BREAD: Broadband Reflector Experiment for Axion Detection

Dark Matter UK Meeting
Imperial College London, UK
22 September 2022

Jesse Liu *for the BREAD Collaboration*
University of Cambridge

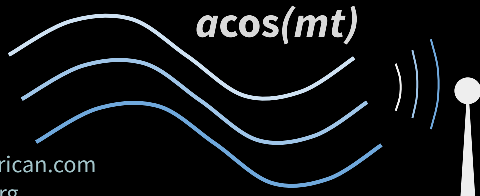
BREAD COLLABORATION · TRINITY COLLEGE CAMBRIDGE · UNIVERSITY OF CAMBRIDGE

TWO DARK MATTER LAMPPOSTS

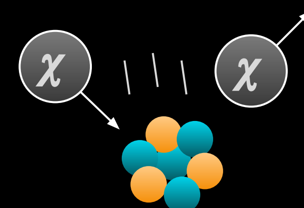
Axion
Wave-like
e.g. ADMX
Non-thermal

WIMP
Particle-like
e.g. LZ, LHC
Thermal relic

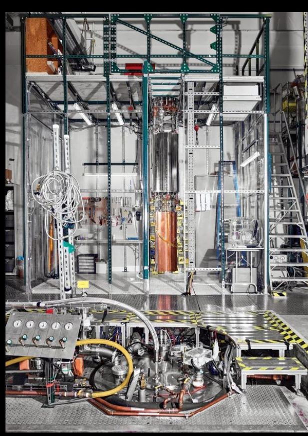
peV | neV | µeV | meV | eV | keV | MeV | GeV | TeV | PeV | EeV

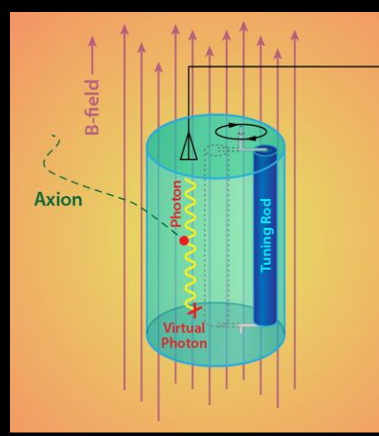


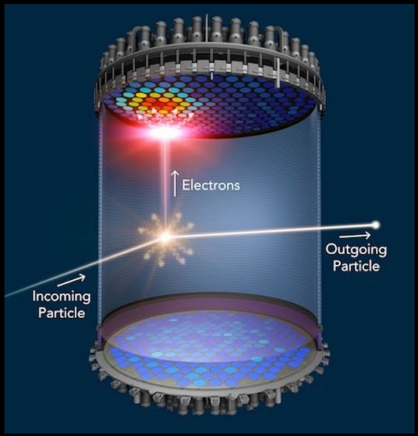
scientificamerican.com
physics.aps.org



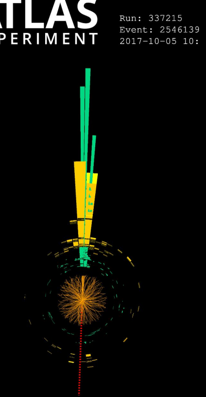
lz.ac.uk
2102.10874



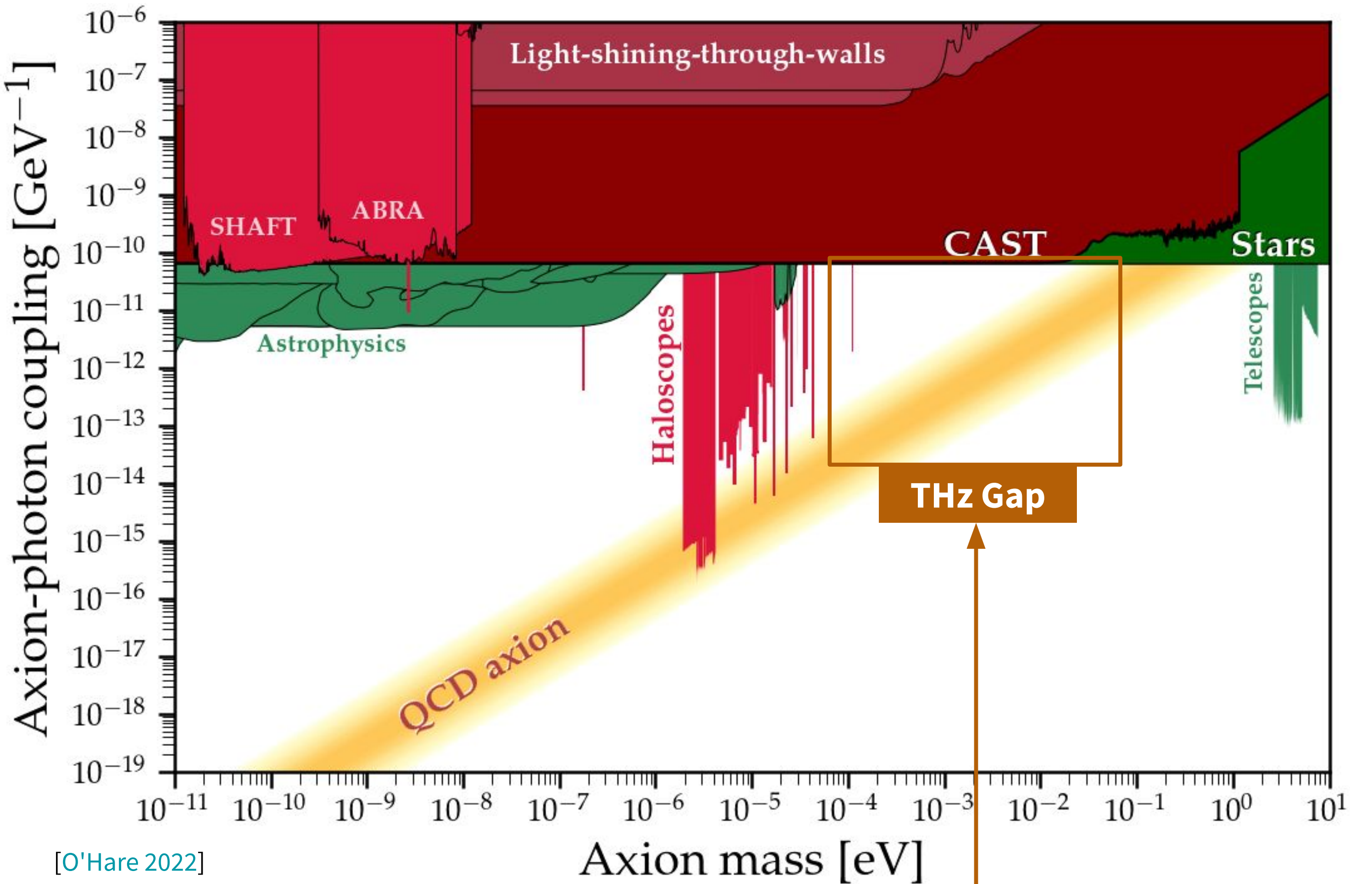




ATLAS EXPERIMENT



The milli-eV/terahertz axion search problem



[O'Hare 2022]

