Visible and Invisible Clues for New Physics

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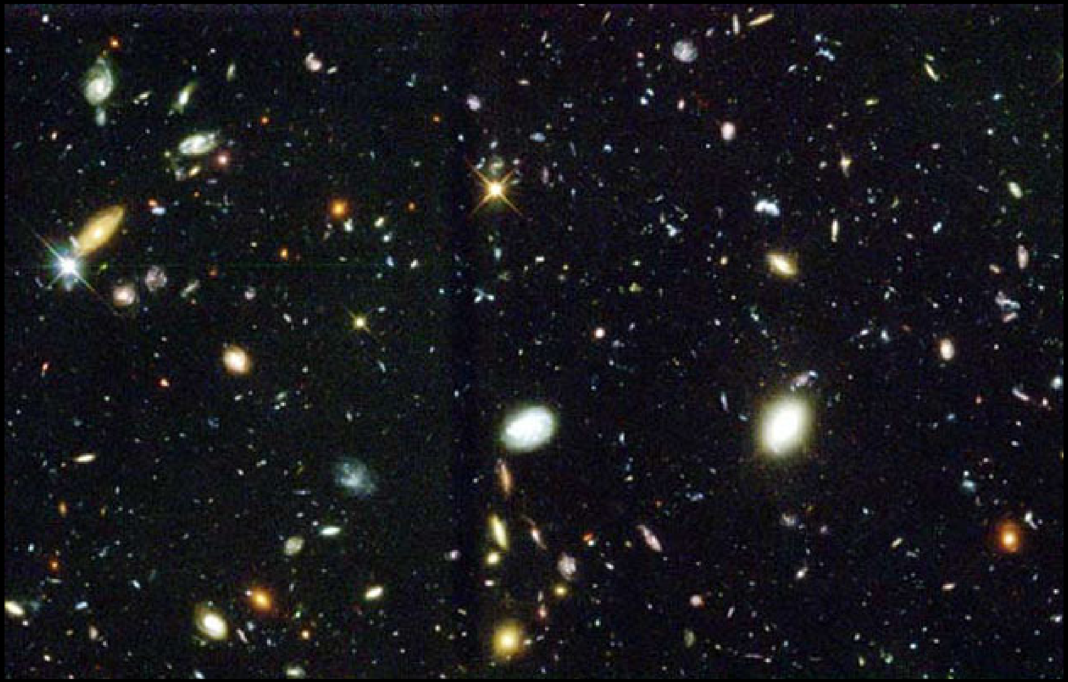


SULI Lecture, Physics Department, BNL

June 7, 2019

BROOKHAVEN NATIONAL LABORATORY

$\hbar \approx 1.05 \times 10^{-34}$ 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)

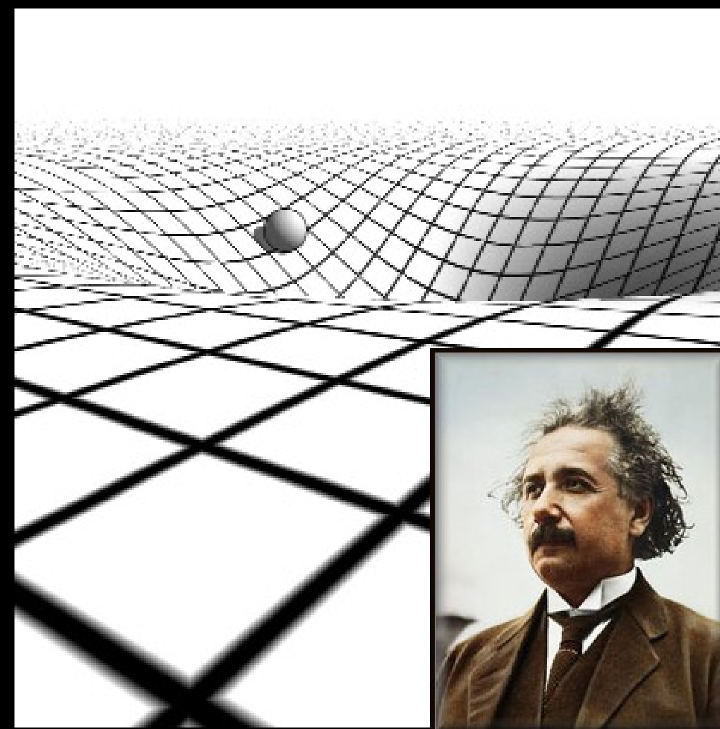
- **<u>Spacetime</u> curved by matter/energy.**

Sun

- **Gravitational Force $\rightarrow$ Geodesic.**

Earth's Orbit

- **Basis of modern cosmology.**



Einstein's equations:

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

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

$\star$ *Detection of Gravitational Waves* $\star$

- Directly confirms 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: ~ 6.5 Billion Solar Masses ; Distance: ~ 55 Million Light Years

Results released April 10, 2019

Apple on the ground: EM

- Atoms in apple and ground: EM forces stop the fall.
- 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:** $SU(3)(\text{strong}) \times SU(2) \times U(1)(\text{electroweak})$

