Cosmological Relaxation of the weak scale

IAS program on High Energy Physics
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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

Profound change in paradigm:

missing SM particle ⇨ tool to explore SM and venture into physics landscape beyond

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 ...

Have the theorists been lying for so many years?

Have the EXP's been too naive to believe the TH's?

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HEP future

exploration/discovery era or consolidation/measurement era?

SM breakdown

Cornell University Library

arXiv.org > physics > arXiv:1503.07735

Physics > Popular Physics

Physics in 100 Years

Frank Wilczek

(Submitted on 26 Mar 2015)

The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

The SM is not free of inadequacies:

1) Only a description of EW symmetry breaking, not an explanation
➠ What separates the EW scale from the Planck scale?

2) No place for the particle(s) that make up the cosmic DM
➠ What are the DM particles?

3) Does not explain the asymmetry matter-antimatter
➠ Are the conditions realized to allow for EW baryogenesis?

we do not understand the Matter the Universe is made from

Where and how does the SM break down?

Which machine(s) will reveal (best) this breakdown?

Naturalness (i.e. quantum stability) is the best guide to guess the scale of New Physics

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
but they require some conspiracy at different scales)

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!**

courtesy to N. Craig @ Blois '15

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

Following the arguments of Wilson, 't Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections

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

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

- 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?

Apparent fine-tunings have always pointed to new degrees of freedom

The Darwinian solution to the Hierarchy

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

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran '15

- Higgs mass-squared promoted to a field
- 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 of the dynamical system

Self-organized criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

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

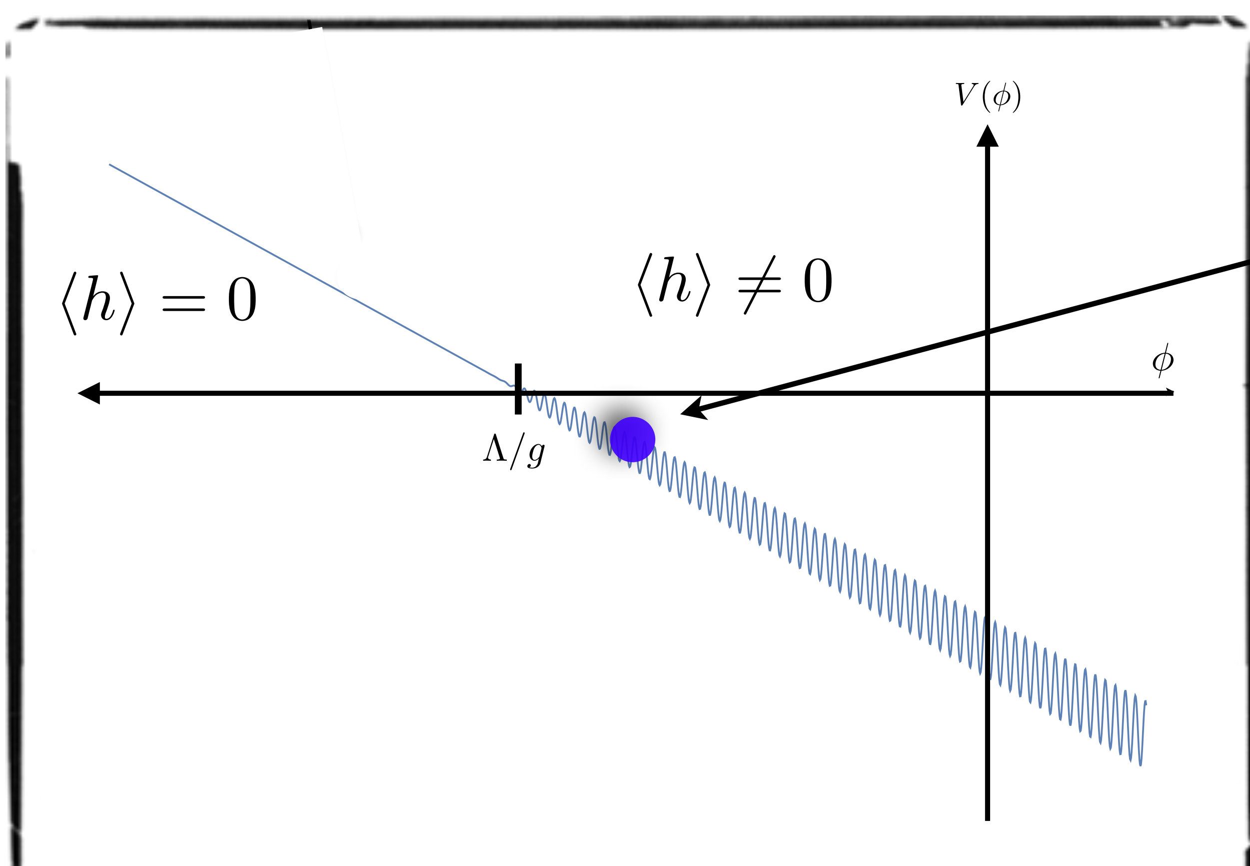
$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

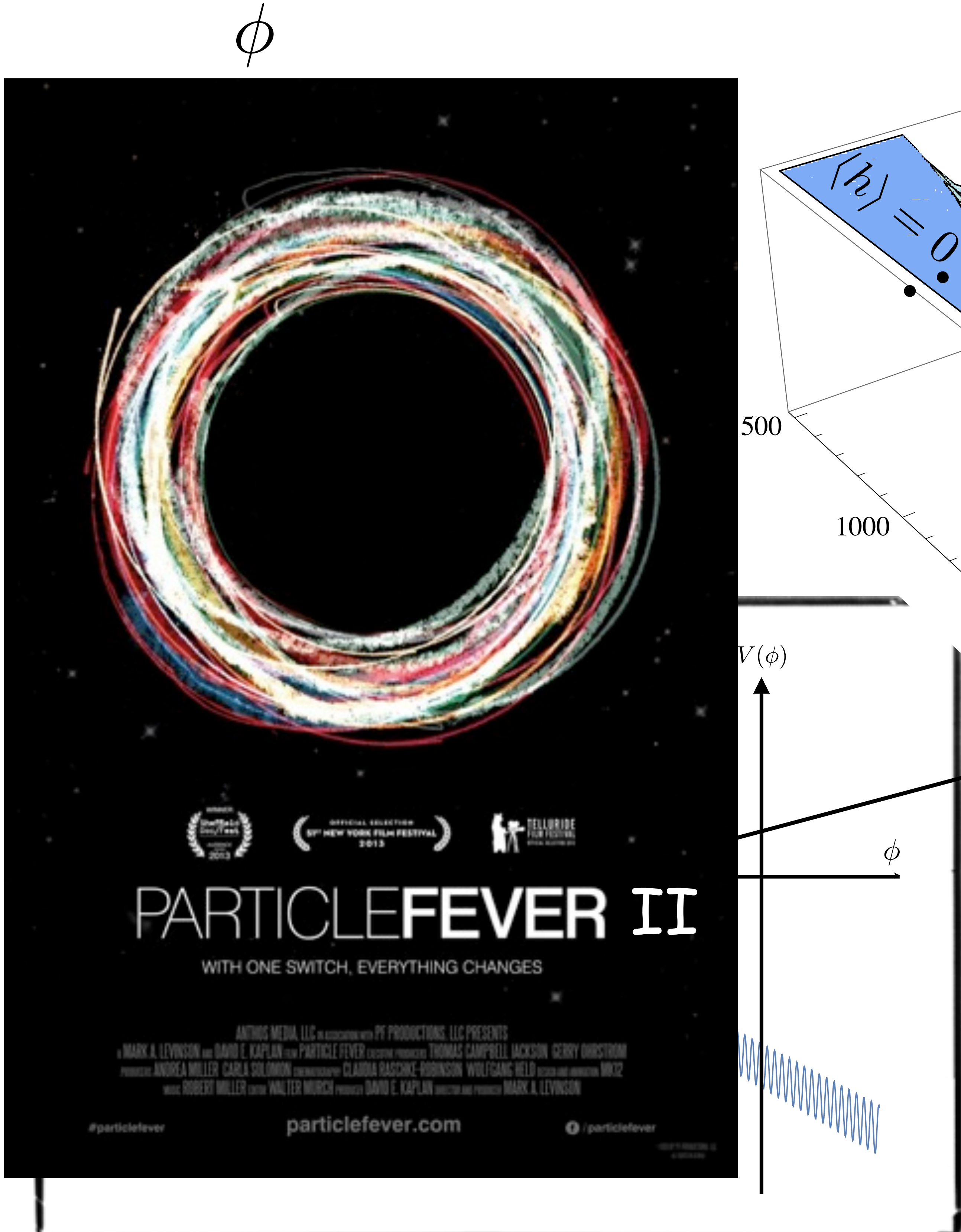
axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

