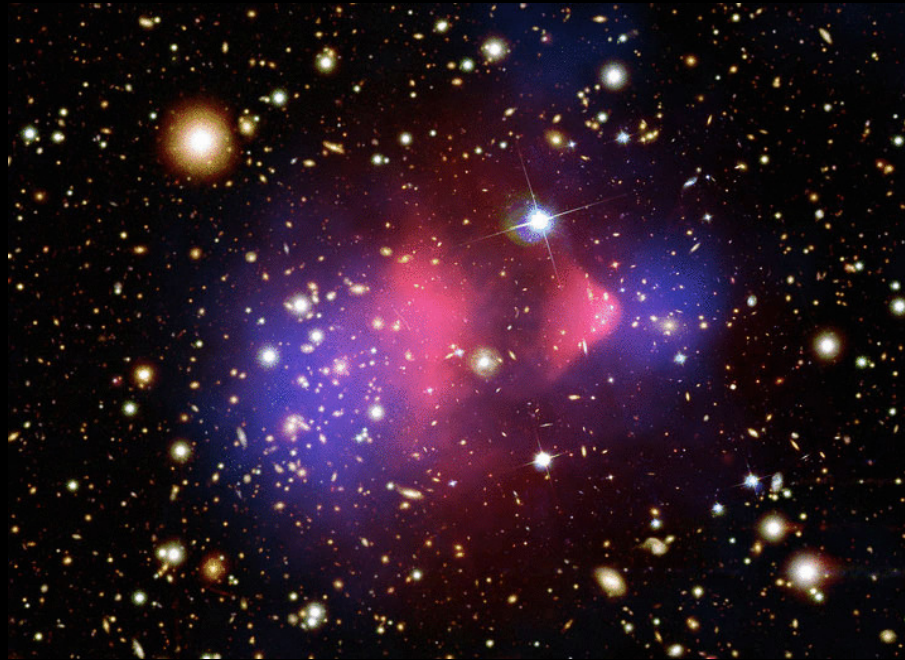


# *The Standard Model and Beyond*

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory



SULI Lecture, Physics Department, BNL

June 12, 2023

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

$\hbar = c = 1$  in what follows

Mass and Energy measured in eV

Length  $\leftrightarrow$  1/Mass

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

proton mass  $\approx$  1 GeV

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

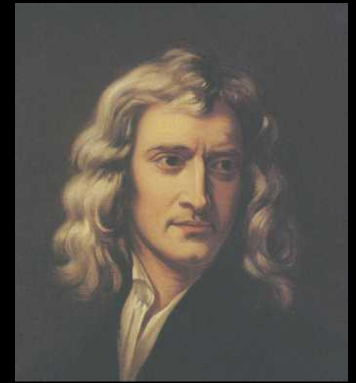
Everyday life:

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 → Geodesic.

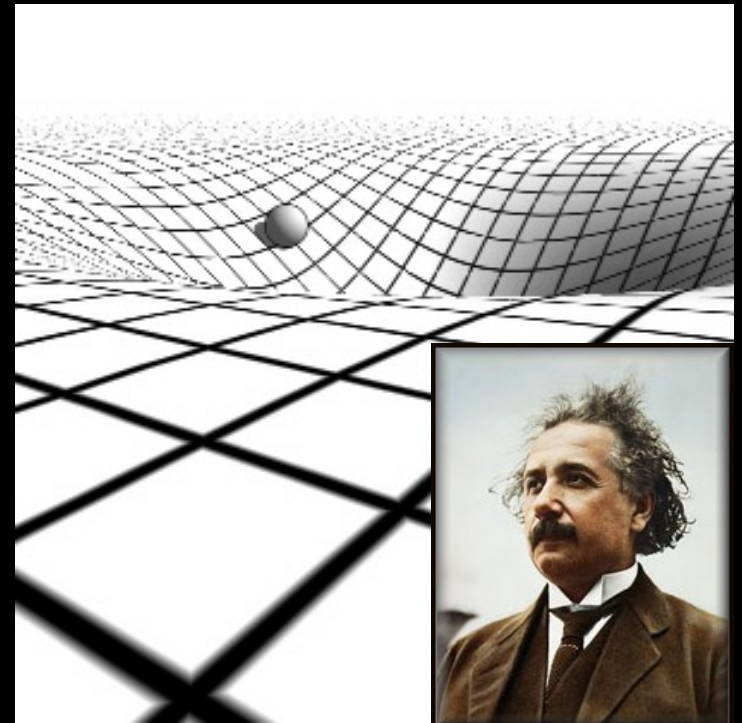
### Earth's Orbit

- 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

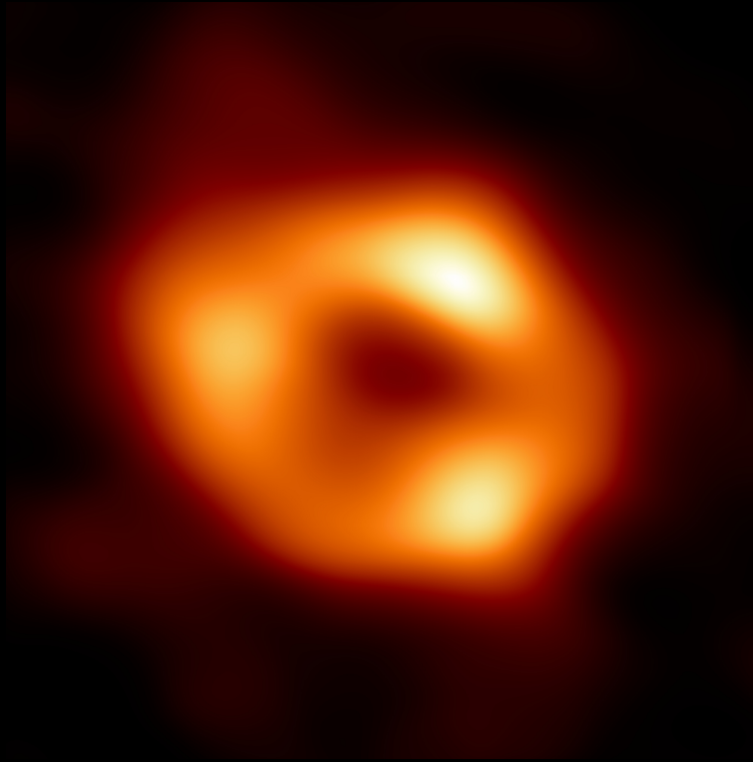
\* 2017 Nobel Prize in Physics: Barish, Thorne, and Weiss



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?

