# *New Physics and the Electron-Ion Collider (I)*

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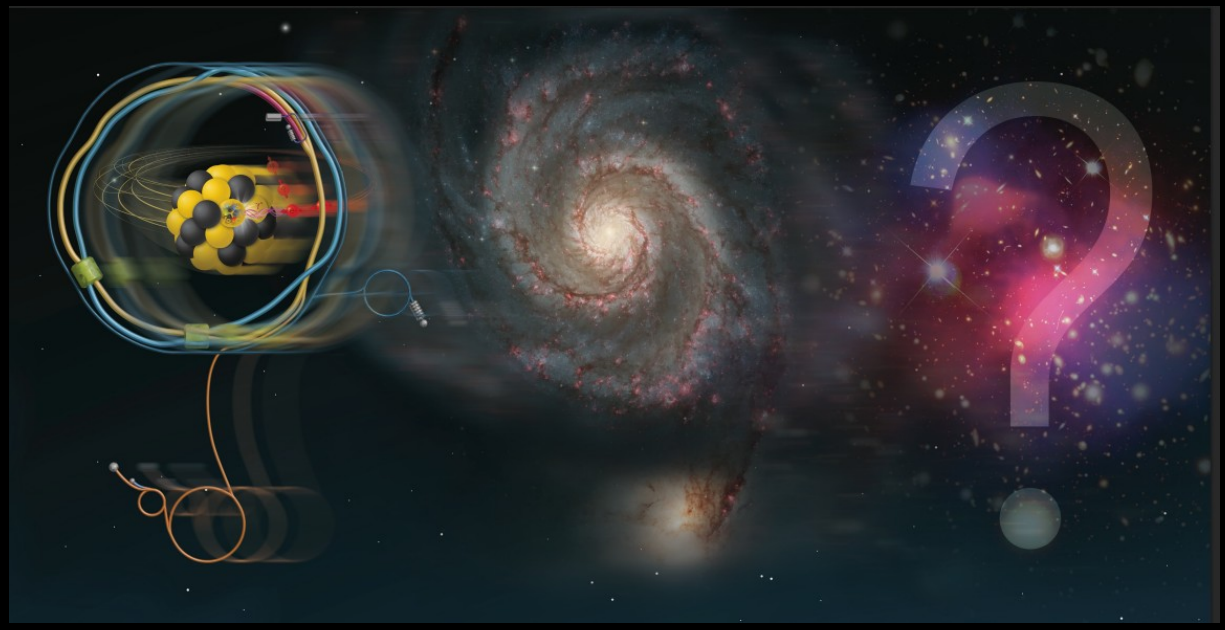


The 2026 CFNS Summer School on the Physics of the Electron-Ion Collider

June 1-12, 2026, Stony Brook University

Brookhaven National Laboratory

# Some key developments of recent past ($\sim$ 15 years)*

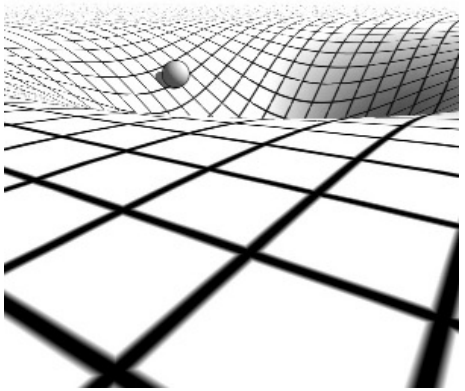
* *incomplete list*

- Neutrino mixing parameter $\theta_{13}$ measurement (Daya Bay, Reno)
- Higgs discovery at the LHC (ATLAS, CMS)
- IceCube observation of astrophysical neutrinos up to $\sim 10^3$ TeV
- LIGO-Virgo detection of gravitational waves
- Multi-messenger astronomy (binary neutron star merger)
- Event Horizon Telescope imaging of supermassive black holes (M87*, SgrA*)
- Evidence for stochastic gravitational wave background
  - Pulsar timing measurements (NANOGrav, EPTA, Parkes, CPTA,...)
- . . .

# Despite all that,

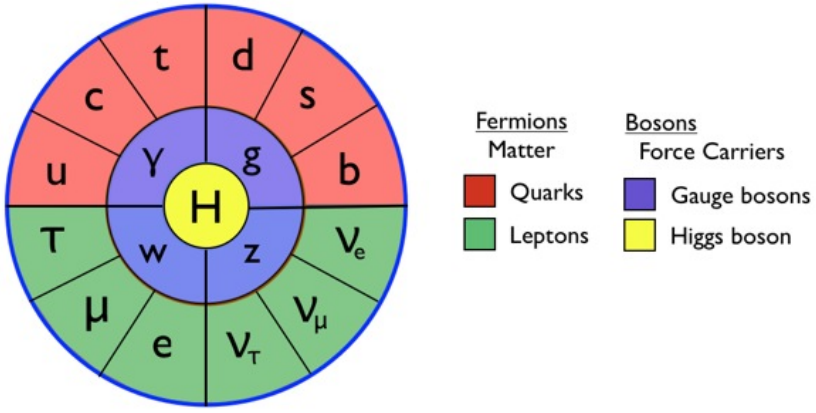
# prior fundamental theories

# have not changed!



State of the art:

- Gravity: still General Relativity ($>$ 100 years!)
- Subatomic phenomena: Standard Model




Particles of the Standard Model

- There are some, often modest and transient, anomalies.

