Beyond the Standard Model

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Theory challenges for LHC physics

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The Plan of BSM Lectures

- Lecture I: Beauty and Problems of the Standard Model
- Lecture II: Effective Field Theory and Supersymmetry
- Lecture III: Extra-dimensions and Technicolor/Composite Higgs models

About these BSM lectures

- Inspired by many different collaborators and lecturers

  [Dmitri Kazakov, Ben Gripaios, Veronica Sasnz, Hitoshi Murayama...]

- These lectures are more kind of **review** - time limit
- Do not hesitate to ask questions **during** the lectures
- There are **exercises** for you

Lecture I:
Beauty and Problems of the Standard Model

Notations

- natural units $\hbar = c = 1$
- metric $\eta^{\mu\nu} = diag(1, -1 - 1, -1)$
- assuming you are familiar with Dirac (4-component) spinors and Dirac gamma-matrices

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \overline{\sigma}^\mu & 0 \end{pmatrix}$$

where

$$\overline{\sigma}^\mu = (1, -\sigma^i)$$

$$\sigma^\mu = (1, \sigma^i)$$

and σ^i are usual 2x2 Pauli matrices:

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Notations

- Properties: $\{\gamma^\mu, \gamma^\nu\} \equiv \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2\eta^{\mu\nu}$
- Definition: $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$
- Representation:
- Dirac fermion carries 4-dim reducible representation (1/2; 0) x (0; 1/2) which is the product of two irreducible ones for 2-component Weyl spinors

Summary of the Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c$$

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$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c$$ → Fermion masses and mixings

$$+ |D_\mu \phi|^2 - V(\phi)$$ → Higgs boson - scalar kinetic term and potential

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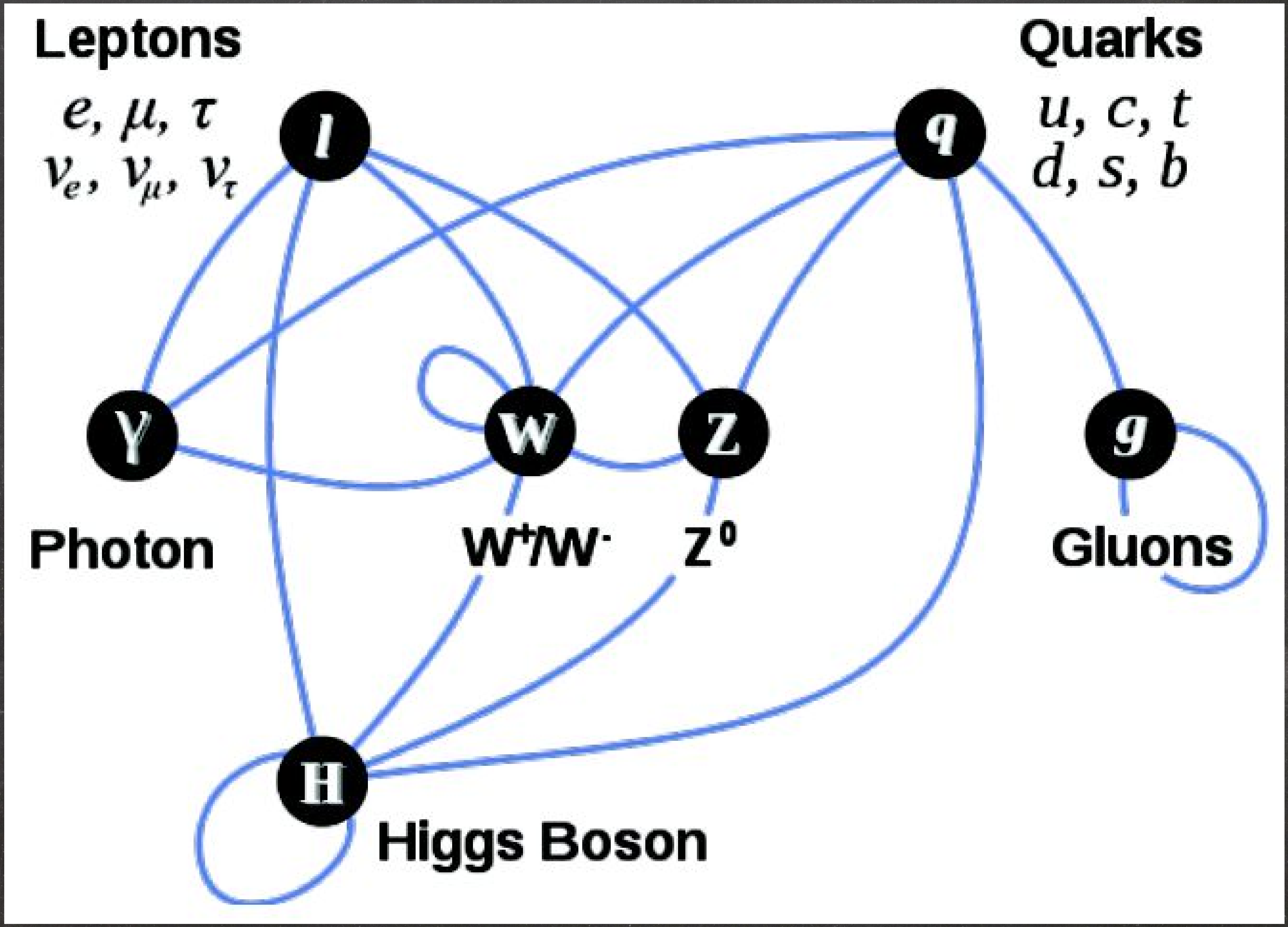

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and one complex scalar, carrying irreps of the gauge groups above

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d^c	$\overline{3}$	1	$+\frac{1}{3}$
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- The lagrangian should contain all terms up to dimension four, such that it is renormalizable.

Gauge-Matter sector of the SM

- Lagrangian $\mathcal{L} = i\overline{\psi}_i \overline{\sigma}^\mu D_\mu \psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$
- 12 gauge fields:
  8 in an adjoint of SU(3)
  3 in an adjoint of SU(2)
  1 for U(1)
- The covariant derivative D_μ contains the three gauge couplings with the gauge group generators in the appropriate reps

The Flavour sector of the SM

- $$\mathcal{L} = \lambda^u q H^c u^c + \lambda^d q H d^c + \lambda^e l H e^c + \text{h. c.}$$

- The λs are three 3x3 complex matrices (in flavour space) - quite a few free parameters and the possibility of CP-violation (since a CP transformation is equivalent to interchanging the λs with their complex conjugates).

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- But not all of these parameters are physical. We are free to do unitary rotations of the different fields without changing other terms in the Lagrangian. There is a basis in which we can write **(exercise)**:

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$$\lambda^u q H^c u^c + \lambda^d V q H d^c + \lambda^e l H e^c + \text{h. c.}$$

- where now all λs the are diagonal, and V is a 3x3 CKM matrix.
This is the only off-diagonal object in the Lagrangian, so it must contain all the information about mixing of flavours in the SM.
Very roughly

$$V \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$ with $\epsilon \simeq 0.2$

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  - If we look back for the Lagrangian, we see that **6** of the real parameters are the quark masses, so there must be **3 physical angles** in the CKM matrix, and **a single phase**. This phase is a source of CP-violation.

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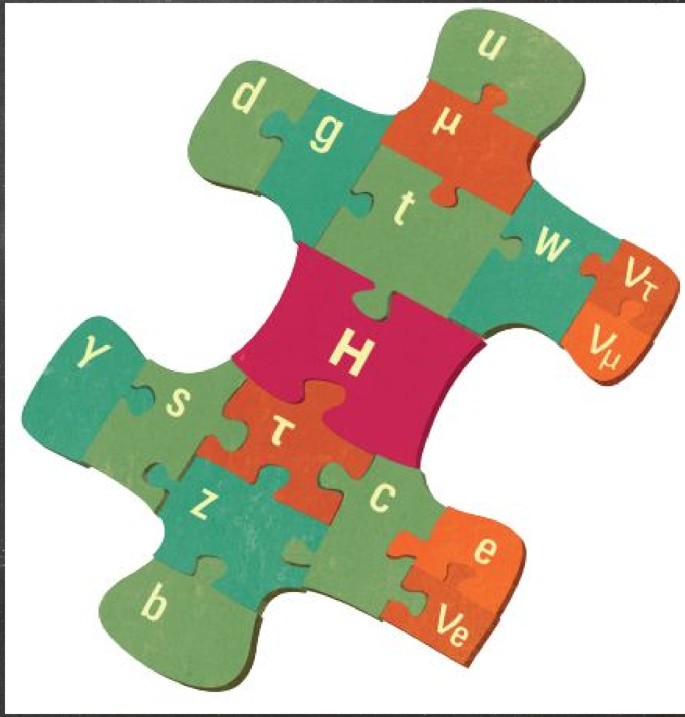

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Miracles of the Standard Model

There certain features of the SM that are very special, and are vital clues in our quest for the form of physics BSM

No Flavour Changing Neutral Currents (FCNC) at tree-level

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- Not necessarily true in a theory with more than one Higgs doublet, where there are extra Yukawa coupling matrices in general, and the VEV is shared between the doublets (**exercise: show explicitly that tree-level FCNC exists in a 2 Higgs doublet model. How is this avoided in the MSSM?**).

