COSMOLOGICAL EXPLANATIONS OF THE HIGGS MASS AND WHERE TO FIND THEM

Raffaele Tito D'Agnolo

1980 — You will find new physics at LEP

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1990 You will find new physics at the Tevatron

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1990 — You will find new physics at the Tevatron

2000 — You will certainly find new physics at the LHC, it's now or never

Cosmological Constant

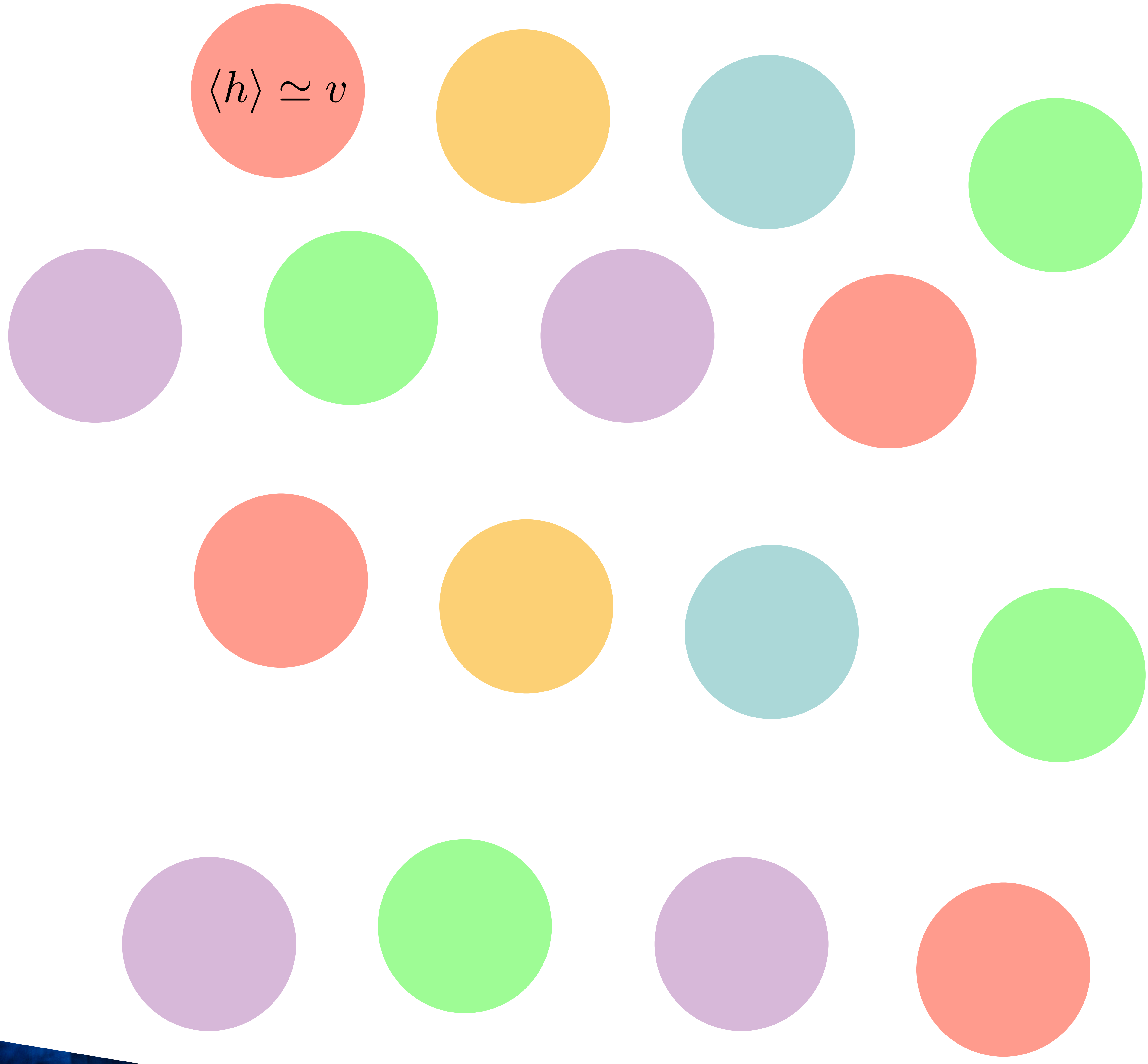
$$\Lambda^4$$

Theory ~ 10^{120} Experiment

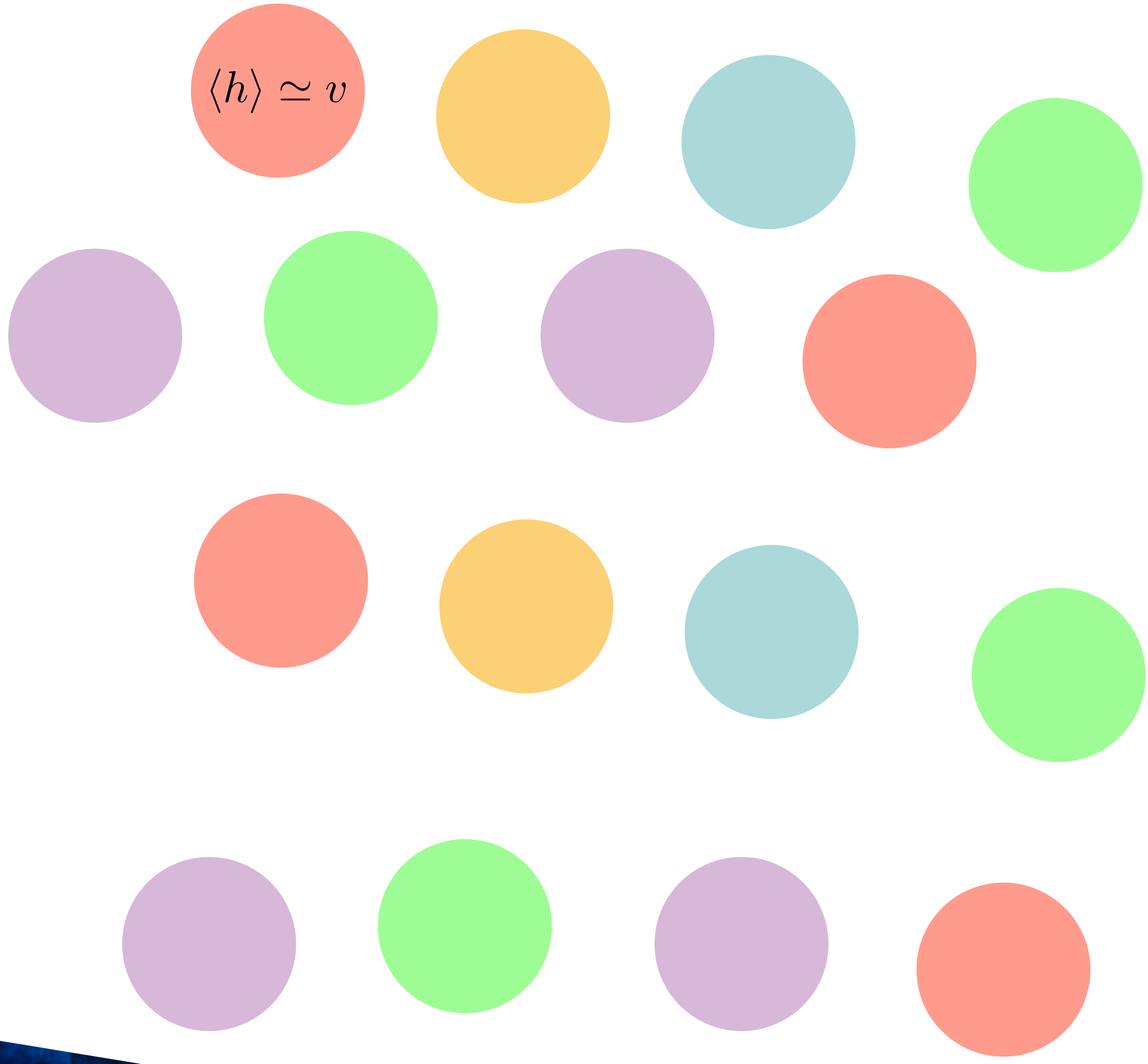
Higgs Mass Squared

$$m_h^2 |H|^2$$

Theory~10^{34} Experiment



Causally Disconnected Universes with different values of the Standard Model parameters, populated by eternal inflation



1. One day it can be tested experimentally

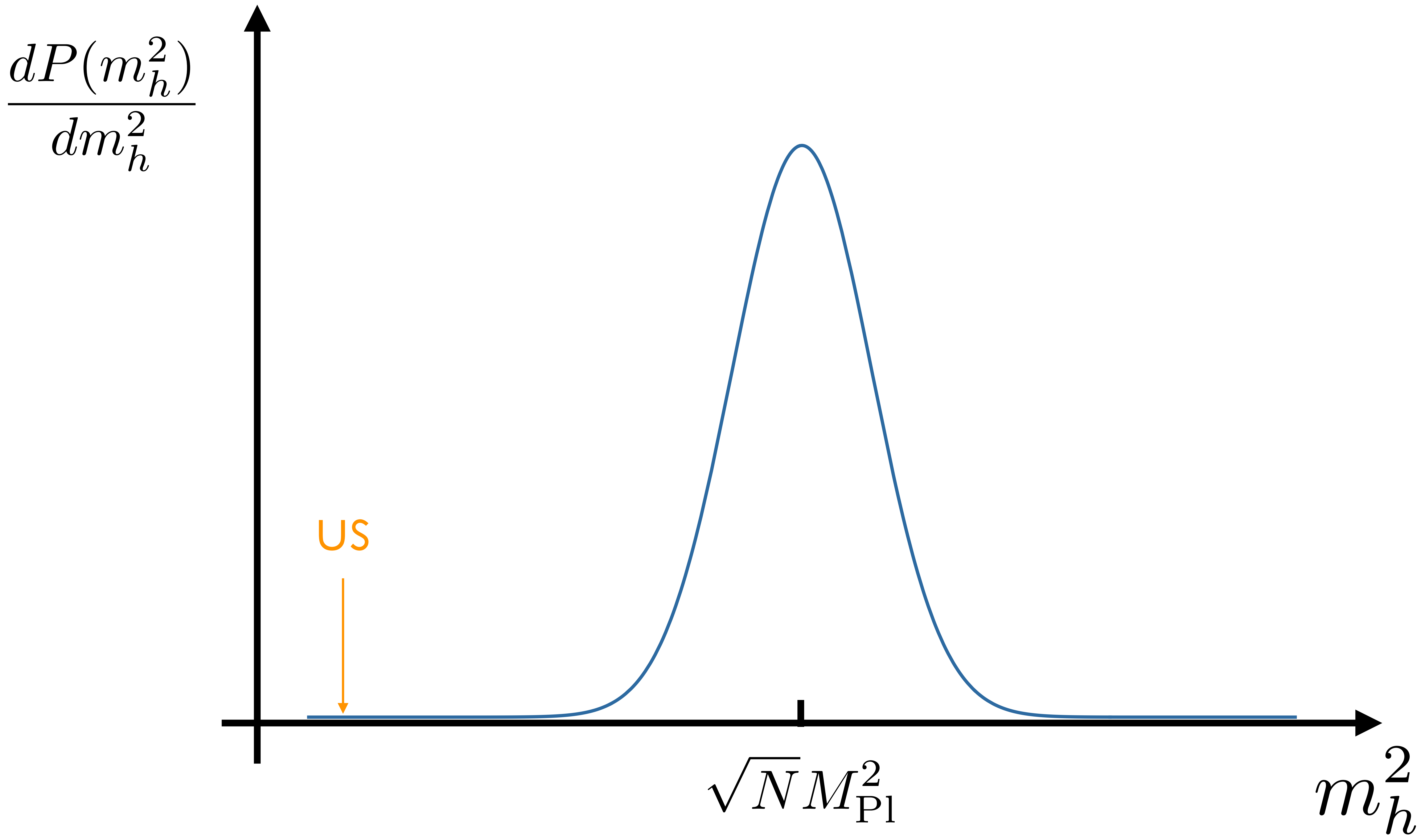
2. Currently our most concrete explanation for the cosmological constant

