Some New Thoughts on the Hierarchy Problem

* My own best bet since ~ 2004-5,
was [+ is] minimal split SUSY
* Heresy: SUSY + tuning ~ 10^{-4} - 10^{-6} for EWSB
[cf ~ 10^{-90} for CC!]
* Simplest WIMP DM EWkinos/Higgsino
~ 1-3 TeV, not made @ LHC & seen in DD.
* Correctly predicted $120 \lesssim m_h \lesssim 135$ GeV
* Gluino might still in reach of LHC,
but both Ewkinos + Gluino seen @ 100 TeV collider
* And, EDM searches!

* UV/IR, Hidden Symmetries, Tuning + Transcendality [w/ Y. Grossman]

* The weak scale as a trigger [w/ R. D'Agnolo + H-D Kim]

17'th → 20'th Century Physics

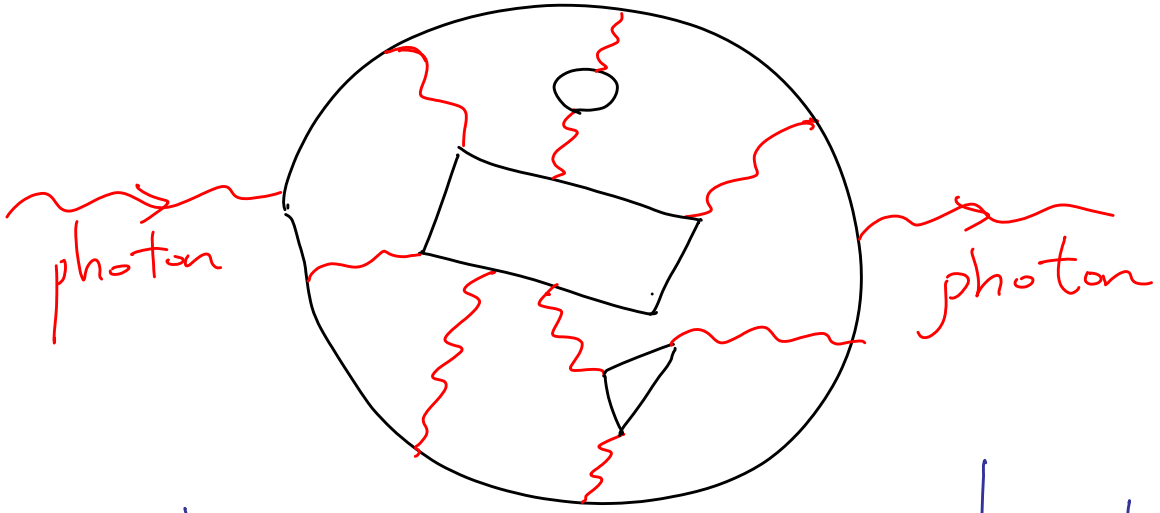
March of REDUCTIONISM

March of SYMMETRIES

21st Century Revolutions

* Doom of Spacetime, End of Reductionism
* Why is the Universe Big?

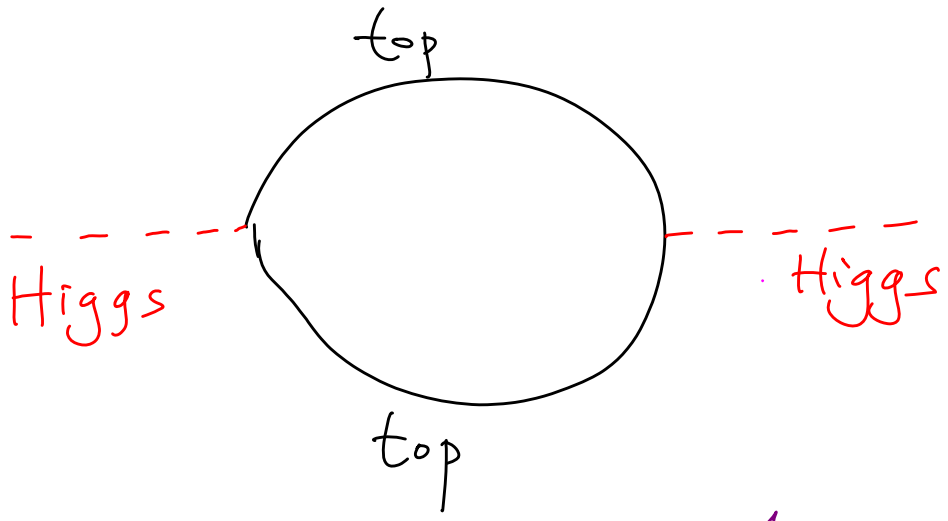
REALLY NEW IDEAS NEEDED,
beyond paradigms of spacetime + internal symmetries



Photon MUST stay massless, because

massless helicities $\rightarrow 2 \neq 3 \leftarrow$ # massive spins

[This is why gauge fields + chiral fermions can be easily engineered in Cond. Matter!]



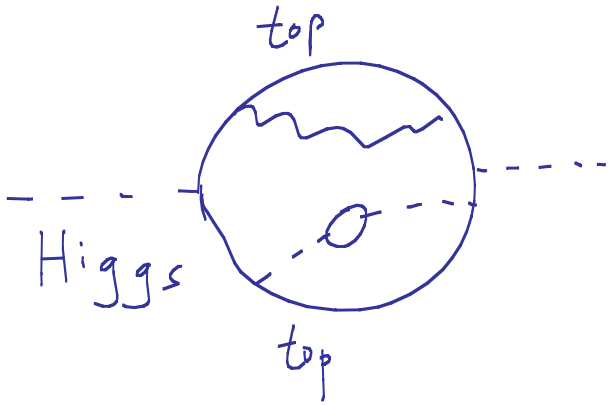
massless spin 0 $\frac{1}{}$ = $\frac{1}{}$ massive spin 0

NO DIFFERENCE

WHY ISN'T HIGGS ENORMOUSLY MASSIVE? PLANCKIAN?

[Higgs is Special! Does NOT naturally arise in Cond. Matter!]

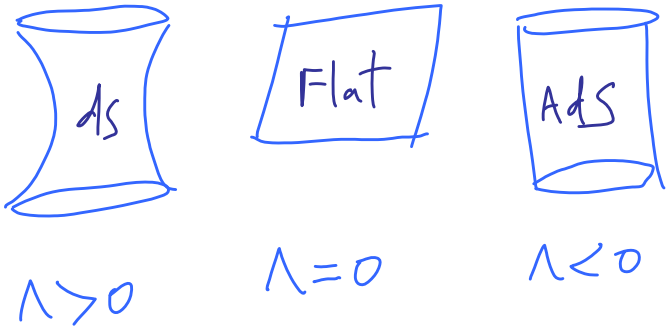
Λ + Higgs ⟶ Beyond Symmetries



1 d.o.f whether $m_h^2 > 0, = 0, < 0$

NO DIFFERENCE

Hierarchy Problem



$\Lambda > 0$ $\Lambda = 0$ $\Lambda < 0$

Same amount of symmetry

$[SO(5,1) \to \text{Poincaré} \to SO(4,2)]$

Cosmological Constant Problem

Emergent Spacetime?

