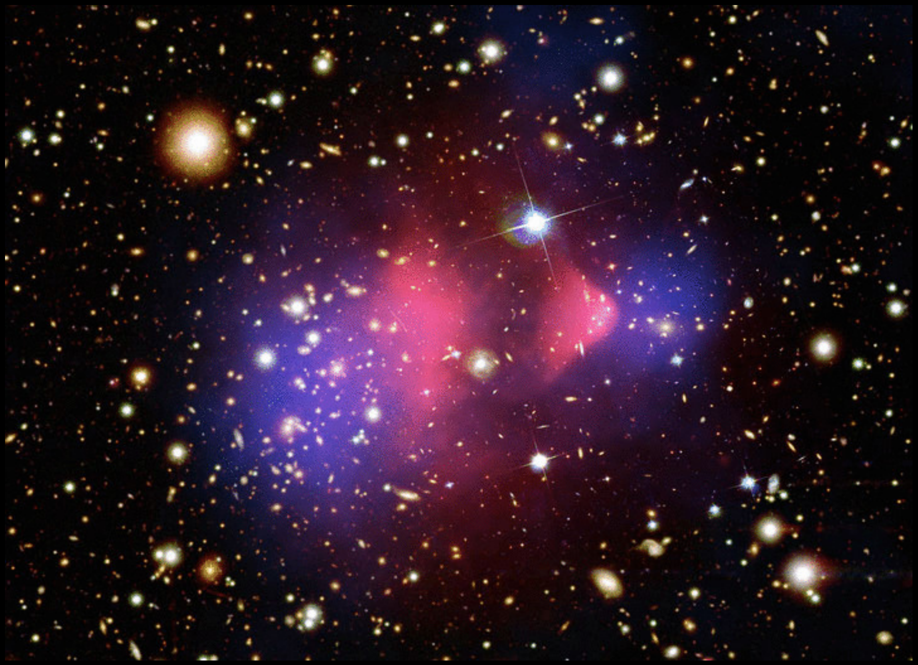
The Standard Model and Beyond

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory



SULI Lecture, Physics Department, BNL

June 15, 2021

Brookhaven National Laboratory

. . . I am induced by many reasons to suspect that they [phenomena of nature] may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other, and cohere in regular figures, or are repelled and recede from each other; which forces being unknown, philosophers have hitherto attempted the search of nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of philosophy.

Sir Isaac Newton (1643-1727)

(Preface to Principia)

$\hbar \approx 1.05 \times 10^{-34}$ J s ; $c \approx 3.0 \times 10^{8}$ m/s

$\hbar = c = 1$ in what follows

Mass and Energy measured in eV

Length $\leftrightarrow$ 1/Mass

GeV (Giga eV) $= 10^{9}$ eV

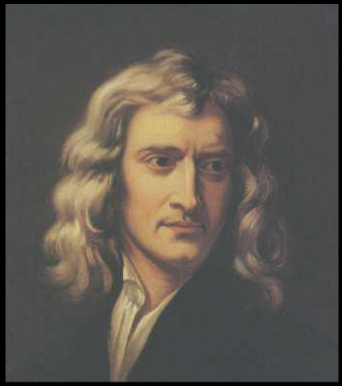
proton mass ≈ 1 GeV

TeV (Tera eV) $= 10^{12}$ eV

Everyday life:

Gravity and Electromagnetism (EM)

Falling Apple: Gravity



Well-described by Newtonian gravity

State of the Art: General relativity (GR)

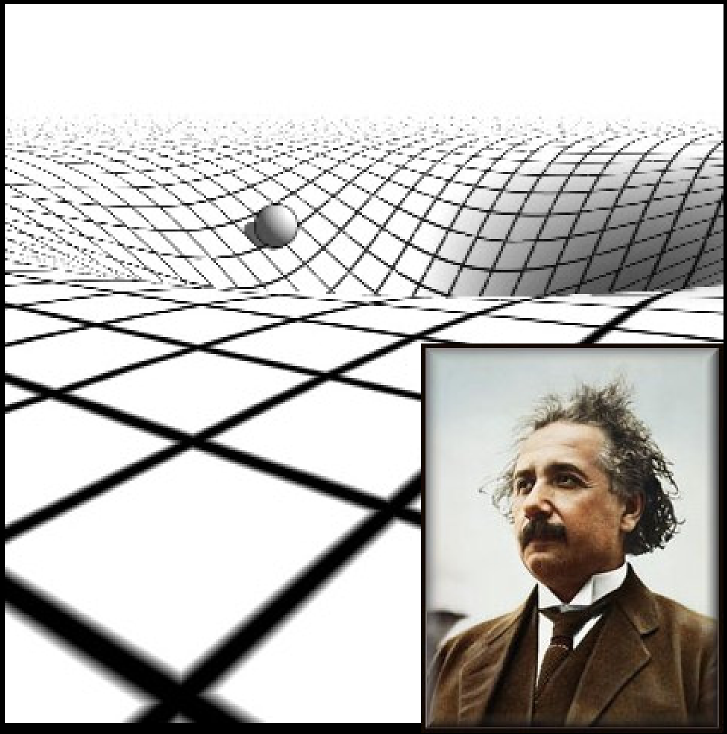
- Spacetime curved by matter/energy.

Sun

- Gravitational Force → Geodesic.

Earth's Orbit

- Basis of modern cosmology.



Einstein's equations:

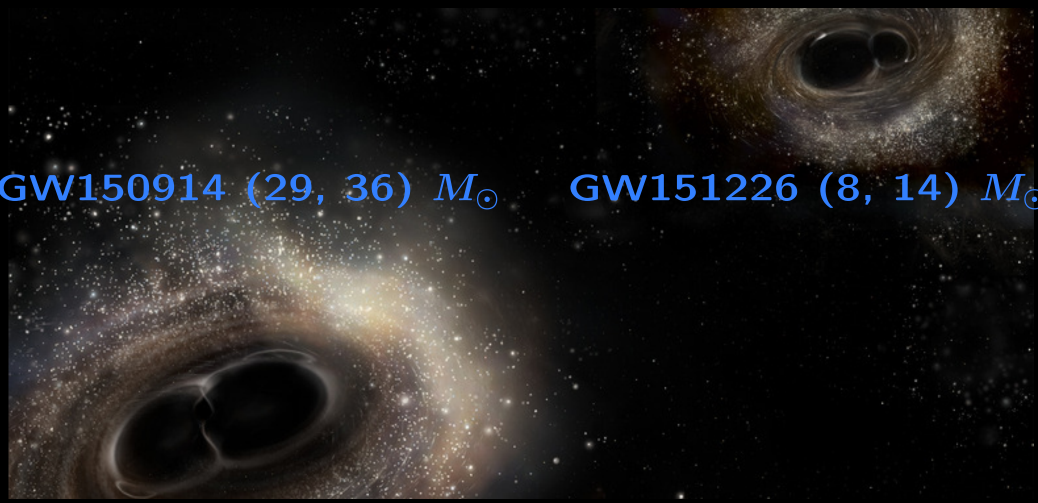
Curvature $\mathcal{G}_{\mu\nu} = 8\,\pi\,G_N\,\mathcal{T}_{\mu\nu}$ Energy Distribution

G_N Newton's constant, $\mu, \nu = 0, 1, 2, 3$ (spacetime).

⋆ *Detection of Gravitational Waves* ⋆

- Directly confirmed a long-standing ($\sim$ 100 year) GR prediction

- Manifestation of the dynamical nature of spacetime



(SXS Project)

- Outstanding experimental achievement: measured strain (distance variation) $\sim 10^{-21}$! (highly sophisticated laser interferometry)

- 2017 Nobel Prize in Physics: Barish, Thorne, and Weiss

Shadow of M87*, Event Horizon Telescope

Mass: $\sim$ 6.5 Billion Solar Masses ; Distance: $\sim$ 55 Million Light Years

Results released April 10, 2019

Apple on the ground: Quantum Mechanics and EM

- Atoms in apple and ground: Electron *cloud* interactions stop the fall.
  - Pauli's exclusion principle for electrons; EM: repulsion.
- Atom: Nucleus (p and n) and electrons; Quantum Mechanics.
- Nuclear forces: weak and strong, not everyday, microscopic.
- Weak and EM forces $\rightarrow$ Unified Electroweak Theory.

