Is there life beyond the Standard Model?

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- The standard model
- Unsolved questions in the SM
- Alternatives at the TeV scale
- Conclusions

Before the SM

Weak interactions described by four-fermion interactions: coupling constants have negative dimensions ($[G_F] = M^{-2}$), therefore, necessarily cross sections grow with energy

$$\sigma \sim G_F^2 E^2 \left(1 + \mathcal{O}\left(G_F E^2\right) + \cdots\right)$$

The theory cannot be valid up to arbitrarily high energies and it is not renormalizable: It breaks down at scales

$$E \sim 1/\sqrt{G_F}$$

Non-renormalizable theories contain a physical scale which signals the end of their applicability and the onset of new physics.

The Standard Model

Each family contains 5 multiplets (6 if right-handed neutrinos are considered $\psi_i = (Q_L, d_R, u_R, L_L, e_R)$

The Lagrangian contains three pieces:

Kinetic and gauge terms:

$$\mathcal{L}_{\text{gauge}} = \sum_i i\,\bar{\psi}_i \gamma^\mu D_\mu \psi_i - \frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu}$$

with $D_\mu \equiv \partial_\mu - ig\frac{\vec{\tau}}{2}\vec{W}_\mu - ig'\frac{Y_i}{2}B_\mu - ig_s\frac{\lambda^a}{2}G^a_\mu$

Only three constants (GUT's can reduce them to a single constant).

The scalar sector (two more arbitrary constants):

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger\ D^\mu \Phi - V(\Phi)$$

$$V(\Phi) = -\mu^2\ \Phi^\dagger \Phi + \lambda\ (\Phi^\dagger \Phi)^2$$

Yukawa sector:

$$\mathcal{L}_Y = -Y_e \bar{L}_L \Phi e_R - Y_d \bar{Q}_L \Phi d_R - Y_u \bar{Q}_L \tilde{\Phi} u_R + \text{h.c.}$$

with Y_e, Y_d, Y_u, arbitrary complex 3x3 matrices = 3x9x2=54 real numbers! Most of them are not observable (only 9+3+1 observable).

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The SM is renormalizable: is selfconsistent and, in principle, it does not contain the scale of possible new physics (or it does contain it?)

Unsolved Questions in the SM

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- ✯ **Masses and mixings:** The Yukawa sector of the SM contains 3+ 6 masses + 3 mixings + 1 phase =13 parameters. Masses from 0.0005 GeV to 175 GeV. Some regularities (hierarchy of masses and mixings) but no one has been able to explain this puzzle.

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The SM parametrizes correctly the flavour sector, but its success looks a colateral consequence of the minimal Higgs sector.

The scale of flavour physics is probably at the few hundreds of TeV (if related to FCNC problems). However, any new physics always has a big impact on the flavour sector.

Hints Beyond the SM

Neutrino masses

Right-handed ν's not needed and not included in the SM: ν's massless. However, solar and atmospheric ν-data suggest tiny ν masses. Can they be accomodated in the SM?

Adding right-handed neutrinos to the SM one can write

$$\mathcal{L}_{YL} = -\bar{L}_L Y_e \Phi e_R - \bar{L}_L Y_\nu \tilde{\Phi} \nu_R + \text{h.c.}$$

but then:

- ✯ Why the neutrino masses are so small?
- ✯ Why not a righthanded neutrino Majorana mass term?

$$\mathcal{L}_{\text{Majorana}} = \frac{1}{2} \overline{\nu_R^c} M \nu_R + \text{h.c.}$$

By adding a righthanded Majorana mass term the first question is answered. If $M \gg v_F$ one obtains the see-saw formula:

$$M_\nu = \frac{Y_\nu^T Y_\nu v_F^2}{M}$$

The mechanism is much more general: in the SM there is only one gauge-invariant dimension five operator (M is the new physics scale):

$$\mathcal{L}_{\rm eff} = \frac{1}{M}\left(\tilde{\Phi}^\dagger \vec{\tau}\Phi\right)\left(\overline{\tilde{L}_L} H_\nu \vec{\tau} L_L\right)$$

After SSB one gets

$$M_\nu = \frac{H_\nu v_F^2}{M}$$

However, $m_\nu < 1\,\mathrm{eV}$ require $M > 10^{14}\,\mathrm{GeV}$ (if $Y_\nu = 1$) but M could be at the TeV scale if Y_ν is very small (as it is for electrons)!