**SM and GR remain consistent with “settled" tests**

*However, we are not done!*

# The Case for New Physics

- Despite great success of SM+GR, new physics is needed

- There is strong experimental evidence for this inference:

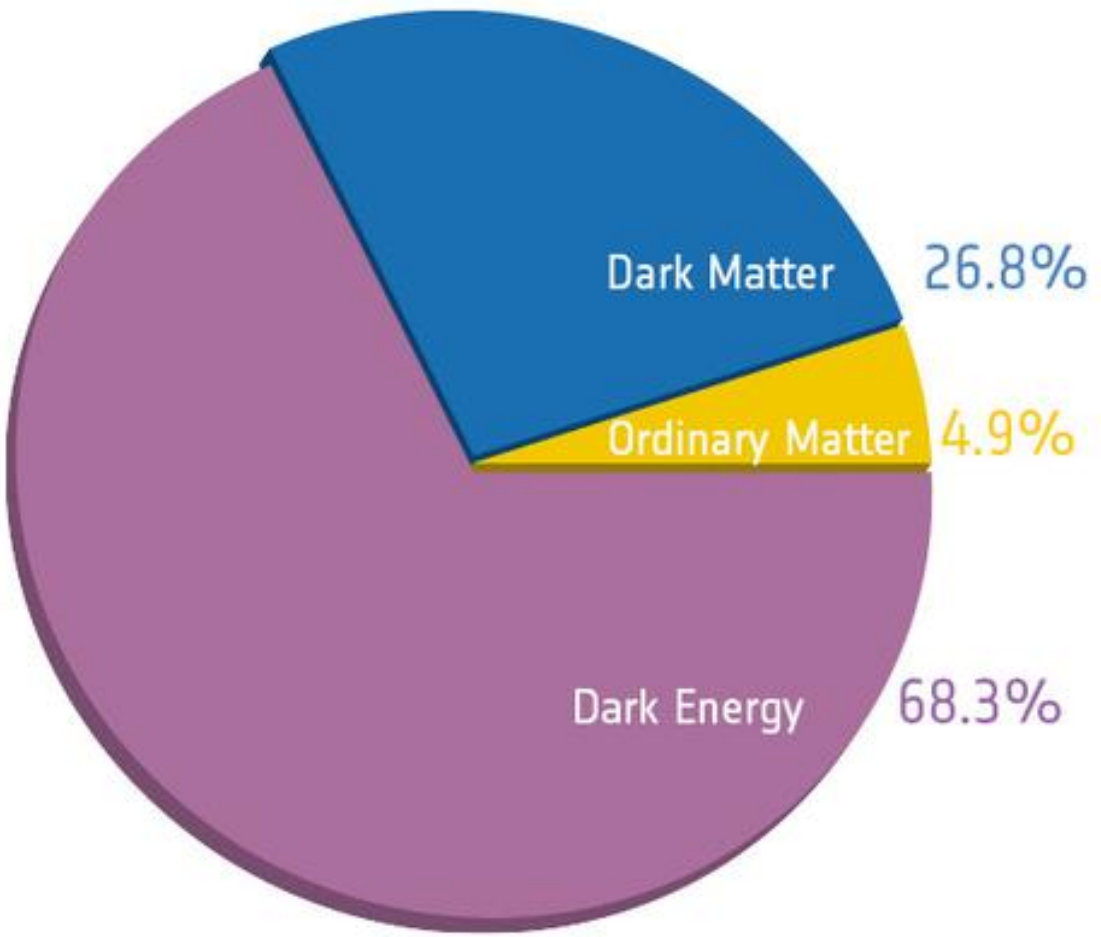
★ **Neutrino flavor oscillations $\rightarrow m_\nu \lesssim 0.1$ eV**

- Much lighter than other fermions ($m_e/m_\nu \gtrsim 10^6$)
- Adding right-handed neutrinos (of a broad range of masses) can explain this

★ **Cosmology**

- What is accelerating cosmic expansion? (dark energy; may be vacuum energy)
- What is holding galaxies together? (dark matter; no match for in the SM)
- What caused ordinary matter asymmetry? (requires new physics)

