Naturalness In Your Face

Particle Physics in the Post-Higgs Era

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How is particle physics doing?

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$$Z = \int D(\text{fields}) \exp \frac{i}{\hbar} \int \sqrt{-g}\, d^4x \Big[\frac{M_{pl}^2}{2}(R - 2\Lambda)$$

$$- \sum_{\substack{i=1,2,3 \\ \text{gauge grps}}} \frac{1}{4g_i^2} F_i F_i + \theta_i F_i \tilde{F}_i - |DH|^2 - \frac{\lambda}{4}(|H|^2 - v^2)^2$$

$$\sum_{\substack{i,j=1,2,3 \\ \text{generations}}} + y_{ij}^u \tilde{H} Q_i u_j + y_{ij}^d H Q_i d_j + y_{ij}^e H L_i e_j + y_{ij}^\nu \tilde{H} L_i \tilde{H} L_j \Big]$$

How is particle physics doing?

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$$\left. \sum_{\substack{i,j=1,2,3 \\ \text{generations}}} + y_{ij}^u \tilde{H} Q_i u_j + y_{ij}^d H Q_i d_j + y_{ij}^e H L_i e_j + y_{ij}^\nu \tilde{H} L_i \tilde{H} L_j \right]$$

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"

Naturalness

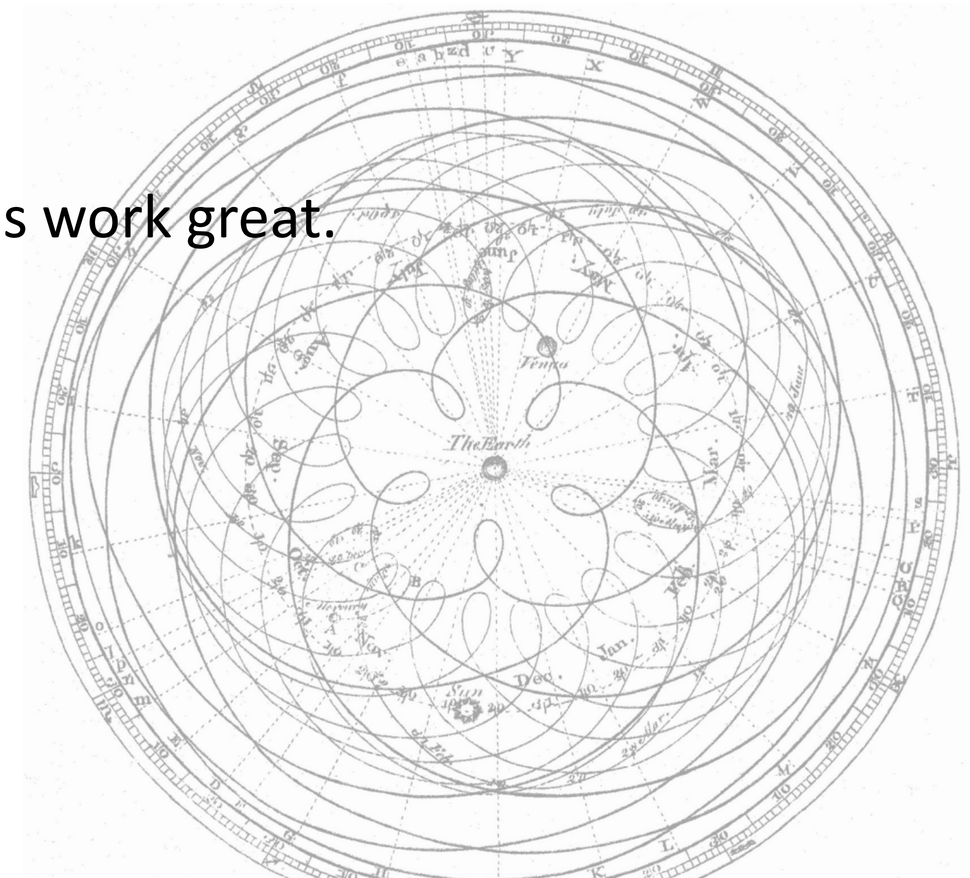
It’s the 1600s. Why prefer heliocentrism to geocentrism?

~~“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.



