Beyond the Standard Model

Andrea Wulzer

Università degli Studi di Padova

INFN Istituto Nazionale di Fisica Nucleare

BSM: What For ?

Physics is the continuos effort towards a deeper understanding of the laws of Nature.

The SM is the state-of-the-art of our knowledge of Fundamental Interactions.

BSM aims to unveil the microscopic origin of the SM, of its fields, Lagrangian and parameters.

BSM $\neq$ **Beyond** the SM

(goal is not ``new physics” per se)

BSM $=$ **Behind** the SM

(goal is explain SM mysteries)

Plan of the lecture

1. **No-Lose Theorems** (or, why the Higgs is revolutionary)

2. **The “SM-only” Option**

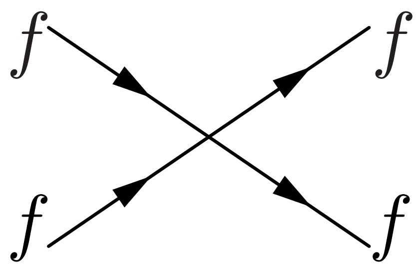
3. **The Naturalness Argument**

4. **What if Un-Natural?**

No-Lose Theorems

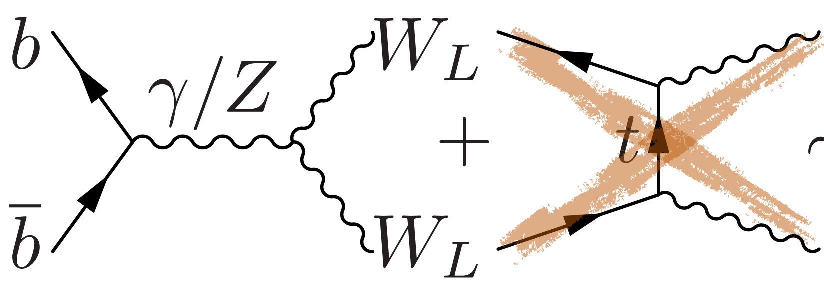
A number of **guaranteed** discoveries in the history of HEP

Beyond the Fermi Theory:



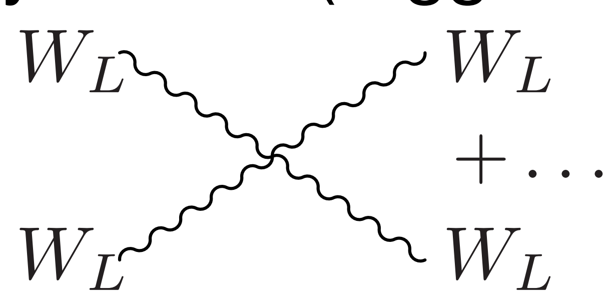
$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \quad \Longrightarrow \quad m_W < 4\pi v$$

Beyond the Bottom Quark:



$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \quad \Longrightarrow \quad m_t < 4\pi v$$

Beyond the (Higgsless) EW Theory:



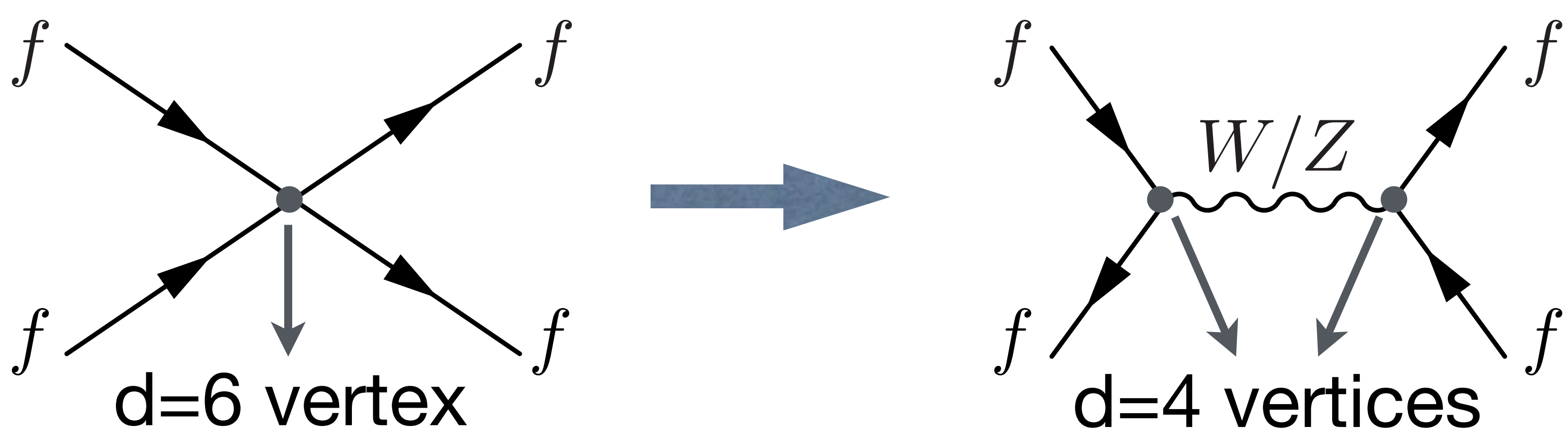
$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \quad \Longrightarrow \quad m_H < 4\pi v$$

Each secretly (ask if interested) due to d=6 non-renorm. operators, signalling nearby new physics.

No-Lose Theorems

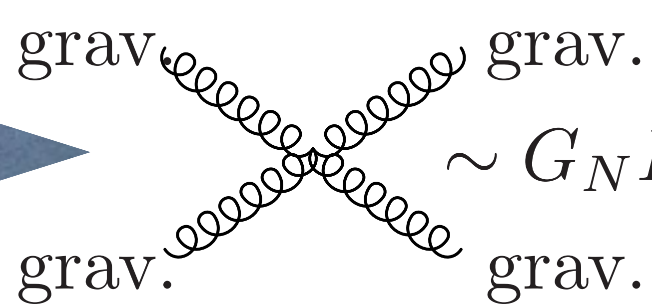
Each time we exploit one No-Lose Theorem, we get rid of one d=6 operator …

e.g.



