

# Naturalness In Your Face

Particle Physics in the Post-Higgs Era

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How is particle physics doing?

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$$\begin{aligned}
 Z = & \int \mathcal{D}(\text{fields}) \exp \frac{i}{\hbar} \int \sqrt{-g} d^4x \left[ \frac{M_{\text{Pl}}^2}{2} (R - 2\Lambda) \right. \\
 & - \sum_{\substack{i=1,2,3 \\ \text{gauge grps}}} \frac{1}{4g_i^2} F_i F_i + \Theta_i F_i \tilde{F}_i - |DH|^2 - \frac{\lambda}{4} (|H|^2 - v^2)^2 \\
 & \left. \sum_{\substack{i,j=1,2,3 \\ \text{generations}}} + y_{ij}^u \tilde{H} Q_i U_j + y_{ij}^d H Q_i D_j + y_{ij}^e H L_i e_j + y_{ij}^{\nu} \tilde{H} L_i \tilde{H} L_j \right]
 \end{aligned}$$

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- \sum_{\substack{i=1,2,3 \\ \text{gauge grps}}} \frac{1}{4} g_i^2 F_i F_i + \Theta_i F_i \tilde{F}_i - |DH|^2 - \frac{\lambda}{4} (|H|^2 - v^2)^2 \\
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27 parameters to describe our world down to  $10^{-19}$  m!  
 (given initial state  $|\psi_{\text{solarsystem}}^{(t_0)}\rangle$  say)

# Naturalness

It's the 1600s. Why prefer heliocentrism to geocentrism?

“Heliocentrism fit the data better”

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~~"Heliocentrism fit the data better"~~

Ptolemaic theory never got the orbits wrong. Epicycles work great.

$$r = \sum_n r_n \sin n\theta$$

We want theories which are simple.



# Naturalness

It's the 1600s. Why prefer heliocentrism to geocentrism?

We want theories which are simple.

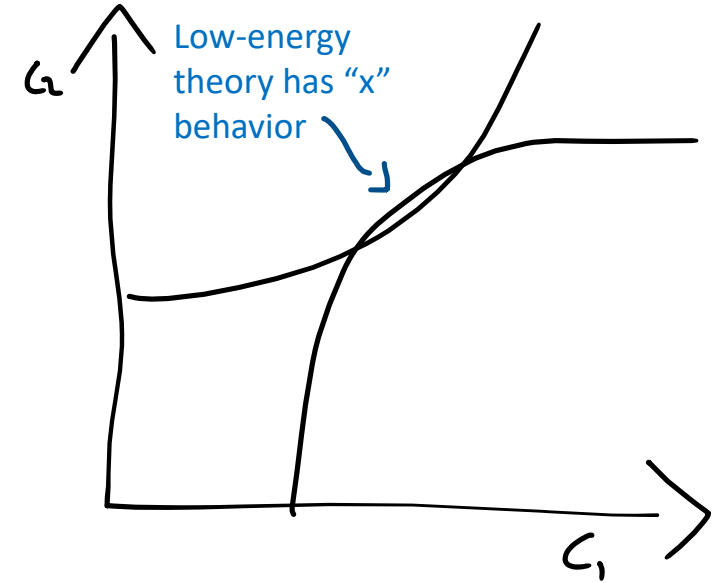
This is a useful guide because theories with many ingredients are not as predictive. And predictivity is the point!

The structure of effective field theory means there will be many models that fit the data. There is a decoupling limit.

See Wells (2020)

# Naturalness and fine-tuning

- Not just some discrete choices in building our theories
- Theories of particle physics come with some parameter space of *inputs* which are required to make physical predictions
  - Fine-tuning is the question of how sensitive some important physical *output* is to exactly where you live in parameter space
  - A theory that must be fine-tuned to produce some feature does not explain that feature!





# So is the Standard Model fine-tuned?

In the SM  $m_H^2, \Lambda_{CC}, y_{ij}, g_i, \theta_{CP} \dots$  are inputs and can't strictly ask about their fine-tuning!

- There is a problem *in the context of a deeper theory* that predicts these parameters
- Given some UV theory, does the familiar physics of the SM generically arise in the IR?
- No reason to worry if  $m_H^2$  will *never* find an explanation
- But this is a *huge* assumption!

