



Naturalness in EFT

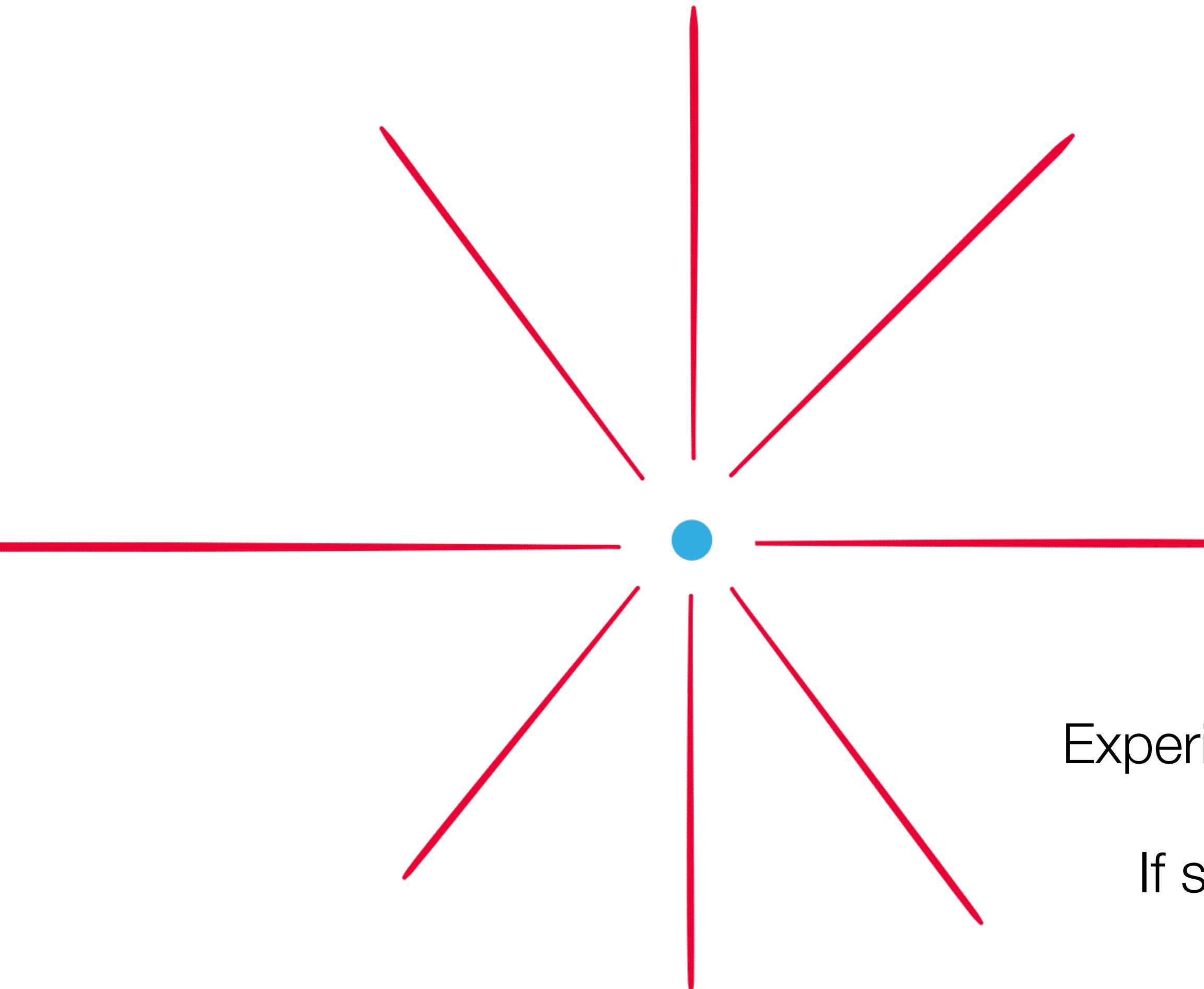
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Naturalness in Snowmass

- N. Blinov, NC, M. Dolan, J de Vries, P. Draper, I. Garcia Garcia, B. Lillard, J. Shelton, *Snowmass White Paper: Strong CP Beyond Axion Direct Detection*, 2203.07218
 - P. Agrawal, K.V. Berghaus, J. Fan, A. Hook, G. Marques-Tavares and T. Rudelius, *Some open questions in axion theory*, 2203.08026
 - P. Berglund, L. Freidel, T. Hubsch, J. Kowalski-Glikman, R.G. Leigh, D. Mattingly et al., *Infrared Properties of Quantum Gravity: UV/IR Mixing, Gravitizing the Quantum – Theory and Observation*, 2202.06890
 - P. Draper, I.G. Garcia and M. Reece, *Snowmass White Paper: Implications of Quantum Gravity for Particle Physics*, 2203.07624
 - B. Batell, M. Low, E.T. Neil and C.B. Verhaaren, *Review of Neutral Naturalness*, 2203.05531
 - C. Dvorkin et al., *The Physics of Light Relics*, 2203.07943
 - P. Asadi et al., *Early-Universe Model Building*, 2203.06680
 - NC, *Naturalness: A Snowmass White Paper*, 2205.05708
- 
 - strong CP problem
 - cosmological constant problem
 - **electroweak hierarchy problem**

The Naturalness Strategy



The naturalness strategy: an **analogy** from E&M

$$\Delta E_C = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{r_e}$$

$$(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \Delta E_C$$

Experimentally $r_e \lesssim 10^{-18} \text{ cm} \Rightarrow \Delta E_C \gtrsim 100 \text{ GeV}$

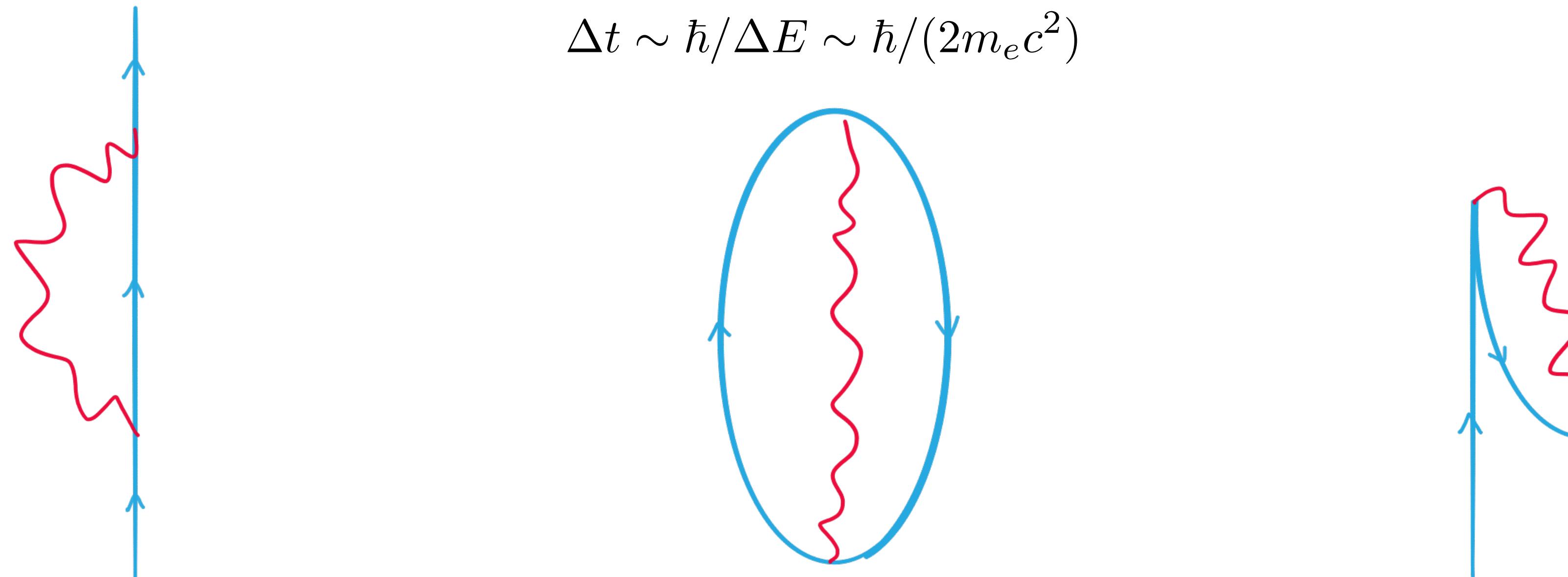
If so, $0.511 = -99999.489 + 100000.000 \text{ MeV}$

To avoid fine-tuning, i.e. for the theory to be “natural”, need picture to change on scales below $2.8 \times 10^{-13} \text{ cm}$

The Naturalness Strategy

Dirac (1928-29): There is a new state in the relativistic quantum theory

Weisskopf (1934-39): Compute the self-energy including the positron



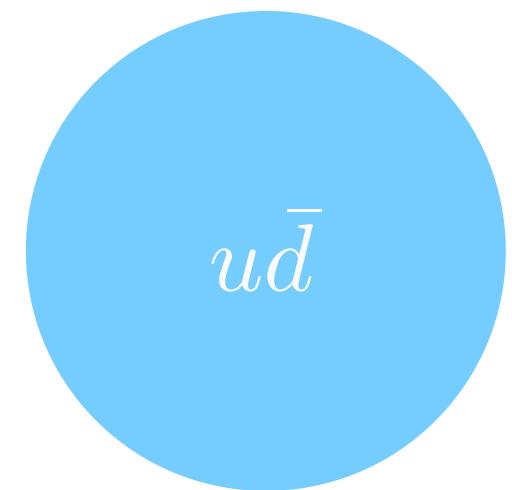
$$\Delta E = \Delta E_C + \dots$$

$$d \sim c\Delta t \sim 200 \times 10^{-13} \text{ cm}$$

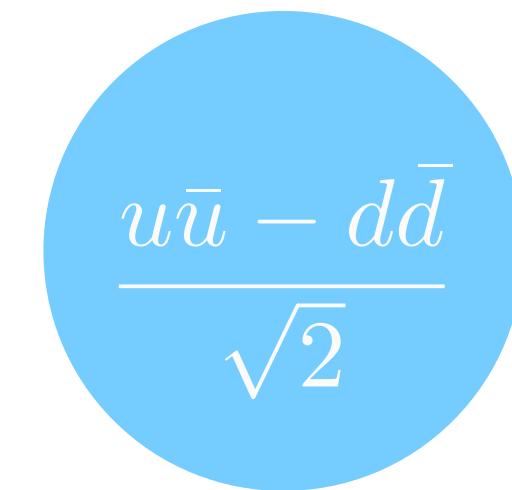
$$\Delta E = -\Delta E_C + \dots$$

$$\Delta E = \Delta E_C - \Delta E_C + \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

The Naturalness Strategy



π^+



π^0

What about scalars?

Consider the charged & neutral pions...

