Higgs inflation

and precision measurement of M_t

Seong Chan Park
(SKKU & KIAS)

[2nd International Workshop on Particle Physics and Cosmology after Higgs and Planck]
NTHU, Taiwan, Oct 8, 2014

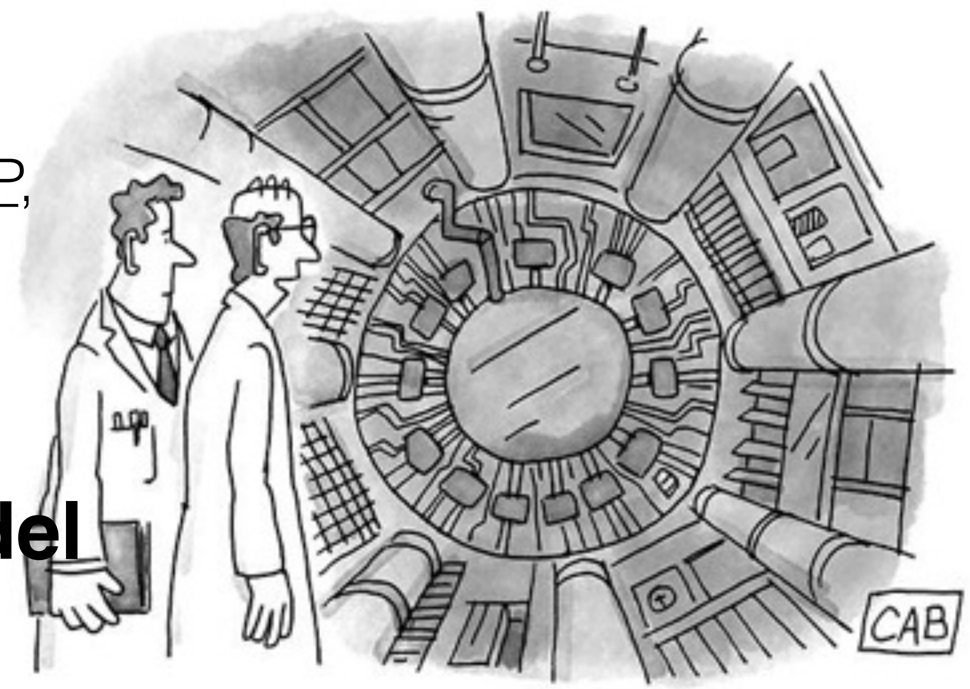
Refs

1. Higgs inflation is still alive

by Yuta Hamada, Hikaru Kawai, Kin-ya Oda, and SCP,
Phys. Rev. Lett. 112 241301 (2014)
arXiv:1403.5043

2. Higgs inflation from Standard Model criticality

by the same authors
arXiv:1408.4864 for full analysis



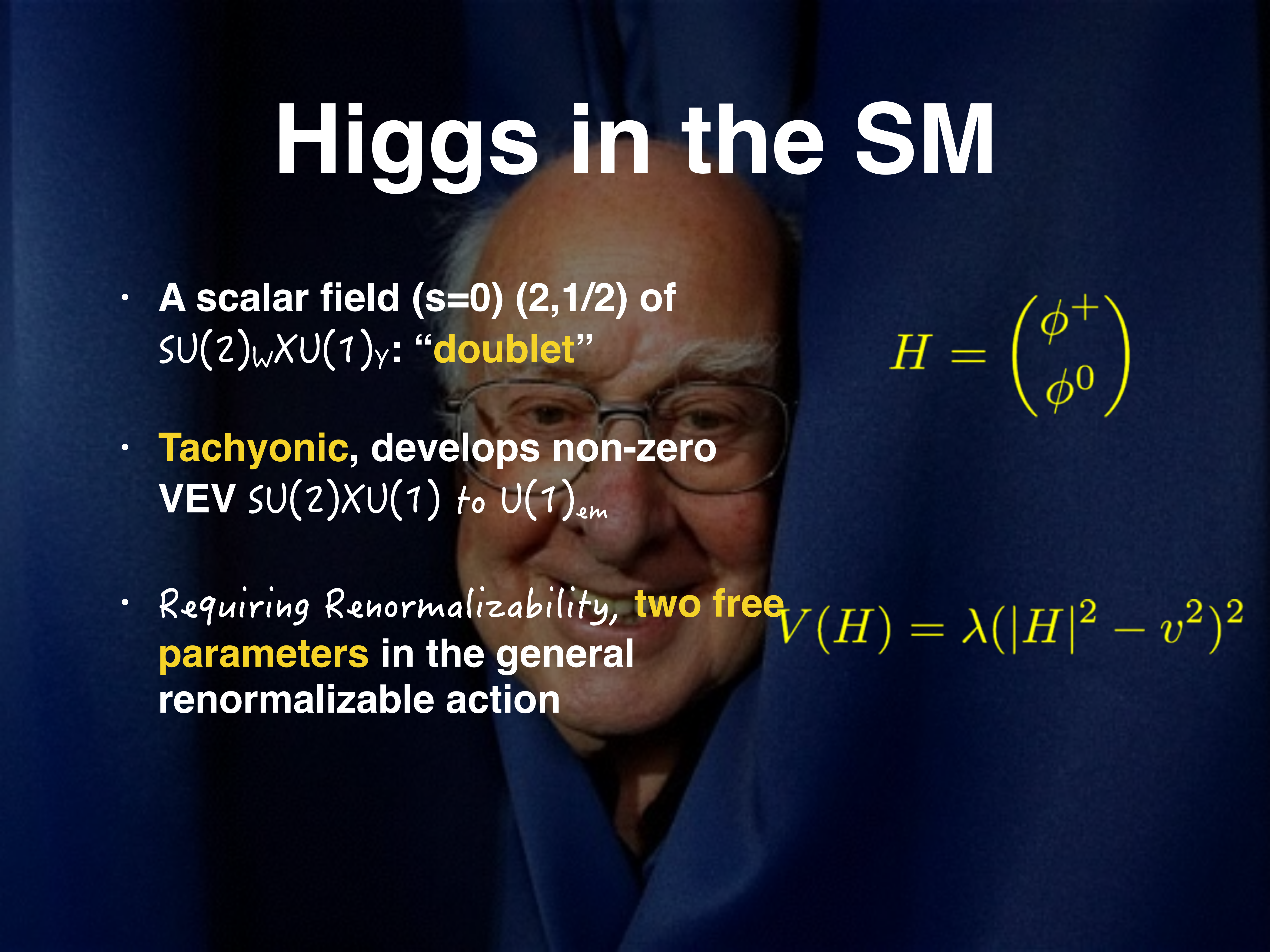
"Once you have a collider, every problem starts to look like a particle."

key message

- We now know that **the SM w/ Higgs is a good effective theory** working below or at TeV scales.
- If the SM still works fine at high scale, **the Higgs field may also play the role of inflaton: “Higgs Inflation”**
- This may open a new possibility of measuring “values” e.g. **M_t with a greater precision using cosmological data**, which may never be achievable at the LHC.

Higgs inflation

- An economical/predictive idea : **Higgs=Inflaton**
- At low scale (~100 GeV) responsible for **EWSB**
- At high scale (~10^{17} GeV) responsible for **cosmic inflation**
- **We can learn about EW scale physics from Cosmology!**



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 $SU(2) X U(1)$ to $U(1)_{em}$

- Requiring Renormalizability, **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 or equivalently G_F :** 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 the Higgs sector are experimentally measured!

Current status of Higgs mass measurement

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

CMS PAS HIG-14-009

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

ATLAS arXiv:1406.3827

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

PDG new

Decay pattern is consistent with the SM, too!

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

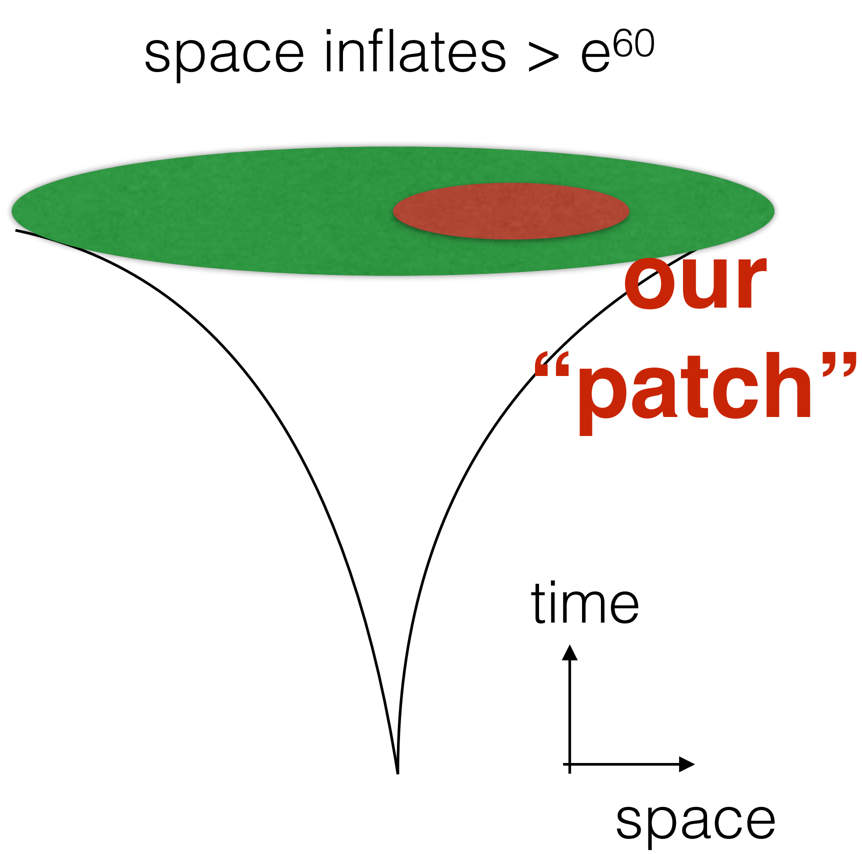
CMS PAS HIG-14-009

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

- The Higgs in the SM plays two main roles: it provides EWSB and also fermion masses
- **Both are experimentally checked already to some extend!**
  - **H-W-W, H-Z-Z**
  - **H-t-t (via H-A-A, H-g-g through 1-loop), H-b-b, M-tau-tau**
  - **I think it is fair to say that the observed boson is very-SM-like-boson or just the Higgs.**

Cosmology demands inflation

Era of inflation

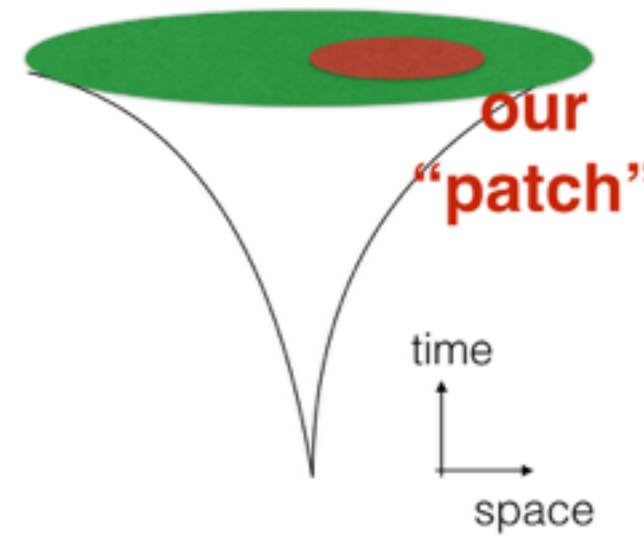


- Inflation gives **a chance to have causal connection in "our patch of universe"**
- **homogeneity and isotropy explained** and also no monopole, domain wall etc.
- It provides **seed** for structure formation provided.
- Now becomes a part of **the SM of cosmology**.

