Relaxing the Weak Scale:

A new approach to the hierarchy problem

Alex Pomarol, CERN & UAB (Barcelona)

Purpose of my talk:

- Discuss a recently proposed new approach to tackle the Hierarchy Problem in particle physics:

“Relaxation” mechanism P.W. Graham, D.E. Kaplan, S.Rajendran arXiv:1504.07551

(see also earlier work by Abbott 85, G.Dvali, A.Vilenkin 04, G.Dvali 06)

☛ First example of **natural solutions** in which **No New-Physics required at TeV**

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Plan

- The idea
- Explicit models
- Drawbacks and reasons for improvement
- Experimental consequences

J.R.Espinosa, C.Grojean, G.Panico, A.P., O.Pujolàs, G.Servant 15

The idea

Your mind will answer most questions

if you learn to relax…

William S. Burroughs

First, the problem…

the Hierarchy Problem as explained
to condensed-matter physicists

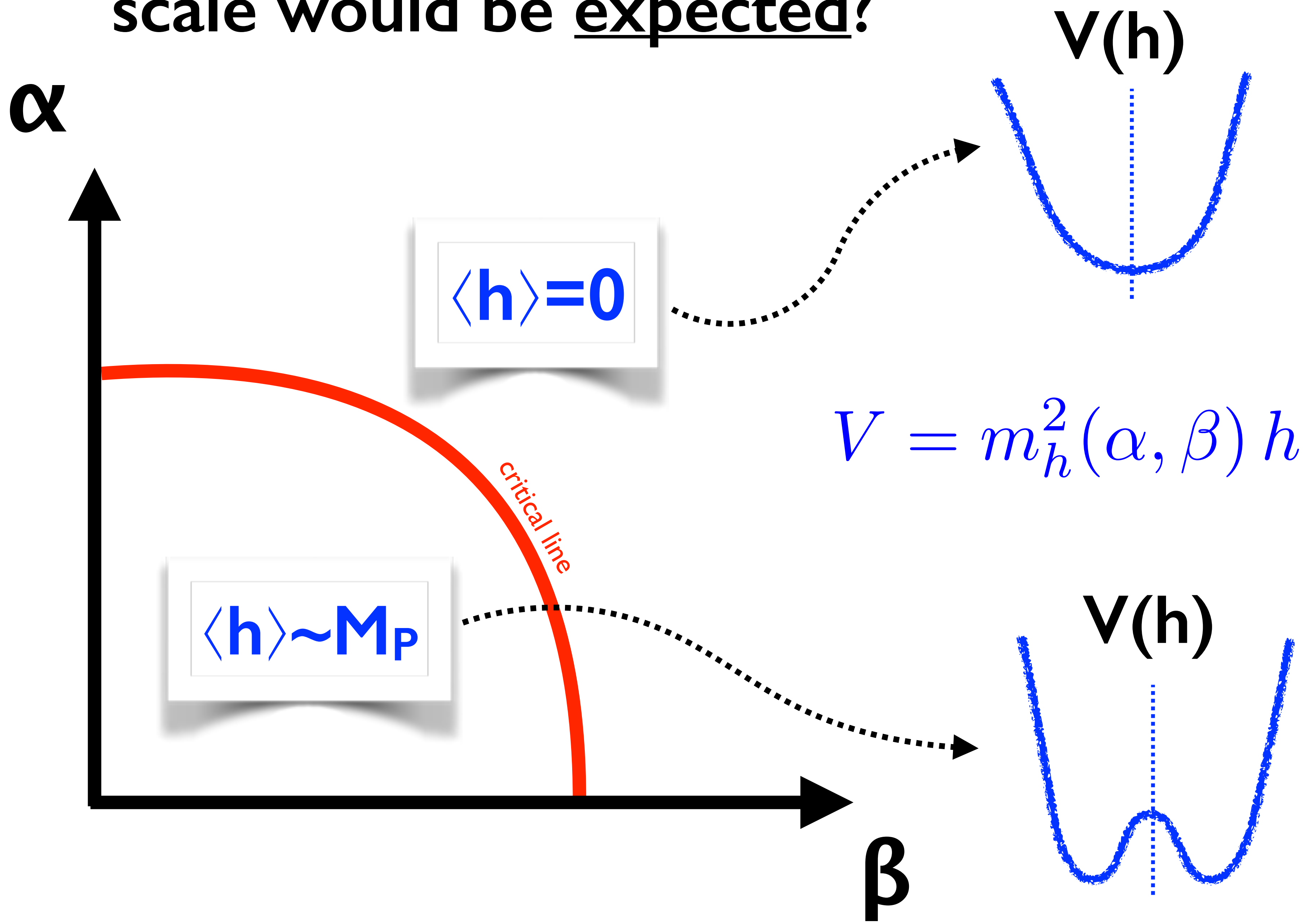
The SM: an EFT below M_P (sets the mass scale)

- **Where the Electroweak Symmetry Breaking (EWSB) scale would be expected?**

$$V = m_h^2(\alpha, \beta)\, h^2 + \lambda\, h^4$$

The SM: an EFT below M_P (sets the mass scale)

- **Where the Electroweak Symmetry Breaking (EWSB) scale would be <u>expected</u>?**



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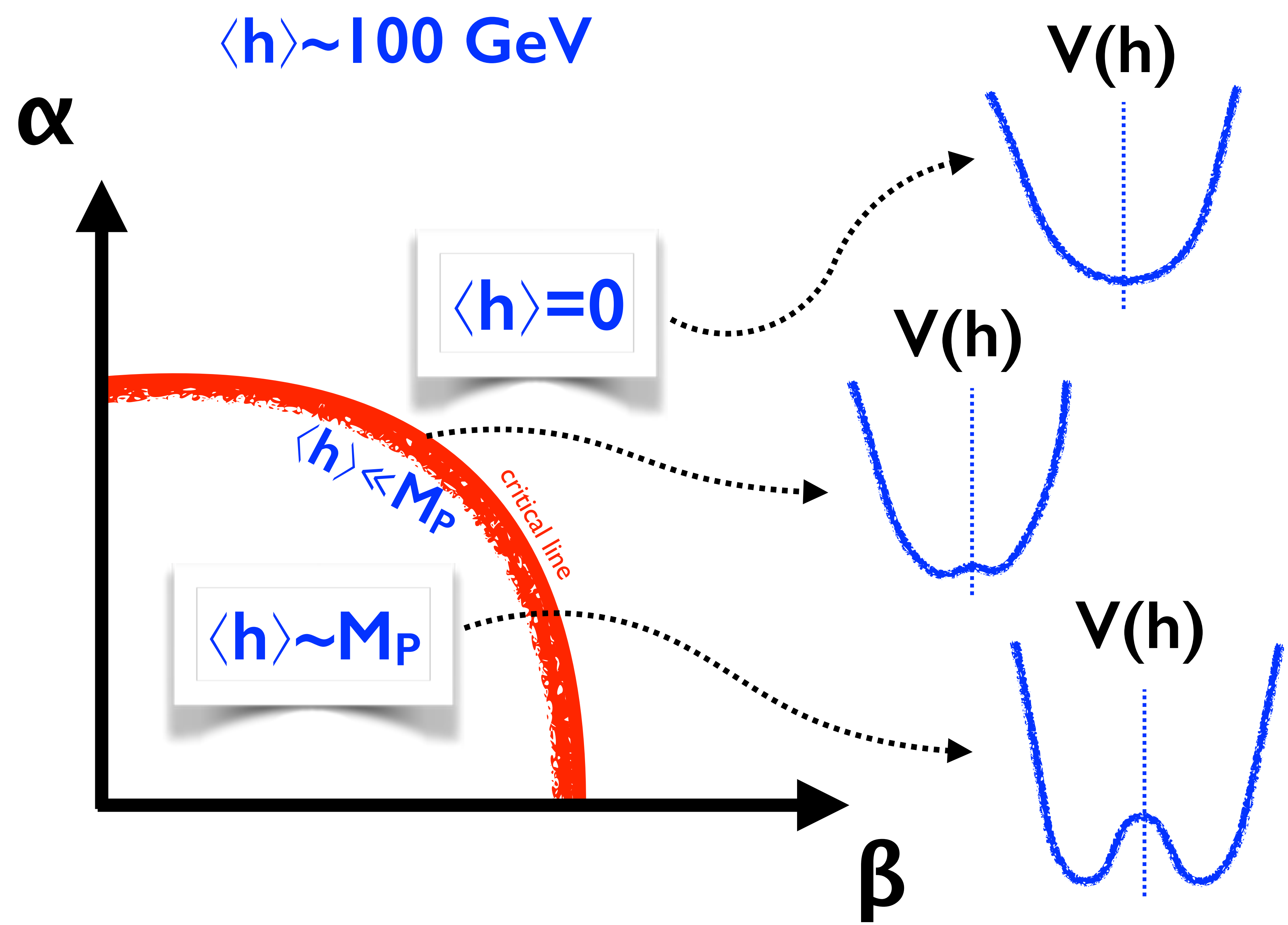
- Where we <u>see</u> in nature the EWSB scale?



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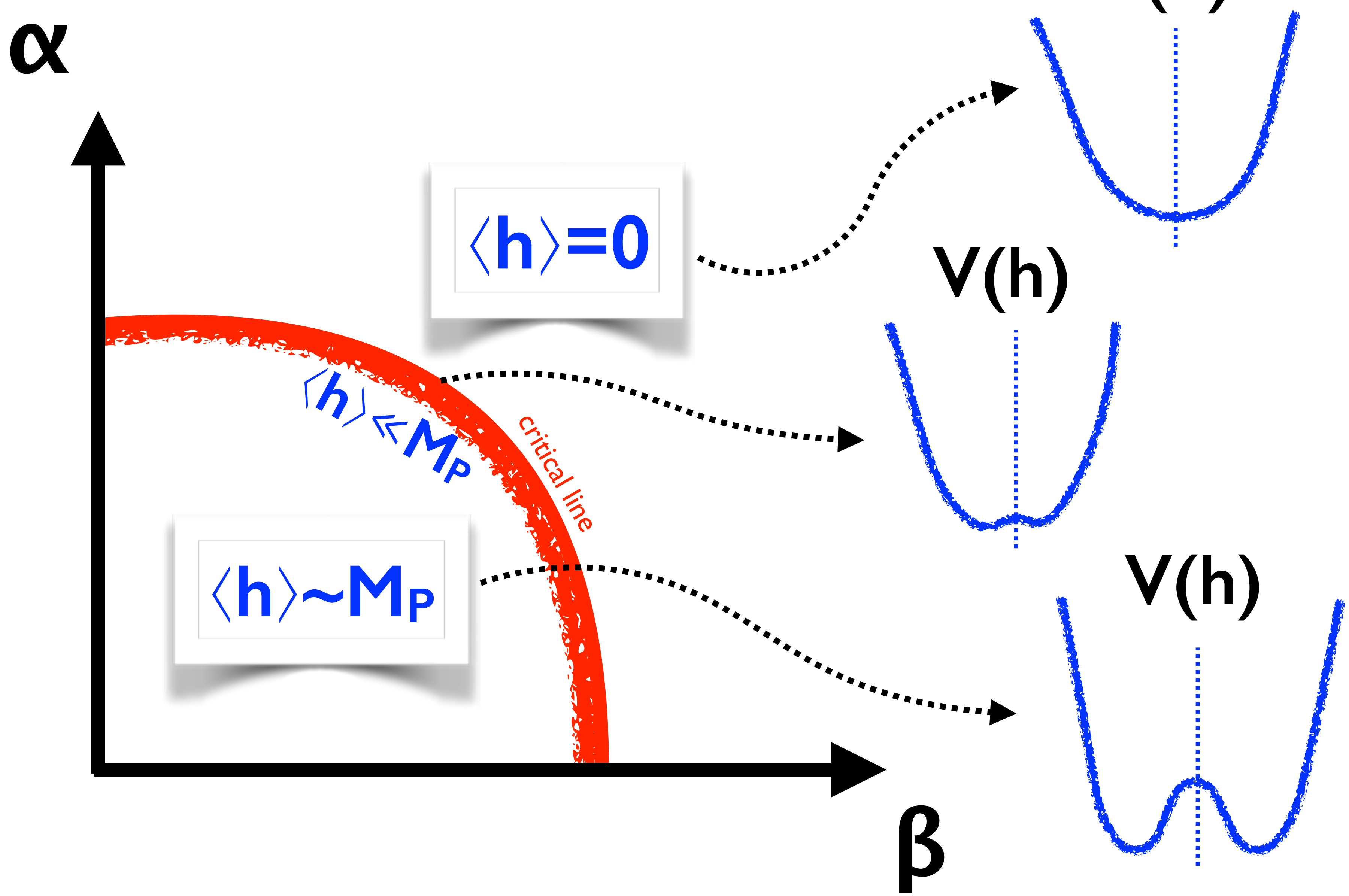
$\langle h \rangle \sim 100$ GeV



expectations≠reality ⇒ Crisis!

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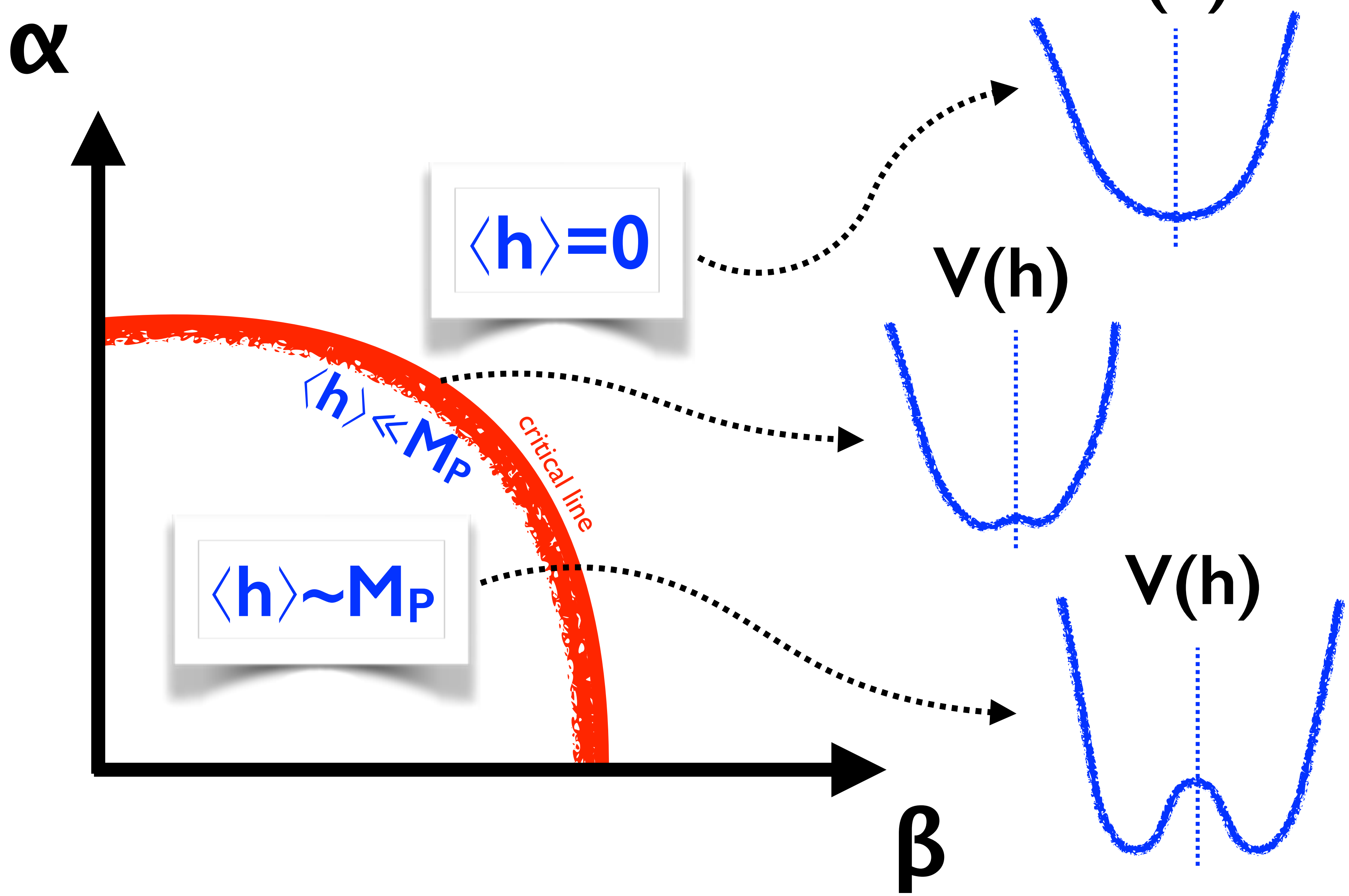
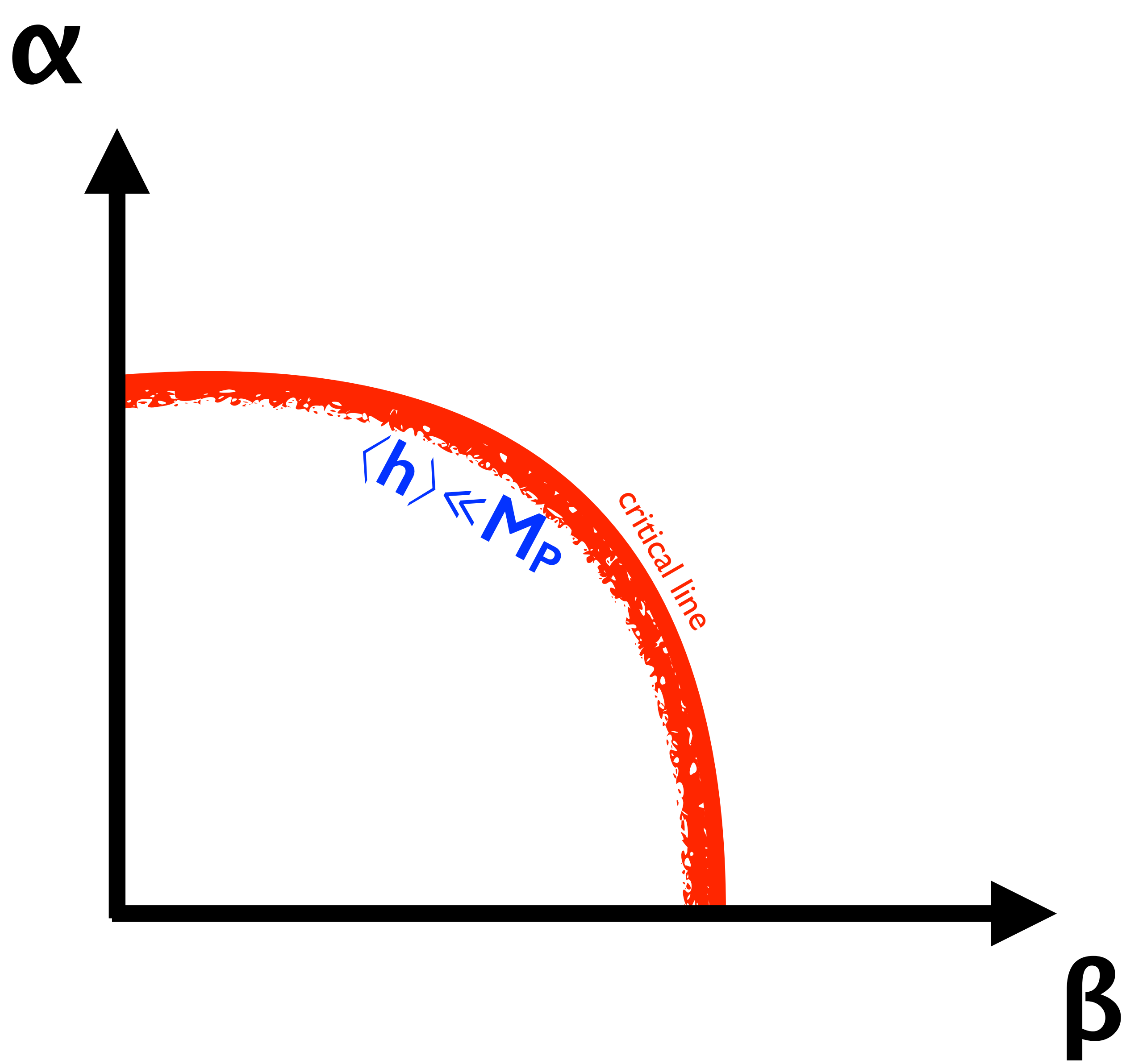


<u>Hierarchy problem</u>: Why nature is so close to the critical line?