We are clearly missing something HUGE about Quantum Mechanics of our Relativistic Vacuum!

Macroscopic Universe?

Higgs Discovery Crucial

Our Relativistic Vacuum is Qualitatively Different than anything we've seen elsewhere in physics

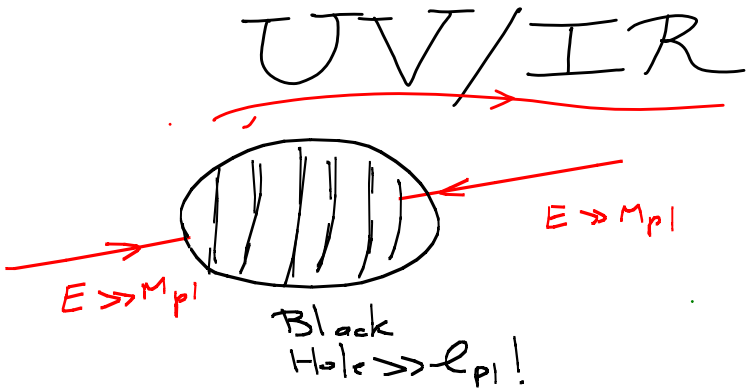
NOT JUST @ Planck scale

ALREADY @ TeV scale

UV/IR,

Hidden Symmetries,

Transcendental Tuning



High Energies ↕ Long Distances!

Reductionism + Wilsonian EFT Paradigm is False

Fundamental Laws Nothing like that of Condensed Matter Physics — FAR DEEPER + MORE RADICAL

[But maybe only at Planck Scale ?]

* Crucial to Probe on-shell (Lorentzian)

+ off-shell (Euclidean) couplings of the

Higgs. Wilsonian paradigm is fundamentally

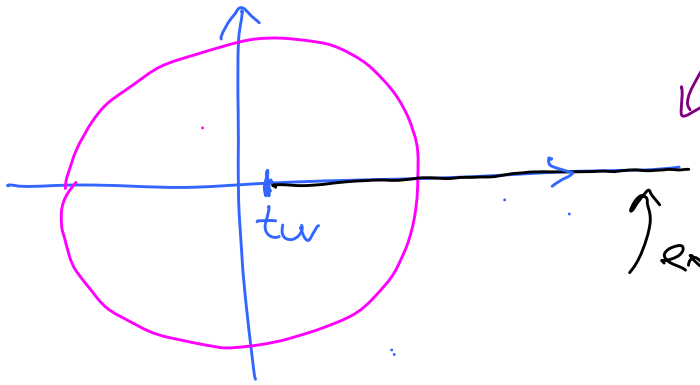
Euclidean, standard local QFT relies

on Euclidean ⟶ Lorentzian continuation,

but UV/IR can radically change this!

Example: $F^{exp}(t) = 1/t$ for $t>0, t \gg t_{uv}$

Effective Field Theorist: "Oh, $F^{exp}(t) = 1/t$!



$\frac{1}{2\pi i}\oint dt\, F(t) = 1$!

Big Circle

Reliable EFT Comp.

* WRONG! $F(t) = \frac{1 - 10^{-120\, t/t_{uv}}}{t}$, $\oint dt\, F(t) = 0$!

{ Mechanism for removing "bulk sing" in AdS/CFT }

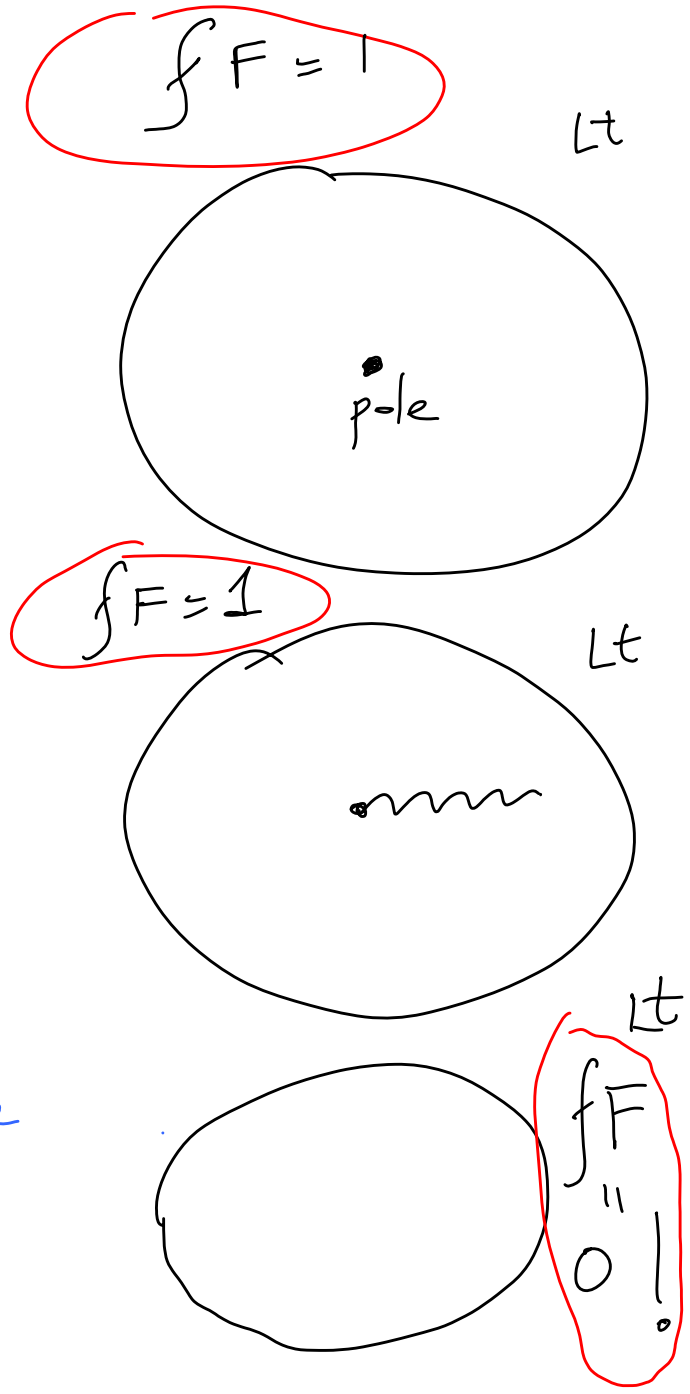
$$\frac{1}{t} = -i \int_0^\infty dE \; e^{iEt}$$

