COSMOLOGICAL RELAXATION OF THE ELECTROWEAK SCALE

Moriond EW'16
La Thuile,
March 18

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50 since 1966

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EXCELENCIA SEVERO OCHOA

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OUTLINE

- The relaxion solution to the hierarchy problem
  - Graham-Kaplan-Rajendran model(s)
  - General issues
- Improved version
  - Some implications
    - Phenomenology
    - Cosmology
- Conclusions and outlook

NATURAL SOLUTIONS TO HIERARCHY PROBLEM

Common lore:

Natural solutions to the hierarchy problem

Supersymmetry
Composite Higgs

$$\left.\begin{array}{l}\text{Supersymmetry}\\ \text{Composite Higgs}\end{array}\right\} \quad \Delta m_H^2 \sim \varnothing \cdot \Lambda^2$$

⇨ Predict BSM at ~ TeV not to spoil naturalness

⇨ Main argument for new physics at LHC

THE RELAXION IDEA

New solution to hierarchy problem that challenges this common lore.

P.W. Graham, D.E. Kaplan, S. Rajendran (GKR)'15

Idea

$$V(h) = \frac{1}{2} m_H^2(\phi) h^2 + \ldots = \frac{1}{2}(-\Lambda^2 + g\phi\Lambda) h^2 + \ldots$$

new field

- Λ^2 not required to cancel
- ϕ changes during cosmological evolution

scanning m_H^2 and stopping at

$$m_H^2(\phi_c) = -\Lambda^2 + g\,\phi_c\Lambda \approx m_{EW}^2 \ll \Lambda^2$$

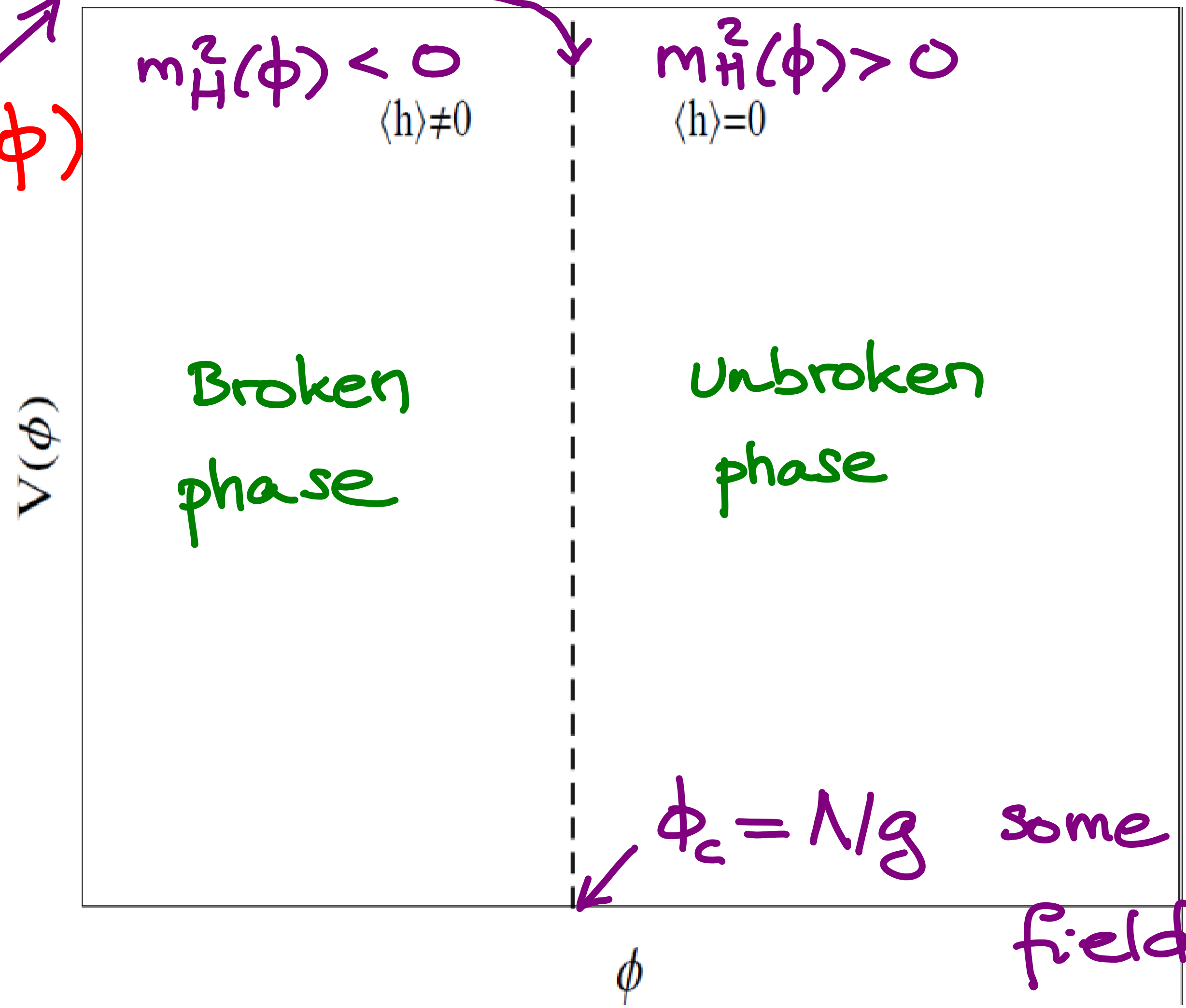
THE RELAXION IDEA

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

THE RELAXION IDEA

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

$m_H^2(\phi)$

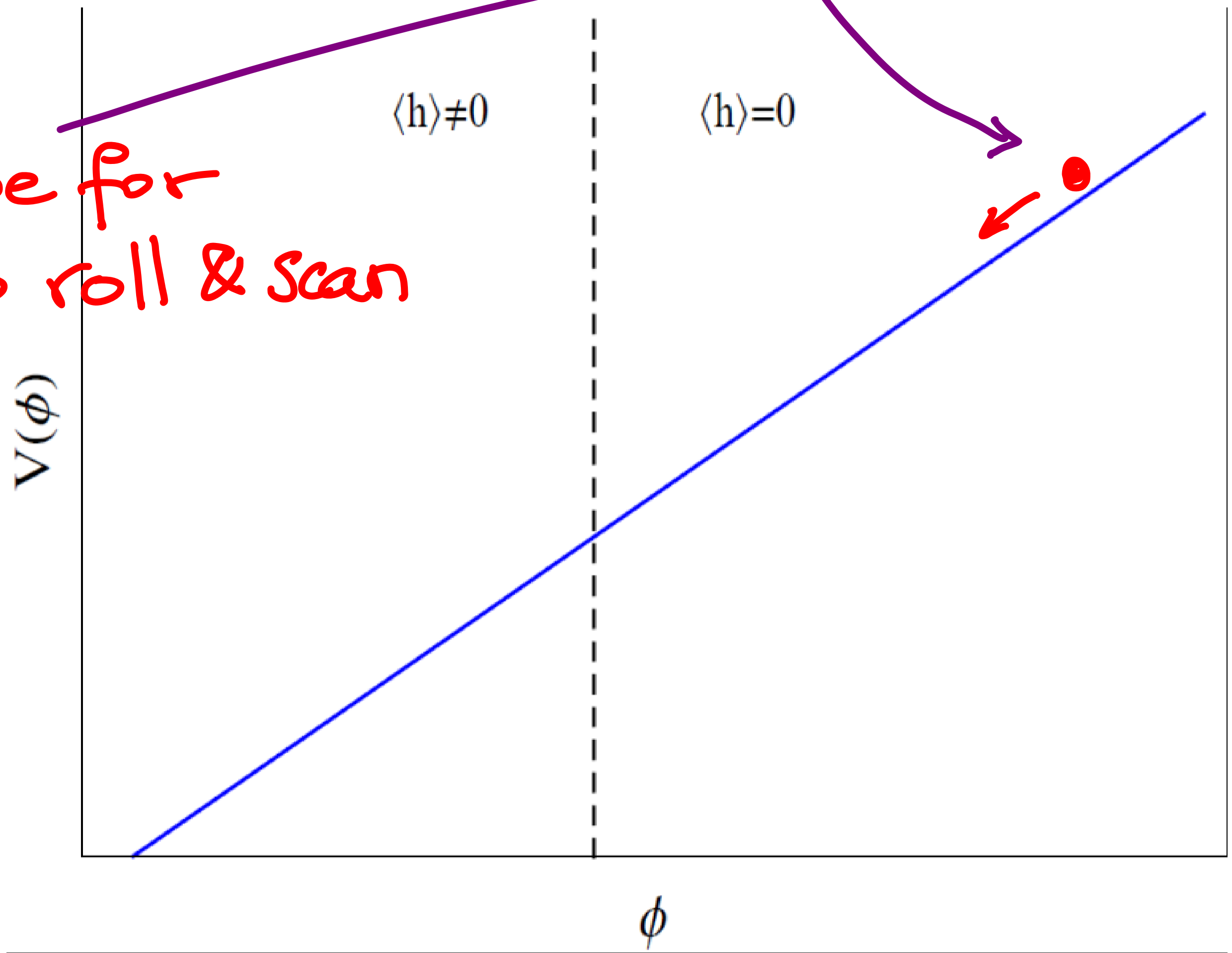


some typical field value

THE RELAXION IDEA

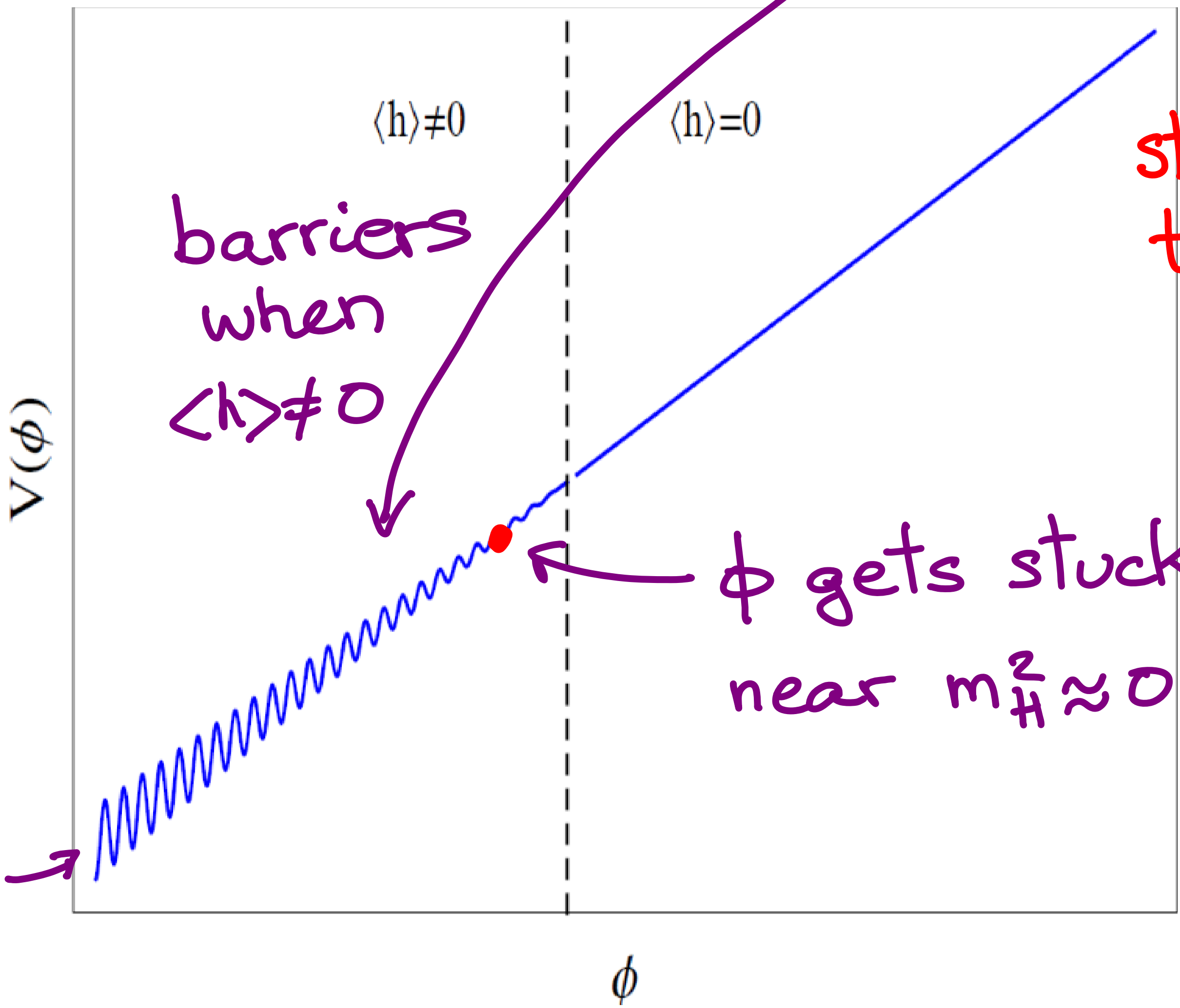
$$V = -\frac{\Lambda^2}{2}\left(1 - \frac{g\phi}{\Lambda}\right)h^2 + g\Lambda^3\phi + \epsilon\Lambda_c^3 h \cos\left(\frac{\phi}{f}\right) + \dots$$

