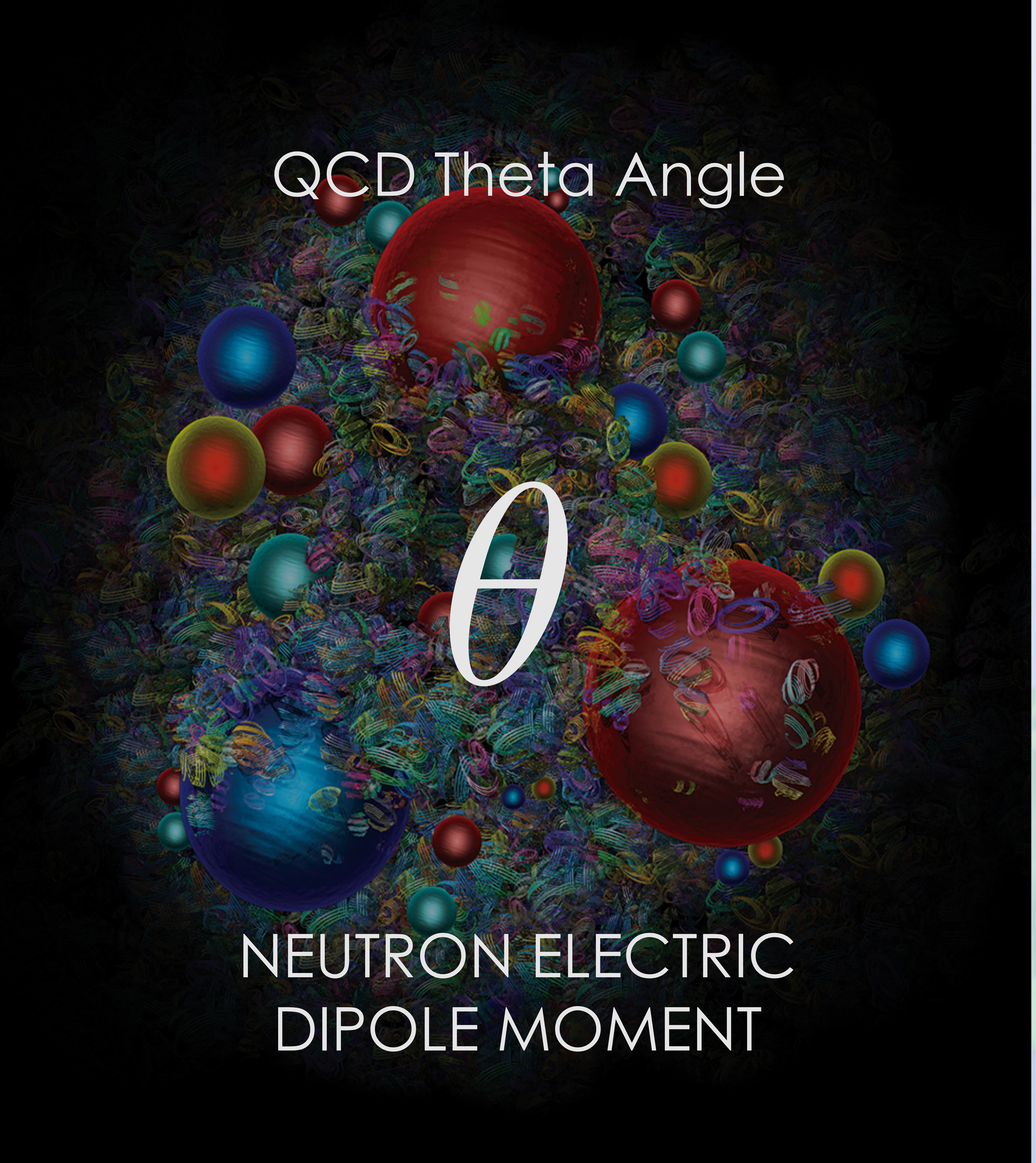
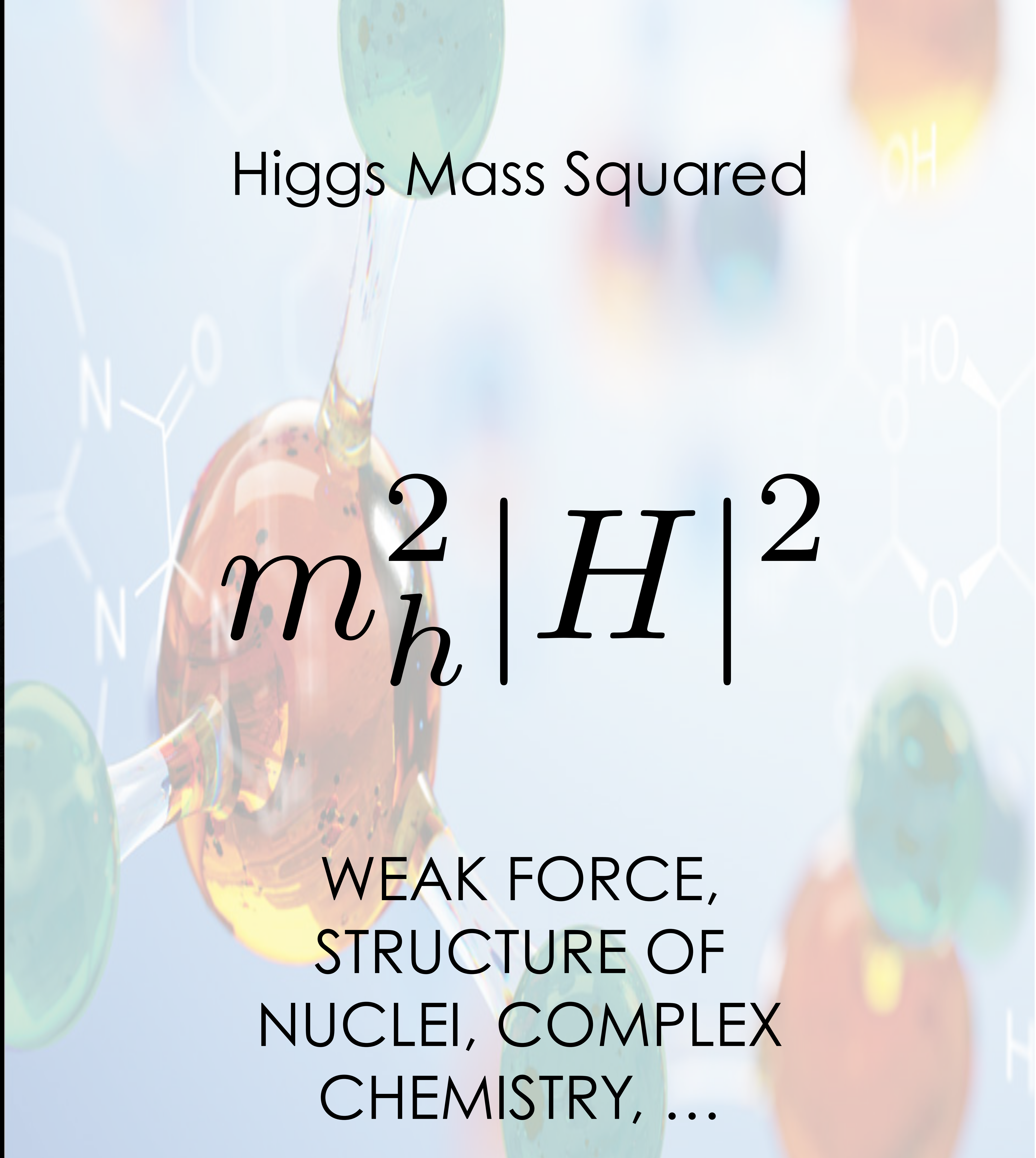
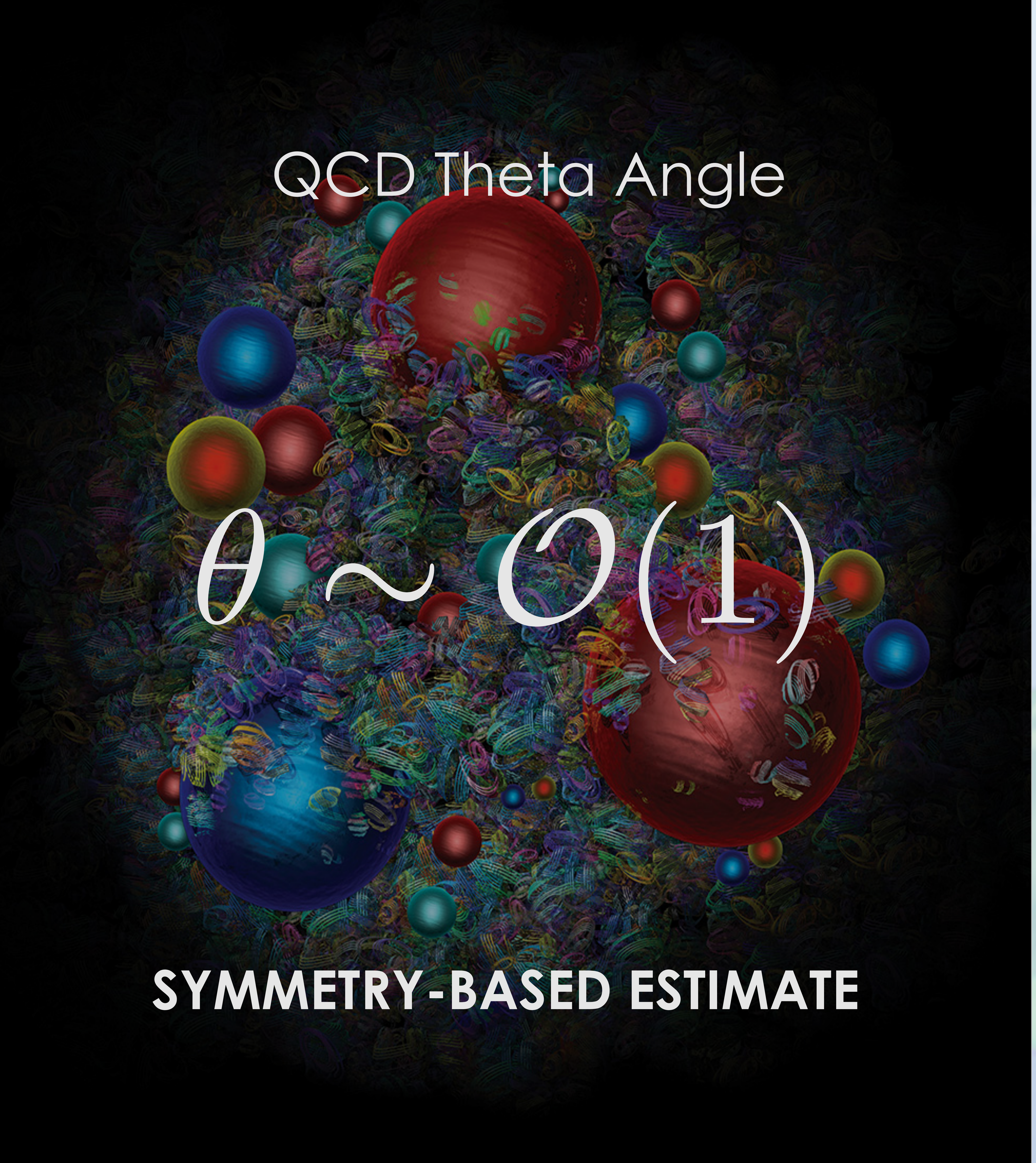
# COSMOLOGICAL SELECTION OF THE WEAK SCALE AND THE QCD THETA ANGLE

