Beyond the Standard Model

Andrea Wulzer

Università degli Studi di Padova

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BSM $=$ **Behind** the SM

(goal is explain SM mysteries)

Behind!

~~Beyond~~ the Standard Model

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Plan of the lectures

1. **No-Lose Theorems** (or, why the Higgs is revolutionary)
2. **The “SM-only” Option**
3. **The Naturalness Argument**
4. **What if Un-Natural?**
5. **Composite Higgs**
6. **The Minimal CH couplings (and other signatures)**
7. **SUSY theory**
8. **SUSY and Naturalness** (or, why to care about SUSY)
9. **Other virtues of SUSY**

No-Lose Theorems

A number of **guaranteed** discoveries in the history of HEP

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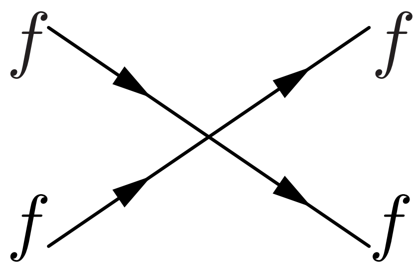
Beyond the Fermi Theory:



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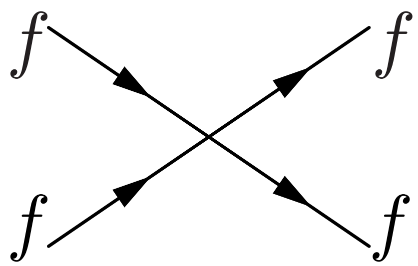

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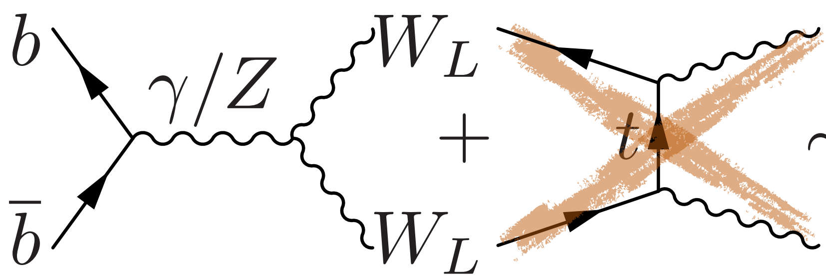

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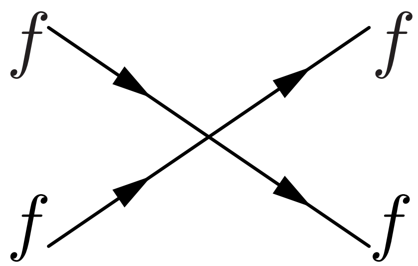

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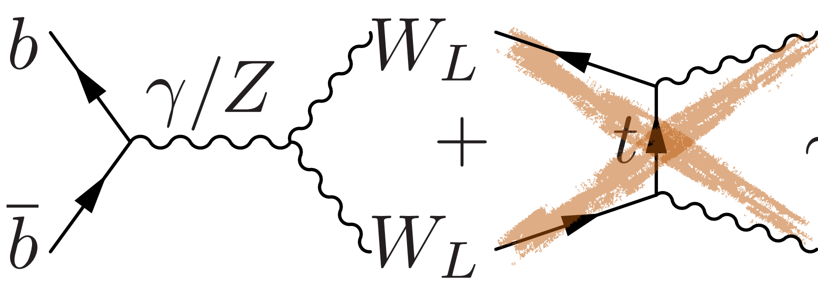

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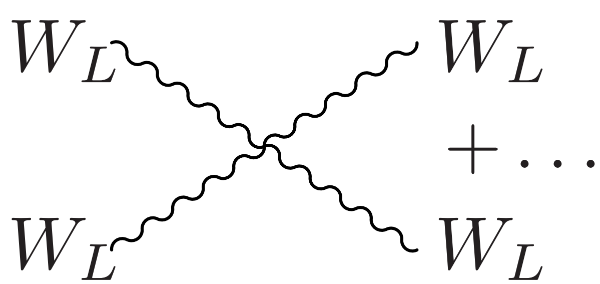

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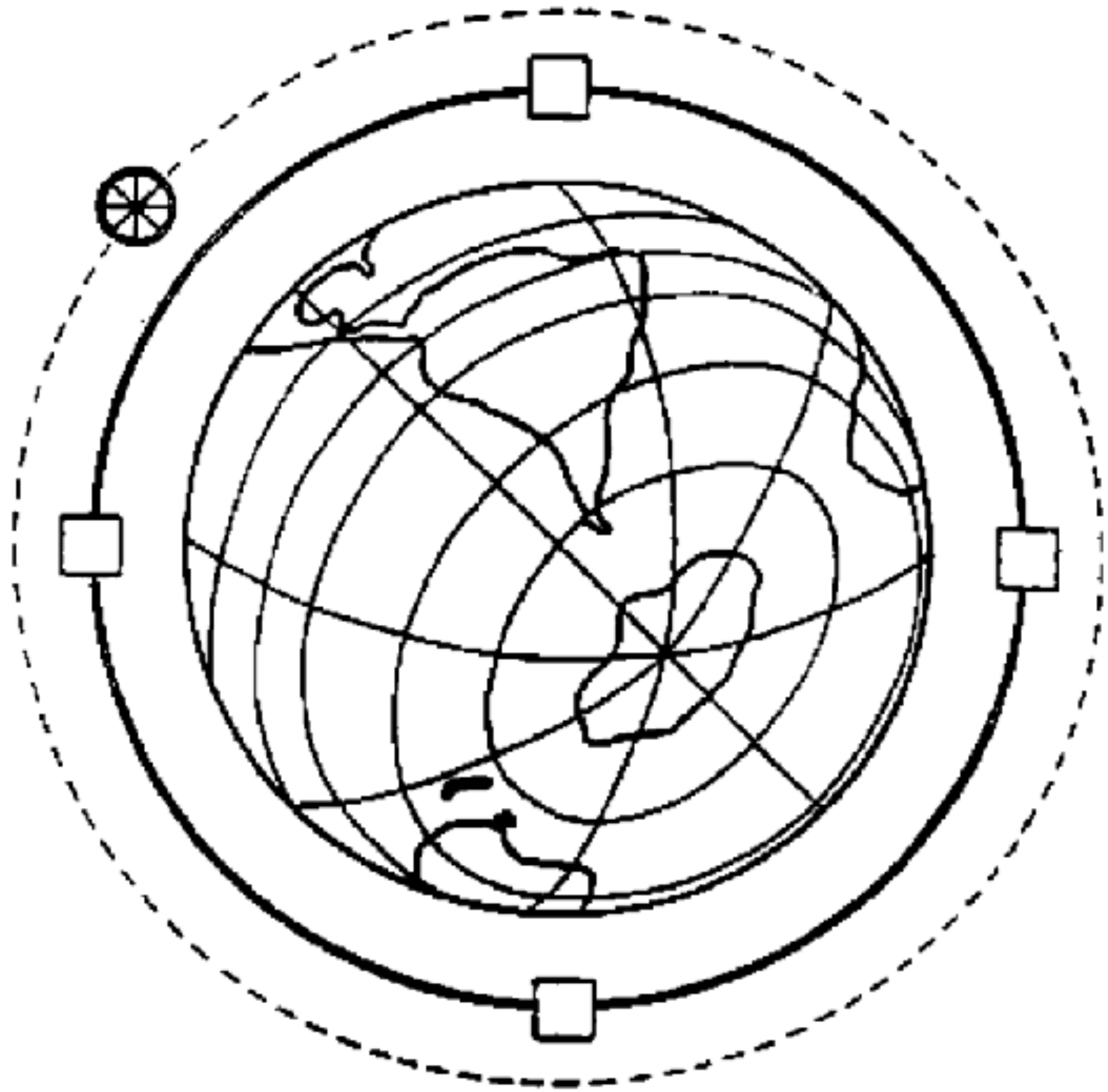
Fermi's
Ultimate Accelerator



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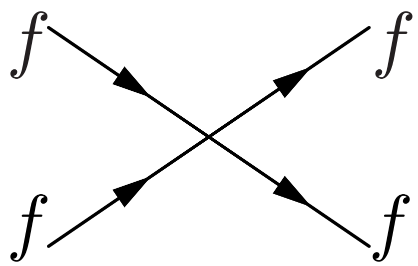

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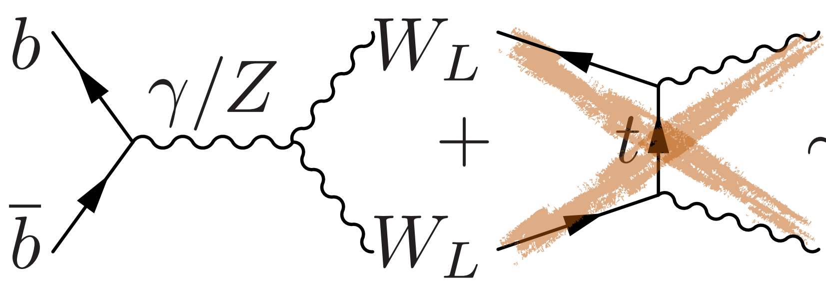

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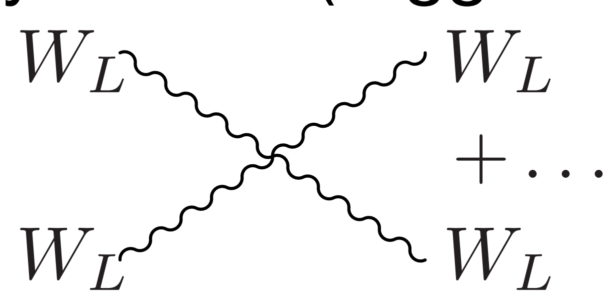

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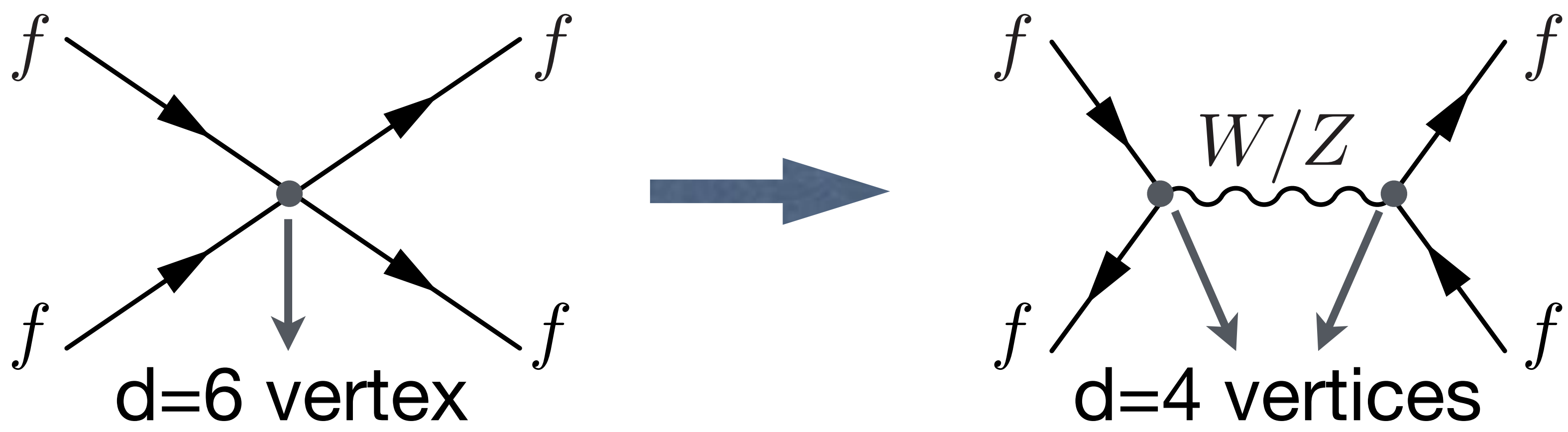
Each secretly due to d=6 non-renormalizable operators, signalling nearby new physics.

No-Lose Theorems

Each time we exploit one No-Lose Theorem, we get rid of one d=6 operator ...

e.g.



