# Higgs inflation

Seong Chan Park
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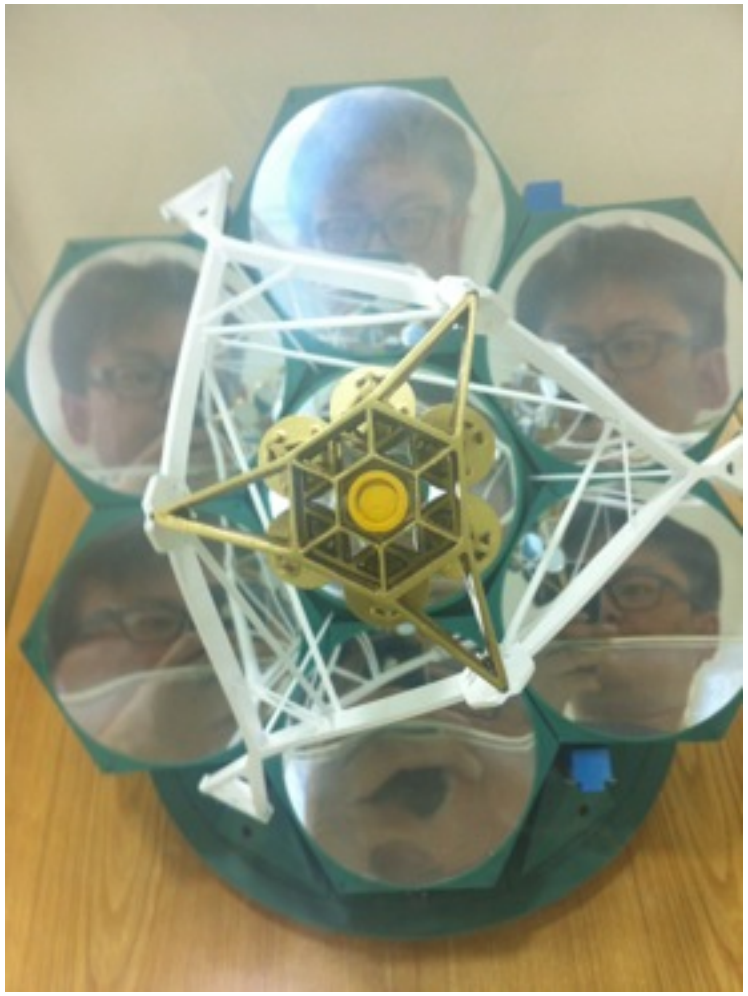
Seminar at KASI, Sep 16, 2014



# Reference

Yuta Hamada, Hikaru Kawai, Kin-ya Oda, and SCP
arXiv:1403.5043, PRL 112 (2014) 241301
& arXiv:1408.4864

http://physics.aps.org/articles/v7/65

Physics
spotlighting exceptional research



# Focus: Theorists Weigh in on BICEP2

Published June 19, 2014 | Physics **7**, 65 (2014) | DOI: 10.1103/Physics.7.65

**Several theorists discuss the next steps for testing inflation theory following the BICEP2 observations of polarization in the cosmic microwave background.**

*Editor's Note: Below, following this article, we provide short explanations of selected BICEP2-related theory papers that are not discussed in the main text.*

The BICEP2 team's detection of polarization features in the cosmic microwave background, reported in *Physical Review Letters*, represents a fundamentally new piece of evidence for inflation, which has been a staple of cosmological theorizing for decades (see 19 June 2014 Viewpoint). Despite some concerns among experts about whether the polarization is truly of cosmological origin, theorists have been considering the next steps. In several other reports in PRL, theorists explain how further observations can test whether BICEP2's reported polarization truly represents a lingering trace of inflation. Their analyses also discuss how such observations can probe differences among the various inflationary scenarios that cosmologists have devised.

How Much Can We Learn about the Physics of Inflation?
Scott Dodelson
Phys. Rev. Lett. **112**, 191301 (2014)
Published May 12, 2014

Inflationary Tensor Perturbations after BICEP2
Jerod Caligiuri and Arthur Kosowsky
Phys. Rev. Lett. **112**, 191302 (2014)
Published May 12, 2014

$\phi^2$ or Not $\phi^2$: Testing the Simplest Inflationary http://physics.aps.org/articles/v7/65

# One of the selected PRL Theory Papers Responding to BICEP2

**Higgs inflation is still alive after the results from BICEP2**
Yuta Hamada, Hikaru Kawai, Kin-ya Oda, and Seong Chan Park, Phys. Rev. Lett. 112 241301 (2014)

Models in which the form of the Higgs potential at energies around $10^{17}$GeV is flat enough to drive slow-roll inflation cannot produce large enough density fluctuations to account for present-day cosmic structure. But a novel coupling of the Higgs field to the Ricci scalar of general relativity leads to an acceptable inflationary cosmology and also produces $r \approx 0.2$.

**“Who cares cosmology?”**

-anonymous particle physicist in 20th century

# “Cosmology and the LHC”?

- Big topic! Lots of possible connections
- Since we don’t know anything from *either* colliders or cosmology/astrophysics about **new physics** near TeV scale, hard to say which ideas are most important

a talk by Matt Reece at US ATLAS meeting, Aug. 4 2014

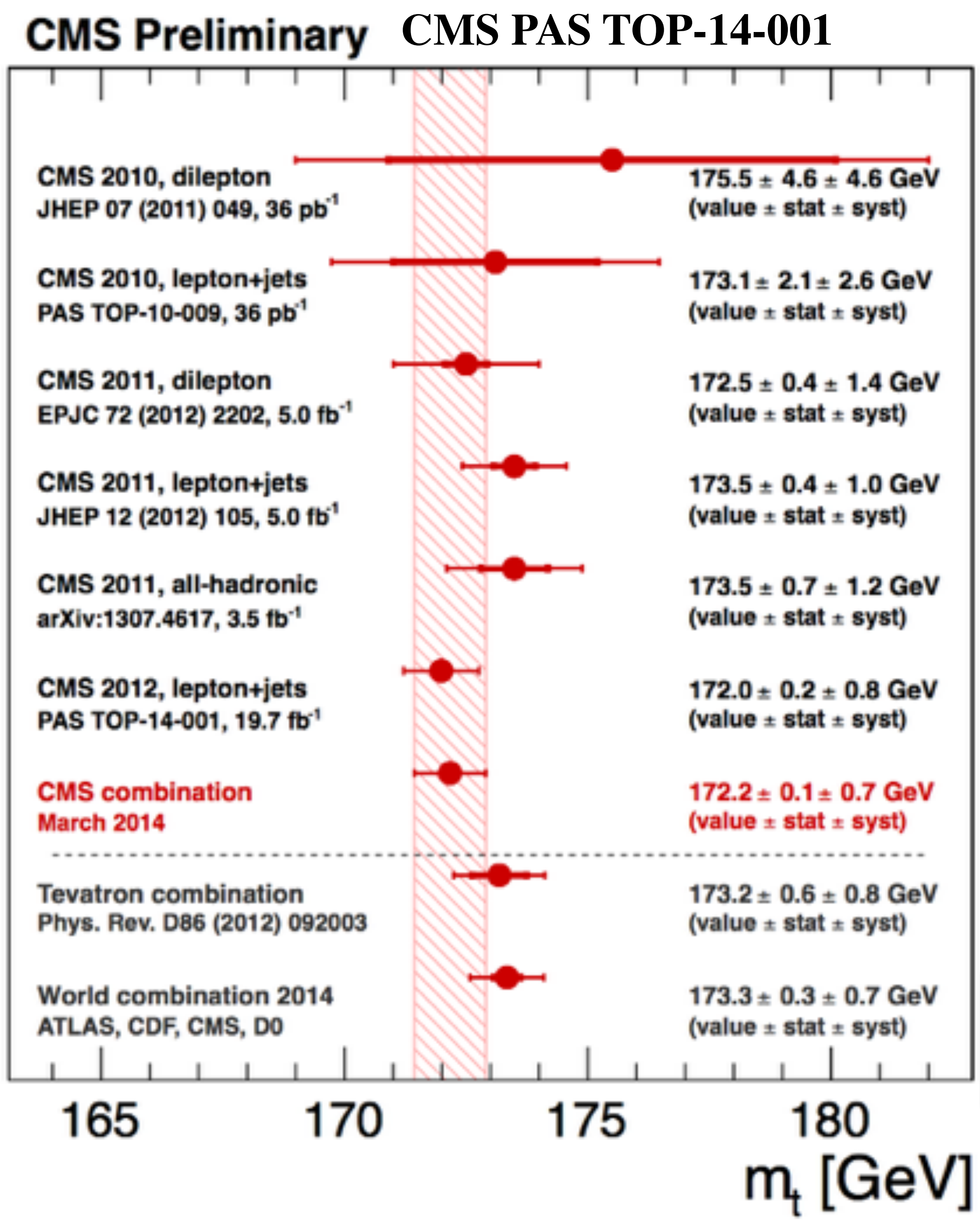
# This Talk

Precise measurement of $M_t$ by cosmological data

$$\Delta m_t \sim \mathcal{O}(1-10)\mathrm{MeV}$$

may be possible in **“Higgs inflation”**

# Current top quark mass measurement




**NEW**

$$172.08 \pm 0.36 \pm 0.83$$

July 2014

[CMS PAS TOP-14-002]

- GeV-sh error
- Question about "pythia mass"

# Higgs inflation

An economical/predictive idea :

**the Higgs = Inflaton**

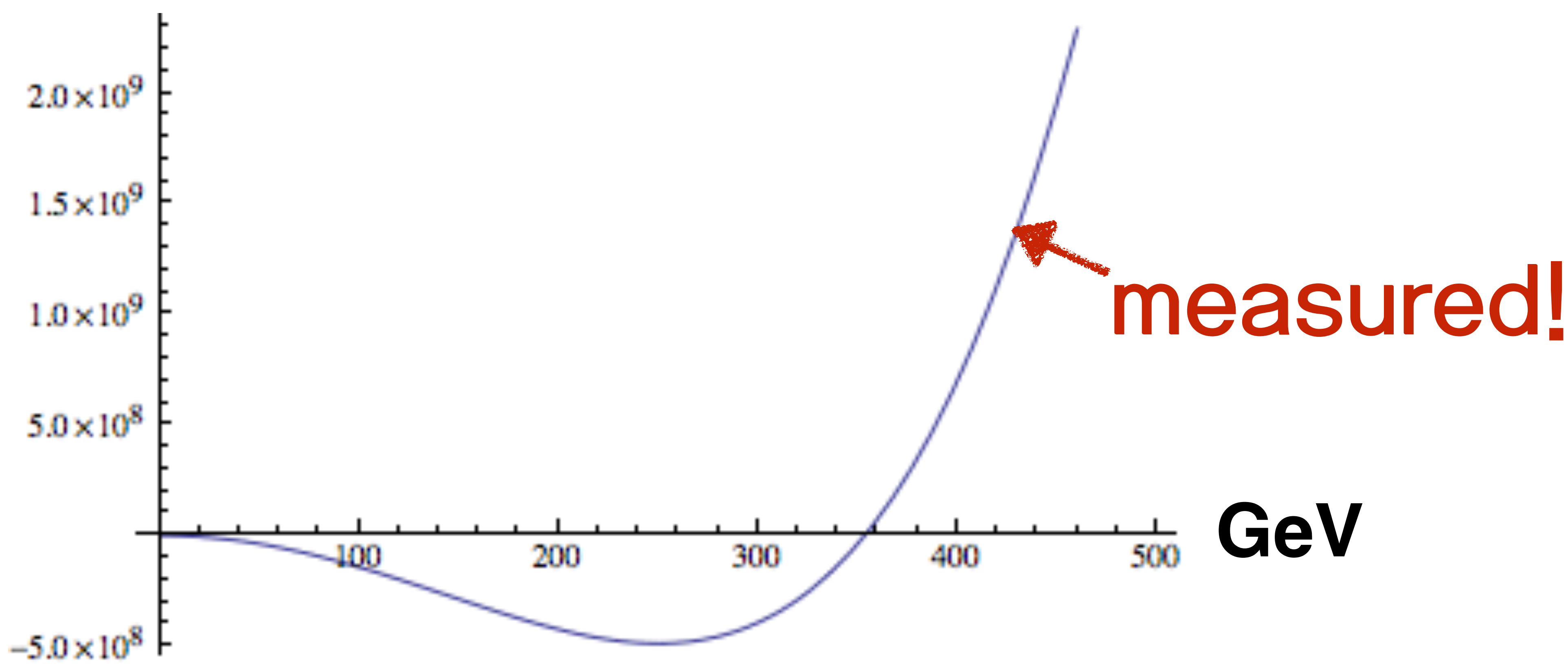
- At low scale (~100 GeV) responsible for **EWSB**
- At high scale (~$10^{16}$ GeV) responsible for **cosmic inflation**