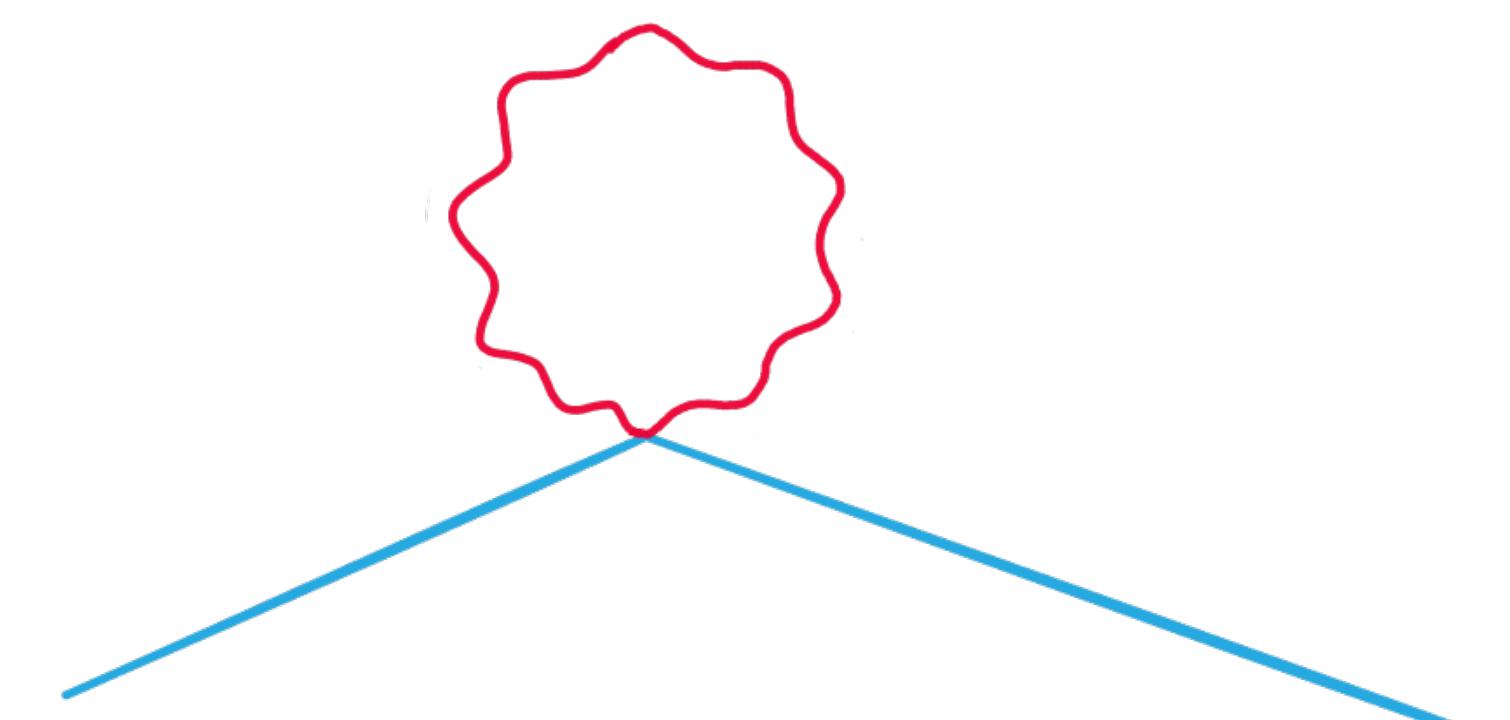
Another divergence!

In terms of scale $\Lambda \sim \hbar c/r$:

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi} \Lambda^2$$

Given observed splitting, *predict* scale of new physics:

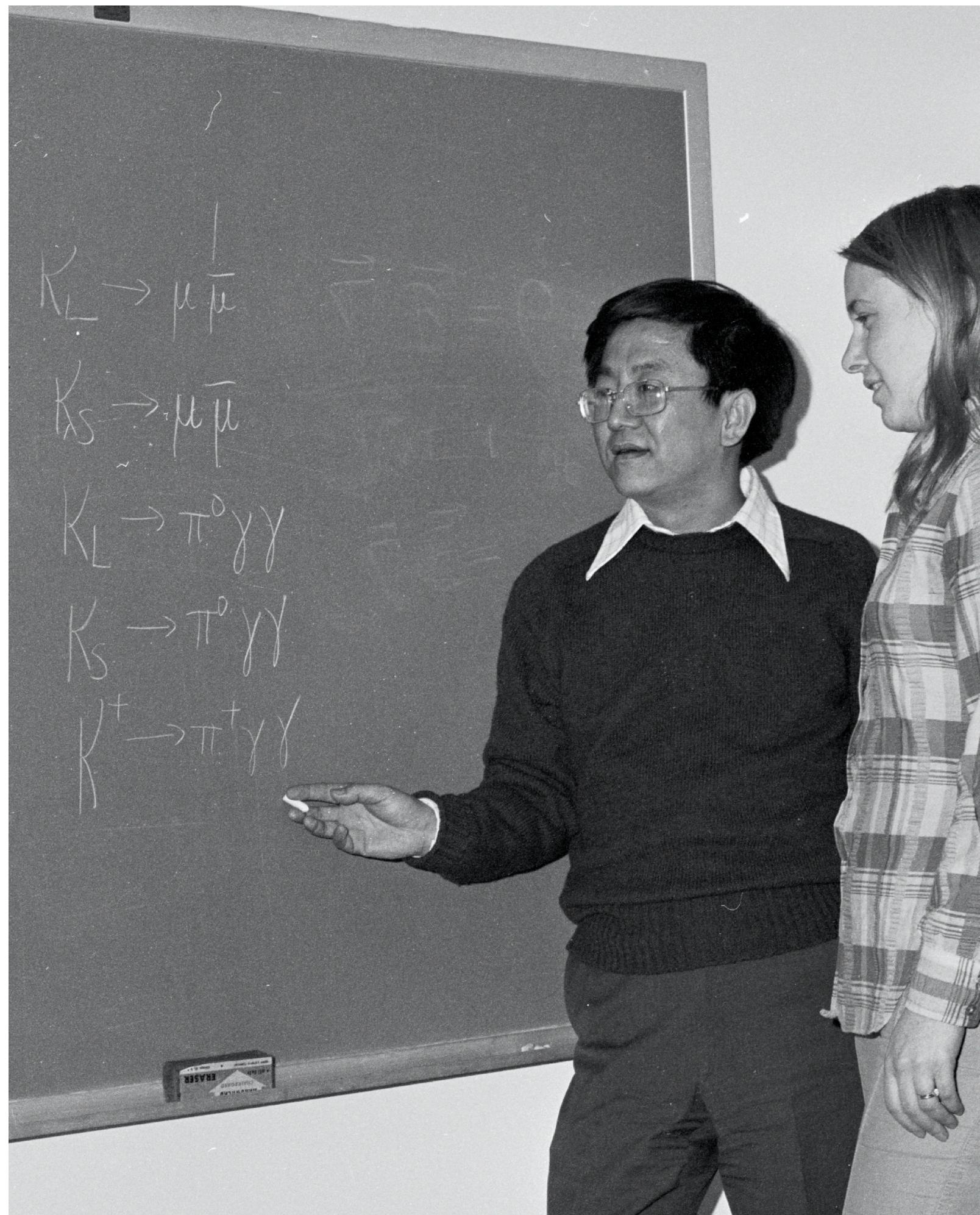
$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = (35.5 \text{ MeV})^2 \Rightarrow \Lambda \lesssim 850 \text{ MeV}$$



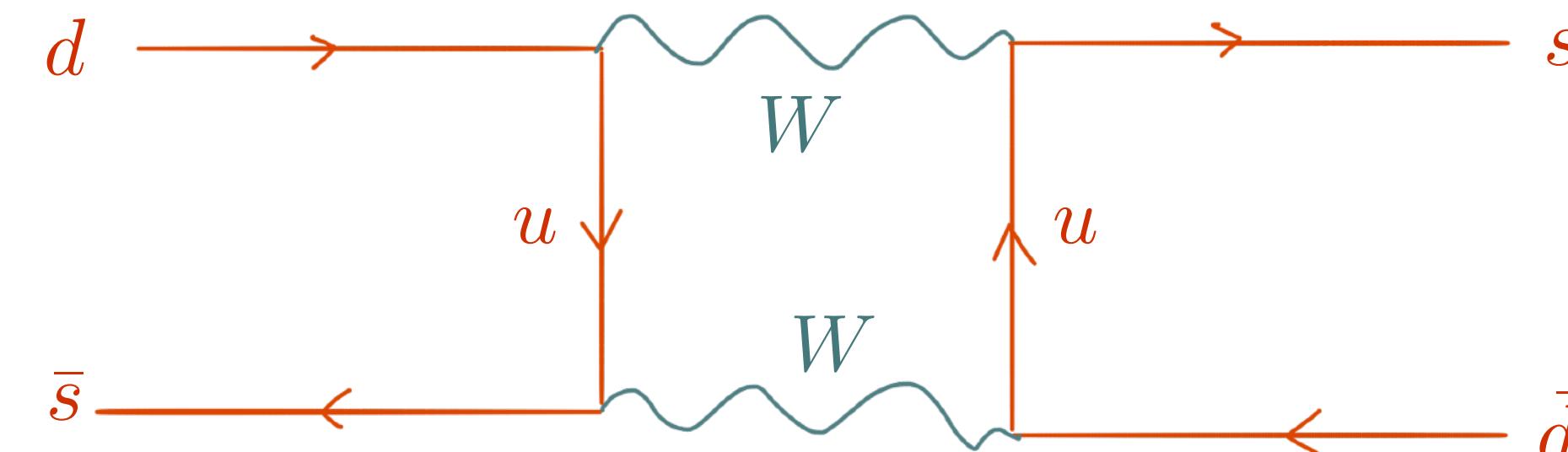
[Das, Guralnik, Mathur, Low, Young '67]

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 \approx \frac{3\alpha}{4\pi} \frac{m_\rho^2 m_{a_1}^2}{m_\rho^2 + m_{a_1}^2} \log \left(\frac{m_{a_1}^2}{m_\rho^2} \right)$$

The Naturalness Strategy



$$\frac{d\bar{s} + s\bar{d}}{\sqrt{2}} \quad K_L$$
$$\frac{d\bar{s} - s\bar{d}}{\sqrt{2}} \quad K_S$$

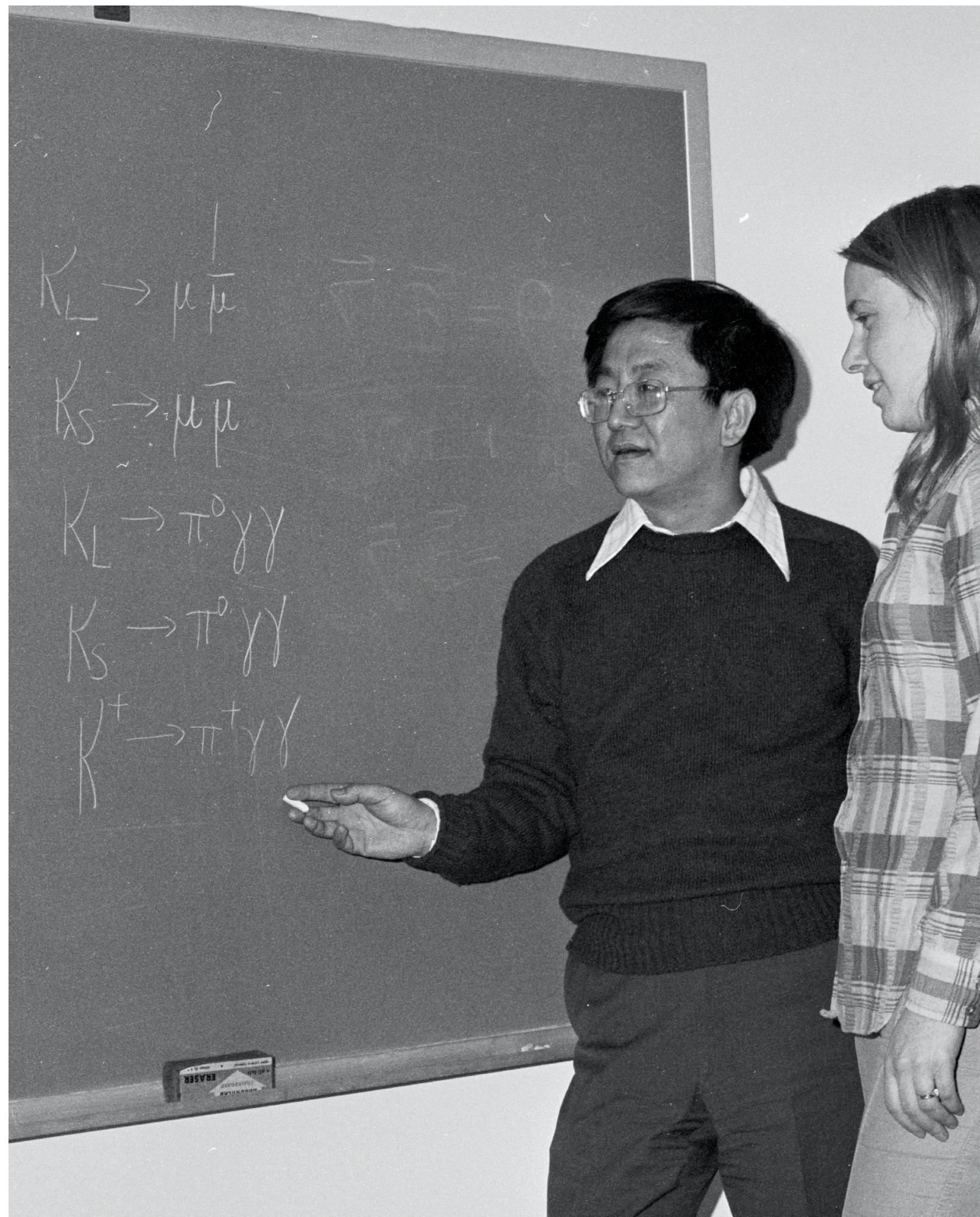


$$m_{K_L} - m_{K_S} \simeq \frac{1}{16\pi^2} m_K f_K^2 G_F^2 \sin^2 \theta_C \cos^2 \theta_C \times \Lambda^2$$

