Dynamical relaxation to critical points

A new approach to the hierarchy problem

Alex Pomarol, 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

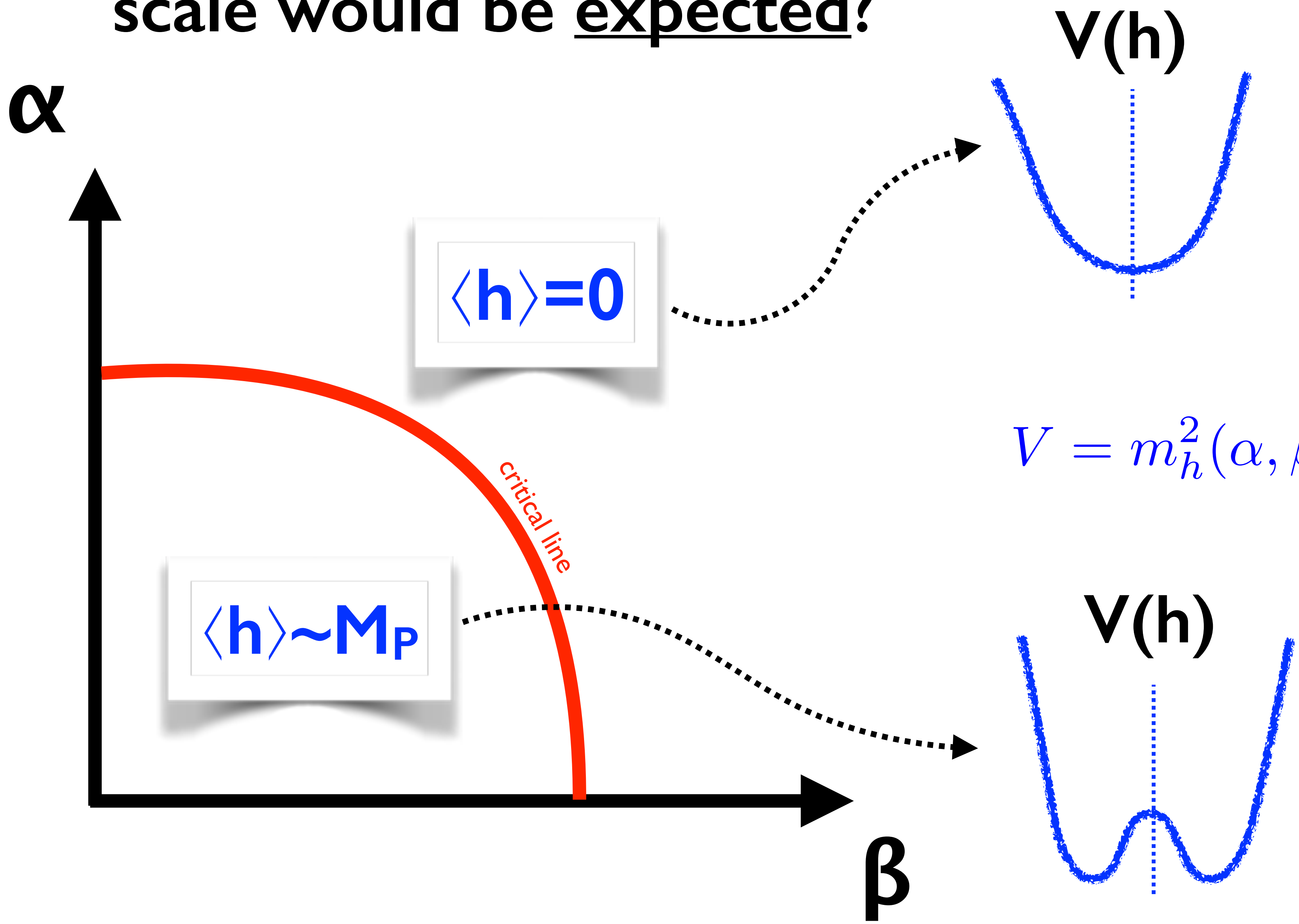
(see also earlier work by
Abbott 85, G.Dvali, A.Vilenkin 04, G.Dvali 06)

- Point out the impressive successes:
  First example of natural solutions
  in which **No New-Physics required at TeV**
- Drawbacks and reasons for improvement

work based on
J.R.Espinosa, C.Grojean, G.Panico, A.P.,
O.Pujolàs, G.Servant
arXiv:1506.09217

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

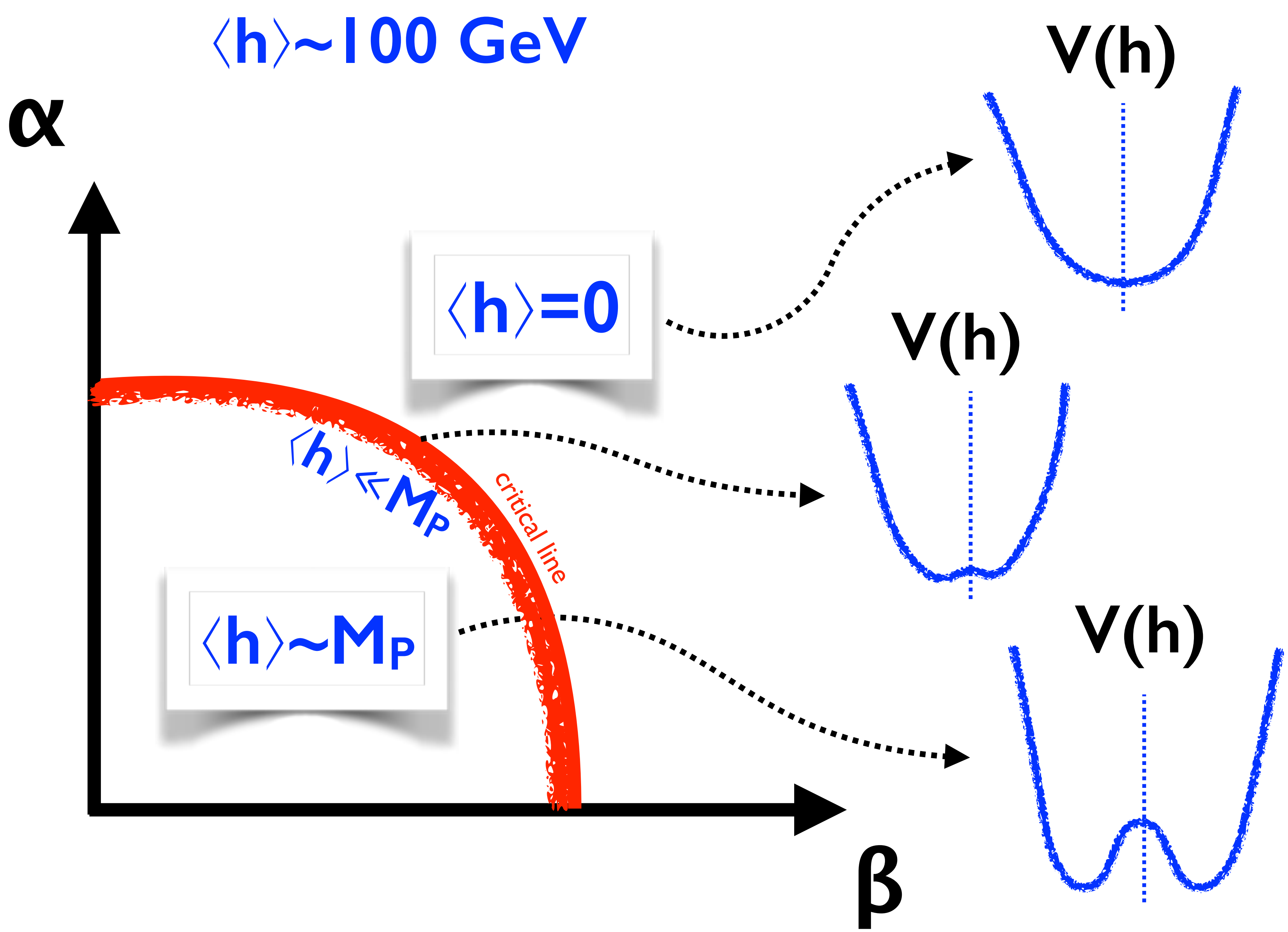
- **Where the Electroweak Symmetry Breaking (EWSB) scale would be <u>expected</u>?**



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

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

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



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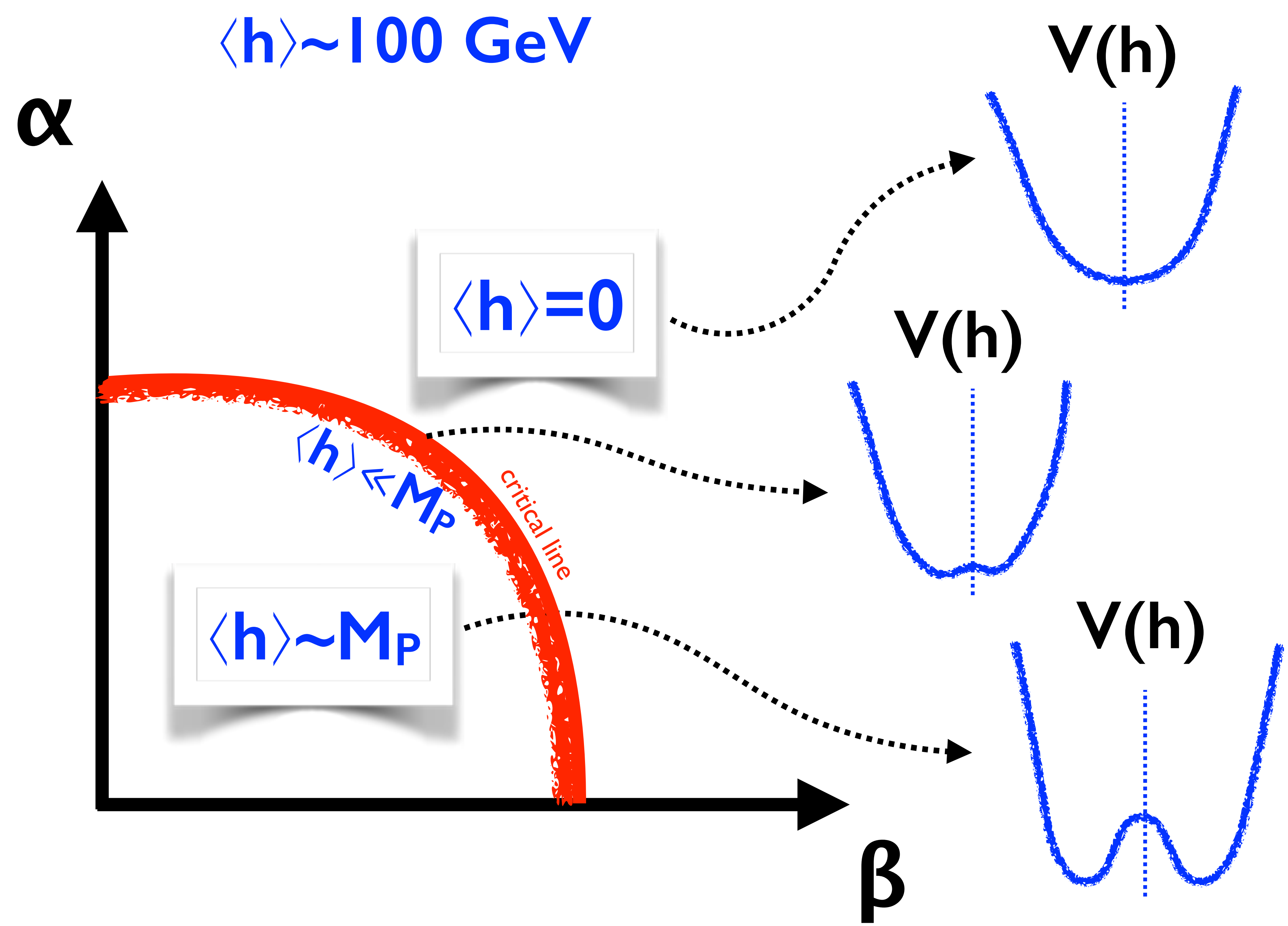


<u>Hierarchy problem</u>: Why nature is so close to the critical line?

