NATURALNESS FOR GEN Z

Raffaele Tito D’Agnolo - CEA IPhT Saclay and ENS Paris


gravityglue.com

THIS IS THE CASE FOR …

The size of the Universe

The mass of all known particles

It is fair to say that we do not understand them at all

In our current theory of Nature we cannot compute them, but we can estimate them using symmetry (i.e. dimensional analysis)

Estimated size of the Universe

$$10^{-35}\ \mathrm{m}$$

Estimated mass of the heaviest particle

$$10^{-8}\ \mathrm{kg}$$

Size of the observable Universe

$$10^{27}\ \mathrm{m}$$

Mass of the heaviest particle

$$10^{-25}\ \mathrm{kg}$$

Measurement	Estimate
10^{27} m	10^{-35} m
10^{-25} kg	10^{-8} kg


?
gravityglue.com

The size of the Universe → Cosmological Constant

The mass of all known particles → Higgs boson mass

The size of the Universe → Cosmological Constant

$$\Lambda = [E^4]$$

The mass of all known particles → Higgs boson mass

$$m_h^2 = [E^2]$$

$$\hbar = c = 1$$

ALL KNOWN SYMMETRIES OF NATURE

$$\Lambda \sim E_{\rm max}^4$$

$$m_h^2 \sim E_{\rm max}^2$$

Largest known energy scale

$$M_{\rm Pl}$$

ALL KNOWN SYMMETRIES OF NATURE

$$\Lambda \sim M_{\rm Pl}^4$$

$$m_h^2 \sim M_{\rm Pl}^2$$

Measurement	Estimate
10^{27} m	10^{-35} m
10^{-25} kg	10^{-8} kg


?
gravityglue.com

ALL KNOWN SYMMETRIES OF NATURE

$$\Lambda = M_{\rm Pl}^4(c_1 + c_2 + ...)$$

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

Dimensional Analysis

$$c_i = \mathcal{O}(1)$$

$$a_i = \mathcal{O}(1)$$

Dimensional Analysis

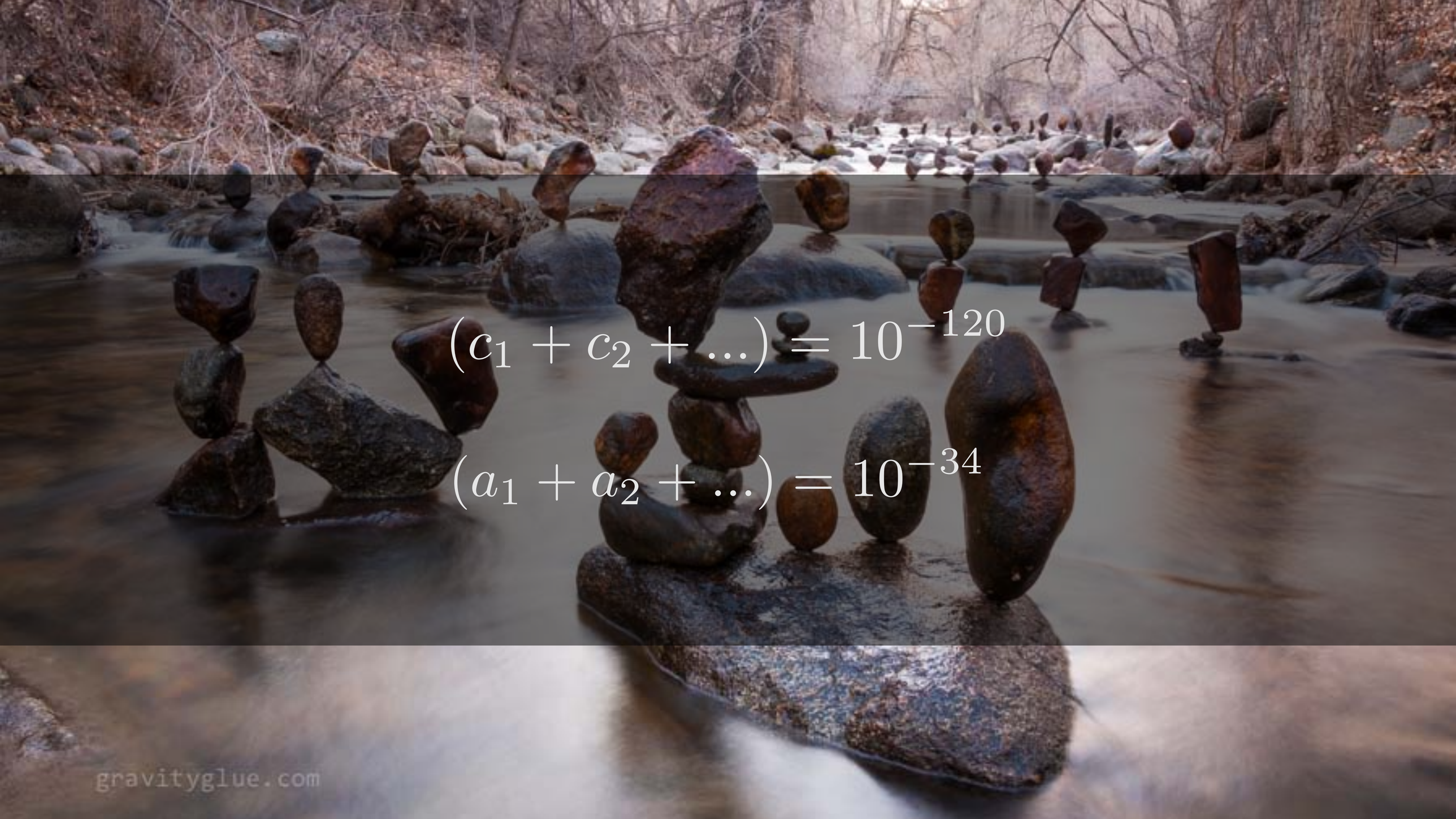
$$c_i = \mathcal{O}(1)$$

$$a_i = \mathcal{O}(1)$$

Measurement

$$(c_1 + c_2 + ...) = 10^{-120}$$

$$(a_1 + a_2 + ...) = 10^{-34}$$


$(c_1 + c_2 + ...) = 10^{-120}$
$(a_1 + a_2 + ...) = 10^{-34}$
gravityglue.com

What happens if we simply accept this accidental cancellation?

Ingredient 1: Selection Rules of Symmetries

Selection Rules of Symmetries

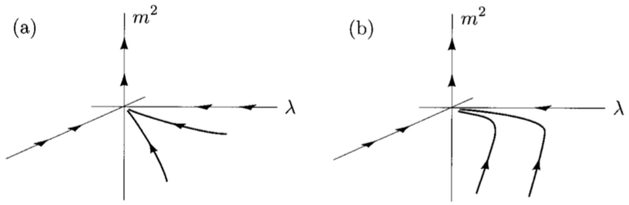
$$A = B$$

Implies that A and B transform in the same way under all symmetries
Including broken ones

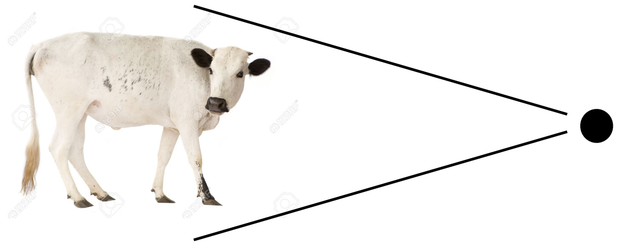
Ingredient 2: Separation of scales

EFFECTIVE THEORIES IN PARTICLE PHYSICS

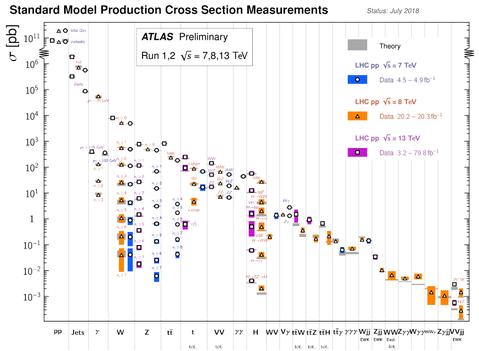
RENORMALIZATION



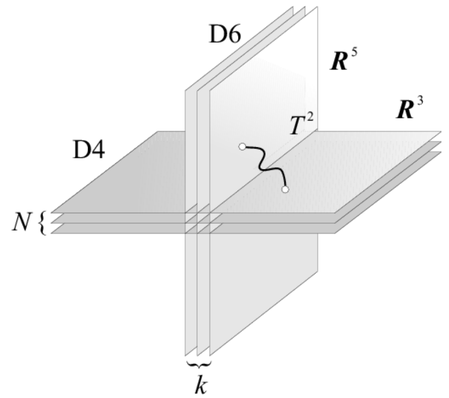
SYMMETRIES FROM COARSE GRAINING



PRECISION CALCULATIONS

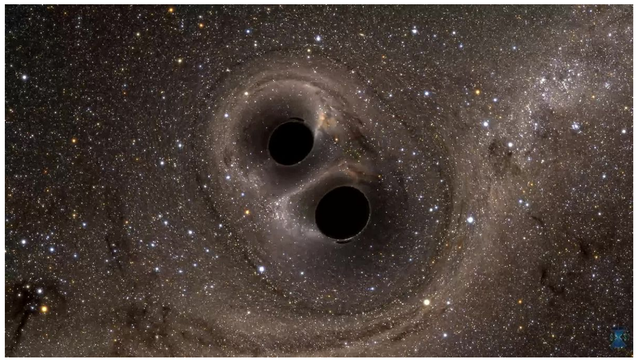


QFT INSIGHTS FROM STRING THEORY

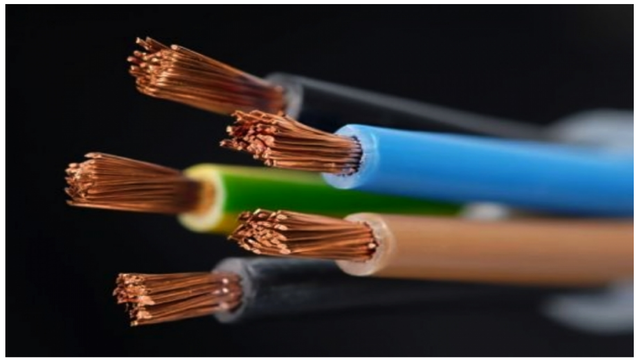


AND BEYOND

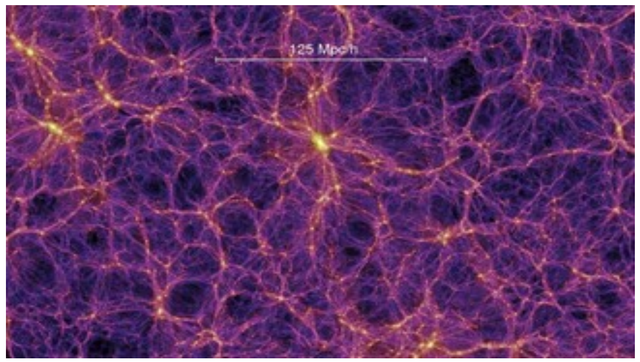
POST-NEWTONIAN EXPANSIONS



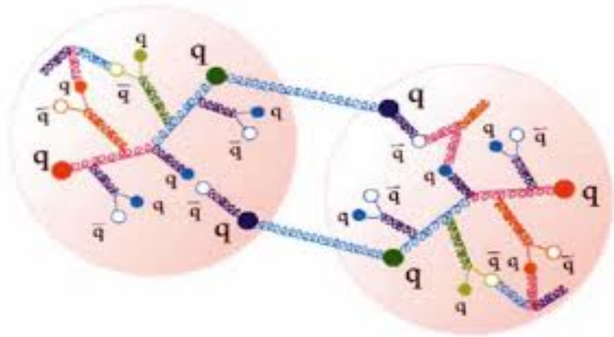
LANDAU THEORY OF FERMI LIQUIDS



LARGE SCALE STRUCTURE



CHIRAL PERTURBATION THEORY




WHAT NOW?

Higgs Mass Squared

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

WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, …

SYMMETRY-BASED ESTIMATE

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

Symmetry~10^{34} Experiment

$$m_h^2 = 0$$

Special

———— Planck

———— New Symmetry

———— SM

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

M_S

——— Planck

——— New Symmetry

——— SM

Planck

Supersymmetry or Scale Invariance

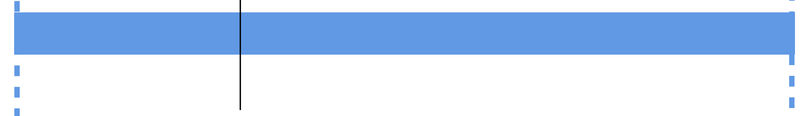
New Symmetry

SM

$$\left(m_h^2 |H|^2 \right)$$

We have been looking for answers at energies close to the Higgs mass for more than 40 years

Higgs Boson



and we have not found them

It doesn’t work at all for the cosmological constant

$$\Lambda \simeq (0.1\ \mathrm{meV})^4$$


WHAT NOW?

1. We tune

1. We tune

2. There is no mass scale beyond the SM [1305.6939]

3. The Higgs mass and the CC are inputs

4. UV/IR Mixing [1909.01365]

5. Swampland on steroids

1. We tune

2. In 4D you get GR with ghosts

3. The Higgs mass and the CC are inputs

4. UV/IR Mixing [1909.01365]

5. Swampland on steroids

1. We tune

2. In 4D you get GR with ghosts

3. We don't know any theory of QG that does it

4. UV/IR Mixing [1909.01365]

5. Swampland on steroids

1. We tune

2. In 4D you get GR with ghosts

3. We don't know any theory of QG that does it

4. Possible, but we don't have any idea how to write a theory that works

5.