… and only one is left after Higgs discovery …

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



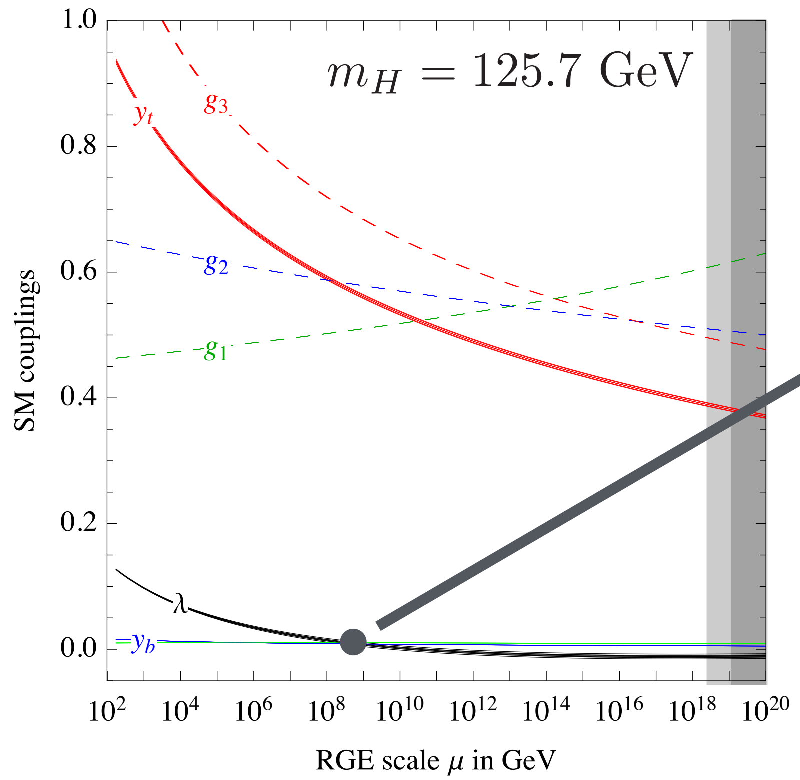
$\sim G_N E^2 \simeq E^2/{M_{\rm P}}^2 < 16\pi^2 \;\Longrightarrow\; \Lambda_{\rm SM} \lesssim M_{\rm P}$

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

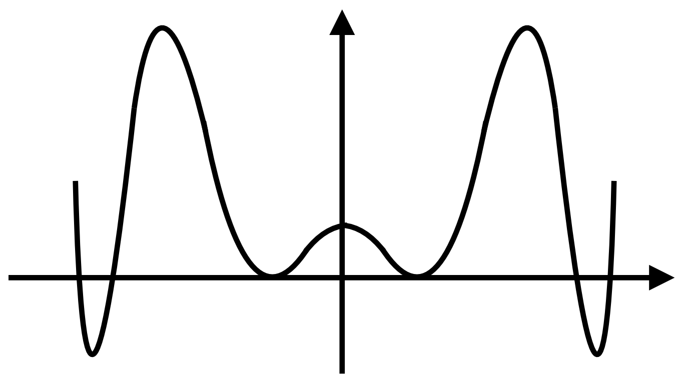
No-Lose Theorems

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

The statement survives quantum corrections:

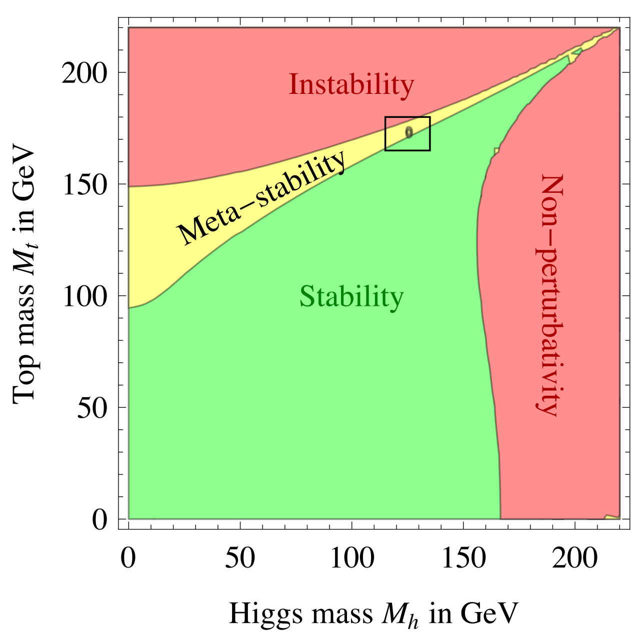


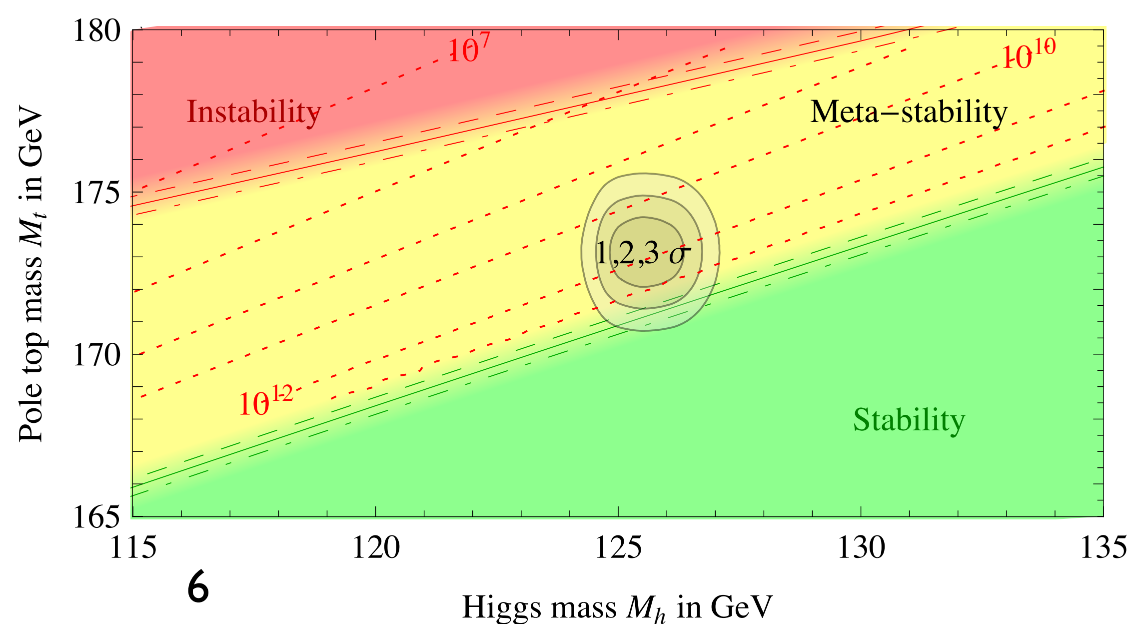
- No relevant Landau Pole
- **Instability scale** $\sim 10^9$ GeV



New vacuum, but no need of N.P.

Non trivial result. Depends on Higgs and Top mass:





No-Lose Theorems

The SM **can be extrapolated** up the Planck scale.

We do have exp. evidences of BSM, but none necessarily pointing to light/strongly-coupled enough new physics.

Higgs was the last guaranteed discovery.