Needs a tuning of parameters to get $\langle h \rangle \ll M_P$

Hierarchy problem: Why nature is so close to the critical line?

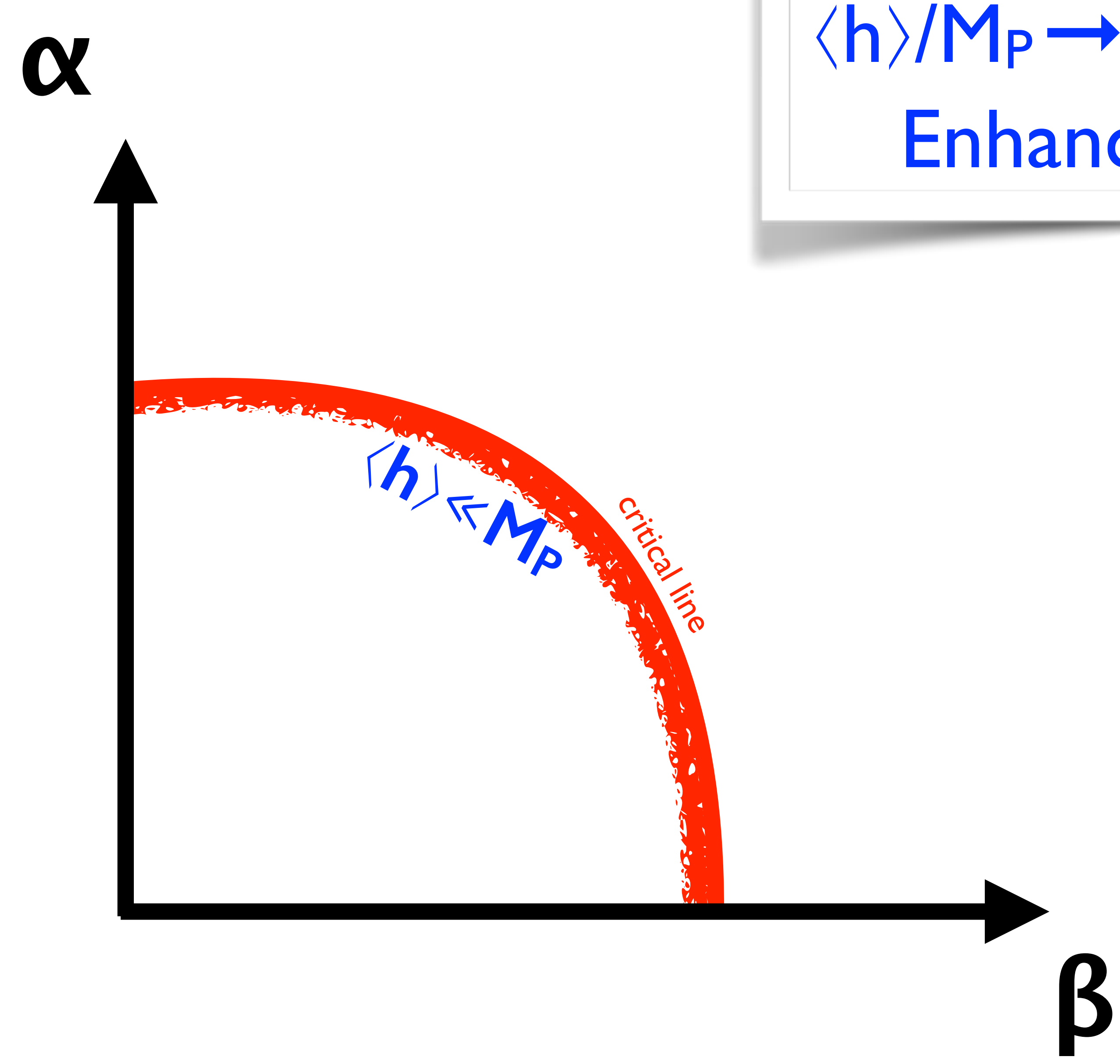


<u>Hierarchy problem</u>: Why nature is so close to the critical line?

One solution:

$\langle h \rangle / M_P \rightarrow 0$ is a special line

Enhanced symmetry?



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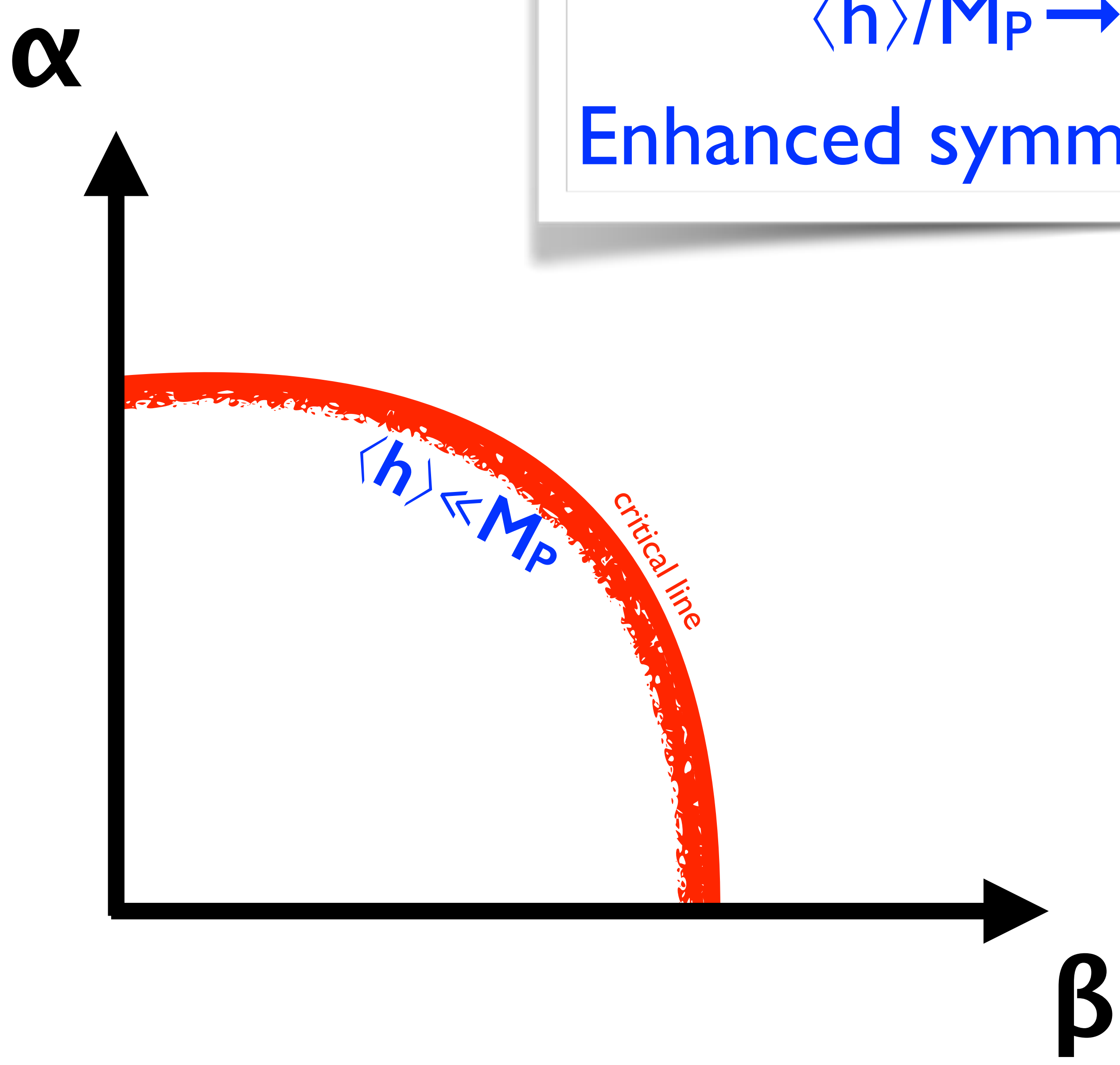

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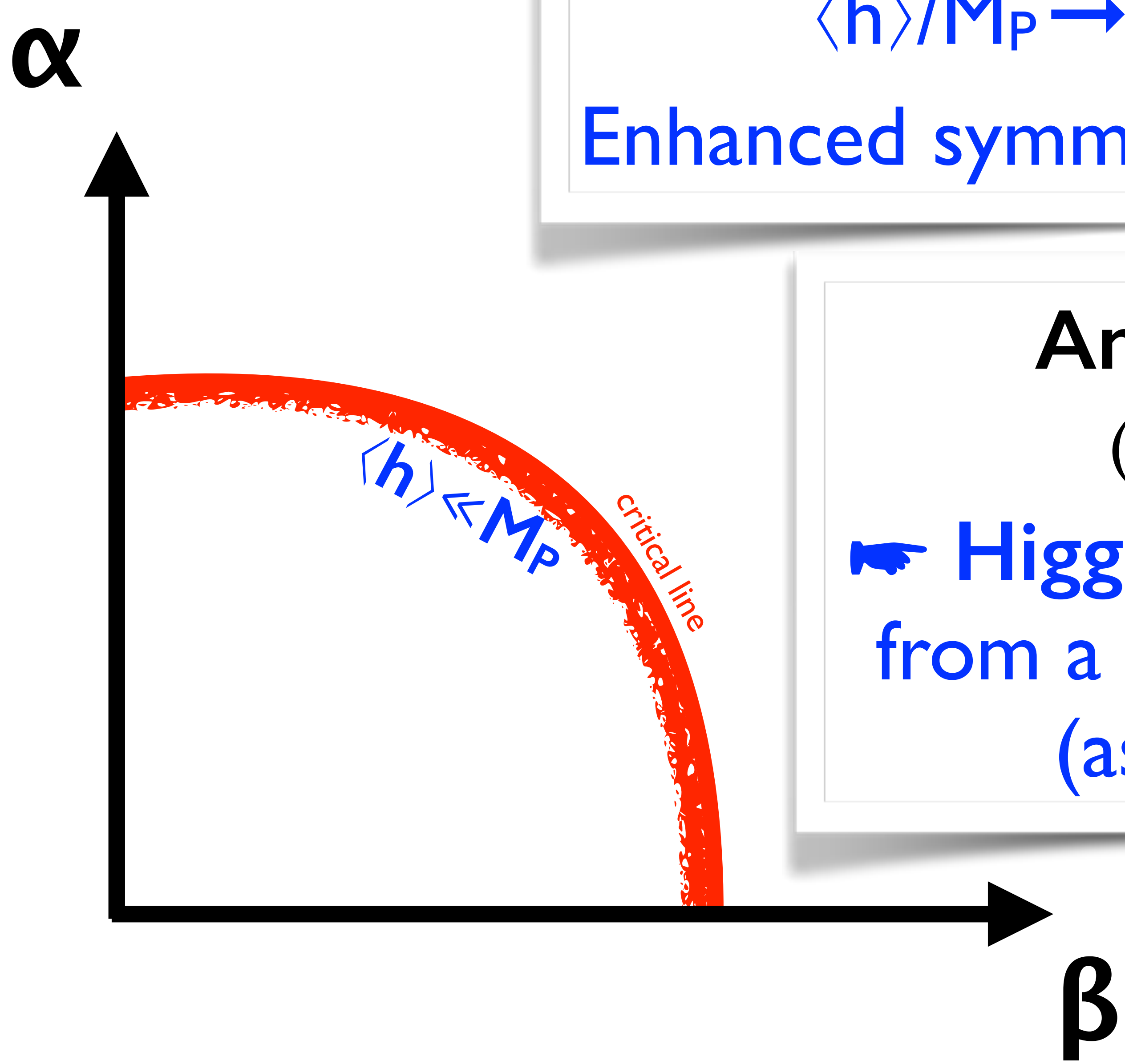

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(*"dead dogs don't bite"*)

☛ **Higgs** as a ***composite*** state from a new strong dynamics (as *pions* in QCD)

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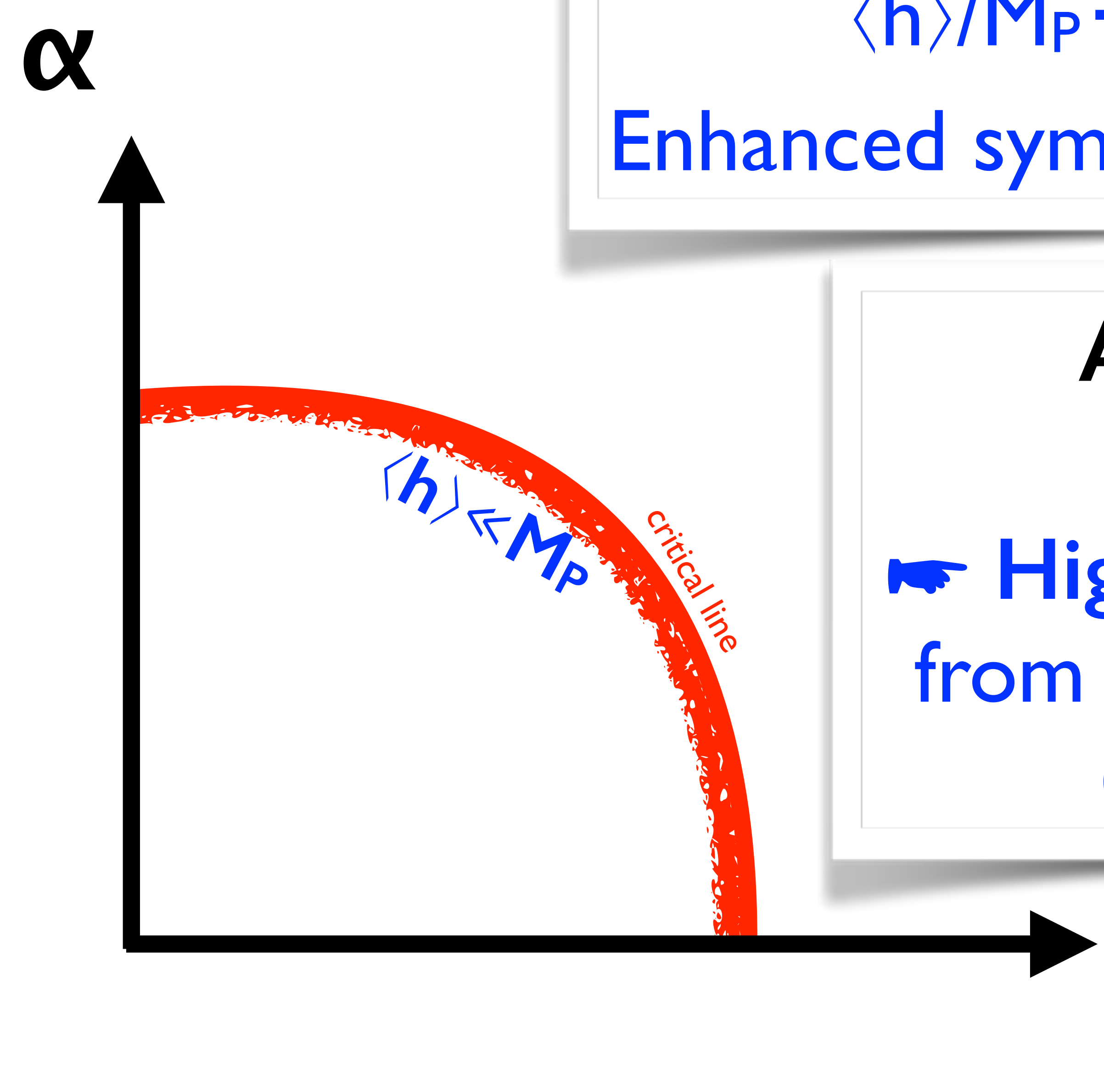

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In both cases, TeV new-physics expected!

New-Physics at the TeV

Pros	**Cons**
Hierarchy problem	**No** new particles seen, **no** new flavor-violations seen, **no** deviations on Higgs couplings seen, **no** deviations on Z/W couplings seen, **no** WIMP detected, **no** EDMs seen,

New-Physics at the TeV

Pros

Hierarchy problem

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No new particles seen,
no new flavor-violations seen,
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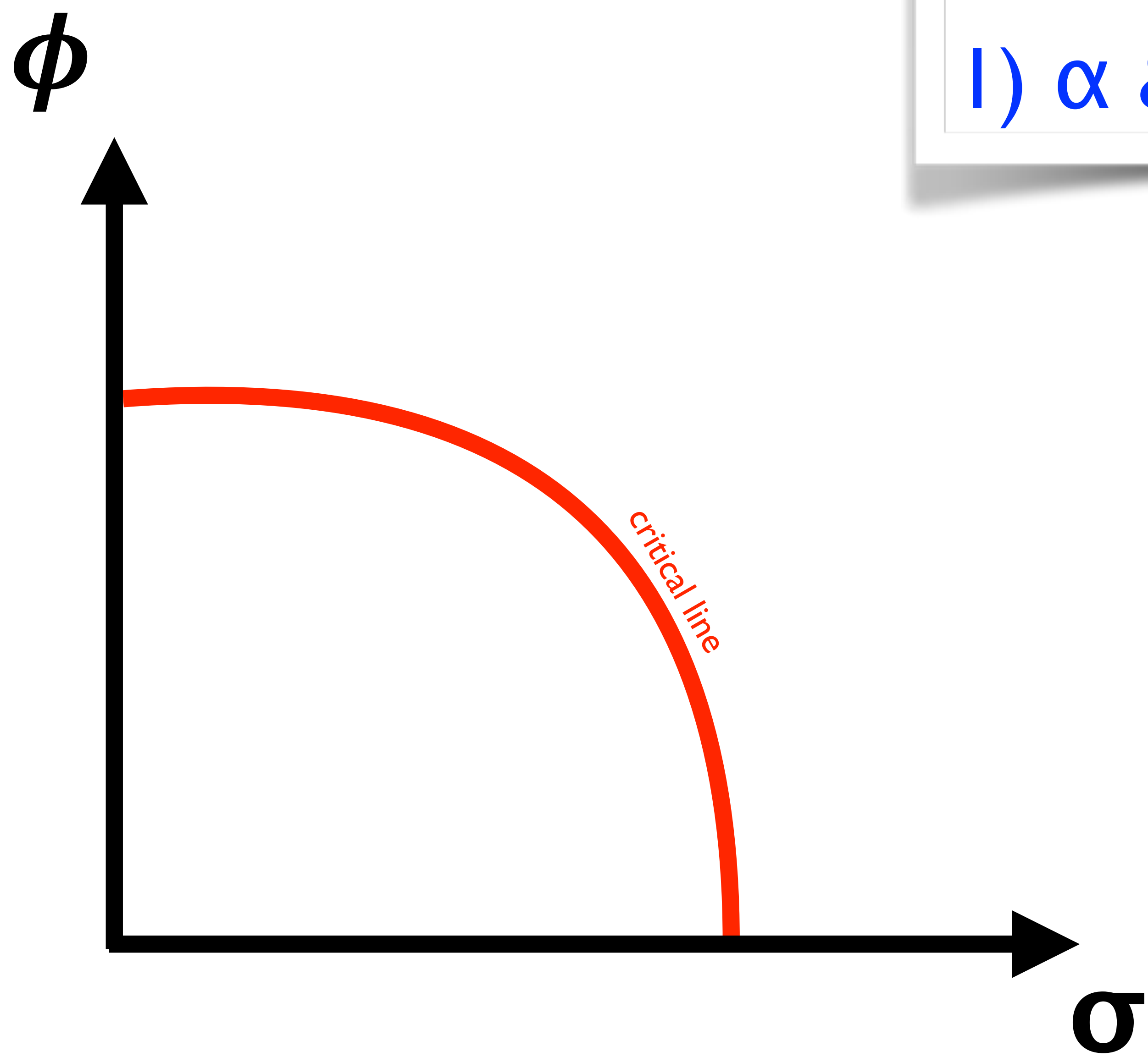
so far, expectations≠reality ⇒ *little* crisis!

Hierarchy problem: Why nature is so close to the critical line?