Triviality

The λ coupling in the scalar potential grows with energy

$$\frac{d\lambda}{d\ln q^2} = +\frac{3\lambda^2}{4\pi^2} + \cdots$$

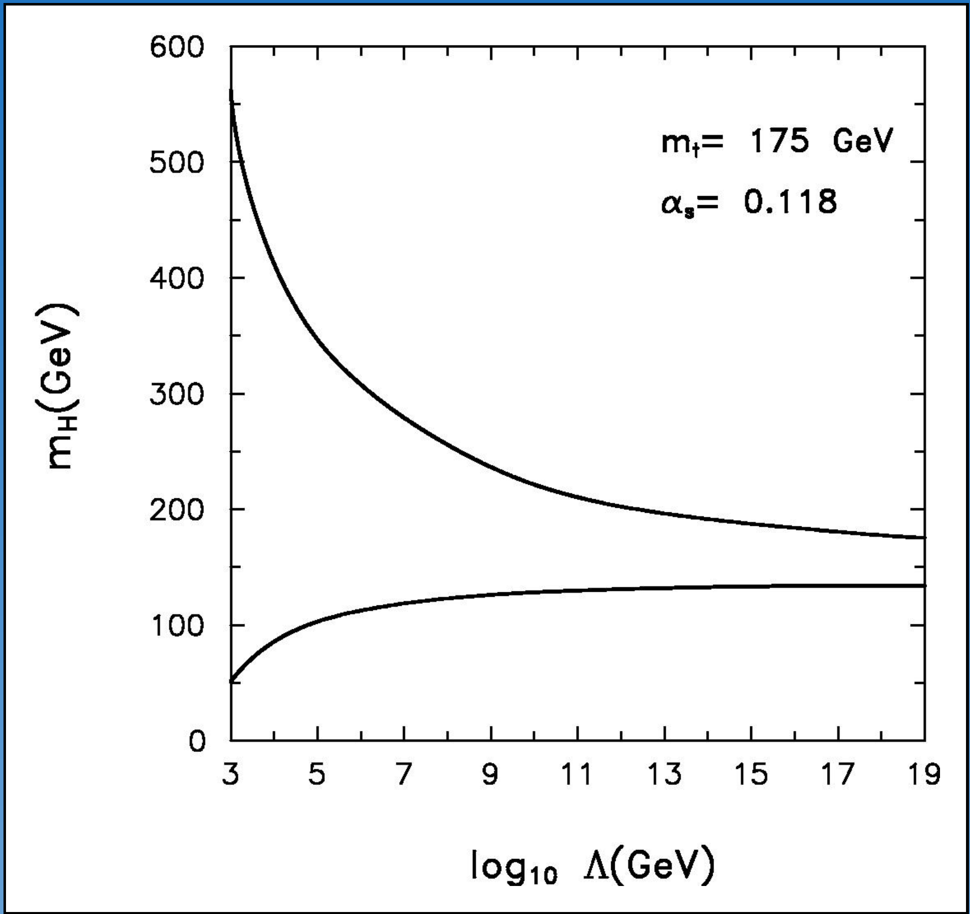
then λ diverges at some scale Λ, (Landau pole) unless it is strictly zero. Taking $\lambda(\Lambda) = \infty$ (the theory only makes sense up to $q^2 \sim \Lambda^2$) one finds

$$\lambda(q^2) = \frac{4\pi^2}{3\log(\Lambda^2/q^2)}$$

$$m_H^2 \leq \frac{4\pi^2}{3\sqrt{2}G_F\log(m_H^2/v_F^2)} \approx (850\,\mathrm{GeV})^2$$

Radiative corrections modify the shape of the Higgs potential and could destabilize it. Requiring this does not happen one finds:

$$m_H > 100\,\mathrm{GeV}$$



Although renormalizable the SM cannot be valid up to arbitrary large scales. It is only valid up to an scale Λ.