# The inflaton potential =Higgs potential @ high scale

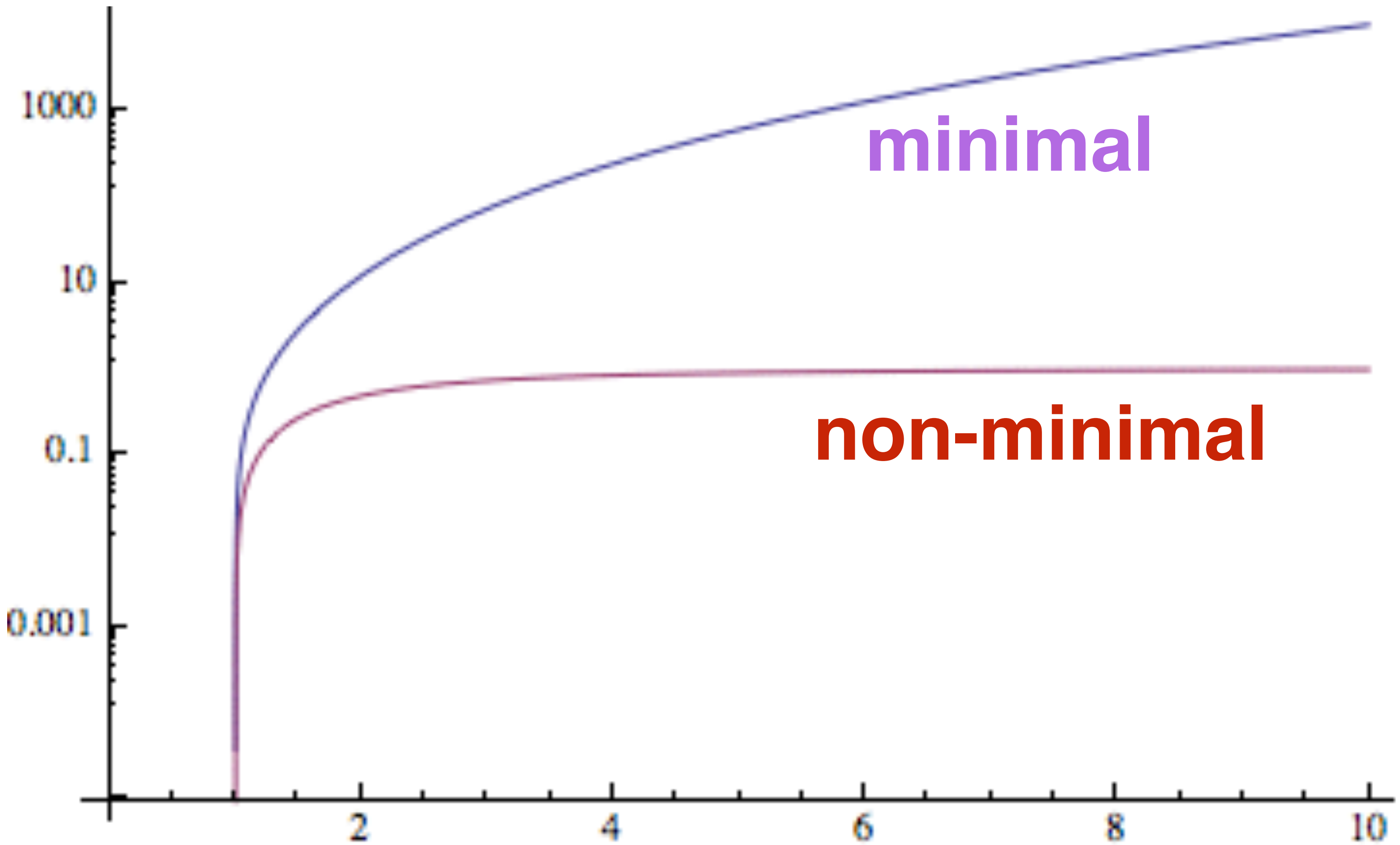
determined by

- Non-minimal coupling ~ $\xi\phi^2 R$
- RGE with low energy data~$m_t, m_h, \alpha_s$

**At the EW scale**, Higgs potential



# At inflaton scale



We can learn about EW scale physics from Cosmology!

# Plan of this talk

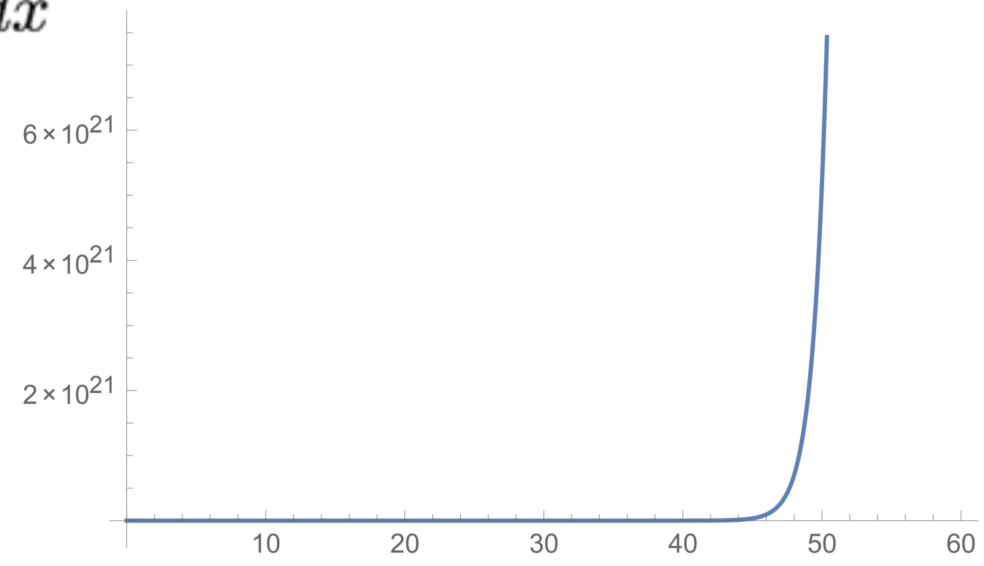
- A short reminder of **cosmological inflation**
- **Basics of Higgs inflation**
- Implications of **BICEP2**
- Conclusion

# Inflation
# :exponential growing of a(t)

scale factor

$$a(t) = a_0 e^{H(t-t_0)}$$

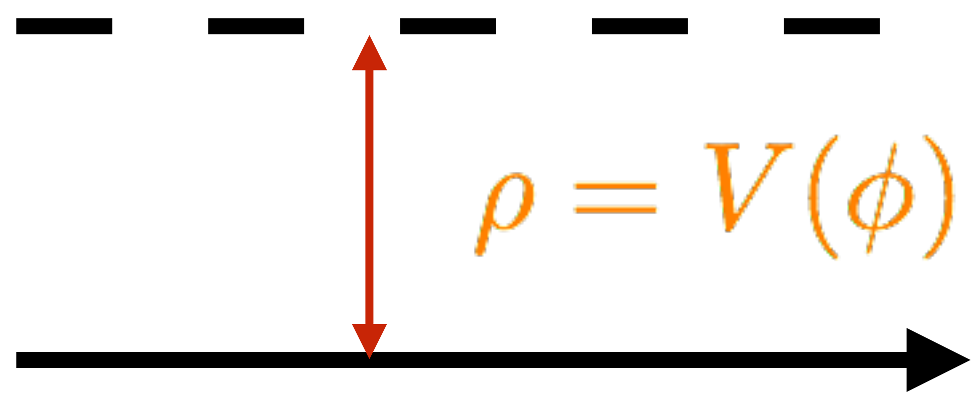
$$ds^2 = dt^2 - \boxed{a(t)^2} d\vec{x} \cdot d\vec{x}$$



# Inflation explains

- Homogeneity, isotropy of **our patch of Universe**
- no monopole, no domain wall, **no unwanted stuffs …**
- **Seed** for structure formation

# Driven by **Inflaton**




"slow-roll potential"

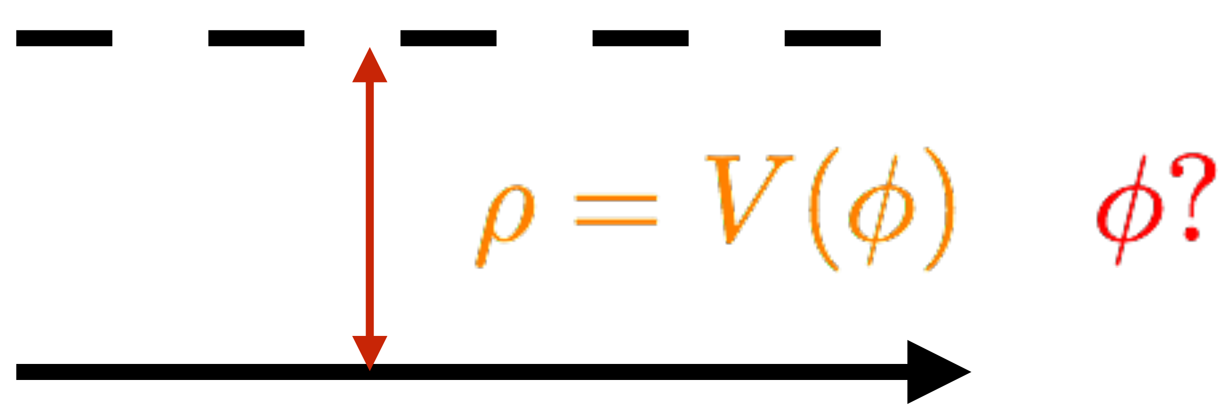
$$(V'/V)^2 \ll 1$$
$$V''/V \ll 1$$

Friedman: $$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_p^2}$$

$$a(\Delta t) = a_0 e^{H\Delta t}$$

60 e-foldings is required

# Candidate of inflaton




| | |
|---|---|
| • Vector? | No! |
| • Spinor? | No! |
| • Scalar? | **Yes!** |
| • Higgs? | **Yes and No. See the next slides.** |

# Higgs in the SM

- A scalar field (s=0) (2,1/2) of $SU(2)_W X U(1)_Y$: "**doublet**"

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- **Tachyonic**, develops non-zero VEV SU(2)XU(1) to $U(1)_{em}$

- **Two free parameters** in the general renormalizable action

$$V(H) = \lambda(|H|^2 - v^2)^2$$

# Higgs in the SM

- W-mass and gauge coupling measurement : vev =246 GeV

- Mass=125.9 GeV from the LHC!

$$v = \frac{2m_W}{g}$$

$$\lambda = \frac{m_H^2}{2v^2} \approx 1/8$$

Now, all the parameters in Higgs sector are experimentally measured!