# 95% of the Universe is unknown to us!




Planck

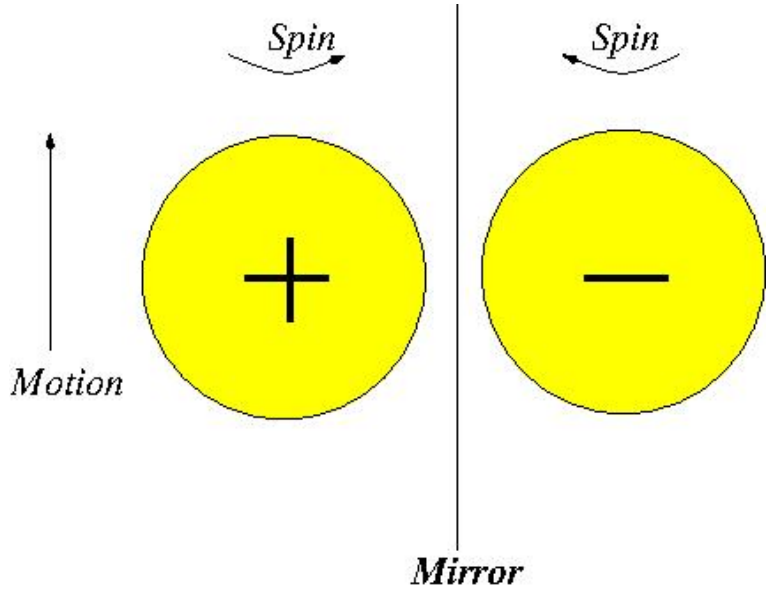
# *There are also theoretical hints:*

- Why is gravity so weak?
  - Hierarchy between Planck scale and Higgs mass: $\frac{M_H^2}{M_{\rm Pl}^2} \sim 10^{-34}$
  - Why is $M_H$ stable against quantum corrections $\sim \mathcal{O}(M_{\rm Pl})$?
- Why is CP violation so suppressed in strong interactions ("strong CP problem")?
  - Neutron electric dipole moment $\lesssim 10^{-26}$ $e$.cm; could have been $\mathcal{O}(10^{10})$ times larger
- Why . . . ?

*Aside*:

CP: Charge conjugation (particle $\leftrightarrow$ antiparticle) – Parity (mirror)

- Violated by SM weak interactions
- SM CPV: insufficient to account for ordinary matter



# Why is there stuff around us?

- $\sim 5\%$ of cosmic energy budget is ordinary matter
  - Atoms: protons, neutrons, ...
- Not known how atoms have survived the Big Bang

NASA

- We need a baryon asymmetry $n_B/n_\gamma \sim 10^{-9}$
  - Otherwise primordial matter and anti-matter annihilation would have left far too little
  - We also do not see any appreciable cosmic relic anti-matter
- This requires a *baryogenesis* mechanism, subject to Sakharov conditions:

(i) Baryon number violation — A. Sakharov, 1967

(ii) $C$ and $CP$ violation

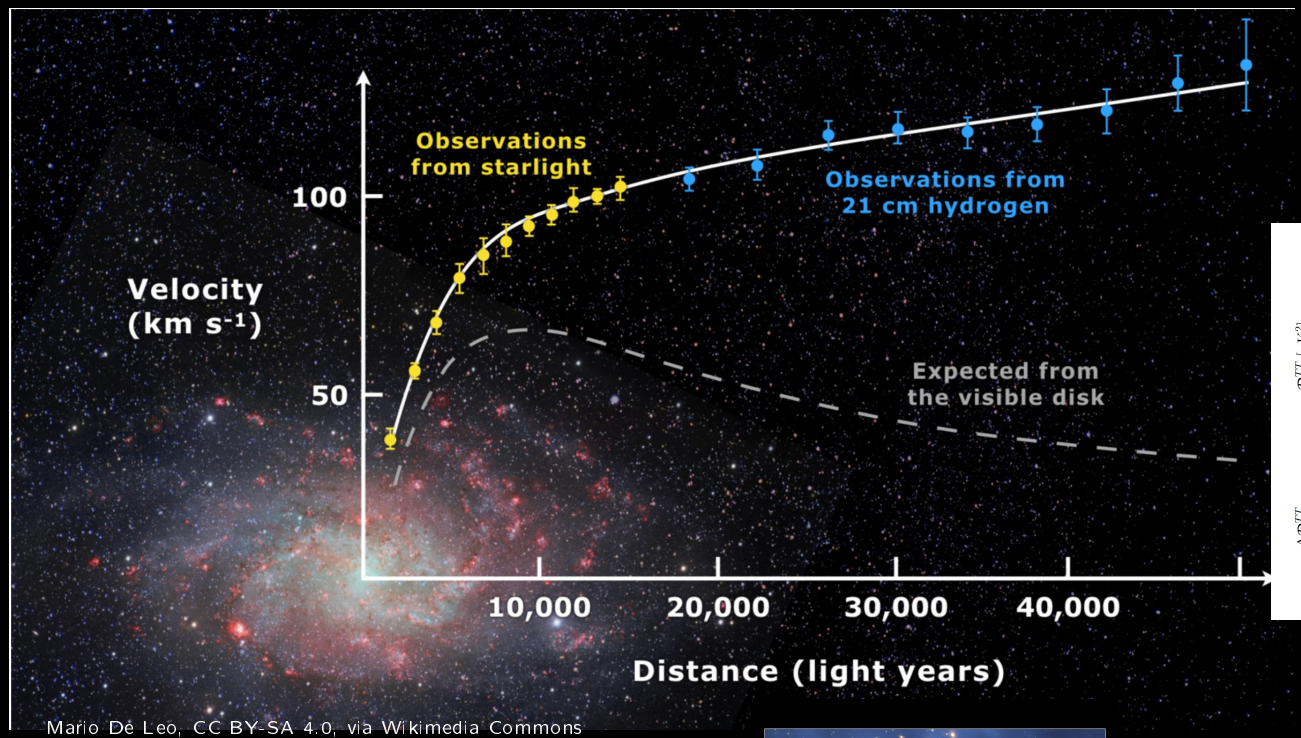
(iii) Departure from equilibrium

- In general, SM either lacks the ingredients or comes up short

$\Rightarrow$ Need new physics!

# Dark matter (DM)

- Robust evidence from cosmology and astrophysics
  - Rotation curves of galaxies, CMB, Bullet Cluster, lensing, ...

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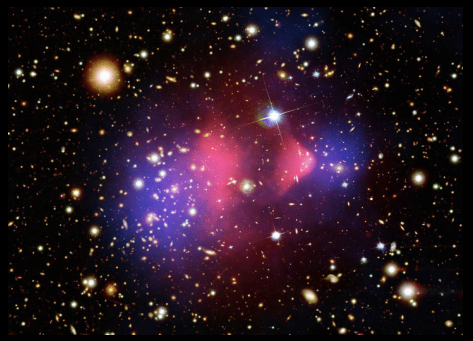
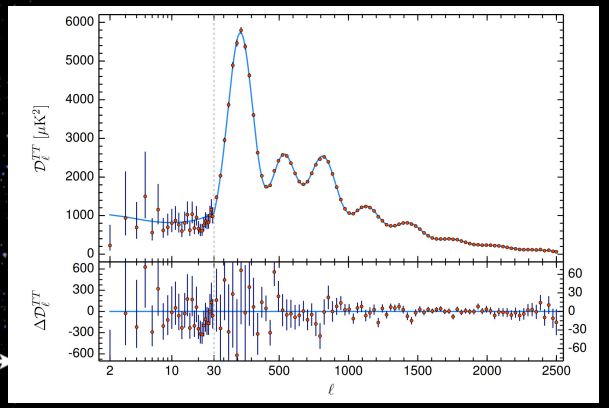




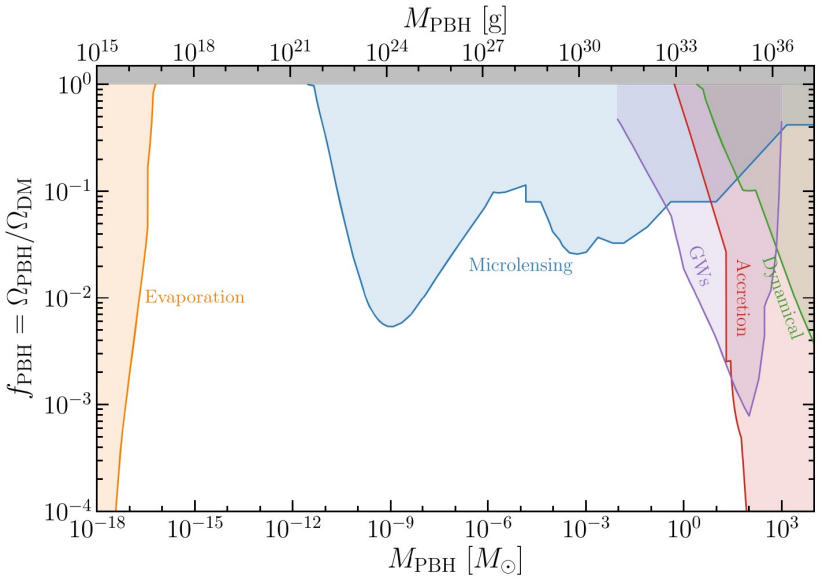

Planck Collaboration; 1807.06209

- $\sim$ 27% of energy density

Dark Matter Ring in Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
*Hubble Space Telescope* • ACS/WFC
NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17a

