Standard Model: Necessary but not Sufficient

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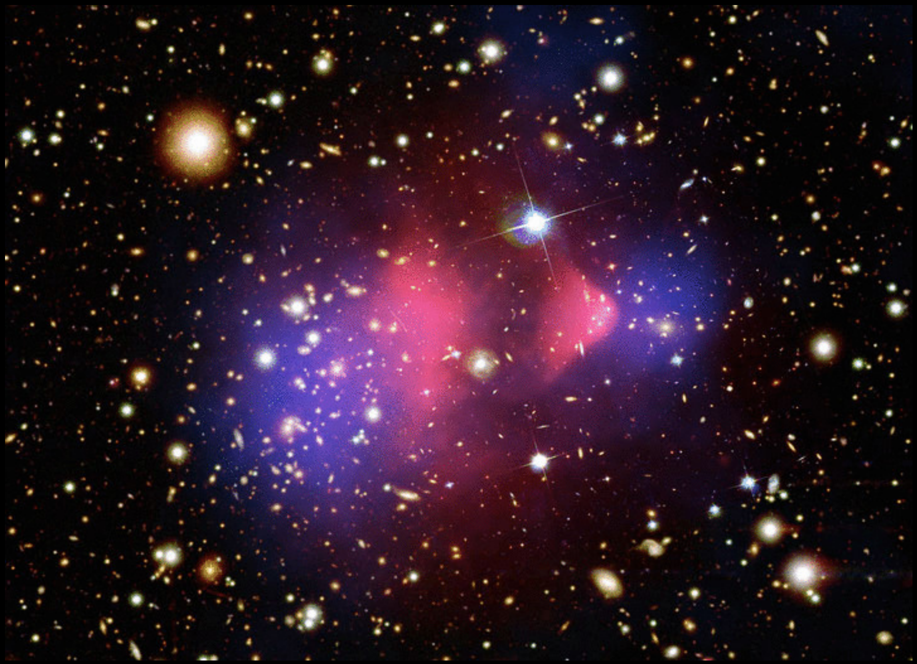


SULI Lecture, Physics Department, BNL

June 9, 2025

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

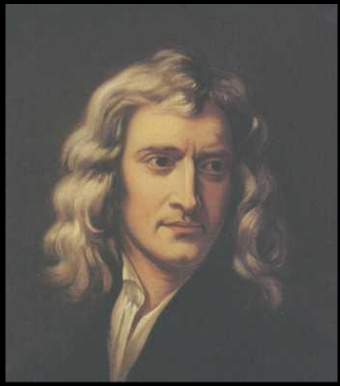
proton mass ≈ 1 GeV

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

Everyday life:

Gravity and Electromagnetism (EM)

Falling Apple: Gravity

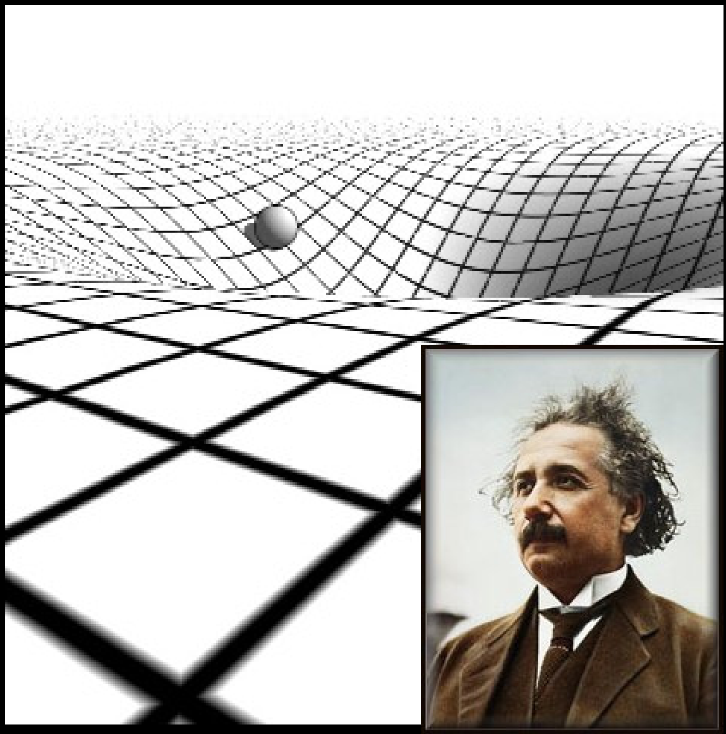


Well-described by Newtonian gravity

State of the Art: General relativity (GR)

- Spacetime curved by matter/energy.

Sun



- Gravitational Force $\rightarrow$ 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)

