Title: The Weak Scale as a Trigger Part I: Crunching Dilaton, Hidden Naturalness

Speakers: Raffaele Dâ€™Agnolo

Series: Particle Physics

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Abstract: I discuss a new approach to the Higgs naturalness problem, where the value of the Higgs mass is tied to cosmic stability and the possibility of a large observable Universe. The Higgs mixes with the dilaton of a CFT sector whose true ground state has a large negative vacuum energy. If the Higgs VEV is non-zero and below O(TeV), the CFT also admits a second metastable vacuum, where the expansion history of the Universe is conventional. As a result, only Hubble patches with unnaturally small values of the Higgs mass support inflation and post-inflationary expansion, while all other patches rapidly crunch. I will also comment on alternative realizations of the mechanism that do not require a CFT sector and have a simple perturbative description.

THE WEAK SCALE AS A TRIGGER

PART I: CRUNCHING DILATON, HIDDEN NATURALNESS

Raffaele Tit [illegible] IPhT Saclay

FINE-TUNING 101

A physical observable can be computed as the sum of multiple unrelated contributions

$$\mathcal{O} = O_1 + O_2 + ...$$

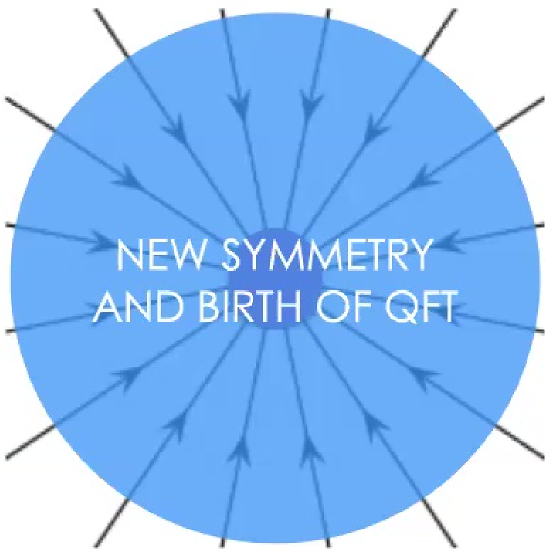
At least two of them are much larger than its observed value

$$\mathcal{O}_{\rm obs} \ll |\mathcal{O}_{1,2}|$$

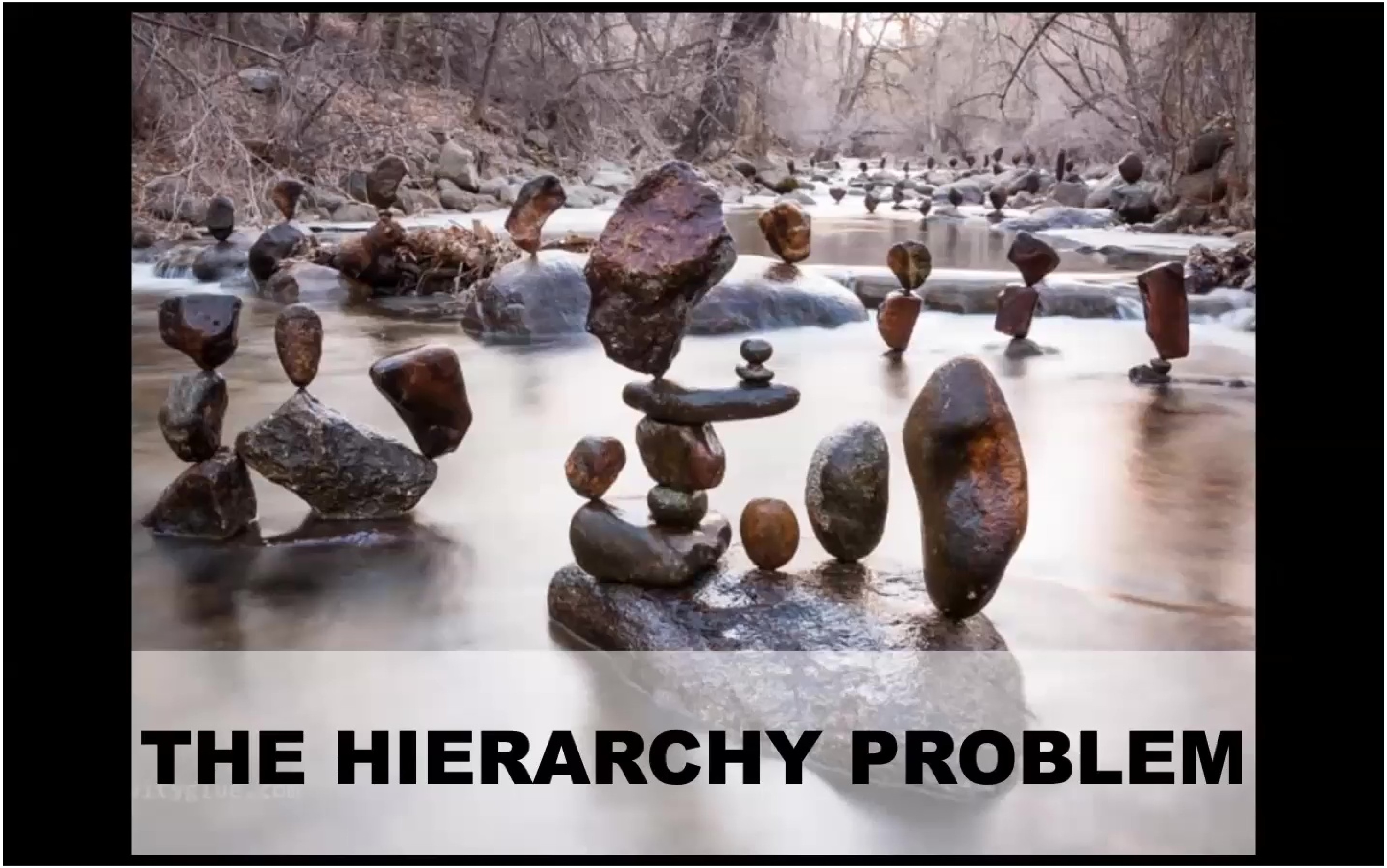
PAST FINE-TUNING PROBLEMS

Mysterium Cosmographicum

Electron Self-Energy



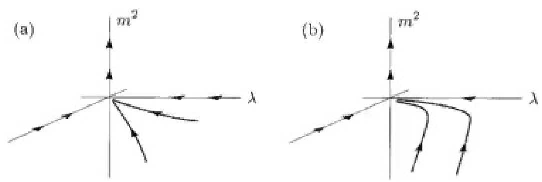
Both have paradigm-shifting resolutions


THE HIERARCHY PROBLEM

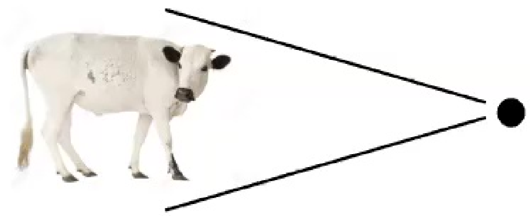
EFFECTIVE FIELD THEORIES

In Quantum Field Theory: Systematic way of integrating out high energy degrees of freedom to obtain a simplified low energy theory

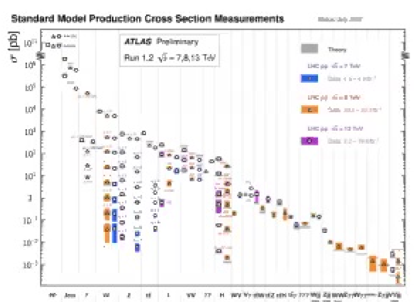
RENORMALIZATION



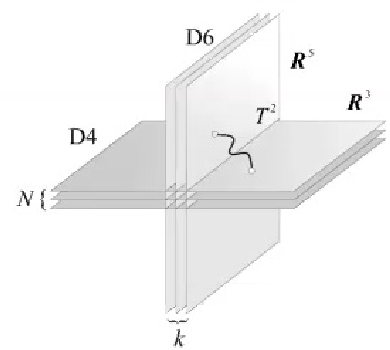
SYMMETRIES FROM COARSE GRAINING



PRECISION CALCULATIONS



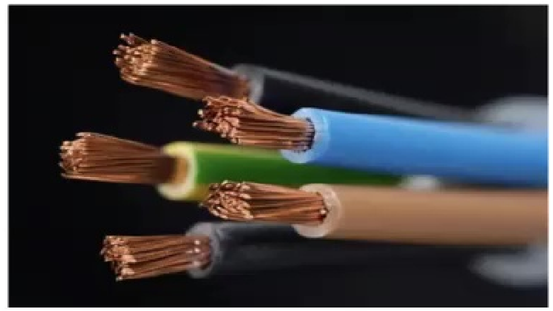
QFT INSIGHTS FROM STRING THEORY



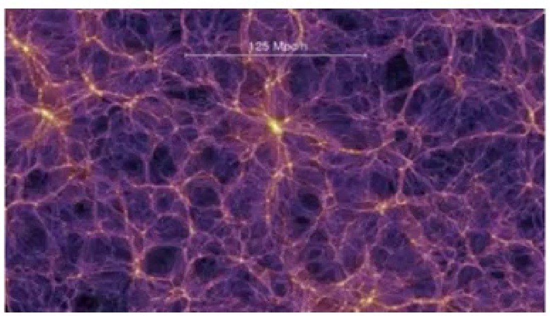
ONE TOOL FOR MULTIPLE APPLICATIONS

POST-NEWTONIAN EXPANSIONS

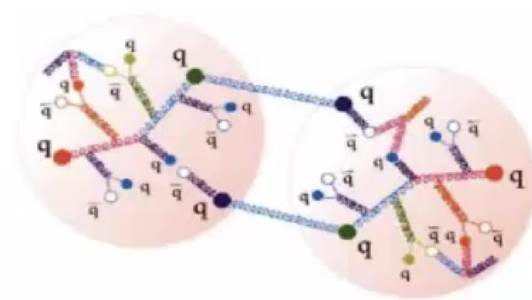
LANDAU THEORY OF FERMI LIQUIDS



LARGE SCALE STRUCTURE



CHIRAL PERTURBATION THEORY



THE HIERARCHY PROBLEMS

Take a heavy mass scale [Gravity] and apply this procedure of integrating out:

SIZE OF THE UNIVERSE ~ 10^{-60} observed

HIGGS BOSON MASS ~ 10^{16} observed

THE HIERARCHY PROBLEMS

Take a heavy mass scale [Gravity] and apply this procedure of integrating out:

These answers are based on something more fundamental than the procedure itself: Symmetry

$\sim 10^{-60}$ observed

$\sim 10^{16}$ observed

HIGGS MASS EXPLANATIONS

There is only a handful of conceptually distinct ways in which we know how to solve the problem. All have deep implications for our understanding of Nature.

