Is Nature Natural?

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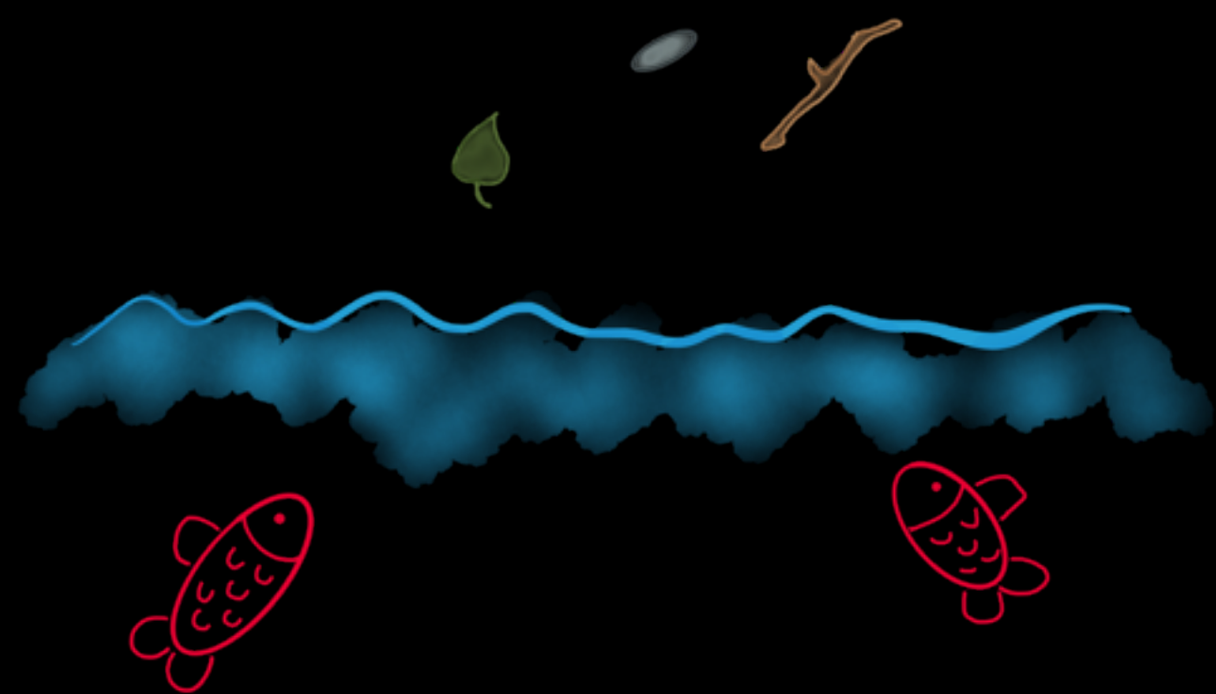
CERN-TH 08.08.18

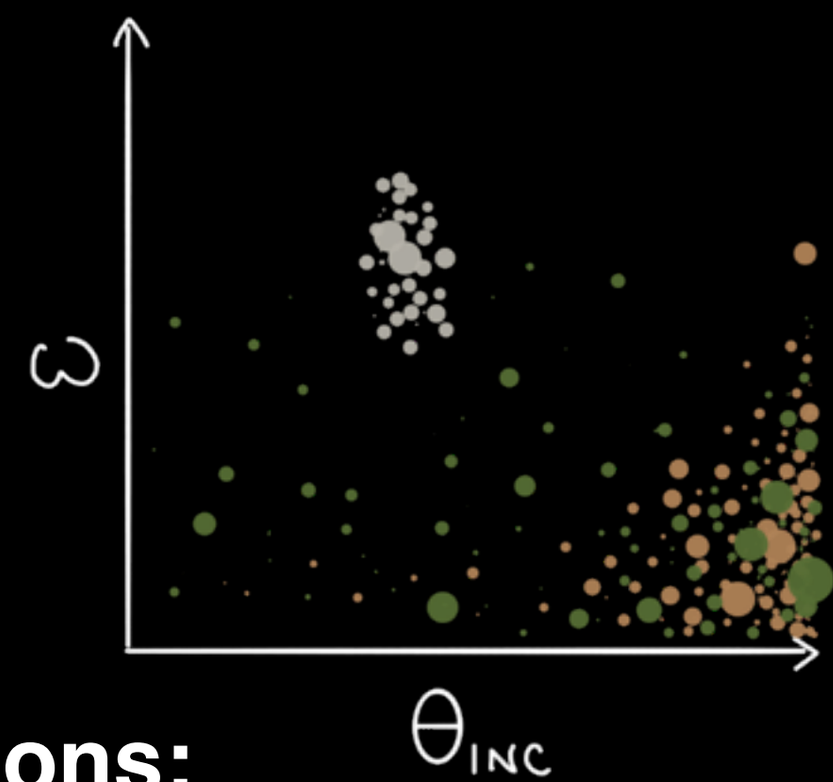
IS HINCHLIFFE'S RULE TRUE? *

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no.

(Craig's Conjecture: Talks are exempt from Hinchcliffe's Rule)

The Parable of the Piscine Physicists





Proposed solutions:

Symmetry: Most incidence angles deflected by partner rocks.

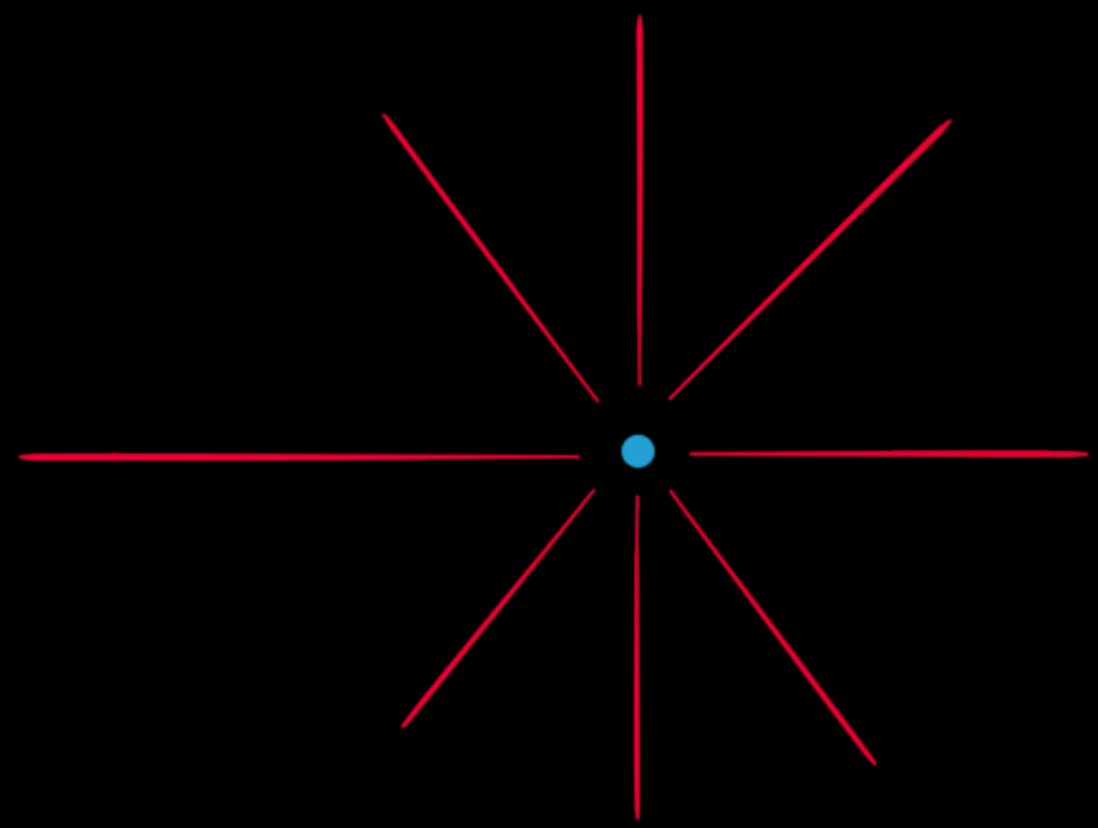
Low Cutoff: Rocks only exist in a finite range of angles.

Piscatorial Reasoning: No fish can survive in rivers where rocks enter at higher incidence angles.

Apathy: Nature doesn't care about finely-tuned rocks.

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

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

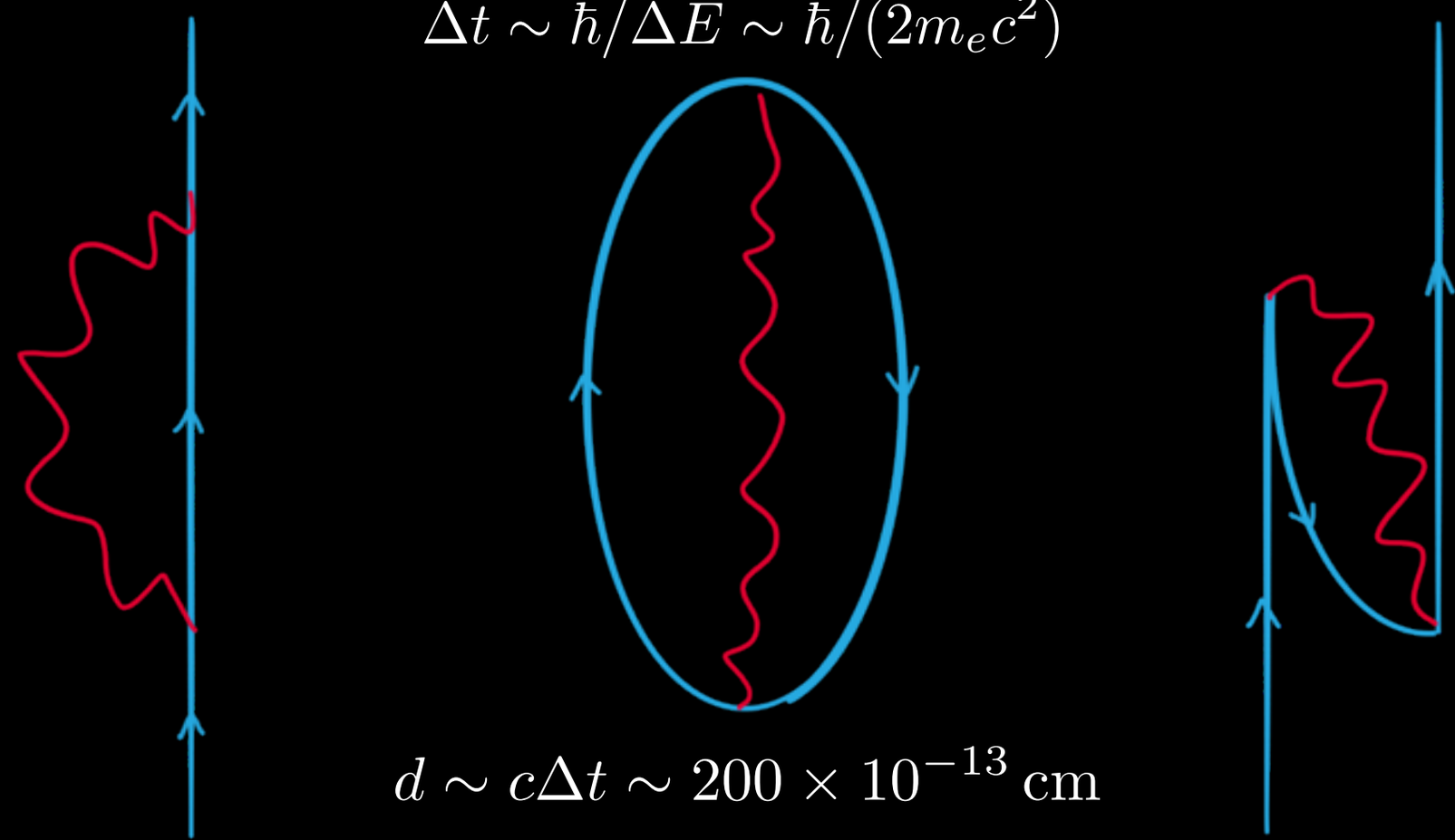
To avoid fine-tuning, i.e. for the theory to be “natural”,
need picture to change on scales below 2.8×10^{-13} cm

The Naturalness Strategy

An analogy

Weisskopf (1939)

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



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

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

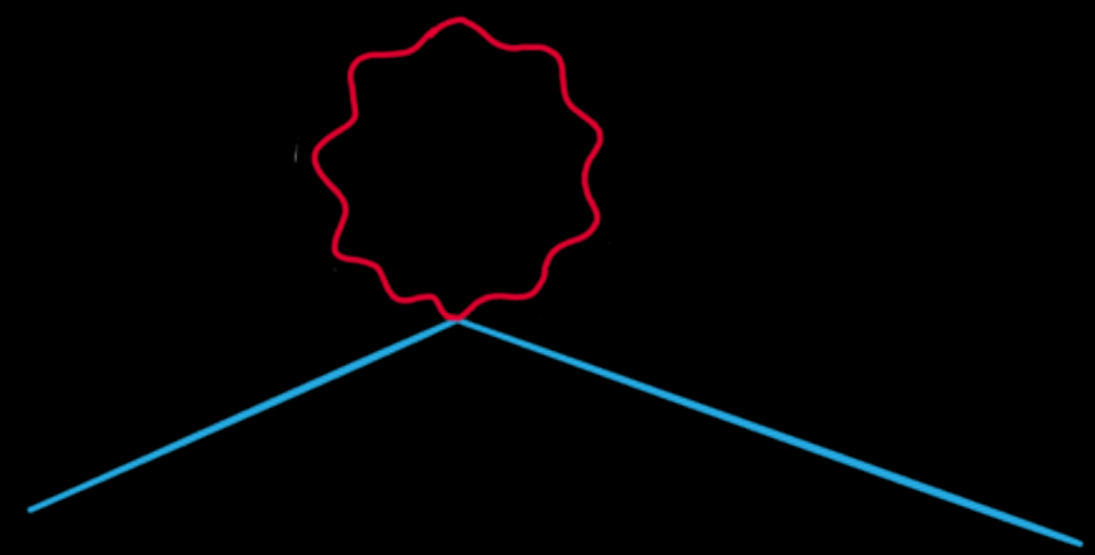
$$\Delta E = -\Delta E_C + \ldots$$

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

The Naturalness Strategy

What about scalars?