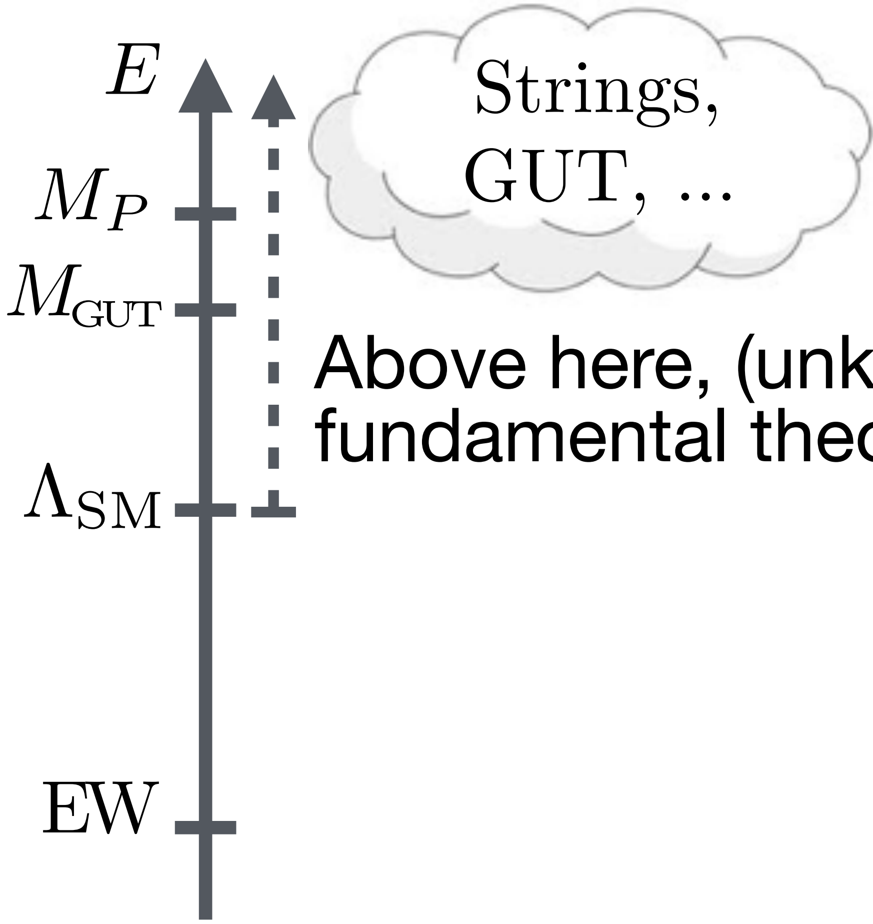
"No guaranteed discoveries" = "post-Higgs depression"

Problem is that Higgs gets read of all the **d>4** operators. But introduces one of **d<4**:

$$\frac{m_H^2}{2} H^\dagger H \longrightarrow$$

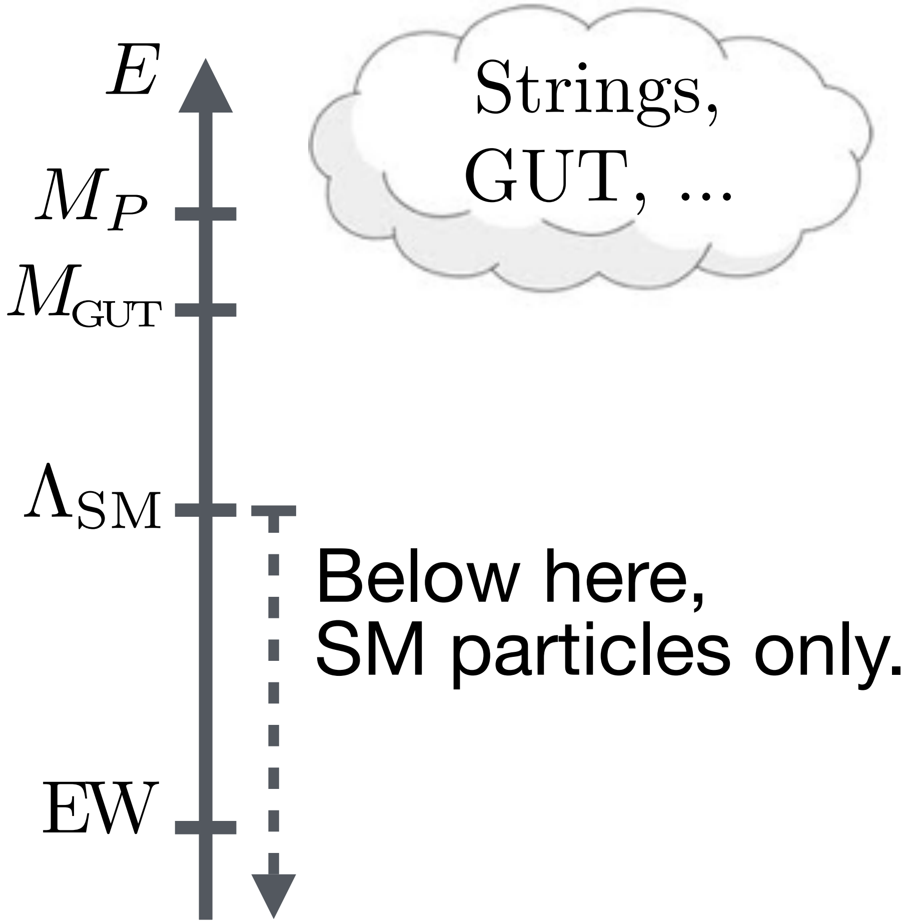
The **Naturalness Problem**:
Why $m_H \ll \Lambda_{\rm SM}$?
(to be discussed later)

The “SM-only” Option



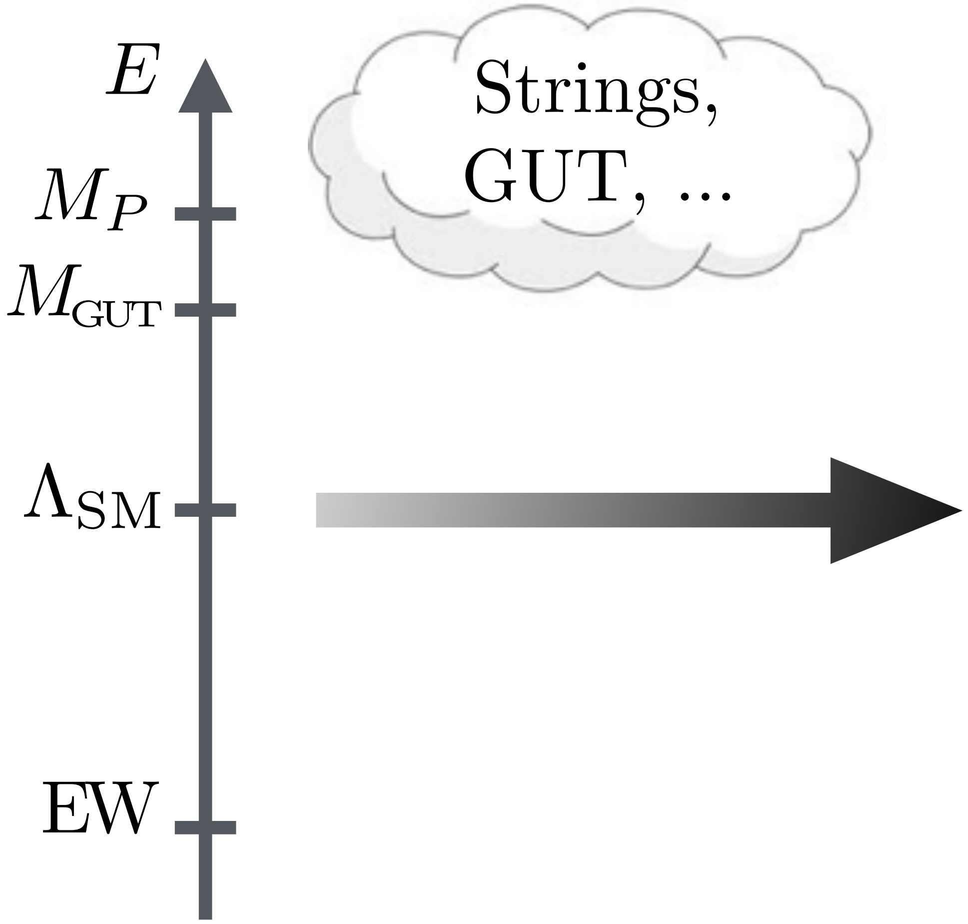
Above here, (unknown) fundamental theory.