Ferguson in EB 1st Edition (1771)

Naturalness

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

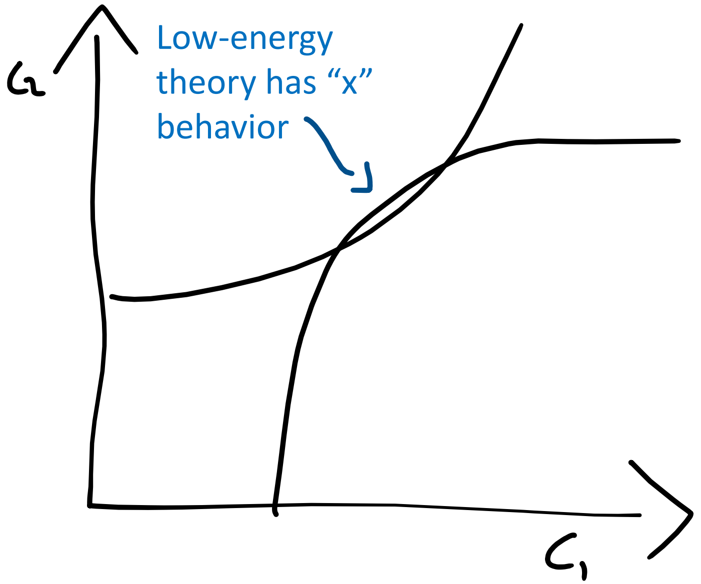
We want theories which are simple.

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 $m_H^2, \Lambda_{CC}, y_{ij}, g_i, \theta_{CP}$ … 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?

$$Z = \int \mathcal{D}(\text{fields}) \exp \frac{i}{\hbar} \int \sqrt{-g}\, d^4x \Bigg[\frac{M_{pl}^2}{2} (R - 2\Lambda) - \sum_{\substack{i=1,2,3 \\ \text{gauge grps}}} \frac{1}{4 g_i^2} F_i F_i + \theta_i F_i \tilde{F}_i - |DH|^2 - \frac{\lambda}{4} \left(|H|^2 - v^2 \right)^2$$

