Now what?

1. wait and see: Run2 finds partners?
2. anthropic principle?
3. re-think everything

a beautiful new idea:

$$m^2(t)\, H^\dagger H$$

m^2 dynamically "relaxes"

$$\Lambda^2_{\text{cut-off}} \xrightarrow{\;t\;} -125^2\,\text{GeV}^2$$

time varying Higgs VEV constraints

$$m_H^2(t)\, H^\dagger H \longrightarrow v(t) \begin{array}{l} \nearrow G_F(t) \\ \rightarrow m_q(t) \\ \searrow \Lambda_{QCD}(t) \\ \searrow \alpha_{em}(t) \end{array}$$

- $\delta\alpha_{em}/\alpha_{em} \lesssim 10^{-16}/\text{year}$ condensed matter / atomic physics
- OKLO "natural" nuclear reactor Gabon $1.5\ 10^9$ yrs ago $\lesssim \%$
- primordial nucleosynthesis H/He $t \approx 1\,\text{min}$ $\lesssim \%$

$\Longrightarrow$ relaxation over by $t =$ nucleosynthesis

a beautiful new idea:

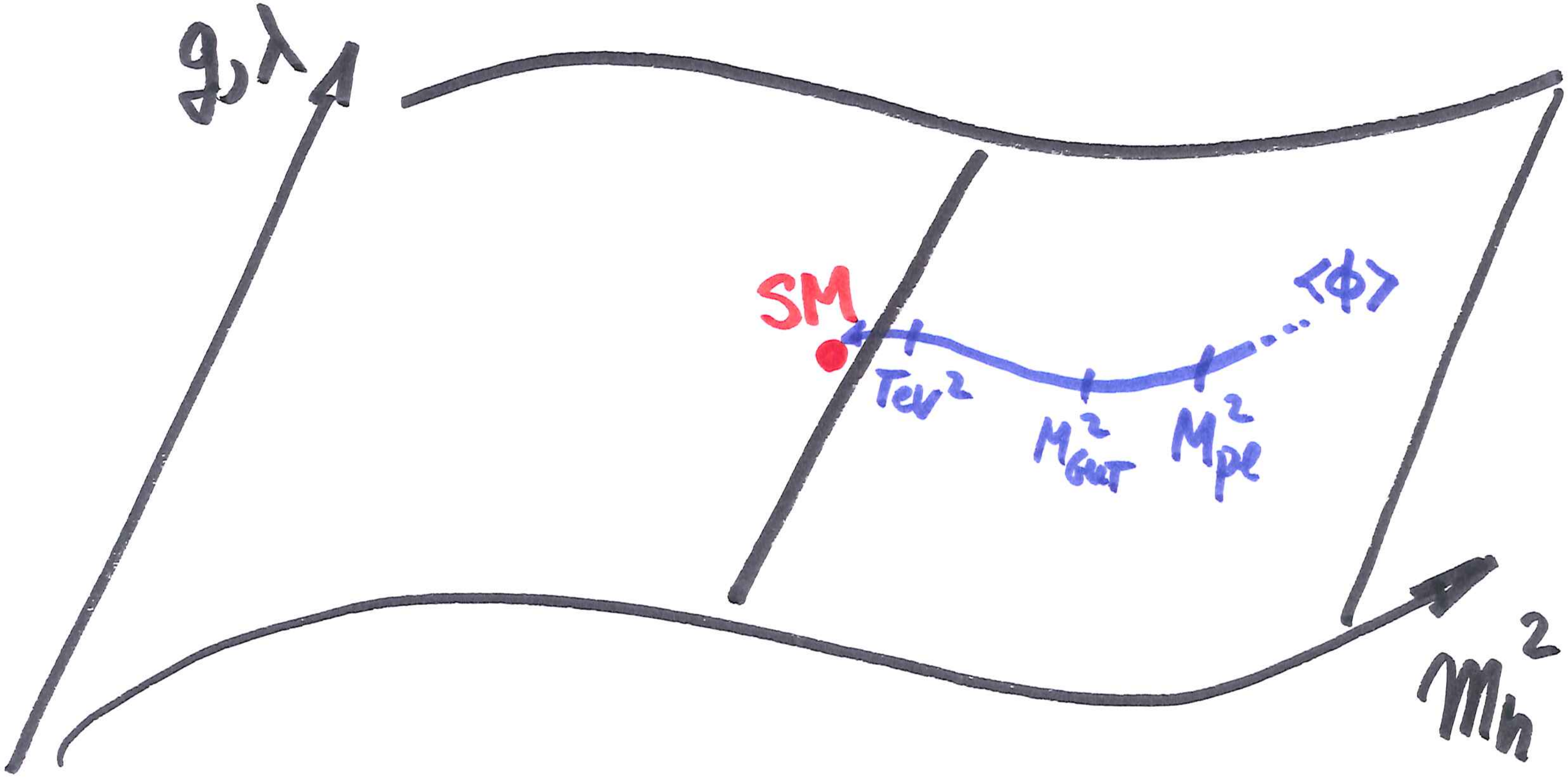
$$m^2(t)\, H^\dagger H$$

m^2 dynamically "relaxes"

$$\Lambda^2_{\text{cut-off}} \xrightarrow{\;t\;} -125^2\,\text{GeV}^2$$

$\Rightarrow$ m^2 depends on a field $\phi(t)$

Hypersurface in coupling/field space



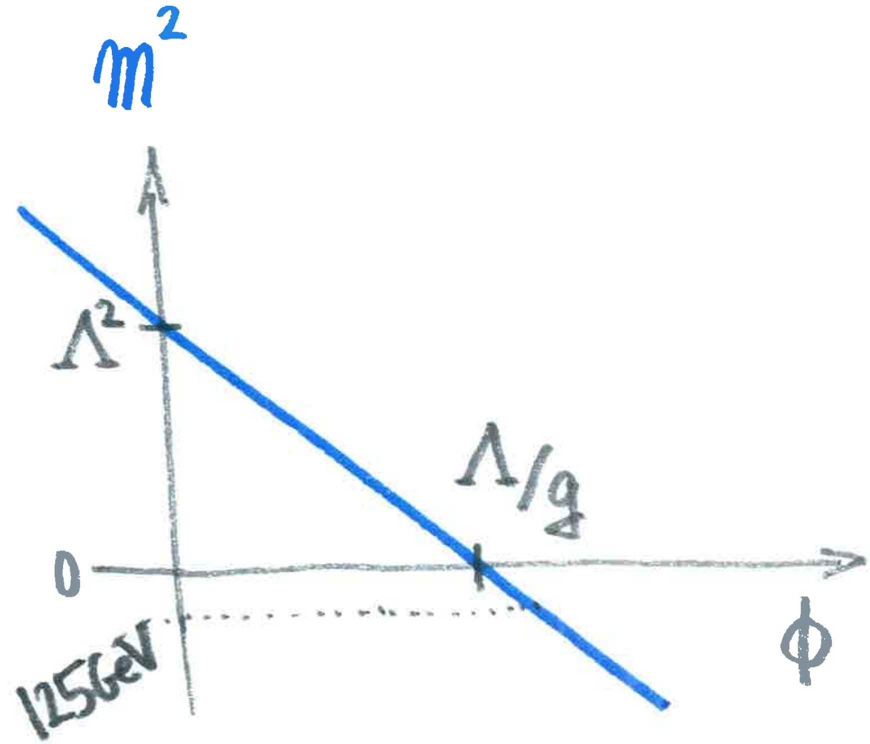
ϕ "relaxion"

A concrete realization:

Graham, Kaplan, Rajendran
1504.07551

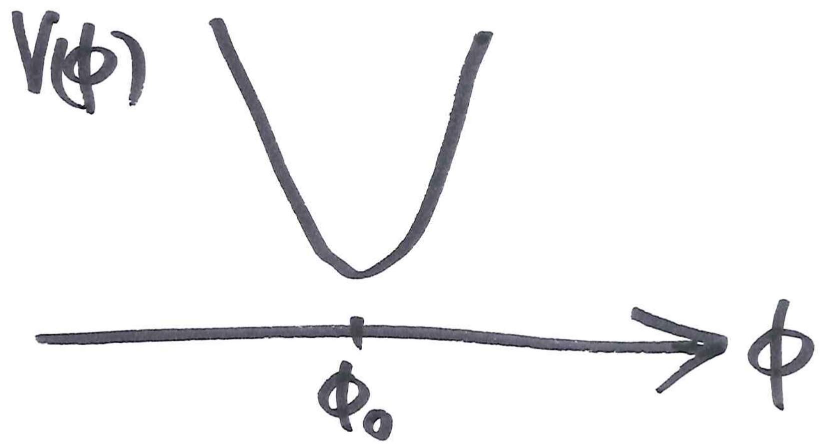
"relaxion"

$$\underbrace{\left(\Lambda^2 - g\Lambda\phi(t)\right)}_{m^2(t)} H^\dagger H$$



How is ϕ fixed so that m^2 is time-independent?