[Ioffe & Shabalin, 1968]

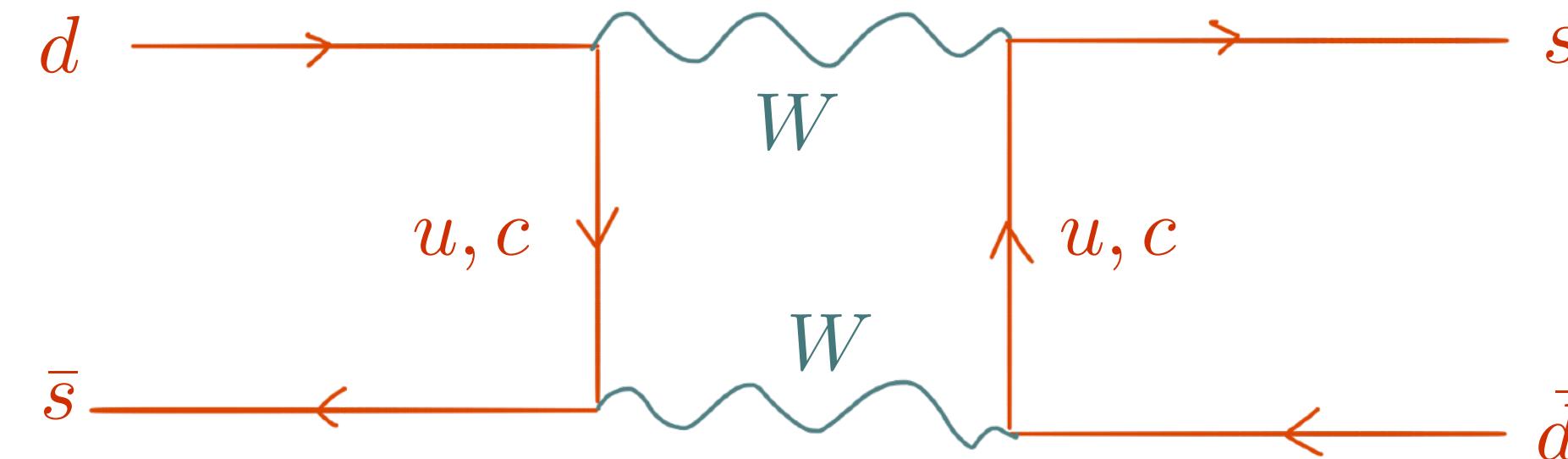
Given observed splitting, expect new physics around $\Lambda \sim 3 \text{ GeV}$

The Naturalness Strategy



[Glashow, Iliopoulos, Maiani, 1970]

Propose a 4th quark, charm



$$m_{K_L} - m_{K_S} \simeq \frac{1}{4\pi^2} m_K f_K^2 G_F^2 \sin^2 \theta_C \cos^2 \theta_C \times m_c^2$$

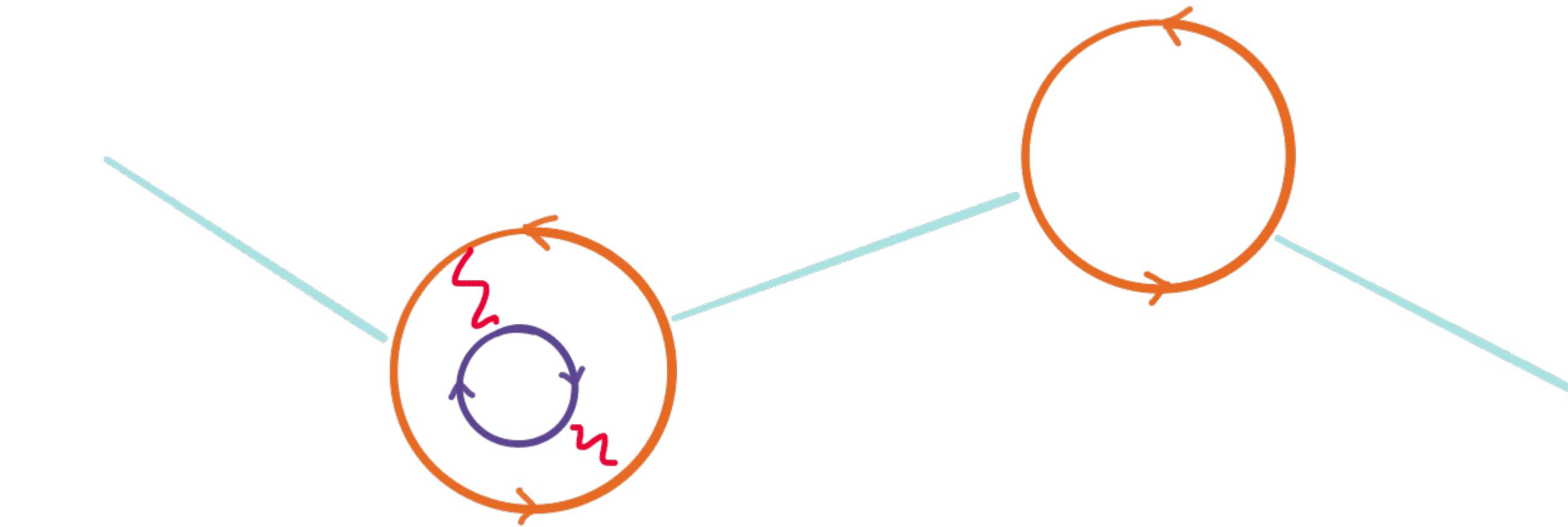
[Gaillard & Lee, 1974]

Predict $m_c \simeq 1.5 \text{ GeV}$

Charm discovered in 1974, $m_c = 1.2 \text{ GeV}$

The “Hierarchy Problem”

The Higgs is an apparently elementary scalar w/ self-energy due to its couplings to Standard Model particles



Assuming SM is valid down to some length scale $r_{\text{new}} \equiv \frac{\hbar c}{\Lambda}$ then we have

$$\Delta m_H^2 = \frac{\Lambda^2}{16\pi^2} \left[-6y_t^2 + \frac{9}{4}g_2^2 + \frac{3}{4}g_Y^2 + 6\lambda + \dots \right]$$

Expecting new physics at Λ such that $\Delta m_H^2 \sim m_H^2$ is a strategy.

The Naturalness Strategy

Param	UV sensitivity	Natural if	NP	Scale	Natural?
“ m_e ”	$e^2 \Lambda$	$\Lambda \lesssim 5 \text{ MeV}$	Positron	511 keV	✓
$m_{\pi^\pm}^2 - m_{\pi^0}^2$	$\frac{3\alpha}{4\pi} \Lambda^2$	$\Lambda \lesssim 850 \text{ MeV}$	Rho	770 MeV	✓
$m_{K_L} - m_{K_S}$	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4} \Lambda^2$	$\Lambda \lesssim 3 \text{ GeV}$	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2} \Lambda^2$	$\Lambda \lesssim 500 \text{ GeV}$?	?	?

A Reminder

Often said that the quadratic divergence “is” the hierarchy problem:

$$\Delta m_H^2 = \frac{\Lambda^2}{16\pi^2} \left[-6y_t^2 + \frac{9}{4}g_2^2 + \frac{3}{4}g_Y^2 + 6\lambda + \dots \right]$$

But this is misleading, as it depends on regularization scheme (try dim reg!).

Only meaningful if Λ is a **physical scale**. From the bottom-up, Λ a proxy for the scale of new physics. Given a UV completion, “quadratic divergence” replaced by finite, calculable, regularization scheme-independent contributions.

Tempting to “solve” hierarchy problem by positing no physical scale above weak scale. Still need to explain why scale of quantum gravity, hypercharge Landau pole do not contribute.

From the “naturalness strategy” to new physics

At this level, we expect

- New physics around the TeV scale...
- ...coupling to the Higgs

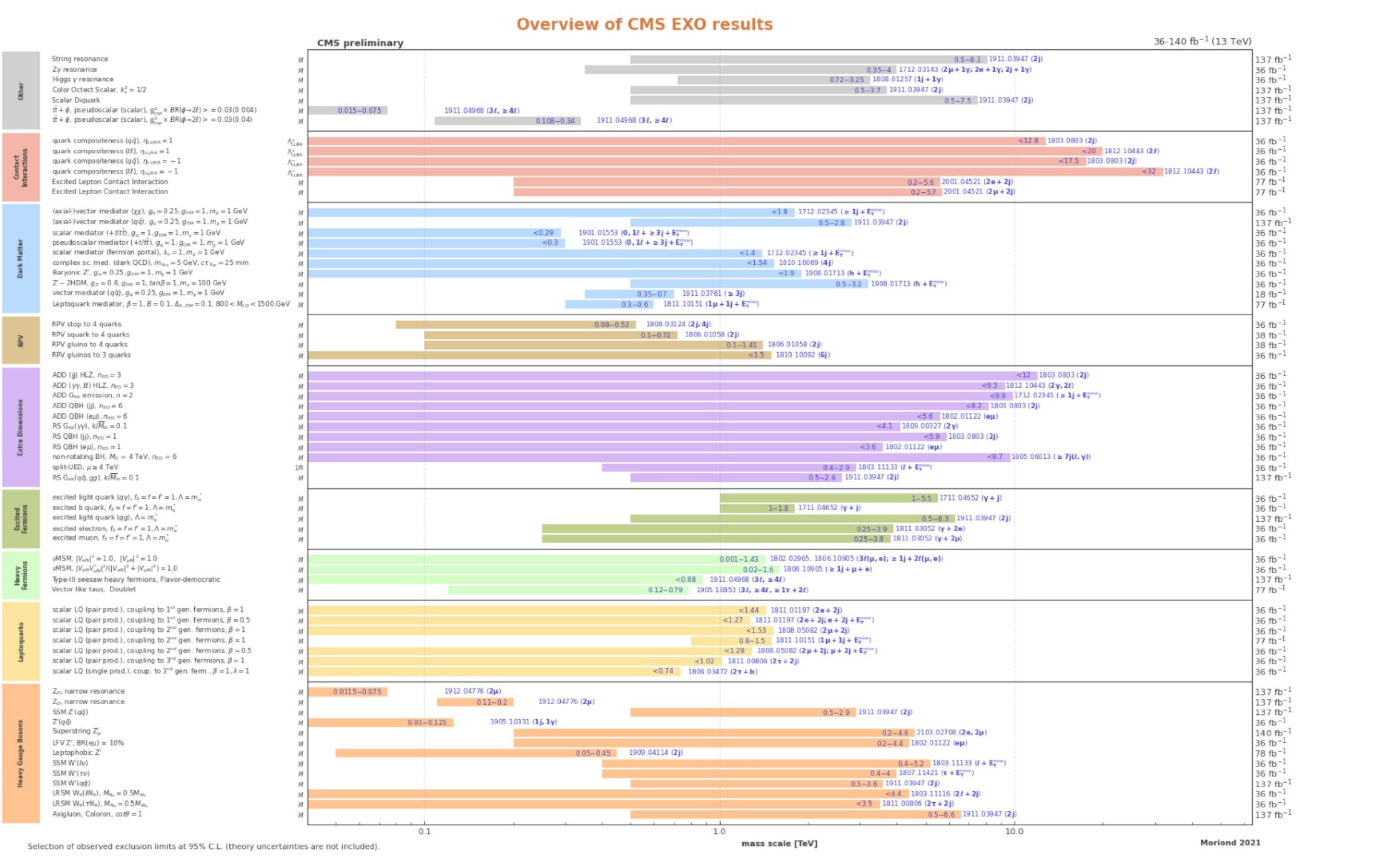
Strong motivation for beyond-the-Standard Model physics connected to Higgs! But maybe too broad to be useful guidance to experiment.

