Higgs-R^2 model as a UV-extension of Higgs inflation and violent preheating

based on:

Minxi He (Tokyo), Ryusuke Jinno (IBS-CTPU), KK, Seong Chan Park (Yonsei), Alexey Starobinsky (Landau), Jun'ichi Yokoyama (Tokyo), PLB 791(2019) 36, arXiv:1812.10099 [hep-ph]

Kohei Kamada
(RESCEU, U-Tokyo)

IBS-CTPU, PTC seminar

20/03/2019 @ IBS-CTPU, Daejeon, Korea

Courtesy H.Oide

1. Introduction:
   UV issues in Higgs inflation
2. UV extension of Higgs inflation with R^2-term
3. Inflaton oscillation and violent preheating
4. Discussion

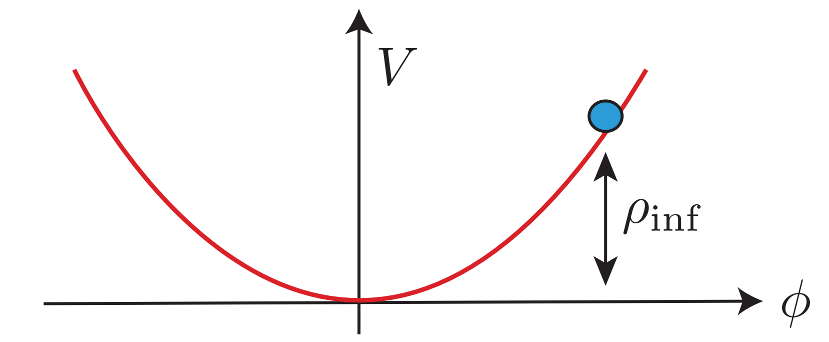
Courtesy H.Oide

Introduction

Courtesy H.Oide

Premise

Inflation is now a main ingredient of the standard Cosmology



$$3H\dot{\phi} + V' = 0, \quad 3H^2 M_{\rm pl}^2 = V$$

- Solution to horizon & flatness problem
- Seed for the structure of the Universe
- Driven (often) by potential energy of scalar field(s).

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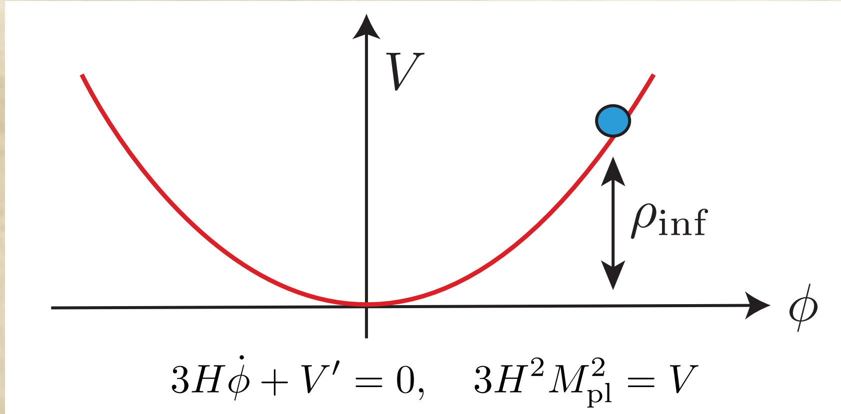

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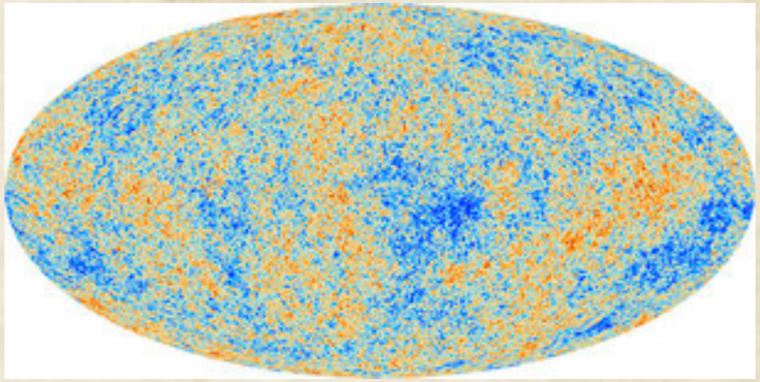

Planck collaboration

- Strongly favored by cosmological obs.

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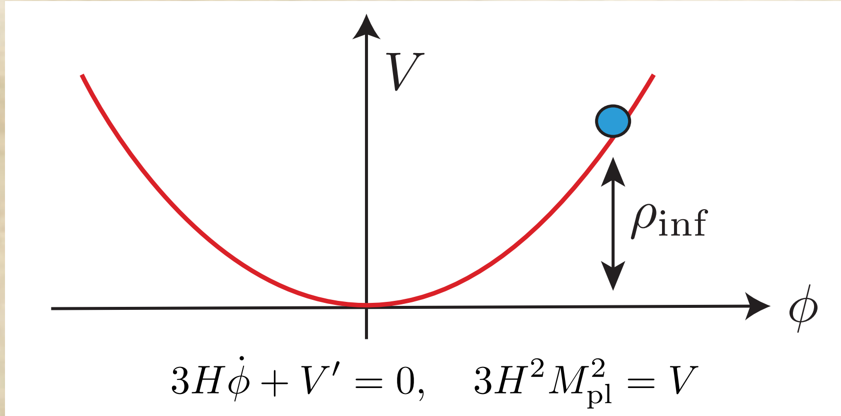

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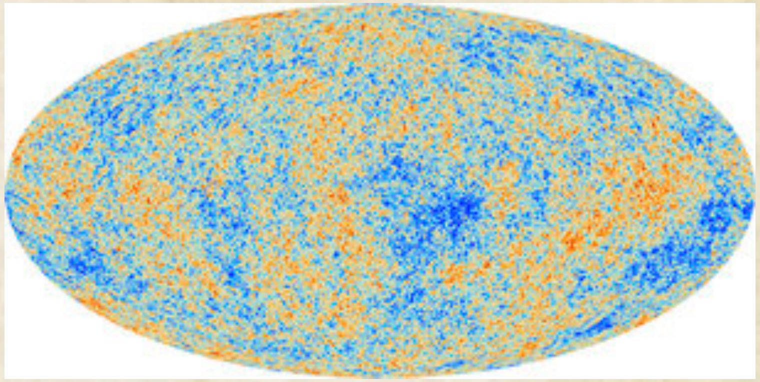

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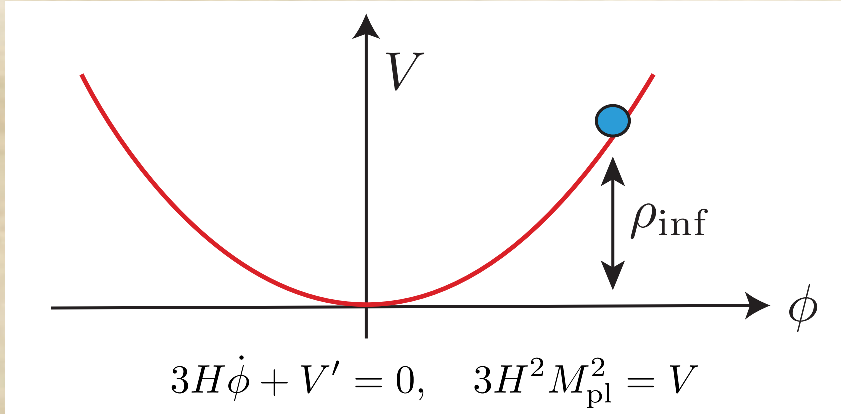

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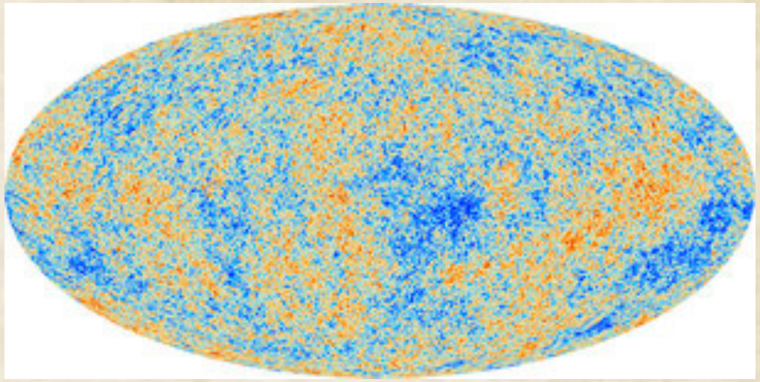

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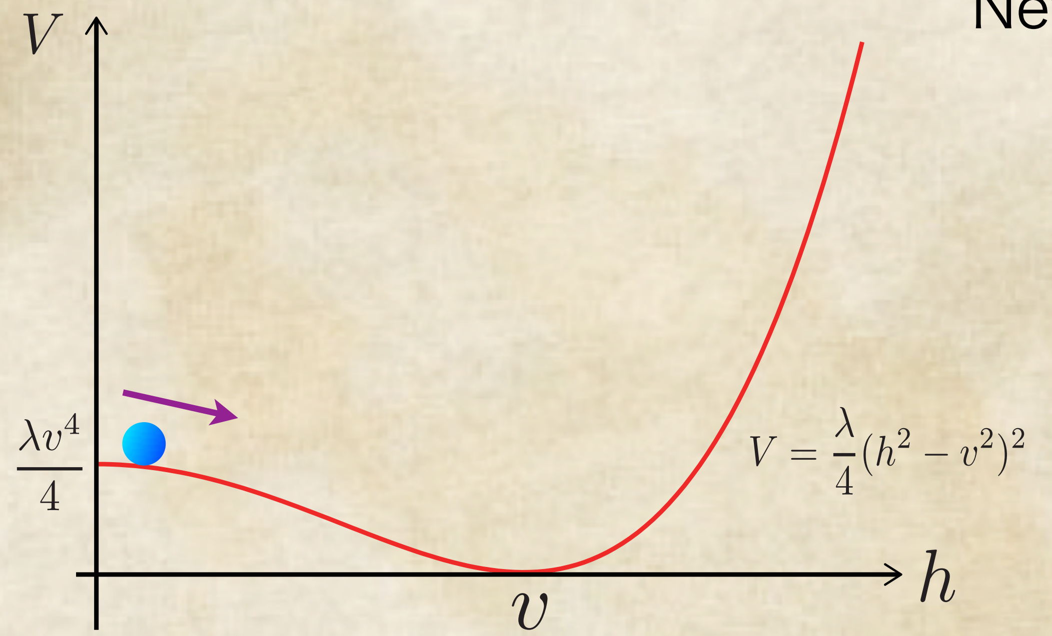
What is the scalar field (inflaton) that drove inflation?

Why don't we use the SM Higgs as inflaton?

Courtesy H.Oide

Question:

Why have people regarded that SM Higgs is not inflaton?



New inflation? ('82, Linde)

: impossible because the potential is too steep to realize accelerating expansion of the Universe.

Courtesy H.Oide

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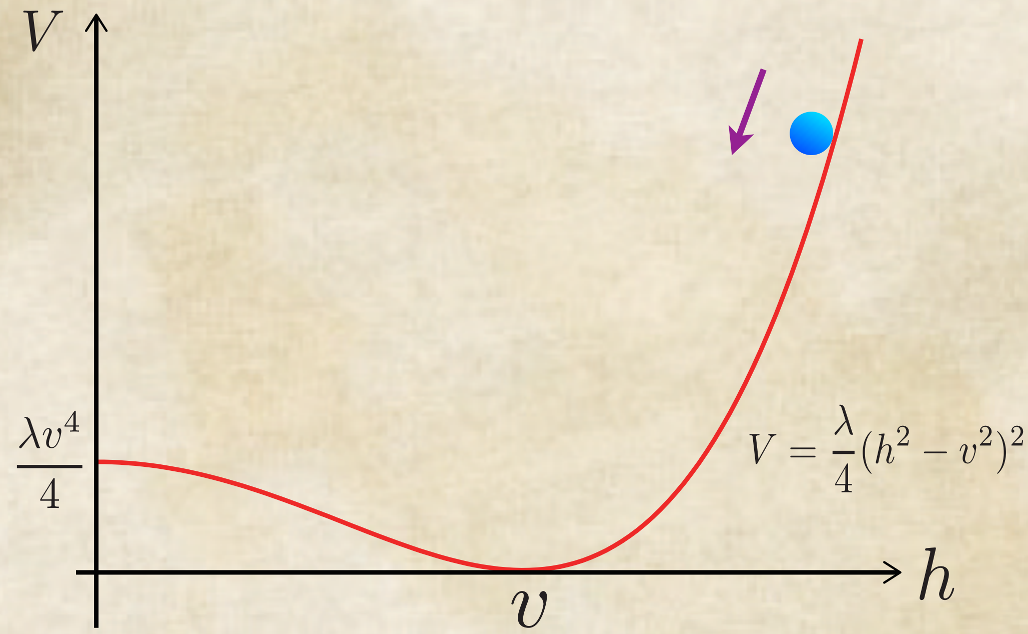

Chaotic inflation? ('83, Linde)

: possible to realize accelerating expansion of the Universe, but the primordial density perturbation becomes too large.

$$\mathcal{P}_\zeta \sim 10^3 \lambda \quad \text{for} \quad V = \frac{\lambda}{4}\phi^4$$

$\lambda_{\rm Higgs} \sim \mathcal{O}(1)$ is inconsistent with the observation $\mathcal{P}_\zeta^{\rm obs} \simeq 2.18 \times 10^{-9}$

Courtesy H.Oide

The problem is too large primordial perturbations.

$$g_{ij} = a^2(t) e^{2\zeta} \delta_{ij}$$

$$\langle \zeta(k)\zeta(k') \rangle = \frac{2\pi^2}{k^3} \mathcal{P}_\zeta(k) \delta^{(3)}(k + k')$$

This should be $\sim 10^{-9}$ from observation.