a potential... try:



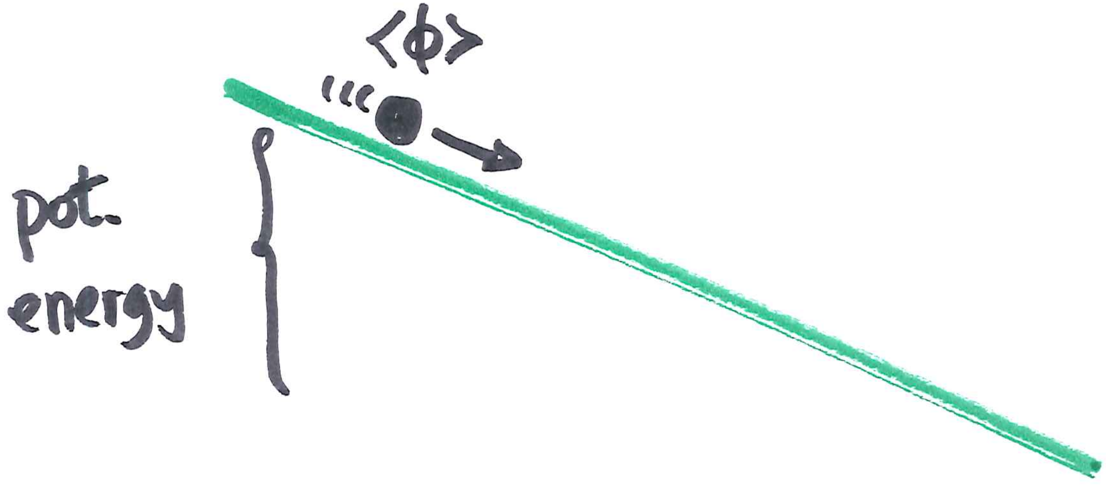
$$V(\phi) = (\phi^2 - \phi_0^2)^2 \quad + (\Lambda^2 - g\Lambda\phi)H^\dagger H$$

stop in correct place: $\Rightarrow \quad \phi_0 g \approx \Lambda$

But that's fine-tuning!

... need to be smarter... postpone question of settling ϕ

How/why does ϕ move ?



$$V(\phi) \cong -g\phi\Lambda^3$$

$$\mathcal{L} \sim \dot{\phi}^2 - (\vec{\nabla}\phi)^2 - V(\phi)$$

$$\Rightarrow \quad \ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{"Hubble friction"}} = -V'(\phi)$$

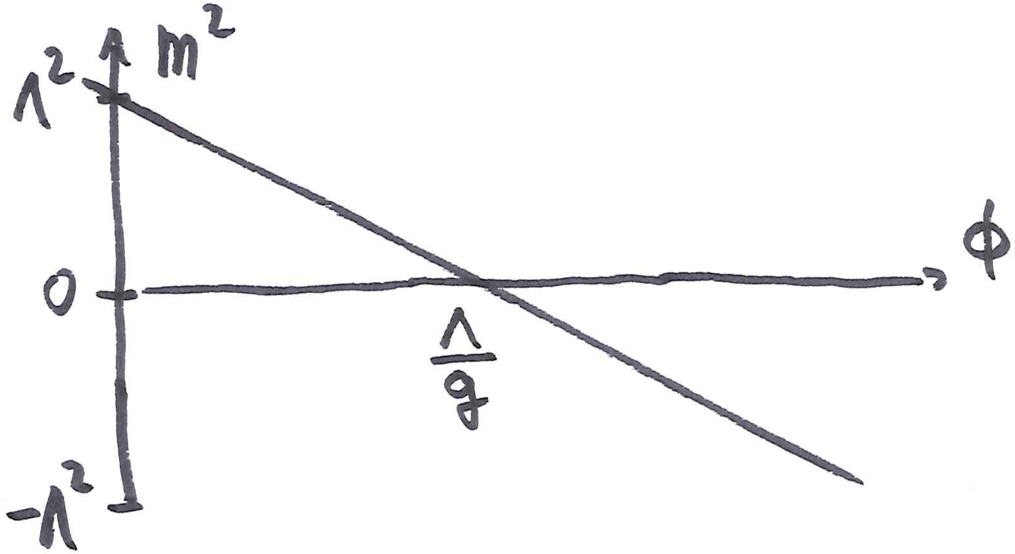
assume V flat enough – "slow roll"

$$\Rightarrow \quad 3H_I\dot{\phi} = g\Lambda^3$$

kinetic energy of ϕ dissipated by Hubble friction

How far do "we" need to roll?