In particle physics, inflation takes place due to a flat potential

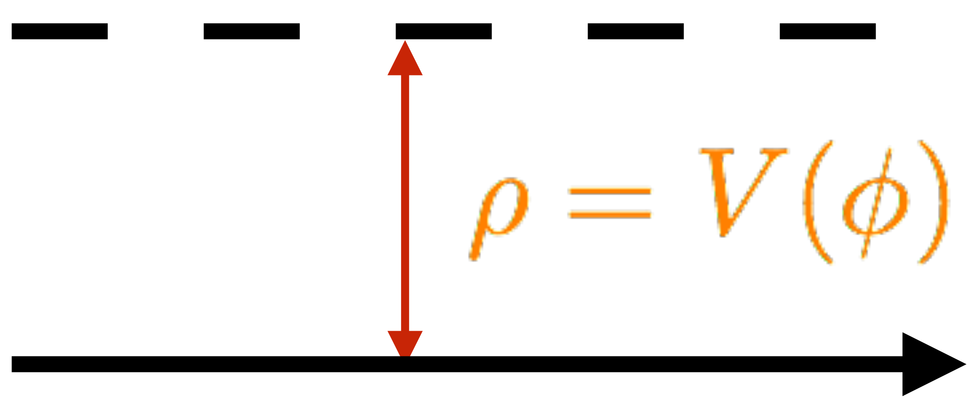
This is what we want: $a(t) = a_0 e^{H(t-t_0)}$

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



This is the equation: $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_p^2}$

It is realized if the potential is "flat"

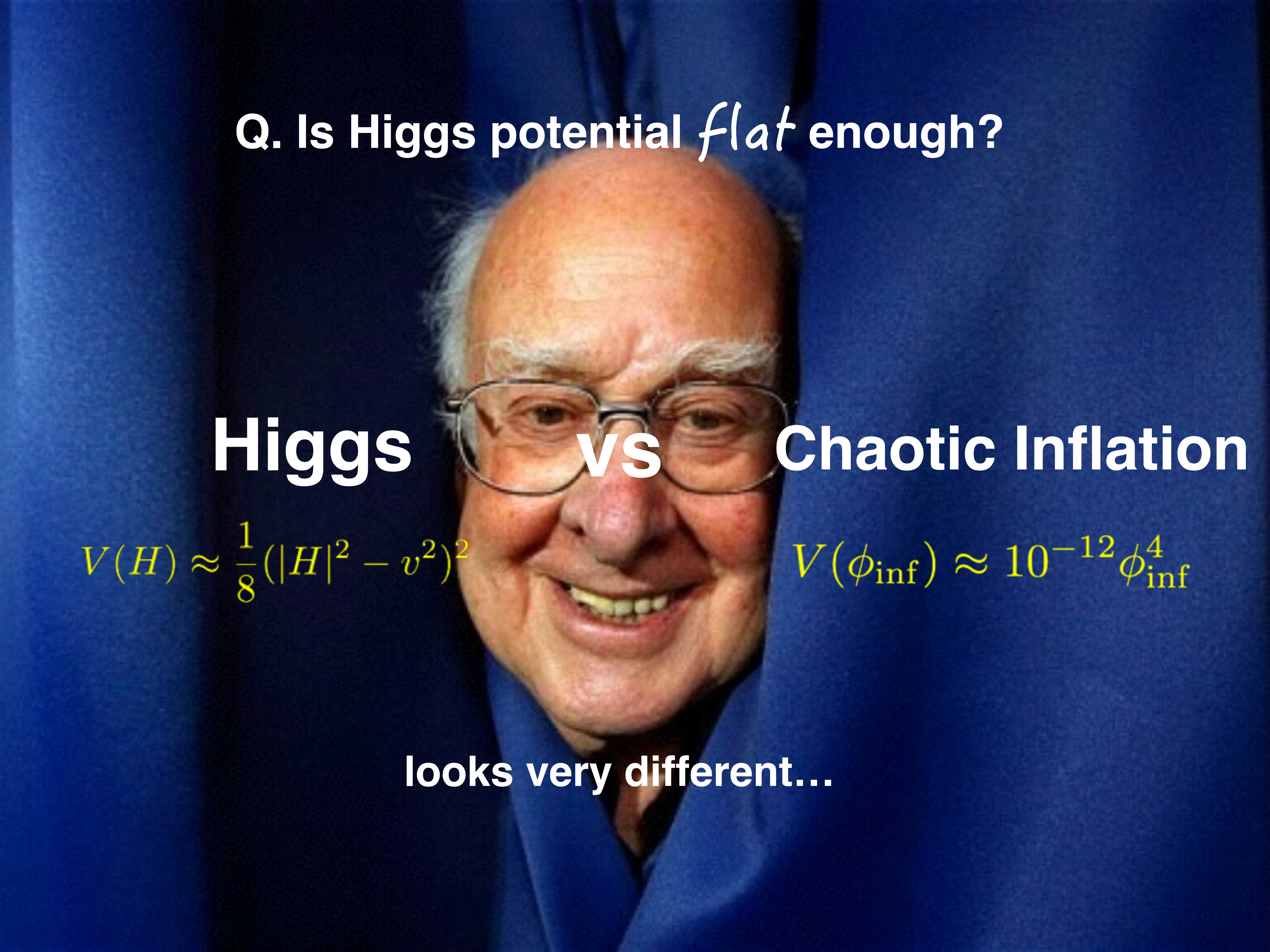


"slow-roll conditions"

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

(ex) $V = \lambda\phi^4, \lambda \sim 10^{-12}$

N.B. This guy is not be a vector or fermion unless it makes a composite state with s=0.


Q. Is Higgs potential *flat* enough?
Higgs
vs
Chaotic Inflation
$V(H) \approx \frac{1}{8}(|H|^2 - v^2)^2$
$V(\phi_{\rm inf}) \approx 10^{-12}\phi_{\rm inf}^4$
looks very different…

But!

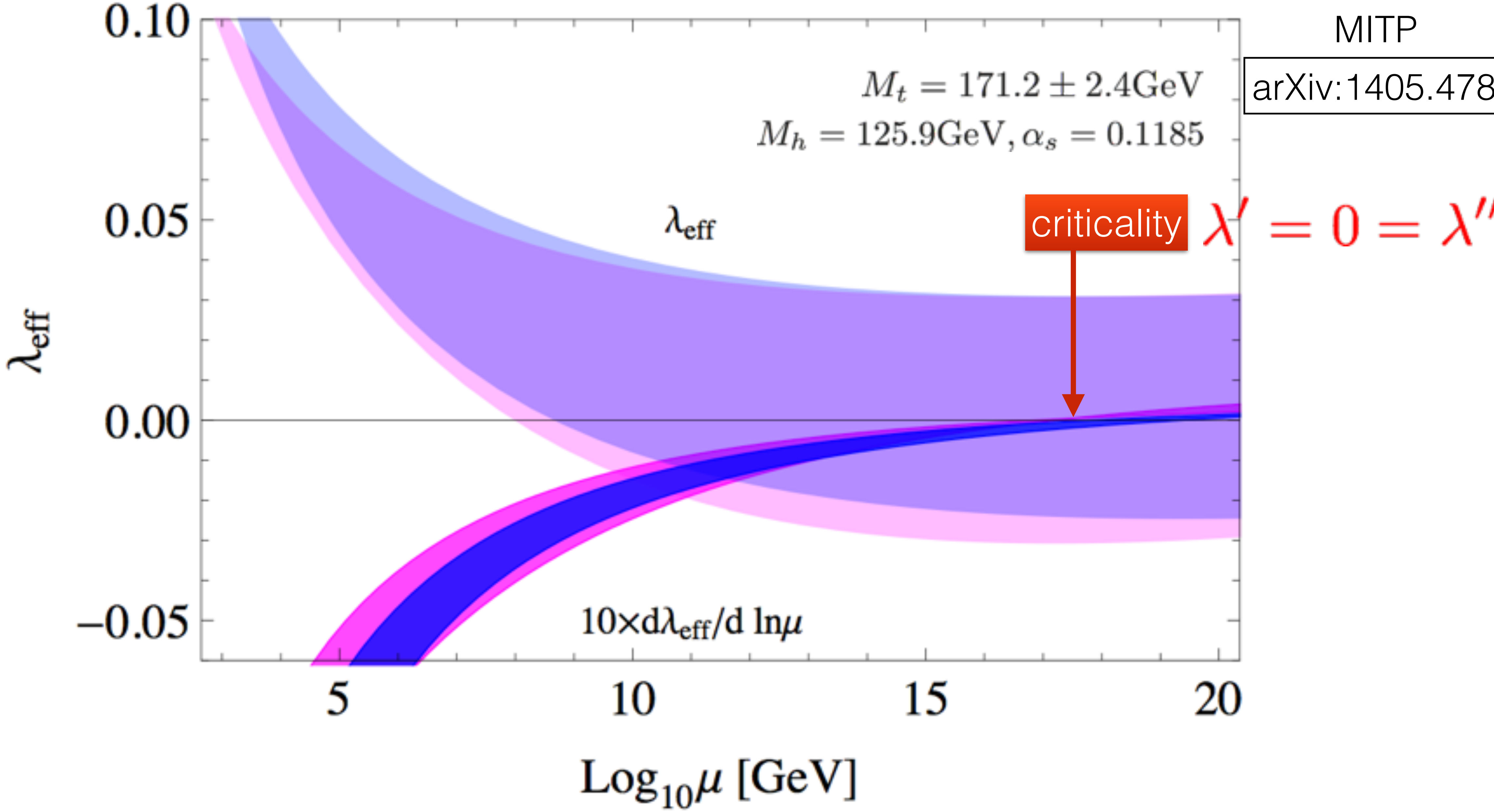
The Higgs potential becomes flat at high energy by RGE!

The SM Higgs

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

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

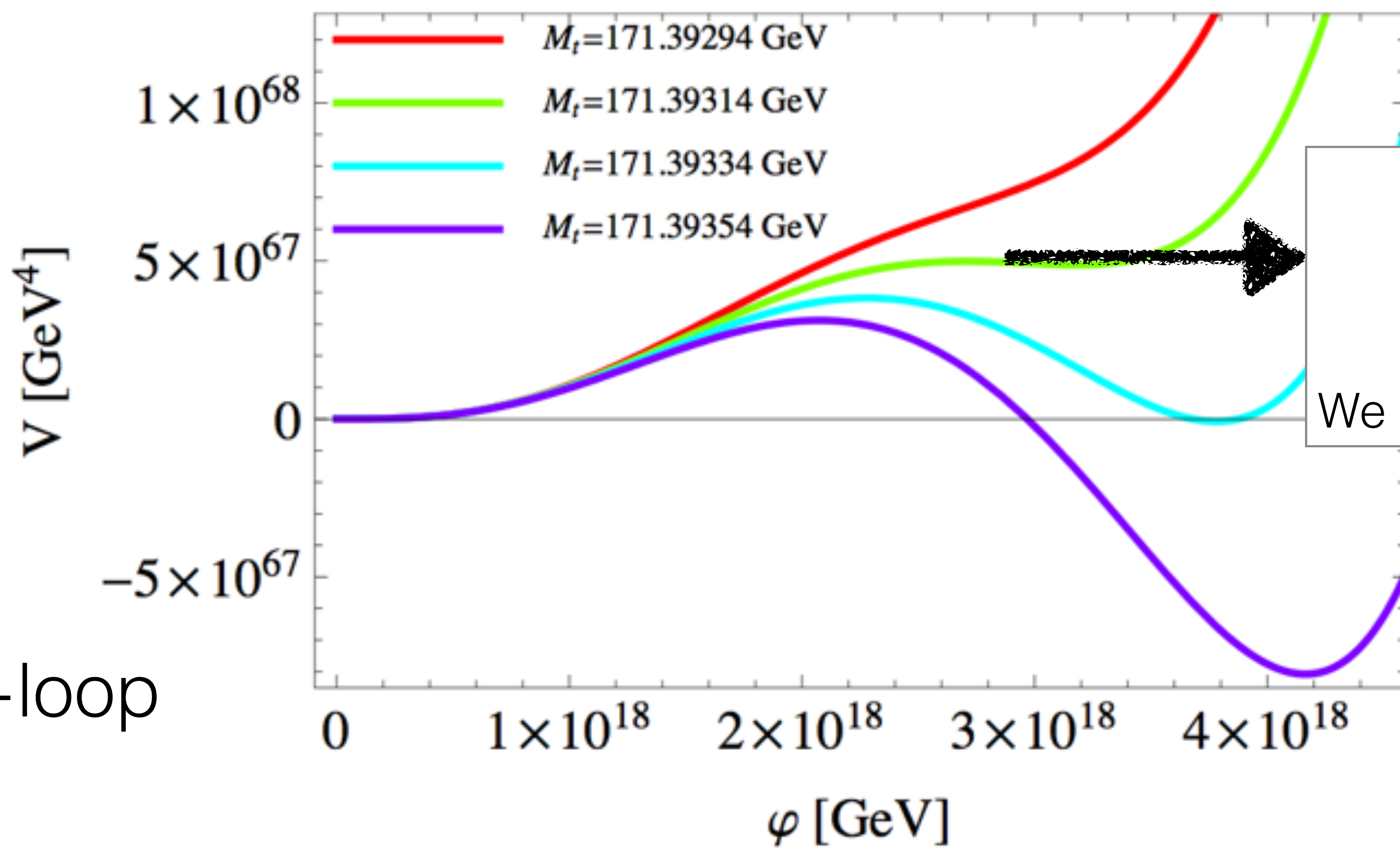
2-loop effective potential



MITP

arXiv:1405.4781

Criticality of the SM



Plateau!
This helps.
But, not enough
for 60 efoldings.
We need **something more!**

+loop

Another source of flatness :“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.
- In effective theory, this term should be included as long as $[K(\phi)] = [M^{D-2}]$

“Inflation by non-minimal couplings”

[SCP, S.Yamaguchi (2008)]

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

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

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

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

(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)]

