What do we know about preheating in Higgs Inflation and its relatives?

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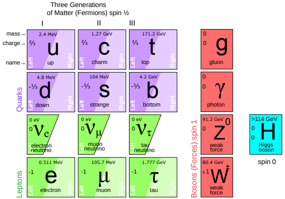
ITMP Seminar

MANCHESTER 1824
The University of Manchester

Outline

1. Introduction: Standard Model and the Universe
2. Inflation
   - Simplest realization
   - How to use Higgs for inflation
3. Quantum corrections
   - UV-completion example – R^2+Higgs inflation
4. Reheating
   - After preheating
5. Interesting related variations
   - Palatiny Higgs inflation
6. Conclusions

Lesson from LHC so far – Standard Model is good



- SM works in all laboratory/collider experiments (electroweak, strong)
- LHC 2012 – final piece of the model discovered – Higgs boson
    - Mass measured $\sim$ 125 GeV – weak coupling!
      Perturbative and predictive for high energies

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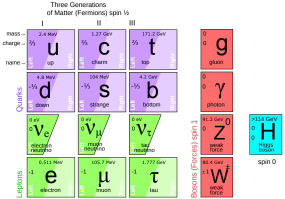


+ Einstein gravity

- SM works in all laboratory/collider experiments (electroweak, strong)
- LHC 2012 – final piece of the model discovered – Higgs boson
  - Mass measured $\sim$ 125 GeV – weak coupling!
    Perturbative and predictive for high energies
- Add gravity
  - get cosmology
  - get Planck scale $M_{Pl} \sim 1.22 \times 10^{19}$ GeV as the highest energy to worry about

Things not explained by SM

Experimental observations: Cosmology

- Dark Matter
- Baryon asymmetry of the Universe
- Inflation

Laboratory

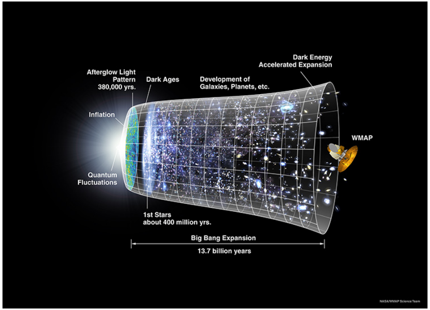
- Neutrino oscillations

Outline

ΛCDM cosmology – describes the Universe

The Universe is

- Hot (I mean 2.73° K photons now)
- Expanding
- Extremely uniform (on large scales)



ΛCDM cosmology – describes the Universe

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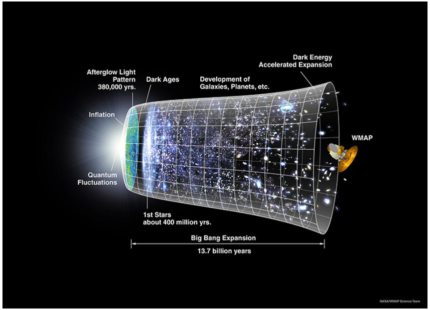
How did it all start?

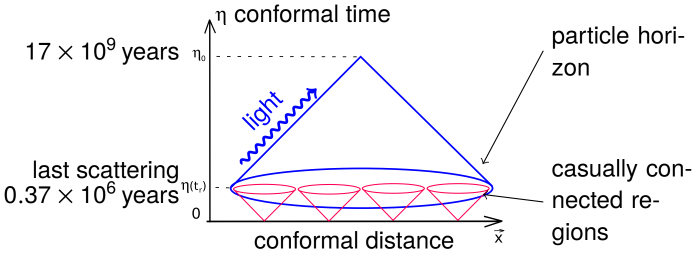


Problem – how all this happened?

Variations of initial conditions problem

- Singularity problem
- Flatness problem
- Entropy problem
- Horizon problem
- Primordial perturbations problem

Horizon problem



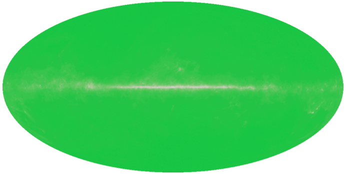
Observed Universe contained

2000 casually disconnected regions on CMB sky

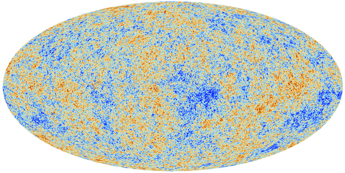
Why they are so similar?

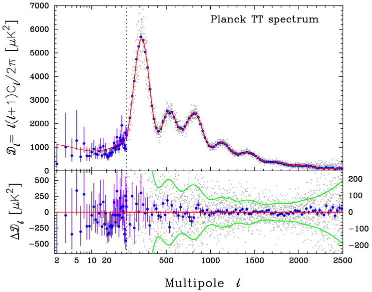
CMB – shape of primordial density perturbations

CMB sky $T = 2.725^\circ$ K



CMB sky in detail $\delta T/T \sim 10^{-5}$





Primordial perturbations

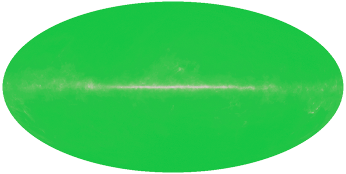
nearly (but not exactly!) scale invariant

$$\mathcal{P}_\mathcal{R}(k) = A_\mathcal{R}\left(\frac{k}{k_*}\right)^{n_s-1}$$

with spectral index $n_s \sim 0.96$

CMB – shape of primordial density perturbations

CMB sky $T = 2.725^\circ$ K



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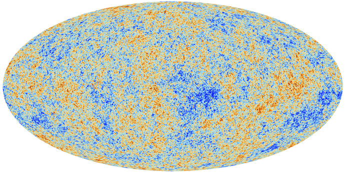
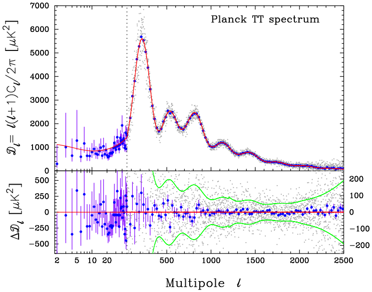
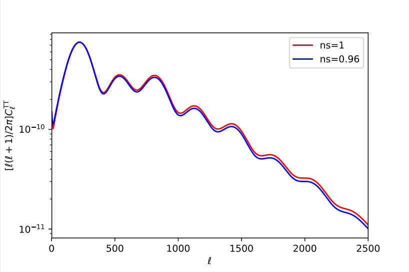




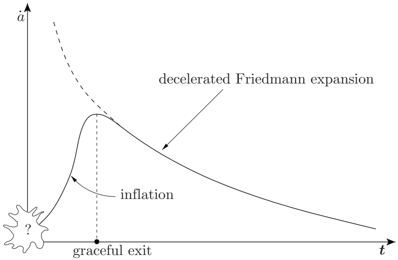
Primordial perturbations

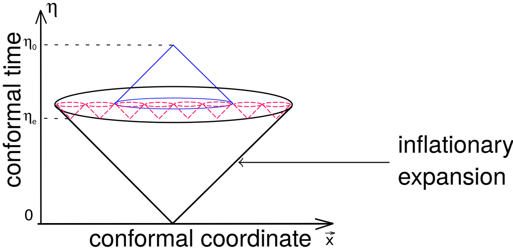


Inflation – accelerated expansion

$$\frac{l_i}{l_c} \sim \frac{\dot{a}_i}{\dot{a}_0}$$

Inflation is a stage of accelerated expansion of the Universe when gravity acts as a repulsive force





Accelerated expansion – vacuum energy?

How to realize inflation?

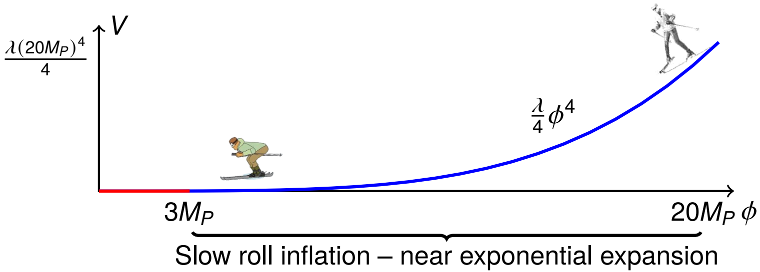
- Vacuum energy is ok for present day accelerated expansion
  - cosmological constant Λ
  - exponential expansion $a \propto \exp(Ht)$ – acceleration
- But: it lasts forever!
- Should stop this expansion somehow after inflation…

Chaotic inflation–a scalar field

gives also primordial perturbations!

$$\mathcal{H}^2 \simeq \frac{1}{3M_P^2}\left(V(\phi) + \dot{\phi}^2/2\right)$$

$$\ddot{\phi} + 3\mathcal{H}\dot{\phi} + V'(\phi) = 0$$



Field quantum fluctuations – primordial perturbations

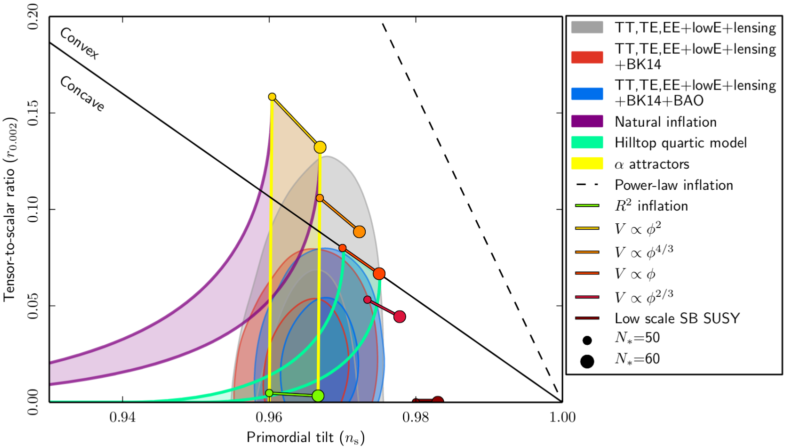
$\delta T/T \sim 10^{-5}$ requires:

quartic coupling: $\lambda \sim 10^{-13}$ (or mass: $m \sim 10^{13}$ GeV)

Where to get such a super weakly coupled field?