Consider the pion…



Another divergence…

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

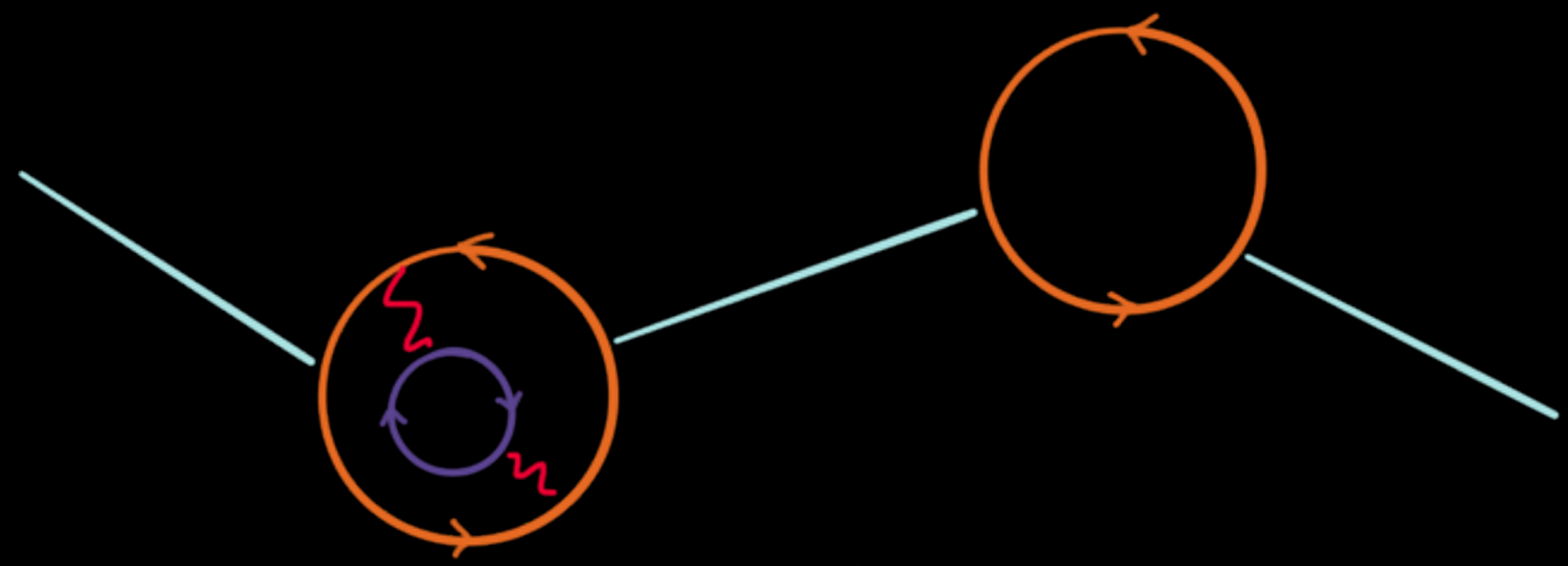
Given observed splitting, *predict* scale of new physics:

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

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

The “Hierarchy Problem”

The Higgs is an apparently elementary scalar

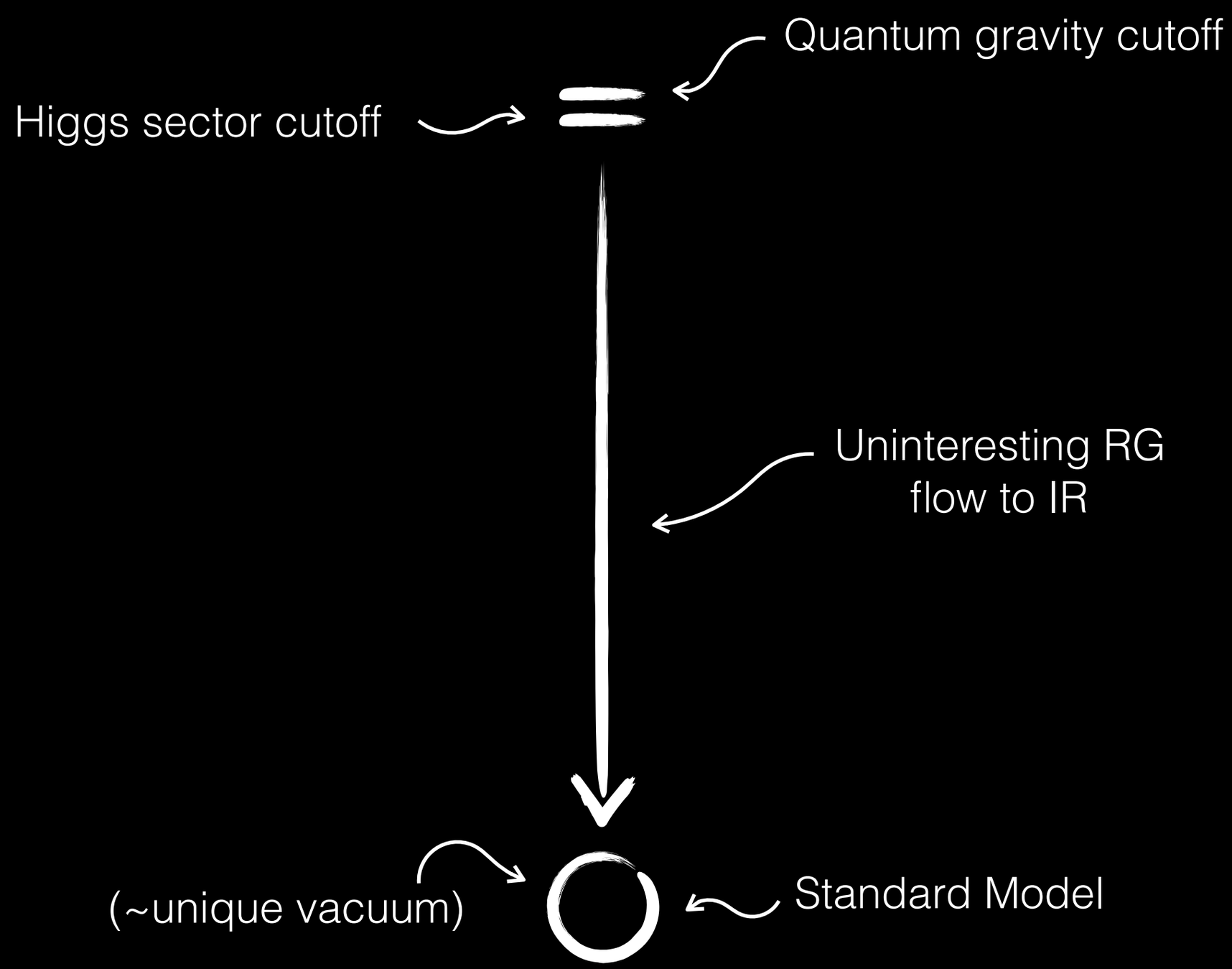


Asssuming the Standard Model is valid down to some length scale $r_{\rm new} \equiv \frac{\hbar c}{\Lambda}$ then we have

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

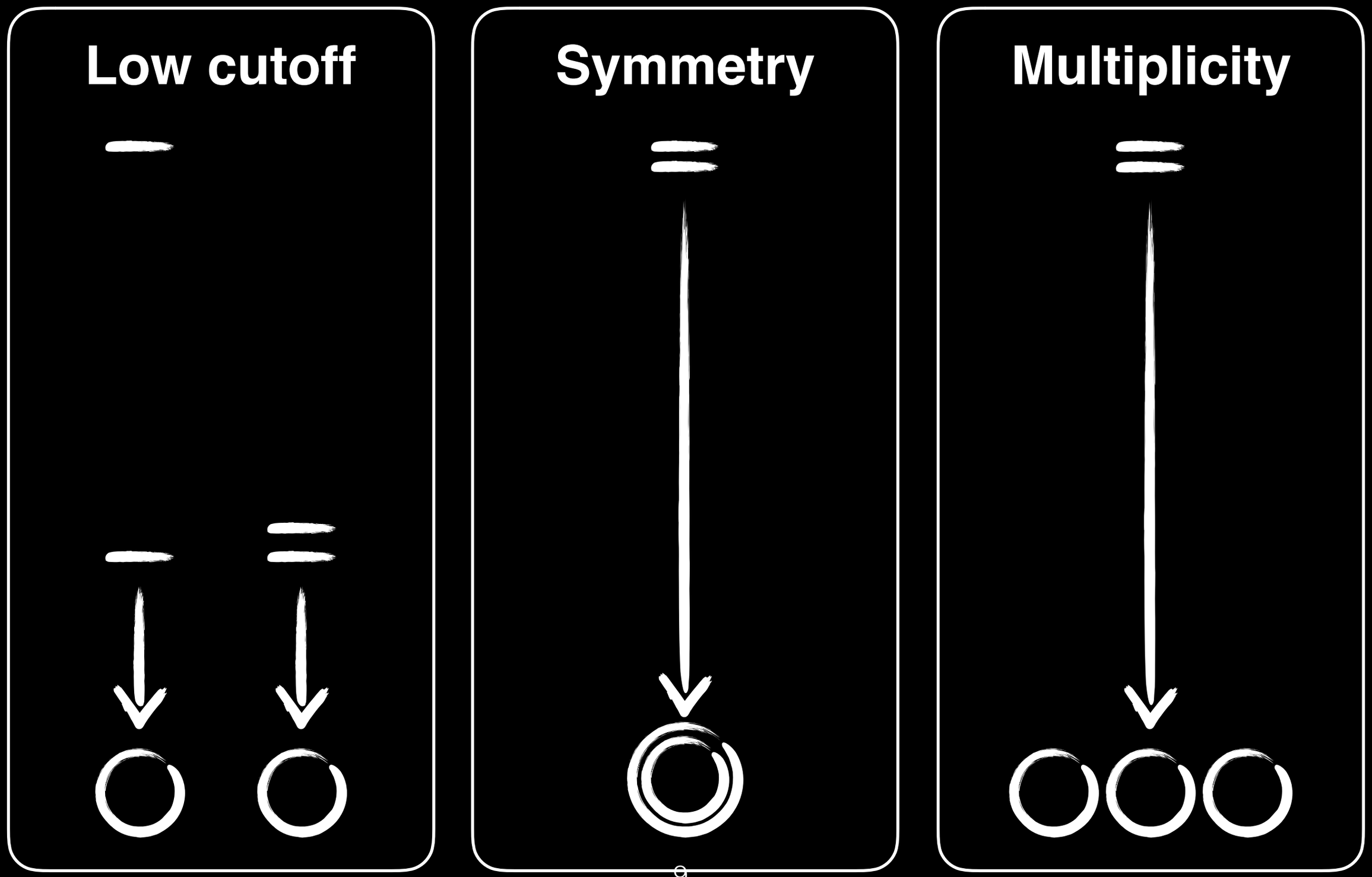
Expecting NP at Λ such that $\Delta m_H^2 \sim m_H^2$ is a *strategy*.

What are the options?

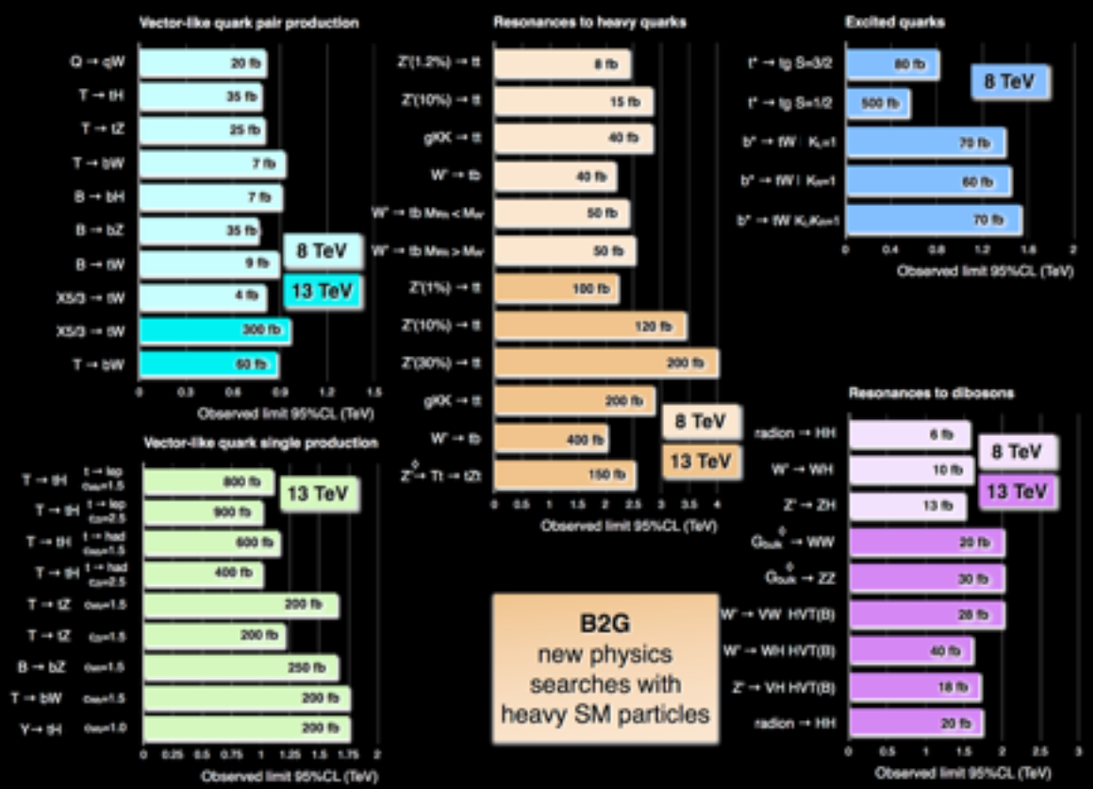


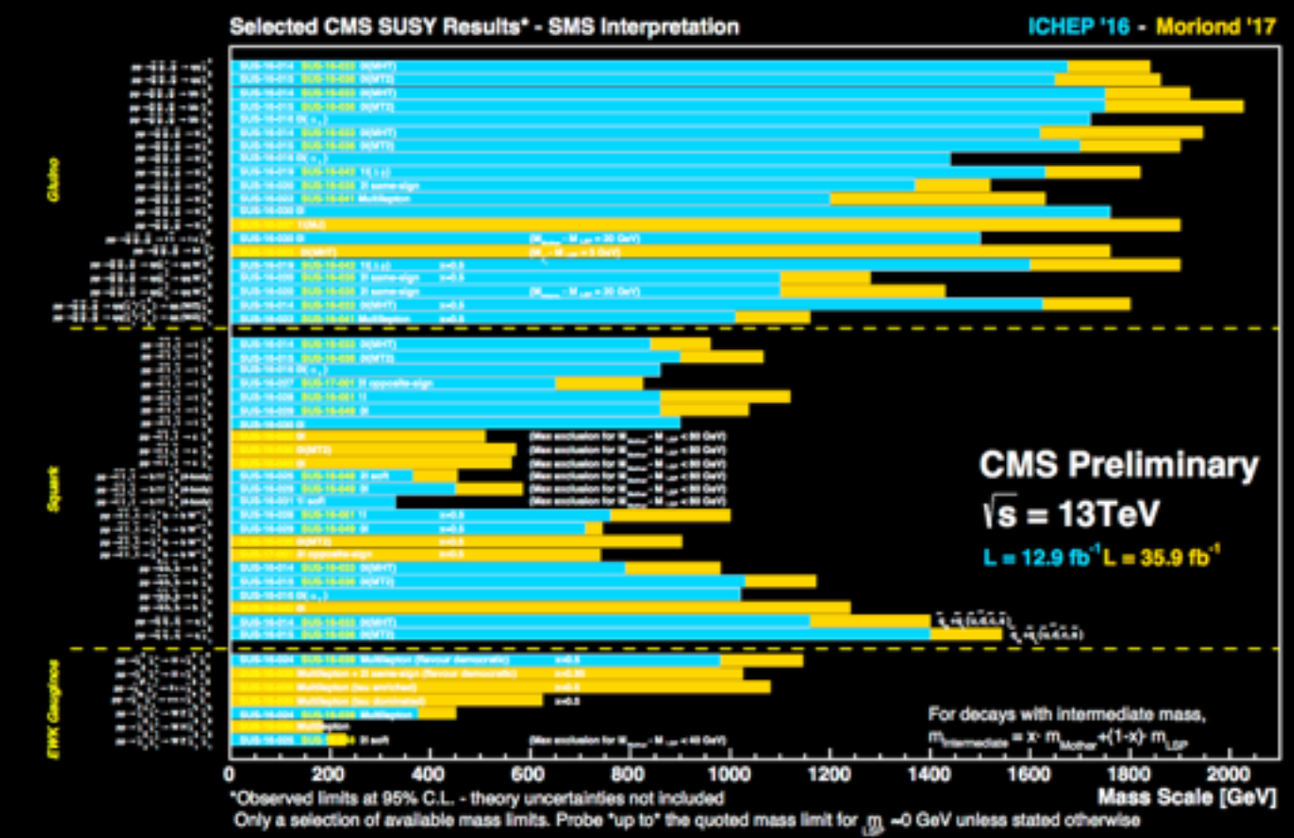
m_H is not technically natural $\Rightarrow$ hierarchy problem