- If the Higgs is light $m_H < 200\,\mathrm{GeV}$, Λ can be very large (although not necessarily)
- If the Higgs is heavy $m_H > 450\,\mathrm{GeV}$, Λ is necessarily of the order of the TeV

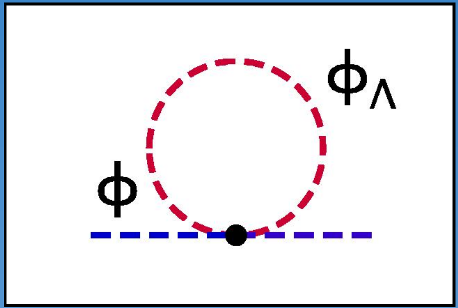
The SM is just an effective theory of something else!

How large can Λ be?

The Hierarchy Problem

Once we accept that the SM is not valid up to arbitrarily large scales we should worry about the effect of particles of mass Λ on the SM parameters.

In the SM the Higgs self-energy suffers from quadratic divergences:



$$m_H^2 = 2\lambda v_F^2 + \frac{\kappa}{16\pi^2}\Lambda^2$$

m_H tends to get corrections proportional to the scale of new physics because the scalar mass is not protected by any symmetry.

If the new physics scale is very large, huge fine tunning needed. This is unnatural. The new physics scale cannot be much larger than