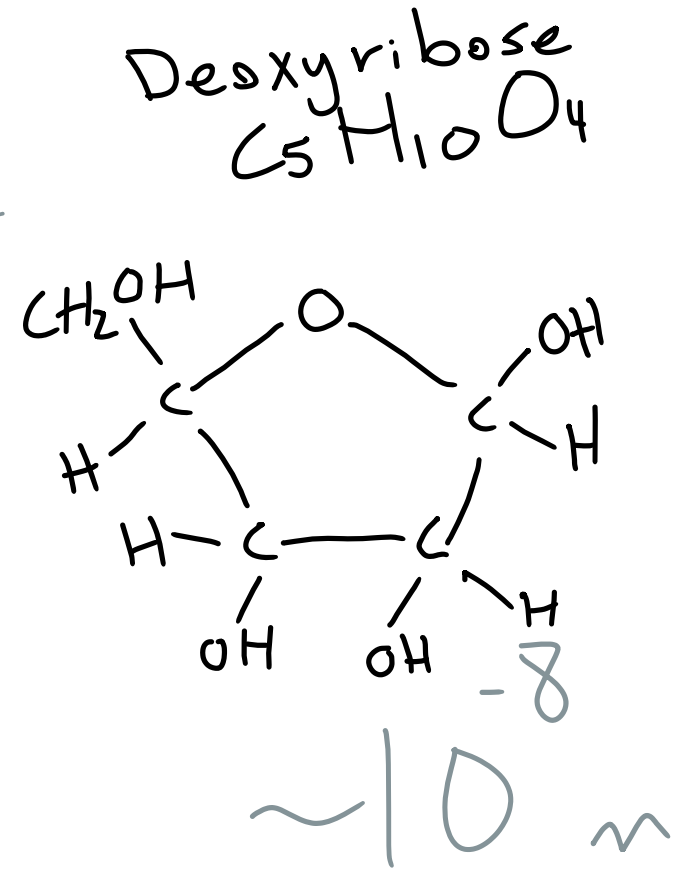
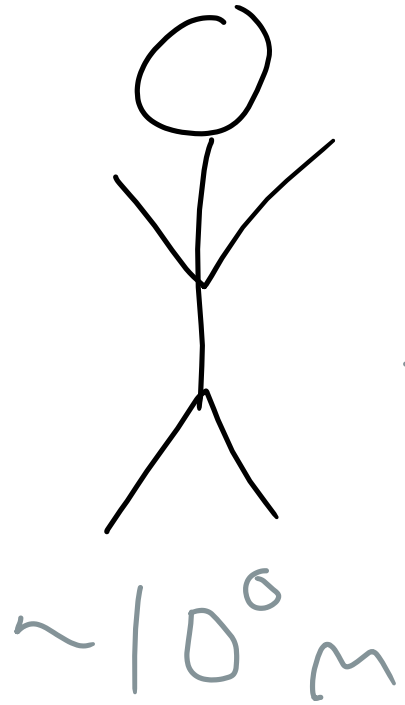
~~Where is particle physics?~~

