Looking for New Physics in Upton, New York

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory

Colloquium at Physics Department, BNL

October 31, 2023

Prelude

- A history of fundamental searches and discovery in Upton, NY
  - Muon neutrino
  - CP violation (CPV)
  - Ω^- (quark model)
  - Charm (J/ψ)
  - Muon $g-2$
  - . . .

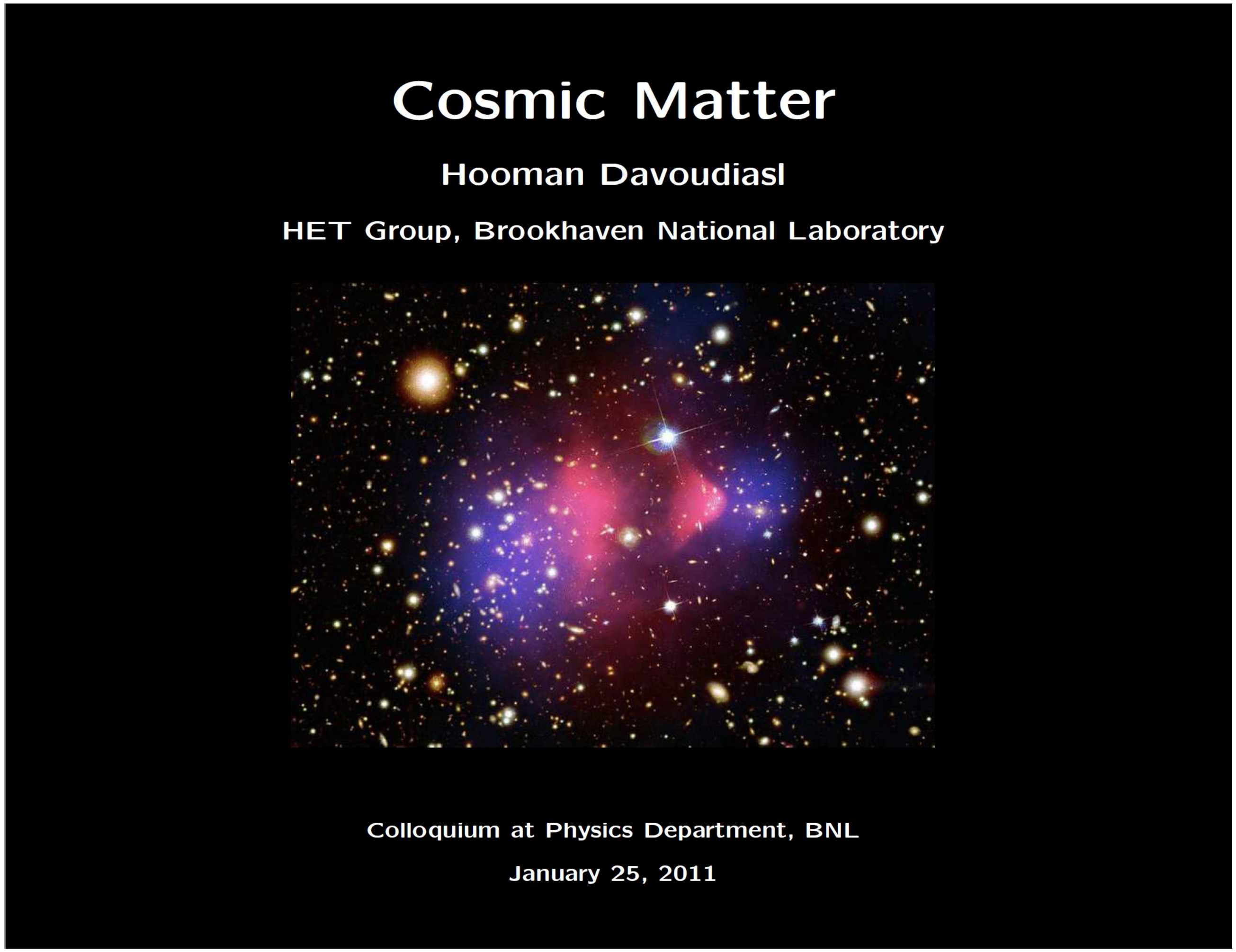
* Many BNL groups engaged in fundamental searches off-site

This talk:

- EIC powerful tool in studying baryonic matter: nucleons and nuclei
- The EIC can also provide excellent opportunities to probe interesting new ideas
  - For example, potential dark sector bosons
- Possible addition of proton EDM experiment in the AGS tunnel
  - Search for new sources of CPV (potential relevance to origin of baryons)
  - New probes of candidates for dark matter and dark energy

Coming decade could continue the legacy of new physics searches hosted at BNL

- The last time I gave a colloquium here was in January of 2011



Cosmic Matter

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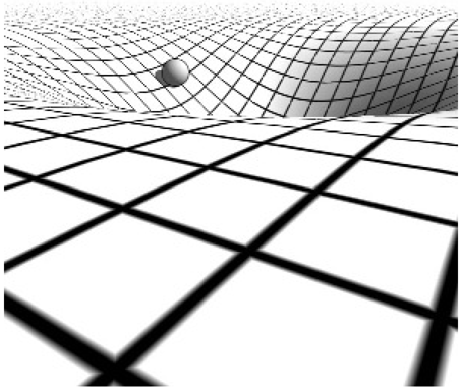
January 25, 2011

- A lot has happened since then!

Some key developments (incomplete list)

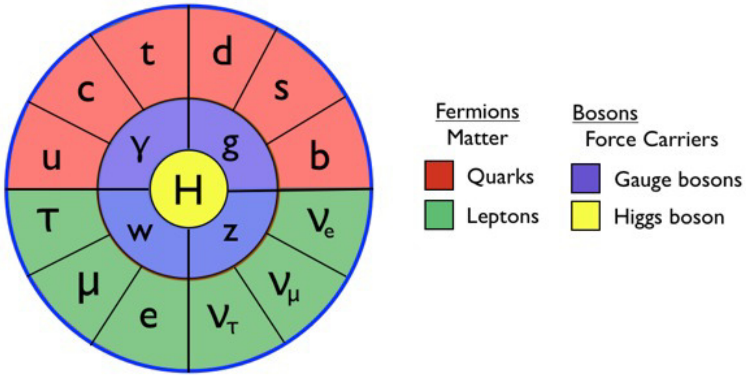
- Neutrino mixing parameter θ_{13} measurement (Daya Bay, Reno)
- Higgs discovery at the LHC (ATLAS, CMS)
- IceCube observation of astrophysical neutrinos up to $\sim 10^3$ TeV
- LIGO-Virgo detection of gravitational waves
- Multi-messenger astronomy (binary neutron star merger)
- Event Horizon Telescope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

Despite all that, the 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*

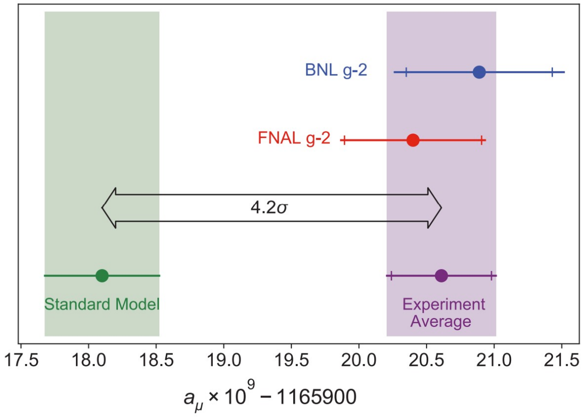
Aside: “*” from last page (can be a separate talk on its own)

- Two prominent instances (also others, largely less significant)

• Muon anomalous magnetic moment $(g-2)$

- $g=2$ (Dirac) gets quantum corrections (SM; possibly other)
- Theory (SM): T. Aoyama, et al., Phys.Rep. 887, 1 (2020)
- Muon g-2 Collaboration 2023 results: discrepancy $\sim 5\sigma$
  - Above prediction under scrutiny, can change
  - Another prediction yields a smaller discrepancy

Borsanyi et al., Nature 593 (2021) 7857, 51-55



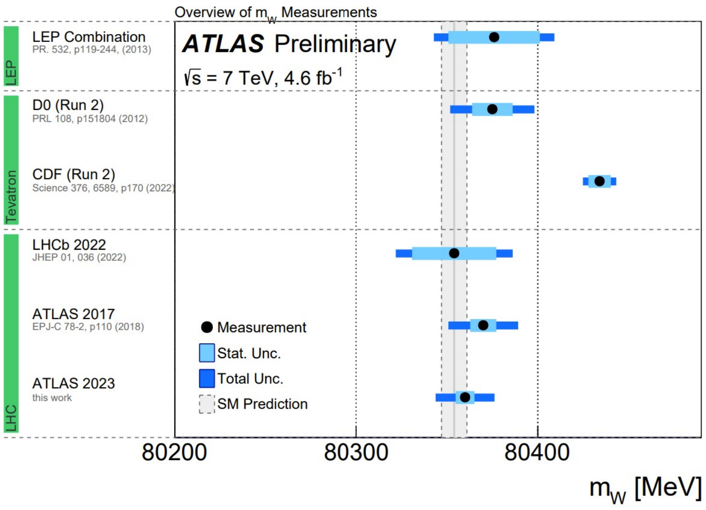
Phys.Rev.Lett. 126 (2021) 14, 141801

• W mass

- CDF II result: $\sim 7\sigma$ discrepancy!

