Higher mass axion dark matter searches

BREAD and MADMAX

Stefan Knirck

Fermi National Accelerator Laboratory

Fermilab

Member of ADMX, BREAD and MADMAX

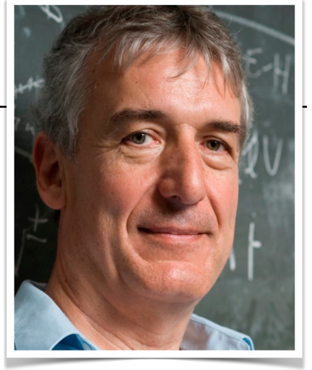
ADMX AXION DARK MATTER EXPERIMENT

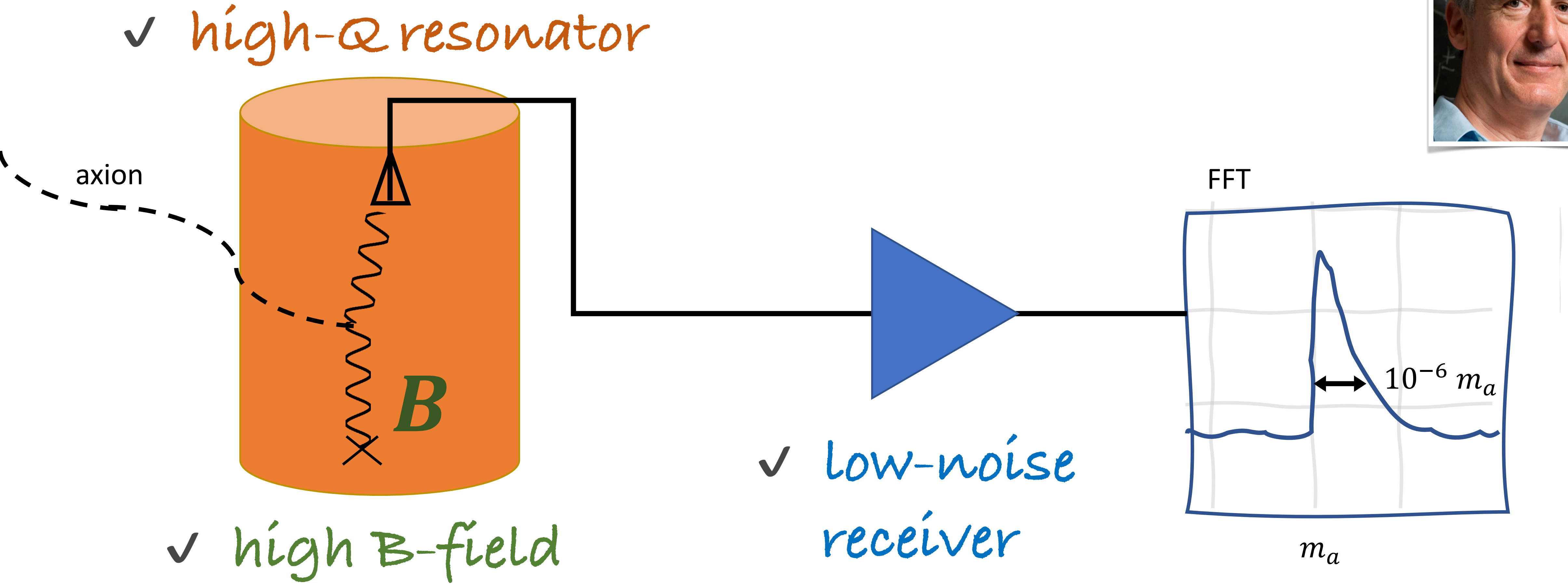
BREAD COLLABORATION

MADMAX

The Resonant Cavity

[P. Sikivie, PRL 51, 1415 (1983)]

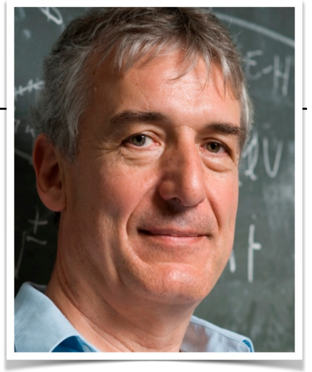


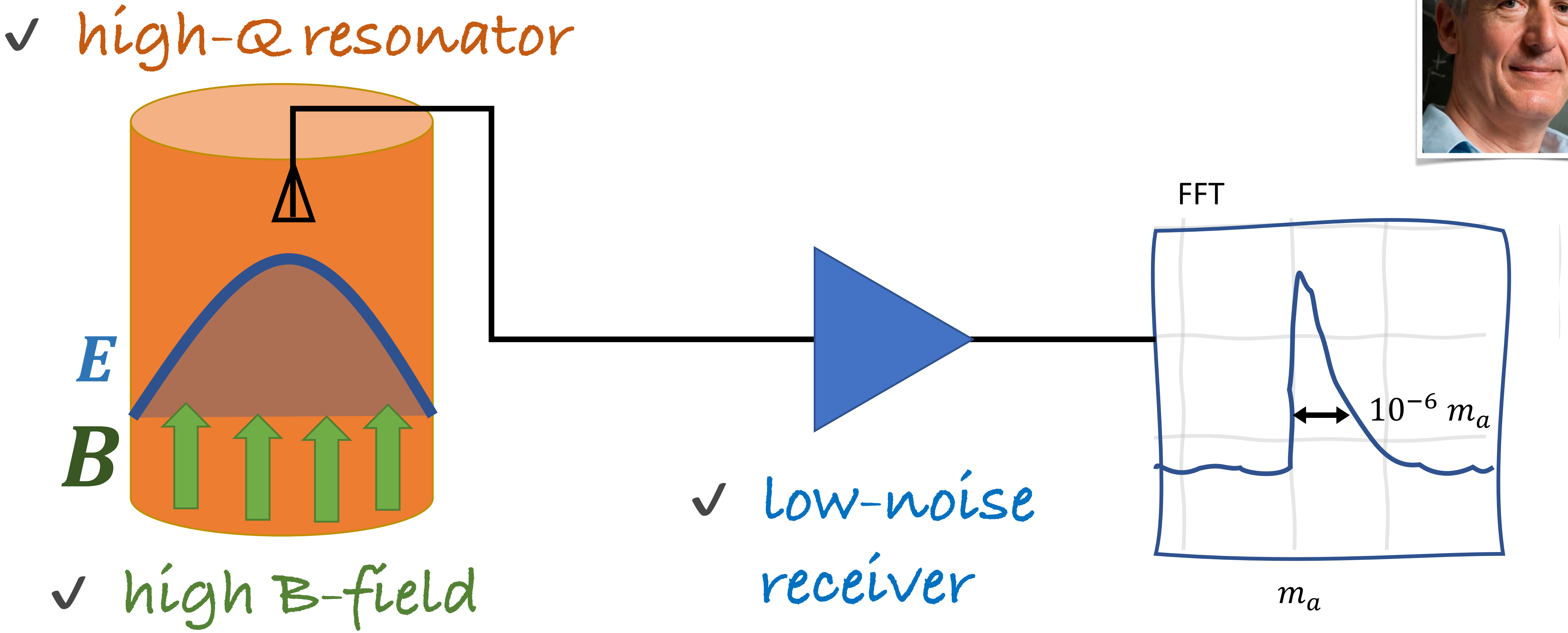


$$P_{\mathrm{sig}} = 2 \cdot 10^{-23}\,\mathrm{W} \cdot \left(\frac{B}{7.6\ \mathrm{T}}\right)^2 \left(\frac{V}{136\ L}\right)\left(\frac{C}{0.4}\right)\left(\frac{Q}{30{,}000}\right)\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{m_a}{3\ \mu\mathrm{eV}}\right)\left(\frac{\rho_{\mathrm{DM}}}{0.45\ \mathrm{GeV\ cm^{-3}}}\right)$$

The Resonant Cavity

[P. Sikivie, PRL 51, 1415 (1983)]





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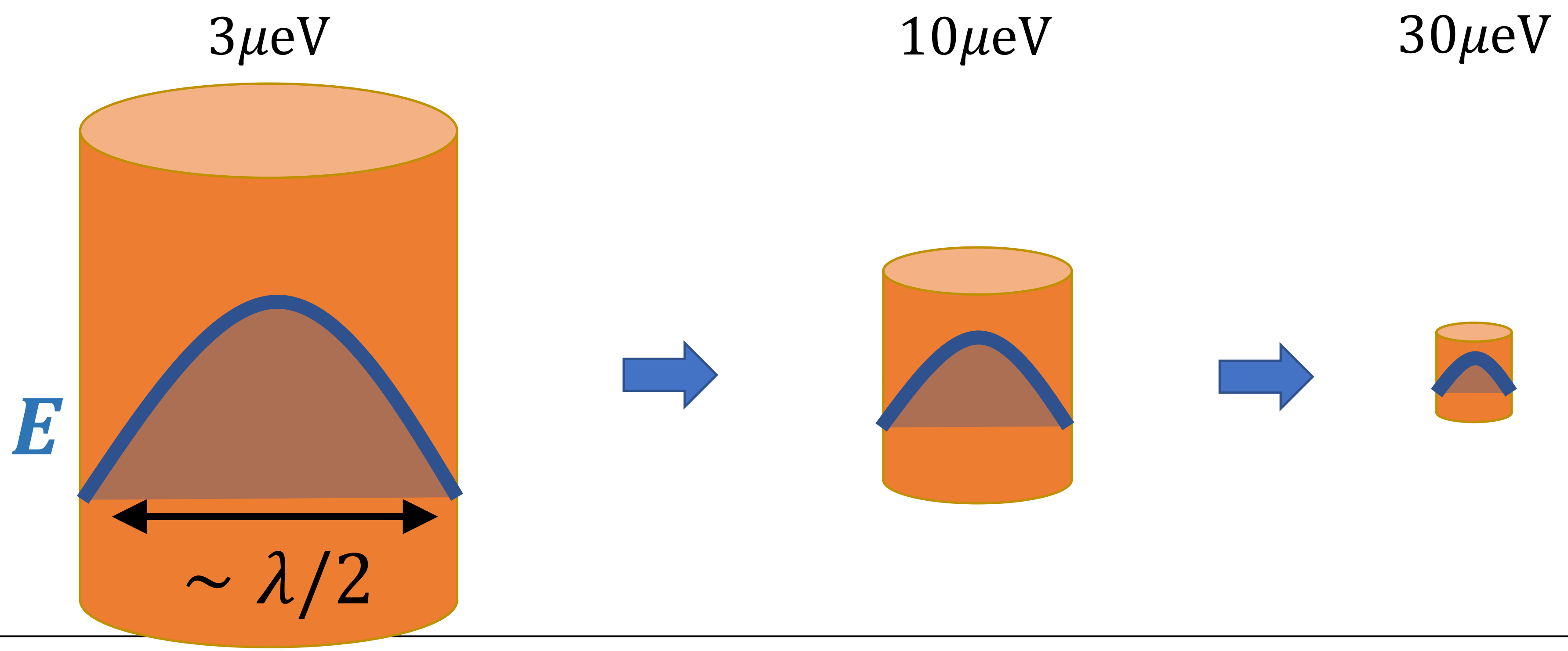
The Resonant Cavity – High Masses

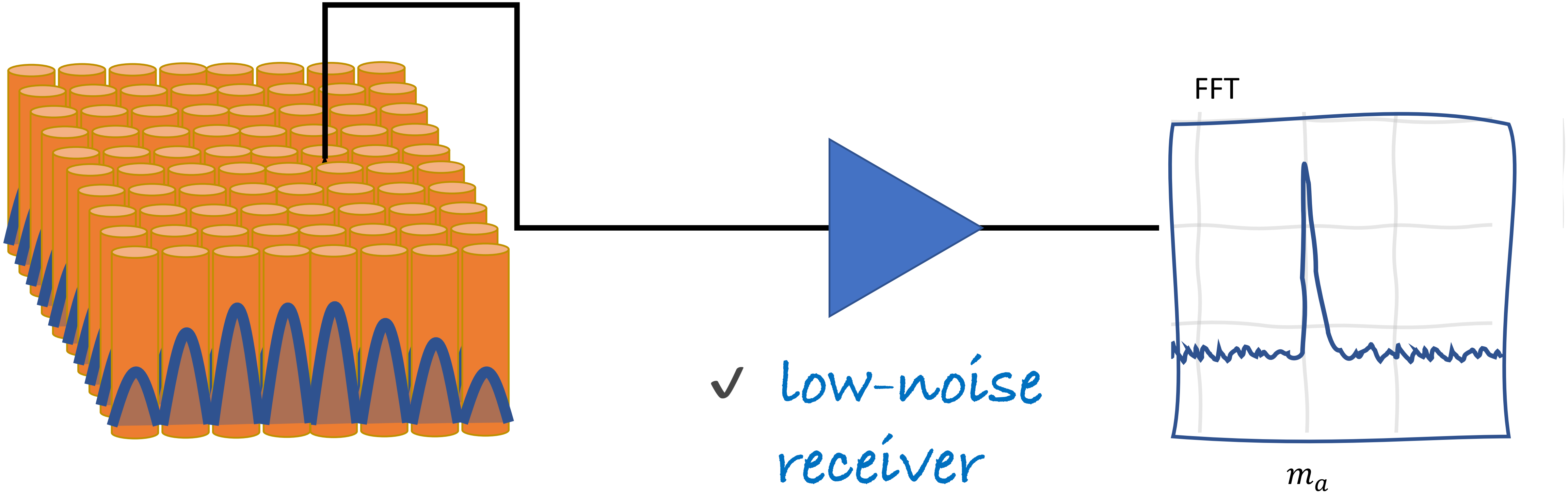


V	100ℓ	3ℓ	0.1ℓ
$Q \propto V/\delta V$	30,000	10,000	3,000

$$P_{\text{sig}} = 2 \cdot 10^{-23}\ \text{W} \cdot \left(\frac{B}{7.6\ \text{T}}\right)^2 \left(\frac{V}{136\ \ell}\right)\left(\frac{C}{0.4}\right)\left(\frac{Q}{30{,}000}\right)\left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{m_a}{3\ \mu\text{eV}}\right)\left(\frac{\rho_{\text{DM}}}{0.45\ \text{GeV cm}^{-3}}\right)$$

The Resonant Cavity

✓ high-Q resonator

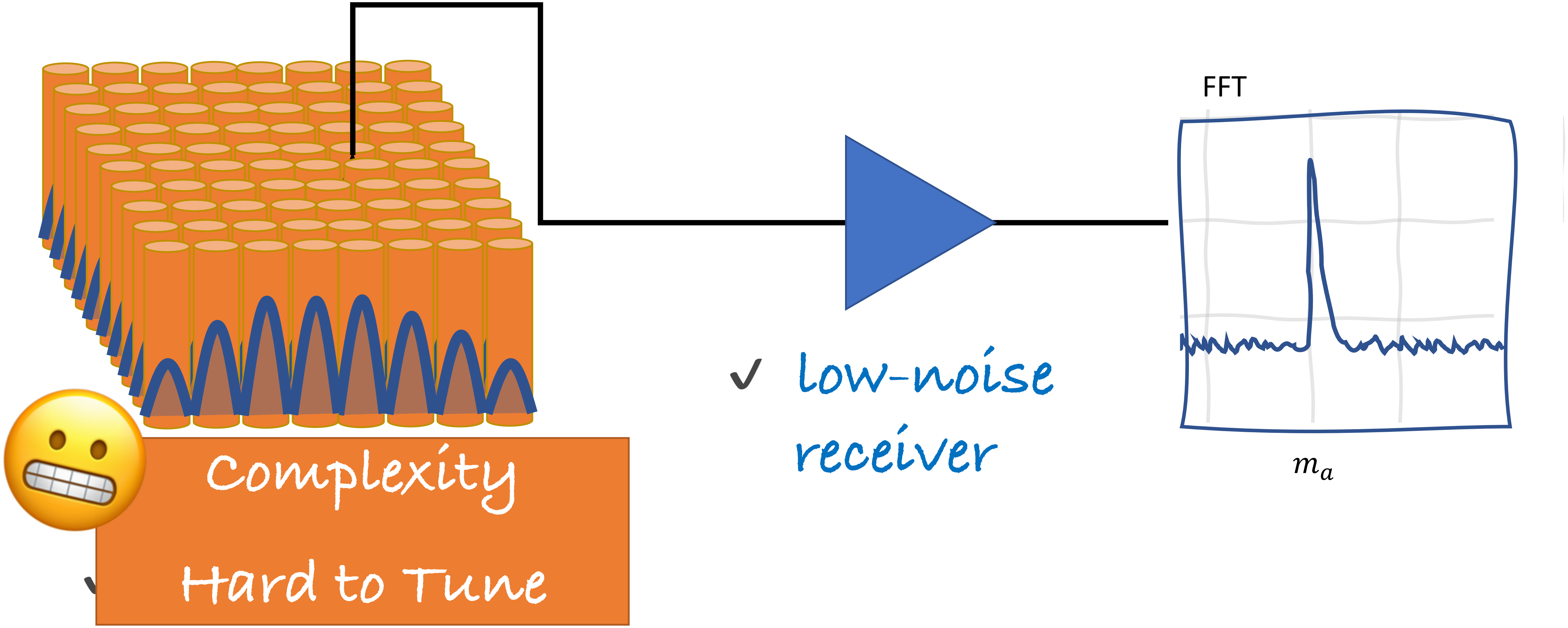


✓ low-noise receiver

✓ high B-field

The Resonant Cavity

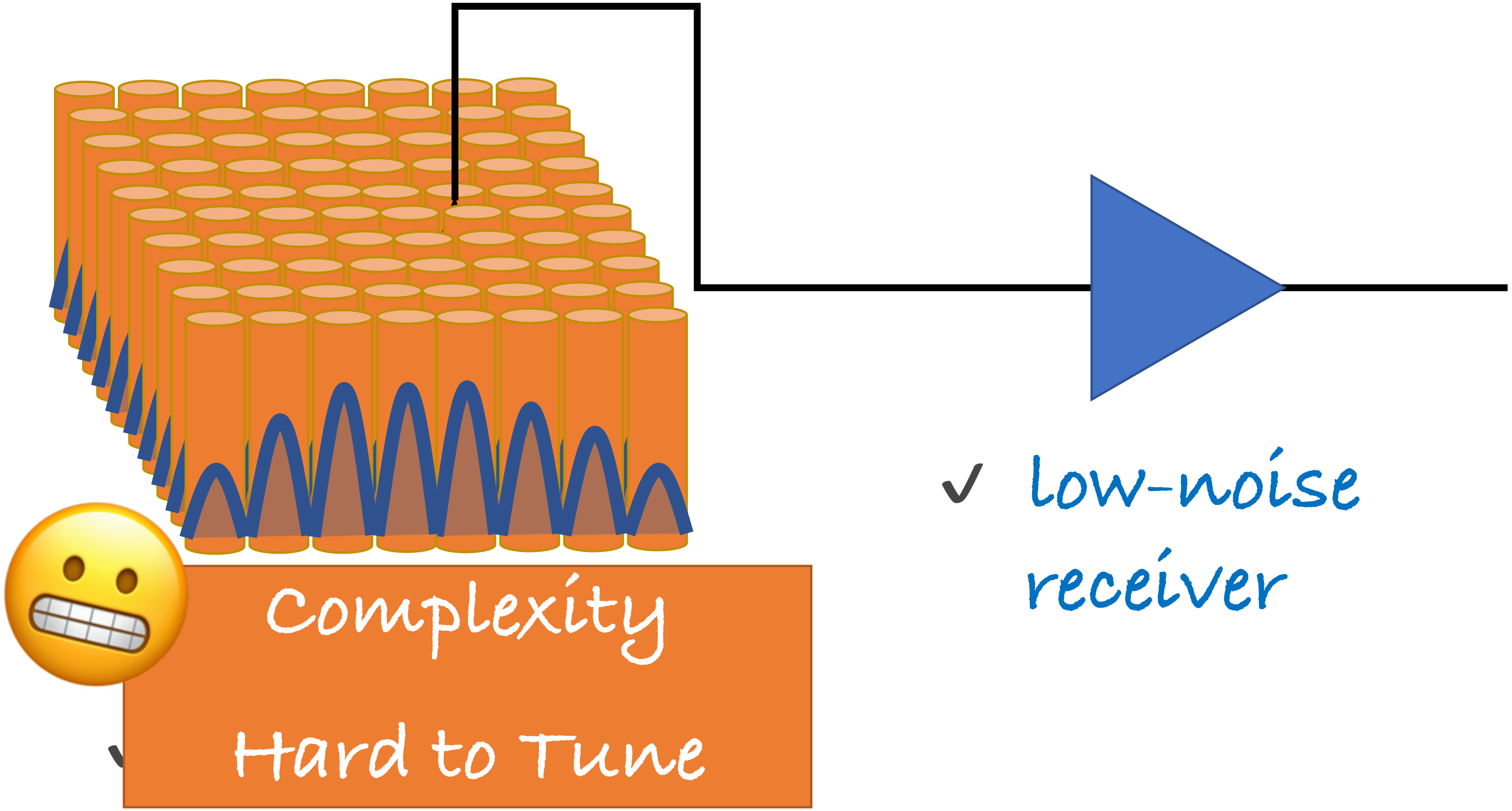
✓ high-Q resonator



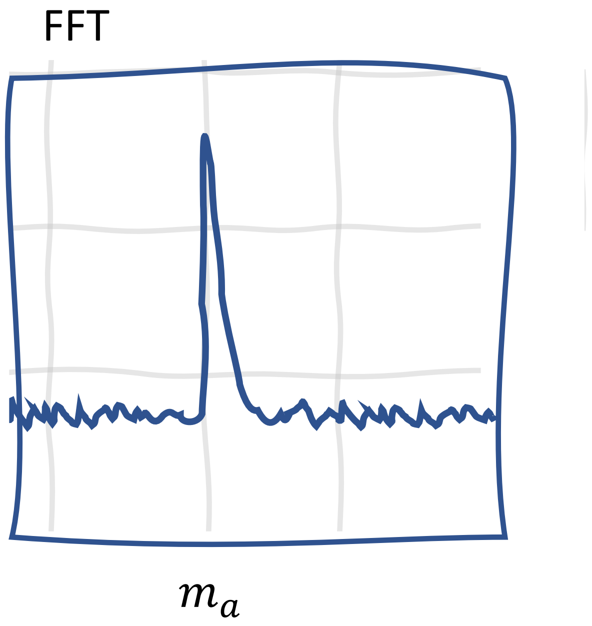
✓ low-noise receiver

The Resonant Cavity

✓ ~~high-Q resonator~~



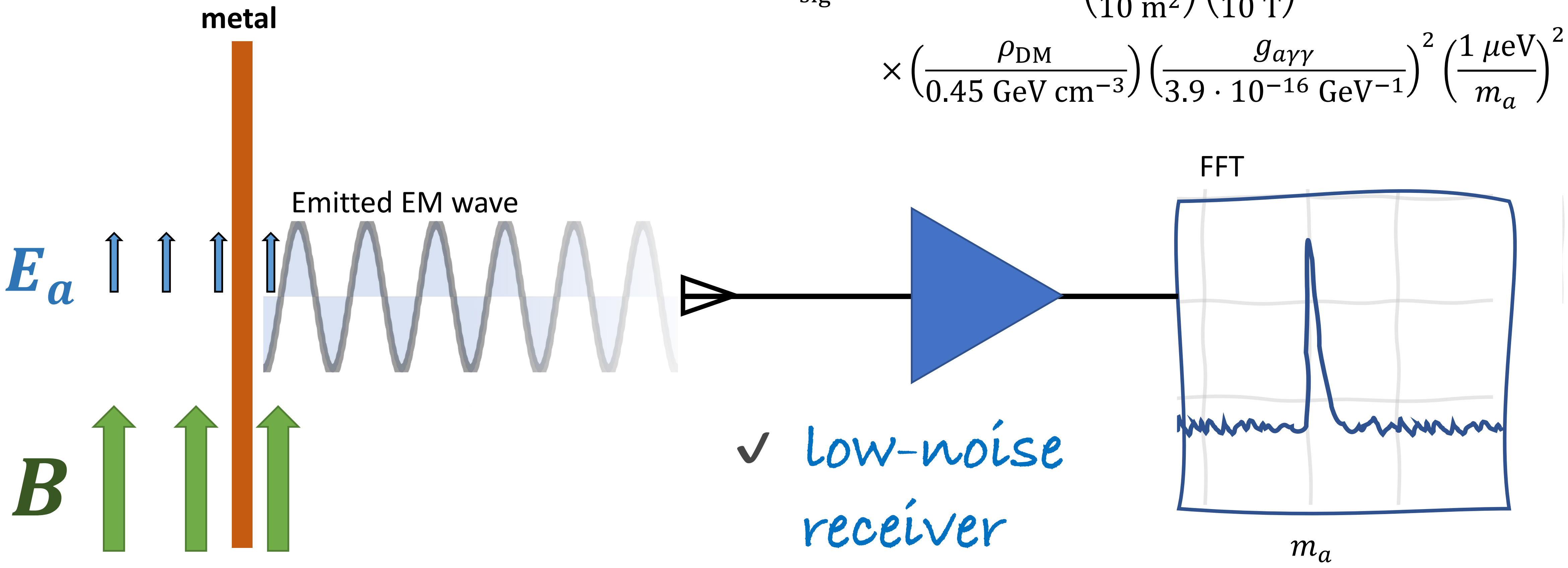
✓ low-noise receiver



Dish Antenna

✓ "dish antenna"
[Horns et al, arXiv:1212.2970]

$$P_{\mathrm{sig}} = 1.2 \cdot 10^{-25}\,\mathrm{W} \cdot \left(\frac{A}{10\ \mathrm{m}^2}\right)\left(\frac{B_{\parallel}}{10\ \mathrm{T}}\right)^2 \times \left(\frac{\rho_{\mathrm{DM}}}{0.45\ \mathrm{GeV\ cm}^{-3}}\right)\left(\frac{g_{a\gamma\gamma}}{3.9 \cdot 10^{-16}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{1\ \mu\mathrm{eV}}{m_a}\right)^2$$



✓ low-noise receiver

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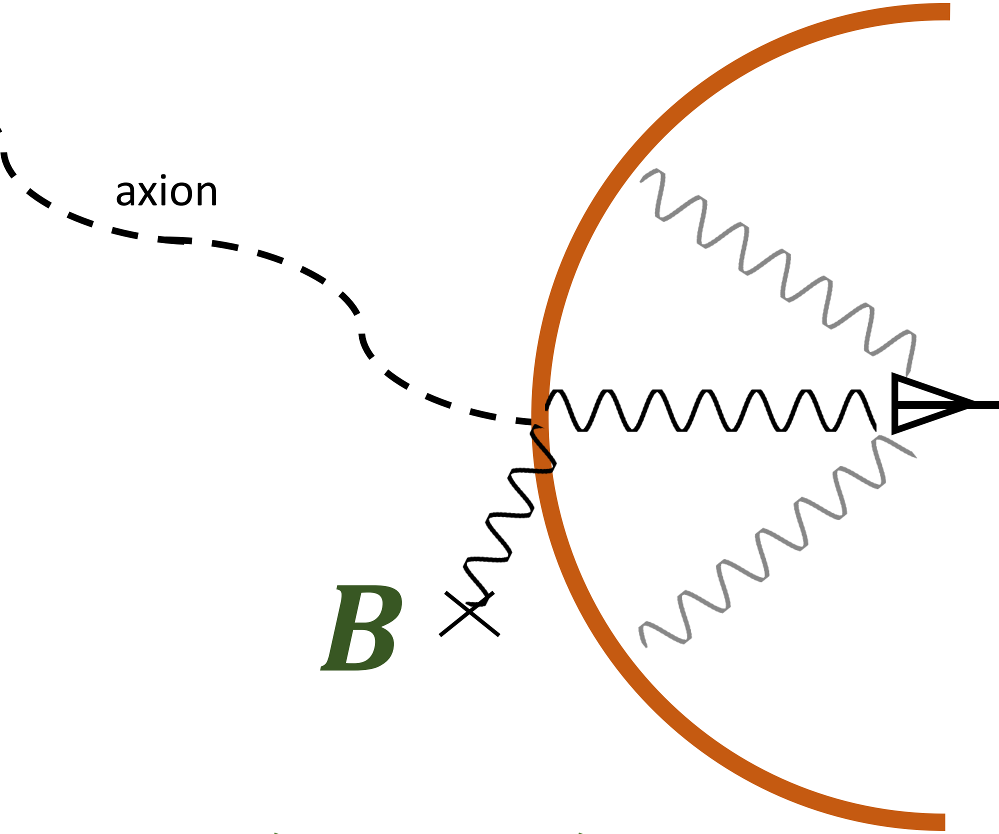

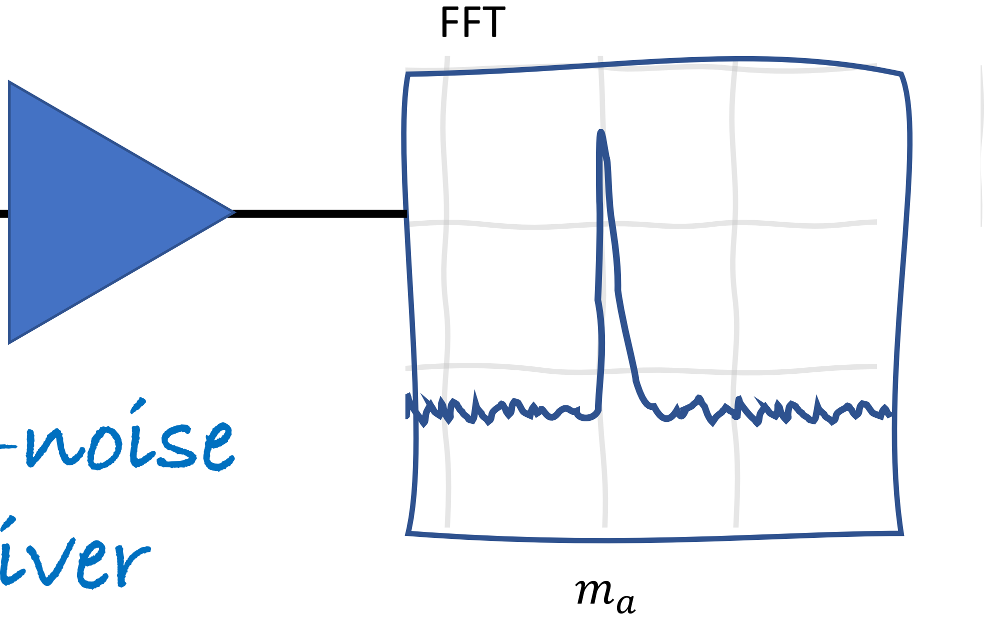

✔ low-noise receiver

✔ high B-field

✅ broadband

Dish Antenna

✔ "dish antenna"
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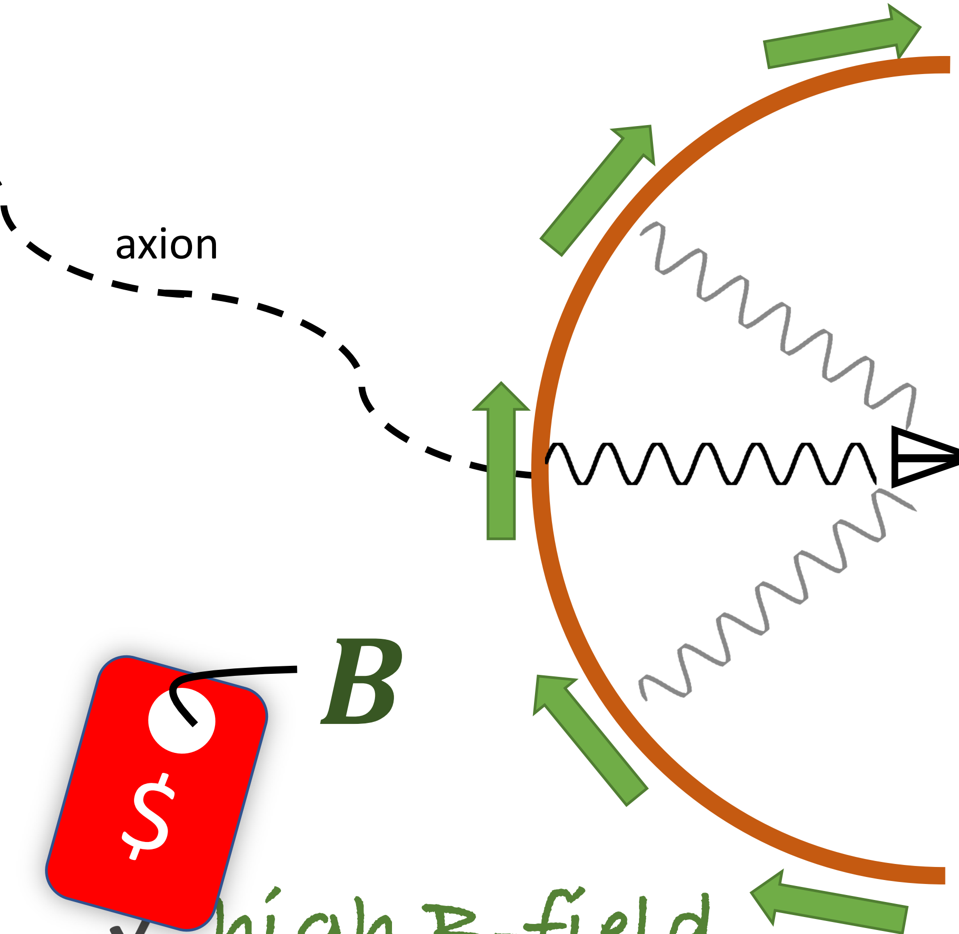
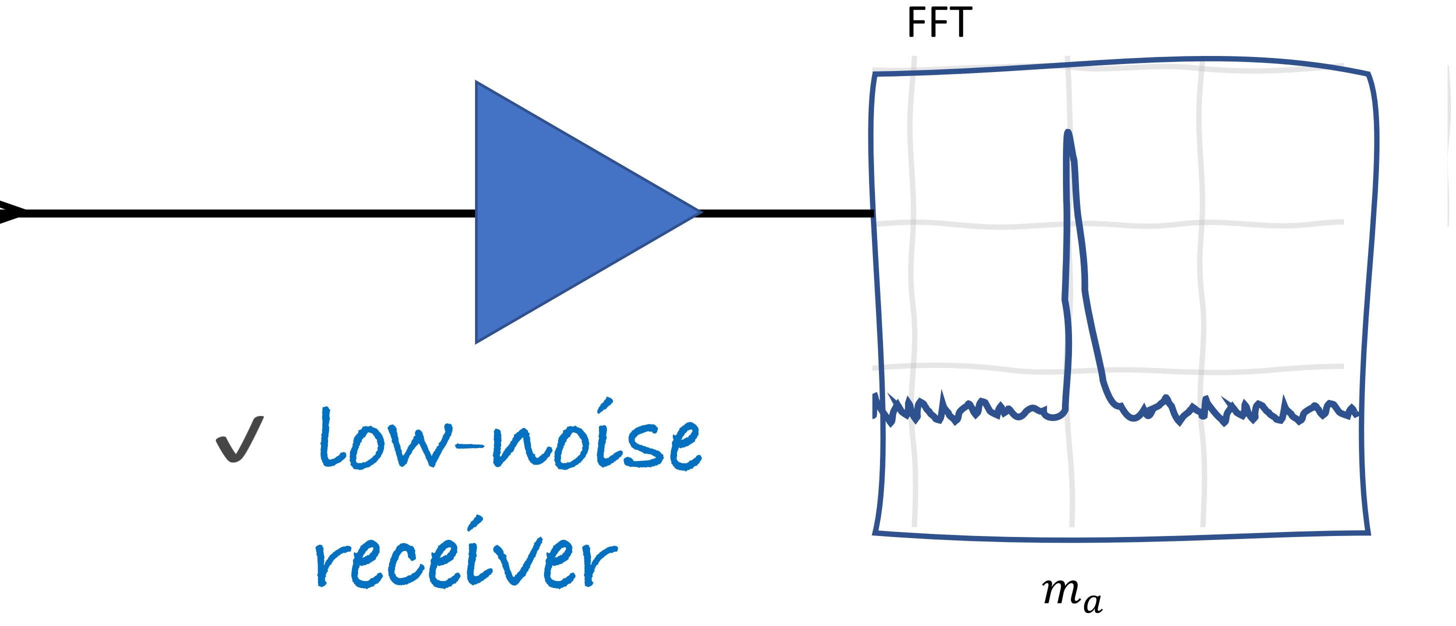
$$P_{\text{sig}} = 1.2 \cdot 10^{-25}\ \text{W} \cdot \left(\frac{A}{10\ \text{m}^2}\right)\left(\frac{B_\parallel}{10\ \text{T}}\right)^2$$
$$\times \left(\frac{\rho_{\text{DM}}}{0.45\ \text{GeV cm}^{-3}}\right)\left(\frac{g_{a\gamma\gamma}}{3.9 \cdot 10^{-16}\ \text{GeV}^{-1}}\right)^2 \left(\frac{1\ \mu\text{eV}}{m_a}\right)^2$$