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- If not the case -> the different irreps would have different couplings to the Z -> the matrix of couplings to the Z would then be diagonal in the interaction basis, but not proportional to the identity matrix -> The matrix would then acquire off-diagonal entries when we rotate to the mass basis.

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- For example, the d and s are both colour anti-triplets with charge -1/3 and can mix, but they also all come from SU(2) doublets with hypercharge +1/6, so there are no FCNC.
(**exercise: before the charm quark was invented, it was thought that the s- quark lived in an SU(2) singlet. Show that this leads to tree-level FCNC.**)

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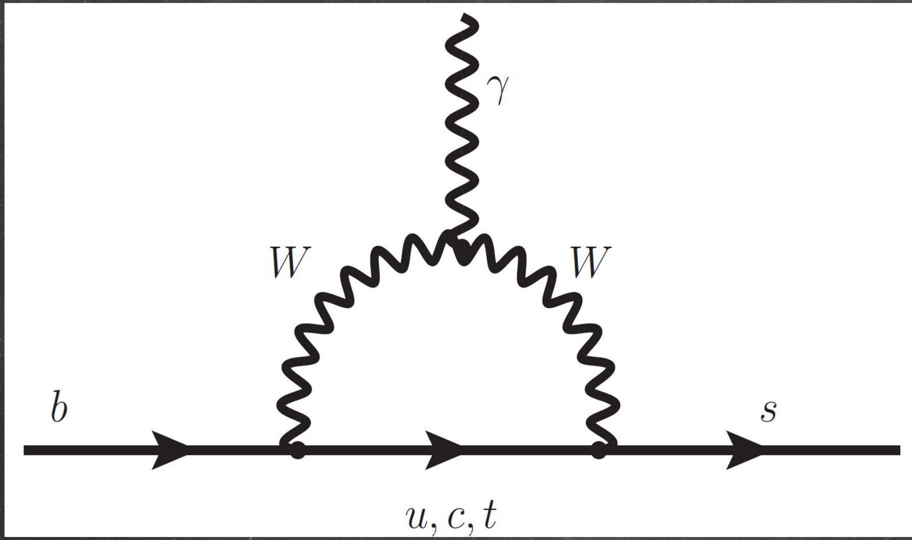

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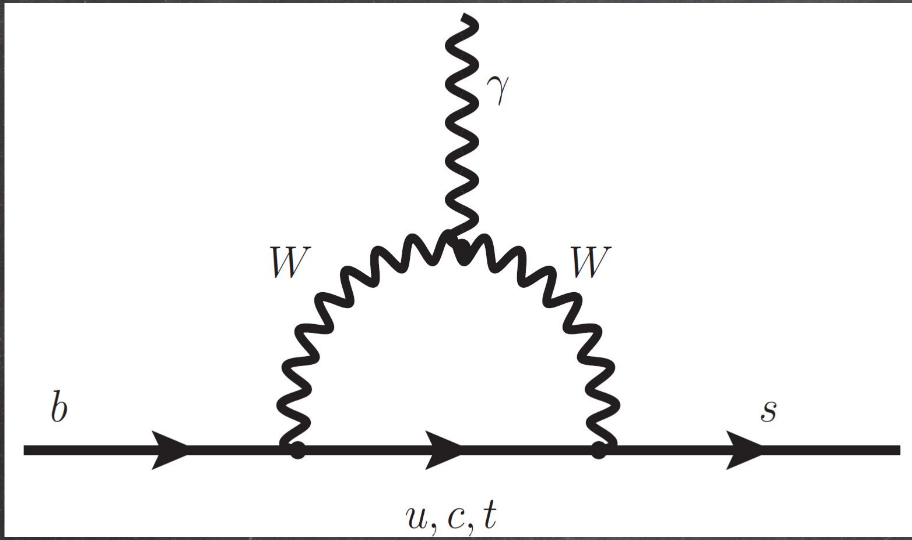

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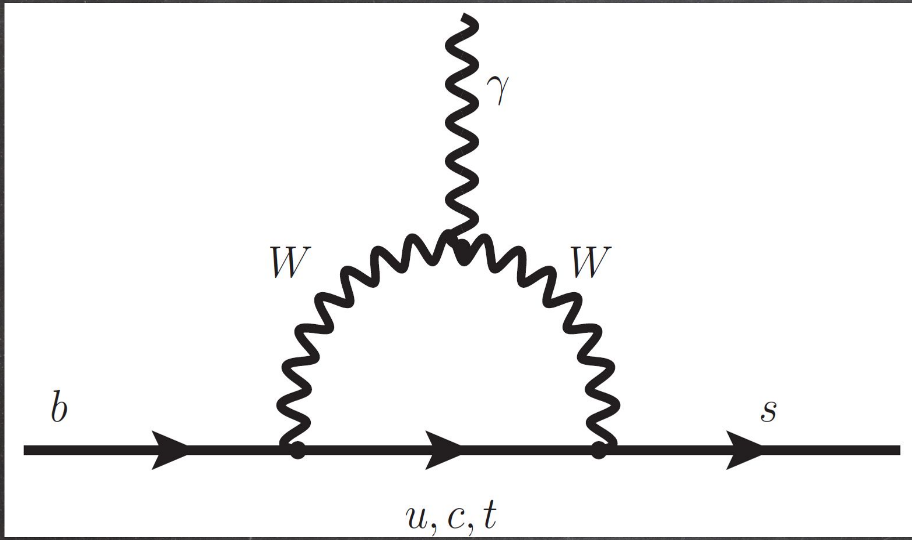

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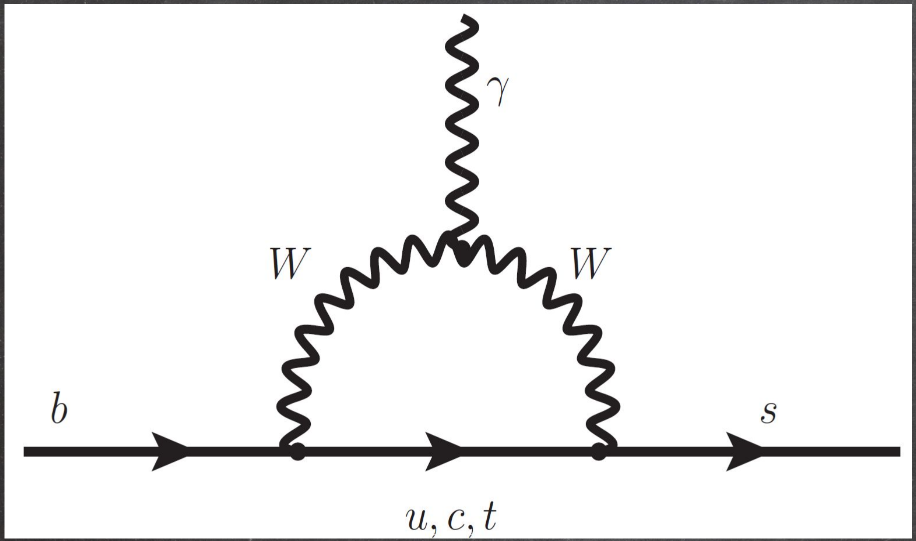

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- Additional factor of $(1/4\pi)^2$ from the loop integral leads to the overall contribution of

$$\frac{1}{(4\pi)^2}\frac{m_c^2}{m_W^2}\frac{1}{m_W^2} \simeq 1/(60\text{TeV})^2(!)$$

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Again, these properties do not hold for generic BSM physics, and so the constraints thereon are strong.

