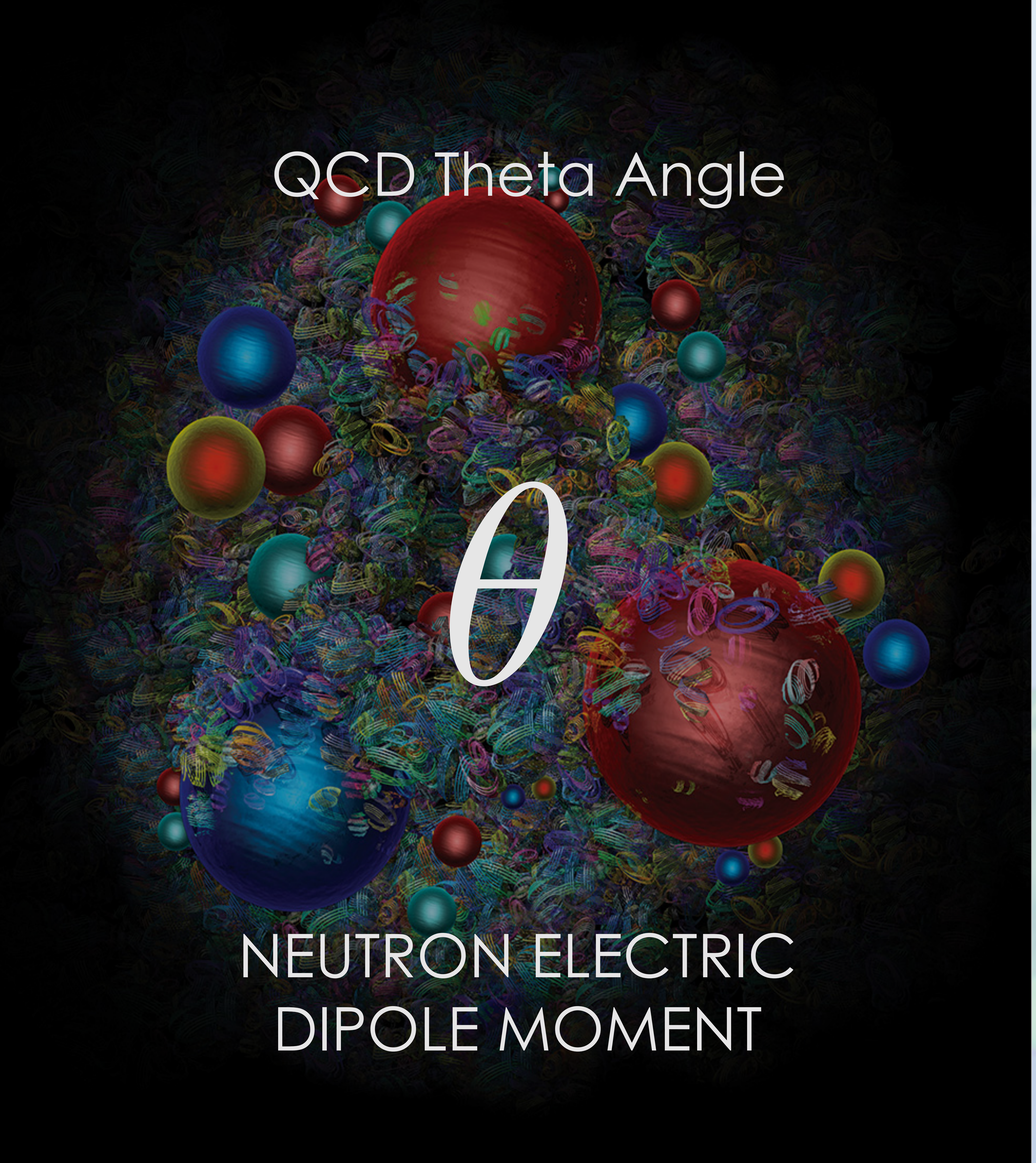
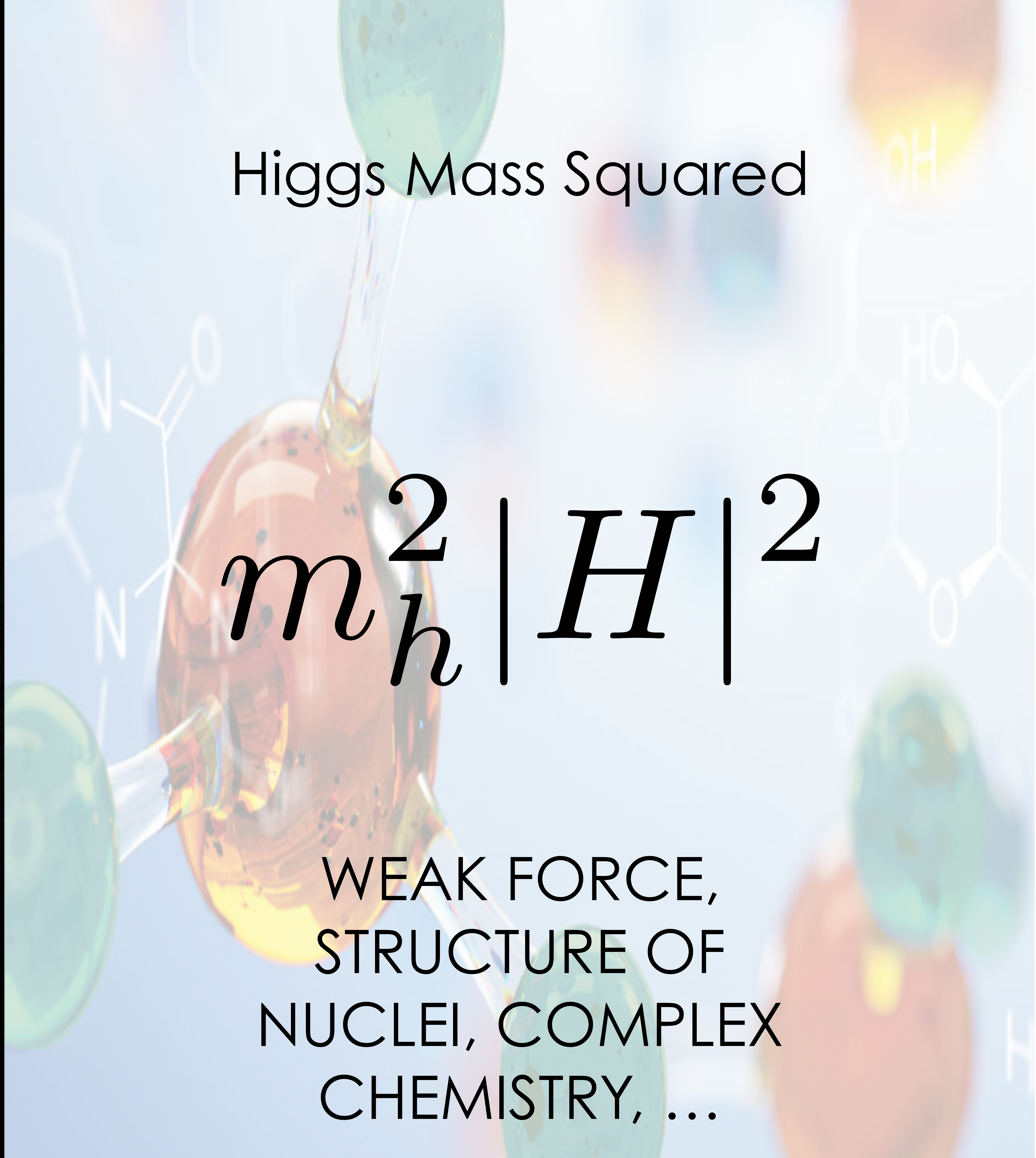
COSMOLOGICAL SELECTION OF THE WEAK SCALE AND THE QCD THETA ANGLE

Raffaele Tito D'Agnolo - IPhT Saclay


QCD Theta Angle
θ
NEUTRON ELECTRIC
DIPOLE MOMENT


Higgs Mass Squared
$m_h^2|H|^2$
WEAK FORCE,
STRUCTURE OF
NUCLEI, COMPLEX
CHEMISTRY, …

QCD Theta Angle

$$\theta \sim \mathcal{O}(1)$$

SYMMETRY-BASED ESTIMATE

Higgs Mass Squared

$$m_h^2 \sim \frac{y_t^2 M_{\rm Pl}^2}{16\pi^2}$$

SYMMETRY-BASED ESTIMATE

QCD Theta Angle

Symmetry ~ 10^{10} Experiment

$$\theta$$

Higgs Mass Squared

Symmetry~10^{34} Experiment

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

1. Property of the SM that relates the two quantities

2. Joint explanation [RTD, Teresi '21]

$$m_h^2 \sim \frac{y_t^2 M_{\mathrm{Pl}}^2}{16\pi^2}$$

Planck

SM

Planck

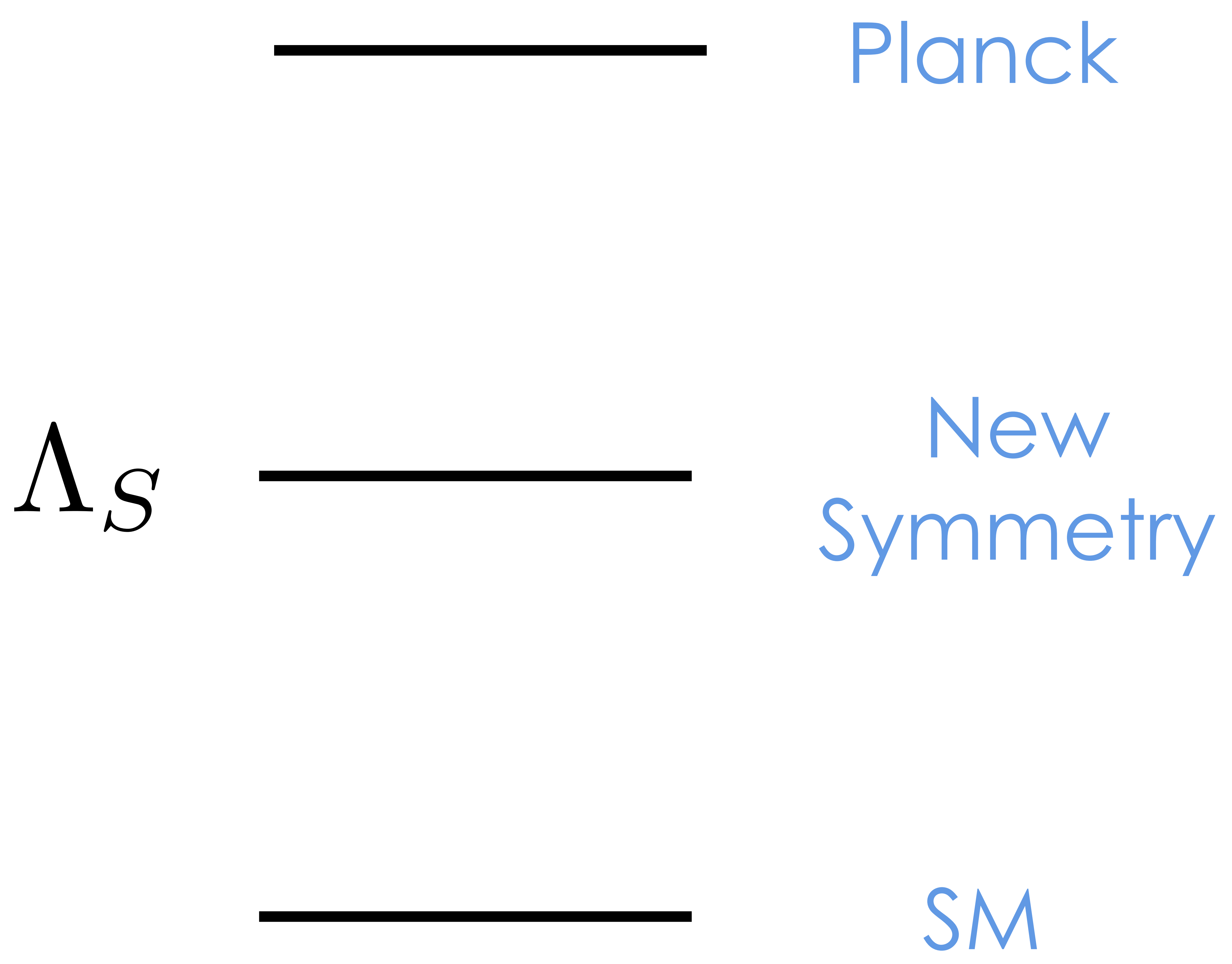
Λ_S New Symmetry

SM

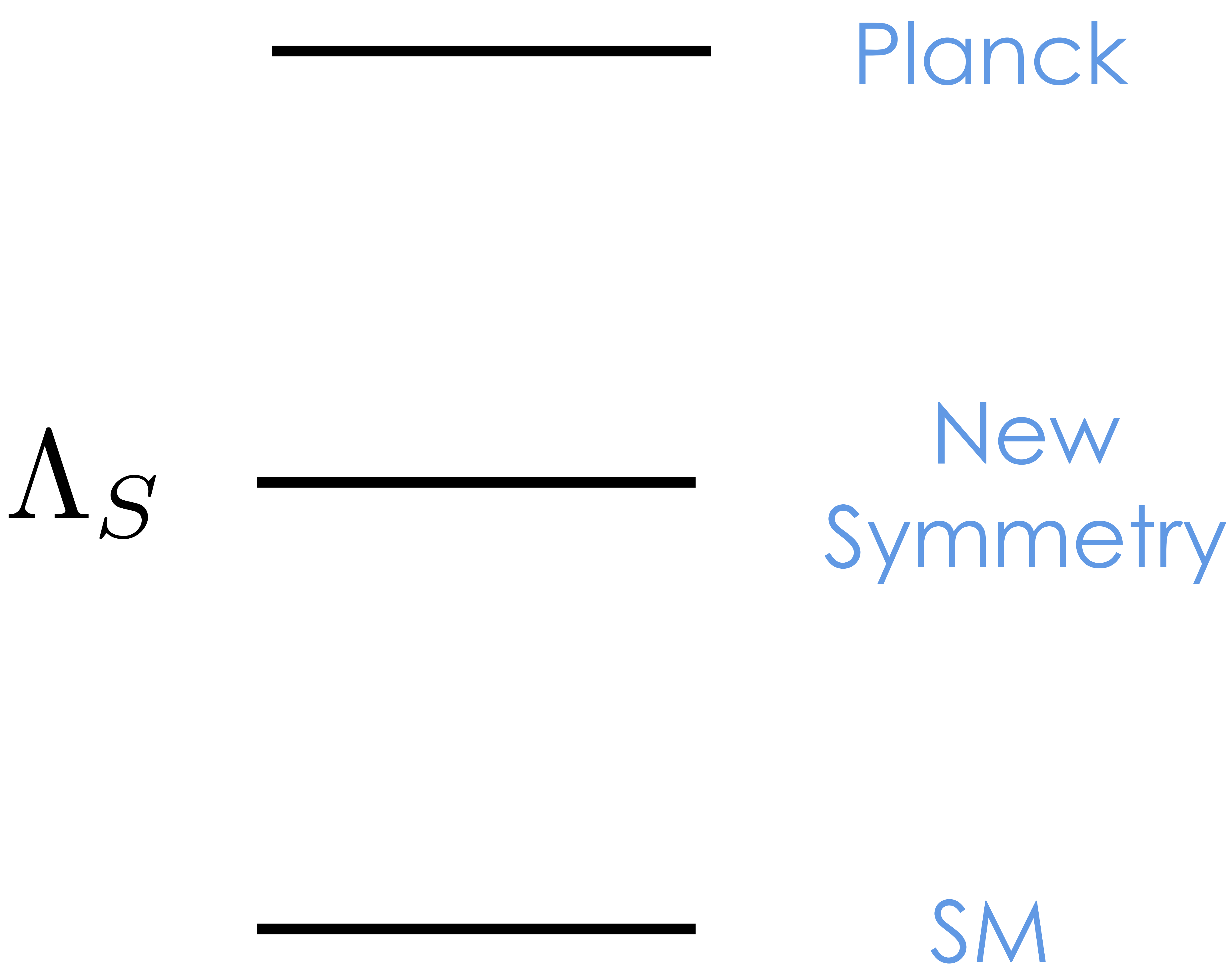
Supersymmetry

Chiral Protection of the Higgs Mass

Scale Invariance

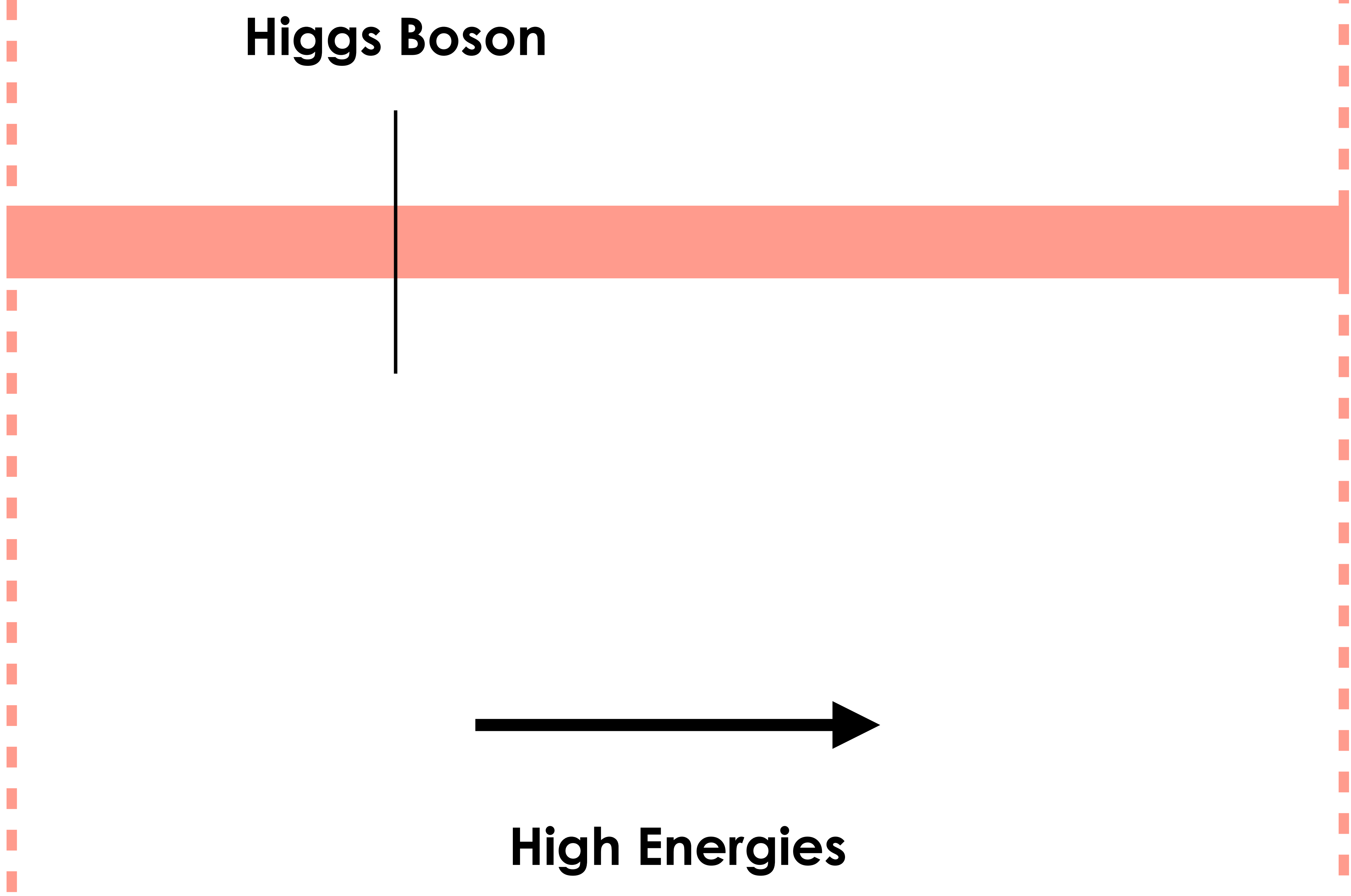


$$m_h^2 \sim \frac{y_t^2 \Lambda_S^2}{16\pi^2}$$



$$\Lambda_S \lesssim 4\pi m_h^{\text{obs}}$$

We have been looking for answers here



We **have been looking** for these simple and elegant solutions for **more than 40 years**