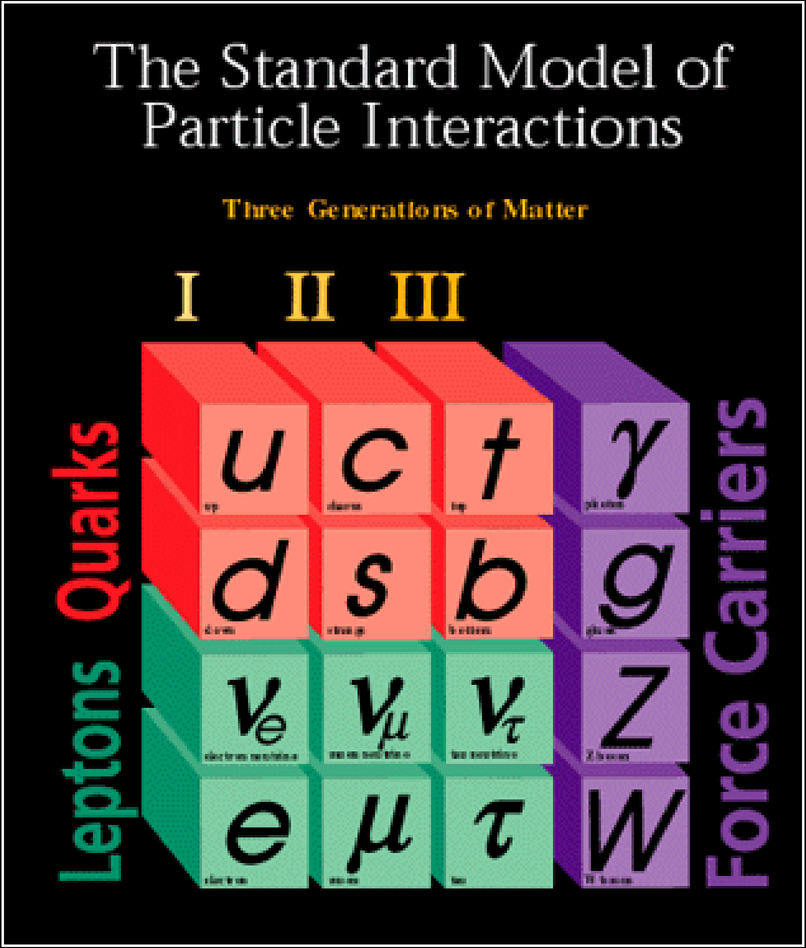
- **Elementary fermions, spin-1/2**

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

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

- **Gauge Fields, spin-1**

Force mediators, generalized photons

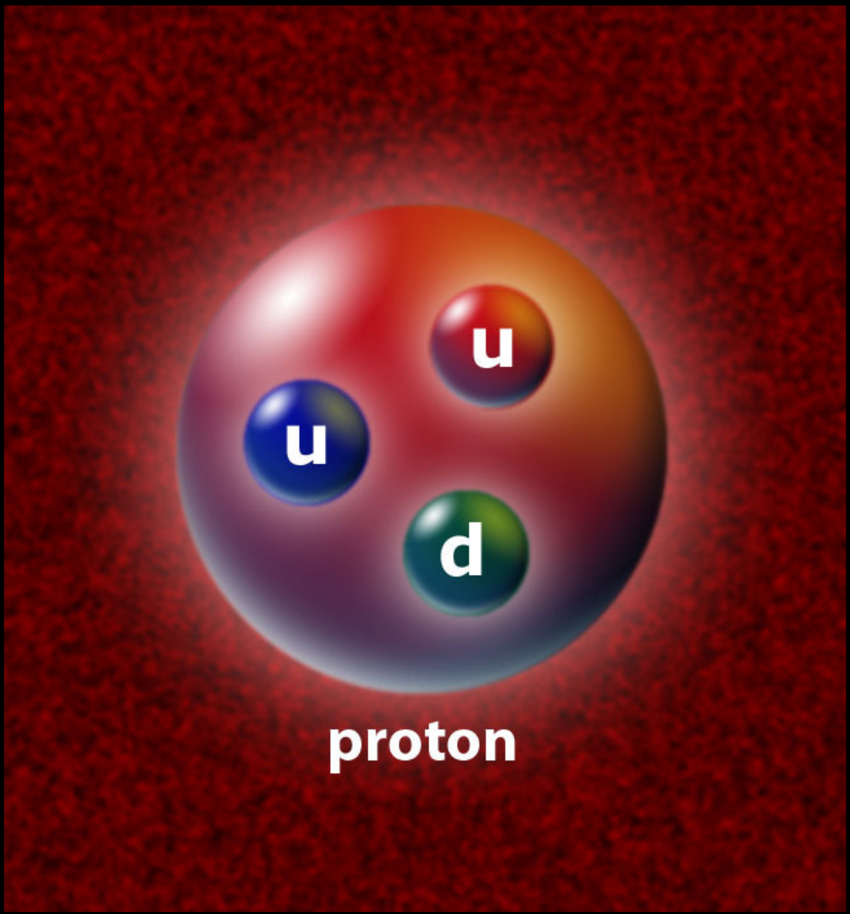


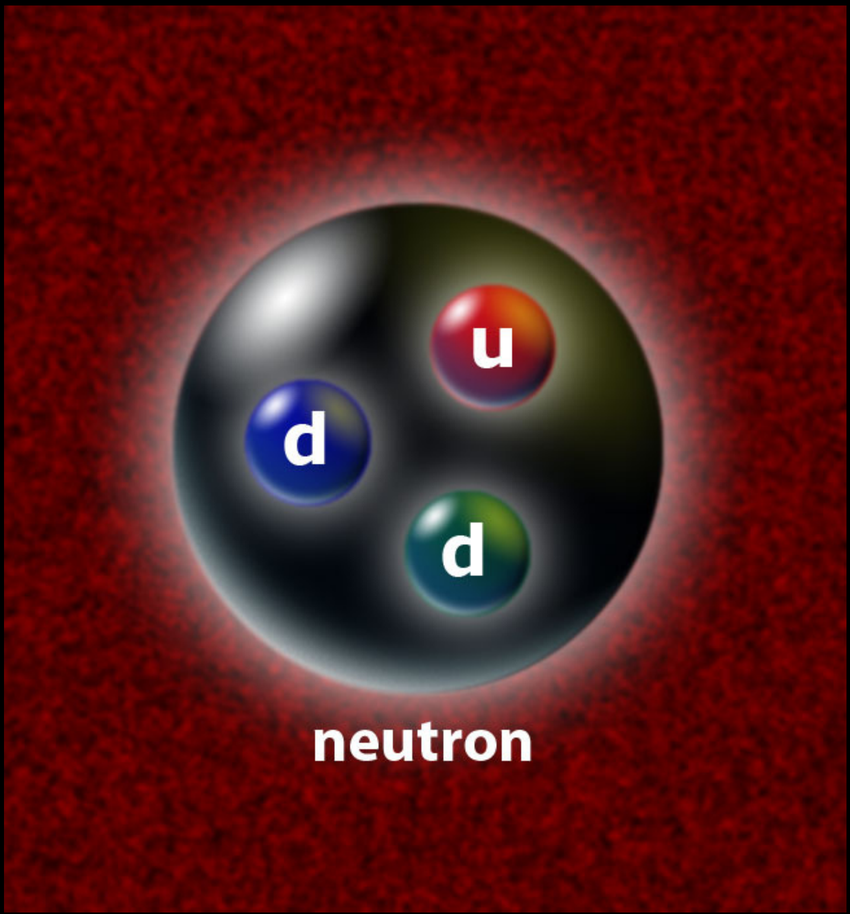
(Pre 2012)

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

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

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



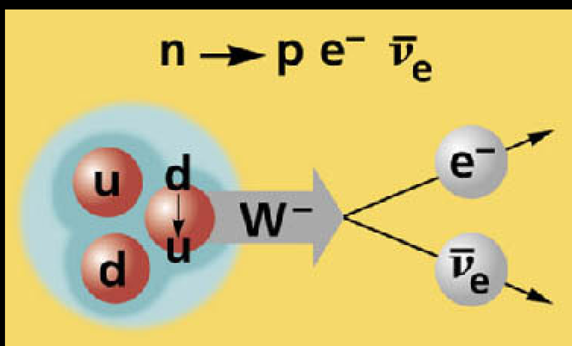


Electroweak Interactions $[SU(2)_L \times U(1)_Y]$:

- Spontaneously* broken to EM

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

Short-ranged: $\Delta x \sim c\,\Delta t \sim \hbar/(mc) \sim 10^{-18}$ m. (Heisenberg uncertainty)