✔ low-noise receiver

✔ high B-field

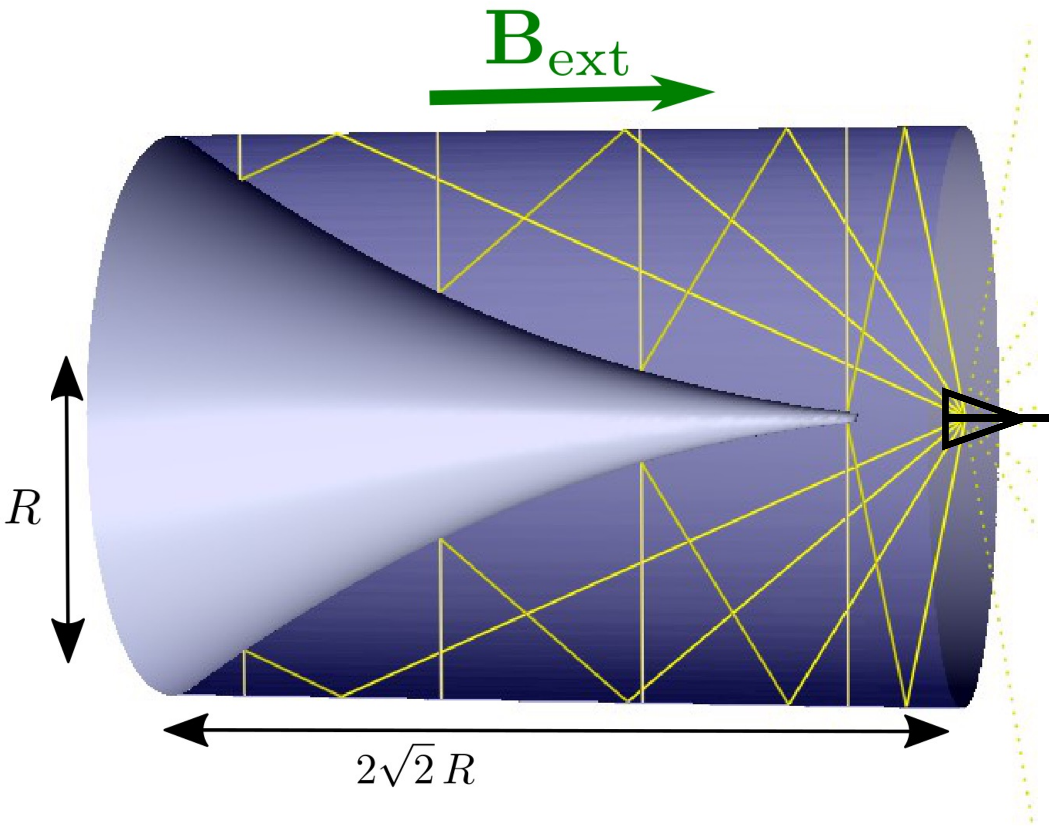
✅ broadband

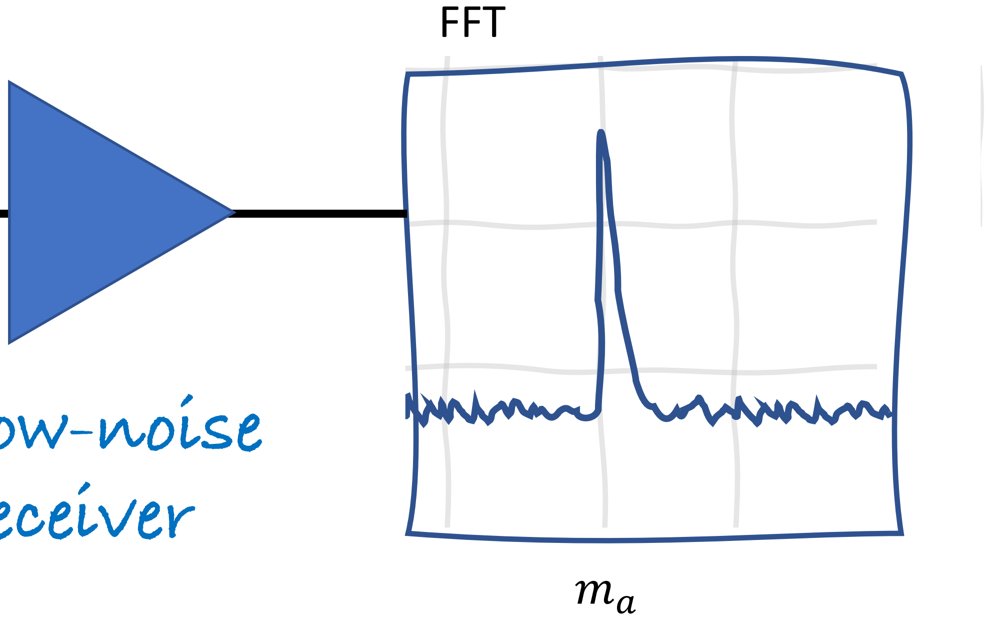
BREAD (Broadband Reflector Experiment for Axion Detection)

BREAD

✓ "coaxial dish antenna"

$$P_{\text{sig}} = 1.2 \cdot 10^{-25}\,\text{W} \cdot \left(\frac{A}{10\,\text{m}^2}\right)\left(\frac{B_{\parallel}}{10\,\text{T}}\right)^2 \times \left(\frac{\rho_{\text{DM}}}{0.45\,\text{GeV cm}^{-3}}\right)\left(\frac{g_{a\gamma\gamma}}{3.9\cdot 10^{-16}\,\text{GeV}^{-1}}\right)^2 \left(\frac{1\,\mu\text{eV}}{m_a}\right)^2$$





✓ low-noise receiver

allows usage of solenoid magnet, e.g., MRI

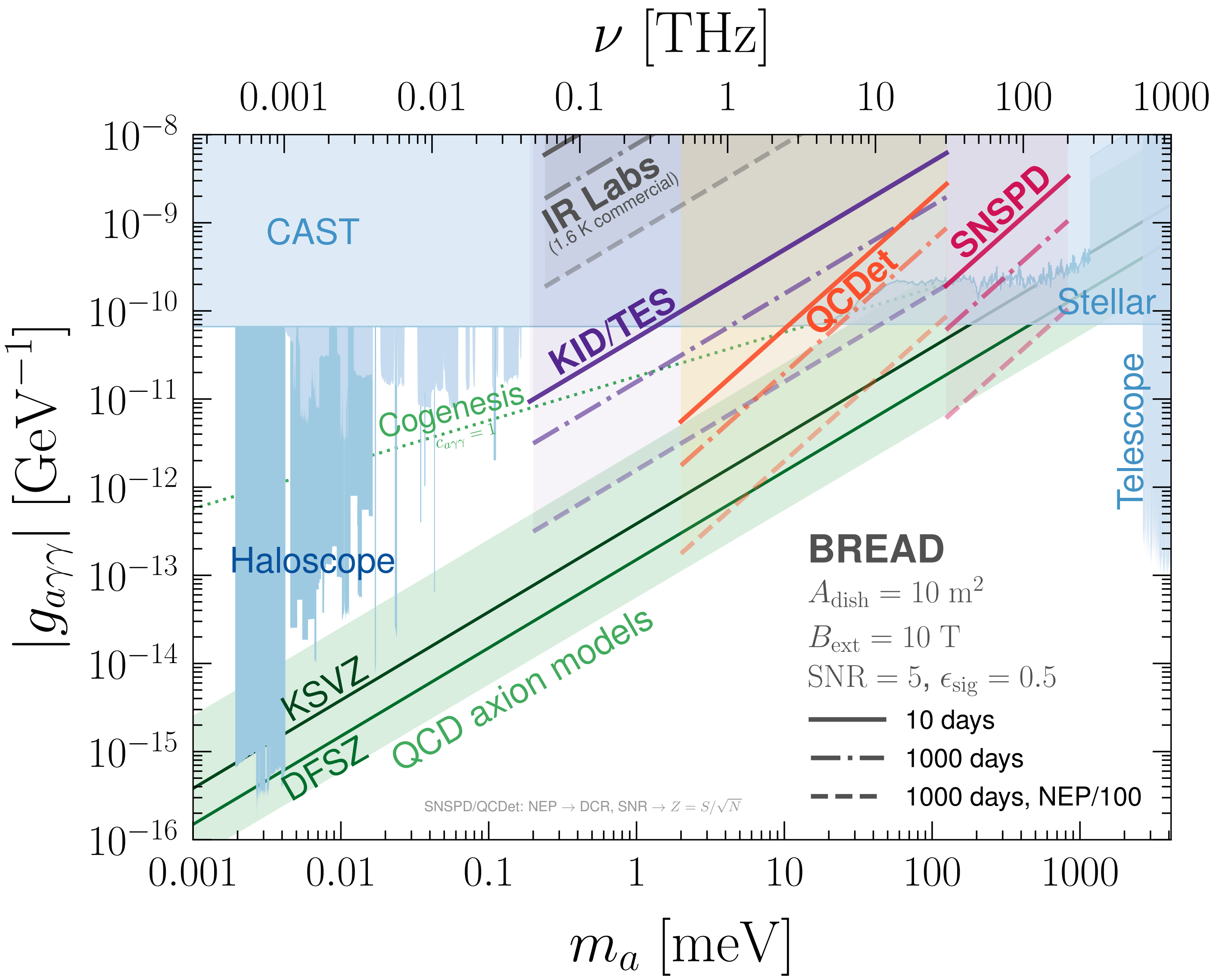
THz Quantum Sensors in Literature

[Liu *et al*, BREAD collab., arXiv:2111.12103, PRL 128 (2022) 131801]

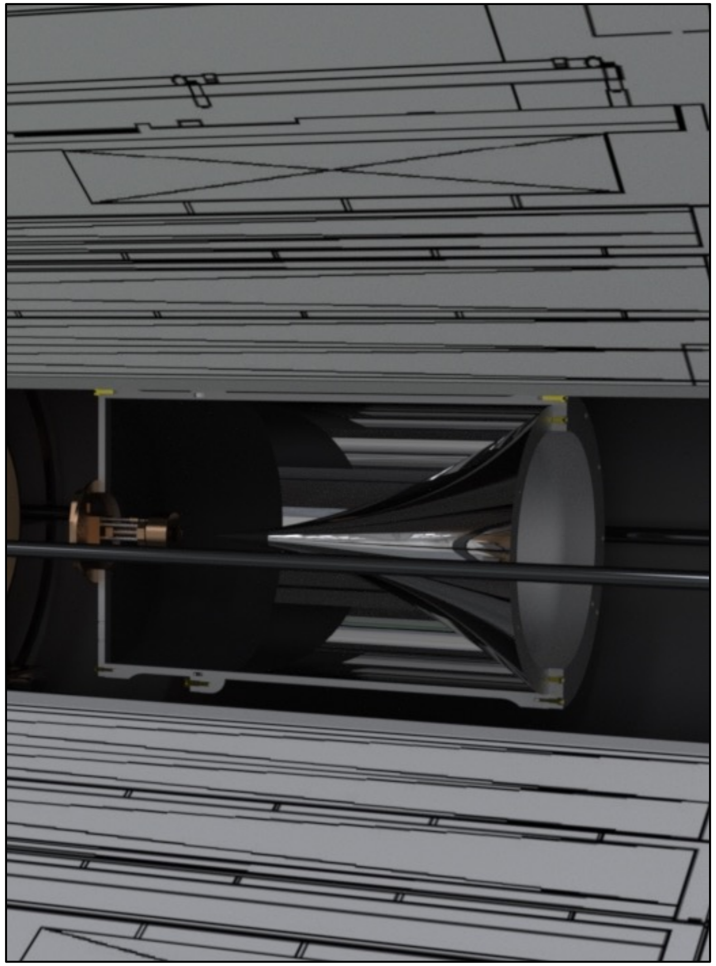
Photosensor	$\frac{E}{\mathrm{meV}}$	$\frac{T_{\mathrm{op}}}{\mathrm{K}}$	$\frac{\mathrm{NEP}}{\mathrm{W}/\sqrt{\mathrm{Hz}}}$	$\frac{A_{\mathrm{sens}}}{\mathrm{mm}^2}$	
Bolometers					
GENTEC	[0.4, 120]	293	$1 \cdot 10^{-8}$	$\pi 2.5^2$	[https://www.gentec-eo.com/]
IR LABS	[0.24, 248]	1.6	$5 \cdot 10^{-14}$	1.5^2	[https://www.irlabs.com/products/bolometers/]
KID/TES	[0.2, 125]	0.3	$2 \cdot 10^{-19}$	0.2^2	[Ridder *et al*, J. Low Temp. Phys. 184, 60–65 (2016)], [Baselmans *et al*, Astro. Astroph. 601, A89 (2017)]
Single Photon Counters					
QCDet	[2, 125]	0.015	$\frac{\mathrm{DCR}}{\mathrm{Hz}} = 4$	0.06^2	[Echternach *et al.*, Nat. Astron. 2, 90–97 (2018)], [Echternach *et al.*, J. Astron. Telesc. Instrum. Syst. 7, 1–8 (2021)]
SNSPD	[124, 830]	0.3	$\frac{\mathrm{DCR}}{\mathrm{Hz}} = 10^{-4}$	0.4^2	[Hochberg, et al., Phys. Rev. Lett. 123, 151802 (2019)] [Verma, *et al.*, arXiv:2012.09979 [physics.ins-det] (2020)]

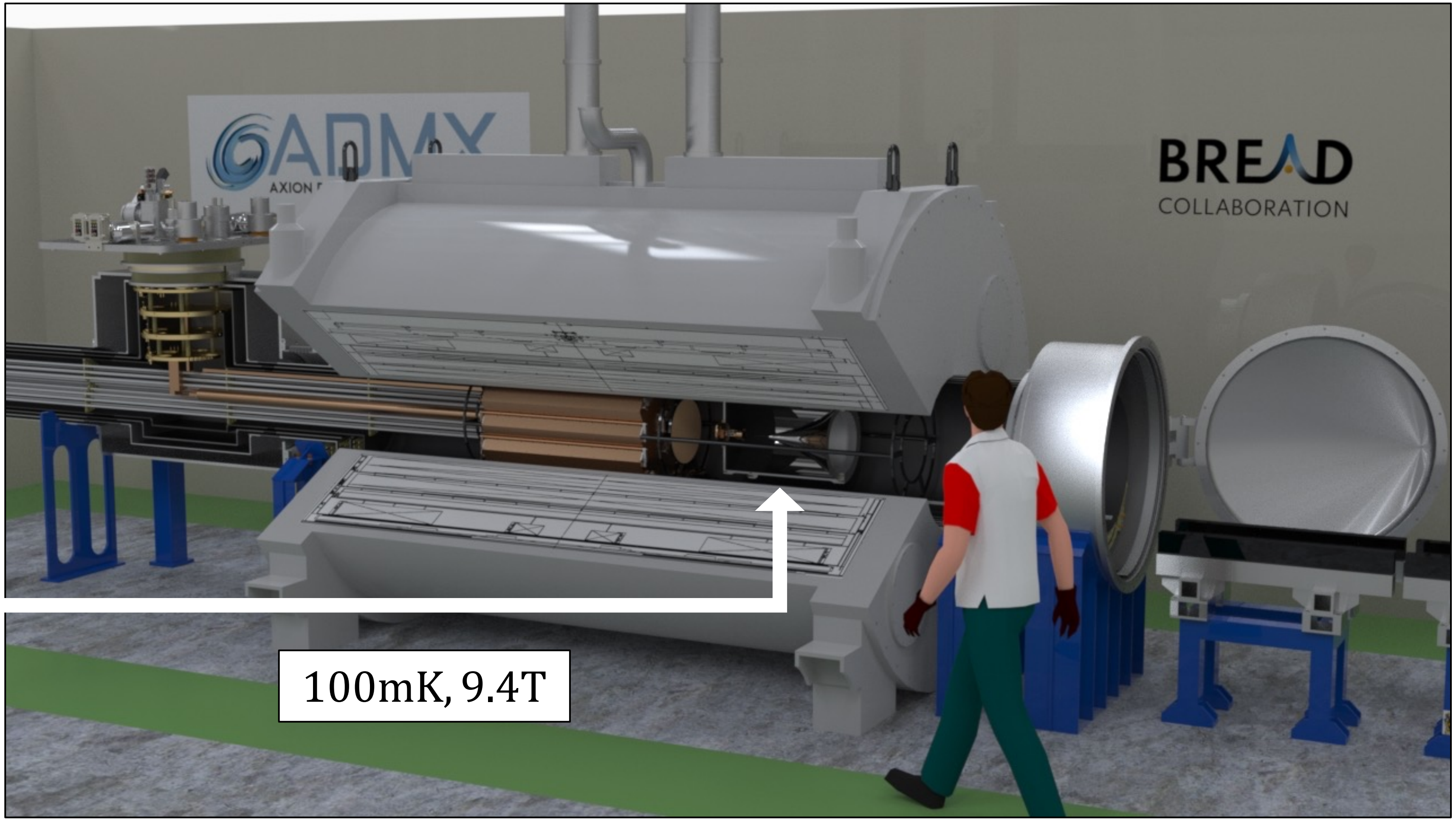
Sensitivity

[Liu *et al*, BREAD collab., arXiv:2111.12103, PRL 128 (2022) 131801]

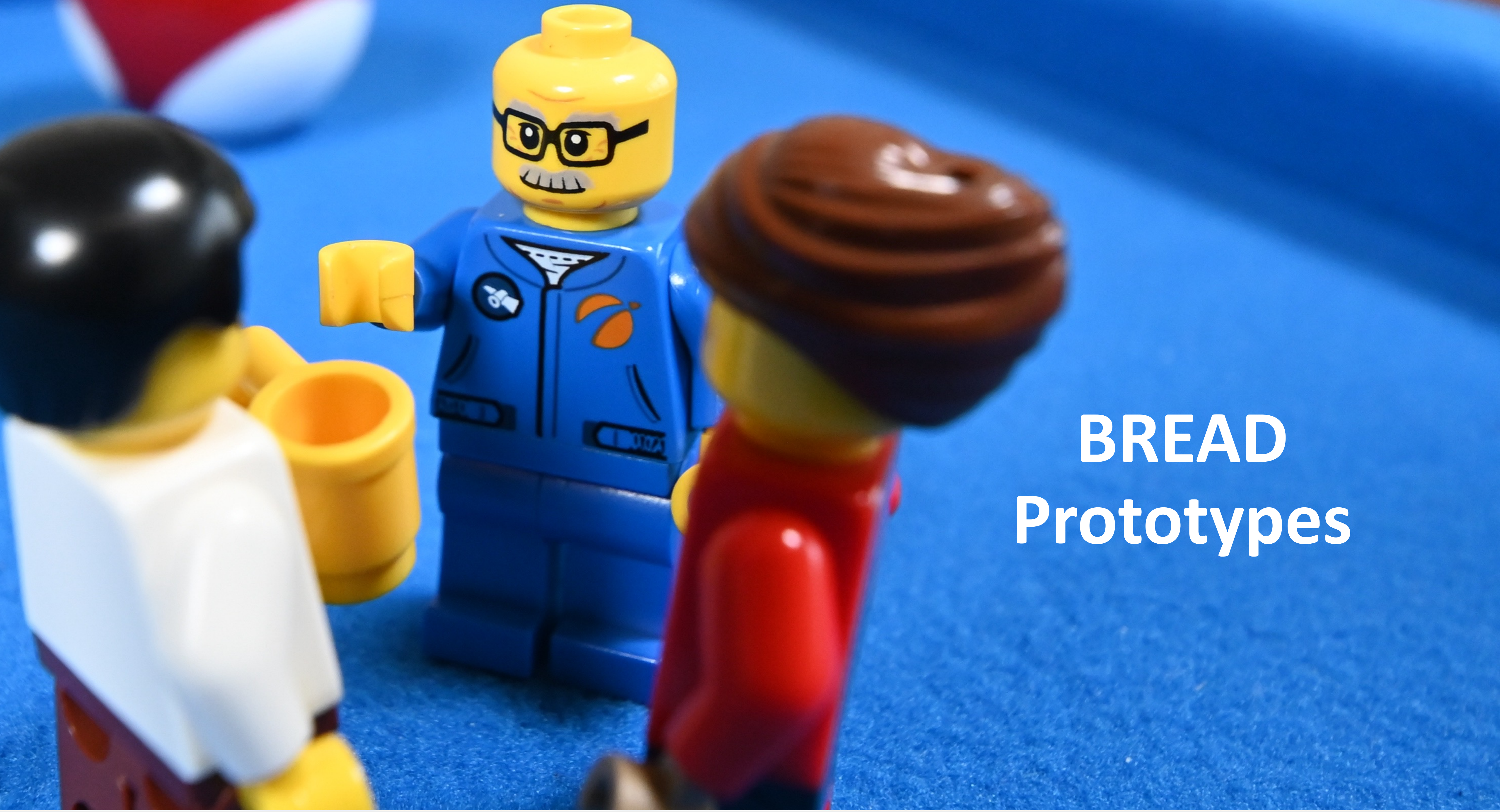


Vision: Large-Scale BREAD



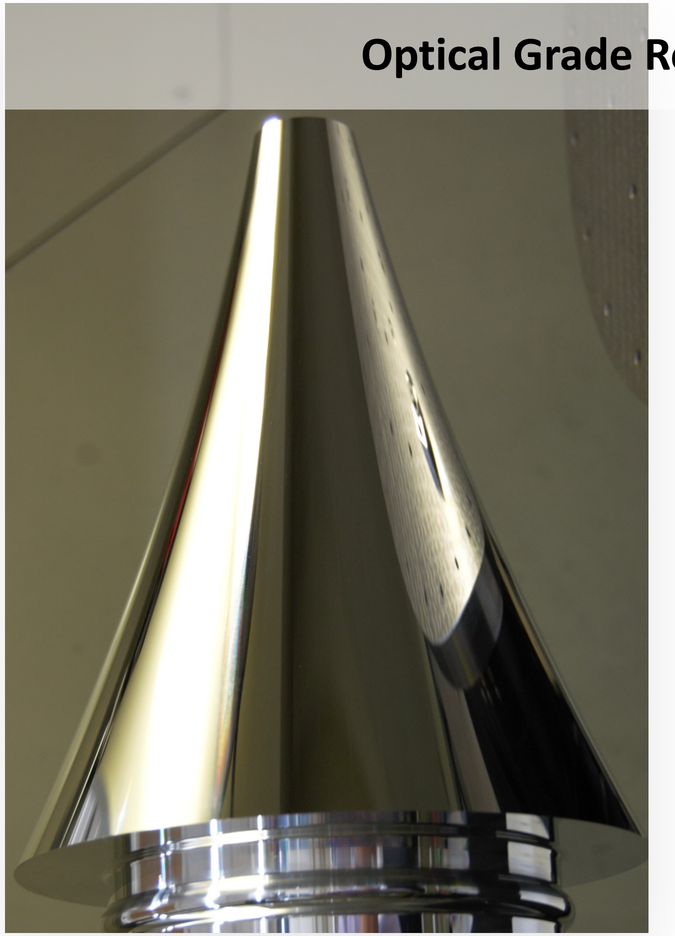


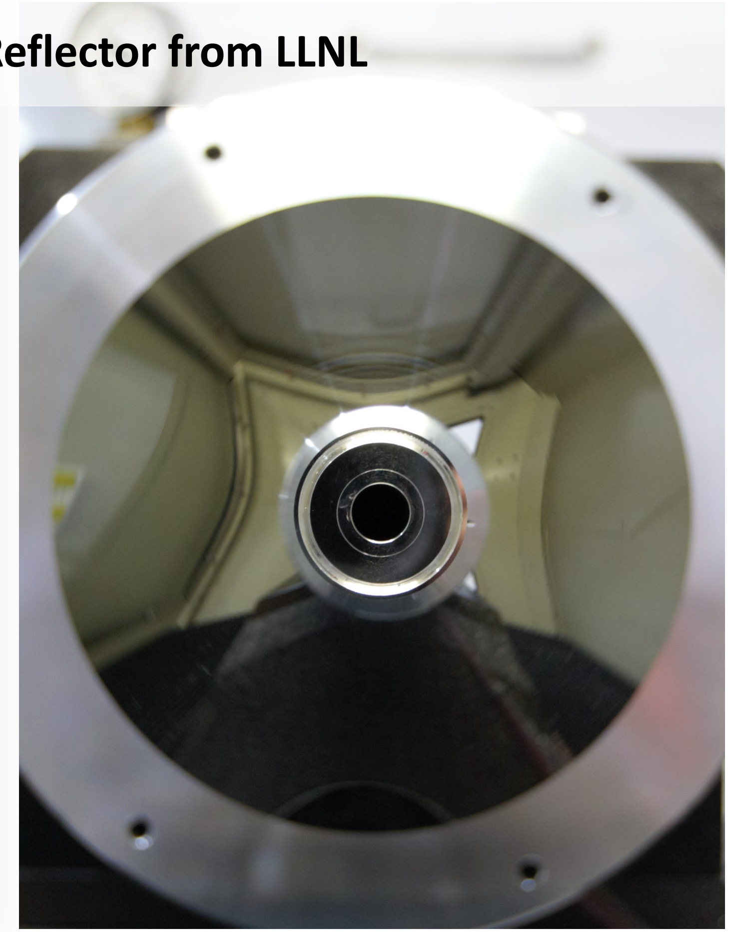
possible larger-scale version as side-experiment to ADMX-EFR at Fermilab



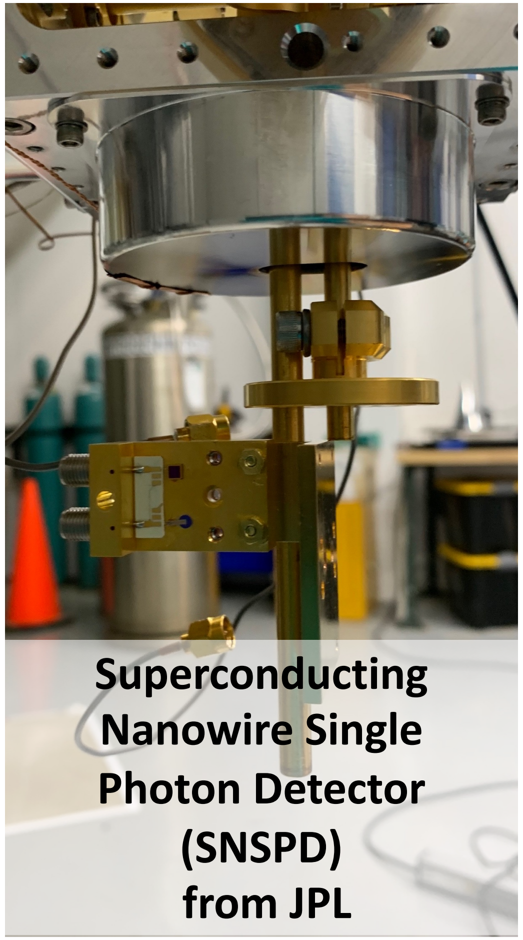
BREAD Prototypes

InfraBREAD Pilot

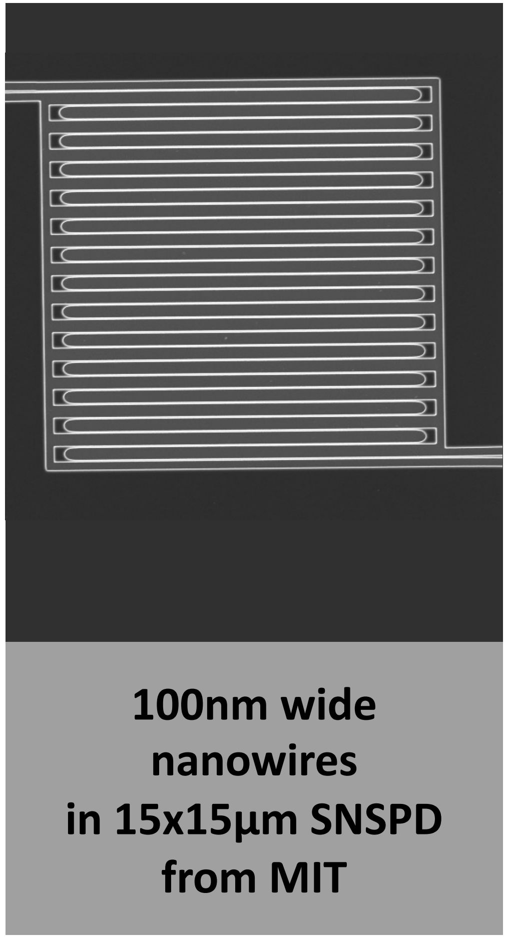




Optical Grade Reflector from LLNL



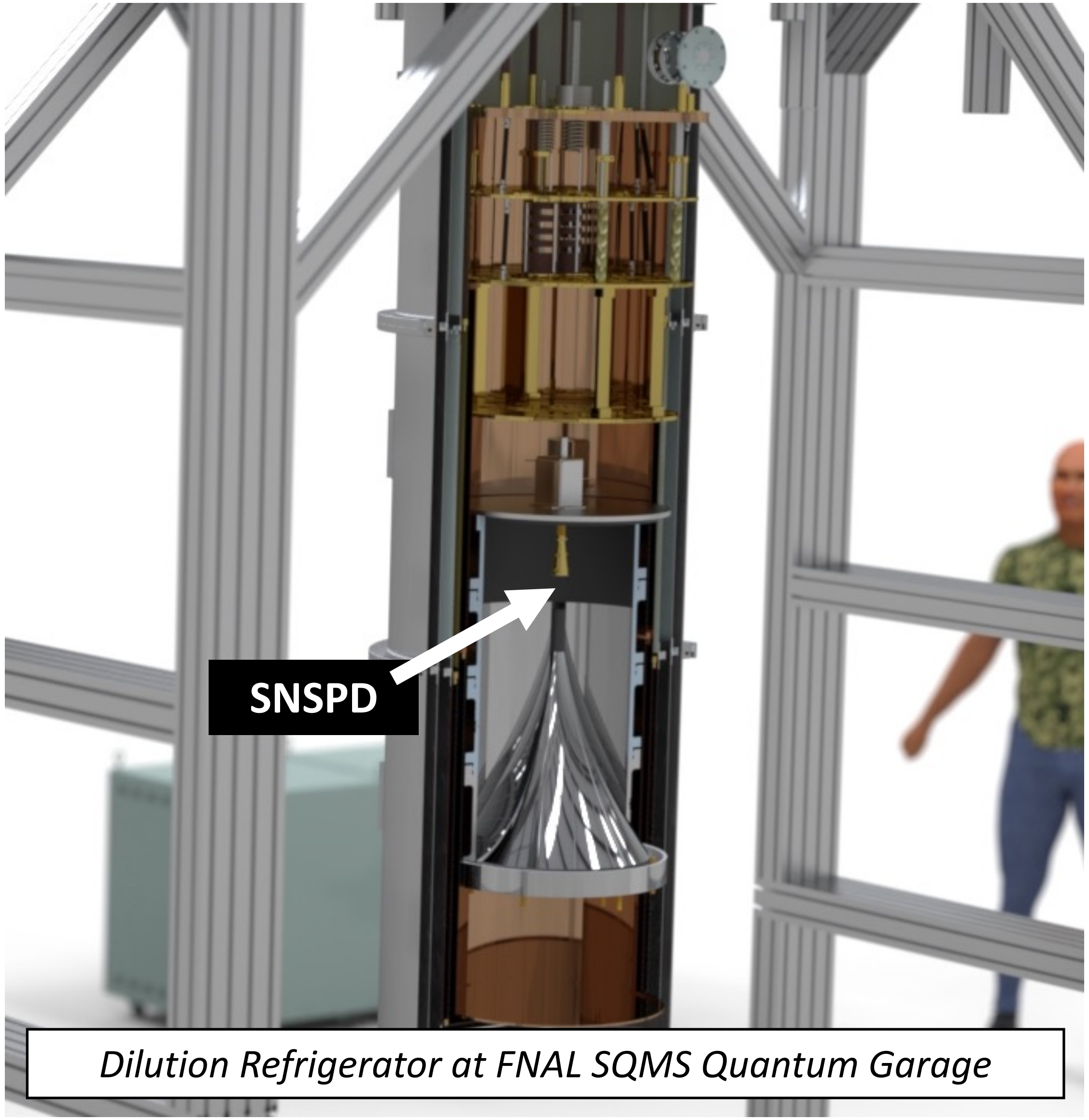
Superconducting Nanowire Single Photon Detector (SNSPD) from JPL



100nm wide nanowires in 15x15µm SNSPD from MIT

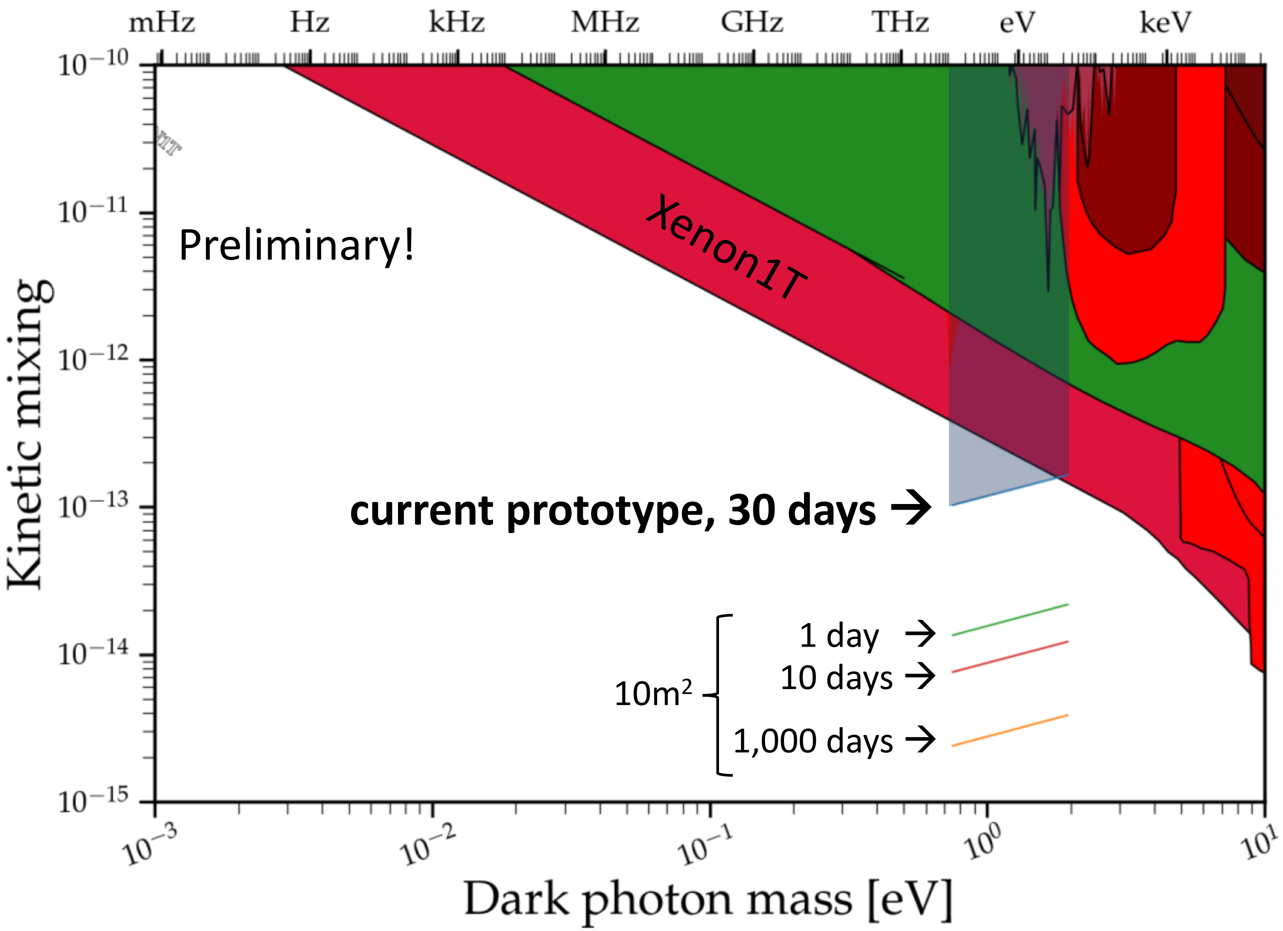
will enable cryogenic dark photon search at infrared (eV)