3. It probably exists independently of the problem

A MULTIVERSE WITHOUT NEW SYMMETRIES

$$m_h^2 = a_1 M_{\rm Pl}^2 + a_2 M_{\rm Pl}^2 + ...$$

A MULTIVERSE WITHOUT NEW SYMMETRIES



One Universe

$$m_h^2$$

Its value is telling us something about the underlying theory of Nature

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$$m_h^2$$

Its value is telling us something about the underlying theory of Nature

One Multiverse

$$m_h^2$$

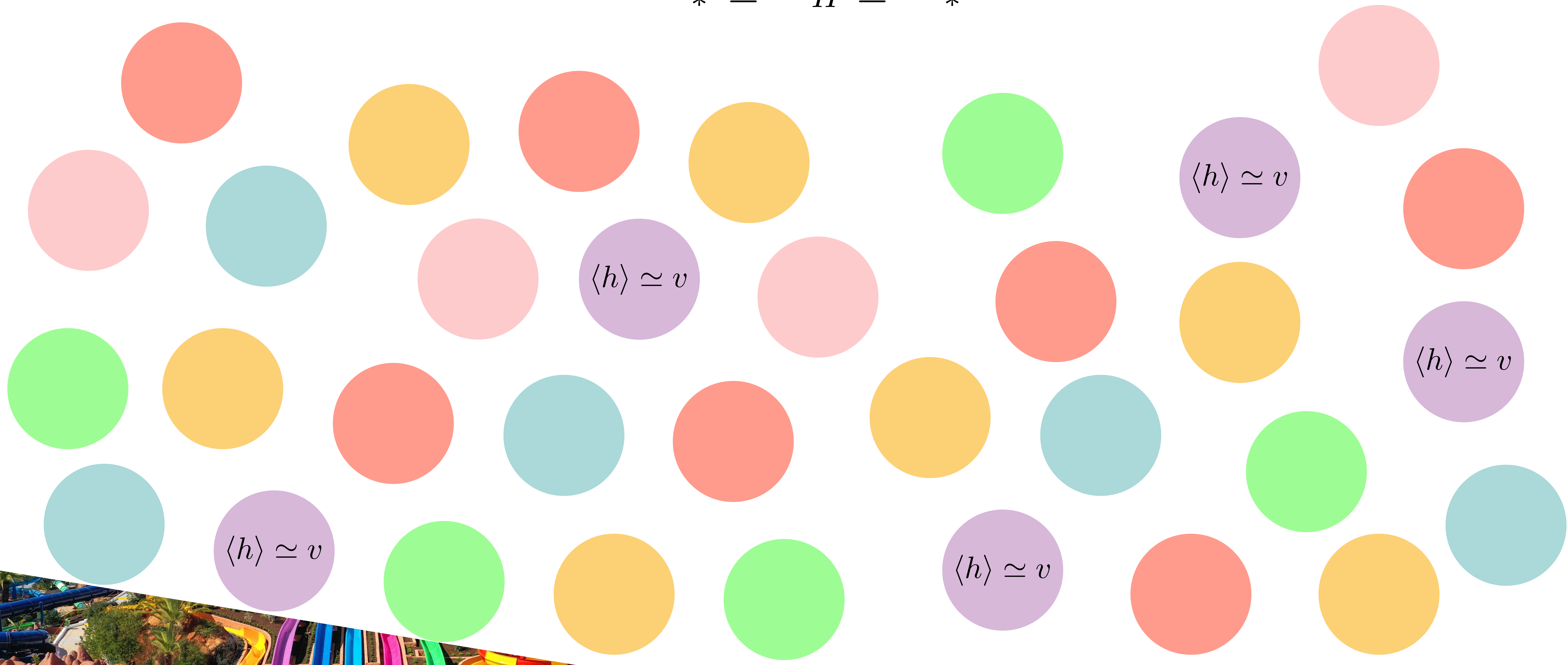
Its value can be accidental

EXAMPLE: SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

Landscape of Higgs Masses populated by inflation

$$-M_*^2 \leq m_H^2 \leq M_*^2$$



SLIDING NATURALNESS

After reheating and a time

$$t_c \sim 1/H(\Lambda_{\rm QCD}) \sim 10^{-5}\ s$$

All patches where the Higgs vev

$\langle h \rangle \simeq v$

$$\langle H^0 \rangle \equiv h$$

$\langle h \rangle \simeq v$

Is outside of a certain range

$$h_{\rm min} \lesssim h \leq h_{\rm crit}$$

$\langle h \rangle \simeq v$

crunch

$\langle h \rangle \simeq v$

$\langle h \rangle \simeq v$

SLIDING NATURALNESS

Only universes with the observed value of the weak scale can live cosmologically long times. **Today the multiverse looks like**:

$$\langle h \rangle \simeq v$$

$$\langle h \rangle \simeq v$$

$$\langle h \rangle \simeq v$$

$$\langle h \rangle \simeq v$$

SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

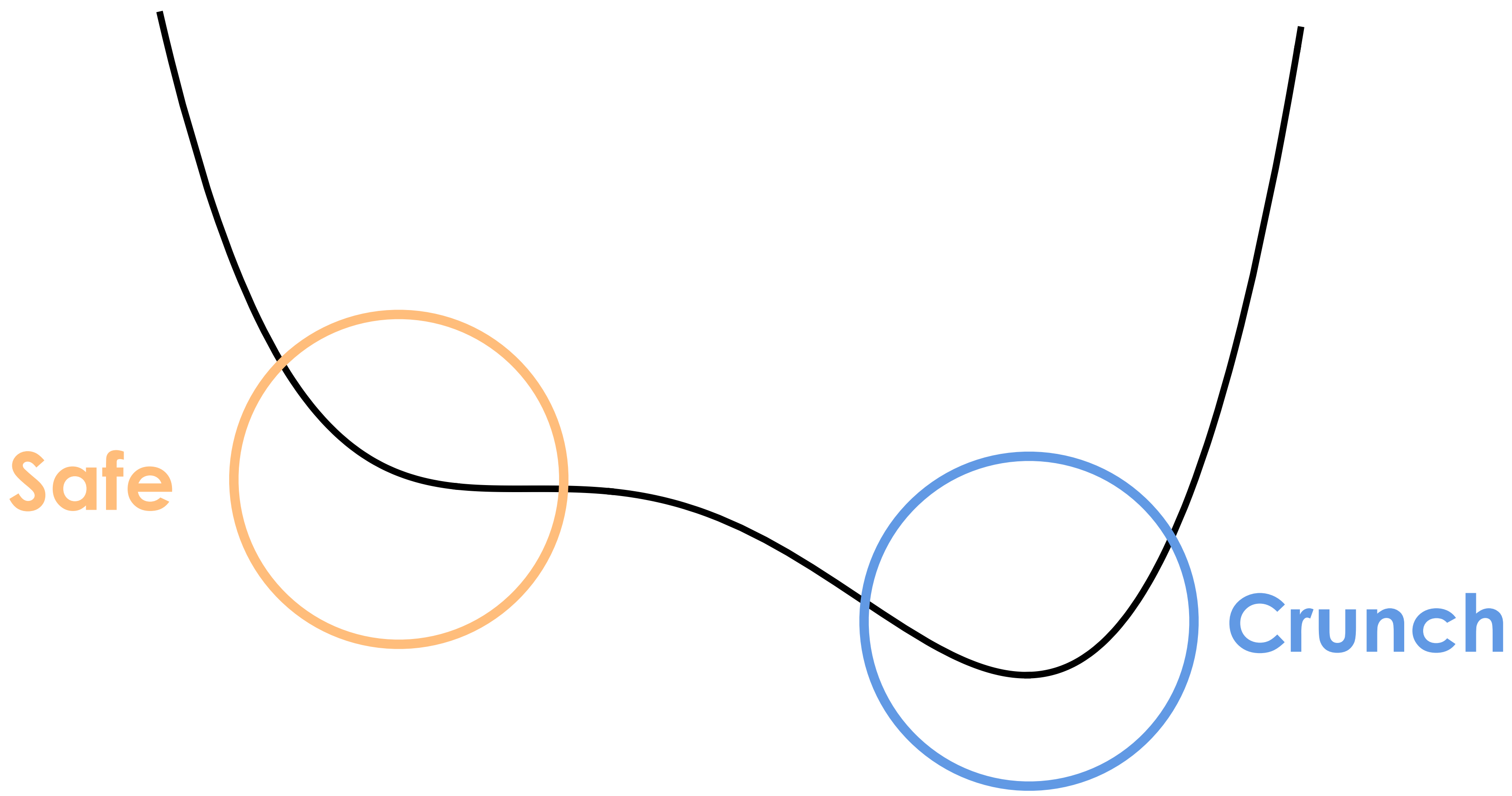
Two new scalars approximately decoupled from each other