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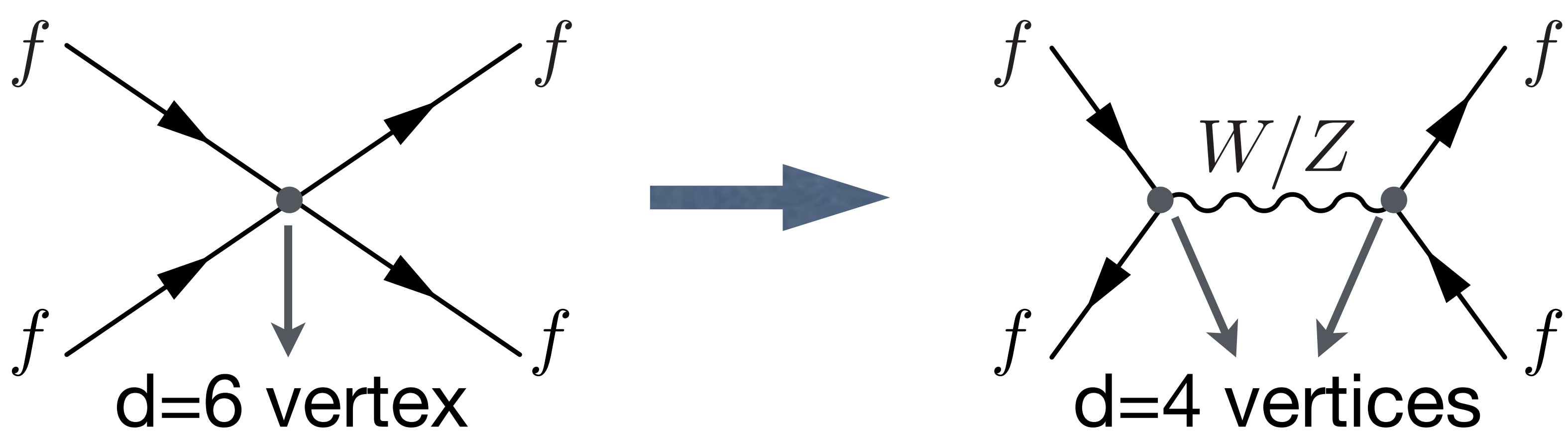
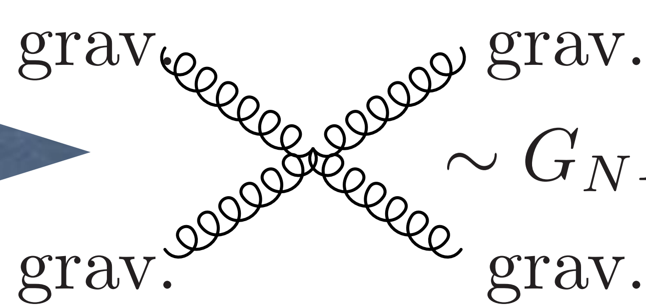


… and only one is left after Higgs discovery …

$\frac{1}{G_N}\sqrt{g}R \;\Longrightarrow$



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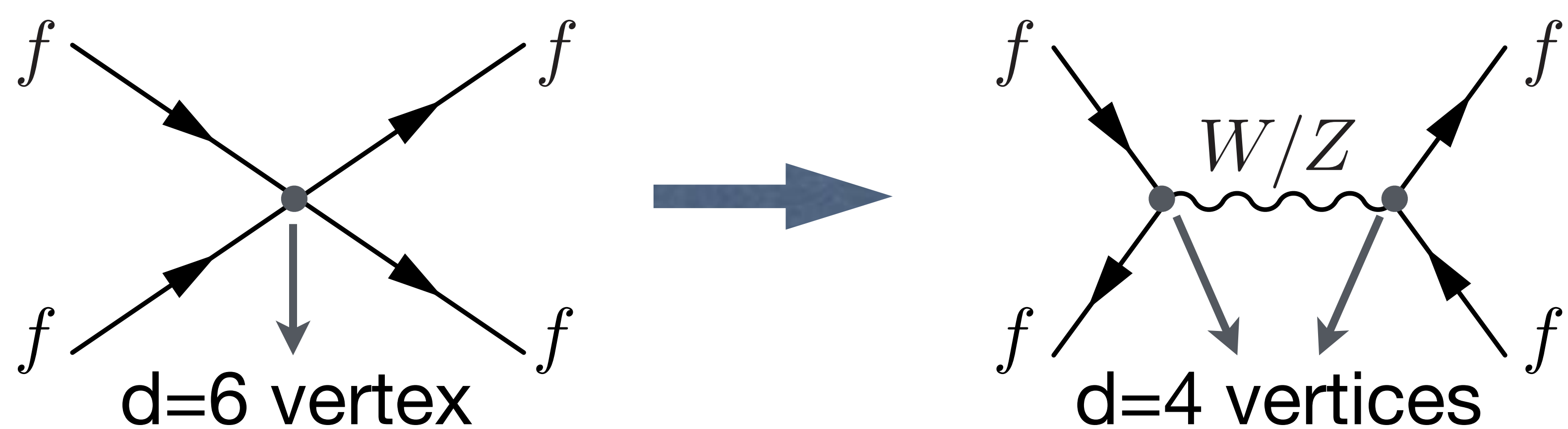

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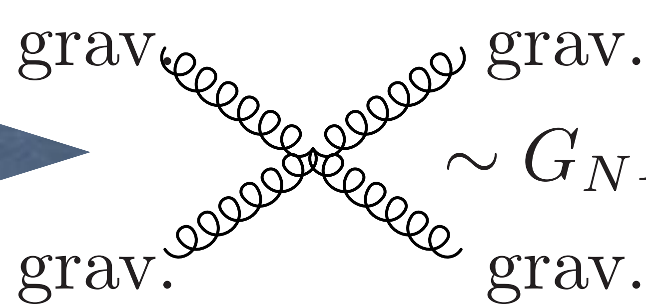

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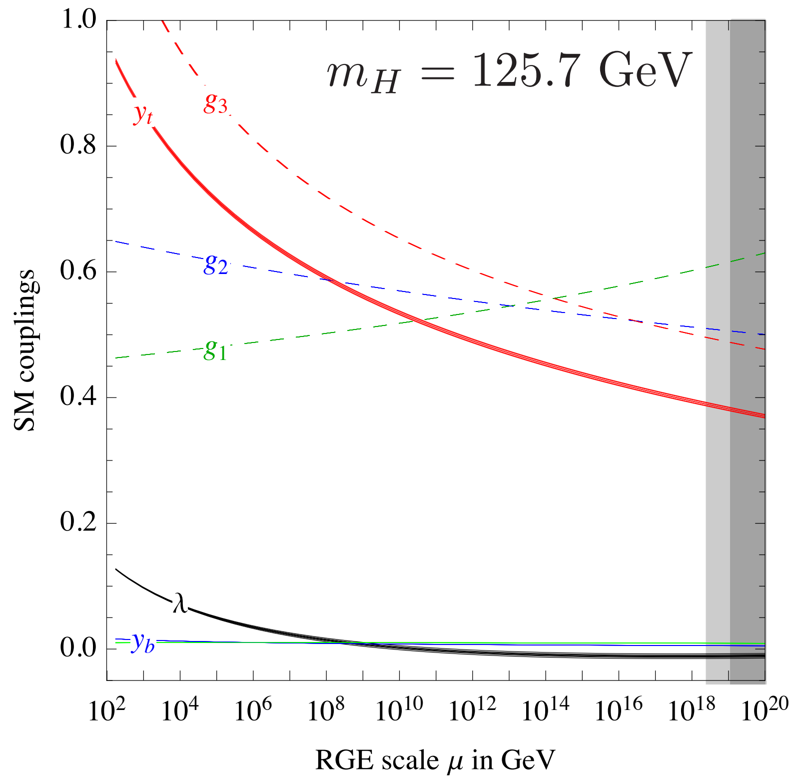
… the last, impractical, No-Lose Theorem is Q.G. at M_{P}!

No-Lose Theorems

[see e.g. De Grassi et.al., 2013]

The statement survives quantum corrections:



- No relevant Landau Pole

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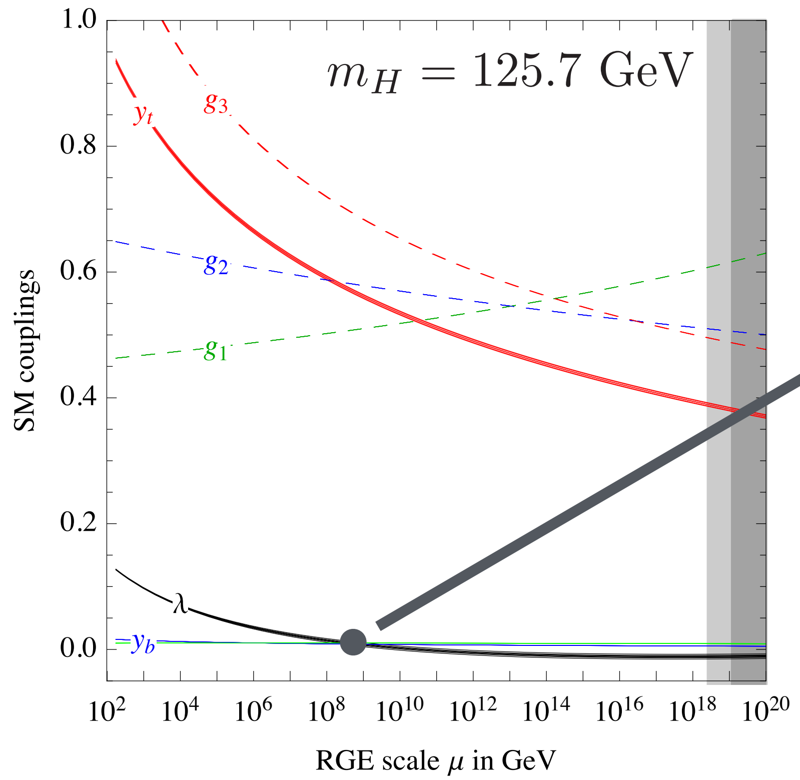

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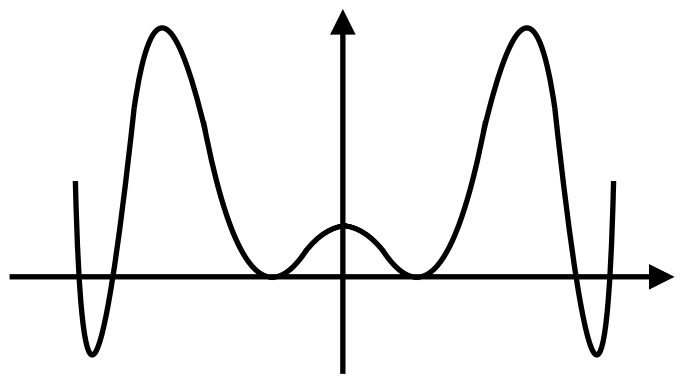
- **Instability scale** $\sim 10^9$ GeV



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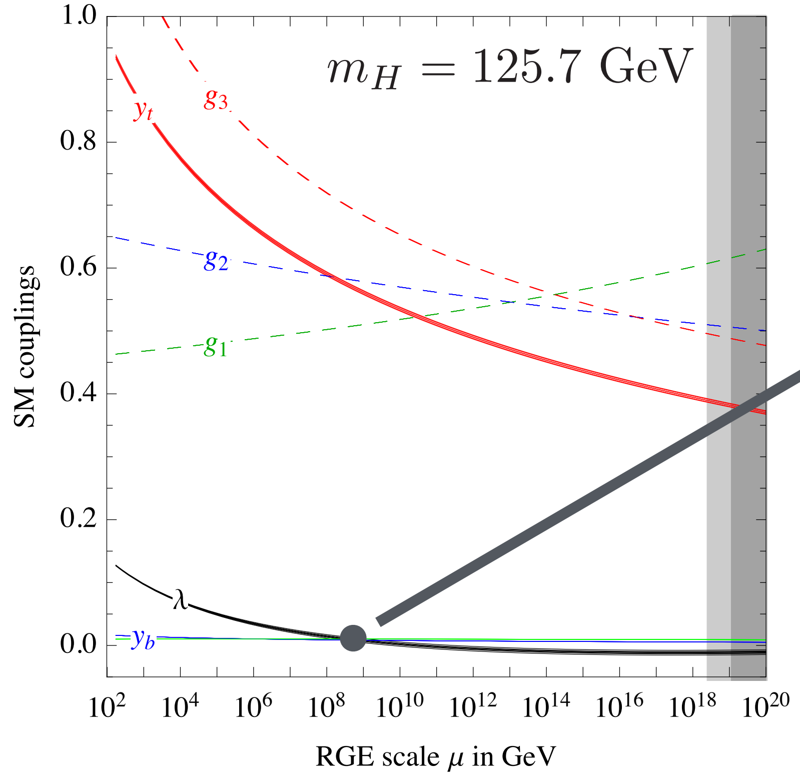

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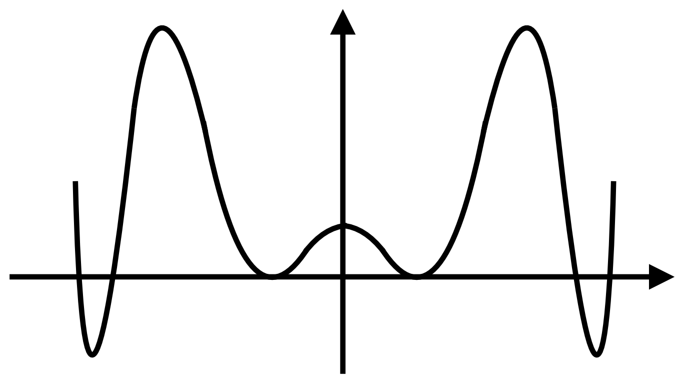

