Behind & Beyond the Standard Model

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The Principles

✦ Quantum Mechanics

✦ Relativity

- spacetime translations ⟶ P^0, P^i
- rotations & boosts ⟶ J^i, K^i

Lorentz

$$[J^i, J^j] = i\epsilon^{ijk} J^k$$
$$[J^i, K^j] = i\epsilon^{ijk} K^k$$
$$[K^i, K^j] = -i\epsilon^{ijk} J^k$$

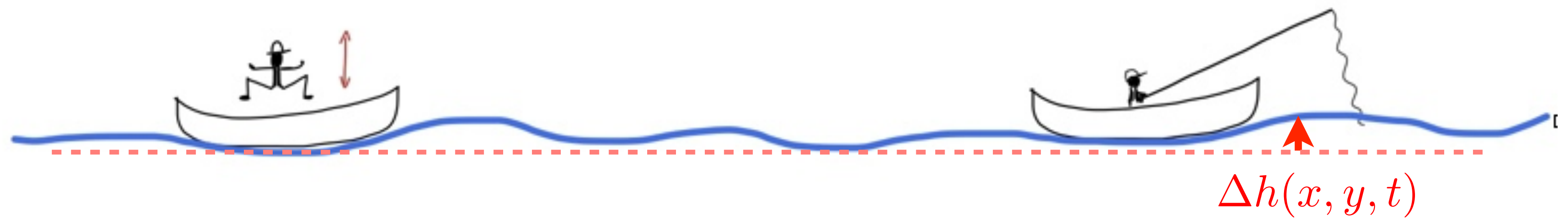
Galilei

$$[J^i, J^j] = i\epsilon^{ijk} J^k$$
$$[J^i, K^j] = i\epsilon^{ijk} K^k$$
$$[K^i, K^j] = 0$$

Consequences

- limiting speed → instantaneous interactions impossible

fields are needed



- Relativity algebra must be represented on Hilbert space $\mathcal{H}$

→ multiplets labelled by two quantum numbers m & s

$$m^2 \equiv P^\mu P_\mu$$

$$-m^2\, s(s+1) \equiv W^\mu W_\mu \qquad\qquad W^\mu \equiv \left(\vec{P}\cdot\vec{J},\ P^0\vec{J}+\vec{P}\wedge\vec{K}\right)$$

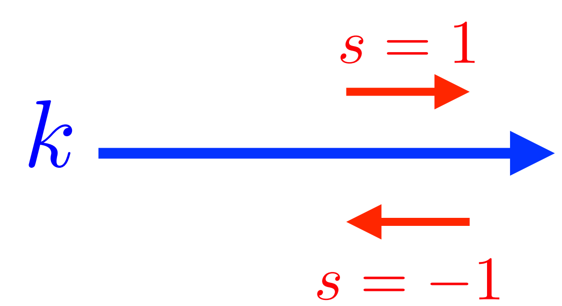
the building blocks are nothing but particles

- particles nicely arise as the smallest amplitude fluctuations of quantum fields

- Relativity ⇨ causality → integer spins ⇨ bosons; half-integer spins ⇨ fermions

- massless particles carry only two spin polarizations for any $s \neq 0$

Ex: photon has spin 1 but only two polarizations



→ interactions subject to powerful geometric constraints : **gauge symmetry**

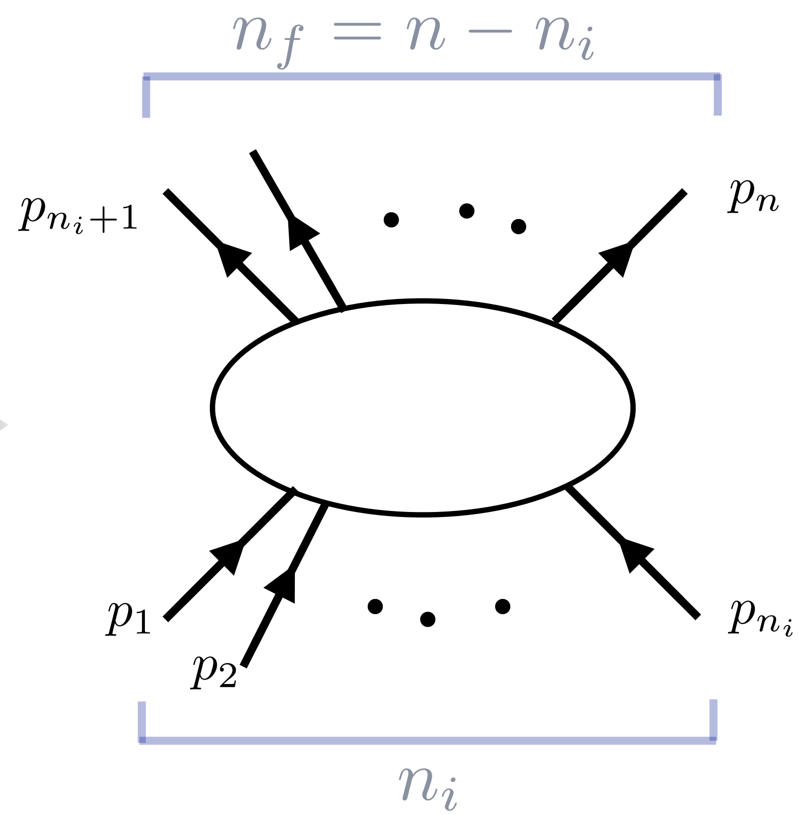
Ex
- Standard Model forces → $SU(3) \times SU(2) \times U(1)$
- gravity → general coordinate transformations