To make further progress, we can come up with models.

Easiest path: work by analogy with known examples.

Supersymmetry: Relate Higgs to a fermion, *a la* electron.

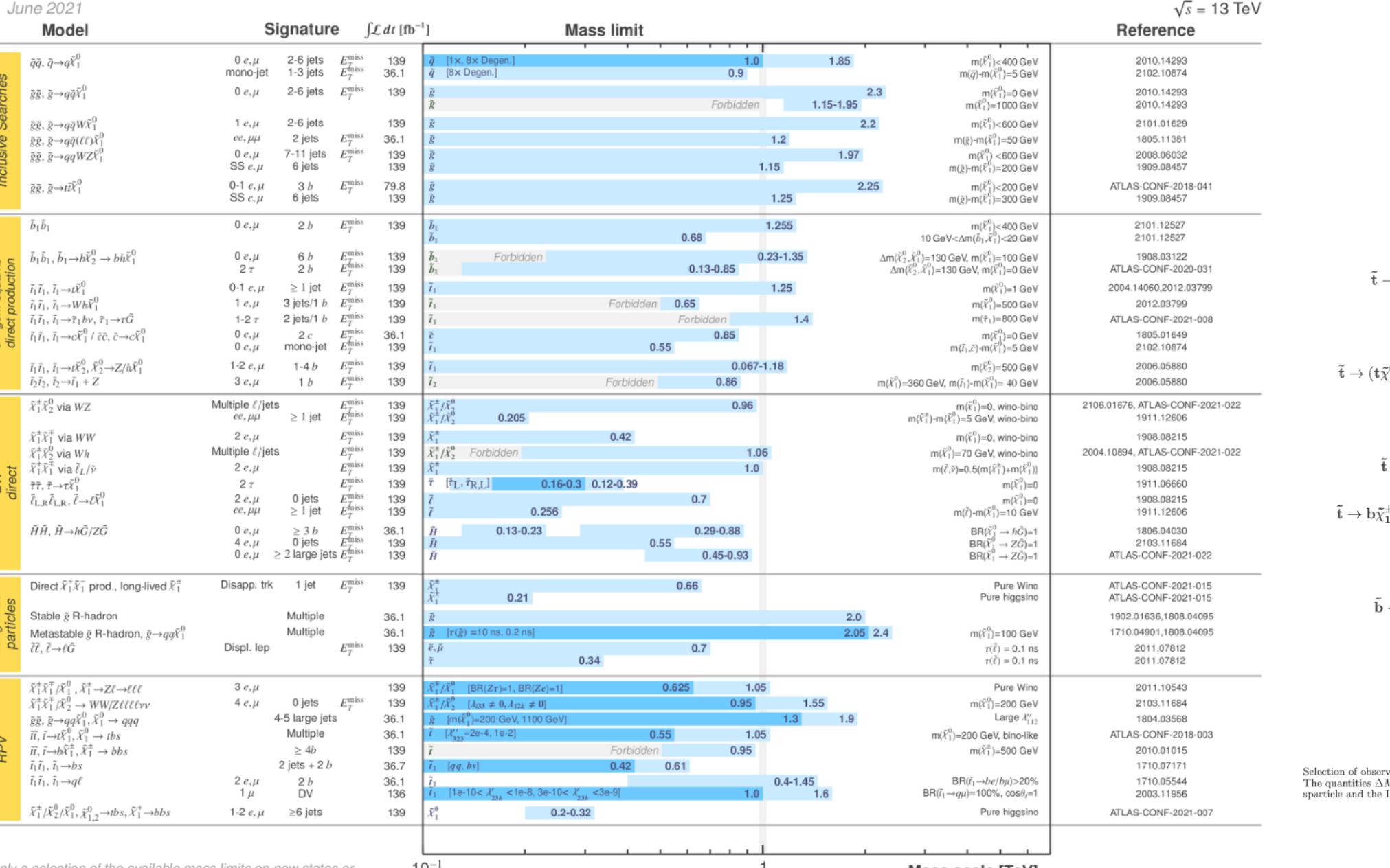
Compositeness: Higgs is a composite particle, *a la* the pion.



t thus far... Magnetic monopoles $\sqrt{s} = 8 \text{ TeV}$ \sqrt{s} par

[†]Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS SUSY Searches* - 95% CL Lower Limits



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limit

status: May 2020

ATLAS Preliminary

$\sqrt{s} = 8, 13 \text{ TeV}$

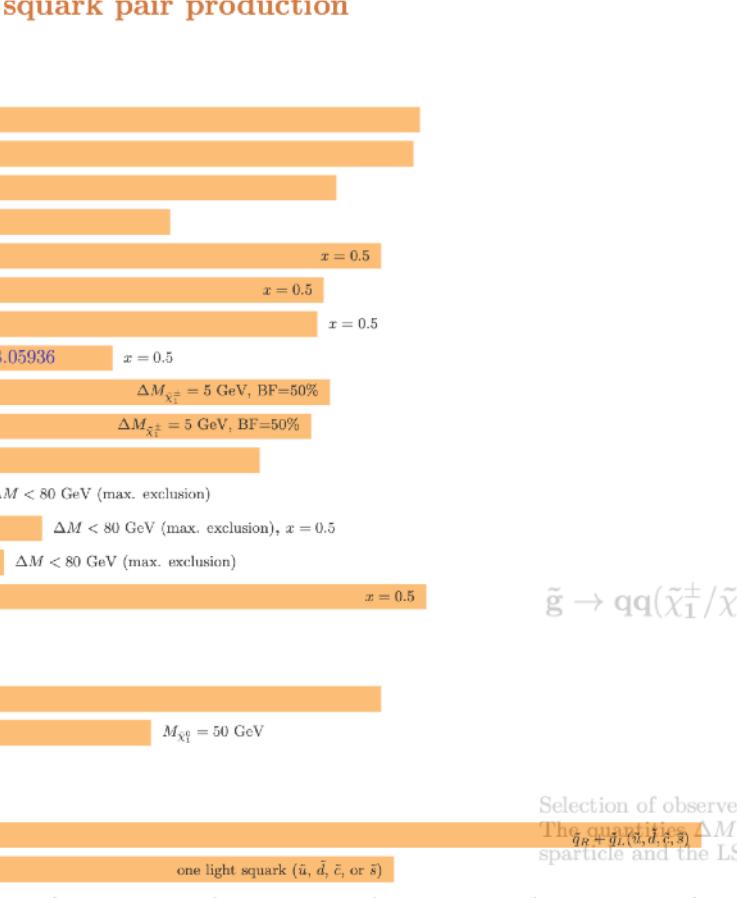
Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV M_S 8.6 TeV M_{th} 8.9 TeV M_{th} 8.2 TeV M_{th} 9.55 TeV	$n = 2$ $n = 3$ HLZ NLO $n = 6$ $n = 6, M_D = 3$ TeV, rot BH $n = 6, M_D = 3$ TeV, rot BH $k/\overline{M}_{Pl} = 0.1$ $k/\overline{M}_{Pl} = 1.0$ $k/\overline{M}_{Pl} = 1.0$ $\Gamma/m = 15\%$ Tier (1,1), $B(A^{(1,1)} \rightarrow tt) = 1$	1711.03301
ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7			1707.04147
ADD QBH	–	2 j	–	37.0			1703.09127
ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	–	3.2			1606.02265
ADD BH multijet	–	$\geq 3 j$	–	3.6			1512.02586
RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV		1707.04147
Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	–	–	36.1	G_{KK} mass 2.3 TeV		1808.02380
Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$		1 e, μ	2 j / 1 J	Yes	G_{KK} mass 2.0 TeV		2004.14636
Bulk RS $g_{KK} \rightarrow tt$		1 e, μ	$\geq 1 b, \geq 1 J/2j$	Yes	g_{KK} mass 3.8 TeV		1804.10823
2UED / RPP		1 e, μ	$\geq 2 b, \geq 3 j$	Yes	KK mass 1.8 TeV		1803.09678
SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
Leptophobic $Z' \rightarrow bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
Leptophobic $Z' \rightarrow tt$	0 e, μ	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
SSM $W' \rightarrow \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV		2004.14636
HVT $V' \rightarrow WV \rightarrow qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV		1906.08589
HVT $V' \rightarrow WH/ZH$ model B	multi-channel	–	–	36.1	V' mass 2.93 TeV		1712.06518
HVT $W' \rightarrow WH$ model B		0 e, μ	$\geq 1 b, \geq 2 J$	139	W' mass 3.2 TeV		CERN-EP-2020-073
LRSM $W_R \rightarrow tb$		–	–	36.1	W_R mass 3.25 TeV		1807.10473
LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) - 0.5$ TeV, $g_L = g_R$	1904.12679
Cl $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
Cl $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	CERN-EP-2020-066
Cl $t t t t$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV	$ C_4 = 4\pi$	1811.02305
Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV		1711.03301
Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV		1711.03301
$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, $\leq 1 j$	Yes	3.2	M_\ast 700 GeV		1608.02372
Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4, \lambda = 0.2, m(\chi) = 10$ GeV	1812.09743
Scalar LQ 1 st gen	1,2 e	$\geq 2 j$	Yes	36.1	LQ mass 1.4 TeV		1902.00377
Scalar LQ 2 nd gen	1,2 μ	$\geq 2 j$	Yes	36.1	LQ mass 1.56 TeV		1902.00377
Scalar LQ 3 rd gen	2 τ	2 b	–	36.1	LQ_1^\ast mass 1.03 TeV	$\mathcal{B}(LQ_3^\ast \rightarrow b\tau) = 1$	1902.08103
Scalar LQ 3 rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^\ast mass 970 GeV	$\mathcal{B}(LQ_3^\ast \rightarrow \tau\tau) = 0$	1902.08103
VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	–	–	36.1	T mass 1.37 TeV		1808.02343
VLQ $BB \rightarrow Wt/Zb + X$		–	–	36.1	B mass 1.34 TeV		1808.02343
VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	2(SS)/ ≥ 3 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	1807.11883
VLQ $Y \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$	1812.07343
VLQ $B \rightarrow Hb + X$	0 e, $\mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$	ATLAS-CONF-2018-024
VLQ $QQ \rightarrow WqWq$	1 e, μ	$\geq 4 j$	Yes	20.3	Q mass 690 GeV		1509.04261
Excited quark $q^\ast \rightarrow qg$	–	2 j	–	139	q^\ast mass 6.7 TeV	only u^\ast and d^\ast , $\Lambda = m(q^\ast)$	1910.08447
Excited quark $q^\ast \rightarrow q\gamma$	1 γ	1 j	–	36.7	q^\ast mass 5.3 TeV	only u^\ast and d^\ast , $\Lambda = m(q^\ast)$	1709.10440
Excited quark $b^\ast \rightarrow bg$	–	1 b, 1 j	–	36.1	b^\ast mass 2.6 TeV		1805.09299
Excited lepton ℓ^\ast	3 e, μ	–	–	20.3	ℓ^\ast mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
Excited lepton ν^\ast	3 e, μ, τ	–	–	20.3	ν^\ast mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Type III Seesaw	1 e, μ	$\geq 2 j$	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	$\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $ q = 5e$	1812.03673
Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $ g = 1g_D$, spin 1/2	1905.10130

selection of the available mass limits on new states or phenomena is shown.

small-radius (large-radius) jets are denoted by the letter j (J)