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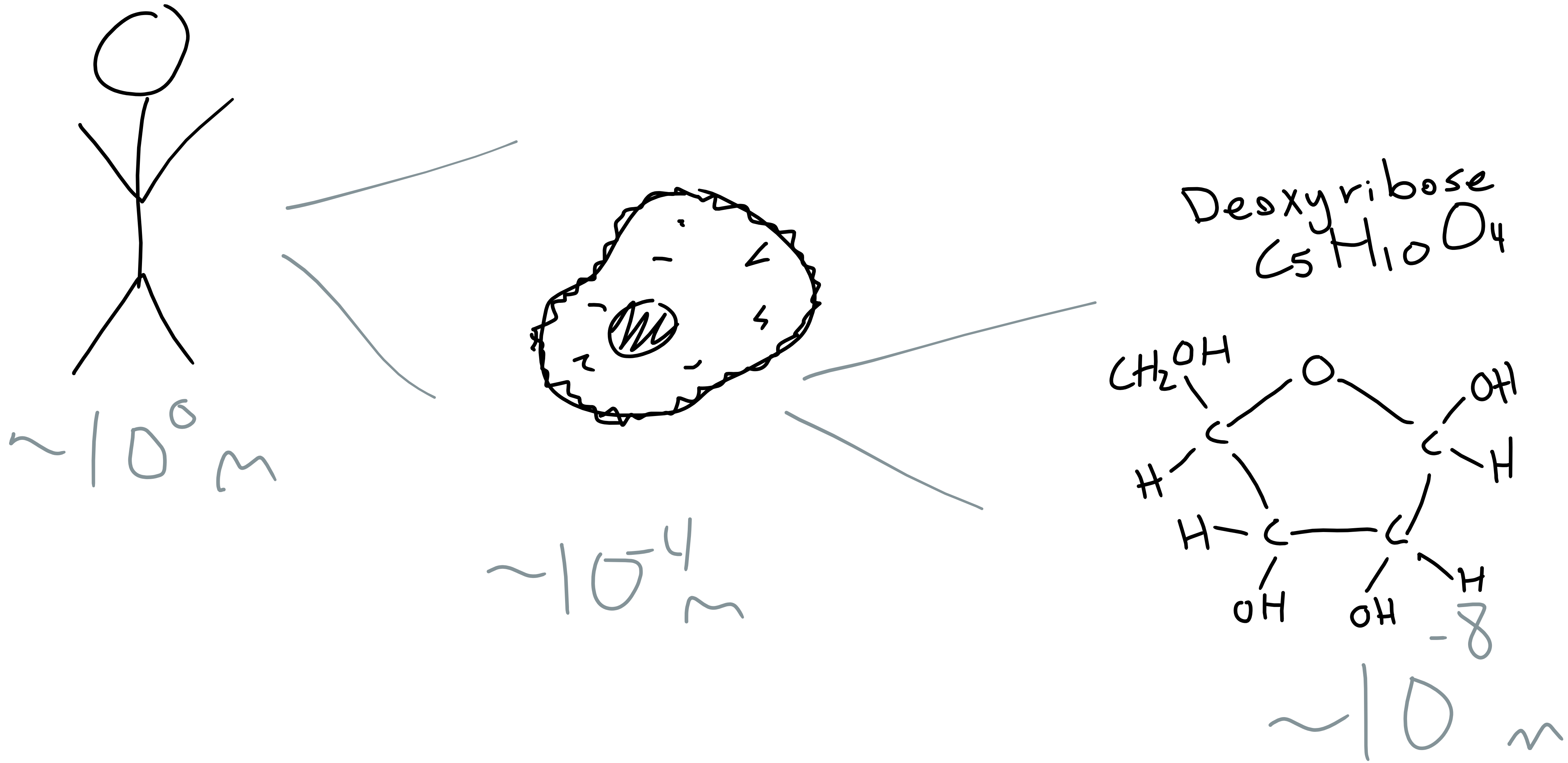