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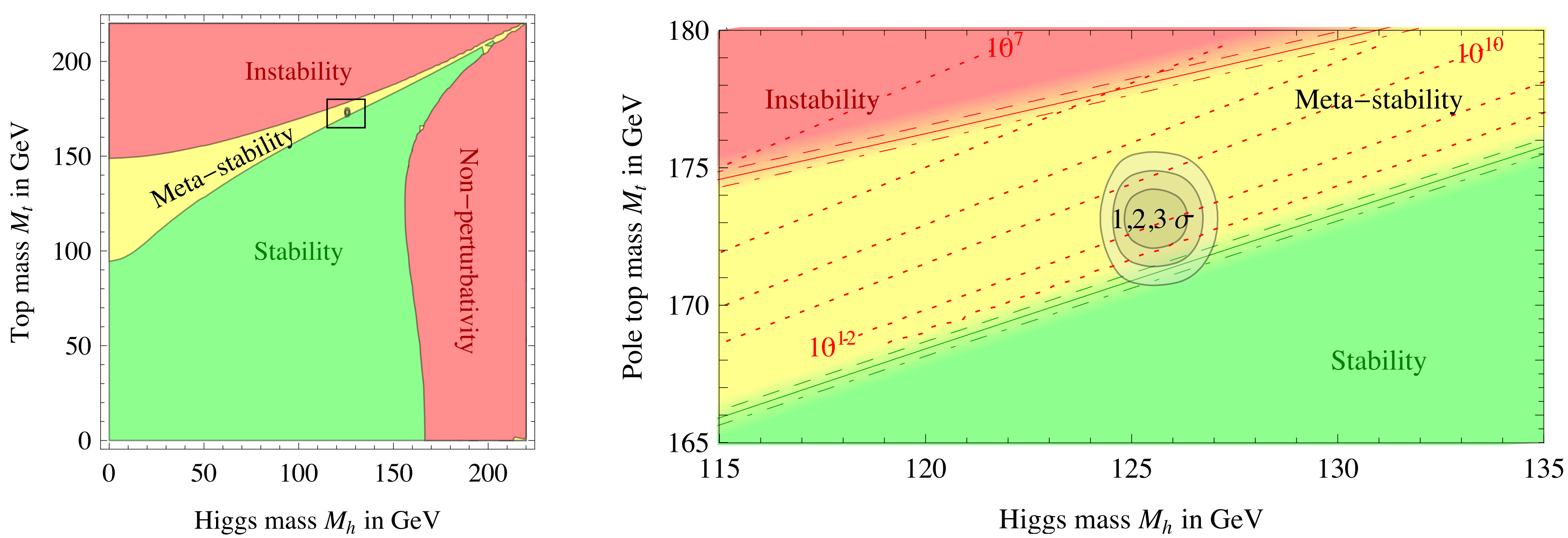
Non trivial result. Depends on Higgs and Top mass:



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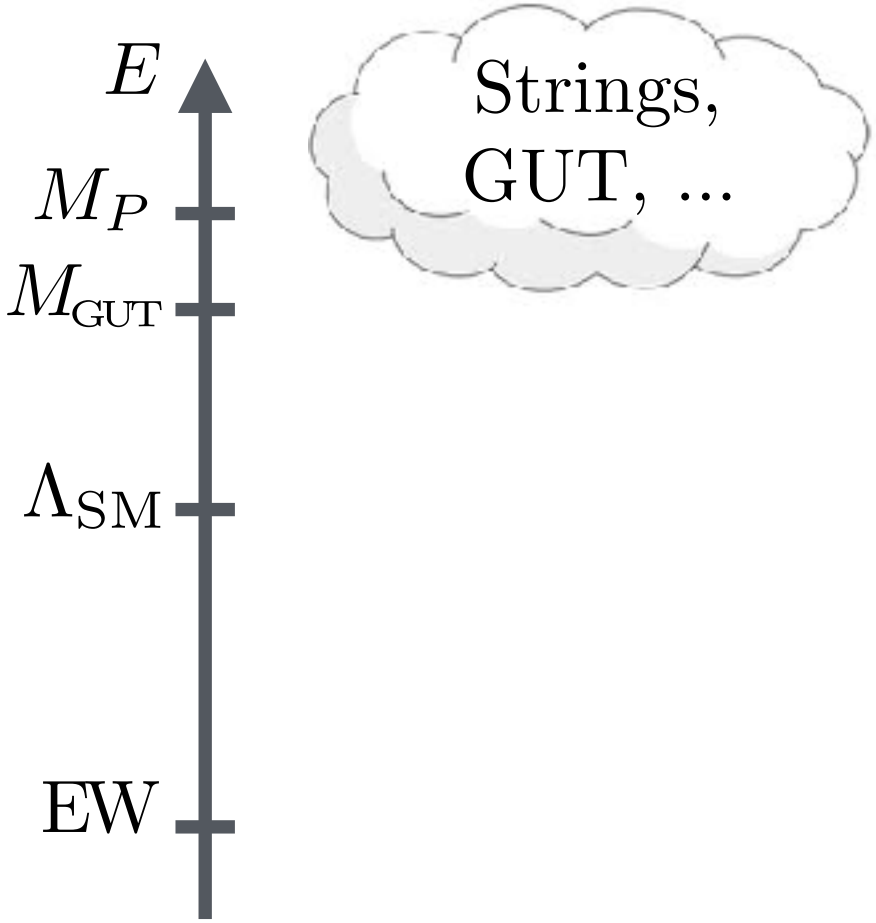
$\boxed{\text{The \textbf{Naturalness Problem}: Why } m_H \ll \Lambda_{\rm SM}\text{? (to be discussed later)}}$

The “SM-only” Option



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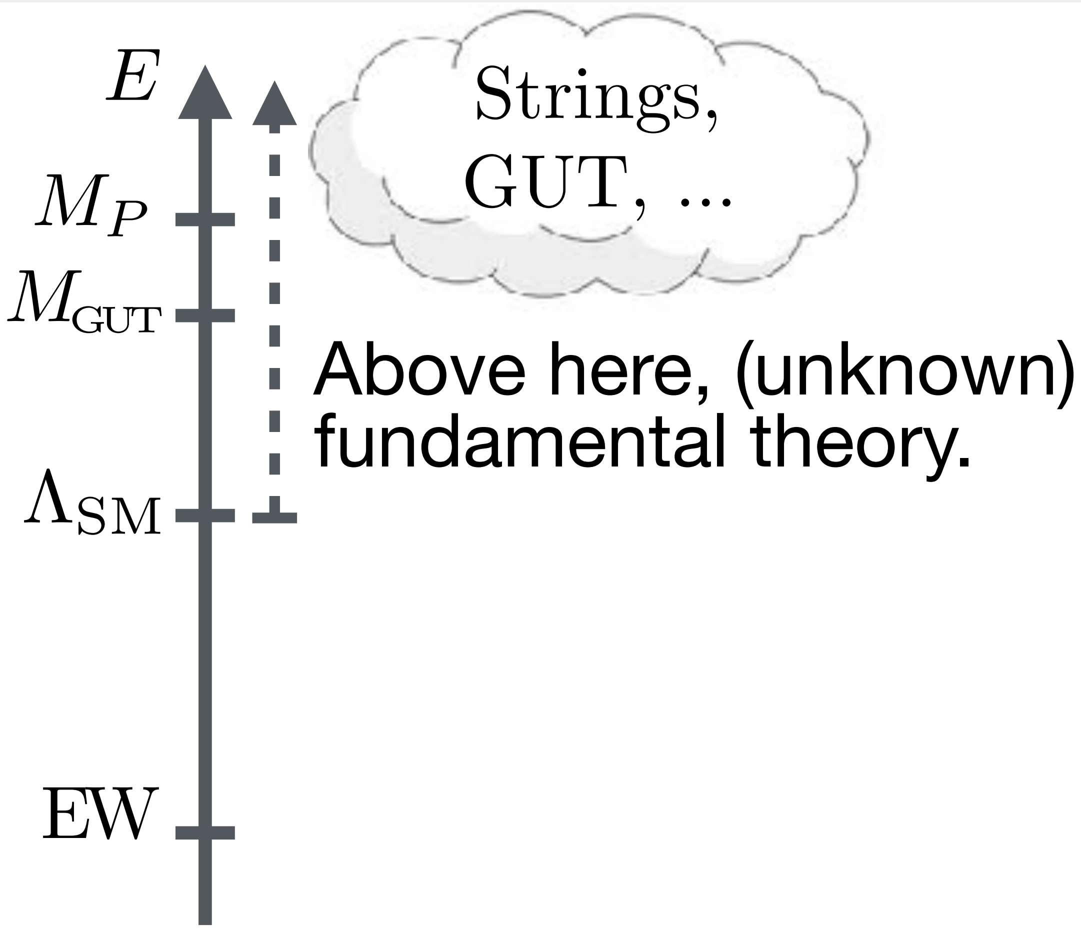

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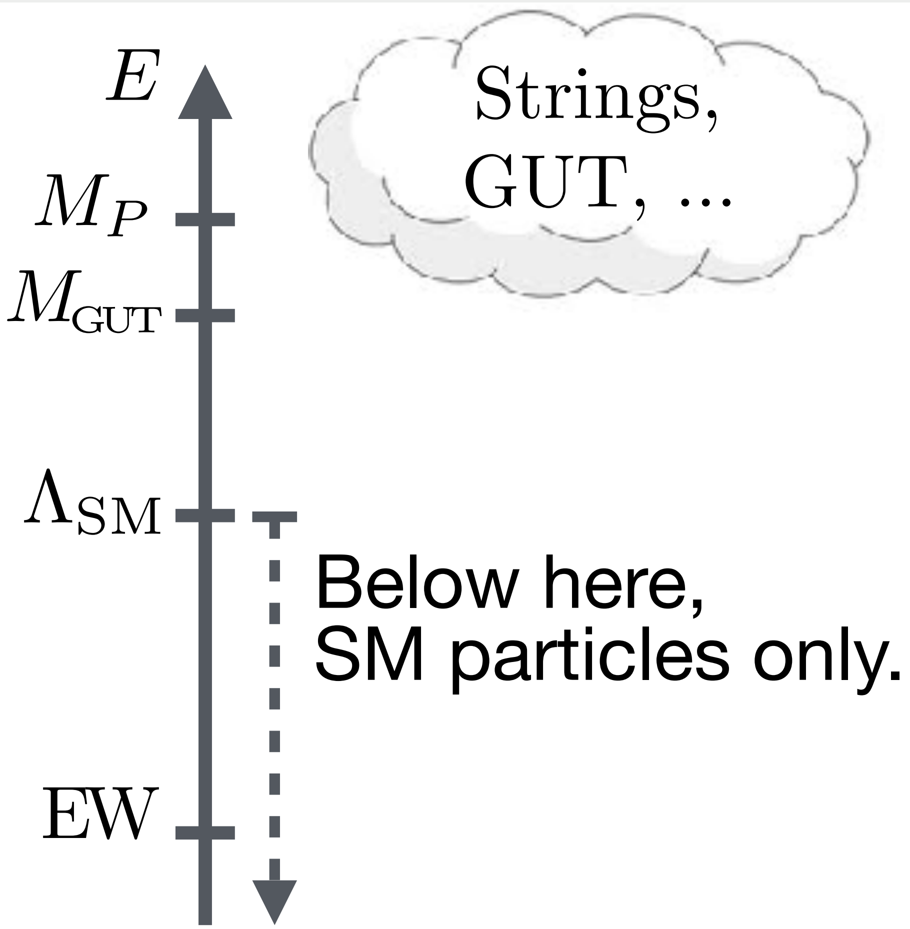

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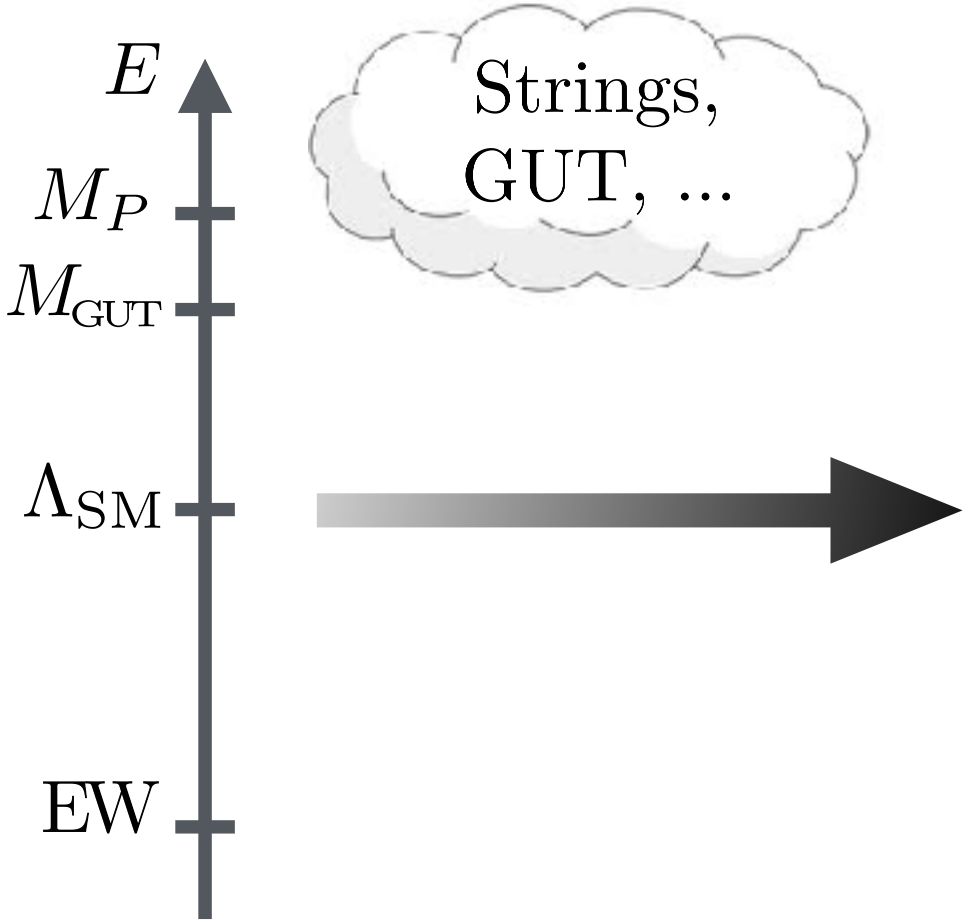

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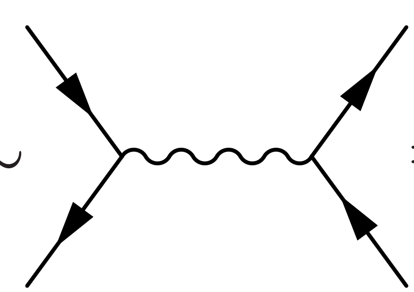
One day, effective SM Lagrangian and parameters will be **derived from the fundamental theory**.