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

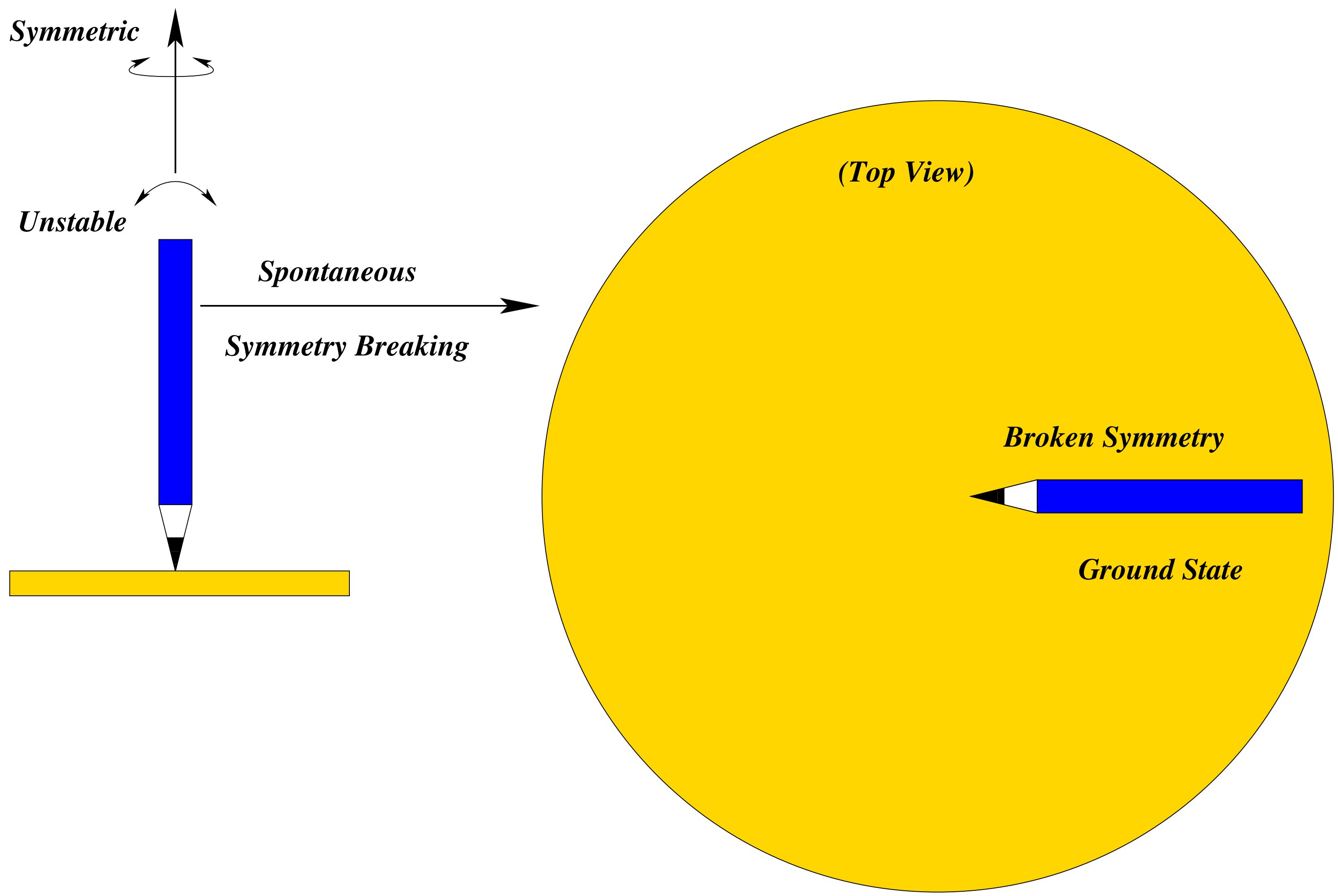
Massless photon, γ, long-ranged

$\star$ What is a spontaneously broken symmetry?

Tabletop Spontaneous Symmetry Breaking

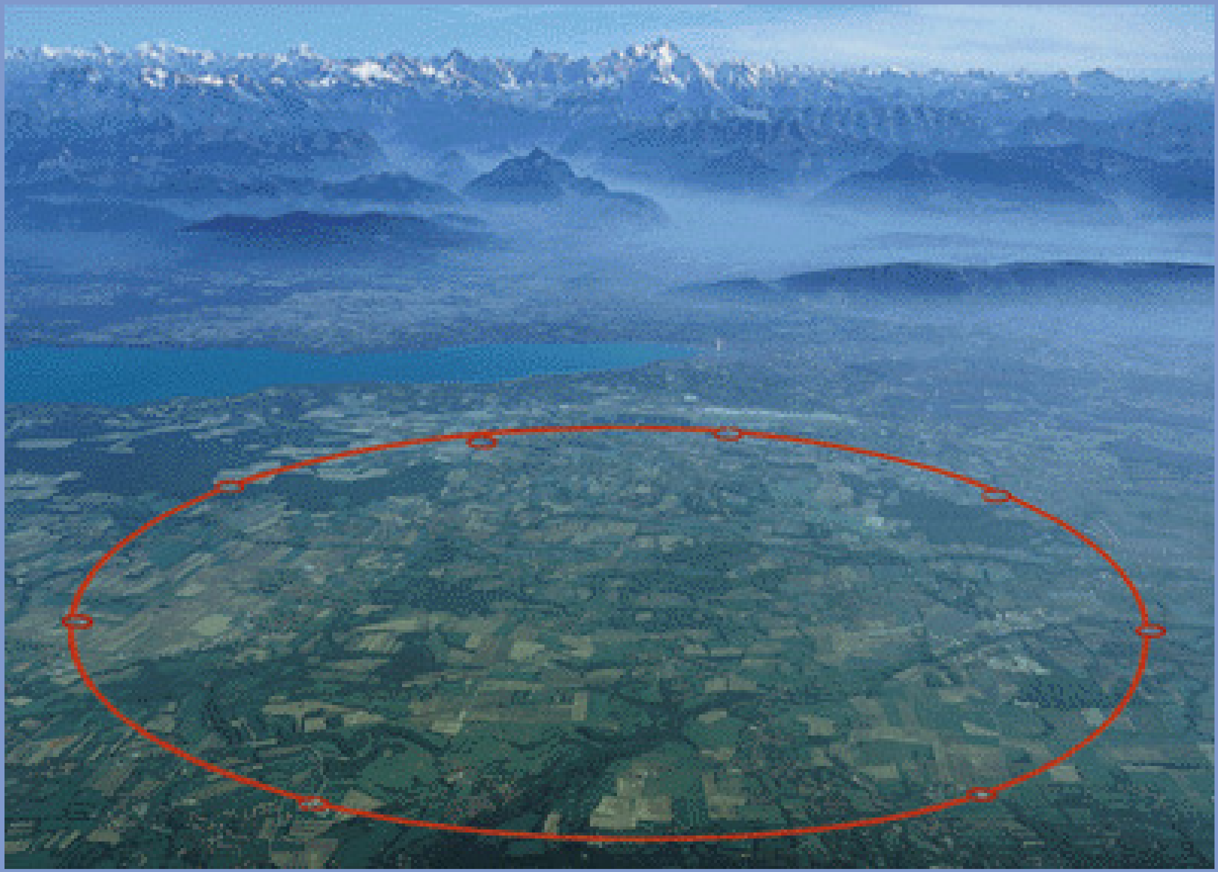
A pencil, standing on its tip: unstable, falls to its "ground state".

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



What breaks electroweak symmetry?

Key question probed at the LHC (pp collider) at CERN



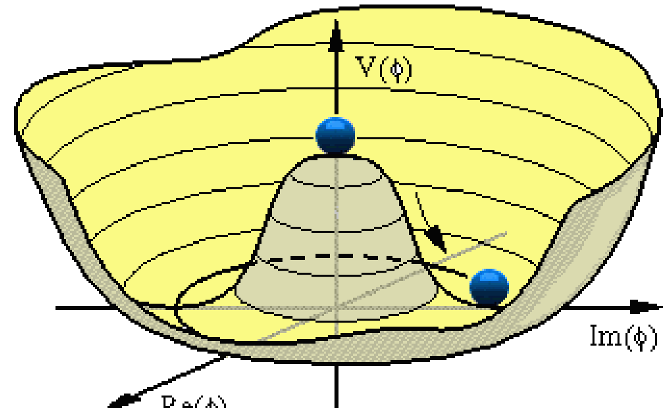
Beam energy: 2×7000 GeV (design)

2×6500 GeV Run finished in 2018; to resume in 2021

Circumference (km): 26.659

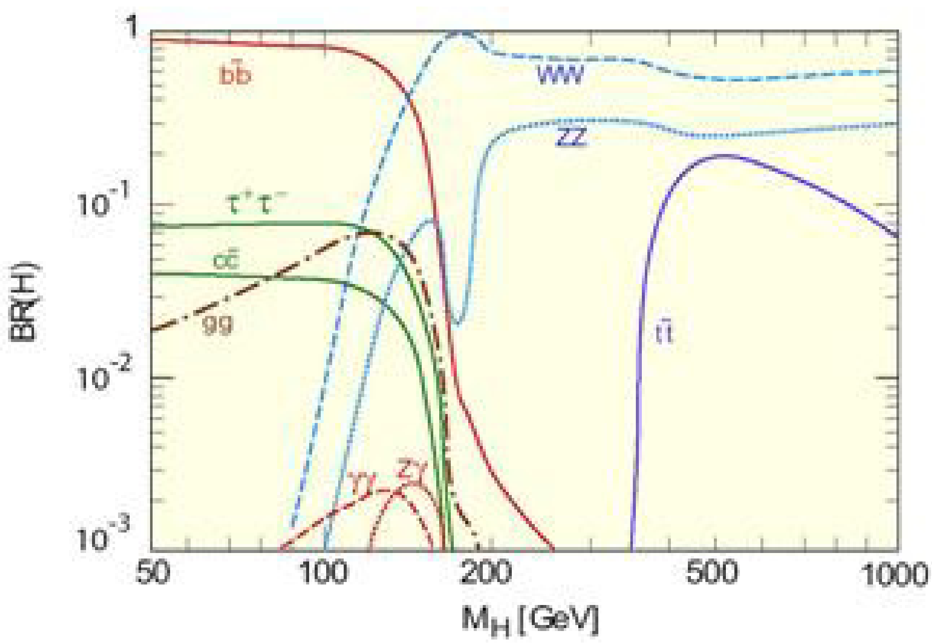
Electroweak Symmetry Breaking in SM

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



- Mass 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?)