New 3rd possibility:

1) α &β are fields → ϕ & σ



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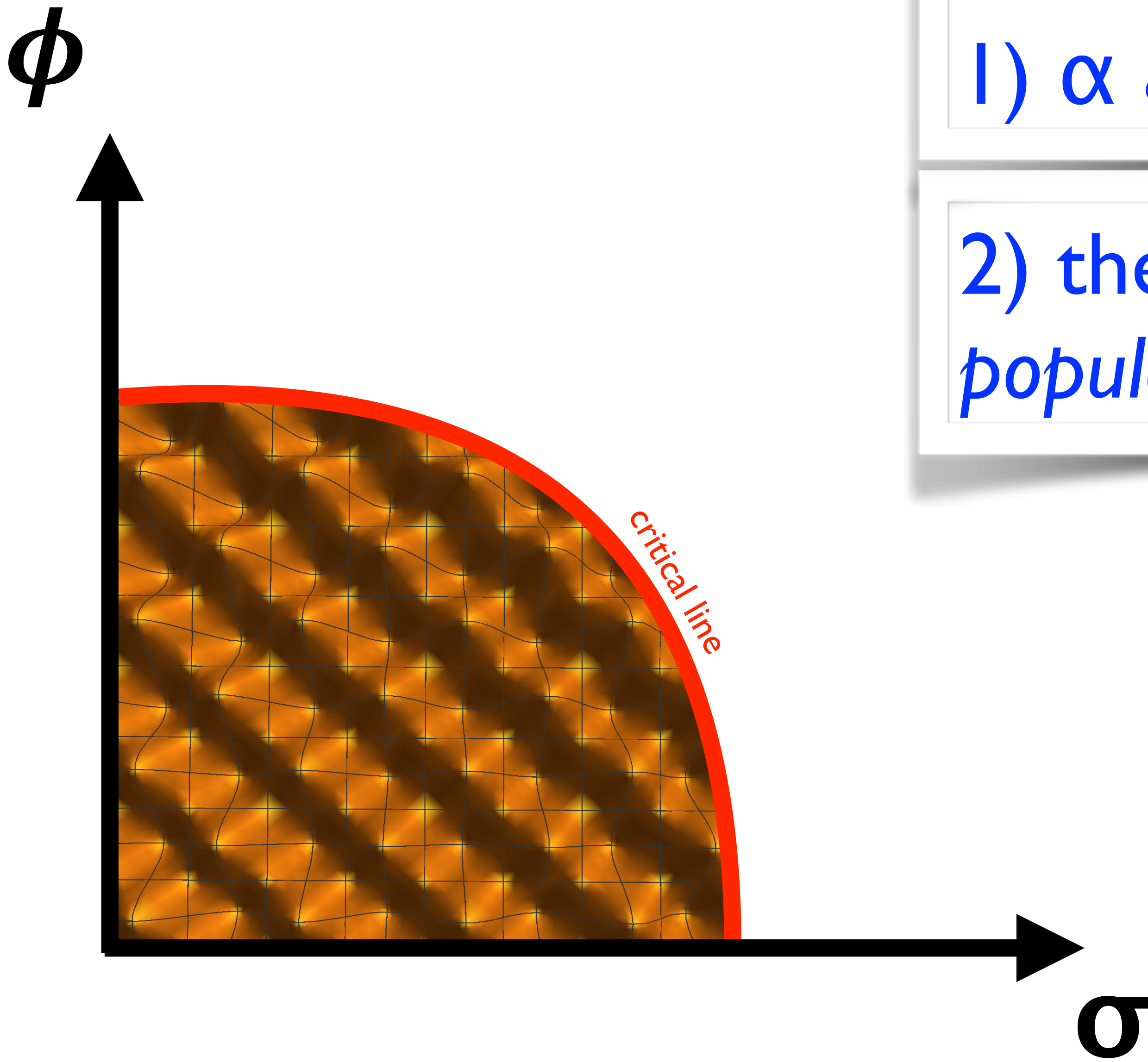

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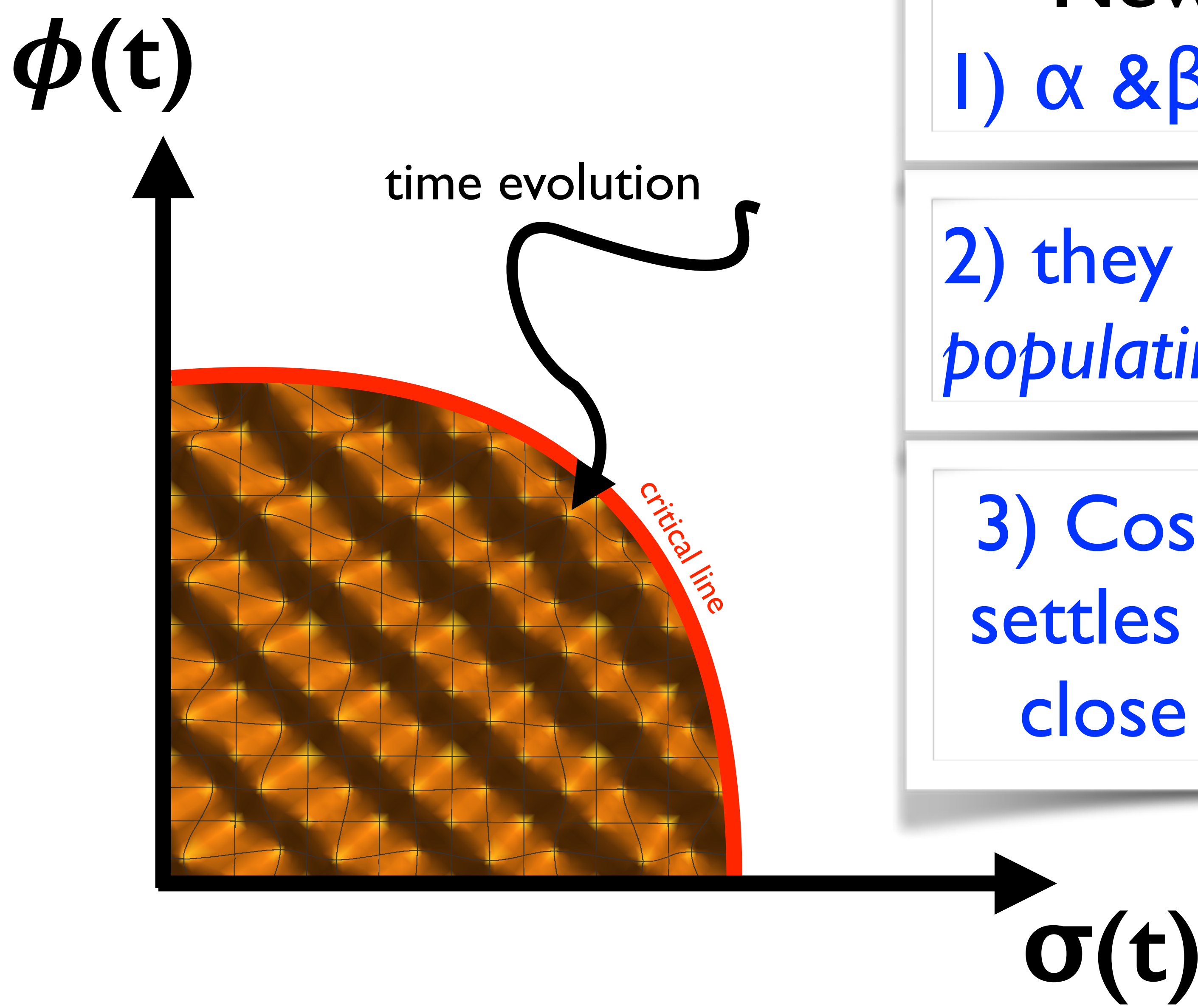

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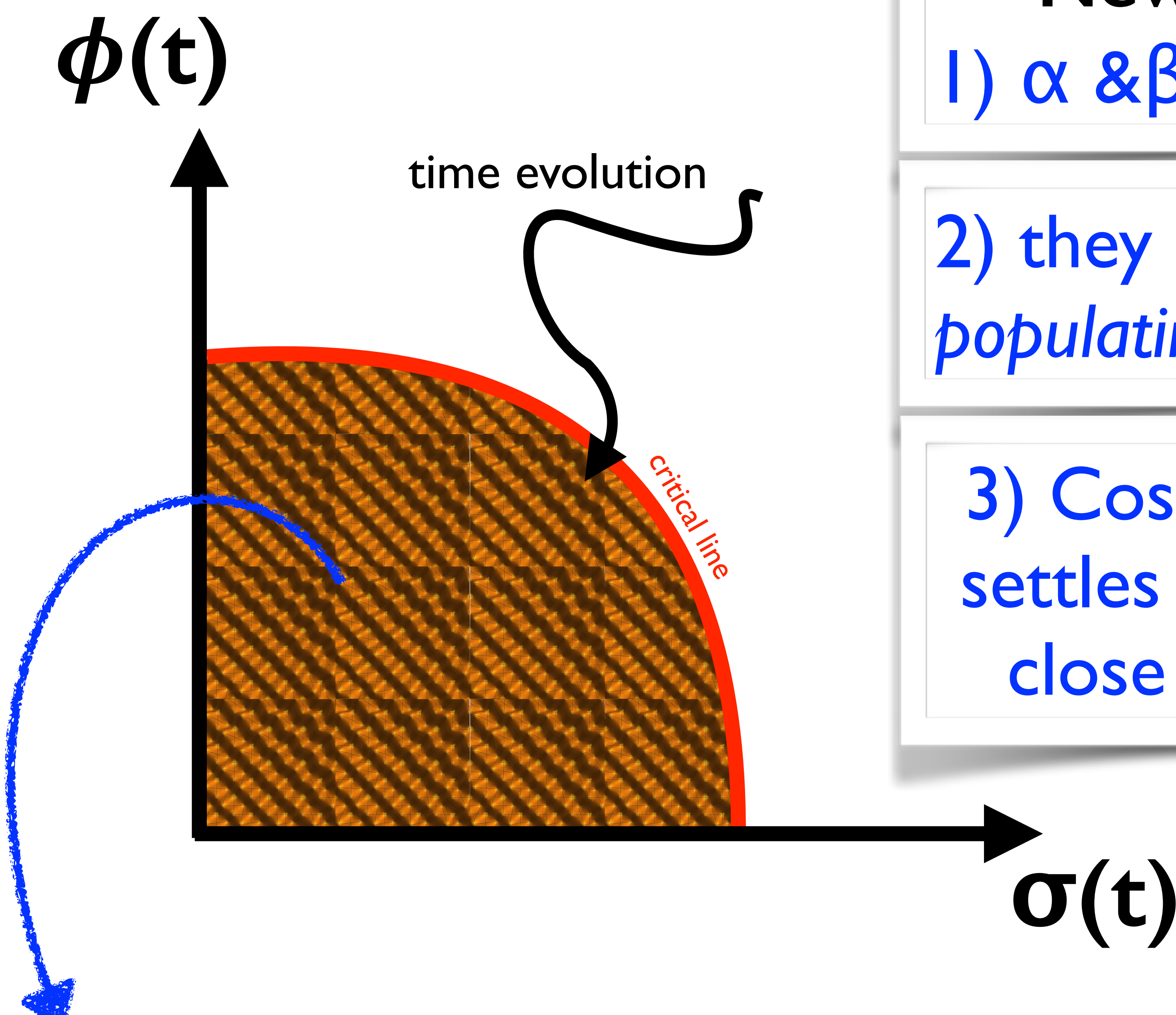

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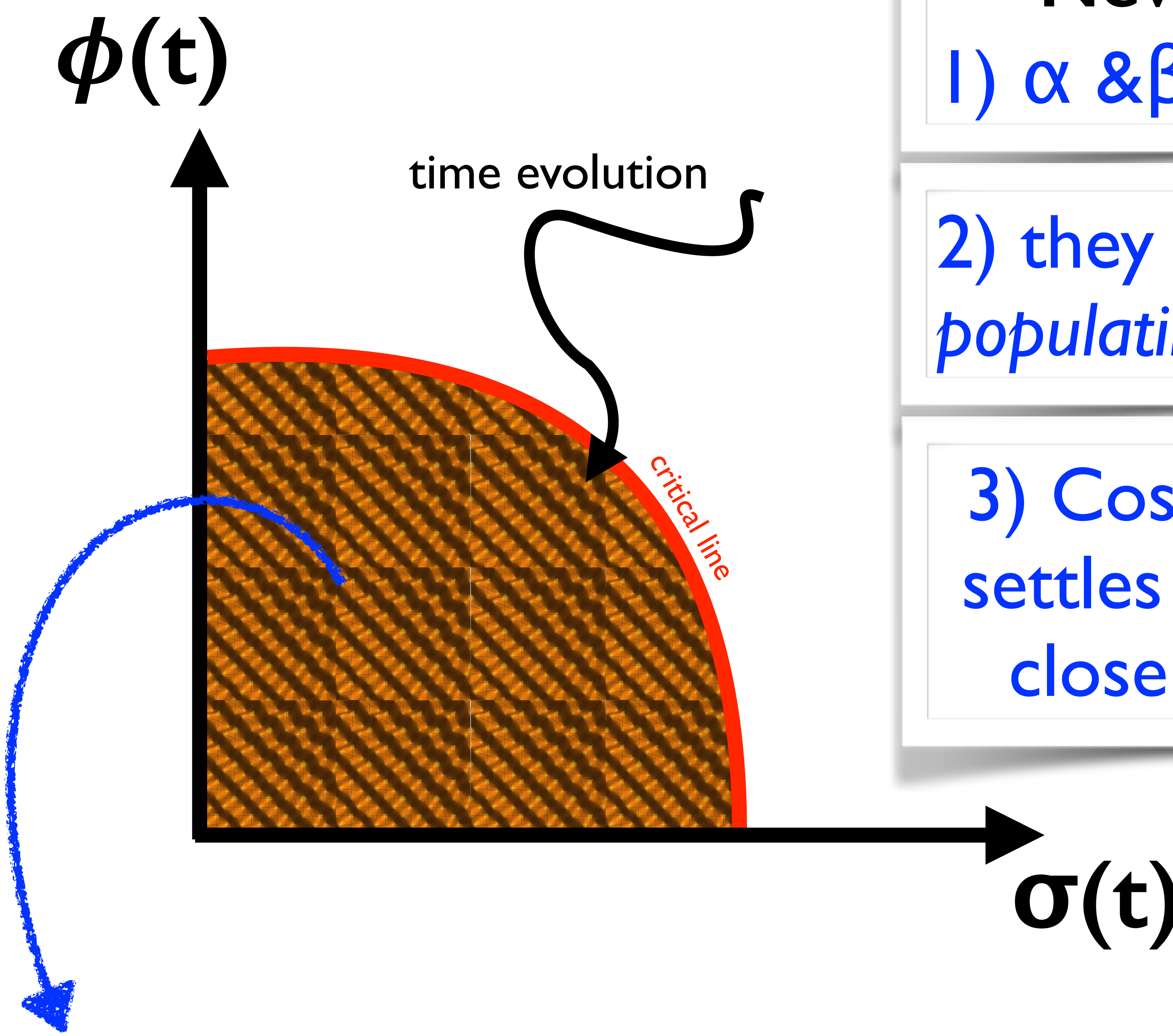

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Reference: 8,874 Summits listed in the Swiss Alps

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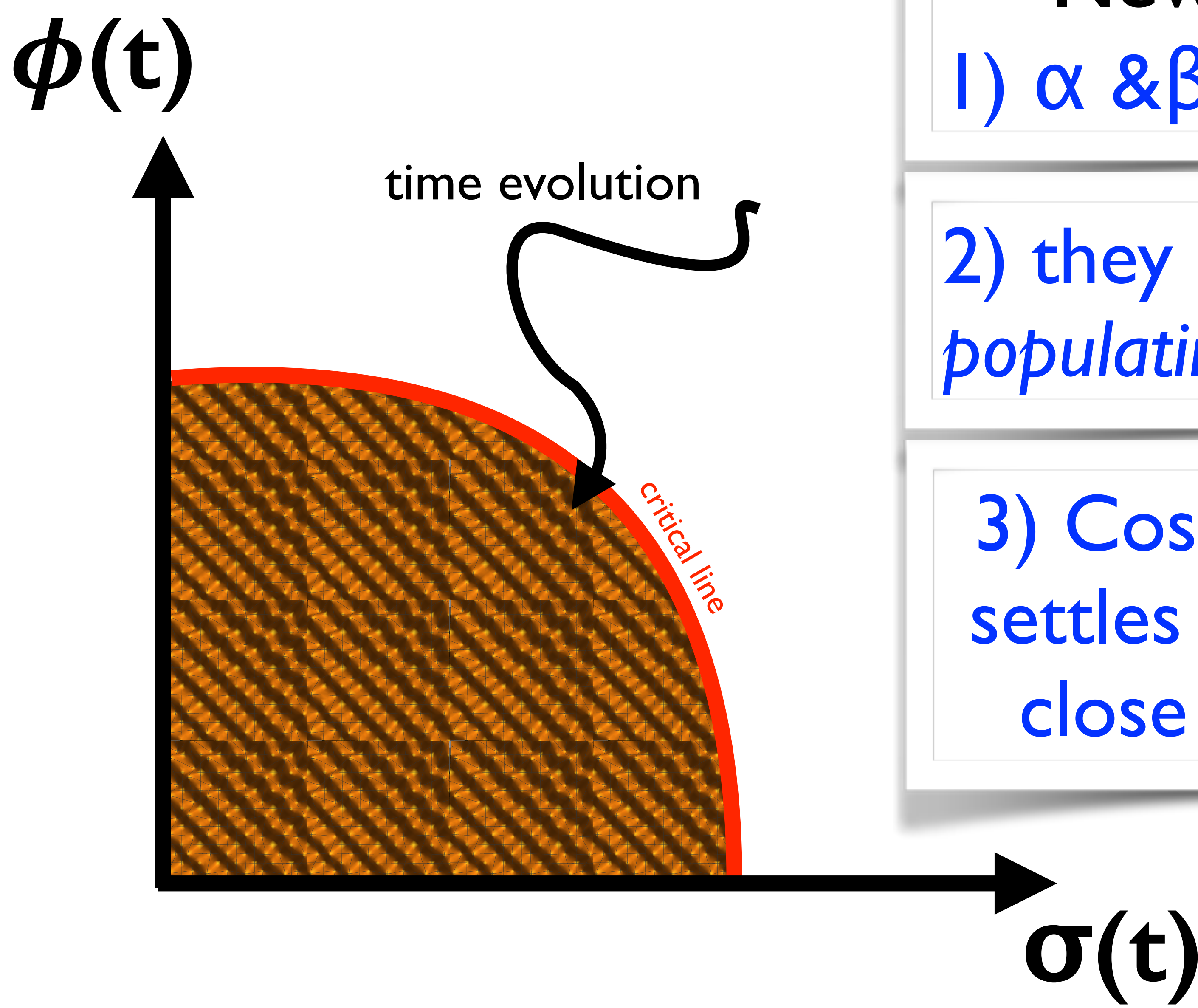

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The hierarchy problem ☛ A historical accident

Explicit Models

Idealized models have a useful role to play,

as ways to clarify your thinking

Paul Krugman

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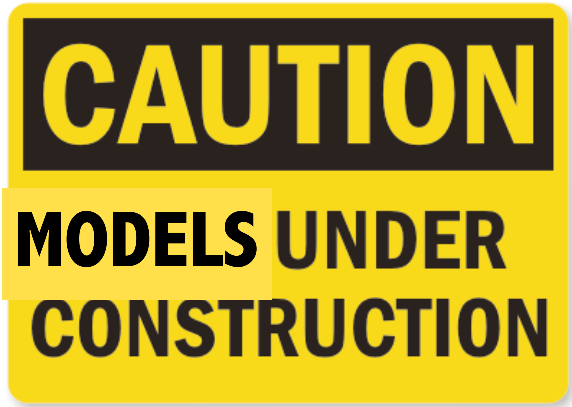
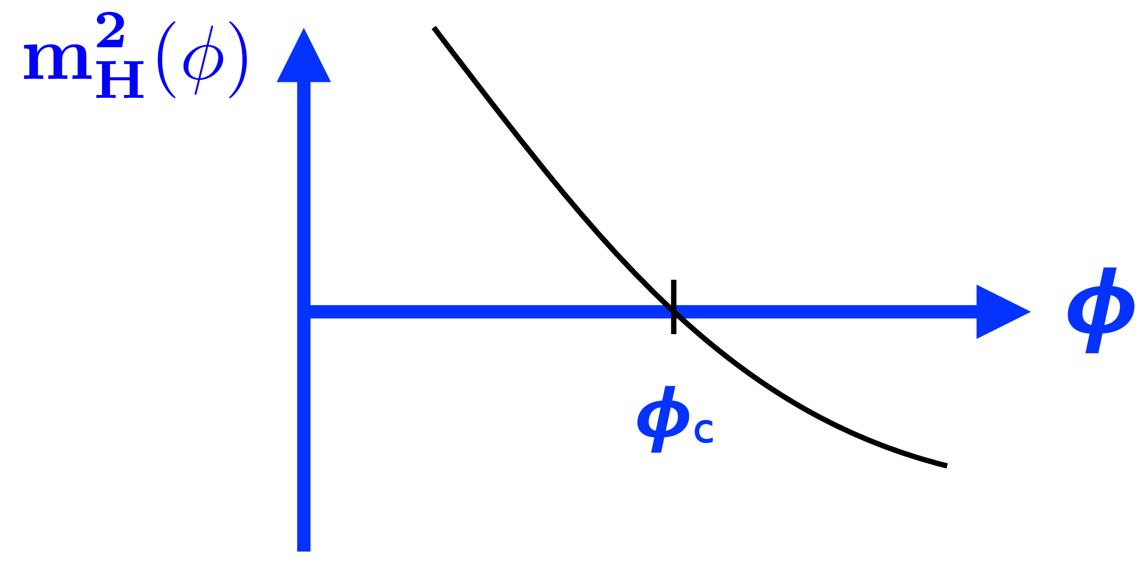