# The current Higgs mass measurement

$$m_H = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$$

CMS PAS HIG-14-009

$$m_H = 125.36 \pm 0.37(\text{stat.}) \pm 0.18(\text{syst.})\text{GeV}$$

ATLAS arXiv:1406.3827

$$m_H = 125.9 \pm 0.4\text{GeV}$$

PDG new

# Consistent with the SM!

$$\mu = \frac{N_{exp}}{N_{theory}}$$

CMS PAS HIG-14-009

$$\mu = 1.00 \pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo}) \pm 0.07(\text{syst.})$$

# Higgs as Inflaton?

| | |
|---|---|
| **The SM Higgs** | $m_H \approx 125.5\ \mathrm{GeV}, \lambda \sim \mathcal{O}(1)$ |
| **Chaotic inflaton** | $m_\phi \approx 10^{13}\ \mathrm{GeV}, \lambda \sim \mathcal{O}(10^{-12})$ |
| | $\sim m_\phi^2 \phi^2 \qquad \sim \lambda \phi^4$ |

**Looks very different···**

**But!**

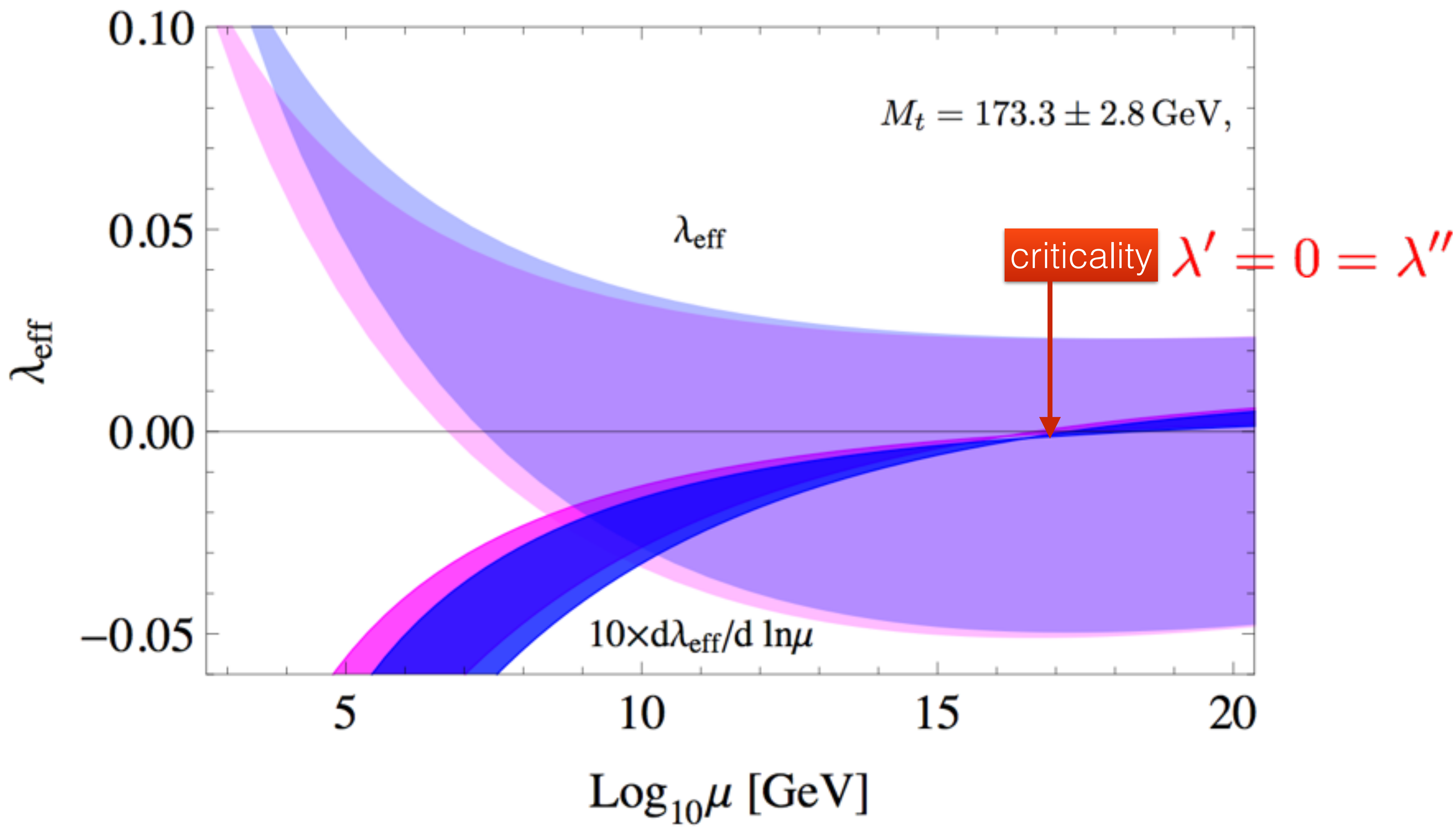
**The Higgs potential becomes flat at high energy by RGE!**

**The SM Higgs**

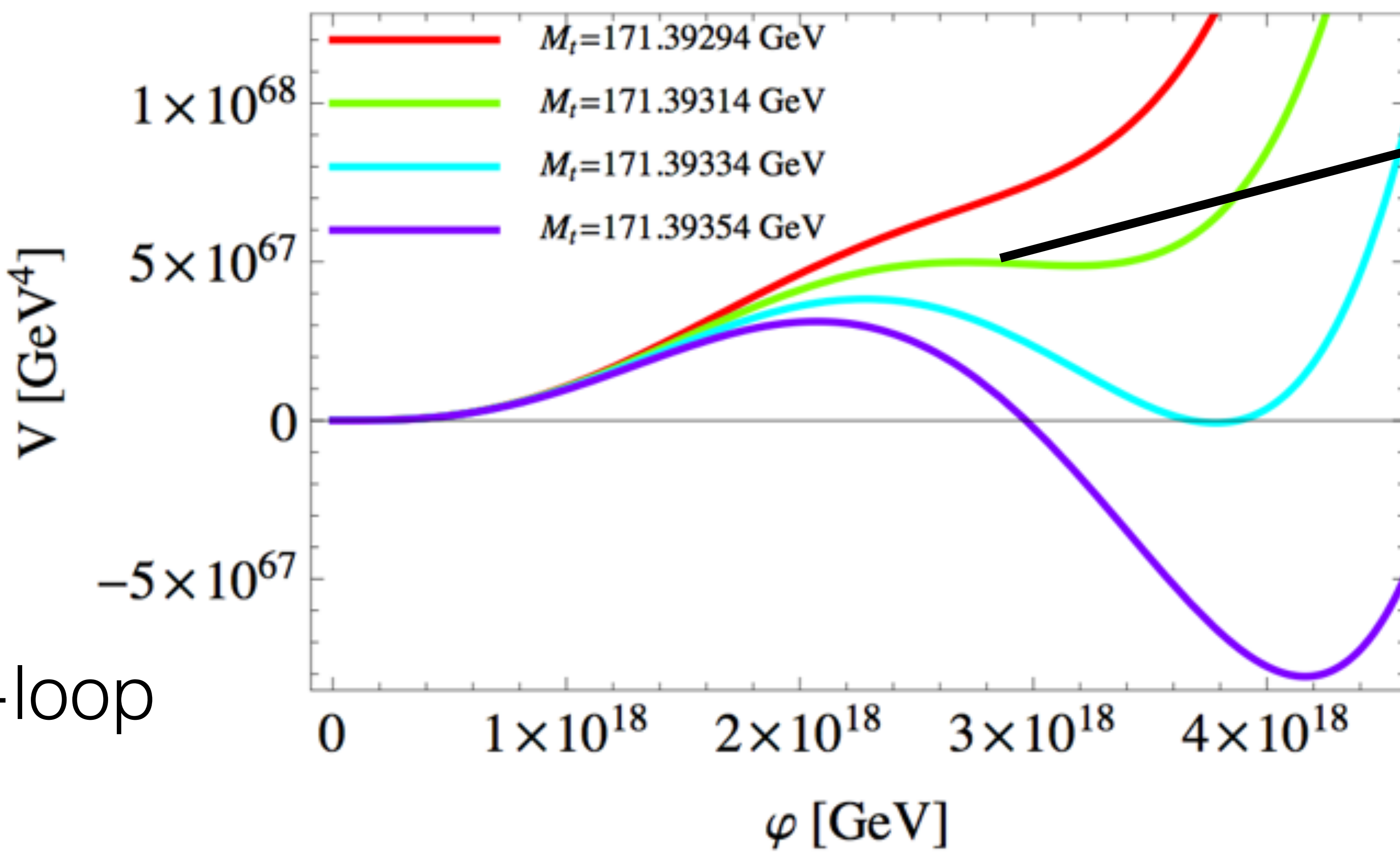
$$\lambda(\mu_{\mathrm{EW}}) \sim \mathcal{O}(1)$$

$$\lambda(\mu_{\mathrm{Inflation}}) \ll \mathcal{O}(1)$$

# 2-loop effective potential



# Criticality of the SM




+loop

**Plateau! This helps.**

# “non-minimal coupling”

$$S_G = \int d^D x \sqrt{g} \frac{M^{D-2} + K(\phi)}{2} R + \mathcal{L}(\phi)$$

- Generically allowed in SUGRA
- Effective theory should have this term as long as

$$[K(\phi)] = [M^{D-2}]$$

# "Inflation by non-minimal couplings"

[SCP, S.Yamaguchi (2008)]

$$S=\int d^4x\sqrt{-g}\left[-\frac{M^2+K(\phi)}{2}R+\frac{1}{2}(\partial\phi)^2-V(\phi)\right]$$

$$g_{\mu\nu}=e^{-2\omega}g^E_{\mu\nu}, \qquad e^{2\omega}:=\frac{M^2+K(\phi)}{M^2_{\rm Pl}}.$$

$$U=\frac{M^4_{\rm Pl}}{(M^2+K(\phi))^2}V(\phi).$$

$$\to M^4_{\rm Pl}\frac{V}{K^2}$$

(ex) monomial

$$K(\phi)=a\phi^m$$

$$V(\phi)=\frac{\lambda}{2m}\phi^{2m}$$

**Thus, as long as $V/K^2$ is asymptotically flat, the slow-roll inflation can take place!**

# This is an interesting topic for model building!

Origin???

$$K(\phi) \sim \sqrt{V}$$

(ex) monomial

$$K(\phi) = a\phi^m$$

$$V(\phi) = \frac{\lambda}{2m}\phi^{2m}$$

**m=2**

$$\phi^2 = HH^\dagger$$

**“Higgs Inflation”**

**[Bezrukov,Shaposhinikov (2008)]**

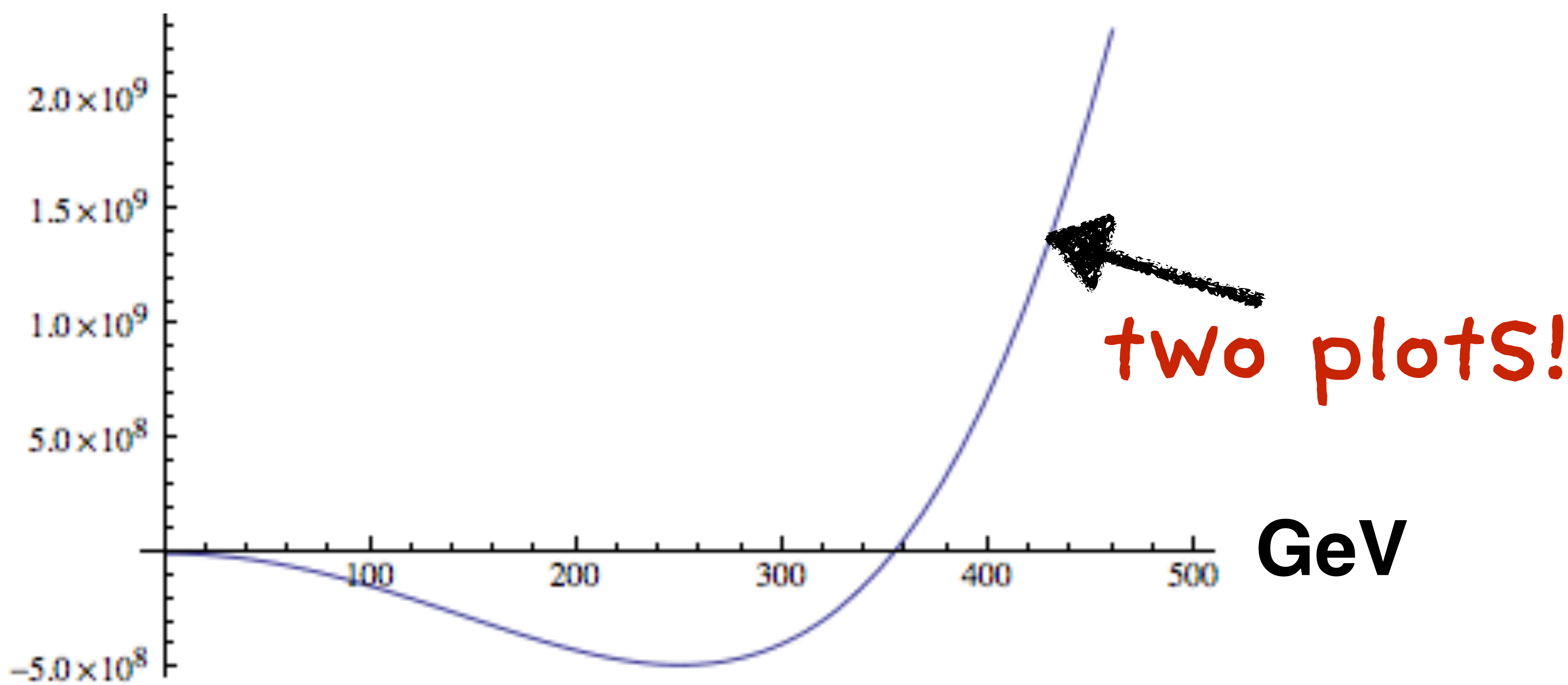
$$K = \xi\phi^2 \qquad V(\phi) \simeq \frac{\lambda(\phi)}{4}\phi^4$$