CMB observations favour flat potentials

PLANCK 2018



- Tensor modes (primordial gravity waves) $\propto V$
- primordial density perturbations $\propto V^{3/2}/V'$

Outline

Non-minimal coupling to gravity solves the problem

Quite an old idea

For a scalar field coupling to the Ricci curvature is possible (actually *required* by renormalization)

- [A.Zee'78, L.Smolin'79, B.Spokoiny'84]
- [D.Salopek J.Bond J.Bardeen'89]

Scalar part of the (Jordan frame) action

$$S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R - \xi \frac{h^2}{2} R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} (h^2 - v^2)^2 \right\}$$

- h is the Higgs field; $M_P \equiv \frac{1}{\sqrt{8\pi G_N}} = 2.4 \times 10^{18}$GeV
- SM higgs vev $v \ll M_P/\sqrt{\xi}$ – can be neglected in the early Universe
- At $h \gg M_P/\sqrt{\xi}$ *all* masses are proportional to h – scale invariant spectrum!

Bezrukov and Shaposhnikov 2008

Conformal transformation – nice way to calculate

It is possible to get rid of the non-minimal coupling by the conformal transformation (change of variables)

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \; , \qquad \Omega^2 \equiv 1 + \frac{\xi h^2}{M_P^2}$$

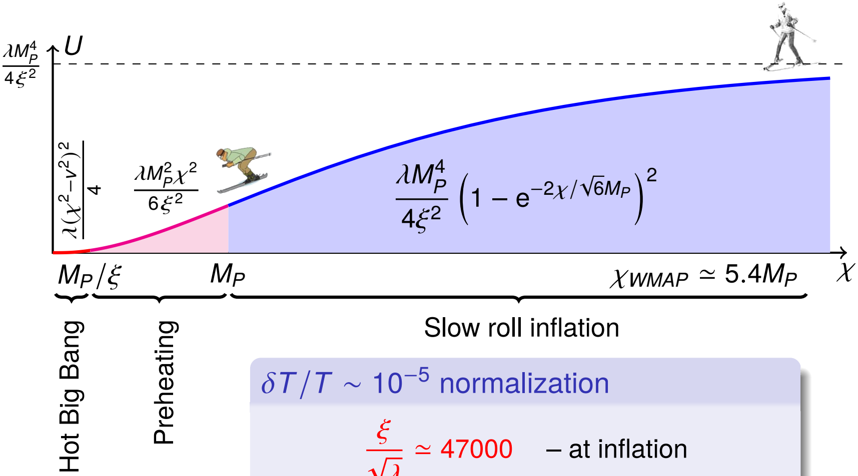
Redefinition of the Higgs field to get canonical kinetic term

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}} \implies \begin{cases} h \simeq \chi & \text{for } h < M_P/\xi \\ \Omega^2 \simeq \exp\left(\frac{2\chi}{\sqrt{6}M_P}\right) & \text{for } h > M_P/\xi \end{cases}$$

Resulting action (Einstein frame action)

$$S_E = \int d^4x \sqrt{-\hat{g}} \left\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - \frac{\lambda}{4}\frac{h(\chi)^4}{\Omega(\chi)^4} \right\}$$

Potential – different stages of the Universe



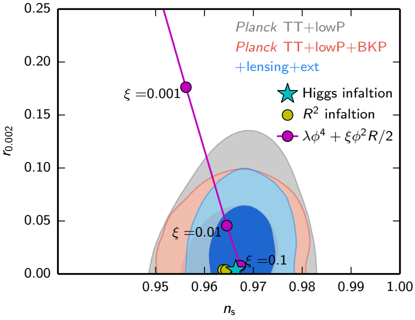
$\delta T/T \sim 10^{-5}$ normalization

$$\frac{\xi}{\sqrt{\lambda}} \simeq 47000 \quad \text{– at inflation}$$

Small λ is traded for large ξ

CMB parameters are predicted

Exactly as preferred by observations



spectral index $\quad n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$

tensor/scalar ratio $\quad r \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$

$$\delta T/T \sim 10^{-5} \quad \Longrightarrow \quad \frac{\xi}{\sqrt{\lambda}} \simeq 47000$$

Why should we care about particle physics?

- What happens at the scales between Electroweak 200 GeV and Planck 10^{19} GeV?
- Is SM consistent at all energies?
- Do any problems appear?
- Are there quantum corrections to the inflationary dynamics?

Consistency

Up to now we neglected the quantum effects, assuming they do not spoil the story.

Consistency

Up to now we neglected the quantum effects, assuming they do not spoil the story.
Is this really the case?

Cut off scale today

Let us work in the Einstein frame

Change of variables: $\frac{d\chi}{dh} = \frac{M_P\sqrt{M_P^2+(\xi+6\xi^2)h^2}}{M_P^2+\xi h^2}$ leads to the higher order terms in the potential (expanded in a power law series)

$$V(\chi) = \lambda\frac{h^4}{4\Omega^4} \simeq \lambda\frac{h^4}{4} \simeq \lambda\frac{\chi^4}{4} + \#\frac{\chi^6}{(M_P/\xi)^2} + \cdots$$

Unitarity is violated at tree level

in scattering processes (eg. $2 \longrightarrow 4$) with energy above the "cut-off"

$$E > \Lambda_0 \sim \frac{M_P}{\xi}$$

Hubble scale at inflation is $H \sim \lambda^{1/2}\frac{M_P}{\xi}$ – not much smaller than the today cut-off Λ_0 :(

Burgess, Lee, and Trott 2009; Barbon and Espinosa 2009; Hertzberg 2010

Quantum effects?

How do quantum effects change the story?

Cut off scale today

Let us work in the Einstein frame for simplicity

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“Cut off” is background dependent!

Classical background   Quantum perturbations

$$\chi(x,t) = \bar{\chi}(t) + \delta\chi(x,t)$$

leads to background dependent suppression of operators of dim $n > 4$

$$\frac{\mathcal{O}_{(n)}(\delta\chi)}{[\Lambda_{(n)}(\bar{\chi})]^{n-4}}$$

Example

Potential in the inflationary region $\chi > M_P$: $U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^2$

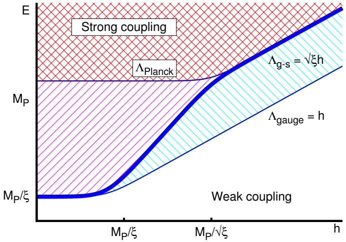
leads to operators of the form: $\frac{\mathcal{O}_{(n)}(\delta\chi)}{[\Lambda_{(n)}(\bar{\chi})]^{n-4}} = \frac{\lambda M_P^4}{\xi^2} e^{-\frac{2\bar{\chi}}{\sqrt{6}M_P}} \frac{(\delta\chi)^n}{M_P^n}$

Leading at high n to the "cut-off" $\Lambda \sim M_P$

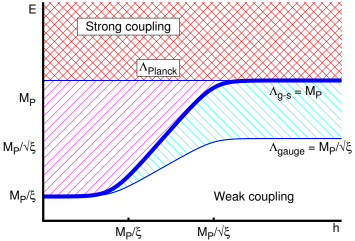
Bezrukov, Magnin, et al. 2011; Bezrukov, Gorbunov, and Shaposhnikov 2011

Cut-off grows with the field background

Jordan frame



Einstein frame



Relation between cut-offs in different frames:

$$\Lambda_{\text{Jordan}} = \Lambda_{\text{Einstein}}\Omega$$

Relevant scales at inflation

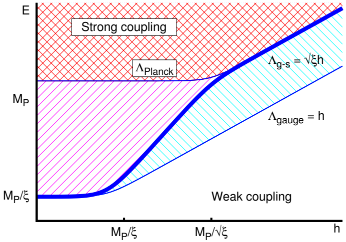
Hubble scale $H \sim \lambda^{1/2}\frac{M_P}{\xi}$

Energy density at inflation

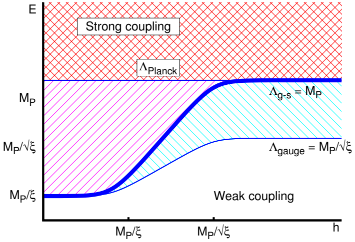
$$V^{1/4} \sim \lambda^{1/4}\frac{M_P}{\sqrt{\xi}}$$

Cut-off grows with the field background

Jordan frame



Einstein frame



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Energy density at inflation

$$V^{1/4} \sim \lambda^{1/4}\frac{M_P}{\sqrt{\xi}}$$

Reheating temperature $M_P/\xi < T_{\text{reheating}} < M_P/\sqrt{\xi}$

Problems during reheating

Outline

Study by UV completion (embed into something well behaved)

- R^2-HI Ema 2017; Gorbunov and Tokareva 2019; He, Jinno, Kamada, Park, et al. 2019

$$S = \int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R - \frac{\xi h^2}{2}R + \frac{\beta}{4}R^2 - \frac{(\partial h)^2}{2} - \frac{\lambda h^4}{4}\right\}$$

  - R^2 is complete up to M_P
  - If scalaron is lighter than the problematic scale: weakly coupled

$$M^2 = \frac{M_P^2}{6\beta} < 4\pi\frac{M_P^2}{6\xi^2}$$

- More generic additional scalar below M_P/ξ Giudice and Lee 2011

No known UV completion without a state with $M < M_P/\xi$

- See, however:
  - “self-healing” Calmet and Casadio 2014
  - “nonlocal” Koshelev and Tokareva 2020

We are in a large class of similar models

Can we distinguish them?