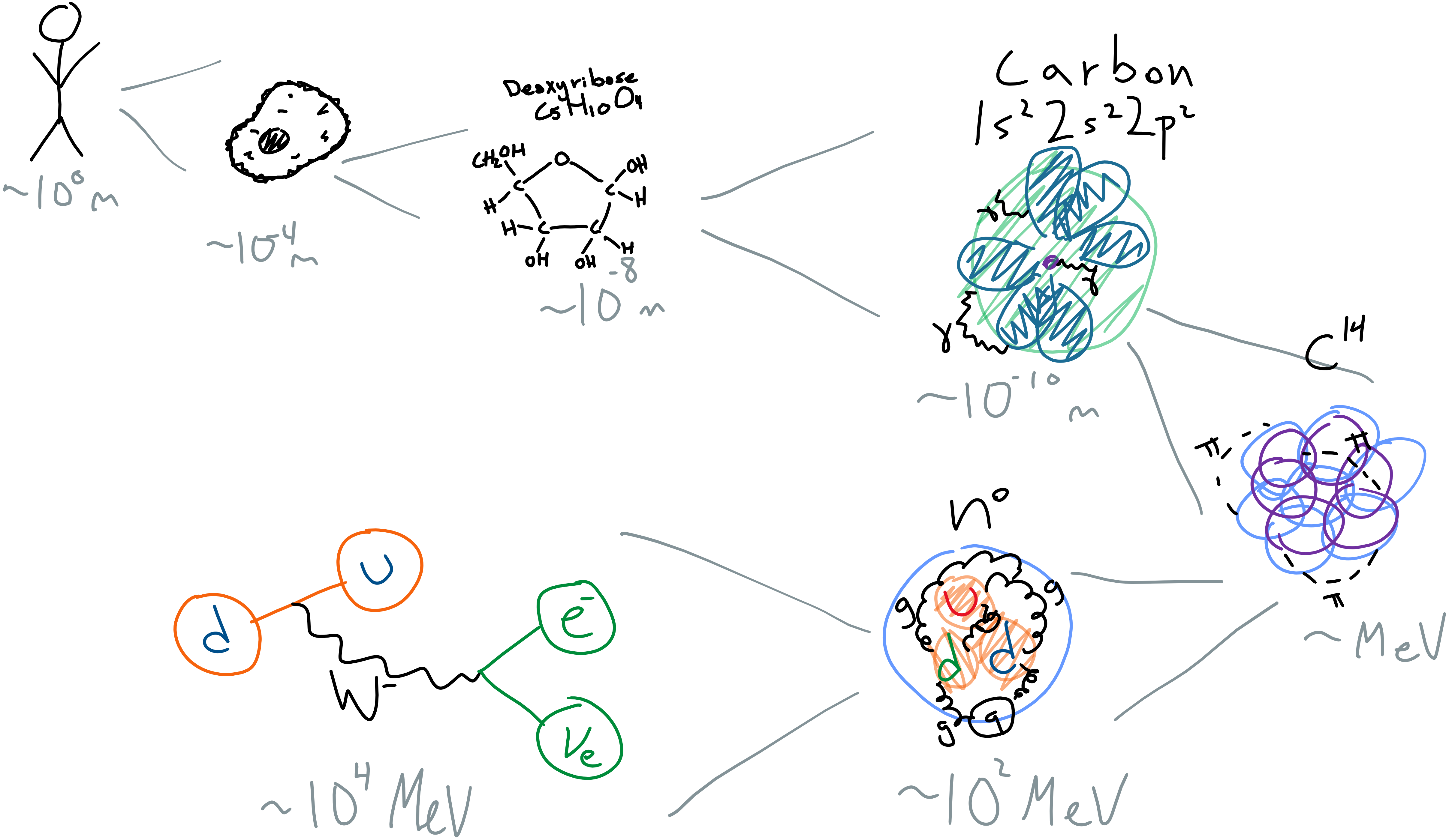
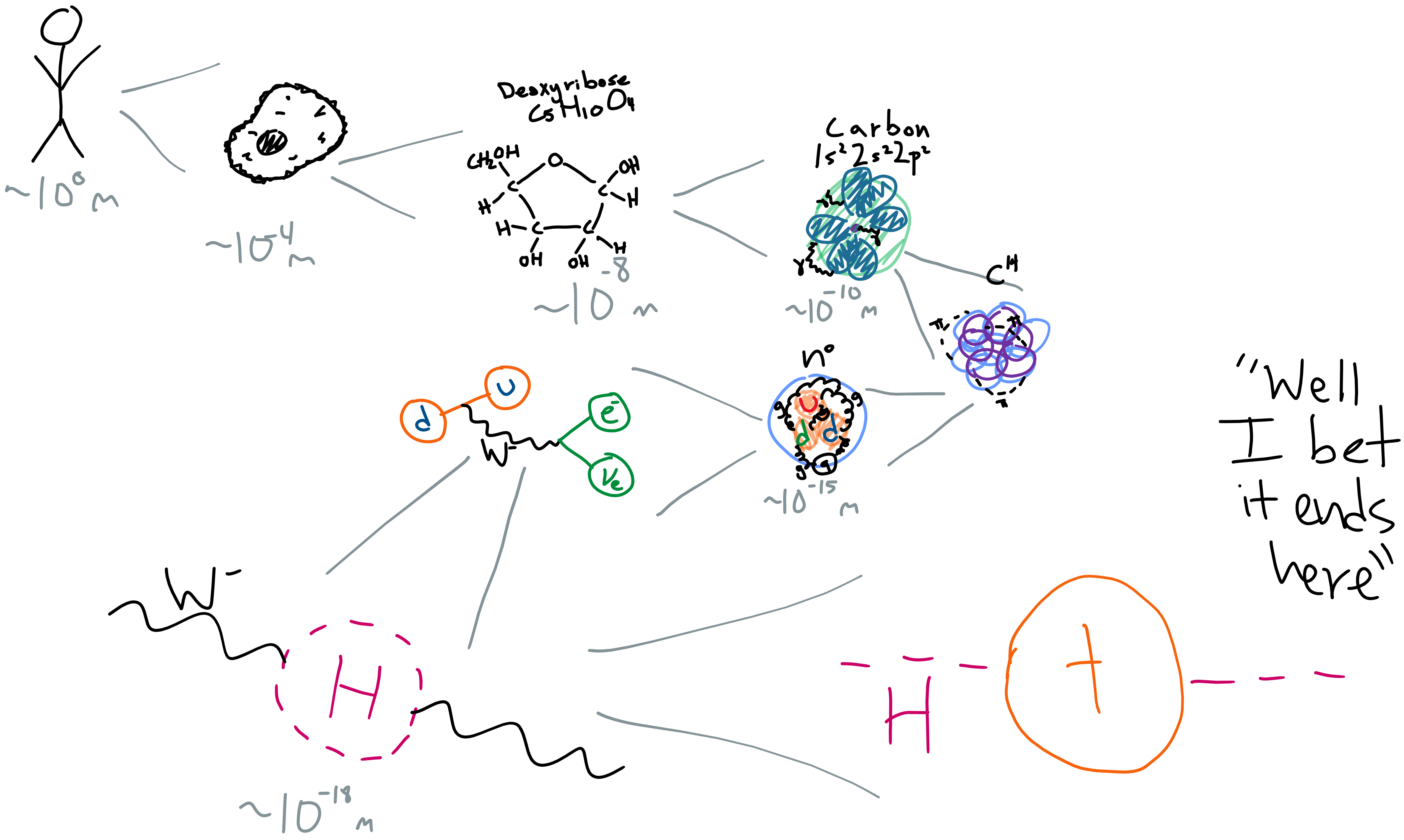
But let me pull back further a moment





