# Higgs inflation

Seong Chan Park
Yonsei University & KIAS


1st IBS-Honam Focus Program on particle physics and cosmology
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Chonbuk National University, 29 Aug 2016

# based on works
# with experts from various fields

<u>string</u>

Hikaru Kawai

Satoshi Yamaguchi

<u>particle</u>

Yuta Hamada

Kin-ya Oda

Jinsu Kim

<u>Gravity</u>

Shinji Mukohyama

# Plan (1/2)

- To bring your attention to EXTREMELY interesting idea of cosmic inflation based on the standard model Higgs field and NOTHING ELSE.
- I will begin with OBERVATIONAL FEATURES of our Universe, which basically support the standard model of cosmology, a.k.a. Lambda-CDM model (= 'conventional' Big Bang theory).
- However, we immediately notice that there exist "INITIAL CONDITION PROBLEMS", which call for explanation.

# Plan (2/2)

- The COSMOLOGICAL INFLATION solves the I.C. problems. Now it is widely accepted as a part of the standard cosmology.
- The best inflationary model, which fits the data best, is Starobinsky's model.
- Very interestingly, the Starobinsky's model is equivalent to the Higgs inflation! I will explain this to you.
- I will also tell you how the Higgs inflation would provide a nice understanding of undetermined parameter in Starobinsky's model.
- Then discuss the future chances for particle physics from cosmological data.

# SM of cosmology

# Cosmology

- "The study of the universe as a whole"
- Very ambitious program of science: We want to know the origin ($t=t_i$), evolution ($t>t_i$) and fate ($t=t_f$) of the Universe.
- has a long long history since ancient time ...
- only relatively recently cosmology has become "precision science" based on well established theoretical framework + observational support.

# Observed features of the Universe

- Universe is spatially flat
- Universe is homogeneous and isotropic on length >100 Mpc
- hierarchy in structure from 1kpc to 100 Mpc scales
- near scale invariant spectrum in CMB fluctuations

initial conditions

- Universe expanding uniformly
- Thermal background of radiation with T=3K
- chemical composition is roughly 75% H, 25% He +trace

Standard Big Bang theory

- ordinary matter is minority (1/6X) of all matter

Dark Matter

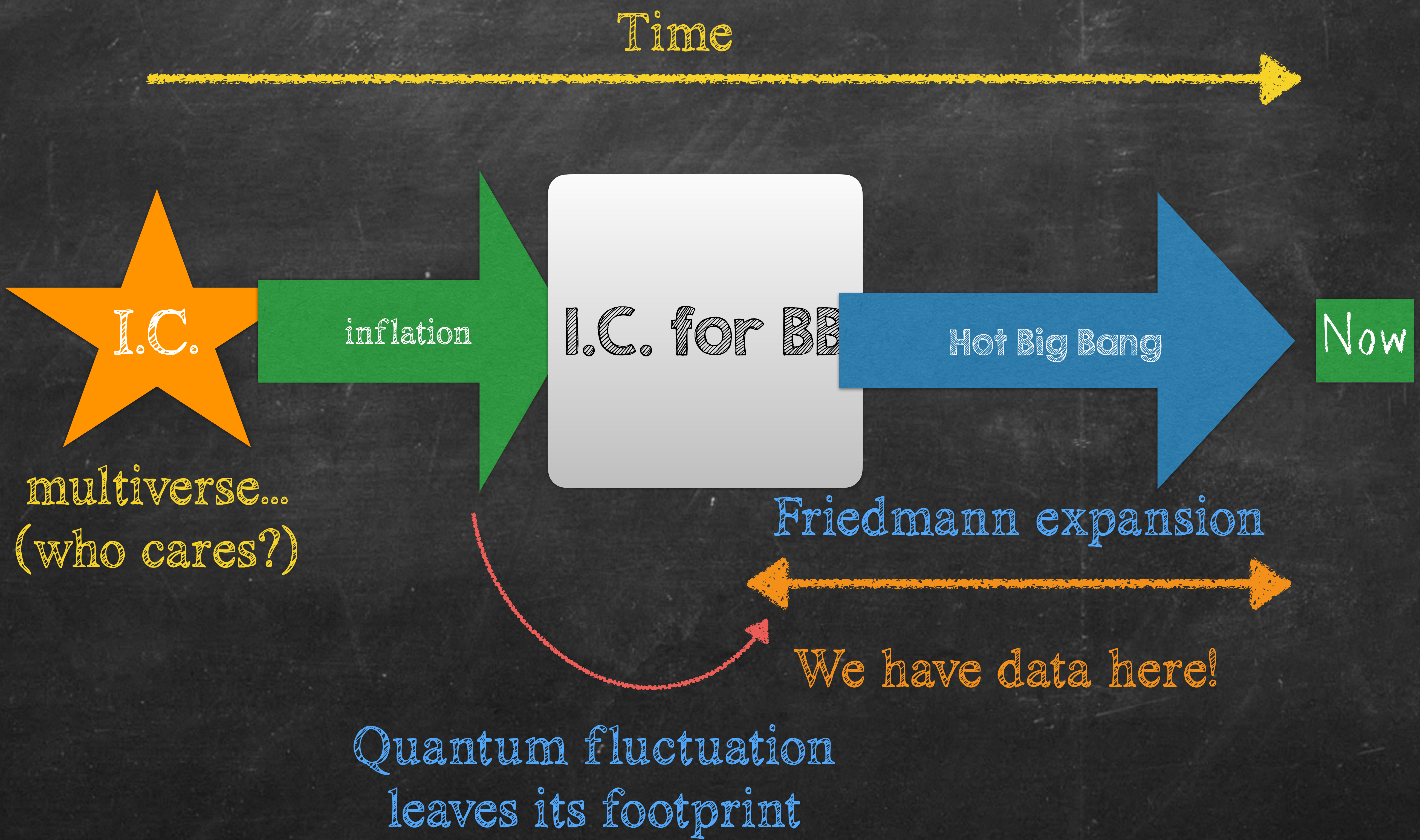
- matter is minority (1/4X) of all energy
- expansion rate accelerating

Dark Energy

# SM of cosmology

- Based on the observational features + GR, we can build a model spacetime.
- Lambda-CDM: Lambda(70%), CDM (25%), only (4-5)% by the SM of particle physics.
- Clearly we can see the room for future development in particle physics
- Not only that, the SM of cosmology has the "initial condition problems", which immediately calls for further extension of the theory: Inflation.
- Inflation resets the I.C. of the universe so that we don't care about the condition before the inflation any more.

# A modern picture of cosmology



Standard Big Bang theory

| Event | time $t$ | redshift $z$ | temperature $T$ |
|---|---|---|---|
| Baryogenesis | ? | ? | ? |
| EW phase transition | 20 ps | $10^{15}$ | 100 GeV |
| QCD phase transition | 20 $\mu$s | $10^{12}$ | 150 MeV |
| Dark matter freeze-out (Alejandro's lecture) | ? | ? | ? |
| Neutrino decoupling | 1 s | $6 \times 10^{9}$ | 1 MeV |
| Electron-positron annihilation | 6 s | $2 \times 10^{9}$ | 500 keV |
| Big Bang nucleosynthesis | 3 min | $4 \times 10^{8}$ | 100 keV |
| Matter-radiation equality | 60 kyr | 3400 | 0.75 eV |
| Recombination | 260–380 kyr | 1100–1400 | 0.26–0.33 eV |
| Photon decoupling | 380 kyr | 1000–1200 | 0.23–0.28 eV |
| Reionization | 100–400 Myr | 11–30 | 2.6–7.0 meV |
| Dark energy-matter equality | 9 Gyr | 0.4 | 0.33 meV |
| Present | 13.8 Gyr | 0 | 0.24 meV |

# Initial condition problems

# Big Bang initial condition problem (I)

universe is spatially flat -> FLATNESS PROBLEM

1. Friedmann eq.:

$$H^2 = \frac{1}{3M_{\rm Pl}^2}\left(\frac{\rho_r}{a^4} + \frac{\rho_m}{a^3} + \cdots\right) - \frac{k}{a^2}$$

$$\boxed{\frac{1}{M_{\rm Pl}^2} = 8\pi G}$$

$$1 = \Omega_{\rm tot} - \frac{k}{a^2H^2} \quad \text{->} \quad |1-\Omega_{\rm tot}| = \frac{1}{a^2H^2} = \frac{1}{\dot{a}^2}$$

Note: universe is decelerating in standard big bang theory

$$\frac{|1-\Omega_{\rm tot}|_{\rm today}}{|1-\Omega_{\rm tot}|_{\rm initial}} = \frac{\dot{a}^2_{\rm initial}}{\dot{a}^2_{\rm today}} \gg 1$$

# Big Bang initial condition problem (II)

universe is homogeneous & isotropic at large scale -> HORIZON PROBLEM

$$R_{\rm obs}(t_0) = \text{radius of observable universe today} \sim 1/H_0 \sim t_0$$

$$R_{\rm obs}(t_i) = R_{\rm obs}(t_0)\left(\frac{a_i}{a_0}\right) = t_0\left(\frac{a_i}{a_0}\right)$$