HI

$$S_J = \int d^4x \left\{ -\frac{M_P + \xi h^2}{2} R + \frac{(\partial h)^2}{2} - \frac{\lambda h^4}{4} \right\}$$

EF potential at inflation

$$U \simeq \frac{\lambda M_P^4}{4\xi^2} \left(1 - e^{-2\chi/\sqrt{6}M_P} \right)^2$$

R^2

$$S_J = \int d^4x \left\{ -\frac{M_P}{2} R + \frac{\beta}{4} R^2 \right\}$$

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EF potential at inflation

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Expect efficient preheating

larger N_*

larger n_s

Expect inefficient preheating

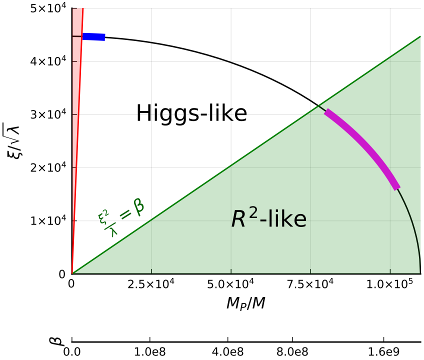
smaller N_*

smaller n_s

We need to study preheating!

Changes to the model properties

- Basic HI
  - Low energy: λ, and high order operators controlled by ξ
  - Inflation: perturbations fixed by ξ^2/λ
- R^2-Higgs
  - Low energy: λ, and high order operators controlled by ξ, M
  - Inflation: perturbations fixed by $\xi^2/\lambda + \beta$
  - Note – λ RG running is modified above M_ϕ

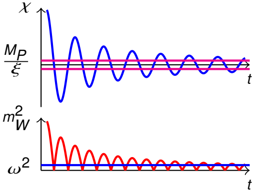


Gorbunov and Tokareva 2019

Outline

Reheating in Higgs inflation (attempt 1)

- Post-inflationary evolution $\chi < M_P$ ($h < M_P/\sqrt{\xi}$)
  - quadratic potential $U \simeq \frac{\omega^2}{2}\chi^2$ with $\omega = \sqrt{\frac{\lambda}{3}}\frac{M_P}{\xi}$
  - matter domination $a \propto t^{2/3}$
- Resonance
  - gauge masses $m_W^2(\chi) \sim g^2 \frac{M_P|\chi|}{\xi}$
  - generate nonrelativistic W
    - ★ $\sqrt{\langle\chi^2\rangle} \lesssim 23\left(\frac{\lambda}{0.25}\right)\frac{M_P}{\xi}$: resonance creation and annihilation of W
  - Creation of Higgs bosons is less efficient $\sqrt{\langle\chi^2\rangle} \sim 2.6\left(\frac{\lambda}{0.25}\right)^{1/2}\frac{M_P}{\xi}$
  - Radiation-dominated stage starts at χ amplitude



$$\frac{3.0M_P}{\xi}\left(\frac{\lambda}{0.25}\right)^{1/2} < \chi_r < \frac{32.7M_P}{\xi}\left(\frac{\lambda}{0.25}\right)$$

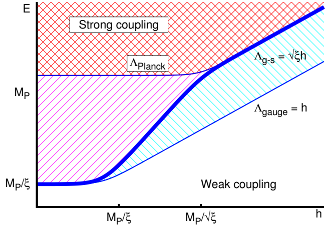
Bezrukov, Gorbunov, and Shaposhnikov 2009, Garcia-Bellido, Figueroa, and Rubio 2009

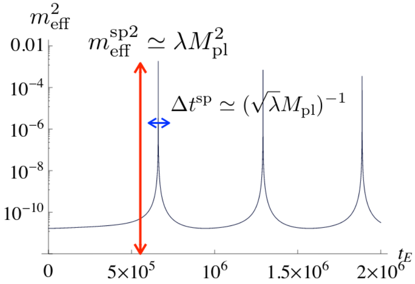
Problems – forgot longitudinal gauge bosons

Seems that at reheating

$$m_W \sim g^2 \frac{M_P |\chi|}{\xi}$$

quite in the region of the validity of the theory





$$S = \int dx \left(-\frac{(F_{\mu\nu})^2}{4} - m_A^2(t) \frac{(A_\mu)^2}{2} \right)$$

For *longitudinal* bosons

$$m^2_{\text{eff},L} = m_A^2 - \frac{k^2}{k^2 + m_A^2} \left(\frac{\ddot{m}_A}{m_A} - \frac{3\dot{m}_A^2}{k^2 + m_A^2} \right)$$

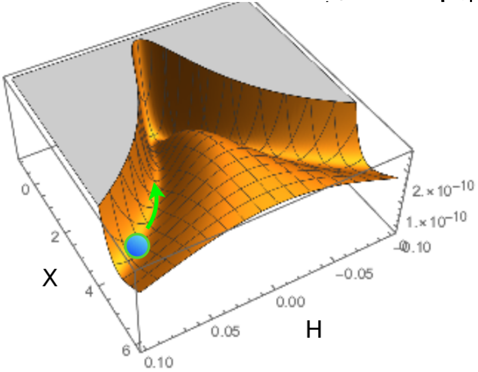
Ema et al. 2017

R^2+Higgs inflation – simple UV completion

In Einstein frame: Higgs doublet h, $|h| \equiv \sqrt{hh^\dagger}$, scalaron ϕ

$$S_{EF} = \int d^4x \left[-\frac{M_P^2}{2} R + e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} \frac{(\partial h)^2}{2} + \frac{(\partial \phi)^2}{2} \right.$$

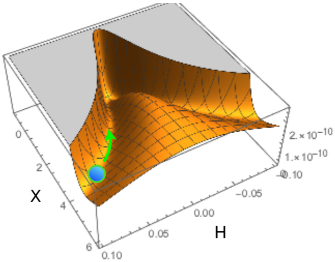
$$\left. - \frac{1}{4} e^{-2\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} \left(\lambda |h|^4 + \frac{M_P^4}{\beta} \left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} - 1 - \xi \frac{|h|^2}{M_P^2} \right)^2 \right) \right]$$



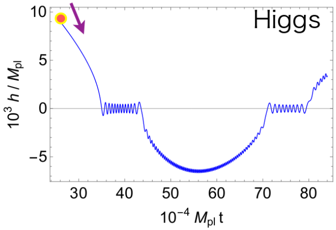
Perturbative up to $E \lesssim M_P$ if

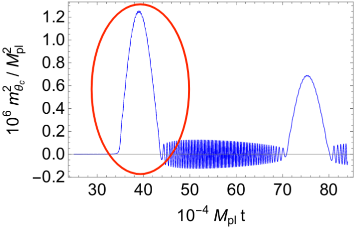
$$\beta \gtrsim \frac{\xi^2}{4\pi}$$

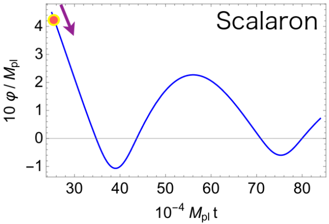
So, how R^2+Higgs reheats?



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



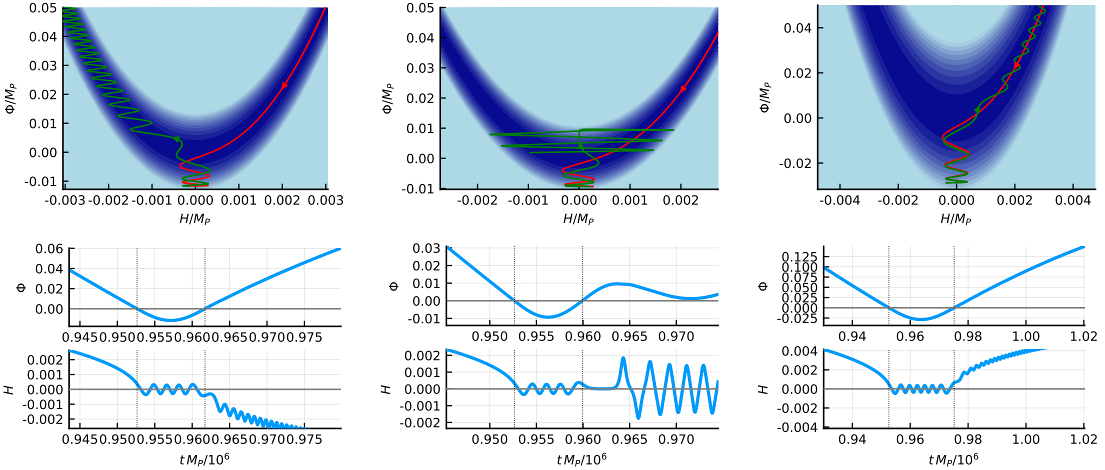




No reheating on the expected mass peak: $\rho_{W_L} \sim \# M_\Phi^{-4} \ll \rho_{\rm infl}$

He, Jinno, Kamada, Park, et al. 2019

So, how it reheats?!