**Raffaele Tito D'Agnolo - IPhT Saclay**


QCD Theta Angle
$\theta$
NEUTRON ELECTRIC
DIPOLE MOMENT

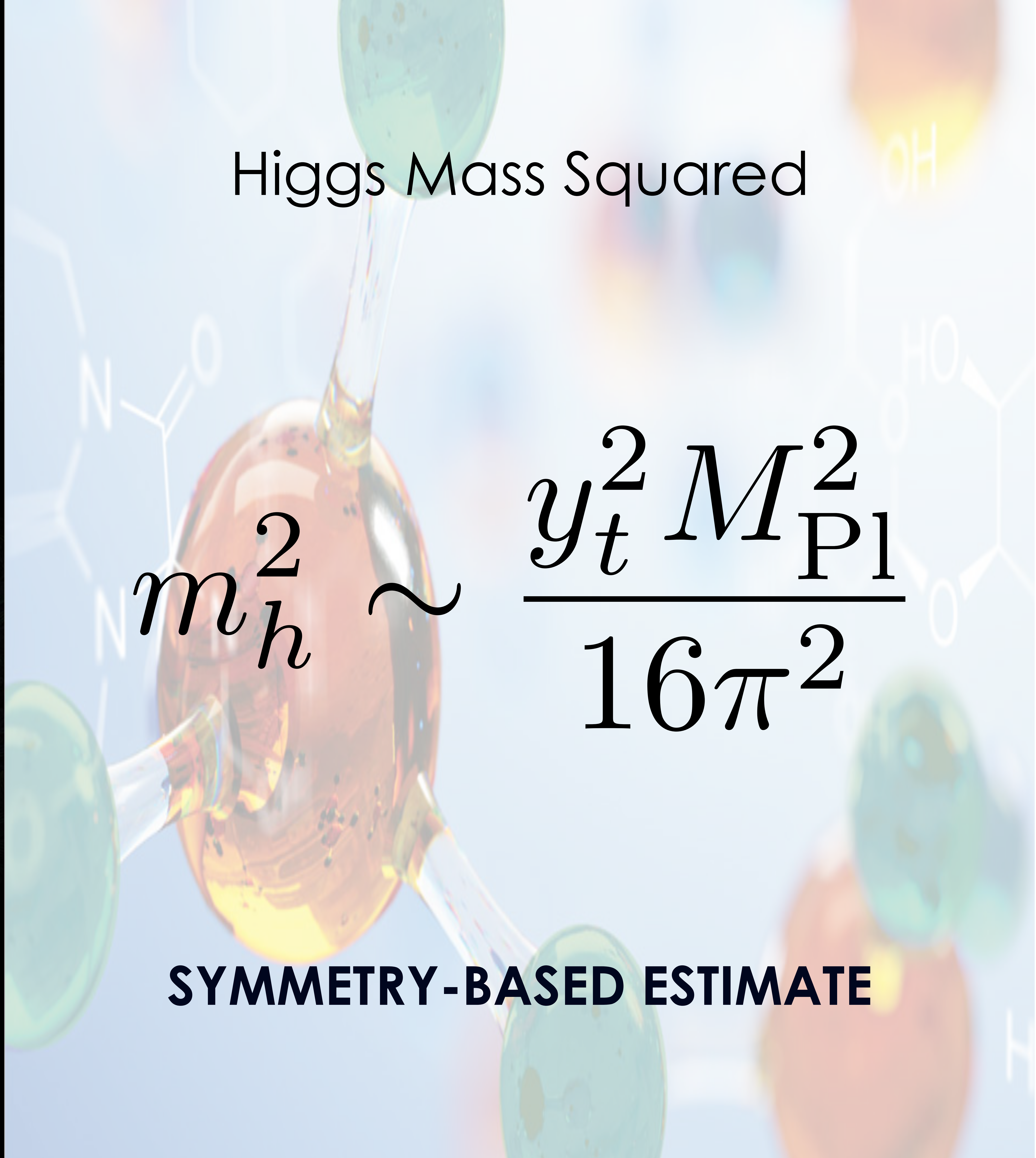

Higgs Mass Squared
$m_h^2|H|^2$
WEAK FORCE,
STRUCTURE OF
NUCLEI, COMPLEX
CHEMISTRY, ...



## 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**]

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

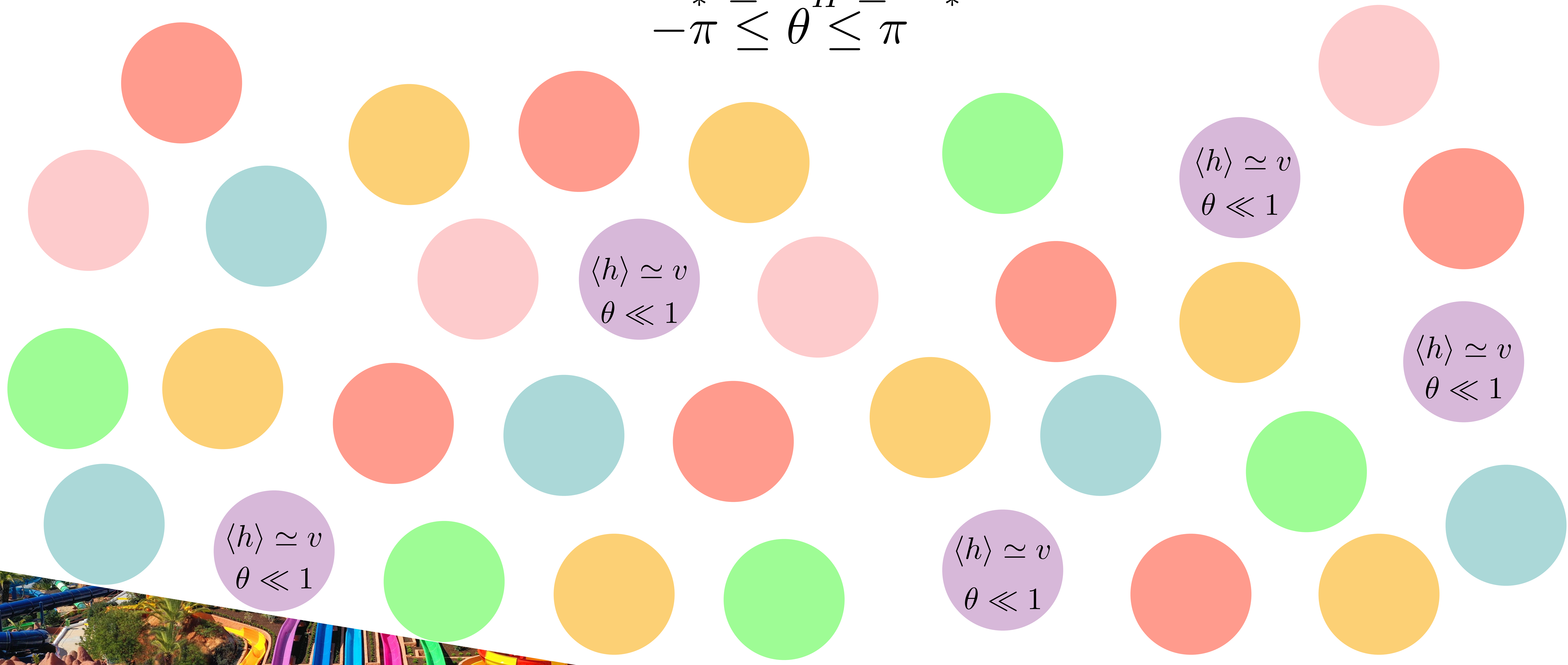
# SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

# SLIDING NATURALNESS

**Landscape** of Higgs Masses and theta-angles populated by inflation

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



# 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

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

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

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**

# 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]

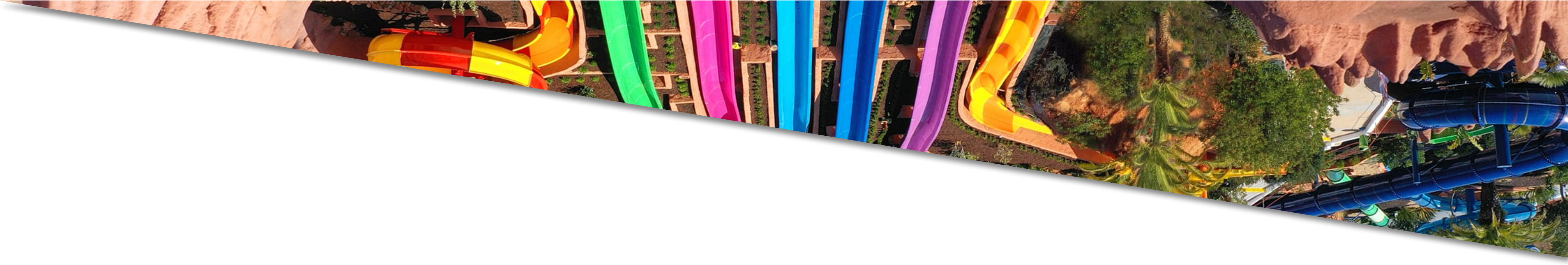
# Caveats on eternal inflation, dS and AdS vacua:

[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



# SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

Addition to the SM: Two very weakly coupled scalars

$$\phi_{\pm}$$

# SLIDING NATURALNESS

[**RTD**, Teresi] '21

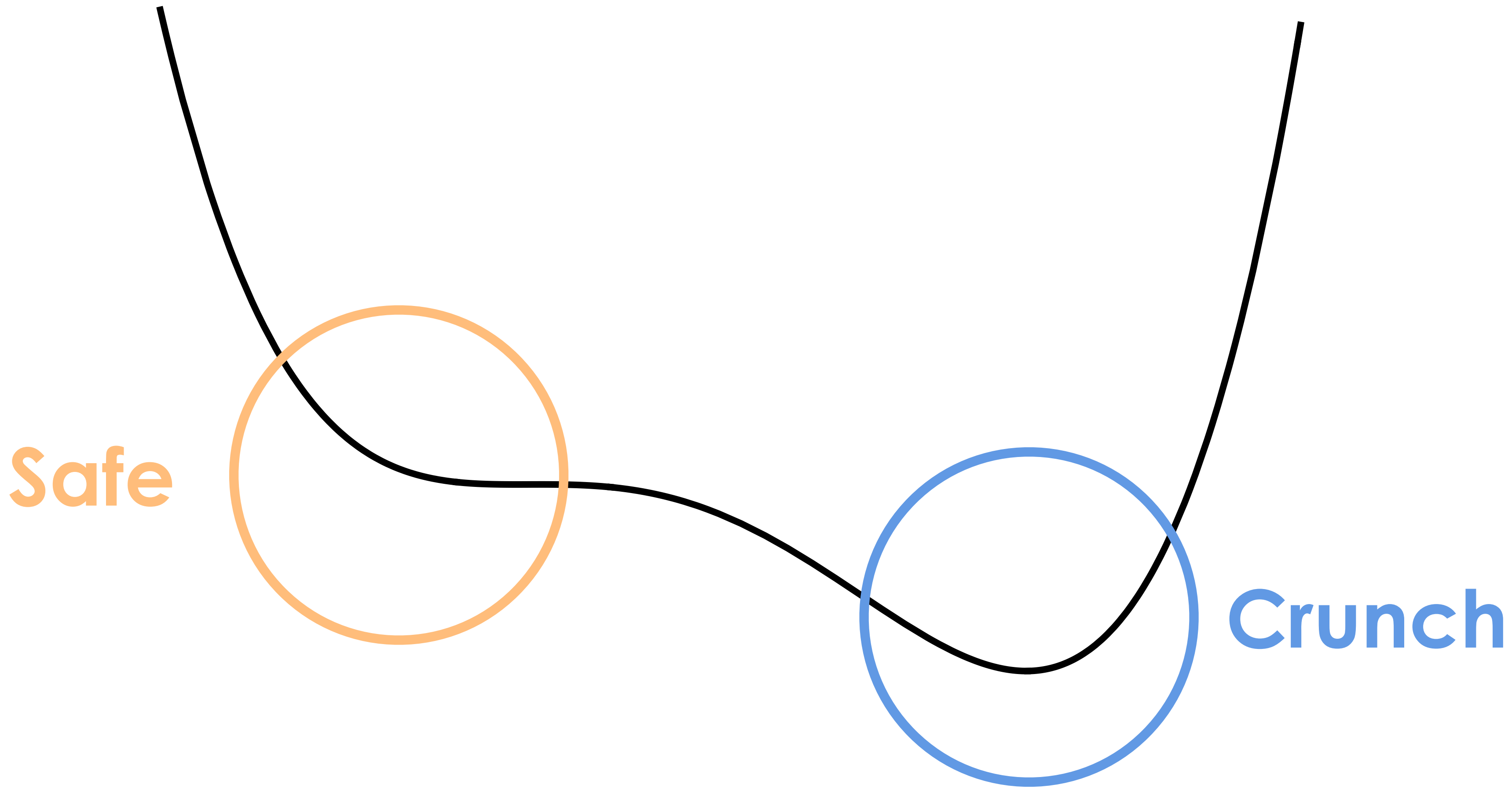
Approximately decoupled from each other

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

# SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

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

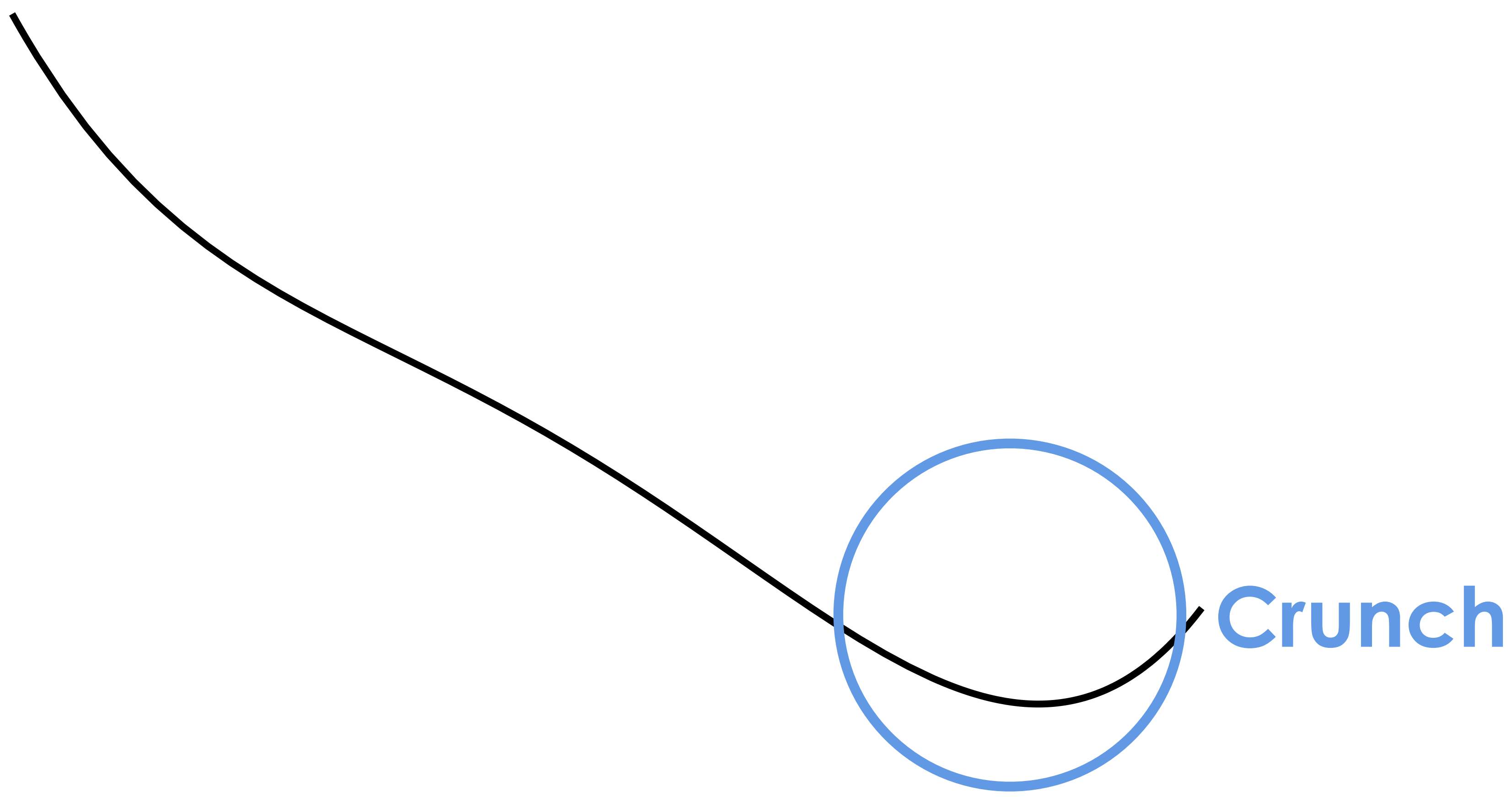


# SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

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

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

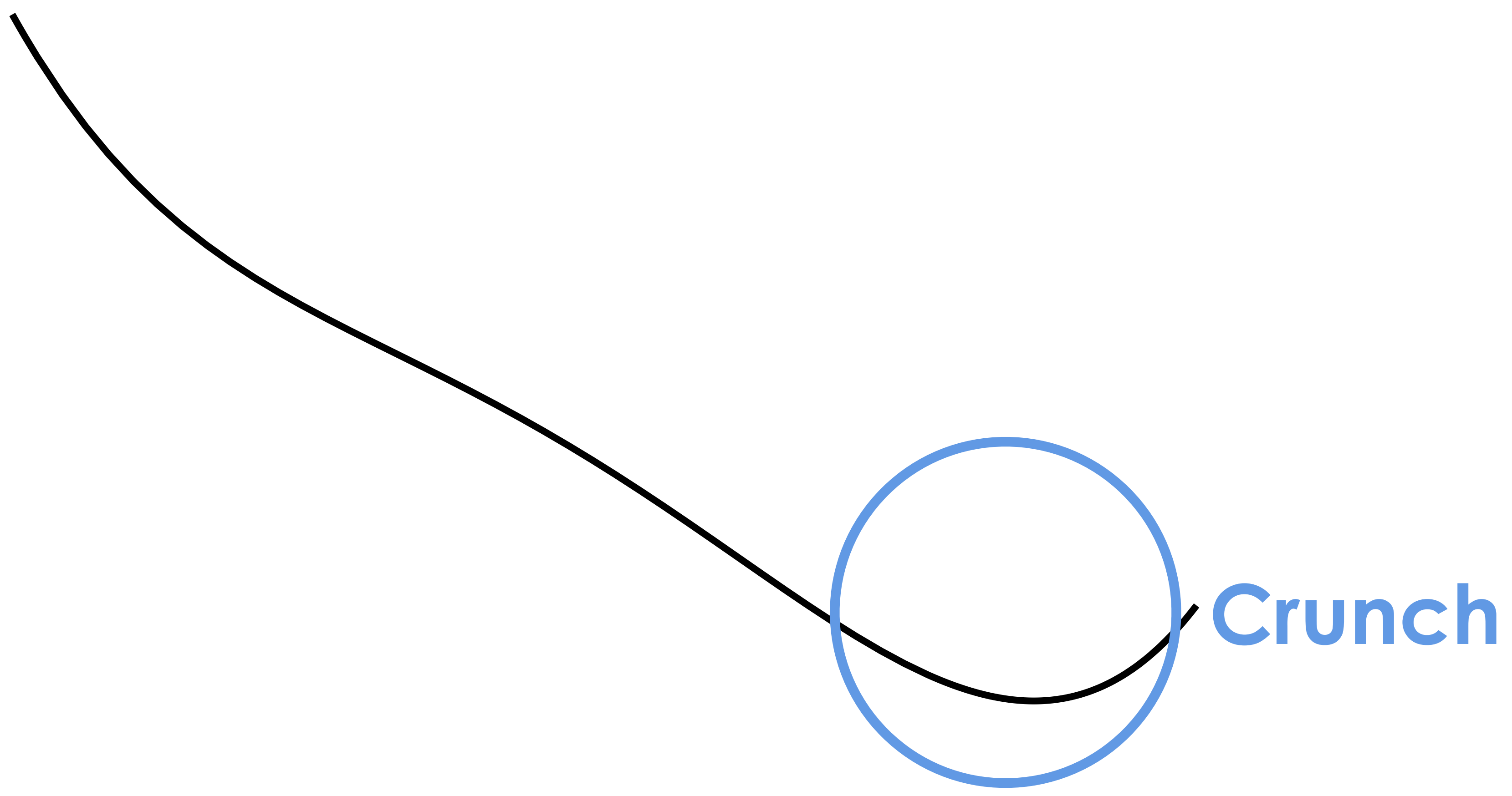


# SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

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

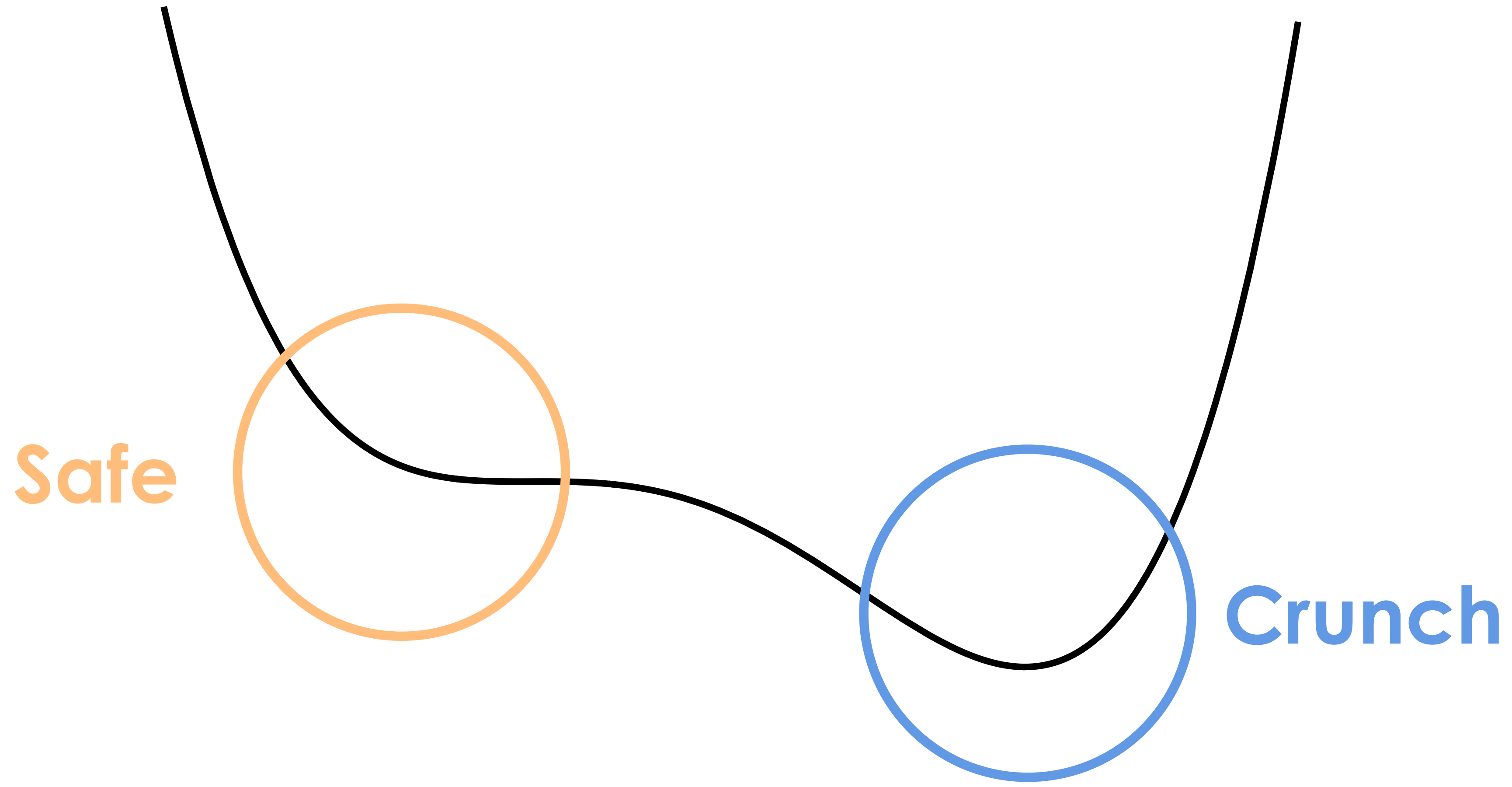


# SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

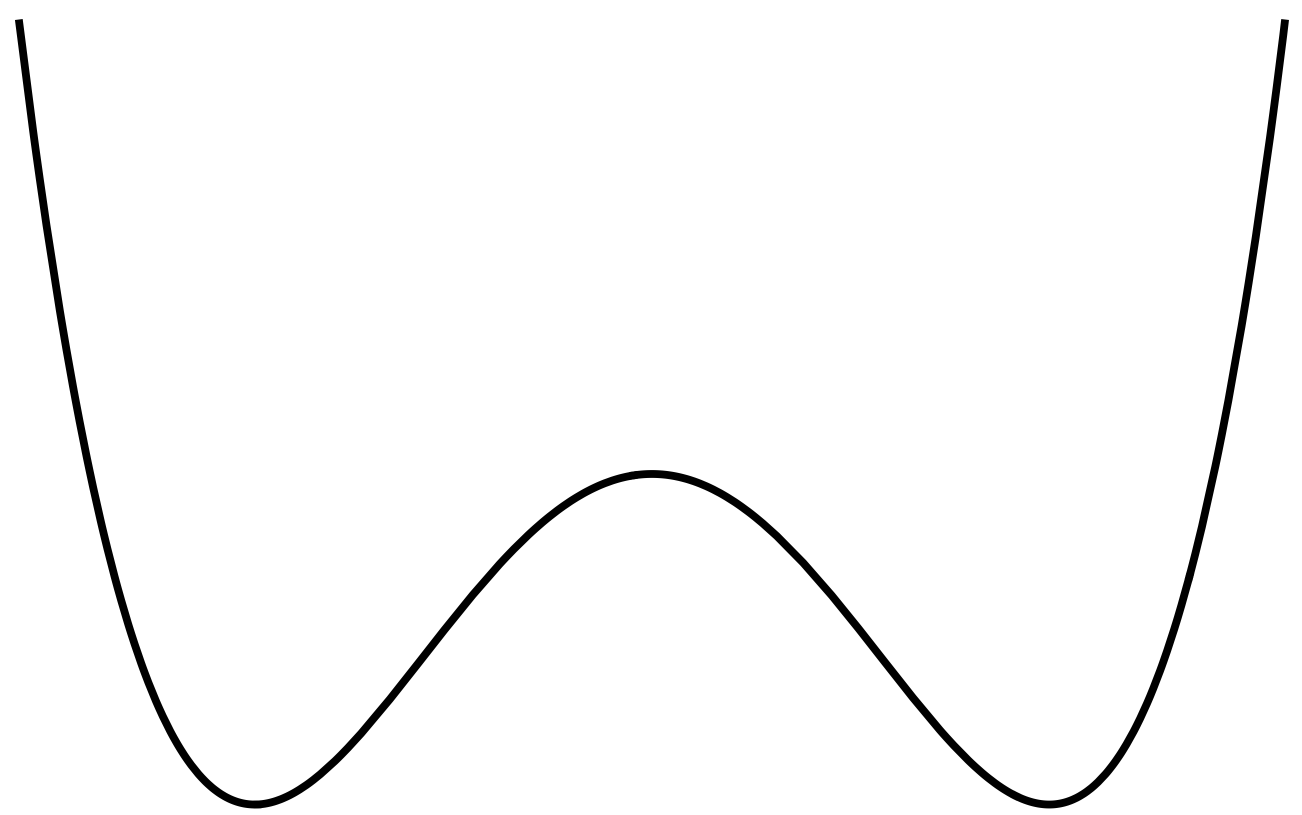
$\langle h \rangle \gtrsim v$ And $\theta \lesssim 10^{-10}$