Moriond 20

squark pair production



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate

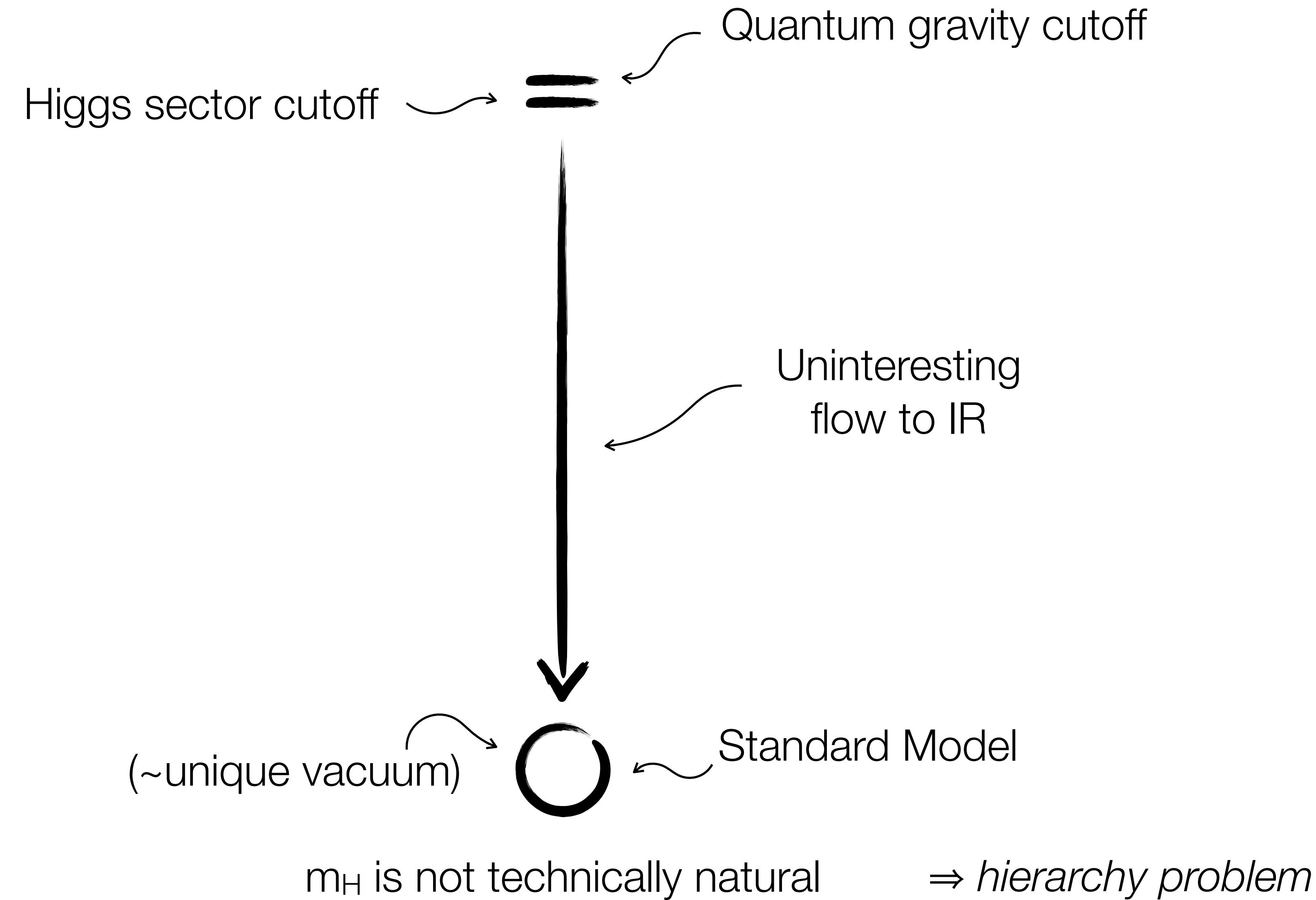
one light squark (\tilde{u} , \tilde{d} , \tilde{c} , or \tilde{s})

750 1000 125
mass scale [GeV]

mass limit for light LSP's unless stated otherwise. SP, and the difference between the intermediate

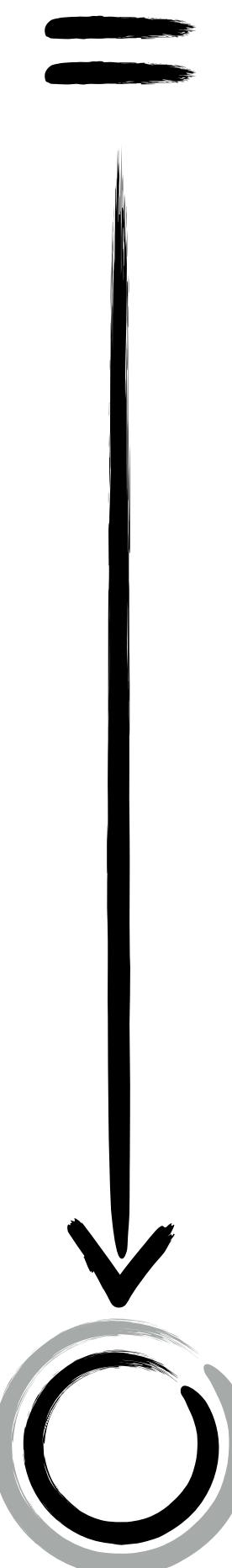


The Hierarchy Problem Cartoon



Adding a symmetry

...and (sometimes) breaking it softly



1. **Supersymmetry** (*a la* the electron)
2. **Global symmetry** (*a la* the pion)
3. **Discrete symmetry**
4. **Modular invariance**

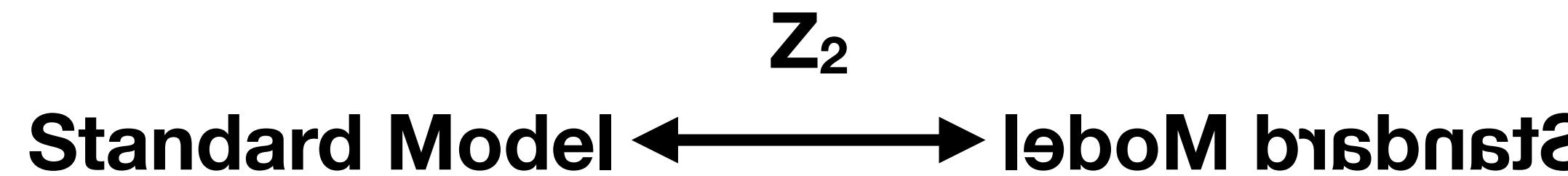
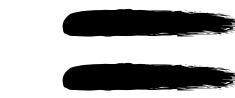
[Dienes et al. '94-'01, ...]

Experimental signals: partner particles

- The familiar host of prompt signals (with or without missing energy)
- Rich variety of displaced decays (RPV, twin higgs, folded SUSY, ...)

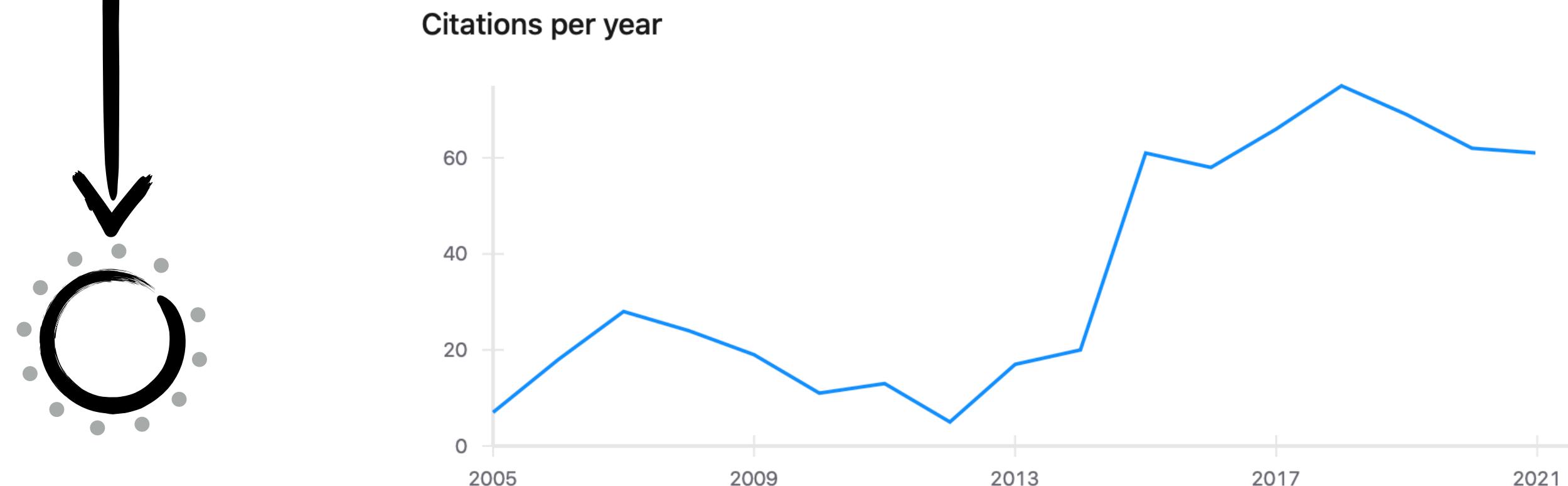
Neutral Naturalness

Twin Higgs [Chacko, Goh, Harnik '05]

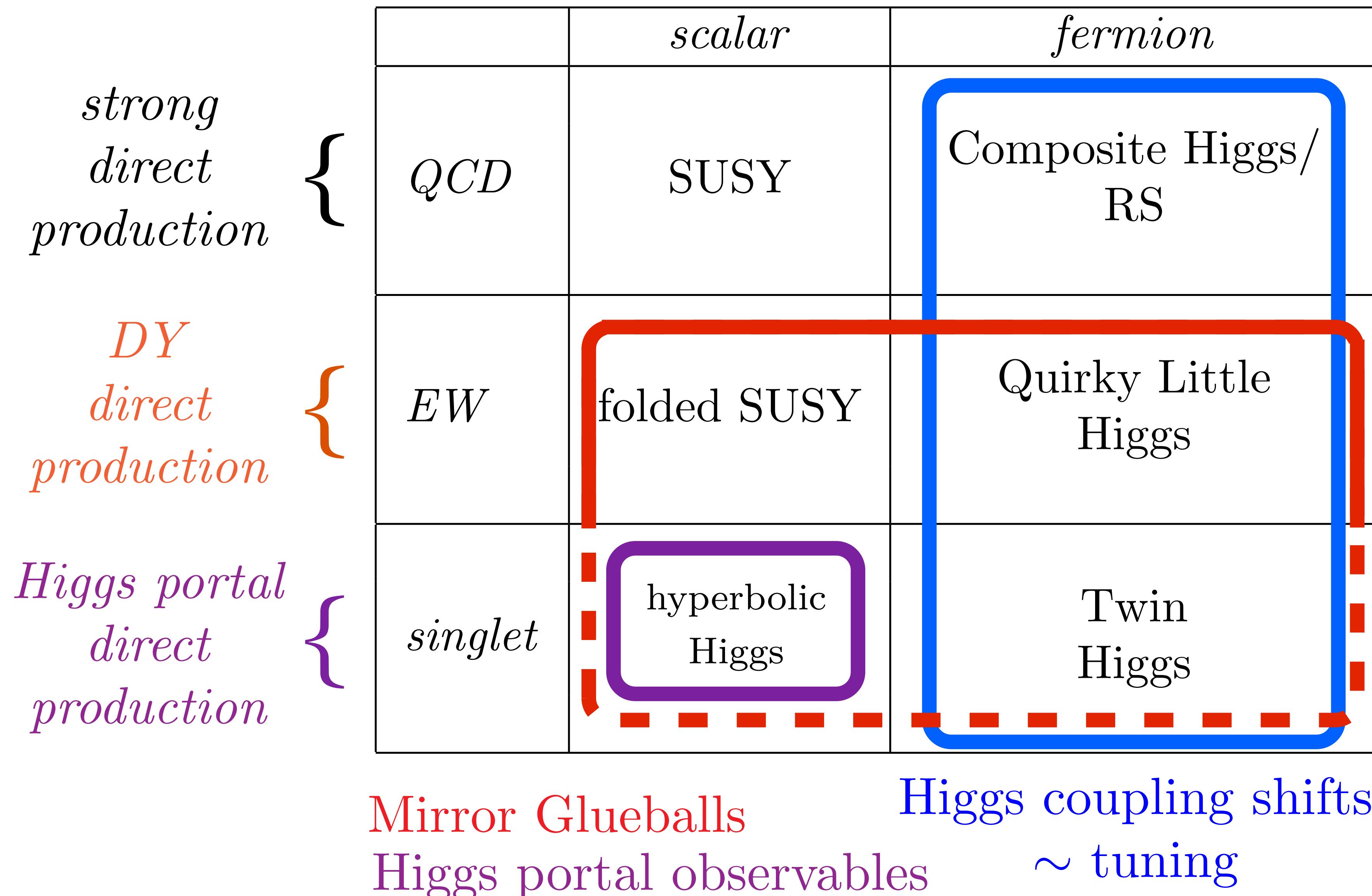


Radiative corrections to mass-squared are SU(4) symmetric thanks to Z_2 :

$$V(H) \supset \frac{\Lambda^2}{16\pi^2} \left(-6y_t^2 + \frac{9}{4}g^2 + \dots \right) (|H_A|^2 + |H_B|^2)$$



