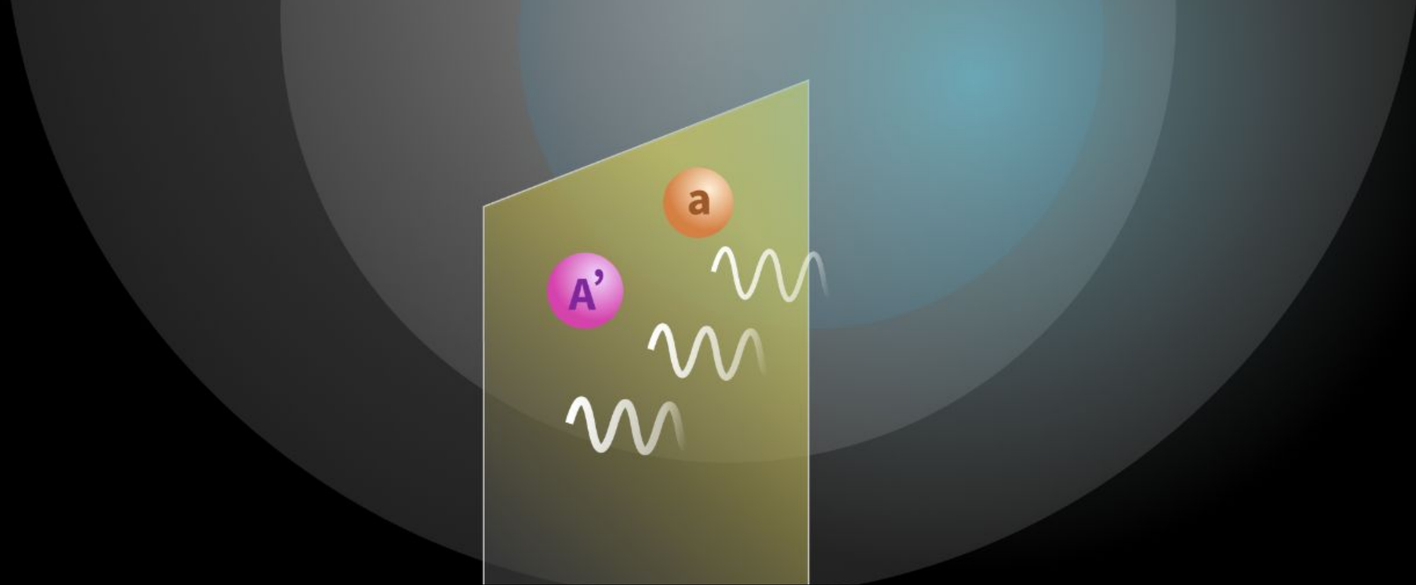


PRIMER: DISH ANTENNA

SENSITIVITY & NEED FOR MORE

BREAD Collaboration Meeting

University of Chicago | 5 October 2023

Jesse Liu

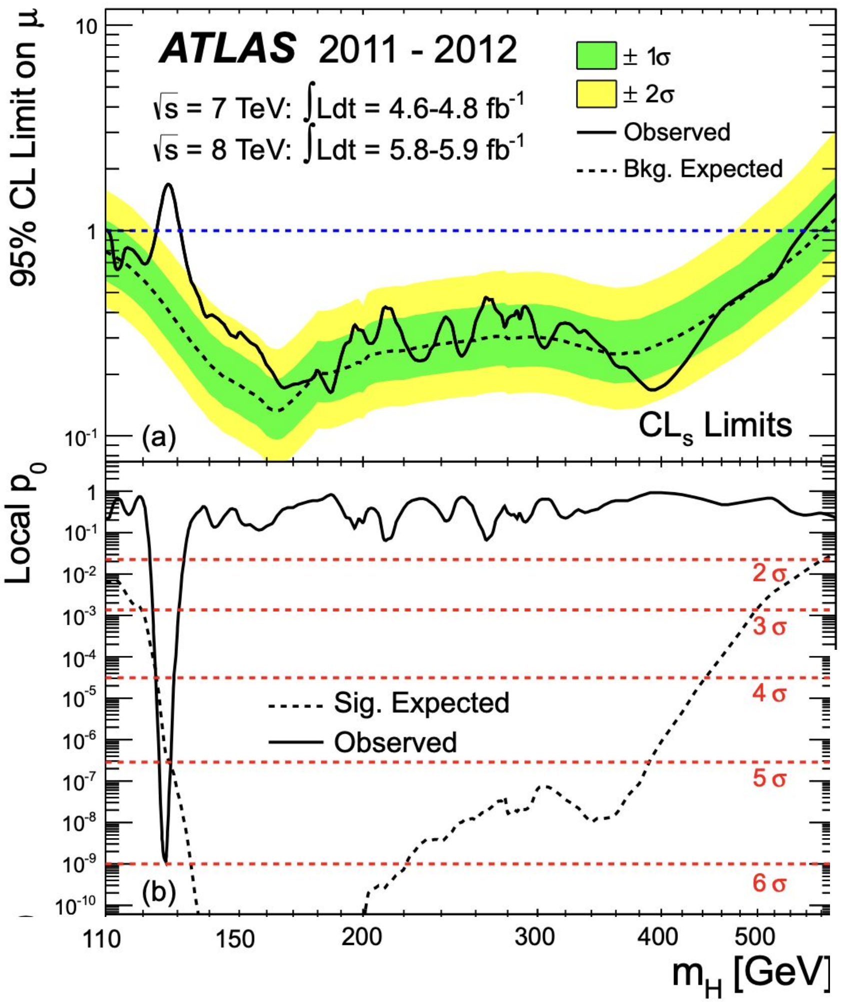
University of Cambridge

BREAD COLLABORATION

TRINITY COLLEGE CAMBRIDGE

UNIVERSITY OF CAMBRIDGE

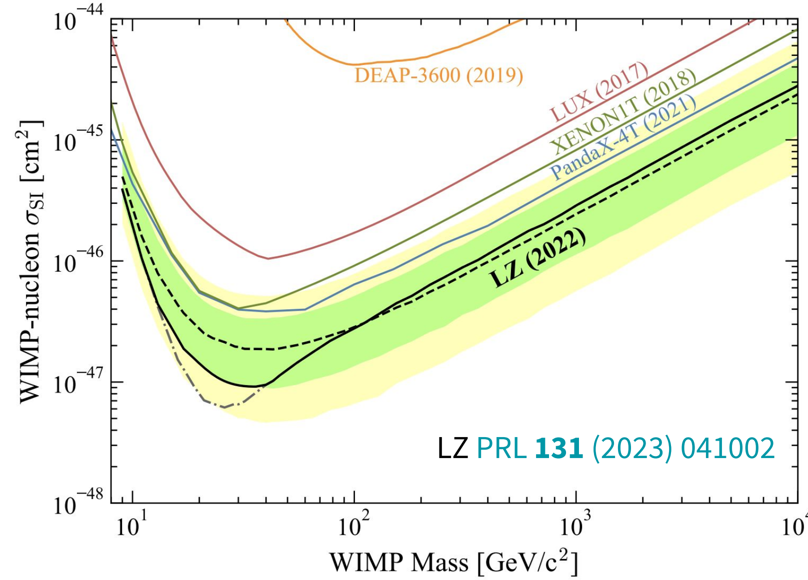
Backdrop: searches ideally broadband in mass