It is a good time to **consider seriously more creative alternatives**

1. Property of the SM that relates the two quantities

2. Joint explanation [RTD, Teresi ’21]

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

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

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

Atomic Principle [Agrawal, Donoghue, Barr, Seckel '97]

Nnaturalness [Arkani-Hamed, Cohen, **RTD**, Hook, Kim, Pinner '16]

Selfish Higgs [Giudice, Kehagias, Riotto, '19]

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

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

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

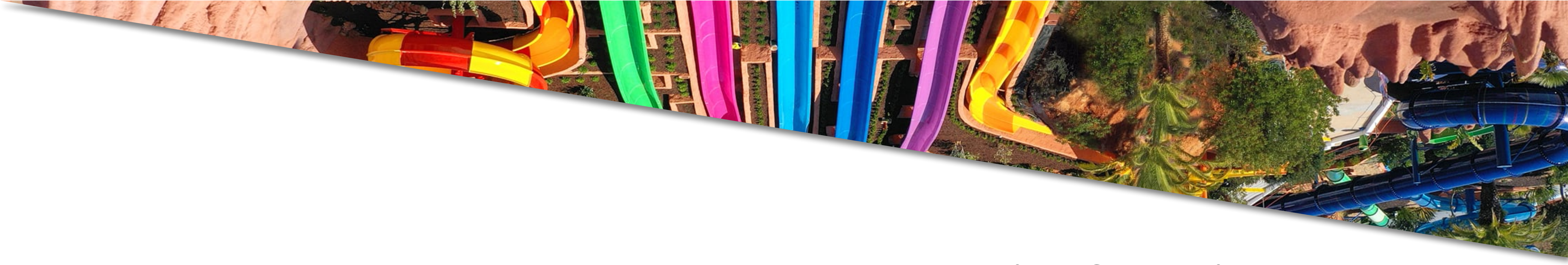
NEXT: **First joint solution** to the two problems

[**RTD**, Teresi '21]

SLIDING NATURALNESS

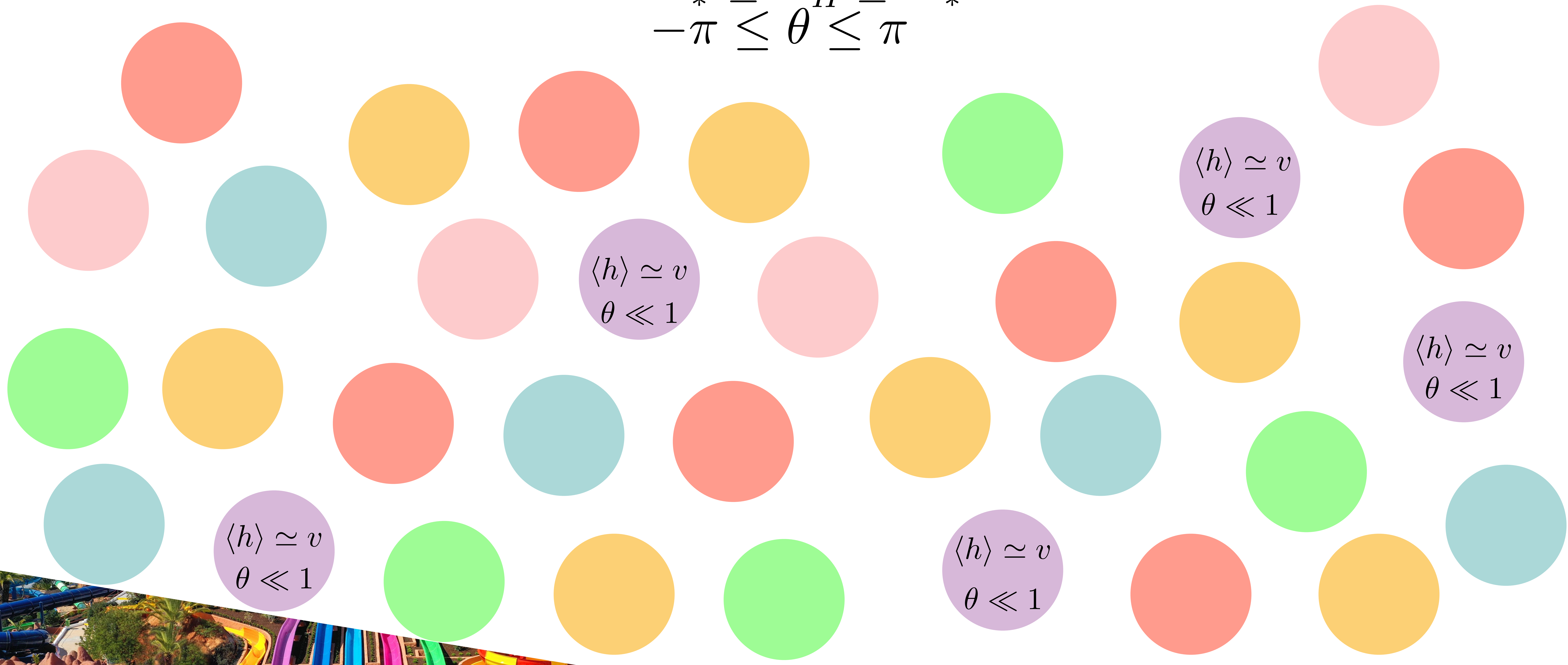
[**RTD**, Teresi] ‘21

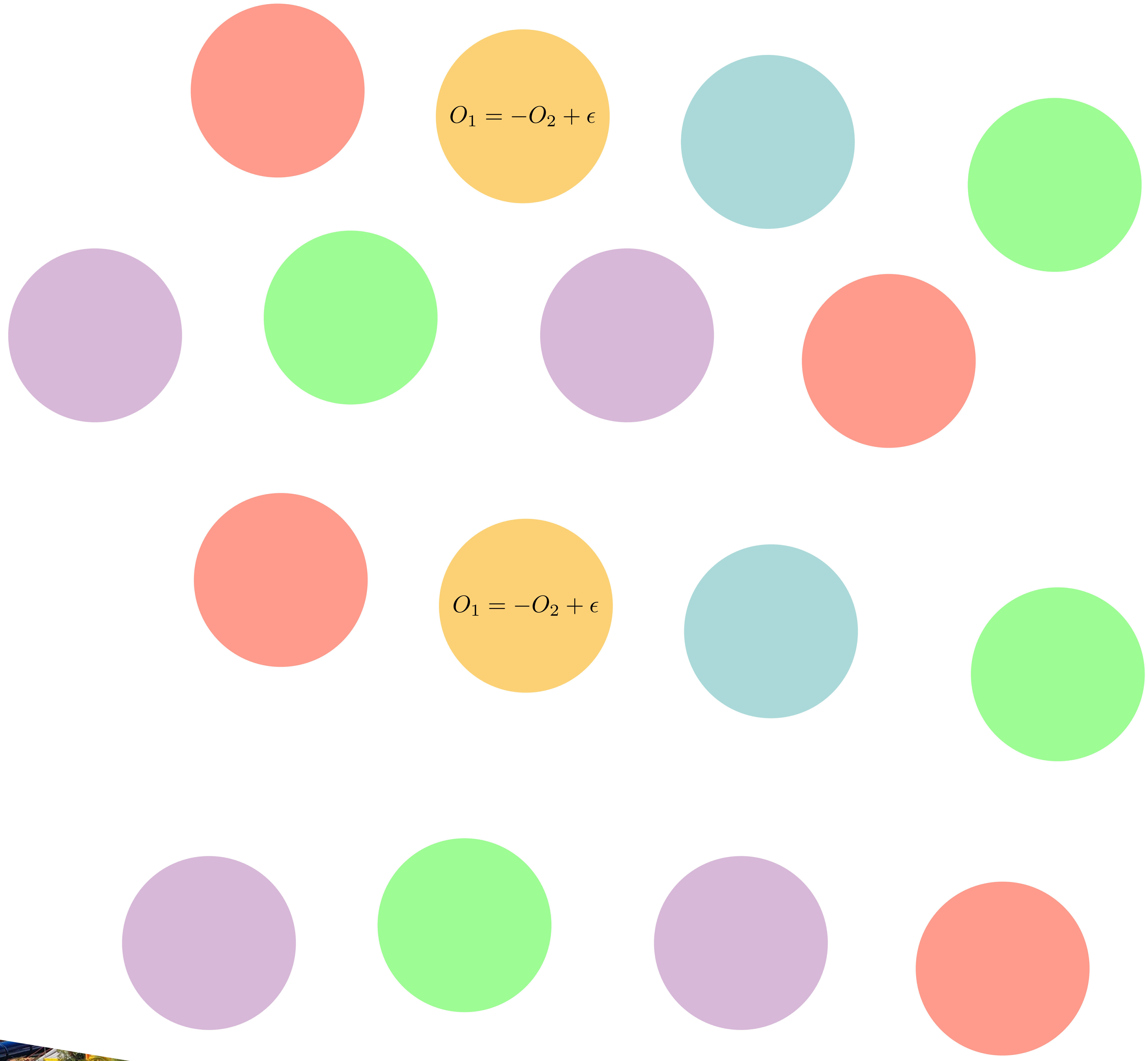
SLIDING NATURALNESS



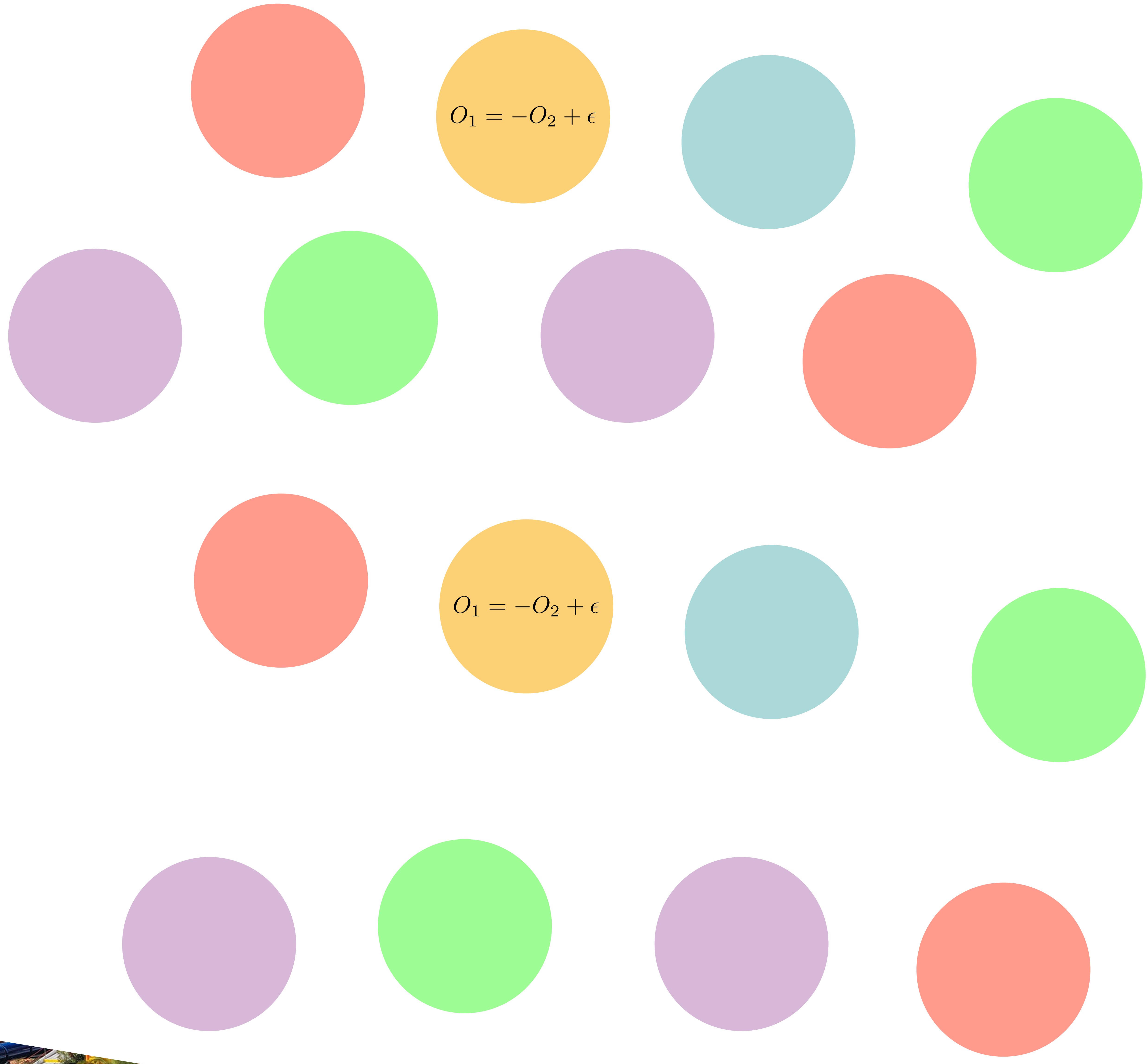
Landscape of Higgs Masses and theta-angles populated by inflation

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





Causally disconnected Universes with different values of the Standard Model parameters, populated by 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