$$\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)H^\dagger H$$



start in generic place: $m^2 \sim \Lambda^2$

$$\Rightarrow \quad \Delta\phi \sim \frac{\Lambda}{g} \gg \Lambda \quad \Rightarrow$$ large field excursions

Some consistency conditions:

Energy density in ϕ small compared with inflaton

$$\Rightarrow \quad H_I \gtrsim \frac{\sqrt{V(\phi)}}{M_{pe}} = \frac{\Lambda^2}{M_{pe}}$$

time needed for ϕ to roll far enough

$$3 H_I \frac{\Delta\phi}{\Delta t} = g\Lambda^3 \quad , \quad \Delta\phi = \frac{\Lambda}{g}$$

$$\Rightarrow \quad \Delta t = N_{e\text{-folds}} \cdot \frac{1}{H_I} = \frac{H_I}{g^2\Lambda^2}$$

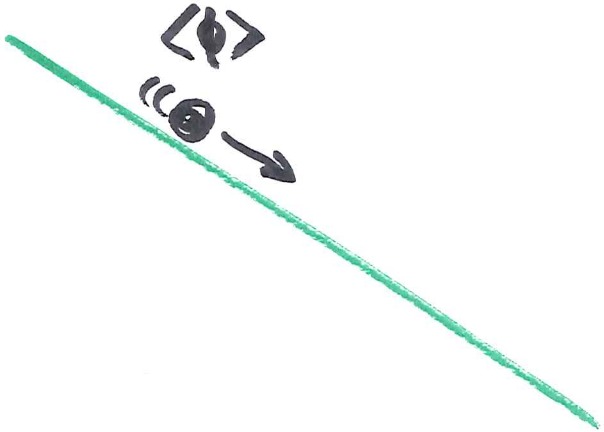
$$\Rightarrow \quad N_{ef} \sim \frac{H_I^2}{g^2\Lambda^2}$$

