New Solutions to Hierarchy Problems

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY THEORY WORKSHOP

Particle Physics Challenges

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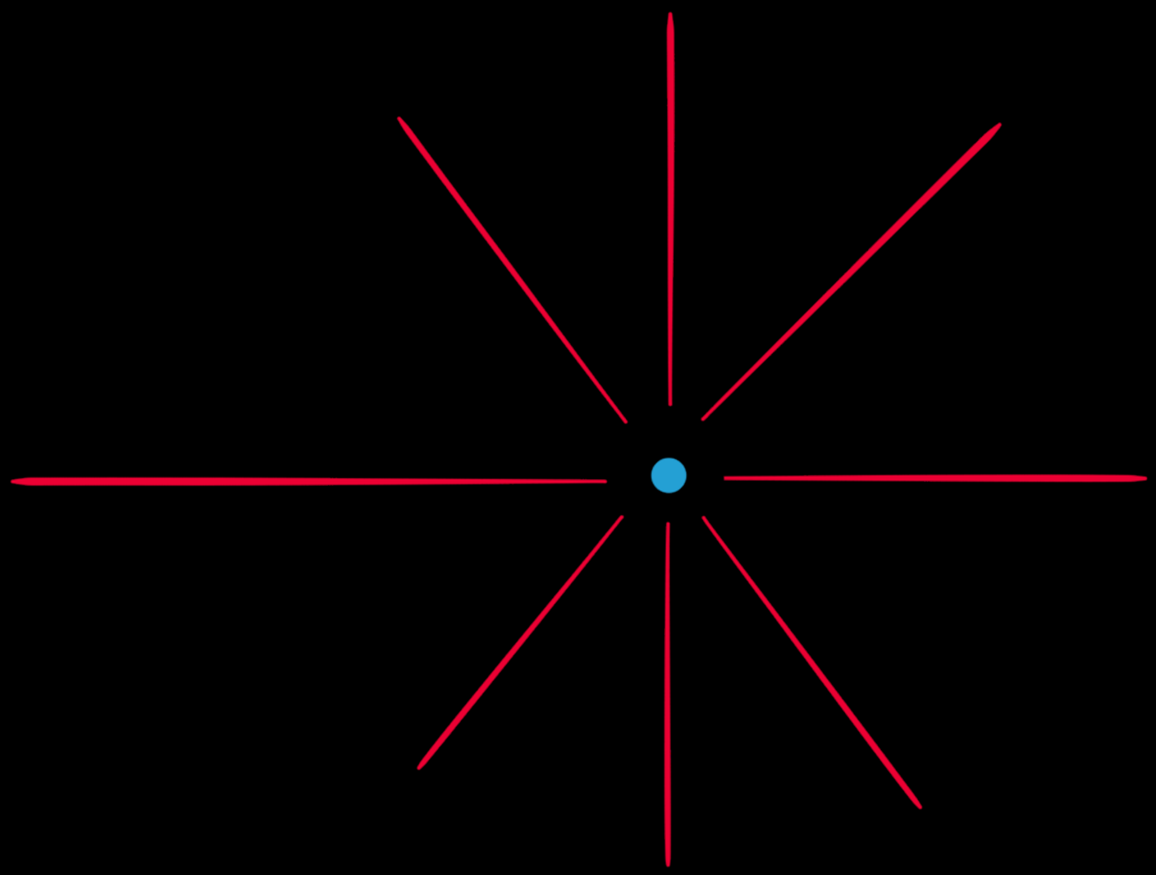
DESY Hamburg, Germany

DESY.

The Naturalness Strategy

An analogy



Classical E&M:
electron + E,B fields

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

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

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

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

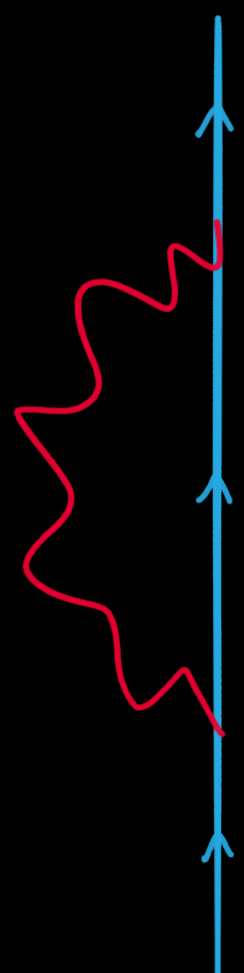
To avoid fine-tuning, i.e. for the theory to be "natural",
need picture to change on scales below 2.8×10^{-13} cm

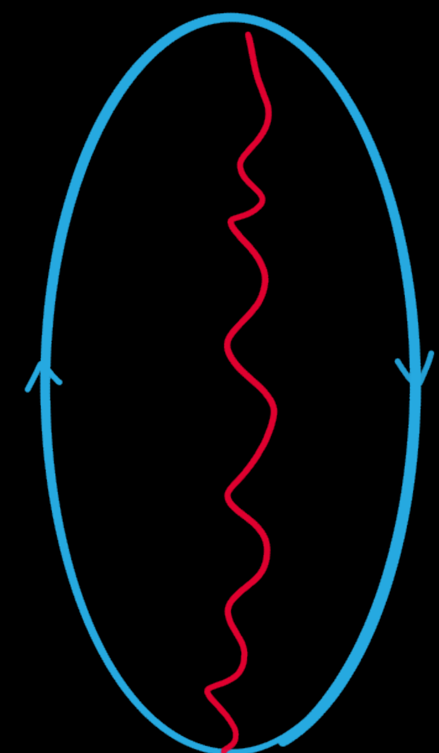
The Naturalness Strategy

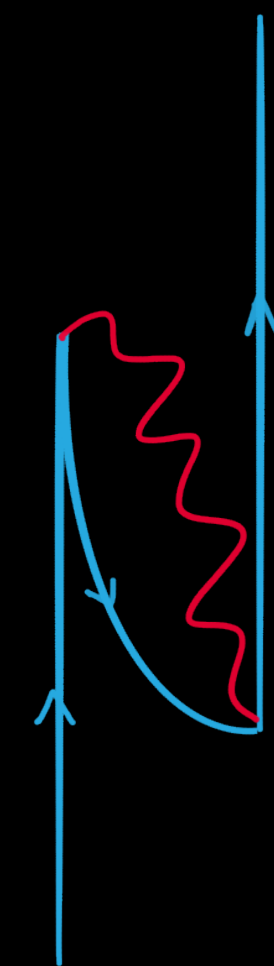
An analogy

Weisskopf (1939)

$$\Delta t \sim \hbar/\Delta E \sim \hbar/(2m_e c^2)$$







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

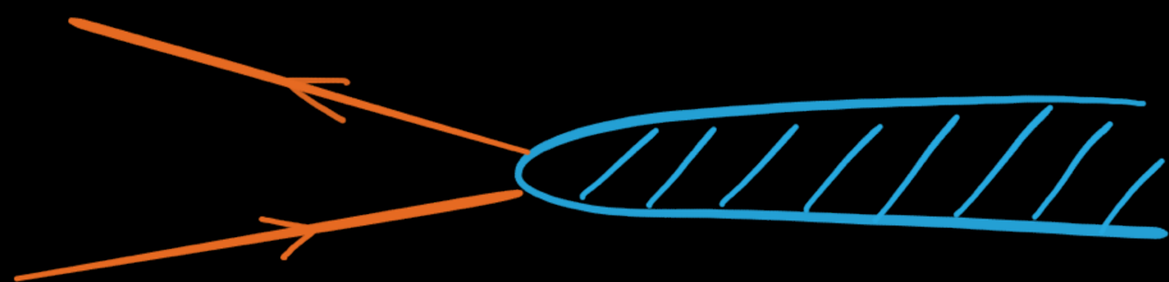
$$\Delta E = \Delta E_C + \ldots$$

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

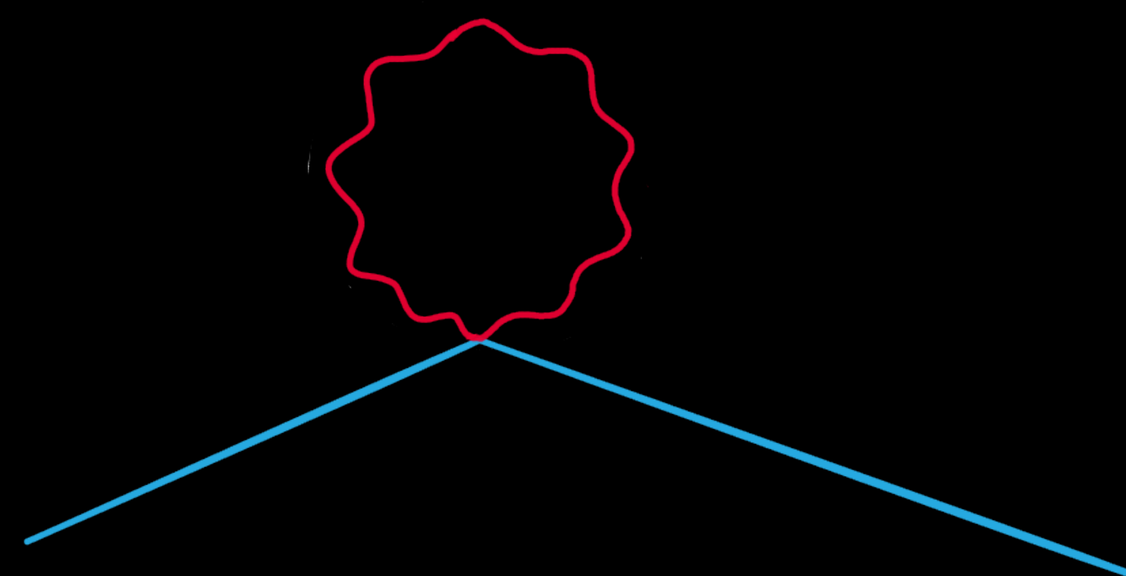
$$\Delta E = \Delta E_C - \Delta E_C + \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

The Naturalness Strategy

What about scalars?



Consider the pion…



Another divergence…

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

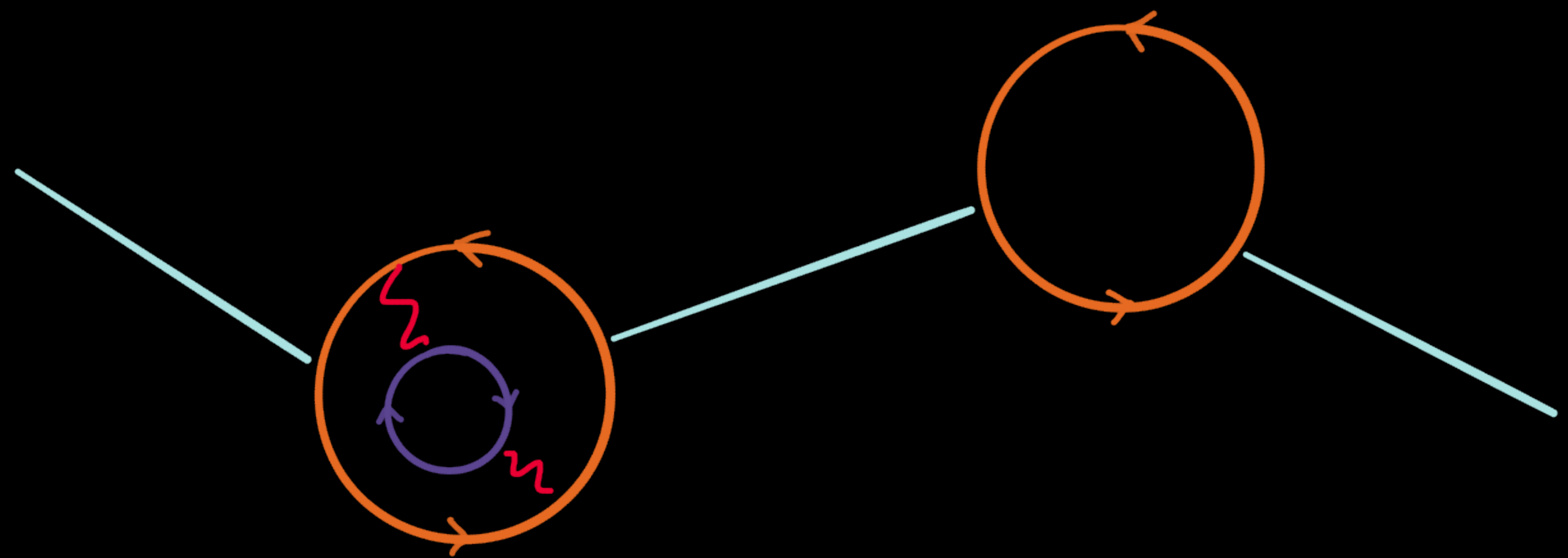
Given observed splitting, *predict* scale of new physics:

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

Another (more predictive) example: K_L-K_S mass difference.