# 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:**  $SU(3)$ (strong)  $\times SU(2) \times U(1)$ (electroweak)

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

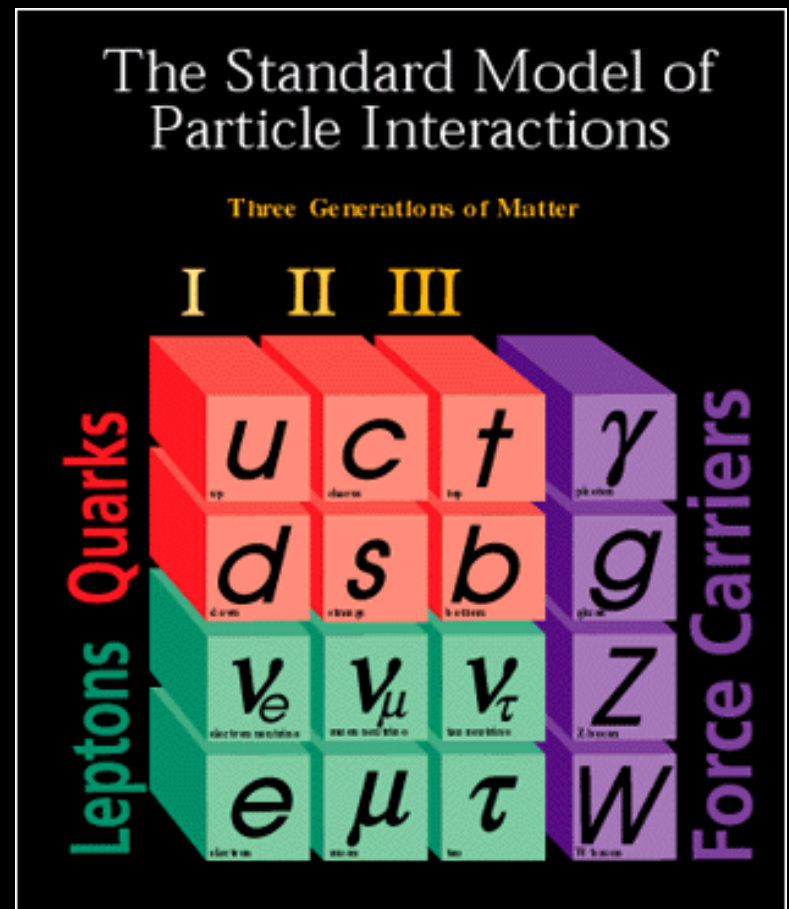
Quarks (+2/3, -1/3): Strong interactions

Leptons (0, -1): No strong interactions

- **Gauge Fields, spin-1**

Force mediators, generalized photons

- **Key piece missing before 2012**

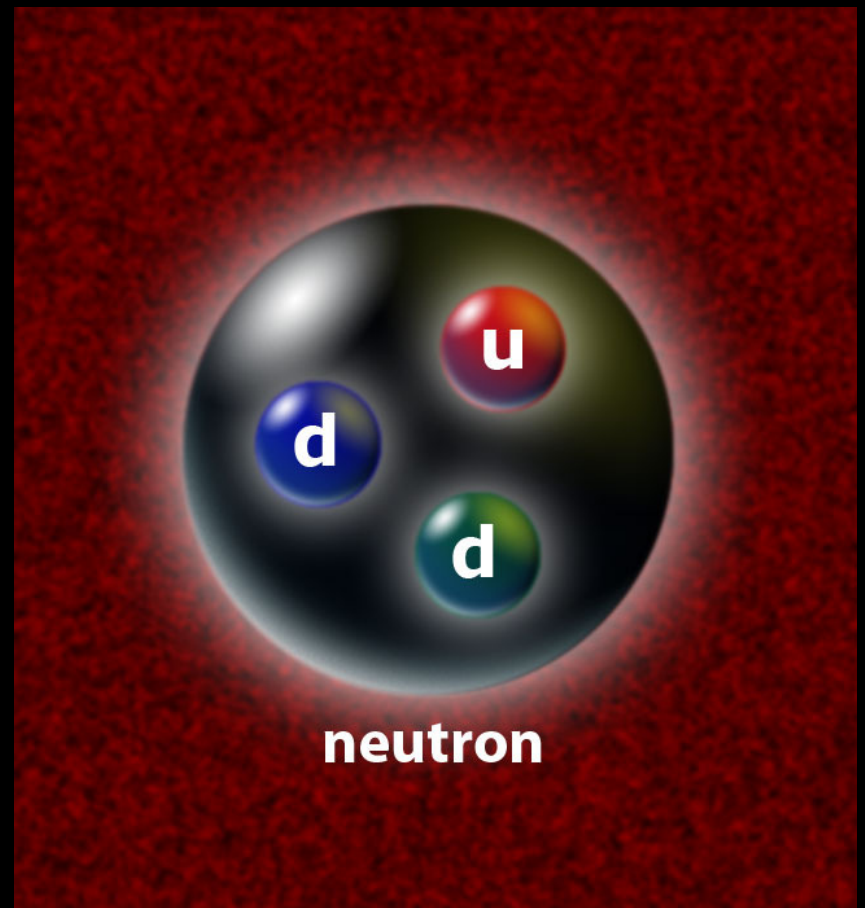
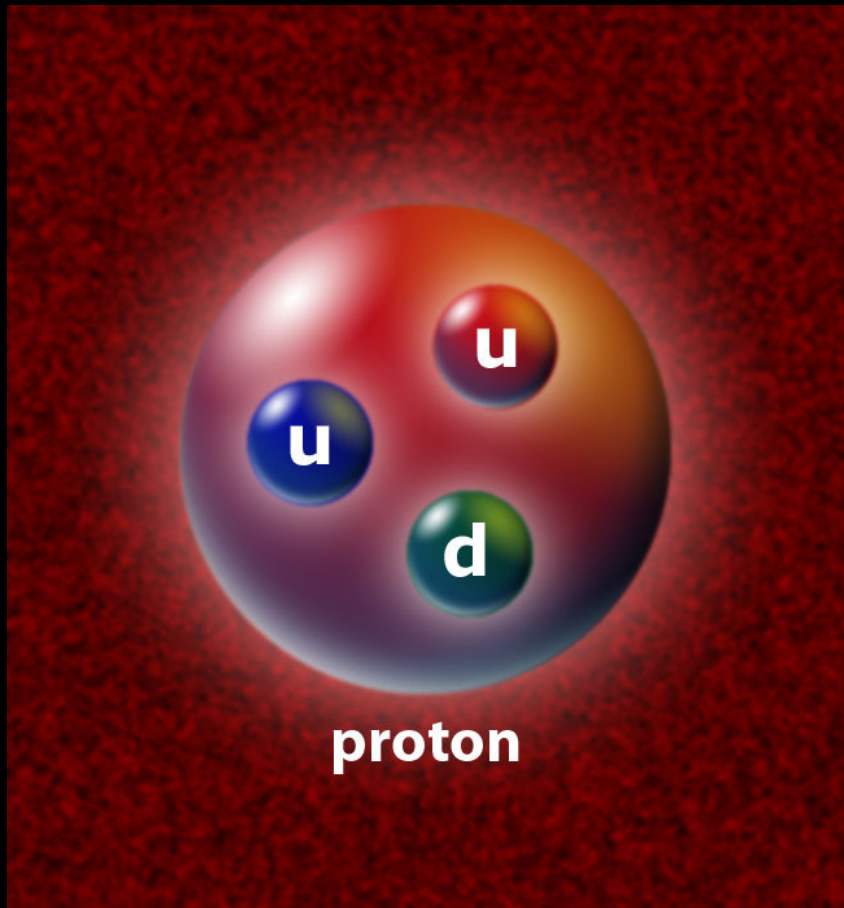