1. We tune

2. In 4D you get GR with ghosts

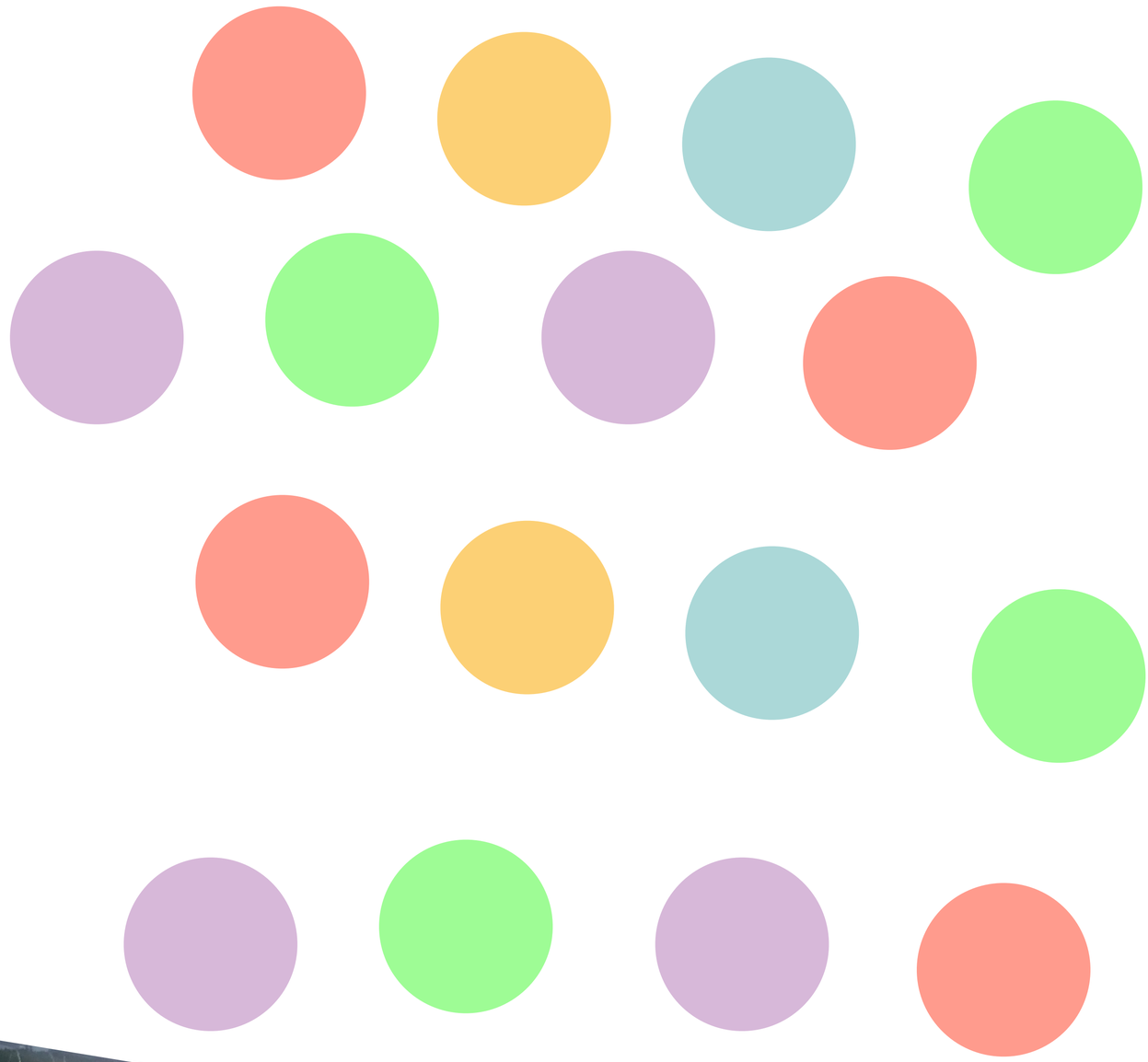
3. We don't know any theory of QG that does it

4. Possible, but we don't have any idea how to write a theory that works

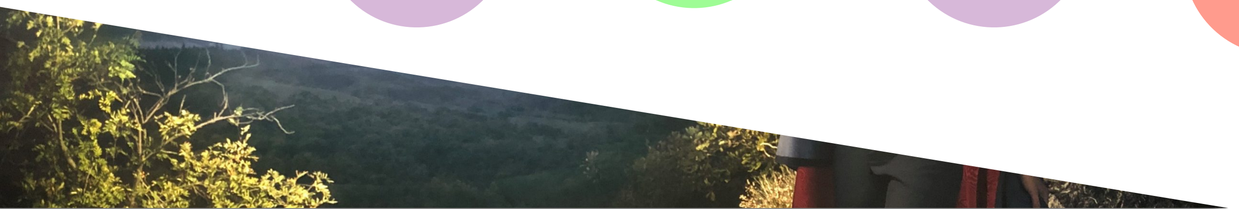
5.

6. **There is a landscape**

A CHANGE OF PERSPECTIVE



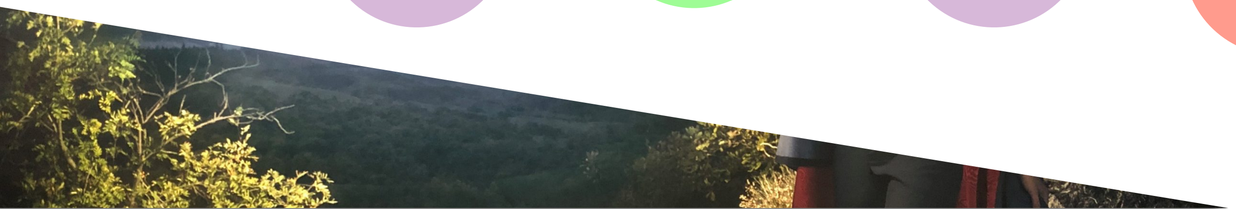
Causally Disconnected Universes with different values of the Standard Model parameters, populated by inflation



1. One day it can be tested experimentally

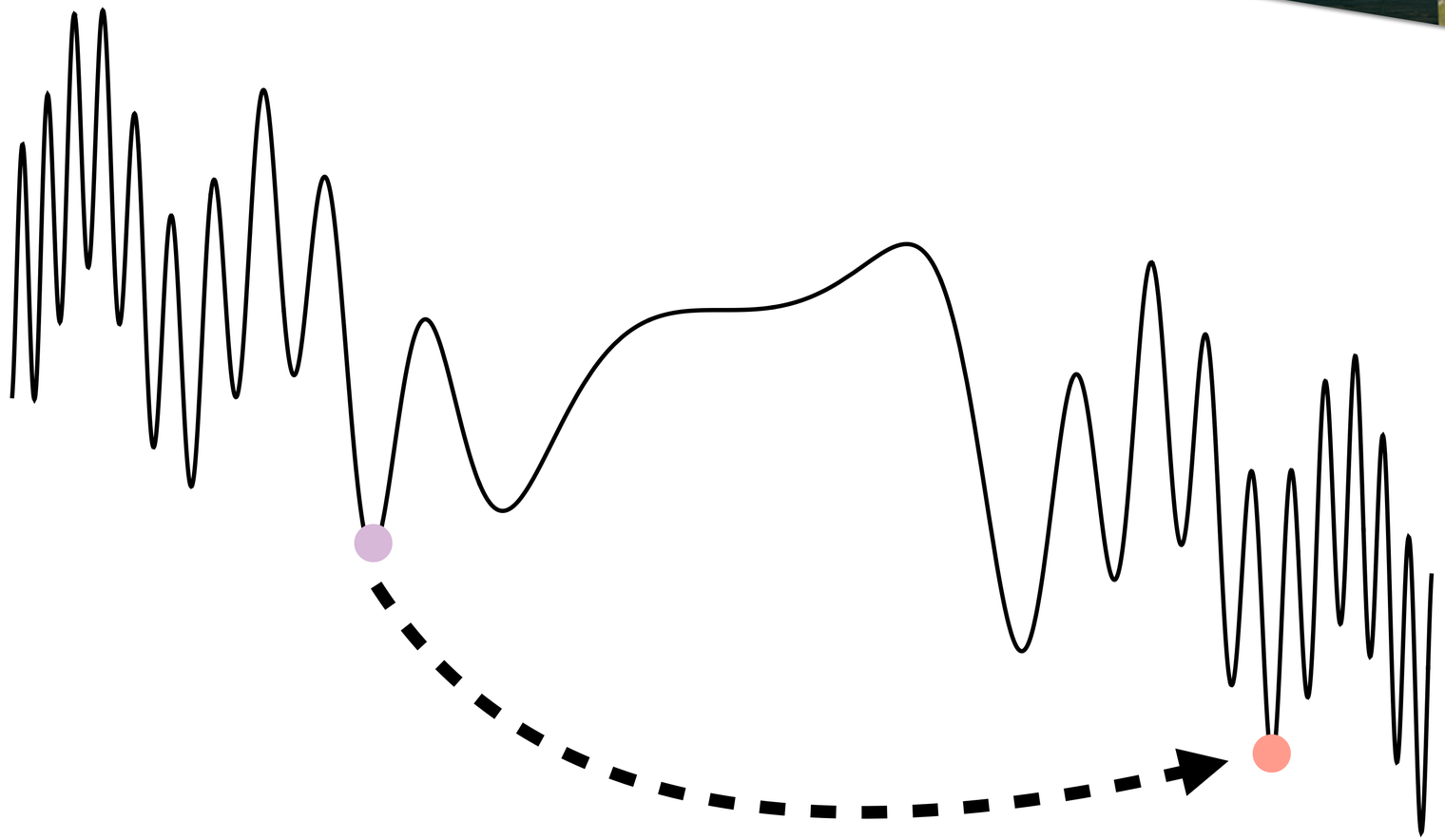
2. Currently our most concrete explanation for the cosmological constant