The “Hierarchy Problem”

The Higgs is an apparently elementary scalar



Asssuming the Standard Model is valid down to some length scale $r_{\text{new}} \equiv \frac{\hbar c}{\Lambda}$ then we have

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

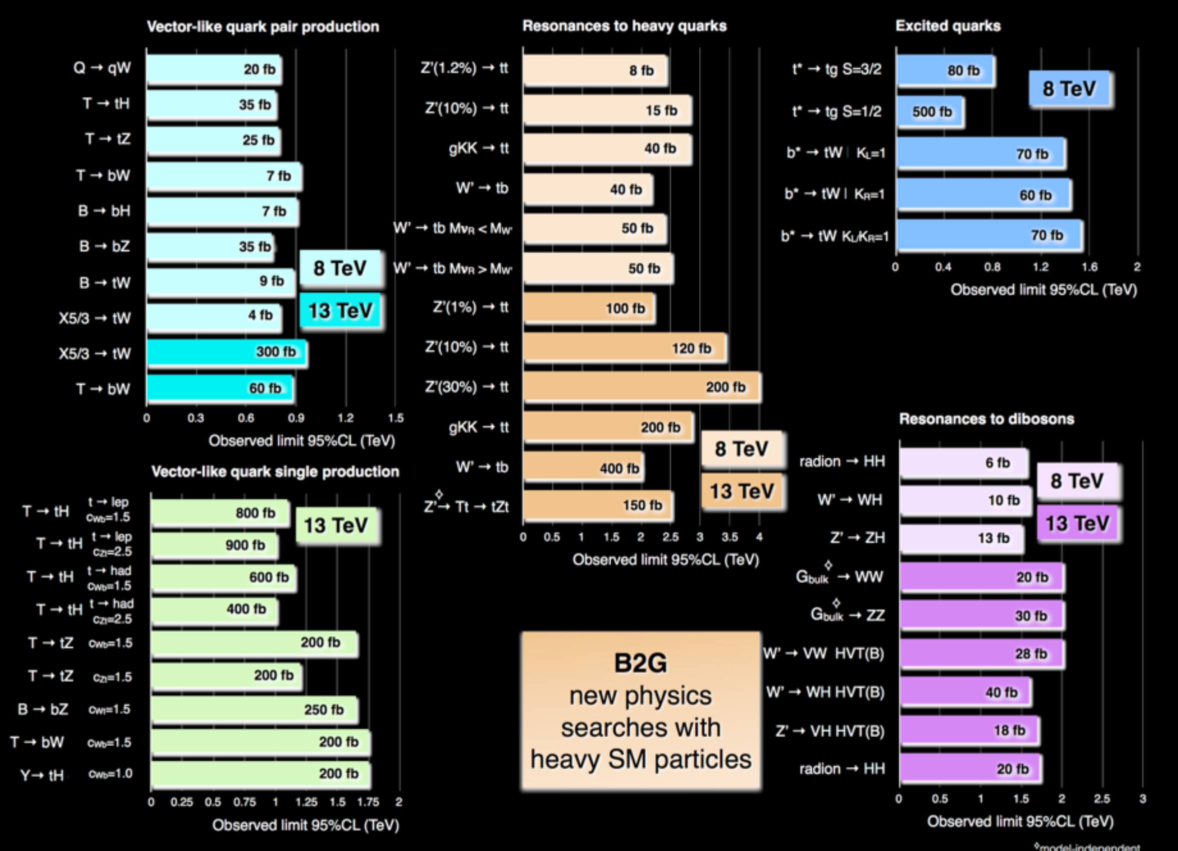
Expecting NP at Λ such that $\Delta m_H^2 \sim m_H^2$ is a *strategy*.

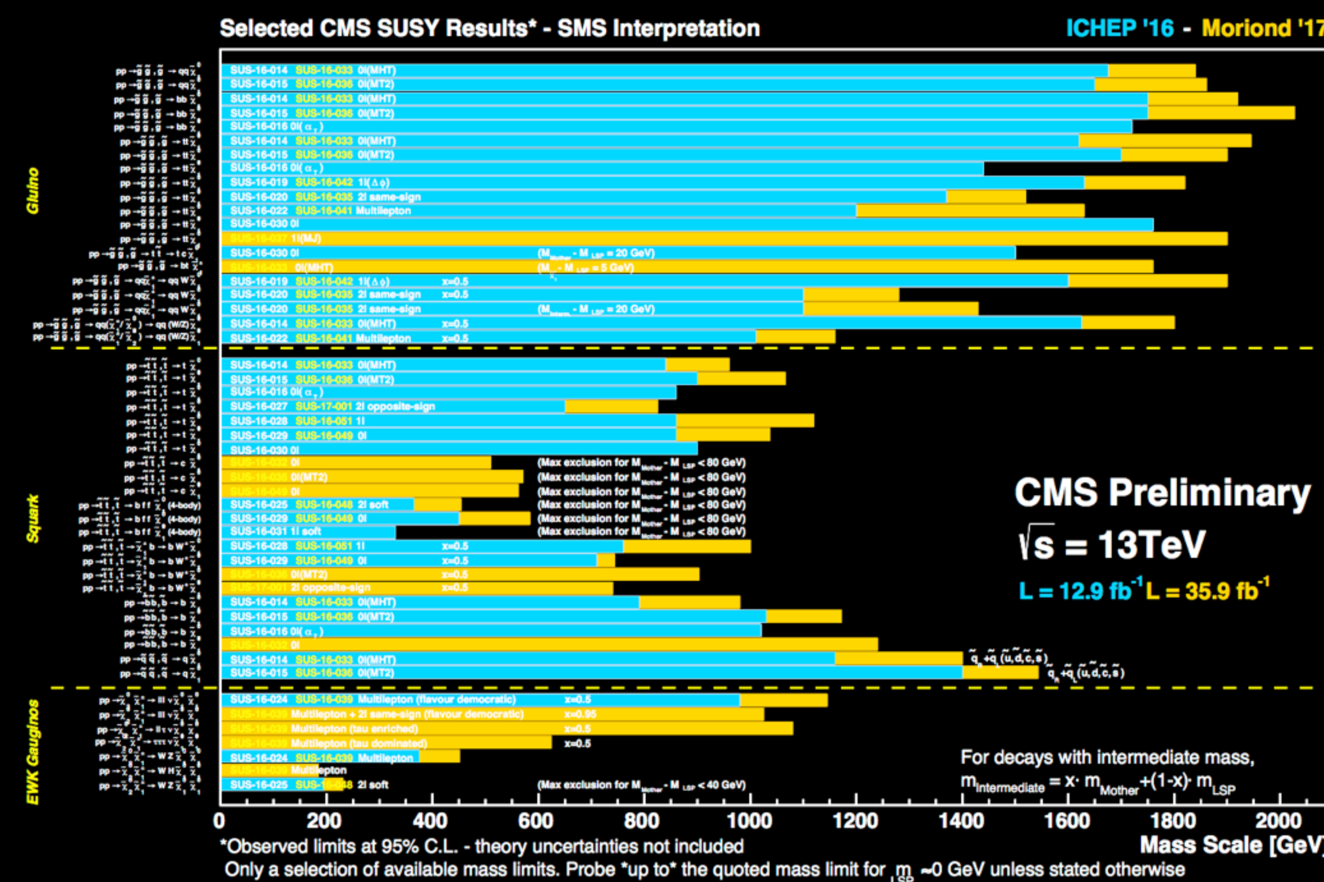
Implementation is up to us

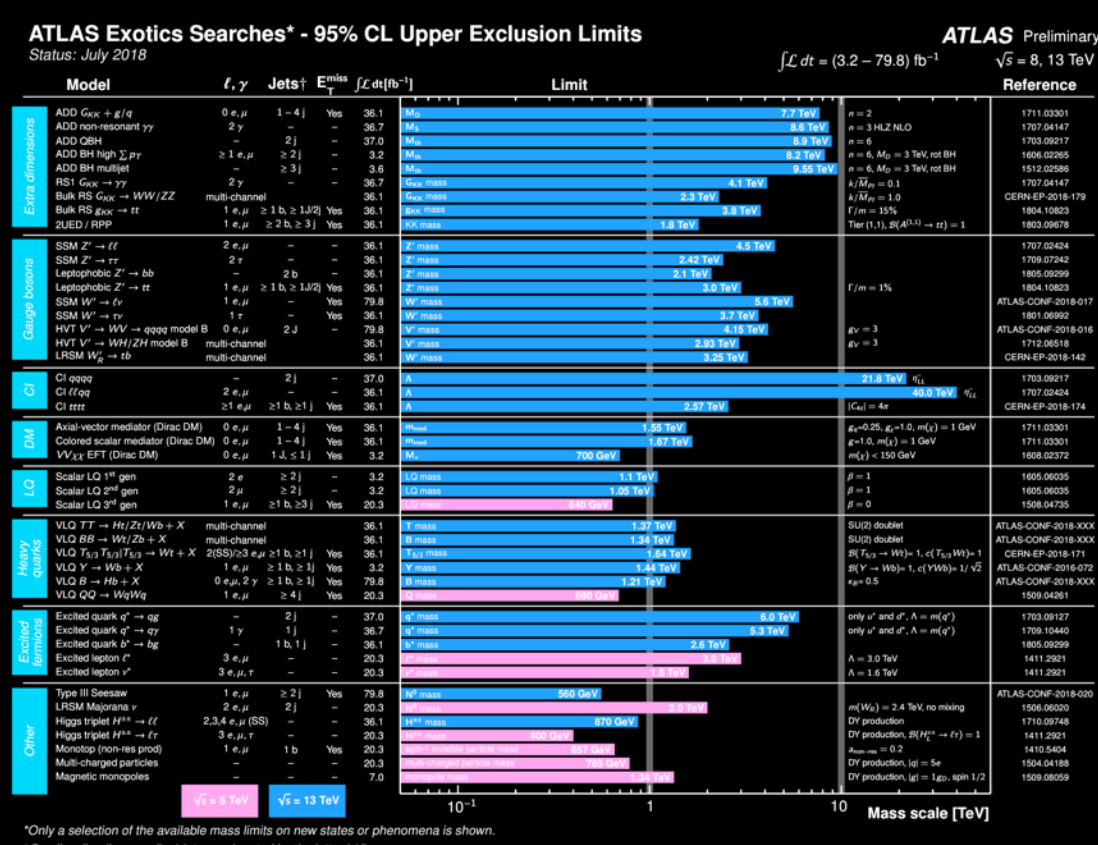
We've refined this strategy using some rules of thumb,
for example…