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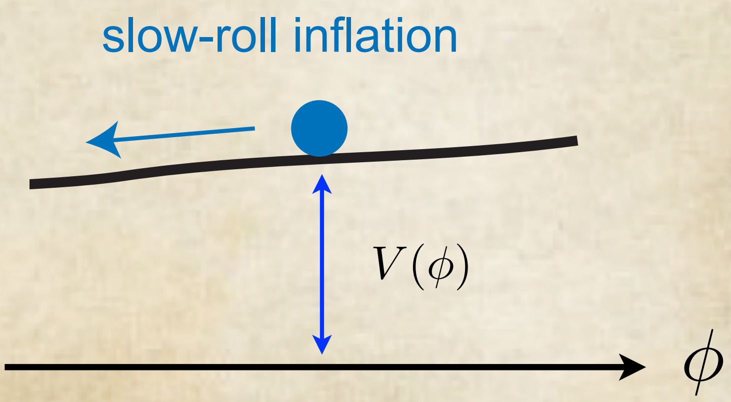
For slow-roll inflation, the power spectrum can be written in terms of the Hubble parameter during inflation $H_{\rm inf}$ and a slow-roll parameter $\epsilon \equiv \frac{M_{\rm pl}^2}{2} \left(\frac{V'}{V} \right)^2$

$$\mathcal{P}_\zeta = \frac{H_{\rm inf}^2}{8\pi^2 \epsilon M_{\rm pl}^2}$$



Courtesy H.Oide

In other words, if one can control the Higgs field dynamics to change the parameters,

- Hubble parameter during inflation
- slow-roll parameter during inflation
- (effective) Planck scale

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the possibility of "Higgs inflation" comes back.

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the possibility of "Higgs inflation" comes back.

It can be realized by introducing additional terms to the Higgs interaction, with taking care not to affect low-energy phenomenology.

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

Unitary gauge

$$H = (0, (h(x) + v)/\sqrt{2})$$

Courtesy H.Oide

In other words, if one can control the Higgs field dynamics to change the parameters,

Non-minimal gravitational and derivative coupling can make inflation driven by the SM Higgs possible.

⇨ Generalized Higgs inflation ('11, '12 KK+)
with the spirit of Horndesky theory.

cf. Gansukh's latest paper 1903.05354.

Higgs interaction, with taking care not to affect low-energy phenomenology.

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

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In other words, if one can control the Higgs field dynamics to change the parameters,

Nor

can

54.

I believe, in the absence of any deviations from the standard prediction of inflation in the CMB observation and any new physics signature at LHC, it is important to investigate the inflation model driven by the SM Higgs in depth.

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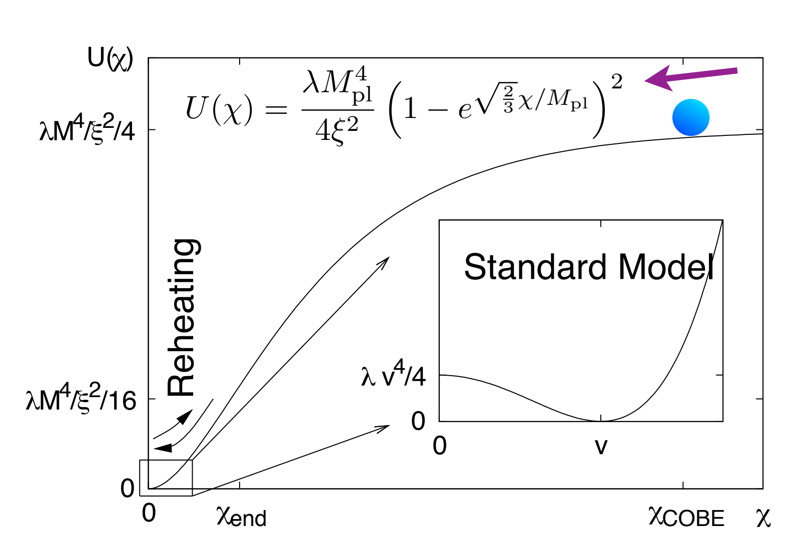
Among many proposals of inflation driven by the SM Higgs, the one with a nonminimal coupling to gravity $\xi|\mathcal{H}|^2 R$

('95 Cerventas-Cota & Dehnen, '08 Bezrukov & Shaposhnikov)

would be the most remarkable one.

Simplest model of inflation driven by the SM Higgs, with a classical *scale-invariant* extension of the SM!



'08 Bezrukov & Shaposhnikov

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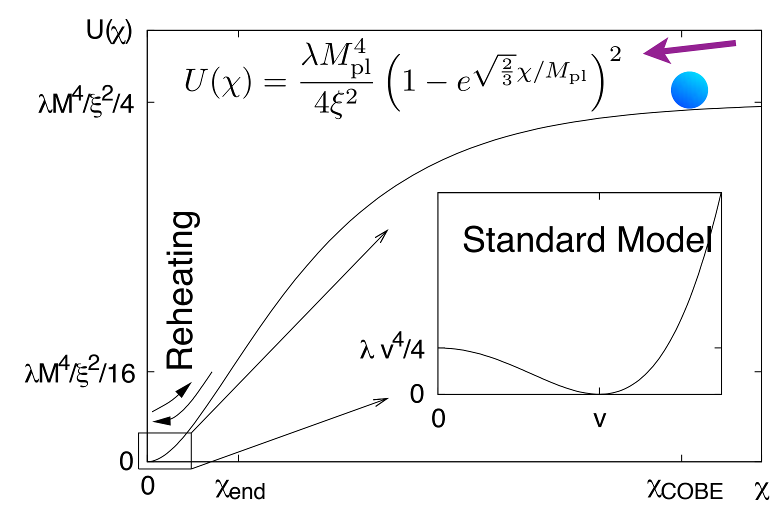

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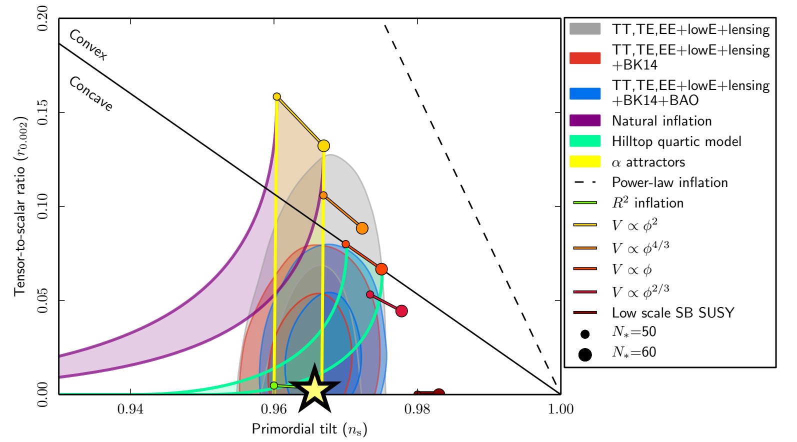


Fig. 8. Marginalized joint 68 % and 95 % CL regions for n_s and r at k = 0.002 Mpc^{-1} from *Planck* alone and in combination with BK14 or BK14 plus BAO data, compared to the theoretical predictions of selected inflationary models. Note that the marginalized joint 68 % and 95 % CL regions assume $dn_s/d\ln k = 0$.

'18 Planck collaboration

It also fits the CMB data ($n_s - r$) very well!!!

Courtesy H.Oide

Obstacles?

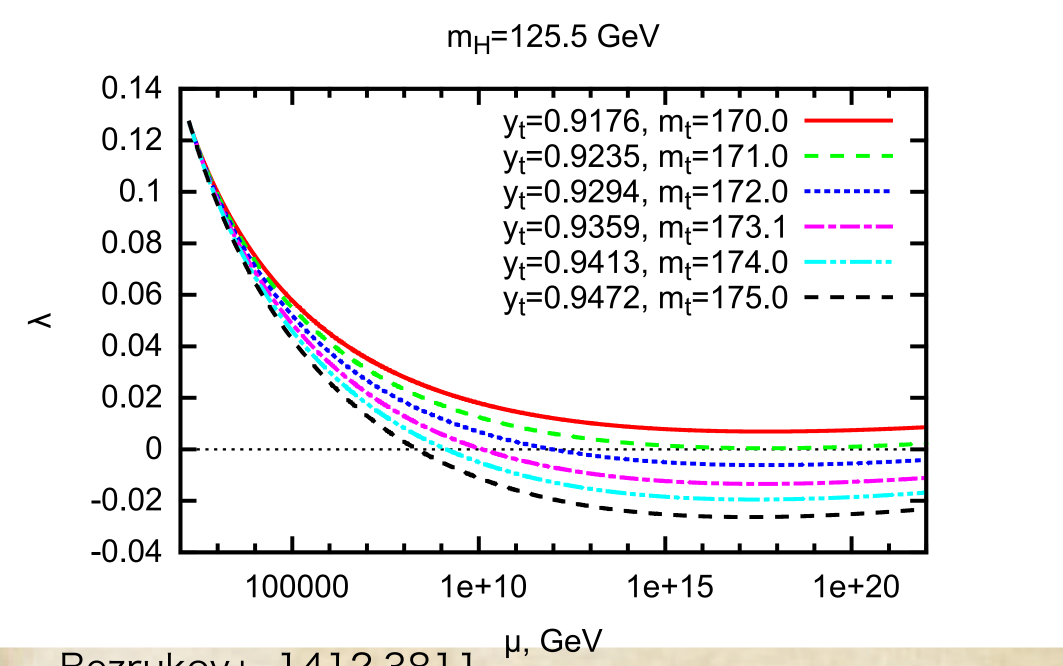
Vacuum stability

&

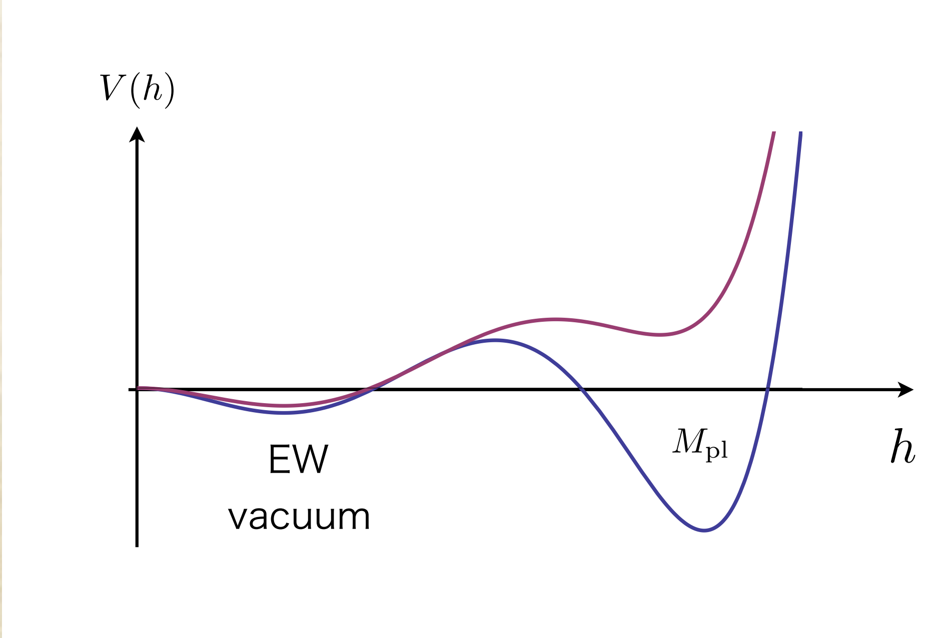
Perturbative unitarity

Courtesy H.Oide

Stability of Higgs potential?



Bezrukov+, 1412.3811



There remain parameter spaces in which Higgs potential is stable, though parameter space is not so large.

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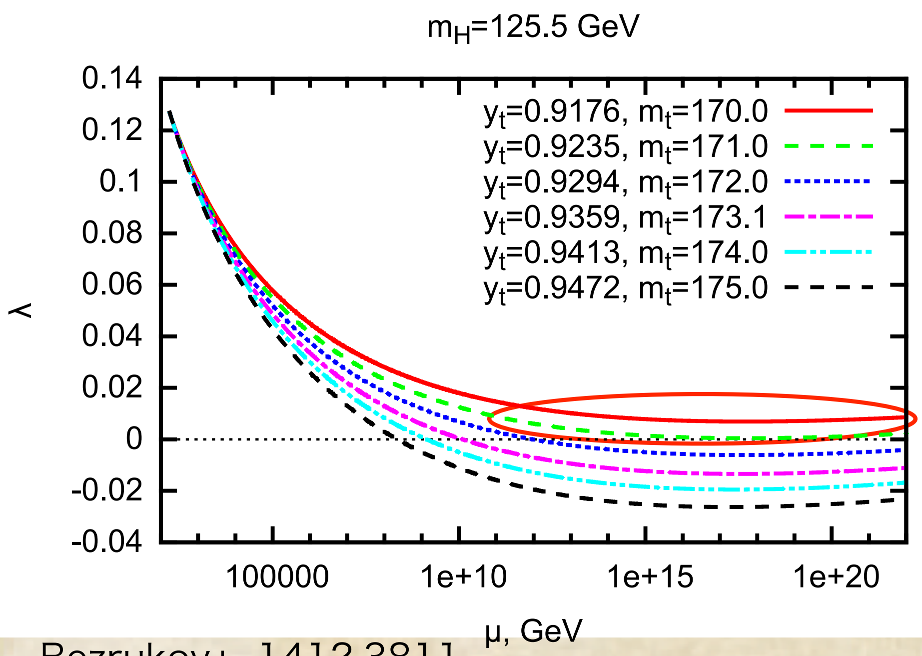

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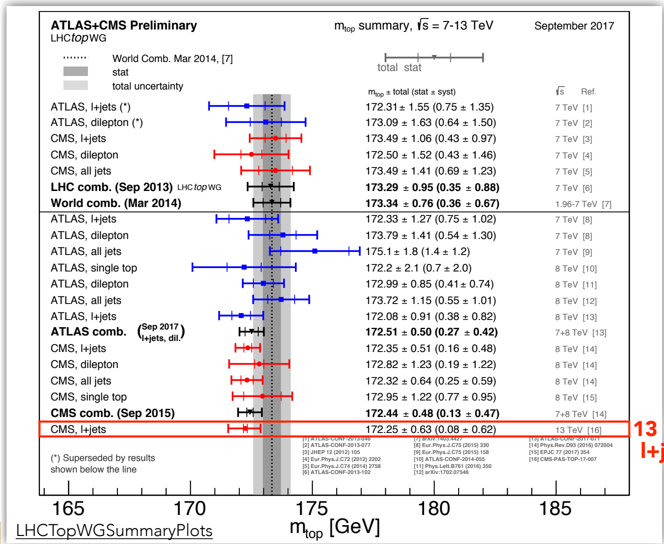
Top properties: *MASS*

- *Key SM parameter*
- *Test EW vacuum stability*

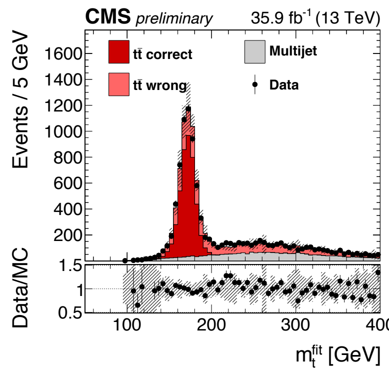
NEW @ ICHEP

CMS-PAS-TOP-17-008



LHCTopWGSummaryPlots

13 TeV, l+jets



CMS all-jet (13 TeV)

172.34 ±0.20 (stat+JSF) ±0.76 (syst) GeV

CMS, talk at ICHEP 2018

There remain parameter spaces in which Higgs potential is stable, though parameter space is not so large.