InfraBREAD Pilot

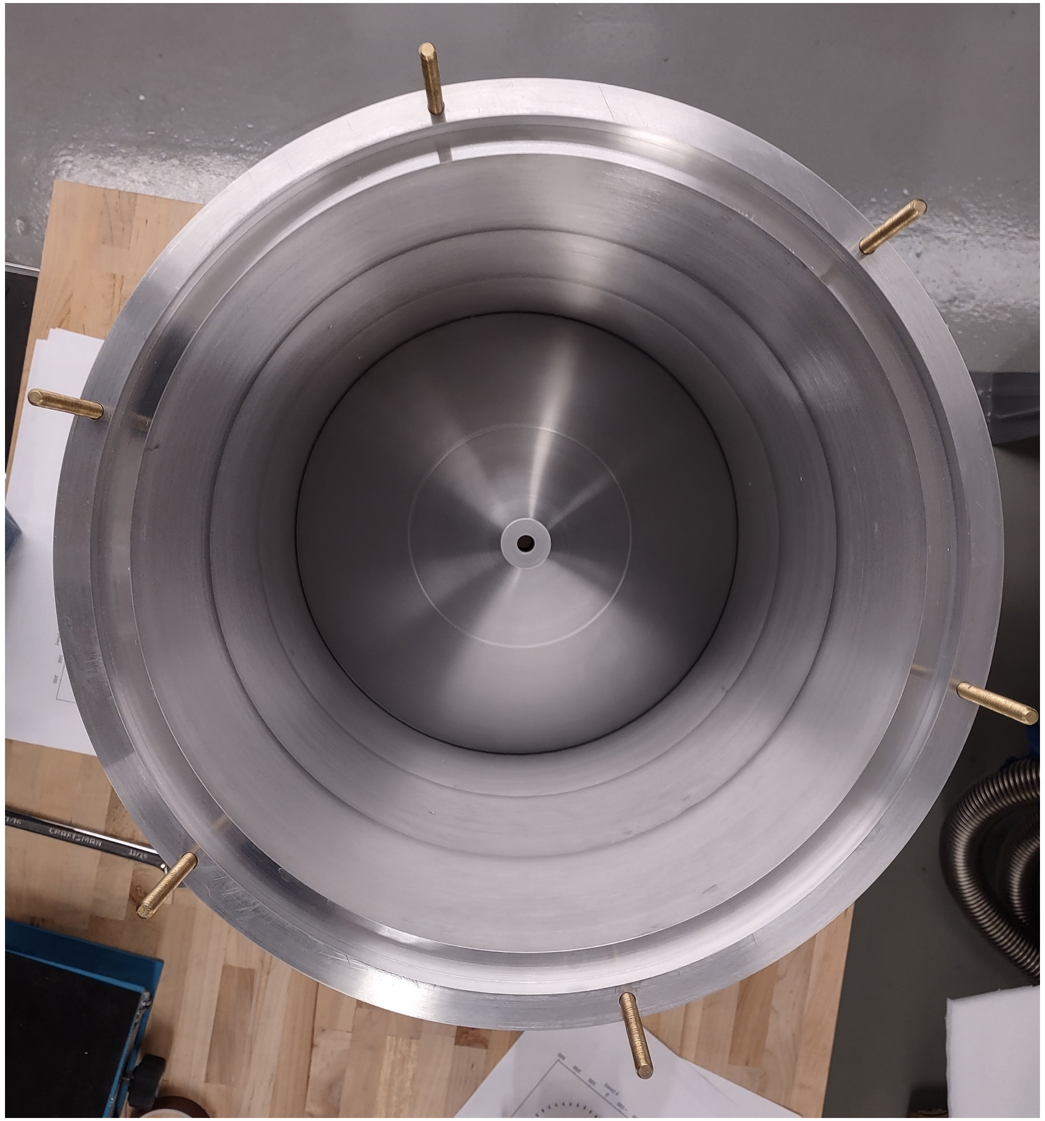


Dilution Refrigerator at FNAL SQMS Quantum Garage

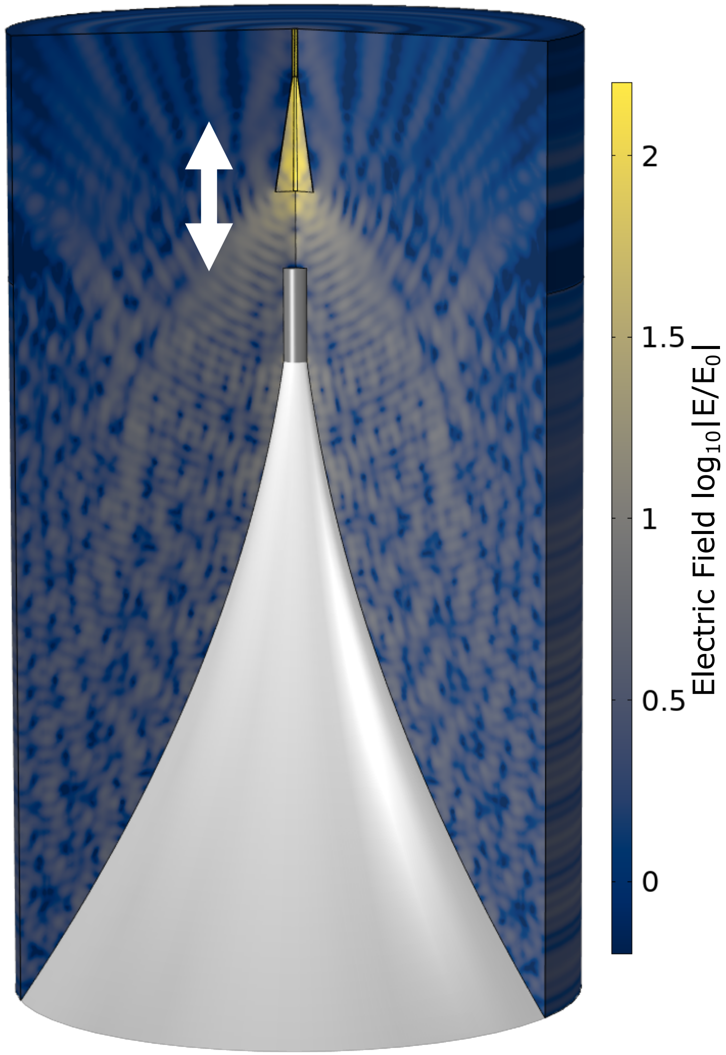
Hidden Photon Sensitivity Projection

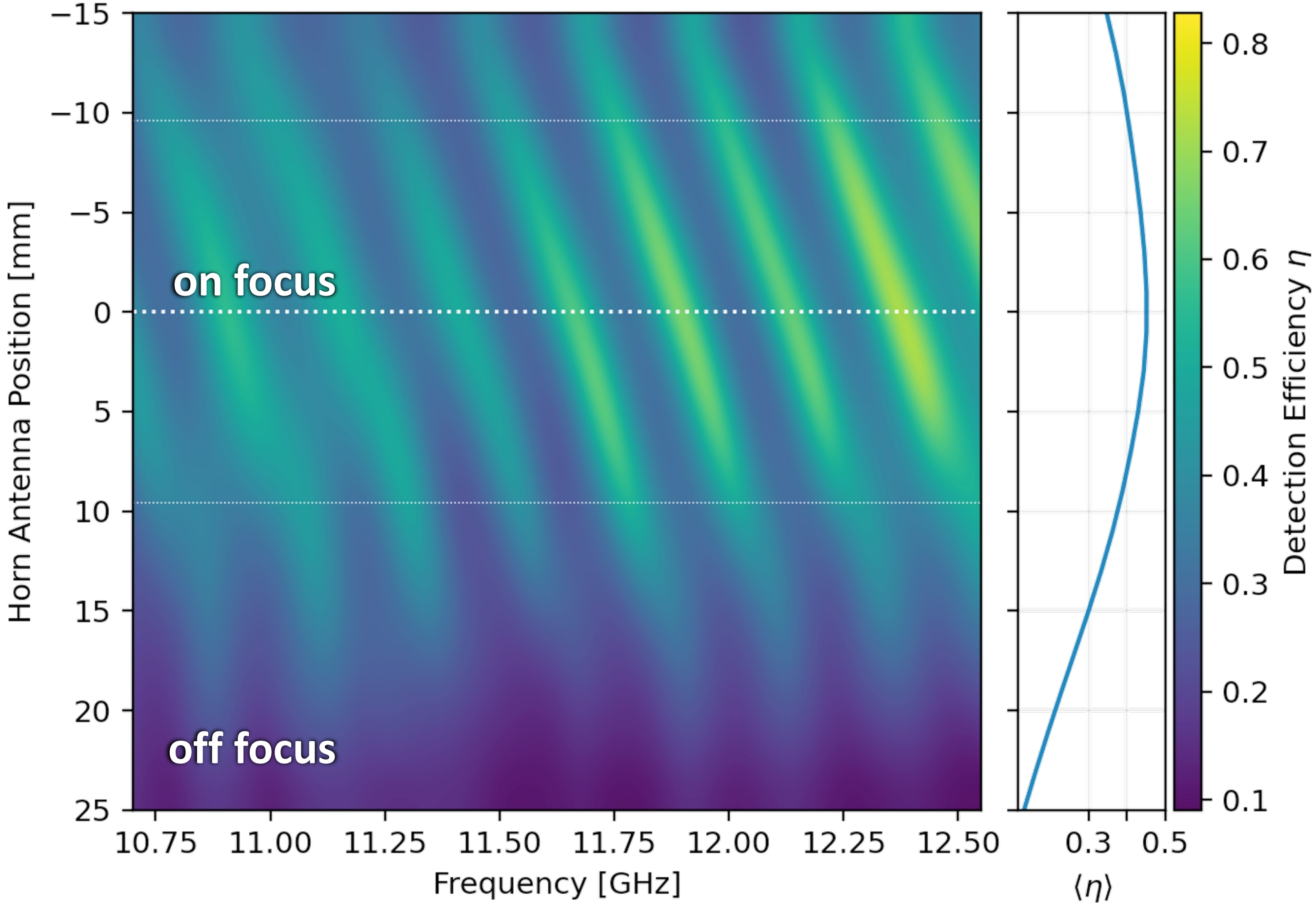


GigaBREAD Pilot: 10-14 GHz (50μeV)



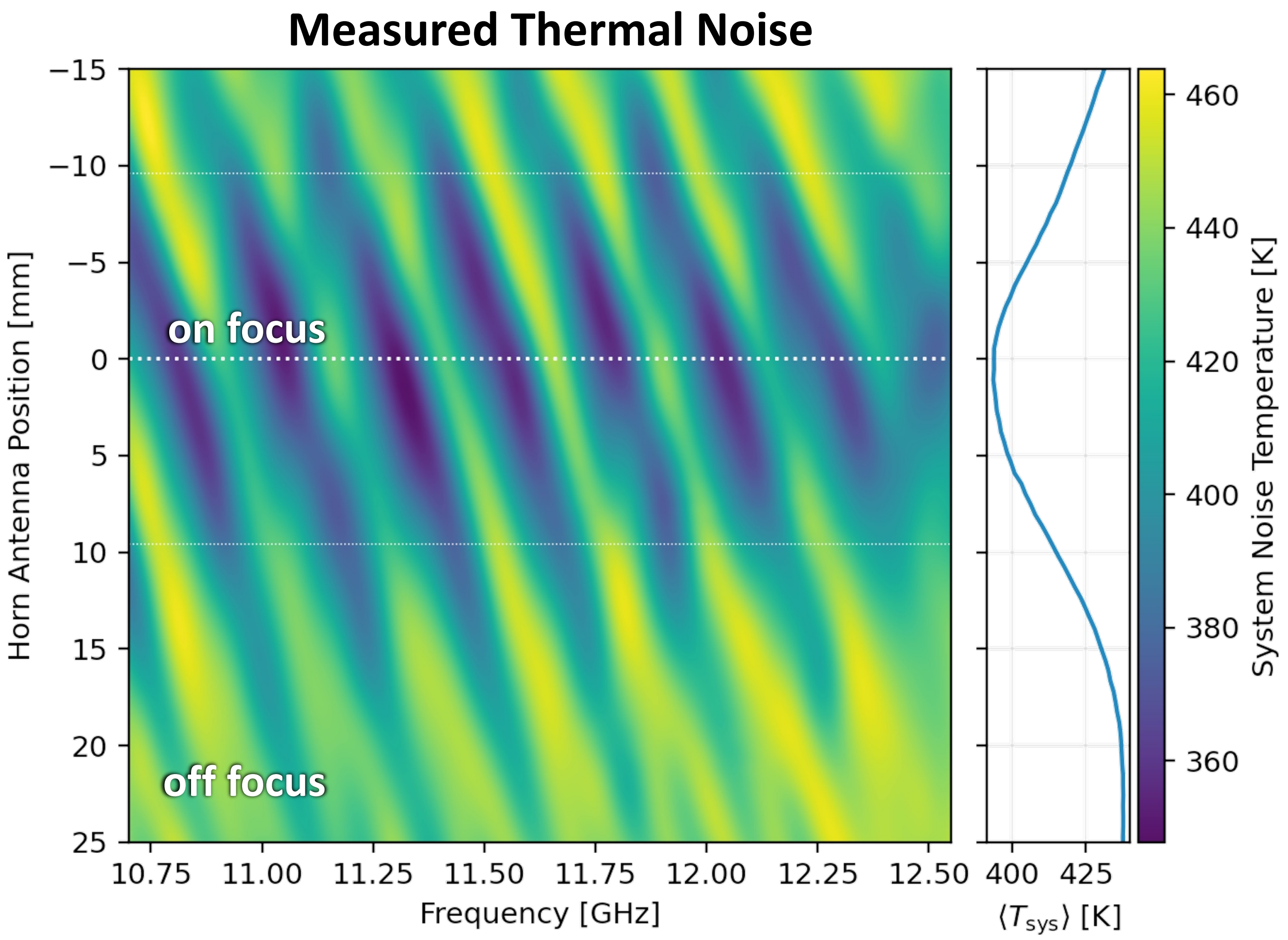
RF Simulation





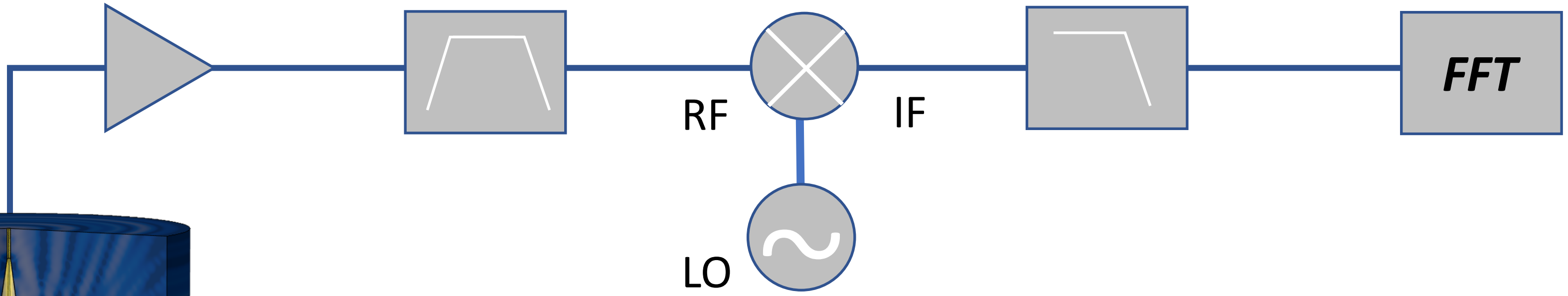
signal suppressed away from focus

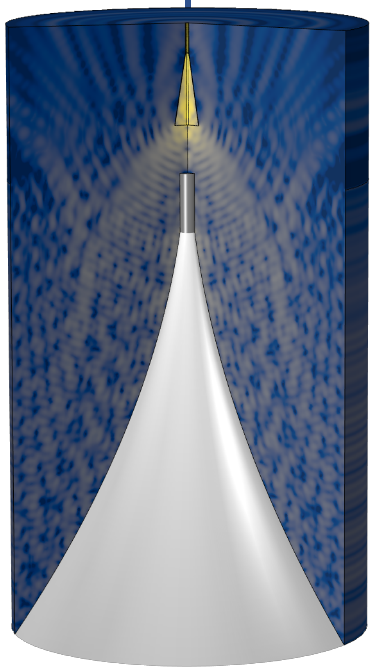
Reflector Characterization Measurement



see focus & resonances

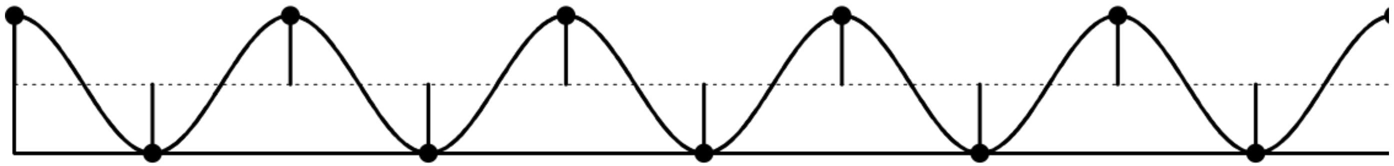
Broadband DAQ





signal bandwidth
(10.7 - 12.5) GHz

Nyquist: Min. Sample Rate = 2 × Bandwidth



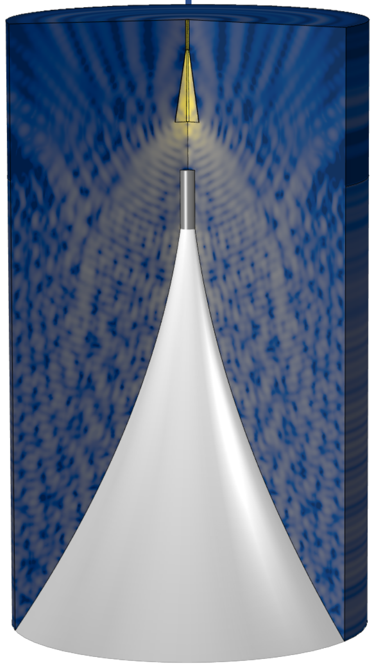
[https://commons.wikimedia.org/wiki/File:Nyquist_Aliasing.svg]

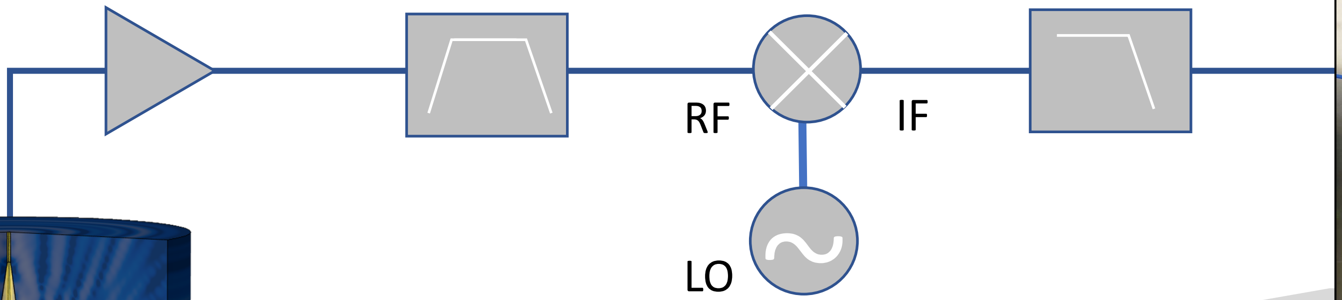
$\sim 2\ \mathrm{GHz}$ bandwidth → $4\ \mathrm{GB/s}$

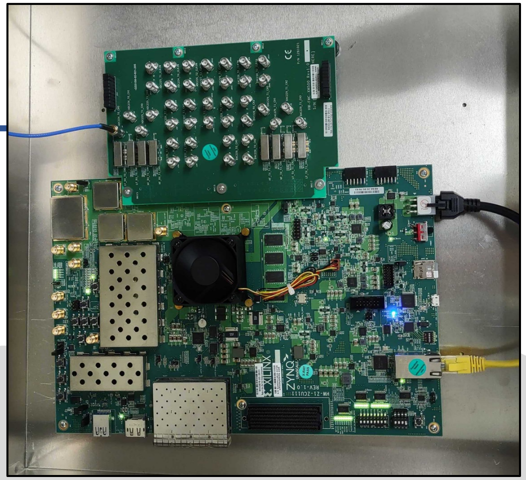
Challenge: Real-Time Data Reduction

Broadband DAQ

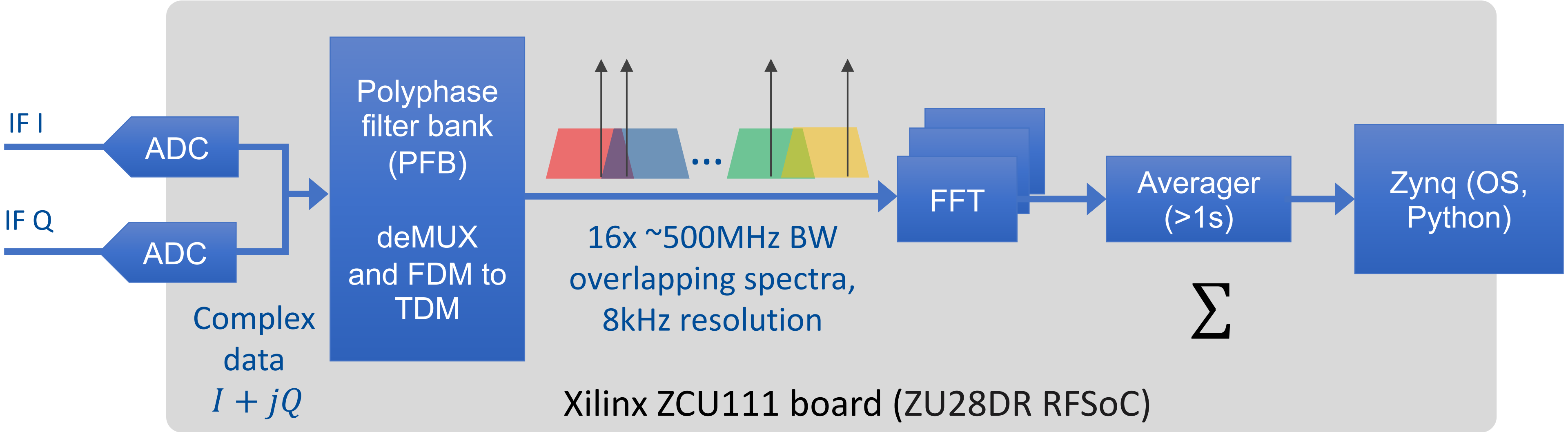
based on **Fermilab** *QICK platform:*







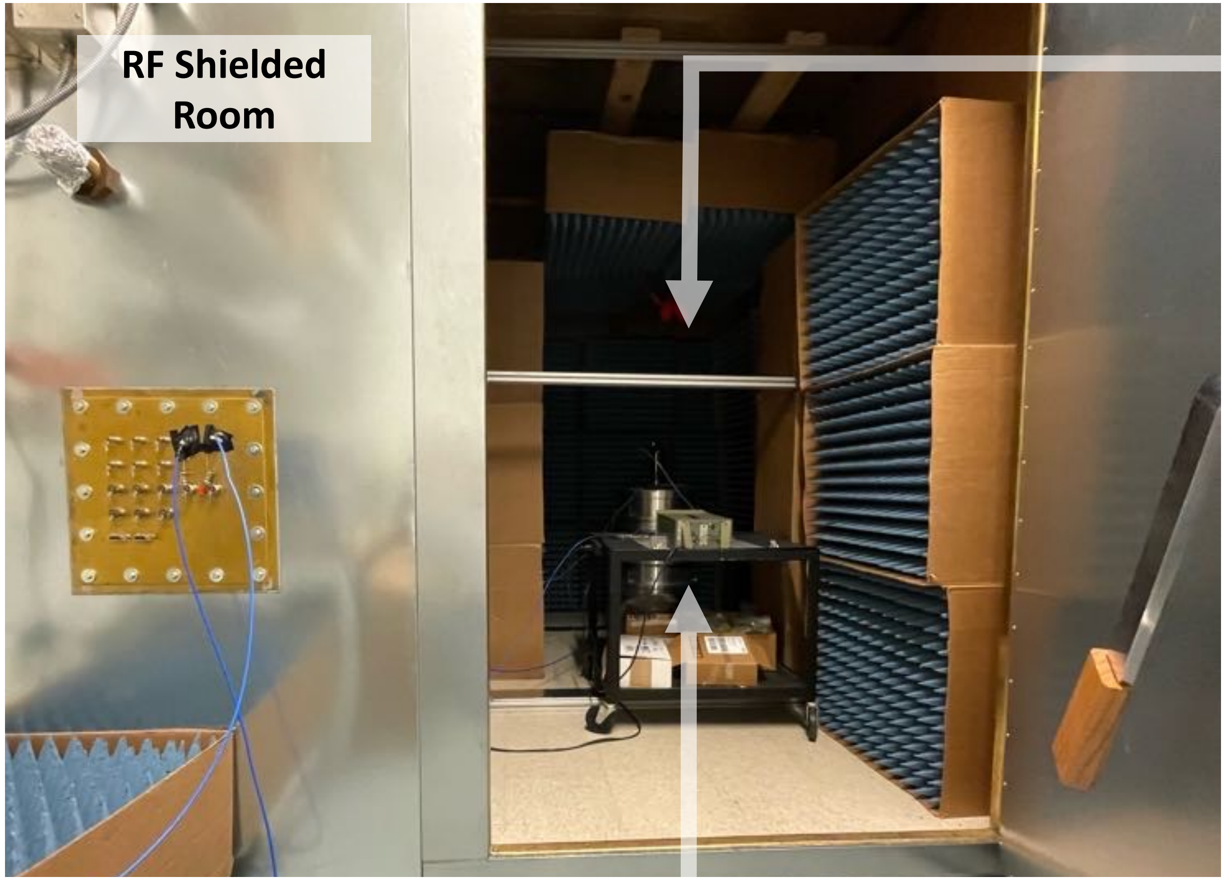
FFT & Averaging on FPGA

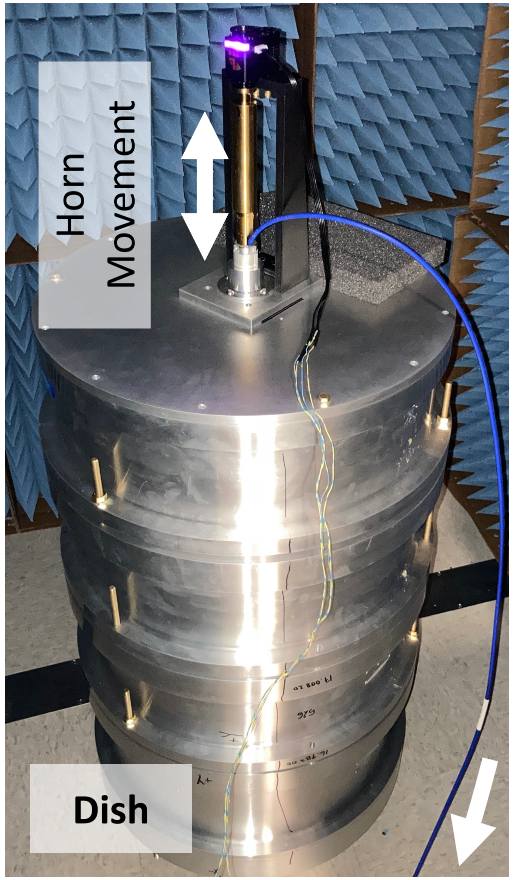


signal bandwidth (10.7 - 12.5) GHz

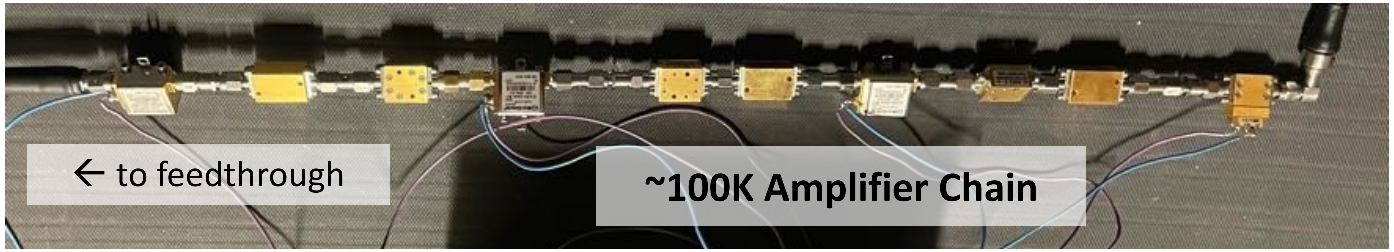
Negligible Dead Time after >1s on-board averaging

First Data Taking Run



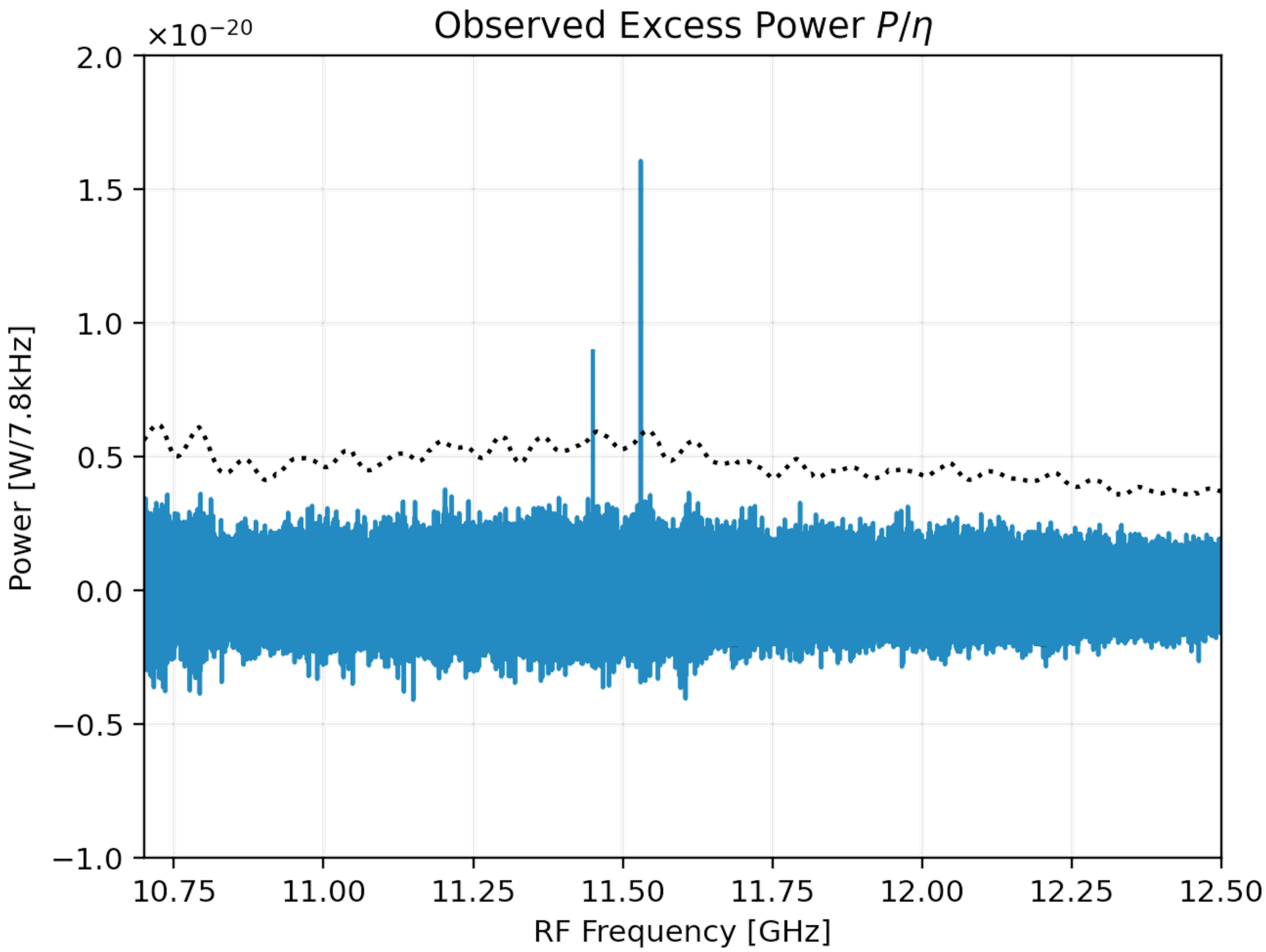


← to DAQ

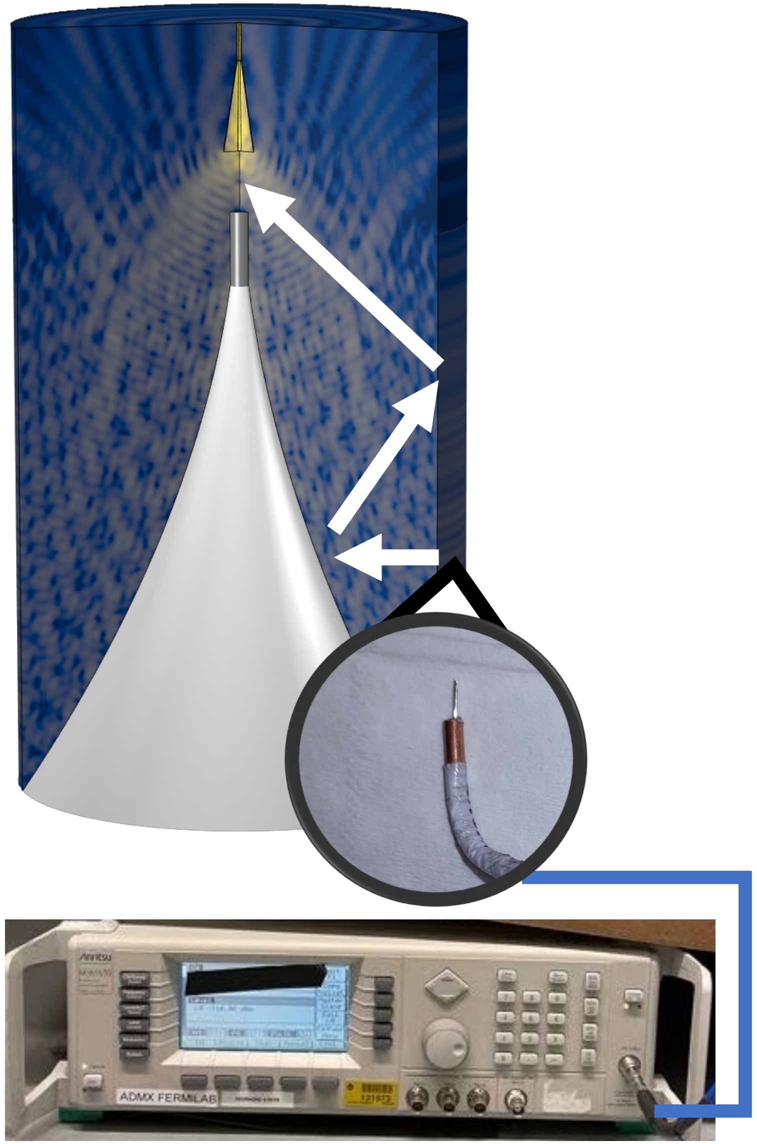


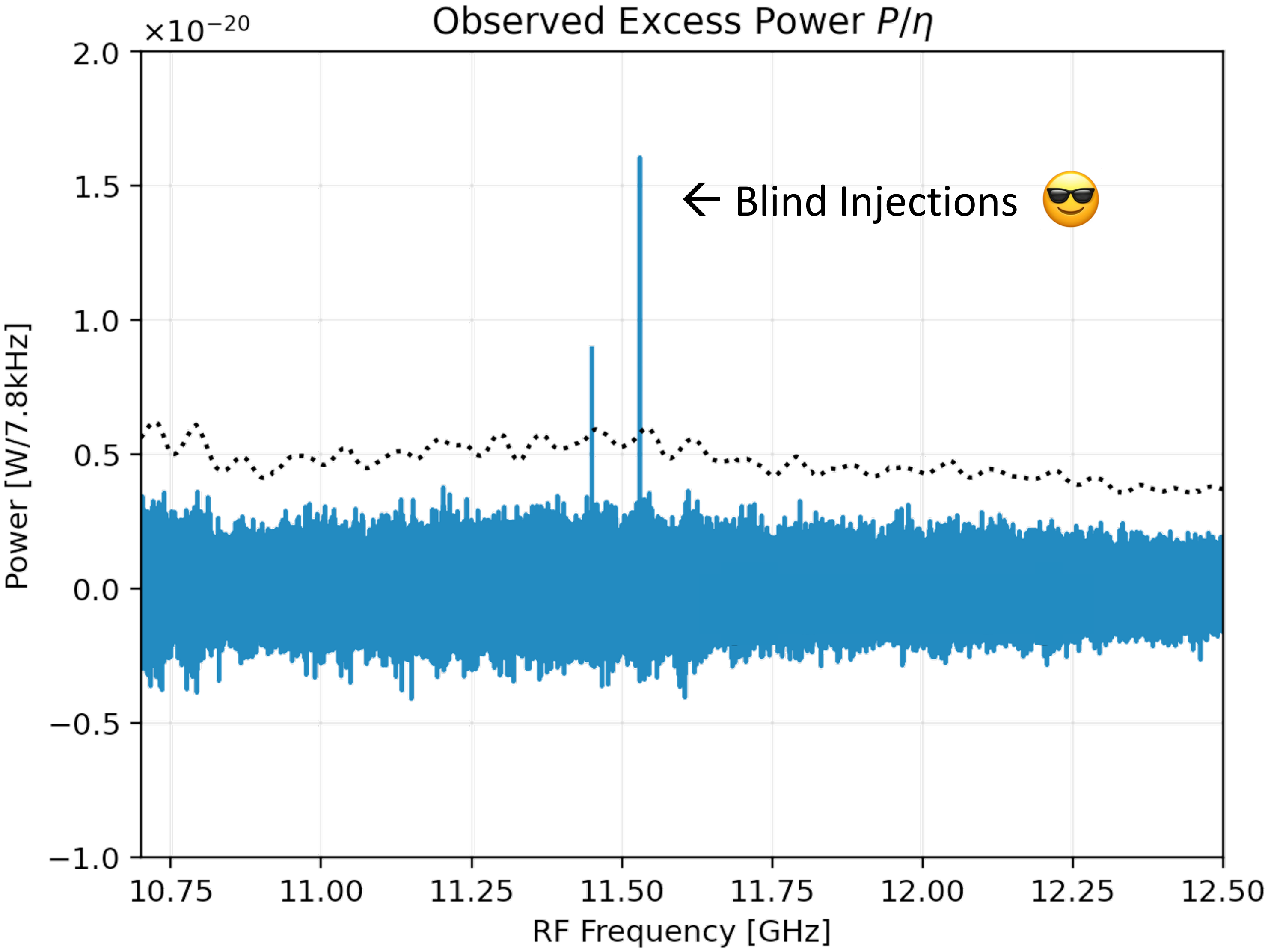
- **24 days science data, June 16 – July 17**
- University of Chicago 41° 47' 31.6098", -87° 36' 6.141"
- sensitive to vertical dark photon polarization
- horn antenna focal spot sweep over every ~ 4hrs
- *RFI shielded Faraday cage:* dish, all RF amplifiers
- *in basement:* down-conversion, DAQ, slow control

