Metastable electroweak vacuum and inflationary Universe

based on: KK, T. Kobayashi, T.Takahashi, M.Yamaguchi, J.Yokoyama, PRD86(2012)023504
M.Asano, KK, O.Lebedev, & A.Westphal, in preparation

Kohei Kamada
(DESY theory group)

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PPP2012 Higaki-san's talk

ArXiv:1207. 2771 [hep-ph]

Higgs, Moduli Problem, Baryogenesis and Large Volume Compactifications

Tetsutaro Higaki

Mathematical Physics Lab., RIKEN Nishina Center, Saitama 351-0198, Japan

Kohei Kamada

Deutsches Elektronen-Synchrotron DESY,

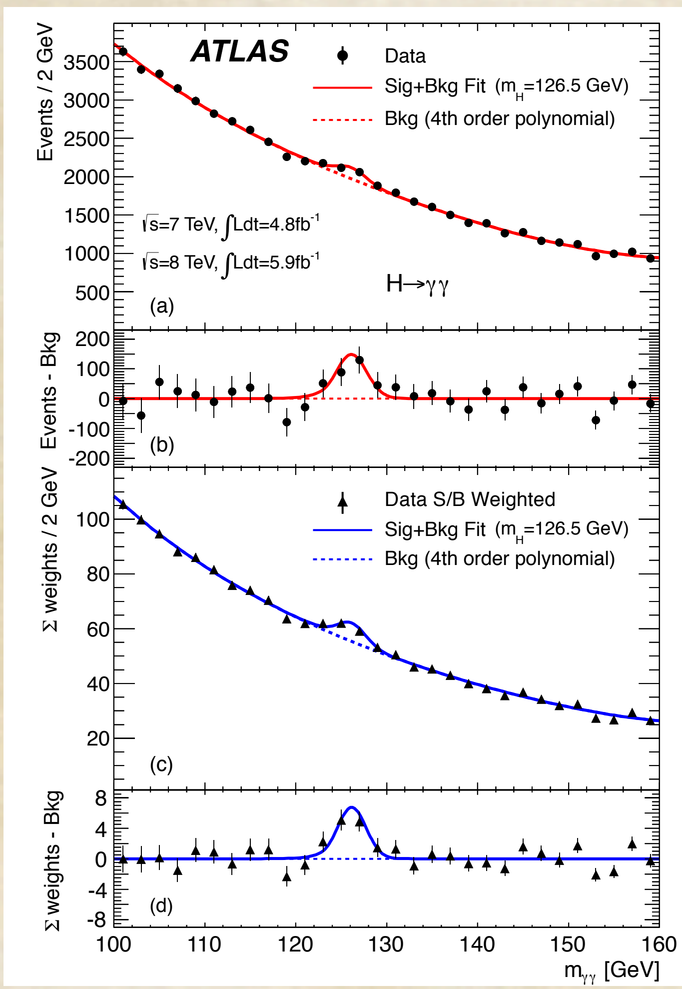
Notkestraße 85, D-22607 Hamburg, Germany

Fuminobu Takahashi

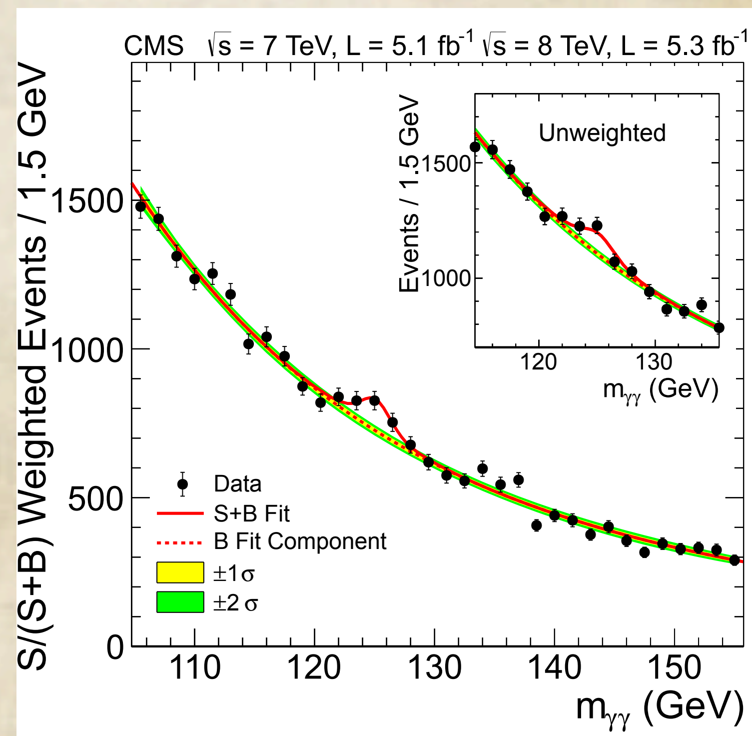
Department of Physics, Tohoku University, Sendai 980-8578, Japan

Two big news from recent experiments/observations

July 2012, a (SM) Higgs boson with mass around 125 GeV is found at LHC!



ATLAS, 1207.7214



CMS, 1207.7235

...and the data supports the SM more and more strongly.

Any deviation from the SM has not been reported thus far.

Two big news from recent experiments/observations

Implication of the Higgs discovery:

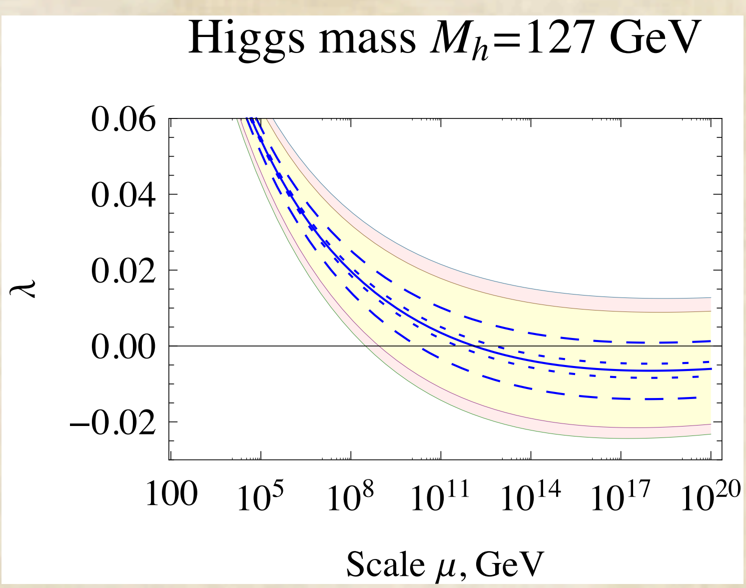
1. Standard Model works well.
2. Supersymmetry or other models beyond the standard model do not give any clues so far.
   (~10 TeV SUSY is favored? Where is naturalness?)

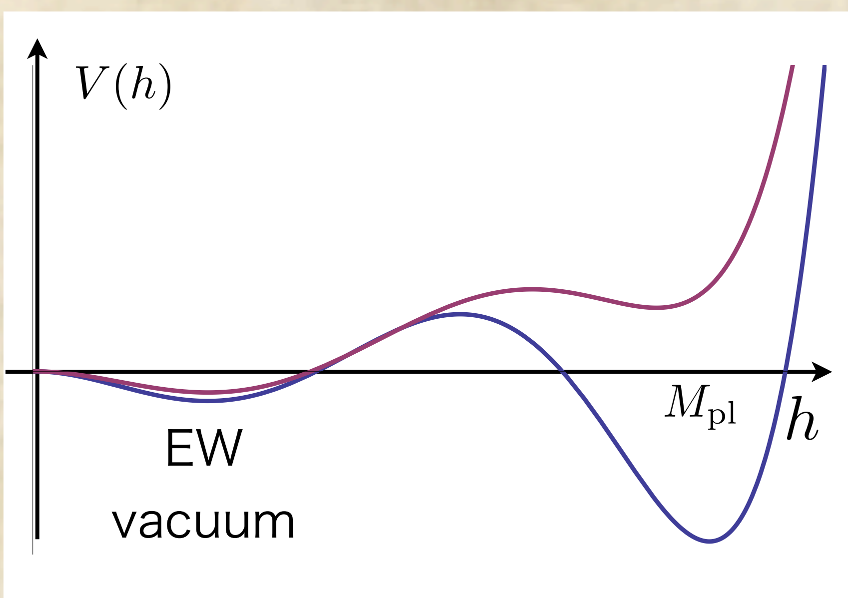
Two big news from recent experiments/observations

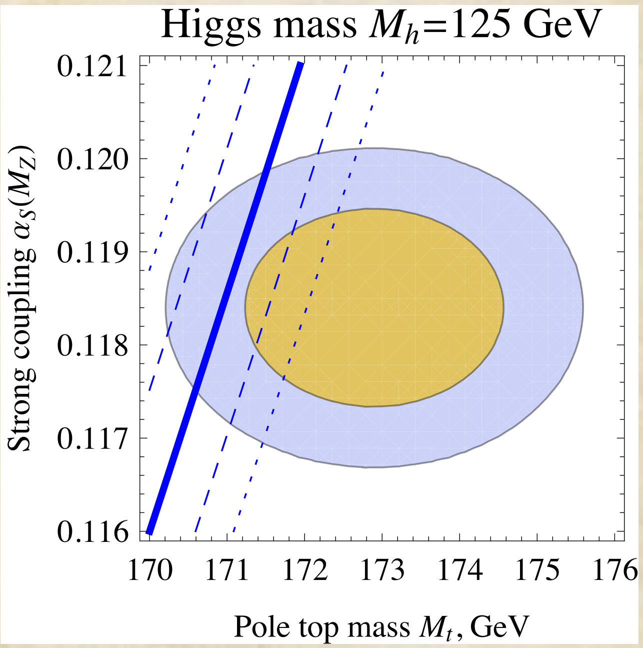
Implication of the Higgs discovery:

1. Standard Model works well.
2. Supersymmetry or other models beyond the standard model do not give any clues so far.
   (~10 TeV SUSY is favored? Where is naturalness?)
3. Stability of the electroweak vacuum is at the boundary.

cf. Kawai-san & Iso-san's talk





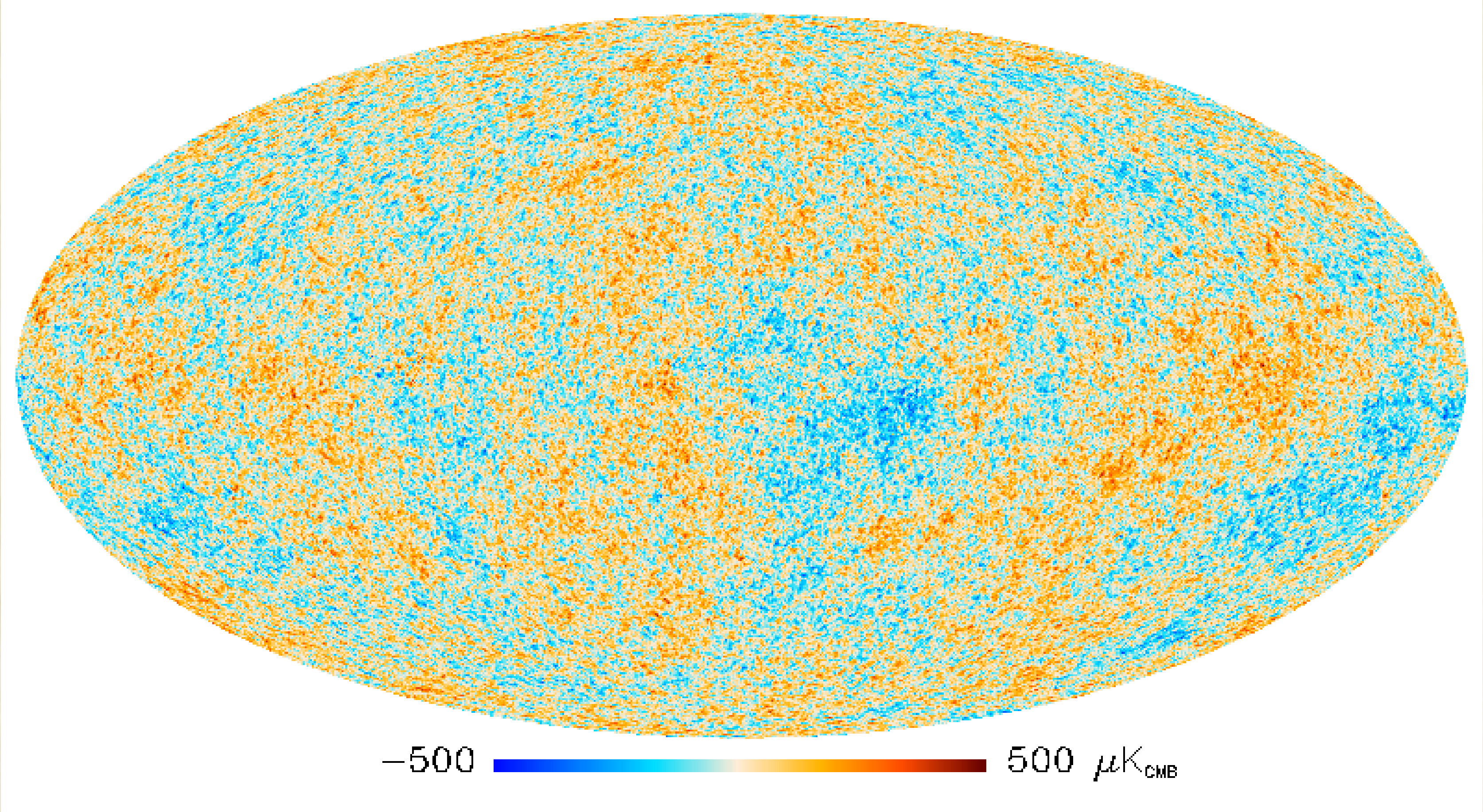


Bezrukov+ (12)

Two big news from recent experiments/observations

March, 2013, Planck Collaboration showed their first result and gave a detailed picture of CMB!

cf. Ichiki-san's talk



Planck collaboration (13)

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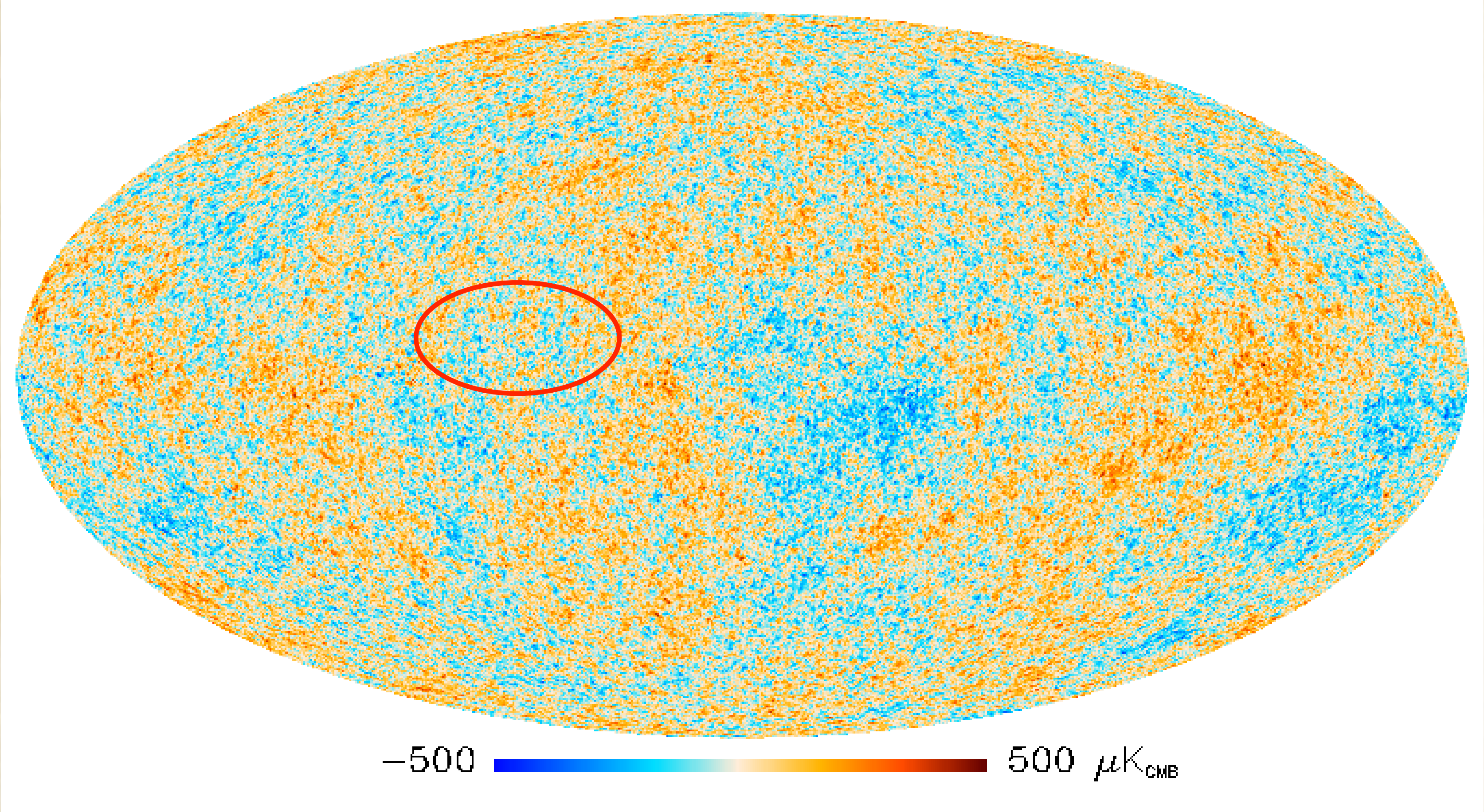