uniform ϕ everywhere in space

$\Rightarrow$ classical rolling $\gg$ quantum fluctuations

$$\frac{1}{H_I}\frac{\Delta\phi}{\Delta t} \gg H_I$$

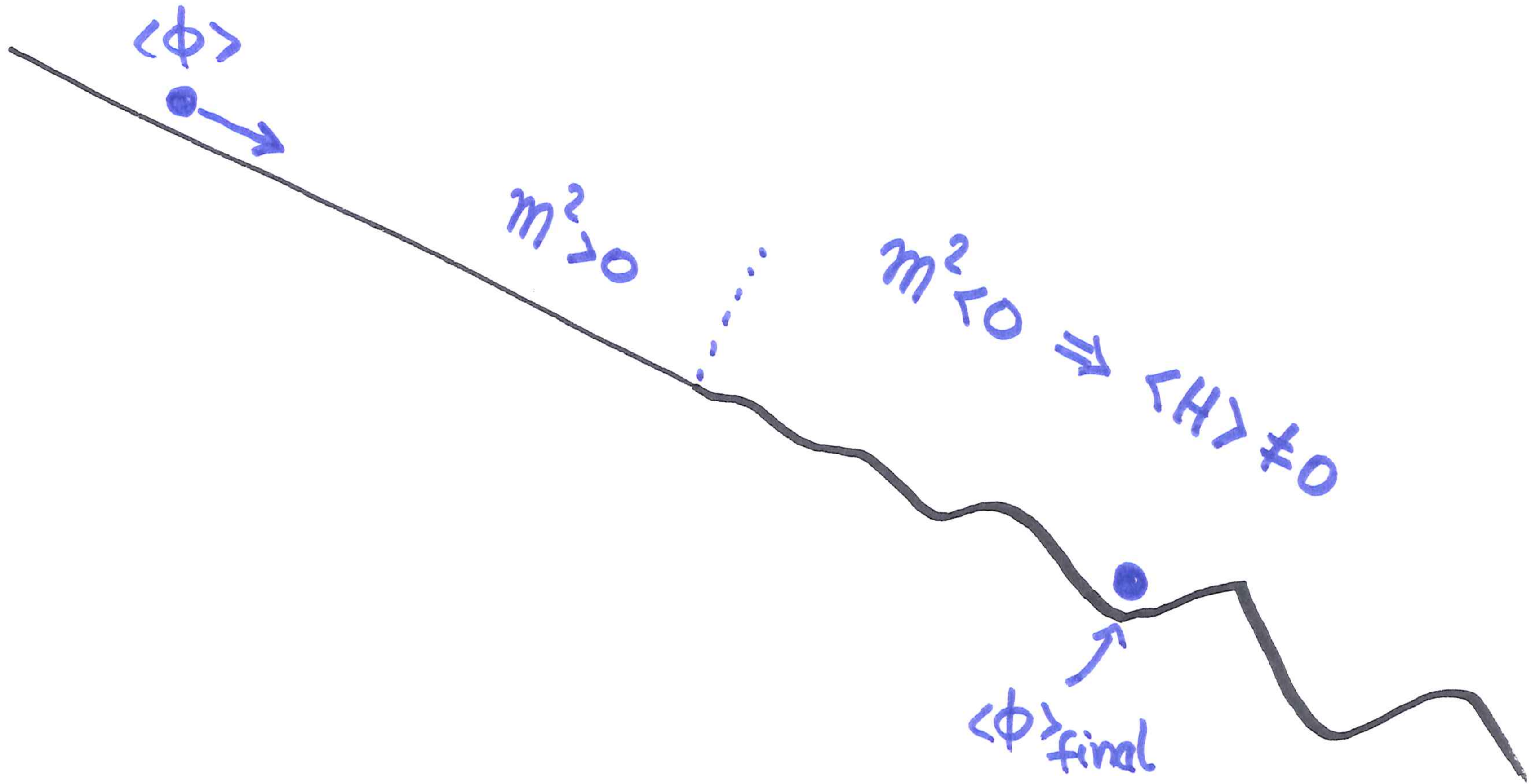
$g\Lambda^3/3H_I$

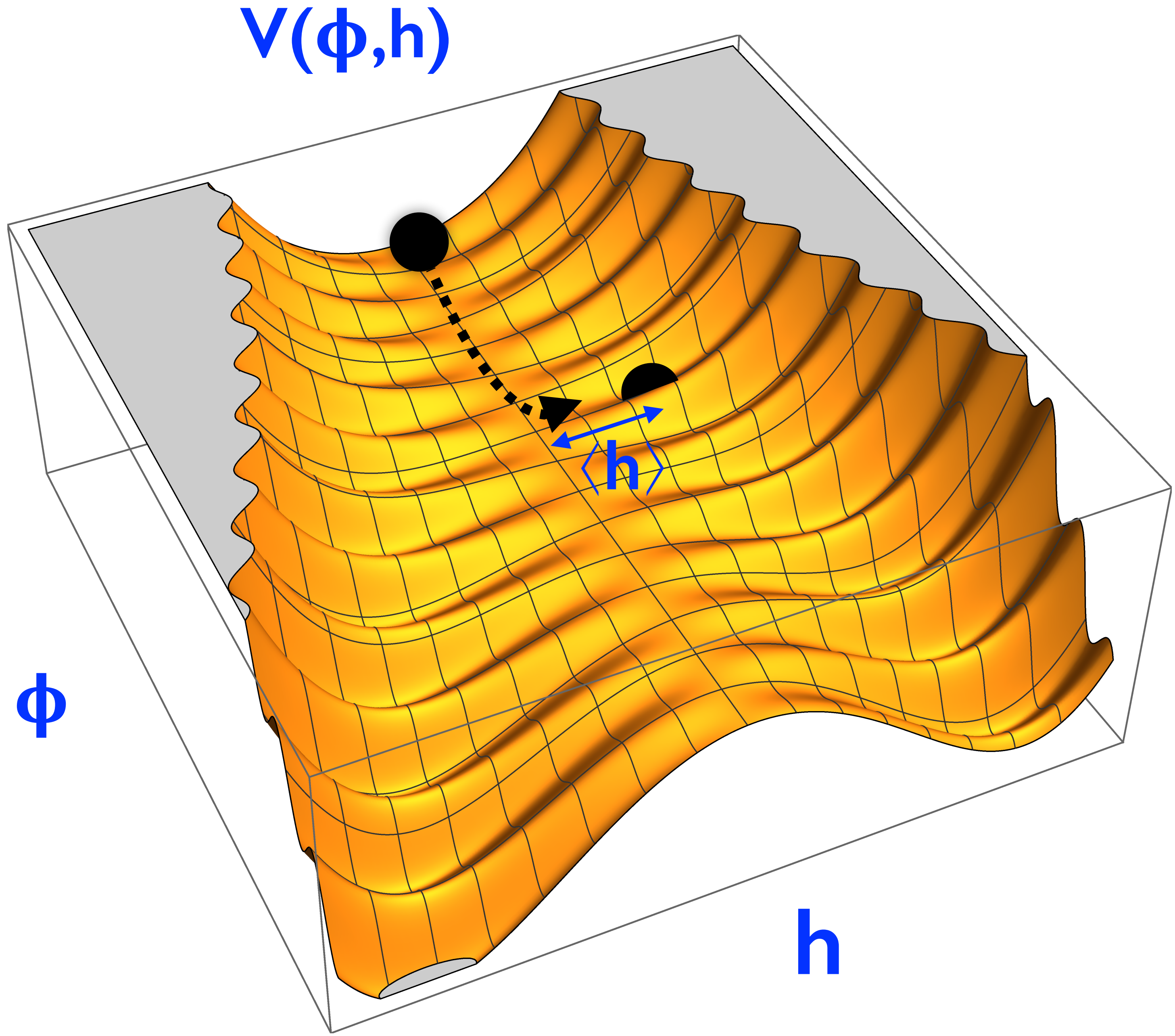


$$\Rightarrow \quad H_I < g^{1/3}\Lambda$$

How do we stop rolling?

$$V(\phi) \sim \underbrace{-\Lambda^3 g \phi}_{\phi\text{-slope}} + \underbrace{\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right) H^\dagger H}_{m^2(\phi)} + \underbrace{\epsilon \Lambda^3 H \cos\left(\frac{\phi}{f}\right)}_{\text{"feedback"}} + \text{Higgs quartic}$$





1506.09217

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

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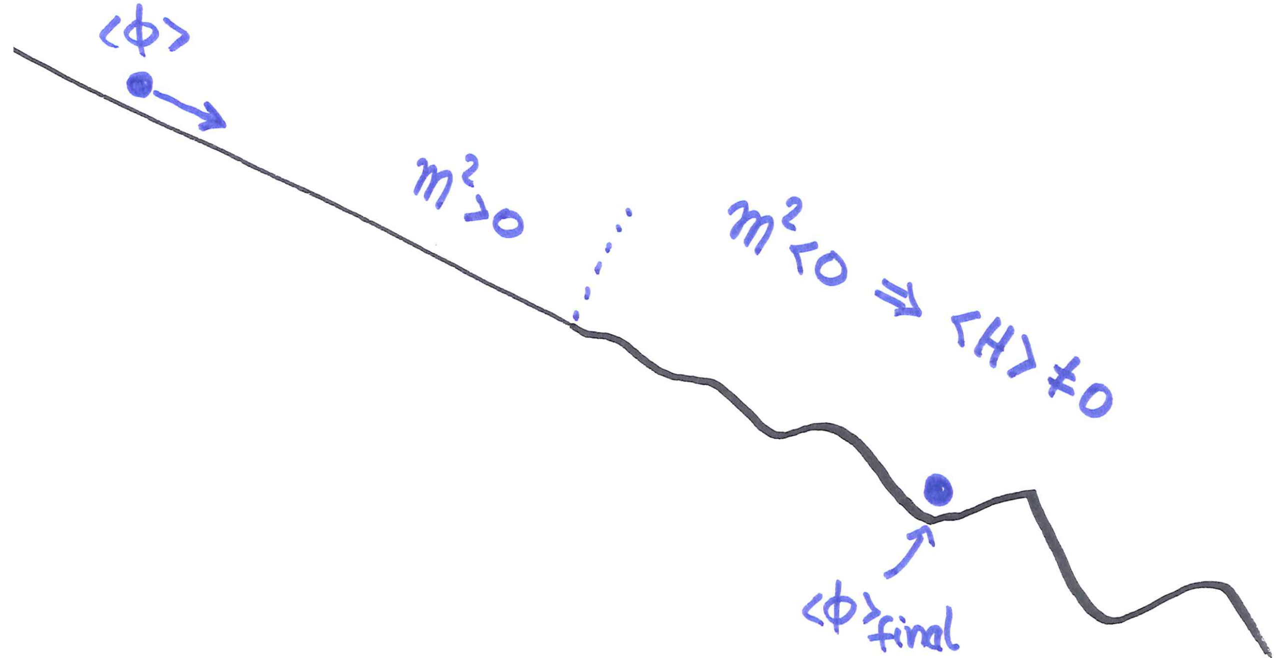