\* Spin: intrinsic angular momentum (quantum mechanics)

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

QCD: Quantum Chromodynamics (Lectures by R. Pisarski, 6/29; L. Ruan, 7/6; Y. Hatta, 7/24)

- Short-ranged, confined to nuclear distances  $\sim 10^{-15}$  m
- Gluons ( $g$ ) bind quarks into **hadrons** (*hadros*: Greek for “bulky”):  
 $p, n, \pi^0 (\bar{q}q), \dots$

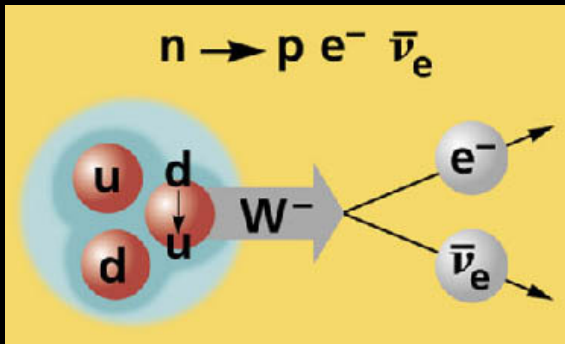


# Electroweak Interactions [ $SU(2)_L \times U(1)_Y$ ]:

- Spontaneously broken to EM

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

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



**Q: Why are there stable neutrons in atomic nuclei?**

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

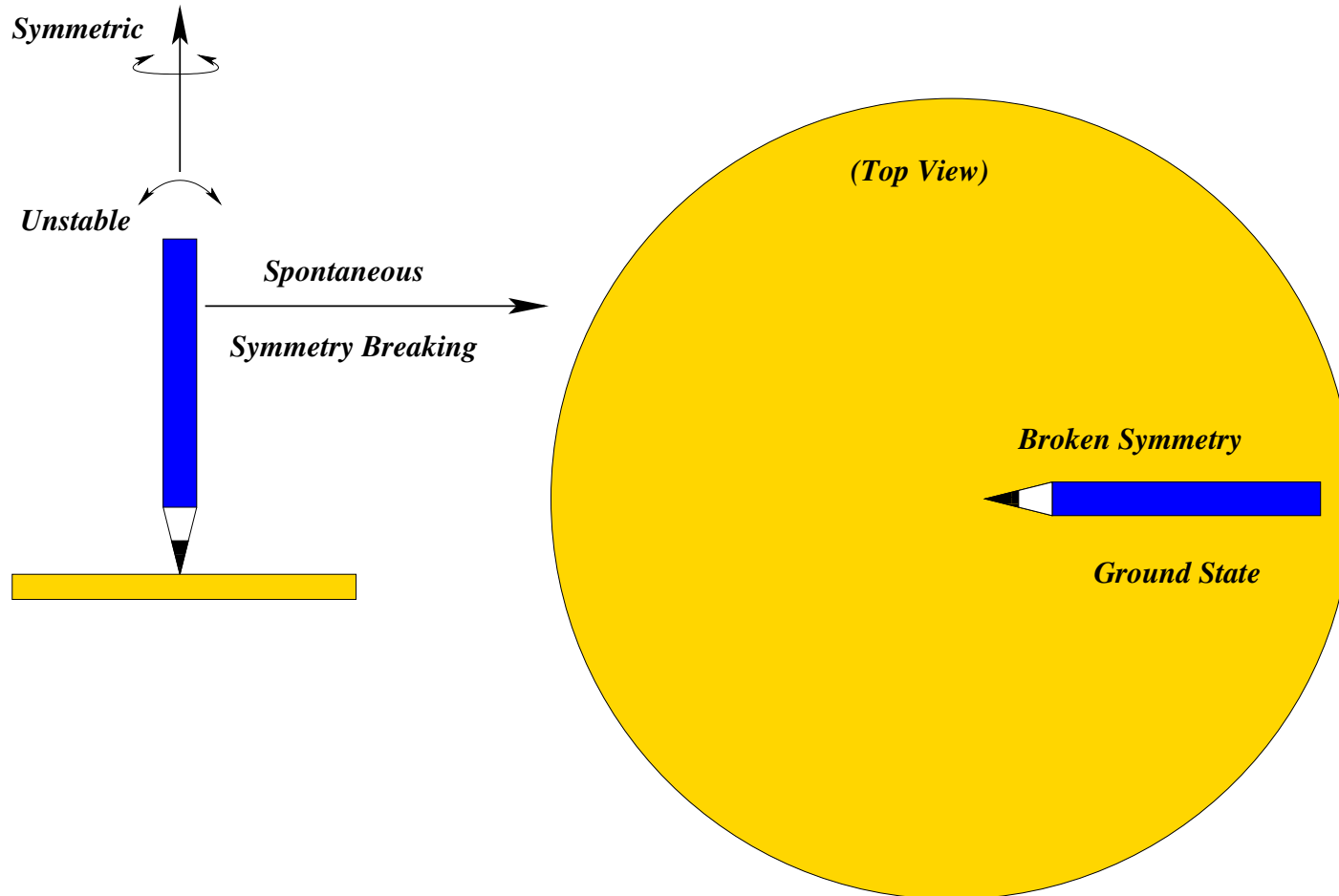
Massless photon,  $\gamma$ , long-ranged



# Tabletop Spontaneous Symmetry Breaking

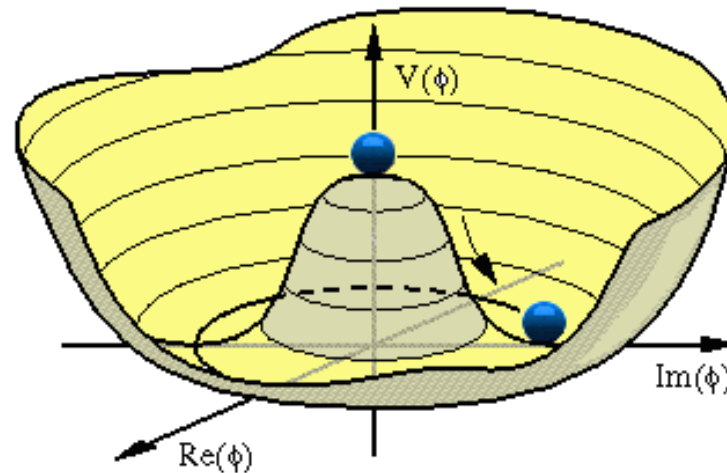
A pencil, standing on its tip: unstable, falls to its “ground state”.