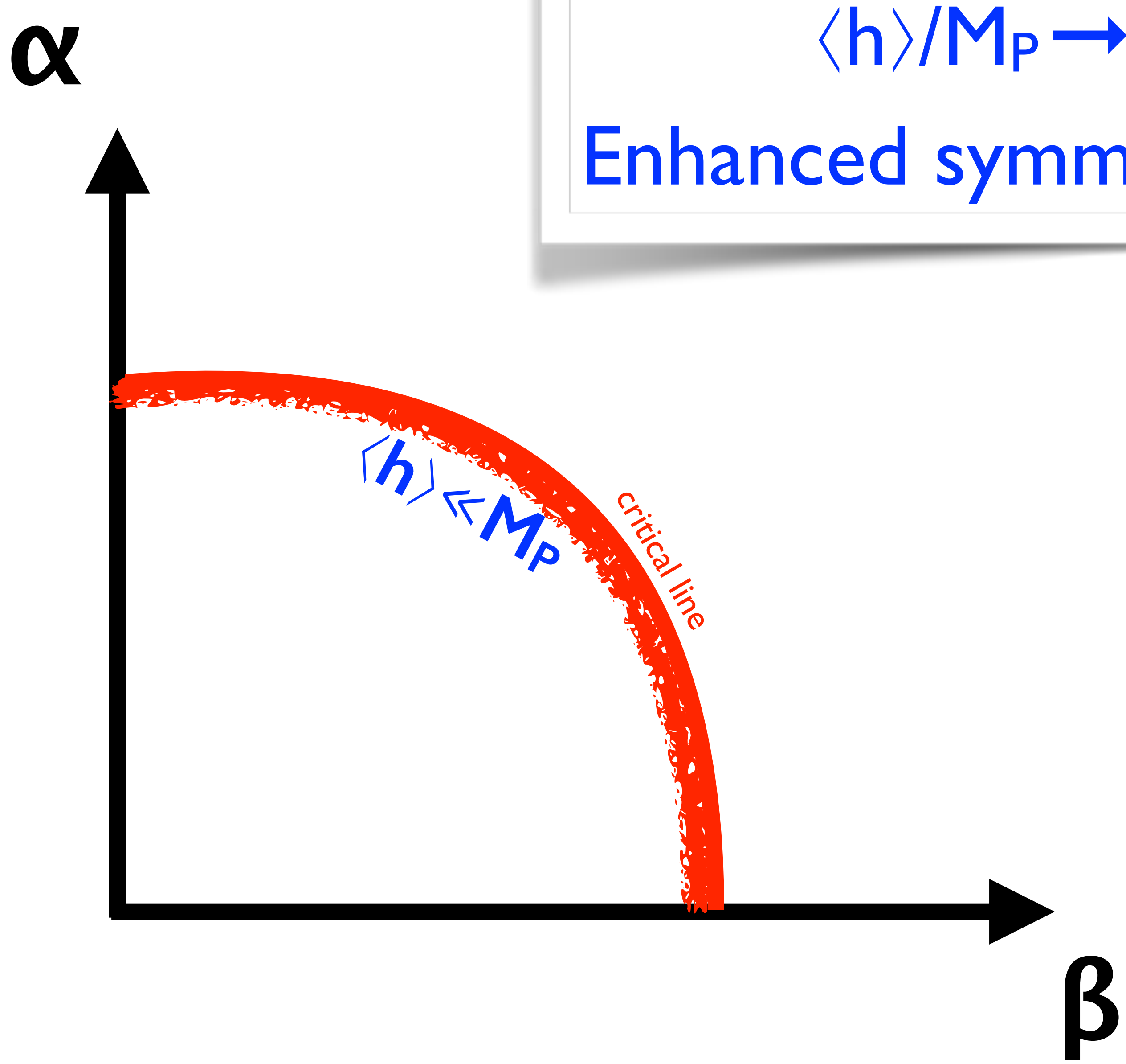
Needs a tuning of parameters to get $\langle h\rangle \ll M_P$

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

One solution:

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

Enhanced symmetry ☛ *Supersymmetry*



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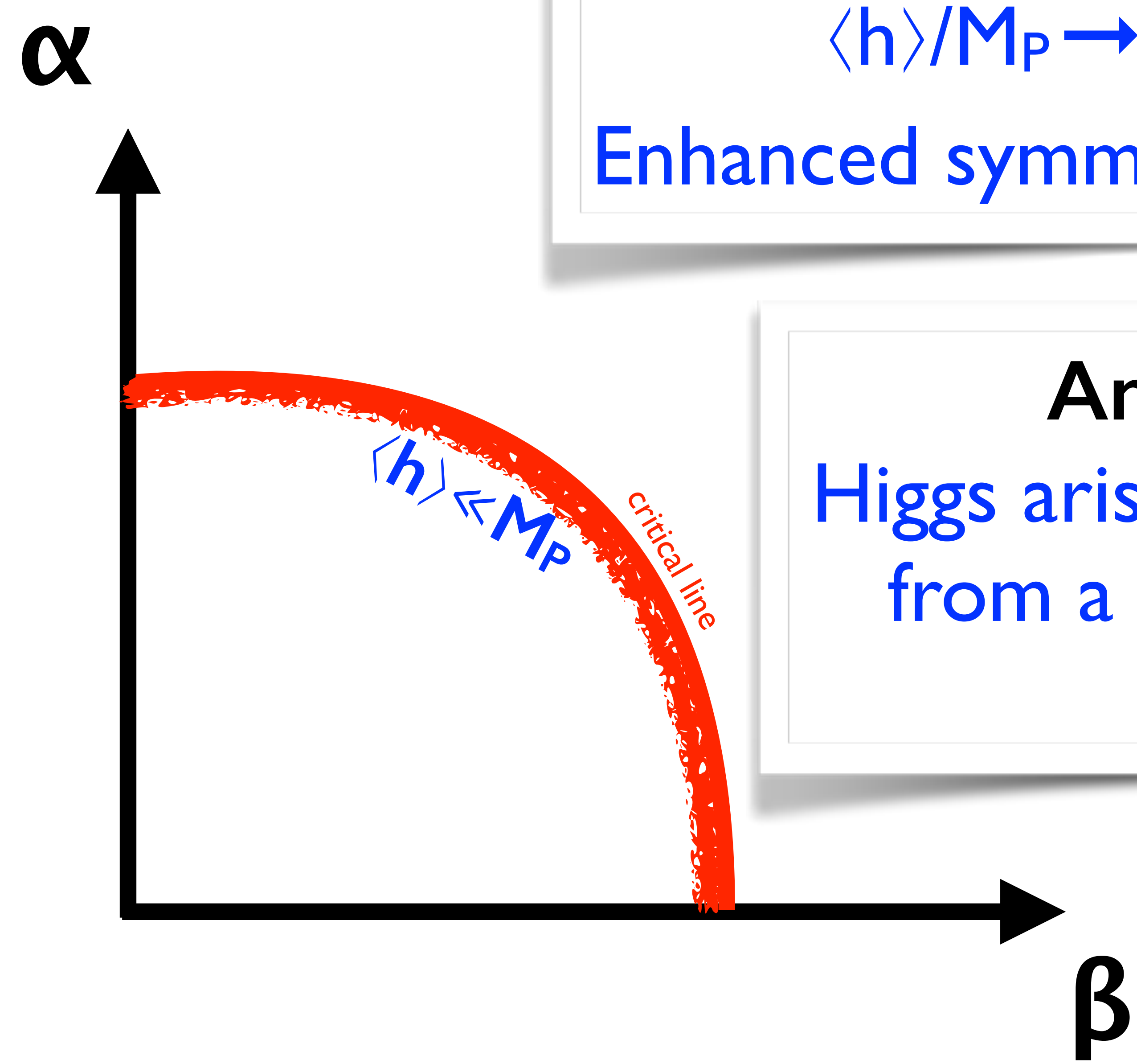

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Higgs arises as a *composite* state
from a new strong dynamics
(a la QCD)

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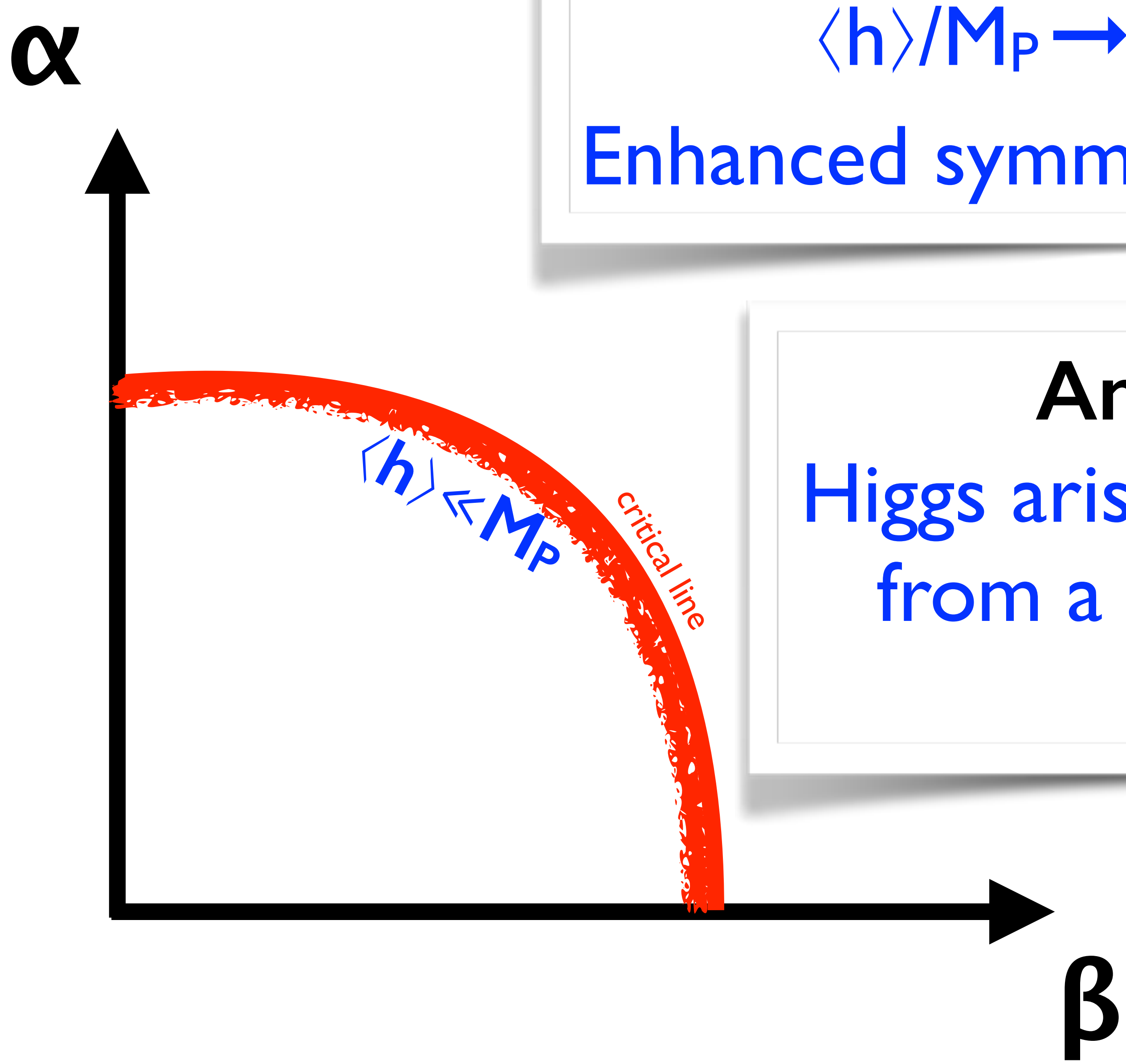

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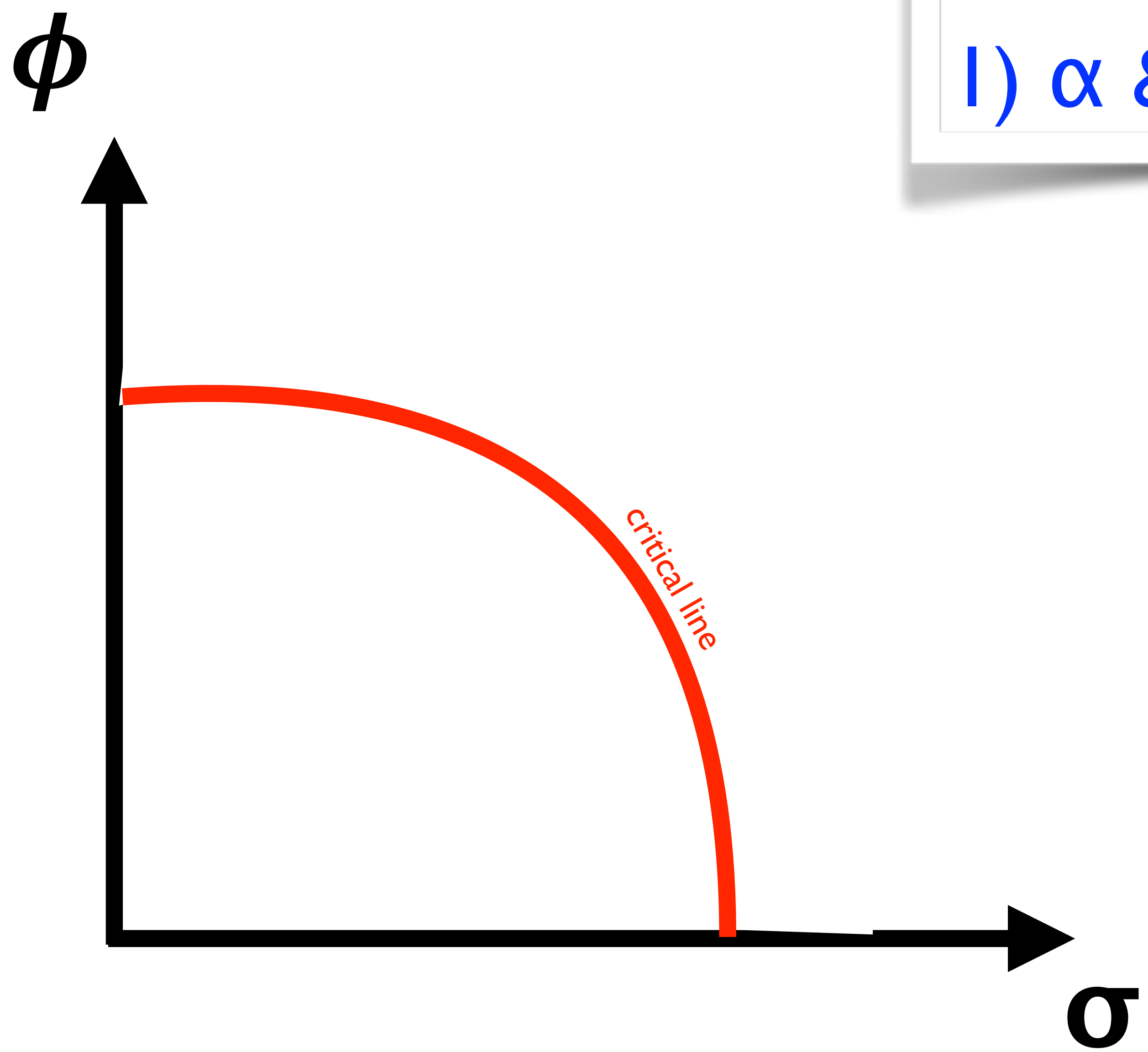
In both cases, TeV new-physics expected!