- **Dark Matter: unknown substance**
  - Feeble interactions with atoms, photons
  - Self-interactions not strong ($\sigma \lesssim 1$ barn)
  - Not explained in SM
  - So far, evidence only from gravity effects
  - Possible mass scale: $\boxed{10^{-22}\ \text{eV} \lesssim M_{\rm DM} \lesssim 10^{55}\ \text{eV}}$ 77 orders of magnitude!
  - Lower bound: ultralight bosons ("Fuzzy DM," must fit within galactic structures) Hu, Barkana, Gruzinov, 2000
  - Upper bound: possibly primordial black holes (sub-solar mass) Hawking, 1971

- Formed in the early ($t \ll$ ps) Universe from over-densities

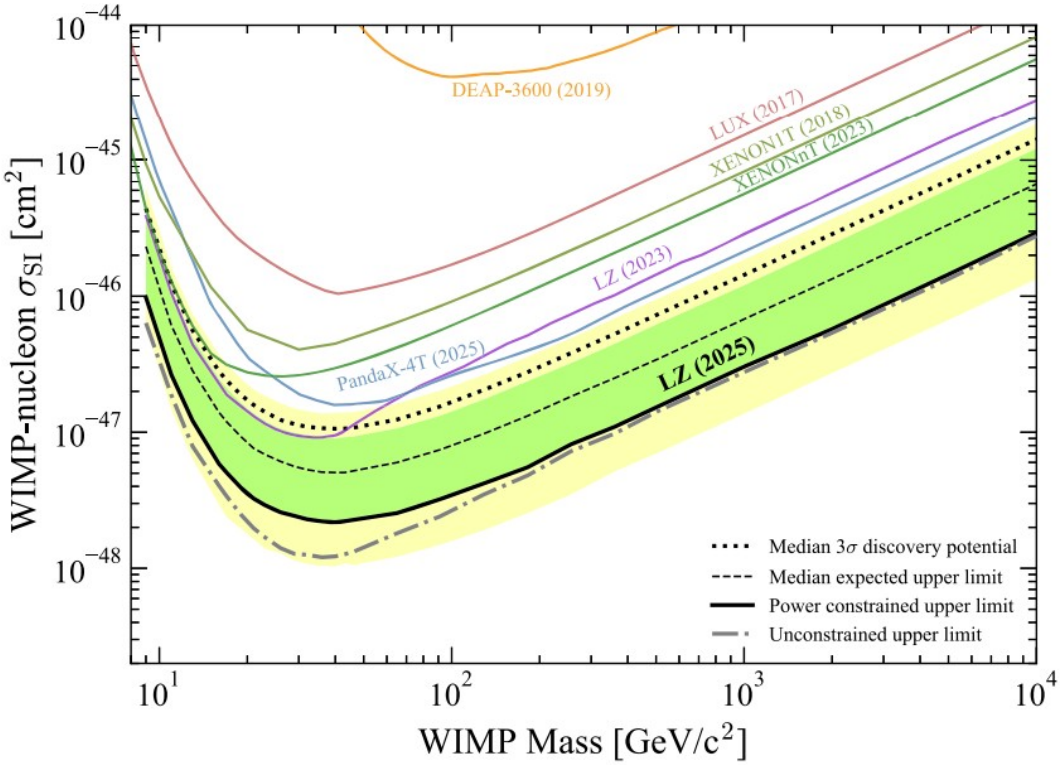



*E.g.*, Green and Kavanagh, J.Phys.G 48 (2021) 4, 043001