Result


Observed Excess Power P/η
$\times10^{-20}$
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
Power [W/7.8kHz]
10.75
11.00
11.25
11.50
11.75
12.00
12.25
12.50
RF Frequency [GHz]

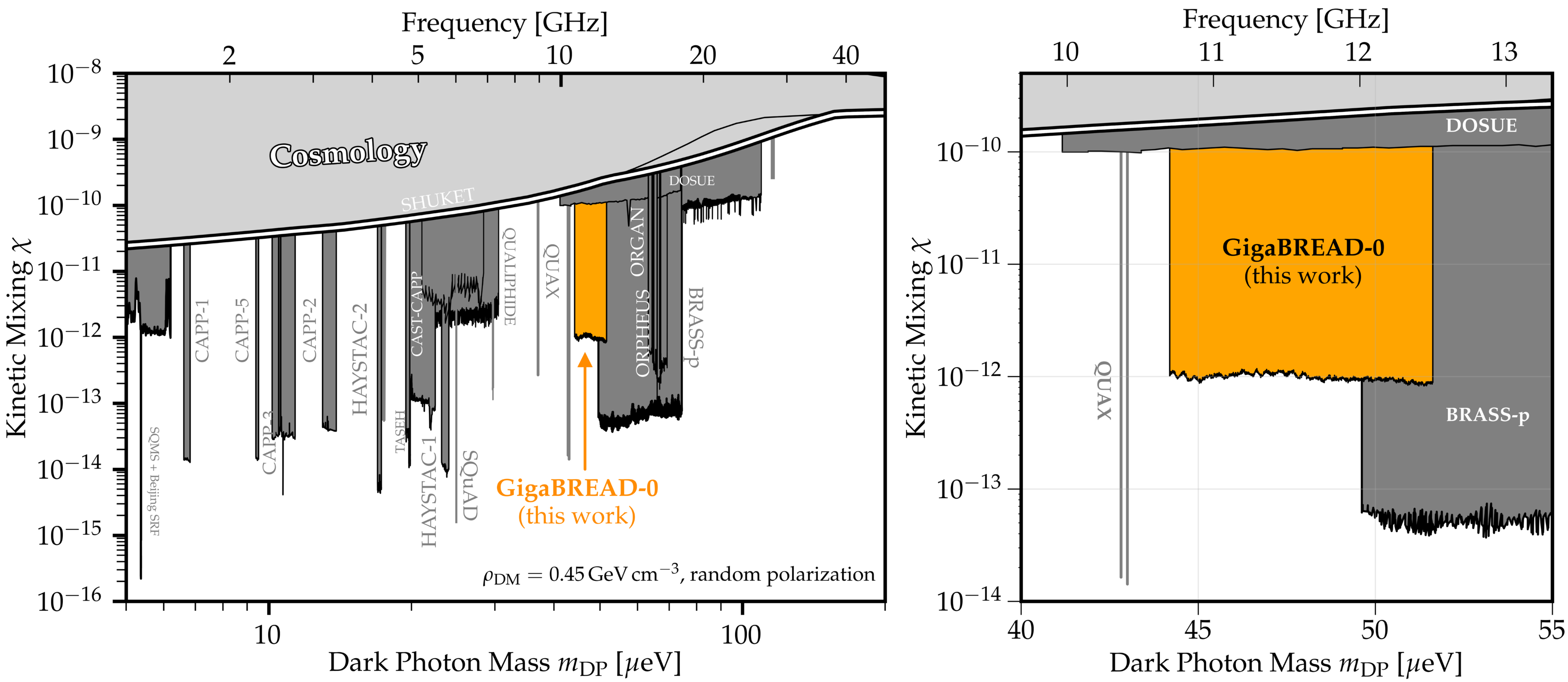
Result


ADMX FERMILAB


Observed Excess Power P/η
$\times 10^{-20}$
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
Power [W/7.8kHz]
10.75
11.00
11.25
11.50
11.75
12.00
12.25
12.50
RF Frequency [GHz]
← Blind Injections 😎

Result – Exclusion Limits

[SK *et al.* (BREAD), PRL 132, 131004 (2024)]



[limit plot adapted from cajohare.github.io/axionlimits]

Result – Exclusion Limits

[SK *et al.* (BREAD), PRL 132, 131004 (2024)]


PHYSICAL REVIEW LETTERS **132**, 131004 (2024)

Editors' Suggestion

First Results from a Broadband Search for Dark Photon Dark Matter in the 44 to 52 μeV Range with a Coaxial Dish Antenna

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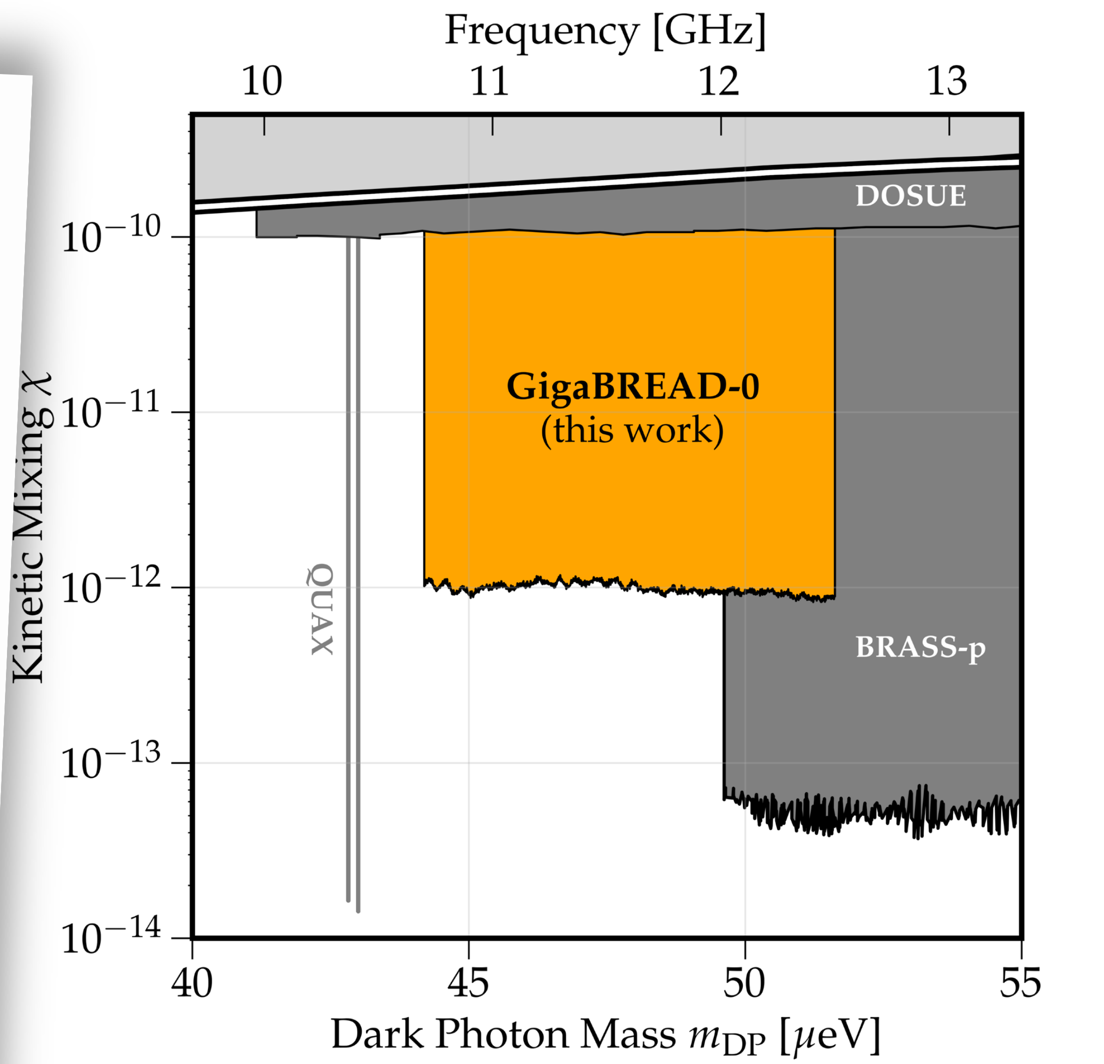
We present first results from a dark photon dark matter search in the mass range from 44 to 52 μeV (10.7–12.5 GHz) using a room-temperature dish antenna setup called GigaBREAD. Dark photon dark matter converts to ordinary photons on a cylindrical metallic emission surface with area 0.5 m² and is focused by a novel parabolic reflector onto a horn antenna. Signals are read out with a low-noise receiver system. A first data taking run with 24 days of data does not show evidence for dark photon dark matter in this mass range, excluding dark photon photon mixing parameters $\chi \gtrsim 10^{-12}$ in this range at 90% confidence level. This surpasses existing constraints by about 2 orders of magnitude and is the most stringent bound on dark photons in this range below 49 μeV.

DOI: 10.1103/PhysRevLett.132.131004

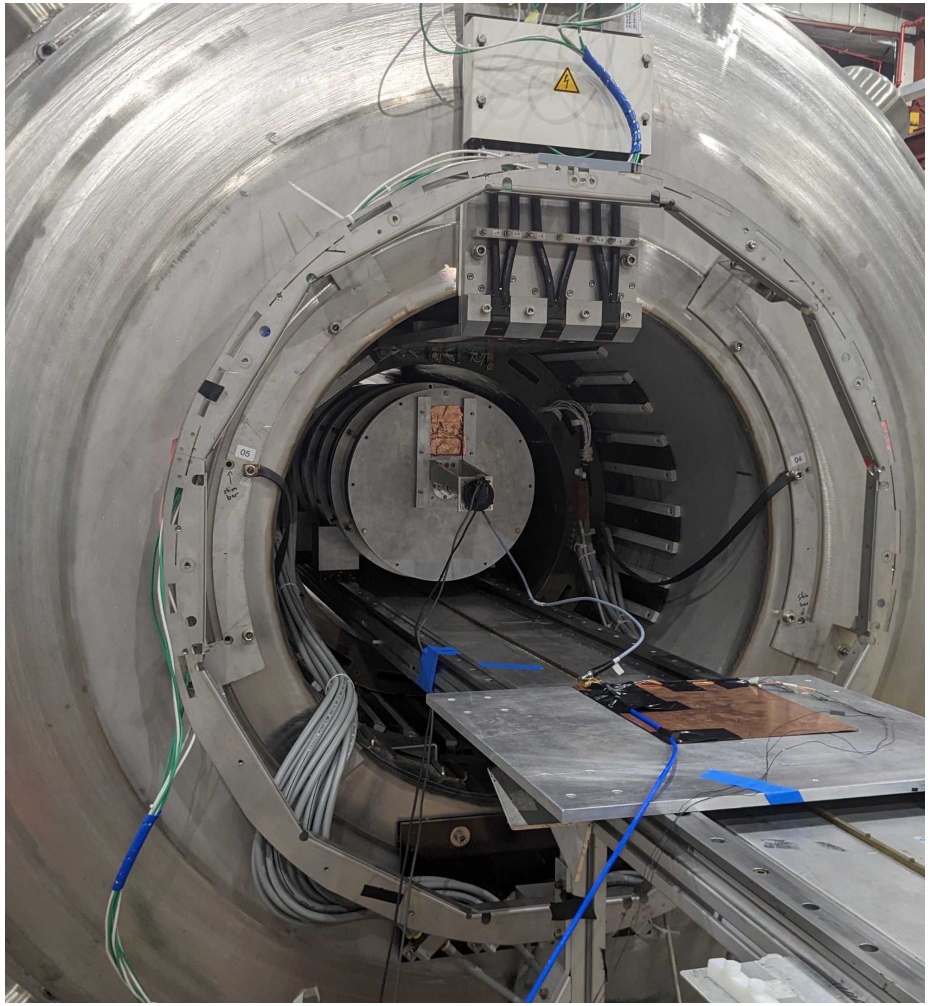
Introduction.—Dark matter (DM) remains one of the most elusive enigmas of modern physics [1–6]. Bosonic particles with masses below ~eV (wavelike DM) are well motivated [7–15], and many experimental efforts ...

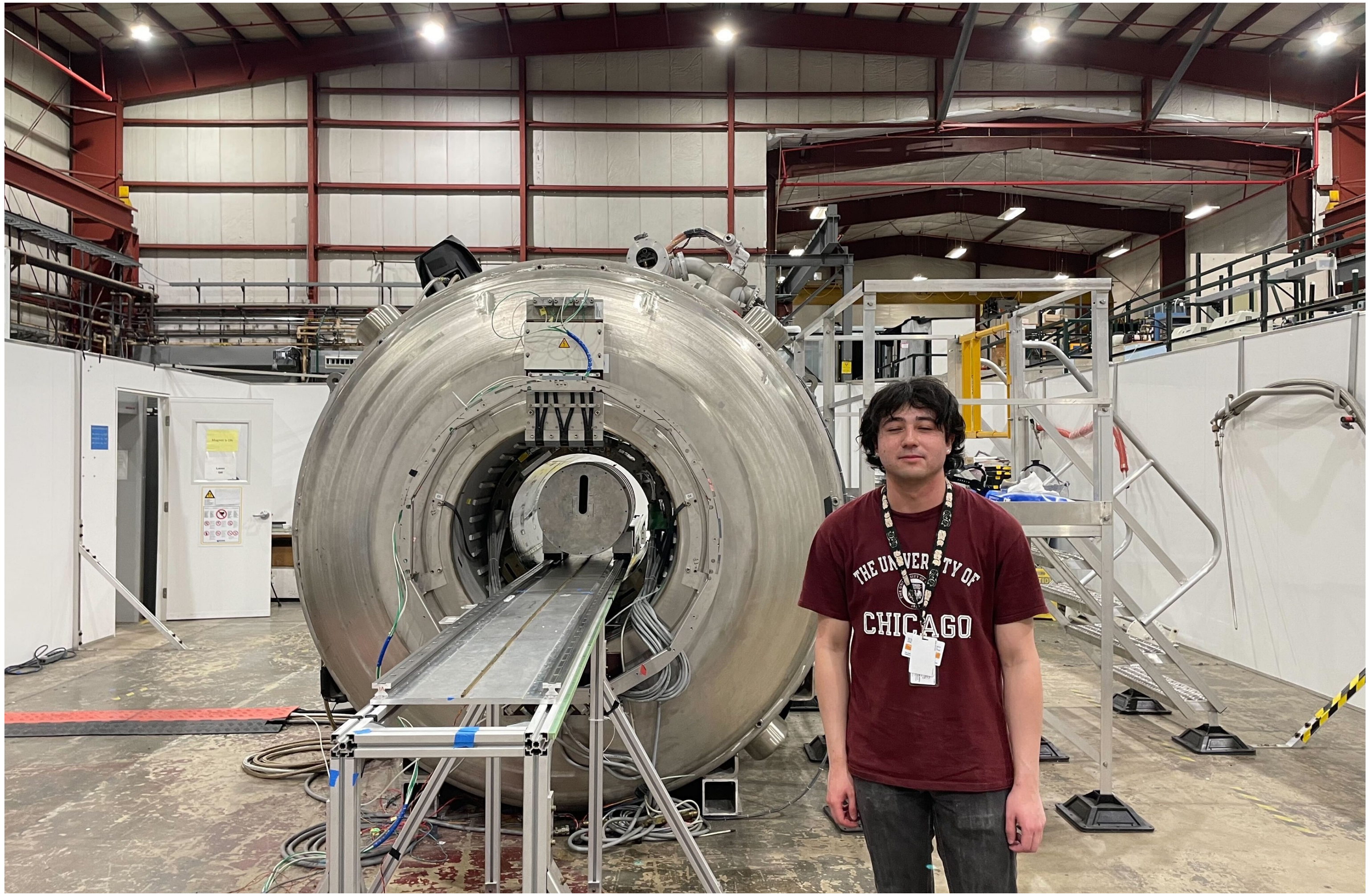
magnitude in mass range are still unprobed due to the narrowband sensitivity and poor higher-mass scalability of resonant cavities. Wavelike DM such as dark photons (DP) ...



[limit plot adapted from cajohare.github.io/axionlimits]

4T MRI Magnet @ Argonne National Lab



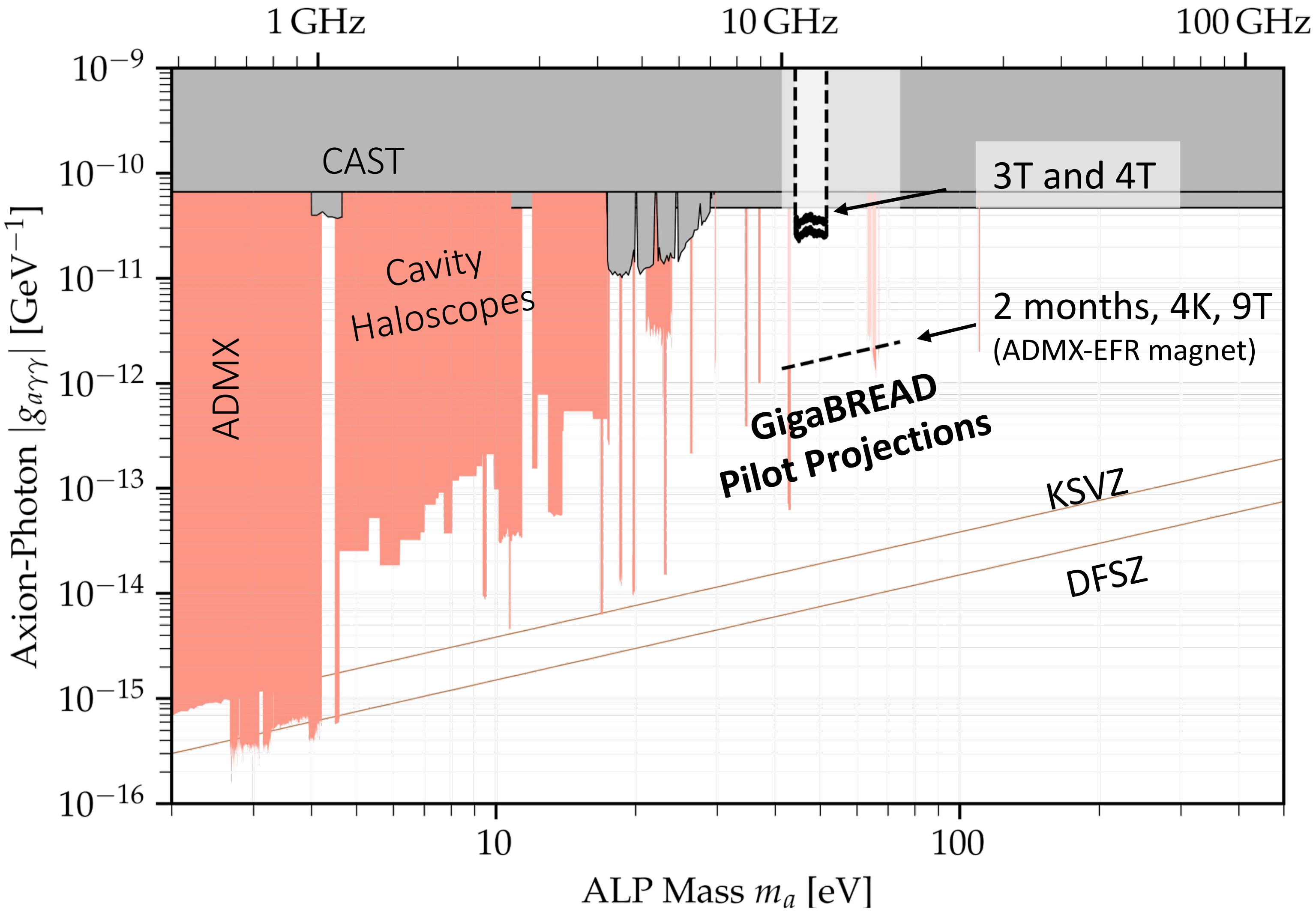


first ALPs science run imminent

Pictured: Gabe Hoshino

Axion-Like Particles – Magnetic Field

4 T MRI magnet at Argonne



[limit plot adapted from cajohare.github.io/axionlimits]

Pictured: Derrick Rodriguez, Gabe Hoshino, Andrew Sonnenschein, SK, Ben Knepper, Mira Littmann

Broadband Reflector Experiment for Axion Detection (BREAD)

Pete Barry, Clarence Chang, Juliang Li, *Argonne National Laboratory*

Christina Wang, *Caltech*

Jesse Liu, *University of Cambridge*

Kristin Dona, Gabe Hoshino, Alex Lapuente, David Miller, Max Olberding, *University of Chicago*

Daniel Bowring, Gustavo I Cancelo, Claudio Chavez, Aaron Chou, Mohamed Hassan, Stefan Knirck, Samantha Lewis, Matthew Malaker, Cristian Pena, Andrew Sonnenschein, Leonardo Stefanazzi, Kevin Zvonarek, *Fermilab*

Rakshya Khatiwada, *Fermilab and Illinois Institute of Technology*

Gianpaolo Carosi, *Lawrence Livermore National Laboratory*

Karl Berggren, Dip Joti Paul, Tony (Xu) Zhou, *Massachusetts Institute of Technology*

Omid Noroozian, *NASA Goddard Space Flight Center*

Sae Woo Nam, *National Institute of Standards and Technology*

Huma Jafree, *Randolph-Macon College*

Noah Kurinsky, *SLAC*

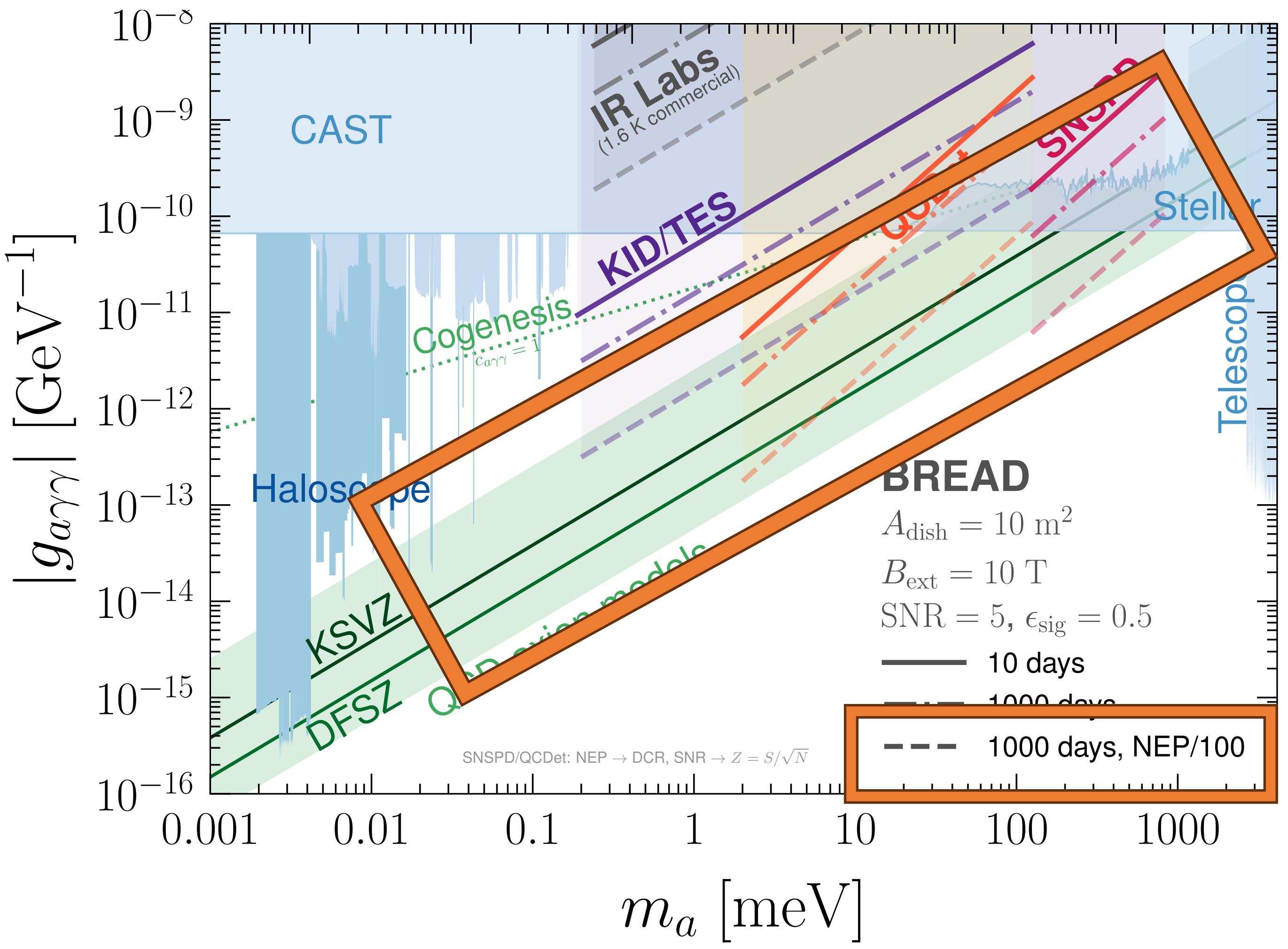
Masha Baryakhtar, University of Washington

…

This work was supported by the Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Sensitivity

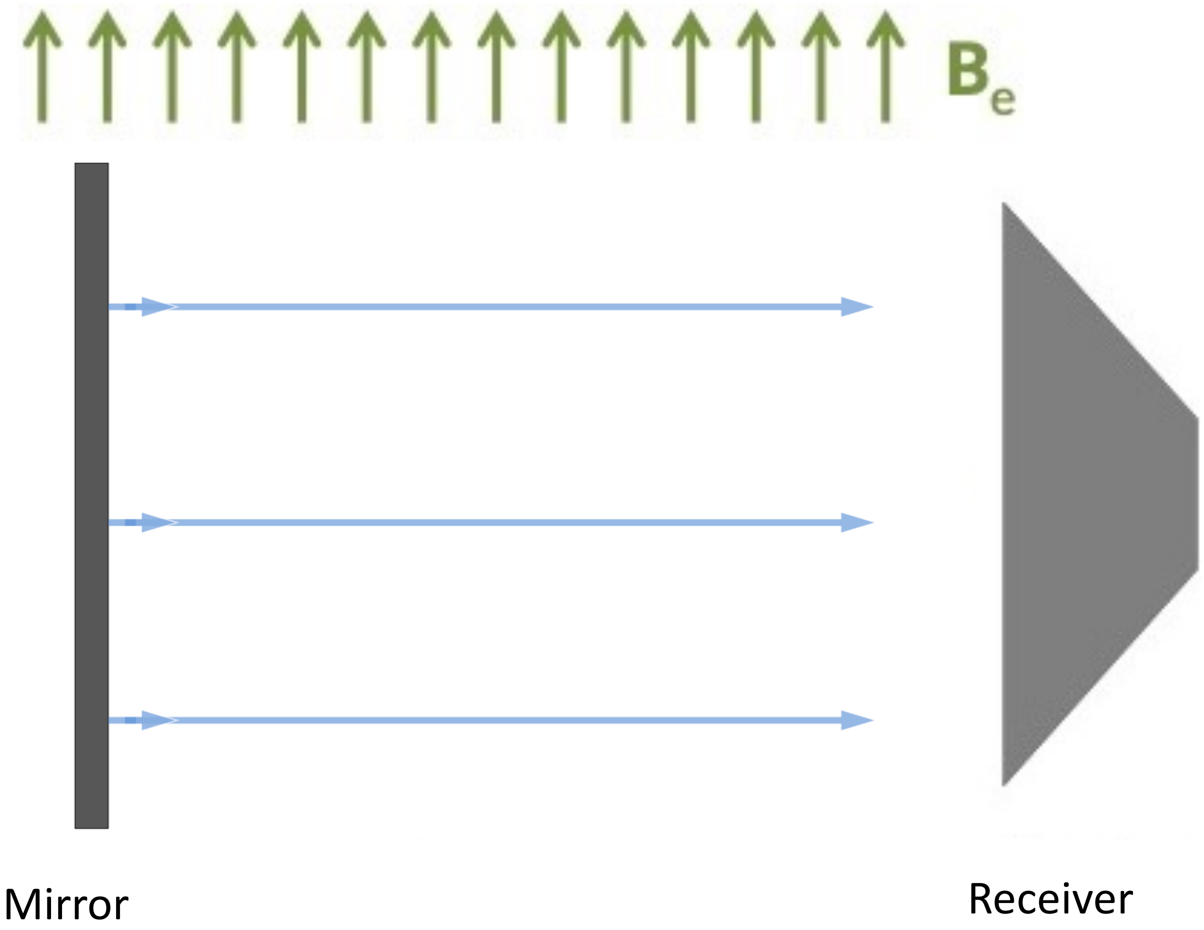
[Liu *et al*, BREAD collab., arXiv:2111.12103, PRL 128 (2022) 131801]



dish antenna alone hard time to reach QCD axion band

Dielectric Haloscope

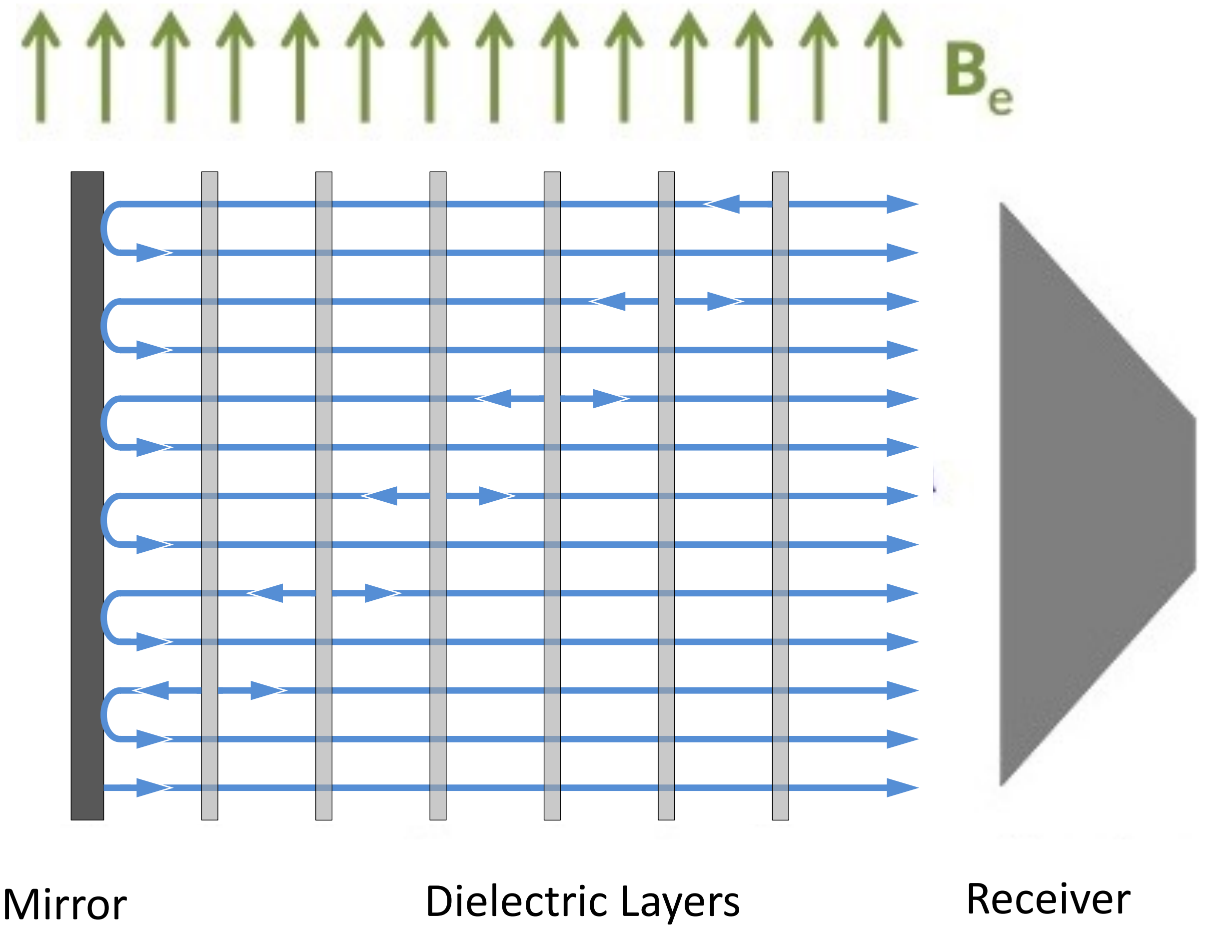
[A. Caldwell *et al.*, PRL 118, 091801 (2017))]
[A. J. Millar *et al.*, JCAP, 061 (2017)]



$$P_{\rm sig} = \qquad P_{\rm dish}$$

Dielectric Haloscope

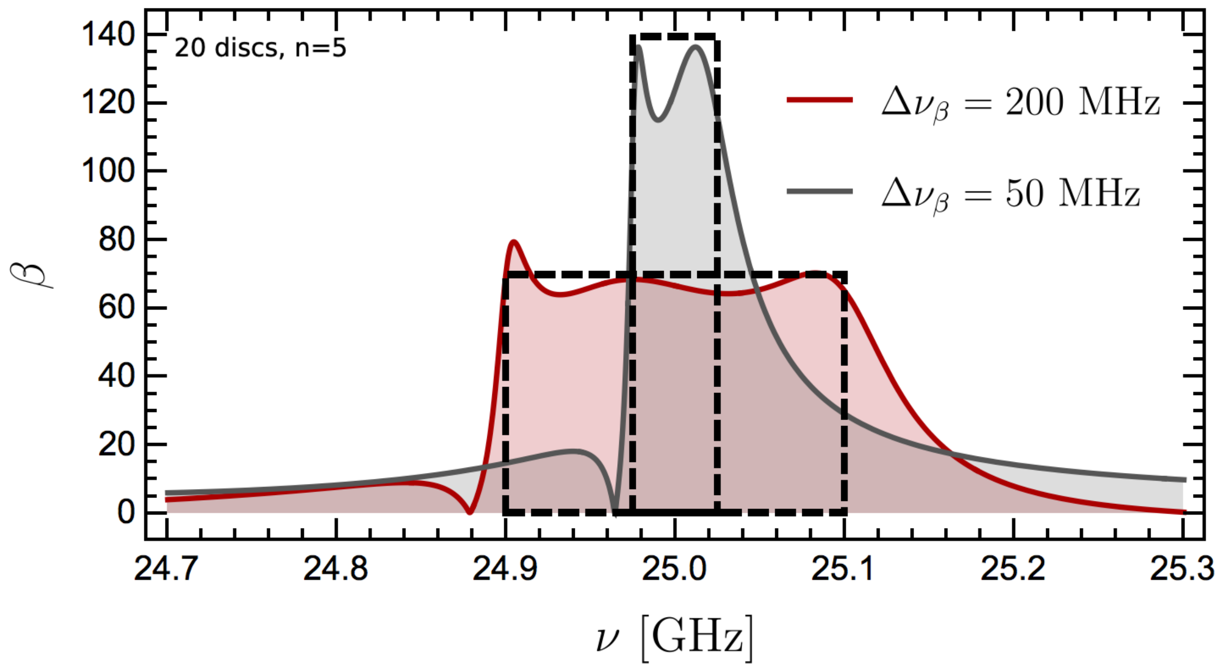
[A. Caldwell *et al.*, PRL 118, 091801 (2017))]
[A. J. Millar *et al.*, JCAP, 061 (2017)]



