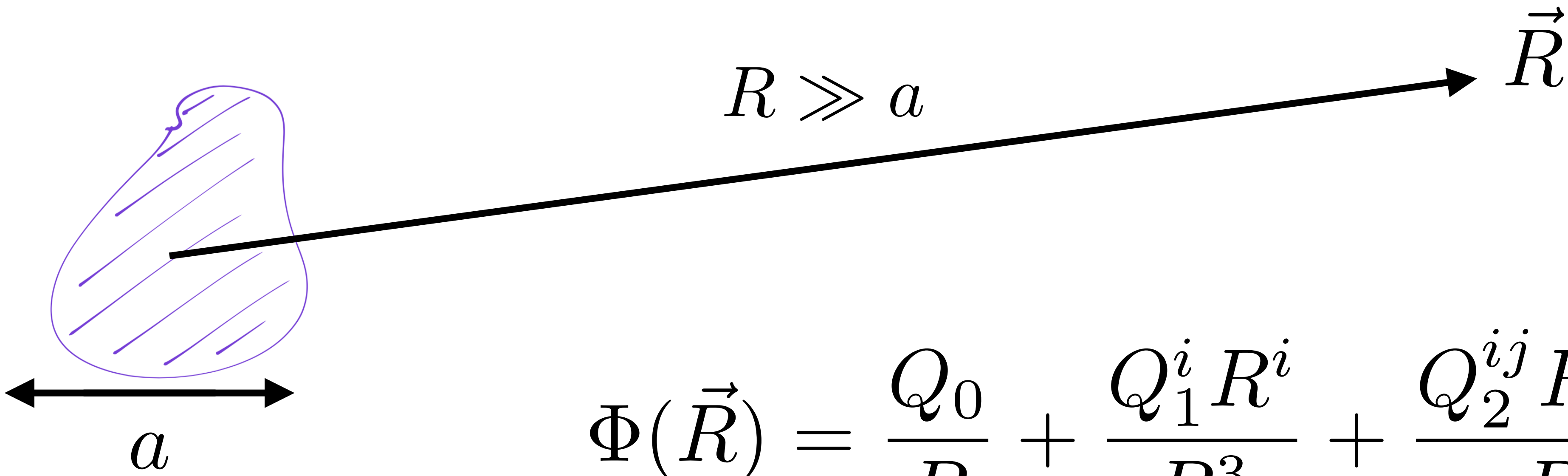
Particle-Physics-So-Far
&
the Hierarchy Paradox

Effective Theories

Example: electrostatic potential at large distance



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

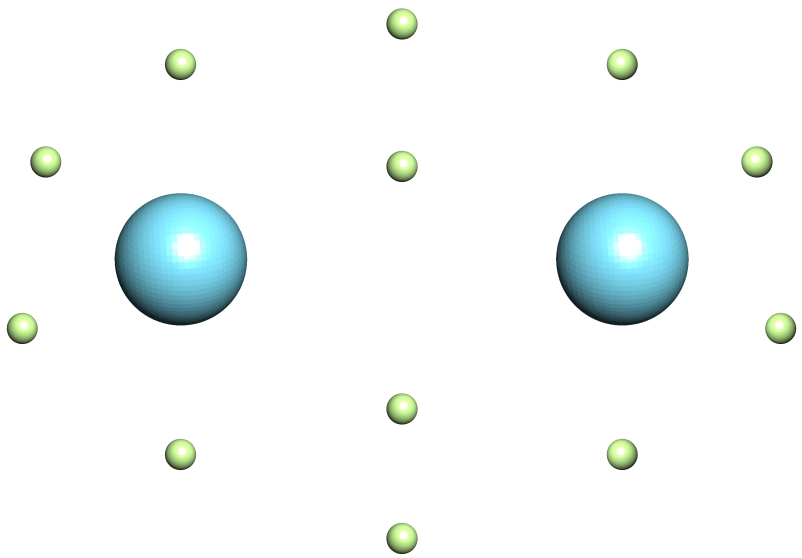
$$\frac{1}{R} \left(1 \quad + \quad \frac{a}{R} \quad + \quad \frac{a^2}{R^2} \quad + \quad \cdots \quad \frac{a^n}{R^n} \right.$$

at fixed accuracy

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

$R \sim a$ expansion breaks down: ∞ number of parameters needed

Example: molecules in Born-Oppenheimer approximation



electrons move faster than nucleons

$m_e \ll m_N \qquad \omega_e \gg \omega_N$

Schroedinger eq. in two steps

- fast electrons first
- slow nucleons later

nucleon dynamics refined in systematic expansion in $\dfrac{\omega_N}{\omega_e} \sim \left(\dfrac{m_e}{m_N}\right)^{\frac{1}{2}}$

Path integral: effective descriptions arise by ***integrating out*** the fast degrees of freedom

$$\{q\} \equiv \{q_{fast},\, q_{slow}\}$$

$$\int Dq\, e^{iS[q]} \equiv \int Dq_{slow}\, Dq_{fast}\, e^{iS[q_{slow}, q_{fast}]} = \int Dq_{slow}\, e^{iS_{eff}[q_{slow}]}$$

$$\langle\, q_{slow}(t_1)\, \ldots\, q_{slow}(t_N)\,\rangle =$$

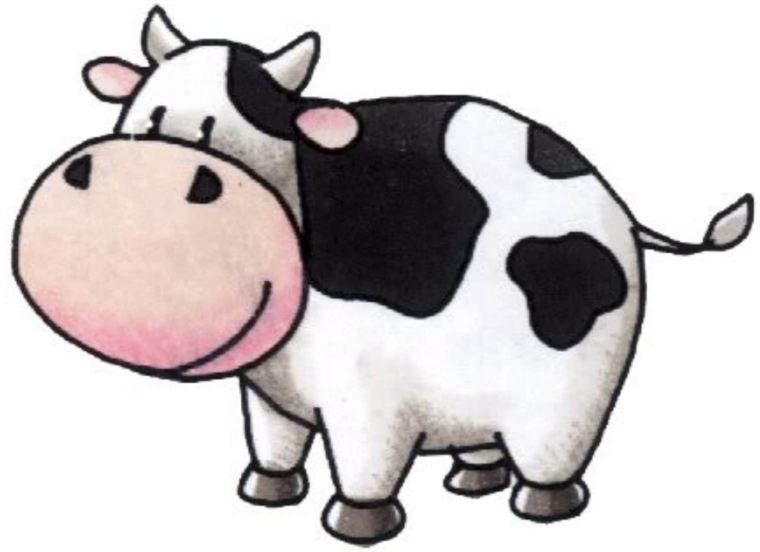
$$\int Dq\, q_{slow}(t_1)\, \ldots\, q_{slow}(t_N)\, e^{iS[q]} = \int Dq_{slow}\, q_{slow}(t_1)\, \ldots\, q_{slow}(t_N)\, e^{iS_{eff}[q_{slow}]}$$

- Effective long distance descriptions are ubiquitous
- Their universality is the very reason we can do physics
- In fact we expect all theories of nature to appear sooner or later as just effective ones
- QFT should also be viewed as effective, like all else.

<u>Simplicity</u> & Accidental Symmetries

- The IR relevance of just a finite number of parameters implies a great structural simplification

- this often entails the effective occurrence in the long distance dynamics of additional, accidental, symmetries



accidental

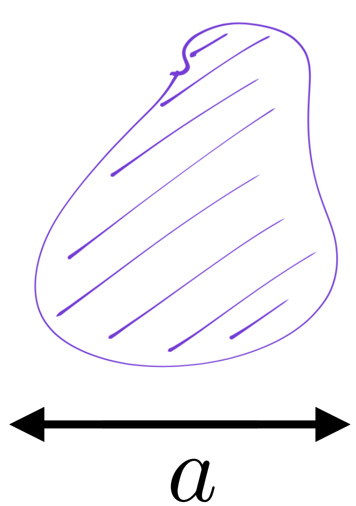
•

$SO(3)$

- accidental

$SO(3)$

Ex.: electrostatic potential at large distance



$$\xrightarrow{R \gg a}$$

$$\begin{array}{ccccccc} & \color{blue}{1/R} & & \color{blue}{a/R^2} & & \color{blue}{a^2/R^3} & \\ \Phi(R) = & \dfrac{Q_0}{R} & + & \dfrac{\vec{Q}_1 \cdot \vec{R}}{R^3} & + & \dfrac{Q_2^{ij} R_i R_j}{R^5} & + \dots \\ & \color{red}{SO(3)} & \color{red}{\supset} & \color{red}{SO(2)} & \color{red}{\supset} & \color{red}{\varnothing} & \end{array}$$

Accidental Symmetries of EFTs

$a \equiv \frac{1}{\Lambda}$

Parity in QED

$$\mathcal{L}^{d\leq 4} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\gamma^{\mu}D_{\mu}\psi - m\bar{\psi}\psi + \frac{a}{4}\tilde{F}_{\mu\nu}F^{\mu\nu}$$

Accidental Symmetries of EFTs

$$a \equiv \frac{1}{\Lambda}$$

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Parity

Accidental Symmetries of EFTs

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Parity in QED

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Parity

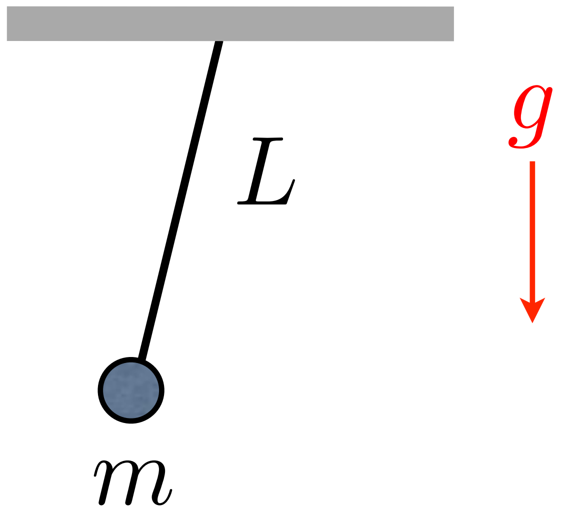
$$\mathcal{L}^{d=6} = -\frac{1}{\Lambda^2}\left(\bar{\psi}\gamma^\mu\psi\right)\left(\bar{\psi}\gamma_\mu\gamma_5\psi\right) + \ldots$$

Symmetries, Selection Rules & Naturalness

can always imagine *symmetry* tranformations of the parameters of a physical system

the dependence of physical observables on such parameters is dictated by covariance under such *symmetries*

Ex.: classical pendulum



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

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

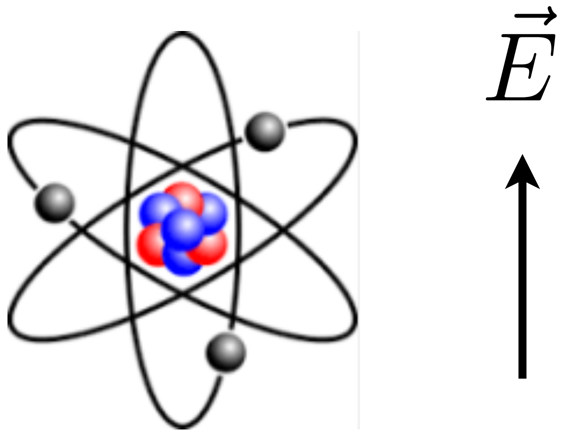
$$L \to \lambda_x L$$

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

$$m \to m$$

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

Ex: atom in external electric field



$$|\Psi_0\rangle \xrightarrow{\text{slowly turn on } \vec{E}} |\Psi_0(\vec{E})\rangle$$

electric dipole

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

Free Field Theory: Higher Spin Symmetry

$$S = \int \mathcal{L} = \int \frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}m^2\varphi^2$$

$$Q_{\vec{k}} = a^\dagger_{\vec{k}} a_{\vec{k}}$$

$$S = \int d^4p \, \frac{1}{2}\hat{\varphi}(-p)\left(p^2 - m^2\right)\hat{\varphi}(p)$$

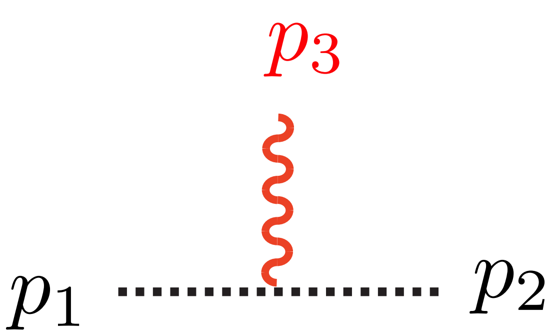
$$\hat{\varphi}(p) \longrightarrow e^{i\theta(p)}\hat{\varphi}(p)$$

$$\theta(-p) = -\theta(p)$$

$$\lambda\varphi^4 \Rightarrow \int \hat{\lambda}(p_1,p_2,p_3,p_4)\,\hat{\varphi}(p_1)\ldots\hat{\varphi}(p_4)$$

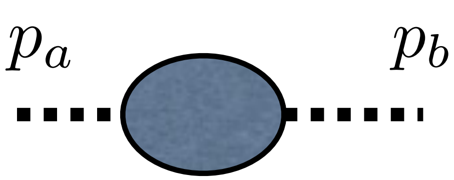
$$\hat{\lambda}(p_1,p_2,p_3,p_4) \longrightarrow e^{-i(\theta(p_1)+\ldots+\theta(p_4))}\hat{\lambda}(p_1,p_2,p_3,p_4)$$

Ex: EM correction to $m_{\pi^+}^2$

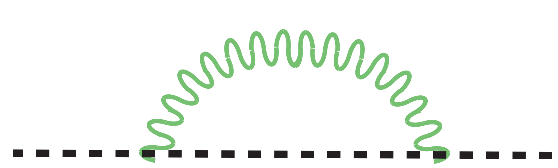
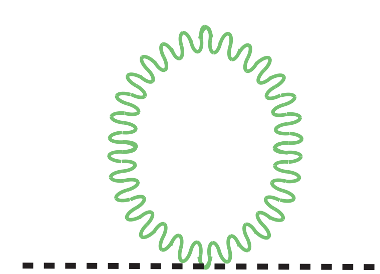


$$\hat{\mathbf{e}}(p_1, p_2, p_3) \to \hat{\mathbf{e}}(p_1, p_2, p_3)\, e^{-i(\theta_\pi(p_1)+\theta_\pi(p_2)+\theta_A(p_3))}$$

$$\Lambda_{QCD} \to \Lambda_{QCD}\, e^{\sigma}$$ **under dilations**



$$\delta m_{\pi^+}^2 \sim \hat{\mathbf{e}}(p_a, p_2, p_3)\hat{\mathbf{e}}(p_b, -p_2, -p_3)\, \Lambda_{QCD}^2 \quad \Rightarrow \quad e^2\, \Lambda_{QCD}^2$$

 +  $\sim \dfrac{e^2}{16\pi^2}\,\Lambda_{QCD}^2$

In general, given couplings $\{\lambda_a\}$, an observable $\mathcal{O}$ is given by

$$\langle \mathcal{O} \rangle = \sum_a \langle \mathcal{O} \rangle_a$$

$$\langle \mathcal{O} \rangle_a = c_a \, \underbrace{\lambda_1^{n_{1a}} \ldots \lambda_N^{n_{Na}}}_{\text{symm. \& dim.}}$$