Quantum Field Theory (QFT)

Fields + Principles

$$S = \int d^4x \, \mathcal{L}(\phi_a, \partial_\mu \phi_a)$$

$$\int D\phi \; \phi_1(x_1) \ldots \phi_n(x_n) \, e^{iS}$$



$$= \mathcal{A}(p_1, \ldots, p_n)$$

SM just particular incarnation of QFT

gauge fields $SU(3) \times SU(2) \times U(1)_Y \times \text{diffs}$

Higgs field $H = (\mathbf{1}, \mathbf{2}, 1)$

spinors $q_L\,,\; u_R\,,\; d_R\,,\; \ell_L\,,\; e_R \;\times\; 3\;\text{families}$

$(\mathbf{3}, \mathbf{2}, 1/3)\;\; (\mathbf{3}, \mathbf{1}, 4/3)\;\; (\mathbf{3}, \mathbf{1}, -2/3)\;\; (\mathbf{1}, \mathbf{2}, -1)\;\; (\mathbf{1}, \mathbf{1}, -2)$

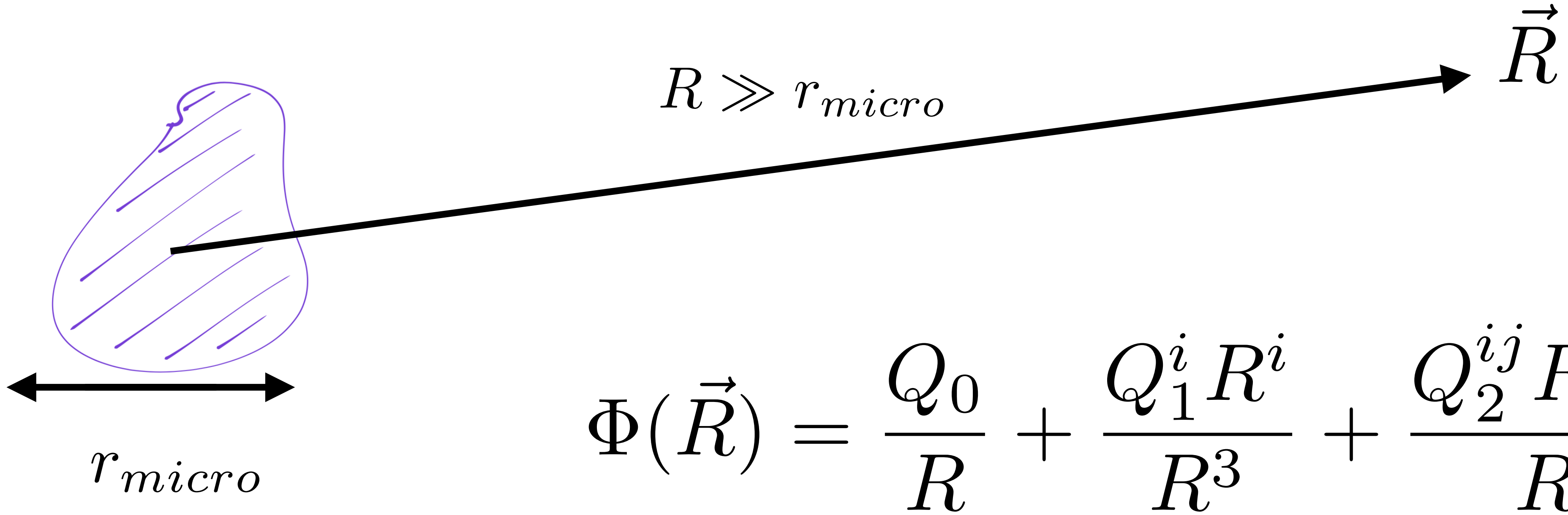
- QFT makes us builders of possible worlds

... but it offers an infinity of them while we only have got one

how was it picked amid such infinity?