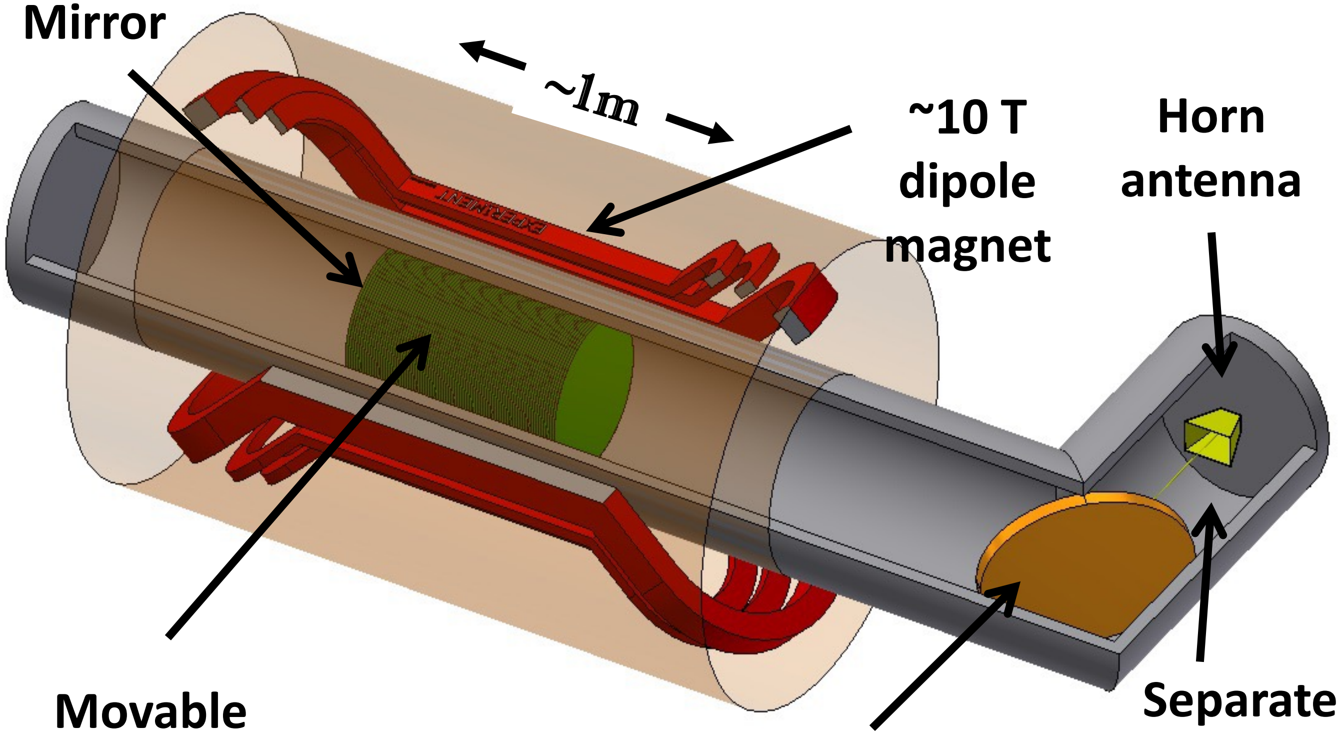
$$P_{\text{sig}} = \beta^2 \times P_{\text{dish}}$$

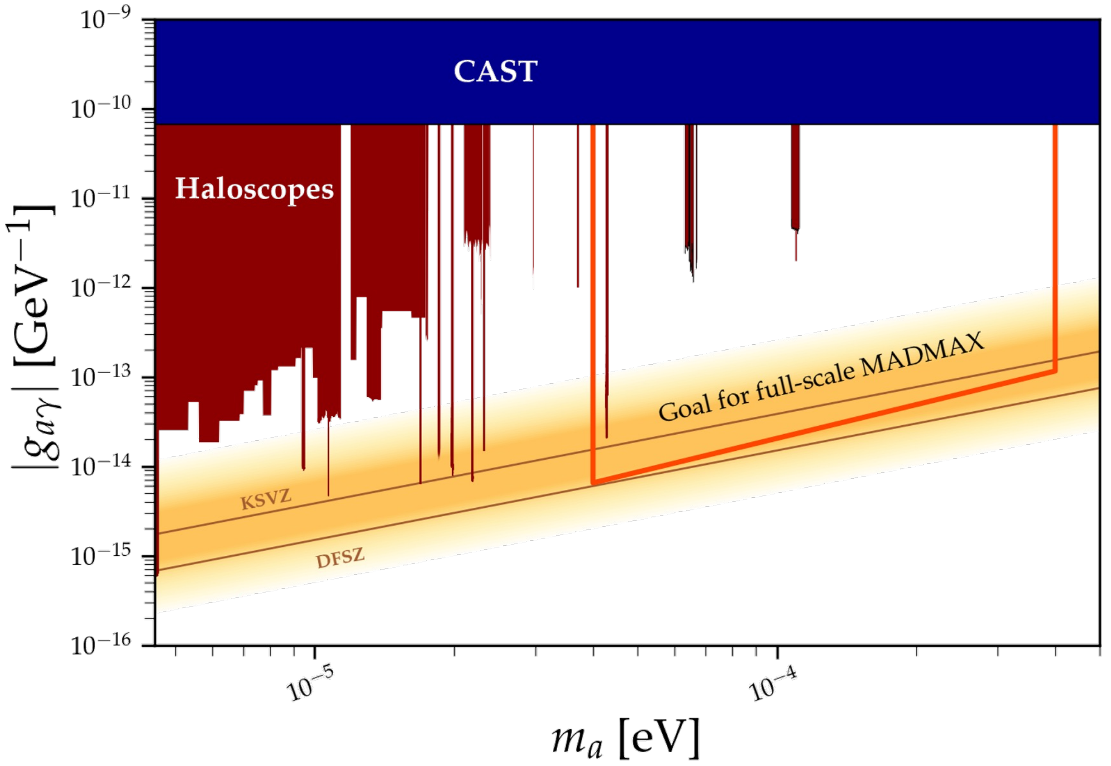
Boost Factor β^2

tunable via disk positions



Magnetized Disk and Mirror Axion eXperiment

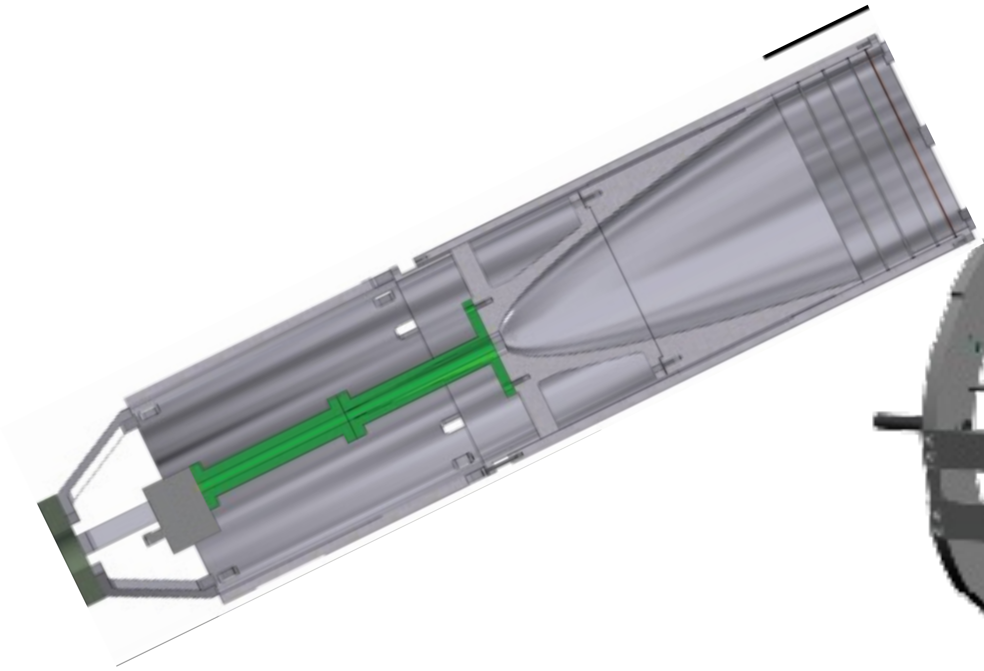
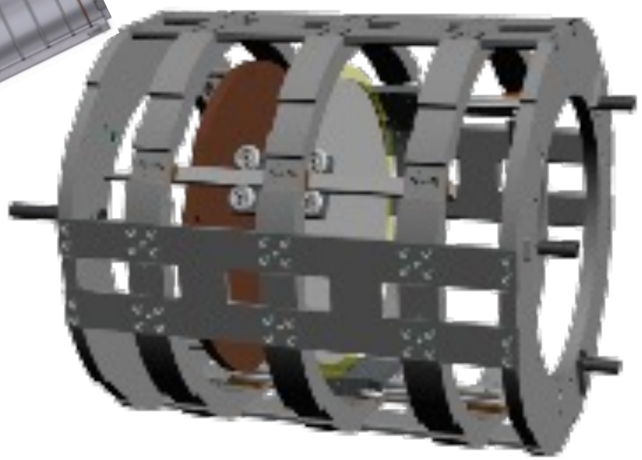
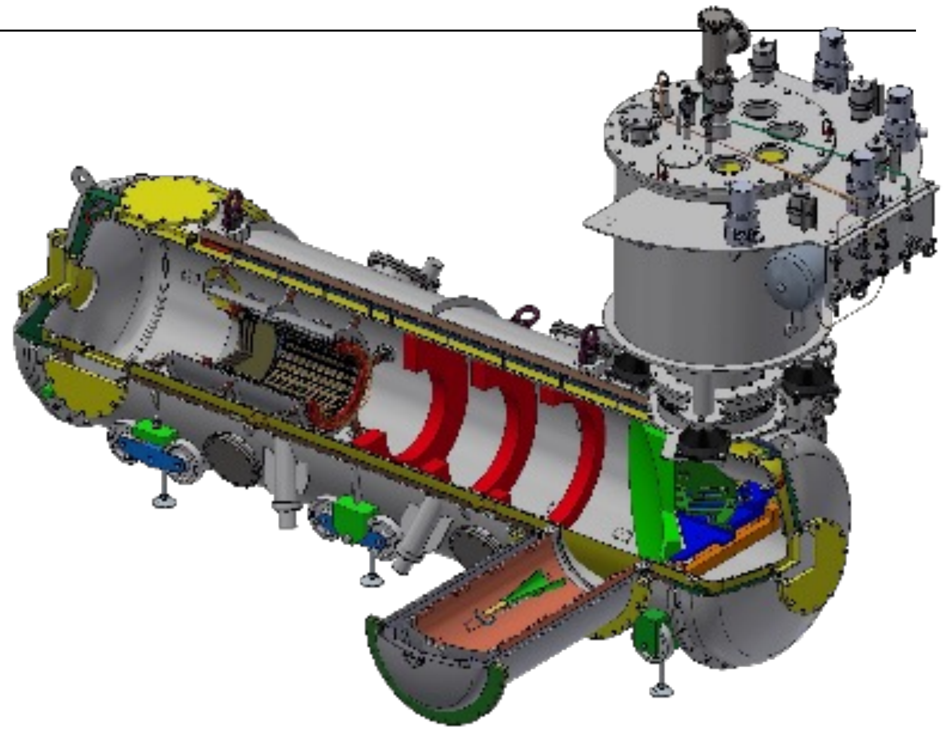




[MADMAX collab., EPJC 79, 186 (2019)]
[A. Caldwell *et al.*, PRL 118, 091801 (2017)]

MADMAX Prototypes

Comprehensive Prototype Program

Closed Boosters (CB):

⌀ = 100 mm (**CB100**), 3 Al_2O_3 disks
⌀ = 200 mm (**CB200**), 3 Al_2O_3 disks

Open Boosters (OB):

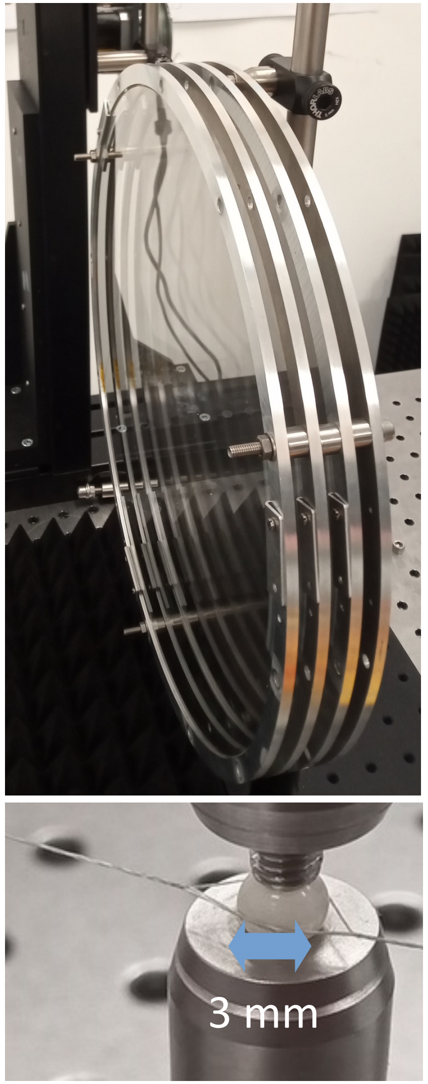
⌀ = 200 mm (**OB200**), 1 Al_2O_3 disk
⌀ = 300 mm (**OB300**), 3 disks (Al_2O_3 & $LaAlO_3$)

Large bore (⌀ = 760 mm) cryostat

Prototype runs @ CERN MORPURGO magnet (1.5T) and Fermilab DWL (9T)

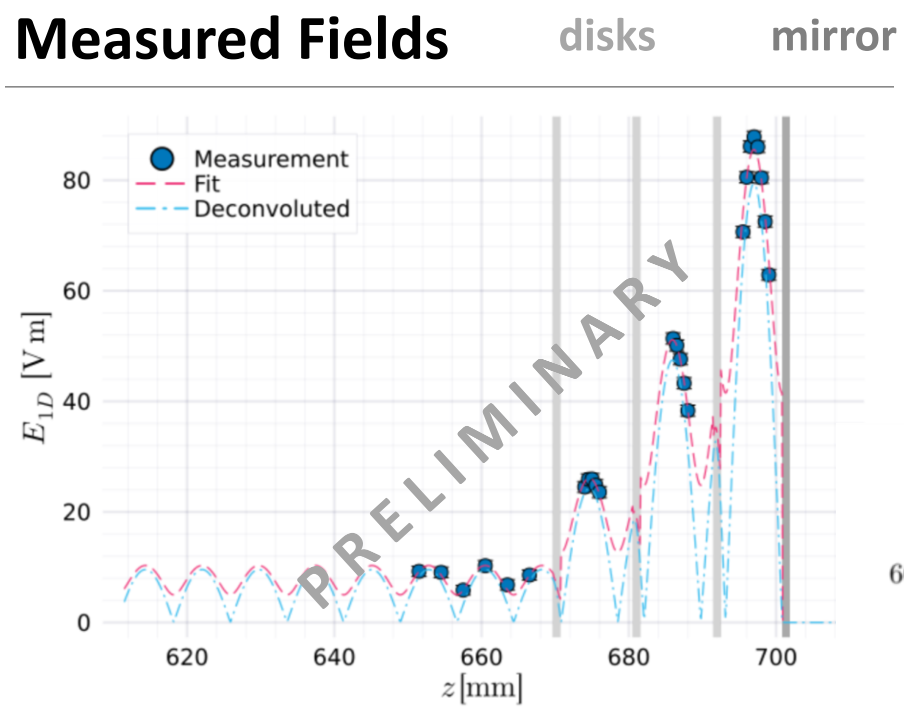
Open Booster Prototype – Bead Pull Method

[J. Egge *et al.* JCAP, 04:005, 2024]
[J. Egge. JCAP, 04:064, 2023]



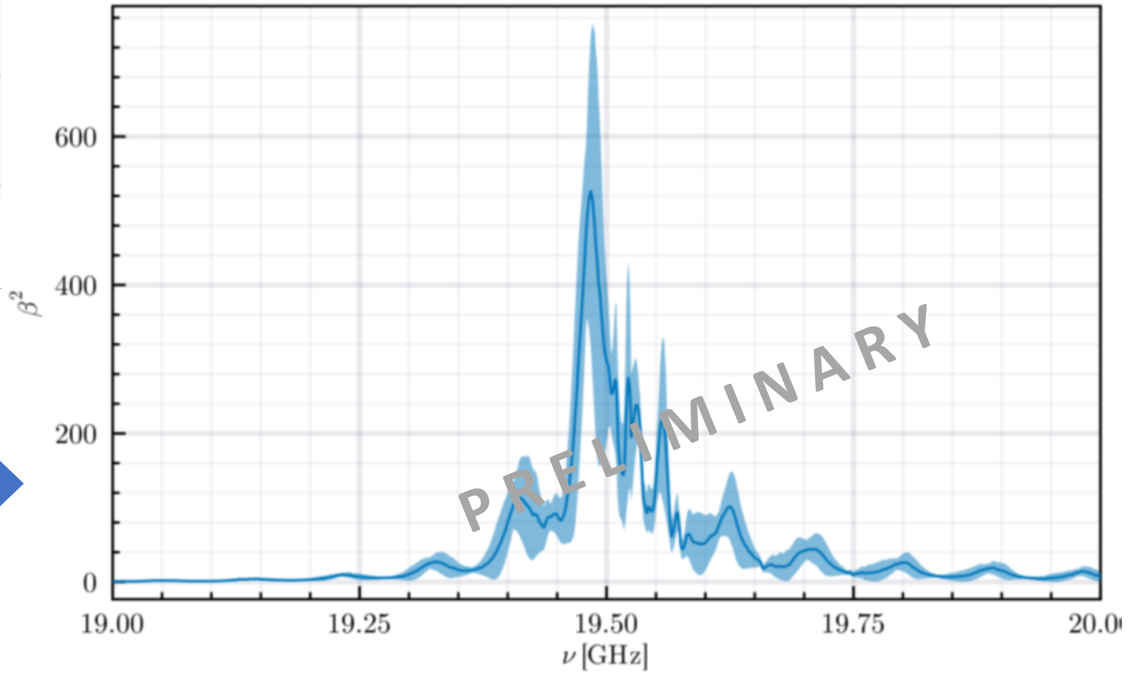
Dielectric bead

Measured Fields



$$\beta^2 \propto \left| \int dV E \right|^2$$

Boost Factor

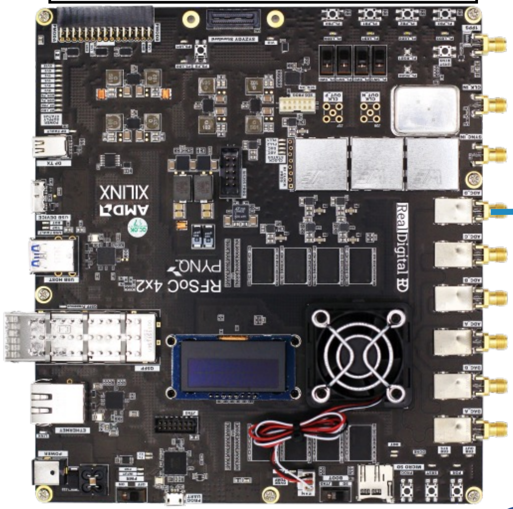


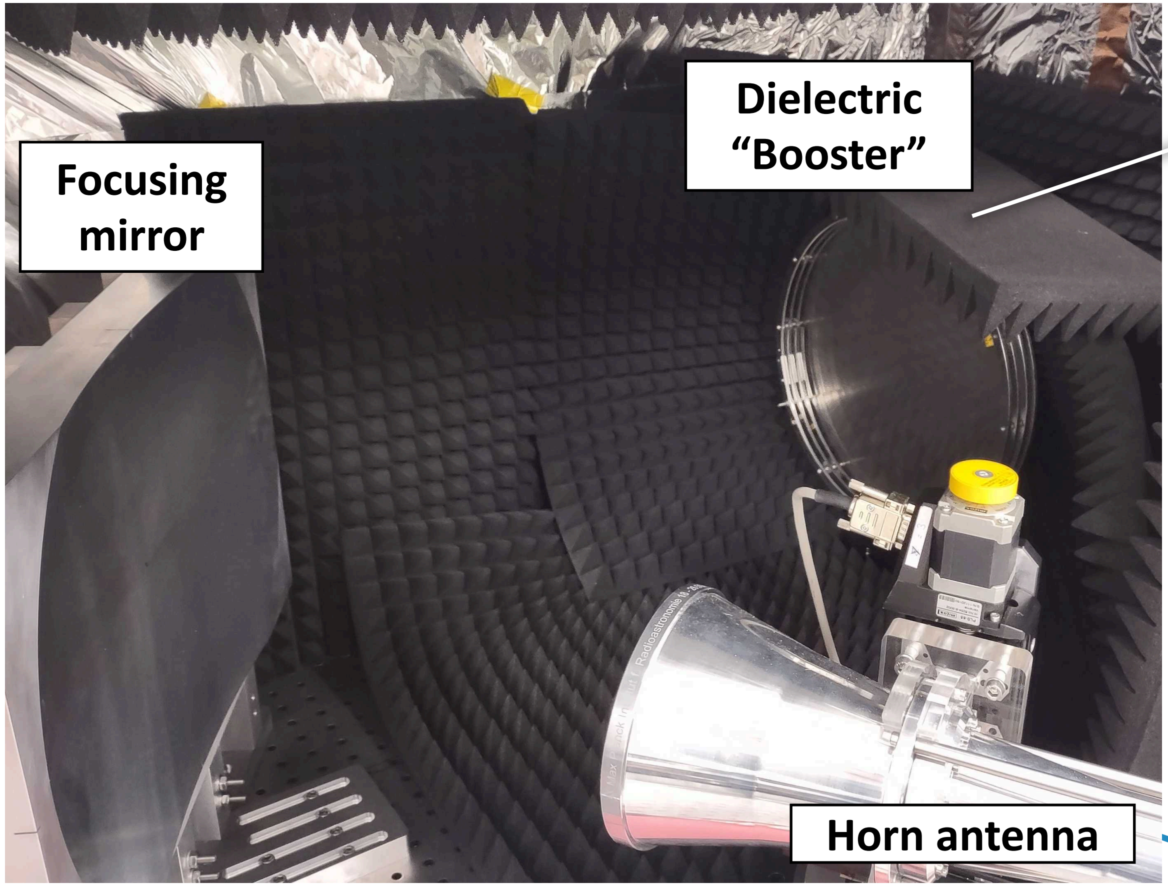
Open Booster Prototype – First Science Run

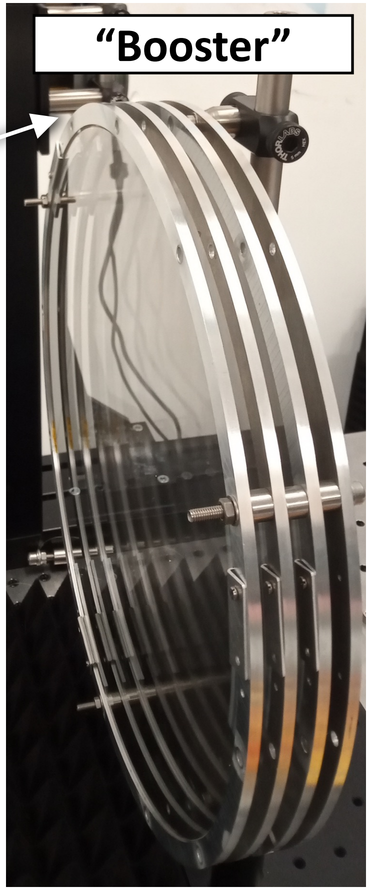
Fermilab

firmware based on BREAD DAQ

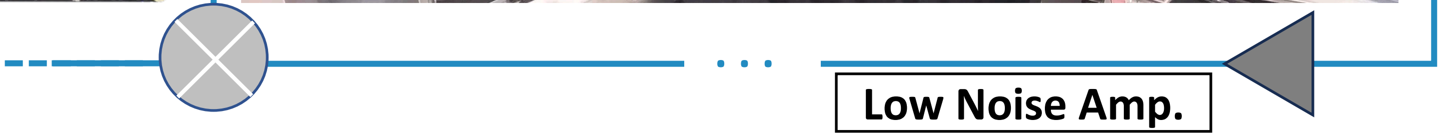
Xilinx RFSoC 4x2







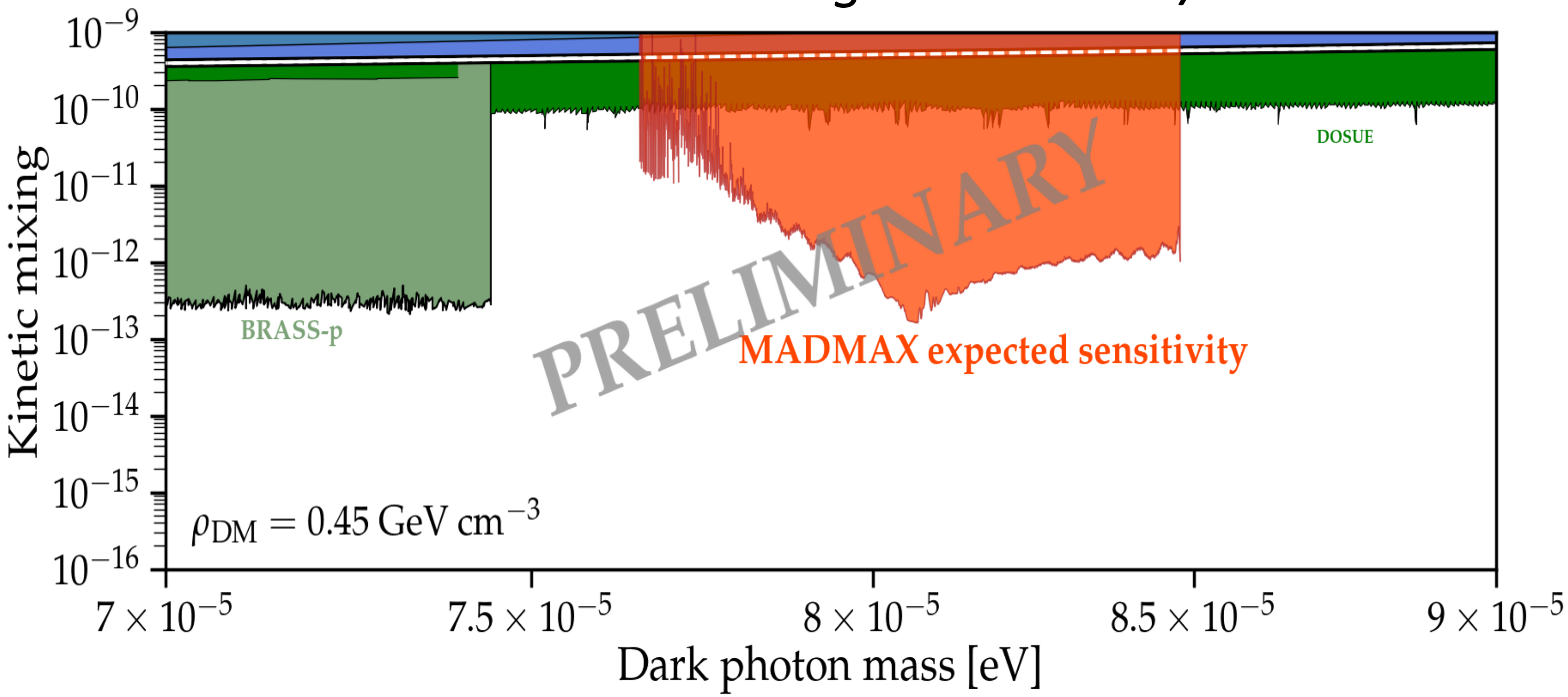
Jacob Egge



2 weeks winter break data taking

MADMAX – First Physics Result

2 weeks data taking winter 2023/24:



first MADMAX physics result

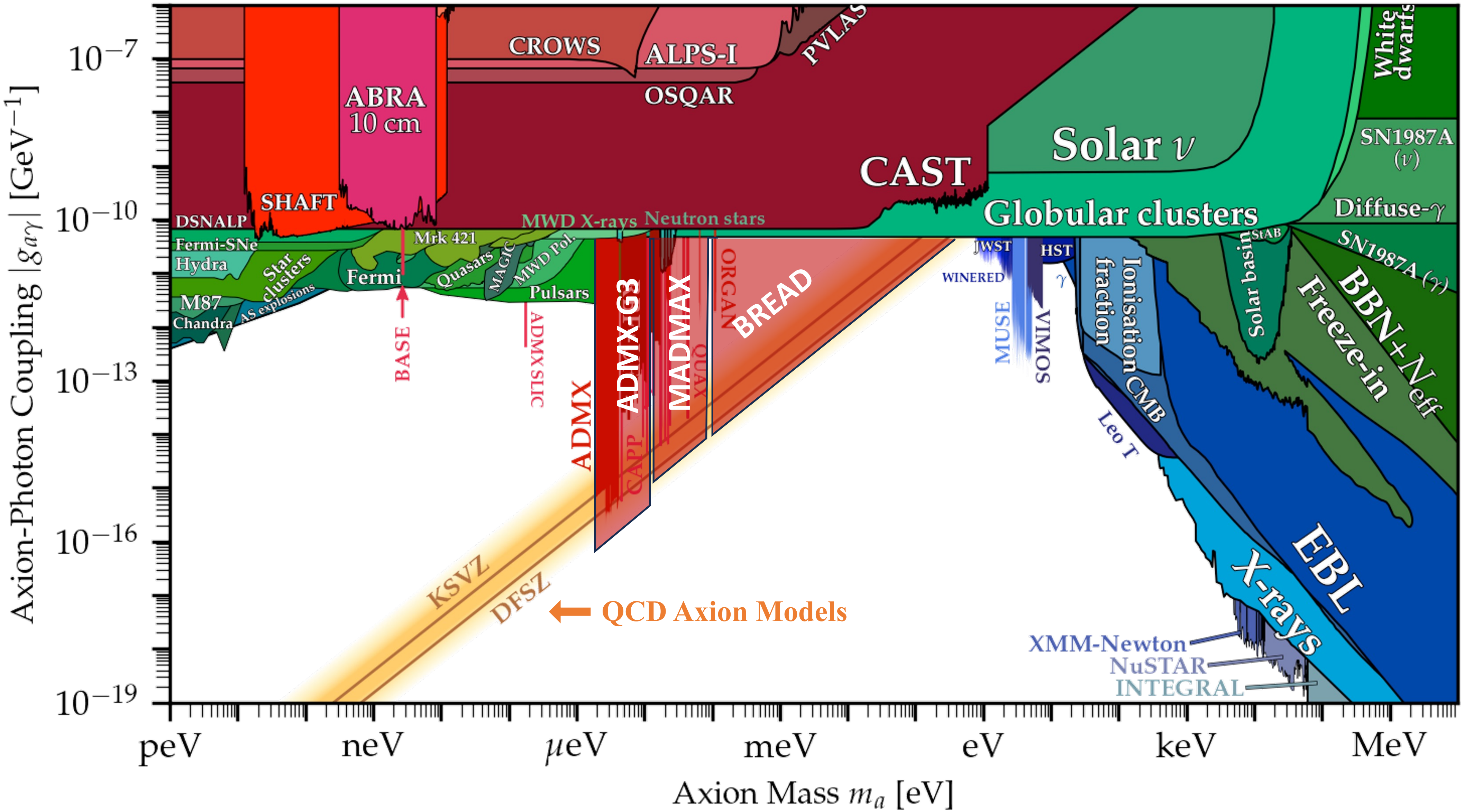
publication in preparation

MADMAX Collaboration

Universidad de Zaragoza
RWTH AACHEN UNIVERSITY
EBERHARD KARLS UNIVERSITÄT TÜBINGEN
NÉEL institut
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM
cea
DESY.
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Max-Planck-Institut für Radioastronomie
Fermilab