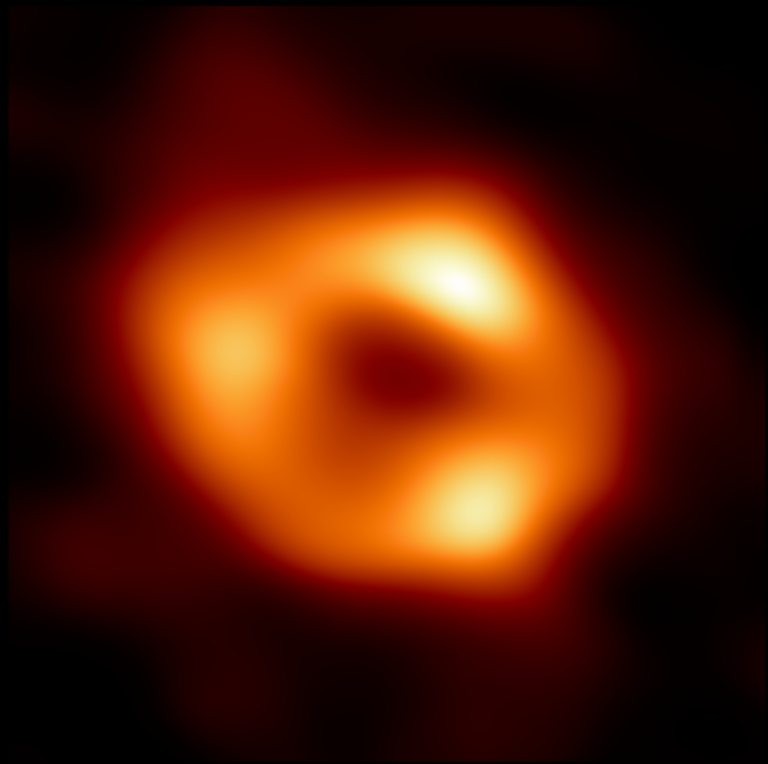
- Has opened a new field of astronomy

⋆ 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



Shadow of SgrA* (center of Milky Way), Event Horizon Telescope

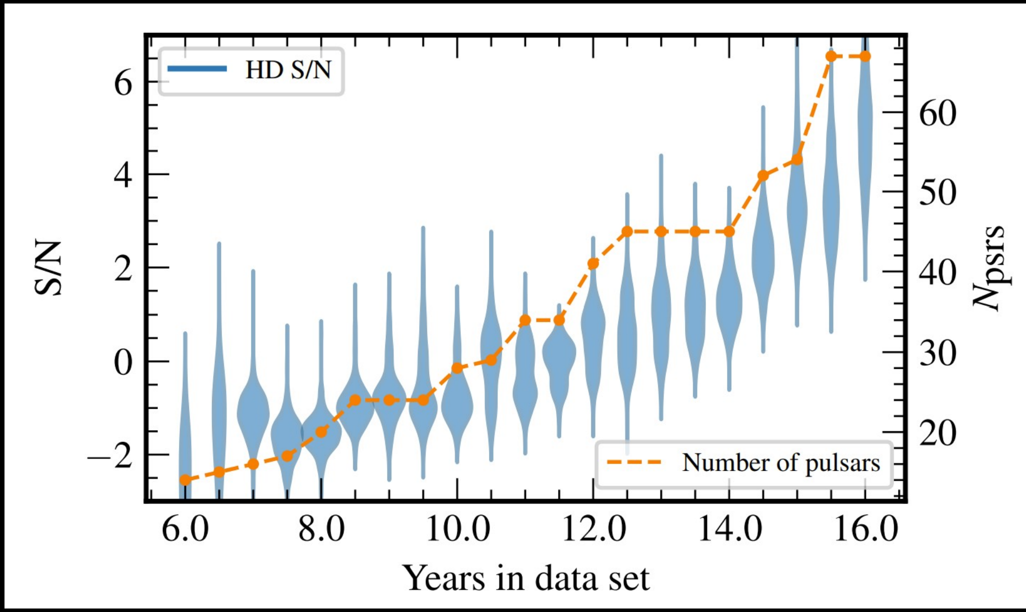
Mass: $\sim$ 4 Million Solar Masses ; Distance: $\sim$ 27000 Light Years

Results released May 12, 2022

Q: Can we deduce something interesting about black holes by looking at the images?

Evidence for stochastic gravitational wave background

- Pulsar timing measurements: NANOGrav, EPTA, Parkes, CPTA,...
- Could be from supermassive black hole binaries
- Alternate potential source: primordial processes ($t \ll 1$ s)
  - For example, a phase transition: colliding bubbles,...



NANOGrav Collaboration, Astrophys.J.Lett. 951 (2023) 1, L8

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):

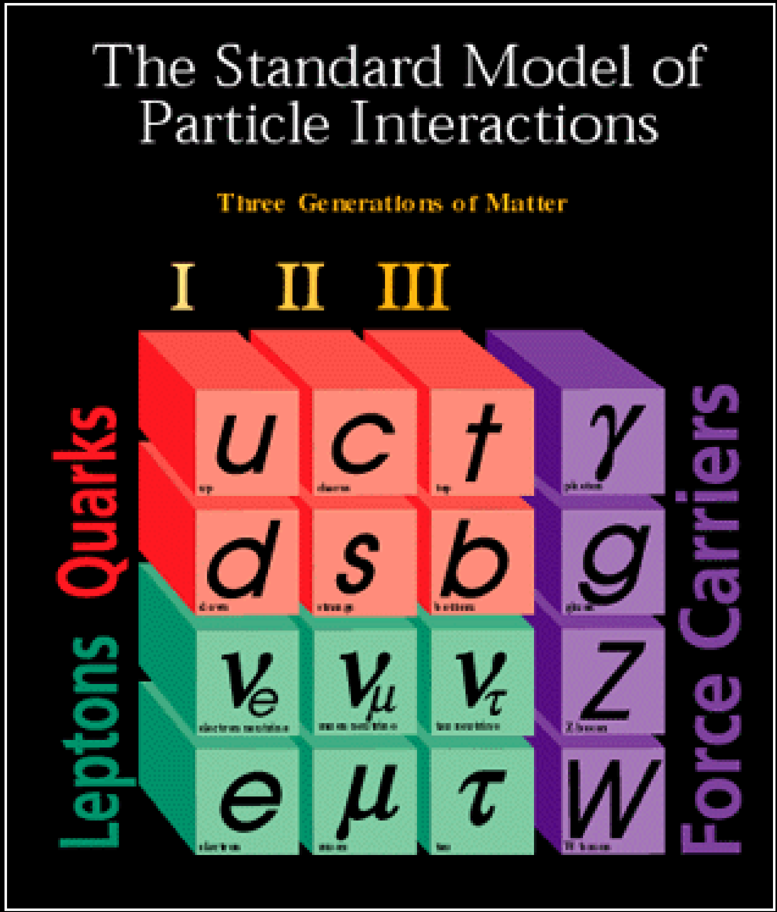
Most precise description of microscopic physics

- **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



- **Gauge Fields, spin-1**

Force mediators, generalized photons

- **Key piece missing before 2012**

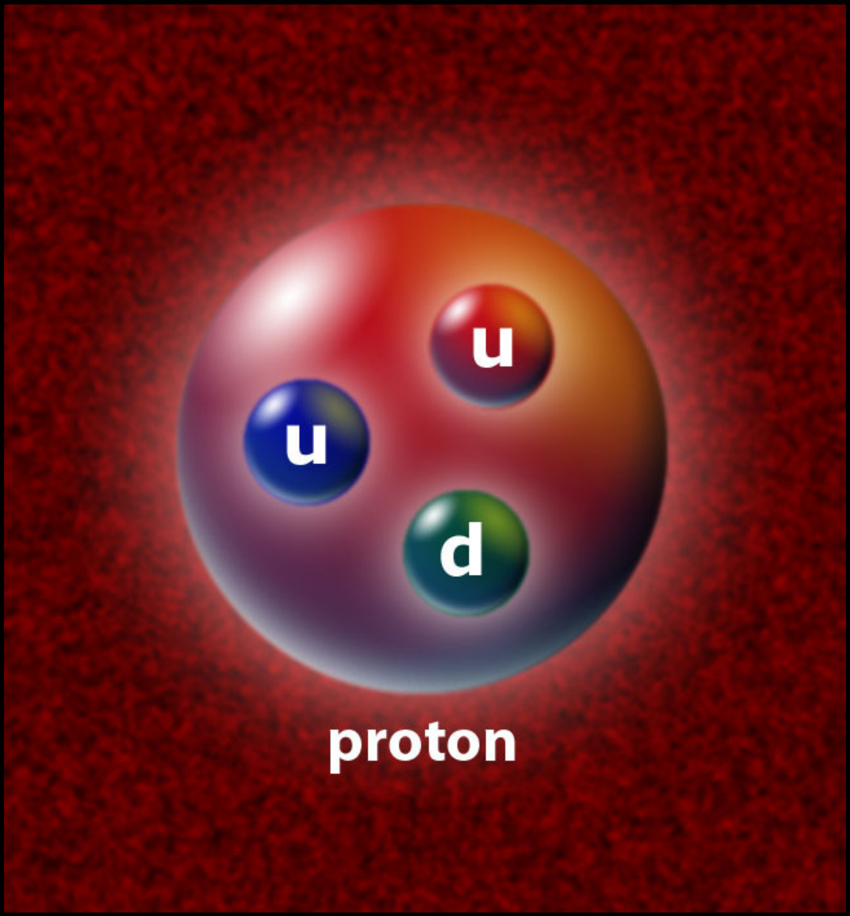
* Spin: intrinsic angular momentum (quantum mechanics)