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

New 3rd possibility:

1) α &β are fields → ϕ & σ



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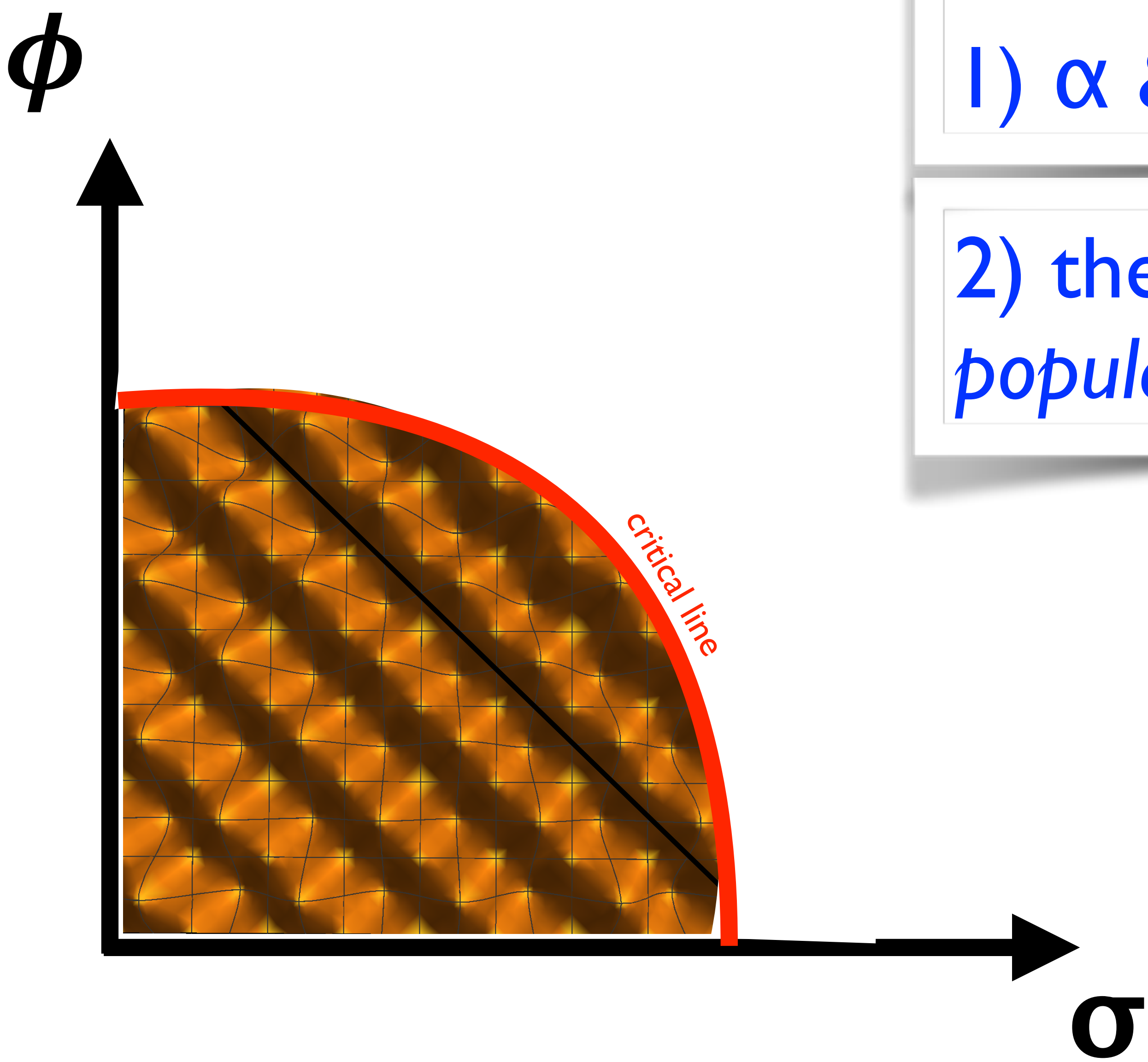

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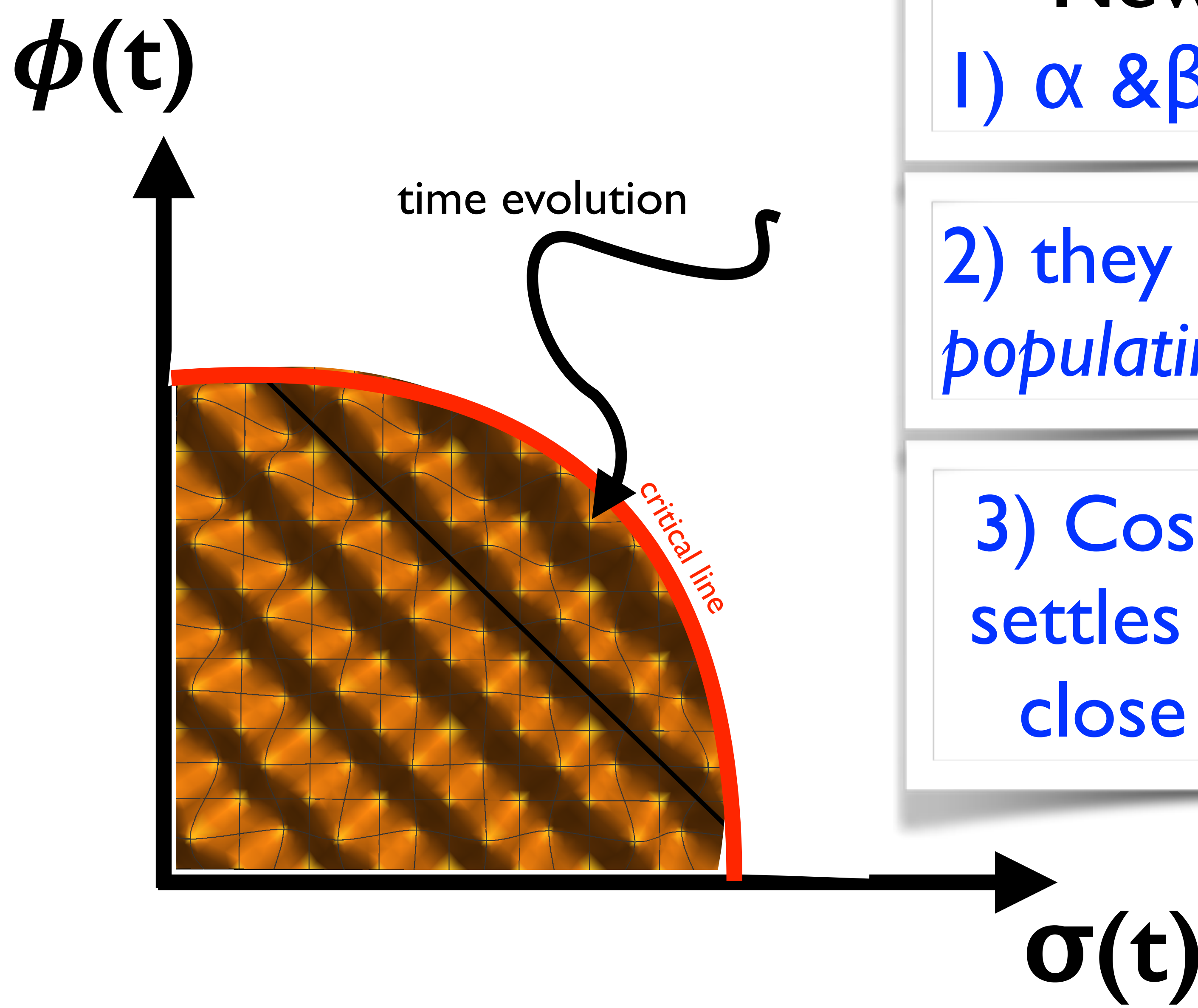
Hierarchy problem: Why nature is so close to the critical line?



New 3rd possibility:

1) α & β are fields $\rightarrow$ ϕ & σ

2) they have local minima *populating* the broken phase

3) Cosmological evolution settles them in a minimum close to the critical line

Explicit example:

Higgs-mass parameter $\longrightarrow$ Field-dependent Higgs mass

$$\frac{1}{2}m^2h^2 \qquad\qquad \frac{1}{2}m^2(\phi)h^2$$

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

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

ϕ must be stabilized where **m²(*ϕ*)** is negative and ≪ **Λ²**:

$$\phi \longleftarrow \overset{m^2<0}{\rule{3cm}{0.4pt}} \underset{\phi_c \equiv \Lambda/g}{|} \overset{m^2>0}{\rule{3cm}{0.4pt}}$$

Notice that large field excursions for ***ϕ*** needed: ***ϕ*~Λ/g≫Λ**

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

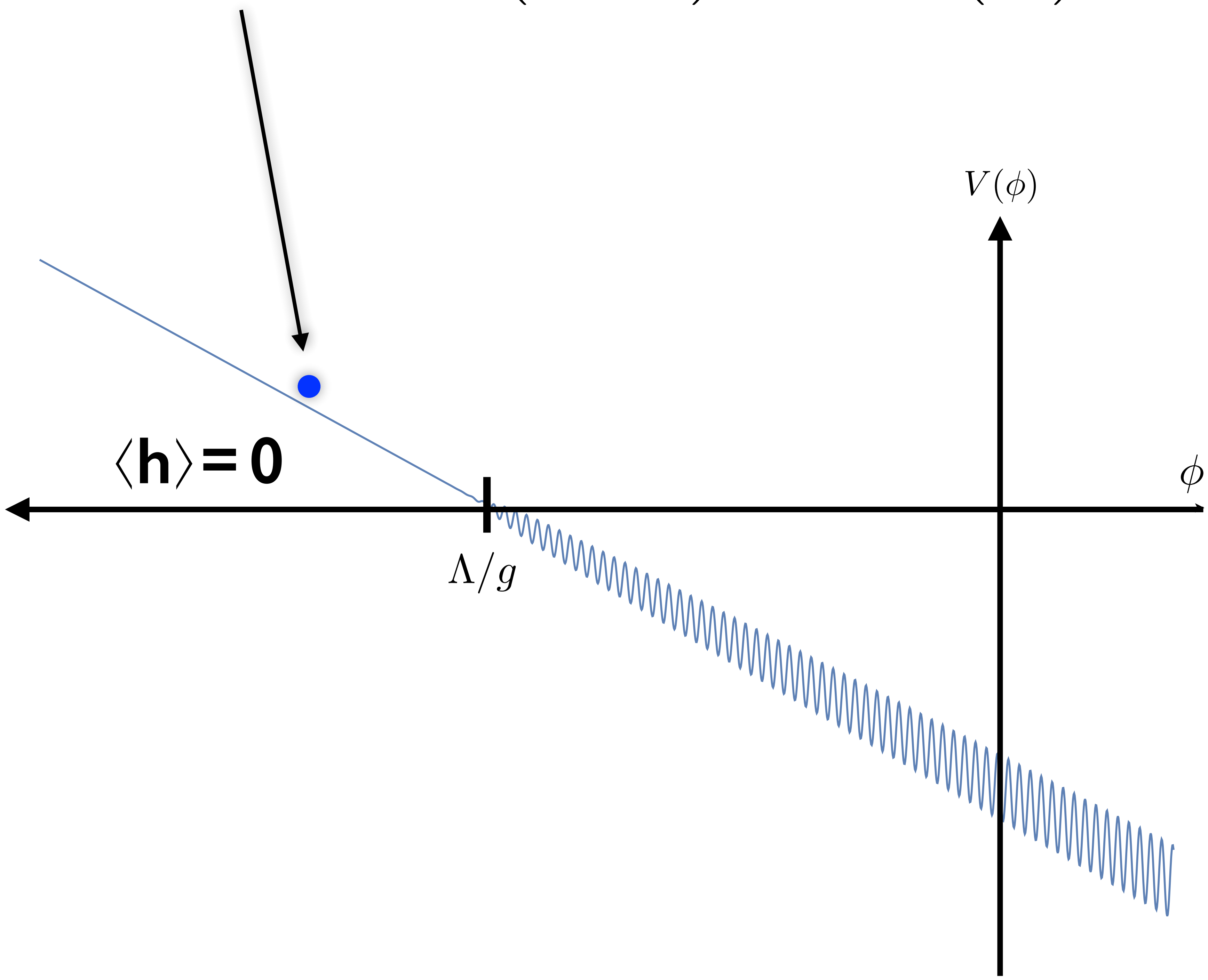
Spurions:

g $\ll$ **1** : breaking shift symmetry $\phi \to \phi + c$

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

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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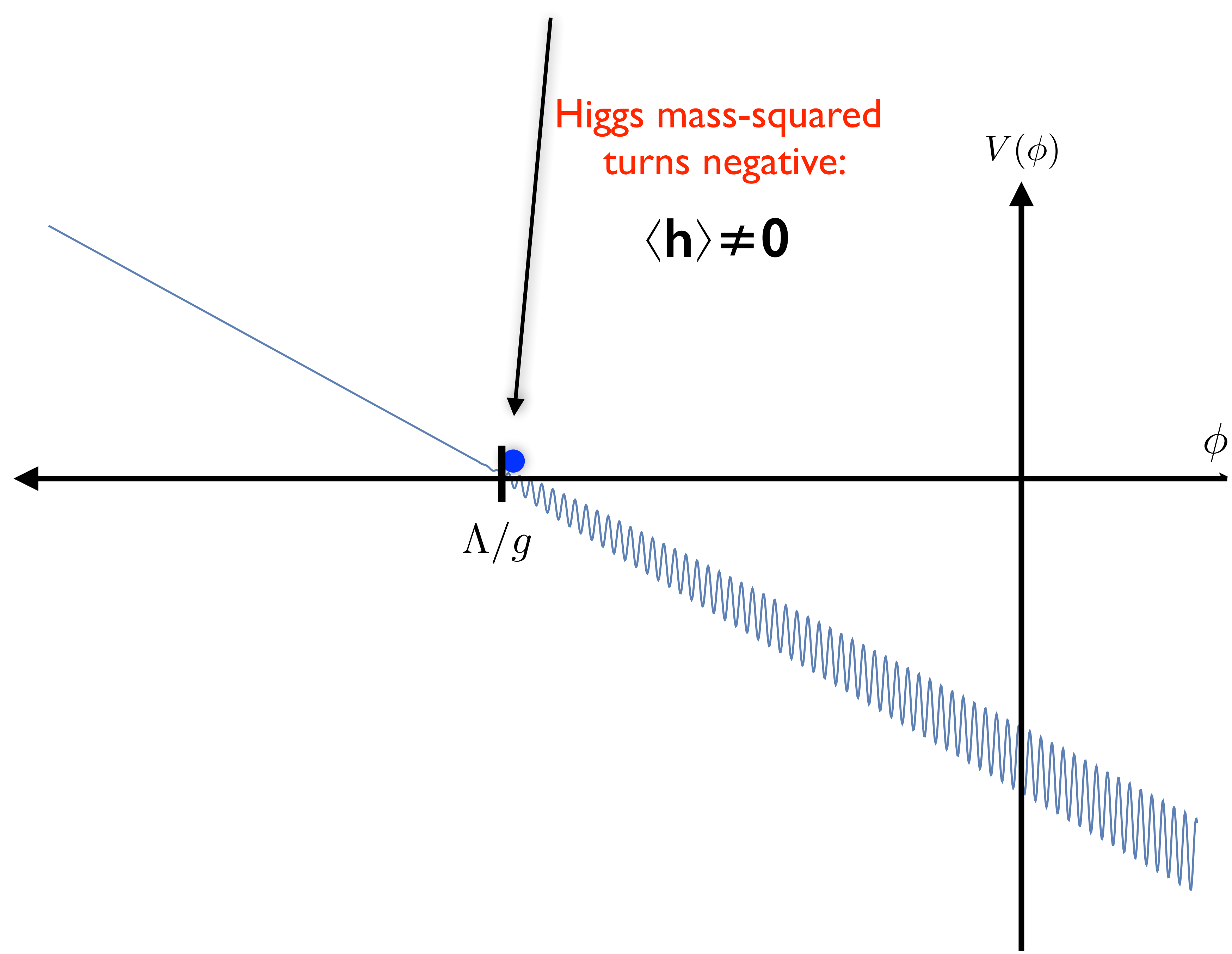

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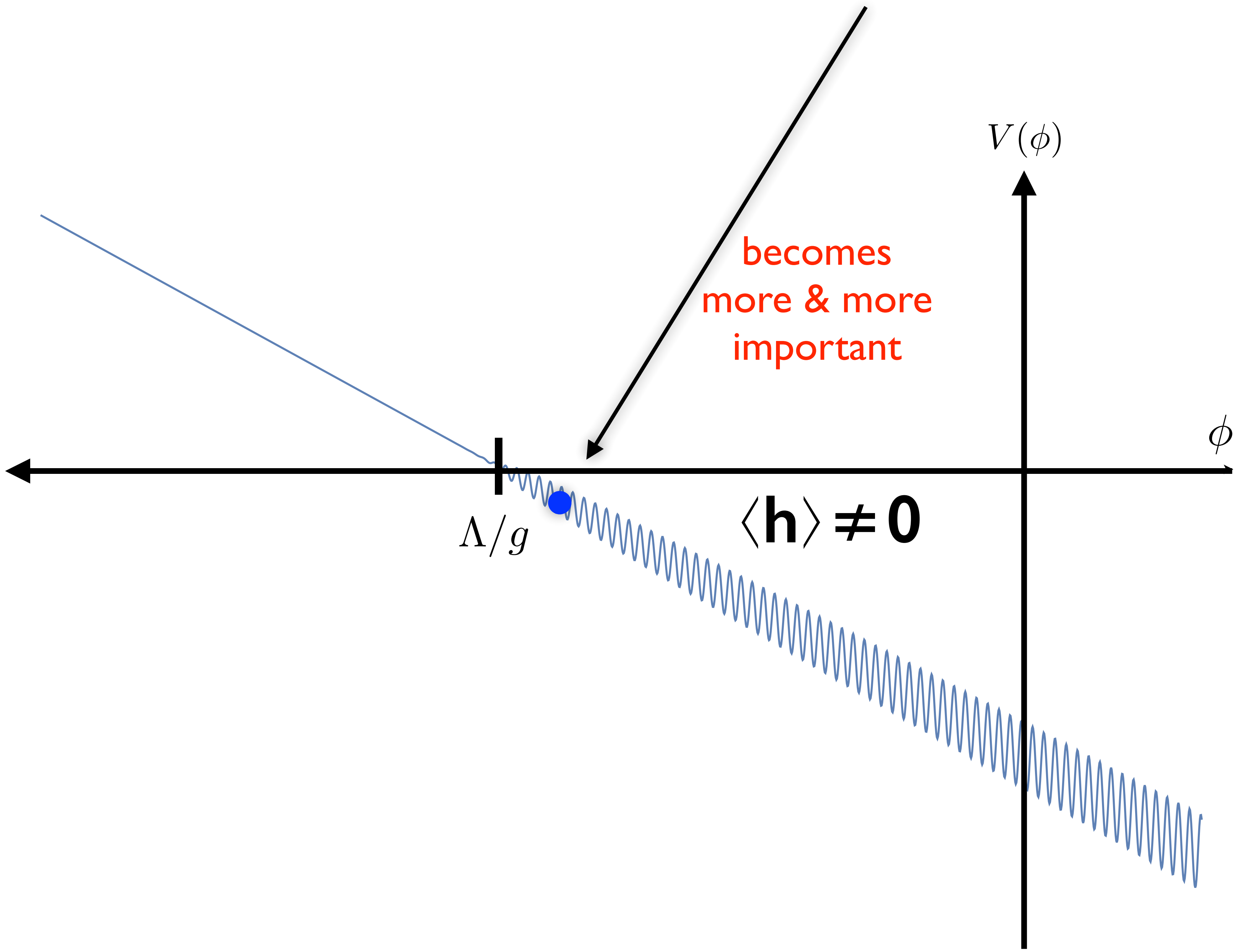

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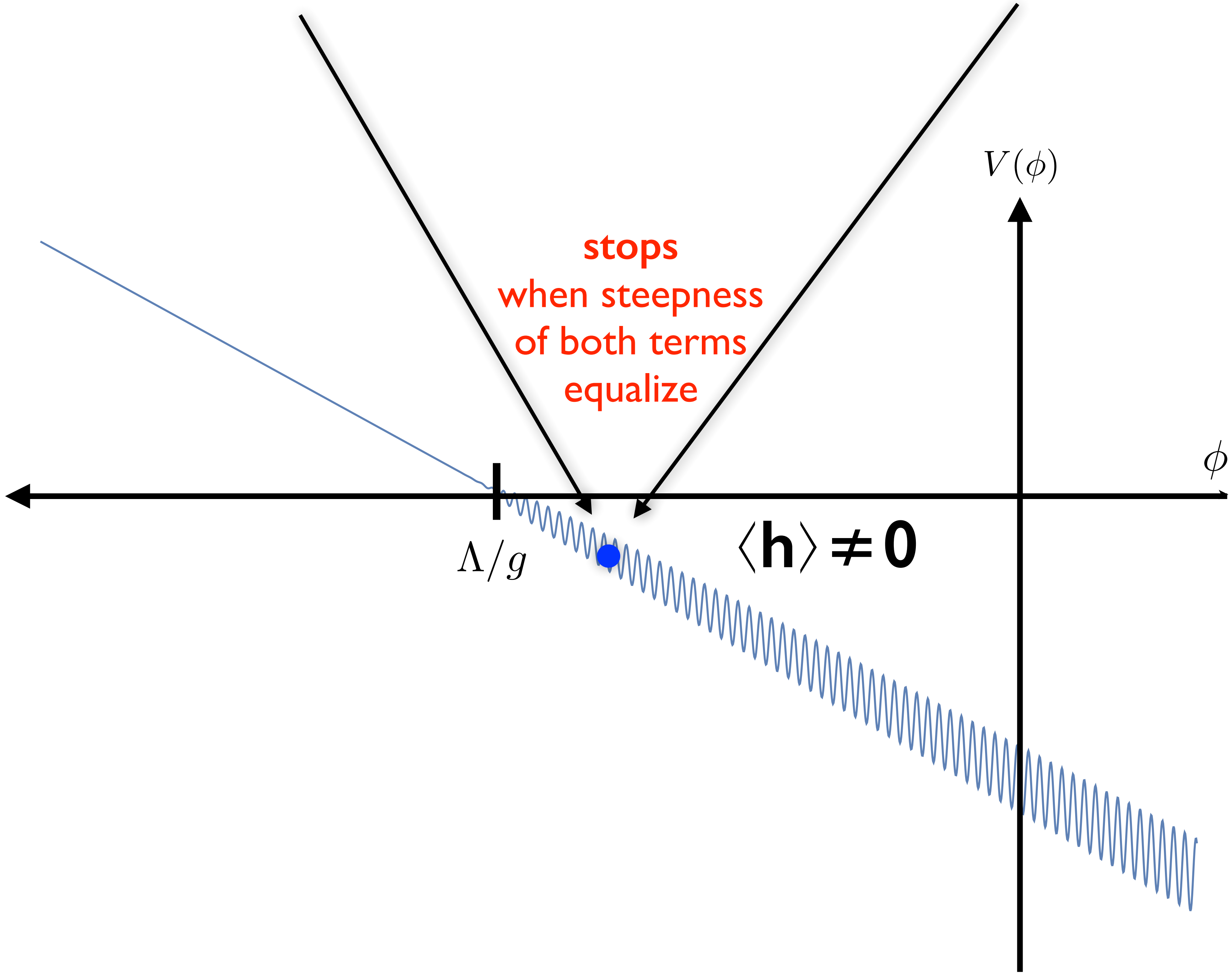