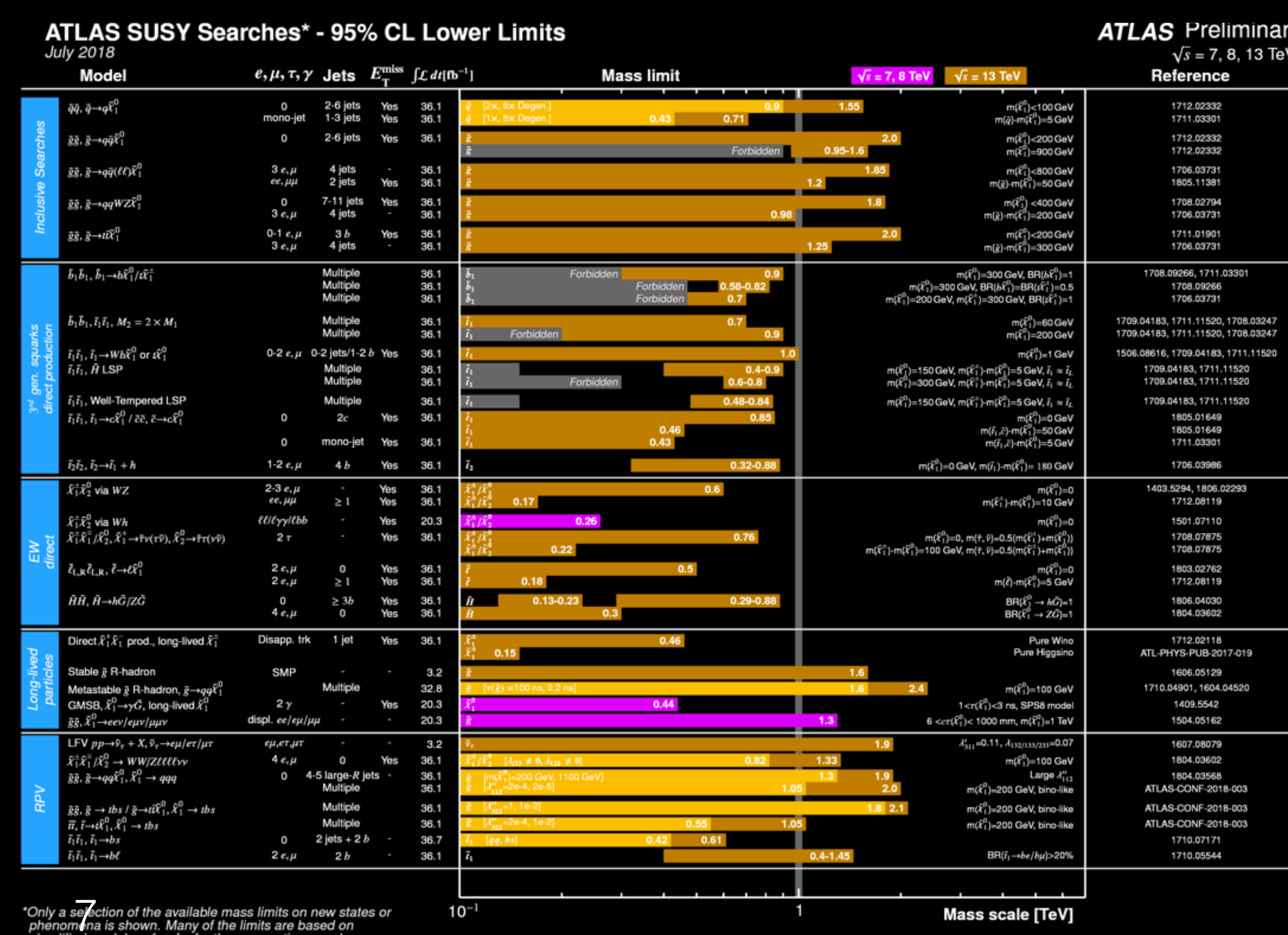
1. The Standard Model coupled to gravity is a generic EFT.
2. The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.
3. Symmetries imply new particles charged under the SM.
4. Low cutoffs imply dimensional transmutation or its equivalents.

Thus far…


Vector-like quark pair production
Observed limit 95%CL (TeV)
Vector-like quark single production
Resonances to heavy quarks
Excited quarks
Resonances to dibosons
8 TeV
13 TeV
B2G
new physics
searches with
heavy SM particles
*model-independent


Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_LSP ~0 GeV unless stated otherwise


ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018
ATLAS Preliminary
√s = 8, 13 TeV
Model
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
Mass scale [TeV]
*Only a 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).


ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
Jets
Mass limit
Reference
Inclusive Searches
EW direct
Long-lived particles
RPV
Mass scale [TeV]
*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.


OH WOW!
PARADIGM
SHIFT!
THAVES

1. The Standard Model coupled to gravity is a generic EFT.

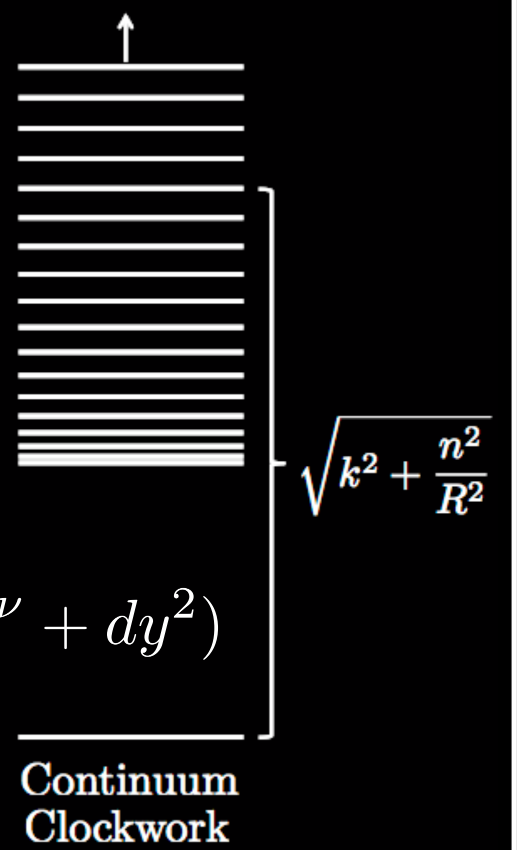
2. The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.

3. Symmetries imply new particles charged under the SM.

4. Low cutoffs imply dimensional transmutation or its equivalents.

Linear Dilaton / Continuum Clockwork

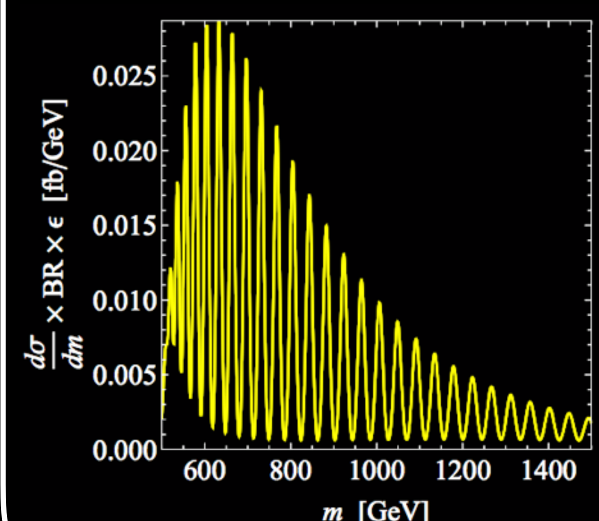
[Giudice, McCullough '16; Giudice, Kats, McCullough, Torre, Urbano '17; Antoniadis, Dimopoulos, Giveon '01; Antoniadis, Arvanitaki, Dimopoulos, Giveon '11; ….]

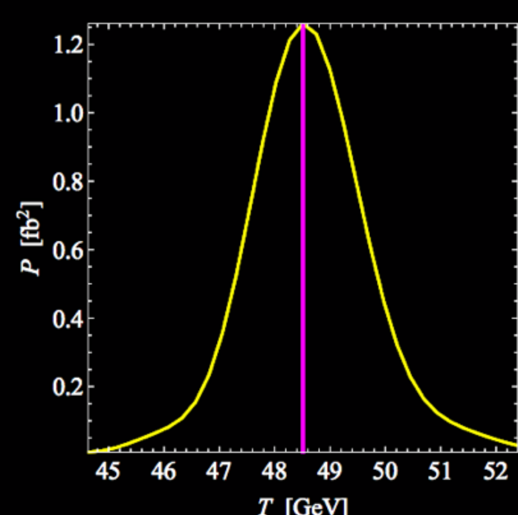


$$ds^2 = e^{\frac{4}{3}k|y|}(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2)$$

$$S(y) = 2k|y|$$

[Giudice, Kats, McCullough, Torre, Urbano '17]



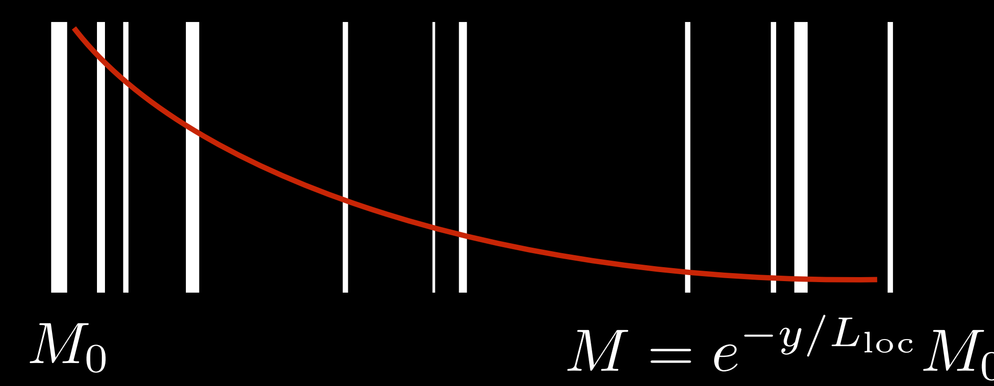


Disorder

[Rothstein '13]

Anderson localization: exponential localization from disorder.

Reasoning by analogy: localize graviton zero mode w/ randomly spaced & tensioned branes



But: not obvious that it works in detail

Related: An interesting source of exponential hierarchies for scalars, fermions, vectors in 4 & 5 dimensions [NC, Sutherland '17]