$\beta = 2.9 \times 10^6$ $\beta = 1.869 \times 10^6$ $\beta = 18.0 \times 10^6$

Critical (bifurcation) case depending on model parameters/or background energy.

Bezrukov, Gorbunov, Shepherd, et al. 2019

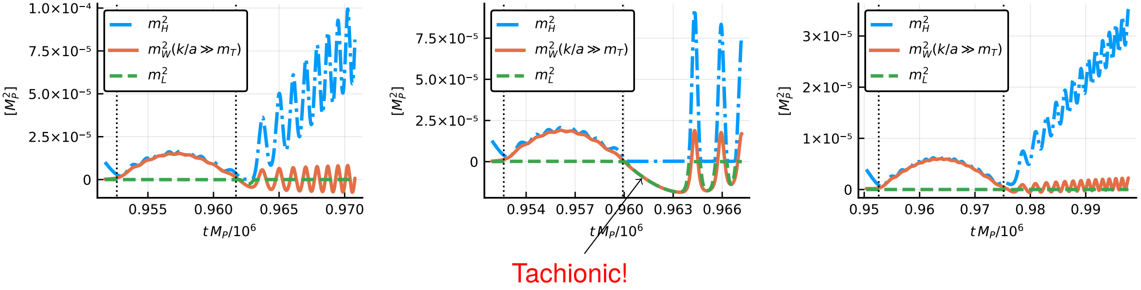
Particles become tachyonic in the critical case

"Higgs" excitation mass

$$m_h^2 \approx 3\left(\lambda + \frac{\xi^2}{\beta}\right) H_0^2 - \frac{\sqrt{2}\xi}{\sqrt{3}\beta} M_P \Phi_0$$

Longitudinal gauge boson energies

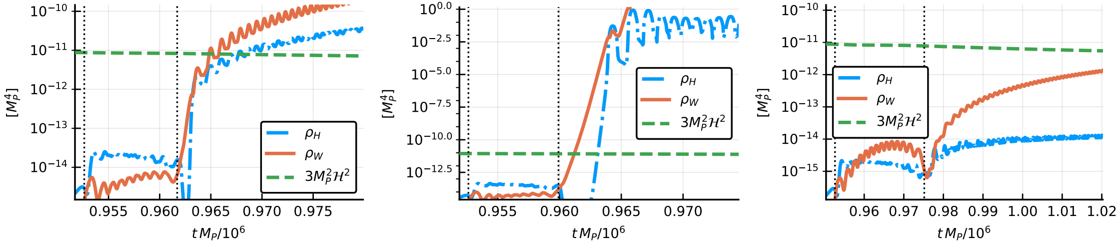
$$\omega_W^2(\mathbf{k}) \approx \frac{k^2}{a^2} + m_T^2 - \frac{k^2}{k^2 + a^2 m_T^2}\left(\frac{\ddot{m}_T}{m_T} - \frac{3(\dot{m}_T)^2}{k^2/a^2 + m_T^2}\right).$$



Very efficient reheating on the “tachyon”

- Write linearized equations for perturbations
- Start with vacuum initial conditions (negative frequency)
- Calculate occupation number of positive frequency modes at the end (i.e. Bogolyubov coefficients)

In the critical case energy in the produced modes grows fast!



Immediate reheating!

Very efficient reheating on the “tachyon”

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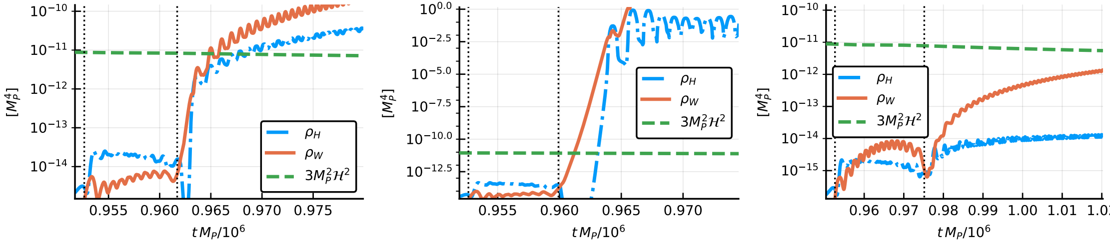
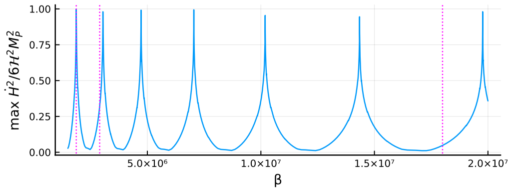
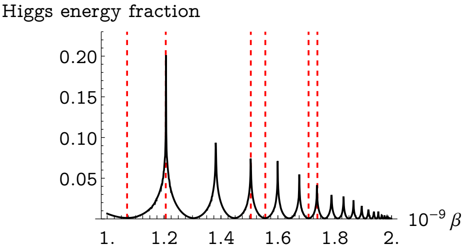


Immediate reheating!

Small print: only if the parameters lead to critical case evolution

What happens in the generic case?





- If β is small (close to $\xi^2/2\pi$) – "Higgs like" case, critical values are relatively frequent.
- Whole range of β is studied in He, Jinno, Kamada, Starobinsky, et al. 2021

Complications

- Can tachyon happen not on the first oscillation?
- Backreaction!
  - Modifies background evolution during the tachyonic regime
  - Modifies background evolution away from tachyonic regime

Outline

Semiclassical approach to reheating

- Quantum theory with small coupling constant ß reaches large occupation numbers while still linear in perturbations
- Large occupation numbers ß classical equations of motion can be used

Semiclassical algorithm

- Set Gaussian random initial conditions for all fields $f_{\mathbf{k}}$, giving $n_{\mathbf{k}} = 1/2$
- Evolve the classical equations of motion

Khlebnikov and Tkachev 1996

Complications (starting the simulations)

- Non-canonical kinetic terms
  - Luckily not too relevant for us after slow-roll
  - We use modified version of GABE
    - ★ It can deal with non-canonical kinetic terms, though this turned out to be not that important.

Complications (starting the simulations)

- Non-canonical kinetic terms
  - Luckily not too relevant for us after slow-roll
  - We use modified version of GABE
    - ★ It can deal with non-canonical kinetic terms, though this turned out to be not that important.
- Relevant reheating processes should
  - “fit” on the lattice
    - ★ $\frac{2\pi}{L} < k_{\text{tachyon}}, k_{\text{rescatering}} < \frac{2\pi N}{L}$
  - be in semiclassical regime – i.e. have large occupation number.

“Vacuum oscillations” as initial conditions

- To simulate the parametric tachyonic resonance initial “seed” is required

$$n_{\mathbf{k}} \equiv \frac{a^3}{2\omega_k}\left(|\dot{f}_{\mathbf{k}}|^2 + \omega_k^2|f_{\mathbf{k}}|^2\right) = \frac{1}{2}$$

Problem of large vacuum oscillations

“vacuum” energy should not be larger, than “tree level” background energy

$$\int_{\text{all lattice momenta}} \frac{\omega_{\mathbf{k}}}{2} d^3\mathbf{k} < V(\phi, h)$$

Or at least

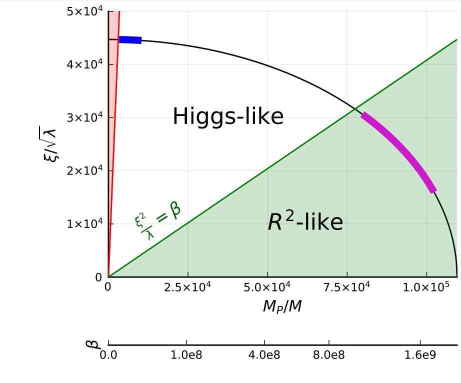
$$\int_{\text{typical tachyonic momenta}} \frac{\omega_{\mathbf{k}}}{2} d^3\mathbf{k} < V(\phi, h)$$

This means that simulations are reliable: small $\lambda \frac{\xi^2}{\lambda\beta}$

Tachyonic dynamics is not semiclassical for small β!