slope for ϕ to roll & scan



THE RELAXION IDEA

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



barriers when $\langle h \rangle \neq 0$

stopping term

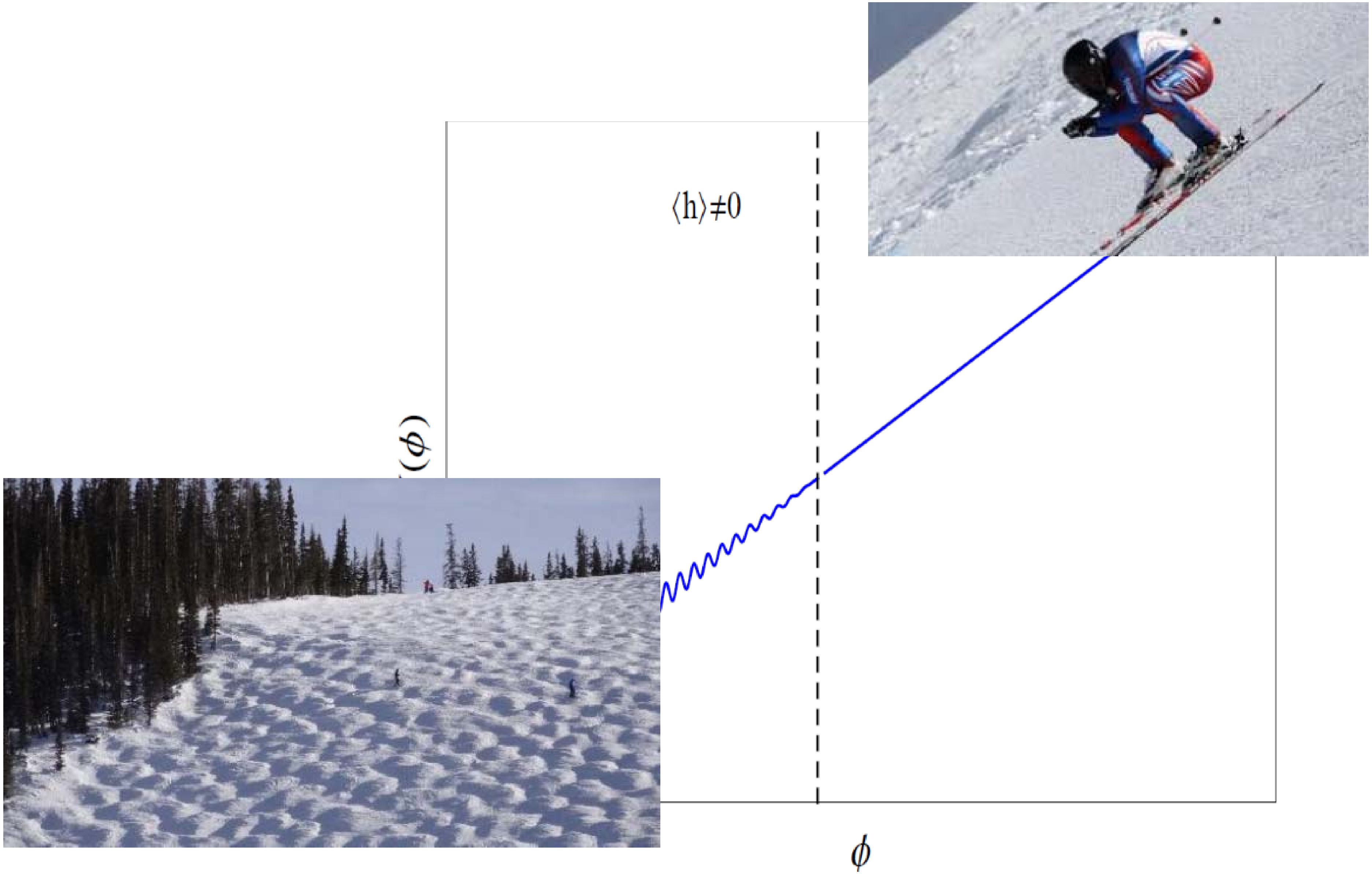
$(f \gtrsim \Lambda)$

$(\Lambda_c \lesssim \Lambda)$

ϕ gets stuck near $m_H^2 \approx 0$

$V(\phi, h(\phi))$

THE RELAXION IDEA



THE RELAXION IDEA

ϕ

EW SCALE AS OUTPUT

ϕ stops at $V'=0$

Interplay between ϕ slope and barriers:

$$\Rightarrow \quad \boxed{\langle h \rangle \sim \Lambda_c \left(\frac{g f \Lambda^3}{\epsilon \Lambda_c^4} \right)}$$

EW Scale in terms of fundamental params.

Goal: $\langle h \rangle \ll \Lambda$ in a technically natural way

- $g \ll 1$ (flat slope) required. Must be natural
- $V(\phi)$ structure must be radiatively stable

FRICTION NEEDED

To avoid overshooting the EW range vacua.

Obvious solution : slow-roll during inflation*

$$\ddot{\phi} + 3H_I\dot{\phi} = -\frac{\partial V}{\partial \phi}$$

$\uparrow$ friction term

Extra inflaton sector to provide required N_e.

$\Rightarrow$ Usually $N_e \gg 1$ and $\Delta\phi \gg M_P$ needed.

*Alternative: thermal evolution of V $\rightarrow$ Hardy'15

ORIGIN OF THE BARRIERS

How is $V_{br} = \epsilon \Lambda_c^3 h \cos\left(\frac{\phi}{f}\right)$ generated ?

GKR model # 1

ϕ QCD axion

$$\delta \mathcal{L} = \frac{g_s^2}{32\pi^2} \cdot \frac{\phi}{f} \cdot G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Axion potential from instanton effects :

$$V(\phi) = (m_u + m_d) \langle q\bar{q} \rangle \cos(\phi/f)$$

$$\Rightarrow \Lambda_c \sim \Lambda_{QCD} \,, \; \epsilon \sim y_u$$

PREDICTIONS OF QCD-RELAXION

$\langle h \rangle$ and $\theta_{QCD} = \langle \Delta\phi / f \rangle$: outputs.

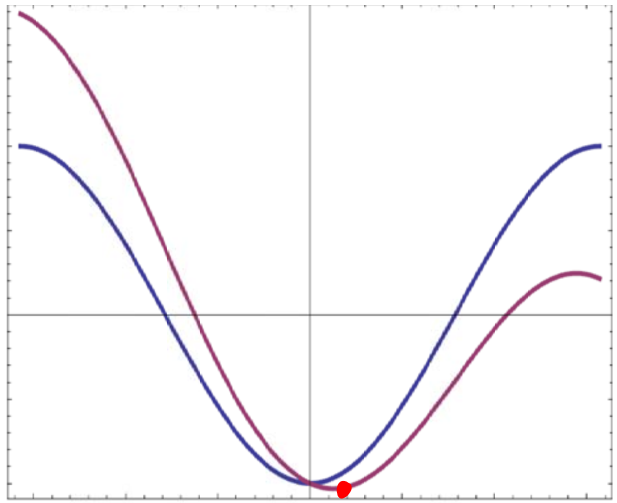
$$\langle h \rangle = \frac{g f \Lambda^3}{y_u \Lambda_{QCD}^3} \ll \Lambda \quad \text{for} \quad g \sim \frac{m_u \Lambda_{QCD}^3}{f \Lambda^3} \ll 1$$

Ex: $\Lambda \sim 10^7\,\mathrm{GeV}$ and $f \sim 10^9\,\mathrm{GeV}$ need $g \sim 10^{-35}$

However

$$\theta_{QCD} \sim O(1) \quad !$$

due to the potential tilt:



$\mapsto \Delta\phi / f = \theta_{QCD}$

BEYOND GKR

Ways out

- Break $\Lambda_c = \Lambda_{QCD}$ link:

non-QCD strong gauge sector with $\Lambda_c \lesssim \text{TeV}$ (as $\Lambda_c \neq 0$ breaks EW). Coincidence problem

- Break $\Lambda_c \Leftrightarrow \text{EW}$ link:

Idea:

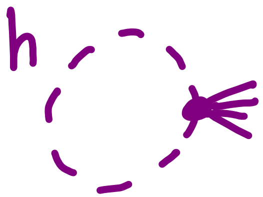
use $\epsilon \Lambda_c^2 |H|^2 \cos(\phi/f)$ and identify $\Lambda_c \to \Lambda$

How high can we make Λ without leaving new matter below TeV ?

BEYOND GKR (1^{st} TRY)

$$V = \frac{1}{2}(-\Lambda^2 + \Lambda g\phi)h^2 + \Lambda^3 g\phi + \epsilon\Lambda^2 h^2 \cos(\phi/f)$$

Potential shape NOT radiatively stable!



$\cos(\phi/f)$ $\quad \epsilon\Lambda^4\cos(\phi/f) \Rightarrow$ high barriers everywhere... (unless $\Lambda < v$)

Solution: Relax!