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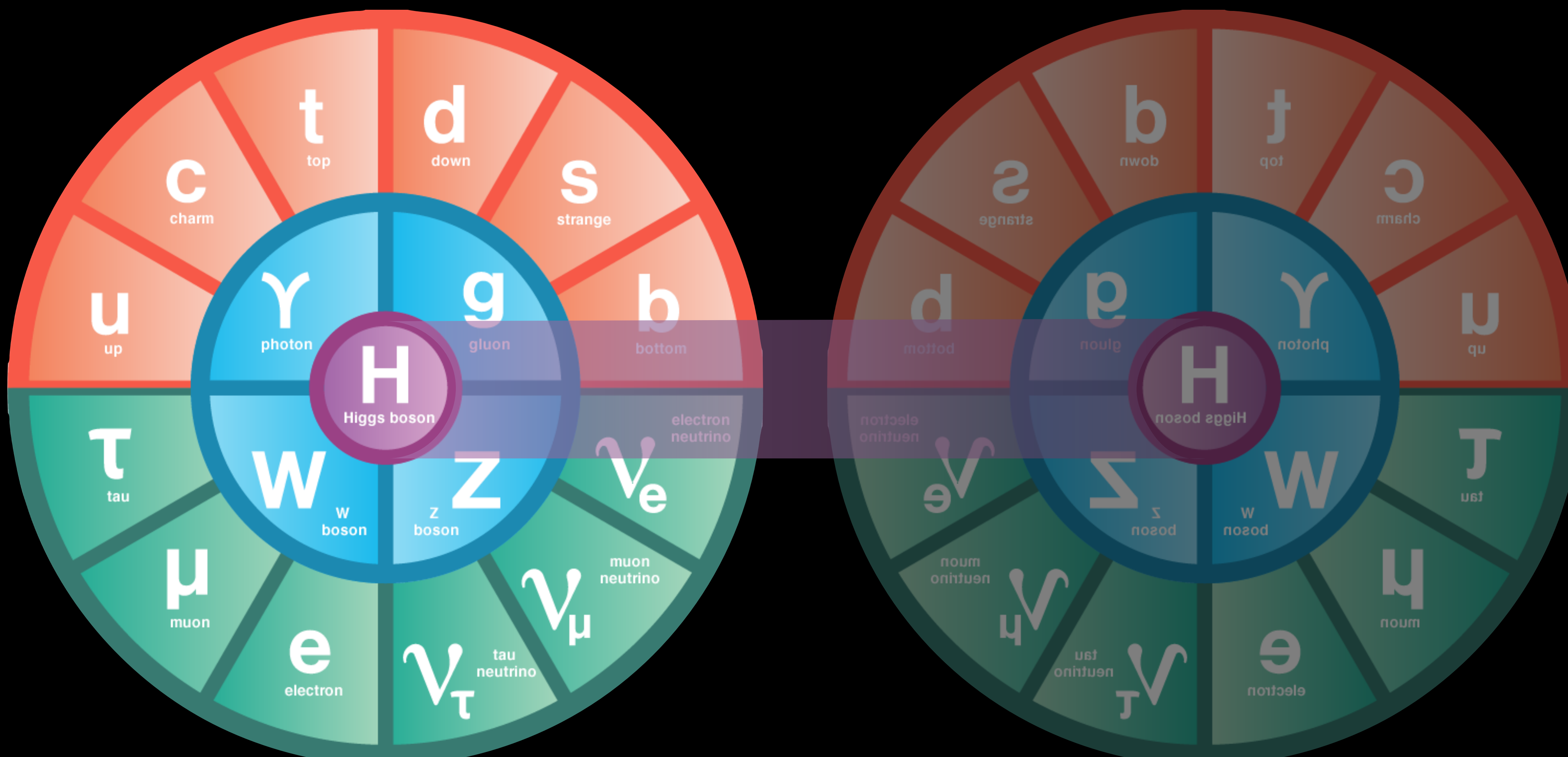
Discrete symmetries

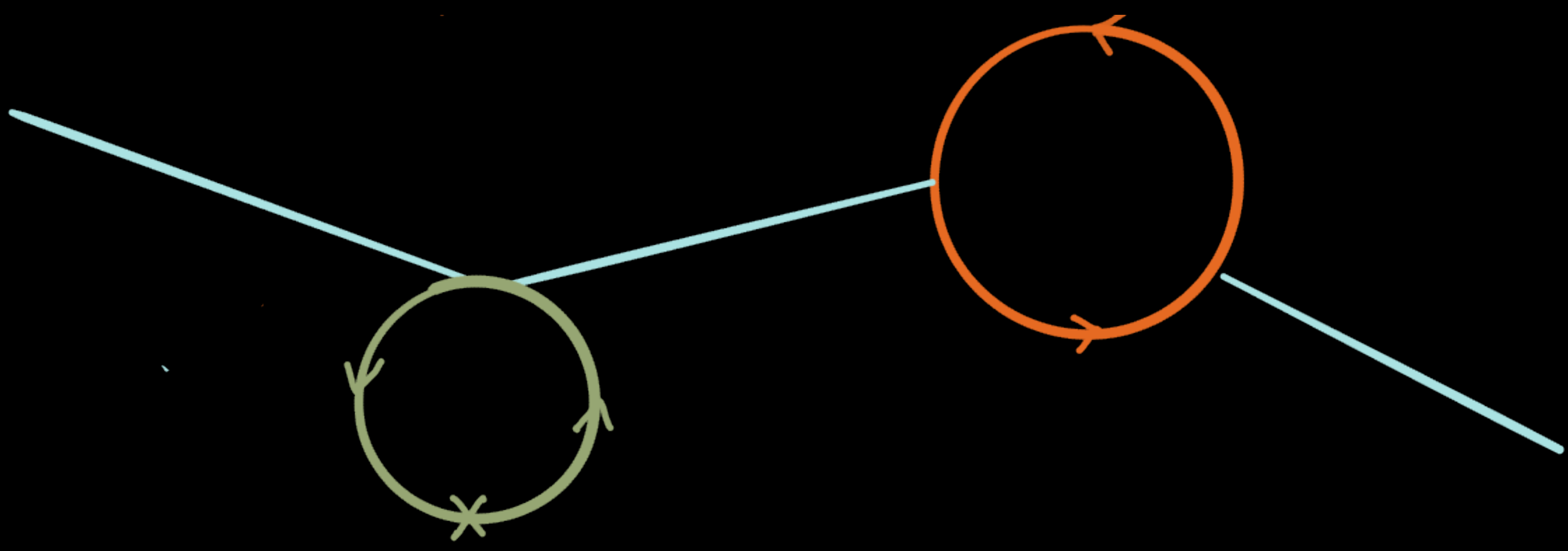


E.g. “Twin Higgs” [Chacko, Goh, Kribs ’05]

Discrete symmetries

Higgs is a pNGB of an accidental SU(4), since Z_2-symmetric mass corrections respect accidental SU(4)

$$\Delta V = -\frac{6y_t^2}{16\pi^2}\Lambda^2\left(|H_A|^2 + |H_B|^2\right) + \ldots$$



Still a plethora of new particles, but not interacting via SM forces.

$$\Delta m_H^2 = -\frac{6y_t^2}{16\pi^2}\Lambda^2 + \frac{6y_t^2}{16\pi^2}\Lambda^2 - 6\frac{y_t^2}{16\pi^2}(m_T^2 - m_t^2)\log\frac{\Lambda^2}{m_T^2}$$

Why Not?

Higgs portal maintains equilibrium down to T~GeV

$\Delta N_{eff} >> 1$

Options are

Change the cosmology

Signals in CMB

- RHN decay
- Saxion decay

[Chacko, NC, Fox, Harnik '16]
[NC, Koren, Trott '16]

Change the spectrum

Copious new physics at ~few TeV
Signals @ LHC

- Fraternal Twin Higgs
- Holographic Twin Higgs
- Composite Twin Higgs
- Orbifold Higgs
- …

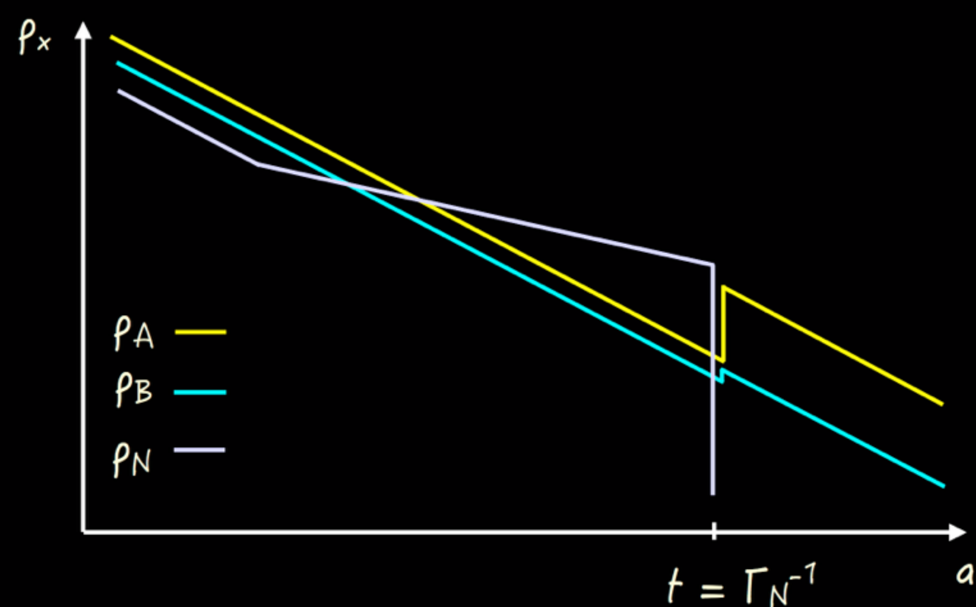
Change the Cosmology

The problem: thermal history of Z_2-symmetric theory has too much energy density in twin ν, γ

$$\Delta N_{\rm eff} \approx 7.4 \left. \frac{\rho_B}{\rho_A} \right|_{\rm BBN} \approx 5.6$$

Introduce an unstable neutral particle *N* that

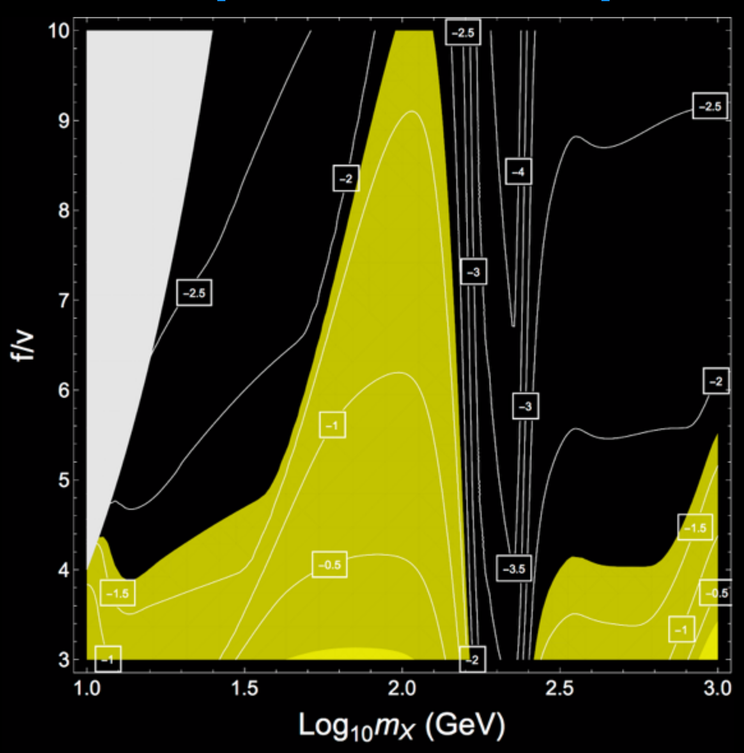
- decouples while relativistic
- decays some time thereafter
- decays primarily to A