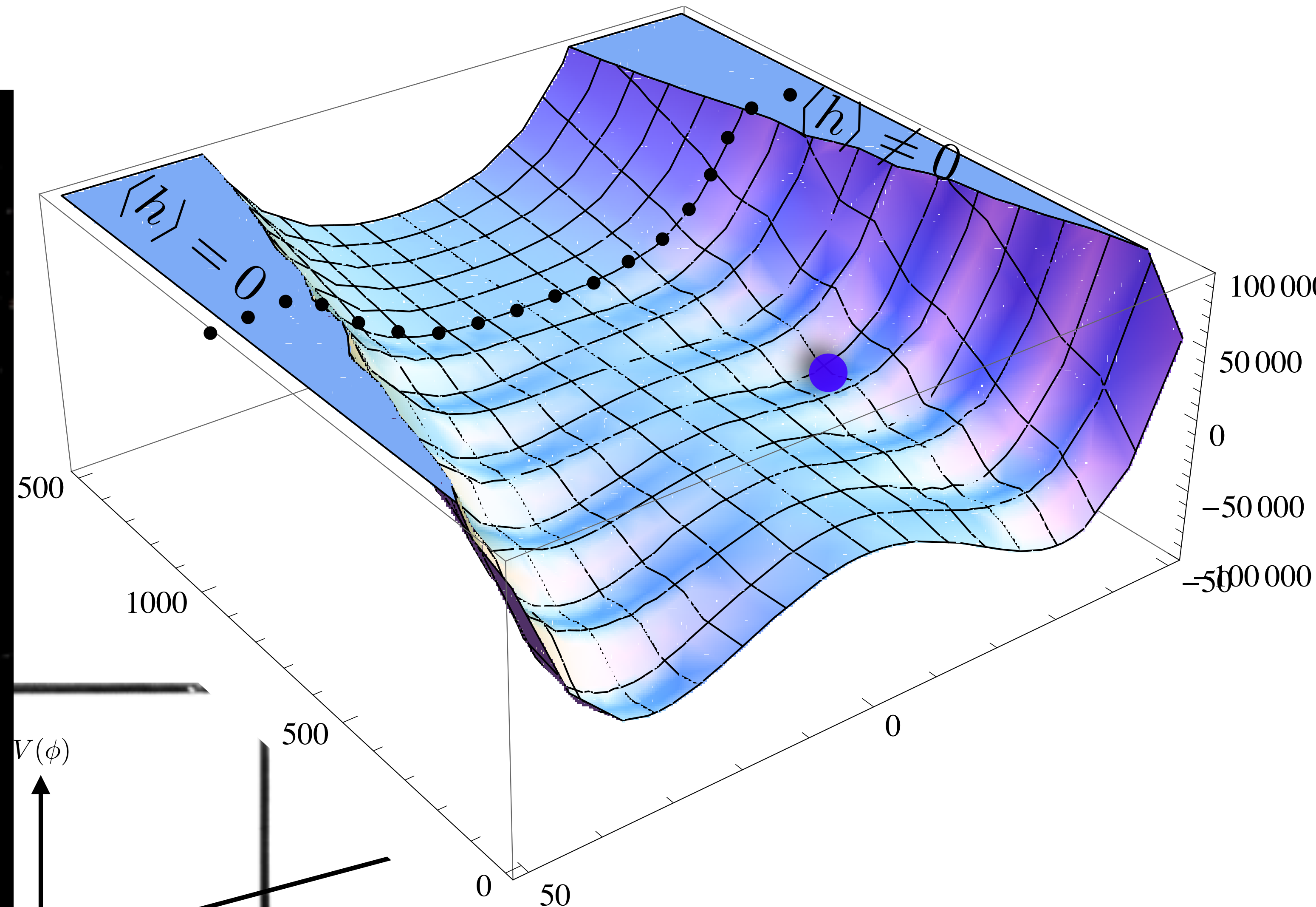
$$\Lambda^3_{\rm QCD}\, h\, \cos\frac{\phi}{f}$$



Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15



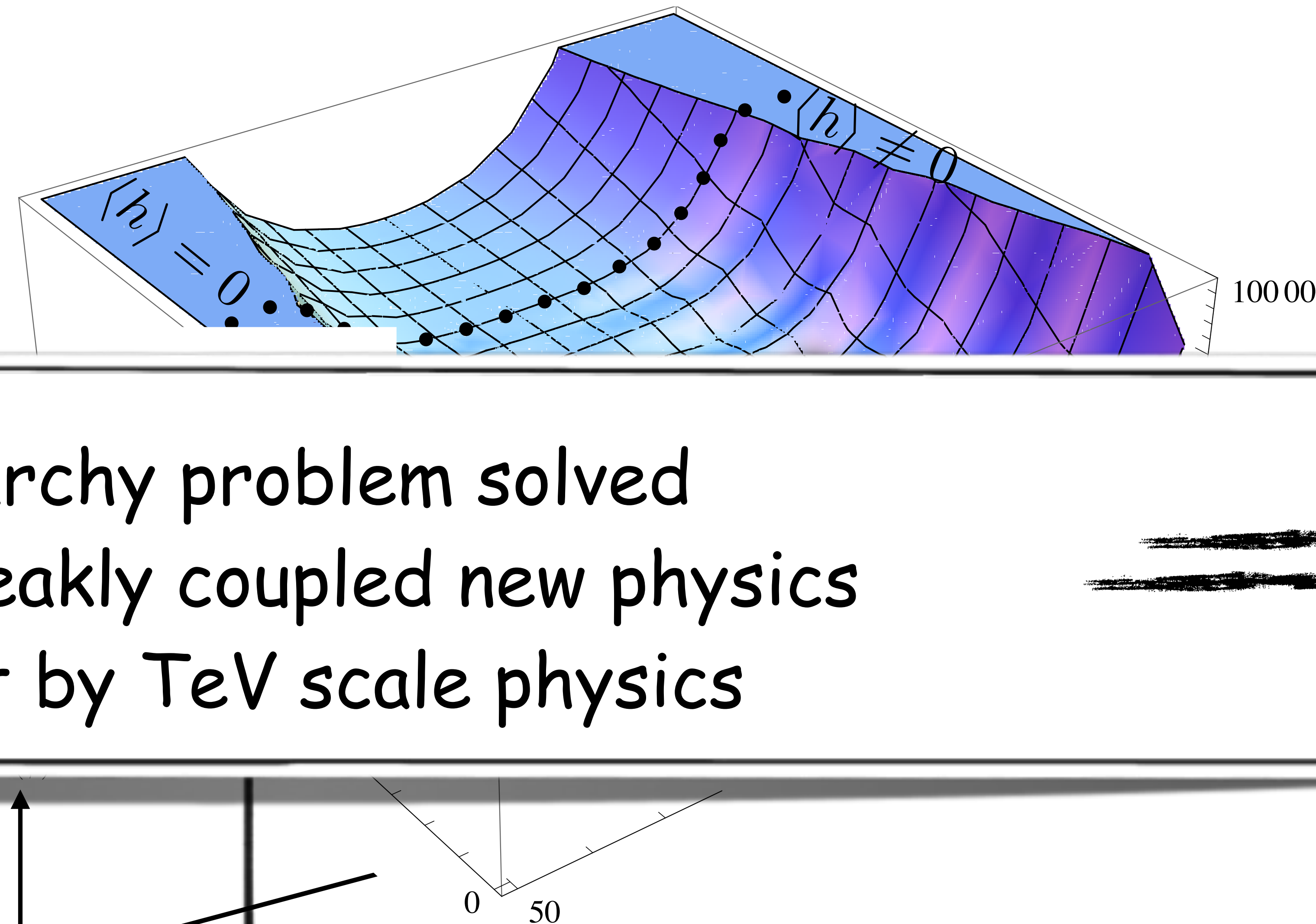


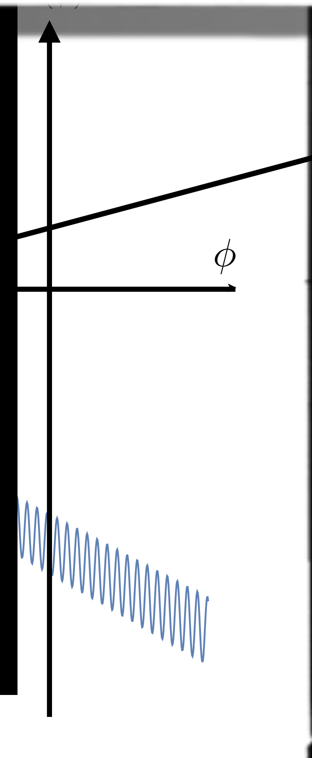
If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ





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

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

Higgs-axion cosmological relaxation

note: v<<Λ provided that g<<1. It doesn't explain why the coupling is small (that question can be postponed to higher energies) but it ensures that the solution is stable under quantum correction.

- Higgs vev stops cosmological rolling

$$\Lambda_{\rm QCD}^3 \frac{v}{f} \sim \frac{\partial}{\partial \phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$$

- Slow rolling: $H_I > \frac{\Lambda^2}{M_P}$ ensures that the energy density stored in ϕ does not affect inflation

- Classical rolling: $H_I^3 < g\Lambda^3$

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

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

Important issue: $\theta_{QCD} \sim 1 \gg 10^{-10}$. Can be solved but Λ < 30 TeV

Classifying relaxing Lagrangians...

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

- n=1: need another source of EWSB
  - QCD condensate <qq>~ Λ_{QCD}
  - new strongly-coupled sector à la Technicolor
    - ⊩ new physics @ TeV, coincidence problem? ⊣
- 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

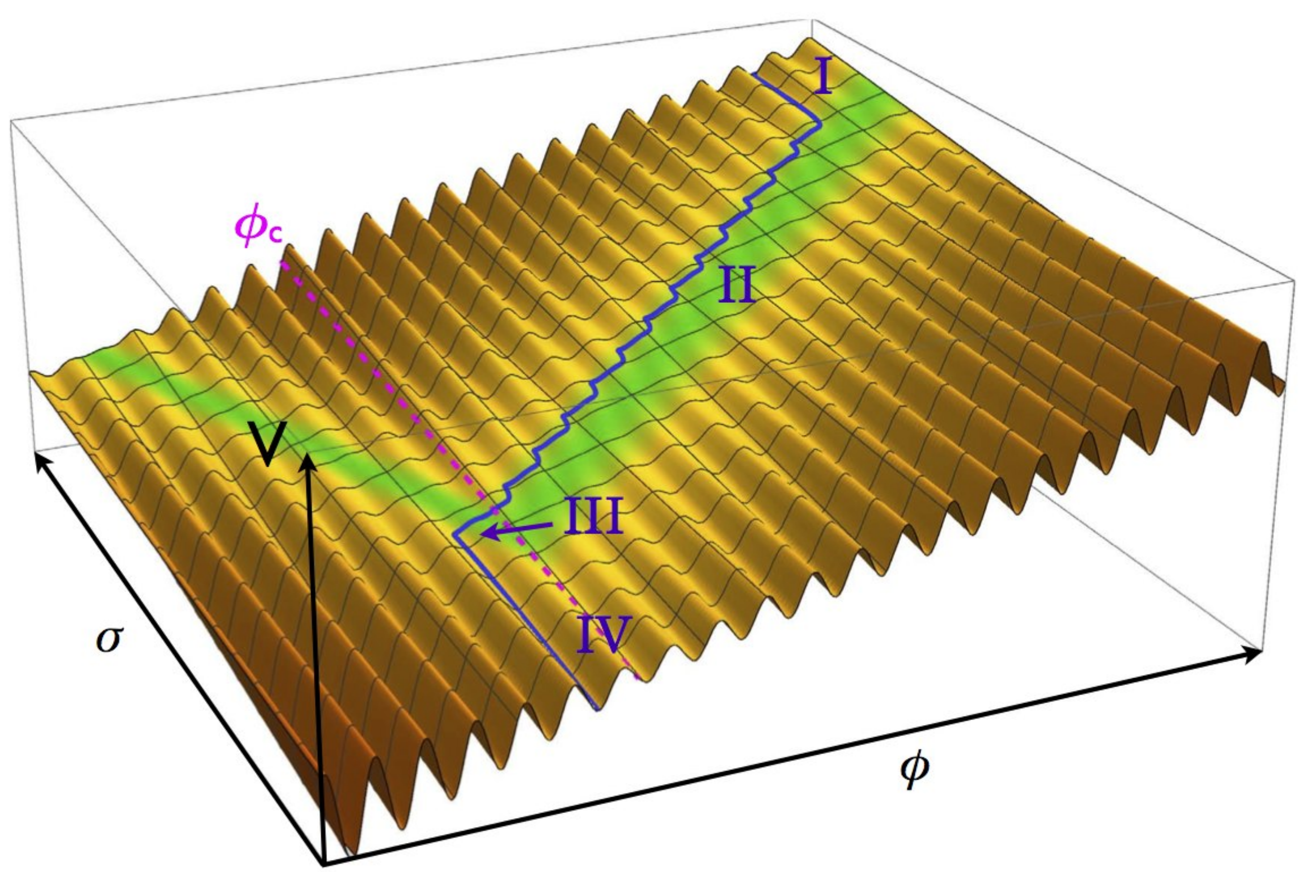
$$V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right) - \Lambda^2\left(\alpha-\frac{g\phi}{\Lambda}\right)|H|^2 + \frac{1}{2}\lambda|H|^4 + A(\phi,\sigma,H)\cos(\phi/f)$$