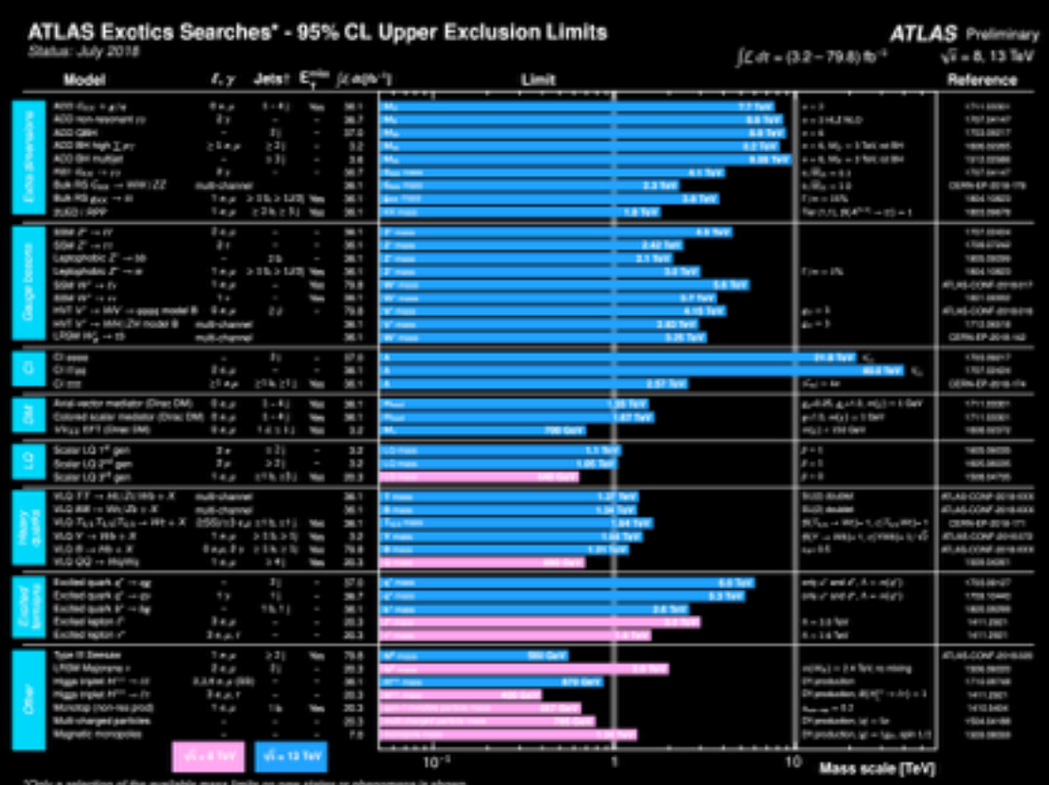
The Usual Suspects

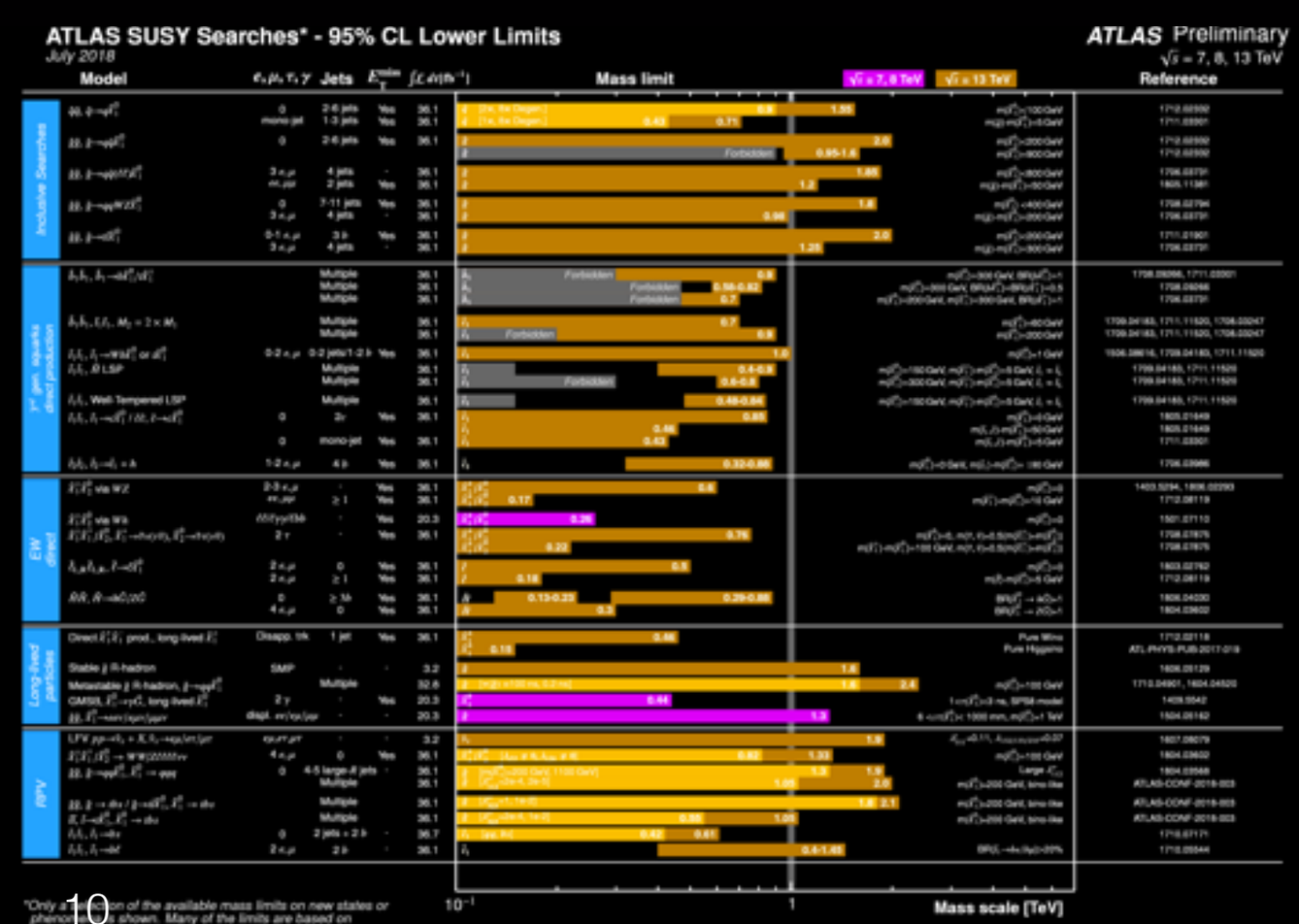


Thus far…

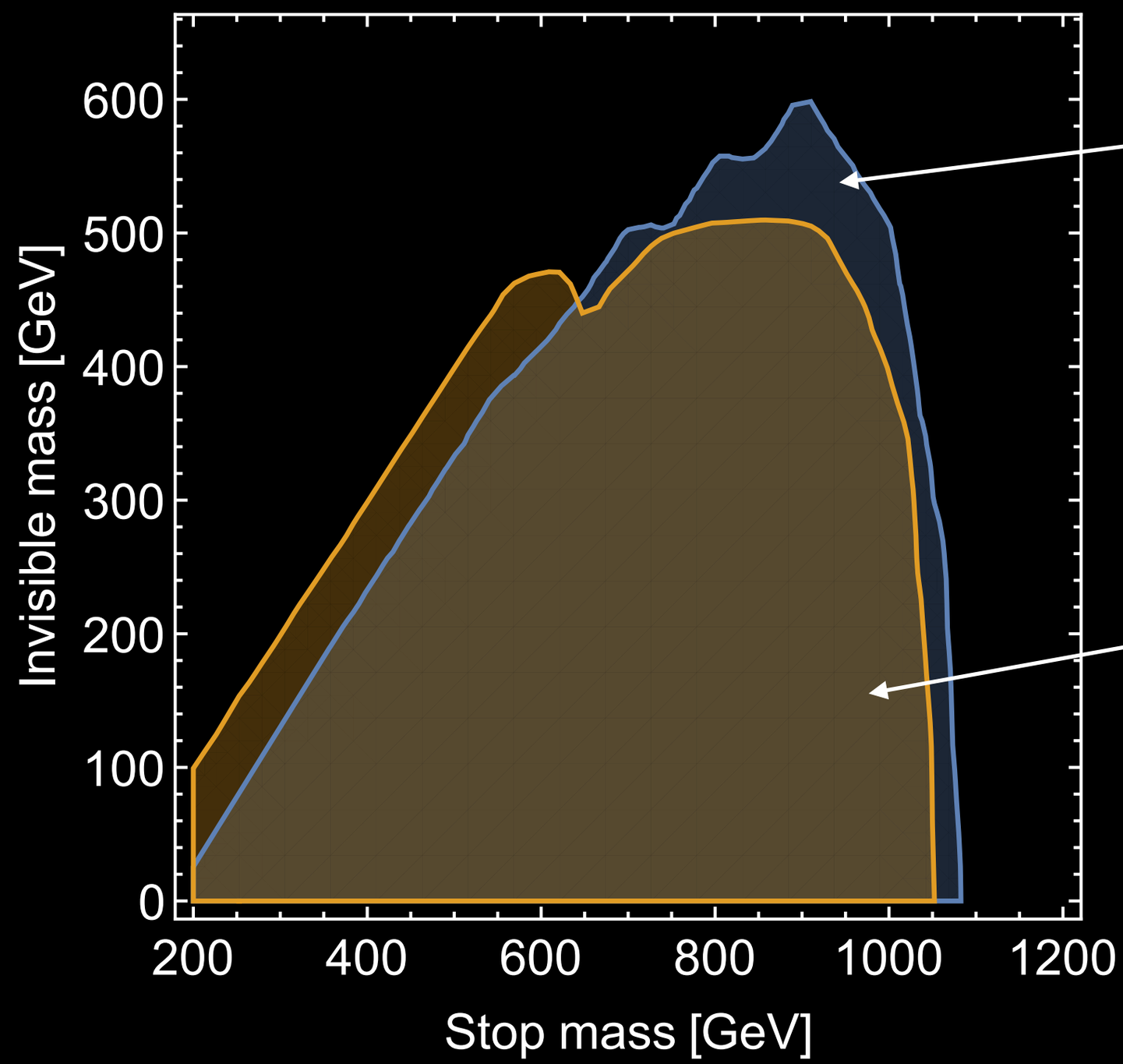

Vector-like quark pair production
Resonances to heavy quarks
Excited quarks
Vector-like quark single production
Resonances to dibosons
8 TeV
13 TeV
Observed limit 95%CL (TeV)
B2G
new physics
searches with
heavy SM particles


Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
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


ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018
ATLAS Preliminary
Model
Limit
Reference
Mass scale [TeV]


ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
Model
Jets
Mass limit
Reference
Mass scale [TeV]