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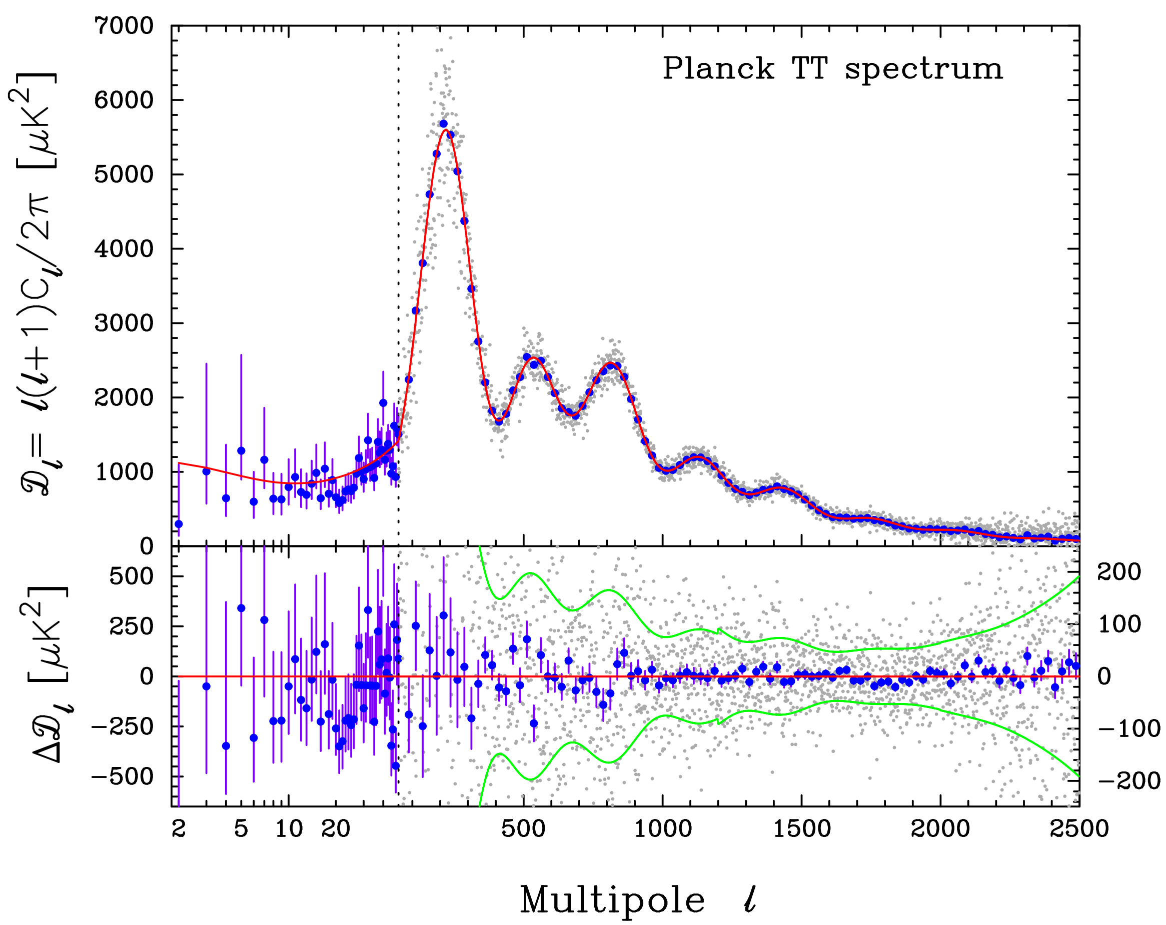
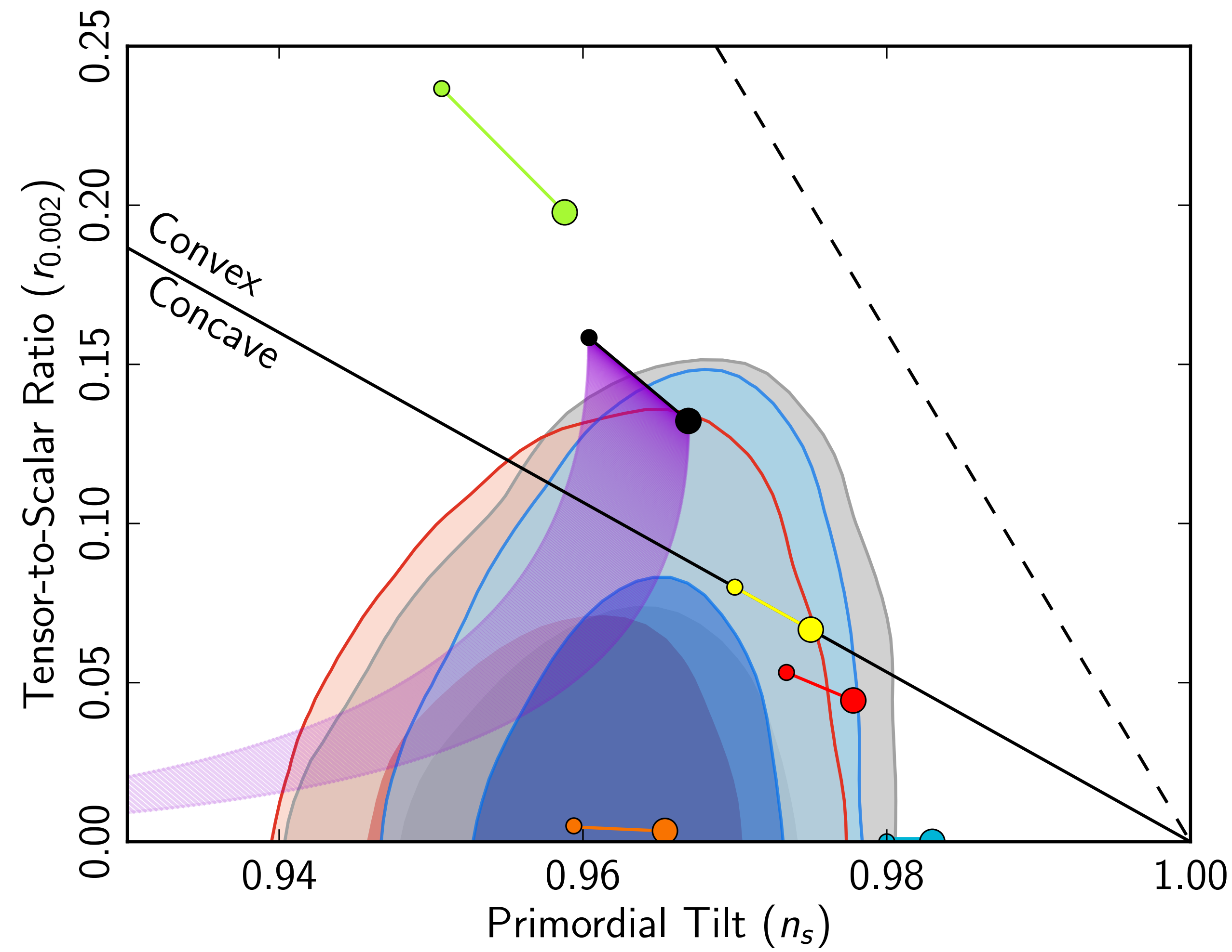




Planck collaboration (13)

Two big news from recent experiments/observations

Planck results tells...

1. Simple type of inflation explains the observation very well.
2. No “anomalies” are confirmed.

- Non-Gaussianity: $f_{\rm NL}^{\rm local} = 2.7 \pm 5.8 \quad f_{\rm NL}^{\rm equil} = -42 \pm 75$

  $f_{\rm NL}^{\rm ortho} = -25 \pm 39$ (68% CL)

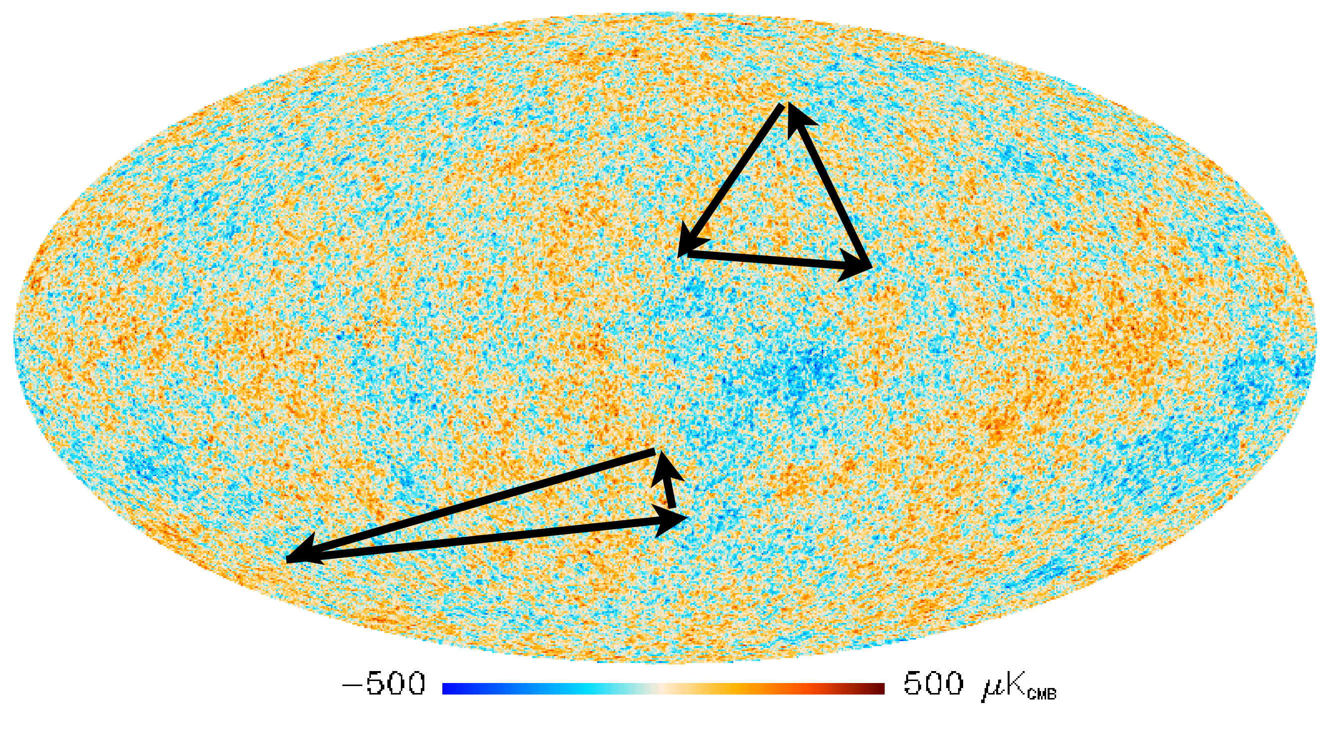
- Dark radiation: $N_{\rm eff} = 3.36^{+0.68}_{-0.64}$ (95% CL)

  # without BAO&H0

- Gravitational waves: $r \equiv \dfrac{A_t}{A_s} < 0.11$ (95% CL)

Nongaussinaity

...Probe of nonminimal interaction of inflation and existence of light field



$$B_\zeta(k_1, k_2, k_3) = \frac{6}{5} f_{\rm NL} [P_\zeta(k_1) P_\zeta(k_2) + P_\zeta(k_2) P_\zeta(k_3) + P_\zeta(k_3) P_\zeta(k_1)]$$

$$\langle \zeta(k_1) \zeta(k_2) \zeta(k_3) \rangle = (2\pi)^3 B(k_1, k_2, k_3) \delta(k_1 + k_2 + k_3)$$

should be slow-roll suppressed for simple type inflation models

(single-field, canonical, slow-roll)

Dark radiation

...Probe of the existence of light particle at the present

Gravitational waves cf. Jinno-san's talk

...Probe of the energy scale of inflation

$$A_T = \frac{8}{M_{\rm pl}^2}\left(\frac{H_{\rm inf}}{2\pi}\right)^2\Bigg|_{H_{\rm inf}=k/a}$$

$$r \simeq 0.1 \leftrightarrow H_{\rm inf} \simeq 10^{13}\mathrm{GeV}$$

$$r \simeq 0.001 \leftrightarrow H_{\rm inf} \simeq 10^{12}\mathrm{GeV}$$

In this talk, I focus on the structure of the Higgs potential and discuss what is the minimal extension of the standard model in light of the recent observations.

In particular,

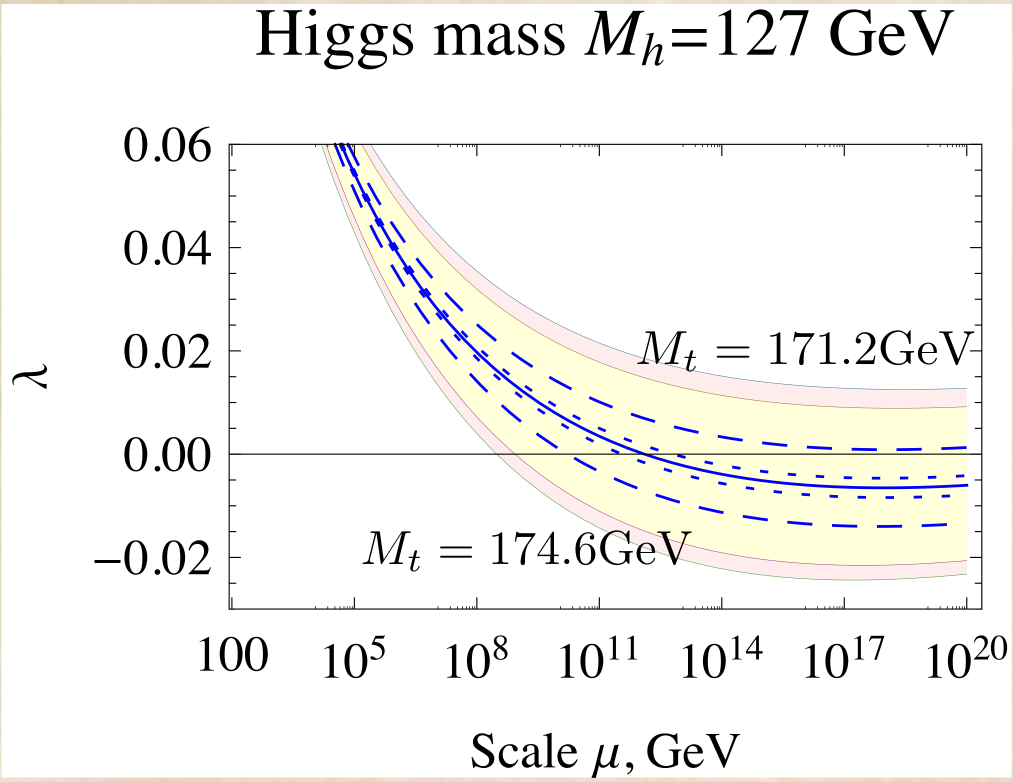
Stable case: Higgs inflation

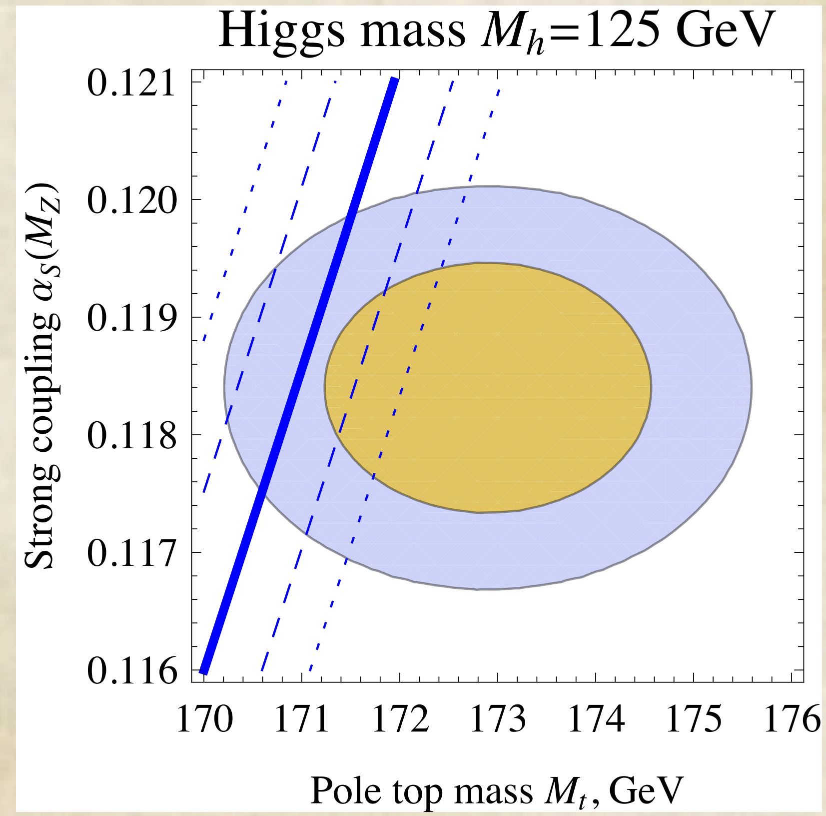
metastable case: stability during inflation

Here I mean “I require minimal extension of the physical degrees of freedom but allow nonrenormalizable interaction”, by using the term “minimal”.