Summed up in the Standard Model of particle physics.

The Standard Model (SM):

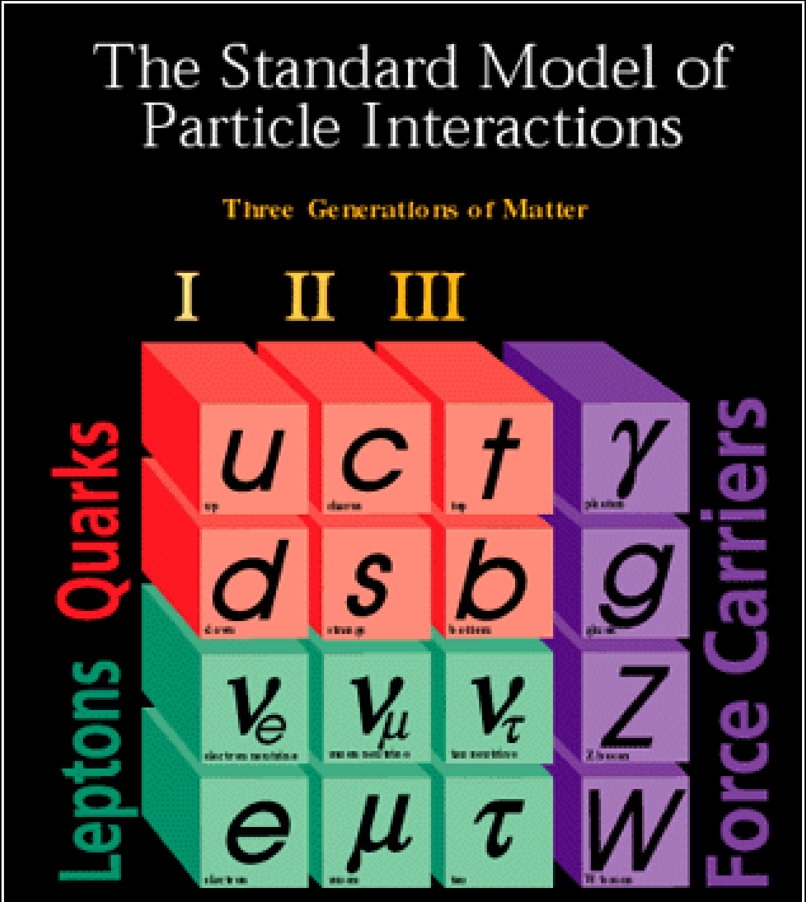
Most precise description of microscopic physics

- **Gauge symmetry:** $SU(3)(\text{strong}) \times SU(2) \times U(1)(\text{electroweak})$

- **Elementary fermions, spin-1/2***

Quarks $(+2/3, -1/3)$: Strong interactions

Leptons $(0, -1)$: No strong interactions



(Pre 2012)

- **Gauge Fields, spin-1**

Force mediators, generalized photons

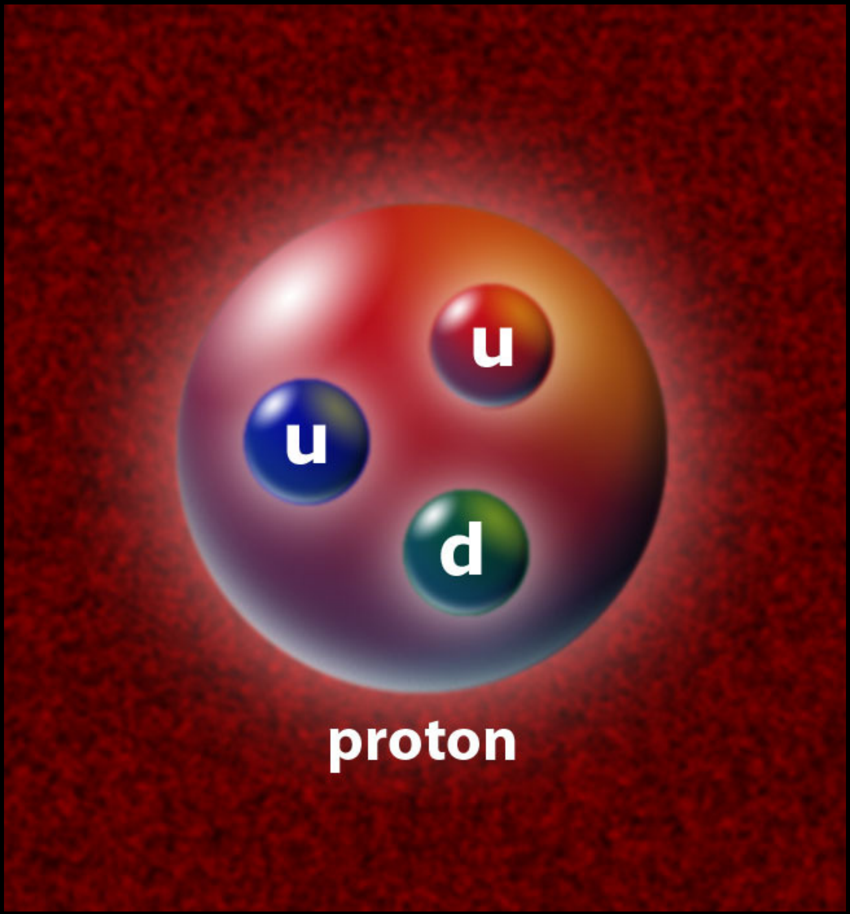
* Spin: intrinsic angular momentum (quantum mechanics)

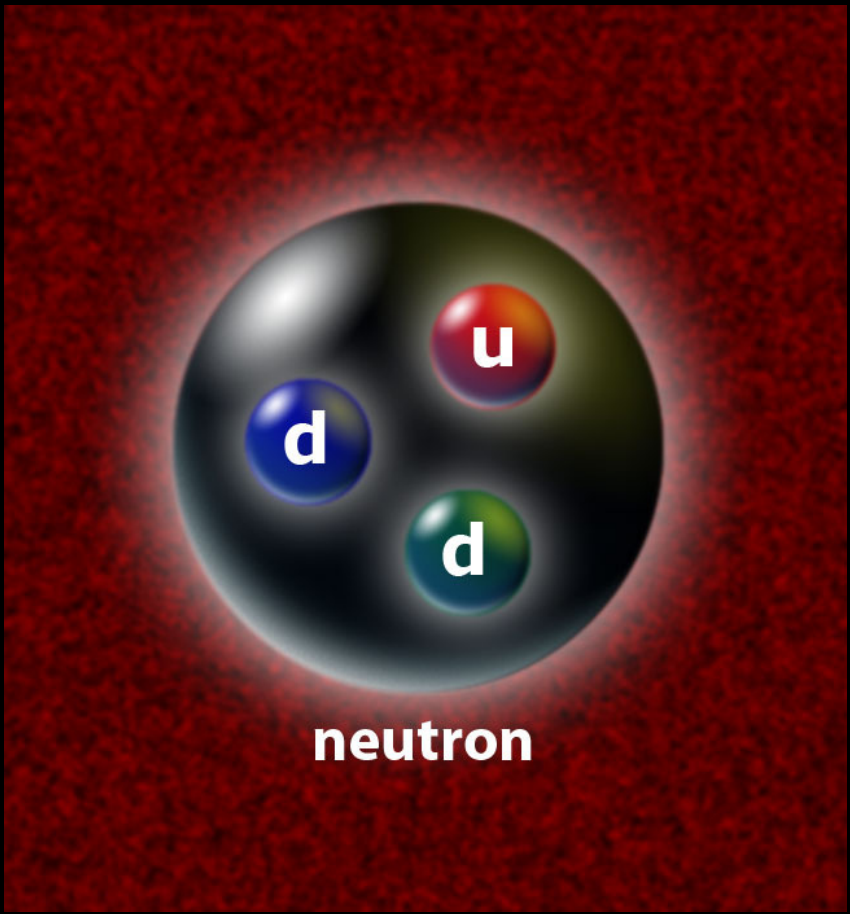
Strong Interactions [$SU(3)$ (QCD)]:

QCD: Quantum Chromodynamics

- **Short-ranged, confined to nuclear distances $\sim 10^{-15}$m**

- Gluons (g) bind quarks into hadrons (*hadros*: Greek for "bulky"):
p, n, π^0 ($\bar{q}q$),. . .