Miracles of the Standard Model

Electroweak precision tests and custodial symmetry

- There is suppression in EW precision tests - not a generic feature for BSMs. For the complex SU(2) there are four real fields and the respective O(4) symmetry. V(H) has the same feature – the function of $|H|^2 = h_1^2 + h_2^2 + h_3^2 + h_4^2$ – manifestly invariant under O(4), with the Lie algebra the same as that of SU(2)xSU(2) (**exercise**).
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- Consider the Lagrangian for the gauge bosons after EWSB. The most general Lagrangian consistent with U(1). At quadratic level, in momentum space

$$\mathcal{L} = \Pi_{+-} W^+ W^- + \Pi_{33} W^3 W^3 + \Pi_{3B} W^3 B + \Pi_{BB} BB$$

where $\Pi_{ab}(p^2)$ are functions of momentum generated by the currents to which W and B couple: $\Pi_{ab} \sim \langle J_a J_b \rangle$

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- The particular combination $\Pi_{+-}(0) - \Pi_{33}(0)$ is symmetric in the two indices and traceless, so transforms as the 5 of $SU(2)_V$
- But since $SU(2)_V$ is a symmetry of the vacuum, only singlets of $SU(2)_V$ can have non-vanishing VEVs. This implies that $\mathrm{T}=0$, which in turn implies a definite relation for, say, m_W/m_Z

Miracles of the Standard Model

Electroweak precision tests and custodial symmetry

- This derivation applies to any theory with $SU(2)_L x SU(2)_R$ broken to the diagonal $SU(2)_V$ in the vacuum. Any such theory will naturally come out with the right value for the measured T- parameter

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- Even if we add only an additional Higgs doublet, we will get in to trouble, because the theory remains $SU(2)_L x SU(2)_R$ symmetric, but $SU(2)_V$ is now broken in the vacuum: a second complex Higgs doublet will break this even further to just electromagnetism. The vacuum is no longer $SU(2)_V$ symmetric

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Accidental symmetries and proton decay

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SM extension to EFT

- **D=0: the cosmological constant**
  - adds an arbitrary constant, to the Lagrangian; no dependence on any fields & derivatives, can be interpreted as the energy density of the vacuum
  - the vacuum energy is measurable - is equivalent to including of Einstein's "cosmological constant" $\rho_{cc} \sim (10^{-3} ev)^4$ into the gravitational field equations
  - good news, on one hand - Universe is observed to accelerate
  - bad news, on the other hand - the size of this operator coefficient Λ^4 while the observed energy density is around But the cut-off of the SM had better not be $10^{-3}~
  - \mathrm{eV}$, because if it were then we could certainly not use it to
  - make predictions at LHC energies of several TeV. So either dynamics or
  - a tuning makes the constant small. If we consider the Planck scale to
  - be to be a real physical cut-off, then we need to tune at the level of 1 part in 10^{120}. It
  - is fair to say, that despite $O(10^{120})$ papers having been written
  - on the subject, no satisfactory
  - dynamical solution has been suggested hitherto. An alternative is to argue that
  - we live in a multiverse in which the constant takes many different
  - values in different corners, and we happen to live in one which is
  - conducive to life. Indeed, it has been argued \cite{Weinberg:1988cp} that if the constant
  - were much larger and positive, structure could never form, while if it

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- Note that if we had not insisted on renormalizability, we could write dimension-six terms e.g. $\overline{\Psi}\gamma^\mu\gamma^5\Psi\overline{\Psi}\gamma_\mu\Psi$, which do violate parity (**exercise**)

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Accidental symmetries and proton decay

- As already discussed, the SM Lagrangian is accidentally invariant
  - under a U(1) baryon number symmetry (an overall rephasing of all quarks)
  - as well as under three U(1) lepton number symmetries, corresponding to individual rephasings of the three different lepton families (which contains an overall lepton number symmetry $U(1)_L$ as the diagonal subgroup)

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- Either $U(1)_B$ or $U(1)_L$ symmetry, together with Lorentz invariance, prevents the proton from decay: a putative final state must (by Lorentz invariance, which implies the fermion number is conserved mod 2) contain an odd number of fermions lighter than the proton. Such states carry lepton number but not baryon number, while the proton carries baryon number but not lepton number.

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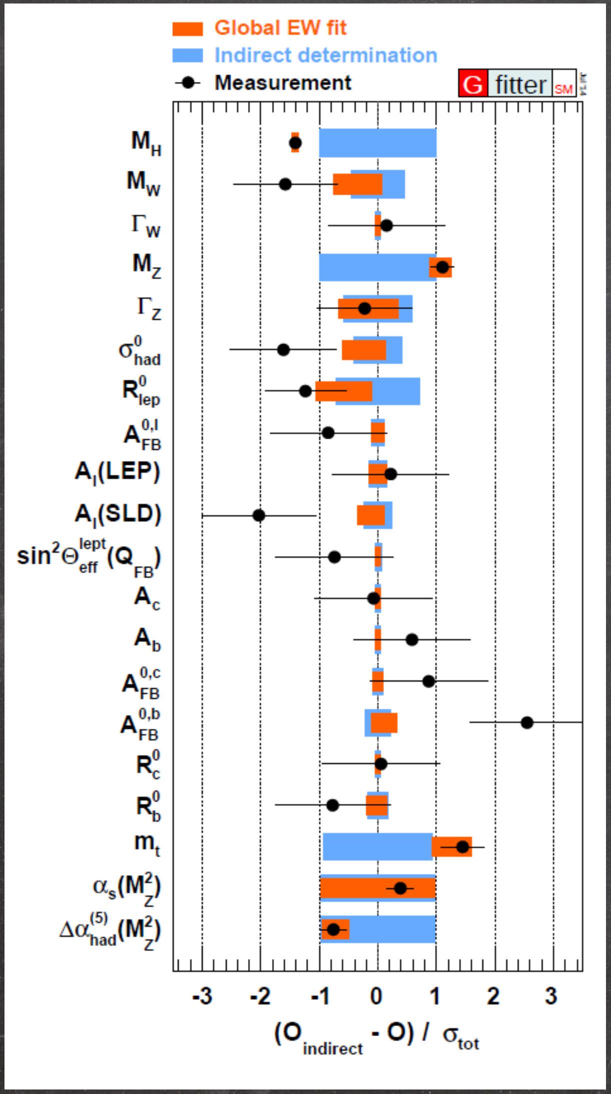
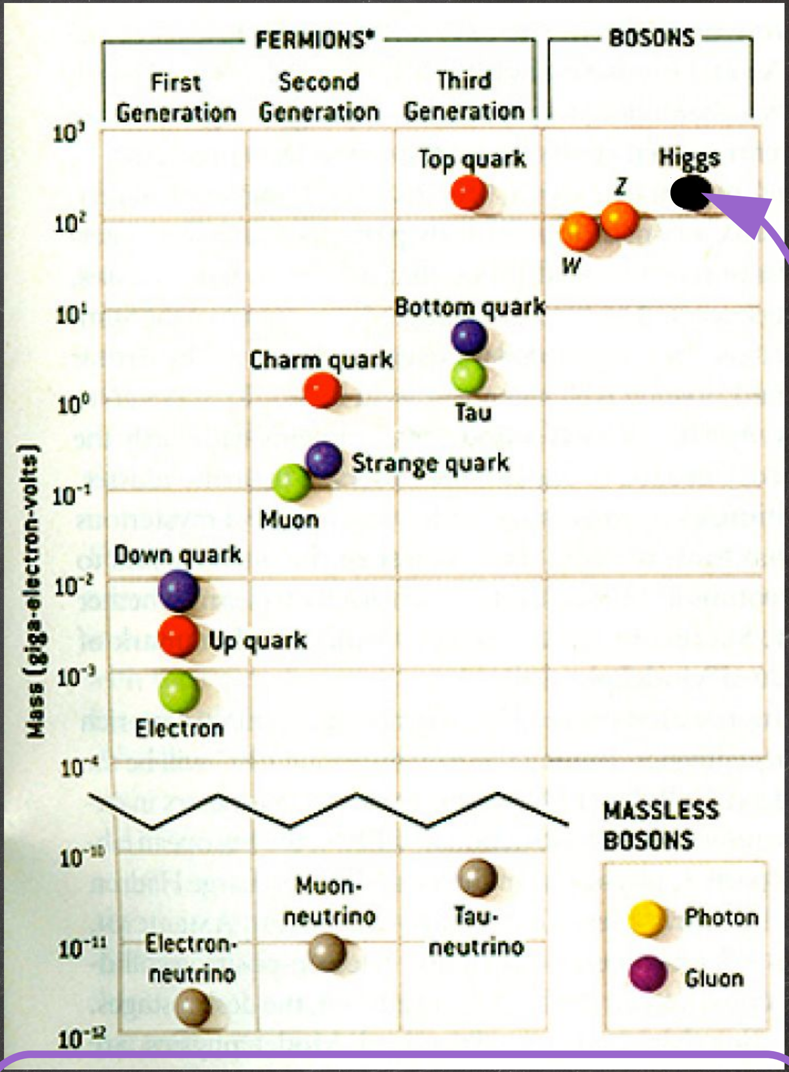
- Again, once we allow higher dimension operators, we will find that lepton and baryon number are violated (by operators of dimension five or six, respectively), meaning that the proton can decay. Similarly, generic theories of physics BSM will violate them and hence will be subject to strong constraints. (**exercise: consider just the Higgs sector coupled to the W-boson. Show that $SU(2)_L x SU(2)_R$ is an accidental symmetry, and find a dimension-six operator that violates it**)