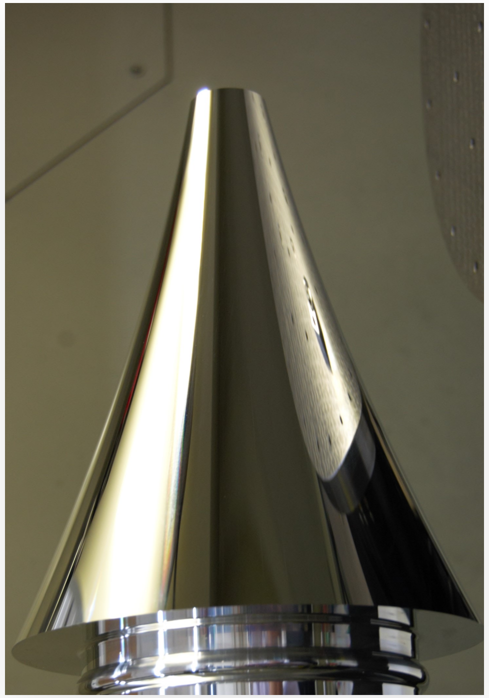
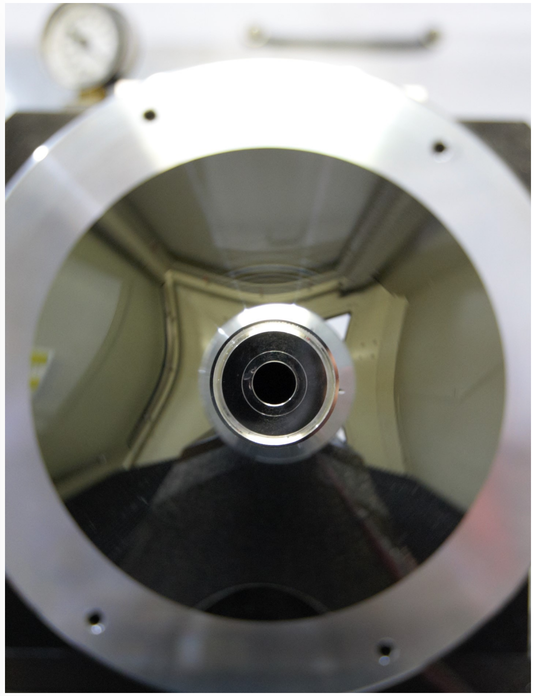
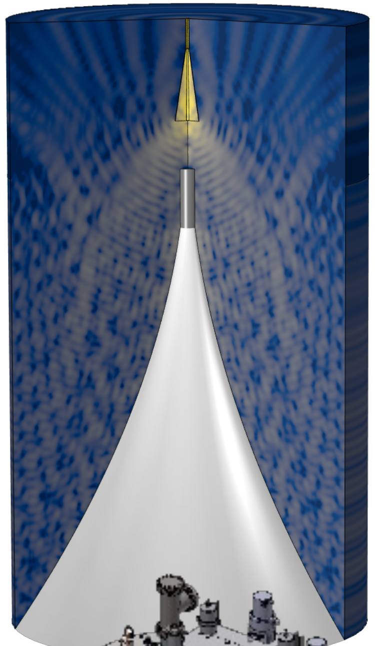
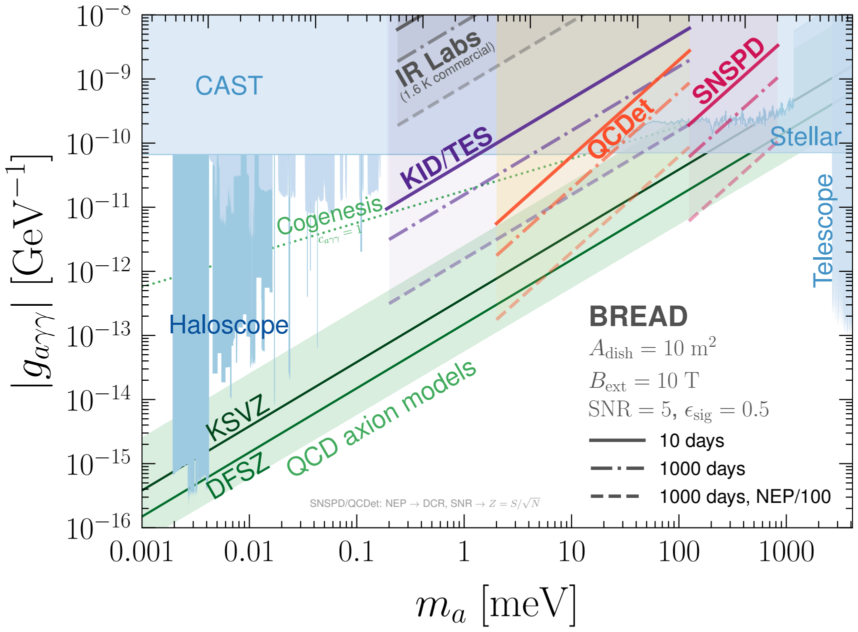
Science Vision

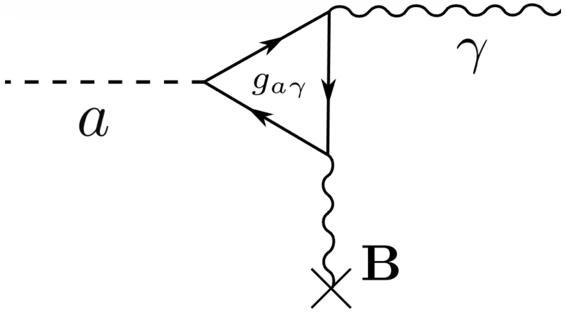
[adapted from cajohare.github.io/axionlimits]

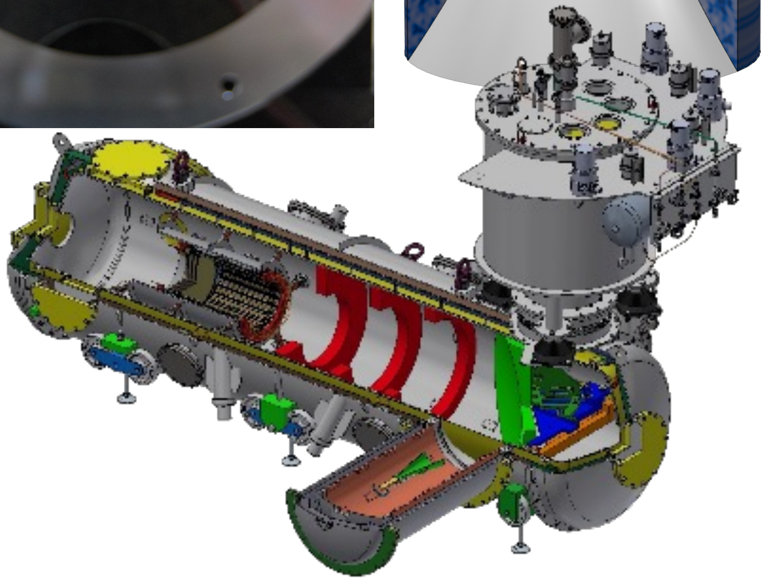


Conclusion

Thank you very much, Pierre!

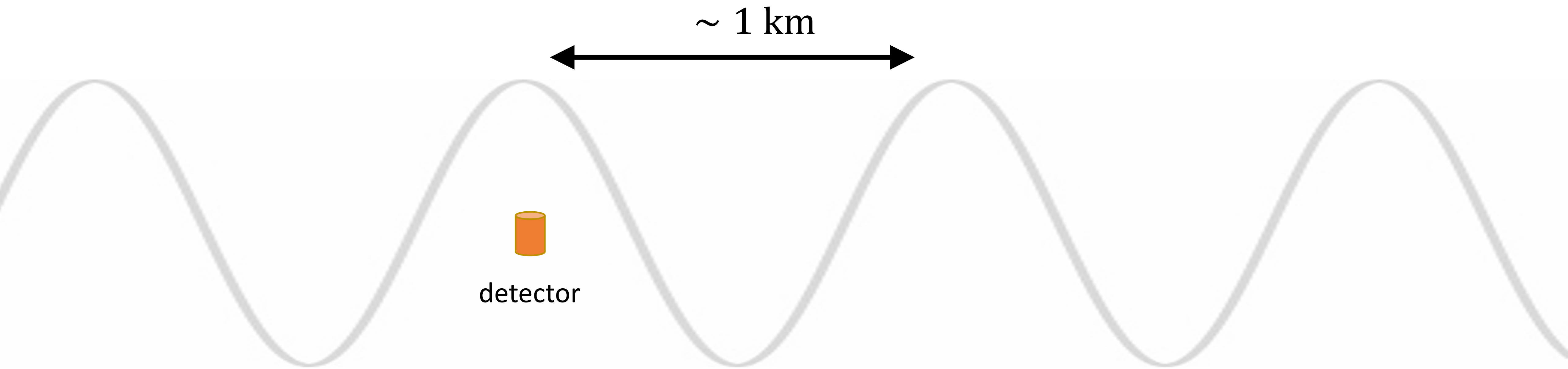





Appendix

Wave-like Dark Matter

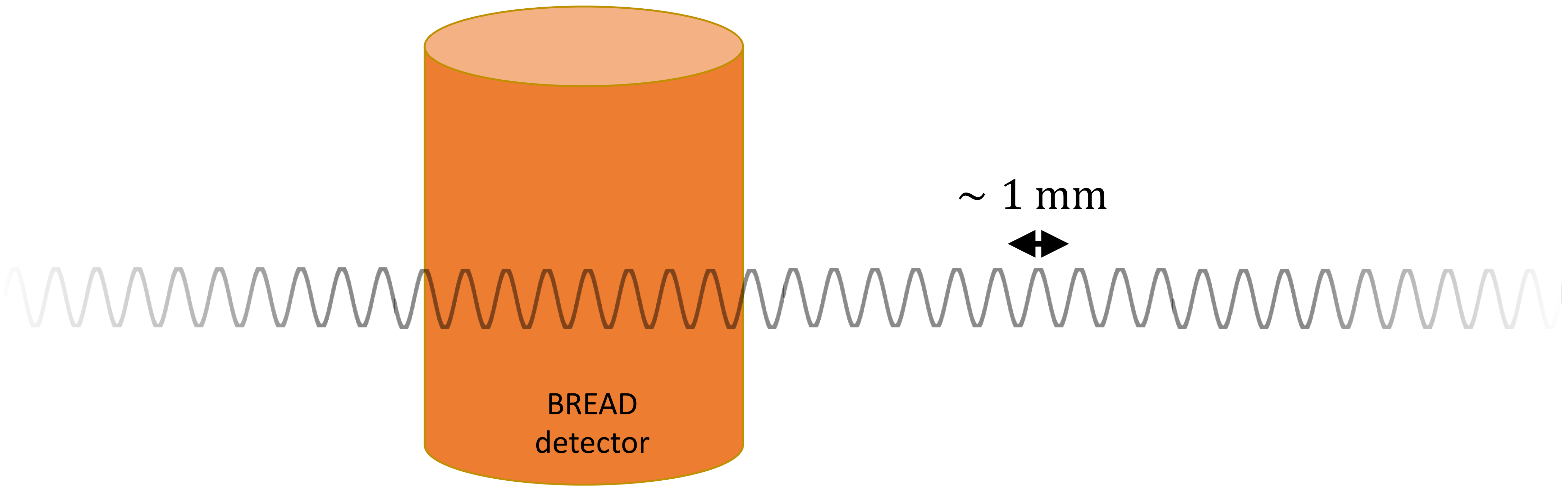
$$\rho_a \sim 0.45\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \qquad \lambda_{\mathrm{DB}} \sim \frac{2\pi}{m_a v} \sim 1\ \mathrm{km}\left(\frac{1\mu\mathrm{eV}}{m_a}\right) \quad \rightarrow \quad \frac{\#\mathrm{particles}}{\lambda_{\mathrm{DB}}^3} \sim 10^{30}\left(\frac{1\mu\mathrm{eV}}{m_a}\right)^4$$



coherent detection

Wave-like Dark Matter

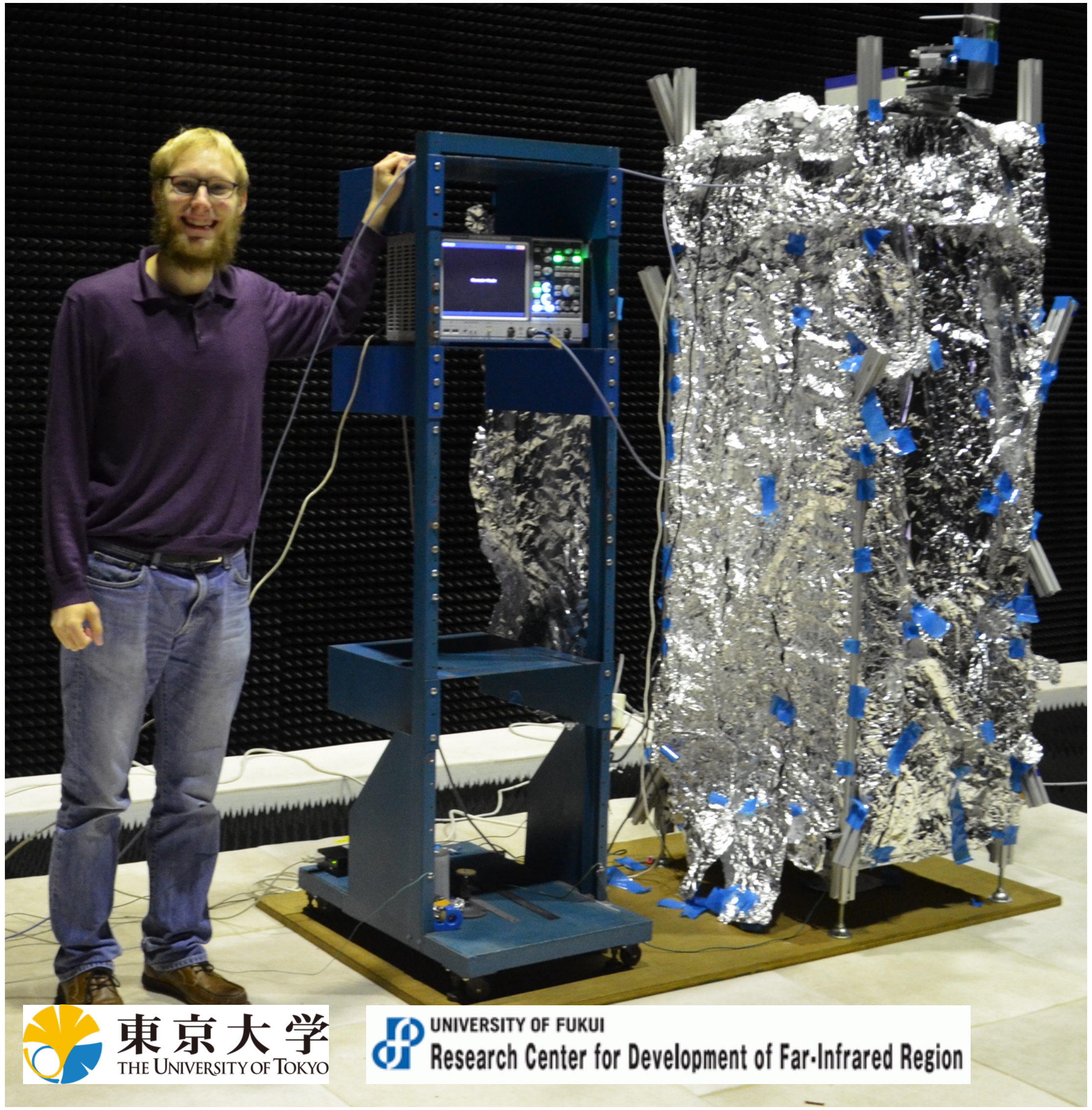
$\rho_a \sim 0.45 \frac{\text{GeV}}{\text{cm}^3}$ $\lambda_{\text{DB}} \sim \frac{2\pi}{m_a v} \sim 1\text{ mm} \left(\frac{1\text{eV}}{m_a}\right)$ → $\frac{\#\text{particles}}{\lambda_{\text{DB}}^3} \sim 10^6 \left(\frac{1\text{eV}}{m_a}\right)^4$

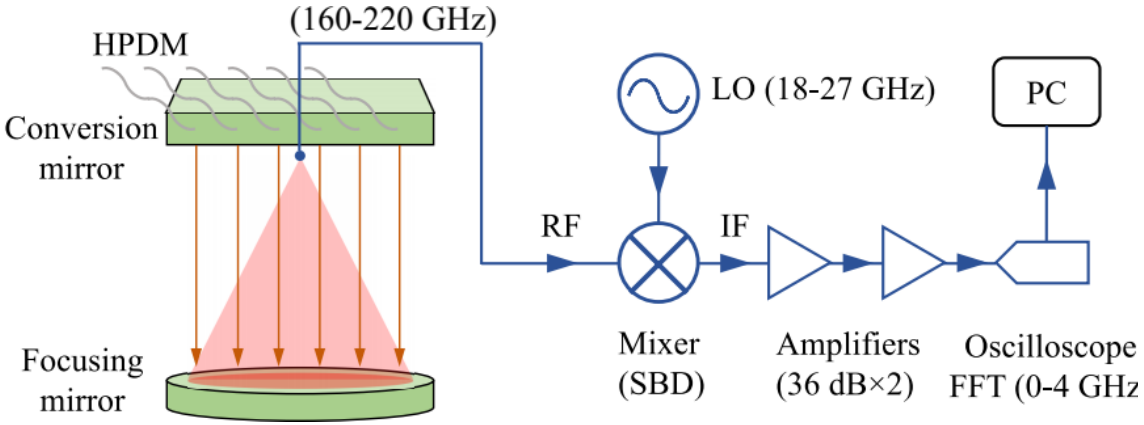


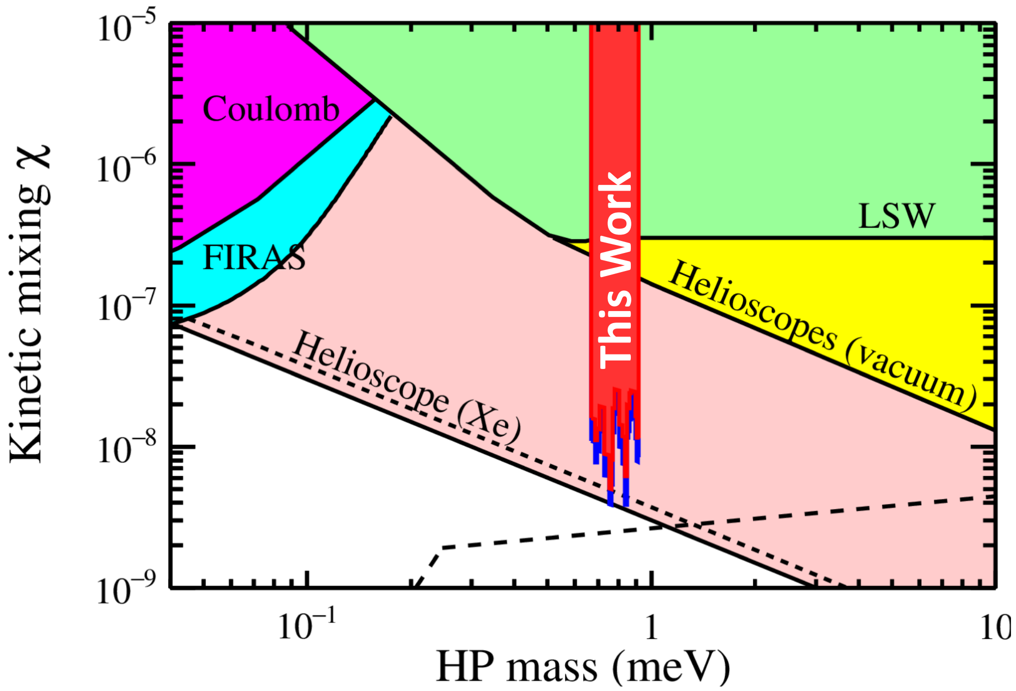
incoherent detection

World's First mm-wave Dish Antenna

[SK, Yamazaki, Okesaku, Asai, Idehara, Inada; JCAP 11(2018)031, arXiv:1806.05120]

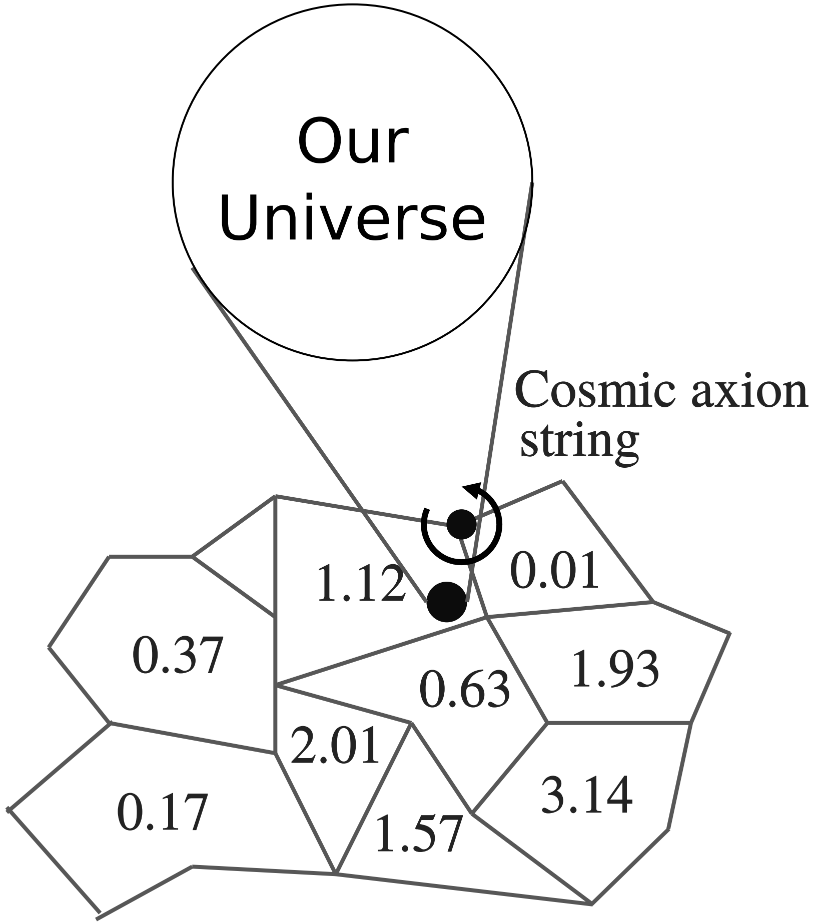






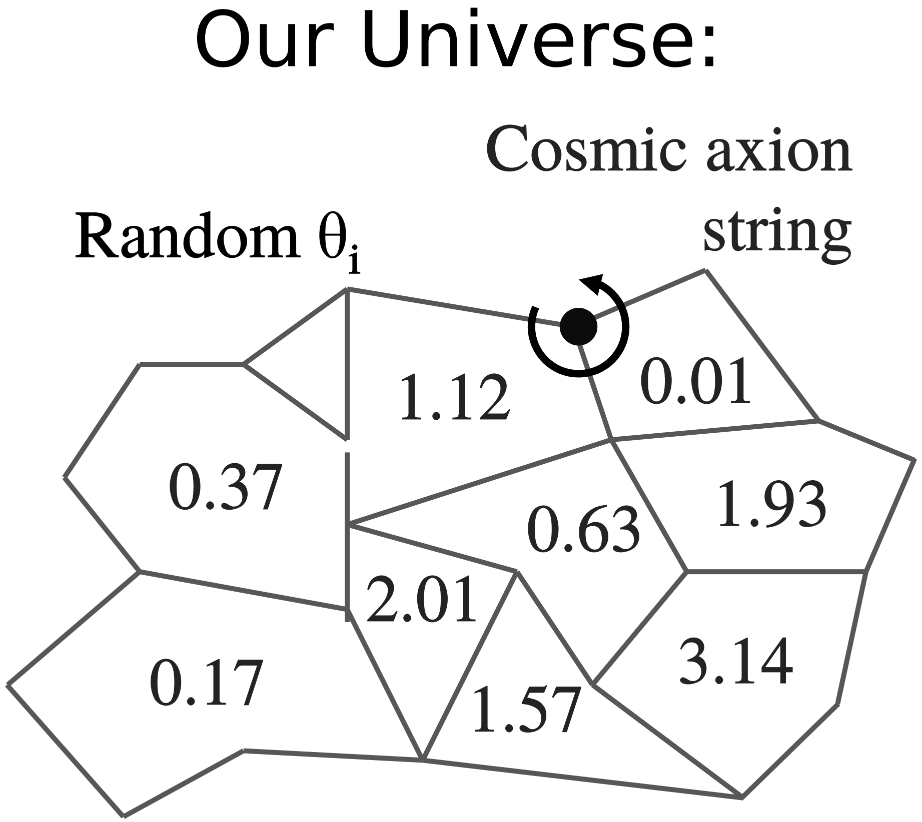
Peccei-Quinn Symmetry Breaking...

before inflation:



$m_a < \text{ eV}$

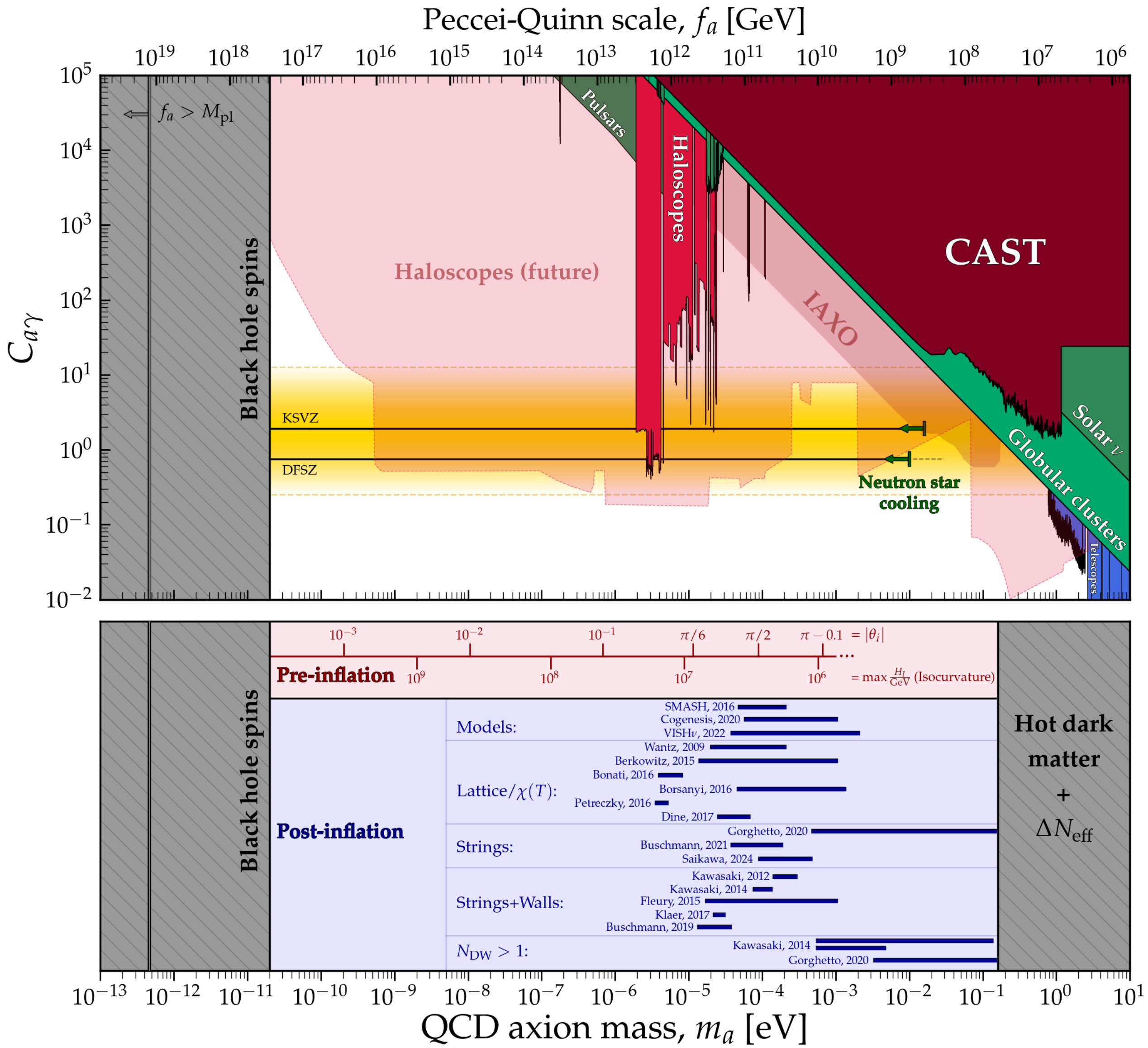
after inflation:



$m_a \sim \mu\text{eV} - \text{meV}$

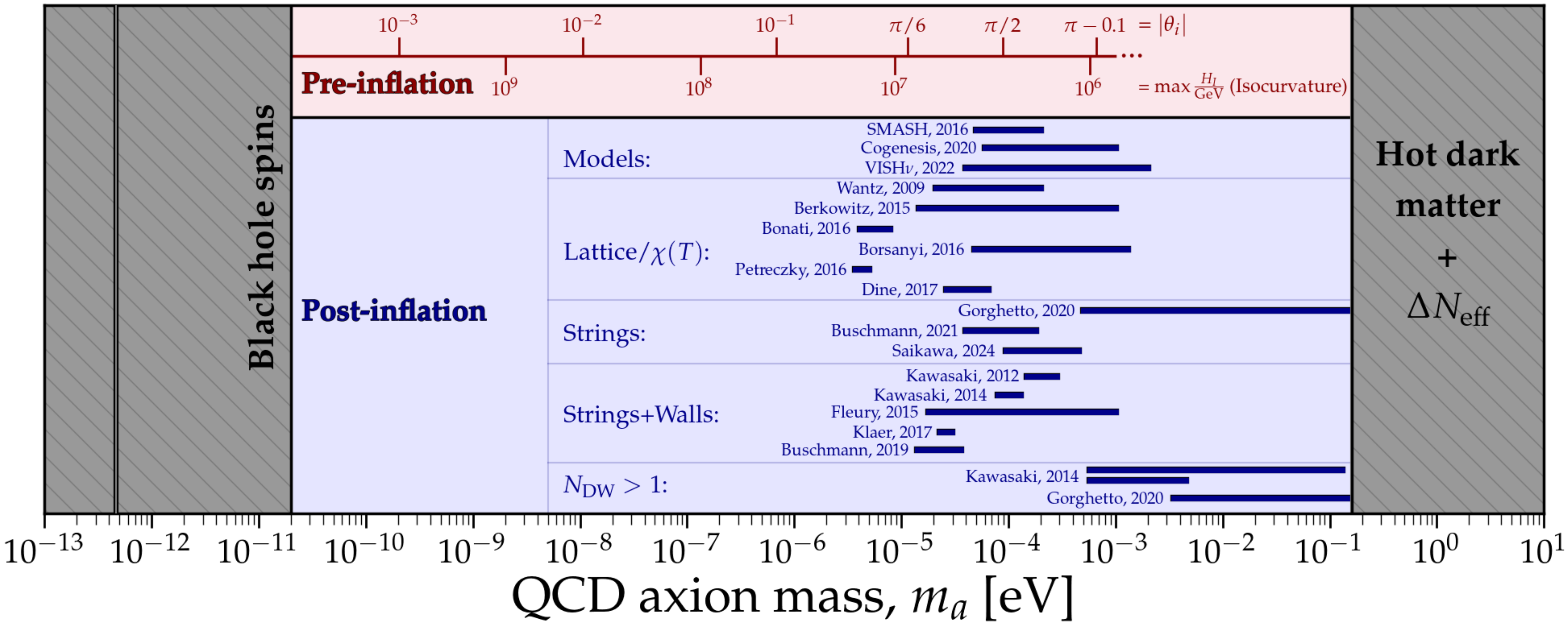
Axion Mass Predictions

[from cajohare.github.io/axionlimits]



Axion Mass Predictions

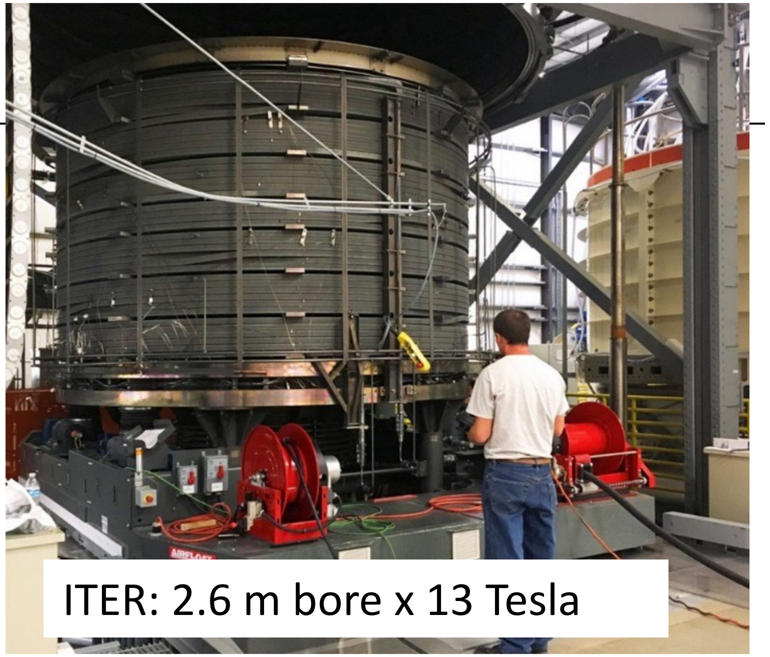
[from cajohare.github.io/axionlimits]

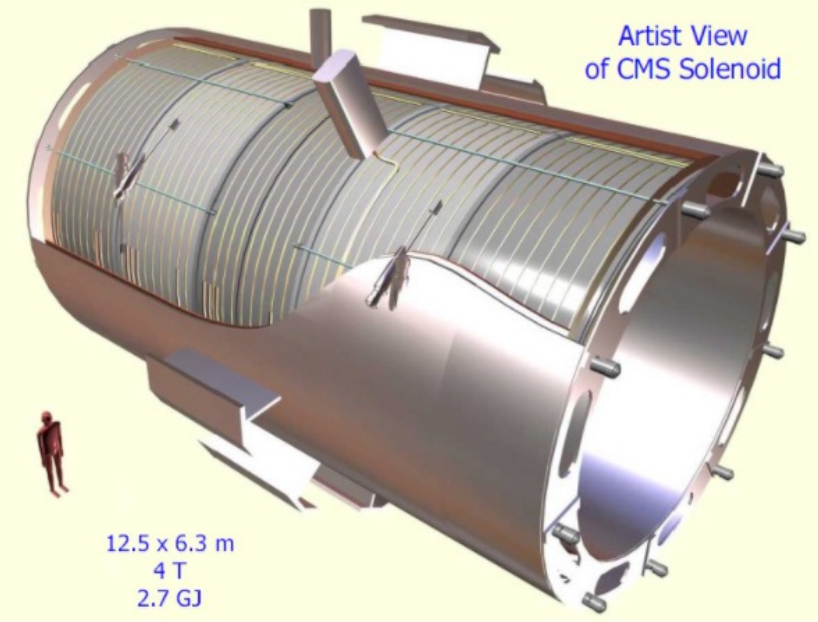


Large-Scale Solenoid Magnets

B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*Magnex*	*MRI/Mono*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	Magnex	MRI/Mono	Juelich	9.4	0.9	3	190	
70	45 T out	HF/Nb_3Sn CICC	MagLab	14	0.7	1	100	14
12	ADMX	Axion/NbTi mono	U Wash	7	0.5	1.1	14	0.4
5	900 MHz	NMR/Sn mono	MagLab	21.1	0.11	0.6	40	15