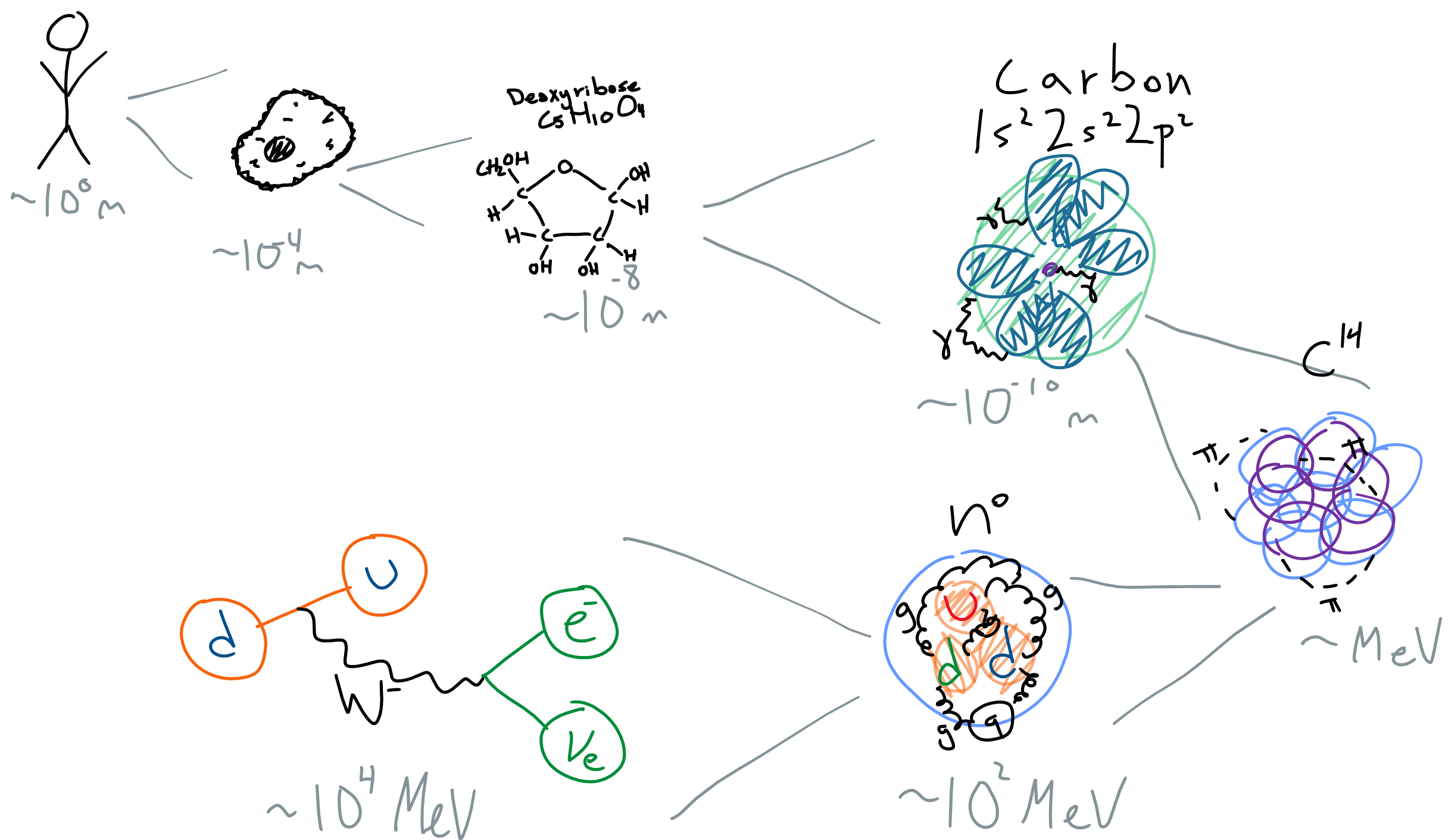
Where is reductionism?