The "SM-only" Option



Below Λ_{SM}, fundamental theory reduces to SM fields and SM (Lorentz+gauge) symmetries.

The “SM-only” Option



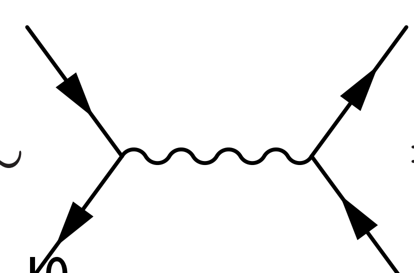
$\mathcal{L} =$ “ sum of op.s made of SM fields and compatible with SM symm. ”

$$= \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\text{SM}}}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\text{SM}}^2}\mathcal{L}^{(d=6)} + \ldots$$

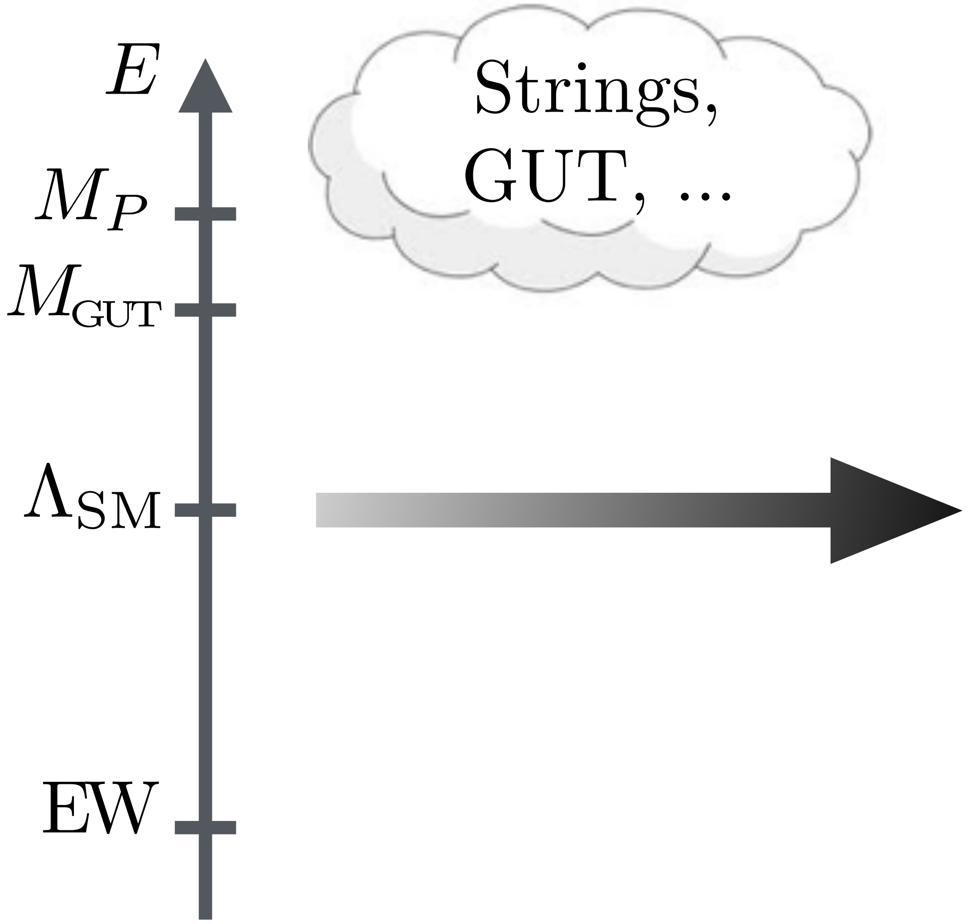
dimensional analysis for coefficients

Below Λ_{SM}, fundamental theory reduces to SM fields and SM (Lorentz+gauge) symmetries.

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

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

The "SM-only" Option



$\mathcal{L} =$ " sum of op.s made of SM fields and compatible with SM symm. "

$$= \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\mathrm{SM}}}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\mathrm{SM}}^2}\mathcal{L}^{(d=6)} + \dots$$

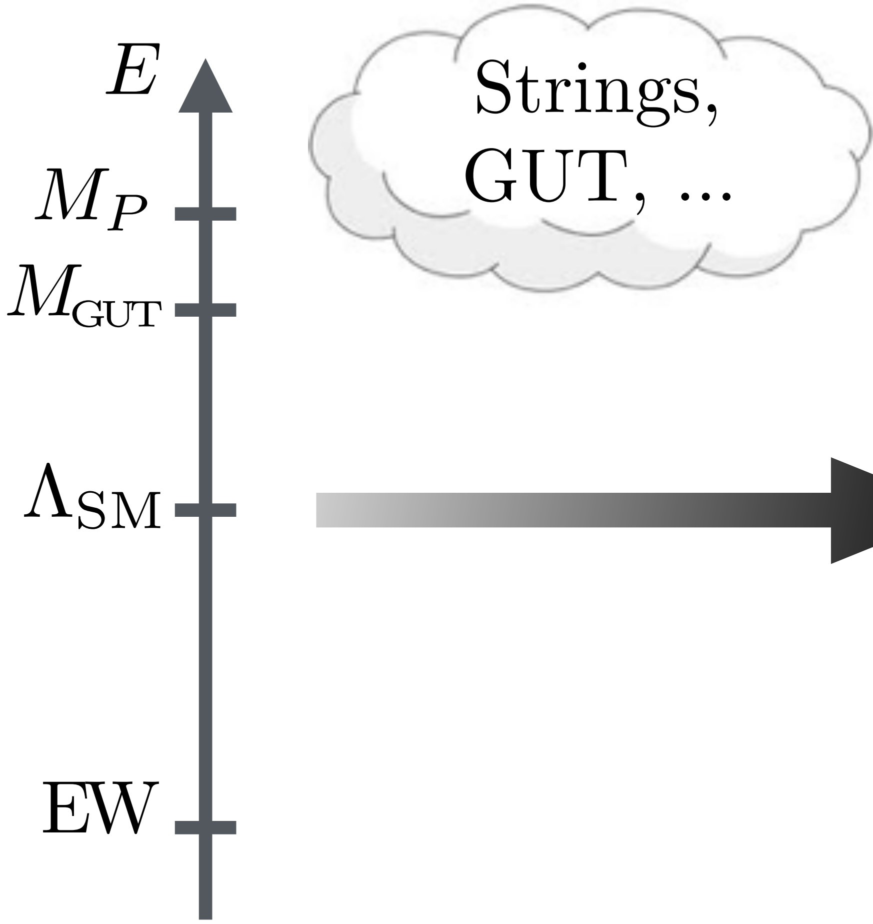
dimensional analysis for coefficients

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

$(\Gamma_{\mathrm{proton}}/m_{\mathrm{proton}})_{\mathrm{exp.}} < 10^{-64}$ **!!** $\longleftrightarrow$ $(\Gamma_{\mathrm{proton}}/m_{\mathrm{proton}})_{(d=4)} = 0$
accidental Baryon num. symm.