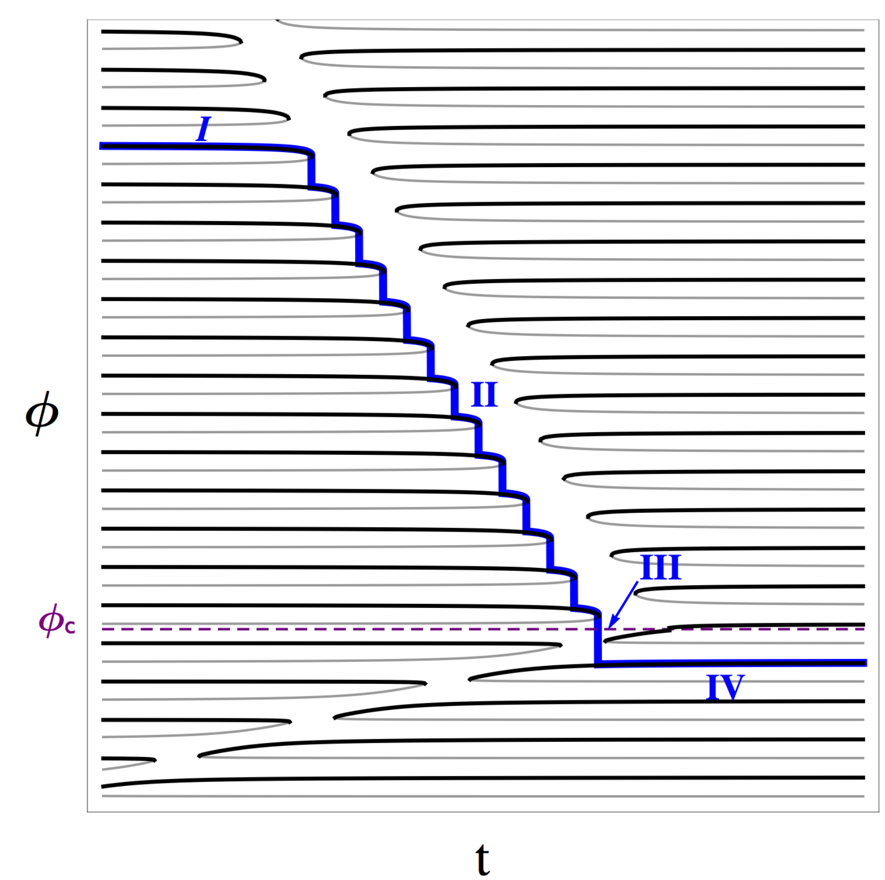
$$A(\phi,\sigma,H) \equiv \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2}\right)$$

quantum generated new terms from the $|H|^2\cos(\phi/f)$ term

the new interaction that saves our day

original relaxion-type term





Same problem, same solution?

EW SCALE AS COSMOLOGICAL ERRATIC

courtesy to JR Espinosa

okotoks glacial erratic,
Alberta, Canada

Unnatural large rocks differing in composition from the typical surrounding ones

Same problem, same solution?

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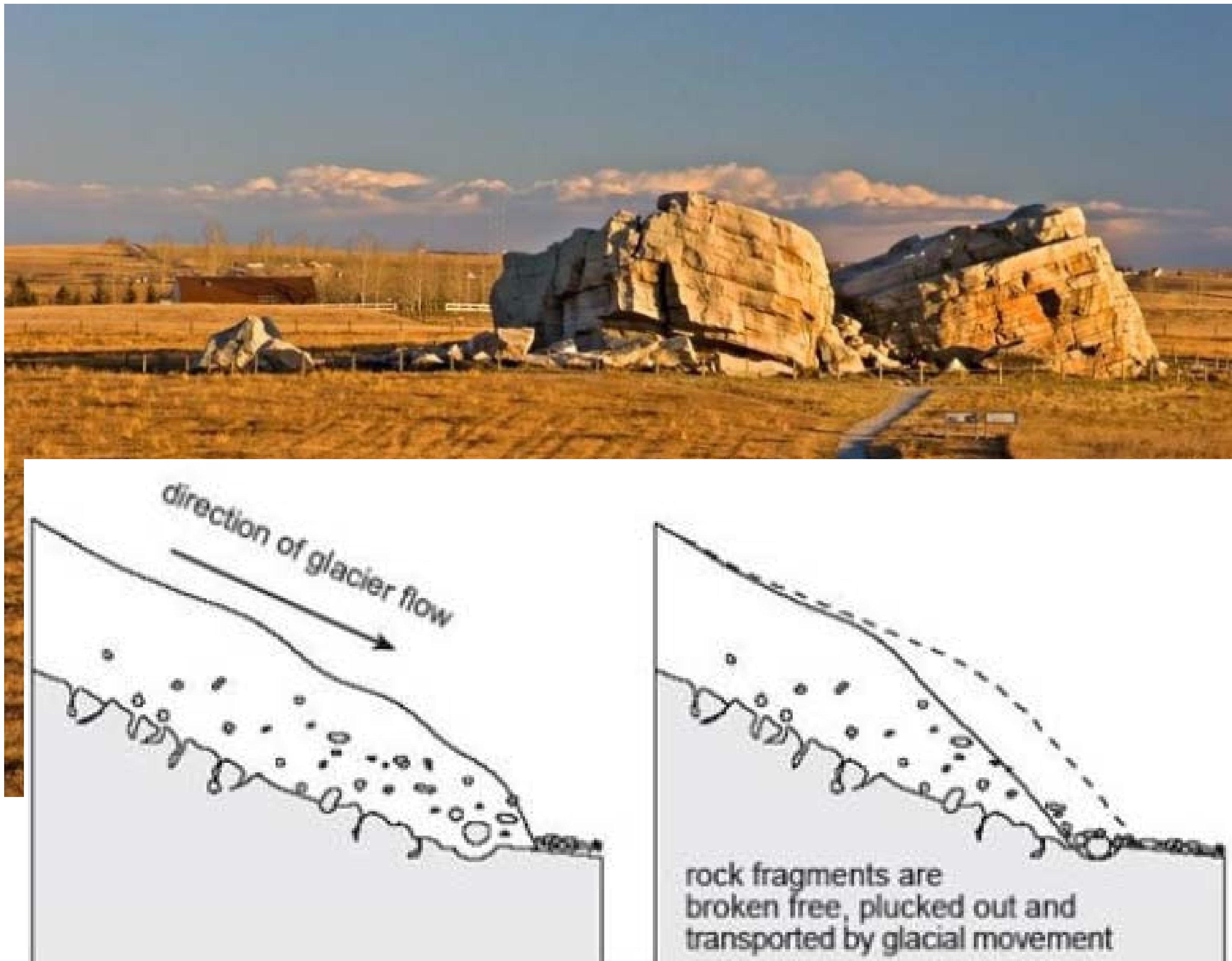


atic,

Unnatural large rocks differing in composition from the typical surrounding ones

Standard geological history:

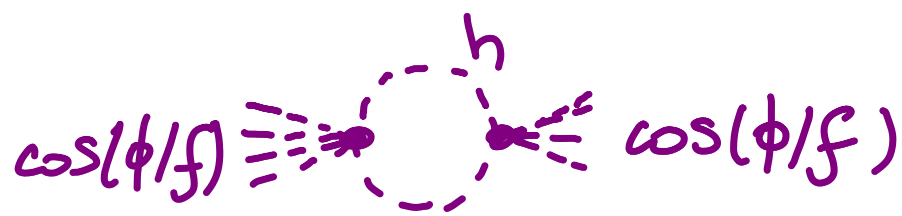
they were transported by ancient glaciers over hundreds of kilometers

Consistency conditions

- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

Ex.