See [B. Batell, M. Low, E.T. Neil and C.B. Verhaaren,
Review of Neutral Naturalness, 2203.05531]



Lowering the cutoff

...in diverse dimensions



5. RS / Technicolor

[Randall, Sundrum '99;
Weinberg '79; Susskind '79]

6. LED / $10^{32} \times$ SM

[Arkani-Hamed, Dimopoulos, Dvali '98;
Antoniadis + ibid. '98; Dvali, Redi '09]

7. LST / Clockwork

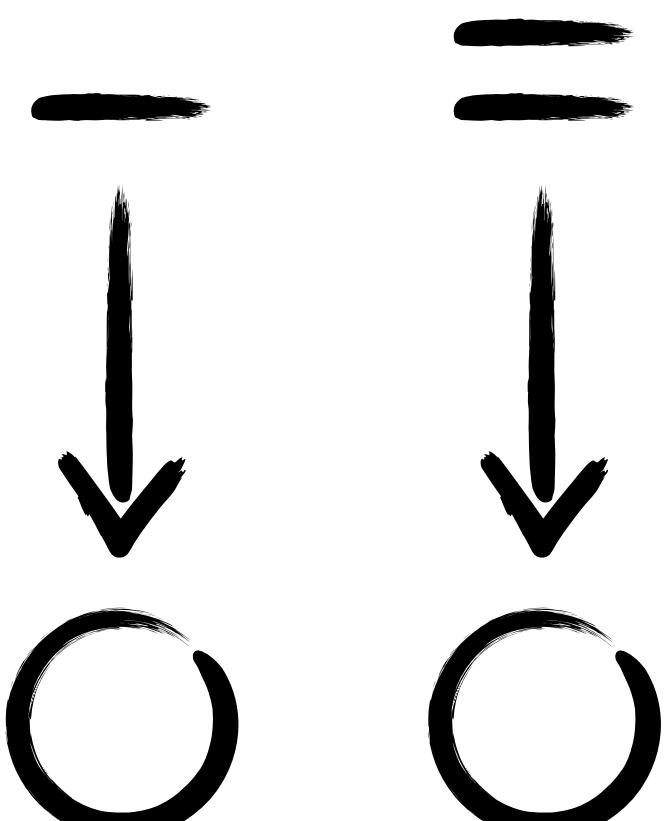
[Antoniadis, Dimopoulos, Giveon '01; Kaplan,
Rattazzi '15; Giudice, McCullough '16]

8. Classicalization

[Dvali, Giudice, Gomez, Kehagias '10]

9. Disorder

[Rothstein '12]



Experimental signals: resonances, ...

- Primary distinctions are in spacing & coupling of resonances
- Potential goldmine of relatively unexplored signals for LST – e.g. perturbative string excitations

Selecting a vacuum

Vacuum is one of many; end up in observed vacuum through dynamical process or anthropic constraint.

10. Anthropics (pressure)

11. Relaxation (rolling) [Graham, Kaplan, Rajendran '15]

12. NNaturalness (reheating) [Arkani-Hamed et al '16]

13. Crunching away (collapse) [Csaki et al '20, see also Geller, Hochberg, Kuflik '18, Cheung & Saraswat '18, ...]

Experimental signals: Diverse, but typically

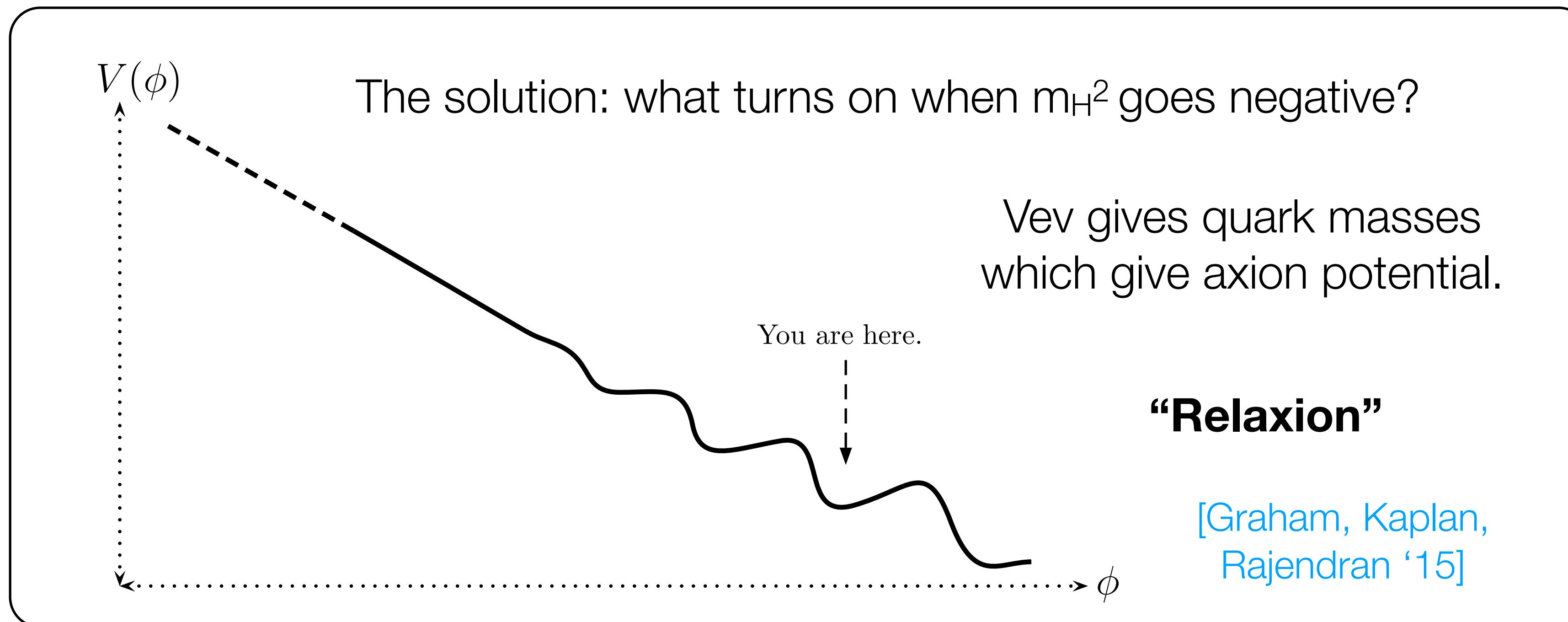
- Cosmology (Bubble collisions; axions; contributions to N_{eff} and $\sum m_v$)
- Exotic lab signals (displaced decays, hidden sector confinement, rare/precision frontier, ...)



Relaxion

What if the weak scale is selected by dynamics, not symmetries?

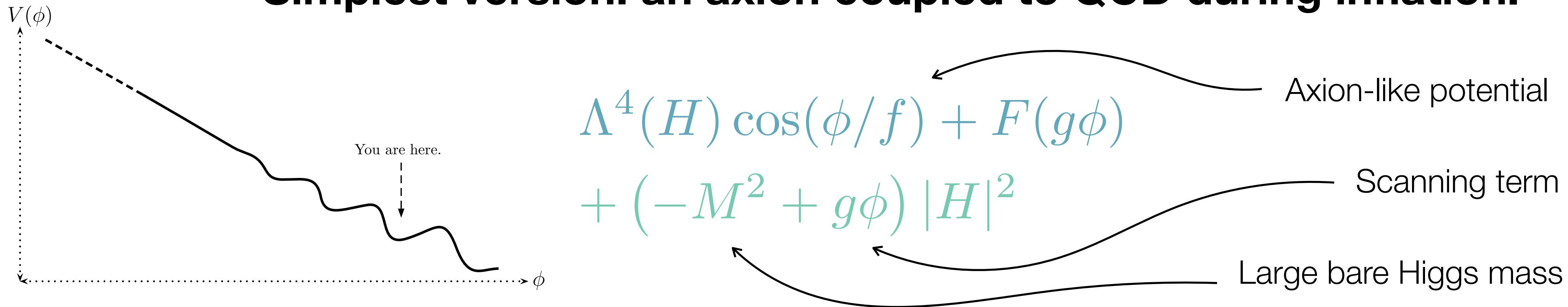
The idea: couple Higgs to field whose minimum sets $m_H=0$
The problem: How to make $m_H=0$ a special point of potential?



But: immense energy stored in evolving field, need dissipation.

Relaxion

Simplest version: an axion coupled to QCD during inflation.



Various other subtleties regarding technical naturalness, trans-Planckian field excursions, fine-tuning to inflationary sector; need to solve strong CP problem. New UV considerations.

Extensive development, e.g. [Espinosa et al. '15; Hardy '15; Gupta et al '15; Batell, Giudice, McCullough '15; Choi, Im '15; Kaplan, Rattazzi '15; Di Chiara et al. '15; Ibanez et al. '15; Hook, Marques-Tavares '16; Nelson, Prescod-Weinstein '17; ...]

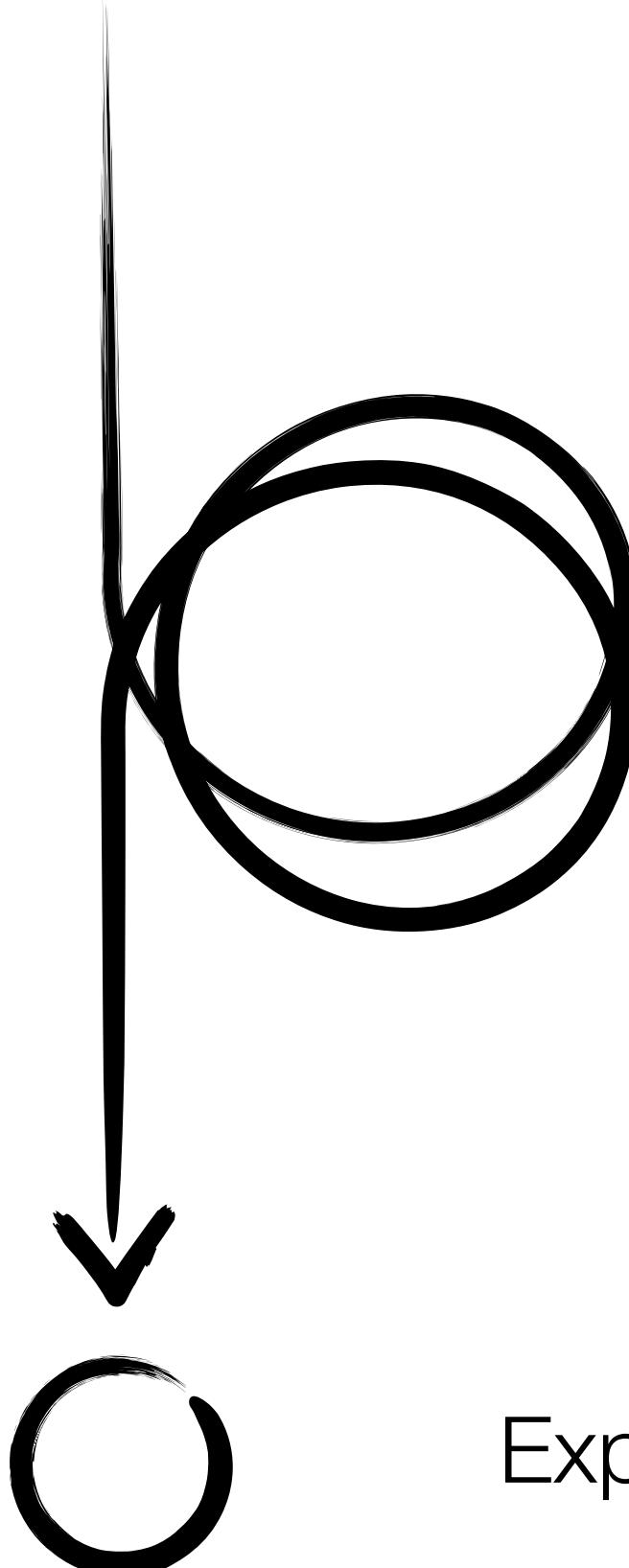
See [P. Asadi et al., *Early-Universe Model Building*, 2203.06680]

Complicating the flow

=

SM is reached from some intermediate fixed point
where, say, a generalized Veltman condition is satisfied

$$\delta m_H^2 = \sum_i c_i \frac{g_{i,\star}^2}{16\pi^2} \Lambda_i^2 = 0$$



This is a sense in which

14. Conformal symmetry

could address the hierarchy problem

Top-down: Embed SM in orbifold of N=4 SYM

[Frampton, Vafa '99; Csaki, Skiba, Terning '99]

Bottom-up: “Little conformal symmetry”

[Houtz, Colwell, Terning '16]

Experimental signals: Not fully explored, but expect new particles w/ SM quantum numbers around the TeV scale. Novelty is that statistics, irreps & couplings differ from more familiar solutions.

