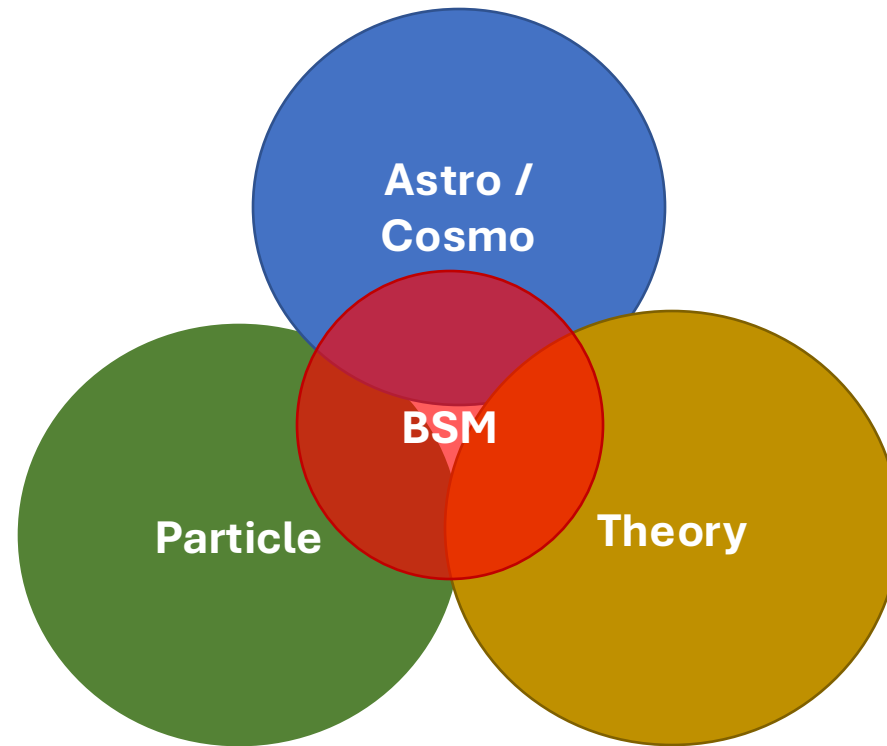


Beyond the Standard Model

Tevong You

Why BSM?

The ultimate goal of fundamental physics is to go **Beyond the Standard Model** (BSM).



BSM combines our **experimental**, **observational**, and **theoretical** knowledge of the Universe.

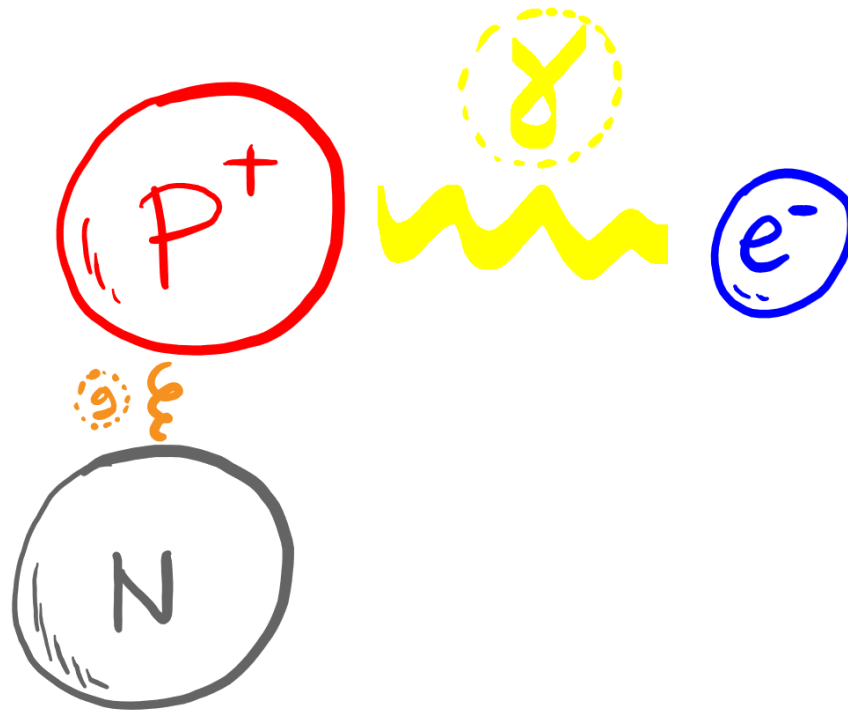
We *are* getting closer to the ultimate truth, empirically, though **many unanswered puzzles** remain.

Outline

1. Lessons in how we got here
2. Naturalness — what's the big deal?
3. Problems of the SM: arbitrary / unnatural / incomplete / inconsistent
4. Supersymmetry, WIMPs, GUTs

How we got here

- 1930s: everything is made of **protons**, **neutrons**, and **electrons**

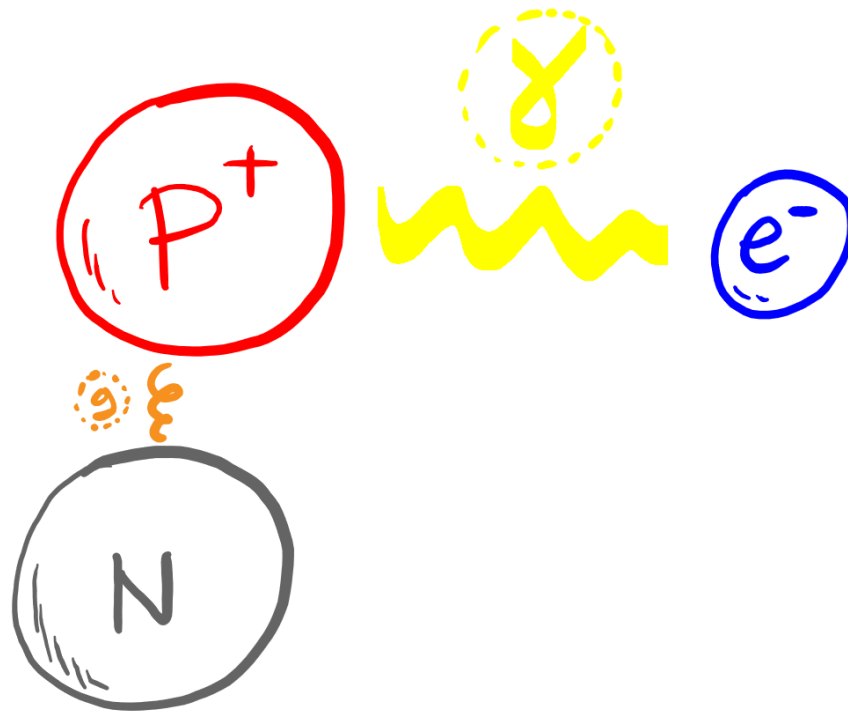


Minimal, economical theory?

- Held together by **electromagnetism** and the **strong force**

How we got here

- 1930s: *everything* is made of **protons**, **neutrons**, and **electrons**



"If we consider protons and neutrons as elementary particles, we would have three kinds of elementary particles [p,n,e].... This number may seem large but, from that point of view, two is already a large number."

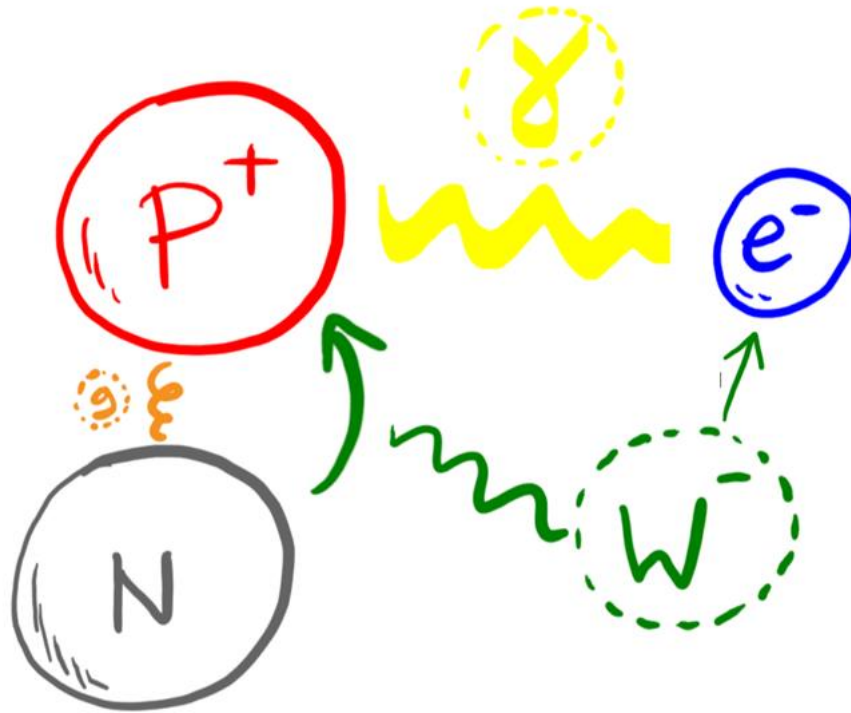
Paul Dirac 1933 Solvay Conference
(From D. Tong slide)

Lesson 1: Beauty in fundamental physics is not an economy of particle multiplicities, it's an *economy of theoretical principles*

- Held together by **electromagnetism** and the **strong force**

How we got here

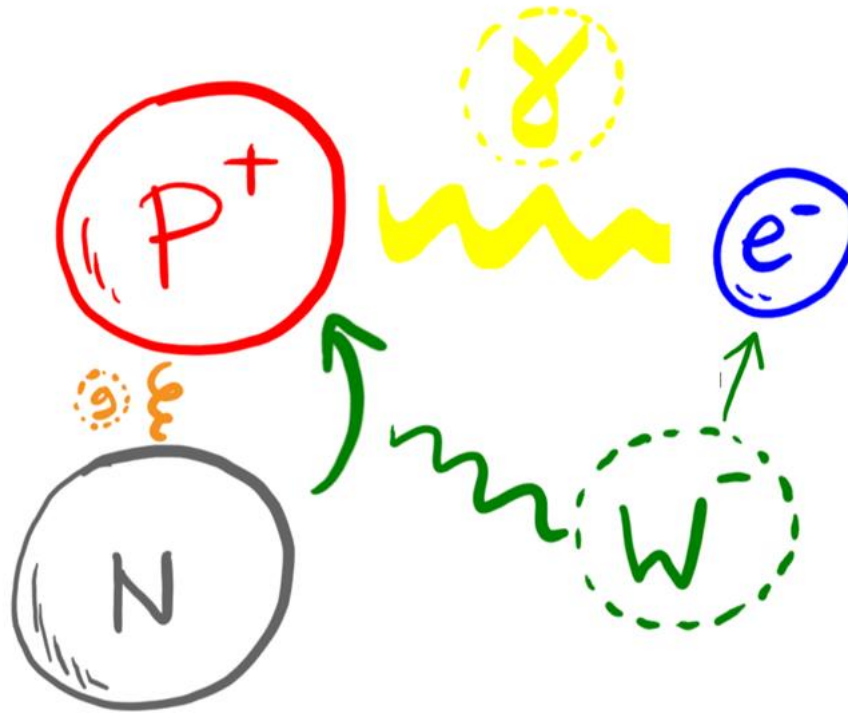
- **Weak force** explains *radioactivity*



- **Neutron** can change into **proton**, emitting **electron**

How we got here

- **Weak force** explains *radioactivity*

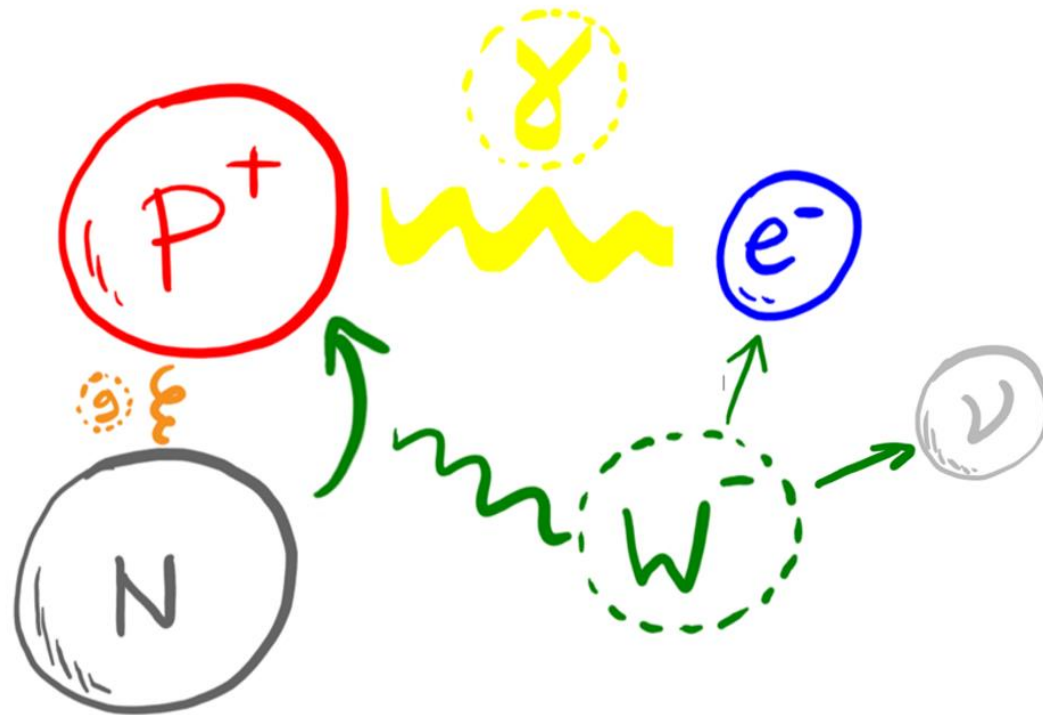


Missing energy? Pauli postulates “a desperate remedy”

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How we got here

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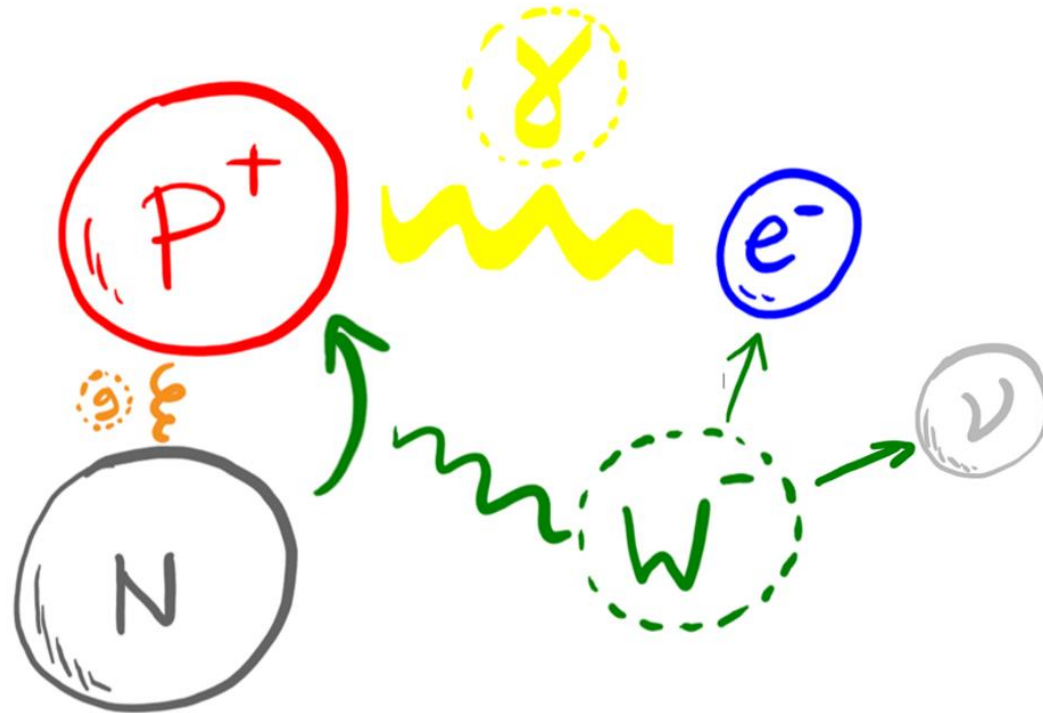