CDF Collaboration, Science 376 (2022) 6589, 170-176

- Are there unaccounted for uncertainties?
- More data from the LHC can be illuminating



ATLAS-CONF-2023-004

Stay tuned!

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 $\rightarrow m_\nu \neq 0$**

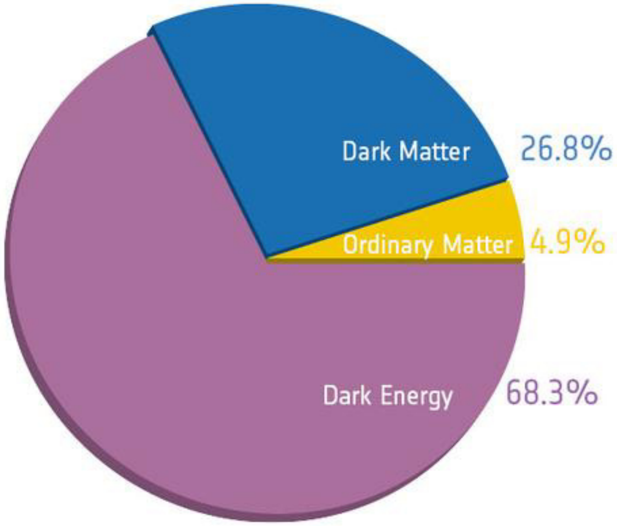
- Adding right-handed neutrinos (of a broad range of masses) can explain this

★ **Cosmology**

- What is accelerating cosmic expansion? (dark energy; may be vacuum energy)
- What is holding galaxies together? (dark matter; may have its own sector)
- What caused ordinary matter asymmetry? (requires more CPV)

95% of the Universe is unknown to us!

Planck



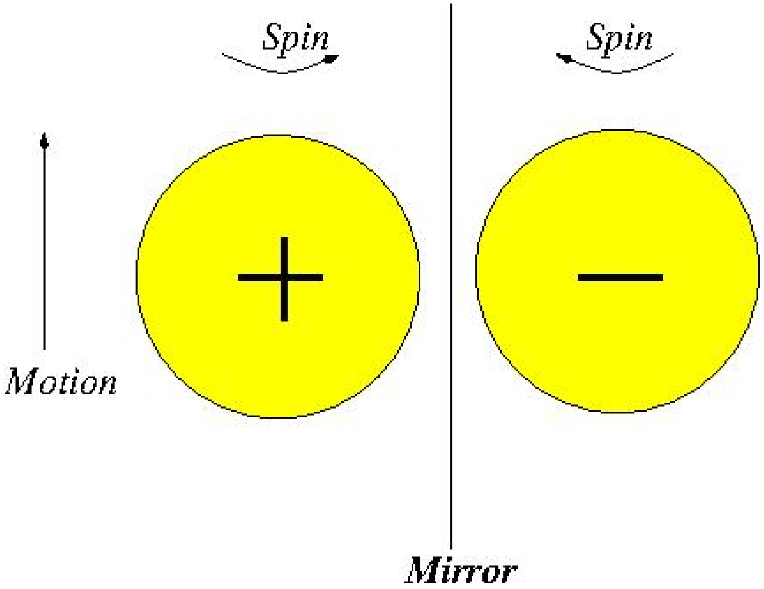
There are also theoretical hints:

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

Aside:

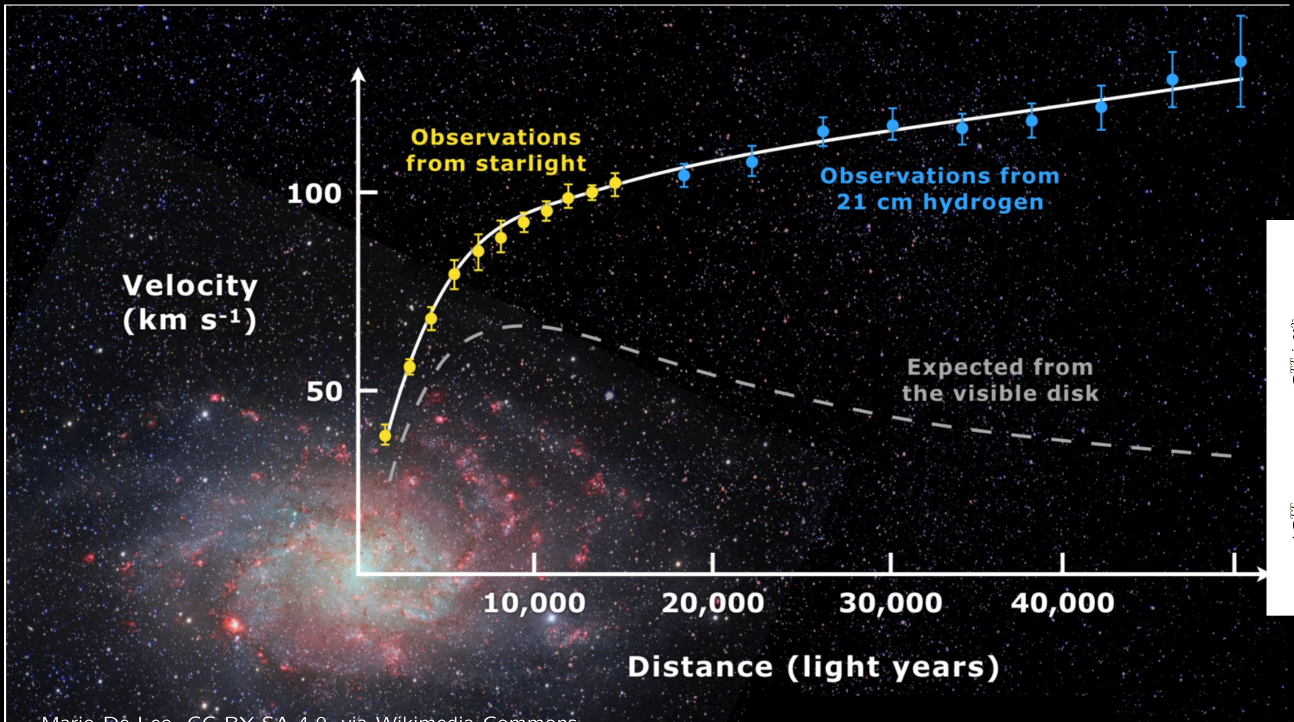
CP: Charge conjugation (particle ↔ antiparticle) – Parity (mirror)

- Violated by SM weak interactions
- SM CPV: not enough to account for ordinary matter

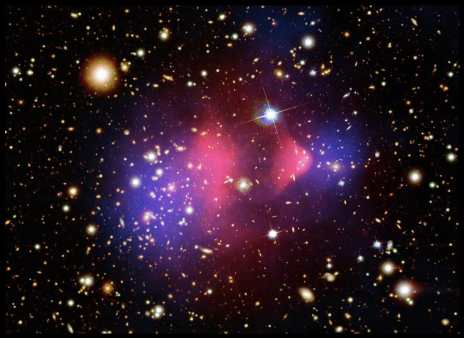


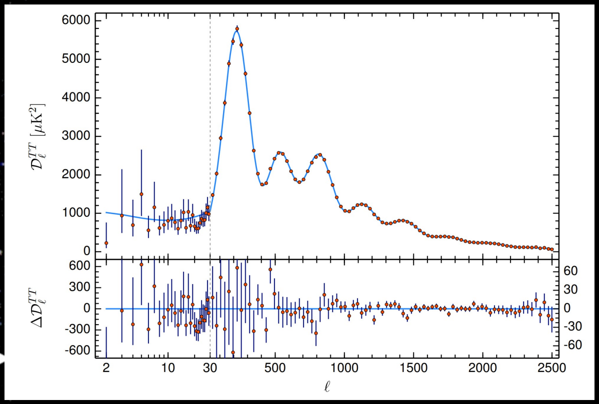
Dark matter (DM)

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



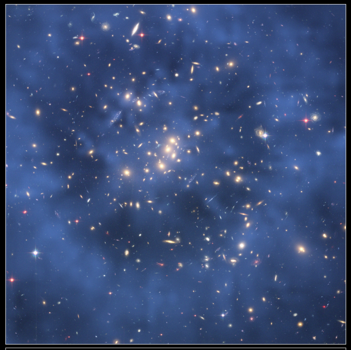
Mario De Leo, CC BY-SA 4.0, via Wikimedia Commons





