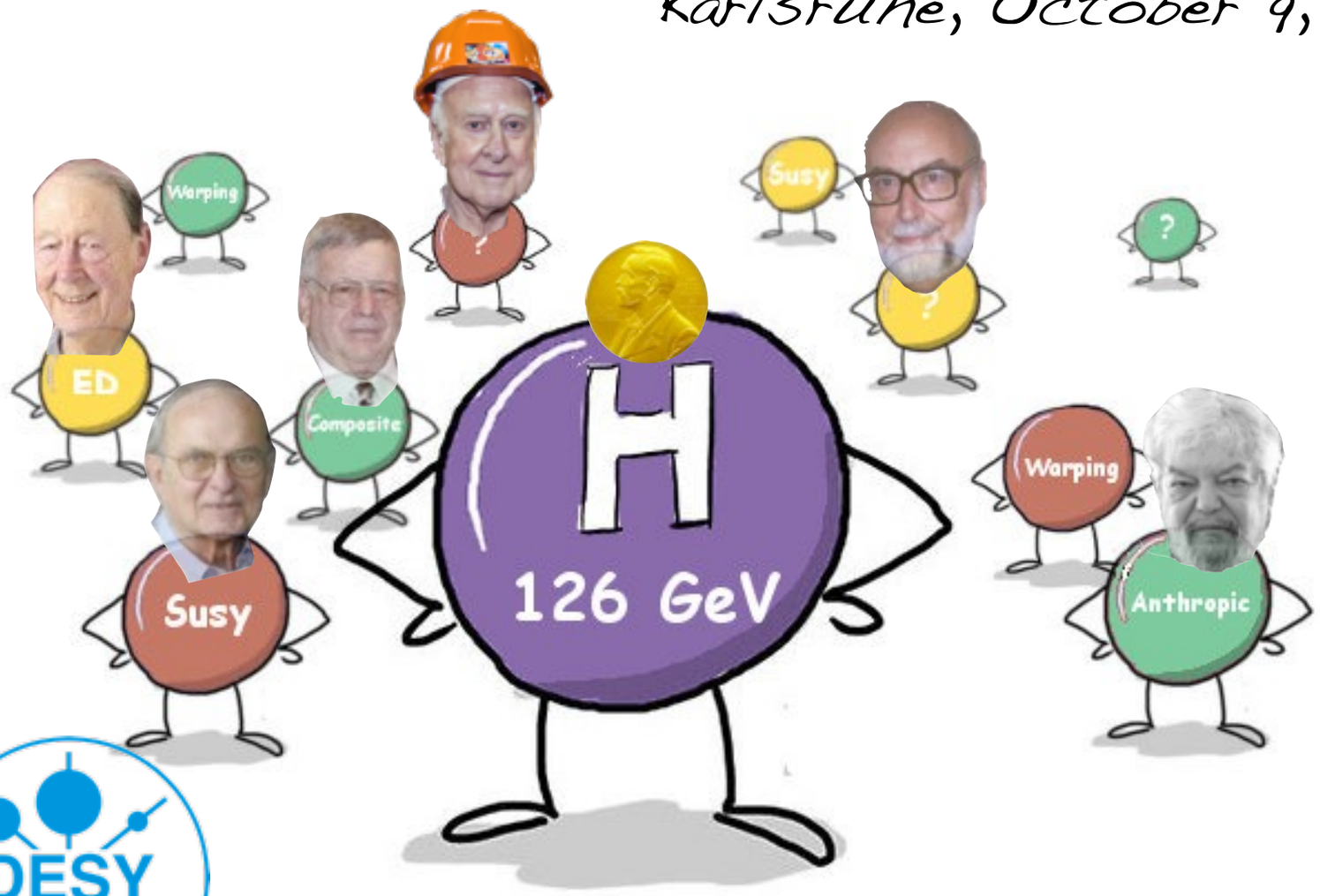
Cosmological Relaxation of the Weak Scale

HEPKIT2015

Shedding light on our Understanding of Nature

Karlsruhe, October 9, 2015



P. Cámara/C. Grojean adapted from phdcomics.com

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The Higgs: Now what? What's Next?

"The experiment worked better than expected and the analysis uncovered a very difficult to find signal"

the words of a string theorist

Great success...

...but the experimentalists haven't found what the BSM theorists told them they will find in addition to the Higgs boson:

no susy, no BH, no extra dimensions, nothing ...

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HEP future

exploration/discovery era or consolidation/measurement era?

Naturalness & TeV scale new physics

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections
(others are not necessarily theoretically inconsistent
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Field	Symmetry as $m \to 0$	Implication
Spin-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\theta}\Psi$ $\bar{\Psi} \to e^{-i\theta}\bar{\Psi}$ (chiral symmetry)	$\delta m \propto m$ **Natural!**
Spin-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (gauge invariance)	$\delta m \propto m$ **Natural!**

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The Higgs mass in the SM doesn't break any (quantum*) symmetry

* it does break classical scale invariance, as the running of the gauge couplings does too!

Naturalness principle @ work

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Beautiful examples of naturalness to understand the need of "new" physics

see for instance Giudice '13 (and refs. therein) for an account

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- the need of the positron to screen the electron self-energy: $\Lambda < m_e/\alpha_{\rm em}$
- the rho meson to cutoff the EM contribution to the charged pion mass: $\Lambda^2 < \delta m_\pi^2/\alpha_{\rm em}$
- the kaon mass difference regulated by the charm quark: $\Lambda^2 < \dfrac{\delta m_K}{m_K}\dfrac{6\pi^2}{G_F^2 f_K^2 \sin^2\theta_C}$
- the light Higgs boson to screen the EW corrections to gauge bosons self-energies
- ...
- new physics at the weak scale to cancel the UV sensitivity of the Higgs mass?

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by the time evolution/the age of the Universe

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- The field evolves in time in the early universe and scans a vast range of Higgs mass
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-evolution

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Self-organized criticality

when the Higgs mass becomes negative, it
back-reacts and generates a potential barrier
that stops the evolution of the scanning field

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

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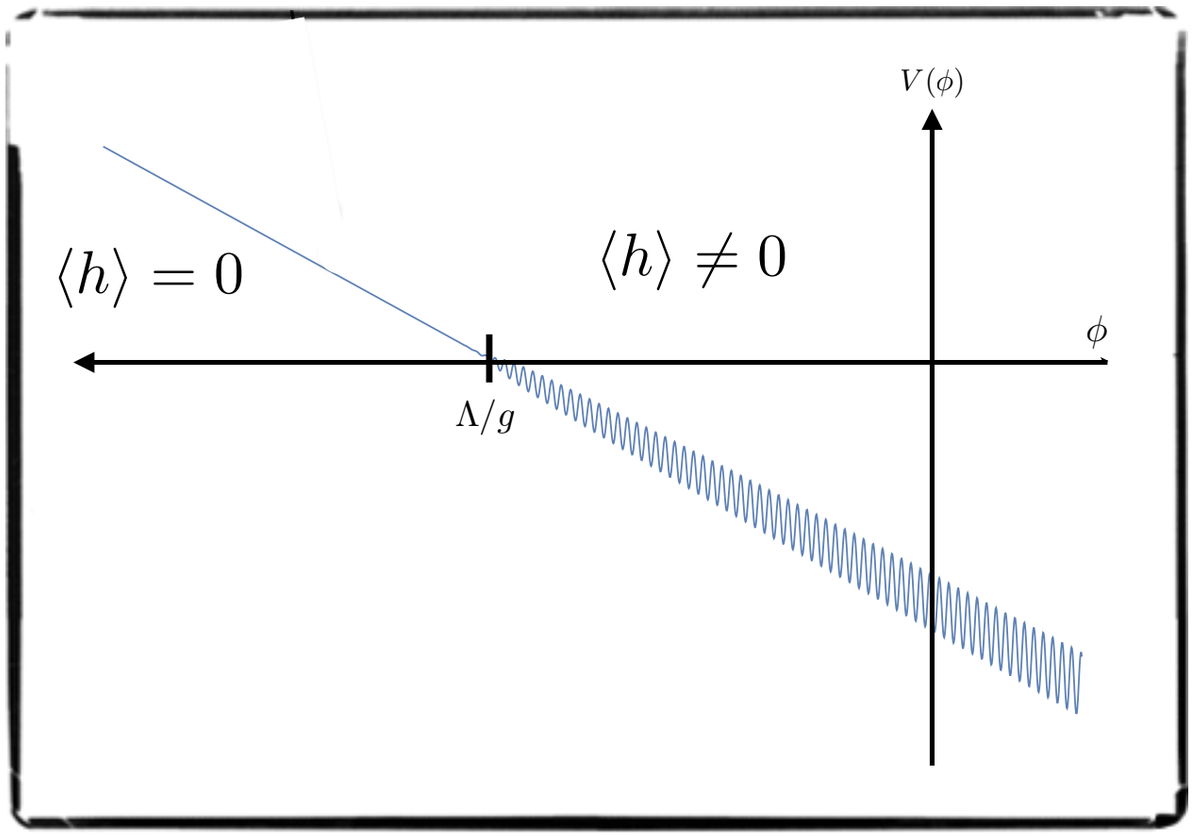

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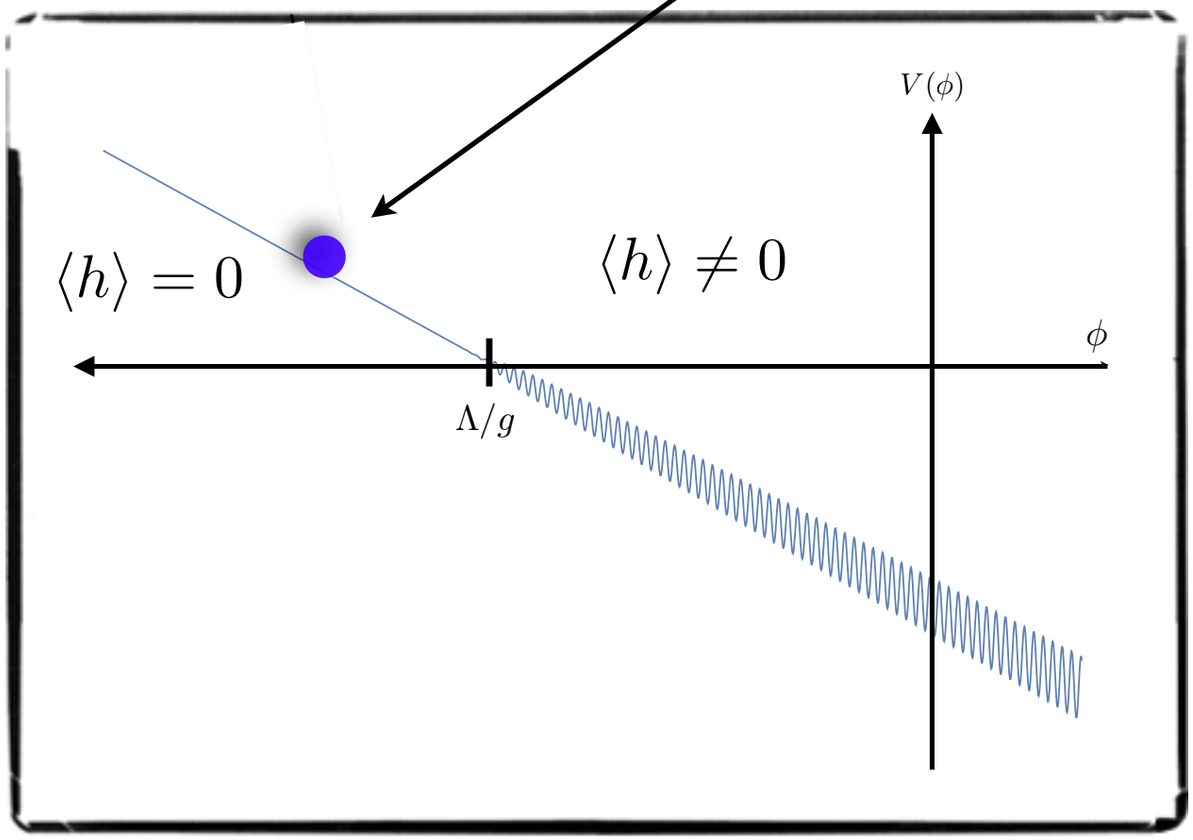

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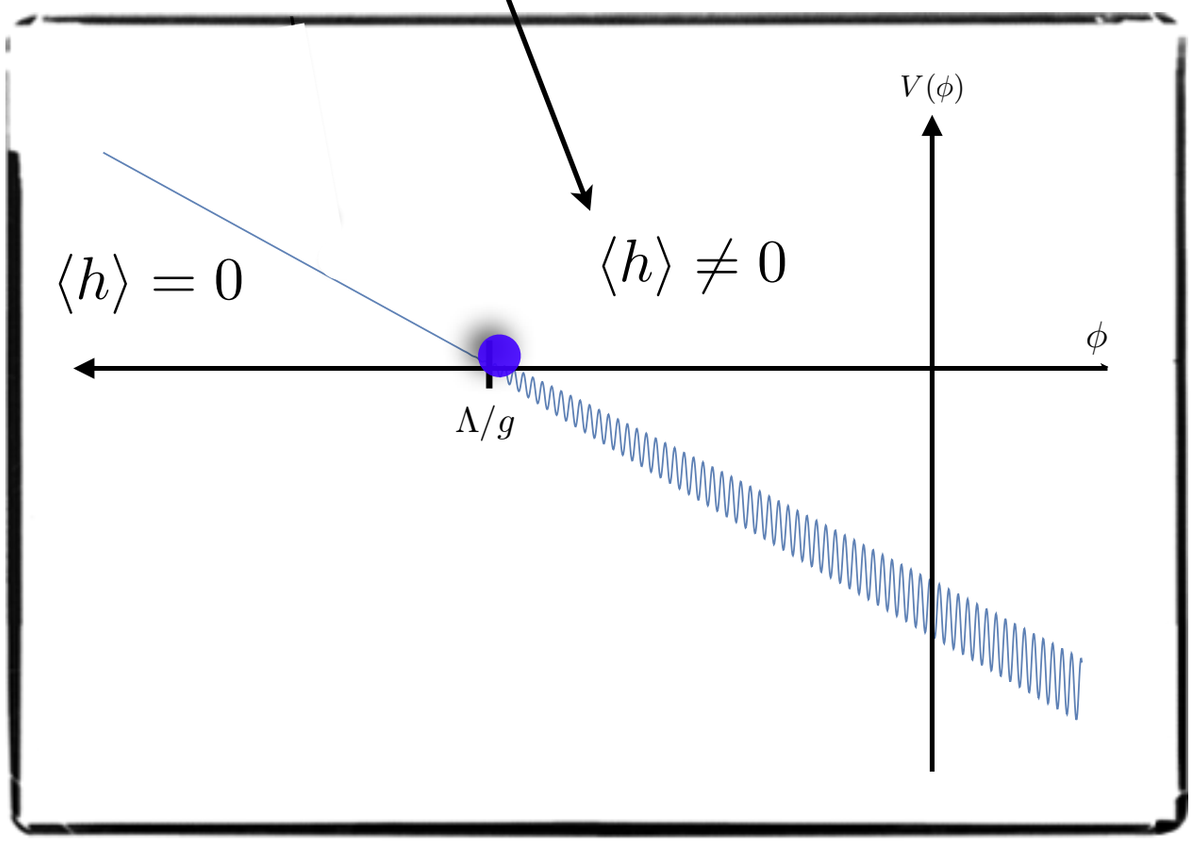

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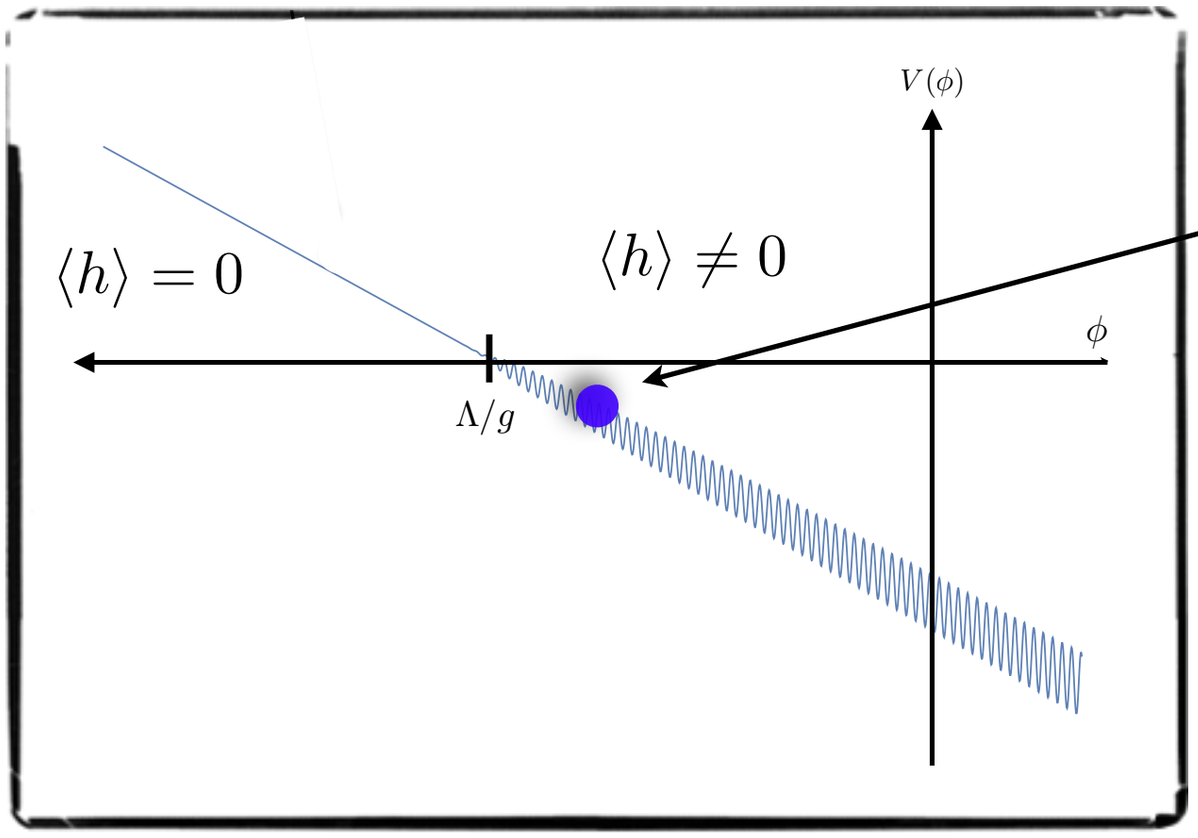