Missing energy? Pauli postulates “a desperate remedy”

- **Neutron** can change into **proton**, emitting **electron** and elusive **neutrino**

How we got here

- **Weak force** explains *radioactivity*



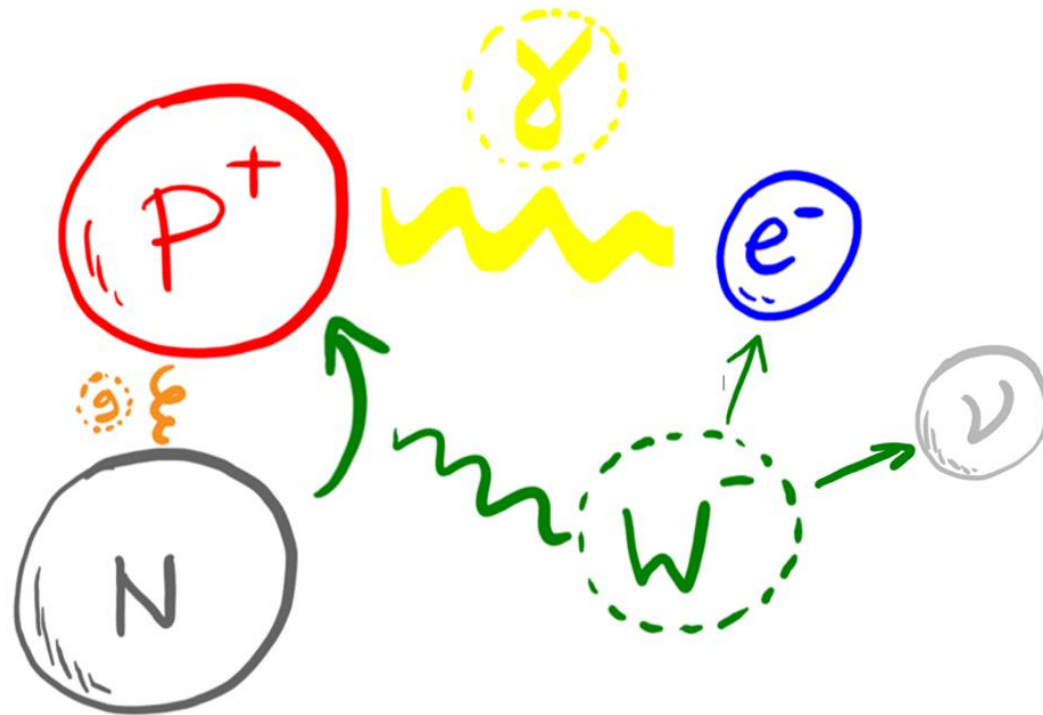
Missing energy? Pauli postulates “a desperate remedy”

Lesson 2: *perceived* prospect of experimental confirmation is *not a useful scientific criteria* for establishing **what nature actually does**

- **Neutron** can change into **proton**, emitting **electron** and elusive **neutrino**

How we got here

- **Weak force** explains *radioactivity*



Missing energy? Pauli postulates “a desperate remedy”

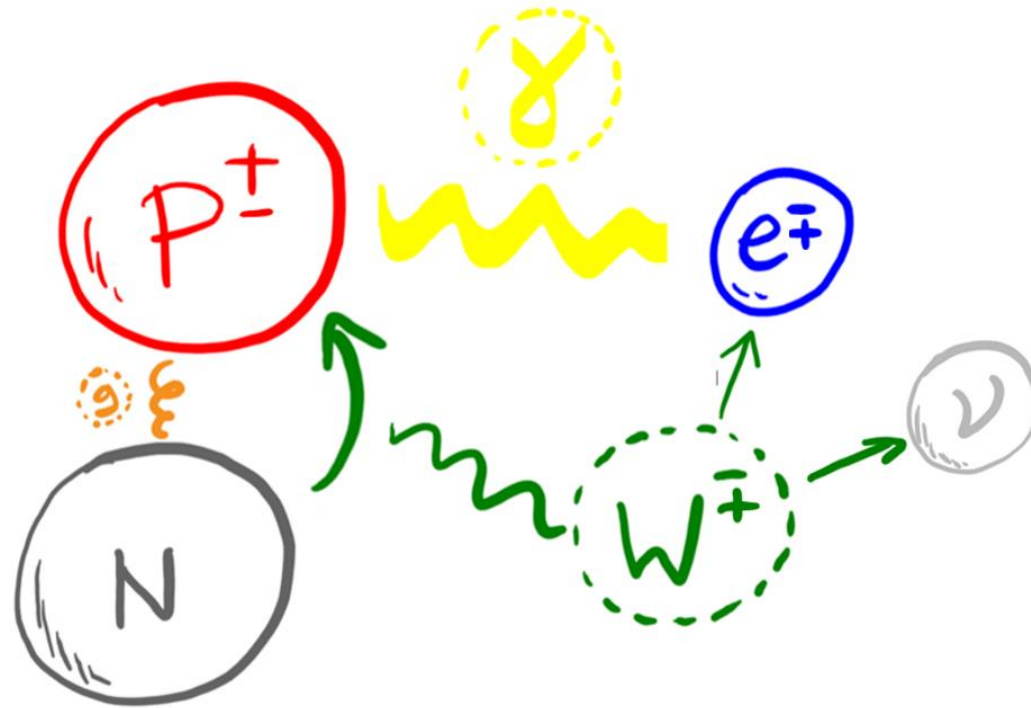
(Bohr postulates fundamental *violation of energy conservation*)

Lesson 2.5: Sometimes nature chooses *the least radical option*

- **Neutron** can change into **proton**, emitting **electron** and elusive **neutrino**

How we got here

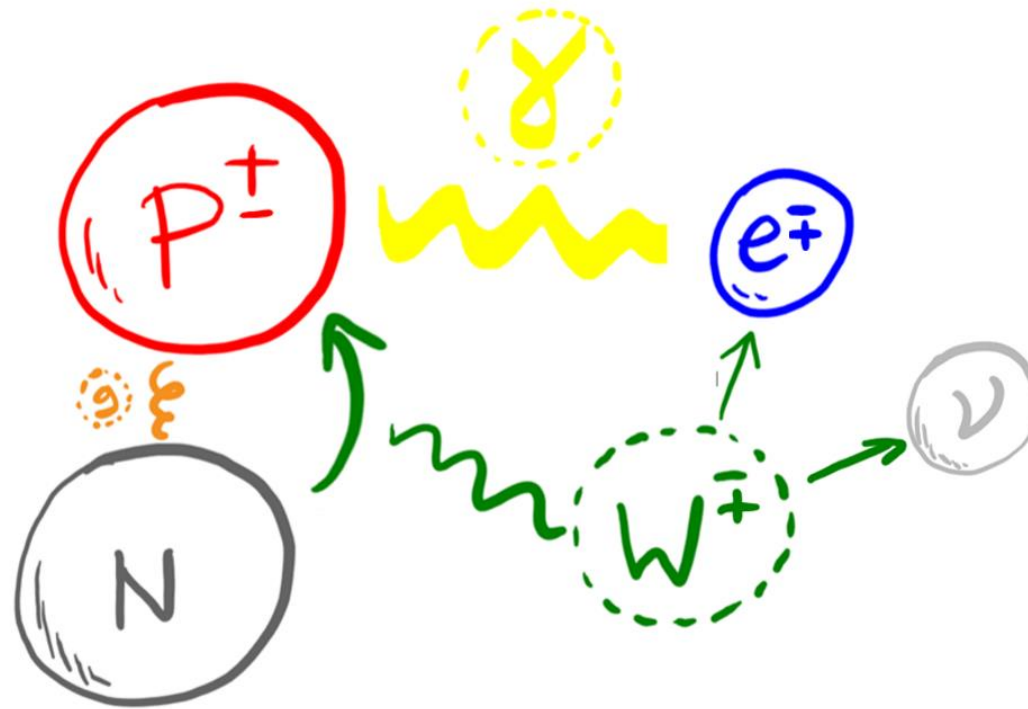
- Dirac: **relativity** + **quantum mechanics** = **antiparticles**



- *Every particle has an oppositely charged antiparticle partner*

How we got here

- Dirac: **relativity** + **quantum mechanics** = **antiparticles**

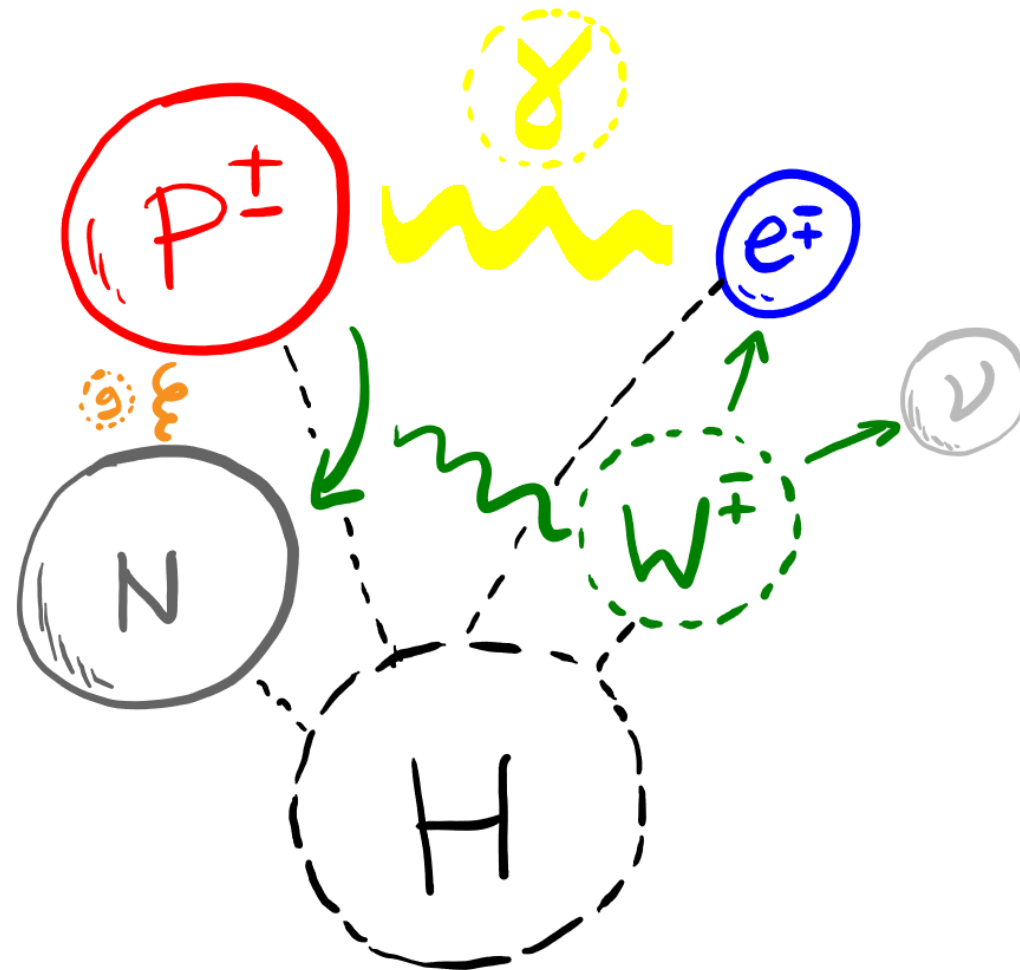


*c.f. Lesson 1: antiparticles double the particle spectrum. Nevertheless, the theory is **much tighter**, **less arbitrary**, and **more elegant***

- *Every particle has an oppositely charged antiparticle partner*

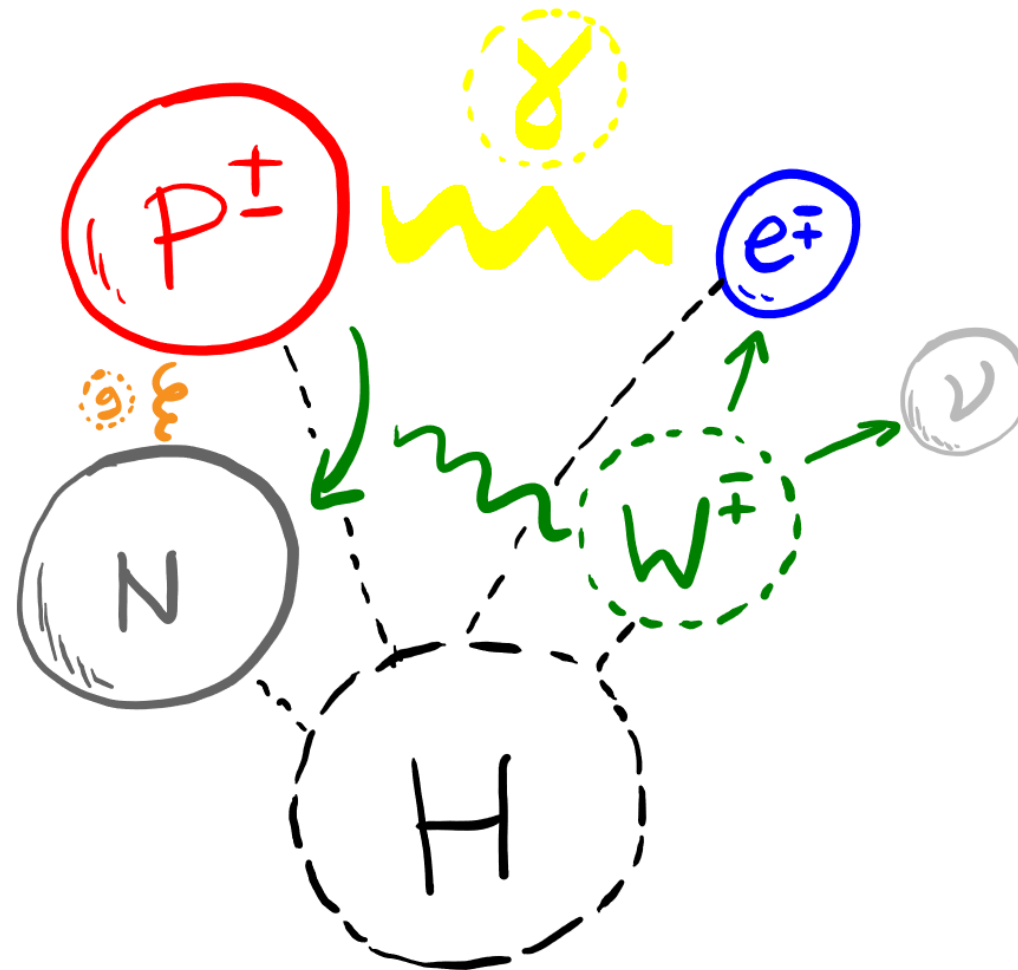
How we got here

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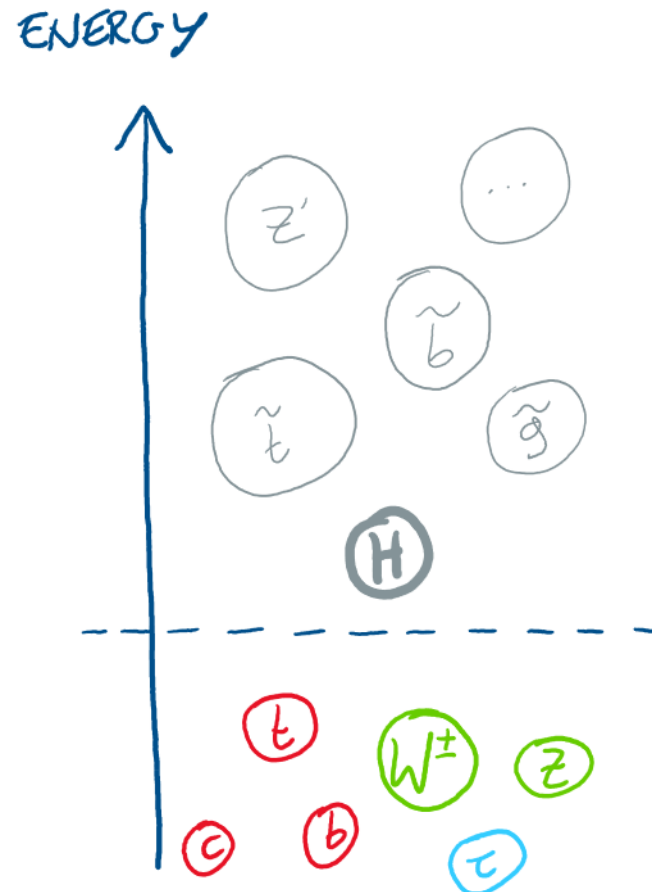


Lesson 3: Keep an open mind.