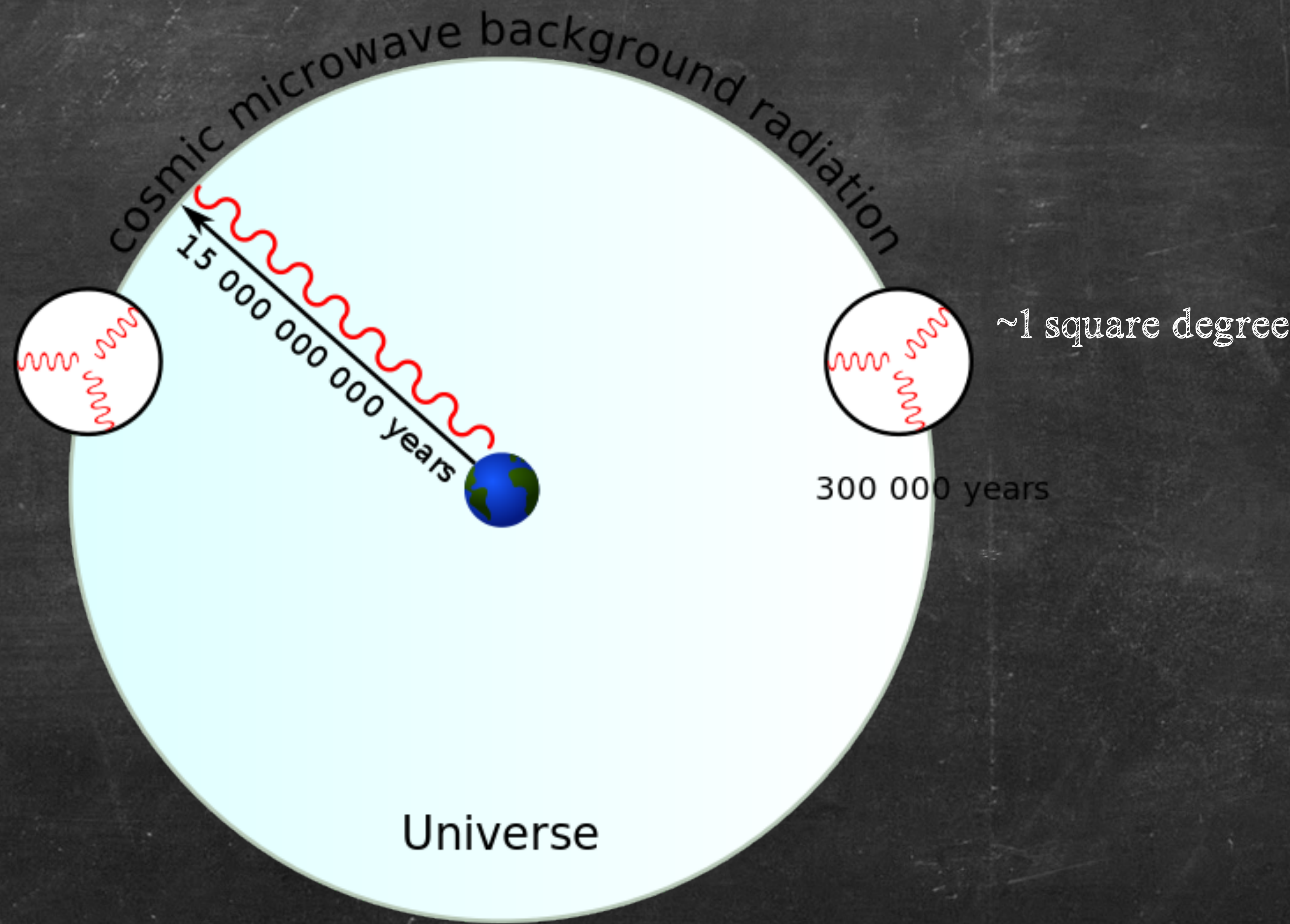
$a \sim t^n, n < 1$

$$R_{\rm causal}(t_i) = a(t_i)\int_0^{t_i}\frac{dt}{a(t)} \approx \frac{t_i}{1-n}$$

“Horizon”

$$\boxed{\frac{R_{\rm obs}(t_i)}{R_{\rm causal}(t_i)} \approx (1-n)\left(\frac{a_i}{a_0}\right)\left(\frac{t_0}{t_i}\right) \sim \left(\frac{\dot a_i}{\dot a_0}\right) \gg 1}$$

Observable radius grows faster than the causal patch in the standard BB theory




~40,000 patches are causally disconnected in CMB!

# Big Bang initial condition problem (III)

Nearly scale invariant spectrum of CMB fluctuation

$$\frac{\delta\rho}{\rho} \sim 10^{-5} \quad \xrightarrow{\text{F.T.}} \quad \Delta_s(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$n_s \sim 1$$

No obvious reason why the CMB spectrum has this feature unless having a common & simple source.

Inflation solves these problems.

# Constraint (I): flatness

recall $$H^2 = \frac{1}{3M_{\rm Pl}^2}\left(\frac{\rho_r}{a^4} + \frac{\rho_m}{a^3} + \cdots\right) \boxed{-\frac{k}{a^2}} \quad \boxed{+\frac{\rho_s}{a^{2\epsilon}}}$$

with $$\epsilon = \frac{3}{2}(1+\omega)$$

"smoothing out"

$$\omega = p/\rho$$ "eq. of state"

0 "matter"

1/3 "radiation"

-1 "cosmological constant"

To solve flatness problem, $\epsilon < 1$ $\qquad \omega < -1/3$

Q. Show the universe is accelerating with this!

# constraint (II): horizon

~amount of inflation

$$N = \log \frac{a_{end}}{a_{beg}} = \int_{t_{beg}}^{t_{end}} H dt$$

"number of e-folds before the inflation ends"

The observable universe was inside the Hubble radius
at the beginning of inflation.

$$(a_I H_I)^{-1} > (a_0 H_0)^{-1}$$

RD

$$\frac{a_0 H_0}{a_E H_E} \sim \frac{a_0}{a_E} \left(\frac{a_E}{a_0}\right)^2 = \frac{a_E}{a_0} \sim \frac{T_0}{T_E} \sim 10^{-28},$$

$$(a_I H_I)^{-1} > (a_0 H_0)^{-1} \sim 10^{28} (a_E H_E)^{-1}$$

$$\frac{a_E}{a_I} > 10^{28} \quad \Rightarrow \quad \ln\left(\frac{a_E}{a_I}\right) > 64$$

To solve the horizon problem
N>60

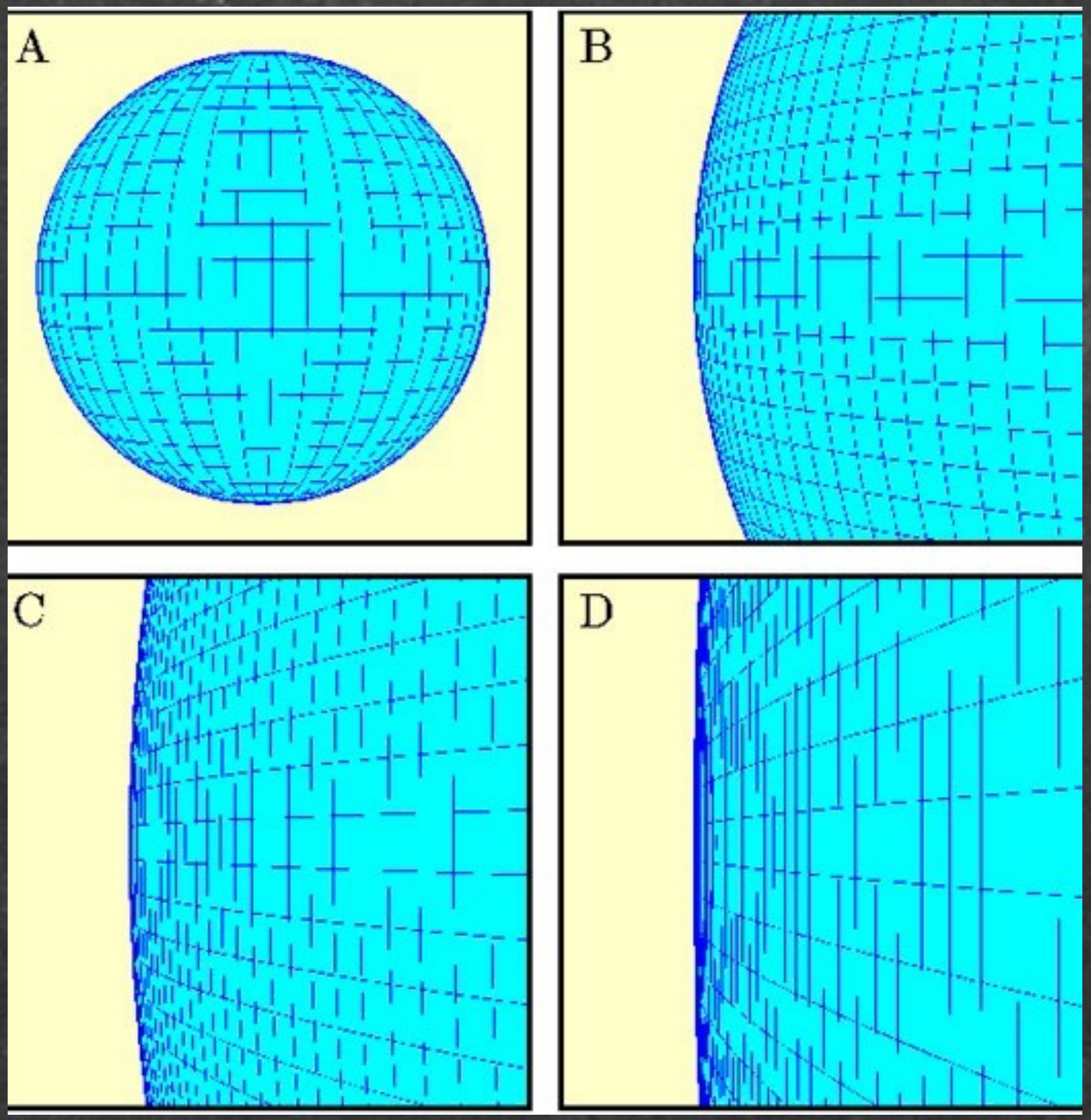
** for a lower scale, N could be smaller...