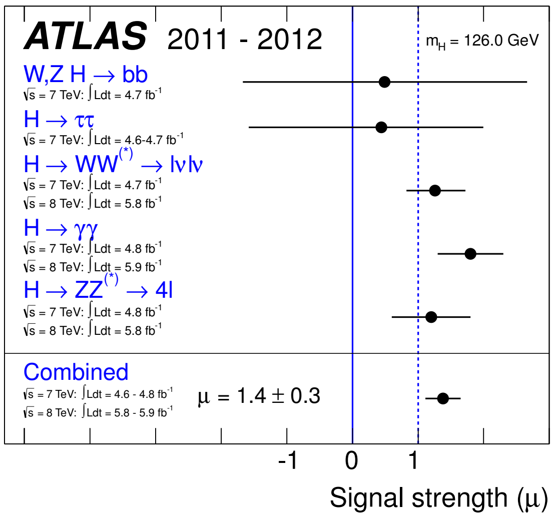
- $\boxed{\mathbf{m_\nu = 0}}$ (Strongly disfavored by data!)

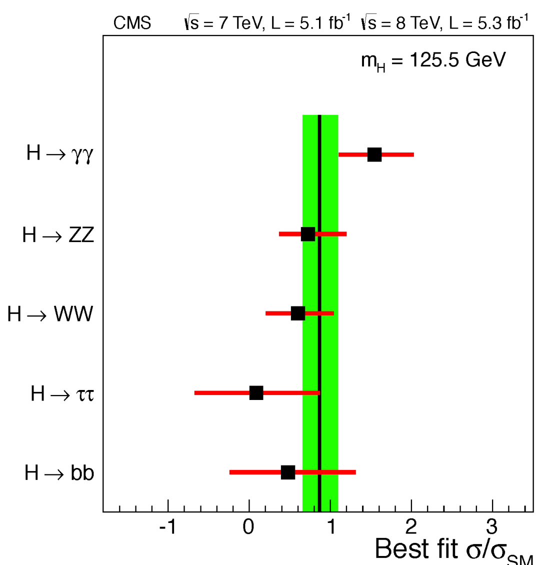


⋆ *Aside: Visible mass in universe mostly from QCD.*

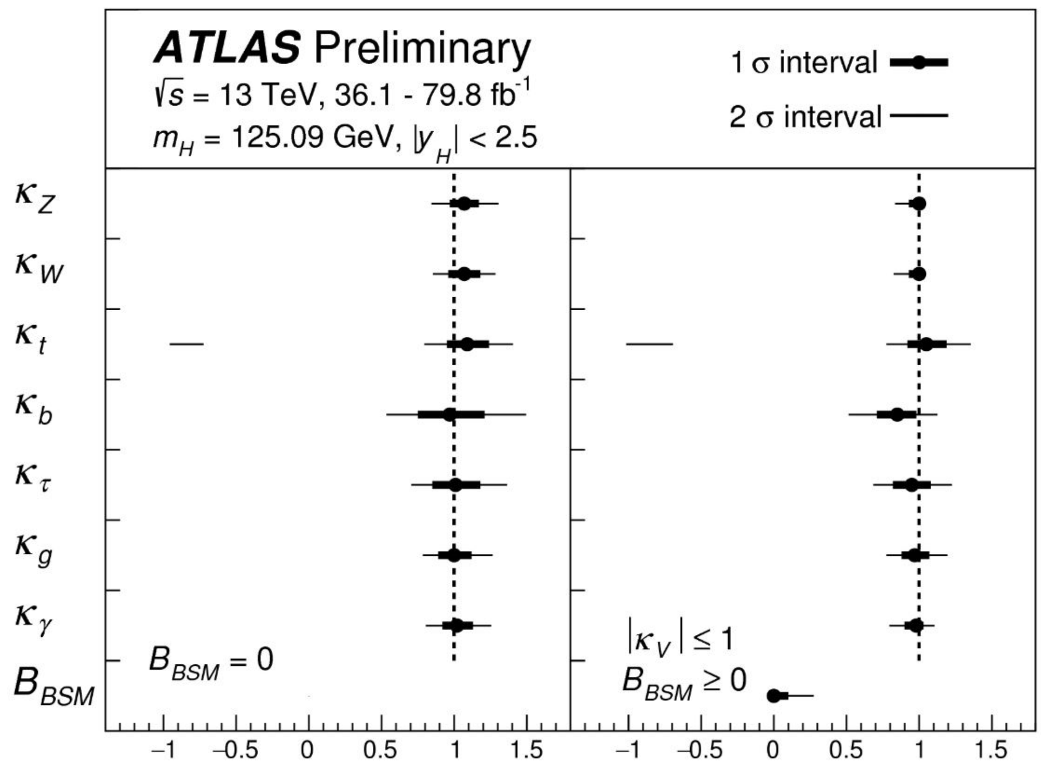
July 4th, 2012, discovery announced at CERN:

New scalar H discovered at ~ 125 GeV!



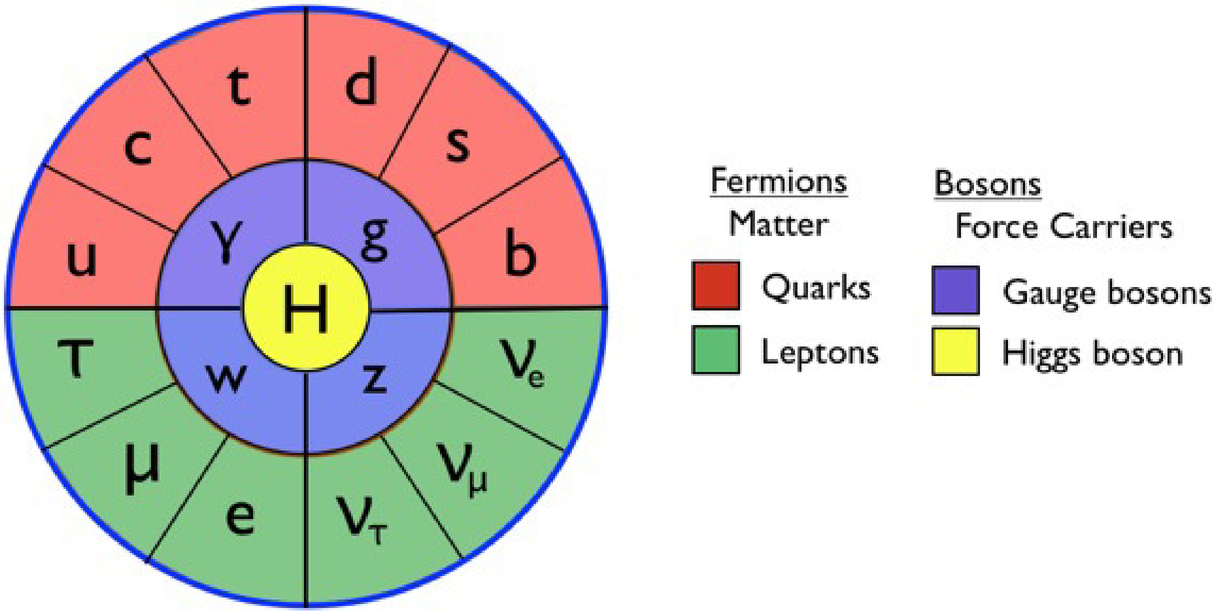


Early Run 1: ~ 10 fb^{-1}



Run 2 data, ATLAS-CONF-2018-031

SM + GR ⇒ Great Success!



Particles of the Standard Model

Nearly all* measurements in agreement with SM+GR.

* Discrepancy in $g_\mu - 2$ at $\sim 3.5\sigma$

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(76) \times 10^{-11} \qquad a_\mu \equiv (g_\mu - 2)/2$$

* Other anomalies (*e.g. some B meson decays*) at similar or lesser significance

SM: An Incomplete Description of Nature

- **Theoretical Hints**

Why is gravity so weak?

Why is the neutron EDM so small ($\bar{\theta} \lesssim 10^{-9}$)?

. . .