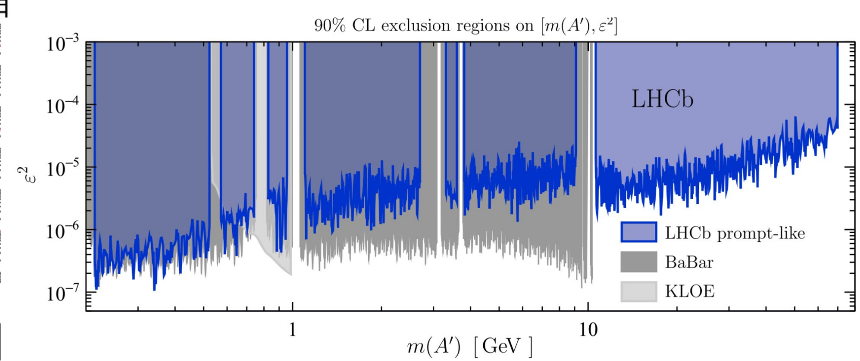


Higgs boson discovery

ATLAS PLB **716** (2012) 1-29

TeV dark matter searches

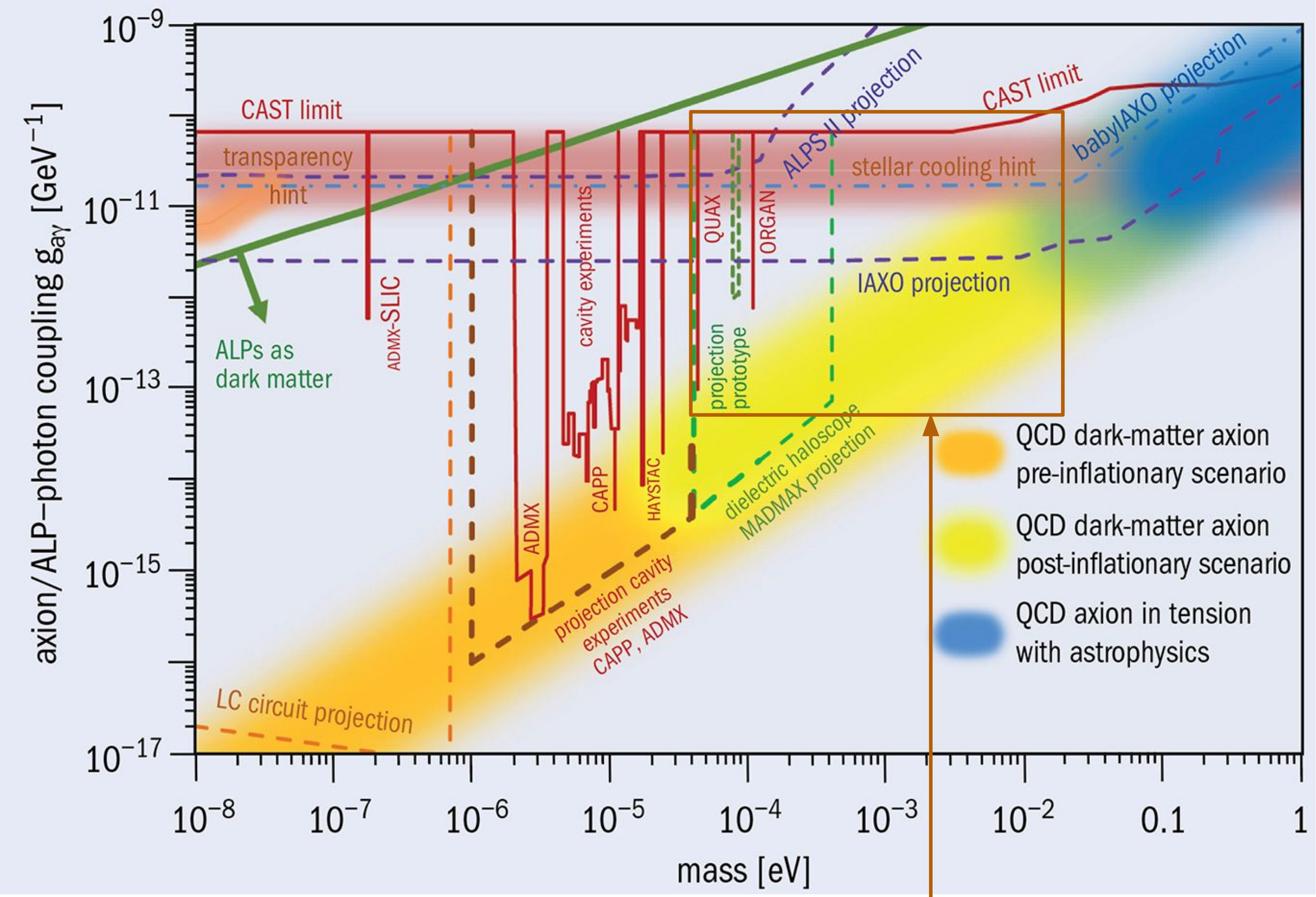




GeV dark photon searches

LHCb PRL **120** (2018) 061801

Need for broadband milli-eV axion searches



CERN Courier 2021

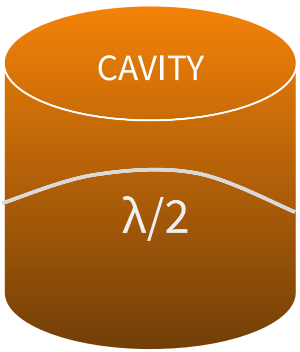
Desire broadband but cavity haloscopes narrowband $\Delta m_{search} / m \ll 1$

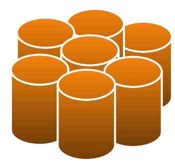
Desire high mass but scan rate* $R \sim m^{-14/3}$ impractical for m > 50 μeV

*Backes et al Nature 590 (2021) 238–242

Obstacle: signal power falls rapidly with mass

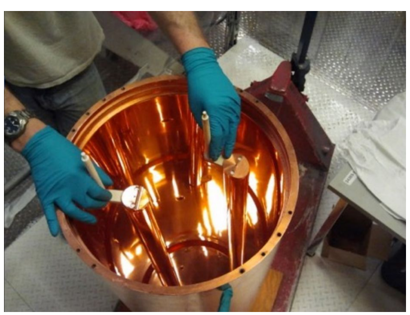
m = 4 μeV	*m* = 40 μeV	*m* = 400 μeV
GHz, λ ~ 30 cm	10 GHz, λ ~ 3 cm	100 GHz, λ ~ 0.3 cm
Power	**Power x 10^{-3}**	**Power x 10^{-6}**

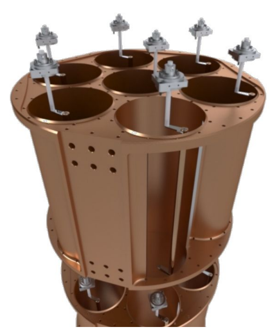




ADMX AXION DARK MATTER EXPERIMENT G2 multicavity

??





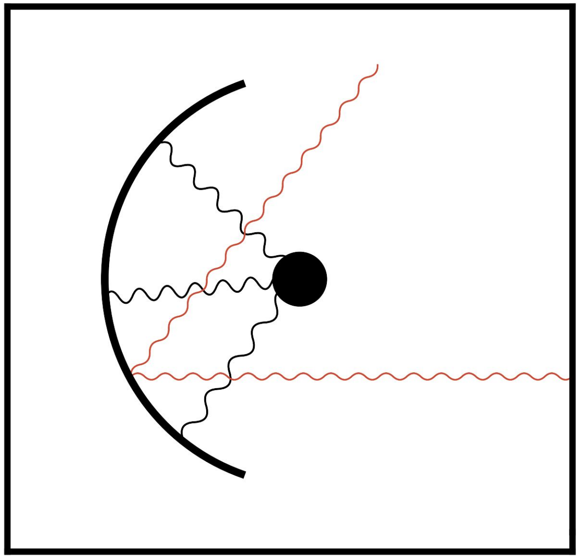
Power ~ cavity volume
N(cavities) ~ mass^3

$$P_{a\to\gamma} = (1.9\times10^{-22}\mathrm{W})\left(\frac{V}{136\ \mathrm{L}}\right)\left(\frac{B}{6.8\ \mathrm{T}}\right)^2\left(\frac{C_{nlm}}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f_a}{650\ \mathrm{MHz}}\right)\left(\frac{Q}{50000}\right)$$

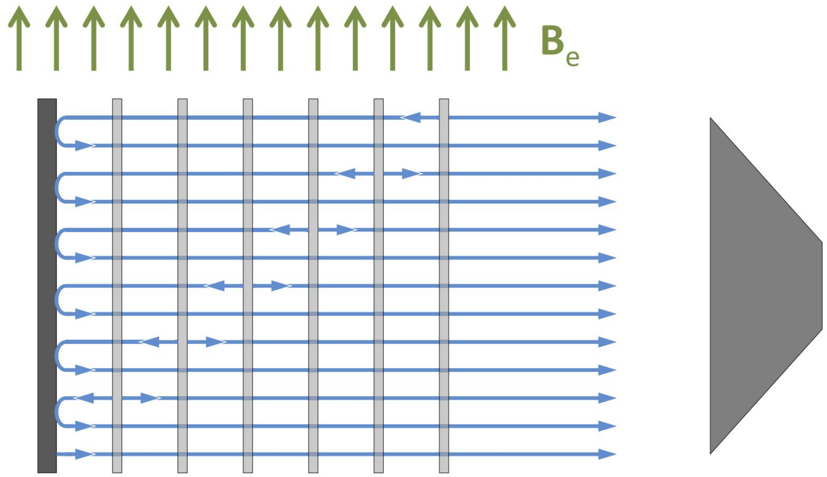
Khatitada et al (ADMX) Rev. Sci. Instrum. 92 (2021) 124502

Radical idea: forgo resonant cavity paradigm

Power ~ coupling^2 × Area



Power ~ coupling^2 × Area × (disks boost)



DISH ANTENNA

Mirror creates & focuses signal

Truly broadband "*N*(disk) → 0 limit"

Horns et al JCAP 04 (2013) 016

DIELECTRIC STACK

Mirror+disks create & boost signal

Enhance signal coherently via N disks

Caldwell et al (MADMAX) PRL 118 (2017) 091801

Overcome longstanding volume scaling penalty for mass ≳ 50 μeV

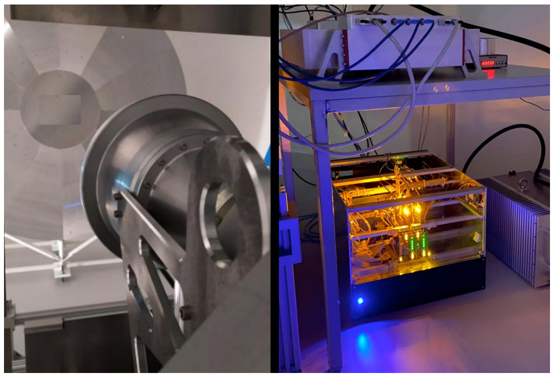
See talks Stefan Knirck Masha Baryakhtar, Andrew Sonnenschein, Jacob Egge for further discussion

Proof-of-principle pilots worldwide

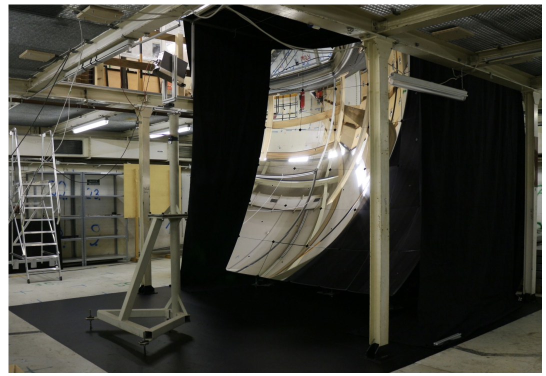
DISH ANTENNA

DIELECTRIC STACK

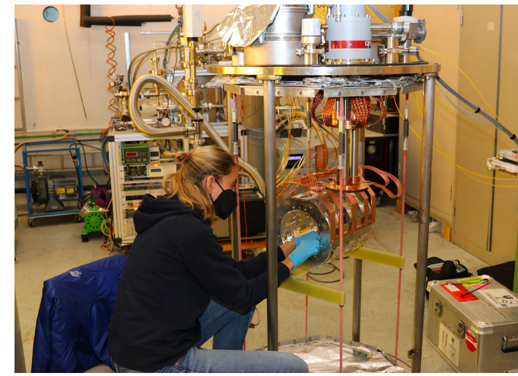
BRASS
Broadband Radiometric Axion SearcheS
Hamburg, Germany
Nguyen et al (BRASS) PATRAS 2022