Scan also the amplitude of $\cos(\phi/f)$

J.R.E, C.Grojean, G.Panico, A.Pomarol, D.Pujolàs, G.Servant '15

NEW MODEL : DOUBLE SCANNING

σ new scanner field $\qquad$ $g_\sigma\,(\sim g)$ new spurion

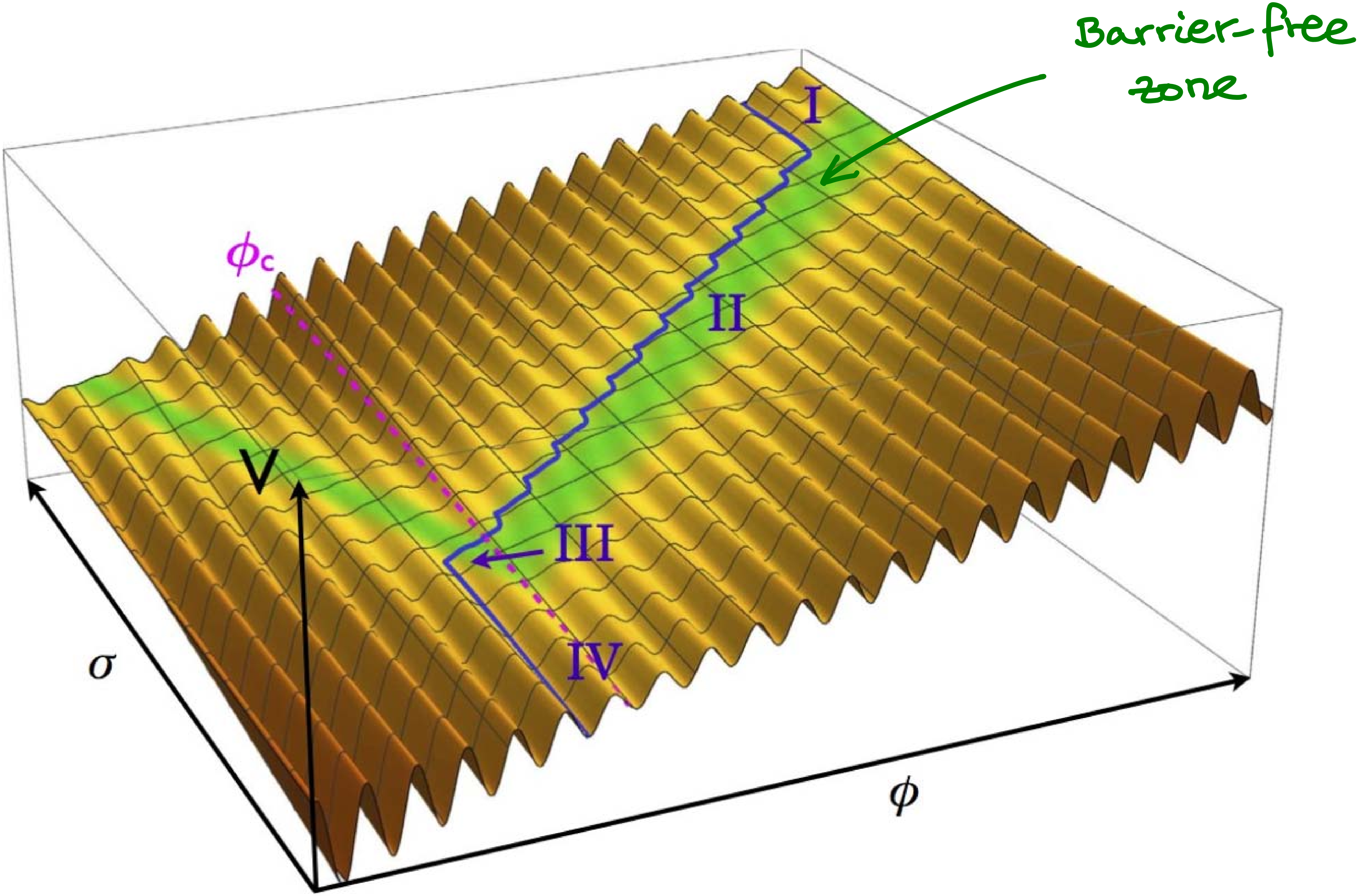
$$V = (-\Lambda^2 + \Lambda g \phi)|H|^2 + \Lambda^3 g \phi + \Lambda^3 g_\sigma \sigma + A \cos(\phi/f)$$

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

V shape is radiatively stable (if $\epsilon \lesssim v^2/\Lambda^2$)

A can be produced by a suitable UV model

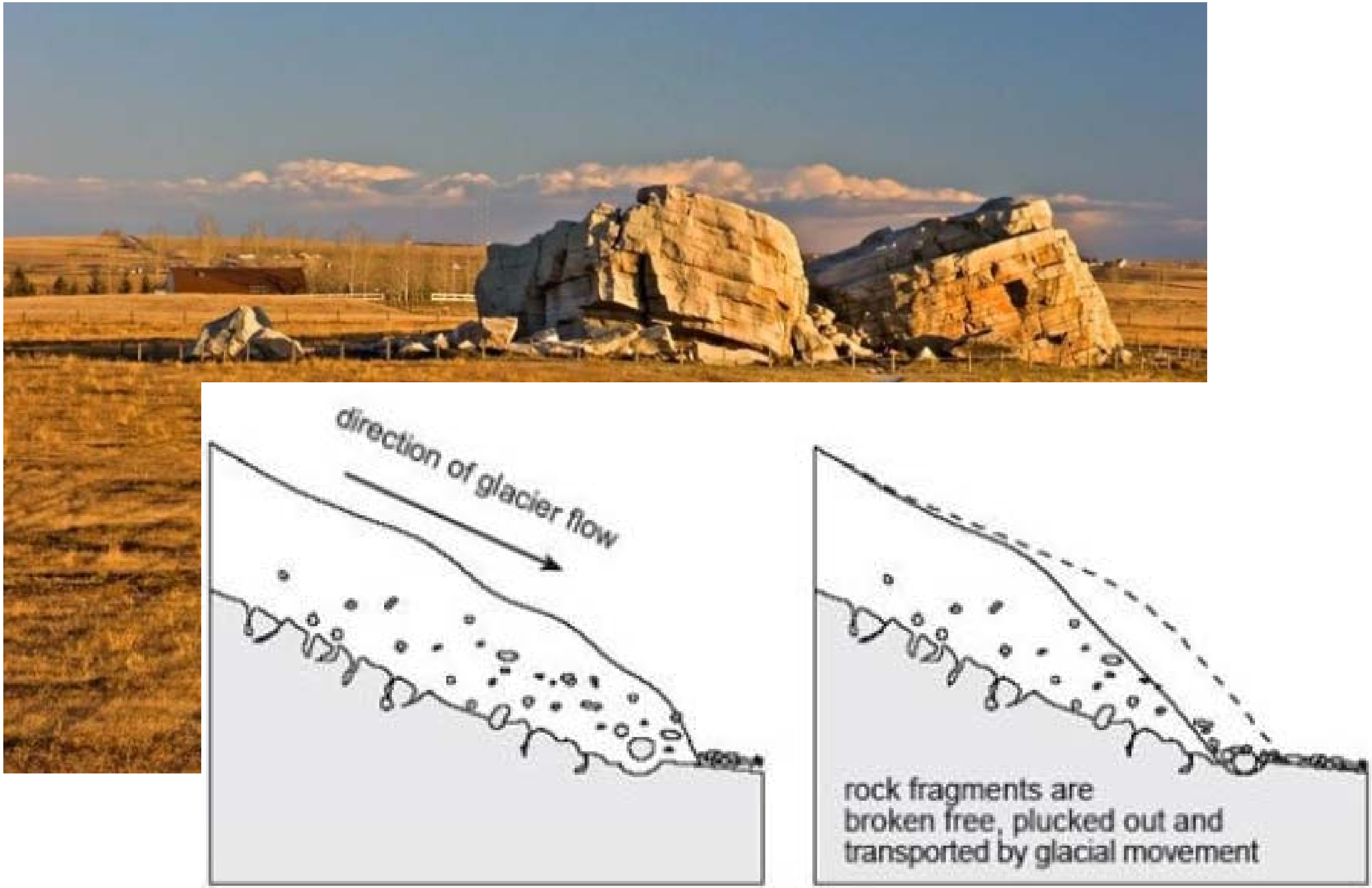
φ,σ EVOLUTION



EW SCALE AS COSMOLOGICAL ERRATIC

okotoks glacial erratic,
Alberta, Canada

EW SCALE AS COSMOLOGICAL ERRATIC



PARAMETER CONSTRAINTS

Constraints from

- Natural $V(\phi, \sigma, h)$
- EW Scale as output
- Inflation and N_e

$$\Lambda \lesssim (v^4 M_p^3)^{1/7} \simeq 2 \times 10^9 \,\mathrm{GeV}$$

Natural model without TeV matter ✓

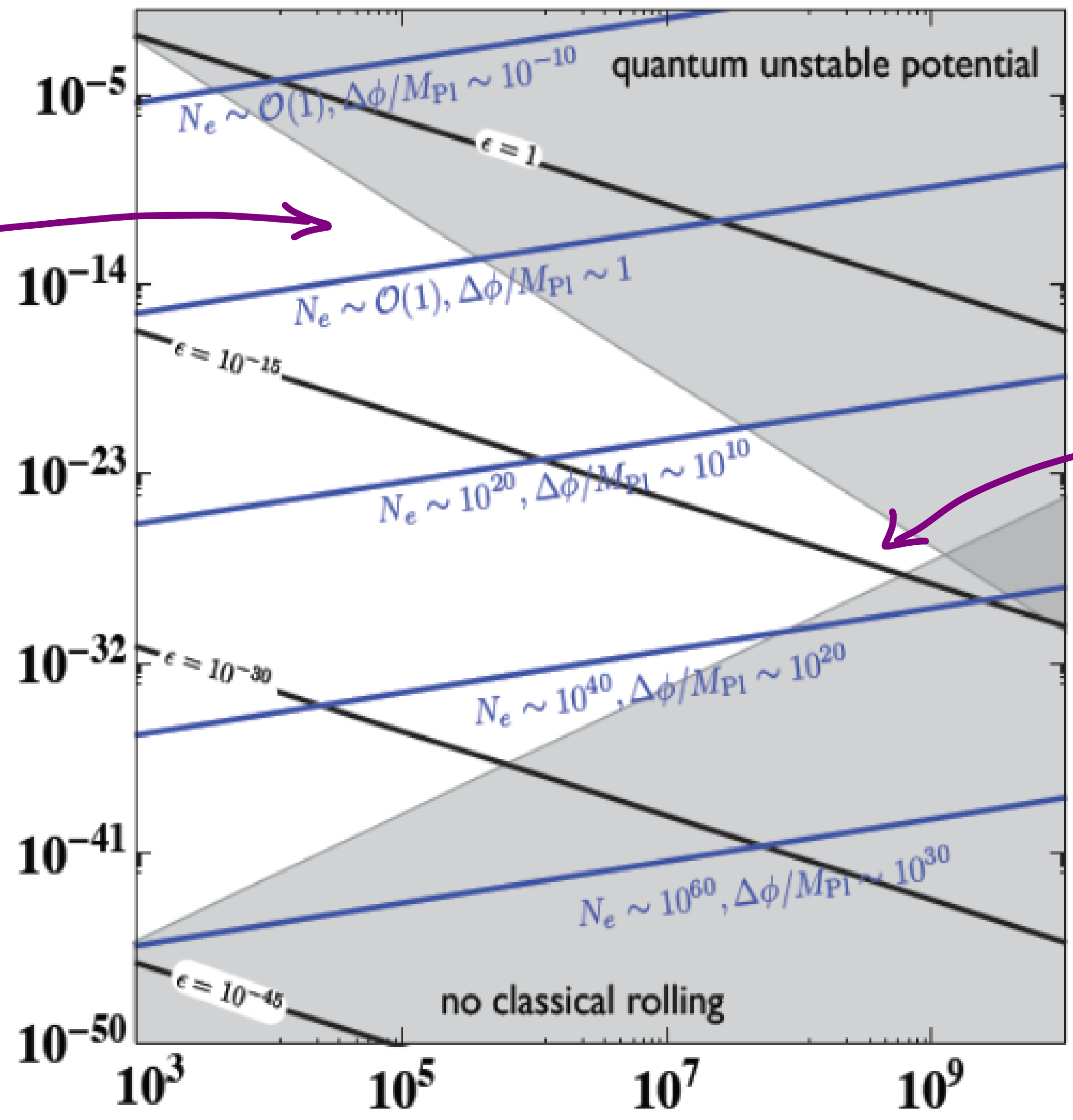
PARAMETER SPACE

$g_\sigma = 0.1 g$
$f = \Lambda$

$N_e, \frac{\Delta\phi}{M_{Pl}} \sim O(1)$

Good for little hierarchy problem.

slope or coupling



$N_e, \frac{\Delta\phi}{M_{Pl}}$ exponentially large

cutoff scale

SIGNATURES ?