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

$\langle h \rangle \simeq v$, $\theta \ll 1$

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

$\langle h \rangle \simeq v$, $\theta \ll 1$

Is outside of a certain range

$\langle h \rangle \simeq v$, $\theta \ll 1$

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

And theta is large

$\langle h \rangle \simeq v$, $\theta \ll 1$

$$\theta \leq \theta_{\rm max}$$

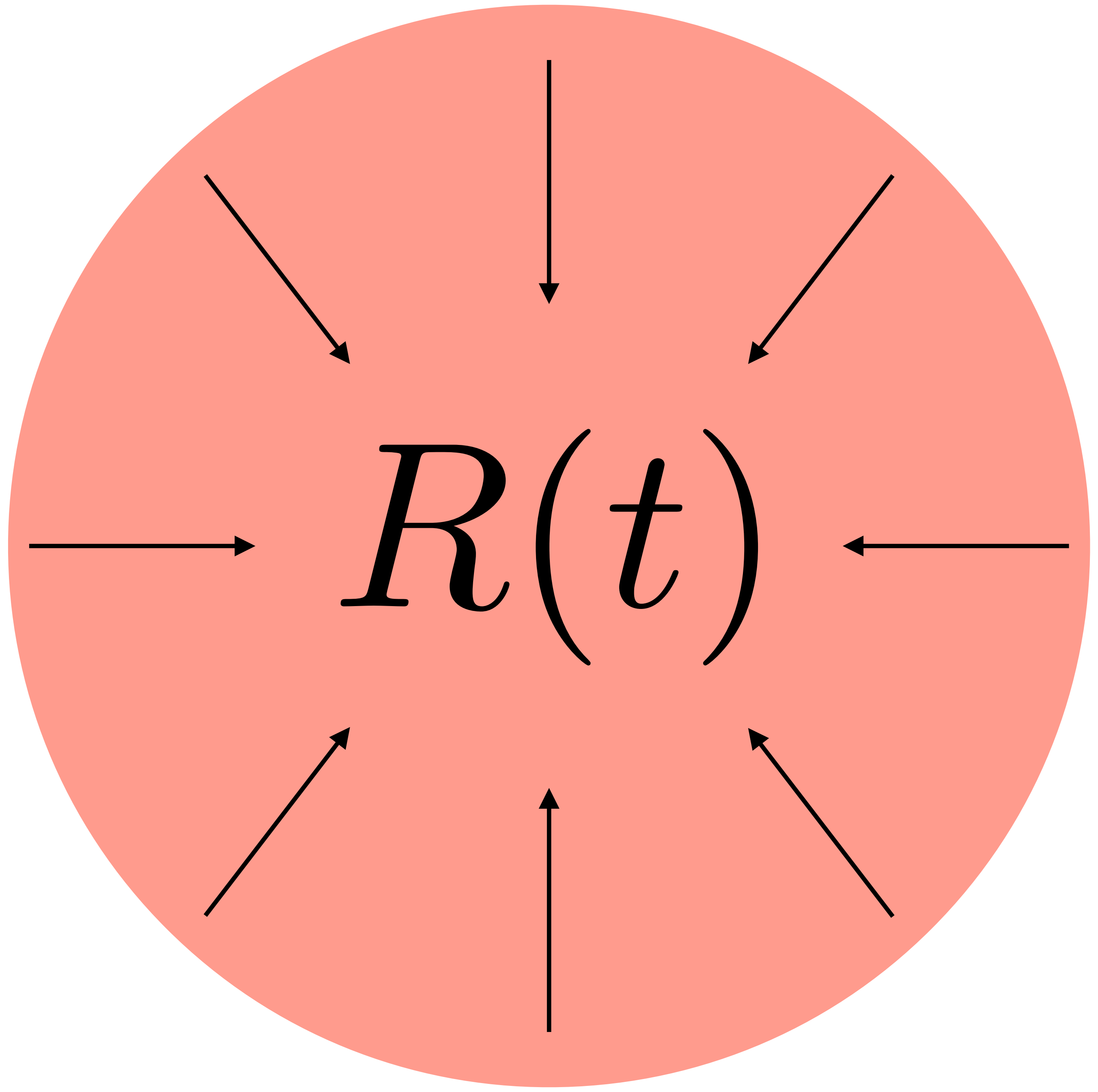
$\langle h \rangle \simeq v$, $\theta \ll 1$

crunch

CRUNCHING

Negative Cosmological Constant

$$R(t) \sim e^{-\frac{\Lambda^2 t}{M_{\mathrm{Pl}}}}$$



SLIDING NATURALNESS

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

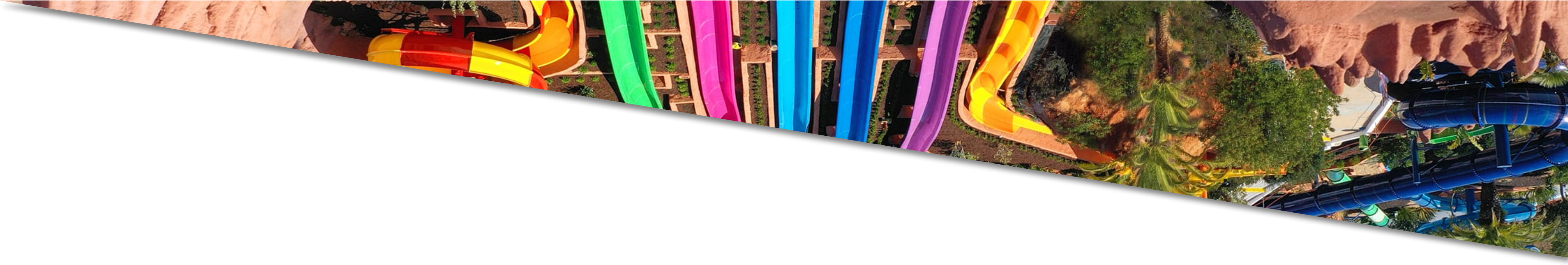
$$\langle h \rangle \simeq v \qquad \theta \ll 1$$

$$\langle h \rangle \simeq v \qquad \theta \ll 1$$

$$\langle h \rangle \simeq v \qquad \theta \ll 1$$

$$\langle h \rangle \simeq v \qquad \theta \ll 1$$

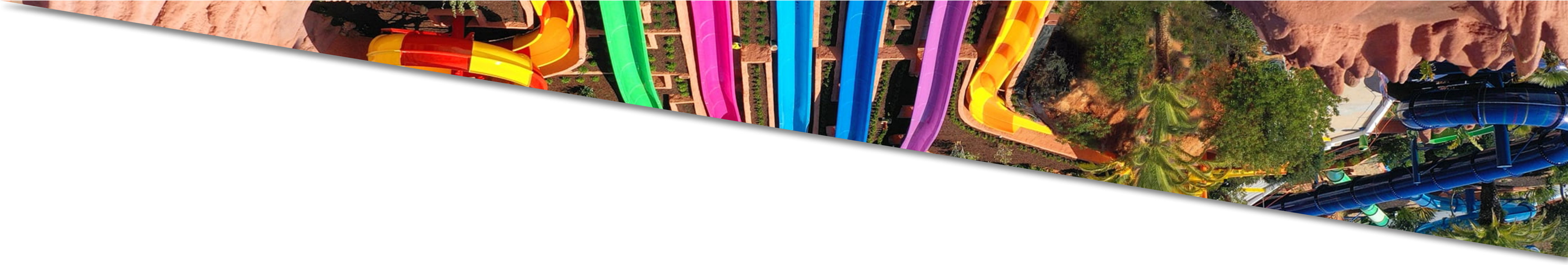
CRUNCHING



[Bloch, Csaki, Geller, Volansky, ’18]
[Csaki, **RTD**, Geller, Ismail, ’20]

SLIDING NATURALNESS

[**RTD**, Teresi] ‘21



Addition to the SM: Two very weakly coupled scalars

$$\phi_{\pm}$$

SLIDING NATURALNESS

[**RTD**, Teresi] '21

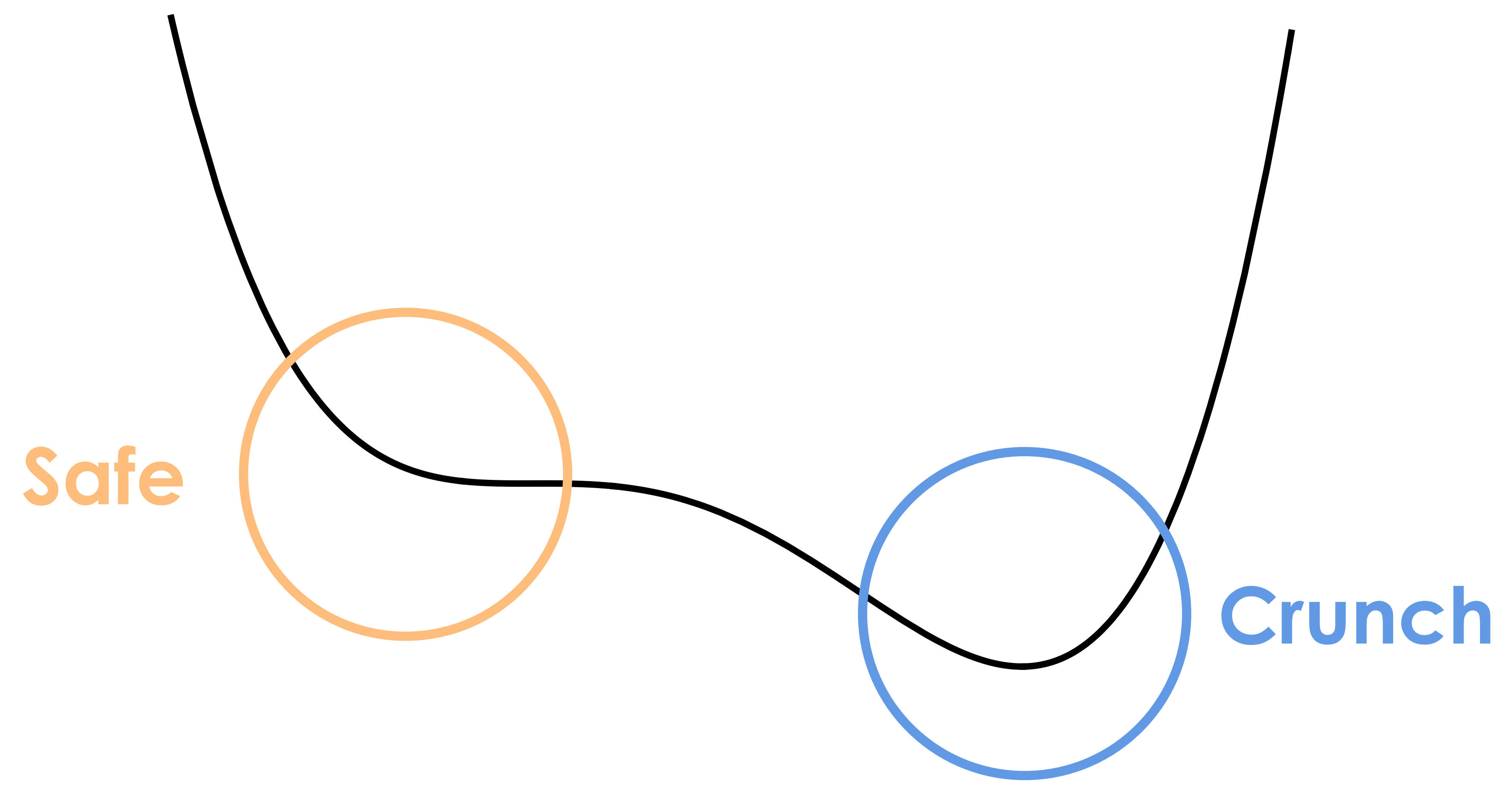
Approximately decoupled from each other

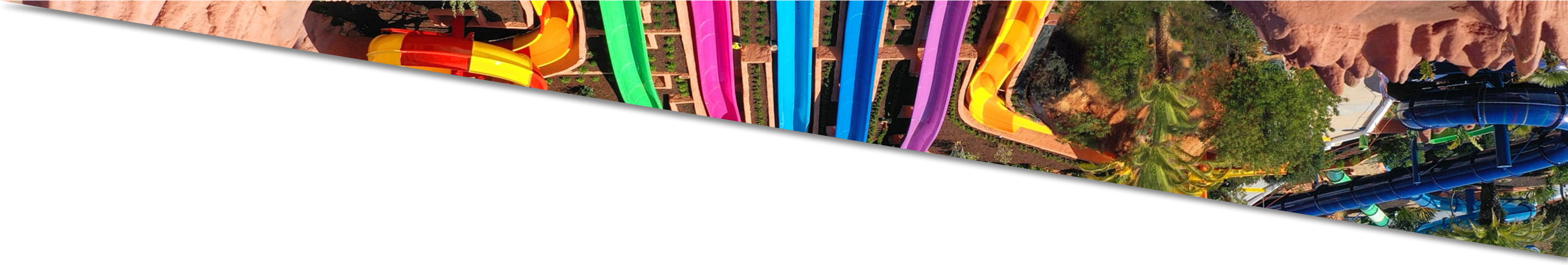
$$V = V_{\phi_-} + V_{\phi_+} + V_{H\phi_-} + V_{H\phi_+}$$