$$\longrightarrow -i \int_0^\infty \frac{dE \; e^{iEt}}{(1 + E/\Lambda)^p}$$

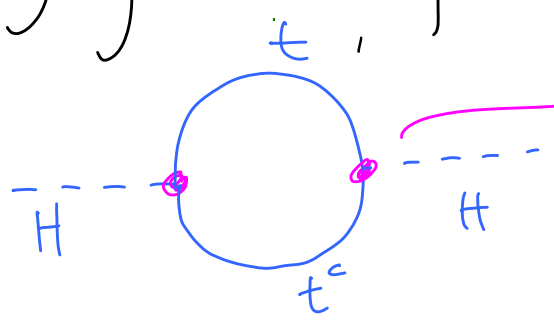
"Field Theoretic"

$$\longrightarrow \int_0^\infty dE \; e^{iEt} \; e^{-E^2/\Lambda^2}$$

"Gravitational"

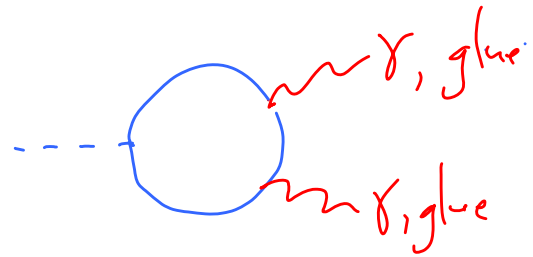


* So, crucial to probe Euclidean, off-shell properties of Higgs:



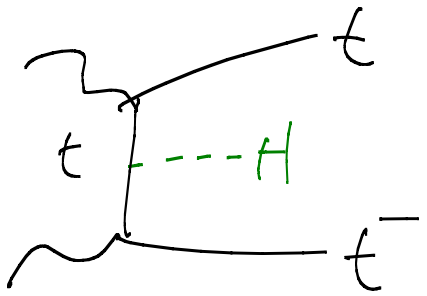
can it shut off for t,t^c off-shell by ~ 500 GeV ?
(NOT standard compositeness!)

$\Rightarrow$

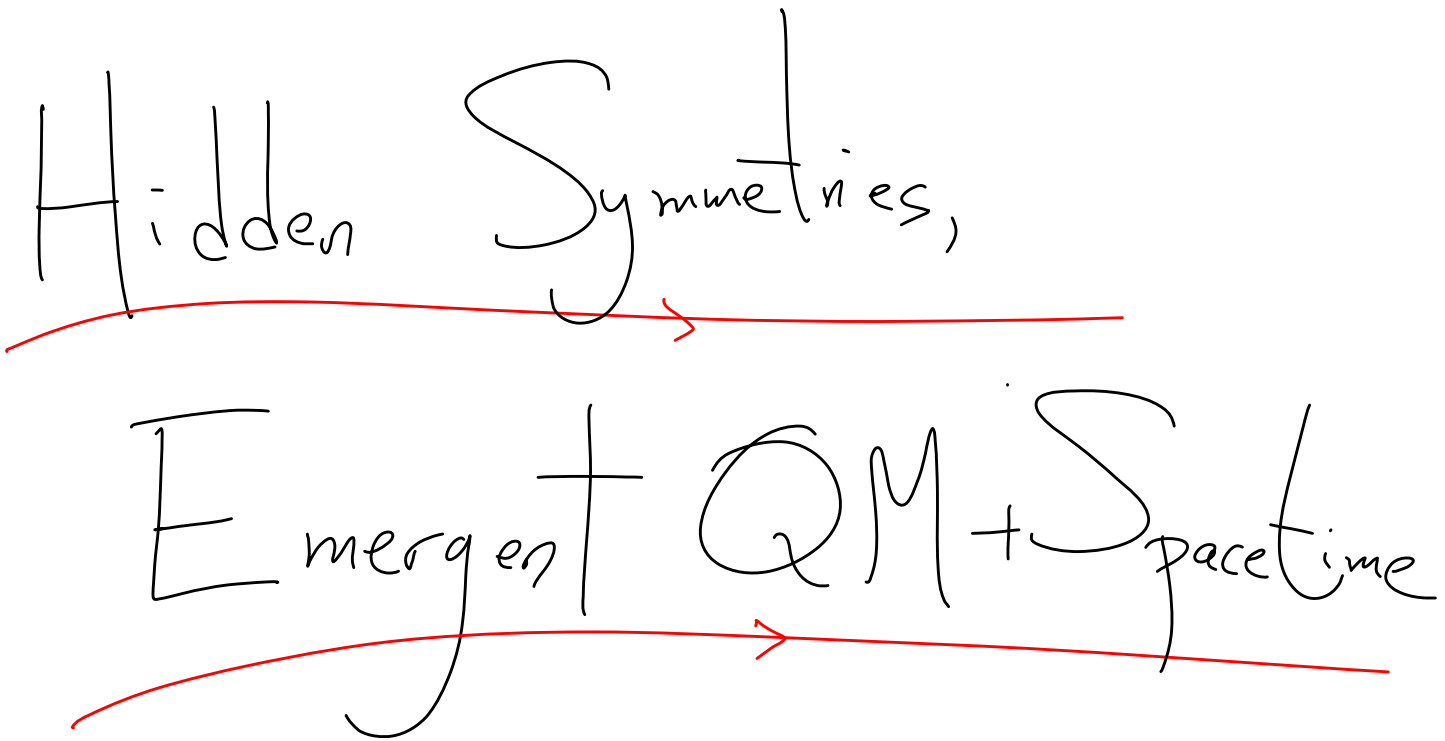


$H \to \gamma\gamma$ modified @ ~ 3%
$H \to gg$ modified @ ~ 10%
[Perfect for Higgs Factory]