$$V_E \to \frac{\lambda M_P^4}{4\xi^2} \to const.$$

COBE normalization

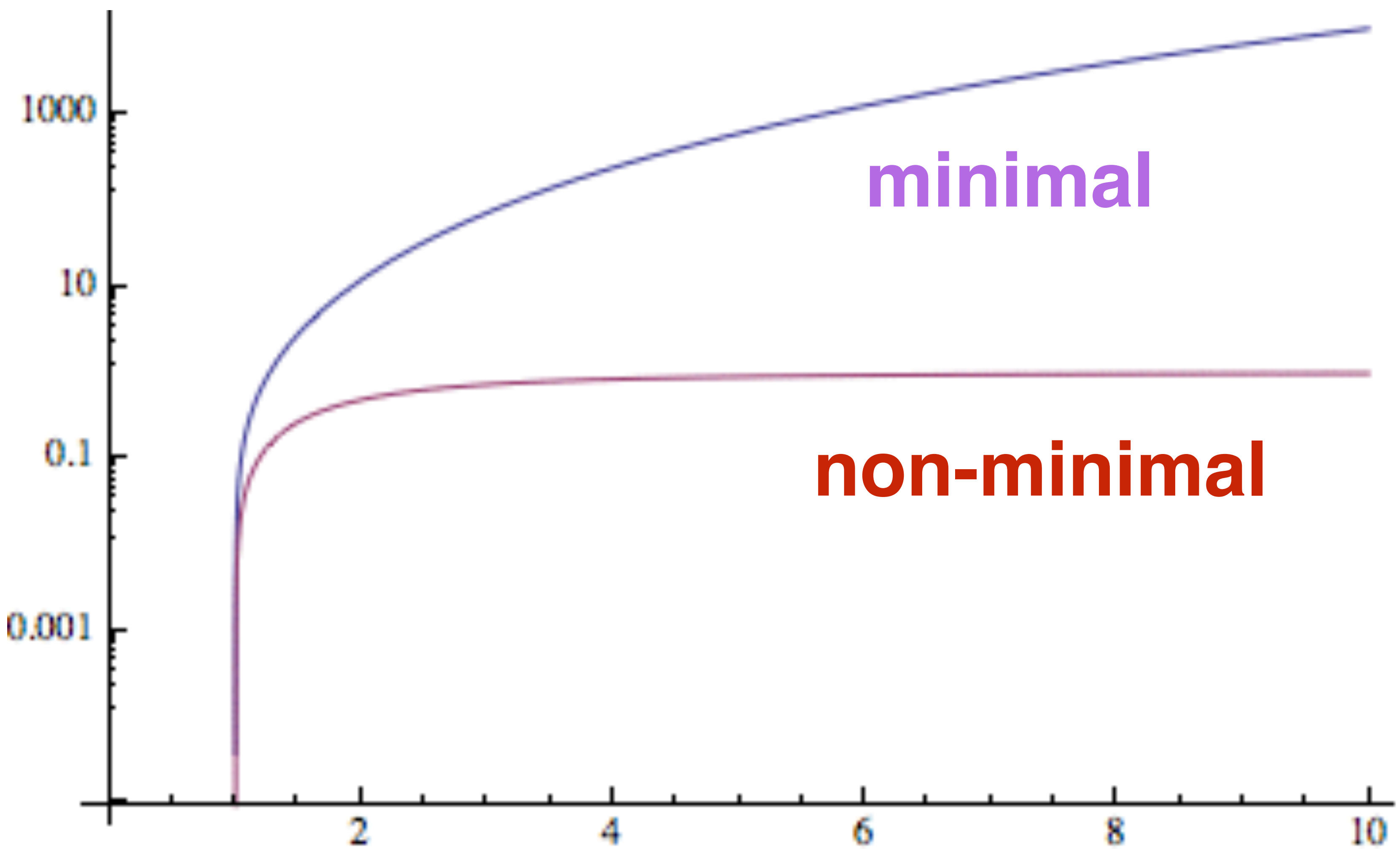
$$\delta\rho/\rho \sim 10^{-5} \Rightarrow \quad \frac{\lambda}{\xi^2} \simeq 10^{-10} \quad \boxed{\xi \simeq 10^5}$$

**At low scale**, Higgs potential
with/without non-minimal coupling term

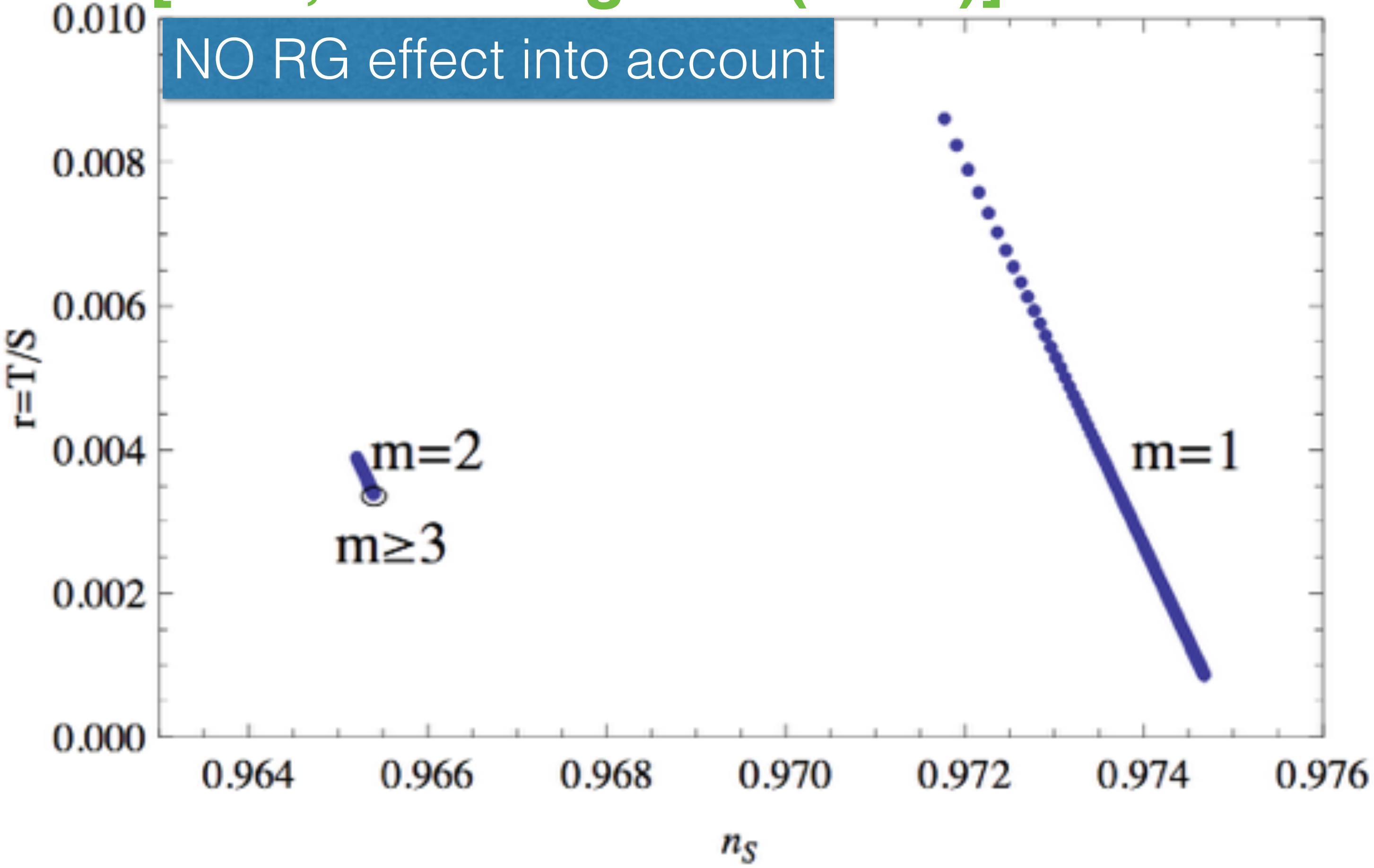



**no difference in low energy!**

## At high scale, they are different!



[SCP, S.Yamaguchi (2008)]




$$K(\phi) = a\phi^m$$

$$V(\phi) = \frac{\lambda}{2m}\phi^{2m}$$

$$V_{Einstein} \sim \frac{V}{K^2}$$

$$n_s = \begin{cases} 1 - \frac{3}{2a_0 N^{3/2}} - \frac{3}{2N}, & (m=1) \\ 1 - \frac{9(1+1/(6a_0))}{2N^2} - \frac{2}{N}, & (m=2) \\ 1 - \frac{9}{2N^2} - \frac{2}{N}, & (m \geq 3) \end{cases}, \qquad r = \begin{cases} \frac{4}{a_0 N^{3/2}}, & (m=1) \\ \frac{12(1+1/(6a_0))}{N^2}, & (m=2) \\ \frac{12}{N^2}, & (m \geq 3) \end{cases}$$

**n is around 0.965**

**r is expected to be 'small' !**

# Higgs inflation=R² inflation

$$\mathcal{L} = \sqrt{g}[R + \xi\phi^2 R - \lambda\phi^4]$$ **"Higgs"**

$$\delta\mathcal{L}/\delta\phi = \sqrt{g}[2\xi\phi R - 4\lambda\phi^3] = 0$$

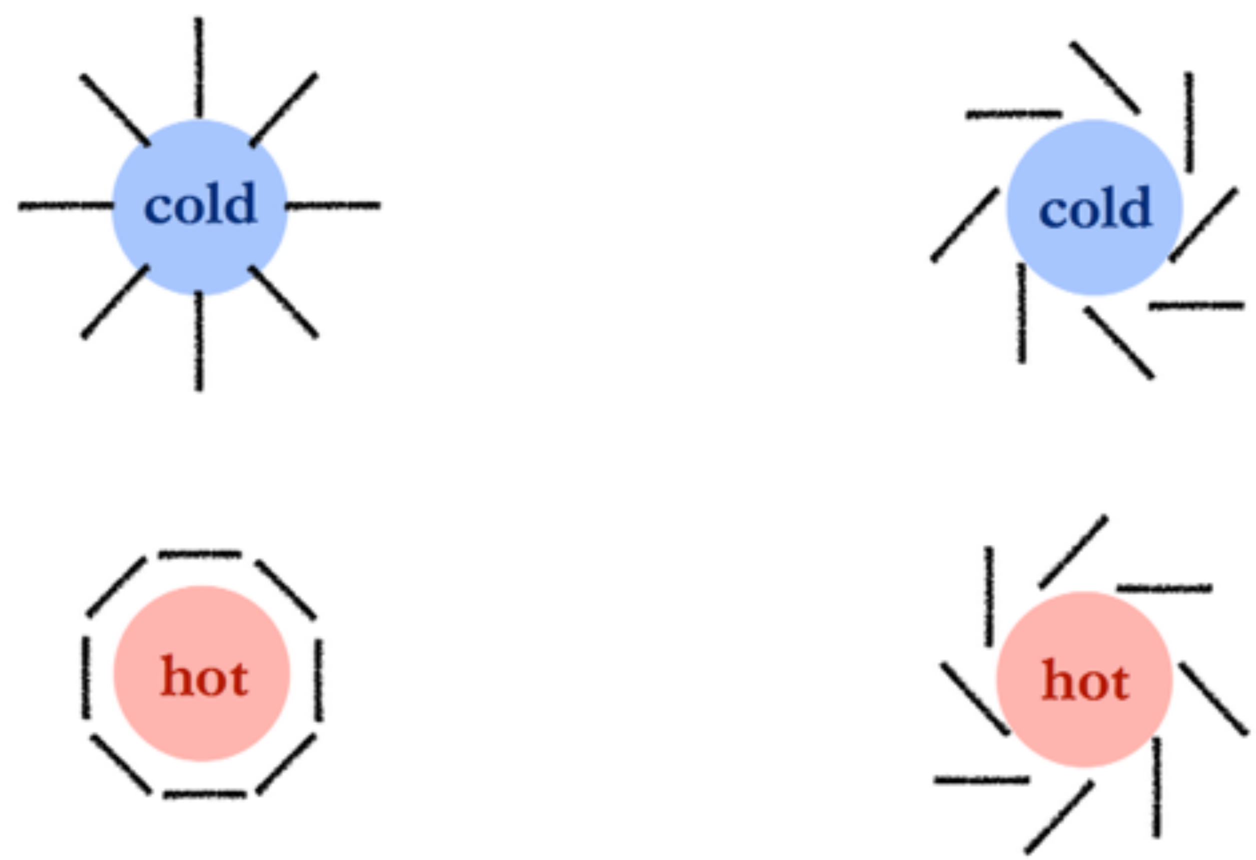
$$\phi^2 = \frac{\xi}{2\lambda}R \qquad \Rightarrow \mathcal{L} = \sqrt{g}[R + \frac{\xi^2}{4\lambda}R^2]$$ **"R2"**

$$\frac{\xi^2}{4\lambda} \approx 10^{10}$$ [COBE]