Fermi theory analogy: $G_F \sim$  $= \dfrac{g_W^2}{4\sqrt{2}m_W^2}$

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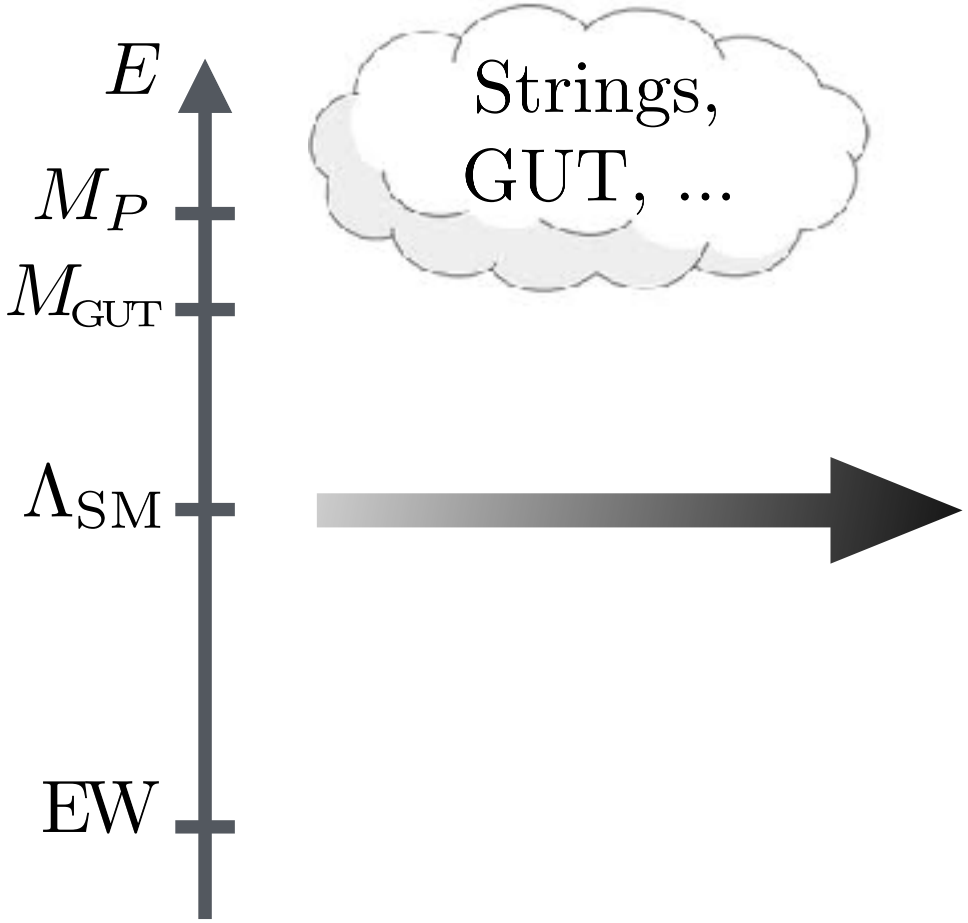

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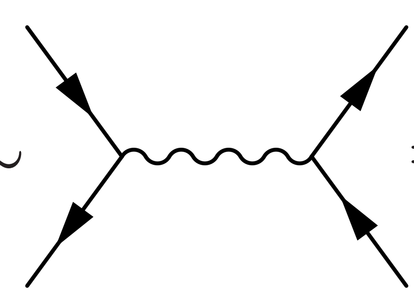
Fermi theory analogy: $G_F \sim$  $= \dfrac{g_W^2}{4\sqrt{2}m_W^2}$

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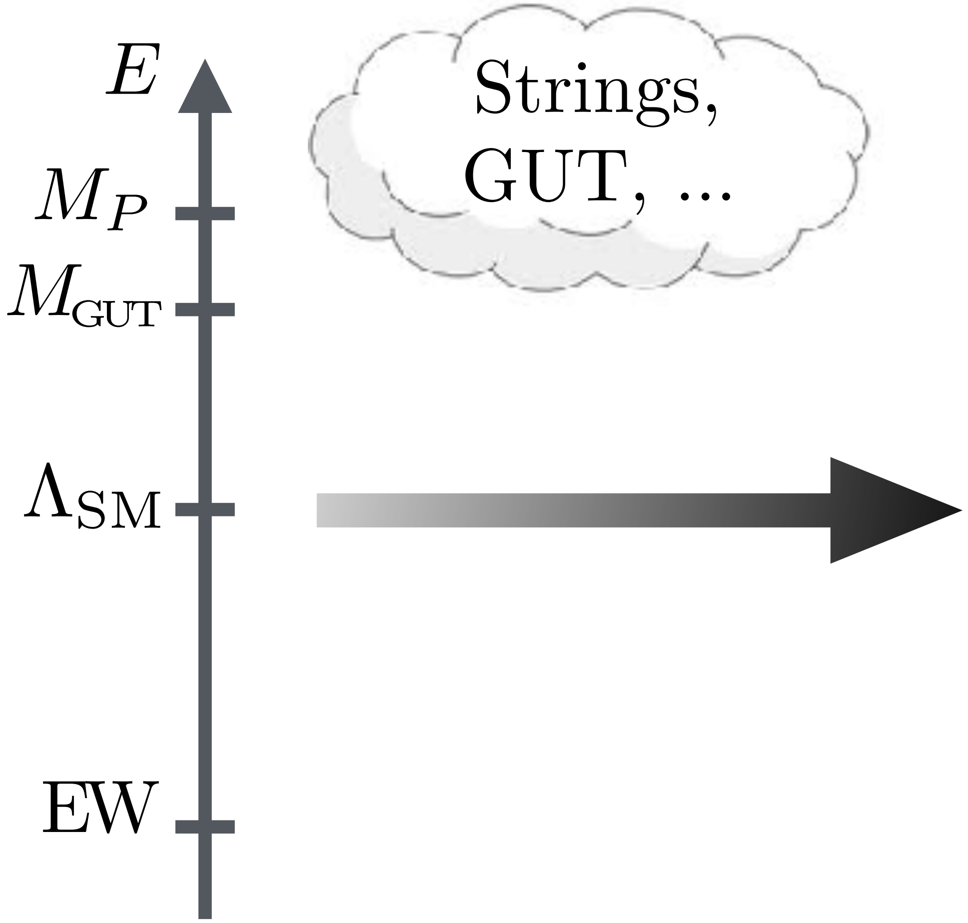

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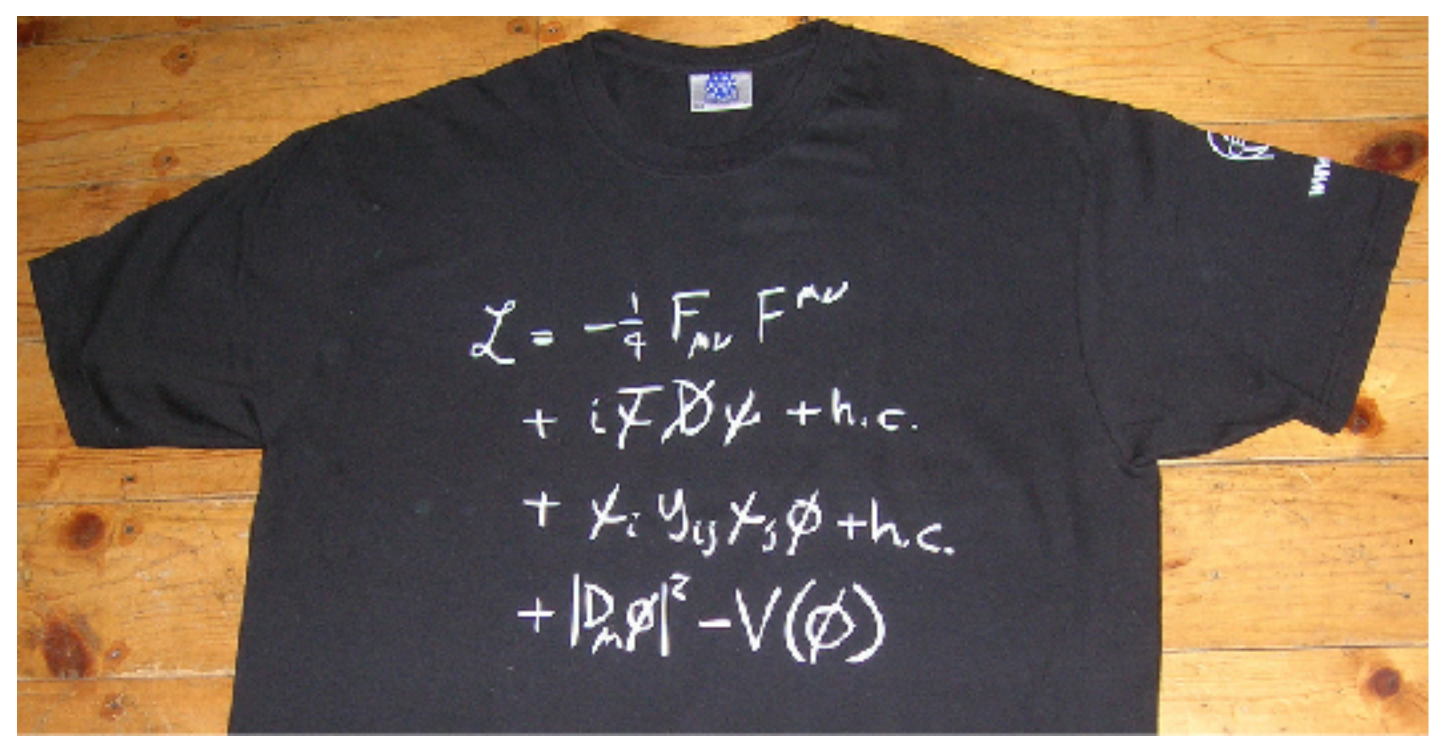
$\mathcal{L}^{(d=4)}$: the CERN T-shirt Lagrangian (almost)



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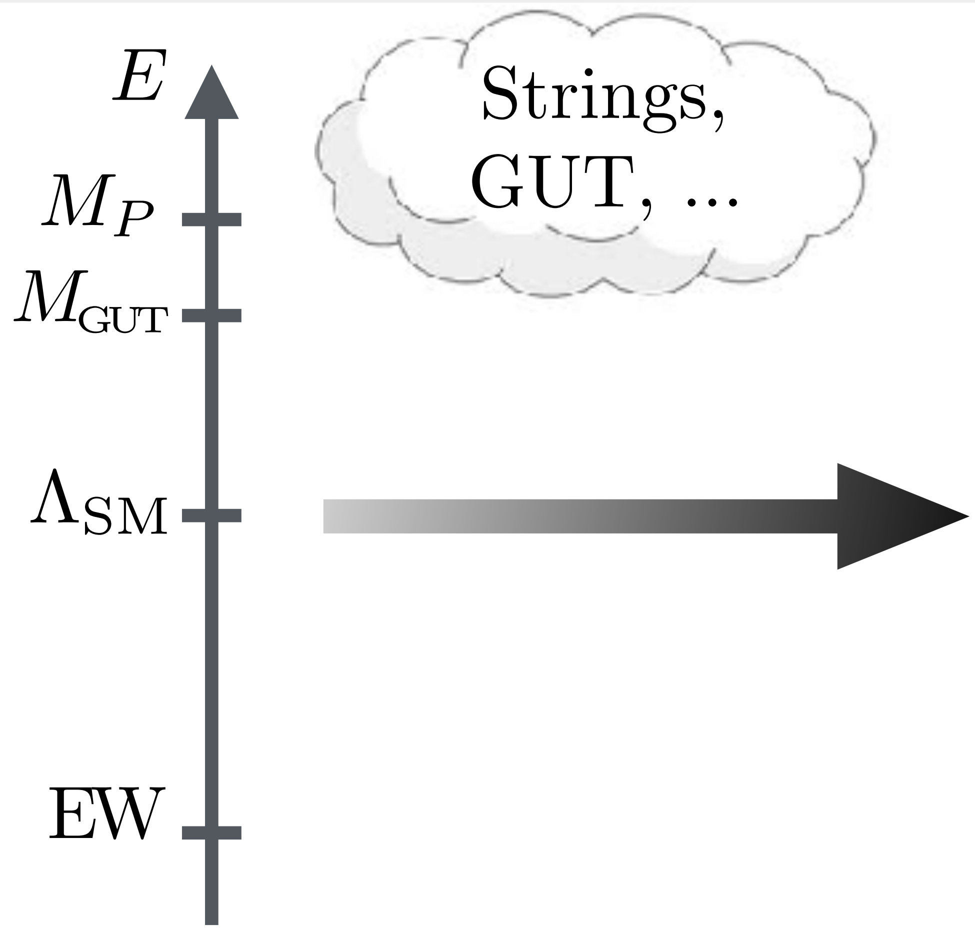

