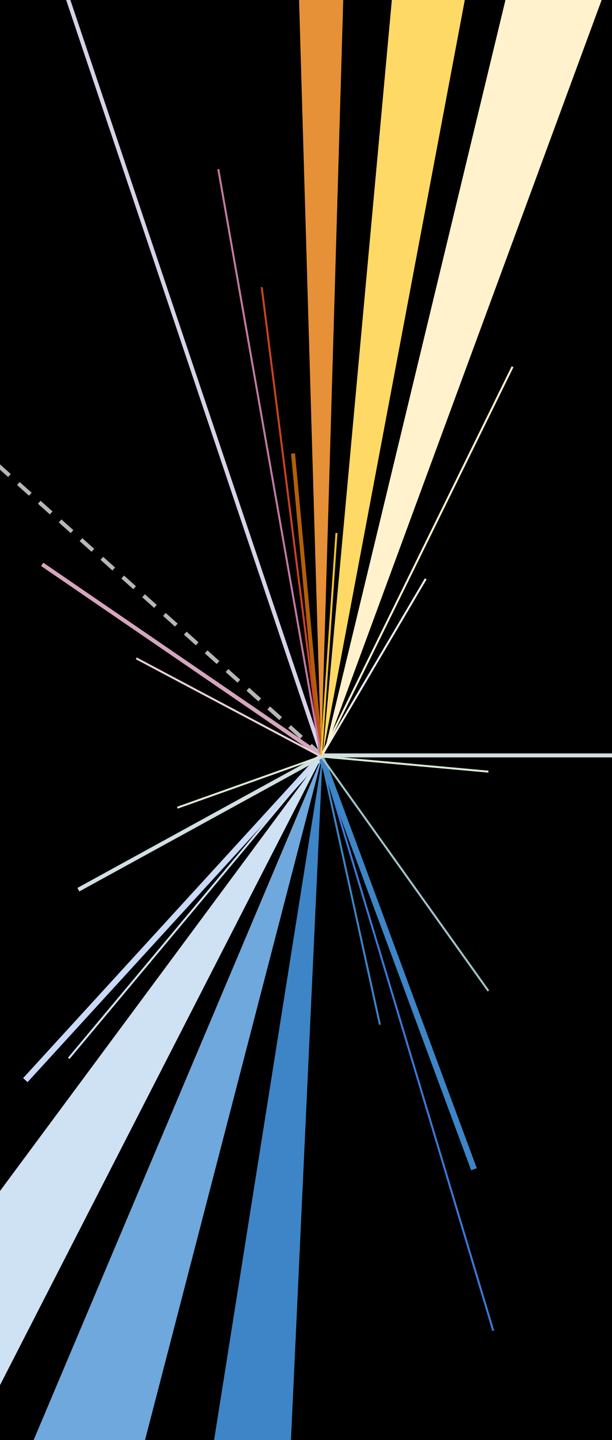


Colliding light, tau $g - 2$, and axion detectors

Institute of Physics Joint APP/HEPP Conference
Rutherford Appleton Laboratory, UK
5 April 2022

Jesse Liu
University of Cambridge

TRINITY COLLEGE CAMBRIDGE

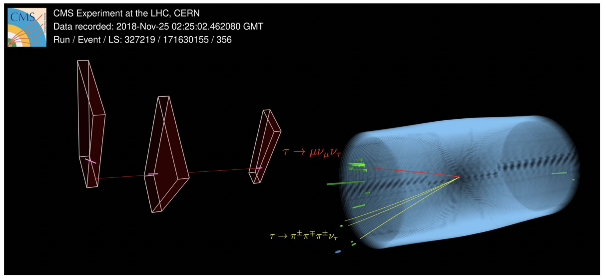
UNIVERSITY OF CAMBRIDGE

TODAY

Two stories of creative interdisciplinary science

New physics and tau $g-2$ using LHC heavy ion collisions

Lydia Beresford and Jesse Liu
Phys. Rev. D **102**, 113008 – Published 22 December 2020



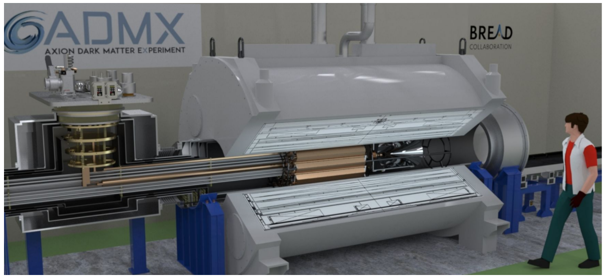
Colliding light for tau g – 2

Invent heavy-ion probe of precision EWK & new physics

Beresford & JL [1908.05180]
PRD 102 (2020) 113008

Broadband Solenoidal Haloscope for Terahertz Axion Detection

Jesse Liu, Kristin Dona, Gabe Hoshino, Stefan Knirck, Noah Kurinsky, Matthew Malaker, David W. Miller, Andrew Sonnenschein, Mohamed H. Awida, Peter S. Barry, Karl K. Berggren, Daniel Bowring, Gianpaolo Carosi, Clarence Chang, Aaron Chou, Rakshya Khatiwada, Samantha Lewis, Juliang Li, Sae Woo Nam, Omid Noroozian, and Tony X. Zhou (BREAD Collaboration)
Phys. Rev. Lett. **128**, 131801 – Published 28 March 2022



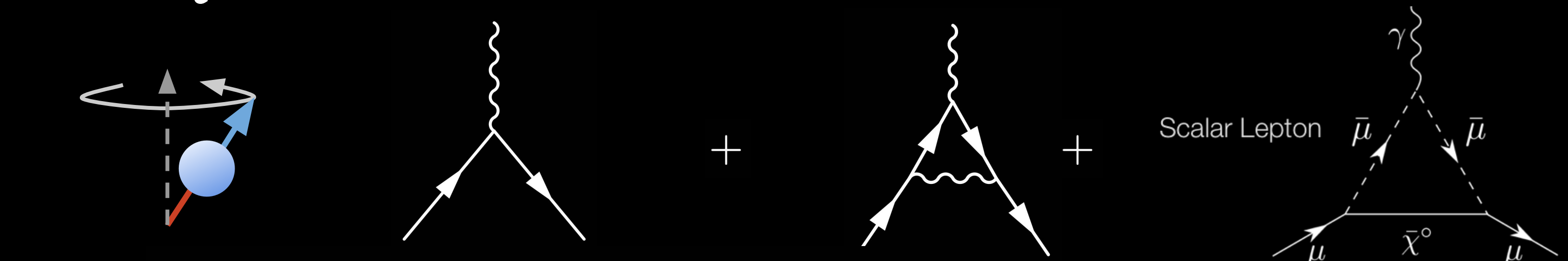
BREAD: new axion detector

meV dark matter observatory using quantum sensors

JL, Dona et al [2111.12103]
PRL 128 (2022) 131801

PART 1

g_ℓ – 2: cracks at the heart of the Standard Model?

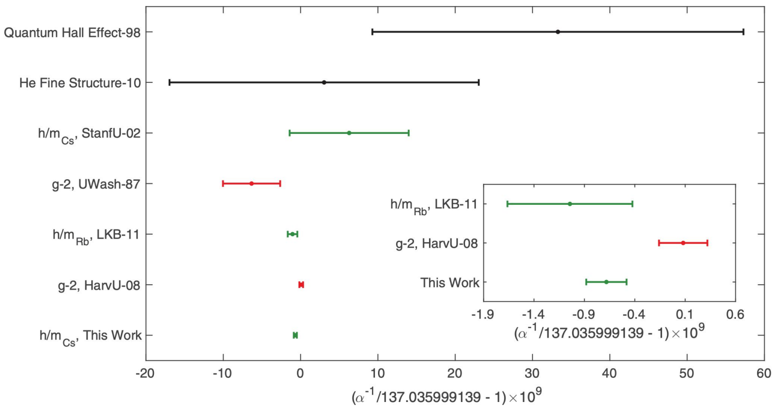


$$g = 2 + \frac{\alpha}{\pi}$$

$$\mu_f \cdot \mathbf{B} = \frac{g_f e}{2m_f}\mathbf{S}\cdot\mathbf{B}$$

Dirac (1928) **Schwinger (1948)** **Dark matter?**

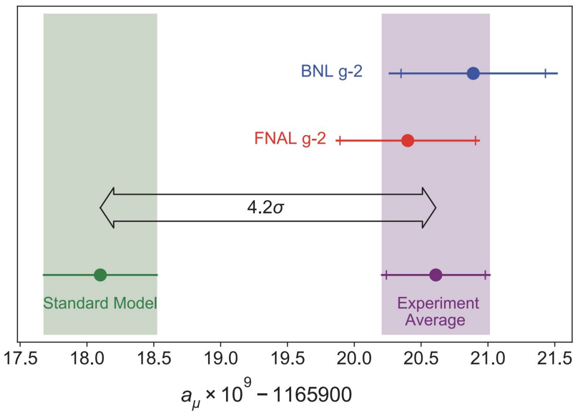
Electron g – 2 (–2.5σ?)



