ASTROPARTICLE PHYSICS

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The Course

- This is a 16 lecture Part III Minor Option.
- Tuesdays and Thursdays 10 am

- Textbooks:
- Perkins – "Particle Astrophysics"
- Bergstrom and Goobar – "Cosmology and Particle Astrophysics"
- Mukhnaov – "The Physical Foundations of Cosmology"
- Kolb and Turner – "The Early Universe"
- Tully – "Elementary Particle Physics in a Nutshell"

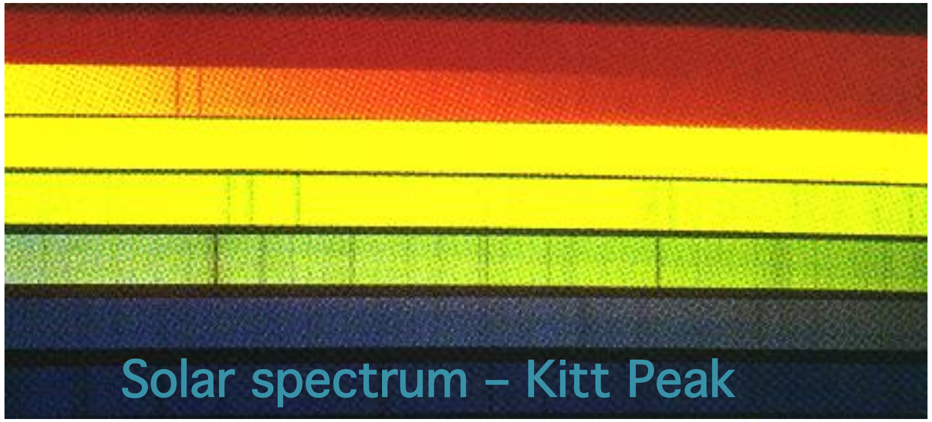
- This is a fast moving field, and we will not follow any textbook very closely.

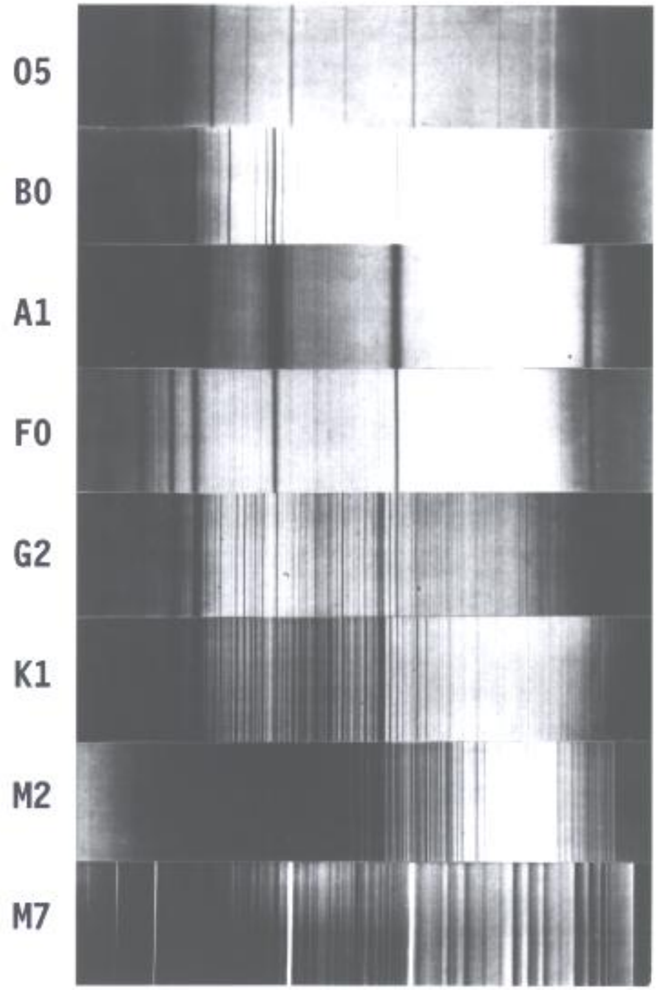
From the cosmos to the quanta

- Astroparticle physics links the observations from astrophysical sources to our measurements of sub-nuclear particles in laboratories.
- This offers a way to test hypotheses about physics taking place in regions of the Universe we can never reach (and which may not even exist any more).
- This use of data is what makes cosmology a science, and not pure speculation.
- Two historical examples…

On the subject of stars, ...We shall never be able by any means to study their chemical composition.

August Comte 1835





ζ Puppis – ionized He

ε Orionis – neutral He

Sirius - hydrogen

Canopus – calcium

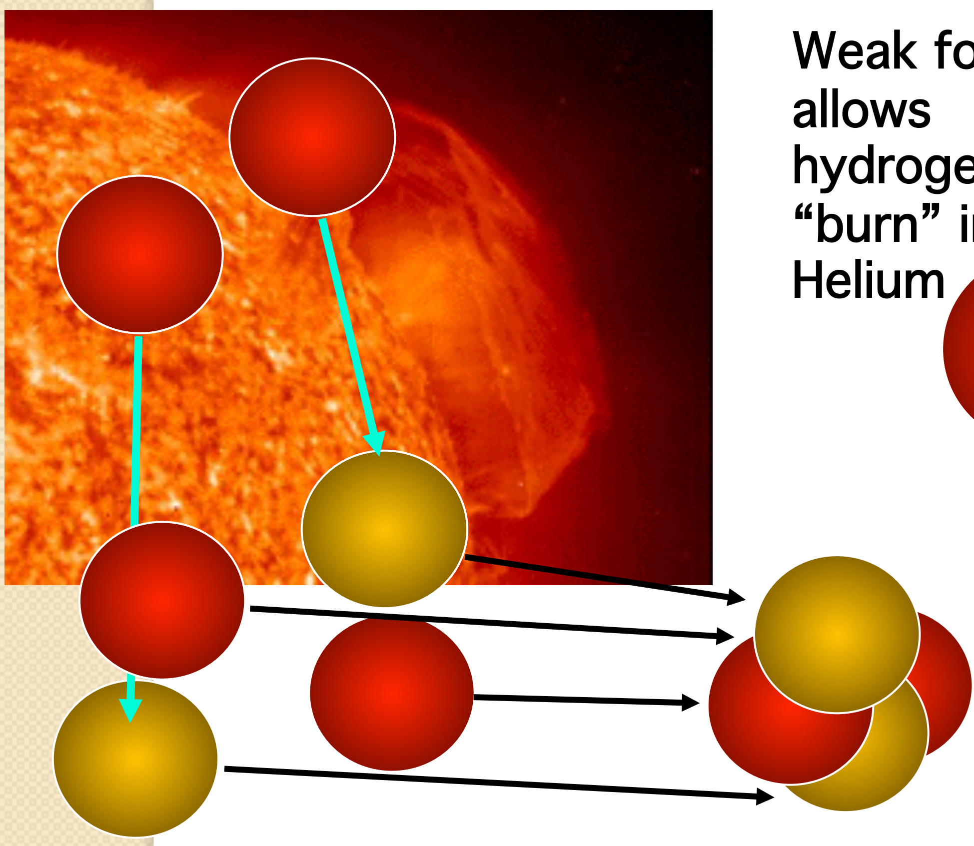
Annals of the Harvard College Observatory, vol. 23, 1901.