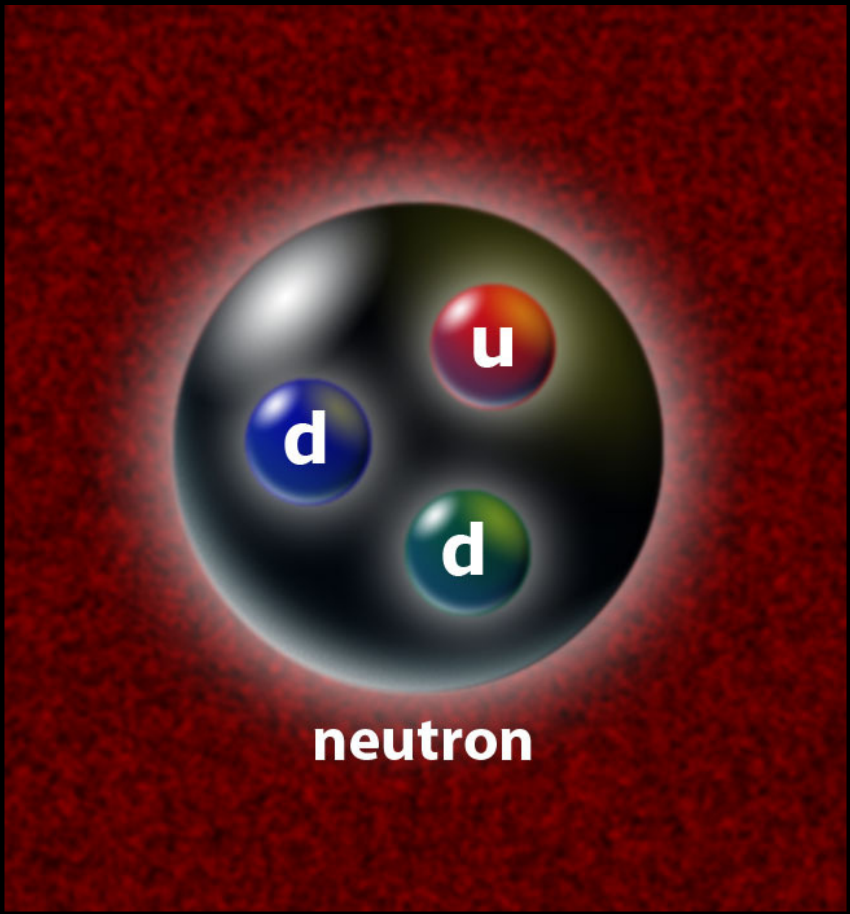
Strong Interactions [$SU(3)$ (QCD)]:

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 ($\bar{q}q$),...



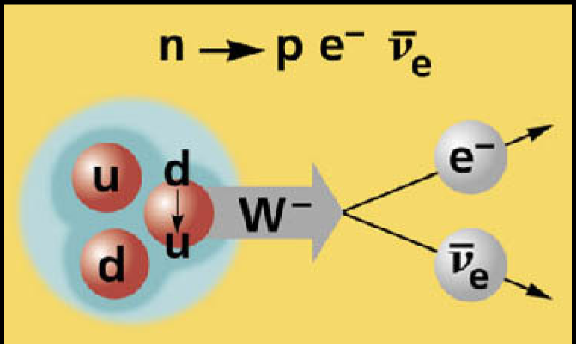


Electroweak Interactions $[SU(2)_L \times U(1)_Y]$:

- Spontaneously broken to EM

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

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?

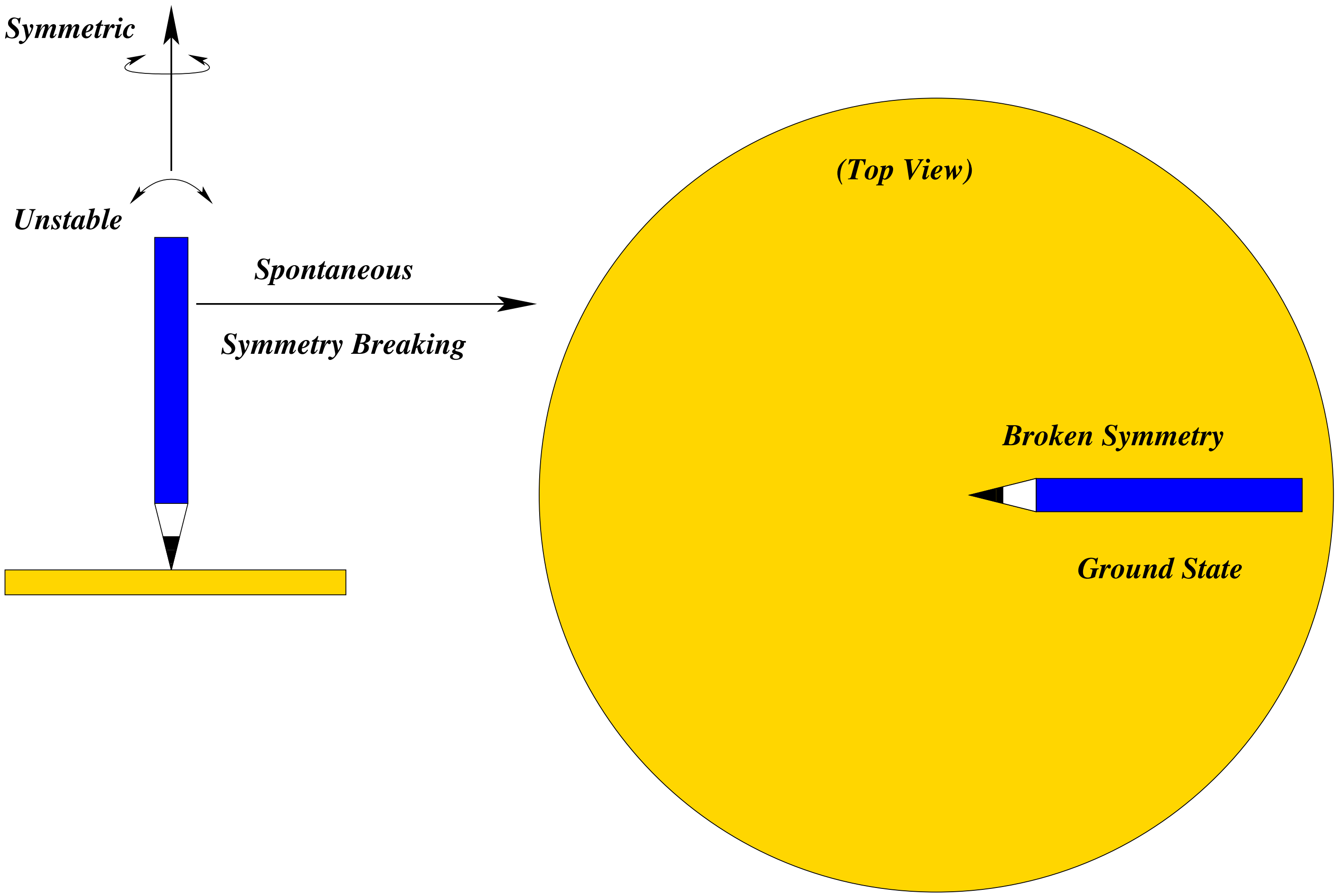
- EM: $U(1)_{EM}$ (QED)

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.