Ideas initially dismissed as **unrealistic** (e.g. non-abelian gauge theories and spontaneous symmetry breaking, because they predicted **unobserved massless** bosons) can turn out to be correct eventually

A crisis in particle physics?

- Until now, there had been a **clear roadmap**



No-lose theorem:

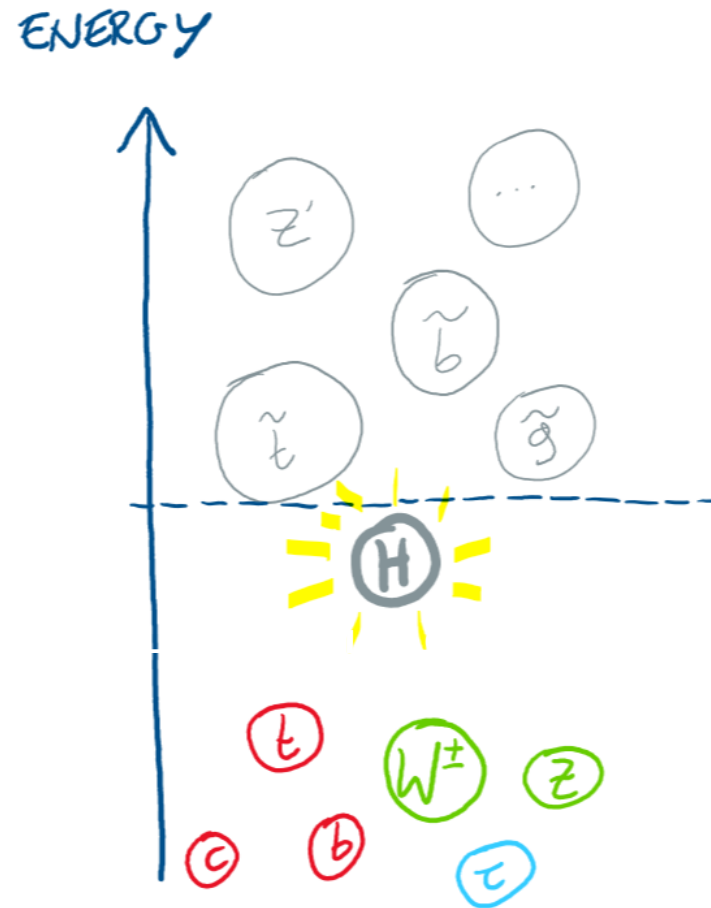
Higgs (or something)
guaranteed to appear.

High anticipation

of accompanying
BSM particles
expected to appear.

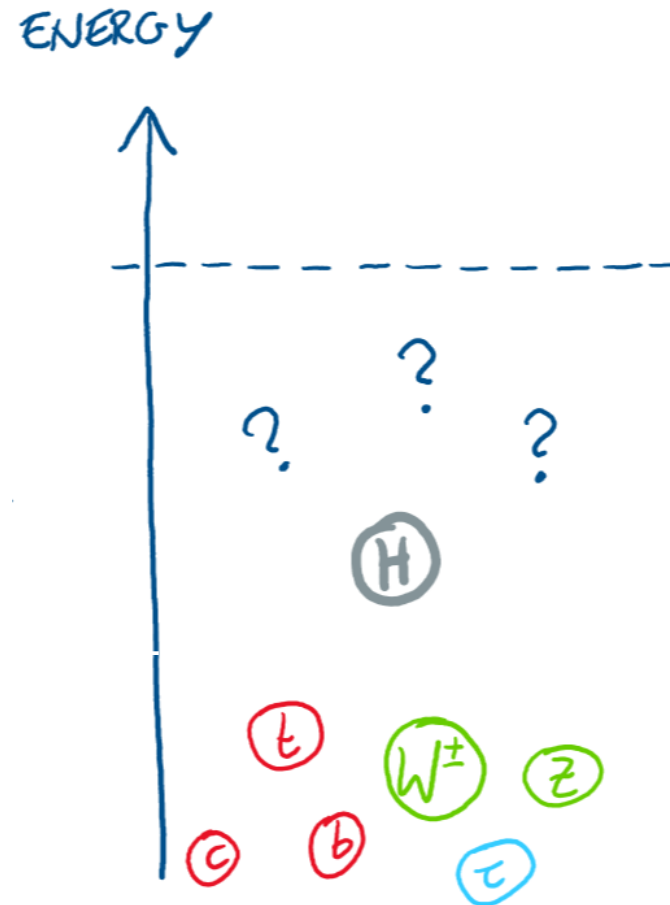
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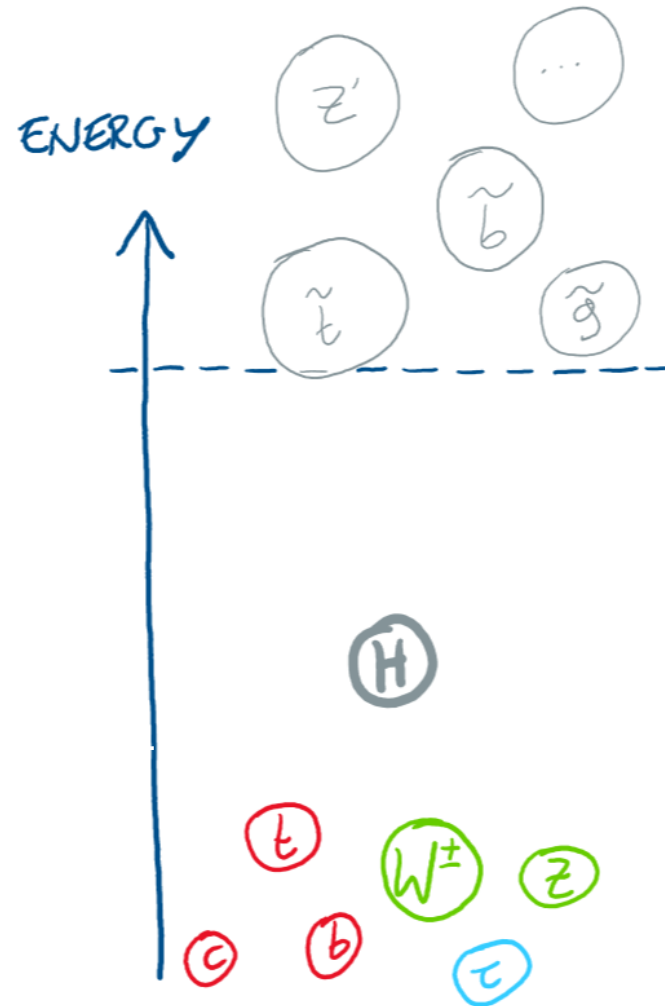
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A crisis in particle physics?

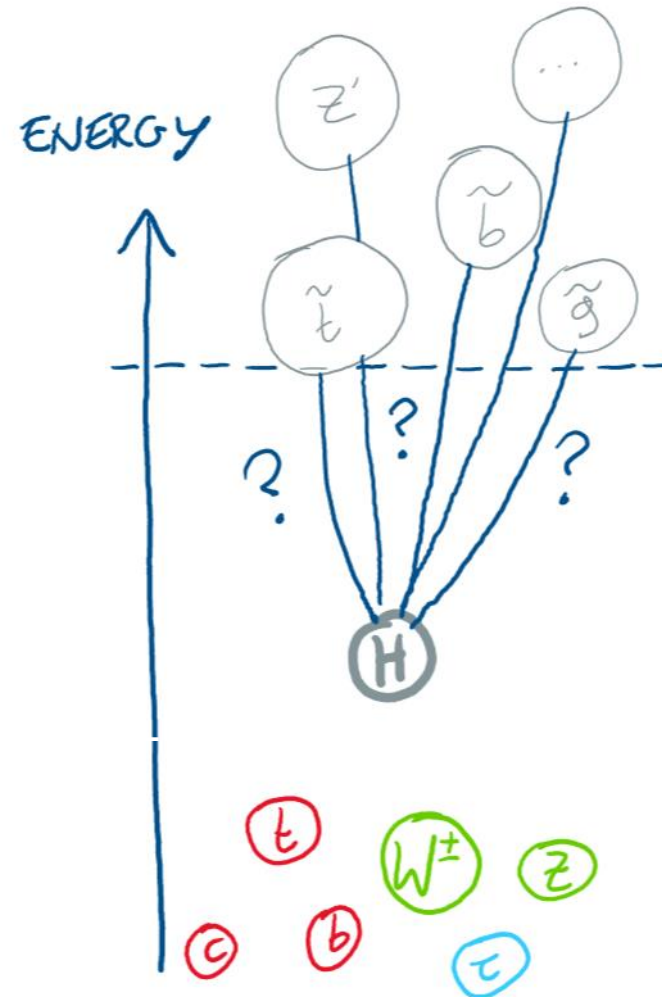
- Until now, there had been a **clear roadmap**



Maybe **just around the corner...**

A crisis in particle physics?

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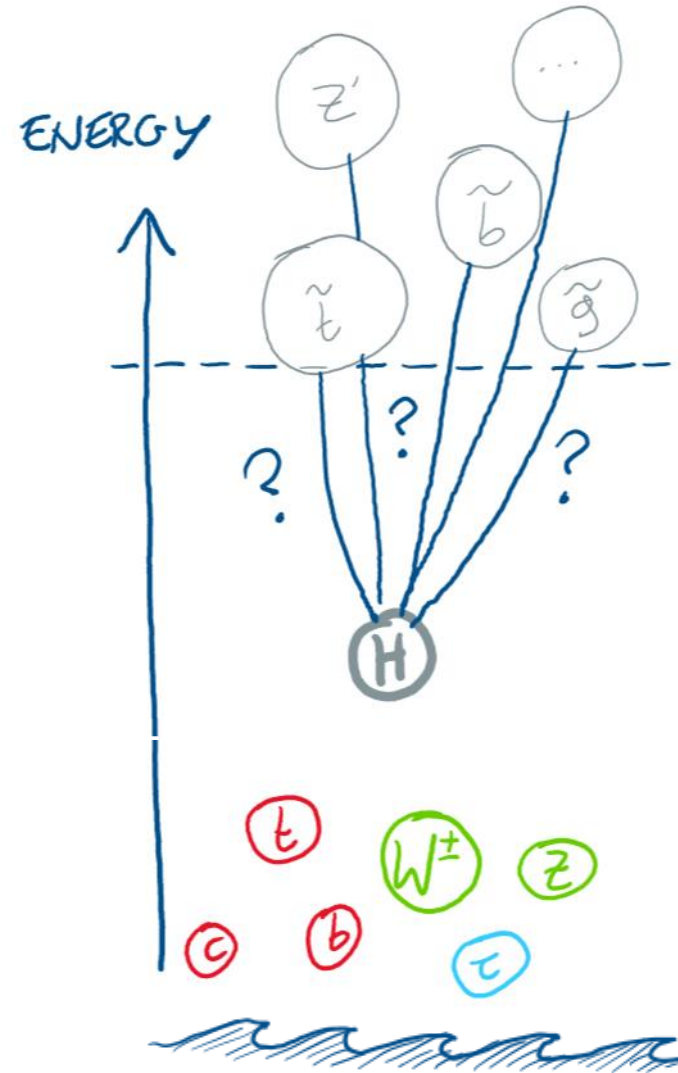
...but the larger the **separation of scales**, the more unnaturally **fine-tuned** the *underlying theory* is!

The Higgs' naturalness problem is **even more perplexing** in the absence of new physics at the LHC.

Our **Michelson-Morley moment?**

A crisis in particle physics?

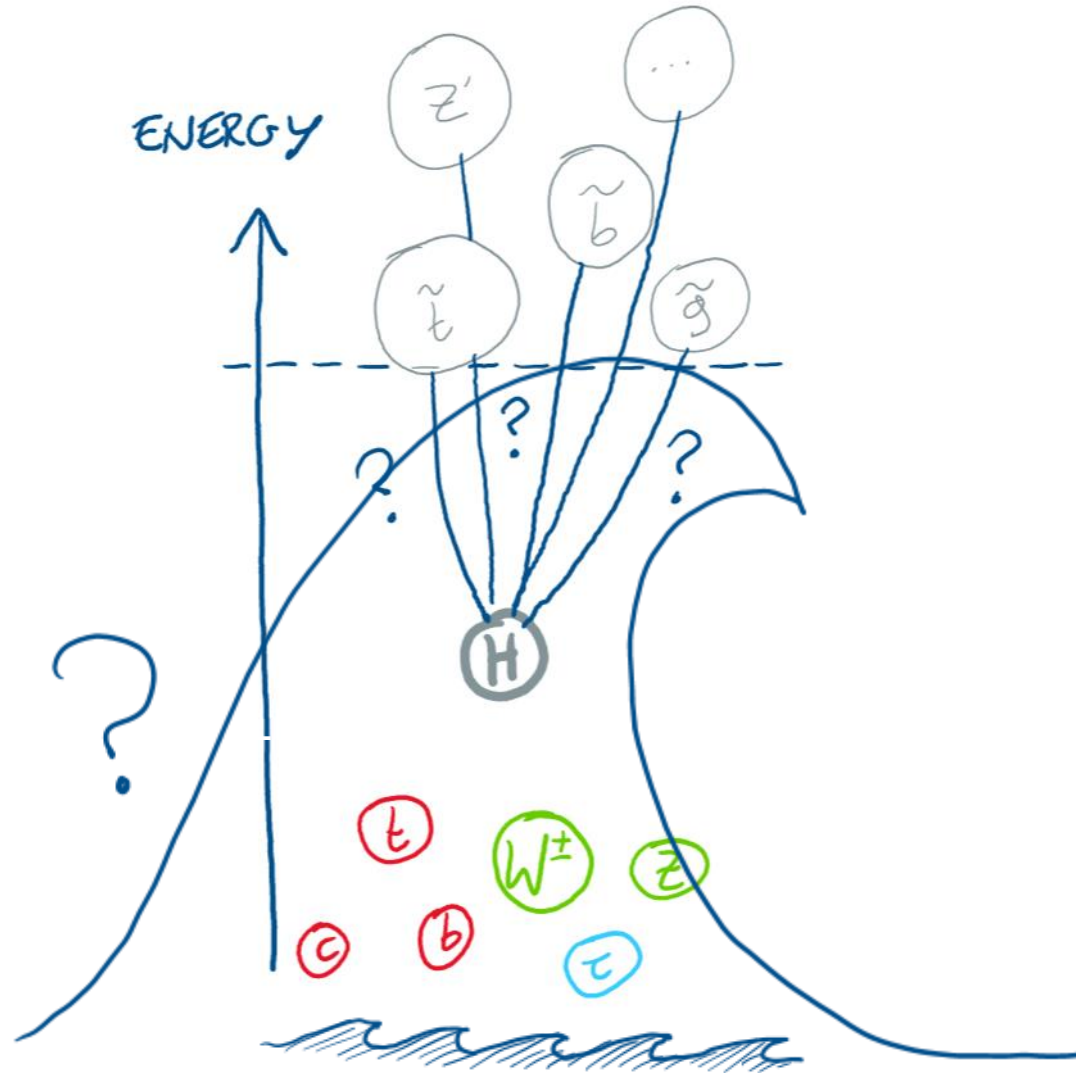
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The cosmological constant problem of a tiny vacuum energy is far worse!