# diluting structure

- Enormous expansion ($e^{60}$ x) makes the Universe featureless (i.e. isotropic and homogeneous) Guth(1981), Albrecht-Steinhardt(1982), Linde(1982), ...
- After inflation, resulting geometry is Robertson-Walker metric

$$ds^2 = dt^2 - a(t)^2 dx^2$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$




$> 0$ during inflation (cf) $<0$, in standard Big Bang theory

# Successful model of inflation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$$\epsilon = \frac{3}{2}(1+\omega)$$

$$\omega = p/\rho$$

1. Inflation: phase with $\varepsilon(N)<1$ for $N_{tot}>N>0$
2. Sufficient inflation: $N_{tot} > 60$
3. Inflation ends: $\varepsilon(0)=1$

# A field theory model

**Coherent:**

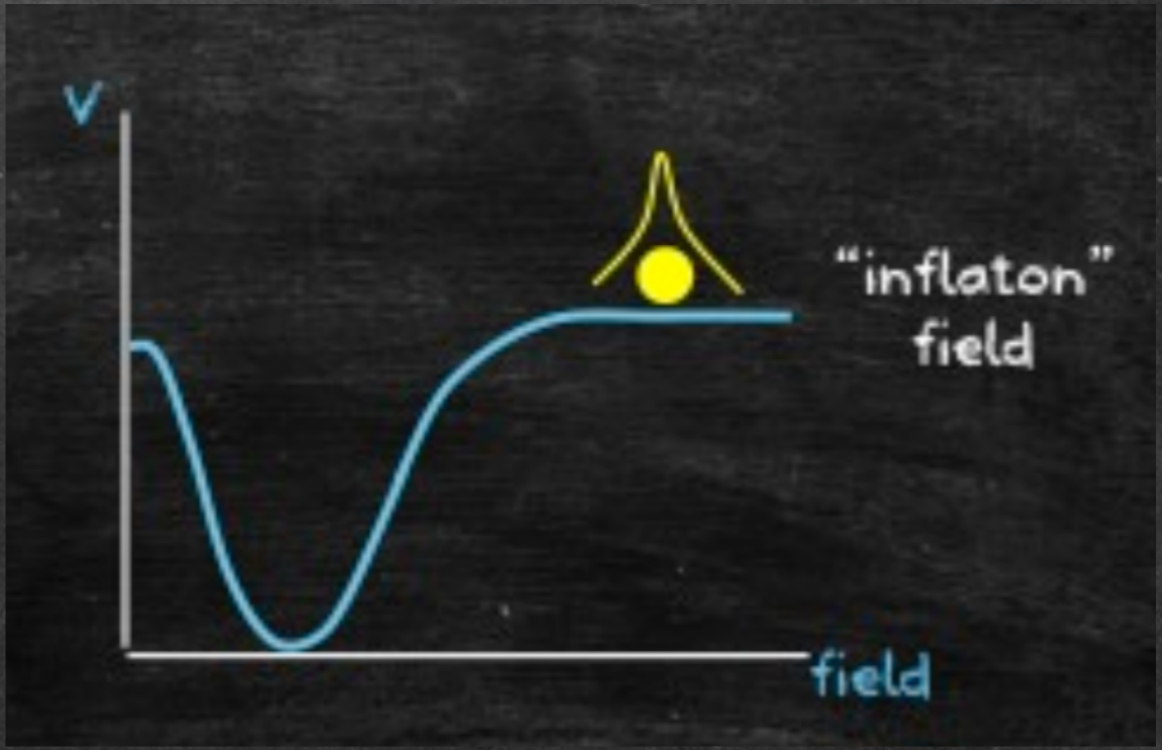
$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$T_{00} = \rho, T_{ij} = -pg_{ij} \qquad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

**slow-roll:**

$$\omega = p/\rho \sim (-V)/V = -1$$

good!




**Bonus:**
**Quantum fluctuations produce variations in time when inflation ends => seed of LSS**

Starobinski(1980), Muhkanov(1981),Linde(1982),Guth, Pi(1982)
Muhkanov(1985), Muhkanov-Sasaki(1986) ~scalar power spectrum

# Comments

- Only scalar is good. (why? vector or spinor, Lorentz symmetry is badly broken during inflation)

- Coherent: no spatial variations entire domain of our interest. BUT! quantum fluctuations are still there and contribute to density perturbation

- Slow-roll: potential energy contributes mainly and generate exponential expansion.

$$H^2 = \frac{1}{3M_{\rm Pl}^2}\rho \quad \Rightarrow \quad \frac{\dot{a}}{a} = const. \quad \Rightarrow \quad a(t) = a_0 e^{Ht}$$

$$\rho \approx V(\phi) \approx const.$$

# Slow-roll parameters

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \ll 1 \qquad \eta = M_p^2\left(\frac{V_{,\phi,\phi}}{V}\right) \ll 1$$

inflation ends when

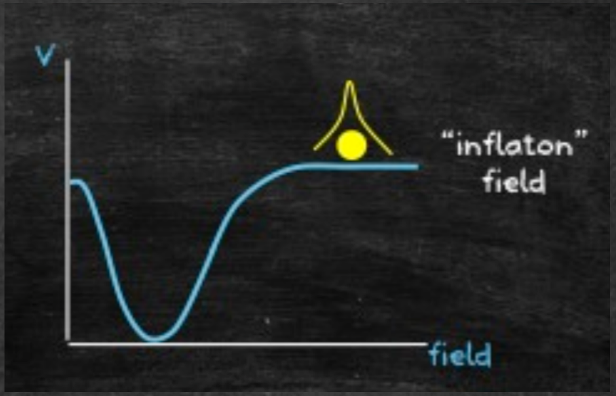
$\varepsilon=1$

# density perturbation

density perturbation ~ spatial variations the scale factor

$$ds^2 = dt^2 - a(t)^2 e^{2\zeta(t,x)} dx^2$$

(gauge invariant)
curvature perturbation




**recall:** $a \sim e^N \sim e^{Ht}$

$$\zeta \sim \delta N_k = H\delta t = (H/\dot{\phi})\delta\phi \sim (H/\dot{\phi})H \sim \sqrt{\frac{\rho}{\epsilon}}$$

$\delta\phi \sim H$ when mode leaves horizon

$$\therefore \sqrt{\frac{V}{\epsilon}} \sim \frac{\delta\rho}{\rho} \sim 10^{-5}$$ COBE

**scale of inflation:** $V^{1/4} \sim \epsilon^{1/4}(\delta\rho/\rho)^{1/2} \sim 10^{-5/2}\epsilon^{1/4}$

# Reheating

- At the end of inflation, the universe gets cold (~ 0 K)
- To reheat the universe, there should be some way to convert the inflaton energy to the standard model particles and possibly BSM particles too. (ex) Inflaton decay, oscillation near the mimimun of the potential with friction(expansion itself!) ...
- $T_{rh}$ is the highest temperature ... GUT/EW/even lower temperature may be allowed.
- The conventional Big Bang expansion gets started after reheating.