Why can we do physics ?

finite # inputs → ∞ many outputs



$$\Phi(\vec{R}) = \frac{Q_0}{R} + \frac{Q_1^i R^i}{R^3} + \frac{Q_2^{ij} R^i R^j}{R^5} + \dots$$

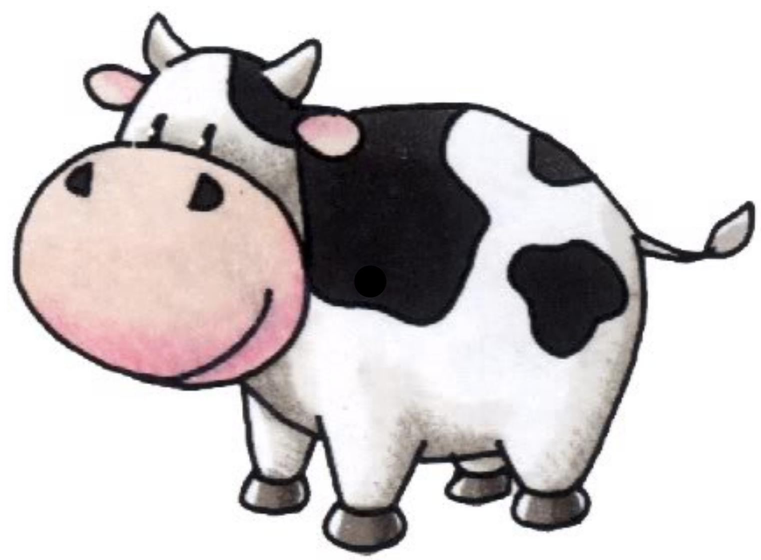
n-multipole contribution $\sim \left(\frac{r_{micro}}{R}\right)^n$

at fixed accuracy

- $R \to$ large: fewer multipoles needed ➡ **Universality**
- $R \to$ small: more multipoles needed ➡ **Reductionism**

Existence of separation of scales is key to Physics

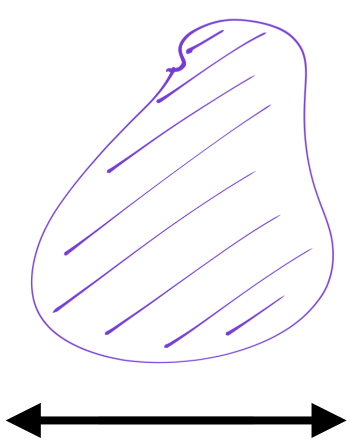
Long Distance Physics: Simplicity & Accidental Symmetries



accidental

$SO(3)$

Ex.: electrostatic potential at large distance



r_{micro}

$R \gg r_{micro}$ $\longrightarrow$

$$\Phi(R) = \frac{Q_0}{R} + \frac{\vec{Q}_1 \cdot \vec{R}}{R^3} + \frac{Q_2^{ij} R_i R_j}{R^5} + \ldots$$

$$SO(3) \supset SO(2) \supset \varnothing$$

long distances &
long times → systematic expansion in powers of

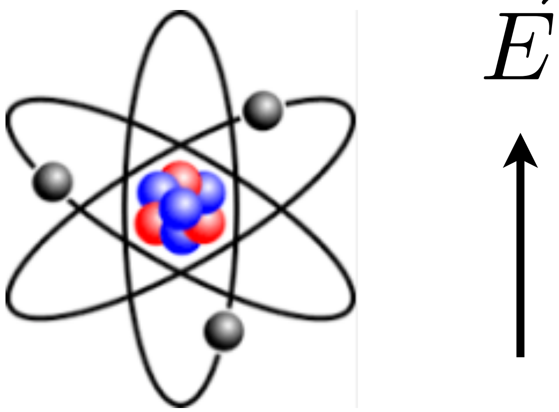
$$\left[\begin{array}{l} \frac{r_{micro}}{R} \\ \frac{t_{micro}}{t} \end{array} \right.$$

finite precision → finite number of parameters to explain experiments → [Infrared Simplicity

Accidental Symmetries

Selection Rules

Ex: atom in external electric field



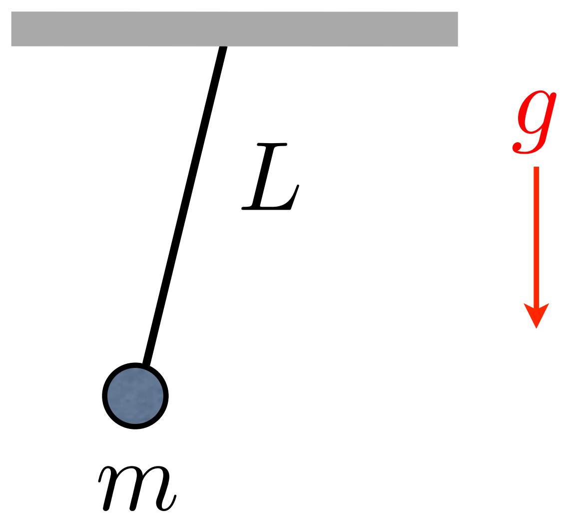
$\vec{E}$

electric dipole

$$\langle \Psi_0(\vec{E}) | d_j | \Psi_0(\vec{E}) \rangle \overset{O(3)}{=} E_j \, f(|\vec{E}|)$$