Mira – Titanium Oxide

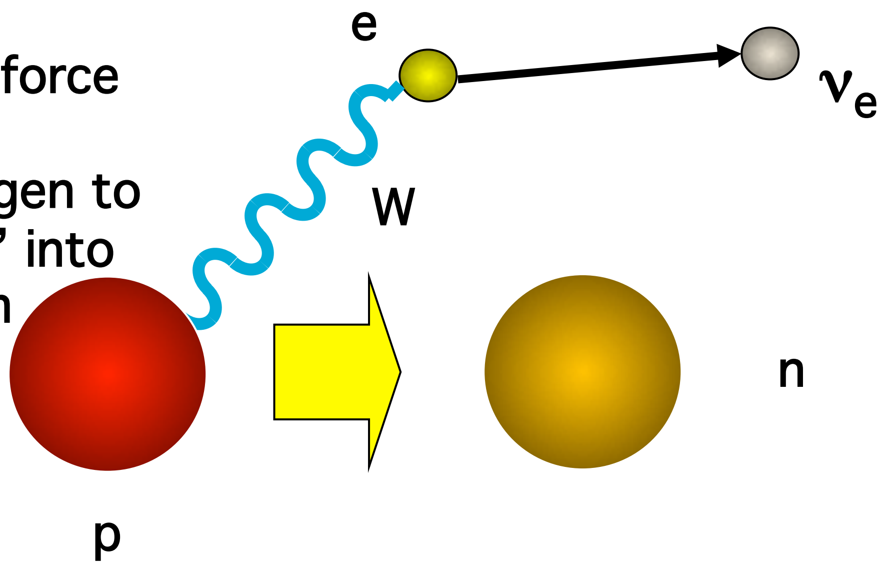
Inferred from lab measurements of spectra from elements

The Beryllium bottleneck

- BB produces hydrogen and helium from quark-gluon plasma – decay of free neutrons leaves excess of H.



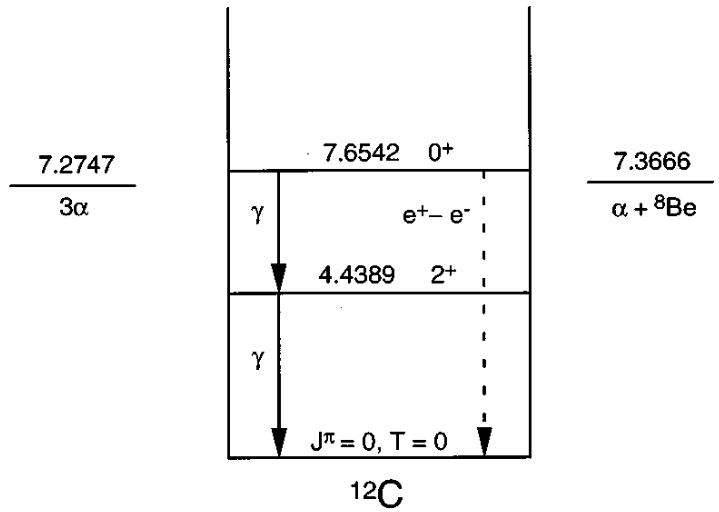
Weak force allows hydrogen to "burn" into Helium



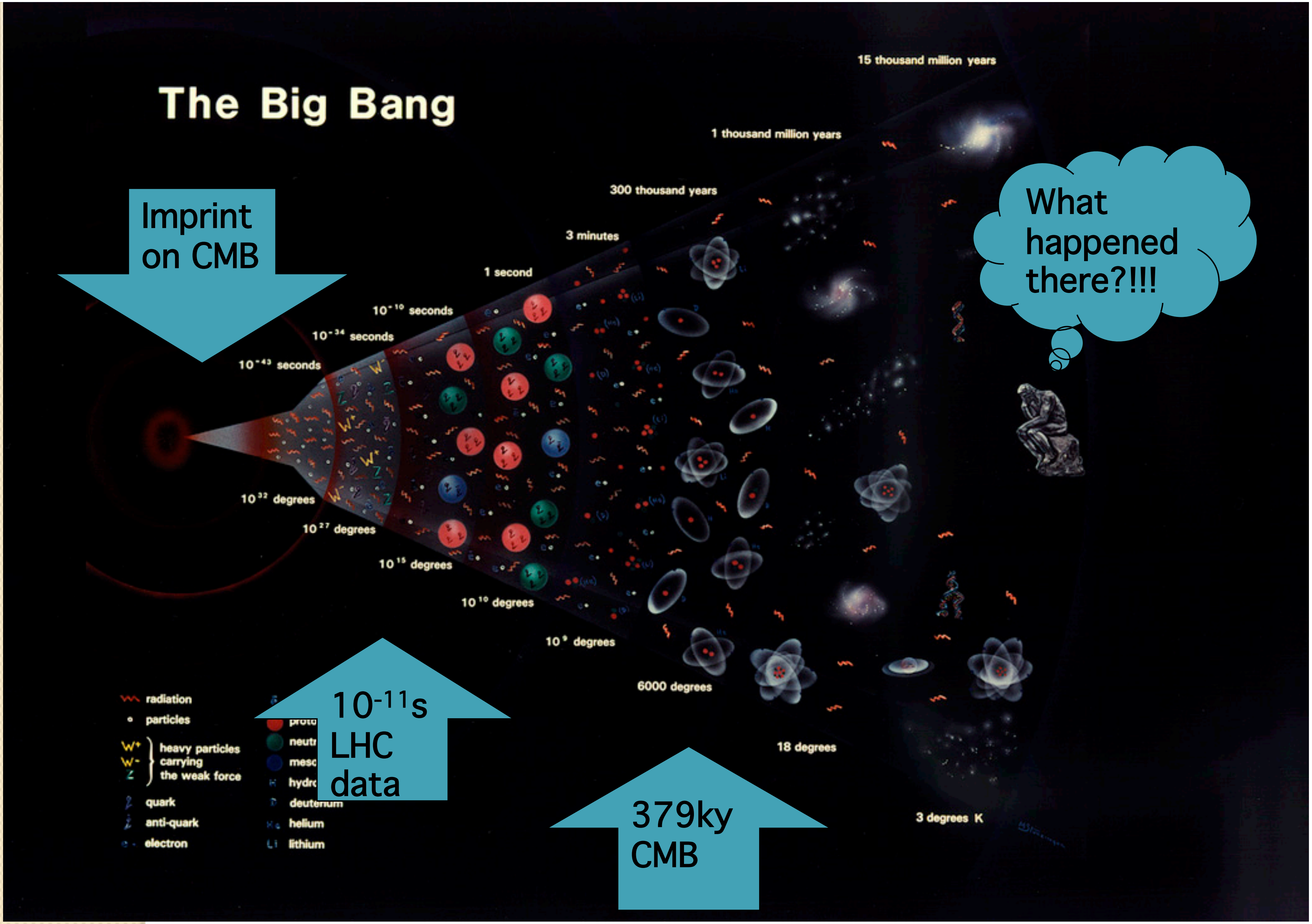
- He+p -> ^{5}Li – highly unstable
- He+He-> ^{8}Be – decays back to 2 α with lifetime of 0.97×10^{-16} s
- Path to heavier nuclei appears to be blocked!
- In stars, density is high enough for
  ^{8}Be + ^{4}He -> ^{12}C**

…but rate should be very low.