Moreover, I focus on inflation and does not study dark matter, dark energy and baryogenesis.

Electroweak vacuum stability





- strongly depends on the top mass
- We must wait at least for ILC.

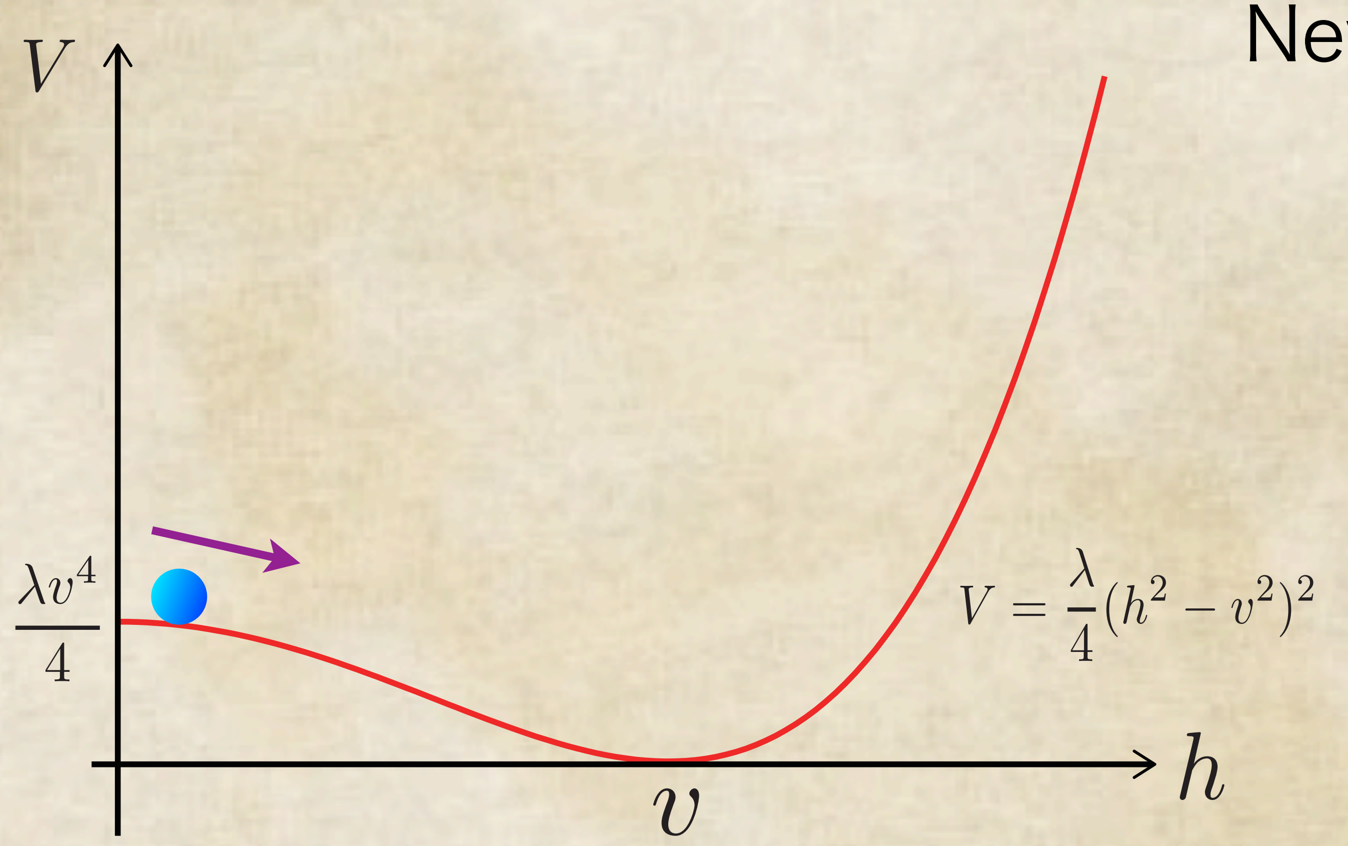
Thus, we should consider both possiblity for a while, though metastable vacuum seems to be favored.

Is the EW vacuum stable?

stable

metastable

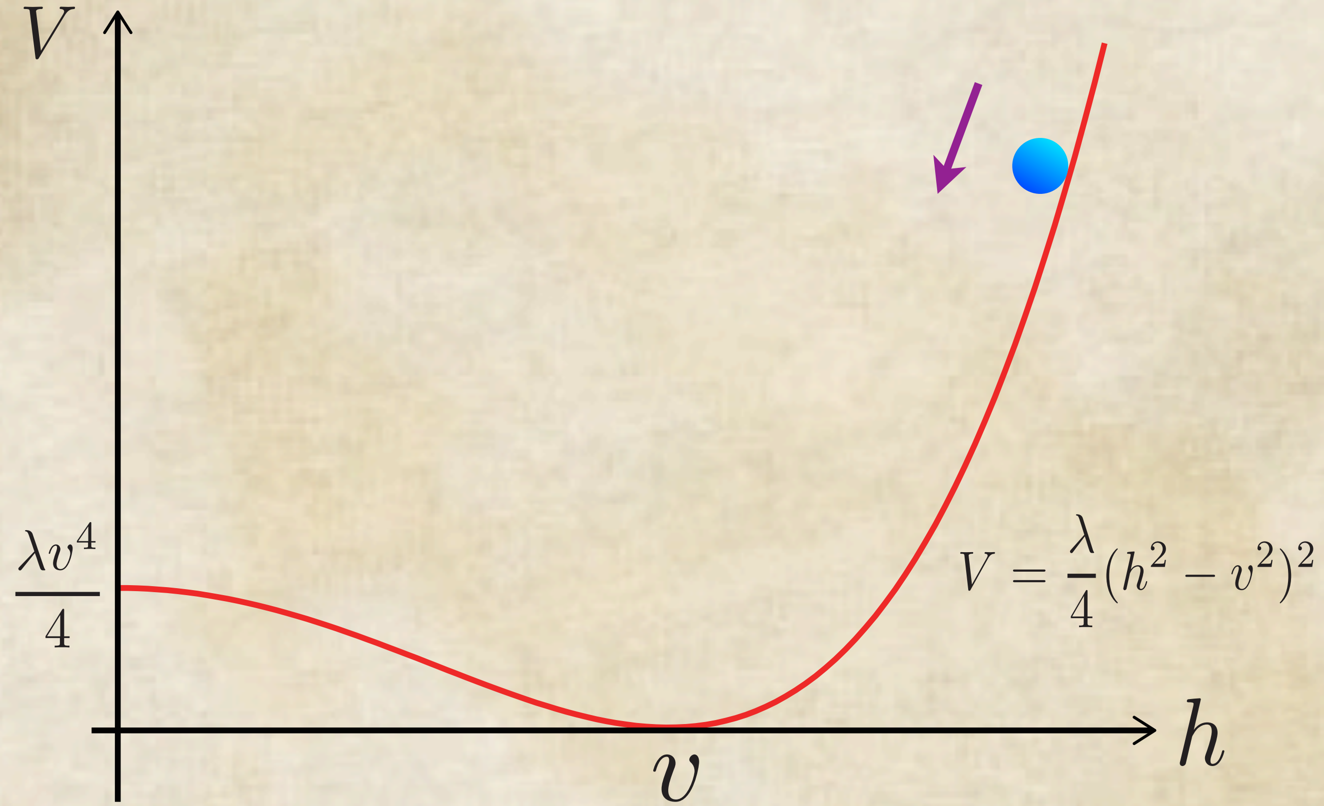
In order to have an inflationary era, we need a scalar field that drives inflation, inflaton.



New inflation? ('82, Linde)

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

In order to have an inflationary era, we need a scalar field that drives inflation, inflaton.



Chaotic inflation? ('83, Linde)

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

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

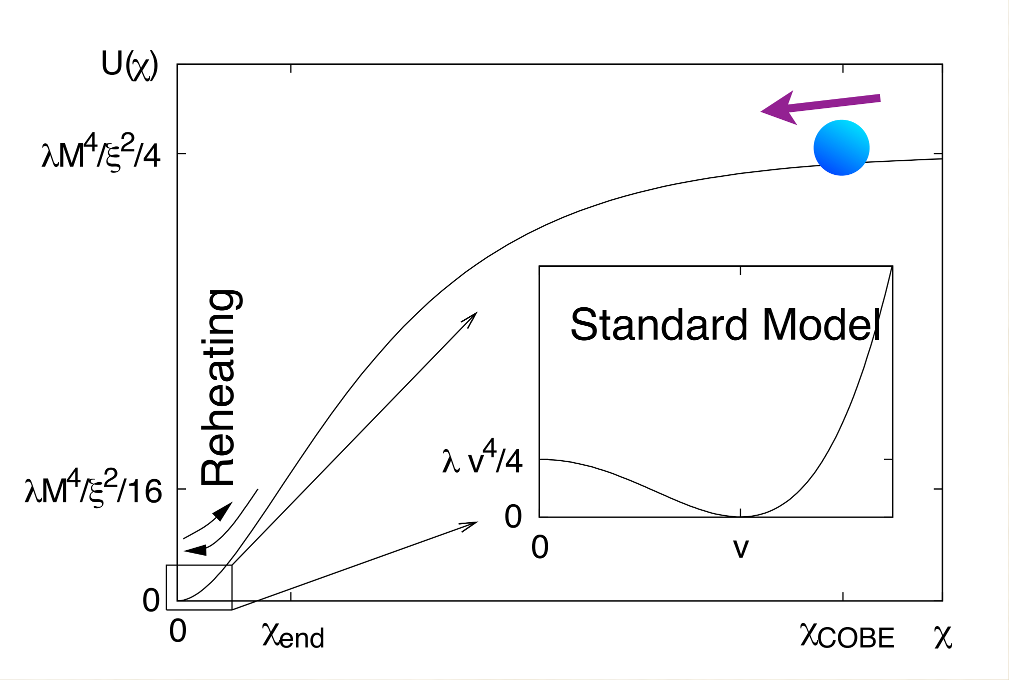
$\lambda_{\rm Higgs} \sim \mathcal{O}(1)$ is inconsistent with the observation $\mathcal{P}_{\mathcal{R}}^{\rm obs} \simeq 2.4 \times 10^{-9}$ (WMAP('12))

In order to have an inflationary era, we need a scalar field that drives inflation, inflaton.

It is known that the SM Higgs can drive inflation that can explain our present Universe.

$\Rightarrow$ Higgs inflation

$$\Delta S = \int d^4x \sqrt{-g} \left[\frac{-\xi h^2}{2} R \right]$$



For $|\xi| h^2 \gg 1$, the effective Planck mass becomes large

$$M_{\rm pl}^{\rm eff\,2} = M_{\rm pl}^2 + |\xi| h^2$$

and hence the primordial density fluctuation is suppressed.

('08, Bezrukov & Shaposhnikov)

(cf. '95, Cervantes-Cota+)

(In this notation, ξ is negative.)

This is the unique possiblity of the extension of the SM at renormalizable level.

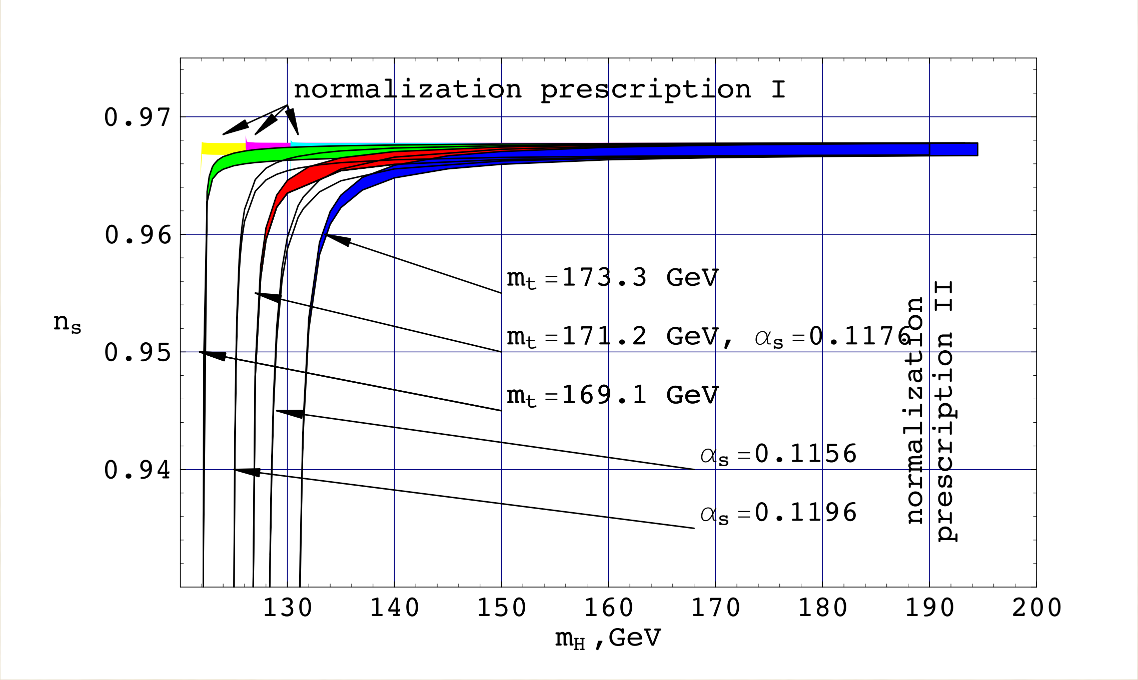
Is the EW vacuum stable?