Exploding the cutoff

Gravity doesn't provide a UV scale & the SM takes care of itself

15. Asymptotic fragility

[Dubovsky, Gorbenko, Mirbabayi '13]

16. Agravity [Salvio, Strumia '14]

Scale M_{Pl} not associated with relevant operator becoming strong, not “felt” by non-grav physics.

In IR, looks like CFT perturbed by irrelevant operators; in UV, no UV fixed point; cannot define local observables.

Example in 2d, no proposal for 4d.

Gravity has no intrinsic length scale and is “renormalizable”

$$S \sim \int d^4x \sqrt{g} \left(\frac{R^2}{f_1^2} + \frac{\frac{1}{3}R^2 - R_{\mu\nu}^2}{f_2^2} + \dots \right)$$

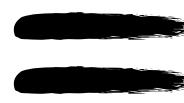
(E-H term via vev of some field)

Can be re-written in terms of 2-derivative fields w/ ghosts.

Experimental signals: Crucially, must render SM couplings asymptotically free. Not a property of the SM itself, so entails low-scale unification.



Not actually the SM

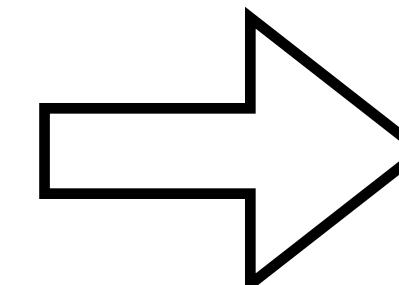


17. Lee-Wick (higher derivative scalar)

[Grinstein, O'Connell, Wise '06]

Lee-Wick: higher-
derivative theory

$$\sim \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2M^2} (\partial^2 \phi)^2 + \dots$$

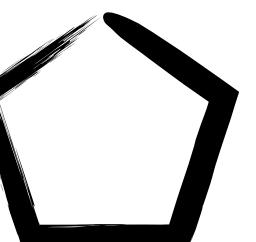


Write as normal field + new field
w/ wrong-sign quadratic action

$$-\frac{1}{2} \partial_\mu \tilde{\phi} \partial^\mu \tilde{\phi} + \frac{1}{2} M^2 \tilde{\phi}^2 + \dots$$

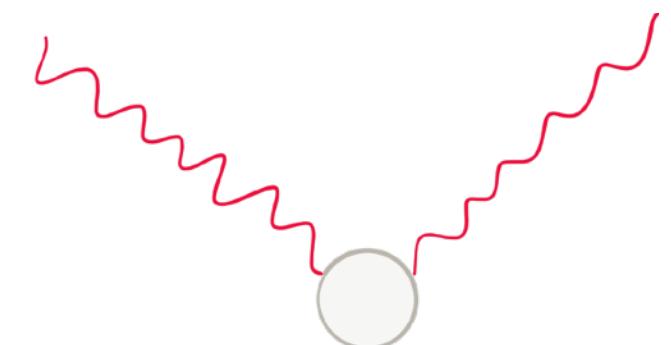
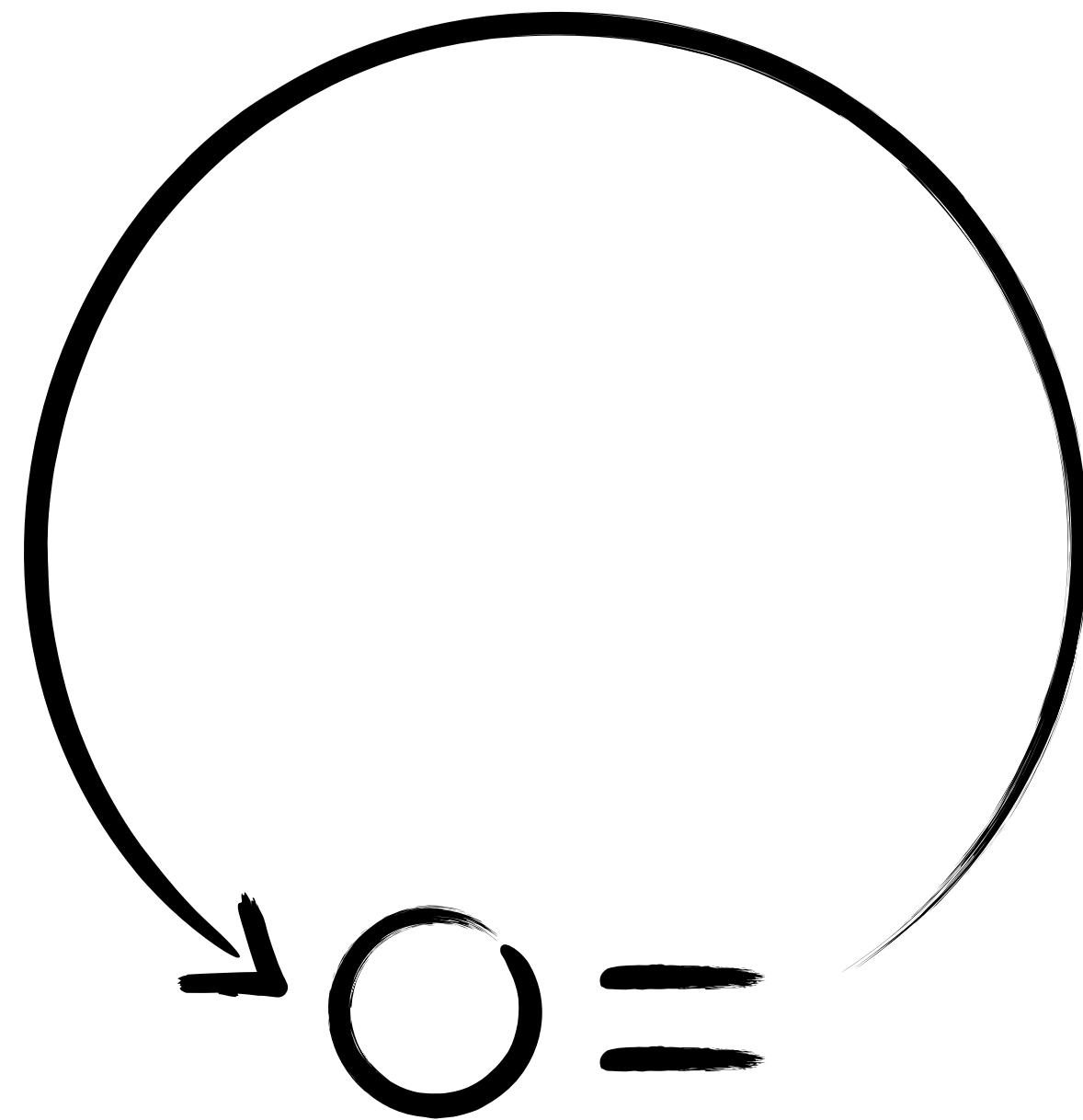
Improves UV convergence of
diagrams, introduce for every SM field

$$\frac{1}{p^2 - m^2} - \frac{1}{p^2 - M^2} = \frac{m^2 - M^2}{(p^2 - m^2)(p^2 - M^2)}$$



Can be defined in a unitary, Lorentz-invariant manner with only
microscopic acausality. But who ordered that?

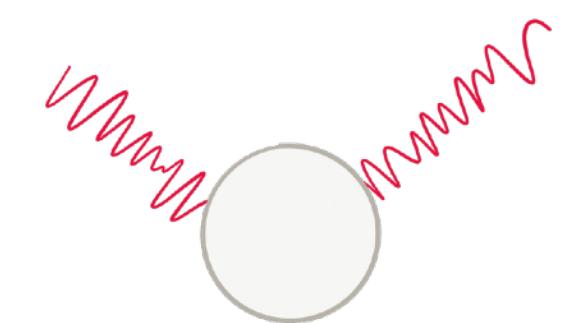
Connecting UV & IR



Essential feature of the hierarchy problem: the UV doesn't know about the IR...unless it does?

Two frameworks exhibiting UV/IR mixing: quantum gravity & non-commutative QFT

QG (cartoon version): collide sufficiently energetic particles, make a black hole. More energetic particles \rightarrow bigger black hole.



NCQFT (cartoon version): non-commutativity of the form $[x^\mu, x^\nu] = i\theta^{\mu\nu}$, qualitatively a position-position uncertainty principle $\Delta x^\mu \Delta x^\nu \geq \theta/2$ [Filk '96, Minwalla, Seiberg, Van Raamsdonk '99, NC, Koren '19]

*Two ways to put this to work
for hierarchy problem:*

18. Indirect UV/IR mixing

19. Direct UV/IR mixing

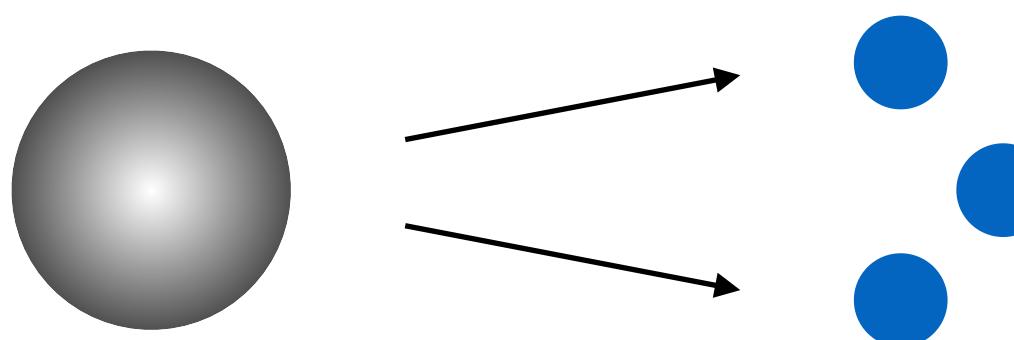
Indirect UV/IR: WGC

(Electric) weak gravity conjecture: an abelian gauge theory must contain a state of charge q and mass m satisfying

$$gq \geq \frac{m}{M_{\text{Pl}}}$$

[Arkani-Hamed, Motl, Nicolis, Vafa '07]

“Justification”: consider BH of charge Q , mass M decaying to this particle



particles produced = Q/q

Energy conservation: $mQ/q < M$

Then BH satisfies

$$Z = Q M_{\text{Pl}} / M < z = q M_{\text{Pl}} / m$$

Extremal BH ($Z=1$) stable unless there exists a state with $z > 1$

$\Rightarrow q > m/M_{\text{Pl}}$ to avoid stable black holes, remnants, in conflict w/ holography

A Family of Conjectures

Electric WGC: $m \leq (gq)M_{\text{Pl}}$

[Arkani-Hamed, Motl, Nicolis, Vafa '07]

Magnetic WGC: $\Lambda \lesssim gM_{\text{Pl}}$

[Arkani-Hamed, Motl, Nicolis, Vafa '07]

+Scalar WGC: $m \leq \sqrt{g^2 q^2 - \mu^2} M_{\text{Pl}}$

[Palti '17]

$m^2 \gtrsim gqM_{\text{Pl}}H$

dS WGC:

[Montero, Van Riet, Venken '19]

Axion WGC: $f \leq (1/S)M_{\text{Pl}}$

[Arkani-Hamed, Motl, Nicolis, Vafa '07]