A crisis in particle physics?

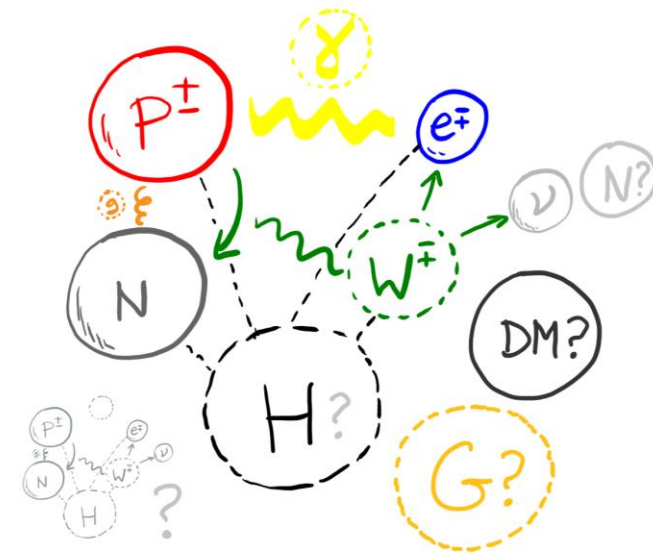
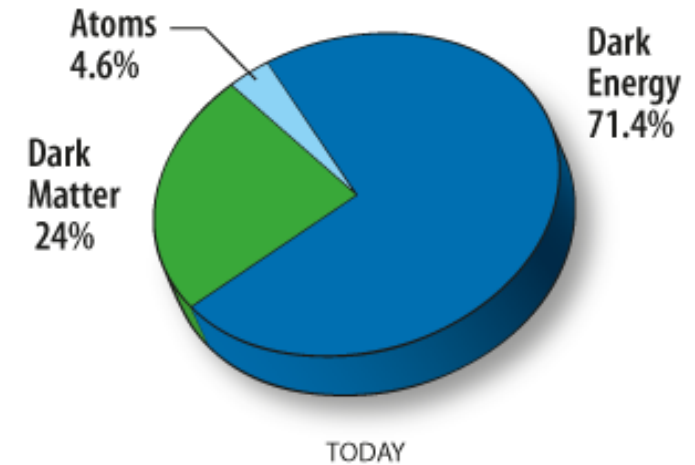
- Until now, there had been a **clear roadmap**



The cosmological constant problem of a tiny vacuum energy is far worse!

Many more open questions

- What is the **origin of the Higgs**?
- What is the **origin of matter**?
- What is the **origin of flavour**?
- What is the **origin of dark matter and dark energy**?
- What is the **origin of neutrino mass**?
- What is the **origin of the Standard Model**?
- ...



Problems of the SM

- **Arbitrary:**

Higgs potential, yukawa couplings, flavour structure, quantized hypercharges, matter-antimatter asymmetry – *arbitrary parameters put in by hand*.

- **Unnatural:**

Higgs mass, cosmological constant, strong-CP problem – *fine-tuned cancellations between independent contributions*.

Problems of the SM

- **Incomplete:**

Experimental & observational evidence: dark matter, neutrino mass.

- **Inconsistent:**

Theoretical evidence: quantum gravity, black hole information paradox.

Problems of the SM

Take problems of arbitrariness seriously.

Example 0

$$F = m_{inertia}a \qquad F \propto \frac{q_1 q_2}{r^2}$$

Inertial mass and charge have nothing to do with each other, and yet for gravity we arbitrarily set by hand

$$q = m_{inertia}$$

Solution to this equivalence problem took centuries: Newtonian gravity → GR

Problems of the SM

Take structural theoretical problems seriously.

Example 1

Maxwell's equations of electromagnetism did not satisfy the principle of Galilean relativity.

$$\nabla \cdot \mathbf{E} = \rho/\epsilon_0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

No inconsistencies – one could calculate perfectly well EM phenomena.

Aether medium expected to reconcile Maxwell with Galileo.

Resolution to this structural problem: Galilean relativity → Special relativity

Problems of the SM

Take fine-tuning problems seriously.

e.g. 2205.05708 N. Craig - Snowmass review,
1307.7879 G. Giudice - Naturalness after LHC

Example 2

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\text{Coulomb}}. \quad \Delta E_{\text{Coulomb}} = \frac{1}{4\pi\epsilon_0} \frac{e^2}{r_e}.$$

Avoiding cancellation between “bare” mass and divergent self-energy in classical electrodynamics requires new physics around

$$e^2/(4\pi\epsilon_0 m_e c^2) = 2.8 \times 10^{-13} \text{ cm}$$

Indeed, the positron and quantum-mechanics appears just before!

$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

Problems of the SM

Take fine-tuning problems seriously.

e.g. 2205.05708 N. Craig - Snowmass review,
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Example 3

Divergence in pion mass: $m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi} \Lambda^2$

Experimental value is $m_{\pi^\pm}^2 - m_{\pi^0}^2 \sim (35.5 \text{ MeV})^2$

Expect new physics at $\Lambda \sim 850 \text{ MeV}$ to avoid fine-tuned cancellation.

ρ meson appears at 775 MeV!

Problems of the SM

Take fine-tuning problems seriously.

e.g. 2205.05708 N. Craig - Snowmass review,
1307.7879 G. Giudice - Naturalness after LHC

Example 4

Divergence in Kaons mass difference in a theory with only up, down, strange:

$$m_{K_L^0} - m_{K_S^0} \simeq \frac{1}{16\pi^2} m_K f_K^2 G_F^2 \sin^2 \theta_C \cos^2 \theta_C \times \Lambda^2 ;$$

Avoiding fine-tuned cancellation requires $\Lambda < 3 \text{ GeV}$.

Gaillard & Lee in 1974 predicted the charm quark mass!

Problems of the SM

Take fine-tuning problems seriously.

e.g. 2205.05708 N. Craig - Snowmass review,
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Higgs?

Higgs also has a quadratically divergent contribution to its mass

$$\Delta m_H^2 = \frac{\Lambda^2}{16\pi^2} \left(-6y_t^2 + \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 6\lambda \right)$$

Avoiding fine-tuned cancellation requires $\Lambda < O(100)$ GeV??

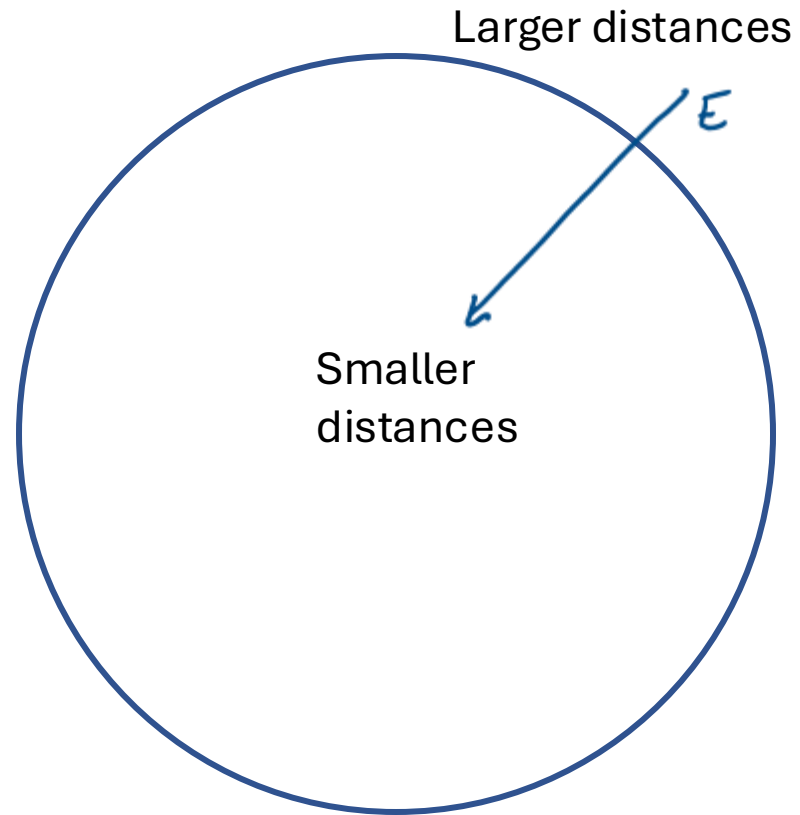
As Λ is pushed to the TeV scale by null results, tuning is around 10% - 1%.

Note for the experts: in the SM the Higgs mass is a parameter to be measured, not calculated. What the quadratic divergence represents (independently of the choice of renormalisation scheme) is the fine-tuning in an underlying theory in which we expect the Higgs mass to be calculable.

Naturalness is still a fundamental problem

- *Why is unnatural fine-tuning such a big deal?* An intuitive picture:

Physical theories govern a huge range of phenomena across vast scales

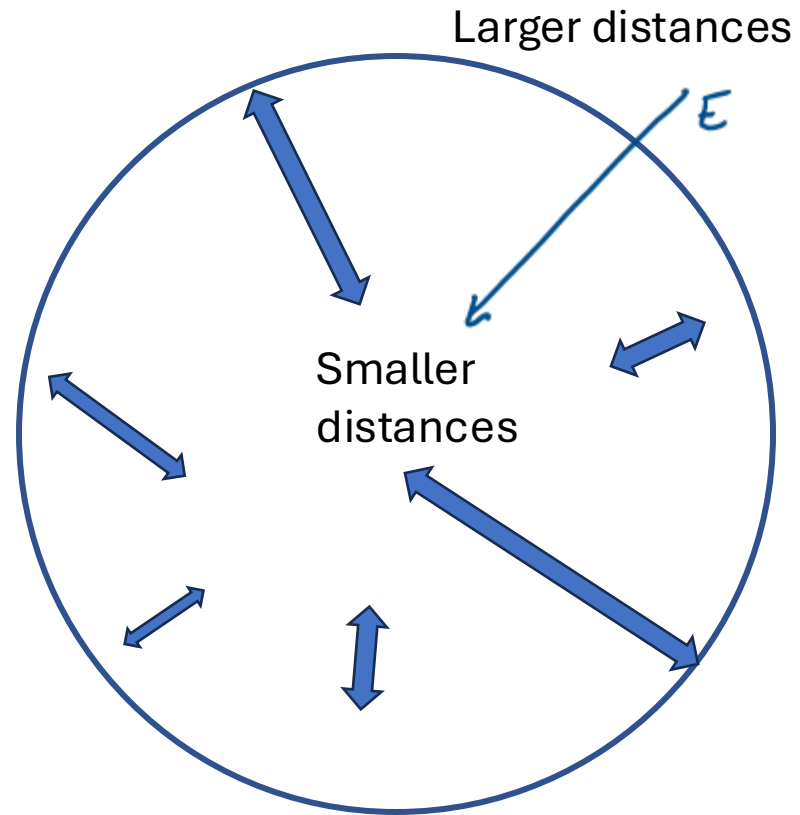


Naturalness is still a fundamental problem

- *Why is unnatural fine-tuning such a big deal?* An intuitive picture:

Everything does **not** depend on everything else equally.

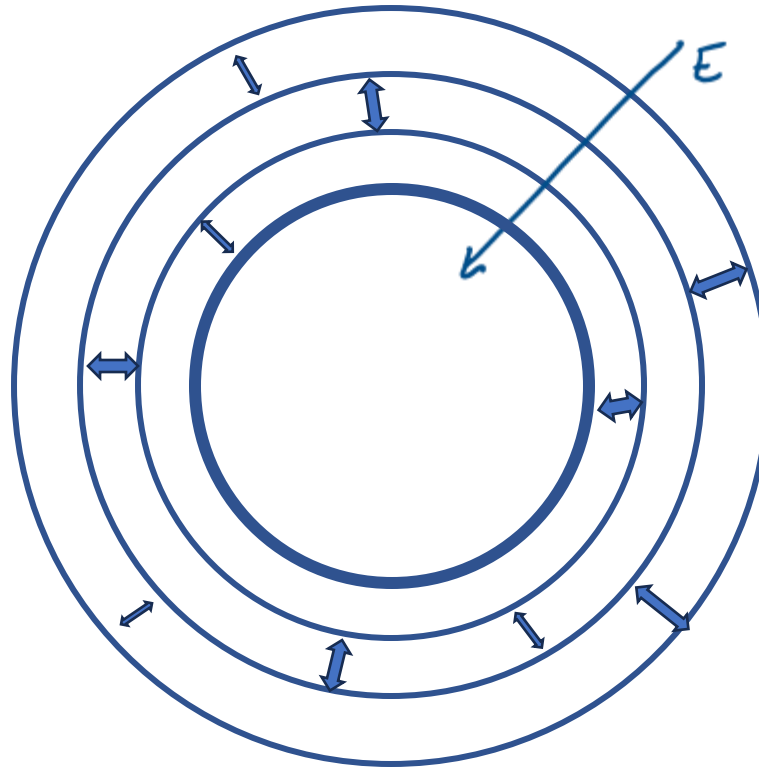
(Otherwise, we would need a Theory of Everything to calculate anything)



Naturalness is still a fundamental problem

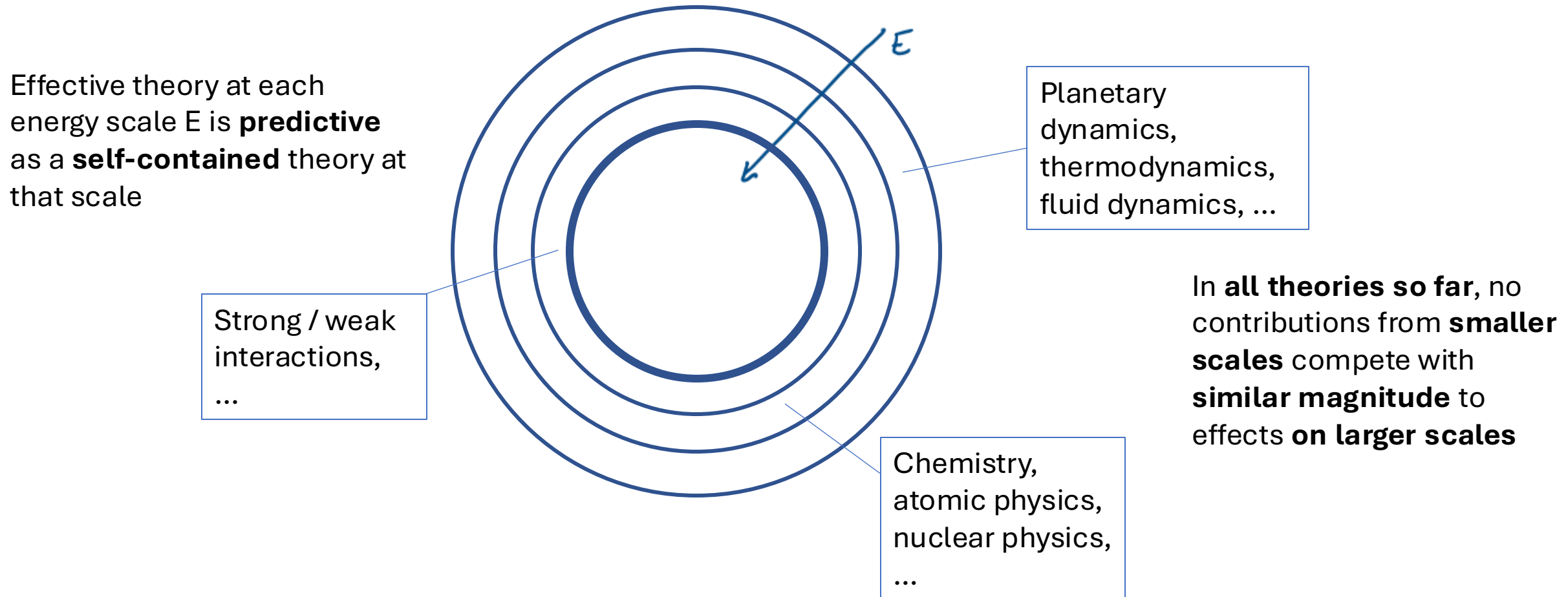
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Effective theory at each energy scale E is **predictive** as a **self-contained** theory at that scale