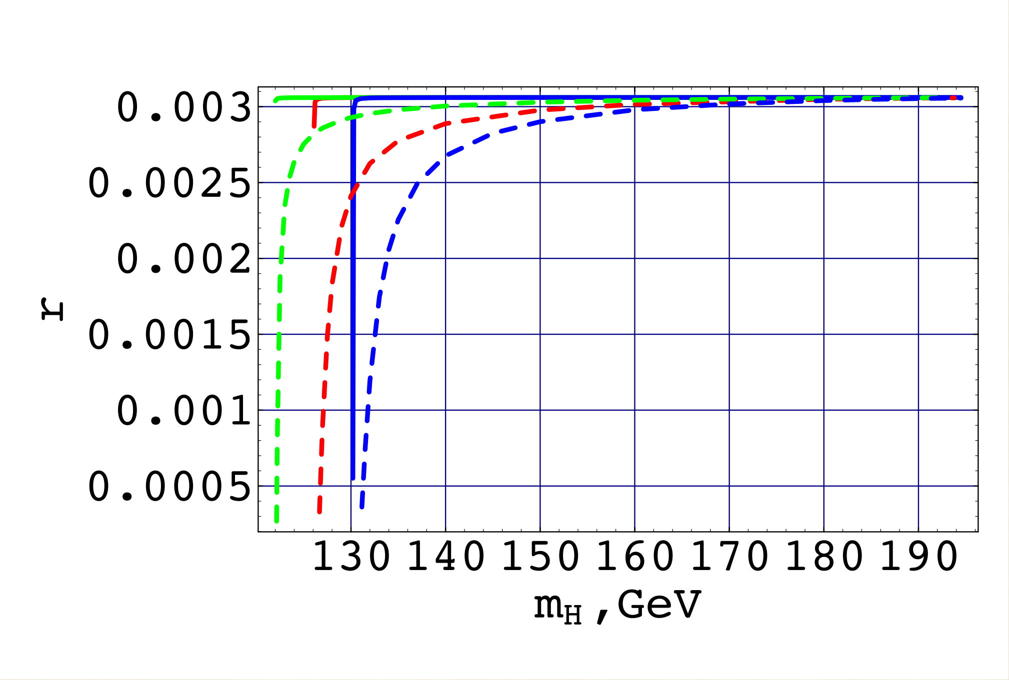
stable

metastable

Higgs inflation

Predictions of (nonminimal) Higgs inflation





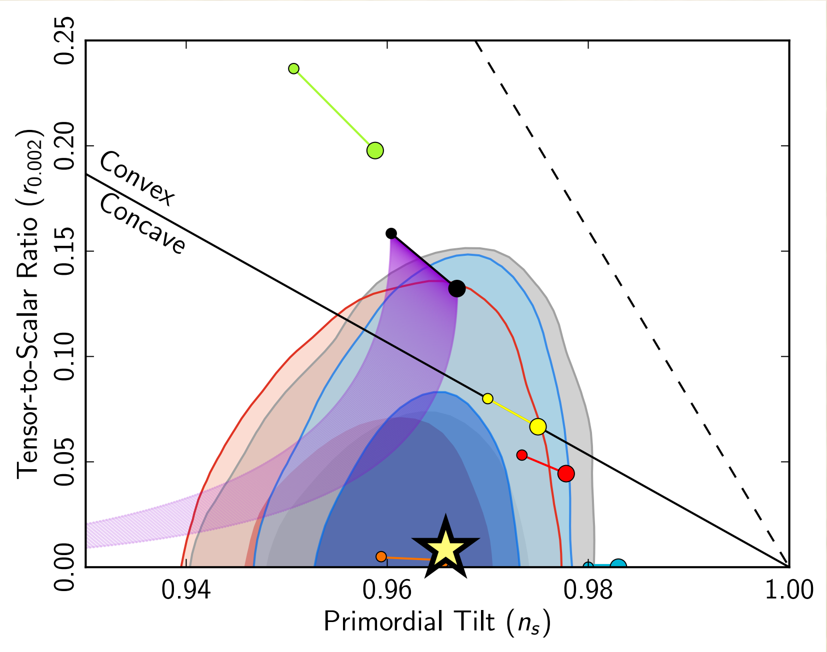
('09, Bezrukov+)

spectral tilt: $n_s \simeq 0.966$

gravitational waves: $r \simeq 0.002 \sim 3$

Non-Gaussianity: slow-roll suppressed.

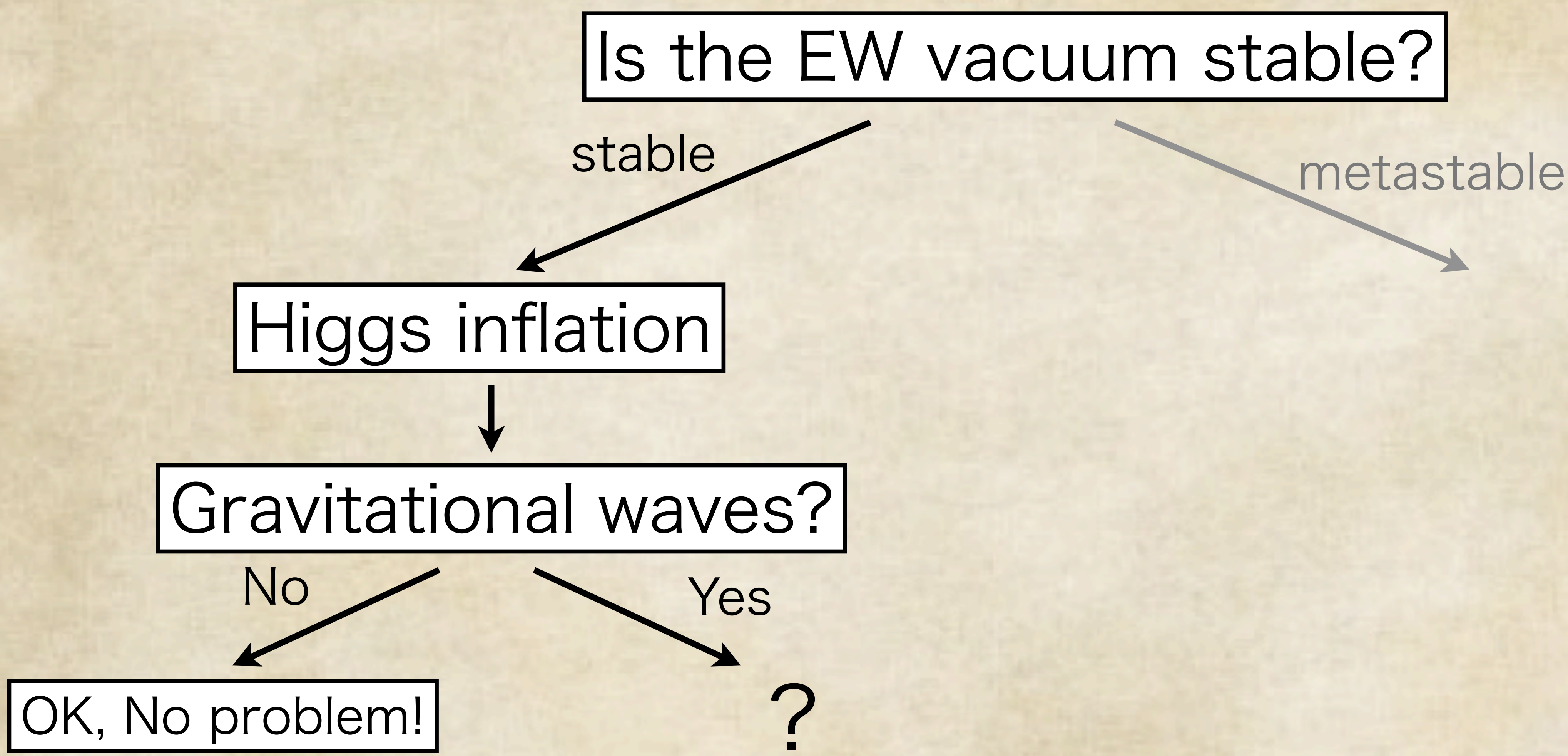
#depending on the top mass...



But we can expect for the detection of gravitational waves by Planck up to

$$r \gtrsim 0.05$$

Should we give up Higgs inflation when Planck will detect gravitational waves?


Is the EW vacuum stable?
stable
metastable
Higgs inflation
Gravitational waves?
No
Yes
OK, No problem!
?

We find that there are several possibilities of Higgs inflation if we allow nonrenormalizable (derivative) interaction for the Higgs field based on the generalized Galileon theory.

'11,'12, KK, T. Kobayashi, T.Takahashi, M.Yamaguchi, J.Yokoyama

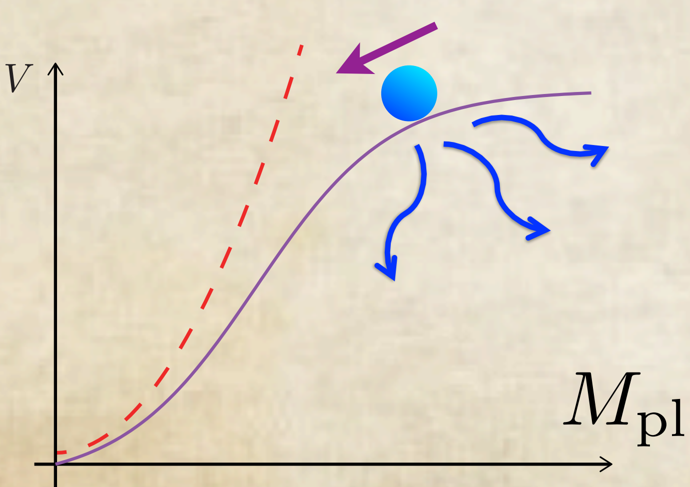
$$\mathcal{L}_2 = K(\phi, X),$$
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi,$$
$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right],$$
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5X}\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right].$$

$$S = \int d^4x\sqrt{-g}\sum_{i=2}^{5}\mathcal{L}_i$$

$$X \equiv -\frac{1}{2}(\nabla\phi)^2, \quad G_{iX} \equiv \frac{\partial G_i}{\partial X}$$

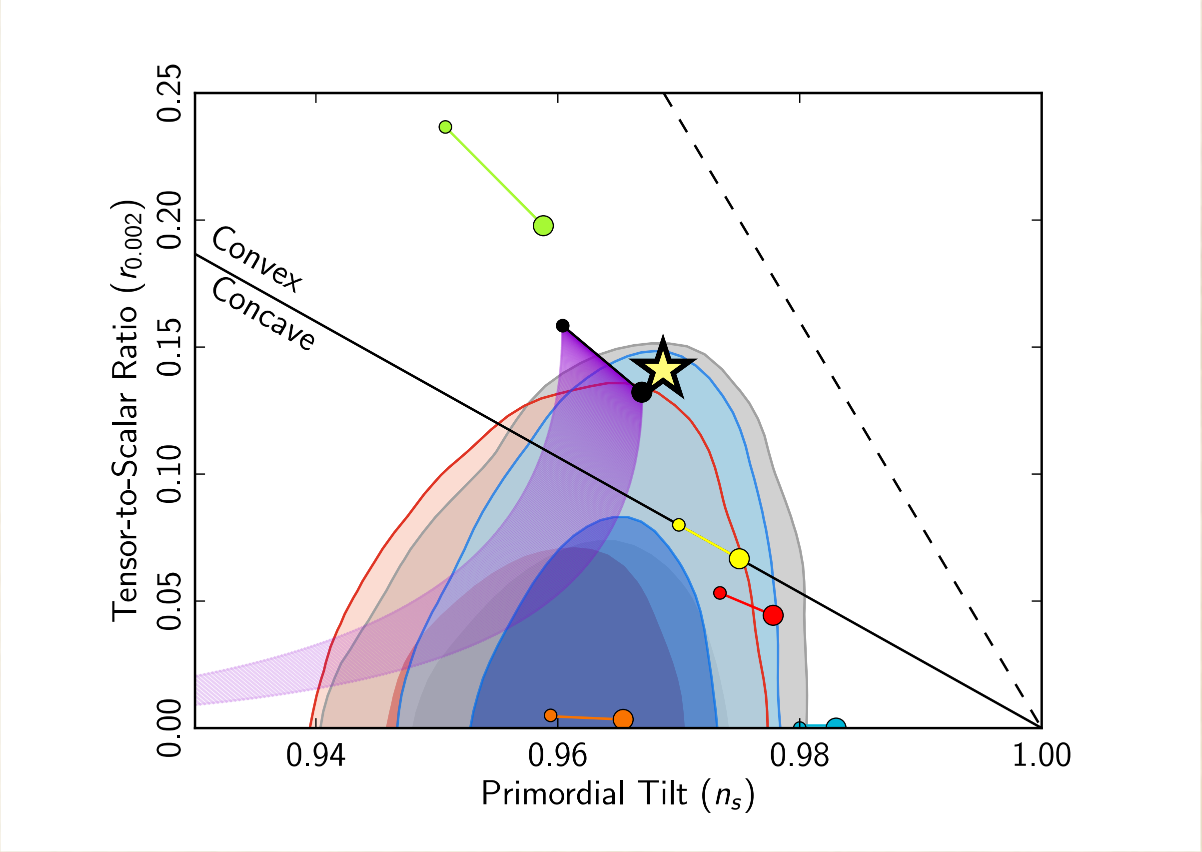
('74, Horndeski; '09, '10, '11, Deffayet+)

Derivative interaction enhance the friction term for the Higgs field and realize sub-Planck inflation



In the simplest case, introducing a term, $h\Box h\partial_\mu h\partial^\mu h$

we have $n_s \simeq 0.967, \quad r \simeq 0.14$ $\quad M \sim 10^{13}\mathrm{GeV}, h_{\mathrm{inf}} \sim 10^{16}\mathrm{GeV}$



This model is found to have a problem in reheating ('12 Ohashi&Tsujikawa) but it can be solved in the context of Generalized Galileon (or generalized Higgs inflation). (See, Kunimitsu+ in preparation.)

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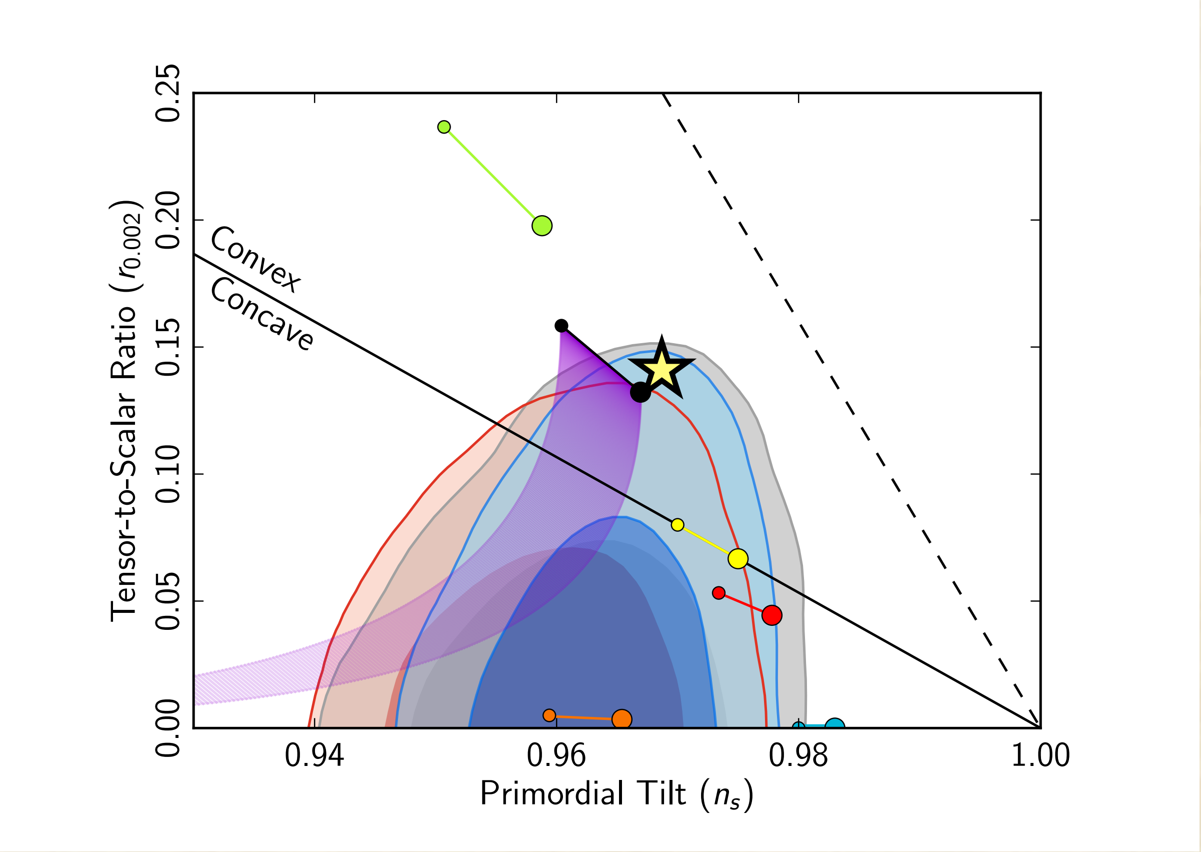