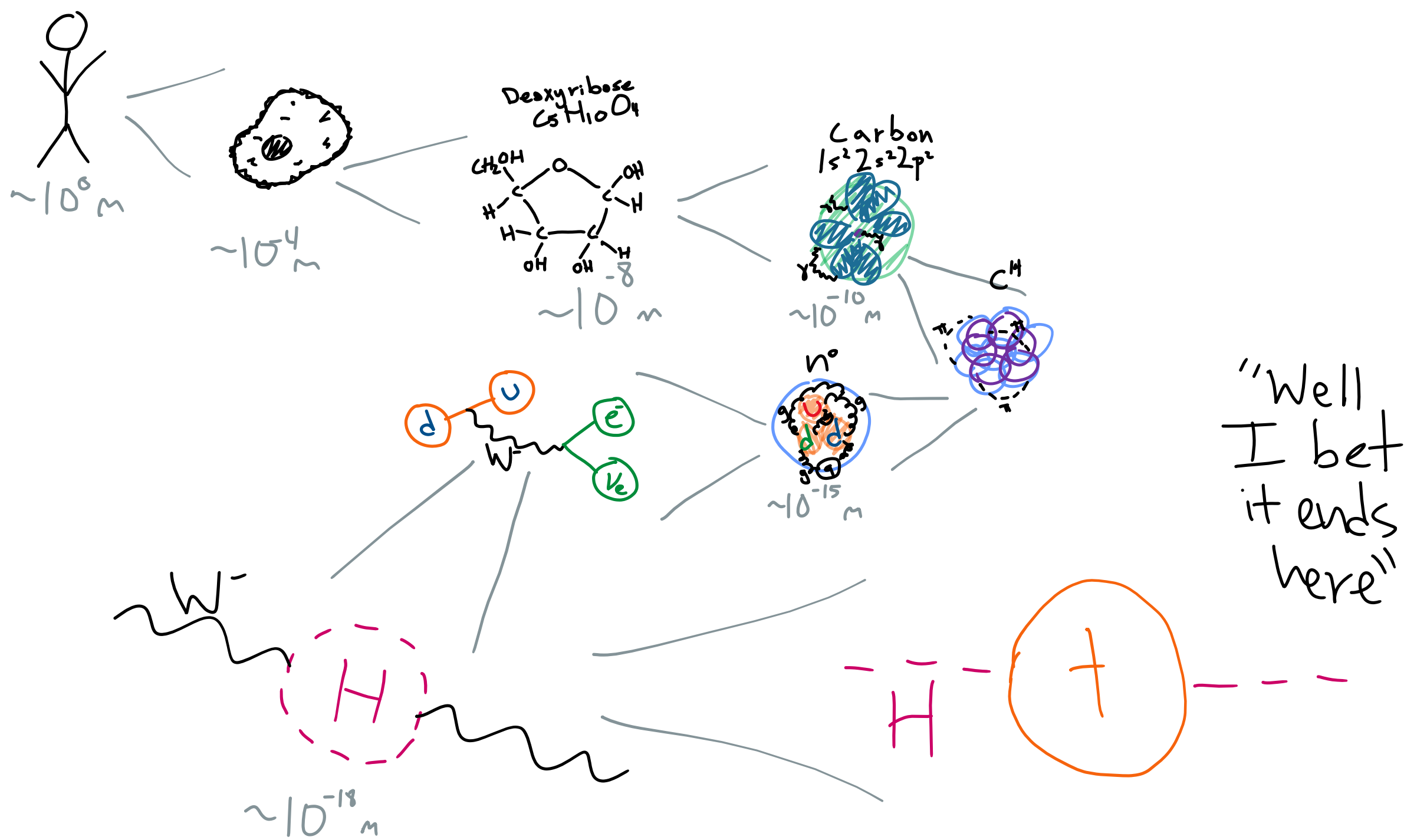
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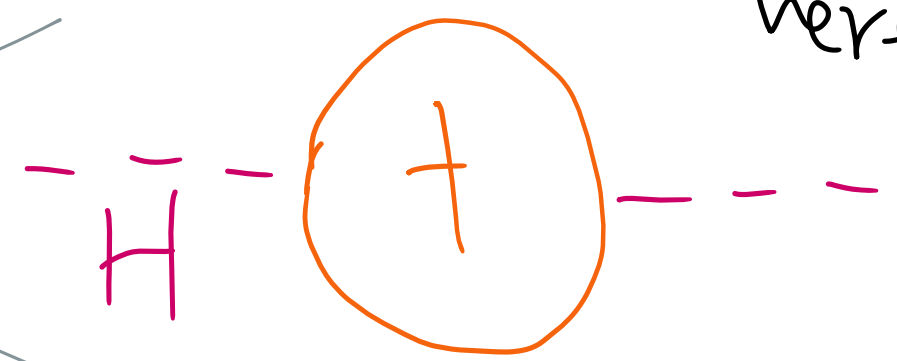
But let me pull back further a moment







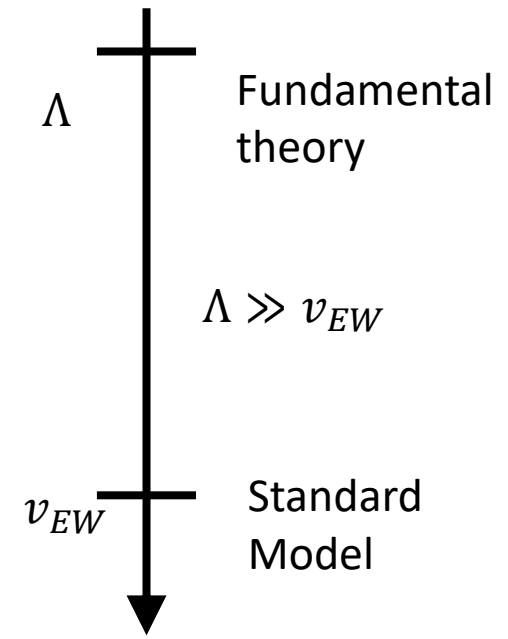
"Well  
I bet  
it ends  
here"



# And there must be more out there!

- Dark matter, neutrino masses, baryogenesis, inflation, ...
- Flavor hierarchies, strong CP, quantum gravity, grand unification

In our best UV theories, the Higgs arises out of some larger structure.  
 $m_H^2$  is an *output*.



