BSM Higgs: New Perspectives

Nathaniel Craig
UC Santa Barbara

Higgs 2020

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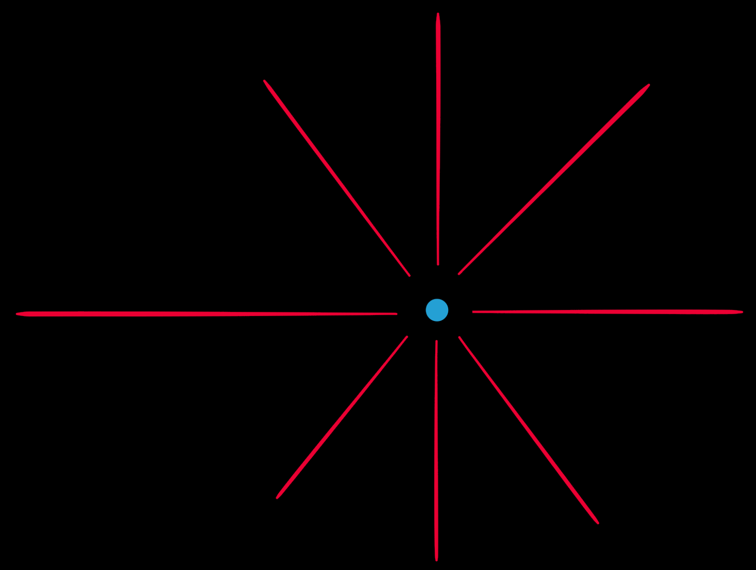
Why BSM Higgs?

~~Why BSM Higgs?~~

Why EWSB? What scale?

The naturalness strategy: an analogy from E&M



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

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

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

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

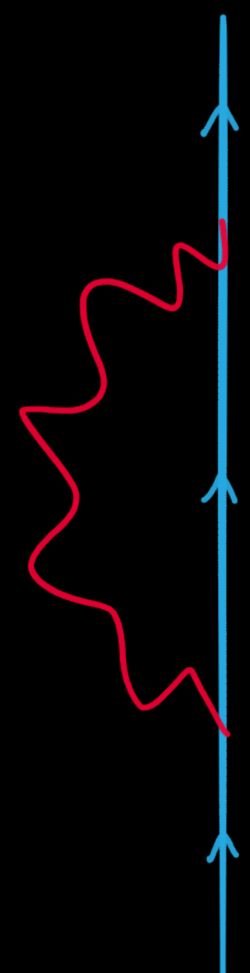
To avoid fine-tuning, i.e. for the theory to be “natural”,
need picture to change on scales below 2.8×10^{-13} cm

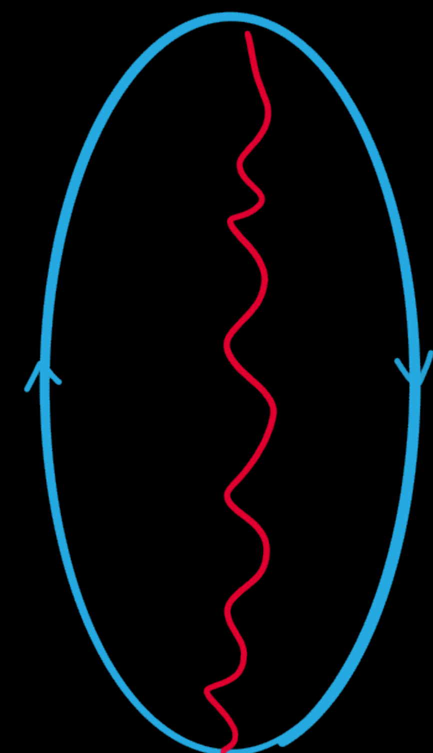
The Naturalness Strategy

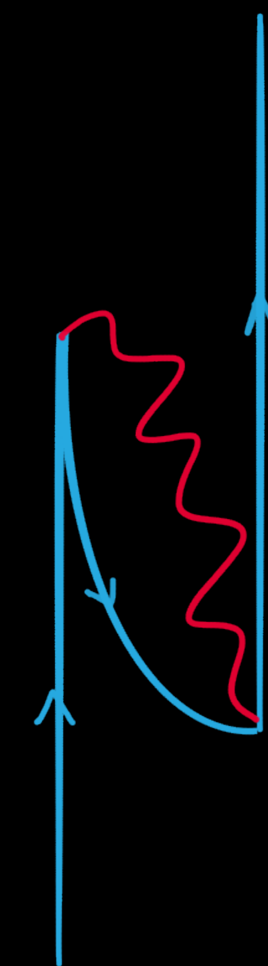
An analogy

Weisskopf (1939)

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







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

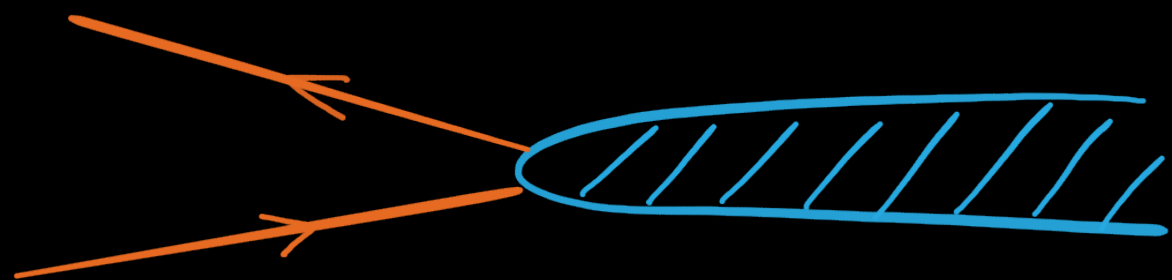
$$\Delta E = \Delta E_C + \ldots$$

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

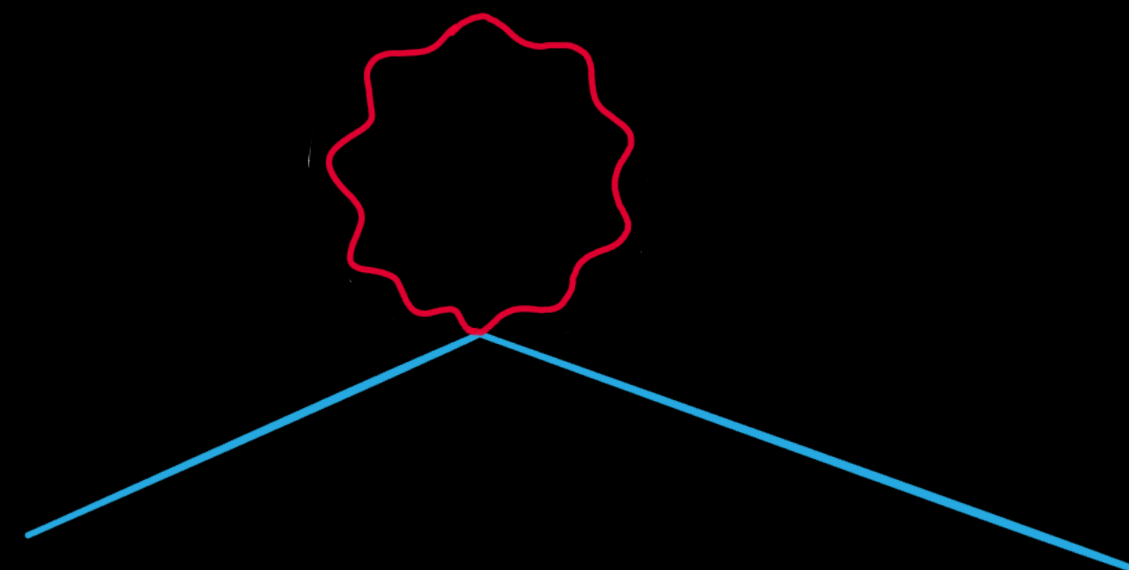
$$\Delta E = \Delta E_C - \Delta E_C + \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

The Naturalness Strategy

What about scalars?



