Symmetry dictates dynamics

- Poincare Invariance (under rotations, boosts, translations and time evolution) leads to particle states described by relativistic de Broglie waves, with spin: |mass, spin>
  - but why the particular pattern of masses that we observe?
- Gauge invariant symmetry groups dictate the form of the couplings between the (otherwise free) particle states
  - but why those particular gauge groups?
- And then we need the Higgs mechanism to break the symmetries that we've so carefully constructed, to get agreement with experiment
  - What the Higgs all about, and how big are the holes in our understanding?
- More than 25 years of precision testing (at the 0.1% level) have been spectacularly successful!
- So, the general principle of "Symmetry dictates dynamics" works; but we have no understanding of why the universe has chosen this specific realization of that general principle…

The structure of the SM interactions

- The mathematical description of the fundamental interactions is built by analogy to Maxwell's theory of EM.
- Maxwell's equations are a natural consequence of gauge symmetry, which
  - greatly constrains the structure of the theory
  - guarantees that physical quantities are finite (avoiding the unphysical divergences that plague quantum field theories); the theories are renormalizable
  - the resulting theories for the EM, weak and strong interactions are spectacularly successful in confronting detailed experimental data
- To describe the weak and strong interactions, we must invoke Non-Abelian symmetries: Yang-Mills theories
- The Standard Model interactions are based on the continuous gauge groups: $U(1)_Y \times SU(2)_L \times SU(3)_c$
- The electroweak symmetry $U(1)_Y \times SU(2)_L$ is spontaneously broken via the Higgs Mechanism to $U(1)_{EM}$
- The nature of this spontaneous symmetry breaking is unknown, and is problematic. We will explore this, as one of the Great Questions in Physics.

Parameters of the Standard Model

- Strong, EM and Weak coupling constants
  (α_S or Λ_{QCD} , α_{EM} or e , α_W or G_F)
- Weak mixing angle ($\sin^2 \theta_W$ or M_Z or Higgs VEV)
- Six quark masses
- Quark CKM mixing matrix (3 angles + 1 phase)
- Three charged lepton masses
- The Higgs mass M_H , (or quartic coupling λ)
- The QCD θ parameter ($\theta=0$ in the SM)

- Three Dirac neutrino masses
- Three Majorana neutrino masses
- Neutrino MNSP mixing matrix
  (3 angles, 1 Dirac phase, 2 Majorana phases)

The “origin of mass” in the Standard Model

- The accommodation of mass in gauge field theories in the Standard Model can only be understood once we study:
    - Gauge symmetries
    - Spontaneous symmetry breaking: the Higgs mechanism
    - Weak interaction gauge boson masses
    - fermion masses, chiral masses
    - mass as self-energy, running mass
    - renormalization, ultraviolet divergence of the Higgs self-energy
    - The hierarchy problem, naturalness
    - Supersymmetry as the solution

How we got to the Higgs

- Fermi constructed a very successful effective theory of the weak interaction (β decay), patterned after QED
- The (now very well tested, and non-trivial) mathematical formalism of QED follows from the requirement of gauge invariance of the Lagrangian describing matter fields (electrons, protons, etc, described by the Dirac eqn for free spin-1/2 particles).
- The requirement of gauge invariance yields a vector field A_μ with exactly the right couplings to the matter fields and exactly the right properties (Maxwell's equations).
- Yang & Mills noted that a simple extension of QED to "non-Abelian" fields (generated by sets of operators that don't commute) with gauge symmetry yielded a promising theory of the weak interactions that improved upon Fermi's and was more predictive.
- Weinberg & Salam put QED and the Y-M weak theory together into a unified EW theory which worked even better, as long as the non-Abelian fields describe massive particles (the intermediate vector bosons $W^\pm$, Z^0).
- EXCEPT that the Y-M vector fields for the weak interaction, like A_μ , must be massless, or gauge invariance is broken.
- But gauge invariance leads so naturally to successful theories that we don't want to break it!

Renormalizability

- More worrisome is that most QFTs are not renormalizable; the calculation of physical observables (like cross-sections and decay rates) beyond lowest-order in perturbation theory are ultraviolet divergent, leading to meaningless results.
- Gauge invariance is (one of the? the?) only ways to ensure a renormalizable theory, yielding finite results to all orders in perturbation theory.
- And in general, QFT has a difficult time incorporating mass; like the couplings, they “run” with energy and are ill-defined.
- Weinberg & Salam, following Higgs (who was inspired by the Ginsburg-Landau theory of superconductivity), figured that they could “trick” the theory by retaining the gauge invariance in the Lagrangian, but break it “spontaneously” in the vacuum state.