3. It probably exists independently of the problem

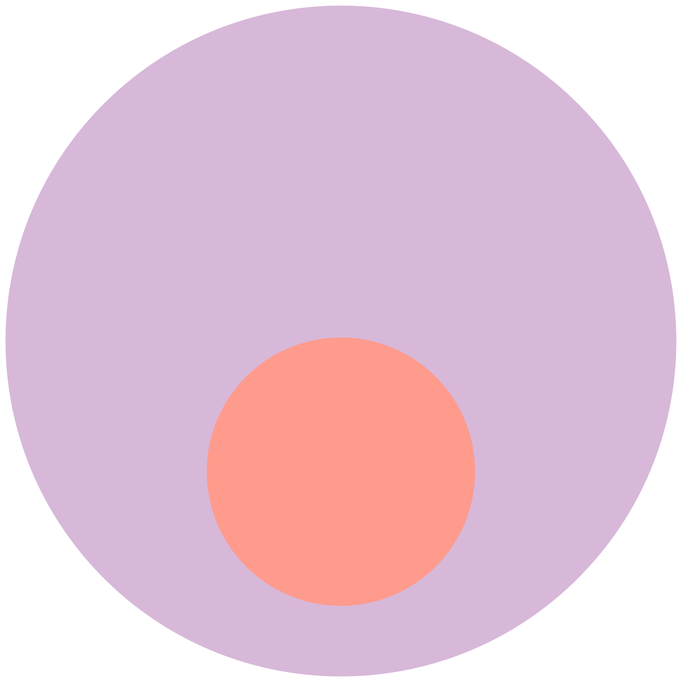


Inflation

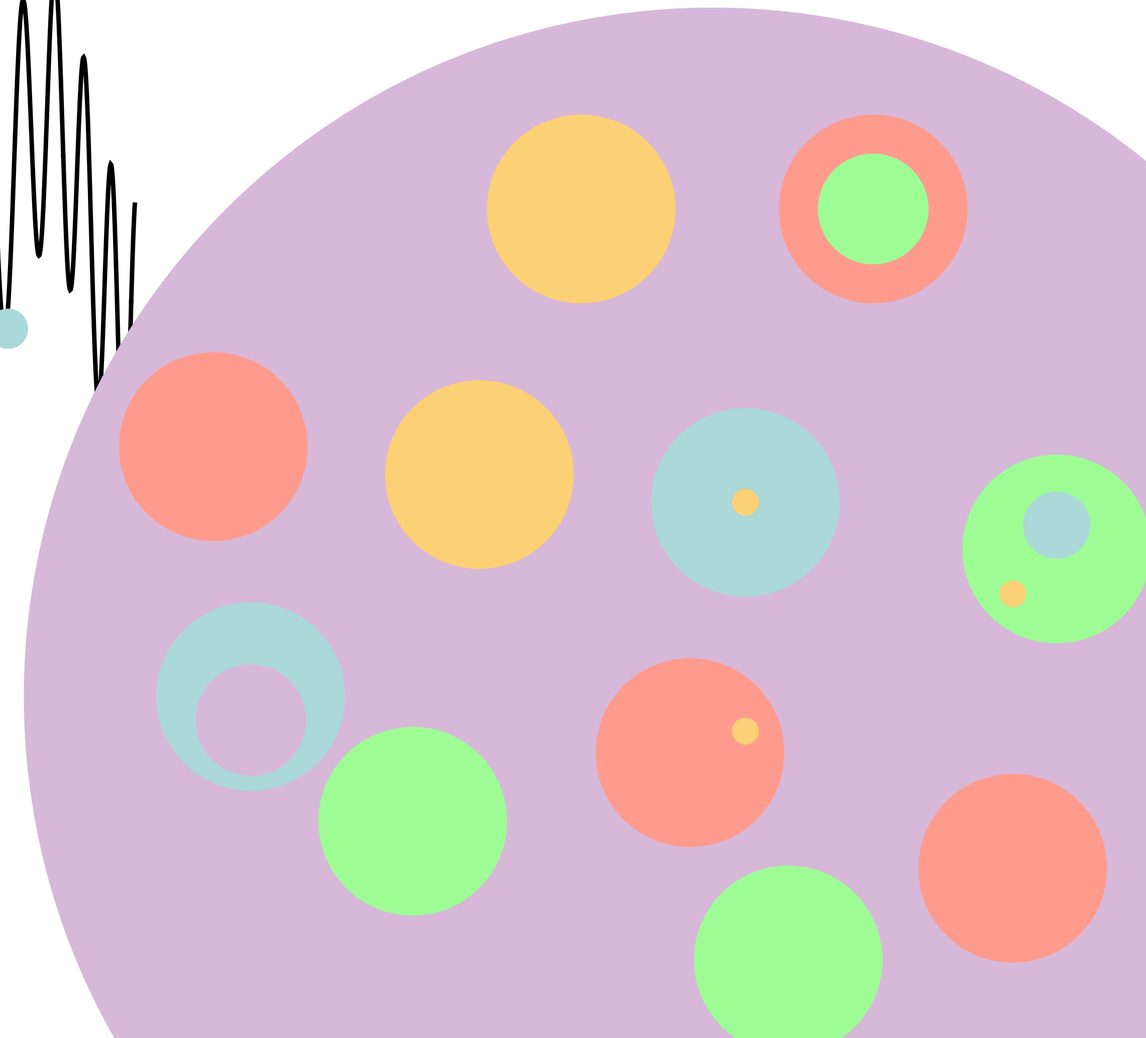
Inflation



Tunneling



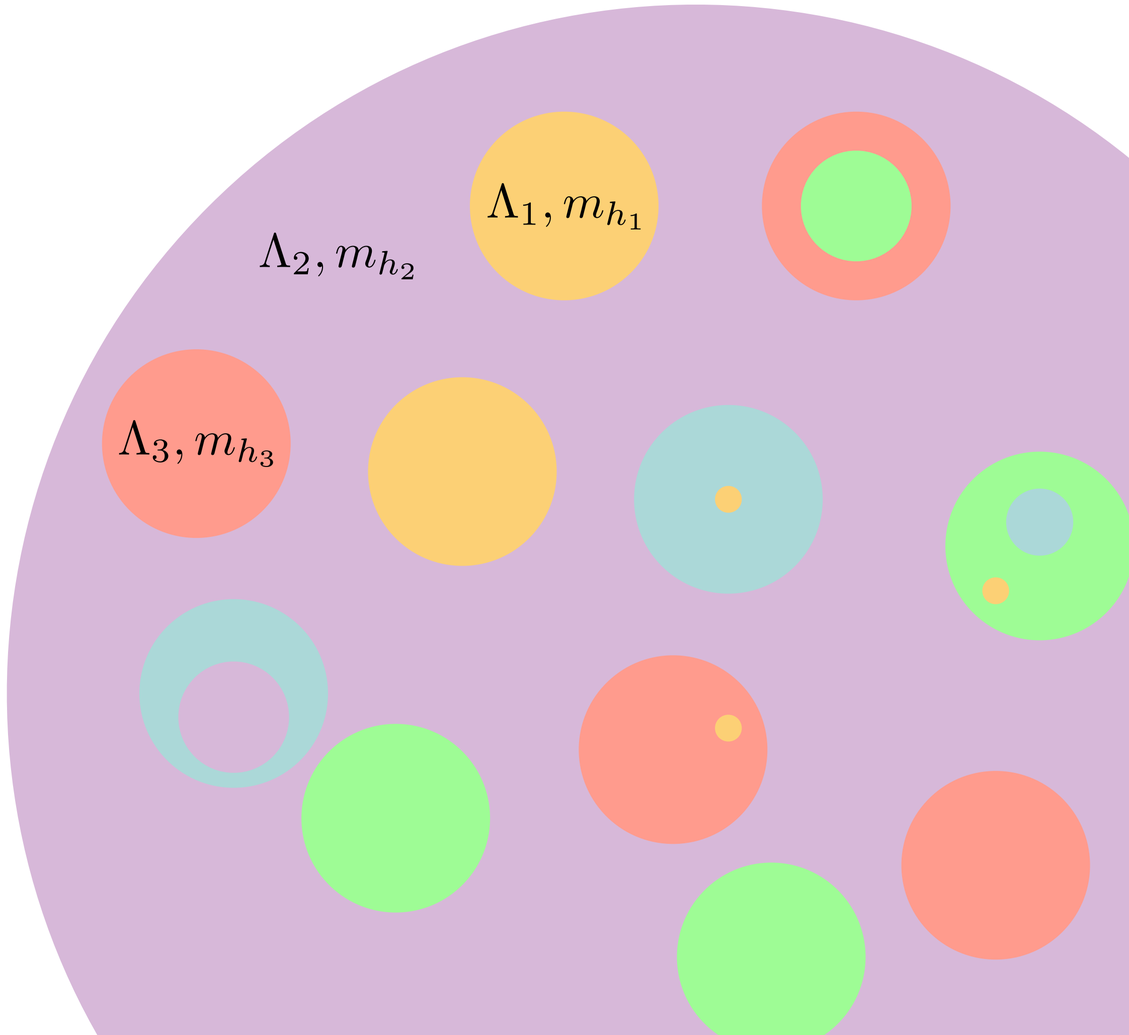
Inflation



Inflation

SCANNING

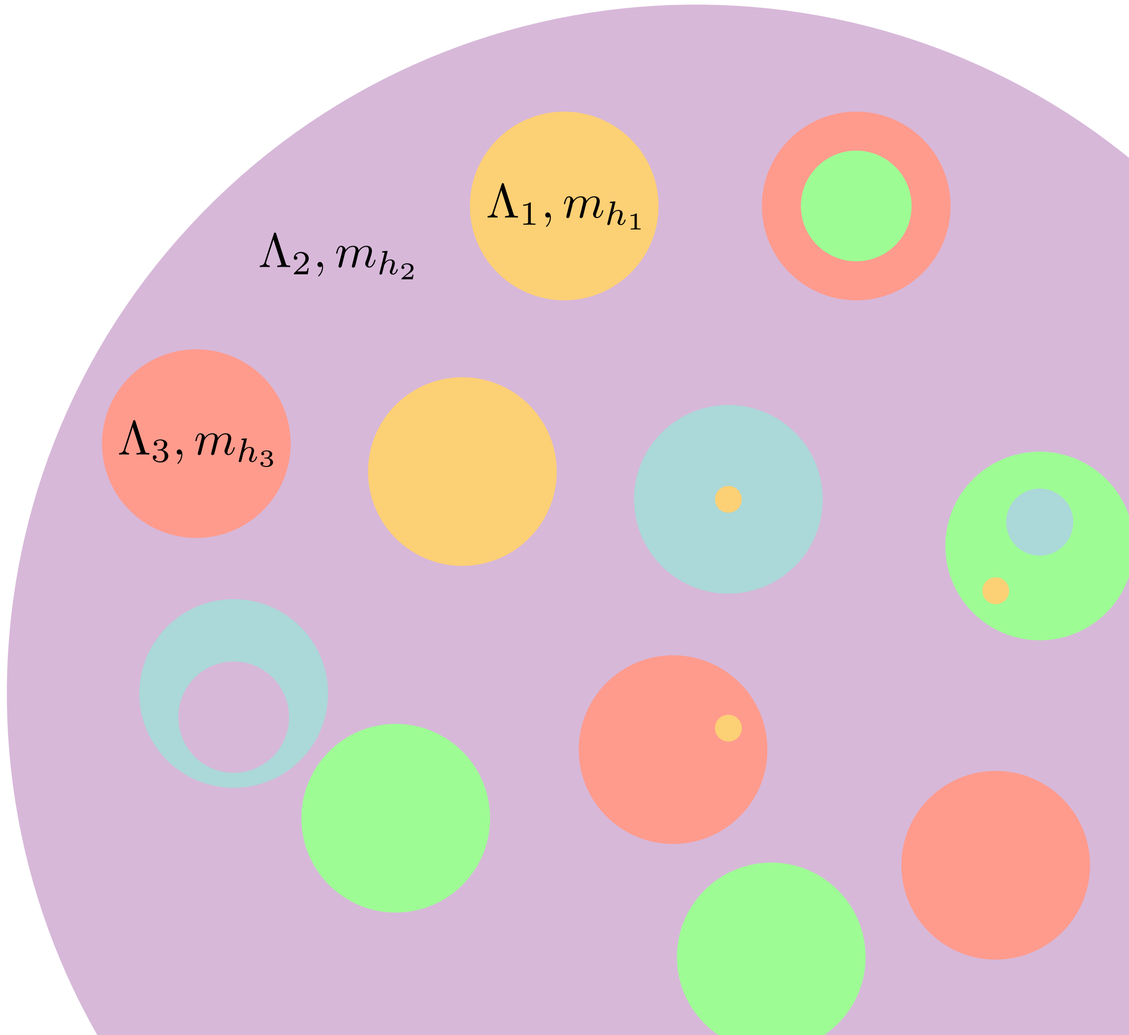
$$\int d^d x \sqrt{-G} \left(\Lambda + m_{h_d}^2 |H|^2 \right)$$