$$V = V_{\phi_-} + V_{\phi_+} + V_{H\phi_-} + V_{H\phi_+}$$

SLIDING NATURALNESS

[**RTD**, Teresi] '21

$$V_- = V_{\phi_-} + V_{H\phi_-}$$

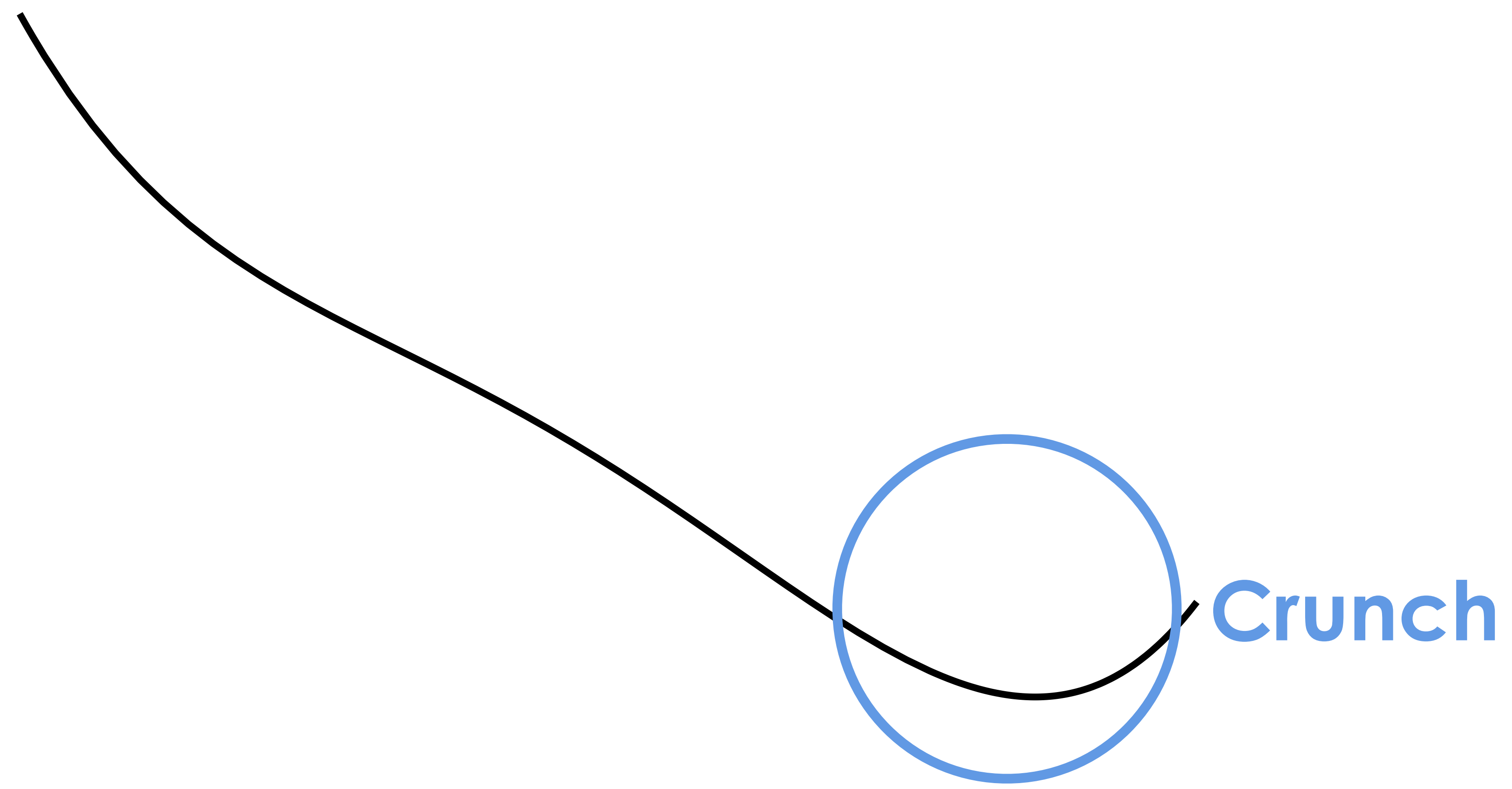


SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

$$V_- = V_{\phi_-} + V_{H\phi_-}$$

$$\langle h \rangle \gg v$$

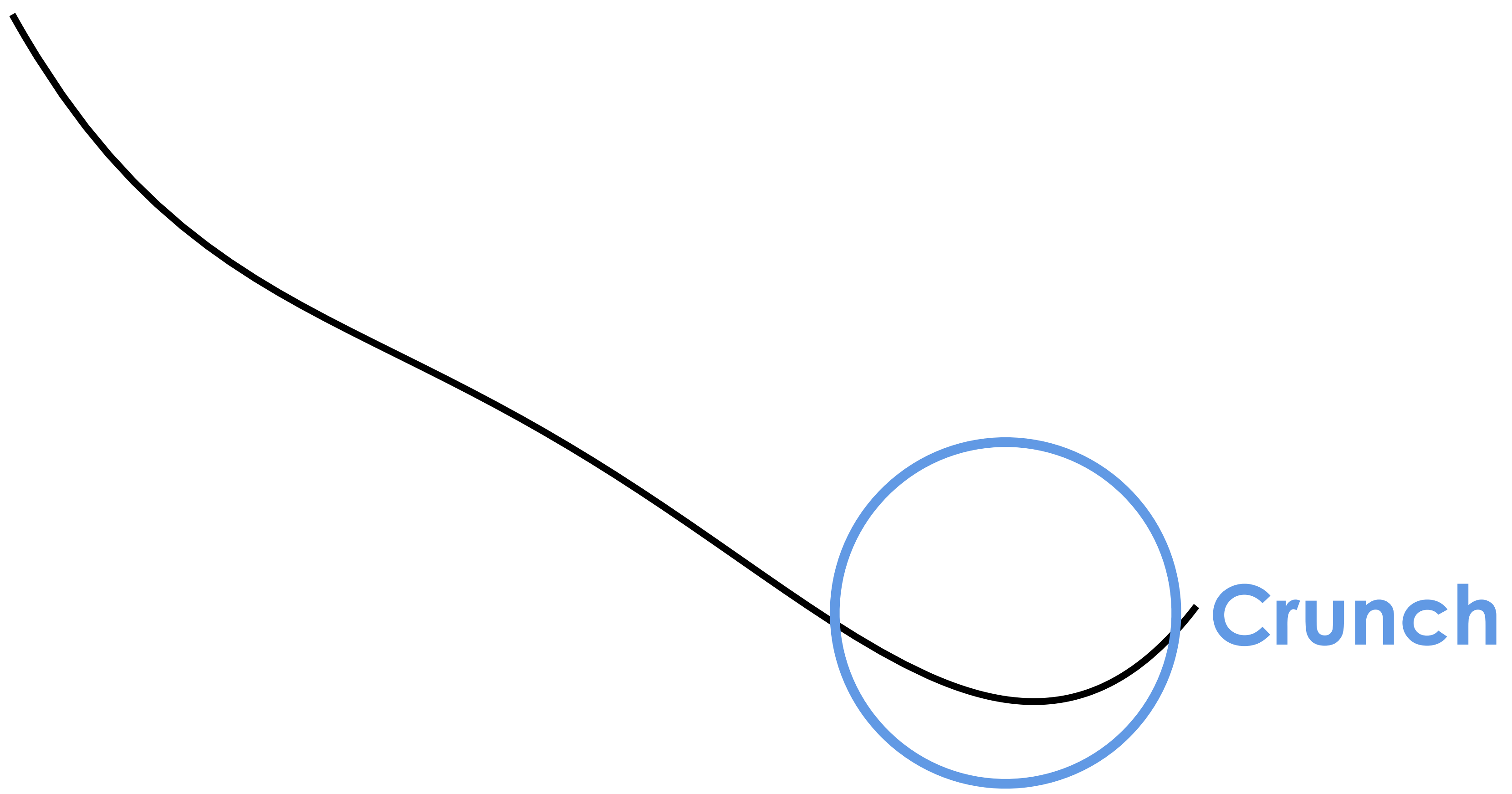


SLIDING NATURALNESS

[**RTD**, Teresi] '21

$$V_+ = V_{\phi_+} + V_{H\phi_+}$$

$\langle h \rangle \ll v$ Or $\theta \gg 10^{-10}$

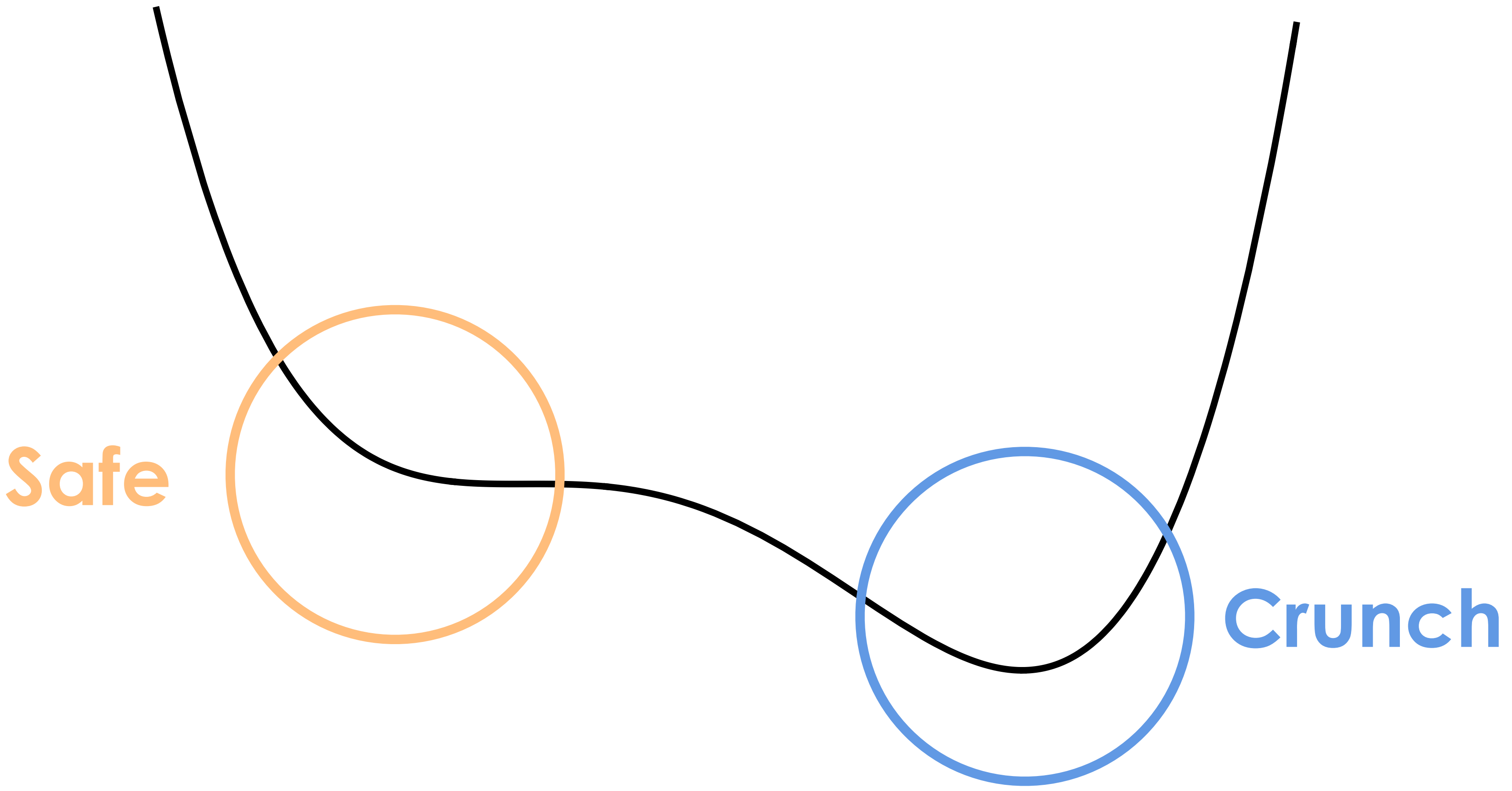


SLIDING NATURALNESS

[**RTD**, Teresi] '21

$$V_+ = V_{\phi_+} + V_{H\phi_+}$$

$\langle h \rangle \gtrsim v$ And $\theta \lesssim 10^{-10}$



MANY OTHER SIMILAR IDEAS

1998 — Atomic Principle

2003 — Attractor Vacua

2004

MANY OTHER SIMILAR IDEAS

Higgs Discovery
2012

1998 — Atomic Principle

2003, 2004 — Attractor Vacua

2015 — Relaxion

2016 — NNaturalness

....

MANY OTHER SIMILAR IDEAS WITH SOMETHING IN COMMON

$$V_- = V_{\phi_-} + \underline{V_{H\phi_-}}$$

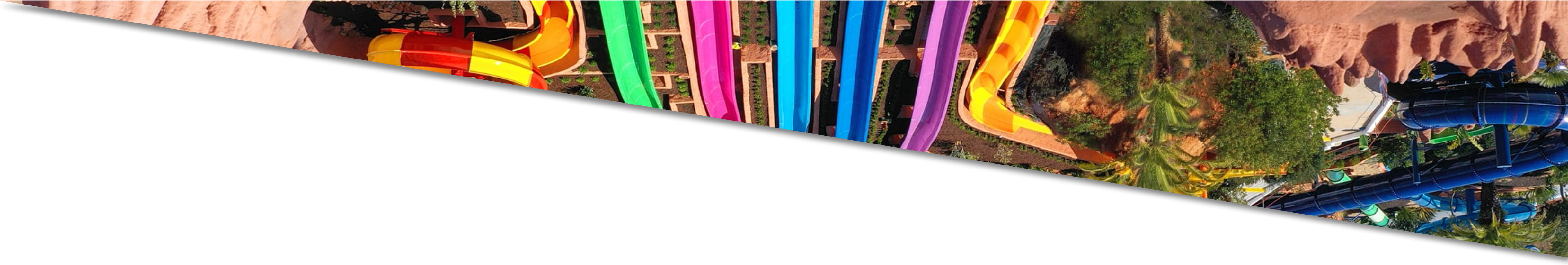
$$V_+ = V_{\phi_+} + \underline{V_{H\phi_+}}$$

MANY OTHER SIMILAR IDEAS WITH SOMETHING IN COMMON

$$V_- = V_{\phi_-} + V_{H\phi_-}$$

$$V_+ = V_{\phi_+} + V_{H\phi_+}$$

$$V_{H\phi_\pm} = \left(\frac{\phi_\pm}{f} + \theta\right) G\widetilde{G} \simeq a\theta(y_u + y_d){\color{red}v} f_\pi^3 \frac{\phi_\pm}{f} + \ldots$$



MANY OTHER SIMILAR IDEAS WITH SOMETHING IN COMMON

$$V_- = V_{\phi_-} + \underline{V_{H\phi_-}}$$

$$V_+ = V_{\phi_+} + \underline{V_{H\phi_+}}$$

$$V_{H\phi_\pm} = \left(\frac{\phi_\pm}{f} + \theta\right) G\widetilde{G} \simeq a\theta(y_u + y_d){\color{red}v} f_\pi^3 \frac{\phi_\pm}{f} + \ldots$$

$$V_{H\phi_\pm} = a\phi_\pm H_1 H_2 \simeq a\phi_\pm {\color{red}v^2} + \ldots$$

General QFT question relevant beyond cosmological naturalness:

Does anything change (in the SM) as we vary the Higgs mass squared?