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

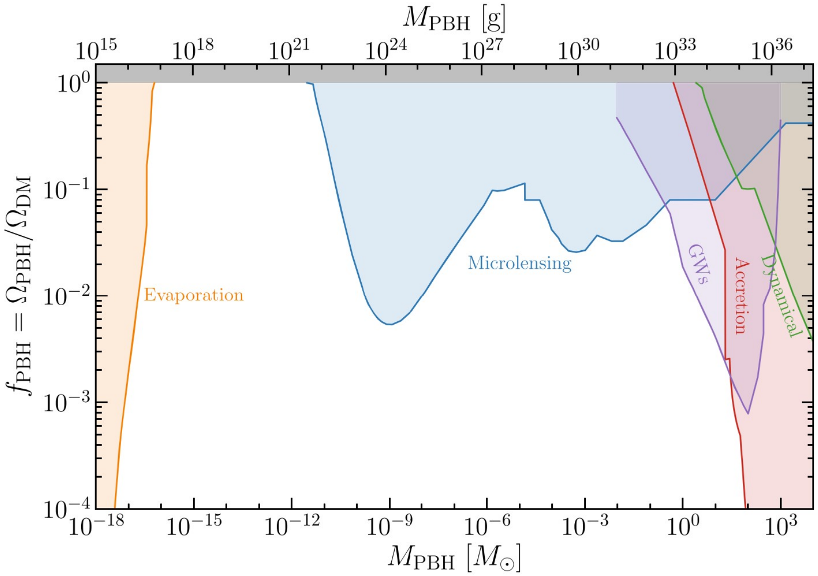
- Feeble interactions with atoms, photons
- Self-interactions not strong ($\sigma \lesssim 1$ barn)
- Not explained in SM
- So far, evidence only from gravity effects
- Possible mass scale: $\boxed{10^{-22}\ \text{eV} \lesssim M_{\text{DM}} \lesssim 10^{55}\ \text{eV}}$ 77 orders of magnitude!

- 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

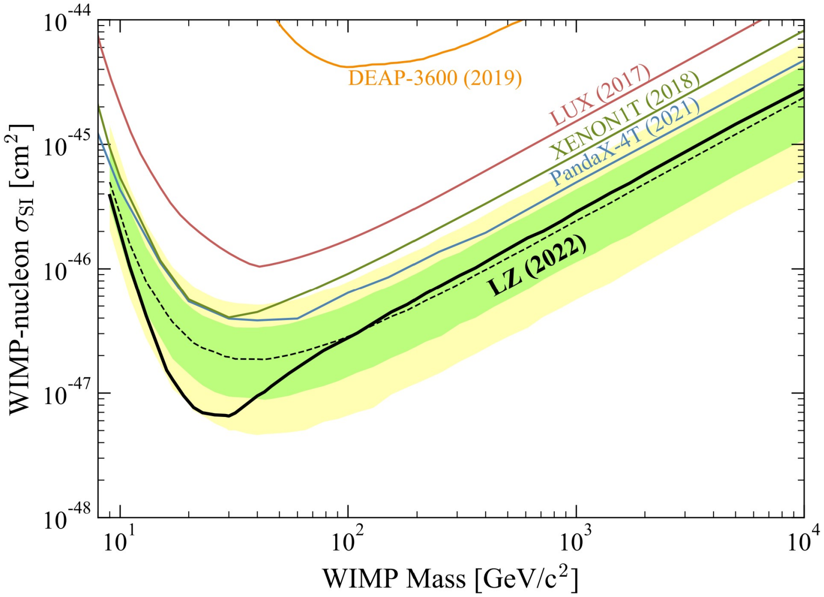
- Weakly interacting massive particles (WIMPs) longtime targets
- Motivation: The hierarchy problem in SM; $M_{\text{new}} \gtrsim M_H \approx 125$ GeV (weak scale)
- Thermal relic density: annihilation, “freeze-out”

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

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

\- $g \sim g_{\text{weak}}$, $M \gtrsim$ weak scale $\to \rho_{\text{WIMP}} \sim \rho_{\text{DM}}^{\text{obs}}$

$\Rightarrow$ *WIMP Miracle*



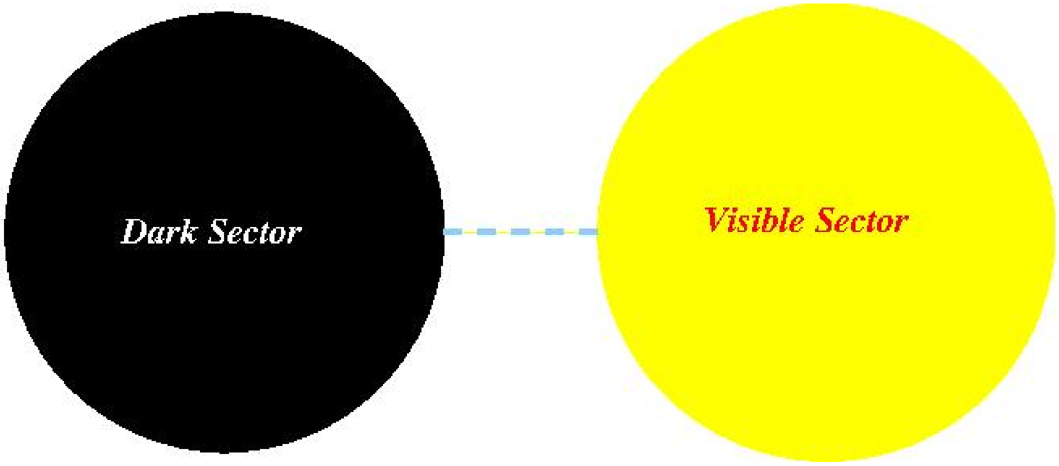
J. Aalbers *et al.*, The LUX-ZEPLIN (LZ) Collaboration, arXiv:2207.03764v3 [hep-ex]

Dark Sectors

- With lack of evidence for new physics near weak scale, alternatives to WIMPs have been put forth in recent years

- Example: DM could be light ($m \lesssim$ GeV) and may reside in a separate sector with its own forces
  - Analogy with SM
  - Maybe set by an asymmetry (not a thermal relic), like ordinary matter

- Visible and dark sectors connected by feeble interactions
  - Mediators could be light, accessible to low energy experiments



Examples of GeV Scale Dark Bosons

Dark vector bosons

- Simplest case: dark $U(1)_d$, analogue of visible electromagnetism
- Dark photon (kinetic mixing) and dark Z (mass mixing)
- Very weakly interacting gauge bosons: $B-L$, $L_e - L_\tau, \ldots$ (anomaly free)

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)

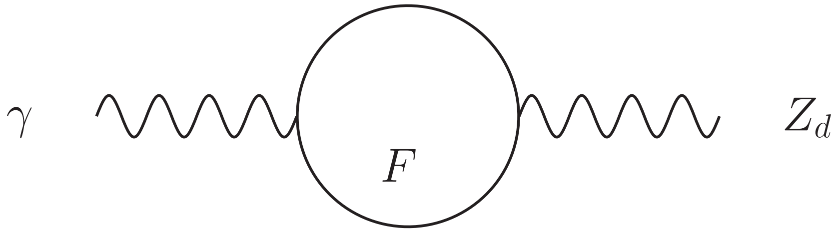
- Can arise in a variety of models, naturally "light" (massless for exact symmetries)

Dark Photon

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

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\mu\nu}Z_d^{\mu\nu}$$

- $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$ (field strength tensor)
- $\tan\theta_W \equiv \dfrac{g'}{g}$ with g' and g gauge couplings of $U(1)_Y$ and $SU(2)$, respectively
- Can be loop induced: $\varepsilon \sim e g_d/(4\pi)^2 \lesssim 10^{-3}$