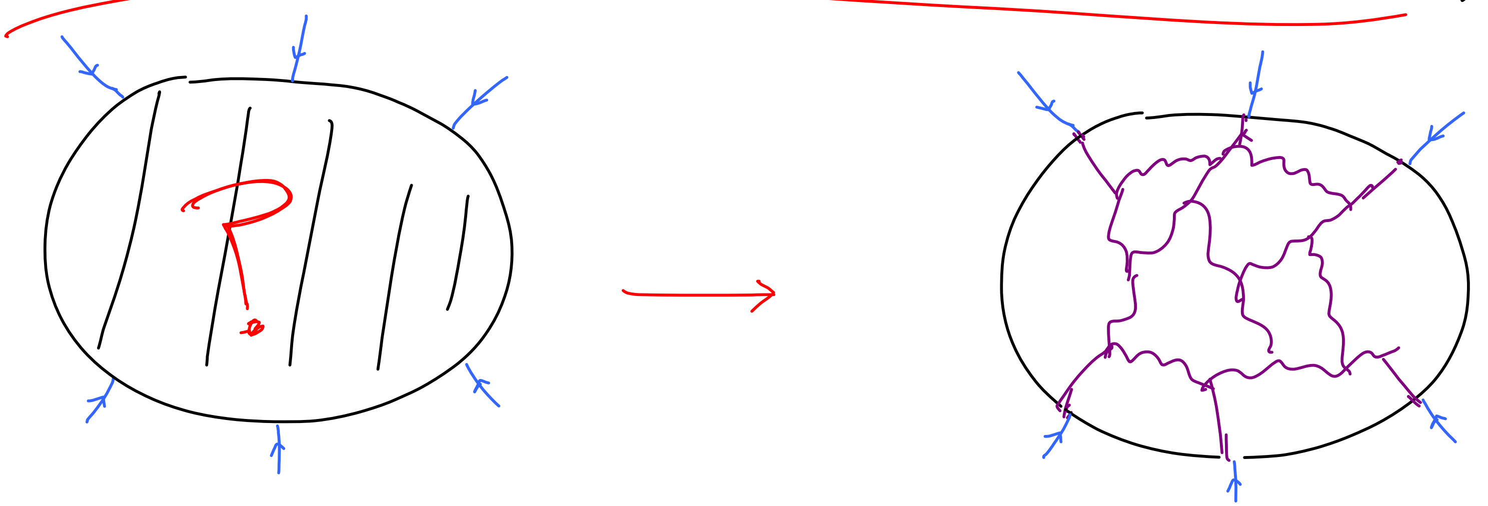
Also



should shut off for $P_T^{Higgs} \gtrsim 500$ GeV
[Perfect for 100 TeV collider]

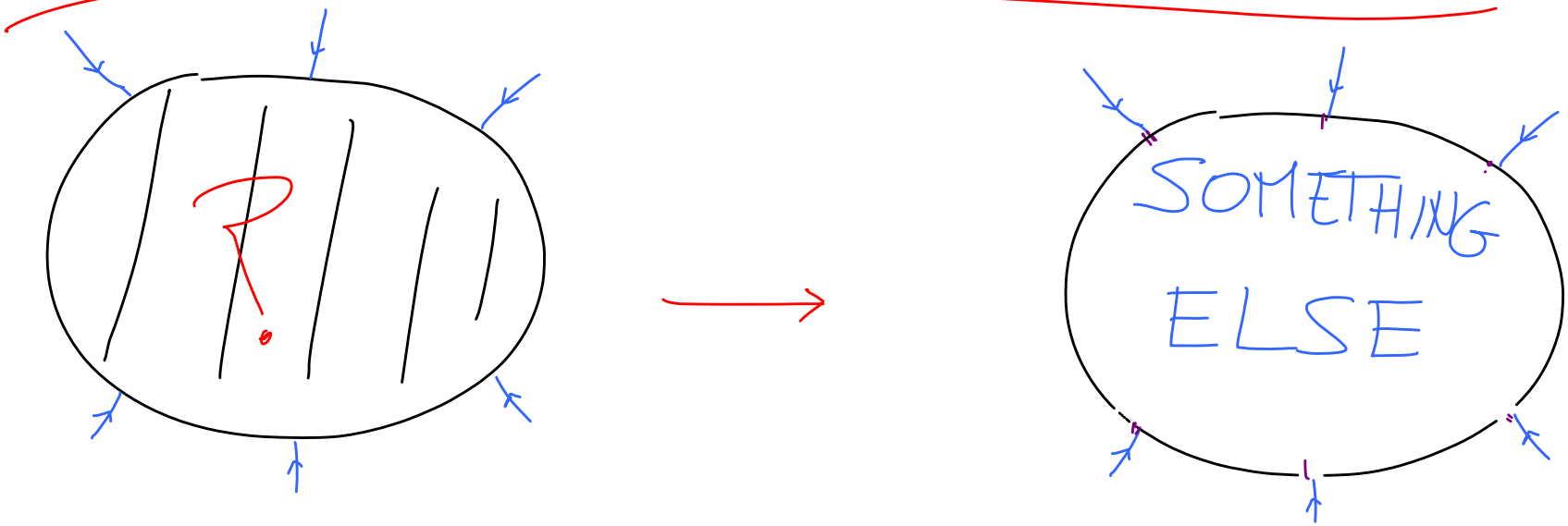

Hidden Symmetries,
Emergent QM + Spacetime

What is the Q to which A is the Answer?



Local, Unitary Evolution in Spacetime

What is the Q to which A is the Answer?



New Strategy: Look For

NEW PRINCIPLES, LAWS

from which CAUSAL, UNITARY

evolution — local Spacetime Physics + QM,

emerge together.

Positive Geometries

* Amplitudes for YM + ϕ^3_{colored} are tied to "Positive Geometries"

Gluons ⟶ "Amplituhedra"
"Associahedra"

ϕ^3 ⟶

* Manifest hidden symmetries, reflected in surprising cancellations at infinite momentum.

(Dual Conformal Invariance, "Projective Invariance")

Speculation

There is a dual formulation of physics that represents physical amplitudes/observables of integrals over abstract geometries. [cf. "positive geometries", amplituhedra, associahedra etc.]

In this formulation — $\Lambda + m_h^2$ obviously exp. small! But not obviously "local physics". Another "fring"... will look like local — but fine-tuned appearing! — physics

Transcental Tuning

UV-IR, Tuning + Transcendality

UV-sensitivity + hierarch problem:

$$V^{1\text{-loop}} = \mathrm{Str}\, M^4(h) \log M^2(h)$$

$$= \lambda_t^4 h^4 \log(\lambda_t^2 h^2) + \underbrace{(M \pm h)^4 \log (M \pm h)^2}_{\text{UV states}}$$

$$\subset \lambda^2 M^2 h^2 + \ldots$$

Calculable...

+ Why should "tree" cancel "loop"?