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 [Nature 590 (2021) 238–242] for how to overcome this scaling in HAYSTAC

Broadband Reflector Experiment for Axion Detection

🥳 Proposal paper on the cover of PRL & Editors' Suggestion 🎉

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

PHYSICAL REVIEW LETTERS

Highlights | Recent | Accepted | Collections | Authors | Referees | Search | Press

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)

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

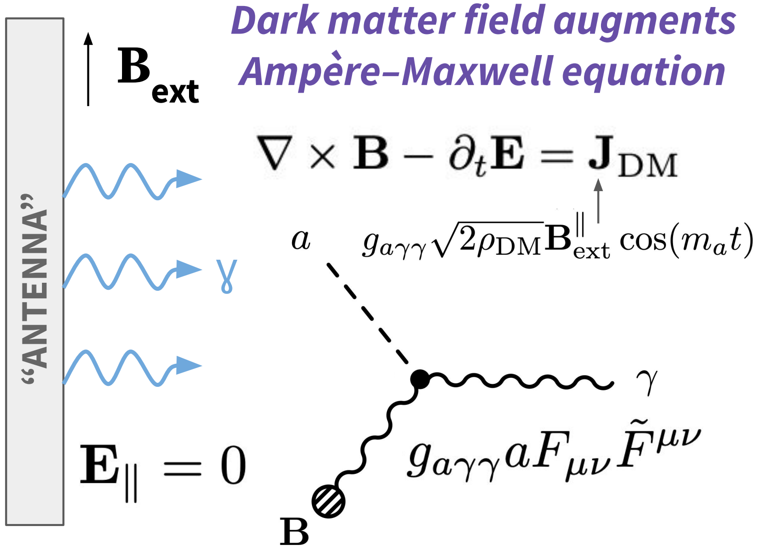
Recent collaborators: Alex Lapuente (UChicago), Gustavo Cancelo, Max Olberding, Cristián Peña, Leonardo Stefanazzi, Kevin Zvonarek (Fermilab); Christina Wang (Caltech); Dip Joti (MIT)

Step 1: convert DM to photons

a) Oscillating axion field makes conductor emit photons

Dark matter field augments Ampère–Maxwell equation

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



INHERENTLY BROADBAND

No tuning to unknown DM mass

Concept proposed in Horns et al [1212.2970]

b) Make cylindrical to embed in standard solenoids & cryostats

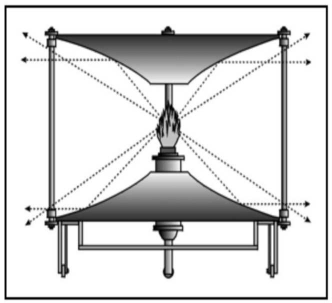
→ Fridge for ADMX science at FNAL
(Photo by Kristin Dona)

↓ Solenoids for Magnetic Resonance Imaging
hopkinsmedicine.org

See also Mark Bird (2020)
"Ultra-High Field Solenoids and Axion Detection"

Step 2: collect photons

Historical inspiration | **Novel parabolic reflector design focuses photons** | **3D-printed prototype @ FNAL** | **Proposed dark photon pilot design**

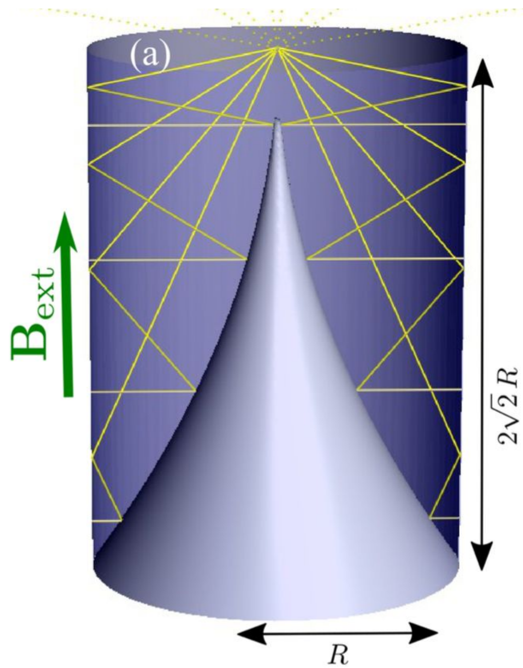


Inverse of 19th century lighthouse

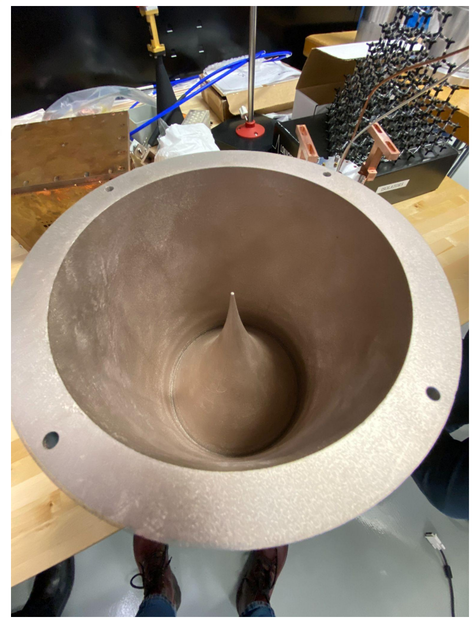
Bordier-Marcet 1811

Cylindrically symmetric co-parallel rays from point source

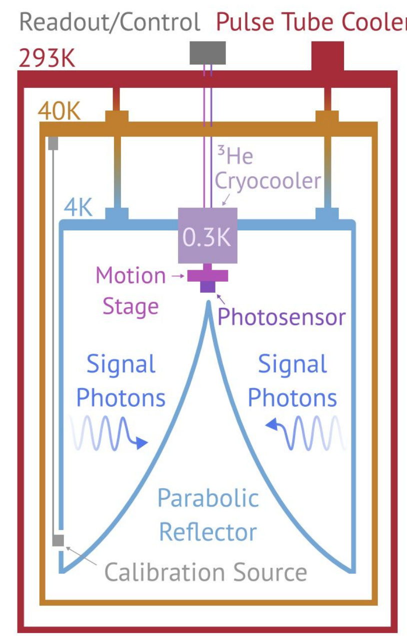
uslhs.org



Ray tracing simulation



Gabe Hoshino led in situ measurements with antenna



Status: iterating reflector design with engineers

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

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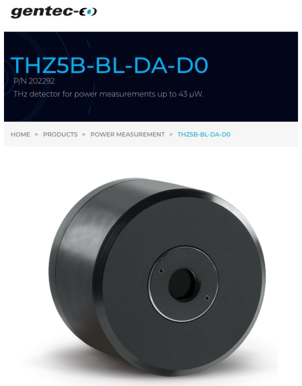
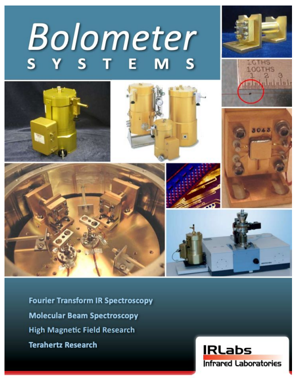
JL, Dona et al [PRL 128 (2022) 131801]