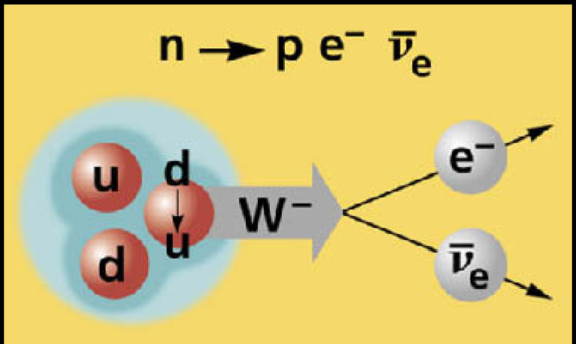


Electroweak Interactions [$SU(2)_L \times U(1)_Y$]:

- Spontaneously broken to EM

$\Rightarrow$ Massive $W^{\pm}\,(80.4 \text{ GeV}/c^2),\ Z^0\,(91.2 \text{ GeV}/c^2)$

Short-ranged: $\Delta x \sim c\,\Delta t \sim c \times \frac{\hbar}{mc^2} \sim 10^{-18}$ m (energy-time uncertainty)



Q: Why are there stable neutrons in atomic nuclei?

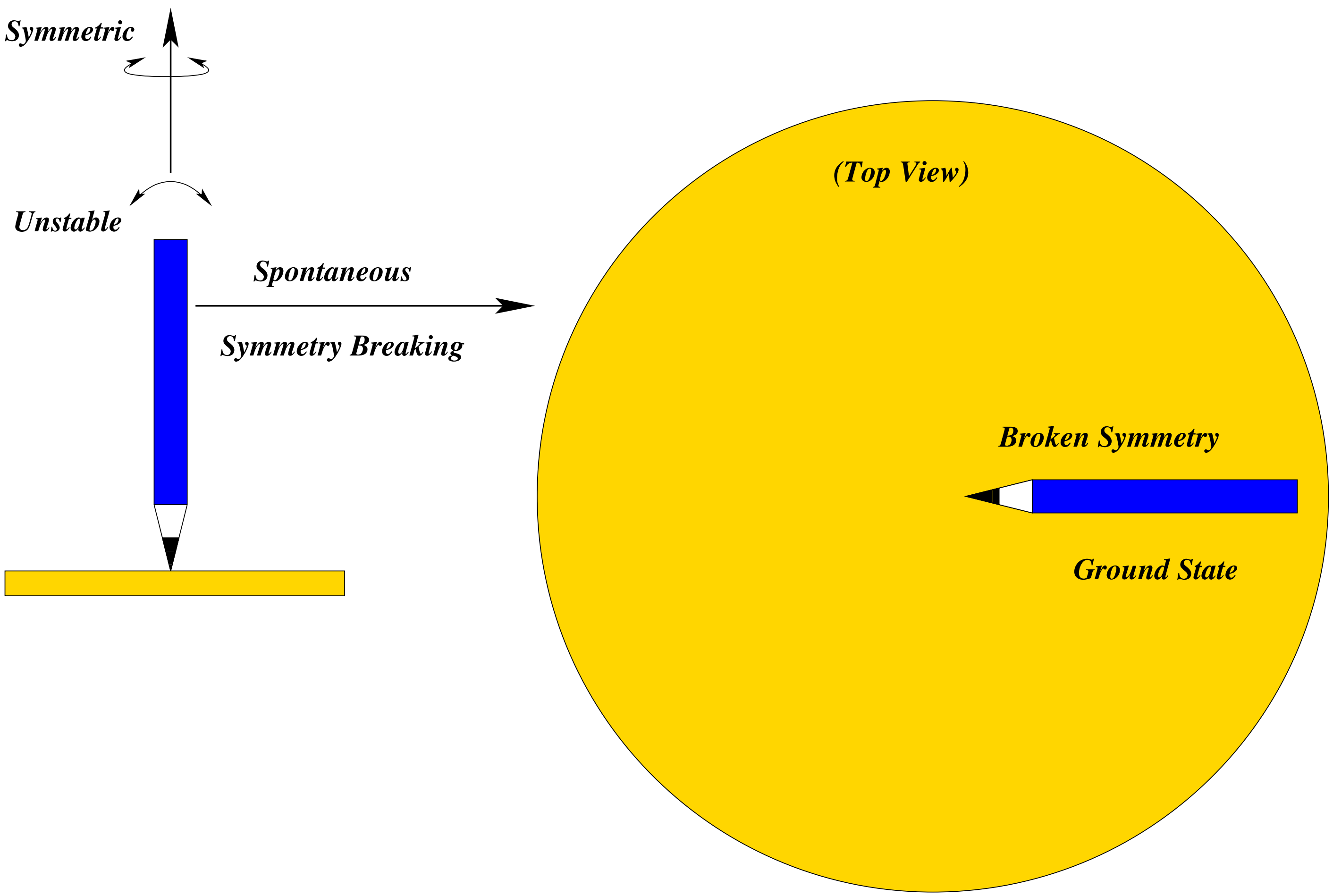
- EM: $U(1)_{EM}$ (QED)

Massless photon, γ, long-ranged

Tabletop Spontaneous Symmetry Breaking

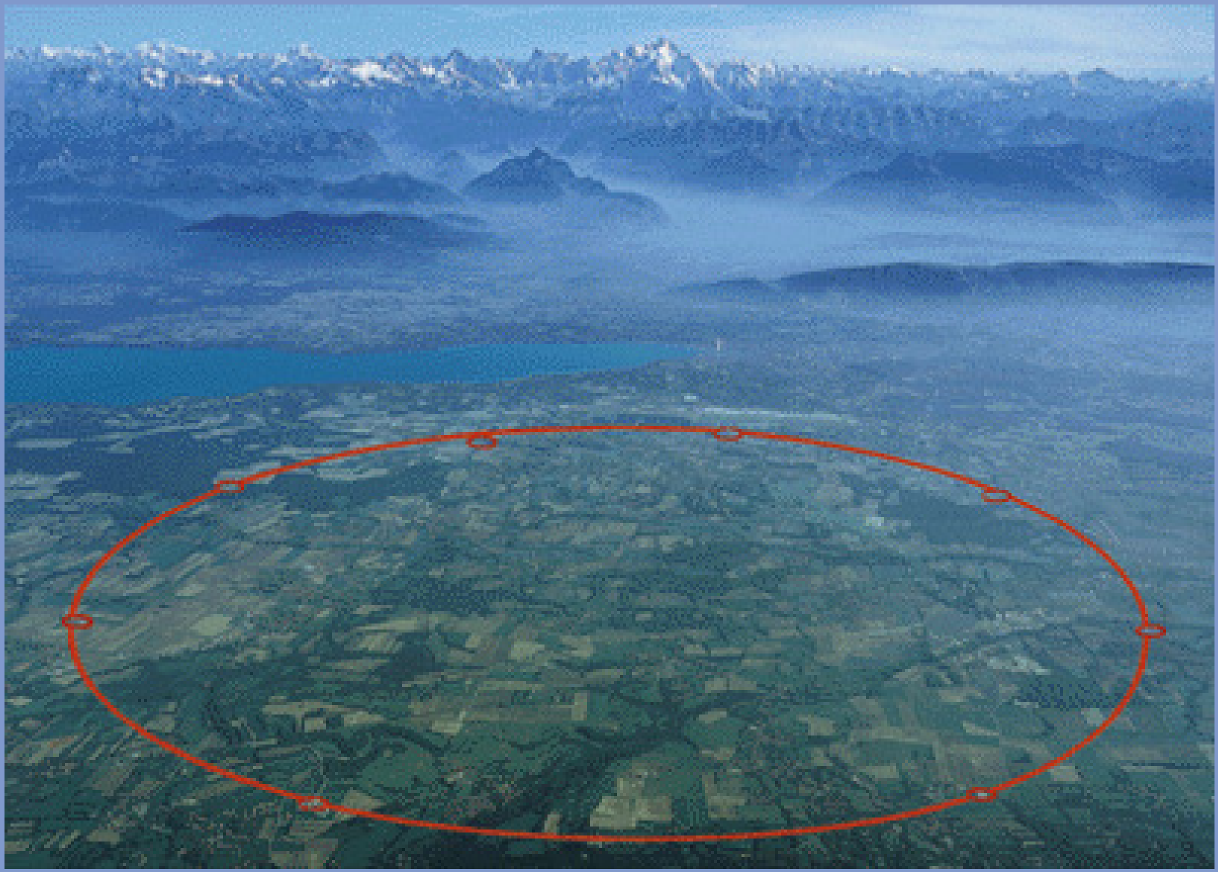
A pencil, standing on its tip: unstable, falls to its "ground state".