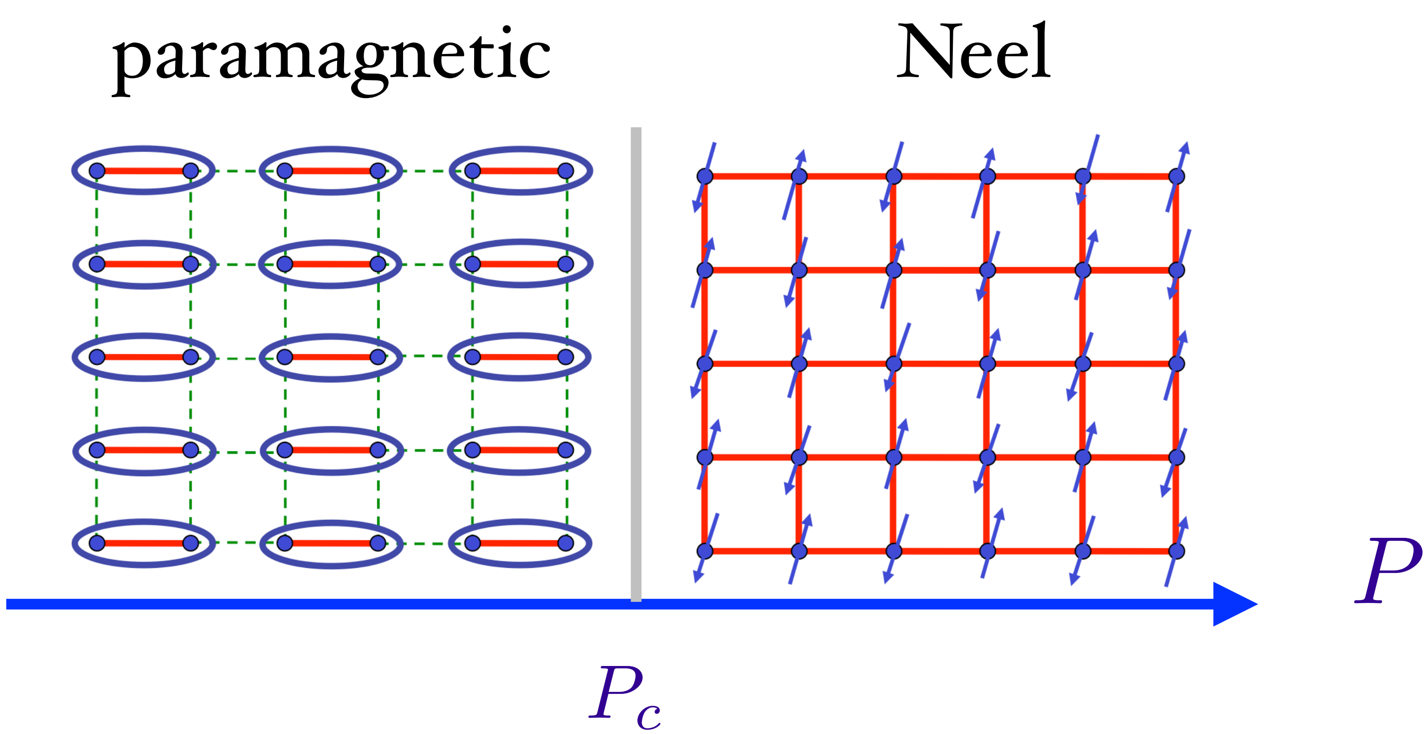
c_a: $O(1)$ coeff.

$$|\langle \mathcal{O} \rangle_{\exp}| \sim \max |\langle \mathcal{O} \rangle_a| \quad \equiv \quad \text{Natural}$$

$$|\langle \mathcal{O} \rangle_{\exp}| \ll \max |\langle \mathcal{O} \rangle_a| \quad \equiv \quad \text{Un-Natural}$$

Ex. quantum criticality in anti-ferromagnet ($TlCuCl_3$)

Sachdev '09



$$\vec{\varphi} \equiv (-1)^{x+y} \vec{S}(x,y)$$

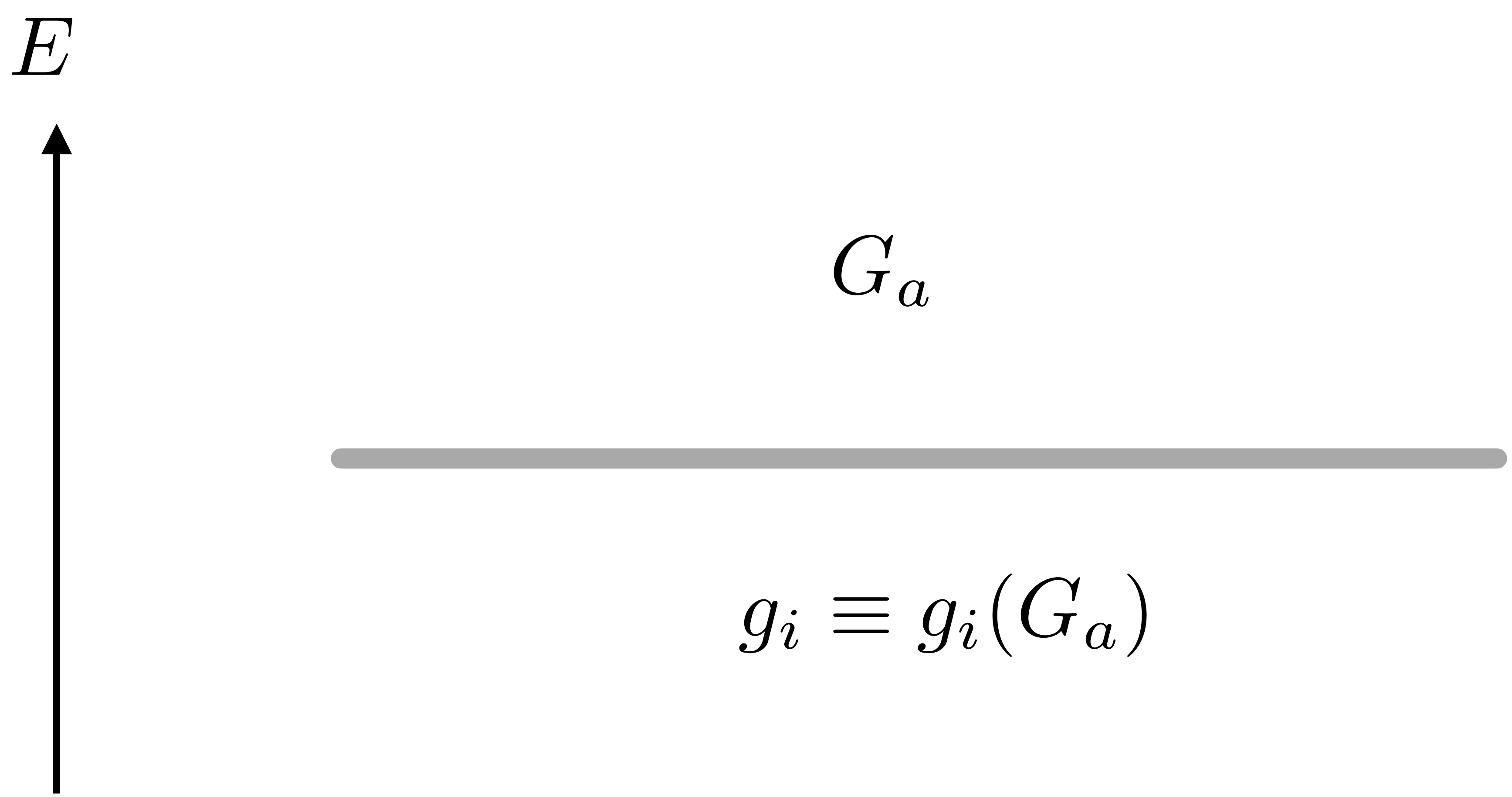
$$V(\vec{\varphi}) = m^2(P)\vec{\varphi}\cdot\vec{\varphi} + \lambda(\vec{\varphi}\cdot\vec{\varphi})^2 \qquad m^2(P) = m_0^2\left(1 - \frac{P}{P_c}\right)$$

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

The Naturalness Criterion

't Hooft 1979

Under what conditions is a QFT natural?



When pattern of g_i is consistent with all selection rules

The Standard Model as an Effective Field Theory

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

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

$m_\nu = 0$

$U(1)_{L_1} \times U(1)_{L_2} \times U(1)_{L_3} \times U(1)_B$

~~Flavor~~ & ~~CP~~ ⟷ Y_u, Y_d, Y_ℓ

GIM mechanism

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

~~$U(1)_L$~~ $m_\nu \neq 0$

$m_\nu = 0$

~~Flavor~~ $\mu \to e\gamma$, Δm_K

$U(1)_{L_1} \times U(1)_{L_2} \times U(1)_{L_3} \times U(1)_B$

~~CP~~ edms

~~Flavor~~ & ~~CP~~ ⟷ Y_u, Y_d, Y_ℓ

GIM mechanism

~~$U(1)_B$~~ $p \to \pi_0\, e^+$

$$\mathcal{L} = \mathcal{L}^{d=2} + \mathcal{L}^{d=4} + \frac{1}{\Lambda_{UV}}\mathcal{L}^{d=5} + \frac{1}{\Lambda_{UV}^2}\mathcal{L}^{d=6} + \dots$$

10^{14} GeV $\quad m_\nu \neq 0$

$m_\nu = 0$

$> 10^6$ GeV $\quad$ [$\mu \to e\gamma$, Δm_K, edms]

$U(1)_{L_1} \times U(1)_{L_2} \times U(1)_{L_3} \times U(1)_B$

~~Flavor~~ & ~~CP~~ $\Longleftrightarrow$ $Y_u,\, Y_d,\, Y_\ell$

GIM mechanism

$> 10^{15}$ GeV $\quad p \to \pi_0\, e^+$

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

10^{14} GeV $\quad m_\nu \neq 0$

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$U(1)_{L_1} \times U(1)_{L_2} \times U(1)_{L_3} \times U(1)_B$

~~Flavor~~ & ~~CP~~ ⟷ $Y_u,\, Y_d,\, Y_\ell$

GIM mechanism

$> 10^{15}$ GeV $\quad p \to \pi_0\, e^+$

$\Lambda_{UV} \gg$ TeV $\quad$ nicely accounts for 'what we see'

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

$$m_H^2 = c\,\Lambda_{UV}^2$$

$$c = 0.008 \left(\frac{\text{TeV}}{\Lambda_{UV}}\right)^2$$

$$m_\nu = 0$$

$$U(1)_{L_1} \times U(1)_{L_2} \times U(1)_{L_3} \times U(1)_B$$

~~Flavor~~ & ~~CP~~ ⟷ $Y_u,\ Y_d,\ Y_\ell$

GIM mechanism

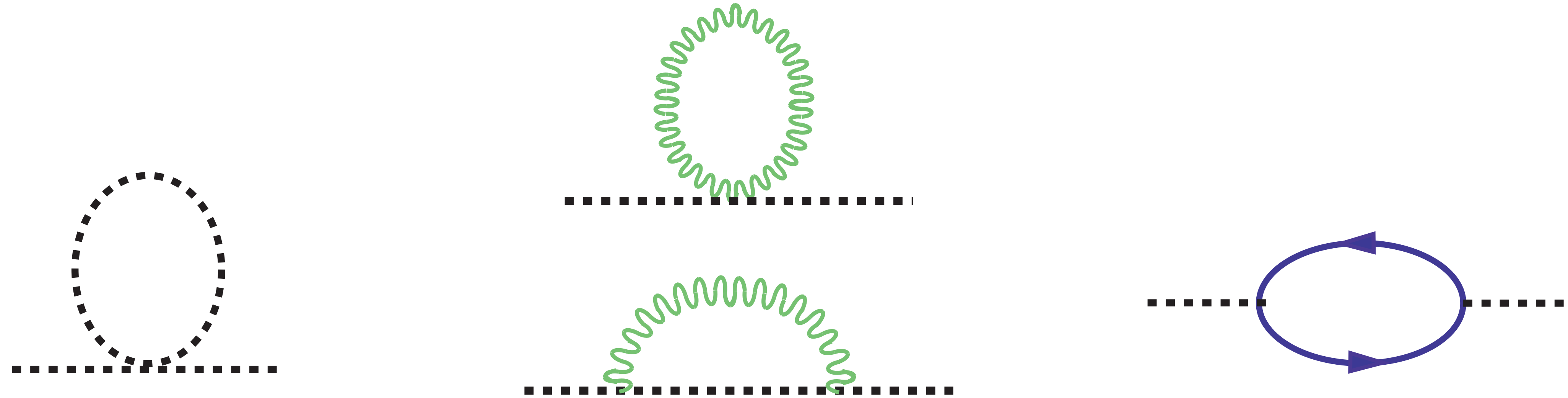
10^{14} GeV $\quad m_\nu \neq 0$

$> 10^6$ GeV

- $\mu \to e\gamma$
- Δm_K
- edms

$> 10^{15}$ GeV $\quad p \to \pi_0\, e^+$

$\Lambda_{UV} \gg$ TeV nicely accounts for 'what we see'

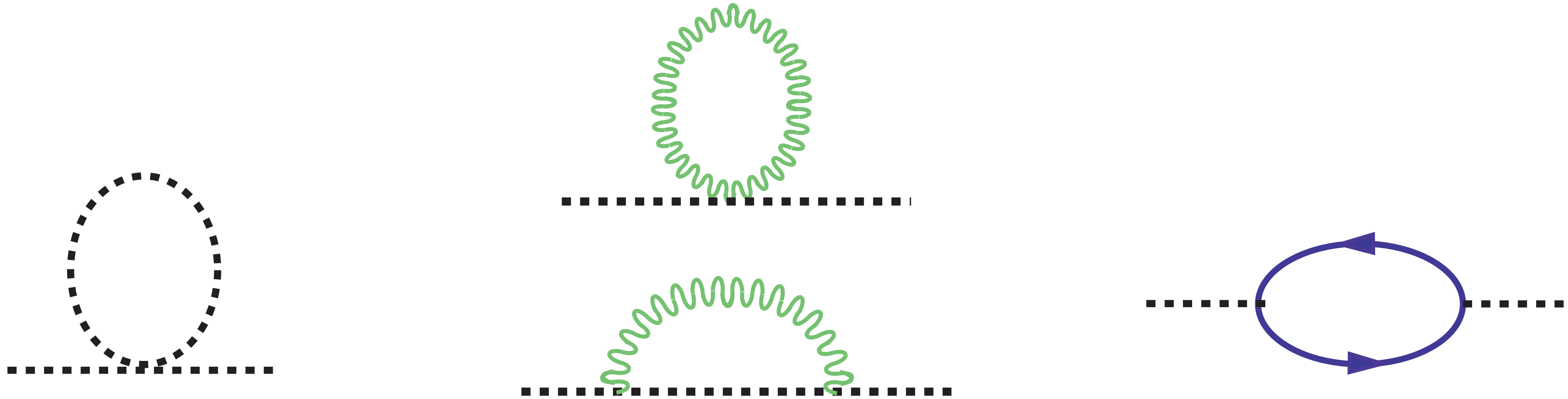


$$\delta m_H^2 = +\frac{3\lambda}{2(2\pi)^4}\int^{\Lambda_{UV}}\frac{d^4p}{p^2} \quad +\frac{9g_W^2}{8(2\pi)^4}\int^{\Lambda_{UV}}\frac{d^4p}{p^2} \quad -\frac{3y_t^2}{(2\pi)^4}\int^{\Lambda_{UV}}\frac{d^4p}{p^2}$$

$$= -\frac{3\lambda}{16\pi^2}\Lambda_{UV}^2 + \frac{9g_2^2}{64\pi^2}\Lambda_{UV}^2 - \frac{3y_t^2}{8\pi^2}\Lambda_{UV}^2$$

