Visible and Invisible Clues for New Physics

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\( \hbar \approx 1.05 \times 10^{-34} \text{ J s} \quad \text{;} \quad c \approx 3.0 \times 10^{8} \text{ m/s} \)

\( \hbar = c = 1 \) in what follows

Mass and Energy measured in eV

Length \( \leftrightarrow \frac{1}{\text{Mass}} \)

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

proton mass \( \approx 1 \) 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 $\rightarrow$ Geodesic.

**Earth’s Orbit**

- Basis of modern cosmology.

Einstein’s equations:

\[ G_{\mu\nu} = 8\pi G_N T_{\mu\nu} \]

$G_N$ Newton’s constant, $\mu, \nu = 0,1,2,3$ (spacetime).
★ Detection of Gravitational Waves ★

- Directly confirms a long-standing (∼100 year) GR prediction
- Manifestation of the dynamical nature of spacetime

![GW150914 (29, 36) \(M_\odot\) \nGW151226 (8, 14) \(M_\odot\) (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
Apple on the ground: EM

- Atoms in apple and ground: EM forces stop the fall.
- Atom: Nucleus \((p\text{ and } n)\) 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 \([SU(3) \text{ (QCD)}]\):

- Short-ranged, confined to nuclear distances \(\sim 10^{-15}\text{m} \).
- Gluons \((g)\) bind quarks into **hadrons** \((\text{hadros: Greek for “bulky”}): p, n, \pi^0 (\bar{q}q), \ldots\)
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: $\Delta x \sim c \Delta t \sim h/(mc) \sim 10^{-18} \text{ m.}$ (Heisenberg uncertainty)

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

Massless photon, $\gamma$, long-ranged

* 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: $2 \times 7000$ GeV (design)
Currently running at $2 \times 6500$ GeV
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?)
- $m_\nu = 0$ (Strongly disfavored by data!)

★ Aside: Visible mass in universe mostly from QCD.
July 4th, 2012, discovery announced at CERN:

New scalar $H$ discovered at $\sim 125$ GeV!

![Graph showing signal strength and mass distribution for ATLAS and CMS experiments.]

Early Run 1: $\sim 10$ fb$^{-1}$

Total Run 1: $\sim 25$ fb$^{-1}$[JHEP08(2016)045]

More data available at 13 TeV (Run 2)
Nearly all* measurements in agreement with SM+GR.

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

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 276(80) \times 10^{-11} \quad a_\mu \equiv (g_\mu - 2)/2$$

* 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: \( \frac{F(\text{Grav})}{F(\text{EM})} \sim 10^{-40!} \)

Gravity: the weakest known interaction

Newton’s Constant: \( G_N = 6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2} \)

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

Gravity scale: Planck mass

\[ M_P \equiv (\hbar c/G_N)^{1/2} \approx 10^{19} \text{ GeV} \sim (10^{-35} \text{ m})^{-1} ! \]

\[ M_P \gg m_W \]

\( \hbar = c = 1. \)
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 \( \langle H \rangle \rightarrow M_P \).

\[
\text{heavy (} M \text{)} \\
\quad \\
\text{light (} m \text{)} \\
\quad \\
\lambda^2 \quad (\text{coupling}) \\
\quad \\
\delta m^2 \sim \lambda^2 M^2
\]

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

0.0000000000000000000000000000000001

- 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 ↔ 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).
    ⇒ 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:
  \[ m_\nu \lesssim 10^{-6} m_e \]

- Simple extension: right-handed neutrinos \( \nu_R \)

- Typically, difficult to test:
  - \( \nu_R \) very massive or else negligible coupling to SM

**Cosmology**

- Dark Matter: neutral, cosmologically stable
95% of Cosmos: unknown!

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

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

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

- 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)

- \( \Delta B \) small, but still too big to explain! ⇒ 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: $10^{-22} \text{ eV} \lesssim M_{DM} \lesssim 10^{68} \text{ eV}$

($\sim 90$ 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 $M_{\text{new}} \gtrsim M_H(\approx 125) \text{ GeV}$: 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

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

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

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

- Weak scale ($\sim \text{TeV}$) theoretically motivated

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

- 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)


- Gray areas: CMSSM favored; dot: $^8$B solar $\nu$-nucleus coherent scattering
- General feature: $m_{DM} \lesssim \text{few GeV}$ 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

- Explaining $3.5\sigma \, g_\mu - 2$ 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 $\varepsilon^2$

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

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

“Dark Matter Search in a Proton Beam Dump with MiniBooNE”

Solid line: quark/nucleon coupling; Dot-dashed: electron coupling; $\chi$: 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), $\bar{\theta}$ (CP violation) in QCD, . . .

• 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 “naturalness” $m_H$ (which is under strain)