# Observables

- The quantum fluctuation of the inflaton grows and eventually form a seed of Large scale structure.
- The amount of perturbation (scalar and tensor) is completely decided by the slow roll parameters and eventually seen in e.g. the CMBR measurements.
- Scalar mode perturbation => tilt in spectral index ($n_s$)
- tensor perturbation => primordial gravitational waves (r =T/S)

$$n_s = 1 + 6\epsilon - 2\eta \qquad r = 16\epsilon$$

The CMB measures distortions in space:

$\zeta$

scalar mode

$$d\ell^2 = a^2(t)\Big[1 + \underbrace{\overset{\text{expansion}}{}2\zeta(t,\boldsymbol{x})}_{\text{curvature perturbation}}\Big]\delta_{ij}x^i dx^j$$

isotropic stretching

$h_{ij}$

tensor mode

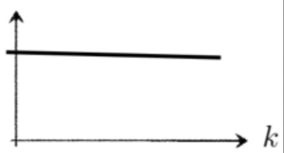
$$d\ell^2 = a^2(t)\Big[\delta_{ij} + \underbrace{h_{ij}(t,\boldsymbol{x})}_{\text{gravitational waves}}\Big]x^i dx^j$$

anisotropic stretching

**_Primordial Perturbations from Inflation_**

We have arrived at a famous result:

$$\boxed{\Delta^2_\zeta(k) = \frac{1}{8\pi^2}\frac{H^4}{\dot\phi^2}} \equiv A_s\left(\frac{k}{k_\star}\right)^{n_s-1}$$




Mukhanov and Chibisov
Bardeen, Steinhardt and Turner
Starobinsky
Hawking

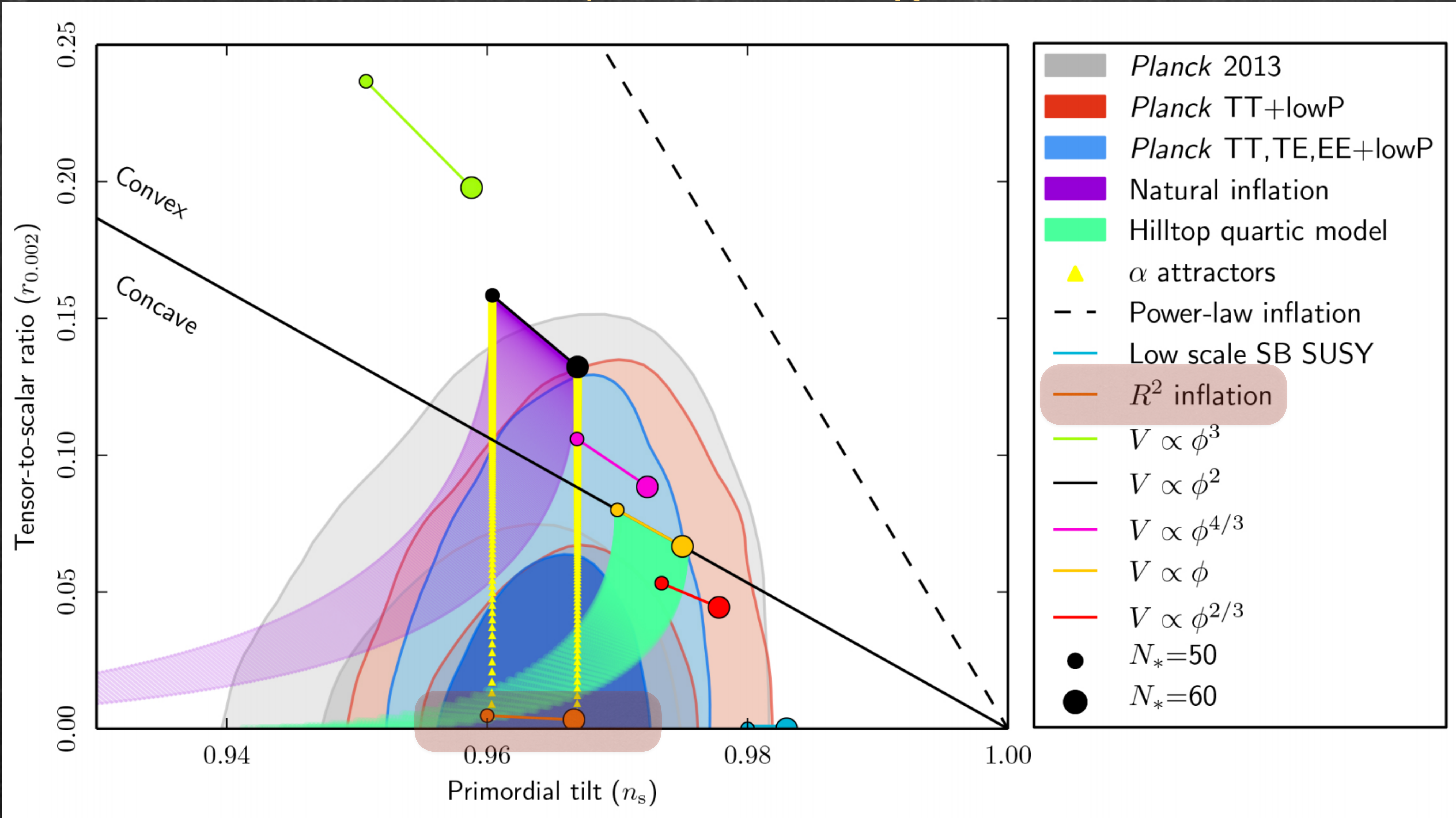
evaluated at $k = aH$

Quantum fluctuations also create gravitational waves:

$$\boxed{\Delta^2_h(k) = \frac{2}{\pi^2}\frac{H^2}{M^2_{\rm pl}}} \equiv A_T\left(\frac{k}{k_*}\right)^{n_T} \qquad r = A_T/A_s$$

Starobinsky

# Planck 2015



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
Convex
Concave
*Planck* 2013
*Planck* TT+lowP
*Planck* TT,TE,EE+lowP
Natural inflation
Hilltop quartic model
$\alpha$ attractors
Power-law inflation
Low scale SB SUSY
$R^2$ inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
$N_*$=50
$N_*$=60

# A New Type of Isotropic Cosmological Models Without Singularity

Alexei A. Starobinsky (Cambridge U. & Landau Inst.)

R$^2$ inflation

1980 - 4 pages

**Phys.Lett. B91 (1980) 99-102**
In *Khalatnikov, I.M. (ed.), Mineev, V.P. (ed.): 30 years of the Landau Institute* 771-774
(1980)
DOI: 10.1016/0370-2693(80)90670-X

**Abstract** (Elsevier)
The Einstein equations with quantum one-loop contributions of conformally covariant matter fields are shown to admit a class of nonsingular isotropic homogeneous solutions that correspond to a picture of the Universe being initially in the most symmetric (de Sitter) state.

$$S = \int d^x \sqrt{g}\, \left[R + \boxed{\alpha R^2} + \cdots\right] \qquad M_P = 1$$

$$\to V(\sigma) = \frac{1}{\alpha}\left(1 - e^{-\sqrt{2/3}\sigma}\right)^2$$

[COBE] $\boxed{\alpha \sim 10^{10}}$ Problem?

# Starobinsky inflation
# =NM inflation (a.k.a. Higgs inflation)

$$S = \int d^4x \sqrt{g}\left((1+\boxed{\xi\phi^2})R + \boxed{(\partial\phi)^2} - \lambda\phi^4\right)$$

**Compatible with all symmetries so that should be allowed in EFT

**During inflation kinetic energy is not important so that ϕ is regarded as an auxiliary field.

$$\delta\phi : 2\xi\phi R - 4\lambda\phi^3 = 0 \quad \rightarrow \quad \phi^2 = \frac{\xi}{2\lambda}R$$

$$S = \int d^4x \sqrt{g}\left(R + \boxed{\frac{\xi^2}{4\lambda}}R^2 + \cdots\right)$$

same as R2 model!

$$\alpha = \frac{\xi^2}{4\lambda}$$

# Further generalization?

$R^2$ => $F(R)$+GB +$C^2$ ⟷ dual ⟷ Higgs inflation

with Emir Gumrukcuoglu, Shinji Mukohayma

(under progress)

# so?

- Inflation is good
- Starobinsky's model ($R^2$) apparently gives the best fit to the data...
- ...and $R^2$ is equivalent to a scalar model with NM coupling
- Can this scalar field = the Higgs in the SM?

# Higgs physics

see e.g. S. Kanemura's talk

# "Higgs precision era"

$H^0$ PDG 2016 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV

**$H^0$ Signal Strengths in Different Channels**

See Listings for the latest unpublished results.