1. Symmetry
2. Lower the cut-off
3. Multiverse + Anthropic selection
4. Nnaturalness [Arkani-Hamed, Cohen, **RTD**, Hook, Kim, Pinner]
5. Dynamical Selection — Last five years

6.* Gravity does not compute in a Wilsonian way

TODAY'S TALK

Crunching Dilaton, Hidden Naturalness

[Csaki, **RTD**, Geller, Ismail] '20

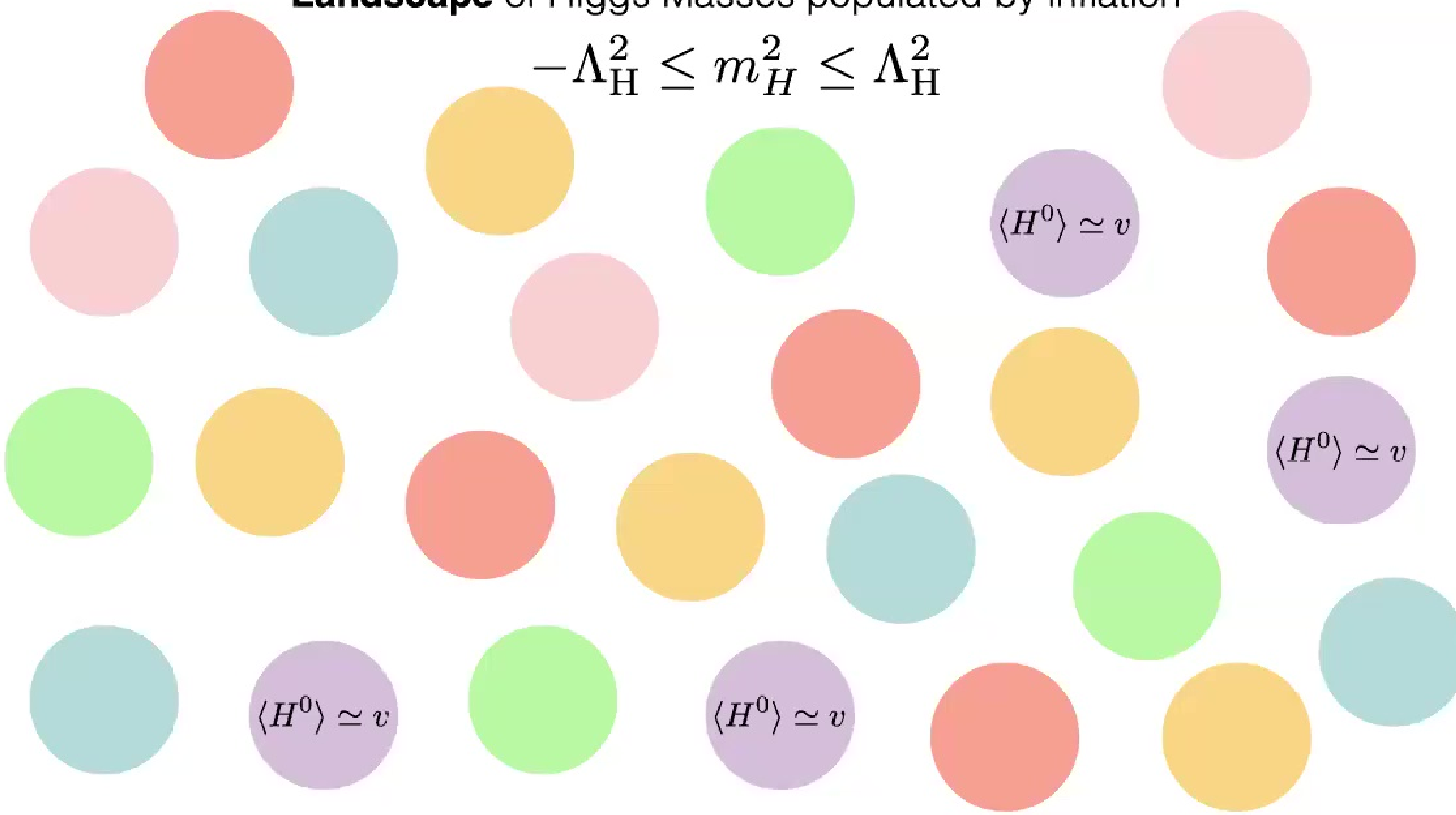
1. Symmetry
2. Lower the cut-off
3. Multiverse + Anthropic selection
4. Nnaturalness [Arkani-Hamed, Cohen, **RTD**, Hook, Kim, Pinner] '16
5. Dynamical Selection