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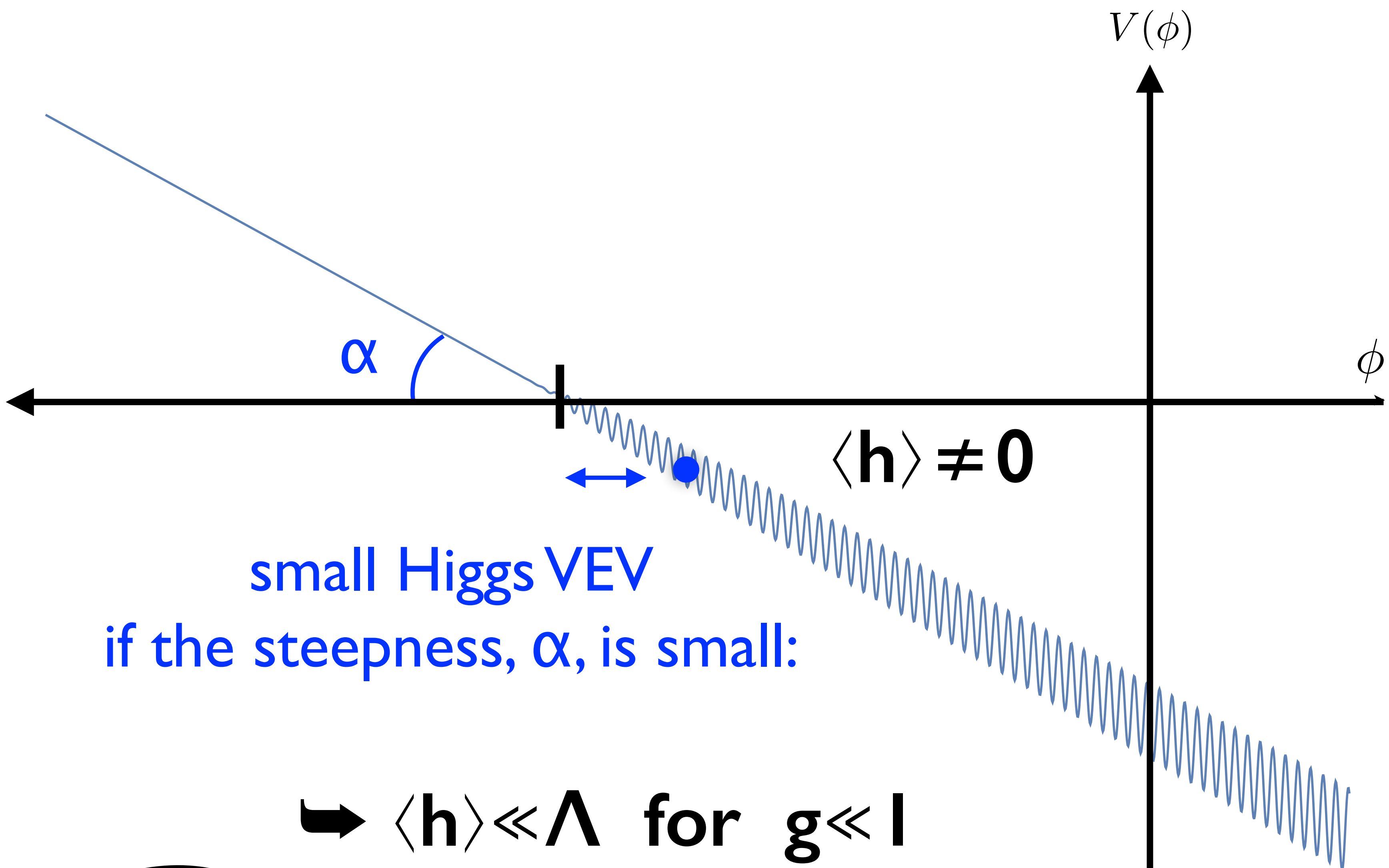
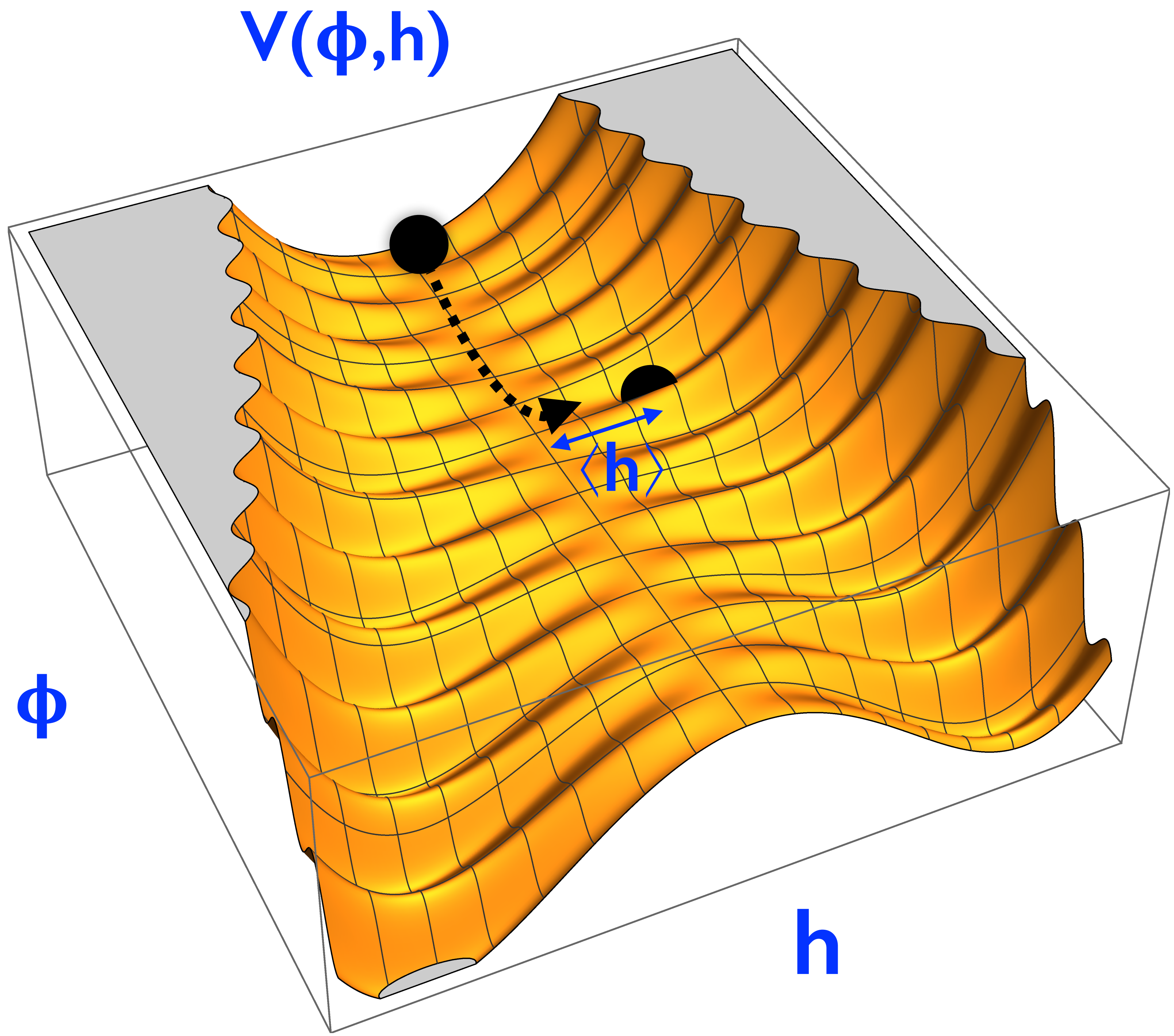


➥ $\langle h \rangle \ll \Lambda$ for $g \ll 1$

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

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

Tuning the initial conditions?

No, if slow rolling due to a friction:

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

can be neglected

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

Long period of inflation needed,
in order for $\boldsymbol{\phi}$ to "scan" large ranges of the Higgs mass

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

☛ **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:

$$\Delta\phi_{class} \sim g\frac{\Lambda^3}{H_I^2} \quad \gtrsim \quad \Delta\phi_{quant} \sim H_I$$

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

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

P.W. Graham, D.E. Kaplan, S.Rajendran
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$\boxed{\textbf{n=1:}}$ axion term from QCD condensate: $\Lambda_c = \Lambda_{QCD}$

$$\frac{\phi}{f}G^{\mu\nu}\widetilde{G}_{\mu\nu} \quad \rightarrow \quad m_u(h)\langle q\bar{q}\rangle\cos(\phi/f)$$

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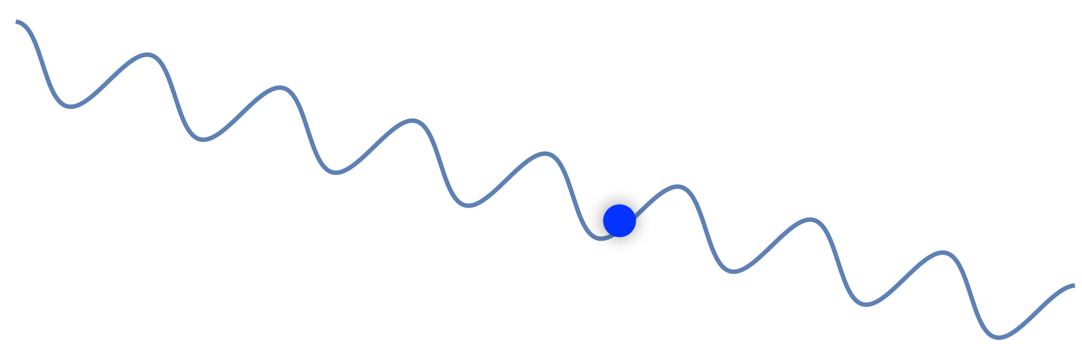
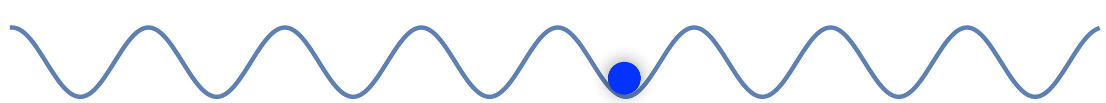
but leads to θ_{QCD}~1 due to the *tilt* !



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



one gets: $\Lambda \lesssim 30$ TeV (1000 TeV if the *tilt* changes sign) **(H_I ~10^{-9} GeV)**

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

$\boxed{\text{n=2:}}$ $\epsilon\Lambda_c^2|H|^2\cos(\phi/f)$ gauge-invariant, no need to rely on QCD

(Λ_c ~ some new-physics scale that can be heavier than Λ_{QCD})

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

gauge-invariant, no need to rely on QCD

(Λ_c ~ some new-physics scale that can be heavier than Λ_{QCD})

at the quantum level, closing *H* in a loop ➡ $\epsilon\Lambda_c^4\cos(\phi/f)$

this term gives minima for ϕ in the unbroken phase (h=0)

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

$$A\cos(\phi/f)$$ $\longrightarrow$ **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

$$A\cos(\phi/f) \longrightarrow$$

Field-dependent amplitude:

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Two "scanners" potential:

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

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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:

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

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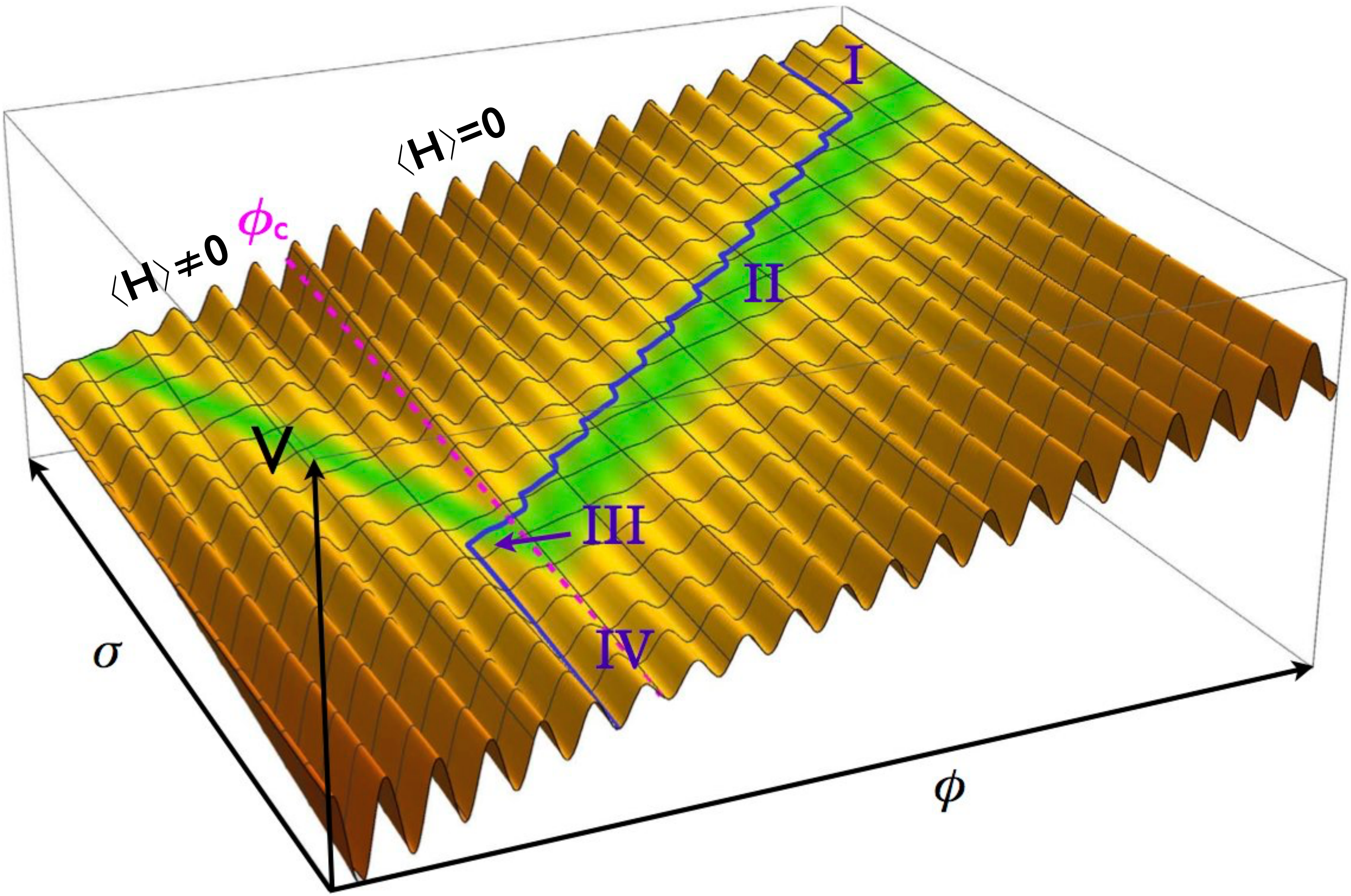