Easy to do w/ symmetric coupling to H_A, H_B

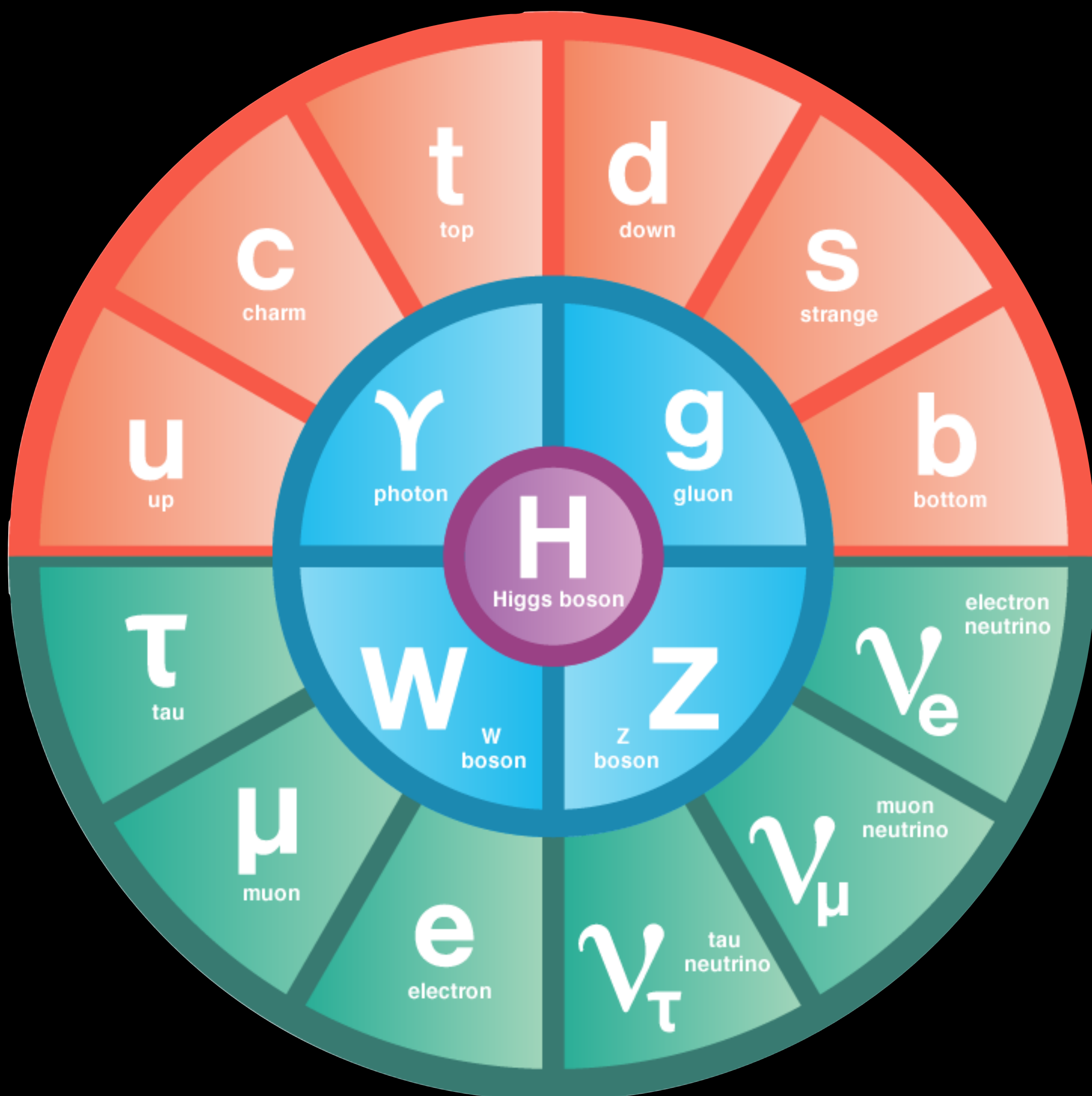
Signals now in future CMB experiments, e.g. CMB Stage-IV

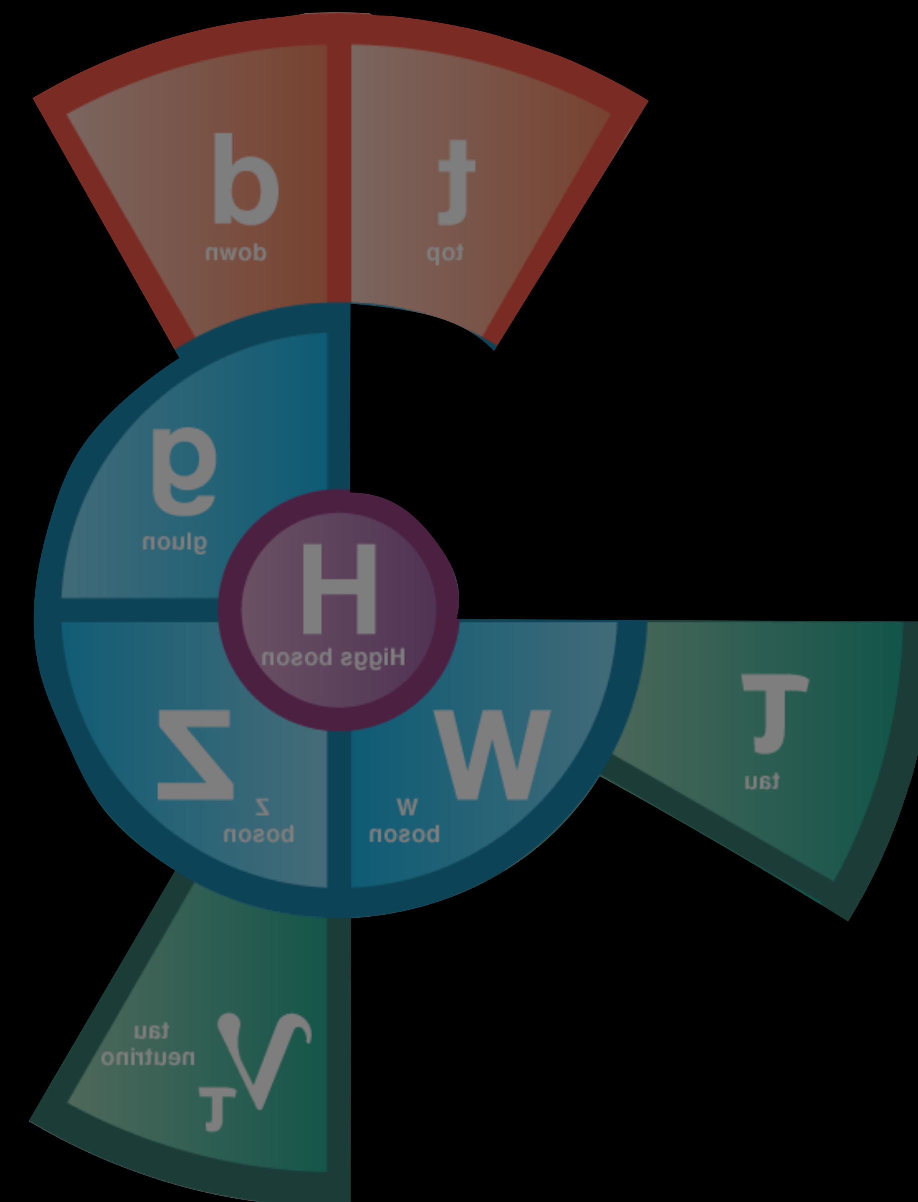
[NC, Koren, Trott '16]



See also: NNaturalness [Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]

Change the Spectrum



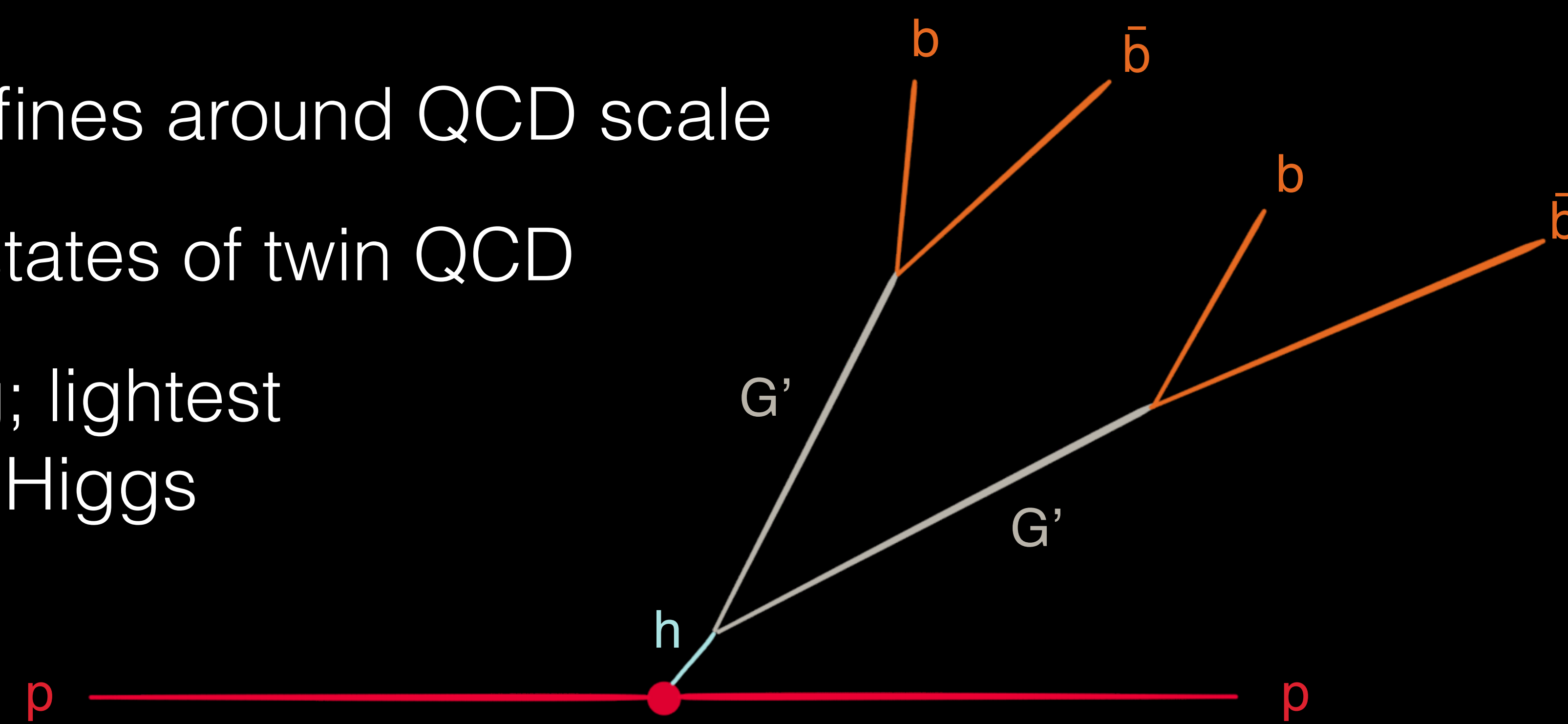


“Fraternal Twin Higgs” [NC, Katz, Strassler, Sundrum ’15]

[NC, Katz, Strassler, Sundrum ’15; Curtin, Verhaaren ‘15]

Exotic Higgs Decays

- Must have twin QCD, confines around QCD scale
- Higgs couples to bound states of twin QCD
- Glueballs most interesting; lightest have same quantum # as Higgs



$$\mathcal{L} \supset \frac{v}{f}\frac{h}{f} G'_{\mu\nu} G'^{\mu\nu}$$

Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

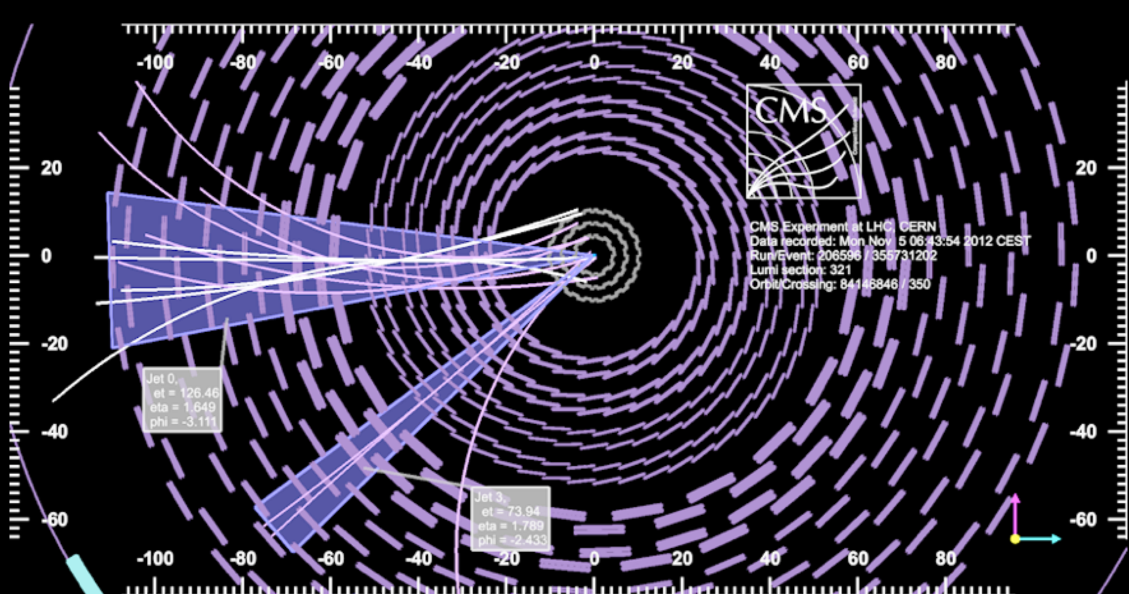
$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