# The Higgs as e.g. a component of a UV multiplet

# Toy GUT with Higgs embedded

$$\mathcal{L} \supset M^2 \Phi^\dagger \Phi \text{ with } \Phi = \begin{pmatrix} H \\ \varphi \end{pmatrix}$$

# Spontaneous breaking of the symmetry splits the multiplets

$$\mathcal{L} \supset M^2 \varphi^\dagger \varphi + (M^2 + \lambda v_{\text{GUT}}^2) H^\dagger H$$

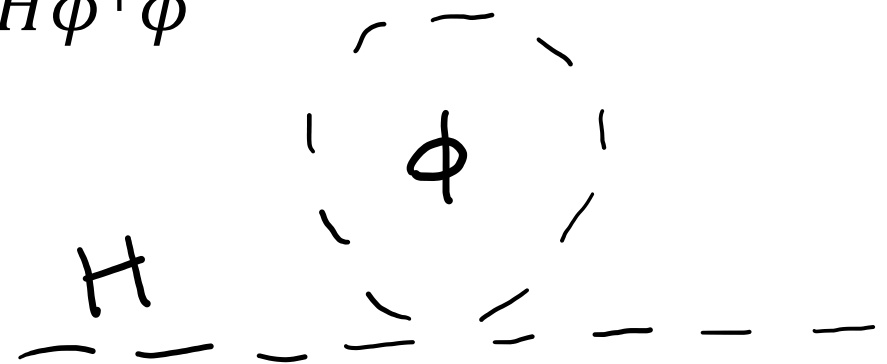
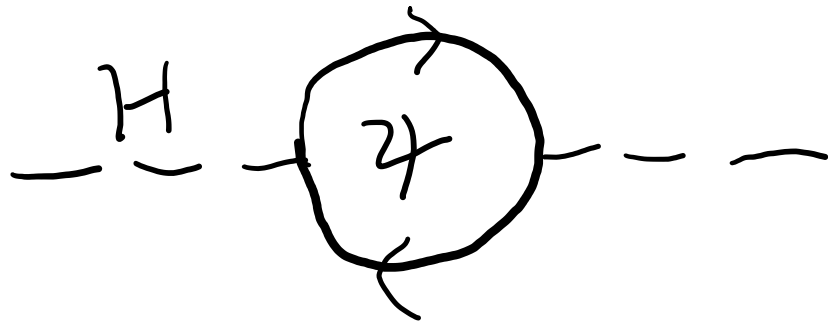
To get  $H$  mass  $\sim v_{EW}^2$  while  $\varphi$  mass  $\sim v_{GUT}^2$  requires

[illegible]

# In fact the problem is worse... and more general

The low-energy value of the Higgs mass is jostled about by *any* degrees of freedom which talk to the Higgs and contribute finite corrections

$$\mathcal{L} \supset y H \tilde{\psi} \psi + c H^\dagger H \phi^\dagger \phi$$



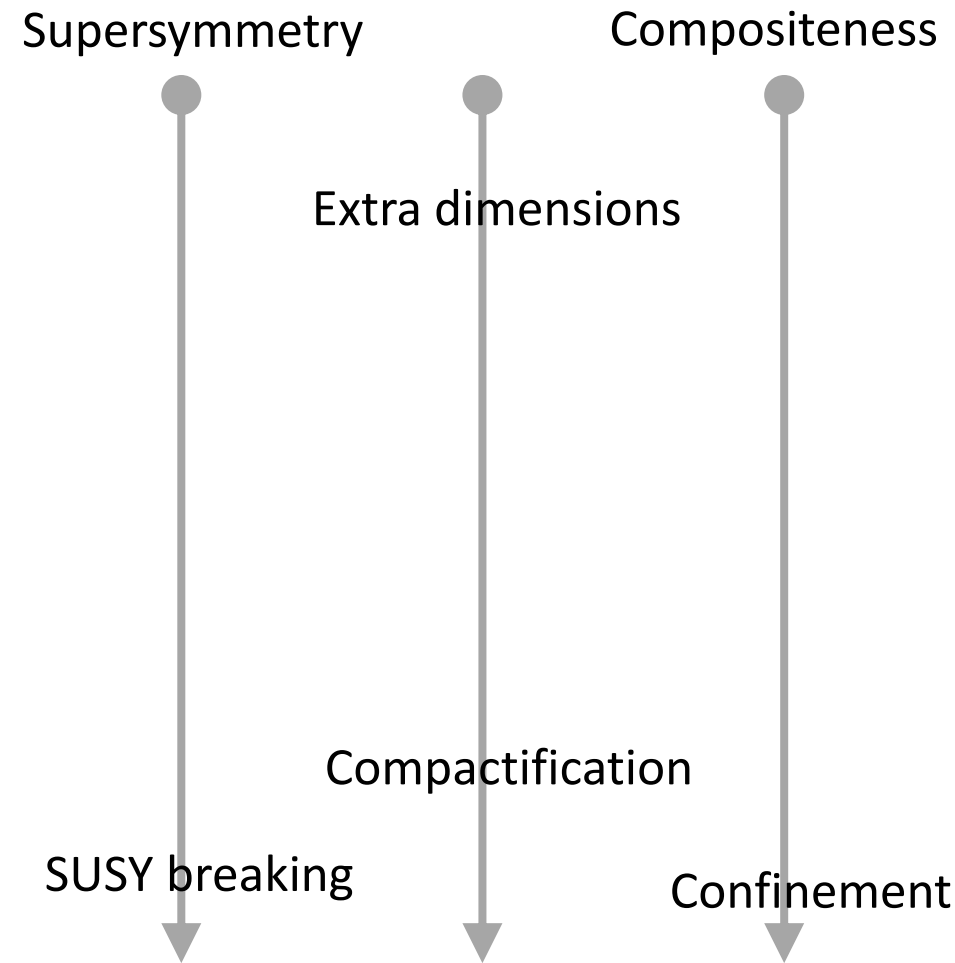
$$\Rightarrow m_H^2 \sim \frac{1}{16\pi^2} (-y^2 m_\psi^2 + c m_\phi^2)$$