Consider the pion…



Another divergence…

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

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

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

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

The "Hierarchy Problem"

The Higgs is an apparently elementary scalar

Assuming 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*.

(Divergence itself not the problem, etc., just a sign of UV sensitivity)

More ambitious: explain $m_H^2 < 0$, explain EWSB.

Related: Why not $m_H \sim \Lambda \sim M_{Pl}$? Neutrons no longer stabilized in nuclei for $\langle H\rangle \gtrsim 5\langle H\rangle_{SM}$!

[Agrawal, Barr, Donoghue, Seckel '97]

Why is there something, rather than nothing?

The Naturalness Strategy

Param	**UV sensitivity**	**Natural if**	**NP**	**Scale**	**Natural?**
"m_e"	$e^2\Lambda$	Λ ≲ 5 MeV	Positron	511 keV	✓
$m_{\pi\pm}^2$ - $m_{\pi 0}^2$	$\frac{3\alpha}{4\pi}\Lambda^2$	Λ ≲ 850 MeV	Rho	770 MeV	✓
m_{KL}-m_{KS}	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4}\Lambda^2$	Λ ≲ 2 GeV	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2}\Lambda^2 + \ldots$	Λ ≲ 500 GeV	?	?	?

From the “naturalness strategy” to BSM Higgs

At this level, we expect

- New physics below the TeV scale…
- …coupling to the Higgs

Strong motivation for BSM Higgs physics!
But maybe too broad to be useful…

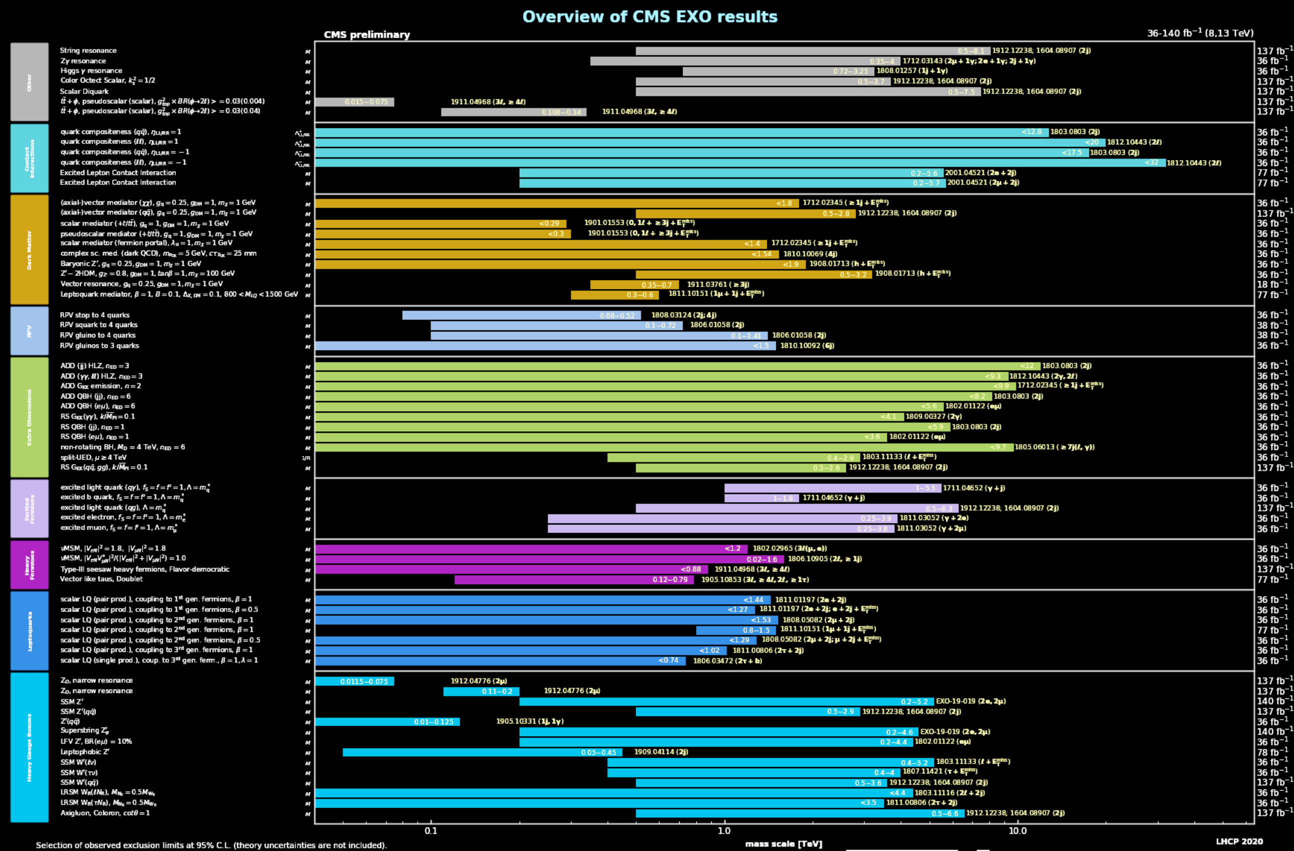
Implementation is up to us

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

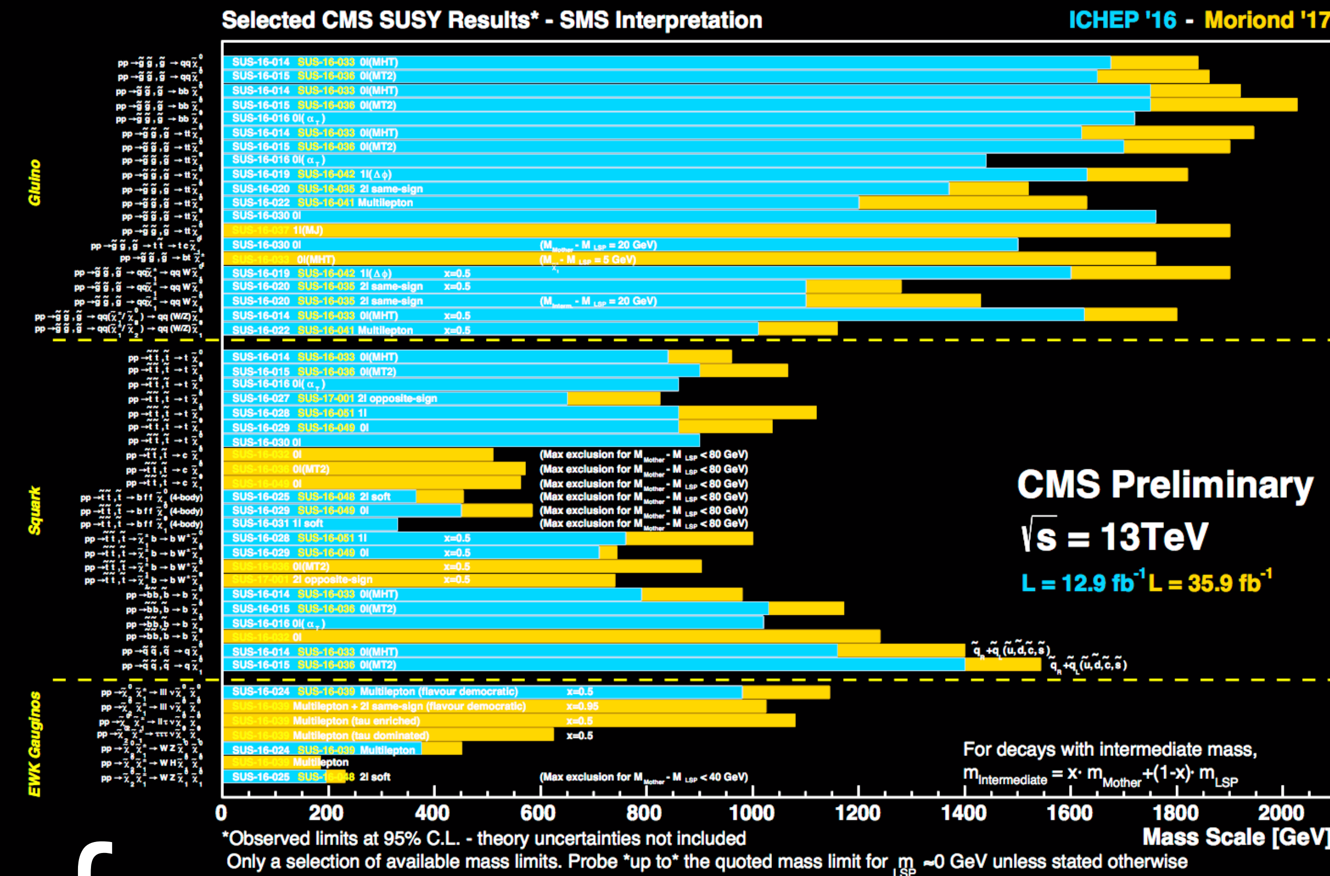
1. The Standard Model coupled to gravity is a generic EFT.
2. The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.
3. Symmetries imply new particles charged under the SM.

In turn, this tells us what kind of "BSM Higgs" to expect.