$$\Lambda \approx 4\pi v_F = 3\,\mathrm{TeV}$$

Alternatives at the TeV scale

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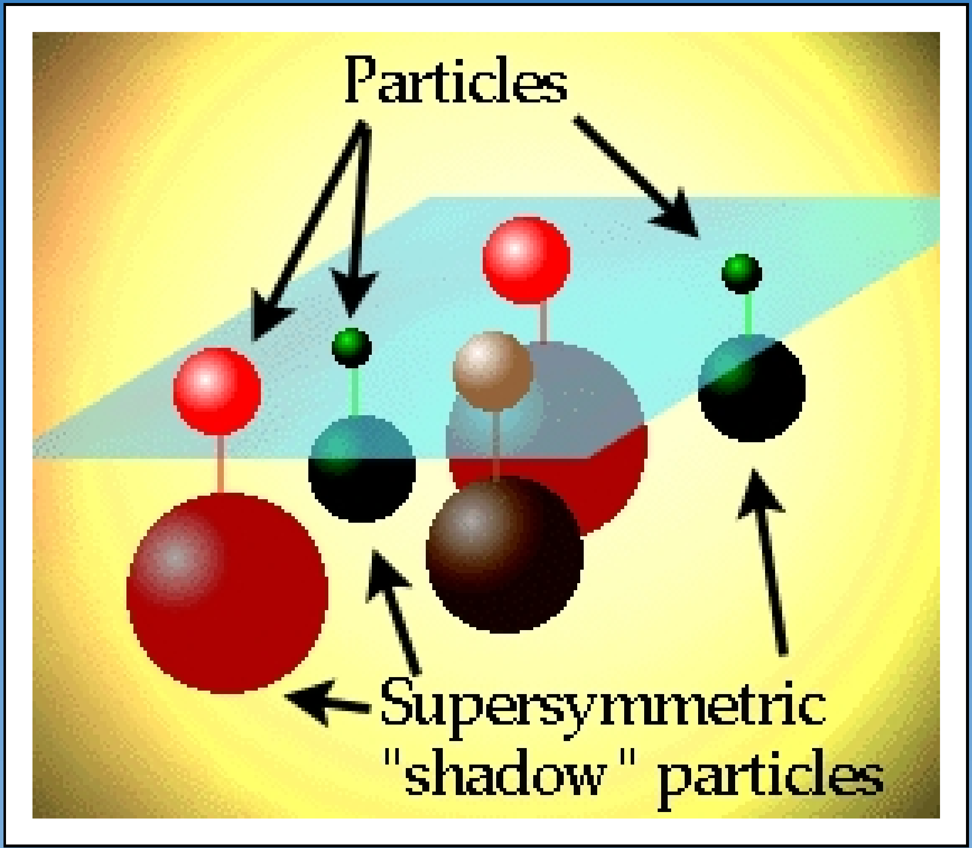
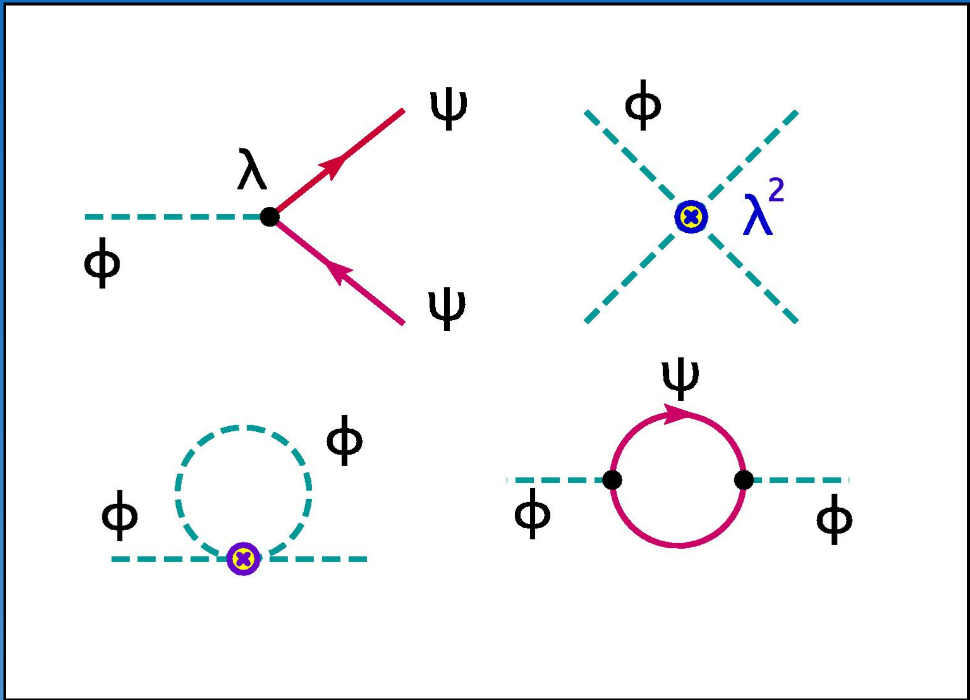


Fermion masses are protected by chiral symmetry $\bar{\psi}\psi \to -\bar{\psi}\psi$ if $\psi \to \gamma_5\psi$: If a fermion is massless, loops will not generate a mass.
A symmetry that puts fermions, ψ, and bosons, ϕ, in the same multiplet requires $m_\psi = m_\phi$, since m_ψ is protected, m_ϕ will also be protected.



In SUSY models one finds diagramatically that quadratic divergences cancel exactly.

In realistic models the SM spectrum is enlarged to include SUSY partners of all SM particles.

SUSY cannot be exact: we do not see the SUSY partners. Then

$$m_H^2 = 2\lambda v_F^2 + \frac{\kappa}{(4\pi)^2}(\tilde{M}_W^2 - M_W^2)\ln\frac{\Lambda}{v_F}$$

$\tilde{M}_W^2$ cannot be much larger than M_W^2 if the hierarchy problem is going to be solved. A detailed analysis gives charginos below 250 GeV and gluinos below 1 TeV. If these ideas are correct these particles should be discovered at LHC (if not before).

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- ✓ Sharp predictions for the lightest Higgs $\lambda_{\rm SM} = \frac{1}{8}(g^2 + g'^2)$; including loop corrections (with the top quark):

$$m_H^2 = M_Z^2 + \frac{3\alpha m_t^4}{2\pi \sin^2\theta_W M_W^2} \ln \frac{\tilde{m}^2}{M_Z^2} \approx (110 - 120\,\mathrm{GeV})^2$$

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- ✓ LSP and gravitino can provide dark matter candidates.
- ✓ Unification of couplings better than in the SM.