Tree = "Rational" → Loop = "Transcendental"

... but long known "funny turnings" in QFT computations .....

e.g. $\Gamma(\text{positronium}) = \ldots\ldots \times \underbrace{(\pi^2 - 9)}_{\text{Accidentally Small?}}$

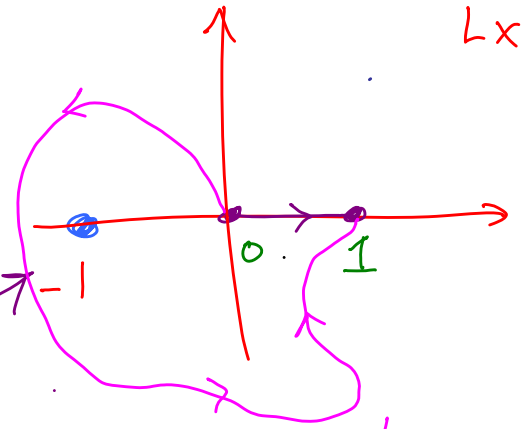
No! There is a mechanism @ work here....

Rational Approximations to Transc. Numbers

$$\log 2 = \int_0^1 \frac{dx}{1+x}$$

transcendental

because of simple pole @ $x=-1$



Different contour differs by $2\pi i$

So: $I = \int_0^1 \frac{dx}{1+x} \cdot P(x) = P(-1)\log 2 + \text{Rational}$

$$\int_0^1 \frac{dx}{(1+x)} \left[\frac{x(1-x)}{2\ 1}\right]^N = \pm \log 2 + \text{Rational}$$

$$< \left(\frac{1}{8}\right)^N !$$

$\Longrightarrow$ Huge "Apparent tuning" $\longrightarrow$ Rational Approx to $\log 2$

e.g. $N=5$: $\log 2 - \frac{2329}{3360} \sim 10^{-5}$!

{ Same idea:

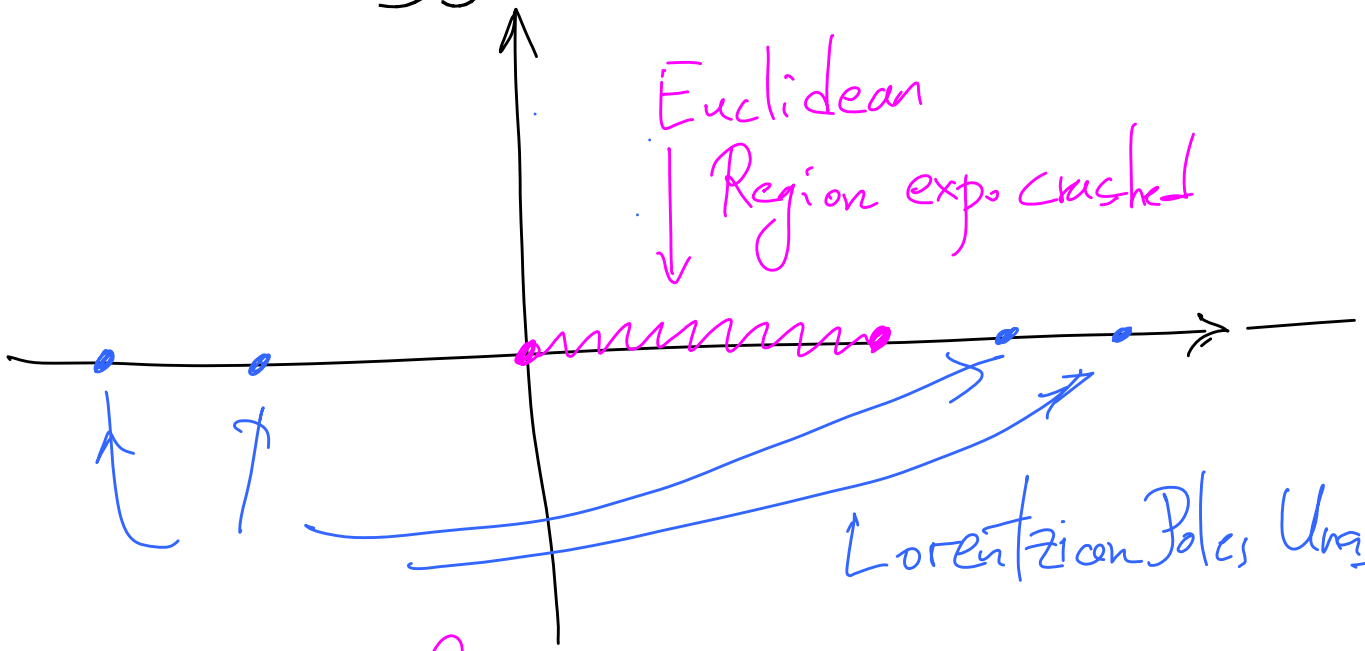
$$4\int_0^1 \frac{dx}{(1+x^2)}\left(\frac{x(1-x)}{4}\right)^{4N} = \pi + \text{rational}$$

$N=1$ $\quad \pi - \frac{22}{7} \sim 10^{-3}$

$N=2$ $\quad \pi - \frac{47171}{15015} \sim 10^{-6}$ }

{ + explains $\pi^2 - 9$! Small phase-space integrals = transc. − rational }

Strategy for Higgs



$$V(h) = \int_{\text{Euclidean}} dK^2 \; F(K^2) = \text{Logs} + \text{Rational}$$

= exp. small but apparently "fine-tuned"

Concrete Example

$$F(h) = \int_h^1 \frac{dx\ (x-h)^4}{1+x} \left(\frac{x(1-x)}{2}\right)^N$$

$$V(h) = F(h) + F(-h)$$

$$= \underbrace{\sum_{\pm} (1 \pm h)^4 \log(1 \pm h)}_{\text{"UV loop"}} + \underbrace{\text{Rational}}_{\text{"free"}}$$

BUT GUARANTEED TO BE "TUNED"!

So e.g. $N=5$:

"tree"

$$V(h) = 142733/102960+(97411\ h^2)/73920-(1557\ h^4)/560+h^6/15+h^8/140+(31\ h^{10})/20160 +h^{12}/3960+h^{14}/160160-\text{Log}[4]-h^4\ \text{Log}[4]-2\ h^2\ \text{Log}[64]+(-1+h)^4\ \text{Log}[1-h]+(1+h)^4\ \text{Log}[1 +h]$$

"1-loop"

$$= (142733/102960-\text{Log}[4])+(614851/73920-2\ \text{Log}[64])\ h^2+(2329/1680-\text{Log}[4])\ h^4-h^{10}/20160$$

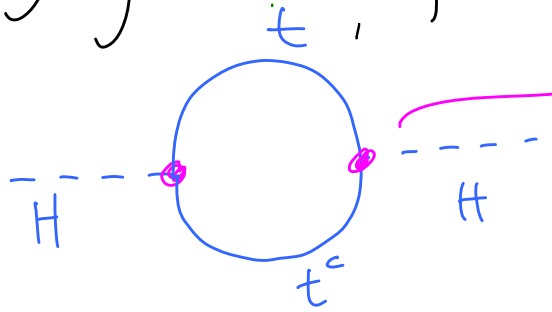
$$= \bar{1}0^6 + \bar{1}0^5 h^2 + \cdots + h^{10}!$$

"tuned" Λ !