- Below Λ only extra states : ϕ and σ

$m_\phi \in [10^{-20}, 10^{2}]\,\mathrm{GeV}$ $\qquad$ $m_\sigma \in [10^{-45}, 10^{-2}]\,\mathrm{GeV}$

Interactions with SM particles through mixing with the Higgs suppressed by $1/f$ and/or small spurious ϵ, g, g_σ

No collider signatures

COSMOLOGICAL CONSTRAINTS

From abundances, post-BBN decays, astrophysics...

Decay widths

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

can be very small.

Compare with

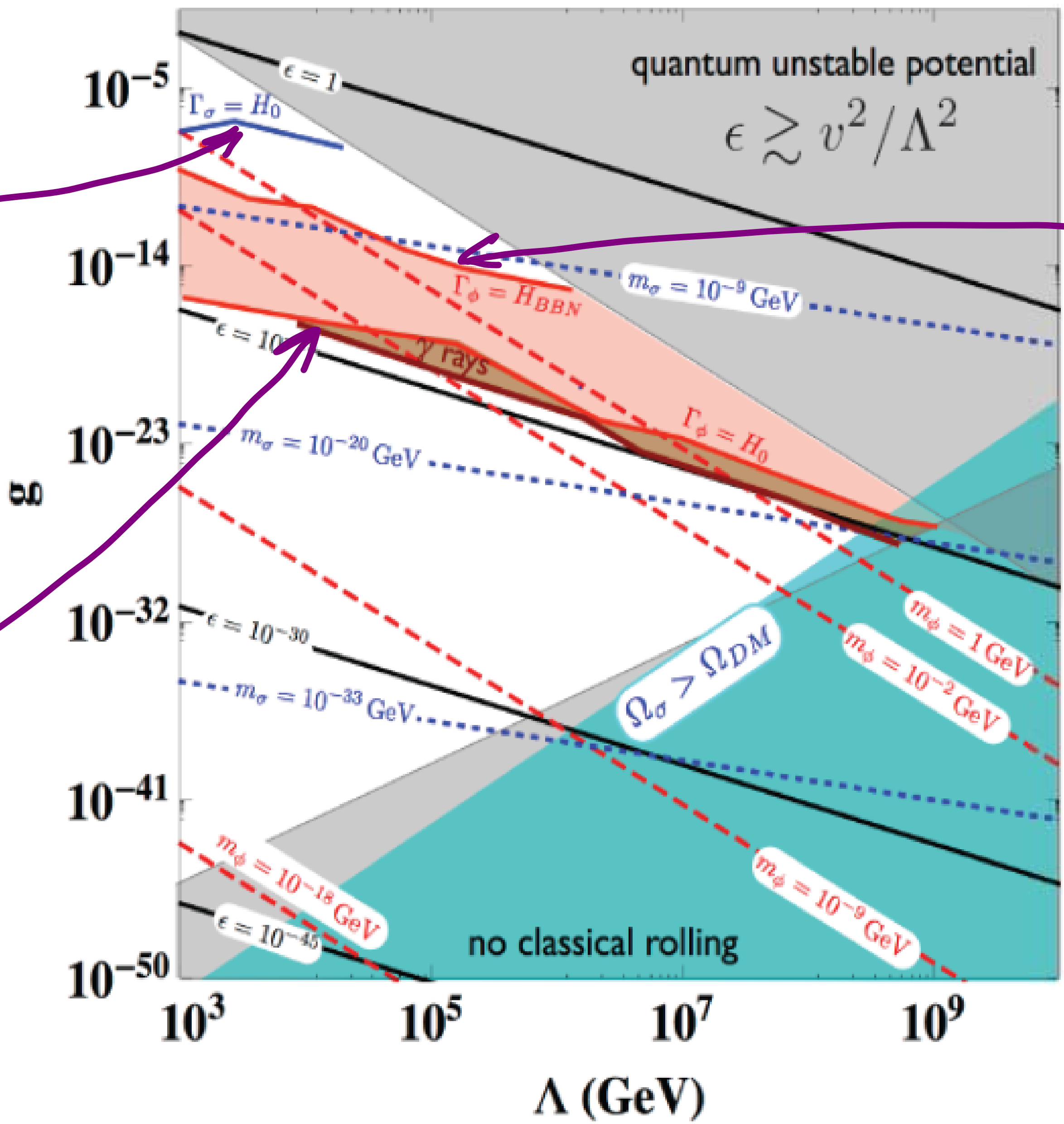
H_0 for cosmological stability

H_{BBN} for potential trouble with BBN

COSMOLOGICAL CONSTRAINTS

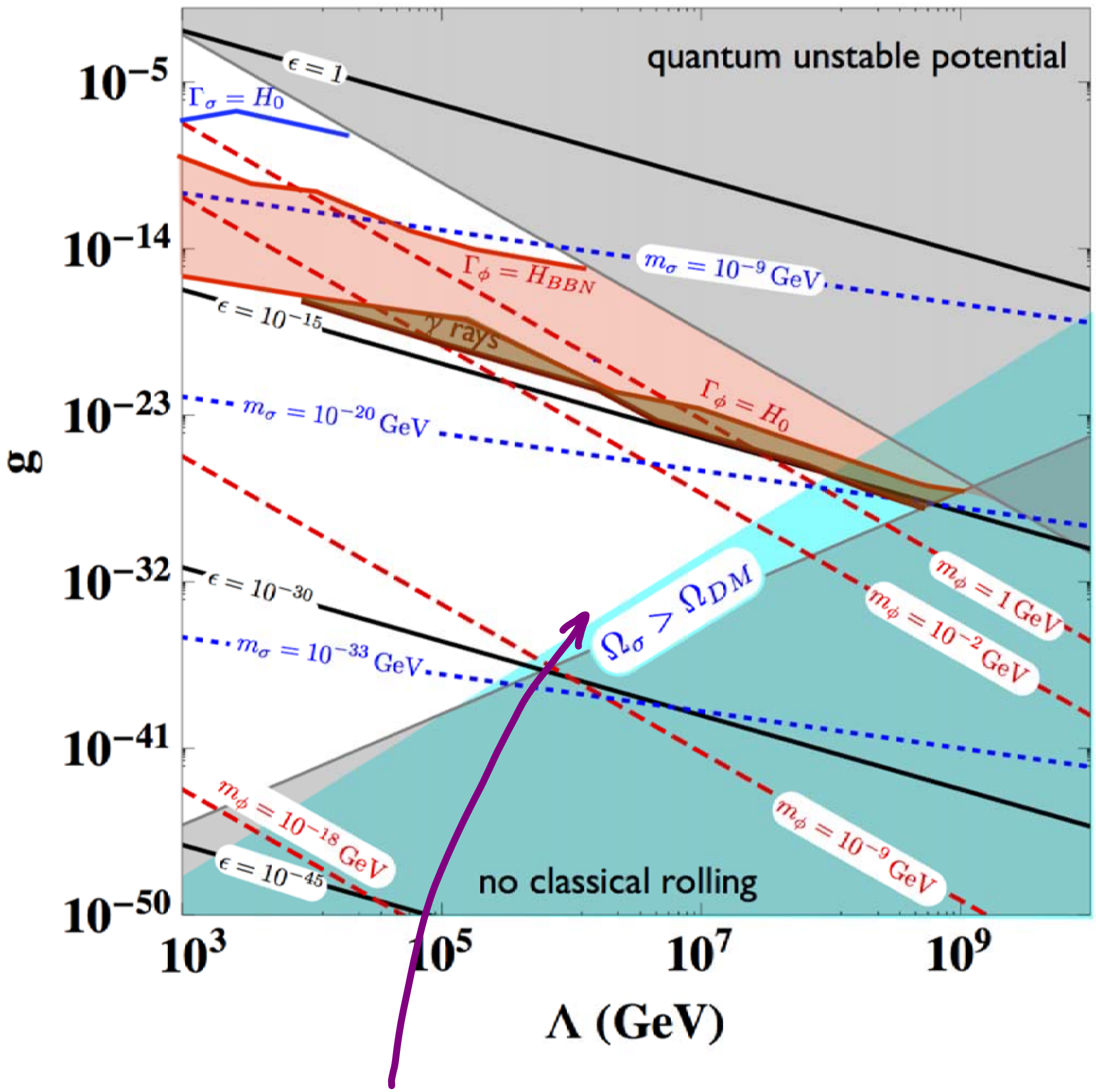
σ stable below (DM ?)

ϕ stable below



ϕ decays after BBN below

DARK MATTER



σ can be a good (axion-like) DM candidate.

CONCLUSIONS

New class of solutions to the hierarchy problem: Relaxion

EW Scale from early Universe dynamics

Typical predictions

- (extremely) light axion-like states

Interesting for DM, astro-ph signals...