- **Underlying theory: rotationally symmetric, no preferred direction.**
- **The pencil spontaneously picks an orientation, breaks the symmetry.**



What breaks electroweak symmetry?

A key question probed at the LHC (pp collider) at CERN



Beam energy: 2×7000 GeV (design)
2×6500 GeV Run finished in 2018 (to resume in 2022)
Circumference (km): 26.659

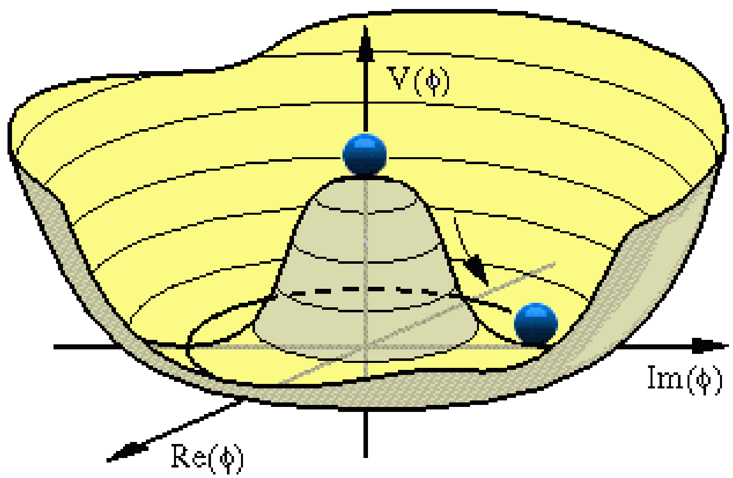
Electroweak Symmetry Breaking in SM

- Higgs (H) boson condensation $\langle H \rangle \neq 0$.

- Elementary particle masses from interactions with $\langle H \rangle \neq 0$:

- $m_W, m_Z, m_{\text{fermion}} \propto \langle H \rangle$
- Fermion flavor: $m_t/m_u \sim 10^5$! (Why?)

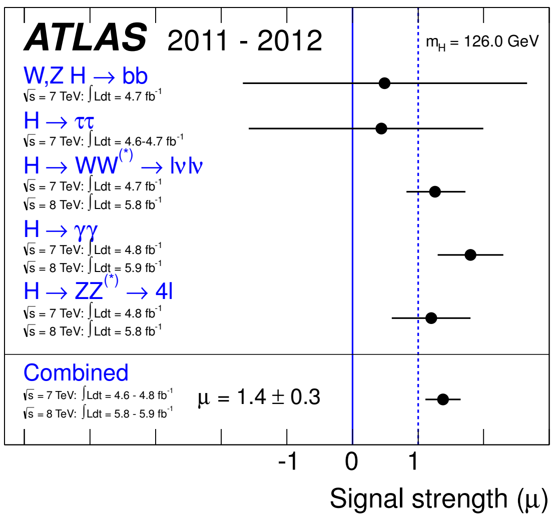
- $\boxed{\mathbf{m_\nu = 0}}$ (Strongly disfavored by data!)

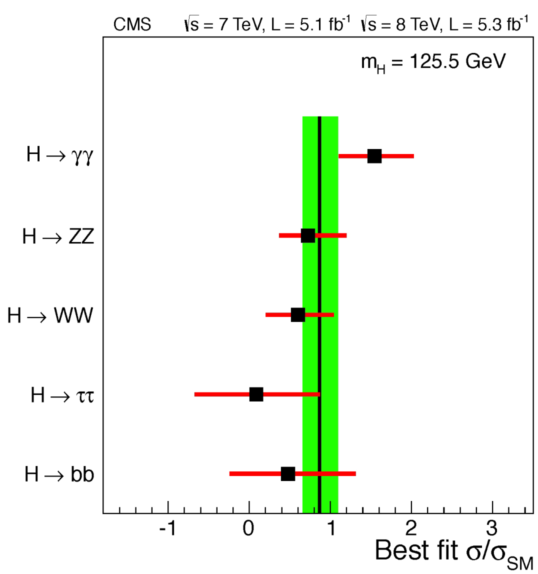


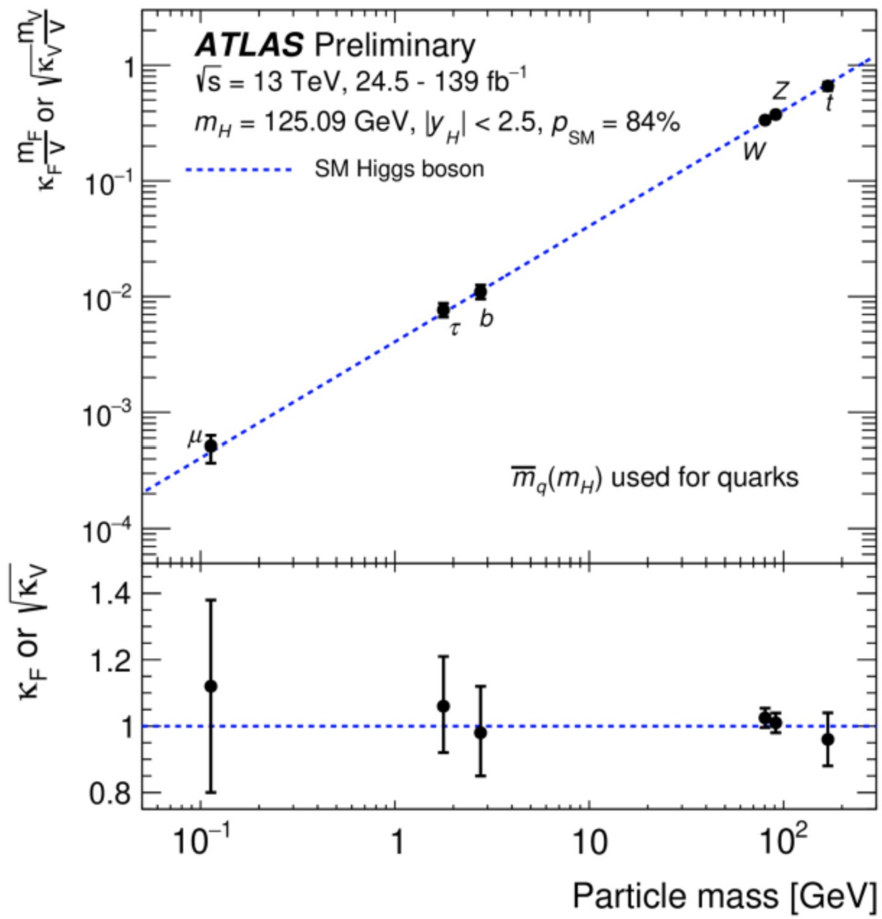
Q: How much of the "visible" mass in Universe is from Higgs?