- Realistic simulations: make modes unoccupied above some initial cut-off
$$n_{\mathbf{k}}|_{k<\Lambda_{in}} = 1/2$$
$$n_{\mathbf{k}}|_{k>\Lambda_{in}} = 0$$
- Large enough lattice to grab tachyonic
$$\frac{2\pi}{L} < k_{\text{tachyonic}} < \Lambda_{in}$$
and late time rescattering evolution
$$k_{\text{rescattering}} < \frac{2\pi N}{L}$$

Possible only for $\beta > 10^{-9}$



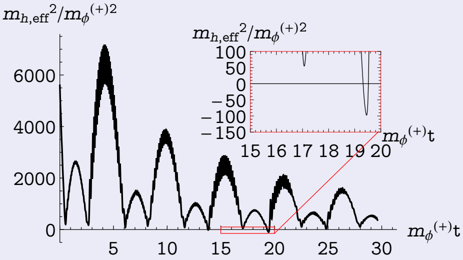
Bezrukov and Shepherd 2020

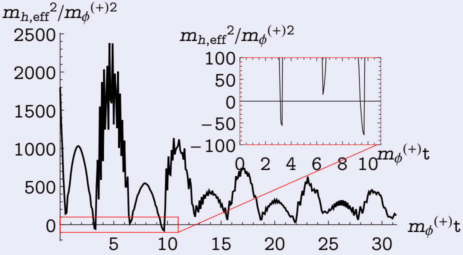
What changes compared to analytic calculation?

1. Tachyonic behaviour may appear not only on first $\chi = 0$ crossing, but also on consequent ones
   - Depends on field background amplitudes, etc.
2. Created particles *suppress* tachyonic behaviour

$$m_{h,\text{eff}}^2 = -\sqrt{\frac{2}{3}}\frac{\xi}{\beta}M_P\,\phi_{(0)} + \left(\lambda + \frac{\xi^2}{\beta}\right)\left(3h_{(0)}^2 + \langle (h_i - \langle h_i\rangle)^2\rangle\right) .$$

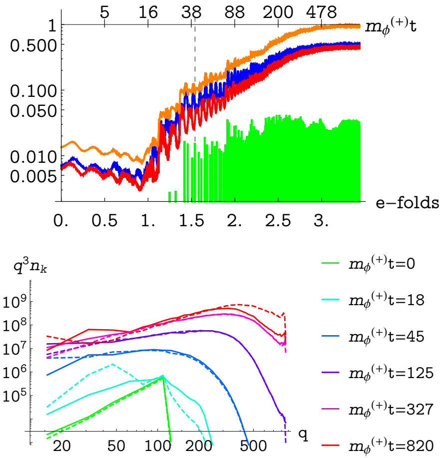
Observation: (1) always happens before (2)!



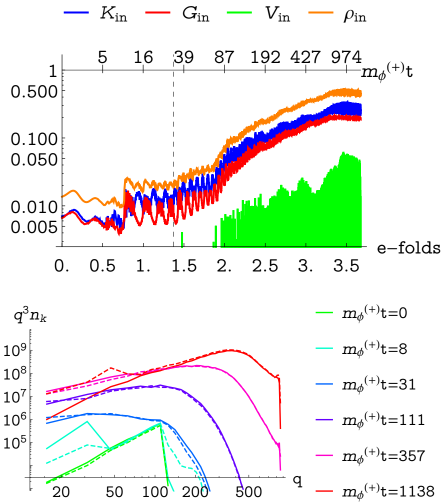


Reheating stages

Energy fraction:



$\beta = 1.060 \times 10^9$

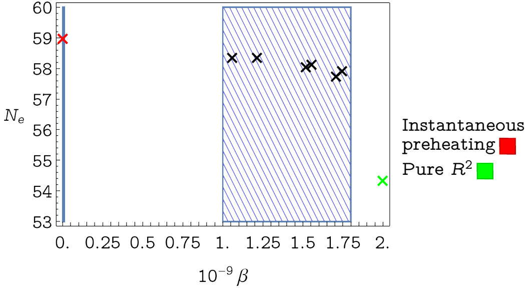


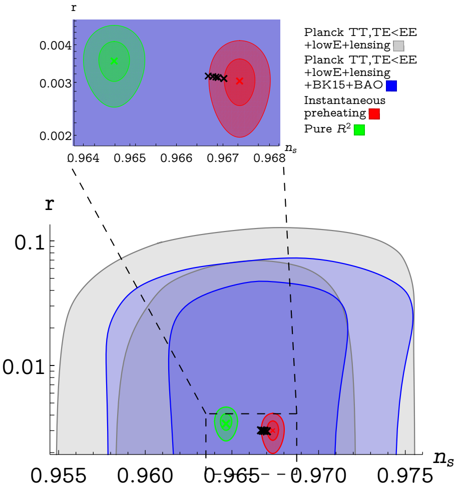
$\beta = 1.745 \times 10^9$

1. Tachyonic
2. scattering on the background
3. perturbative decay of the scalaron (relevant for larger β)

Does it lead to observable effects?

Preheating is fast!





For precise absolute numbers second order in slow-roll is needed, c.f. Gorbunov and Tokareva 2012

Outline

Not yet finished after preheating

- We get to the model with long lived heavy scalaron
- Additional entropy release!

To appear

Outline

Further note on variable choice:

We really need to know how quantum gravity works

- How do we interpret the gravity action:
  - Metric – $g_{\mu\nu}(x)$ is an independent field, Connection – $\Gamma^{\lambda}_{\mu\nu} \equiv \frac{g^{\lambda\rho}}{2}(g_{\rho\mu,\nu} + g_{\rho\nu,\mu} - g_{\mu\nu,\rho})$
  - Palatiny – $g_{\mu\nu}(x)$, $\Gamma^{\lambda}_{\mu\nu}(x)$ are independent fields
- Different *classical* dynamics if $\xi \neq 0$
  Can be seen as different transformation under $g_{\mu\nu} \to \Omega(x) g_{\mu\nu}$

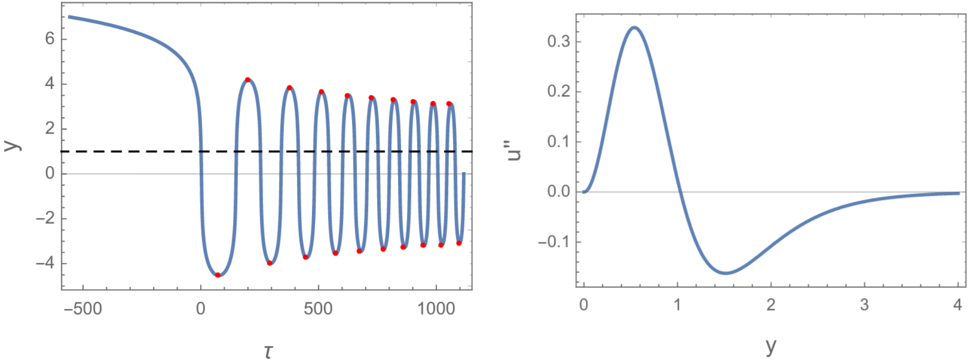
Rather different inflationary predictions!

Metric	Palatini
$R \to \Omega^2 R + 6 g^{\mu\nu} \partial_\mu \ln \Omega \partial_\nu \ln \Omega$	$R \to \Omega^2 R$
$\xi \sim 5 \times 10^4 \sqrt{\lambda}$ $r \sim 3.2 \times 10^{-3}$	$\xi \sim 1.5 \times 10^{10} \lambda$ $r \sim 3.5 \times 10^{-14} \lambda^{-1}$

e.g. Rasanen,Wahlman'17; Järv,Racioppi,Tenkanen'17

Another preheating possibilities in HI: Palatini HI

- Fast again, but for a different reason:



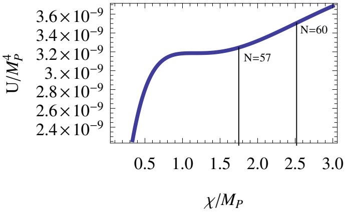
Tachyonic regime on maxima of higgs oscillations!

- A bit care for longitudinal gauge bosons may be needed…

Rubio and E. S. Tomberg 2019

Another preheating possibilities in HI: Critical HI

$$U_{\text{RG improved}}(\chi) = \frac{\lambda(\mu)}{4}\frac{M_P^4}{\xi^2}\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2$$



- Small $\xi \lesssim 10$ – λ vs. $\delta\lambda$ significant, may give interesting "features" in the potential ("critical inflation", large r)
- Preheating is inefficient for small λ. Both for longitudinal modes, and expected due to transverse modes:

$$\frac{3.0 M_P}{\xi}\left(\frac{\lambda}{0.25}\right)^{1/2} < \chi_r < \frac{32.7 M_P}{\xi}\left(\frac{\lambda}{0.25}\right)$$

Maybe we can compute everything in HI!

to be confirmed

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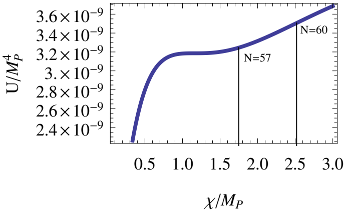

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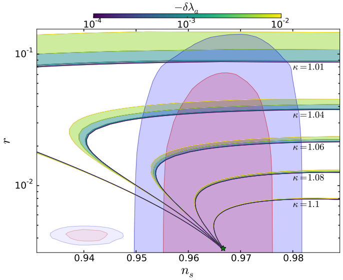
  Maybe we can compute everything in HI!