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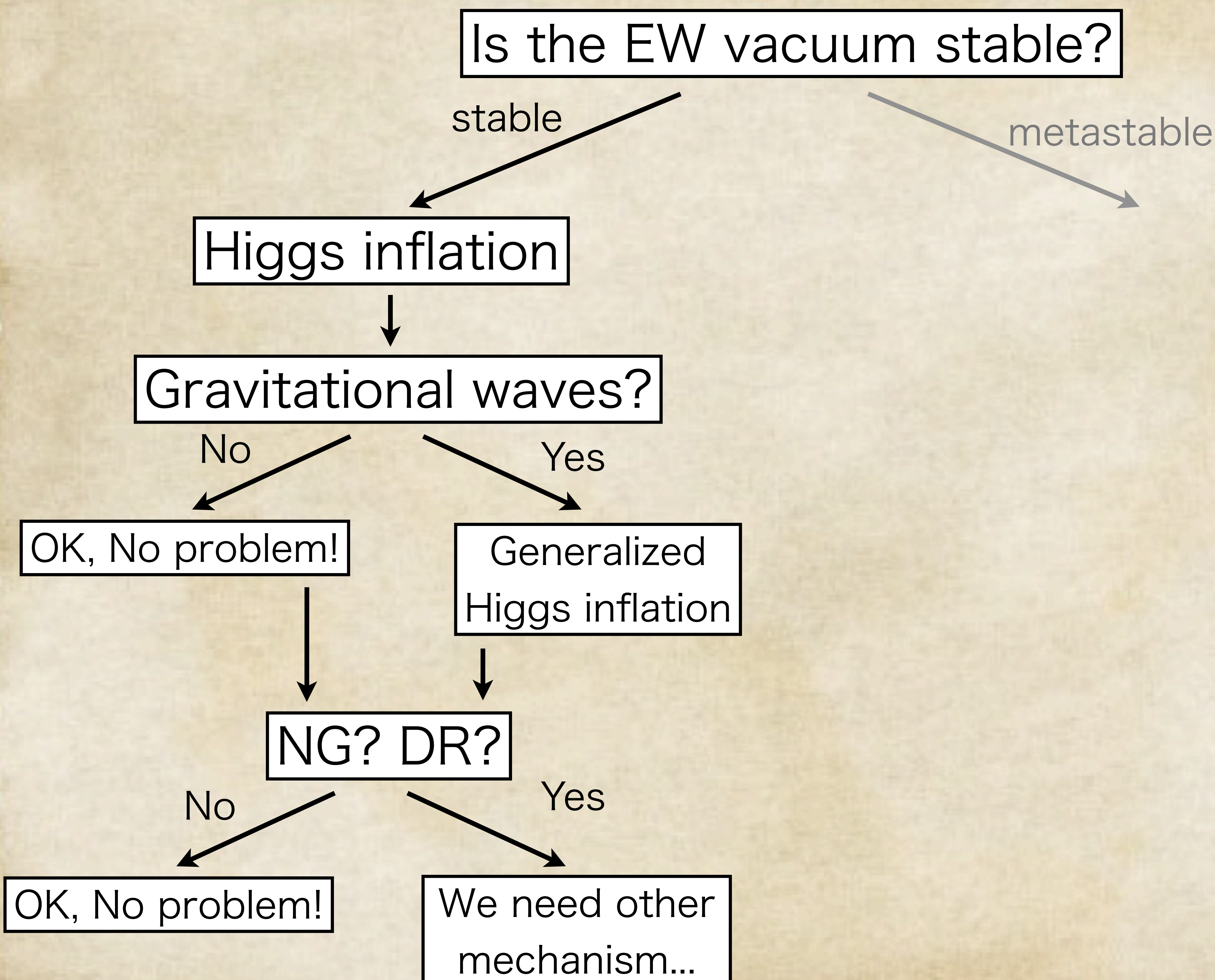
We can still hope for nongaussianity or dark radiation, but generalized Higgs inflation cannot explain it and it needs some other degrees of freedom.


Is the EW vacuum stable?
stable
metastable
Higgs inflation
Gravitational waves?
No
Yes
OK, No problem!
Generalized
Higgs inflation
NG? DR?
No
Yes
OK, No problem!
We need other
mechanism...

Is the EW vacuum stable?

stable

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Higgs inflation

Gravitational waves?

No

Yes

OK, No problem!

Generalized Higgs inflation

NG? DR?

No

Yes

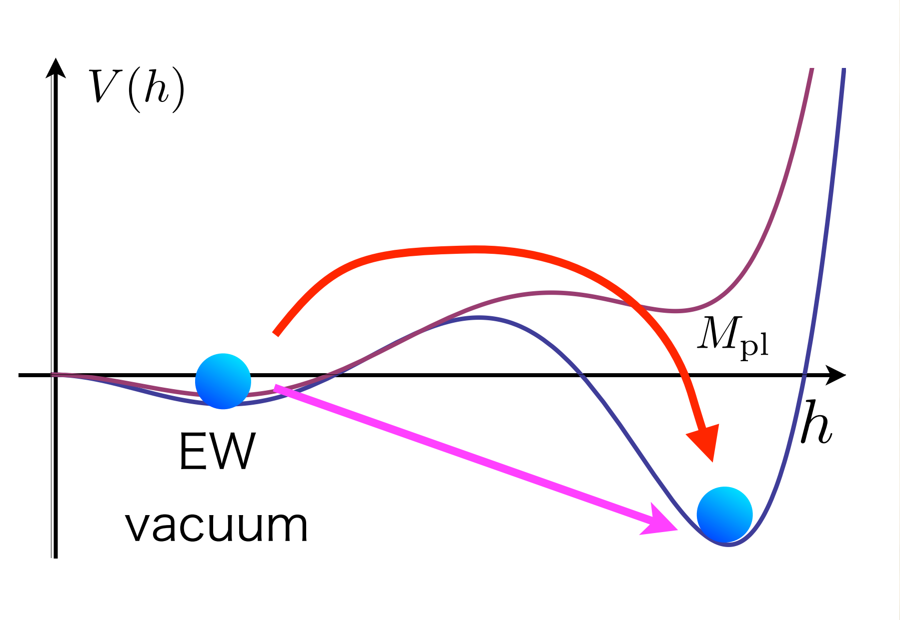
OK, No problem!

We need other mechanism...

Metastable EW vacuum

Metastable EW vacuum

Can we live in a metastable electroweak vacuum?

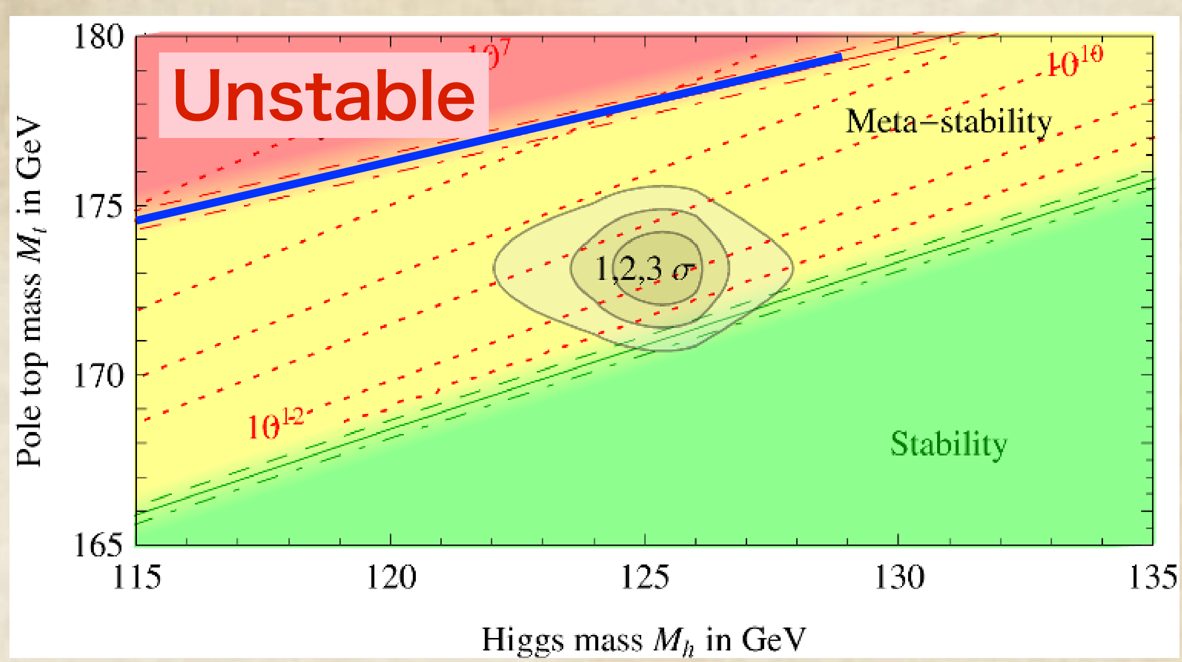


Metastable EW vacuum

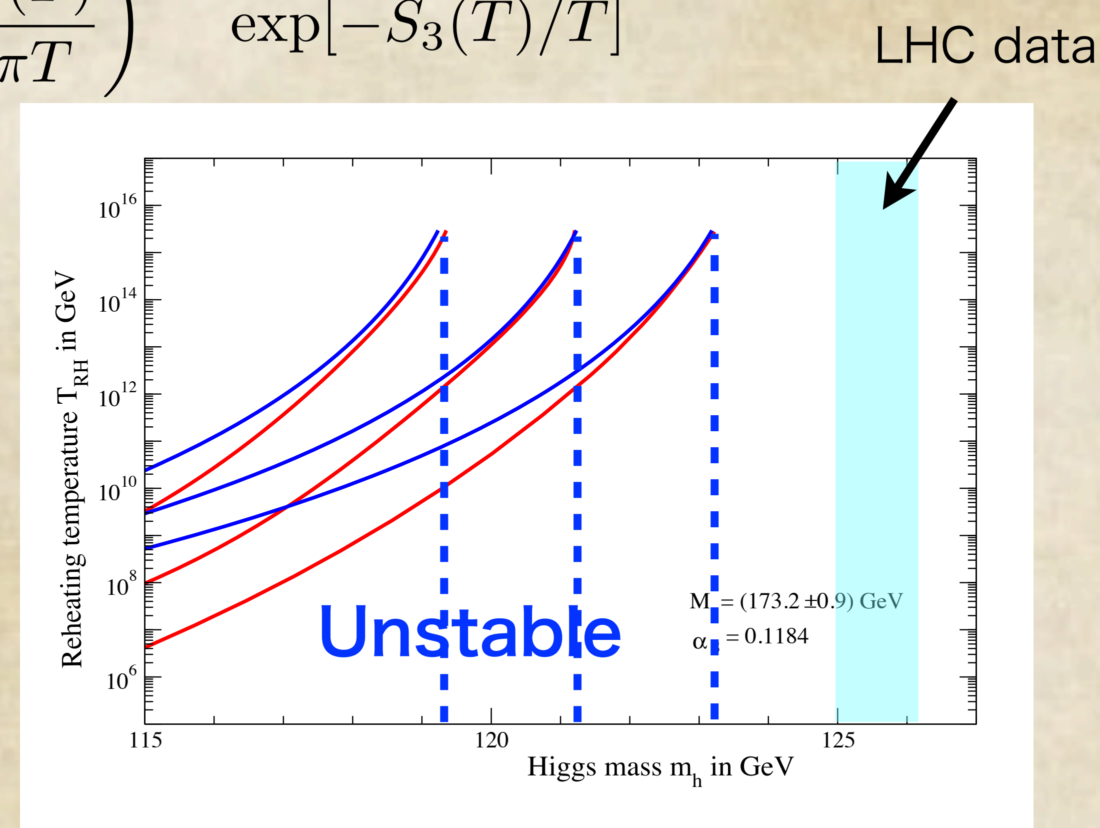
Can we live in a metastable electroweak vacuum?

-zero temperature decay : $p \sim \max \left\{ \tau^4 h^4 \exp[-8/3|\lambda(h)|] \right\}$

-thermal decay : $\Gamma(T) \sim T^4 \left(\frac{S_3(T)}{2\pi T} \right)^{3/2} \exp[-S_3(T)/T]$



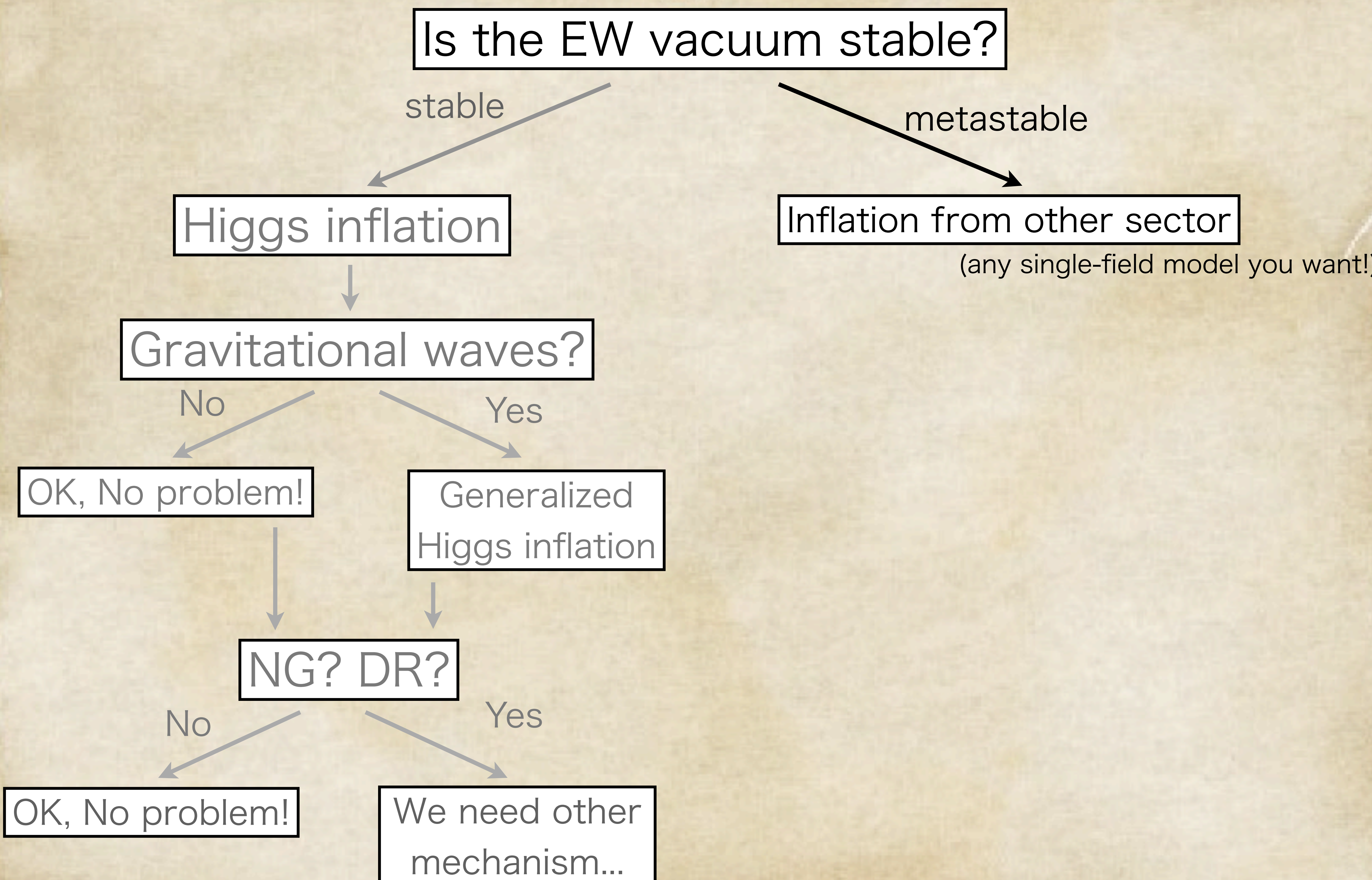
Degrassi+ (12)



Elias-miró+ (12)

Current data suggests that

we live in a “safe” meta-stable vacuum.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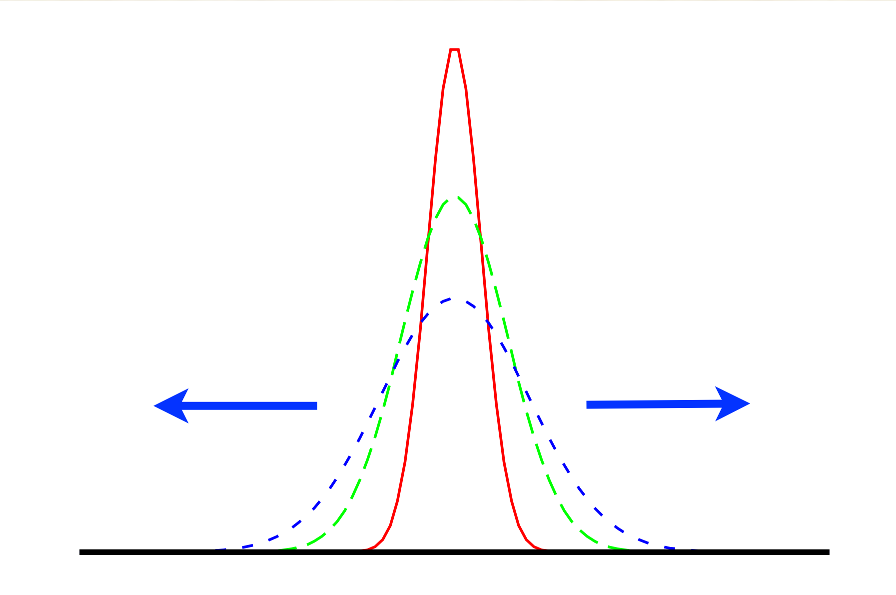
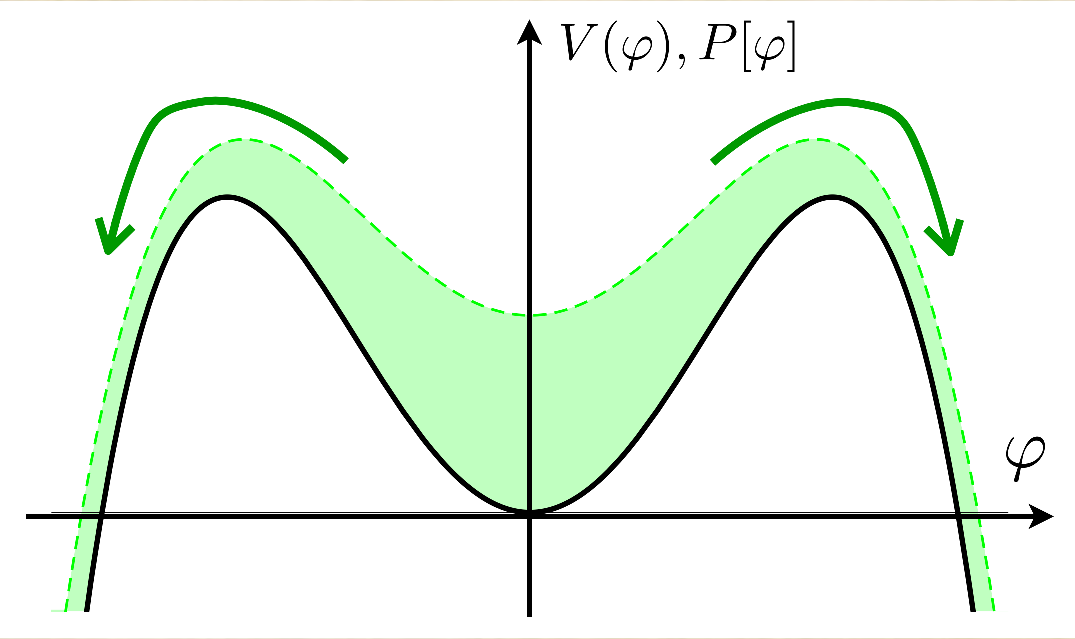
Higgs inflation
Inflation from other sector
(any single-field model you want!)
Gravitational waves?
No
Yes
OK, No problem!
Generalized Higgs inflation
NG? DR?
No
Yes
OK, No problem!
We need other mechanism...