Hoyle et al, 1953, predicted existence of resonance at 7.65 MeV to enhance rate. Found experimentally with required 0^{+} quantum numbers.



Wallerstein 1997


The Big Bang
Imprint on CMB
What happened there?!!!
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
deuterium
helium
lithium
10^{-11}s LHC data
379ky CMB

Data sources for the early Universe

- Can observe light from sky back to 379,000 years after the Big Bang – before this the temperature of the Universe was too high for neutral atoms to survive, and the sky would have appeared like a hot flame.
- Light scattered continuously from the free electrons and nuclei.
- The cosmic microwave background (CMB) is the "surface of last scattering" for light, and the furthest back we can ever see using EM radiation
- We could reach further back by observing relic neutrinos, which decoupled earlier, but the observation is very challenging

- Previous accelerator measurements allow us to reach energy scales of 100 GeV, corresponding to times of 100 ps after the BB. There is very little uncertainty about particle content or dynamics below this scale (with some interesting exceptions).

- The LHC is reaching energies of a few TeV => a few ps after BB.
- The CMB still stores the imprint of earlier times.

The Standard Cosmology

- ΛCDM model appears to fit all data at present. Requires the Universe to contain:
  - 4% visible matter (stars, galaxies etc)
  - 22% cold dark matter (CDM)
  - 74% dark energy

and there must be a cosmological constant or its equivalent (Λ)

=> We do not understand 96% of the content of the Universe, or its dynamics!

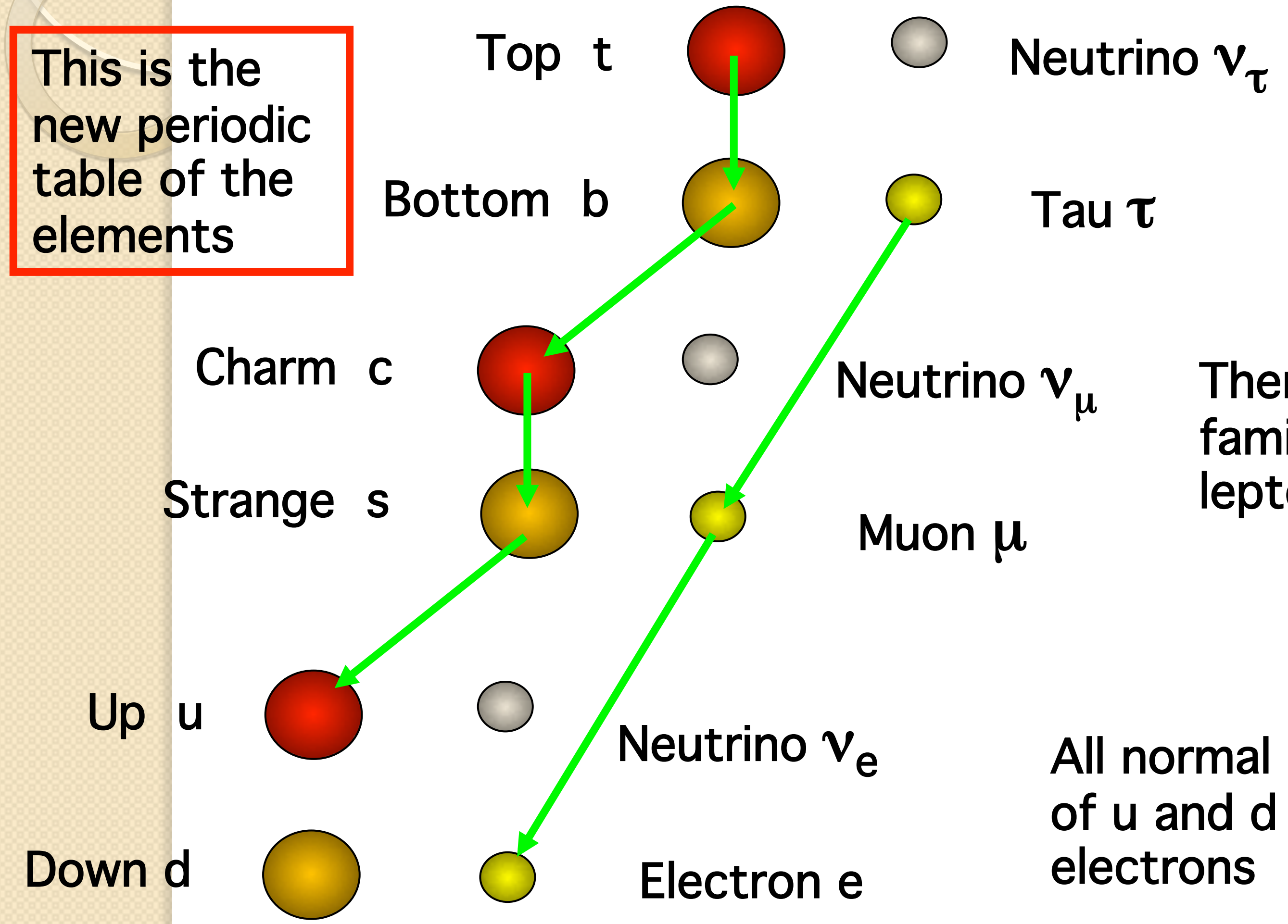
Cosmological problems

- Why is the Universe so uniform?
- Why is space-time flat?
- Why are galaxies/clusters rotating too fast to be bound by gravity?
- Why is the Universal expansion accelerating?
- How did Big Bang start?

These issues are addressed in ΛCDM by a combination of dark matter and dark energy, and an early era of inflation.

Standard Model of Particle Physics

This is the new periodic table of the elements

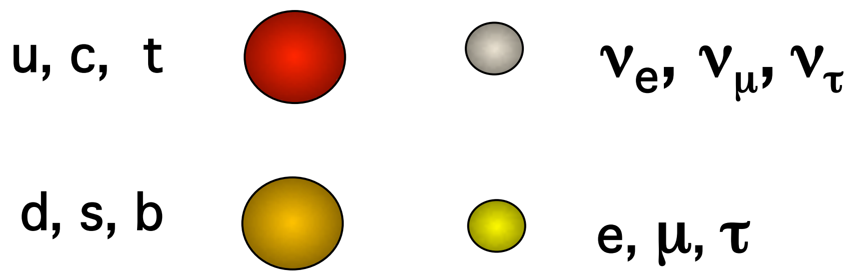


The heavier particles decay to lighter ones

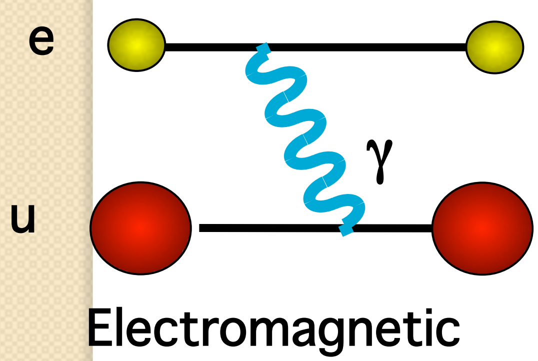
There are two other families of quarks and leptons, which are heavier