- 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?)
- $m_\nu = 0$  (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  $\sim 125$  GeV

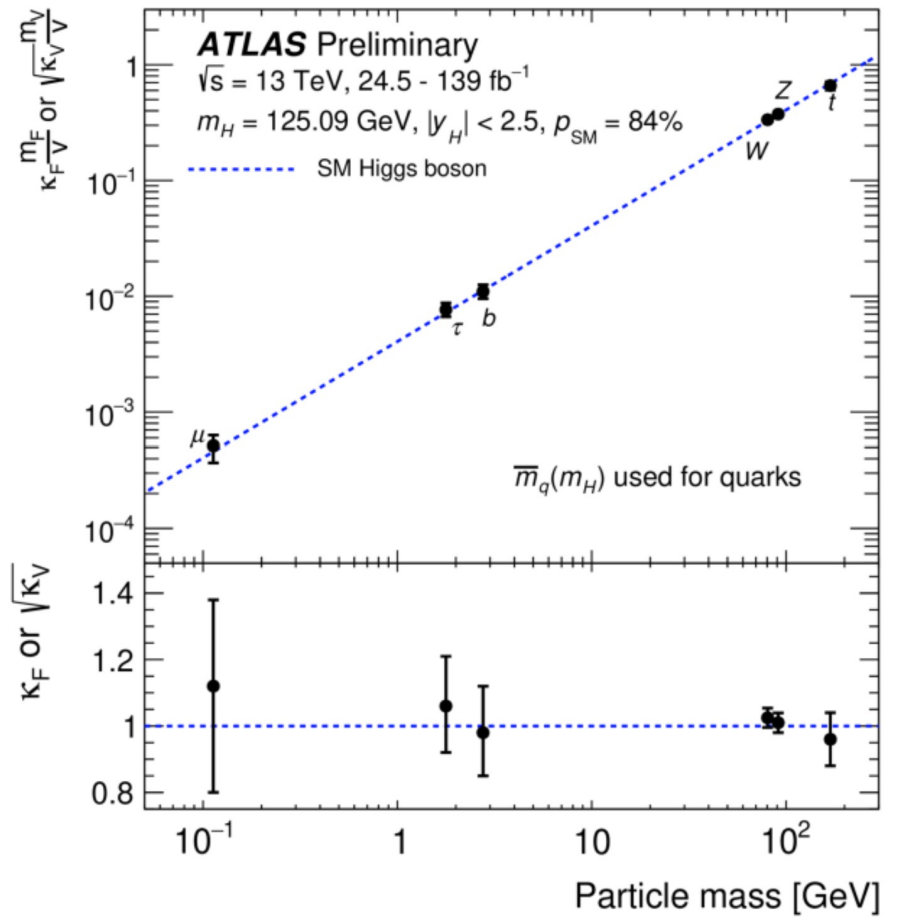
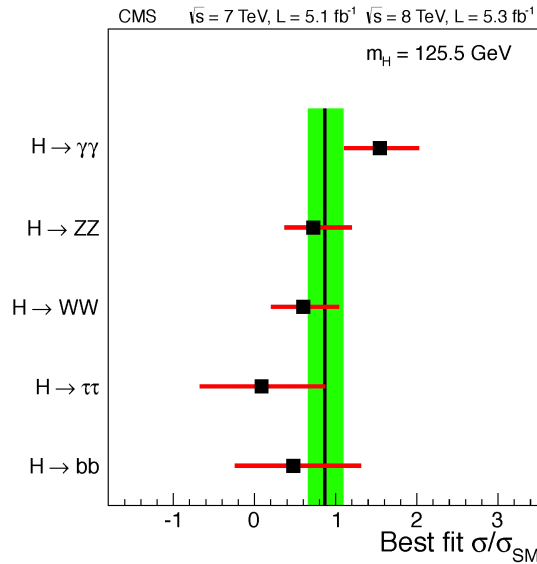
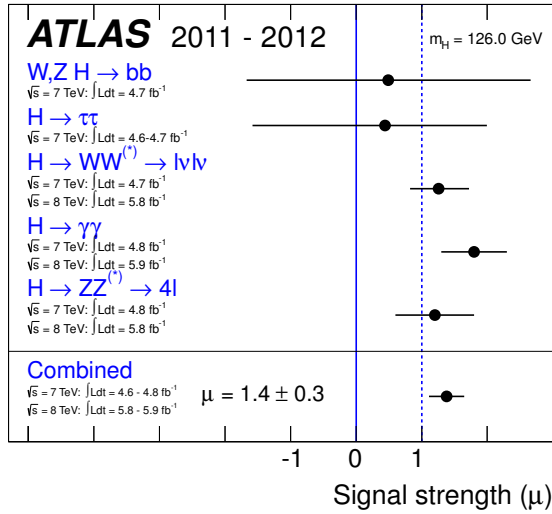
LHC:  $pp$  collider Design beam energy:  $2 \times 7000$  GeV

Circumference (km): 26.659



$2 \times 6500$  GeV Run finished in 2018

$2 \times 6800$  GeV Run: Summer 2022

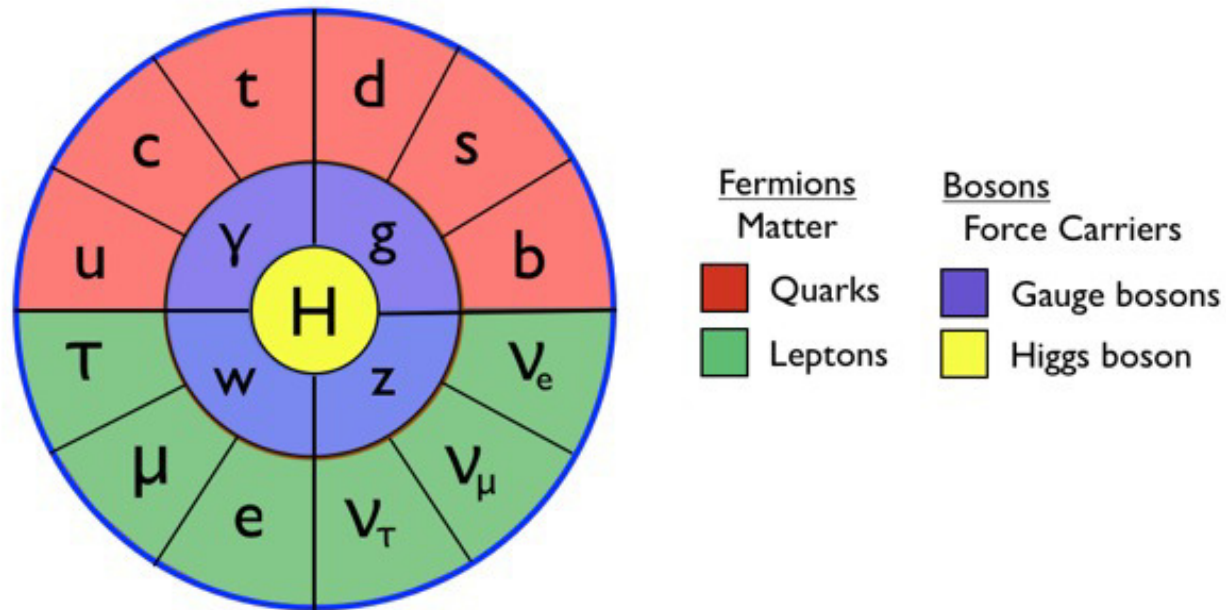


(Image: ATLAS Collaboration/CERN)

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

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

# SM + GR $\Rightarrow$ Great Success!



Particles of the Standard Model

Nearly all\* measurements in agreement with SM+GR.

\* Except, for example, potential hints from muon  $g - 2$  (Lecture by W. Morse, 7/17), some  $B$  meson (bound state of  $b$  quark with a light quark) decays,...