Are we all right?

No! During inflation, the expectation value of the light (massless) scalar field evolves as

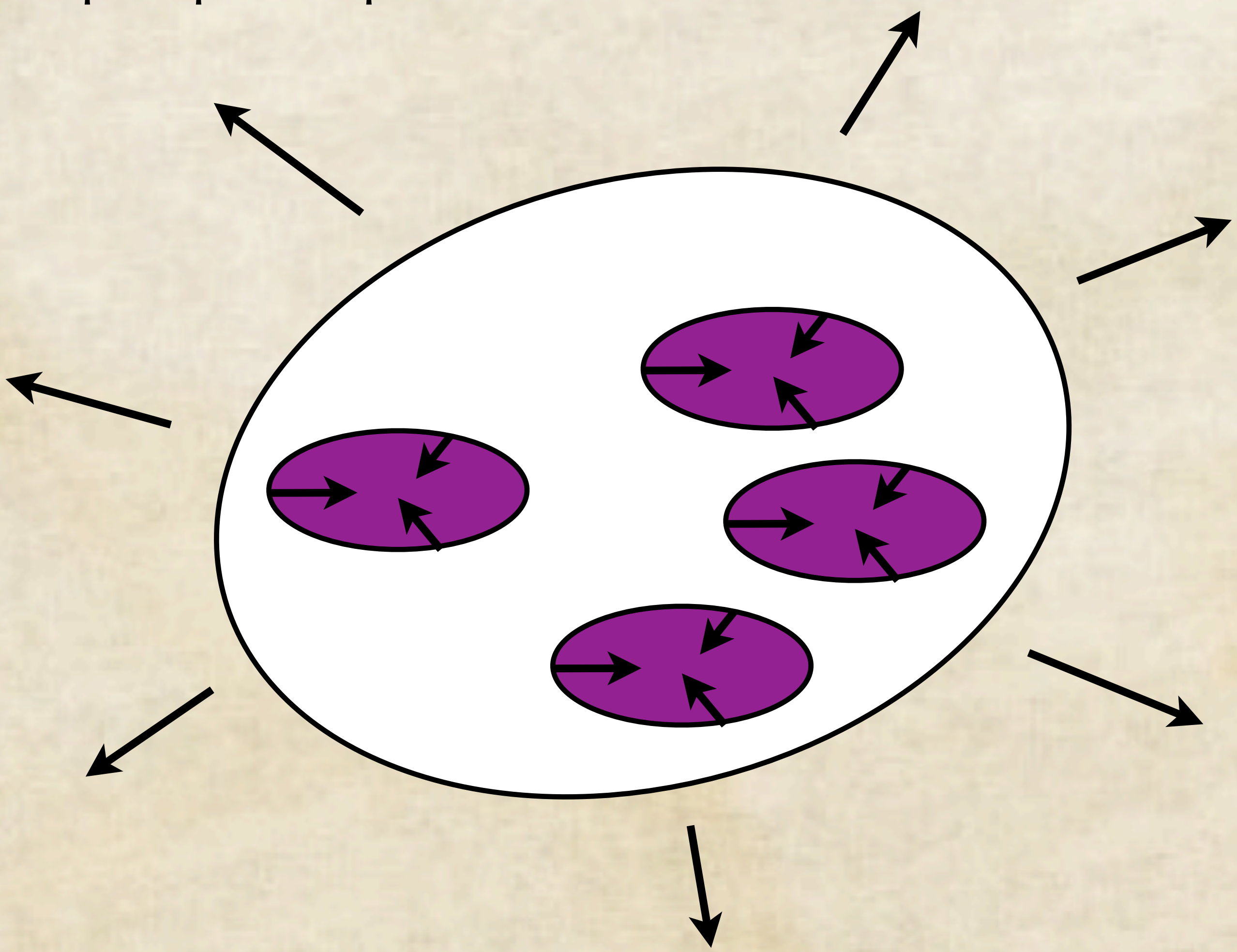
$$\langle \varphi^2 \rangle = \frac{H_{\rm inf}^2}{4\pi^2}\mathcal{N}_e$$





See Starobinsky & Yokoyama (93)

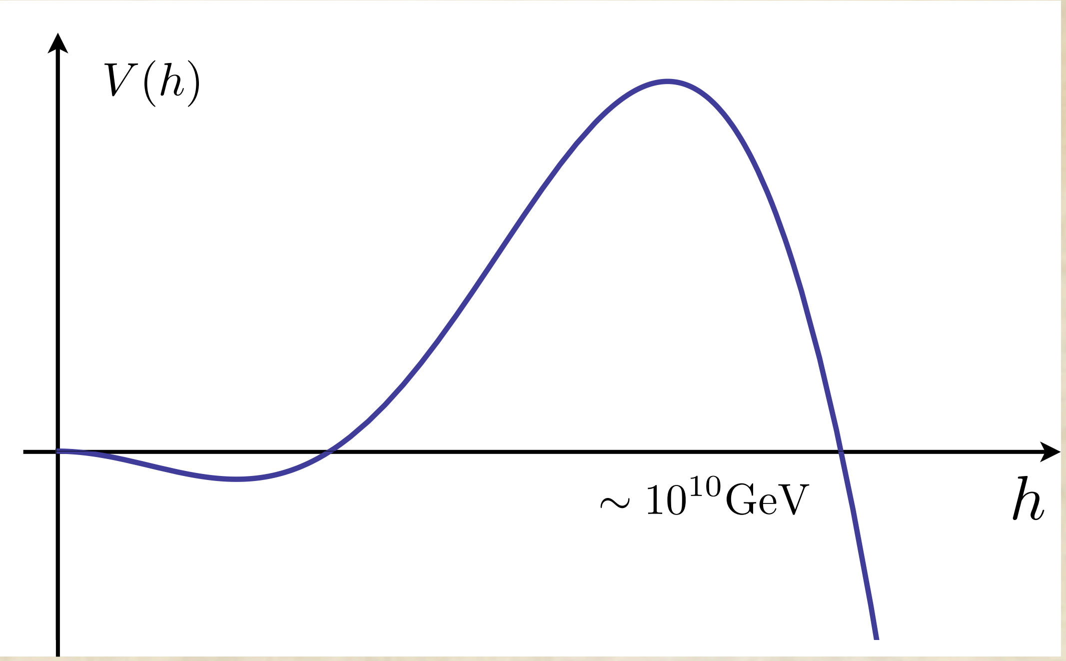
The region where the Higgs falls down to the true vacuum will collapse and inflation does not continue any more in such a region. It may be a matter of anthropic principle, but …



The probability that our Universe has experienced inflation with e-fold ~50 is very rare and it would be better to require that the square root of the Higgs expectation value squared does not overwhelm the barrier of the potential.

Higgs potential, typically, has a potential barrier at $h \sim 10^{10}$ GeV.

For the nearly ϕ^4 potential, the expectation value during inflation reads, $\sqrt{\langle h^2 \rangle} \sim H$.

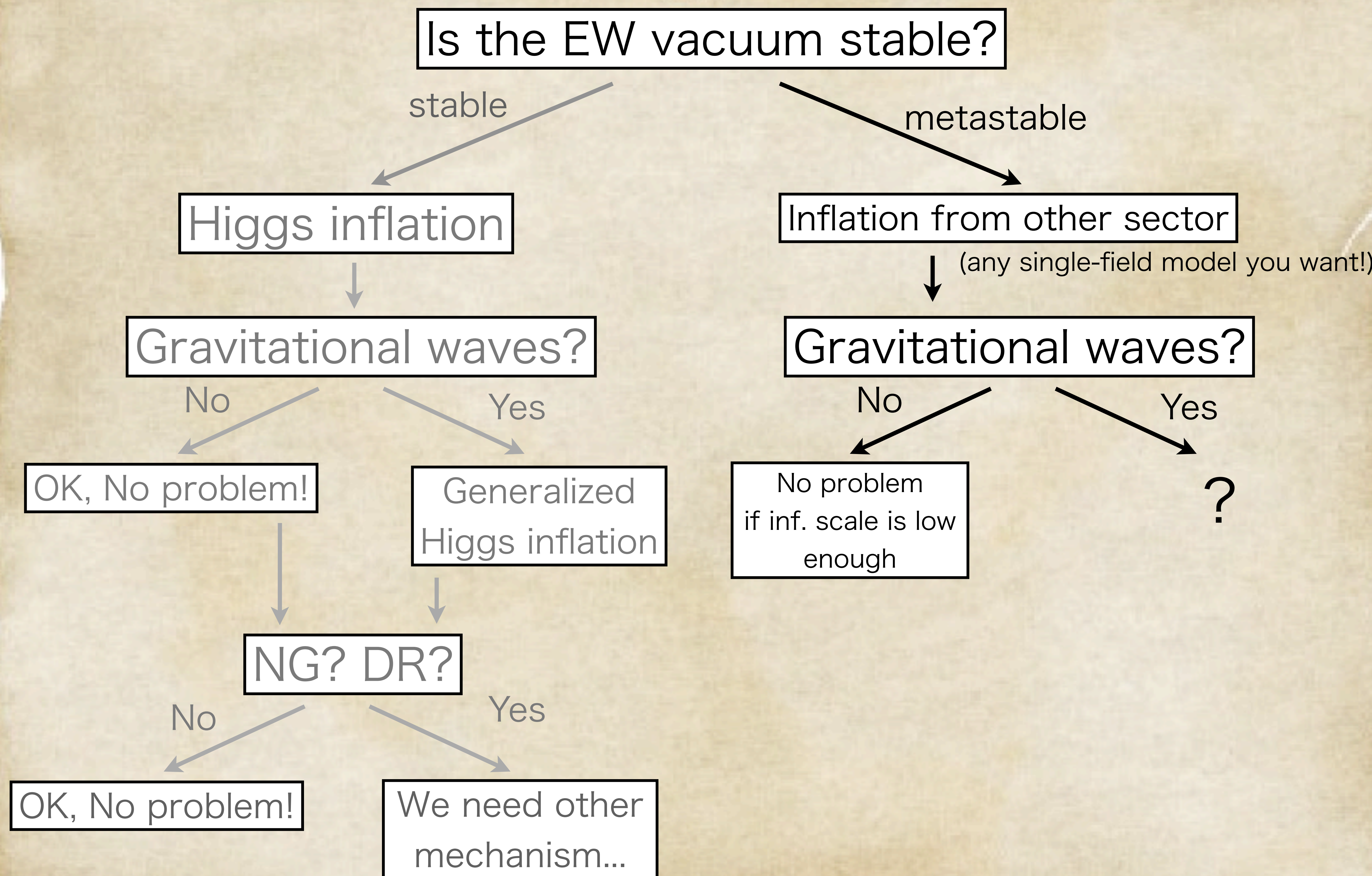


Thus, we have no problem if the inflationary scale is small enough, $H_{\rm inf} \lesssim 10^{10}$ GeV.

But, again, we can expect for the detection of gravitational waves by Planck up to

$$r \gtrsim 0.05$$

that means the Hubble parameter during inflation is $H_{\rm inf} \gtrsim 0.7 \times 10^{13}$ GeV.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Gravitational waves?
Gravitational waves?
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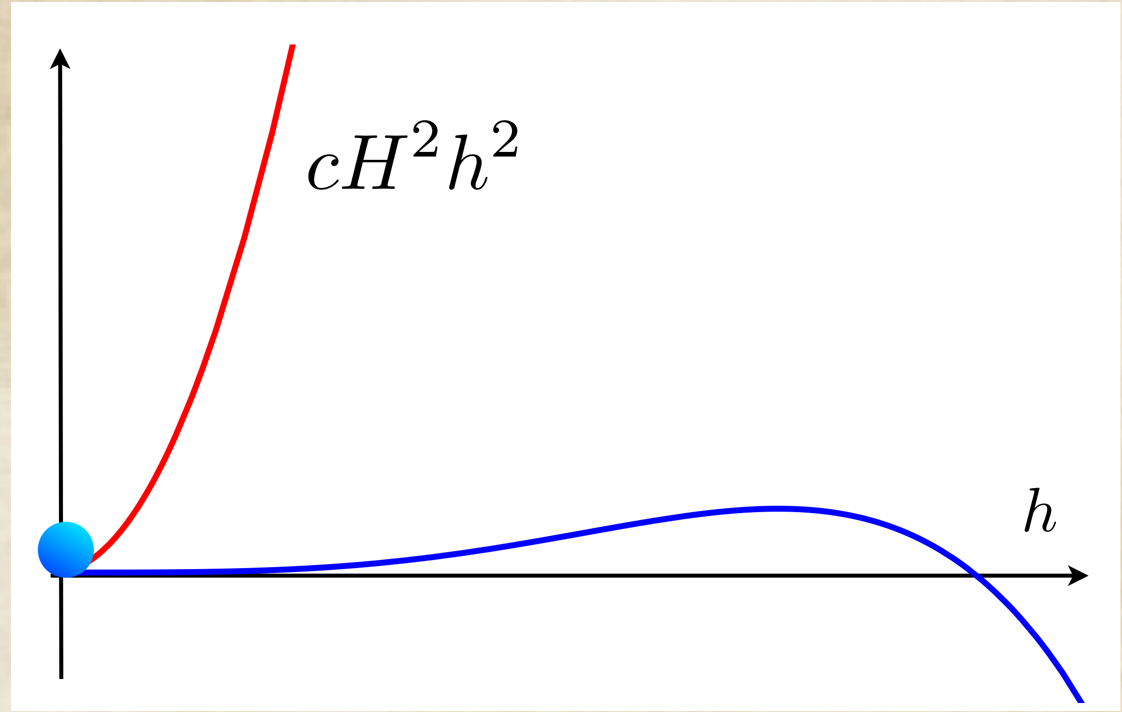
Yes
No
Yes
OK, No problem!
Generalized Higgs inflation
No problem if inf. scale is low enough
?
NG? DR?
No
Yes
OK, No problem!
We need other mechanism...