$\sim 10^{0}$ m
$\sim 10^{-4}$ m
Deoxyribose
$C_5H_{10}O_4$
CH_2OH
O
OH
H
OH
OH
$\sim 10^{-8}$ m
Carbon
$1s^2 2s^2 2p^2$
γ
$\sim 10^{-10}$ m
C^{14}
π
~MeV
n^0
g
u
d
$\sim 10^{2}$ MeV
u
d
W^-
e^-
ν_e
$\sim 10^{4}$ MeV

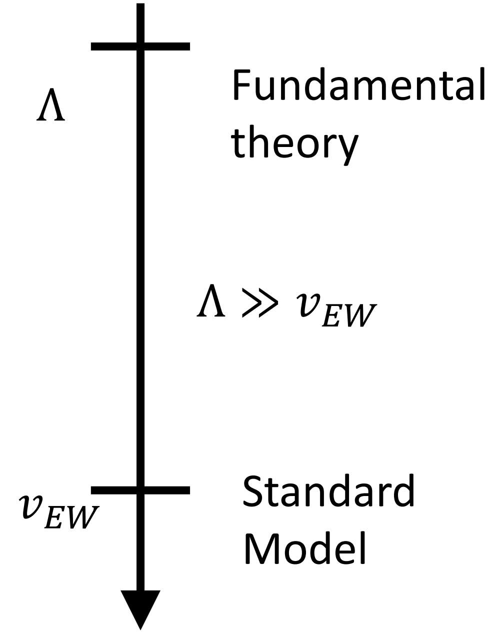


~10^0 m
~10^-4 m
Deoxyribose
C5H10O4
CH2OH
OH
H
O
C
~10^-8 m
Carbon
1s^2 2s^2 2p^2
~10^-10 m
n°
~10^-15 m
d
u
W-
e-
νe
W-
H
~10^-18 m
H
t
"Well I bet it ends here"

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

$$\mathcal{L} \supset M^2 \varphi^\dagger \varphi + \left(M^2 + \lambda \mathrm{v}_{\mathrm{GUT}}^2\right) H^\dagger H$$

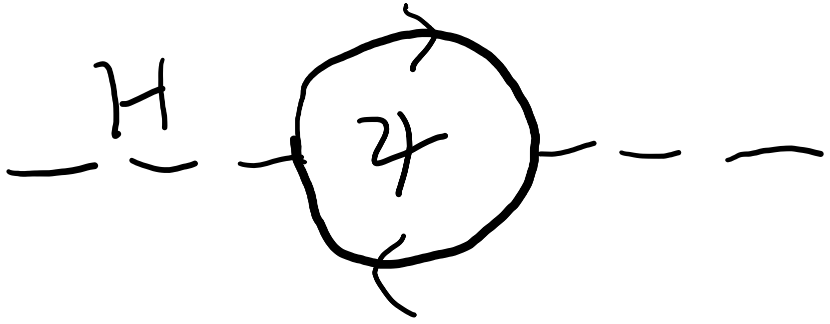
To get H mass $\sim \mathrm{v}_{\mathrm{EW}}^2$ while φ mass $\sim \mathrm{v}_{\mathrm{GUT}}^2$ requires

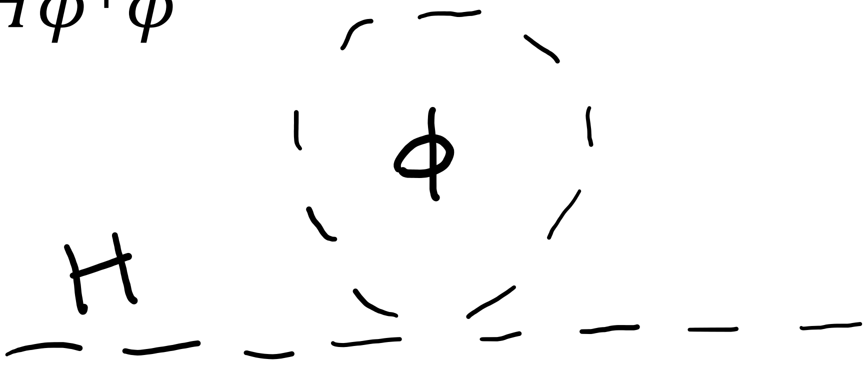
$$\lambda = -1.0000000000000000000000000001 \, \frac{M^2}{\mathrm{v}_{\mathrm{GUT}}^2}$$