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$WW^* = 0.81 \pm 0.16$
$ZZ^* = 1.15^{+0.27}_{-0.23}$ (S = 1.2)
$\gamma\gamma = 1.17^{+0.19}_{-0.17}$
$b\bar{b} = 0.85 \pm 0.29$
$\mu^+\mu^- < 7.0$, CL = 95%
$\tau^+\tau^- = 0.79 \pm 0.26$
$Z\gamma < 9.5$, CL = 95%
$t\bar{t}H^0$ Production $= 2.5^{+0.9}_{-0.8}$

# The SM Higgs potential

$$V(h) = \boxed{\frac{1}{2}(125\mathrm{GeV})^2} h^2 + \boxed{\frac{1}{8}(246\mathrm{GeV})} h^3 + \boxed{\frac{1}{32}} h^4$$

$$\lambda v^2 = \frac{m_h^2}{2} \qquad \lambda v \qquad \frac{\lambda}{4}$$

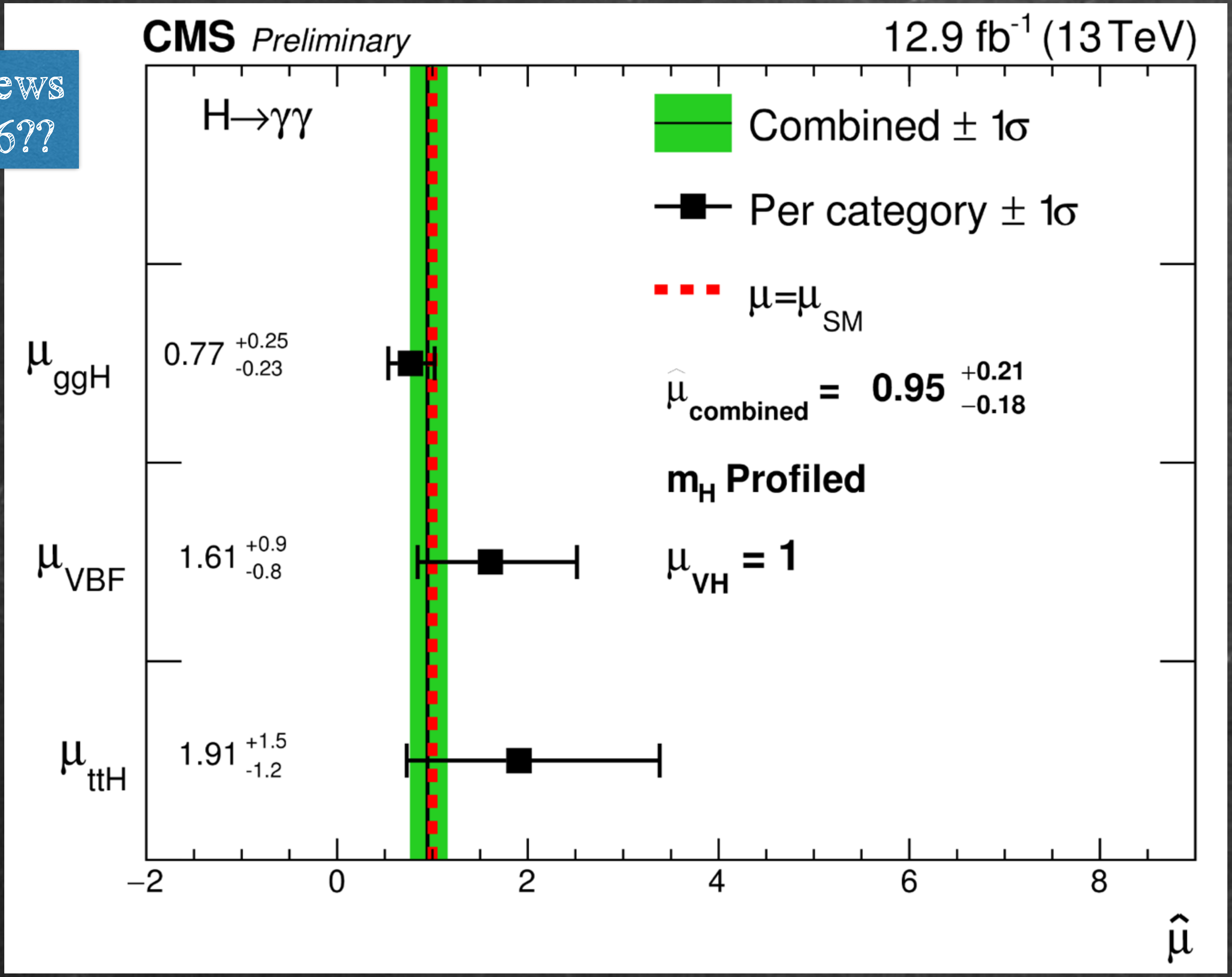
measured predicted predicted

see Shinya's talk

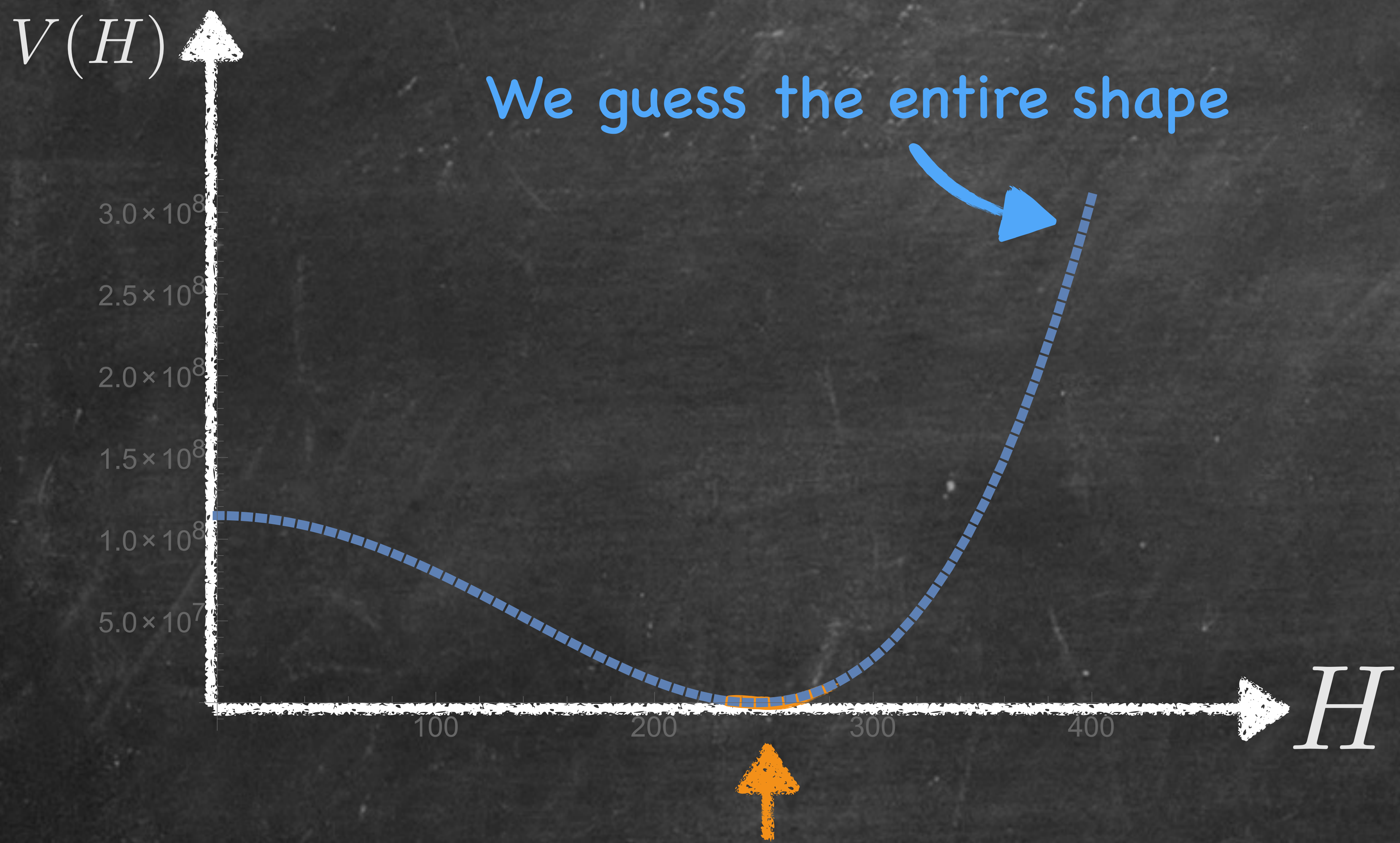
# All consistent with the SM (LHC Run-2)

NEW! 2016

The only good news from ICHEP2016??



# wait!




We guess the entire shape

We've measured V''(=mass^2) only here!

# Self interactions of the Higgs (never been checked so far)

h-h-h

$\lambda v$

h-h-h-h

$\frac{\lambda}{4}$

**predicted** **predicted**

**These provide good motivation for future colliders

Finally!