stop when:

$$V'_{feedback} \approx V'_{slope}$$

$$\epsilon \Lambda^3 \frac{v}{f} \sim g \Lambda^3$$

$$v \sim \frac{g}{\epsilon} f$$

Origin of crazy cos-potential? (axion)

in UV, colored quark $\lambda \Phi \bar{\Psi} \Psi$ $\quad \langle \Phi \rangle = f e^{i\phi/f}$

$$\Longrightarrow \quad \frac{1}{32\pi^2} \frac{\phi}{f} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

ϕ = QCD axion

$\Rightarrow f > 10^9$ GeV astrophysics

QCD confines

$$\longrightarrow \quad V_{QCD} \sim \frac{m_u m_d}{m_u + m_d} \Lambda^3_{QCD} \cos\left(\frac{\phi}{f}\right) \sim \underbrace{\lambda_{up} \langle H \rangle \Lambda^3_{QCD}}_{\epsilon V = m_u \frac{\Lambda^3_{QCD}}{\Lambda^3}} \cos\left(\frac{\phi}{f}\right)$$

Combine constraints ...

$$H_I > \frac{\Lambda^2}{M_{pl}}$$ inflaton dominates

$$H_I < g^{1/3}\Lambda$$ classical rolling

$$v \sim \frac{g}{\epsilon} f$$ stop in minima

$$\Lambda \lesssim \left[\frac{m_u}{f}\right]^{1/6} \left[\Lambda_{QCD} M_{pl}\right]^{1/2} = 10^7\,\mathrm{GeV} \left[\frac{10^9\,\mathrm{GeV}}{f}\right]^{1/6}$$

OK... what did we accomplish ?

$$V \sim g\Lambda^3\phi + (\Lambda^2 - g\Lambda\phi)H^\dagger H + \frac{\phi}{f} G\tilde{G}$$

- technically natural theory : $\phi \to \phi + 2\pi f$ approximate symmetry broken by g $\Rightarrow$ small $g\phi$ tech. nat.
- raised cutoff $\Lambda \to 10^4$ TeV
- only one new field ϕ in eff. theory
- a new approach

important ingredients...

- dissipation — Hubble friction — so we can stop
- self-similar potential for ϕ — so that we can stop when $m_{Higgs} \sim 0$
- Higgs back-reaction
- very long inflation — enough time to scan ϕ

Caveats / outlook

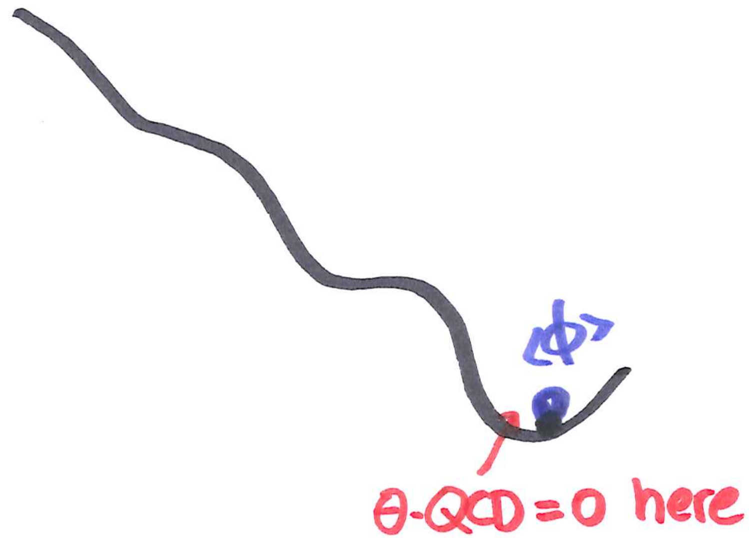
- strong CP, a problem

  can be solved

- $\Delta\phi > \dfrac{\Lambda}{g}$ (in progress)