All normal matter consists of u and d quarks and electrons

The Standard Model

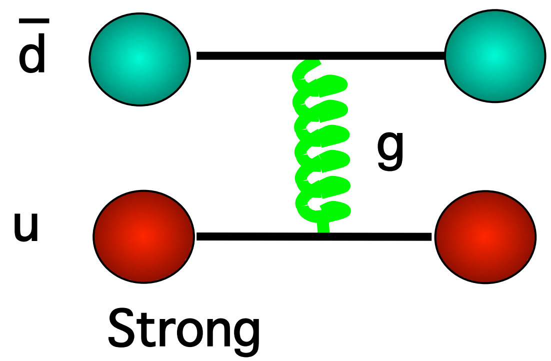


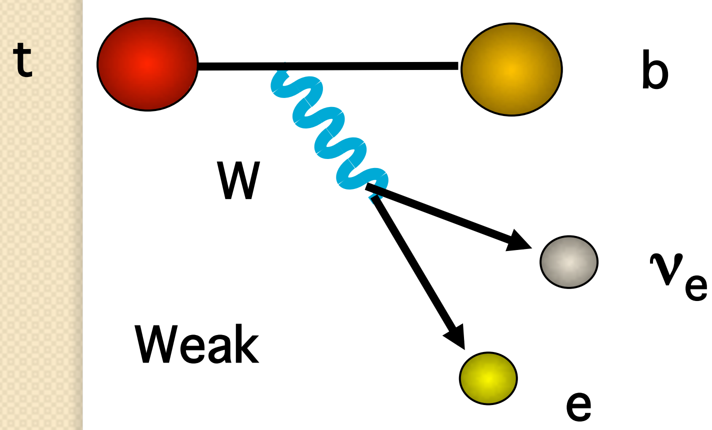
3 families of quarks and leptons

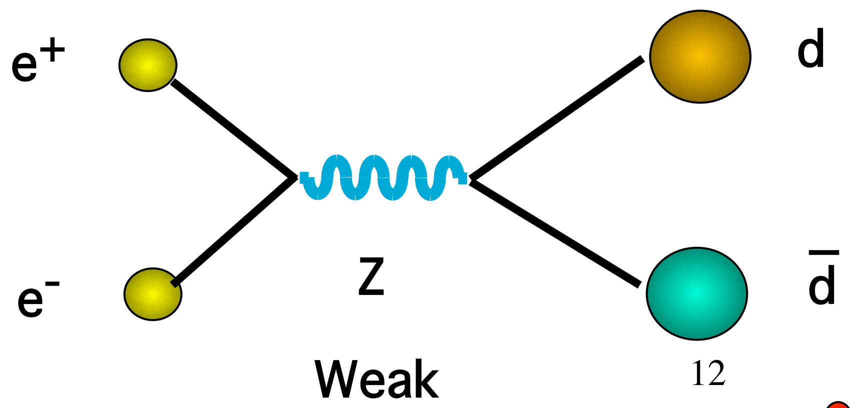


3 forces

(plus gravity)







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Gauge theories

QED: consider a free, non-interacting electron with wavefunction ψ

U is spinor

$$\psi = U\exp(-i(Et - \vec{p}.\vec{x}))$$
$$= U\exp(-ip_\mu x^\mu)$$

ψ satisfies the Dirac equation:

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

with the Dirac Lagrangian:

Kinetic

Mass

$$L = i\hbar c\overline{\psi}\gamma^\mu \partial_\mu \psi - mc^2\overline{\psi}\psi$$

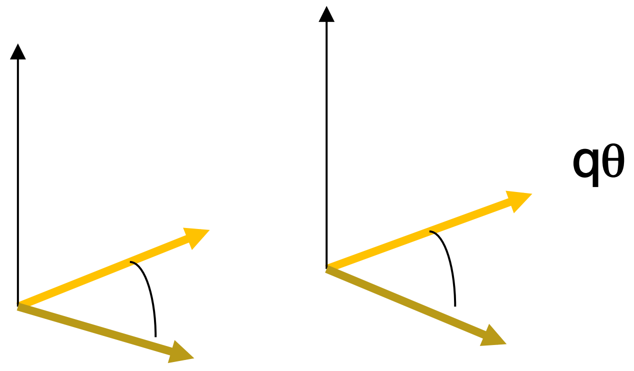
Global transformation: rotate phase of ψ by -qθ/hc (where q is the electron charge) at every point in space time

$$\psi \rightarrow e^{-iq\theta/\hbar c}\psi$$

Global U(1)

$\bar{\psi}\psi$ and $\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi$ unchanged

2 electrons in different places – same rotation of phase

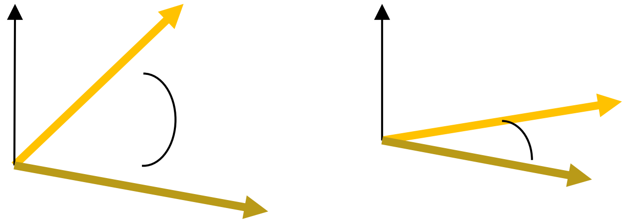


No change to any observable

Dirac Lagrangian is invariant under global U(1) transformations.

Try LOCAL U(1): rotate by a different amount -qθ(x)/hc at each point

$$\psi \rightarrow e^{-iq\theta(x)/\hbar c}\psi \qquad \text{Local U(1)}$$



qθ(x) Different rotations of phases

Now we expect an observable difference since we have changed the E,p state of the electrons by different amounts.

$$\partial_\mu \psi \rightarrow \partial_\mu \left(e^{-iq\theta(x)/\hbar c}\psi\right)$$

$$= e^{-iq\theta(x)/\hbar c}\partial_\mu \psi - i\frac{q}{\hbar c}(\partial_\mu \theta)e^{-iq\theta(x)/\hbar c}\psi$$

$$= e^{-iq\theta(x)/\hbar c}\left[\partial_\mu \psi - i\frac{q}{\hbar c}(\partial_\mu \theta)\right]\psi$$

$$\overline{\psi}\gamma^\mu \partial_\mu \psi \rightarrow \overline{\psi}\gamma^\mu \partial_\mu \psi - i\frac{q}{\hbar c}(\partial_\mu \theta)\overline{\psi}\gamma^\mu \psi$$

$$L \rightarrow L + q(\partial_\mu \theta)\overline{\psi}\gamma^\mu \psi$$

Hence Dirac Lagrangian for a free particle is NOT invariant under local U(1) transformations.