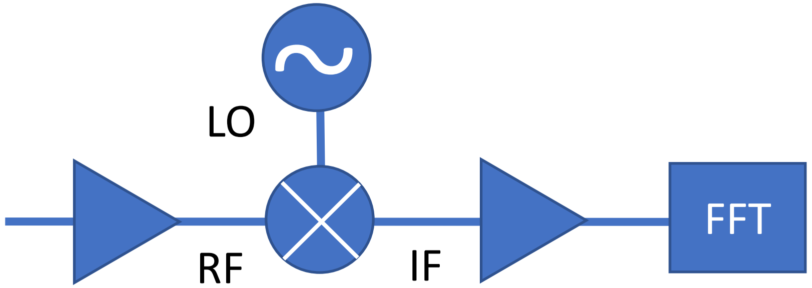
Compilation by Mark Bird, NHMFL





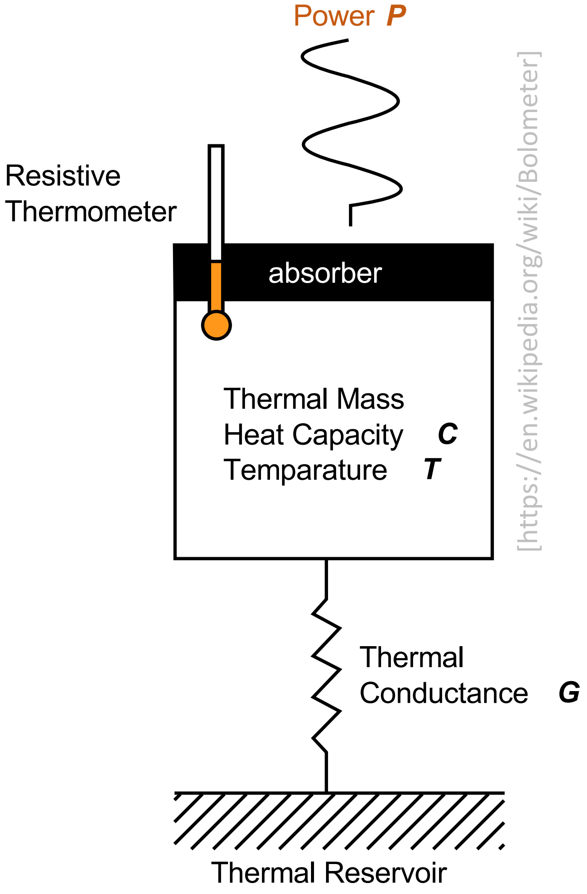
Sensors

Heterodyne



- high resolution
- **Standard Quantum Limit (SQL):**
  $k_B\, T_{noise} = hf$

Bolometer



[https://en.wikipedia.org/wiki/Bolometer]

NEP ~ $10^{-20}\, W/\sqrt{Hz}$

Single Photon Counting

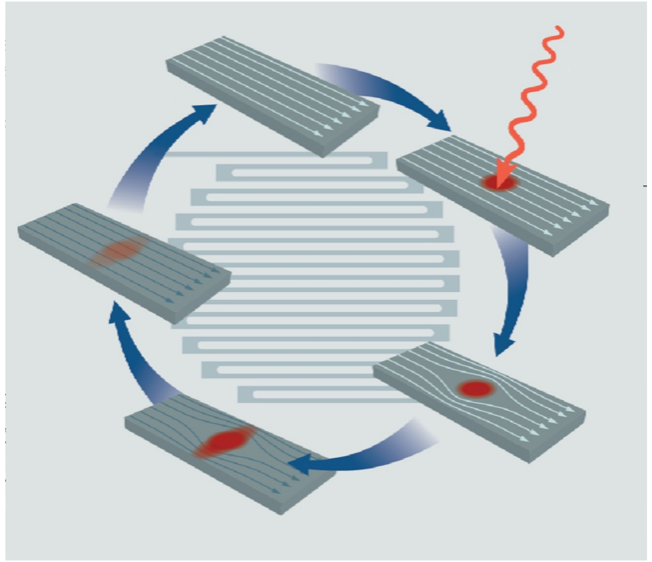


Fig.: Sae Woo Nam (NIST)

e.g., nanowire detectors

SNSPDs, KIDs, QCDs, …

down to ~ 1 photon/day

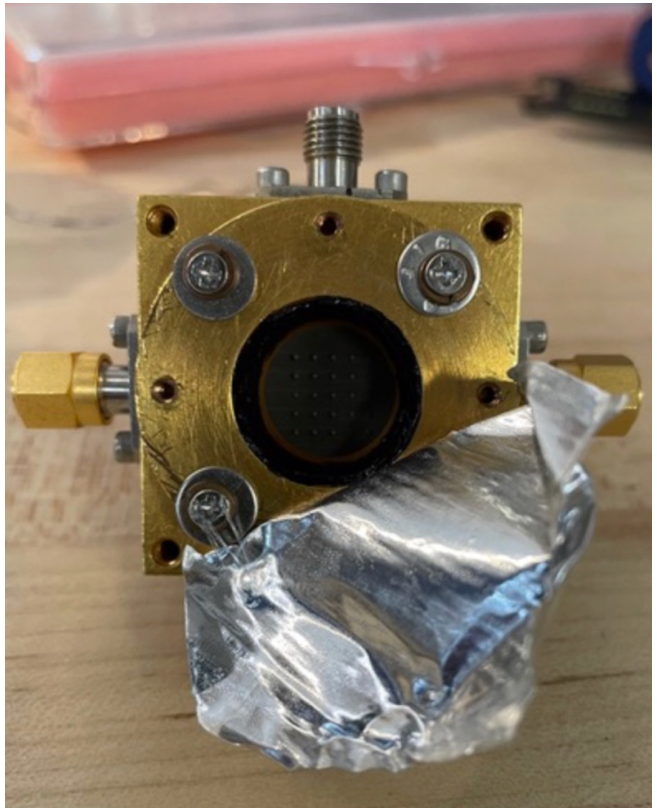
THz Sensors in Literature

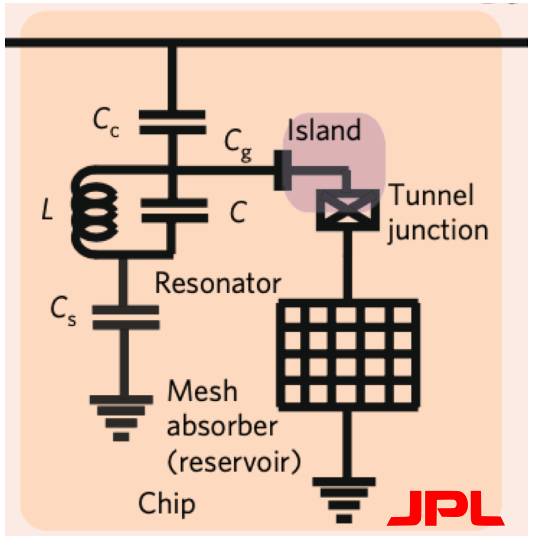
[Liu *et al*, BREAD collab., arXiv:2111.12103, PRL 128 (2022) 131801]

Photosensor	$\frac{E}{\text{meV}}$	$\frac{T_{\text{op}}}{\text{K}}$	$\frac{\text{NEP}}{\text{W}/\sqrt{\text{Hz}}}$	$\frac{A_{\text{sens}}}{\text{mm}^2}$	
Bolometers					
GENTEC	[0.4, 120]	293	$1 \cdot 10^{-8}$	$\pi 2.5^2$	[https://www.gentec-eo.com/]
IR LABS	[0.24, 248]	1.6	$5 \cdot 10^{-14}$	1.5^2	[https://www.irlabs.com/products/bolometers/]
KID/TES	[0.2, 125]	0.3	$2 \cdot 10^{-19}$	0.2^2	[Ridder *et al*, J. Low Temp. Phys. 184, 60–65 (2016)], [Baselmans *et al*, Astro. Astroph. 601, A89 (2017)]
Single Photon Counters					
QCDet	[2, 125]	0.015	$\frac{\text{DCR}}{\text{Hz}} = 4$	0.06^2	[Echternach *et al.*, Nat. Astron. 2, 90–97 (2018)], [Echternach *et al.*, J. Astron. Telesc. Instrum. Syst. 7, 1–8 (2021)]
SNSPD	[124, 830]	0.3	$\frac{\text{DCR}}{\text{Hz}} = 10^{-4}$	0.4^2	[Hochberg, et al., Phys. Rev. Lett. 123, 151802 (2019)] [Verma, *et al.*, arXiv:2012.09979 [physics.ins-det] (2020)]

Single Photon Sensors

Quantum Capacitance Detectors (QCDet, ~ 1.5THz)

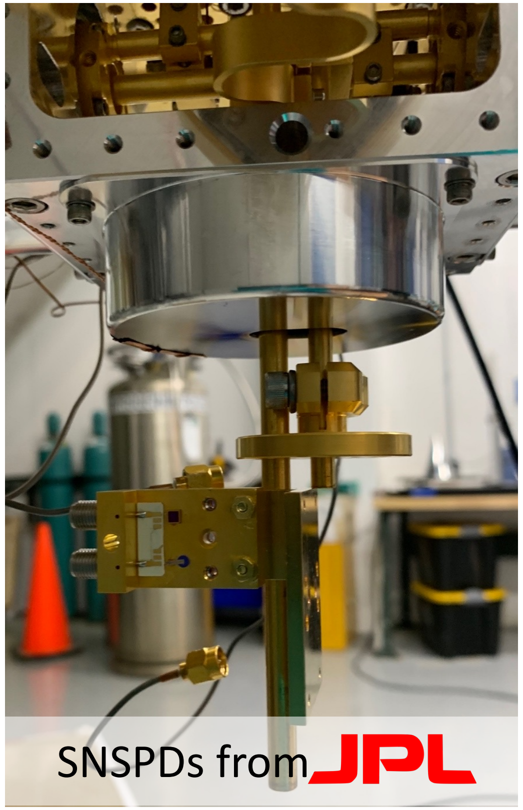


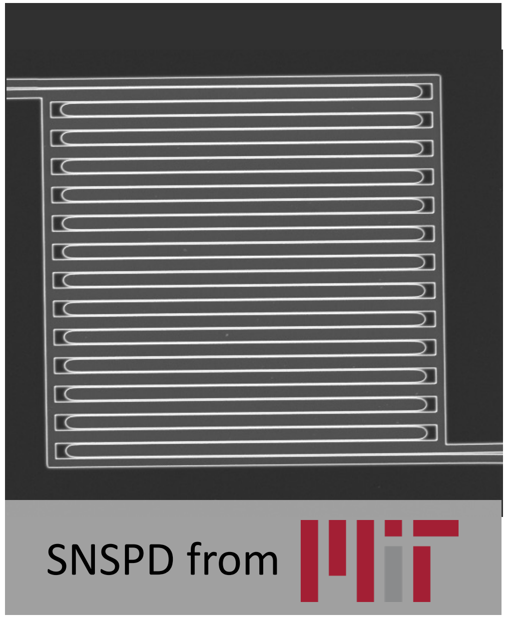


Credit: Rakshya Khatiwada et. al.

→ TeraBREAD

Superconducting Nanowire Single Photon Detectors (SNSPD, Infrared)





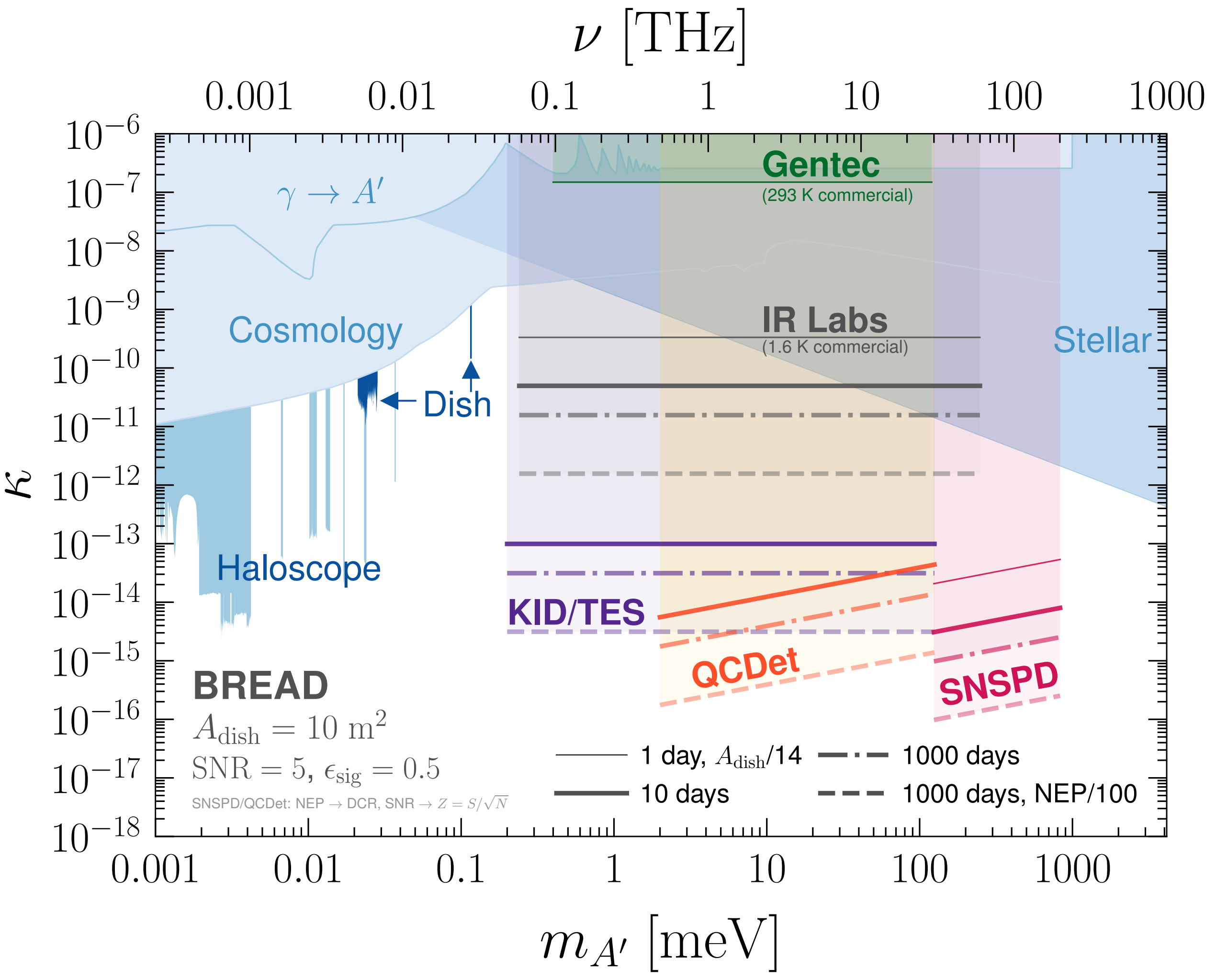
Credit: Cristian Pena et. al.

→ InfraBREAD

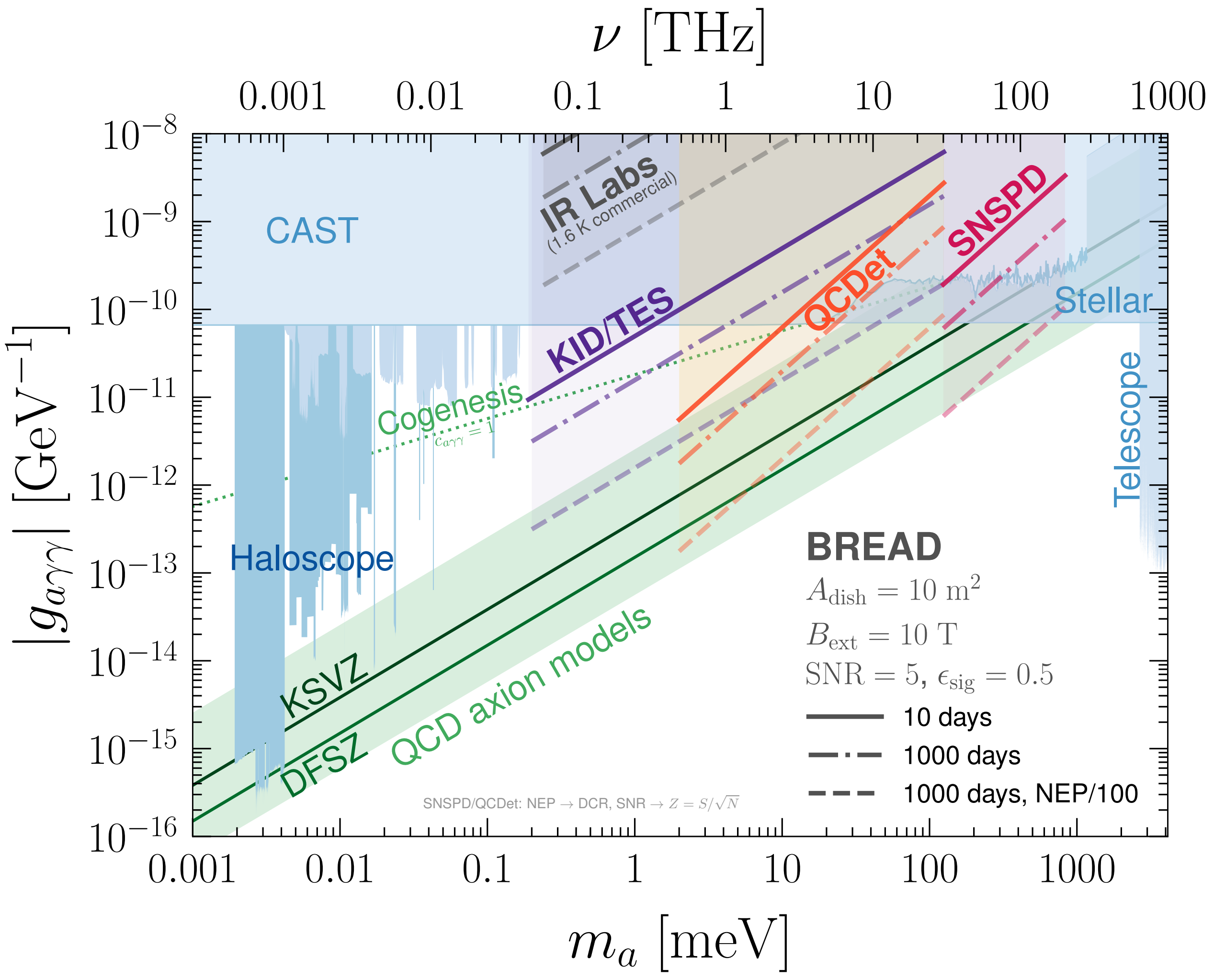
Sensitivities with Literature Sensors

[Liu *et al*, BREAD collab., arXiv:2111.12103, PRL 128 (2022) 131801]