6.* Gravity does not compute in a Wilsonian way

BASIC PICTURE

Landscape of Higgs Masses populated by inflation

$$-\Lambda_{\rm H}^2 \leq m_H^2 \leq \Lambda_{\rm H}^2$$



BASIC PICTURE

After a time

$$t_c < M_{\rm Pl}/\Lambda_{\rm H}^2$$

All patches where the Higgs vev

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

Is outside of a certain range

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

crunch

$\langle H^0 \rangle \simeq v$

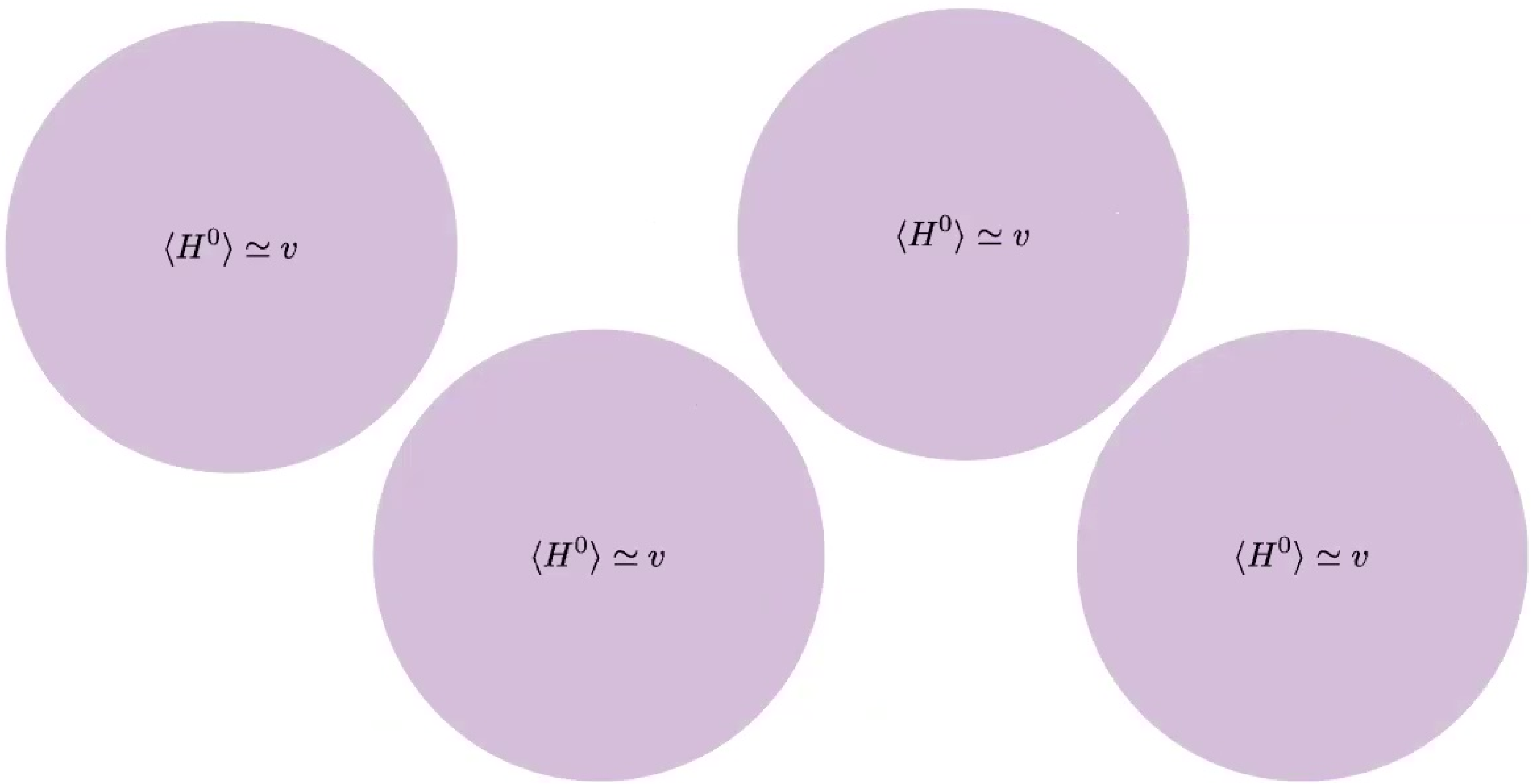
$\langle H^0 \rangle \simeq v$

$\langle H^0 \rangle \simeq v$

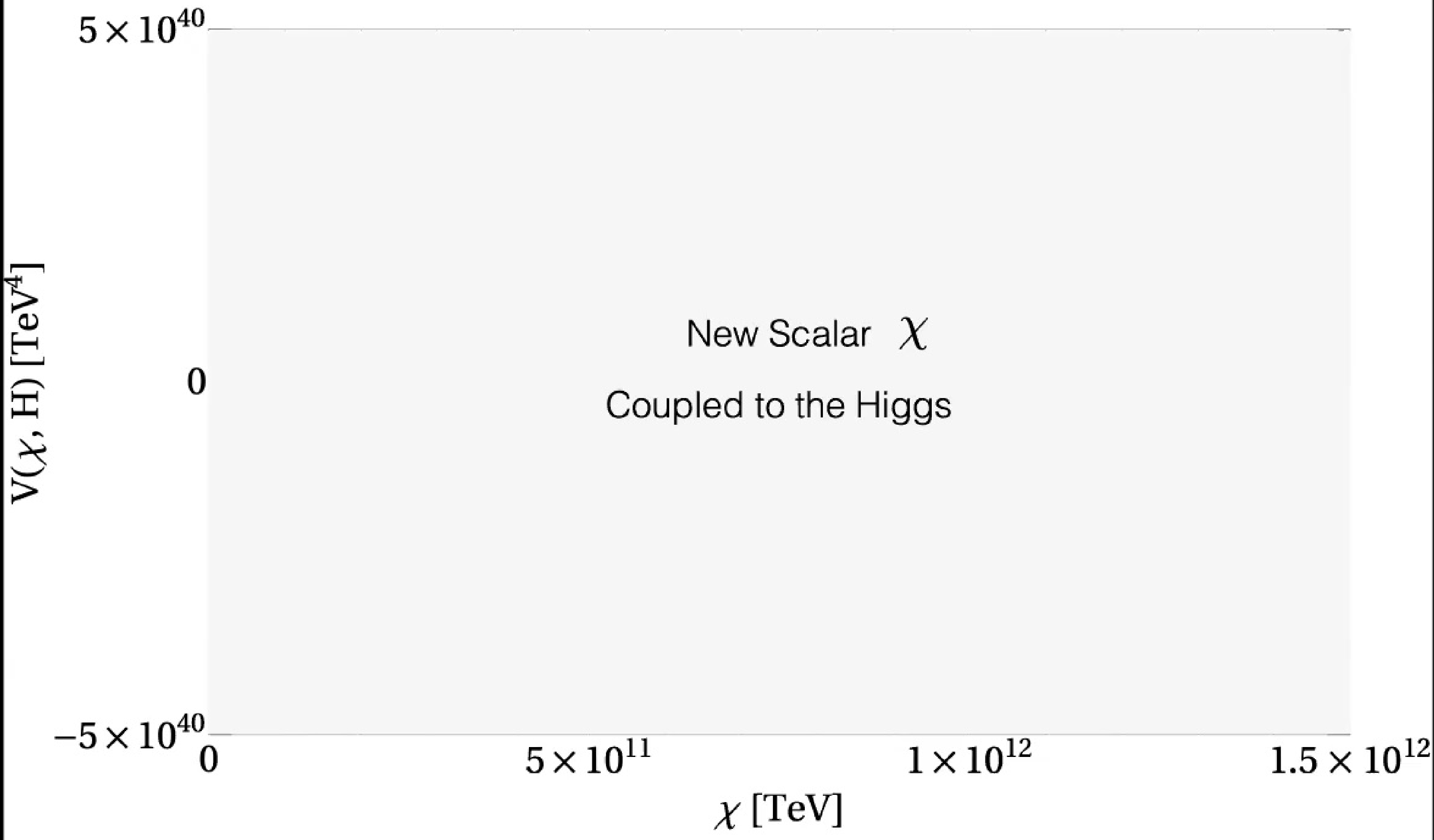
$\langle H^0 \rangle \simeq v$

BASIC PICTURE

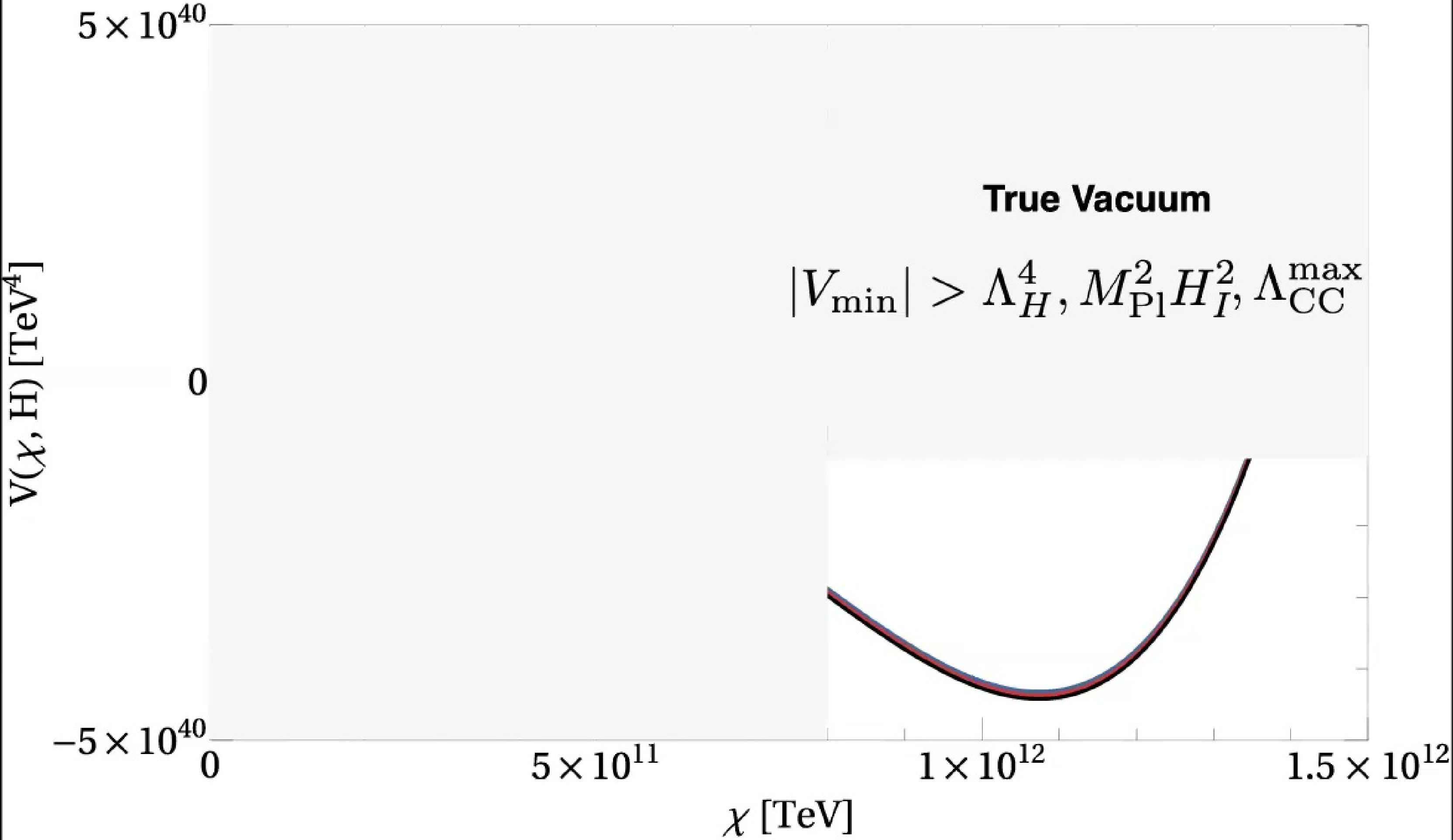
Only universes with the observed value of the weak scale can live longer than a Planck time and inflate. **Today the multiverse looks like**:



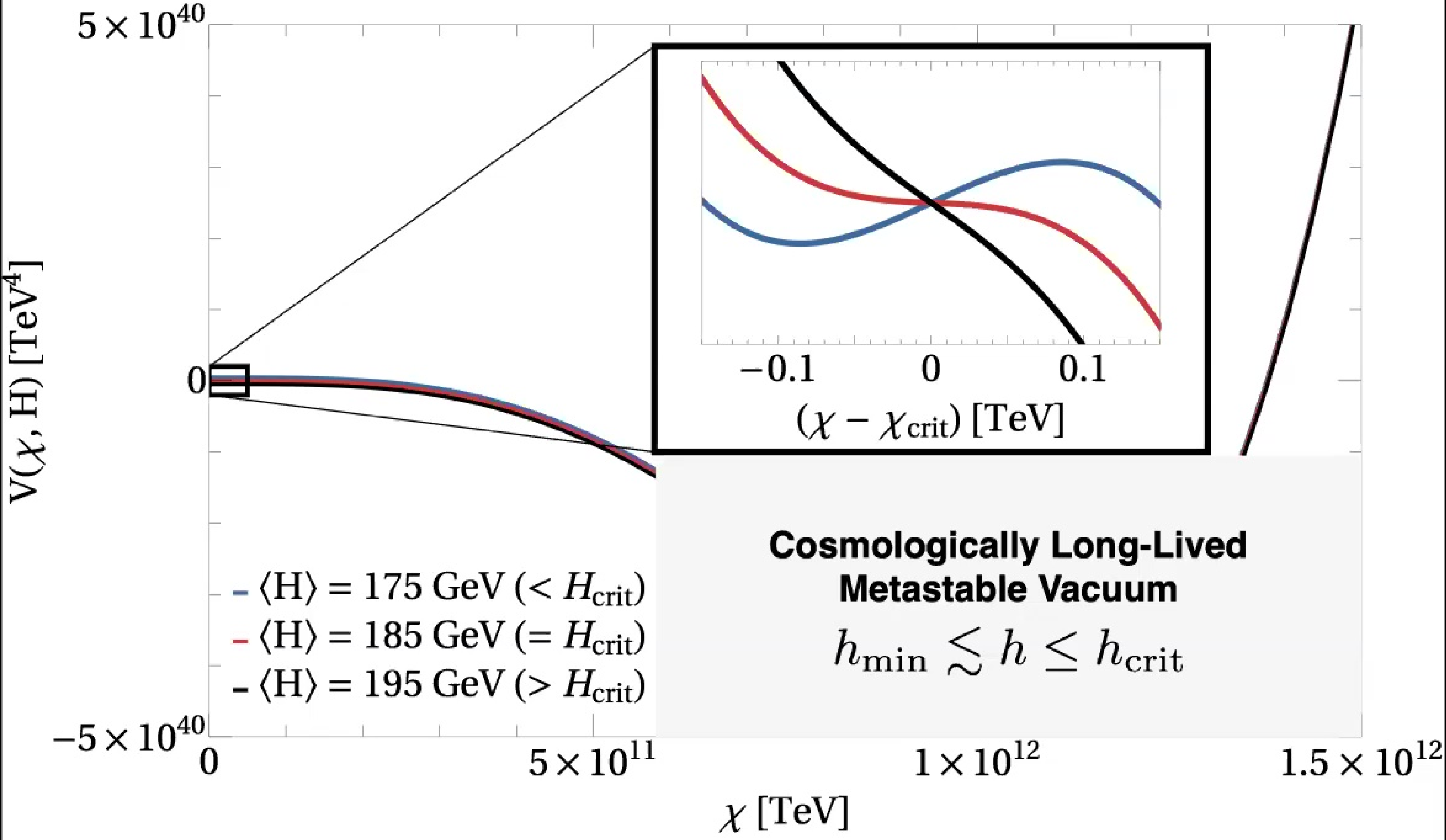
CRUNCHING MECHANISM



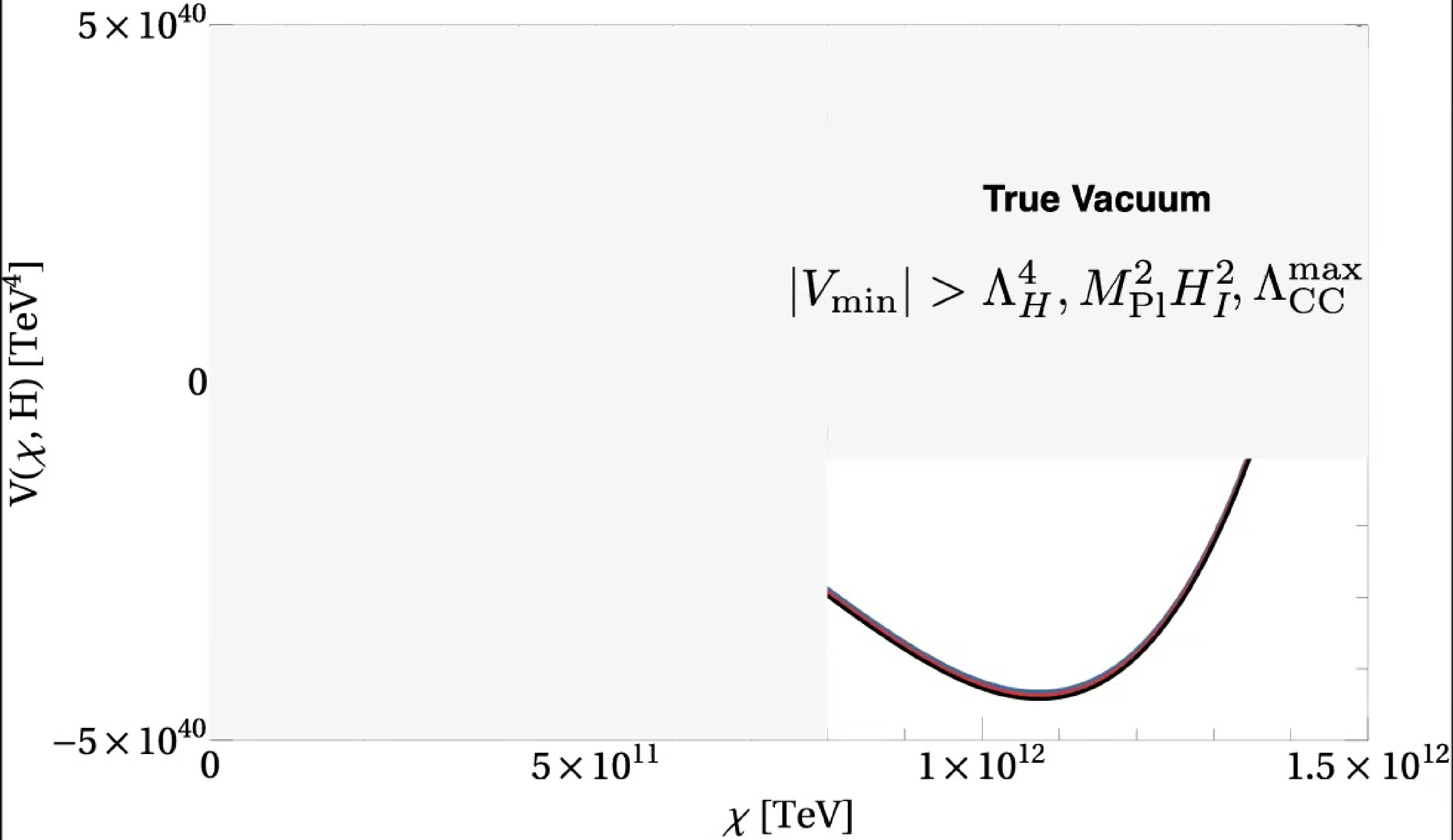
CRUNCHING MECHANISM



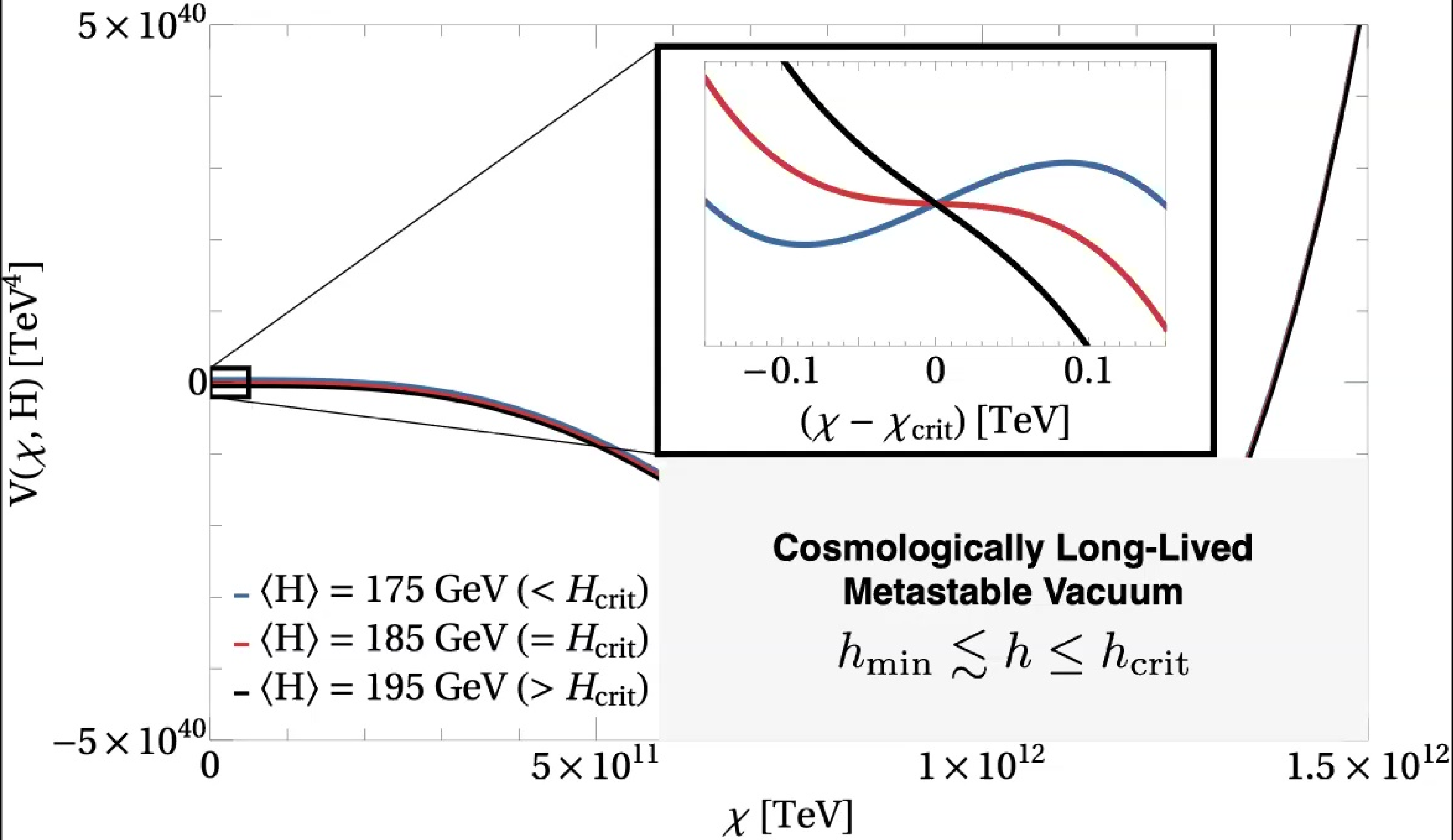
CRUNCHING MECHANISM



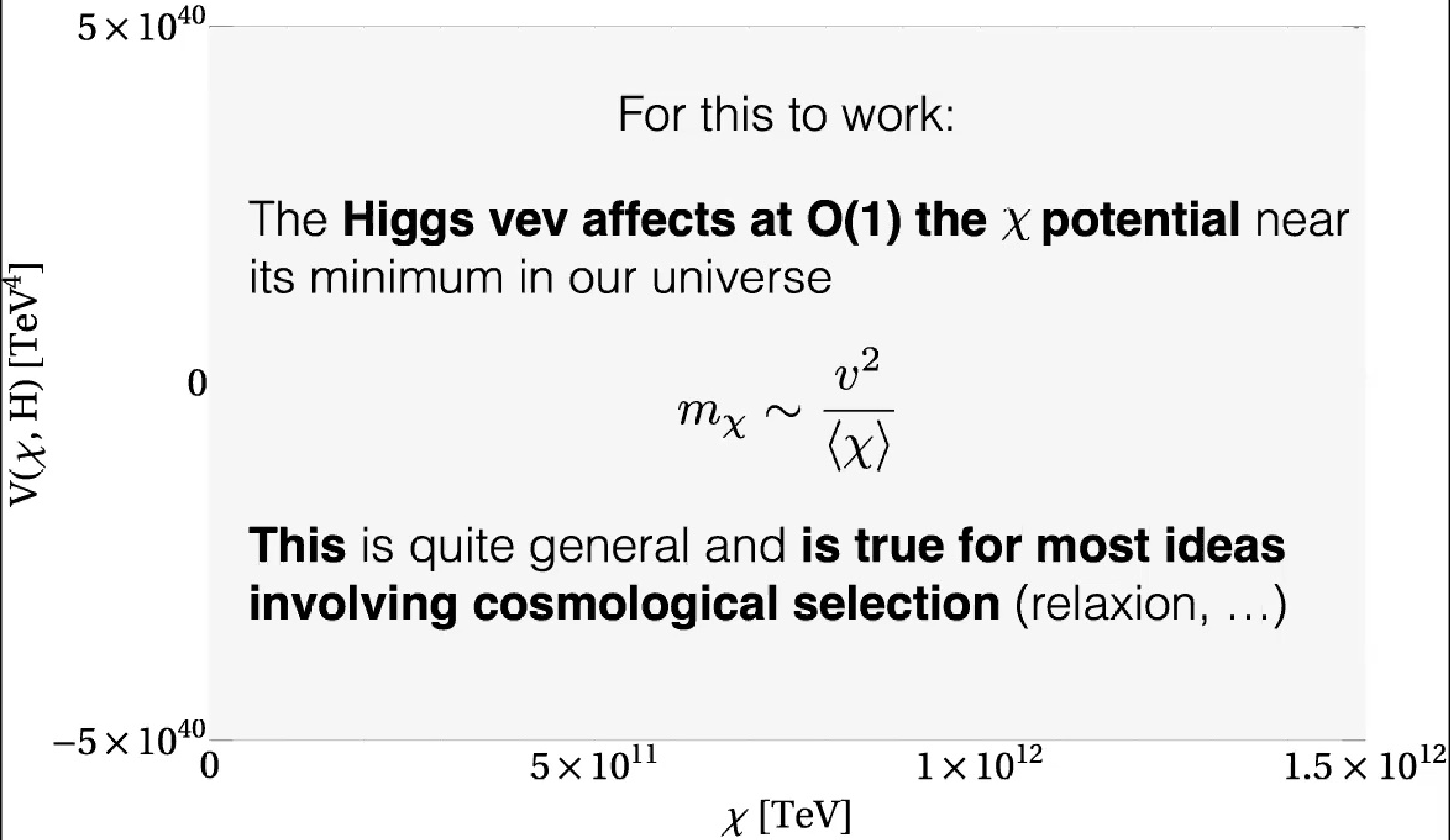
CRUNCHING MECHANISM



CRUNCHING MECHANISM



CRUNCHING MECHANISM



For this to work:

The **Higgs vev affects at O(1) the χ potential** near its minimum in our universe

$$m_\chi \sim \frac{v^2}{\langle \chi \rangle}$$

This is quite general and **is true for most ideas involving cosmological selection** (relaxion, …)