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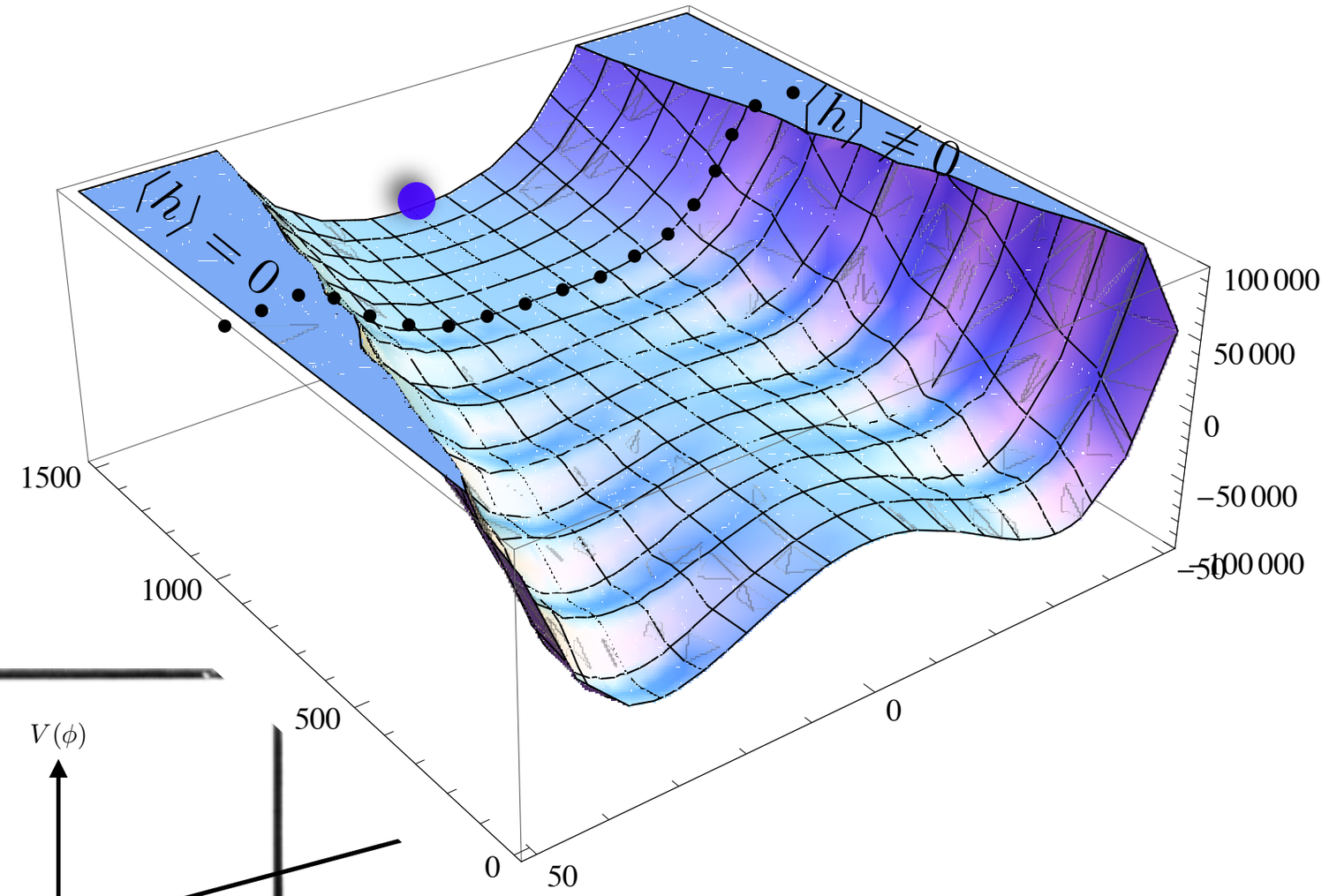

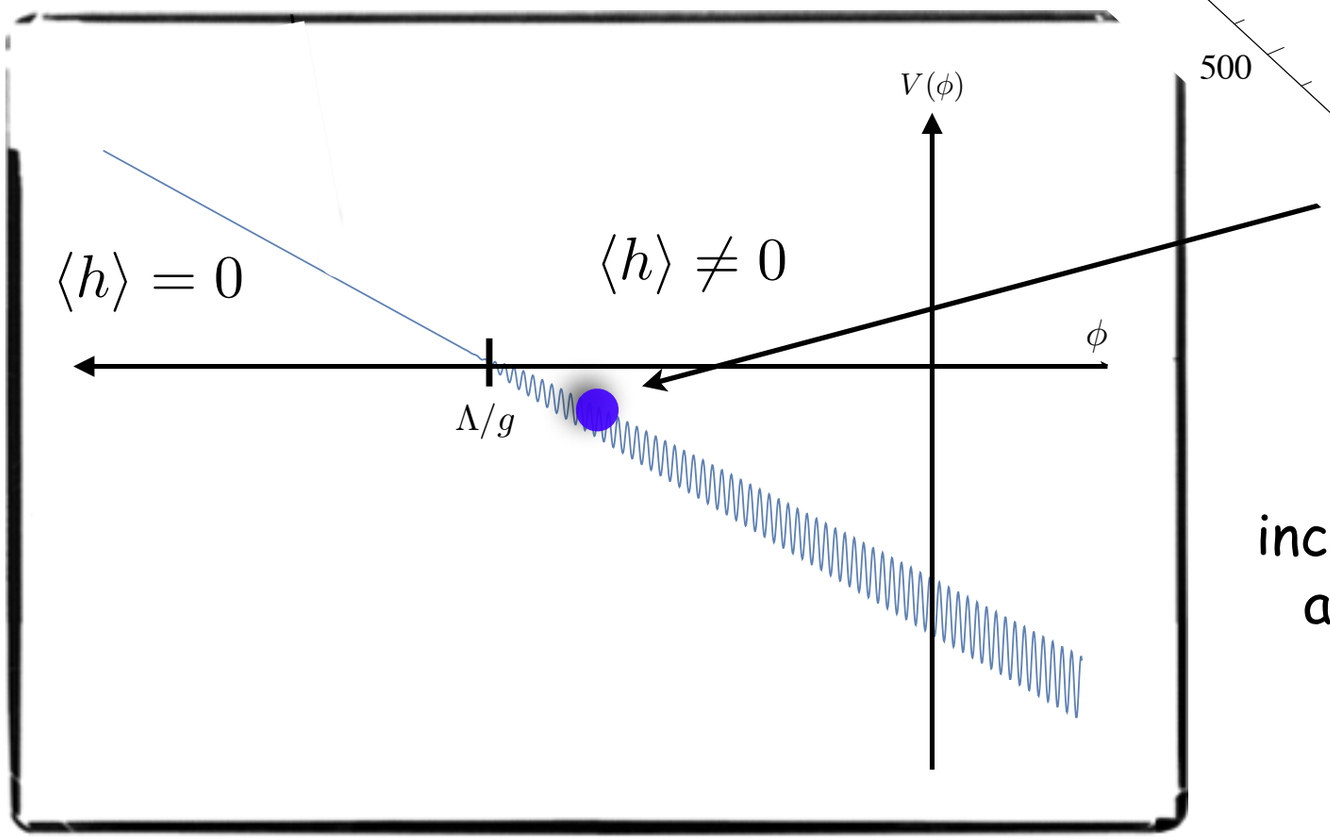

If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

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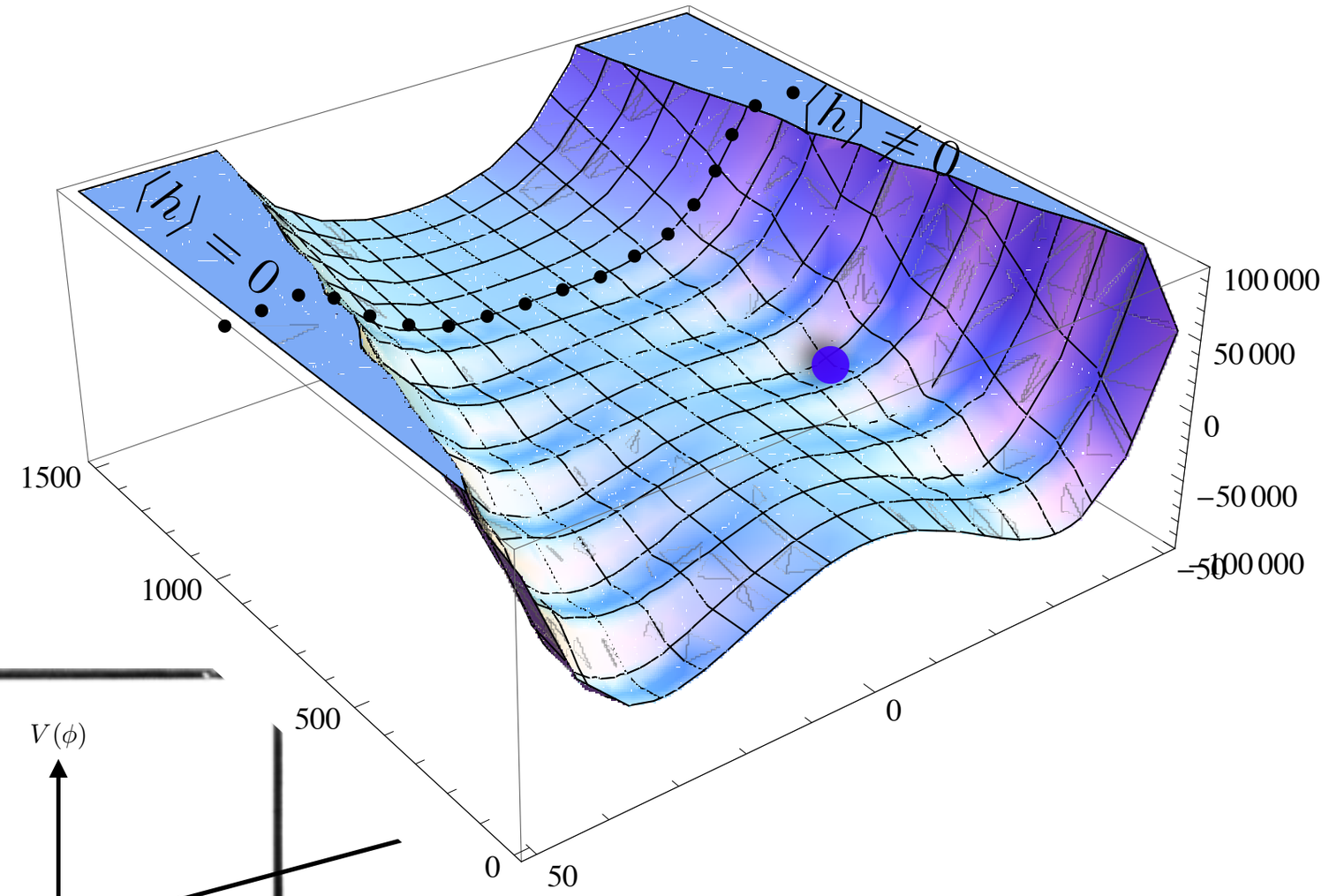

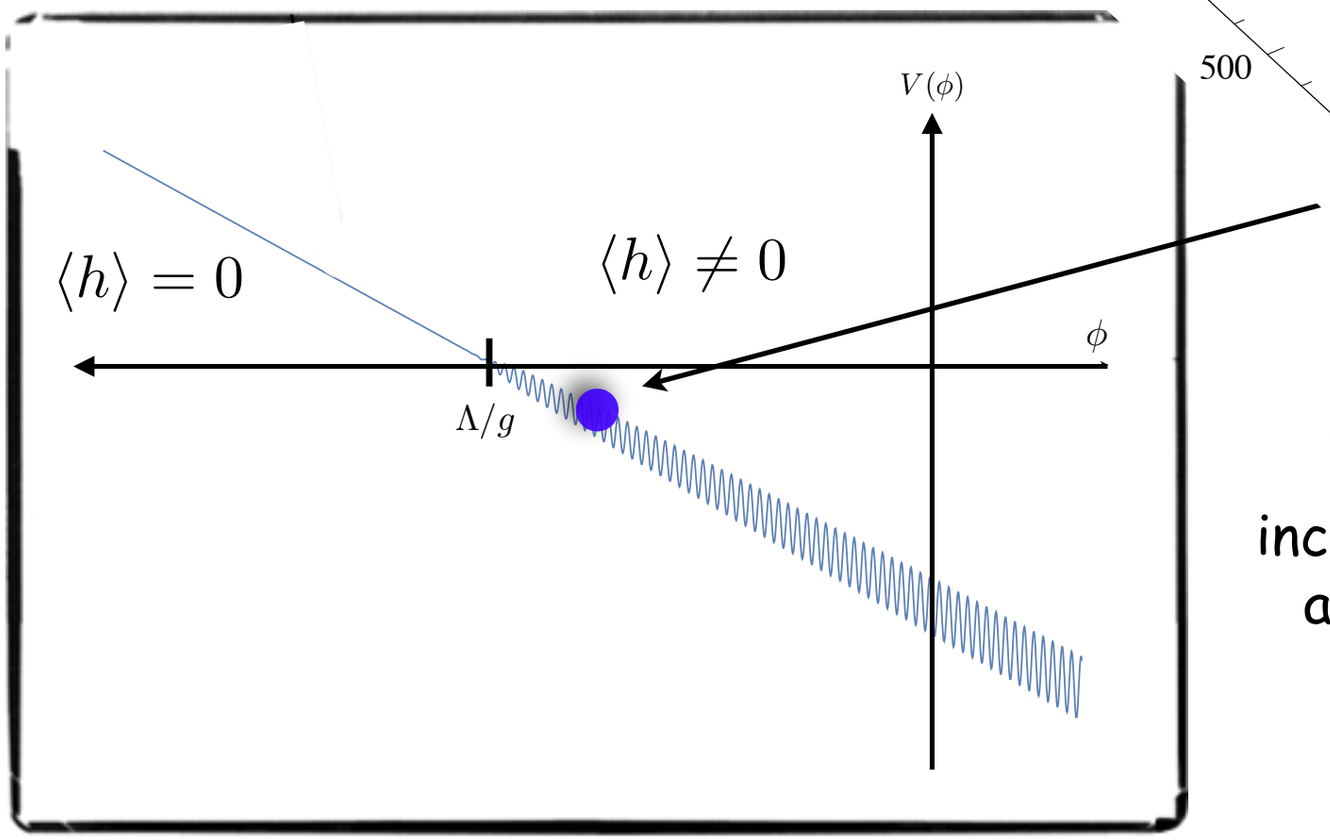

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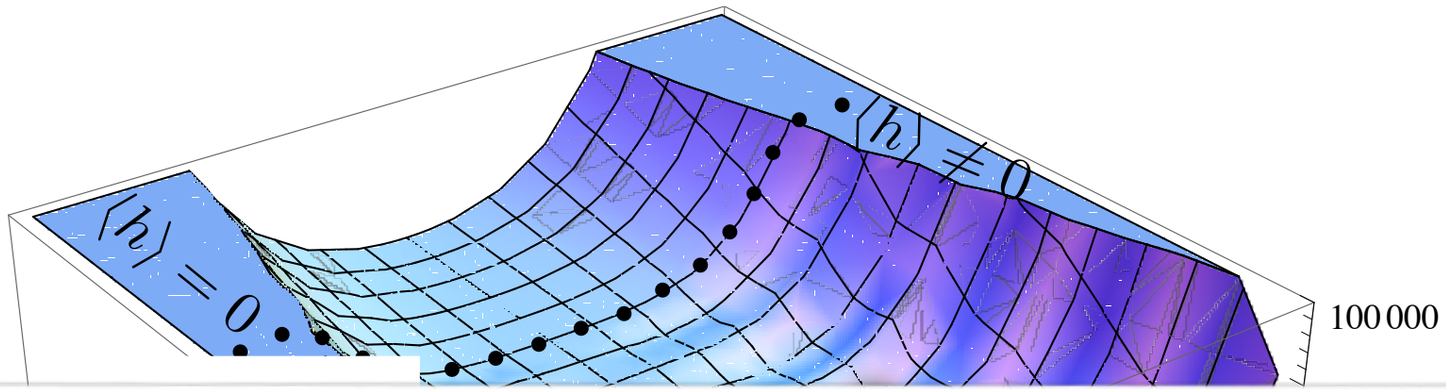
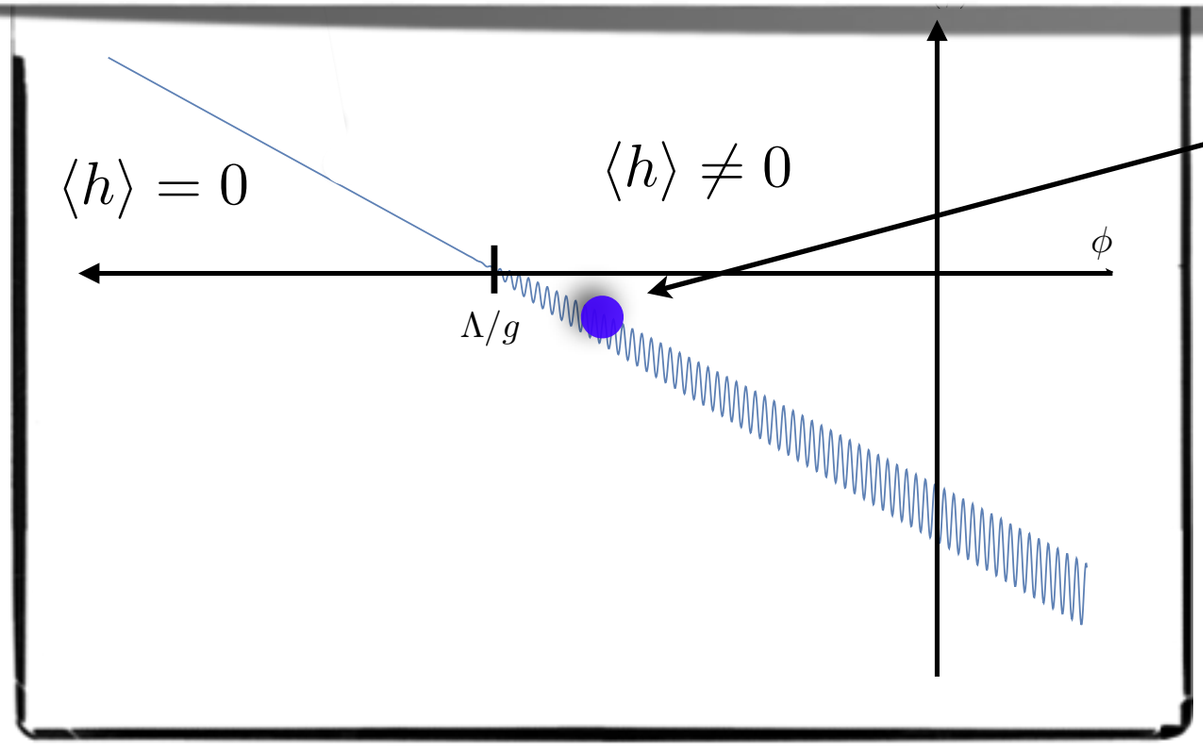


Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics



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classical displacement over one Hubble time

$$\frac{1}{H_I}\frac{d\phi}{dt} = \frac{1}{H_I^2}\frac{dV}{d\phi} = \frac{g\Lambda^3}{H_I^2}$$

$>$

quantum fluctuation

$$H_I$$

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classical displacement over one Hubble time $\dfrac{1}{H_I}\dfrac{d\phi}{dt} = \dfrac{1}{H_I^2}\dfrac{dV}{d\phi} = \dfrac{g\Lambda^3}{H_I^2}$ > quantum fluctuation H_I

$$\frac{\Lambda^6}{M_P^3} < g\Lambda^3 = \Lambda_{\rm QCD}^3 \frac{v}{f} \qquad \text{i.e.} \qquad \Lambda < 10^7\,{\rm GeV}\left(\frac{10^9\,{\rm GeV}}{f}\right)^{1/6}$$

Important issue: θ_{QCD}~ 1 >>10^{-10}. Can be solved but Λ < 30 TeV

Higgs-axion cosmological relaxation

$$V(\phi,h)=\Lambda^3 g\phi-\frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2+\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n\cos(\phi/f)+\cdots$$

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  - QCD condensate <qq>~ Λ_{QCD}
  - new strongly-coupled sector à la Technicolor

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- n=2: no extra source of EWSB needed
  - quantum stability? h-loops generate extra interactions that will stop ϕ before the Higgs vev develops unless Λ_c<v (coincidence pb and new physics @ TeV again?)

    $$\epsilon\Lambda_c^4\cos(\phi/f)\ ,\quad \epsilon\Lambda_c^3\, g\phi\cos(\phi/f)$$
  - our solution: make the envelop of the oscillatory potential a field

Cosmological Higgs-Axion Interplay (CHAIN)

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

$$V(\phi,\sigma,H)=\Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right)-\Lambda^2\left(\alpha-\frac{g\phi}{\Lambda}\right)|H|^2+\frac{1}{2}\lambda|H|^4+A(\phi,\sigma,H)\cos\left(\phi/f\right)$$

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the new interaction that saves our day

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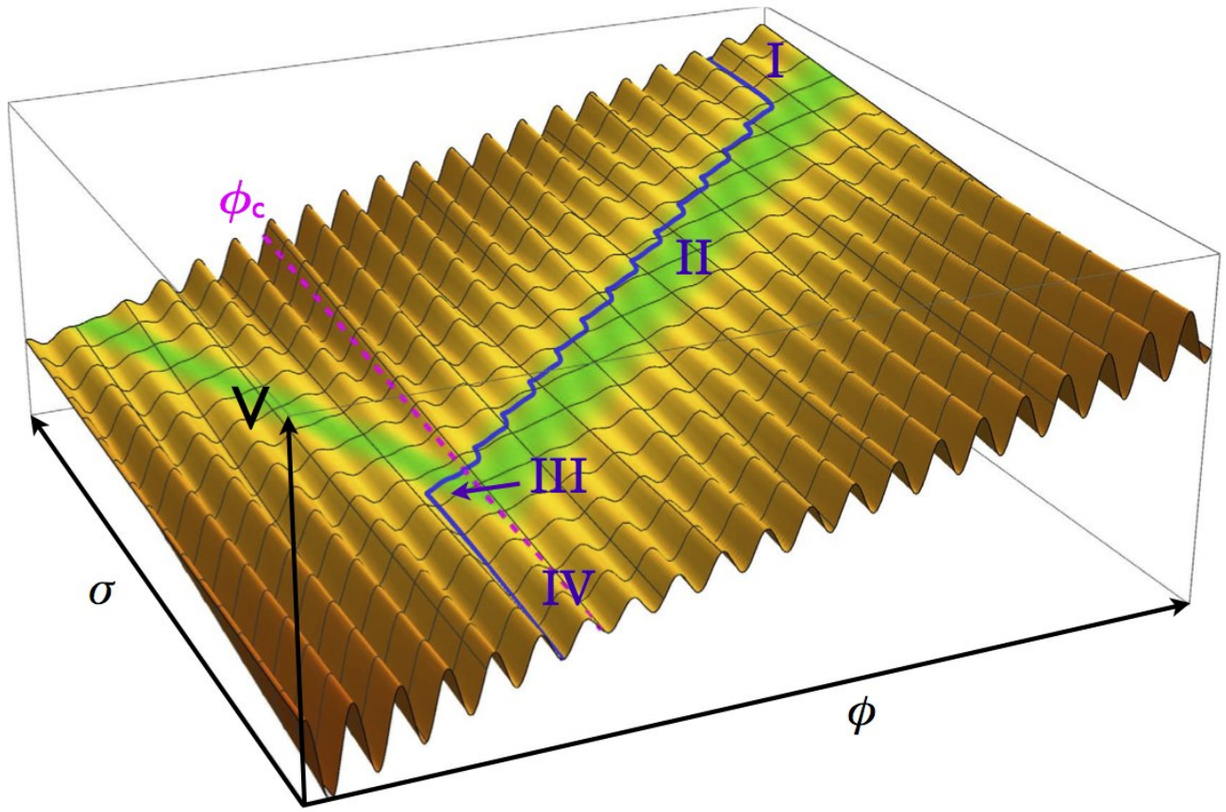

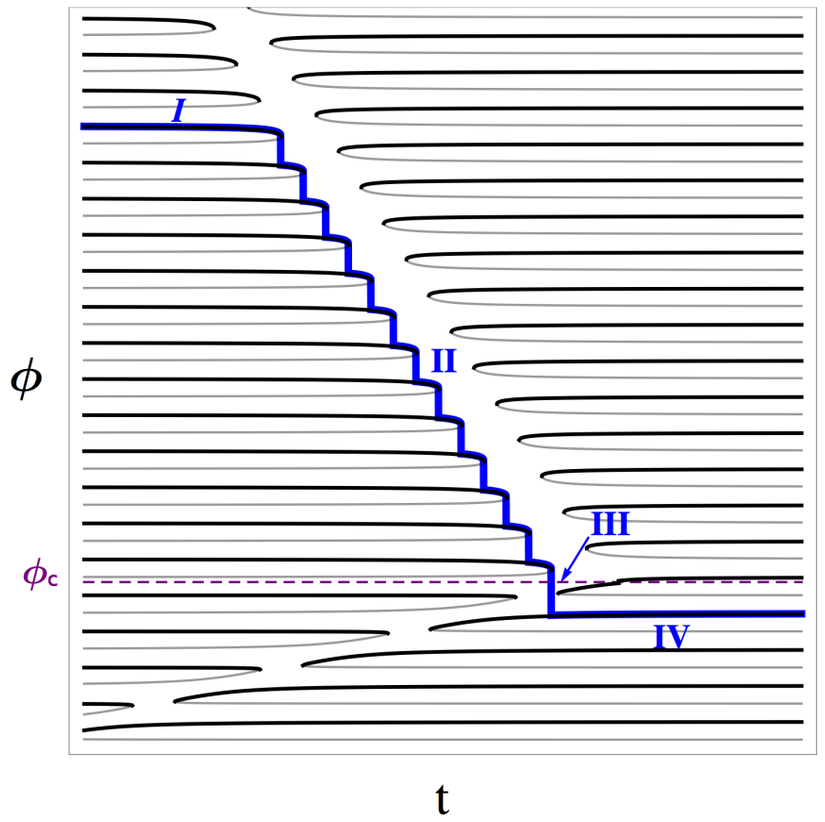

Cosmological Higgs-Axion INterplay dynamics

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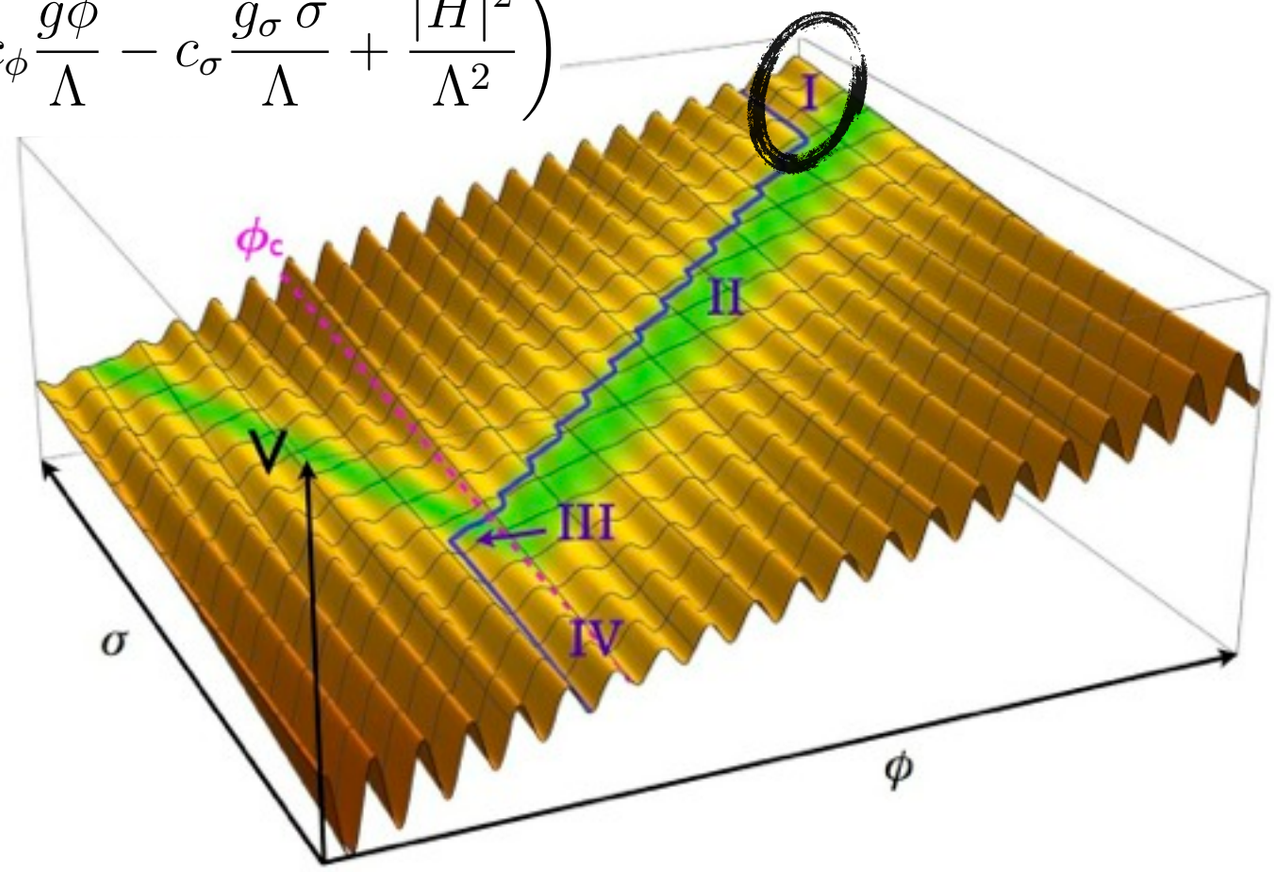

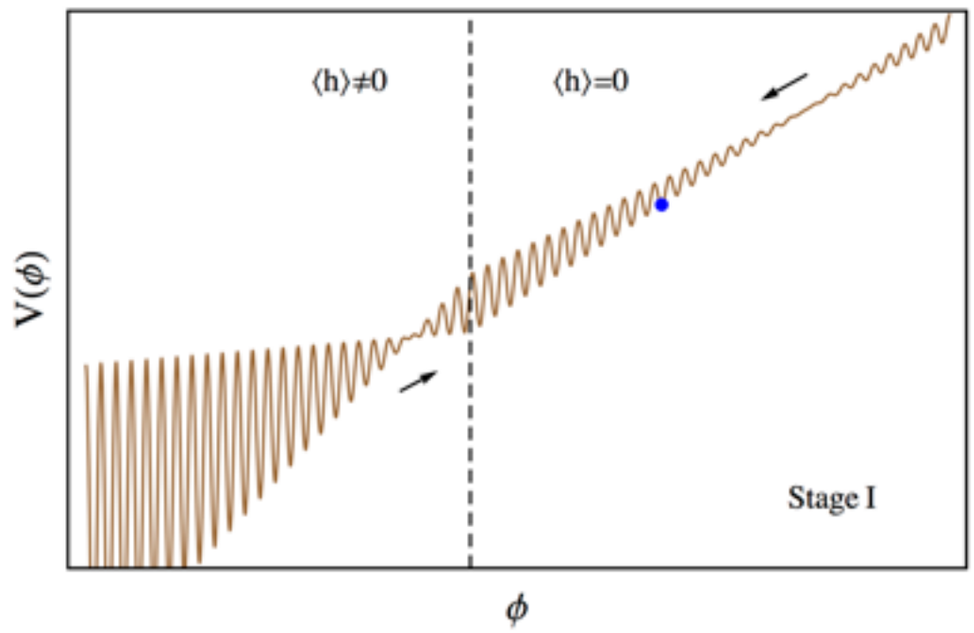

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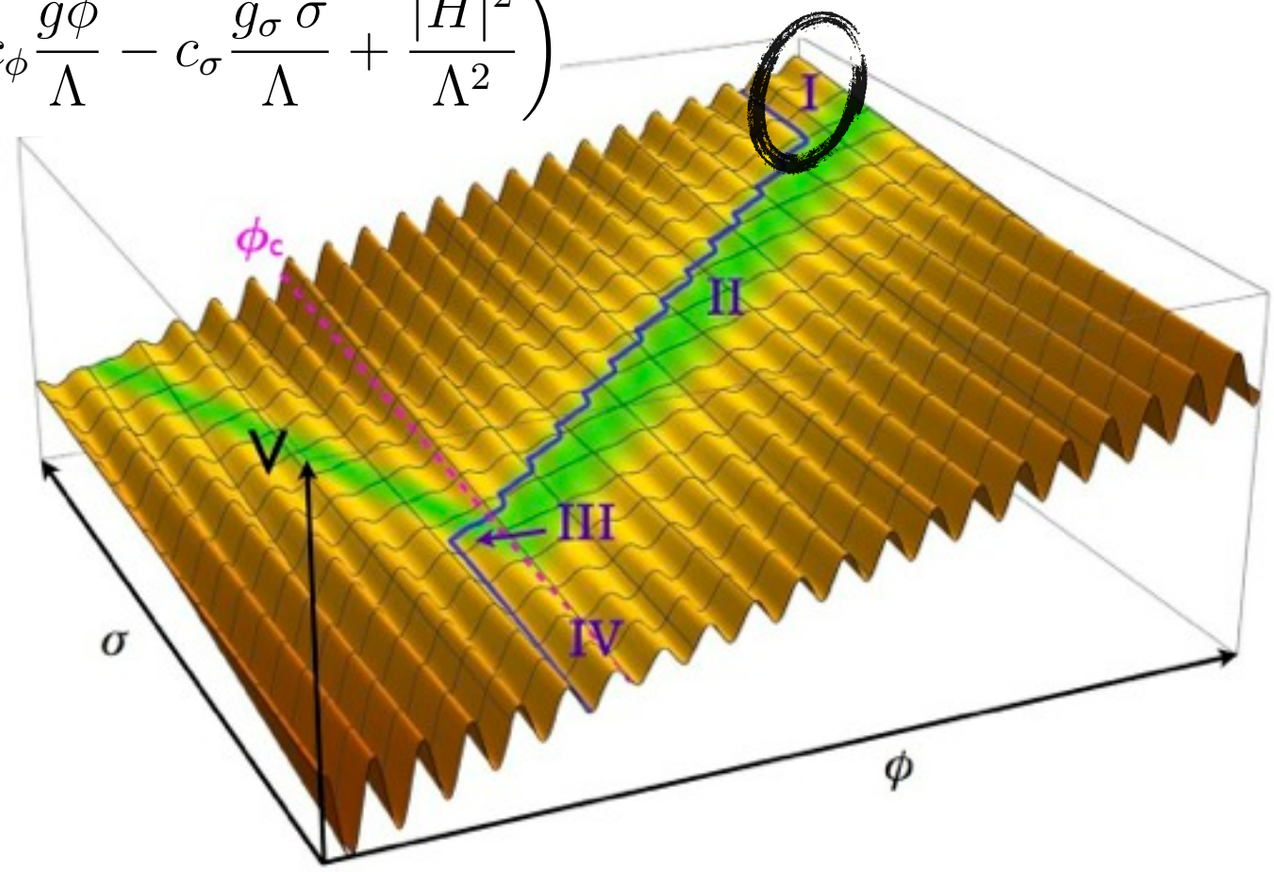
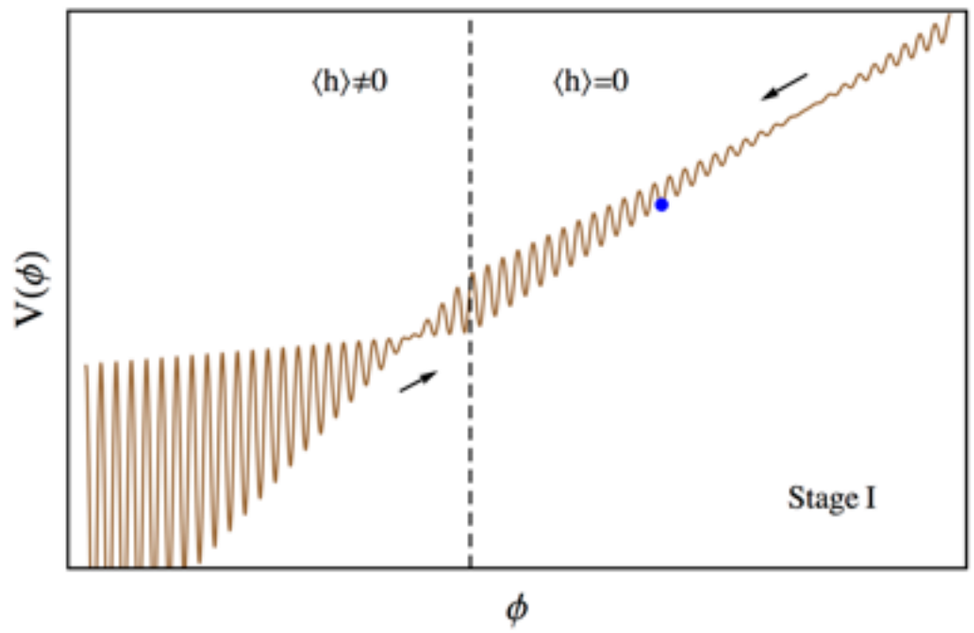
potential barrier ~ $O(\varepsilon\Lambda^4)$