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- ✗ Does not say much on neutrino masses (although it opens new possibilities).

Technicolor

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When compared to QCD the electroweak sector looks awfull (so many parameters unexplained!).
QCD has only one parameter, $\Lambda_{\rm QCD}$ (the scale at which α_s becomes strong). In principle, from $\Lambda_{\rm QCD}$ one should be able to derive the scale of SB of chiral symmetry and the masses of all hadrons, π, ρ, p, n, etc.

Unfortunatelly this is not yet possible...
The idea can be extended to the electroweak sector: no fundamental scalars, but additional fundamental fermions, F, which feel new strong interactions.

These interactions become strong at some scale Λ_F

$$\langle \bar{F} F \rangle \sim \Lambda_F^3 \sim v_F^3.$$

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- ✓ In principle, one could derive everything from few parameters.

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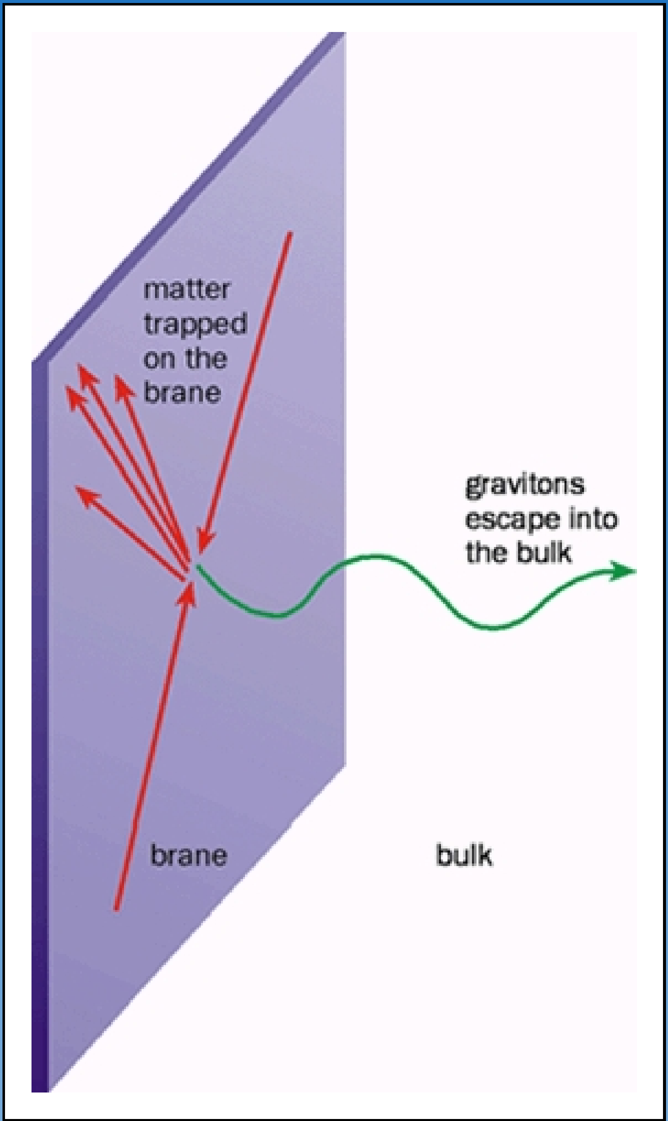
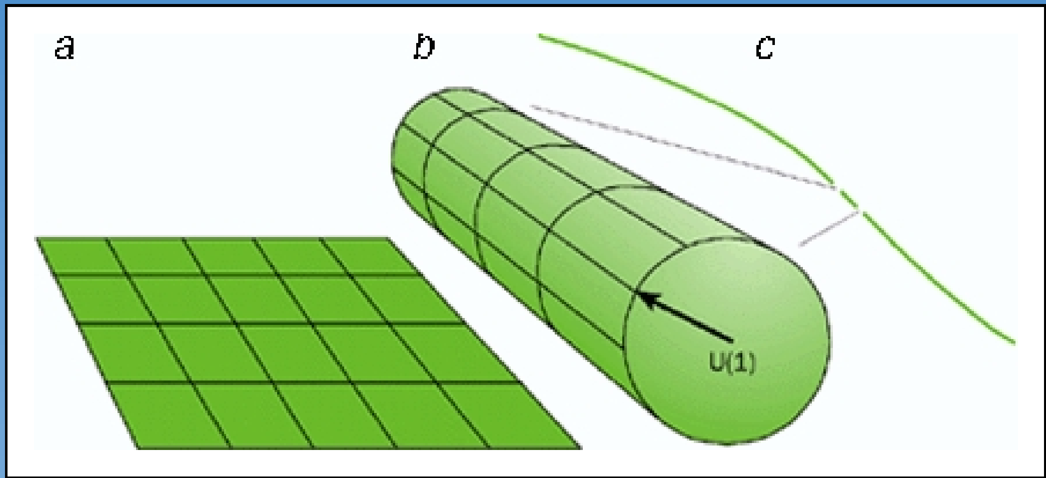
But, perhaps, these are consequences of our limitations not nature's fault.