July 4th, 2012, discovery announced at CERN

Scalar (spin-0) H boson discovered at ~ 125 GeV





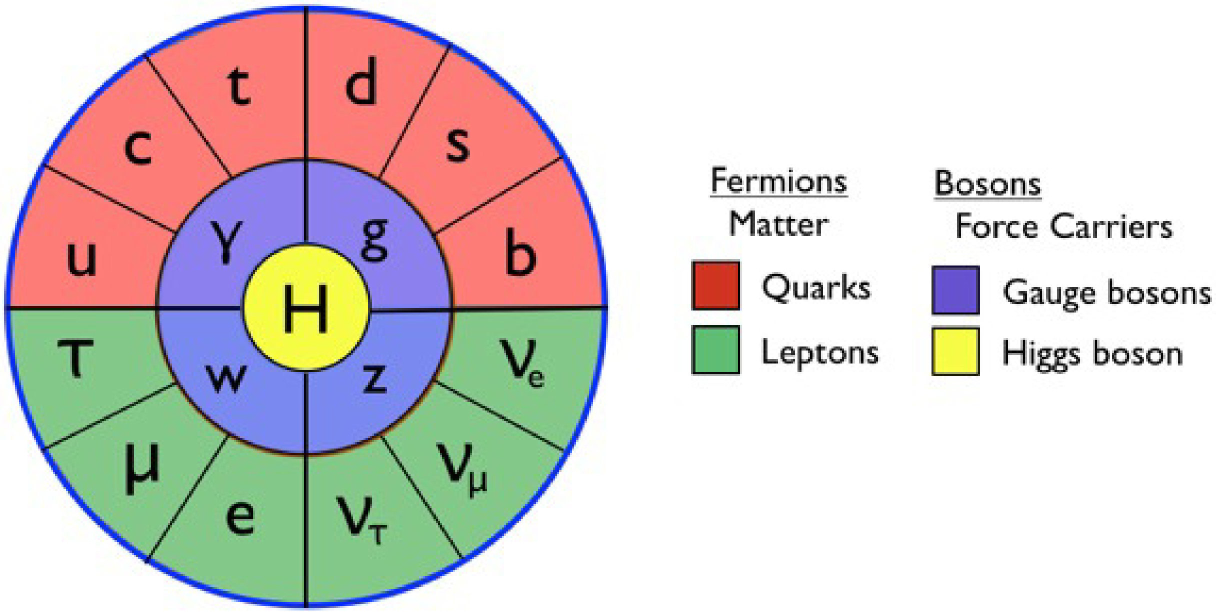


(Image: ATLAS Collaboration/CERN)

Early Run 1: ~ 10 fb^{-1}

Q: What is significant about having the muon in the plot?

SM + GR ⇒ Great Success!



Particles of the Standard Model

Nearly all* measurements in agreement with SM+GR.

* Except, for example, potential hints from muon $g-2$ (more later), some B meson (bound state of b quark with a light quark) decays,. . .

SM: An Incomplete Description of Nature

- Theoretical Hints

Why is gravity so weak?

Why is the neutron electric dipole moment so small?

...

- Experimental Evidence

Non-zero neutrino masses, dark matter, ...

Conceptual Mystery: Why is gravity so weak?

Force between e and p in an atom: $\frac{F(\mathtt{Grav})}{F(\mathtt{EM})} \sim 10^{-40}$!

Gravity: the weakest known interaction

Newton's Constant: $G_N = 6.67 \times 10^{-11}$ m^{3}kg^{-1}s^{-2}

Gravity scale: Planck mass

$$M_P \equiv (\hbar c/G_N)^{1/2} \approx 10^{19}\ \mathrm{GeV} \sim (10^{-35}\ \mathrm{m})^{-1}\,!$$

(mass $\leftrightarrow$ 1/length; uncertainty)

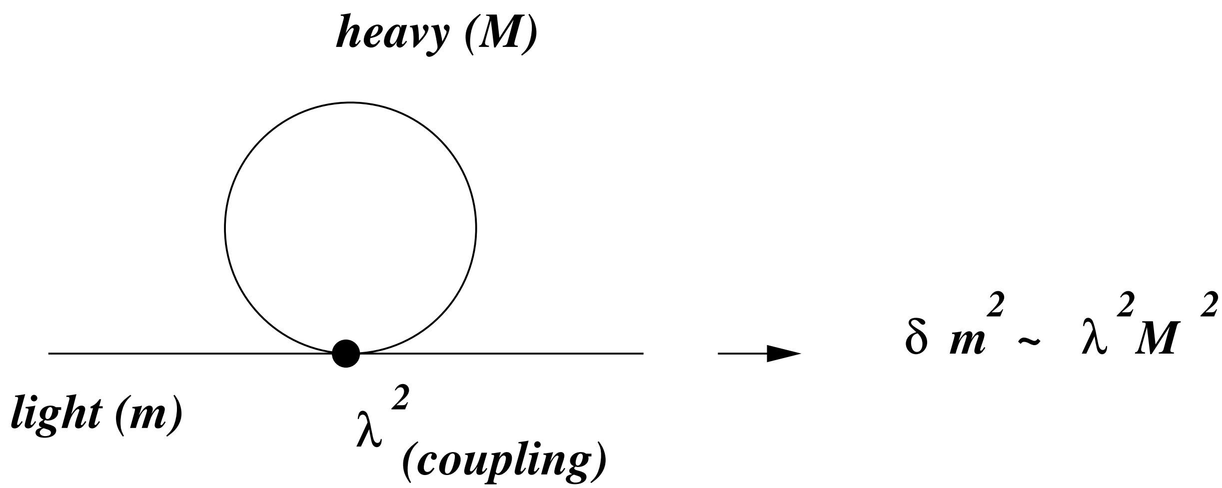
$$M_P \gg m_W$$

$\hbar = c = 1$.

Rephrase the question: Why is $m_W \sim 10^{-17} M_P$?

The Hierarchy Problem:

- Higgs mass $m_H \approx 125$ GeV, but quantum effects imply $m_H \to M_P$.



$\Rightarrow m_H^2 \sim (100 \text{ GeV})^2$: cancellations to

0.0000000000000000000000000000000001 !

- Conceptually "unnatural"

A much more severe case (Cosmological Constant Problem):
Energy density of empty space ($\sim 10^{-120} M_P^4$)

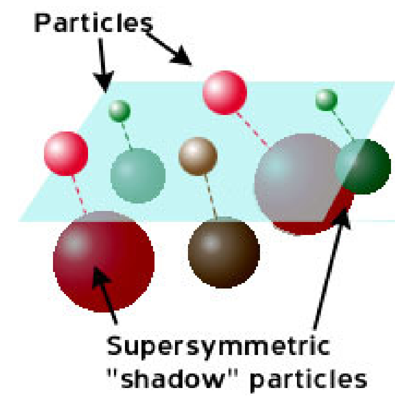
Hierarchy and New Physics Near m_H

- **Strong Interactions near m_H**

- Composite Higgs (analogue of a QCD hadron)

- Extra dimensions (lowering the fundamental mass scale of gravity by diluting it in compact extra dimensions)

- **Supersymmetry: Fermions $\leftrightarrow$ Bosons.**



- Quantum effects on $\langle H \rangle$ cancel

- *So far, no firm evidence at LHC for new physics near $m_H \approx 125$ GeV*

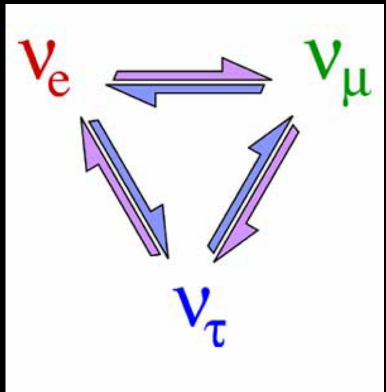
- *New physics elusive, or perhaps "naturalness" not the right guide*

Strong Empirical Evidence for Beyond SM

- **Neutrino Flavor Oscillations**

- **Solar, atmospheric, and terrestrial data:**

$$m_\nu \lesssim 10^{-6}\, m_e$$



The periodic change of neutrino flavor from one type into another is referred to as neutrino oscillations.