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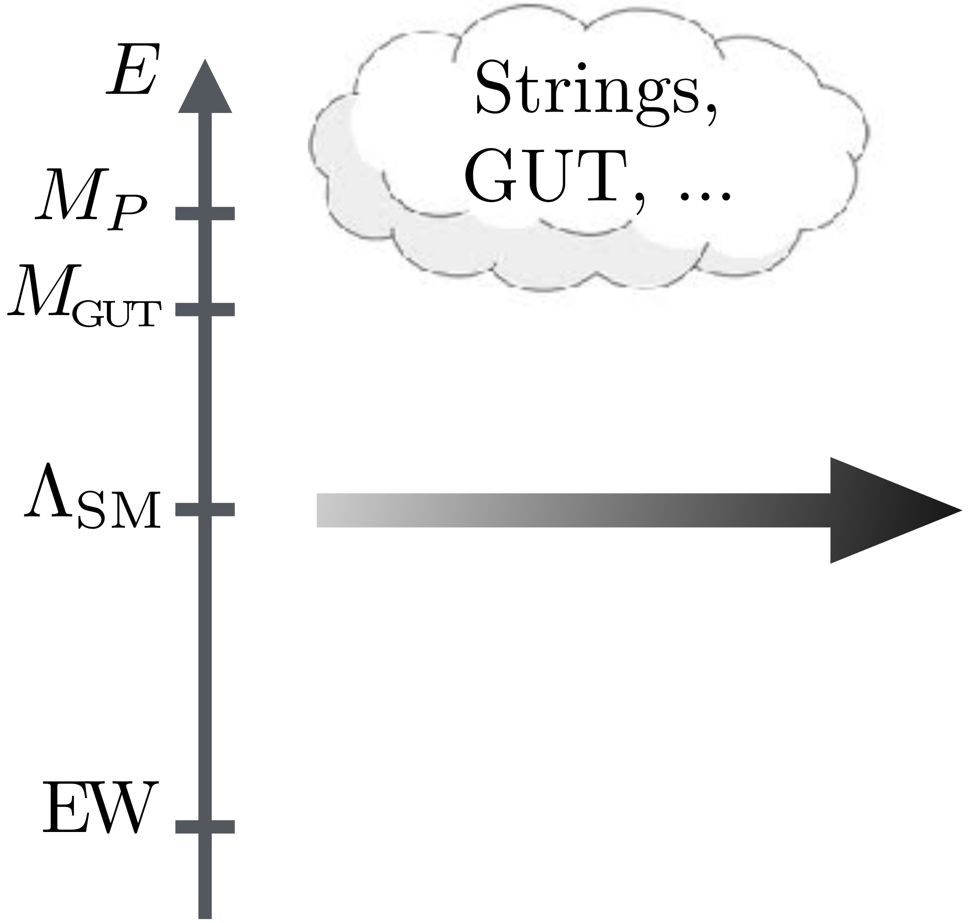

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$\mathcal{L}^{(d=4)}$: describes all what **we see** (almost) …
… and what **we don’t see.**

$(\Gamma_{\rm proton}/m_{\rm proton})_{\rm exp.} < 10^{-64}$ **!!** $\Longleftrightarrow$ $(\Gamma_{\rm proton}/m_{\rm proton})_{(d=4)} = 0$

accidental Baryon num. symm.

$\mathrm{BR}(\mu \to e\gamma)_{\rm exp} < 10^{-12}$ **!!** $\Longleftrightarrow$ $\mathrm{BR}(\mu \to e\gamma)_{(d=4)} = 0$

accidental Lepton family symm.

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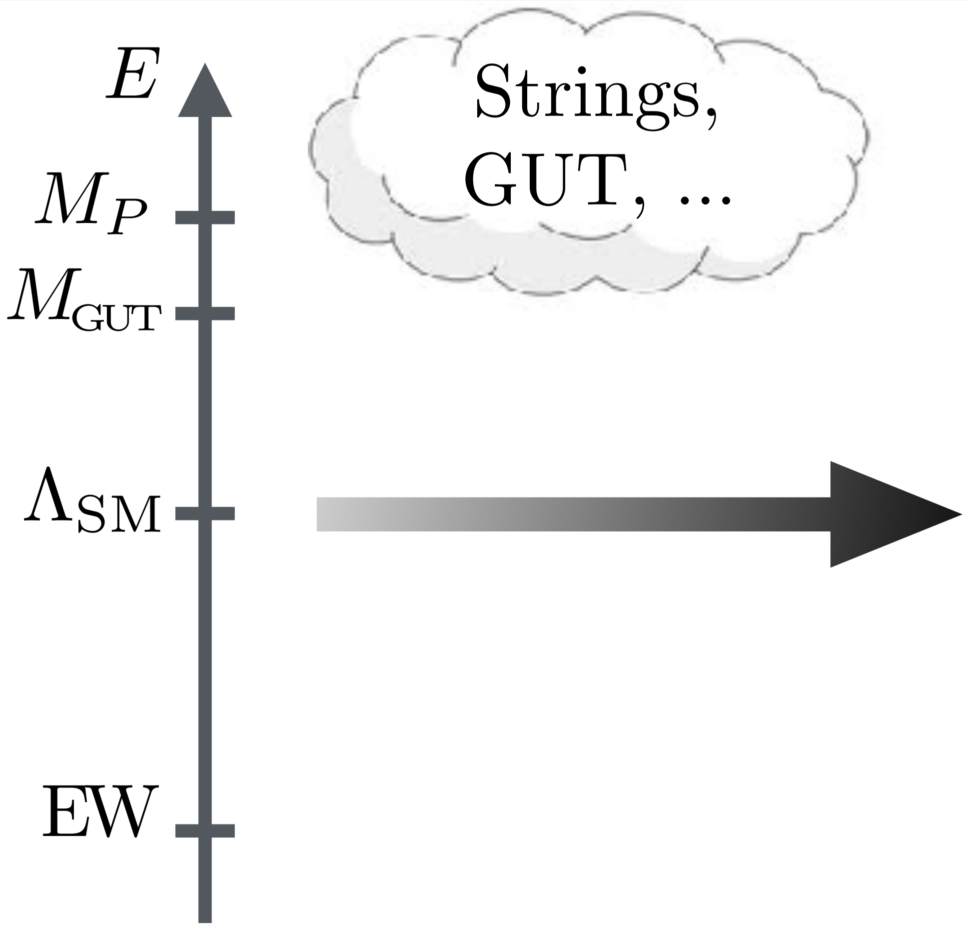

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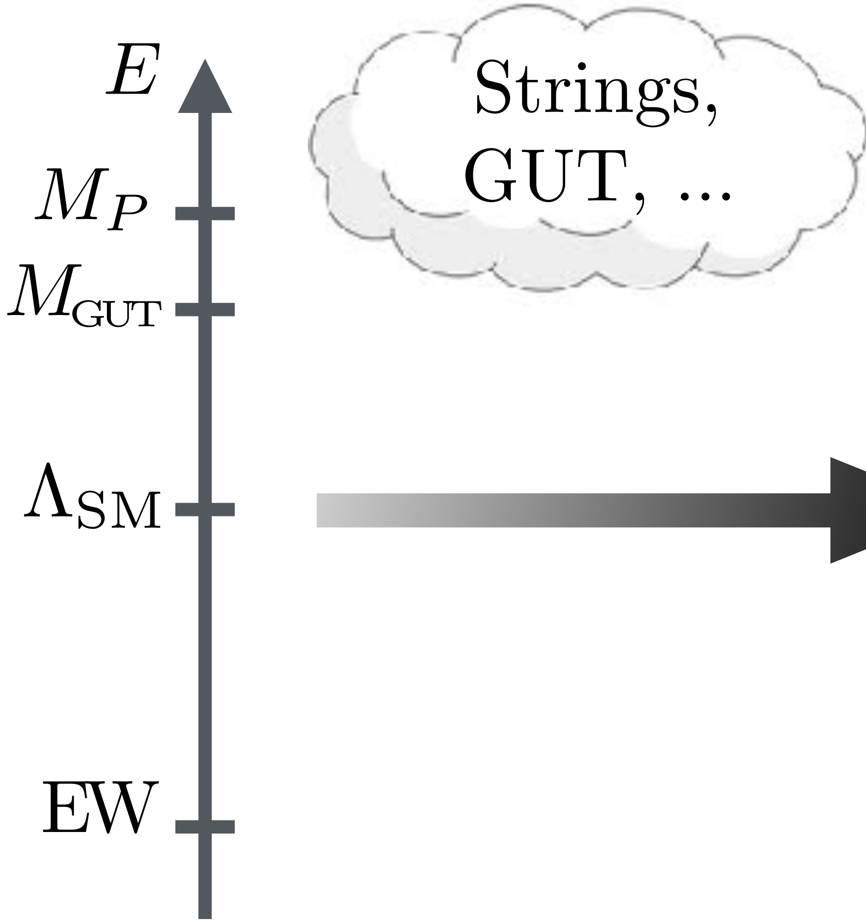

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Majorana neutrino mass-matrix

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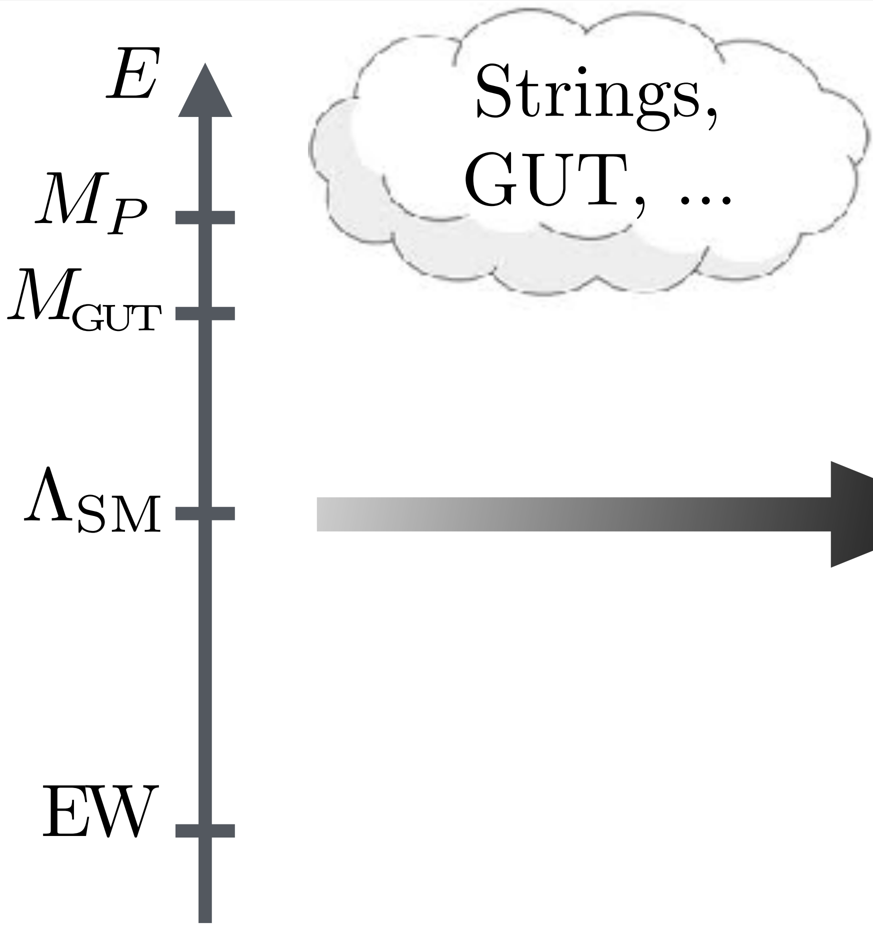