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

$$\mathcal{L} \supset yH\tilde{\psi}\psi + cH^{\dagger}H\phi^{\dagger}\phi$$



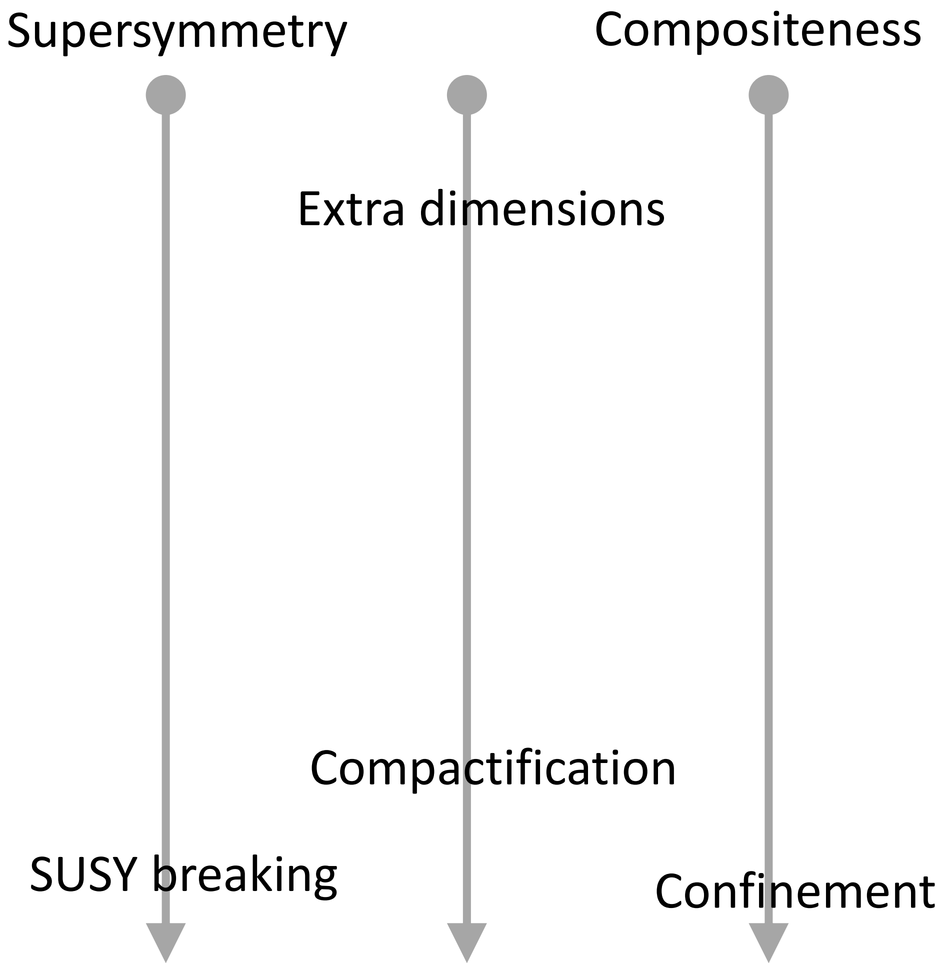


$$\rightsquigarrow m_H^2 \sim \frac{1}{16\,\pi^2}\,(-y^2 m_\psi^2 + c m_\phi^2)$$