- **Simple extension: right-handed* neutrinos ν_R**

* Spin and momentum aligned

- **Typically, difficult to test:**

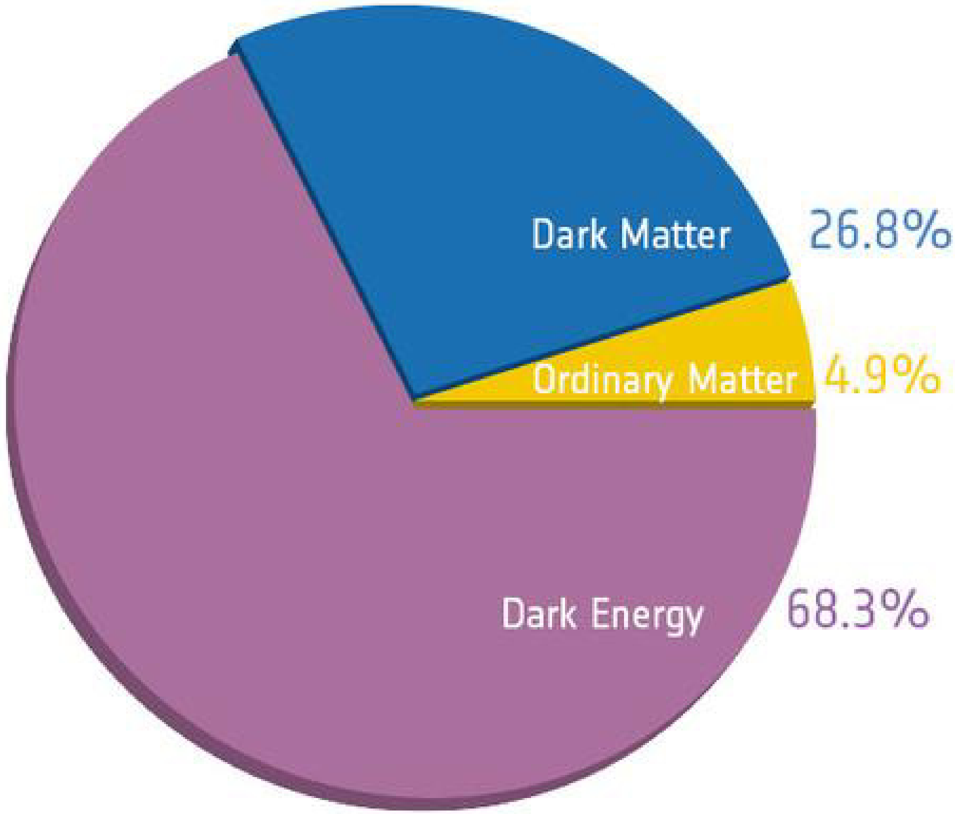
\- ν_R **very massive or else negligible coupling to SM**

- **Cosmology**

- **Dark Matter: neutral, cosmologically stable**

Cosmos: 95% unknown!

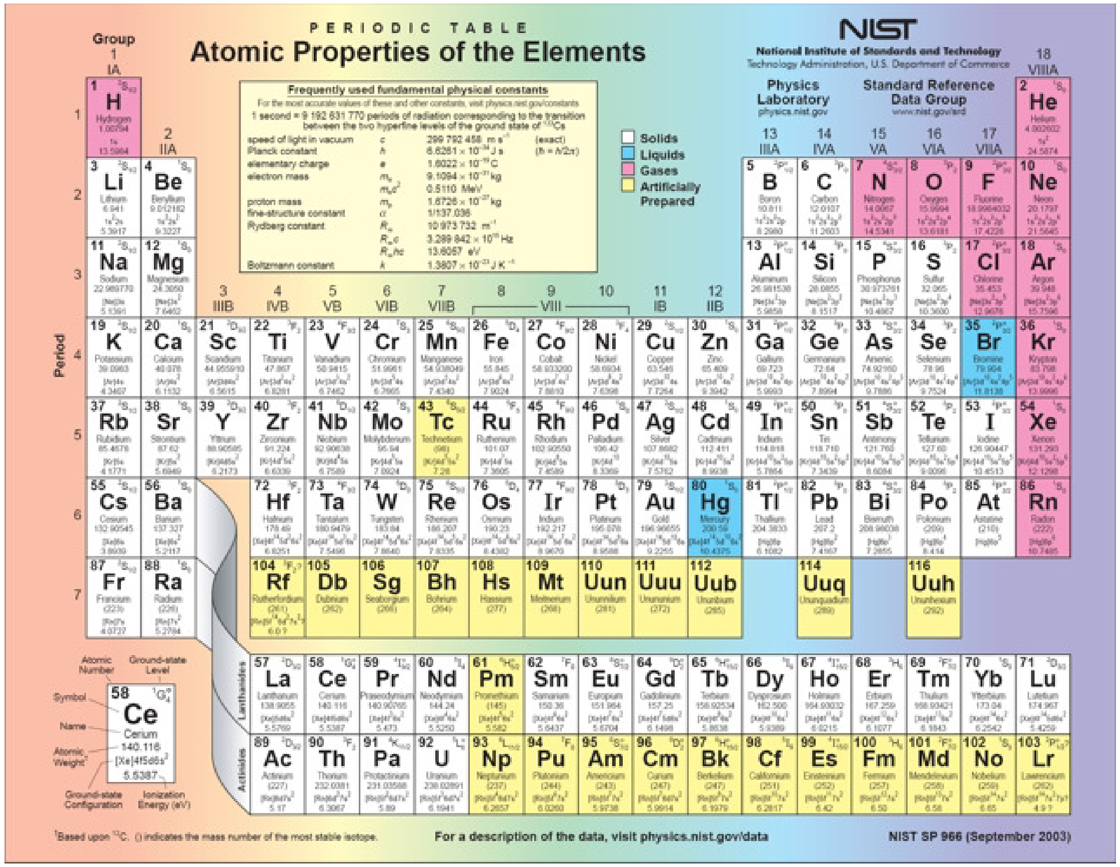
Planck



Cosmic acceleration (dark energy):

Could be vacuum energy (cosmological constant); no dynamics

Visible (Everyday) Matter



- $\sim$ 5% of energy budget
- Baryonic: protons, neutrons
- Asymmetric: $\Delta B \neq 0$ (negligible anti-matter today)

Generation of Baryon Asymmetry

- Requires Sakharov's conditions for *baryogenesis*:

(i) Baryon number violation

(ii) C and CP violation (distinguishing particles from anti-particles)

(iii) Departure from equilibrium

- Conditions absent [(iii)] or not at sufficient levels [(ii)] in the SM

- ΔB small, $n_B/n_\gamma \sim 10^{-9}$, but still too big to explain!