"tuned" m_h^2

Surprise: h^6, h^8 MISSING!

* So, crucial to probe Euclidean, properties of Higgs:



off-shell t, t^c

can it shut off for t, t^c off-shell by ~ 500 GeV ?

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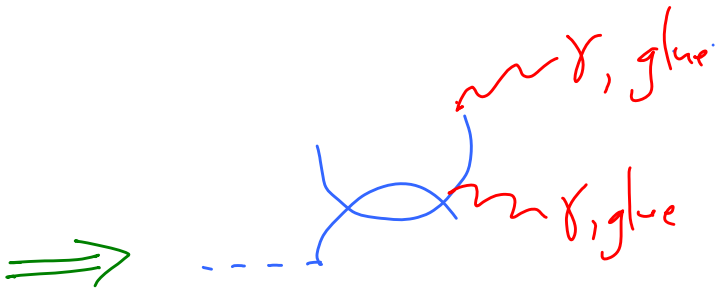

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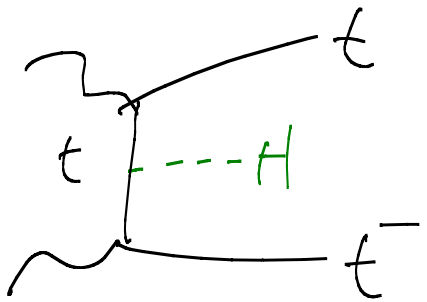


should shut off for $p_T^{Higgs} \gtrsim 500$ GeV

[Perfect for 100 TeV collider]

The Weak Scale

as a

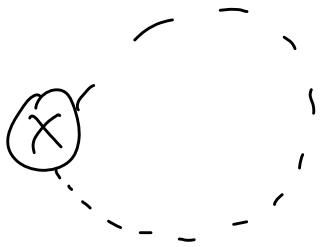
Trigger

Q: What happen in the SM as we vary m_h^2? What $\langle \mathcal{O}\mathcal{O}\cdots\mathcal{O}\rangle$ care about m_h^2?

A: Obviously, spectrum! But these are not $\langle \mathcal{O}(x)\rangle = \langle \mathcal{O}\rangle$, rather $\langle \mathcal{O}(x)\mathcal{O}(y)\rangle \longrightarrow \langle \mathcal{O}\mathcal{O}\rangle(p^2)$ .....

* Indeed this is a sharp characterization of the hierarchy problem. In SM:

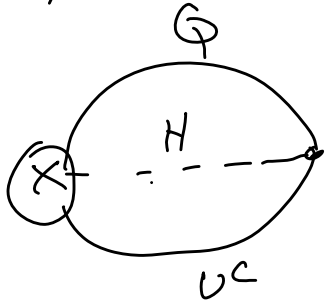
$\langle h^\dagger h \rangle \longrightarrow$ can't compute! since



usual $\sim \Lambda^2$

* Similarly for (almost) all local ops e.g.

$\langle Q H U^c \rangle$:



$\sim \lambda_u \sim \lambda_u \Lambda^4$ etc.

Said another way: imagine weakly coupling $(h^\dagger h)$ to some field ϕ:

$\epsilon \; \phi \; h^\dagger h$ but same symmetries as $\epsilon \phi M_*^2$

$\Downarrow$

$\sim \mu^3 \phi$, μ not calculable, "take from experiment"

* Well-known exception – the anomaly:

$\langle G\tilde{G} \rangle = 0$ naively since total derivative.. but,

$$= \Lambda_{QCD}^3 \, m_u$$

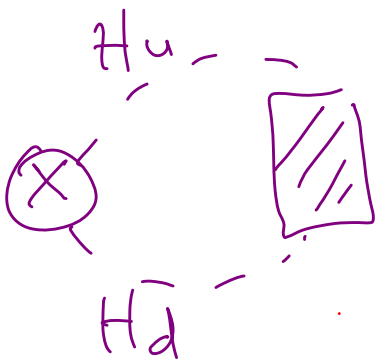
which depends sensitively on m_h^2!

* $\langle G\tilde{G} \rangle$ is "frigged" by weak scale

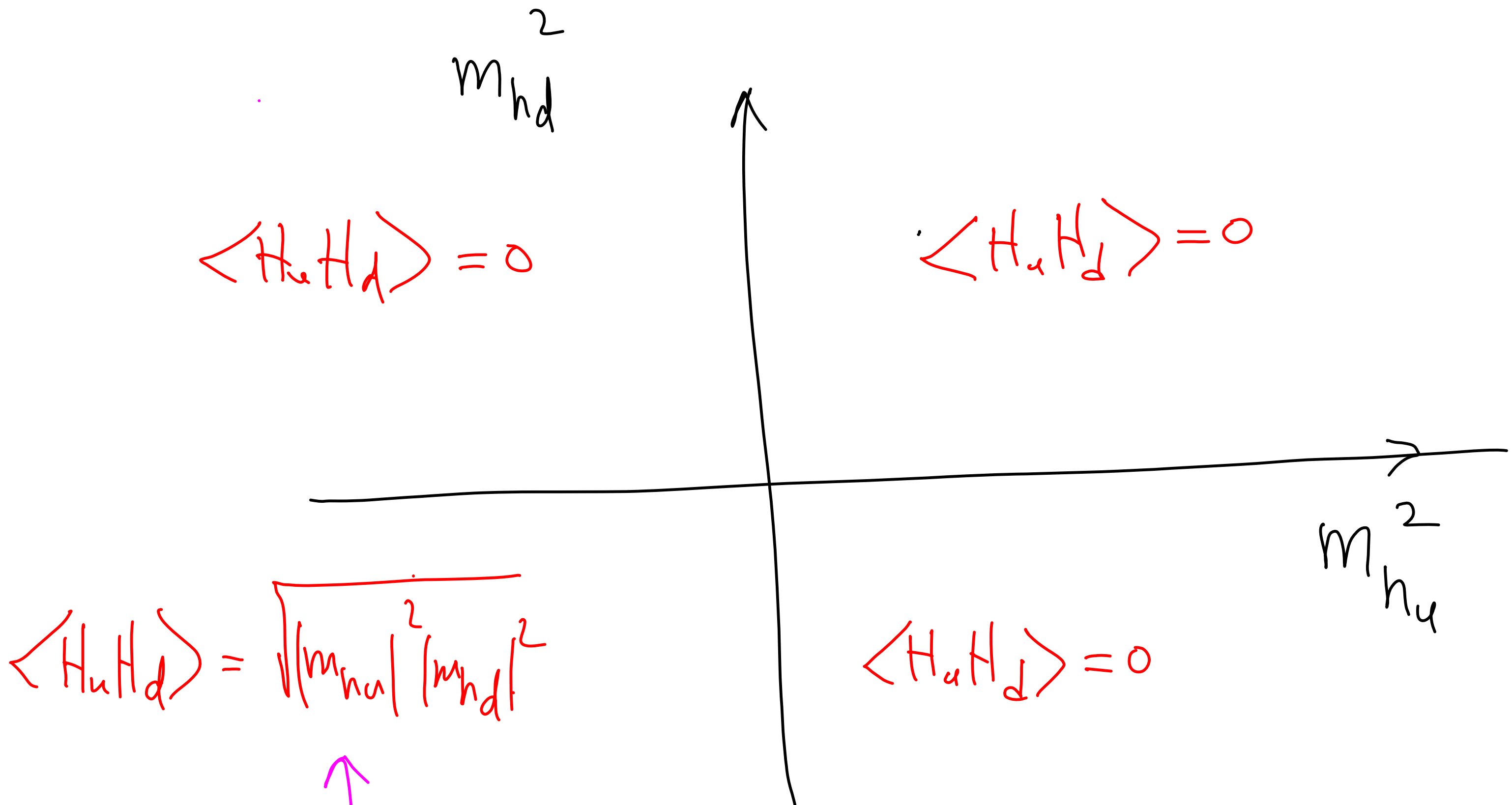
* ~~X~~ "Trigger" used cosmologically in Relaxion models