Higgs inflaton

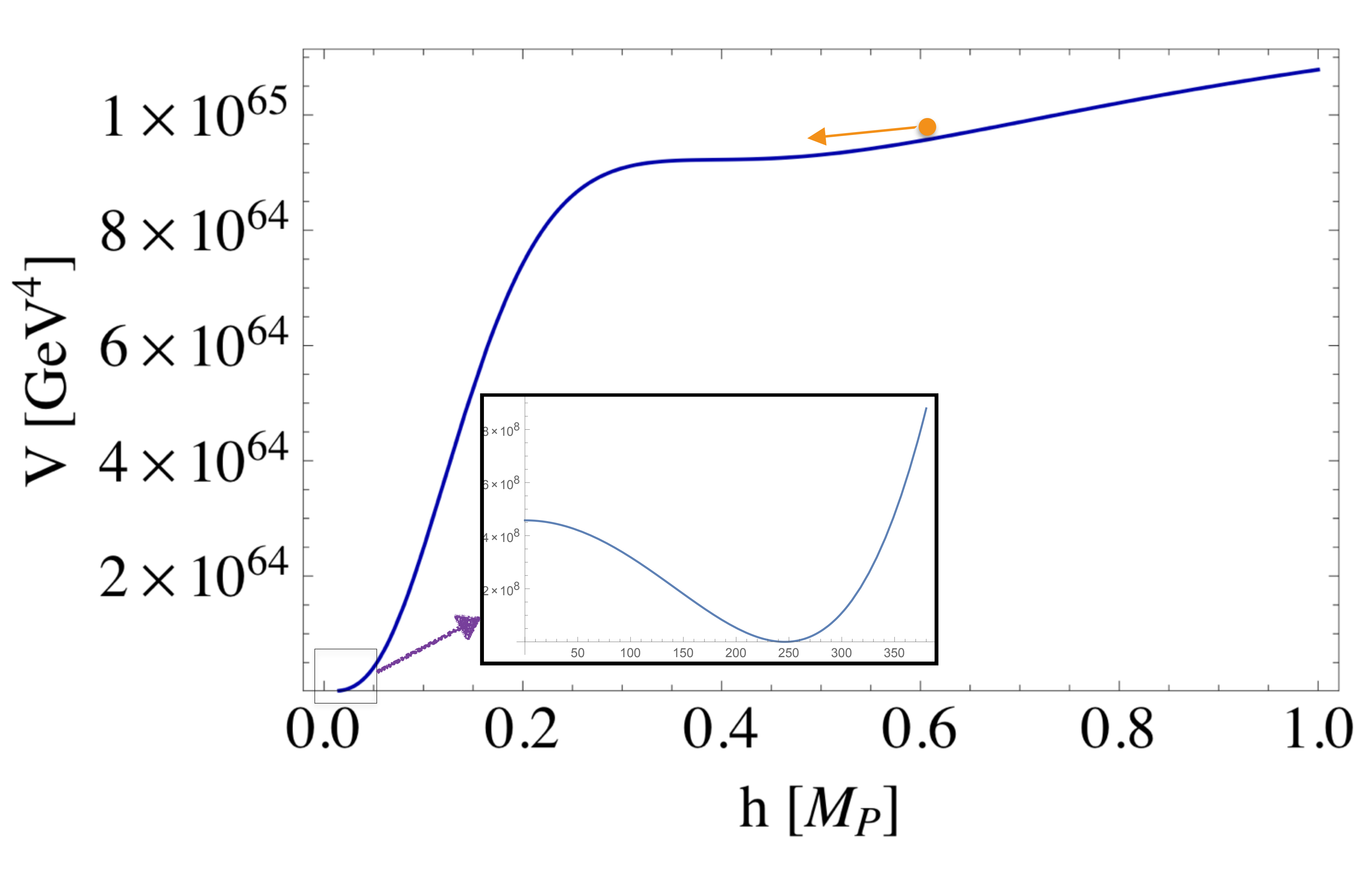
# Higgs inflation

An economical and predictive idea :

**Higgs=Inflaton**

- at low scale (~100 GeV) responsible for EWSB
- at high scale (~$10^{17}$ GeV) responsible for cosmic inflation

# Higgs potential
# 2-loop + NM




[Hamada, Kawai, Oda, SCP, PRL 2014]

# Lagrangian

$$S = \int d^4x\sqrt{g}\left[\frac{M_P^2 + \xi|H|^2}{2}R + |DH|^2 - V(H) + \mathcal{L}_{\mathrm{SM}}\right]$$

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

- Non-minimal coupling has the same energy dimension with Planck^2
- Self coupling~1/8 @ EW scale but the value reduced @ GUT scale.
- We can always find a Weyl transformations s.t. find Einstein frame.

# Jordan->Einstein

SCP, Yamaguchi (2008)

Bezrukov, Shaposhnikov (2008) for K(ph)=xi ph^2

$$S_J = \int d^4x\sqrt{g}\left[\frac{M^2+K(\phi)}{2}R + |DH|^2 + V(H)\right]$$

$$g_{\mu\nu} \to g^E_{\mu\nu} = e^{2\omega} g_{\mu\nu}$$

$$e^{2\omega} = \frac{M^2+K}{M_P^2}$$

for monotonic K

$$V_E = \frac{M_P^4}{(M^2+K)^2}V_J \to \frac{V_J}{K^2} \to const.$$

$$\frac{\partial H_E}{\partial H_J} = \sqrt{e^{-2\omega} + \frac{3}{2}e^{2\omega}K'^2}$$

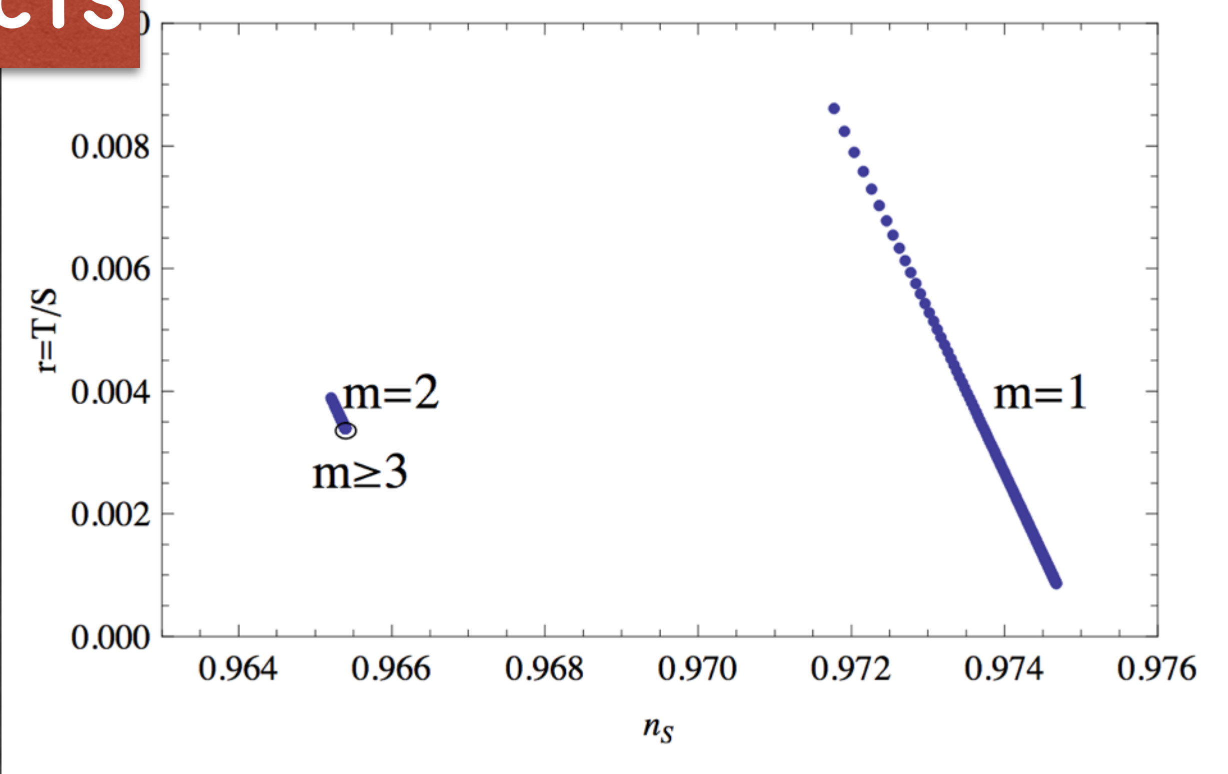
$$S_E = \int d^4x\sqrt{g_E}\left[\frac{M_P^2}{2}R_E + |DH_E|^2 - V(H_E)\right]$$

famous flat potential

for Higgs inflation: $V_J = \lambda H_J^4, K = \xi H_J^2$ -> $V_E \to \frac{\lambda}{\xi^2}M_P^4$

# Park-Yamaguchi (2007)

**w/o RG-effects**




$$U(\varphi) := \frac{V(\varphi)}{A(\varphi)^2}.$$

$$A(\phi) = 1 + a\phi^m$$
$$V(\phi) = \frac{\lambda}{2m}\phi^{2m}$$

monomial potential

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

# COBE normalization

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

$$\frac{V_E}{\epsilon} = (0.027 M_P)^4$$

$$\boxed{\frac{\lambda}{\xi^2} = 0.027^4 \epsilon \sim 4 \times 10^{-10}}$$

or $\xi \sim \frac{\sqrt{\lambda} \cdot 10^5}{2}$

Problem?