If Technicolor ideas are correct, a lot of work will be needed; from the experimental side to obtain the spectrum, and from the theoretical side to understand it.

Extra dimensions



It could be that there exist additional dimensions which we cannot see because they are "compactified" on tiny scales or because we are confined to move in only four dimensions (like electrons only move on the surface of metals).



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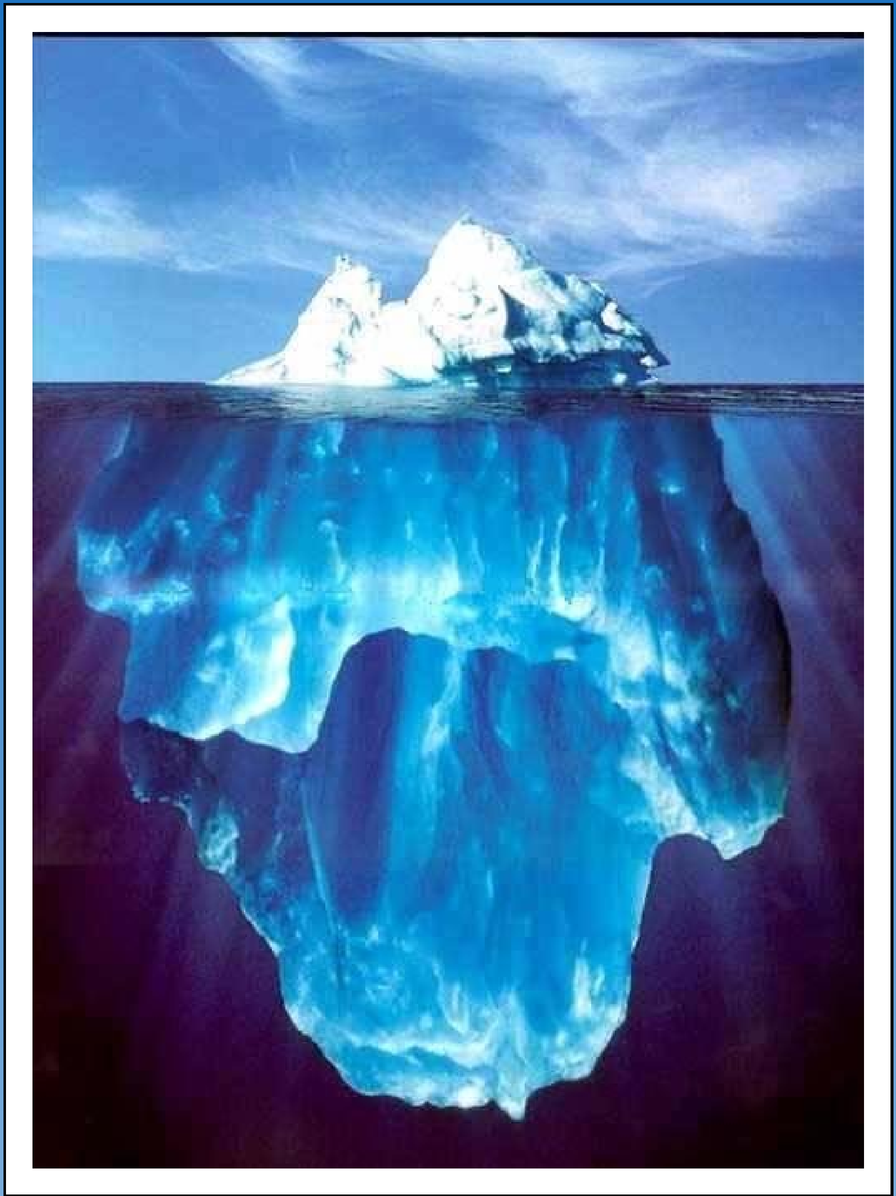