Not for lack of trying

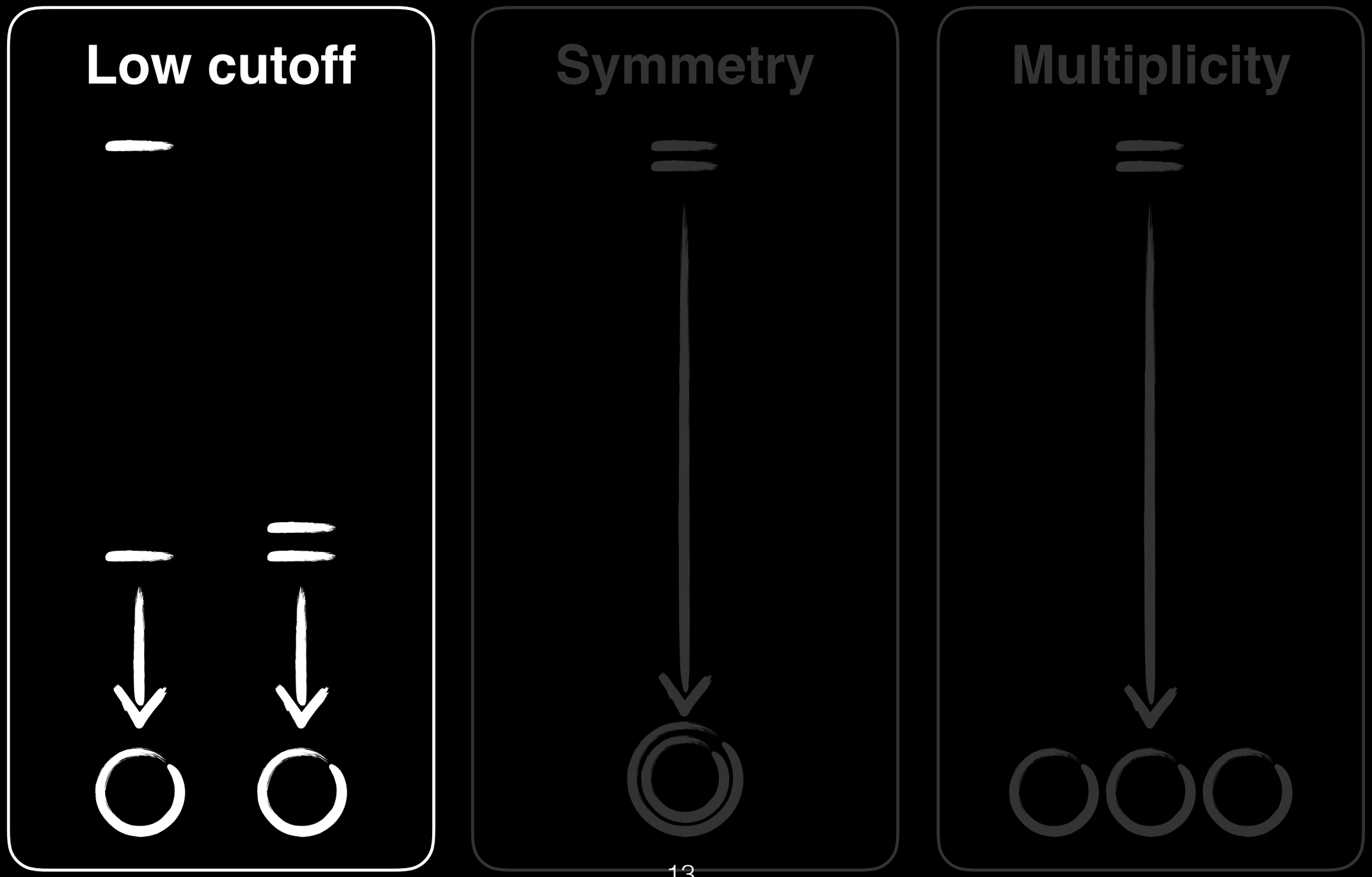


Projected reach
(c. 2012)
full LHC run
@ 14 TeV

CMS (e.g.)
exclusion w/
1/100 of full
LHC data set

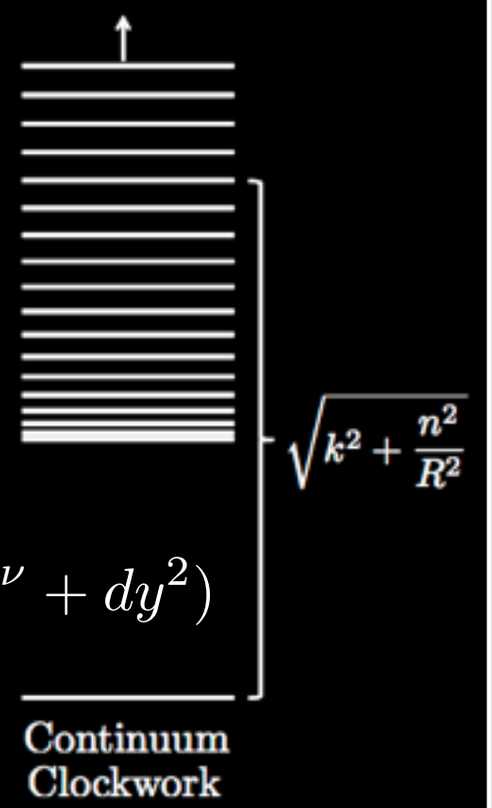

OH WOW! PARADIGM SHIFT!
THAVES

The Unusual Suspects



Linear Dilaton / Continuum Clockwork

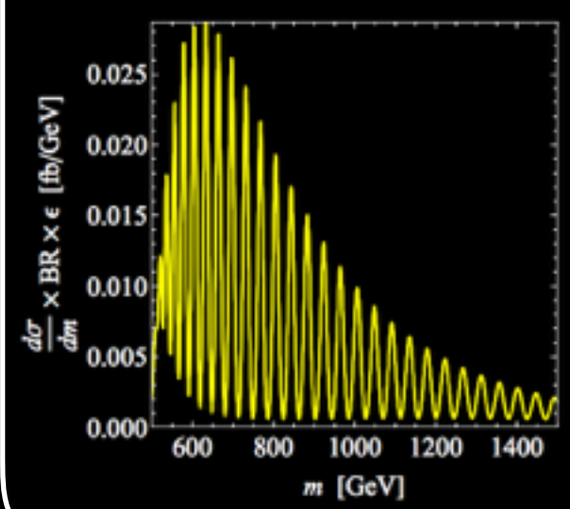
[Giudice, McCullough '16; Giudice, Kats, McCullough, Torre, Urbano '17; Antoniadis, Dimopoulos, Giveon '01; Antoniadis, Arvanitaki, Dimopoulos, Giveon '11; ....]

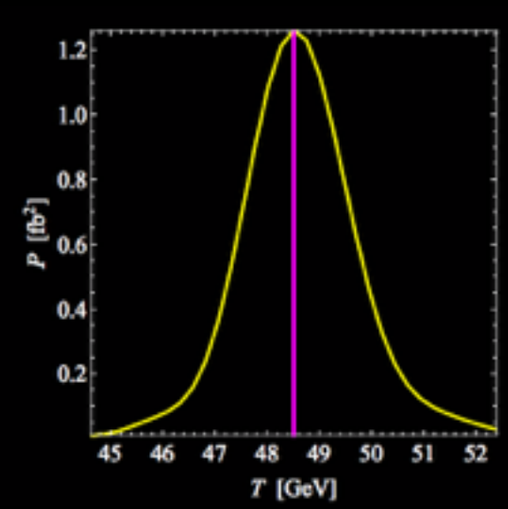


$$ds^2 = e^{\frac{4}{3}k|y|}(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2)$$

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

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



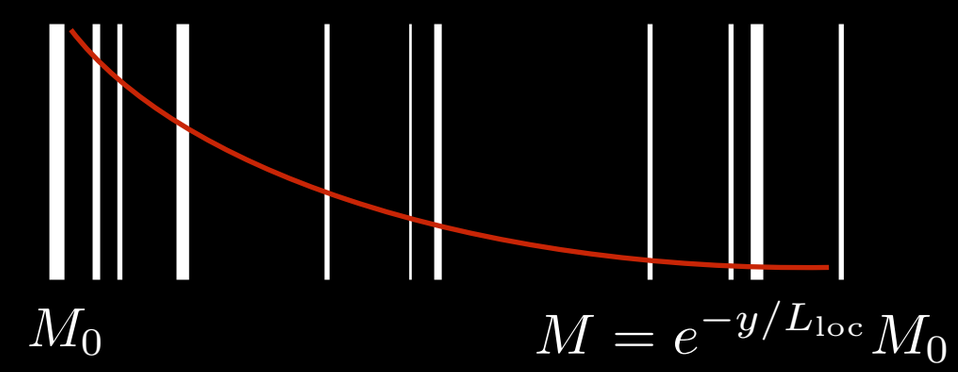


Disorder

[Rothstein '13]

Anderson localization: exponential localization from disorder.

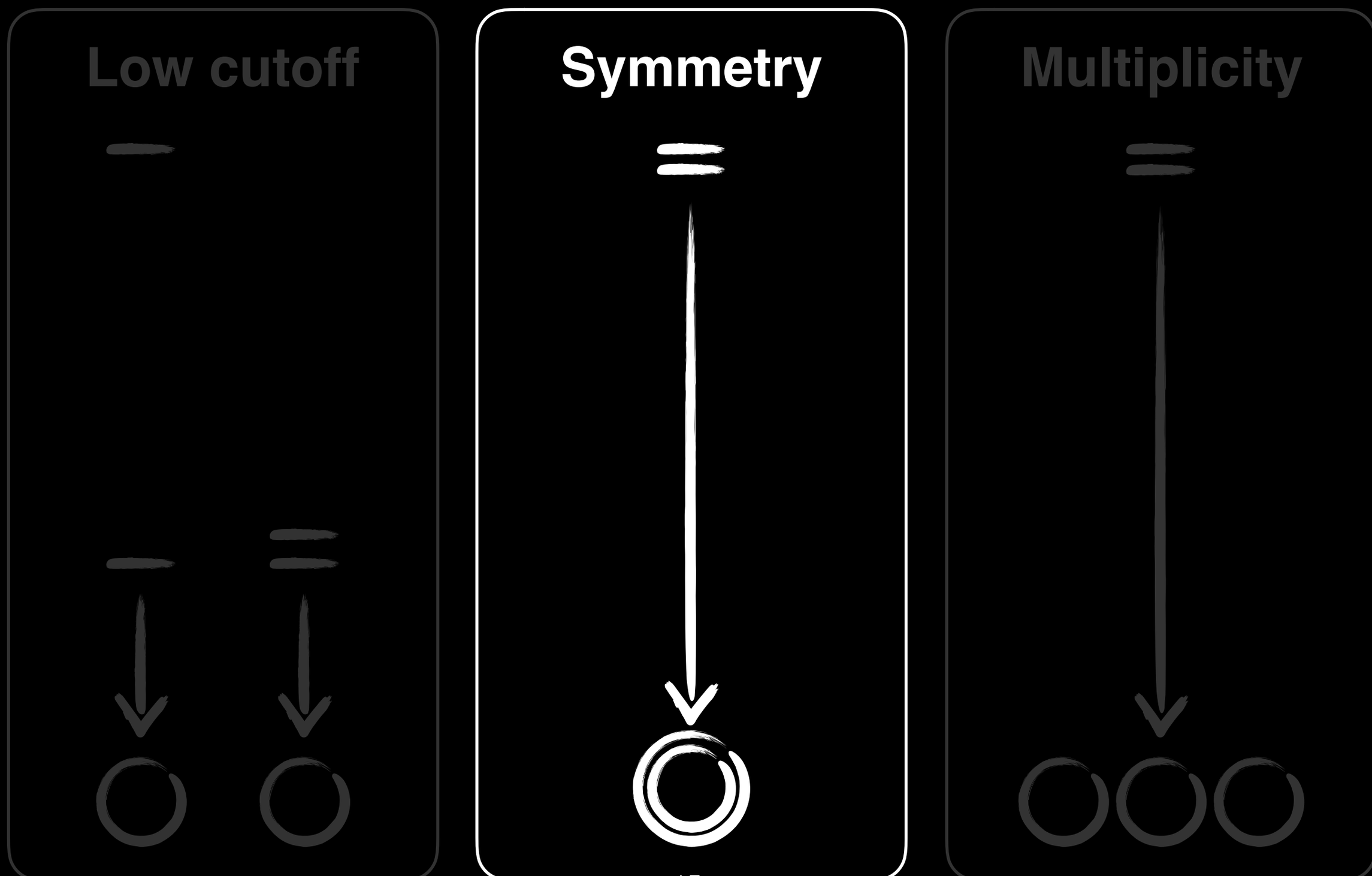
Reasoning by analogy: localize graviton zero mode w/ randomly spaced & tensioned branes



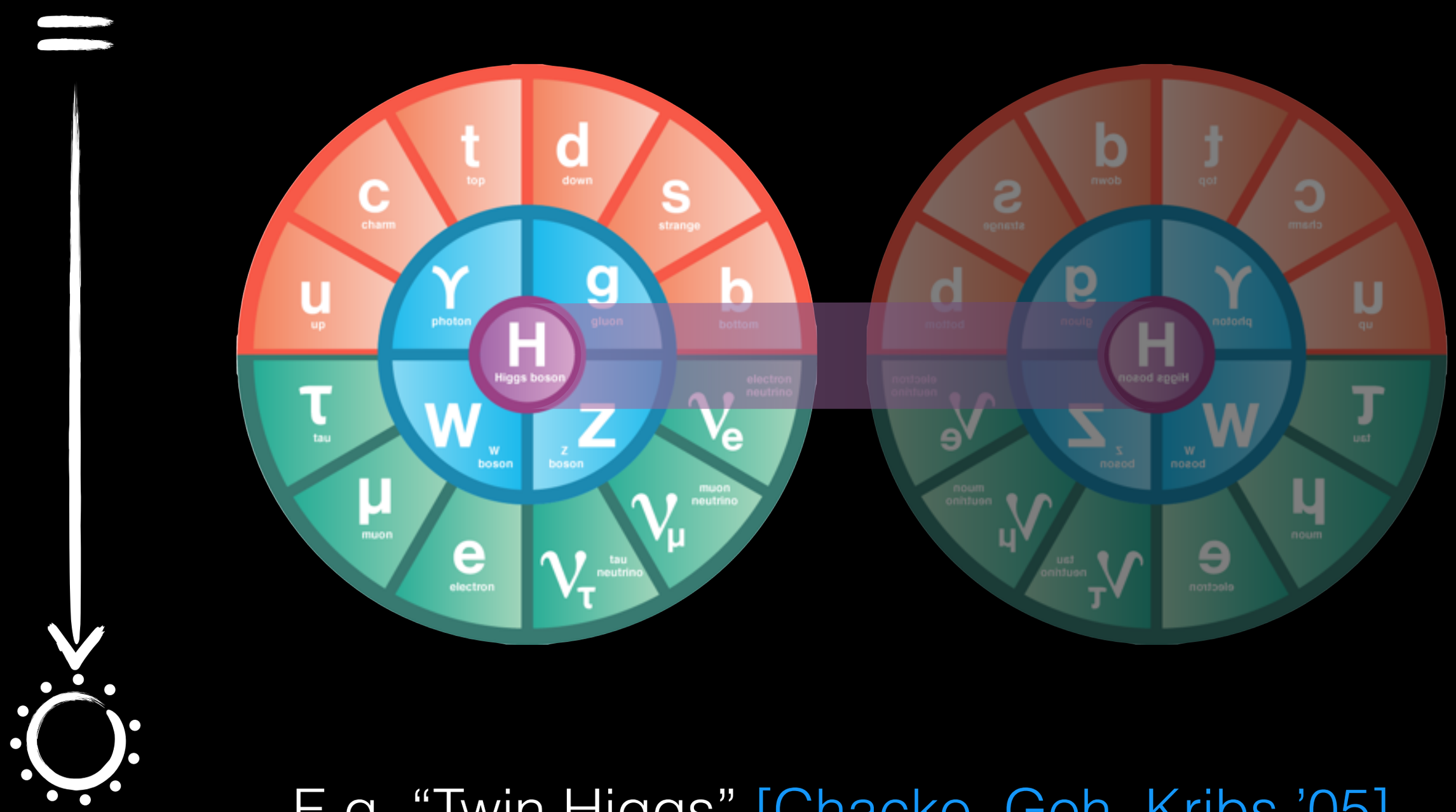
But: not obvious that it works in detail