SLIDING NATURALNESS

[**RTD**, Teresi] '21

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



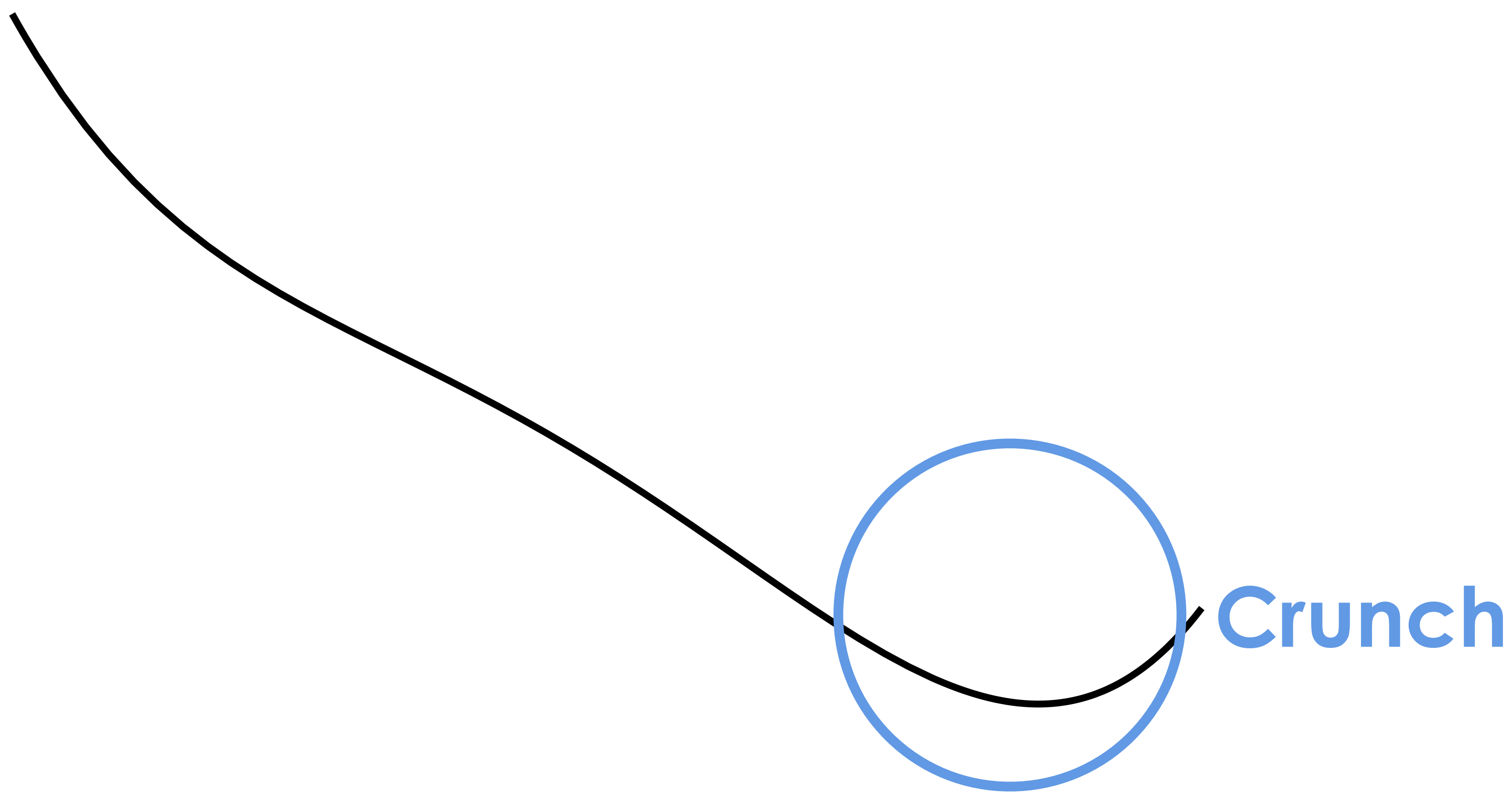


SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

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

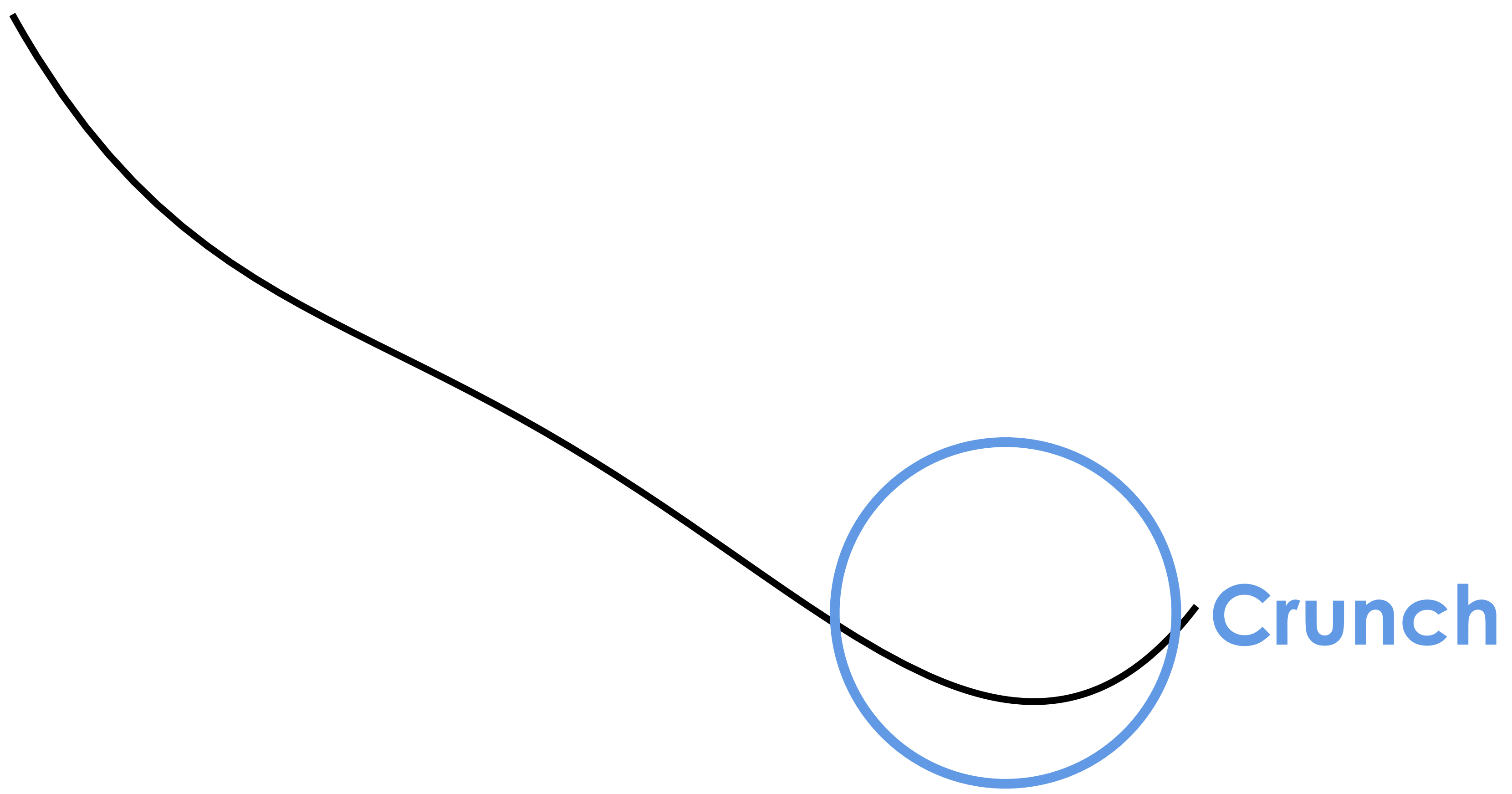


SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

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

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

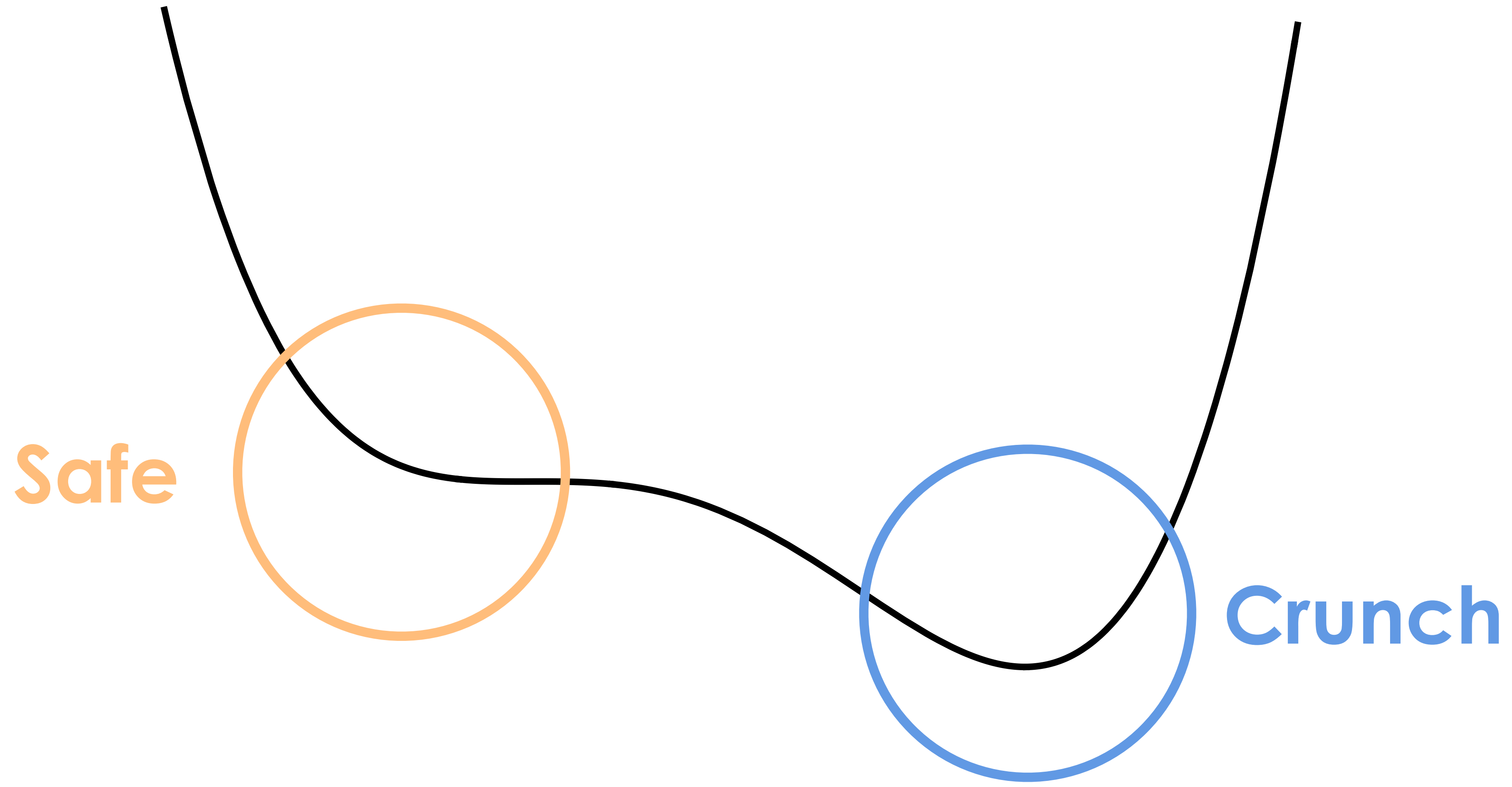


SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

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



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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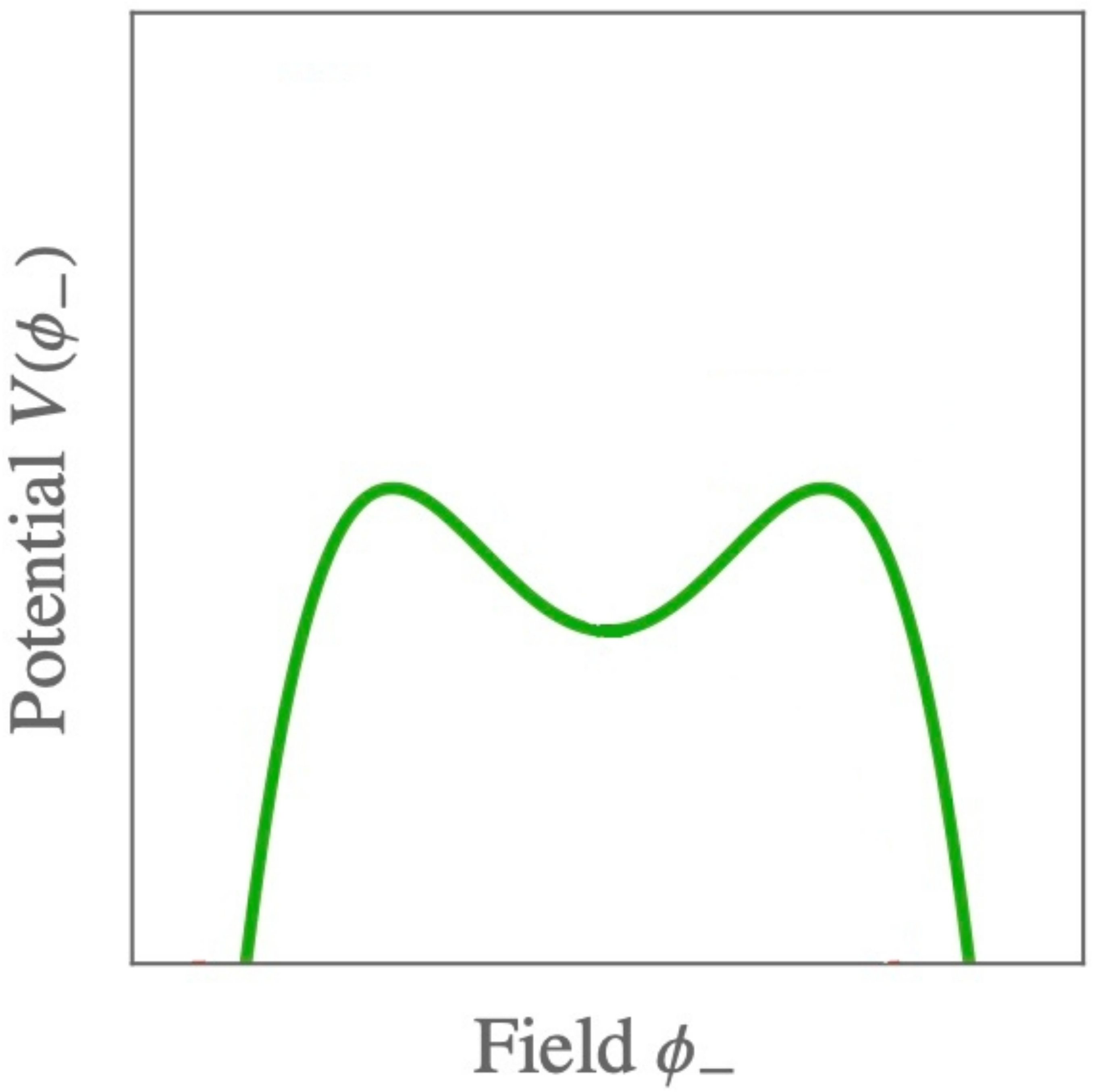

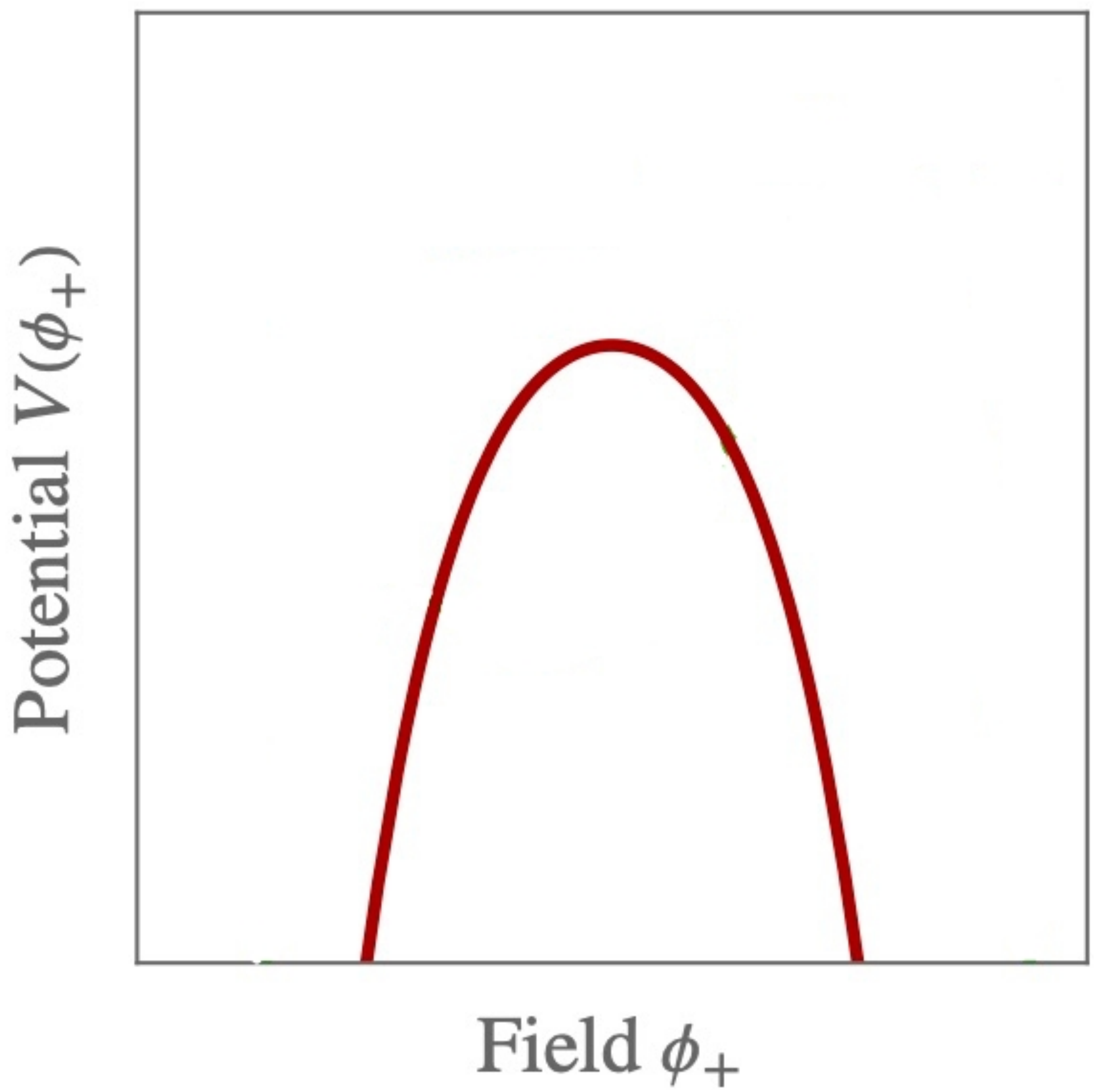

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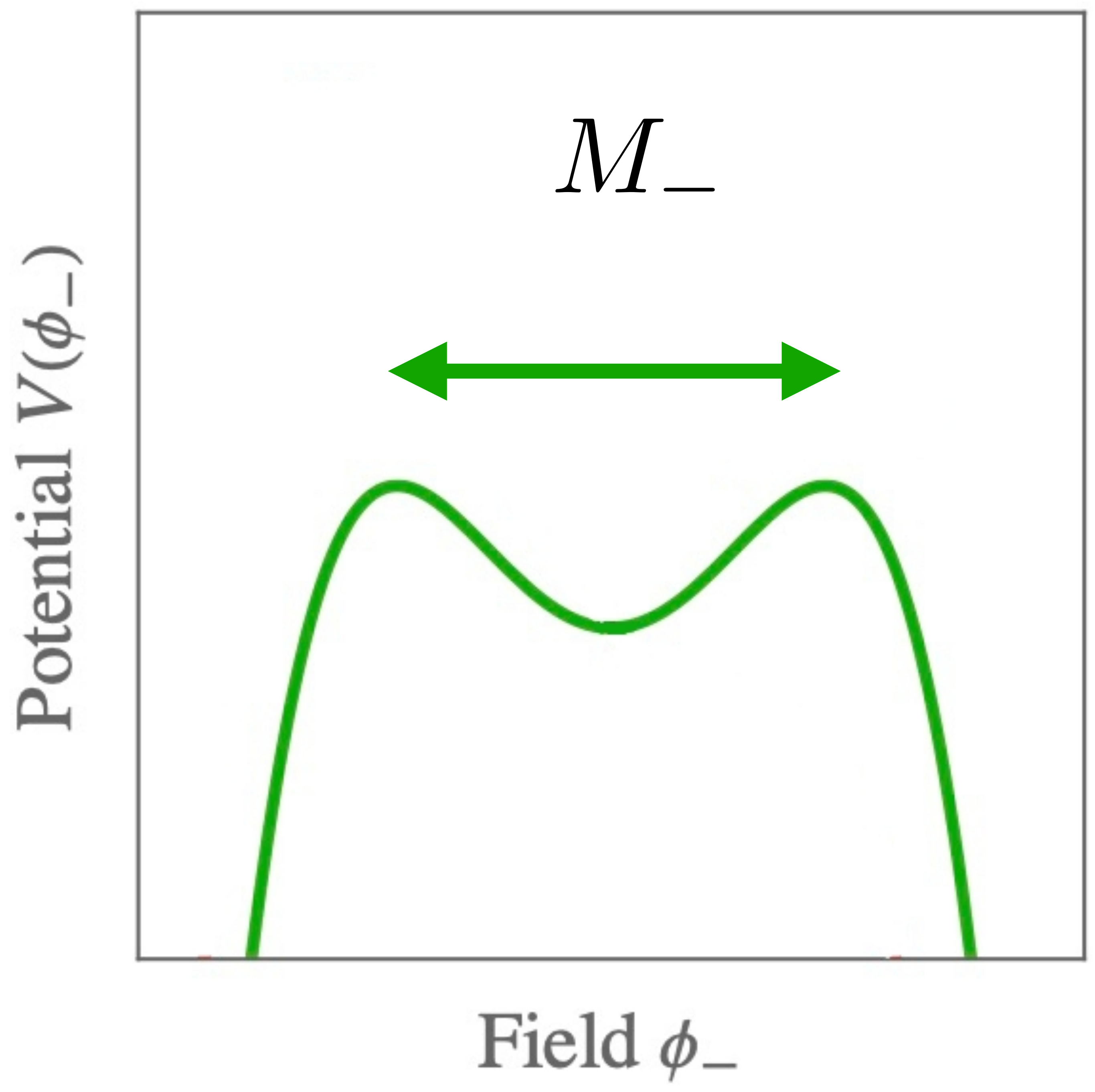
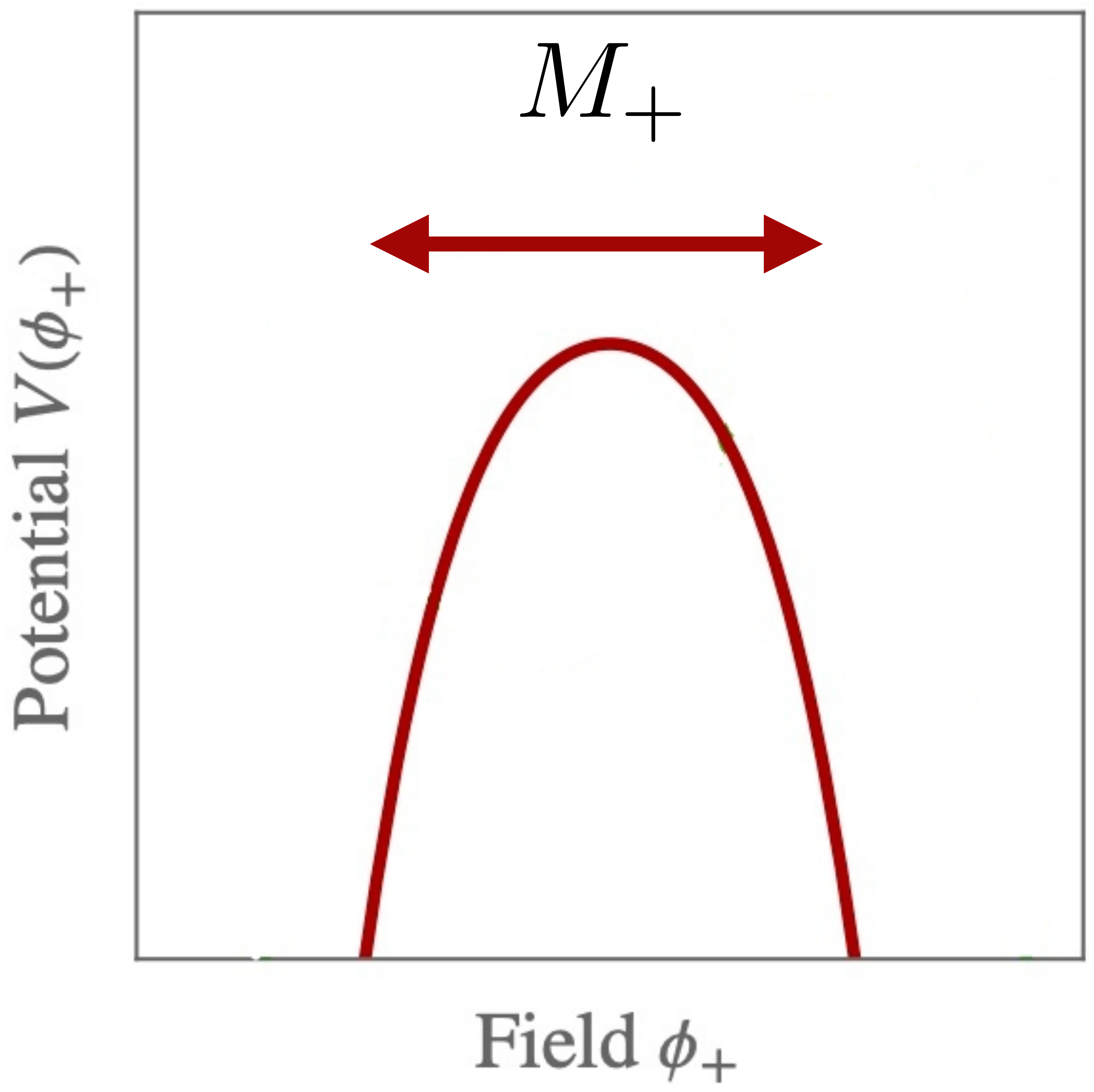