Naturalness is still a fundamental problem

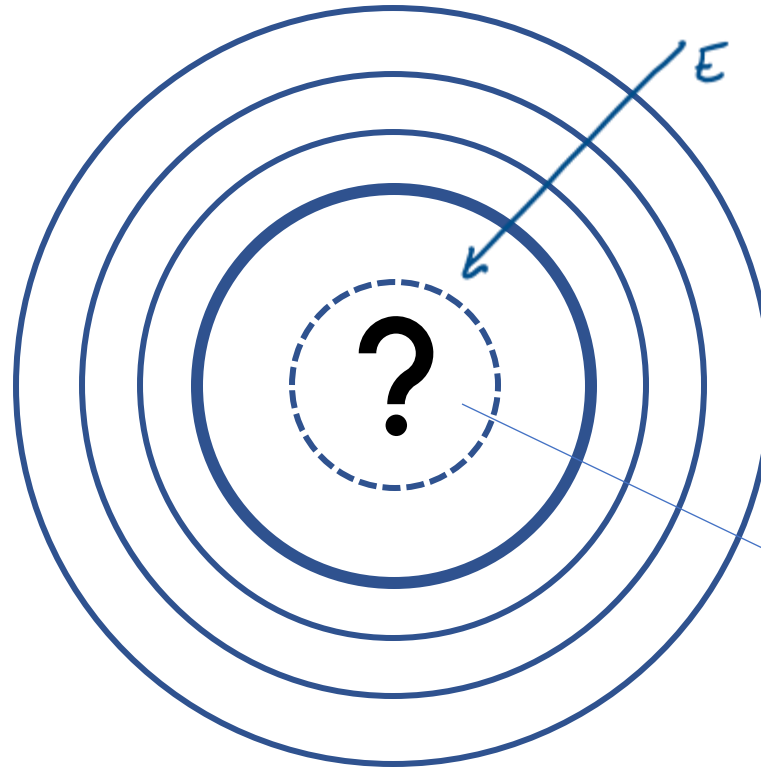
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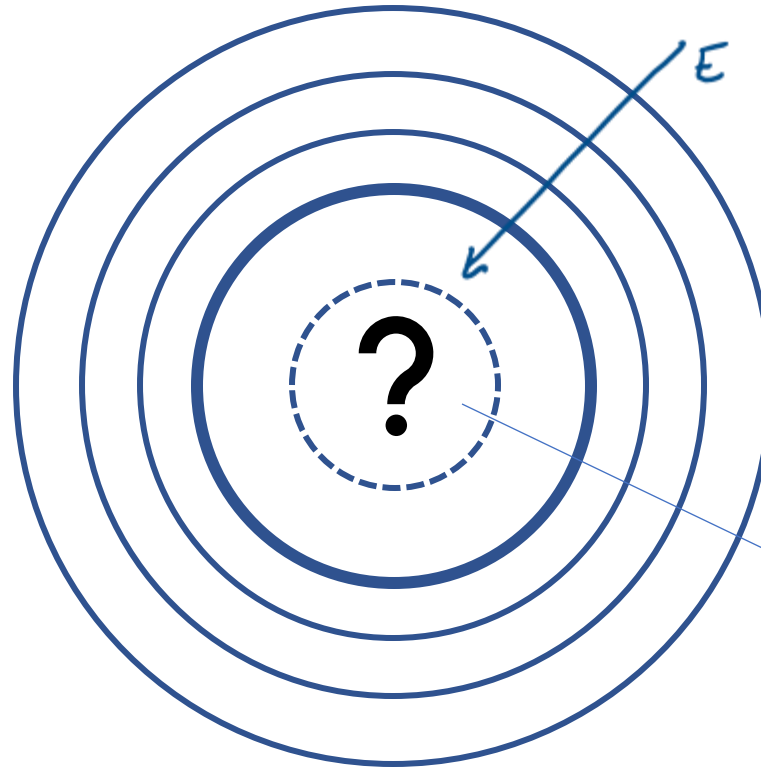


Unnatural Higgs means the next layer is no longer predictive without including contributions from much smaller scales

Naturalness is still a fundamental problem

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- Indicates **an unprecedented breakdown** of the **effective theory** structure of nature

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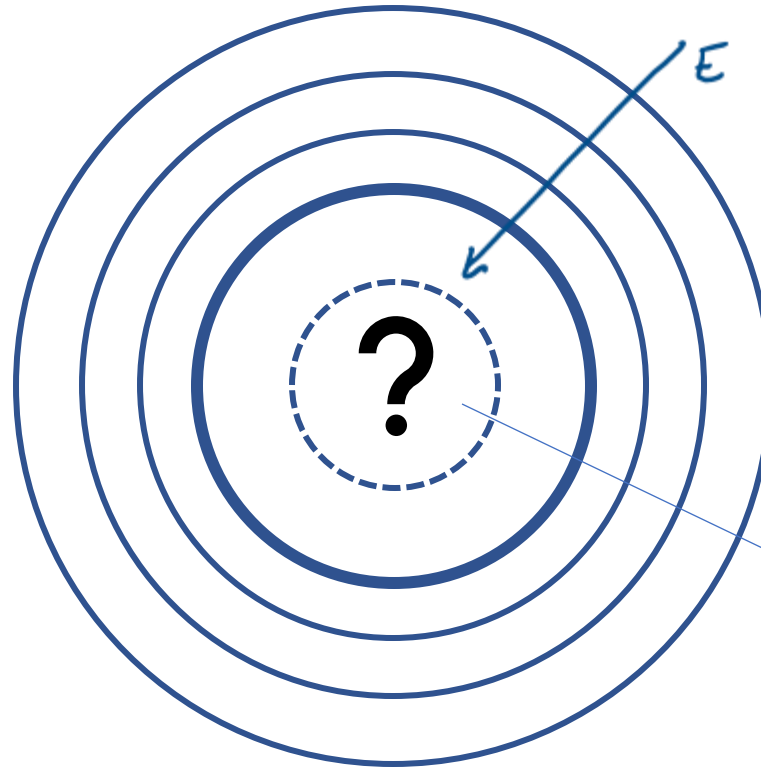


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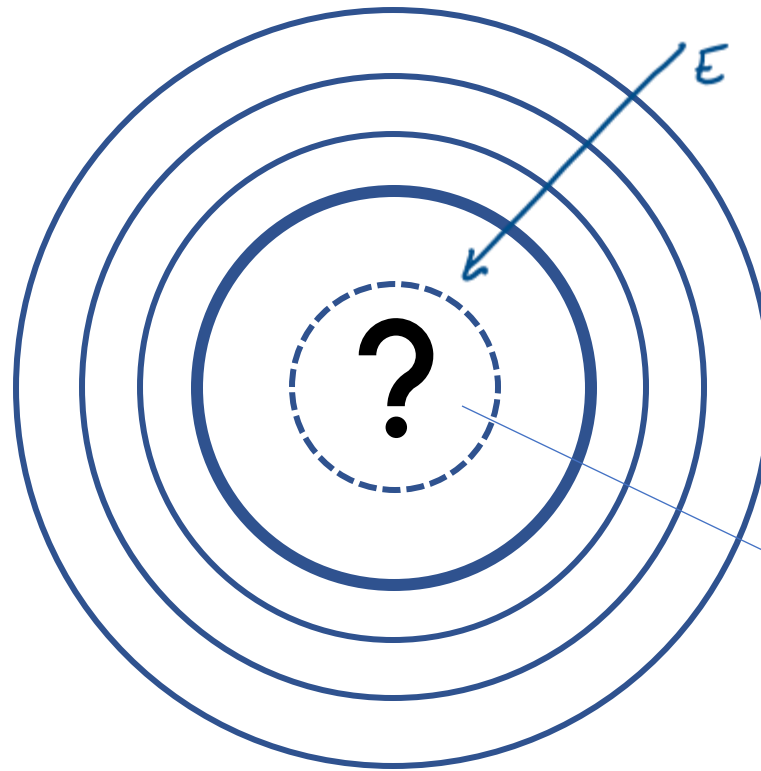
Unnatural Higgs means the next layer **is no longer predictive** without including contributions from much smaller scales

- Are we missing a **fundamentally new** “*post-naturalness*” principle? (c.f. *null results in search for aether*)

Naturalness is still a fundamental problem

- *Why is unnatural fine-tuning such a big deal?* An intuitive picture:
- Indicates **an unprecedented breakdown** of the **effective theory** structure of nature

Effective theory at each energy scale E is **predictive** as a **self-contained** theory at that scale



Unnatural Higgs means the next layer is **no longer predictive** without including contributions from **much smaller scales**

- **Future colliders** are **essential** for finding out experimentally **what nature actually does** at higher energies

BSM exists!

Neutrino oscillations imply neutrinos have mass.

The **Standard Model** does not allow a mass term for neutrinos to be written down.

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i \gamma^\mu D_\mu^L Q_L + \bar{q}_R i \gamma^\mu D_\mu^R q_R + \bar{L}_L i \gamma^\mu D_\mu^L L_L + \bar{l}_R i \gamma^\mu D_\mu^R l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu}$$

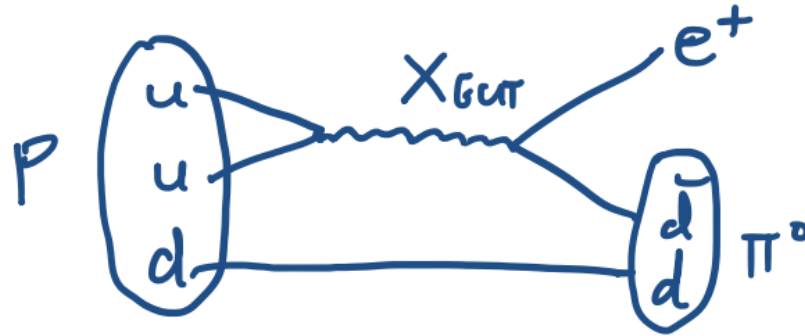
$$\mathcal{L}_H = (D_\mu^L \phi)^\dagger (D^{L\mu} \phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

Grand Unified Theories

Grand Unified Theories (GUTs) unify all $SU(3) \times SU(2) \times U(1)$ into a single GUT group, e.g. $SO(10)$, at higher energies.

Proton decay via a GUT gauge boson is a generic consequence:

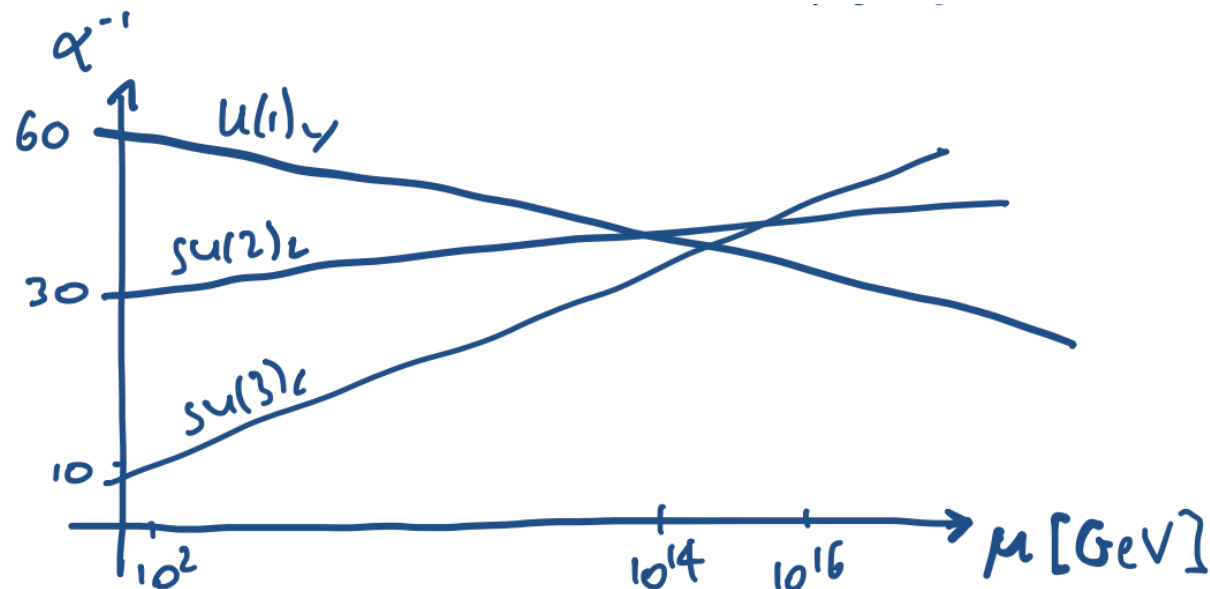


GUT scale must therefore be at least 10^{15} GeV.

Grand Unified Theories

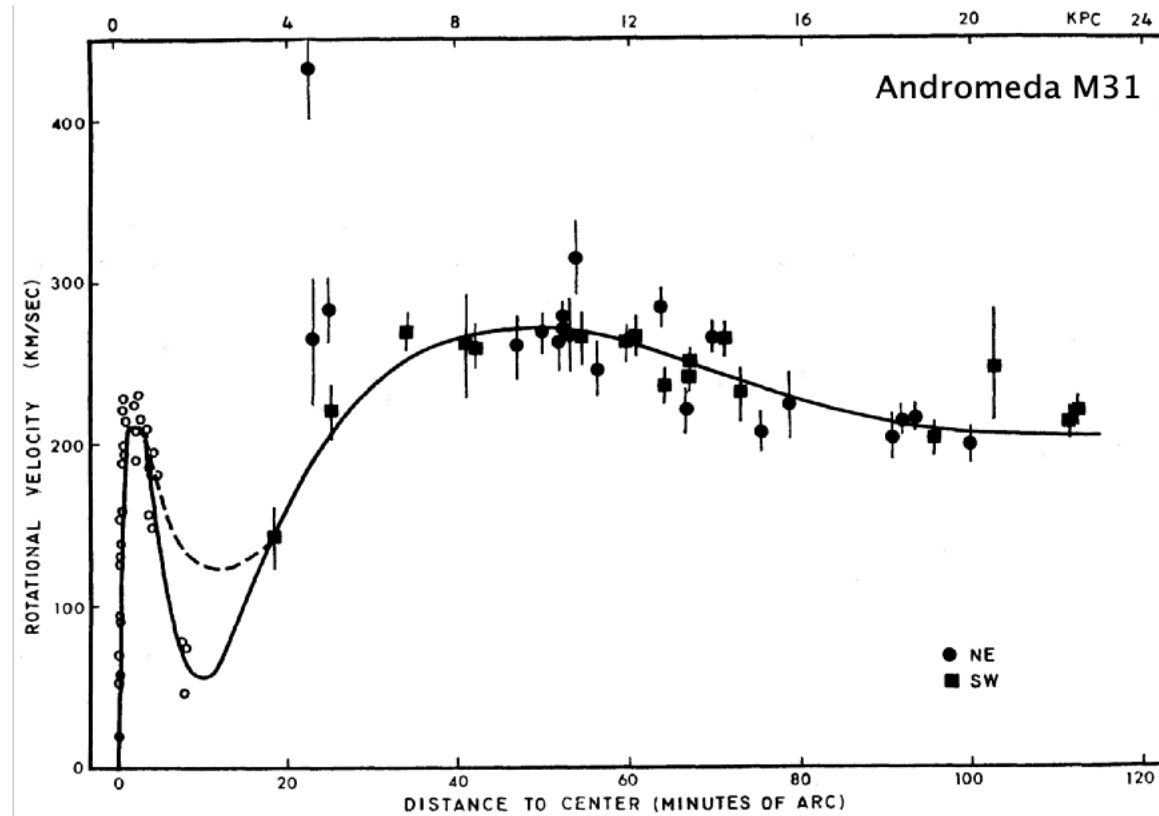
GUTs are desirable rather than necessary. However, there are hints suggesting this may be the case:

- Electroweak unification makes it reasonable to consider unifying the strong force too.
- U(1) hypercharges of SM particles are quantised with fractional charges.
- Standard Model particle content fits neatly into multiplets of GUT group representations.
- Running of gauge couplings suggest they meet at high energy scales $\sim 10^{15}$ GeV (*but not quite*).