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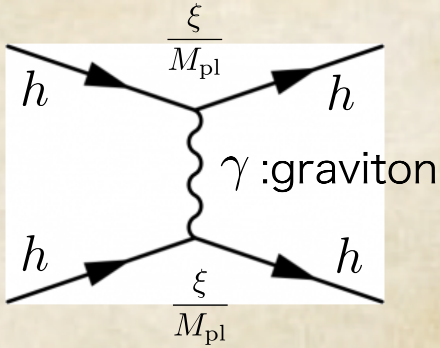
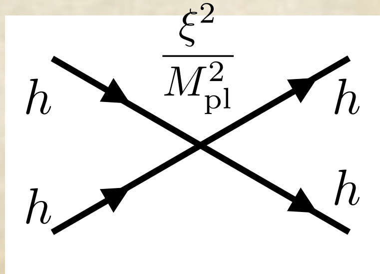
The model is non-renormalizable. Is it well controlled?

Jordan frame: $\xi h^2 R \ni \dfrac{\xi}{M_{\rm pl}} h^2 \partial^2 \gamma$



$$\mathcal{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h \end{pmatrix}$$

Einstein frame: $\xrightarrow[\text{trans.}]{\text{conformal}} \dfrac{3}{2} \dfrac{\xi^2}{M_{\rm pl}^2} h^2 (\partial h)^2$



Cutoff scale of the theory : $\Lambda \simeq \dfrac{M_{\rm pl}}{\xi}$

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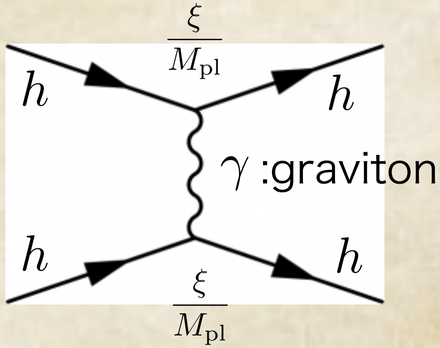

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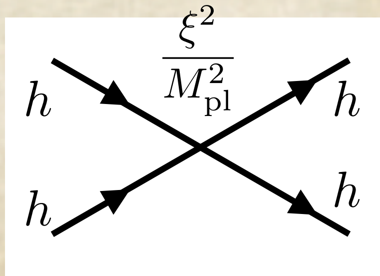


Cutoff scale of the theory : $\Lambda \simeq \dfrac{M_{\rm pl}}{\xi}$

$\wedge\!\wedge$

Typical energy scale during inflation : $\rho_{\rm inf}^{1/4} \simeq \dfrac{\lambda^{1/4} M_{\rm pl}}{\sqrt{\xi}}$

Is the predictions in Higgs inflation unreliable?

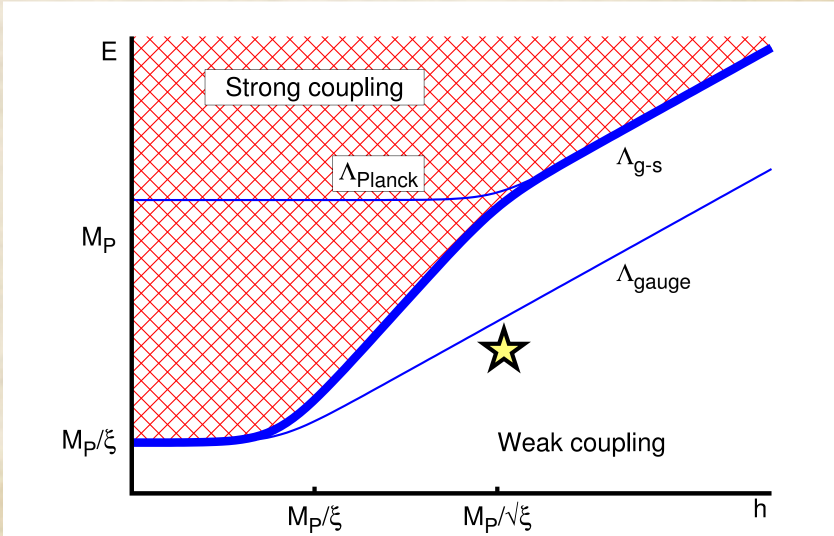
('09 Barbon&Espinosa, '10 Burgess, Lee, &Trott, '10 Hertzberg)

Courtesy H.Oide

No. The cutoff scale *during* inflation is background dependent and different from the one in the vacuum.

('11 Bezrukov, Magnin, Shaposhnikov, &Sibiryakov)

$$\mathcal{L} \ni \frac{\xi\sqrt{M_{\rm pl}^2 + \xi\bar{h}^2}}{M_{\rm pl}^2 + (\xi + 6\xi^2)\bar{h}^2}\delta h^2 \partial^2 \gamma$$



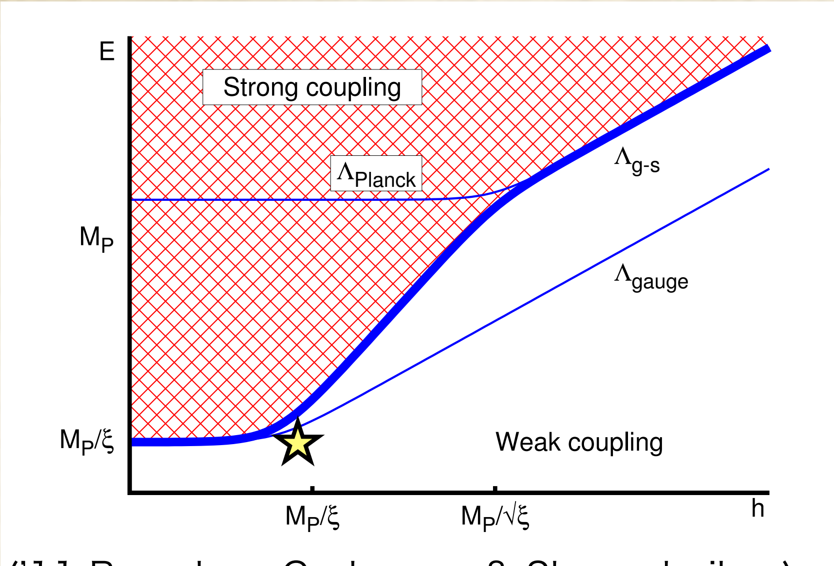
('11 Bezrukov, Gorbunov, & Shaposhnikov)

Quantum fluctuations are well under-controlled during inflation!

Courtesy H.Oide

But it is not the end of the story…

At the reheating stage, this issue is very subtle.



('11 Bezrukov, Gorbunov, & Shaposhnikov)

At the higgs oscillation, parametric resonance of weak gauge bosons occurs and reheats the Universe.

('09 Bezrukov, Gorbunov, & Shaposhnikov
'09 Garcia-Bellido, Figueroa, & Rubio
'16 Repond & Rubio)

For the transverse mode,

particles with $k \sim \dfrac{\sqrt{\lambda} M_{\rm pl}}{\xi}$

are excited.

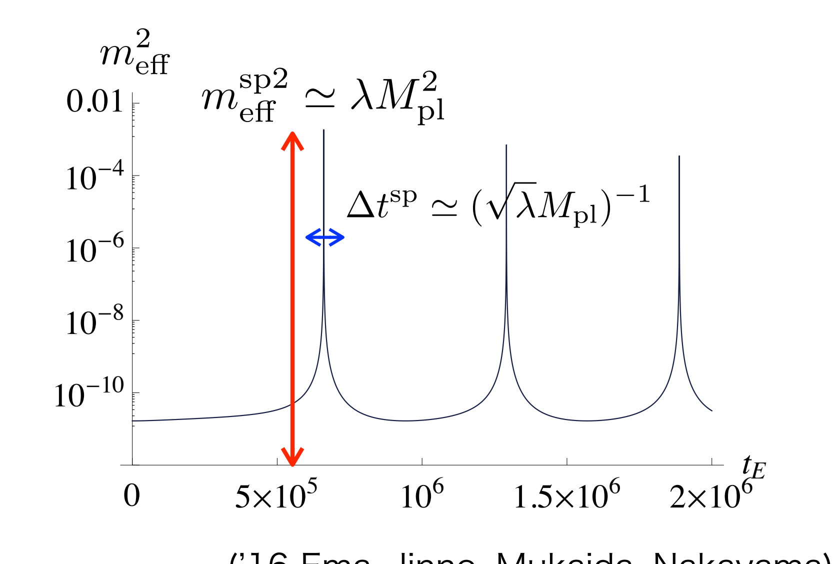
Courtesy H.Oide

But it is not the end of the story…

At the reheating stage, this issue is very subtle.

It is recently found that the longitudinal mode of the weak gauge bosons (or the NG mode) receives mass with spiky feature.

('15 DeCross, Kaiser, Prabhu, Prescod-Weistein, Sfakianakis, '16 Ema, **Jinno**, Mukaida, Nakayama)



('16 Ema, Jinno, Mukaida, Nakayama)

$$m_{\rm eff}^2 \ni \frac{\xi(1+6\xi)\dot{h}^2}{M_{\rm pl}^2 + \xi(1+6\xi)h^2}$$

When the Higgs pass through the origin, potential energy turns to the kinetic energy, which generates the spike in the effective mass.

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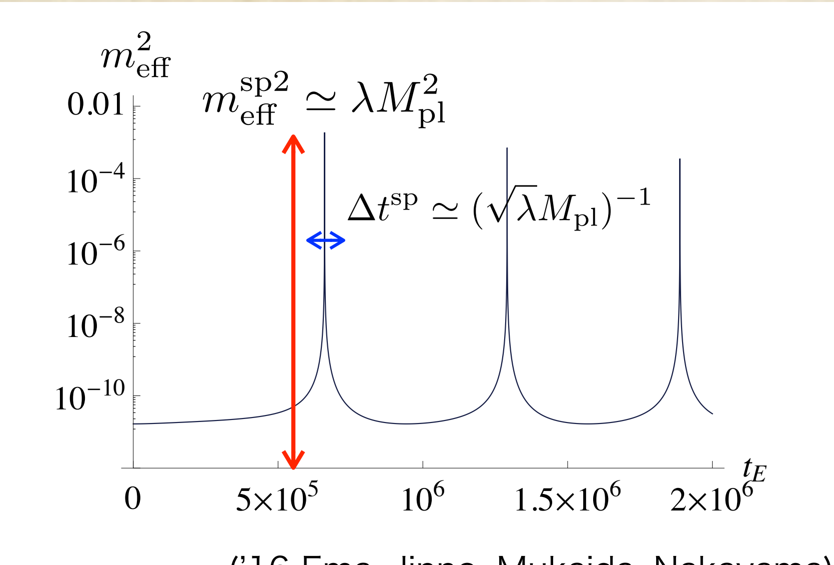

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Longitudinal mode of weak gauge bosons with $k \simeq \sqrt{\lambda} M_{\rm pl}$ are excited. ('16 Ema, Jinno, Mukaida, Nakayama)

Without backreaction

$$\rho_{\rm long} \simeq \frac{\lambda^2 M_{\rm pl}^4}{4\pi^2} \left(\gg \rho_{\rm inf} \simeq \frac{\lambda M_{\rm pl}}{\xi^2} \right)$$

after one oscillation. for $\lambda \xi^2 \gg 10^2$

Violent preheating!?

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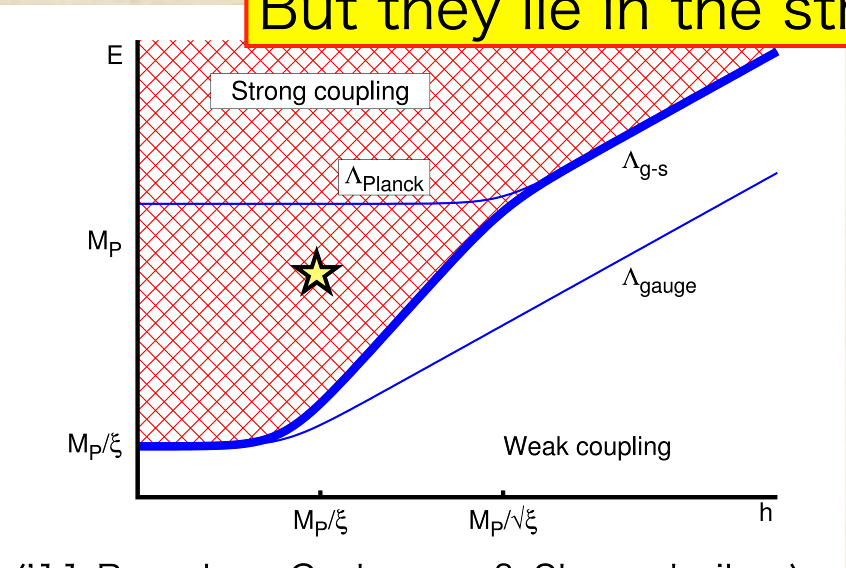
But they lie in the strong coupling region…



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UV extension of Higgs inflation with R^2-term

Courtesy H.Oide

We need UV extension of Higgs inflation to understand its reheating stage.

(e.g. '11 Giudice&Lee, '15 Barbon, Casas, Elias-Miro, Espinosa, '18 Lee)

It has been noticed that Higgs inflation + R^2 inflation

('17 Wang&Wang, '17 Ema, '18 **He**, Starobinsky, &Yokoyama, '18 Gundhi&Steinwachs)

act as the UV extension of Higgs inflation

('17 Ema, '18 Gorbunov&Tokareva)

$$\frac{\mathcal{L}}{\sqrt{-g}} = \left(\frac{M_{\rm pl}^2}{2} + \xi |\mathcal{H}|^2 \right) R + \frac{M_{\rm pl}^2}{12 M^2} R^2 - |D_\mu \mathcal{H}|^2 - \lambda |\mathcal{H}|^4$$

Classically scale-invariant extension!