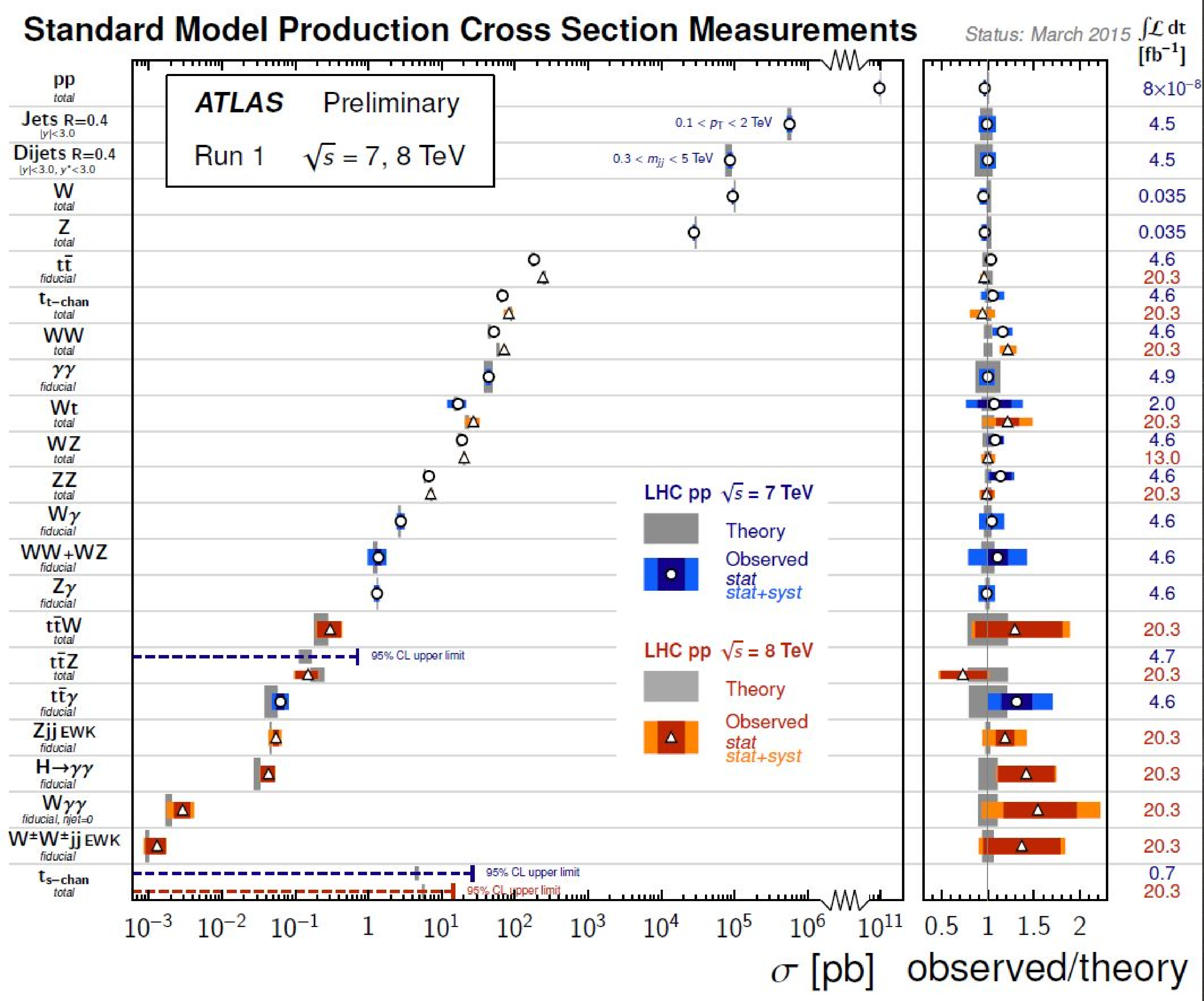
The the Standard Model is very successful !





Confirmed to better than 1% precision by 100's of precision measurements

The last missing particle – Higgs boson with ~125 GeV mass is discovered on the 4th of July 2012



Standard Model Production Cross Section Measurements
Status: March 2015
∫ℒ dt [fb⁻¹]
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
pp total
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0, y*<3.0
W total
Z total
tt̄ fiducial
t t-chan total
WW total
γγ fiducial
Wt total
WZ total
ZZ total
Wγ fiducial
WW+WZ fiducial
Zγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
H→γγ fiducial
Wγγ fiducial, njet=0
W±W±jj EWK fiducial
t s-chan total
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
95% CL upper limit
LHC pp √s = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Observed
stat
stat+syst
8×10⁻⁸
4.5
4.5
0.035
0.035
4.6
20.3
4.6
20.3
4.6
20.3
4.9
2.0
20.3
4.6
13.0
4.6
20.3
4.6
4.6
4.6
20.3
4.7
20.3
4.6
20.3
20.3
20.3
20.3
0.7
20.3
10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
0.5 1 1.5 2
σ [pb]
observed/theory

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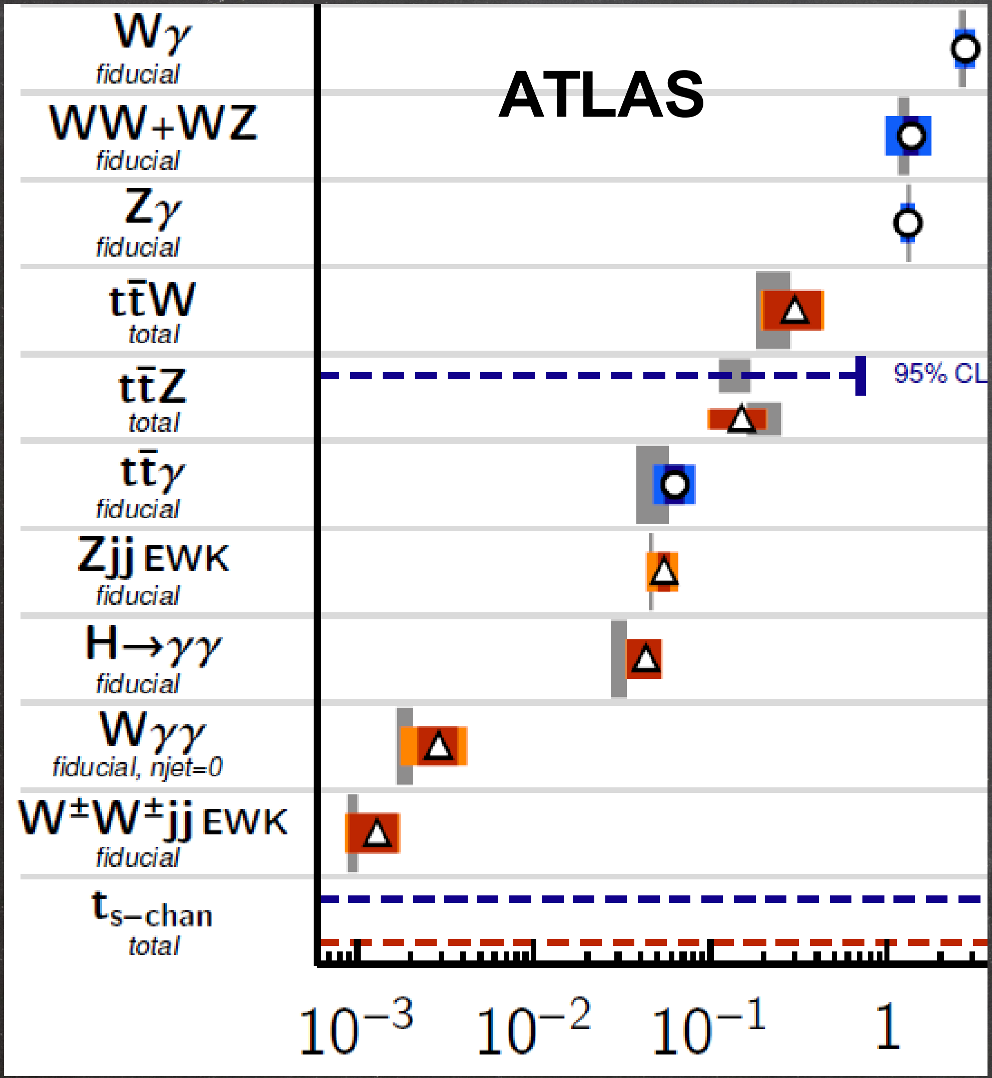