CRUNCHING POTENTIAL FROM ADS

$$ds^2 = \left(\frac{R}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

SM

H, W, Z, γ

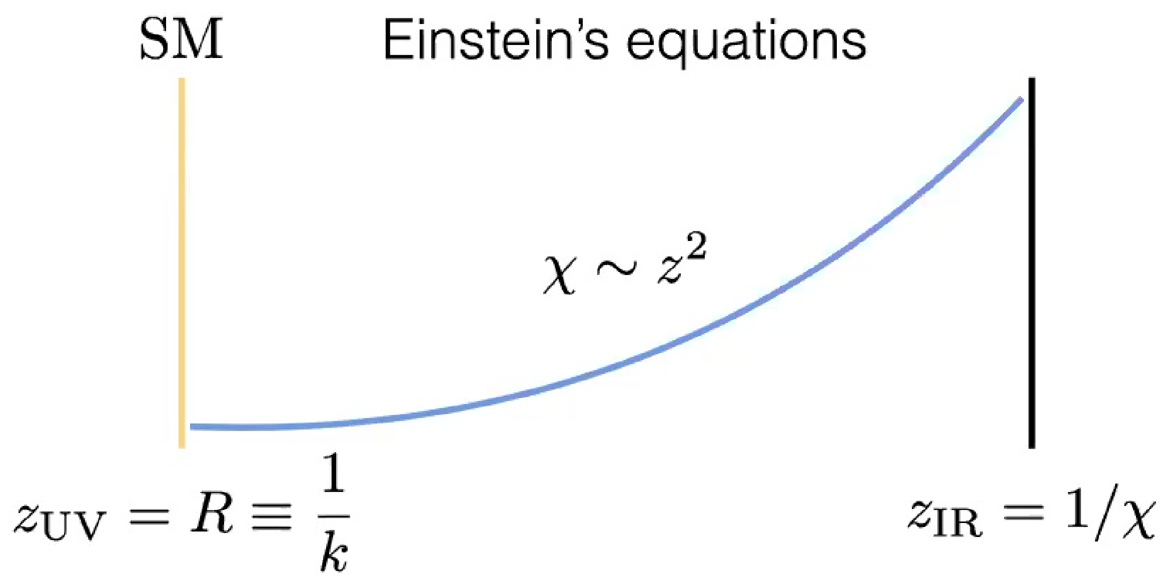
ϕ_{GW}

$z_{\mathrm{UV}} = R \equiv \frac{1}{k}$

$z_{\mathrm{IR}} = 1/\chi$

CRUNCHING POTENTIAL FROM ADS

$$ds^2 = \left(\frac{R}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$



CRUNCHING POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

Usual GW stabilization of the dilaton

$$V_{\rm GW}(\chi) = -\lambda\chi^4 + \lambda_{\rm GW}\frac{\chi^{4+\delta}}{k^\delta}$$

Scale invariant (detuning of brane and bulk tension)

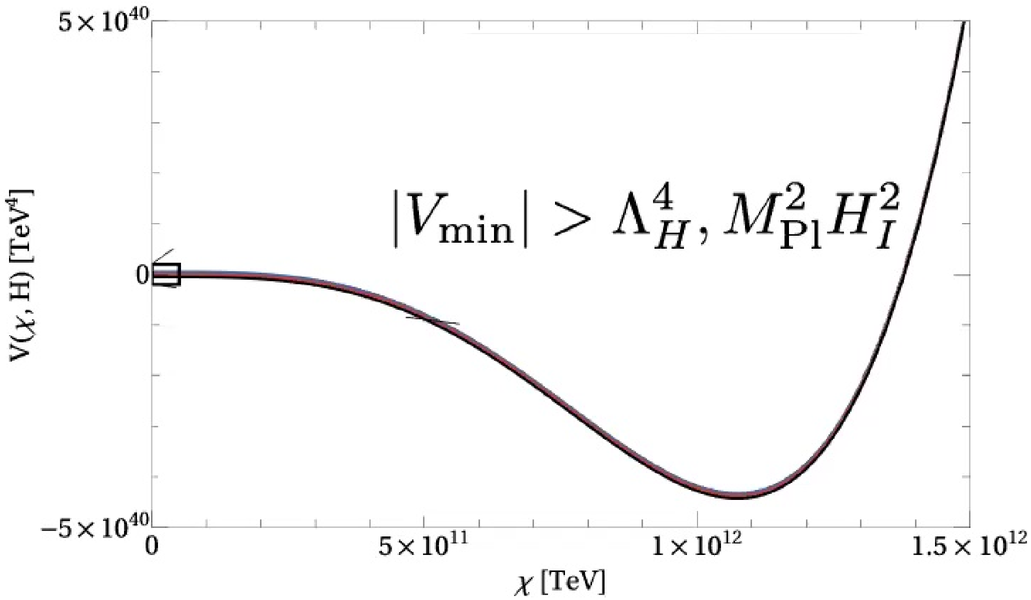
Breaking of scale invariance from GW scalar mass

$$\delta = \frac{m_{GW}^2 z_{\rm UV}^2}{4}$$

CRUNCHING POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

Usual GW stabilization of the dilaton



CRUNCHING POTENTIAL

$$V(\chi, H) = V_{\mathrm{GW}}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

Higgs UV brane Potential

$$V_H(H) = -m_H^2|H|^2 + \lambda_H|H|^4$$

The Higgs mass is scanning in the landscape

CRUNCHING POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

Generation of a metastable minimum around a TeV

$$V_{H\chi}(\chi, H) = \lambda_2 |H|^2 \frac{\chi^{2+\alpha}}{k^\alpha} - \lambda_{H\epsilon}|H|^2 \frac{\chi^{2+\alpha+\epsilon}}{k^{\alpha+\epsilon}} - \lambda_4 |H|^4 \frac{\chi^{2\alpha}}{k^{2\alpha}}$$

Localized Higgs mass

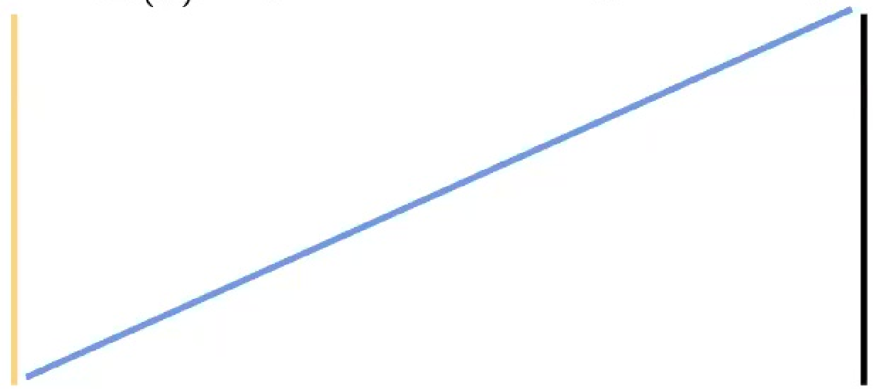
Interaction with GW scalar

Localized Higgs quartic

CRUNCHING POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

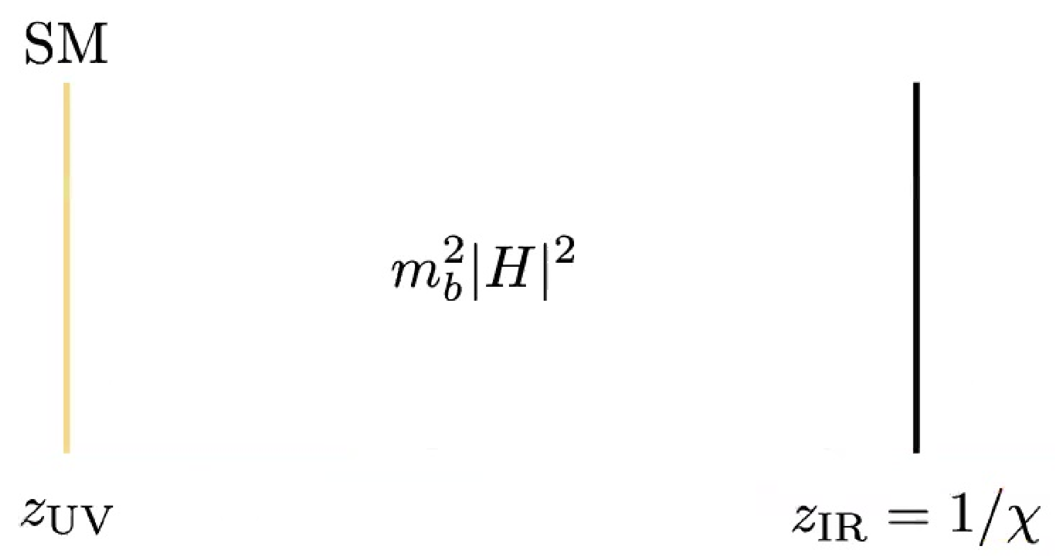
SM $\quad H(z) \sim z^{2-\sqrt{4+m_b^2 R^2}} \equiv z^{1-\alpha/2} \simeq z$



$$|H_{\rm IR}|^2 \longrightarrow |H_{UV}|^2 \chi^{2+\alpha}$$

CRUNCHING POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$



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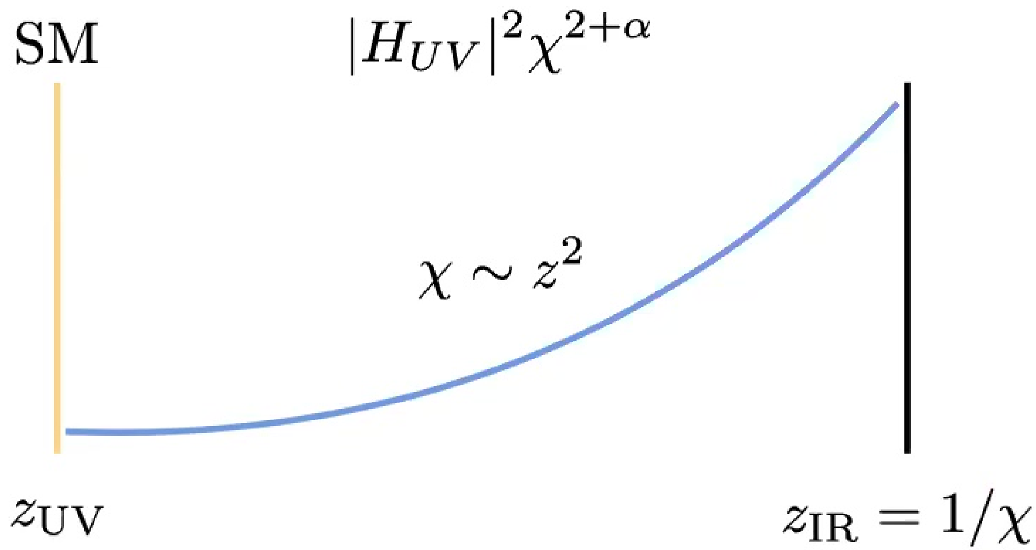
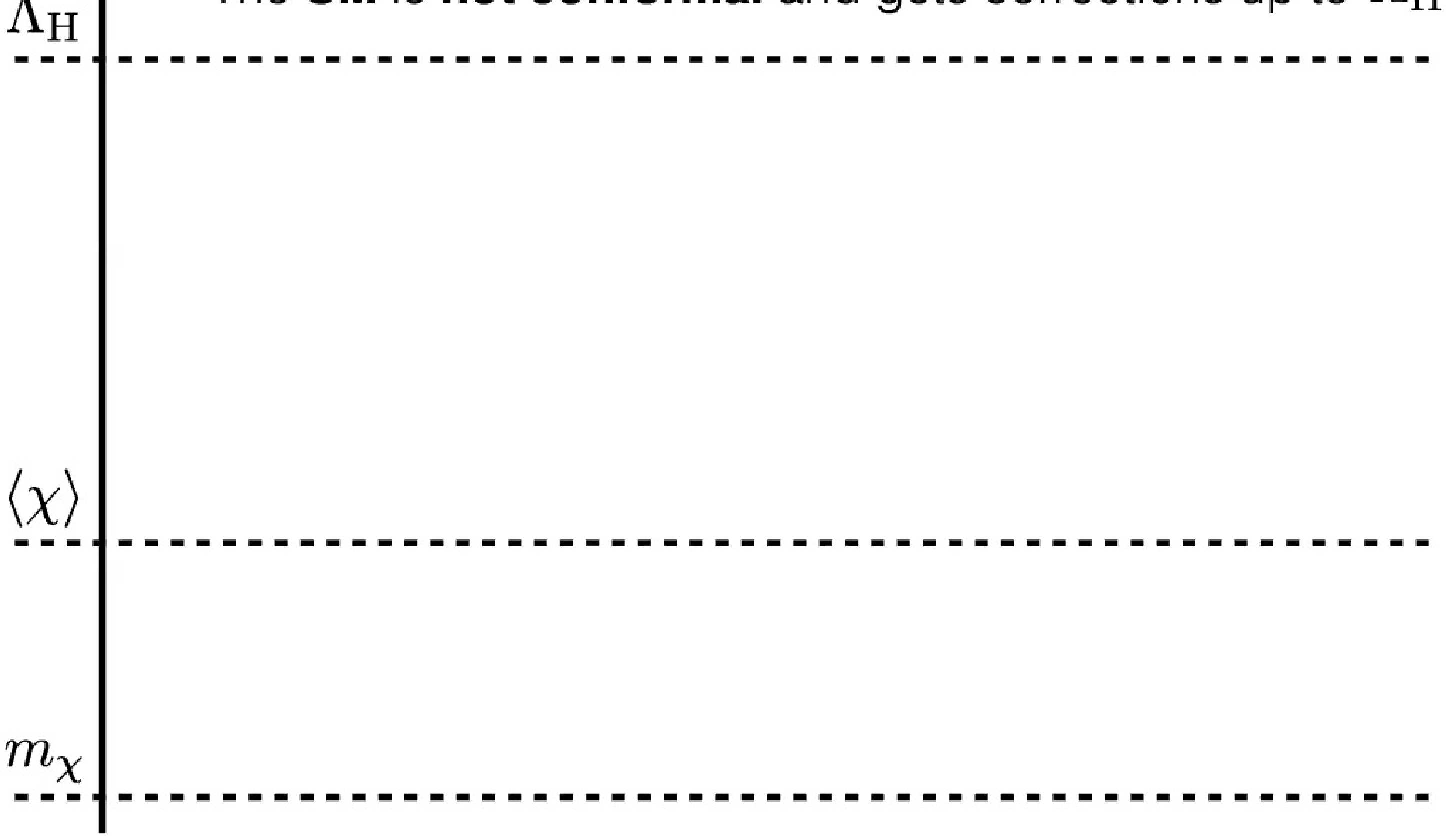