$\mathrm{BR}(\mu \to e\gamma)_{\mathrm{exp}} < 10^{-12}$ **!!** $\longleftrightarrow$ $\mathrm{BR}(\mu \to e\gamma)_{(d=4)} = 0$
accidental Lepton family symm.

The "SM-only" Option



$\mathcal{L} =$ " sum of op.s made of SM fields and compatible with SM symm. "

$$= \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\rm SM}}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\rm SM}^2}\mathcal{L}^{(d=6)} + \dots$$

dimensional analysis for coefficients

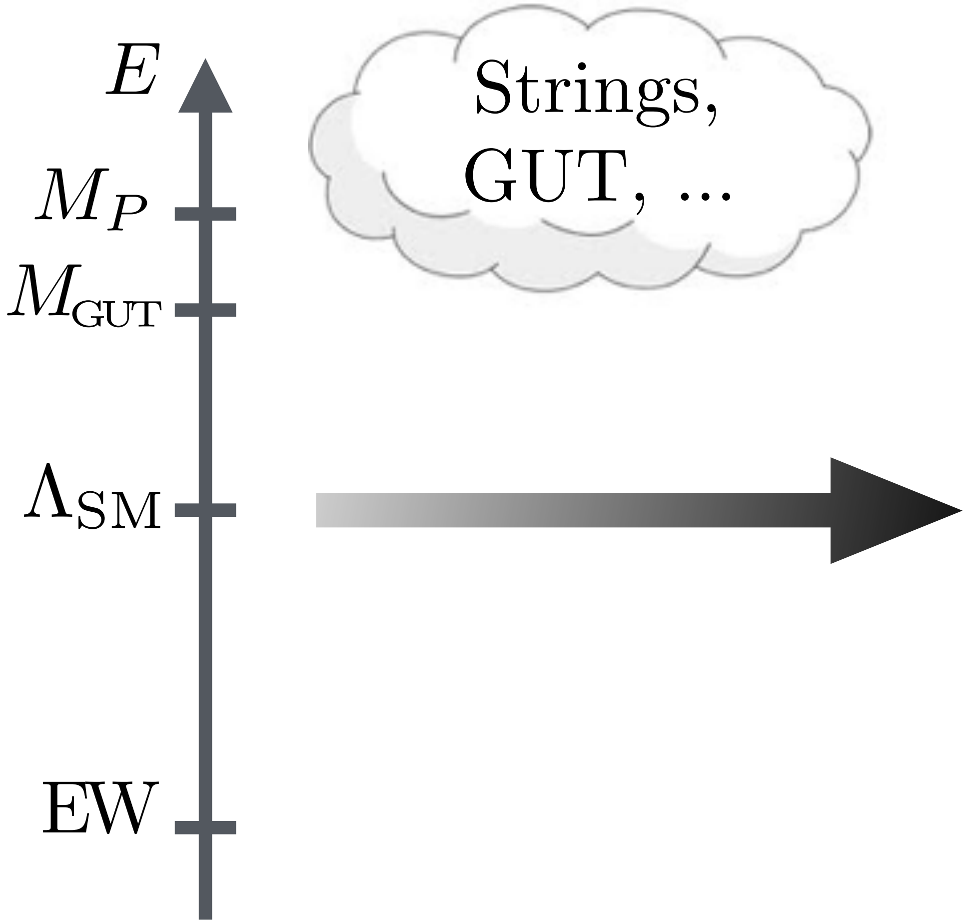
$\mathcal{L}^{(d=4)}$: describes all what **we see** (almost) …
… and what **we don't see.**

$\mathcal{L}^{(d=5)}$: can describe what **we see small**
right ν mass size if $\Lambda_{\rm SM} \sim 10^{14}\,{\rm GeV} \sim M_{\rm GUT}$!!

$$\mathcal{L}^{(d=5)} = (\overline{L}_L H^c)(L_L^c H^c) \quad \longleftrightarrow \quad m_\nu \sim v^2/\Lambda_{\rm SM}$$

unique (Weinberg) operator — Majorana neutrino mass-matrix

The "SM-only" Option



$\mathcal{L} =$ " sum of op.s made of SM fields and compatible with SM symm. "

$$= \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\rm SM}}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\rm SM}^2}\mathcal{L}^{(d=6)} + \dots$$

dimensional analysis for coefficients

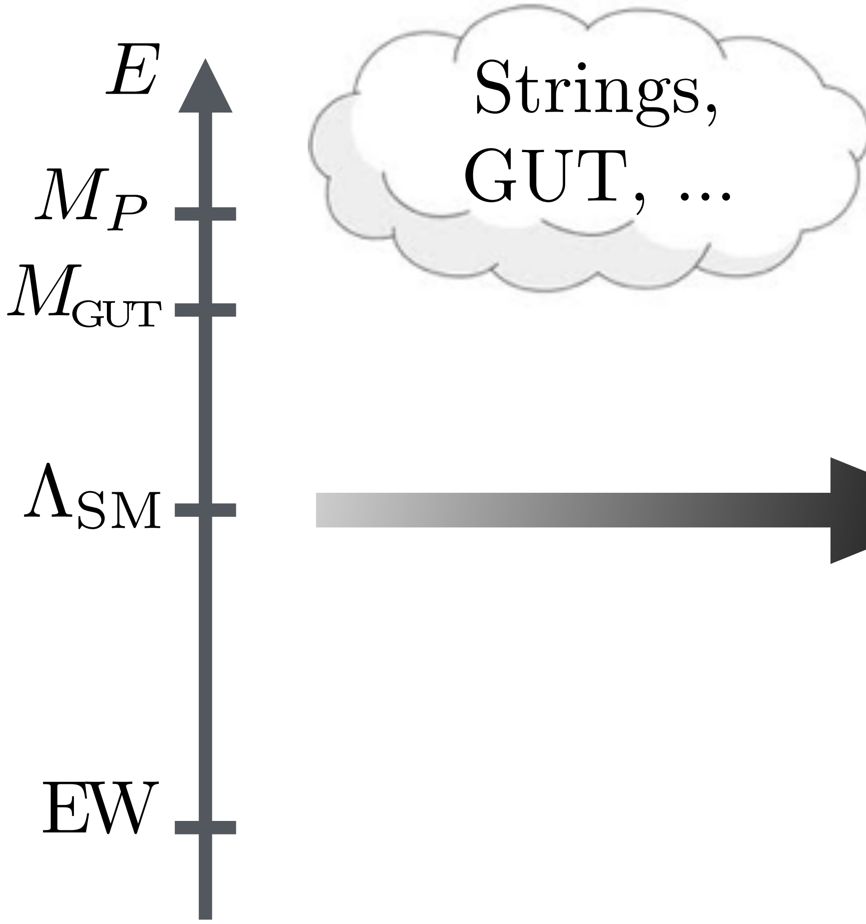
$\mathcal{L}^{(d=4)}$: describes all what **we see** (almost) …
… and what **we don't see.**

$\mathcal{L}^{(d=5)}$: can describe what **we see small**
right ν mass size if $\Lambda_{\rm SM} \sim 10^{14}{\rm GeV} \sim M_{\rm GUT}$!!