\* Recent CDFII (Tevatron detector; shut down in 2011) result for measured  $W$  mass;  $7 \sigma$  away from SM expectation (!)(?)



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

**Gravity: the weakest known interaction**

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

Gravity scale: Planck mass

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

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

$$M_P \gg m_W \quad (\hbar = c = 1)$$

$\Rightarrow$  Hierarchy problem: one may expect quantum effects to push Higgs mass ( $m_W$ ) close to  $M_P$ ; Higgs mass seems “unnatural”

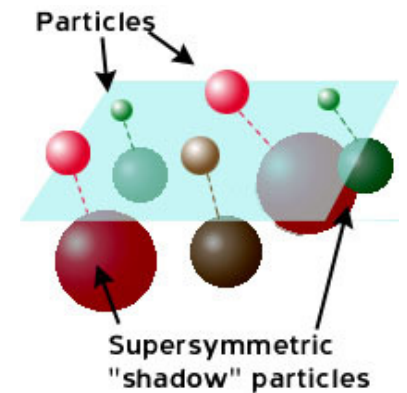
# Hierarchy and New Physics Near $m_H$

- 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** (Lecture by P. Denton, 6/22)

- Solar, atmospheric, and terrestrial laboratory data:

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

- Simple extension: right-handed\* neutrinos  $\nu_R$

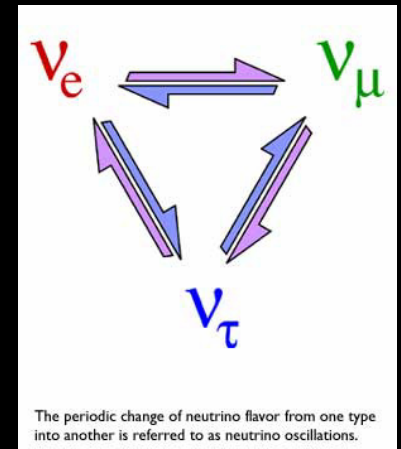
\* Spin and momentum aligned

- Typically, difficult to test:

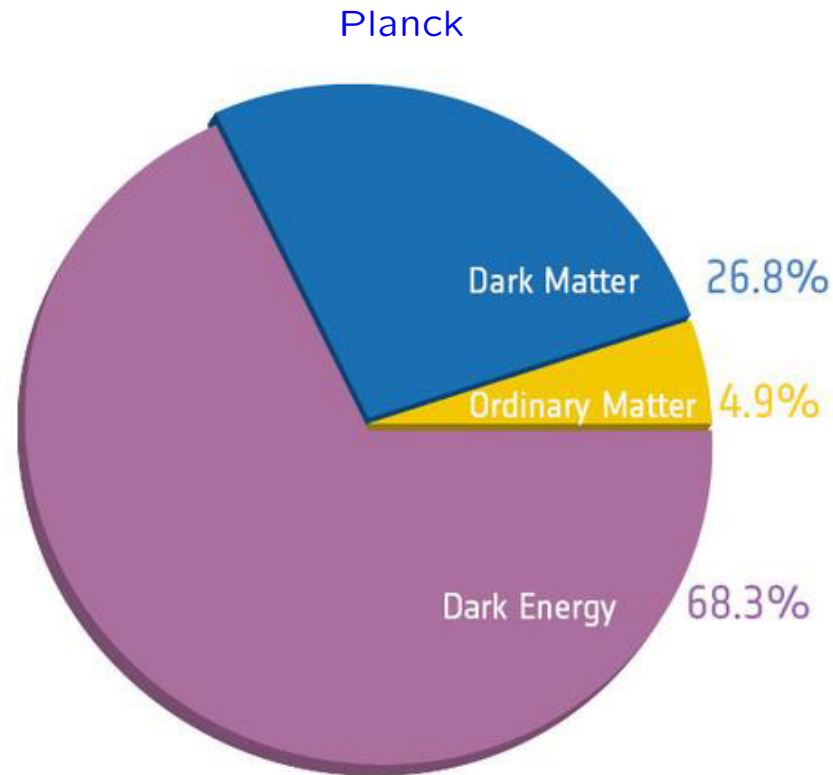
-  $\nu_R$  very massive or else negligible coupling to SM

- **Cosmology** (Lecture by V. Miranda, 7/31)

- Dark Matter: neutral, cosmologically stable



# Cosmos: 95% unknown!



- Dark energy: accelerated expansion of the Universe; could be vacuum energy (cosmological constant) with no dynamics
- Dark matter: what is it?
- Ordinary matter: asymmetry, but how?

# Visible (Everyday) Matter

**PERIODIC TABLE**  
**Atomic Properties of the Elements**

**NIST** National Institute of Standards and Technology  
U.S. Department of Commerce  
Physical Measurement Laboratory www.nist.gov/pml  
Standard Reference Data www.nist.gov/srd

**FREQUENTLY USED FUNDAMENTAL PHYSICAL CONSTANTS<sup>1</sup>**

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of <sup>133</sup>Cs

speed of light in vacuum	$c$	299 792 458 m s <sup>-1</sup>	(exact)
Planck constant	$h$	6.626 070 15 × 10 <sup>-34</sup> J Hz <sup>-1</sup>	(exact)
elementary charge	$e$	1.602 176 634 × 10 <sup>-19</sup> C	(exact)
Avogadro constant	$N_A$	6.022 140 76 × 10 <sup>23</sup> mol <sup>-1</sup>	(exact)
Boltzmann constant	$k$	1.380 649 × 10 <sup>-23</sup> J K <sup>-1</sup>	(exact)
electron volt	eV	1.602 176 634 × 10 <sup>-19</sup> J	(exact)
electron mass	$m_e$	9.109 383 70 × 10 <sup>-31</sup> kg	(exact)
energy equivalent	$m_e c^2$	0.510 998 950 MeV	(exact)
proton mass	$m_p$	1.672 621 924 × 10 <sup>-27</sup> kg	(exact)
energy equivalent	$m_p c^2$	938.272 088 MeV	(exact)
fine-structure constant	$\alpha$	1/137.035 999	(exact)
Rydberg energy	$R_\infty$	13.605 693 1230 eV	(exact)
Newtonian constant of gravitation	$G$	6.674 × 10 <sup>-11</sup> m <sup>3</sup> kg <sup>-1</sup> s <sup>-2</sup>	(exact)

<sup>1</sup>For the most accurate values of these and other constants, visit [pml.nist.gov/constants](http://pml.nist.gov/constants).