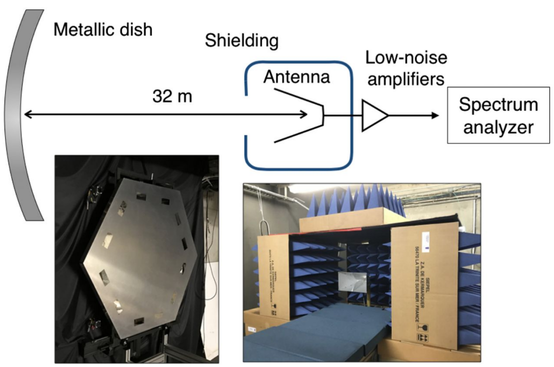


FUNK
Finding U(1)s of a Novel Kind
Karlsruhe, Germany
Andrianavalomahefa et al PRD 102 (2020) 042001

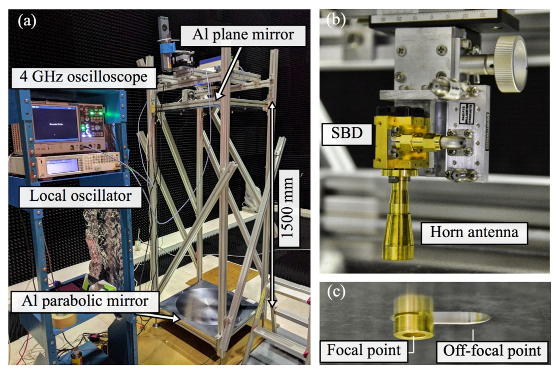


MADMAX
MAgnetized Disk and Mirror Axion eXperiment
Hamburg, Germany/CERN, Switzerland
Egge et al (MADMAX) EPJC 80 (2020) 392

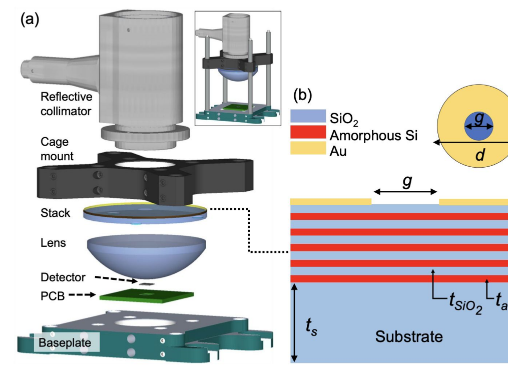




SHUKET
SearcH for U(1) darK matter with Electromagnetic Telescope
Paris-Saclay, France
Brun et al PRL 122 (2019) 201801



Tokyo
No official name except location
Tokyo, Japan
Knirck et al JCAP 11 (2018) 031

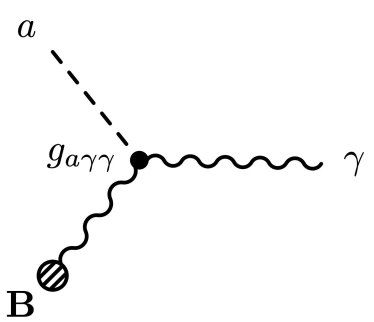


LAMPOST
Light A' Multilayer Periodic Optical SNSPD Target
Boulder, Colorado, USA
Chiles et al PRL 128 (2022) 231802

Step 1: convert DM to photons

Axion–photon coupling

$$g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



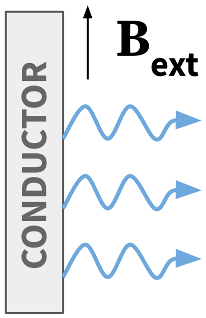
Augment Ampère–Maxwell

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

$$\uparrow$$

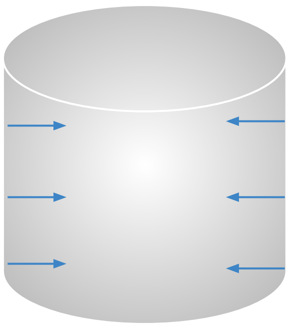
$$g_{a\gamma\gamma} \sqrt{2\rho_{\mathrm{DM}}} \mathbf{B}^{\parallel}_{\mathrm{ext}} \cos(m_a t)$$

Emit photons

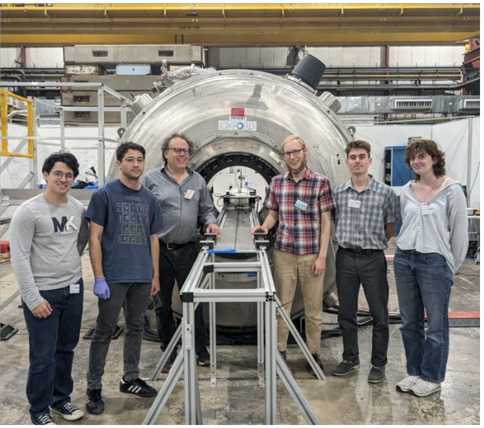


$$\mathbf{E}_{\parallel} = 0$$

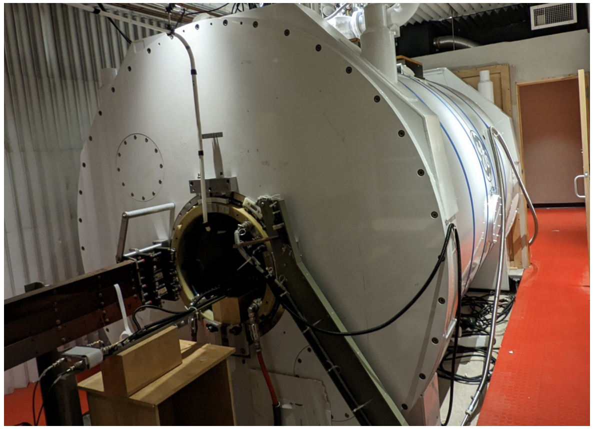
Optimise geometry



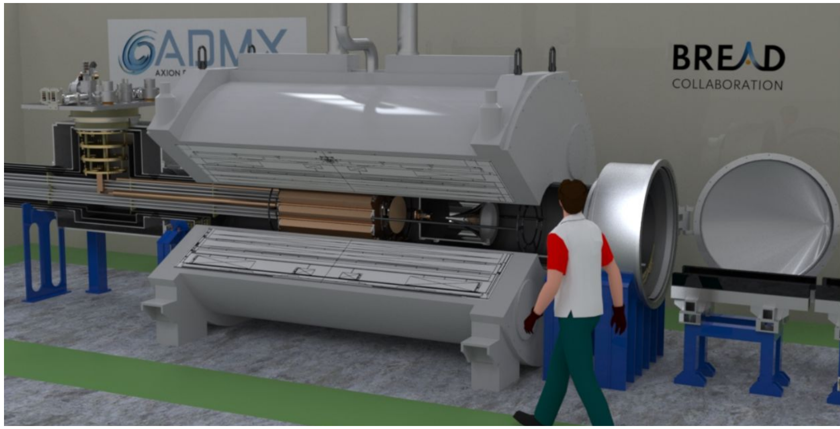
Solenoids & cryostats are *cylindrical* ↓



Argonne 4 T magnet



9.4 T 80 cm bore solenoid @ UIC

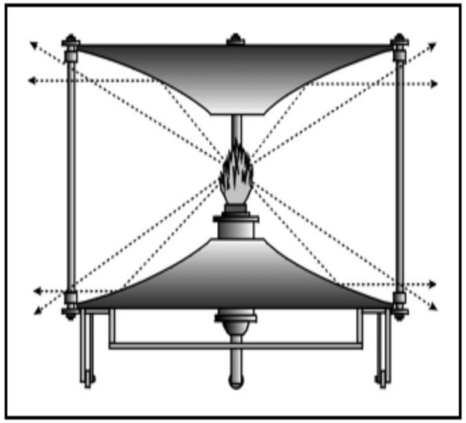


Vision 2025+: BREAD anchors Fermilab axion center

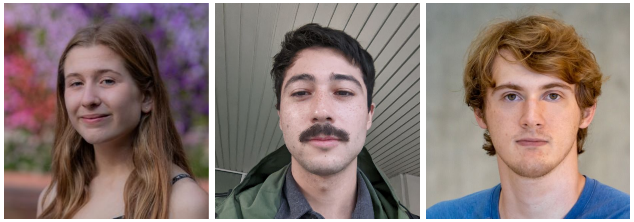
Pics from Stefan Knirck, Don Mitchell, Andrew Sonnenschein

Step 2: focus photons

Historical inspiration: classical lighthouse



Bordier-Marcet 1811 [uslhs.org]

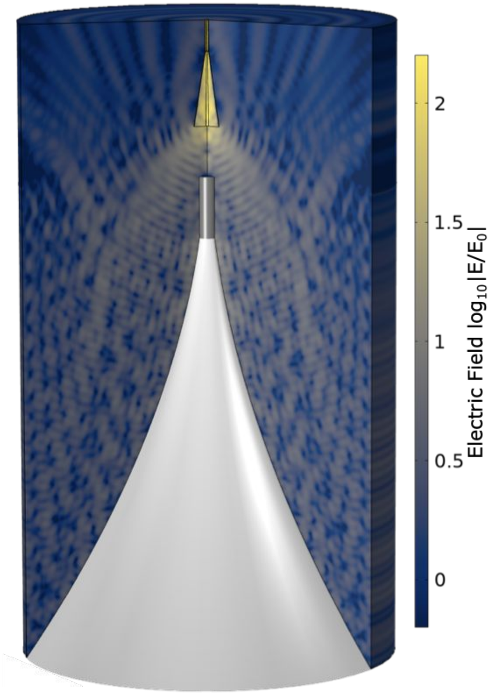


Kate Azar (Wellesley) **Gabe Hoshino** (Yale) **Matthew Malaker** (IIT)

Fermilab undergraduate summer students led initial simulation studies

SLAC group (Noah Kurinsky, Chiara Salemi, Lionel Whitehead et al) studying mid-frequency simulations