Dark Matter

Multiple independent observational evidence for dark matter on all scales:

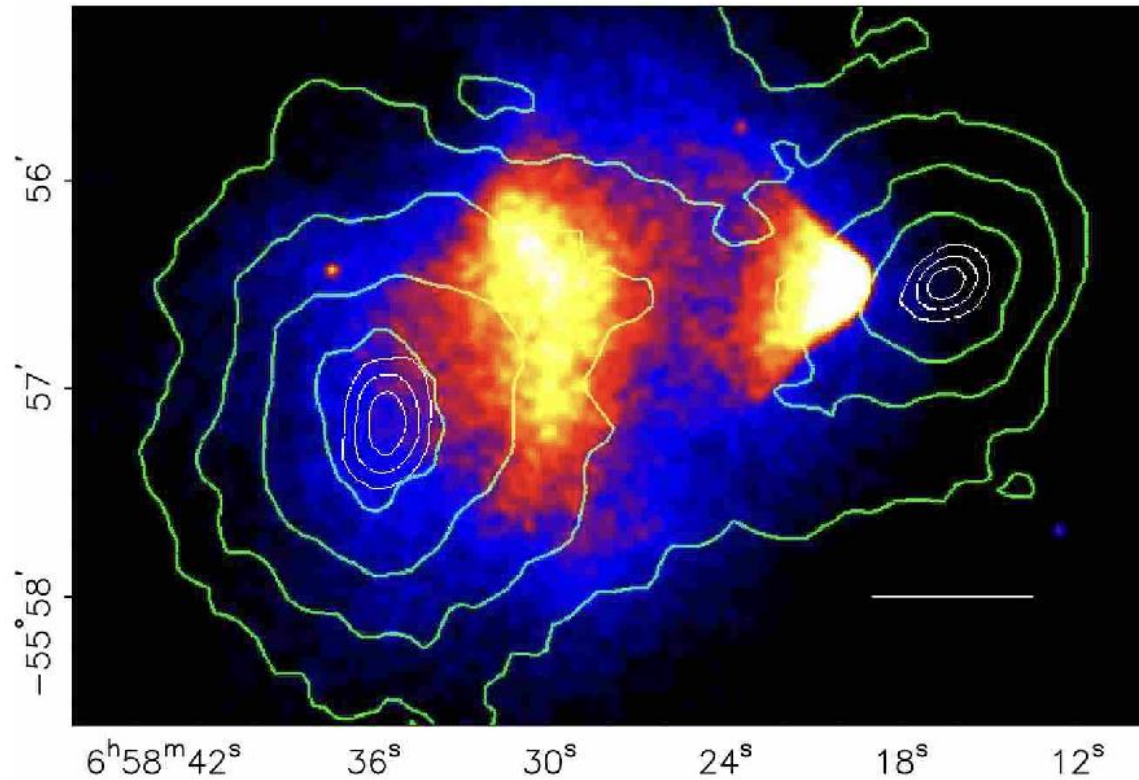


Rubin and Ford 1970

See e.g. 2406.01705 Cirelli, Strumia, Zupan for a comprehensive review.

Dark Matter

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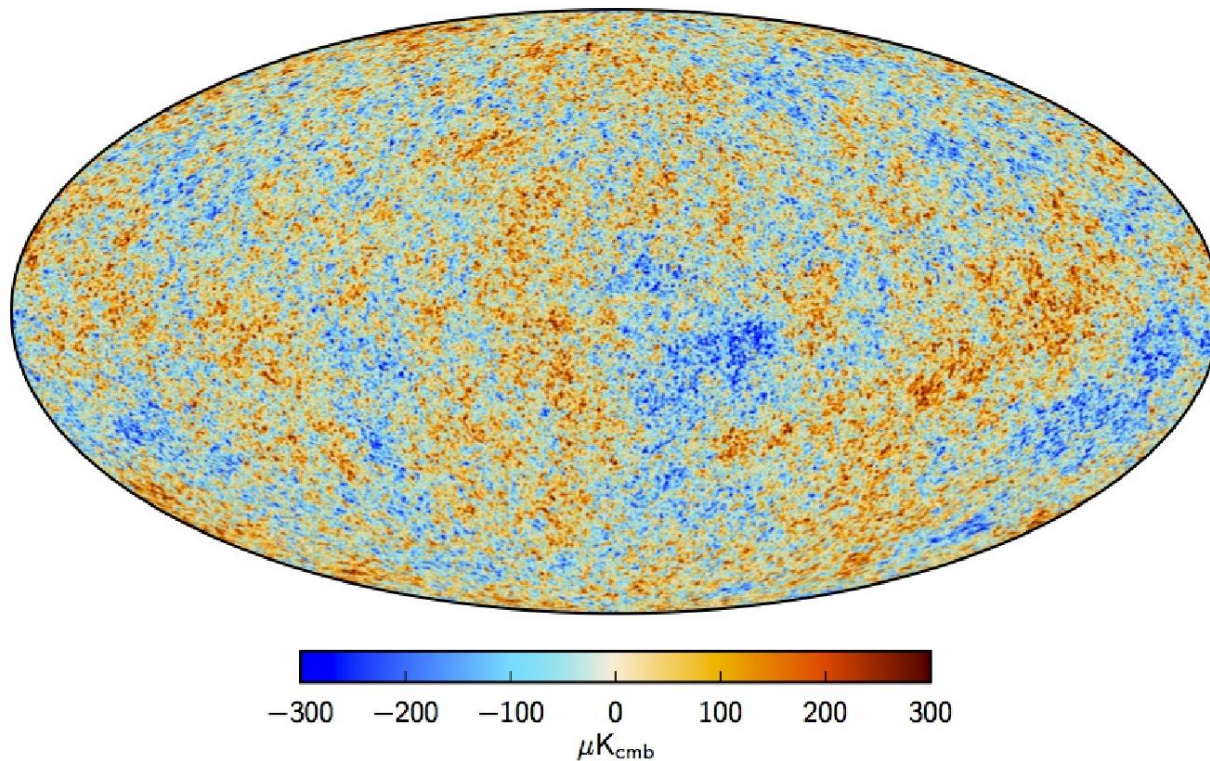


Clowe et al 2006

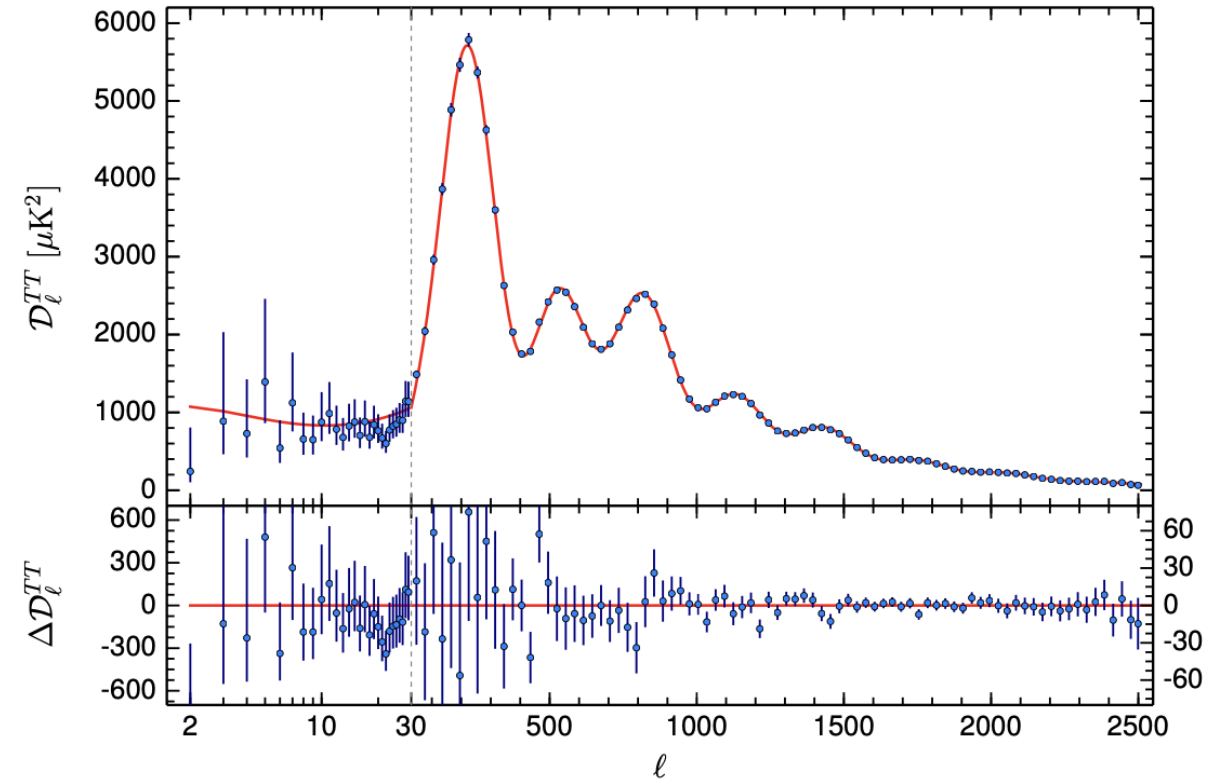
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Dark Matter

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Planck



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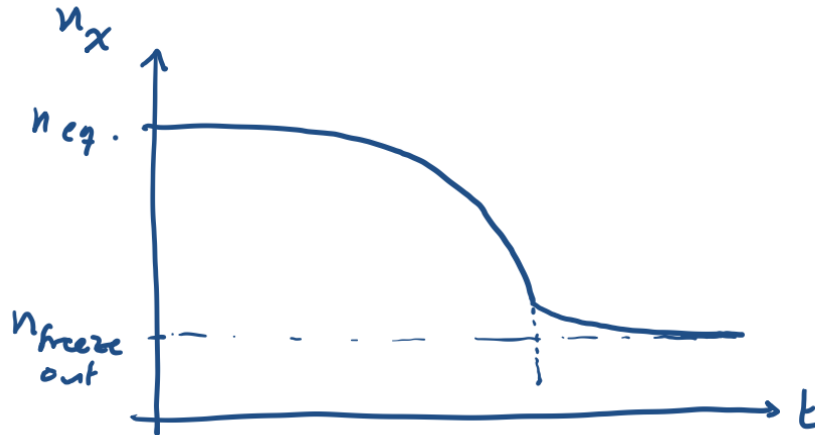
WIMP Dark Matter

Weakly Interacting Massive Particles (WIMP) are a simple candidate for dark matter.

Add to the Standard Model a DM particle χ with mass m and coupling α through which it annihilates.

Its averaged annihilation cross-section is $\langle \sigma v \rangle \sim \frac{\alpha^2}{m^2}$.

Relic abundance of DM is set by thermal freeze-out as the Universe expands and temperature falls.



$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)$$

WIMP Dark Matter

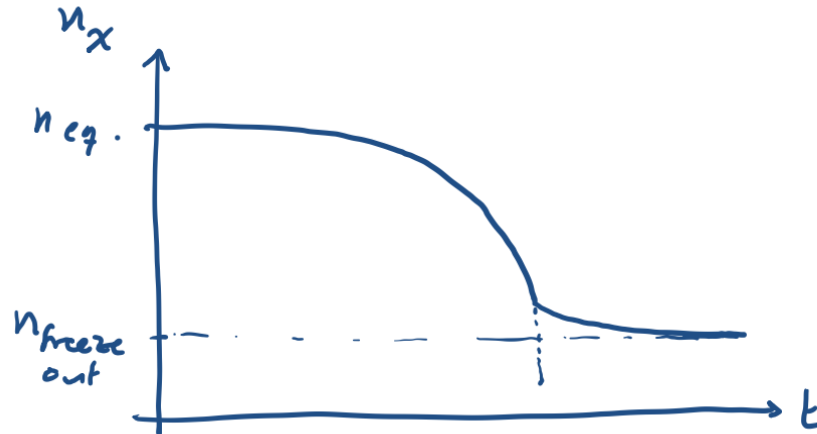
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This gives the observed relic abundance for a typical weak coupling with weak-scale mass!



$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)$$

$$\Omega_\chi h^2 \sim \frac{10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle} \approx 0.1 \left(\frac{0.01}{\alpha} \right)^2 \left(\frac{m}{100 \text{ GeV}} \right)^2$$

Supersymmetry

Historically, the success of classifying particles into representations of symmetry groups led to a search for a symmetry that included not just matter particles but also the force particles.

Coleman-Mandula theorem: **impossible**.

- Fermions and bosons behave differently under Lorentz transformations.
- A symmetry that interchanges them therefore doesn't commute with Lorentz generators.
- But internal (non-spacetime) symmetry generators must be Lorentz scalars.

Haag-Lopuszanski-Sohnius: **possible**, *only if the supersymmetry generators are fermionic*.

Supersymmetry is the **unique extension** allowed of spacetime symmetries.

Supersymmetry

Supersymmetrising the Standard Model introduces a *superpartner* for every SM particle – the **Minimal Supersymmetric Standard Model** (MSSM).