Dimensional Analysis

Ex.: classical pendulum



$$D_x : \vec{x} \to \lambda_x \vec{x}$$

$$D_t : t \to \lambda_t t$$

$$L \to \lambda_x L$$

$$g \to \lambda_x \lambda_t^{-2} g$$

$$m \to m$$

$$\omega = \# \sqrt{\frac{g}{L}}$$

Effective Quantum Field Theory

relativity

$$r_{\text{micro}} \equiv t_{\text{micro}} \equiv \frac{1}{M}$$

QM

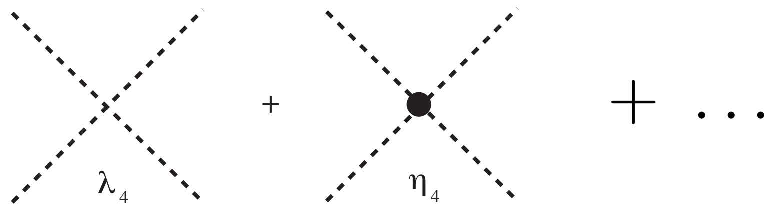
Systematic infinite expansion in powers of $\frac{1}{M}$

emphasized by K. Wilson and S. Weinberg in 70's

$$\mathcal{L} = \partial_\mu\varphi\partial^\mu\varphi - m^2\varphi^2 - \lambda_4\varphi^4 - \frac{\lambda_6}{M^2}\varphi^6 - \frac{\eta_4}{M^2}\varphi^2(\partial_\mu\varphi\partial^\mu\varphi) + \ldots$$

$$m \ll E \ll M$$

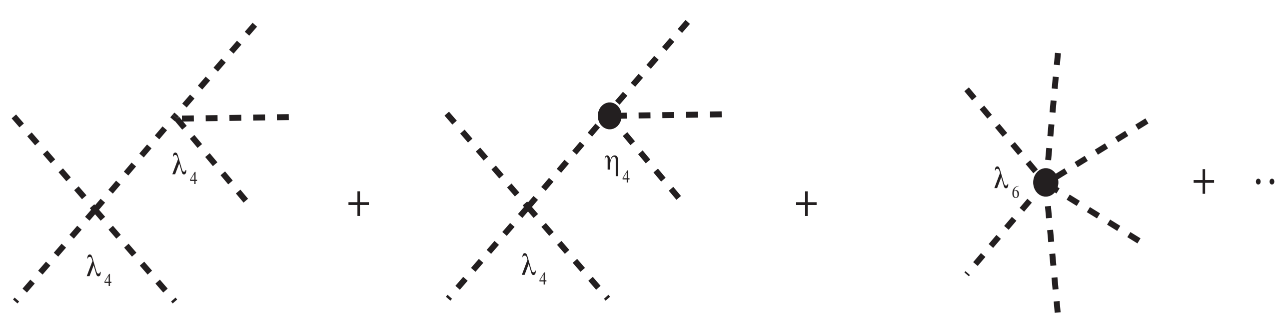
$\mathcal{A}_{2\to2} =$



$$= \lambda_4 + \eta_4 \frac{E^2}{M2} + \ldots$$

$$\xrightarrow{E \to 0} \quad \mathcal{A}_{2\to2} \simeq \lambda_4$$

$\mathcal{A}_{2\to4} =$



$$= \frac{1}{E^2}\left\{\lambda_4^2 + \lambda_4\eta_4\frac{E^2}{M^2} + \lambda_6\frac{E^2}{M^2} + \ldots\right\}$$

$$\longrightarrow \quad \mathcal{A}_{2\to2} \simeq \frac{\lambda_4^2}{E^2}$$

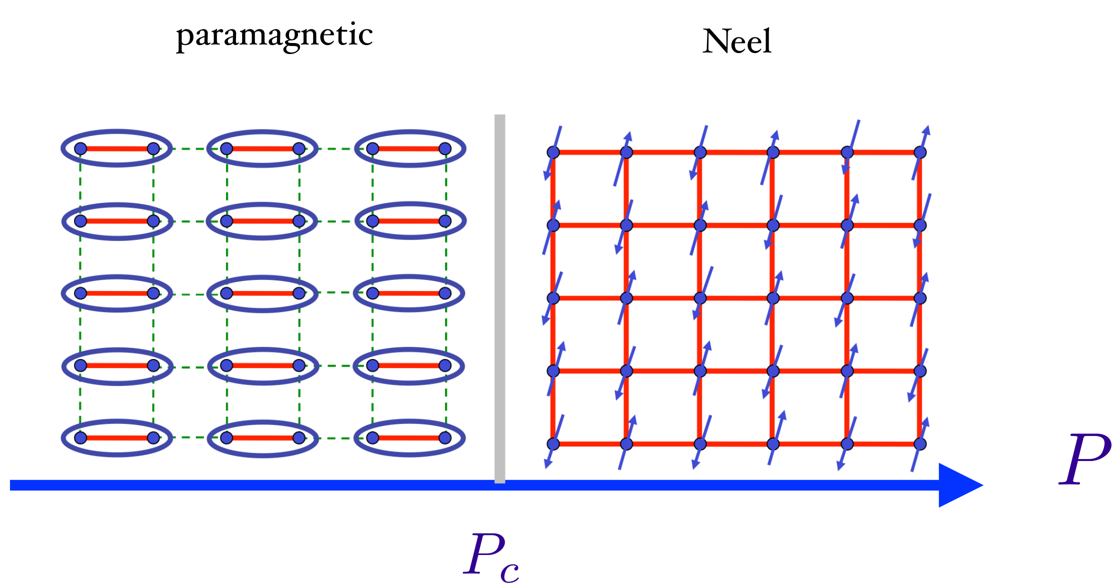
$m \ll M$ is necessary to obtain a simplified description

the most naive dimensional guess seems $m \sim M$

under what conditions can we escape this naive guess ?