- F charged under both $U(1)_Y$ and $U(1)_d$

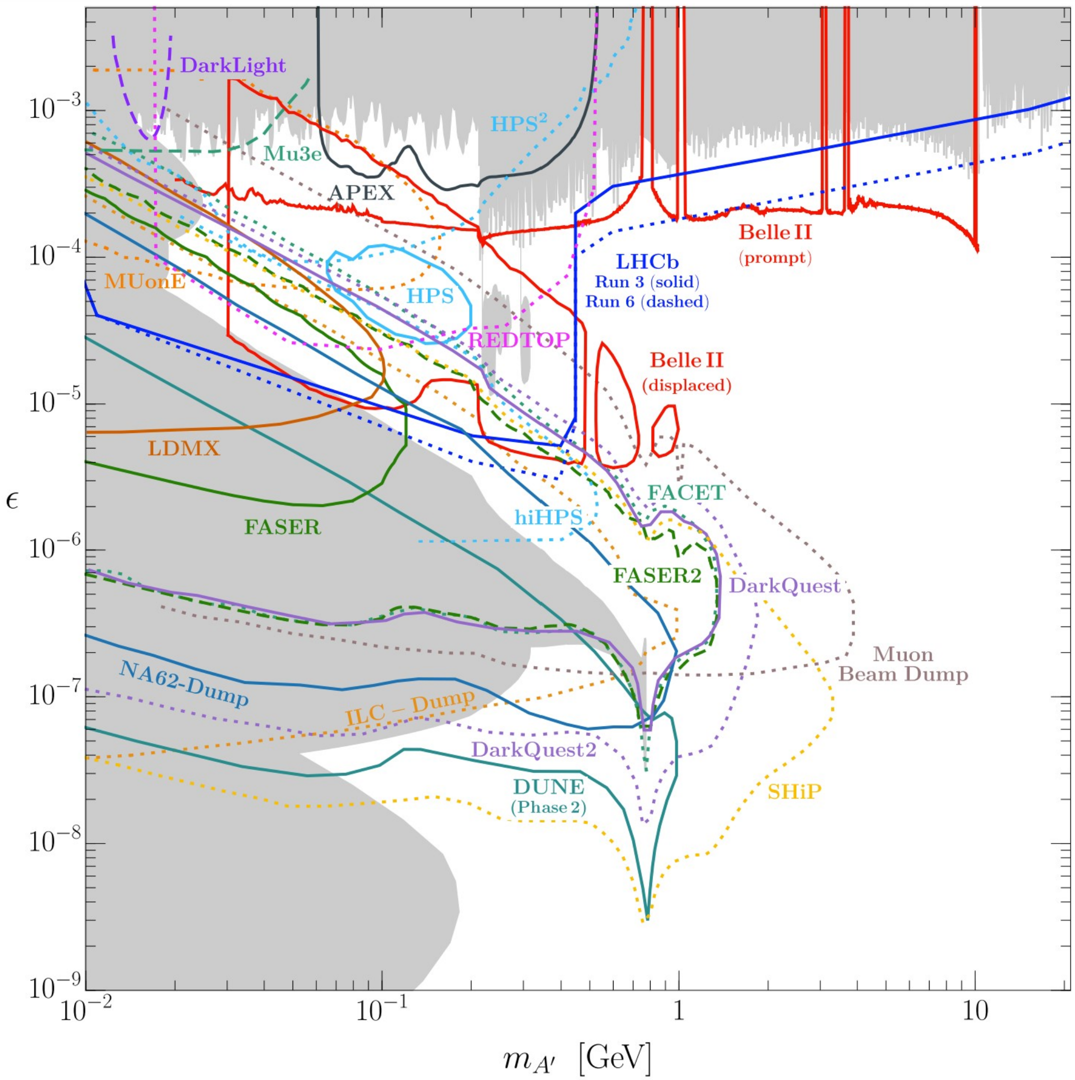
$$\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$$

$J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$ (electromagnetic current)

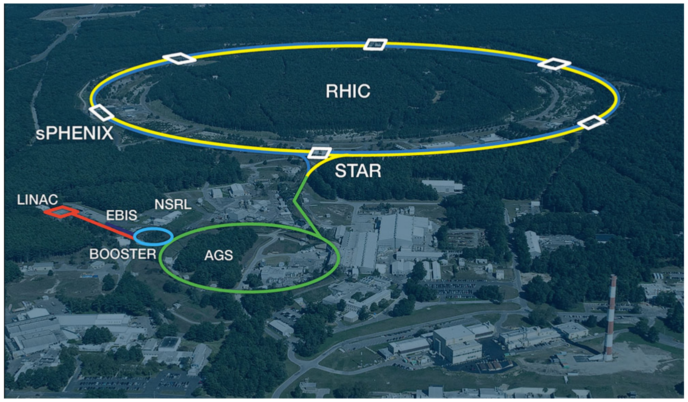
- Active experimental program to search for the dark photon

Pioneering early work by Bjorken, Essig, Schuster, Toro, 2009

From Batell, Blinov, Hearty, McGehee, 2207.06905, visibly decaying Z_d

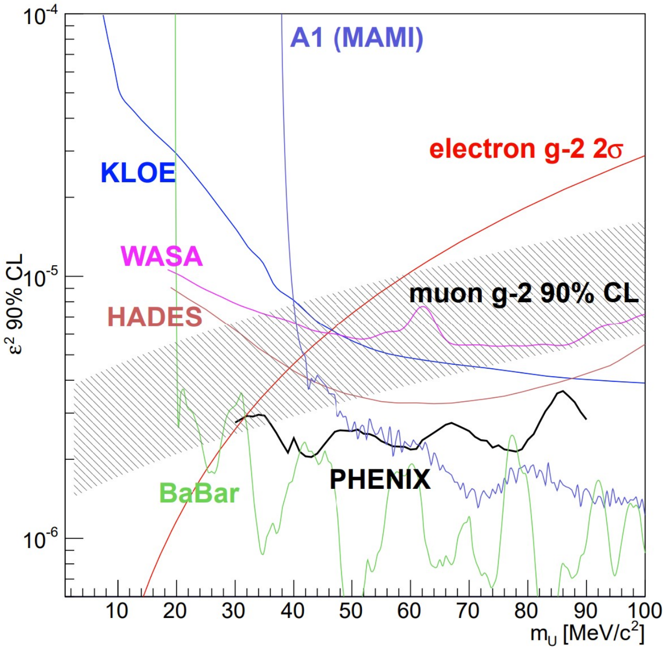


- Also a local industry! (RHIC)



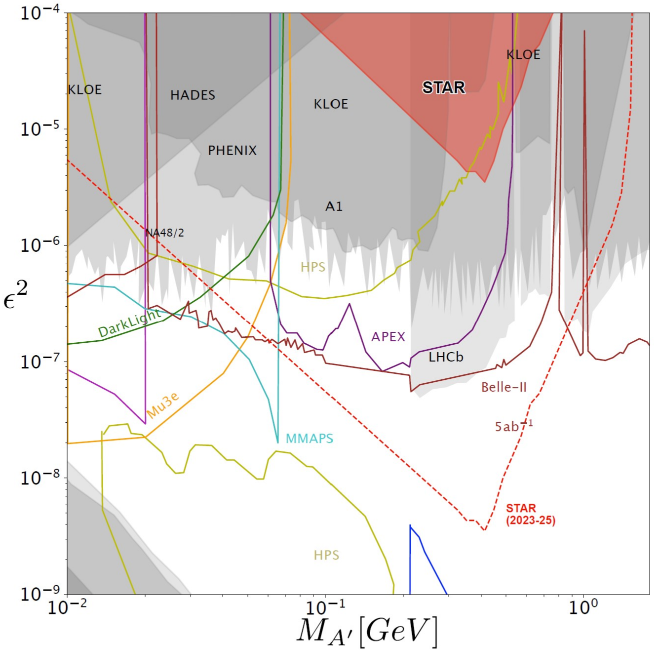
- PHENIX: $\pi^0, \eta \to \gamma A'(\to e^+e^-)$

Phys.Rev.C 91 (2015) 3, 031901, (PHENIX Collaboration)



- STAR: ultra-peripheral $\gamma A' \to e^+e^-$

Xu, Lewis, Wang, Brandenburg, Ruan, 2211.02132



Other $U(1)$ Gauge Interactions

- $B{-}L$; anomaly free with the addition of three right-handed neutrinos

- Leptophilic interactions: $L_i - L_j$, with $i, j = e, \mu, \tau$, $i \neq j$

- Gauge one at a time

- Anomaly free

- We will consider $m_{A'}$ at or below GeV scale

- Direct coupling to SM: gauge coupling must be tiny $g_{A'} \ll 1$

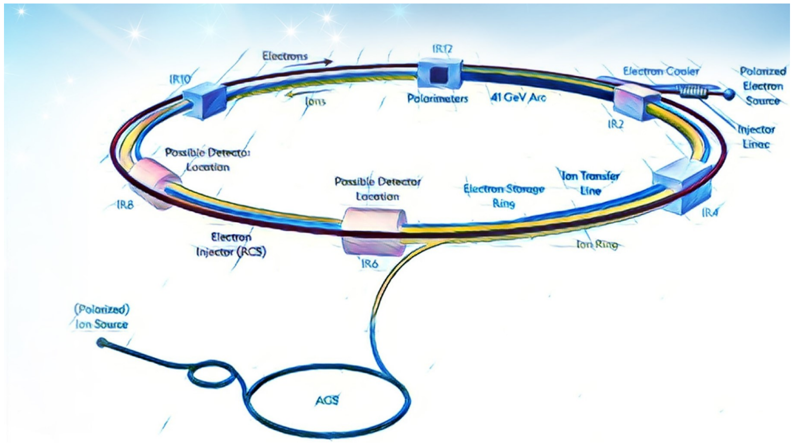
- Various experimental probes, akin to dark photons

- Light and feebly interacting states can be long-lived

- Displaced vertex signals in collider experiments

- Good prospects for suppressing SM backgrounds

The Electron Ion Collider (EIC)



2103.05419, EIC Yellow Report

- New frontier in studying hadronic systems, to be built at BNL

\- *E.g.*, spin composition of nucleons,....