# BICEP2

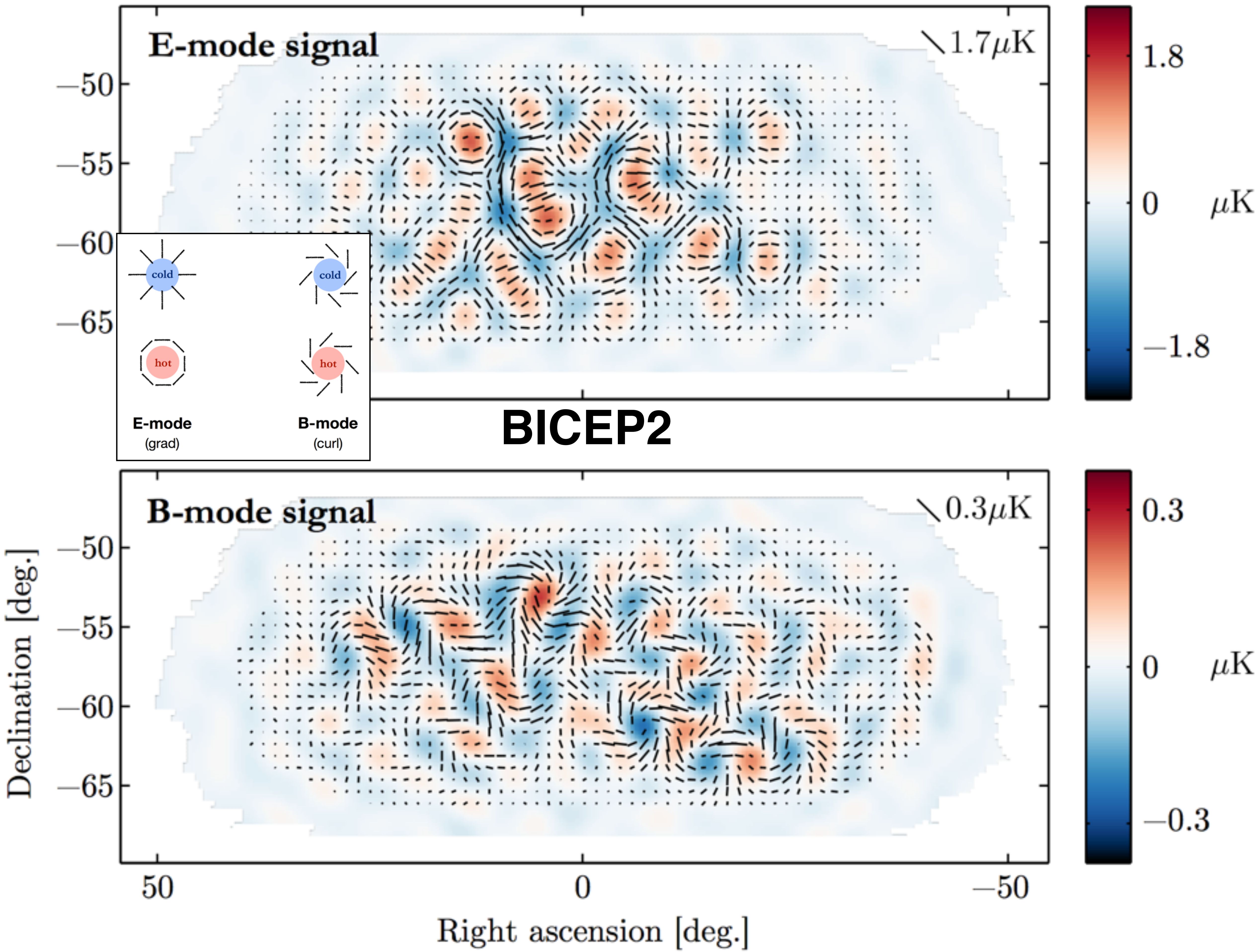
# Helmholtz theorem

$$\vec{C} = -\overset{\text{curl-free}}{\nabla \Phi} + \overset{\text{divergence free}}{\nabla \times \vec{A}}$$




**E-mode**
(grad)

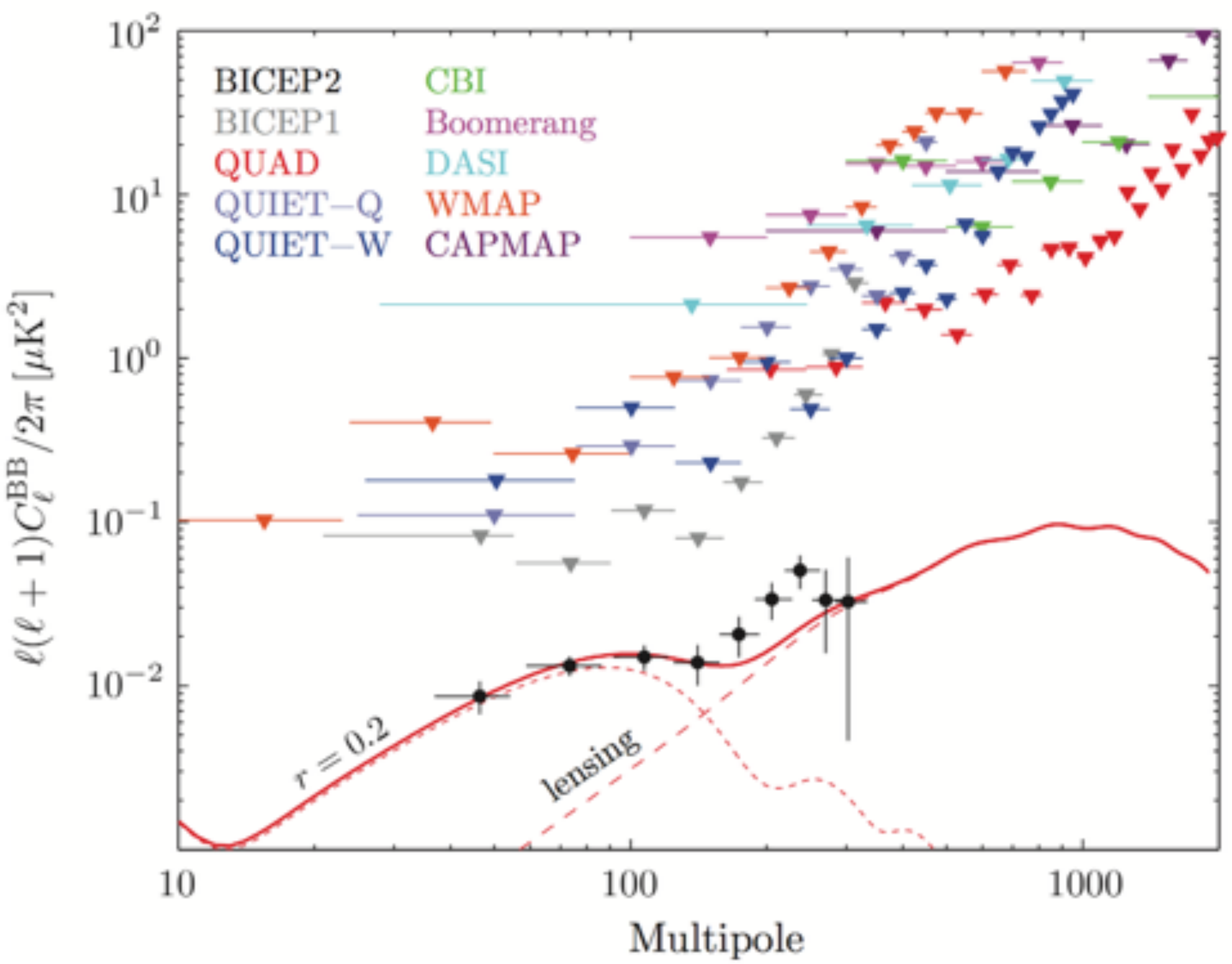
**B-mode**
(curl)



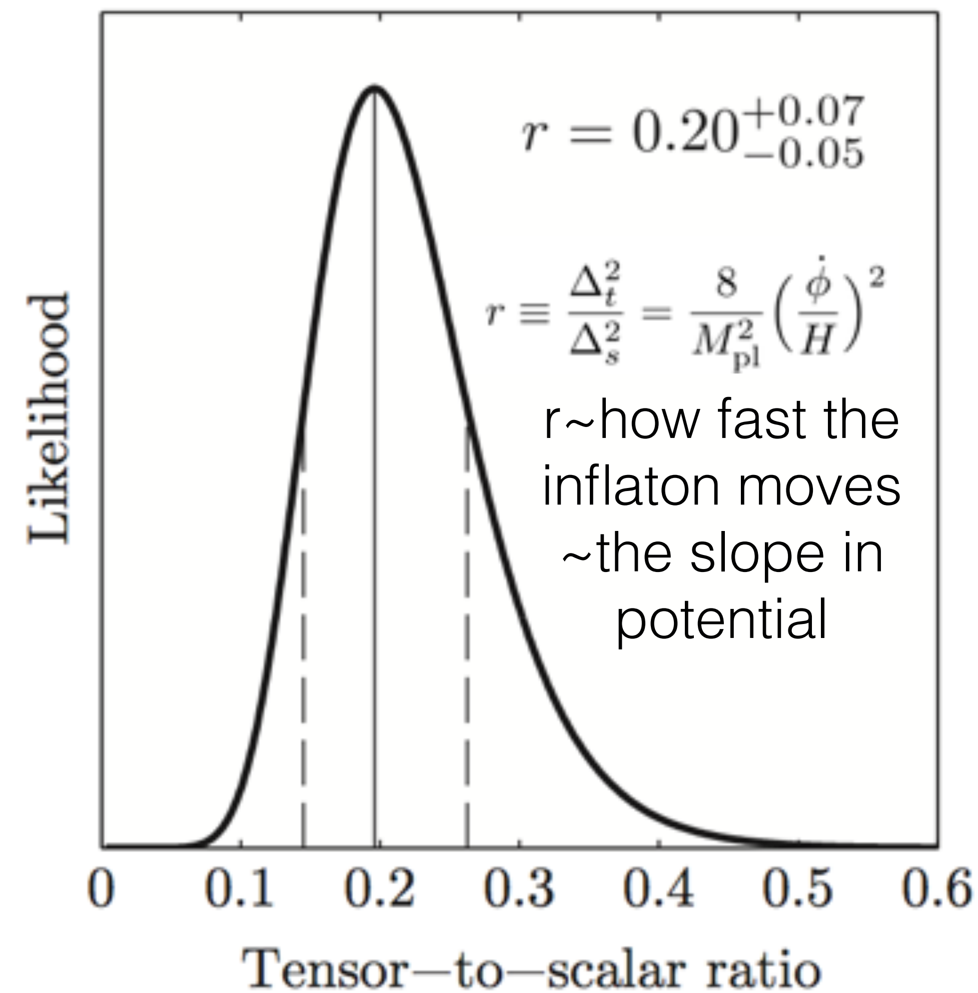
E-mode signal
1.7μK
B-mode signal
0.3μK
cold
hot
E-mode
(grad)
B-mode
(curl)
BICEP2
Declination [deg.]
Right ascension [deg.]
−50
−55
−60
−65
50
0
−50
1.8
0
−1.8
0.3
−0.3
μK