The Higgs mass is not protected by a global symmetry, so our infrared understanding of technical naturalness tells us the problem will be general.



# Solving the Hierarchy Problem

- Familiar solutions introduce some new structure in the UV to control the form of corrections to the Higgs mass
- But that isn't present in the SM, so must be broken to give a nonzero Higgs mass



# The 'Hierarchy' Problem

- The success of the LHC has turned naturalness into a sharp empirical problem: Where is the new physics that protects the Higgs mass?

Supersymmetry

Compositeness

Extra  
dimensions

Superpartners

Kaluza-Klein  
Modes

Higher-spin  
Excitations

ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits  
Status: July 2022

ATLAS Preliminary  
 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$   
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_{\text{miss}}^{\text{T}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
<b>Extra dimensions</b>						
ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	$M_0$	2102.10874
ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$	1707.04147
ADD OBH	-	2 j	-	139	$M_{\text{BH}}$	1910.08447
ADD BH multijet	-	-	$\geq 3 j$	3.6	$M_{\text{BH}}$	1512.02596
RST $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	139	$G_{KK} \text{ mass}$	2102.13405
Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK} \text{ mass}$	1808.02380
Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q\bar{q}$	$1 e, \mu$	$2 j / 1 j$	Yes	139	$G_{KK} \text{ mass}$	2004.14636
Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1 b, \geq 1 j / 2 j$	Yes	36.1	$G_{KK} \text{ mass}$	1804.10823
2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	$RK \text{ mass}$	1803.09678
<b>Gauge bosons</b>						
SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	$Z' \text{ mass}$	1903.06248
SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	36.1	$Z' \text{ mass}$	1709.07242
Leptophobic $Z' \rightarrow b\bar{b}$	-	$2 b$	-	36.1	$Z' \text{ mass}$	1805.06299
Leptophobic $Z' \rightarrow t\bar{t}$	$0 e, \mu$	$\geq 1 b, \geq 2 j$	Yes	139	$Z' \text{ mass}$	2005.05138
SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	$W' \text{ mass}$	1906.05609
SSM $W' \rightarrow \tau\nu$	$1 \tau$	-	Yes	139	$W' \text{ mass}$	ATLAS-CONF-2021-025
SSM $W' \rightarrow b\bar{b}$	-	$\geq 1 b, \geq 1 j$	-	139	$W' \text{ mass}$	ATLAS-CONF-2021-043
HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B	$1 e, \mu$	$2 j / 1 j$	Yes	139	$W' \text{ mass}$	2004.14636
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	$W' \text{ mass}$	ATLAS-CONF-2022-005
HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$ model B	$1 e, \mu$	$1-2 b, 1-0 j$	Yes	139	$W' \text{ mass}$	2207.00230
HVT $Z' \rightarrow ZH \rightarrow \ell\ell\nu\bar{\nu} b\bar{b}$ model B	$0, 2 e, \mu$	$1-2 b, 1-0 j$	Yes	139	$Z' \text{ mass}$	2207.00230
LRSM $W_R \rightarrow \mu N_R$	$2 \mu$	$1 j$	-	80	$W_R \text{ mass}$	1904.12679
<b>CI</b>						
CI $q\bar{q}q\bar{q}$	-	2 j	-	37.0	$A$	1703.09127
CI $\ell\ell q\bar{q}$	$2 e, \mu$	-	-	139	$A$	2006.12946
CI $e\bar{e}b\bar{b}$	$2 e$	$1 b$	-	139	$A$	2105.13847
CI $\mu\bar{\mu}b\bar{b}$	$2 \mu$	$1 b$	-	139	$A$	2105.13847
CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$A$	1811.02305
<b>DM</b>						
Axial-vector med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	$\rho_{\text{DM}}$	2102.10874
Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	$\rho_{\text{DM}}$	2102.10874
Vector med. $Z'$ -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	$\rho_{\text{DM}}$	2108.13391
Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	$\rho_{\text{DM}}$	ATLAS-CONF-2021-036
<b>LQ</b>						
Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	Yes	139	$LQ \text{ mass}$	$\beta = 1$
Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	Yes	139	$LQ \text{ mass}$	$\beta = 1$
Scalar LQ 3 <sup>rd</sup> gen	$1 \tau$	$\geq 2 b$	Yes	139	$LQ \text{ mass}$	$\beta(LQ \rightarrow b\tau) = 1$
Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu$	$\geq 1 j, \geq 2 b$	Yes	139	$LQ \text{ mass}$	$\beta(LQ \rightarrow \tau\tau) = 1$
Scalar LQ 3 <sup>rd</sup> gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 b$	-	Yes	139	$LQ \text{ mass}$	$\beta(LQ \rightarrow \tau\tau) = 1$
Scalar LQ 3 <sup>rd</sup> gen	$0 e, \mu, \geq 1 \tau, 0-2 j, 2 b$	-	Yes	139	$LQ \text{ mass}$	$\beta(LQ \rightarrow b\tau) = 1$
Vector LQ 3 <sup>rd</sup> gen	$1 \tau$	$2 b$	Yes	139	$LQ \text{ mass}$	$\beta(LQ \rightarrow b\tau) = 1, Y, M \text{ coupl.}$
<b>Vector-like fermions</b>						
VLO $TT \rightarrow Zt + X$	$2e, 2\mu, 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	$T \text{ mass}$	ATLAS-CONF-2021-024
VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	$B \text{ mass}$	1908.02343
VLO $T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3 e, \mu, \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3} \text{ mass}$	$\beta(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	1807.11883
VLO $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	$T \text{ mass}$	ATLAS-CONF-2021-040
VLO $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 j$	Yes	36.1	$Y \text{ mass}$	1812.07343
VLO $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1 j, \geq 1 j$	-	139	$B \text{ mass}$	ATLAS-CONF-2021-018
VLL $\tau^+ \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	$\tau^+ \text{ mass}$	ATLAS-CONF-2022-044
<b>Excited fermions</b>						
Excited quark $q^* \rightarrow qg$	-	2 j	-	139	$q^* \text{ mass}$	1910.08447
Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	1 j	-	36.7	$q^* \text{ mass}$	1709.10440
Excited quark $q^* \rightarrow b\bar{g}$	$1 b, 1 j$	-	-	139	$q^* \text{ mass}$	1910.0447
Excited lepton $\ell^* \rightarrow \ell g$	$3 e, \mu$	-	-	20.3	$\ell^* \text{ mass}$	1411.2921
Excited lepton $\ell^* \rightarrow \ell\gamma$	$3 e, \mu, \tau$	-	-	20.3	$\ell^* \text{ mass}$	1411.2921
Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	$N^0 \text{ mass}$	2202.02039

# Where do we go from here?

- SUSY is right around the corner
  - Continued, robust experimental program important
- Hide LHC signatures with additional one-loop protection
  - Great idea, can only get you so far
- Cosmological dynamical evolution to 'relax' the Higgs mass
  - Really intriguing, needs better understanding
- Past Wilsonian effective field theory?
  - UV/IR mixing well-motivated

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- ‘Swampland’ of EFTs [e.g. Cheung & Remmen '14; Lust & Palti '17; Ibanez, Martin-Lozano, Valenzuela '17; Craig, Garcia Garcia, SK '18, '19]
- More direct UV/IR? [e.g. Dienes '94-; Minwalla, van Raamsdonk, Seiberg '00; Craig & SK '19]

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# Conclusion

- We want theories that explain infrared physics simply
- There's more out there to be discovered, and some deeper theory should predict the Higgs mass
- All known such theories predict lots of weak scale particles
- We haven't seen them! Something is wrong.
- We need further clever ideas.