- No collider signals guaranteed

Constructed natural model with

$$\Lambda \sim 10^{9}\,\mathrm{GeV}$$

OUTLOOK

- Current models have unpleasant features

$$N_e \gg 1 \qquad \Delta\phi \gg M_P$$

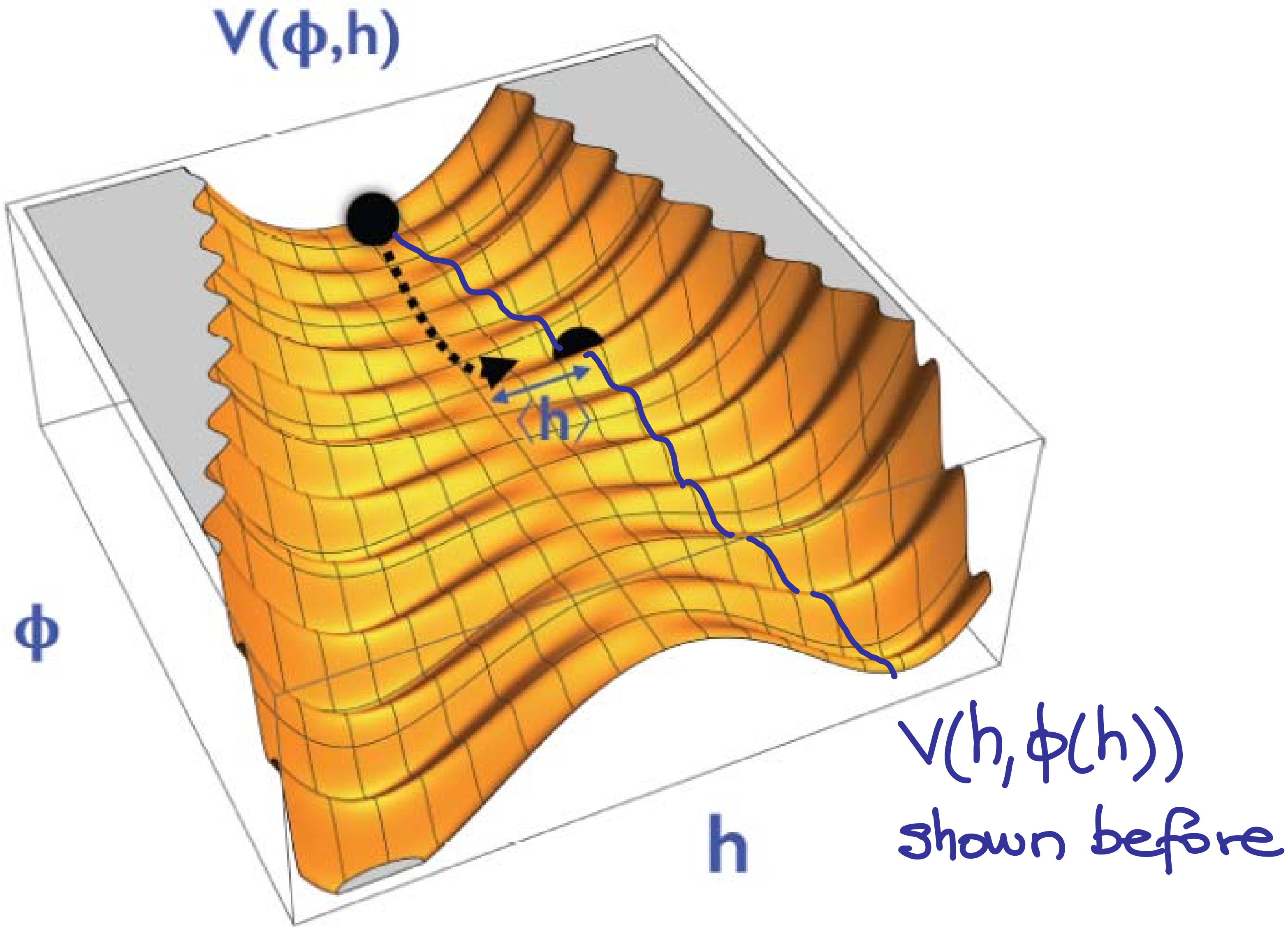
$\Rightarrow$ Room for improvement in inflation sector and model-building.

- Friction: alternatives to inflation?
- Possible to push Λ even higher?
- UV completions?
- Other applications? (~~SUSY~~, c.c.)

Giudice et al '15, Gherghetta et al.'16

BACK-UP SLIDES

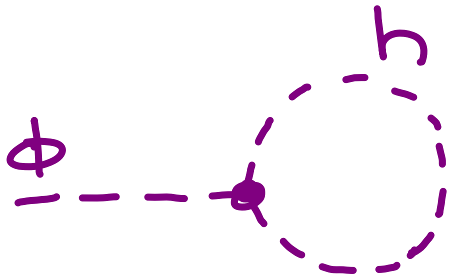
2-FIELD POTENTIAL



TECHNICAL NATURALNESS

Besides $g, \epsilon \ll 1$ being natural, also $V(h,\phi)$ should be radiatively natural

E.g



$<$

$$g\Lambda \times \frac{\Lambda^2}{16\pi^2} < g\Lambda^3 \quad \checkmark$$

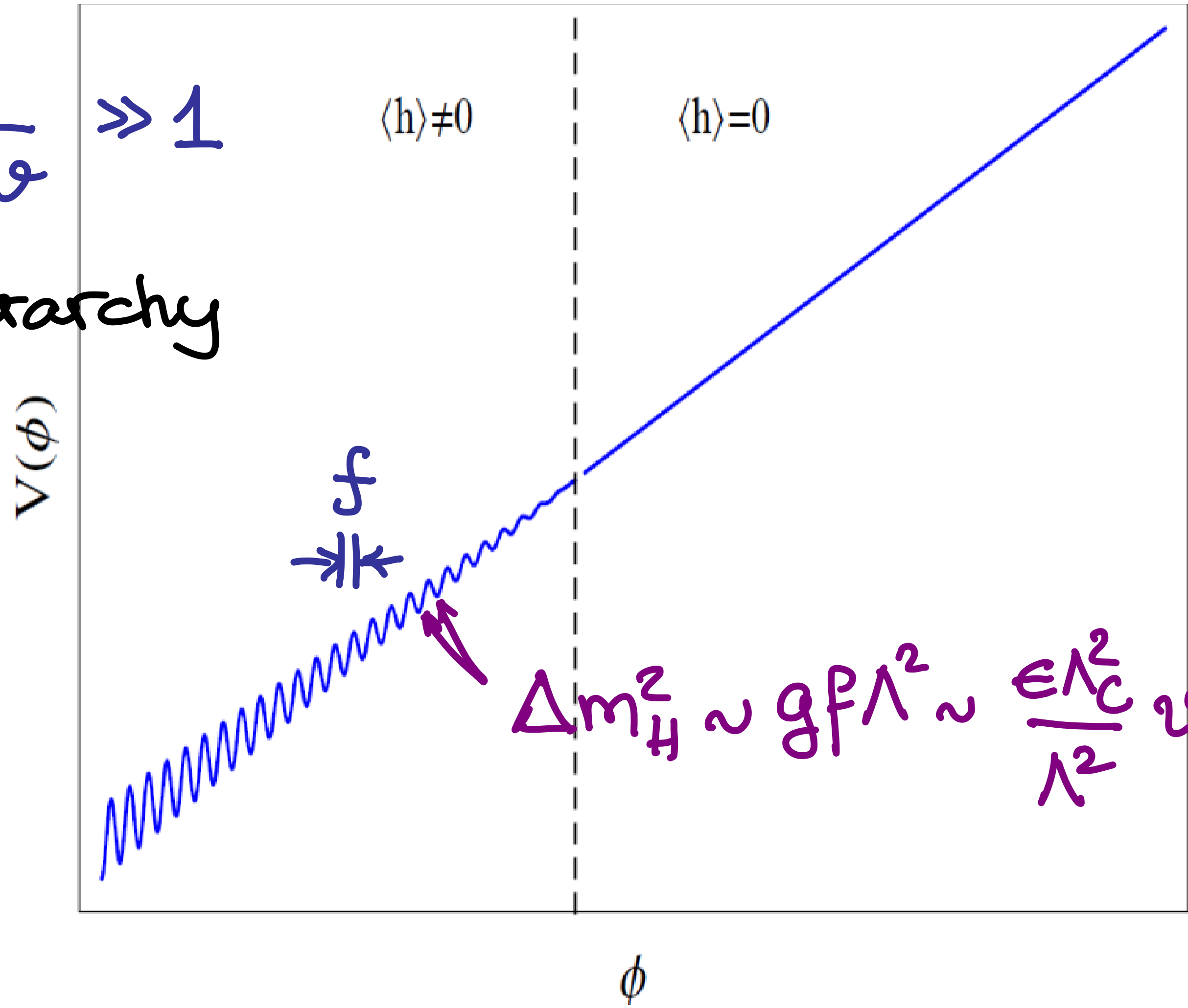
(Explains why we use single spurion g in both terms)

SCALES

$$\frac{\Delta\phi}{f} \gtrsim \frac{\Lambda^4}{\epsilon \Lambda_c^3 v} \gg 1$$

$n = 1$

Is this hierarchy natural?



f

$$\Delta m_H^2 \sim g f \Lambda^2 \sim \frac{\epsilon \Lambda_c^2}{\Lambda^2} v^2 \ll v^2 \checkmark$$

$\Delta\phi$

$\sim \Lambda/g \gg \Lambda$ problematic?

CONCERNS ABOUT $V(\phi)$?

ϕ starts as an angular dof.

PNGBs have compact field range.

$g \neq 0$ makes the field range non compact.

Komargodski et al.'15 stressed (known) concerns

about the consistency of this:

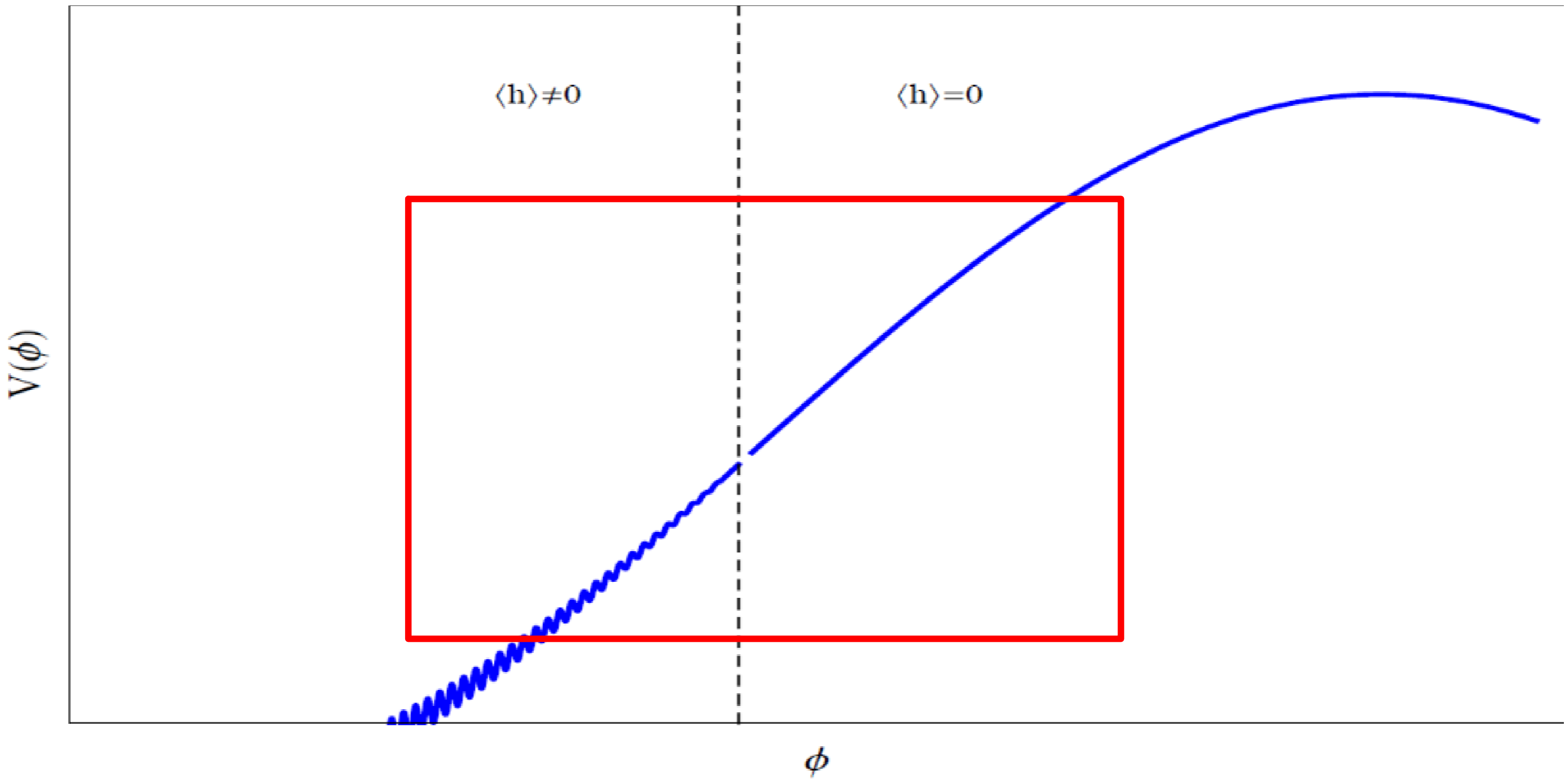
Can't break a gauge symmetry. ($\equiv$ redundancy)

$\Rightarrow$ All ϕ operators should be periodic.