$$\Delta_s^2 \sim H^4/\dot{\phi}^2$$
$$\Delta_t^2 \sim H^2/M_p^2$$

**B-mode Power Spectrum**




**w/o foreground noise**



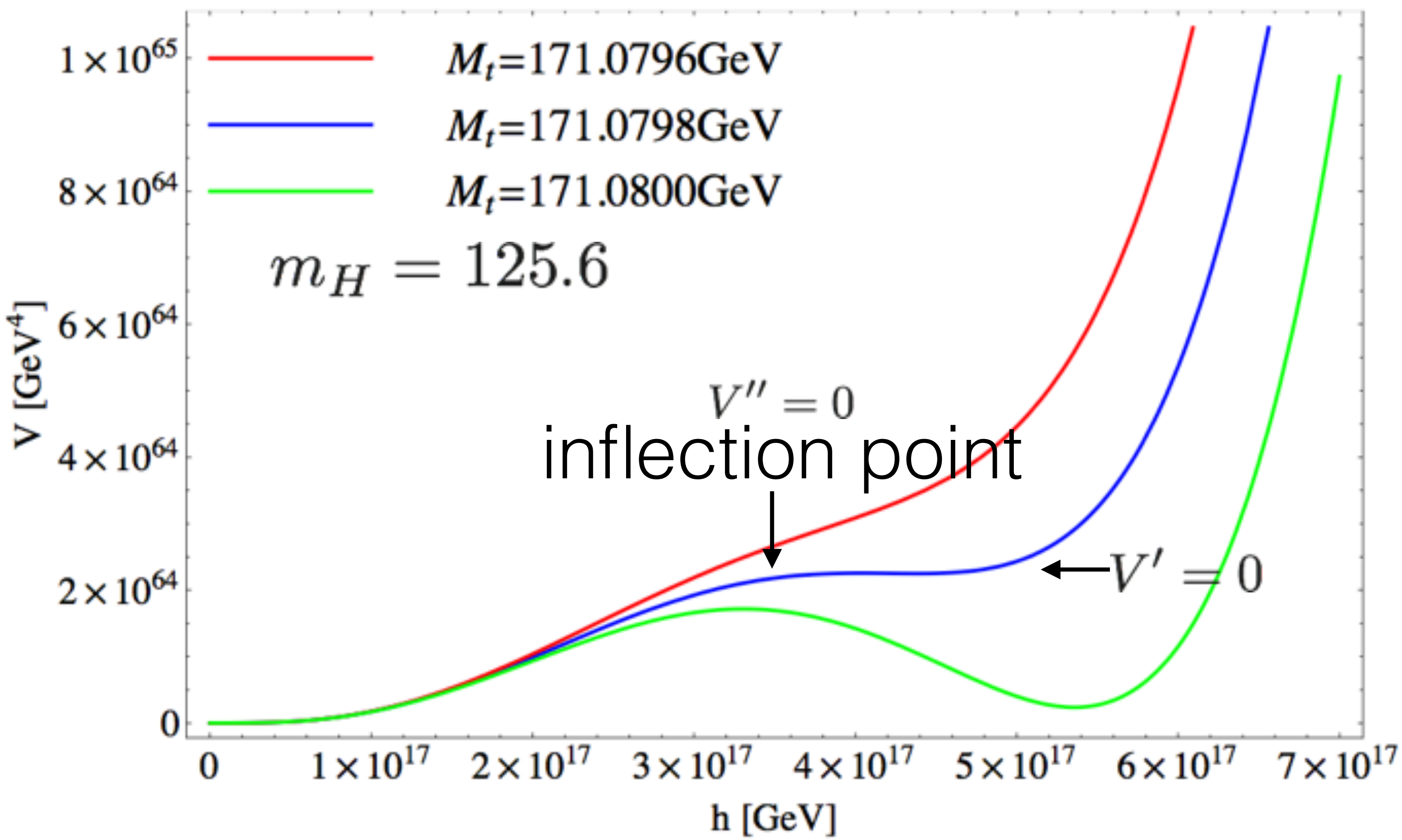
## -Foreground dust must be better understood!

| r | unsubtracted | DDM2 cross | DDM2 auto |
| --- | --- | --- | --- |
| BICEP2 | $0.2^{+0.07}_{-0.05}$ | $0.16^{+0.06}_{-0.05}$ | $0.12^{+0.05}_{-0.04}$ |
| BICEP2×Keck | $0.13^{+0.04}_{-0.03}$ | $0.10^{+0.04}_{-0.03}$ | $0.06^{+0.04}_{-0.03}$ |

1405.7351 by Faluger, Hill and Spergel

## Also, "astro-5 sigmas" often disappear (rate~1/2)

## **RG effects** in the SM Higgs potential




RGE improved n-loop:

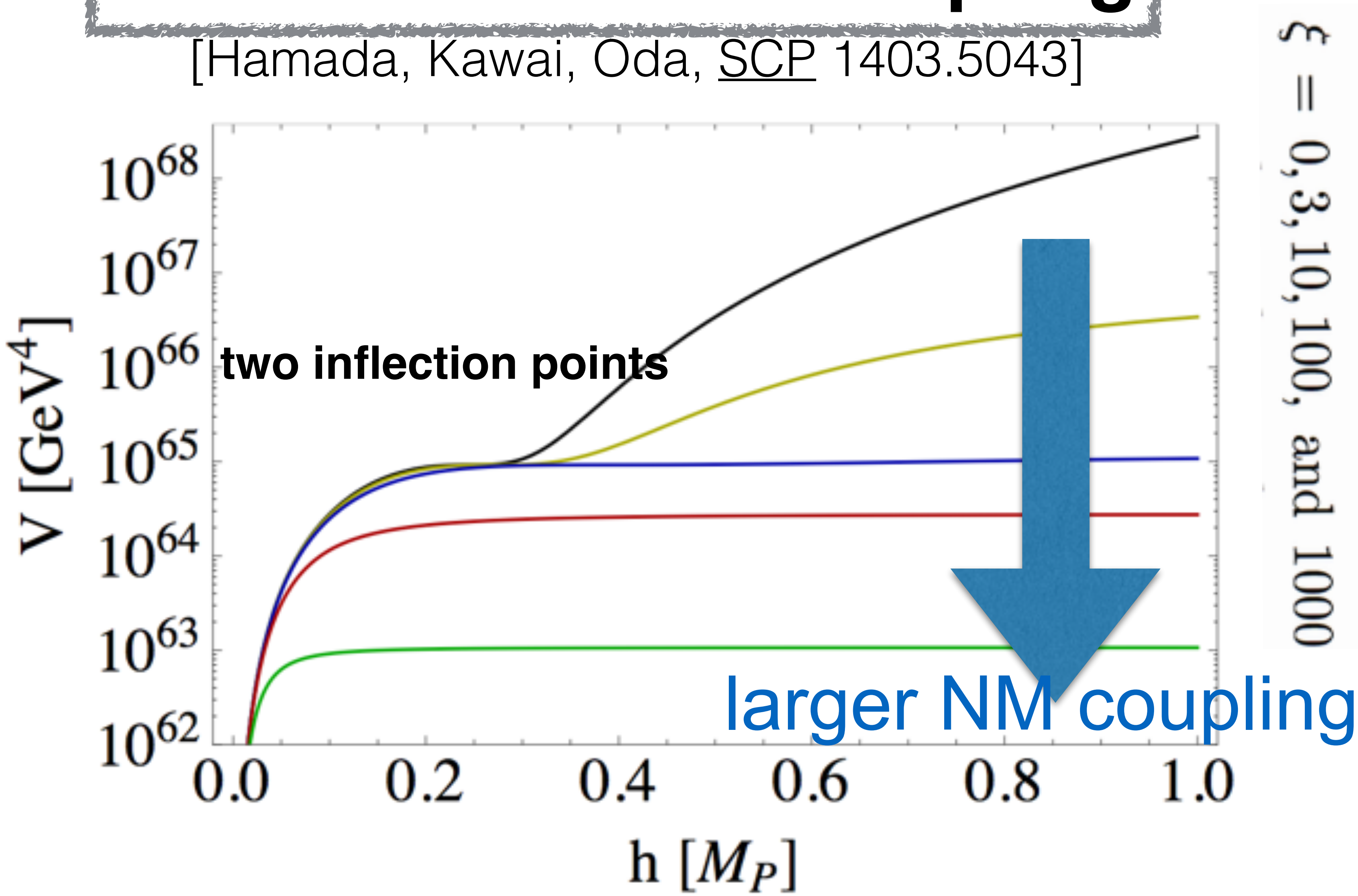
$$\lambda(\mu) = \lambda_{\rm min} + \frac{\beta_2}{(16\pi^2)^2}\left(\ln\frac{\mu}{\mu_{\rm min}}\right)^2 + \frac{\beta_3}{(16\pi^2)^3}\left(\ln\frac{\mu}{\mu_{\rm min}}\right)^3 + \cdots$$

$\mu_{\rm min} \sim 10^{17-18}$ GeV $\qquad \beta_2(SM) \simeq 0.6$

$$\xi(\mu) \simeq \xi_0 + \frac{\beta_{\xi 0}}{16\pi^2}\ln\frac{\mu}{\mu_{\rm min}}, \qquad \beta_{\xi 0} = -\left(\frac{3}{2}g_Y^2 + 3g_2^2 - 6y_t^2\right)\xi\Big|_{\mu=\mu_{\rm min}}$$

# SM+ Non-minimal coupling

[Hamada, Kawai, Oda, SCP 1403.5043]




For the potential $V(\varphi)$ to be monotonically increasing around the inflection point, it is necessary and sufficient that

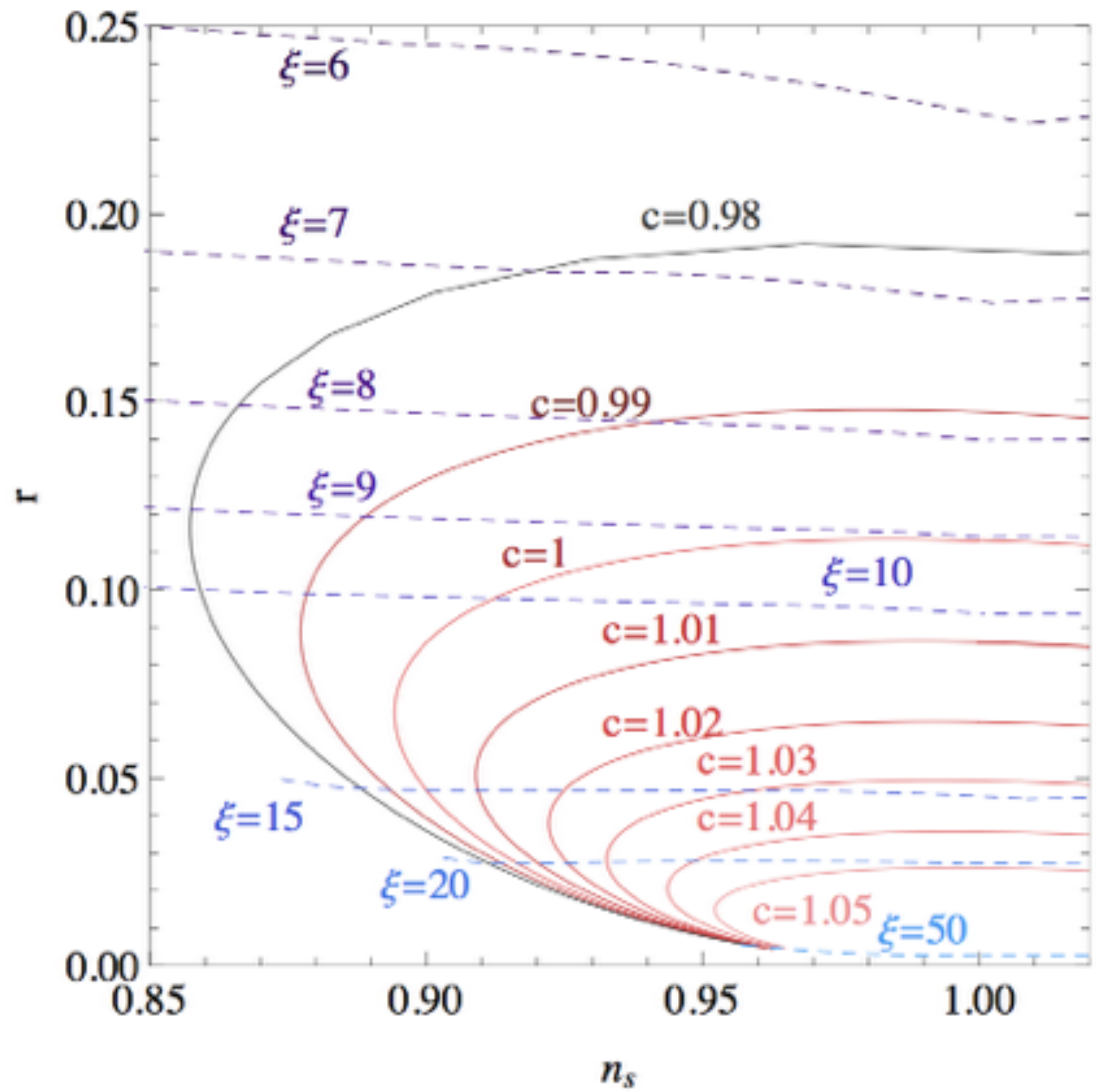
"saddle point"