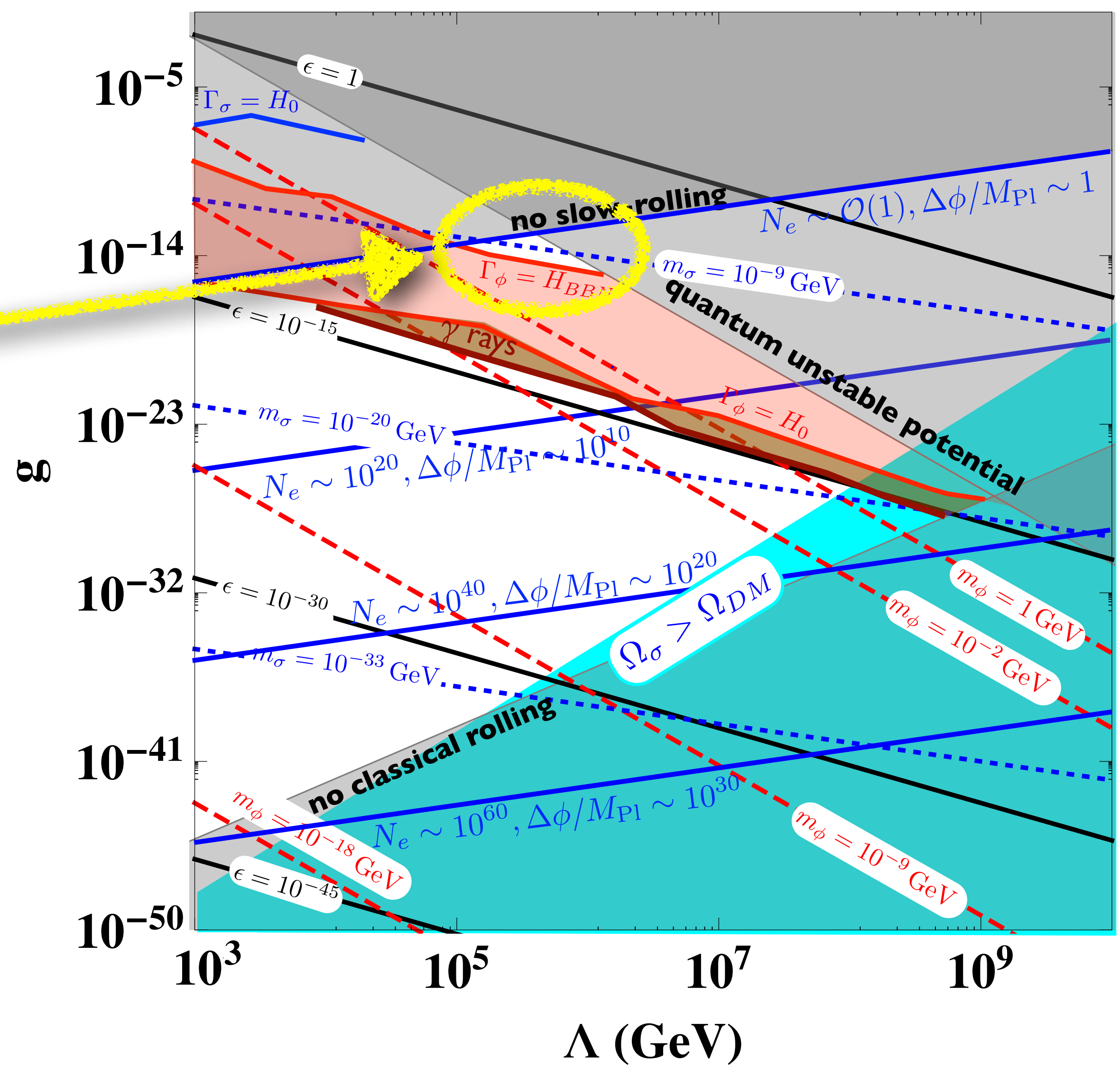
- $n_s = 1$ and not 0.97 ± 0.005

  2-stage inflation



f=Λ

`reasonable' region with moderately small coupling, moderately large field winding, and a cut off scale @100-1000 TeV



$g = 10 g_\sigma$