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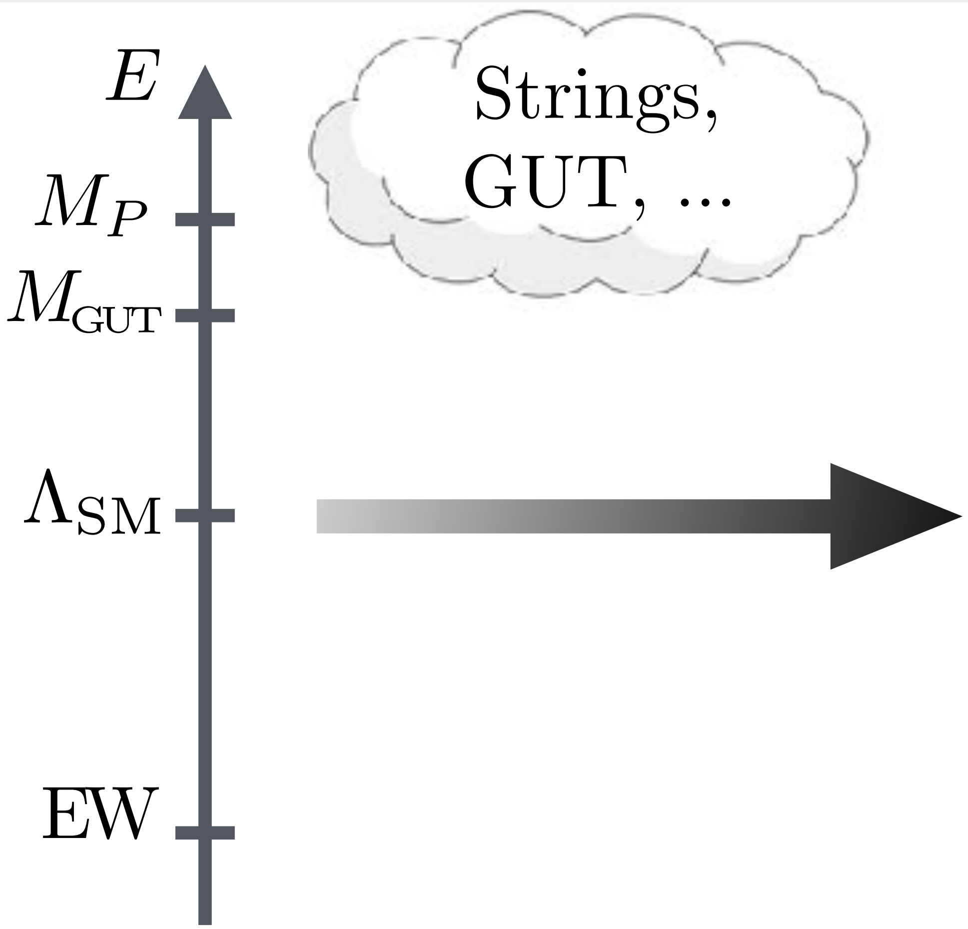

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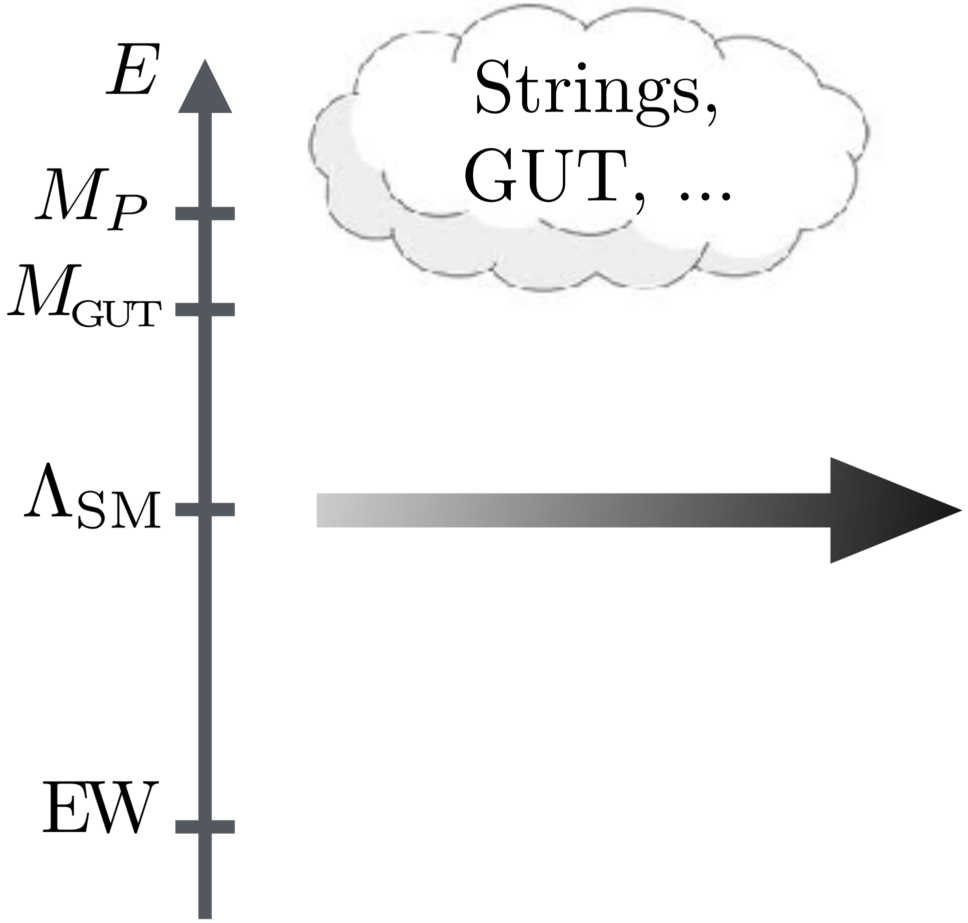

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Majorana ν’s and p-decay would be indications of SM-only

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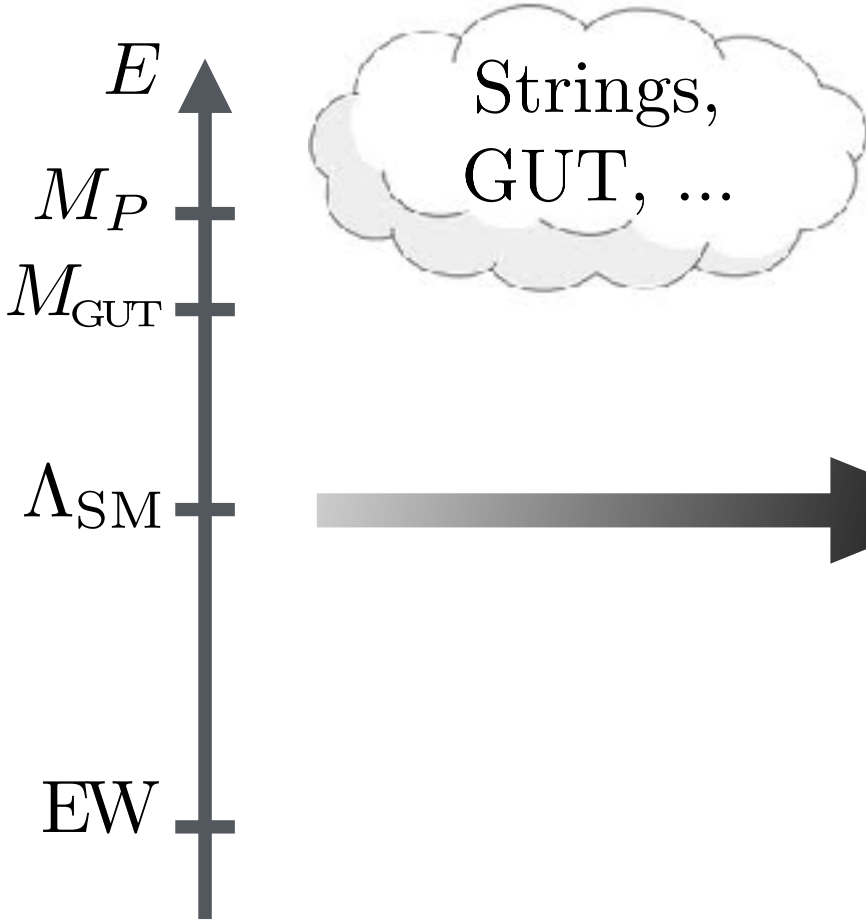

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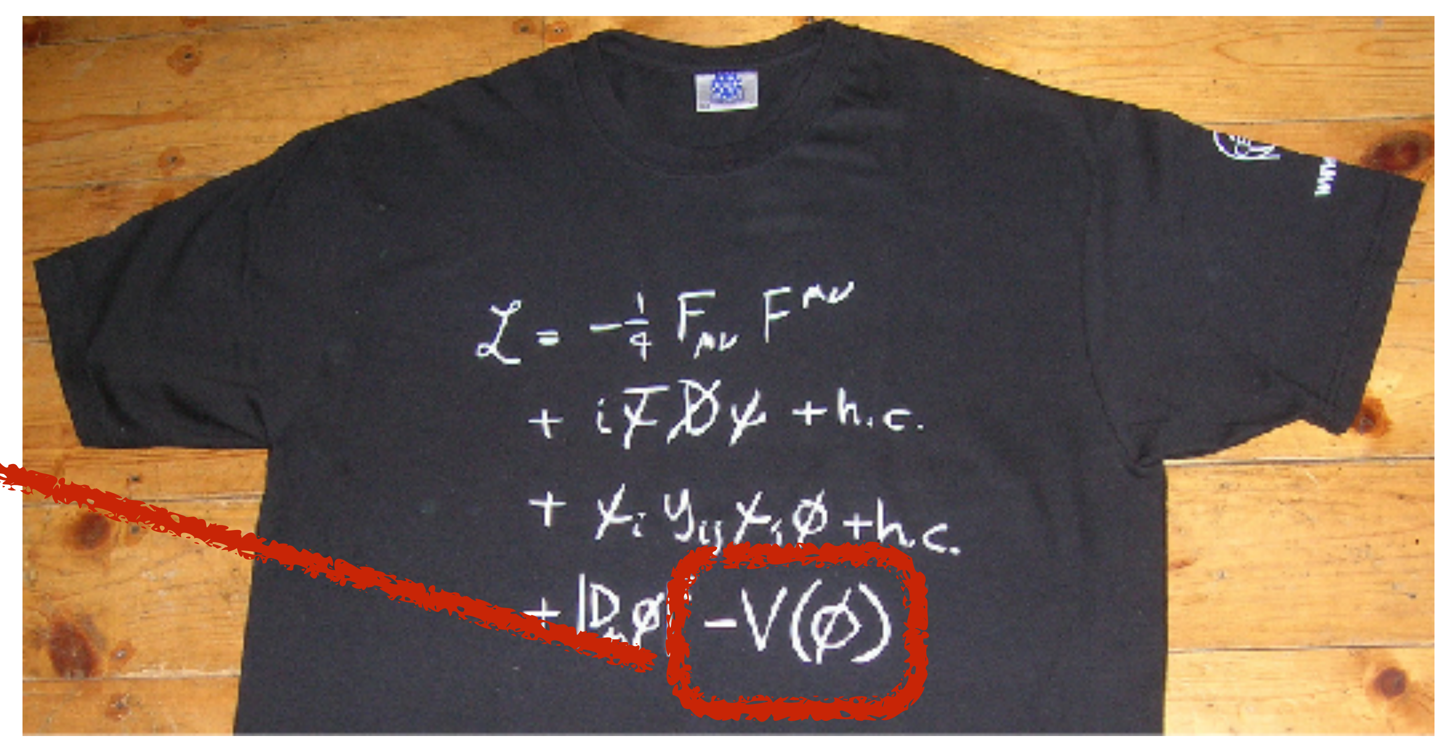

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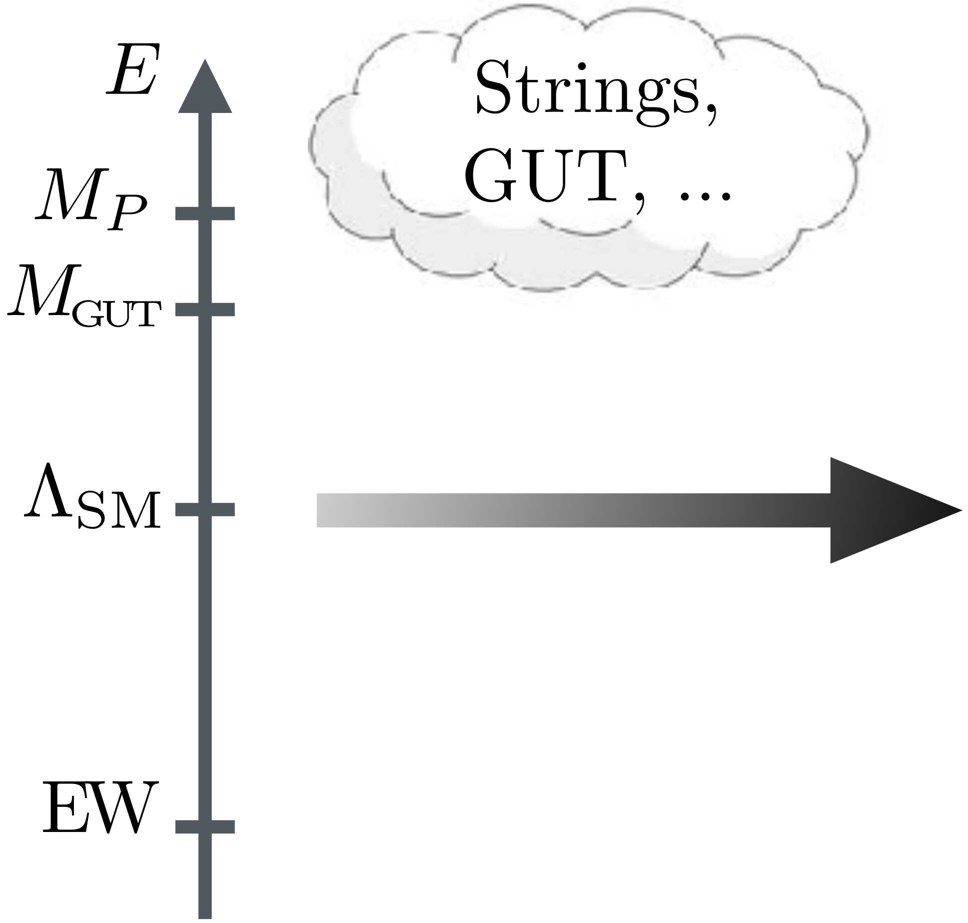