$\epsilon^2\Lambda^4\cos^2(\phi/f)$

should be subleading compared to $\epsilon\Lambda^2 h^2\cos(\phi/f)$

Requires $\epsilon \lesssim v^2/\Lambda^2$

courtesy to JR Espinosa

Consistency conditions

- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

  ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

- Higgs vev stops cosmological rolling $\quad \dfrac{\epsilon\Lambda^2 v^2}{f} \sim \dfrac{\partial}{\partial\phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$

- Slow rolling: $\quad H_I > \dfrac{\Lambda^2}{M_P}$ $\quad$ ensures that the energy density stored in σ and ϕ does not affect inflation

- Classical rolling: $H_I^3 < g\Lambda^3$

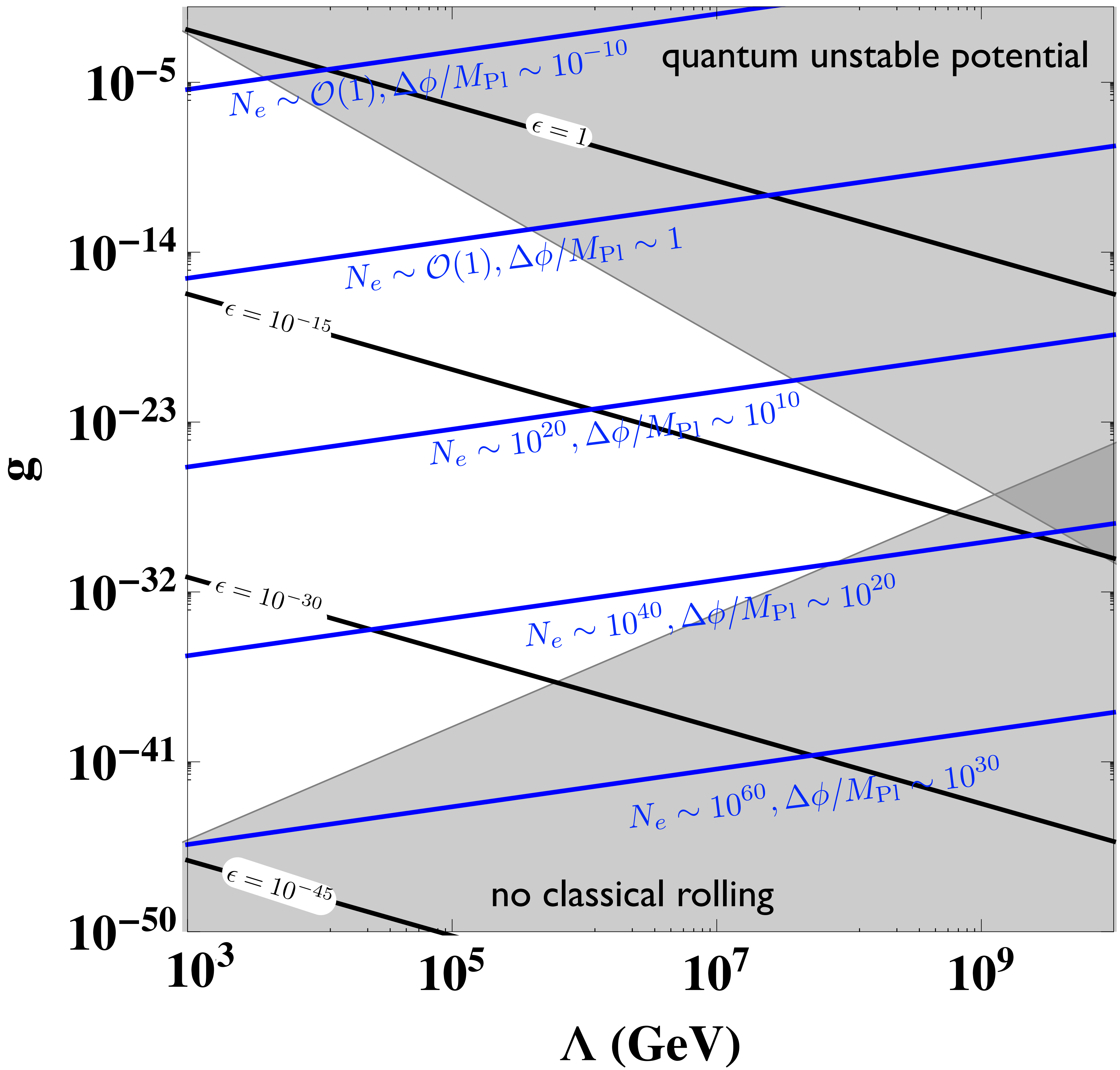
- ϕ tracks σ in the barrier-free valley before EWSB: $c_\phi g^2 > c_\sigma g_\sigma^2$

- ϕ exits the barrier-free valley after EWSB: $(c_\phi - \frac{1}{2\lambda})g^2 < c_\sigma g_\sigma^2$

- large field excursions: $\Delta\phi, \Delta\sigma > \Lambda/g$ $\quad$ to ensure that the Higgs mass scans values Λ from to the weak scale