Step 3: detect photons

gentec-eo.com



irlabs.com

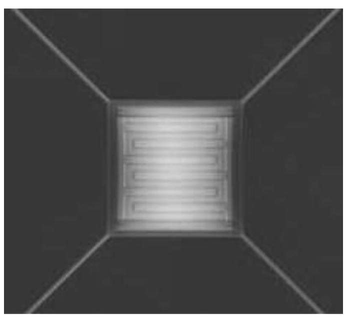


Commercial bolometers

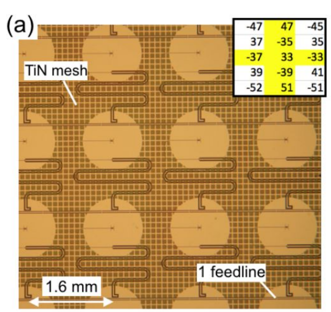
Lower noise is better ↓

Photosensor	E / meV	T_{op} / K	NEP / $\mathrm{W}/\sqrt{\mathrm{Hz}}$	A_{sens} / mm^2
Gentec [97]	[0.4, 120]	293	$1 \cdot 10^{-8}$	$\pi 2.5^2$
IR Labs [98]	[0.24, 248]	1.6	$5 \cdot 10^{-14}$	1.5^2
KID/TES [99, 100]	[0.2, 125]	0.3	$2 \cdot 10^{-19}$	0.2^2
QCDet [101, 102]	[2, 125]	0.015	$\frac{\mathrm{DCR}}{\mathrm{Hz}} = 4$	0.06^2
SNSPD [103, 104]	[124, 830]	0.3	$\frac{\mathrm{DCR}}{\mathrm{Hz}} = 10^{-4}$	0.4^2

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

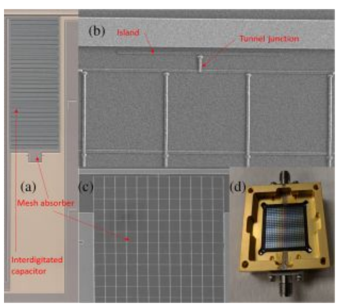


Transition Edge Sensor
Goldie et al [JLTP 2016]

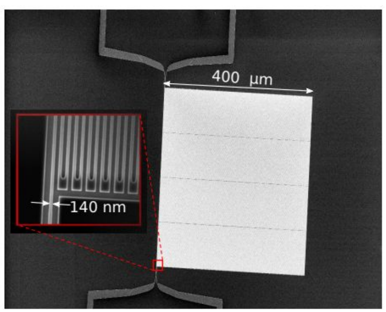


Kinetic Inductance Detector
Baselmans et al [A&A 2017]

Established technology for astronomy/CMB*



Quantum Capacitance Detector
Echternach et al [JATIS 2021]



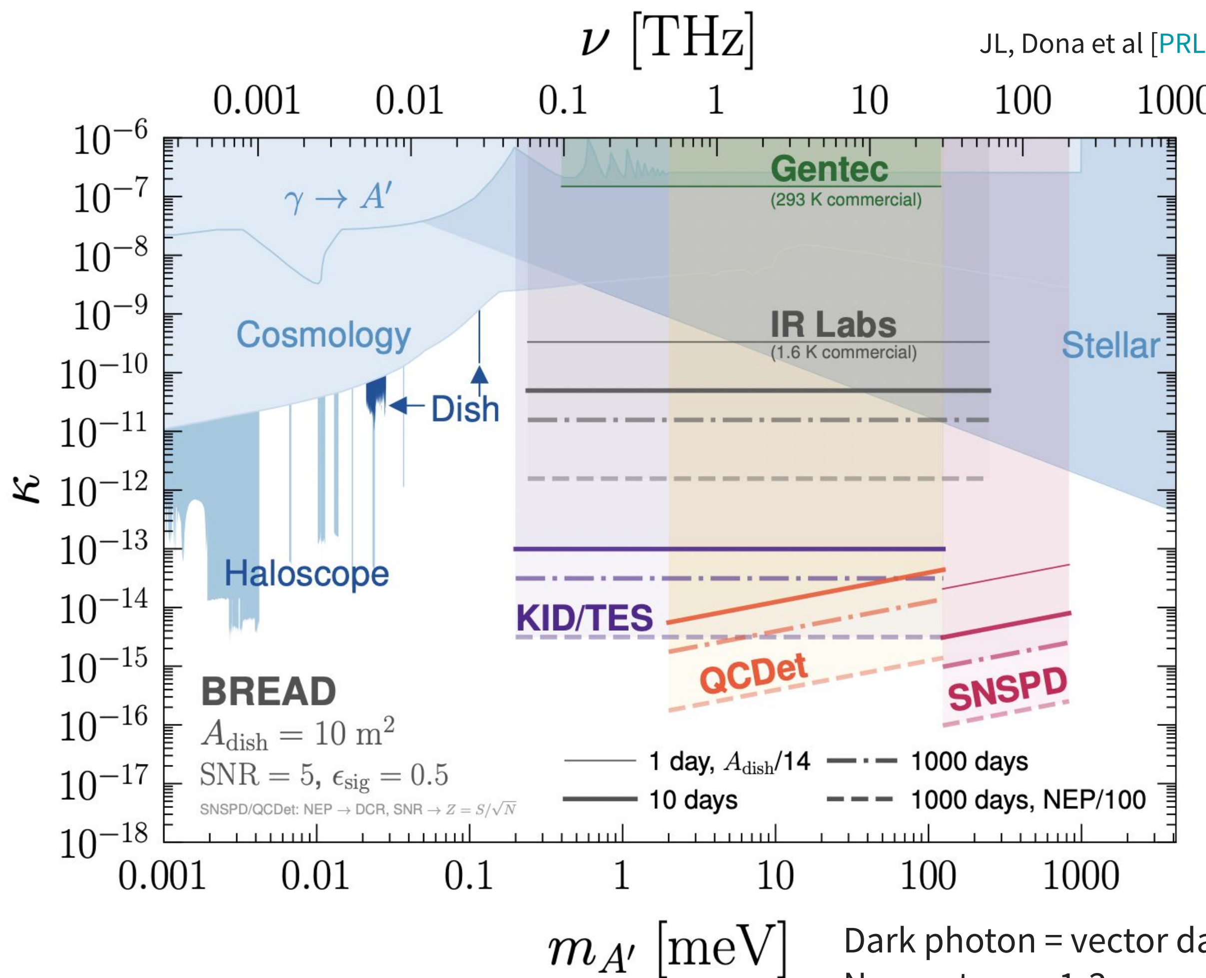
Superconducting Nanowire Single Photon Detector
Hochberg et al [1903.05101]

Emerging technology for infrared photon counting

*E.g. UK efforts: TES @ Cambridge (S Withington et al), KID @ Cardiff (Pete Barry et al)

Sensitivity: dark photon pilot "sourdough starter"

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



Dark photon = vector dark matter A'