0.2 parts per billion

“Triumph of quantum electrodynamics”

Muon g – 2 (+4.2σ?)



0.5 parts per million

“Hadronic ignorance or harbinger of new physics?”

Parker et al [Science (2018)], Muon g–2 Experiment [2104.03281]

What about tau *g* – 2?

SHOCKING EXPERIMENTAL IGNORANCE!

Pressing problem: barely measured

$$a_\tau^{\text{exp}} = -0.018\,(17)$$

DELPHI [hep-ex/0406010]

$$a_{\tau,\,\text{SM}}^{\text{pred}} = 0.001\,177\,21\,(5)$$

Eidelman, Passera [hep-ph/0701260]

Not even testing 70 year old 1-loop QED

$$\alpha/2\pi = 0.001162$$

Schwinger [1948]

But 280× more sensitive to SUSY than muon

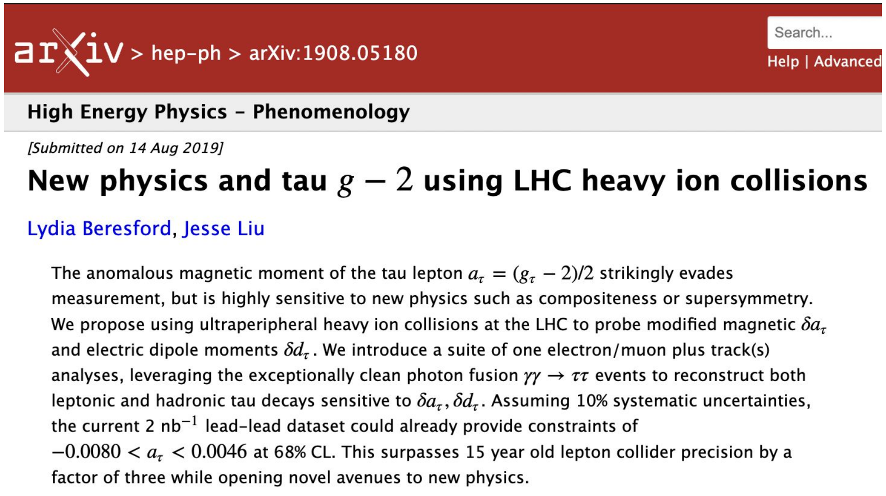
$$\delta a_\ell \sim m_\ell^2/M_{\text{SUSY}}^2 \qquad m_\tau^2/m_\mu^2 \sim 280$$

Martin, Wells [hep-ph/0103067]

SUMMER 2019

PROPOSE CREATIVE SOLUTION

To important & interesting open problem



High Energy Physics – Phenomenology

[Submitted on 14 Aug 2019]

New physics and tau $g-2$ using LHC heavy ion collisions

Lydia Beresford, Jesse Liu

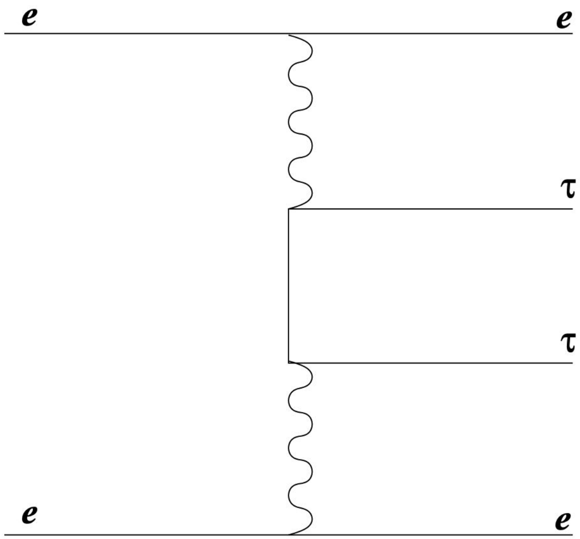
The anomalous magnetic moment of the tau lepton $a_\tau = (g_\tau - 2)/2$ strikingly evades measurement, but is highly sensitive to new physics such as compositeness or supersymmetry. We propose using ultraperipheral heavy ion collisions at the LHC to probe modified magnetic δa_τ and electric dipole moments δd_τ. We introduce a suite of one electron/muon plus track(s) analyses, leveraging the exceptionally clean photon fusion $\gamma\gamma \to \tau\tau$ events to reconstruct both leptonic and hadronic tau decays sensitive to $\delta a_\tau, \delta d_\tau$. Assuming 10% systematic uncertainties, the current 2 nb^{-1} lead-lead dataset could already provide constraints of $-0.0080 < a_\tau < 0.0046$ at 68% CL. This surpasses 15 year old lepton collider precision by a factor of three while opening novel avenues to new physics.

Beresford & JL PRD 102 (2020) 113008 [1908.05180]

If you like this, see also our dark matter paper PRL 123 (2019) 141801 [1811.06465]

Think different: invent new heavy-ion analysis

PDG constraint of tau *g*– 2



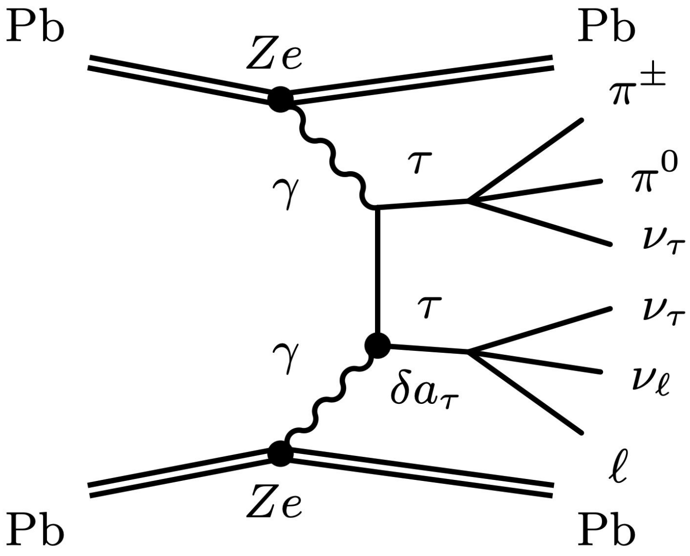
LEP photon collisions

σ ~ 400 pb

⇒ 200k events all years

DELPHI [EPJC 35 (2004) 159-170]

Proceed analogously @ LHC?



Not been seen at LHC

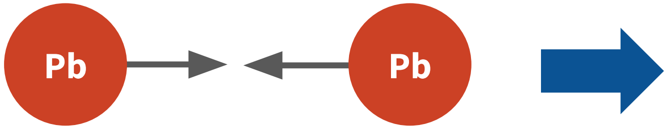
σ ~ Z^4 ~ 500 000 nb (Z_{Pb} = 82)

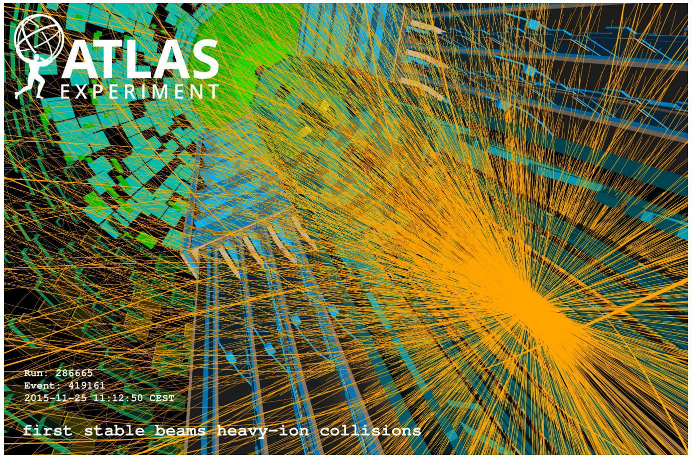
⇒ 1 million events *already*

del Aguila, Cornet, Illana (PLB 1991)
Beresford, JL [PRD 102 (2020) 113008]