What if we impose invariance?
We will need a new term in the Lagrangian to cancel the unwanted term from $\partial_\mu \theta$.
Introduce a new field A_μ into the original Lagrangian and insist that

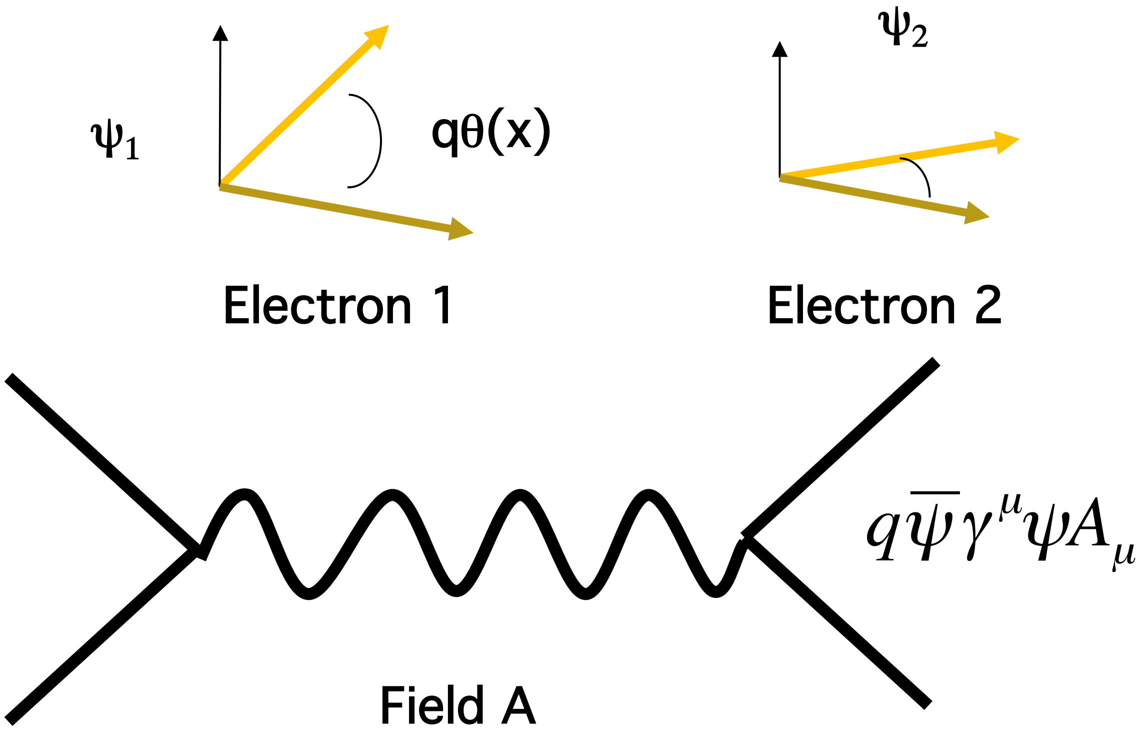
$$A_\mu \rightarrow A_\mu - \partial_\mu \theta$$

under local U(1).
Now L is invariant, as required:

$$L = [i\hbar c\overline{\psi}\gamma^\mu \partial_\mu \psi - mc^2 \overline{\psi}\psi] + q\overline{\psi}\gamma^\mu \psi A_\mu$$

$$L \rightarrow L + q(\partial_\mu \theta)\overline{\psi}\gamma^\mu \psi - q(\partial_\mu \theta)\overline{\psi}\gamma^\mu \psi$$
$$= L$$

Physical interpretation:



The phase of an electron specifies its E,p.
Local changes in phase ⇔ changes in E,p
Field A carries the E,p changes around: Virtual photons
A_μ is the photon wavefunction
Photon must carry changes to all x: Photons are massless
q must not vary in time/space: Conserved electric charge

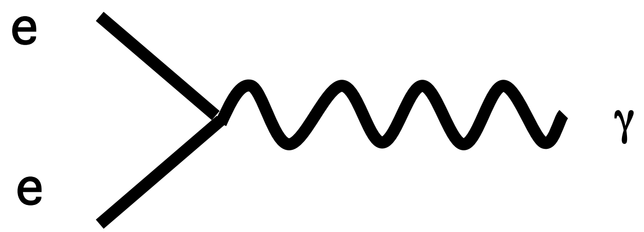
Look at the QED Lagrangian:

$$L = i\hbar c\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi$$ Kinetic term

$$-mc^{2}\overline{\psi}\psi$$ Mass term

$$+q\overline{\psi}\gamma^{\mu}\psi A_{\mu}$$ Interaction term

Interaction term specifies that field interacts with particles according to their quantum number q=electric charge; ie a vertex exists like



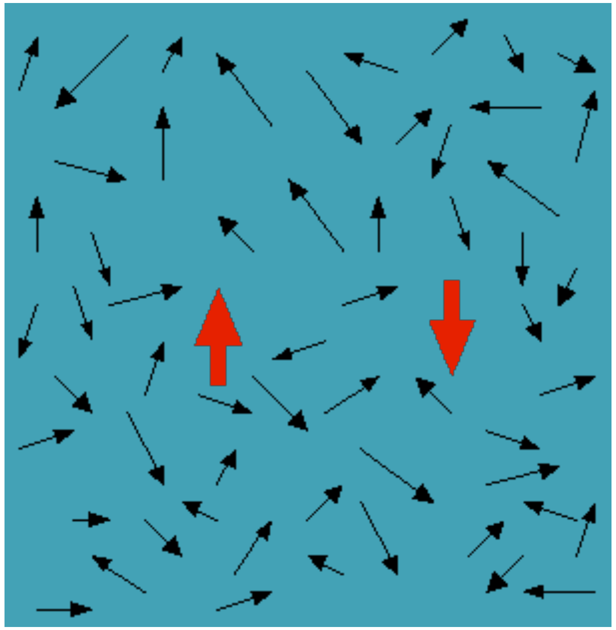
$q\overline{\psi}\gamma^{\mu}\psi$ gives the current density

Get free photons: $-\frac{1}{16}F^{\mu\nu}F_{\mu\nu}$ where $F^{\mu\nu} = \partial^{\mu}A^{\nu} - \partial_{\nu}A_{\mu}$

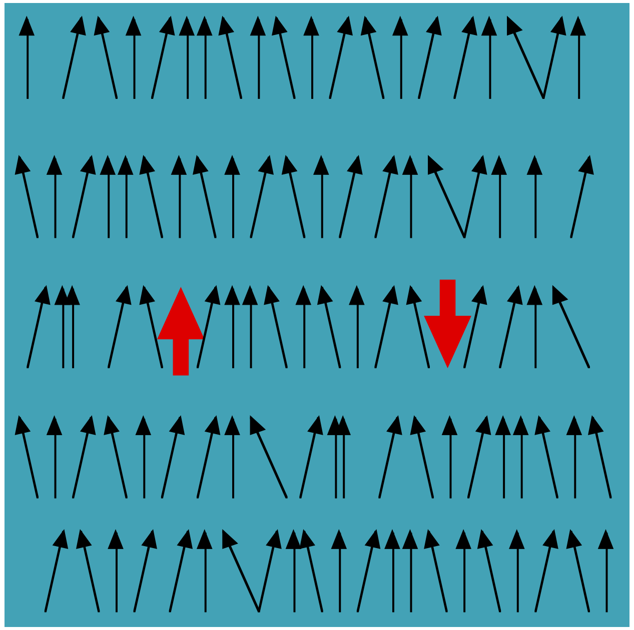
Spontaneous Symmetry Breaking and the Higgs