Cosmological Higgs-Axion INterplay dynamics

$$A(\phi,\sigma,H) \equiv \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2}\right)$$

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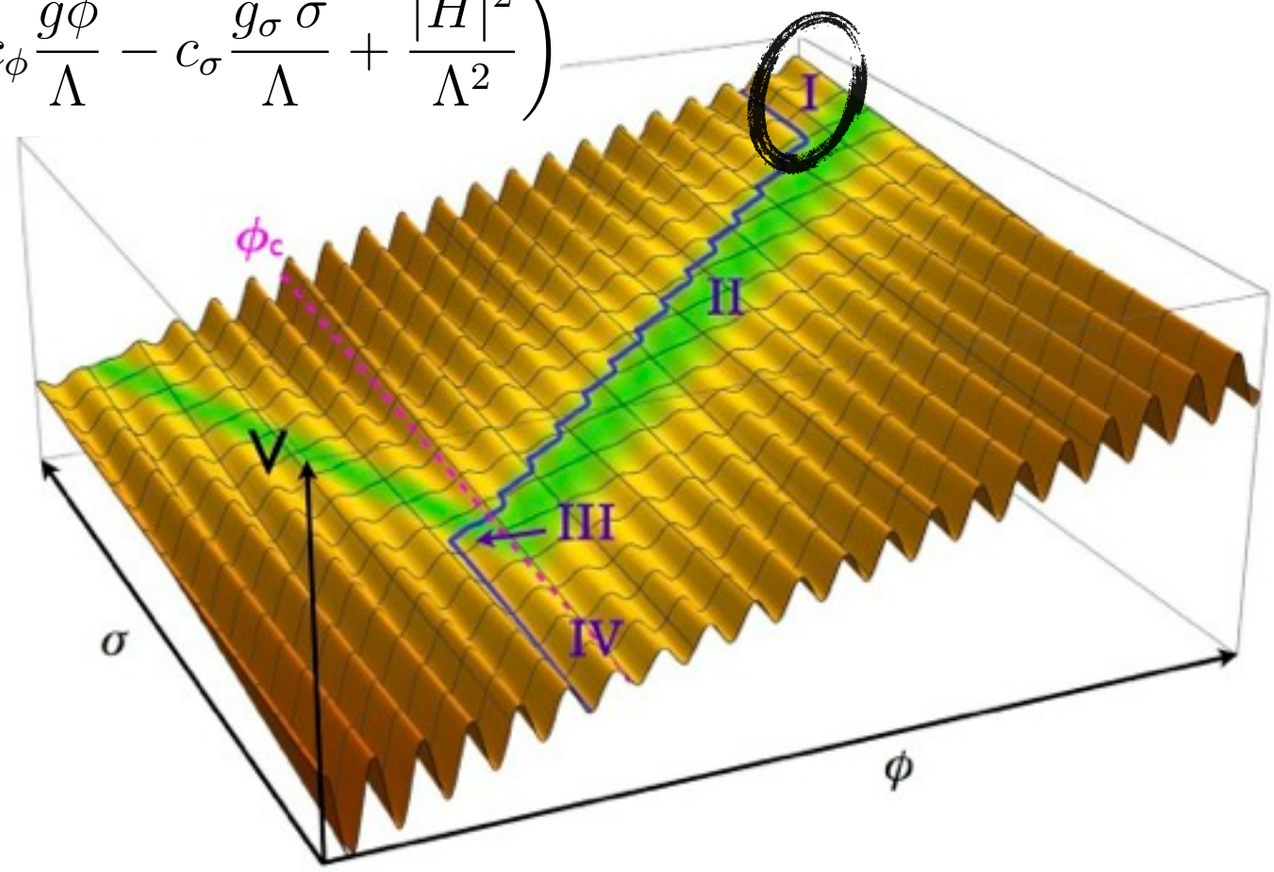
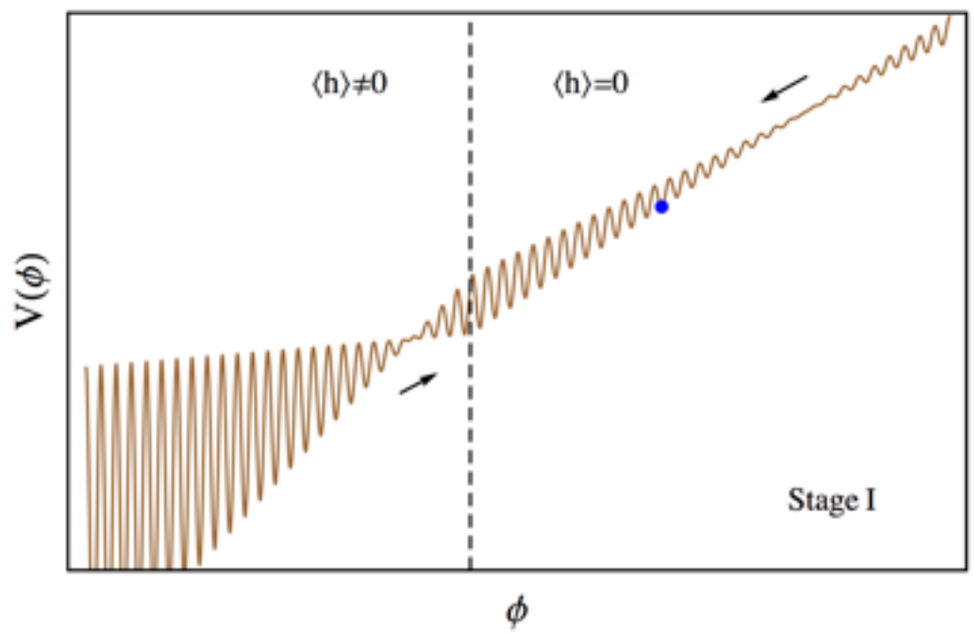


- σ starts with large value
- high potential barrier
- ϕ is stuck in some deep minimum
- σ slowly rolls down $\sigma(t) = \sigma_0 - g_\sigma\Lambda^3 t/(3H_I)$
- inflation prevents it from accelerating



Cosmological Higgs-Axion INterplay dynamics

- Phase II:

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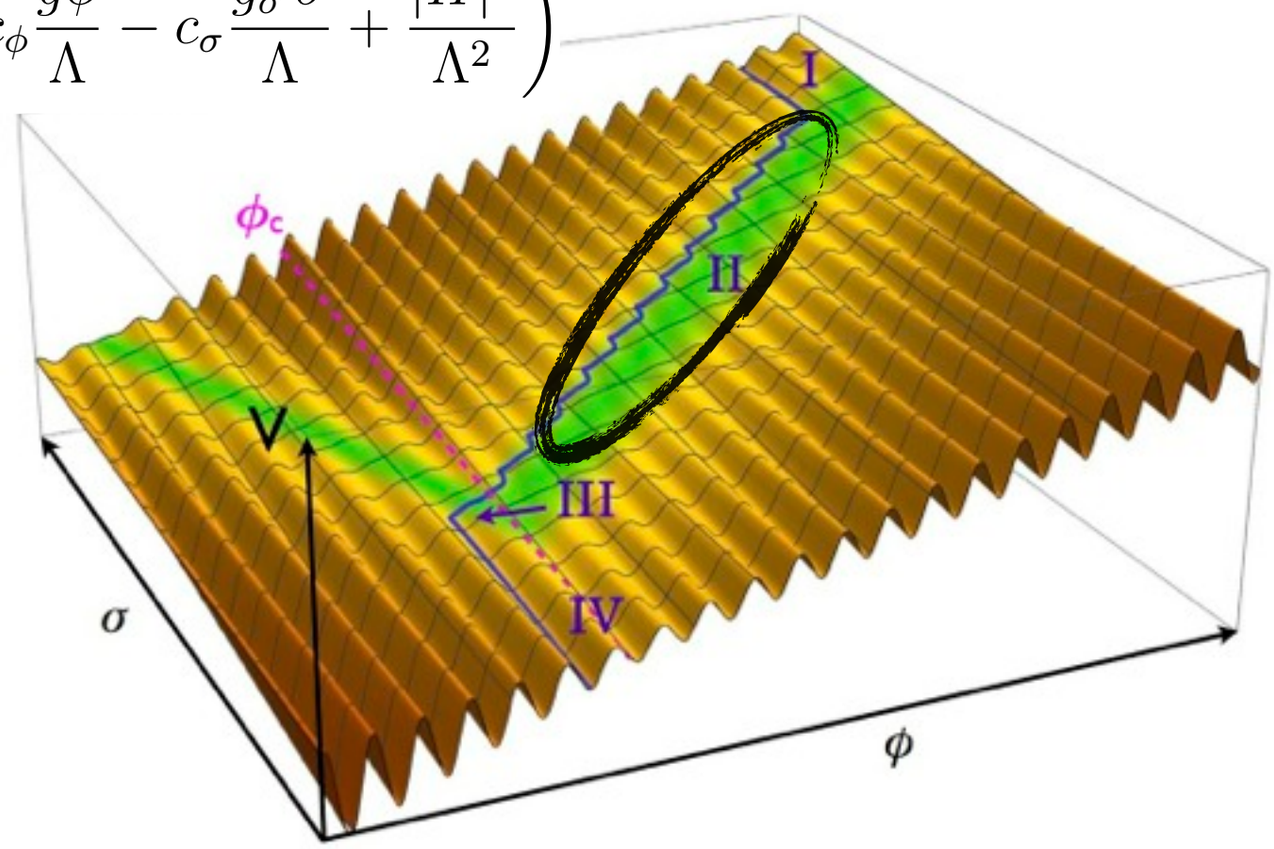

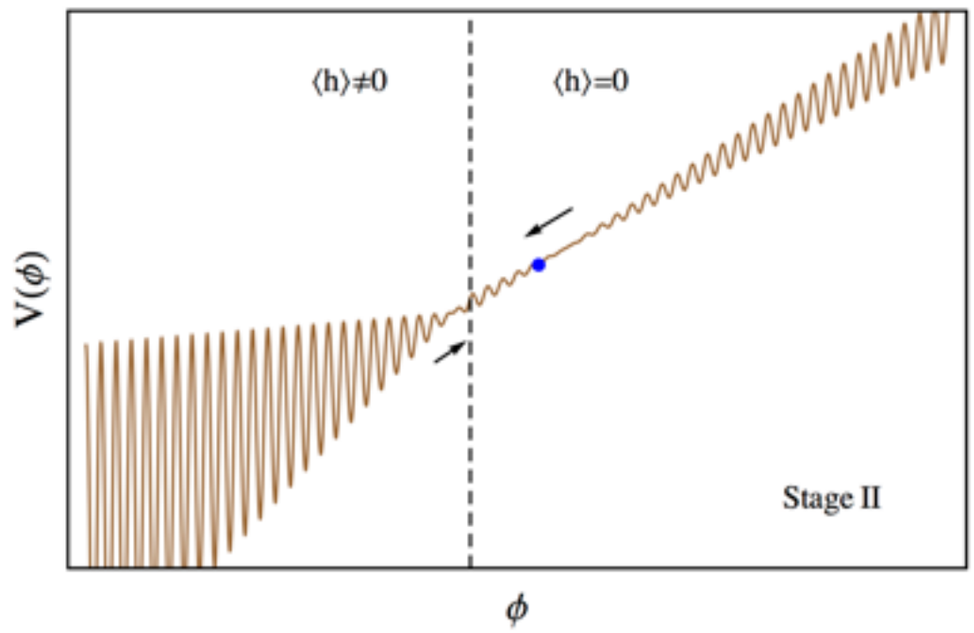

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Phase II:

potential barrier "<" linear potential
(steepness of the oscillatory potential
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$$A(\phi,\sigma,h)/f < g\Lambda^3$$

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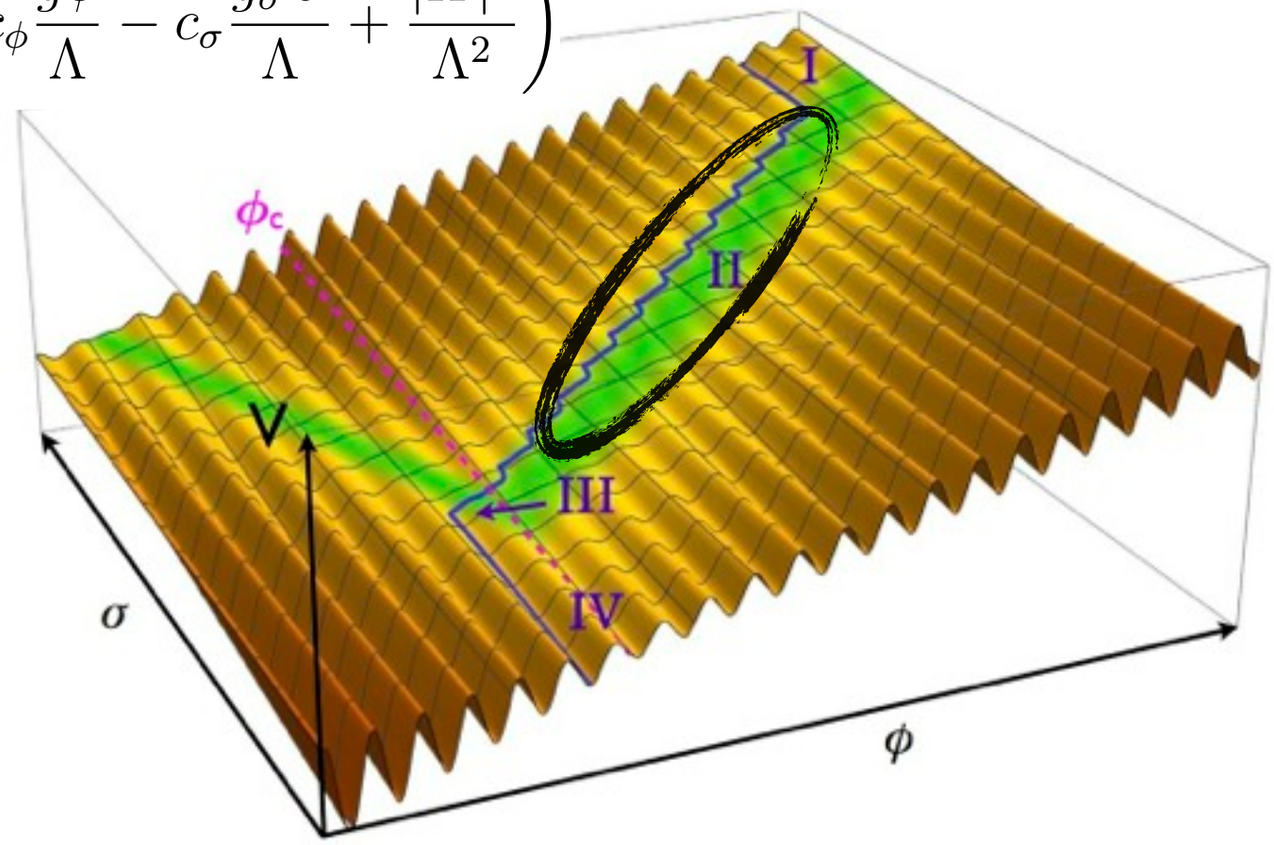