$\Rightarrow$ New Physics

Dark matter (DM)

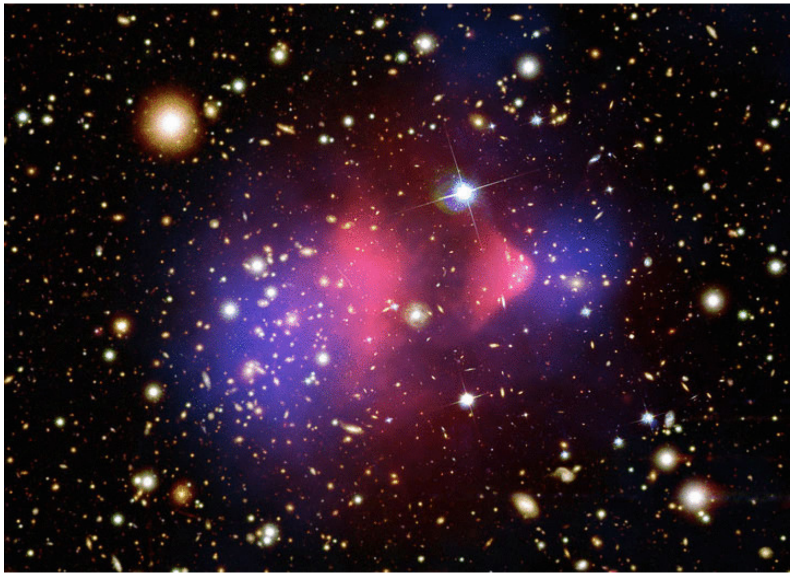
- $\sim$ 27% of energy density

- Robust evidence from cosmology and astrophysics

  - CMB, BBN, rotation curves of galaxies, lensing, Bullet Cluster, ...

- **Unknown origin**

  - Feeble interactions with atoms and photons
  - Self-interactions not strong ($\sigma \lesssim 1$ barn)
  - Not explained in SM



Strongly motivates new physics

So far, evidence limited to gravity effects

How do you look for something of unknown nature?

Possible DM mass scale: 10^{-22} *eV* $\lesssim M_{\text{DM}} \lesssim 10^{68}$ *eV*

($\sim$ 90 orders of magnitude!)

Q: Why is there a lower bound ($\sim 10^{-22}$ eV)?

Searches often guided by *theoretical motivation*

- New physics to address unresolved questions in SM

Example:

- The hierarchy problem in SM:

- New particles with masses $M_{\text{new}} \gtrsim M_H (\approx 125)$ GeV: supersymmetry, ...

- Energy scale often referred to as the "weak scale" (weak interactions)

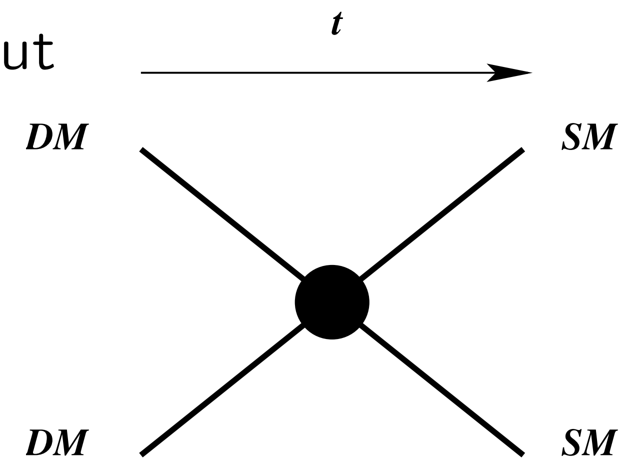
$\Rightarrow$ **Weakly Interacting Massive Particles** (WIMPs)

- SM extensions often introduce/require new symmetries

- Symmetry $\rightarrow$ Charge conservation

$\Rightarrow$ Stable or long-lived particles: DM candidates

WIMPs



- Thermal relic density: annihilation, freeze-out

- $\rho_{\text{WIMP}} \propto 1/\sigma_{ann}$

- $\sigma_{ann} \sim g^4/M^2$

- $g \sim g_{\text{weak}}$, $M \sim$ TeV: roughly the right amount of DM

- Weak scale ($\sim$ TeV) theoretically motivated

- However, g^4/M^2 may be achieved otherwise (WIMPless Miracle)

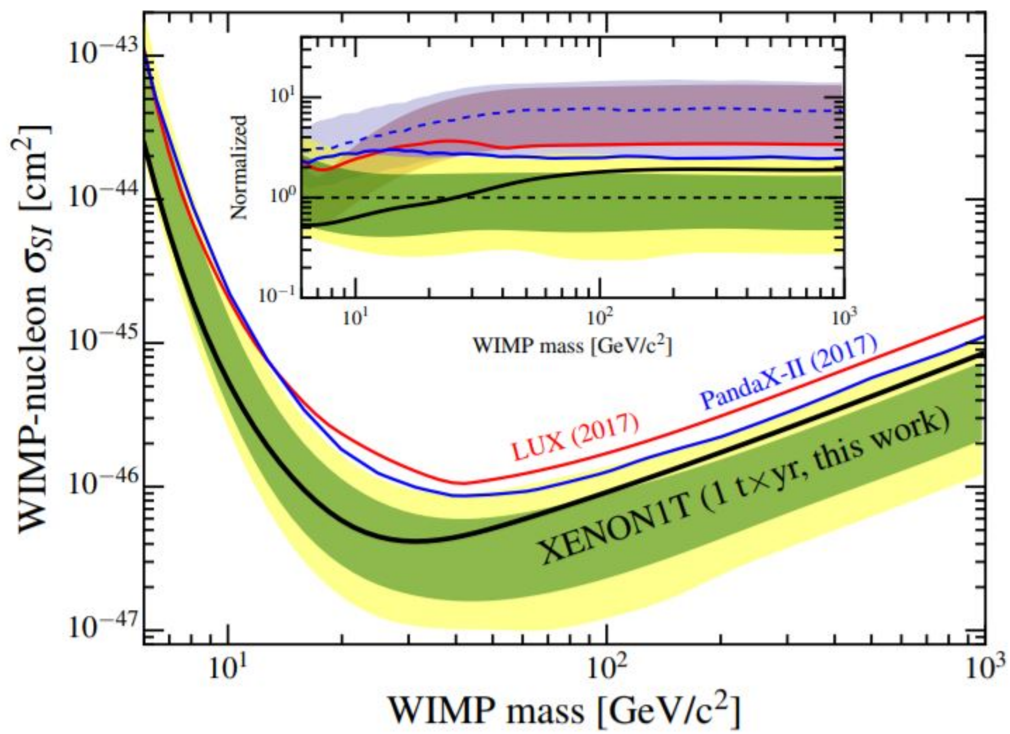
Feng and Kumar, 2008

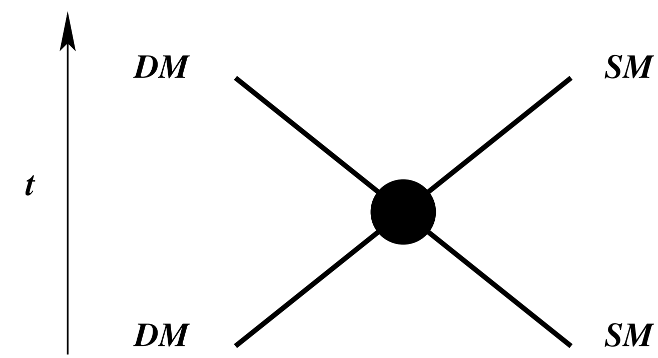
- **WIMPs: have been a main focus of DM searches**

- DAMA/LIBRA, CDMS, Xenon10, CDMSII, Xenon100, LUX, Fermi GST...

Direct WIMP DM Searches

- Recoil off atomic nuclei (electrons)





E. Aprile *et al.* [XENON Collaboration], Phys. Rev. Lett. **121**, no. 11, 111302 (2018)

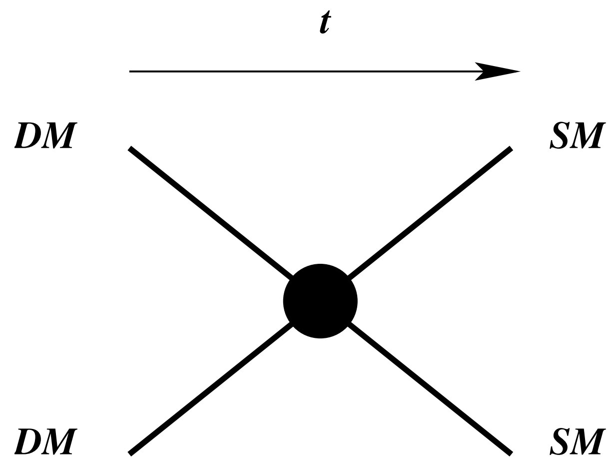
Q: Why do the constraints get weaker towards lower and higher DM masses?