Most relevant phenomenologically:

Physics coupled to the Higgs with

$$m \lesssim v$$

One trigger = **Many solutions** to the hierarchy problem

WEAK SCALE TRIGGERS AND WHERE TO FIND THEM

[Arkani-Hamed, RTD, Kim, '20]

Does anything change in Nature as we vary the Higgs mass squared?

$$\frac{d \log f(\langle h \rangle)}{d \log \langle h \rangle} = O(1)$$

Does anything change
as we vary the Higgs mass?

LOCAL

$$\mathrm{Tr}[G \wedge G] \equiv G\widetilde{G}$$

NON-LOCAL

On-shell N-point
functions of massive SM
particles

STANDARD MODEL TRIGGERS

$$G\widetilde{G}$$

Axion-Like Phenomenology

[Graham, Rajendran, Kaplan, '15],
Arkani-Hamed, RTD, Kim, '20], [Csaki, RTD, Geller, Ismail, '20], [RTD, Teresi, '21],
[Geller, Hochberg, Kuflik,'18], …

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$$W\widetilde{W}$$

Axion-Like Phenomenology

BSM TRIGGERS

$$F\widetilde{F} + yLHE^c$$

$$m \lesssim v \simeq 174 \text{ GeV}$$

HL-LHC!

$$H_1 H_2$$

$$m \lesssim v \simeq 174 \text{ GeV}$$

HL-LHC!

[Arkani-Hamed, RTD, Kim, ’20]

$$H_1 H_2$$

Protected by the **Z2 symmetry**

$$H_1 H_2 \to -H_1 H_2$$

H1H2 **without Z2** first considered as ‘paleo’-trigger in: [Espinosa, Grojean,Panico, Pomarol, Pujolas ’15], [Dvali, Vilenkin ’01]. Today these models require **two coincidences of scales to be alive at the LHC**.

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

$$V_{H_1 H_2} = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4$$
$$+\lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1 H_2|^2 + \left(\frac{\lambda_5}{2} (H_1 H_2)^2 + \text{h.c.} \right)$$

$$H_1 H_2 \left(B\mu + \lambda_6 |H_1|^2 + \lambda_7 |H_2|^2 \right)$$
$$B\mu = \lambda_{6,7} = 0$$

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

$$m_{A,H^{\pm}}^2 \sim \lambda v^2, \quad \lambda \lesssim 2$$

$$m_H^2 \sim \lambda_1 v_1^2 \leq m_h^2 = (125\ \mathrm{GeV})^2$$

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

For quarks and leptons we choose the **phenomenologically safest Z2 charge assignments**

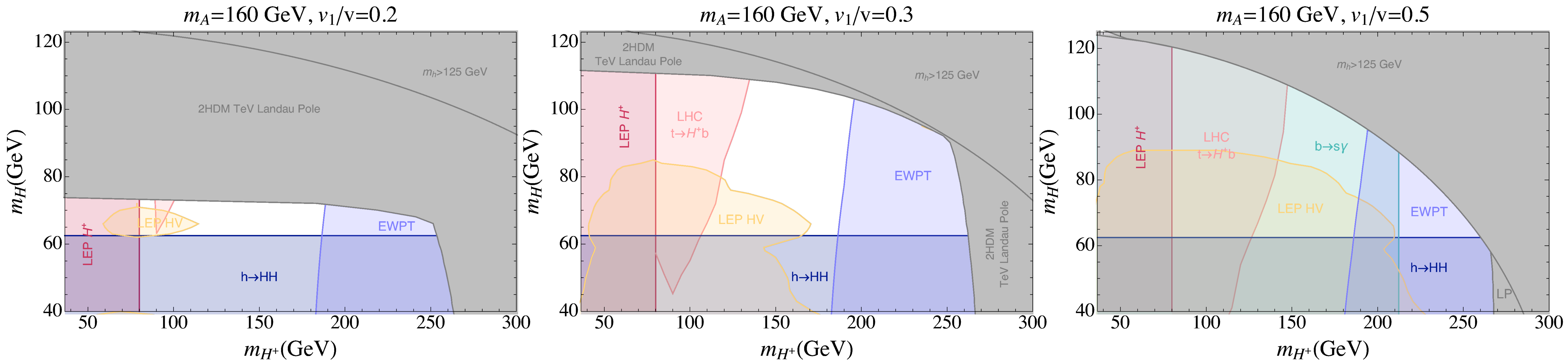
$$H_2 \to -H_2, \quad (qu^c) \to -(qu^c), \quad (qd^c) \to -(qd^c), \quad (le^c) \to -(le^c)$$

This gives

$$V_Y = Y_u q H_2 u^c + Y_d q H_2^\dagger d^c + Y_e l H_2^\dagger e^c$$

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

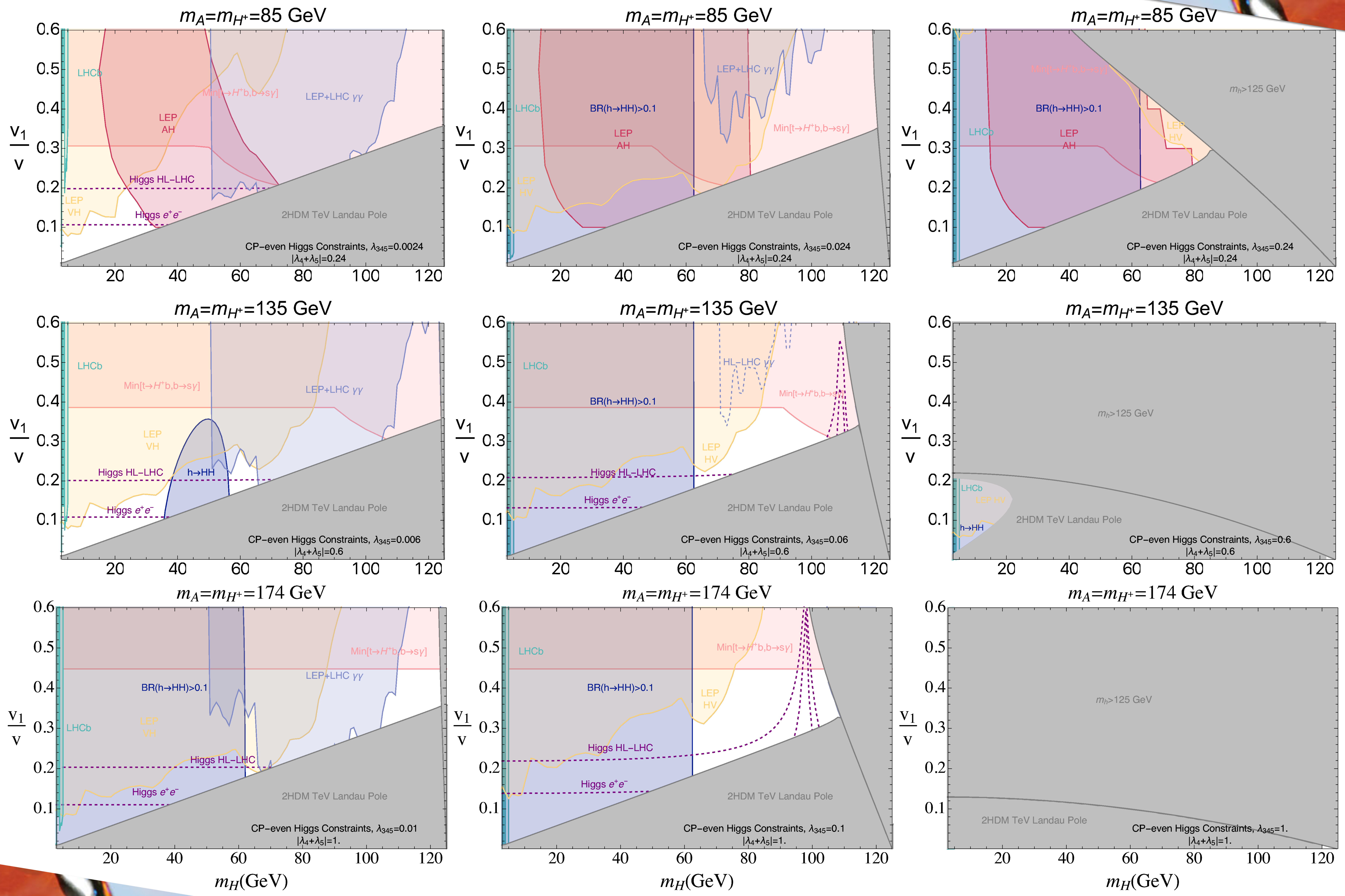


Sharp target for HL-LHC and FCC

which **can't be decoupled**!

(See also the next slide)

[Arkani-Hamed, RTD, Kim, ’20]



One trigger = **Many solutions** to the hierarchy problem

EVERY SINGLE TRIGGER

$$G\widetilde{G}$$

$$W\widetilde{W}$$

Axion-Like Phenomenology

$$F\widetilde{F} + yLHE^c$$

Vector-like Leptons

$$H_1 H_2$$

Second Higgs doublet

BSM triggers = Physics coupled to the Higgs with

$$m \lesssim v$$

BACKUP

$$\langle G\widetilde{G}\rangle \simeq (y_u + y_d)\langle h\rangle f_\pi^3(\langle h\rangle)\theta$$

Non-trivial!