The problem can be solved if the Higgs field acquires large mass, “Hubble-induced mass”, from inflation

’13 Lebedev&Westphal



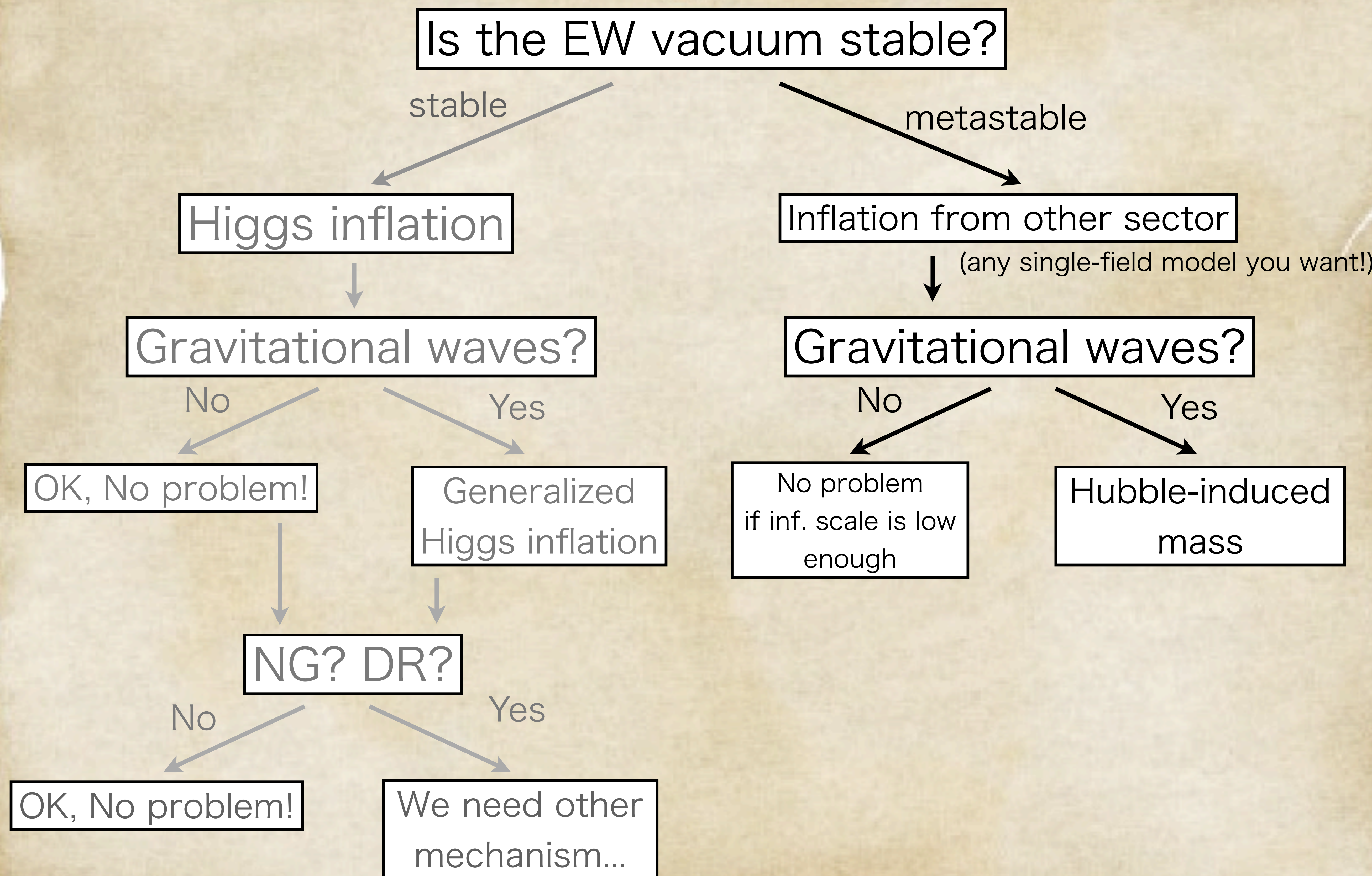
Possible origins;

direct coupling to inflaton

$$\lambda_i h^2 \phi_{\rm inf}^2 \rightarrow \frac{m_{h,\rm eff}^2}{2} h^2$$

nonminimal coupling to gravity

$$\xi R h^2 \rightarrow 12\xi H^2 h^2$$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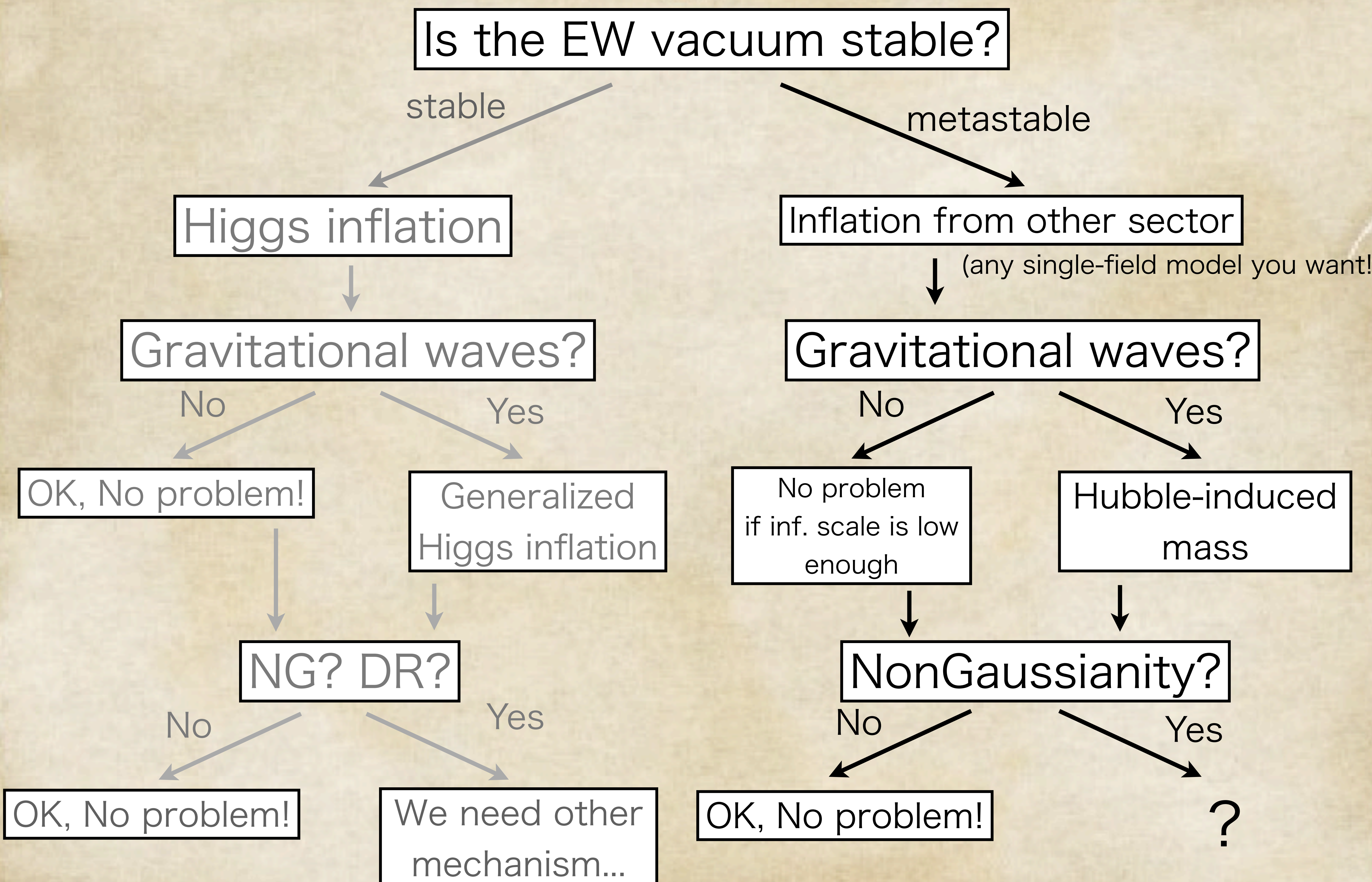
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Hubble-induced mass
NG? DR?
NonGaussianity?
No
Yes
No
Yes
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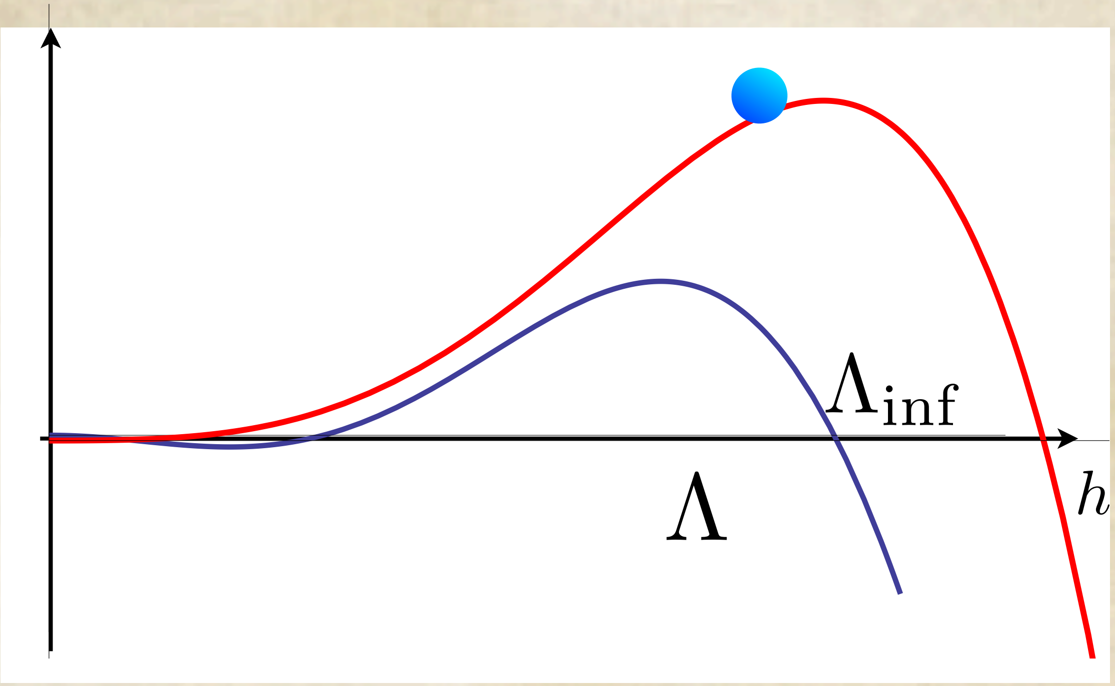
We need other mechanism...
OK, No problem!
?

Detection of non-Gaussianity means
that there is a light scalar during inflation.

Detection of non-Gaussianity means
that there is a light scalar during inflation.

We find that the Hubble induced mass can be relatively small during inflation, $m_H = c_{\rm inf} H_{\rm inf} \lesssim H_{\rm inf}$.



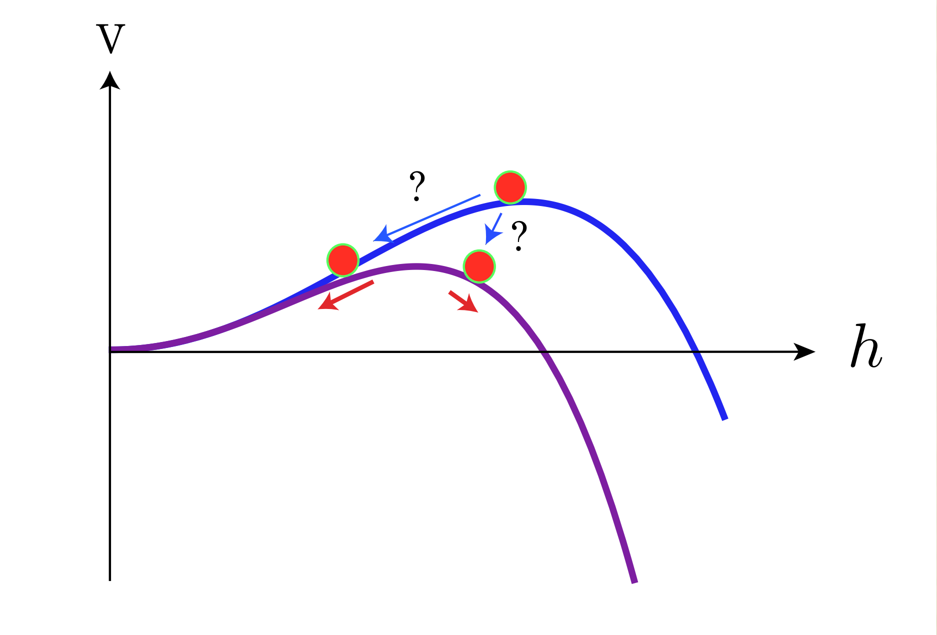
$$c_{\rm inf} > \sqrt{\frac{-3\tilde{\lambda}}{8\pi^2}} \simeq 1.9 \times 10^{-2} \left(\frac{\tilde{\lambda}}{-0.01} \right)^{1/2}$$

After inflation, the Higgs field evolves as

$$\ddot{h} + 3H(t)\dot{h} + \frac{\partial V(H(t), h)}{\partial h} = 0$$

with an initial condition, typically, $h_{\rm ini} = \langle h^2 \rangle_{\rm inf}^{1/2} = \frac{\sqrt{3} H_{\rm inf}}{2\sqrt{2}\pi\sqrt{c_{\rm inf}}}$

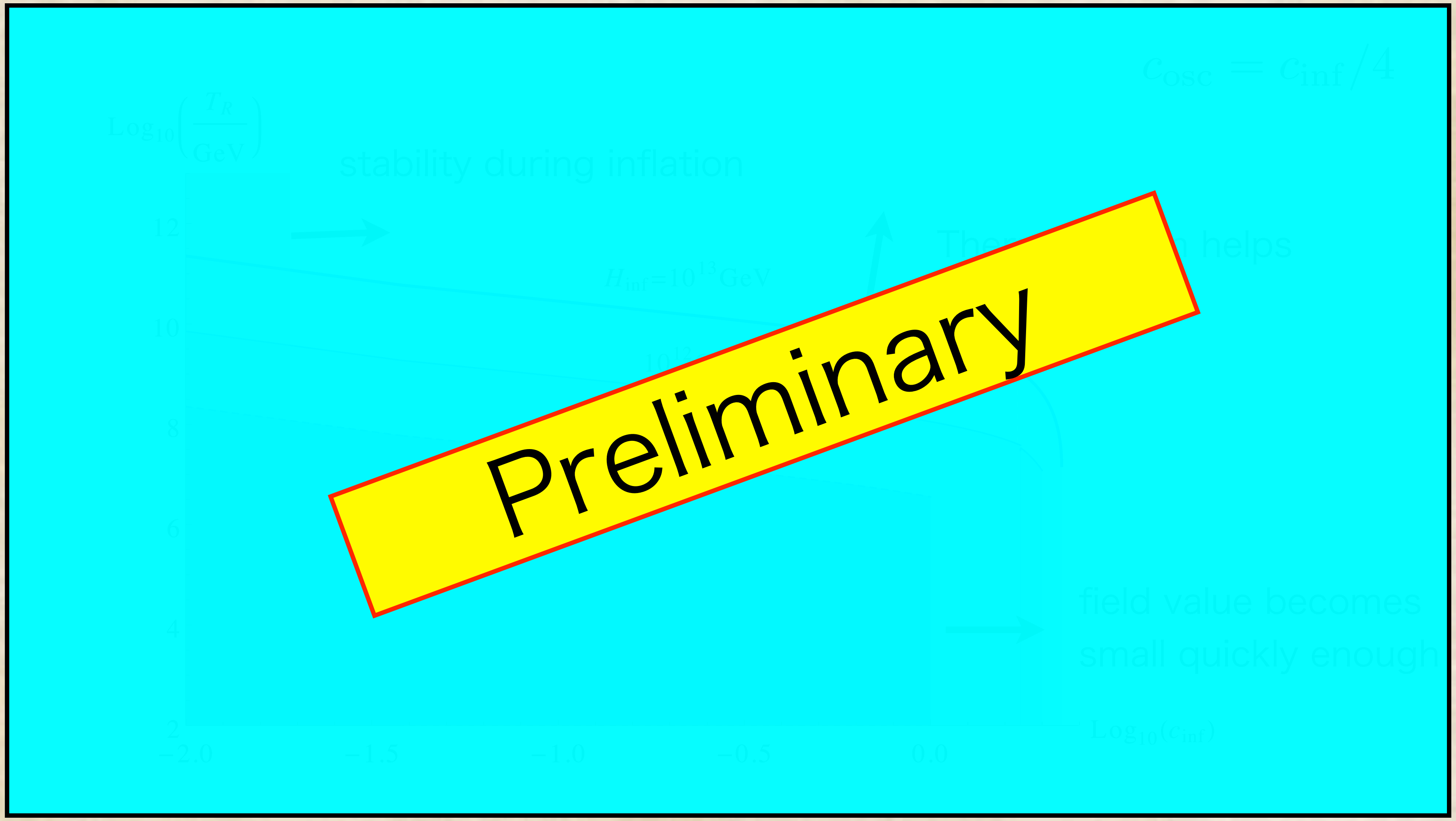
For small coefficient, $c_{\rm osc} < 9/16$, the Higgs field decreases much slower than the potential barrier and may be taken over by it.