Low mass: *GigaBREAD* coherent microwave field

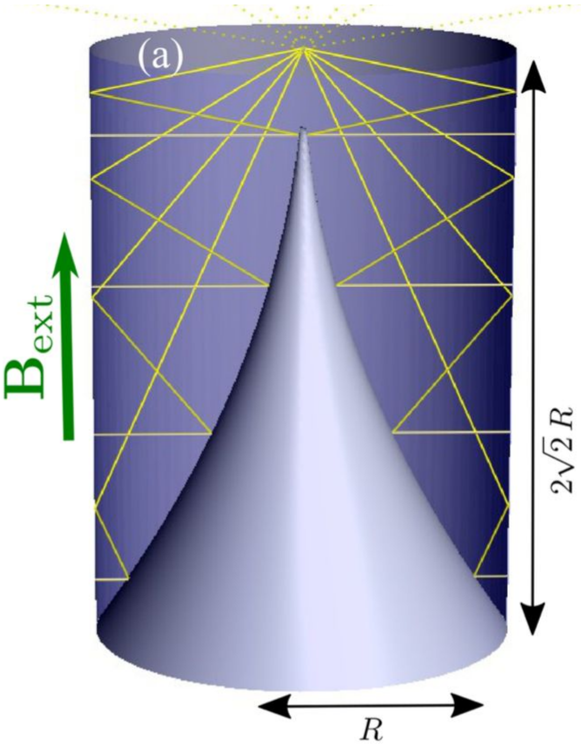


Diffraction limited

Numerical Maxwell's equations (COMSOL) for 15 GHz signal

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

High mass: *InfraBREAD* infrared ray optics



Shot-noise limited

Focal spot smeared by non-zero halo velocity

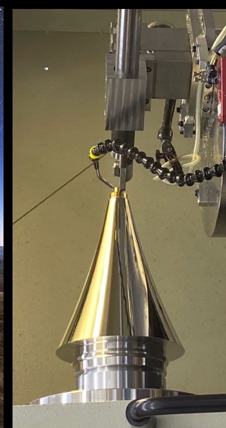
BREAD COLLABORATION

BREAD geometric analogue of reflector telescopes

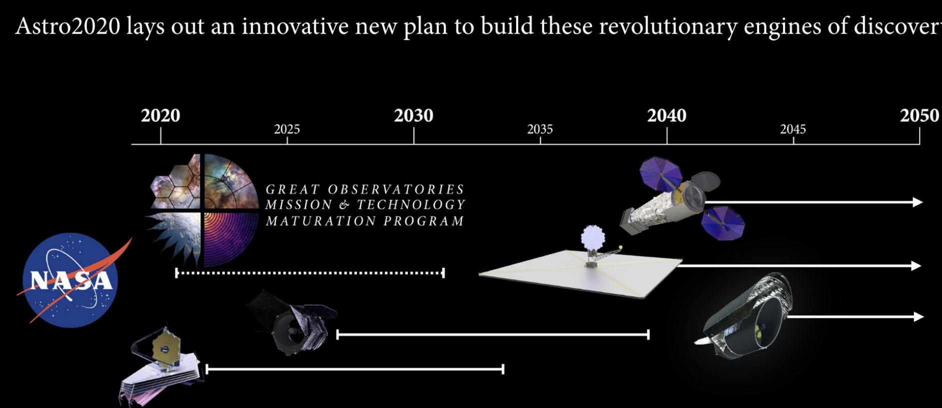
Leverage 400 years of understanding light & optical engineering

Galileo 1610
Newton 1668

21st century ground based telescopes 2027+ [39m ELT]



BREAD optical grade reflector*



Next generation space telescopes
Astro 2020 decadal survey, greatobservatories.org

Dovetail with astronomy/cosmology instrumentation R&D

Vision 2030+: towards axion dark matter observatories

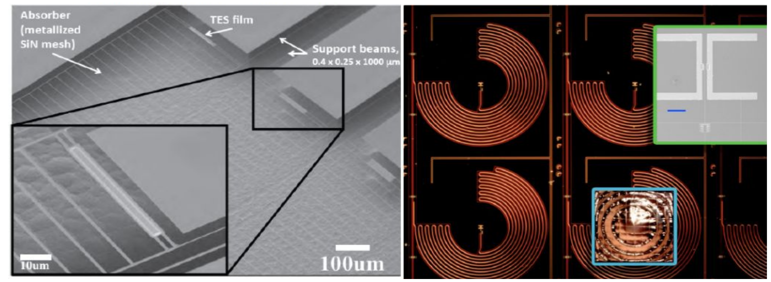
* See talks by Gianpaolo Carosi, Aiman Imran, Robert Browning

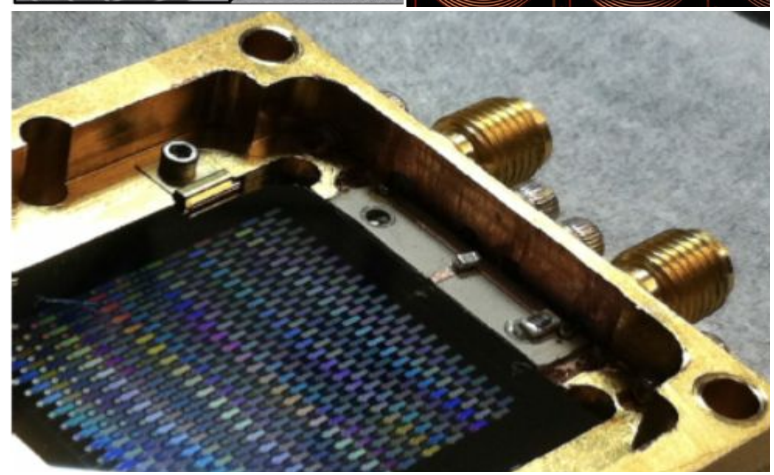
Innovation at interdisciplinary interfaces

ASTRONOMY
Origins of habitability & life

↔ BREAD COLLABORATION ↔

QUANTUM TECHNOLOGY
Information & sensing





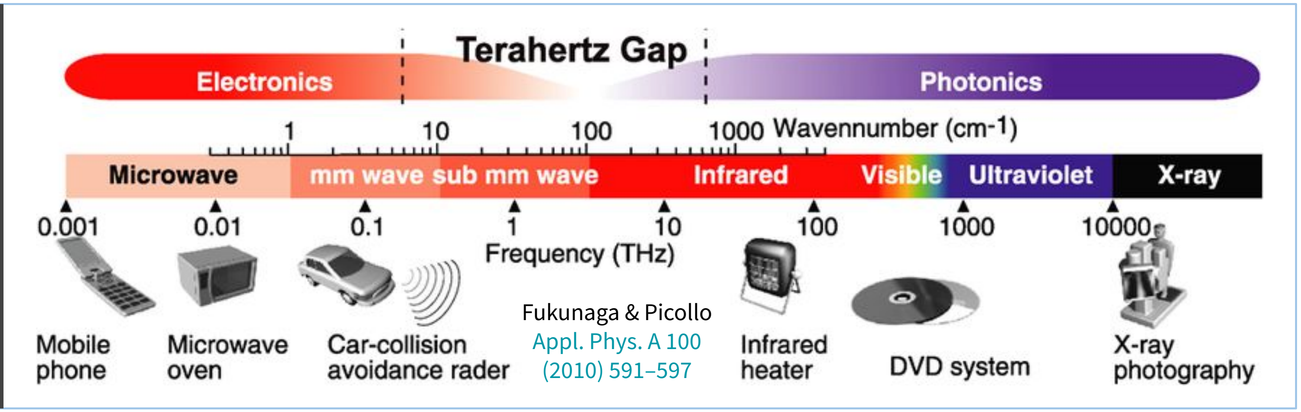
**"Think *Inside*, Think *Outside* the box.
Make connections to other fields"**
NSF Program Director at Snowmass Oct 2020

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

Images: origins.ipac.caltech.edu

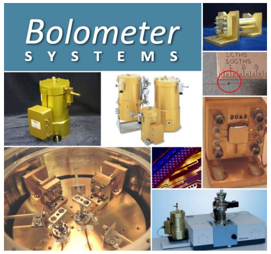
Step 3: detect photons via quantum sensing

→ THz technology gap reflected in cost & availability
"Can't buy a $100 room-temp THz laser from Target"

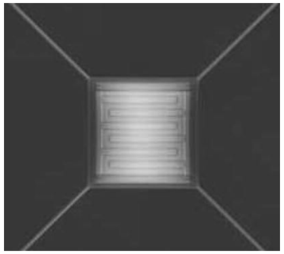


Fukunaga & Picollo
Appl. Phys. A 100 (2010) 591–597

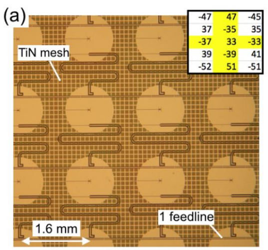
GigaBREAD	TeraBREAD	InfraBREAD
~ 0.001 meV, 20 GHz	~ 0.1 meV, THz	~ 1 eV, 200 THz



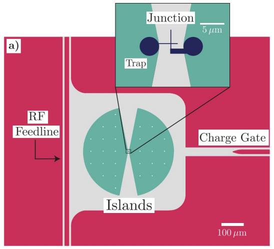
Commercial thermistors & bolometers
irlabs.com



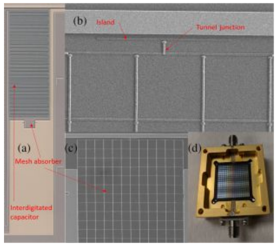
Transition Edge Sensor
Goldie et al
[JLTP 2016]



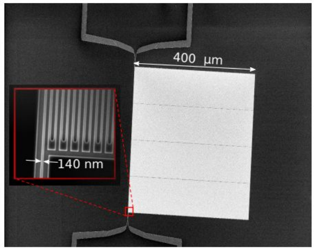
Kinetic Inductance Detector
Baselmans et al
[A&A 2017]



Superconducting Quasiparticle Amplifying Transmon
Fink et al
[2310.01345]



Quantum Capacitance Detector
Echternach et al
[JATIS 2021]