- However – tend to get both inflation and $\delta\lambda$ "jumps" at the same scale around M_P/ξ
- Loop corrections change result – harder to control

  Bezrukov, Pauly, and Rubio 2018



to be confirmed

Conclusions

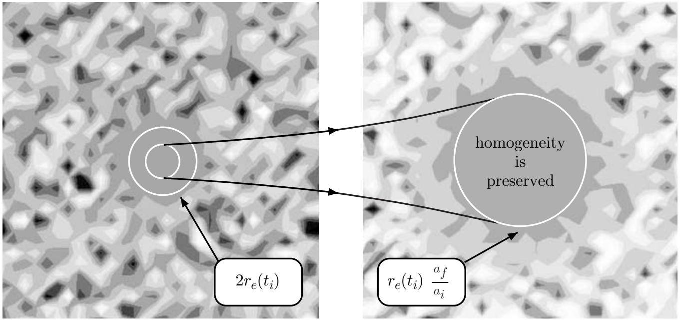
- To get exact predictions from a theory:
  The theory should be properly defined first!
- Simplest UV completion of Higgs inflation – R^2+HI
  - Reheats nearly immediately for not too light scalaron mass!
  - Tachyonic dynamics is achieved after several scalaron oscillations, and then blocked by backreaction
- Details of reheating for even lighter scalaron – connection with R^2 case – yet to study.
- Possibly can hide from complications in critical HI case!
- Interesting features due to tachyonic dynamics at preheating? GW? Imprint on CMB perturbations?

Small homogeneous patch is expanded to the whole observed Universe

In the accelerated Universe *event horizon* (region of the Universe that can be in principle affected by an event) exists

$$r_e(t) = a(t) \int_t^{t_{\max}} \frac{dt}{a} = a(t) \int_{a(t)}^{a_{\max}} \frac{da}{\dot{a}a}$$

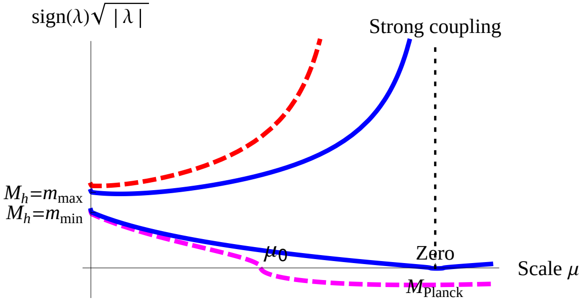
converges for growing $\dot{a}$



Standard Model self-consistency and Radiative Corrections

- Higgs self coupling constant λ changes with energy due to radiative corrections.

$$(4\pi)^2 \frac{d\lambda}{d\log\mu} = 24\lambda^2 - 6y_t^4 + \frac{3}{8}(2g_2^4 + (g_2^2 + g_1^2)^2) + (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda$$

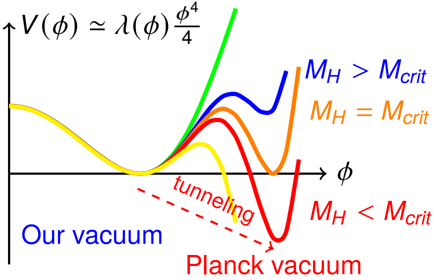


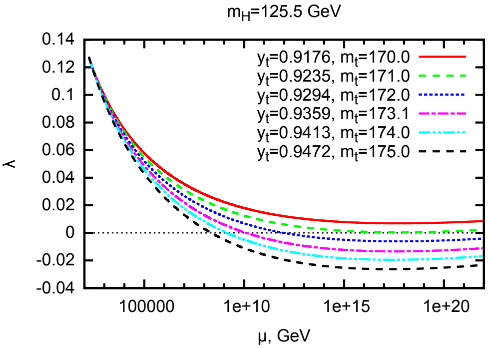
- Behaviour is determined by the masses of the Higgs boson $m_H = \sqrt{2\lambda}v$ and other heavy particles (top quark $m_t = y_t v/\sqrt{2}$)
- If Higgs is heavy $M_H > 170$ GeV – the model enters *strong coupling* at some low energy scale – new physics required.

RG corrections change Higgs potential

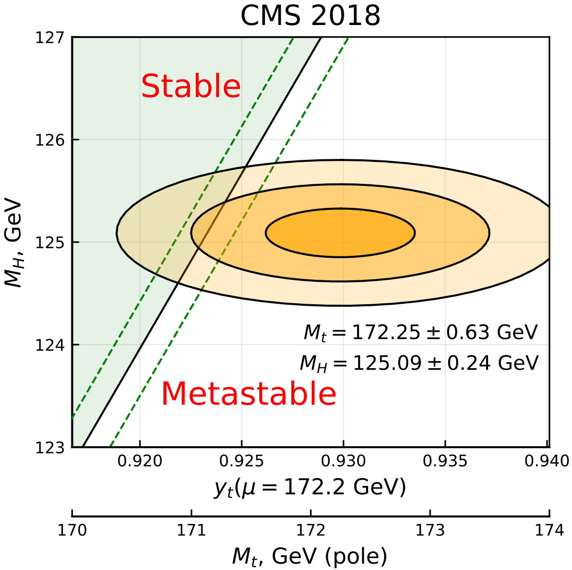
Realistic Higgs mass options

- For Higgs masses $M_H < M_{\text{critical}}$ coupling constant is negative above some scale μ_0.
- The Higgs potential may become negative!
  - Our world is not in the lowest energy state!
  - Problems at some scale $\mu_0 > 10^{10}$ GeV?





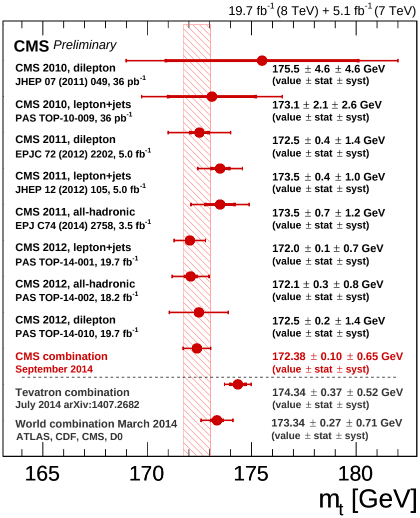
Experiment: we are in the critical case



Determination of top quark Yukawa

- Hard to determine mass in the events
- Hard to relate the "pole" (even worse for "Mont-Carlo") mass to the $\overline{\text{MS}}$ top quark Yukawa
  - NLO event generators
  - Electroweak corrections – important at the current precision goals!

- Build a lepton collider! FCC-ee! $\delta m_t \sim 100$ MeV
- Improve analysis on a hadron collider?

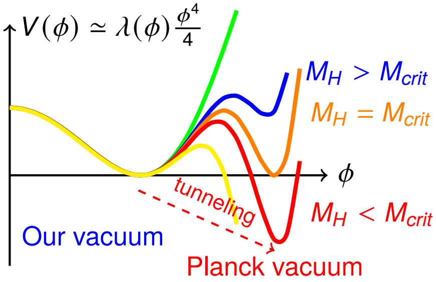


Outline

7 Backup slides
- What can happen?

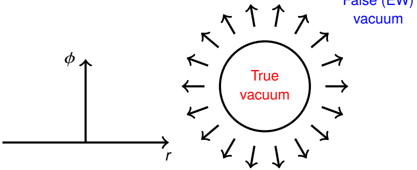
Options for Higgs potential

- Higher m_H, lower m_t
  - stable EW vacuum
  - Higgs inflation as in the first part of the talk
- Lower m_H, higher m_t
  - unstable EW vacuum?!
- Critical m_H for given m_t
  - Interesting coincidence:
    - ★ $m_H \simeq 126$ GeV predicted
    - ★ λ_{min} is at scale $\mu \sim M_P$



What to do if we are metastable?

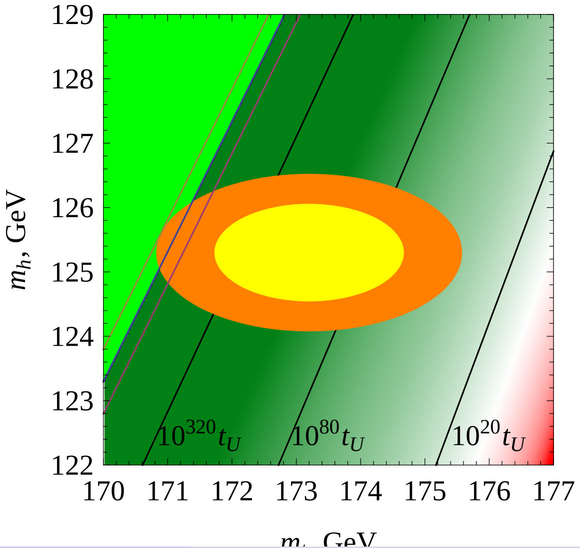
Vacuum decays by creating bubbles of true vacuum, which then expand very fast ($v \to c$)



Tunneling suppression:

$$p_{\text{decay}} \propto e^{-S_{\text{bounce}}} \sim e^{-\frac{8\pi^8}{3\lambda(h)}}$$

Lifetime $\gg$ age of the Universe!