# SIMPLE UV COMPLETION

[**RTD**, Teresi] '21

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



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

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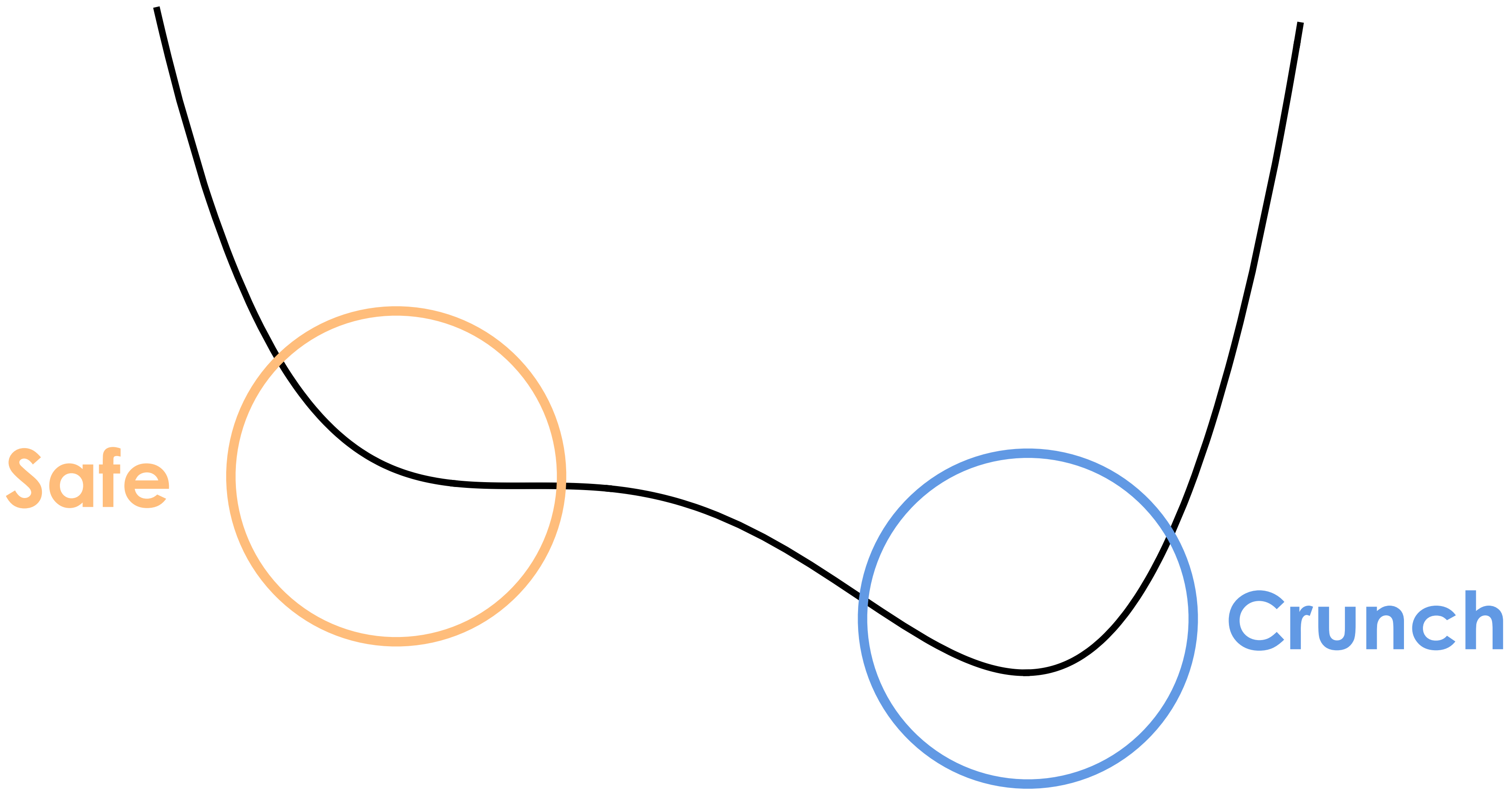


$$V_{\mathrm{b}} = \epsilon\mu\phi^3 + \mathrm{h.c.}$$

# 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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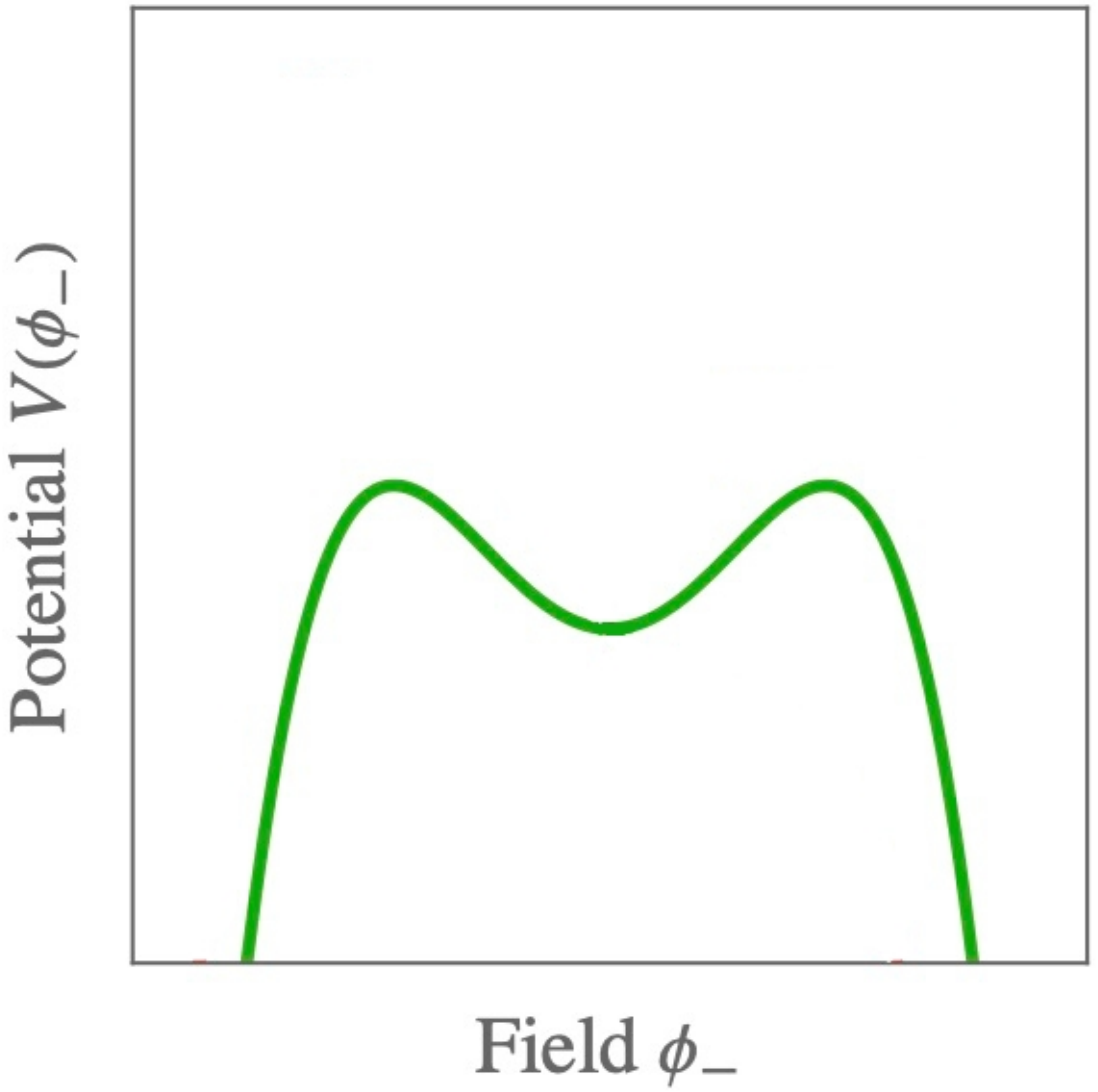