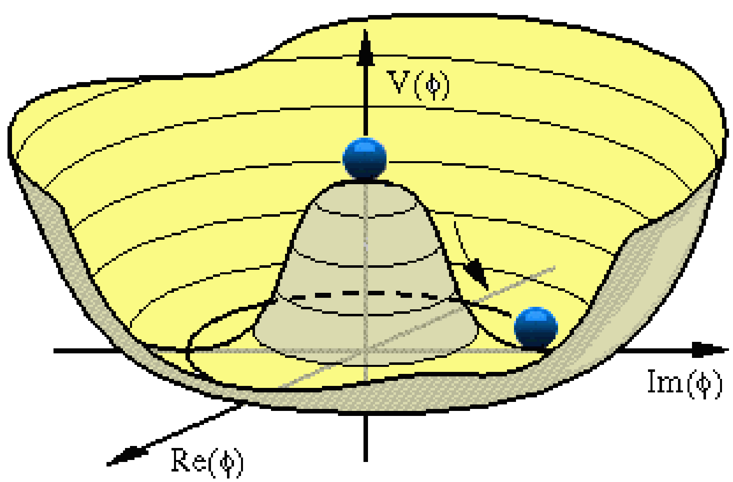
Electroweak Symmetry Breaking in SM

- 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!)

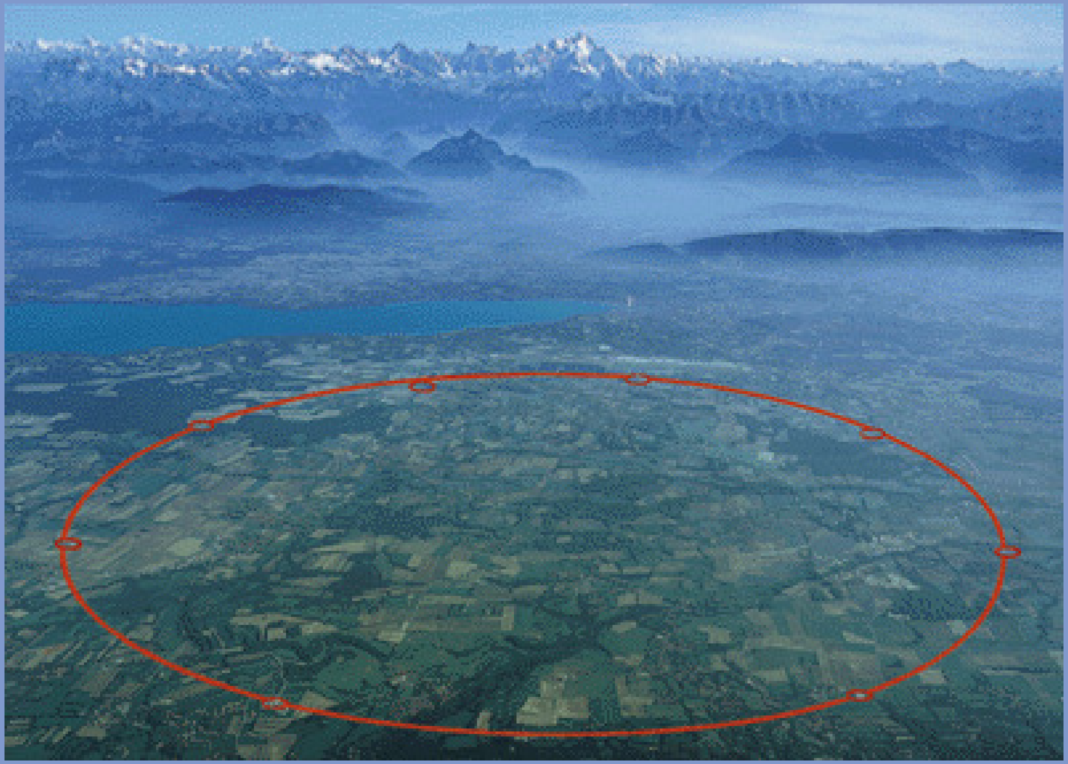


Q: How much of the "visible" mass in Universe is from $\langle H \rangle$?

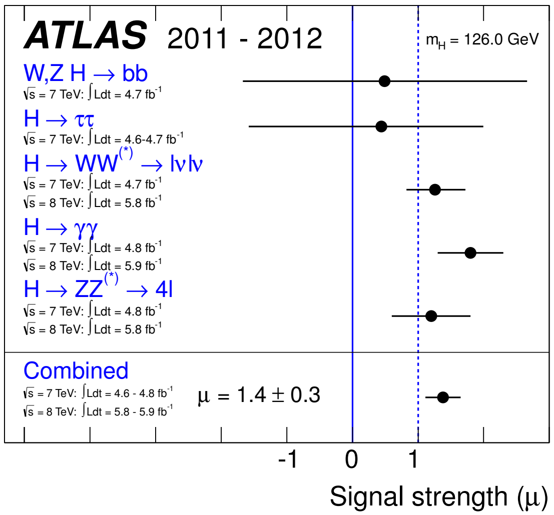
July 4th, 2012, discovery announced at CERN

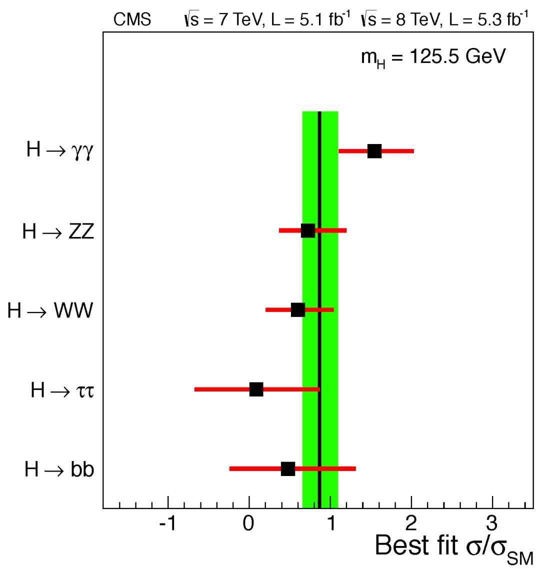
Scalar (spin-0) H boson discovered at the LHC, mass ~ 125 GeV