Decay back to SM via Higgs

$$0^{++} \to h^* \to f \bar{f}$$

Long-lived, length scale ~ LHC detectors

Hidden Valley signature [Strassler, Zurek ’06]



New searches & experiments

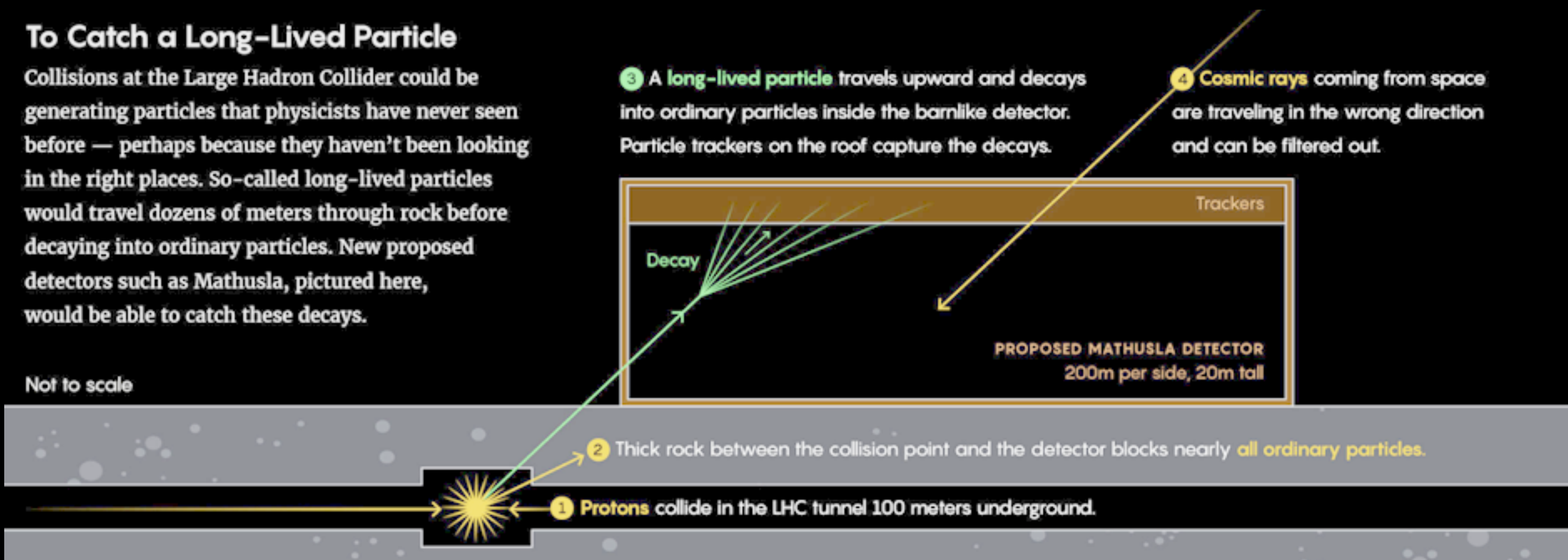
MATHUSLA

John-Paul Chou
David Curtin
Henry Lubatti

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

Methuselah (Hebrew: מְתוּשֶׁלַח / מְתוּשָׁלַח, Modern *Metušélah* / *Metušálah* Tiberian *Məṯûšélaḥ* / *Məṯûšālaḥ* ; "Man of the dart/spear", or alternatively "his death shall bring judgment"[1]) is the man reported to have lived the longest at the age of 969 in the Hebrew Bible.[2]

Quanta magazine



[Curtin, Verhaaren '15]

		scalar	*fermion*
strong direct production	*QCD*	SUSY	Composite Higgs/ RS
DY direct production	*EW*	folded SUSY	Quirky Little Higgs
Higgs portal direct production	*singlet*	?	Twin Higgs

Mirror Glueballs

Higgs portal observables

Higgs coupling shifts

$\sim$ tuning

Hyperbolic Higgs

[Cohen, NC, Giudice, McCullough '18]
(Related: Accidental SUSY, [Cheng, Li, Salvioni, Verhaaren '18])

Instead of accidental SU(4) from Z_2, what about "accidental SU(2,2)?"
(NB, not a symmetry of the full quadratic action)

- Take 2 copies of the MSSM, related by exchange:

$$\text{MSSM} \xleftrightarrow{Z_2} \text{MSSM}_{\mathscr{H}}$$

- Introduce SU(2,2) symmetric tree-level potential:

$$V(H, H_{\mathcal{H}}) = \lambda \left(|H|^2 - |H_{\mathcal{H}}|^2\right)^2$$

- Lift scalars in MSSM, fermions in $\text{MSSM}_{\mathscr{H}}$ (e.g. via 5D SSSB)

$$\delta V(H, H_{\mathcal{H}}) = -c\Lambda^2 \left(|H|^2 - |H_{\mathcal{H}}|^2\right) + \ldots$$

Hyperbolic Higgs

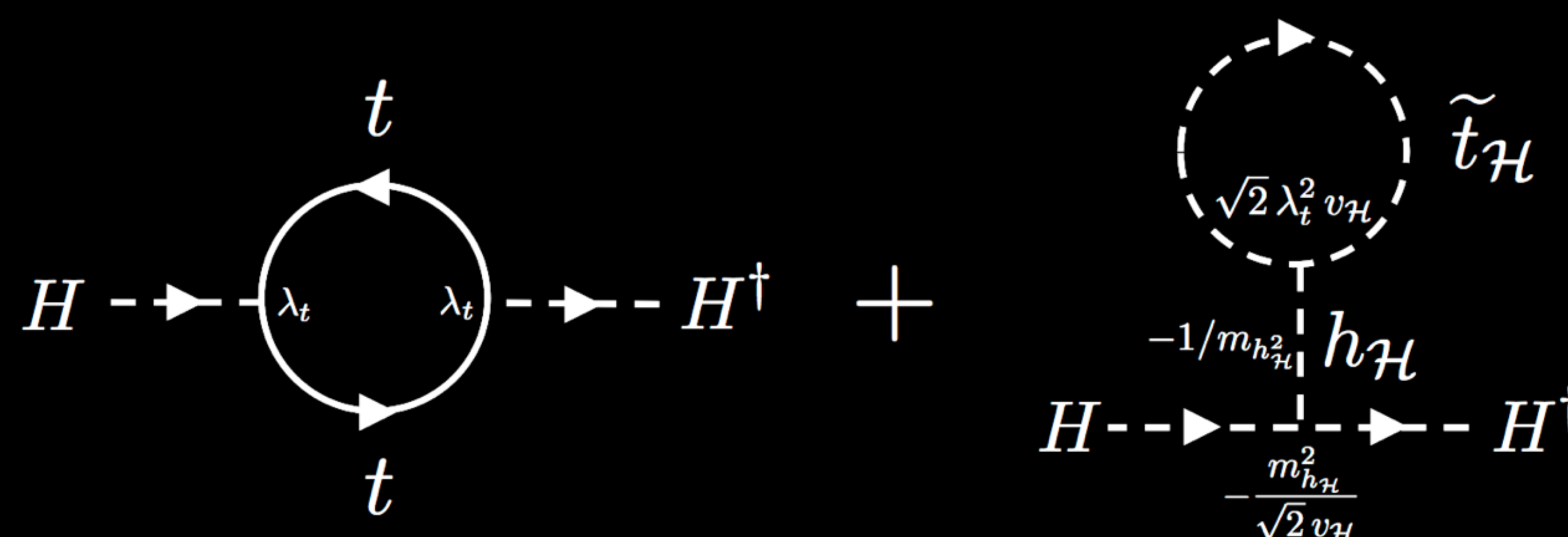
Flat direction ("goldstone" of spontaneously broken SU(2,2))

$$H = H_0 \sinh \frac{H_{\rm flat}}{f} , \qquad H_{\mathcal{H}} = H_0 \cosh \frac{H_{\rm flat}}{f}$$

Identification w/ SM-like Higgs,

$$h_{\rm SM} = h \cos\theta + h_{\mathcal{H}} \sin\theta , \qquad \tan\theta = \frac{v}{v_{\mathcal{H}}}$$

Light top partner is SM-neutral stop of MSSM$_{\mathscr{H}}$



Novel dark sector phenomenology, especially if there are hyperbolic charge- and color-breaking minima

		scalar	fermion
strong direct production {	*QCD*	SUSY	Composite Higgs/ RS
DY direct production {	*EW*	folded SUSY	Quirky Little Higgs
Higgs portal direct production {	*singlet*	Hyperbolic Higgs / Accidental SUSY	Twin Higgs

Mirror Glueballs

Higgs portal observables

Higgs coupling shifts $\sim$ tuning

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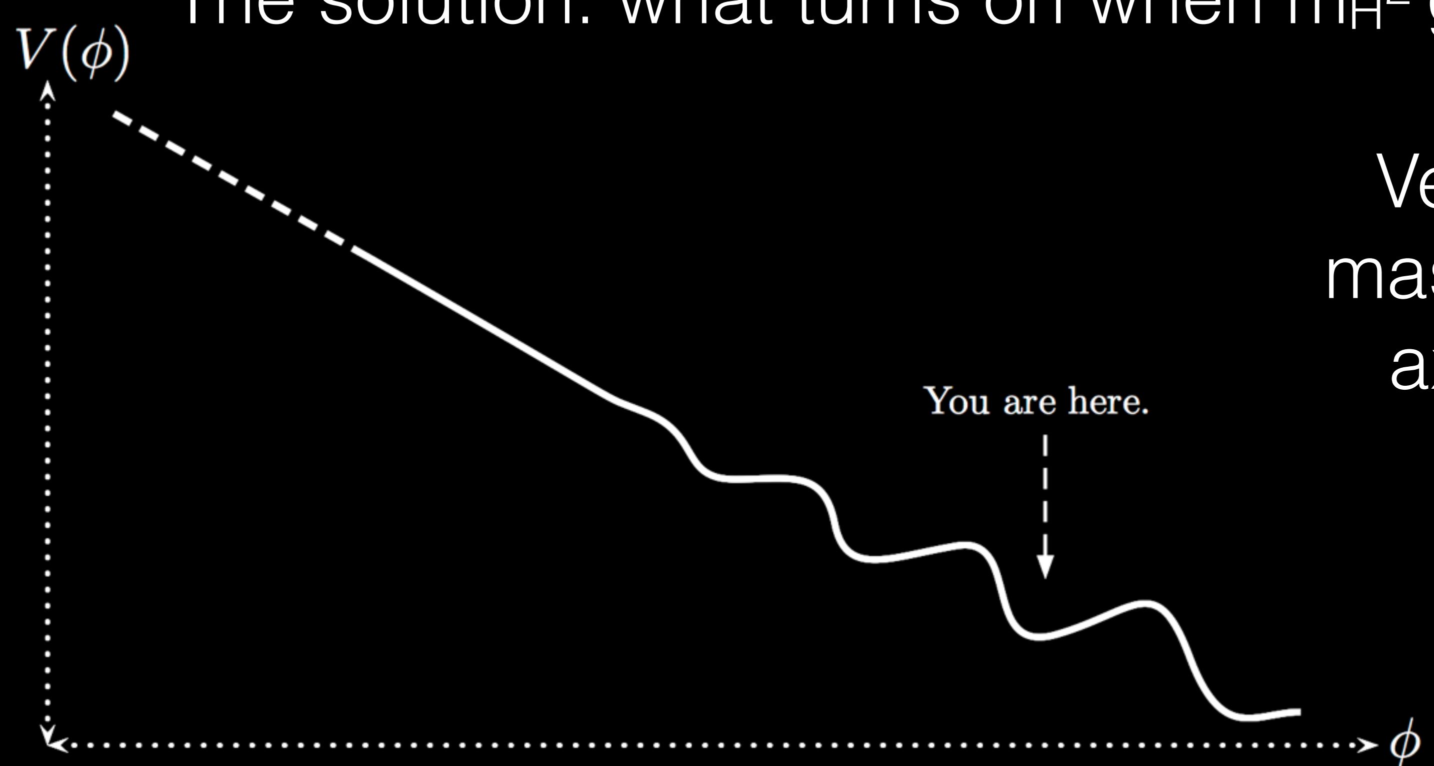
Relaxion

What if the weak scale is selected by scanning?