Higgs-mass parameter → Field-dependent Higgs mass

$$m_H^2 |H|^2 \qquad\qquad m_H^2(\phi)|H|^2$$



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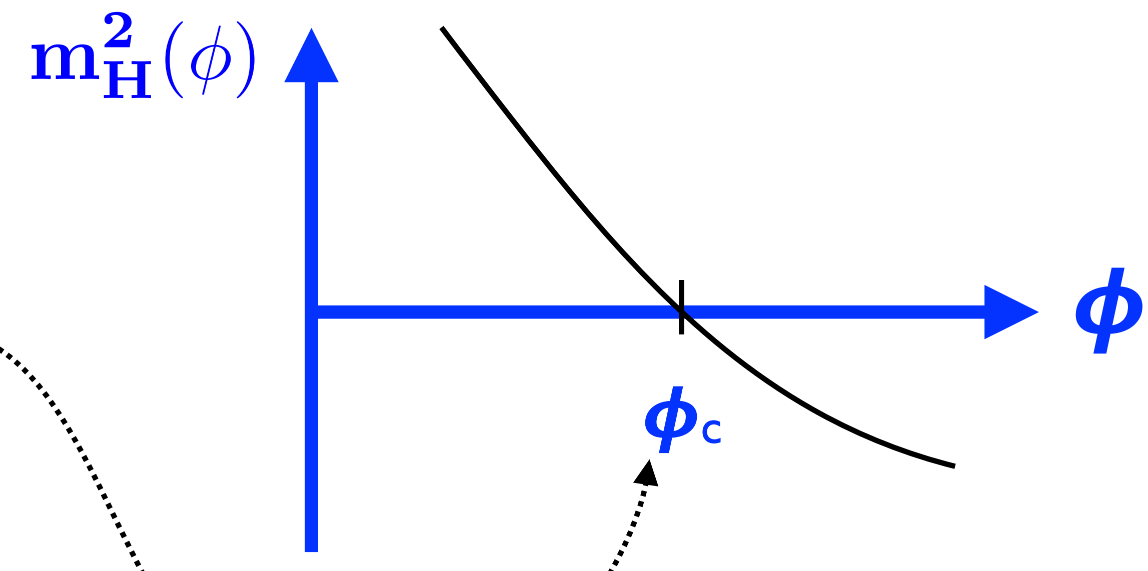

ϕ must settle close to ϕ_c

e.g. $$m_H^2(\phi) = \Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)$$

Λ = sets the UV cut-off scale of the SM (M_P?)

$\phi_c = \Lambda/g \qquad (g \ll 1)$

Notice that <u>large field excursions</u> for ϕ needed: $\phi \sim \Lambda/g \gg \Lambda$

Higgs (h) & axion-like (ϕ) potential:

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551

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

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“Kicking” term

Slope for ϕ to move forward

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ϕ "scans" the Higgs-mass

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n=1,2,…

term affording local minima for ϕ in the broken phase (when h≠0)

periodic-function of ϕ as for axion-like states

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Λ: cutoff of the theory

Λ_c : scale that originates the periodic term

Spurions:

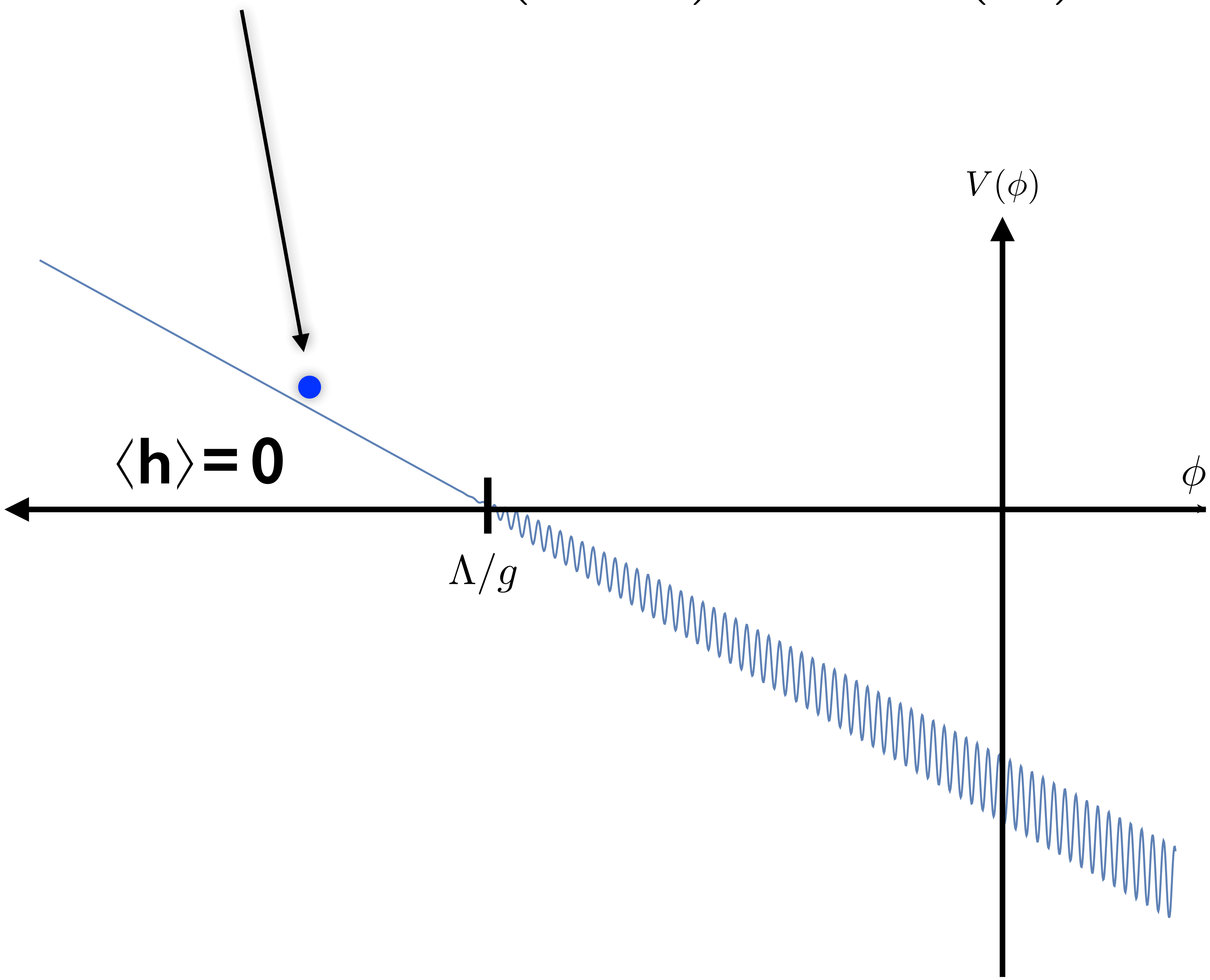
$\epsilon \ll 1$: breaking of shift symmetry, respecting $\phi \to \phi + 2\pi f$

$g \ll 1$: breaking of shift symmetry $\phi \to \phi + c$ $(\forall c)$

Potential stable under radiative corrections!

Cosmological evolution:

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



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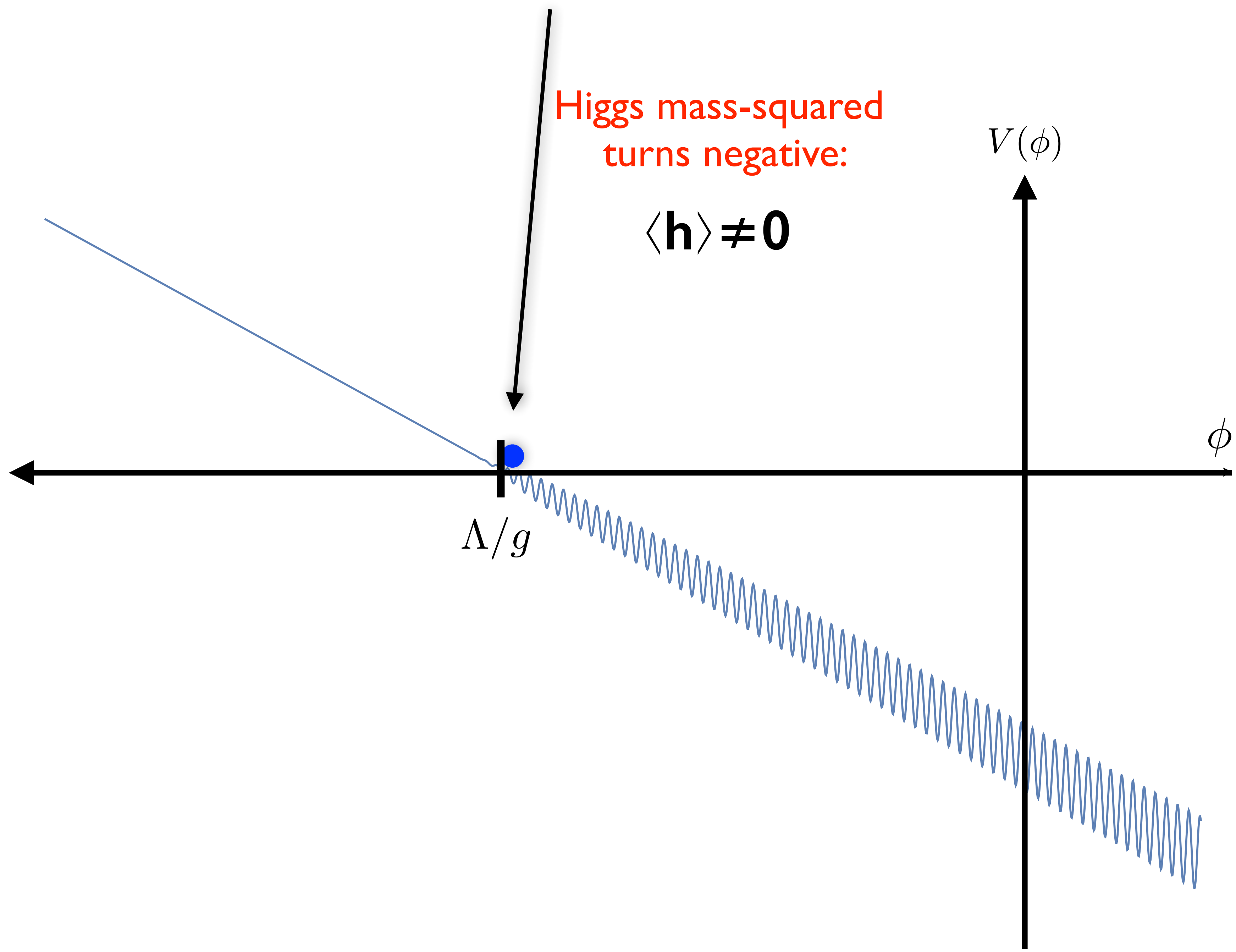

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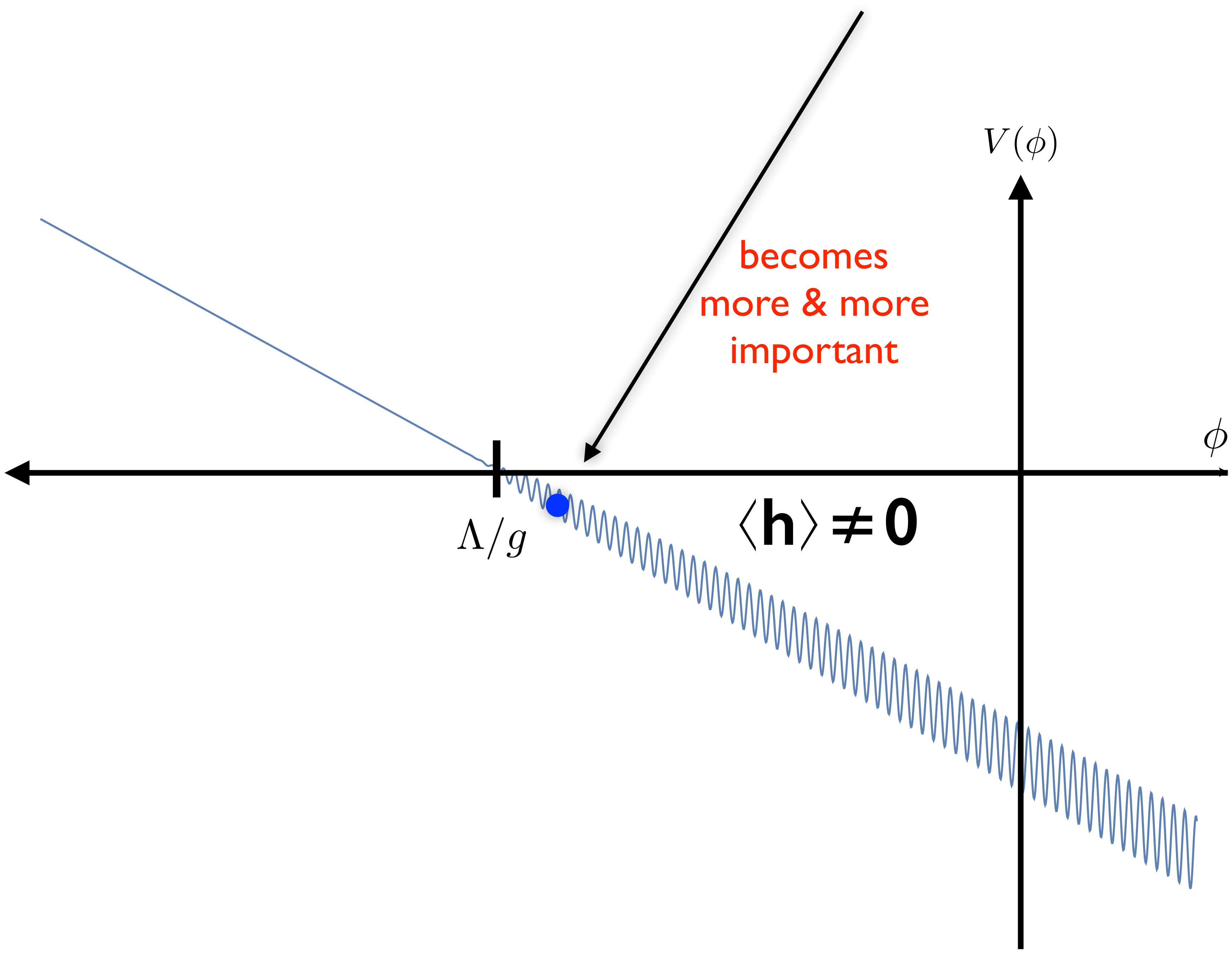

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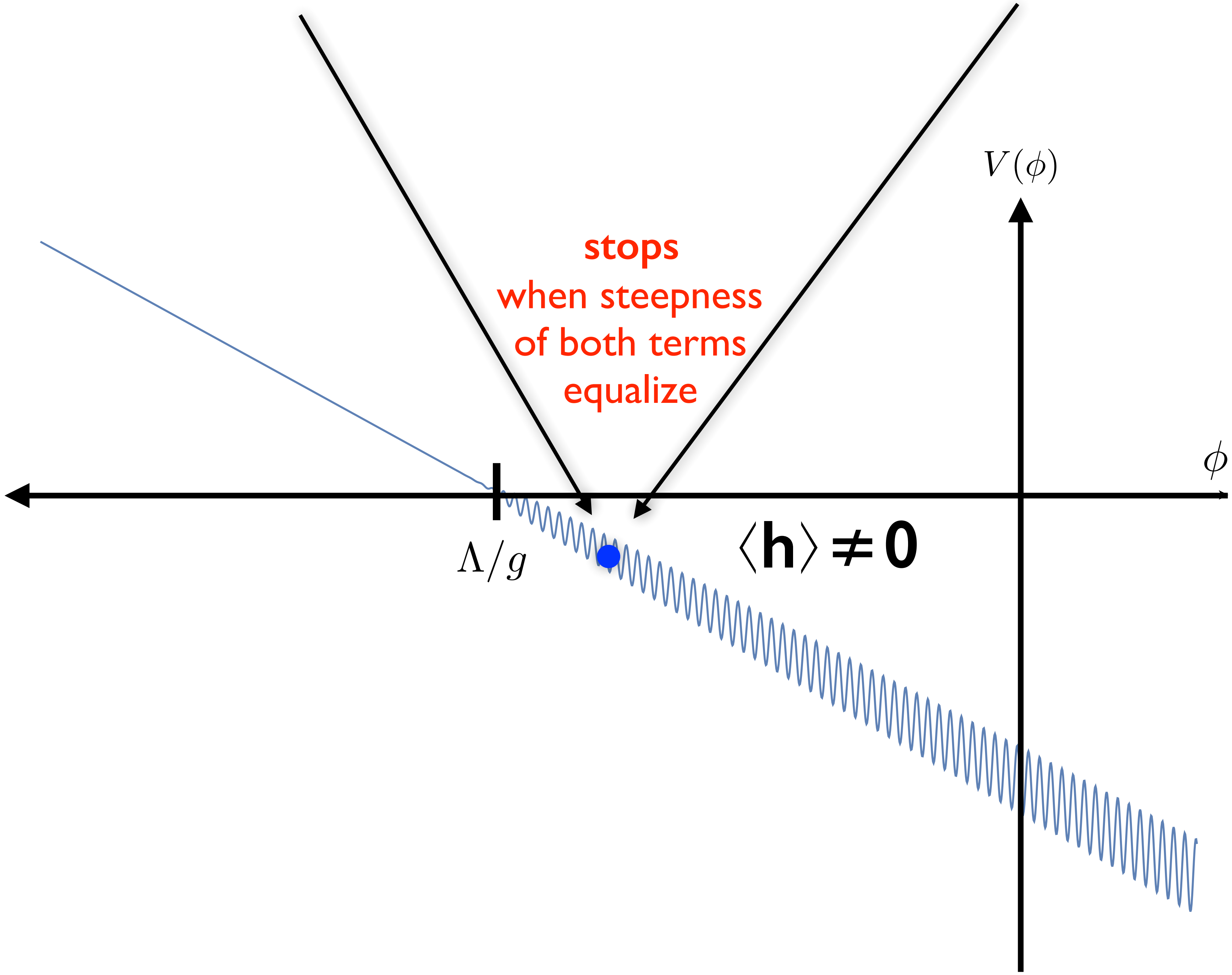