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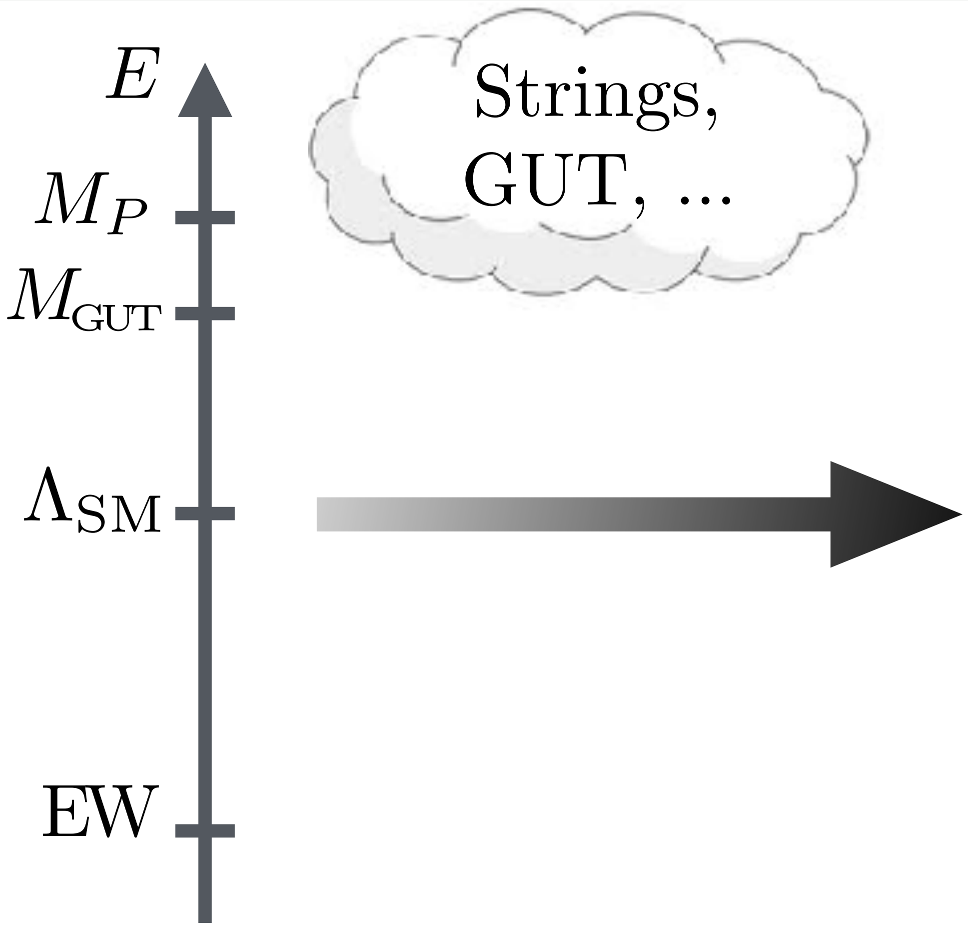

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The **Naturalness Problem**: Why $m_H \ll \Lambda_{\text{SM}}$?

(or, why dim. analysis works for d>4 and not for d<4?)

Exercise: Accidental Dark Matter

Extend the SM field content by one colour-neutral $SU(2)_L$ multiplet "X", considering the following possibilities:

1. X is a complex scalar doublet (with $U(1)_Y$ such that has neutral comp.)
2. X is a Majorana fermion triplet (Wino-like)
3. X is a Dirac fermion fourplet (with $U(1)_Y$ such that has neutral comp.)
4. X is a Majorana fermion quintuplet

Which of these choices respects the SM Accidental symmetries* at d=4?

Which one also respects, at d=4, an accidental Z_2 symmetry under which X is odd and all SM particles are even?

Which one breaks the accidental Z_2 symmetry at d=5? Which one at d=6? Denoting Λ_X the cutoff of the SM + X theory, estimate the lifetime of the lightest particle of the X multiplet in the two cases.

* the quark flavour group, broken only by the Yukawa's, is also an accidental symmetry

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(not a Theorem)

To understand Naturalness, think to the “Final Theory” formula that **predicts** m_H. It will look like this:

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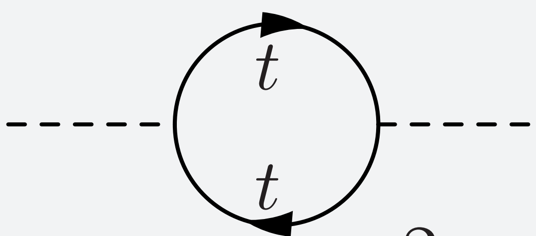

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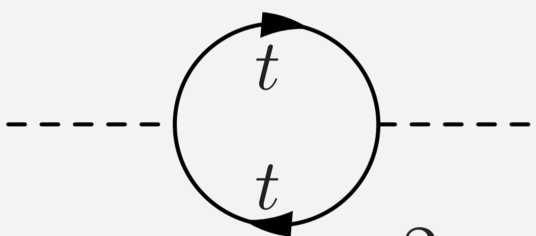

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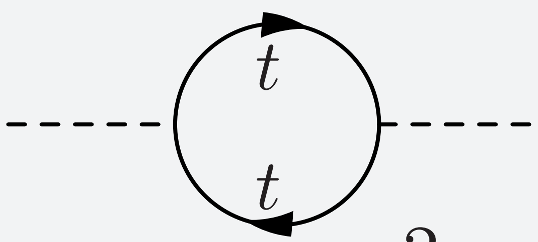

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Fine-tuning: quantifies the “degree of Un-Naturalness”

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Where to stop?

$\Delta \sim 10$ definitely **OK**

$\Delta \sim 1000$ probably **not OK**

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(to present-day understanding)

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It could:

- be a fundamental input par. of the Final Theory
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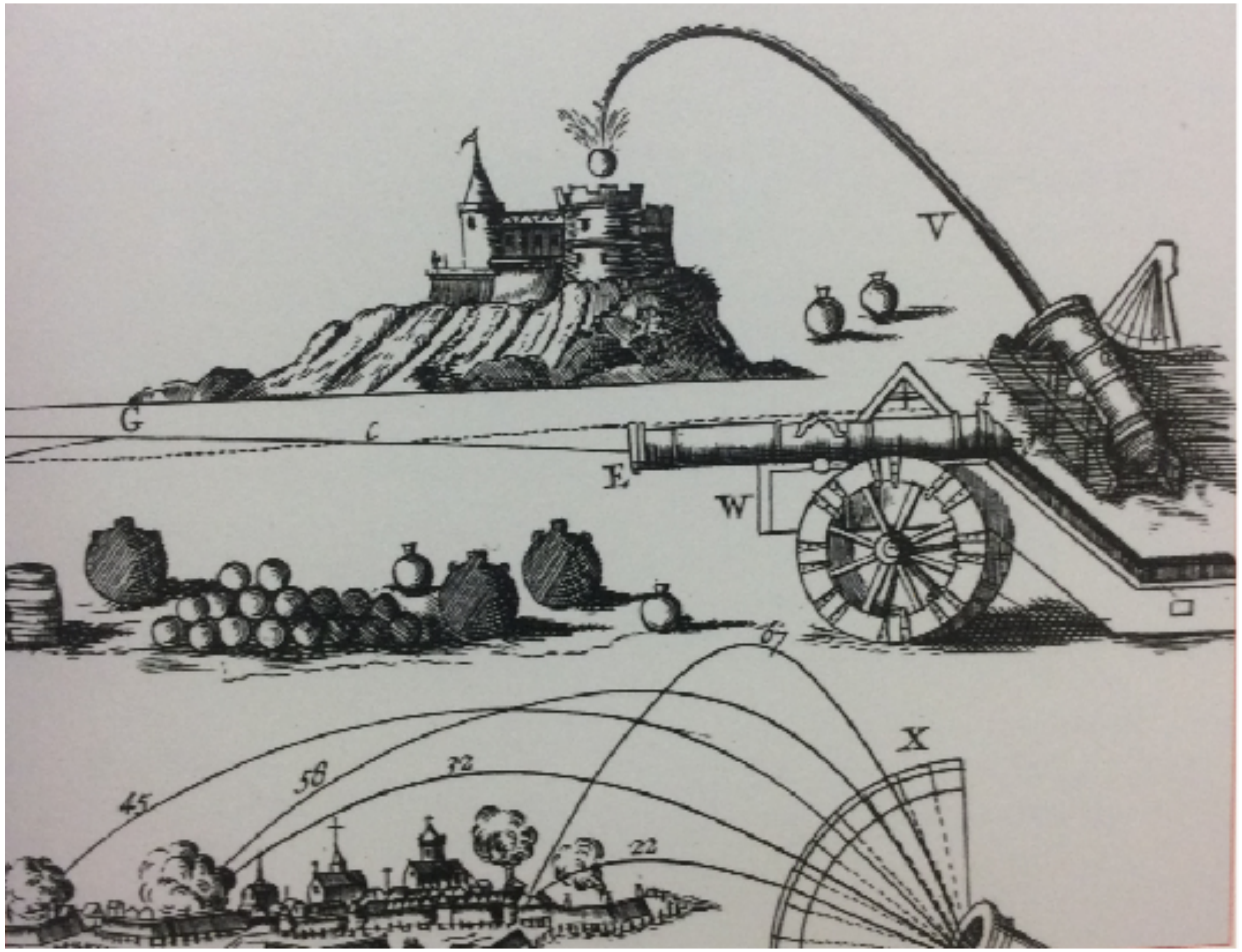

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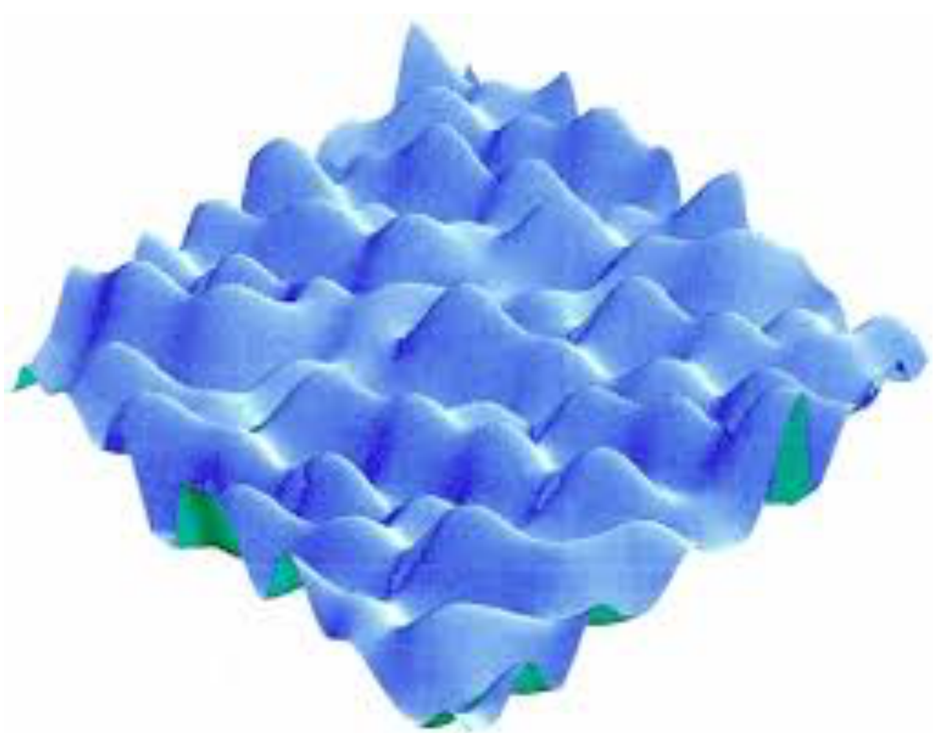

Landscape of vacua

Higgs mass depends on the vacuum where we live.

Not quite like g. Vacua are **causally disconnected**. Cannot go there and check.