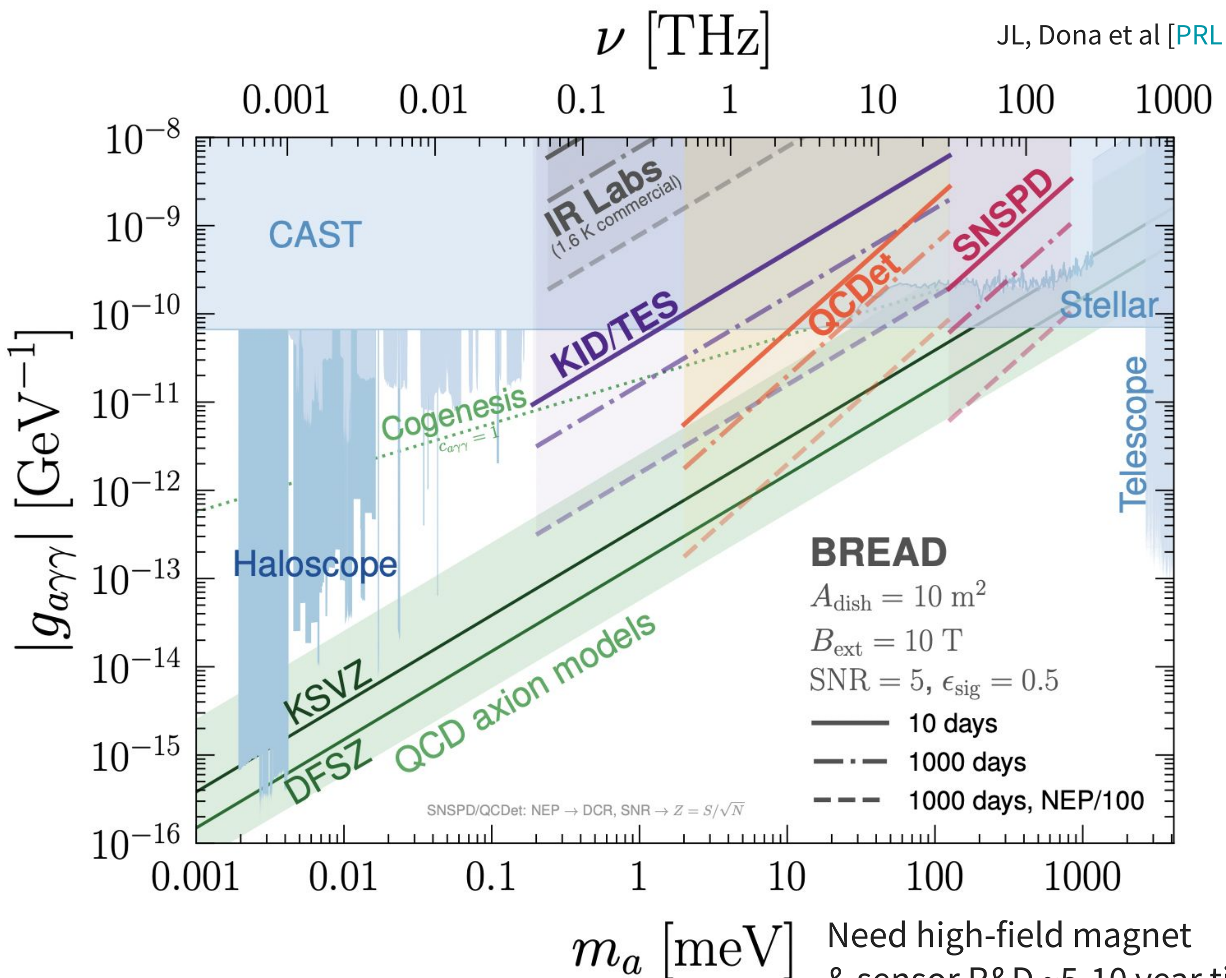
Nearer-term ~1-3 year pilots ongoing

BREAD COLLABORATION

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

Sensitivity: axion science programme

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



Need high-field magnet
& sensor R&D ~5-10 year timescale

BREAD COLLABORATION

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

Well-aligned with Quantum Sensors for the Hidden Sector (Ed Daw et al, qshs.org)
See also UK Quantum Technologies for Fundamental Physics, Strategic Detector R&D proposal

BREAD roadmap to flagship next-gen axion experiment

BREAD	Pilot	Stage 1	Stage 2a	Stage 2b
Axion a	—	✓	✓	✓
Dark photon A'	✓	✓	✓	✓
Experimental parameters				
$A_{\rm dish}$ [m^2]	0.7	10	10	10
$B_{\rm ext}$ [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)				
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\rm KSVZ}\rvert$	—	280	9.0	0.90
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\rm DFSZ}\rvert$	—	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)

2203.14923 (JL contributing author)

Snowmass 2021 White Paper
Axion Dark Matter

J. Jaeckel[1], G. Rybka[2], L. Winslow[3], and the Wave-like Dark Matter Community [4]

[1]Institut fuer theoretische Physik, Universitaet Heidelberg, Heidelberg, Germany
[2]University of Washington, Seattle, WA, USA
[3]Laboratory of Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA, USA
[4]Updated Author List Under Construction

Figs: Don Mitchell

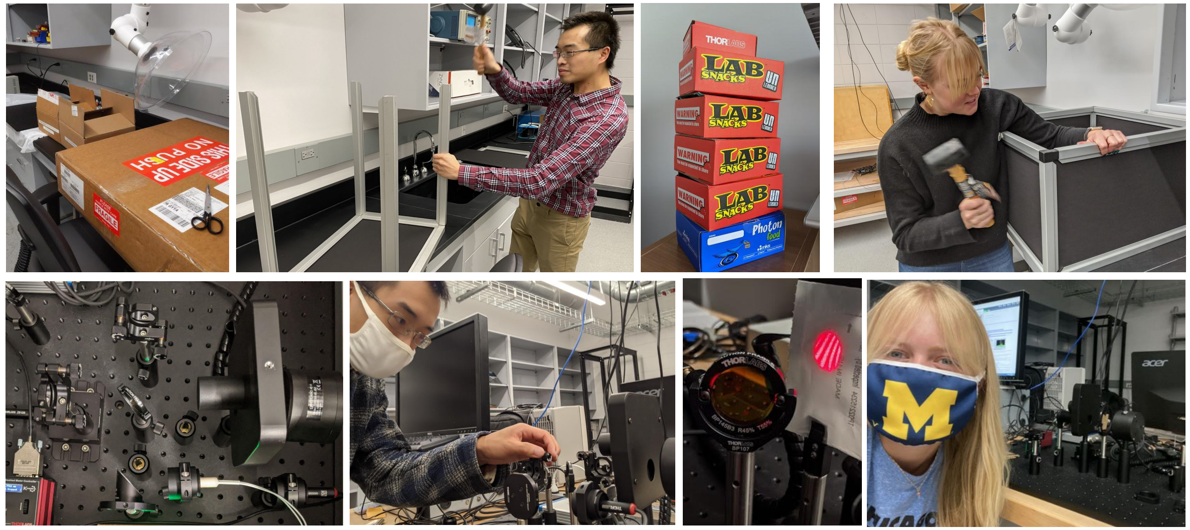
Hands on 1: build spectrometer to characterize optics