Warping Trick: **the dilaton is sensitive to the Higgs vev** because loops in the **UV** are **redshifted to the weak scale** in the IR

CFT INTERPRETATION

(broken) CFT down to a scale $\langle \chi \rangle$

The **SM** is **not conformal** and gets corrections up to Λ_H



CFT INTERPRETATION

(broken) CFT down to a scale $\langle \chi \rangle$

Λ_{H}

The **SM** is **not conformal** and gets corrections up to Λ_{H}

$\mathcal{O}_H$, $\Delta_H = 3 + \alpha/2$ $SU(2)_L$ Doublet

$\mathcal{O}_\epsilon$, $\Delta_\epsilon = 4 + \epsilon$ $SU(2)_L$ Singlet

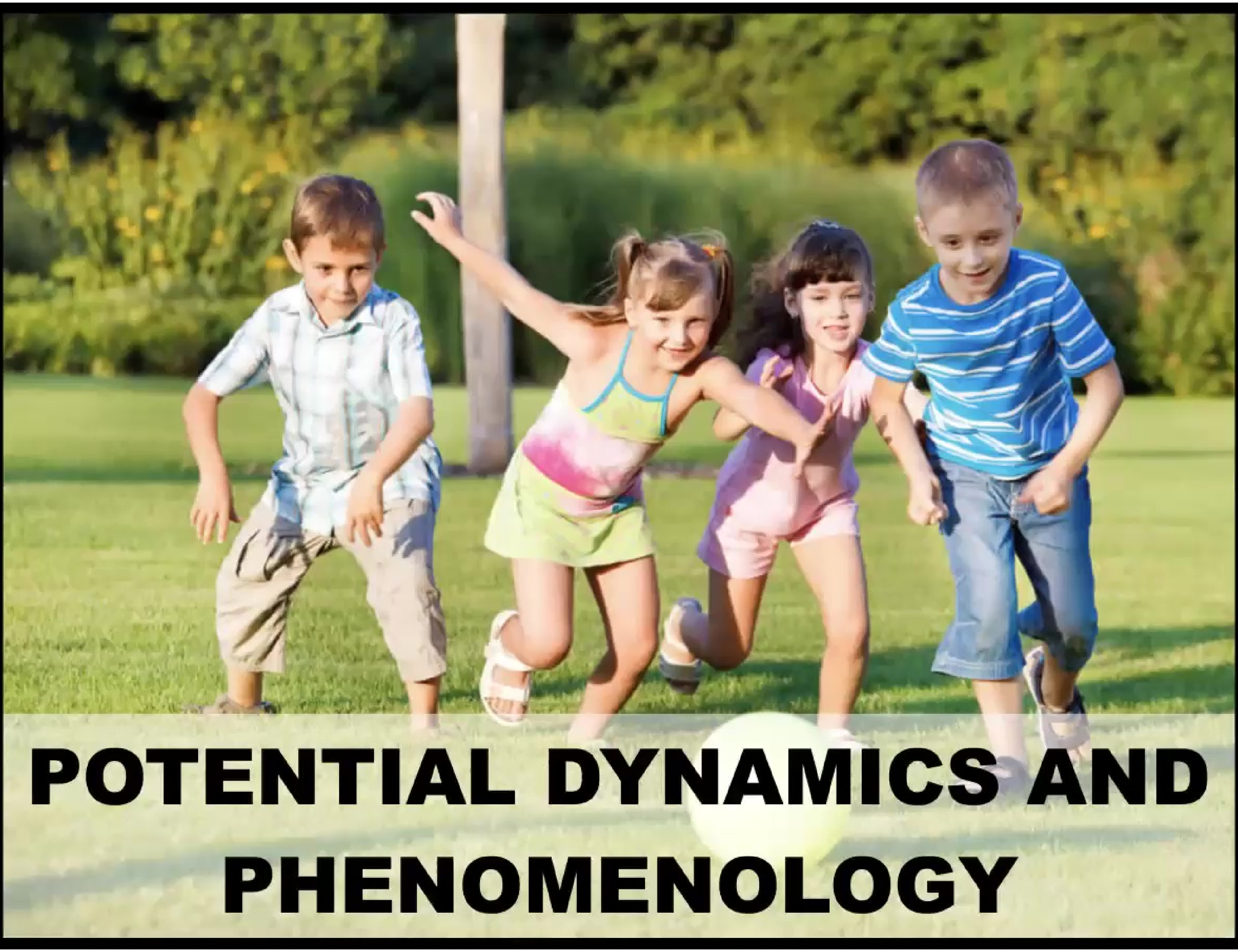
$$\tilde{\lambda}_H \mathcal{O}_H^\dagger H + \tilde{\lambda}_\epsilon \mathcal{O}_\epsilon$$

$\langle \chi \rangle$

Gap between m_χ and $\langle \chi \rangle$

$$V_{\mathrm{eff}} = a_0 \chi^4 + a_1 \tilde{\lambda}_H^2 H^2 \chi^{2+\alpha} + a_2 \tilde{\lambda}_H^4 H^4 \chi^{2\alpha} + a_3 \tilde{\lambda}_\epsilon \chi^{4+\epsilon} + a_4 \tilde{\lambda}_\epsilon \tilde{\lambda}_H^2 H^2 \chi^{2+\alpha+\epsilon}$$

m_χ


POTENTIAL DYNAMICS AND
PHENOMENOLOGY

DYNAMICS OF THE DILATON POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

For simplicity take the GW potential such that at the metastable minimum

$$V_{\rm GW}(\chi_{\rm min}) \ll V_{H\chi}(\chi_{\rm min})$$

Then we need to examine only the cross terms to see if a universe is “alive”

$$V_{H\chi}(\chi, H) = \lambda_2 |H|^2 \frac{\chi^{2+\alpha}}{k^\alpha} - \lambda_{H\epsilon} |H|^2 \frac{\chi^{2+\alpha+\epsilon}}{k^{\alpha+\epsilon}} - \lambda_4 |H|^4 \frac{\chi^{2\alpha}}{k^{2\alpha}}$$

DYNAMICS OF THE DILATON POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

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$\langle H^0 \rangle \equiv h = 0$	$V_{H\chi} = 0$ No low energy minimum
$h \lesssim H_I$	The minimum is not sensitive to the Higgs during inflation
$h \gtrsim h_{\rm crit}$	$V_{H\chi} \sim -\lambda_4 \chi^{2\alpha}$ No low energy minimum

DYNAMICS OF THE DILATON POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

The critical Higgs vev can be computed exactly

$$h_{\rm crit} = k\left(\frac{\lambda_2}{\lambda_{H\epsilon}}\frac{4-\alpha^2}{(2+\epsilon)^2-\alpha^2}\right)^{\frac{1-\alpha/2}{\epsilon}}\sqrt{\frac{\lambda_2}{\lambda_4}\frac{\epsilon(2+\alpha)}{2\alpha(2-\alpha+\epsilon)}}$$

$$\epsilon, \alpha \lesssim 1 \quad \rightarrow \quad h_{\rm crit} \ll k$$

Interpretation: $\epsilon \rightarrow 0$ **approximate scale invariance** at low energy

DYNAMICS OF THE DILATON POTENTIAL

$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

The size of the extra dimension depends on the Higgs vev

$$\chi_{\rm min} \simeq \left(\frac{h^2}{k^\alpha} \frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2} \right)^{\frac{1}{2-\alpha}}$$

So also in this case parametrically

$$\epsilon, \alpha \lesssim 1 \quad \rightarrow \quad \chi_{\rm min} \ll k$$

BARE BONES PREDICTIONS

PHENOMENOLOGY

1. Low-energy Extra-Dimension (**KK W, Z, photon**, but no gluons or fermions)

$$1/R' = \langle \chi \rangle \equiv \chi_{\min} \simeq h$$

2. But not very low-energy (little hierarchy)

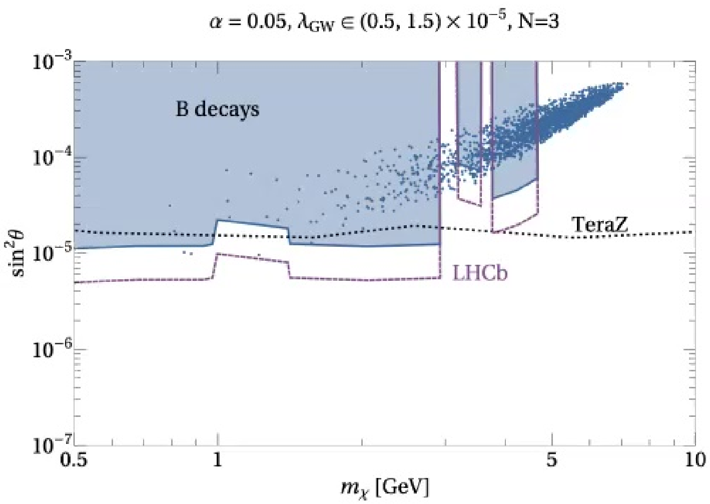
$$\chi_{\min} \simeq \left(\frac{h^2}{k^\alpha} \frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2} \right)^{\frac{1}{2-\alpha}} \gtrsim \mathrm{TeV}$$