- Large $\sqrt{s}$, luminosity

\- Up to $E_e = 18$ GeV and 110 GeV per nucleon (e-Au)

\- Fixed target equivalent of ~ 4 TeV e-beam

\- ~ 100 fb^{-1} per nucleon possible

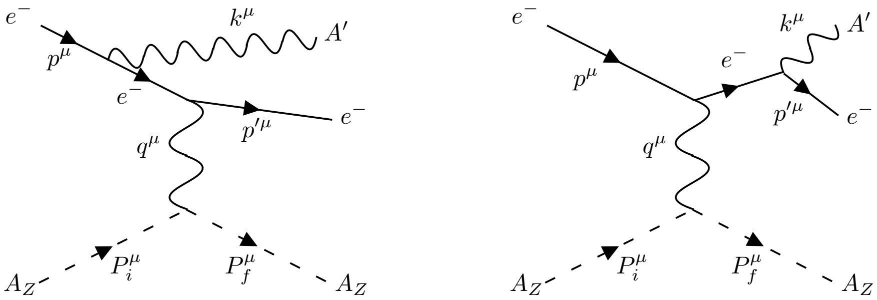
- Polarization: $\sim 70\%$ for e and p beams

- Large nuclei (high Z): *e.g.* gold, lead

Displaced Hidden Vectors at the EIC

H.D., Marcarelli*, Neil, Phys.Rev.D 108 (2023) 7, 075017, 2307.00102

- Coherent production from gold ion, $Z = 79$: $eA_Z \to eA_Z A'$ $\quad (Z_d \leftrightarrow A')$
- $q^2 \lesssim \mathcal{O}(10 \text{ MeV})$
- Large Z^2 enhancement of electromagnetic scattering



- Probability of detection of displaced decay: $P_{\text{disp}} = e^{-d_{\text{min}}/(\gamma_k v_k \tau)} - e^{-d_{\text{max}}/(\gamma_k v_k \tau)}$
- d_{min} from detector resolution, d_{max} from geometry
- Kinematic variables: laboratory frame
- Signal cross section: $\sigma_{\text{sig}}(g_{A'}) = \int P_{\text{disp}} \frac{d\sigma}{d\gamma_k\, d\eta_k} d\gamma_k\, d\eta_k\, \mathcal{B}(A' \to e^+ e^-)$

* Roman Marcarelli, SCGSR awardee from U. Colorado, Boulder (advisor Prof. E. Neil, former RBRC fellow); January-April, 2024, HET group

Signal Selection:

- EIC Comprehensive Chromodynamics Experiment (ECCE) detector

arXiv:2209.02580 [physics.ins-det]

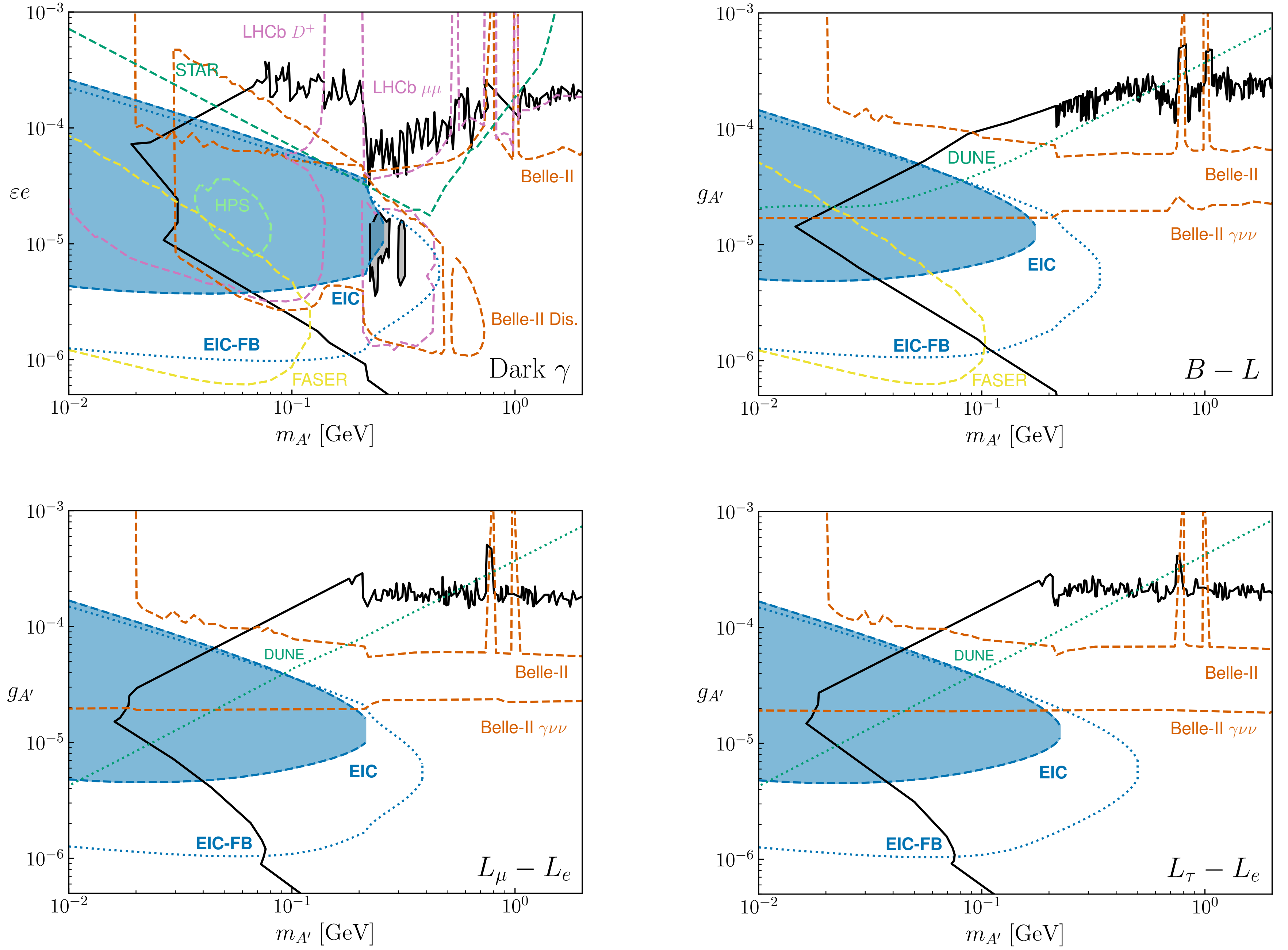
- ePIC Collaboration
- Signal requires both e^+ and e^- from vector decay

\- $\mu^+\mu^-$ also available for much of the parameter space

- We estimated: $d_{\text{min}} \approx \gamma_k(\text{DCA}_{\text{2D}}^{\text{min}})/(v_k \cos\theta_k^{\text{lab}})$
- For pions: $\text{DCA}_{\text{2D}}^{\text{min}} < 100\ \mu\text{m}$
- $\Rightarrow d_{\text{min}} \gg 0.1$ mm, $d_{\text{max}} = 1$ m

DCA: distance of closest approach

- ECCE tracking: $\boxed{|\eta| < 3.5}$
- We also considered a detector at $z = -5$ m
- Assumed: $\text{DCA}_{\text{2D}}^{\text{min}} = 200\,\mu\text{m}$, $d_{\text{max}} = 5$ m
- Covering far backwards (FB): $\boxed{-6 < \eta < -4}$

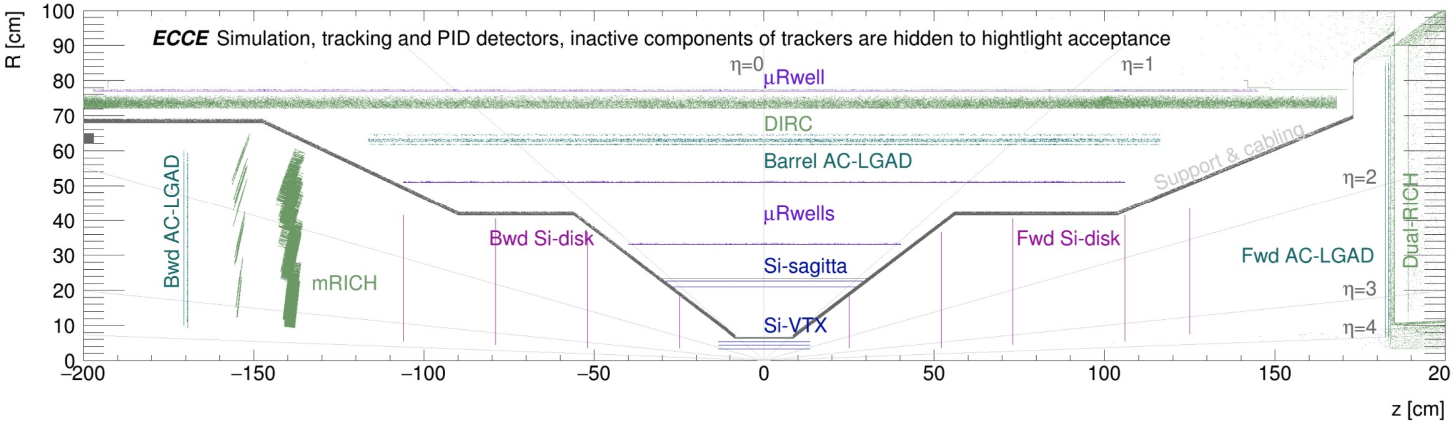


From H.D., Marcarelli, Neil, 2307.00102

Background considerations

- We assumed zero background
- Photon conversion: sparse backwards detector systems   Adkins *et al.*, 2209.02580