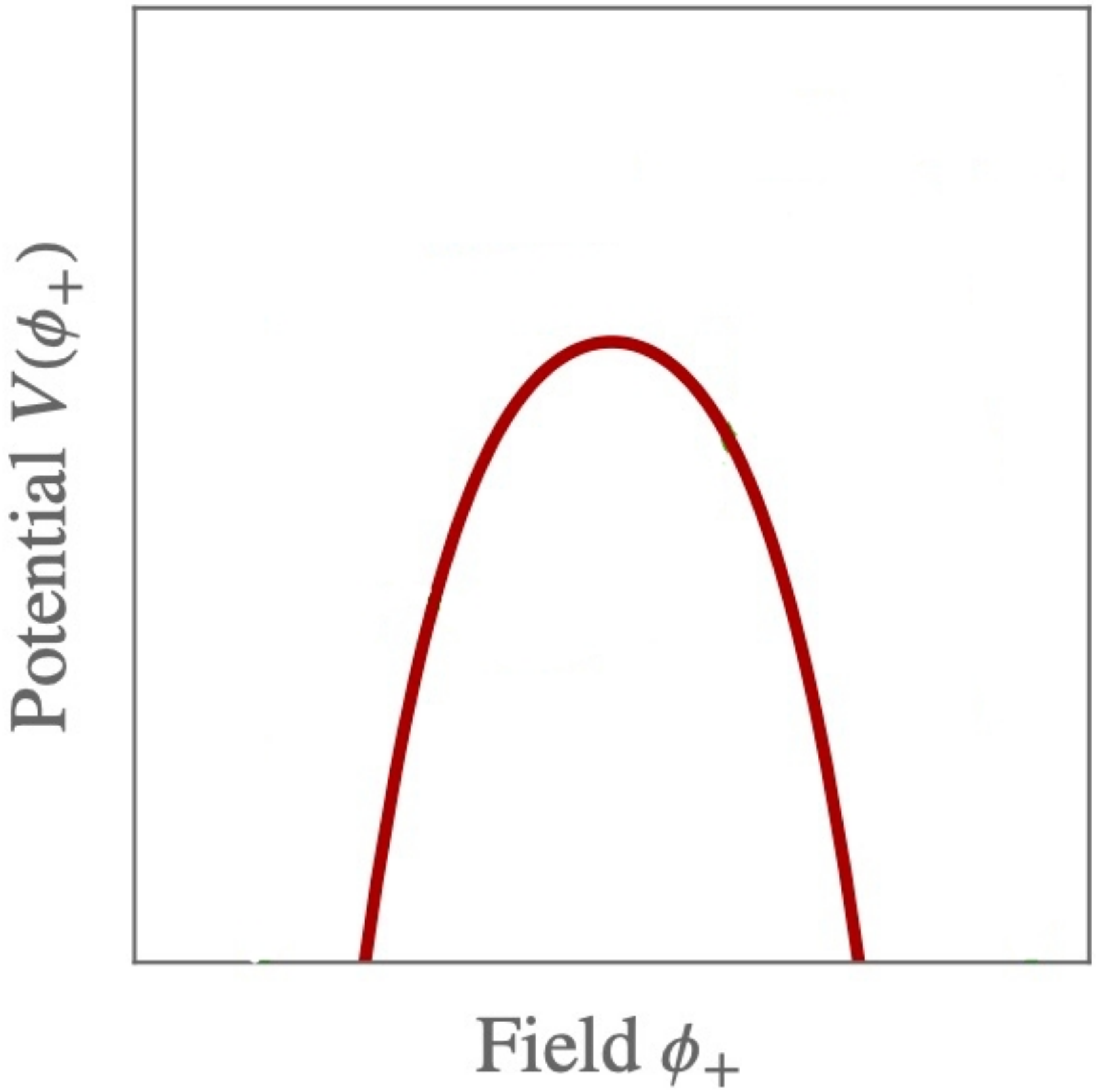

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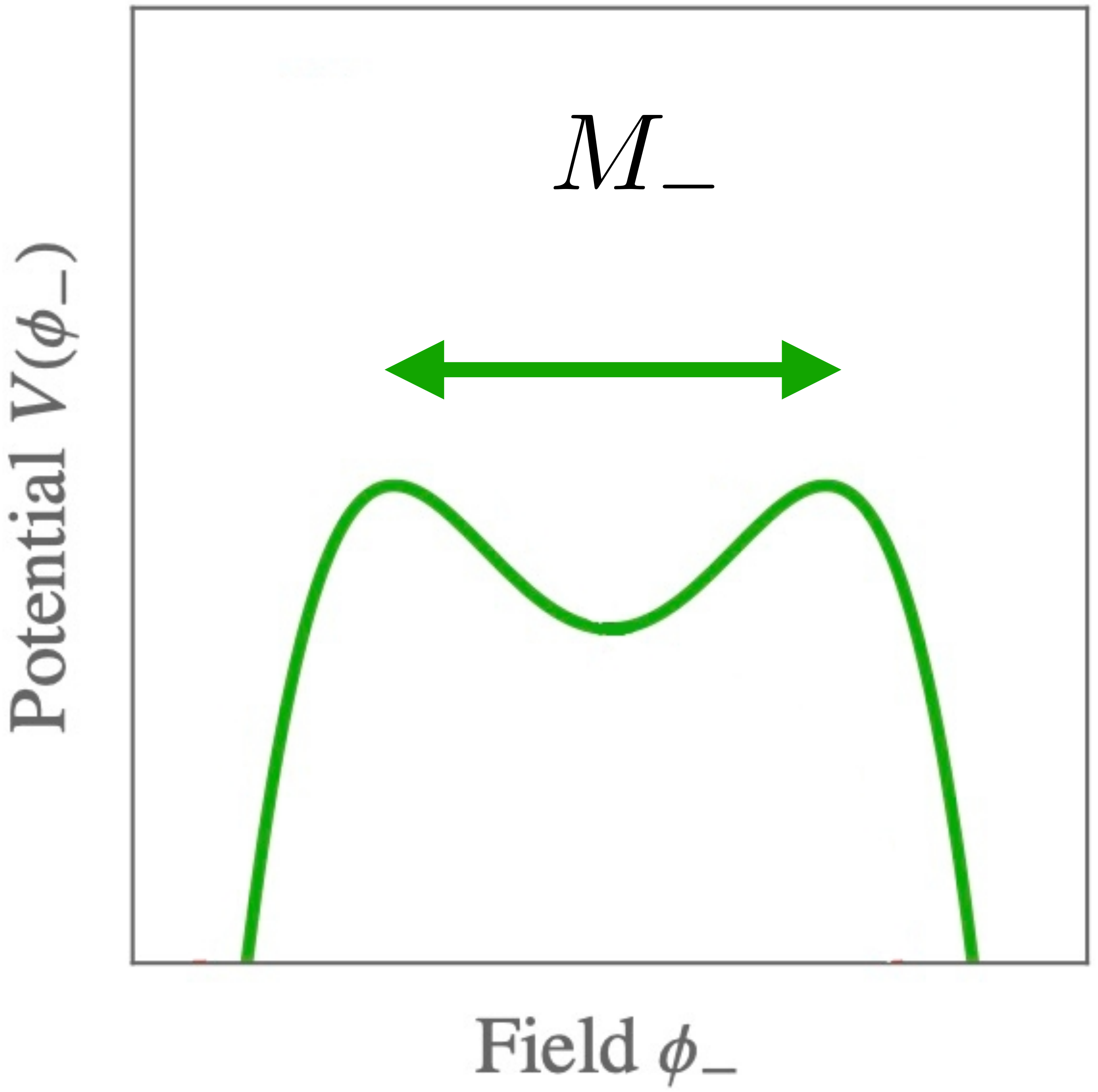
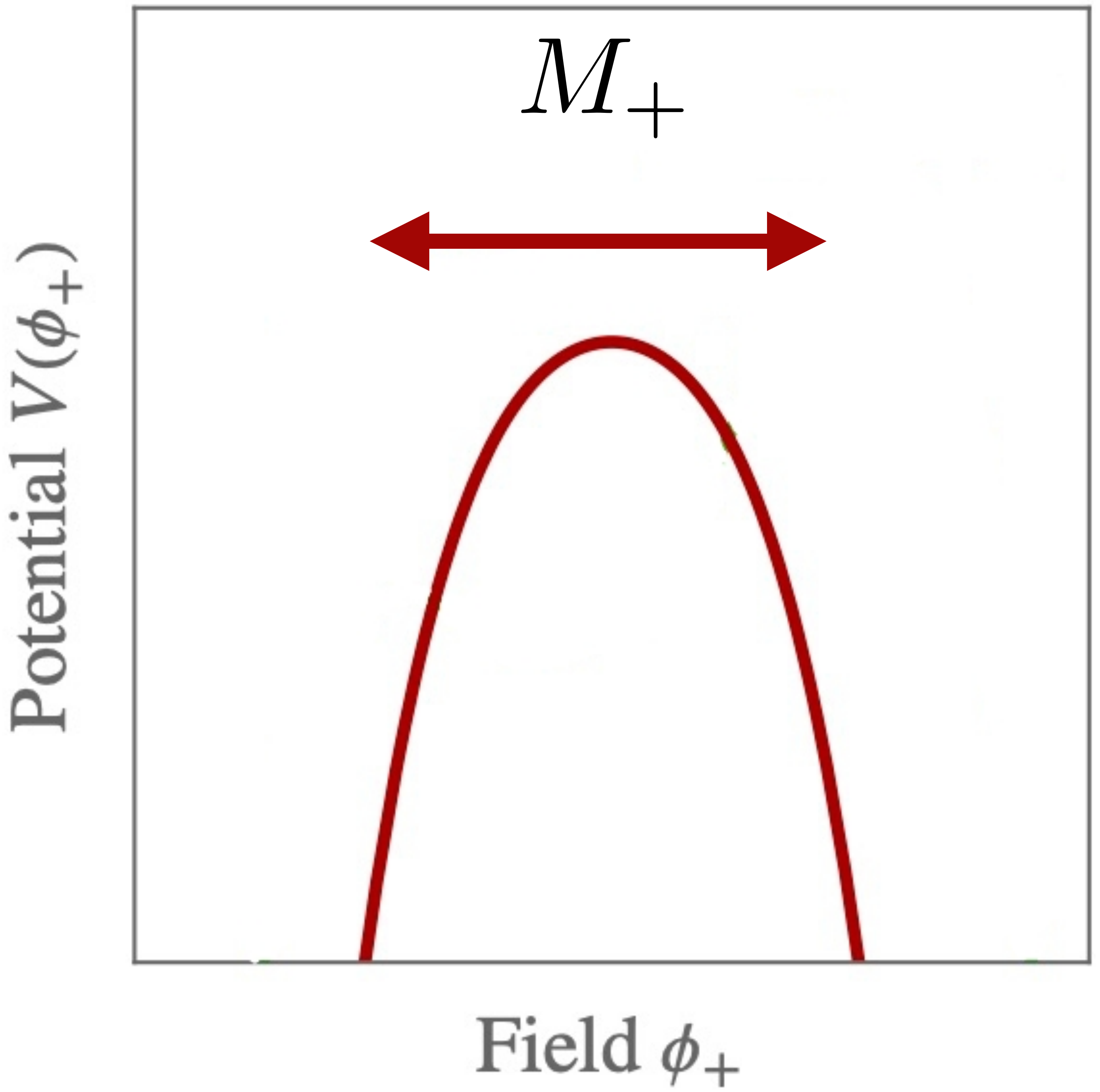
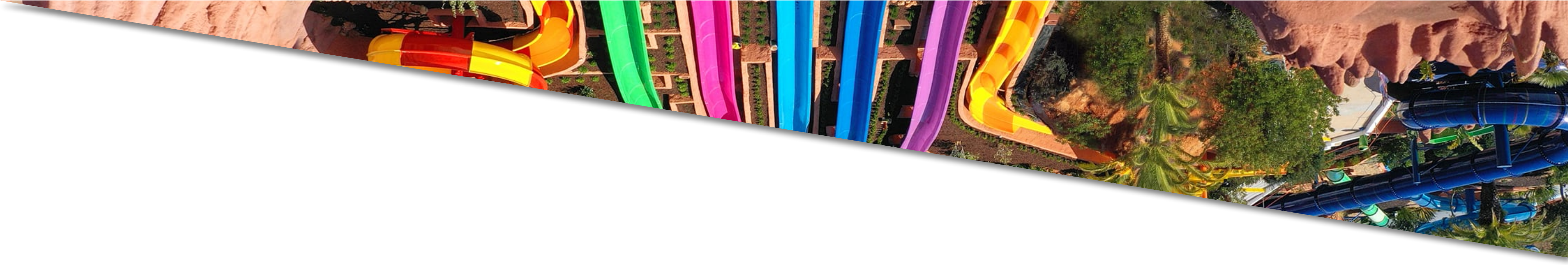


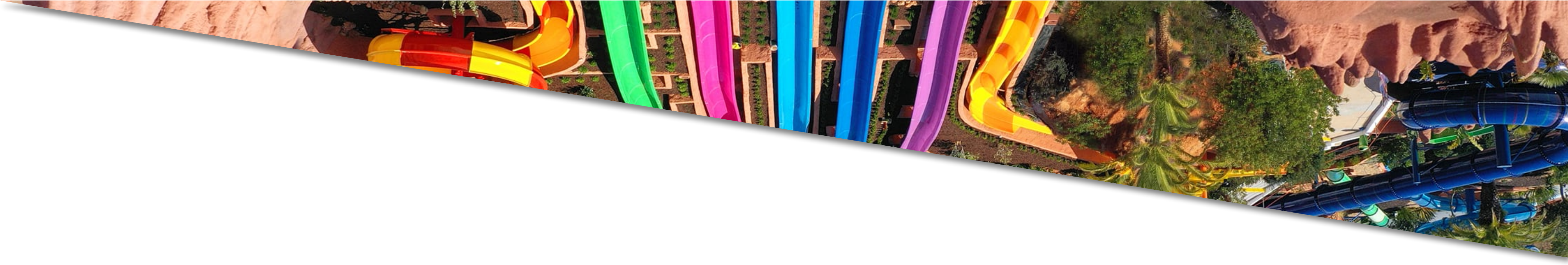
# SLIDING NATURALNESS [**RTD**, Teresi] '21



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

# 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

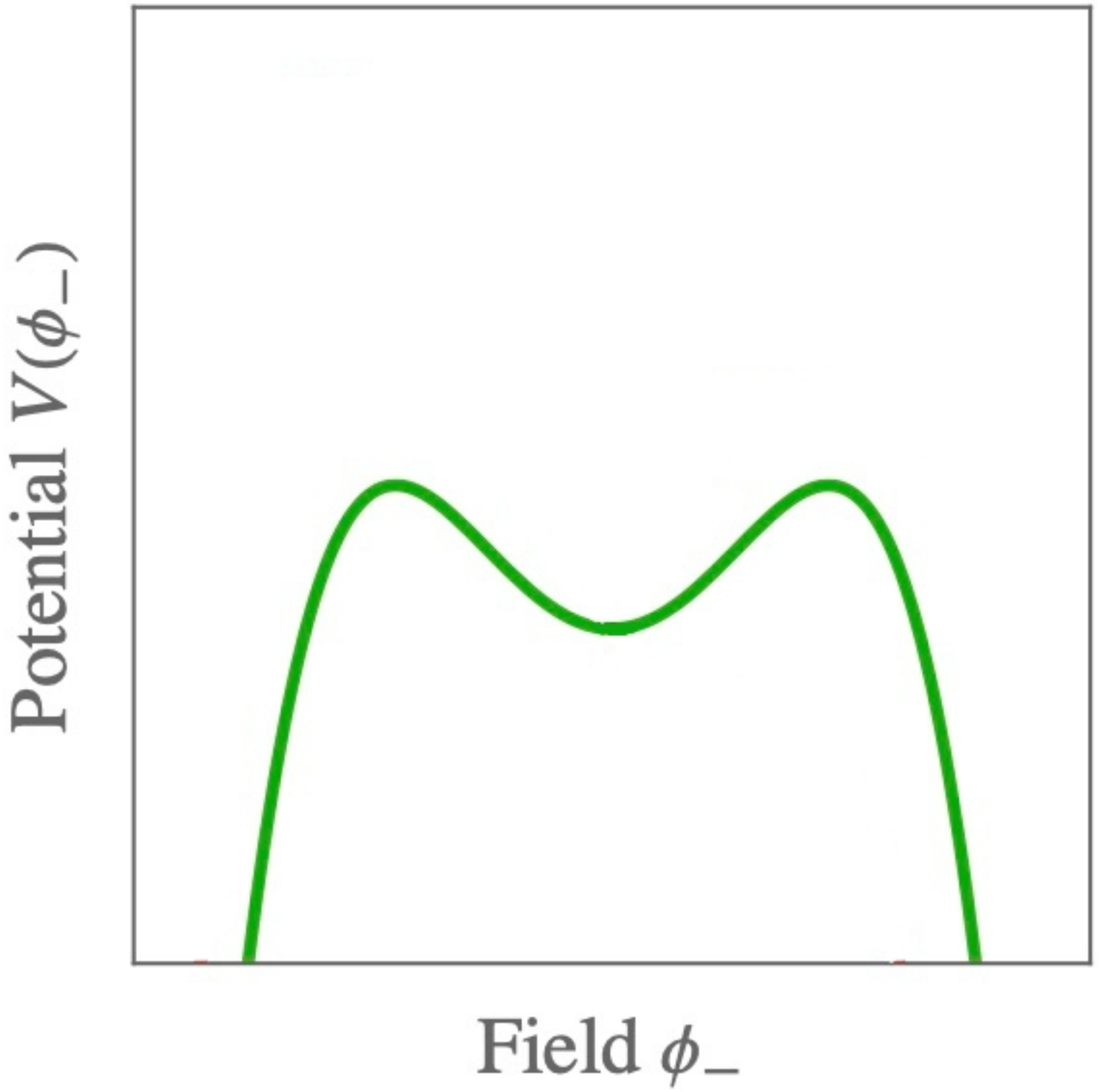
$$V_{H\phi_\pm} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right)\widetilde{G}G$$