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

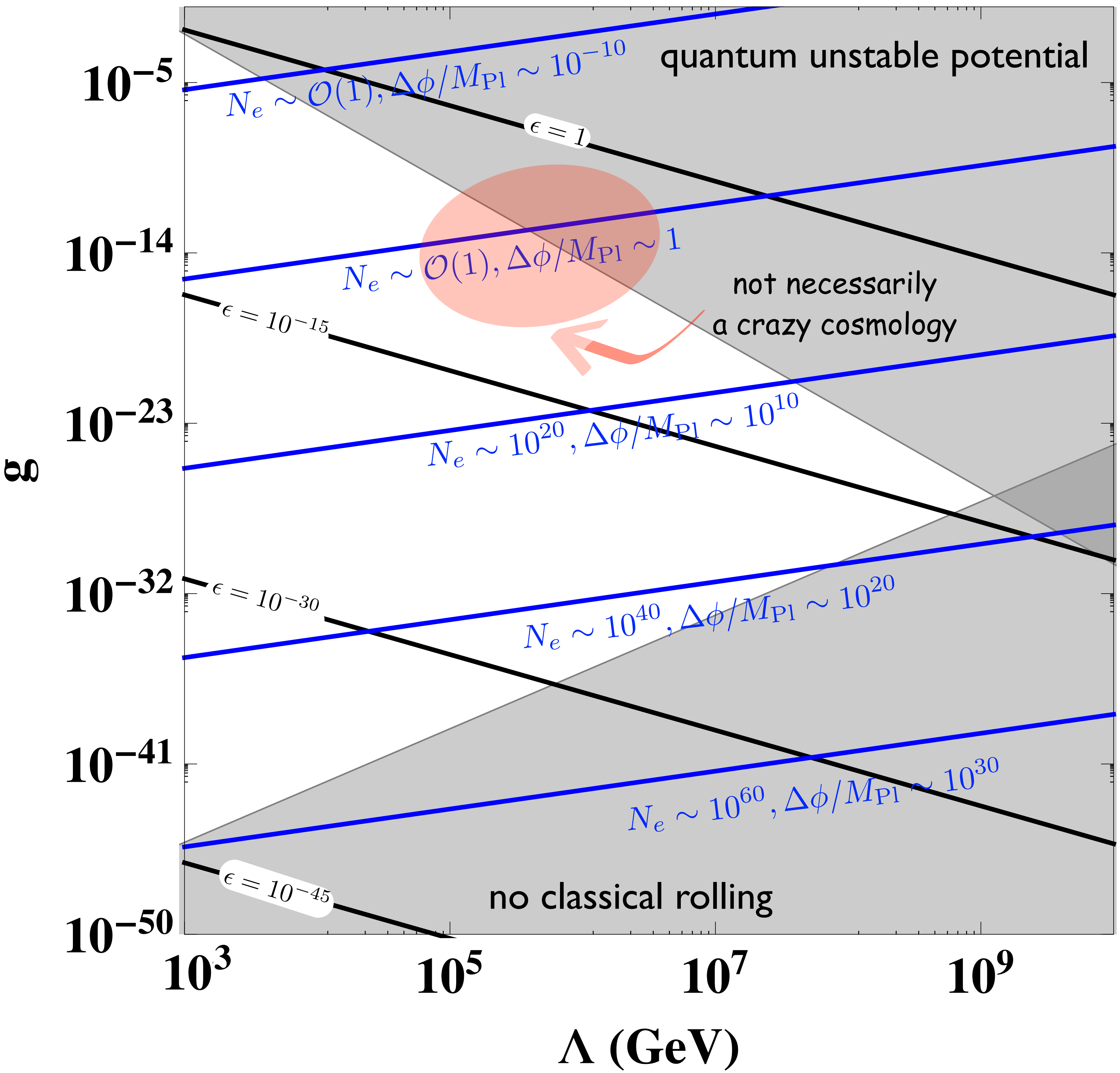
Consistency conditions



$g = 10 g_\sigma$

$f = \Lambda$

Consistency conditions



$g = 10 g_\sigma$

$f = \Lambda$

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

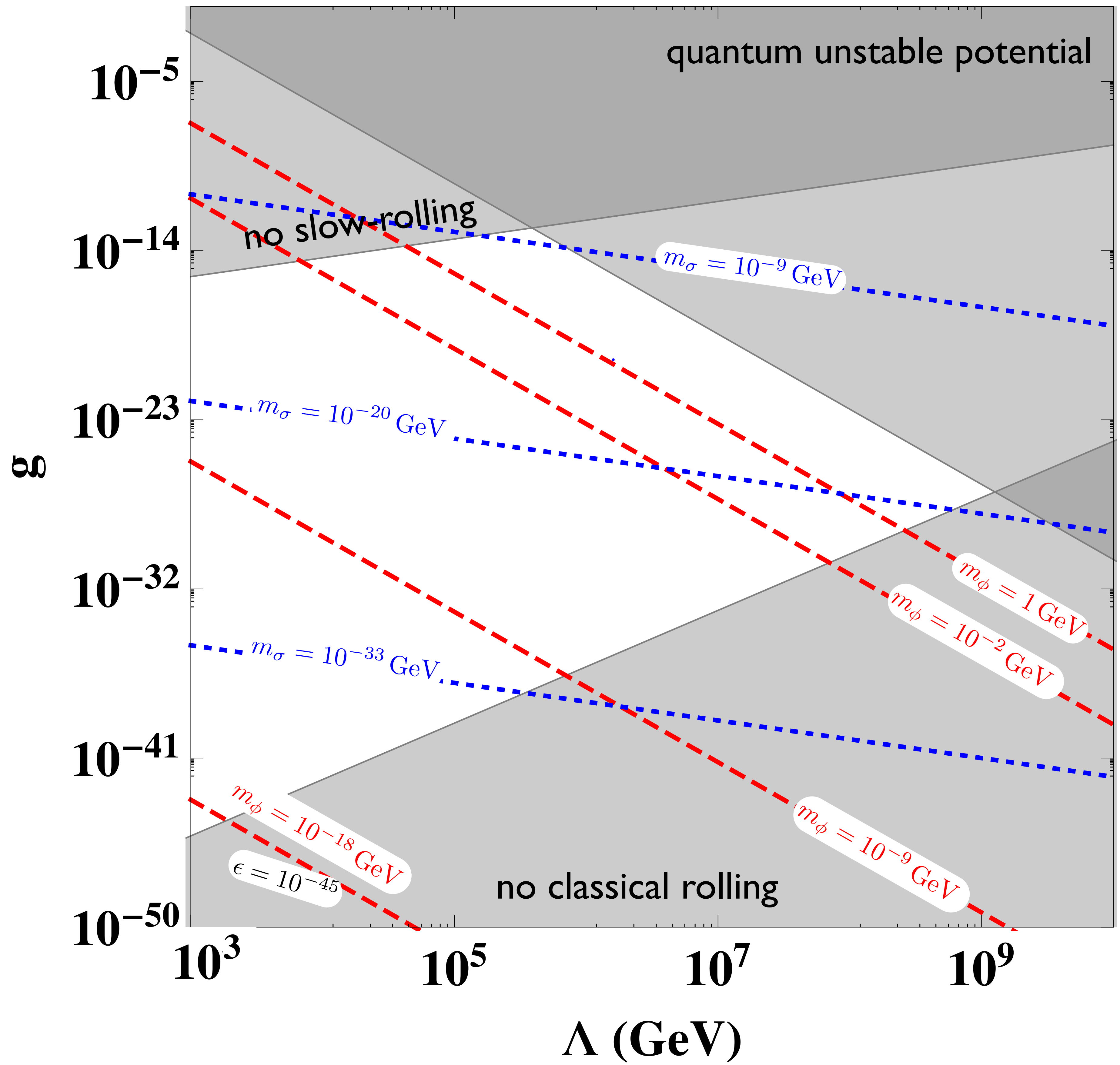
only BSM physics below Λ

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



$g = 10 g_\sigma$

$f = \Lambda$

Phenomenological signatures

interesting signatures in cosmology and possibly at SHiP

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

$$\theta_{\phi h} \sim \frac{g\Lambda v}{m_h^2}\,, \quad \theta_{\sigma\phi} \sim \frac{g_\sigma f v^2}{\Lambda^3}\,, \quad \theta_{\sigma h} \sim \mathrm{Max}\left\{\theta_{\sigma\phi}\theta_{\phi h}\,,\ \frac{g^2}{16\pi^2}\frac{g_\sigma \Lambda^7}{f^2 v^3 m_h^2}\right\}$$

from oscillatory potential

tree-level

quantum mixing from ϕ-loop

unsuppressed quartic interaction with the Higgs: $\phi\phi hh: \ \epsilon\Lambda^2/f^2$

ϕ and σ decay to SM particles

(mostly photons in a large region of parameter space)