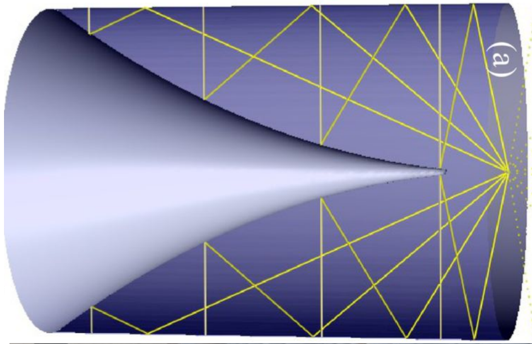


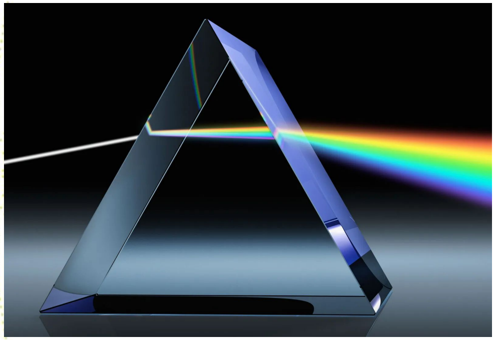
Superconducting Nanowire Single Photon Detector
Hochberg et al
[1903.05101]

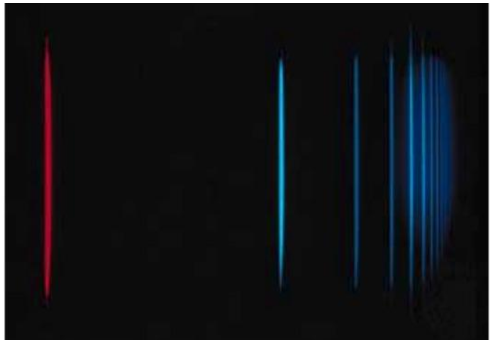
See also talks by Chiara Salemi, Christian Peña, Dylan Temples, Christina Wang

Step 4: spectroscopy for discovery

Fourier transform via fast electronics, diffraction grating, interferometry…

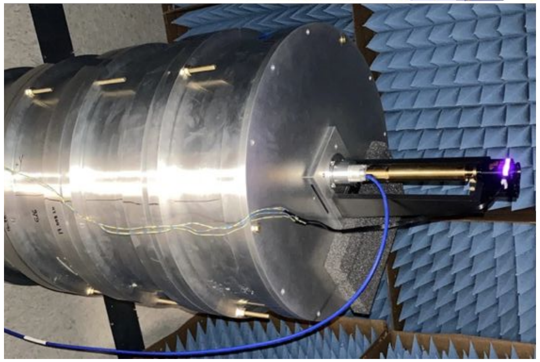


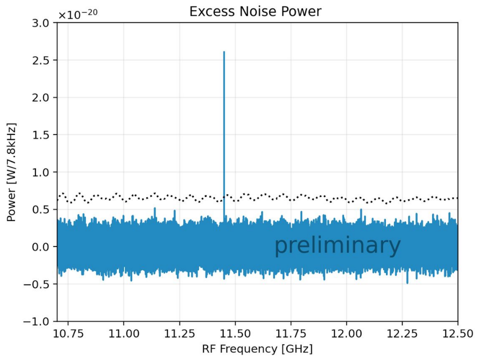




Encyclopædia Britannica

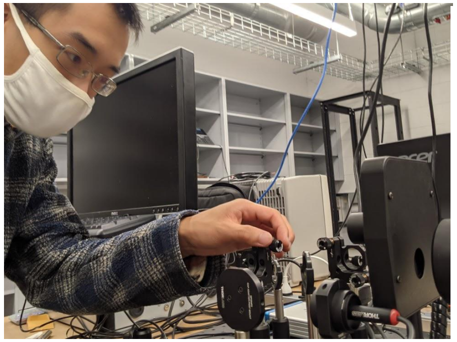
→ GigaBREAD

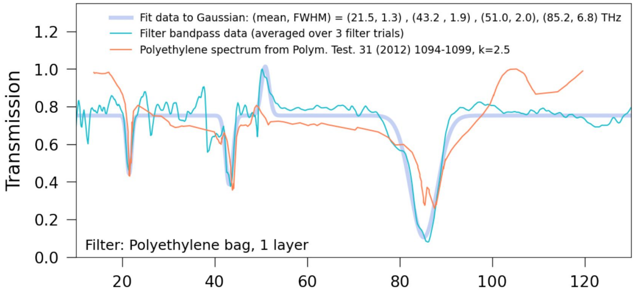




See on-chip FTS talk by Ritoban Basu Thakur

→ Kristin Dona (UChicago)

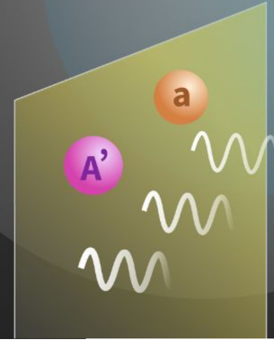




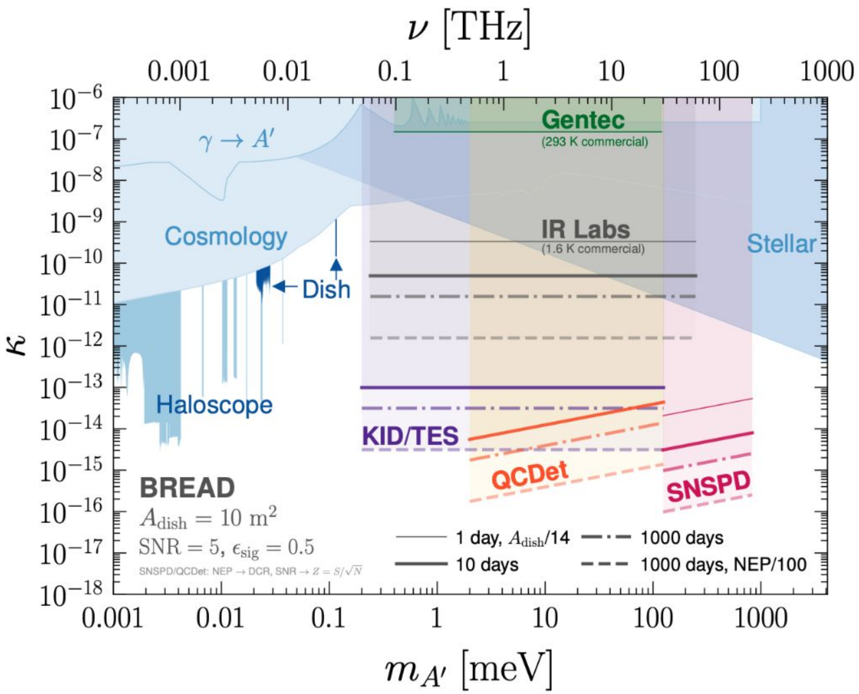
Frequency [THz] Dona et al 2104.07157 (JINST)

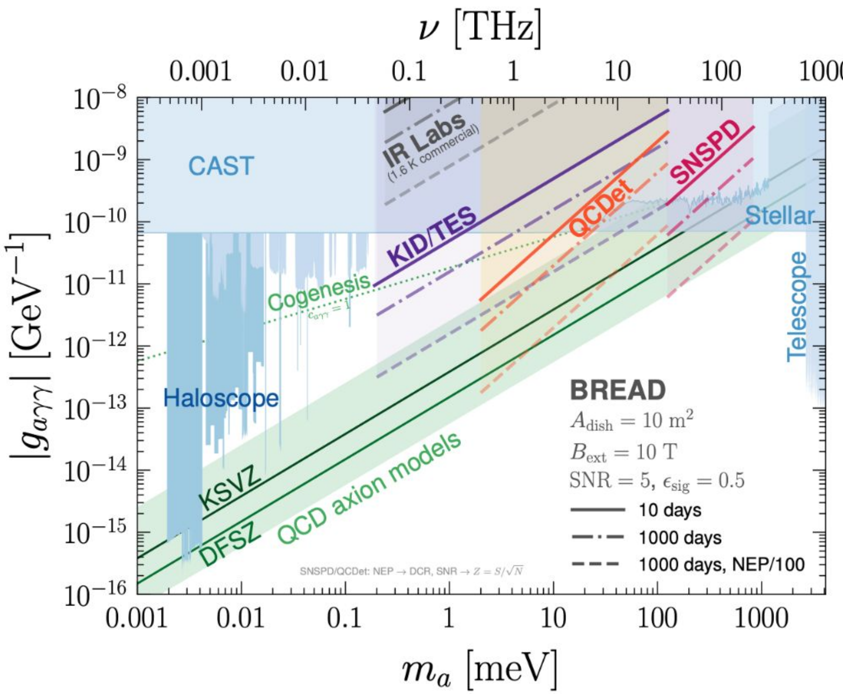
Spectral resolution crucial for search sensitivity & signal characterisation

BREAD COLLABORATION | SCIENCE TARGETS AND SENSITIVITY



Unprecedented reach also opens unanticipated discoveries





DARK PHOTON (VECTOR)

Preparing “sourdough starter” pilots
First GHz results 2023, IR pilot target 2024

AXION (PSEUDOSCALAR)

GHz pilot target 2024, QCD axion requires high-field magnet & sensor R&D 5+ years

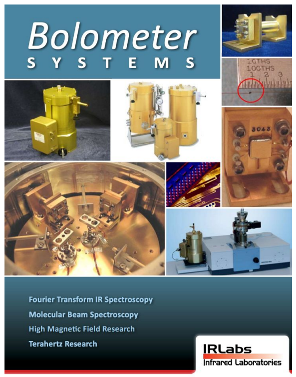
JL, Dona et al [PRL 128 (2022) 131801]

EXTRAS

Step 3: detect photons

gentec-eo.com

irlabs.com

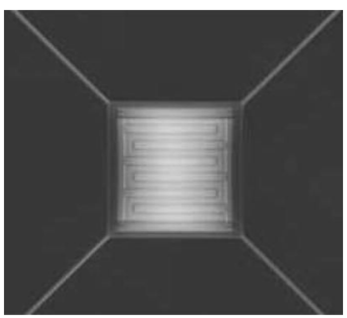


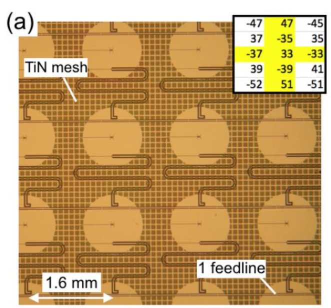
Commercial bolometers

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]