$$\delta m_H^2 \lesssim m_H^2|_{exp}$$

$$\Lambda_{UV} \lesssim 500\,\mathrm{GeV}$$



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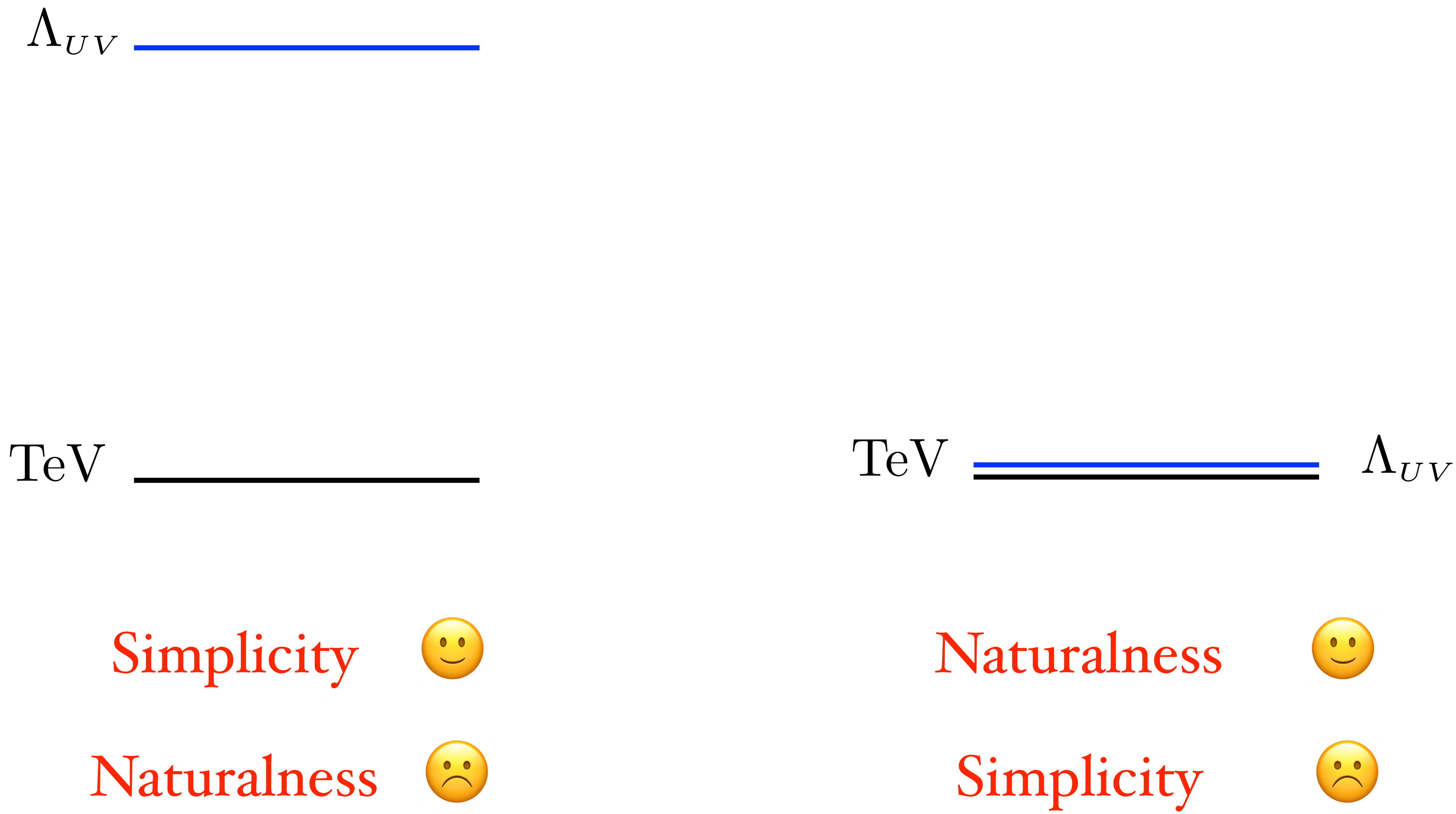
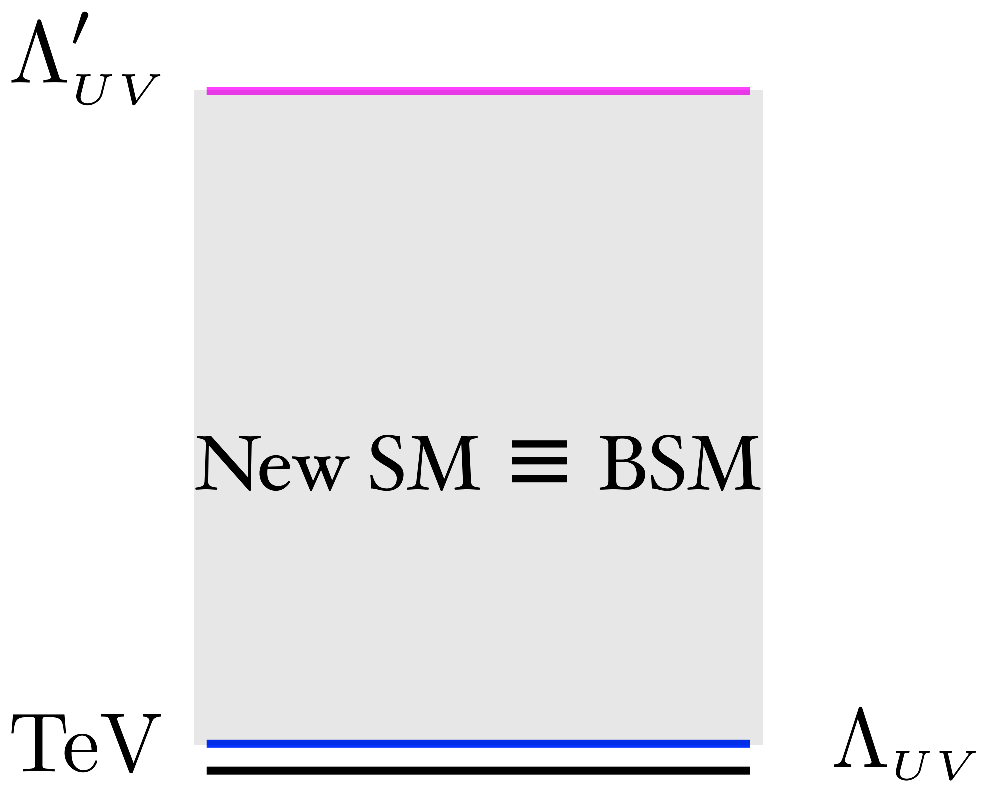
$$= +\#\,\frac{3\lambda}{16\pi^2}\Lambda_{UV}^2 \quad + \quad \#\,\frac{9g_2^2}{64\pi^2}\Lambda_{UV}^2 \quad - \quad \#\,\frac{3y_t^2}{8\pi^2}\Lambda_{UV}^2$$

$$\delta m_H^2 \lesssim m_H^2|_{exp} \quad \Rightarrow \quad \Lambda_{UV} \lesssim 500\,\mathrm{GeV}$$


Λ_{UV}
TeV
Simplicity
Naturalness
TeV
Λ_{UV}
Naturalness
Simplicity

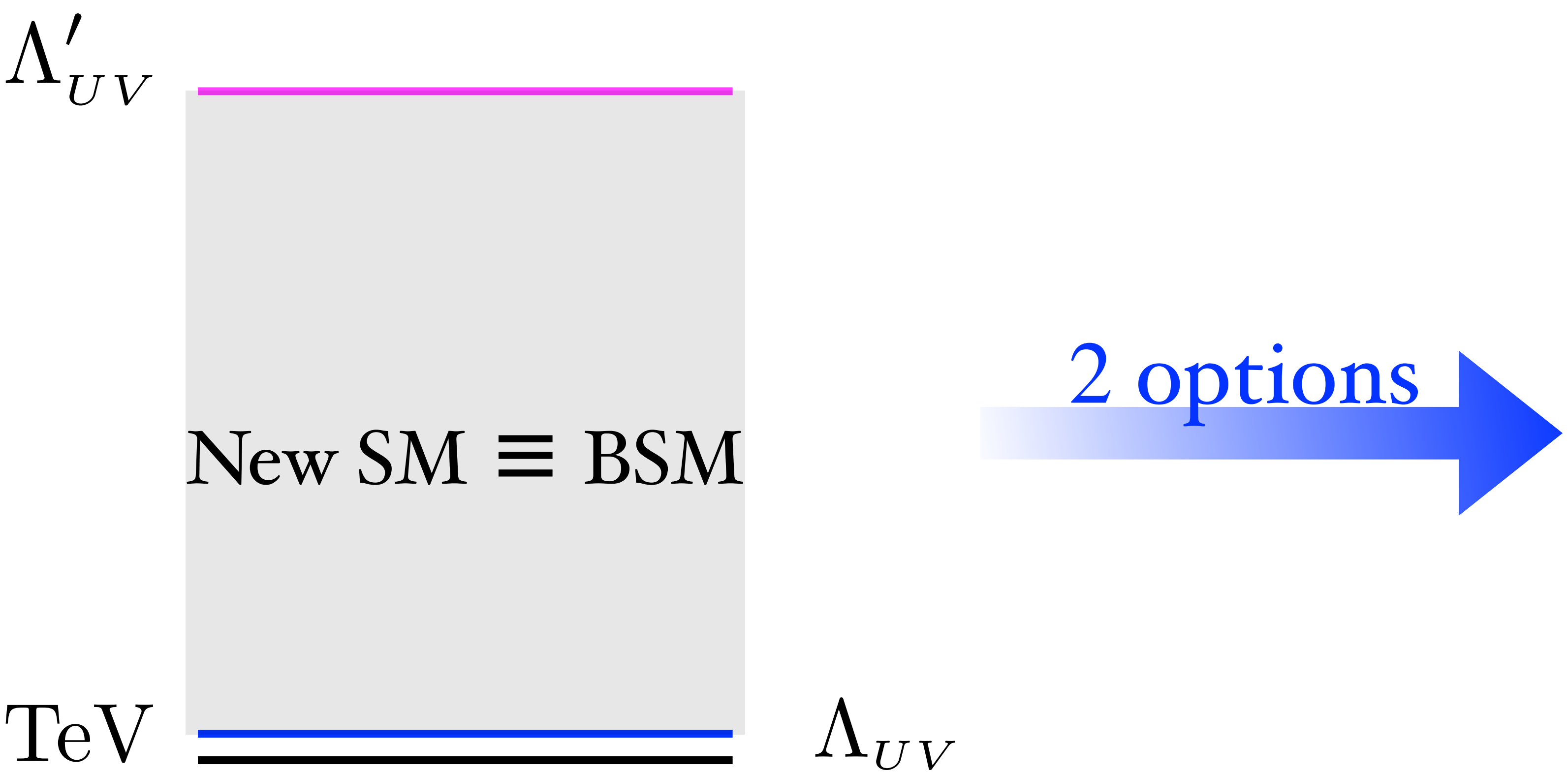
BSM and the Hierarchy Paradox

Ideally



- $\Lambda_{UV} \ll \Lambda'_{UV}$ natural in BSM
- $\mathcal{L}_4$ in BSM shares as much magic as possible with $\mathcal{L}_4$ in SM

Can this ideal be realized ?



- Supersymmetry
- Composite Higgs

Supersymmetry

~~Flavor~~

~~CP~~ $\in \mathcal{L}^{d\leq 4}$

~~B, L~~

Compositeness

H = composite field with d > 1

$H \bar{f} f \in \mathcal{L}^{d>4}$

Automatic

Simplicity

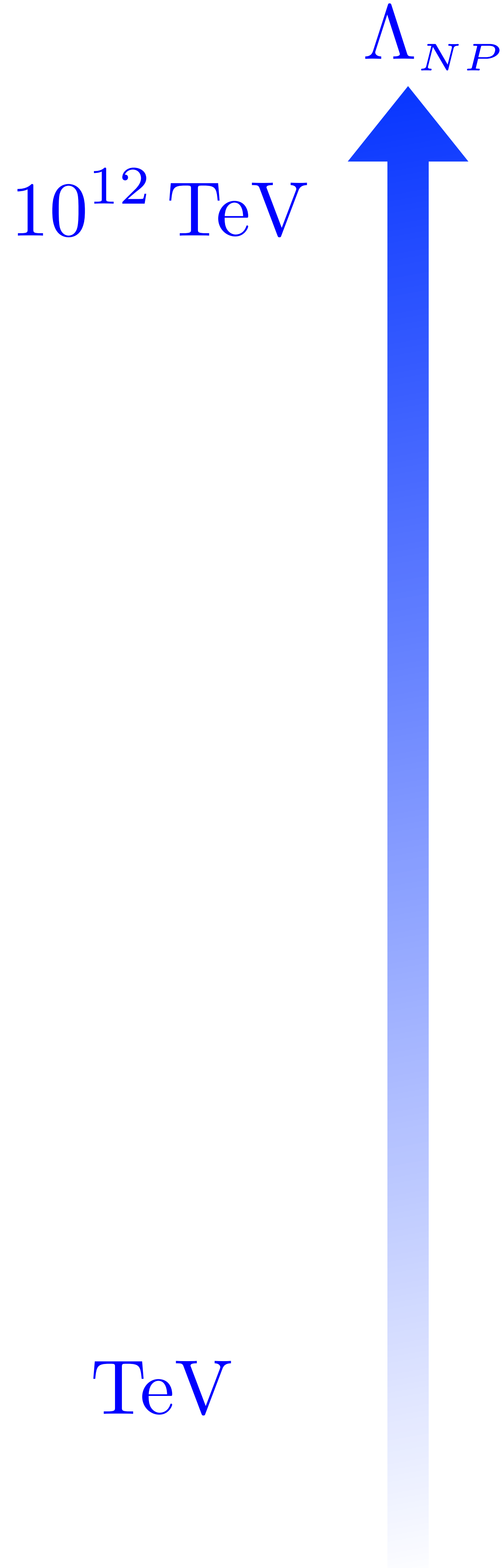
Lost

It seems there is no free lunch

- ✦ $\Lambda_{UV} \gg m_H$ beautifully accounts for the observed structural simplicity of particle physics, but is un-natural

- ✦ All natural extensions of the SM need to be retrofitted with some ad hoc mechanism in order to reproduce the simplicity of observations