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

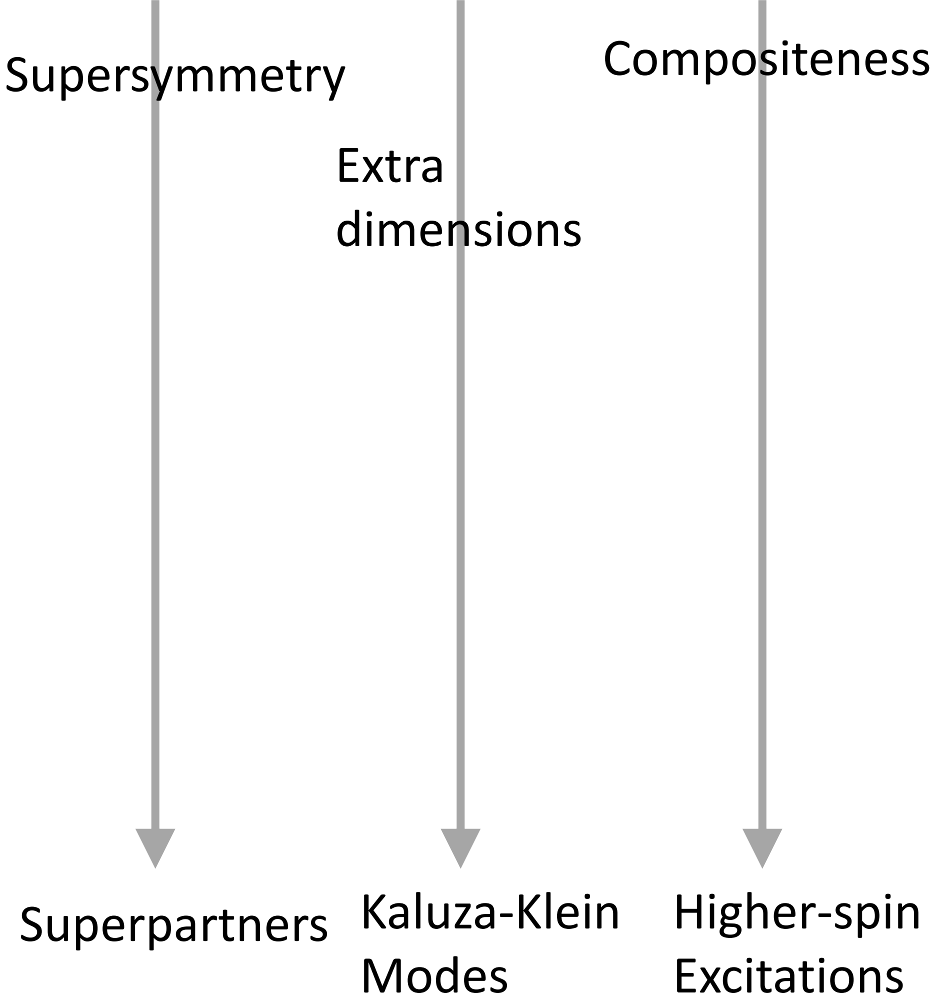
Solving the Hierarchy Problem

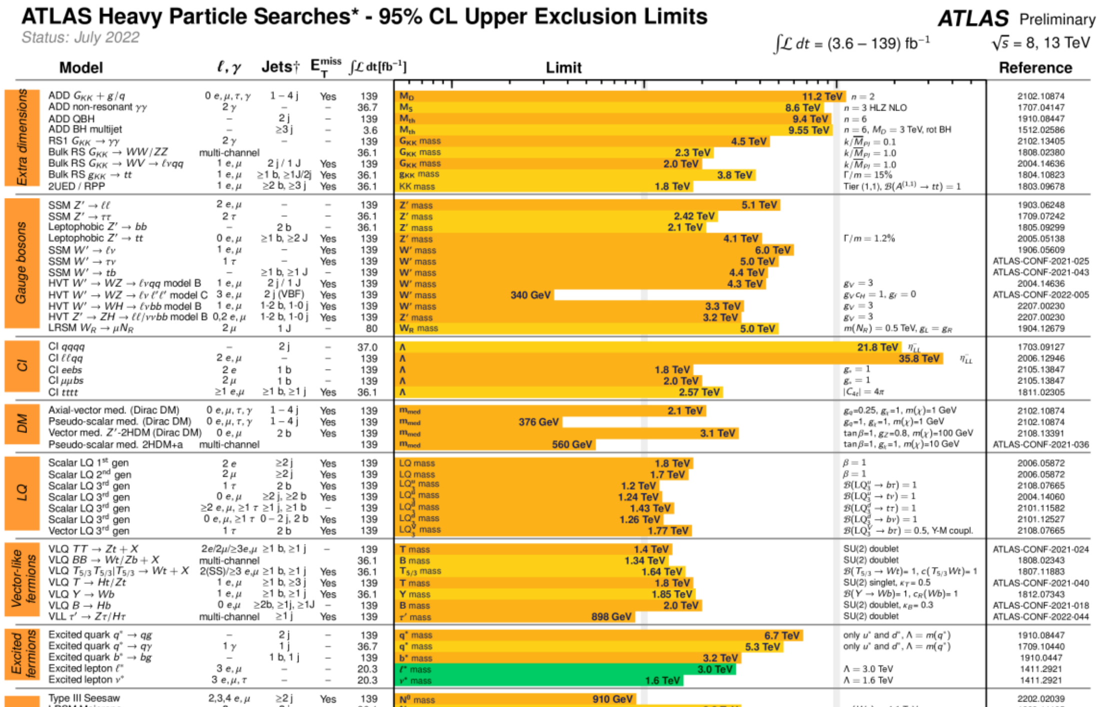
- Familiar solutions introduce some new structure in the UV to control the form of corrections to the Higgs mass
- But that isn't present in the SM, so must be broken to give a nonzero Higgs mass