\- Si disks separated by $\sim$ 25 cm: cut out thin regions from signal



- Misidentified pions as electrons: electron end cap fake rate $\sim 10^{-4}$

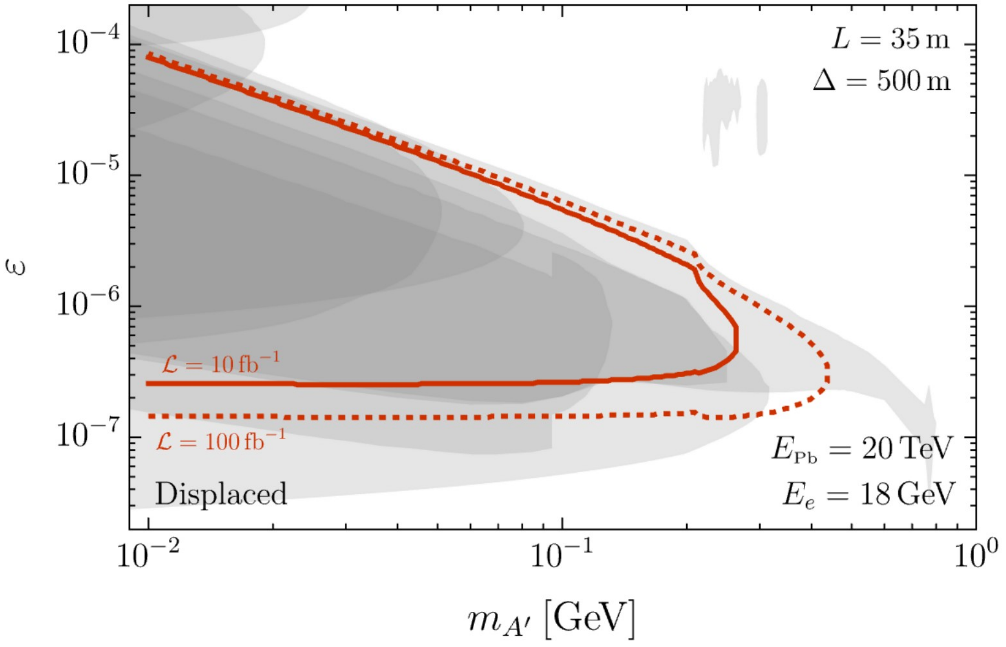
\- Requiring both e^+ and e^-

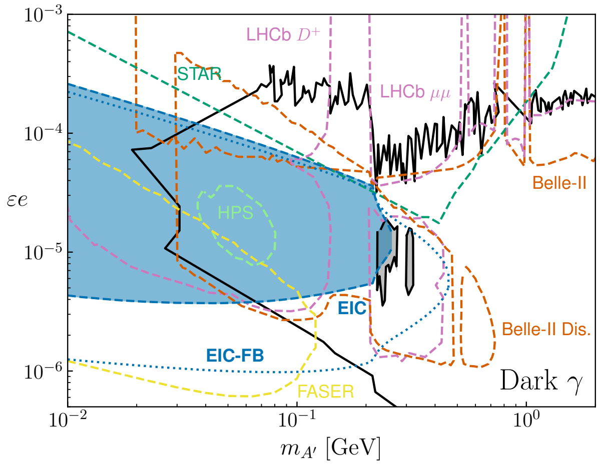
\- Additional signals if muon detectors added

- Losing signal events down the beam pipe: our estimate $\sim$ (20-30) %, manageable
- These are (theorist) projections, using rough approximations

\- Detailed and more realistic simulations required for definitive results

Recently, also Balkin *et al.*, 2310.08827





2307.00102

- $eN \to eNA'$, coherent scattering from Pb
- Dark photon decay $A' \to \mu^+\mu^-$ (to reduce background)
- Decay volume $\Delta = 500$ m long (shielded) at $L = 35$ m from interaction point
- Does not exceed current bounds
  - Our work assumed much smaller ($\gtrsim$ mm) displacement
  - Worthwhile to determine efficiency of our suggested background suppression

Charged Lepton Flavor Violating (LFV) ALPs at the EIC

- EFT for ALP interactions

$$\mathcal{L}_\ell = \frac{C_{\ell\ell'}}{\Lambda}\partial_\mu a \sum_{\ell\ell'} \bar{\ell}\gamma^\mu \left(\sin\theta_{\ell\ell'} - \cos\theta_{\ell\ell'}\gamma_5\right)\ell' + \text{H.C.}$$

$$(\text{EoM}) \longrightarrow \frac{C_{\ell\ell'}}{\Lambda} a \sum_{\ell\ell'} \bar{\ell}\left(m^- \sin\theta_{\ell\ell'} - m^+ \cos\theta_{\ell\ell'}\gamma_5\right)\ell' + \text{H.C.}$$

$m^\pm \equiv m_\ell \pm m_{\ell'}$
See, *e.g.*, Bauer, Neubert, Renner, Schnubel, Thamm, 2019; Cornella, Paradisi, Sumensari, 2019

- $\theta_{\ell\ell'} = 0$: parity even; maximal PV for $\theta_{\ell\ell'} = \pi/4, 3\pi/4$

\- This can be probed with EIC e-beam polarization

Earlier work on charged LFV at EIC includes:

Gonderinger, Ramsey-Musolf, 2010; Zhang *et al.*, 2022 (Leptoquark mediated $ep \to \tau X$)

Cirigliano, Fuyuto, Lee, Emanuele Mereghetti, Yan, 2021 (SMEFT)

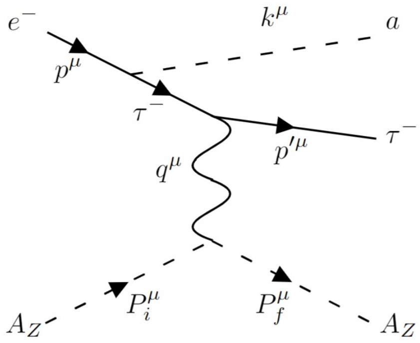
See also: Boughezal *et al.*, 2022 (EW physics, SMEFT); Boughezal, de Florian, Petriello, Vogelsang, 2023, (SMEFT, fermion dipole moments)

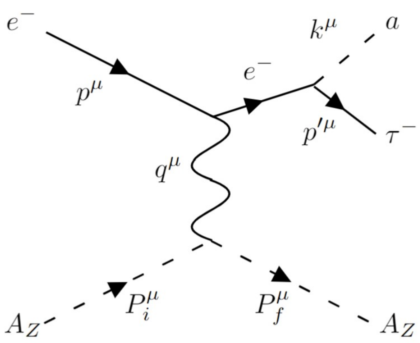
Search for $e - \tau$ LFV: a "Golden Opportunity" at the EIC

H.D., Marcarelli, Neil, JHEP 02 (2023) 071; 2112.04513

- Consider coherent scattering, as before: $eA_Z \to \tau A_Z a$

\- Gold ion, $Z = 79$





- Only three significant decay channels: (i) $a \to \tau^- \tau^+$, (ii) $a \to \tau^- e^+$, (iii) $a \to \tau^+ e^-$
- Consider $a(\to e^+ \tau^-)\tau^-$ final state; veto on e^-
- Focus on three-pronged decays

\- Adopt τ identification efficiency $\epsilon_\tau \approx 1\%$ from Zhang *et al.*, 2207.10261

\- Including other decay modes and veto on ion break-up can enhance the search

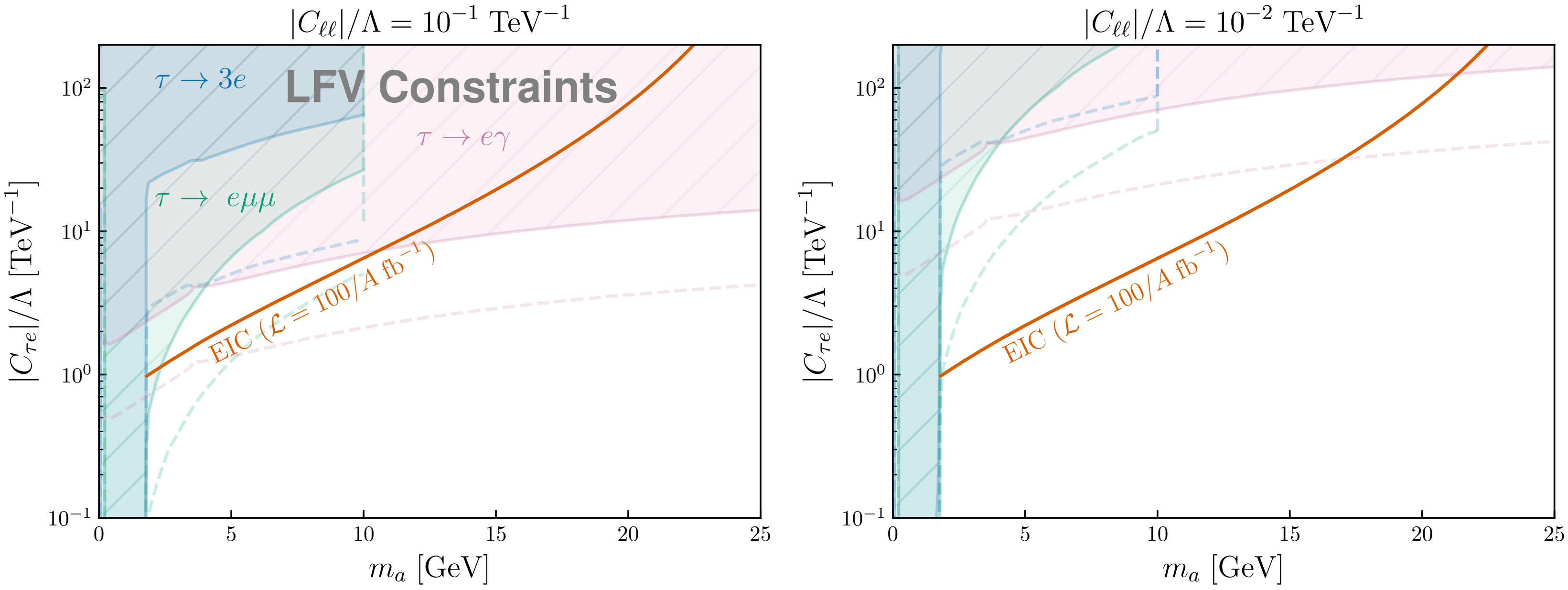
- Main background from τ pairs through Bethe-Heitler process