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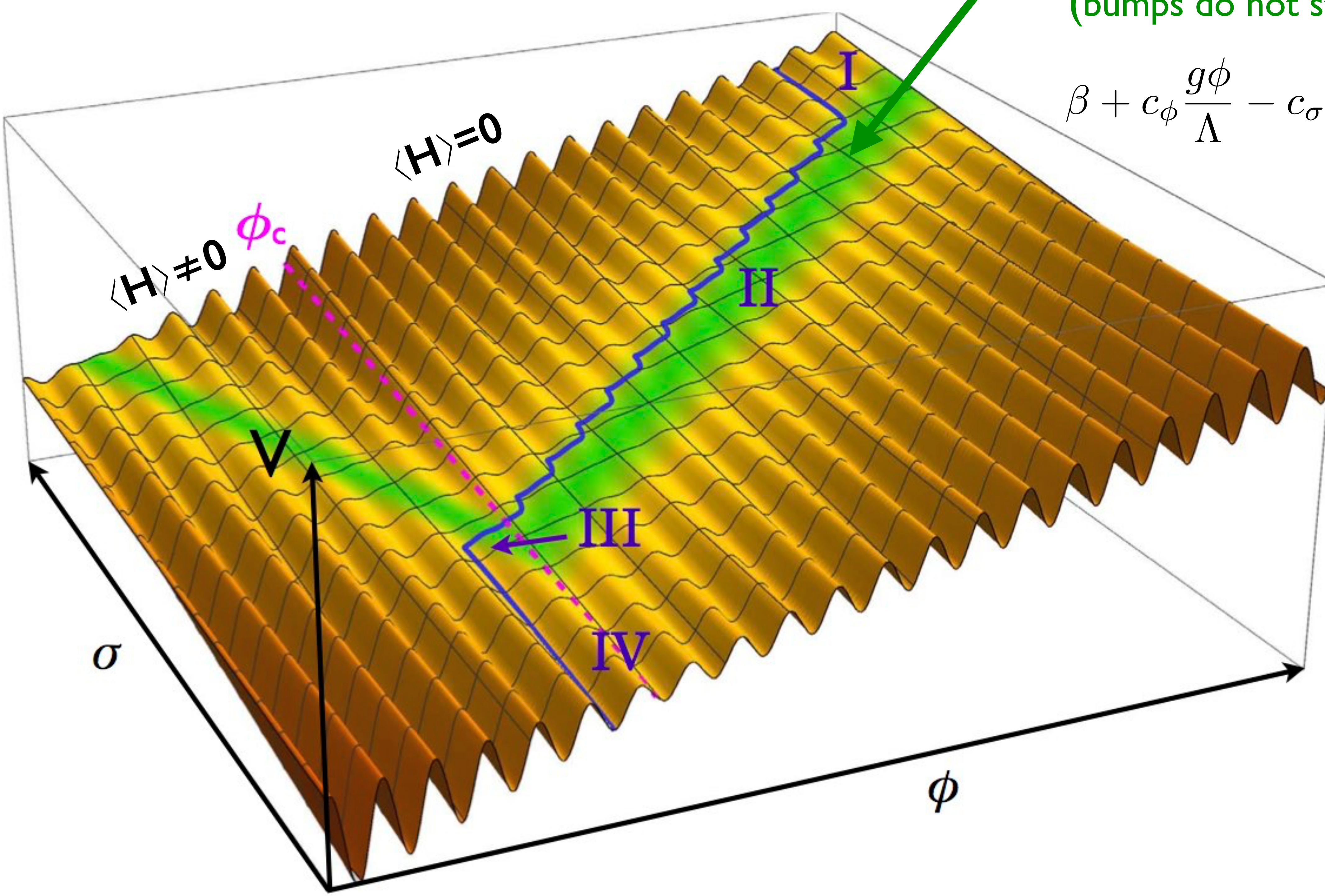
area where A≈0

(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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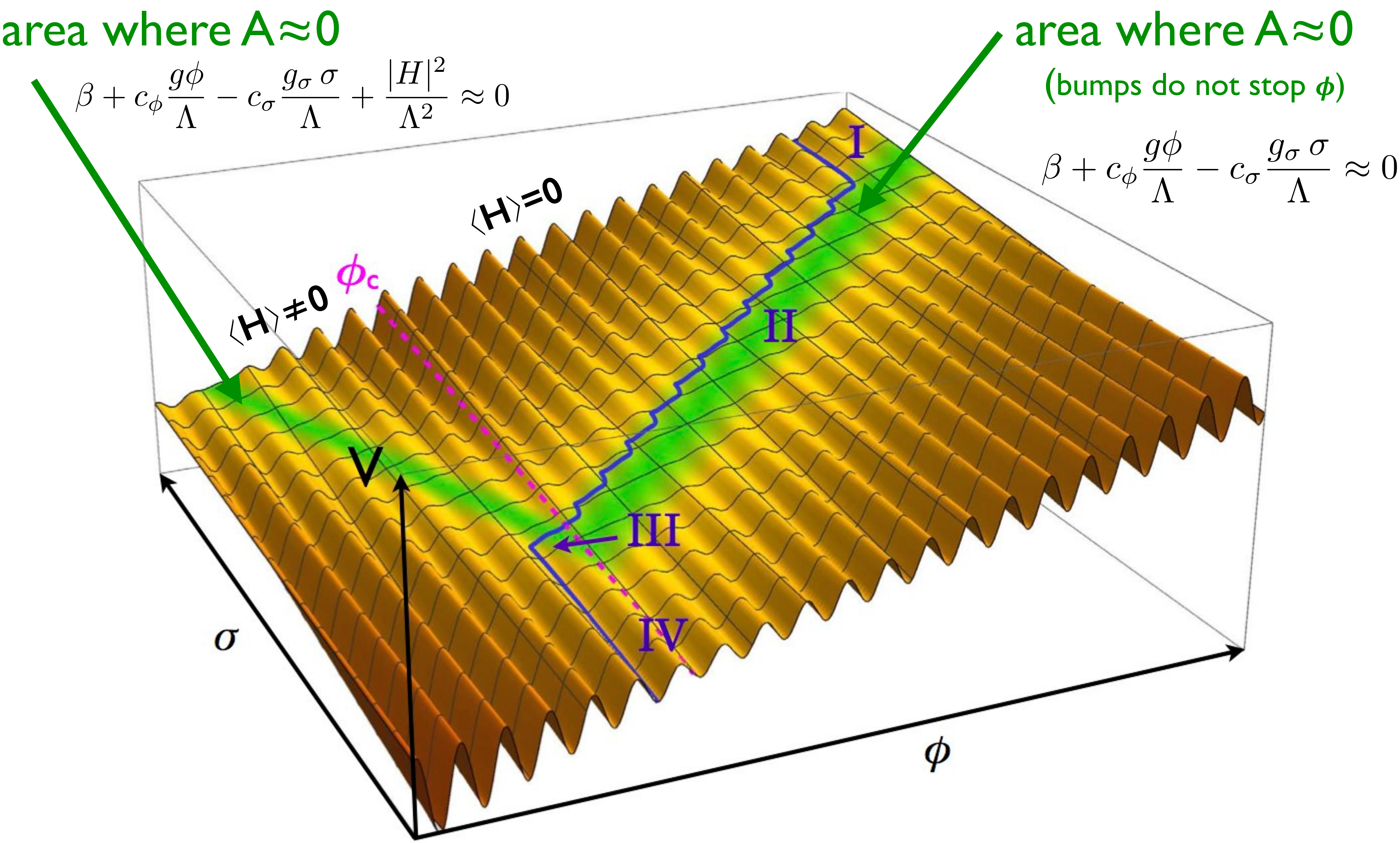

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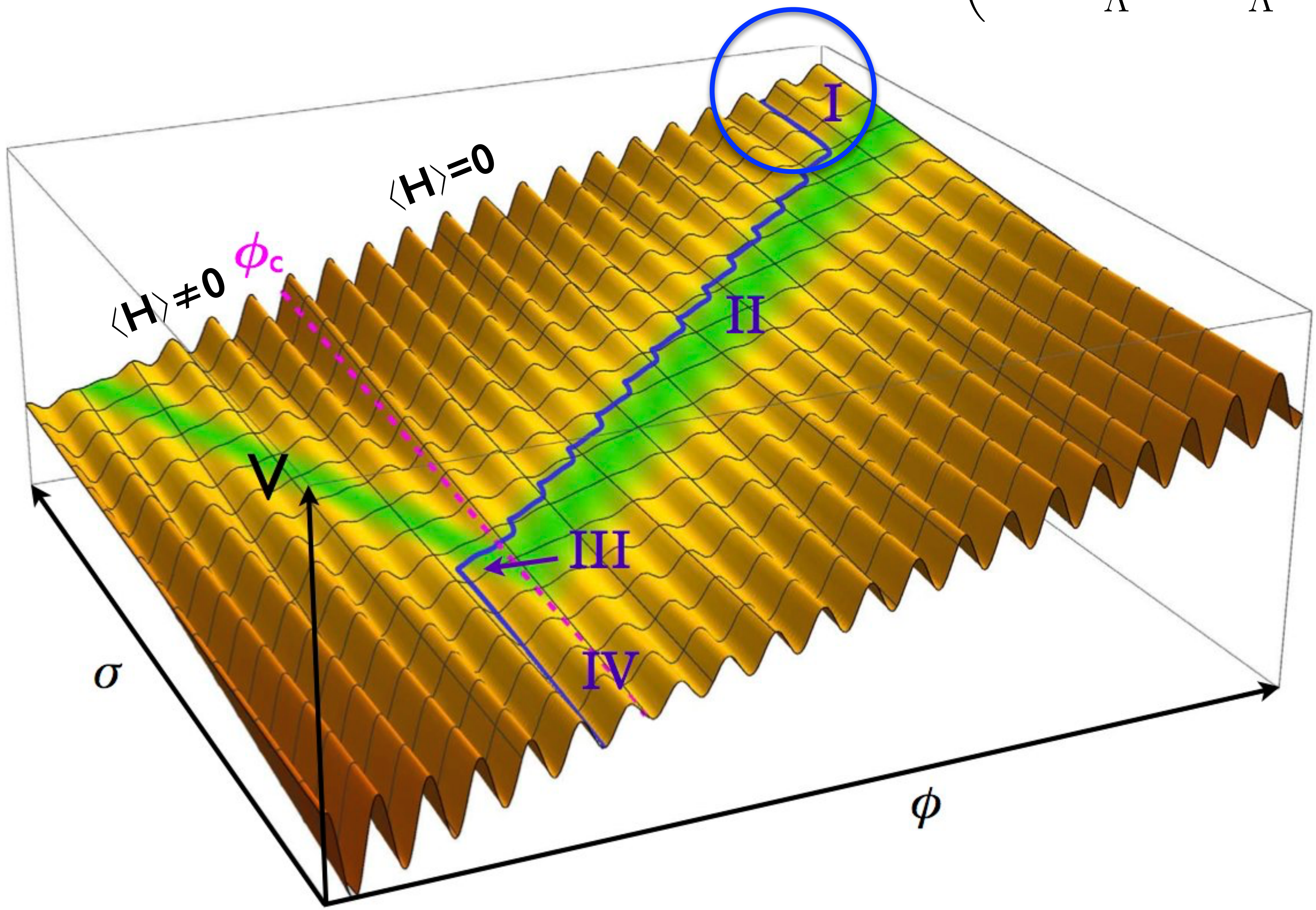