Ex.: Anti-ferromagnet $V(\vec{\varphi}) = m^2(P)\vec{\varphi}\cdot\vec{\varphi} + \lambda(\vec{\varphi}\cdot\vec{\varphi})^2$ $m^2(P) = m_0^2\left(1 - \frac{P}{P_c}\right)$

Sachdev '09



Can undo ***natural*** expectation from atomic physics by ***tuning*** the pressure at a ***critical*** value in a ***landscape*** of options

The Standard Model as an Effective Field Theory

$$\mathcal{L} = \mathcal{L}^{d=2} + \mathcal{L}^{d=4} + \frac{1}{M}\mathcal{L}^{d=5} + \frac{1}{M^2}\mathcal{L}^{d=6} + \ldots$$

$$
\begin{aligned}
\mathcal{L}^{d\leq 4} \;=\; & -\frac{1}{4g_3^2}G_{\mu\nu}^2 - \frac{1}{4g_2^2}W_{\mu\nu}^2 - \frac{1}{4g_Y^2}B_{\mu\nu}^2 \\
& +|D_\mu H|^2 + \frac{1}{2}m_h^2|H|^2 - \lambda|H|^4 \\
& +\bar{q}_L \, \not{D} q_L + \bar{u}_R \, \not{D} u_R + \bar{d}_R \, \not{D} d_R + \bar{\ell}_L \, \not{D} \ell_L + \bar{e}_R \, \not{D} e_R \\
& +Y_u^{ij}\bar{q}_L^i H^\dagger u_R^j + Y_d^{ij}\bar{q}_L^i H d_R^j + Y_e^{ij}\bar{\ell}_L^i H e_R^j
\end{aligned}
$$

$$
+\frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}^a G_{\rho\sigma}^a
$$

$$\mathcal{L} = \mathcal{L}^{d=2} + \mathcal{L}^{d=4} + \frac{1}{M}\mathcal{L}^{d=5} + \frac{1}{M^2}\mathcal{L}^{d=6} + \ldots$$

beautifully explains all that we see in labs and cosmo (except dark matter)

peculiar structure of flavor & CP violation observed in multitude of very precise data

Baryon & Lepton number arise as accidental symmetries

- the neutrini are massless 🙂
- matter is stable 🙂

$m_h \simeq 0.125\ \text{TeV}$

effects we either do not observe or observe as super-tiny

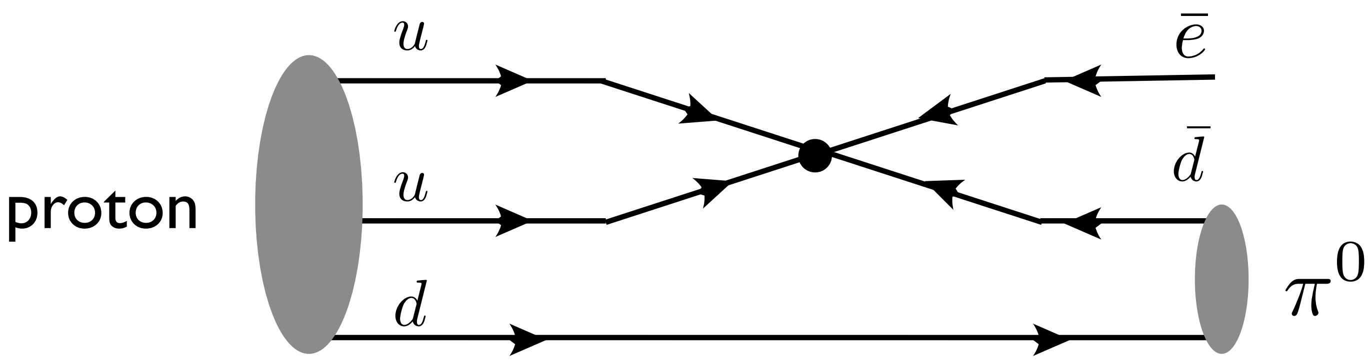
allows structure of flavor violation other than the observed one

Baryon & Lepton number are broken

- the neutrini acquire mass
- matter is unstable 😱

M must be large !!

$$\frac{1}{M^2}\mathcal{L}^{d=6} \supset \frac{\kappa_{uude}}{M^2}\, u_R u_R d_R e_R \quad \longrightarrow \quad \text{proton decay}$$



$$p \to e^+ \pi^0$$

$$\tau_{\rm proton} > 10^{34}\ \text{yrs} \quad \longrightarrow \quad \boxed{M > \sqrt{\kappa_{uude}}\ 10^{12}\ \text{TeV}}$$

$$\text{neutrino mass} \quad \longrightarrow \quad \boxed{M \sim \kappa_{\ell\ell} \times 10^{11}\ \text{TeV}}$$