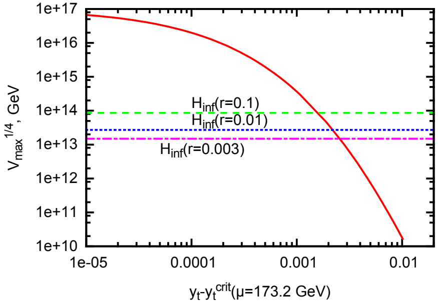


Stability in Early Universe

As far as we are “safe” now (i.e. at low energies), what about Early Universe?
What happens with the Higgs boson at inflation?

Metastable vacuum during inflation *is* dangerous

- Let us suppose Higgs is not at all connected to inflationary physics (e.g. R^2 inflation)
- All fileds have vacuum fluctuation
- Typical momentum $k \sim H_{\rm inf}$ is of the order of Hubble scale



- If typical momentum is greater than the potential barrier – SM vacuum would decay if

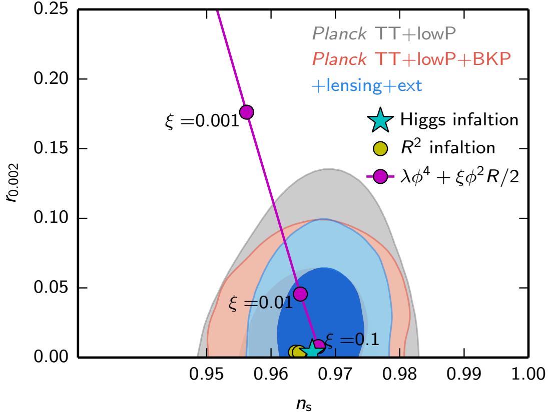
$$H_{\rm inf} > V_{\rm max}^{1/4}$$

Most probably, fluctuations at inflation lead to SM vacuum decay…

- Observation of any tensor-to-scalar ratio r by CMB polarization missions would mean great danger for metastable SM vacuum!

Measurement of primordial tensor modes determines scale of inflation

$$H_{\rm inf} = \sqrt{\frac{V_{\rm infl}}{3M_P^2}} \sim 8.6\times 10^{13}\,\text{GeV}\left(\frac{r}{0.1}\right)^{1/2}$$



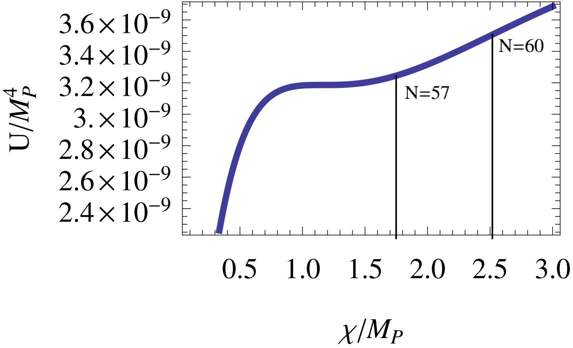
Does inflation contradict metastable EW vacuum?

Of course we do not know

- Higgs interacting with inflation can cure the problem. Examples
  - Higgs (ϕ)–inflaton (χ) interaction may stabilize the Higgs
    $$L_{\rm int} = -\alpha\phi^2\chi^2$$
  - Higgs-gravity *negative* non-minimal coupling stabilizes Higgs in de-Sitter (inflating) space
    $$L_{\rm nm} = \xi\phi^2 R$$
- New physics *below* μ_0 may remove Planck scale vacuum and make EW vacuum stable – many examples

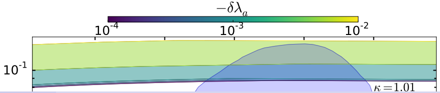
Near critical Higgs mass – critical HI

$$U_{\text{RG improved}}(\chi) = \frac{\lambda(\color{red}{\mu})}{4}\frac{M_P^4}{\xi^2}\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2$$



$1 \ggg \lambda_{min} > 0$

- Small $\xi \lesssim 10$ – λ vs. $\delta\lambda$ significant, gives "feature" in the potential
- Very flat potential – large perturbations.
- different inflationary predictions – large r
- Production of primordial black holes – even Dark Matter
  - Solar mass?
  - Ezquiaga, Garcia-Bellido, and



Threshold effects at M_P/ξ summarized by two new arbitrary constants $\delta\lambda$, δy_t

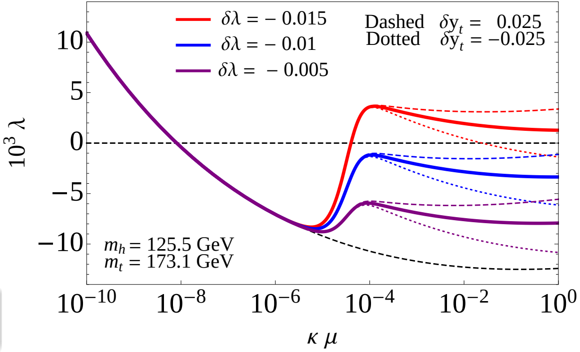
- Low and high scale coupling constants may be different

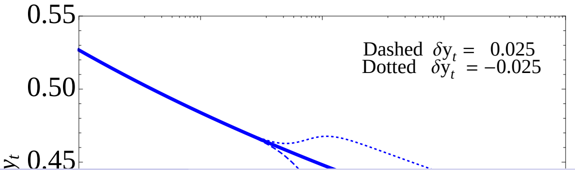
$$\lambda(\mu) \to \lambda(\mu) + \delta\lambda \left[\left(F'^2 + \tfrac{1}{3}F''F\right)^2 - 1\right]$$

$$y_t(\mu) \to y_t(\mu) + \delta y_t \left[F'^2 - 1\right]$$

Attempts to improve

- UV complete theories

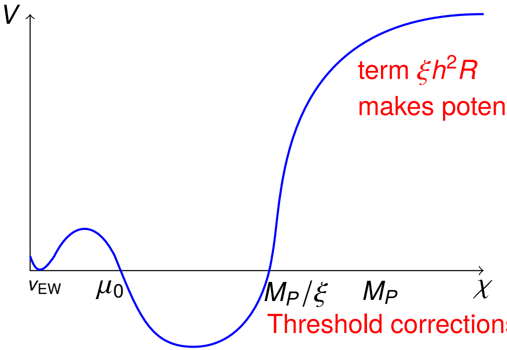




Higgs inflation and radiative corrections

Can be also used to “save” the metastable vacuum

$$S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R - \xi \frac{h^2}{2} R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} (h^2 - v^2)^2 \right\}$$



term $\xi h^2 R$
makes potential flat

Threshold corrections at scale M_P/ξ
“shift” λ back to positive values

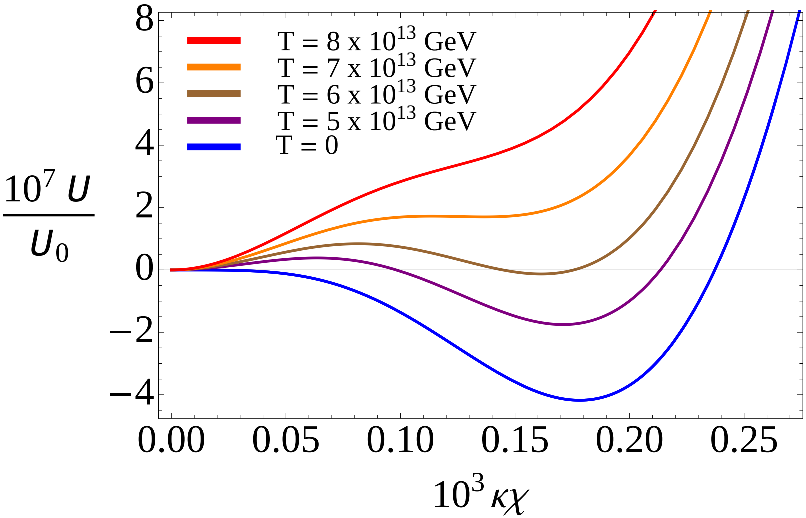
New physics *above* μ_0 may solve the problem

Requirements

- Minimum at Planck scale should be removed (but can remain near $\mu_0 \sim 10^{10}$ GeV)
- Reheating after inflation should be fast.