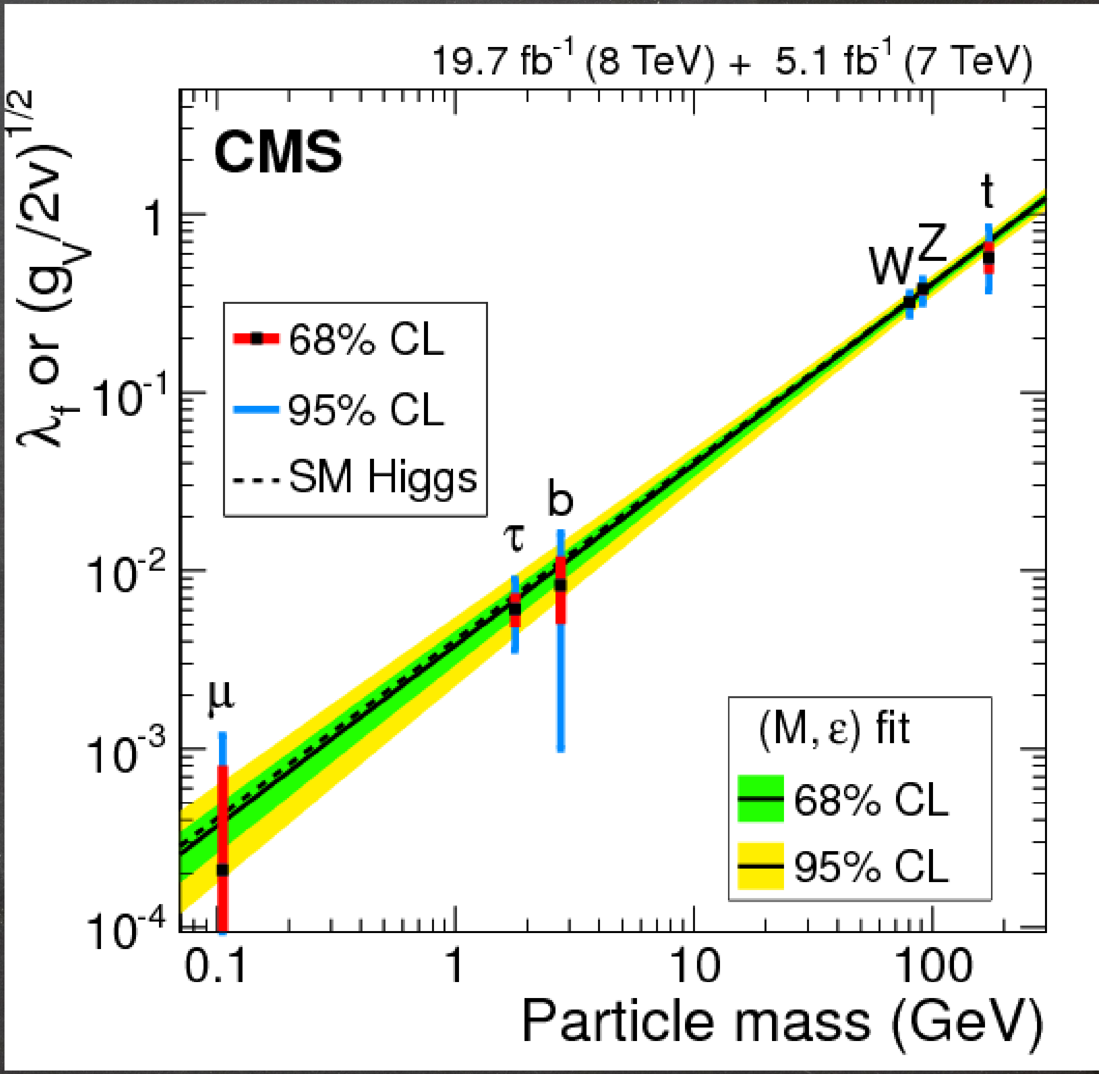

So, if SM works so good, why we are looking beyond?!

SM is empirically incomplete

SM does a wonderful job of explaining a lot of data, and it does so by means of a delicate structure that is not preserved by generic BSM theories. This means that it is hard to write down BSM models that are consistent with all the data.

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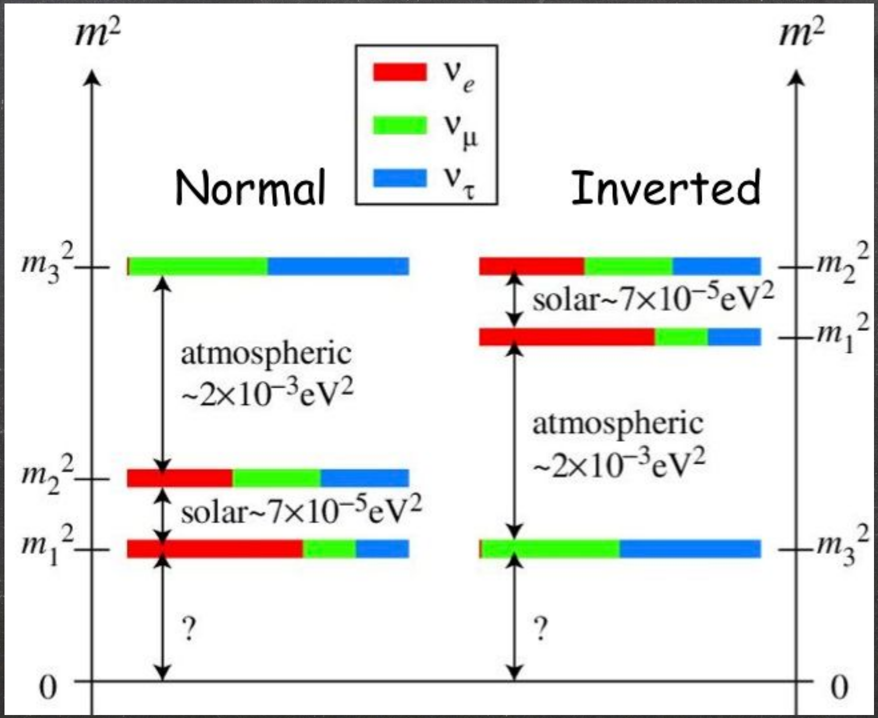
But there are, by now, also plenty of data that the SM cannot describe:

- **neutrino masses and mixings: no term in SM Lagrangian yields these**



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- **the presence of non-baryonic, cold dark matter:** dark matter is neutral, colourless, non-baryonic, and massive. The only such particles in the SM are neutrinos, but these are too light, making instead hot dark matter

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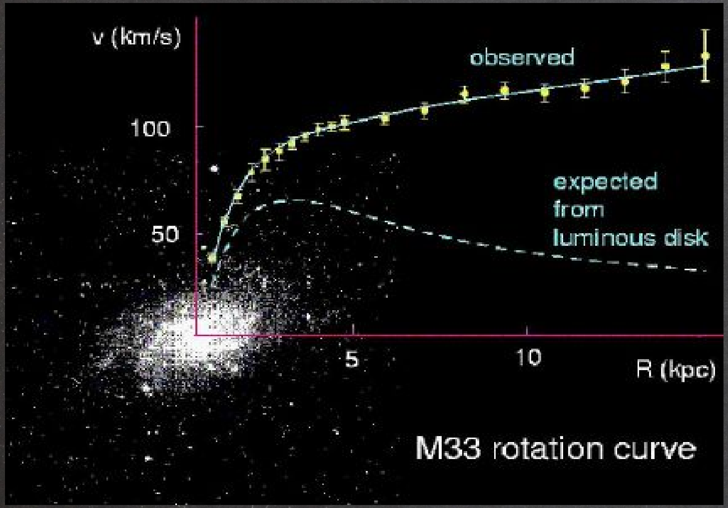

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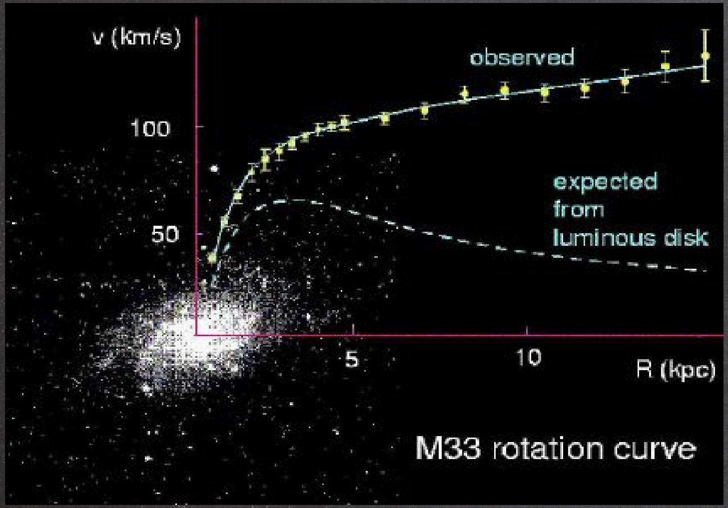
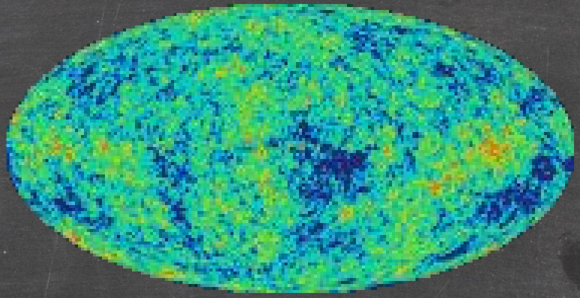


CMB: WMAP and PLANCK



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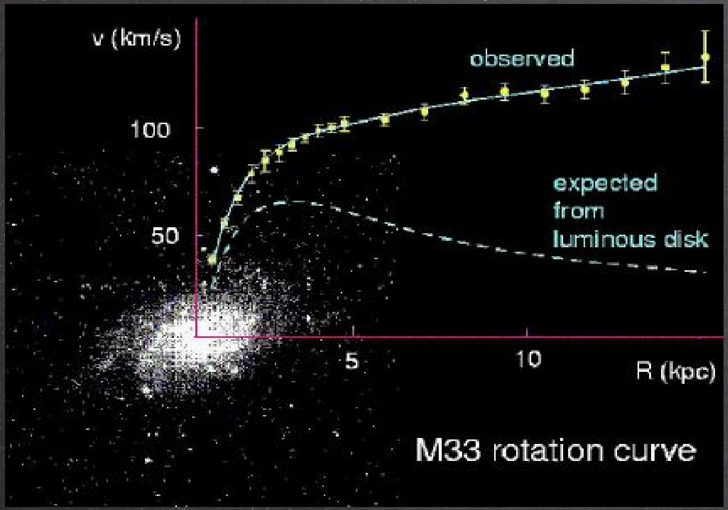