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

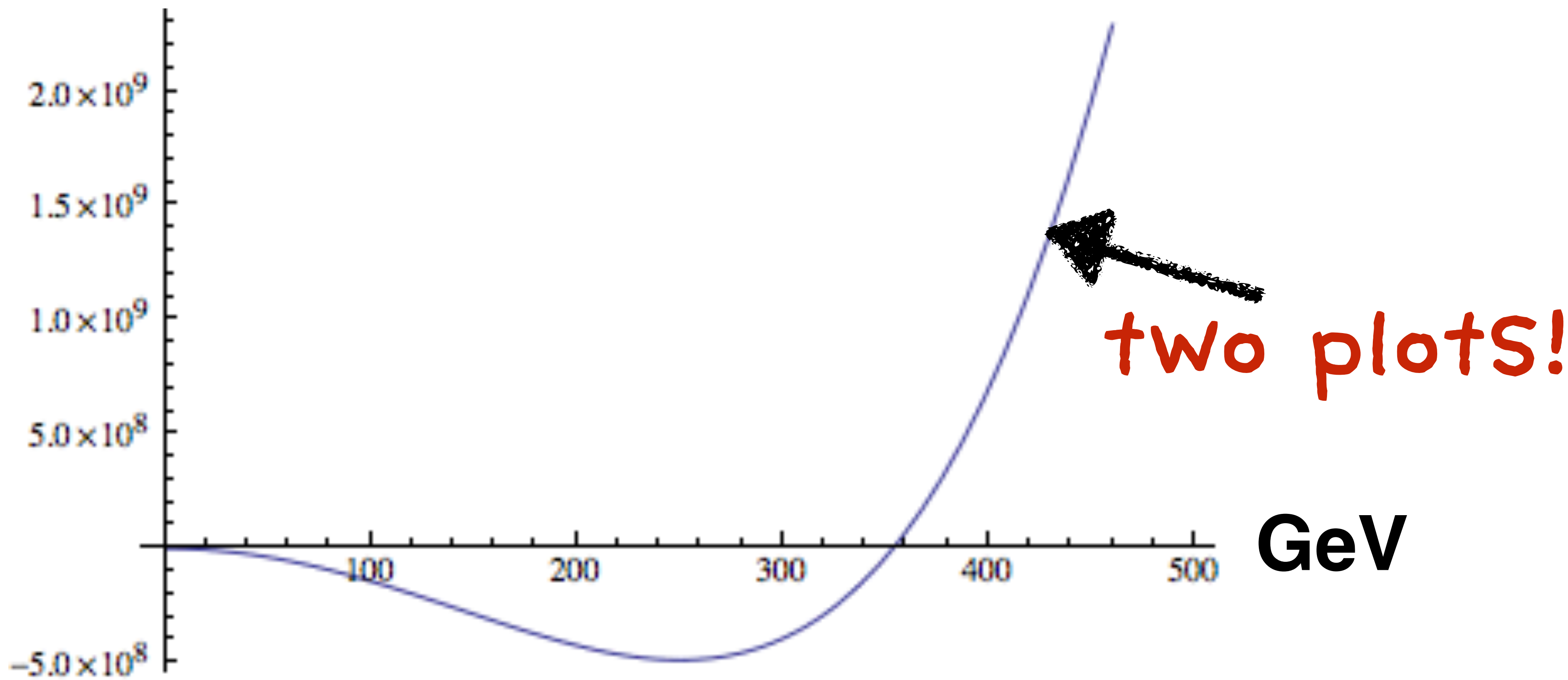
$$V_E \to \frac{\lambda M_P^4}{4\xi^2} \to const.$$

COBE normalization

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

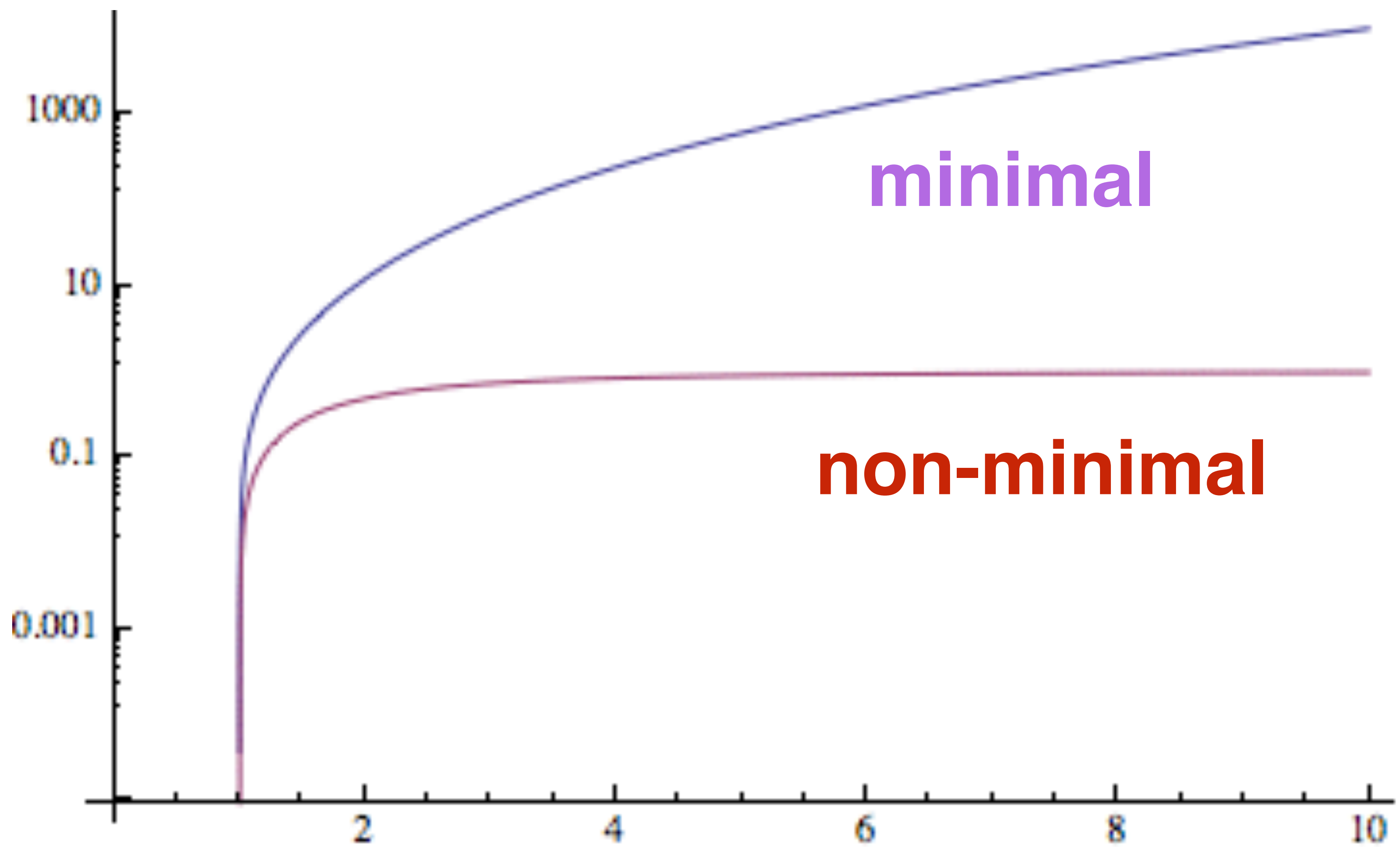
(hard to swallow…)

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



no difference in low energy!

At high scale, they are different!



Observables

"Scalar spectral Index"

$$\delta(\vec{x}) = \frac{\rho(\vec{x})}{\rho_0} - 1 = \int d^3k \delta_{\vec{k}} e^{i\vec{k}\cdot\vec{x}}$$

$$\langle \delta_{\vec{k}} \delta_{\vec{k}'} \rangle = \frac{2\pi^2}{k^3} \delta^3(\vec{k} - \vec{k}') \mathcal{P}(k)$$

$$\mathcal{P}_s(k) \propto k^{n_s - 1}$$

"scale invariance"

"Tensor-to-scalar ratio"

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

$$r \equiv \frac{\Delta_t^2}{\Delta_s^2} = \frac{8}{M_{\rm pl}^2}\left(\frac{\dot{\phi}}{H}\right)^2$$

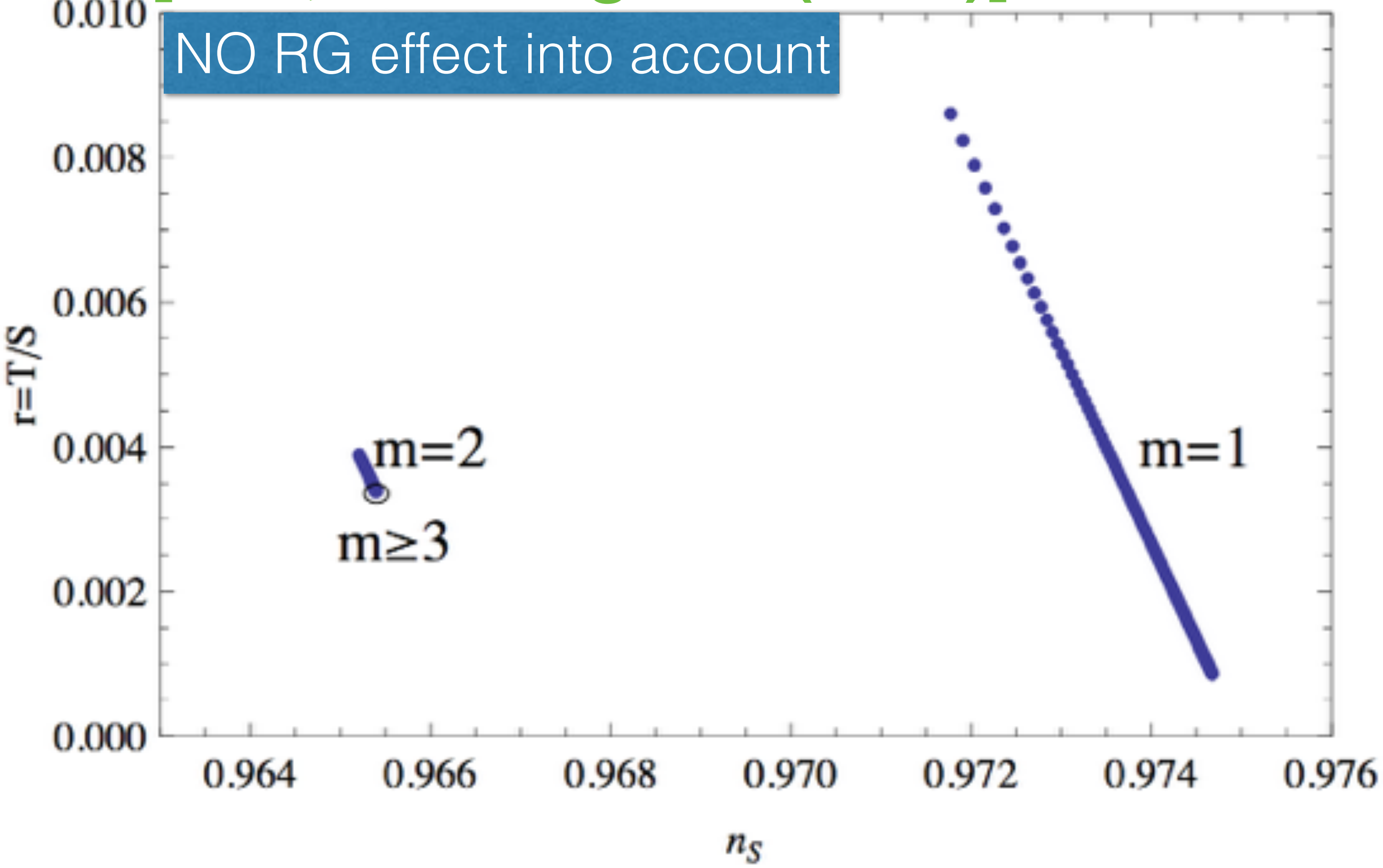
"movement"
~ "gravitational wave"

(also running spectral index, Non-Gaussianity etc…)

$$r \equiv \frac{\Delta_t^2}{\Delta_s^2} = \frac{8}{M_{\rm pl}^2}\left(\frac{\dot\phi}{H}\right)^2$$

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

[SCP, S.Yamaguchi (2008)]