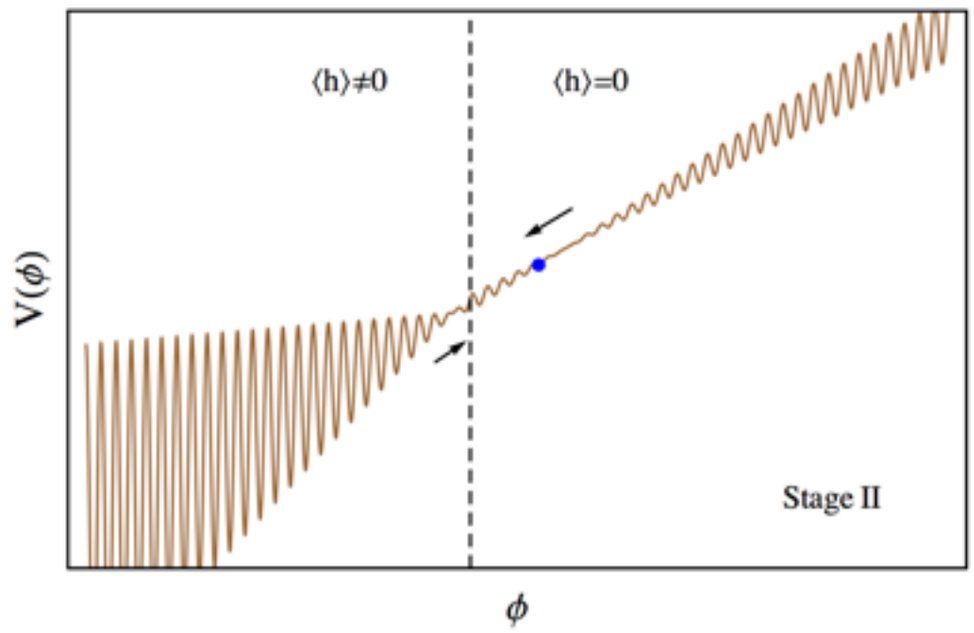

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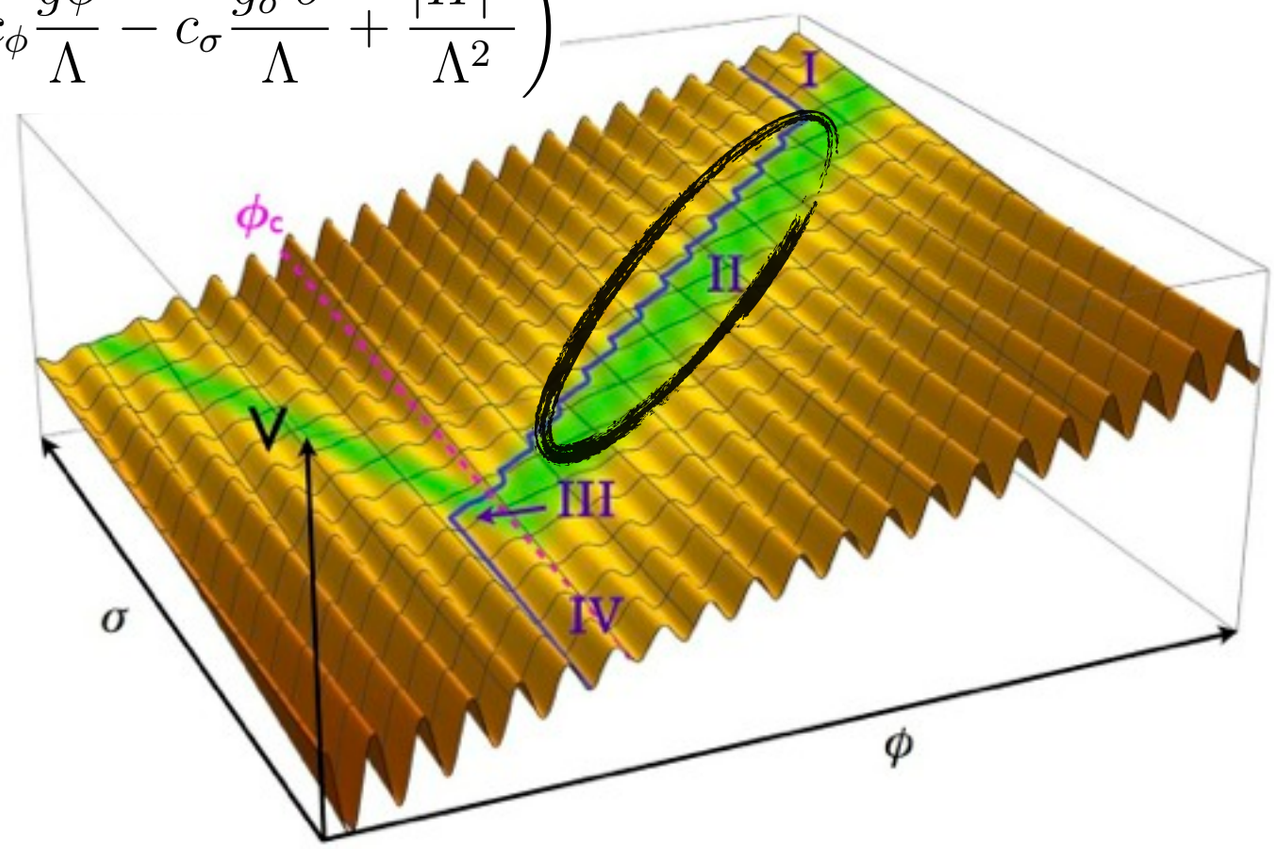
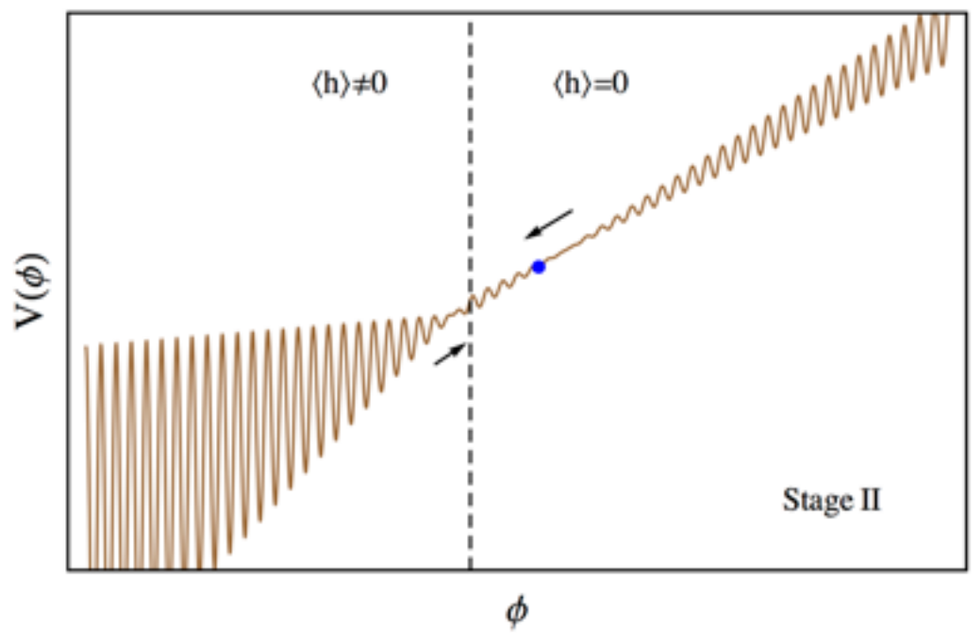


- σ reaches a value where the barrier vanishes
- ϕ can start rolling down $\quad \phi(t) = \phi_0 - g\Lambda^3 t/(3H_I)$
- σ and ϕ roll down along the barrier-free valley



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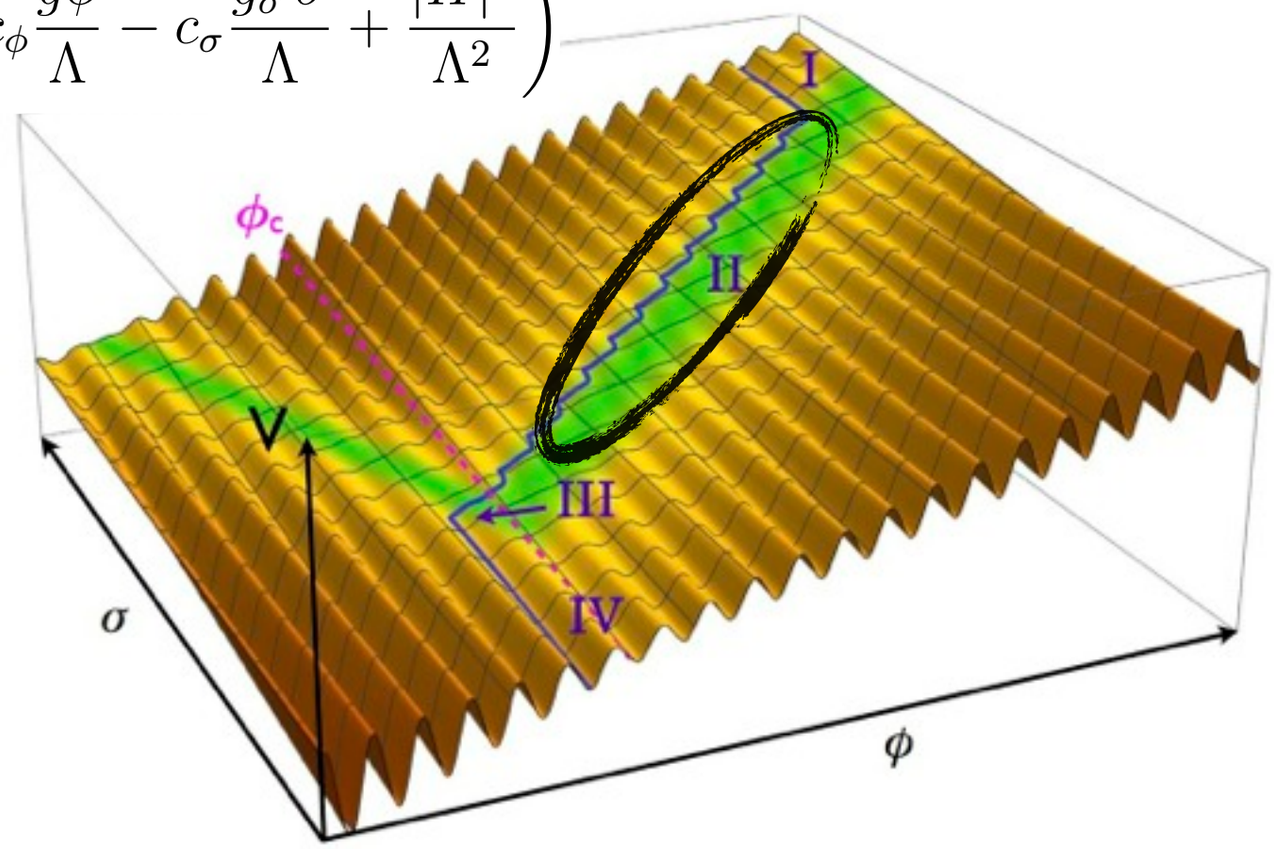

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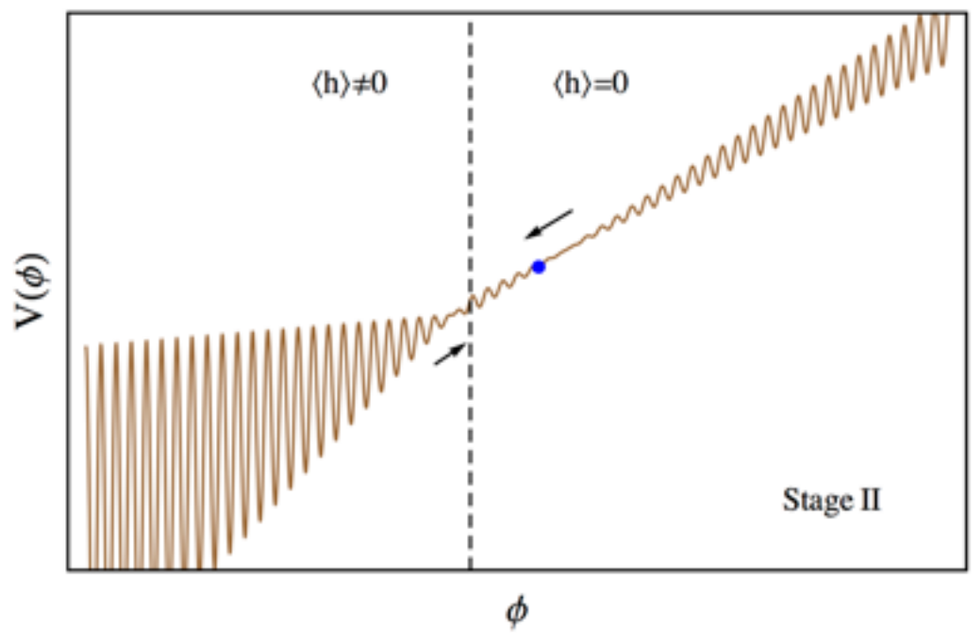
ϕ stays in the barrier-free region iff
the gradient of the dynamical trajectory
$(d\phi(t)/dt)/(d\sigma(t)/dt) = g/g_\sigma$
is larger than the gradient $d\phi/d\sigma$ of the valley

$$c_\phi g^2 > c_\sigma g_\sigma^2$$



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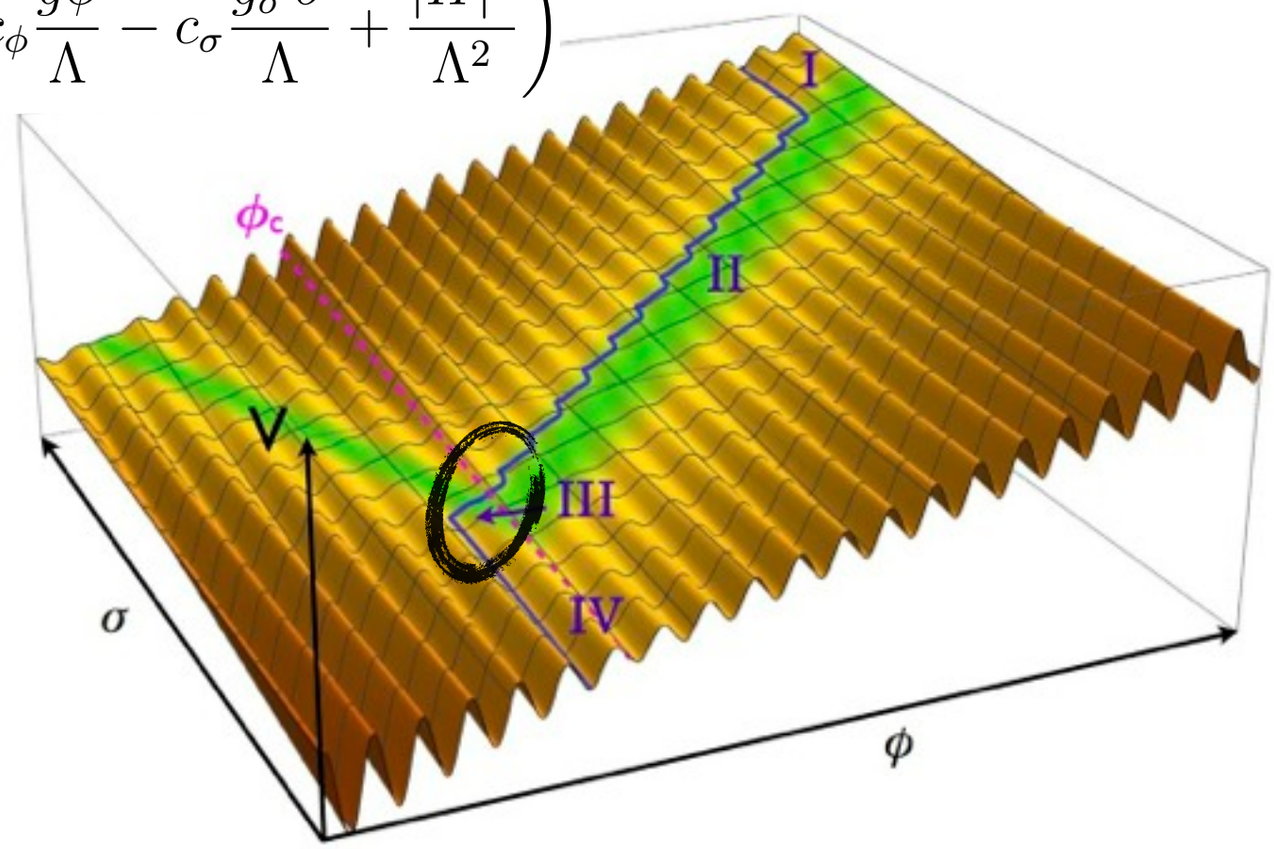