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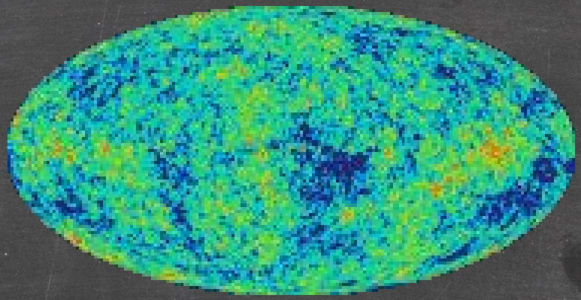
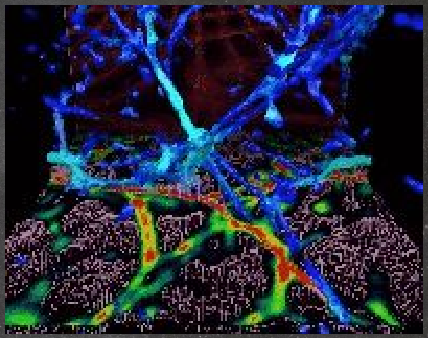


Large Scale Structures



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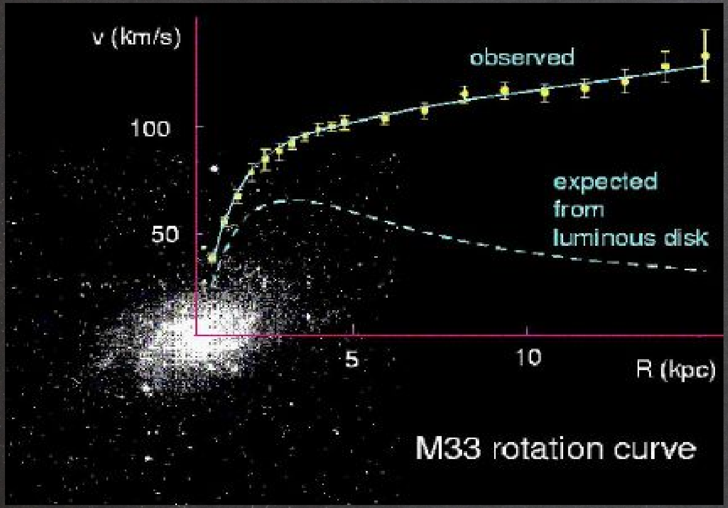

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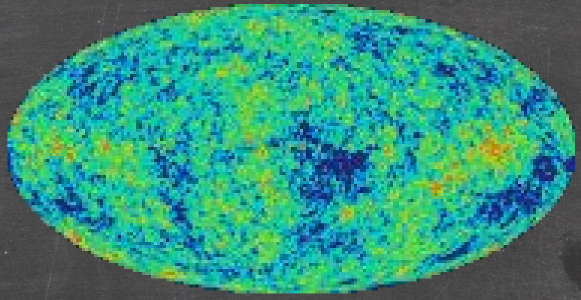

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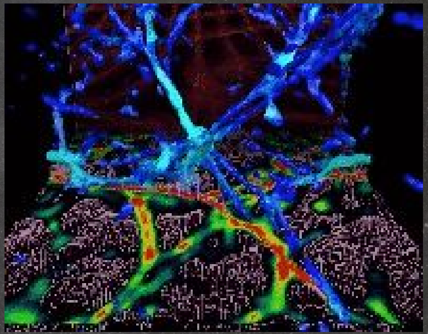
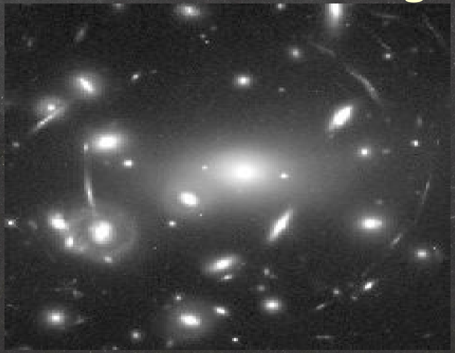


Gravitational lensing



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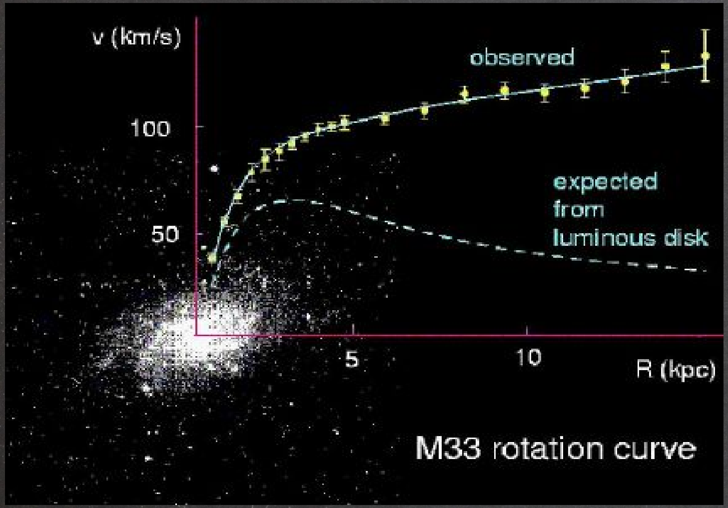

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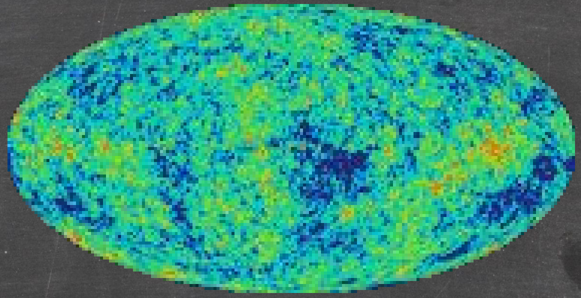

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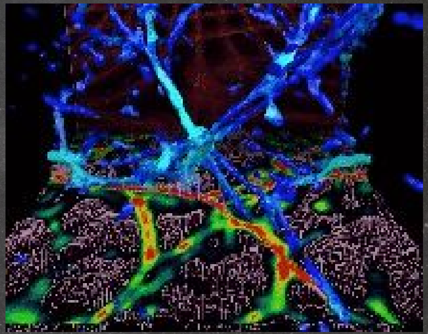

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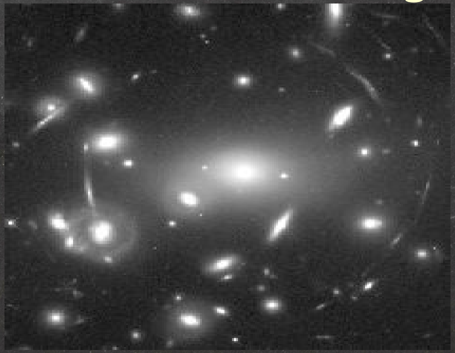

Bullet cluster

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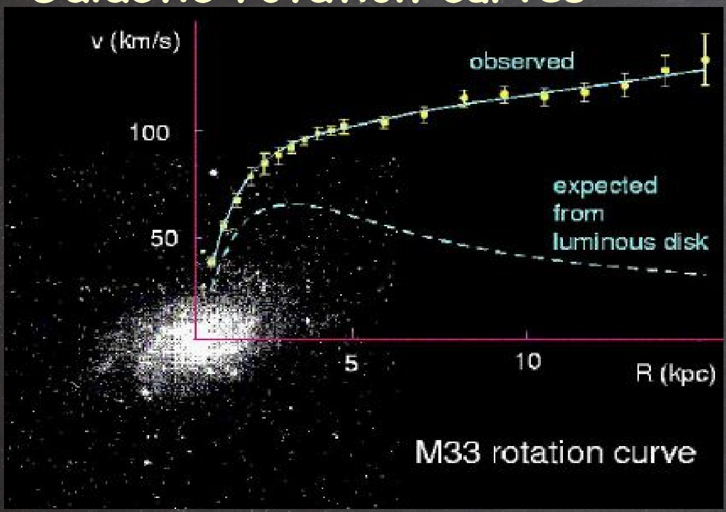

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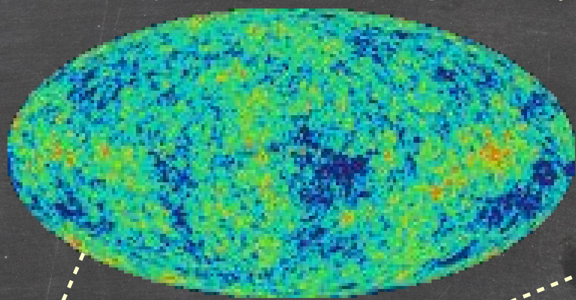