LHC: pp collider design beam energy: 2×7000 GeV
Circumference (km): 26.659

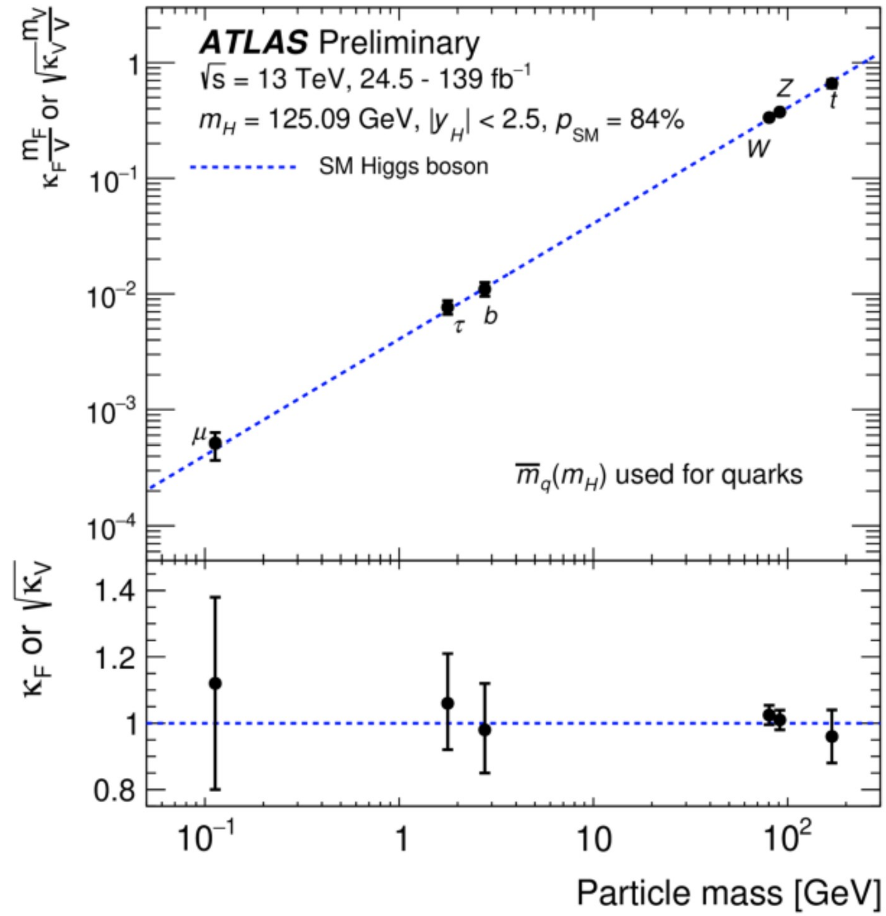


2×6800 GeV Run: since summer 2022





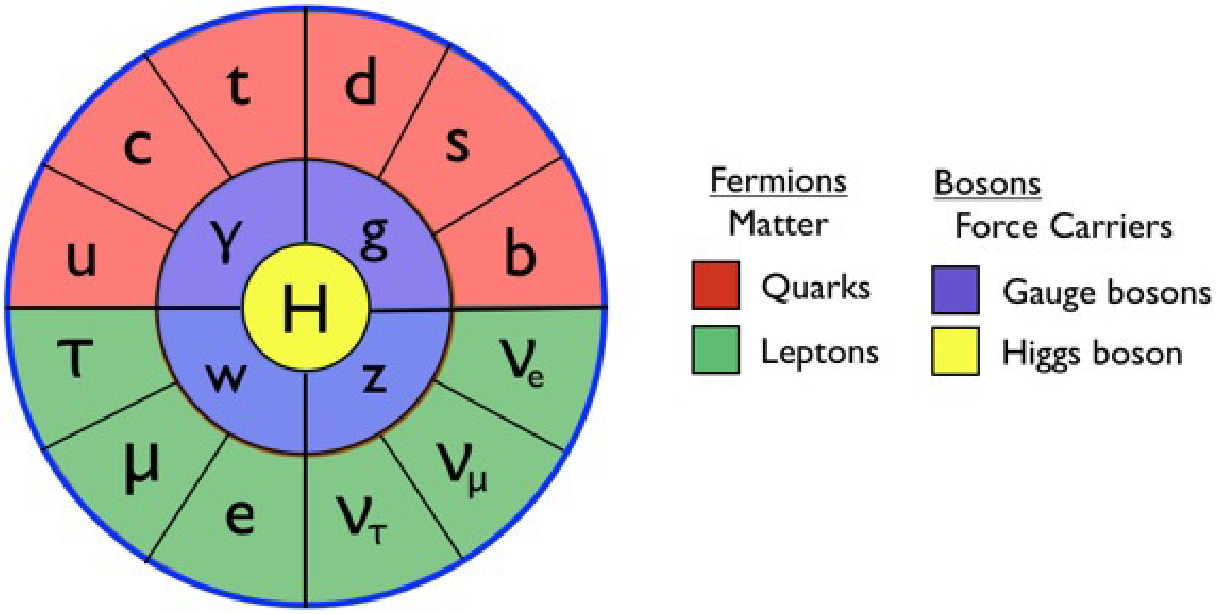
Early Run 1: $\sim 10\ \text{fb}^{-1}$



(Image: ATLAS Collaboration/CERN)

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 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)

$$M_P \gg m_H \qquad\qquad (\hbar = c = 1)$$

$\Rightarrow$ Hierarchy problem: one may expect quantum effects to push Higgs mass close to M_P; Higgs mass seems "unnatural"

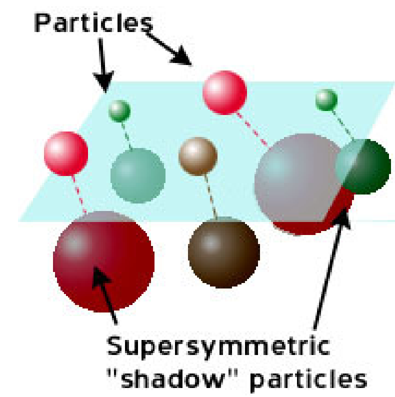
Hierarchy and New Physics Near m_H

- **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*

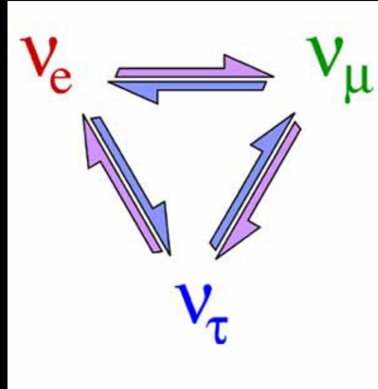
- *New physics elusive, or perhaps "naturalness" not the right guide*

Strong Empirical Evidence for Beyond SM

- ## Neutrino Flavor Oscillations

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

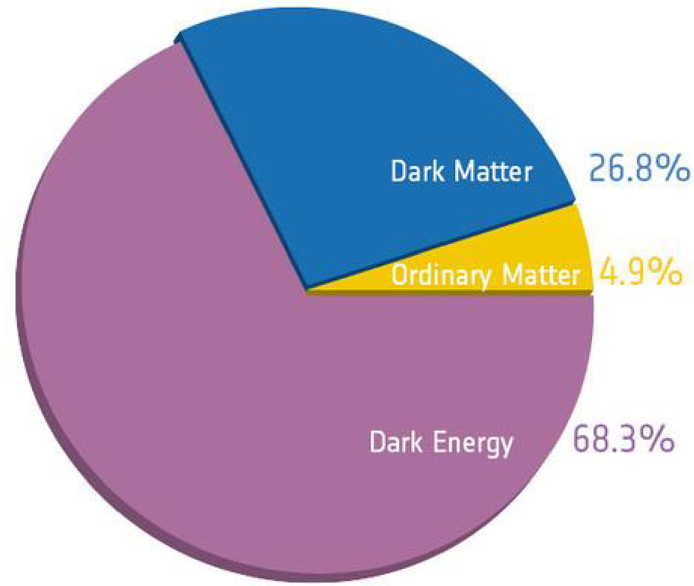
- ν_R very massive or else negligible coupling to SM