Colliding light @ LHC

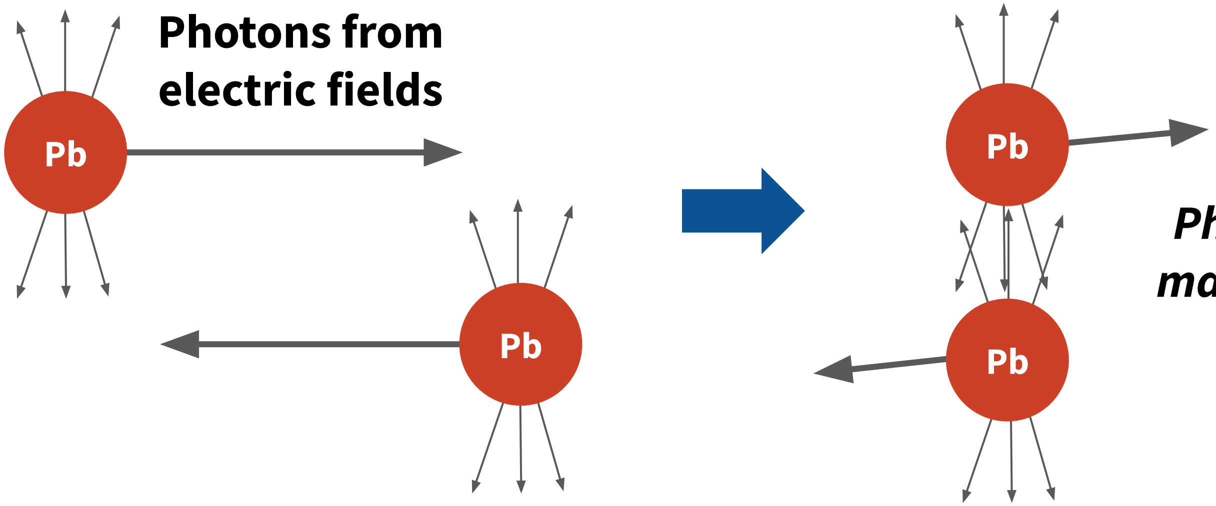
Head-on Pb–Pb collisions





Partons collide to make new particles

Photons from electric fields



Photons collide to make new particles

Fermi (1925) [hep-th/0205086], Weizsäcker (1934), Williams (1934), Schwinger (1952), Budnev, Ginzburg, Meledin, Serbo (1975)
ATLAS [ATLAS HION Event Display], Bruce et al [1812.07688]

STUNNING EVENTS

PbPb → Pb (γγ → ττ) Pb

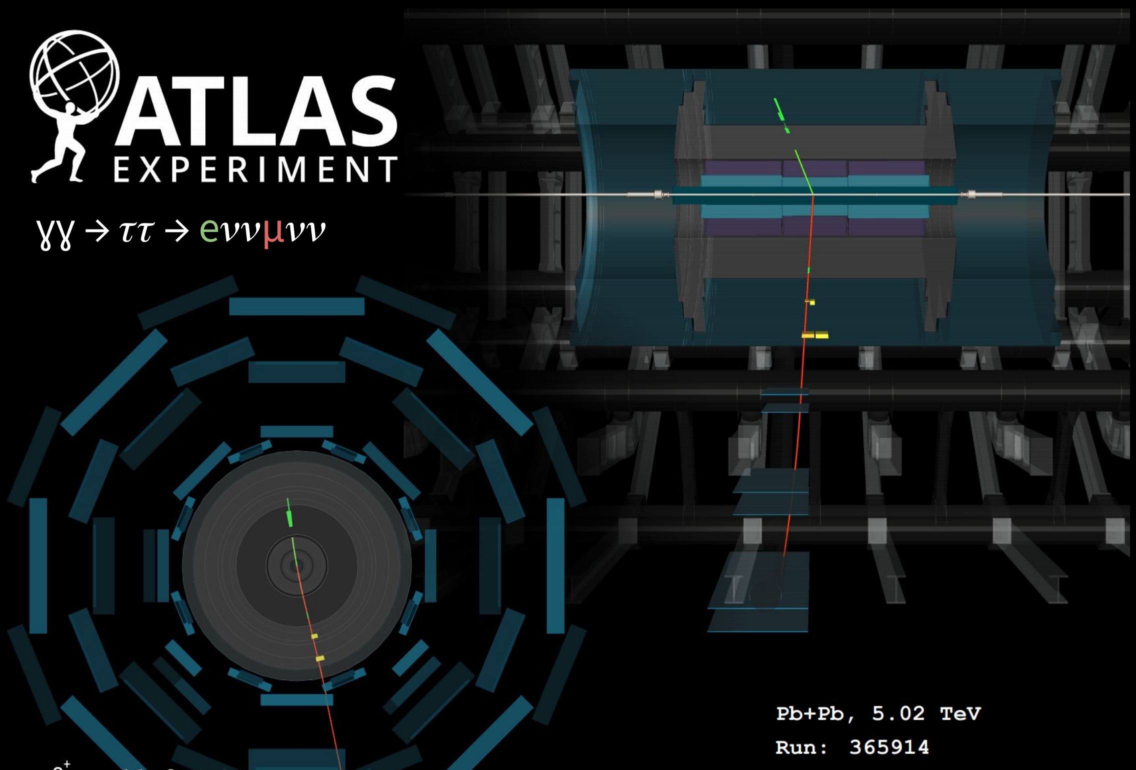
1 month to collect data

No pileup μ ~ 0.001

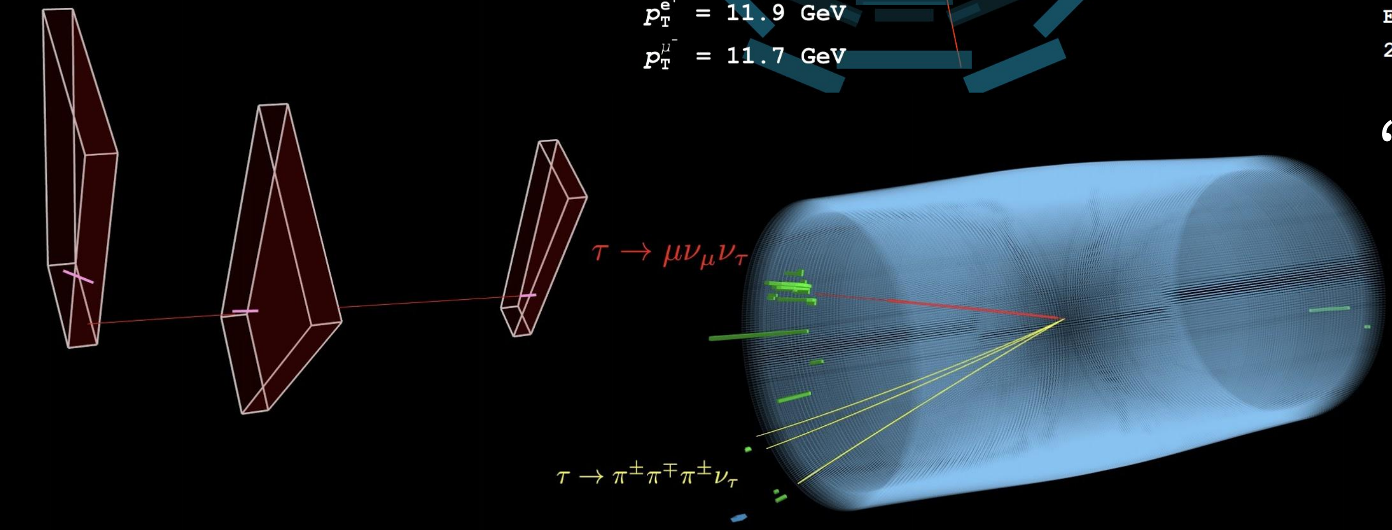
Ultra loose triggers

→ ATLAS-EVENTDISPLAY-2018-009
↓ SNOWMASS21-EF7_EF6

ATLAS EXPERIMENT



CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-25 02:25:02.462080 GMT
Run / Event / LS: 327219 / 171630155 / 356

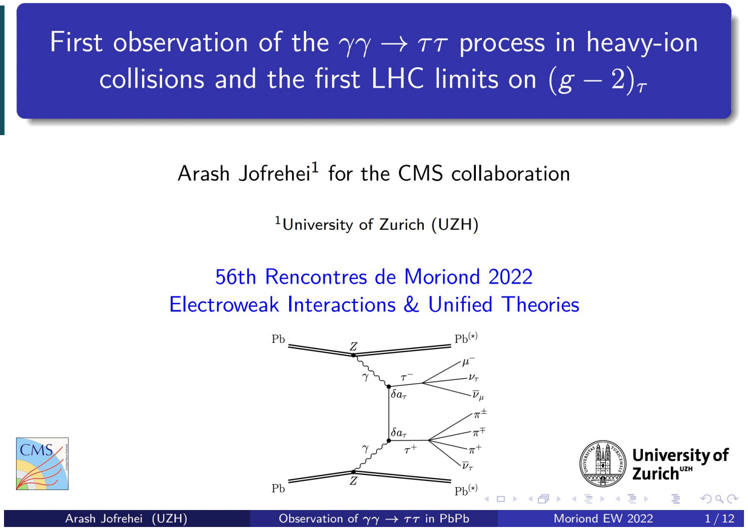


“ All calorimeter cells with a transverse energy above 500 MeV are shown ↑

🥳 CMS announces breakthrough realizing our idea 🎉

CMS-PAS-HIN-21-009: following 1μ + 3-track strategy proposed by Beresford & JL [1908.05180]