1. If Higgs self coupling λ is O(1), xi=O(10^5)
2. However, in the SM, λ becomes small at a high scale! Indeed, even λ=0 is within the current uncertainty.
3. If λ is small enough @ inflation scale, xi can be O(1).

# RG running of lambda

self int.

gauge int.

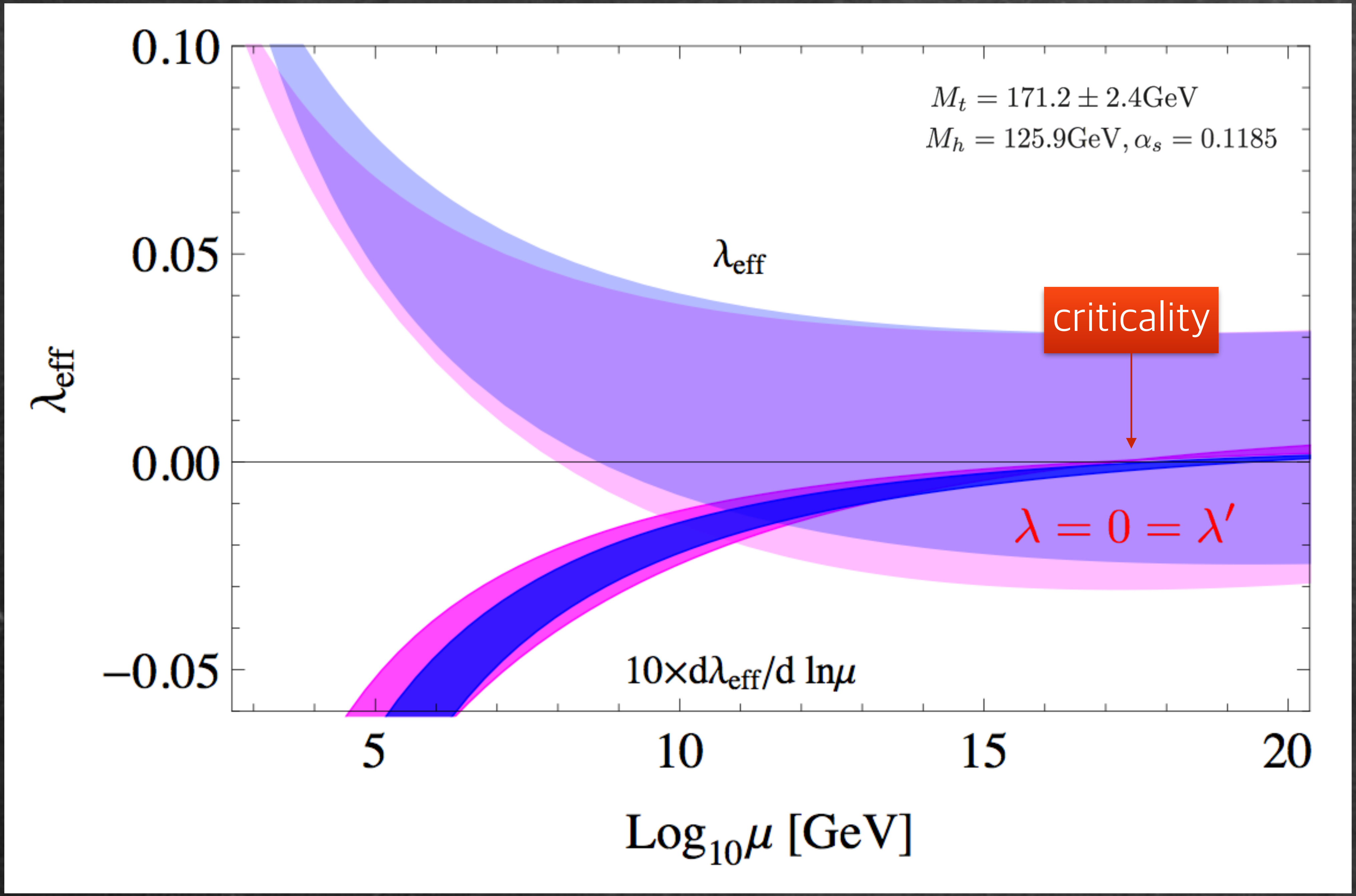
$$(4\pi)^2 \frac{d\lambda}{d\ln\bar{\mu}^2} = -3y_t^4 + 6y_t^2\lambda + 12\lambda^2 + \frac{9}{16}\left(g_2^4 + \frac{2}{5}g_2^2 g_1^2 + \frac{3}{25}g_1^4\right) - \frac{9}{2}\lambda\left(g_2^2 + \frac{g_1^2}{5}\right) + \cdots$$

Top quark Yukawa

$$y_t = \frac{\sqrt{2}m_t}{v} \approx 0.98$$

This dominates over other interactions.

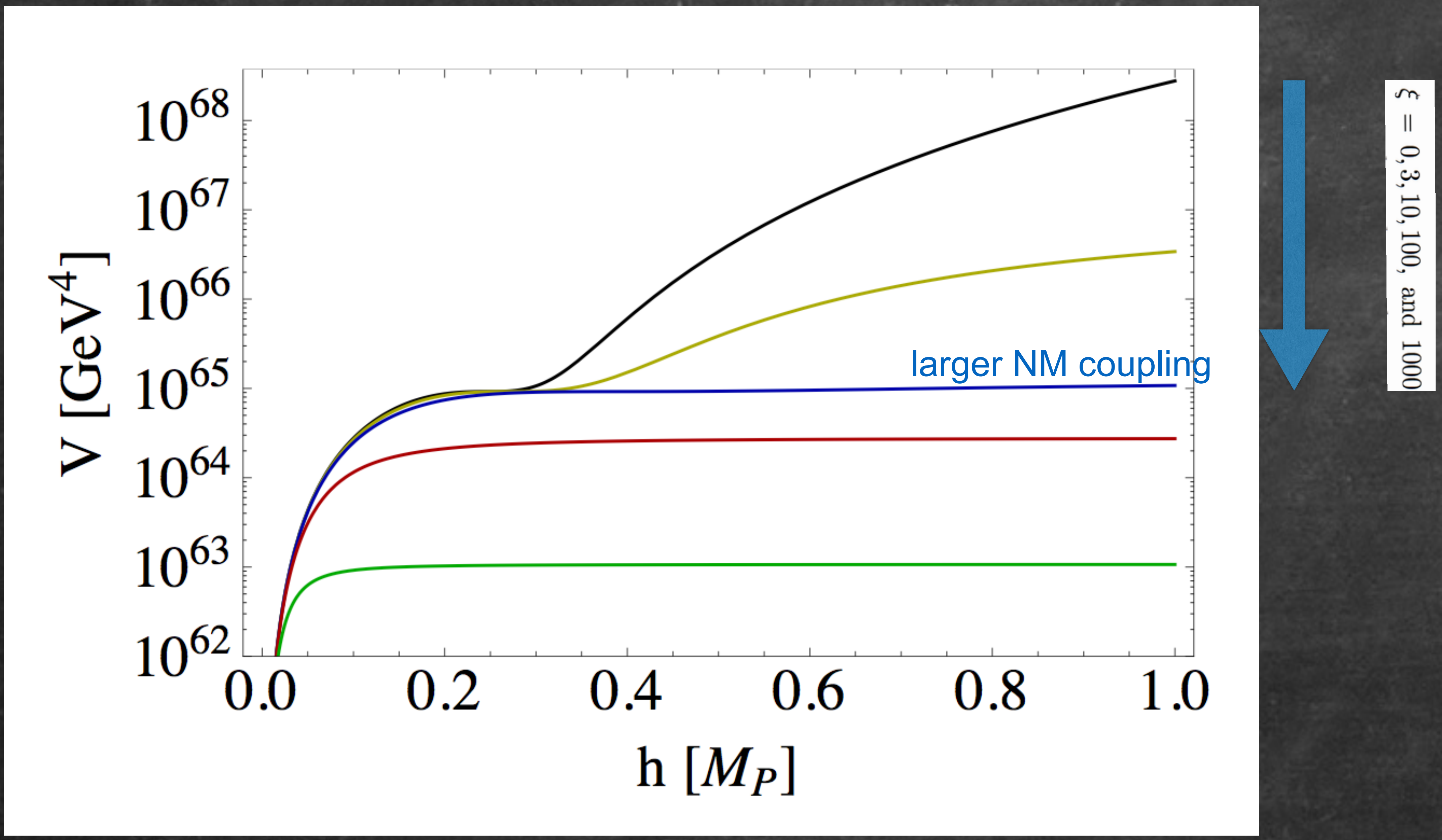
# 2-loop effective coupling




[Hamada, Kawai, Oda, SCP, PRL 2014]