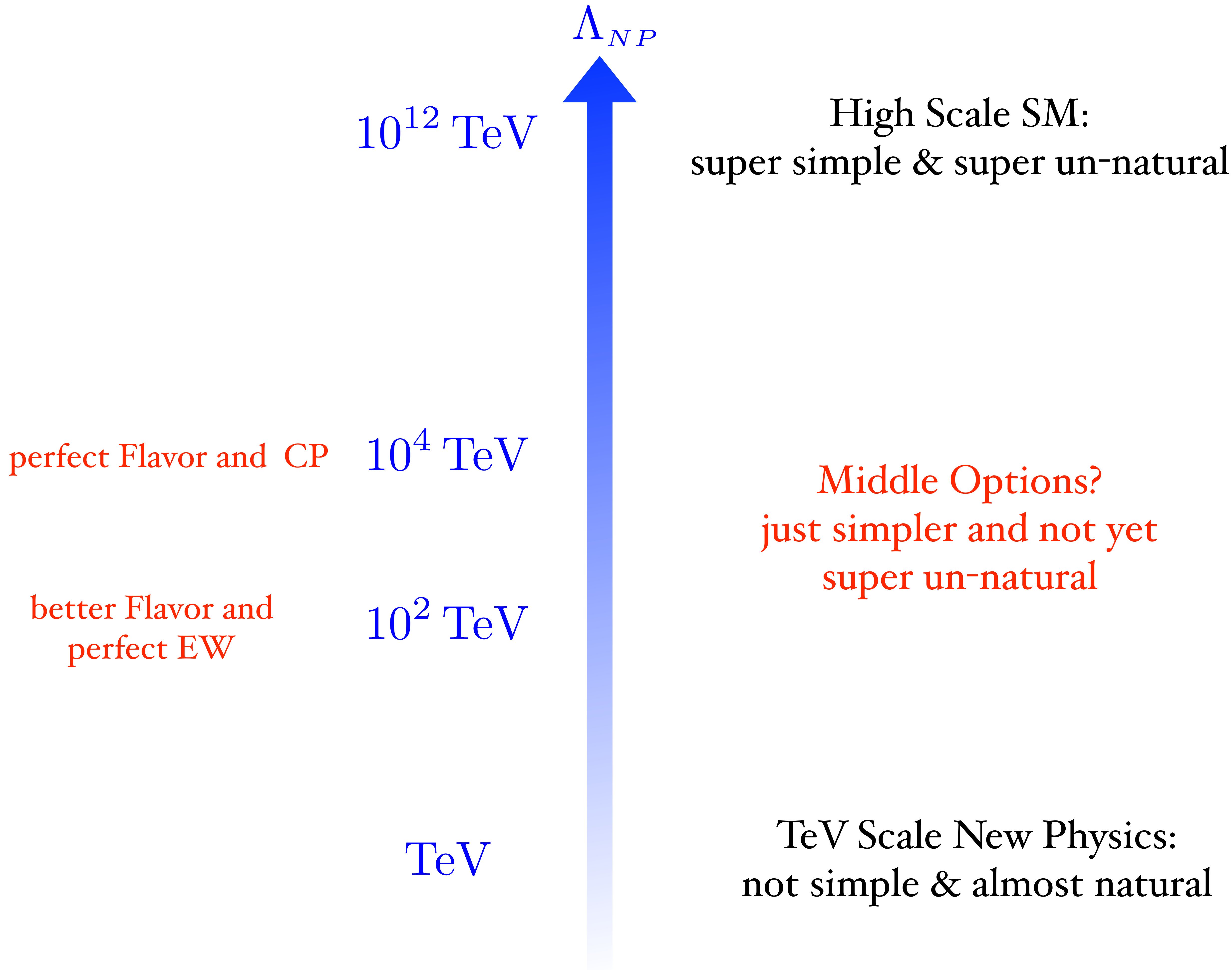
This is the Hierarchy Paradox



High Scale SM:
super simple & super un-natural

TeV Scale New Physics:
not simple & almost natural

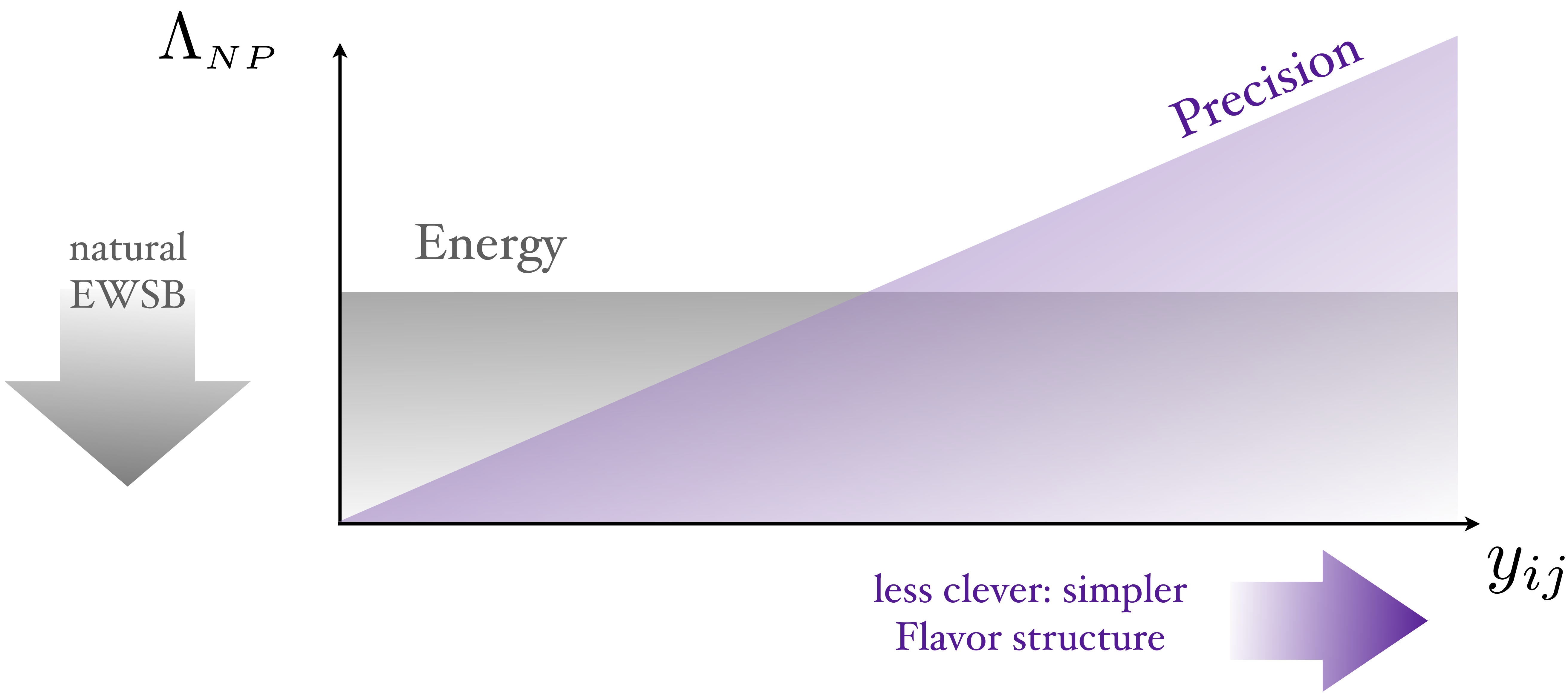
See also talk by R. Sundrum HEFT 2016



See also talk by R. Sundrum HEFT 2016

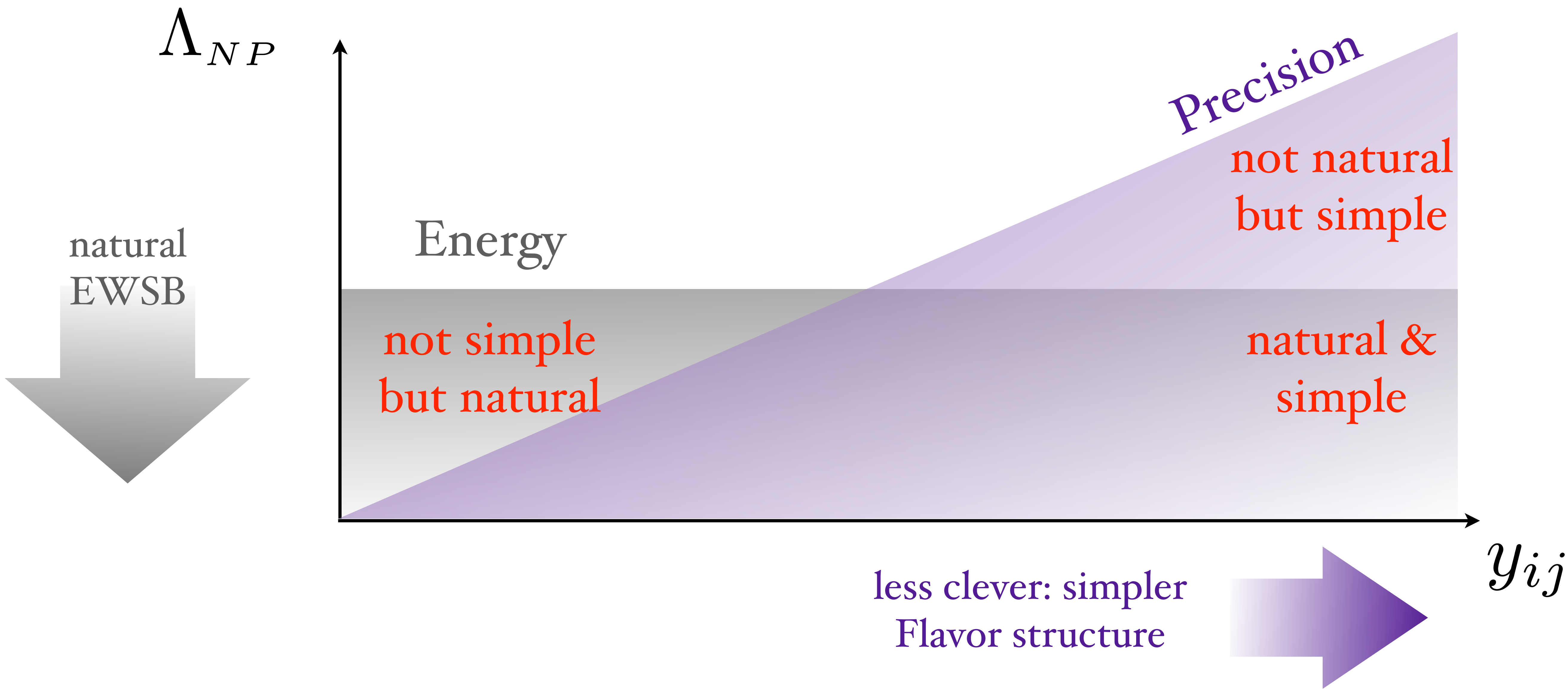
Complementarity of Energy and Precision

$$\mathcal{L}_{eff} = \frac{y_{ijk\ell}}{\Lambda_{NP}^2}\,\bar{q}_i q_j \bar{q}_k q_\ell + m_i \frac{y_{ij}}{\Lambda_{NP}^2}\,\bar{q}_i \sigma_{\mu\nu} q_j F^{\mu\nu} + \ldots$$

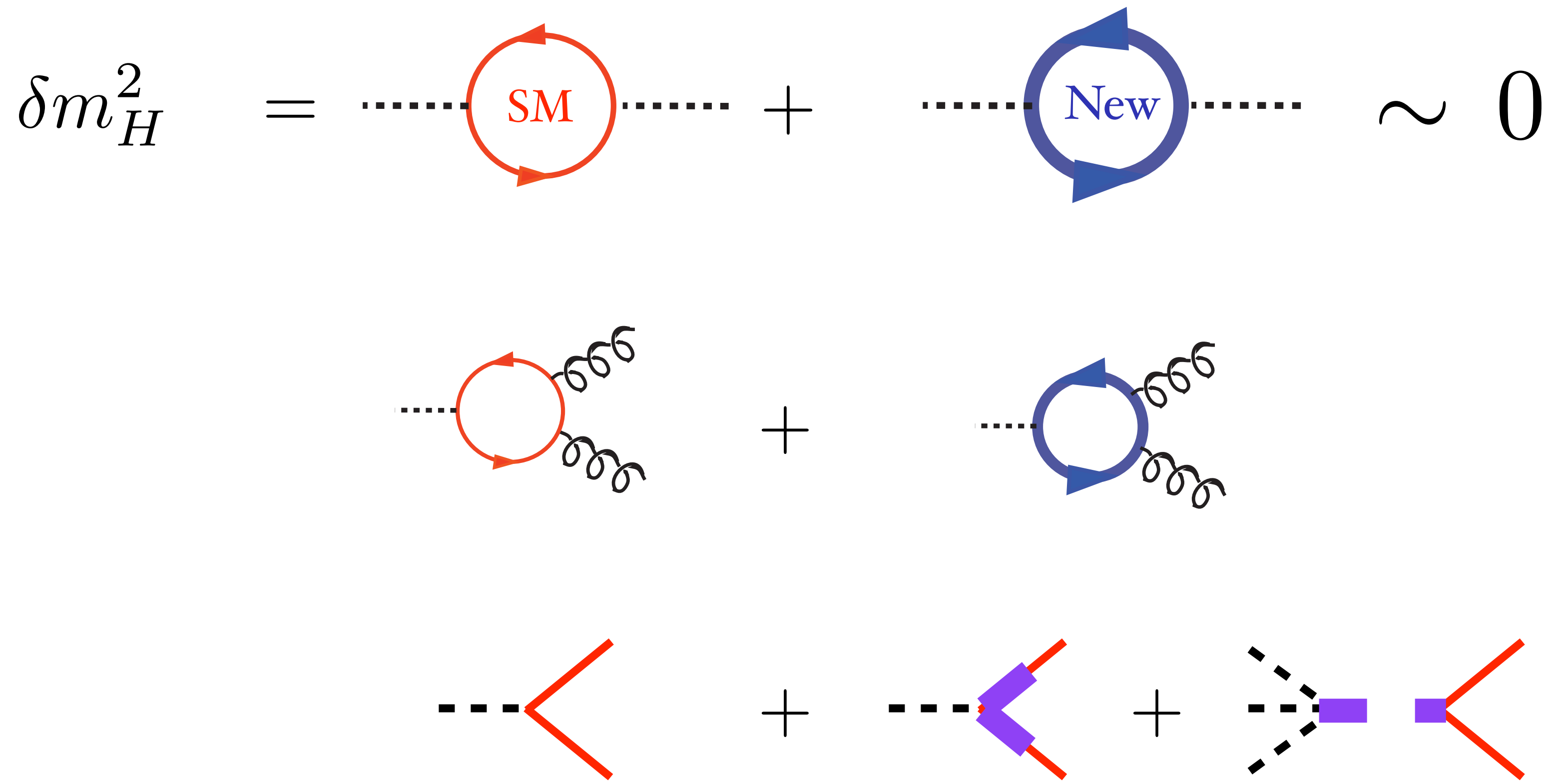


Complementarity of Energy and Precision

$$\mathcal{L}_{eff} = \frac{y_{ijk\ell}}{\Lambda^2_{NP}}\,\bar{q}_i q_j \bar{q}_k q_\ell + m_i \frac{y_{ij}}{\Lambda^2_{NP}}\,\bar{q}_i \sigma_{\mu\nu} q_j F^{\mu\nu} + \ldots$$