# Weak Scale DM

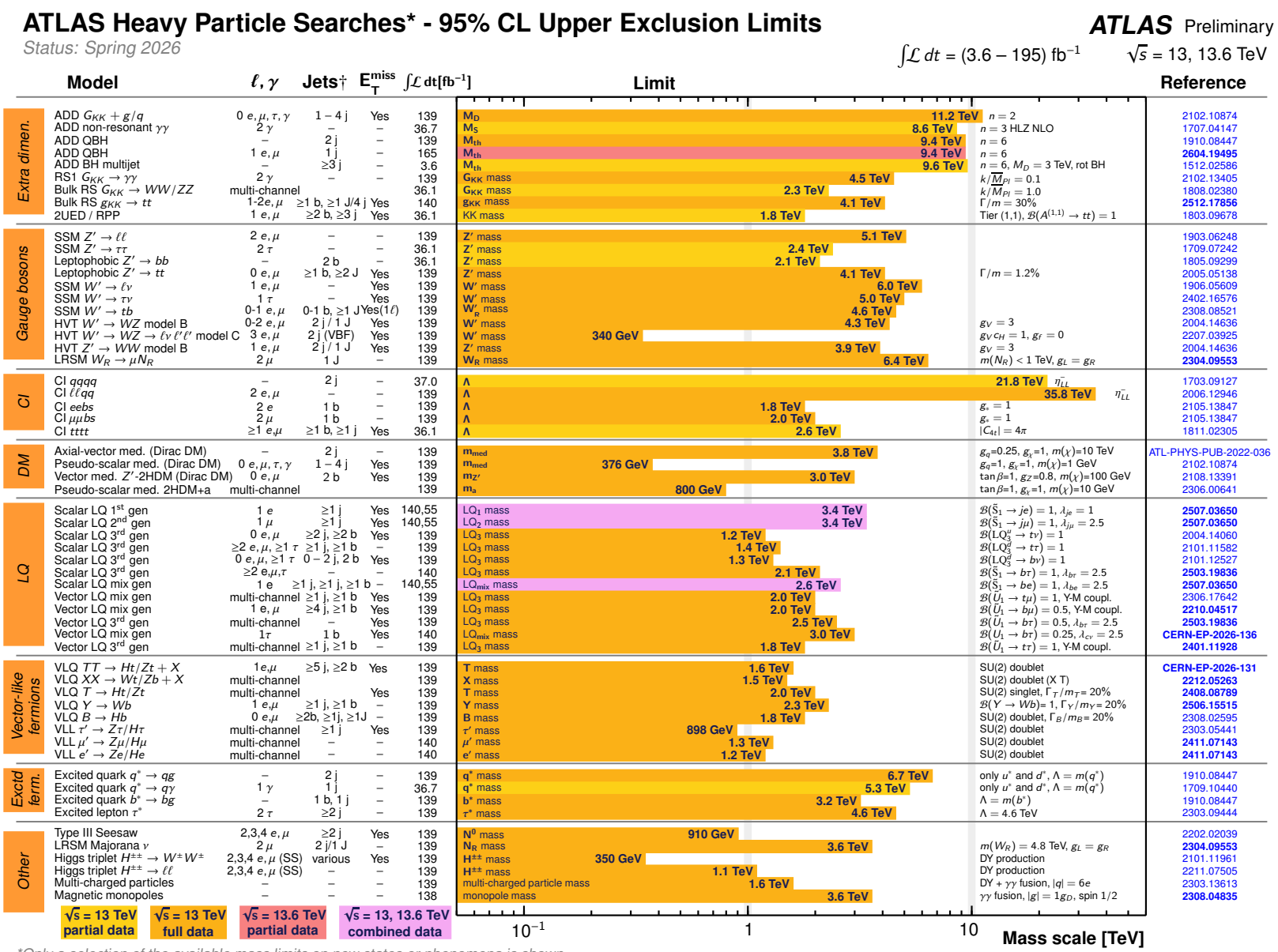
- Weakly interacting massive particles (WIMPs): longtime targets
- Motivation: extensions of SM Higgs sector
- Hierarchy problem (natural solution): $M_{\text{new}} \gtrsim M_H \approx 125$ GeV (weak scale)
- Thermal relic density: annihilation, "freeze-out"

- $\rho_{\text{WIMP}} \propto 1/\sigma_{ann}$
- $\sigma_{ann} \sim g^4/M^2$
- $g \sim g_{\text{weak}}$, $M \gtrsim$ weak scale $\rightarrow \rho_{\text{WIMP}} \sim \rho_{\text{DM}}^{\text{obs}} \Rightarrow$ *"WIMP Miracle"*




J. Aalbers *et al.*, LUX-ZEPLIN (LZ) Collab., PRL 135 (2025) 1, 011802

- New physics: apparently not close to $M_H$ (sample below)