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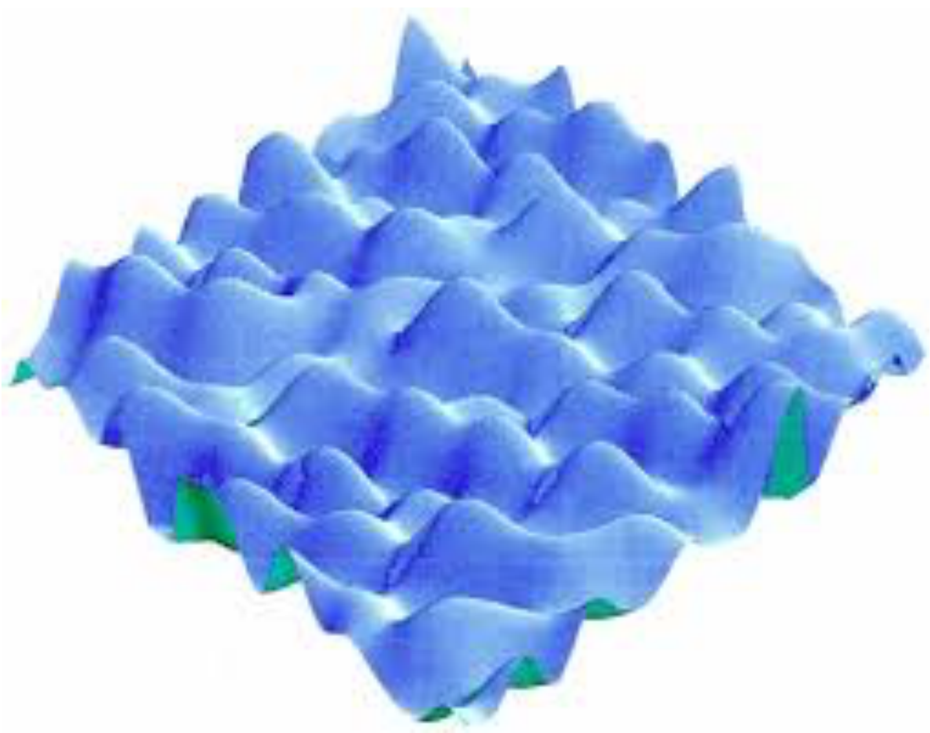

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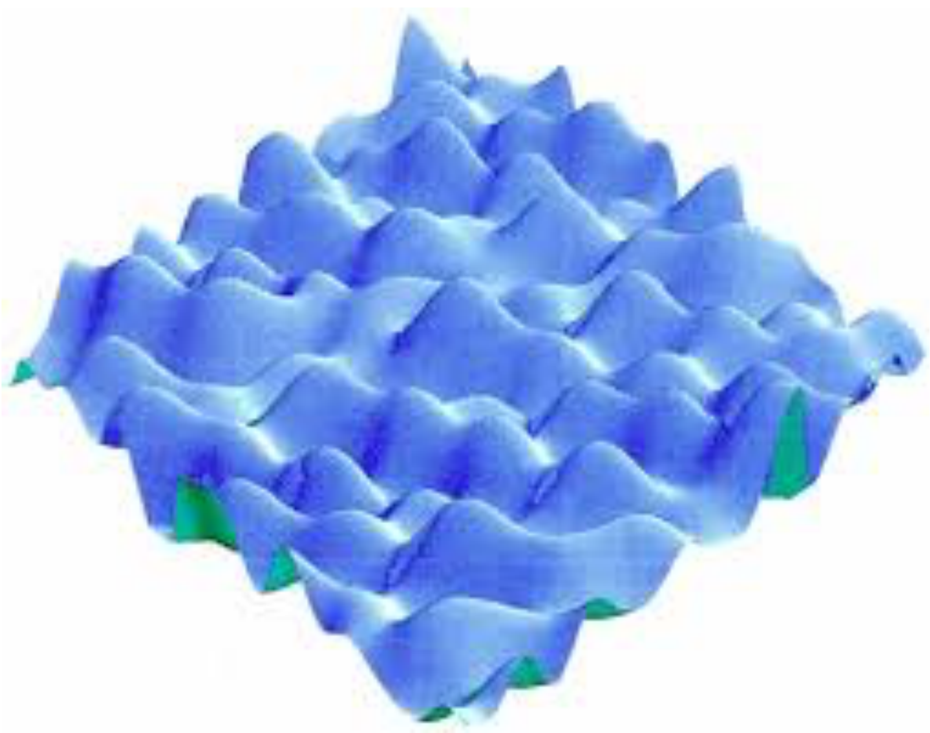

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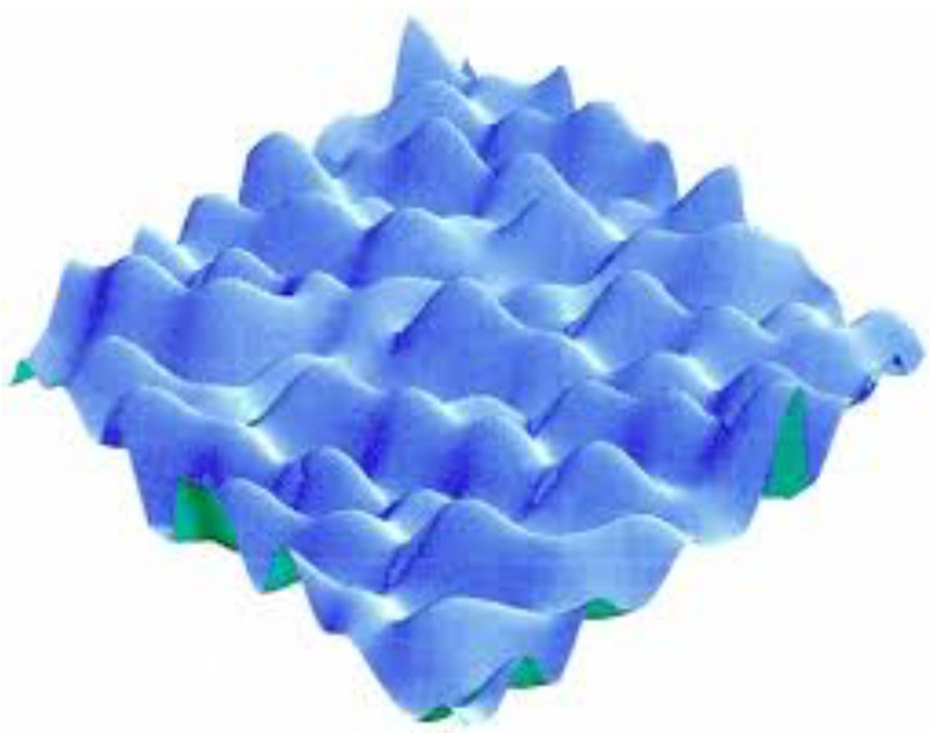

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We live where we can. There might be **upper bound** on m_H for us to exist.

Landscape distribution peaks at $\Lambda_{\rm SM}$, but has a tail. Likely to live **close to the upper bound**.

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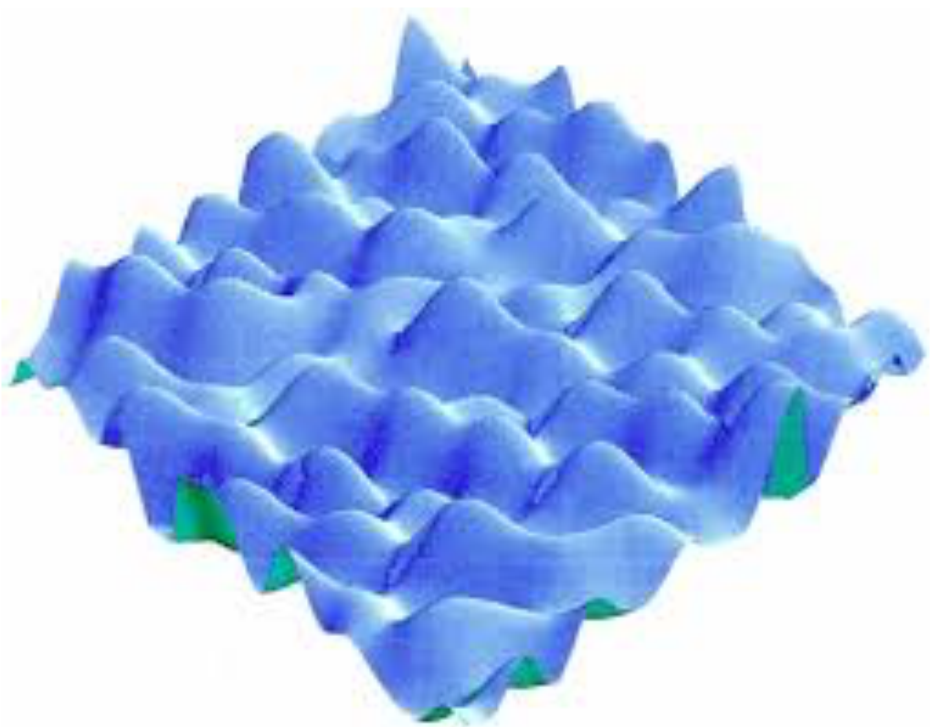

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Successful Weinberg prediction of the Cosmological Constant:

For galaxies to form, it must be:

$$\Lambda_{\rm c.c.} \lesssim ({\rm few}\cdot 10^{-3}{\rm eV})^4 \sim 10^{-120} M_P^4$$

Observed value:

$$\Lambda_{\rm c.c.} \simeq (2\cdot 10^{-3}{\rm eV})^4$$

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(to present-day understanding) [Graham, Kaplan, Rajendran, 2015]

Dynamical is a parameter whose value is set by **time evolution**.

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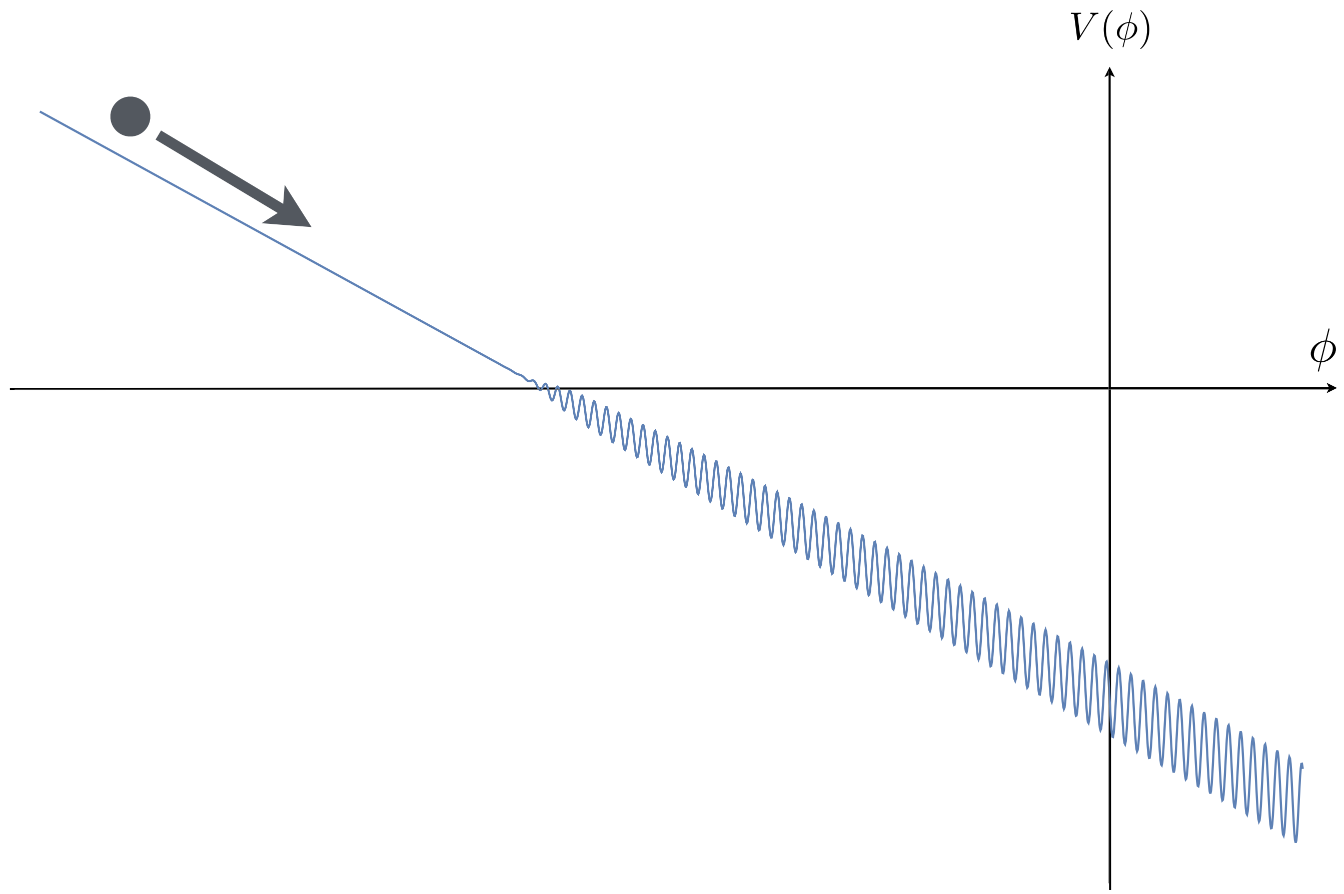
Recent proposal: **Relaxion**

Field-dependent Higgs mass **Proportional to Higgs VEV**

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4 \cos(\phi/f)$$



Field rolls during Inflation.

Stops right after $m_H^2 < 0$. Because of the cos term.

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