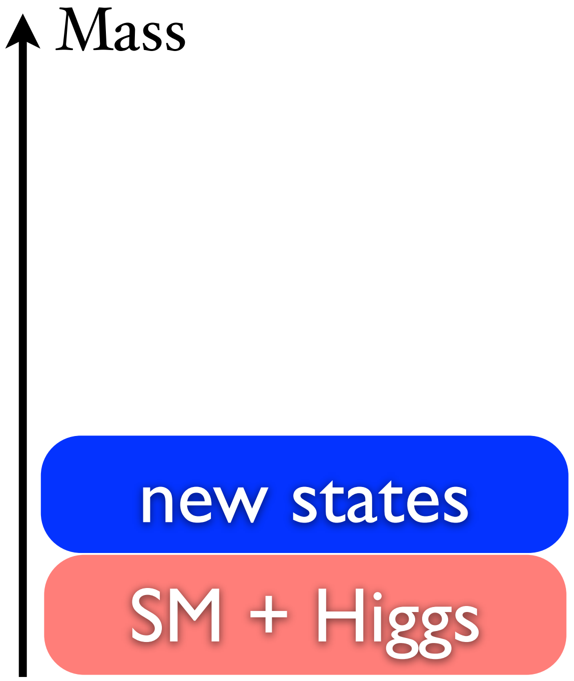
Higgs couplings and naturalness

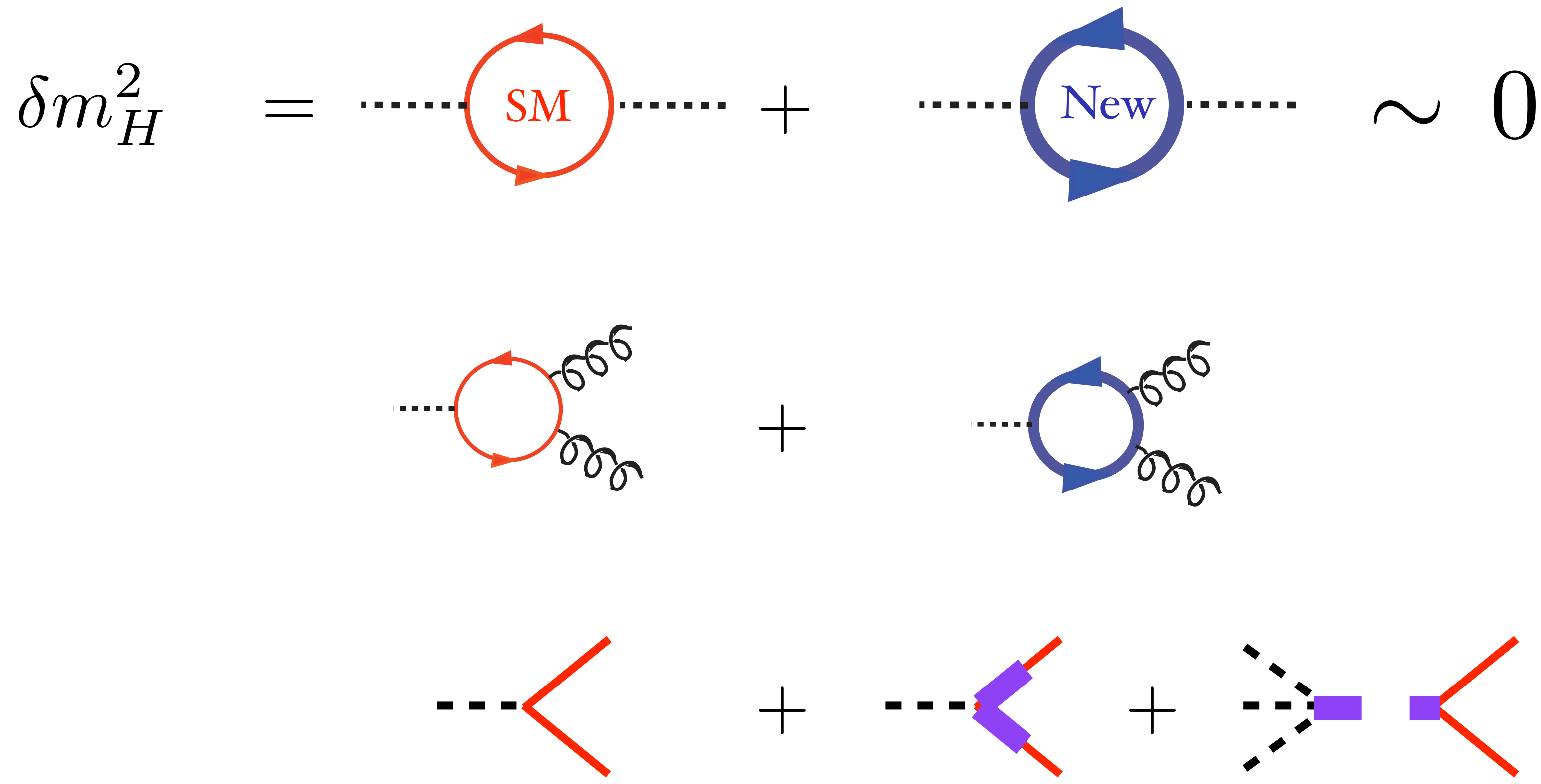


Higgs coupling deviations measure Naturalness

$$\frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon \equiv \text{fine tuning}$$

Higgs couplings and naturalness





Higgs coupling deviations measure Naturalness

$$\frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon \equiv \text{fine tuning}$$

Simplicity vs. Naturalness: outstanding paradox of modern physics

The future of experimental particle physics can be read in this vein

as quantified by
'Fine Tuning Theorems'

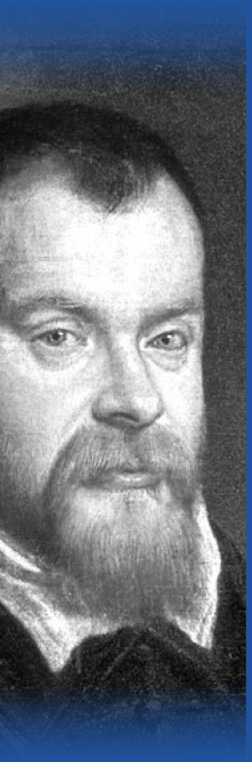
$$\frac{\delta g_h}{g_h} \sim \epsilon$$

$$\left(\frac{m_h}{m_{NP}}\right)^2 \div \left(\frac{500\,\mathrm{GeV}}{m_{NP}}\right)^2 \sim \epsilon$$

$$O_{EW} \sim 10^{-2} \div 10^{-3} \times \epsilon$$

GGI Focus Meeting, 19 May 2021

Naturalness and the Future of High-Energy Physics



G. F. Giudice

- Naturalness is a powerful tool provided by QFT to explore the properties of a theory beyond the boundaries of what has been tested experimentally.

- It gives information about the maximum energy up to which you can extrapolate your low-energy description.

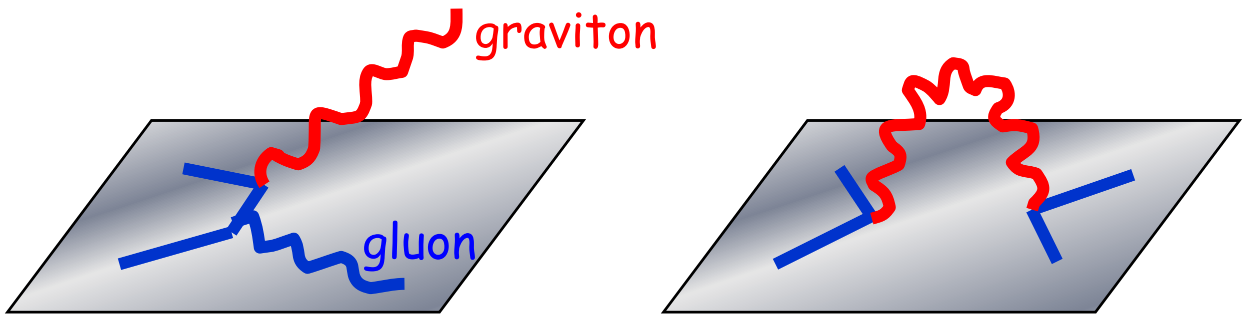
- What happens when you don't find the missing pieces?

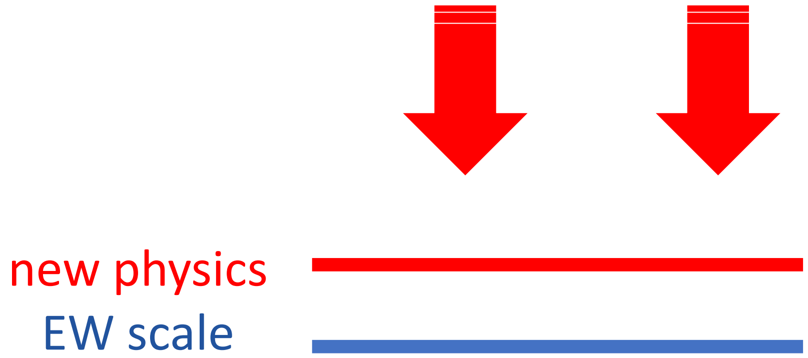
- One must question the hypotheses on which the naturalness principle rests.

1) Scale separation

Are there any new energy scales above the weak scale?
Quantum gravity?
Neutrino masses, the strong CP problem, inflation,
gauge coupling unification, …?
Flavour?

Large Extra Dimensions





Asymptotic safety in quantum gravity?

2) EFT validity

Naturalness: parameters being sensitive to heavy modes integrated out from the low-energy theory.

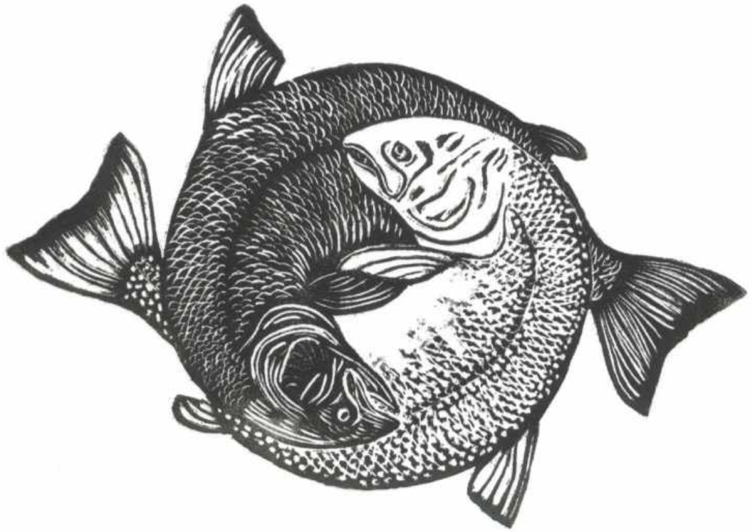
Could it be that the rules of EFT break down?

- This hypothesis has been the very reason for why physics could progress.
- Progress can proceed step by step, without requiring simultaneous knowledge of physics at all scales.

Could it be that the rules of EFT break down?

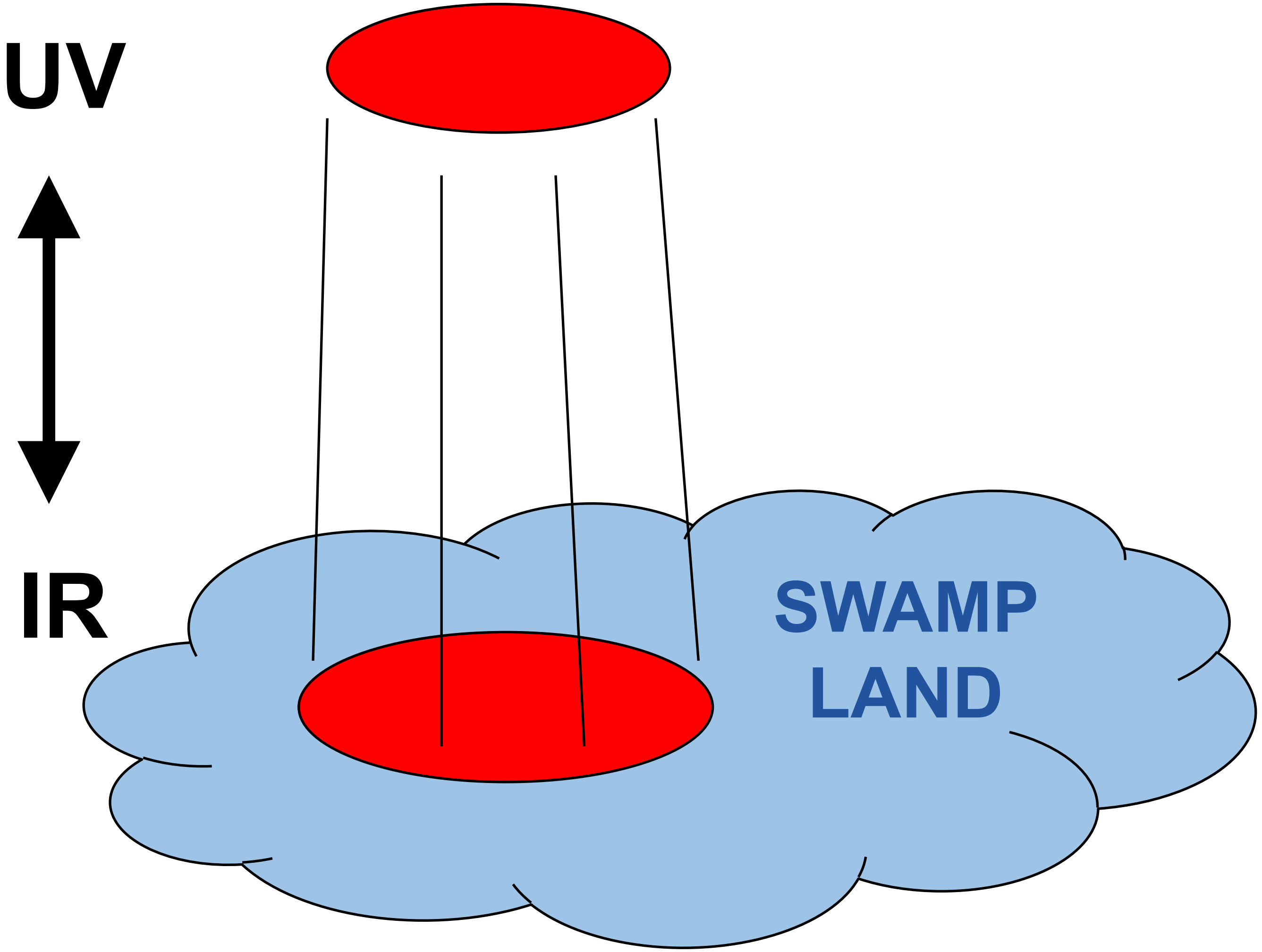
IR/UV correlation

Breakdown of locality in QFT



See N. Arkani-Hamed, BSM Pandemic Seminar, Apr 6

Some theories allowed by EFT symmetries live in the swampland



It challenges EFT intuition

and naturalness is based on EFT intuition

3) IR free parameters are calculable quantities in the UV completion

Example: supersymmetry

breaks chiral symmetry

$$m_H^2 = |\mu|^2 - \frac{3h_t^2}{8\pi^2} m_{\tilde{q}}^2 \ln \frac{\Lambda^2}{m_{\tilde{q}}^2}$$

breaks supersymmetry

Example: composite Higgs

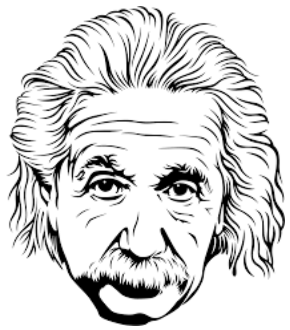
$$m_H^2 = \frac{3h_t^2}{4\pi^2} m_*^2 \xi$$

breaks shift symmetry

Can we give up hypothesis 3)?

The Higgs mass is not a calculable quantity

Nature is comprehensible



A more scientific approach:

IR parameters are functions of some fields whose value vary during the cosmological history or throughout a complex vacuum structure

- Naturalness allows us to infer the scale where an EFT must break down
- Some “postdictions”

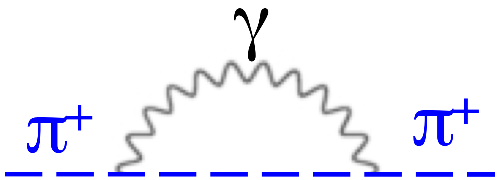
1. Classical electron self-energy

electrostatic energy: $E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70 \text{ MeV}$

magnetic energy: $E \approx \frac{\mu^2}{r^3}, \mu = \frac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha^{1/3}} \approx 3 \text{ MeV}$

New physics (positron) at $m_e < \Lambda$ ($m_e = 0.5$ MeV)

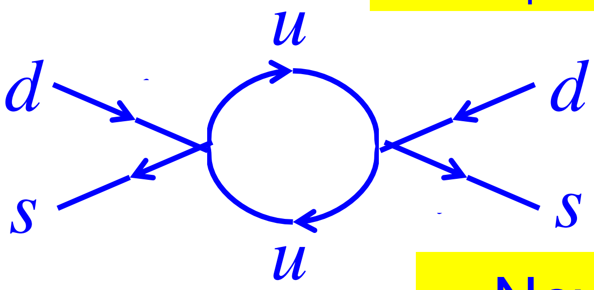
2. QED contribution to pion mass difference



$$\frac{3\alpha}{4\pi}\Lambda^2 < M^2_{\pi^+} - M^2_{\pi^0} \Rightarrow \Lambda < 850 \text{ MeV}$$

New physics (hadrons) at $M_\rho < \Lambda$ ($M_\rho = 770$ MeV)

3. Neutral kaon mass difference



$$\frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_c \Lambda^2 < \frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} \Rightarrow \Lambda < 2 \text{ GeV}$$

New physics (charm) at $m_c < \Lambda$ ($m_c = 1.2$ GeV)

Giving up naturalness by relaxing one of its hypotheses often leads to consequences that are even more radical than those of naturalness itself.