Moriond EWK 2022



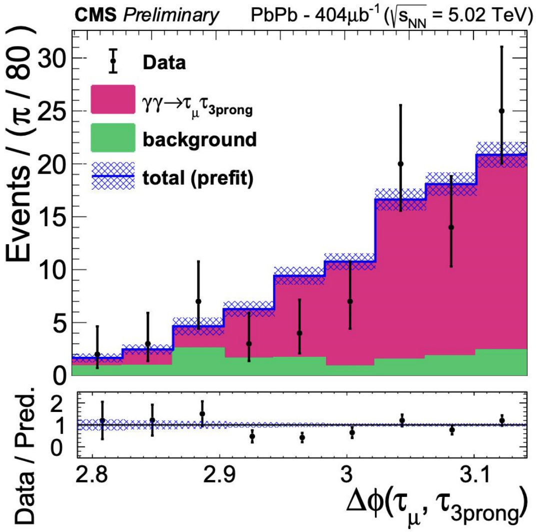
First observation of the $\gamma\gamma \to \tau\tau$ process in heavy-ion collisions and the first LHC limits on $(g-2)_\tau$

Arash Jofrehei[1] for the CMS collaboration

[1] University of Zurich (UZH)

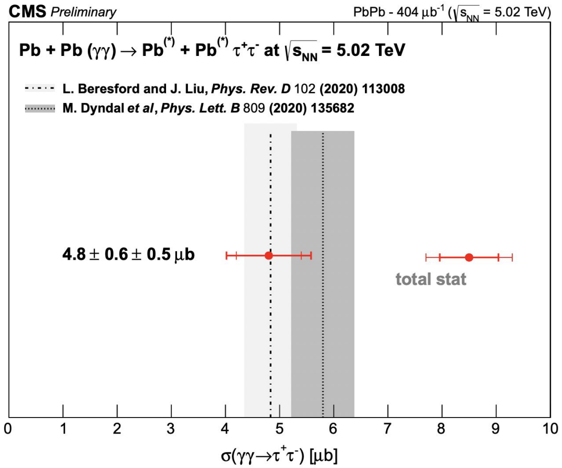
56th Rencontres de Moriond 2022
Electroweak Interactions & Unified Theories

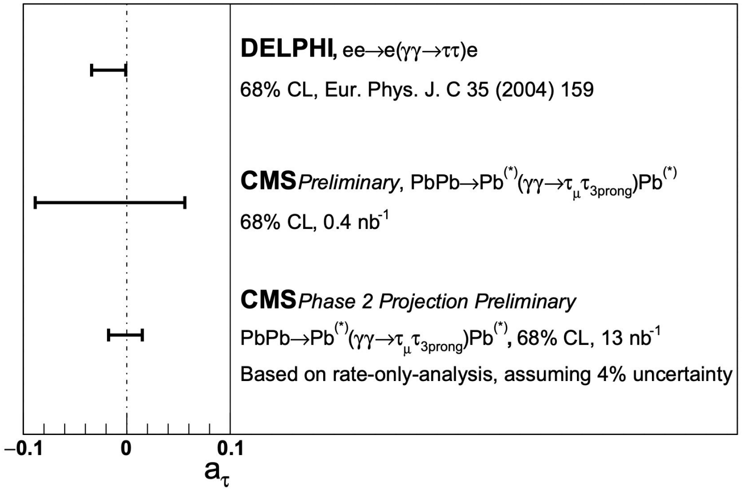
Arash Jofrehei (UZH) | Observation of $\gamma\gamma \to \tau\tau$ in PbPb | Moriond EW 2022 | 1 / 12



> 5σ observation

Cross section





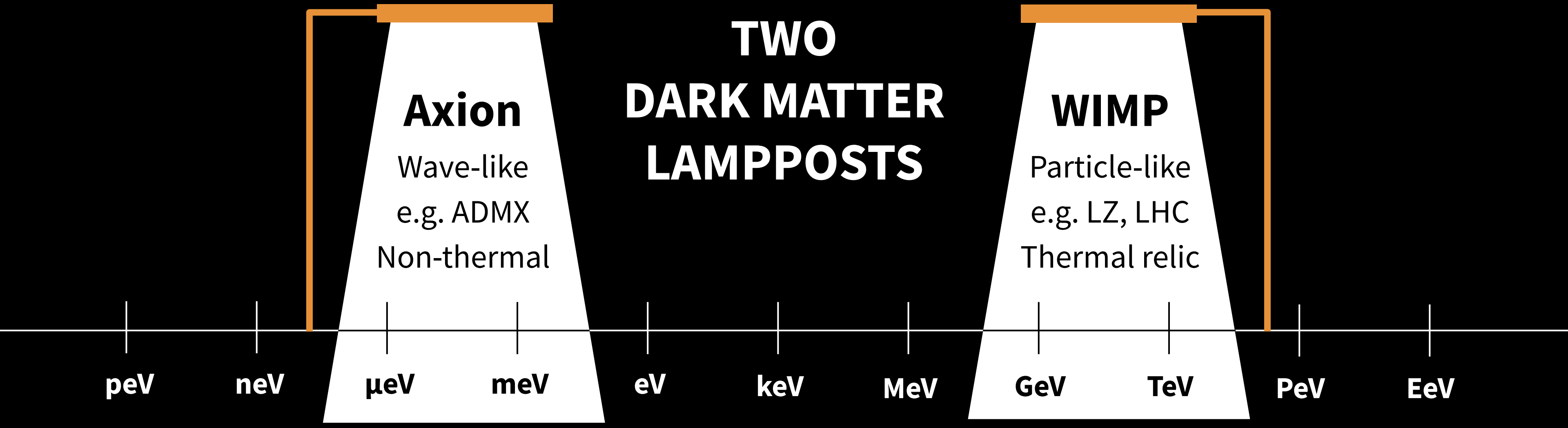
Measure $g_\tau - 2$

Remarkable results 🤩 ...and just getting started!