Legend:  
■ Solids  
■ Liquids  
■ Gases  
■ Artificially Prepared

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
IA	IIA	IIIB	IVB	VB	VIB	VII B	VIII	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA	
1	<b>H</b> Hydrogen 1.008 1 13.5984																		<b>He</b> Helium 4.0026 4 24.5874
2	<b>Li</b> Lithium 6.94 3 11.224	<b>Be</b> Beryllium 9.0122 4 14.0030											<b>B</b> Boron 10.81 5 11.224	<b>C</b> Carbon 12.011 6 11.224	<b>N</b> Nitrogen 14.007 7 11.224	<b>O</b> Oxygen 15.999 8 11.224	<b>F</b> Fluorine 18.998 9 11.224	<b>Ne</b> Neon 20.180 10 11.224	
3	<b>Na</b> Sodium 22.990 11 13.5984	<b>Mg</b> Magnesium 24.305 12 13.5984											<b>Al</b> Aluminum 26.982 13 13.5984	<b>Si</b> Silicon 28.085 14 13.5984	<b>P</b> Phosphorus 30.974 15 13.5984	<b>S</b> Sulfur 32.06 16 13.5984	<b>Cl</b> Chlorine 35.45 17 13.5984	<b>Ar</b> Argon 39.948 18 13.5984	
4	<b>K</b> Potassium 39.098 19 4.3407	<b>Ca</b> Calcium 40.078 20 6.1132	<b>Sc</b> Scandium 44.956 21 6.5615	<b>Ti</b> Titanium 47.867 22 6.6261	<b>V</b> Vanadium 50.942 23 6.7462	<b>Cr</b> Chromium 51.996 24 6.7865	<b>Mn</b> Manganese 54.938 25 6.7865	<b>Fe</b> Iron 55.845 26 7.5025	<b>Co</b> Cobalt 58.933 27 7.8810	<b>Ni</b> Nickel 58.693 28 7.6396	<b>Cu</b> Copper 63.546 29 7.7264	<b>Zn</b> Zinc 65.38 30 9.3942	<b>Ga</b> Gallium 69.723 31 5.9993	<b>Ge</b> Germanium 72.630 32 7.8994	<b>As</b> Arsenic 74.922 33 8.7898	<b>Se</b> Selenium 78.971 34 9.7824	<b>Br</b> Bromine 79.904 35 11.8138	<b>Kr</b> Krypton 83.798 36 13.9996	
5	<b>Rb</b> Rubidium 85.468 37 4.1771	<b>Sr</b> Strontium 87.62 38 6.0951	<b>Y</b> Yttrium 88.906 39 6.2173	<b>Zr</b> Zirconium 91.224 40 6.6341	<b>Nb</b> Niobium 92.906 41 6.7889	<b>Mo</b> Molybdenum 95.96 42 7.0924	<b>Tc</b> Technetium (97) 43 7.1194	<b>Ru</b> Ruthenium 101.07 44 7.4589	<b>Rh</b> Rhodium 106.42 45 7.4589	<b>Pd</b> Palladium 106.42 46 8.3369	<b>Ag</b> Silver 107.87 47 7.5762	<b>Cd</b> Cadmium 112.41 48 8.9936	<b>In</b> Indium 114.82 49 7.3439	<b>Sn</b> Tin 118.71 50 7.3439	<b>Sb</b> Antimony 121.76 51 8.6084	<b>Te</b> Tellurium 127.60 52 9.0097	<b>I</b> Iodine 126.90 53 10.4513	<b>Xe</b> Xenon 131.29 54 12.1298	
6	<b>Cs</b> Cesium 132.91 55 3.8939	<b>Ba</b> Barium 137.33 56 5.2117	<b>Hf</b> Hafnium 178.49 72 6.8251	<b>Ta</b> Tantalum 180.95 73 7.5496	<b>W</b> Tungsten 183.84 74 7.8840	<b>Re</b> Rhenium 186.21 75 7.8335	<b>Os</b> Osmium 190.23 76 8.4382	<b>Ir</b> Iridium 192.22 77 8.9670	<b>Pt</b> Platinum 195.08 78 8.9588	<b>Au</b> Gold 196.97 79 9.2256	<b>Hg</b> Mercury 200.59 80 10.4375	<b>Tl</b> Thallium 204.38 81 6.1083	<b>Pb</b> Lead 207.2 82 7.4167	<b>Bi</b> Bismuth 208.98 83 7.2855	<b>Po</b> Polonium (209) 84 8.414	<b>At</b> Astatine (210) 85 9.3175	<b>Rn</b> Radon (222) 86 10.7485		
7	<b>Fr</b> Francium (223) 87 4.0727	<b>Ra</b> Radium (226) 88 5.2784	<b>Rf</b> Rutherfordium (261) 104 6.02	<b>Db</b> Dubnium (262) 105 6.8	<b>Sg</b> Seaborgium (263) 106 7.8	<b>Bh</b> Bohrium (264) 107 7.7	<b>Hs</b> Hassium (265) 108 7.6	<b>Mt</b> Meitnerium (266) 109 7.6	<b>Ds</b> Darmstadtium (267) 110 7.6	<b>Rg</b> Roentgenium (268) 111 7.6	<b>Cn</b> Copernicium (285) 112 7.6	<b>Nh</b> Nihonium (286) 113 7.6	<b>Fl</b> Flerovium (289) 114 7.6	<b>Mc</b> Moscovium (289) 115 7.6	<b>Lv</b> Livermorium (293) 116 7.6	<b>Ts</b> Tennessine (294) 117 7.6	<b>Og</b> Oganesson (294) 118 7.6		
			<b>La</b> Lanthanum 138.91 57 5.0789	<b>Ce</b> Cerium 140.12 58 5.0789	<b>Pr</b> Praseodymium 140.91 59 5.0789	<b>Nd</b> Neodymium 144.24 60 5.0789	<b>Pm</b> Promethium (145) 61 5.0789	<b>Sm</b> Samarium 150.36 62 5.0789	<b>Eu</b> Europium 151.96 63 5.0789	<b>Gd</b> Gadolinium 157.25 64 5.0789	<b>Tb</b> Terbium 158.93 65 5.0789	<b>Dy</b> Dysprosium 162.50 66 5.0789	<b>Ho</b> Holmium 164.93 67 5.0789	<b>Er</b> Erbium 167.26 68 5.0789	<b>Tm</b> Thulium 168.93 69 5.0789	<b>Yb</b> Ytterbium 173.05 70 5.0789	<b>Lu</b> Lutetium 174.97 71 5.0789		
			<b>Ac</b> Actinium (227) 89 5.3802	<b>Th</b> Thorium 232.04 90 6.3007	<b>Pa</b> Protactinium 231.04 91 6.3007	<b>U</b> Uranium 238.03 92 6.1941	<b>Np</b> Neptunium (237) 93 6.2655	<b>Pu</b> Plutonium (244) 94 6.0258	<b>Am</b> Americium (243) 95 5.9738	<b>Cm</b> Curium (247) 96 5.9914	<b>Bk</b> Berkelium (247) 97 6.1976	<b>Cf</b> Californium (251) 98 6.2817	<b>Es</b> Einsteinium (252) 99 6.3678	<b>Fm</b> Fermium (257) 100 6.50	<b>Md</b> Mendelevium (258) 101 6.58	<b>No</b> Nobelium (259) 102 6.66	<b>Lr</b> Lawrencium (260) 103 4.96		

<sup>1</sup>Based upon <sup>12</sup>C. ( ) indicates the mass number of the longest-lived isotope.