Courtesy H.Oide

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Classically scale-invariant extension!

R^2 - term gives a new scalar degree of freedom (scalaron), which pushes up the cutoff scale.

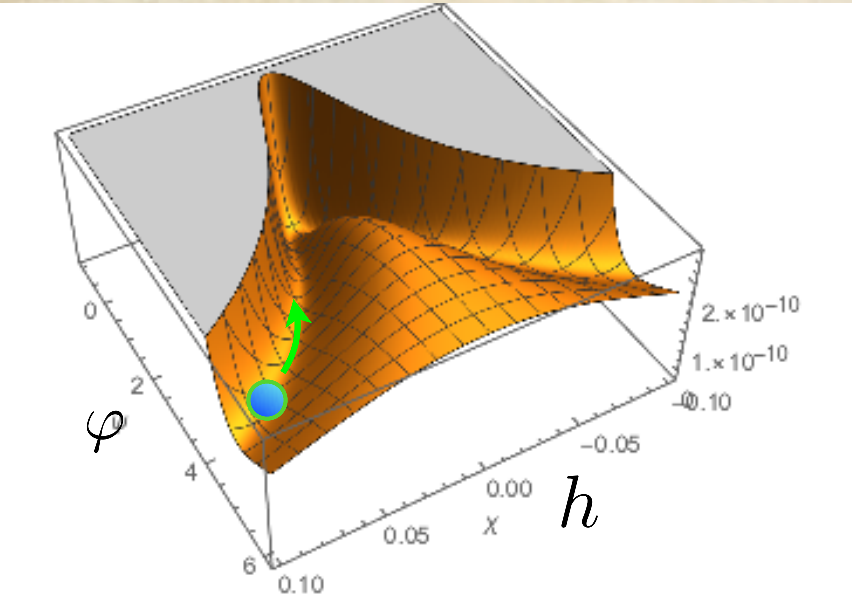
M : scalaron mass

Courtesy H.Oide

After conformal transformation, the system is now given by

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm pl}^2}{2}R - \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{1}{2}e^{-\sqrt{2/3}\varphi/M_{\rm pl}}|D_\mu\mathcal{H}|^2 - U(\varphi,\mathcal{H})$$

$$U(\varphi,\mathcal{H}) = \lambda e^{-2\sqrt{2/3}\varphi/M_{\rm pl}}|\mathcal{H}|^4 + \frac{3}{4}M_{\rm pl}^2M^2\left[1-\left(1+\frac{2\xi}{M_{\rm pl}^2}|\mathcal{H}|^2\right)e^{-\sqrt{2/3}\varphi/M_{\rm pl}}\right]^2$$



'18 He, Starobinsky, &Yokoyama

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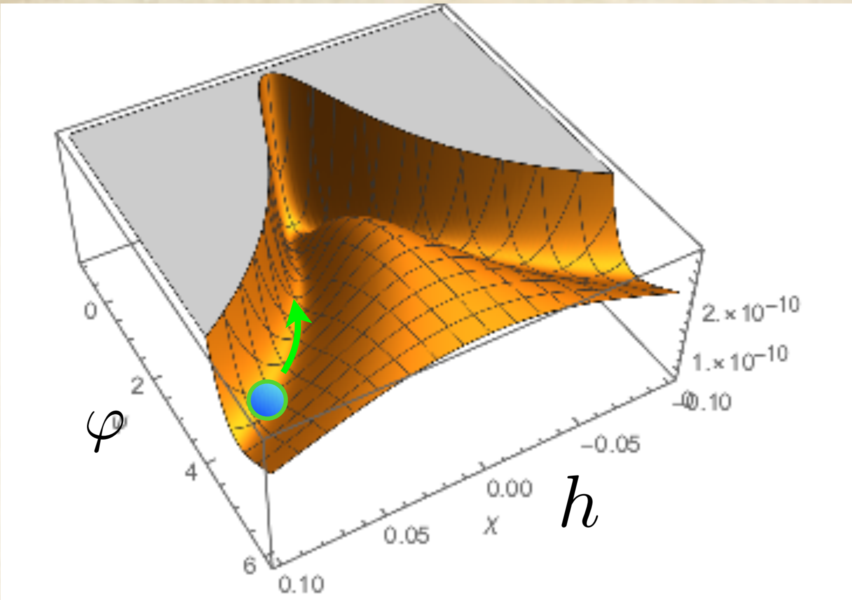

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Dim. 4 op. $3\left(\frac{\xi M}{M_{\rm pl}}\right)^2|\mathcal{H}|^4$

Dim. ≧5 op. $4\left(\frac{\xi M}{M_{\rm pl}^2}\right)^2|\mathcal{H}|^4 s^2\cdots$

For $M < \sqrt{\frac{4\pi}{3}}\frac{M_{\rm pl}}{\xi}$ dim. 4 op. is weakly coupled and the cutoff scale from dim. ≧5 op. is $\Lambda \simeq M_{\rm pl}$

('17 Ema, '18 Gorbunov&Tokareva)

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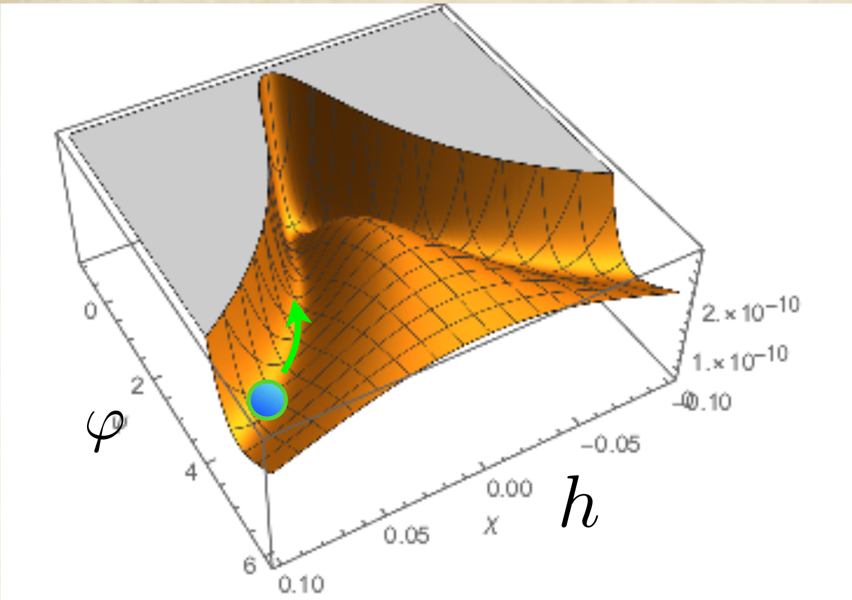
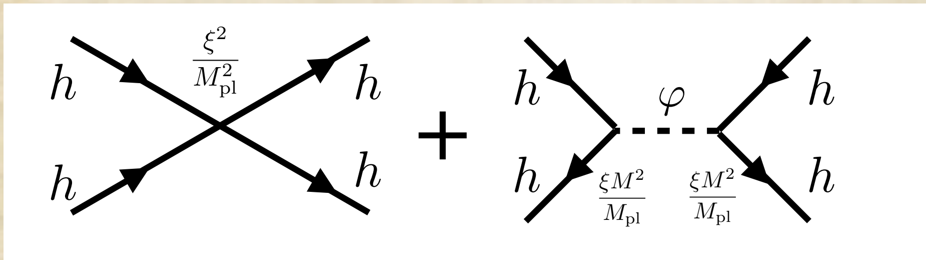
$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm pl}^2}{2} R - \frac{1}{2}(\partial_\mu \varphi)^2 - \frac{1}{2} e^{-\sqrt{2/3}\varphi/M_{\rm pl}} |D_\mu \mathcal{H}|^2 - U(\varphi, \mathcal{H})$$

$$U(\varphi, \mathcal{H}) = \lambda e^{-2\sqrt{2/3}\varphi/M_{\rm pl}} |\mathcal{H}|^4 + \frac{3}{4} M_{\rm pl}^2 M^2 \left[1 - \left(1 + \frac{2\xi}{M_{\rm pl}^2} |\mathcal{H}|^2 \right) e^{-\sqrt{2/3}\varphi/M_{\rm pl}} \right]^2$$



'18 He, Starobinsky, &Yokoyama

Scalaron cancels the divergence in pure Higgs inflation



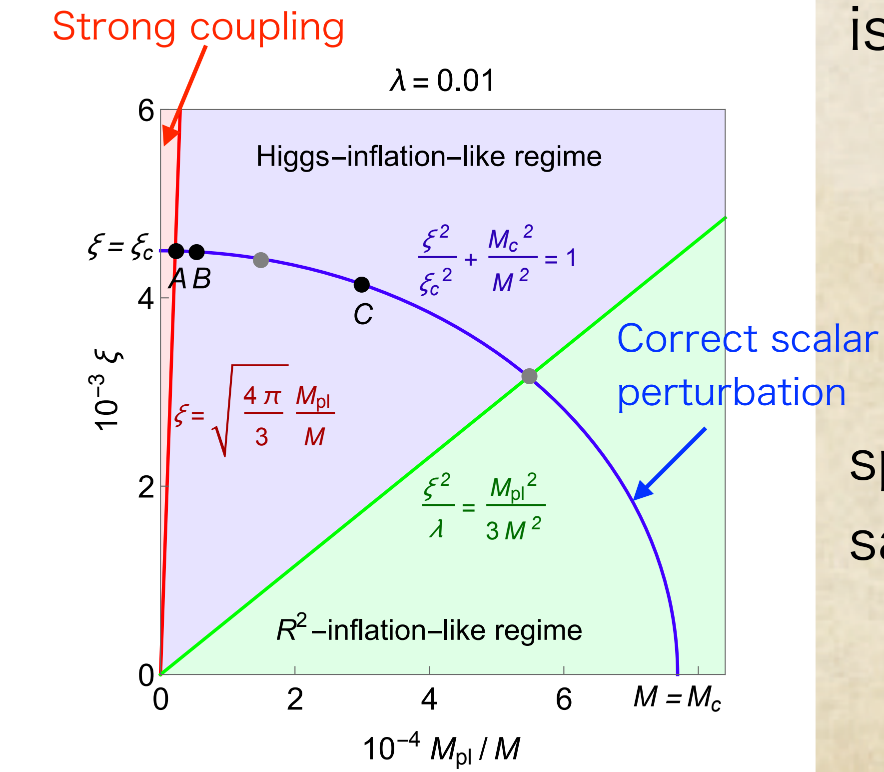
Courtesy H.Oide

During inflation it is effectively described by a single field with

$$V(\chi) \simeq \frac{3}{4}\tilde{M}^2 M_{\rm pl}^2 \left(1 - e^{-\sqrt{2/3}\chi/M_{\rm pl}}\right)^2 \qquad \tilde{M}^2 \equiv \frac{M^2}{1 + 3\xi^2 M^2/\lambda M_{\rm pl}^2}$$

for sufficiently large λ

('17 Ema, '18 **He**, Starobinsky, &Yokoyama)



'18 He, Jinno, KK, Park, Starobinsky, Yokoyama

Correct amplitude of scalar perturbation is realized for

$$\frac{\xi^2}{\xi_c^2} + \frac{M_c^2}{M^2} = 1$$

$$\xi_c \simeq 4.4 \times 10^3 \left(\frac{\lambda}{0.01}\right)^{1/2} \frac{N}{54}$$

$$M_c \simeq 1.3 \times 10^{-5} \left(\frac{N}{54}\right)^{-1} M_{\rm pl}$$

('17 Ema, '18 **He**, Starobinsky, &Yokoyama)

spectral tilt/tensor-to-scalar ratio are the same to the pure Higgs inflation/R^2 inflation

$$n_s \simeq 1 - \frac{2}{N} \simeq 0.97 \qquad r \simeq \frac{12}{N^2} \simeq 0.003$$

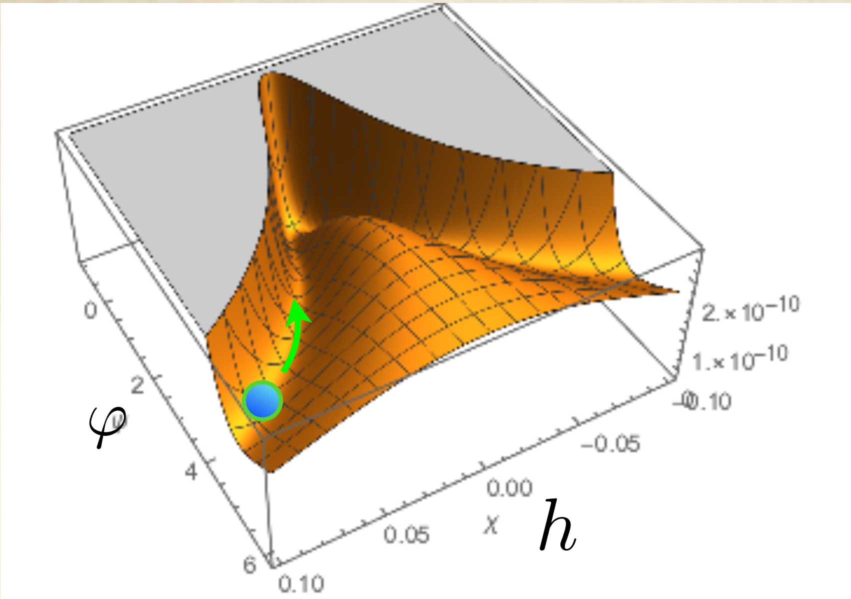
\# N depends on reheating temp.