"What we can easily see is only a small part of what is possible!".

There are not different scales; it happens that we only see a small part of objects which "live" mainly in other dimensions.

This can be applied to any small parameter (Newton's constant, Yukawa couplings, neutrino masses, etc).

For instance if gravity propagates in δ extra dimensions compactified on a radius R we can compare Newtonian forces in $\delta+4$ dimensions and in 4 dimensions.

If $M_{\rm P}=G_N^{-1/2}\simeq 10^{19}$ GeV and M is the Planck mass in $\delta+4$ dimensions. One has

$$F_4=\frac{1}{M_{\rm P}^2}\frac{m_1 m_2}{r^2}$$

$$F_{4+\delta}=\frac{1}{(M)^{2+\delta}}\frac{m_1 m_2}{r^{\delta+2}}$$

Then

$$M_{\rm P}=M(MR)^{\delta/2}$$

If $M\sim v_F$, R is fixed: for $\delta=2$, $R\sim 10^{-1}$ cm, and for $\delta=6$, $R\simeq 10^{-13}$ cm.

For $r < R$ deviations from the r^{-2} law:

$$V(r) = -\frac{G_N m_1 m_2}{r} \left\{ 1 + 2\delta e^{-r/R} + \dots \right\}$$

Can be tested at $R \sim 1\,\mathrm{mm}$.

The presence of compact dimensions of size R allows gravitons to get produced, at energies of order $(\sqrt{s})_{\mathrm{parton}} \sim M$, with a probability proportional to M^{-2} not M_{P}^{-2}.

LEP and Tevatron: $e^+e^- \to \gamma\, G$ and $p\bar{p} \to \mathrm{jet}\, G$, ($e^+e^- \to \gamma\nu\bar{\nu}$ analyses and bounds for monojet production):

$$M \gtrsim 600\,\mathrm{GeV}\,(\delta = 6) \qquad M \gtrsim 750\,\mathrm{GeV}\,(\delta = 2)$$

LHC will be sensitive to much greater values of M (SN bounds, however, give $M \gtrsim 30$ TeV for $\delta = 2$).

Another solution not involving gravity:

A gauge boson propagating in extra dimension contains additional components: in 5 dimensions $A_M = (A_\mu, A_5)$. In 4 dimensions A_5 is seen as a scalar.
The nice thing is that A_M is massless because gauge invariance, therefore the mass of A_5 is protected. Similar to the SUSY solution.

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- ✓ Can explain small neutrino masses.
- ✓ Flavour problem attacked by putting fermions on different branes.

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- ✗ Additional physics needed at scales few orders of magnitud beyond the compactification scale.

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- ✯ Triviality and Hierarchy problems suggest that there is physics beyond the SM related to the origin and magnitude of the Fermi scale.
- ✯ We have considered three solutions of the Hierarchy problem: supersymmetry, technicolor and extra compact dimensions. All of them predict an explosion of new particles at scales of the TeV or below.
- ✯ Each of the solutions has its beauties and problems, and at the moment, it is not possible to select among them. It is even possible that none of them or a combination of them is the one selected by nature.

In any case, if the ideas presented here are correct, the origin of the Fermi scale should become clear once the LHC starts running.