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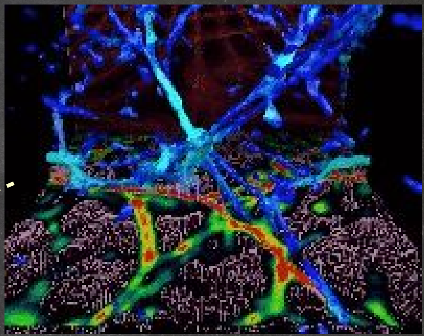

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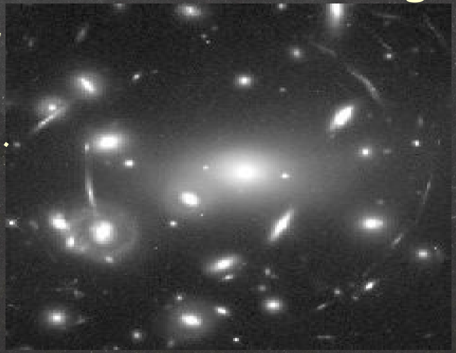

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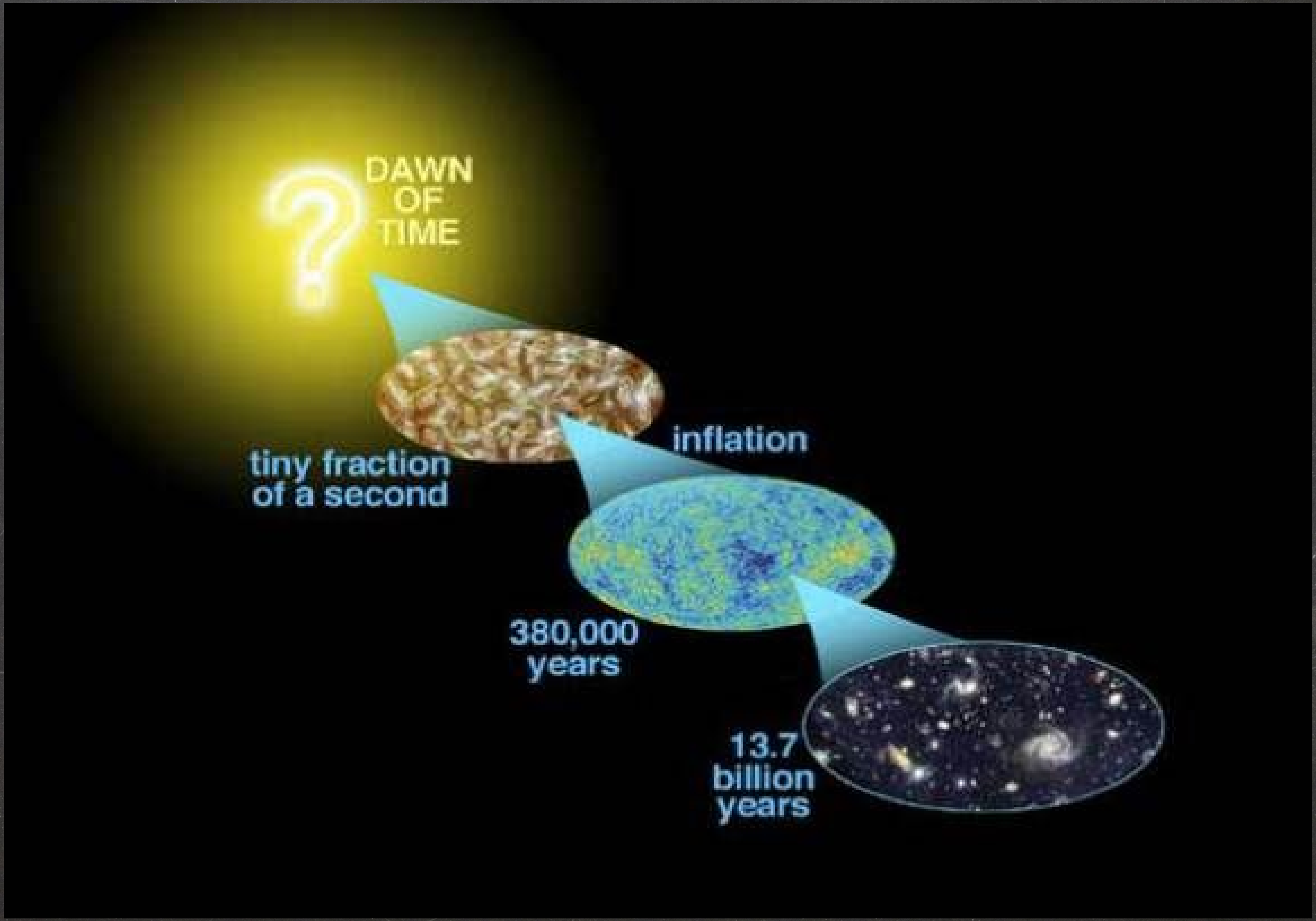
- **the presence of scale-invariant, Gaussian, and apparently acausal density perturbations:** consistent with a period of inflation at early times



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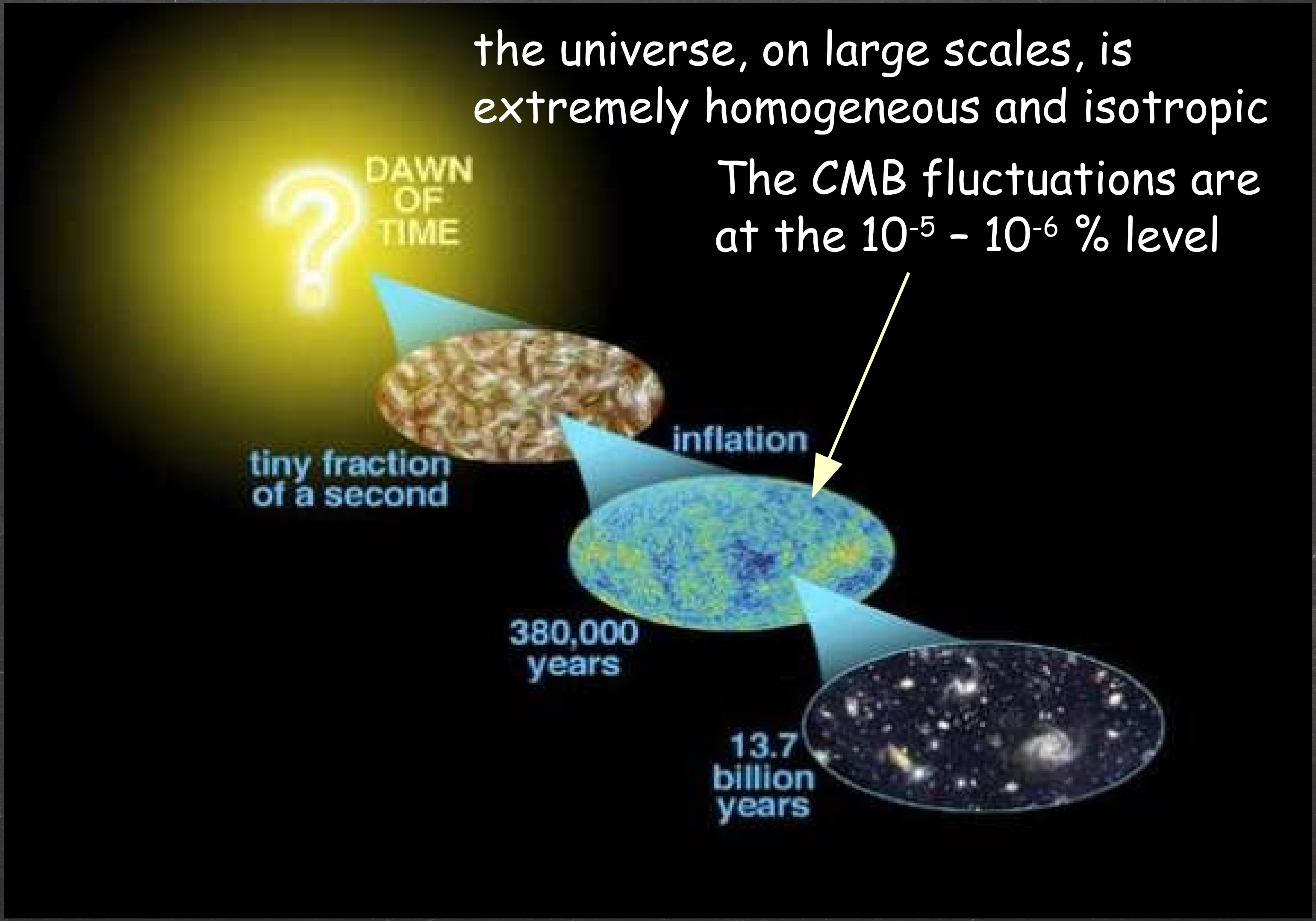