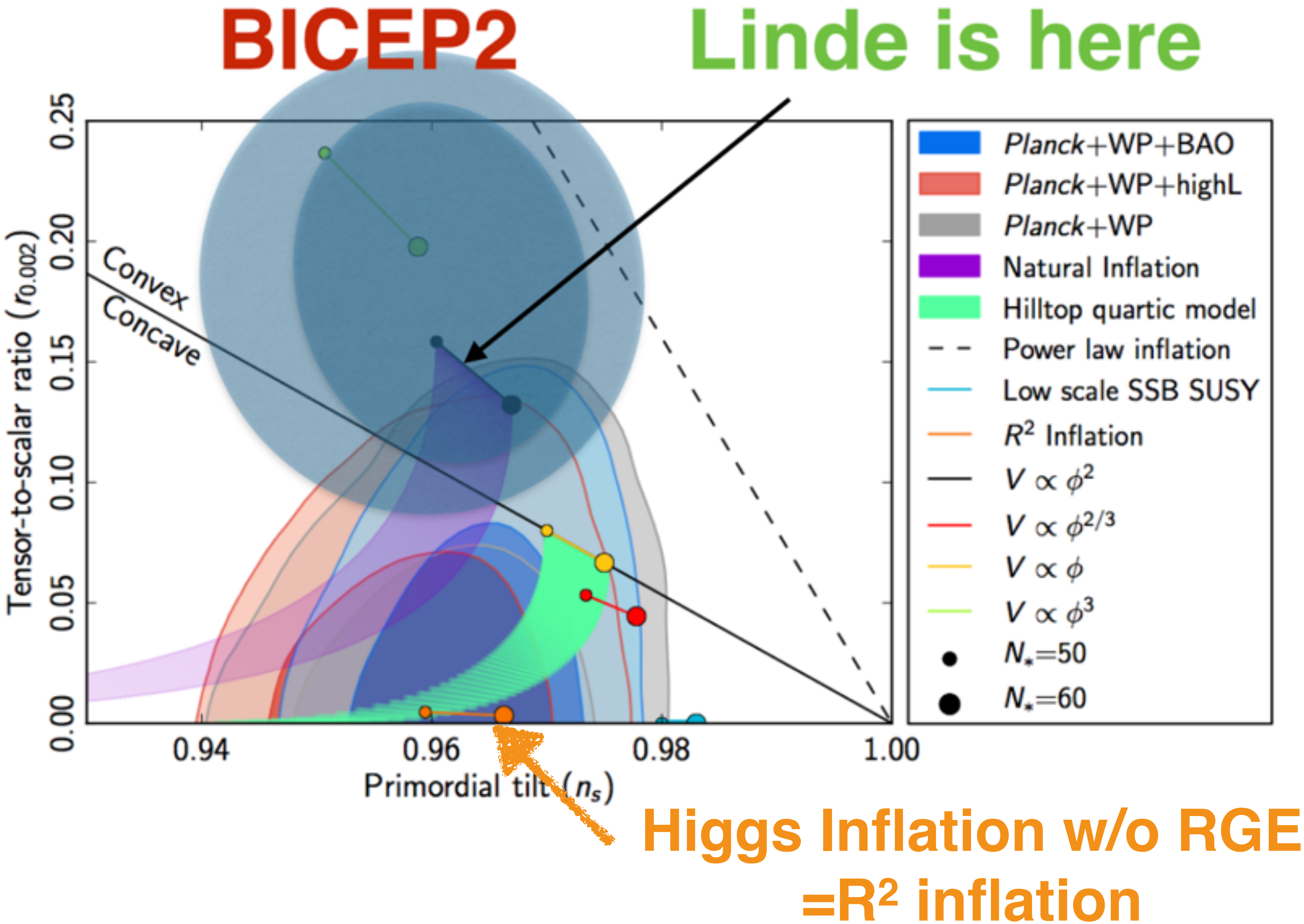


$$K(\phi) = a\phi^m$$
$$V(\phi) = \frac{\lambda}{2m}\phi^{2m}$$
$$V_{Einstein} \sim \frac{V}{K^2}$$

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

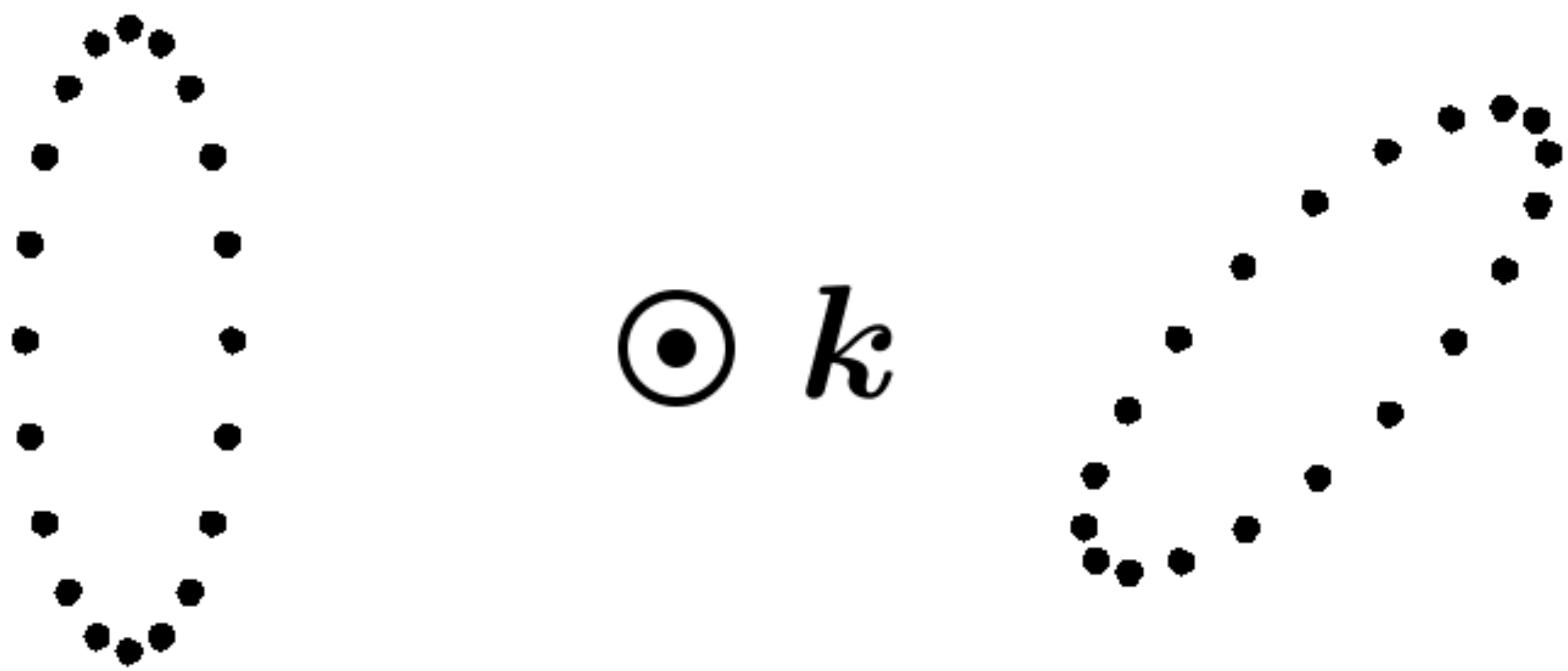
n is around 0.965

r is expected to be 'small'~0.003 !

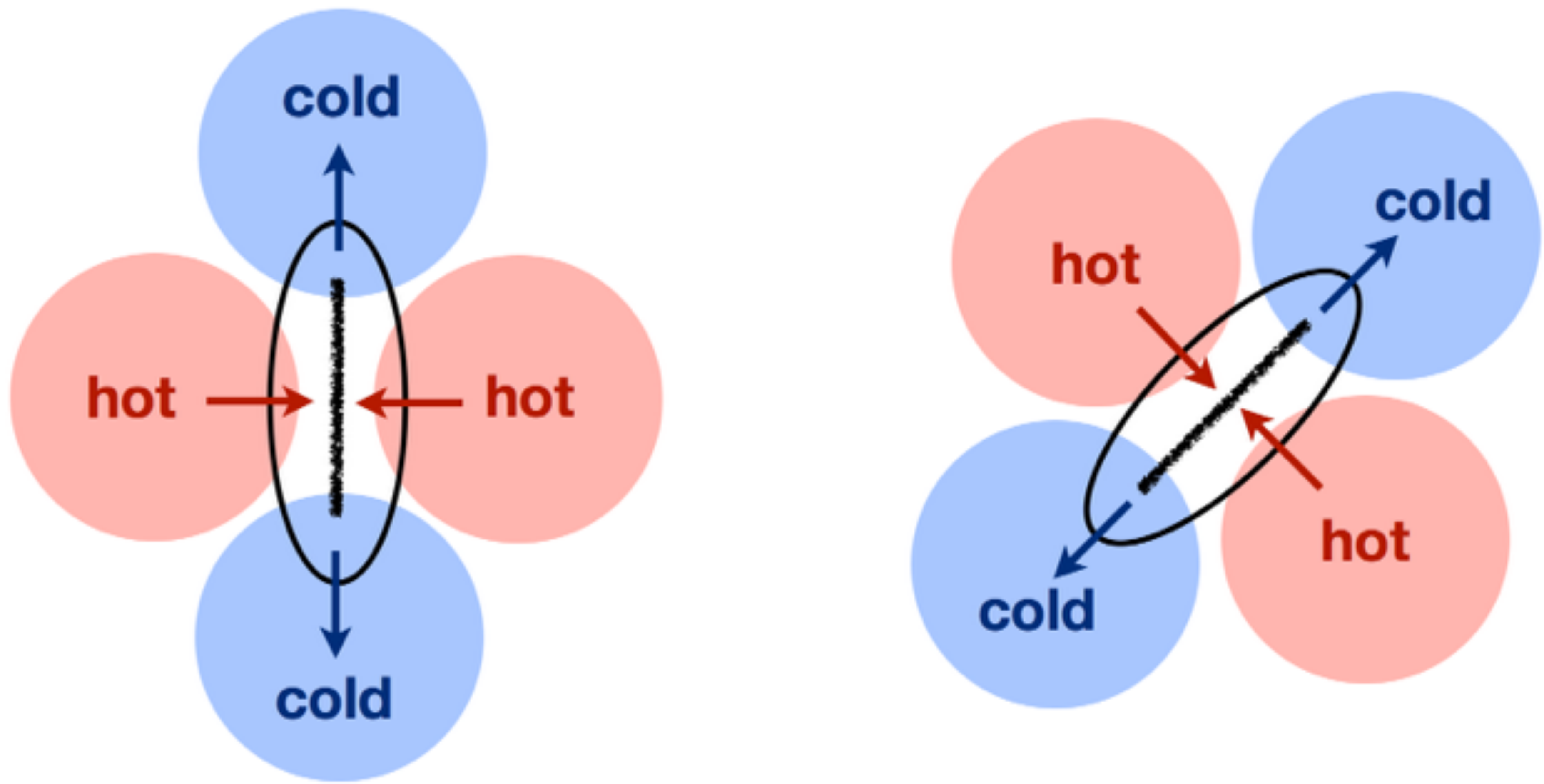

BICEP2
Linde is here
Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Planck+WP+BAO
Planck+WP+highL
Planck+WP
Natural Inflation
Hilltop quartic model
Power law inflation
Low scale SSB SUSY
R^2 Inflation
$V \propto \phi^2$
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^3$
N_*=50
N_*=60
Higgs Inflation w/o RGE
=R² inflation

Implications of Planck+BICEP2 and RGE effects

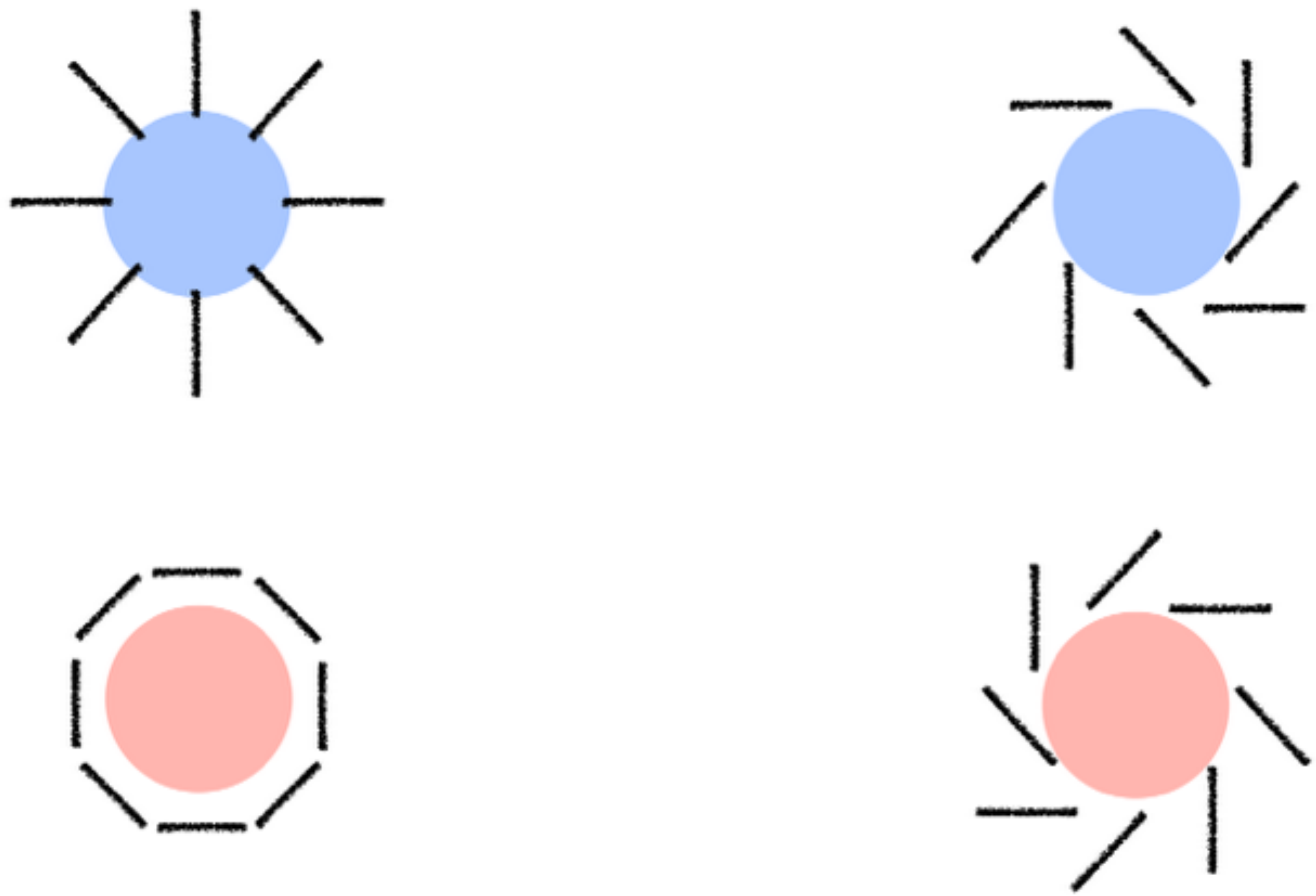
Recall the two polarization modes of a gravitational wave:



The anisotropic stretching of space induces a temperature quadrupole
and scattering produces two types of polarization



Summing over many waves, we get the following polarization patterns around **hot** and **cold** spots:

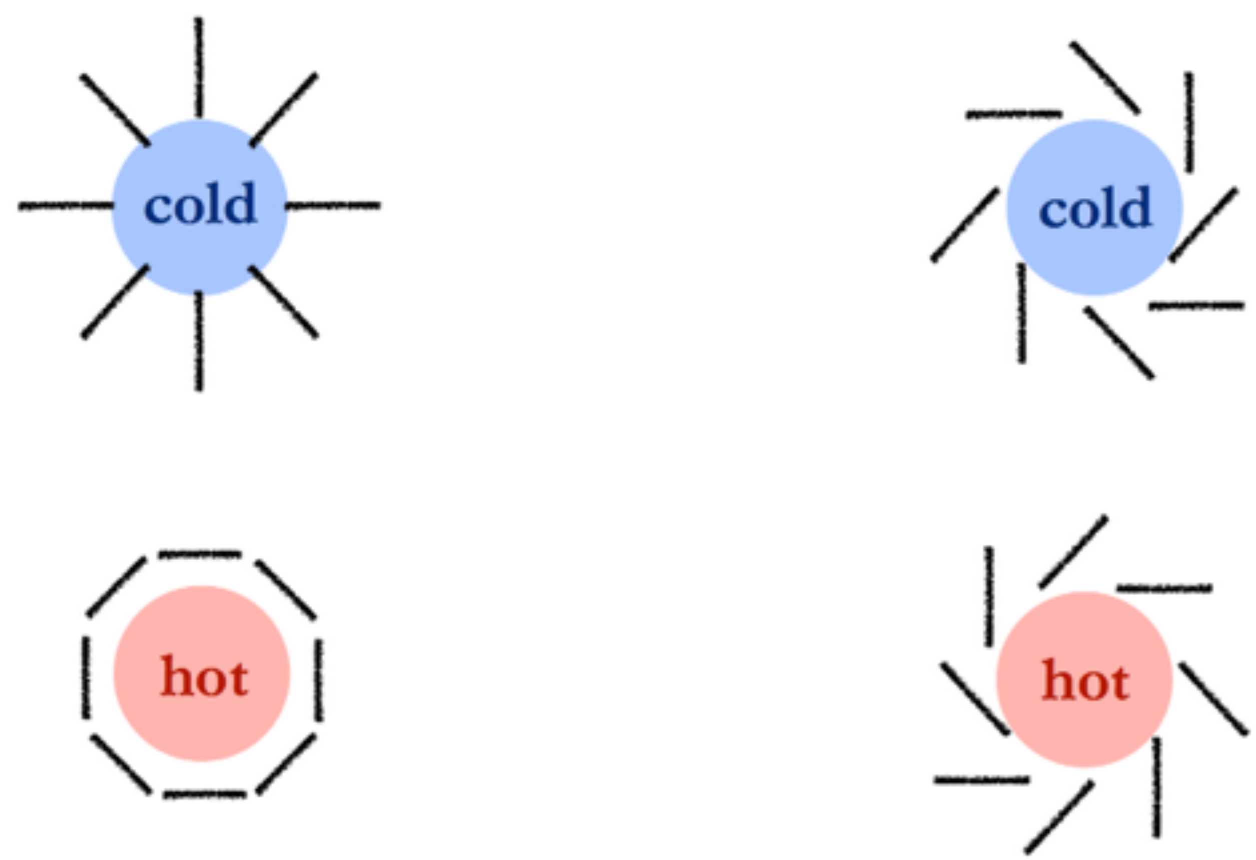


E-mode
(grad)

B-mode
(curl)

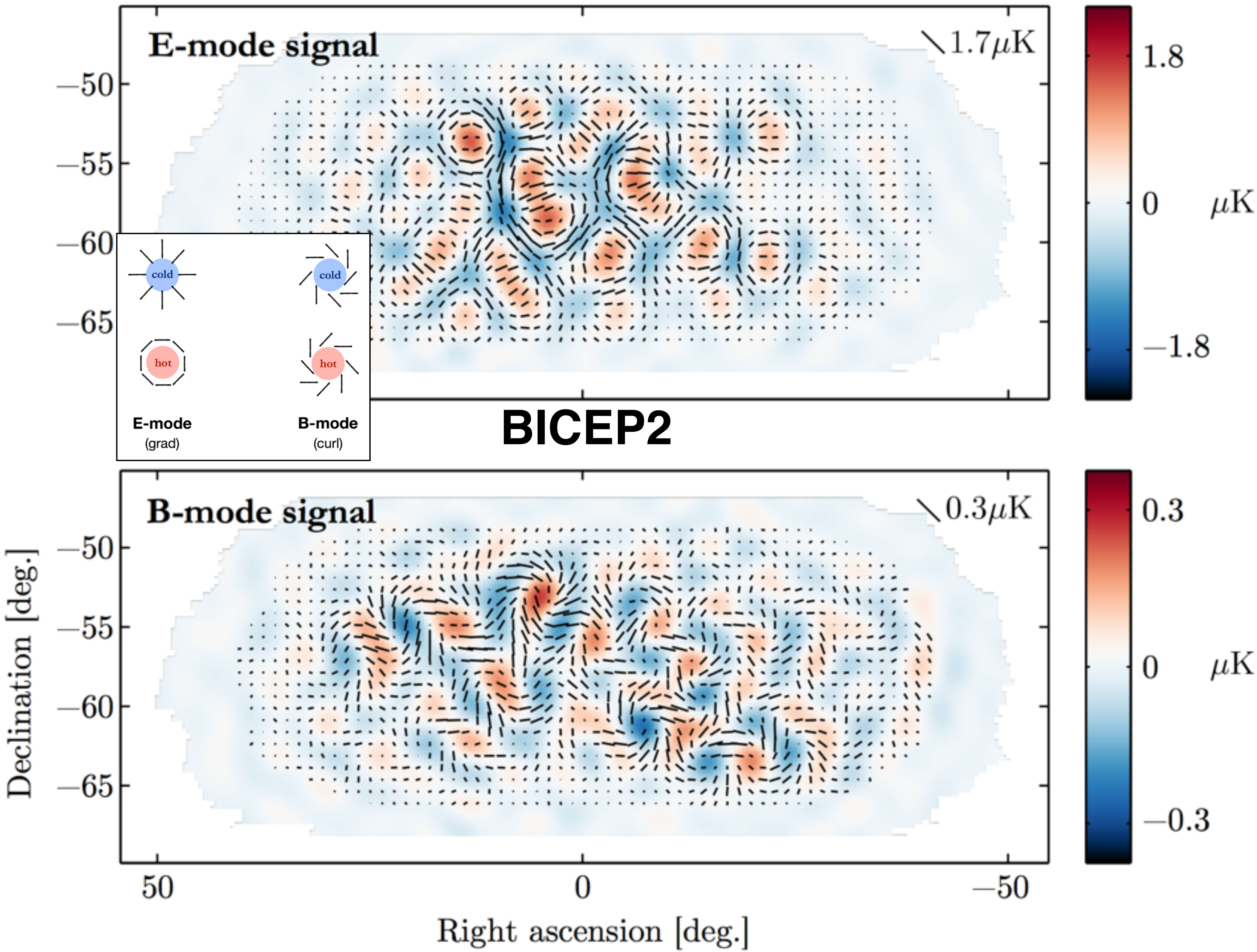
Helmholtz theorem

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



E-mode
(grad)

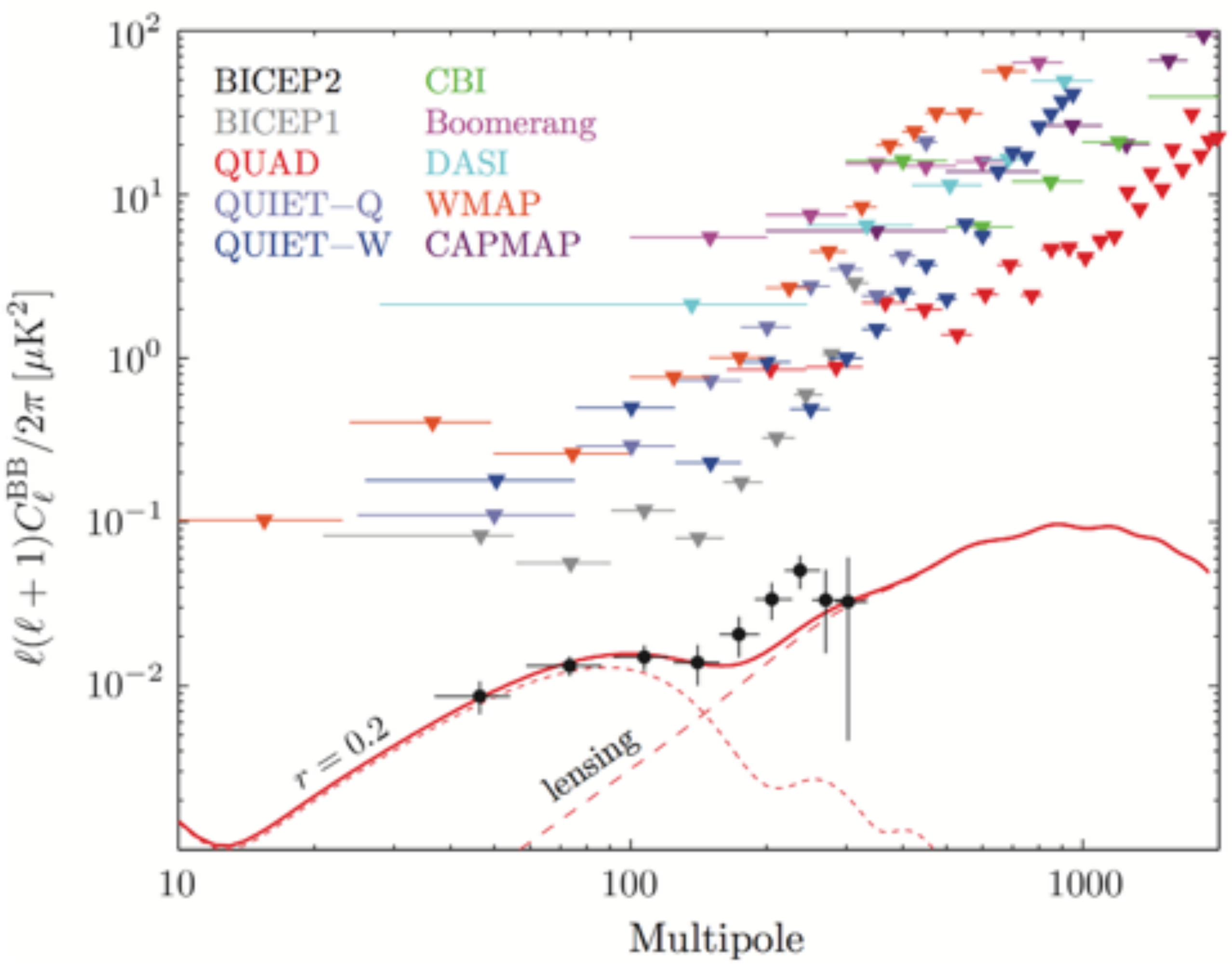
B-mode
(curl)