- Estimated from cross section for τ pair production in rock by cosmic ray muons
Bulmahn, Reno, 2008

- Good EIC prospects for probing charged LFV ALPs, especially when diagonal couplings are suppressed

- Weakened τ decay constraints

- Adding μ detection may improve the search (τ identification)



Solid line BABAR, dashed line Belle II with 50 ab^{-1}; tree-level $a\gamma\gamma$ ignored

From H.D., Marcarelli, Neil, JHEP 02 (2023) 071; 2112.04513

- Recent work on ALP-photon coupling using coherent scattering at the EIC

\- Z^2 enhanced From Balkin *et al.*, 2310.08827

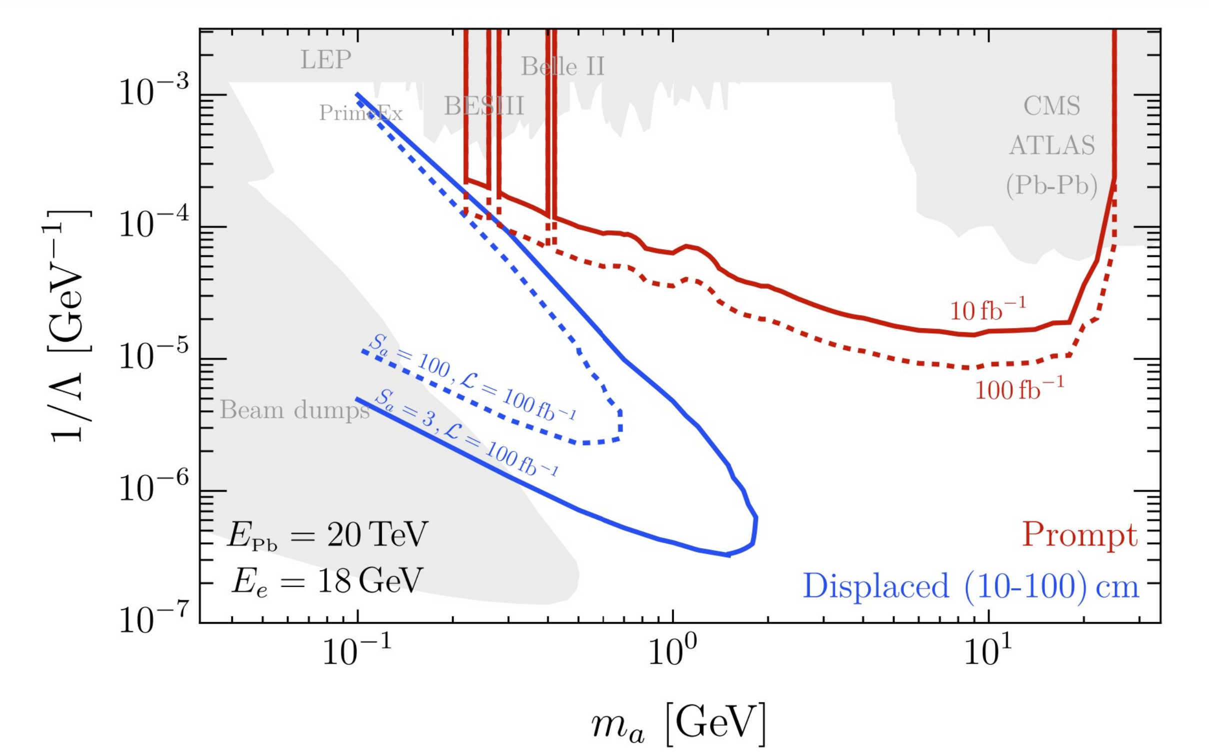
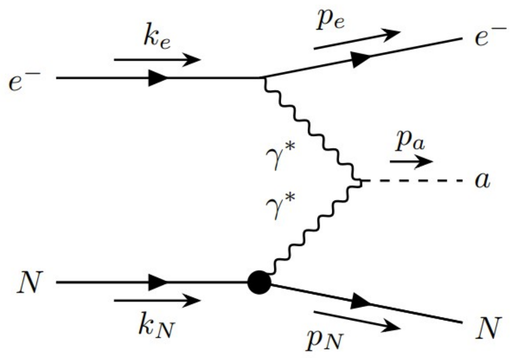


Figure 7: The EIC projections from the ALP searches with $E_e = 1,118\,\mathrm{GeV}$ and $E_{\mathrm{Pb}} = 20\,\mathrm{TeV}$. The solid (dashed) red lines show the prompt search results with 10 (100) fb^{-1} integrated luminosity. The solid (dashed) blue lines show the displaced search results with $S_a = 3$ ($S_a = 100$) with 100 fb^{-1} integrated luminosity, assuming the diphoton spatial resolution $L_R = 10\,\mathrm{cm}$ and the distance between the interaction point and the EM calorimeter $L_{\mathrm{EM}} = 100\,\mathrm{cm}$.



See also Liu, Yan, 2112.02477 (e, p initial states)

CPV and Strong Interactions

- CPV is quite suppressed in strong interactions of hadrons
- This is a puzzle, since $\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$ could be part of QCD
- $\bar{\theta} = \theta + \arg\det(M_q)$ is the actual physical parameter
- Neutron EDM $d_N < 1.8 \times 10^{-26}$ e.cm (90% CL)→ $\bar{\theta} \lesssim 10^{-10}$

Abel *et al.*, 2020

- No obvious reason for $\bar{\theta} \ll 1$ (“strong CP problem”)
- CPV observed, so $\bar{\theta}$=0 not justified
- Cancellation between two terms not motivated by any principle
- Dynamical solution: Peccei-Quinn mechanism Peccei-Quinn, 1977
- Leads to the appearance of a light scalar, the axion Weinberg, 1978; Wilczek, 1978
- Note: beyond SM CPV necessary for typical baryogenesis mechanisms

Proton Storage Ring EDM Experiment

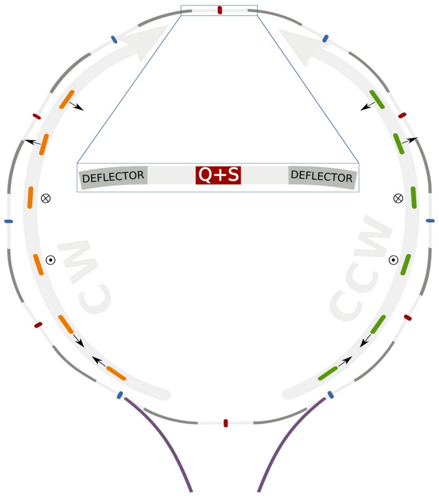
- Proposal for a p storage ring experiment to search for p-EDM

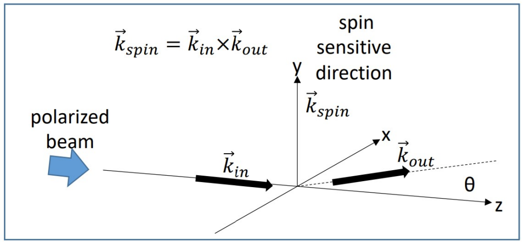
See for example, Omarov *et al.*, Phys. Rev. D 105, 032001 (2022); Alarcon *et al.*, 2203.08103

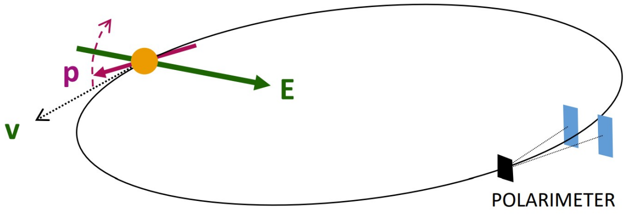
- Symmetric-hybrid design (E bending, B focusing)
- Simultaneous CW, CCW beams
- p magic momentum: 0.7 GeV
- 800 m circumference
- Can fit in AGS tunnel at BNL