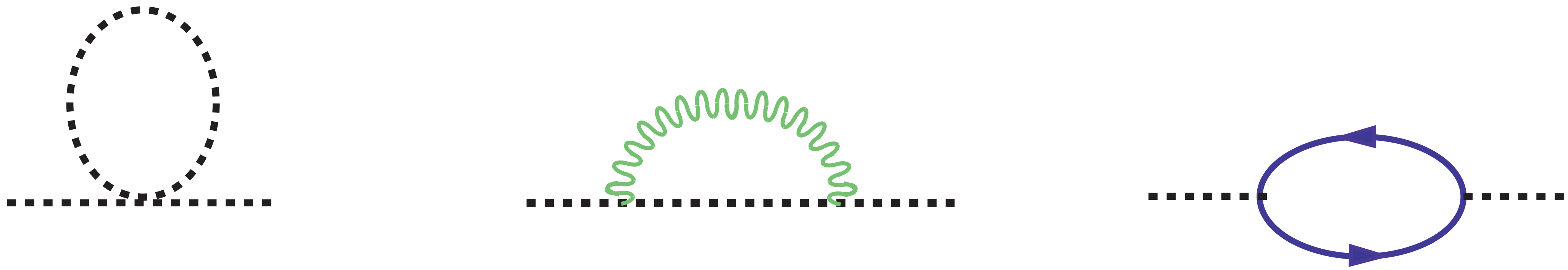
$$\text{flavor \& CP} \quad \longrightarrow \quad \boxed{M \gtrsim 10 - 10^4\ \text{TeV}}$$

$$M_{\rm Planck} \simeq 10^{16}\ \text{TeV}$$

- $M >>>> m_h$ explains a lot!
- $m_h <<<< M$ can we explain it?
- reductionist expectation $m_h^2 = c_h M^2$

?

Dimensional Analysis & Selection Rules



$$\delta m_h^2 = -\frac{3\lambda_h}{8\pi^2}\int dp^2 - \frac{9g_W^2}{32\pi^2}\int dp^2 + \frac{3y_t^2}{4\pi^2}\int dp^2$$

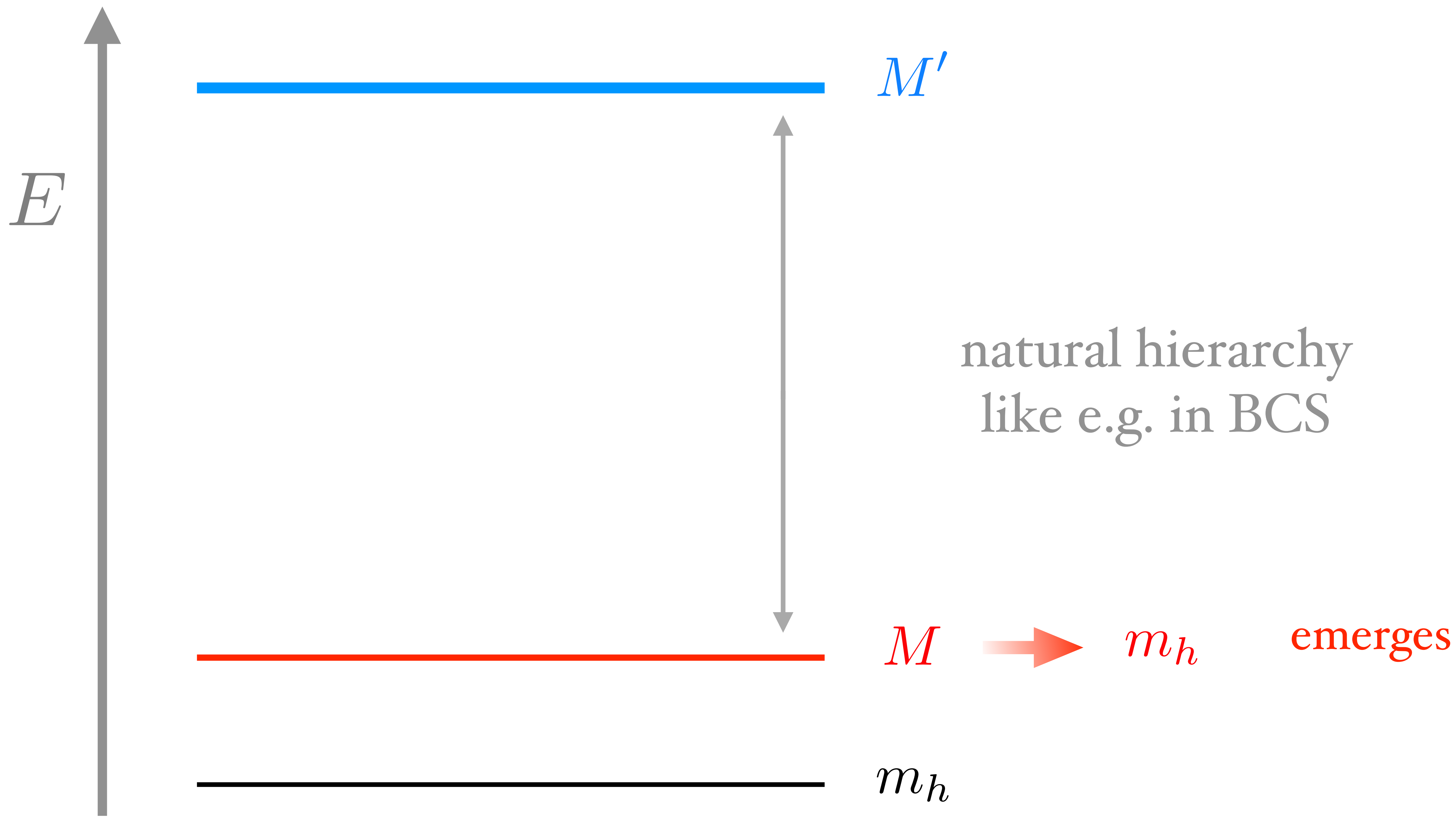
$$= -\#\frac{3\lambda}{8\pi^2}M^2 - \#\frac{9g_2^2}{32\pi^2}M^2 + \#\frac{3y_t^2}{4\pi^2}M^2$$