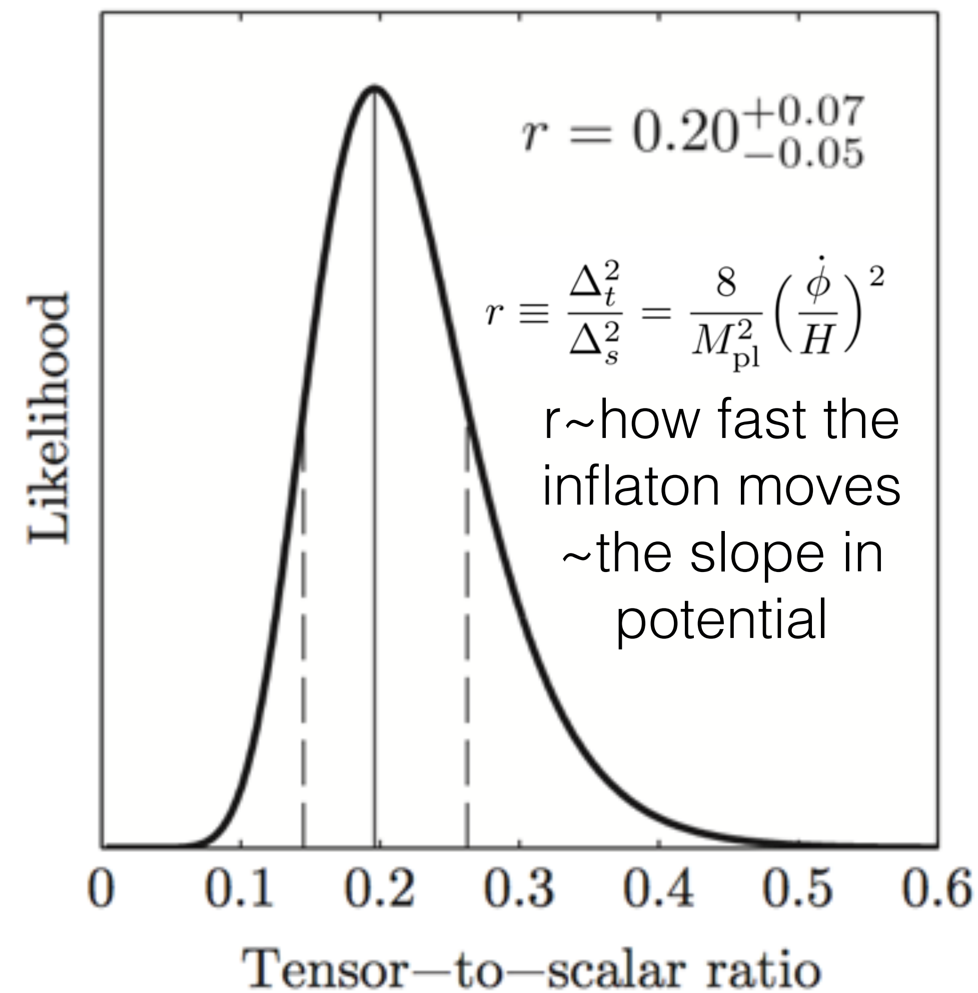
E-mode signal
1.7μK
B-mode signal
0.3μK
BICEP2
cold
hot
E-mode
(grad)
B-mode
(curl)
1.8
0
−1.8
μK
0.3
−0.3
−50
−55
−60
−65
50
0
−50
Declination [deg.]
Right ascension [deg.]

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

B-mode Power Spectrum



w/o foreground noise

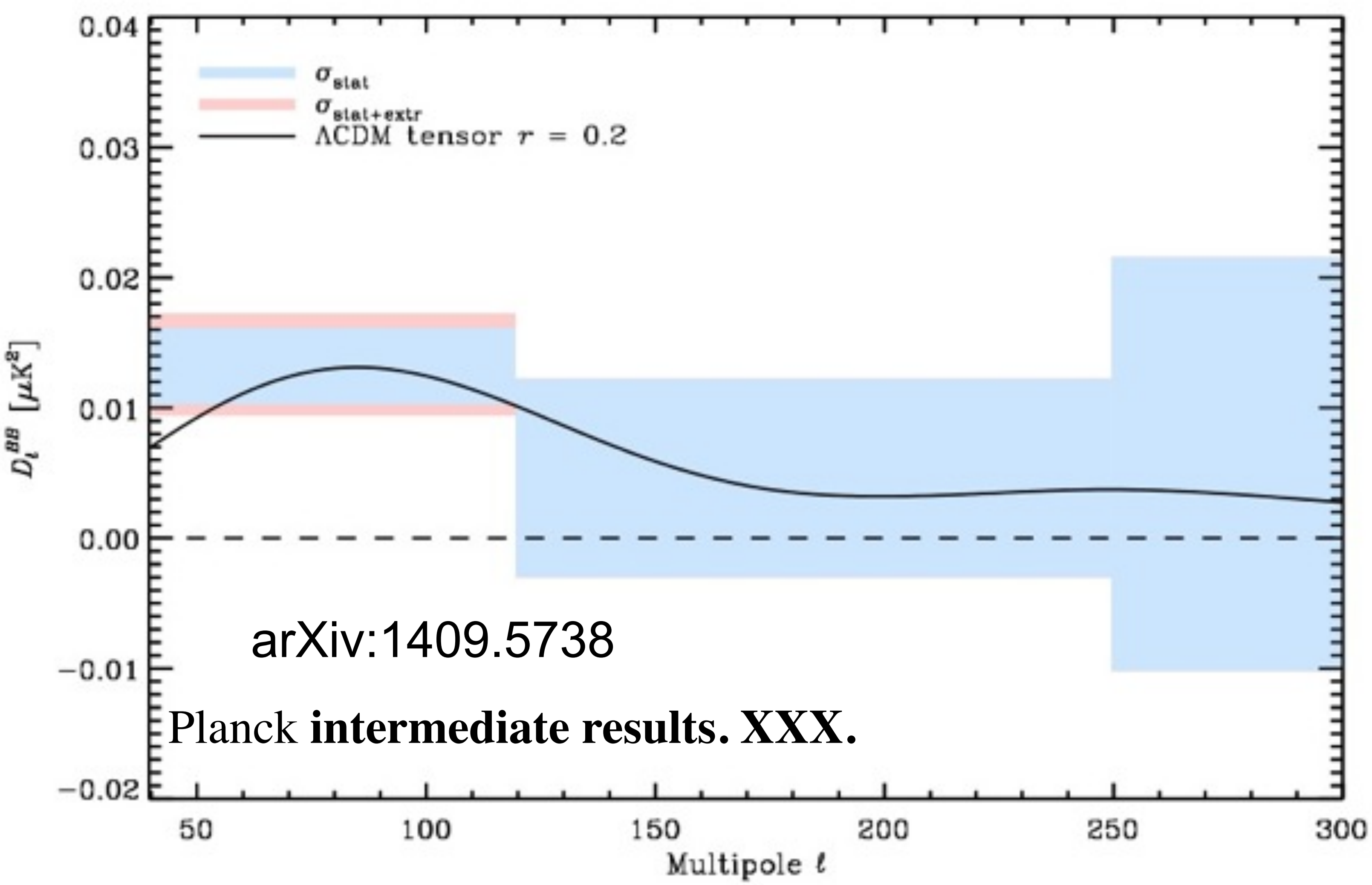


-Foreground dust must be better understood!

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

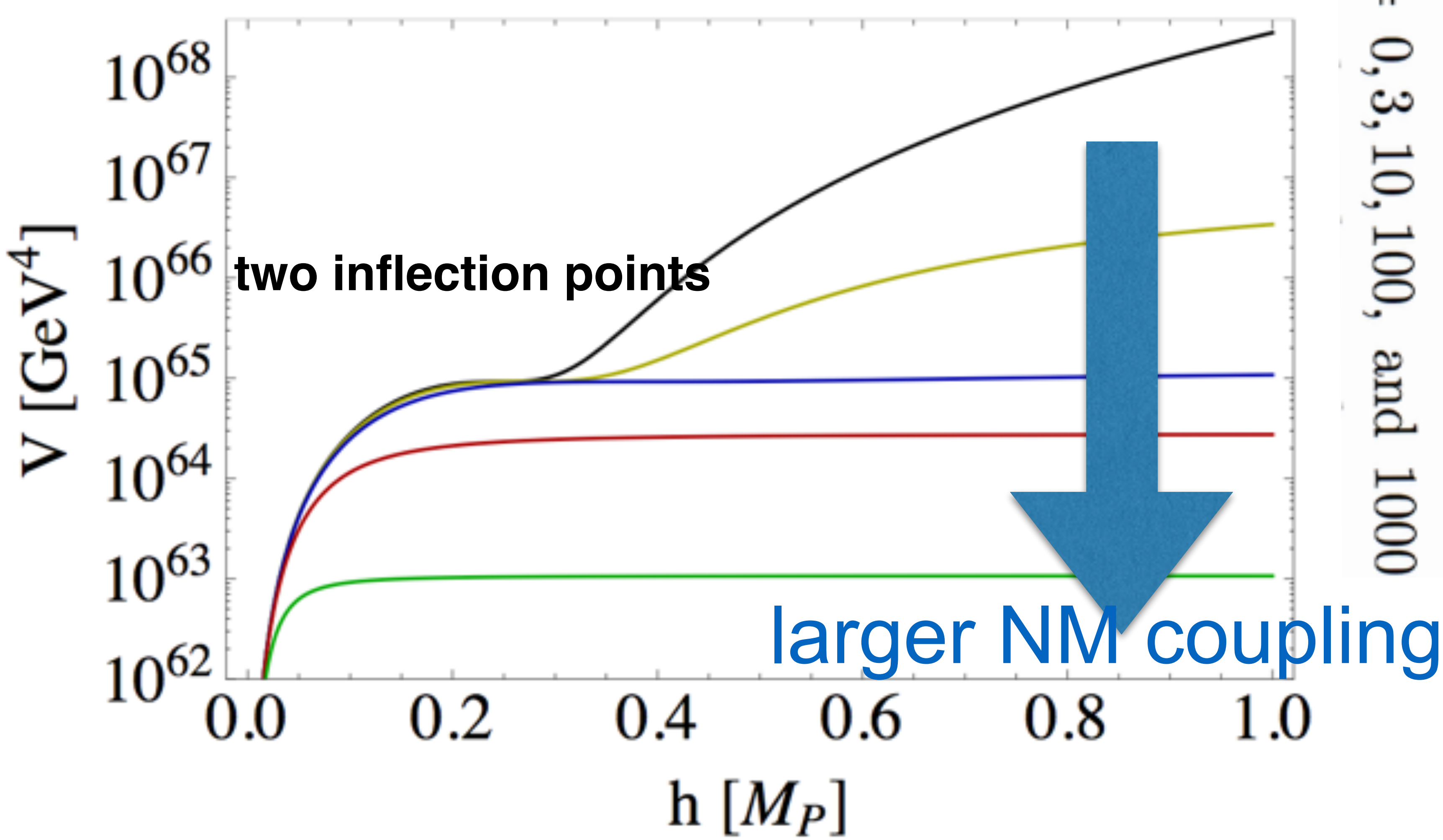
Planck showed that the power spectrum indicates that the **uncertainty is comparable in magnitude to the BICEP2** measurements at these multipoles.



Assessing the dust contribution to the B-mode power measured by the BICEP2 experiment requires a dedicated joint analysis with Planck, incorporating all pertinent observational details of the two data sets, such as masking, filtering, and color corrections. (Further analysis is needed to rule out any sign of B-Mode observation by BICEP2.)

SM w/ RGE+ 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

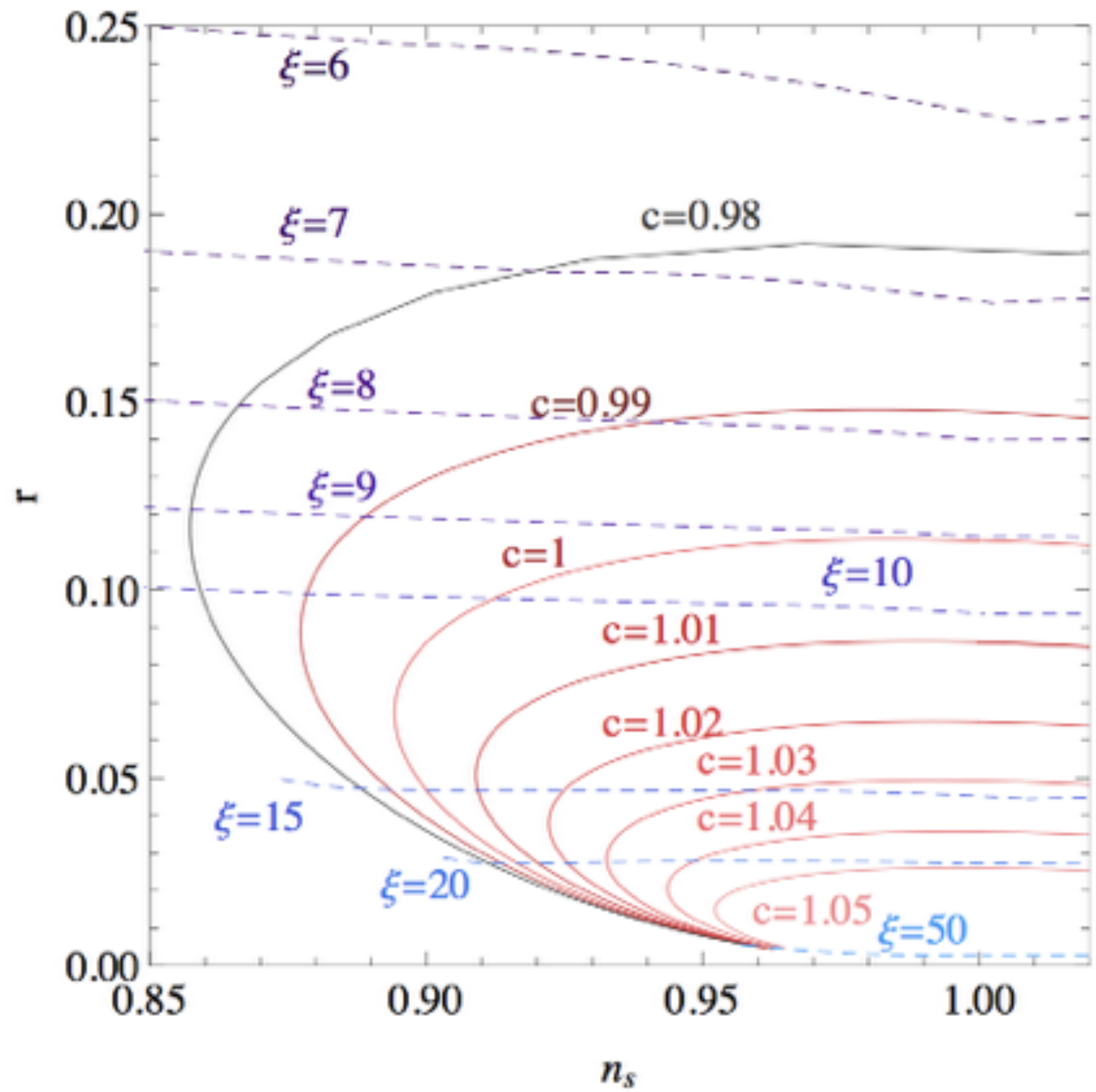
“saddle point”