- **Experimental Evidence**

$m_\nu \neq 0$, **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}

Interaction $\rightarrow$ mass scale ($\propto$ 1/length)   (Heisenberg)

Gravity scale: Planck mass

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

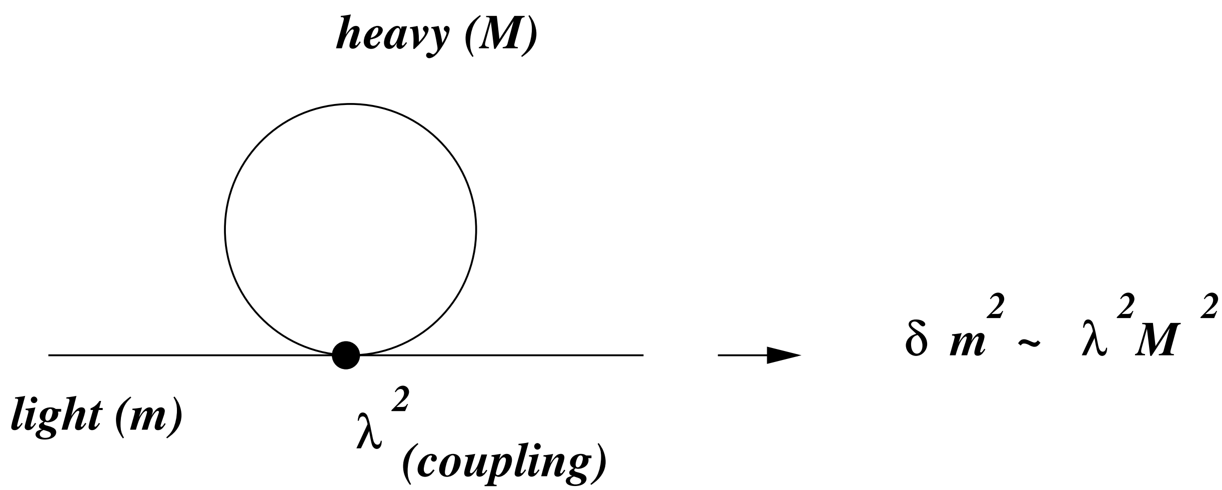
$$M_P \gg m_W$$

$\hbar = c = 1.$

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

The Hierarchy Problem:

- SM requires $m_W \sim \langle H \rangle$, but quantum effects imply $\langle H \rangle \to M_P$.



$\Rightarrow m_W^2 \sim (100\text{ GeV})^2$: cancelations to

0.000000000000000000000000000000001 !

- Conceptually “unnatural.”

A much more severe case:
Energy density of empty space (10^{-120}); Cosmological Constant problem.

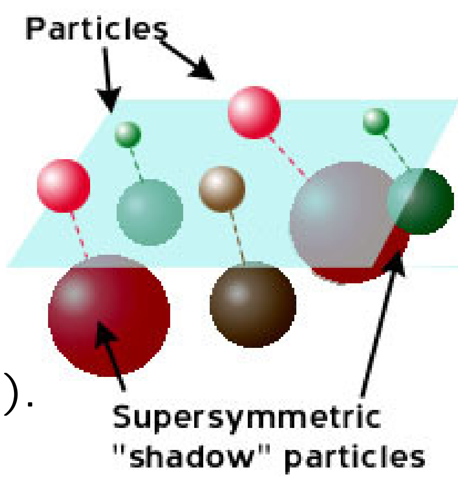
Hierarchy and New Physics Near m_H

- **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 other compact dimensions)

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



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

- Spontaneously broken:

Very short distance: Higgs cannot "see" it (back to hierarchy).

Very long distances: We should "see" it (we do not).

$\Rightarrow$ *Superpartners near Higgs mass*

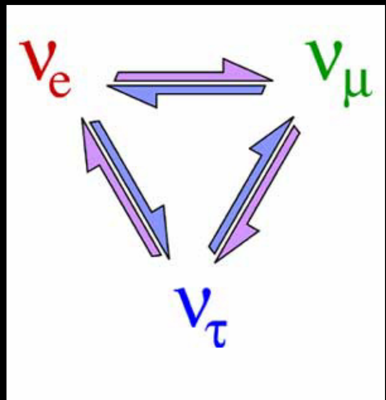
- *So far, no evidence at LHC for new physics near m_H*
- *More elusive physics, or perhaps "naturalness" not the right guide*

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.

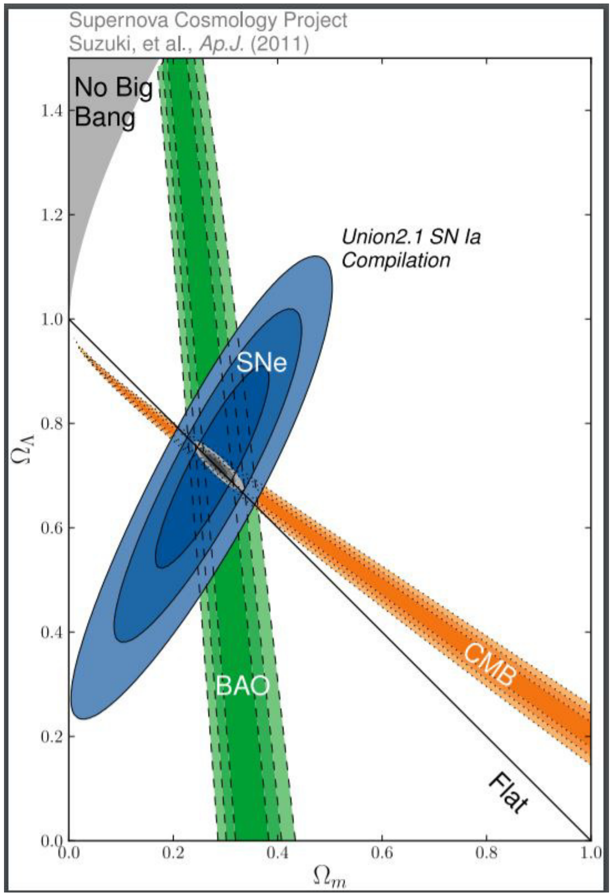
- Simple extension: right-handed neutrinos ν_R

- Typically, difficult to test:

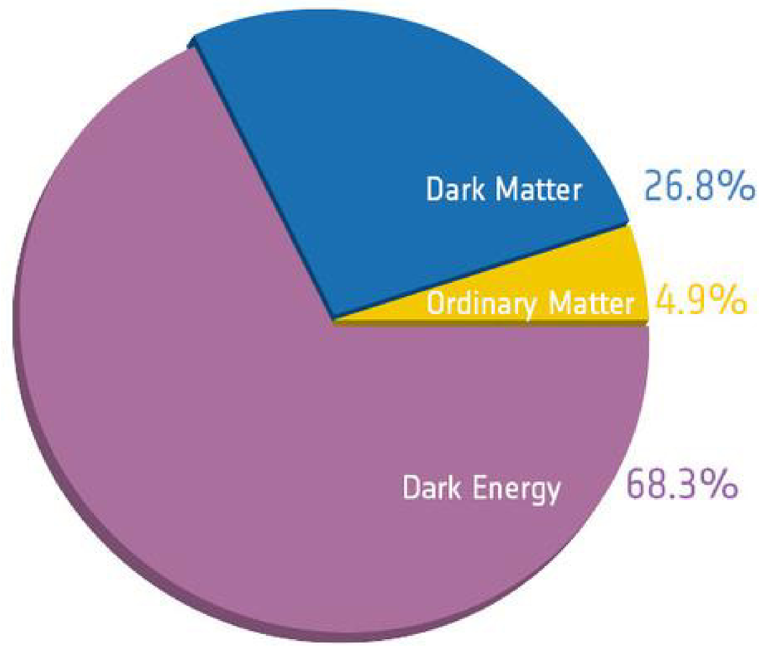
- ν_R very massive or else negligible coupling to SM