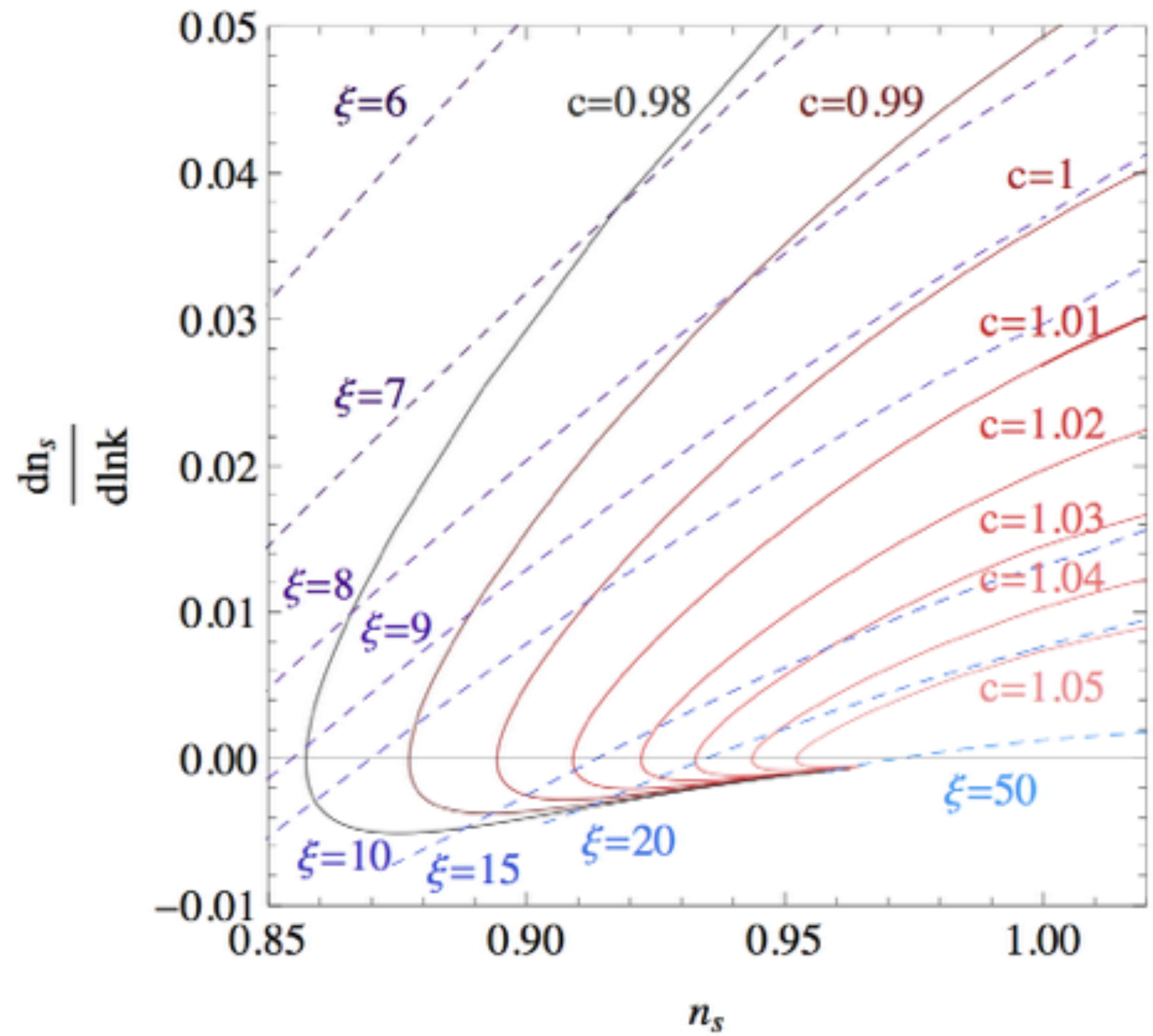
$$\lambda_{\min} \geq \lambda_c := \frac{\beta_2}{(64\pi^2)^2} \sim 10^{-6}. \quad \lambda' = 0 = \lambda'' \quad (5)$$

The equality holds when the potential has a plateau. That is, when we put $\lambda_{\min} = \lambda_c$, the point $\varphi_{\text{inflection}} = e^{-1/4}\mu_{\min} \simeq 0.8\mu_{\min}$ becomes a saddle point with vanishing first and second derivatives.[6]

$e^{-11/12}\mu_{\min}$

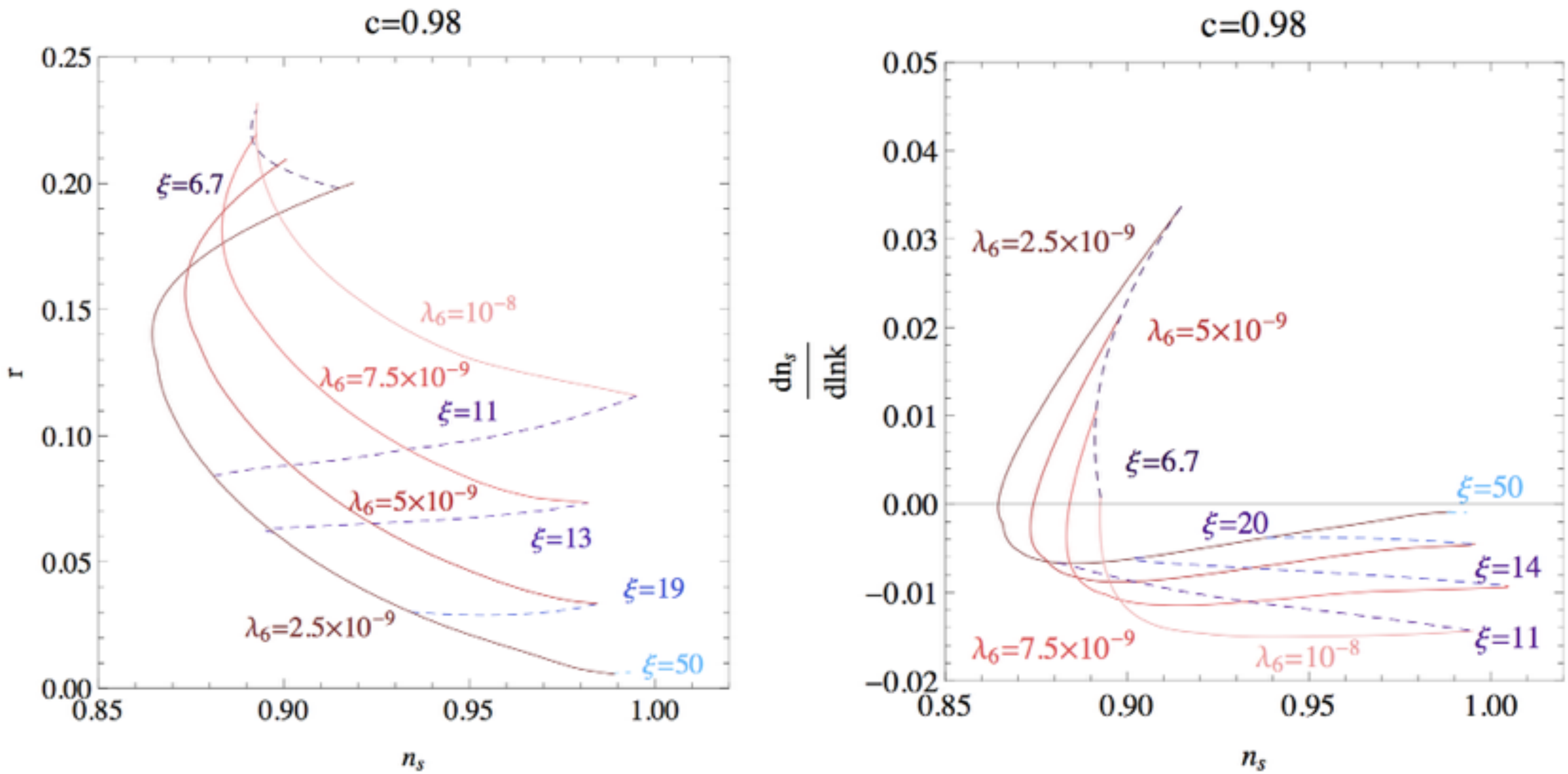
"saddle point" $\lambda_{\min} = \lambda_c := \frac{\beta_2}{(64\pi^2)^2}$



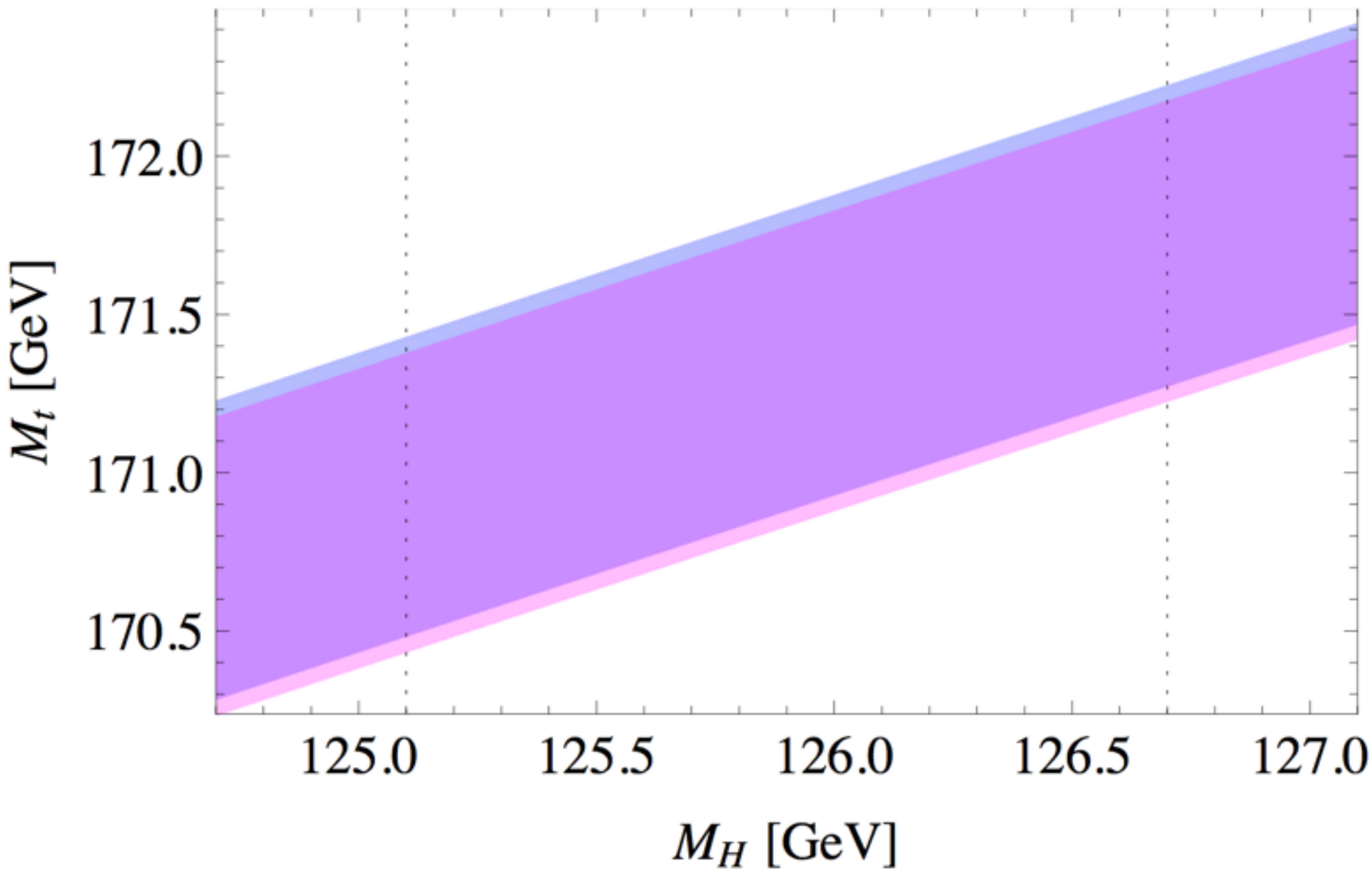

$$\mu_{\min} = c\frac{M_p}{\sqrt{\xi}}$$

$$V(\varphi) = \frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \left(\lambda_6 \frac{\varphi^6}{M_P^2} + \lambda_8 \frac{\varphi^8}{M_P^4} + \cdots\right)$$