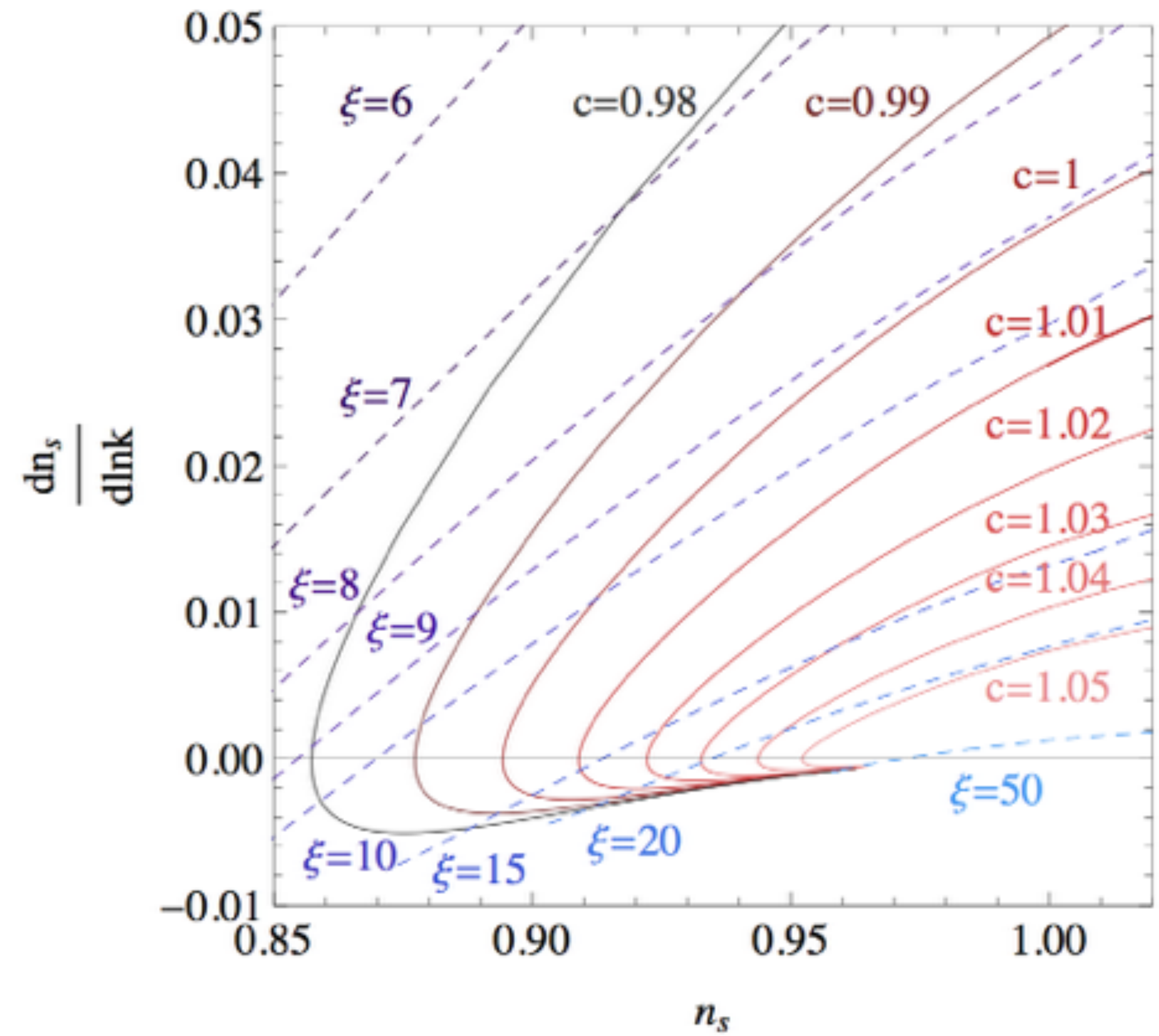
$$\lambda_{\min} \geq \lambda_c := \frac{\beta_2}{(64\pi^2)^2} \sim 10^{-6}. \qquad \lambda' = 0 = \lambda'' \tag{5}$$

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]

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

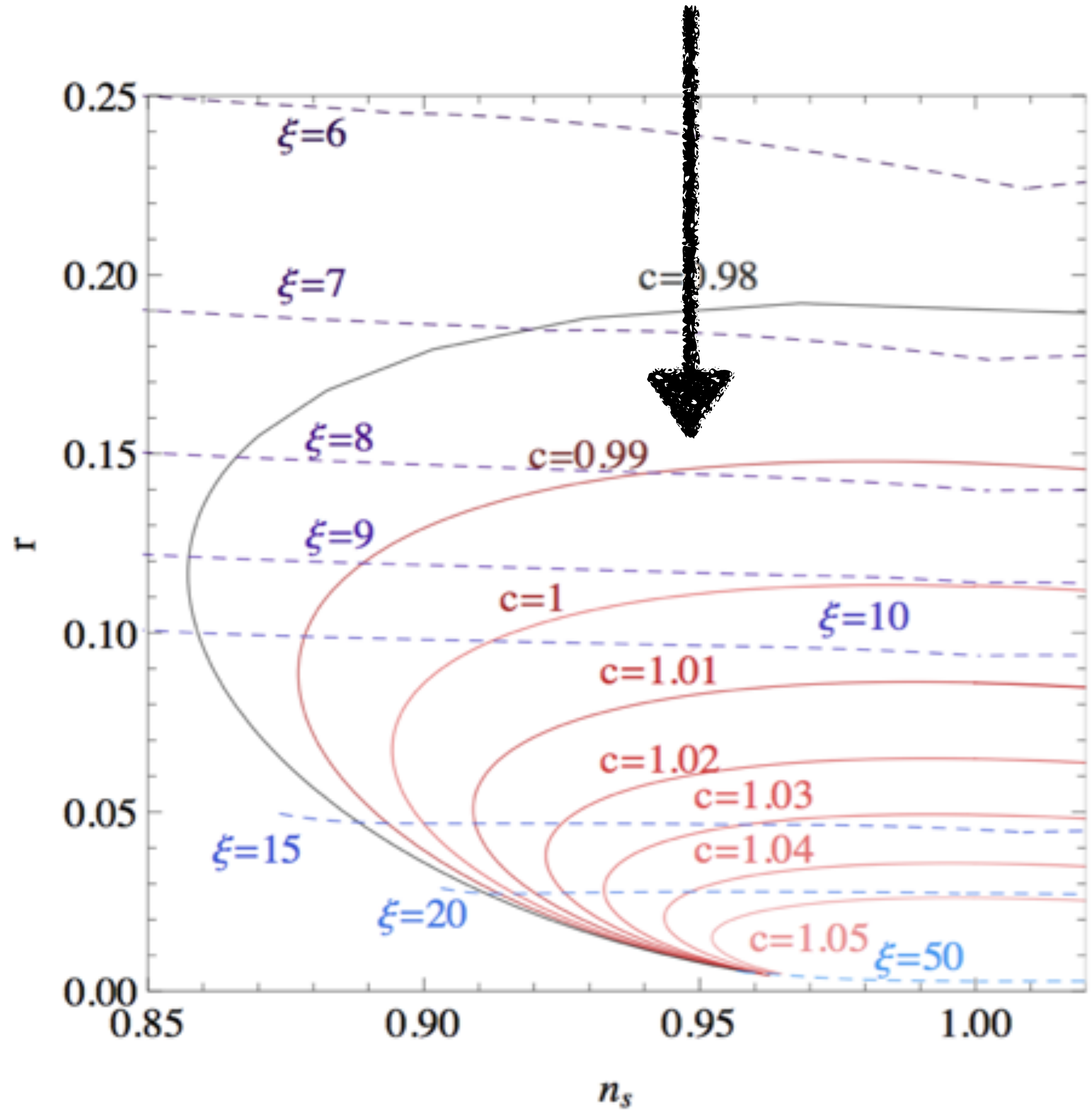
“Bigger possibilities w/ RGE, criticality”

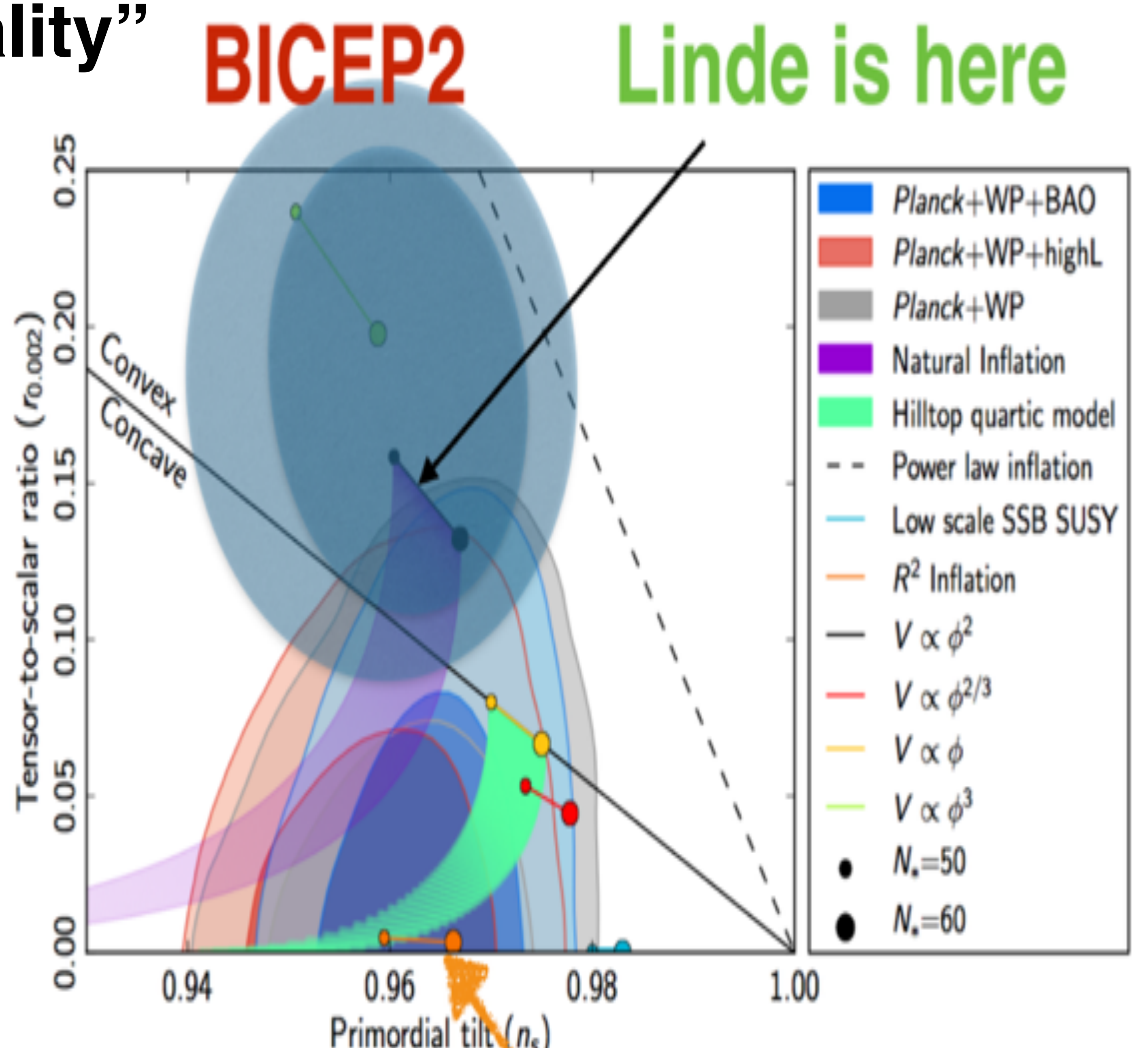




$$\mu_{\rm min} = c\frac{M_p}{\sqrt{\xi}} \qquad \lambda_{\rm min} = \lambda_c := \frac{\beta_2}{(64\pi^2)^2}$$