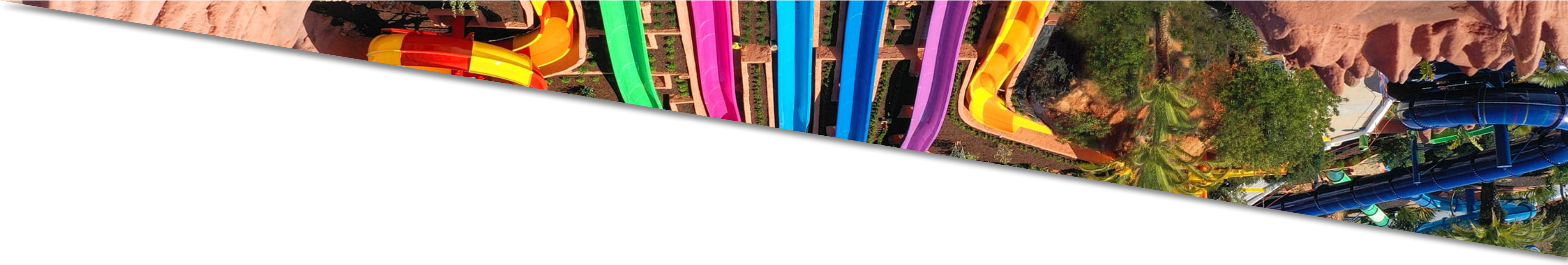
SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

SLIDING NATURALNESS

[**RTD**, Teresi] '21



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

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

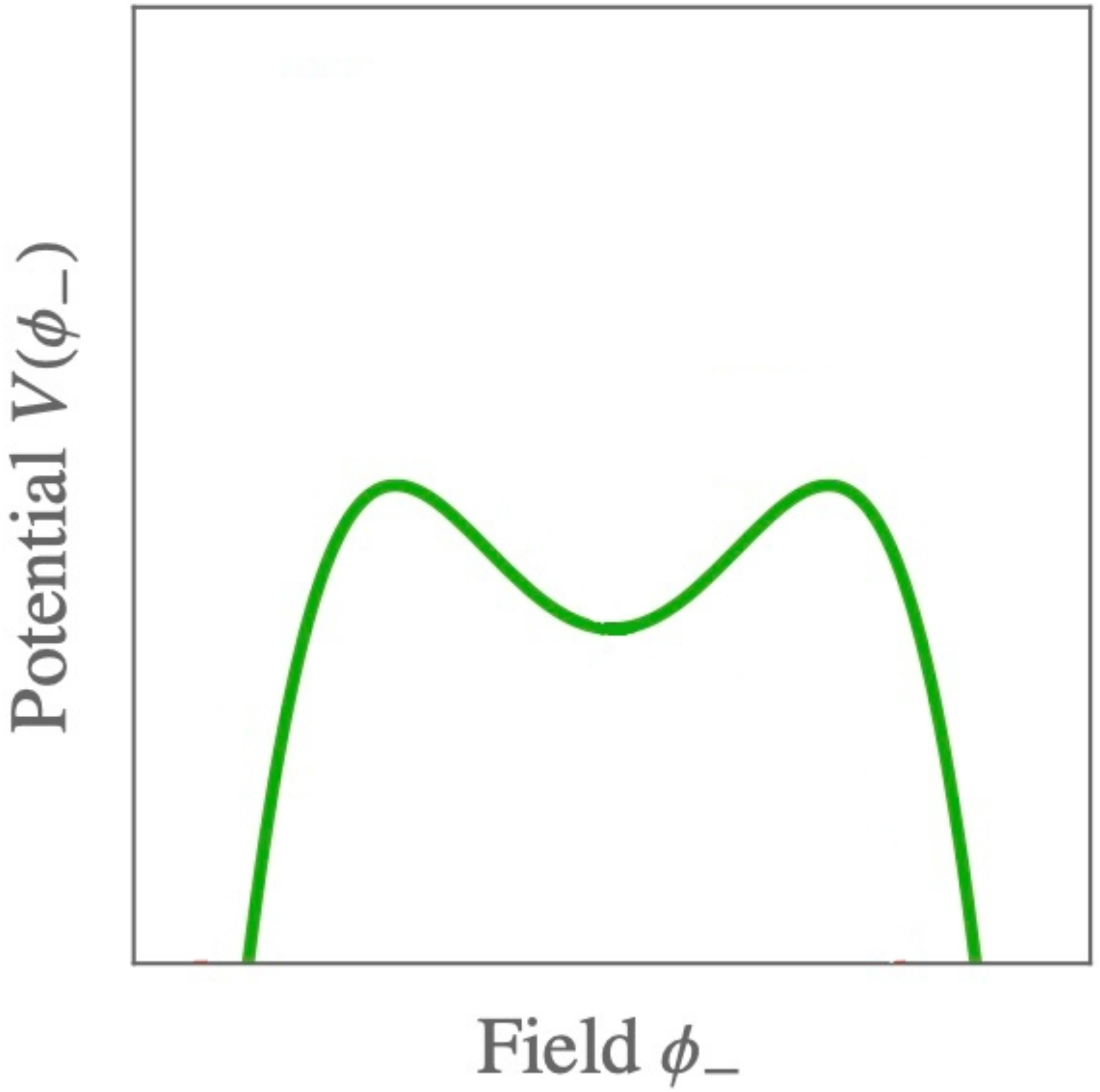
$$V_{H\phi_\pm} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)\widetilde{G}G$$

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

SLIDING NATURALNESS

[**RTD**, Teresi] '21

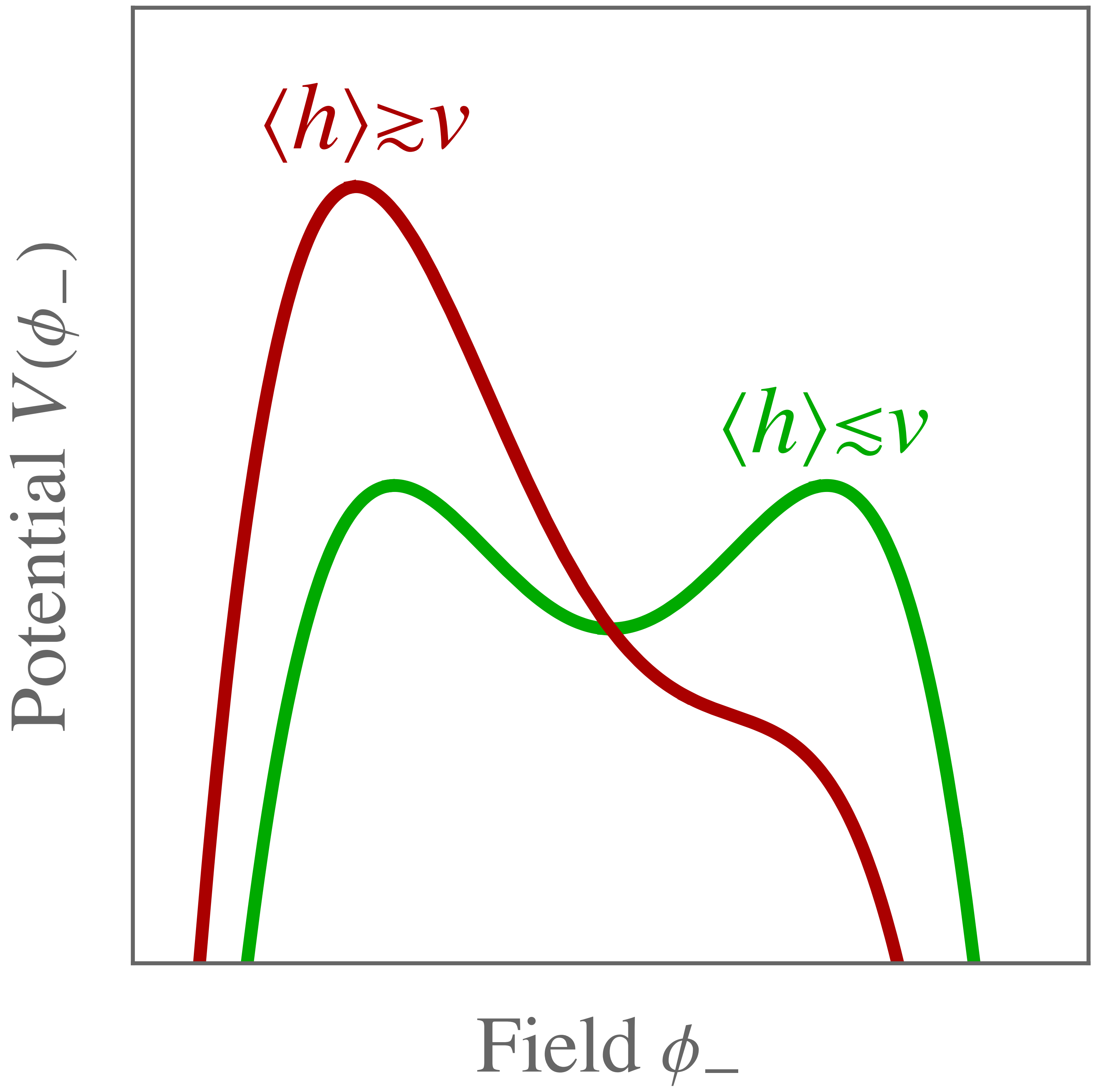
$$V_{H\phi_-} \simeq \theta_{\text{eff}} \Lambda^4_{\text{QCD}}(\langle h \rangle) \frac{\phi_-}{F_-}$$



SLIDING NATURALNESS

[**RTD**, Teresi] '21

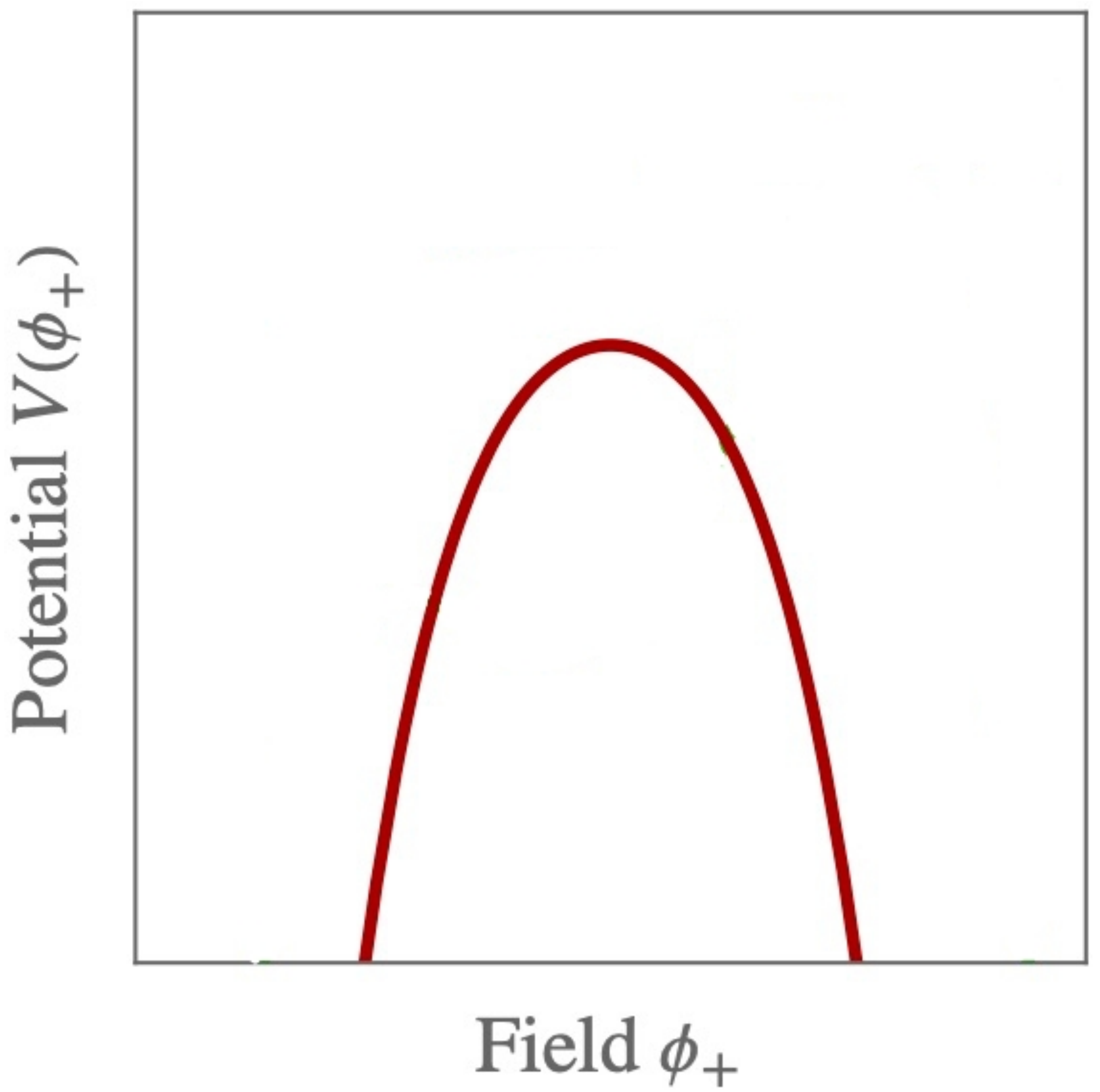
$$V_{H\phi_-} \simeq \theta_{\rm eff}\Lambda^4_{\rm QCD}(\langle h\rangle)\frac{\phi_-}{F_-}$$



SLIDING NATURALNESS

[**RTD**, Teresi] '21

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



SLIDING NATURALNESS

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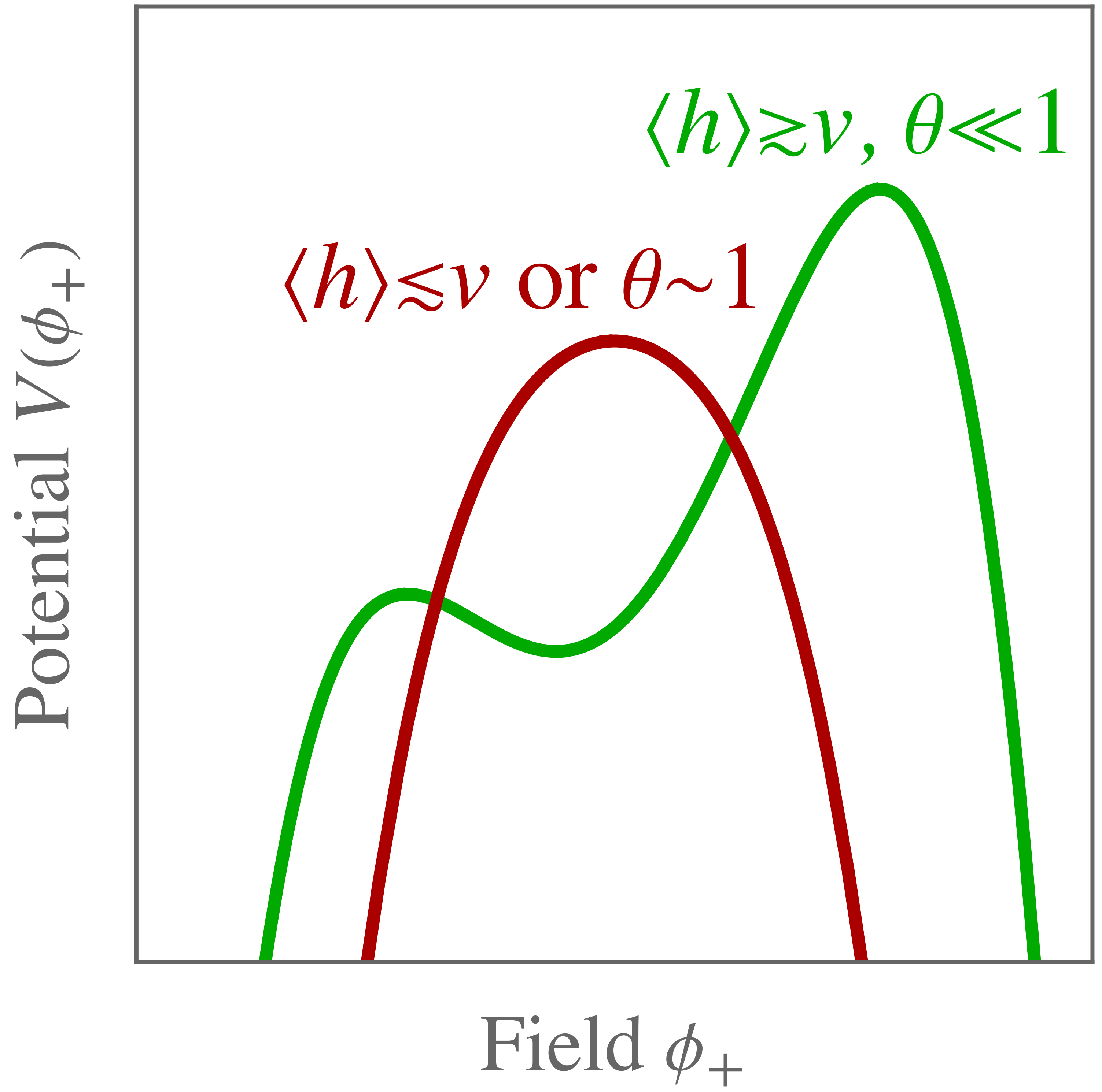