- ## Cosmology

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

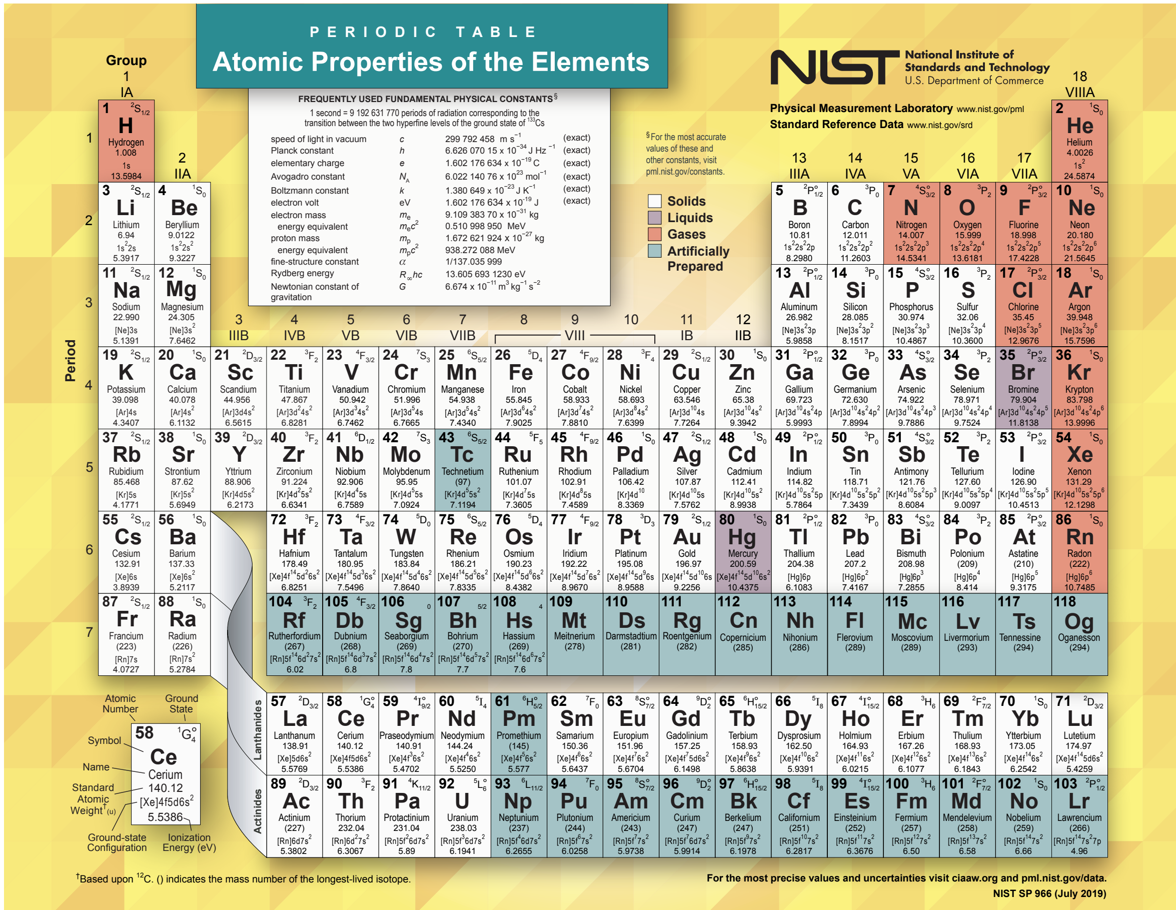
Cosmos: 95% unknown!

Planck



- **Dark energy: accelerated expansion of the Universe**
  - Unknown source
  - Could be vacuum energy, a cosmological constant (CC), no dynamics
  - CC may be in tension with recent results potentially hinting at time evolution
- **Dark matter: what is it?**
- **Ordinary matter: asymmetry (much more matter than anti-matter), but how?**

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

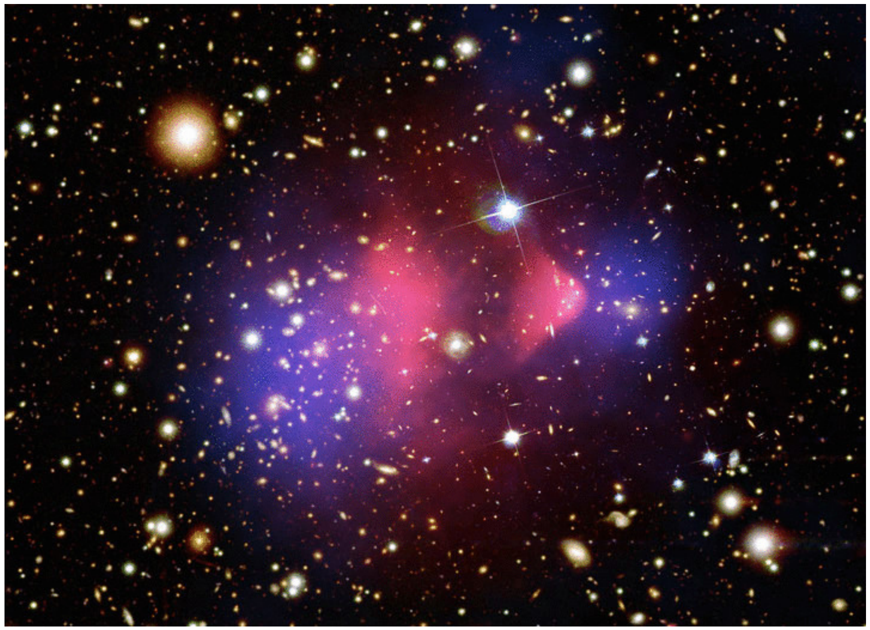
- Could be related to neutrino mass generation (heavy $\boldsymbol{\nu_R}$ states)

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, photons
  - Self-interactions not strong ($\sigma \lesssim 1$ barn)
  - Not explained in SM



Strongly motivates new physics

So far, evidence limited to gravity effects

Q: What is the significance of this image?

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!)

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

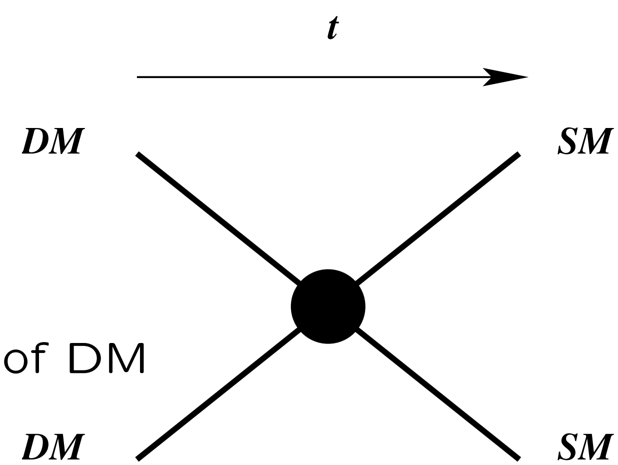
Searches often guided by *theoretical motivation*

- Example: The hierarchy problem in SM:

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

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

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



- Thermal relic density: annihilation, freeze-out

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

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

\- $g \sim g_{\rm weak}$, $M \gtrsim$ weak scale: roughly the right amount of DM

- Weak scale theoretically motivated

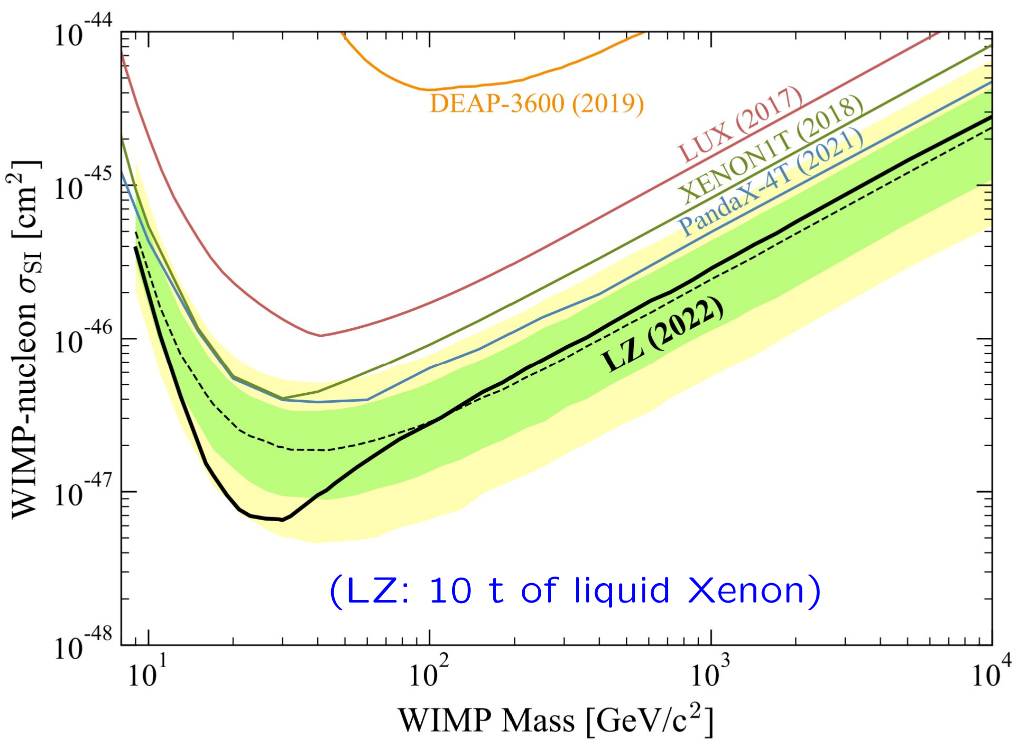
\- However, g^4/M^2 may be achieved otherwise (WIMPless Miracle)

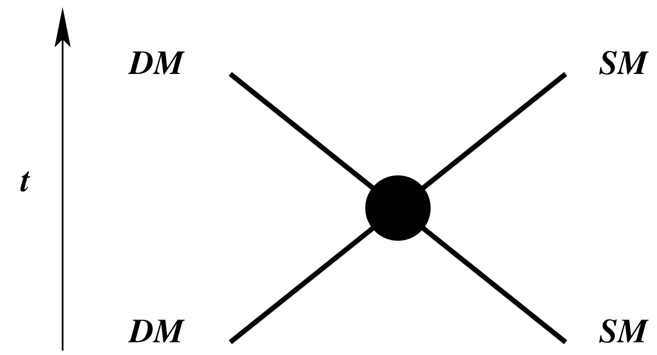
Feng and Kumar, 2008

Direct WIMP DM Searches

- WIMPs: have been a main focus of DM searches

- Recoil off atomic nuclei (electrons)





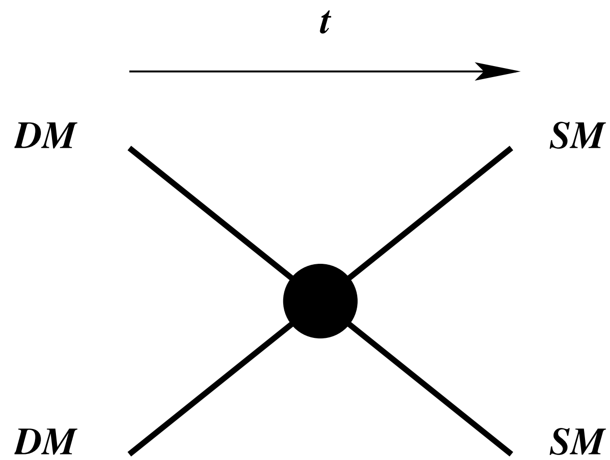
J. Aalbers *et al.*, The LUX-ZEPLIN (LZ) Collaboration, arXiv:2207.03764v3 [hep-ex]

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

Other avenues for WIMP search:

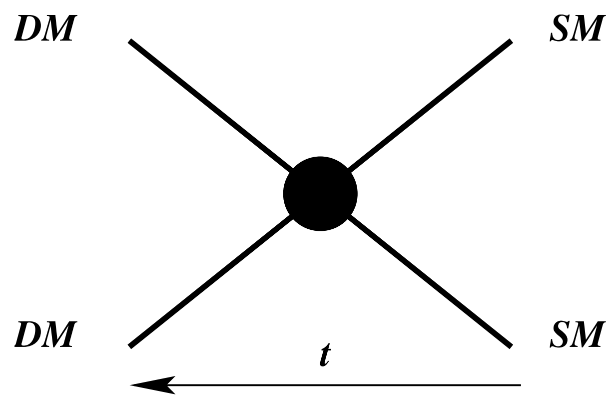
- Indirect searches: self-annihilation signals

- 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

• With lack of evidence for new physics near weak scale, other DM scenarios have been put forth in recent years

• Example: DM could be light and may reside in a separate sector with its own forces

• Analogy with SM

• DM interactions with SM are indirect

• Simple possibility: a "dark" sector $U(1)_d$

• Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d

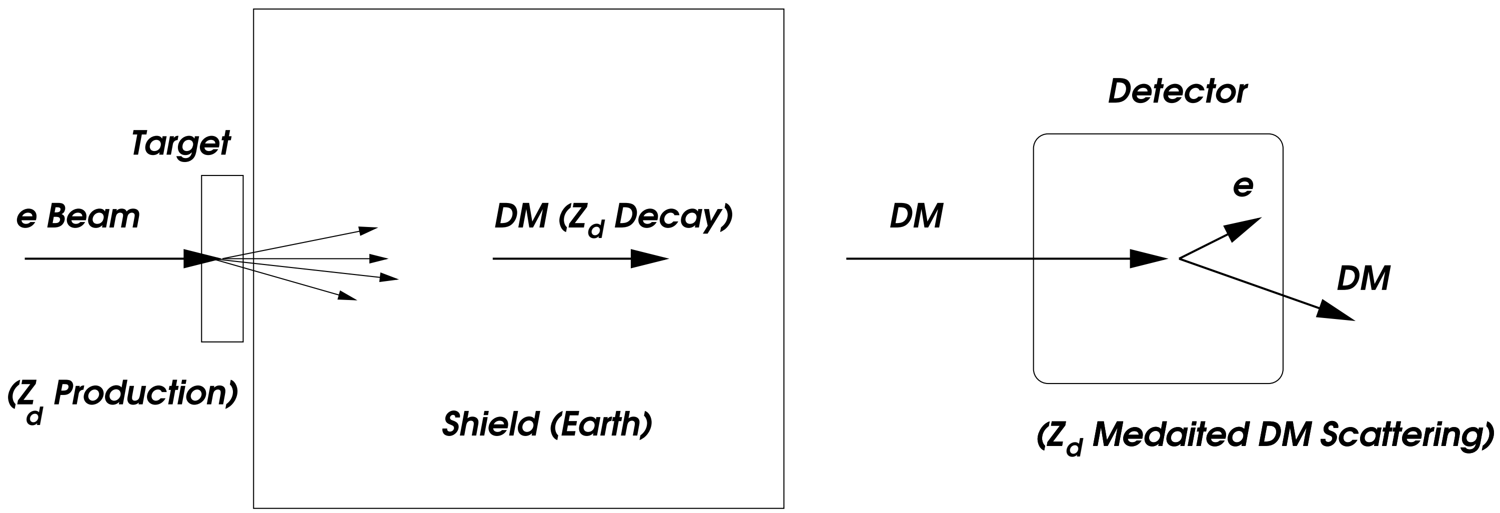
• $m_{Z_d} \lesssim 1$ GeV has been invoked in various contexts