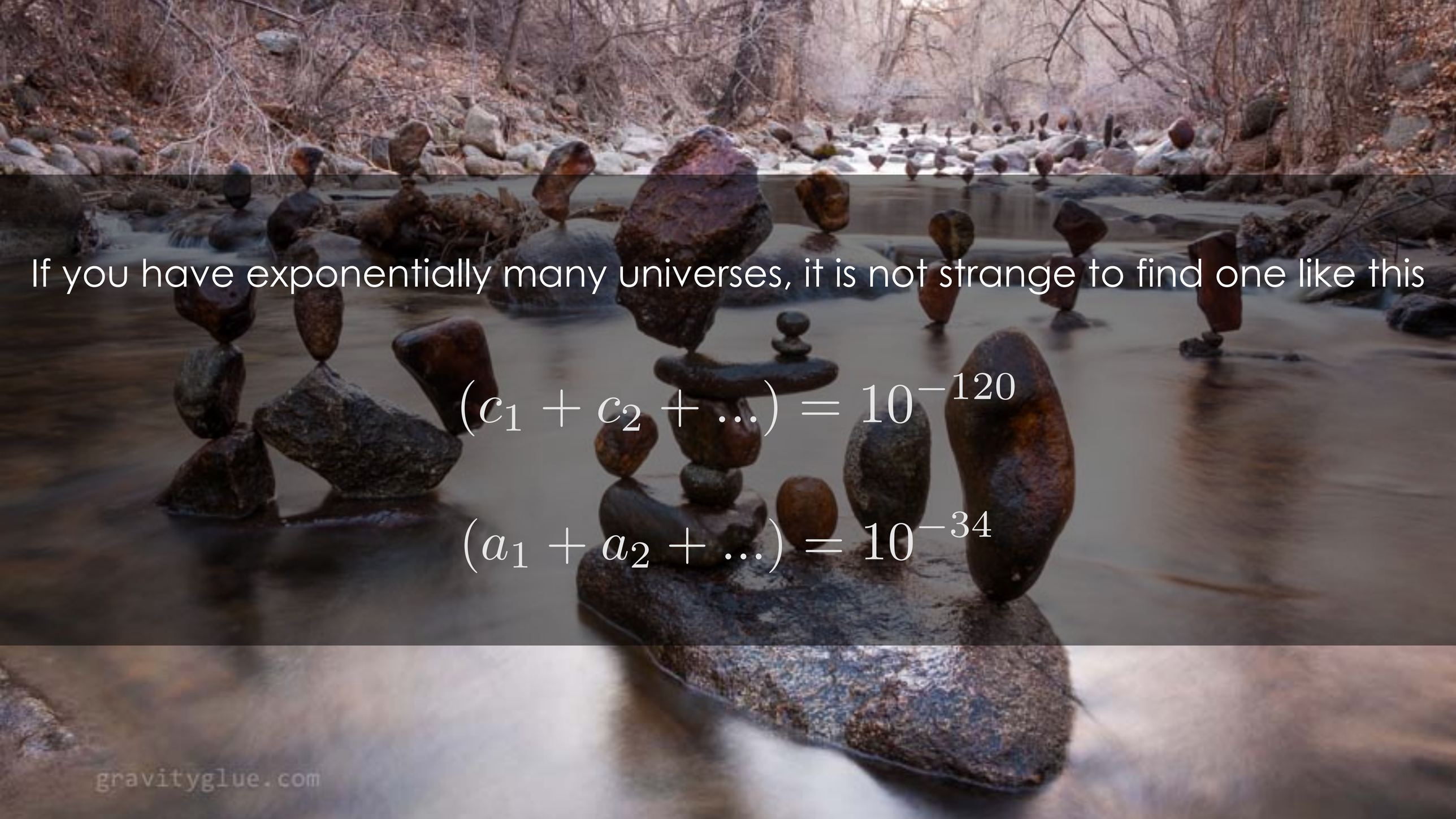


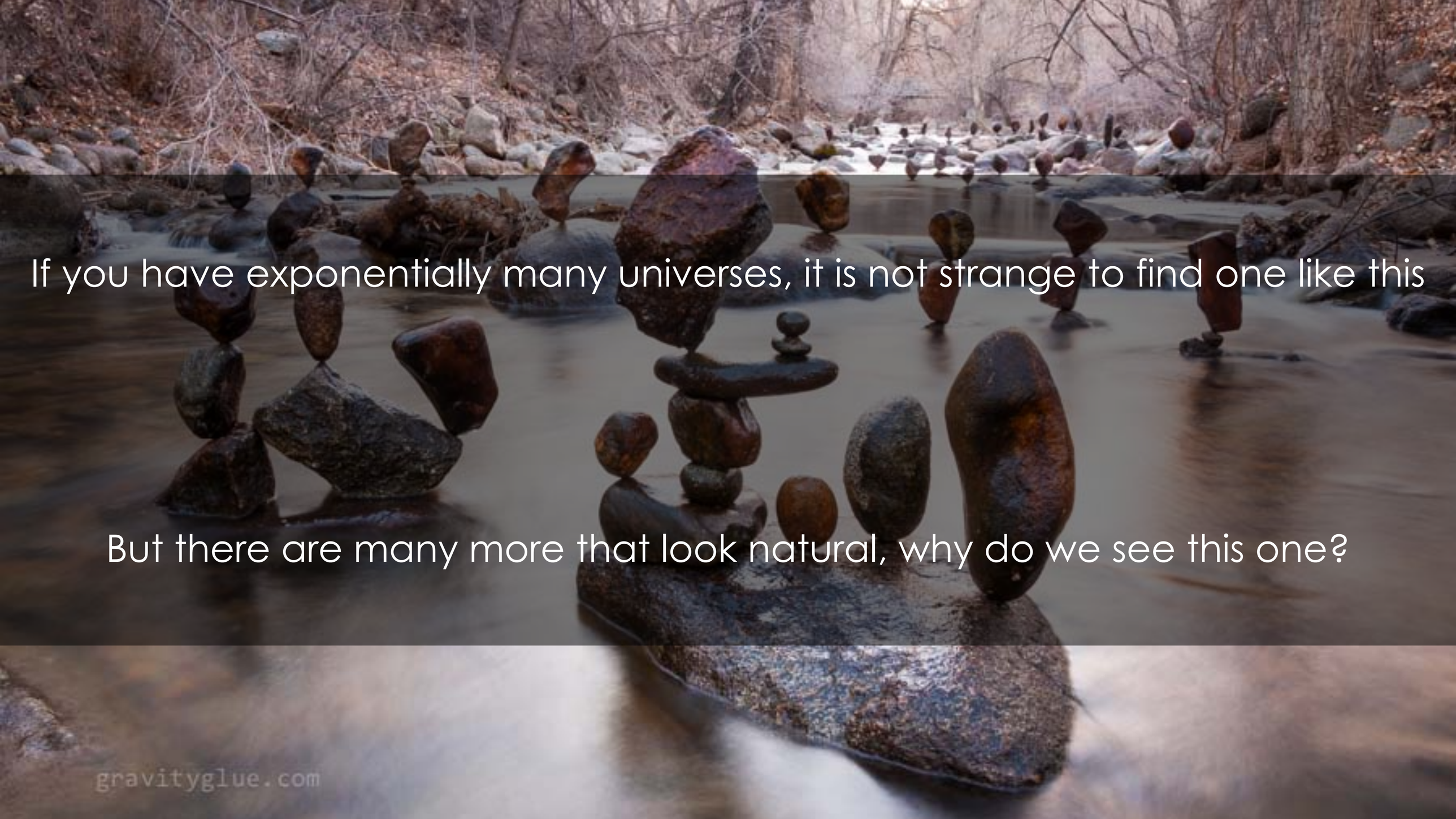
SCANNING

$$\int d^d x \sqrt{-G} \left(\Lambda + m_{h_d}^2 |H|^2 \right)$$

$$\int d^4 x \sqrt{-g} \left(\Lambda' + m_h^2 |H|^2 \right)$$




If you have exponentially many universes, it is not strange to find one like this
$(c_1 + c_2 + ...) = 10^{-120}$
$(a_1 + a_2 + ...) = 10^{-34}$
gravityglue.com

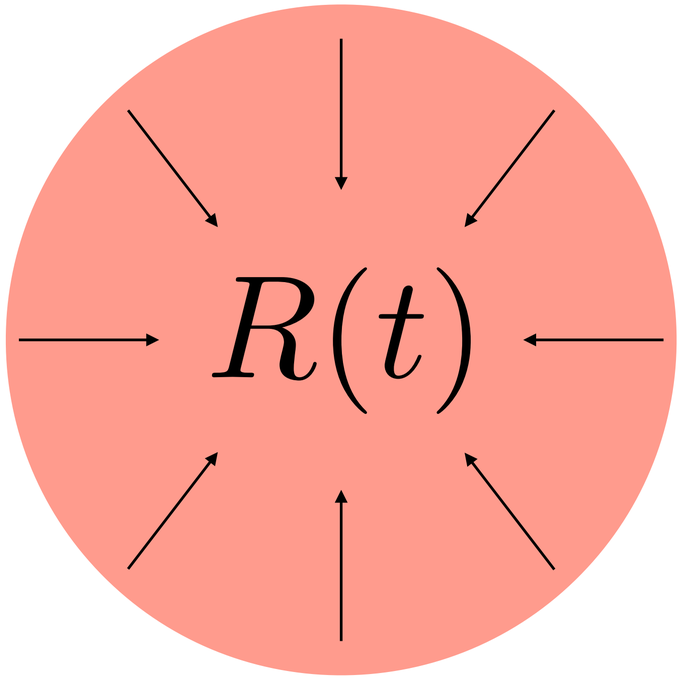

If you have exponentially many universes, it is not strange to find one like this
But there are many more that look natural, why do we see this one?
gravityglue.com

The cosmological constant has a dramatic impact on spacetime

$$R(t) \sim e^{\pm \frac{\sqrt{|\Lambda|}t}{M_{\rm Pl}}}$$

The cosmological constant has a dramatic impact on spacetime

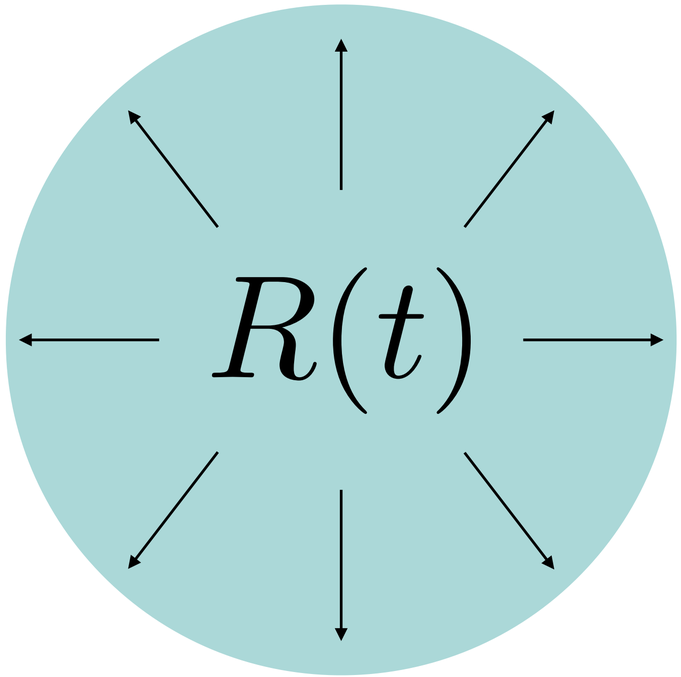
$$R(t) \sim e^{\pm \frac{\sqrt{|\Lambda|}t}{M_{\rm Pl}}}$$



$$\Lambda < 0$$

The cosmological constant has a dramatic impact on spacetime

$$R(t) \sim e^{\pm \frac{\sqrt{|\Lambda|}t}{M_{\rm Pl}}}$$



$$\Lambda > 0$$

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 [RTD, Mangini, Rigo, Wang, '24]
2. Not every landscape is a multiverse

Symmetry

$$\Lambda, m_h^2 = 0$$

Is special in the underlying theory of Nature

Landscape

$$\Lambda, m_h^2 = 0$$

Is special just for the evolution of the universe

Higgs Mass Squared

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

WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, …

Historically:

Multiverse
+Anthropic selection

Recently:

New class of ideas that can be tested in the laboratory in the near future

Historically:

Multiverse
+Anthropic selection

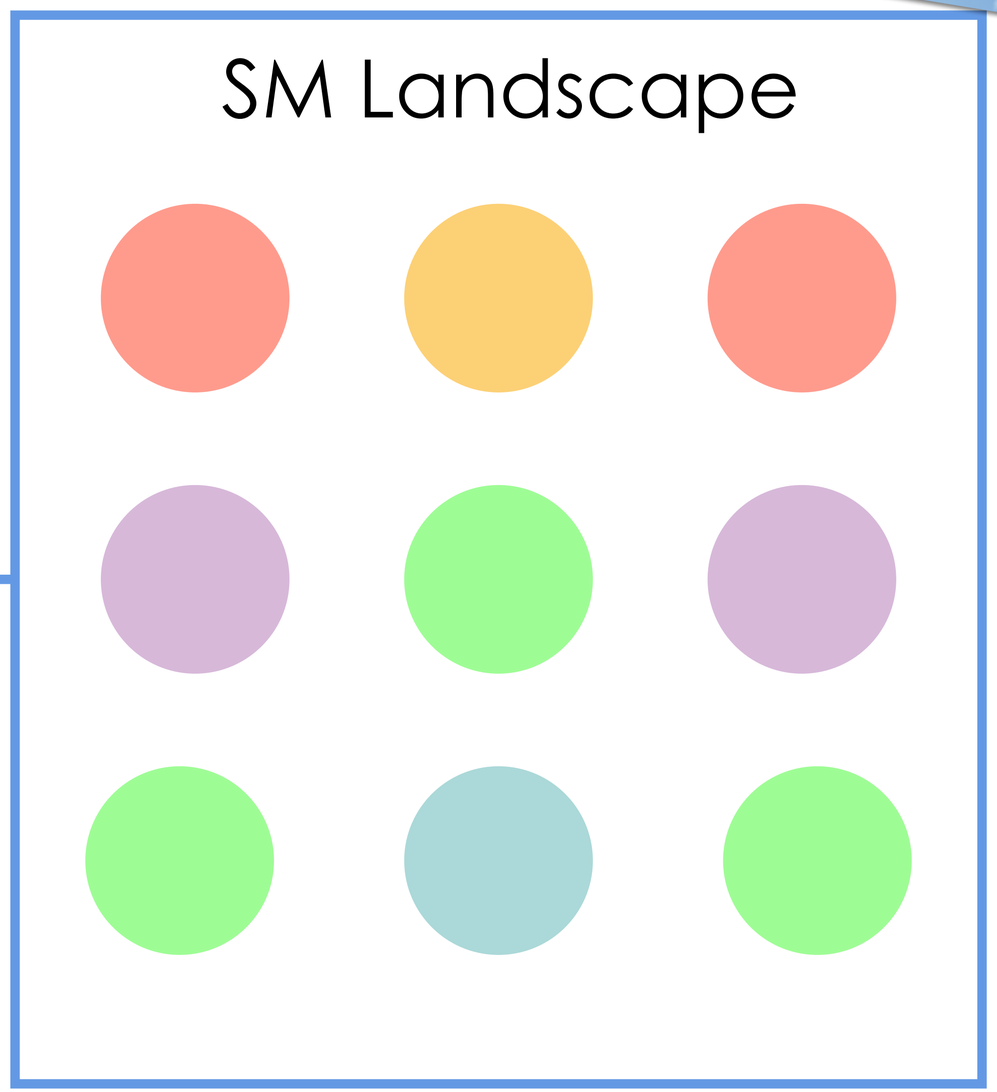
Recently:

New class of ideas that can be tested in the laboratory in the near future

GENERAL STRUCTURE

Symmetric Sector

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



Symmetric Sector

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

SM Landscape

An event triggered by the symmetric sector selects the observed

$$m_h^2$$

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],

…

Symmetric Sector

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

Sensitive to the Higgs mass

SM Landscape

General QFT question relevant beyond naturalness:

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

Does anything change
as we vary the Higgs mass?