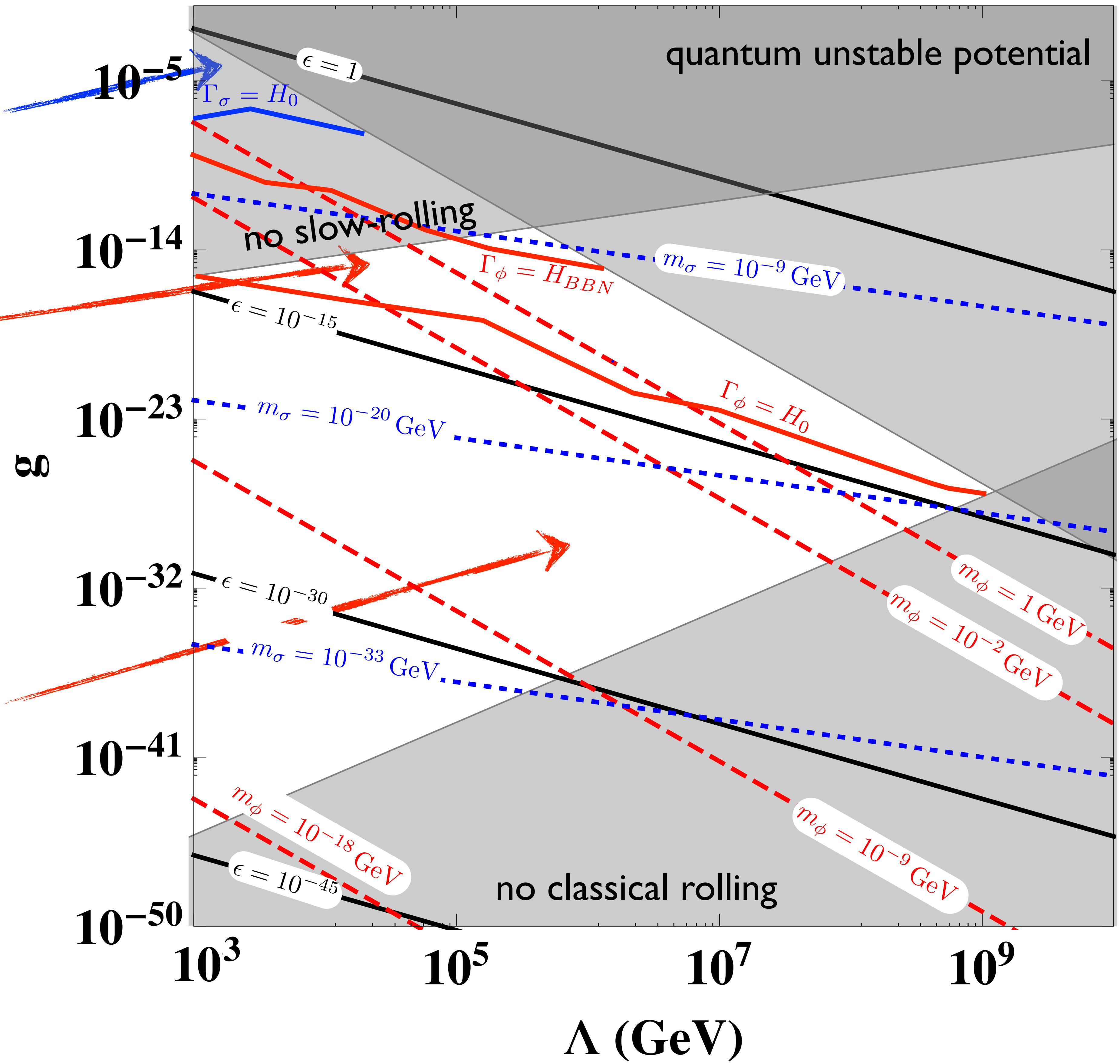
$$\Gamma_\phi \sim \theta_{\phi h}^2 \Gamma_h(m_\phi)\,, \quad \Gamma_\sigma \sim \theta_{\sigma h}^2 \Gamma_h(m_\sigma)$$

Phenomenological signatures

σ decays within the age of the Universe

ϕ decays after BBN

ϕ cosmologically stable



Phenomenological signatures

vacuum misalignment: (after reheating)
quantum spreading makes the scalars oscillate around their minima

$$\Delta\sigma \sim \Delta\phi \sim \sqrt{N_e} H_I$$

the energy stored in these field oscillations behave like cold DM

$$\rho^{\sigma}_{\rm ini} \sim m_\sigma^2 (\Delta\sigma)^2_{\rm ini} \sim H_I^4 \qquad\qquad \rho^{\phi}_{\rm ini} \sim H_I^4$$

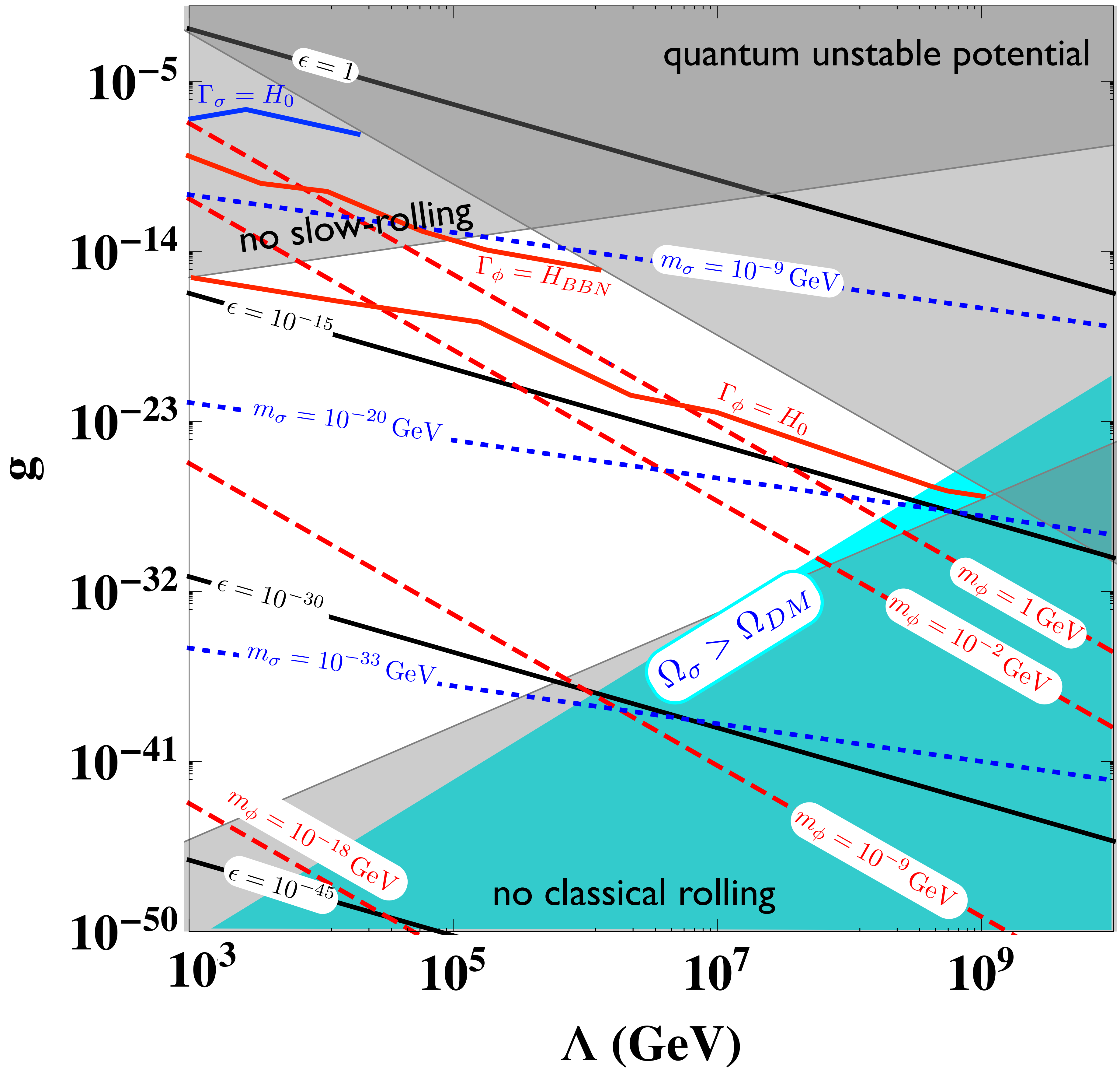
the oscillations start when H~mi i.e. $T^i_{\rm osc} \sim \sqrt{m_i M_{\rm Pl}}$