Immediate benefits

Fermion superpartners of the Higgs and weak gauge bosons **can be WIMP dark matter!**

Controls quantum corrections to the Higgs mass to **solve the unnatural fine-tuning problem**:

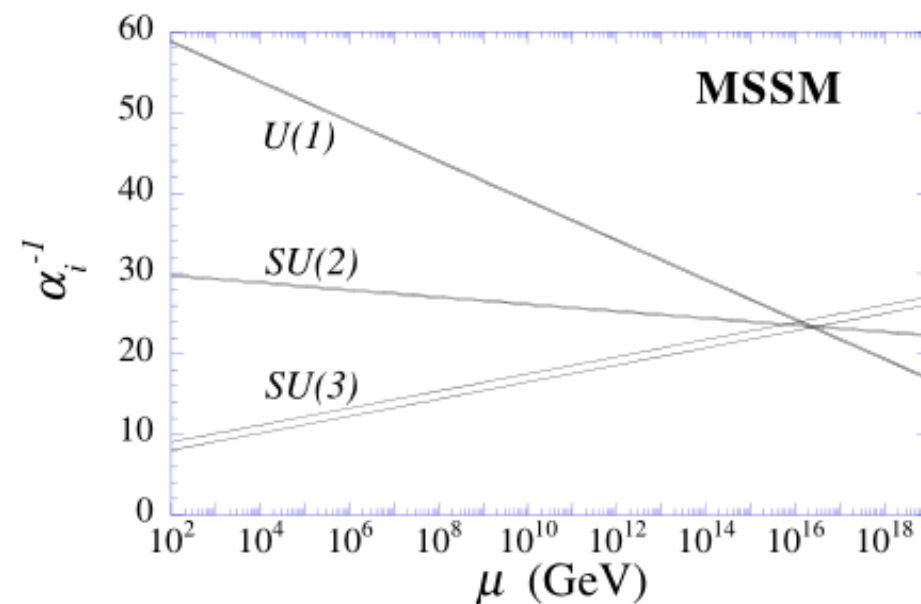
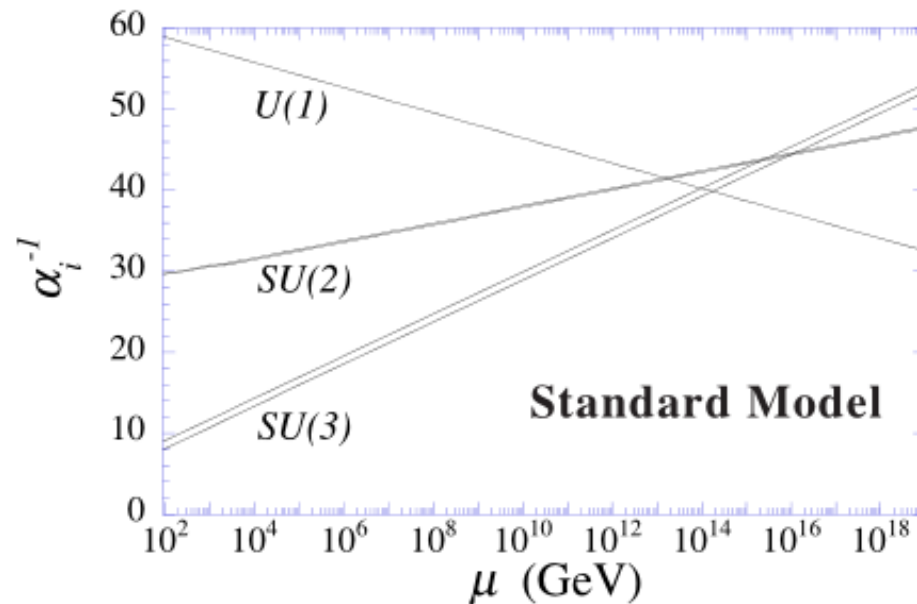
$$- \text{bubble}(t) + - \text{bubble}(\tilde{t}) \sim -6 \frac{y_L^2}{4\pi^2} (m_{\tilde{t}}^2 - m_t^2) \log\left(\frac{m_{\tilde{t}}^2}{m_{\tilde{t}}^2}\right)$$

Supersymmetry

Supersymmetrising the Standard Model introduces a *superpartner* for every SM particle – the **Minimal Supersymmetric Standard Model** (MSSM).

Immediate benefits

Gauge couplings unify at a single GUT scale!



Supersymmetry

Supersymmetrising the Standard Model introduces a *superpartner* for every SM particle – the **Minimal Supersymmetric Standard Model** (MSSM).

But also downsides

- A degree of arbitrariness is reintroduced by supersymmetry breaking.
- Many more free parameters due to ignorance of supersymmetry breaking mechanism.
- Extra structure must be imposed to control violation of symmetries that were automatically small in the Standard Model Effective Field Theory.
- *No WIMPs discovered yet?*
- *No superpartners discovered yet?*

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

The historical line of reasoning may make it seem that way:

Generalising **Abelian** gauge theories to **non-Abelian** gauge theories,

$$[B_r, B_s] = 0 \quad \longrightarrow \quad [B_r, B_s] = iC_{rs}^t B_t$$

Generalising the **Poincare** algebra to a **supersymmetry** algebra,

$$\begin{aligned} [P_\mu, P_\nu] &= 0 \\ [M_{\mu\nu}, M_{\rho\sigma}] &= ig_{\nu\rho}M_{\mu\sigma} - ig_{\mu\rho}M_{\nu\sigma} - ig_{\nu\sigma}M_{\mu\rho} + ig_{\mu\sigma}M_{\nu\rho} \\ [M_{\mu\nu}, P_\rho] &= -ig_{\rho\mu}P_\nu + ig_{\rho\nu}P_\mu \end{aligned} \quad \longrightarrow \quad \begin{aligned} [P_\mu, Q_\alpha^I] &= 0 \\ [P_\mu, \bar{Q}_{\dot{\alpha}}^I] &= 0 \\ \{Q_\alpha^I, Q_\beta^J\} &= \epsilon_{\alpha\beta}Z^{IJ} \\ \{\bar{Q}_{\dot{\alpha}}^I, \bar{Q}_{\dot{\beta}}^J\} &= \epsilon_{\dot{\alpha}\dot{\beta}}(Z^{IJ})^* \\ \{Q_\alpha^I, \bar{Q}_{\dot{\beta}}^J\} &= 2\sigma_{\alpha\dot{\beta}}^\mu P_\mu \delta^{IJ} \\ [M_{\mu\nu}, Q_\alpha^I] &= i(\sigma_{\mu\nu})_\alpha^\beta Q_\beta^I \\ [M_{\mu\nu}, \bar{Q}_{\dot{\alpha}}^I] &= i(\bar{\sigma}_{\mu\nu})_{\dot{\beta}}^{\dot{\alpha}} \bar{Q}_{\dot{\beta}}^I \end{aligned}$$

Supersymmetry

Perhaps supersymmetry does not solve the Higgs fine-tuning problem but still exists at some energy scale in nature. *Is this just wishful thinking?*

Not just any generalisation; it is the *last* of a finite set of allowed interactions of massless particles!

Relativity + quantum mechanics forbids all but the following possibilities:

- spin 0
- spin $\frac{1}{2}$
- spin 1
- spin $\frac{3}{2}$
- spin 2

Spin > 2 is not allowed.

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Consider all allowed interactions of *massless* particles:

Relativity + quantum mechanics forbids all but the following possibilities:

- spin 0
- spin $\frac{1}{2}$
- spin 1 – can only self-interact consistently as a Yang-Mills non-Abelian gauge theory.
- spin $\frac{3}{2}$
- spin 2 – can only interact universally as in General Relativity.

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- spin 0 – Higgs boson.
- spin $\frac{1}{2}$ – matter.
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- spin $\frac{3}{2}$ – can only interact **supersymmetrically!** ?
- spin 2 – can only interact universally as in General Relativity. ✓

Spin > 2 is not allowed.

“Everything not forbidden is compulsory”

Conclusion

The SM is incomplete.

The Higgs boson is still fundamentally mysterious. What is the underlying theory?

Neutrino masses and dark matter are concrete evidence for beyond the Standard Model particles.

GUTs are desirable and appealing extensions of the Standard Model, but not necessary.

Supersymmetry arises uniquely out of strong theoretical consistency constraints and solves several phenomenological problems automatically. However, there is no experimental evidence for it yet.

New ideas and more data needed!

Concluding Remarks

- *“What would be the use of such extreme refinement in the science of measurement? [...] The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. [...]”*

–A. Michelson 1903

Concluding Remarks

- “What would be the use of such extreme refinement in the science of measurement? **Very briefly and in general terms the answer would be that in this direction the greater part of all future discovery must lie.** The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. **Nevertheless, it has been found that there are apparent exceptions to most of these laws, and this is particularly true when the observations are pushed to a limit, i.e., whenever the circumstances of experiment are such that extreme cases can be examined.”**

—A. Michelson 1903

Backup

The QCD axion

Recall the **strong CP problem**:

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i \gamma^\mu D_\mu^L Q_L + \bar{q}_R i \gamma^\mu D_\mu^R q_R + \bar{L}_L i \gamma^\mu D_\mu^L L_L + \bar{l}_R i \gamma^\mu D_\mu^R l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu} - \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \quad ?$$

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

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

“Everything not forbidden is compulsory”

Experiments probing the neutron electric dipole moment do not see any CP violation from this term: $\theta < 10^{-10}$

Not only is there **no reason for it to be small**, but it is also a contribution of **two independent terms** – the intrinsic theta parameter and a quark mass phase – *that must cancel out to 1 part in 10 billion!*

The QCD axion

Add a naturally **light axion** scalar field, a , that originates from some UV theory at a heavy scale f_a :

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad \boxed{+\mathcal{L}_a}$$

$$\mathcal{L}_m = \bar{Q}_L i \gamma^\mu D_\mu^L Q_L + \bar{q}_R i \gamma^\mu D_\mu^R q_R + \bar{L}_L i \gamma^\mu D_\mu^L L_L + \bar{l}_R i \gamma^\mu D_\mu^R l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu} - \frac{\alpha_s}{8\pi} \left(\theta + \boxed{\frac{a}{f_a}} \right) \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

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

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

$$\boxed{\mathcal{L}_a = \partial_\mu a \partial^\mu a - m_\pi^2 f_\pi^2 \cos(\theta + a/f_a)}$$

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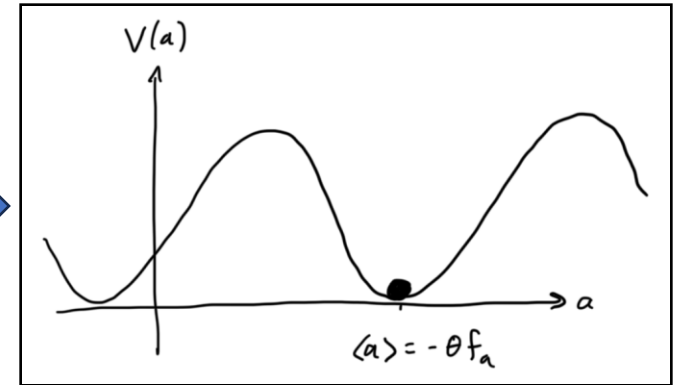
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$$\mathcal{L}_a = \partial_\mu a \partial^\mu a - \boxed{m_\pi^2 f_\pi^2 \cos(\theta + a/f_a)}$$



Potential energy is minimized for vanishing effective theta angle $\theta_{eff} \equiv \theta + \frac{a}{f_a} = 0$.

The QCD axion

Add a naturally **light axion** scalar field, a , that originates from some UV theory at a heavy scale f_a :

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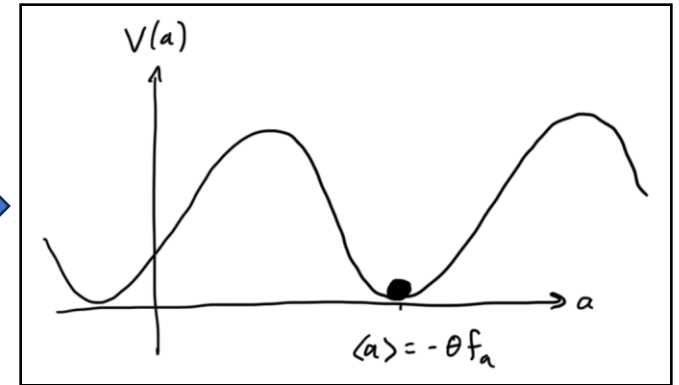
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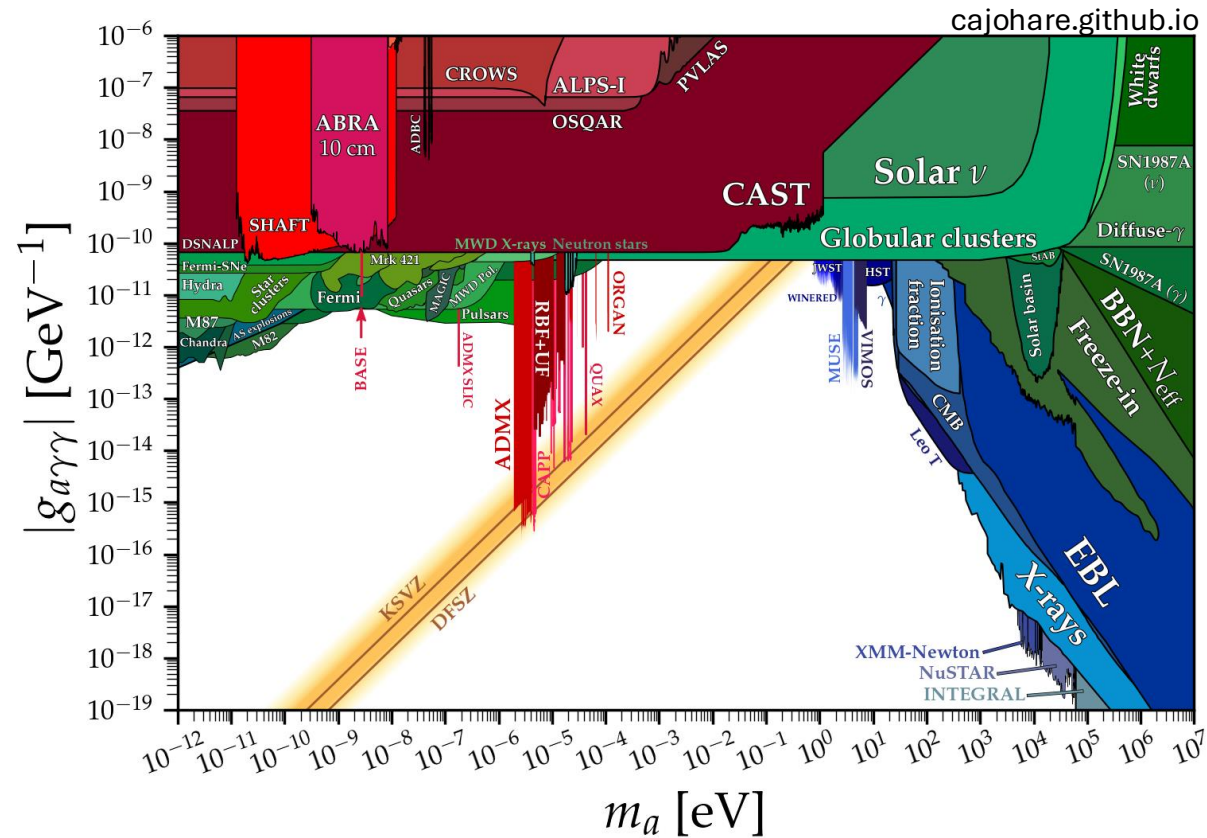
$$\mathcal{L}_a = \partial_\mu a \partial^\mu a - m_\pi^2 f_\pi^2 \cos(\theta + a/f_a) \quad \longrightarrow$$



Potential energy is minimized for vanishing effective theta angle $\theta_{eff} \equiv \theta + \frac{a}{f_a} = 0$.

The QCD axion

Many experimental searches and observational constraints on a light QCD axion, e.g. through photon coupling.



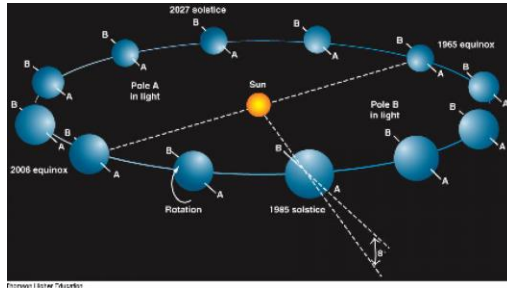
QCD axion could also be dark matter.

Many more Axion-Like Particle (ALP) possibilities that have nothing to do with QCD or strong CP.

Radically new BSM?

Sometimes an anomaly in **indirect precision** measurement = *something missing*:

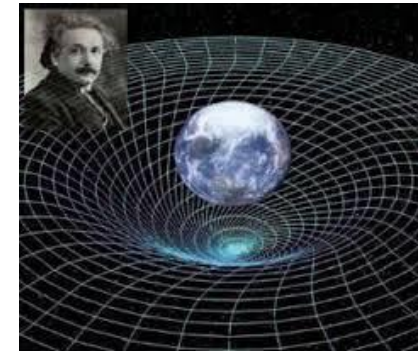
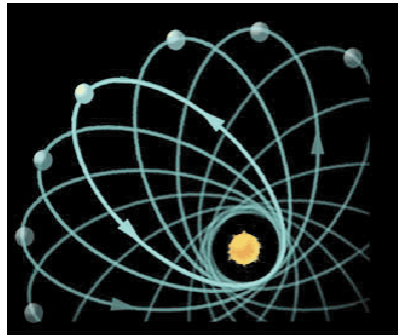
Anomaly in orbit of Uranus



Discovery of Neptune

Other times its implications are *far more radical*:

Anomaly in orbit of Mercury



Explained by General Relativity

(Could have been **anticipated** by **Effective Theory** and **naturalness**!)