Spontaneous symmetry breaking

Spontaneous symmetry breaking in physics takes place when a system that is symmetric with respect to some symmetry group goes into a vacuum state that is not symmetric.

Examples of spontaneous symmetry breaking in physical systems:

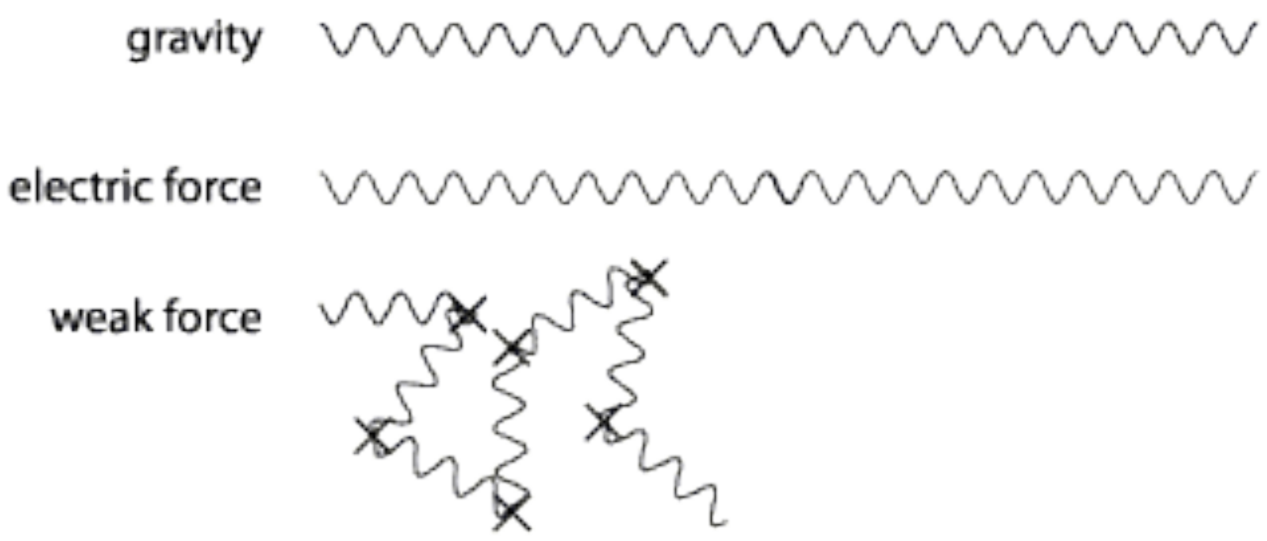
- The ferromagnet (crystalline array of classical spins that tend to align with nearest neighbors). Above the Curie temperature, the magnetization is zero, and there is spherical symmetry (isotropy). Below the Curie temperature, however, the magnetization acquires a constant nonzero value which points in a certain direction. An axial symmetry remains.
- The laws of physics are spatially invariant, but here on the surface of the Earth, we have a background gravitational field which points downwards, breaking the full rotational symmetry. Symmetry in the horizontal directions remains.
- General relativity has a Lorentz gauge symmetry, but the cosmic microwave background selects a preferred frame, as does the mean 4-velocity field defined by averaging over the velocities of the galaxies (Mach’s principle).
- Here on Earth, Galilean invariance (in the nonrelativistic approximation) is broken by the velocity field of the Earth/atmosphere, which acts as the order parameter here. This explains why people thought moving bodies tend towards rest before Galileo. We tend not to be aware of broken symmetries.

The Higgs and the Origin of Mass

- The trick is to have the masses be generated dynamically, through interaction with something like the “Higgs” field – a field that exists everywhere in space, in the vacuum.
- The weak bosons couple to this field, and its presence even in the vacuum effectively “slows down” the bosons, so they behave like they have mass.
- For similar reasons, it is believed that the quarks and leptons gain their masses through interactions with the Higgs field.
- The Higgs field is some kind of “ether” that is the same everywhere, at all times, touching everything.

The Higgs “ether”

- It fills the universe
- it doesn’t disturb gravity or electromagnetism
- it greatly disturbs the weak force and makes it short-ranged



The Higgs field is some kind of “ether” that is the same everywhere, at all times, touching everything.