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

# SLIDING NATURALNESS

[**RTD**, Teresi] '21

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



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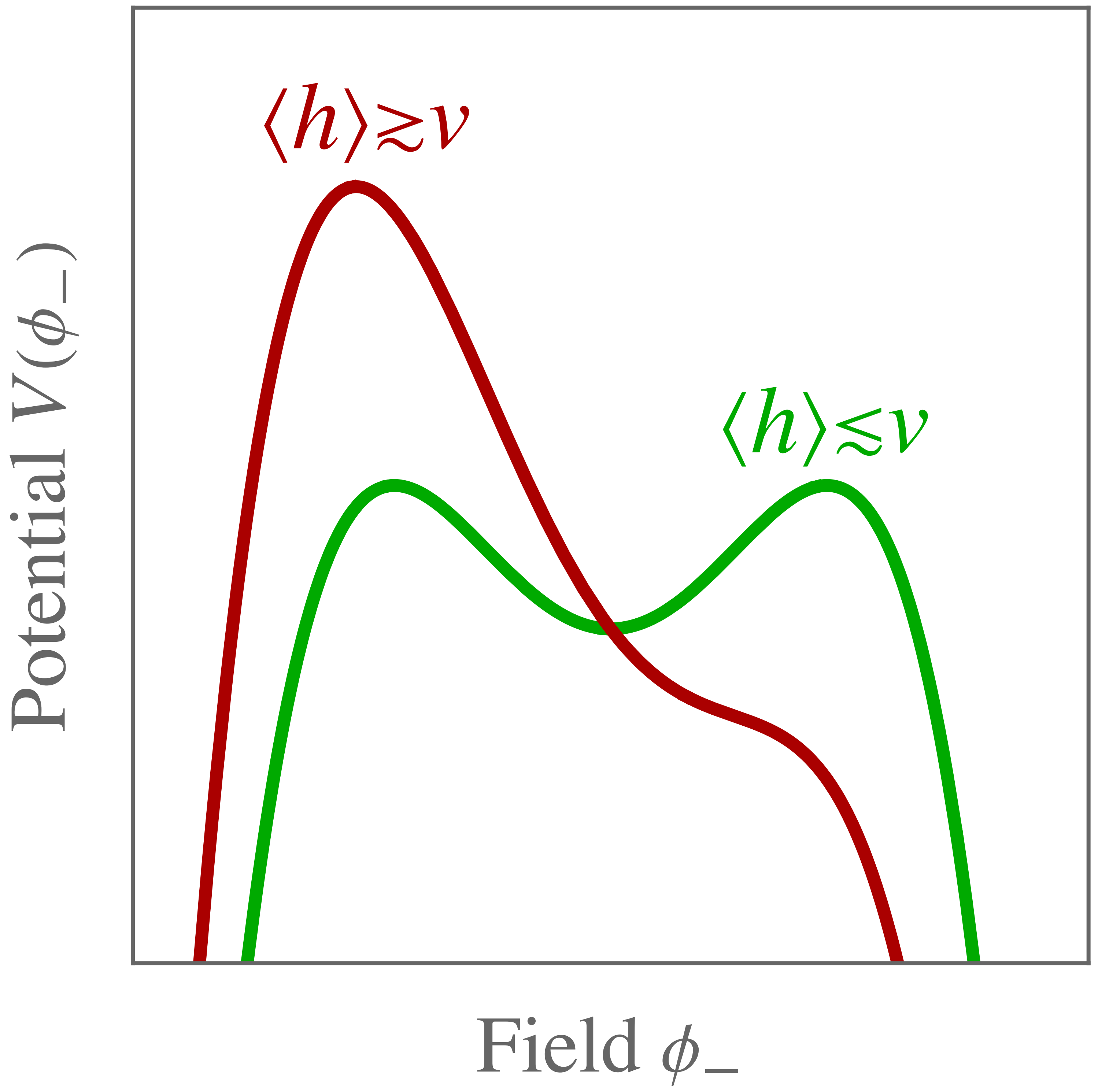
[**RTD**, Teresi] ‘21

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



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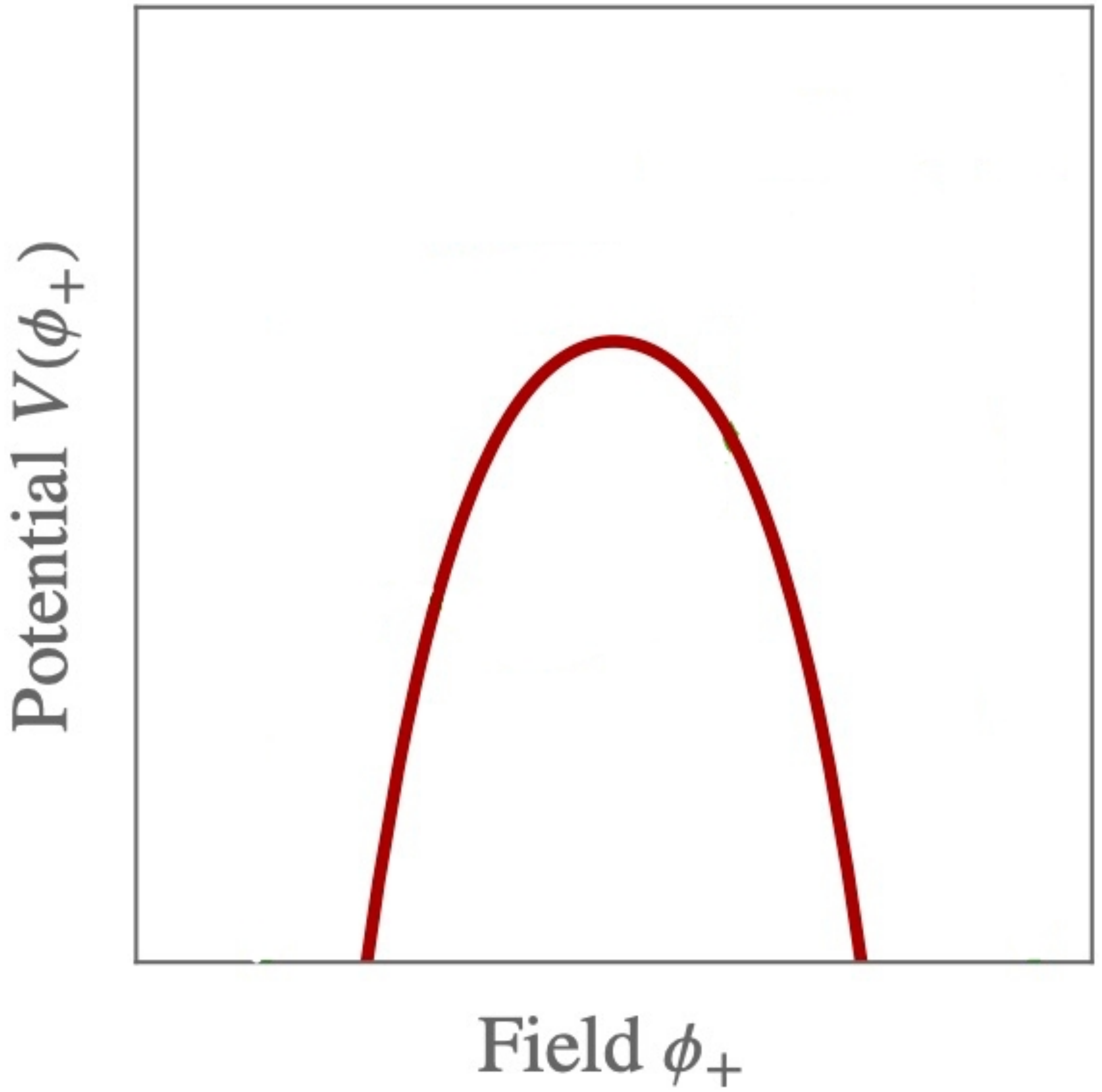

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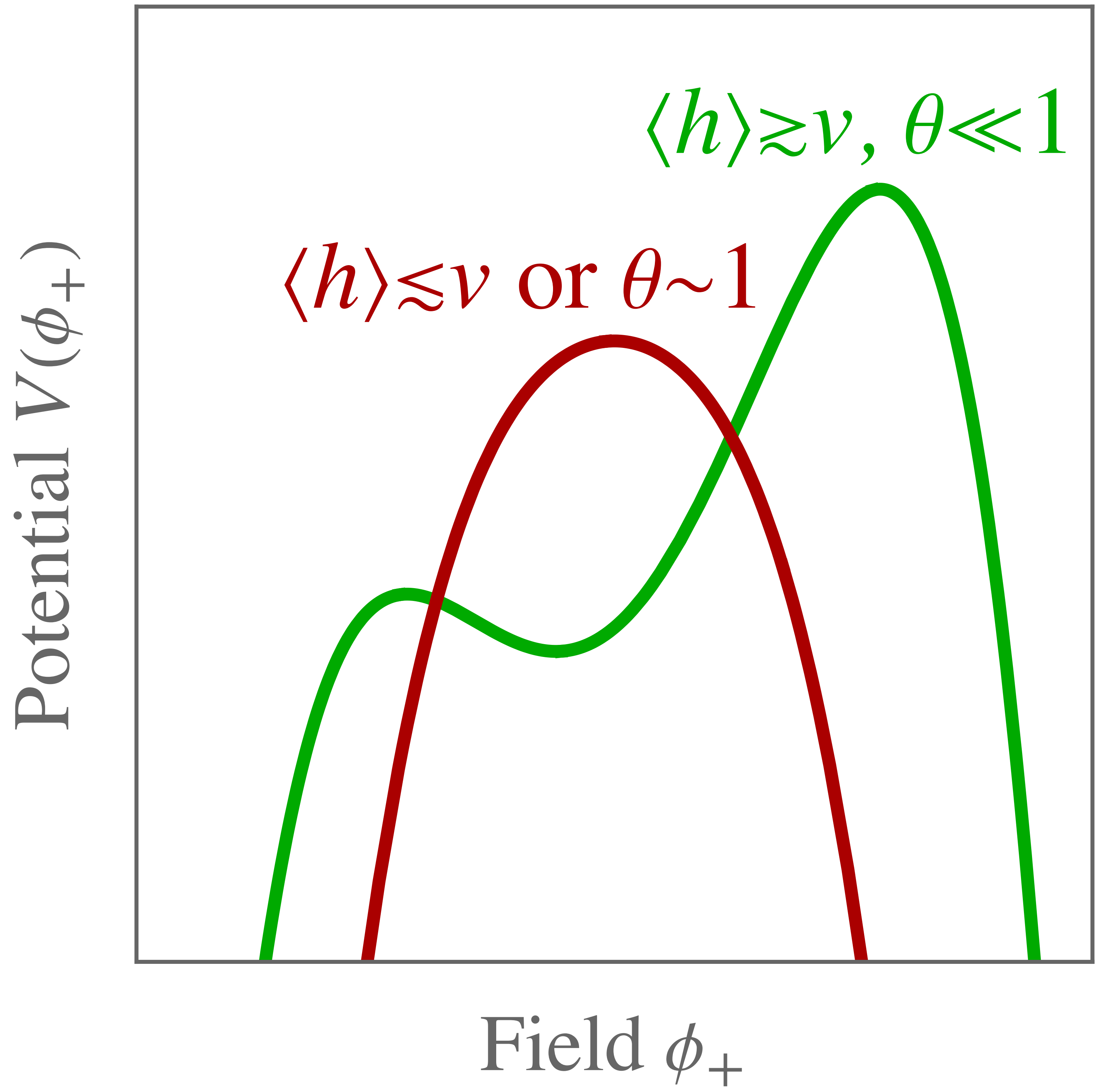
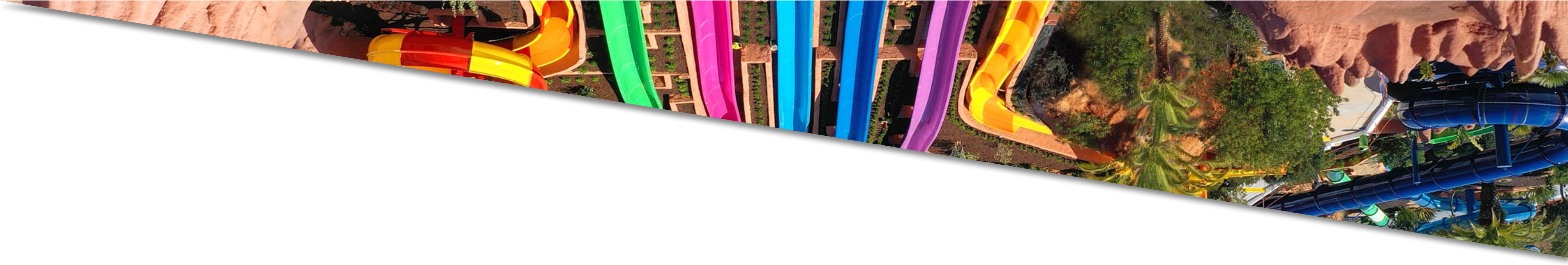




# SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

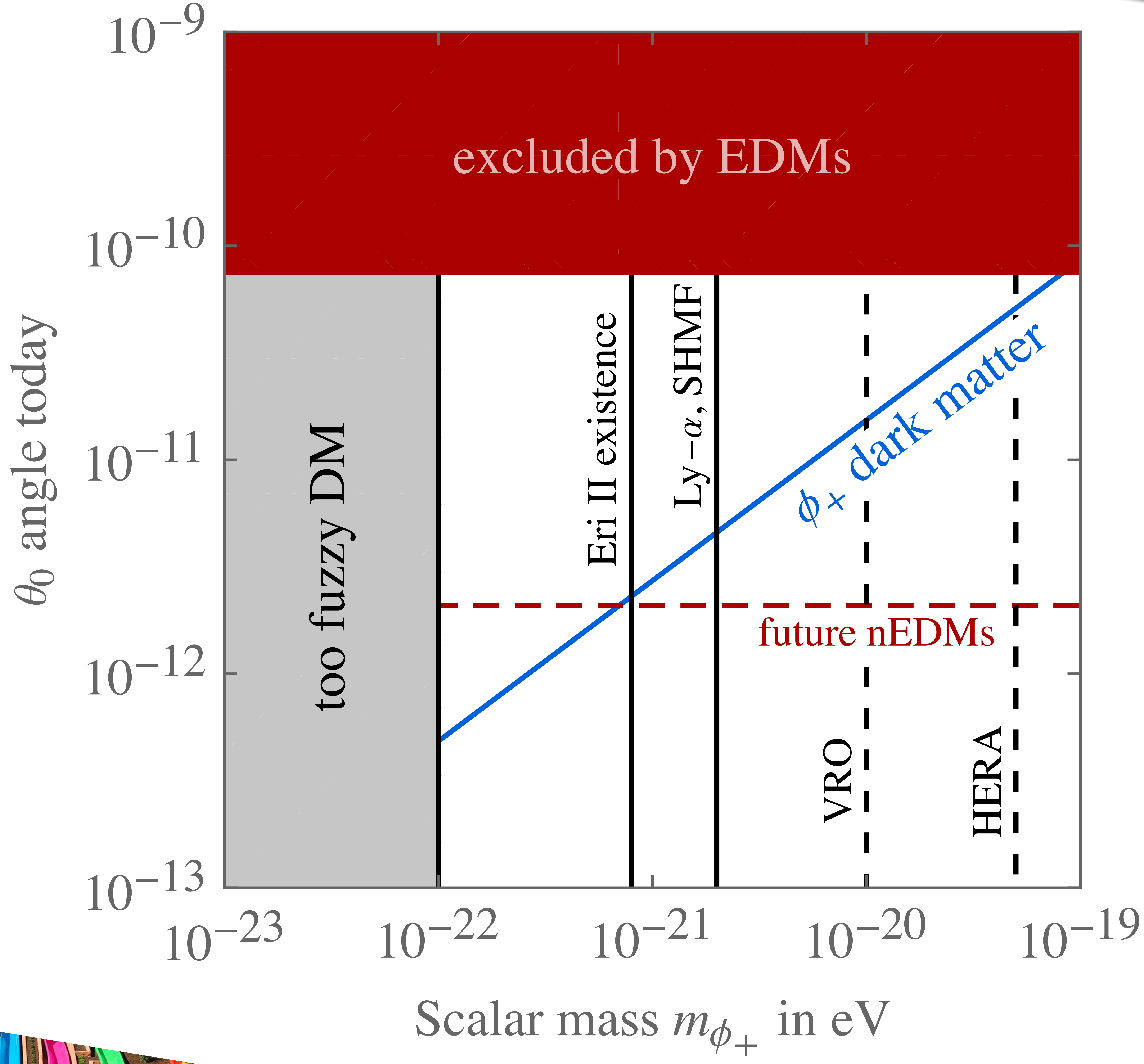
$$V_{\phi_\pm} = \mp \frac{m^2_{\phi_\pm}}{2} \phi^2_\pm - \frac{\lambda}{4} \phi^4_\pm$$

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

Solve Strong-CP and Hierarchy problem!

# SLIDING NATURALNESS

[**RTD**, Teresi] '21



$$\phi_{\pm}$$

**Symmetric Sector**

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

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

**SM Landscape**

$O_1 = -O_2 + \epsilon$

# 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)

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

**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


A BSM TRIGGER

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

$$\boxed{H_1 H_2}$$

Protected by the **Z2 symmetry**

$$\boxed{H_1 H_2 \to -H_1 H_2}$$

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]

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

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

# TYPE-0 2HDM

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

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

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

## TYPE-0 2HDM

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

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

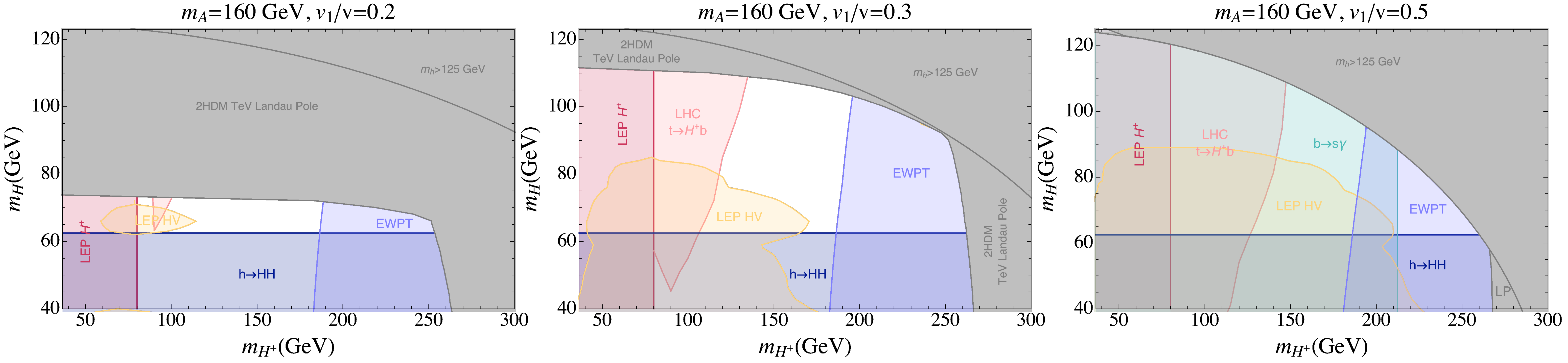
$$H_2 \to -H_2, \quad (qu^c) \to -(qu^c), \quad (qd^c) \to -(qd^c), \quad (le^c) \to -(le^c)$$

This gives

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

# TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, ’20]

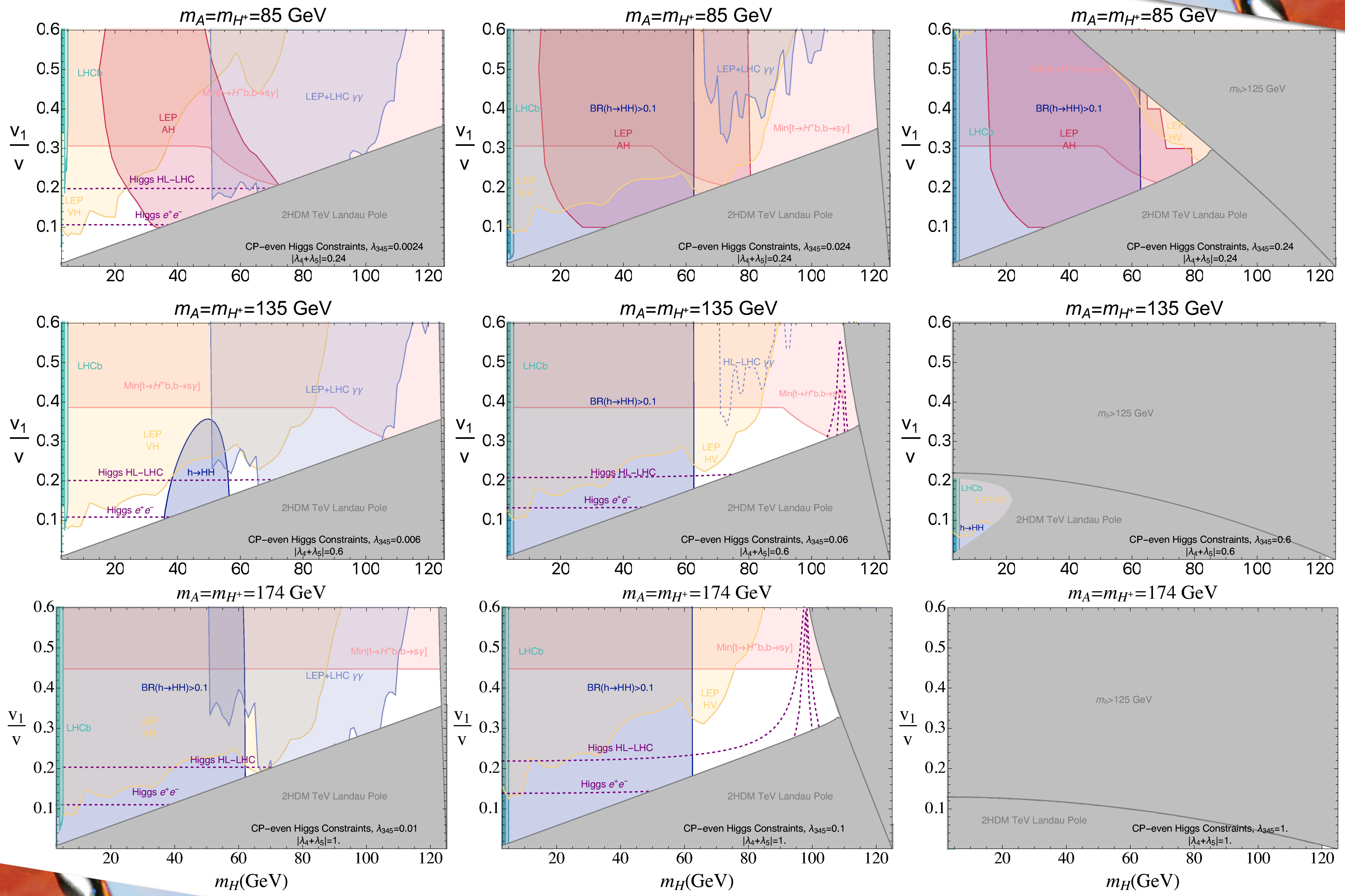



Sharp target for HL-LHC and FCC

which **can’t be decoupled**!

(See also the next slide)

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




New vector-like leptons

+

Dark confining gauge group

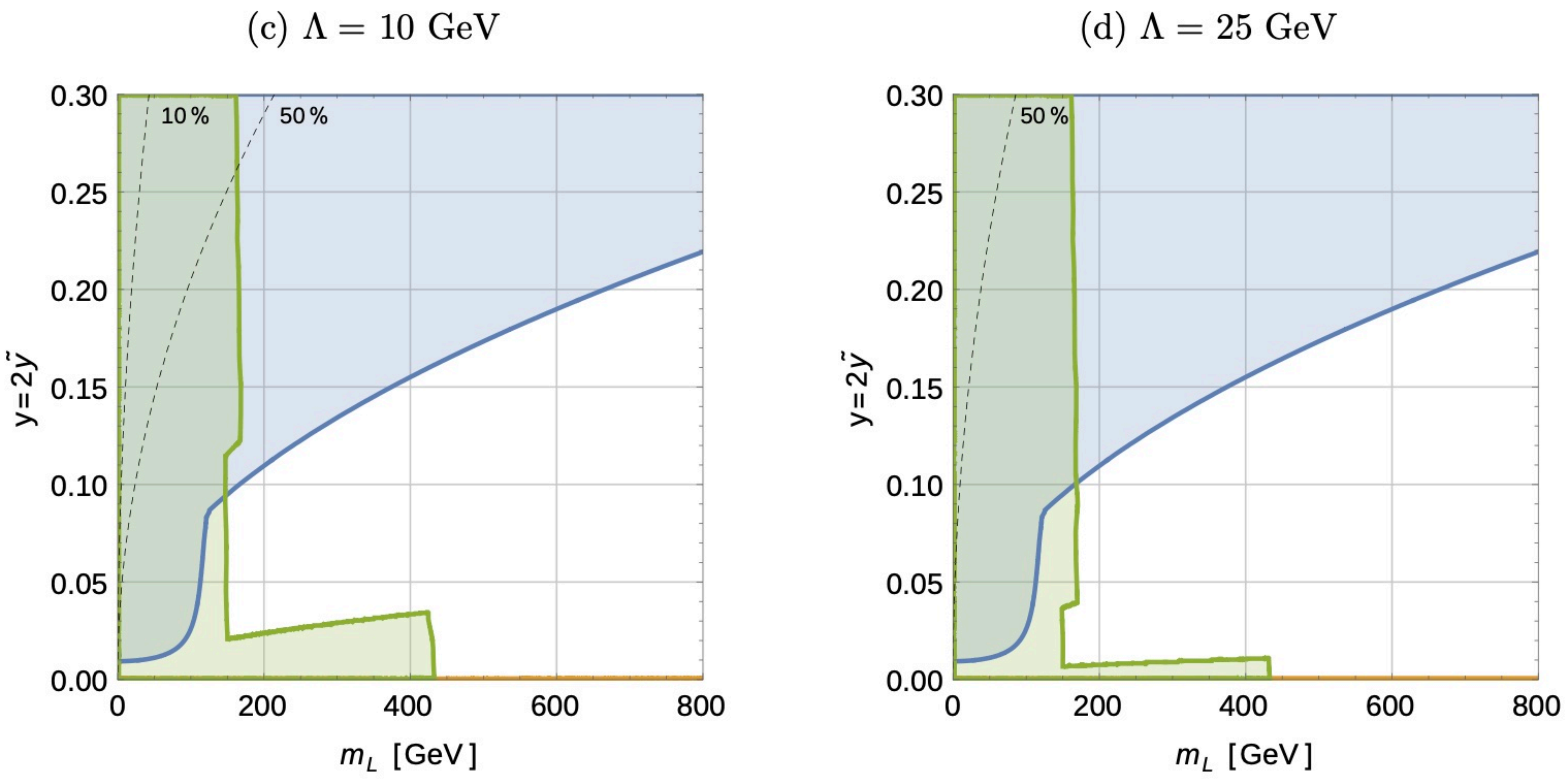
$$\mathcal{L} \supset -m_L L L^c - m_N N N^c - y L H N^c - y^c L^c H N + \text{h.c.} - \frac{\phi}{32\pi^2 f} F\widetilde{F}$$