PART 2

BABY STEPS TOWARDS BREAD

TWO DARK MATTER LAMPPOSTS



Axion

Wave-like

e.g. ADMX

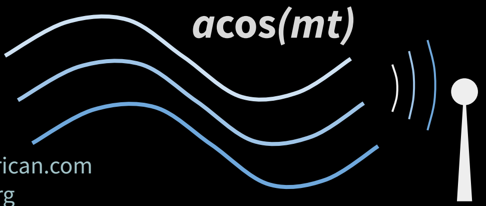
Non-thermal

WIMP

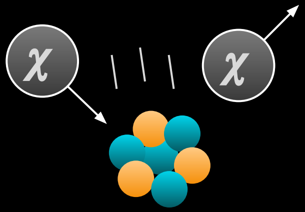
Particle-like

e.g. LZ, LHC

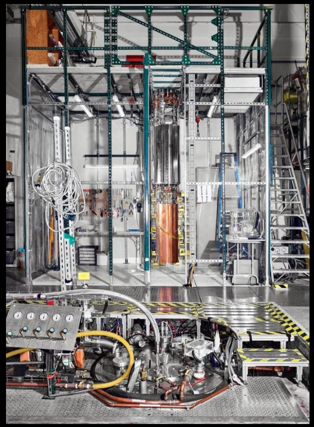
Thermal relic

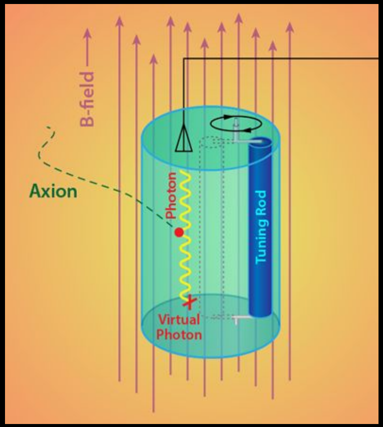


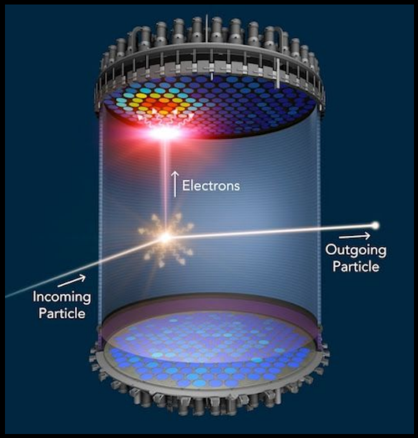
scientificamerican.com
physics.aps.org

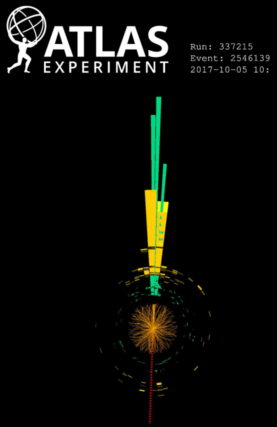


lz.ac.uk
2102.10874







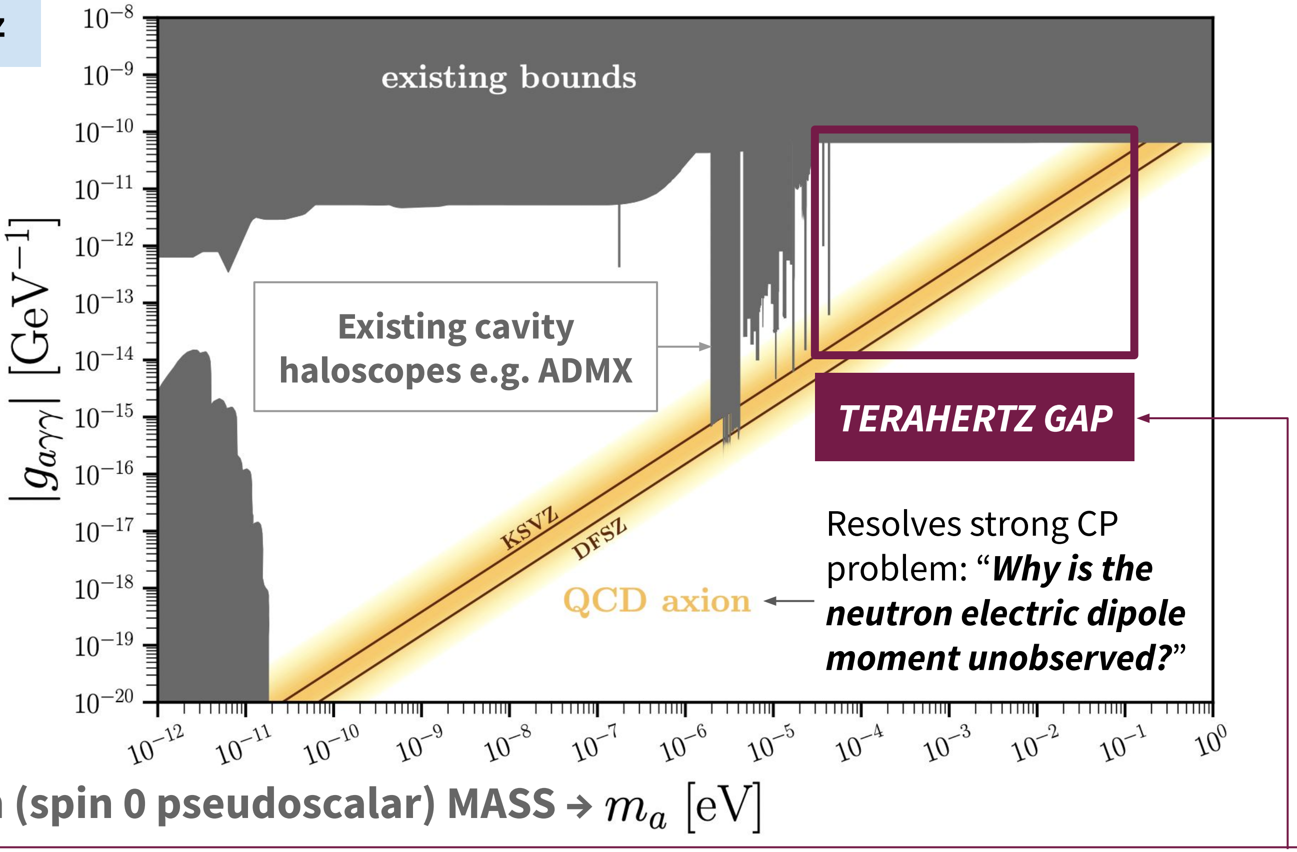


Problem: terahertz axions evade current searches

1 eV = 240 THz

Snowmass CF Meeting 31 Mar 2022

A. Berlin and others



Axion-photon COUPLING →

Existing cavity haloscopes e.g. ADMX

TERAHERTZ GAP

Resolves strong CP problem: “***Why is the neutron electric dipole moment unobserved?***”

Axion (spin 0 pseudoscalar) MASS → m_a [eV]

Problem 1: Desire broadband but cavity haloscopes narrowband $\Delta m/m \ll 1$

Problem 2: Desire high mass but scan rate* $R \sim f^{-14/3}$ impractical for m > 50 μeV

NEED CREATIVITY TO OVERCOME BOTH LONGSTANDING OBSTACLES

*See e.g. Backes et al [2008.01853] for how to overcome this scaling in HAYSTAC

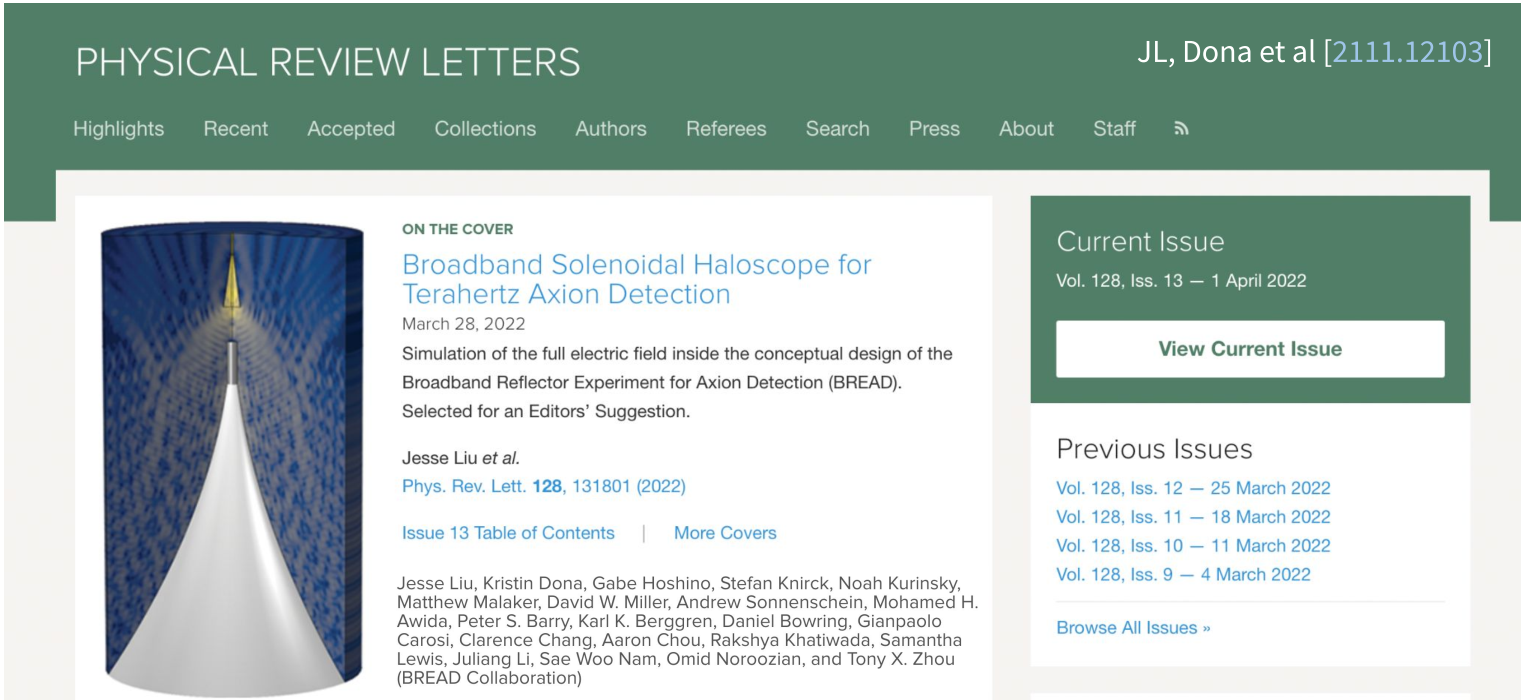
New: Broadband Reflector Experiment for Axion Detection

BREAD COLLABORATION

SLAC NIST Lawrence Livermore National Laboratory THE UNIVERSITY OF CHICAGO UNIVERSITY OF CAMBRIDGE

Argonne NATIONAL LABORATORY Fermilab MIT NASA Goddard SPACE FLIGHT CENTER ILLINOIS TECH

JL, Dona et al [2111.12103]



ON THE COVER

Broadband Solenoidal Haloscope for Terahertz Axion Detection

March 28, 2022

Simulation of the full electric field inside the conceptual design of the Broadband Reflector Experiment for Axion Detection (BREAD). Selected for an Editors' Suggestion.