Other Triggers?

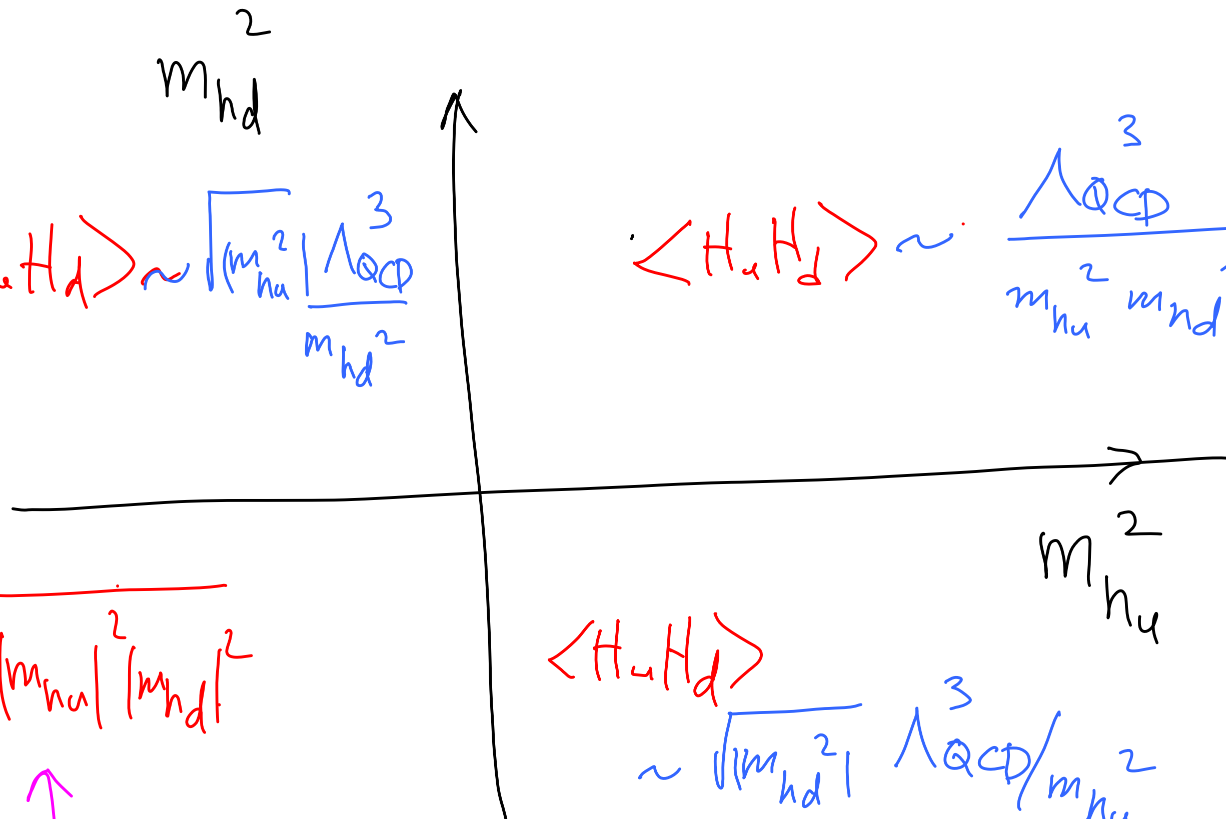
* No in SM
* But possible in 2HDM extensions of SM.
* Consider $H_{u,d}$ with $(H_u H_d)$ charged under PQ.

Note 

can't close because of PQ, calculable!



must have **both** $m_{h_u}^2, m_{h_d}^2 < 0$ to trigger $\langle H_u H_d \rangle$



$\langle H_u H_d \rangle \sim \sqrt{|m_{h_u}^2|}\, \dfrac{\Lambda_{QCD}^3}{m_{h_d}^2}$

$\langle H_u H_d \rangle \sim \dfrac{\Lambda_{QCD}^3}{m_{h_u}^2 m_{h_d}^2}$

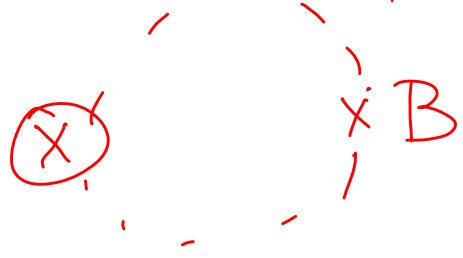
$\langle H_u H_d \rangle = \sqrt{|m_{h_u}|^2 |m_{h_d}|^2}$

$\langle H_u H_d \rangle \sim \sqrt{|m_{h_d}^2|}\, \Lambda_{QCD}^3 / m_{h_u}^2$

must have <u>both</u> $m_{h_u}^2, m_{h_d}^2 < 0$ to trigger $\langle H_u H_d \rangle$

* Of course, the PQ symmetry must be broken [otherwise weak-scale axion...].

* Conventionally: B-term $B H_u H_d$, ruins trigger mechanism:



$\Rightarrow \langle H_u H_d \rangle \sim B$, independent of $m^2_{H_u,d}$.