Courtesy H.Oide

Inflaton oscillation
and violent preheating

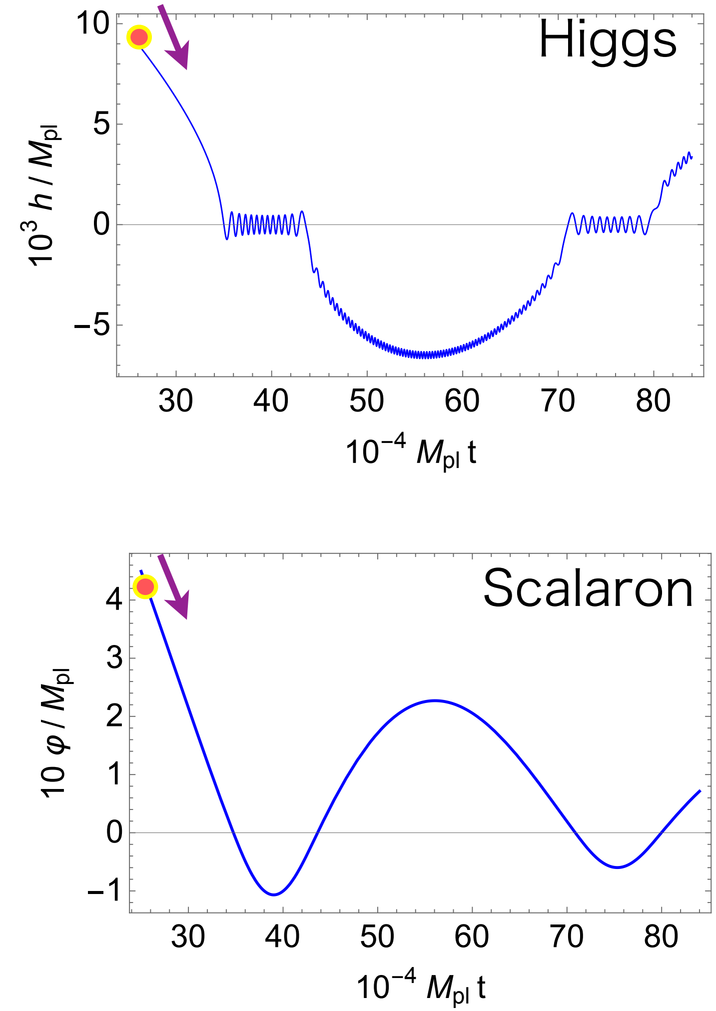
Courtesy H.Oide

For sufficiently small M (especially for weakly coupled case) the dynamics at inflaton oscillation is no longer single field like.



'18 He, Starobinsky, &Yokoyama

$\lambda = 0.01 \quad \xi \simeq 4089 \quad M_{\rm pl}/M = 3 \times 10^4$



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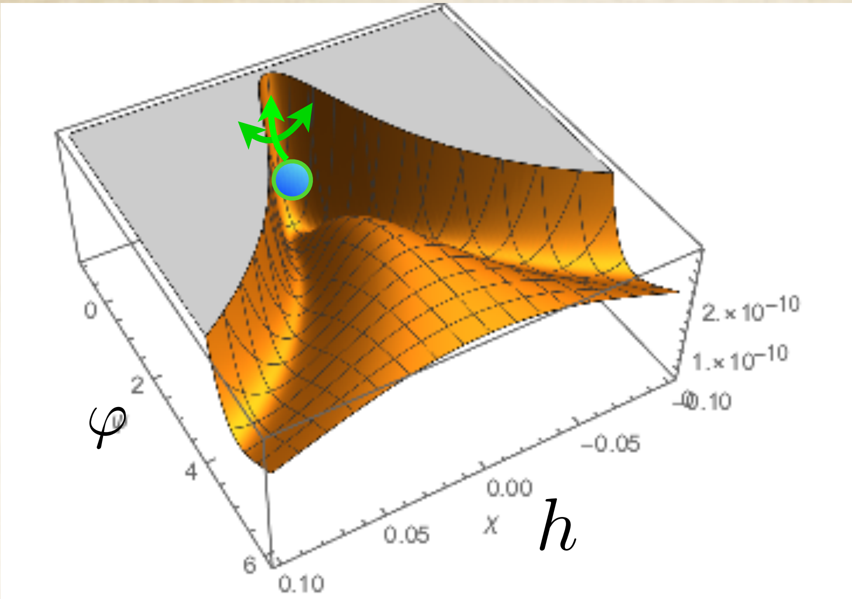

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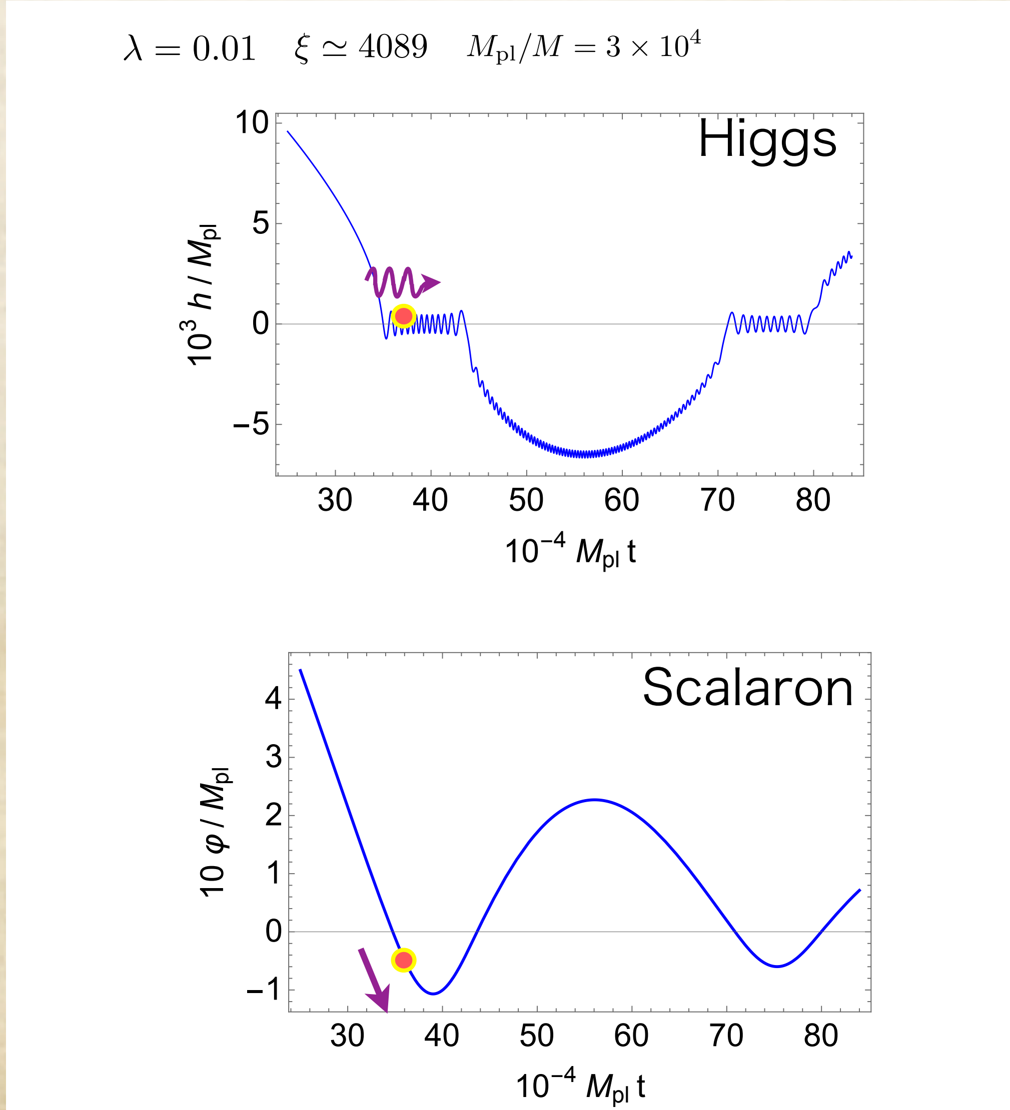

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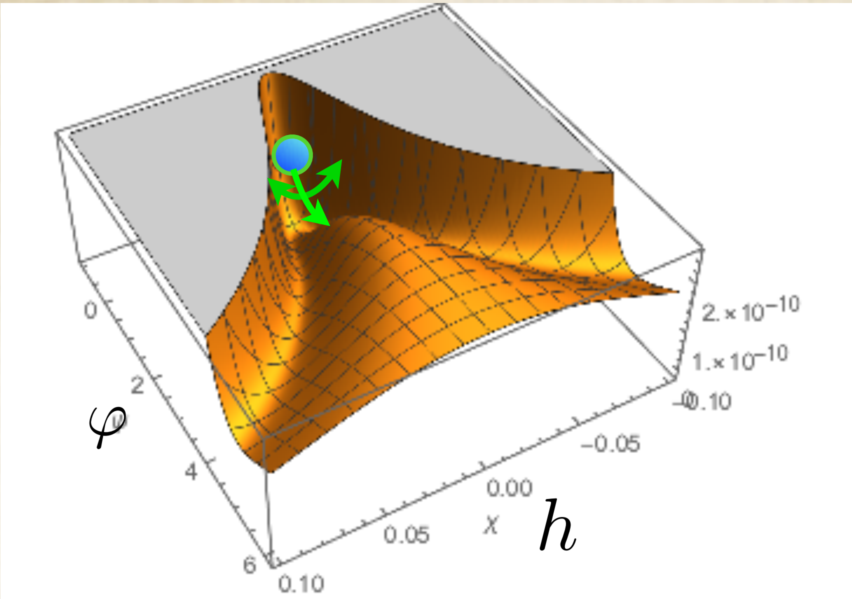

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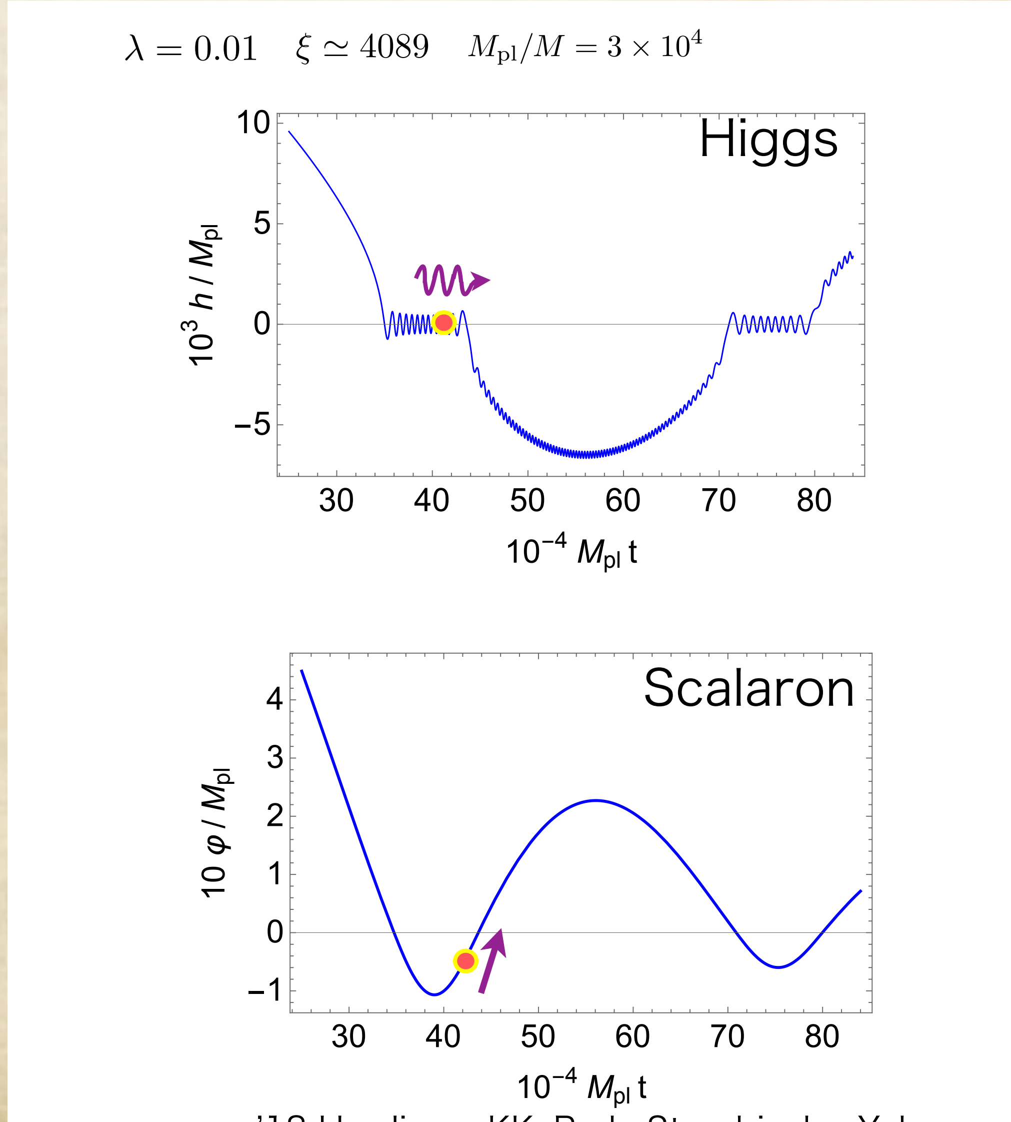

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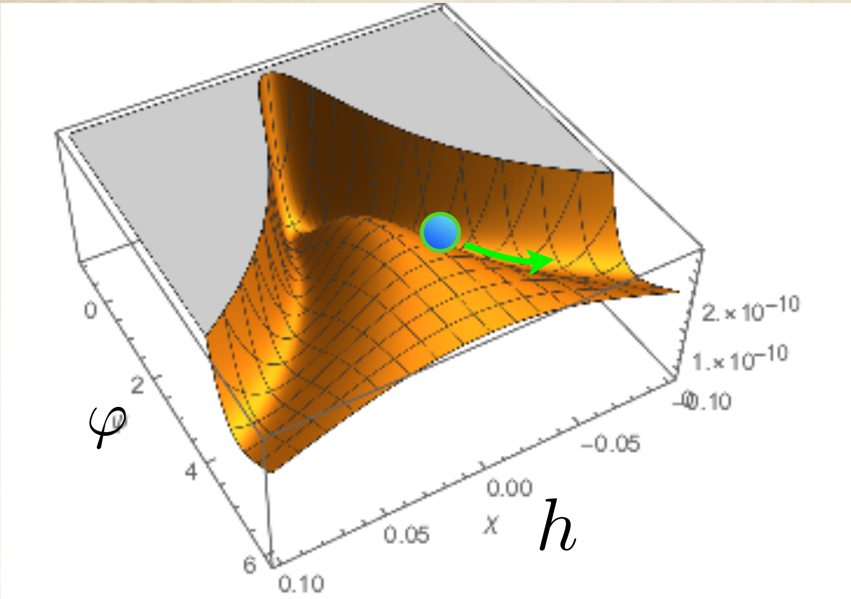