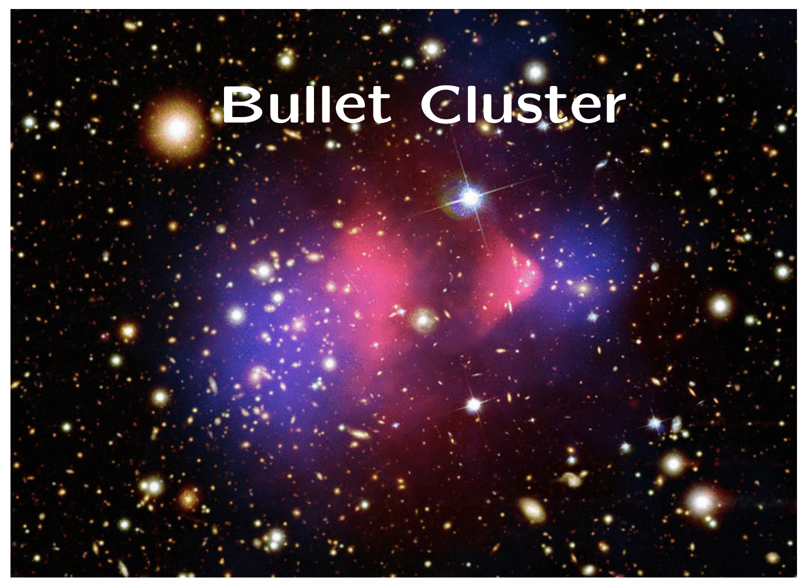
- **Cosmology**

- Dark Matter: neutral, cosmologically stable



Planck

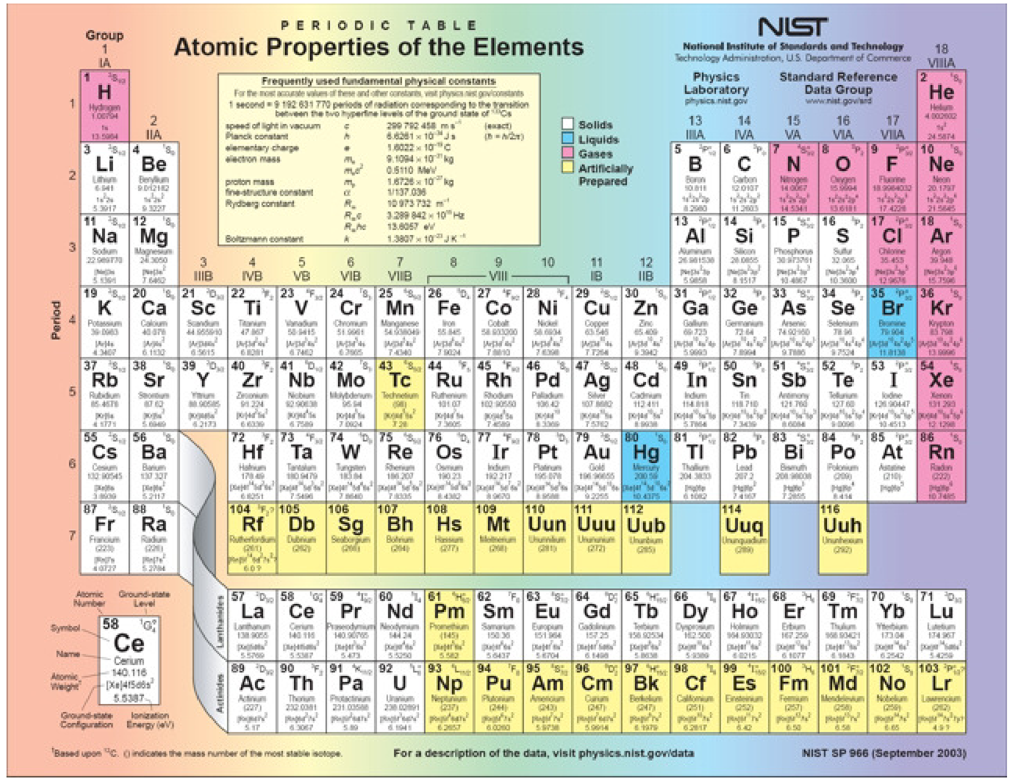




95% of Cosmos: unknown!

Cosmic acceleration (dark energy):
Could be vacuum energy; no dynamics

Visible (Everyday) Matter



- $\sim$ 5% of energy budget
- Baryonic: protons, neutrons
- Asymmetric: $\Delta B \neq 0$.

$$\eta_B = n_B/s \sim 10^{-10}$$

- Negligible anti-matter today:

- No annihilation signals nearby

- Cosmic ray $\bar{p}$ consistent with secondaries,...

- Matter/antimatter separation unlikely on large scales

- Note: $e^{-m/T} \sim 10^{-10}$ at $T \sim 40$ MeV; horizon contains $\sim 10^{-7} M_\odot$

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

- Present in Standard Model (SM), but not in sufficient amounts

(i): EW anomaly: tunneling (suppressed), thermal, sphalerons ($T \gg M_W$)

(ii): Quark mass matrix (Cabbibo-Kobayashi-Maskawa), but CP violation too small

(iii) EW phase transition: not strongly first order (Higgs too heavy)

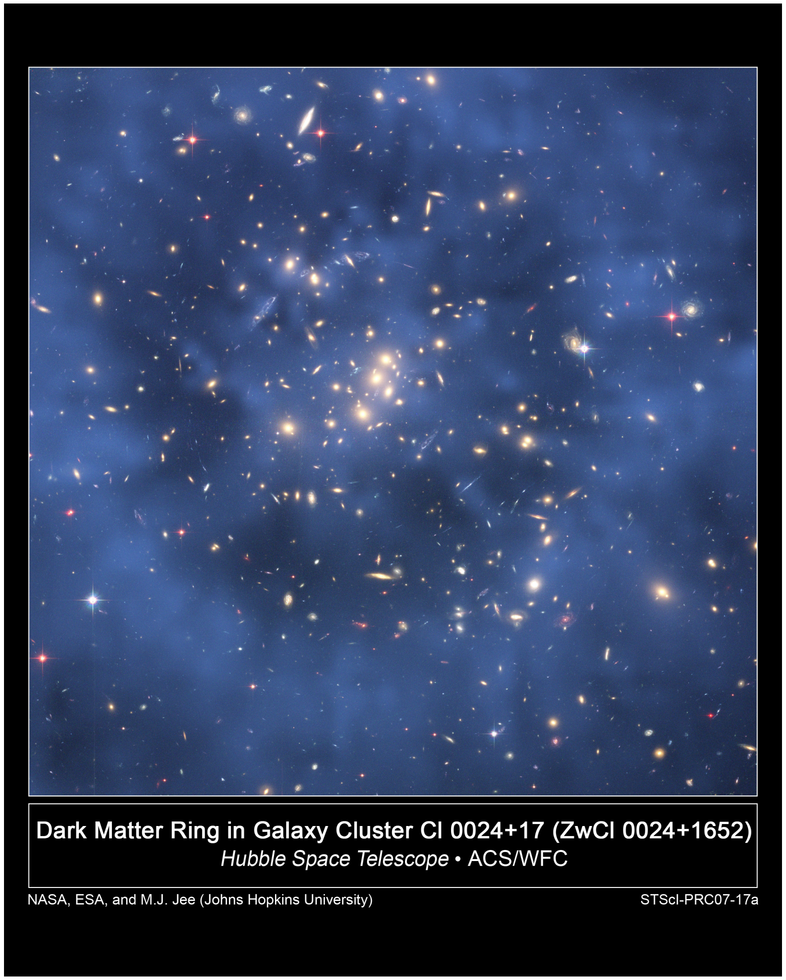
- ΔB small, but still too big to explain! $\Rightarrow$ New Physics

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, light
  - 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* $\lesssim M_{\rm DM} \lesssim 10^{68}$ *eV*

($\sim$ 90 orders of magnitude!)