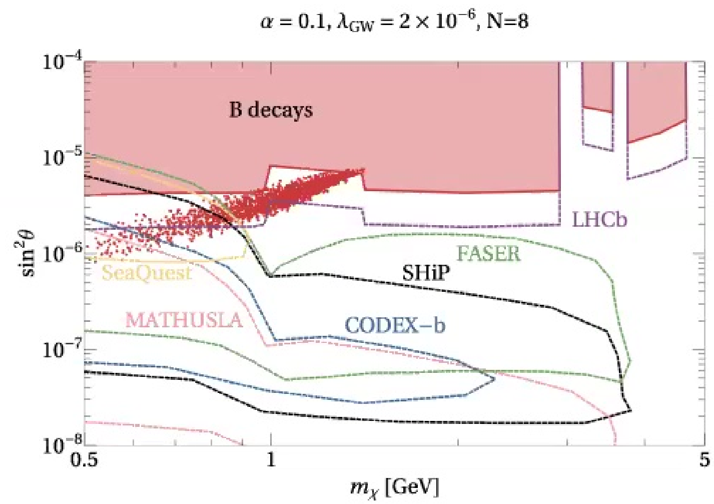
$$\lambda_2 \simeq 10^{-2} \lambda_4$$

3. **Light dilaton** (little hierarchy)

$$m_\chi \sim m_h \sqrt{\frac{h}{\chi_{\min}}}$$

A LIGHT DILATON





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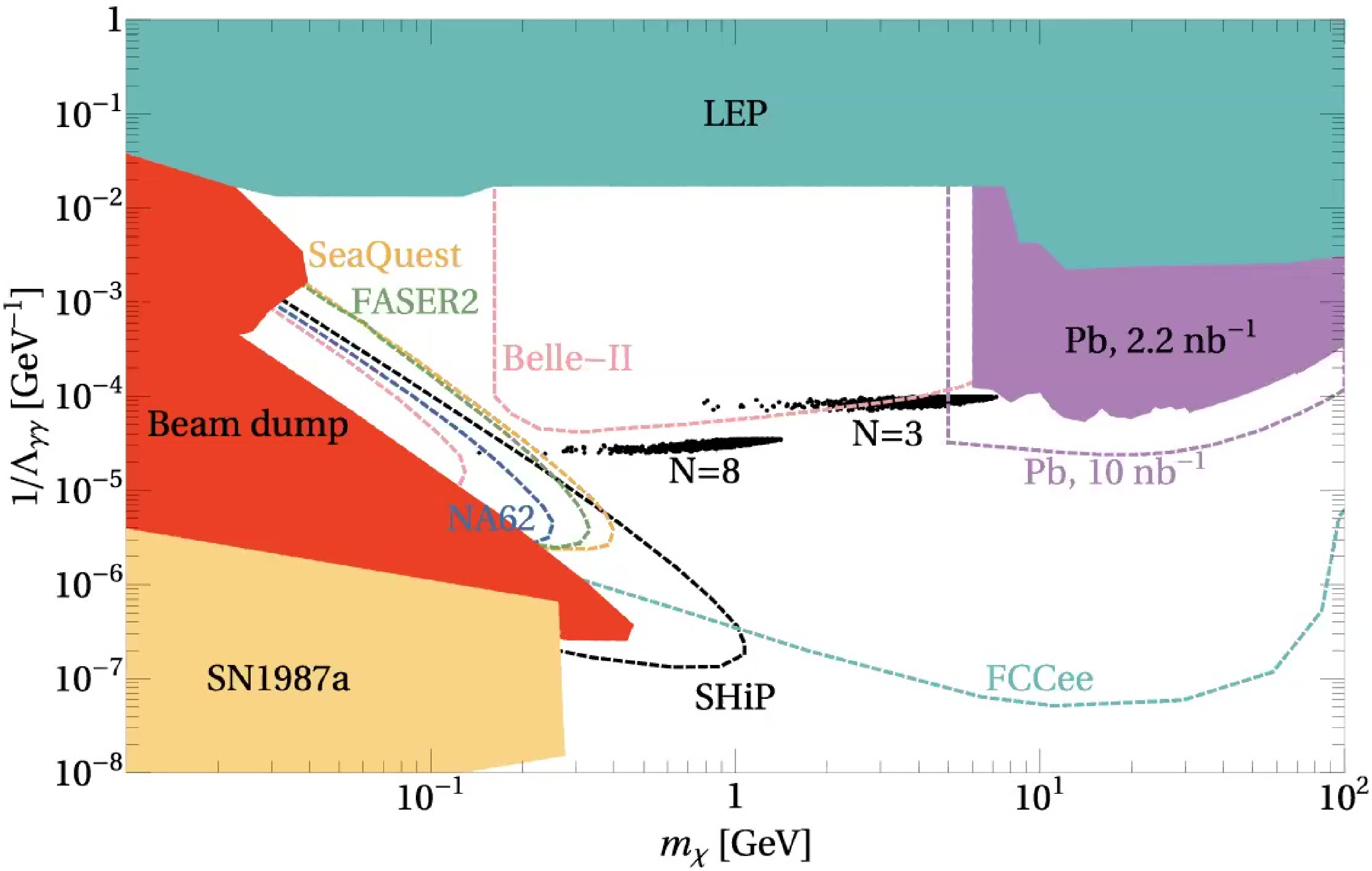