Jesse Liu *et al.*

Phys. Rev. Lett. **128**, 131801 (2022)

Issue 13 Table of Contents | More Covers

Jesse Liu, Kristin Dona, Gabe Hoshino, Stefan Knirck, Noah Kurinsky, Matthew Malaker, David W. Miller, Andrew Sonnenschein, Mohamed H. Awida, Peter S. Barry, Karl K. Berggren, Daniel Bowring, Gianpaolo Carosi, Clarence Chang, Aaron Chou, Rakshya Khatiwada, Samantha Lewis, Juliang Li, Sae Woo Nam, Omid Noroozian, and Tony X. Zhou (BREAD Collaboration)

Current Issue

Vol. 128, Iss. 13 — 1 April 2022

Previous Issues

- Vol. 128, Iss. 12 — 25 March 2022
- Vol. 128, Iss. 11 — 18 March 2022
- Vol. 128, Iss. 10 — 11 March 2022
- Vol. 128, Iss. 9 — 4 March 2022

Browse All Issues »

🥳 **Hot off the press: proposal paper published last week!** 🎉

On The Cover & Editors' Suggestion of PRL 🤩

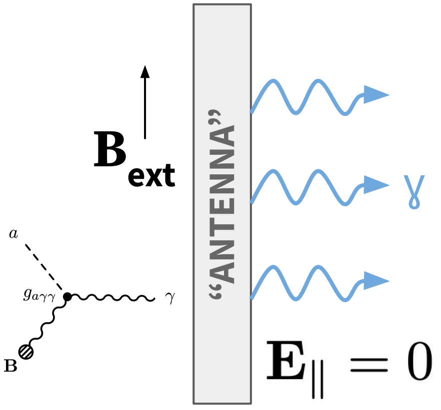
R&D supported by US DOE HEP-QIS QuantISED & FNAL LDRD

BREAD observatory: convert → focus → detect

1 CONVERT
axion dark matter into photons

2 FOCUS
photons with parabolic reflector design

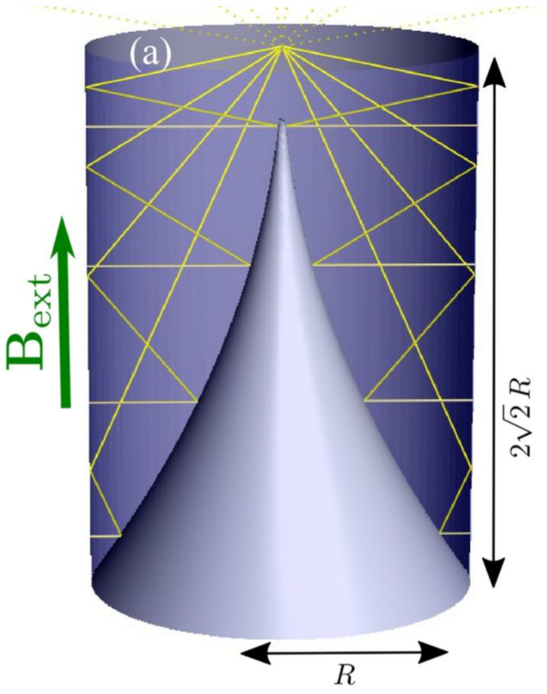
3 DETECT
photons with low-noise quantum sensors



Dark matter augments Ampère–Maxwell eq'n

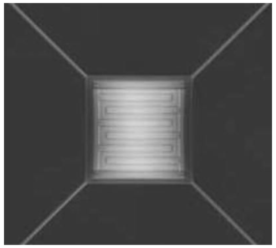
$$\nabla\times\mathbf{B}-\partial_t\mathbf{E}=\mathbf{J}_{\mathrm{DM}}$$

$$g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\,\mathbf{B}^{\parallel}_{\text{ext}}\cos(m_a t)$$



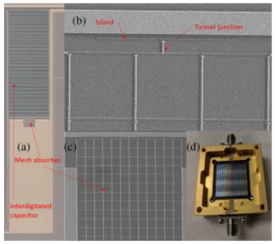
JL, Dona et al [2111.12103]

EXAMPLE SENSORS



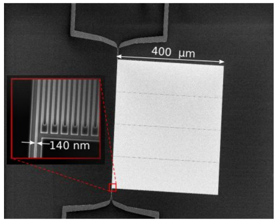
Transition Edge Sensor

Goldie et al [JLTP 2016]



Quantum Capacitance Detector

Echternach et al [JATIS 2021]

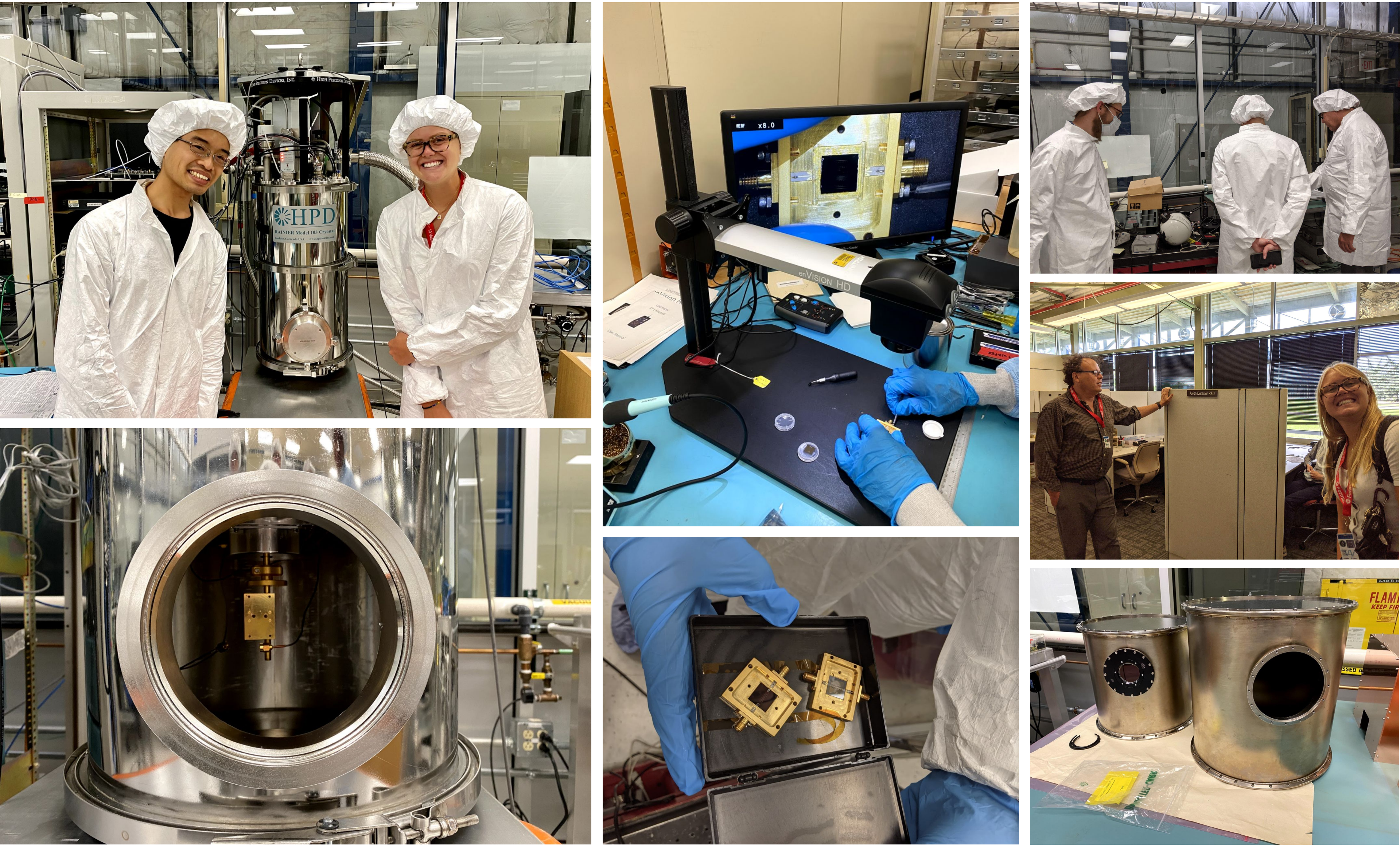


Superconducting Nanowire Single Photon Detector

Hochberg et al [1903.05101]

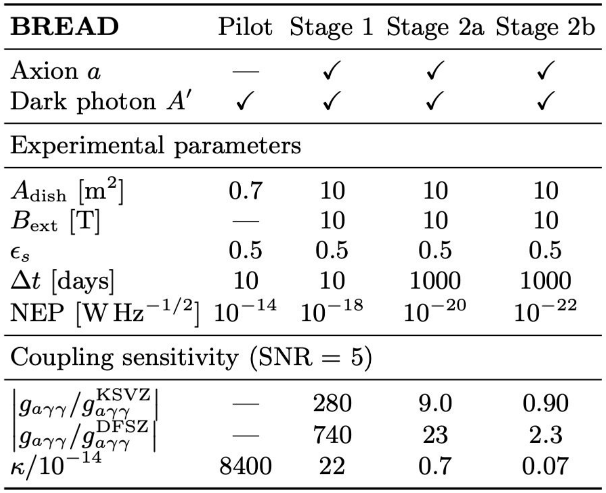
Kate Azar, Matthew Malaker, Gabe Hoshino
(summer students) led detailed simulation studies