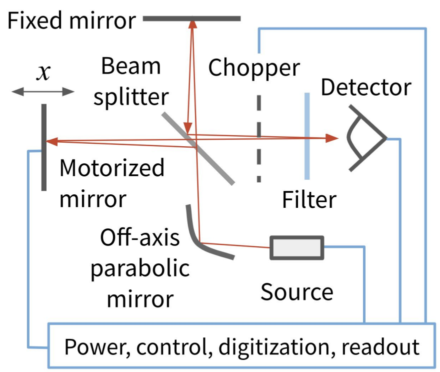
JANUARY 2020
Hardware arrival & assembly

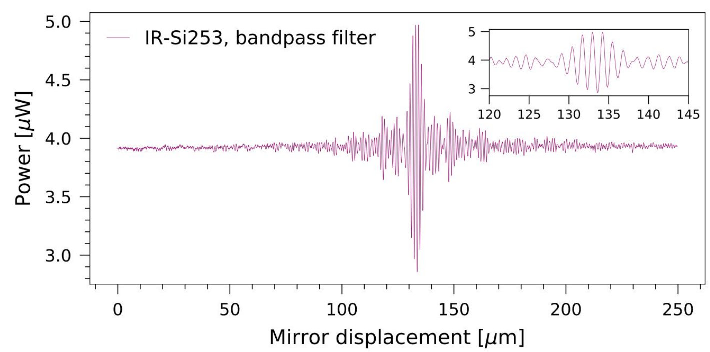
AUGUST
Laser alignment

OCTOBER
Begin measurements

APRIL 2021
Dona, JL et al
2104.07157 (JINST)







PAPER

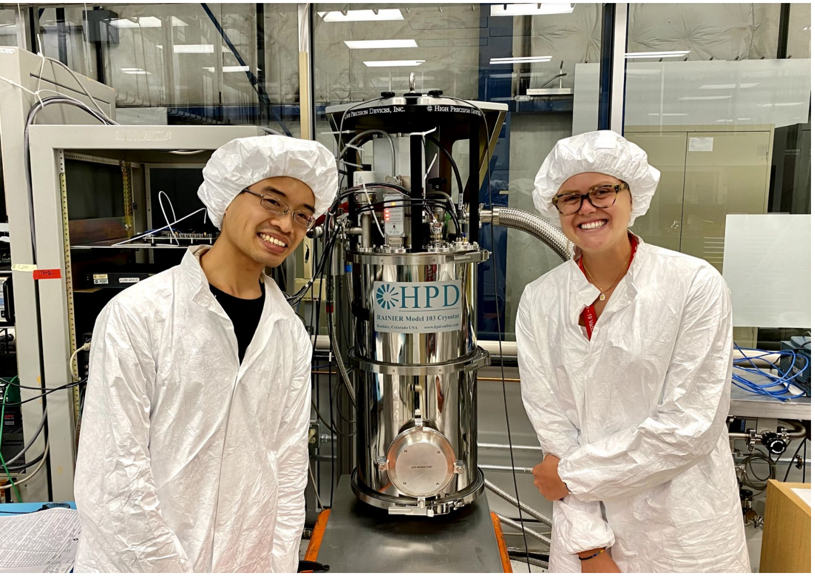
Design and performance of a terahertz Fourier transform spectrometer for axion dark matter experiments

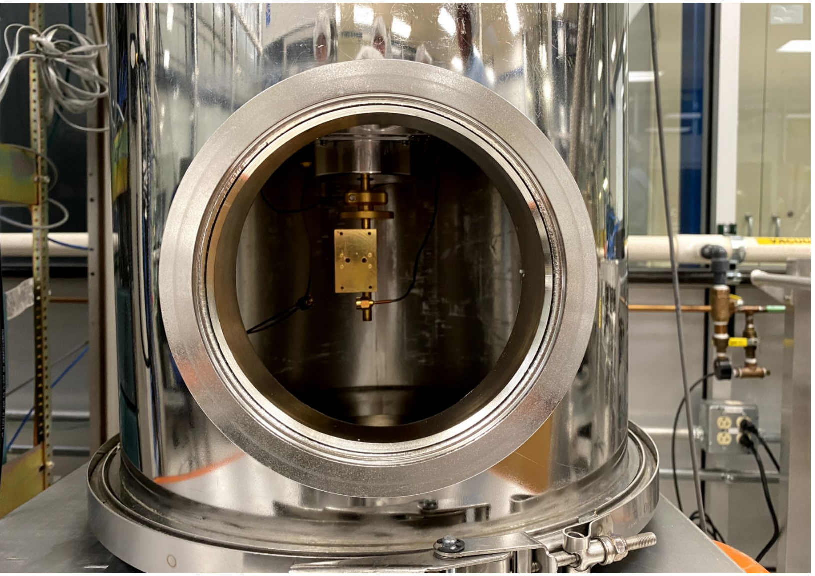
K. Dona[1], J. Liu[1], N. Kurinsky[2,3], D. Miller[1], P. Barry[2,4], C. Chang[2,4] and A. Sonnenschein[3]

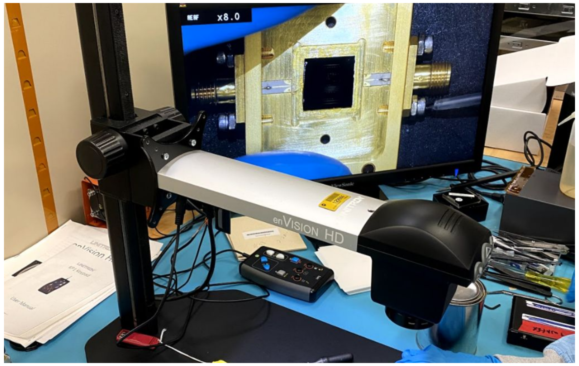
Published 13 June 2022 • © 2022 IOP Publishing Ltd and Sissa Medialab
Journal of Instrumentation, Volume 17, June 2022
Citation K. Dona *et al* 2022 *JINST* **17** P06014

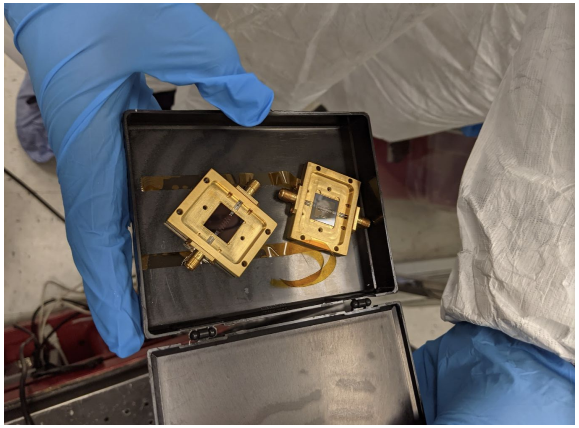
Funded by DOE HEP-QIS QuantISED grant with FNAL and Argonne collaborators