SLIDING NATURALNESS

[**RTD**, Teresi] '21

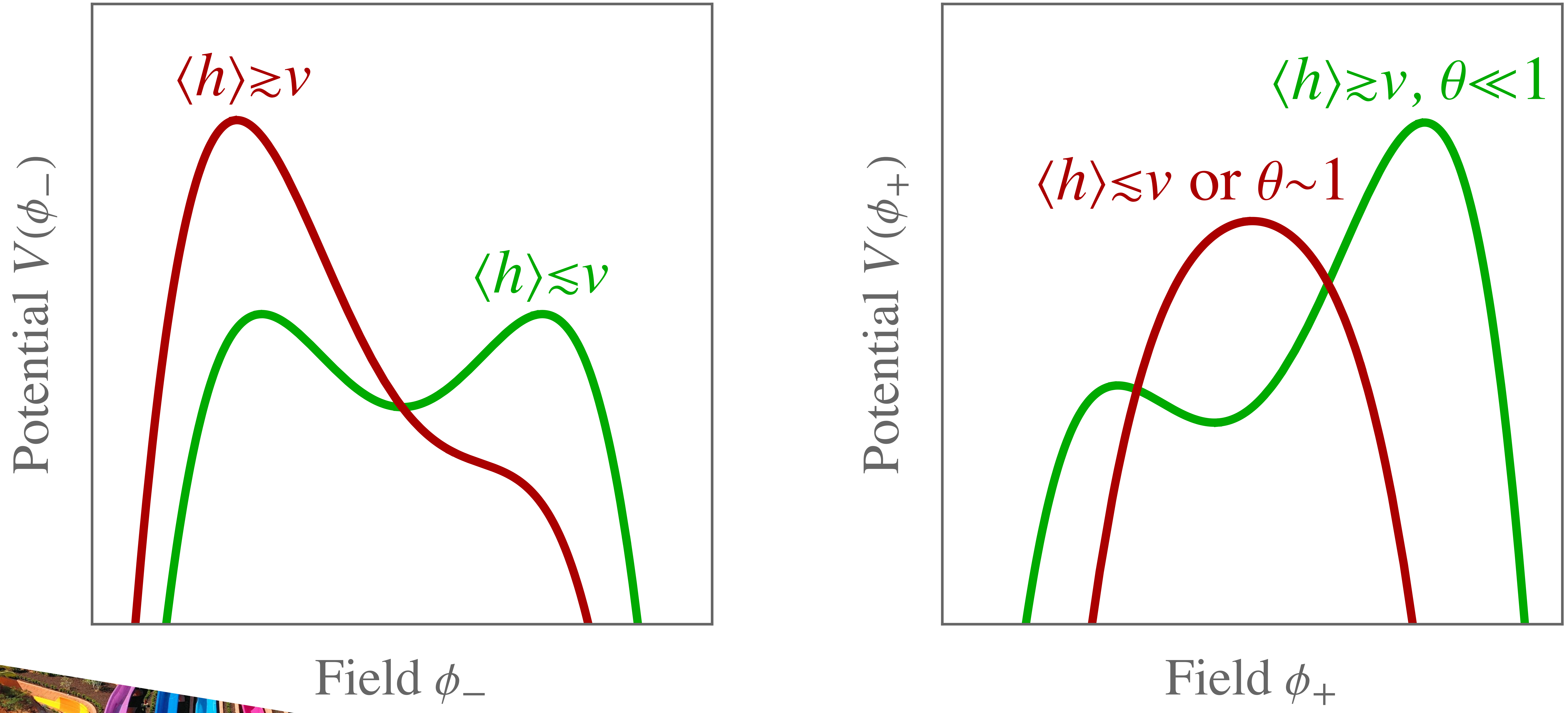
$$V_{\phi_\pm} = \mp \frac{m_{\phi_\pm}^2}{2} \phi_\pm^2 - \frac{\lambda}{4} \phi_\pm^4$$

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

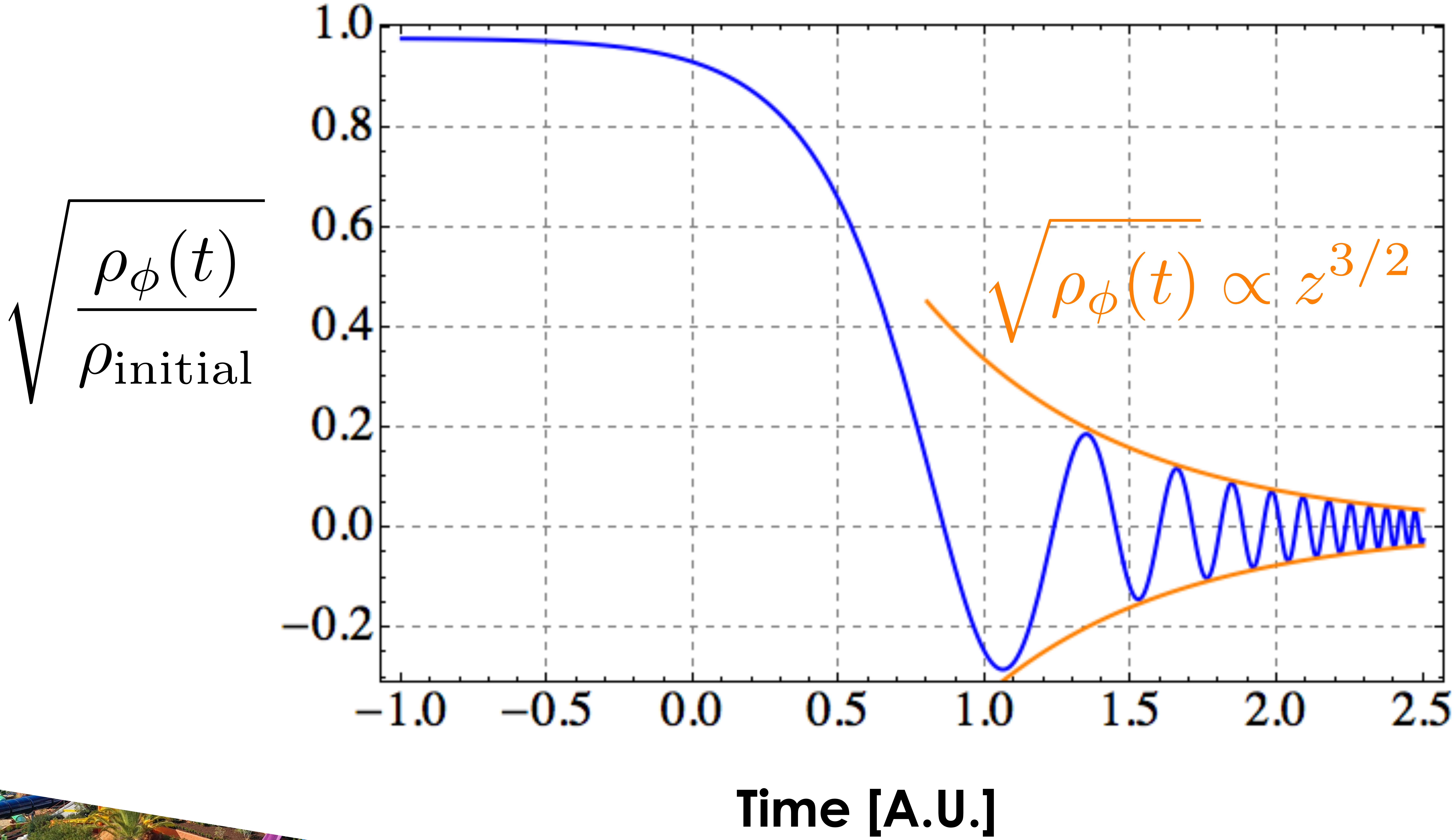
Solve Strong-CP and Hierarchy problem!

[**RTD**, Teresi ’21]

$$V = \mp m_\pm^2 \phi_\pm^2 - \lambda_\pm \phi_\pm^4 + \frac{\alpha_s}{8\pi}\left(\theta + \frac{\phi_+}{F_+} + \frac{\phi_-}{F_-}\right) G\widetilde{G}$$



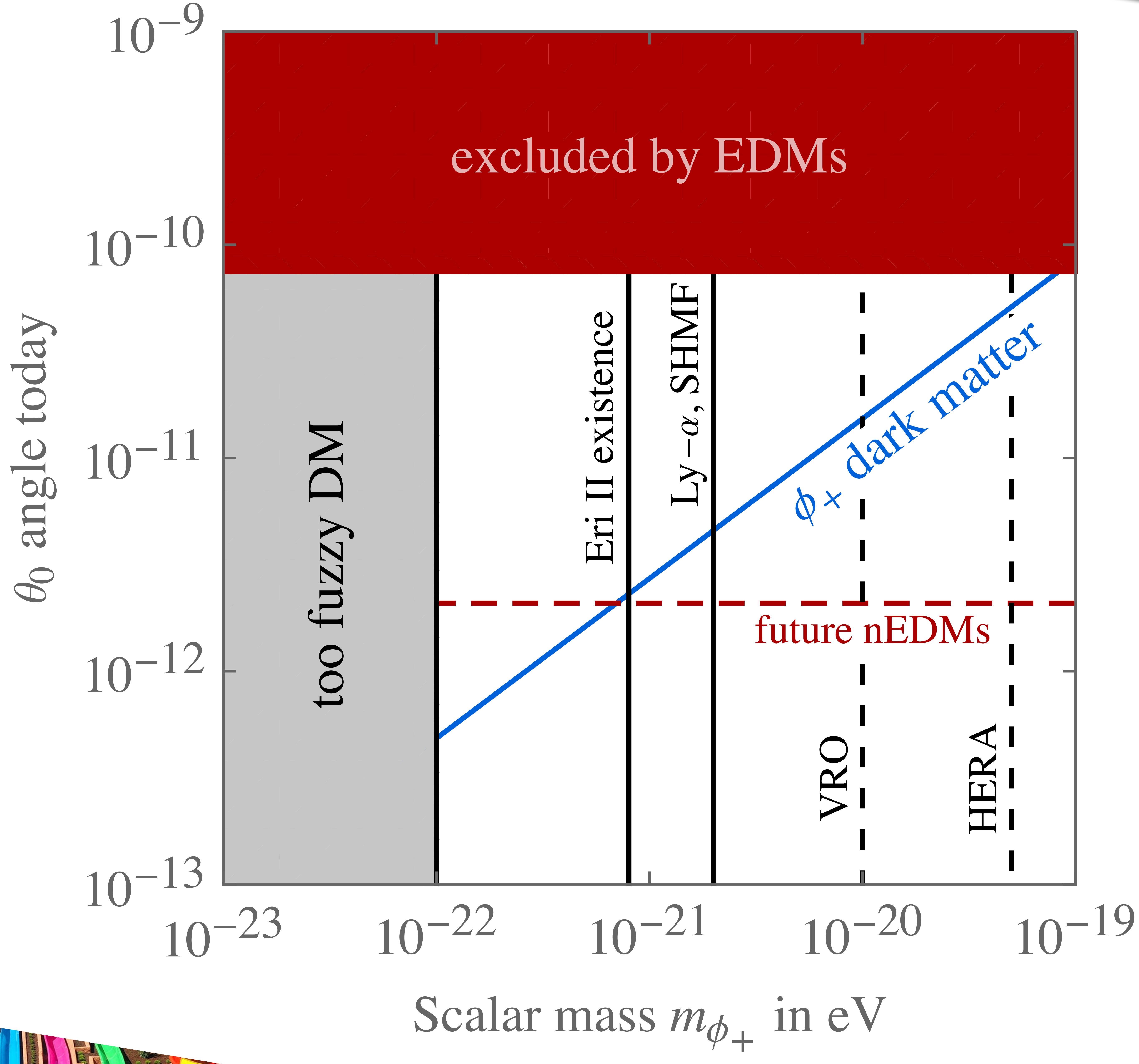
$f_\phi \bar{\theta}$



Redshifts as cold dark matter

SLIDING NATURALNESS

[**RTD**, Teresi] '21



n2EDM @ PSI
nEDM @ SNS (Caltech)

CONCLUSION

1. Hierarchy and strong CP in one go

2. Minimal extension of the SM (two extra d.o.f.s)

3. No funny business with inflation (it even works without)

4. No upper bound on the maximal cutoff

5. No real problem of measure

6. No relaxion-like obstructions to UV completion (non-compact potential lives on much smaller scales than the decay constant)

7. Potentially smoking gun signals (EDM correlated to DM)

$$\phi_{\pm}$$

Symmetric Sector

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

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

SM Landscape

$O_1 = -O_2 + \epsilon$

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

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

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

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

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

Most relevant phenomenologically:

Physics coupled to the Higgs with

$$m \lesssim v$$

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

$$G\widetilde{G}$$

$$H_1 H_2$$

$$F\widetilde{F}$$


BRENTON
A BSM TRIGGER

[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]

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

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

TYPE-0 2HDM

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

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

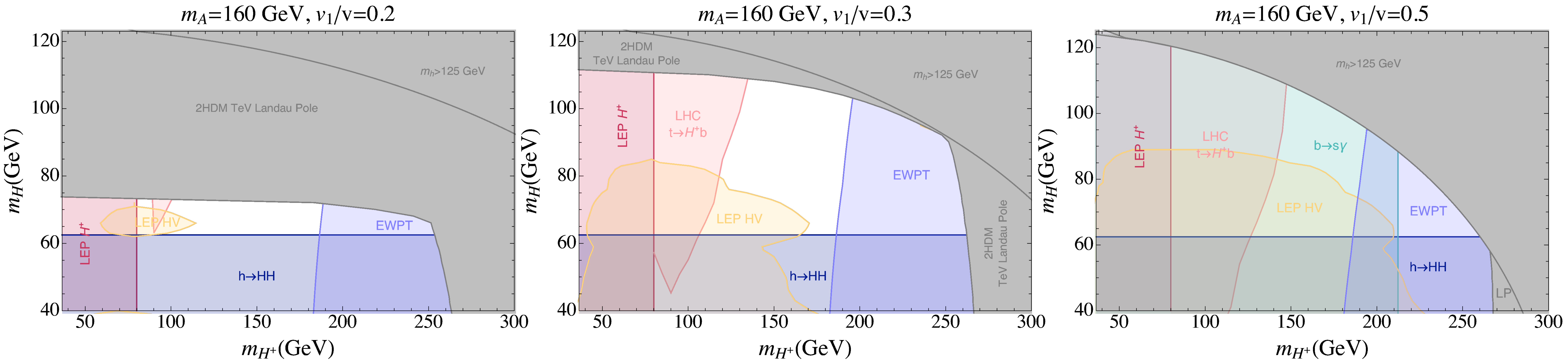
$$H_2 \to -H_2, \quad (qu^c) \to -(qu^c), \quad (qd^c) \to -(qd^c), \quad (le^c) \to -(le^c)$$