We are safe if...

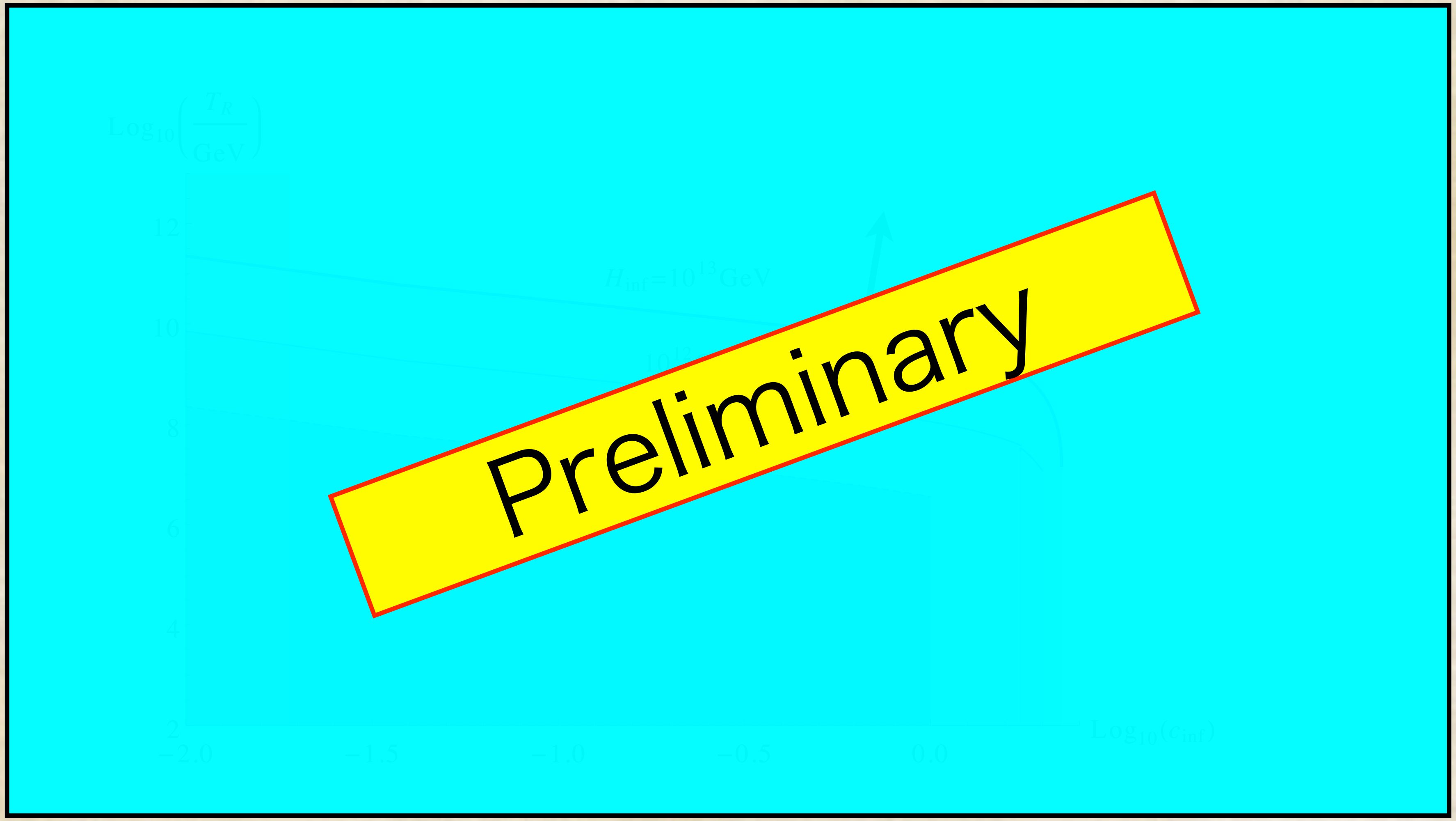
- Thermalization takes place earlier.
- The Higgs field value becomes small enough, $h(t) < \Lambda_0$ sufficiently quickly.

Then we get the constraint on the model parameters.



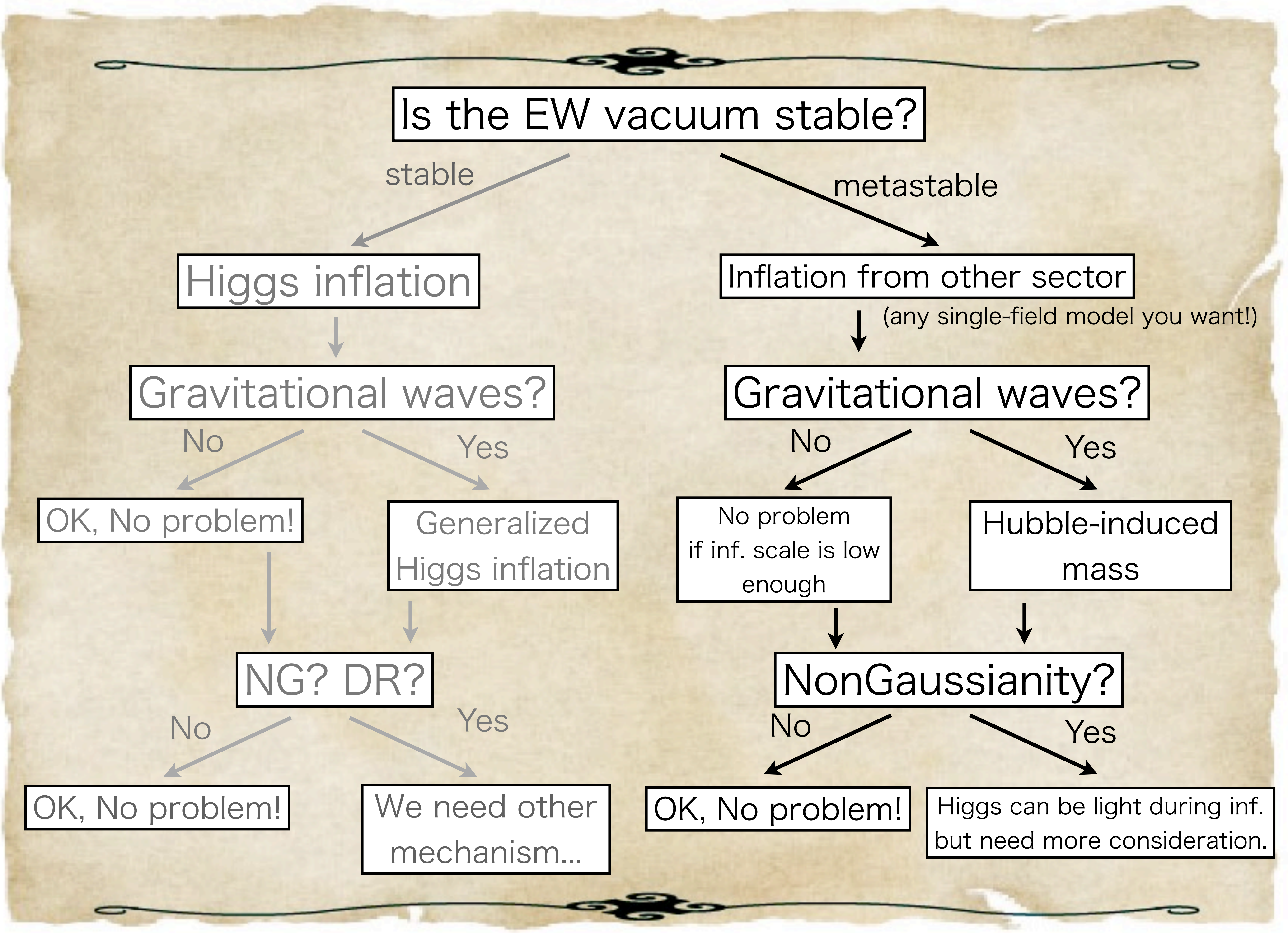
Relatively large reheating temperature is required, which can be tested by future gravitational wave experiments.

Then we get the constraint on the model parameters.

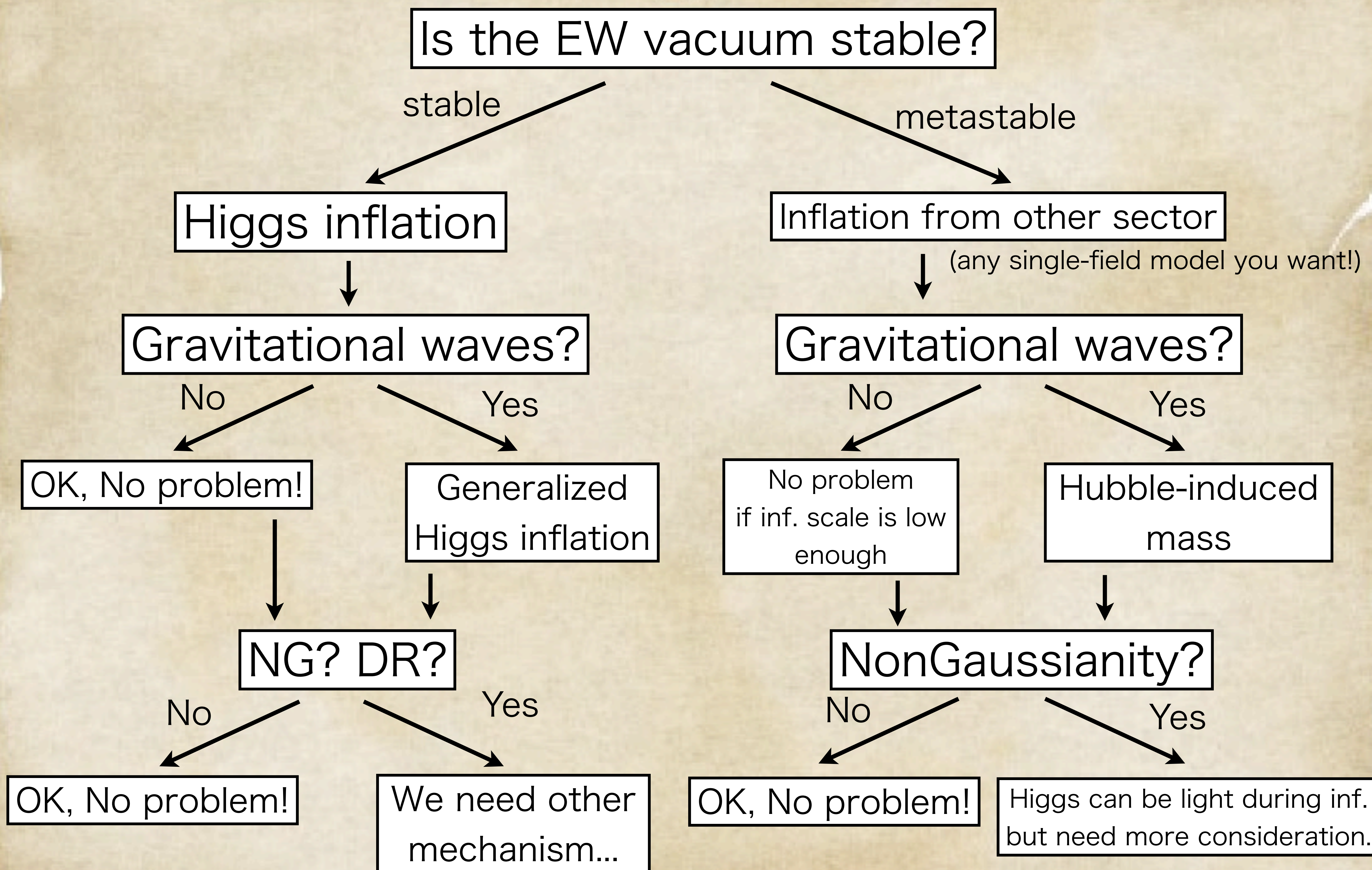


Relatively large reheating temperature is required, which can be tested by future gravitational wave experiments.

But we need some more technique to generate non-Gaussianity from light Higgs.


Is the EW vacuum stable?
stable
metastable
Higgs inflation
Inflation from other sector
(any single-field model you want!)
Gravitational waves?
No
Yes
OK, No problem!
Generalized Higgs inflation
NG? DR?
No
Yes
OK, No problem!
We need other mechanism...
Gravitational waves?
No
Yes
No problem if inf. scale is low enough
Hubble-induced mass
NonGaussianity?
No
Yes
OK, No problem!
Higgs can be light during inf. but need more consideration.

Summary


Is the EW vacuum stable?
stable
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Inflation from other sector
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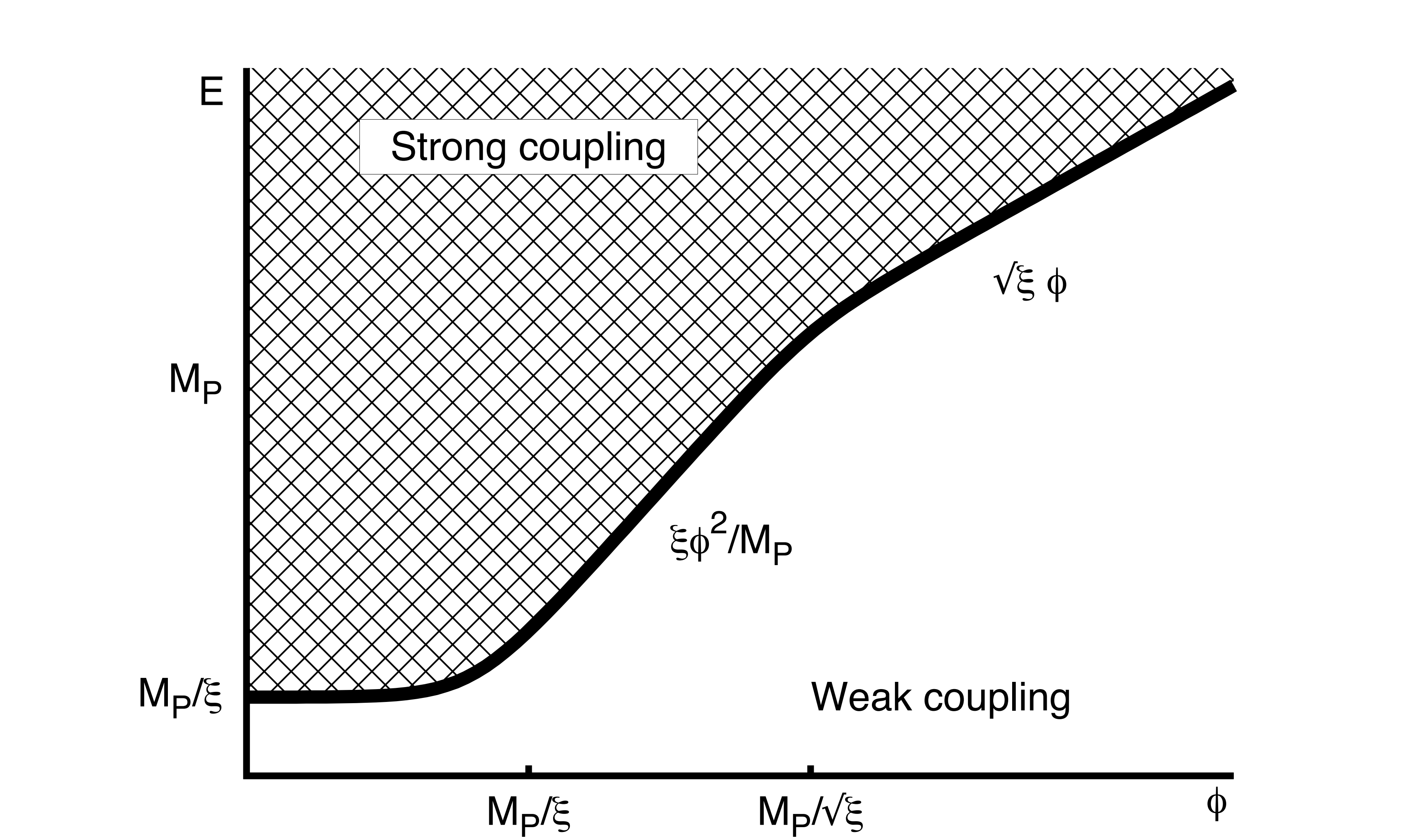
Gravitational waves?
Gravitational waves?
No
Yes
No
Yes
OK, No problem!
Generalized Higgs inflation
No problem if inf. scale is low enough
Hubble-induced mass
NG? DR?
NonGaussianity?
No
Yes
No
Yes
OK, No problem!
We need other mechanism...
OK, No problem!
Higgs can be light during inf. but need more consideration.

Appendix

Unitarity problem in Higgs inflation



'11 Bezrukov+

Determination of reheating temperature by GWB