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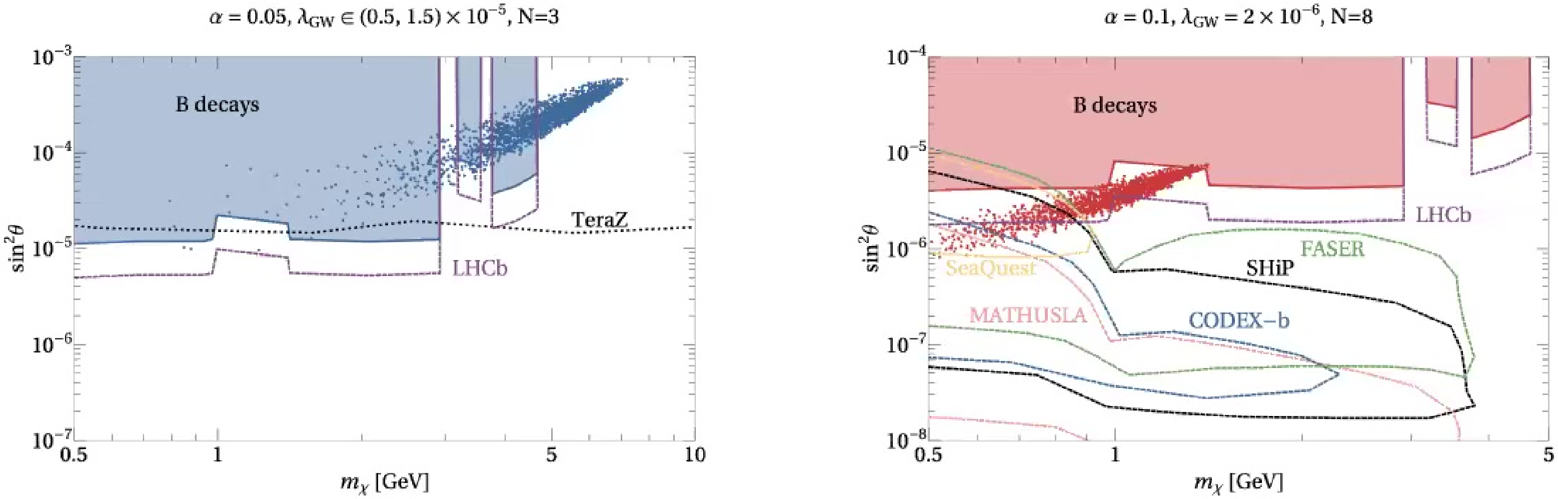
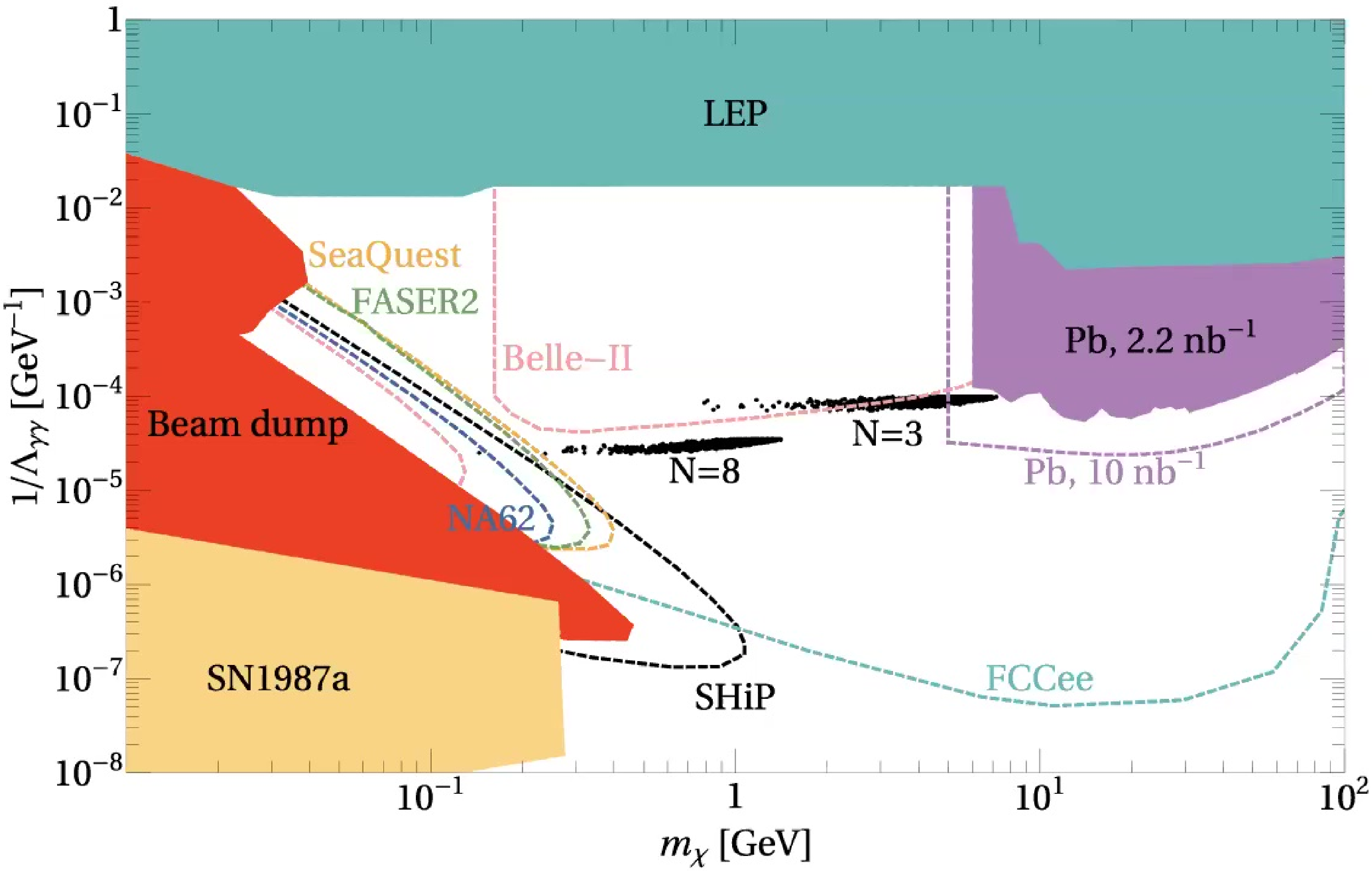
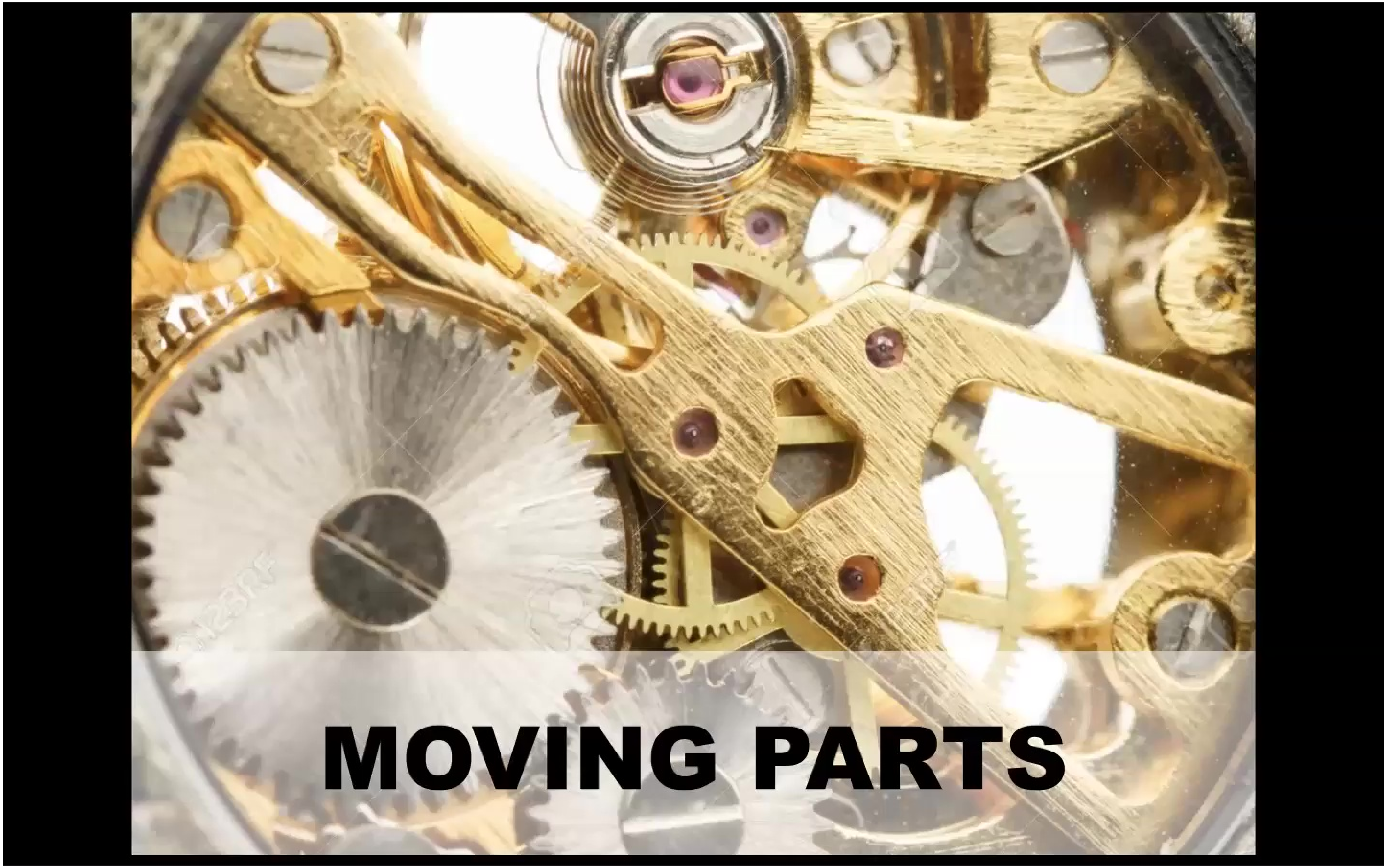


A LIGHT DILATON




MOVING PARTS

LOW SCALE SUSY

$$\lambda_4 = \mathcal{O}(1)$$

Natural lower bound:

$$\lambda \sim \frac{1}{16\pi^2}\frac{\Lambda^4}{\chi^4} \simeq \lambda_2, \lambda_{H\epsilon}$$

Metastable minimum: $V_{\rm GW}(\chi_{\rm min}) < V_{H\chi}(\chi_{\rm min})$

$$\lambda, \lambda_{\rm GW} \lesssim 10^{-5}$$

LOW SCALE SUSY

Low scale **bulk SUSY**?
Note that SUSY is not solving the hierarchy problem

Natural lower bound:

$$\lambda \sim \frac{1}{16\pi^2}\frac{\Lambda^4}{\chi^4} \simeq \lambda_2, \lambda_{H\epsilon}$$

Metastable minimum: $V_{\rm GW}(\chi_{\rm min}) < V_{H\chi}(\chi_{\rm min})$

$$\lambda, \lambda_{\rm GW} \lesssim 10^{-5}$$

COSMOLOGY OF THE CRUNCH

When $h = 0 \to V_\chi \simeq -\lambda\chi^4$

The dilaton can be stuck near the origin for a long enough time that patches with the wrong vev inflate

Solution: new gauge group in the bulk (or QCD)

$$V_{H\chi} \supset c\chi^\beta \Lambda_{\rm QCD}^{4-\beta}$$

Below $\chi_* \sim \Lambda_{\rm QCD}$

Hard breaking of the CFT and new phase transition

PERTURBATIVE CRUNCH

Sliding Naturalness

[**RTD**, Teresi] In Preparation

BSM Ingredients:

$$\phi, \phi_+, H_d$$

Predictions:

- New Higgs below 125 GeV (still alive!)
- Two ultralight scalars that can mediate long-range forces and be dark matter (target for 5th force searches!)

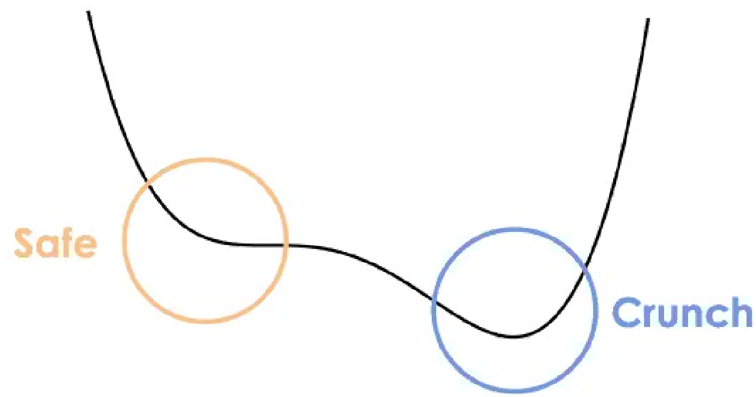
PERTURBATIVE CRUNCH

Sliding Naturalness

[**RTD**, Teresi] In Preparation

$$V_\phi = \frac{\epsilon^2 M_*^2}{2}\phi^2 + \epsilon' M_* \phi^3 + \frac{\epsilon^2}{4}\phi^4 + (\kappa \epsilon M_* \phi H_u H_d + \text{h.c.})$$

$$\langle H_u H_d \rangle = 0$$



PERTURBATIVE CRUNCH

Sliding Naturalness

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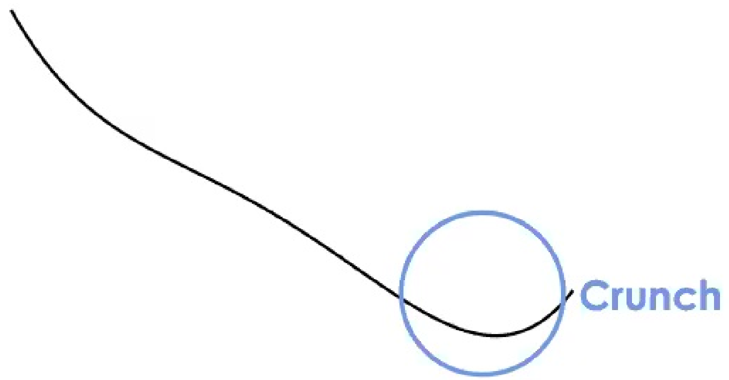
$$\langle H_u H_d \rangle \gg v^2$$



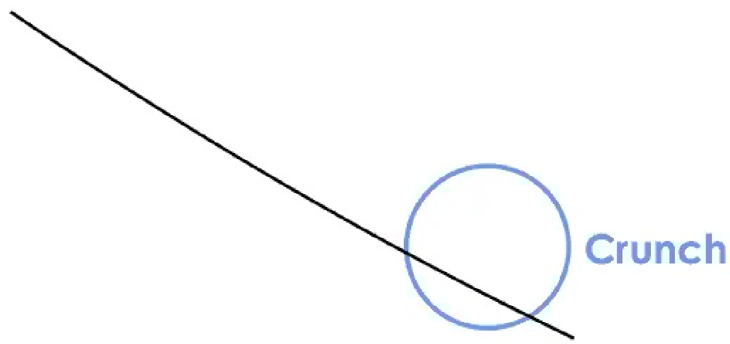
PERTURBATIVE CRUNCH

Sliding Naturalness

[**RTD**, Teresi] In Preparation

$$V(\phi_+) = \eta M_*^3 \phi_+ + \eta^2 M_*^2 \phi_+^2 + \left(\lambda \phi_+^2 H_u H_d + \text{h.c.}\right)$$

$$\langle H_u H_d \rangle = 0$$



CONCLUSION

- A **qualitatively new solution** to the **hierarchy problem**
- Unique predictions for natural ED models: light dilaton, no fermionic (or coloured) KK states
- In its perturbative incarnation, unique predictions for fifth force searches and the LHC