$\mathcal{L}^{(d=6)}$: not yet seen. $\Lambda_{\rm SM} \gtrsim 10^{15}{\rm GeV}$ from proton decay.

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

The "SM-only" Option



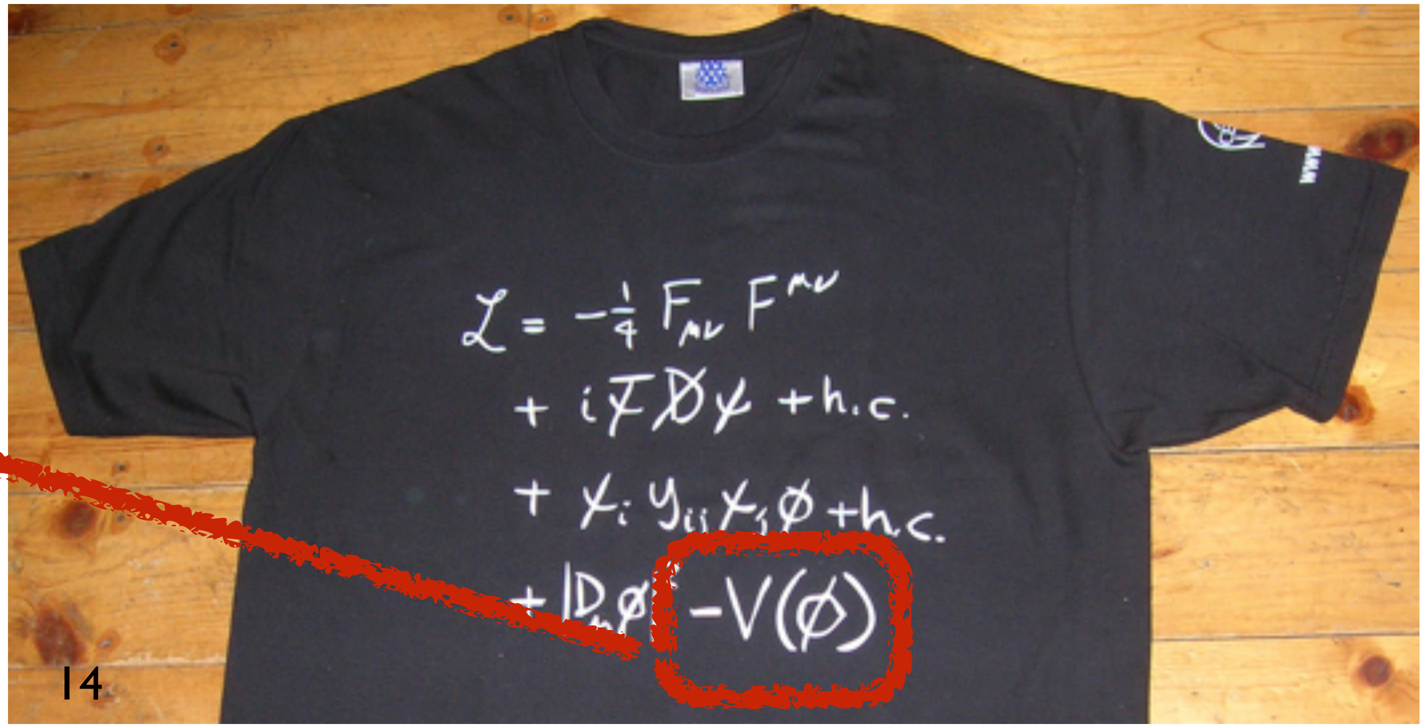
$$\mathcal{L} = \text{“ sum of op.s made of SM fields and compatible with SM symm. ”}$$

$$= \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\text{SM}}}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\text{SM}}^2}\mathcal{L}^{(d=6)} + \dots$$

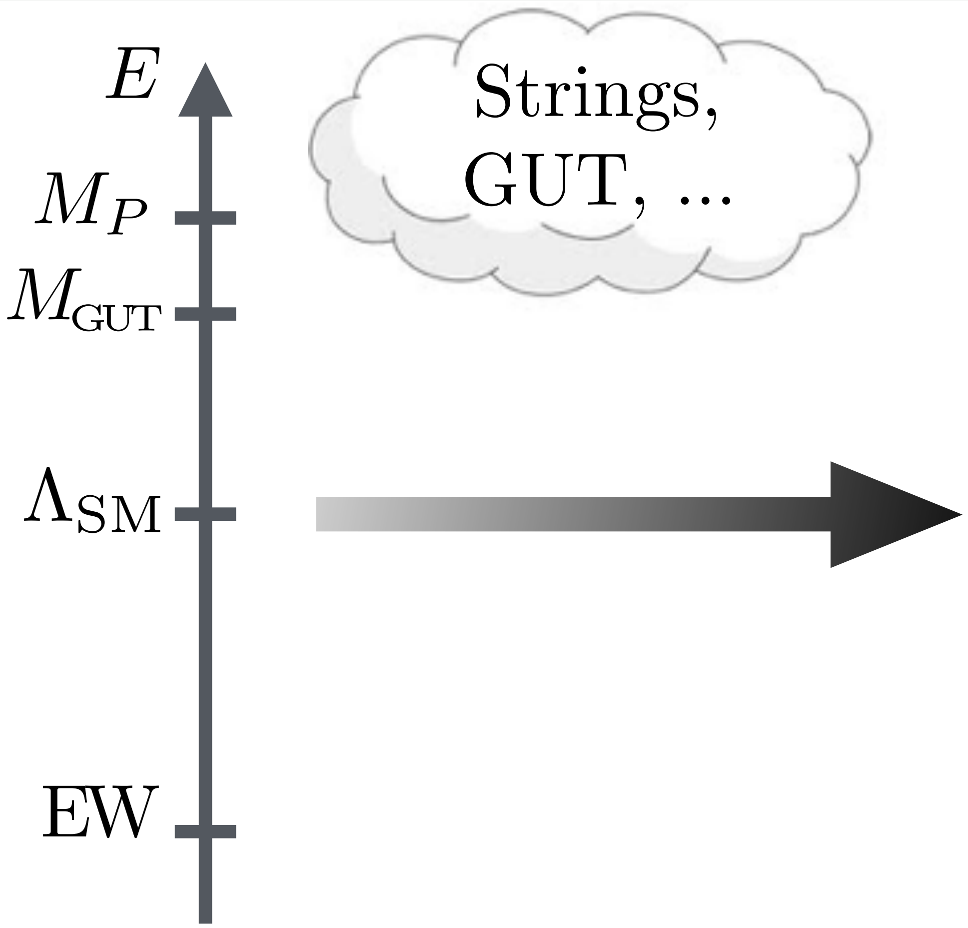
dimensional analysis for coefficients

But we forgot one operator.