barring cancelations $\delta m_h^2 \lesssim m_h^2|_{exp}$ ⇒ $M \lesssim 0.5\,\mathrm{TeV}$

Beyond the Standard Model

or

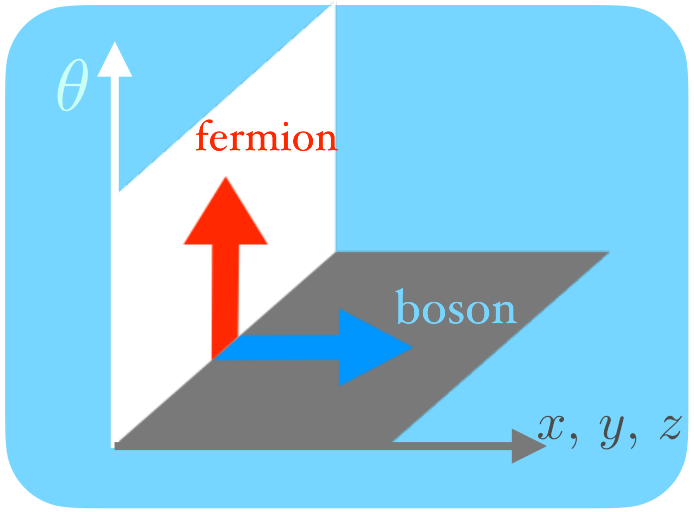
“Making m_h Calculable”



E
M'
natural hierarchy
like e.g. in BCS
M
m_h
emerges
m_h

Two options

✦ Supersymmetry

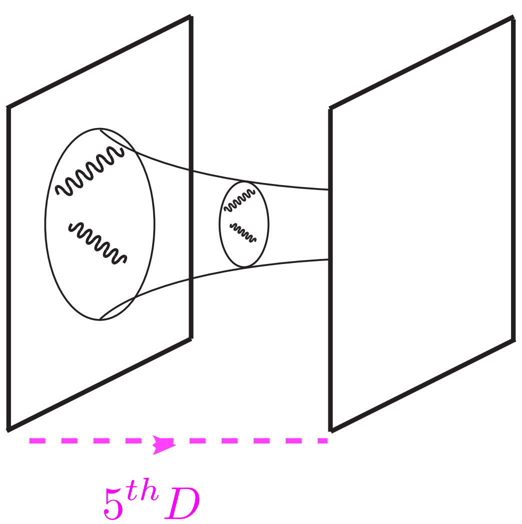


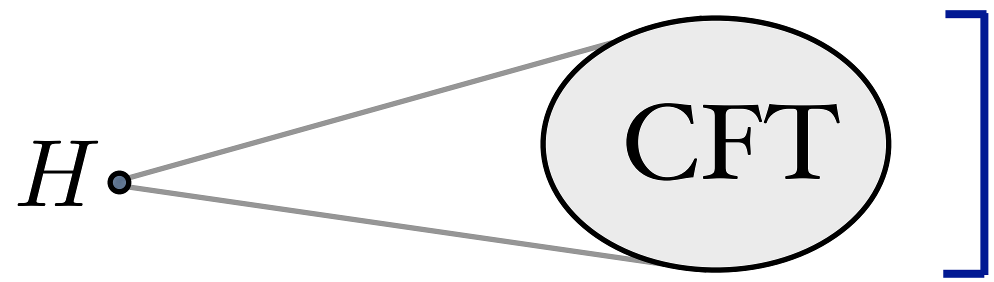
boson ⟺ fermion

$$h \Longleftrightarrow \tilde{h}$$

$$m_h^2 = m_{\tilde{h}} m_{\tilde{h}}^*$$

✦ Compositeness





$$\frac{1}{M}$$

$$m_h \simeq 0.2 \times \sqrt{\epsilon} \times M \xrightarrow{\text{no tuning}} M \lesssim 1\,\text{TeV}$$