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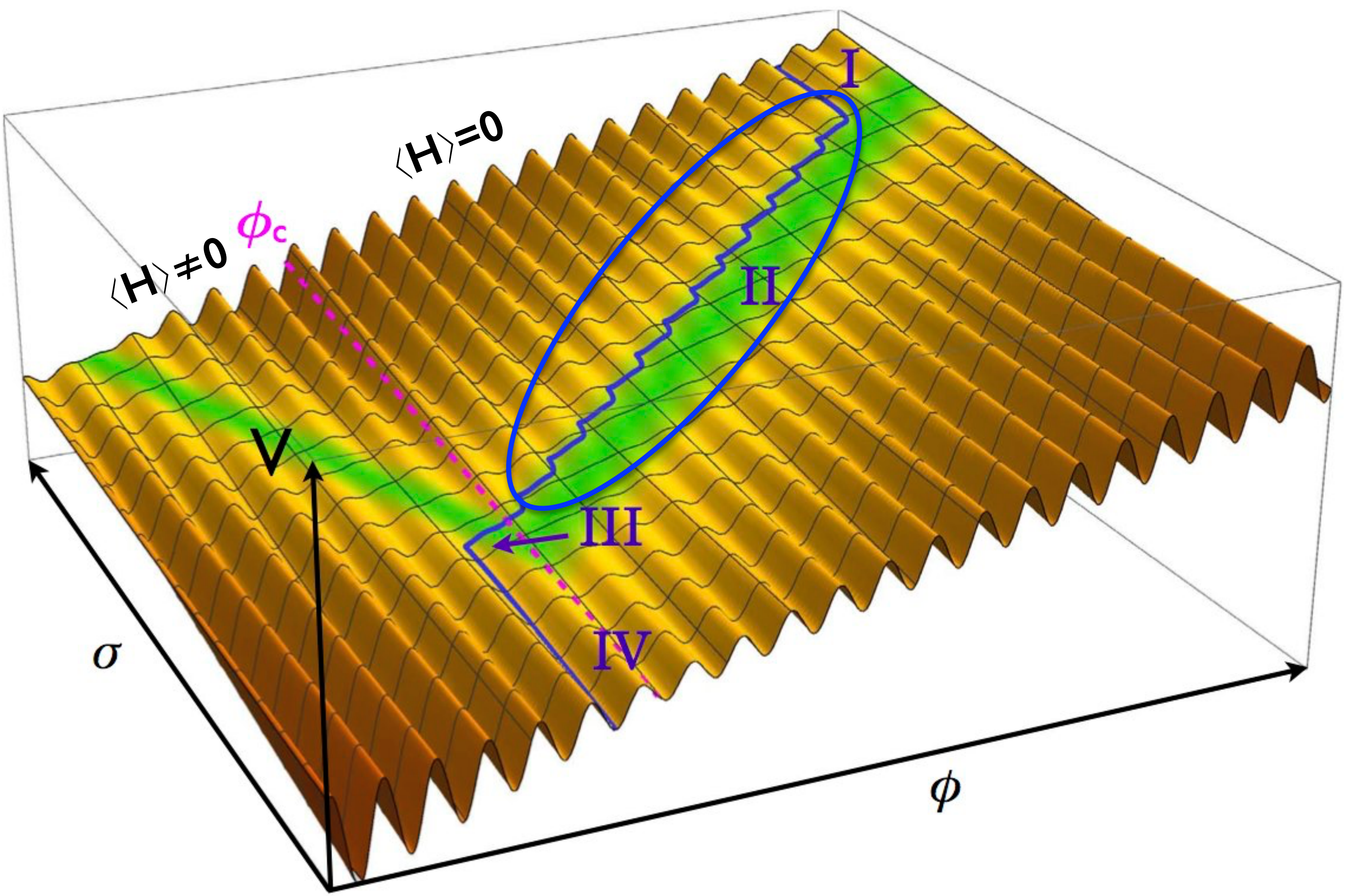

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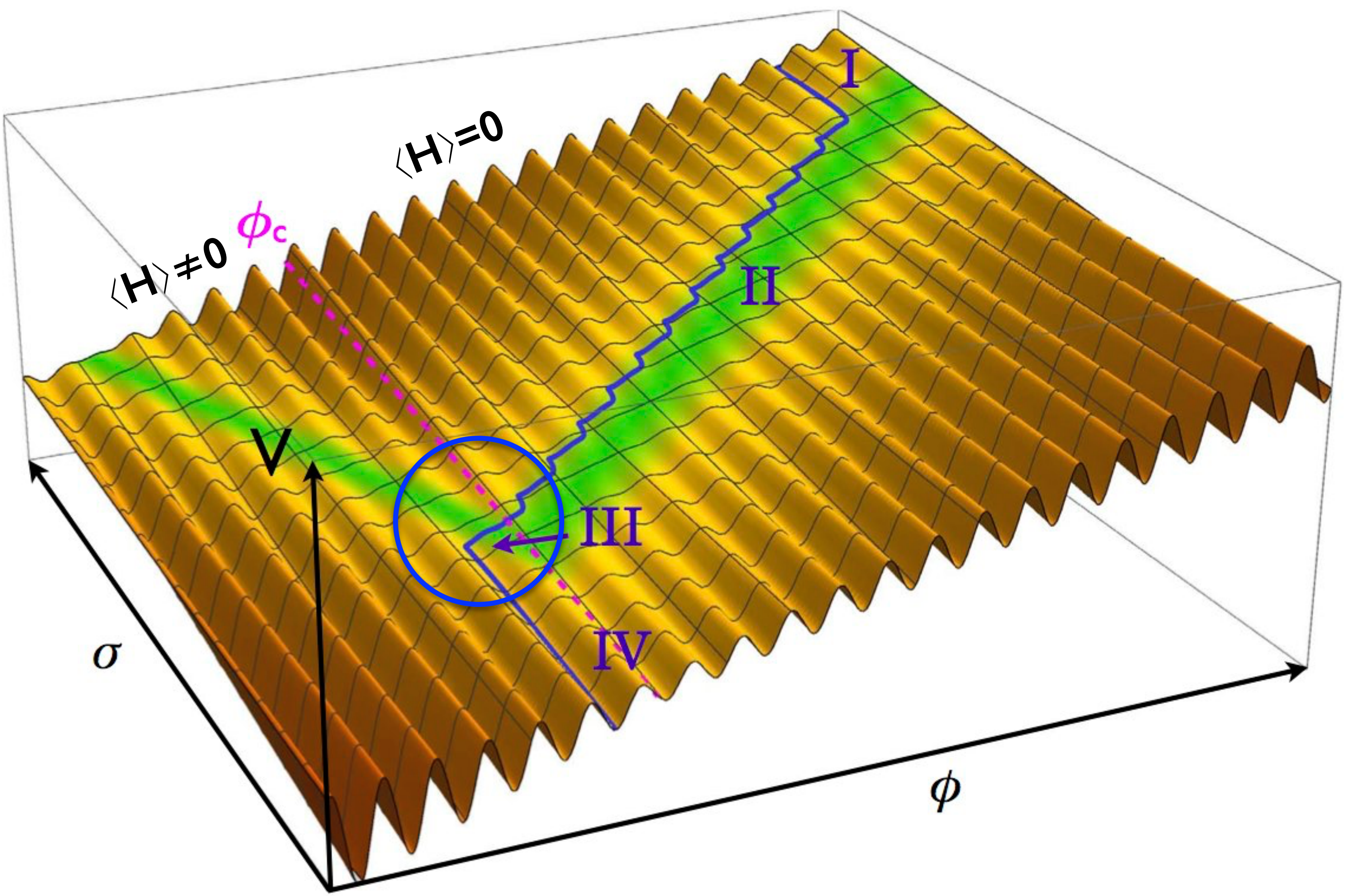

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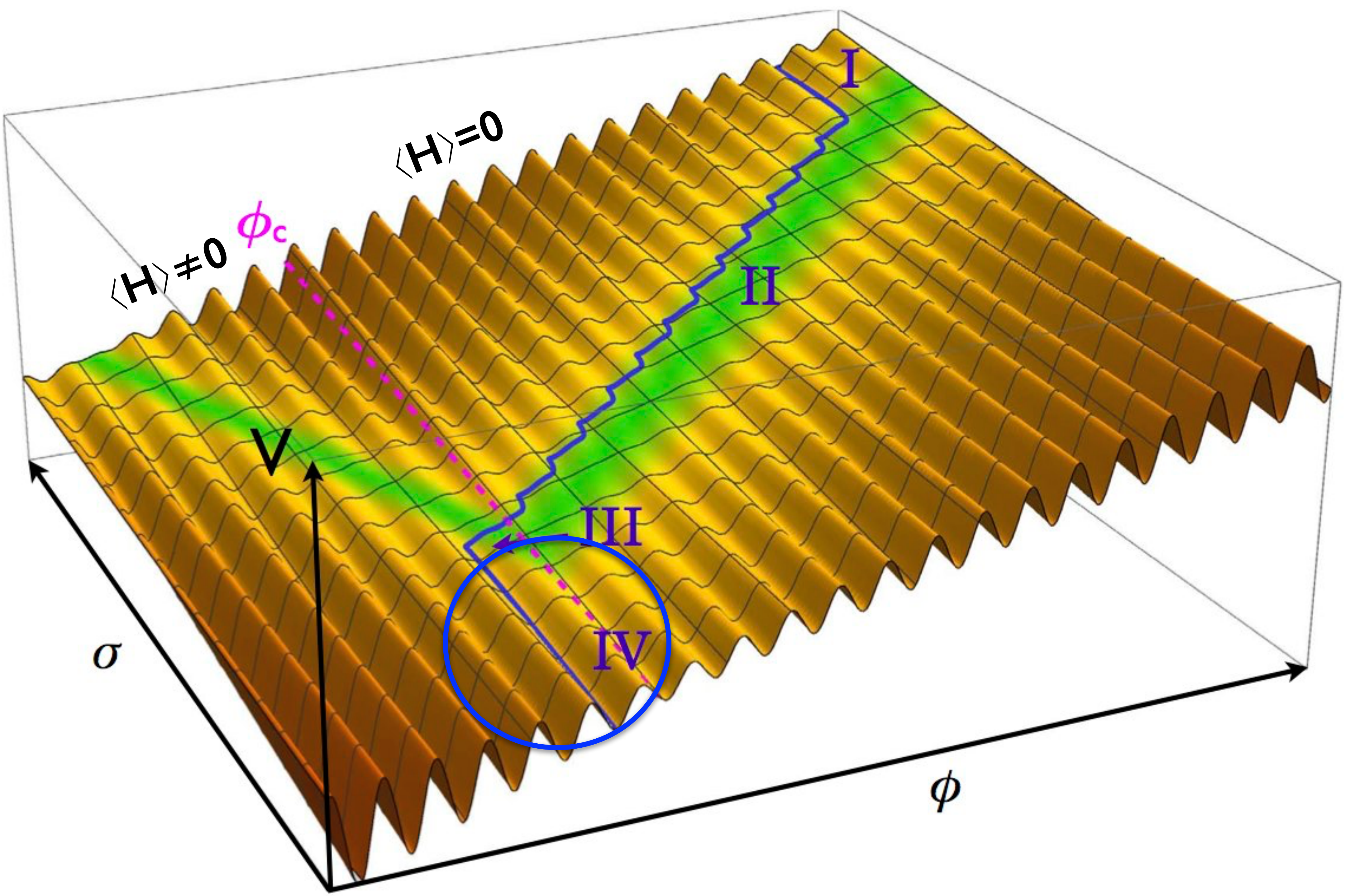
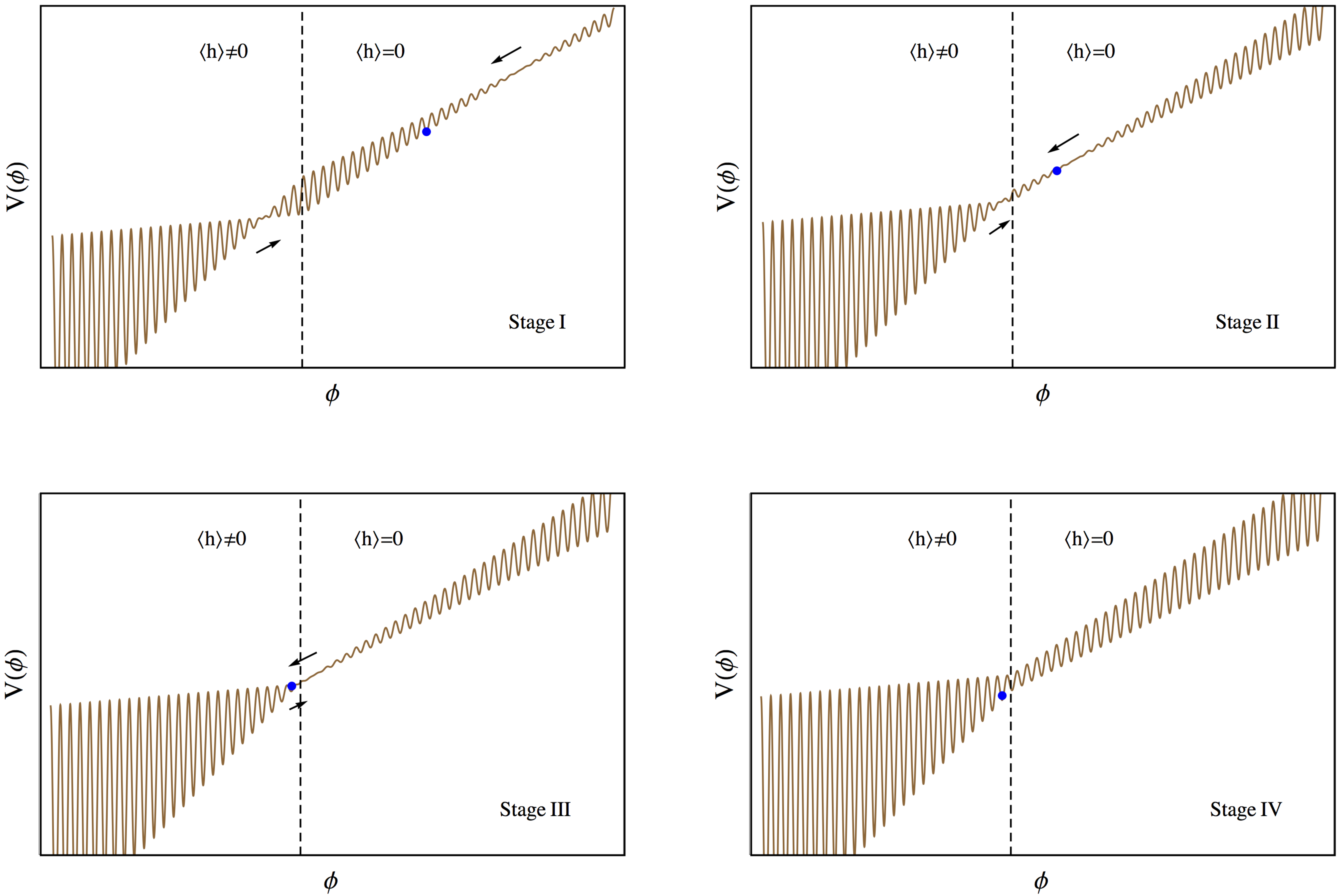