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



Phenomenological signatures

ϕ thermal production via interaction with the Higgs

$$h + h \to \phi + \phi \qquad \text{or} \qquad SM + SM \to h^{(*)} \to \phi + \phi$$

single production is subdominant since linear interactions are suppressed by small mixing angle

ϕ almost never in thermal equilibrium (except above Γ_{BBN} line)

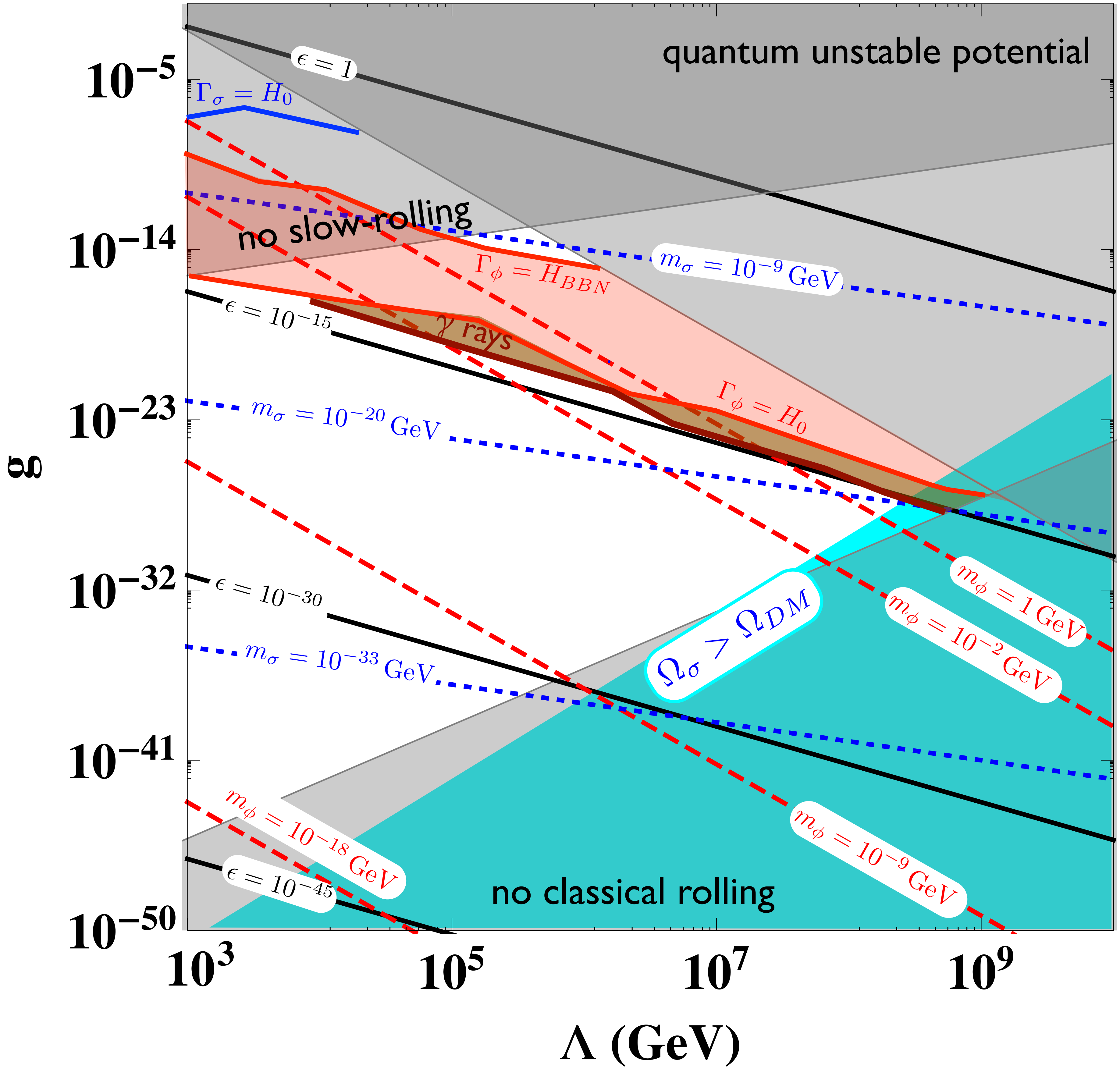
number density is obtained from Boltzmann equation

$$\frac{dn_\phi}{dt} + 3Hn_\phi = -\langle \sigma_A \mathrm{v} \rangle (n_\phi^2 - n_{\phi,eq}^2) \quad \Rightarrow \quad Y_\phi \sim 10^{-4} \epsilon^2 \frac{\Lambda^4}{f^4} \frac{M_{\text{Pl}}}{m_h}$$

◎ BBN constraints

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

Phenomenological signatures



Some open questions

- large field excursions ↪ monodromy? McAllister, Schwaller, Servant, Westphal ‘in progress
  Ibanez, Montero, Uranga, Valenzuela ’15
- non-periodic potential for an axion-like particle?
  Gupta, Komargodski, Perez, Ubaldi ’15
- hierarchy of decay constants: F>>f is ~ to non-periodid potential
  Choi, Im ’15 Kaplan, Rattazzi ’15
- eternal inflation vs classical evolution?
  Arvanitaki, Dimopoulos, Villadoro ‘private communication
- long period of inflation? Riotto et al ‘in progress
- other source of friction to prevent over-shooting the EW scale? Hardy ’15
- UV completion?
- weak gravity conjecture? Heidenreich, Reece, Rudelius ’15 Hebercker, Rompineve, Westphal ’15
- can other scales be relaxed too? SUSY breaking scale?
  Batell, Giudice, McCullough ’15
- signatures in atomic physics?

A new playground for model builders
at the cross-road between exp/cosmo/pheno/strings
Joined forces needed

Conclusions

- Neutral naturalness: new physics stabilizing the weak scale may escape detection
- Now, existence proof that technical naturalness doesn't require new physics at the weak scale.
- Is technical naturalness the right criterion?
- The energy frontier might be different than what we thought for many years!

let us think further and be prepared to be surprised