Magnetic dipoles in a ferromagnet

High temperature



Low temperature



Field symmetric

Test dipoles have same energy

Field along unique direction

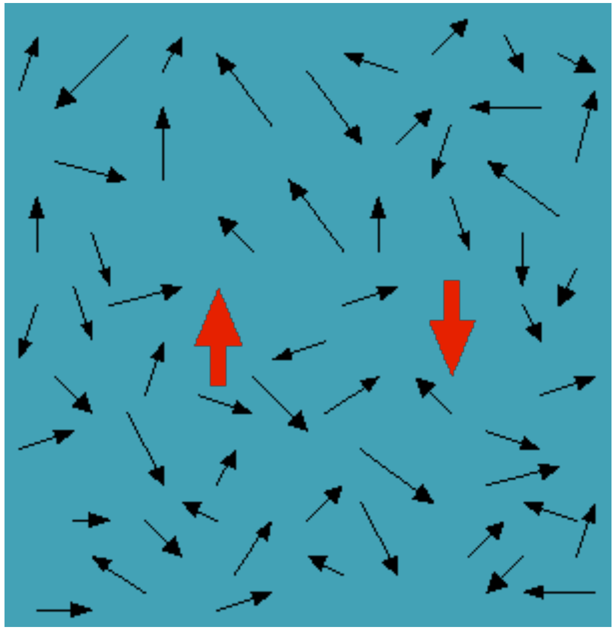
Test dipoles have different energies

The Higgs

Need standing Higgs field in vacuum:
Non-zero Vacuum Expectation Value

Particles in Higgs field

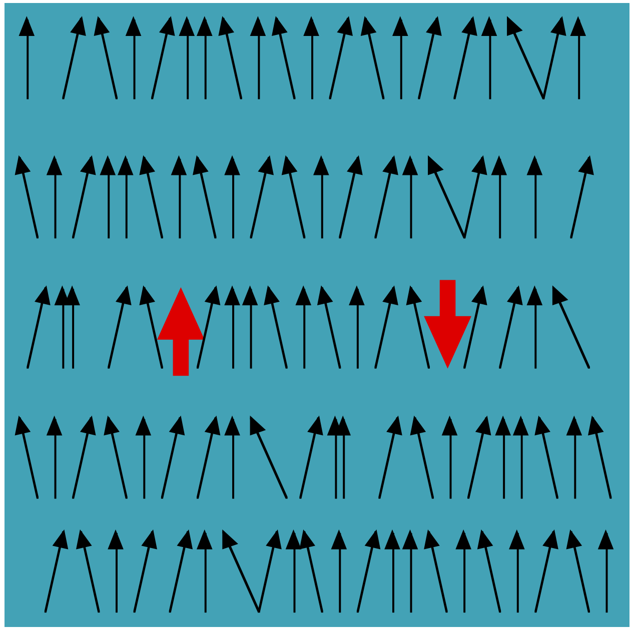
High temperature



Field symmetric

SU(2) states have same energy

Low temperature



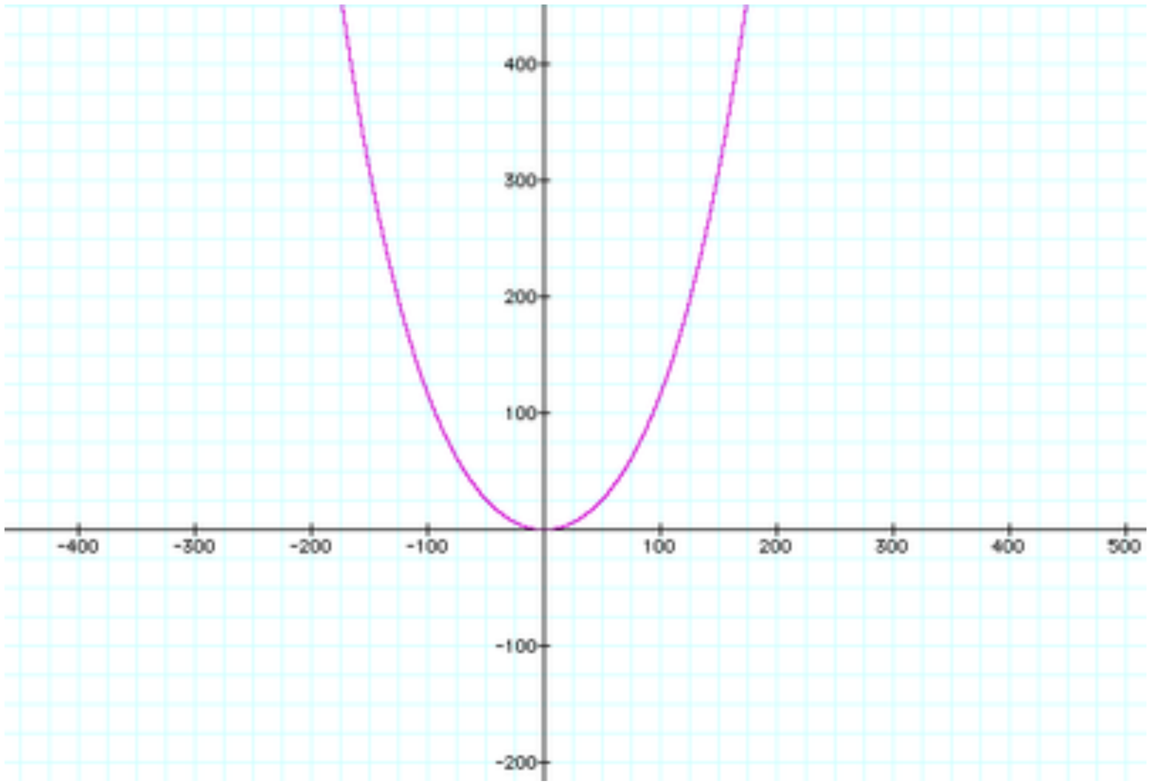
Field along unique direction

SU(2) states have different energies

The Higgs potential

The potential associated with the Higgs field ϕ is given by

$$V = -\frac{1}{2}\mu^2 |\phi|^2 + \frac{1}{4}\lambda^2 |\phi|^4$$



For a -ve μ^2 term, minimum gives non-zero

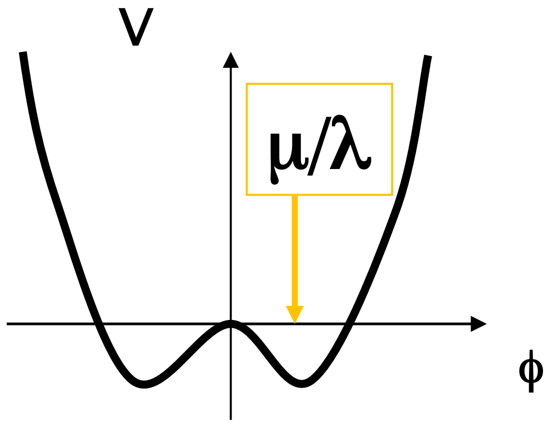
The Higgs Lagrangian

$$L = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) + \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda^2\phi^4$$

Mass term has wrong sign, compared to Klein-Gordon:

$$L_{KG} = \frac{1}{2}\left(\partial_\mu \phi\right)\left(\partial^\mu \phi\right) - \frac{1}{2}\left(\frac{mc}{\hbar}\right)^2 \phi^2$$

But minimum of potential is at $\phi = \pm\mu/\lambda$
Must expand about true minimum for pertubation theory.