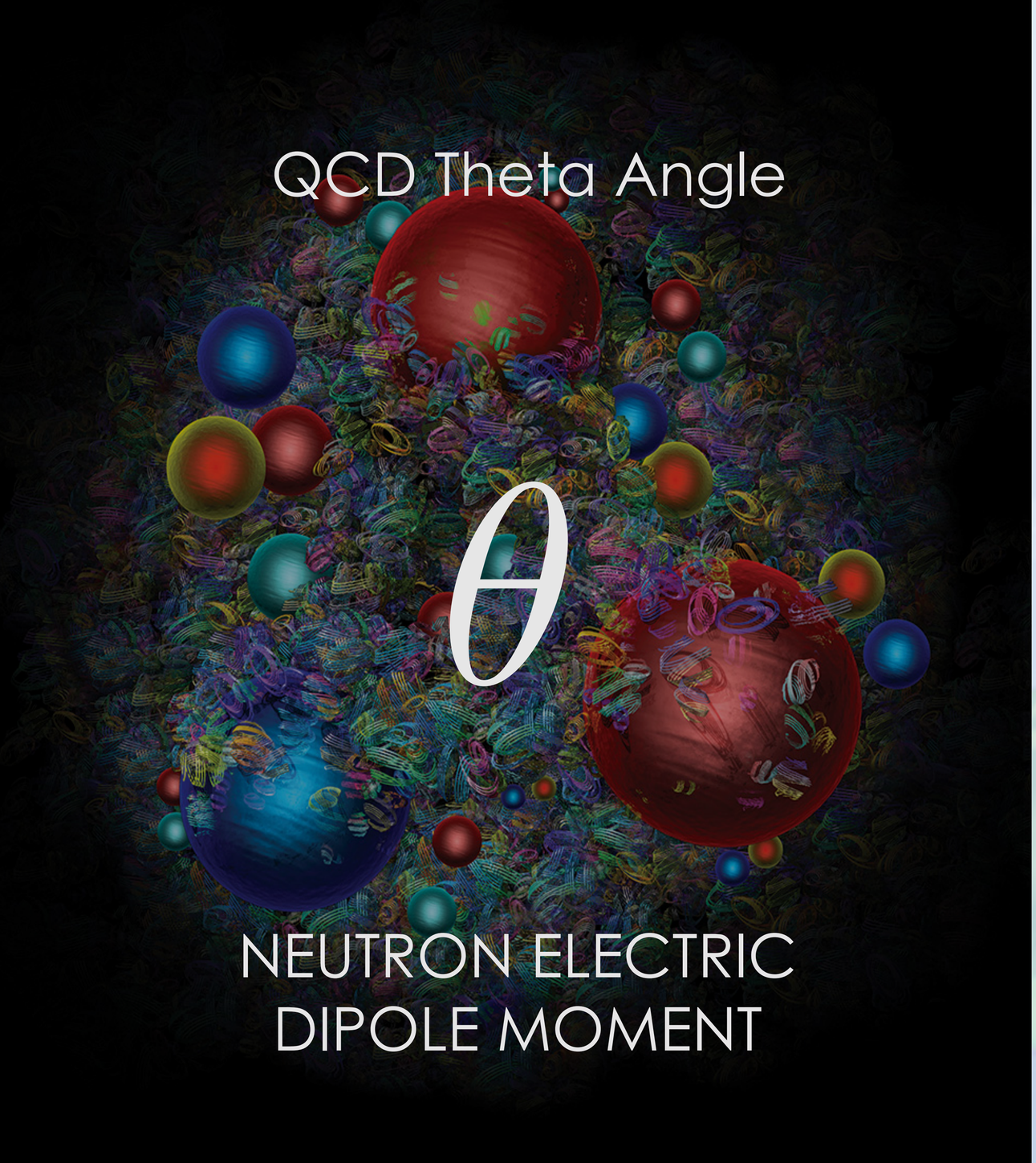
LOCAL

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

NON-LOCAL

On-shell N-point
functions of massive SM
particles

QCD Theta Angle



$$\theta$$

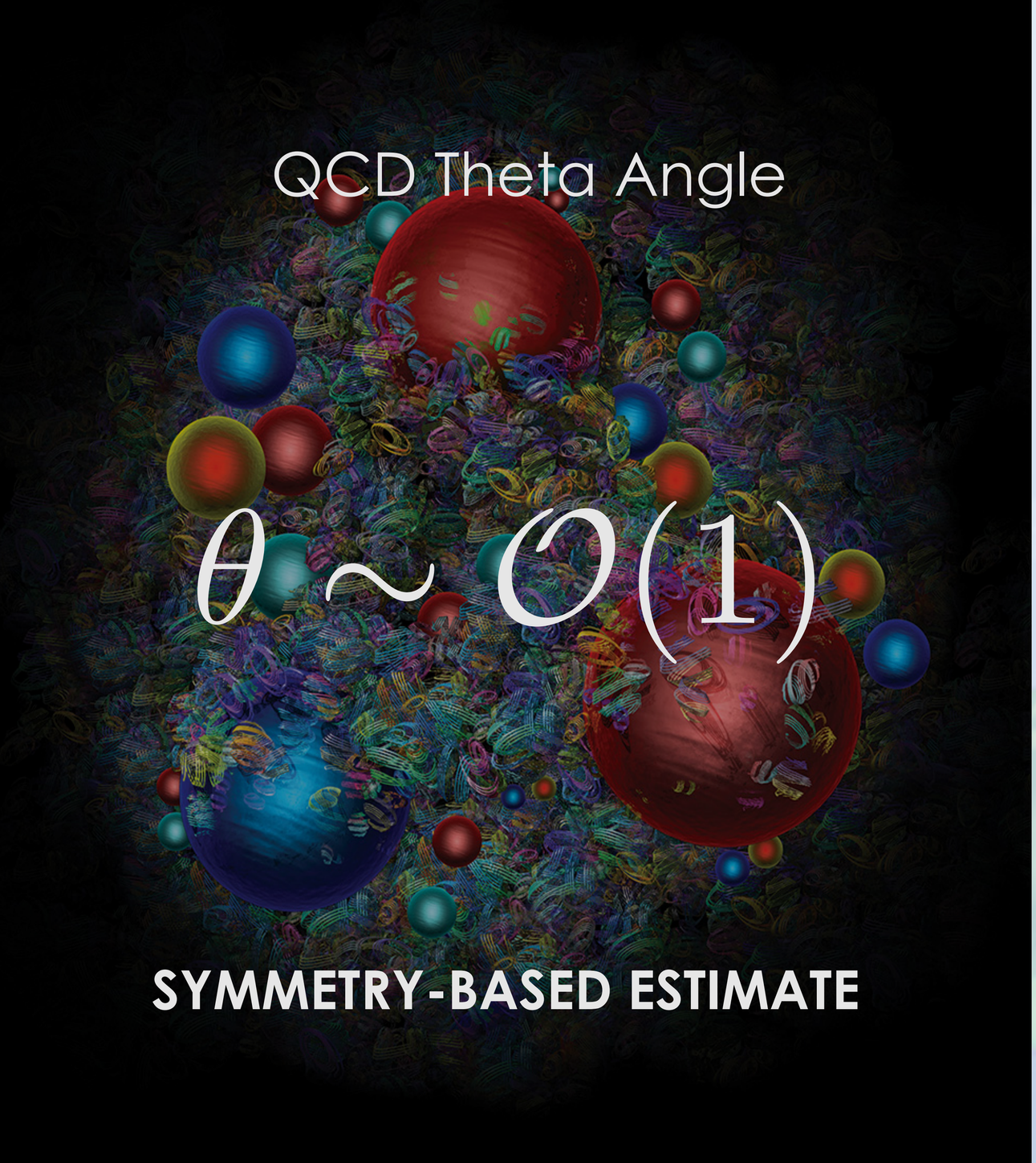
NEUTRON ELECTRIC DIPOLE MOMENT

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

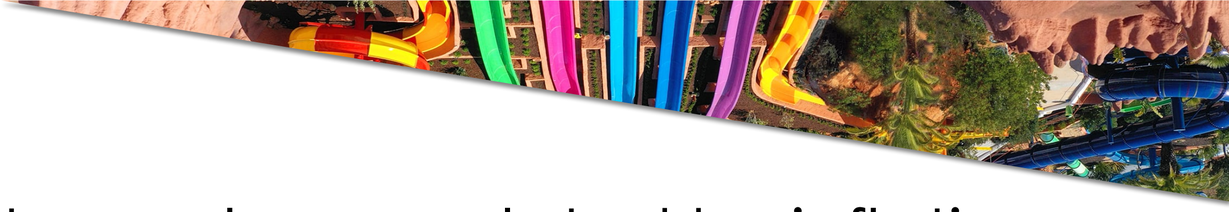
Symmetry~10^{34} Experiment

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

SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

SLIDING NATURALNESS



Landscape of Higgs Masses and theta-angles populated by inflation

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

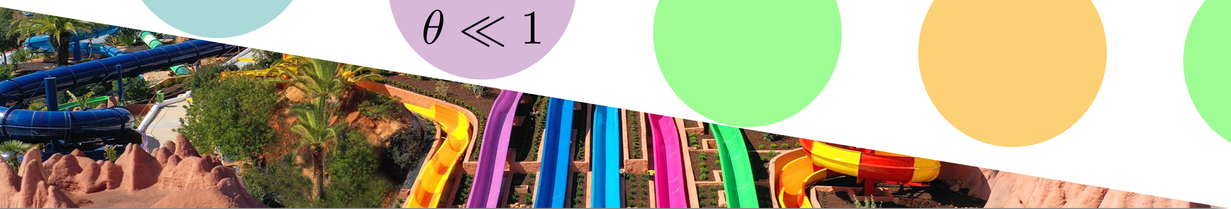
$\langle h \rangle \simeq v$
$\theta \ll 1$

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

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

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

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



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

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

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

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

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

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

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

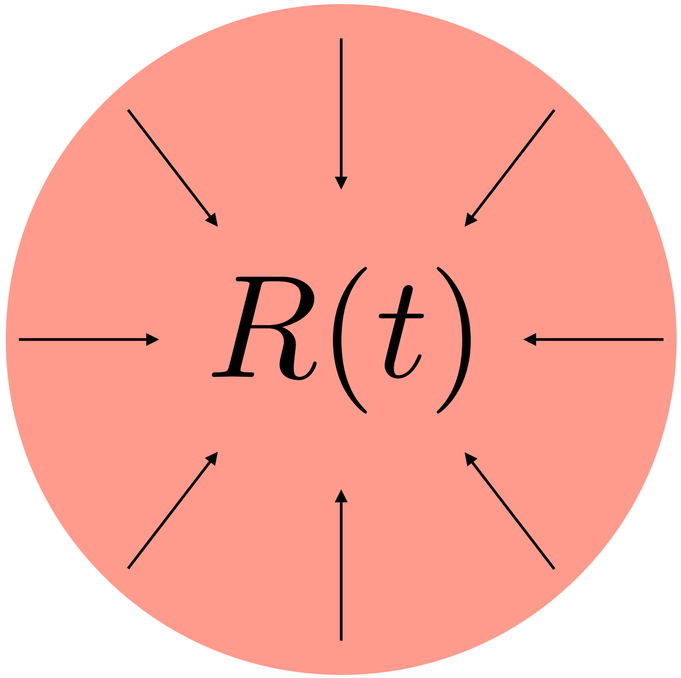
$\langle h \rangle \simeq v$
$\theta \ll 1$

crunch

CRUNCHING

Negative Cosmological Constant

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



$$\Lambda < 0$$

SLIDING NATURALNESS

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

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

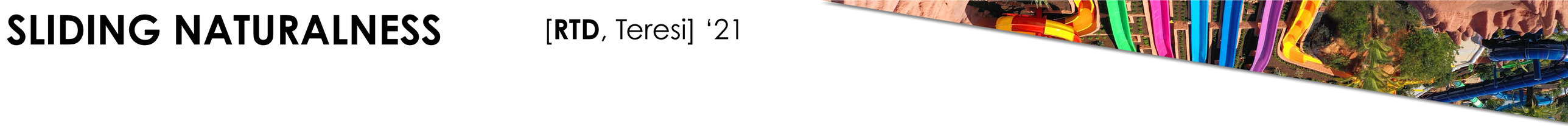
$$\langle h \rangle \simeq v$$
$$\theta \ll 1$$

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

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

SLIDING NATURALNESS

[**RTD**, Teresi] ‘21

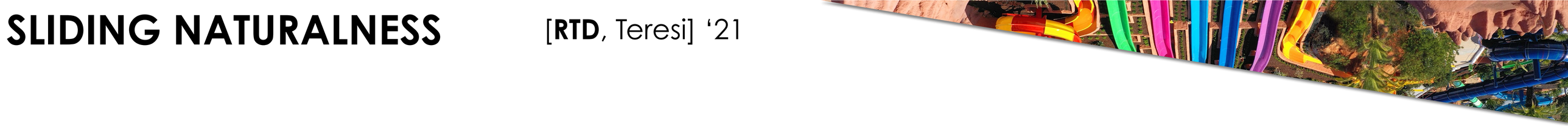


Addition to the SM: Two very weakly coupled scalars

$$\phi_{\pm}$$

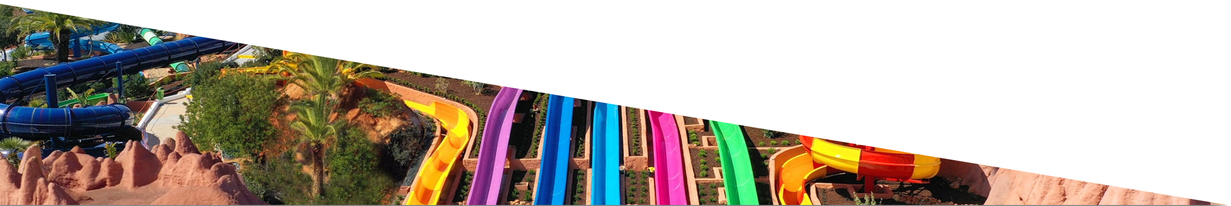
SLIDING NATURALNESS

[**RTD**, Teresi] '21



Approximately decoupled from each other

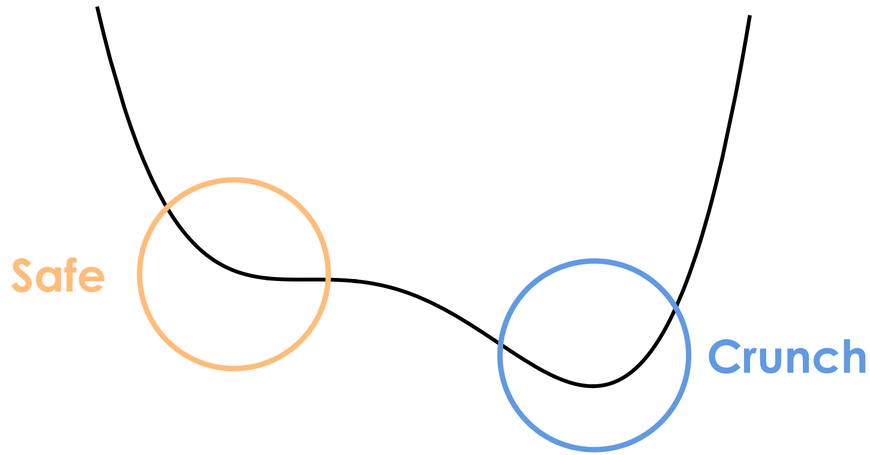
$$V = V_{\phi_-} + V_{\phi_+} + V_{H\phi_-} + V_{H\phi_+}$$



SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

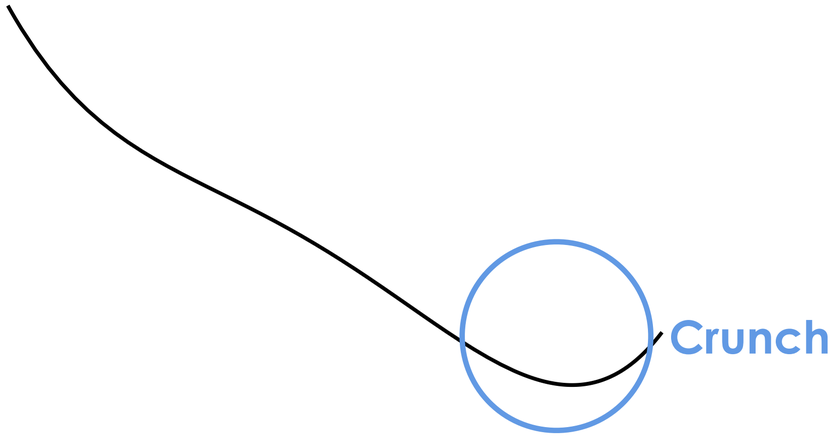


SLIDING NATURALNESS

[**RTD**, Teresi] '21

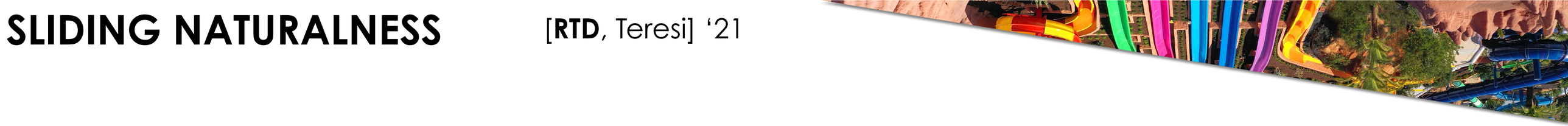
$$V_- = V_{\phi_-} + V_{H\phi_-}$$

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



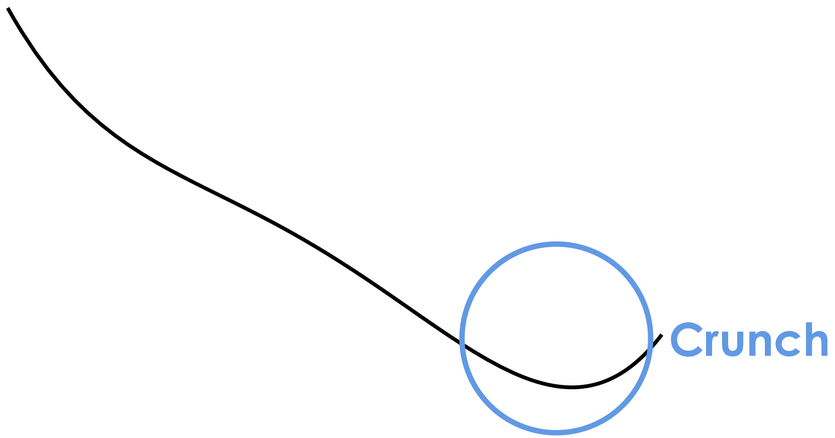
SLIDING NATURALNESS

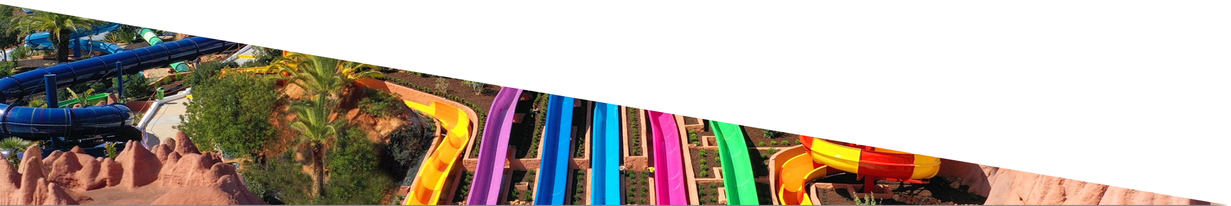
[**RTD**, Teresi] '21



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

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



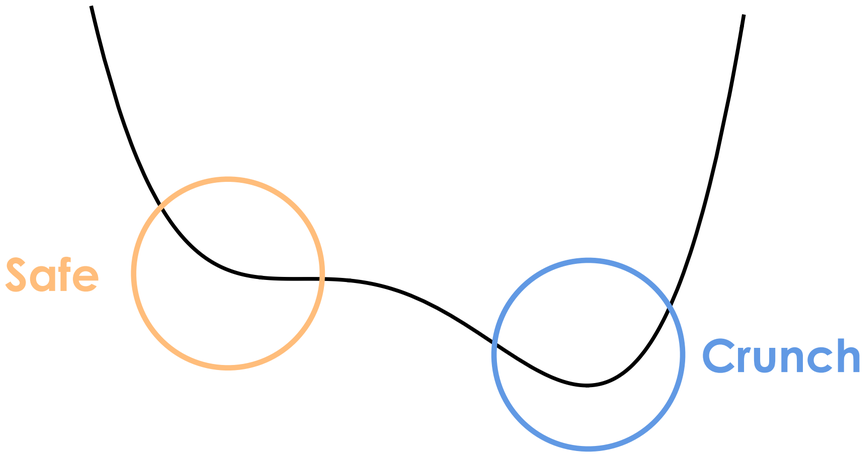


SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

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



SLIDING NATURALNESS

[**RTD**, Teresi] '21

$$V_{H\phi_\pm} = \left(\frac{\phi_-}{F_-} + \frac{\phi_+}{F_+} + \overline{\theta} \right) G\tilde{G}$$

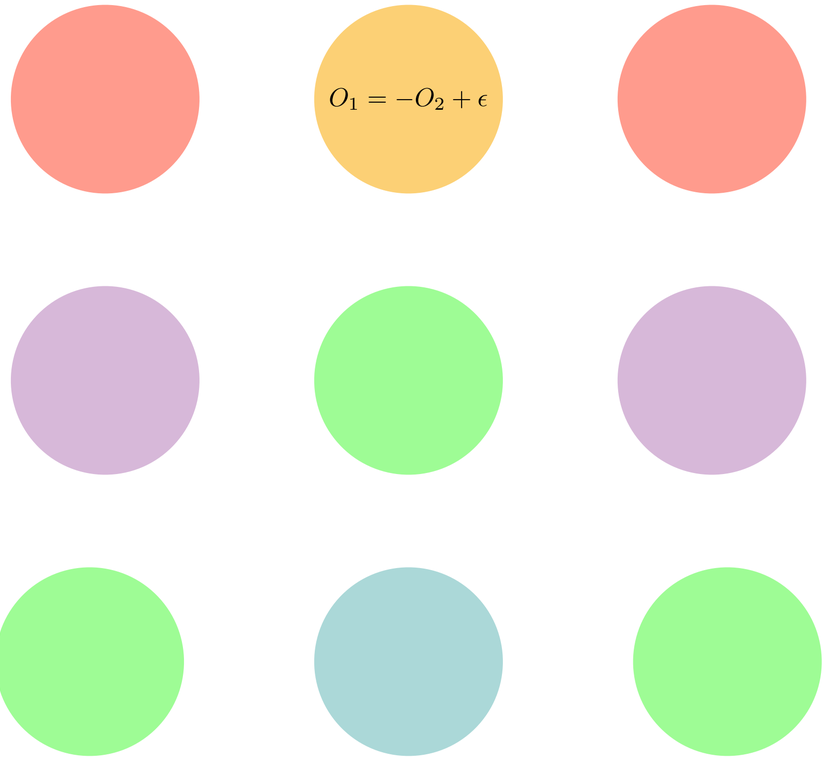
$\phi_\pm$

Symmetric Sector

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

$\phi_\pm G\tilde{G}$

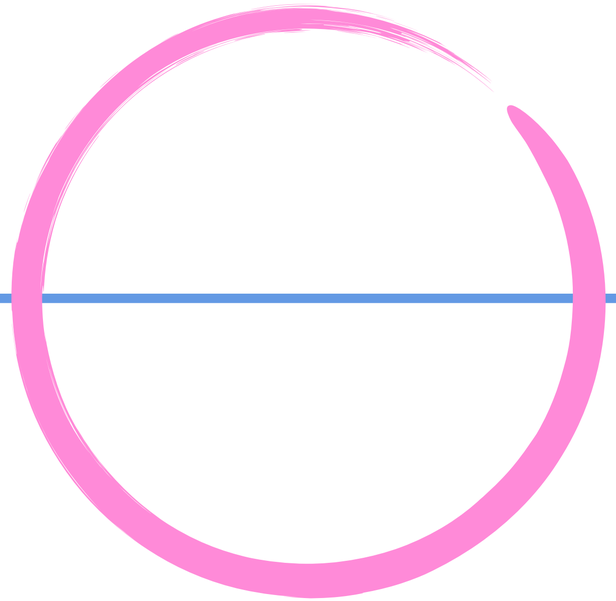
SM Landscape



HOW DO WE OBSERVE THIS GENERAL IDEA?

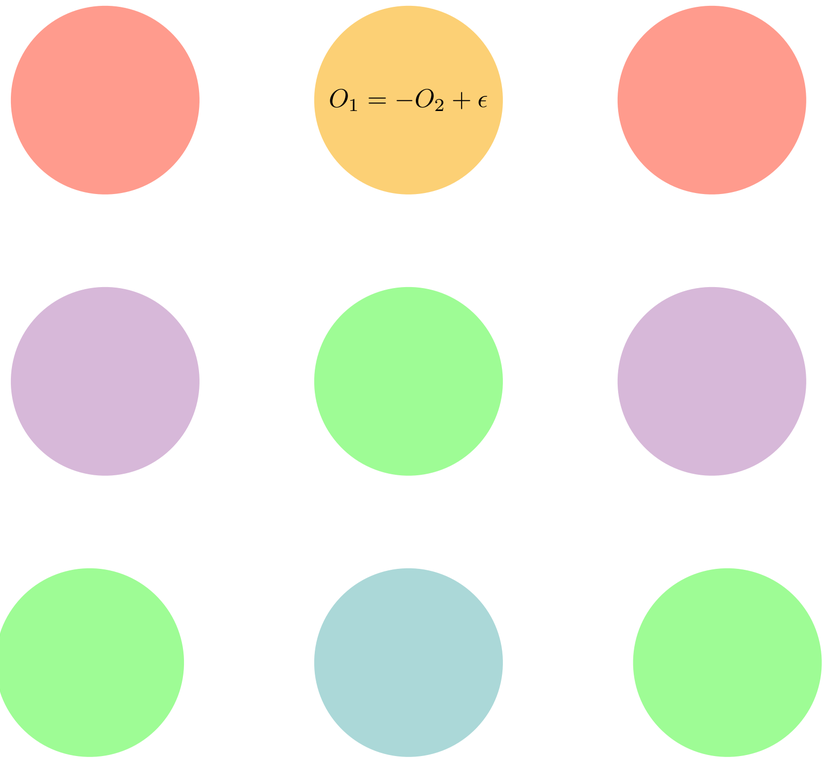
Symmetric Sector

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



Sensitive to the Higgs mass

SM Landscape



$G\widetilde{G}$

ALPs

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

$m \lesssim v \simeq 174$ GeV

HL-LHC!

$H_1 H_2$

$m \lesssim v \simeq 174$ GeV

HL-LHC!

WE DO NOT UNDERSTAND AT ALL

The size of the Universe

The mass of all known particles


Symmetry
+
Accident
Landscape
Beyond
local, unitary
QFTs


Symmetry
+
Accident
Landscape
Beyond
local, unitary
QFTs

BACKUP

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

Non-trivial!

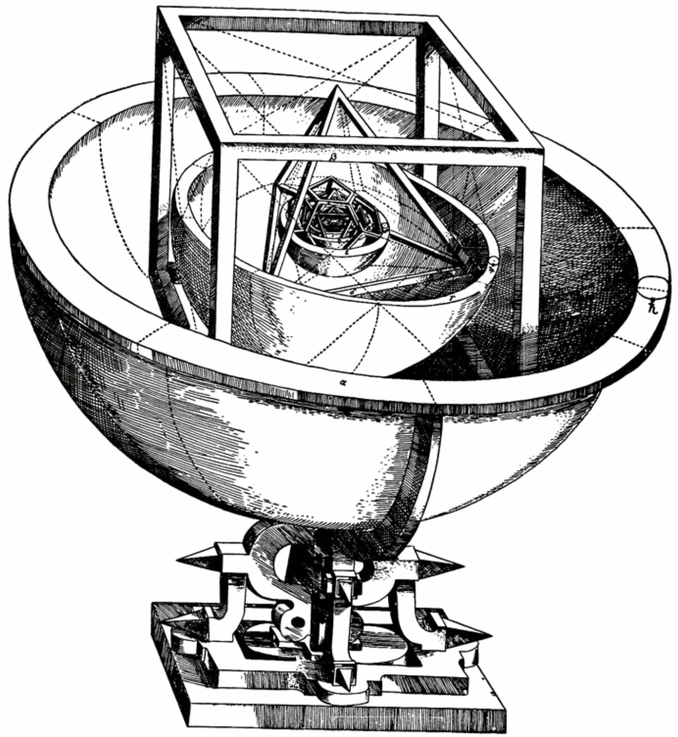
1. $U(1)_A$ breaking that can interfere with QCD instantons

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

Change of perspective:

Can we find their origin early in the history of the Universe?