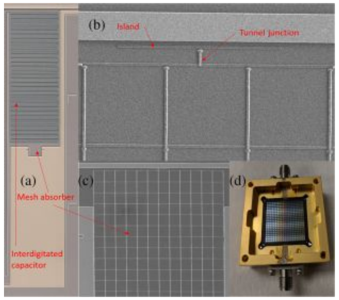
Transition Edge Sensor

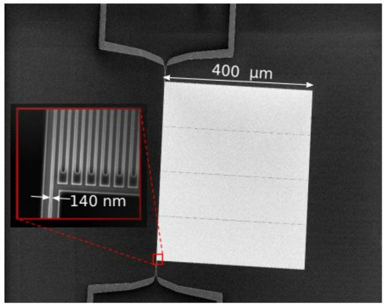
Goldie et al [JLTP 2016]

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

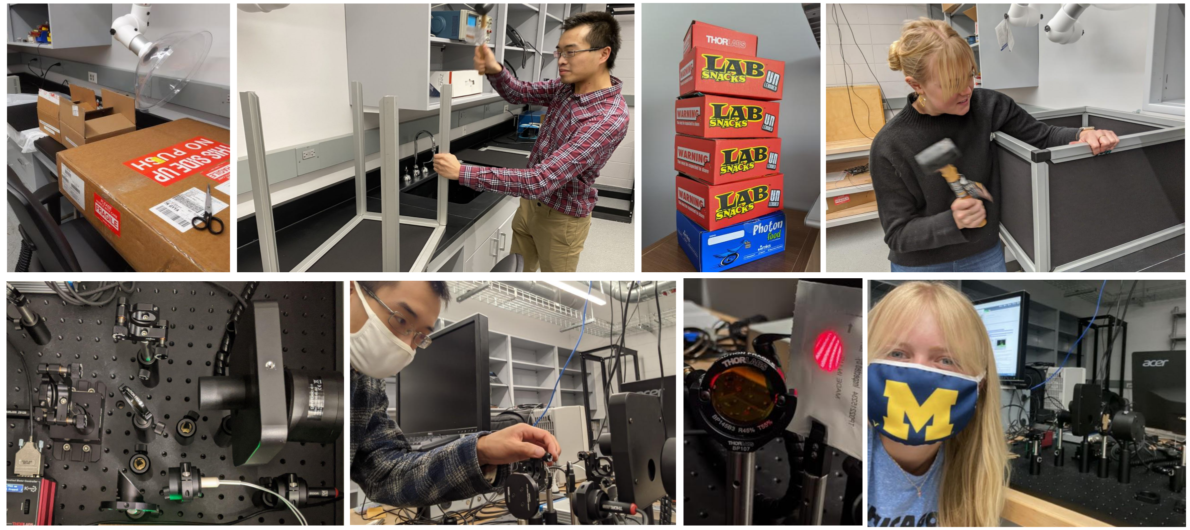
R&D 1: build spectrometer for calibration optics

JANUARY 2020
Hardware arrival & assembly

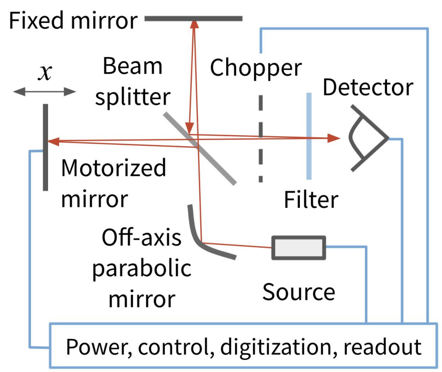
AUGUST
Alignment & operations

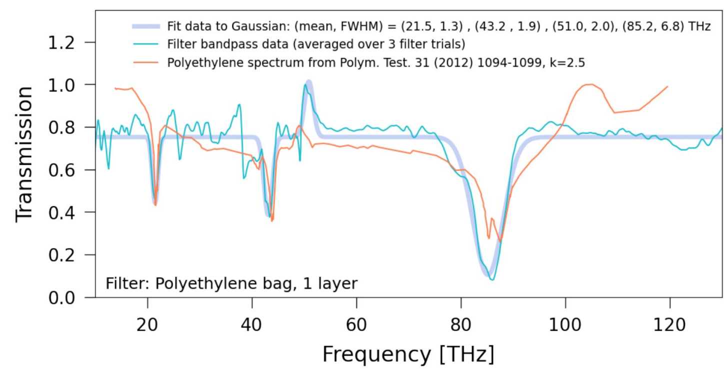
OCTOBER
Measurements & analysis

APRIL 2021
Write up & publish
2104.07157 (JINST)



← Kristin Dona (UChicago)





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]

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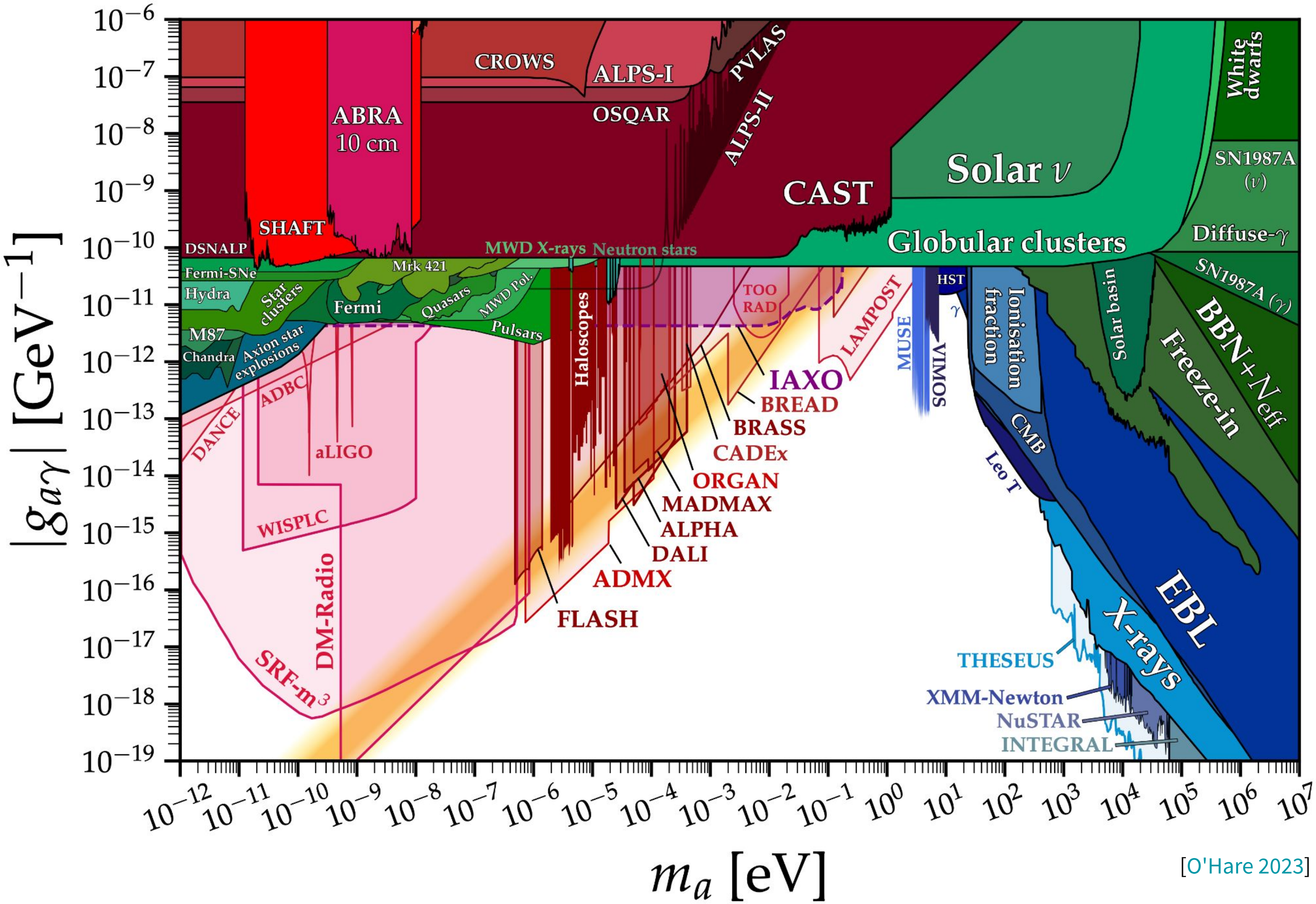
Journal of Instrumentation, Volume 17, June 2022

Citation K. Dona *et al* 2022 *JINST* **17** P06014

R&D supported by Department of Energy HEP-QIS QuantISED grant

Axion landscape circa 2035: how do we arrive here?