CONCERNS ABOUT $V(\phi)$?

In practice, it's enough to have a hierarchy of decay coustants : $F = nf \gg f$

$$V \sim A\cos(\phi/F) + B(h)\cos(\phi/f)$$



CONCERNS ABOUT $V(\phi)$?

But, an exponential hierarchy $F \gg f$ does not seem natural ?

Choi, Im + Kaplan, Rattazzi :

QFT examples with N fields, with field-range f leading in the IR to a PNGB (linear comb. of the N fields) with field-range

$$F \sim e^{aN} f \qquad a \sim O(1)$$

Directly relevant for relaxion potentials.

BEYOND THE SIMPLE QCD-RELAXION

Ways out :

- Tilt decreases after inflation ($\theta_{QCD} < 10^{-10}$)

  eg. by including $\delta V = \kappa \sigma_I^2 \phi^2$ (σ_I = inflaton)

  $\Rightarrow \Lambda \lesssim 3 \times 10^4$ GeV only

- non-QCD strong gauge sector with

  $\Lambda_c \lesssim$ TeV and extra fermions at EW scale

GKR model #2

$\Rightarrow \Lambda \lesssim 10^8$ GeV

Coincidence problem : why $\Lambda_c \lesssim$ TeV ?

INFLATION SECTOR

Largely unspecified, except

- ϕ subdominant

$$V(\phi) \sim \Lambda^4 < V_I \sim H_I^2 M_P^2$$

- ϕ classical roll dominates

$$(\Delta\phi)_{class} \sim V'_\phi / H_I^2 > (\Delta\phi)_{quant} \sim H_I$$

Window for H_I :

$$\frac{\Lambda^2}{M_P} < H_I < (\underbrace{V'_\phi}_{\Lambda^3 g})^{1/3} \quad \Rightarrow \quad g > \left(\frac{\Lambda}{M_P}\right)^3$$

INFLATION SECTOR

Also, inflation long enough for ϕ to scan its typical field range $\sim \frac{\Lambda}{g}$

$$\Delta\phi \sim N_e \cdot \frac{V'_\phi}{H_I^2} \gtrsim \frac{\Lambda}{g}$$

$$\Rightarrow \quad N_e \gtrsim \left(\frac{H_I}{g\Lambda}\right)^2 \geq \left(\frac{\Lambda}{gM_P}\right)^2$$

Usually $N_e \gg 1$ and $\Delta\phi \gg M_P$ needed.

(Assumes constant H_I. Can be much better otherwise $\rightarrow$ Patil, Schwaller)

SYMMETRIES

Axion Lagrangian

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu \phi)^2 + \frac{g_s^2}{32\pi^2}\frac{\phi}{f} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

invariant under $\phi \to \phi + c$ (ϕ ~~PQ~~ Goldstone)

Instantons induce $V \sim \epsilon \cos(\phi/f)$: $\phi \to \phi + 2\pi n f$

ϵ : ~~sym~~ spurion

Relaxion couplings $\delta V = \Lambda^3 g \phi + \frac{1}{2} g \phi h^2$

break completely the symmetry

g : ~~sym~~ spurion $\Rightarrow$ $\epsilon, g \ll 1$ Natural

Moreover $V(\phi)$ shape rad. stable

OUR MODEL : DOUBLE SCANNING

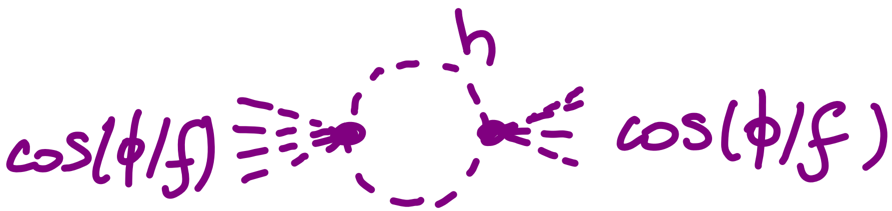
V is now technically natural

Ex.

$\epsilon \Lambda^4 \cos(\phi/f)$ ✓

$g\phi \cdot \epsilon \Lambda^3 \cos(\phi/f)$ ✓

Ex.



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

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

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

NEW MODEL : DOUBLE SCANNING

σ evolution quite trivial :

$$\sigma(t) = \sigma(0) - g_\sigma \Lambda^3 t/(3H_I)$$

Take $\sigma(0) \gtrsim \Lambda/g_\sigma$.

$\Rightarrow$ Evolution of ϕ in time-dep. potential

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

$\Rightarrow$ there are t-dependent ϕ field values with $A \approx 0$ (ϕ_*)

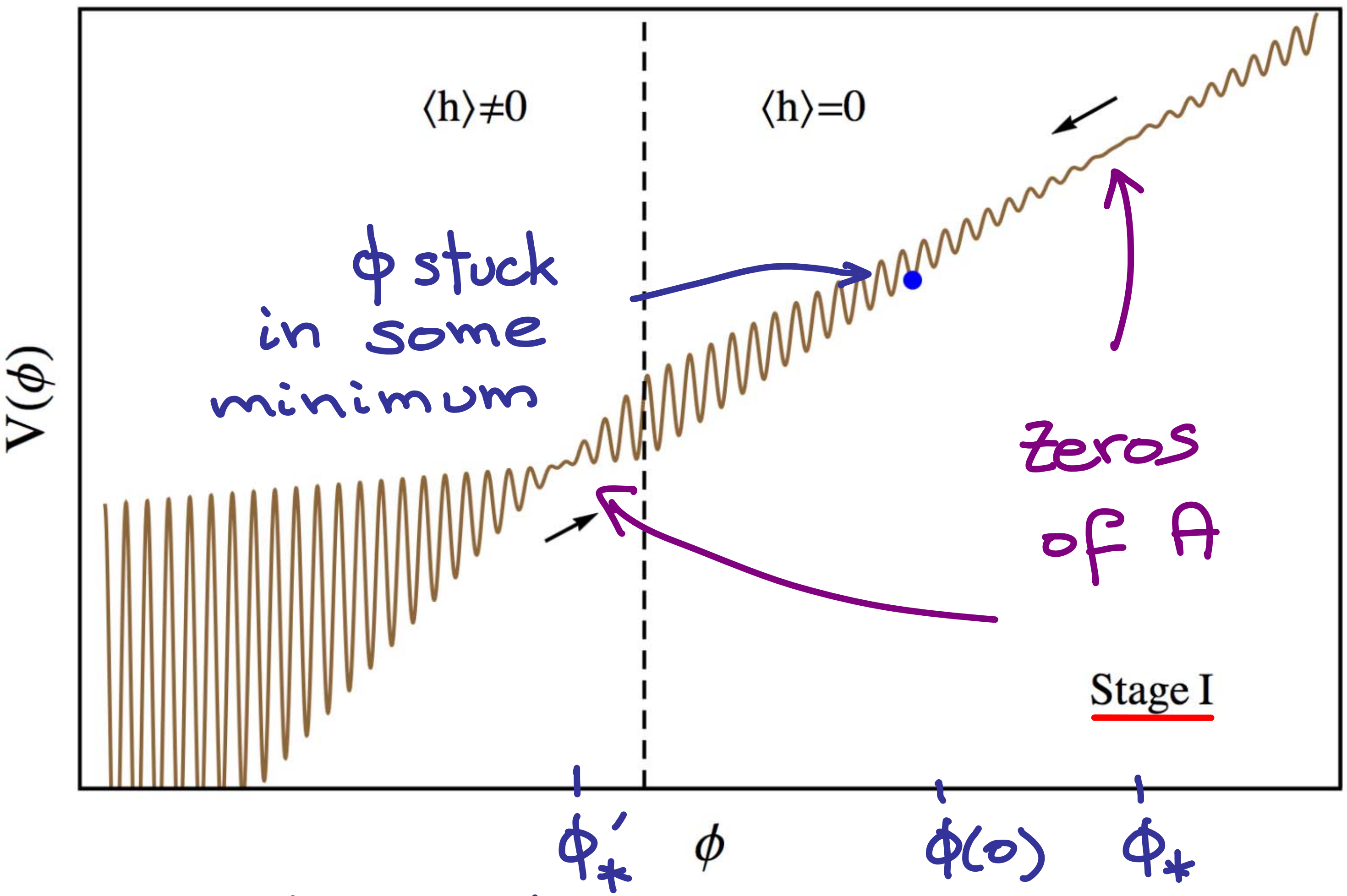
$\Rightarrow$ No barriers

Two branches, depending on $\langle h \rangle$ zero or not.

ϕ EVOLUTION

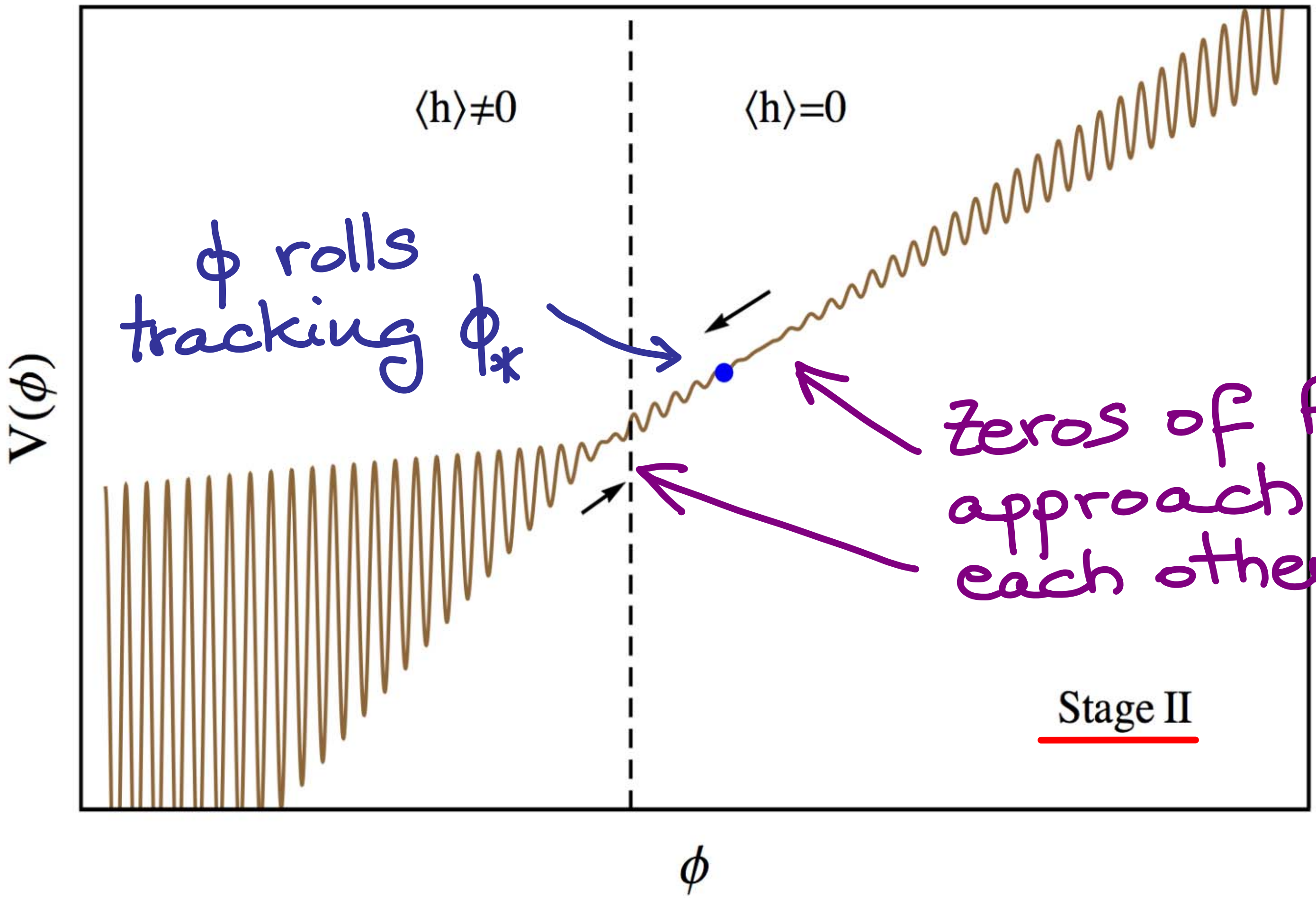
Four stages:

$t=0$



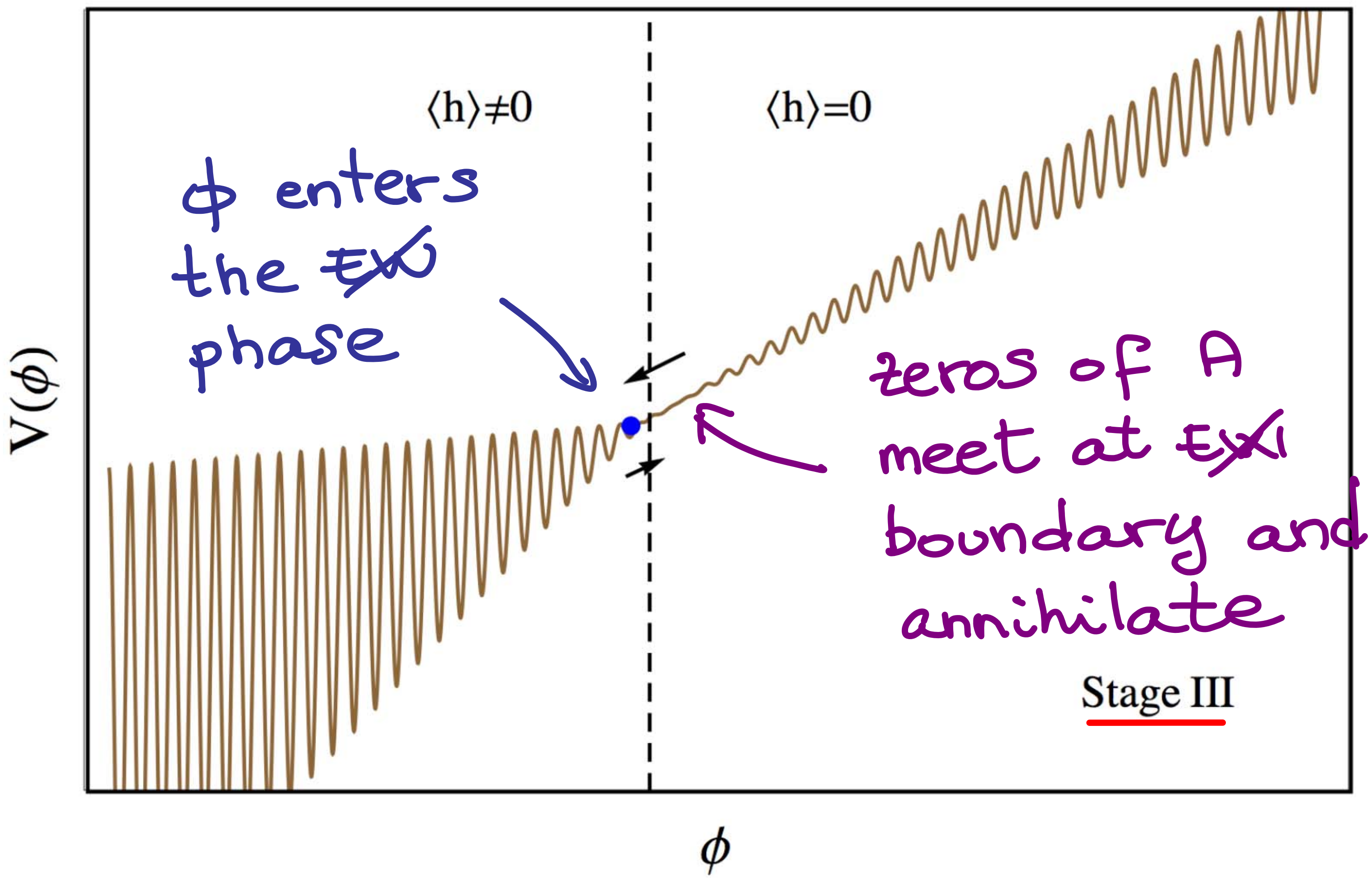
Assumes $\phi_c < \phi(0) < \phi_*$

ϕ EVOLUTION

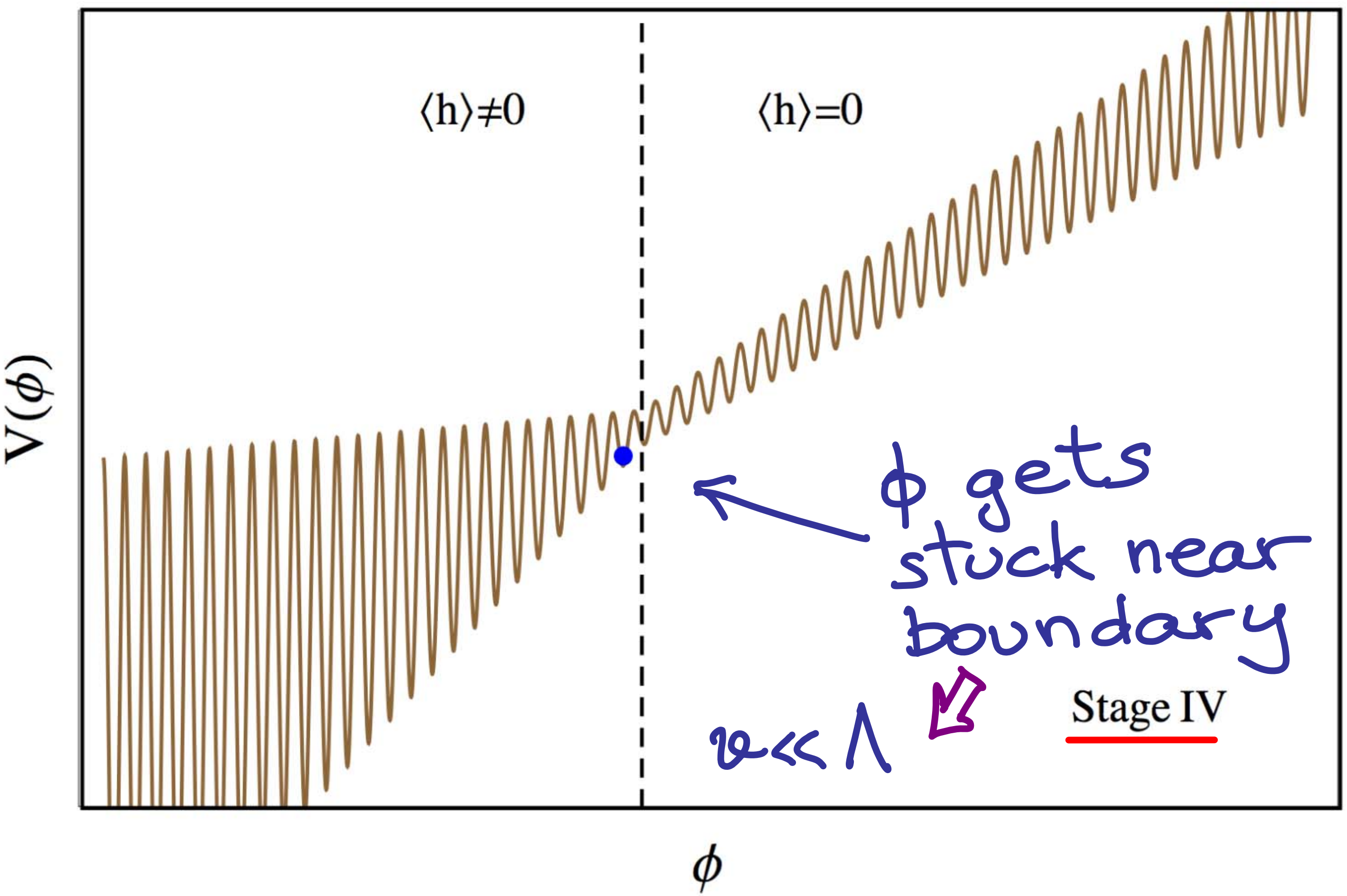


ϕ faster than ϕ_* requires $g \gtrsim g_\sigma$

ϕ EVOLUTION



ϕ EVOLUTION



PARAMETER CONSTRAINTS

- Natural V

$$\epsilon \lesssim (v/\Lambda)^2$$

- EW Scale as output

$$v^2 \simeq \frac{g\Lambda f}{\epsilon} \qquad \text{(requires } g \ll \epsilon\text{)}$$

- Inflation window

$$\Lambda^2/M_P \lesssim H_I \lesssim g_\sigma^{1/3}\Lambda$$

- Long enough inflation

$$N_e \gtrsim \frac{H_I^2}{g_\sigma^2 \Lambda^2}$$

PARAMETER CONSTRAINTS

The previous constraints give

$$(\Lambda/M_P)^3 \lesssim g_\sigma \leq g \lesssim v^4/(f\Lambda^3)$$

and using $f \gtrsim \Lambda$

$$\Lambda \lesssim (v^4 M_P^3)^{1/7} \simeq 2\times 10^9\,\mathrm{GeV}$$

Natural model without TeV matter ✓

No coincidence problem ✓

UV ORIGIN OF BARRIERS

Non-QCD sector strong at Λ + fermions L, N

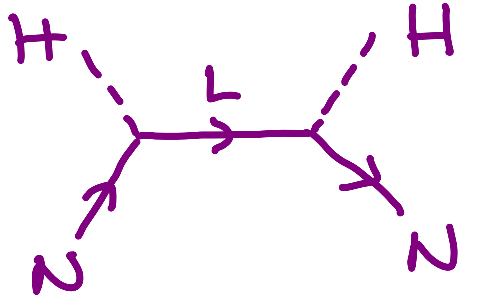
N : Light singlet fermion with $\langle \bar{N} N \rangle = \Lambda^3$

and axion coupling $\phi \, G'_{\mu\nu} \tilde{G}'^{\mu\nu}$

$$\Rightarrow \quad V \sim \Lambda^3 m_N \cos(\phi/f)$$

Just need $\mathcal{L} = \Lambda \bar{L} L + \epsilon(\Lambda + g\phi + g_\sigma \sigma) \bar{N} N + \sqrt{\epsilon} \bar{L} H N + h.c.$