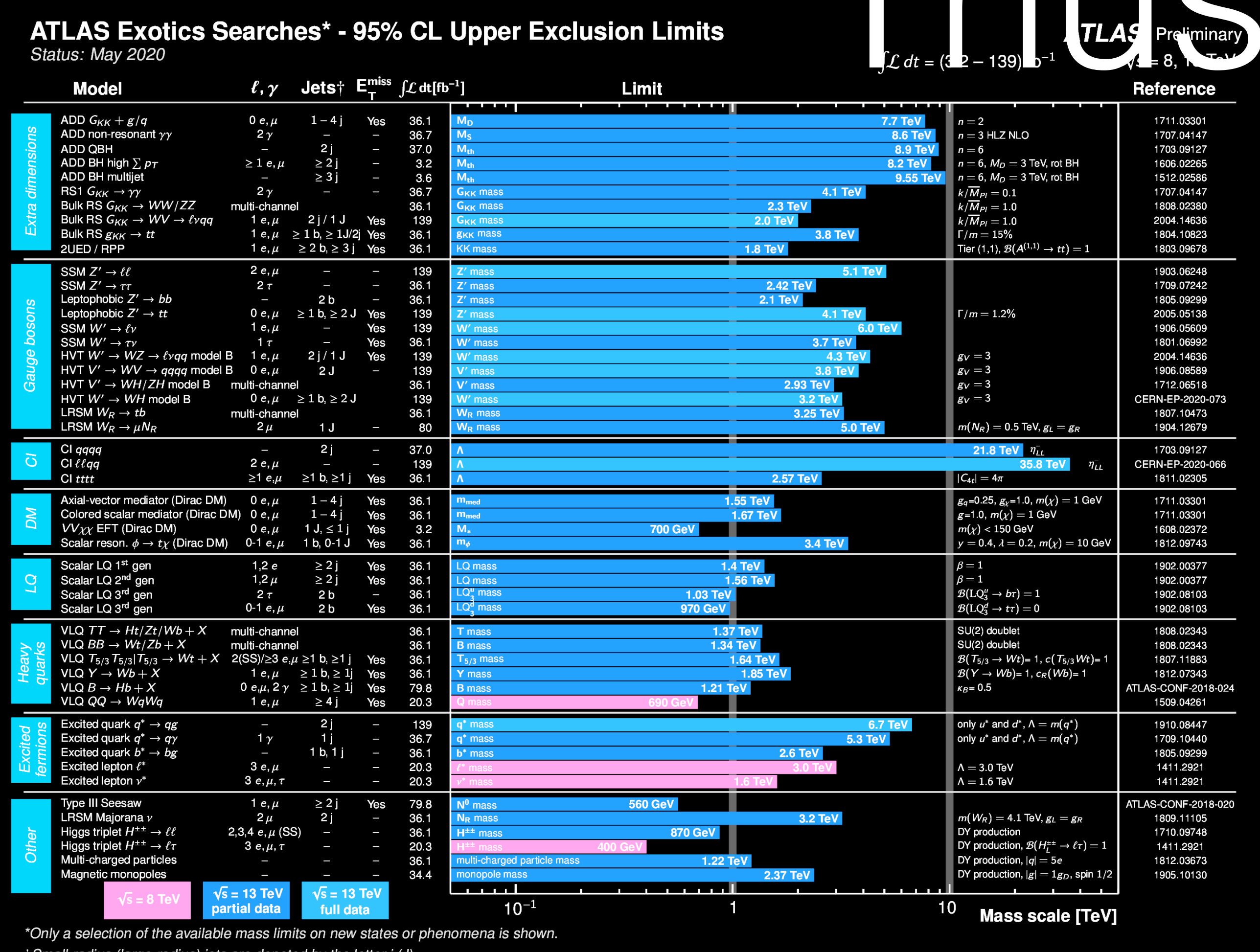
Thus far



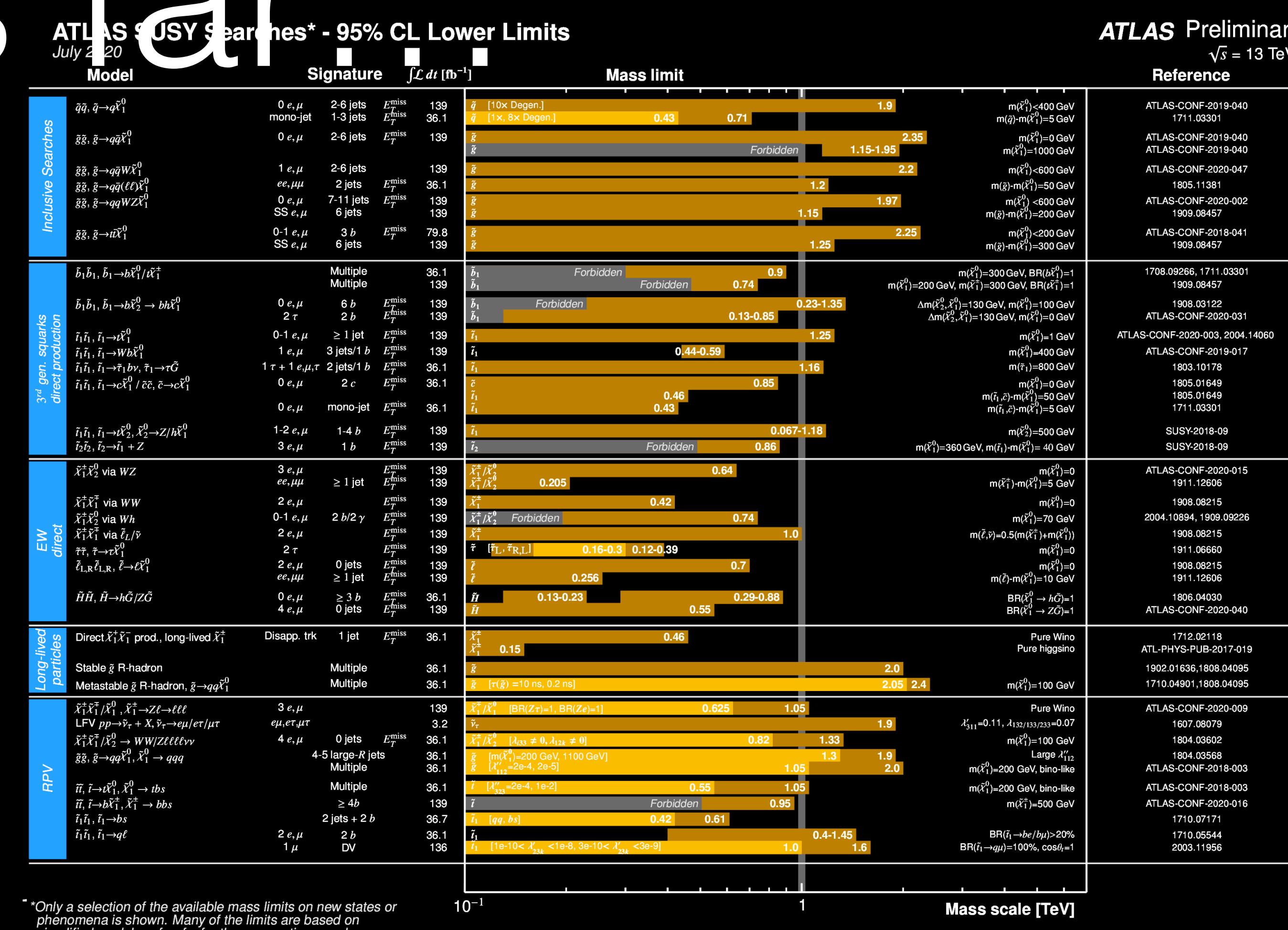
Overview of CMS EXO results
CMS preliminary
36-140 fb⁻¹ (8,13 TeV)
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).
mass scale [TeV]
LHCP 2020



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,
m_Intermediate = x· m_Mother + (1-x)· m_LSP
0 200 400 600 800 1000 1200 1400 1600 1800 2000
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