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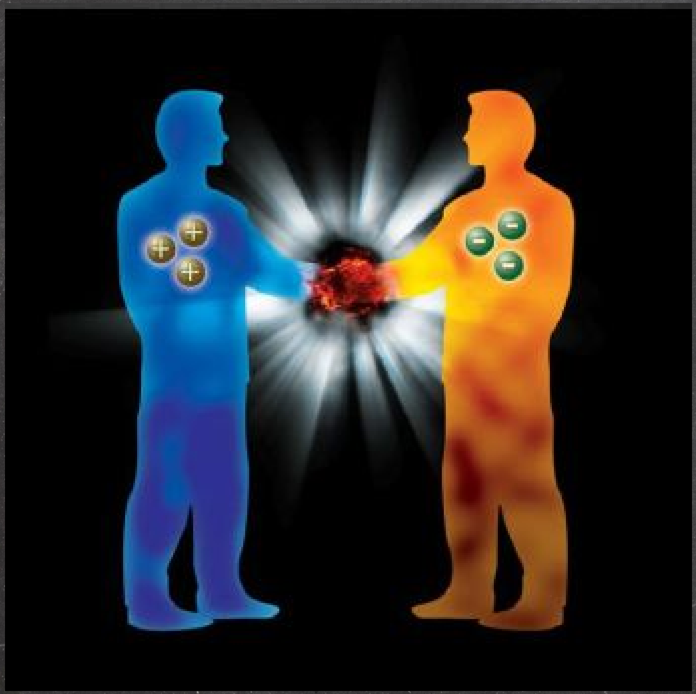

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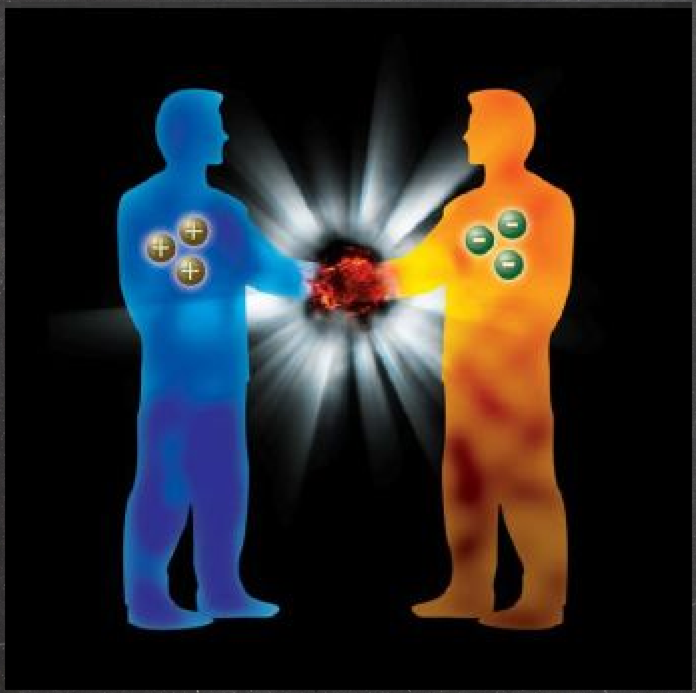

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Empirical problems of the SM stated above have been established beyond reasonable doubt.

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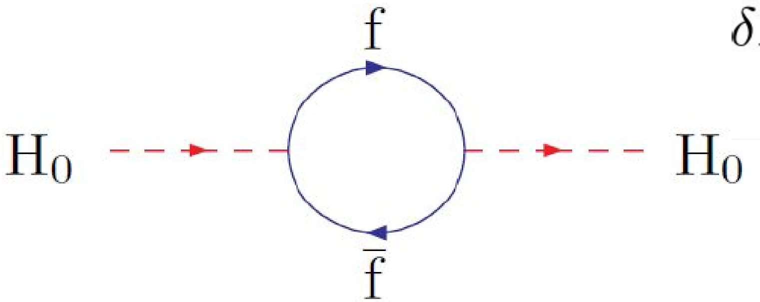

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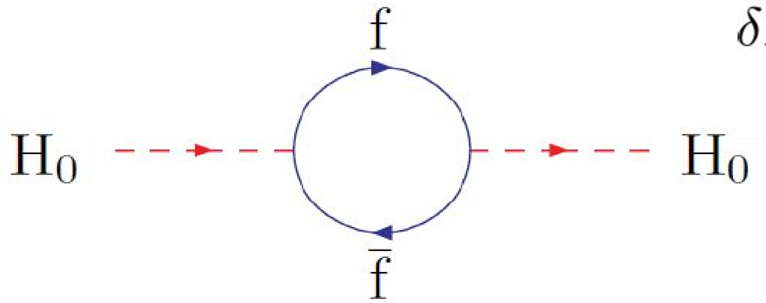

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there is a cancellation of over 30 orders of magnitude to have 125 GeV Higgs

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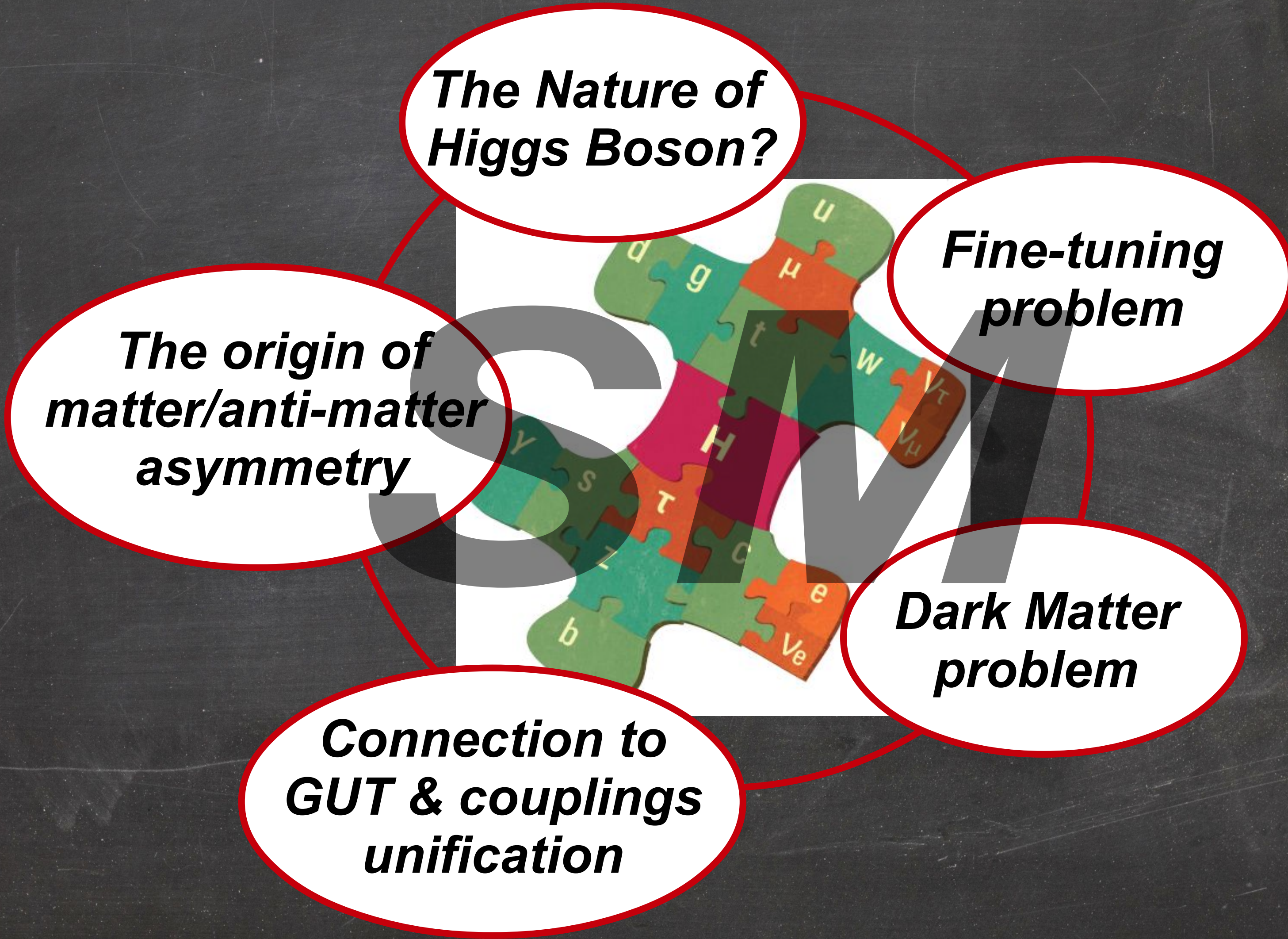
Explanation & exp confirmation of any of these merit a Nobel prize!

So, while Higgs Boson Discovery has completed the puzzle of the Standard model ...

But it has raised even more questions than the number of answers it has given!



Higgs boson properties are consistent with main compelling BSM theories, so the pattern we have is just a piece of a much bigger puzzle!