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

The Unusual Suspects



Discrete symmetries

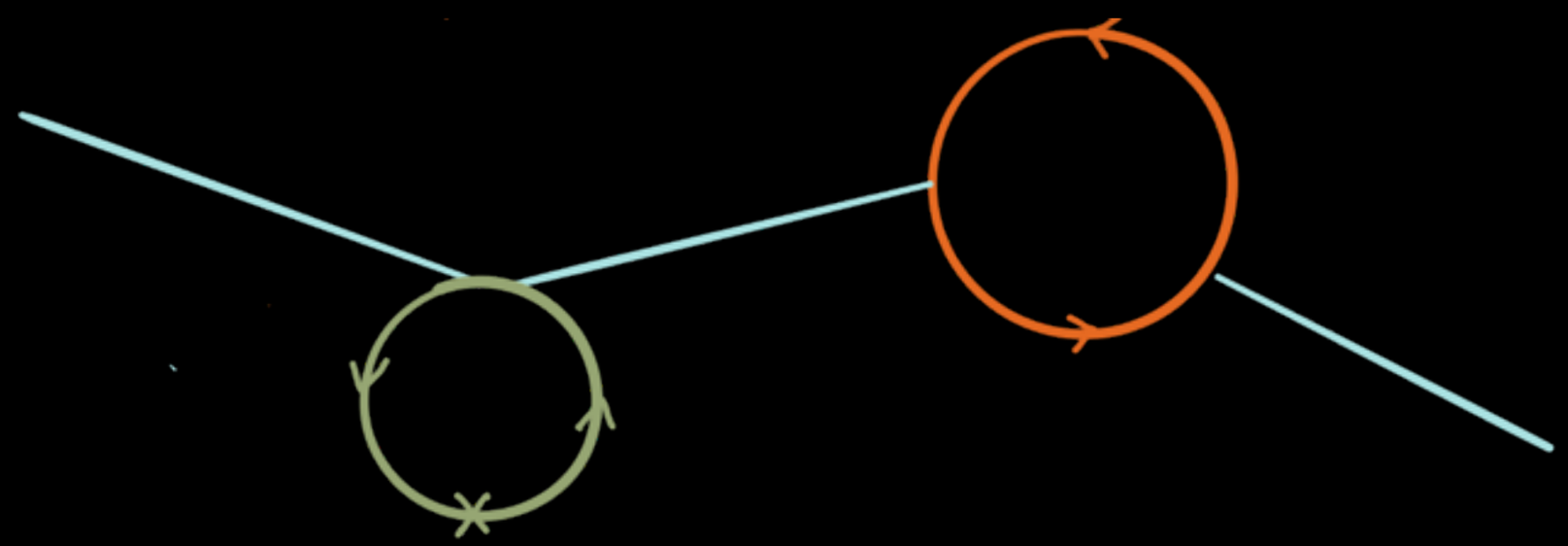


E.g. “Twin Higgs” [Chacko, Goh, Kribs ’05]

Discrete symmetries

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

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



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

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

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
- …

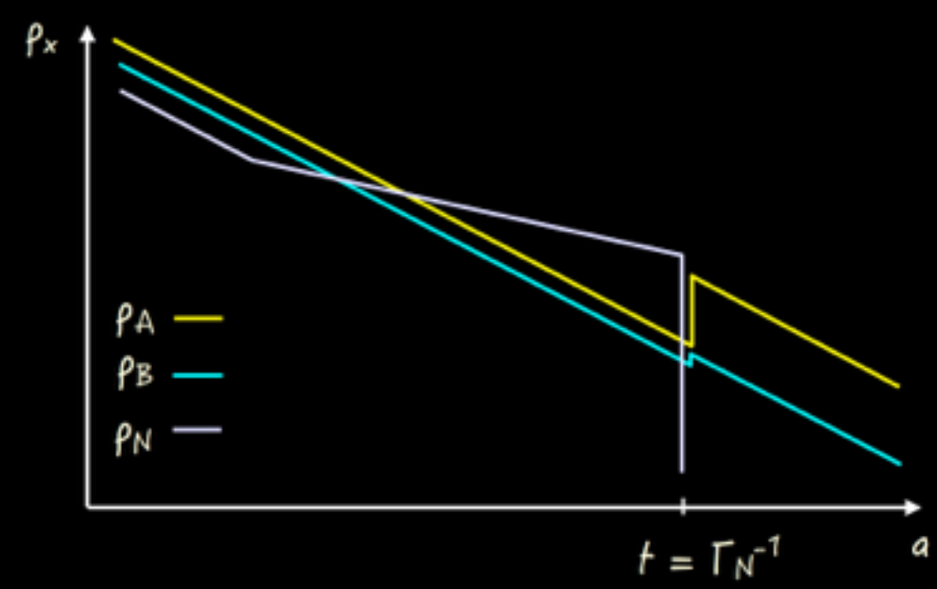
Change the Cosmology

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

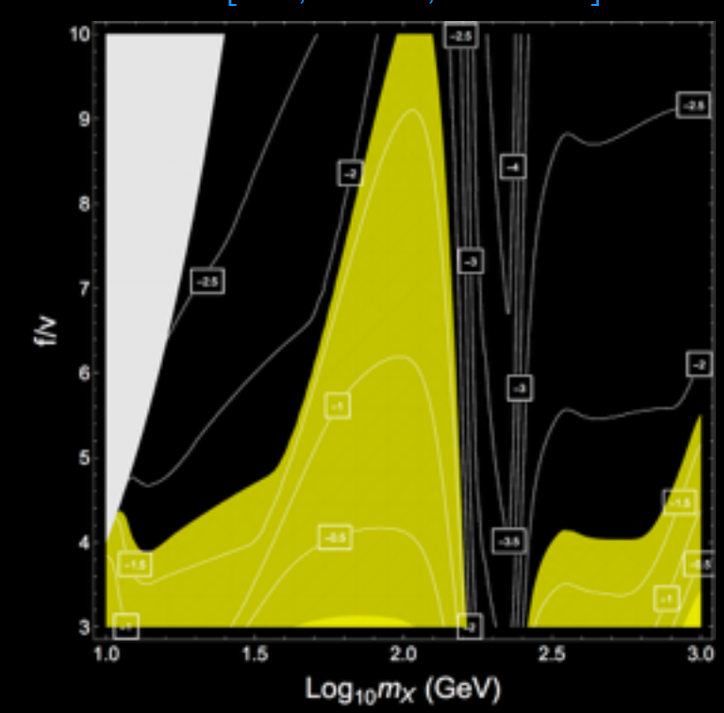
- decouples while relativistic
- decays some time thereafter
- decays primarily to A



Easy to do w/ symmetric coupling to H_A, H_B

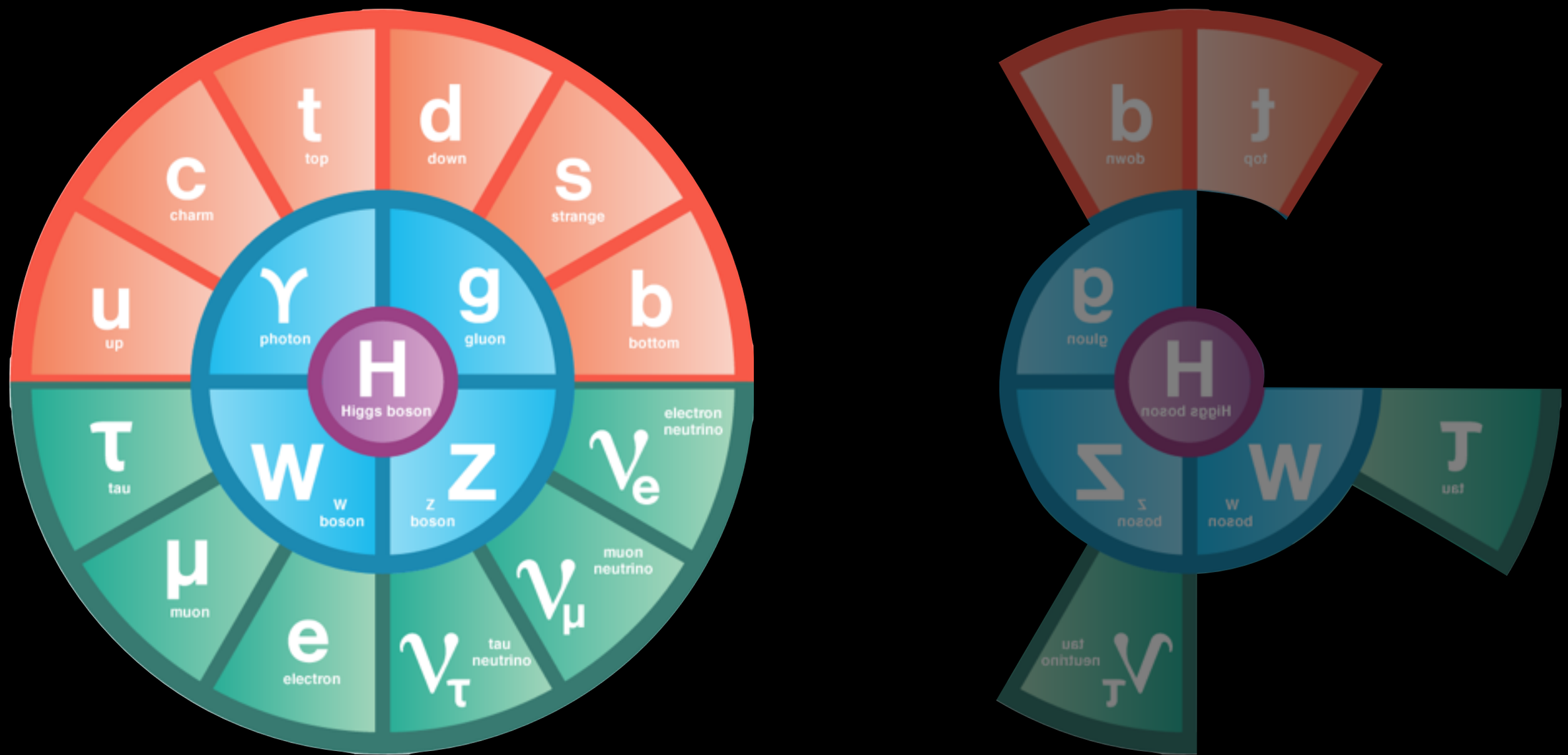
Signals now in future CMB experiments, e.g. CMB Stage-IV

[NC, Koren, Trott '16]



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

Change the Spectrum

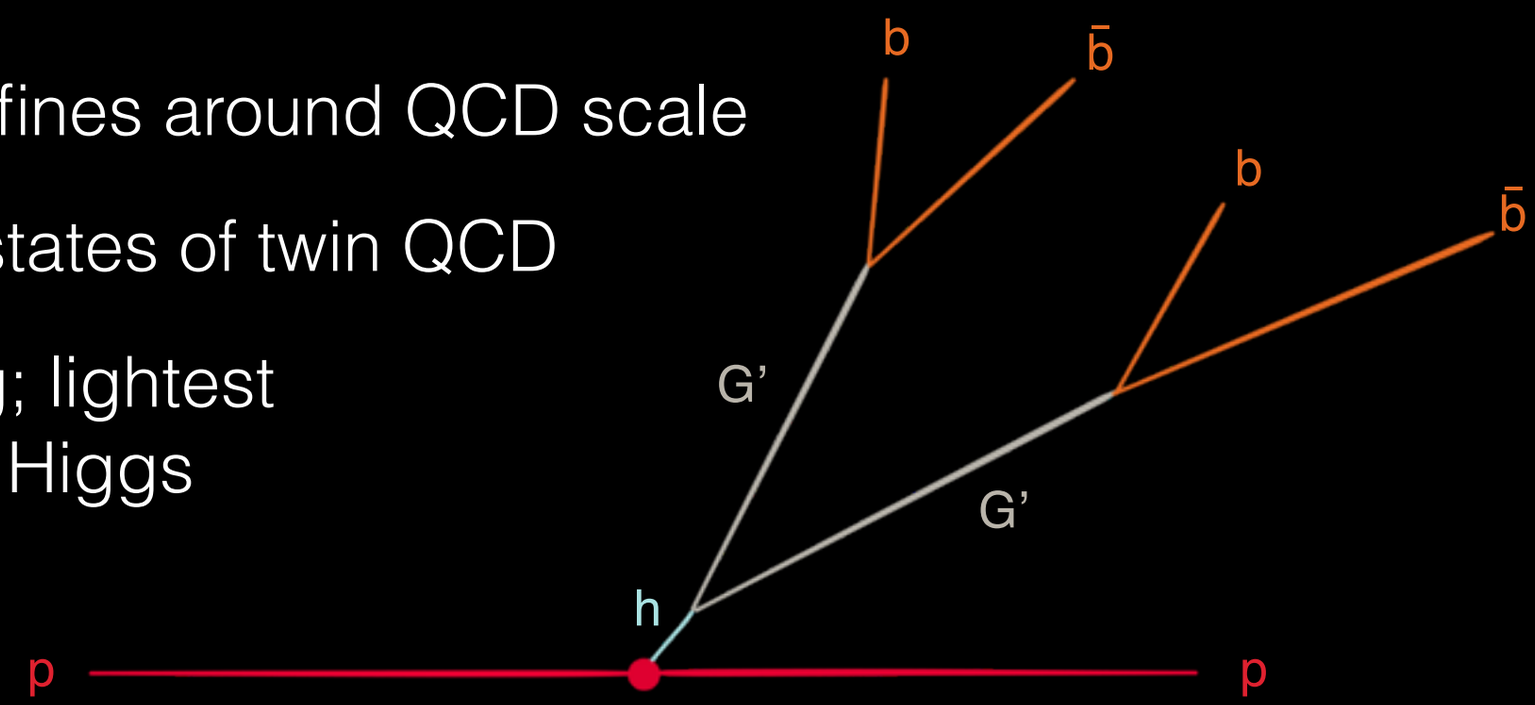


"Fraternal Twin Higgs" [NC, Katz, Strassler, Sundrum '15]

[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



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

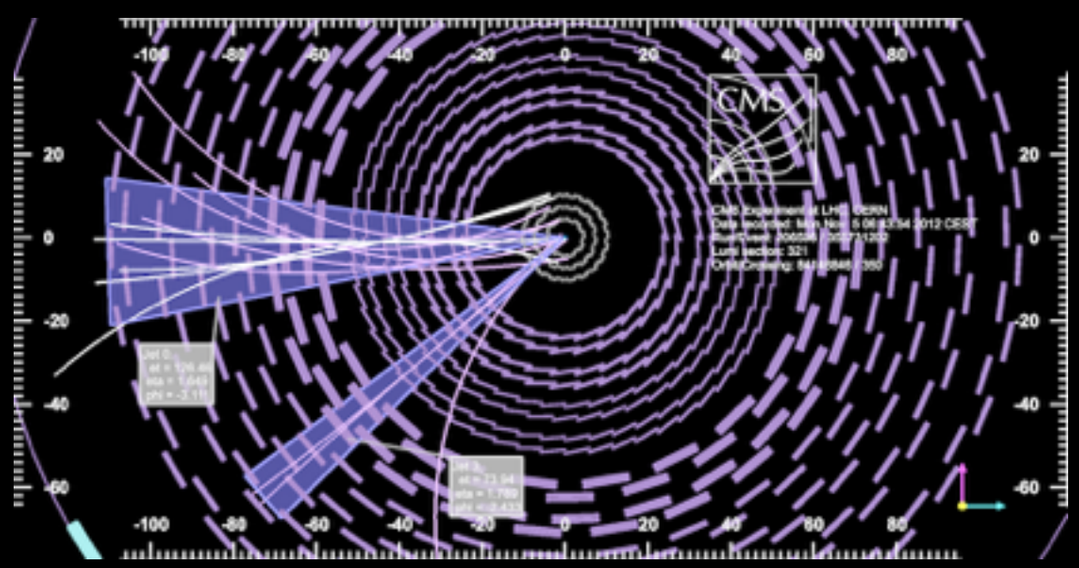
Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