1. $U(1)_A$ breaking that can interfere with QCD instantons

2. Sensitivity to the Higgs mass ($U(1)_A$ breaking and/or SU(3) running)

3. $\Lambda_{\rm QCD} \lesssim m_h$

INSTANTONS

$$\phi \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

$$V(\phi) \sim \int_0^\infty \frac{d\rho}{\rho^4} e^{-\frac{8\pi^2}{g^2(\rho)}} \times \ldots$$

Approximate scale invariance of gauge theory = big hierarchy of scales

EXAMPLE: SU(2) CONSTRAINED INSTANTONS

SM

$$W\widetilde{W}$$

Not observable

EXAMPLE: SU(2) CONSTRAINED INSTANTONS

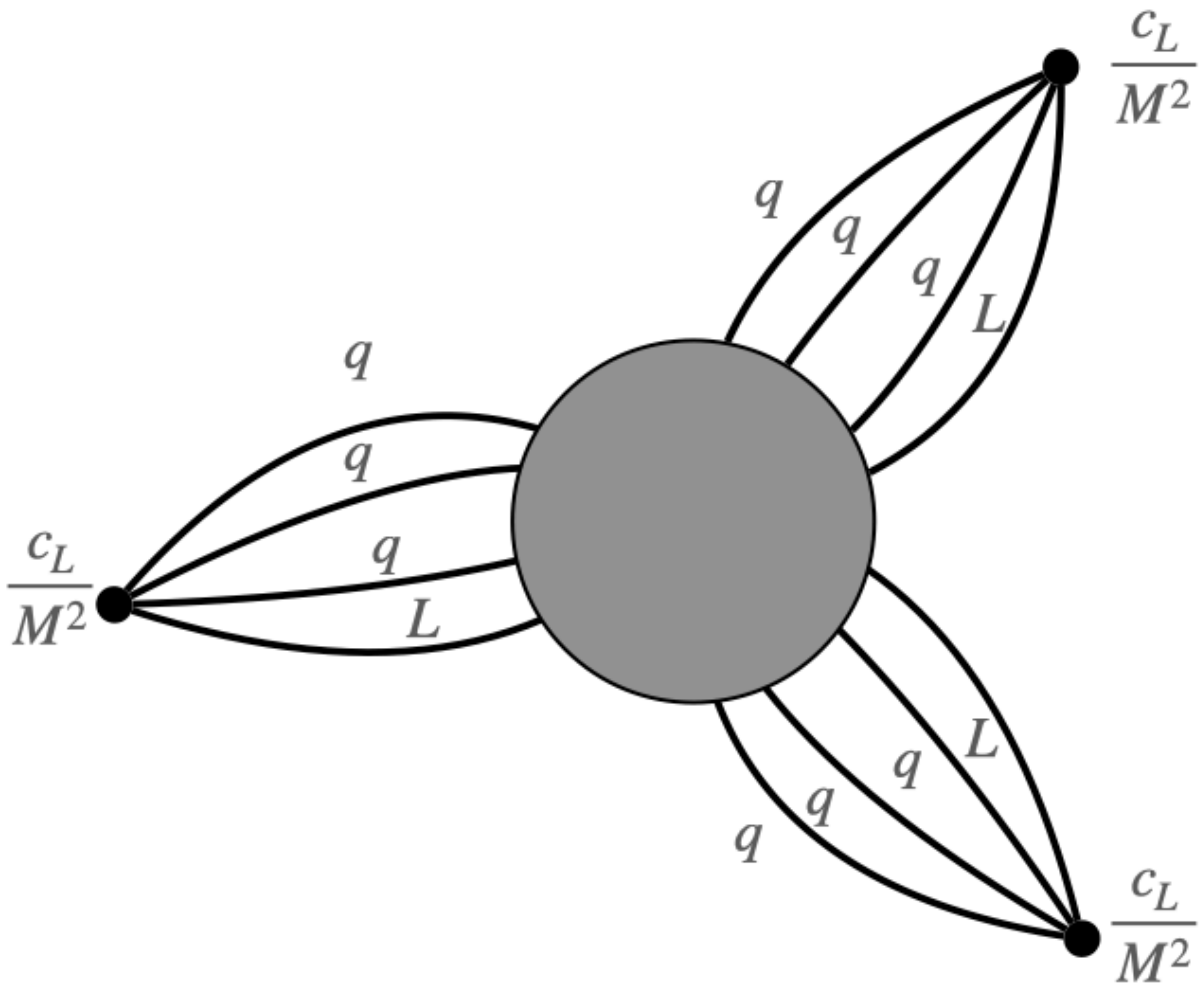
SM

$$W\widetilde{W}$$

Not observable

SM+GUT

$$W\widetilde{W} + \frac{QQQL}{M^2}$$



EXAMPLE: SU(2) CONSTRAINED INSTANTONS

$$W\widetilde{W} + \frac{QQQL}{M^2}$$

$$V(\phi) \sim \frac{\langle h \rangle^{10}}{M^6} e^{-\frac{2\pi}{\alpha_2(\langle h \rangle)}} + M^4 e^{-\frac{2\pi}{\alpha_2(M)}}$$

Tantalizing T=0 connection between B+L breaking and Higgs mass

TOY MODEL (zoom in on shallow minimum)

$$V_{\phi_\pm} = \mp \frac{m_{\phi_\pm}^2}{2}\phi_\pm^2 - \frac{\lambda}{4}\phi_\pm^4$$

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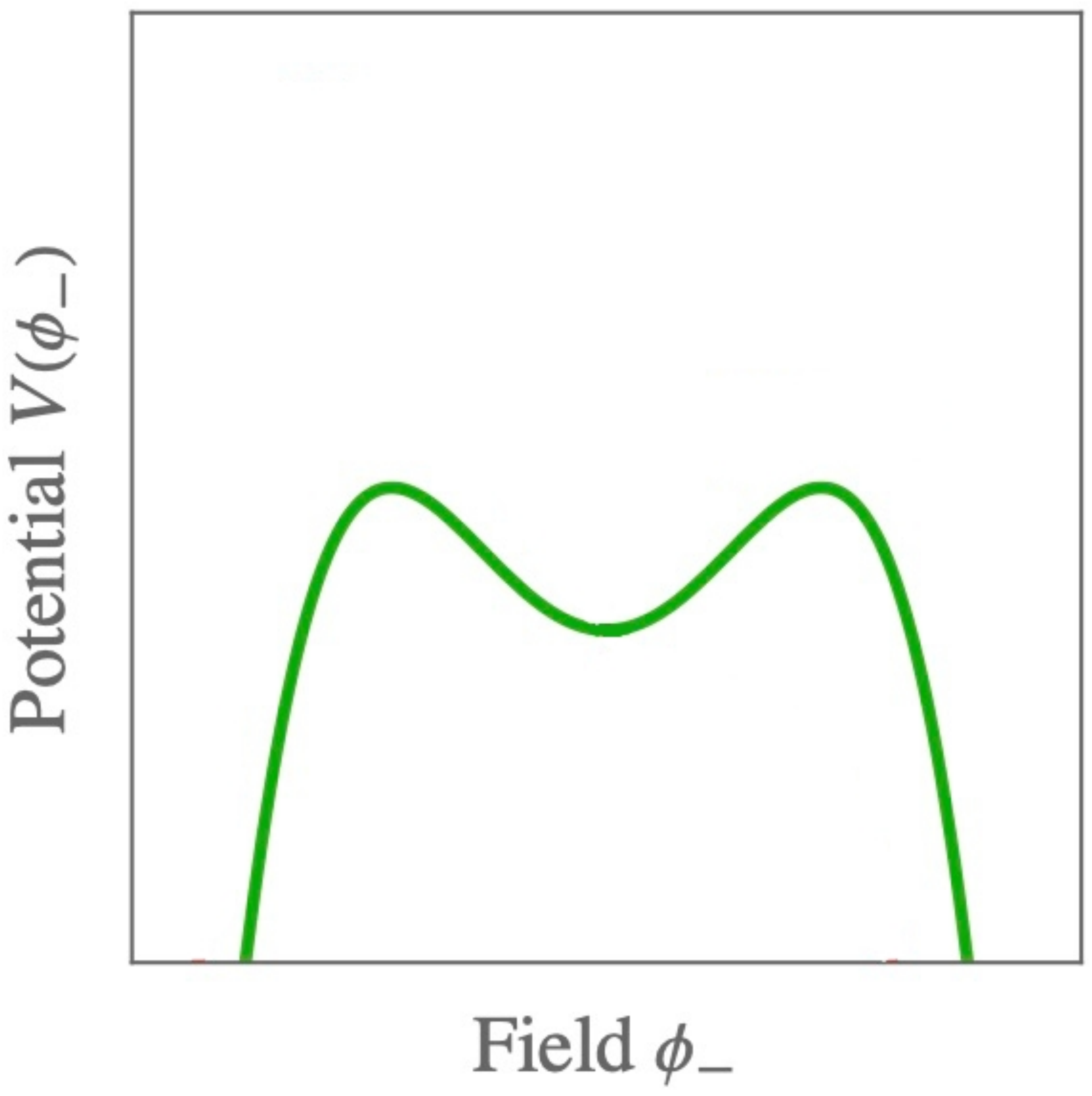
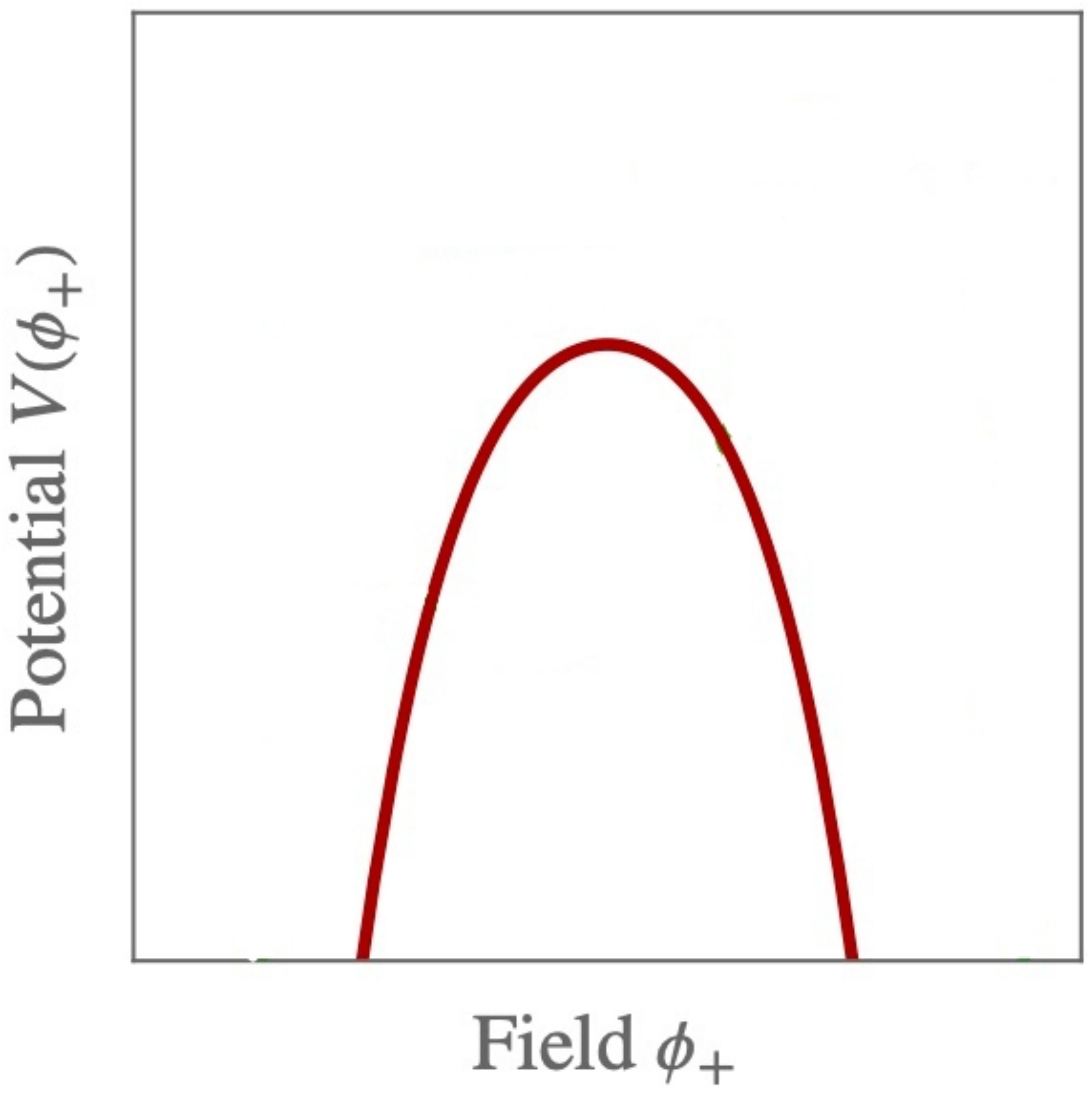
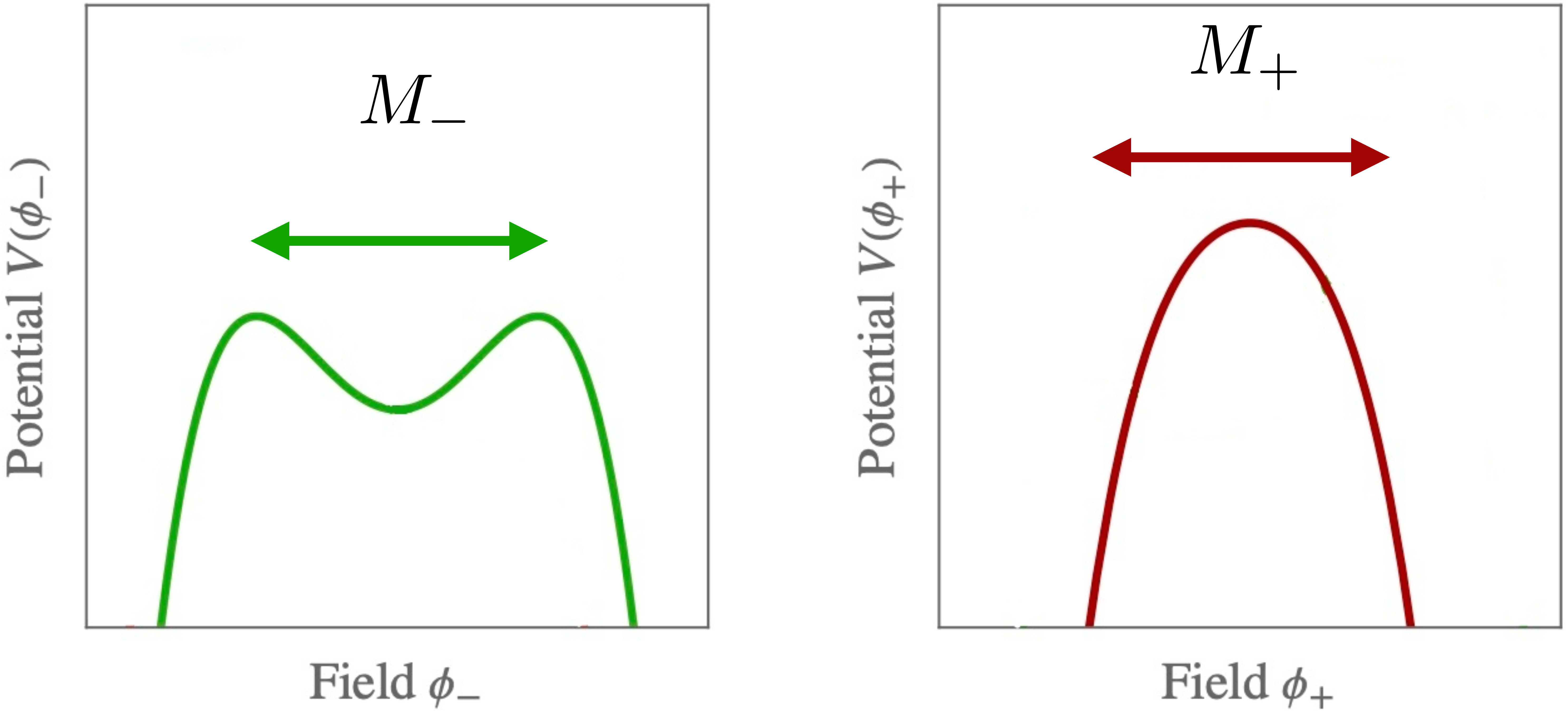
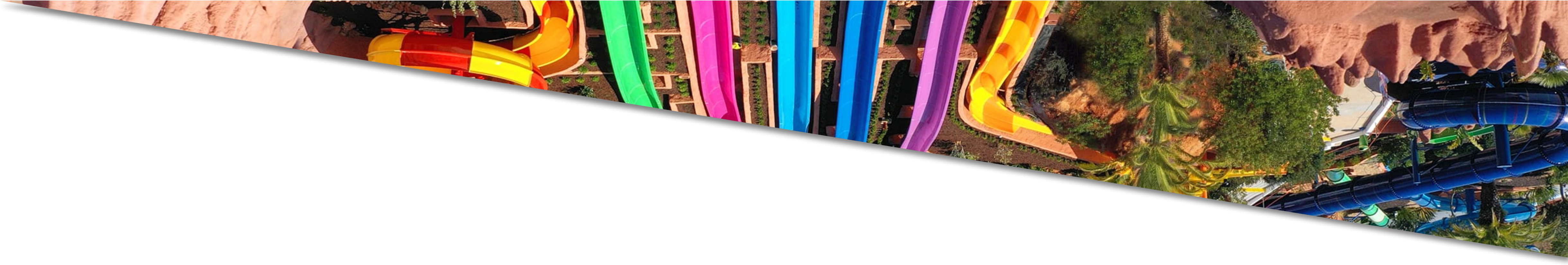