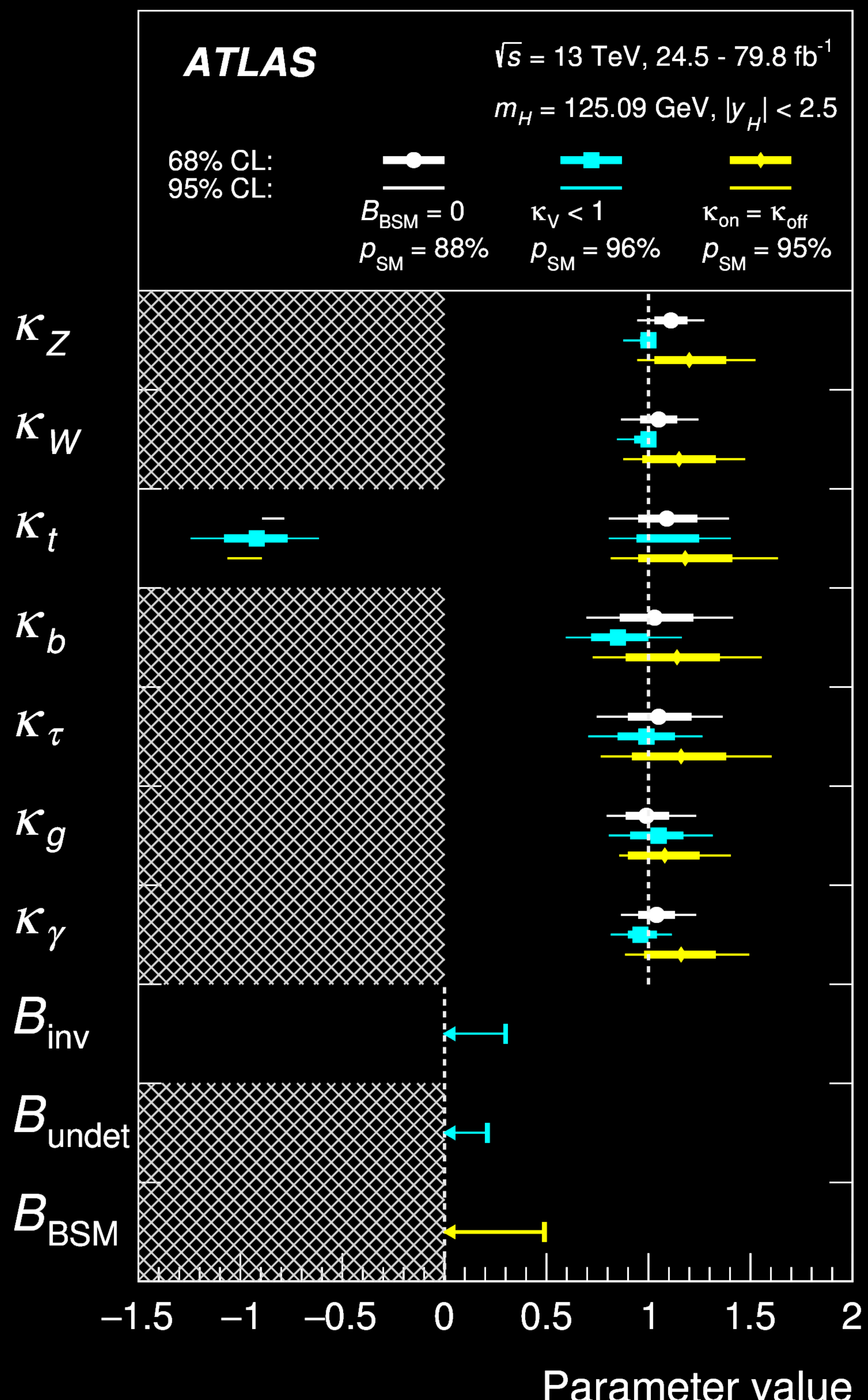


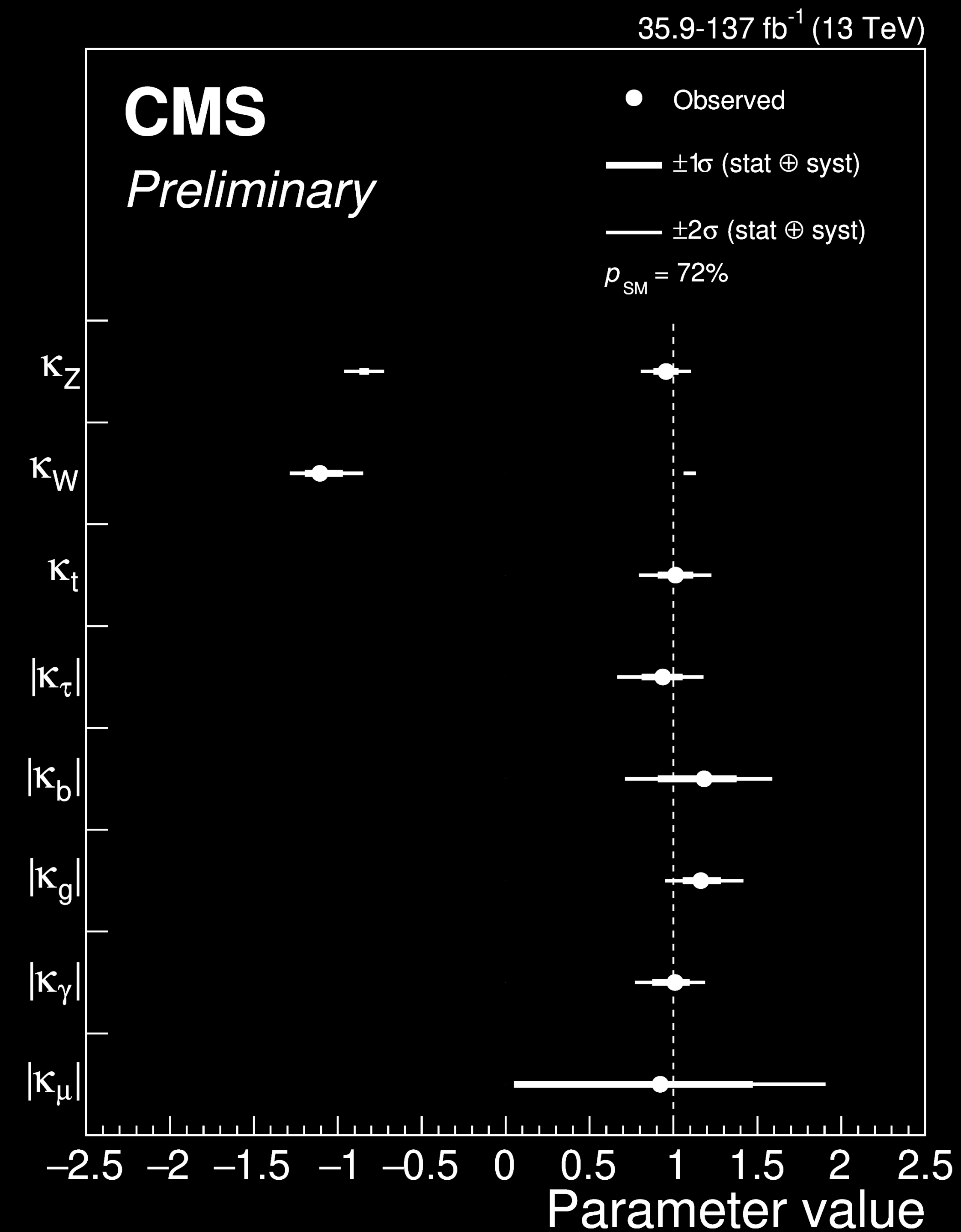
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: May 2020
ATLAS Preliminary
∫L dt = (3.2 – 139) fb⁻¹
√s = 8, 13 TeV
Model
Jets†
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
√s = 8 TeV
√s = 13 TeV partial data
√s = 13 TeV full data
Mass scale [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 2020
ATLAS Preliminary
√s = 13 TeV
Model
Signature
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
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.

Perhaps more to the point…





Rules of thumb still useful; continuing to test them experimentally is an excellent idea!

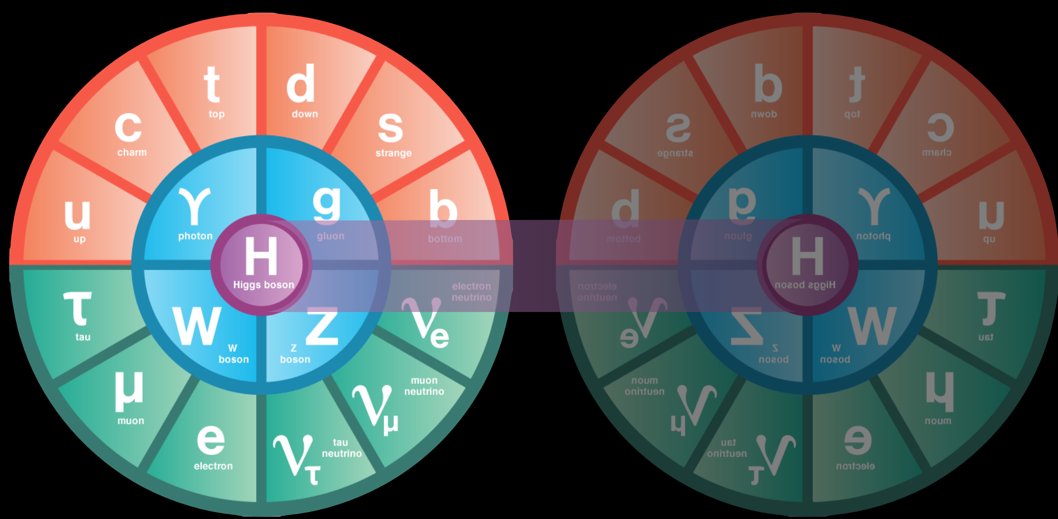
But hard to say much new along these lines; null results invite exploring other avenues, finding new "BSM Higgses"

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.~~

Discrete symmetries



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

Higgs is a pNGB of an accidental SU(4), but spectrum only respects a Z_2

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

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

Still a plethora of new particles, not interacting via SM gauge forces but coupling to Higgs.

Why Not?

Higgs portal maintains equilibrium down to T~GeV

$\Delta N_{eff} >> 1$

Options are

Change the cosmology

Signals in CMB: N_{eff}, $\sum m_\nu$, twin BAO…

- RHN decay
- Saxion decay
- Early ν' decoupling

[Chacko, NC, Fox, Harnik '16; NC, Koren, Trott '16; Chacko, Curtin, Geller, Tsai '18, …]

Change the spectrum

Copious new physics at ~few TeV
Higgs signals @ LHC

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

[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*	Hyperbolic Higgs / Accidental SUSY	Twin Higgs