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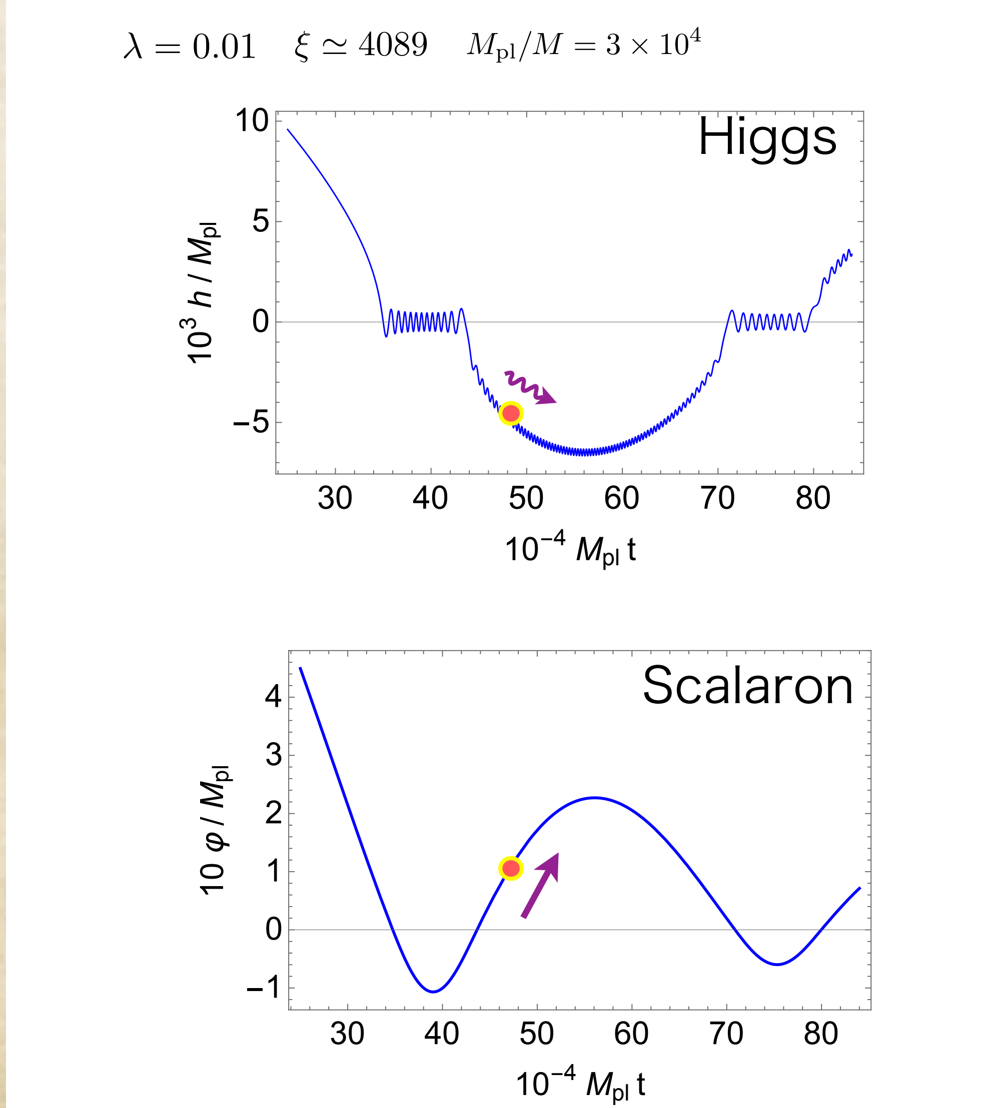

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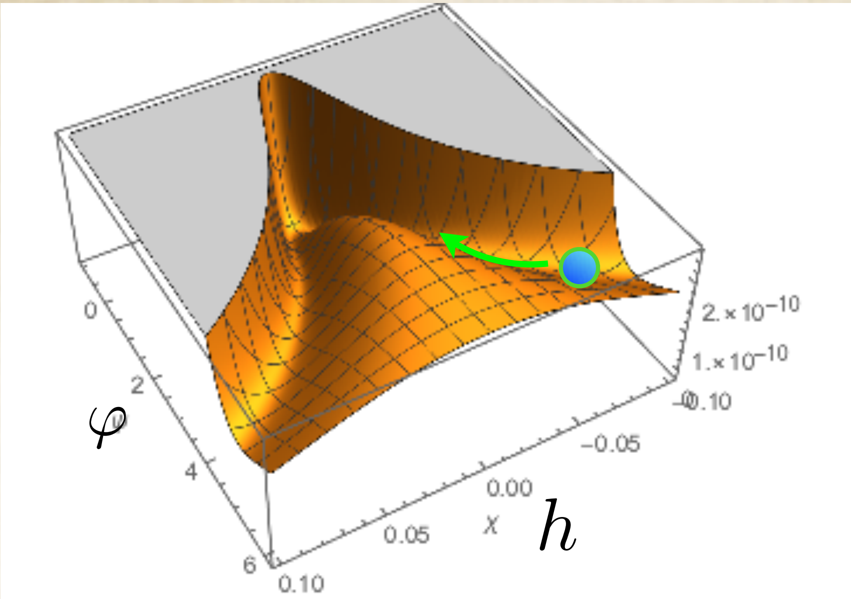

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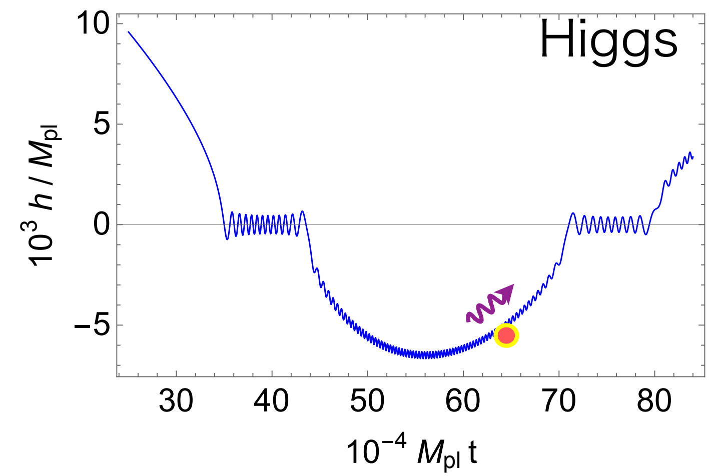

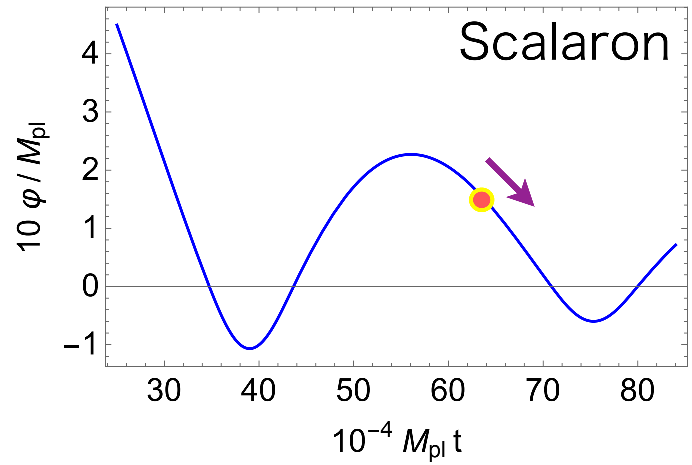

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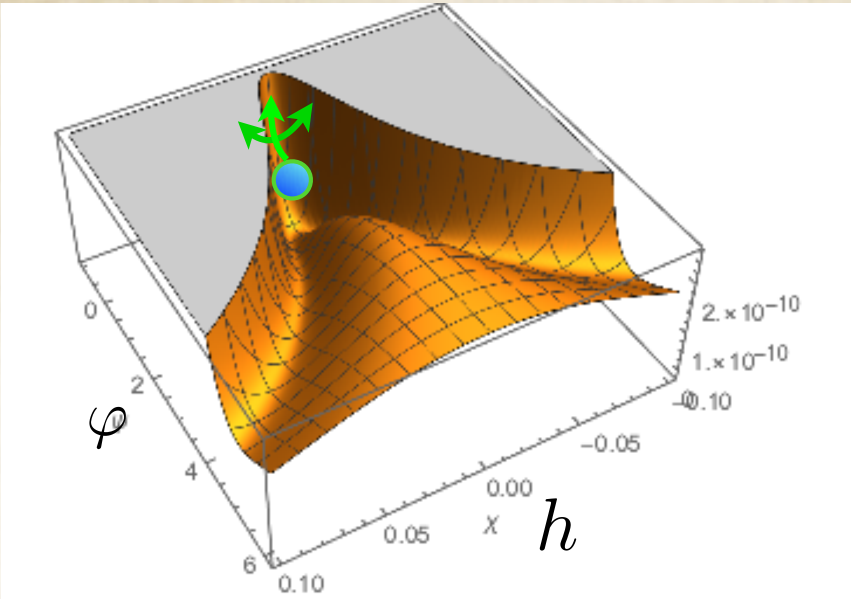

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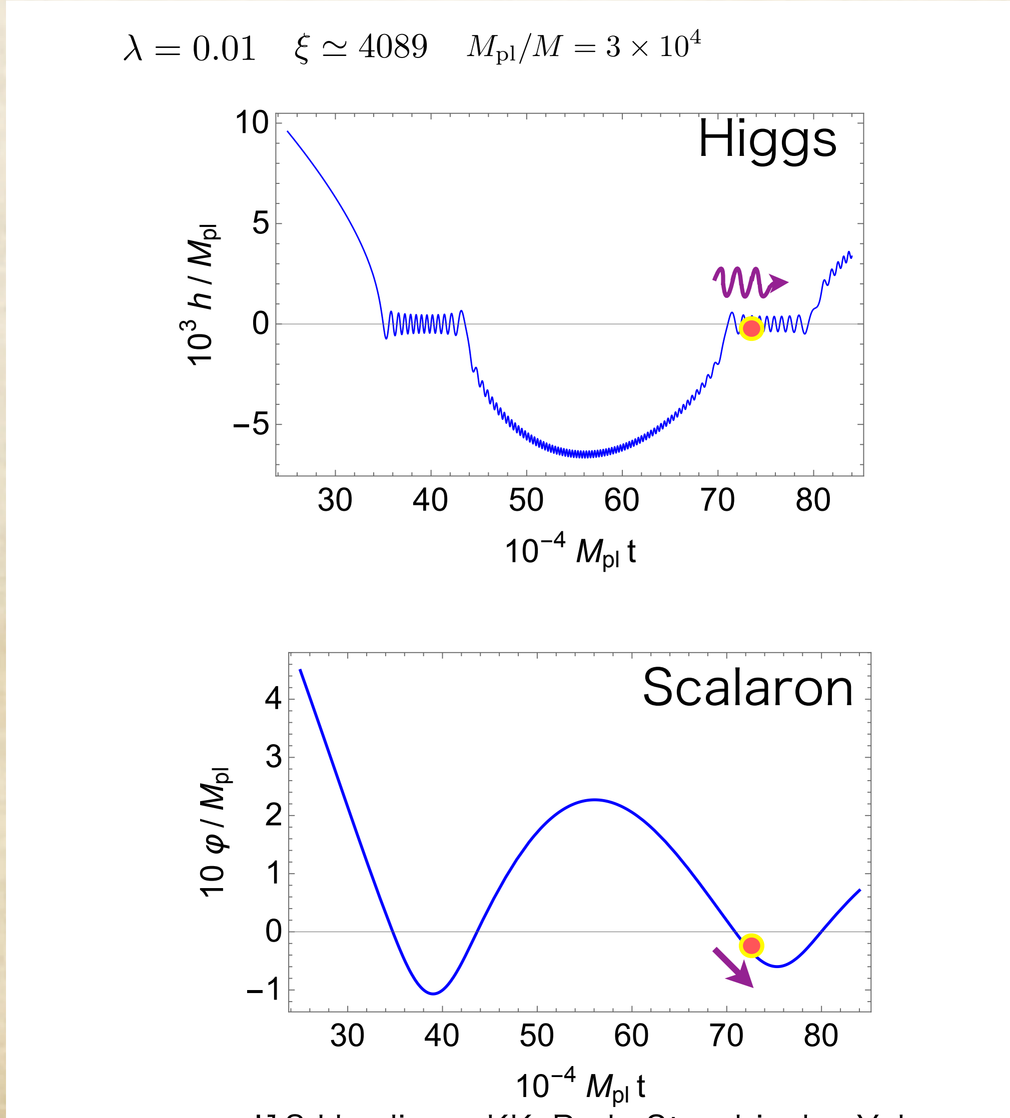

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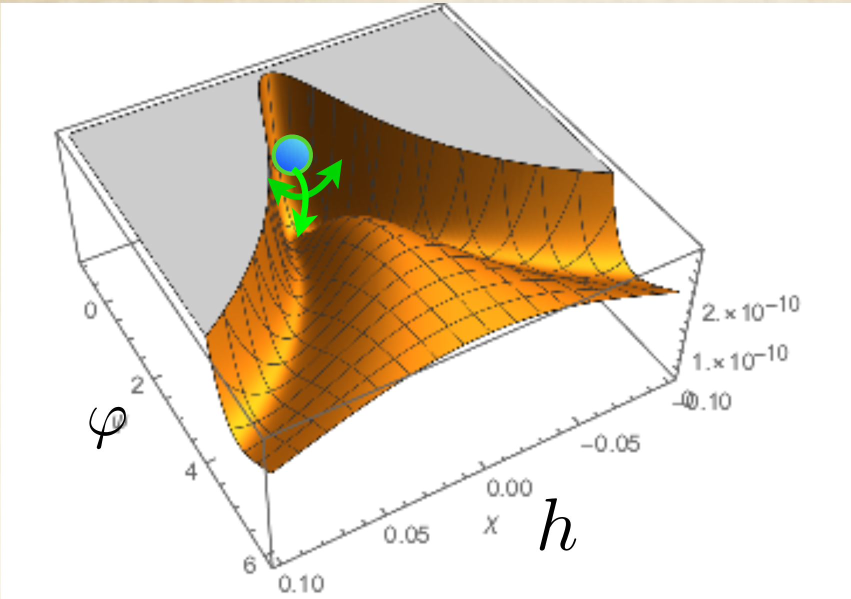