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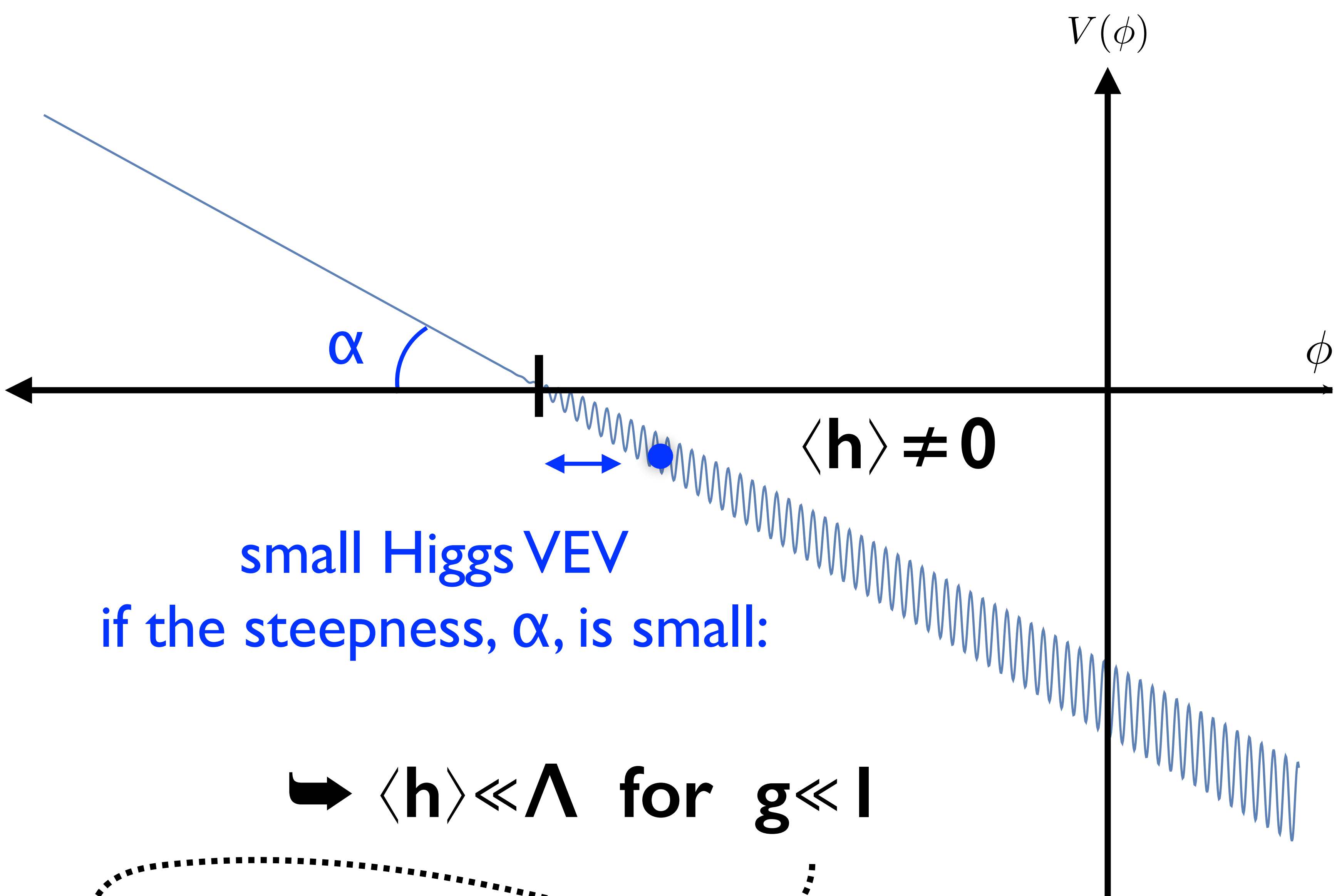
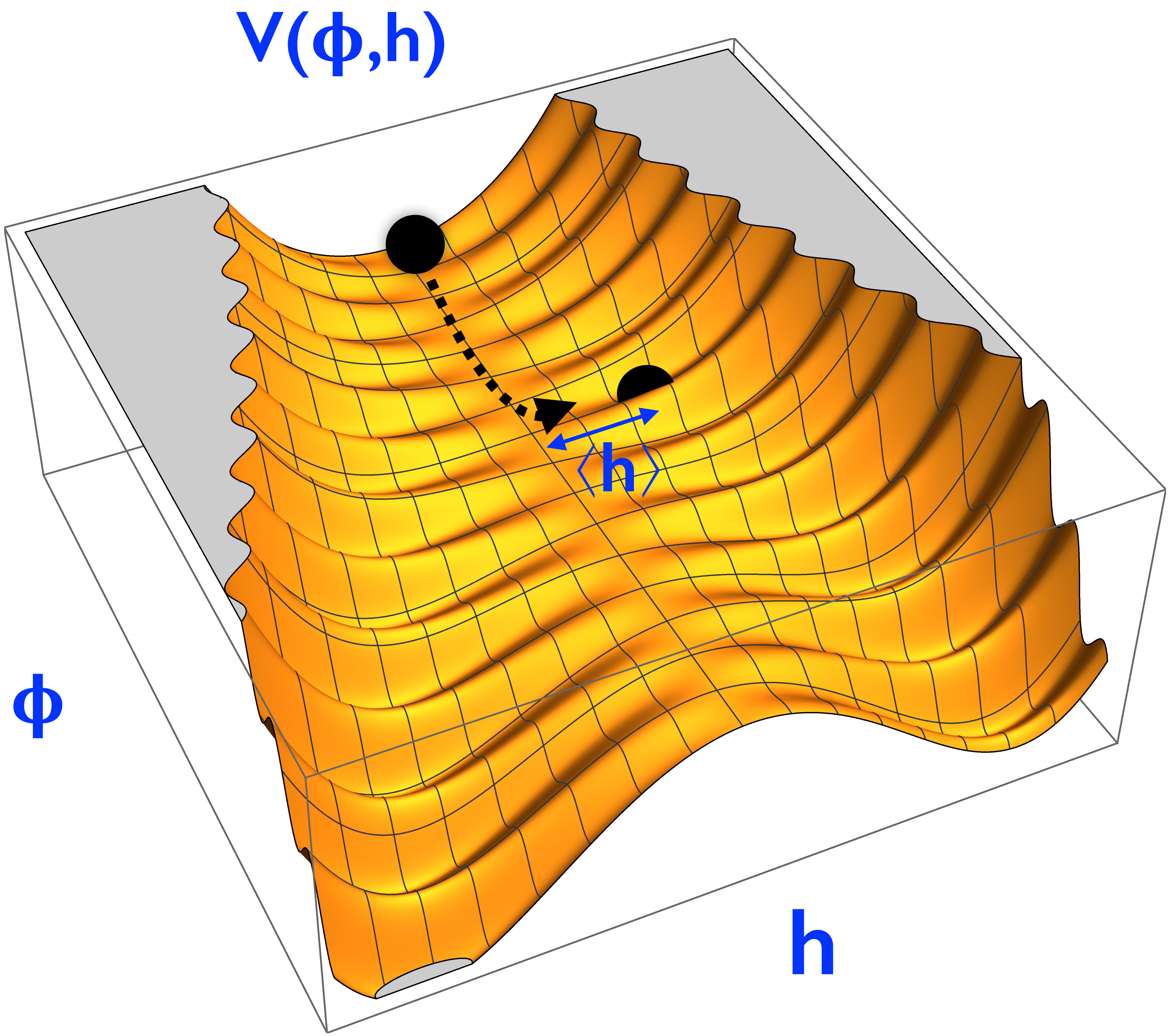


small Higgs VEV
if the steepness, α, is small:

➥ $\langle h \rangle \ll \Lambda$ for $g \ll 1$

technically natural since g=0 is a point of enhanced symmetry


V(ϕ,h)
⟨h⟩
ϕ
h

Tuning the initial conditions?

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No, if slow rolling due to a friction:

possible in the **inflationary epoch!** (Hubble friction)

can be neglected

$$\ddot{\phi} + 3H_I\dot{\phi} = -\partial_\phi V(\phi)$$

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Long period of inflation needed,

in order for $\boldsymbol{\phi}$ to "scan" large ranges of the Higgs mass

e-folds needed: $N_e \gtrsim \dfrac{H_I^2}{g^2\Lambda^2} \sim 10^{40}$

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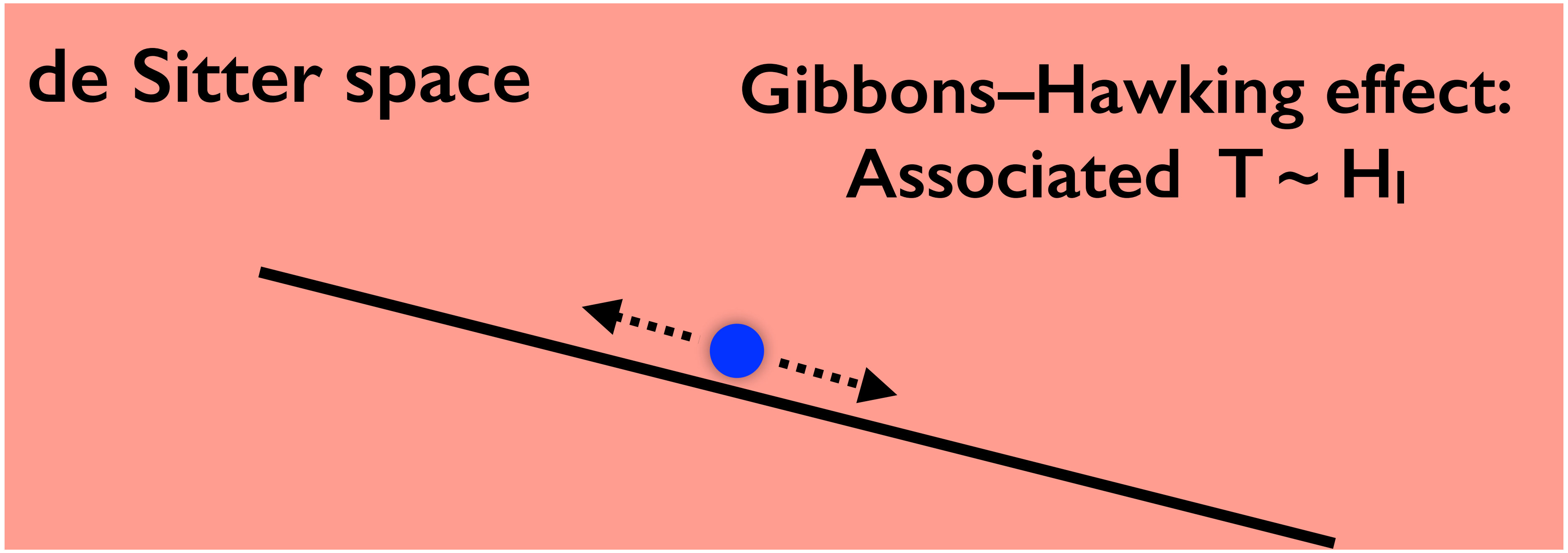
☛ **For simplicity, we will assume that inflation is driven by other fields**

Important limitation:



$\boldsymbol{\phi}$ must roll-down classically and not *wiggle* by quantum effects:

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$$g \gtrsim (H_I/\Lambda)^3$$

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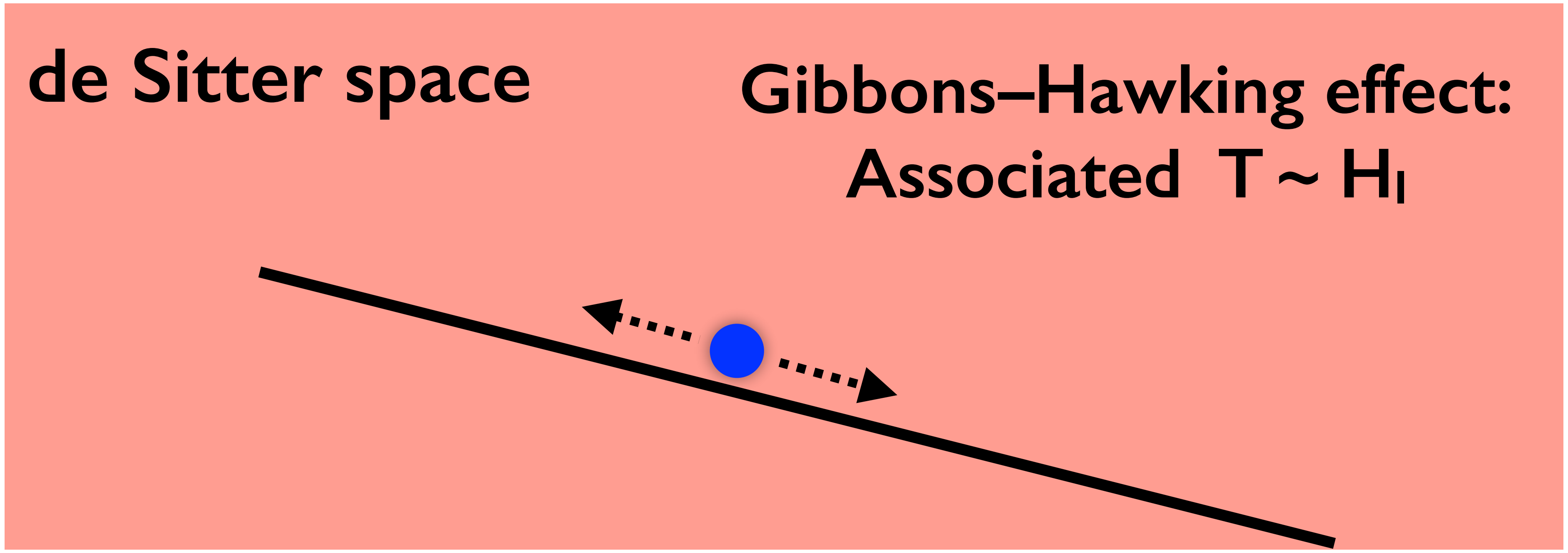

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+ ***ϕ* should not inflate more than the inflaton**

$$H_I \gtrsim \Lambda^2/M_P$$

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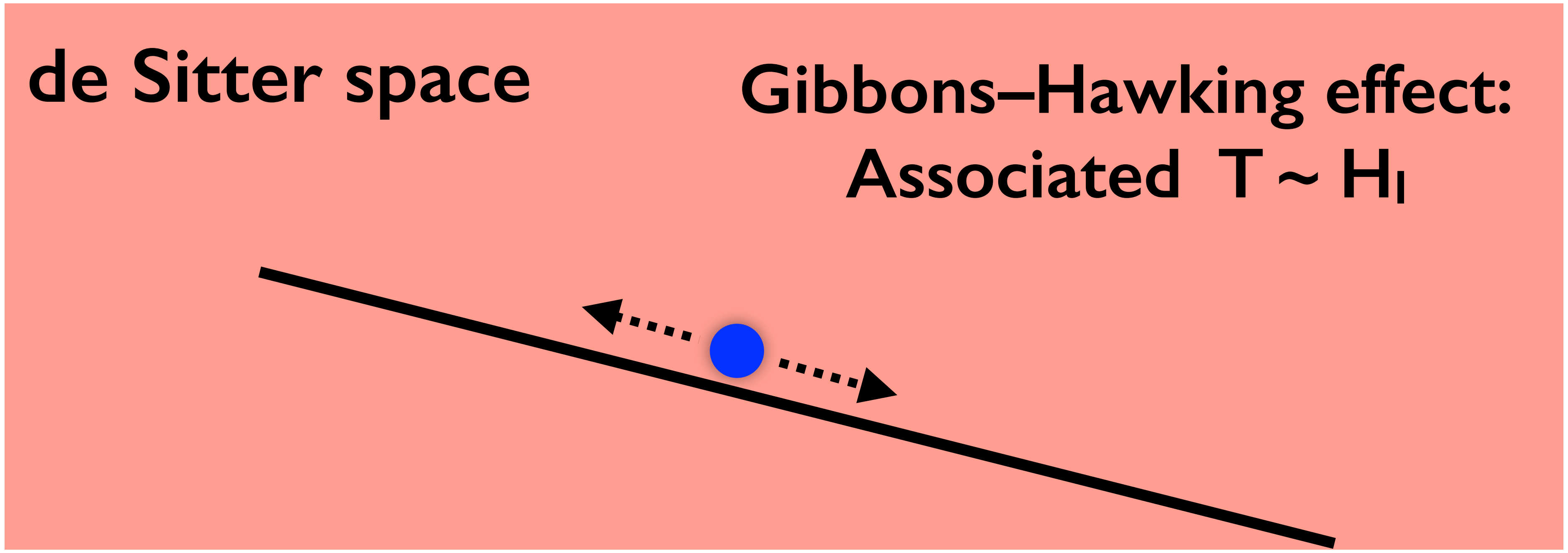

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$$\left.\begin{aligned} g &\gtrsim (H_I/\Lambda)^3 \\ H_I &\gtrsim \Lambda^2/M_P \end{aligned}\right\} \quad \mathbf{g \gtrsim (\Lambda/M_P)^3}$$

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lower bound on g (i.e. upper bound on Λ)

Origin of $\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n\cos(\phi/f)$?

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$\Lambda_c=\Lambda_{QCD}$
$\epsilon=Y_u$

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But $\boldsymbol{\phi}$ cannot be the *genuine* QCD-axion
clash with the linear terms for $\boldsymbol{\phi}$!

Though <u>consistent</u> QFT as **g** is very small

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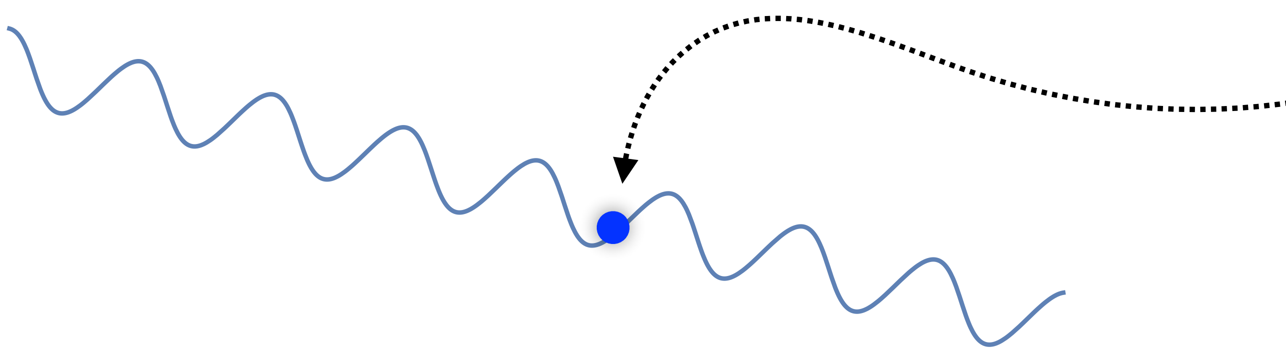
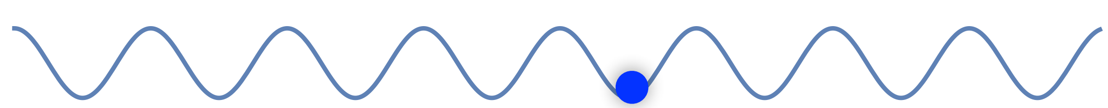


<u>Consequence</u>: $\boldsymbol{\phi}$ displaced from the minimum of the cos-term, leading to $\langle\boldsymbol{\phi}\rangle\sim\theta_{QCD}\sim 1$!

It must be arranged such that at the end of inflation, the *tilt* disappears:



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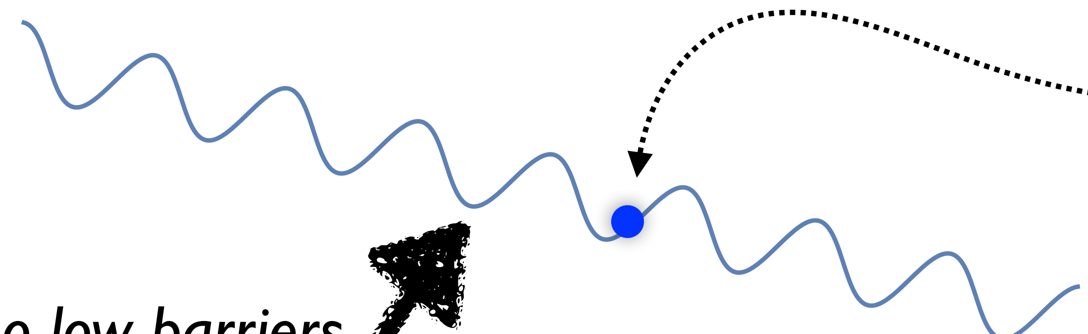
$\boxed{\textbf{n=1:}}$ axion potential if $\boldsymbol{\phi}$= QCD-axion (Pseudo-Goldstone of a $U(1)_{PQ}$)
$\boldsymbol{\phi\rightarrow\phi+\alpha}$

$U(1)_{PQ}$-anomaly: $\frac{\phi}{f}G^{\mu\nu}\widetilde{G}_{\mu\nu}$ ➔ $V(\phi)\sim m_u(h)\langle q\bar{q}\rangle\cos(\phi/f)$

But $\boldsymbol{\phi}$ cannot be the *genuine* QCD-axion
clash with the linear terms for $\boldsymbol{\phi}$!