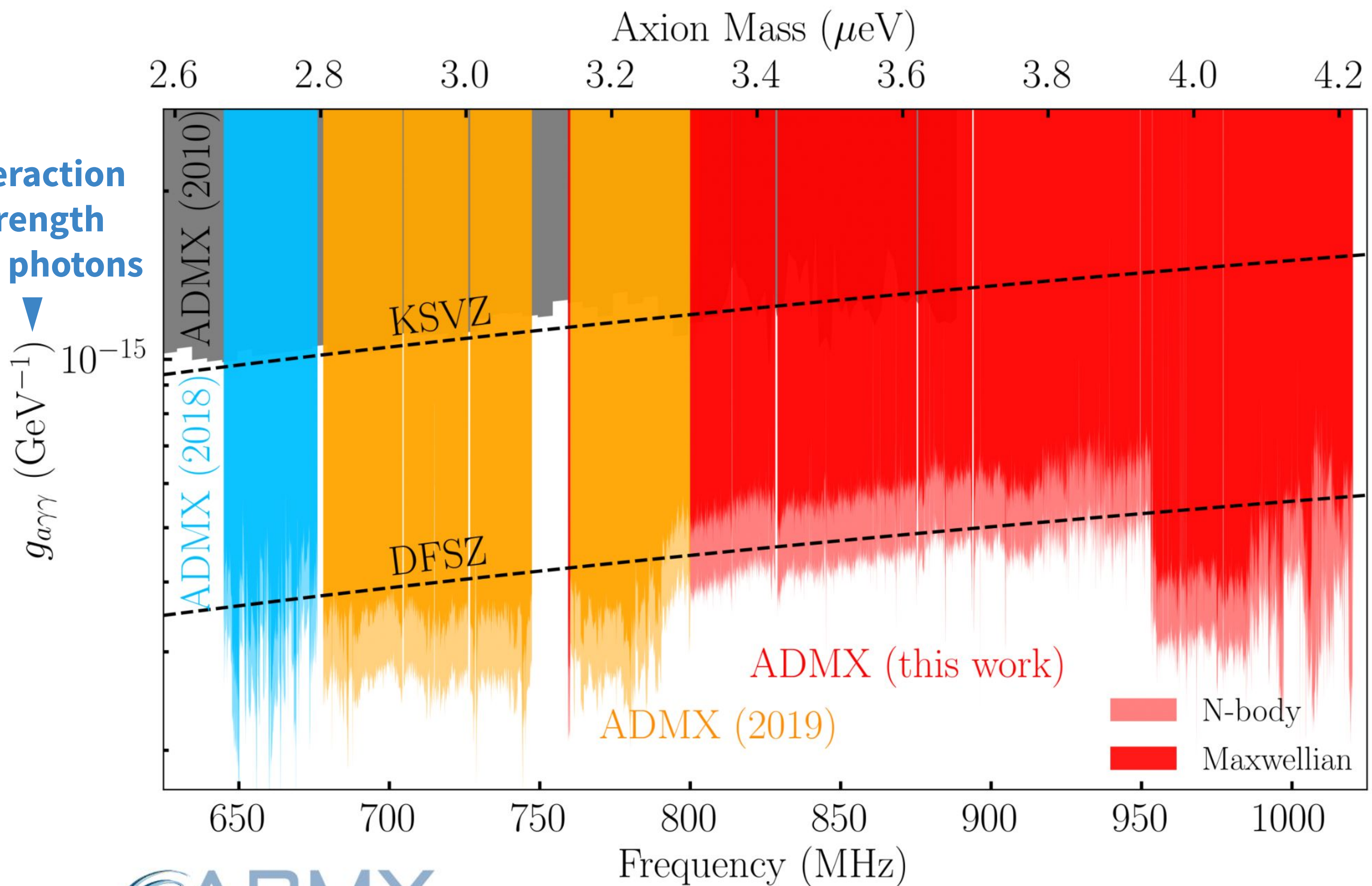
[O'Hare 2023]

Strength in breadth: support **diverse portfolio** of distinct 1–10 million £/$/€ experiments

Invest in **quantum sensor R&D**, **high-field magnet R&D** & **talent via flexible fellowships**

Success story: decisively test canonical axion targets

Interaction strength with photons



ADMX AXION DARK MATTER EXPERIMENT

Bartram et al (ADMX) PRL 127 (2021) 261803

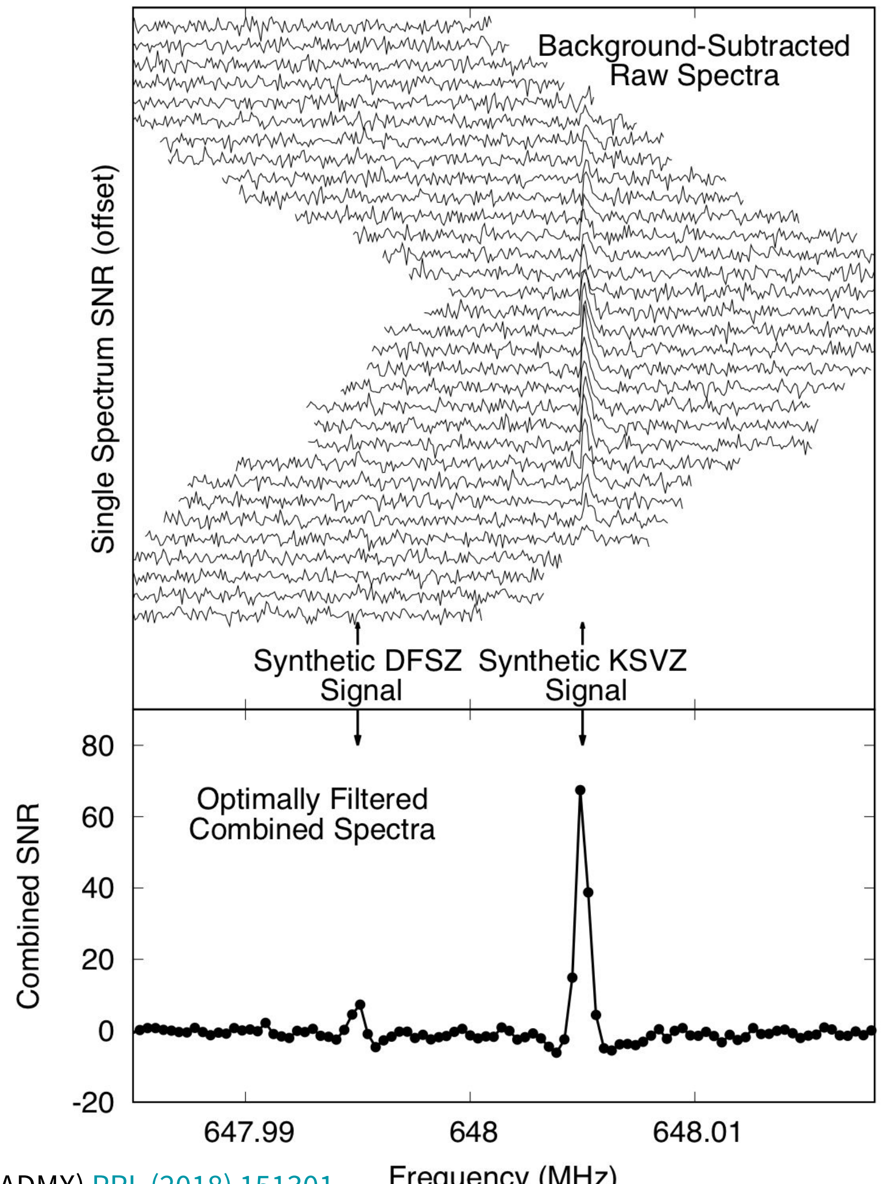
KSVZ/DFSZ = canonical particle physics benchmarks that solve strong CP problem

Narrowband searches very slow

Narrowband ⇒ small search range per scan $\Delta m_{search}/m_{axion} \ll 1$

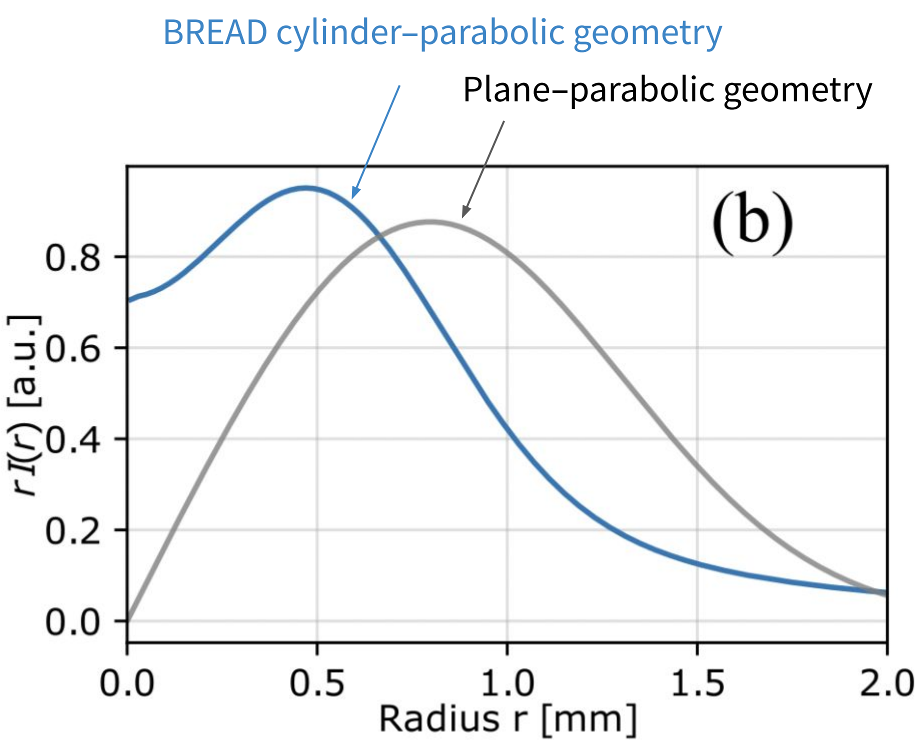
Cavities tuned to unknown axion mass ⇒ scan & wait

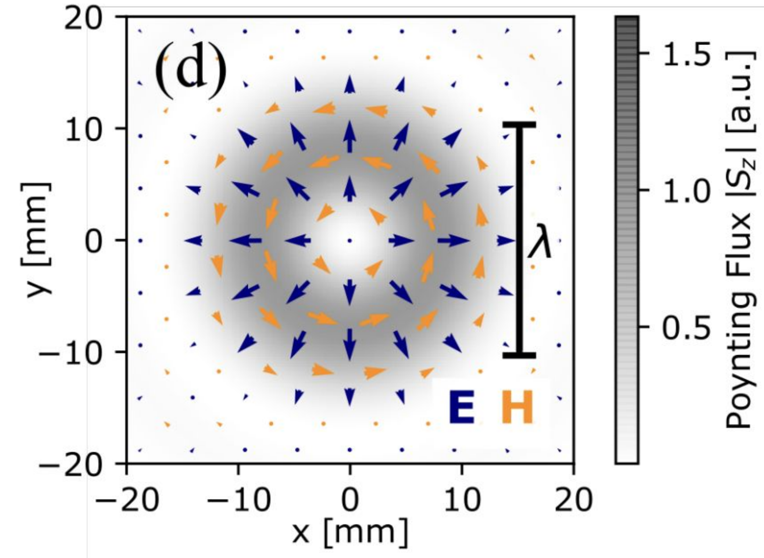
$$\mathrm{SNR} = \frac{P_{\rm axion}}{k_B T_{\rm sys}/\epsilon}\sqrt{\frac{t}{b}}$$