The ‘Loerarchy’ Problem

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





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]

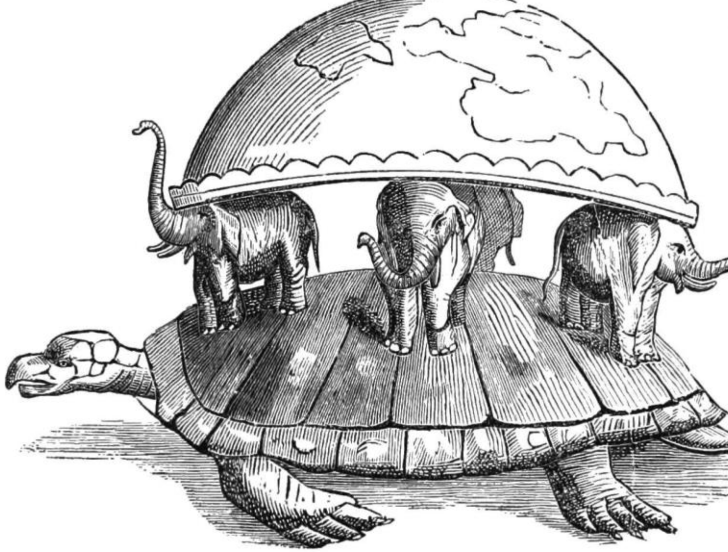
- More direct UV/IR? [e.g. Dienes ‘94-; Minwalla, van Raamsdonk, Seiberg ‘00; Craig & SK ‘19]

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.

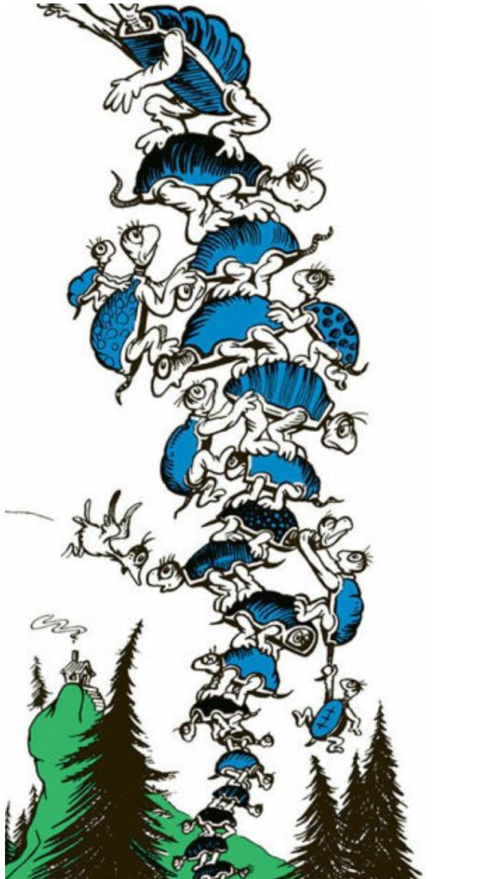
The Hierarchy Problem: From the Fundamentals to the Frontiers
2009.11870
APS 2022 Sakurai Dissertation Award

“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 QED⊂SM natural?

- m_p now explained by α_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.

$\mathrm{SU}(2) \to \mathrm{U}(1)$?

- 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 Σ gets a vev Λ, and we want a light electron, $\Psi = \begin{pmatrix} e \\ \bar{e} \end{pmatrix}$, must tune M against $y\Lambda$