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)

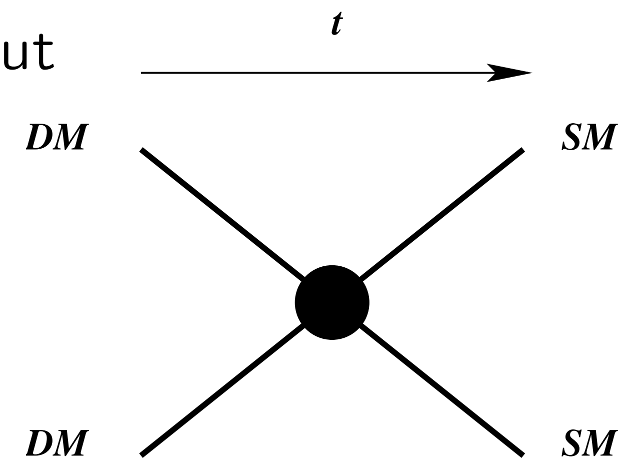
- SM extensions often introduce/require new symmetries

- 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)

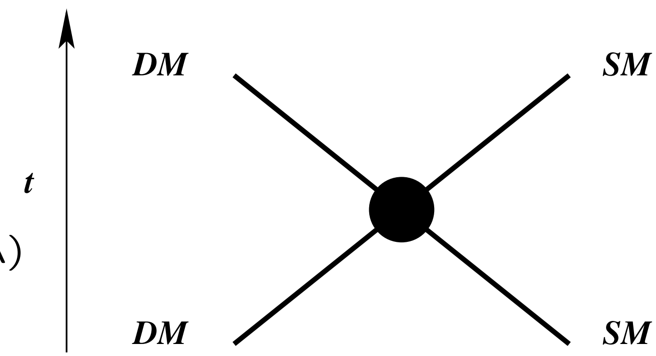
Feng and Kumar, 2008

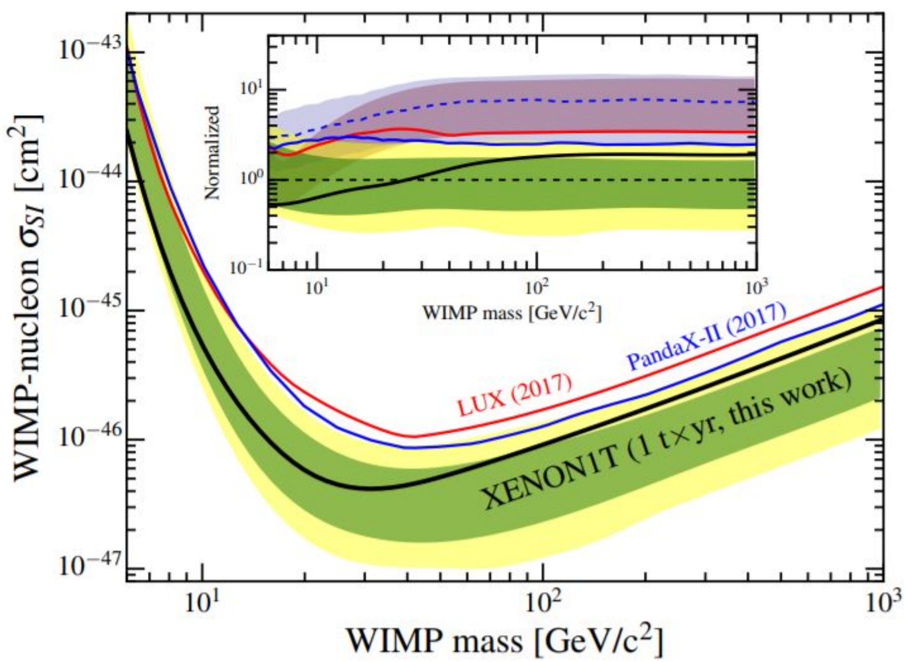
- **WIMPs: the main focus of DM searches**

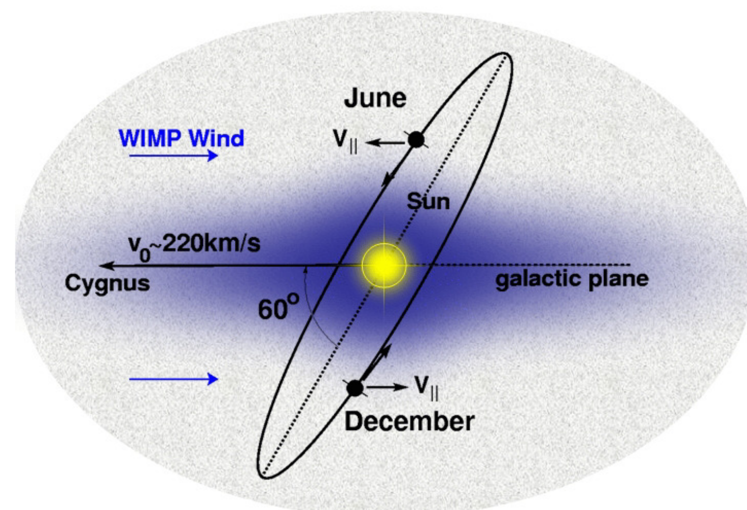
- DAMA/LIBRA, CDMS, Xenon10, CDMSII, Xenon100, LUX, Fermi GST...

Direct WIMP DM Searches

- Recoil off atomic nuclei (electrons)
  - Energy deposition (ionization, scintillation, . . .)
  - Motion of Sun within Galaxy: WIMP wind
  - Earth's motion: seasonal modulation (DAMA/LIBRA)







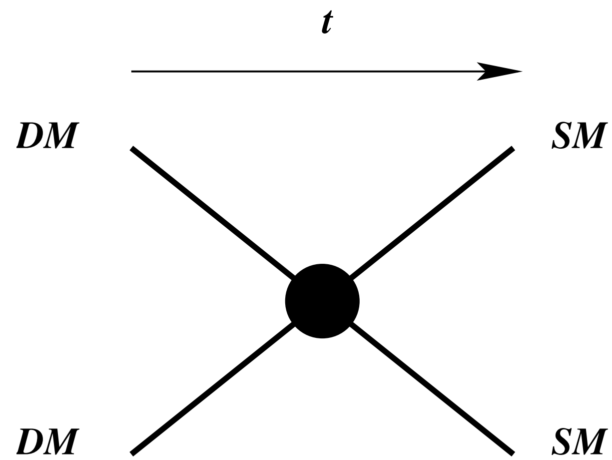
E. Aprile *et al.* [XENON Collaboration], Phys. Rev. Lett. **121**, no. 11, 111302 (2018)

- General feature: $m_{\rm DM} \lesssim$ **few GeV** poorly constrained (low recoil energy)

Other avenues for WIMP search:

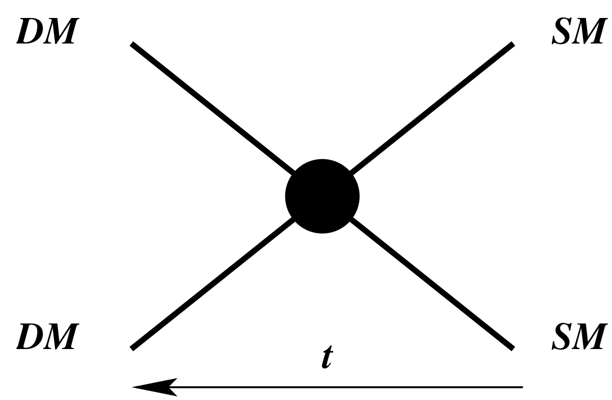
- Indirect searches: self-annihilation signals

- Related to thermal relic density
- Complicated by astrophysical backgrounds



- Collider production: LHC

- Search for missing energy in events



Dark Sectors and Dark Forces

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

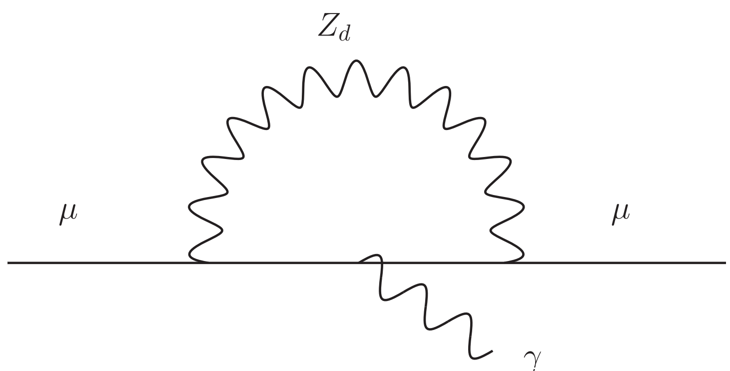
- Simple example: a “dark” sector $U(1)_d$
- Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d
- Interaction with SM: dim-4 operator (portal) via *mixing*