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

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

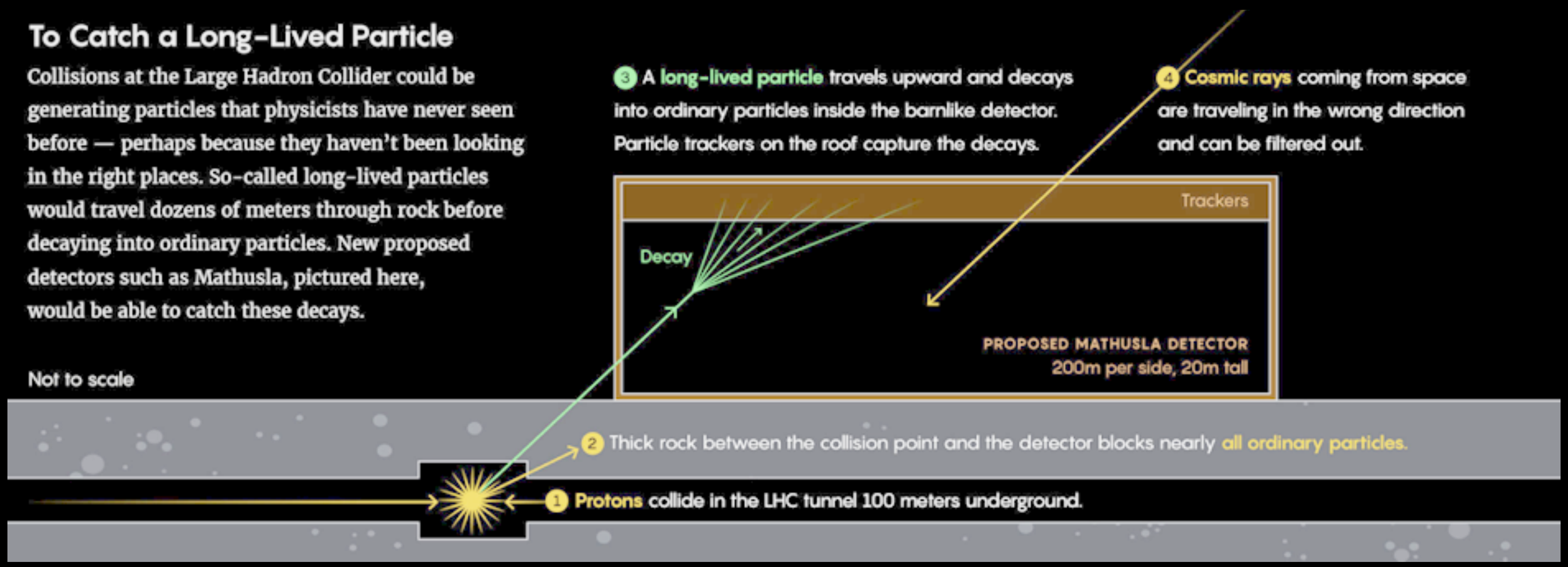
Methuselah (Hebrew: מְתוּשֶׁלַח / מְתוּשָׁלַח, Modern *Metuŝélah* / *Metuŝálah* Tiberian *Məṯûŝélaḥ* / *Məṯûŝálaḥ* ; "Man of the dart/spear", or alternatively "his death shall bring judgment"[1]) is the man reported to have lived the longest at the age of 969 in the Hebrew Bible.[2]

Quantamagazine

To Catch a Long-Lived Particle

Collisions at the Large Hadron Collider could be generating particles that physicists have never seen before — perhaps because they haven't been looking in the right places. So-called long-lived particles would travel dozens of meters through rock before decaying into ordinary particles. New proposed detectors such as Mathusla, pictured here, would be able to catch these decays.

Not to scale



[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:

$$\textbf{MSSM} \xleftrightarrow{Z_2} \mathcal{H}\textbf{MSSM}$$

- 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 MSSM$_{\mathcal{H}}$ (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

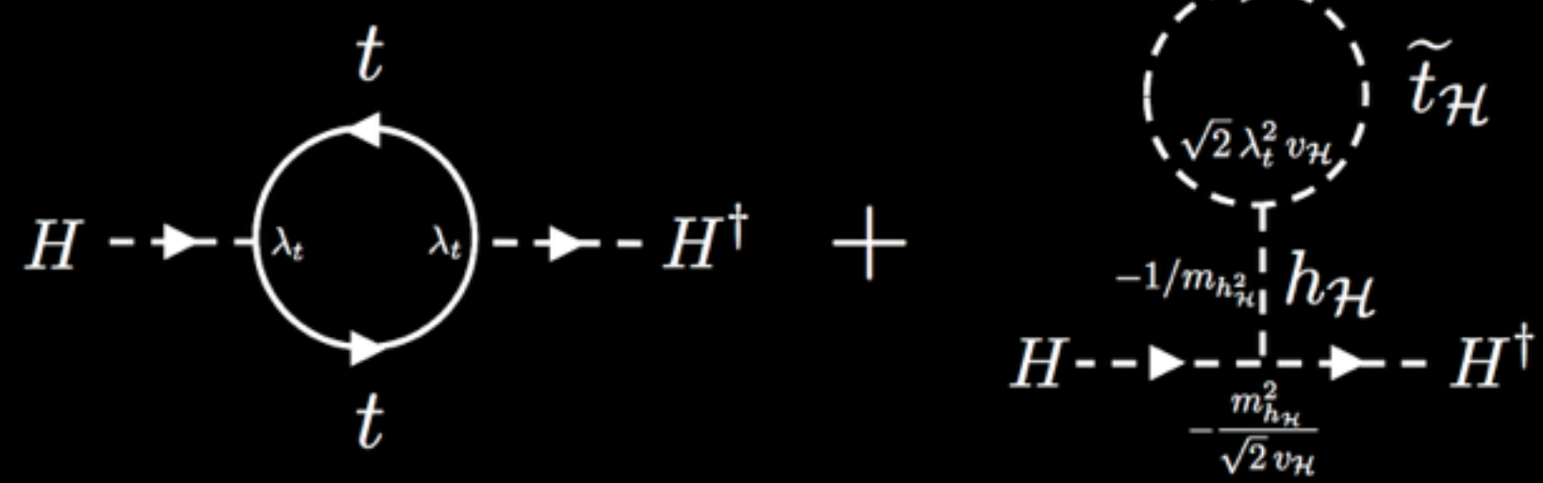
Flat direction ("goldstone" of spontaneously broken SU(2,2))

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

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$_{\mathscr{H}}$



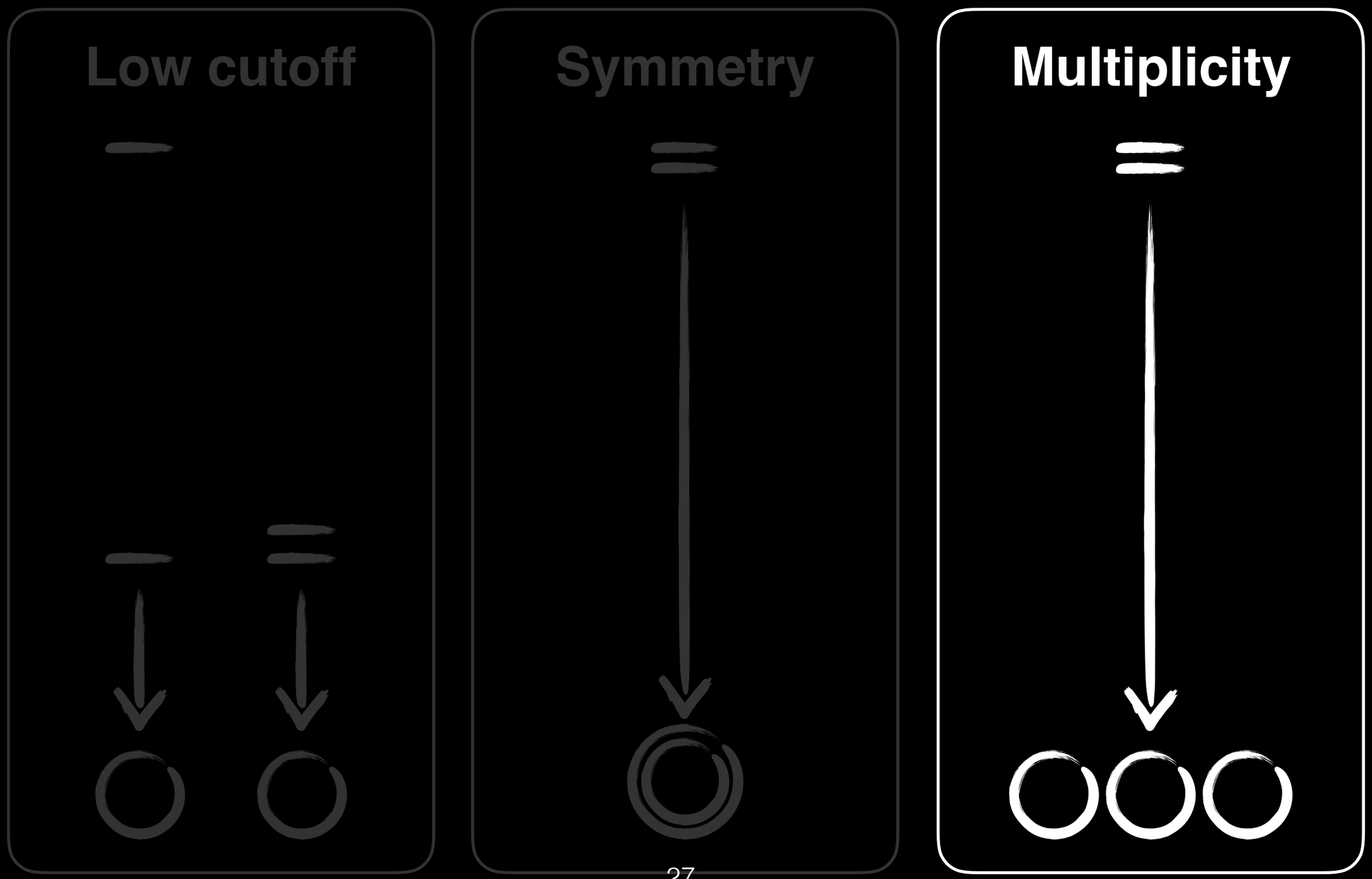
Novel dark sector phenomenology, especially if there are hyperbolic charge- and color-breaking minima

		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

The Unusual Suspects

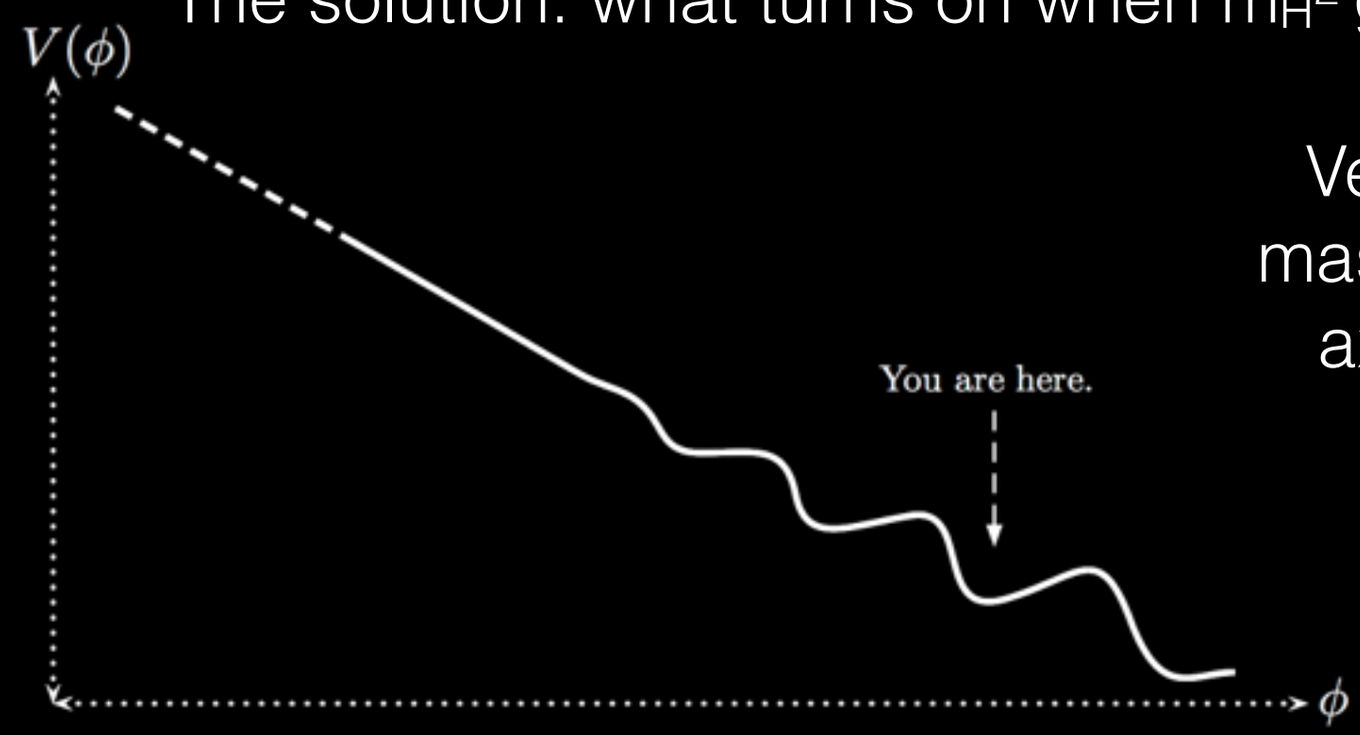


Relaxion

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"

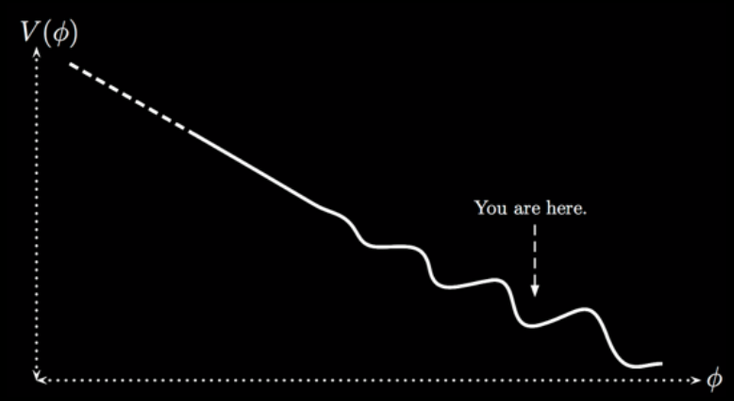
[Graham, Kaplan, Rajendran '15]