\- Saves cost

\- Under study (4 m electric dipole)
Huang, Morse, BNL LDRD







- Sensitivity goal 10^{-29} e.cm for proton
- SM prediction for nucleons $\sim 10^{-32}$ e.cm, far from ultimate sensitivity
- New CPV physics, coupling g, phase φ, at scale M_{NP} $m_q \sim 5$ MeV, $g \sim 1$, $\varphi \sim 1$

$$\boxed{d_N \sim \frac{e g^2\, m_q}{16\pi^2 M_{\rm NP}^2}\sin\varphi \sim\sim 10^{-29}\left(\frac{300\text{ TeV}}{M_{\rm NP}}\right)^2 \sin\varphi\ \ e.\text{cm}}$$

- Impressive indirect reach, beyond envisioned future colliders

Probing Ultralight Scalars at a p-Storage Ring

Graham *et al.*, Phys.Rev.D 103 (2021) 5, 055010; 2005.11867

- Ultralight axions (not QCD): natural Fuzzy DM candidates: $a \sim \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a}\sin(m_a t)$

- Local DM density $\rho_{\mathrm{DM}} \sim 0.3$ GeV/cm^3

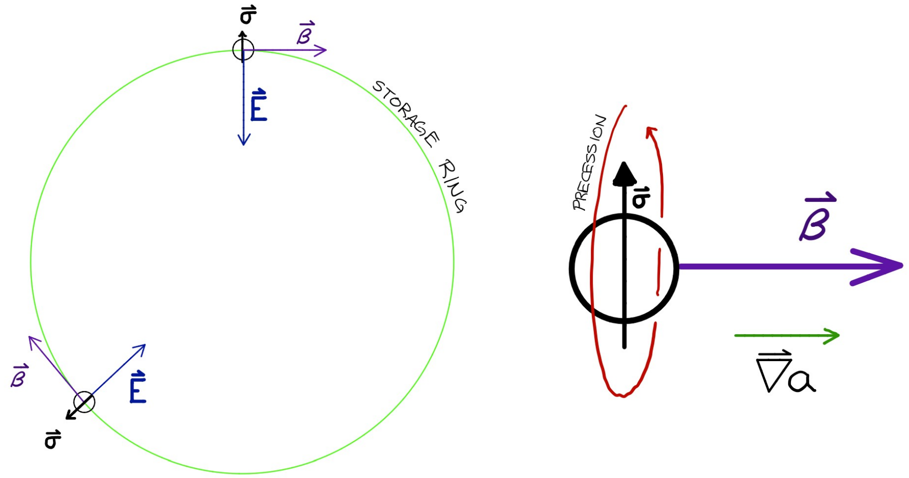
- Coupling to p:

$$g_{aNN}\partial_\mu a\bar{p}\gamma^\mu\gamma_5 p \;\rightarrow\; \mathcal{H} = -g_{aNN}\vec{\nabla}a.\vec{\sigma}_p + \ldots$$

- Proton spin (radial) precesses around $\vec{\nabla}a$, which mimics a magnetic field

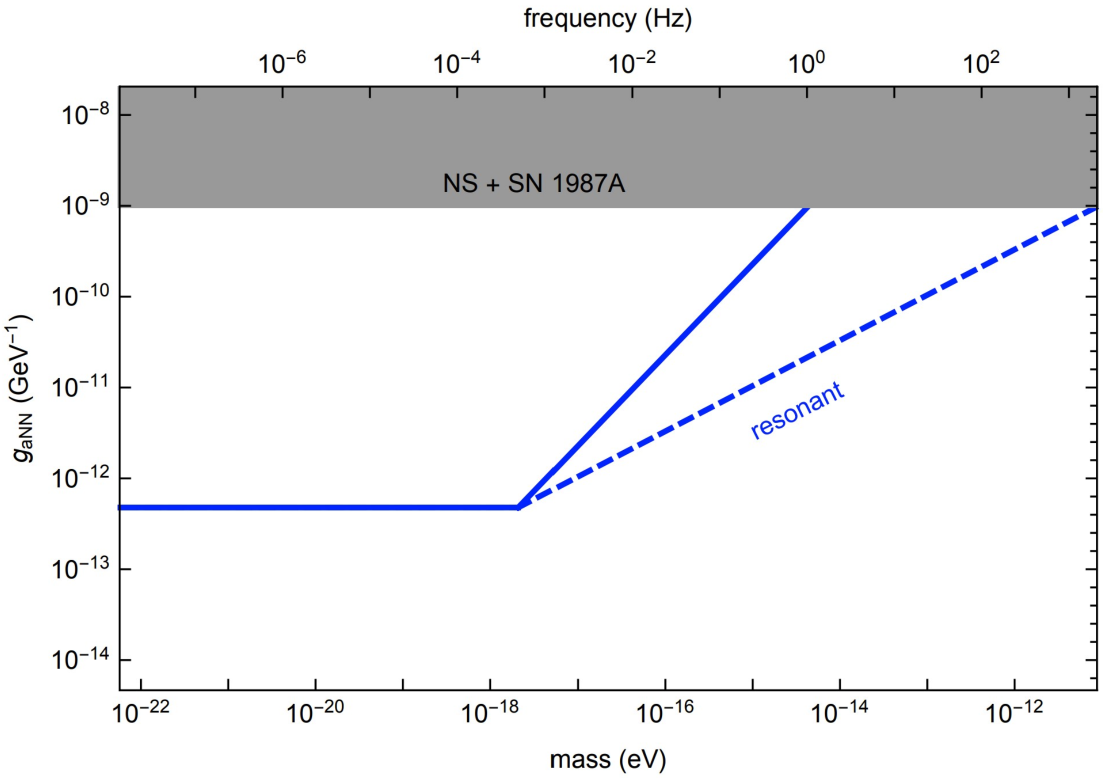
$$\vec{\nabla}a \sim \gamma\beta m_a a$$

- β axion velocity in proton frame: $\mathcal{O}(10^{-3})$ (virial velocity) $\rightarrow$ $\mathcal{O}(1)$ (storage ring)



From Graham et al., 2005.11867

- Proton spin precession after time T (storage time): $\Delta\theta \sim g_{aNN}\beta\frac{\sqrt{2\rho_{\rm DM}}}{m_a}\sin(m_a T)$
- Assuming $T \sim 10^3$ s and sensitivity $\sim 10^{-9}$ rad/s (same as p-EDM search)



From Graham et al., 2005.11867

- Loss of coherence for $m_a \gg T^{-1}$: detuning (magic momentum) to get resonance
- Sensitivity far below astrophysical bounds!

Extra Wobble from a Geocentric Force


NASA

H.D., Szafron, Phys.Rev.Lett. 130 (2023) 18, 181802; 2210.14959

- a may have both scalar and derivative couplings
- Scalar (PV) coupling to bulk matter: $g^s_\psi a\bar{\psi}\psi$; $\psi = N, e$
- Earth can generate a profile $a \propto 1/r$
- $m_a < R_\oplus^{-1}$; $R_\oplus^{-1} \approx 3 \times 10^{-14}$ eV ; $g^N_s < 8 \times 10^{-25}$ MICROSCOPE Coll., 2022; Fayet, 2018
- Assuming also $g^a_\mu \, \partial_\mu a \, \bar{\mu}\gamma^\mu\gamma_5\mu \Rightarrow \vec{\nabla} a$ couples to muon spin like a radial B-field
- This may explain the BNL/FNAL $g_\mu - 2$ anomaly (excess precession)

See also Agrawal, Kaplan, Kim, Rajendran, Reig, Phys.Rev.D 108 (2023) 1, 015017; 2210.17547

- Corresponding to $\Delta a_\mu \sim 2.5 \times 10^{-9}$
- No "particles in the loop" but a new force!
- Effect depends on distance from Earth (null in empty space)
- A different injection direction (new setup) can test this hypothesis 2210.17547
- Signal in the p-storage ring, assuming also derivative coupling to protons
- $\vec{\nabla} a$ would show up as a spurious B-field

Concluding Remarks

- New physics may be distributed across a wide range of mass scales

- A broad approach can perhaps optimize chances of discovery

- We could leverage BNL infrastructure and expertise to facilitate new efforts

- Capabilities of the EIC lend themselves to this endeavor

- One can envision a complementary research program (BSM at ECCE, second detector)

- Additional features like muon identification, "backward" detectors, . . . can enhance and enable beyond SM physics investigations

- Interactions among different physics communities would be essential as designs take form and specifications become finalized

- A proposed proton EDM experiment in the AGS tunnel would be a great complement to BNL's portfolio of research: CPV and more

- Determining the proton EDM could point to a new "Fermi scale" and a target for future high energy experiments

- An intrepid scientific spirit, a strong vision, and relatively modest investments would allow BNL to continue and enhance its legacy of hosting and leading experiments in search of new fundamental phenomena

Happy Halloween!