Define new field H=$\phi-\mu/\lambda$:
Higgs acquires a mass because of the broken symmetry.

Recompute Lagrangian in terms of H

$$-\frac{1}{4}\lambda^2\left(H+\frac{\mu}{\lambda}\right)^4$$

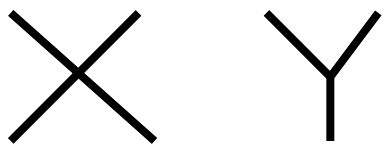
$$=-\frac{1}{4}\lambda^2\left(H^4+4\frac{\mu}{\lambda}H^3+6\frac{\mu^2}{\lambda^2}H^2+4\frac{\mu^3}{\lambda^3}H+\frac{\mu^4}{\lambda^4}\right)$$

$$=-\frac{1}{4}\lambda^2H^4-\mu\lambda H^3-\frac{3}{2}\mu^2H^2-\frac{\mu^3}{\lambda}H-\frac{1}{4}\frac{\mu^4}{\lambda^2}$$

$$\frac{1}{2}\mu^2\left(H+\frac{\mu}{\lambda}\right)^2=\frac{1}{2}\mu^2H^2+\frac{\mu^3}{\lambda}H+\frac{\mu^4}{2\lambda^2}$$

$$L=\frac{1}{2}(\partial_\mu H)(\partial^\mu H)-\mu^2H^2-\frac{1}{4}\lambda^2H^4-\mu\lambda H^3+\frac{1}{4}\left(\frac{\mu^4}{\lambda^2}\right)$$

$$\boxed{\begin{aligned}\mu^2&=\frac{1}{2}(m_Hc/\hbar)^2\\ m_H&=\sqrt{2}\mu\hbar/c\end{aligned}}$$



Constant

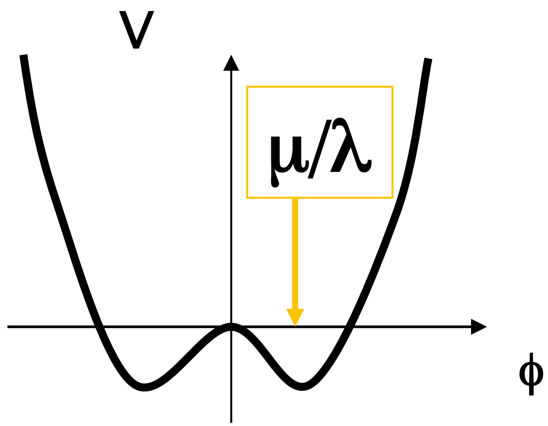
Higgs self-couplings

Scalar fields in cosmology

Field strength given by vacuum Expectation value – VEV

Low T – Higgs VEV=μ/λ = 174 GeV

High T – Higgs VEV = 0



Phase change when energy drops below peak of potential.

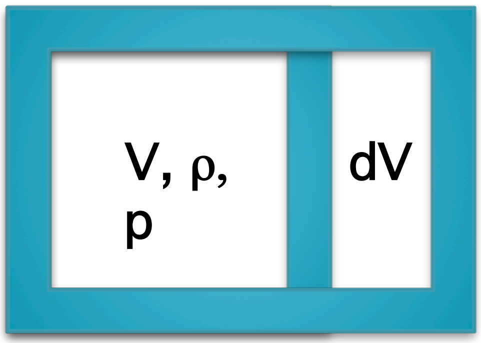
VEV means that energy is stored in the vacuum, and must be taken into account in the energy budget of the Universe.

$$m_H = \sqrt{2}\mu = 126 \text{ GeV}$$

$$\mu = 89 \text{ GeV}$$

$$\lambda = 0.47 \quad \Rightarrow \quad \frac{1}{4}\left(\frac{\mu^4}{\lambda^2}\right) = 7.1\times 10^7 \text{ GeV}^4 = 8.9\times 10^9 \text{GeV/fm}^3$$

Since field has a constant energy per unit volume, it takes work to expand a region of space:



$$\rho = U/V$$

$$dU = \rho\, dV$$

$$dW = -p\, dV \quad \Rightarrow \quad p = -\rho$$

We shall see later that this is the form of field needed to drive rapid expansion of the Universe -> “inflation”:

Matter/fields with positive pressure, generate a gravitational field which causes the Universe to collapse.

Fields with negative pressure generate a gravitational repulsion: energy required comes from the gravitational field (-PE).
-can cause the early Universe to expand exponentially
-can cause acceleration of expansion: dark energy.

Problems in the Standard Model

- 19 free parameters: m_e, m_μ, m_τ , m_u, m_d, m_s, m_c, m_b, $m_{t,}$ e, G_F, θ_W, α_s, A, λ, ρ, η, m_H, θ_{CP}
- Why SU(3)xSU(2)xU(1)?
- Why 3 generations?
- Why Q_e=Q_p?
- Is the Higgs mechanism responsible for masses?
- What is the origin of CP violation?
- Are B and L really conserved? (no underlying symmetry)
- What is dark matter?
- How can we include gravity?
- The Hierarchy problem….

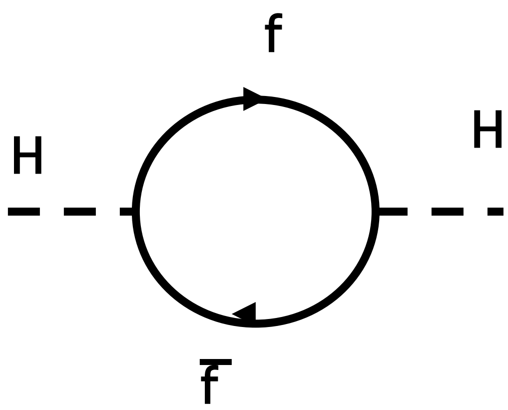
The Hierarchy problem

First order prediction of m_H is $m_H = \sqrt{2}\mu\hbar/c$

But Higgs couples to fermions as

$$-\lambda_f H\bar{f}f$$

Need to compute contribution of every fermion loop diagram.