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

Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- Explaining 3.5σ $g_\mu - 2$ anomaly: $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 276(80) \times 10^{-11}$

Fayet, 2007 (direct coupling)
Pospelov, 2008 (kinetic mixing)



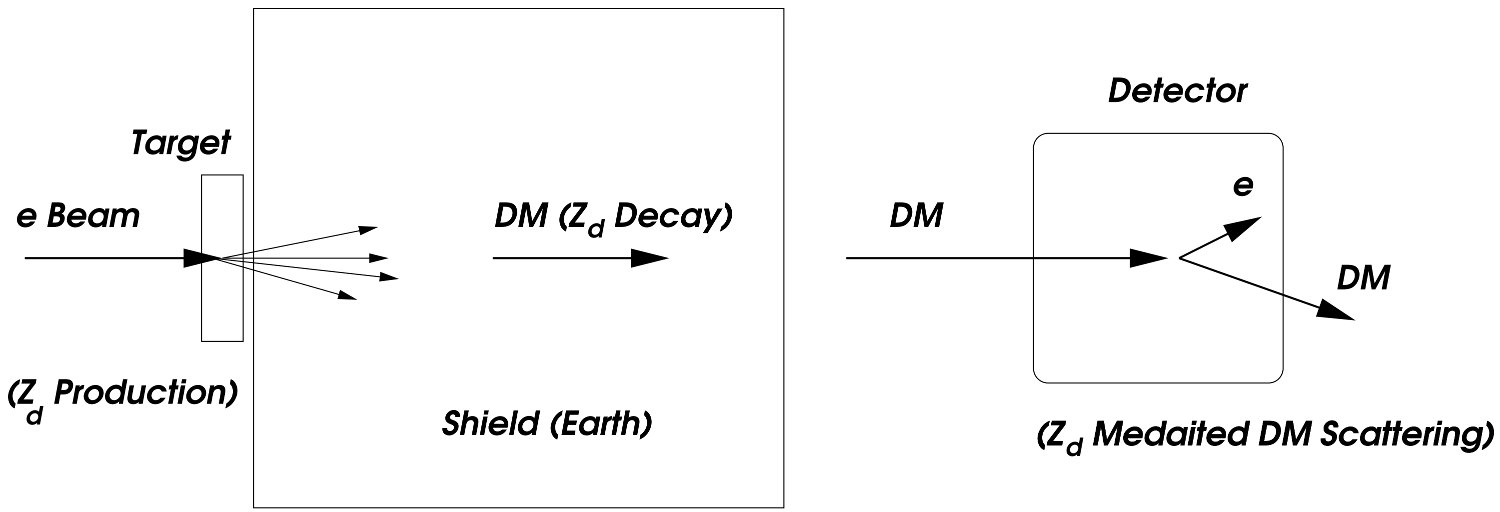
Invisible Z_d and Low Mass DM Production

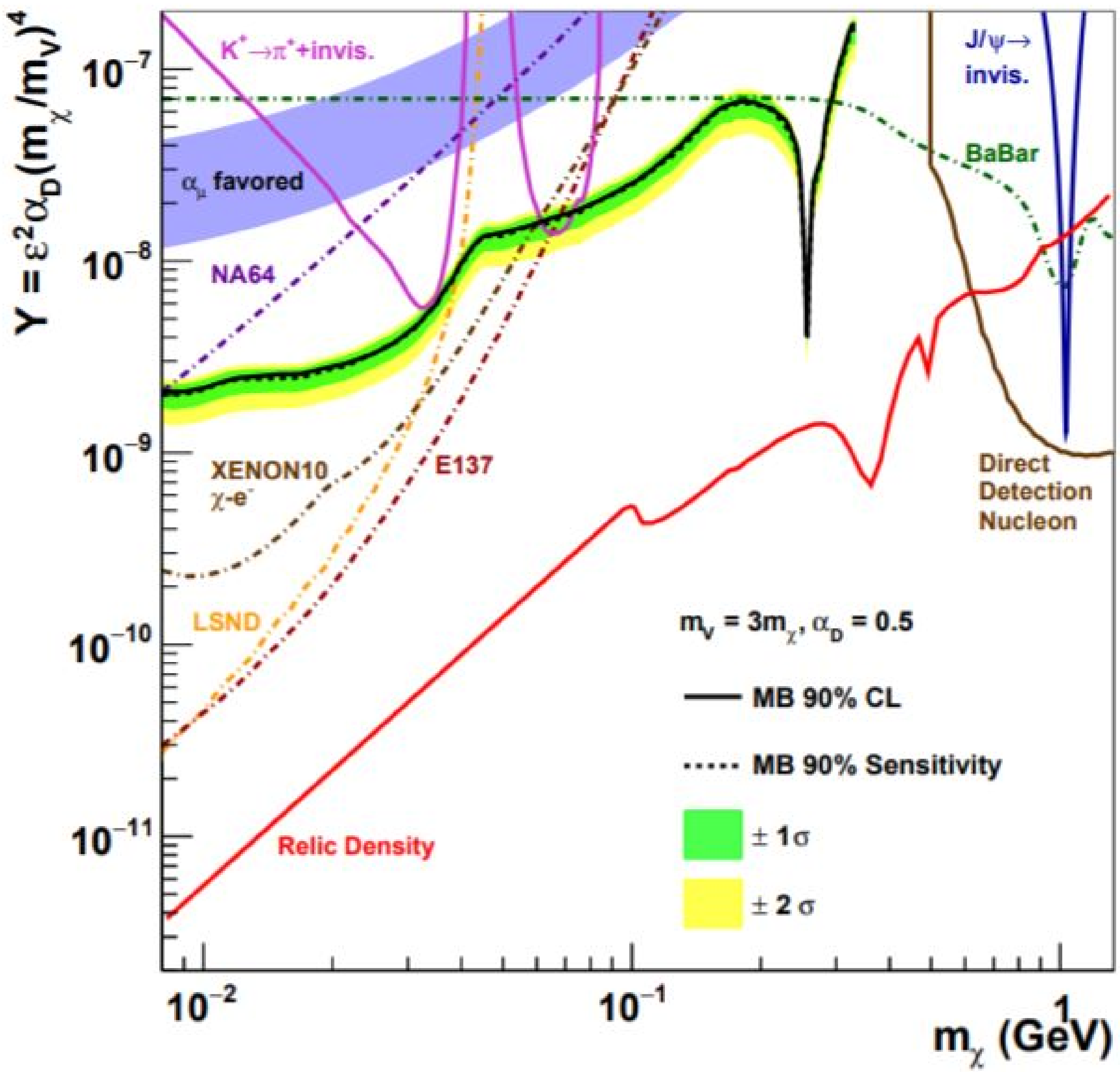
- Possible production and detection of *DM beams* in experiments

- p or e on fixed target $\Rightarrow$ production of boosted Z_d (meson decays, bremsstrahlung,. . .)
- Z_d beam decays into DM which can be detected via Z_d exchange
- Event rate depends on $\alpha_d \equiv g_d^2/(4\pi)$ and ε^2

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

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





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

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

Solid line: quark/nucleon coupling; Dot-dashed: electron coupling; χ: scalar DM

Concluding Remarks

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

- Higgs discovered at LHC, appears to conform to and complete SM
- The "no-lose" theorem $\lesssim 1$ TeV for SM; no "guarantees" henceforth

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

- No firm evidence for any of the associated proposed physics
- Perhaps still early, but new organizing principles may be needed

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

- Neutrino masses: requires physics beyond SM, but typically elusive
- Dark matter: robust evidence for new physics, potentially accessible
- Wide range of possibilities at this point
- WIMP dark matter: Motivated by "naturlaness" of m_H (under strain)