Consequence: $\boldsymbol{\phi}$ **displaced from the minimum of the cos-term, leading to** $\langle\boldsymbol{\phi}\rangle\sim\theta_{QCD}\sim 1$**!**

too low barriers

It must be arranged such that at the end of inflation, the *tilt* disappears:

even if so, one gets: $\Lambda\lesssim 30$ TeV (1000 TeV if the *tilt* changes sign)

Main message of the first explicit model:

QCD-axion + Higgs affords *almost* a "relaxation" mechanism

Main drawbacks:

- Extra $U(1)_{PQ}$-breaking terms needed (origin?)
- θ-problem strikes back
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Beyond the QCD-axion

Origin of $\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n\cos(\phi/f)$

$\boxed{\textbf{n=2:}}$ $\epsilon\Lambda_c^2|H|^2\cos(\phi/f)$

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Λ_c ~ some new-strong sector scale that can be much heavier than Λ_{QCD}

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J.R.Espinosa,C.Grojean,G.Panico,A.P., O.Pujolàs,G.Servant 15

Proposal to go further:
Make the amplitude of the *cos(ϕ/f)*-term also field dependent

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$$A\cos(\phi/f) \longrightarrow$$ Field-dependent amplitude:

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

new field σ "scanning" the amplitude

J.R.Espinosa,C.Grojean,G.Panico,A.P.,
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$$\boxed{V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda} + \frac{g_\sigma\sigma}{\Lambda}\right) + m^2(\phi)|H|^2 + A(\phi,\sigma,H)\cos\left(\phi/f\right)}$$

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spurions

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we'll be taking $\Lambda \sim \Lambda_c$ and try to see how far away can be pushed up

ALPine Cosmology:

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

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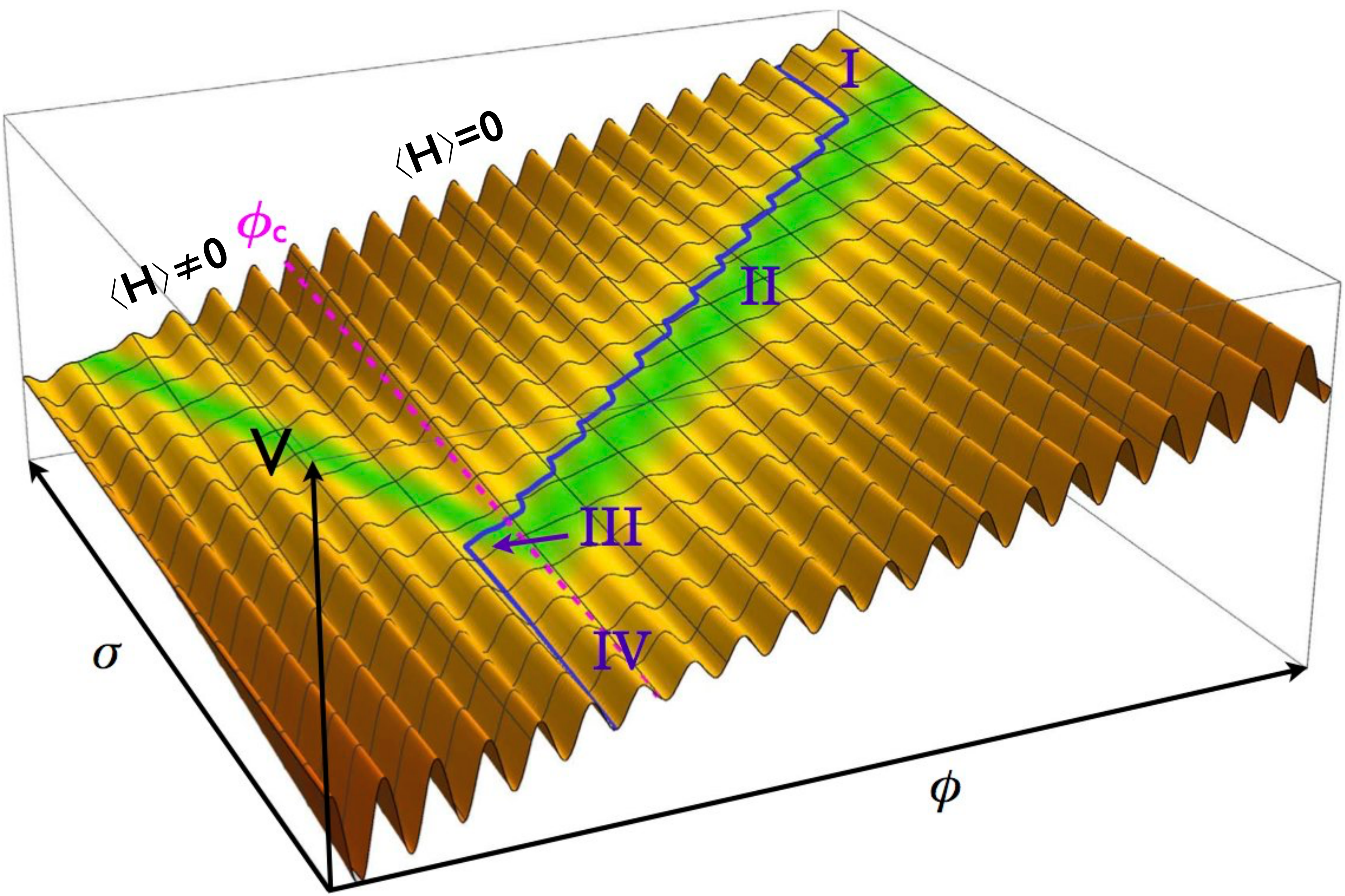

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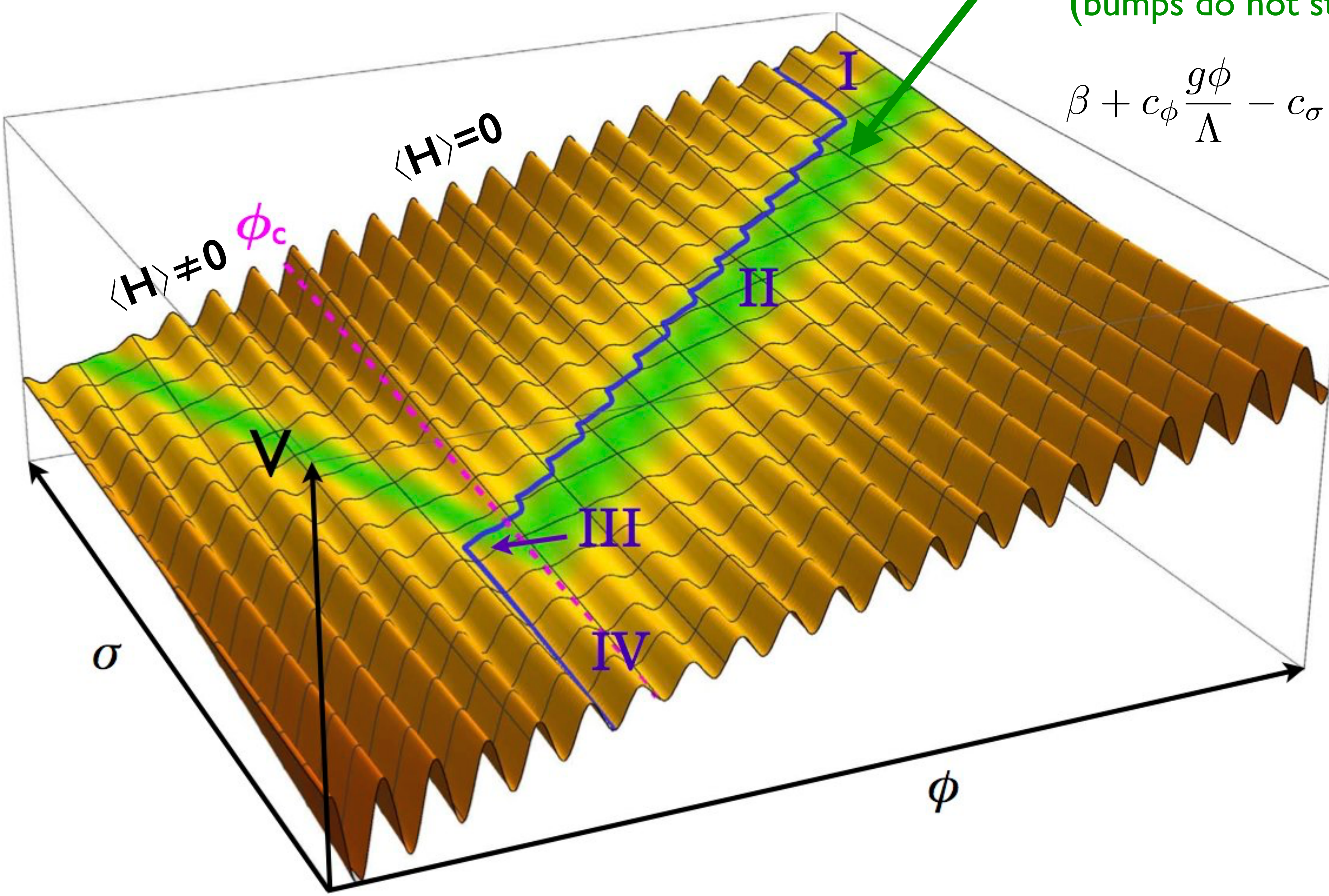
area where A≈0

(bumps do not stop ϕ)

$$\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda}\approx 0$$



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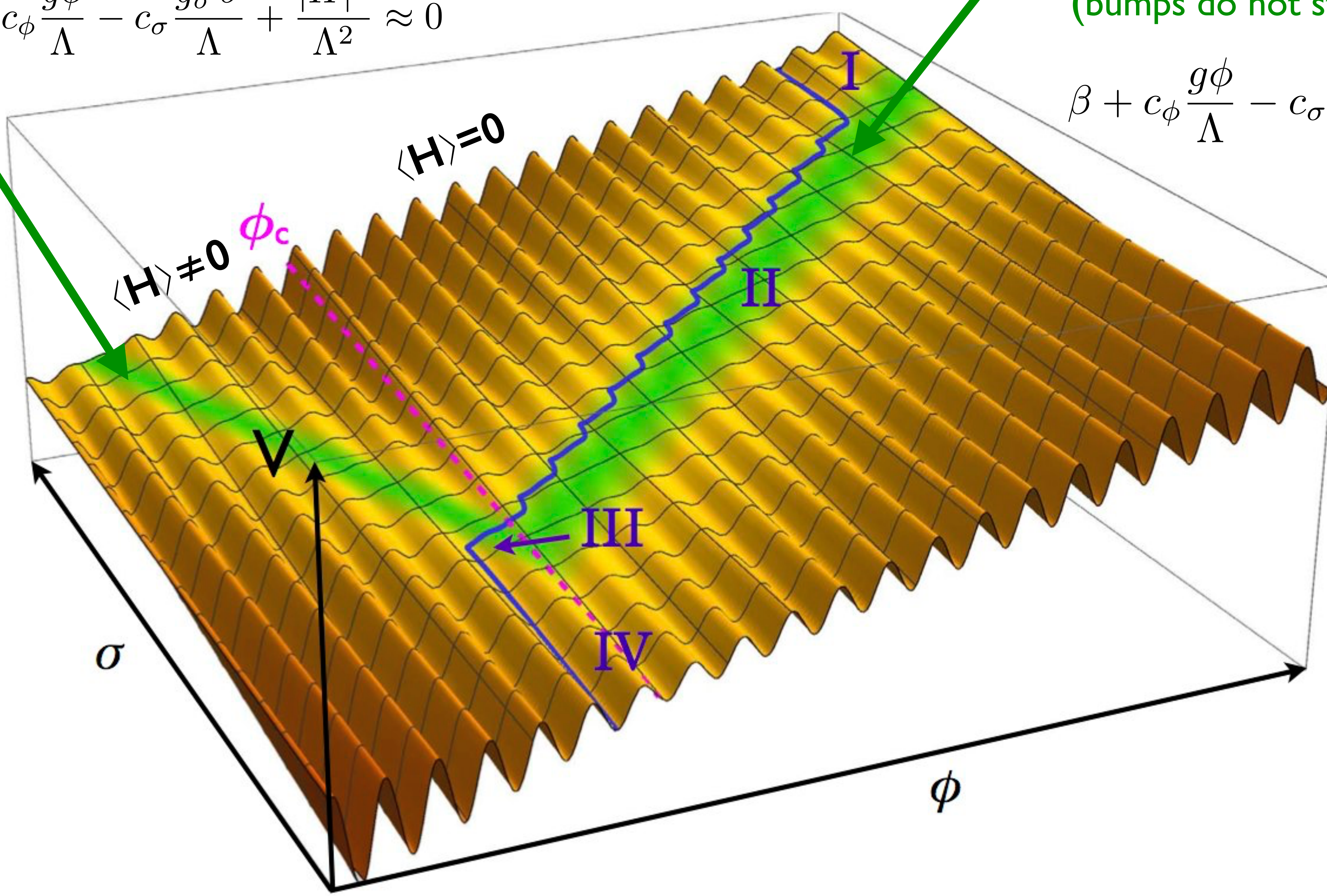

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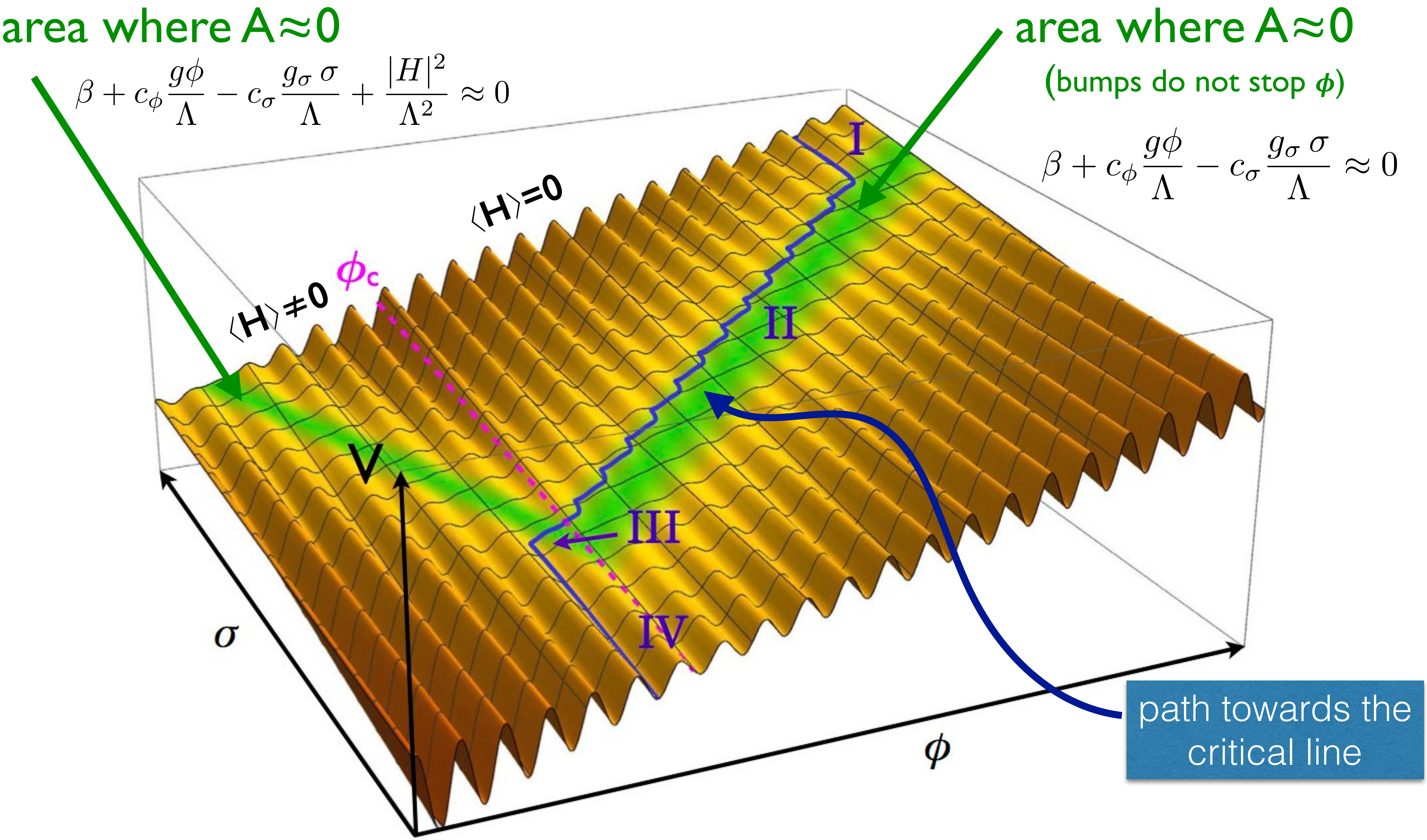
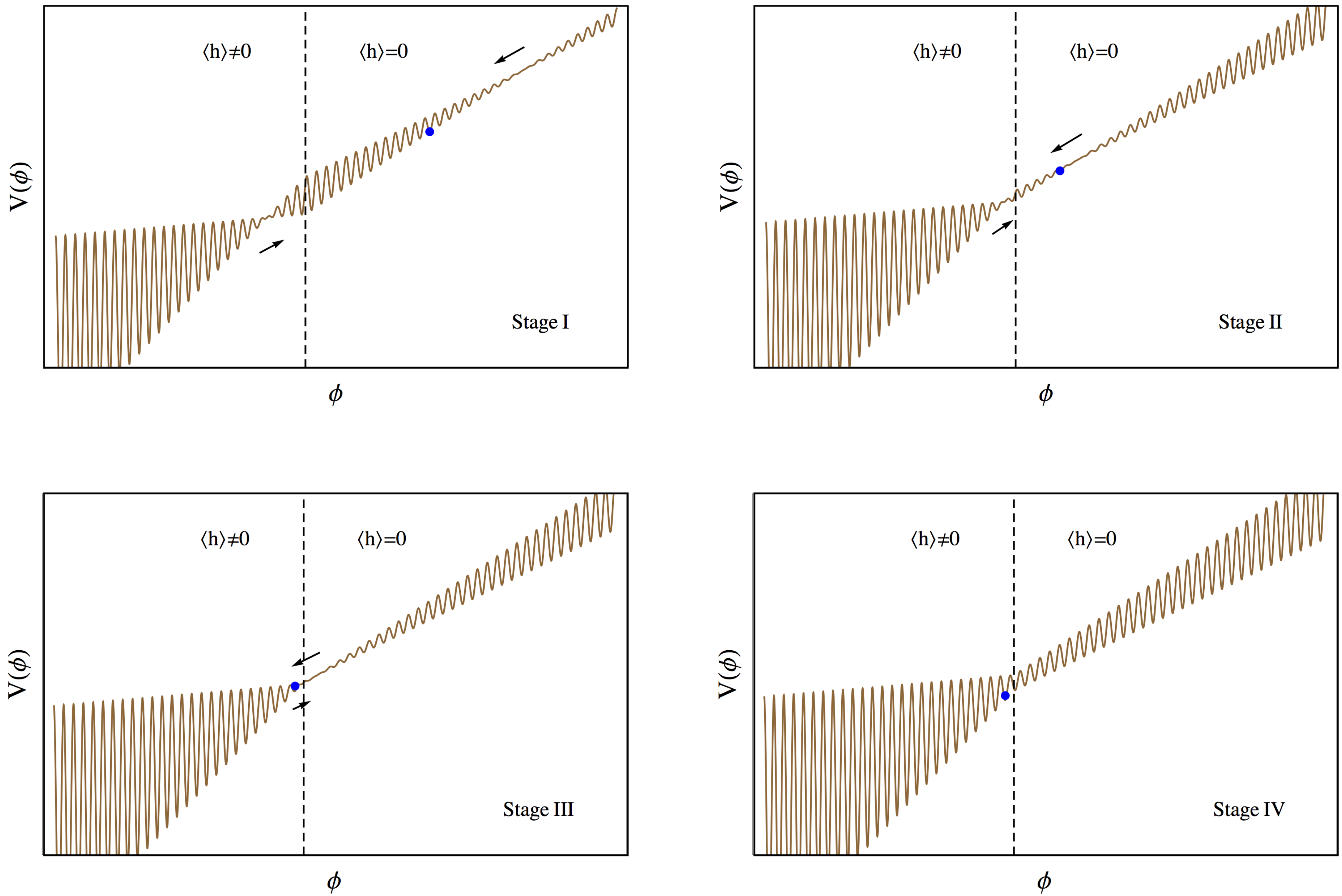