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.*

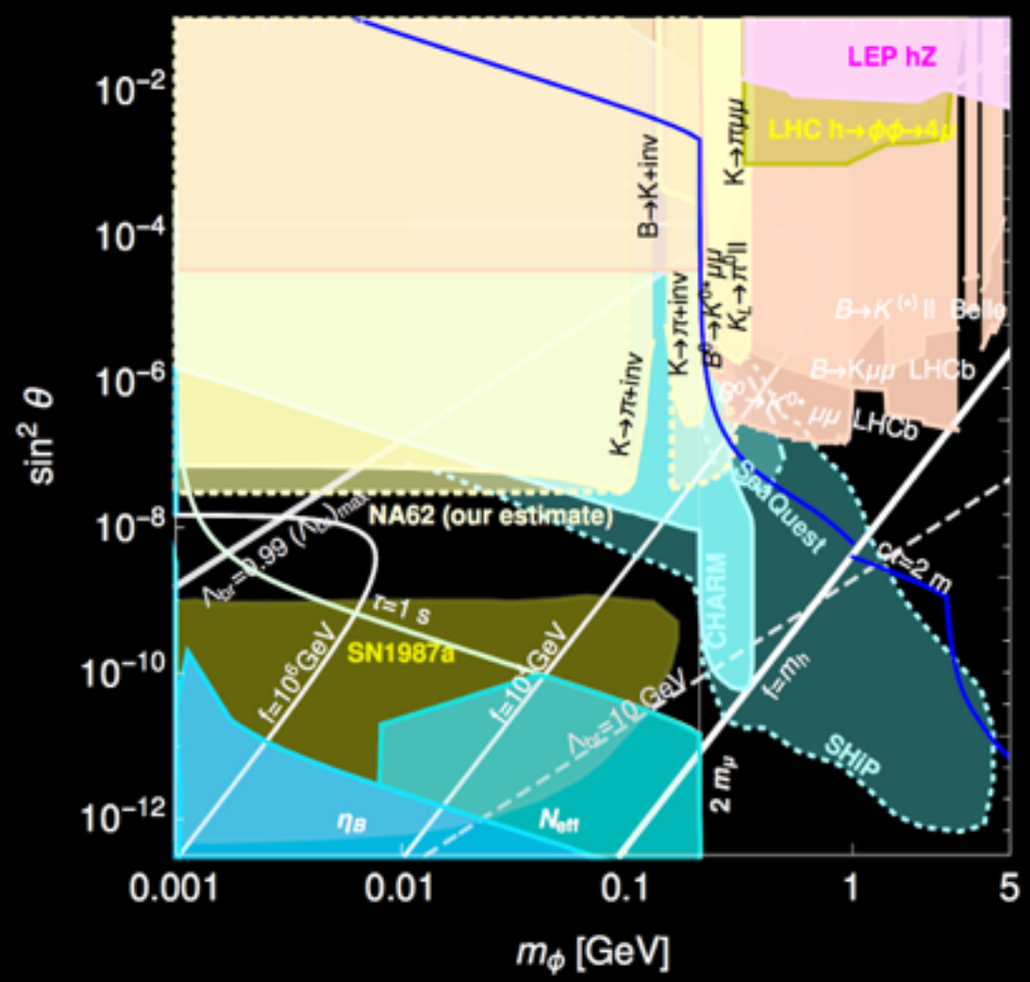
Extensive development, e.g. [Espinosa et al. '15; Hardy '15; Gupta et al '15; Batell, Giudice, McCullough '15; Choi, Im '15; Kaplan, Rattazzi '15; Di Chiara et al. '15; Ibanez et al. '15; Hook, Marques-Tavares '16; Nelson, Prescod-Weinstein '17; …]

New Signals

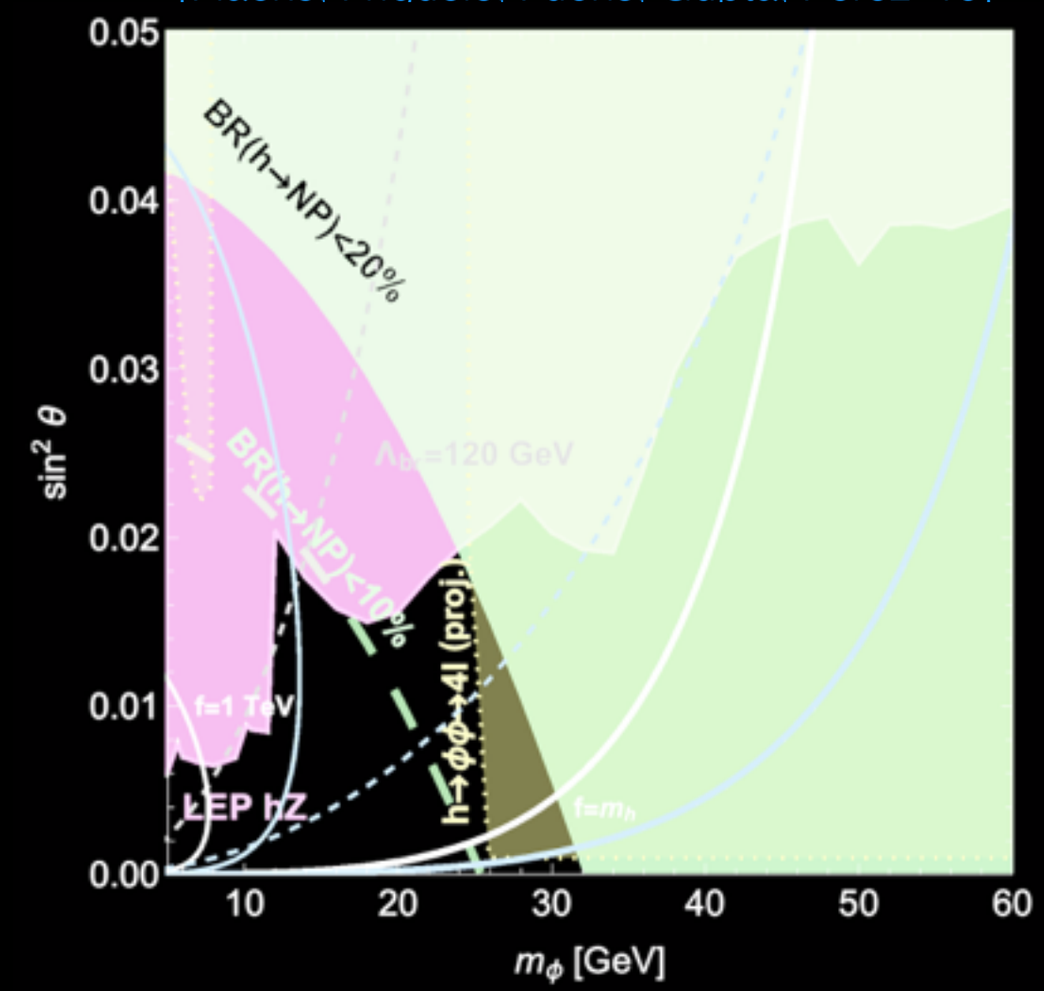
Higgs portals $g\phi|H|^2$ $\Lambda^4(H)\cos(\phi/f)$

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

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



[Flacke, Friguele, 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

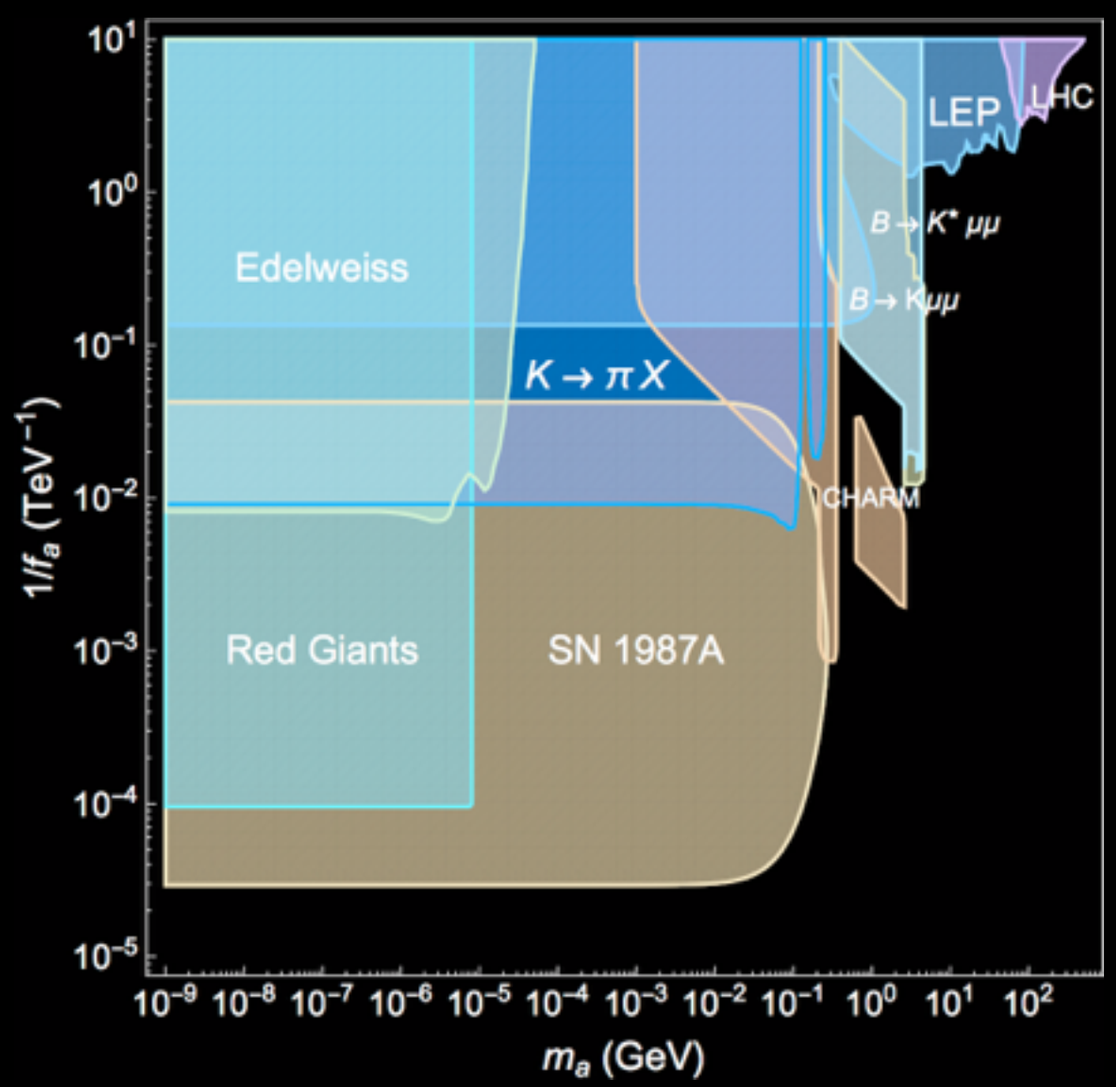
Important subtlety: can't couple to pairs of photons!

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

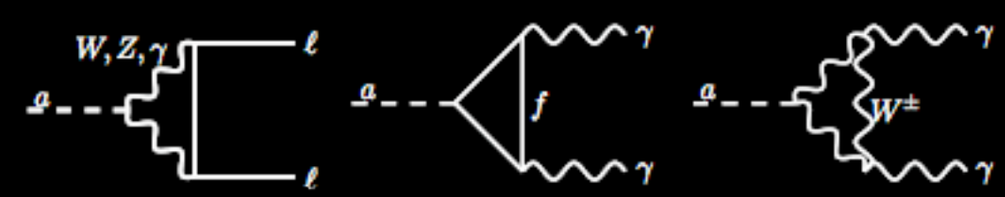
New Signals

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]



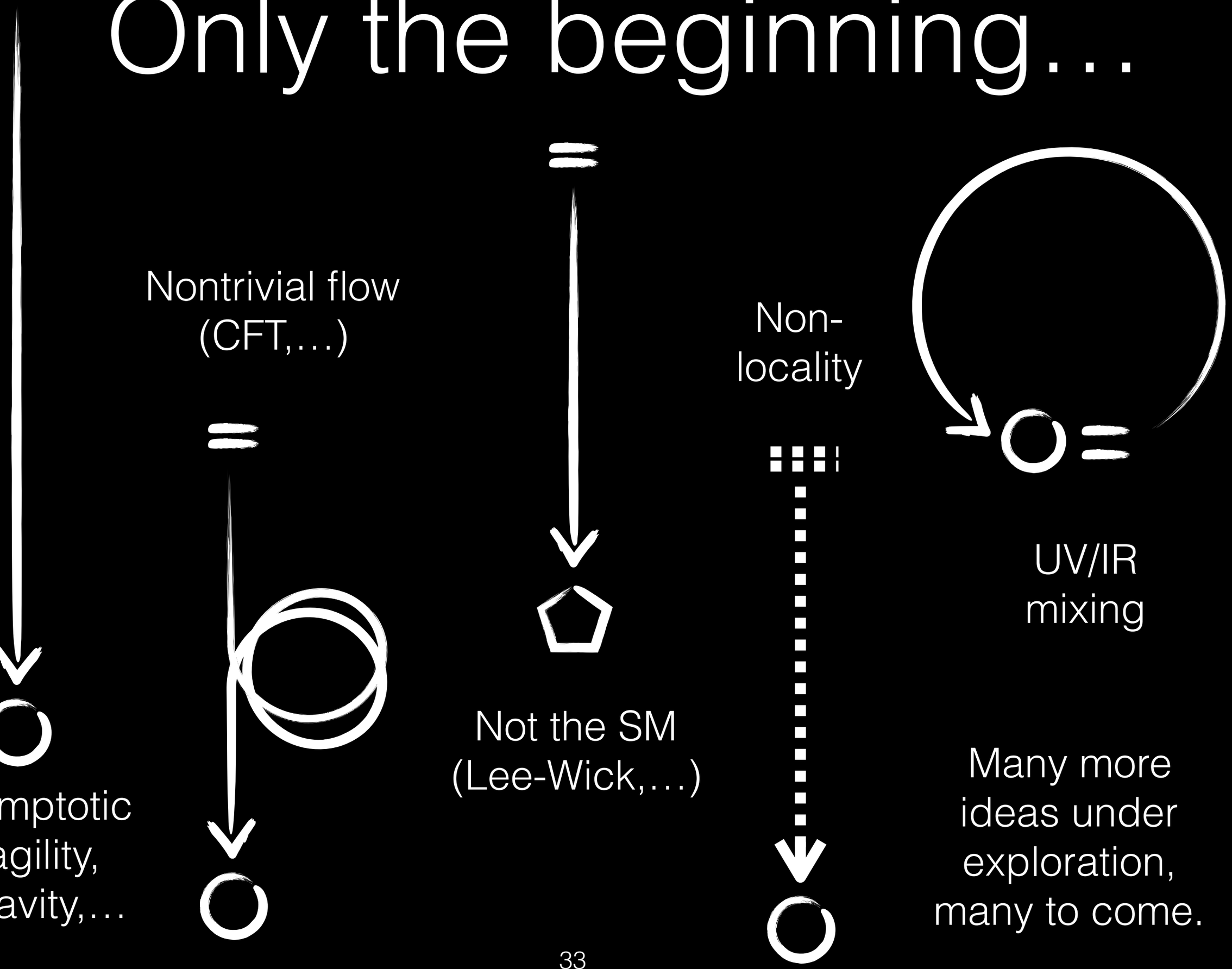
...radiative couplings to fermions induced at one loop, photon pairs at one & two loops [Bauer, Neubert, Thamm '17; NC, Hook, Kasko '18]