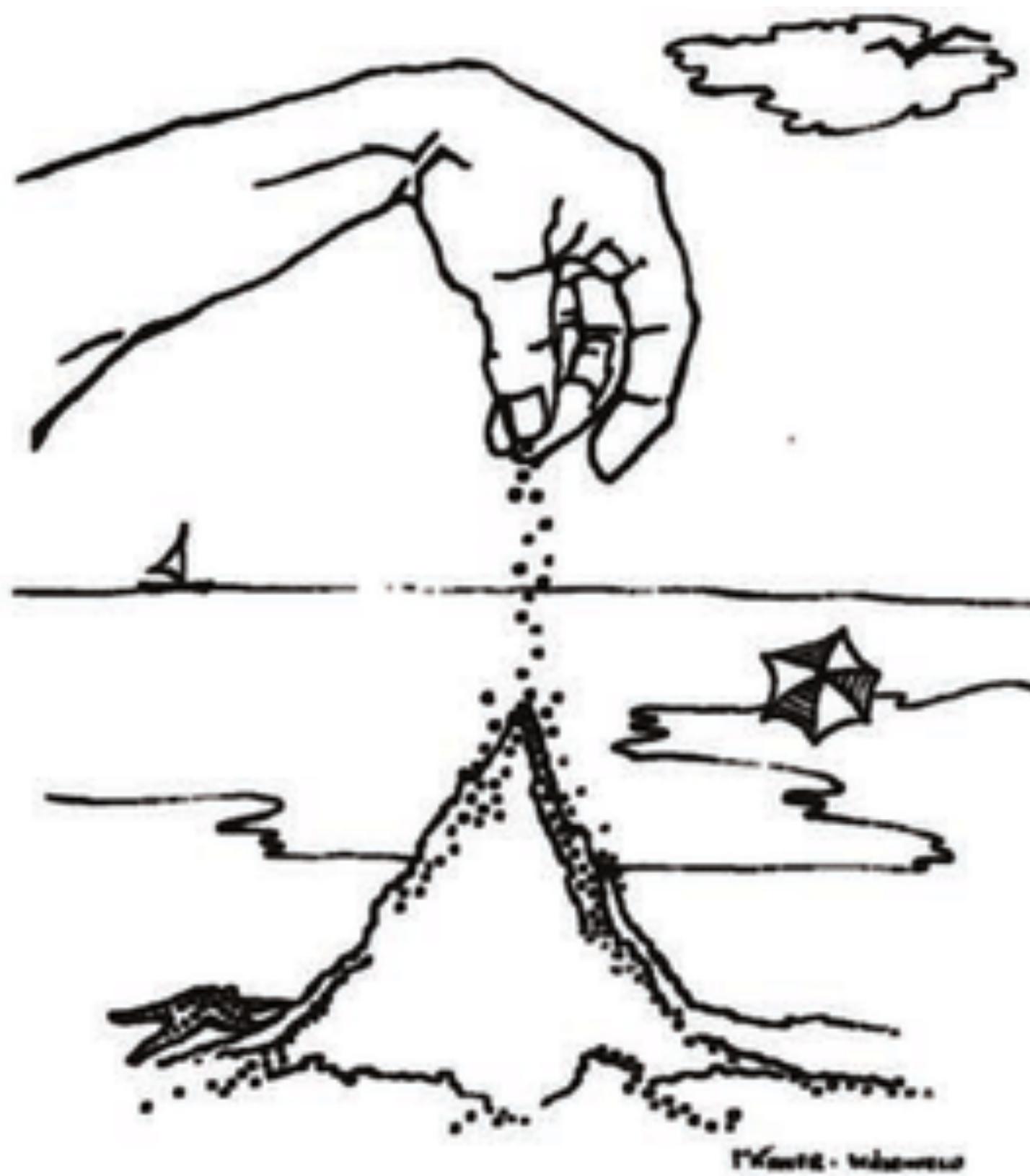
See [P. Draper, I.G. Garcia and M. Reece, Snowmass *White Paper: Implications of Quantum Gravity for Particle Physics*, 2203.07624]

New hierarchies from EFT + gravity.

Relevant for the hierarchy problem [Cheung & Remmen '14; Ibañez, Martin-Lozano, Valenzuela '17; NC, Garcia Garcia, Koren '19; March-Russell, Petrossian-Byrne '20]

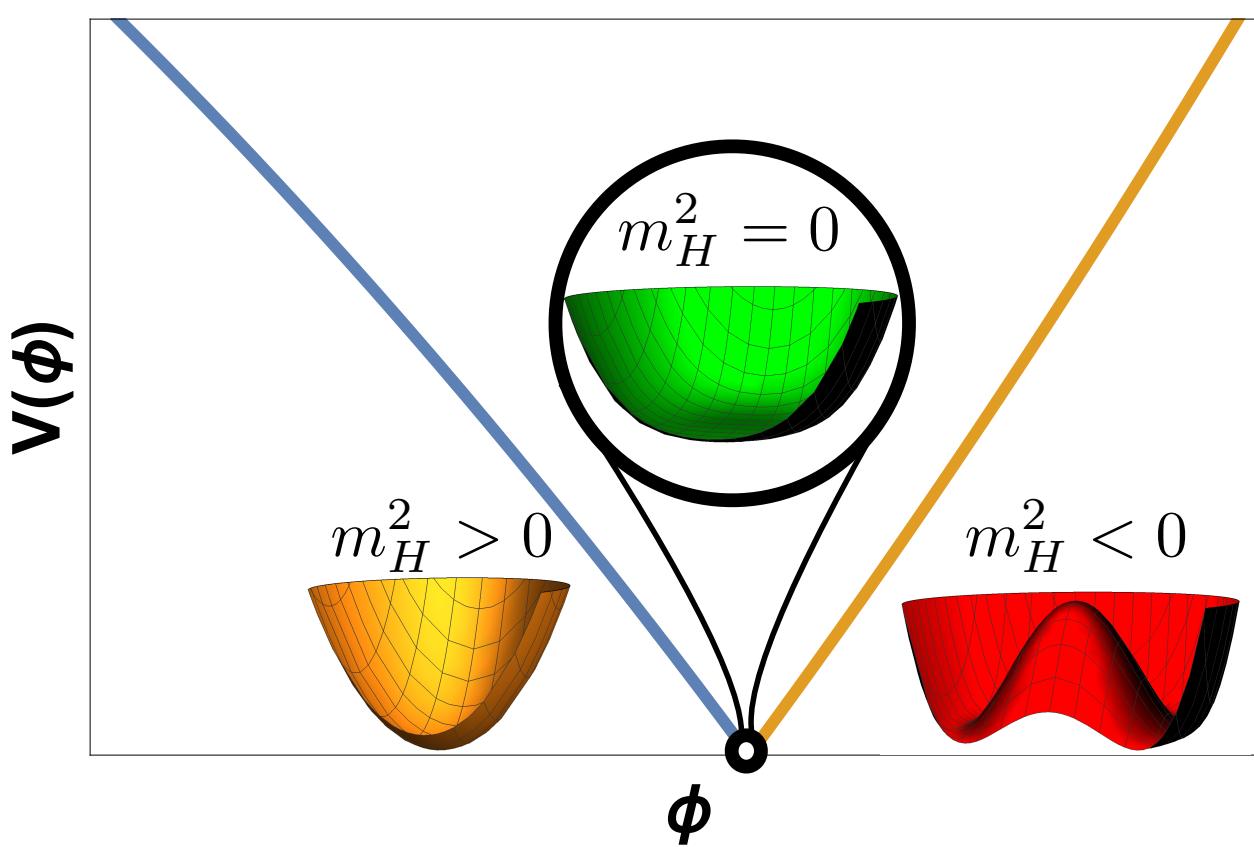
Self-Organized Criticality

Some systems evolve into critical states on their own (sandpiles, a la [Bak, Tang, Wiesenfeld '84]).
Wouldn't that be nice? [Giudice '08, Kaplan '97]

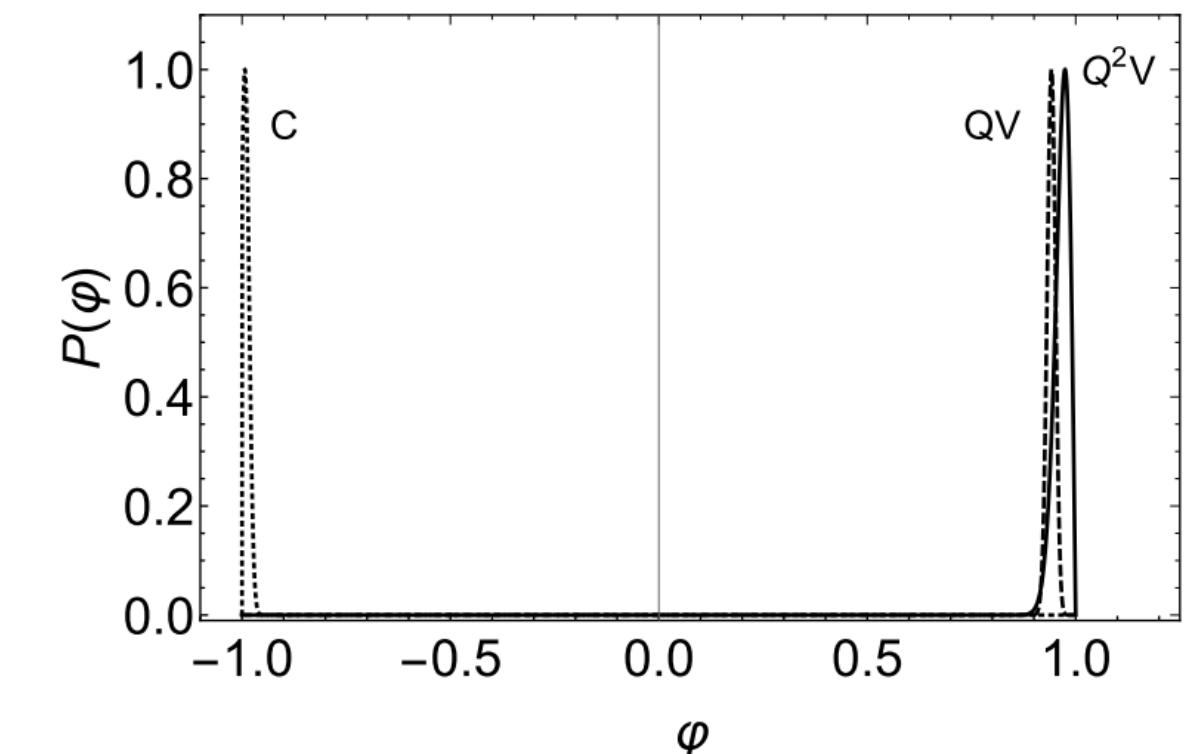


20. Self-organized Criticality

Vanishing Higgs mass coinciding
with potential minimum for an
extra-dimensional modulus field
[Eroencel, Hubisz, Rigo '18]



Localization of scalar fields
exponentially close to critical
points during eternal inflation
[Giudice, McCullough, You '21]
[Khoury et al. '19-'20]



- | | | |
|-----------------------------|------------------------|--------------------------------|
| 1. Supersymmetry | 8. Classicalization | 15. Asymptotic fragility |
| 2. Global symmetry | 9. Disorder | 16. Agravity |
| 3. Discrete symmetry | 10. Anthropics | 17. Lee-Wick Theory |
| 4. Modular invariance | 11. Relaxation | 18. Weak gravity conjecture |
| 5. RS/Technicolor | 12. NNaturalness | 19. Non-commutative QFT |
| 6. LED/ $10^{32} \times$ SM | 13. Crunching away | 20. Self-organized criticality |
| 7. LST/Clockwork | 14. Conformal symmetry | 21. ... |

With apologies for the many omissions...

What next?

See [C.Cordova, T. Dumitrescu,
K. Intriligator, S-H, Shao,
Snowmass White Paper:
Generalized Symmetries in QFT
and Beyond, 2205.09545]

Generalized Global Symmetry

Properties of symmetry op.	Ordinary symmetry	Higher-form symmetry	Non-invertible symmetry
Codimension in spacetime	1	> 1	≥ 1
Topological	yes	yes	yes
Fusion rule	group $g_1 \times g_2 = g_3$	group $g_1 \times g_2 = g_3$	fusion ring $a \times b = \sum_c N_{ab}^c c$

From [Shu-Heng Shao, KITP Snowmass Theory Frontier Conference]





A photograph of a dark night sky filled with stars. A prominent, bright purple streak, likely the path of the International Space Station, cuts across the center of the frame. The foreground is dark, showing the silhouette of a landscape and some distant lights.

Thank you!