Two scanner model: "The Movie"



from J.R. Espinosa

EW SCALE AS COSMOLOGICAL ERRATIC

okotoks glacial erratic,
Alberta, Canada

Conditions on parameters:

- $\epsilon \lesssim v^2/\Lambda^2$ to avoid to be dominated by terms like $\epsilon^2\Lambda^4\cos^2(\phi/f)$
- $H_I^3 \lesssim g_\sigma \Lambda^3$ to avoid quantum wiggles spoiling classical rolling
- $g_\sigma \lesssim g$ to avoid ϕ not tracking σ
- $\dfrac{\Lambda^2}{M_P} \lesssim H_I$ to avoid ϕ & σ affect inflation

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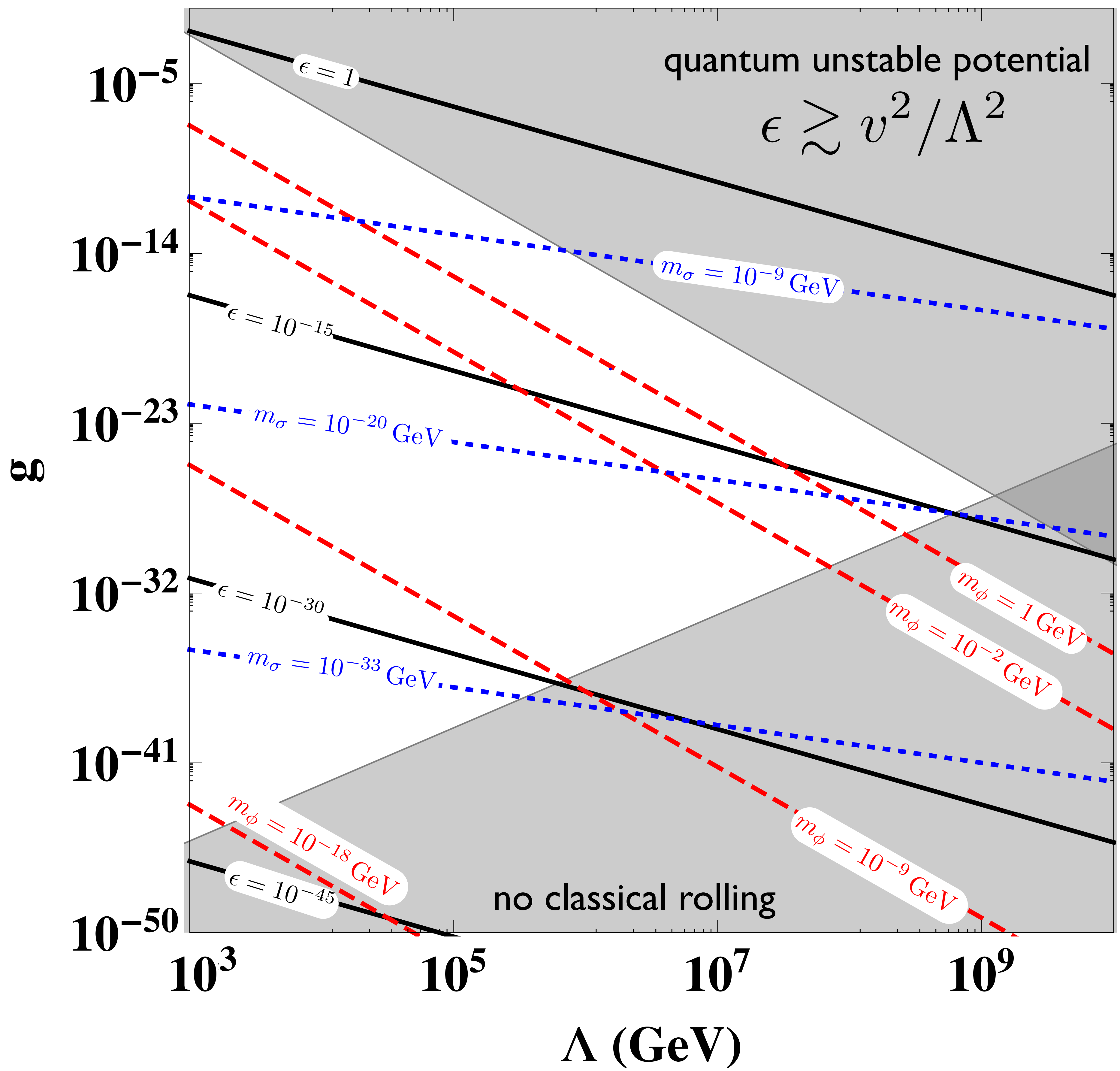
Minimization: $v^2 \simeq \dfrac{g\Lambda f}{\epsilon}$

$$\frac{\Lambda^3}{M_P^3} \lesssim g_\sigma \lesssim g \lesssim \frac{v^4}{f\Lambda^3} \longrightarrow \boxed{\Lambda \lesssim (v^4 M_P^3)^{1/7} \simeq 2\times 10^9\,\mathrm{GeV}}$$

not yet fully solving the hierarchy problem
but pushing Λ beyond LHC & future colliders reach !

Taking $g_\sigma \sim 0.1g$ & $f \sim \Lambda$



Phenomenological consequences

Phenomenological consequences

- Nothing at the LHC to be discovered!
- Only BSM below Λ:

ϕ & σ: Light scalars weakly-coupled to the SM

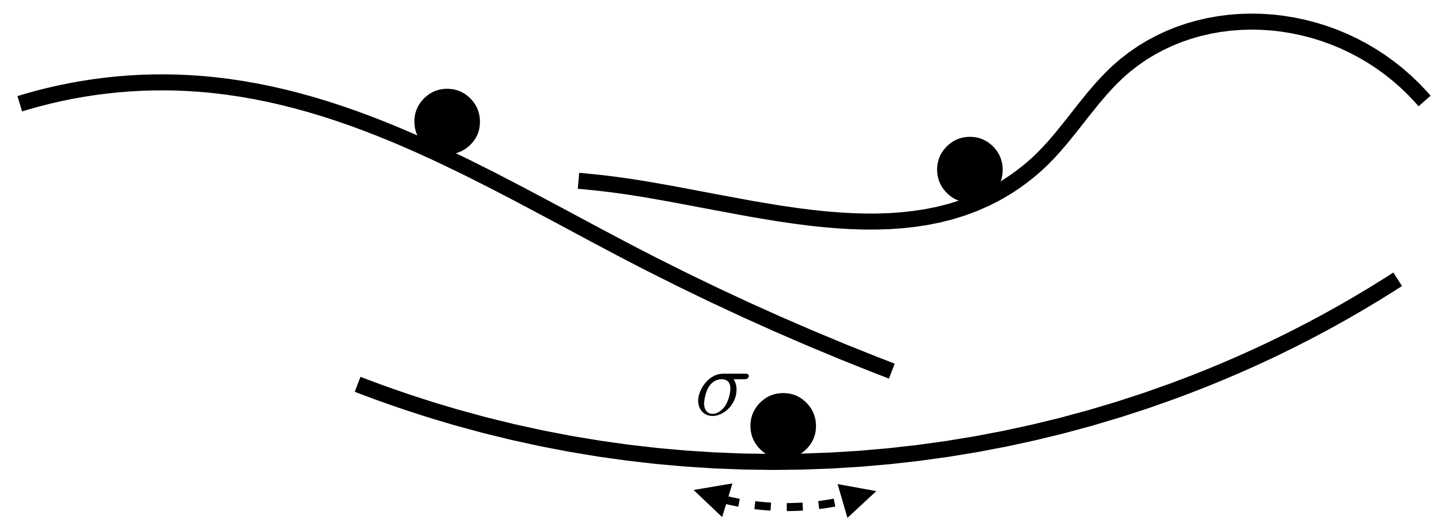
e.g. $m_\phi \sim 10^{-20} - 10^{2}$ GeV

$m_\sigma \sim 10^{-45} - 10^{-2}$ GeV

coupled to the SM through the Higgs:

$$\epsilon\, |H|^2 \cos \phi/f\,, \quad g\phi|H|^2$$

Physics of the *Slow-Rollers*



quantum spreading $\sim \sqrt{N_e} H_I$

Obvious consequences:

- Epochs of inflation
- Late classical oscillations (Dark Matter)

$$\rho^{\sigma}_{ini} \sim H_I^4$$

$$\rho_\sigma(T) \sim \rho^{\sigma}_{ini}(T/T_{osc})^3 \rightarrow \boxed{\Omega_\sigma \gtrsim \left(\frac{10^{-27}}{g_\sigma}\right)^{3/2} \left(\frac{\Lambda}{10^8 \text{ GeV}}\right)^{13/2}}$$

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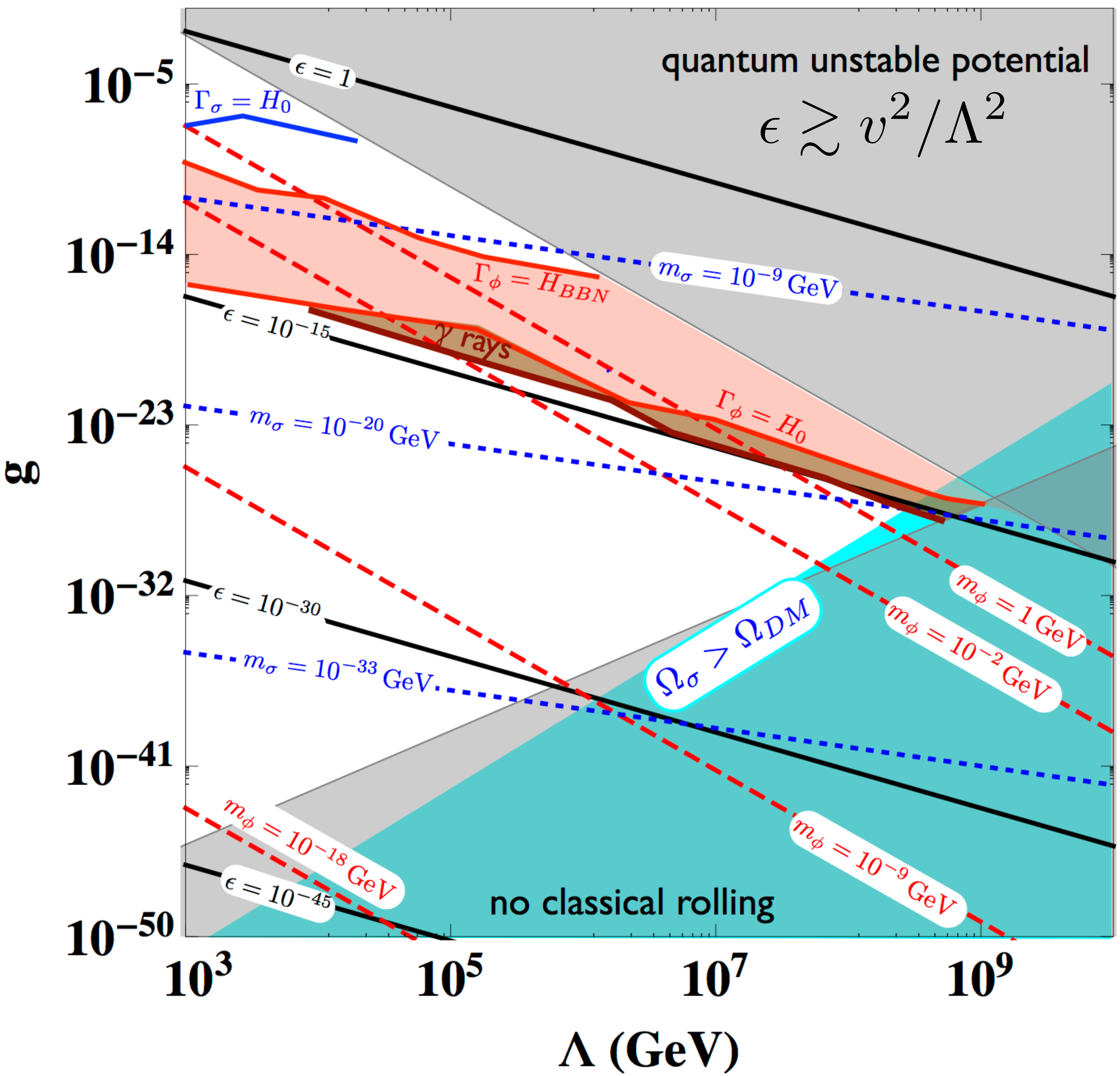

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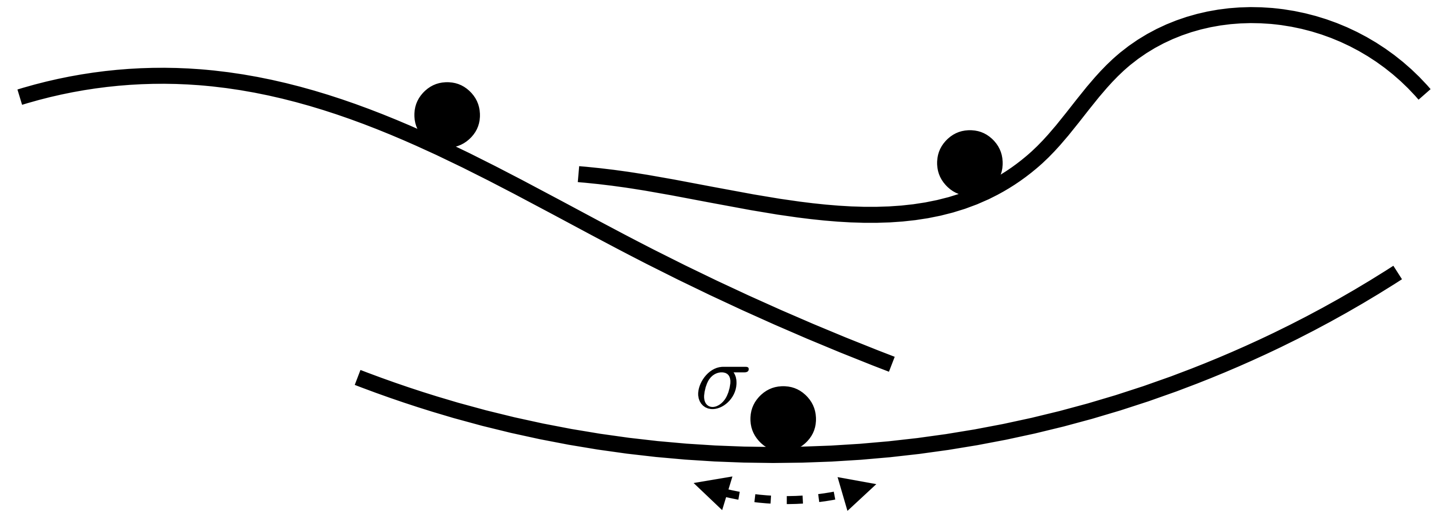

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- Oscillations can affect the gravitational potential/waves:

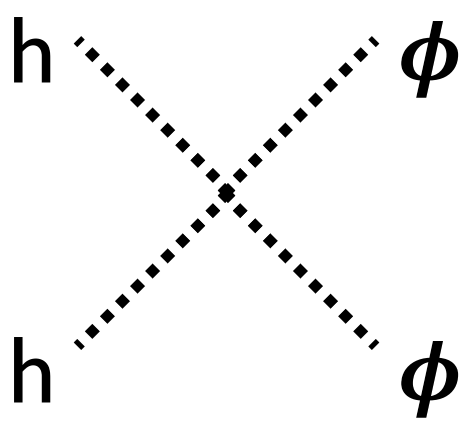
Structure formation: $10^{-32}\ \mathrm{eV} \lesssim m_\sigma \lesssim 10^{-25.5}\ \mathrm{eV}$ astro-ph.CO/1410.2896

Pulsar timing: $m_\sigma \sim 10^{-24}\ \mathrm{eV}$ astro-ph.CO/1309.5888

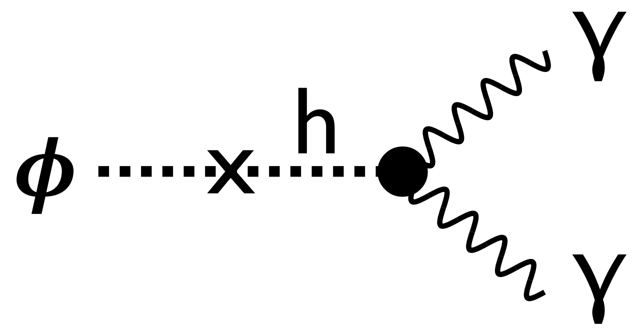
Grav. waves from BH+Axion systems: $m_\sigma \sim 10^{-11}\ \mathrm{eV}$ hep-ph/1411.2263

Indirect detection:

- Late decays of ϕ, produced in the early universe, can affect Big Bang Nucleosynthesis, CMB or the (extra) galactic diffuse γ-ray background:

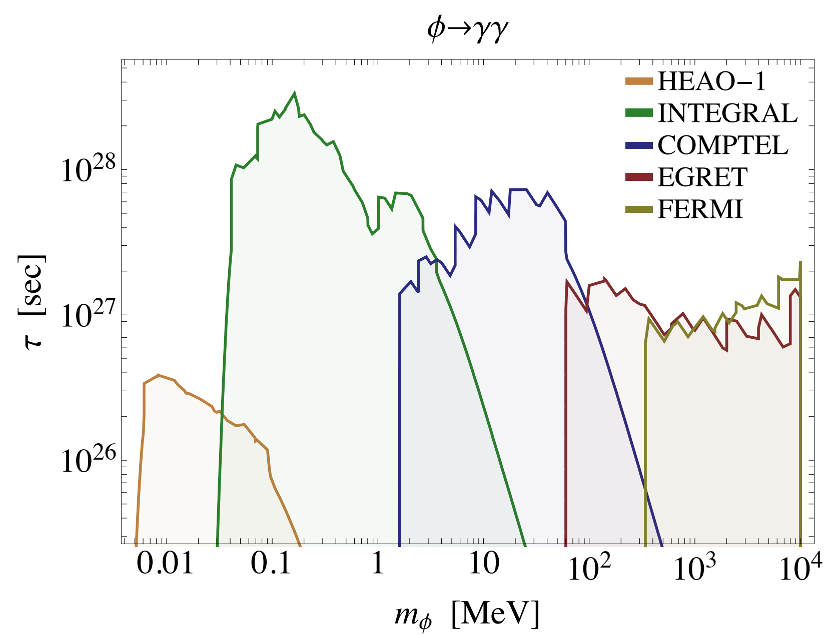


&

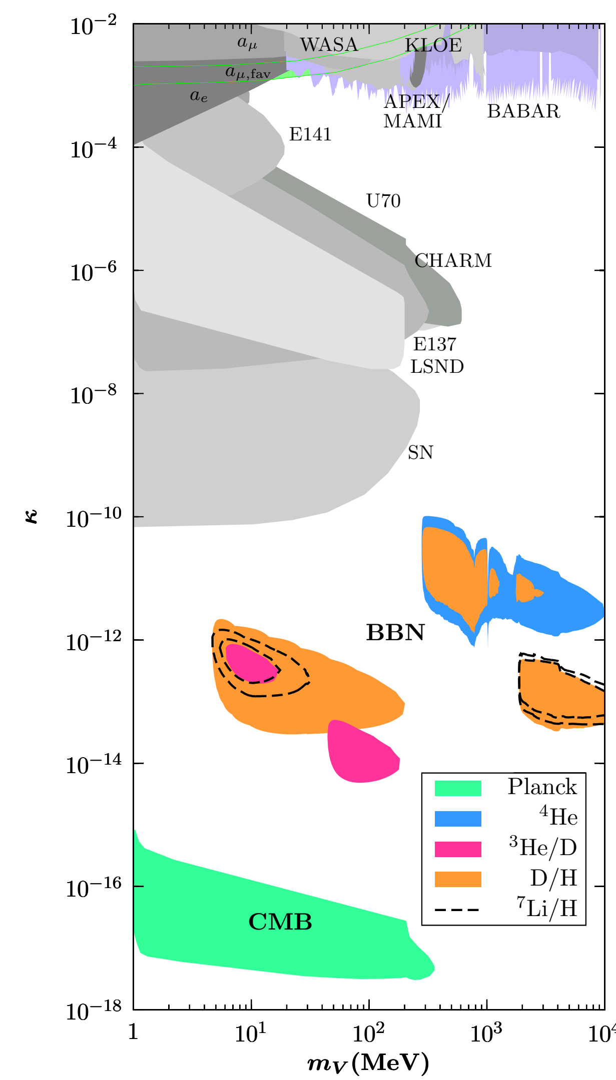


for a vector DM mixing with γ:

Bounds:



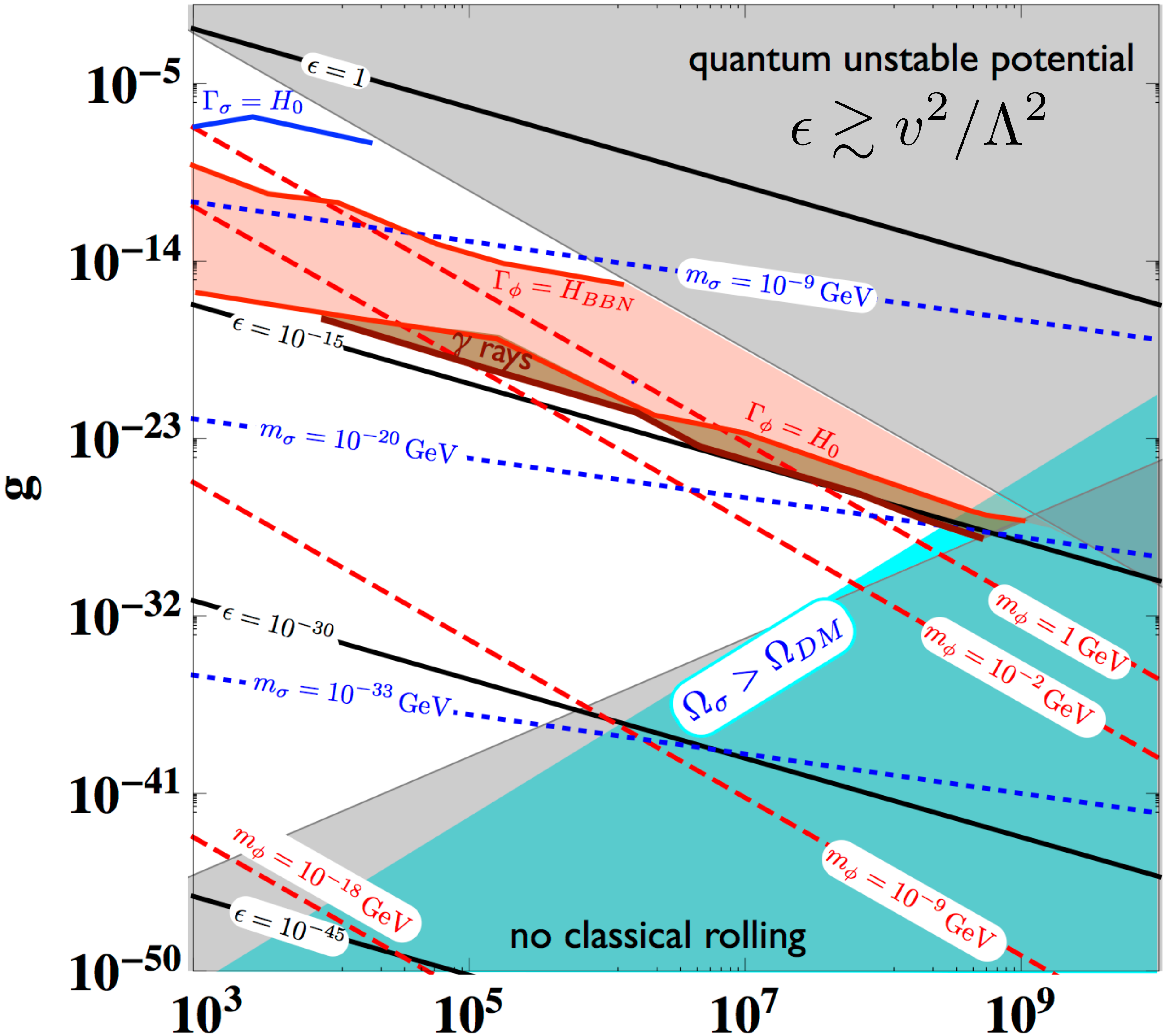
arXiv:1309.4091



arXiv:1407.0993

- Table-top experiments (fifth-force, EPV) ? Hopeless at present!

Taking $g_\sigma \sim 0.1g$ & $f \sim \Lambda$



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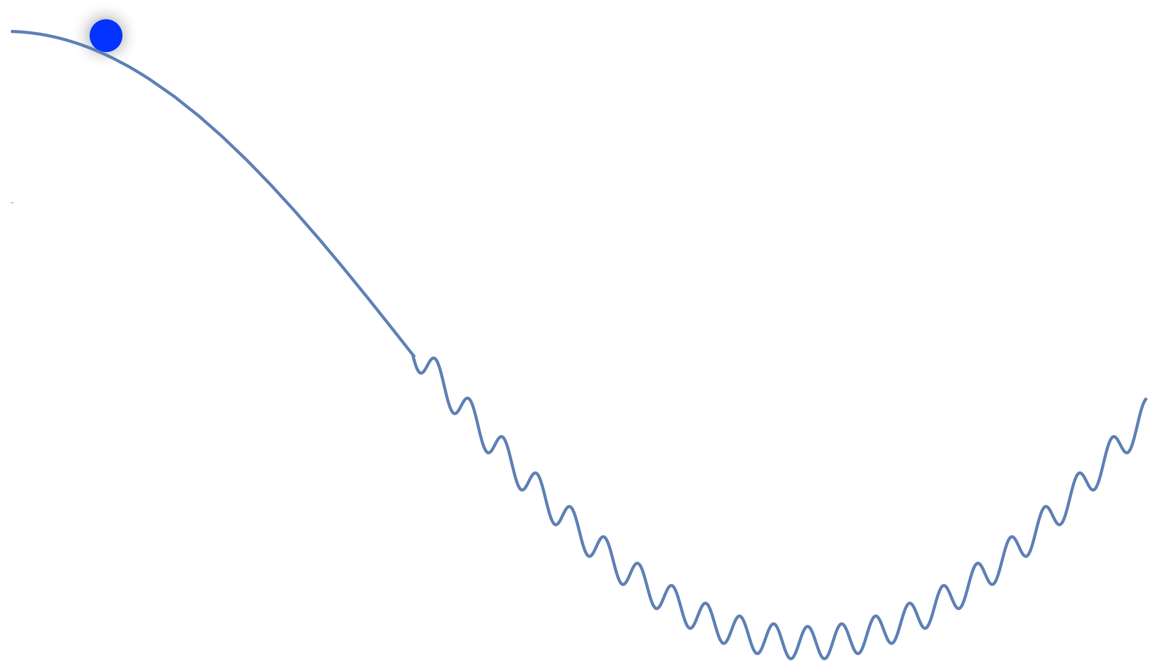
K.Choi and S.H.Im 15

D.Kaplan,R.Rattazzi 15

"Kicking" term *via* mixing with other axions:

Generate two cos-terms with different decay-constants, f and F, with F≫f

$$\cos(\phi/F) \qquad\qquad h^2 \cos(\phi/f)$$



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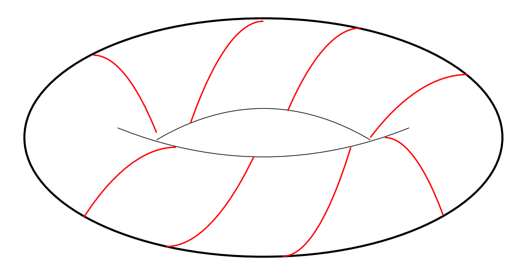

light axion has an elongated field range by winding *n*-times around the torus

K.Choi and S.H.Im 15
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$$\Lambda^4 \gg \epsilon f_2^4 \gg \Lambda_{\rm br}^4$$

Lighter-axion eff. terms:

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$$\Lambda_{\rm br}^4(h)\cos\left(\frac{\phi}{f} + \delta_1\right)$$

$$f_{\rm eff} \;=\; \sqrt{n^2 f_1^2 + f_2^2} \equiv n f.$$

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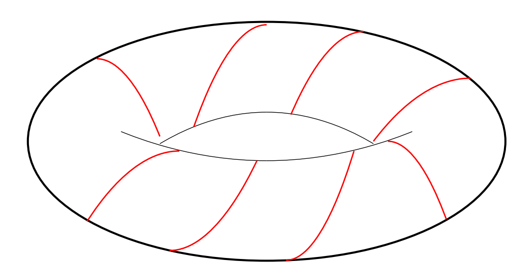

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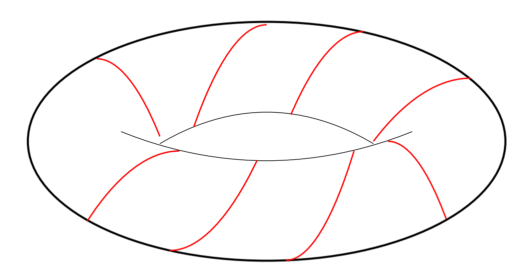


light axion has an elongated field range by winding *n*-times around the torus

One axion ➔ … ➔ N-axions: $f_{\rm eff} \sim n^N f$

Supersymmetric UV completion (at Λ)

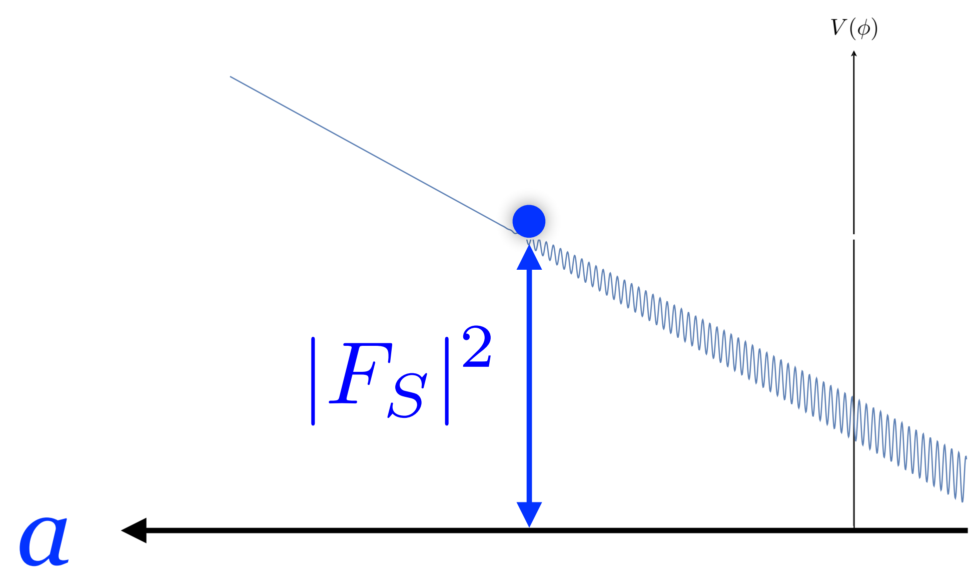
Batell,Giudice,McCullough 15

Fits nicely:

axion

$$S = \frac{s + i\,a}{\sqrt{2}} + \sqrt{2}\,\theta\,\tilde{a} + \theta^2\,F$$

$$\boxed{\textbf{MSSM} \quad + \int d^2\theta \left[S\mathcal{W}^a\mathcal{W}^a + mS^2 \right]}$$



For nonzero a,

supersymmetry is broken,

Higgs mass notice this breaking → $m_H(a)$

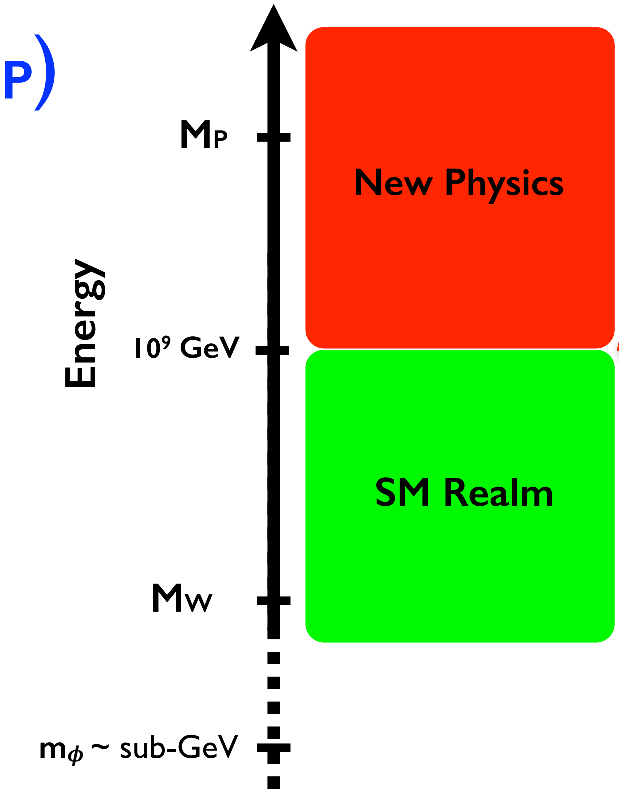
Conclusions

"Relaxation" mechanism can give a natural explanation for

$\langle h\rangle \sim 100$ **GeV** $\ll \Lambda \sim 10^9$ **GeV** (not yet $\Lambda \sim M_P$)

based on a cosmological history of the

Higgs & axion-like states



The good: Change of paradigm:

- No big colliders needed!
- The new-physics are weakly-coupled light states

Other type of experiments needed:

- Astro (γ-rays, pulsar timing, …), CMB, table-top (fifth-force searches, EPV), …

The bad & ugly: it cannot (yet) fully solve the hierarchy problem, $N_e > 10^{38}$, super-Plankian field excursions, explanation of the smallness of g


RESTRICTED AREA
MONITORED
BY VIDEO
CAMERA

UV origin of the periodic term beyond QCD:

Strong sector

a la QCD

with a light fermion: *N*

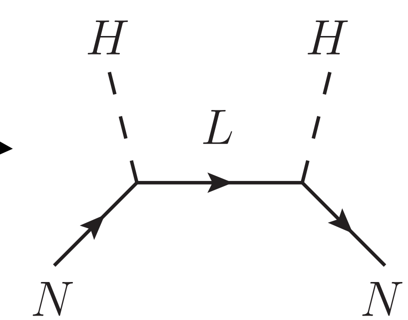
+ Axion-like ϕ

$$\frac{\phi}{f} G'_{\mu\nu} \widetilde{G}'^{\mu\nu}$$

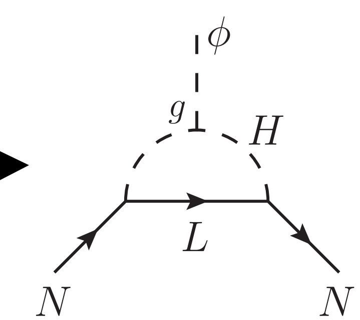
Axion potential: $\boxed{V \simeq \Lambda^3 m_N \cos(\phi/f)}$

Assuming mass of ***N*** given by:

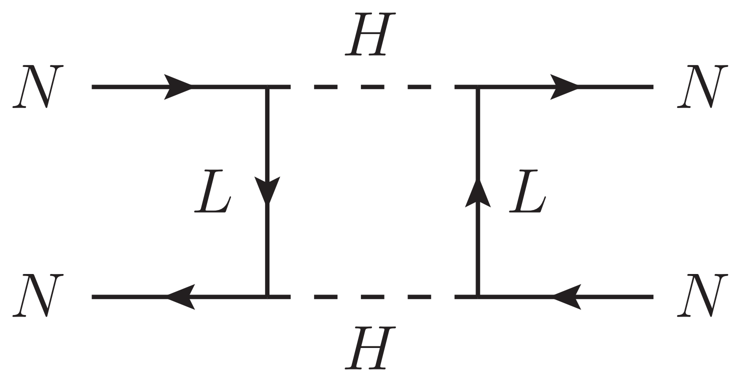
from integrating
a fermion-doublet *L*



$$m_N \simeq \epsilon \left(\Lambda + g_\sigma \sigma + g\phi - \frac{|H|^2}{\Lambda} \right)$$



Dangerous terms from



$$(\overline{N} N e^{i\phi/f})^2$$

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

gives a barrier for $\boldsymbol{\phi}$
independent of H !

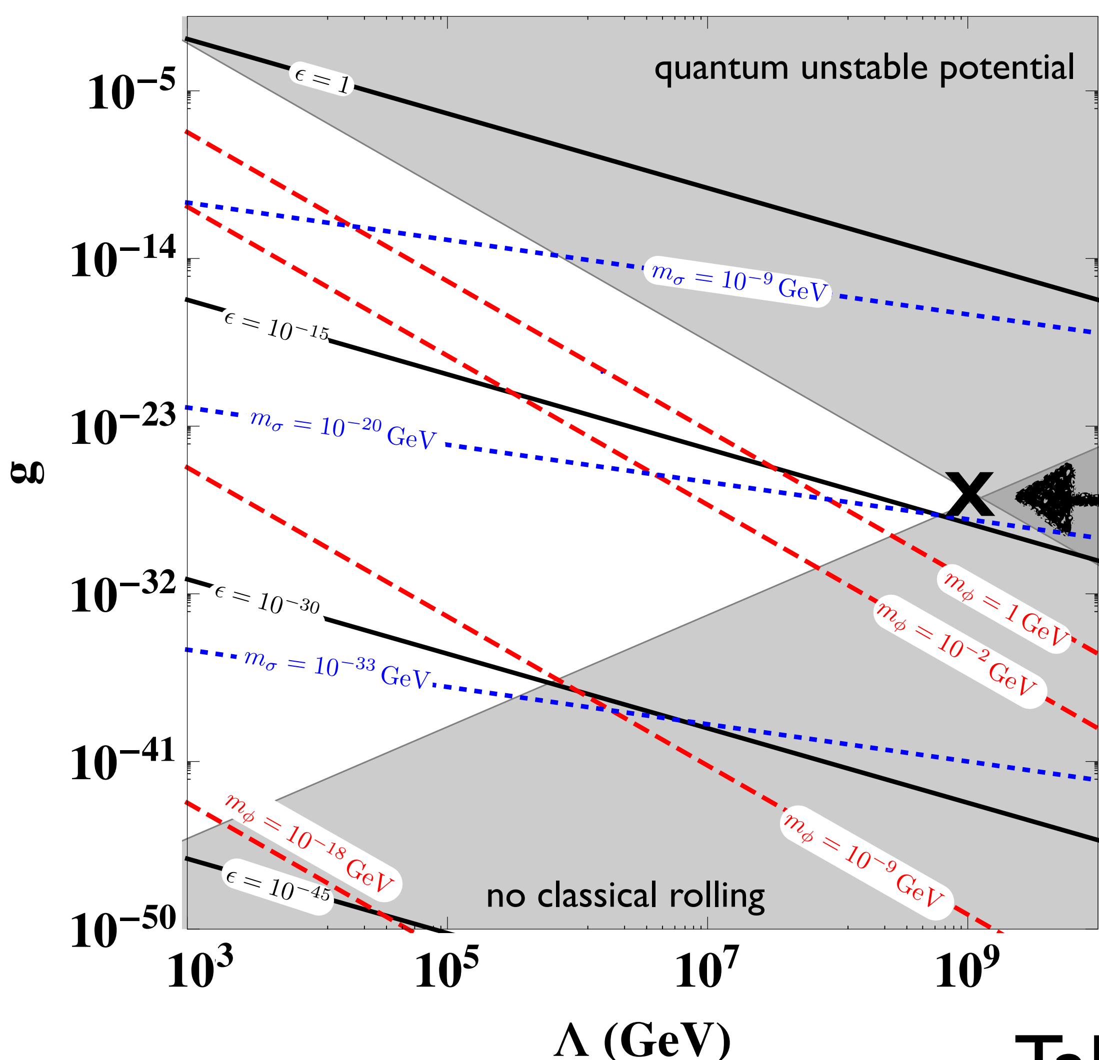
Benchmark values: $\Lambda \sim 10^9$ GeV ☛ $m_\phi \sim 100$ GeV

$\theta_{\phi h} \sim 10^{-21}$

$\phi\phi$hh-coupling ~ 10^{-14}

$m_\sigma \sim 10^{-18}$ GeV

$\theta_{\sigma h} \sim 10^{-50}$



Taking $g_\sigma \sim 0.1g$ & $f \sim \Lambda$