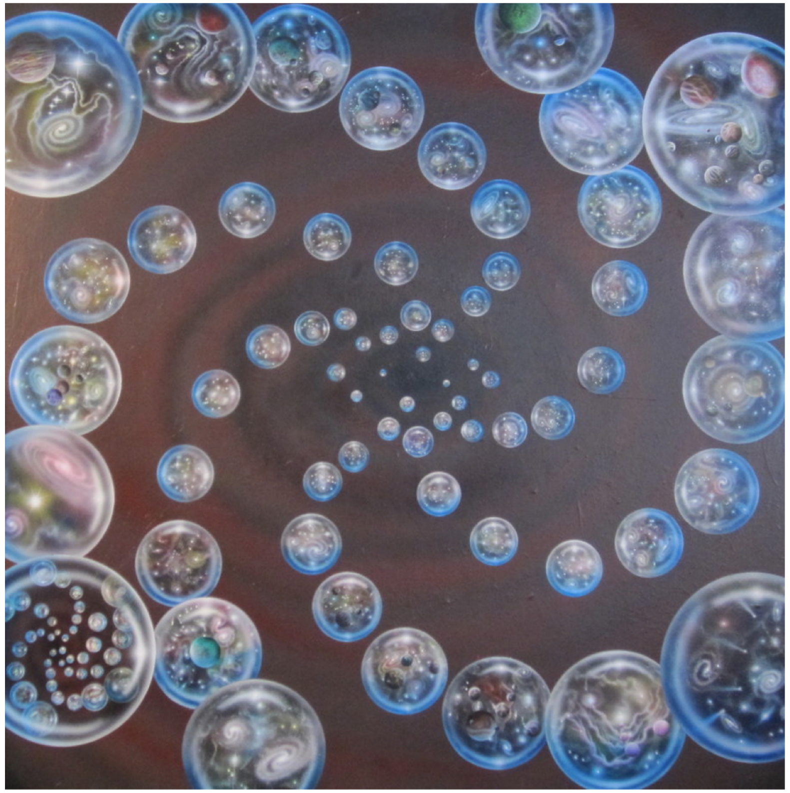
The “symmetry paradigm”: extending the successful gauge principle beyond the SM (technicolor, supersymmetry, composite Higgs, …)

Are gauge symmetries a fundamental principle or an emergent phenomenon?

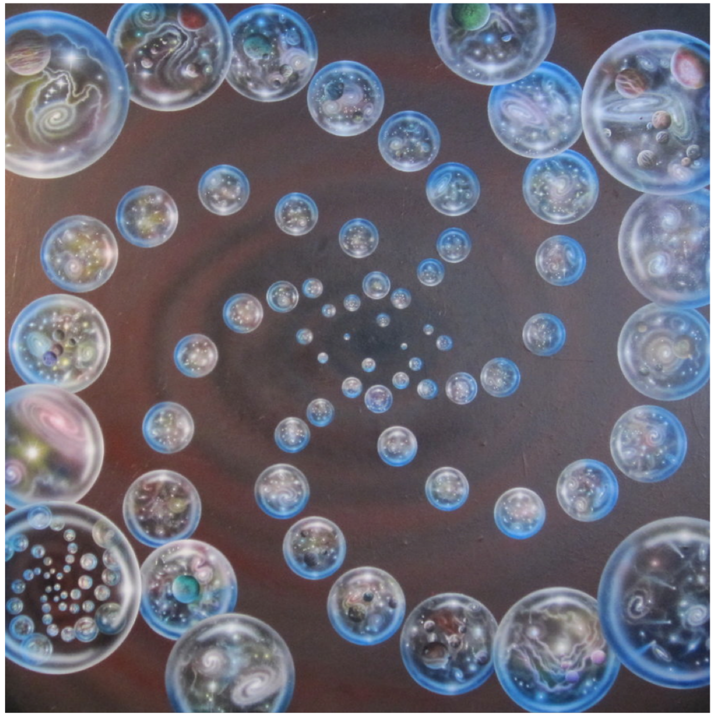
Is the LHC telling us that it is time to look for radically different paradigms?

Another clue: the cosmological constant

$$V_{\text{eff}}(H) = \Lambda_{\text{CC}}^4 + m_H^2|H|^2 + \lambda|H|^4 + \ldots$$

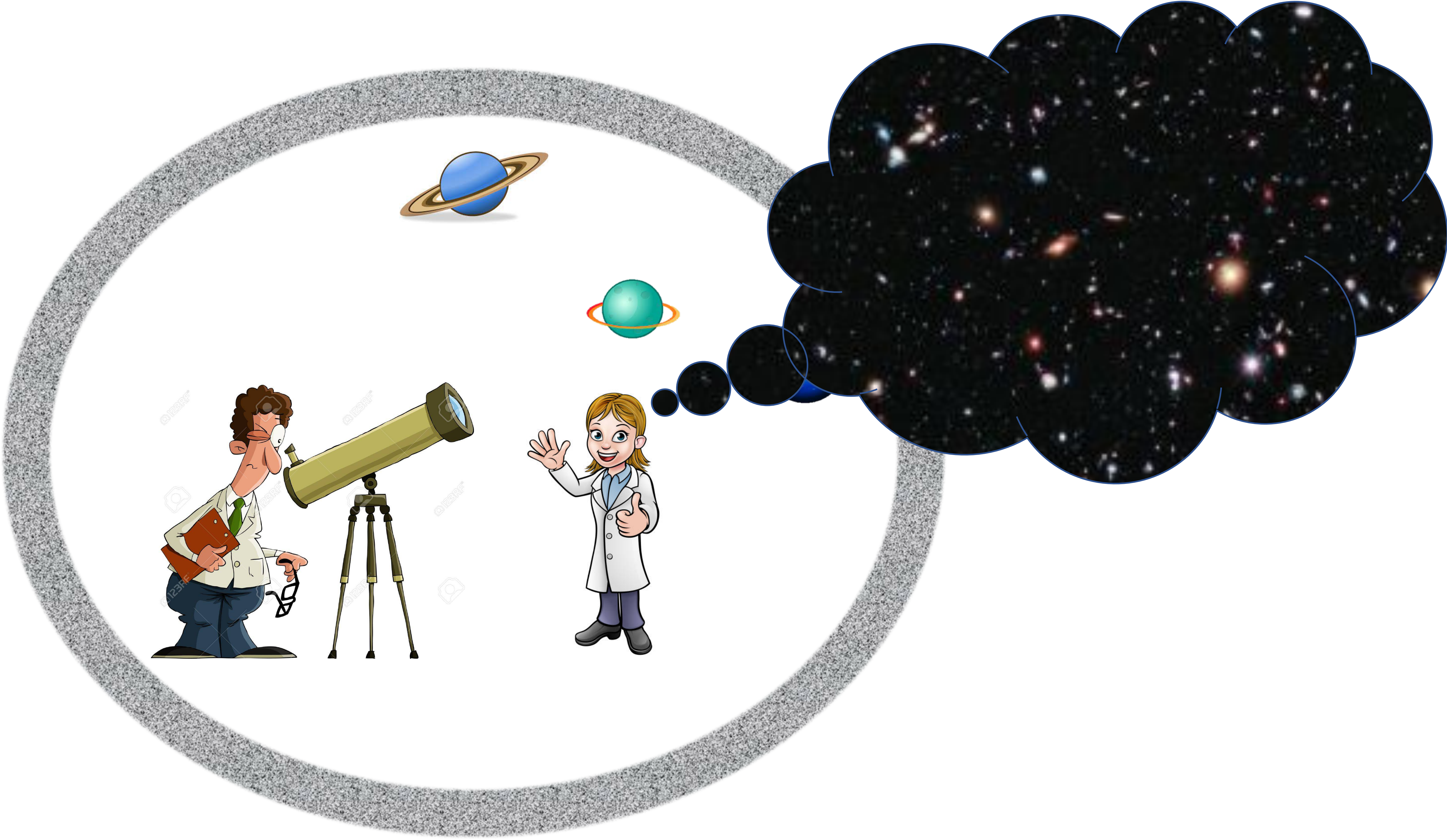


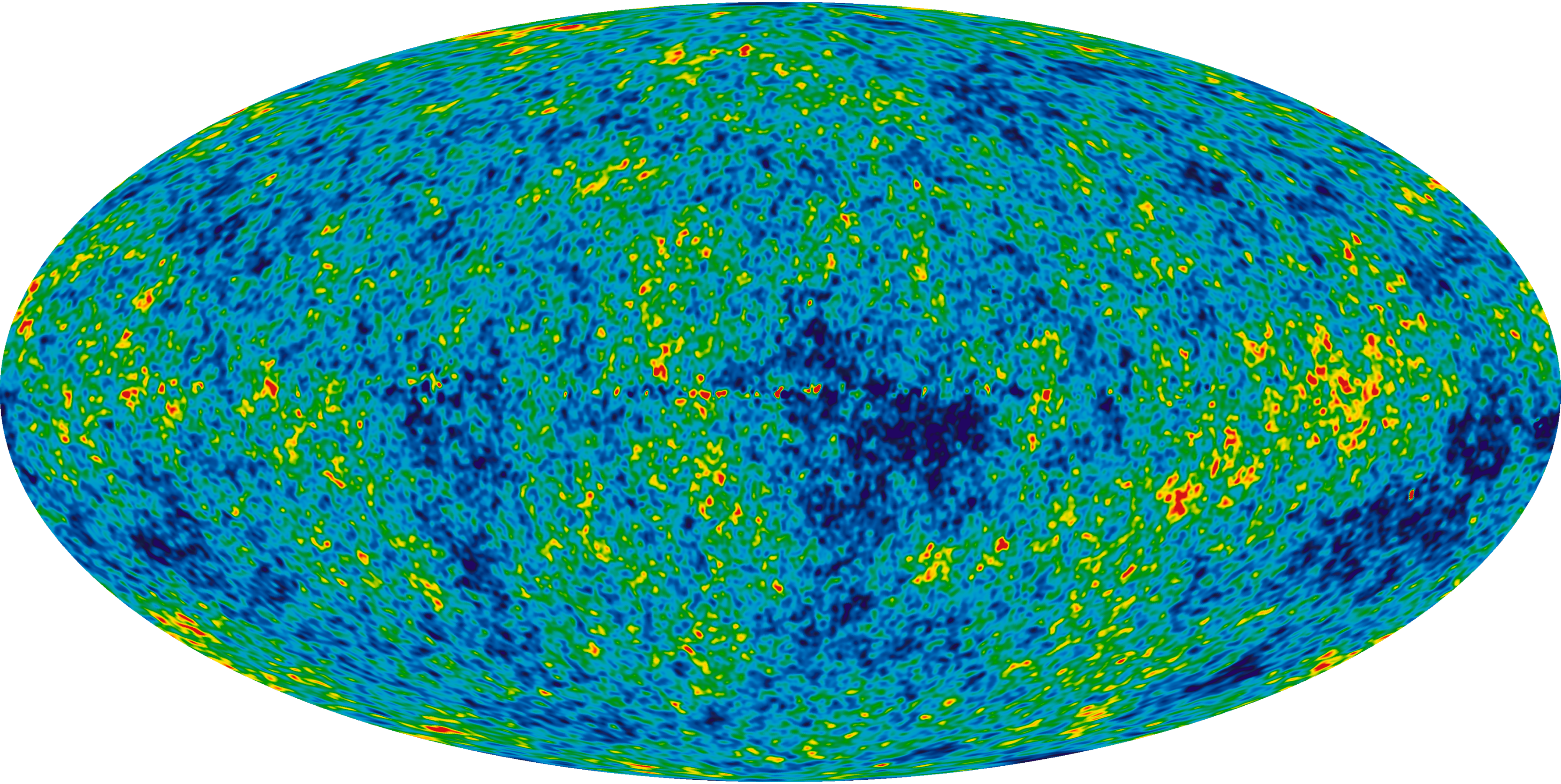
The multiverse

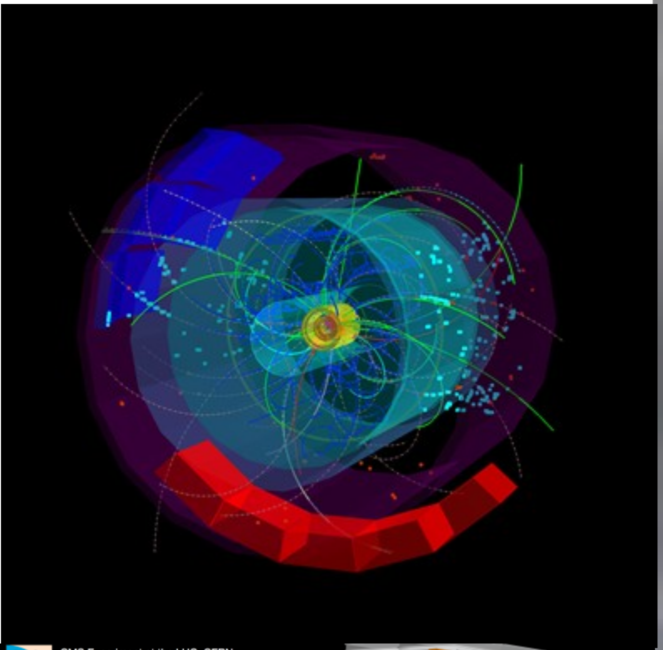


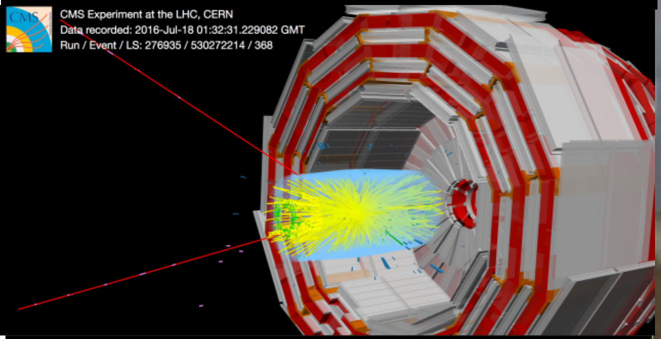
A new Copernican revolution $\Longrightarrow$
not even the patch of the universe we live in is special.

A total revision of the cosmological principle $\Longrightarrow$
the universe is approximately homogeneous and isotropic only within our horizon, but globally highly non-homogeneous.