This gives

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

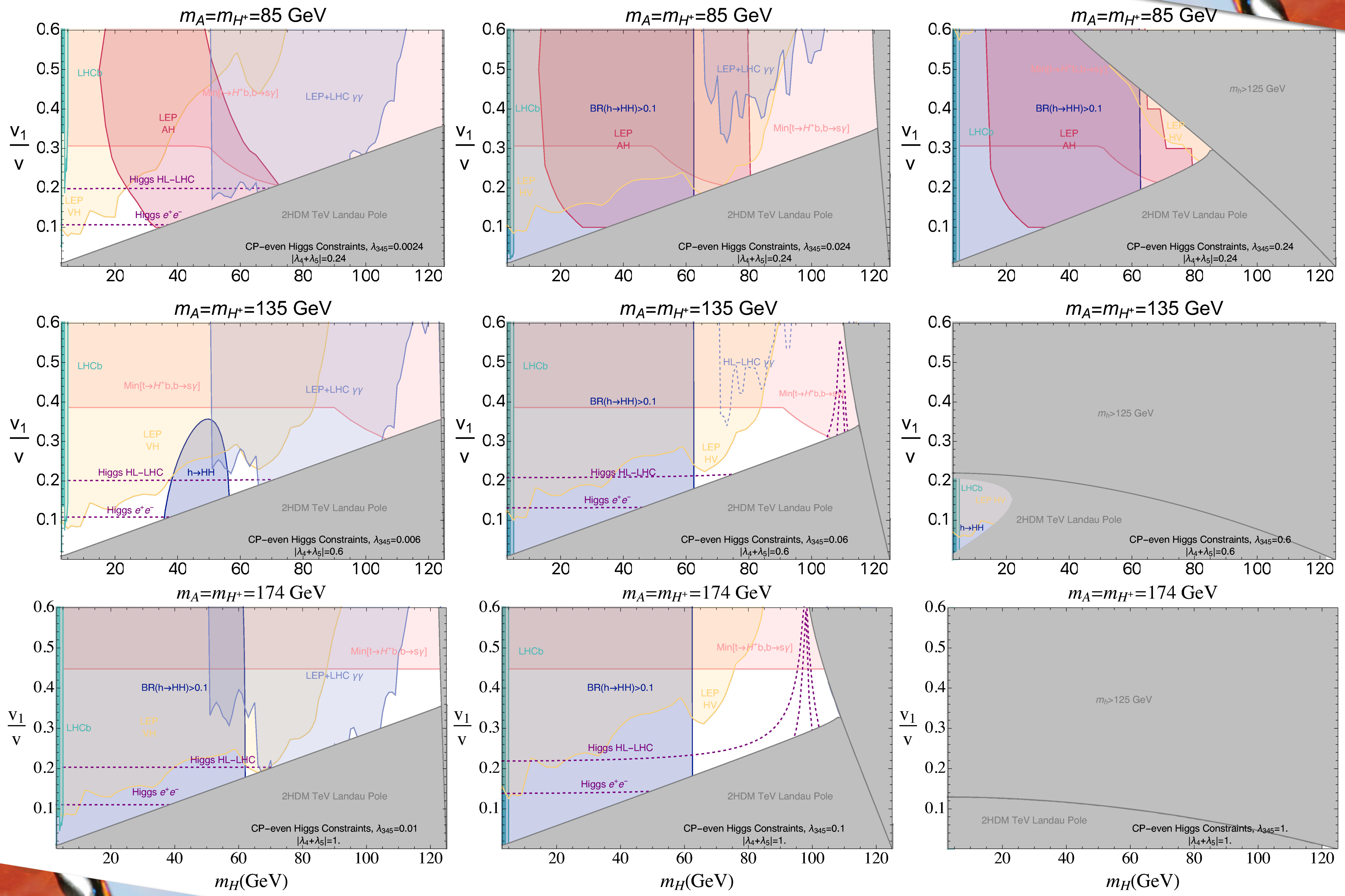
TYPE-0 2HDM

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



Sharp target for HL-LHC and FCC
which **can't be decoupled**!
(See also the next slide)

TYPE-0 2HDM



mA=mH+=85 GeV
mA=mH+=135 GeV
mA=mH+=174 GeV
v1/v
mH(GeV)
LHCb
LEP AH
LEP VH
LEP HV
LEP+LHC γγ
HL-LHC γγ
Min[t→H+b,b→sγ]
BR(h→HH)>0.1
h→HH
Higgs HL-LHC
Higgs e+e−
mh>125 GeV
2HDM TeV Landau Pole
CP-even Higgs Constraints, λ345=0.0024
CP-even Higgs Constraints, λ345=0.024
CP-even Higgs Constraints, λ345=0.24
|λ4+λ5|=0.24
CP-even Higgs Constraints, λ345=0.006
CP-even Higgs Constraints, λ345=0.06
CP-even Higgs Constraints, λ345=0.6
|λ4+λ5|=0.6
CP-even Higgs Constraints, λ345=0.01
CP-even Higgs Constraints, λ345=0.1
CP-even Higgs Constraints, λ345=1.
|λ4+λ5|=1.

New vector-like leptons

+

Dark confining gauge group

$$\mathcal{L} \supset -m_L L L^c - m_N N N^c - y L H N^c - y^c L^c H N + \text{h.c.} - \frac{\phi}{32\pi^2 f} F\widetilde{F}$$

$$G\widetilde{G}$$

$$H_1 H_2$$

$$F\widetilde{F}$$

BACKUP

n2EDM

$$H = -\vec{\mu}_{\rm n} \cdot \vec{B} - \vec{d}_{\rm n} \cdot \vec{E} \,, \tag{1}$$

where $\vec{\mu}_{\rm n}$ is the magnetic dipole moment, $\vec{d}_{\rm n}$ the electric dipole moment, $\vec{B}$ and $\vec{E}$ are the magnetic and electric fields.

Since the first nEDM result in 1957, almost all experiments have been using the Ramsey method of time separated oscillating fields [20]. With this method measurements of the Larmor precession frequency of polarized neutrons in a magnetic field are performed. In our apparatus, the Larmor frequency is measured in the two cases of parallel/anti-parallel $\vec{B}$ and $\vec{E}$ fields. The Larmor frequencies are given following Eq. (1)

$$h\nu_{\uparrow\uparrow} = -2(\mu_{\rm n} B_{\uparrow\uparrow} + d_{\rm n} E_{\uparrow\uparrow}) \tag{2}$$

$$h\nu_{\uparrow\downarrow} = -2(\mu_{\rm n} B_{\uparrow\downarrow} - d_{\rm n} E_{\uparrow\downarrow}) \,, \tag{3}$$

where $\uparrow\uparrow$ stands for parallel $\vec{B}/\vec{E}$-fields and $\uparrow\downarrow$ stands for anti-parallel $\vec{B}/\vec{E}$-fields.

The nEDM, $d_{\rm n}$, can be extracted from a differential measurement between the frequencies $\nu_{\uparrow\uparrow}$ and $\nu_{\uparrow\downarrow}$ with

$$d_{\rm n} = \frac{h(\nu_{\uparrow\downarrow} - \nu_{\uparrow\uparrow}) - 2\mu_{\rm n}(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}{2(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})} \,. \tag{4}$$

The statistical sensitivity of a single measurement with this method is given by

$$\sigma(d_{\rm n}) = \frac{\hbar}{2\alpha |E| T \sqrt{N}} \,, \tag{5}$$

where $|E|$ is the electric field strength, T is the free precession time of the neutrons, N is the number of counted neutrons and α is a measure of the neutron polarization. The

TYPE-0 2HDM

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

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

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

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

1. Strong-CP problem **known for 50 years**

2. Higgs hierarchy problem **known for 50 years**

3. Sensitivity to theta-angle and Higgs vev **known for 50 years**

Anthropic Selection

[Agrawal, Barr, Donoghue, Seckel ’97], [Arvanitaki, Dimopoulos, Gorbenko, Huang, Van Tilburg ’16],

[Arkani-Hamed, RTD, Kim, ‘20],

[Giudice, Kehagias, Riotto, ’20],

…

Statistical Selection

[Dvali, Vilenkin ’03], [Dvali ’04], [Geller, Hochberg, Kuflik,’18], [Giudice, McCullough, You, ’21],

…

Dynamical Selection

[Graham, Rajendran, Kaplan, ’15], [Arkani-Hamed, Cohen, RTD, Kim, Pinner, ’16], [Csaki, RTD, Geller, Ismail, ’20], [Strumia, Teresi, ’20], [RTD, Teresi, ’21],

…

POTENTIAL TRIGGERS

In the SM we can try other options

$$\mathrm{Tr}\left[W\widetilde{W}\right]$$

Needs extra B+L breaking
Beyond the SM

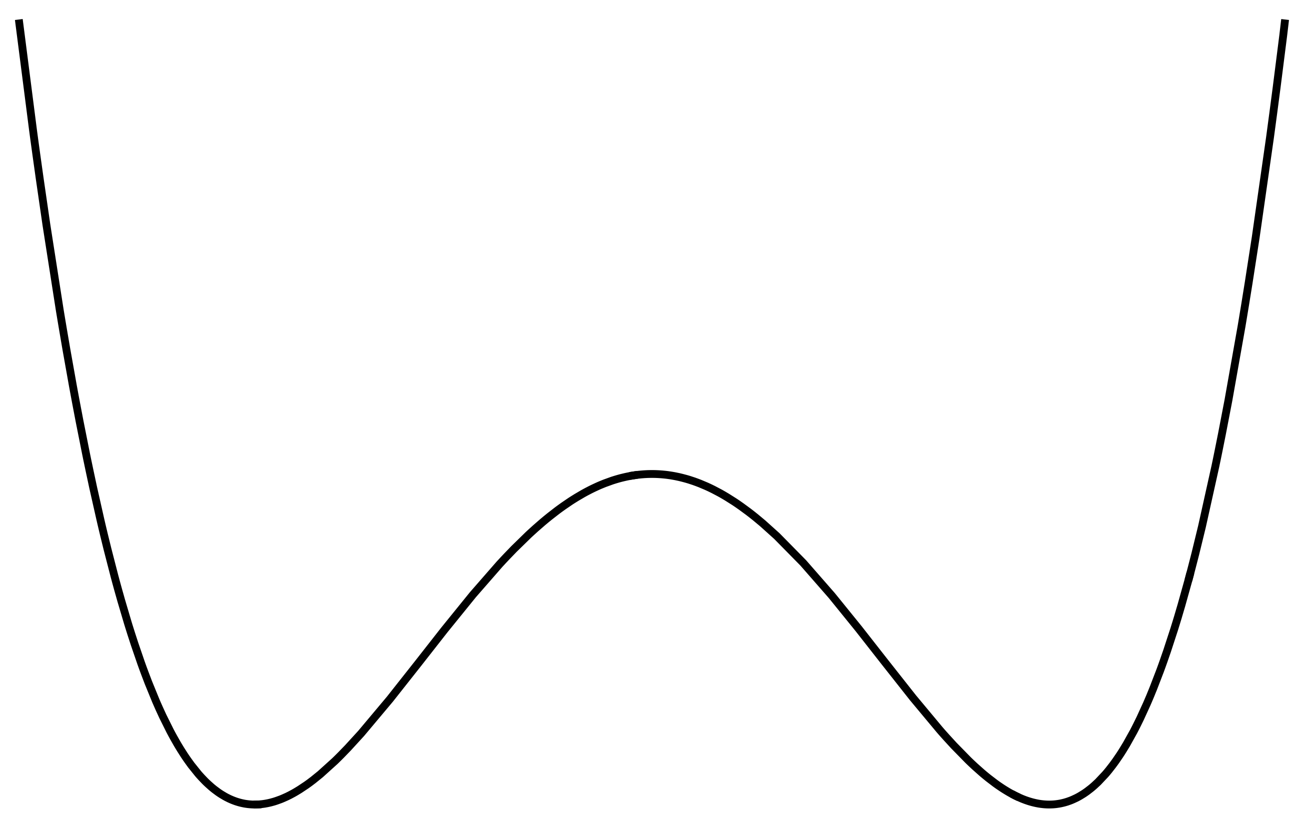
$$\frac{(Qu^c)(Qd^c)}{M^2}$$

Works only in 2HDM or for little HP
In the SM at 3 loops it's sensitive to flavor breaking by Yukawas

SIMPLE UV COMPLETION

[**RTD**, Teresi] '21

$$W_\phi = L\Phi + \mu\Phi^2 + \lambda\Phi^3$$



$\phi \sim L/\mu$ $\phi \sim \mu/\lambda$

SIMPLE UV COMPLETION

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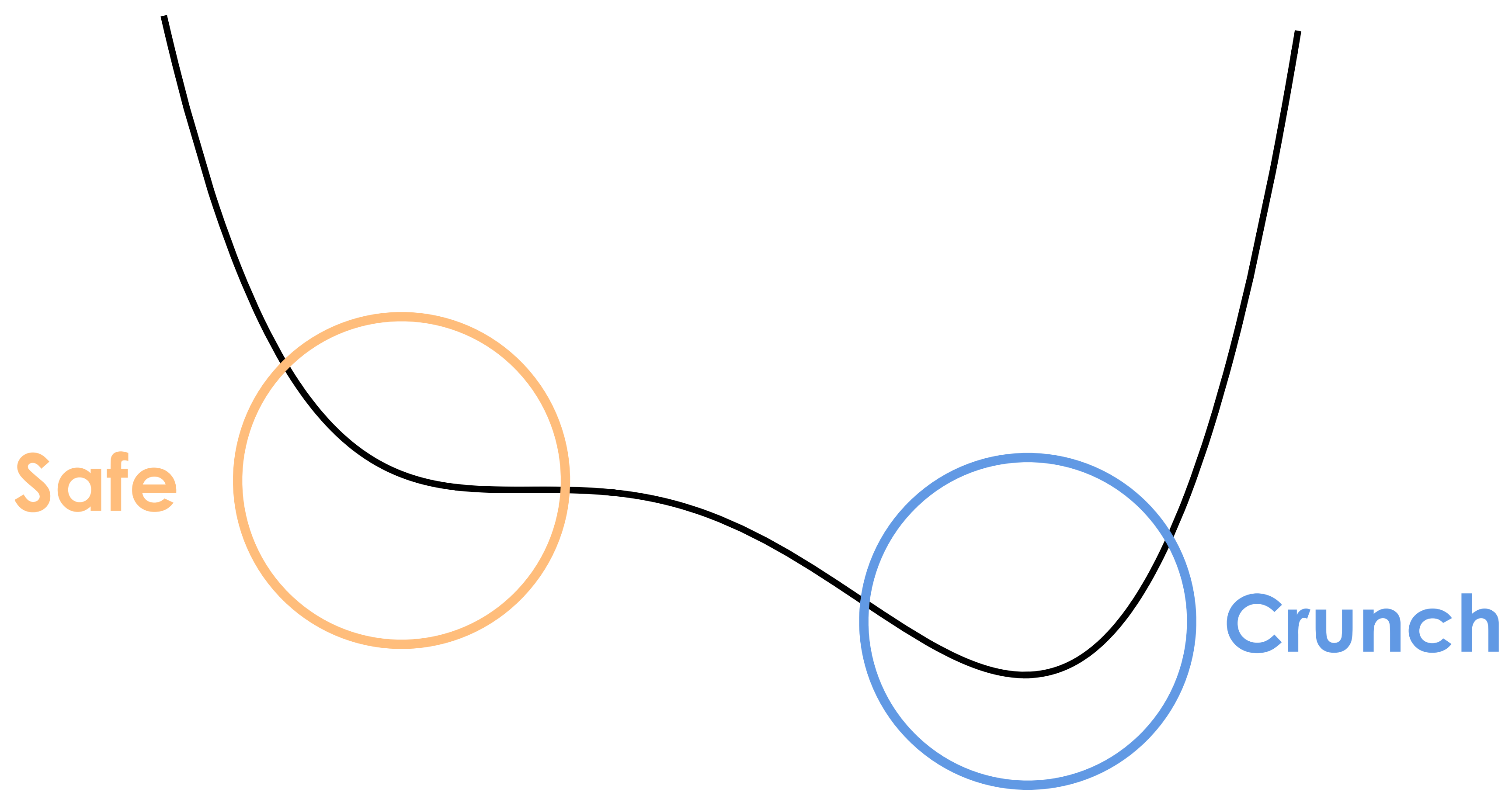
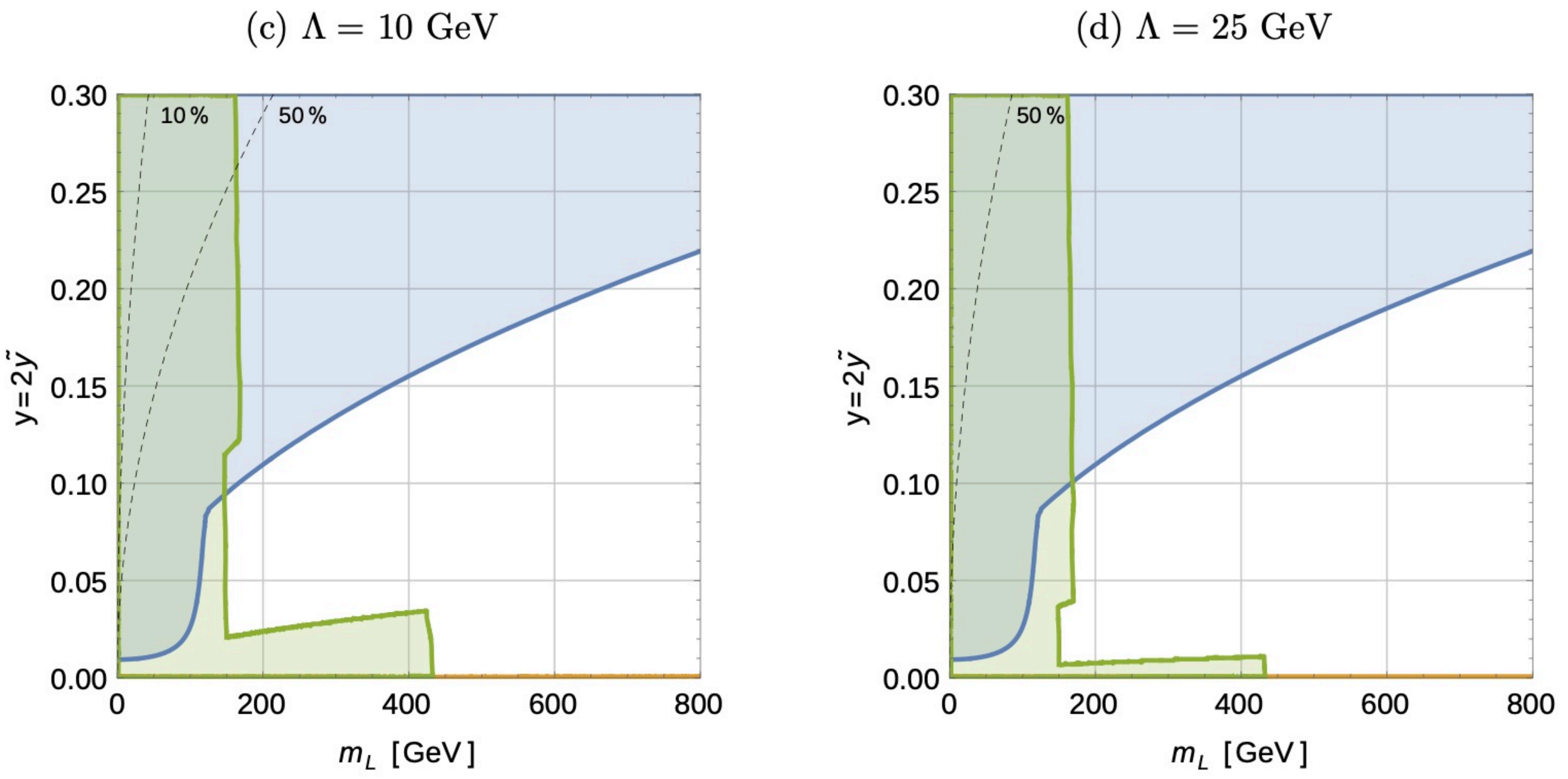


$$V_{\rm b} = \epsilon\mu\phi^3 + {\rm h.c.}$$



[Beauchesne, Bertuzzo, Grilli di Cortona '17]