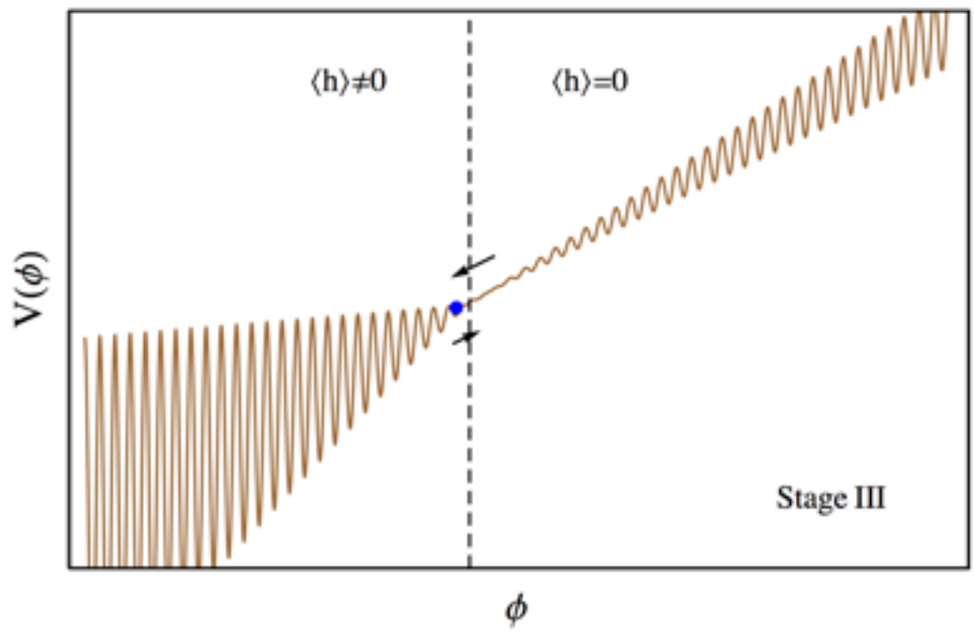

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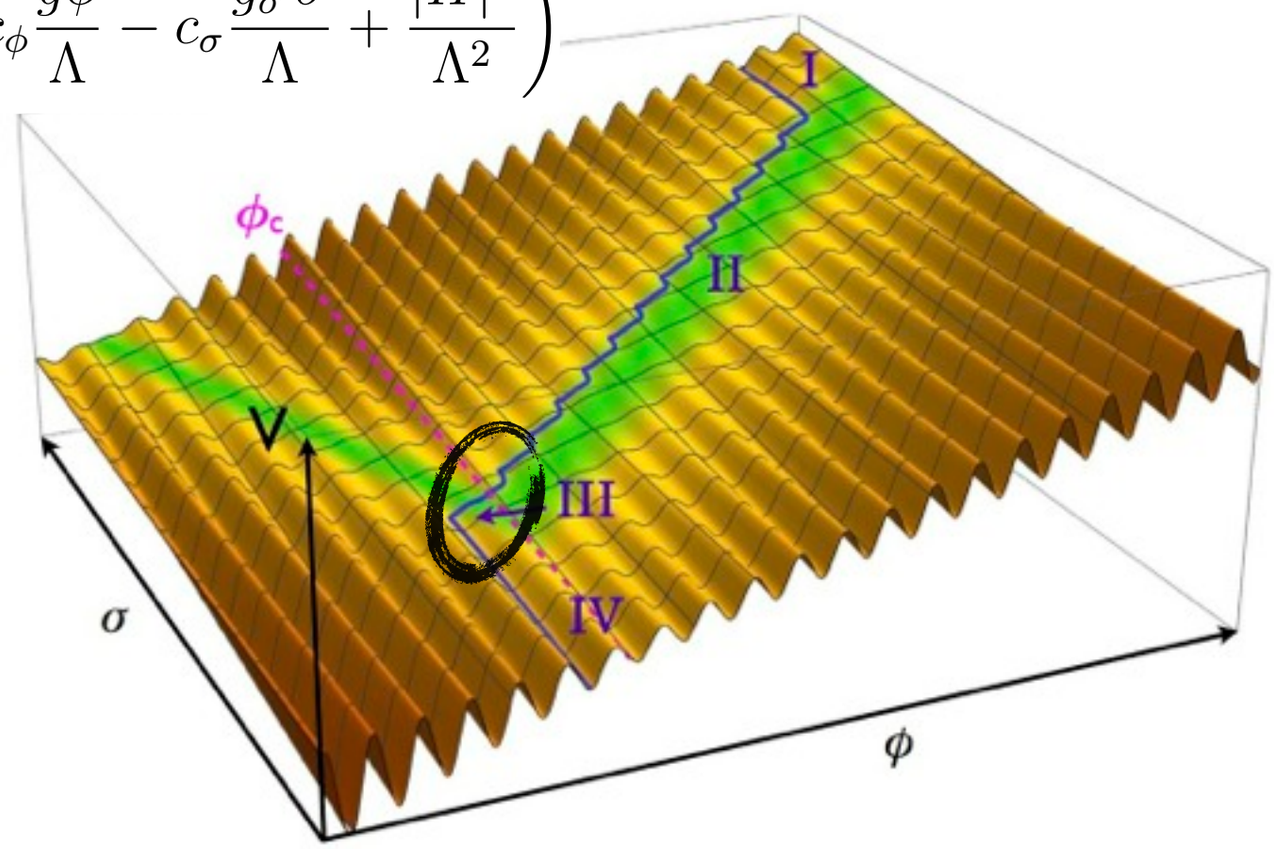
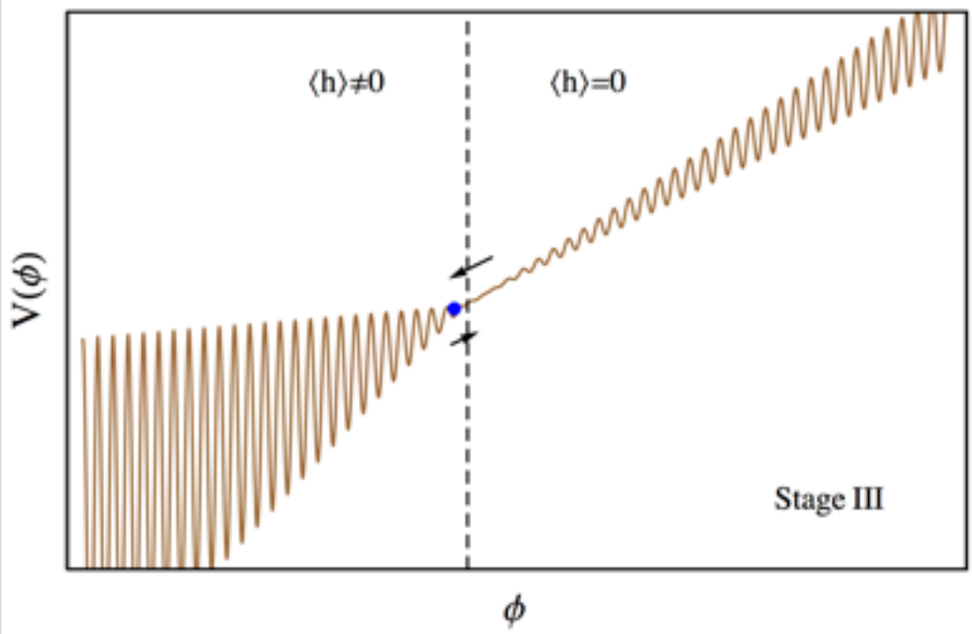


- ϕ reaches the critical value
- the Higgs mass becomes tachyonic*
- a ϕ-dependent Higgs vev turns on
- new contribution to the barrier $\quad c'_\phi = c_\phi - 1/(2\lambda)$
- change in the slope of the tracking valley in the σ-ϕ plane
- ϕ crosses/exits the barrier-free valley: $\quad c'_\phi g^2 < c_\sigma g_\sigma^2$
- the size of barrier start increasing



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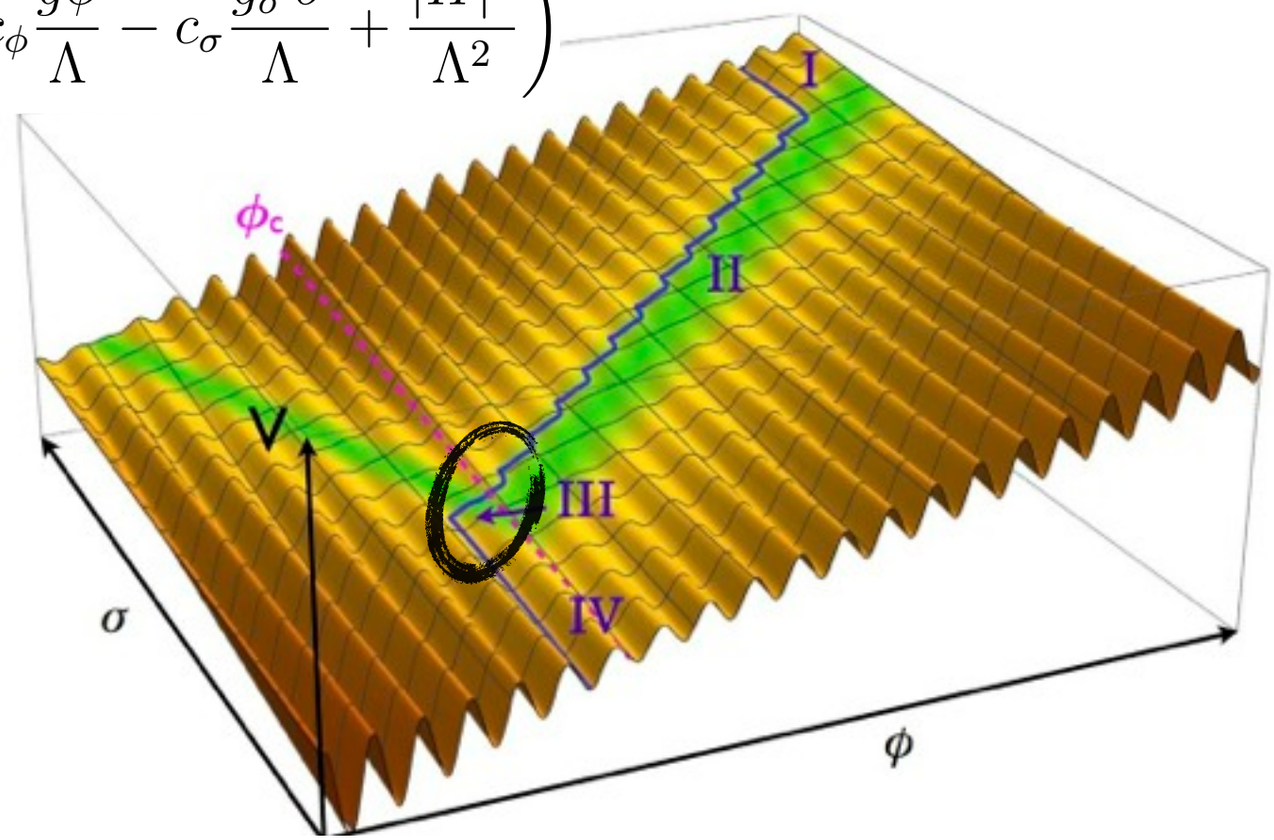

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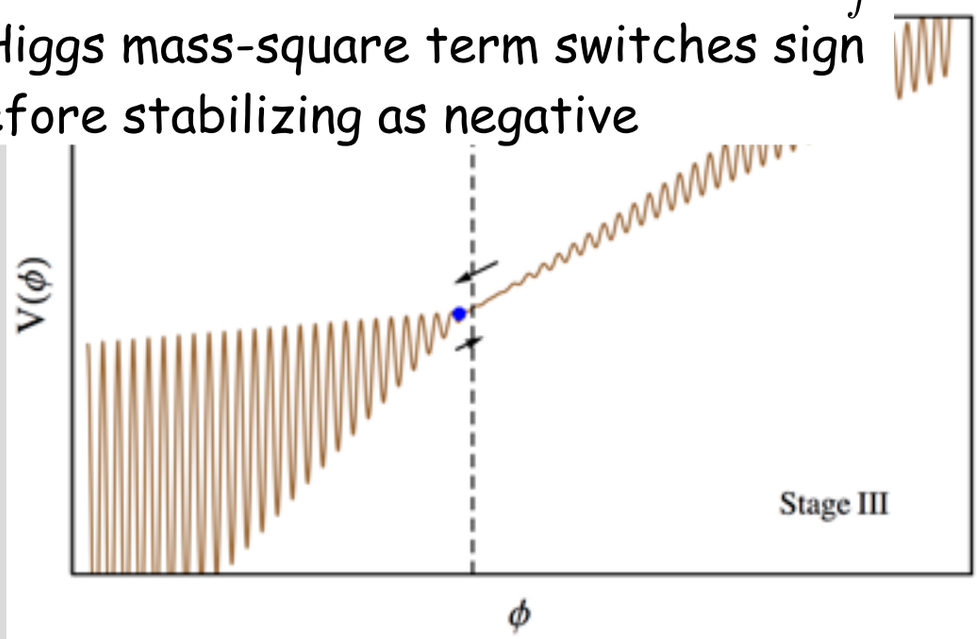
* transitory period in which the term $\epsilon\Lambda^2|H|^2\cos\frac{\phi}{f}$
makes the Higgs mass-square term switches sign
before stabilizing as negative



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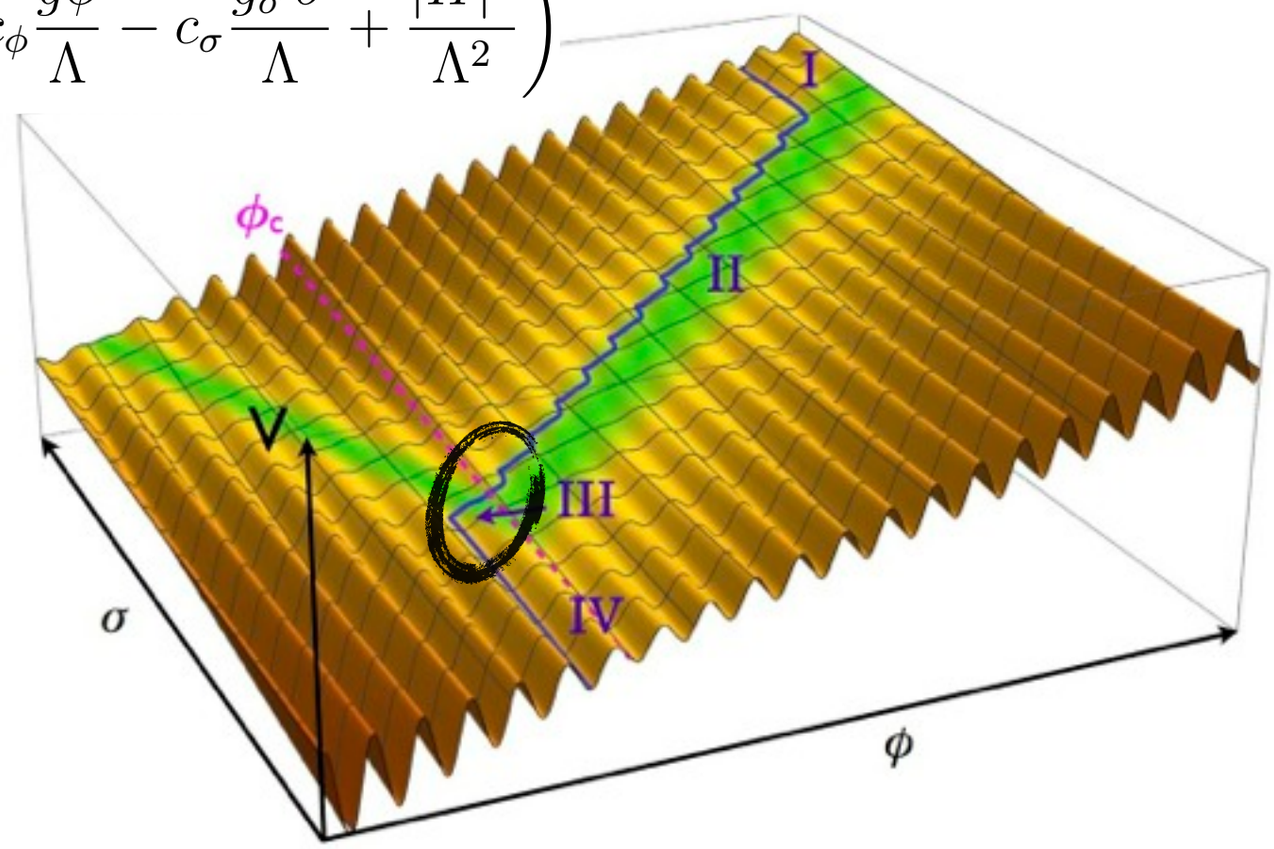

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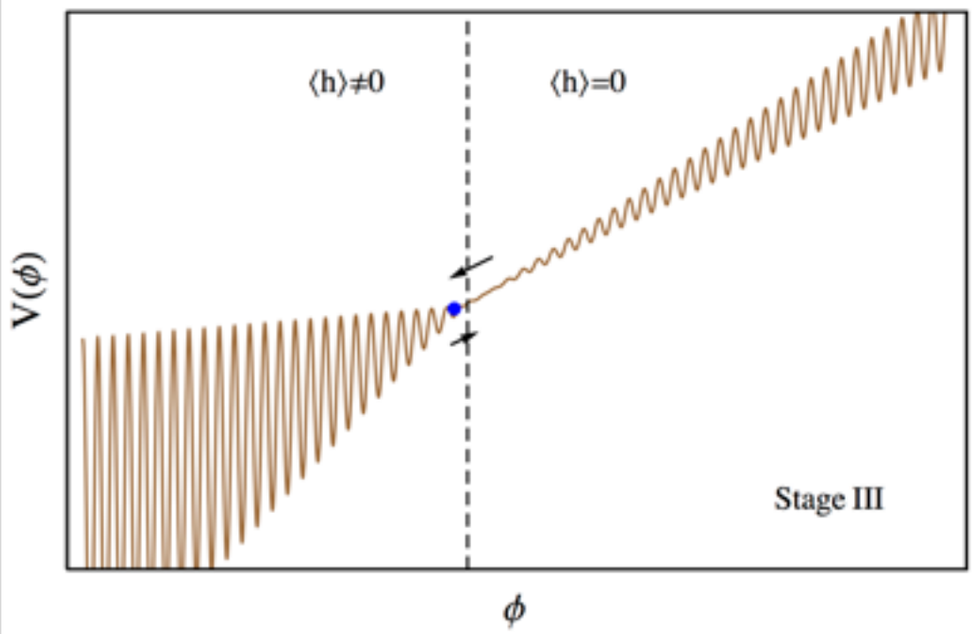

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Phase IV:

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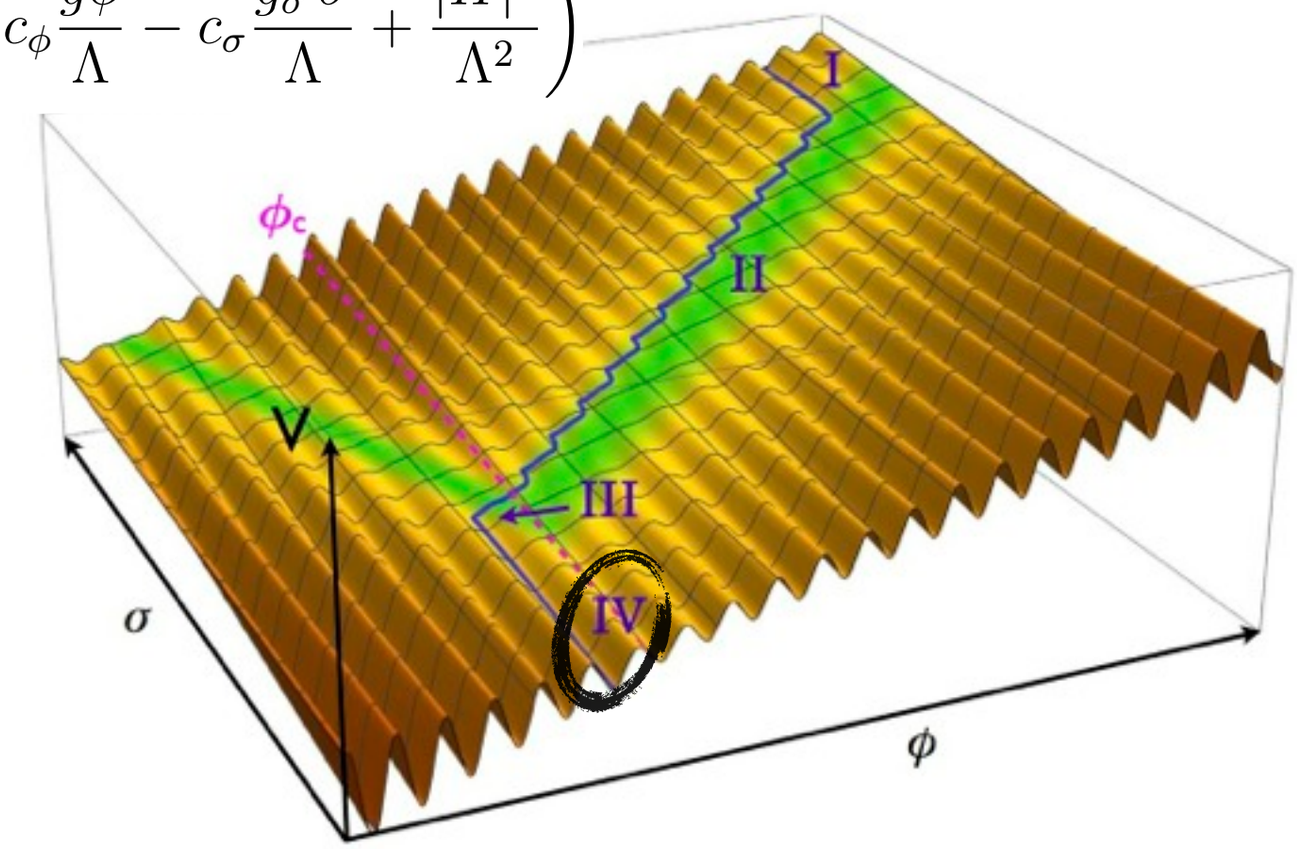

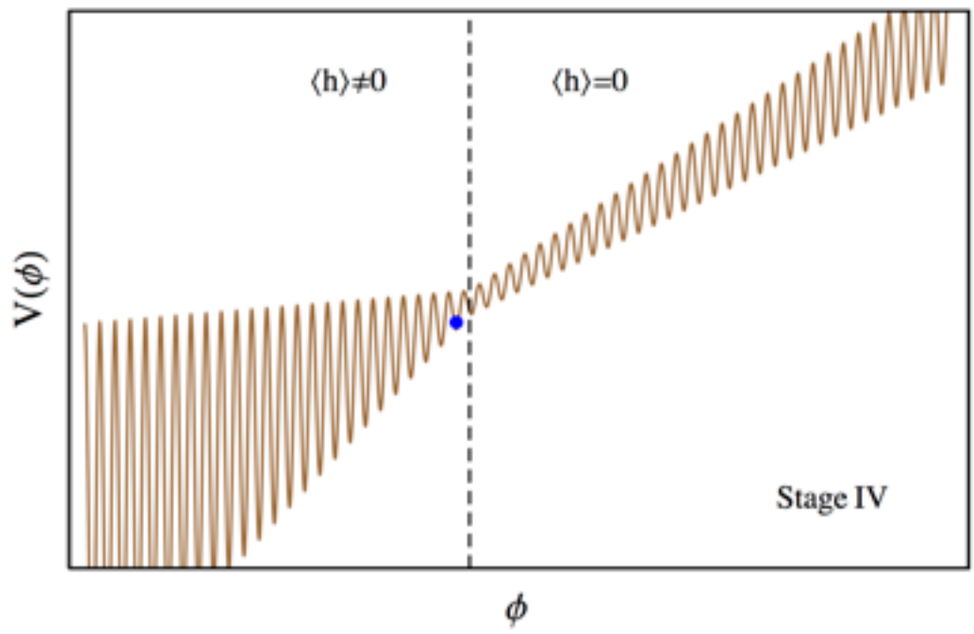

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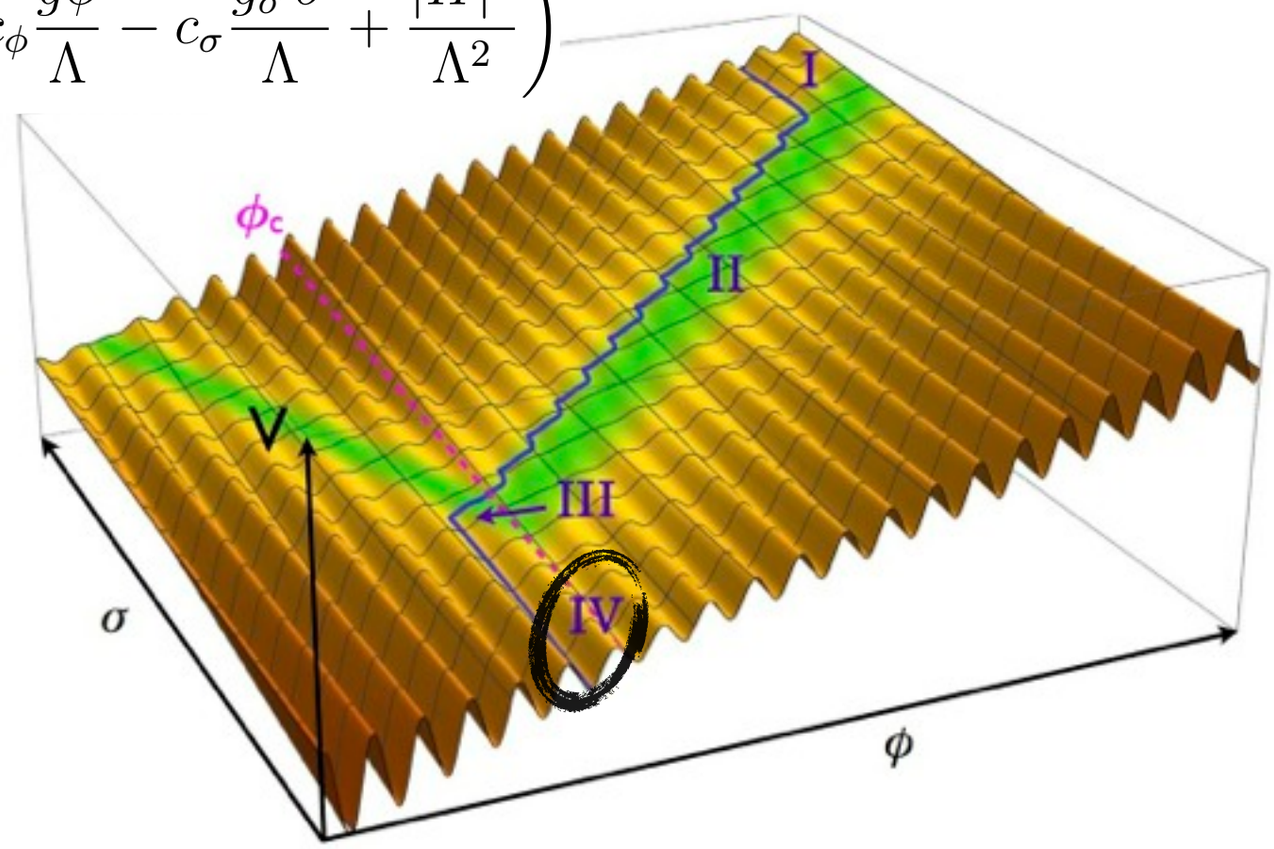
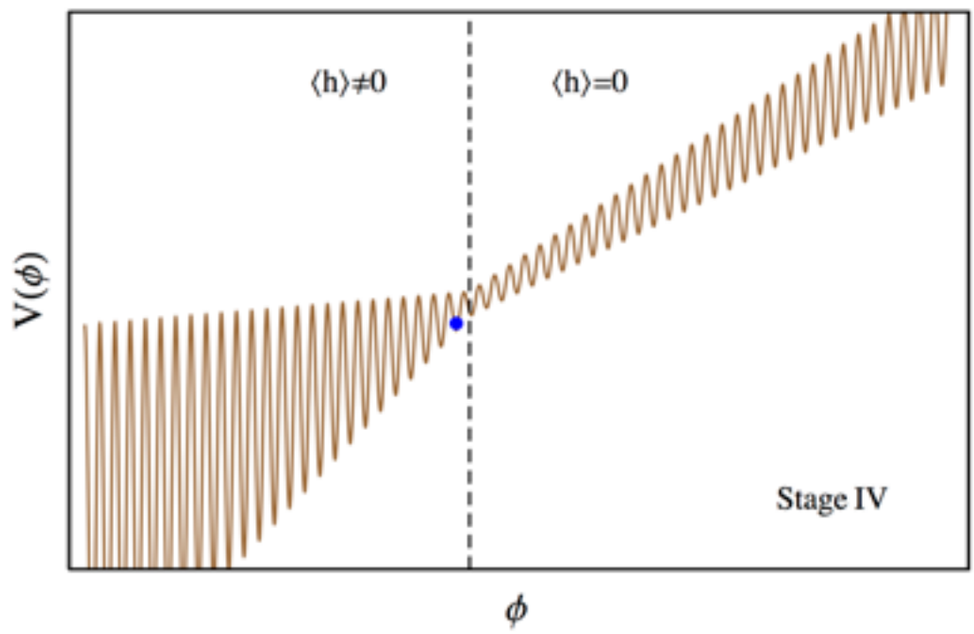


- potential barrier is large
- ϕ is stuck in a deep minimum
- σ continues rolling down until it reaches its own minimum
- all the fields are frozen



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$$\boxed{\frac{\Lambda^3}{M_{\rm Pl}^3} \lesssim g_\sigma \lesssim g \lesssim \frac{v^4}{f\Lambda^3}}$$

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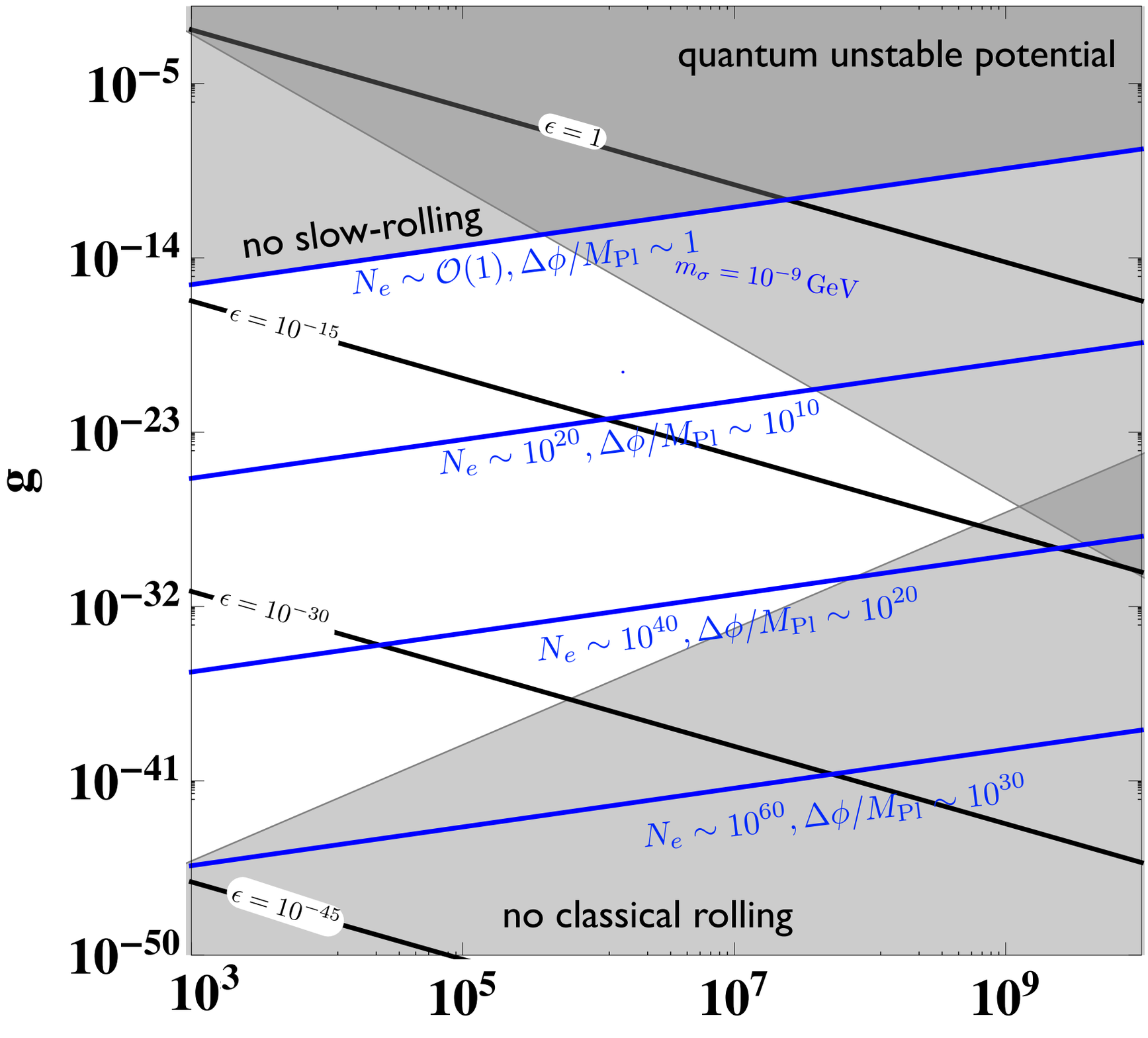
$$\frac{\Lambda^3}{M_{\rm Pl}^3} \lesssim g_\sigma \lesssim g \lesssim \frac{v^4}{f\Lambda^3} \quad \Rightarrow \quad \Lambda \lesssim \left(v^4 M_{\rm Pl}^3\right)^{1/7} \simeq 2\times 10^9\,{\rm GeV}$$

Consistency conditions



UV completion: where CHAIN can come from?