Higgs inflation w/ RGE, criticality”

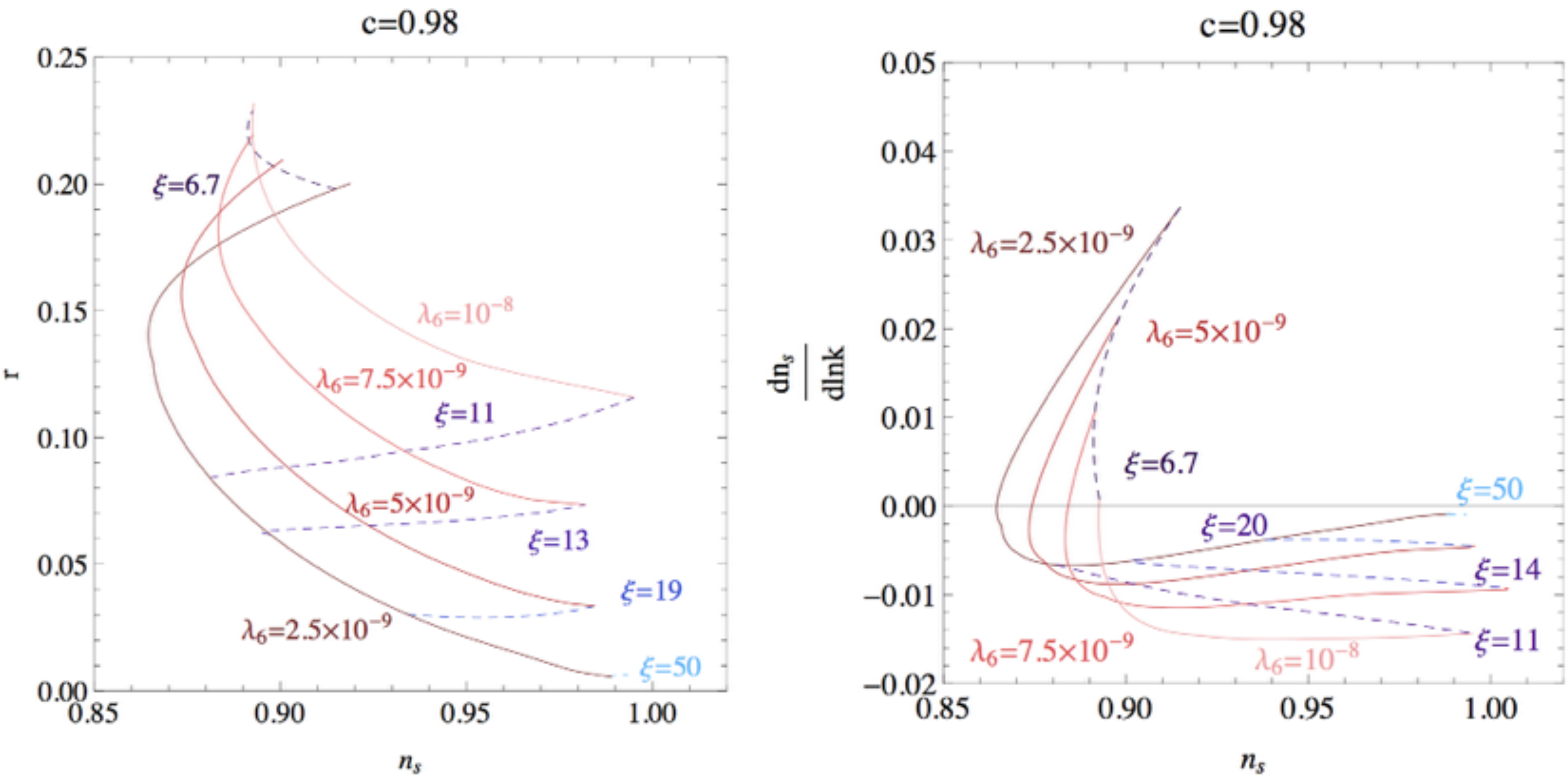




Higgs Inflation (w/o RGE
=R^2 inflation

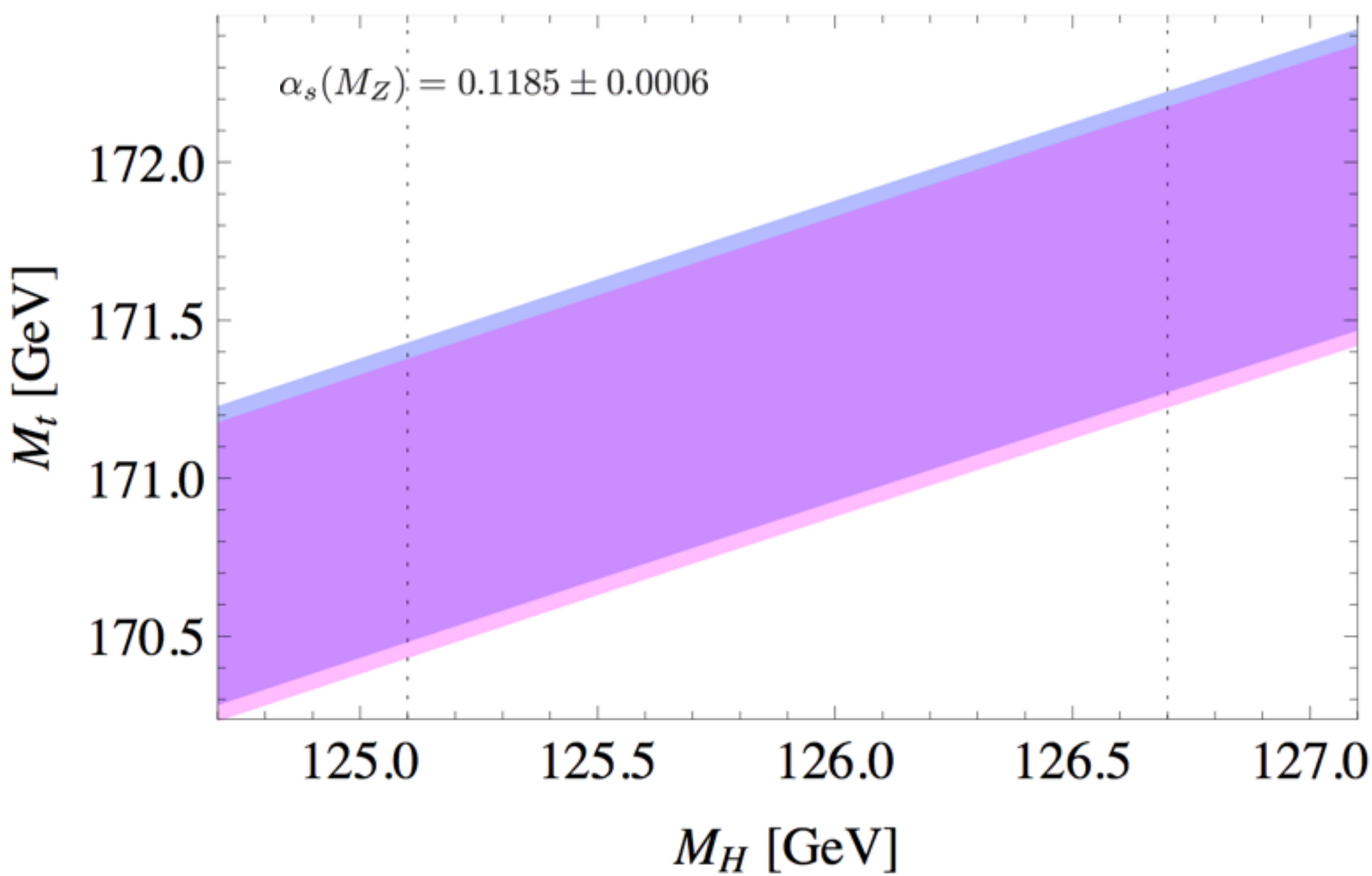
"higher order terms"

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



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

M_t in Higgs Inflation



example

Precise measurement of M_t by cosmological data

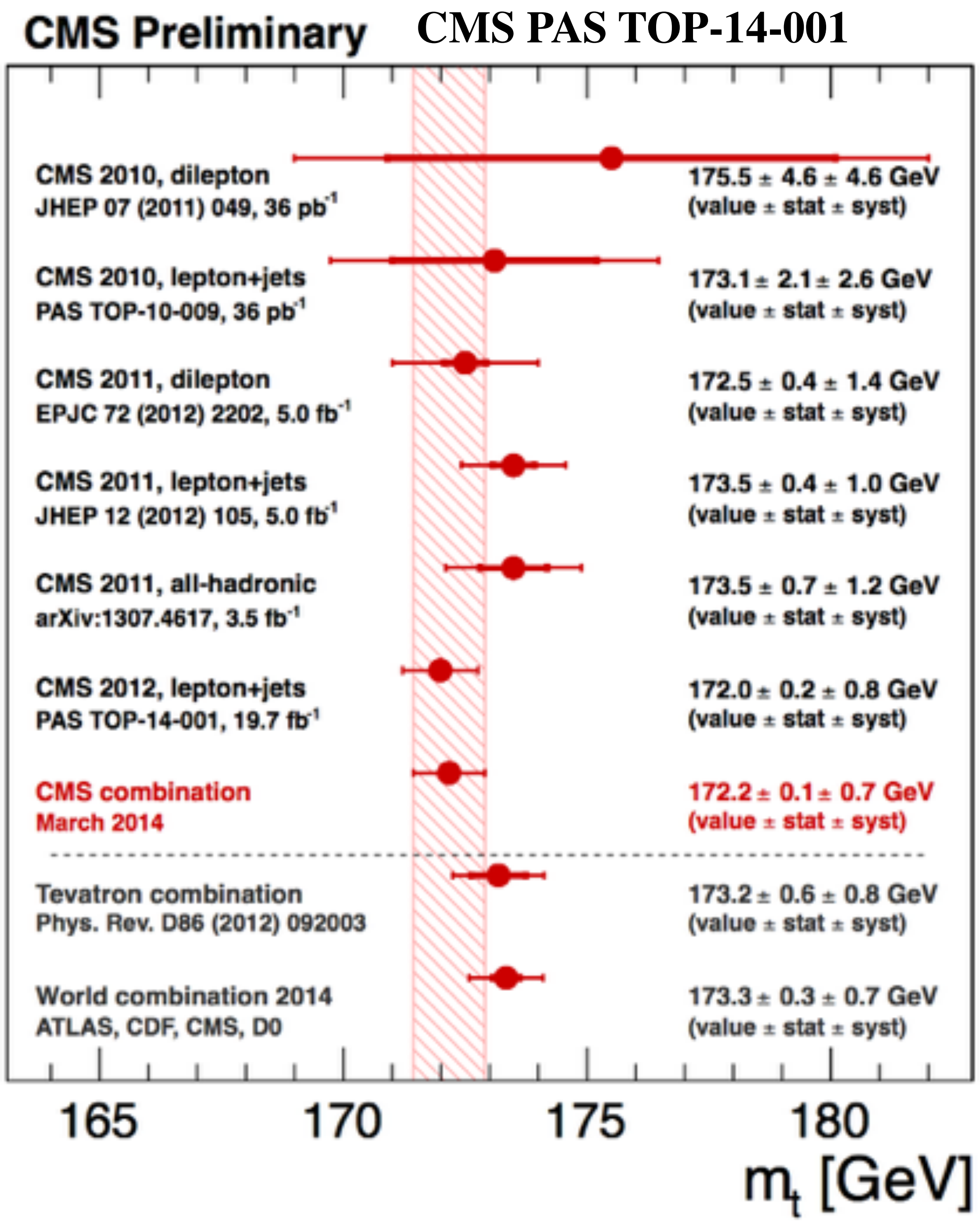
$$\Delta m_t \sim \mathcal{O}(1-10)\mathrm{MeV}$$

may be achievable in **"Higgs inflation"**

$\boxed{\textbf{This is not a small thing!}}$

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]

- 175->173->172 … keep reducing in its measured value
- Error remains still big~GeV
- To reduce the error, one should have better understanding of “MC mass” but this is tough!

conclusion

- BICEP + Planck, if confirmed, fantastic!!
- If not, we will learn more about dust any way.
- **Higgs may play a role of inflaton and compatible with data:** predictions are n=0.967 and r=0.003 or ~0.1 with or without criticality, NG is expected to be small.
- With criticality (r~0.1), **Mh and Mt may be (best) measured by cosmological data!**
- PLANCK and BICEP upgrades(BICEP3, KECK array) result will tell us more. Let's stay tuned.