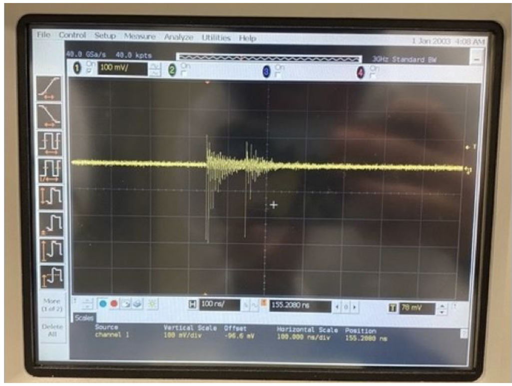
Hands on 2: quantum photosensor testing @ Fermilab









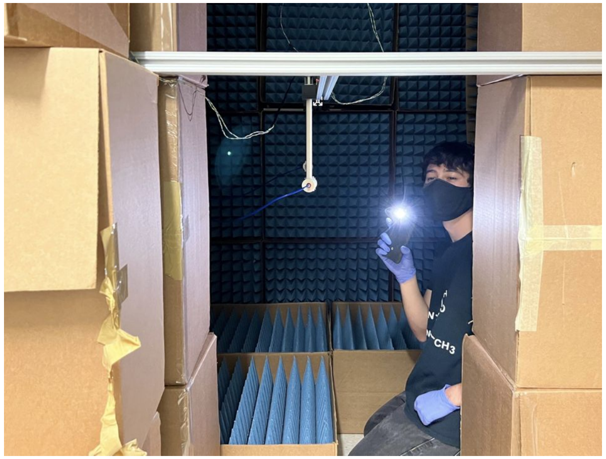


Kester Anyang, Aaron Chou, Kristin Dona, Israel Hernandez, Rakshya Khatiwada, Stefan Knirck, Robert McDermott, David Miller, Max Olberding, Cristián Peña, David Harrison, Andrew Sonnenschein, Christina Wang, Jialin Yu, Tony Zhou, et al

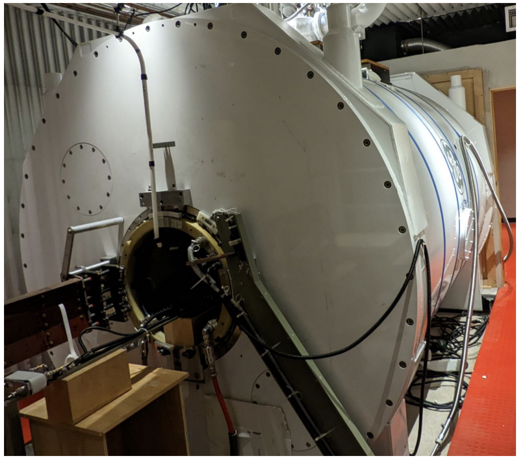
Hands on 3: horn receiver, pilot reflector, magnet scouting

GHz horn receiver

Gabe Hoshino @ Chicago RF isolation room

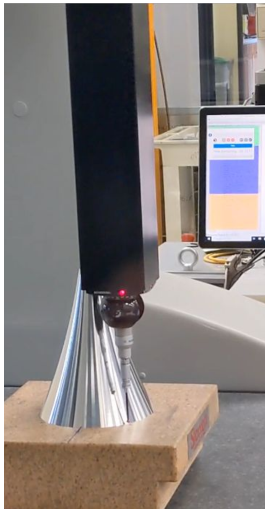


9.4 T MRI magnet @ UIC



BREAD meeting 🍞

Pilot dish antenna & reflector



Touch probe CMM

4 T MRI magnet @ Argonne

1st BREAD Collaboration meeting (Aug 2022)

Photos: Stefan Knirck, Andrew Sonnenschein

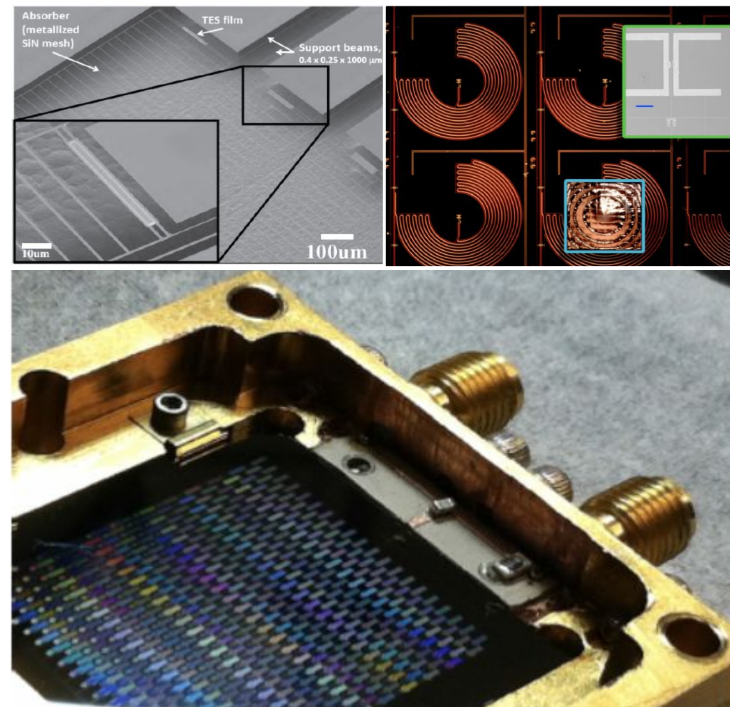
Innovation at interdisciplinary interfaces

Quantum sensors to discover extraterrestrial life and dark matter

ASTRONOMY
Origins of habitability & life

↔ BREAD COLLABORATION ↔

QUANTUM TECHNOLOGY
Information & sensing



**"Think *Inside*, Think *Outside* the box.
Make connections to other fields"**
NSF Program Director at Snowmass Oct 2020

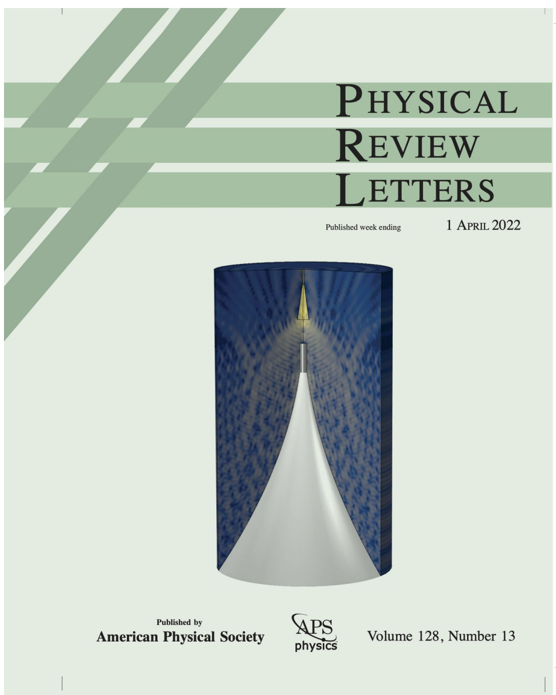
"Synergies between particle and astroparticle physics should be strengthened"
European Strategy Update Jun 2020

Images: origins.ipac.caltech.edu
Space-based far-IR mission recommended in US Astro 2020 Decadal Survey