$$\mu_{\min} = c\frac{M_p}{\sqrt{\xi}}$$

# $M_{top}$



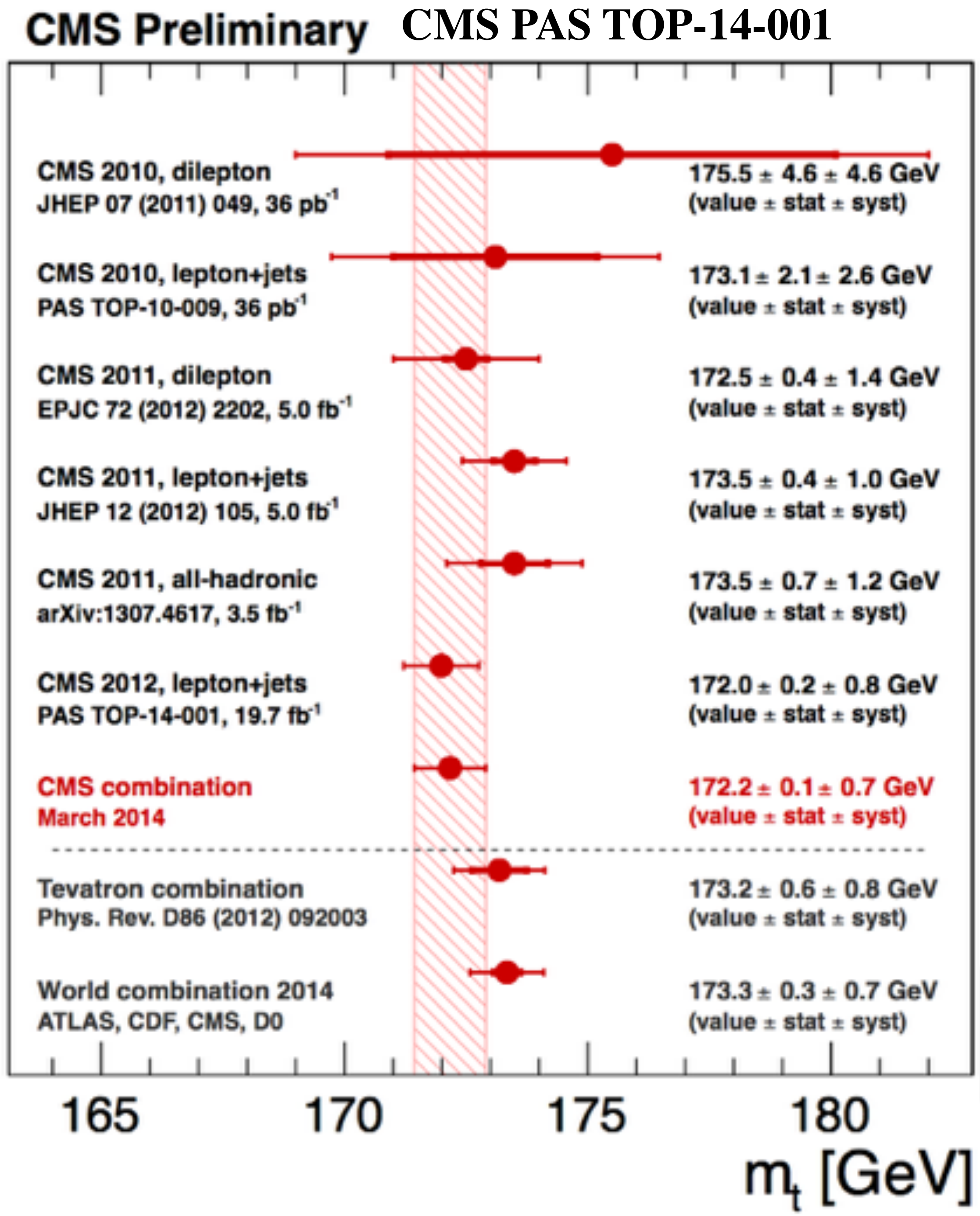
Precise measurement of $M_t$ by cosmological data

$$\Delta m_t \sim \mathcal{O}(1 - 10)\mathrm{MeV}$$

may be possible in **“Higgs inflation”**

# Current top quark mass measurement

CMS PAS TOP-14-001




**NEW**

$$172.08 \pm 0.36 \pm 0.83$$

July 2014

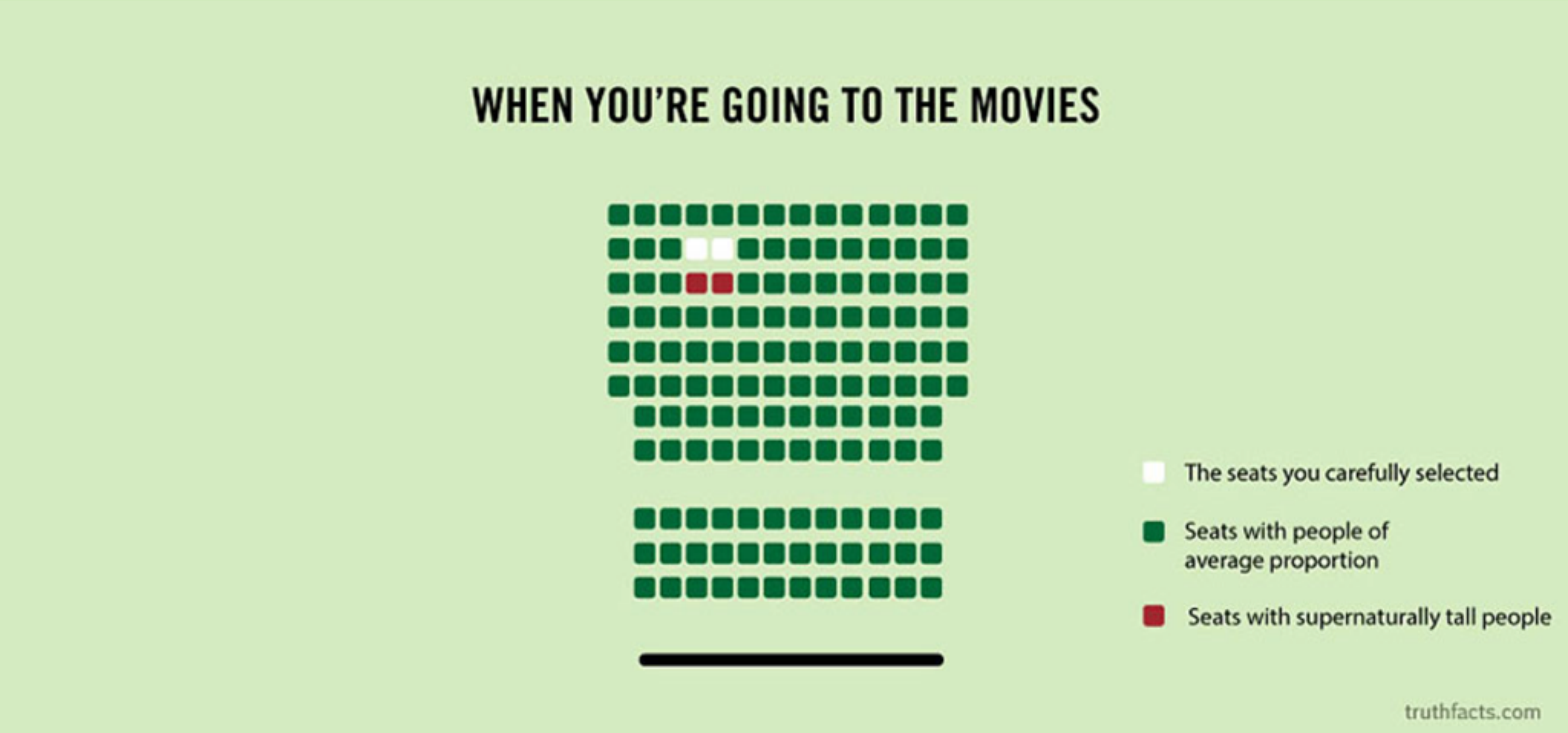
[CMS PAS TOP-14-002]

- GeV-sh error
- Question about “pythia mass”

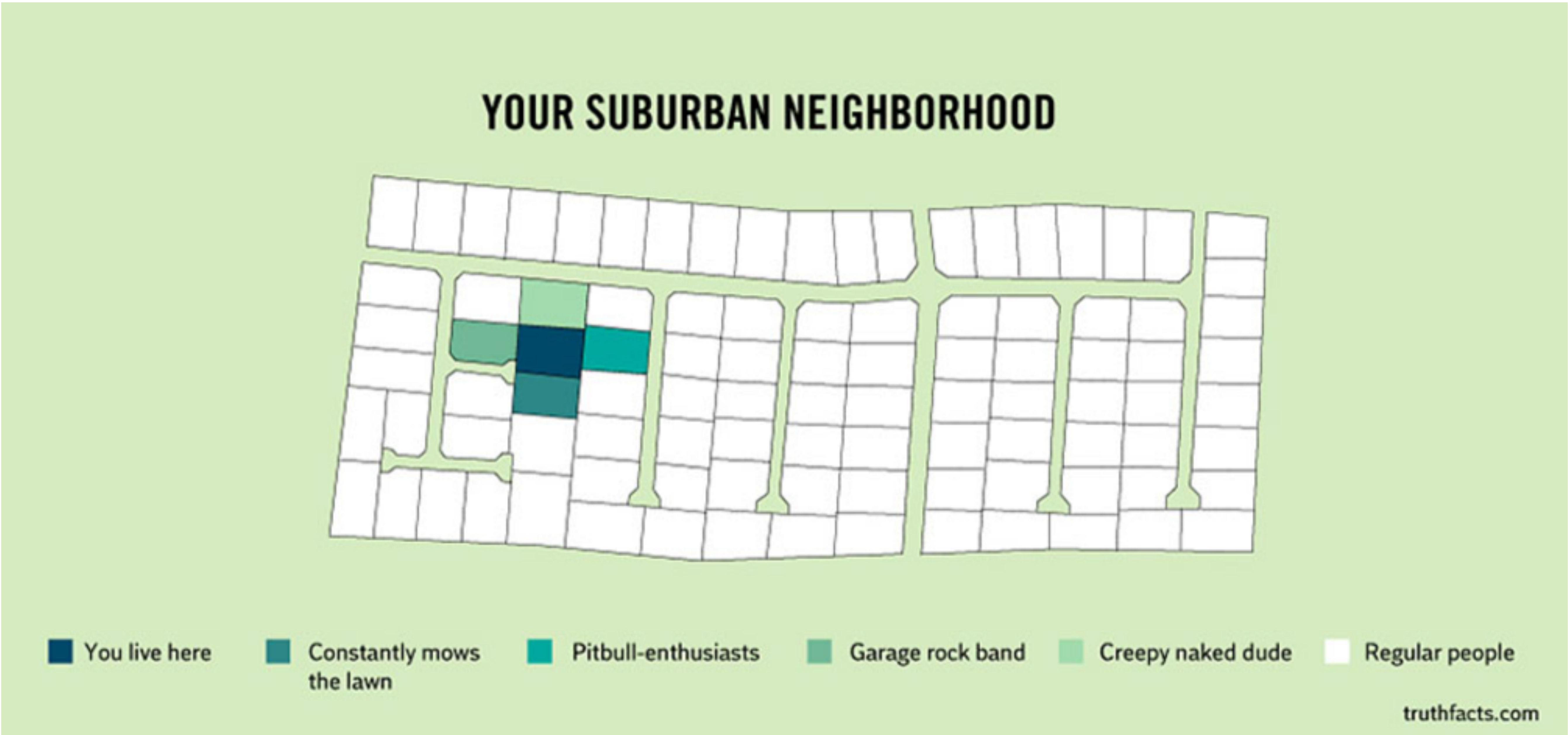
# Do we live near criticality?

Yes! we live near criticality

Yes! we live near criticality



Yes! we live near criticality



# Conclusion

- BICEP2, if confirmed, fantastic!!
- if not, we will learn more about dust as well as B-mode any way.
- Higgs inflation explains the data well (w/ & w/o BICEP).
- If Higgs inflation is true, $M_h$ and $M_t$ can be (best) measured by cosmological data.
- PLANCK and BICEP upgrades(BICEP3, KECK array) result will tell us more on the dust.