Hands on: prepare sensor testing @ Fermilab for pilot

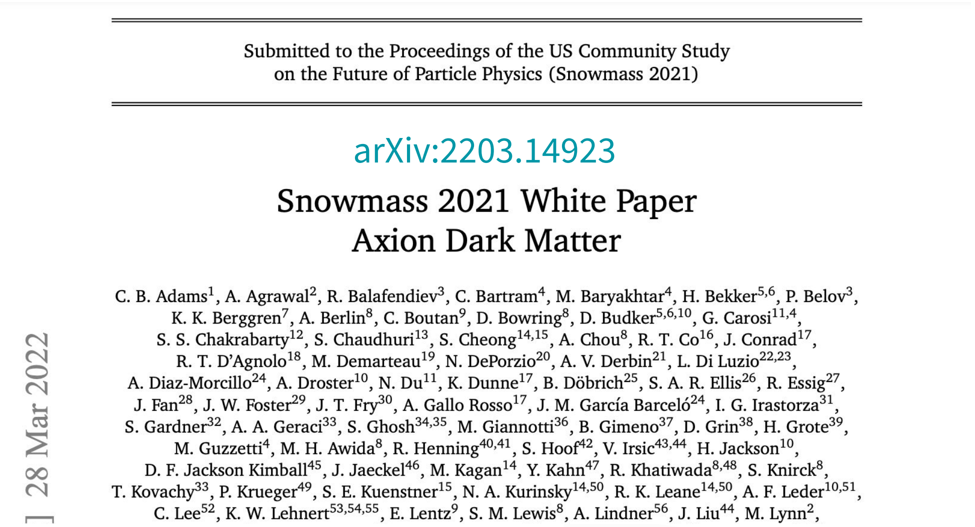


Kristin Dona, Stefan Knirck, JL, Andrew Sonnenschein pictured;
thanks to Israel Hernandez, David Miller, Tony Zhou et al

Towards BREAD as flagship next-gen axion experiment



BREAD	Pilot	Stage 1	Stage 2a	Stage 2b
Axion a	—	✓	✓	✓
Dark photon A'	✓	✓	✓	✓
Experimental parameters				
A_{dish} [m^2]	0.7	10	10	10
B_{ext} [T]	—	10	10	10
ϵ_s	0.5	0.5	0.5	0.5
Δt [days]	10	10	1000	1000
NEP [W Hz$^{-1/2}$]	10^{-14}	10^{-18}	10^{-20}	10^{-22}
Coupling sensitivity (SNR = 5)				
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\text{KSVZ}}\rvert$	—	280	9.0	0.90
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\text{DFSZ}}\rvert$	—	740	23	2.3
$\kappa/10^{-14}$	8400	22	0.7	0.07



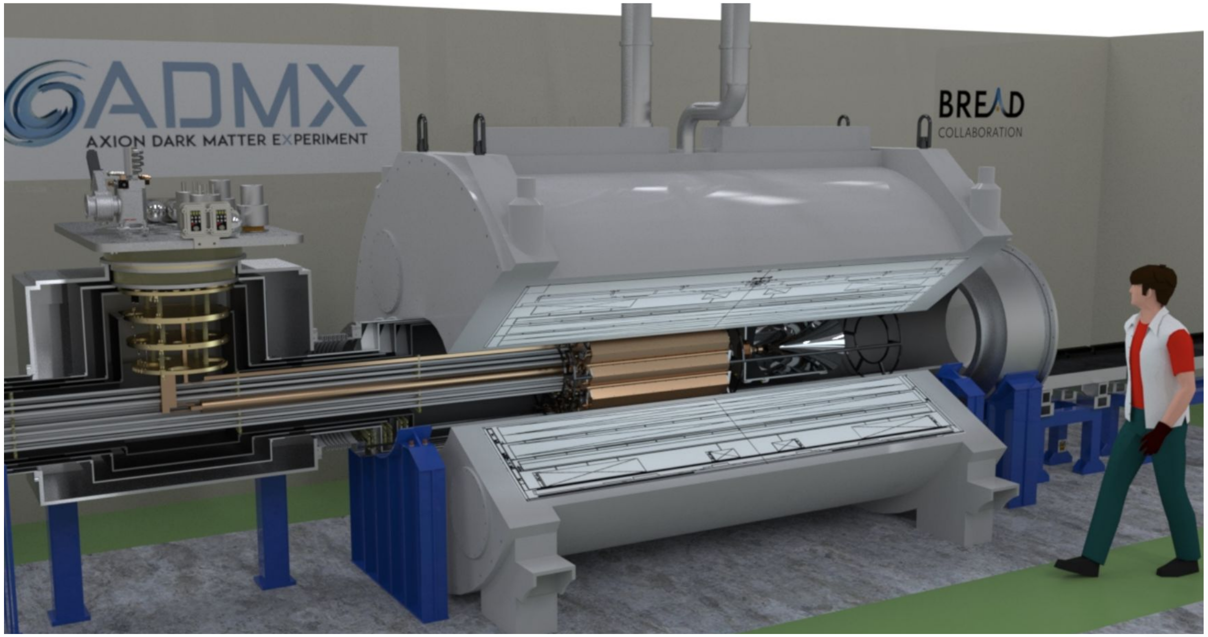
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

] 28 Mar 2022

arXiv:2203.14923

Snowmass 2021 White Paper
Axion Dark Matter

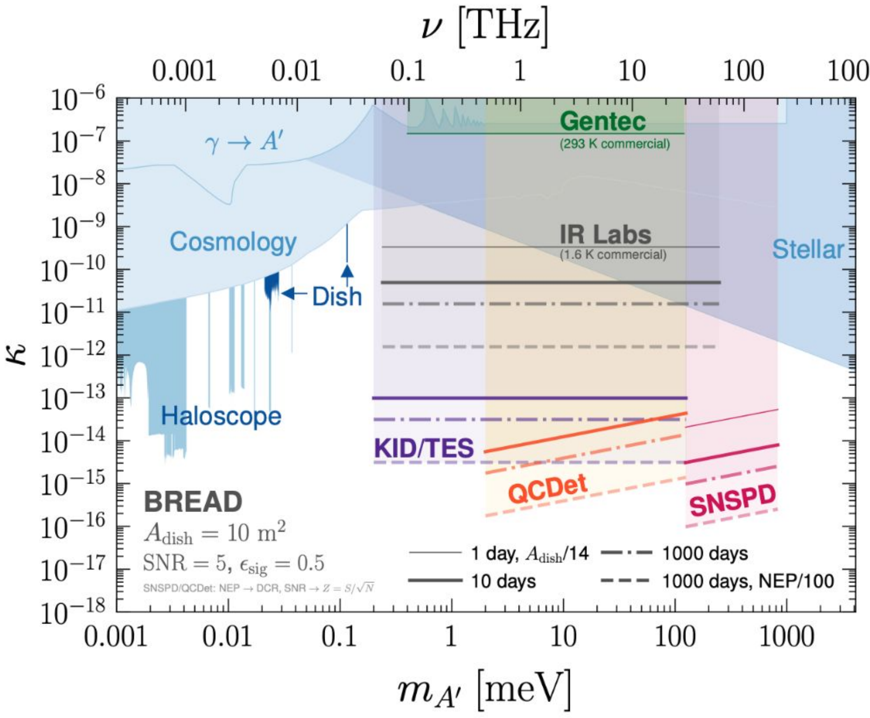
C. B. Adams[1], A. Agrawal[2], R. Balafendiev[3], C. Bartram[4], M. Baryakhtar[4], H. Bekker[5,6], P. Belov[3], K. K. Berggren[7], A. Berlin[8], C. Boutan[9], D. Bowring[8], D. Budker[5,6,10], G. Carosi[11,4], S. S. Chakrabarty[12], S. Chaudhuri[13], S. Cheong[14,15], A. Chou[8], R. T. Co[16], J. Conrad[17], R. T. D'Agnolo[18], M. Demarteau[19], N. DePorzio[20], A. V. Derbin[21], L. Di Luzio[22,23], A. Diaz-Morcillo[24], A. Droster[10], N. Du[11], K. Dunne[17], B. Döbrich[25], S. A. R. Ellis[26], R. Essig[27], J. Fan[28], J. W. Foster[29], J. T. Fry[30], A. Gallo Rosso[17], J. M. García Barceló[24], I. G. Irastorza[31], S. Gardner[32], A. A. Geraci[33], S. Ghosh[34,35], M. Giannotti[36], B. Gimeno[37], D. Grin[38], H. Grote[39], M. Guzzetti[4], M. H. Awida[8], R. Henning[40,41], S. Hoof[42], V. Irsic[43,44], H. Jackson[10], D. F. Jackson Kimball[45], J. Jaeckel[46], M. Kagan[14], Y. Kahn[47], R. Khatiwada[8,48], S. Knirck[8], T. Kovachy[33], P. Krueger[49], S. E. Kuenstner[15], N. A. Kurinsky[14,50], R. K. Leane[14,50], A. F. Leder[10,51], C. Lee[52], K. W. Lehnert[53,54,55], E. Lentz[9], S. M. Lewis[8], A. Lindner[56], J. Liu[44], M. Lynn[2],