<sup>2</sup>For the most precise values and uncertainties visit [ciaw.org](http://ciaw.org) and [pml.nist.gov/data](http://pml.nist.gov/data).  
NIST SP 966 (July 2019)

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

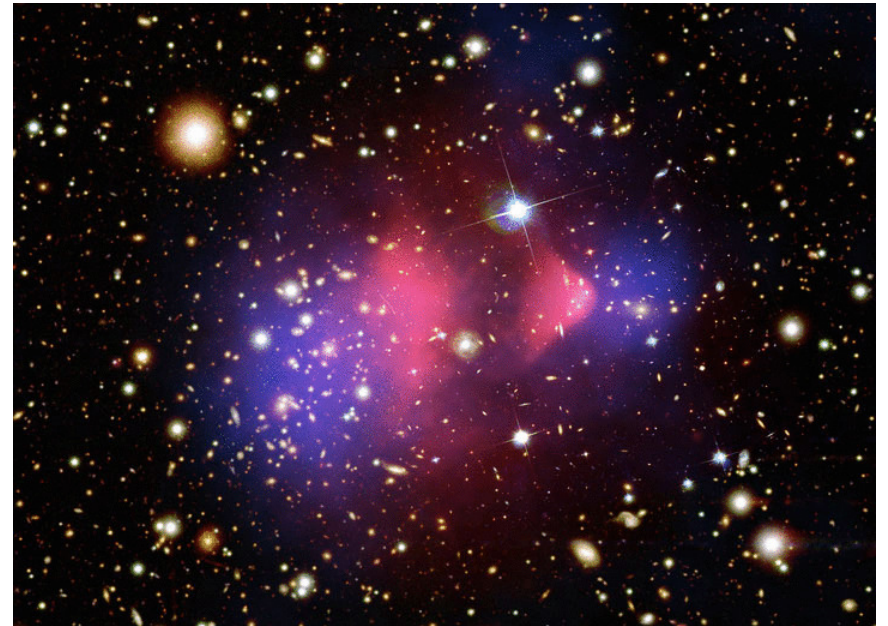
$\Rightarrow$  **New Physics**
- Could be related to neutrino mass generation (heavy  $\nu_R$  states)

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

( $\sim 90$  orders of magnitude!)

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

# Searches often guided by *theoretical motivation*

- **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)

⇒ **Weakly Interacting Massive Particles** (WIMPs)

- Thermal relic density: annihilation, freeze-out

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

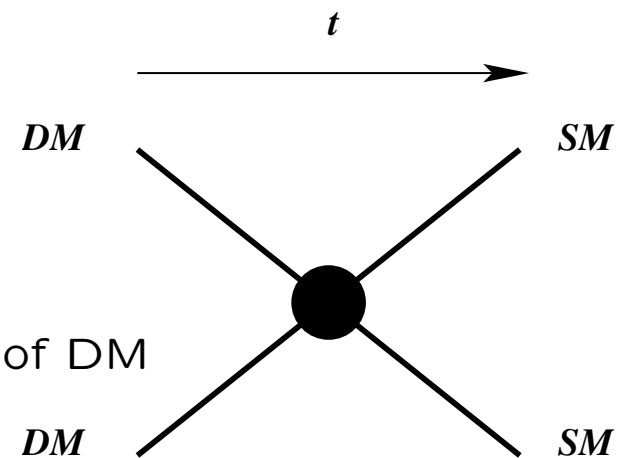
- $\sigma_{\text{ann}} \sim g^4/M^2$

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

- Weak scale theoretically motivated

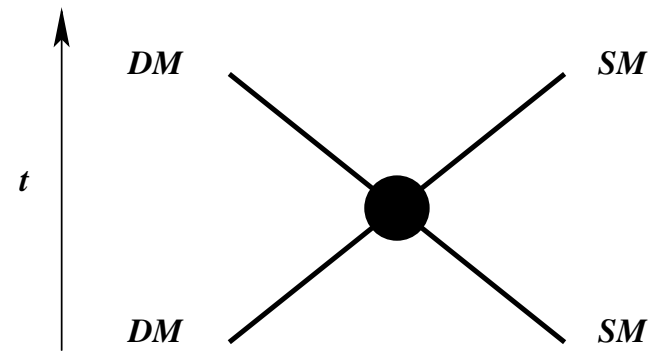
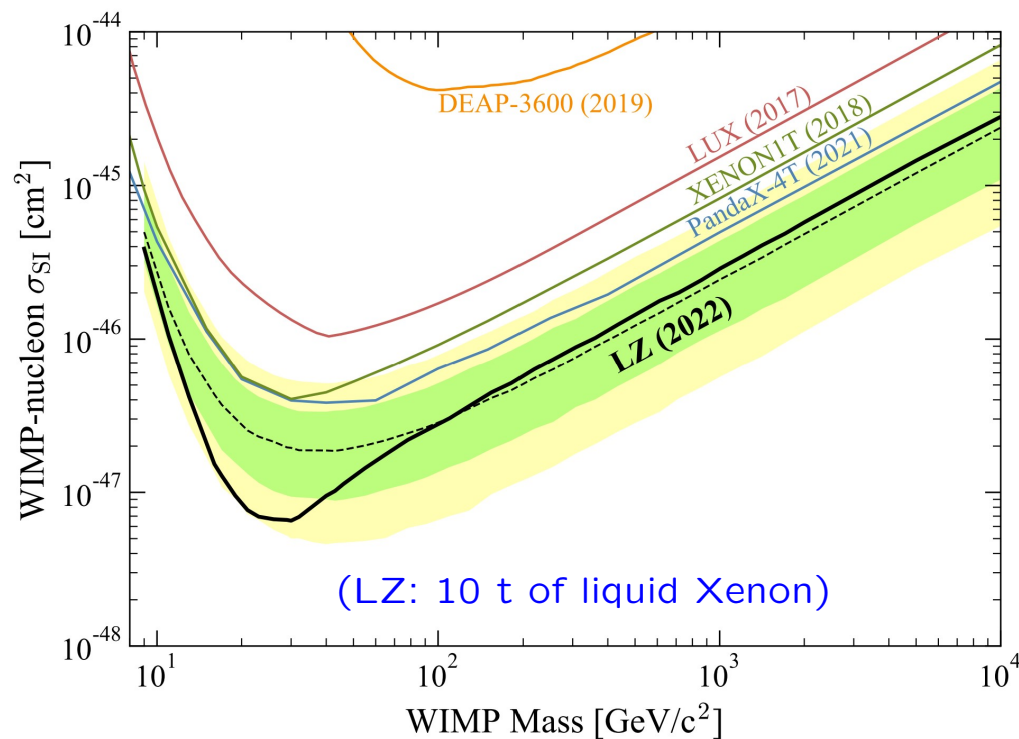
- However,  $g^4/M^2$  may be achieved otherwise (WIMPlless Miracle)

Feng and Kumar, 2008



# Direct WIMP DM Searches

- WIMPs: have been a main focus of DM searches
- Recoil off atomic nuclei (electrons)