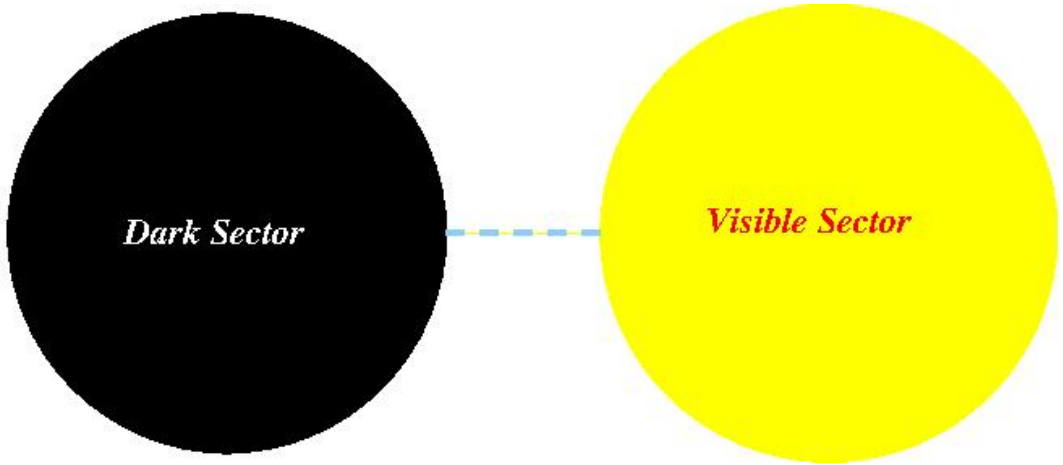



*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

# Dark Sectors

- With lack of evidence for new physics near weak scale ($M_H$), alternatives to WIMPs have been put forth in recent years
- DM could be light ($m \lesssim$ GeV), not associated with EW symmetry breaking (EWSB)
- DM may reside in a separate *sector* with its own forces
  - Analogy with SM, the "visible sector"
- Visible and dark sectors connected by feeble interactions (typically expected)
  - Mediators could be light, accessible to low energy experiments ($\sqrt{s} \ll 100$ GeV)




**Absent any strong hints, one should leverage every available tool**

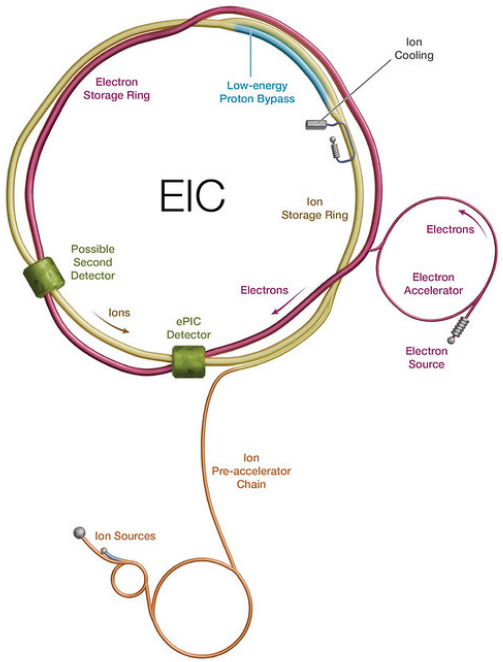
# The Electron-Ion Collider

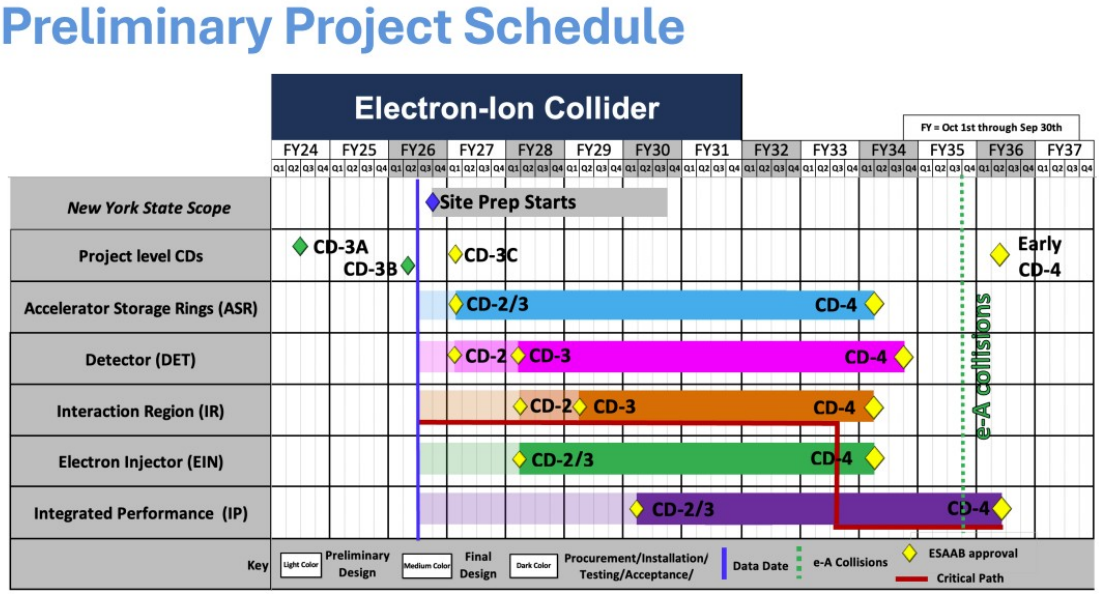
2103.05419, EIC Yellow Report

- *A future collider*, the only one to be built in the coming decade (site: BNL)
- New frontier in studying hadronic systems: spin composition of nucleons,....
- Large $\sqrt{s}$, luminosity