Trigger-happy 2HDM

* Break $PQ \to Z_4$ with quartic

$$\lambda (H_u H_d)^2 , \quad B = 0$$

λ: charge -2, $H_u H_d$: charge 1

* $\langle H_u H_d \rangle$ can't be created by λ, odd w/ even P charge!

* And crucially, need both $m^2_{h_u, h_d} < 0$ to trigger!

Trigger-happy 2HDM

$$V = m_{h_u}^2 |h_u|^2 + m_{h_d}^2 |h_d|^2 + \lambda_u |h_u|^4 + \lambda_d |h_d|^4 + \lambda_{ud} |h_u|^2 |h_d|^2$$

$$+ \lambda (h_u h_d)^2 + \text{h.c.}$$

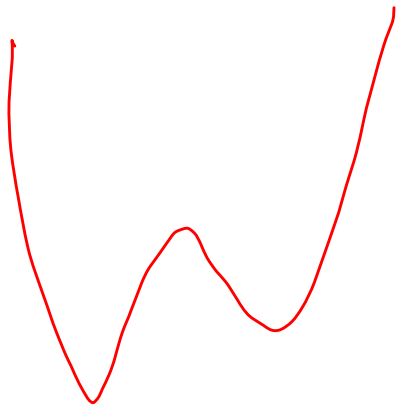
only PQ breaking has charge 2

* Can't make λ's too big (Landau poles).
* Must have $m_{h_{u,d}}^2 < 0 \Longrightarrow$ ALL STATES LIGHT!

Impossible to Decouple!

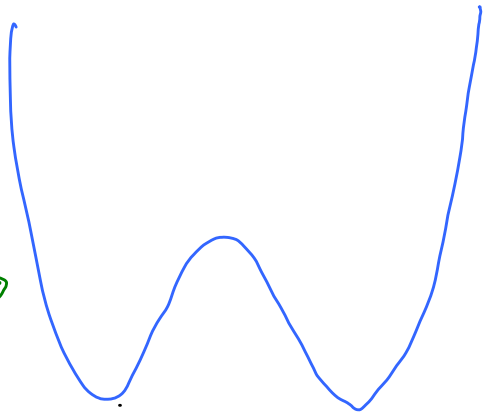
* 2HDM w/ Z_4 PQ symmetry, $B = 0$
* Must have $m^2_{h_u, h_d} < 0$
* Must have $v_d / v_u \lesssim 0.3$
* $m_{\tilde{d}} \lesssim 100$ GeV
* Everyone else $\lesssim$ 100's GeV
* Can't hide — but remarkably seems alive!
* Might get 3σ evidence @ LHC, HUGE signals @ Higgs Factory

$\Lambda \pm m_h^2$ Low-Energy Landscape Trigger



Φ_A 2^{N_A} minima

$\epsilon\left(\varphi_i^2 - \mu^2\right)^2 \rightarrow$



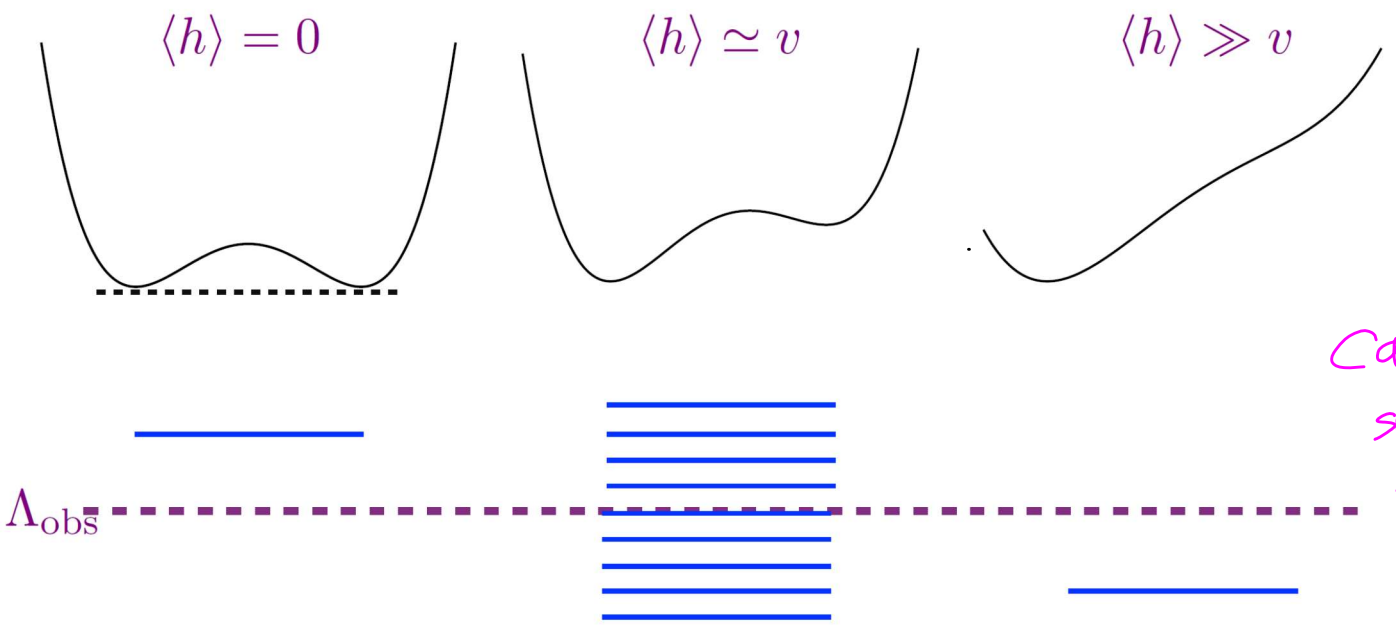
φ_i 2^{N_i} but degenerate minima.

$\epsilon \sum k_i \varphi_i \; H_u H_d$ ... can trigger Z_2 breaking!

$\Lambda + m_h^2$ Low-Energy Landscape Trigger

Low Energy Landscape

$m_\phi \sim v^2/M_* \quad \langle\phi\rangle \sim M_*$



$$V_\phi = \sum_{i=1}^{N_2} \frac{\epsilon_i^2}{4}\left(\phi_i^2 - M_{*,i}^2\right)^2 + \kappa_i \frac{\epsilon_i M_{*,i}}{\sqrt{N_2}}(\phi_i H_u H_d + \text{h.c.})$$

2^{N_2} vacua

Can only split vacua + get small CC. if $\langle H_u H_d\rangle$ triggered.

* For high scales, ~100's of ultralight ϕ_i's, bounds/signals from long-range forces

* Also: EWSB triggers displacement of $\phi_i \longrightarrow$ ahent oscillations as DM.