SUMMARY

BREAD COLLABORATION

Broadband Reflector Experiment for Axion Detection



Multidecade discovery reach

Target meV–eV axion & dark photon dark matter

UK–USA collaboration potential

Aligned with UK Quantum Sensors for the Hidden Sectors

Preparing proof-of-concept in USA

At UChicago and Fermilab for near-term pilots

Interdisciplinary synergies

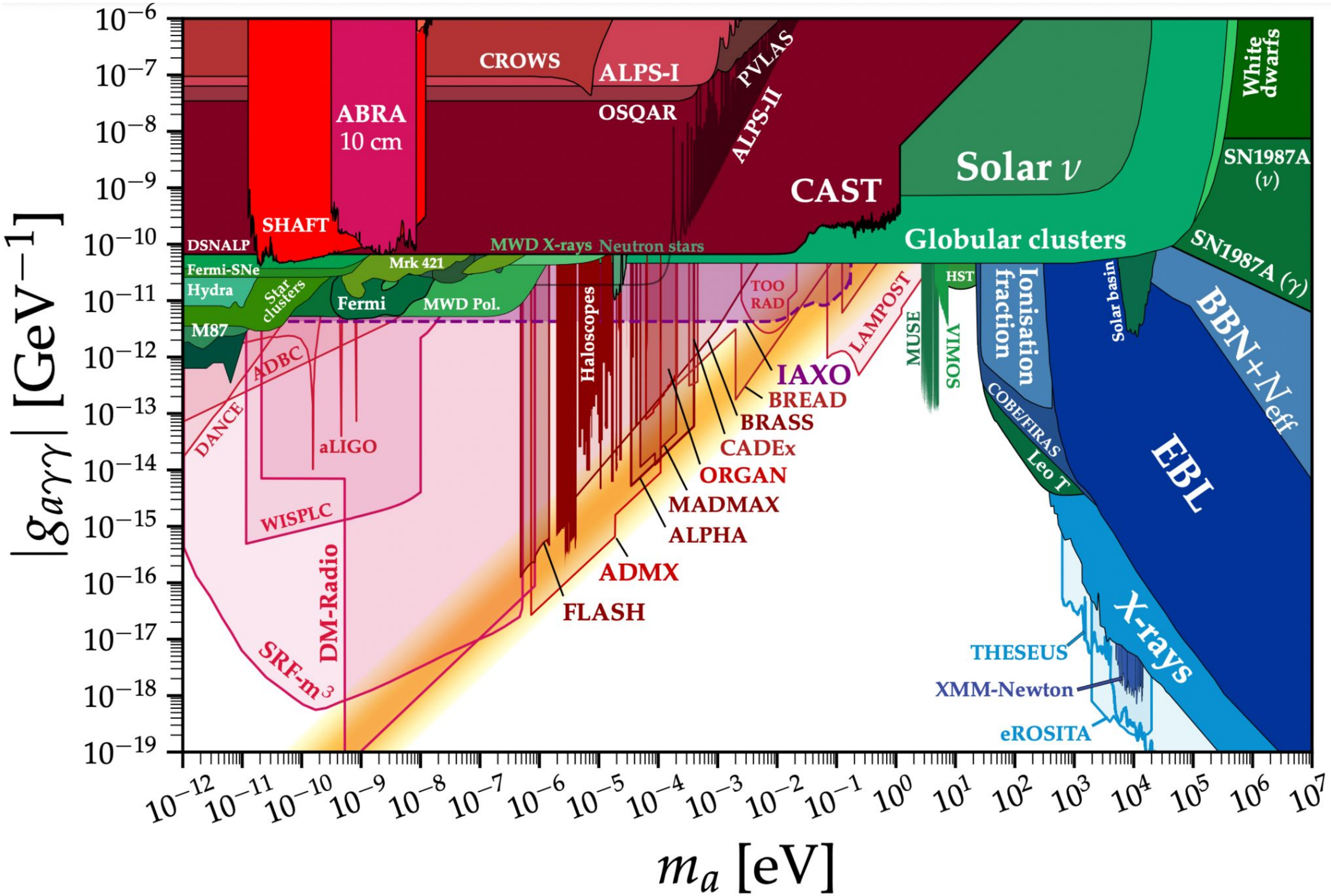
Across HEP, astronomy & quantum technology