Mirror Glueballs
Higgs portal observables

Higgs coupling shifts
$\sim$ tuning

When all is said and done, scale of new charged states (c.f. usual continuous symmetry solutions)
[NC, Howe '13; Contino et al. '17]

$$m_*^2 \sim m_{*,\text{cts}}^2 \times \left(\frac{g_*}{g_{SM}}\right)^2$$

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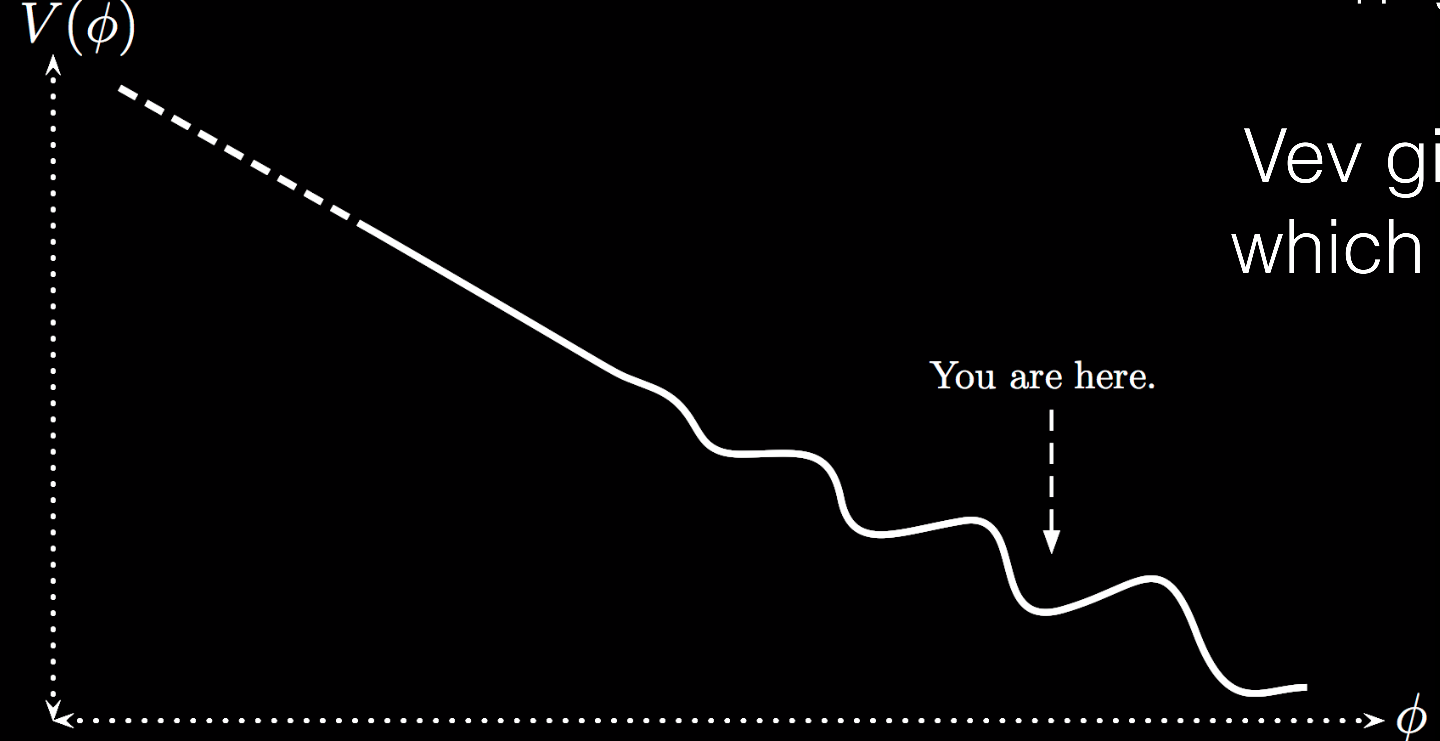
Relaxion

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 contribute to axion potential.

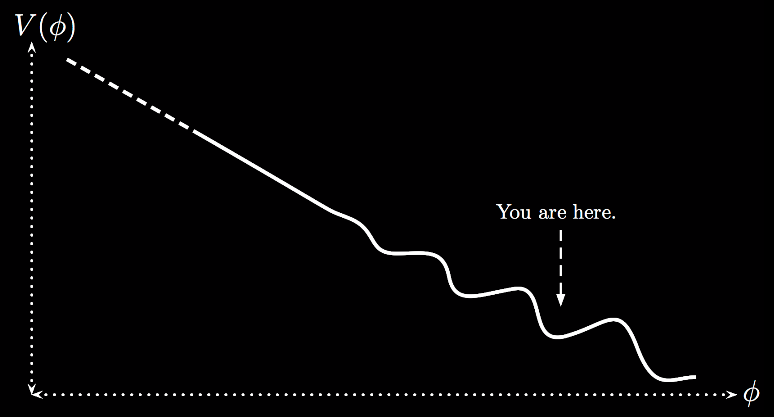
“Relaxion”

[Graham, Kaplan, Rajendran ‘15]

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

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

Why not? Various other subtleties regarding technical naturalness, trans-Planckian field excursions, CC, 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; …]

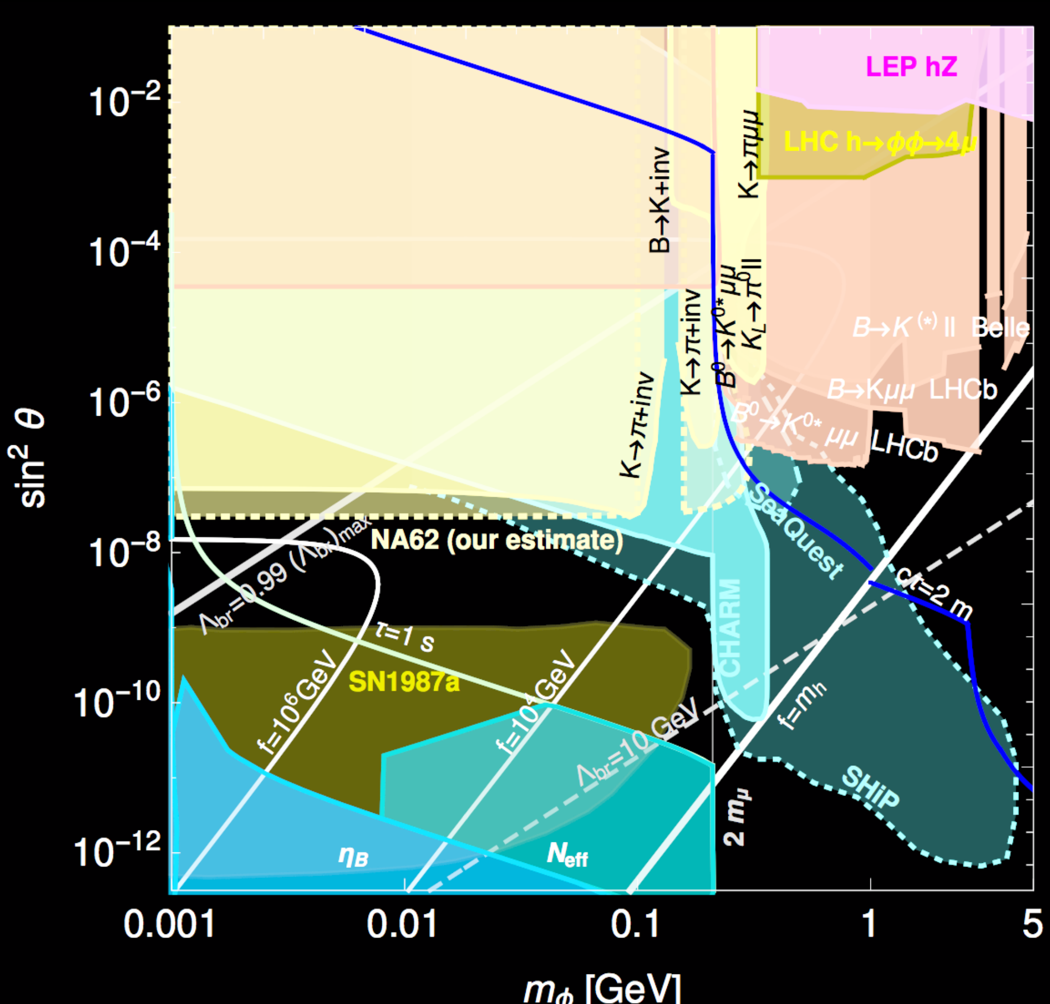
See also: NNaturalness [Arkani-Hamed et al. '16]