TOY MODEL (zoom in on shallow minimum)

$$V_{\phi_\pm} = \mp \frac{m^2_{\phi_\pm}}{2}\phi^2_\pm - \frac{\lambda}{4}\phi^4_\pm$$

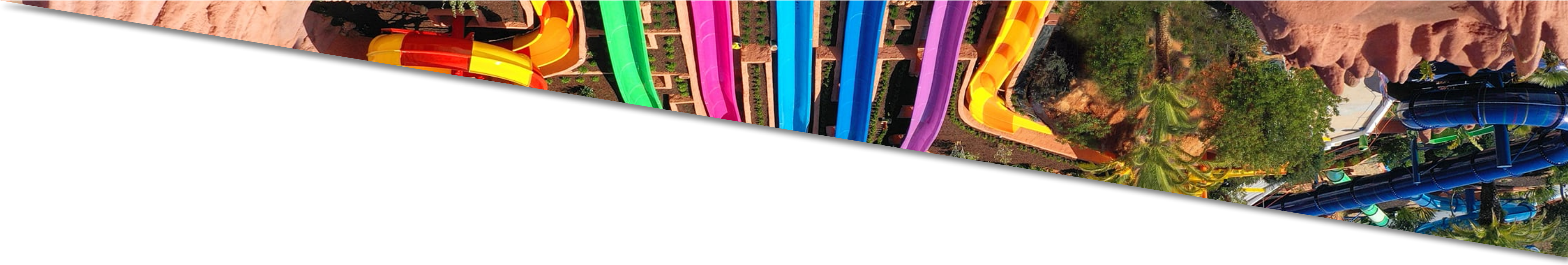




SLIDING NATURALNESS

[**RTD**, Teresi] '21

$$V_{H\phi_\pm} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)\widetilde{G}G$$



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Small Breaking of Shift-Symmetry at low Energy

$$M_\pm/F_\pm \ll 1$$

$$M_-/F_- \ll \theta$$

Familiar from QCD

$$F_\pm \leftrightarrow f_\pi$$

$$M_\pm \leftrightarrow m_q$$

SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

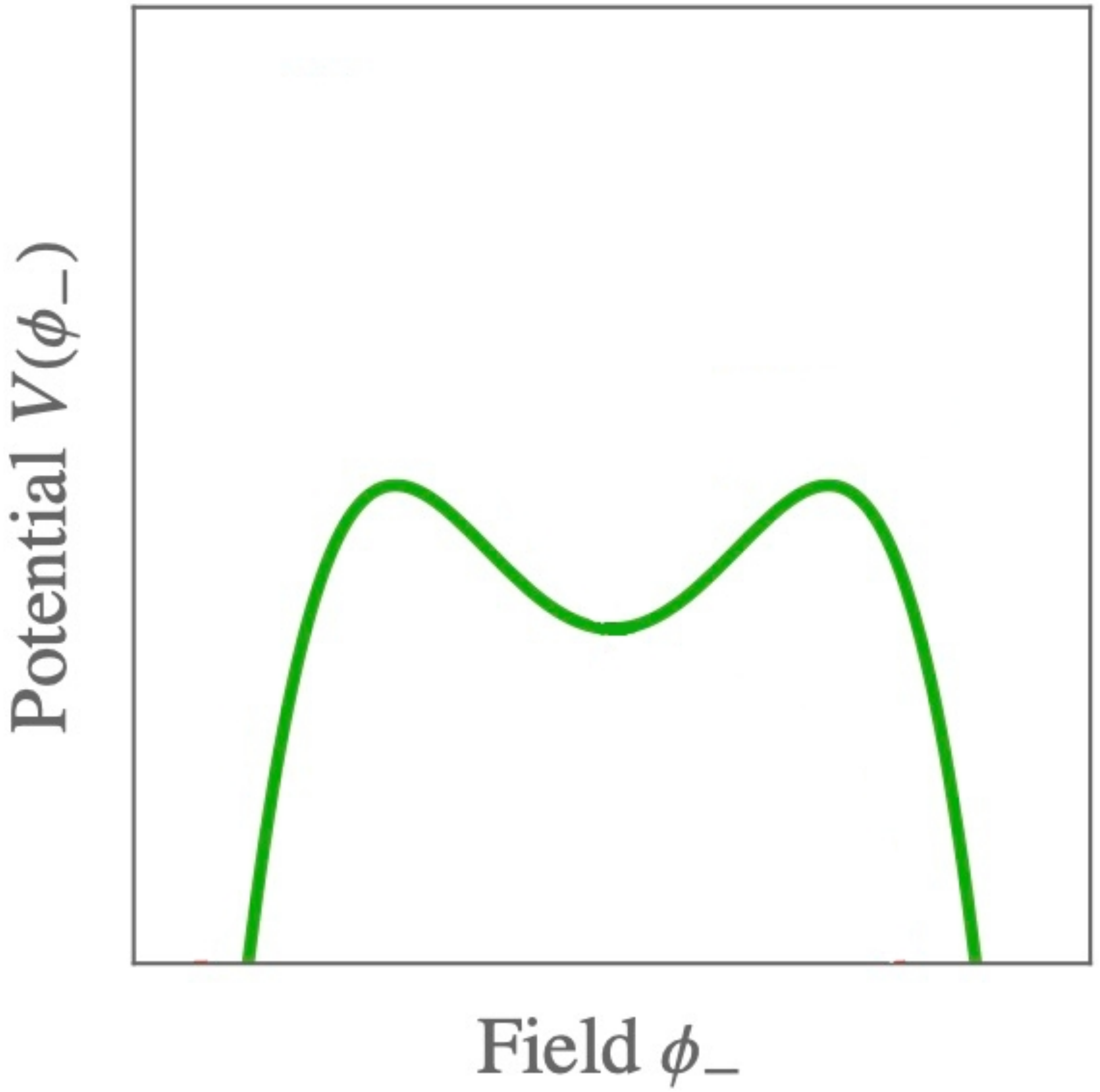
$$V_{H\phi_\pm} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)\widetilde{G}G$$

$$\simeq \Lambda^4_{\rm QCD}(\langle h\rangle)\left[\left(\theta\frac{\phi_+}{F_+} + \frac{\phi_+^2}{F_+^2}\right) + \theta\frac{\phi_-}{F_-} + \ldots\right]$$

SLIDING NATURALNESS

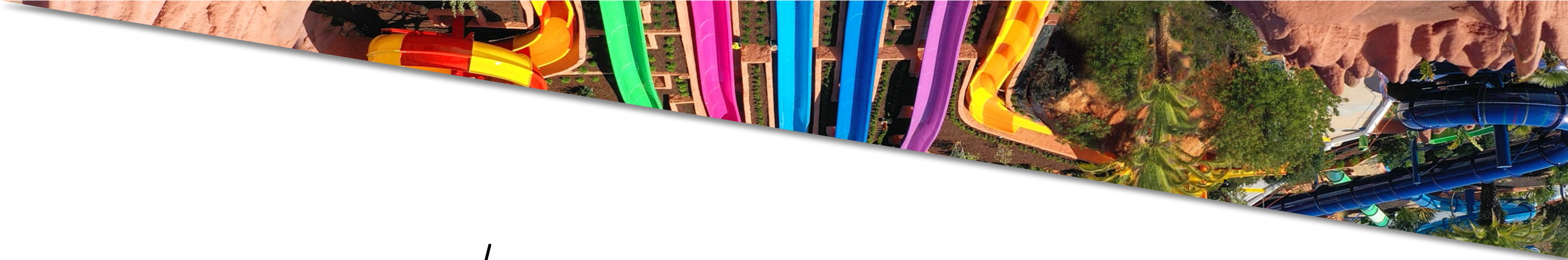
[**RTD**, Teresi] ‘21

$$V_{H\phi_-} \simeq \theta_{\rm eff}\Lambda^4_{\rm QCD}(\langle h\rangle)\frac{\phi_-}{F_-}$$