✦ Supersymmetry and Compositeness lack the Simplicity of the SM

realistic models must be rigged with ***clever*** mechanisms

$M \gg m_h$	Un-Natural but structurally Simple
$M \sim m_h$	Natural but structurally Complicated

This is the Hierarchy Paradox

Testing origin of m_h at colliders

	LHC	HL-LHC	FCC
direct searches for new particles $m_h \sim 0.1 \times \sqrt{\epsilon} \times M$	$\epsilon < 10^{-1} \div 10^{-3}$		$\epsilon < 10^{-3} \div 10^{-5}$
measurements of Higgs couplings $\frac{\Delta g}{g_{SM}} \sim \epsilon$	$\epsilon \lesssim 10^{-1}$	$\epsilon \lesssim 2 \times 10^{-2}$	$\epsilon \lesssim 10^{-3}$

Another story: do we understand why the Universe is so big?

vacuum energy density

$$\rho \sim \frac{1}{16\pi^2}\left(c_0 M^4 + c_1 g^2 M^2 H^\dagger H + \ldots \right)$$

gravity

$$\frac{1}{R^2} = 8\pi G_N \, \rho \quad \longrightarrow \quad R = \left(\frac{\mathrm{TeV}}{M}\right)^2 \times 1\,\mathrm{cm}$$

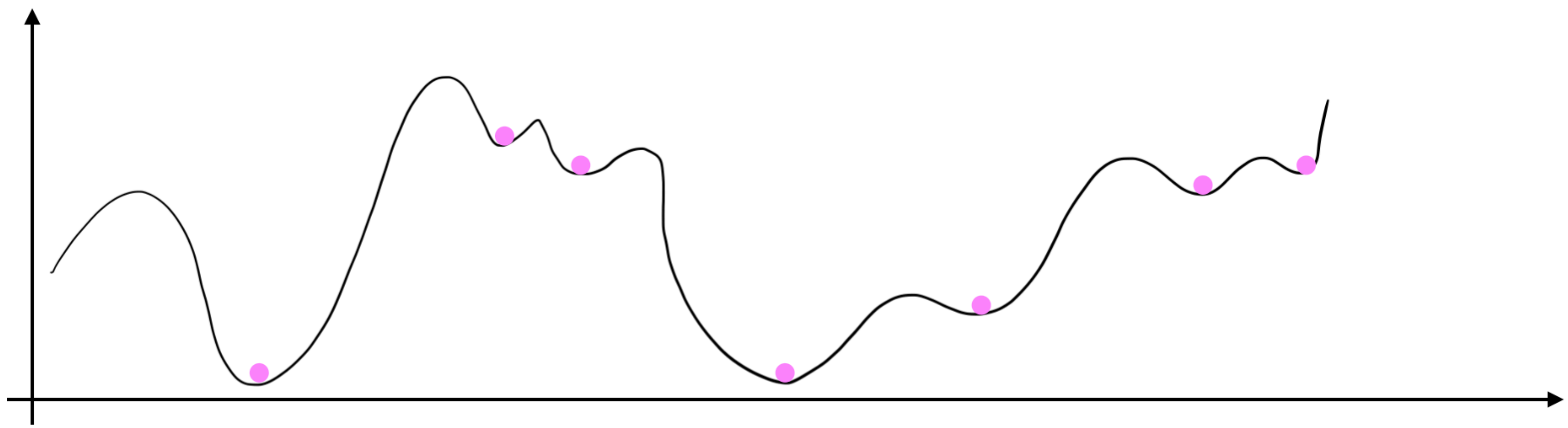
observation $\longrightarrow$

$$R \equiv \frac{1}{H} \sim 10^{28}\,\mathrm{cm}$$

!!!!!!!!

and concrete dynamical solution yet to be found

Multiverse & Anthropic Principle



Weinberg 1987
Barrow - Tipler 1986

$\rho > (\text{a few}) \times \rho_c$ → no observers

generic prediction $\rho \sim \rho_c$ later confirmed by discovery of accelerated expansion

Riess et al - Perlmutter et al. 1998

Could also m_h be the result of anthropic selection?

Agrawal, Donoghue, Barr, Seckel 1997
....
Hall, Nomura 2007

$m_{quark} \propto y_q \, m_h$

$m_{electron} \propto y_e \, m_h$

structure in nuclear & atomic physics very sensitive to value of

$m_h \to \frac{m_h}{2}$ $\quad p \to n + e^+ + \nu$

$m_h \to 5 m_h$ $\quad uuu$ only stable baryon

The Multiverse would be the ultimate Copernican Revolution
but how can we test it?

Where do we go from here?

Particle physics raises deep structural questions

The answer may lie outside the present framework, beyond QFT

QFT remains a necessary and fertile ground for exploration as shown by its continuous renewal

Work technical and try to think deep but, please, do not loose sight of particle physics, waiting for that crazy enough idea

In the meanwhile experiments will go on, little by little...

The most beautiful thing we can experience is the mysterious....