See also [Banta, Cohen, Craig, Lu, Sutherland '21]

AN AXION THAT IS NOT AN AXION

$$\mathcal{L} \supset V(\phi) - y\phi\bar{Q}\gamma^5 Q$$

$$\mathcal{L} \supset V(\phi) - \frac{\partial_\mu \phi}{f}\bar{Q}\gamma^\mu\gamma^5 Q$$

$$\longrightarrow \quad \mathcal{L} \supset V(\phi) - \frac{\phi}{f'}G\widetilde{G}$$

Integrate out Q

AN AXION THAT IS NOT AN AXION

The gauge symmetry

$$\phi \to \phi + 2\pi n F$$

Can be non-linearly realized

(for instance axion monodromy)

AN AXION THAT IS NOT AN AXION

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$$F_4 = dA_3$$

[Dvali 0507215]

AN AXION THAT IS NOT AN AXION

$$\mathcal{L} = -\frac{1}{48} F_{\mu\nu\rho\sigma} F^{\mu\nu\rho\sigma} + \frac{(\partial_\mu \phi)^2}{2} - \frac{m_\phi}{24\sqrt{2}} \phi \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu\rho\sigma}$$

Total derivative (respects the full shift-symmetry)

AN AXION THAT IS NOT AN AXION

$$\mathcal{L} = -\frac{1}{48} F_{\mu\nu\rho\sigma} F^{\mu\nu\rho\sigma} + \frac{(\partial_\mu \phi)^2}{2} - \frac{m_\phi}{24\sqrt{2}} \phi \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu\rho\sigma}$$

New gauge group

$$A_\mu = A_\mu^a T^a$$

$$A_{\mu\nu\rho} = \frac{g^2}{8\pi^2} \mathrm{Tr}\left(A_{[\mu} A_\nu A_{\rho]} - \frac{3}{2} A_{[\mu} \partial_\nu A_{\rho]} \right)$$

$$\phi \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu\rho\sigma} = \frac{g^2 \phi}{32\pi^2} \mathrm{Tr}\left(F_{\mu\nu} \widetilde{F}^{\mu\nu} \right)$$

AN AXION THAT IS NOT AN AXION

$$\mathcal{L} = -\frac{1}{48} F_{\mu\nu\rho\sigma} F^{\mu\nu\rho\sigma} + \frac{(\partial_\mu \phi)^2}{2} - \frac{m_\phi}{24\sqrt{2}} \phi \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu\rho\sigma}$$

↓

Integrate out the non-dynamical 3-form

↓

$$\mathcal{L} = \frac{(\partial_\mu \phi)^2}{2} - \frac{m_\phi^2}{2} \phi^2$$

AN AXION THAT IS NOT AN AXION

$$\mathcal{L} = -\frac{1}{48} F_{\mu\nu\rho\sigma} F^{\mu\nu\rho\sigma} + \frac{(\partial_\mu \phi)^2}{2} - \frac{m_\phi}{24\sqrt{2}} \phi \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu\rho\sigma}$$

$$-\Lambda^4 K \left(\frac{\epsilon^{\mu\nu\rho\sigma} F_{\mu\nu\rho\sigma}}{\Lambda^2} \right)$$

Integrate out the non-dynamical 3-form

↓

Get arbitrary potential for the axion (the fundamental scale need not be tied to its decay constant)

AN AXION THAT IS NOT AN AXION

$$S_{IIB} \supset \frac{1}{\alpha'^4} \int |F_1 \wedge B \wedge B|^2 \qquad b^{(i)} \equiv \frac{1}{\alpha'} \int_{T^2_{(i)}} B$$

$$ds^2 = G_{mn} dy^m dy^n = \sum_{i=1}^{3} L_1^2 (dy_1^{(i)})^2 + L_2^2 (dy_2^{(i)})^2$$

$$F_1 = \frac{Q_1}{\sqrt{\alpha'}} \sum_{i=1}^{3} dy_1^{(i)} \qquad B = \sum_{i=1}^{3} b^{(i)} dy_1^{(i)} \wedge dy_2^{(i)} + \dots$$

$$\mathcal{L} = \frac{a(t)^3}{\alpha'} \left\{ \frac{L^6}{g_s^2} \left(\frac{\dot{u}}{u}\right)^2 + \frac{L^6}{g_s^2} \left(\frac{\dot{L}}{L}\right)^2 + \boxed{\frac{L^6}{g_s^2} \frac{\dot{b}^2}{L^4} - \frac{L^6}{\alpha'} \frac{Q_1^2}{L_1^2} \left[\frac{b^4}{L^8} + \frac{b^2}{L^4} + 1\right]} - \frac{L^6}{\alpha'} \left(\frac{Q_{31}^2}{L_1^6} + \frac{Q_{32}^2}{L_2^6}\right) \right\}$$

SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

Classically scale invariant
(or supersymmetric)

$$V_{\phi_\pm} = \lambda'_\pm S_\pm^2 \phi_\pm^2 + \lambda_\pm \phi_\pm^4$$

$F_\pm$

Break scale invariance
but not shift symmetry

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

$M_\pm$

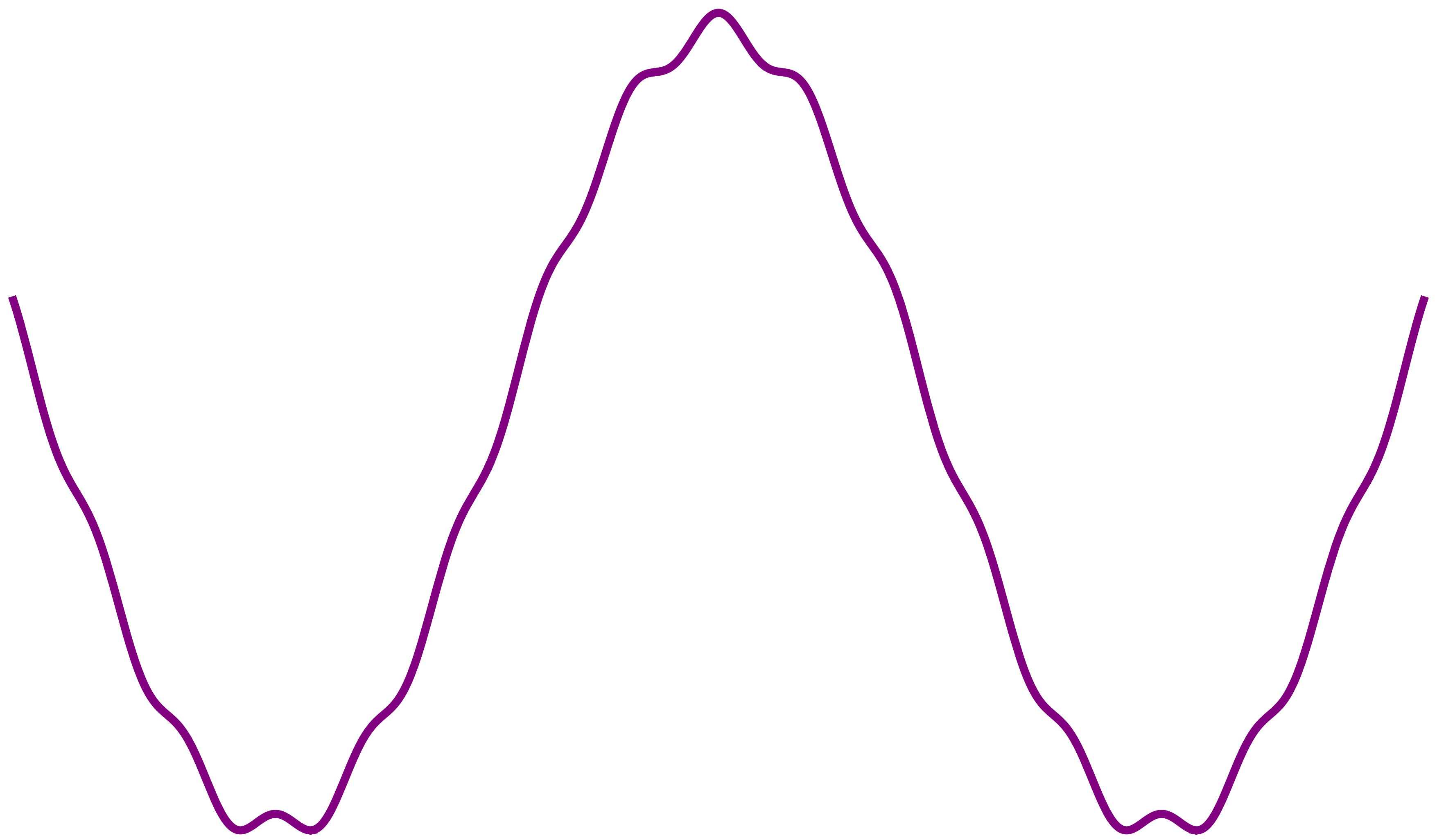
Breaks scale invariance
and shift symmetry

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

AN AXION THAT IS AN AXION

$$V_\phi = \Lambda_1^4 \cos\left(\frac{\phi}{f_1}\right) + \Lambda_2^4 \cos\left(\frac{\phi}{f_2} + \theta_2\right)$$

$$\Lambda_1 \gg \Lambda_2 \qquad\qquad f_1 \gg f_2$$



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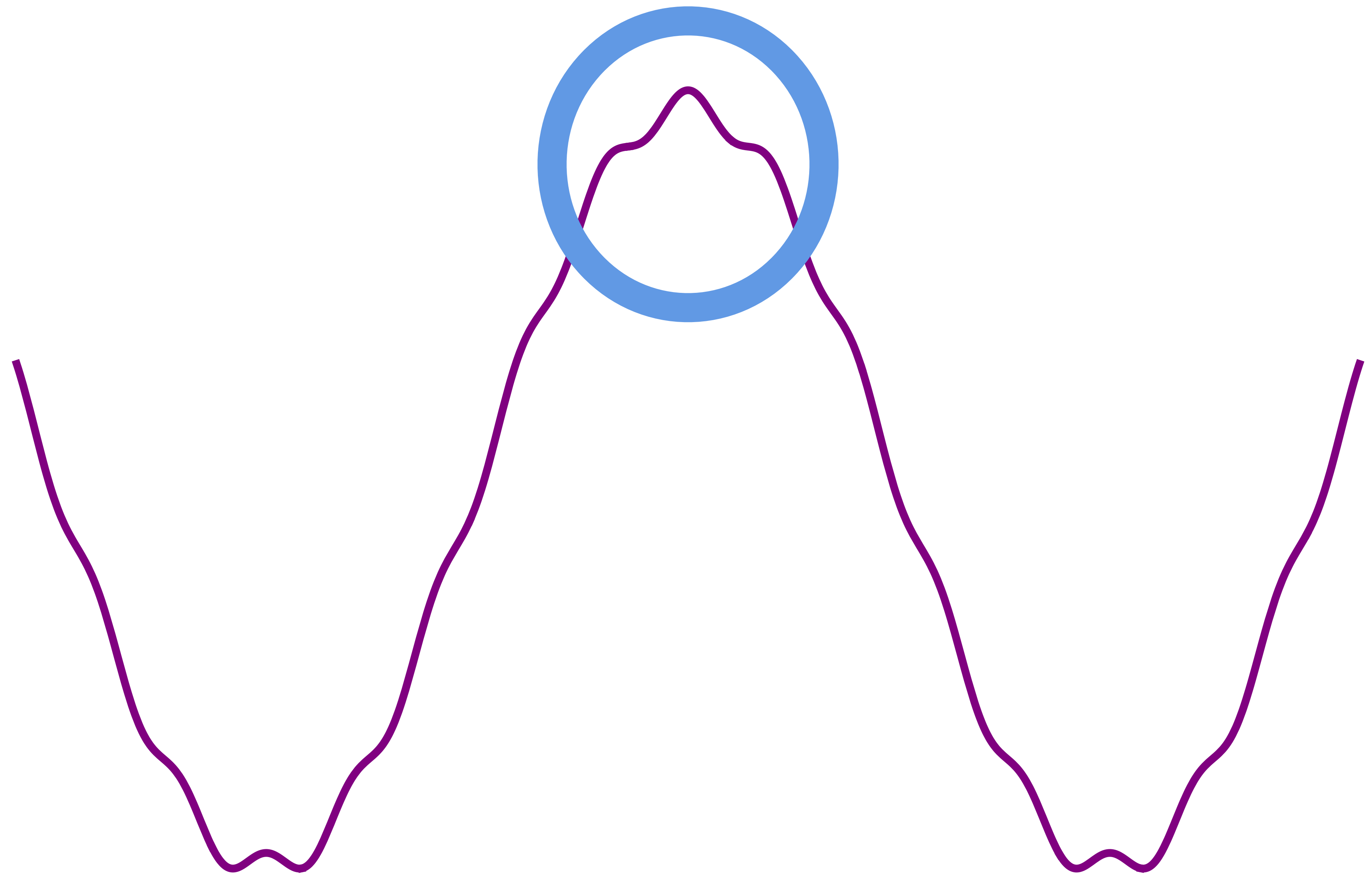

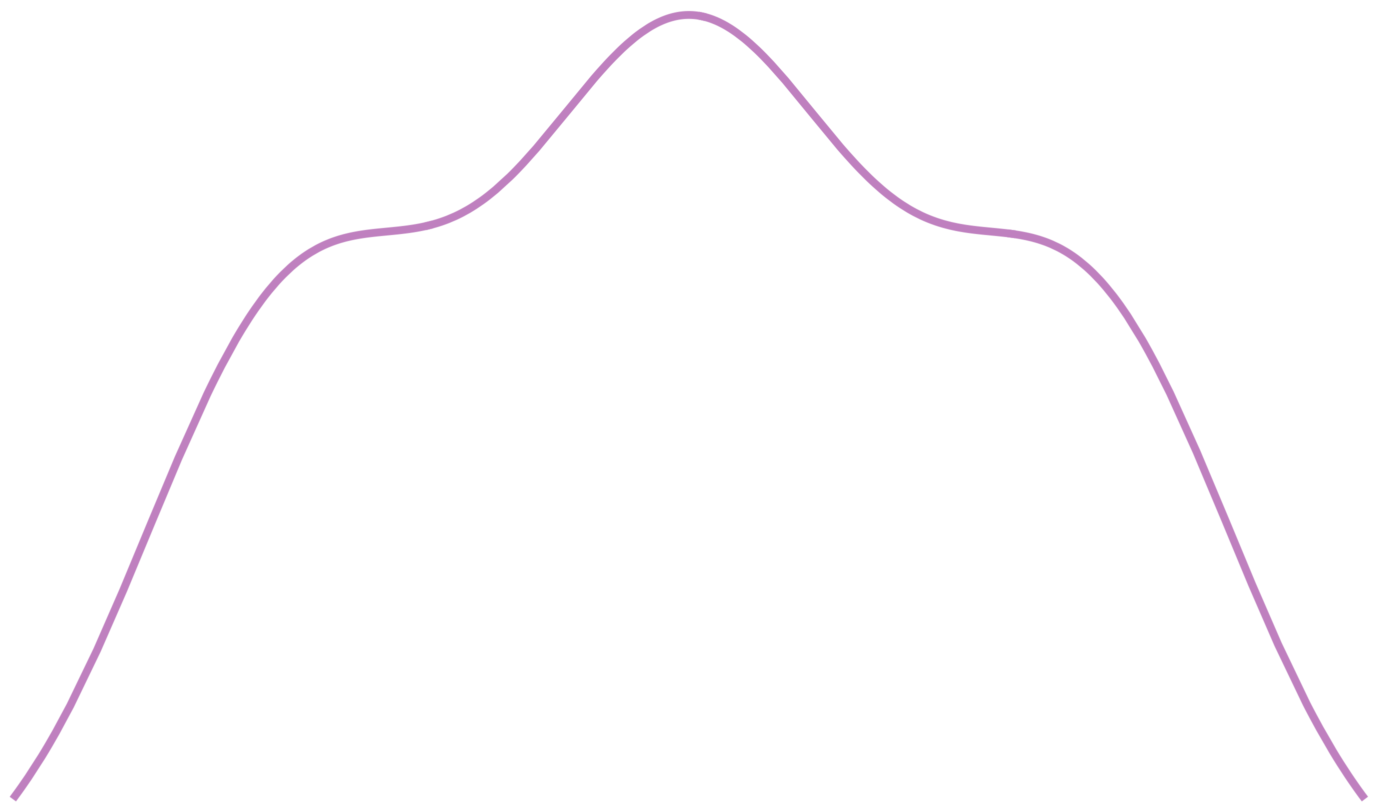

CONCLUSION

1. Strong assumption on the landscape

2. UV completion [work in progress]

Caveats on eternal inflation, dS and AdS vacua:

[Dvali ’21],[Dvali, Gomez ’13-’14],
[Dvali, Gomez, Zell ’17], [Dvali ‘20]

[Ooguri, Vafa ’06], [Garg, Krishnan ’18],
[Obied, Ooguri, Spodyneiko, Vafa ’18],
[Ooguri, Palti, Shiu, Vafa ’18], …

Is there a landscape?

1. Not that many e-folds needed to populate a landscape
2. Multi-field inflation [1905.07495], [1906.05772]
3. Not every landscape is a multiverse