- $E_e = 5, 10\,(18)$ GeV (original design), 41 GeV, 100-275 GeV hadrons ($p$ to $U$)
- $\sim 100$ fb$^{-1}$ per nucleon possible

- Polarization: $\sim 70\%$ for $e$ and $p$ beams
- Large nuclei (high $Z$): *e.g.* gold, lead




John Lajoie; talk at DIS2026

**What can we learn about new physics at the EIC?**

# EIC and New Physics

- We will consider two large classes of beyond SM (BSM) physics*:

  (I) Heavy physics, indirect signals

  (II) Light physics, perhaps from dark/hidden sectors, direct signals

- Class (I) signals generally require precision
  - Could be formulated in the language of SM effective field theory (SMEFT)
  - Beam polarization can be leveraged
- Class (II) physics could lead to direct detection of new particles
  - A variety of models
  - Access to new states around the GeV scale
  - Large atomic number ions can provide $Z^2$ enhanced coherent cross sections

* These lectures: only a sample of possibilities; unfortunately many interesting works not covered

# Heavy New Physic and SMEFT

- Physics above weak scale, may be accessible to LHC, future colliders
- Integrate out heavy states $\rightarrow$ higher-dimension operators (point-like interactions)
- BSM encoded in SMEFT: $\Lambda > \langle H \rangle$ scale of new physics

$$\boxed{\mathcal{L} = \mathcal{L}_{\text{SM}} + c_5^1 \frac{HLHL}{\Lambda} + \sum_i c_6^i \frac{O_i}{\Lambda^2} + \dots}$$

  - Wilson coefficients $c_d^i$; operators $O_i$ of dimension $d \geq 5$, made of SM fields
  - First correction, dim-5: can yield (Majorana) neutrino masses
    - Lepton number violating "Weinberg operator"

Example:

- $c_5^1 \sim 1$ and $\Lambda \sim 10^{14}$ GeV *

$$\frac{HLHL}{\Lambda} \rightarrow \frac{\langle H \rangle L \langle H \rangle L}{\Lambda} \rightarrow m_\nu \bar{\nu}^c \nu \;\Rightarrow\; \boxed{m_\nu \sim 0.1 \text{ eV}}$$

* However, it could be that $c_5^1 \ll 1$ (weakly coupled new physics) and $\Lambda \ll 10^{14}$ GeV

# Direct Detection of New GeV Scale Physics

- Dark vector bosons

- Simplest case: dark $U(1)_d$, analogue of visible electromagnetism
- Dark photon (kinetic mixing) and dark $Z$ (mass mixing)
  - Coupled to SM via a small mixing parameter
- Gauge bosons with tiny gauge couplings: *e.g.* $L_e - L_\tau$,. . . (anomaly free)

- Dark fermions

- Heavy neutral leptons (right-handed neutrinos)
  - Akin to those from seesaw mechanism for generating $m_\nu \neq 0$

- Dark scalars

- Axion-like particles (ALPs), analogues of QCD pions (pseudo-scalars)
  - Like pions, manifestations of spontaneously broken approximate global symmetries
  - QCD pions: broken chiral symmetry (approximate due to small quark masses)
  - ALPs can arise in a variety of models, naturally "light" (massless for exact symmetries)
- Could be a regular scalar, a "dark Higgs"

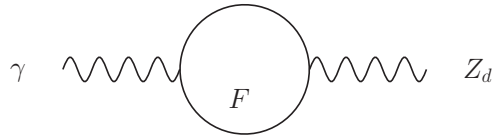
# Dark Photon

- Kinetic mixing: $Z_{d\mu}$ of $U(1)_d$ and $B_\mu$ of SM $U(1)_Y$ Holdom, 1986

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_{\mathbf{W}}}\mathbf{B}_{\mu\nu}\mathbf{Z}_{\mathbf{d}}^{\mu\nu} - \frac{1}{4}\mathbf{Z}_{\mathbf{d}\mu\nu}\mathbf{Z}_{\mathbf{d}}^{\mu\nu}$$

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$

  - May be loop induced: $\varepsilon \sim e g_d/(4\pi)^2 \lesssim 10^{-3}$




- Remove cross term, via field redefinition
  - $B_\mu \to B_\mu + \frac{\varepsilon}{\cos\theta_W} Z_{d\mu}$
  - $Z$-$Z_d$ mass matrix digonalization

- After redefinition, $Z_d$ couples to EM current $J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$

$$\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$$

  - Like a photon, but $\varepsilon$-suppressed couplings: "dark" photon

- Neutral current coupling suppressed further by $O(m_{Z_d}/m_Z) \ll 1$

*Next time, we will discuss how the EIC can shed light on potential new physics, originating from heavy or light states, using a few illustrative examples.*