CMS Experiment at the LHC, CERN
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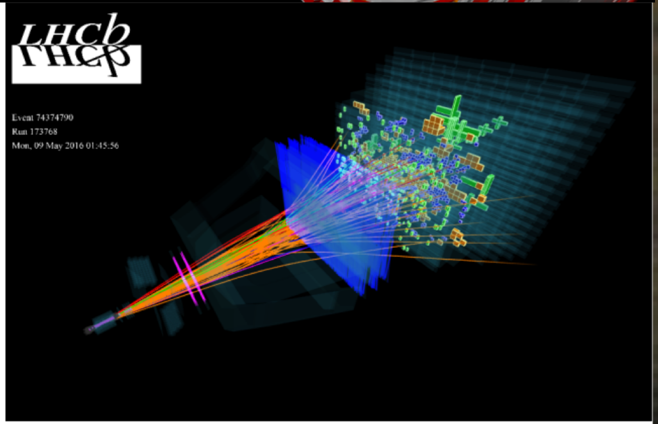
Run / Event / LS: 276935 / 530272214 / 368


LHCb
Event 74374790
Run 173768
Mon, 09 May 2016 01:45:56


Symmetry paradigm

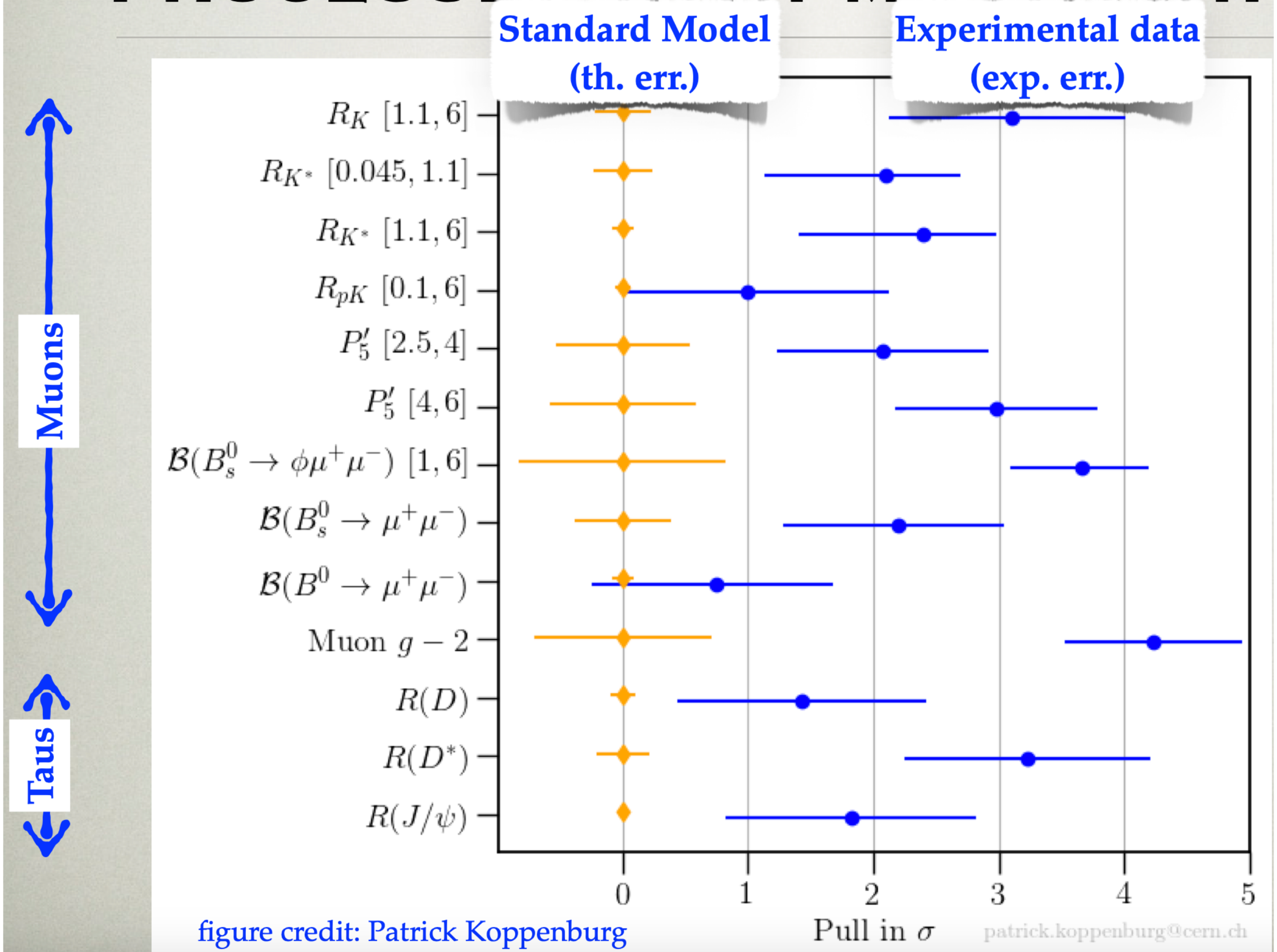
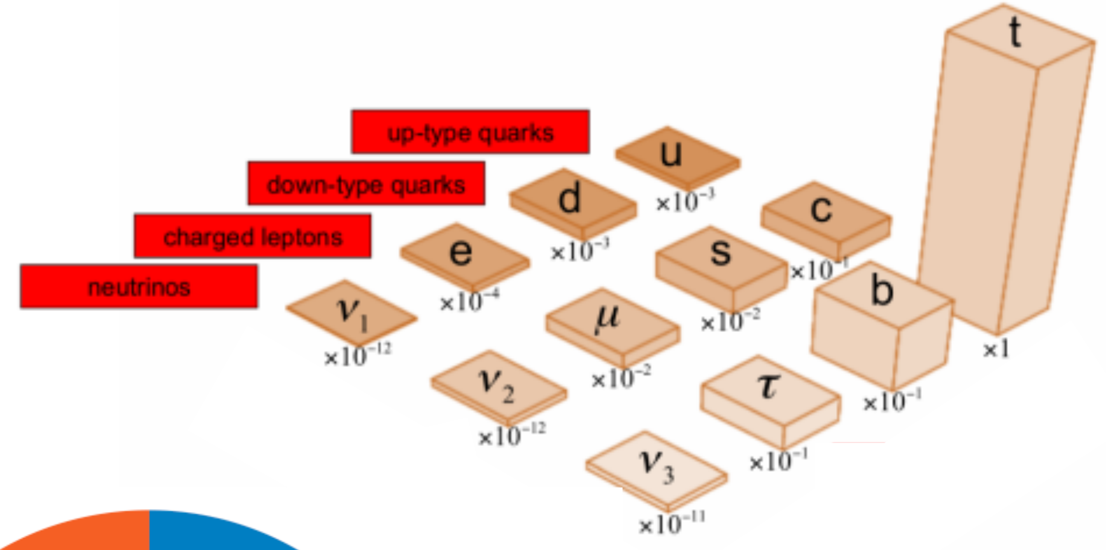
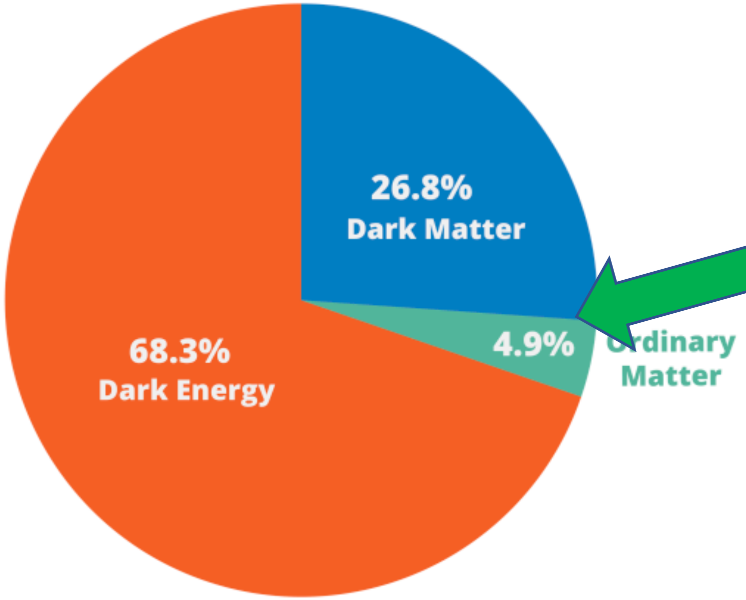


figure credit: Patrick Koppenburg

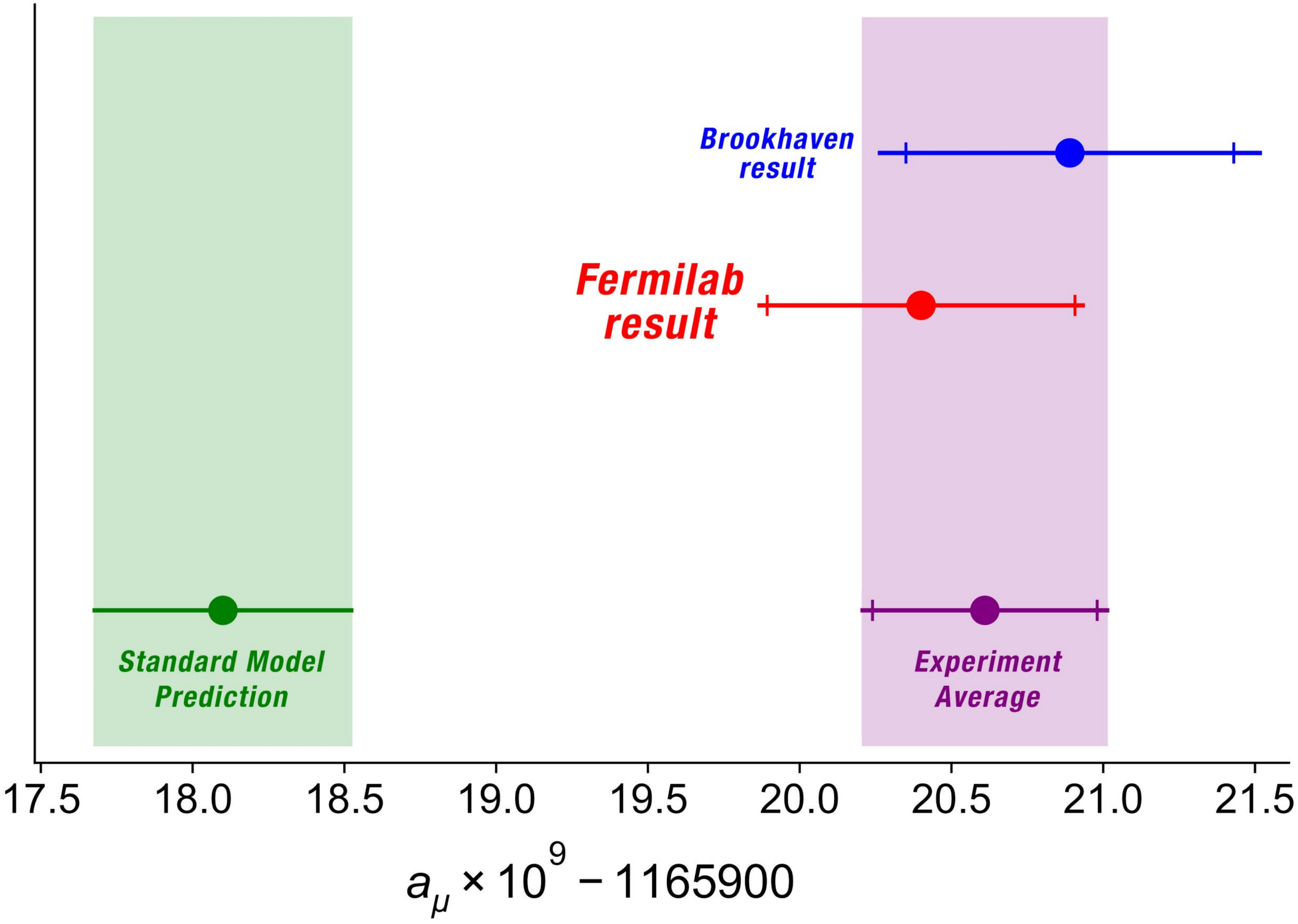




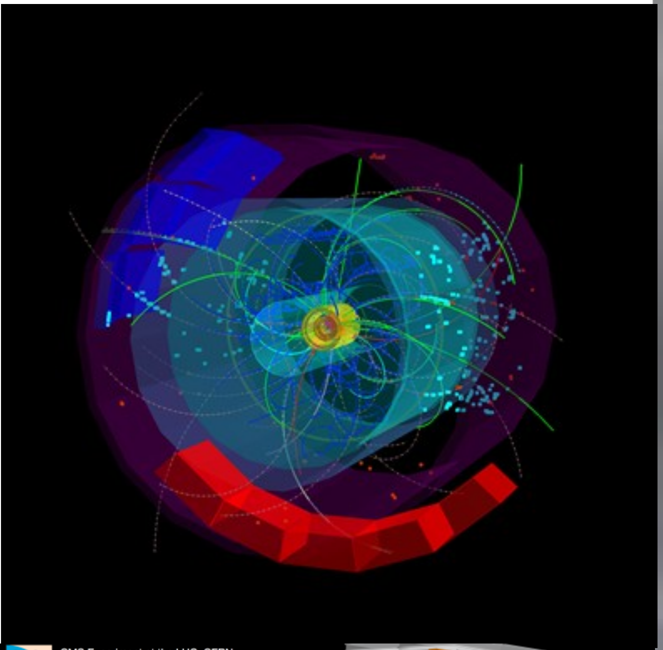
Do we understand this?

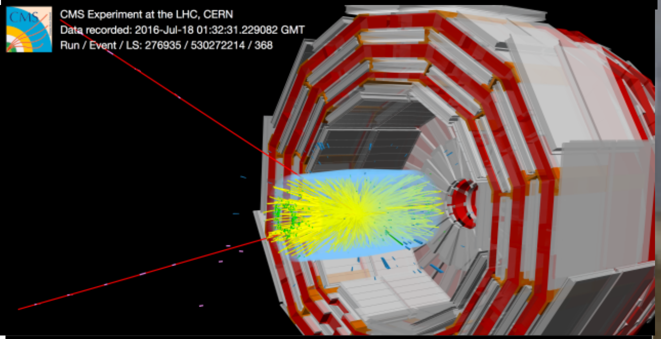
How do we compute m_H ? (The Higgs was discovered 9 yrs ago)

How do we compute m_e ???? (The electron was discovered 124 yrs ago!)



Brookhaven
result
Fermilab
result
Standard Model
Prediction
Experiment
Average
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$

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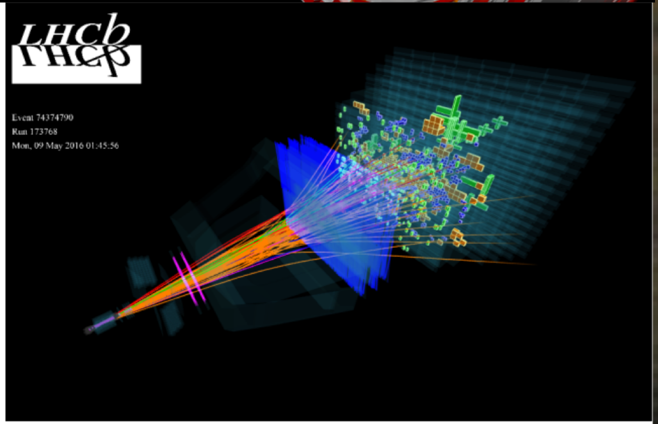
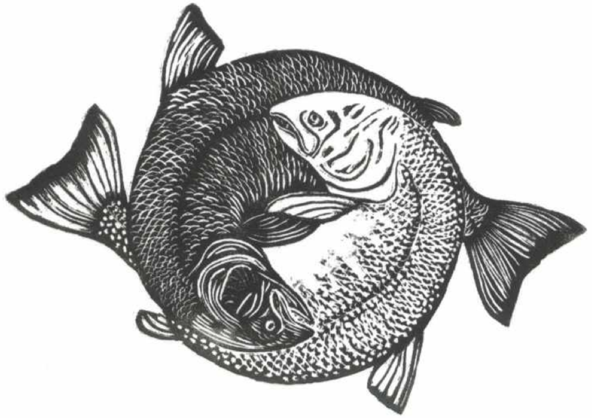
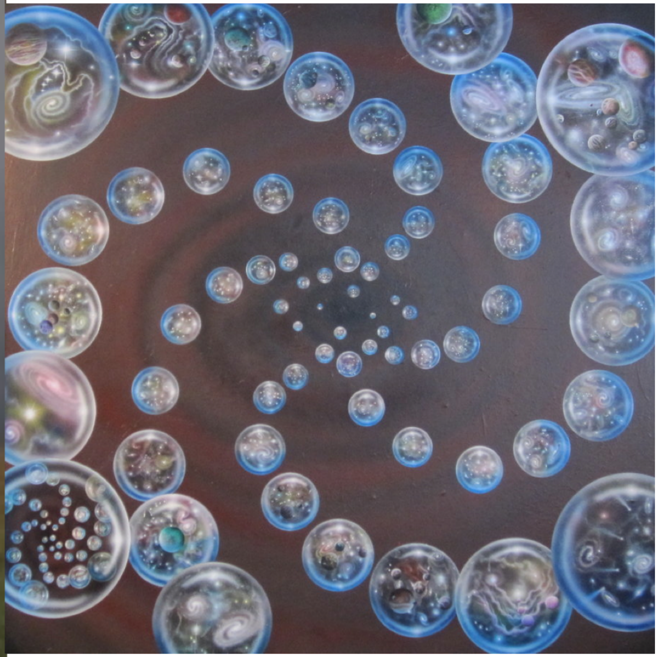

LHCb


Symmetry paradigm
A new paradigm?





?

A bottom-up approach?

“The fabulous five”: millicharged particles, axion-like particles, heavy neutral leptons, dark photons, dark Higgs bosons.