Strong sector à la QCD with vector-like elementary quarks

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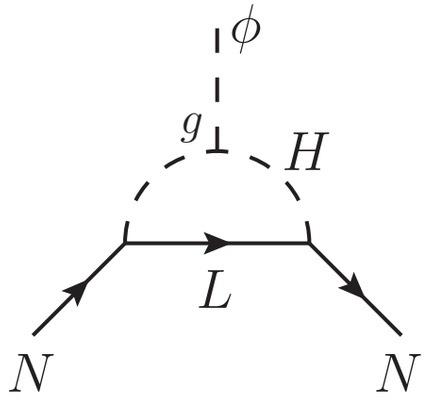

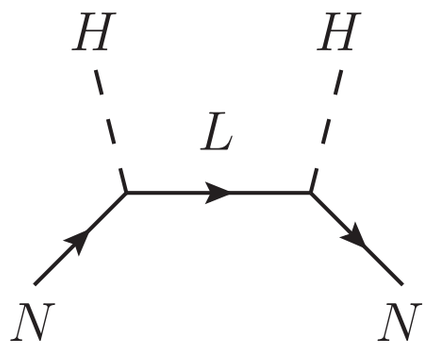

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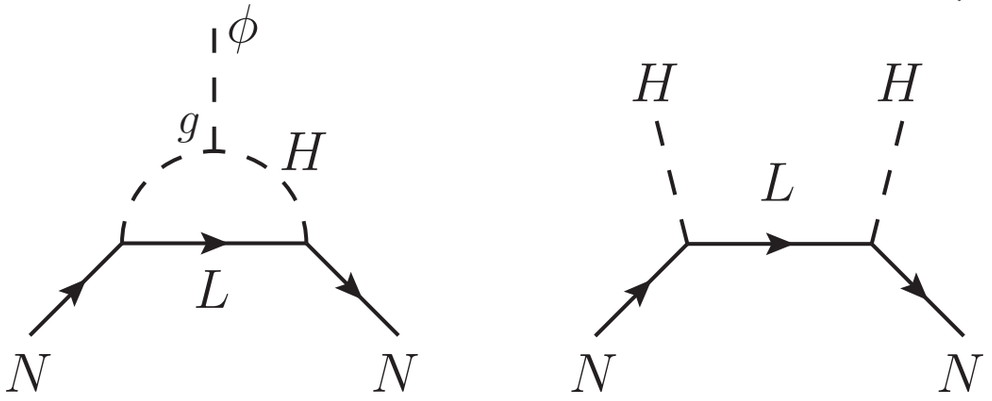

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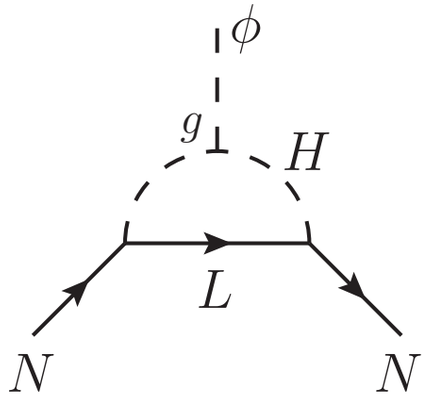

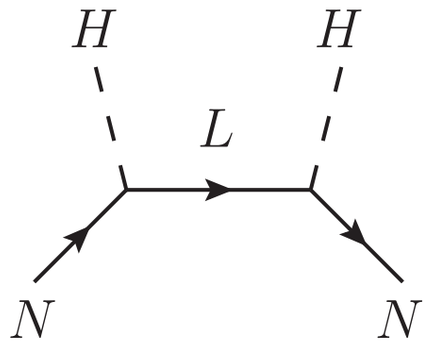

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composite baryons and mesons @ Λ but no light meson since axial U(1) is anomalous

Phenomenological signatures

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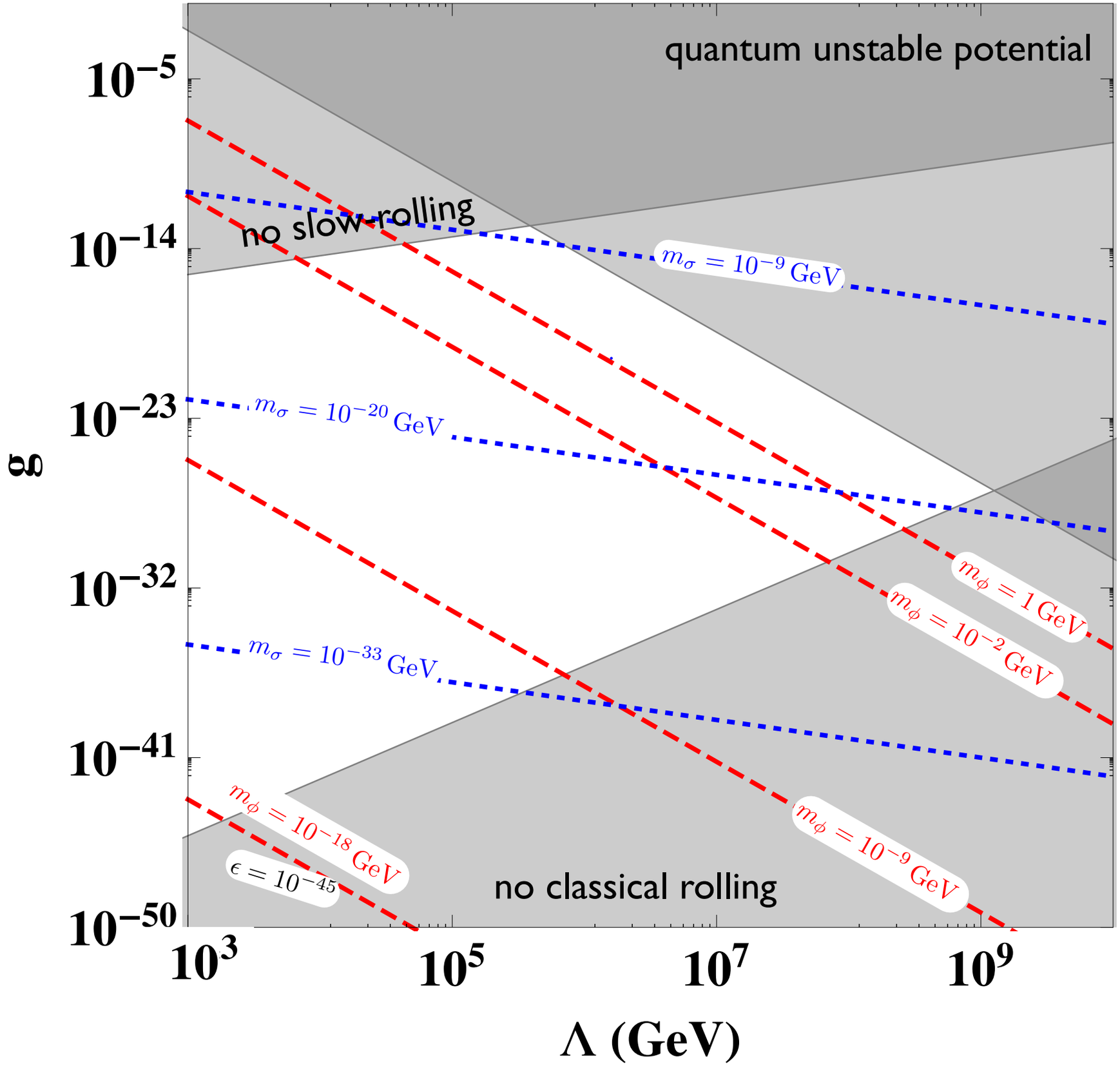
only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^{2})\,\mathrm{GeV}$$

$$m_\sigma \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

Phenomenological signatures



$g = 10 g_\sigma$

$f = \Lambda$

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interesting signatures in cosmology and possibly at SHiP

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ϕ and σ couple to SM matter via their mixing with the Higgs

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from oscillatory potential — tree-level — quantum mixing from ϕ-loop

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ϕ and σ decay to SM particles

(mostly photons in a large region of parameter space)

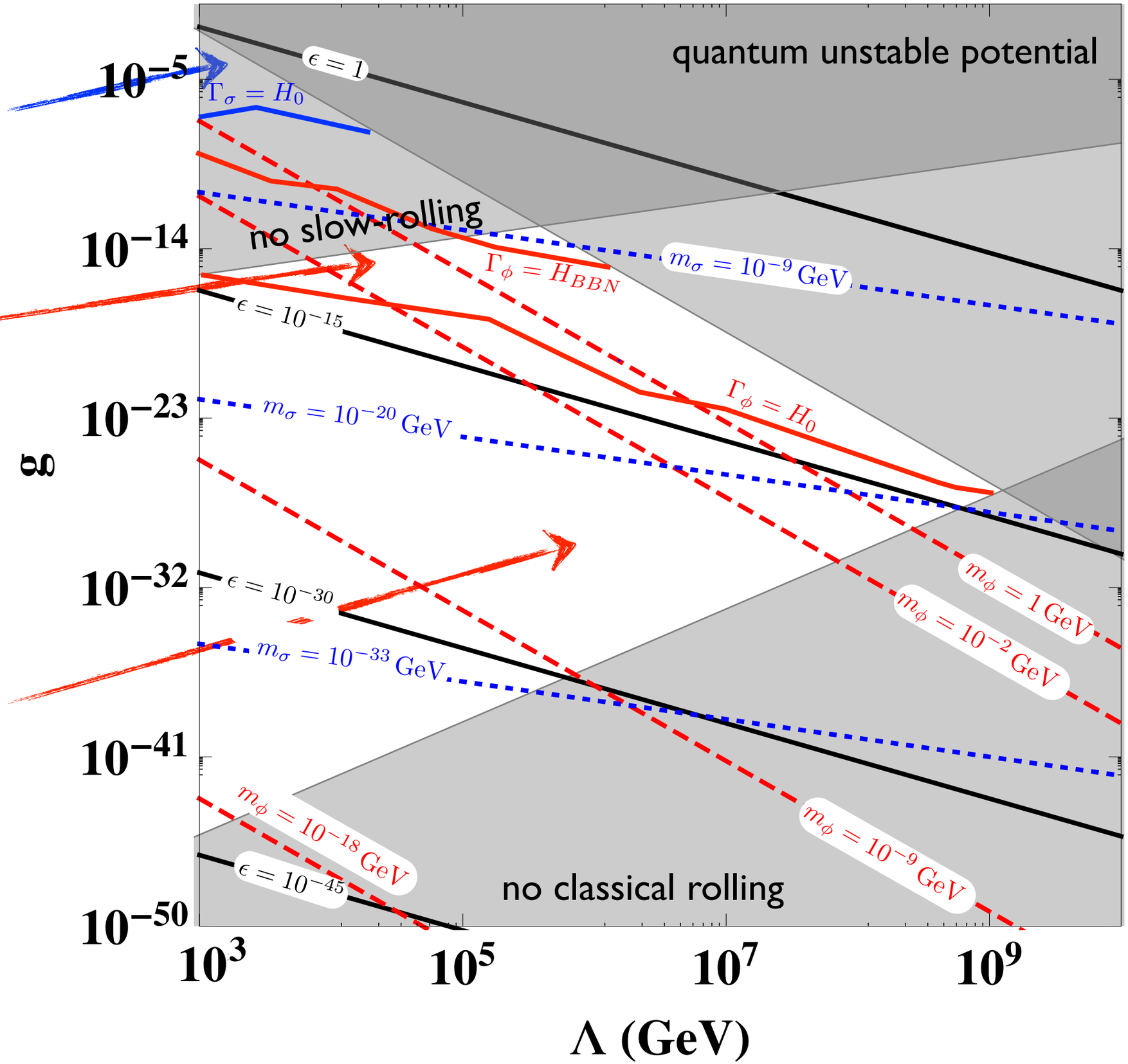
$$\Gamma_\phi \sim \theta_{\phi h}^2 \Gamma_h(m_\phi) \ , \quad \Gamma_\sigma \sim \theta_{\sigma h}^2 \Gamma_h(m_\sigma)$$

Phenomenological signatures

σ decays within the age of the Universe

ϕ decays after BBN

ϕ cosmologically stable



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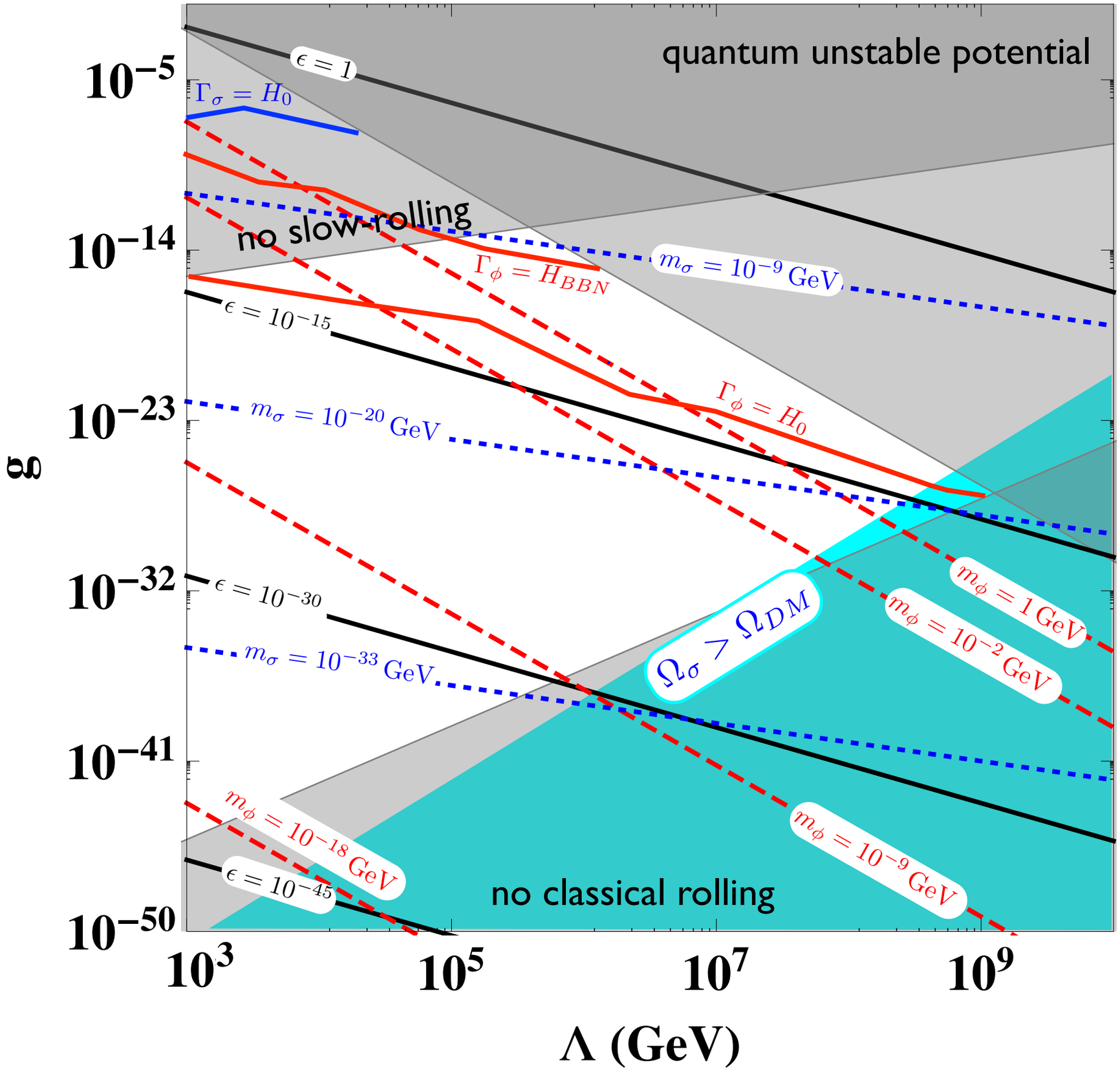
the energy density is then redshifted till today

$$\Omega_\sigma \sim \left(\frac{4\times 10^{-27}}{g_\sigma}\right)^{3/2} \left(\frac{\Lambda}{10^8\ {\rm GeV}}\right)^{13/2}$$

Ω_ϕ always very small since $m_\phi \gg m_\sigma$ i.e. $T^\phi_{\rm osc} \gg T^\sigma_{\rm osc}$

Phenomenological signatures



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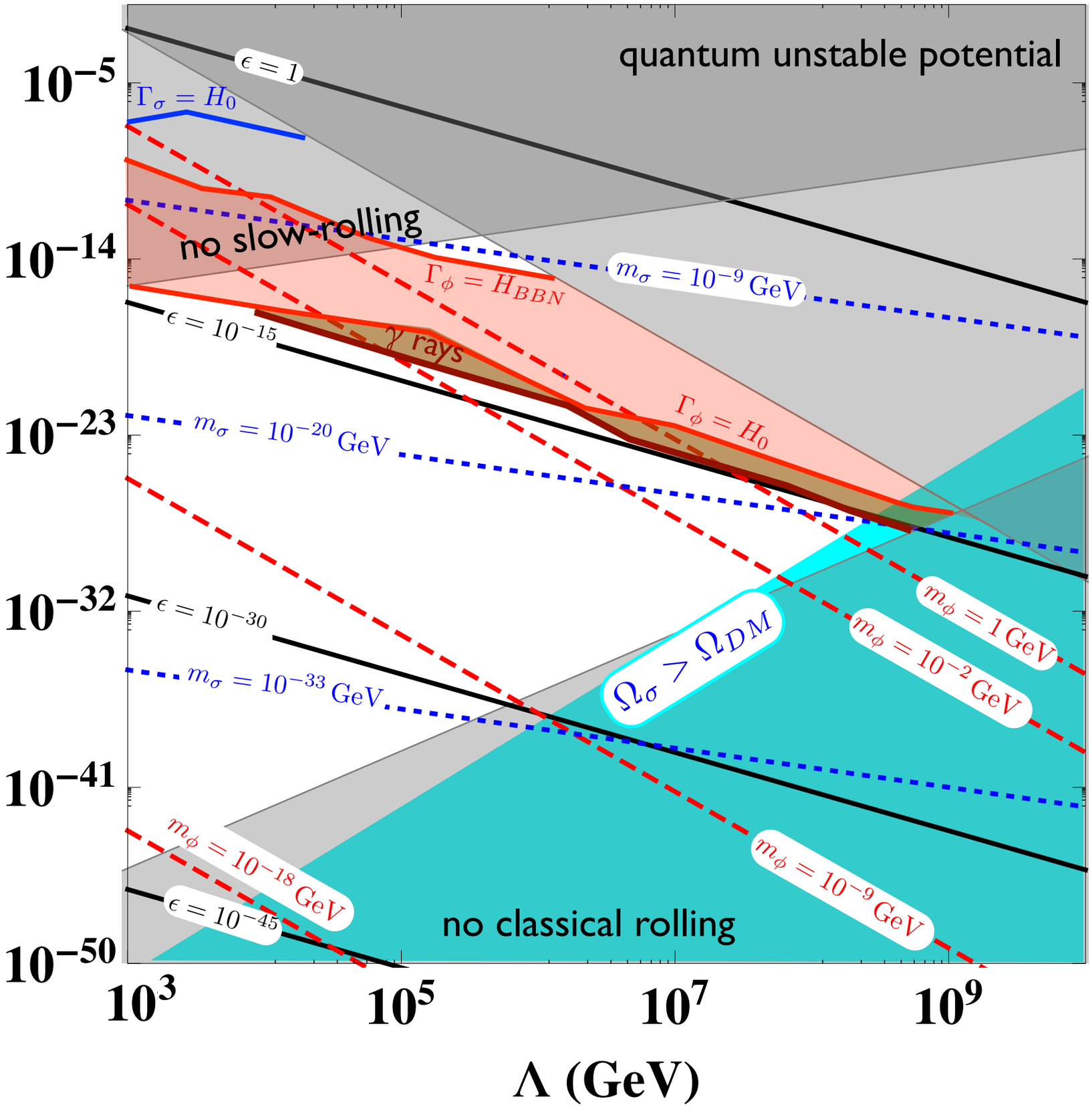
◎ BBN constraints

◎ distortions in galactic and extra galactic diffuse X-ray and γ-ray backgrounds

Phenomenological signatures



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let us think further and be prepared to be surprised