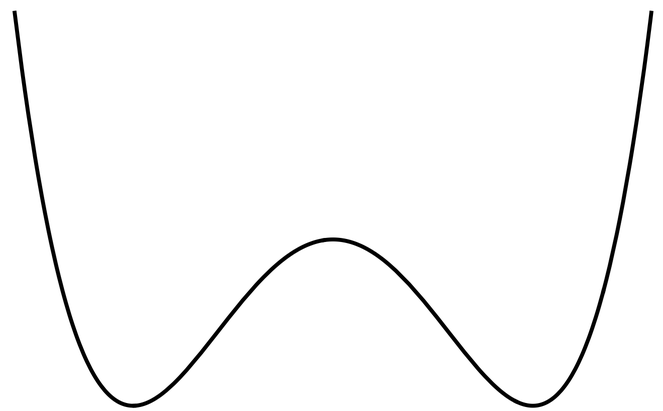
Mysterium Cosmographicum



SIMPLE UV COMPLETION

[**RTD**, Teresi] '21

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

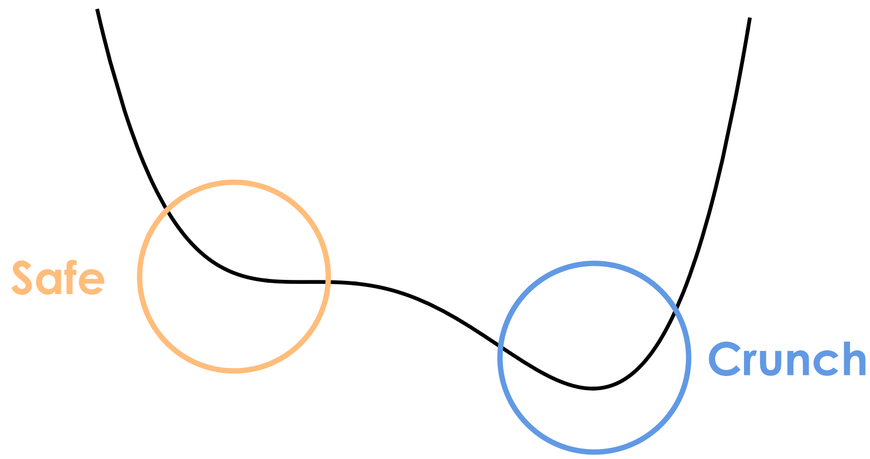


$\phi \sim L/\mu$ $\qquad$ $\phi \sim \mu/\lambda$

SIMPLE UV COMPLETION

[**RTD**, Teresi] '21

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



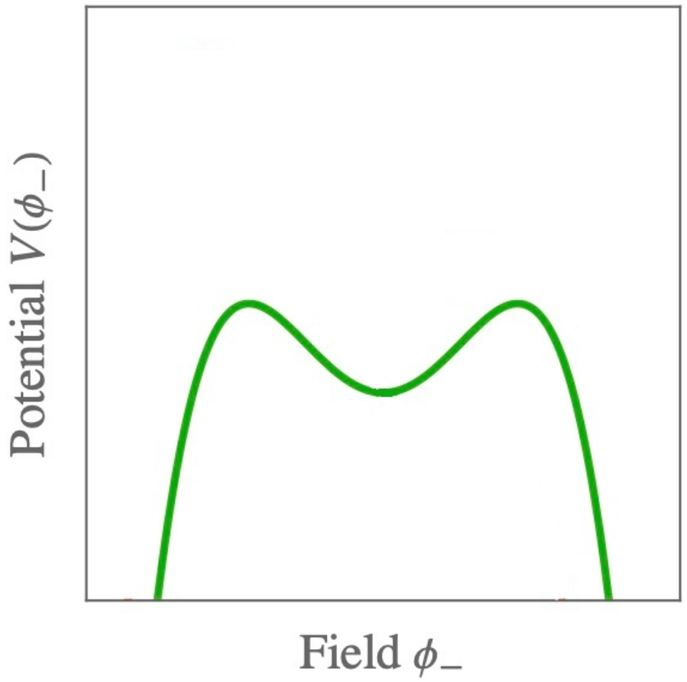
$$V_{\rm b} = \epsilon\mu\phi^3 + {\rm h.c.}$$

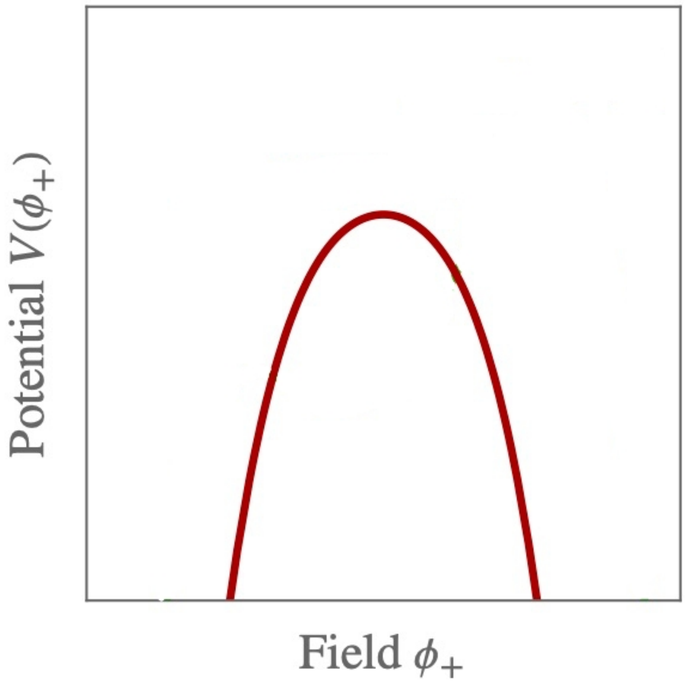
TOY MODEL (zoom in on shallow minimum)

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

TOY MODEL (zoom in on shallow minimum)

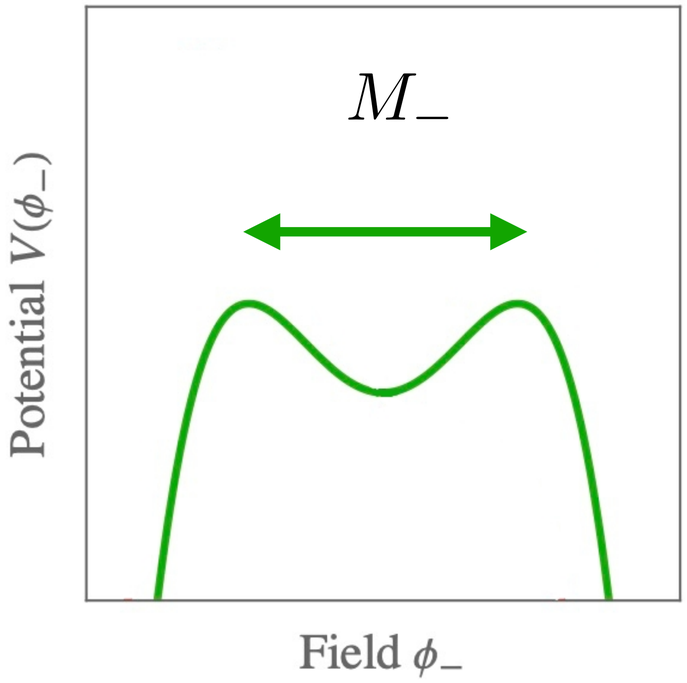
$$V_{\phi_\pm} = \mp \frac{m^2_{\phi_\pm}}{2} \phi^2_\pm - \frac{\lambda}{4} \phi^4_\pm$$

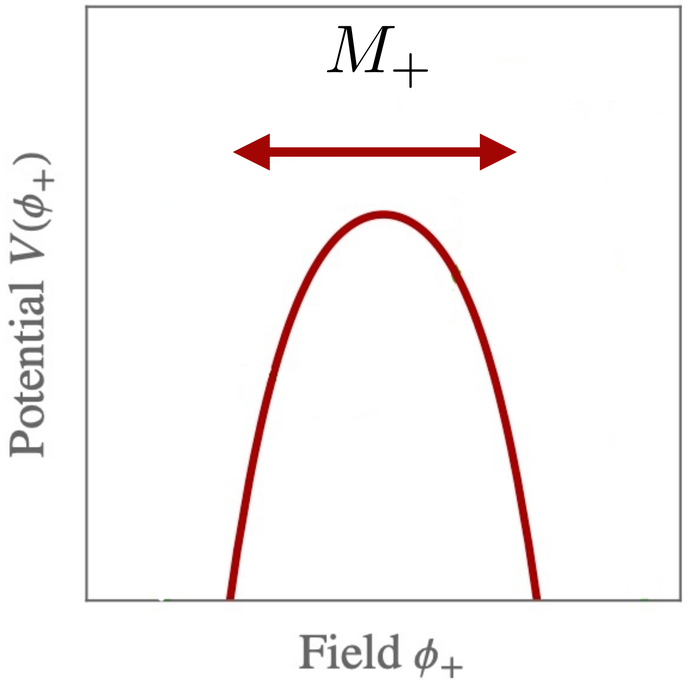




TOY MODEL (zoom in on shallow minimum)

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





SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

Small Breaking of Shift-Symmetry at low Energy

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

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

Familiar from QCD

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

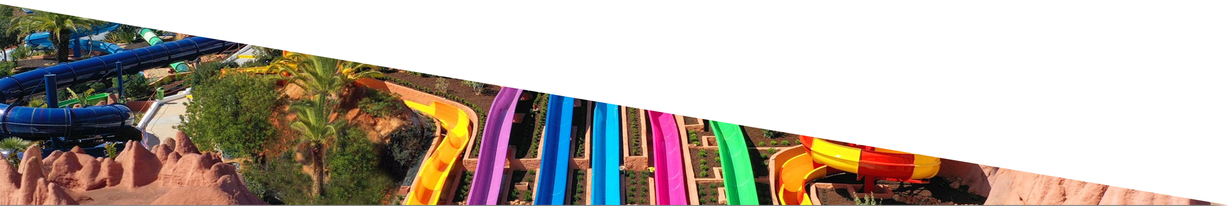
$$M_\pm \leftrightarrow m_q$$

SLIDING NATURALNESS

[**RTD**, Teresi] '21

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

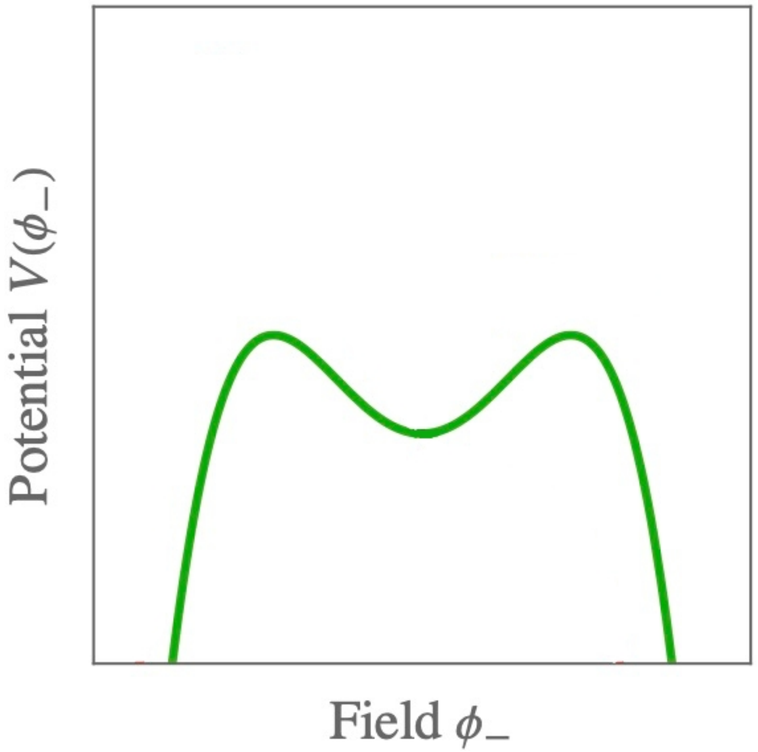
$$\simeq \Lambda^4_{\rm QCD}(\langle h\rangle)\left[\left(\theta\frac{\phi_+}{F_+} + \frac{\phi_+^2}{F_+^2}\right) + \theta\frac{\phi_-}{F_-} + ...\right]$$



SLIDING NATURALNESS

[**RTD**, Teresi] '21

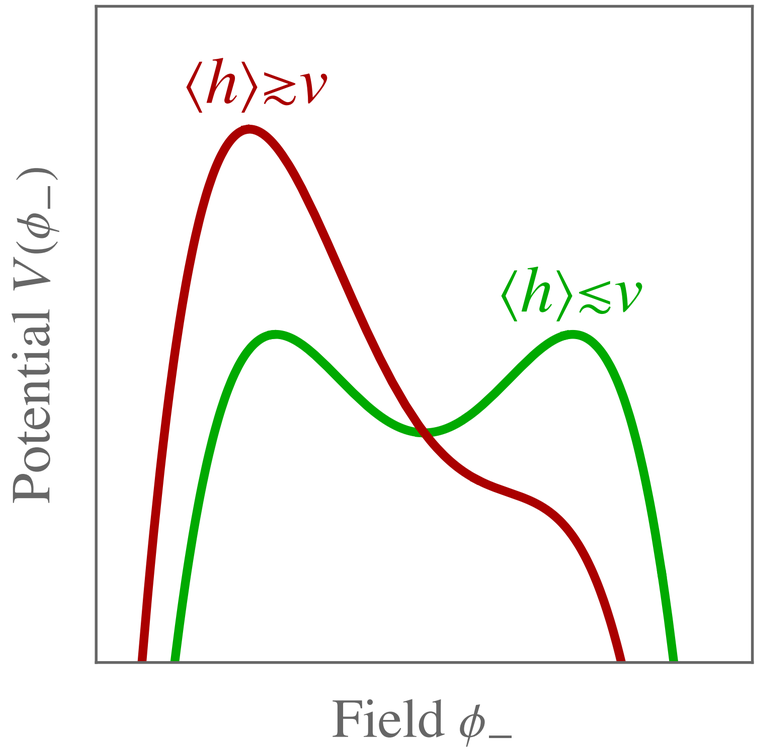
$$V_{H\phi_-} \simeq \theta_{\rm eff}\Lambda^4_{\rm QCD}(\langle h\rangle)\frac{\phi_-}{F_-}$$



SLIDING NATURALNESS

[**RTD**, Teresi] '21

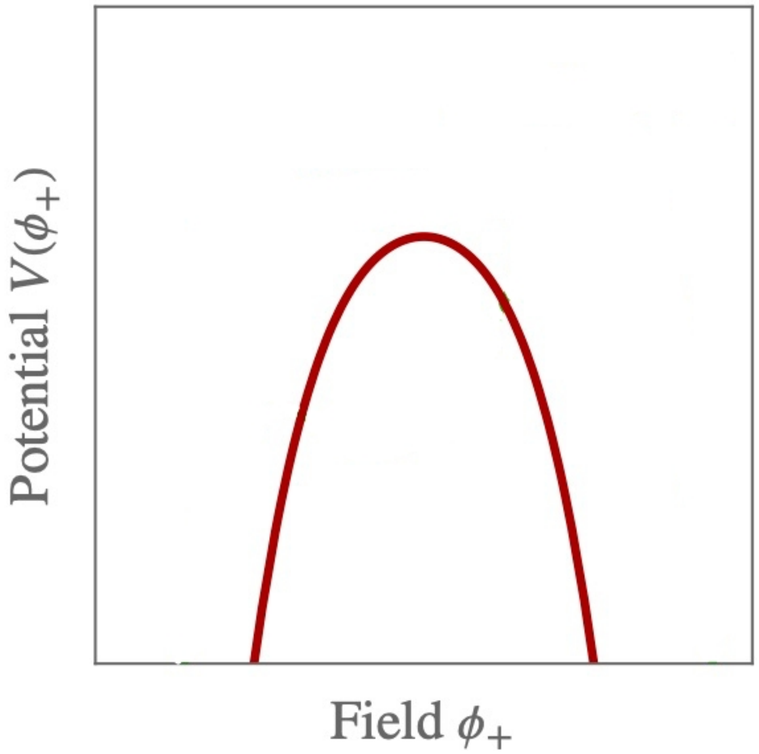
$$V_{H\phi_-} \simeq \theta_{\rm eff}\Lambda^4_{\rm QCD}(\langle h\rangle)\frac{\phi_-}{F_-}$$