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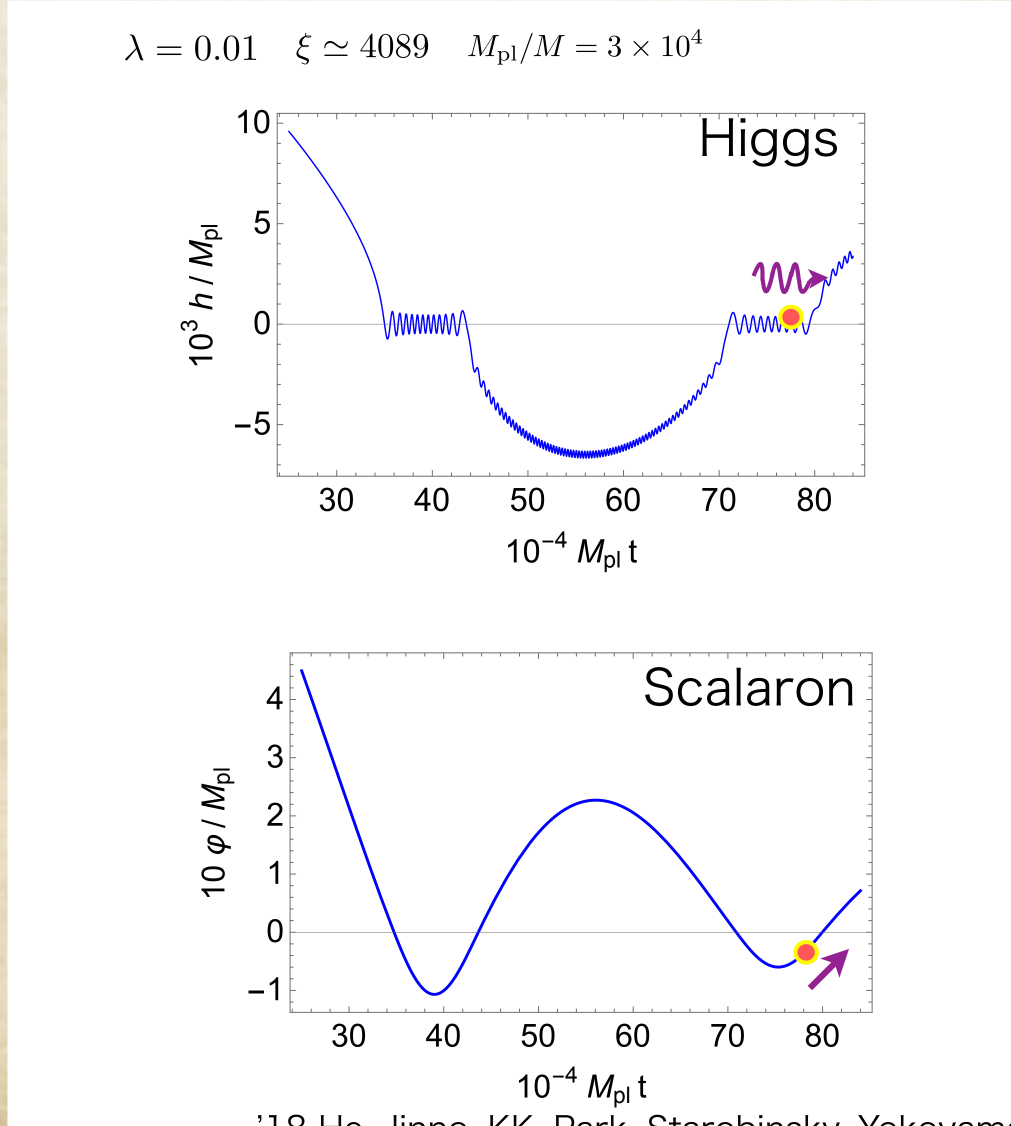

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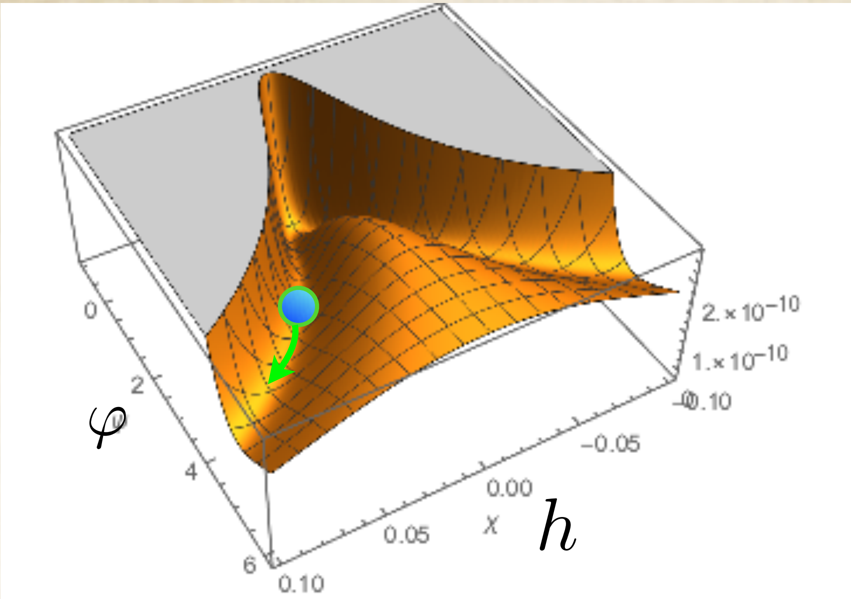

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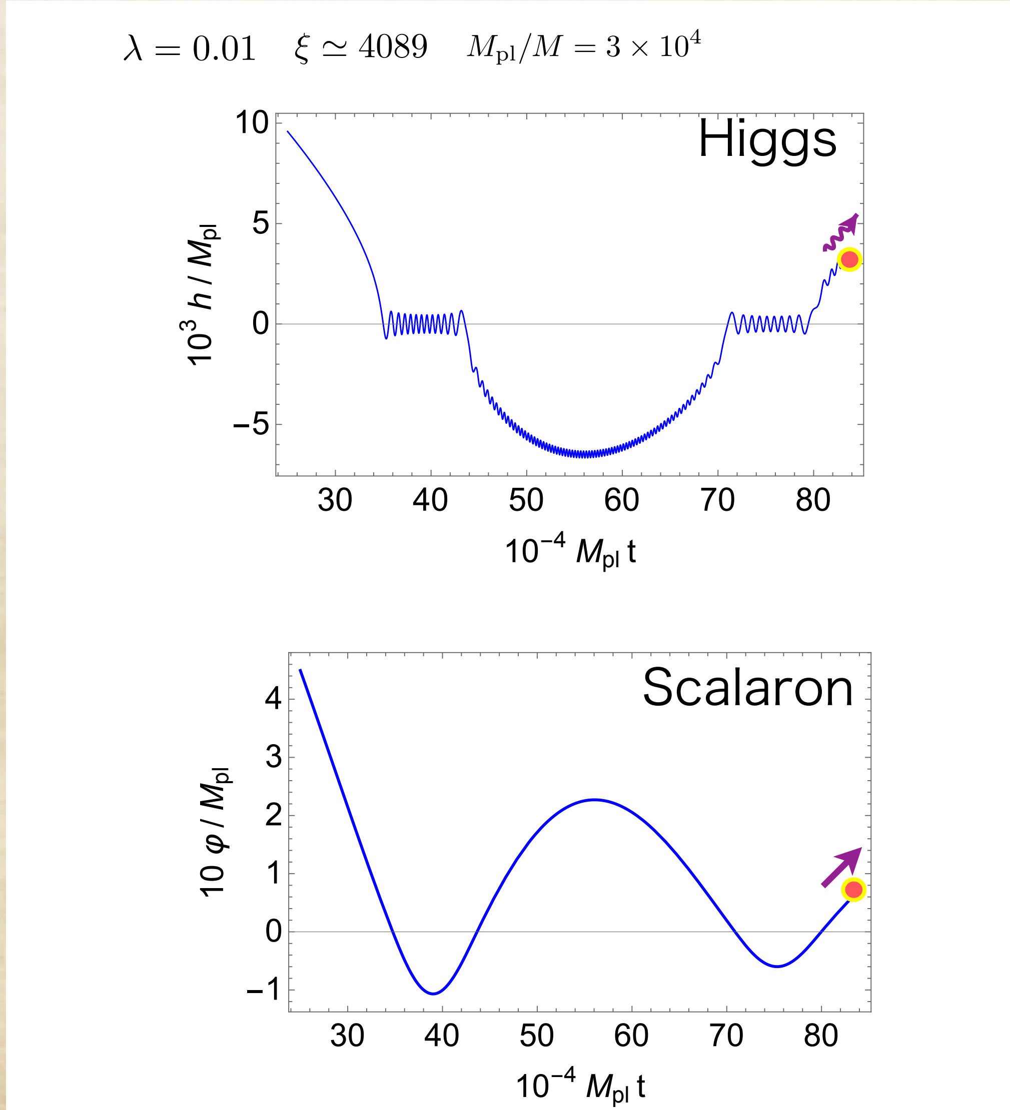

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Courtesy H.Oide

Effective mass for the NG mode?

$$m_\theta^2 = -\sqrt{\frac{1}{6}}\frac{\partial U}{\partial \varphi} + \frac{e^{\sqrt{2/3}\varphi/M_{\rm pl}}}{h}\frac{\partial U}{\partial h} - \frac{3}{4}\frac{U}{M_{\rm pl}^2} + \frac{5}{24M_{\rm pl}^2}\left(\dot{\varphi}^2 + e^{-\sqrt{2/3}\varphi/M_{\rm pl}}\dot{h}^2\right)$$

Longitudinal mode of weak gauge bosons should exhibit a similar behavior

Courtesy H.Oide

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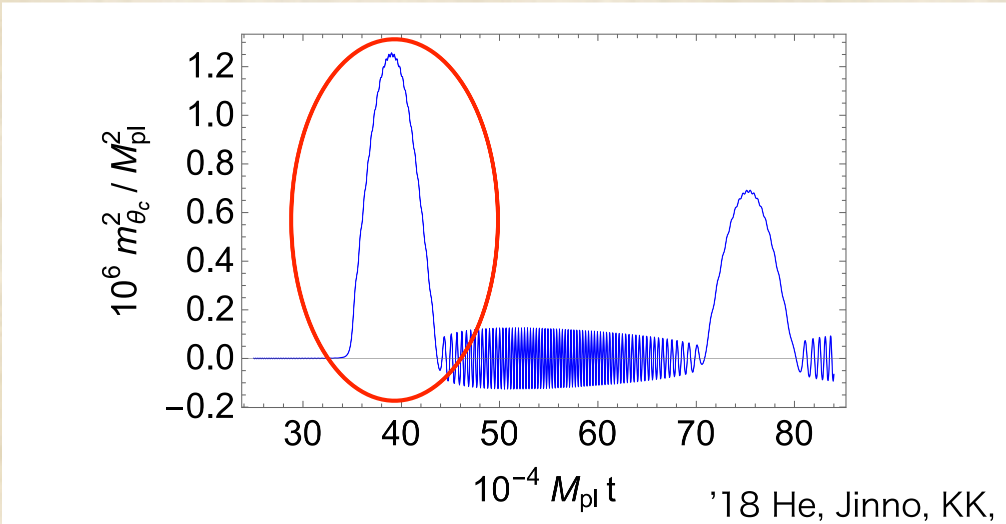
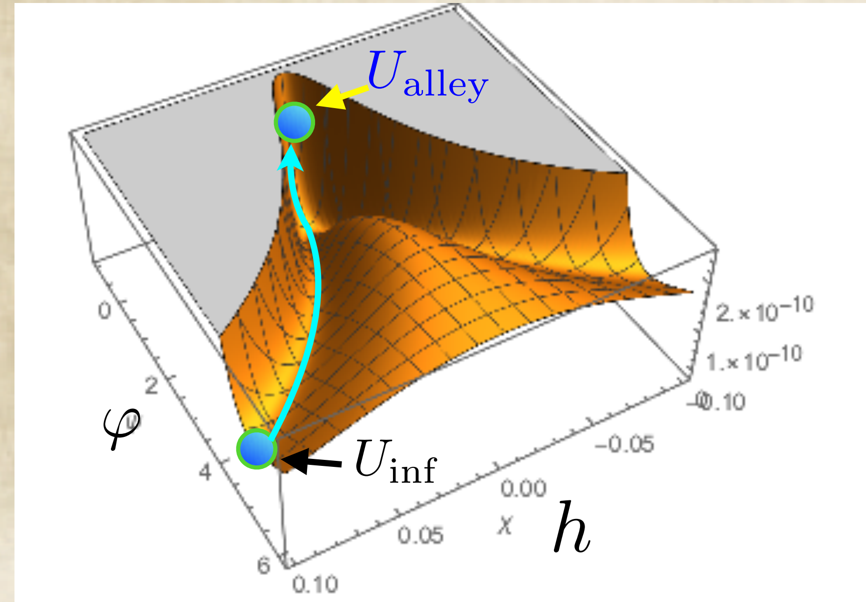


'18 He, Jinno, KK, Park, Starobinsky, Yokoyama

Spiky behavior still appears!

Courtesy H.Oide

How to understand it analytically?



'18 He, Starobinsky, &Yokoyama

Peak appears when the inflaton climbs up the alley with vanishing kinetic energy => $U_{\rm alley} \simeq U_{\rm inf}$ @ $h=0$

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This term gives much larger value than the Hubble scale when the scalaron climbs up the alley.