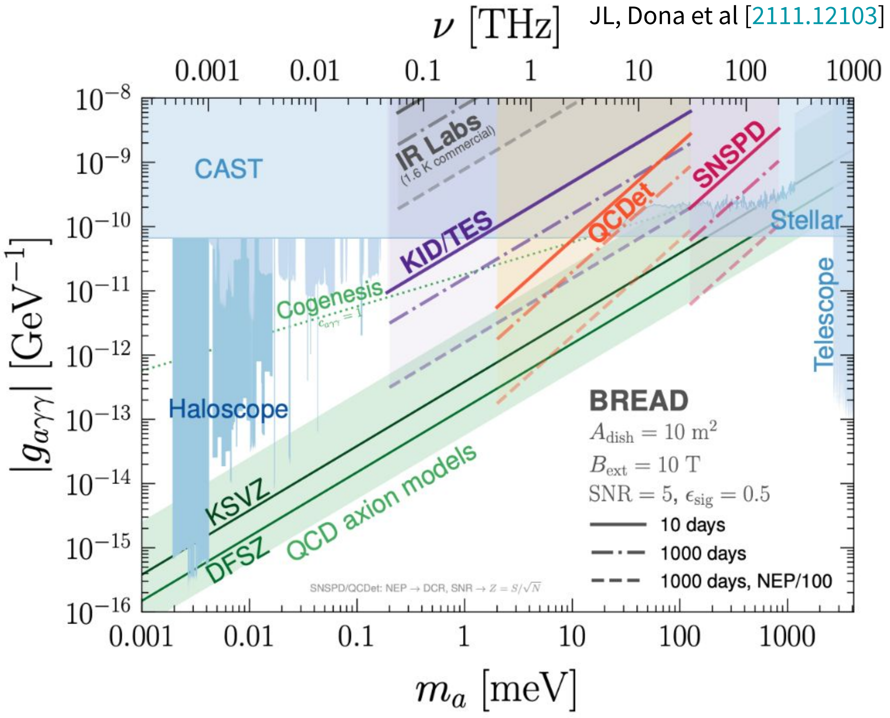


Figs: Don Mitchell

Sensitivity: concept → pilot → full science program

JL, Dona et al [2111.12103]





DARK PHOTON (VECTOR)

Preparing "sourdough starter" pilot

Near term ~3 years proof of principle

AXION (PSEUDOSCALAR)

Need high-field magnet & sensor R&D

Longer term ~5-10 year timescale

BREAD
COLLABORATION

$$\left\{\begin{matrix}\left(\frac{g_{a\gamma\gamma}}{10^{-12}}\right)^2 \\ \left(\frac{\kappa}{10^{-15}}\right)^2\end{matrix}\right\} = \left\{\begin{matrix}\frac{3.0}{\mathrm{GeV}^2}\left(\frac{m_a}{\mathrm{meV}}\right)^3\left(\frac{10\,\mathrm{T}}{B_{\mathrm{ext}}}\right)^2 \\ 11.9\,\frac{2/3}{\alpha_{\mathrm{pol}}^2}\,\frac{m_{A'}}{\mathrm{meV}}\end{matrix}\right\}\left(\frac{\mathrm{hour}}{\Delta t}\right)^{1/2}\frac{10\,\mathrm{m}^2}{A_{\mathrm{dish}}}\,\frac{Z}{5}\,\frac{0.5}{\epsilon_s}\left(\frac{\mathrm{DCR}}{10^{-2}\,\mathrm{Hz}}\right)^{1/2}\frac{0.45\,\mathrm{GeV/cm}^3}{\rho_{\mathrm{DM}}}$$

EPILOGUE

Neutron magnetic moment

When nature laughed in our 1930s faces

Theory: **zero as it's neutral & pointlike**

Nature: **large *AND* negative haha (g – 2 = –5.8)**

Chadwick (1932), Bacher (1933), Tamm & Altshuler (1934), Rabi (1934), Alvarez & Bloch (1940), CODATA (2018)

Completely confounded expectation!

TRANSFORMATIVE

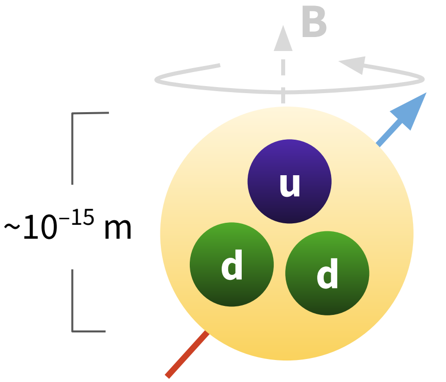
Neutron magnetic moment

When nature laughed in our 1930s faces

Theory: zero as it's neutral & pointlike

Nature: large *AND* negative haha ($g - 2 = -5.8$)

Chadwick (1932), Bacher (1933), Tamm & Altshuler (1934), Rabi (1934), Alvarez & Bloch (1940), CODATA (2018)



NUCLEAR SUBSTRUCTURE

New confining force

hopkinsmedicine.org

Today nuclear moments save lives with MRI medical imaging

Nobel prize in Physiology or Medicine 2003

CLIFFHANGER

Neutron electric moment

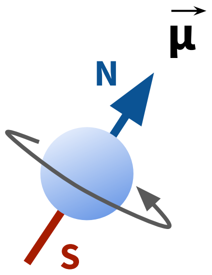
REMAINS DEEPLY MYSTERIOUS TODAY

MAGNETIC DIPOLE MOMENT (MDM)

Expectation: $g - 2 = 0$ (Dirac theory)

Reality: huge & negative! :O

Solved: new physics → QCD ✔

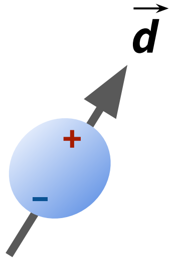


ELECTRIC DIPOLE MOMENT (EDM)

Expectation: large (strong CP violation)

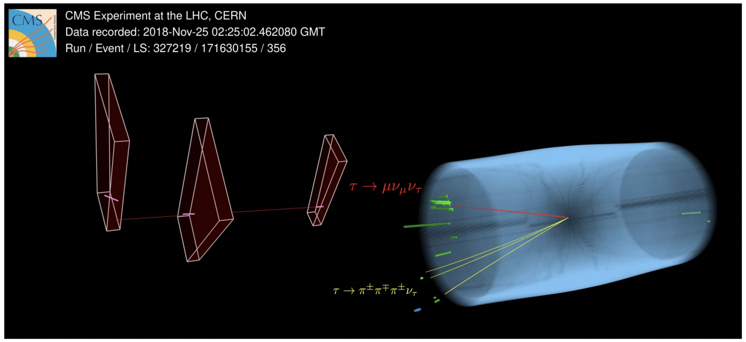
Reality: 0 to 1 part per billion! :O

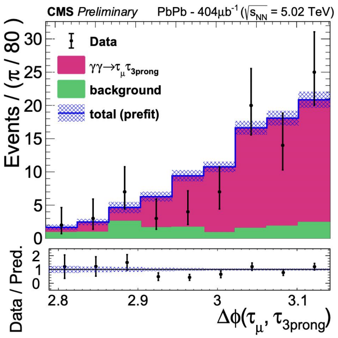
Solution: new physics → axions?

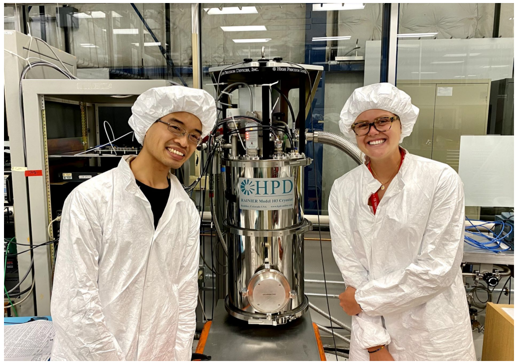


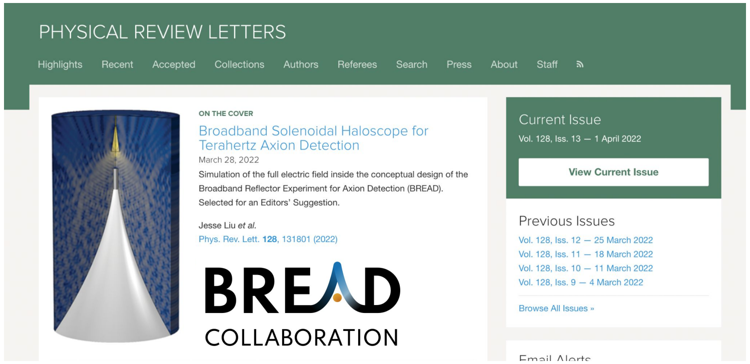
SUMMARY

We must keep looking at Nature in unprecedented ways
Even if — especially if — it completely defies expectation









ON THE COVER

Broadband Solenoidal Haloscope for Terahertz Axion Detection

March 28, 2022

Simulation of the full electric field inside the conceptual design of the Broadband Reflector Experiment for Axion Detection (BREAD). Selected for an Editors' Suggestion.

Jesse Liu *et al.*
Phys. Rev. Lett. **128**, 131801 (2022)

BREAD COLLABORATION

Current Issue
Vol. 128, Iss. 13 — 1 April 2022

Previous Issues
Vol. 128, Iss. 12 — 25 March 2022
Vol. 128, Iss. 11 — 18 March 2022
Vol. 128, Iss. 10 — 11 March 2022
Vol. 128, Iss. 9 — 4 March 2022