Welcoming friendly community 😊

Early stages with much room for individual creativity

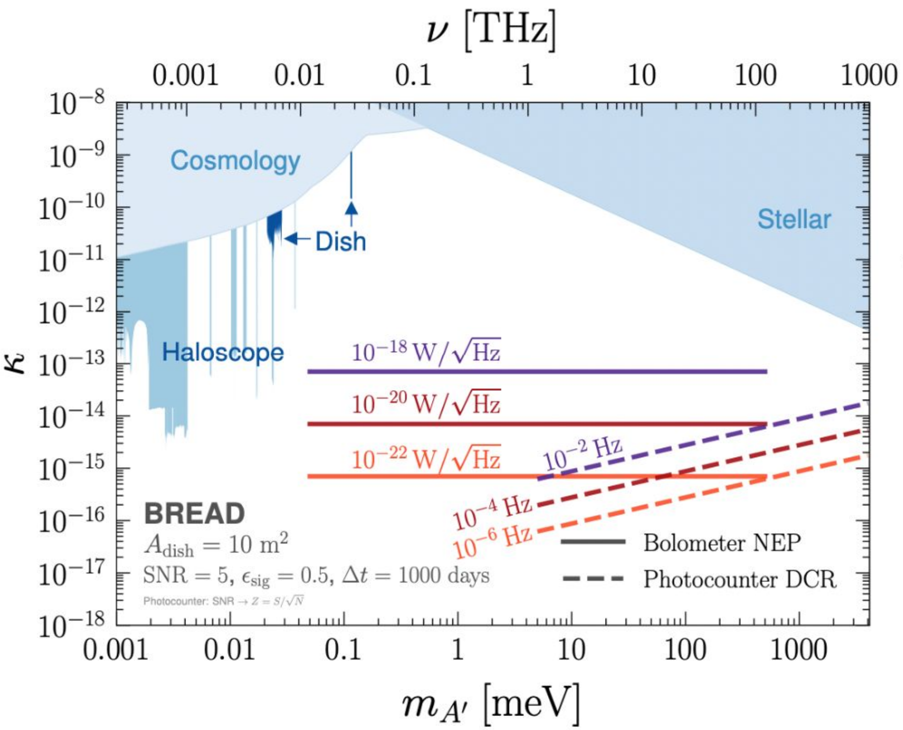
EXTRAS

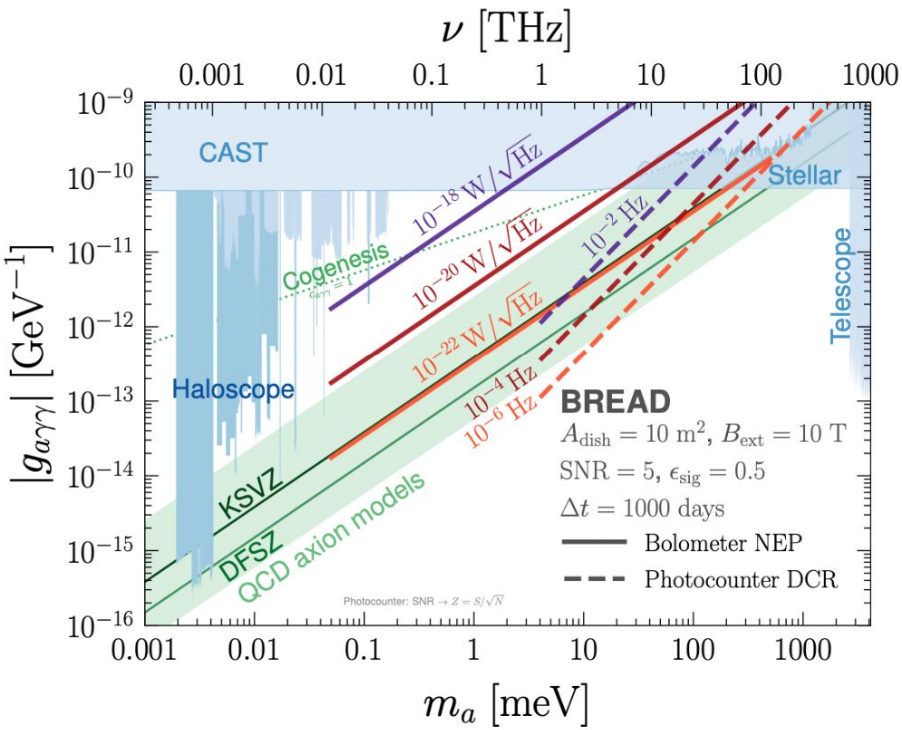
Landscape of axion–photon searches with projections



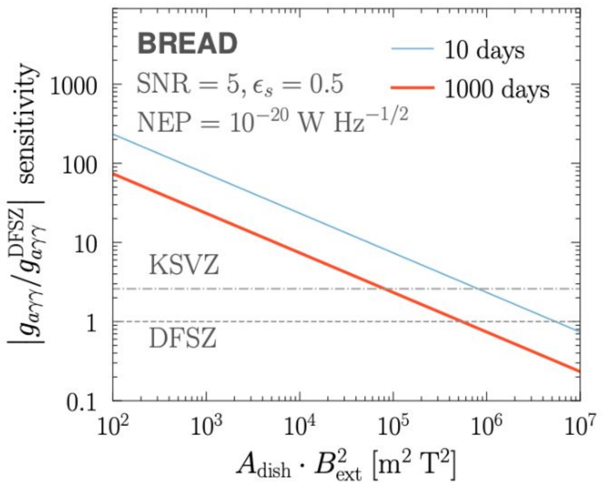
[O'Hare 2022]

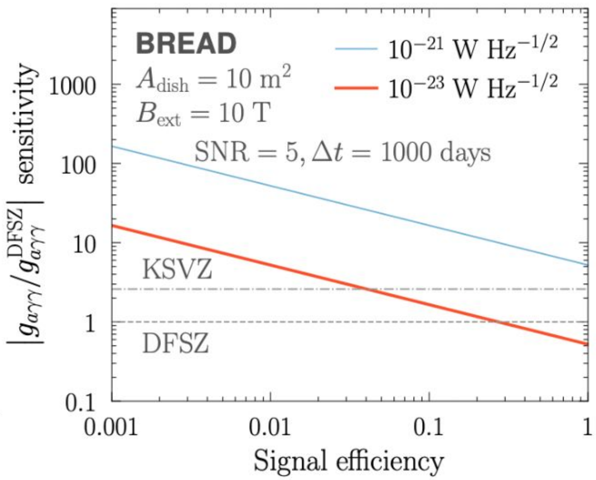
BREAD generic sensitivity

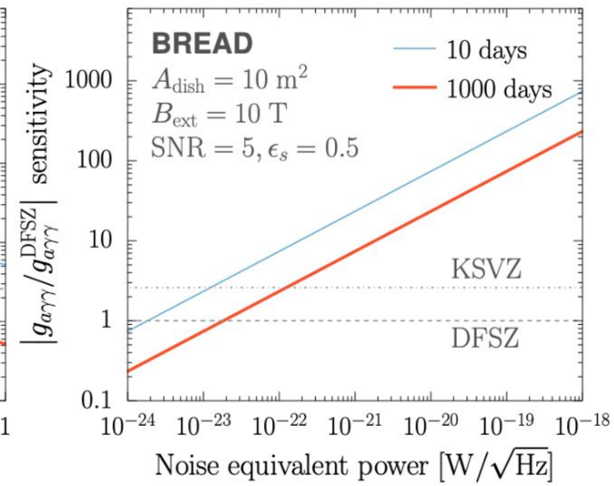


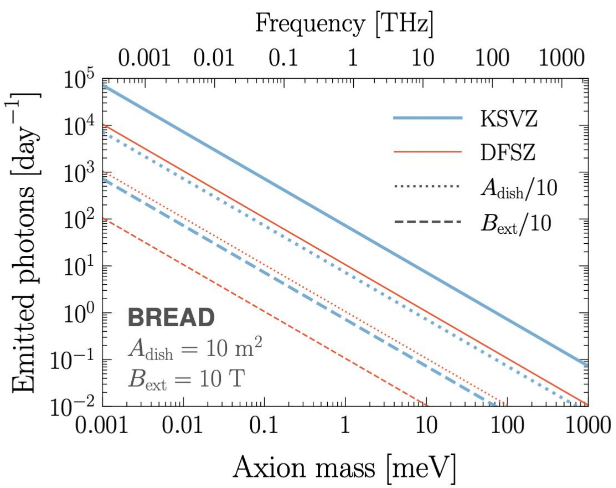


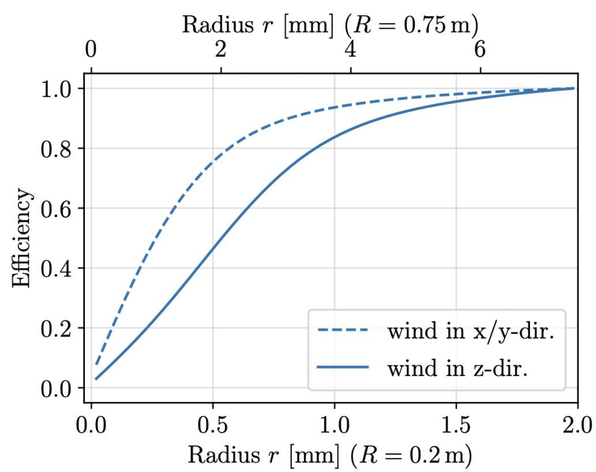
BREAD experimental considerations











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Δt [days]	10	10	1000	1000
NEP [W Hz$^{-1/2}$]	10^{-14}	10^{-18}	10^{-20}	10^{-22}
Coupling sensitivity (SNR = 5)				
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\rm KSVZ}\rvert$	—	280	9.0	0.90
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\rm DFSZ}\rvert$	—	740	23	2.3
$\kappa/10^{-14}$	8400	22	0.7	0.07

Focal spot size