$$\mathcal{L}^{(d=2)} = H^\dagger H$$



The “SM-only” Option



$\mathcal{L} =$ “ sum of op.s made of SM fields and compatible with SM symm. ”

$$= \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\rm SM}}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\rm SM}^2}\mathcal{L}^{(d=6)} + \dots$$

dimensional analysis for coefficients

But we forgot one operator. Using again **dim. analysis**:

$$\mathcal{L}_{H\text{-mass}} = \Lambda_{\rm SM}^2 \mathcal{L}^{(d=2)} = \Lambda_{\rm SM}^2 H^\dagger H$$

Instead, $\mathcal{L}_{H\text{-mass}} = \dfrac{m_H^2}{2} H^\dagger H$

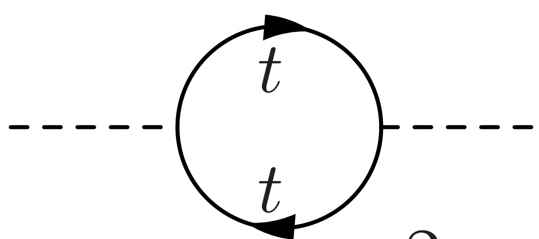
The **Naturalness Problem**: Why $m_H \ll \Lambda_{\rm SM}$?

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

The Naturalness Argument
(not a Theorem)

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

SM Contribution



$$\delta_{\rm SM} m_H^2 = \frac{3y_t^2}{8\pi^2}\Lambda_{\rm SM}^2$$

(NOT a quadratic divergence calculation!!)

$$m_H^2 = \int_0^\infty dE \frac{dm_H^2}{dE}(E; p_{\rm FT})$$

$$= \int_0^{\lesssim\Lambda_{\rm SM}} dE(\ldots) + \int_{\lesssim\Lambda_{\rm SM}}^\infty dE(\ldots)$$

$$= \delta_{\rm SM} m_H^2 + \delta_{\rm BSM} m_H^2$$

UV (BSM) Contribution

$$\delta_{\rm BSM} m_H^2 = c\Lambda_{\rm SM}^2$$

Since the result must be $(125\,{\rm GeV})^2$, two terms must be ~ equal and opposite and cancel, by an amount

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125\,{\rm GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\rm SM}}{500\,{\rm GeV}}\right)^2$$

Fine-tuning: quantifies the "degree of Un-Naturalness"

The Naturalness Argument
(not a Theorem)

"Is m_H Natural?" $=$ "Is m_H Predictable?"

What to do with that?

Measure what is measurable,
and make measurable what is not so.

G.Galilei

We must search for "Natural" new physics at the TeV.

- If we find it, go out and celebrate!
(than come back and measure it better)
- If we don't, **measure Un-Naturalness**

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{\mathrm{SM}}}{500\,\mathrm{GeV}}\right)^2$$

The Naturalness Argument
(not a Theorem)

"Is m_H Natural?" $\quad = \quad$ "Is m_H Predictable?"

What to do with that?

Measure what is measurable,
and make measurable what is not so.

G.Galilei

We must search for "Natural" new physics at the TeV.

- If we find it, go out and celebrate!
  (than come back and measure it better)
- If we don't, **measure Un-Naturalness**

Where to stop?

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

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

What if Un-Natural?
(to present-day understanding)

(Un-)Naturalness searches might result in either:

1) "Natural" new physics discoveries
2) The discovery of Un-Naturalness

Case 1) is easy … what case 2) means?

If Un-Natural, m_H has no **microscopic** origin (e.g. $\neq G_F$).

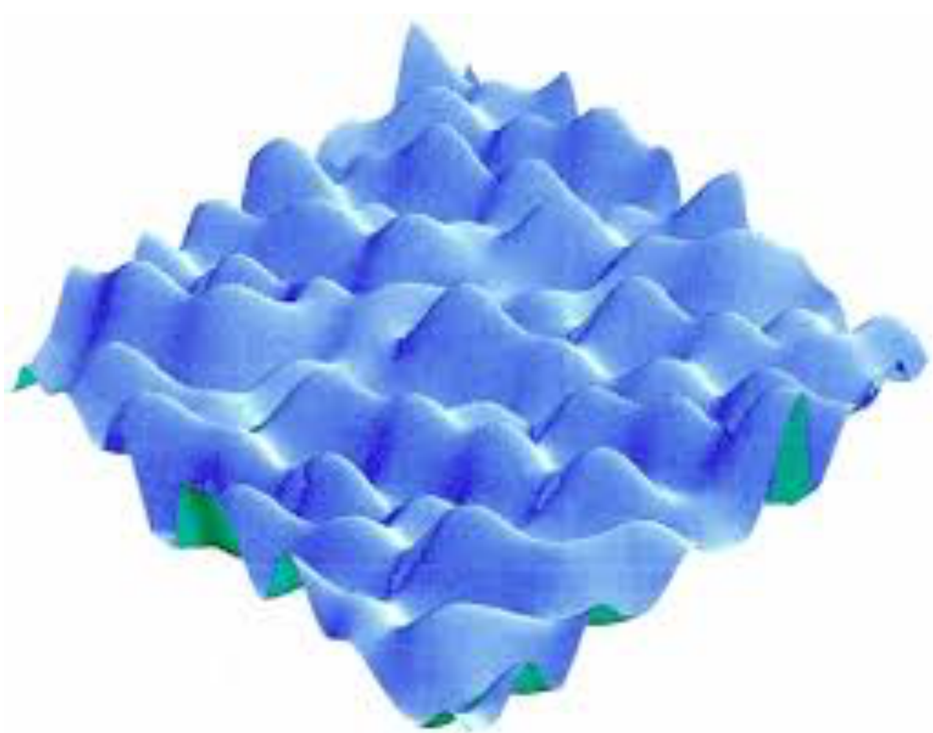
It could:

- be a fundamental input par. of the Final Theory
- have **environmental**, perhaps **anthropic** origin
- have **dynamical** (set by time evolution) origin

What if Un-Natural?
(to present-day understanding)

Environmental is a parameter whose value is dictated by **external conditions**

Example is gravity of Earth $\mathrm{g} = 9.81\mathrm{m/s^2}$. Fundamental input parameter of the theory of **Ballistics**.
Set by Earth mass and radius. Different on other planets.



Landscape of vacua

Higgs mass depends on the vacuum where we live.