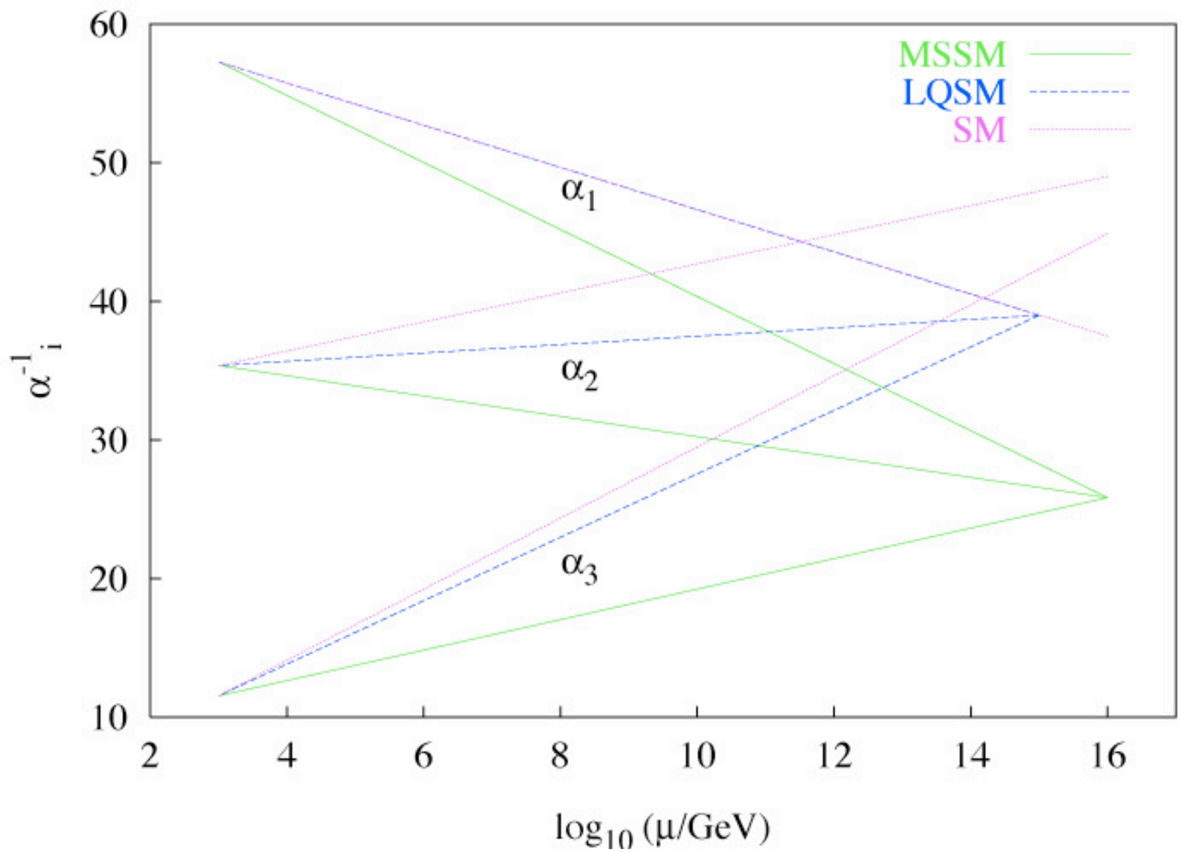


Integral over all possible momentum states is divergent, since there is no limit to the momentum k which can circulate in the loop - Higgs mass is infinite!

Conclude new physics is needed to keep Higgs mass in the allowed range <1 TeV: will affect cosmology at early times

Grand Unification

Extrapolate coupling constants to high energy: no unification in SM, but OK in supersymmetric models and leptoquark model



Conclude: grand unification is possible in most models with new physics near 1 TeV.

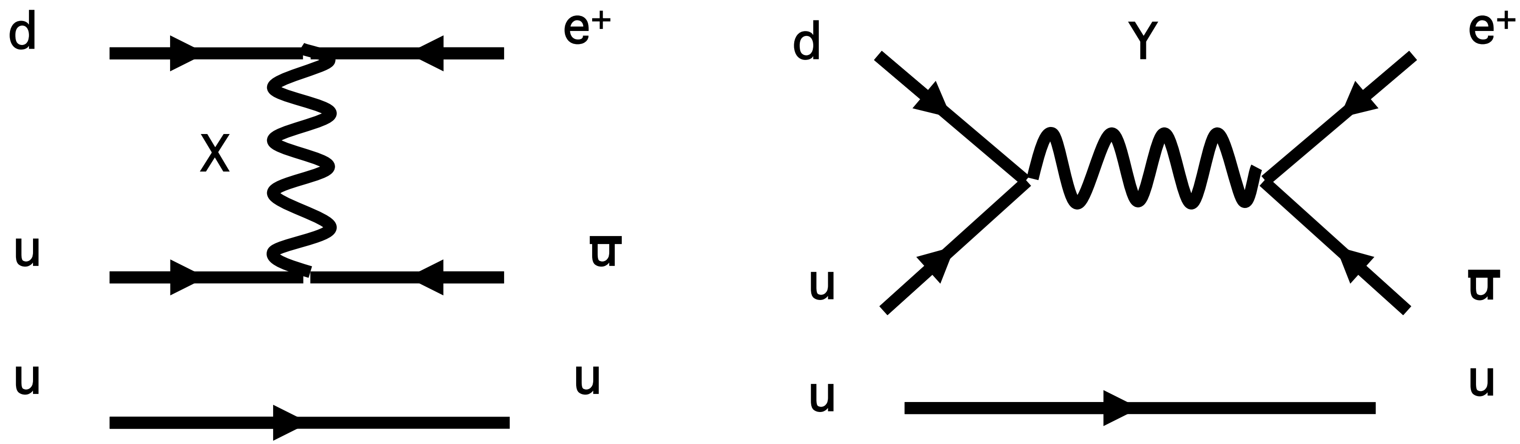
SU(5) is the smallest group which can contain $SU(2)_L x(U1) x SU(3)$

It is possible to get all the SM states into an SU(5) 10-plet and 5-plet, using only left-handed states:

$$\begin{array}{cc} \begin{bmatrix} \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \\ e^- \\ \nu_e \end{bmatrix} & \begin{array}{c} g \\ \\ X \\ \\ W \end{array} \end{array} \qquad \begin{bmatrix} 0 & \bar{u}_b & \bar{u}_g & u_r & d_r \\ -\bar{u}_b & 0 & \bar{u}_r & u_g & d_g \\ -\bar{u}_g & -\bar{u}_r & 0 & u_b & d_b \\ -u_r & -u_g & -u_b & 0 & e^+ \\ -d_r & -d_g & -d_b & -e^+ & 0 \end{bmatrix}$$

Apply local SU(5) gauge symmetry - get 24 gauge bosons: γ, W^+, W^-, Z, 8 gluons and 12 X,Y bosons mediating quark-lepton transitions.

These violate baryon and lepton number: needed for baryogenesis



X and Y bosons mediate proton decay. Calculate proton lifetime:

M_X=3x10^{14} GeV α_{Unif}=0.04 => τ =10^{29} years

$$\tau \propto \frac{\alpha_{unif}^2 m_p^5}{M_X^4}$$

m_p^5 from density of final states (3 body decay)

α_{unif}^2 from X - q coupling

M_X^4 from X propagator

- Higgs mass instability and proton lifetime are serious problems for BSM models.
- Supersymmetry cancels Higgs loop diagrams, and can produce longer proton lifetimes. Also offers DM candiates and large CP-violation effects needed for baryogenesis – but many parameters.
- Extra space dimensions can fix Higgs mass , and unify with gravity.
- Theorists have developed all of these, and SUSY-GUTs and superstrings.

Summary

- Astronomy and particle physics give complementary information:
  - Particle data provides secure foundation for extrapolation to early times
  - Astronomy data indicates that we still do not understand much of the content of the Universe
  - Scalar fields like the Higgs can have a large impact on cosmology.

Next: review of standard cosmology.