SLIDING NATURALNESS

[**RTD**, Teresi] '21



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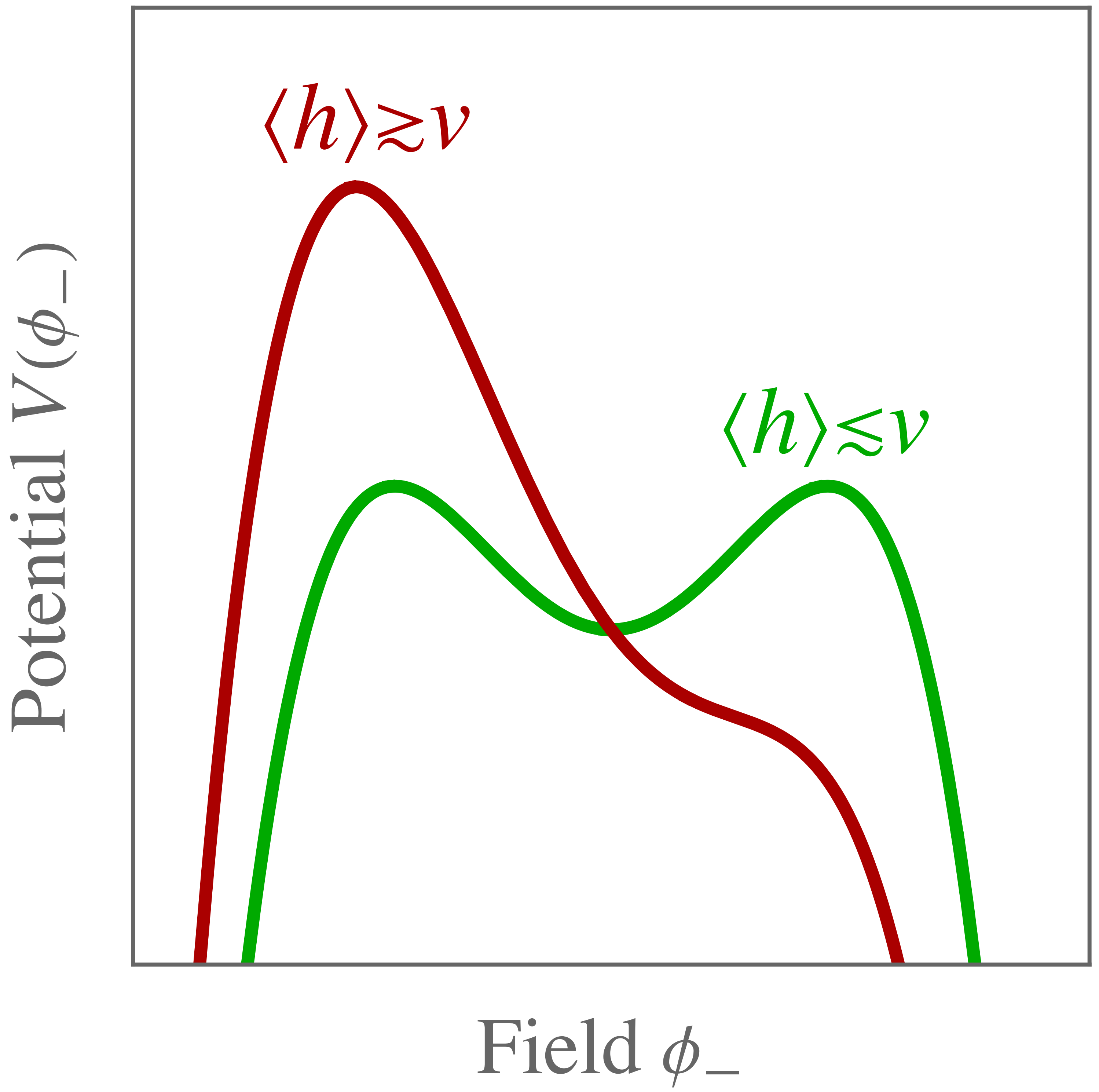
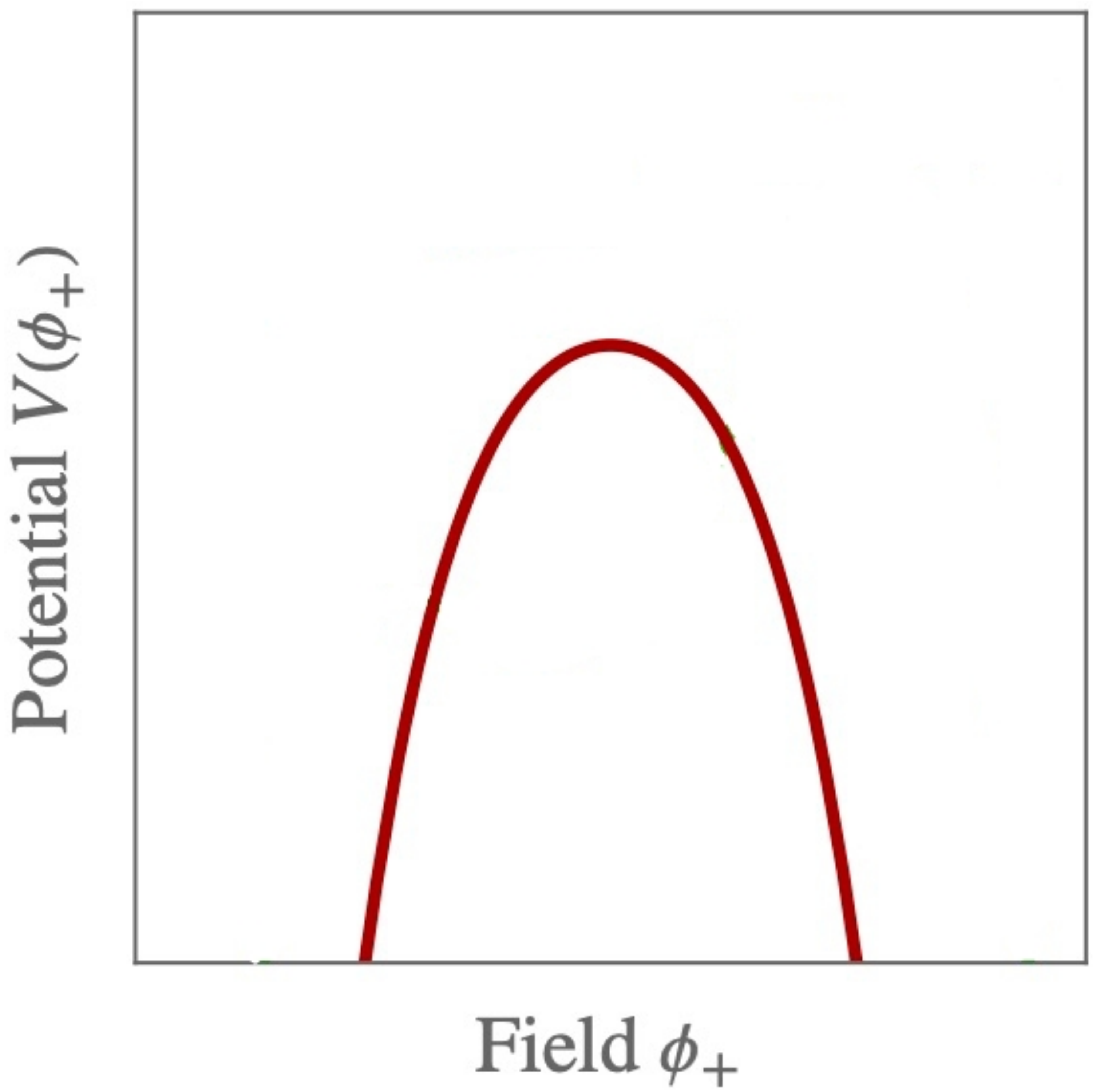


SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

$$V_{H\phi_+} \simeq \Lambda^4_{\rm QCD}(\langle h\rangle)\left(\theta\frac{\phi_+}{F_+}+\frac{\phi_+^2}{F_+^2}\right)$$



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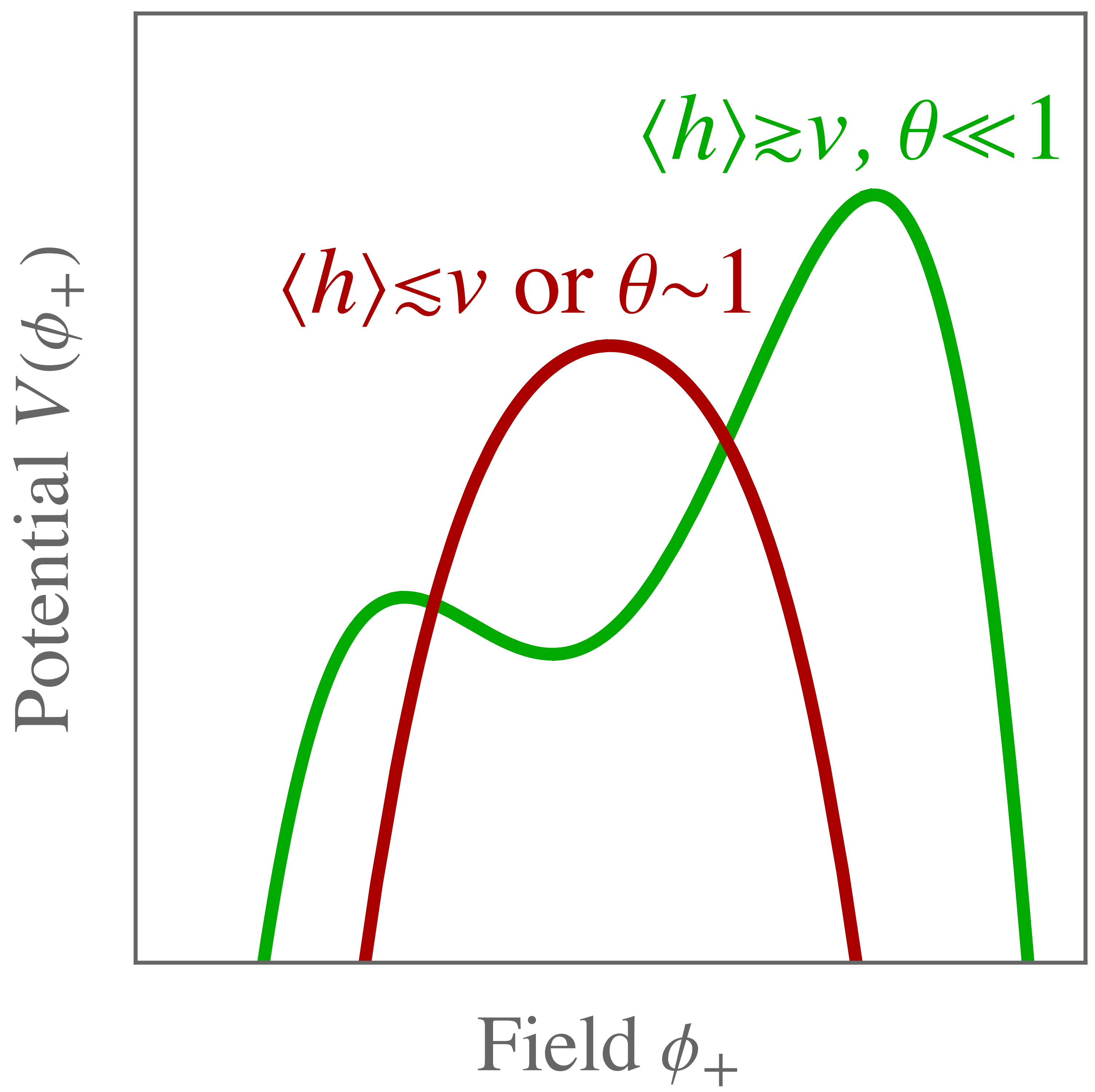

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$$V_{H\phi_\pm} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)\widetilde{G}G$$

Solve Strong-CP and Hierarchy problem!