A valuable approach

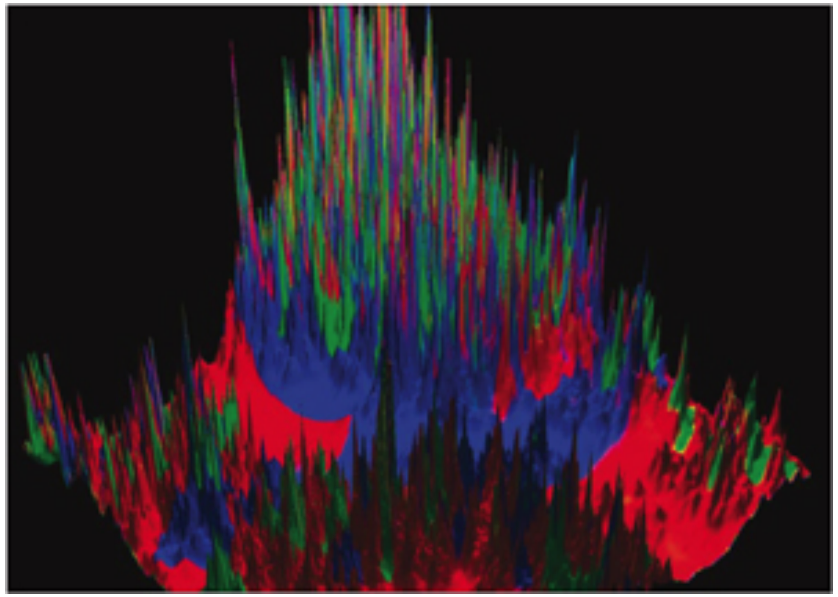
- It helps theorists to think out-of-the-box
- It helps theorists to think about new experimental techniques
- it helps to create a strong th/exp collaboration
- It helps to build links with other fields (astro, atomic, nuclear, condensed matter...)
- It creates a more diversified spectrum of experimental activities
- Serendipity means opportunity

- The goal of theoretical physics is to identify principles.
- Models are useful, but they must be the consequence of principles, not the starting point.

"Despite its value, positivism has done as much harm as good. [... Today] positivism has preserved its heroic aura, so that it survives to do damage in the future."

- Pure thought is the warp drive that propels physics into revolutions.
- Is there a context in which we can formulate a paradigm alternative to symmetry?

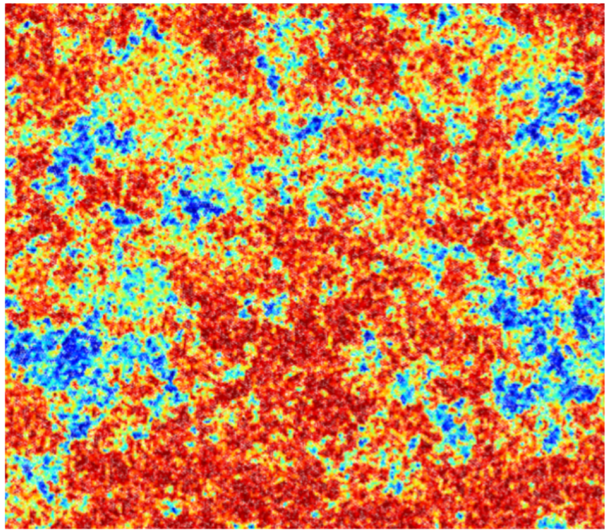
Multiverse: low-energy parameters are functions of fields with a non-trivial vacuum structure which is explored during the history of the universe.

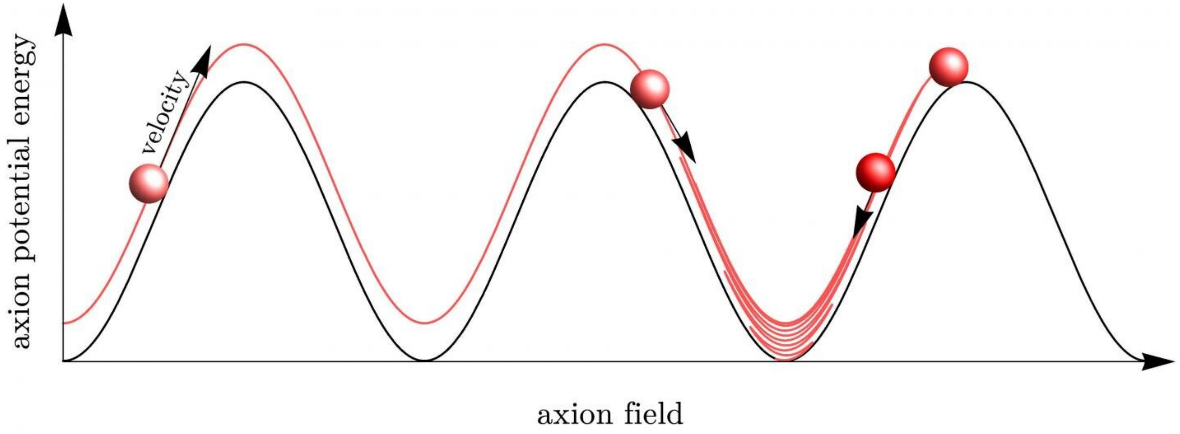


Axion

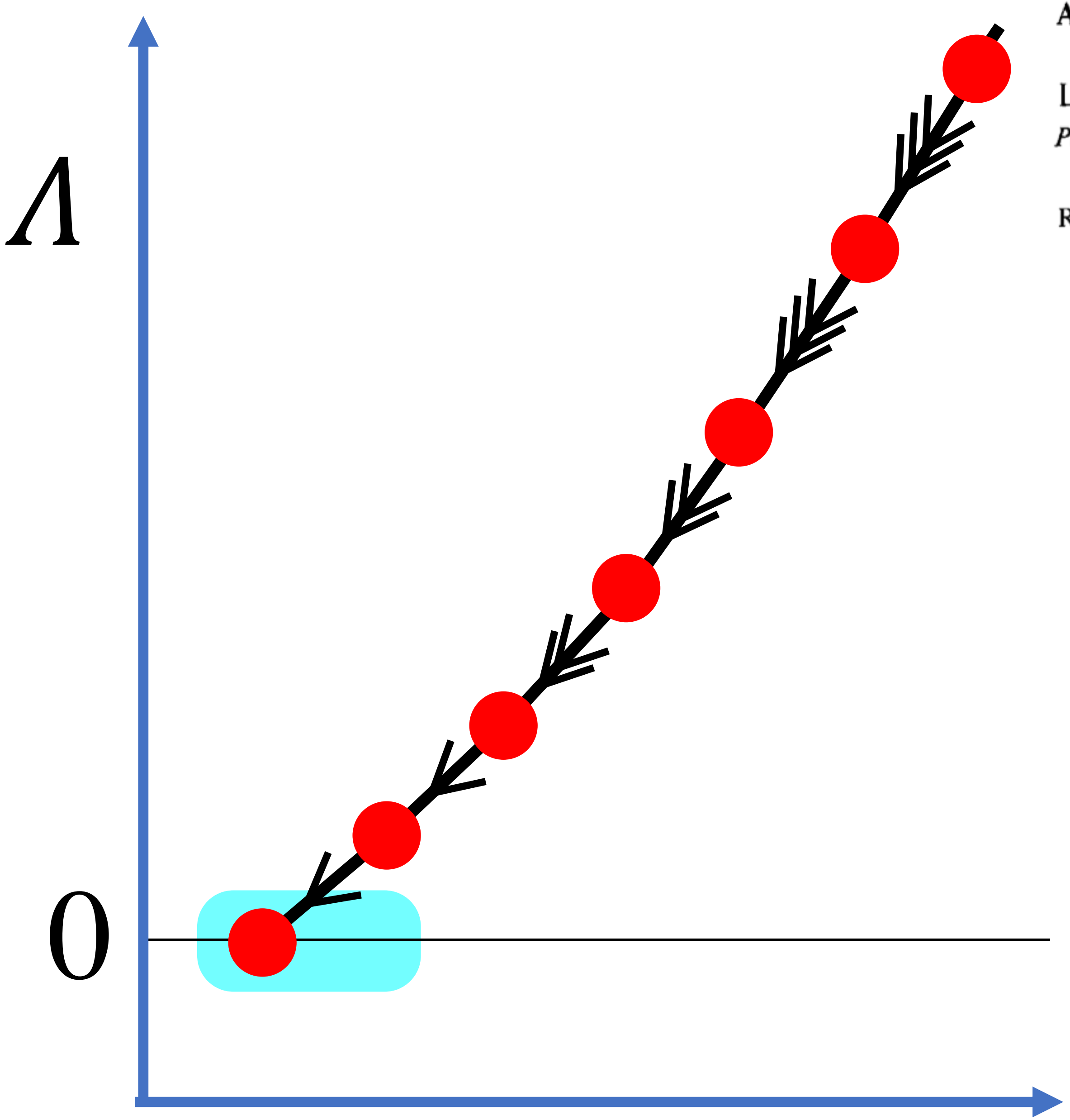
$$\mathcal{L}_{\text{dim}=4} = \frac{g_s^2}{32\pi^2}\,\bar{\theta} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a} \qquad d_n \sim e\,\frac{\bar{\theta} m_*}{\Lambda^2_{\text{had}}} \sim \bar{\theta}\cdot(6\times 10^{-17})\;e\,\text{cm} \qquad |\bar{\theta}| < 10^{-10}$$

$$\bar{\theta} \Longrightarrow a$$





$\Longrightarrow$ multiverse explanation of a low-energy parameter



A MECHANISM FOR REDUCING THE VALUE OF THE COSMOLOGICAL CONSTANT

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Received 30 October 1984

DYNAMICAL NEUTRALIZATION OF THE COSMOLOGICAL CONSTANT

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Received 27 March 1987

Two problems

- Smallness of scanning steps
- Empty Universe

Quantization of four-form fluxes and dynamical neutralization of the cosmological constant

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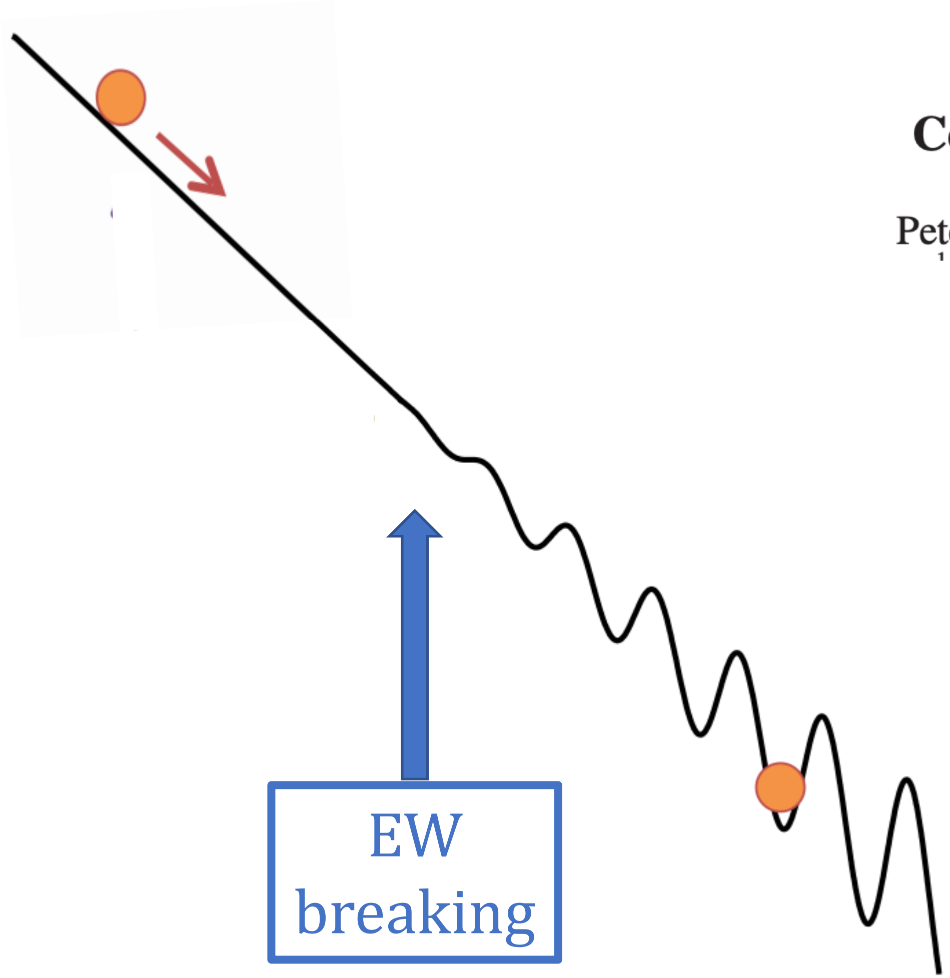
Cosmic attractors and gauge hierarchy

Gia Dvali[1] and Alexander Vilenkin[2]



Cosmological Relaxation of the Electroweak Scale

Peter W. Graham,[1] David E. Kaplan,[1,2,3,4] and Surjeet Rajendran[3]

$$V_{\rm QCD} = f_\pi^3 \, m_q \cos(\phi / f_{\rm PQ})$$

CERN-TH-2021-077

Self-Organised Localisation

Gian F. Giudice,[a] **Matthew McCullough**,[a,b*] **Tevong You**[a,b,c]

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[c] *Cavendish Laboratory, University of Cambridge, Cambridge, UK*

Abstract

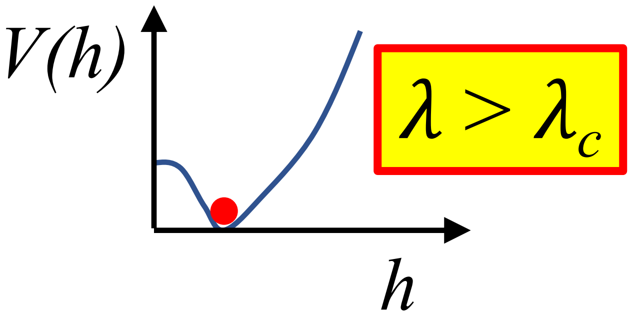
We describe a new phenomenon in quantum cosmology: self-organised localisation. When the fundamental parameters of a theory are functions of a scalar field subject to large fluctuations during inflation, quantum phase transitions can act as dynamical attractors. As a result, the theory parameters are probabilistically localised around the critical value and the Universe finds itself at the edge of a phase transition. We illustrate how self-organised localisation could account for the observed near-criticality of the Higgs self-coupling, the naturalness of the Higgs mass, or the smallness of the cosmological constant.

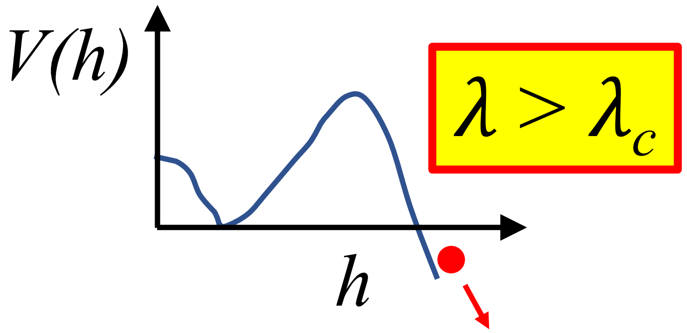
1) Microscopic theory

$$\mu \longrightarrow \mu(\phi)$$

2) Microscopic theory

$\mu = \mu_c$ phase transition





Emergent property out of inflationary dynamics: parameters are probabilistic driven towards a condition of near-criticality, such that the universe is at the verge of collapsing.

Self-Organised Localisation (SOL)

SOL could explain the near criticality of the Higgs quartic coupling, the smallness of the Higgs mass and the cosmological constant.

CONCLUSIONS

- Relaxing the hypotheses on which naturalness is based has consequences that are even more radical than naturalness itself.
- The LHC is having a gigantic impact on theoretical particle physics, leading us to a conceptual crossroads.
- Radically new paradigms are opening up new vistas and self-organised criticality offers a new tool in quantum cosmology which could unlock some of the mysteries of particle physics.