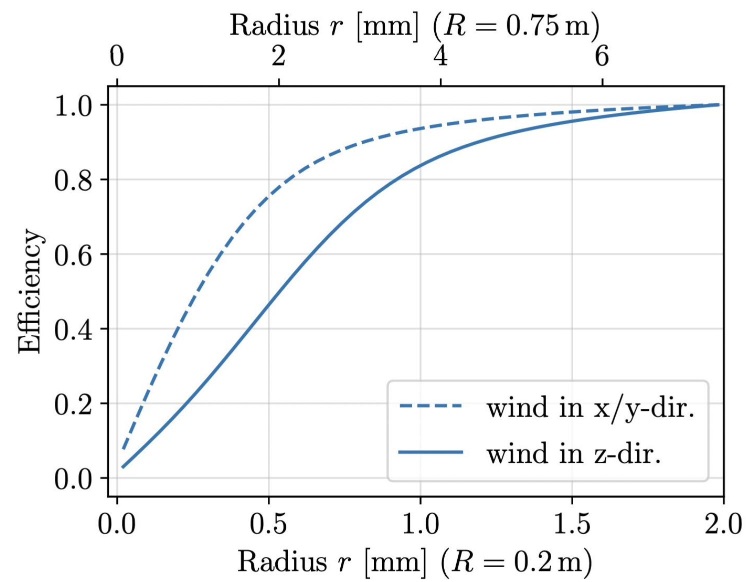


Du et al (ADMX) PRL (2018) 151301

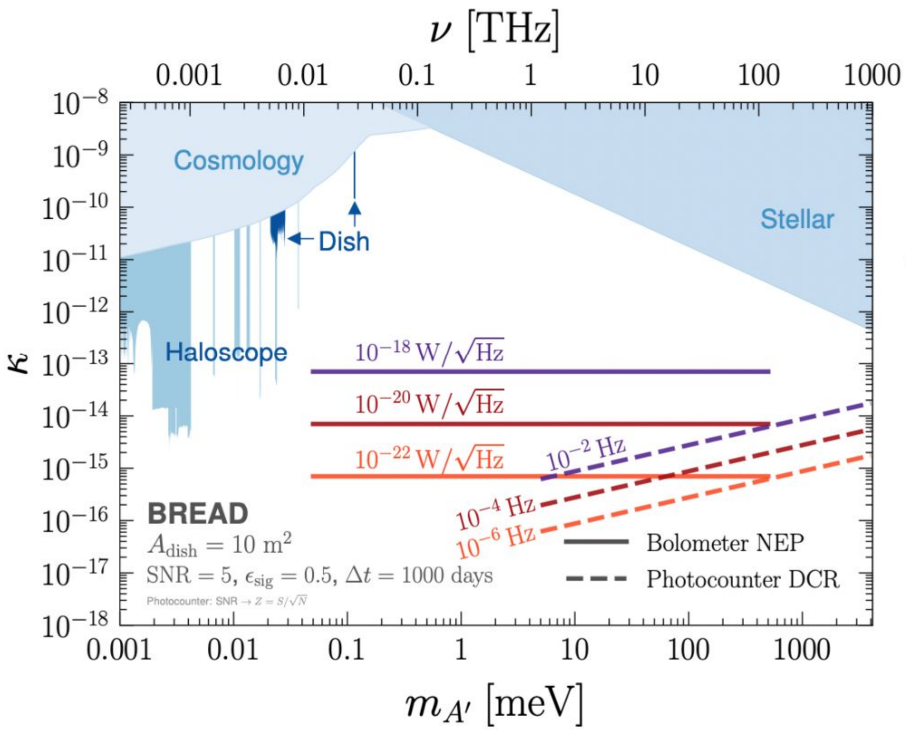
Focal spot size

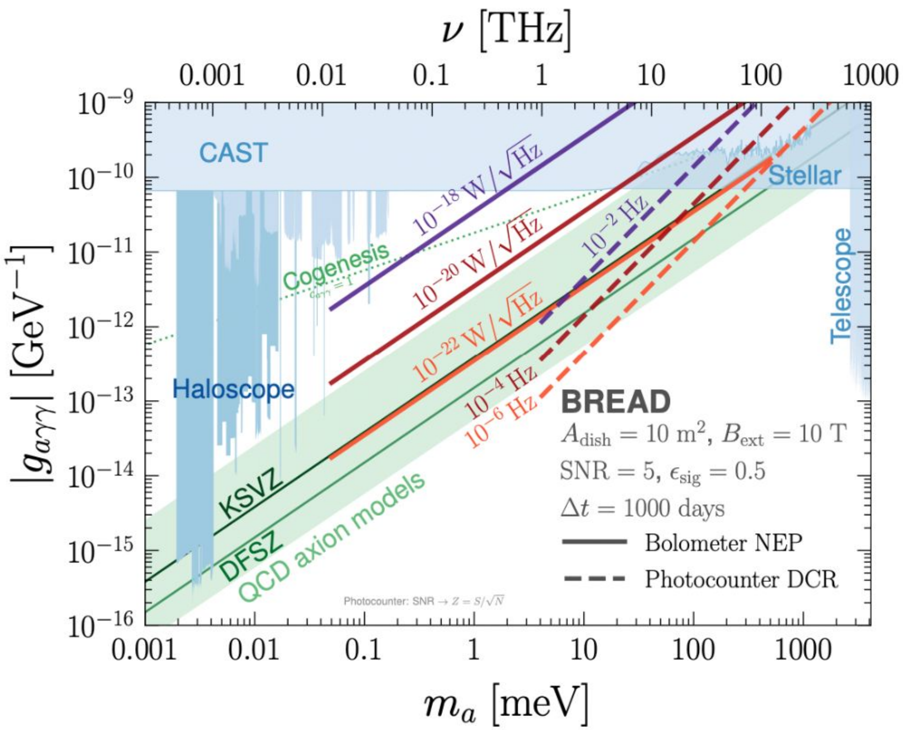




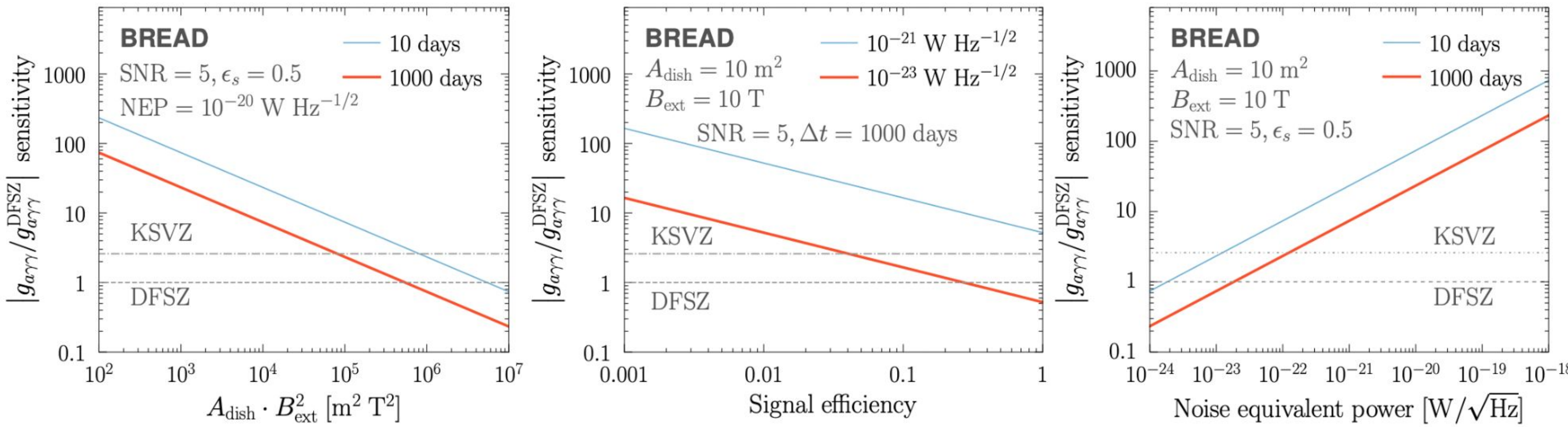


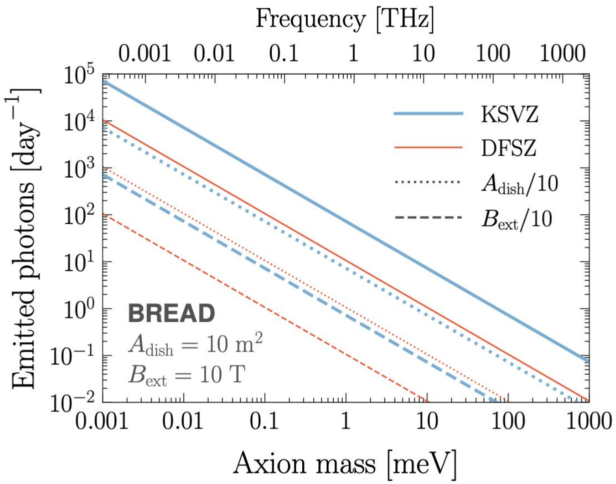
BREAD generic sensitivity

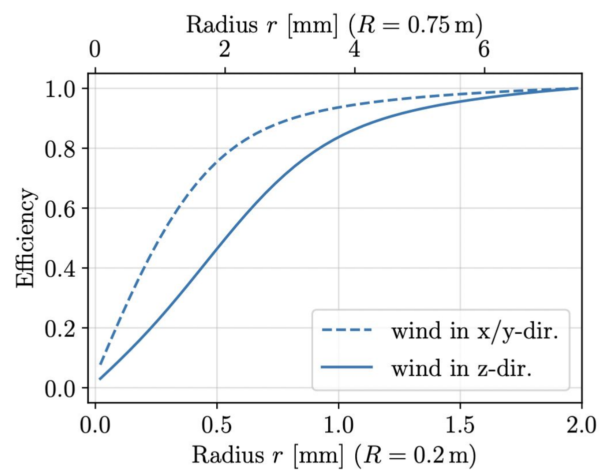




BREAD experimental considerations







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