SLIDING NATURALNESS

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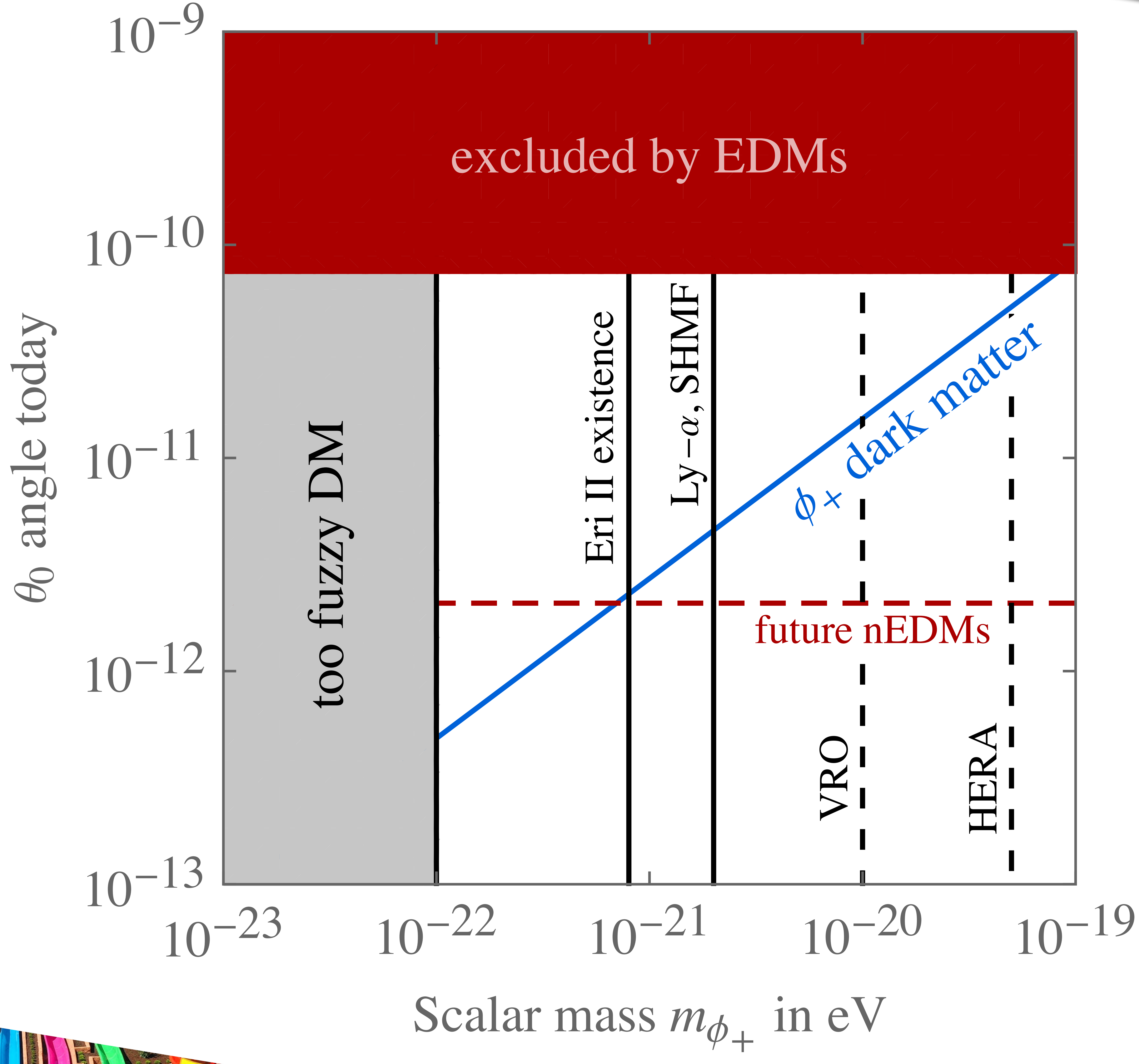


$\phi_\pm$

Symmetric Sector

$\Lambda_S \ll M_{\rm Pl}$

$\phi_\pm G\widetilde{G}$

SM Landscape

$O_1 = -O_2 + \epsilon$

EXAMPLE 1: ANTHROPIC ARGUMENTS

[Agrawal, Barr, Donoghue, Seckel ’97]

SM Landscape

Symmetric Sector

$$\Lambda_{\mathrm{QCD}} \ll M_{\mathrm{Pl}}$$

QCD

$$W_{qq}(x-y)$$

“Friendly”
String Landscape?

[Arakni-Hamed, Dimopoulos, Kachru, ‘05]

EXAMPLE 2: STATISTICAL ARGUMENTS

[Dvali, Vilenkin ’03], [Dvali ’04]

$$F_4 = dA_3$$

$$S \supset \int d^4x\sqrt{-g}\left(\frac{F_4^2}{48} + M_{\mathrm{Pl}}^2(-1 + \frac{F_4^2}{M_{\mathrm{Pl}}^2} + \ldots)|\phi|^2 + \ldots\right) + q(\phi)\int d^3\xi A_{\mu\nu\rho}\frac{\partial x^\mu}{\partial \xi^a}\frac{\partial x^\nu}{\partial \xi^b}\frac{\partial x^\rho}{\partial \xi^c}\epsilon^{abc}$$

EXAMPLE 2: STATISTICAL ARGUMENTS

[Dvali, Vilenkin ’03], [Dvali ’04]

$$q(\phi) = \frac{\phi^N}{M_{\mathrm{Pl}}^{N-2}}$$

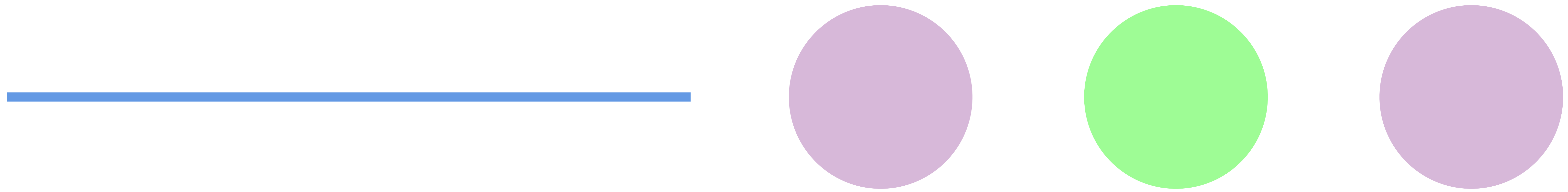
$$\Delta\langle\phi\rangle^2 / \langle\phi\rangle^2 \sim \langle\phi\rangle^{N-2}$$

At every step the brane charge is smaller
-> most vacua are at small vev

EXAMPLE 2: STATISTICAL ARGUMENTS

[Dvali, Vilenkin '03], [Dvali '04]

SM Landscape



Symmetric Sector

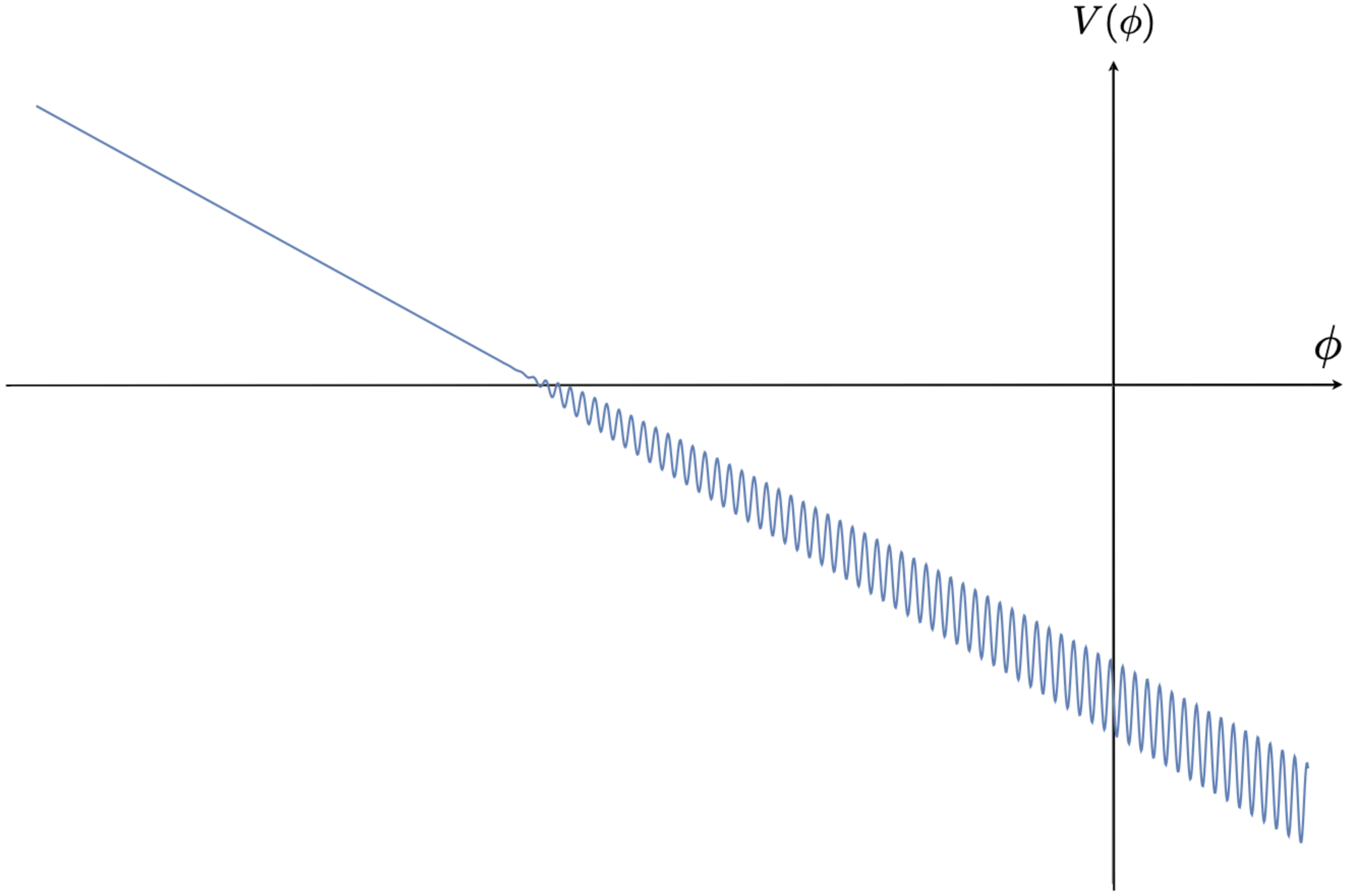
$$q(\phi) \lesssim M_{\rm Pl}^2$$

$$A_3 \qquad \frac{\phi^N}{M_{\rm Pl}^{N-2}} \int_{2+1} A_3 \qquad \frac{F_4^2}{M_{\rm Pl}^2} |\phi|^2$$

EXAMPLE 3: DYNAMICAL ARGUMENTS

[Graham, Kaplan, Rajendran '15],

$$V(\phi) = g\phi + ... + (M^2 + g\phi + ...)|H|^2 + \frac{\phi}{f} G\widetilde{G}$$



EXAMPLE 3: DYNAMICAL ARGUMENTS

[Graham, Kaplan, Rajendran ’15],

SM Landscape

Symmetric Sector

$$g \ll M_{\rm Pl}^3$$

$$\phi \qquad \phi G\widetilde{G} \qquad \phi|H|^2$$