Two scanner model: “The Movie”



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

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

UV origin of the periodic term:

Strong sector

a la QCD

with a light fermion: ***N***

+ Axion-like $\boldsymbol{\phi}$

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

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+ **Axion-like *ϕ***

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

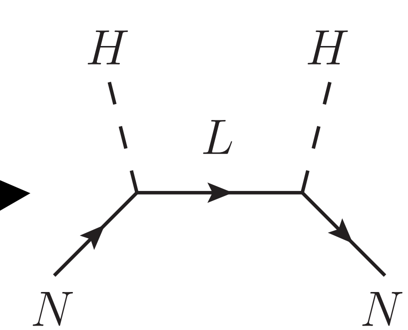
Axion potential:

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

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

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

from integrating
a fermion-doublet *L*



Phenomenological implications:

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

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

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

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

mixing to the SM through the Higgs: $|H|^2 \cos\phi/f$, $g\phi|H|^2$

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

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

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

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

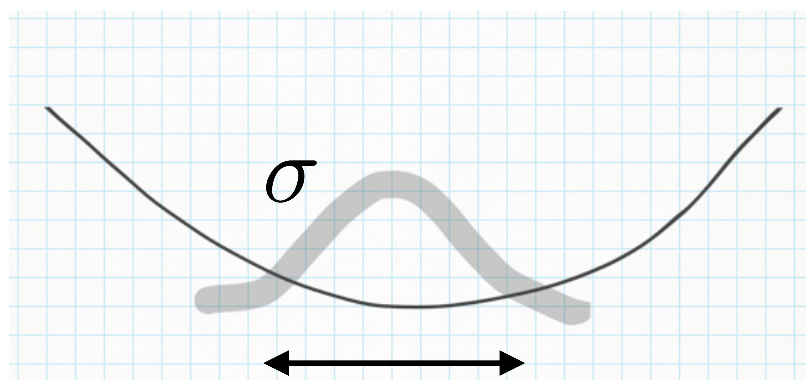
$\theta_{\sigma h} \sim 10^{-50}$

Experimental constraints:

From cosmological overabundances, late decays, BBN bounds, γ-rays, CMB, pulsar timing observations, …

Interestingly, σ as it oscillates around its minimum can be a good Dark Matter candidate (as axions)

$$V(g_\sigma \sigma/\Lambda)$$



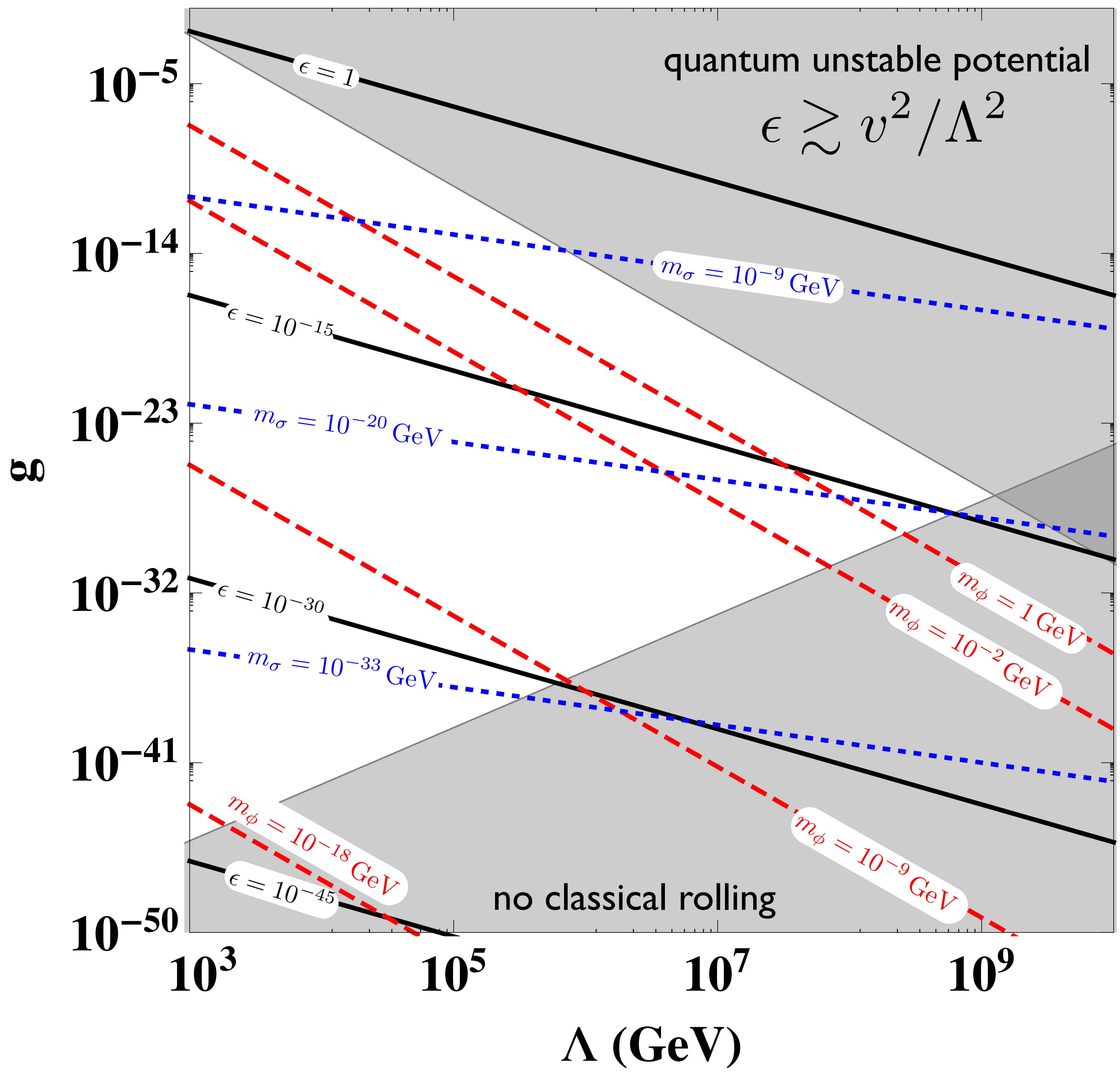
quantum spreading

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

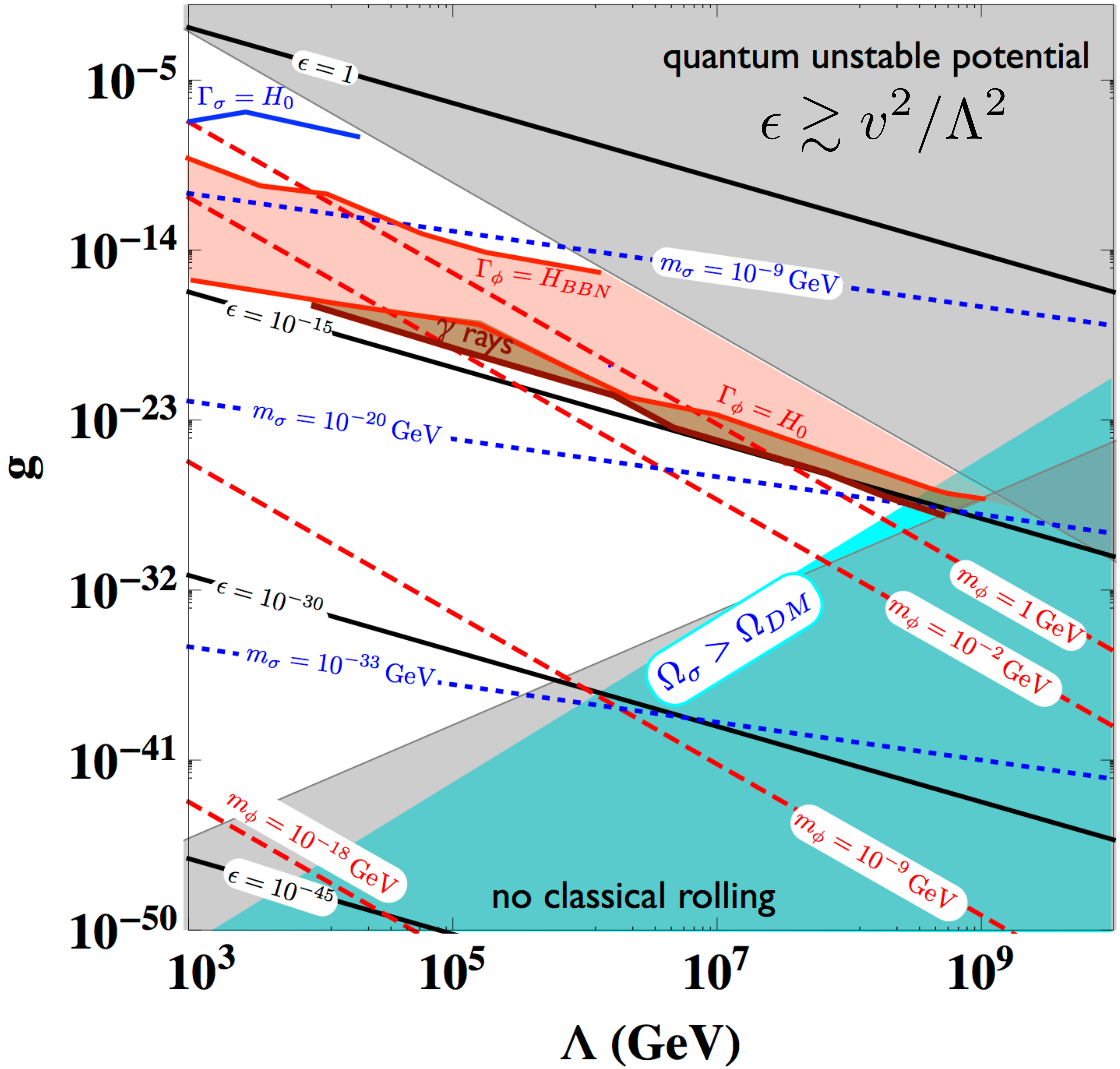
☛ $$\rho^\sigma_{ini} \sim H_I^4$$

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

Taking $g_\sigma \sim 0.1g$



Taking $g_\sigma \sim 0.1g$



Supersymmetric UV completion (at Λ)

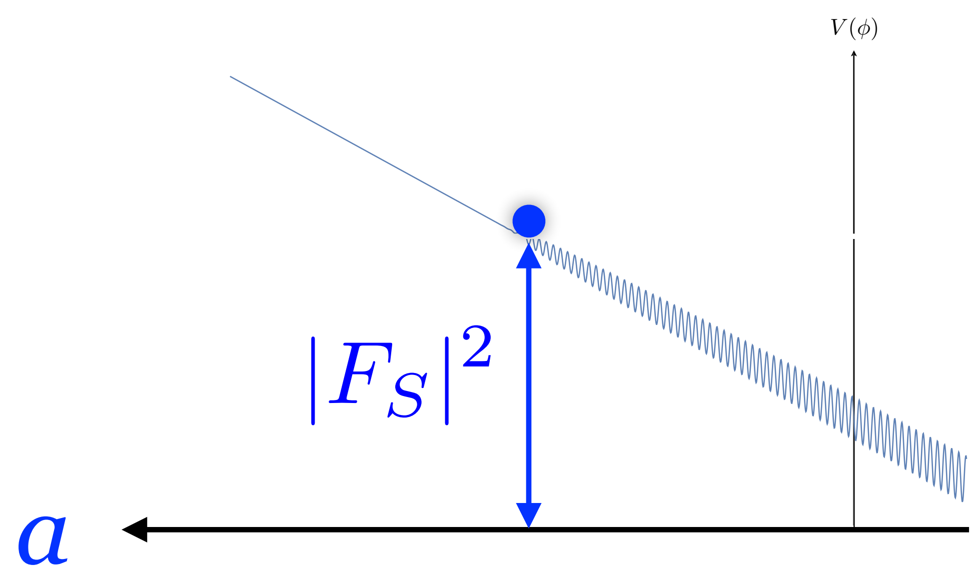
Batell,Giudice,McCullough 15

Fits nicely:

axion

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

$$\text{MSSM} \;+\; \int d^2\theta\,\left[S\mathcal{W}^a\mathcal{W}^a + mS^2\right]$$



For nonzero a,

supersymmetry is broken,

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

Conclusions

"Relaxation" mechanism can give a natural explanation for

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

based on a cosmological history of the Higgs and axion-like states

The good: Change of paradigm:

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

Other type of experiments needed:

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

The bad & ugly: $N_e > 10^{38}$ & super-Plankian field excursions