Radically new BSM?

Keep an open mind.

1900s:

Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*

1920s:

A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson-Morley), and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

Radically new BSM?

Keep an open mind.

2020s:

Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*

2050s?

A combination of **precision measurements** (flavour, Hubble), **aesthetic arguments** (naturalness) supported by **null experimental results** (LHC), and **theoretical inconsistencies** (black hole information paradox) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

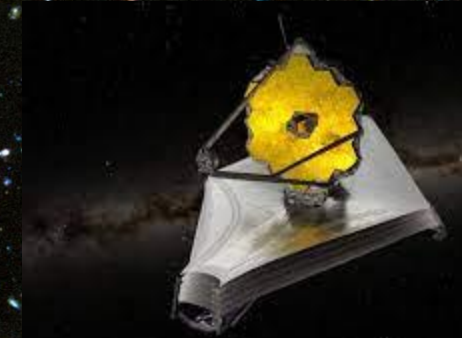
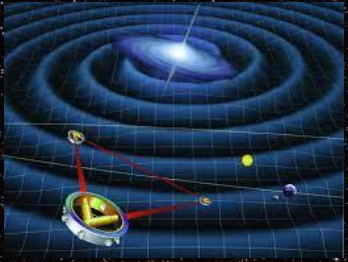
Concluding Remarks

It is a non-trivial empirical fact that universe is **comprehensible** and a **unified whole**.

(It didn't have to be that way; Universe could have been much simpler, or hopelessly complex / random)

To keep making progress in probing the fundamental foundations will require more data.

Concluding Remarks

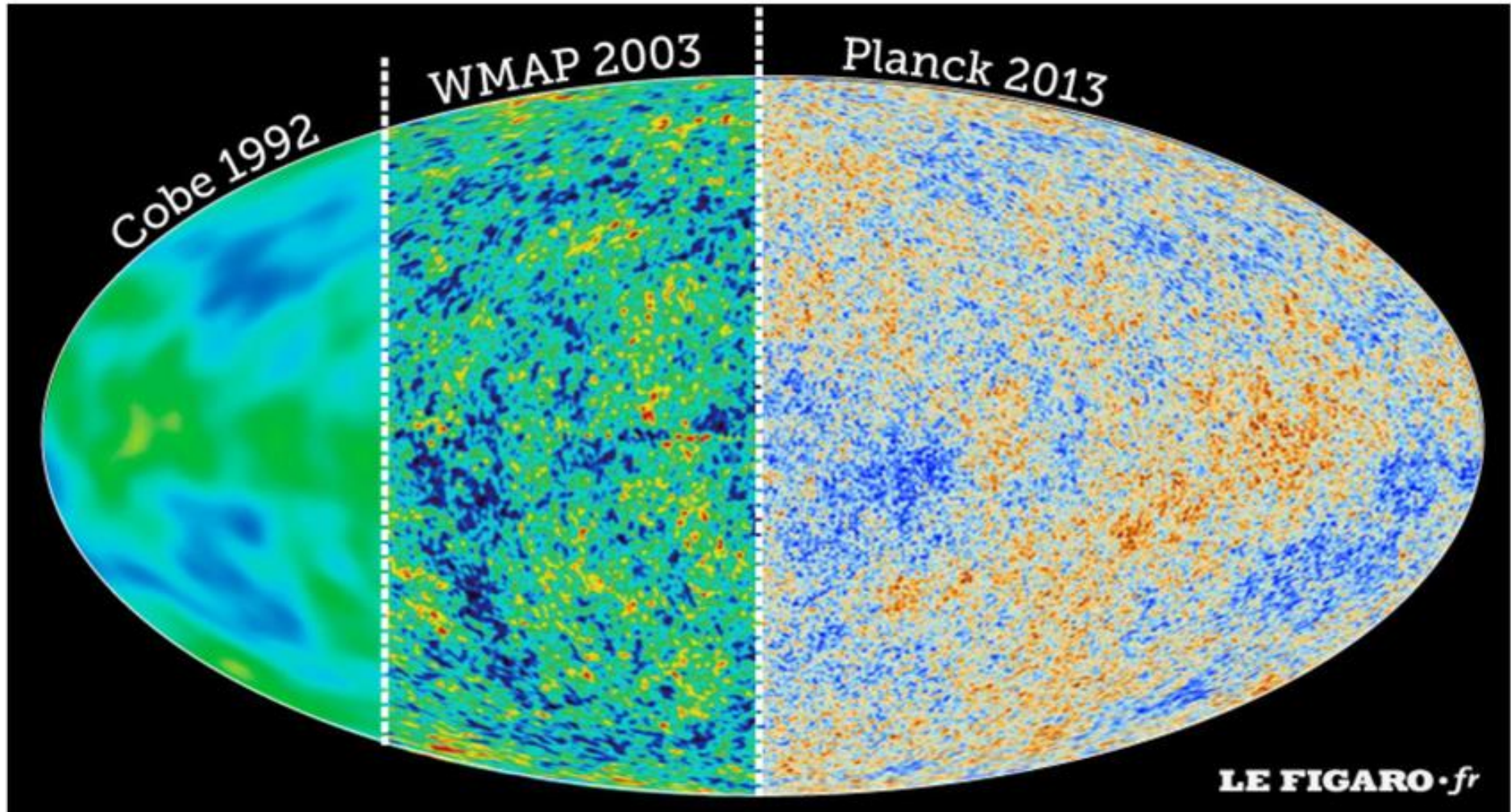


- Telescopes are observatories for exploring *outer space*.
- Colliders are *experimental* observatories for exploring *inner space*.
- We need *all eyes open on all scales* in our universe



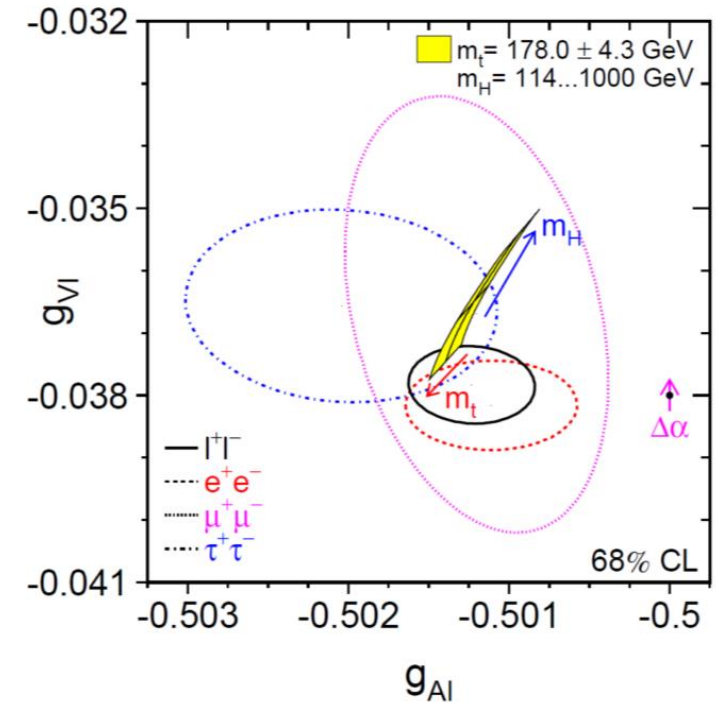
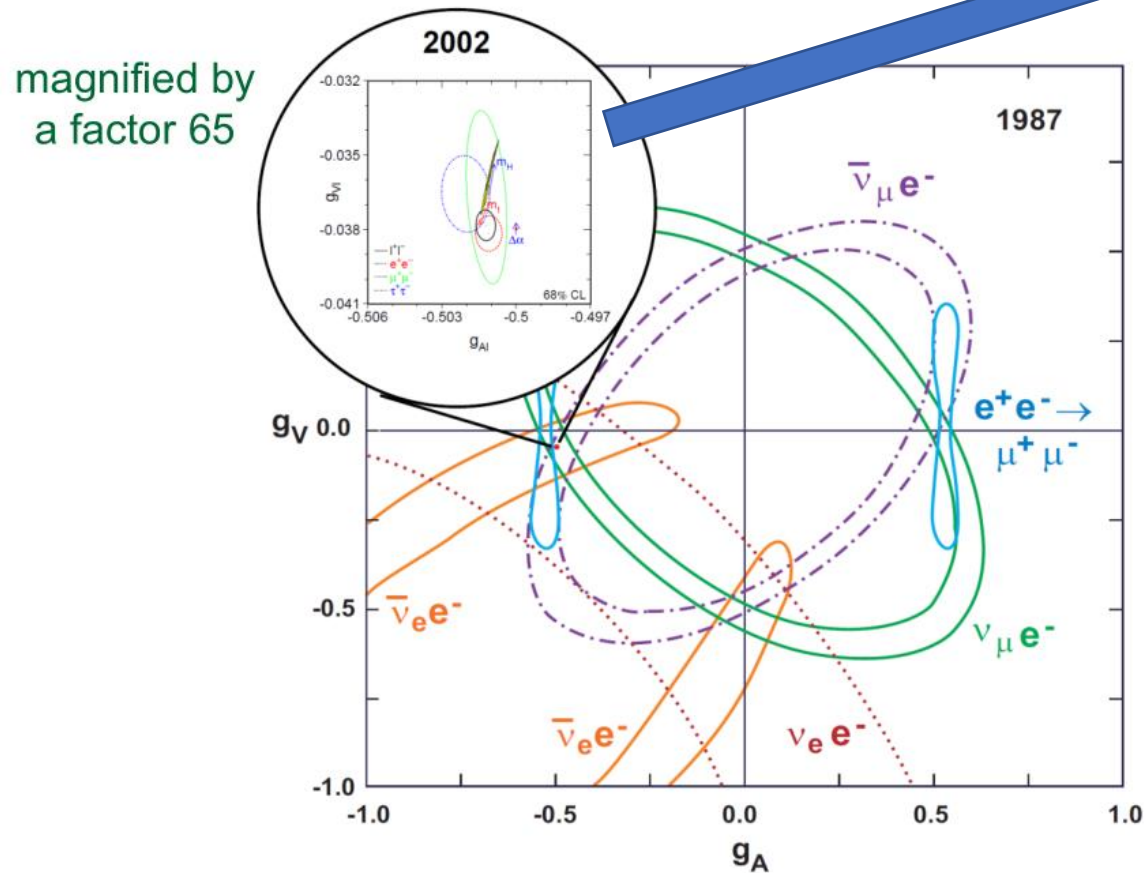
Concluding Remarks

Sharpen our picture of the Universe, e.g. *before and after Planck*.



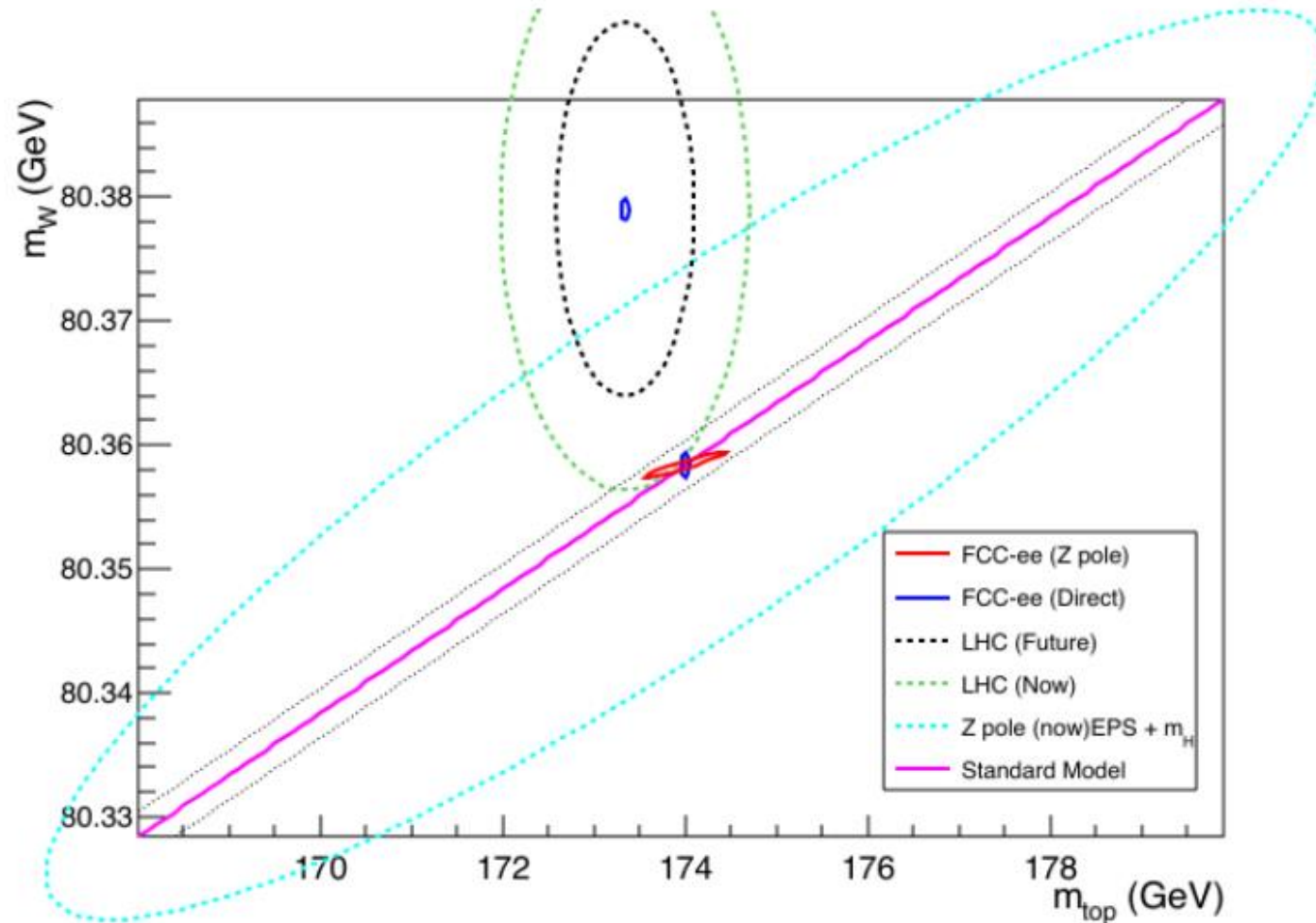
Concluding Remarks

Sharpen our picture of the Universe, e.g. *before and after LEP*.



Concluding Remarks

Sharpen our picture of the Universe, e.g. *before and after FCC-ee*.



Concluding Remarks

There are **no guarantees** of BSM discovery at future colliders. There are no guarantees of BSM discovery *anywhere else* either.

What we can guarantee is a **rich and wide-ranging programme** of fundamental physics at the **smallest scales** *experimentally* accessible.

Concluding Remarks

Future colliders are **not just a wild punt for BSM**, any more than JWST or LISA is only about breaking Λ CDM. Particle physics must be reframed in same way as astro/cosmo: **about doing good science**.

They are scientific laboratories for doing all kinds of fundamental experiments on small scales – a general-purpose “*particle observatory*” for the zeptoscopic world.

The wealth of information they provide about the most fundamental quantum processes we can directly access experimentally make colliders a unique, irreplaceable, and crucial instrument for the job of fundamental physics: **to better understand our universe**.

Concluding Remarks

There is **value in pushing frontiers** – *definite questions are answered*, and we learn something regardless of the outcome.

A **new generation** of improved measurements, analysis techniques, theoretical calculational tools, data management, hardware development, cutting-edge engineering, large international collaboration, popular culture inspiration, and spirit of fundamental exploration, *can only benefit humanity* regardless of our own short-sighted disappointment at lack of BSM. **Doing good science is its own reward.**

Progress in science is about **continuously refining existing knowledge** and **exploring the unknown**.

Questions?

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