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)

Also looking in the forward direction at LHC for neutrinos and light weakly interacting new physics; Faser, with early results   H. Abreu *et al.*, Faser Collaboration, Phys. Lett. B **848**, 138378 (2024)

Electron-Ion Collider

- New facility to be built at BNL; start of operation in early 2030's
- Main mission: study structure of nuclear matter and its constituents
- May also allow investigations of some possible dark sectors

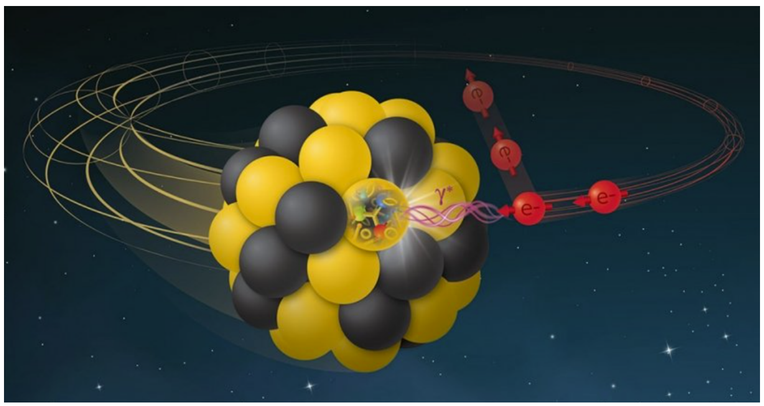
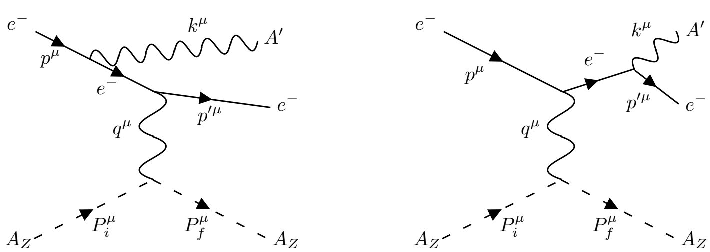
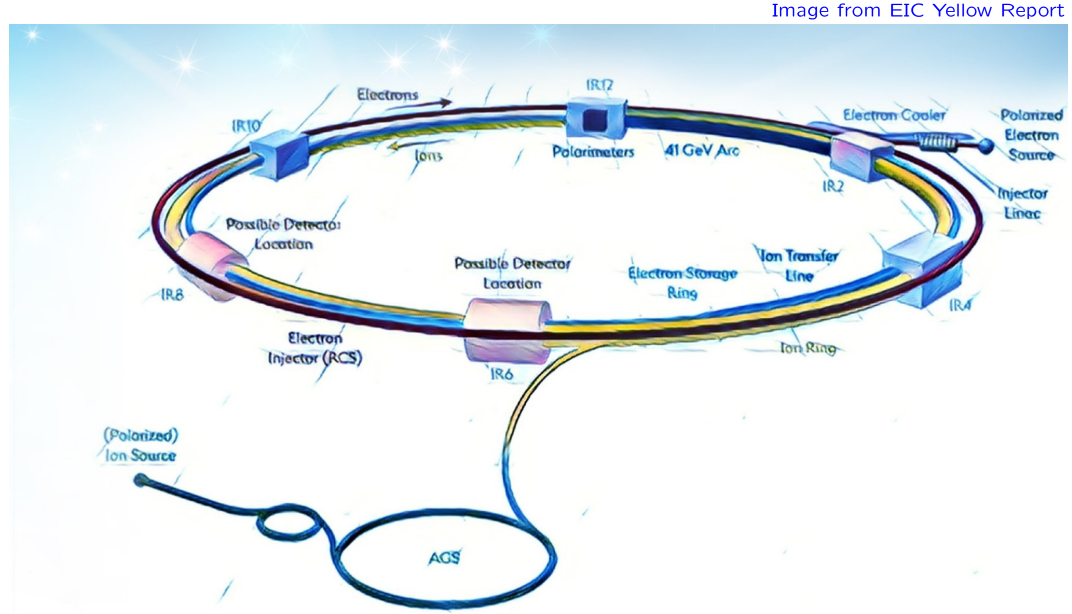


Image: Office of Science, DOE



From: H.D., Marcarelli, Neil, 2307.00102

Image from EIC Yellow Report

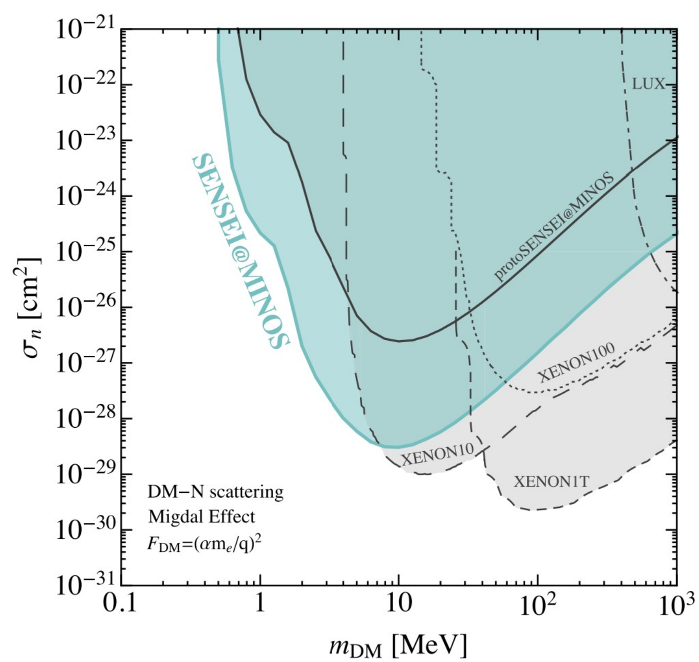


New Light DM Direct Detection Methods

- Example: Sub-Electron-Noise Skipper CCD Experimental Instrument (SENSEI)

"SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD," Phys. Rev. Lett. **125**, no.17, 171802 (2020)

We present the first direct-detection search for sub-GeV dark matter using a new ~2-gram high-resistivity Skipper CCD from a dedicated fabrication batch that was optimized for dark matter searches. Using 24 days of data acquired in the MINOS cavern at the Fermi National Accelerator Laboratory, we measure the lowest rates in silicon detectors of events containing one, two, three, or four electrons, and achieve world-leading sensitivity for a large range of sub-GeV dark matter masses. Data taken with different thicknesses of the detector shield suggest a correlation between the rate of high-energy tracks and the rate of single-electron events previously classified as "dark current." We detail key characteristics of the new Skipper CCDs, which augur well for the planned construction of the ~100-gram SENSEI experiment at SNOLAB.



(Among other results)

Concluding Remarks

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

- Higgs boson discovered at LHC, appears to complete SM
- Some potential modest deviations in current data; so far inconclusive

★ **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
- New detection methods required to cover viable parameter space

. . . 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)