SLIDING NATURALNESS

[**RTD**, Teresi] '21

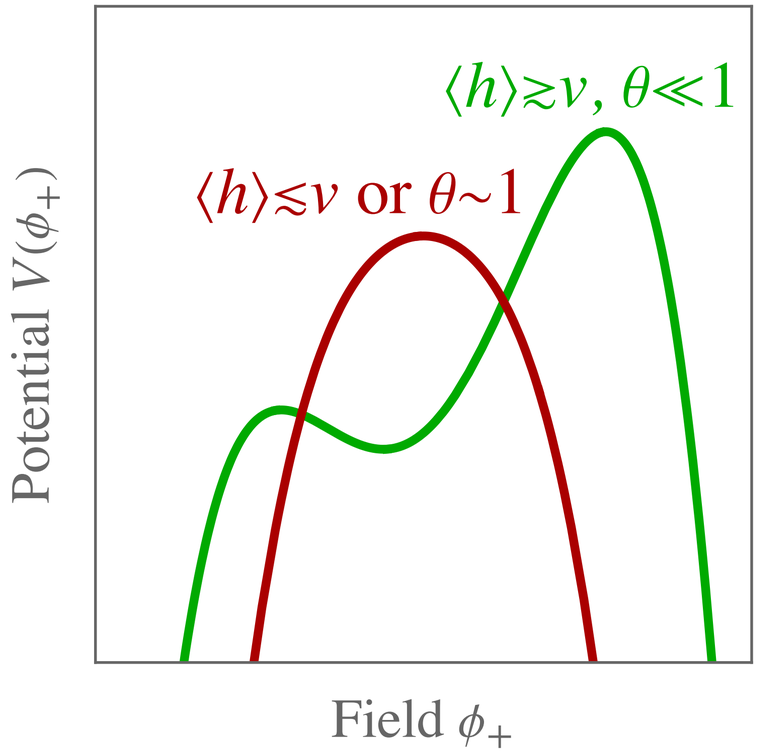
$$V_{H\phi_+} \simeq \Lambda^4_{\rm QCD}(\langle h \rangle) \left(\theta \frac{\phi_+}{F_+} + \frac{\phi_+^2}{F_+^2} \right)$$



SLIDING NATURALNESS

[**RTD**, Teresi] '21

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



SLIDING NATURALNESS

[**RTD**, Teresi] '21

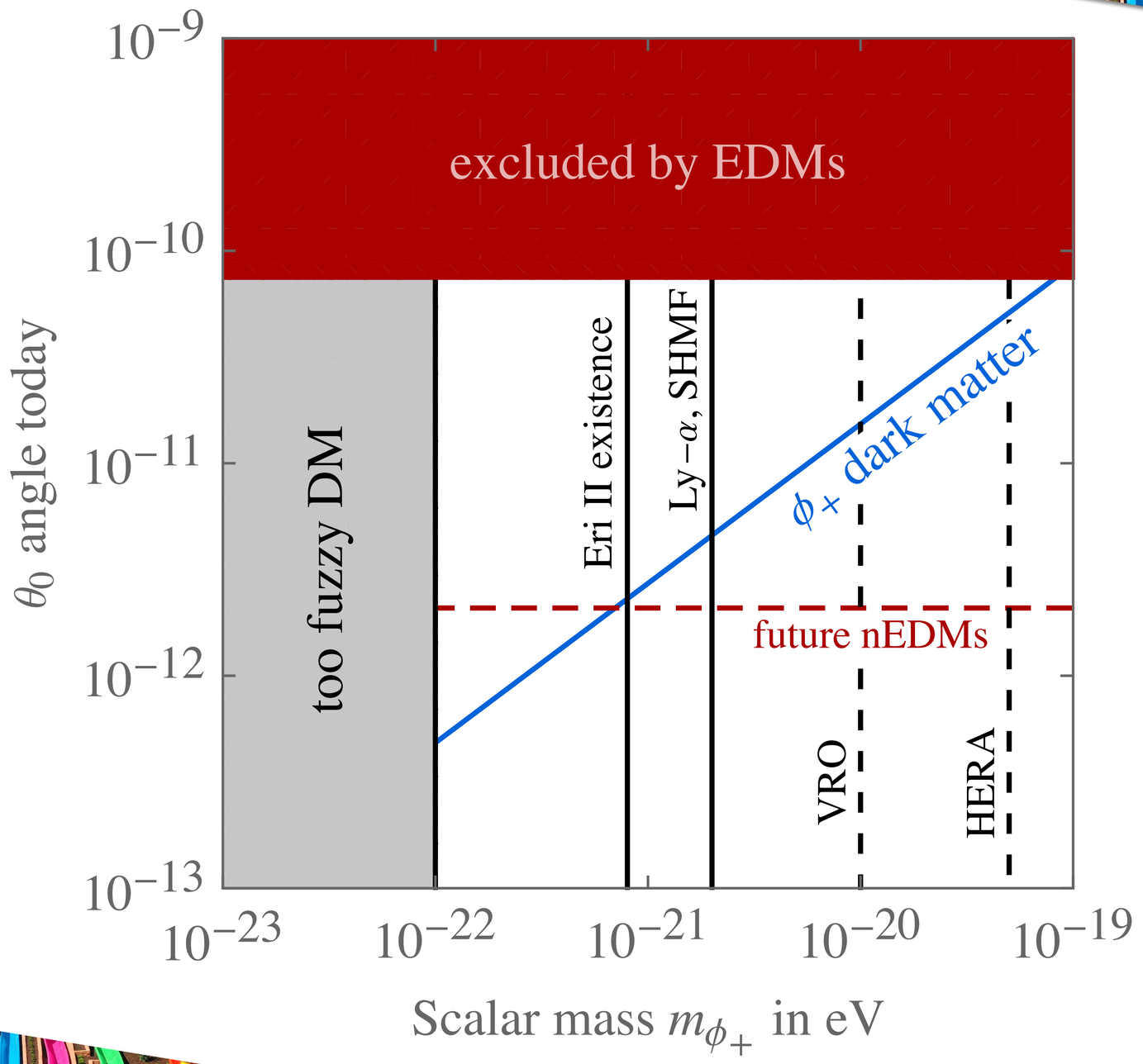
$$V_{\phi_\pm} = \mp \frac{m^2_{\phi_\pm}}{2}\phi^2_\pm - \frac{\lambda}{4}\phi^4_\pm$$

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

Solve Strong-CP and Hierarchy problem!

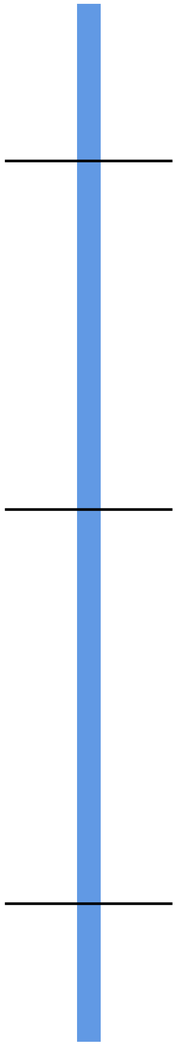
SLIDING NATURALNESS

[**RTD**, Teresi] '21



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

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

$M_\pm$

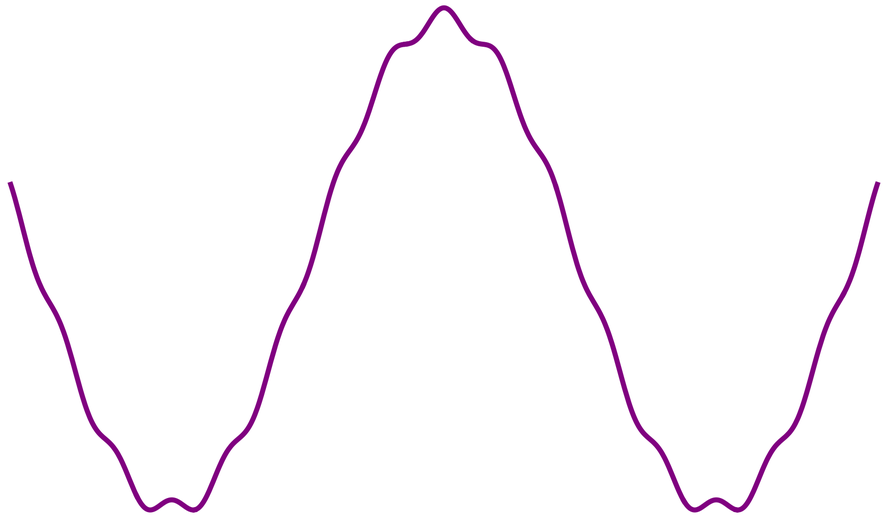
Breaks scale invariance
and shift symmetry

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

AN AXION THAT IS AN AXION

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

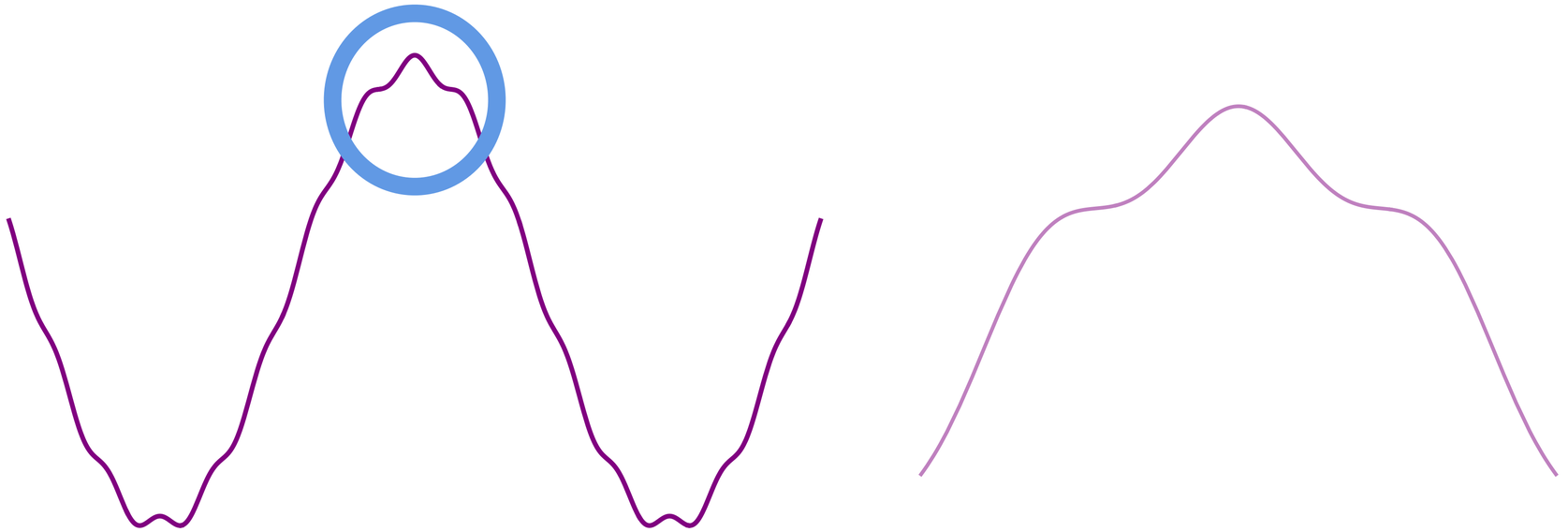
$$\Lambda_1 \gg \Lambda_2 \qquad\qquad f_1 \gg f_2$$



AN AXION THAT IS AN AXION

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

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



[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]

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

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

TYPE-0 2HDM

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

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

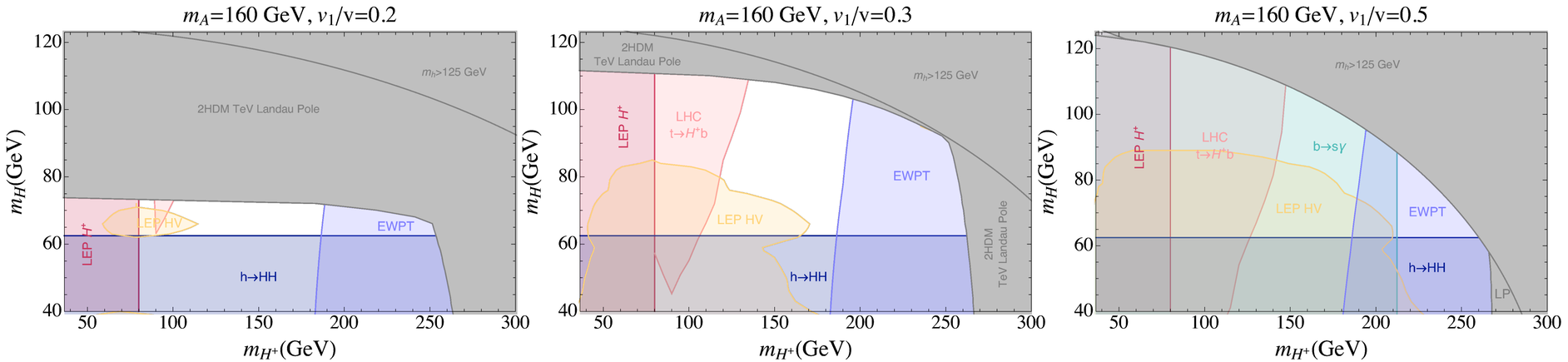
$$H_2 \to -H_2, \quad (qu^c) \to -(qu^c), \quad (qd^c) \to -(qd^c), \quad (le^c) \to -(le^c)$$

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]