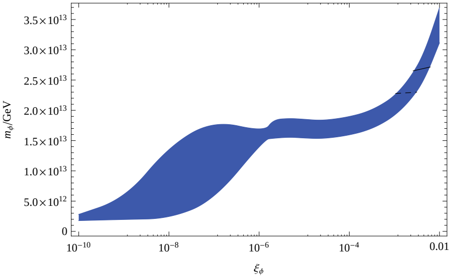
U_ϕ around v_ϕ



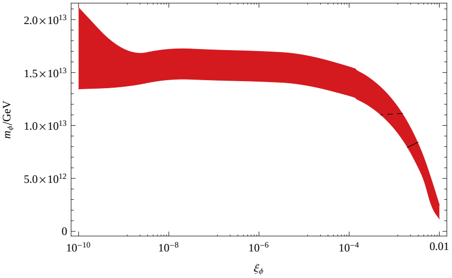
- Around the VEV, we can expand:

$$\lambda_\phi(\phi) = \lambda_\phi(v_\phi) + \lambda'_\phi(v_\phi)(\phi - v_\phi) + \frac{1}{2}\lambda''_\phi(v_\phi)(\phi - v_\phi)^2 + \mathcal{O}(\phi^3)$$

m_ϕ vs ξ_ϕ

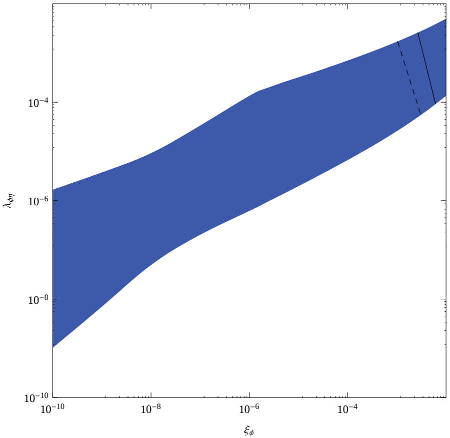


small field

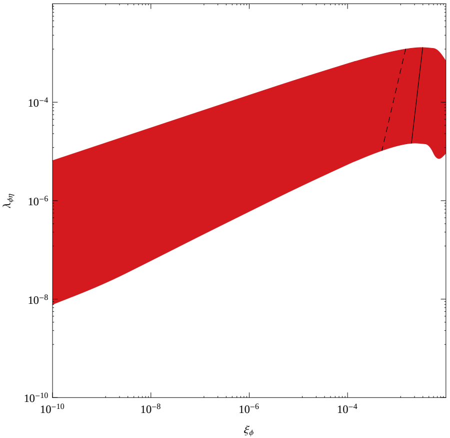


large field

$\lambda_{\phi\eta}$ vs ξ_ϕ

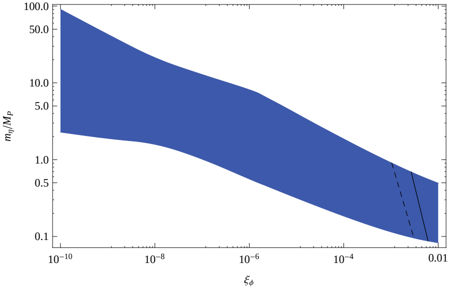


small field

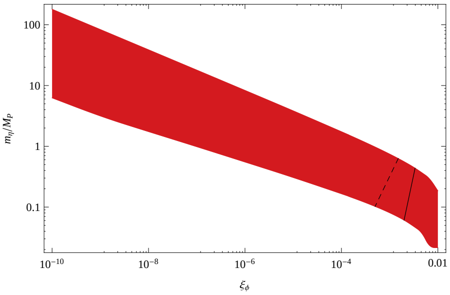


large field

m_η vs ξ_ϕ

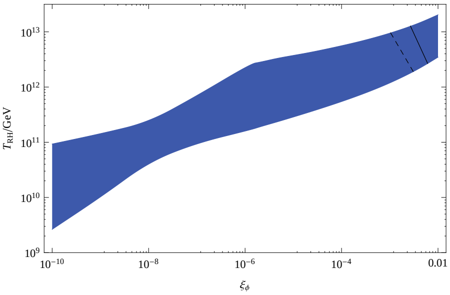


small field

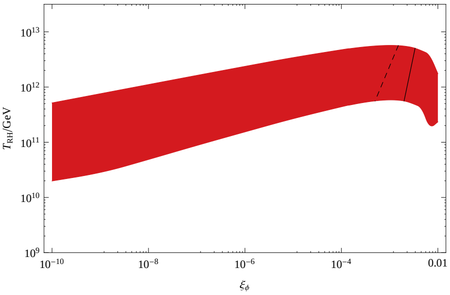


large field

T_{RH} vs ξ_ϕ



small field



large field