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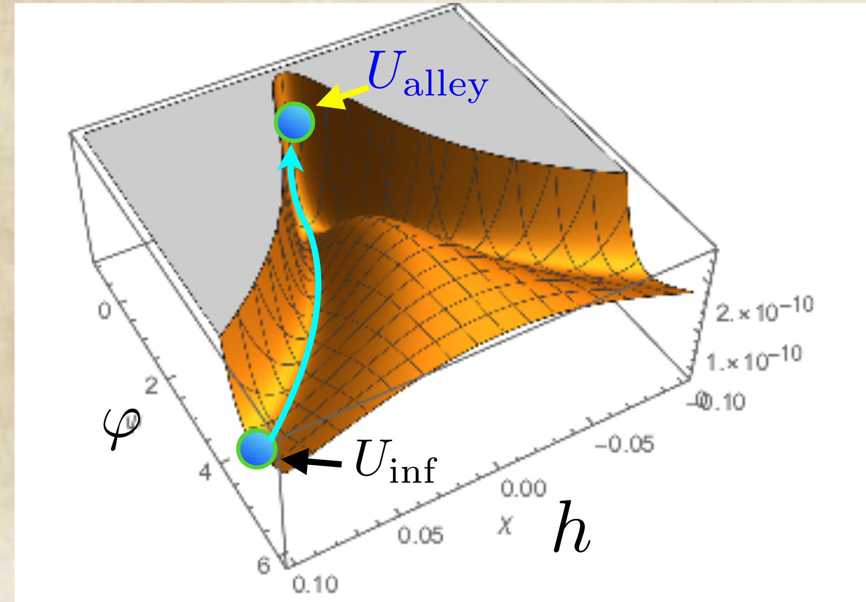

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Courtesy H.Oide

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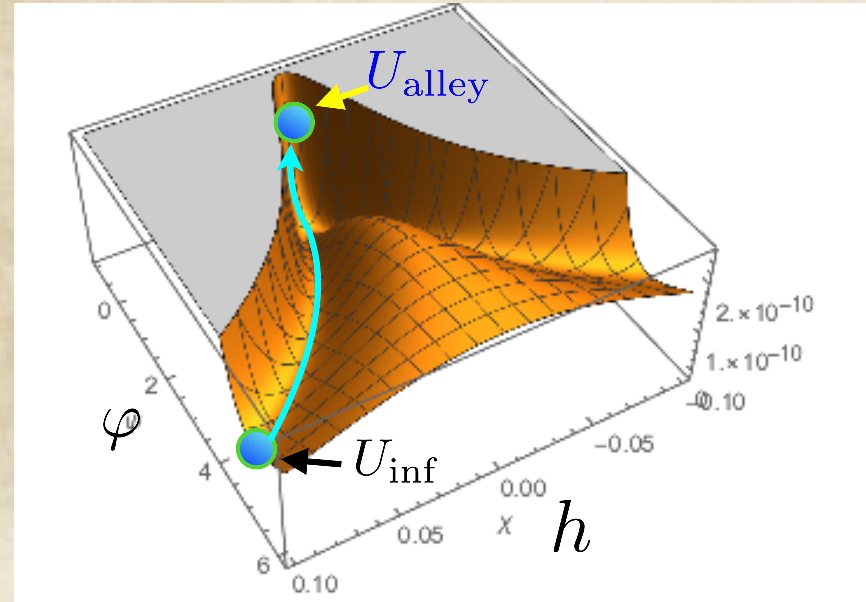

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$$\Delta t_{\rm sp} \simeq M^{-1}$$

Courtesy H.Oide

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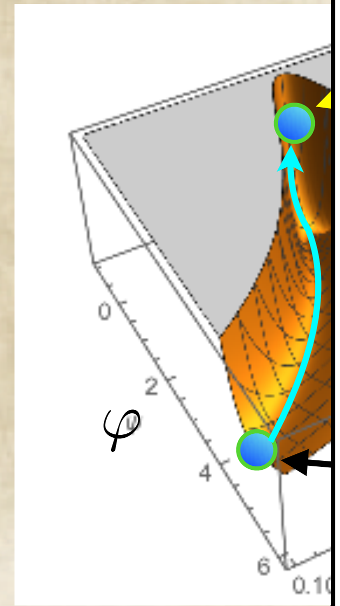

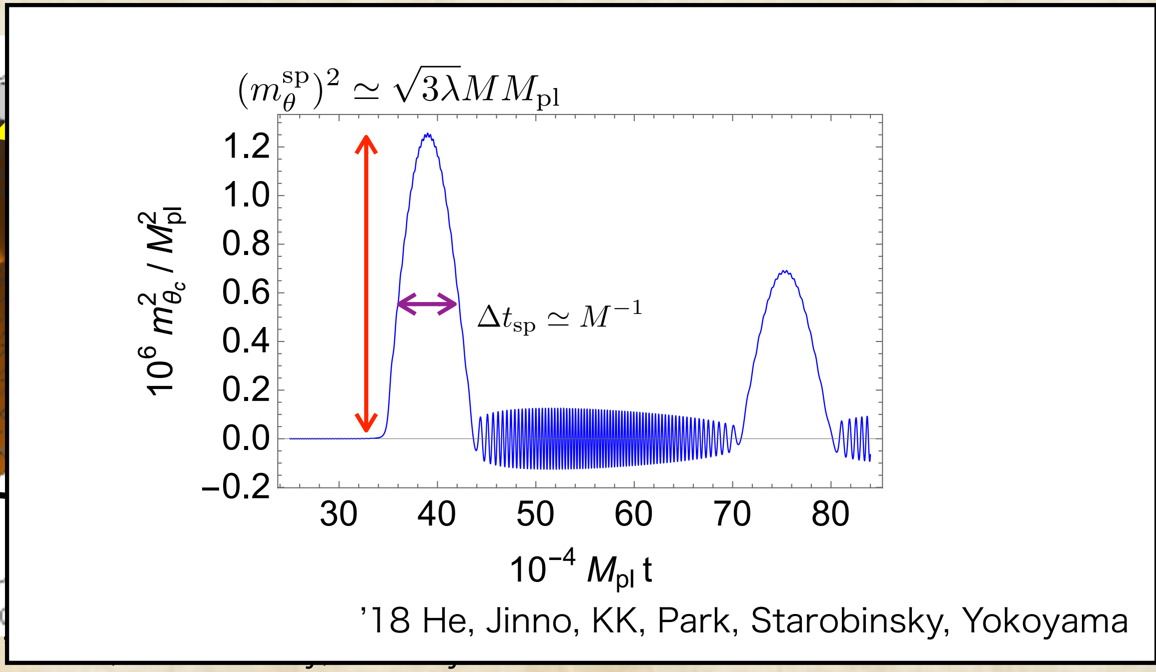

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vith vanishing

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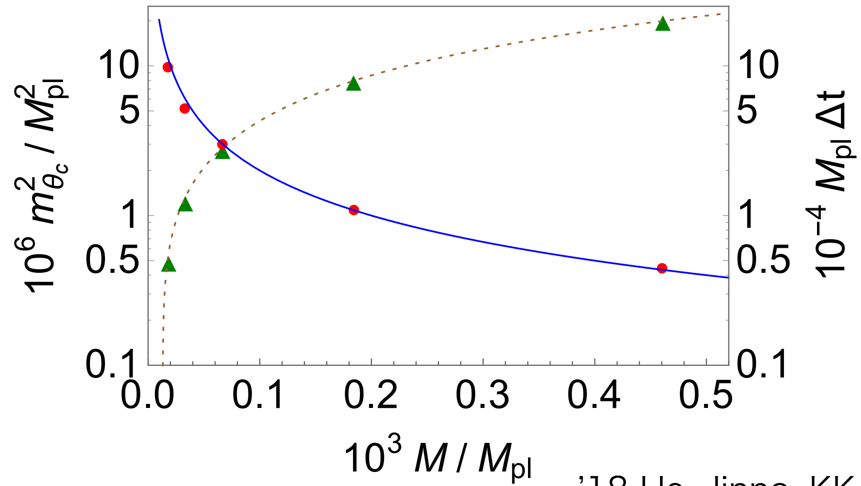
Courtesy H.Oide

More precisely with the parameter to fit the cosmological data

$$(m_\theta^{\rm sp})^2 = C_{\rm m}\sqrt{3\lambda(M^2 - M_c^2)}M_{\rm pl} \qquad \Delta t_{\rm sp} = C_t M^{-1}$$

$C_{\rm m} \simeq 0.25 \qquad C_t \simeq 0.2$



'18 He, Jinno, KK, Park, Starobinsky, Yokoyama

Smaller M gives lower spike and wider duration.

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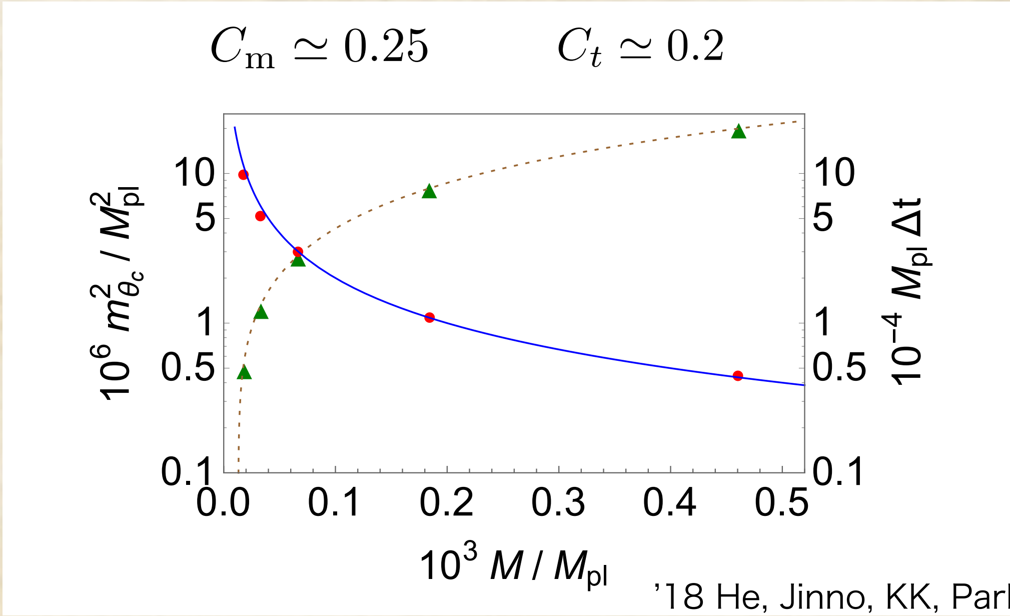

'18 He, Jinno, KK, Park, Starobinsky, Yokoyama

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Too high energy scales observed in pure Higgs inflation now disappear!

Courtesy H.Oide

NG particle production?

Evaluate the mode equation

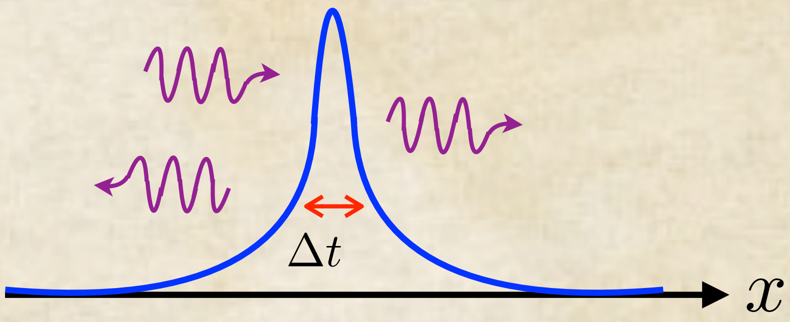
$$\ddot{\theta}_c(k,\tau) + (k^2 + m_\theta^2(\tau))\theta_c(k,\tau) = 0$$

with spiky mass $m_\theta^2(\tau)$ and evaluate the Bogoliubov coef.

$$\theta_c(k,\tau) = \frac{1}{\sqrt{2\omega_k(\tau)}}\left[\alpha_k(\tau)e^{-i\int_{-\infty}^{\tau} d\tau'\omega_k(\tau')} + \beta_k(\tau)e^{i\int_{-\infty}^{\tau} d\tau'\omega_k(\tau')}\right]$$

Just a tunneling problem for the spiky wall in quantum mechanics.

(e.g. Landau&Lifshitz)



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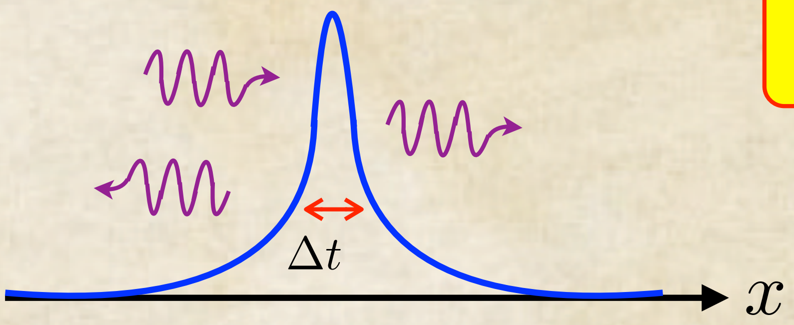
After one oscillation



$$\rho_\theta \simeq 2.8 \times \left(\frac{C_t}{0.2}\right)^{-4} M^4 \ll \rho_{\rm inf}$$

with $m_\theta^2(t) = \frac{\mu}{2\Delta t}\frac{1}{\cosh^2(t/\Delta t)}$ approximation.

('18 He, Jinno, KK, Park, Starobinsky, Yokoyama)

Courtesy H.Oide

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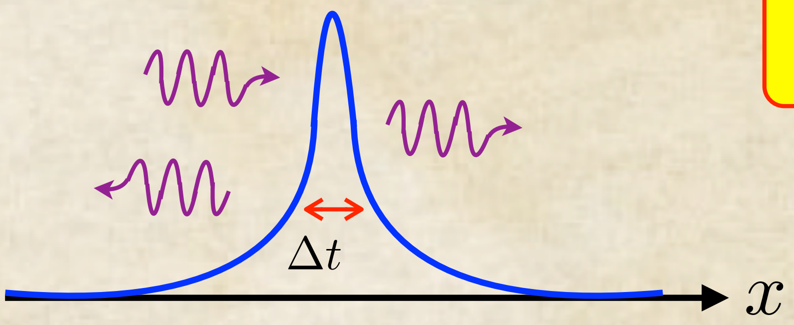

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Reheating will not complete by the violent preheating for the NG mode!

Courtesy H.Oide

Discussion

Courtesy H.Oide

- Higgs inflation with a nonminimal coupling to gravity is an interesting model.
- Violent preheating for the NG mode is theoretical challenge in it.
- (Classically) scale-invariant R^2 extension can push up its cutoff scale and make the model healthier.
- Spiky feature in the mass of NG mode at the inflaton oscillation still appear and is really physical, but it gets lower and broader. The physical origin is a bit different.
- Violent particle production occurs, but it is not sufficient to complete reheating.
- Usual perturbative and non-perturbative decay of the Higgs and scalaron will reheat the Universe.
- Since the inflaton oscillation is completely two-field nature, and hence results of previous studies on preheating in pure Higgs inflation cannot be applied directly.

Courtesy H.Oide