The Hierarchy Problem: From the  
Fundamentals to the Frontiers  
2009.11870  
APS 2022 Sakurai Dissertation Award

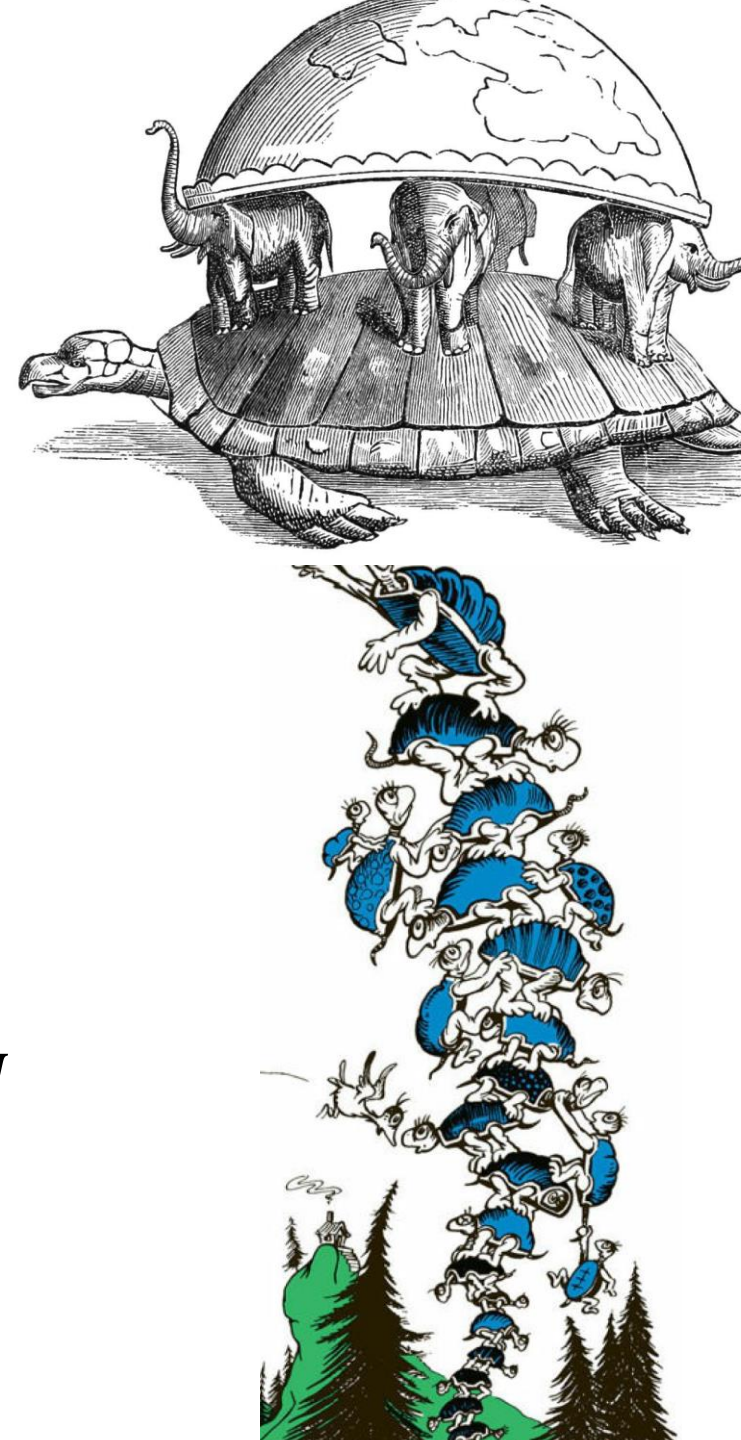
“So what, it’s turtles all the way down?”

No! Reductionism ends with quantum gravity when distances themselves are dynamical.

Gravity is different because the far UV is controlled by infrared physics

Large masses  $M$  can have low-scale effects  $m \sim M_{pl}^2/M$

How will this UV/IR mixing affect particle physics?





# Is QED natural?

- On general grounds, elementary particle masses  $m_i \in [0, M_{pl}]$
- So why are  $m_e, m_p \ll M_{pl}$ ?
- In the context of QED, these are just inputs.

# Is $\text{QED} \subset \text{SM}$ natural?

- $m_p$  now explained by  $\alpha_3$  and QCD confinement
- $m_e$  explained by small Yukawa coupling  $y_e$
- In both cases, small change to input gives small change to output

# A fine-tuned UV completion of QED

- In the SM, the masses of QED arise from a chiral theory.
- A vector-like UV completion does not explain them.

## $SU(2) \rightarrow U(1)?$

- A vector-like theory means we can write a mass in the UV
$$\mathcal{L} = M\bar{\Psi}\Psi + y\bar{\Psi}\Sigma\Psi$$
- If  $\Sigma$  gets a vev  $\Lambda$ , and we want a light electron,  $\Psi = \begin{pmatrix} e \\ \bar{e} \end{pmatrix}$ , must tune  $M$  against  $y\Lambda$