New Signals

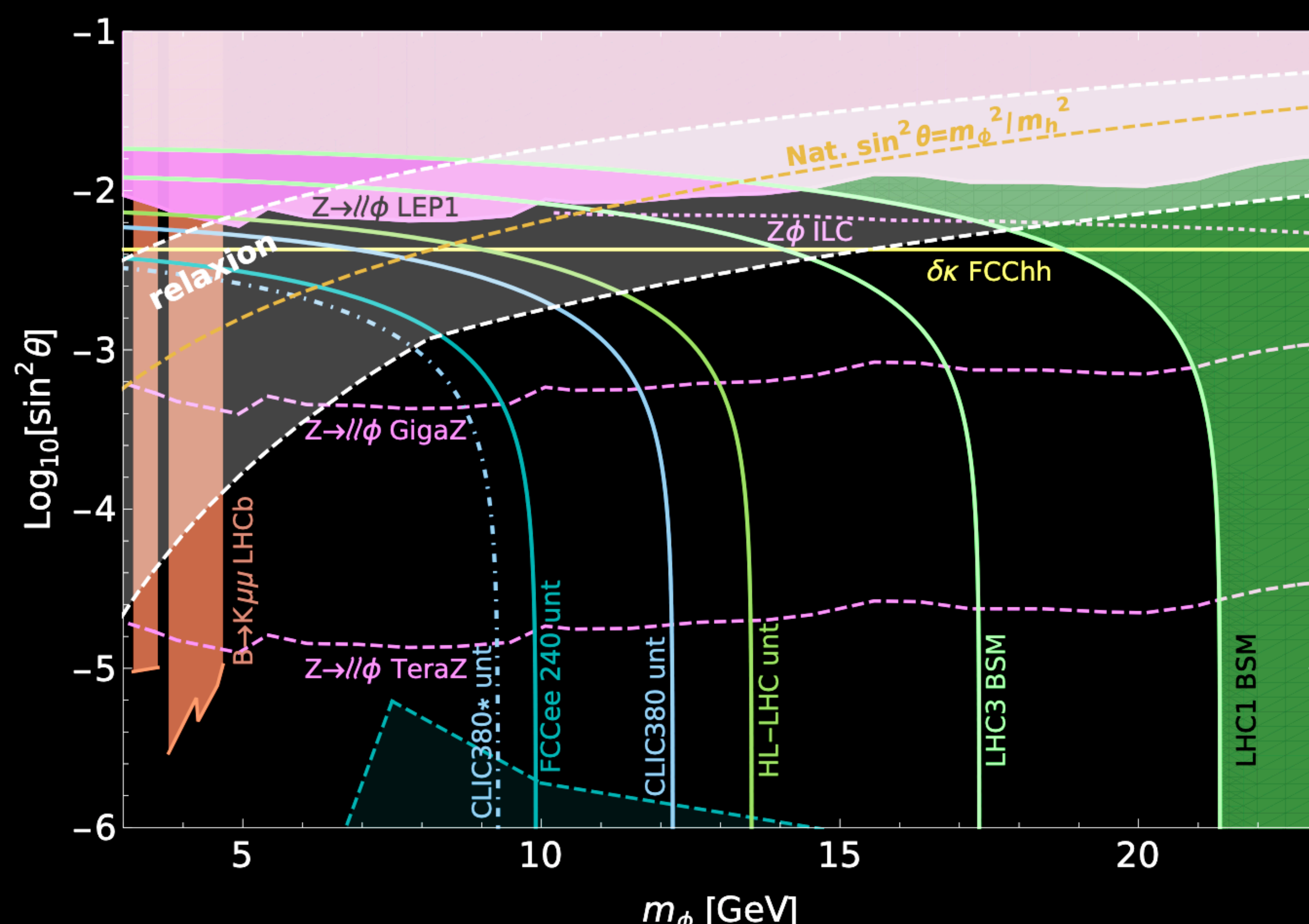
Higgs portals $g\phi|H|^2$ $\Lambda^4(H)\cos(\phi/f)$

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

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



[Fuchs, Matsedonskyi, Savoray, Schlaffer '20]



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

*assuming ⟨ϕ⟩ breaks CP

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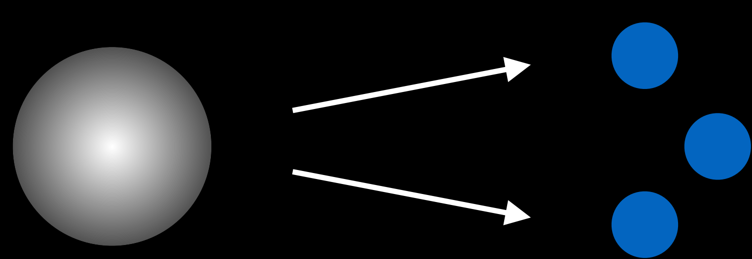
The End of EFT?

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

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

$$qg > \frac{m}{M_{\rm Pl}}$$

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



particles produced = Q/q

Energy conservation: $mQ/q < M$

Then BH satisfies $Z = Q\,M_{Pl}/M < z = q\,M_{Pl}/m$

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

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

The End of EFT?

Electric WGC: [Arkani-Hamed, Motl, Nicolis, Vafa ‘07]	$m \leq (gq) M_{\rm Pl}$
Magnetic WGC: [Arkani-Hamed, Motl, Nicolis, Vafa ‘07]	$\Lambda \lesssim g M_{\rm Pl}$
+Scalar WGC: [Palti ‘17]	$m \leq \sqrt{g^2 q^2 - \mu^2} M_{\rm Pl}$
dS WGC: [Montero, Van Riet, Venken ‘19]	$m^2 \gtrsim gq M_{\rm Pl} H$
Axion WGC: [Arkani-Hamed, Motl, Nicolis, Vafa ‘07]	$f \leq (1/S) M_{\rm Pl}$

New hierarchies from EFT + gravity.

WGC & BSM Higgs

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

$$qg > \frac{m}{M_{\text{Pl}}}$$

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

[Cheung, Remmen '14]: If mass of WGC particle is UV sensitive, then for fixed UV-insensitive parameters, satisfying the WGC would mandate fine-tuning. (Or: would orchestrate correlations among UV contributions)

Application to SM: 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 from EWSB

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

If lightest neutrino is WGC particle, $m_\nu \sim 0.1$ eV, $q \gtrsim 10^{-29}$

For fixed y, q, satisfying WGC places an upper bound on v

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

WGC & BSM Higgs

Things that could go wrong:

- WGC could be satisfied by states outside EFT
- Satisfying WGC could compel the appearance of a new light state that enforces apparent UV correlations (e.g. relaxion)
- Apparently UV-sensitive parameters might control apparently UV-insensitive ones (e.g. emergent gauge fields)

Thing that certainly goes wrong:

- Magnetic WGC implies cutoff of U(1) at $\Lambda \lesssim g M_{Pl}$

WGC & BSM Higgs

First order of business: can m, Λ be raised to the weak scale?