No need for new physics at "low" ($< \mu_0$) scales!
Example: Higgs inflation with threshold corrections at M_p/ξ

After inflation symmetry is restored in preheating



- Thermal potential removes the high scale vacuum

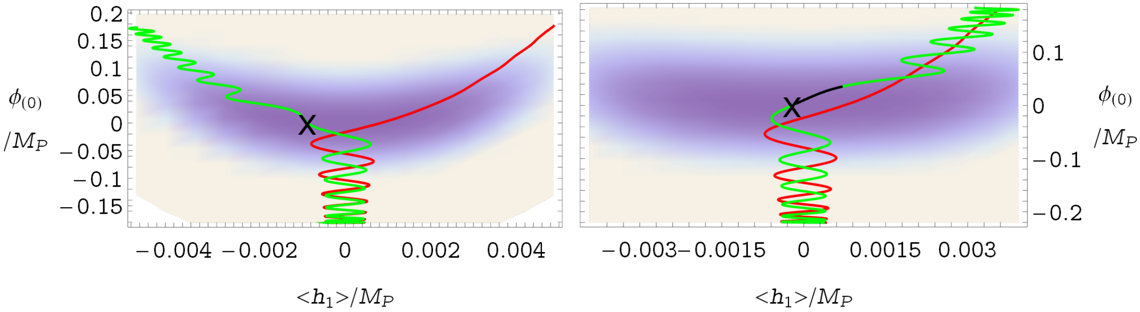
Effective theories at high and low h

- Below M_P/ξ
  - Renormalizable ϕ^4-like Standard Model
  - + M_P/ξ suppressed operators
- Above $M_P/\sqrt{\xi}$
  - Non-renormalizable, but the potential nicely arranges

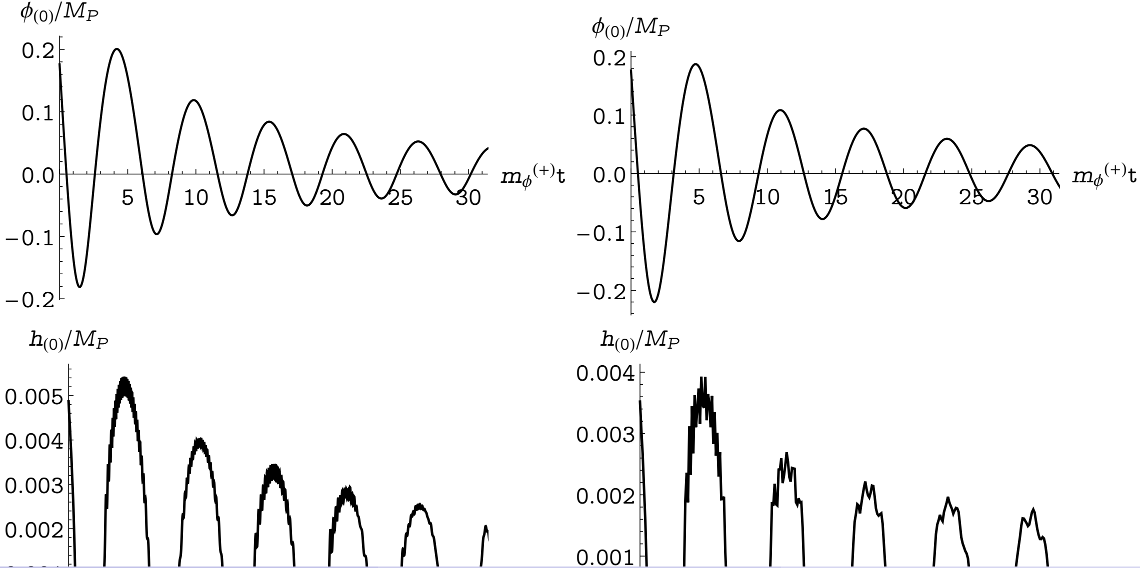
$$\#e^{-\chi/M} + \#e^{-2\chi/M} + \#e^{-3\chi/M} + \cdots$$

Higher terms are irrelevant

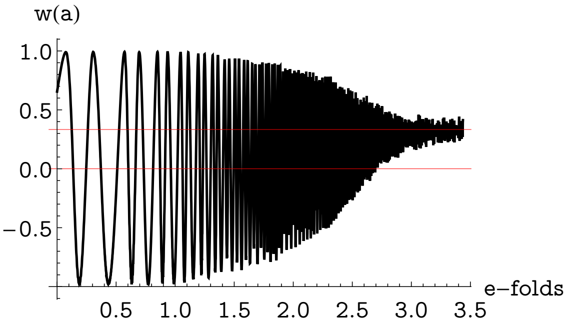
Field evolution

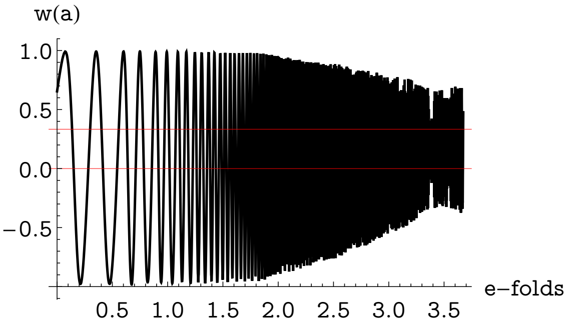


Field evolution

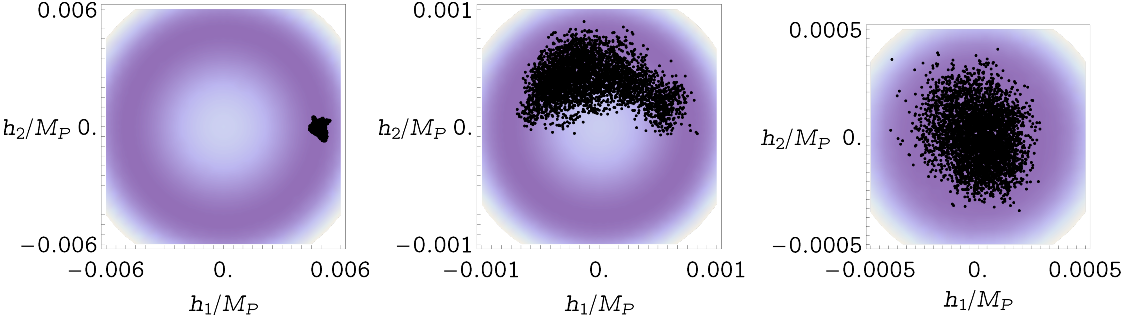


Equation of state





Symmetry restoration



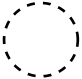
Decay widths

$$\Gamma_\phi \approx \frac{1}{24\pi m_\phi^{(-)}} \left(M_P \frac{\xi}{\beta} \right)^2 \sqrt{1 - 2\frac{m_{h,\text{eff}}^2}{m_\phi^{(-)\,2}}}.$$

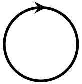
$$m_\phi^{(-)\,2} = \frac{M_P^2}{6\beta}.$$

Counterterms: λ modification

Calculating vacuum energy



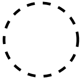
$$
\begin{aligned}
&= \frac{1}{2}\,\mathrm{Tr}\ln\left[\Box - \left(\frac{\lambda}{4}(F^4)''\right)^2\right] \\
&= \frac{9\lambda^2}{64\pi^2}\left(\frac{2}{\bar\epsilon} - \ln\frac{\lambda(F^4)''}{4\mu^2} + \frac{3}{2}\right)\left(F'^2 + \frac{1}{3}F''F\right)^2 F^4,
\end{aligned}
$$



$$
\begin{aligned}
&= -\,\mathrm{Tr}\ln\left[i\partial\!\!\!/ + y_t F\right] \\
&= -\frac{y_t^4}{64\pi^2}\left(\frac{2}{\bar\epsilon} - \ln\frac{y_t^2F^2}{2\mu^2} + \frac{3}{2}\right)F^4
\end{aligned}
$$

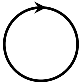
Counterterms: λ modification

Calculating vacuum energy



$$= \frac{1}{2}\,\mathrm{Tr}\ln\left[\Box - \left(\frac{\lambda}{4}(F^4)''\right)^2\right]$$

$$\delta\mathcal{L}_{\rm ct} = \frac{9\lambda^2}{64\pi^2}\left(\frac{2}{\bar\epsilon}+{\color{red}\delta\lambda_{1a}}\right)\left(F'^2+\frac{1}{3}F''F\right)^2 F^4,$$



$$= -\,\mathrm{Tr}\ln\left[i\partial\!\!\!/ + y_t F\right]$$

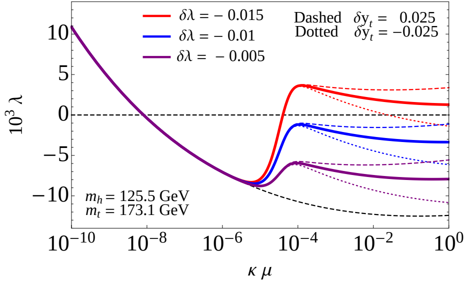
$$\delta\mathcal{L}_{\rm ct} = -\frac{y_t^4}{64\pi^2}\left(\frac{2}{\bar\epsilon}+\delta\lambda_{1b}\right)F^4$$

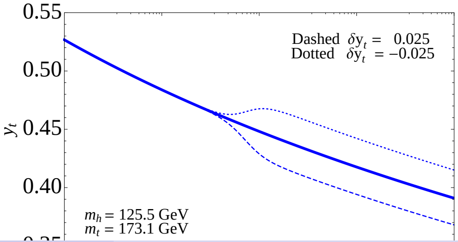
Small χ : $F'^4F^4 \sim \chi \sim F^4$
Large χ : $F'^4F^4 \sim e^{-4\chi/\sqrt{6}M_P}$, and $F^4 \sim M_P^4/\xi^2$
$\delta\lambda_{1b}$ – just λ redefinition, while ${\color{red}\delta\lambda_{1a}}$ is not!

Threshold effects at M_P/ξ summarized by two new arbitrary constants $\delta\lambda$, δy_t

$$\lambda(\mu) \to \lambda(\mu) + \delta\lambda \left[\left(F'^2 + \frac{1}{3} F'' F \right)^2 - 1 \right]$$

$$y_t(\mu) \to y_t(\mu) + \delta y_t \left[F'^2 - 1 \right]$$





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