Other avenues for WIMP search:

- Indirect searches: self-annihilation signals

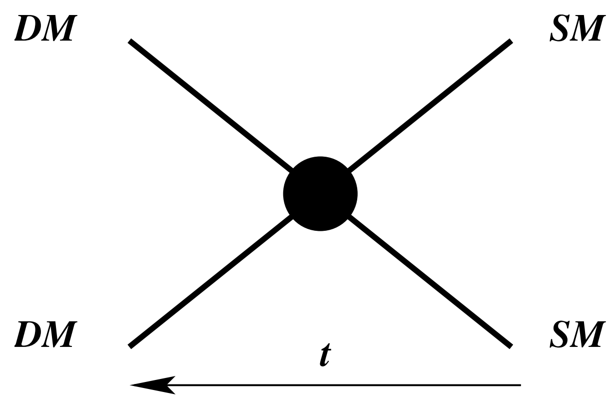
- Related to thermal relic density

- Complicated by astrophysical backgrounds



- Collider production: LHC

- Search for missing energy in events



Dark Sectors and Dark Forces

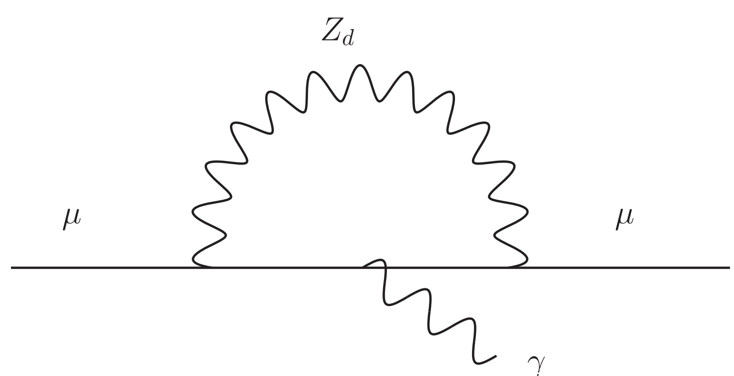
For example: Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- DM may reside in a separate sector with its own forces
- Analogy with SM

- DM interactions with SM are indirect

- Simple example: a "dark" sector $U(1)_d$
- Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d

- $m_{Z_d} \lesssim 1$ GeV has been invoked in various contexts
- DM interpretation of astrophysical data
- Explaining muon $g - 2$



Muon $g-2$

- There are some experimental hints for deviations from the SM

- A significant one is the apparent tension between SM prediction and measured muon $g-2$

$$\vec{\mu}_l = e\frac{g}{2m_l}\vec{S} \qquad \text{(Magentic dipole moment, lepton mass } m_l\text{, spin } \vec{S}\text{)}$$

$$g = 2\left(1 + \frac{\alpha}{2\pi} + \ldots\right) \qquad \text{(J. Schwinger, 1948)}$$

- Long-standing Brookhaven experimental results* recently confirmed by an ongoing measurement at Fermilab Phys. Rev. Lett. 126, 141801 (2021)

* Phys.Rev.D73:072003,2006

- A set of precision calculations suggest a 4.2σ deviation, $(251 \pm 59) \times 10^{-11}$, averaging Brookhaven and Fermilab results, but status of SM prediction is still under scrutiny

- The results could be pointing to new phenomena

- Stay tuned over the coming few years

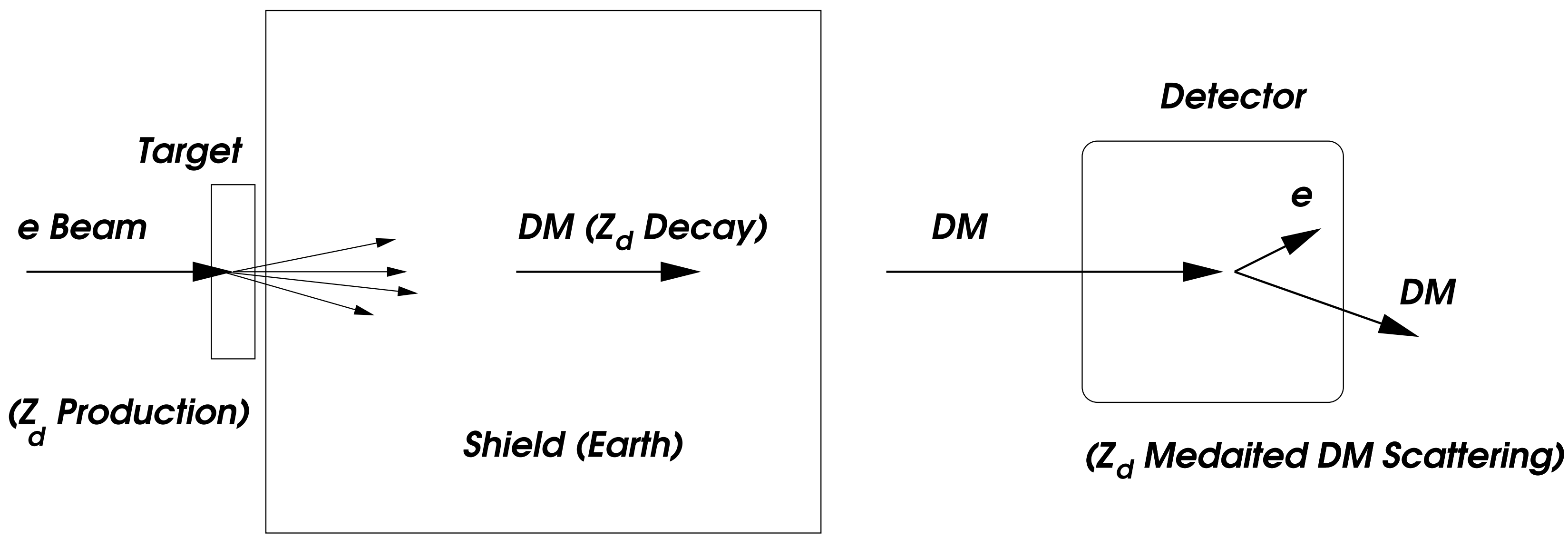
- Upcoming lecture by W. Morse will provide many more details

Invisible Z_d and Low Mass DM Production

- Possible production and detection of *DM beams* in experiments

Batell, Pospelov, Ritz, 2009 (p beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 (e beam dump)

- Interesting probe of GeV-scale DM (challenge for direct detection)



Motivated a search at Fermilab:

"Dark Matter Search in a Proton Beam Dump with MiniBooNE"

A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **118**, no. 22, 221803 (2017)

Concluding Remarks

★ **Standard Model and GR successfully describe wide range of phenomena.**

• Higgs boson discovered at LHC, appears to complete SM

• Some potential deviations in current data

• In particular, muon $g-2$ could be hinting at new physics; more data and further theory investigations are needed

★ **SM conceptual difficulties: hierarchy (Higgs mass "naturalness"),. . .**

• No firm evidence for any new physics associated with a "natural" Higgs mass

• Perhaps still early, but new organizing principles may be needed

★ **Empirical shortcomings: neutrino masses, dark matter, baryogenesis, . . .**

• Neutrino mass generation: requires physics beyond SM, but typically elusive

• Dark matter: robust gravitational evidence for new physics, potentially accessible

• WIMP dark matter: Motivated by "naturlaness" of m_H (under strain)

• Wide range of other possibilities for DM currently viable