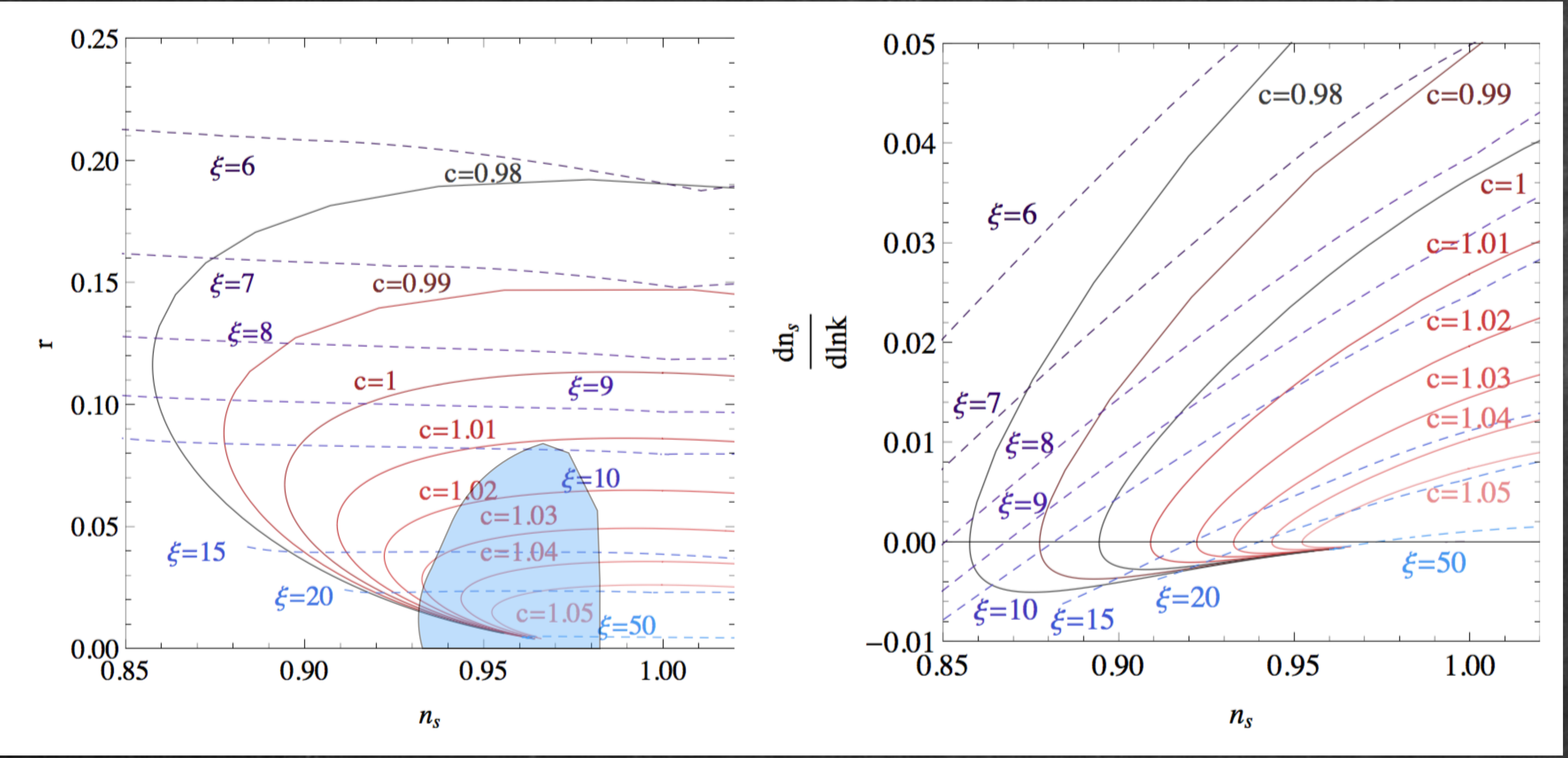
# w/ RG Effect

[Hamada, Kawai, Oda, SCP, PRL 2014, PRD2015]



# w/ RG Effect

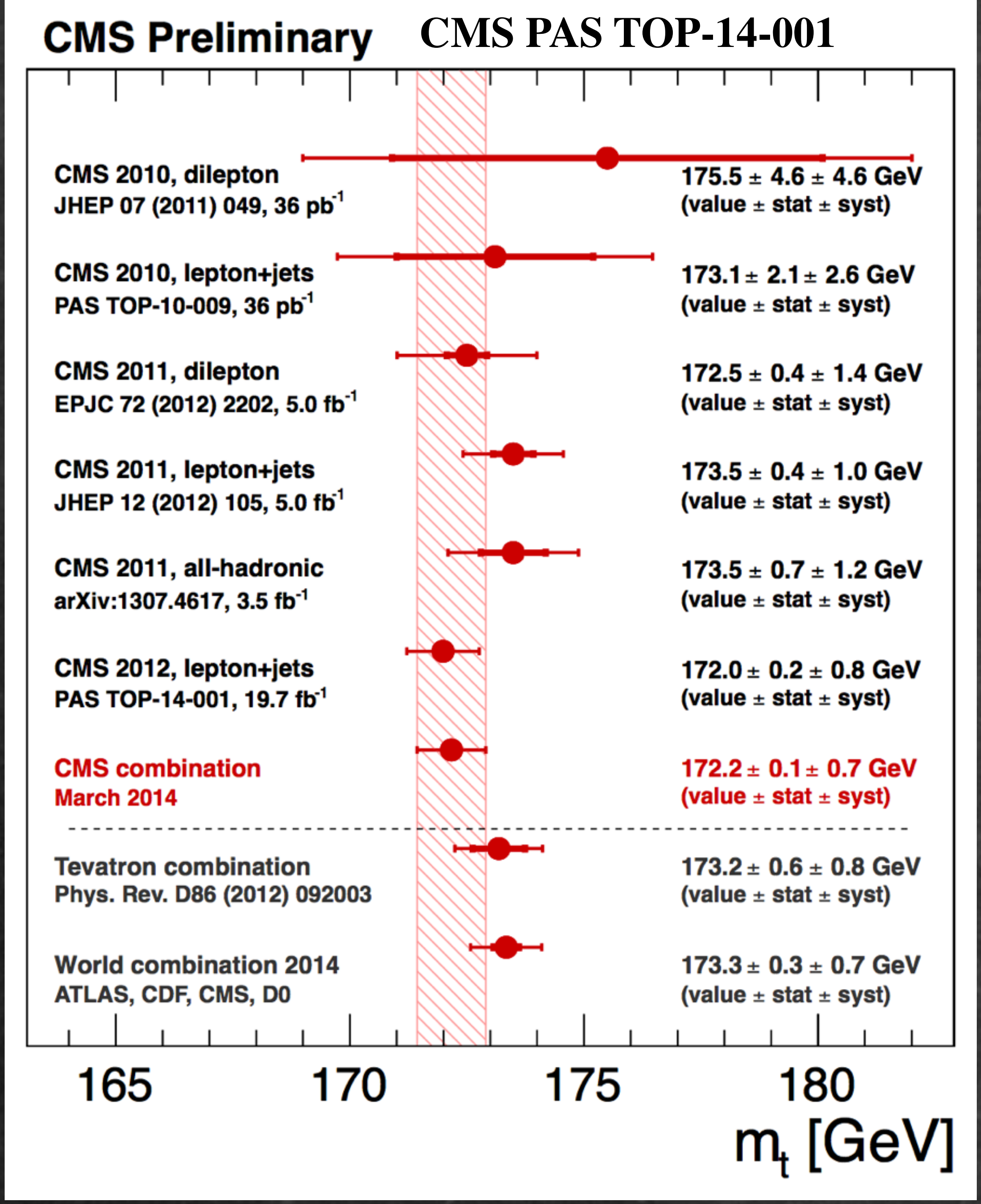
[Hamada, Kawai, Oda, SCP, PRL 2014, PRD2015]



# interesting correlation

- The shape of the Higgs potential at high scale is deeply connected to the cosmological inflation
- The shape is provided from the quantum corrections with the top quark Yukawa coupling.
- By measuring inflationary data, we may be able to measure the Top quark mass with great precision!

# Current status of top quark mass




**NEW**

$$172.08 \pm 0.36 \pm 0.83$$

[CMS PAS TOP-14-002]

- Error remains still big~GeV
- To reduce the error, one should have better understanding of "MC mass" but this is tough!

# Criticality predicts Top quark mass with a great precision!

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

# summary

- Inflation provides I.C. for the conventional Big Bang expansion.
- Higgs inflation is a compelling framework, which accommodates not only EWSB but also cosmological inflation.
- Particle physics data is directly relevant to cosmology and vice versa.
- Precision measurement from cosmology (e.g. r=T/S) would provide a way to measure the particle physics properties (e.g. mt, alphas, etc.)