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?

The solution: what turns on when m_H^2 goes negative?



Vev gives quark masses which give axion potential.

"Relaxion"

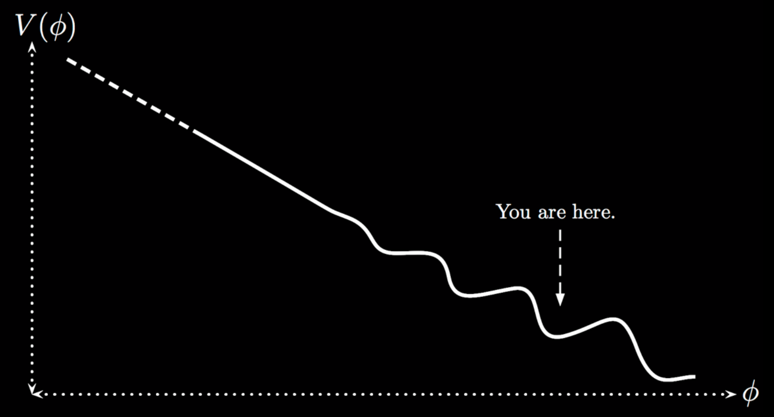
[Graham, Kaplan, Rajendran '15]

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

[Graham, Kaplan, Rajendran ‘15]

Relaxion

Simplest version: an axion coupled to QCD during inflation.



$$\Lambda^4(H)\cos(\phi/f) + F(g\phi) + \left(-M^2 + g\phi\right)|H|^2$$

Viable for Higgs + non-compact axion + inflation w/

- Very low Hubble scale ($\ll\Lambda_{QCD}$)
- 10 Giga-years of inflation

Various other subtleties regarding technical naturalness, CC, avoidance of fine-tuning to inflationary sector; need to solve strong CP problem. *Forces us to grapple with new UV considerations.*

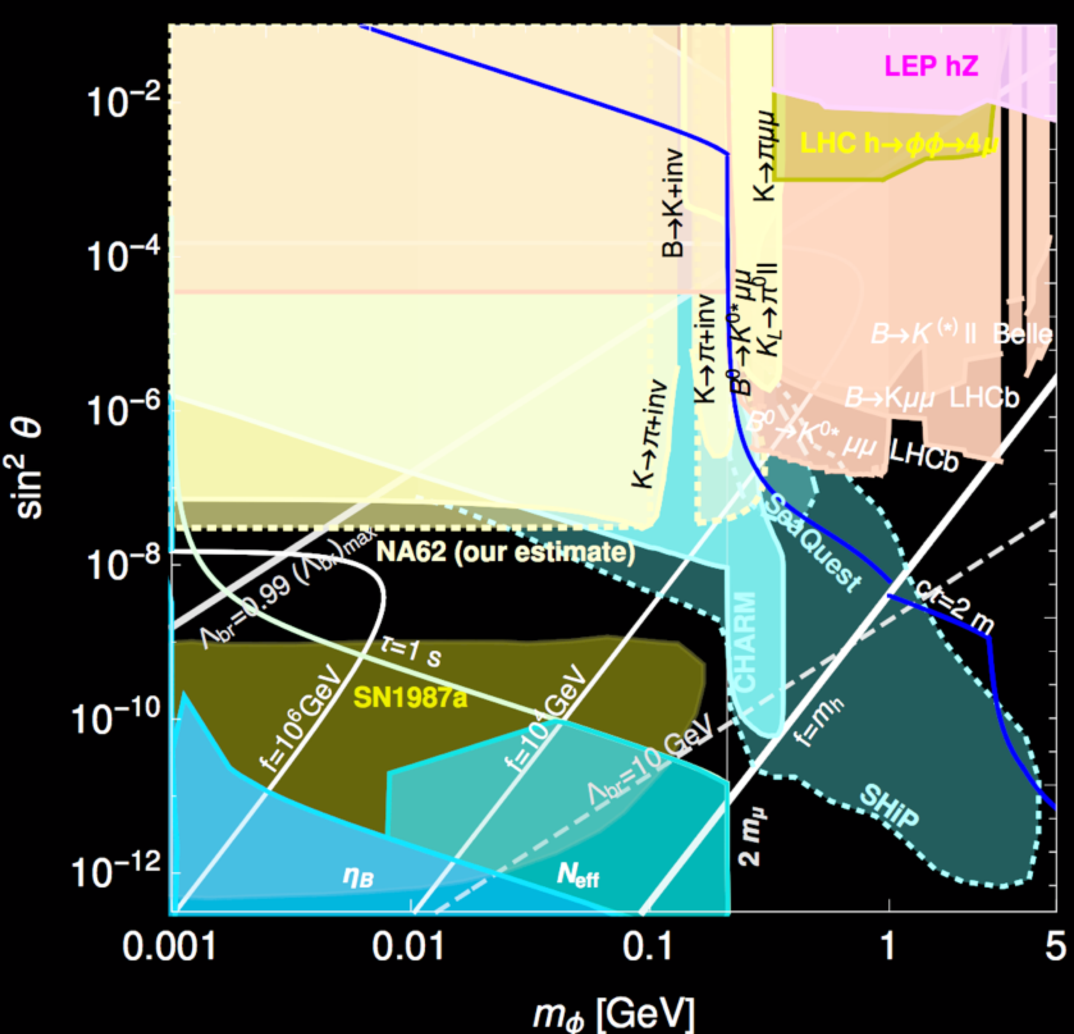
Extensive development, e.g. [Espinosa et al. ’15; Hardy ’15; Gupta et al ’15; Batell, Giudice, McCullough ’15; Choi, Im ’15; Kaplan, Rattazzi ’15; Di Chiara et al. ’15; Ibanez et al. ’15; Hook, Marques-Tavares ’16; Nelson, Prescod-Weinstein ’17; …]

New Signals

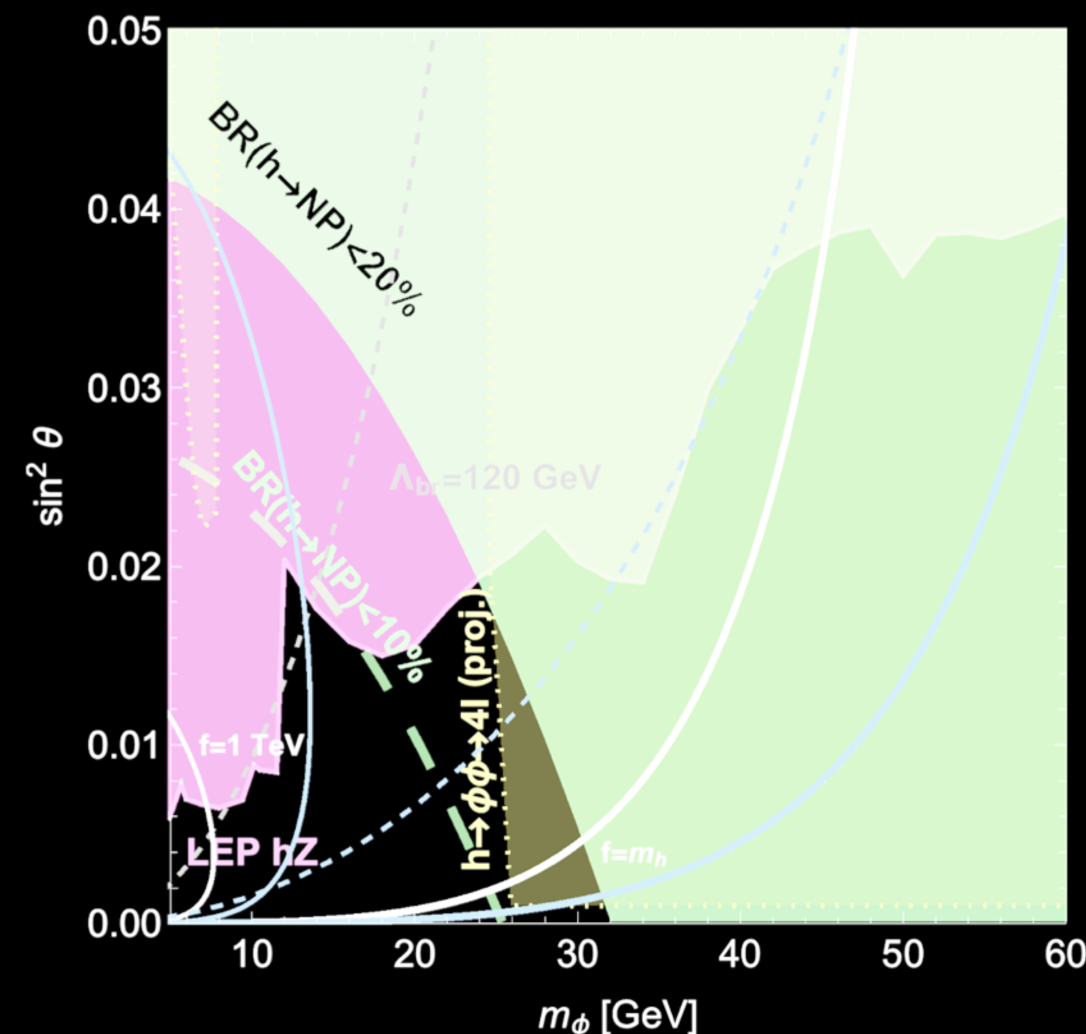
Higgs portals $g\phi|H|^2$ $\Lambda^4(H)\cos(\phi/f)$

$\Lambda^4(H)\cos(\phi/f)$ gives ϕ - H mixing* w/ $\sin\theta \approx \frac{\Lambda^4}{v f m_h^2}$

[Flacke, Friquele, Fuchs, Gupta, Perez '16]



[Flacke, Friquele, Fuchs, Gupta, Perez '16]



+5th force for m_ϕ < eV & cosmology for eV < m_ϕ < MeV

**assuming ⟨ϕ⟩ breaks CP*

[Hook, Marques-Tavares '16; Fonseca, Morgante, Servant '18]

Particle production relaxion

Alternative possibility: keep bumps across entire potential, turn on dissipation at a special point of potential.