New $U(1)_X$ plus matter acquiring some mass from the Higgs. E.g…

[NC, Garcia Garcia, Koren '19]

	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
L	$\square$	$+1/2$	$+1$
L^c	$\square$	$-1/2$	-1
N	-	0	$+1$
N^c	-	0	-1

$$-\mathcal{L} \supset \left\{ m_L L L^c + m_N N N^c + y H^\dagger L N^c + \tilde{y} H L^c N \right\} + \text{h.c.}$$

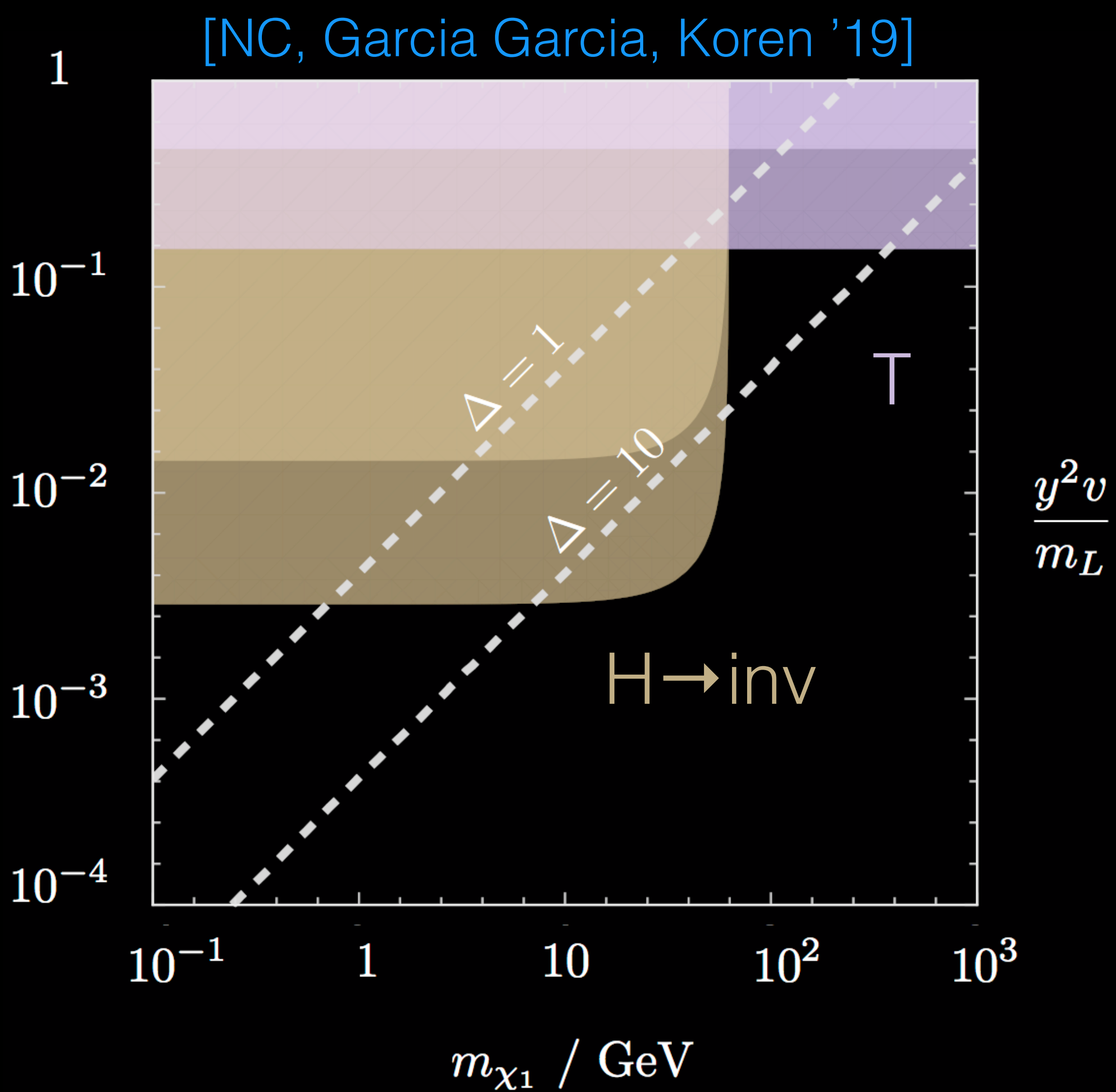
Best option: $m_N < m_L$, lightest mass eigenstate χ_1 is WGC particle

Then for fixed (technically natural) g, m_L, m_N, y,

$$v^2 \lesssim \frac{2}{y^2}\left(m_{\chi_1}^2 + m_{\chi_1}(m_L - m_N) - m_L m_N\right)$$

WGC & BSM Higgs

Still have a notion of sensitivity of the weak scale to parameters involved in the bound



Quantify with e.g.

$$\Delta_x \equiv \left| \frac{\partial \log v^2}{\partial \log x} \right|$$

Here

$$\Delta_{\max} \sim \frac{m_N m_L}{y^2 v^2}$$

Not surprising: WGC particle should get "most of" its mass from EWSB.

Surprisingly predictive: look for new singlet fermions coupled to the Higgs at/below the weak scale.

DM story interesting…

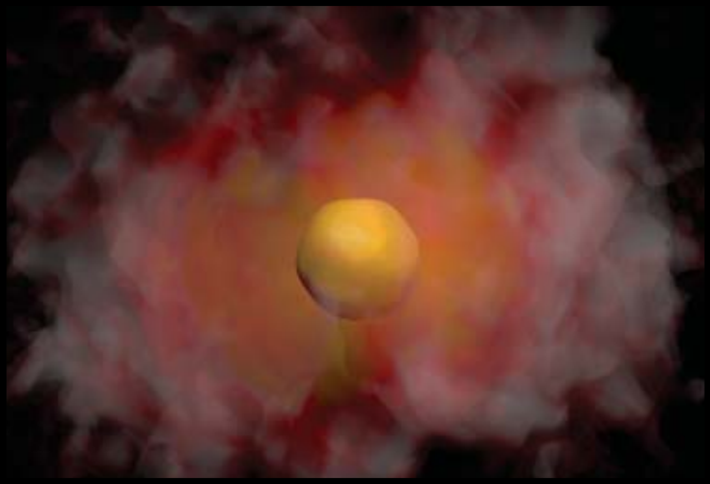
WGC & BSM Higgs

Second order of business: can the magnetic WGC scale be something less severe than the SM cutoff? Only confident that Λ ~ scale associated w/ structure of magnetic monopoles

E.g. t' Hooft-Polyakov monopoles $SU(2)_X \underset{\langle \text{Adj} \rangle}{\rightarrow} U(1)_X$

$$\text{“}\Lambda\text{”} = m_W = g_2 f = 2gf \lesssim 2g M_{\text{Pl}}$$

W's would trivialize bound from vanilla electric WGC, but not e.g. unit charge version (charge ±2 under $U(1)_X$)



Resolution of physics at Λ ~ weak scale implies additional exotic physics coupling directly or indirectly to the Higgs.

Conclusions

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Relaxing these rules of thumb is constructive and leads to new “BSM Higgses” compatible w/ data.

Only beginning to explore the possibilities….

Thank you!