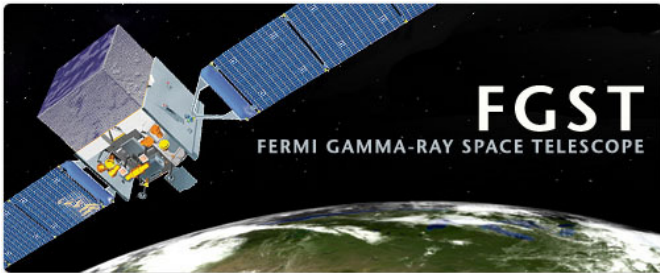


J. Aalbers *et al.*, The LUX-ZEPLIN (LZ) Collaboration, arXiv:2207.03764v3 [hep-ex]

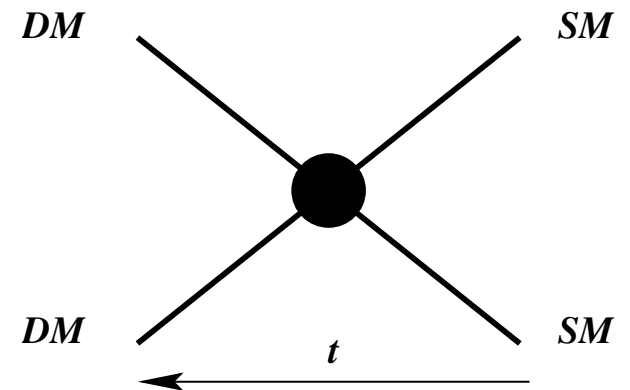
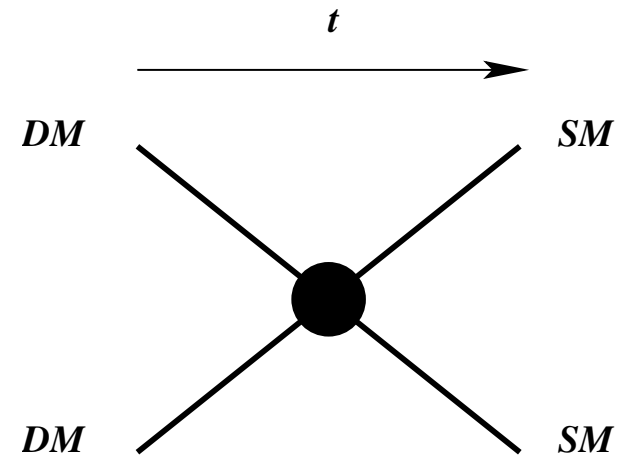
**Q: Why do the constraints get weaker towards lower and higher DM masses?**

# Other avenues for WIMP search:

- Indirect searches: self-annihilation signals
  - Related to thermal relic density
  - Complicated by astrophysical backgrounds



- Collider production: LHC (Lecture by K. Assamagan, 7/10)
  - Search for missing energy in events



# Dark Sectors and Dark Forces

For example: [Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008](#)

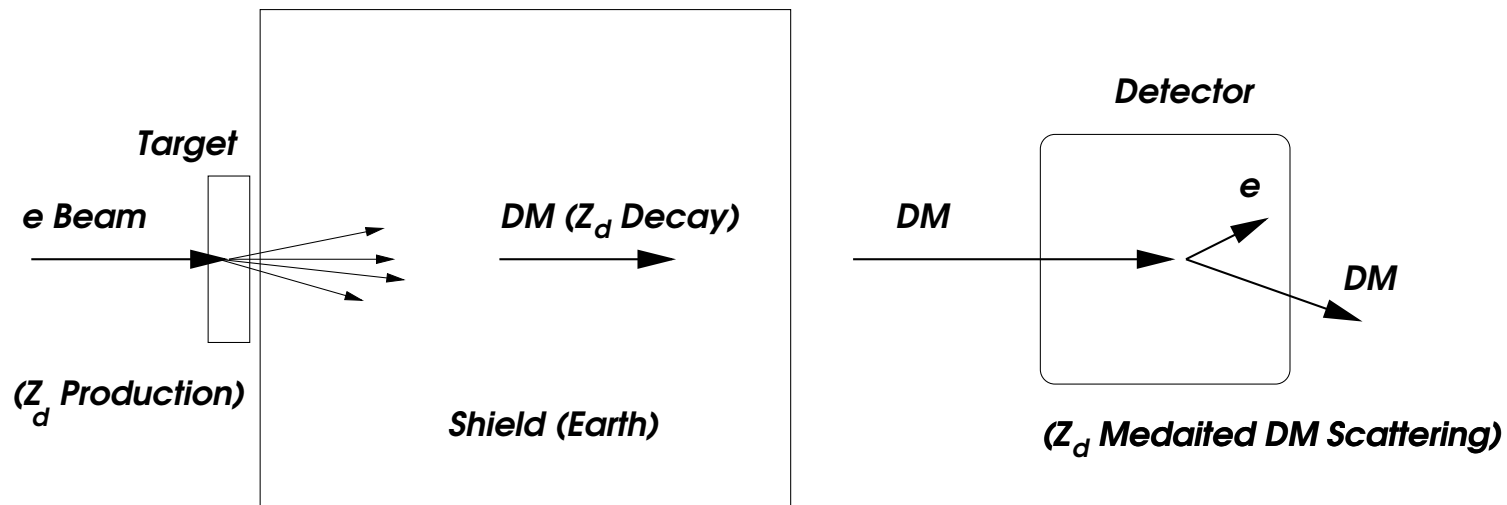
- With lack of evidence for new physics near weak scale, other DM scenarios have been put forth in recent years
- Example: DM could be light and may reside in a separate sector with its own forces
  - Analogy with SM
- DM interactions with SM are indirect
- Simple possibility: a “dark” sector  $U(1)_d$ 
  - 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
  - DM interpretation of astrophysical data, explaining some potential deviations (e.g. muon  $g - 2$ )

## 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, and possibly a future “Forward Physics Facility”

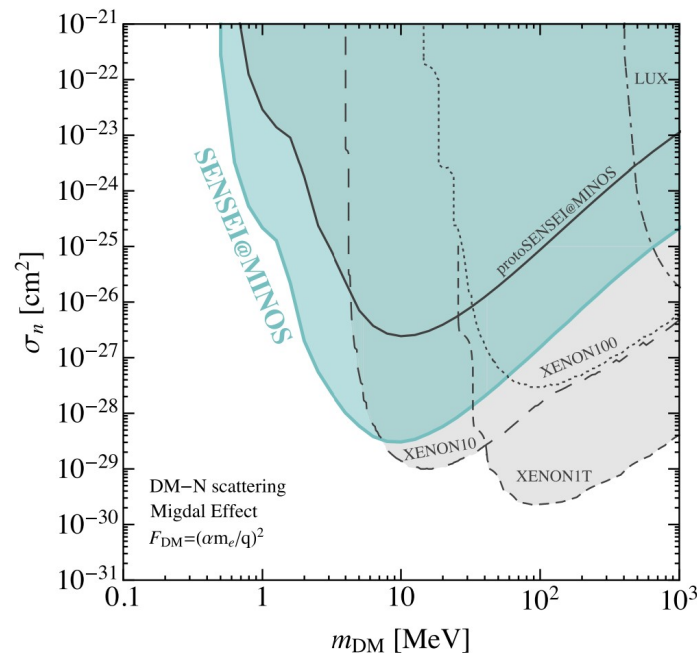
H. Abreu *et al.*, Faser Collaboration, arXiv:2303.14185v1 [hep-ex]

# 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 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 “naturalness” 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)