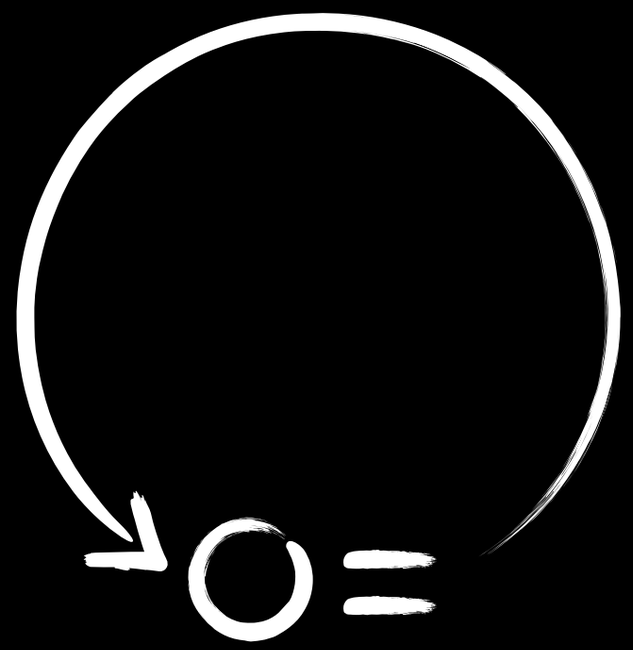


$$f_\gamma \sim 16\pi^2 \frac{m_W^2}{m_a^2} f_a + (16\pi^2)^2 \frac{m_f^2}{m_a^2} f_a$$

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

Only the beginning…



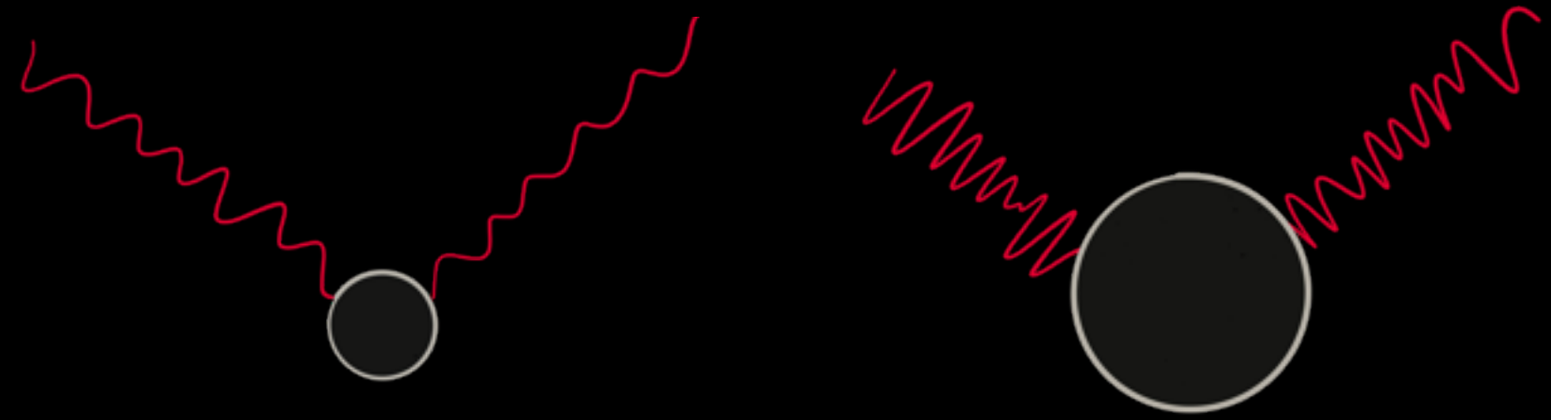


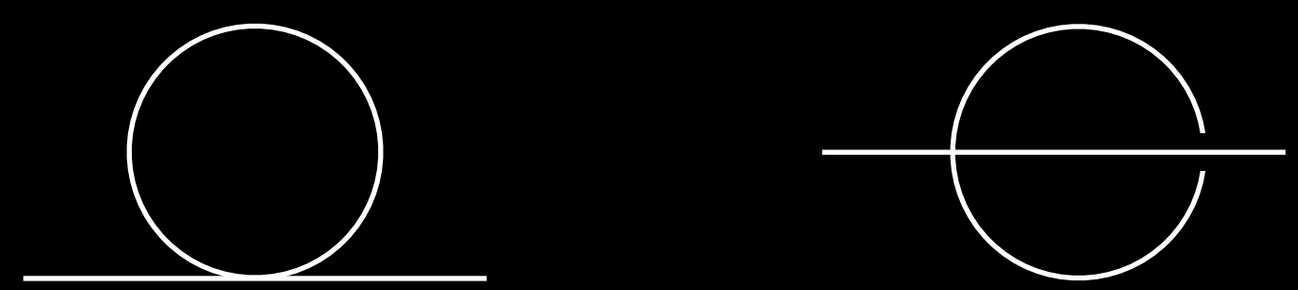
UV/IR Mixing

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

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

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





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

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

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 '06]

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

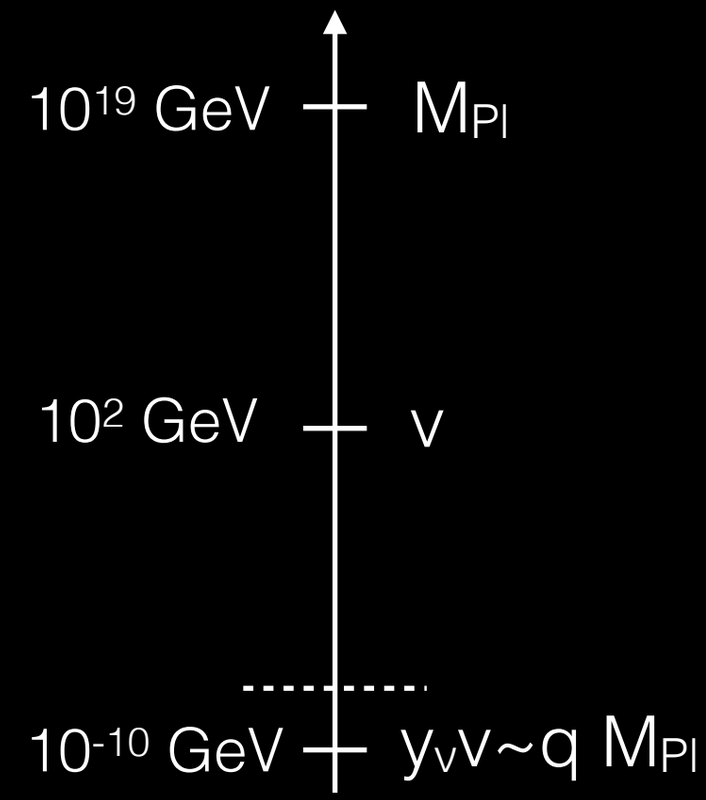
Neutrino mass is

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

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,...]

Direct UV/IR Mixing

Take the bull by the horns…

Study field theories with UV/IR mixing

Canonical example:

QFT on non-commutative spacetime $[\hat{x}^\mu, \hat{x}^\nu] = i\theta^{\mu\nu}$

UV/IR mixing from "uncertainty principle" $\Delta\hat{x}^\mu \Delta\hat{x}^\nu \geq \frac{1}{2}|\theta^{\mu\nu}|$

Caveats: Lorentz violating; Minkowski NCQFT unitary only for space-space non-commutativity (i.e. $\theta^{0i}=0$).

Not the theory of our universe, but a useful toy model. (See e.g. [Heckman & Verlinde '14])

NCQFT

Two common approaches:

1. QFT on commutative coordinates w/ star product:

$$f(x) \star g(x) = \exp\left(\frac{i}{2}\theta_{\mu\nu}\partial_y^\mu \partial_z^\nu\right) f(y)g(z)\Big|_{y=z=x}$$

2. Seiberg-Witten map [Seiberg, Witten '99]:

I.e., $f \star g = f \cdot g + \frac{i}{2}\theta^{\mu\nu}\partial_\mu \cdot \partial_\nu g + \mathcal{O}(\theta^2)$ and e.g.

$$\hat{A}_\mu[A] = A_\mu + \frac{1}{4}\theta^{\rho\sigma}\{A_\sigma, \partial_\rho A_\mu\} + \frac{1}{4}\theta^{\rho\sigma}\{F_{\rho\mu}, A_\sigma\} + \mathcal{O}(\theta^2)$$

Equivalent to any finite order in θ (i.e., option (2) defines a low-energy effective action), but UV/IR mixing only apparent in (1).

[Filk '96]

NCQFT: ϕ^4

Consider just ϕ^4 in Euclidean d=4:

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 + \frac{1}{2} m^2 \phi^2 + \frac{1}{4!} g^2 \phi \star \phi \star \phi \star \phi$$

Quadratic terms identical to commutative theory

Interactions associated w/ additional phases:

$$V(k_1, k_2, k_3, k_4) = e^{-\frac{i}{2}\sum_{i<j} k_{i\mu}\theta^{\mu\nu}k_{j\nu}}$$

Not invariant under arbitrary permutations of k

Planar graphs: reduces to an overall phase involving external momenta

Nonplanar graphs: additional phases from crossing lines

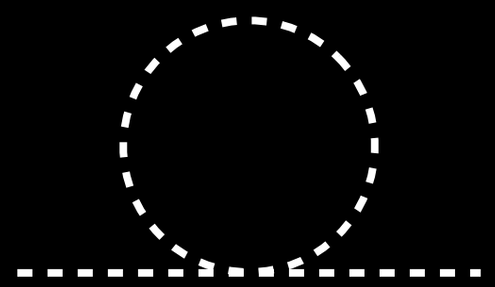
Feynman rules as usual modulo phases in nonplanar diagrams:

$$\sim e^{ip_\mu \theta^{\mu\nu} k_\nu}$$

[Minwalla, Seiberg, Van Raamsdonk '99]

NCQFT: ϕ^4

Compute one-loop radiative corrections to scalar 2-pt function.
Both "planar" and "non-planar" diagrams at one loop:

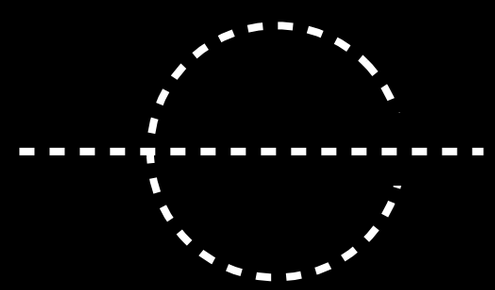


$$\sim \int \frac{d^4k}{k^2}$$

UV divergent

$$\Gamma_1^{2,p} = \frac{g^2}{48\pi^2}\left(\Lambda^2 - m^2 \log\left(\frac{\Lambda^2}{m^2}\right) + \dots\right)$$

Akin to commutative theory



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

IR divergence!

$$\Gamma_1^{2,np} = \frac{g^2}{96\pi^2}\left(\Lambda_{\text{eff}}^2 - m^2 \log\left(\frac{\Lambda_{\text{eff}}^2}{m^2}\right) + \dots\right)$$

Likewise, but with $\Lambda \to \Lambda_{eff}$

Appearance of a new "scale":

$$\Lambda_{\text{eff}}^2 = \frac{1}{1/\Lambda^2 + p \circ p}$$

where $p \circ k = |p^\mu \theta^2_{\mu\nu} k^\nu|$

$$\Lambda_{\text{eff}}^2 \to \begin{cases} \Lambda^2 & p \circ p \to 0 \\ \frac{1}{p \circ p} & \Lambda \to \infty \end{cases}$$

[Minwalla, Seiberg, Van Raamsdonk '99
Alvarez-Gaume, Vazquez-Mozo '03]

New poles

1-loop 1PI quadratic effective action:

$$\frac{1}{2}\left(p^2 + M^2 + \frac{g^2}{96\pi^2(p\circ p + 1/\Lambda^2)} + \ldots\right)\phi(p)\phi(-p)$$

w/ renormalized mass M:

$$M^2 = m^2 + \frac{g^2\Lambda^2}{48\pi^2} - \frac{g^2 m^2}{48\pi^2}\ln\frac{\Lambda^2}{m^2}$$

Action @ infinite cutoff:

$$\frac{1}{2}\left(p^2 + M^2 + \frac{g^2}{96\pi^2 p\circ p} + \ldots\right)\phi(p)\phi(-p)$$

Two poles in $\Lambda \to \infty$ action:

1. Usual one (ϕ quanta) at $p^2 + m^2 = \mathcal{O}(g^2)$
2. New one at $p\circ p = -\frac{g^2}{96\pi^2}\frac{1}{p_c^2 + m^2} + \ldots$

Second pole signals existence of new light "particle" arising from high-momentum modes of ϕ

[Minwalla, Seiberg, Van Raamsdonk '99]

Wilsonian interpretation

Normally require renormalizable Wilsonian action to satisfy

1. Correlation functions well-defined as $\Lambda \to \infty$
2. Correlation functions at finite Λ differ from limiting value by $O(1/\Lambda)$ at all momenta

Badly violated here *at small p.*

$$\frac{1}{2}\left(p^2 + M^2 + \frac{g^2}{96\pi^2(p \circ p + 1/\Lambda^2)} + \dots\right)\phi(p)\phi(-p)$$

Restore Wilsonian interpretation w/ new particle χ:

$$\delta\mathcal{L} = \frac{1}{2}\partial\chi \circ \partial\chi + \frac{1}{2}\Lambda^2(\partial \circ \partial\chi)^2 + i\frac{1}{\sqrt{96\pi^2}}g\chi\phi$$

Quadratic, so integrate out:

$$+\frac{1}{2}\frac{1}{96\pi^2}\left(\frac{g^2}{p \circ p} - \frac{g^2}{p \circ p + 1/\Lambda^2}\right)\phi(p)\phi(-p)$$

What have we learned?

High-momentum modes of massive fields in a non-commutative scalar theory are “dual” to additional (peculiar) light fields

4d fields in case of quadratic divergences, 5d for linear divergences, 6d for logarithmic divergences

In a fantasy application to the hierarchy problem, apparently light scalars are the χ fields, not the ϕ fields

$$\delta\mathcal{L} = \frac{1}{2}\partial\chi \circ \partial\chi + \frac{1}{2}\Lambda^2(\partial \circ \partial\chi)^2 + i\frac{1}{\sqrt{96\pi^2}}g\chi\phi$$

Just a fantasy in this setting, but worth understanding basic features & trying to extract lessons [NC, Koren, *in progress*]
Other controlled QFTs with similar features?

Conclusions

- Naturalness a compelling strategy for physics beyond the Standard Model *within experimental reach.*
- Robust program of LHC searches for conventional approaches based on continuous symmetries…
- …and entirely new approaches now being explored, based on exotic cutoffs, discrete symmetries, dynamics, etc.
- New signals abound: LLPs, Higgs properties, diverse ALPs,…
- Next step: apparent failure of naturalness strategy might signal breakdown of EFT. Opportunity/challenge to make this concrete.


Thank you!