Novel source of dissipation: particle production

Instead of

$$\frac{\phi}{f} G\widetilde{G}$$

+ inflation

$\Rightarrow$

Use coupling to EWK gauge bosons:

$$\frac{\phi}{f}\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right) + \Lambda_c^4 \cos\frac{\phi}{f'}$$

Exponential production of EWK gauge bosons around h~v slows evolution

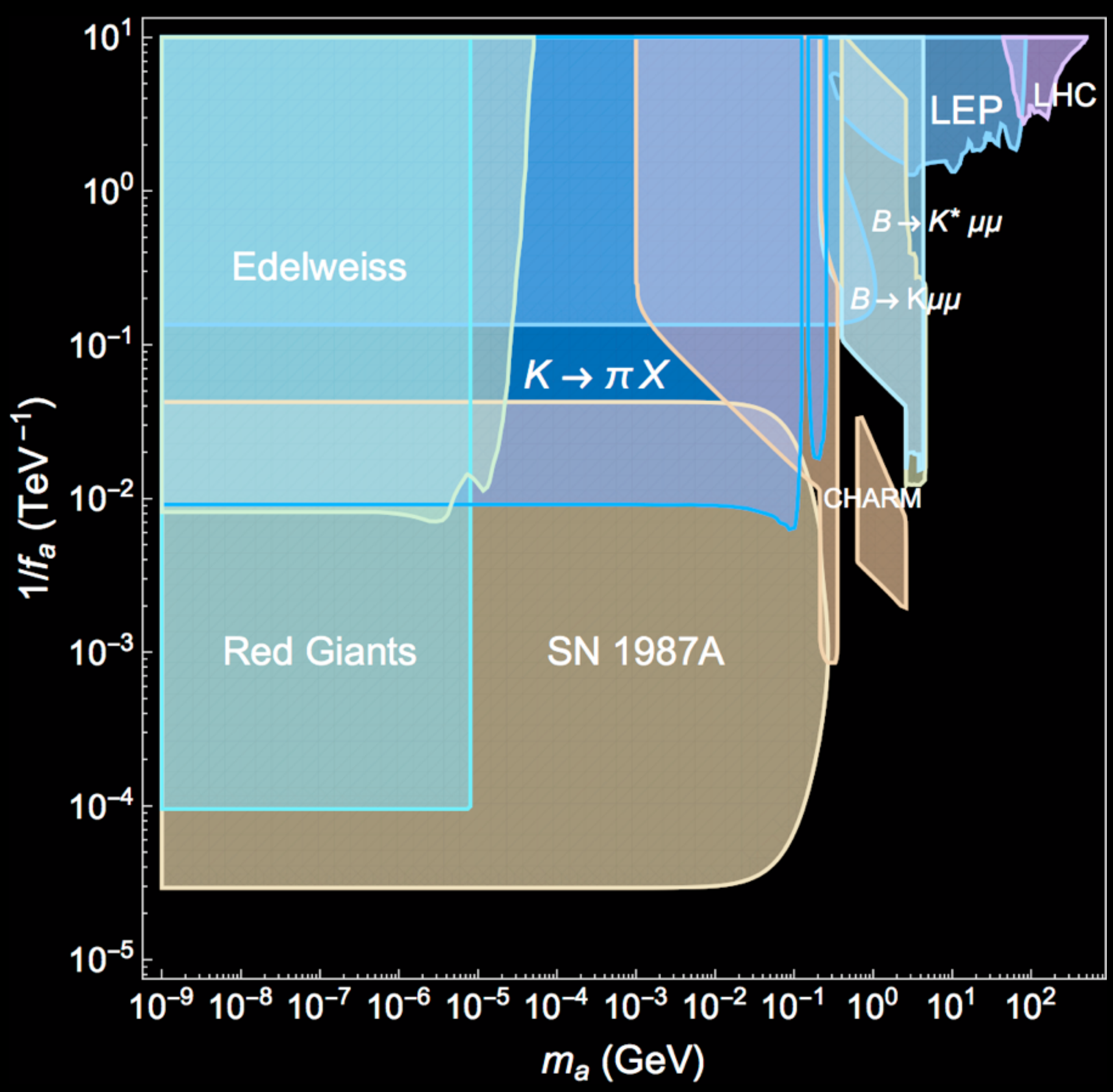
Important subtlety: can't couple to pairs of photons!

(*Not a tuning, can be made natural with symmetries, e.g., $SU(2)_L$ x $SU(2)_R$*)

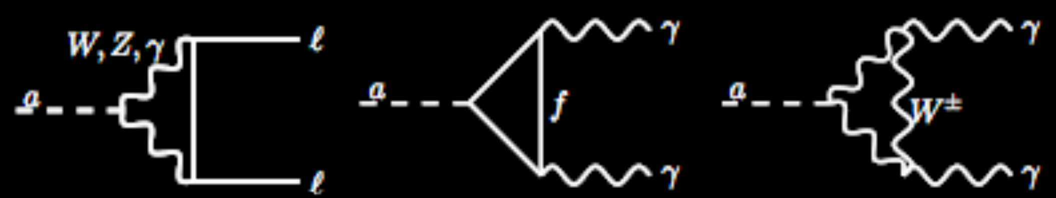
New Signals

Even if tree-level relaxion couplings to SM states are engineered to be $\frac{\phi}{f}\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right)$ in the UV…

[NC, Hook, Kasko '18]



…radiative couplings to fermions induced at one loop, photon pairs at one & two loops [Bauer, Neubert, Thamm '17; NC, Hook, Kasko '18]



$$f_\gamma \sim 16\pi^2 \frac{m_W^2}{m_a^2} f_a + (16\pi^2)^2 \frac{m_f^2}{m_a^2} f_a$$

Astrophysical and collider signatures abound; still viable parameter space [Fonseca, Morgante, Servant '18]

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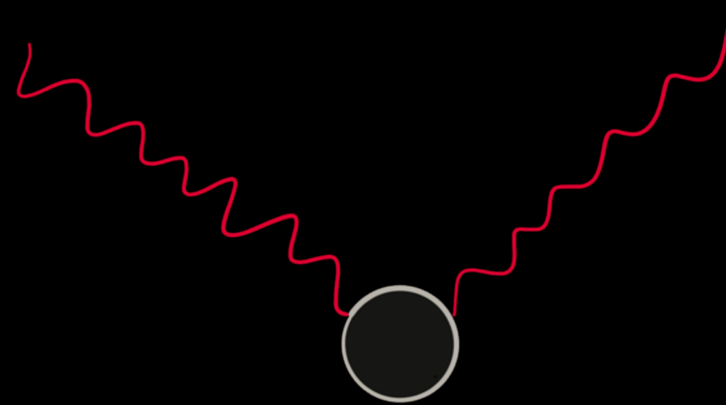
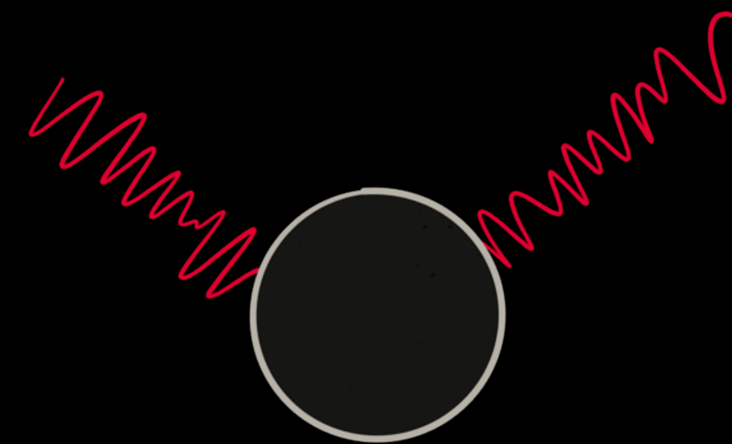
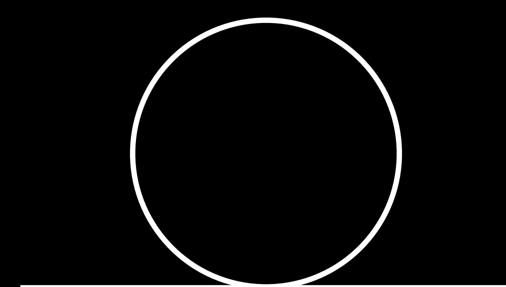
UV/IR Mixing

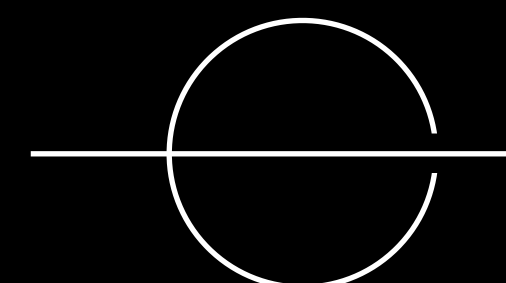
Two examples of UV/IR mixing: Quantum gravity….





…and non-commutative QFT. For example [Minwalla, Seiberg, Van Raamsdonk ’99]





$$\sim \int \frac{d^4k}{k^2} \sim \Lambda^2$$

$$\sim \int \frac{d^4k}{k^2} e^{ip\Theta k} \sim \frac{1}{\Theta^2 p^2}$$

$$[x^\mu, x^\nu] = i\Theta^{\mu\nu}$$

Indirect UV/IR: WGC

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

$$q > \frac{m}{M_{Pl}}$$

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

Ride the coattails [Cheung, Remmen ’14]: Charge SM fermions under weakly gauged (unbroken) $U(1)_{B-L}$ (bounds currently $q \lesssim 10^{-24}$). Cancel anomalies with RHN ν_R

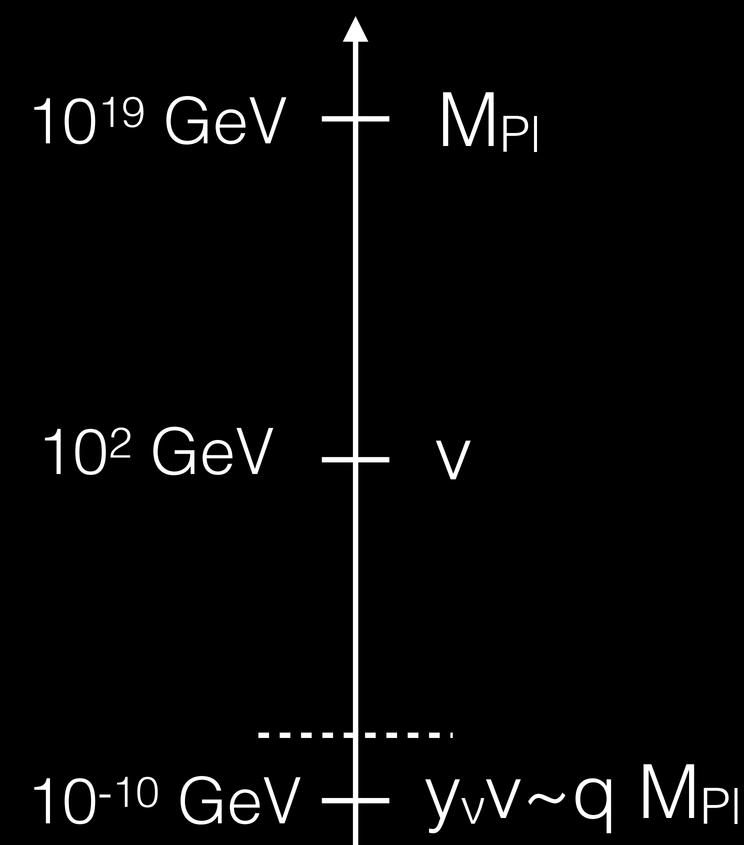
Neutrino mass is

$$y_\nu H \bar{L} \nu_R \to m_\nu \sim y_\nu v$$

so $m_\nu \sim 0.1$ eV, $q \gtrsim 10^{-29}$

For fixed yukawa, WGC violated if *v* much larger

But: *magnetic* WGC implies cutoff of U(1) field theory is $\Lambda \sim q\, M_{Pl}$



See also: [Ibañez, Martin-Lozano, Valenzuela ’17,…]

Conclusions

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2. The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.

3. Symmetries imply new particles charged under the SM.

4. Low cutoffs imply dimensional transmutation or its equivalents.

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New approaches & new signatures abound.

Thank you!