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



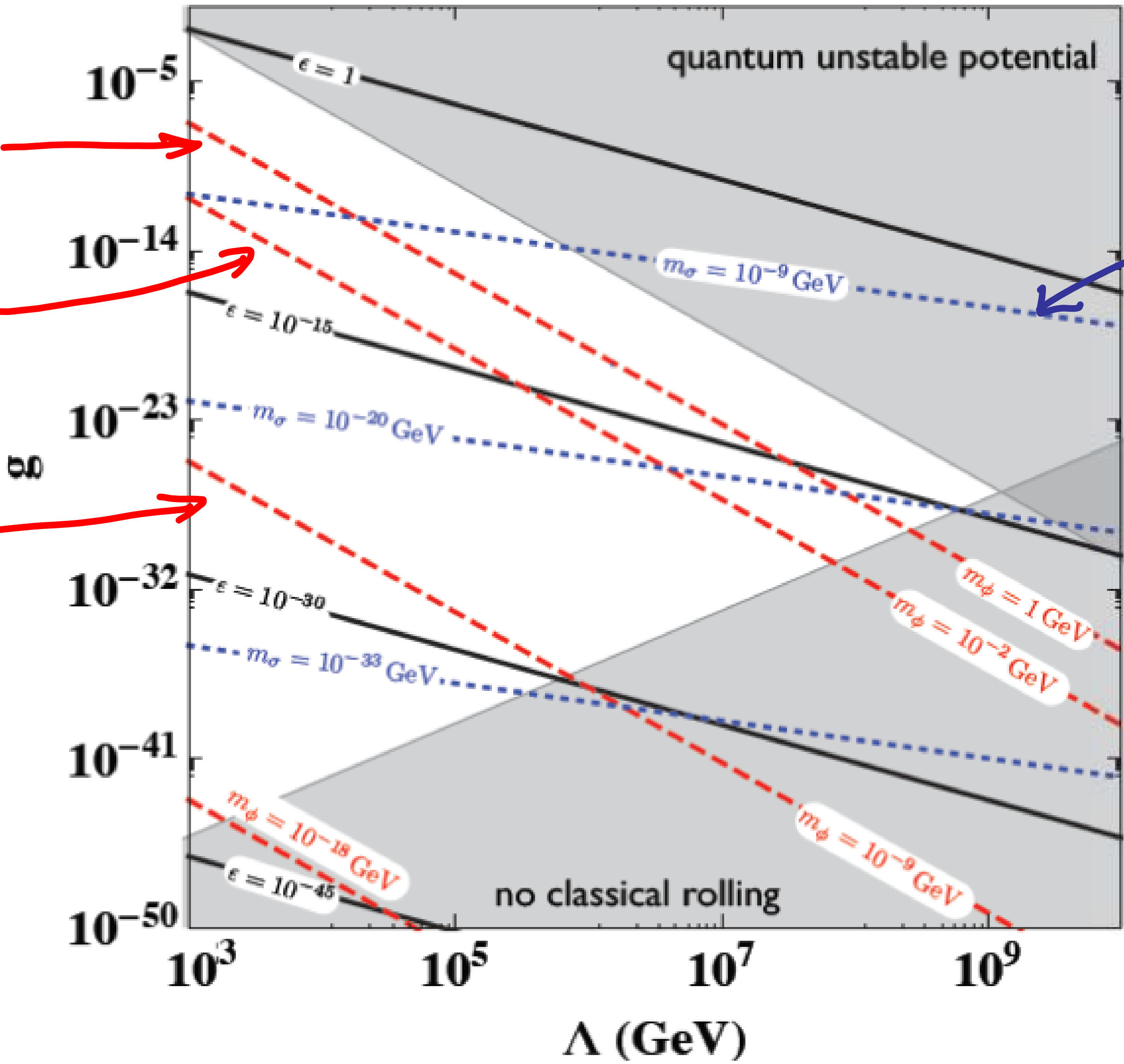
SiGNATURES ?

- Below Λ only extra states : ϕ and σ

$m_\phi = 1\,\text{GeV}$

$10^{-2}\,\text{GeV}$

$10^{-9}\,\text{GeV}$



$m_\sigma = 10^{-9}\,\text{GeV}$

$10^{-20}\,\text{GeV}$

$10^{-33}\,\text{GeV}$

DARK MATTER

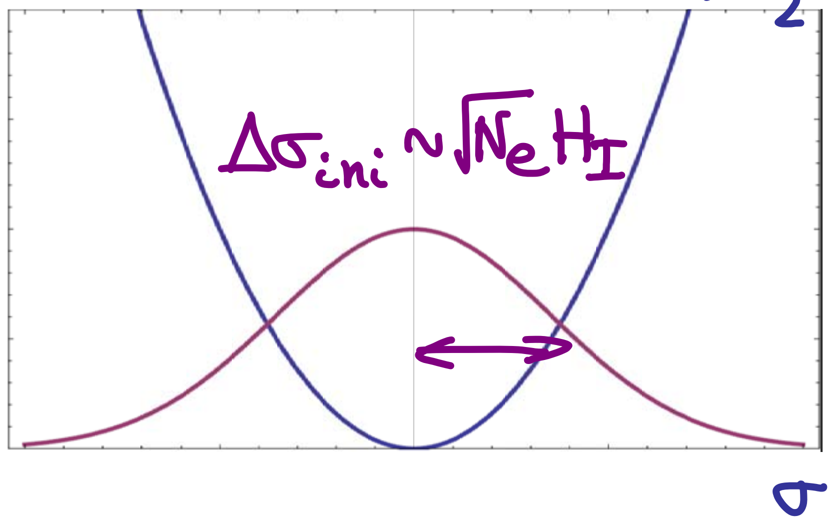
σ can be a good DM candidate.

After inflation:

σ typically displaced from its minimum with

$$\rho_{ini}^{\sigma} \sim m_\sigma^2 \Delta\sigma_{ini}^2 \sim H_I^4$$

$V(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 + \ldots$



Below $T_{osc,\sigma}^{\sigma} \sim \sqrt{m_\sigma M_P}$ it oscillates with energy density scaling like nonrelativistic matter

$$\rho_\sigma(T) \sim \rho_{ini}^{\sigma} \left(\frac{T}{T_{osc}^{\sigma}}\right)^3 \Rightarrow \Omega_\sigma \gtrsim \left(\frac{4\times10^{-28}}{g_\sigma}\right)^{3/2} \left(\frac{\Lambda}{10^8 \,\mathrm{GeV}}\right)^{13/2}$$

(Ω_ϕ always subdominant)

OTHER PROBES

- σ could be searched by SKA pulsar timing array experiment for $m_\sigma \sim 10^{-23}$ eV

Khmelnitsky, Rubakov '13

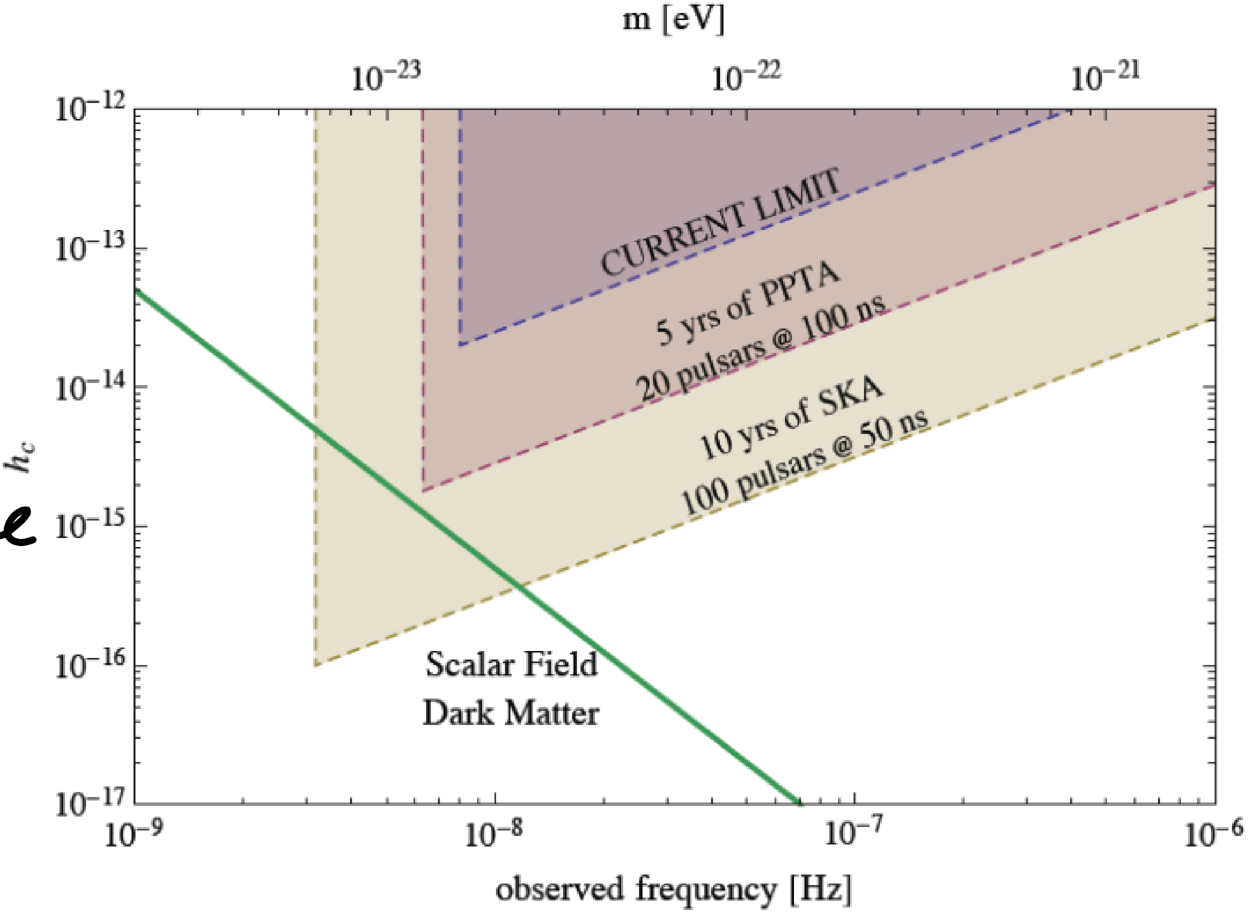
Oscillating σ $\Rightarrow$ oscillating pressure and gravitational potentials of DM halo

Effect similar to a monochromatic gravitational wave with $\nu \sim m_\sigma \sim 10^{-9}$ Hz

OTHER PROBES

- σ could be searched by SKA pulsar timing array experiment for $m_\sigma \sim 10^{-23}$

signal amplitude



Khmelnitsky, Rubakov '13

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Previous work with similar ideas

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'03 Cosmic Attractors and Gauge Hierarchy
G. Dvali, A. Vilenkin

'04 Large Hierarchies from Attractor Vacua
G. Dvali

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E. Hardy

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