$G\widetilde{G}$

$H_1 H_2$

$F\widetilde{F}$

# BACKUP




[Beauchesne, Bertuzzo, Grilli di Cortona ’17]

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

# AN AXION THAT IS NOT AN AXION

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

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

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

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)

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The gauge symmetry

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

Can be non-linearly realized

(for instance axion monodromy)

$$F_4 = dA_3$$

[Dvali 0507215]

# AN AXION THAT IS NOT AN AXION

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

Total derivative (respects the full shift-symmetry)

# AN AXION THAT IS NOT AN AXION

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

New gauge group

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

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

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

# AN AXION THAT IS NOT AN AXION

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

$$\Downarrow$$

Integrate out the non-dynamical 3-form

$$\Downarrow$$

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

# 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

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

$M_\pm$

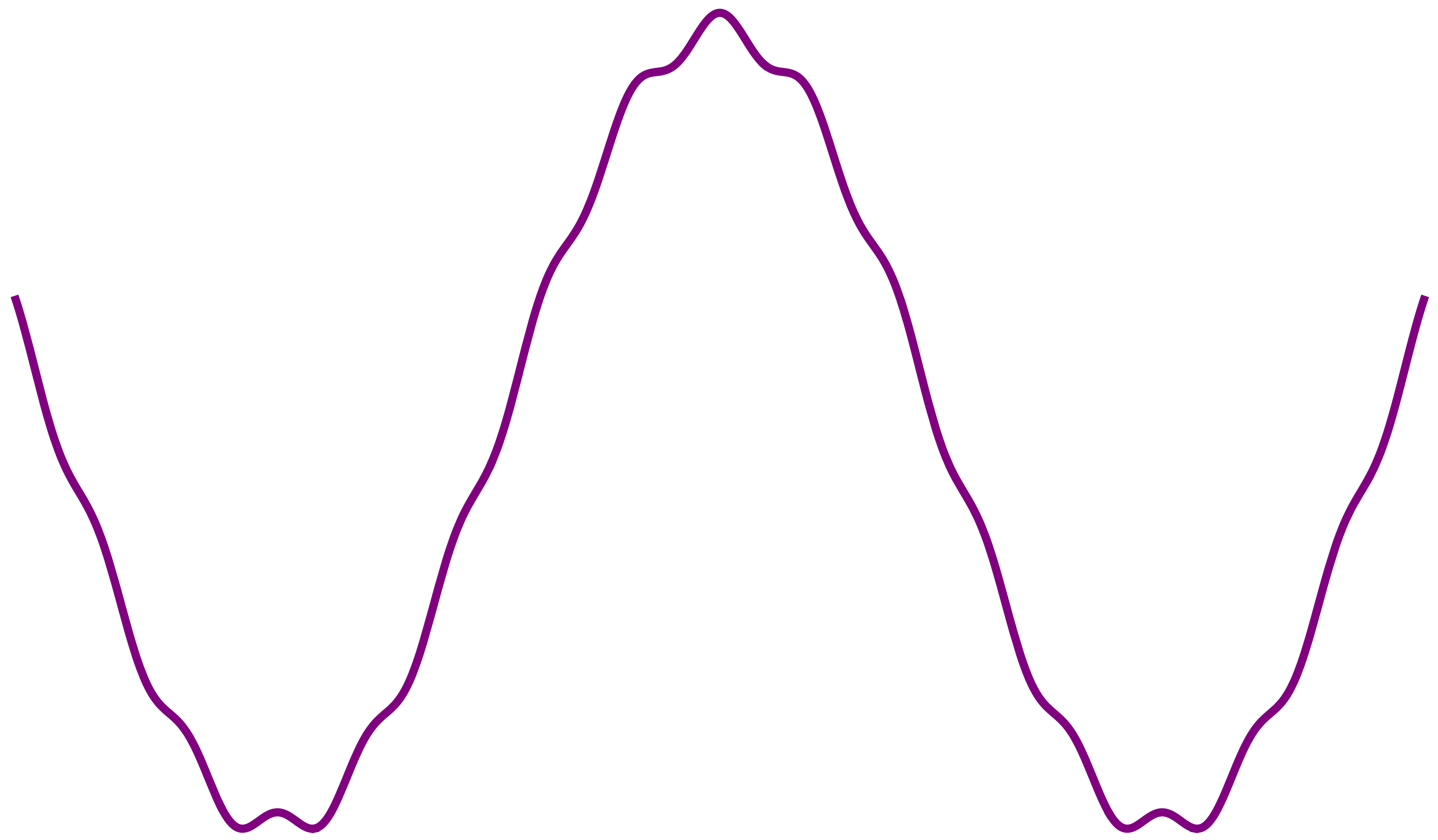
Breaks scale invariance
and shift symmetry

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

# 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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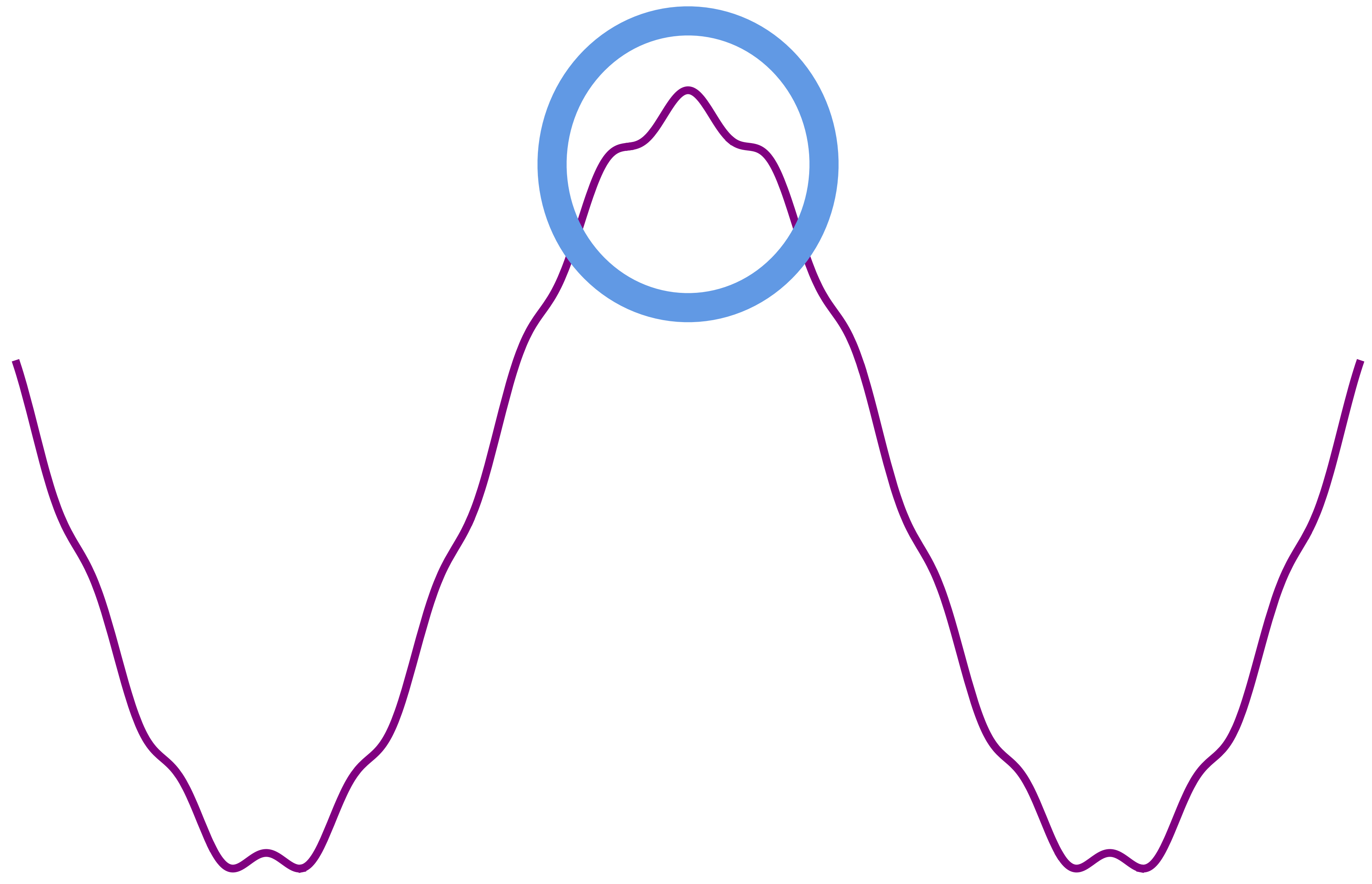

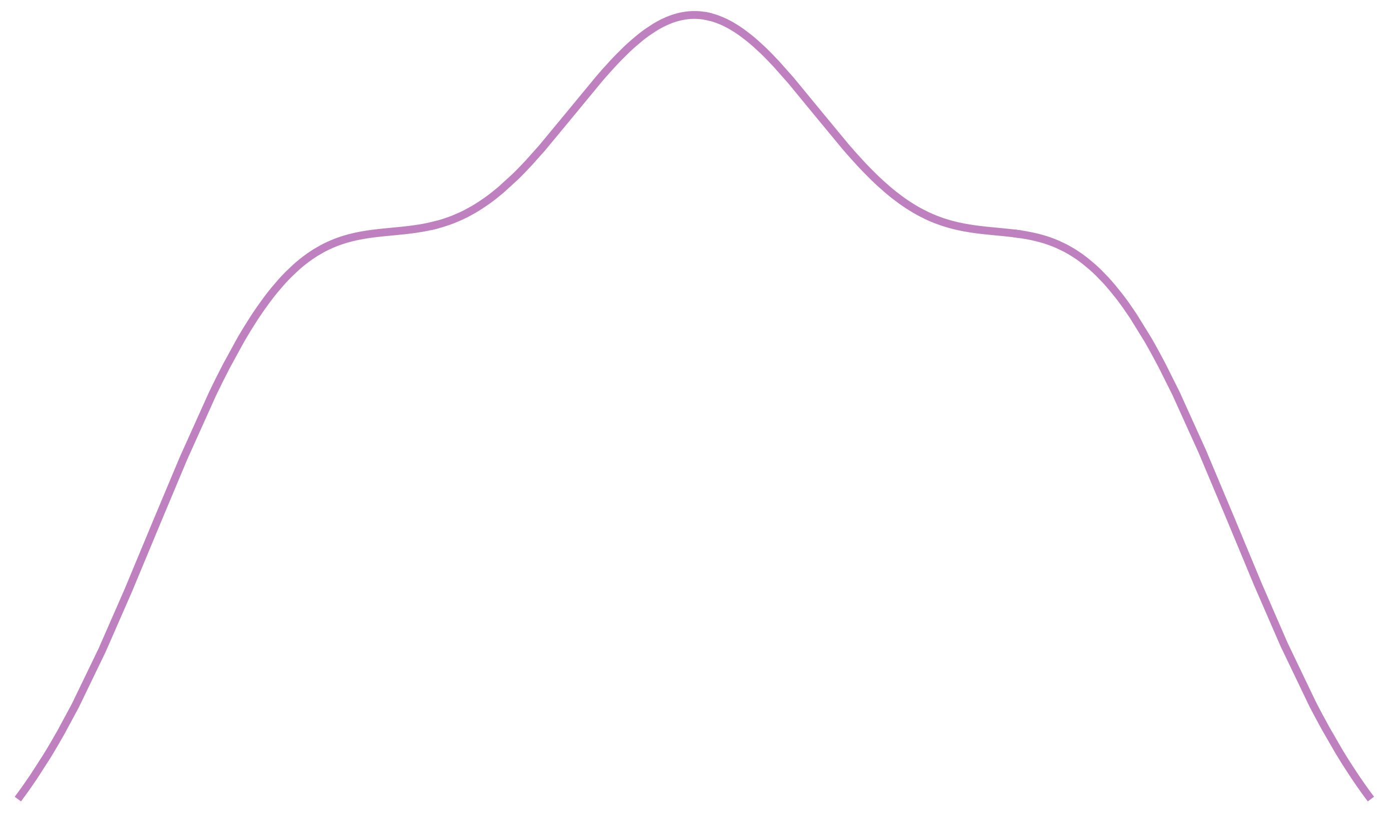

# CONCLUSION

1. Strong assumption on the landscape
2. UV completion [work in progress]