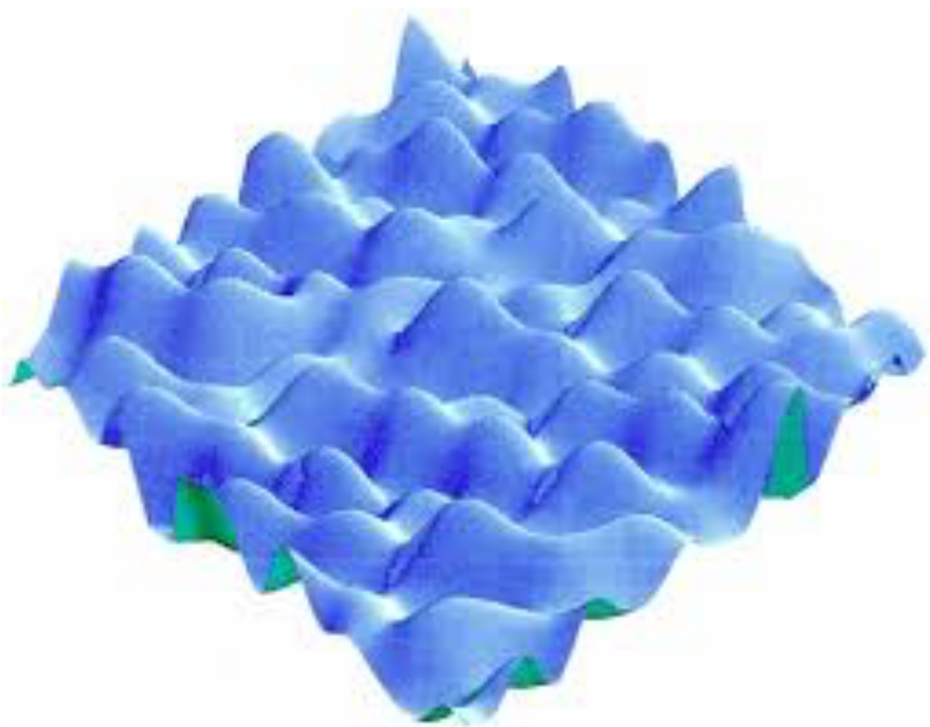
Not quite like g. Vacua are **causally disconnected**.
Cannot go there and check.

Not a solution. Why $m_H \ll \Lambda_{\mathrm{SM}}$?
Maybe **Anthropic selection**.

What if Un-Natural?
(to present-day understanding)

Environmental is a parameter whose value is dictated by **external conditions**

Anthropic selection: we live where we can.
There might be upper bound on m_H for us to exist.
Distribution of vacua peaks at $\Lambda_{\rm SM}$, but has a tail.
Likely to live **close to the upper bound**.



Landscape of vacua

Successful Weinberg prediction of the Cosmological Constant:

For galaxies to form, it must be:

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

Observed value:

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

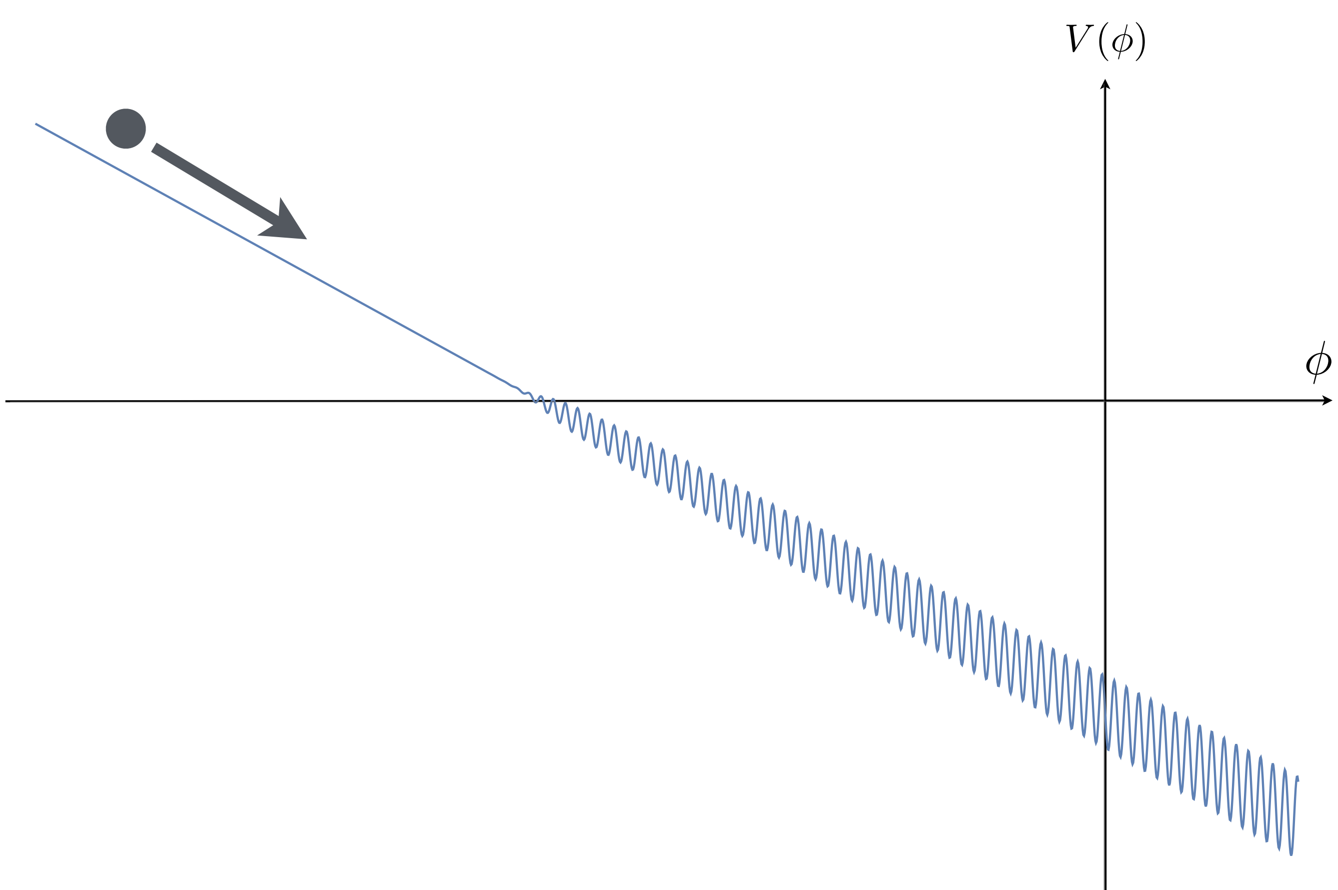
What if Un-Natural?
(to present-day understanding) [Graham, Kaplan, Rajendran, 2015]

Dynamical is a parameter whose value is set by time evolution. In a **deterministic, not statistical** way.

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.

What if Un-Natural?
(to present-day understanding)

IN SUMMARY: You might like/believe these radical speculations or not. Still, they show the dramatic impact Un-Naturalness discovery would have on our field.