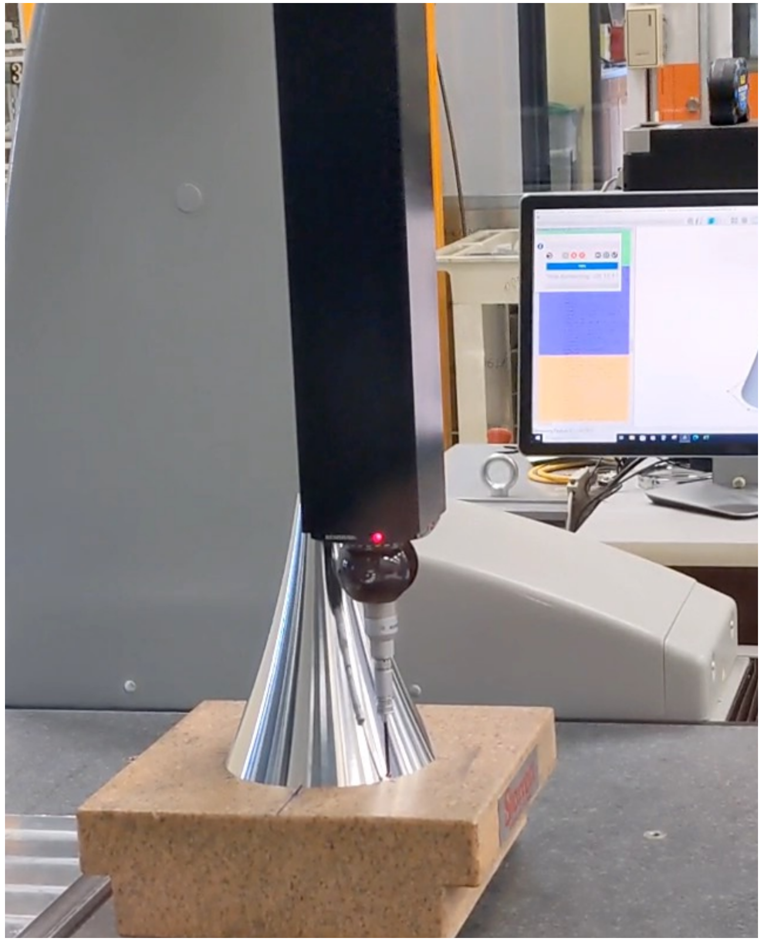
Hidden Photons



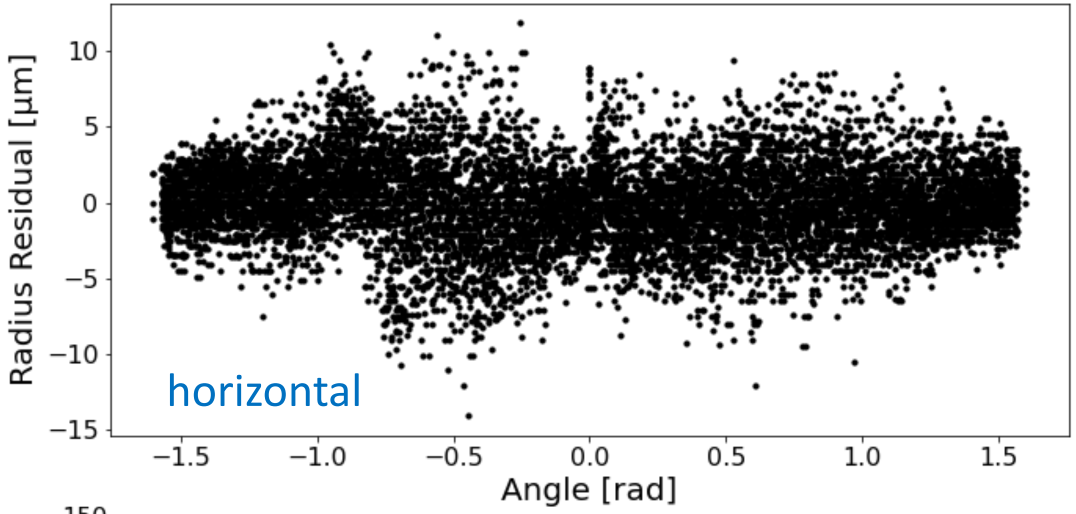
Axions

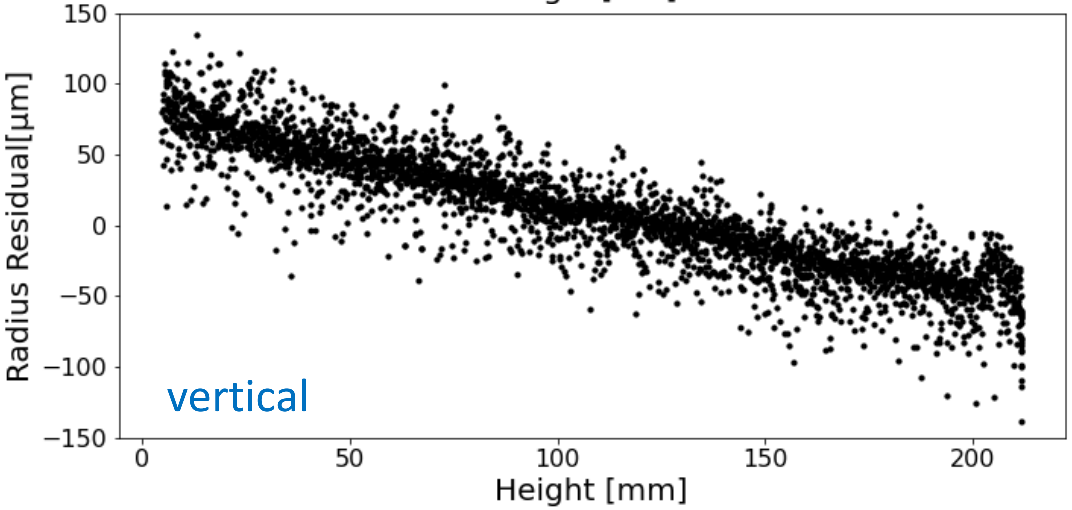


First Prototype Reflector Characterization



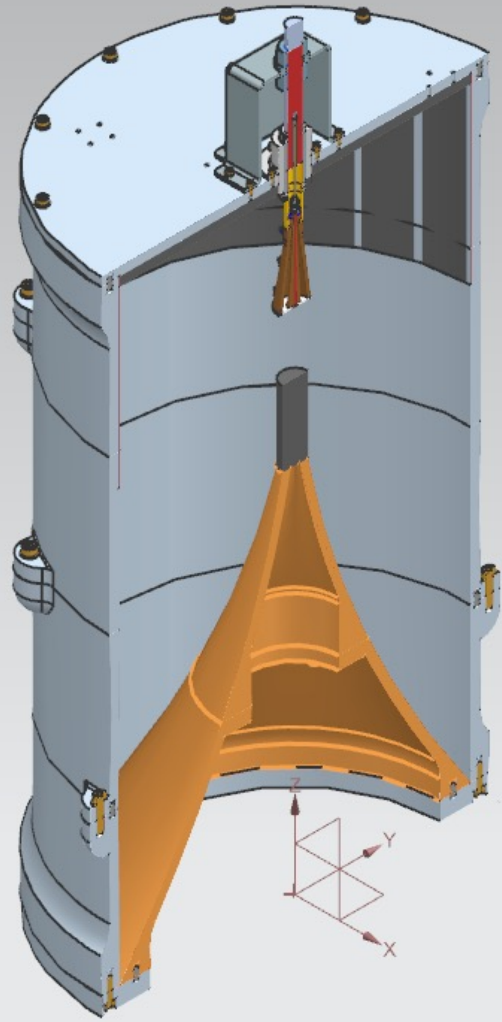
Mechanical Touches

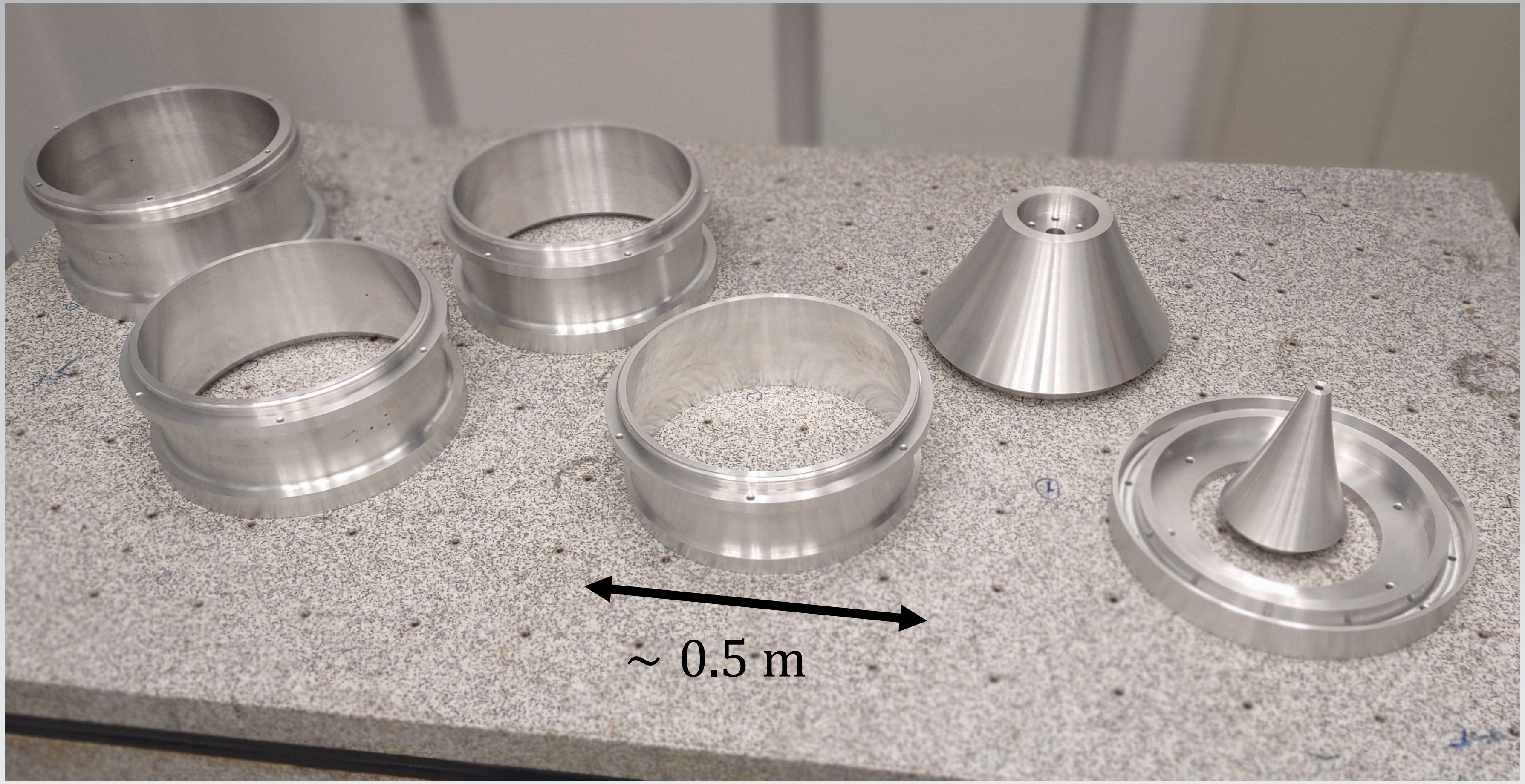




Horizontal Machine Marks *O(100μm)*

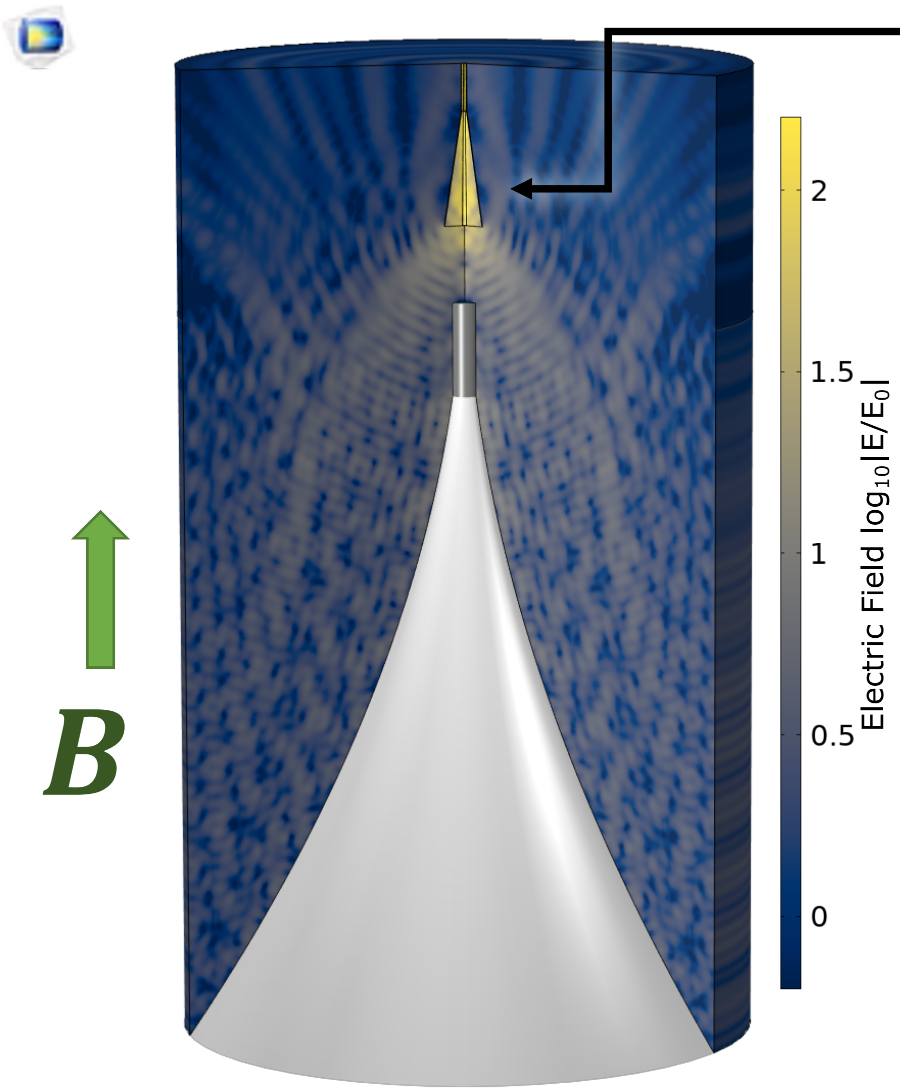
First Complete BREAD Reflector



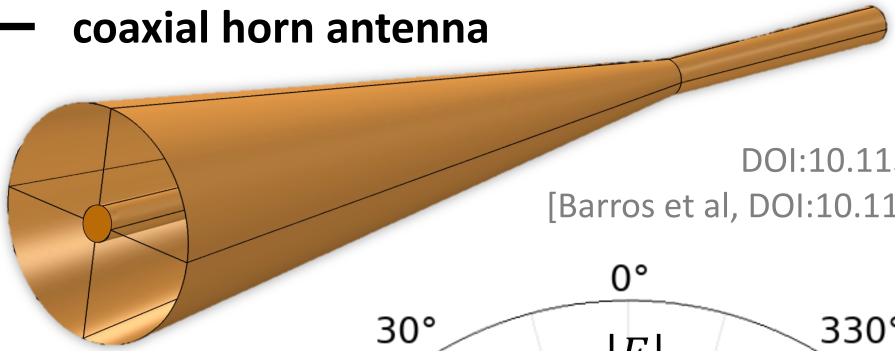


dish area: $\mathbf{A \approx 0.7\ m^2}$

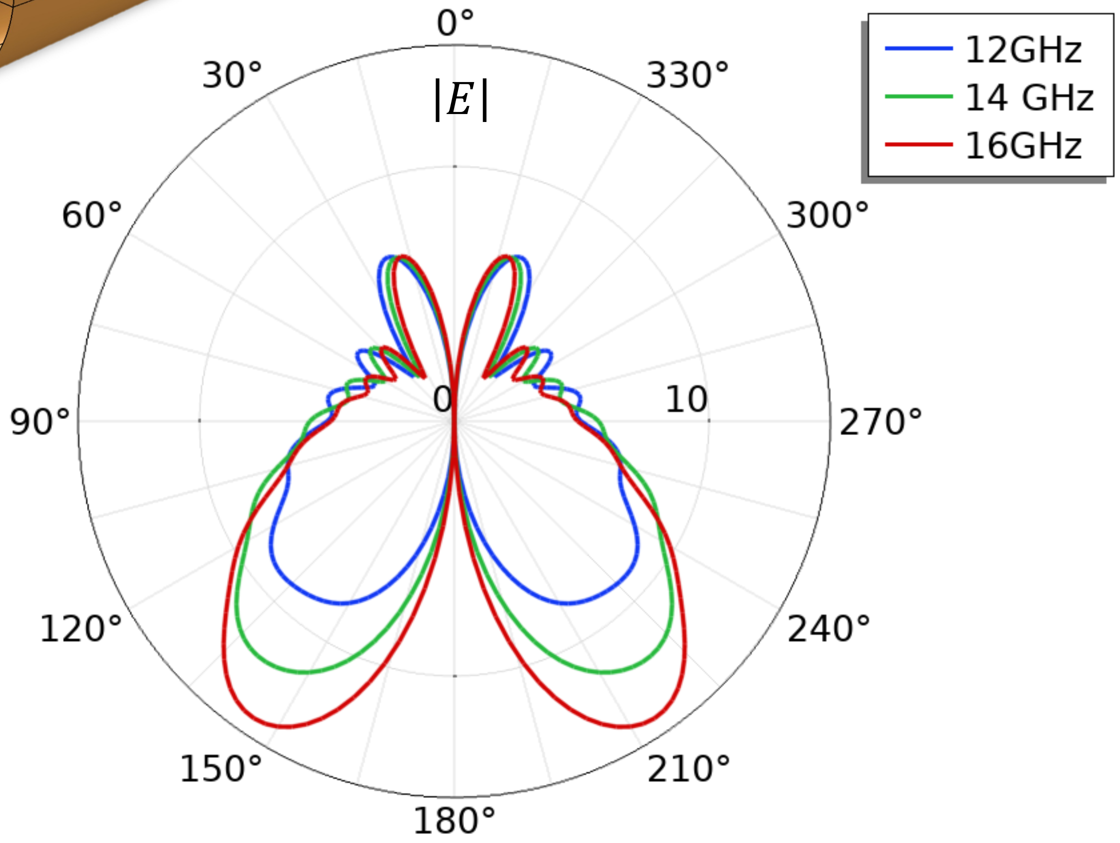
GigaBREAD: RF Simulation



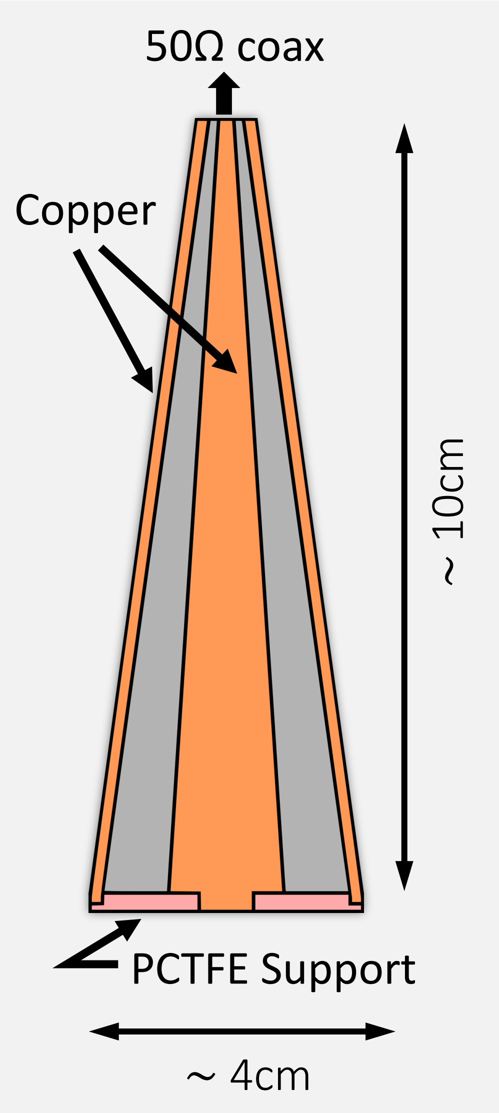
coaxial horn antenna



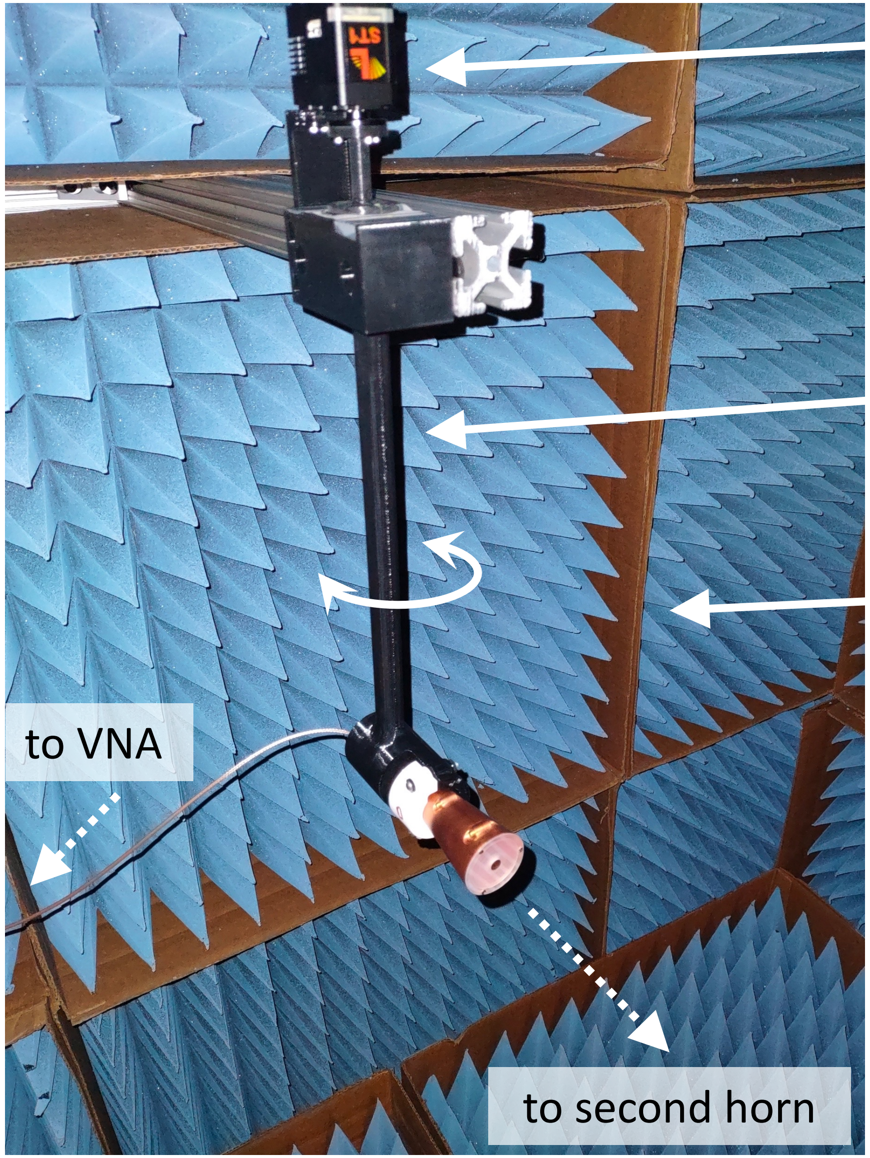
e.g. [Bykov et al, DOI:10.1134/S0020441208050126]
[Barros et al, DOI:10.1109/IMOC.2013.6646569]



GigaBREAD: Coaxial Horn



GigaBREAD: Horn Characterization



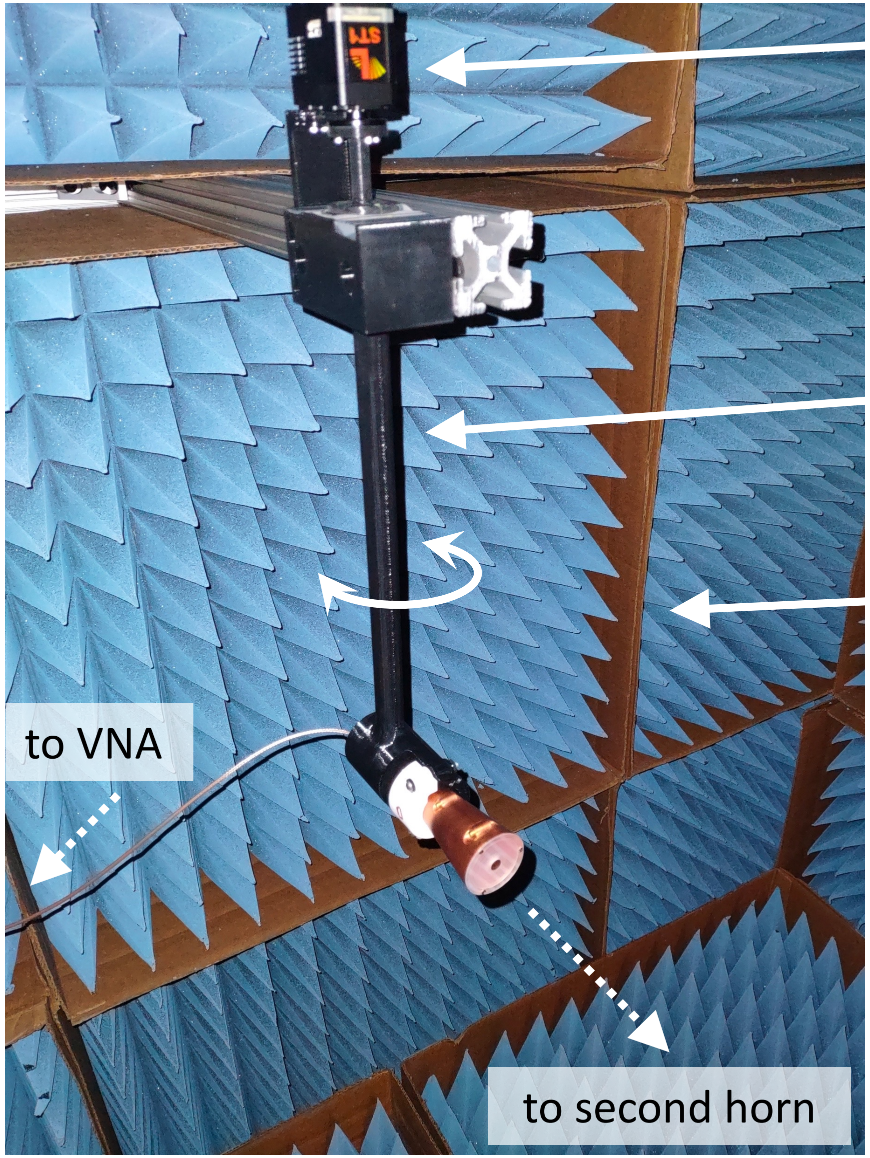
servo rotary motor

3D printed plastic mount

RF absorbers

Right: Gabe Hoshino

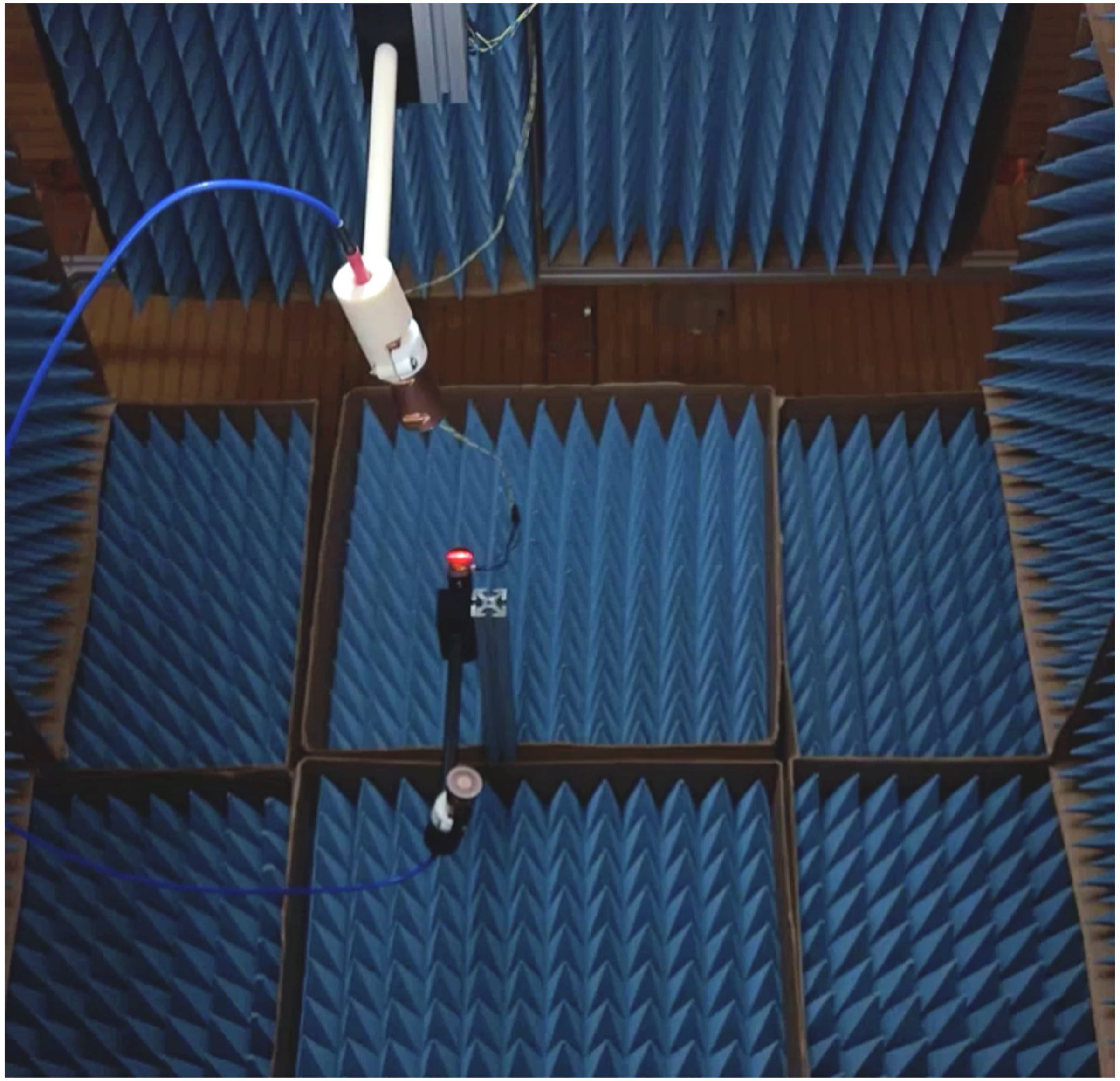
GigaBREAD: Horn Characterization



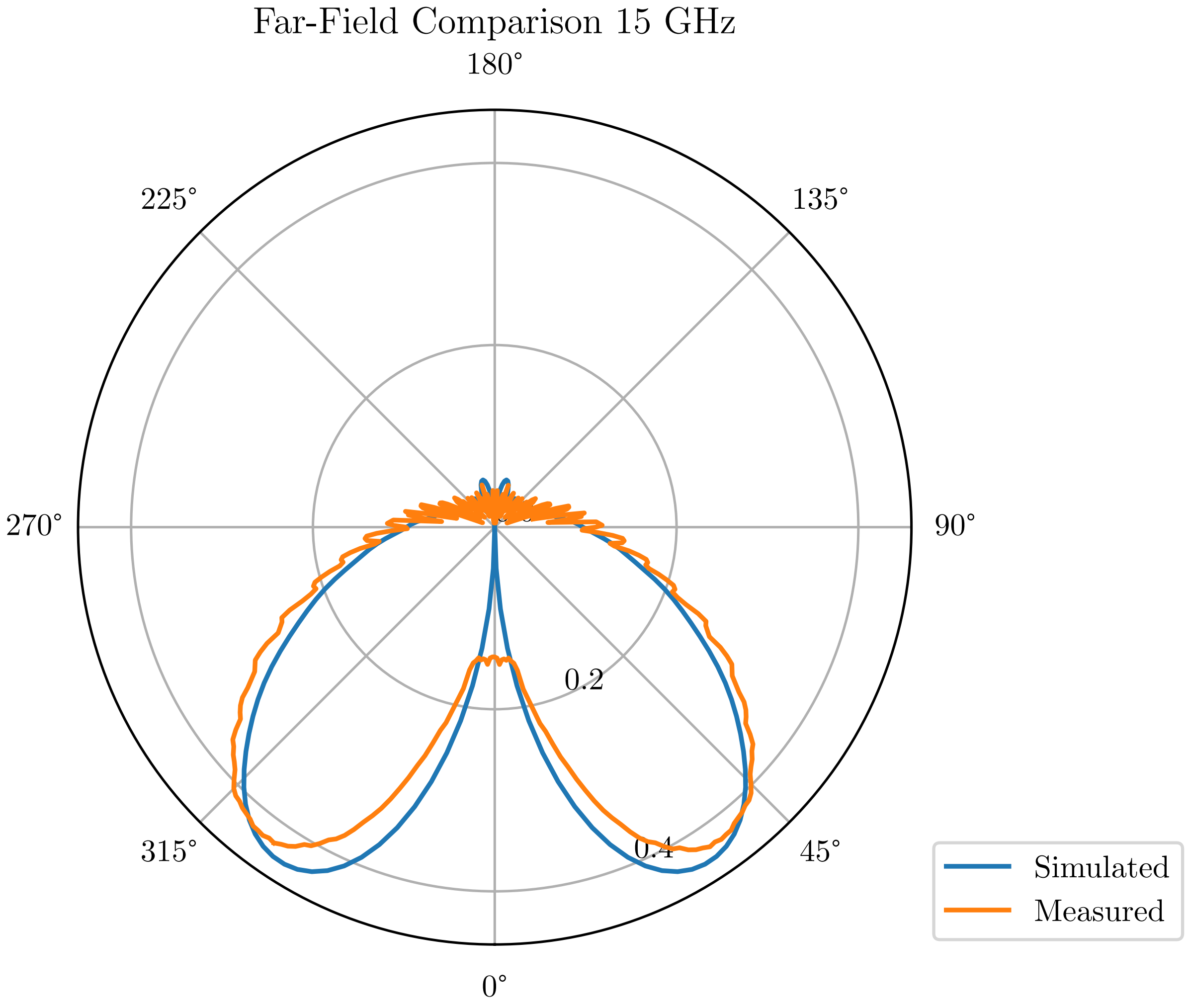
servo rotary motor

3D printed plastic mount

RF absorbers



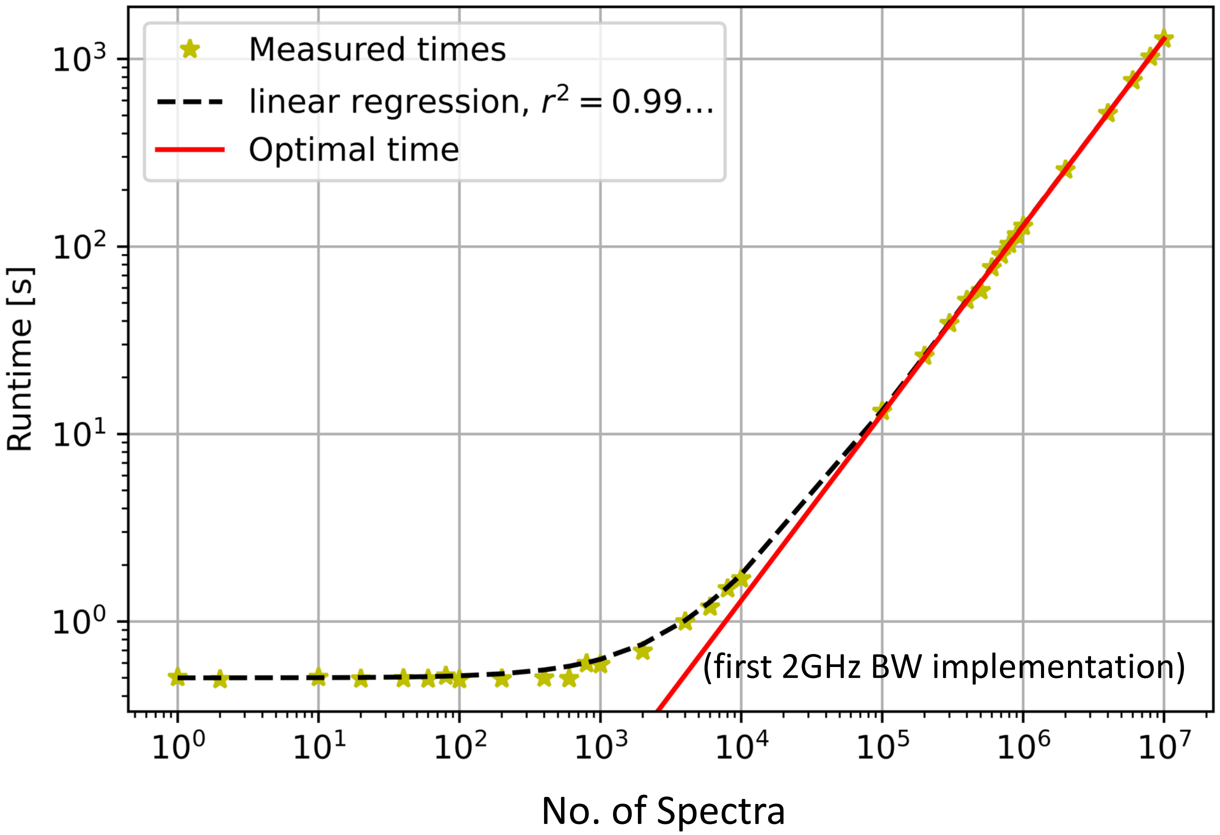
GigaBREAD: Horn Characterization



horns show close to expected performance

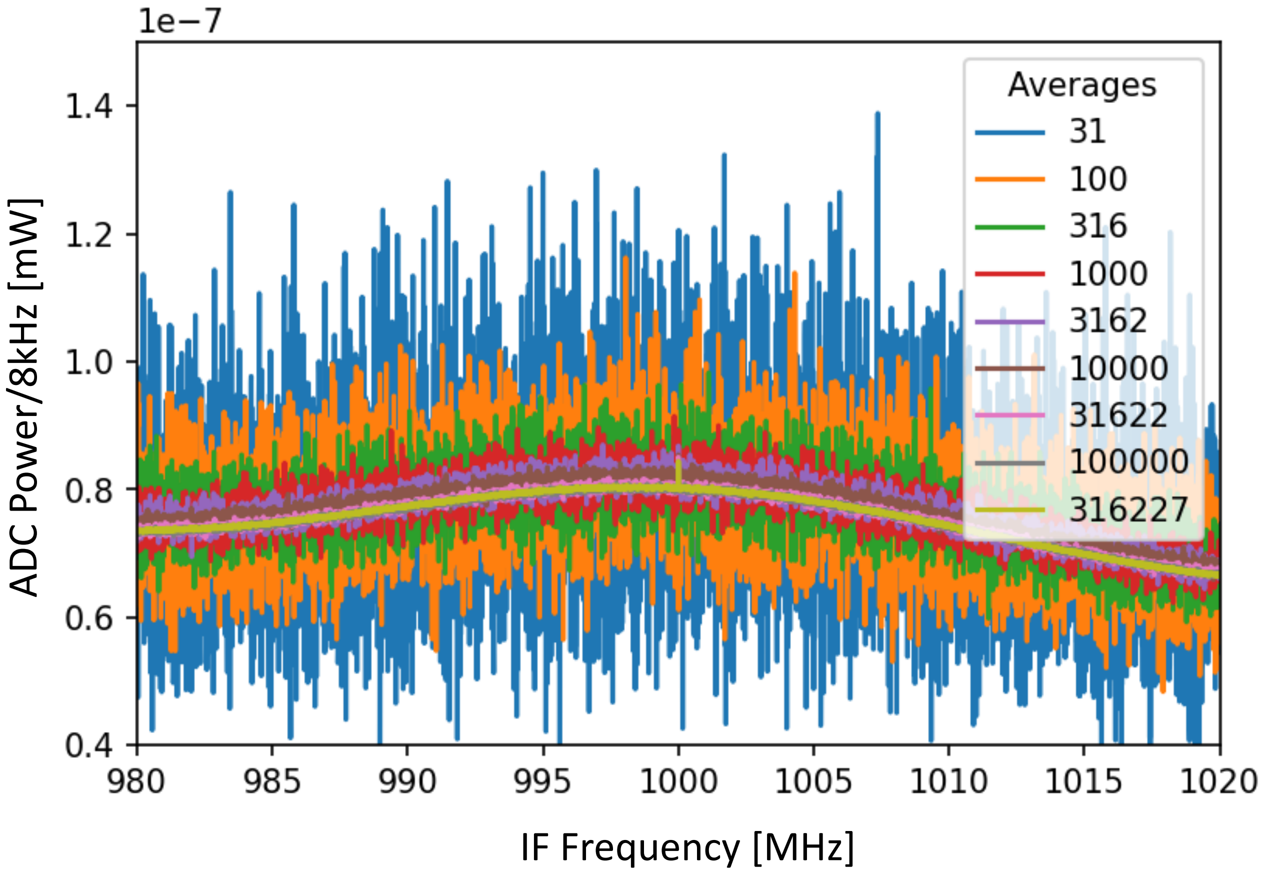
GigaBREAD: Preliminary DAQ Tests

Deadtime



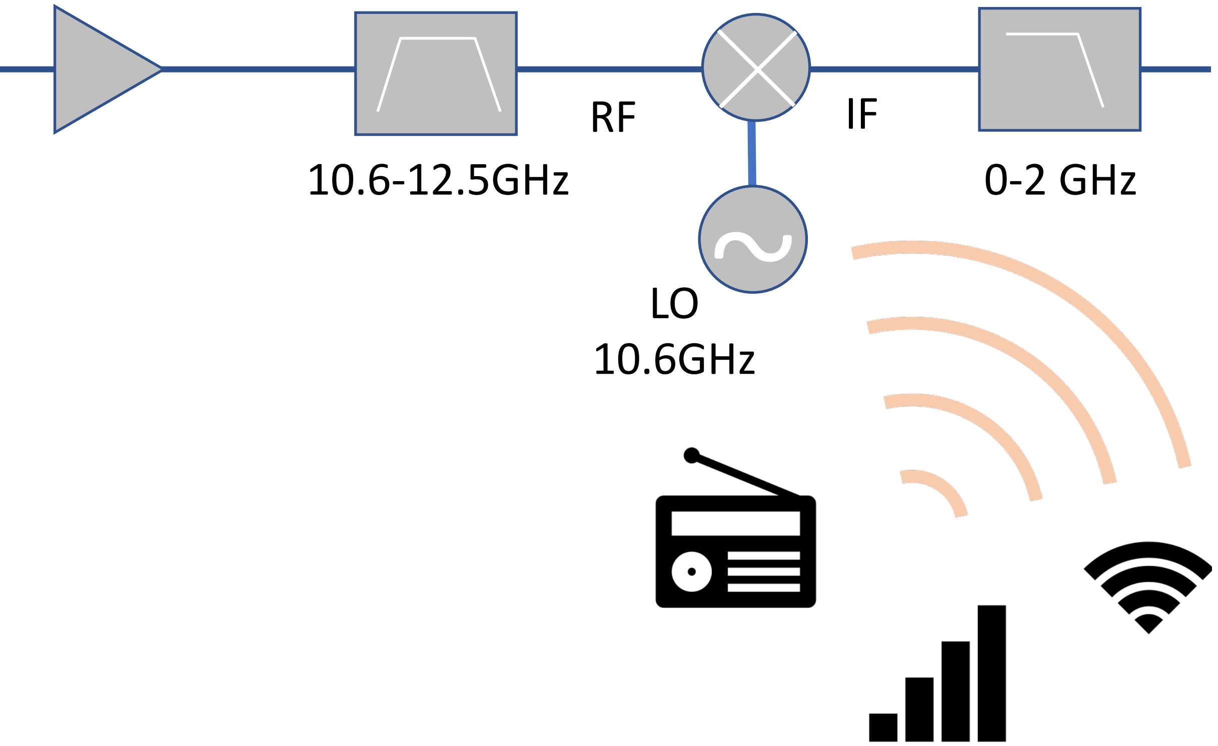
Deadtime: ~0.5s, negligible after many spectra

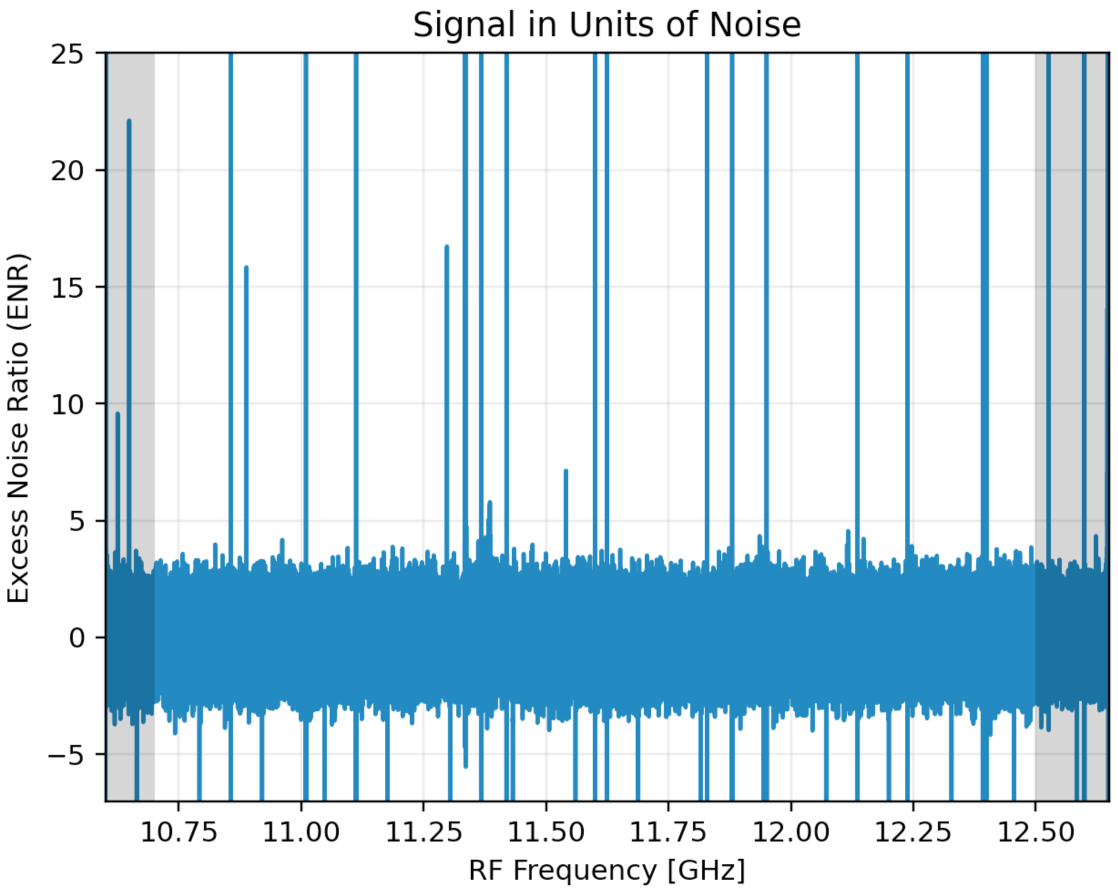
Real-Time Averager



Averaging working

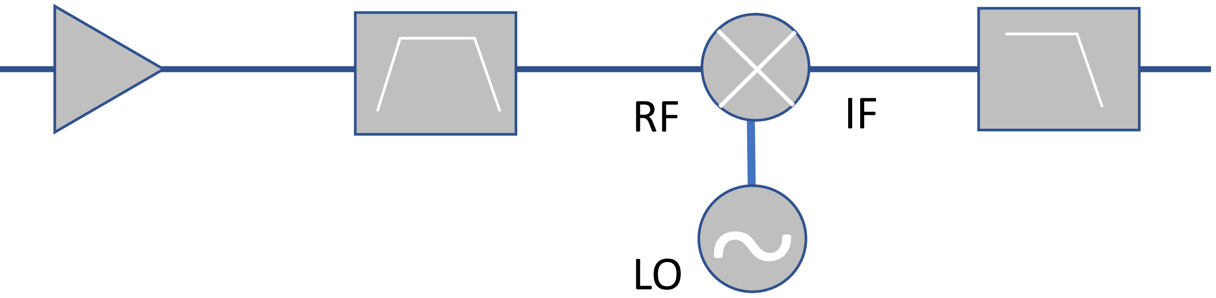
DAQ RFI Rejection Scheme



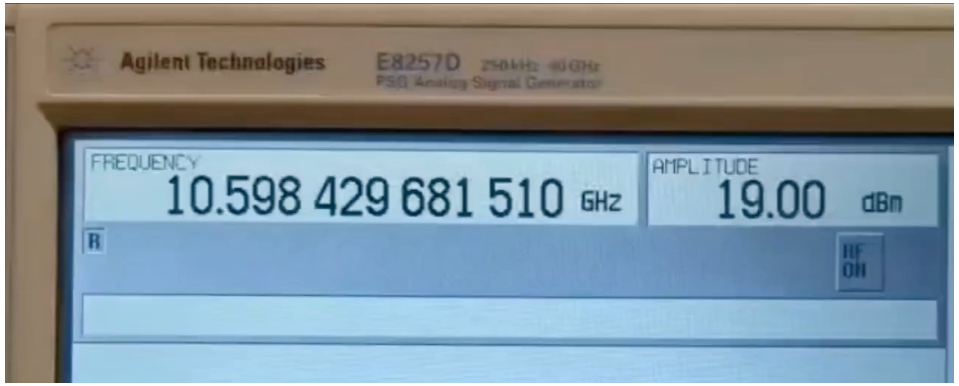


common issue: external RFI sources couple into large bandwidth DAQ

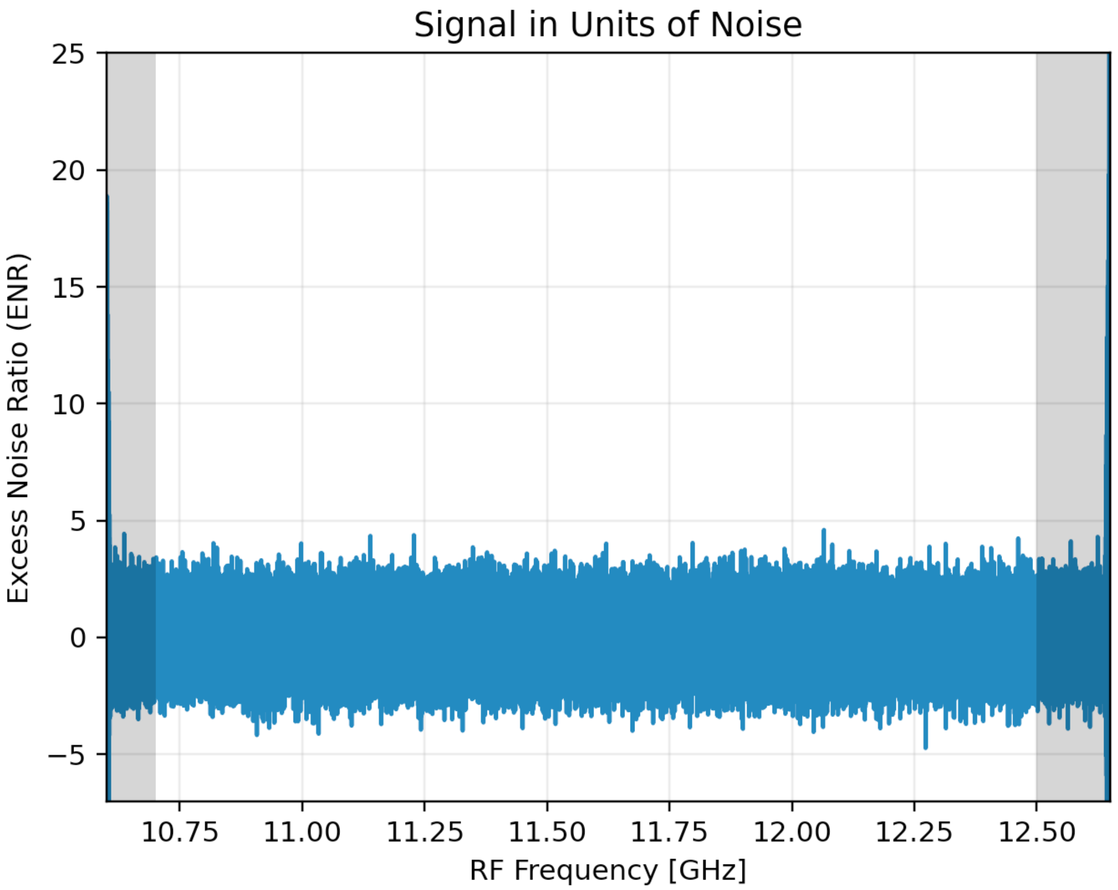
DAQ RFI Rejection Scheme



LO frequency hopping:

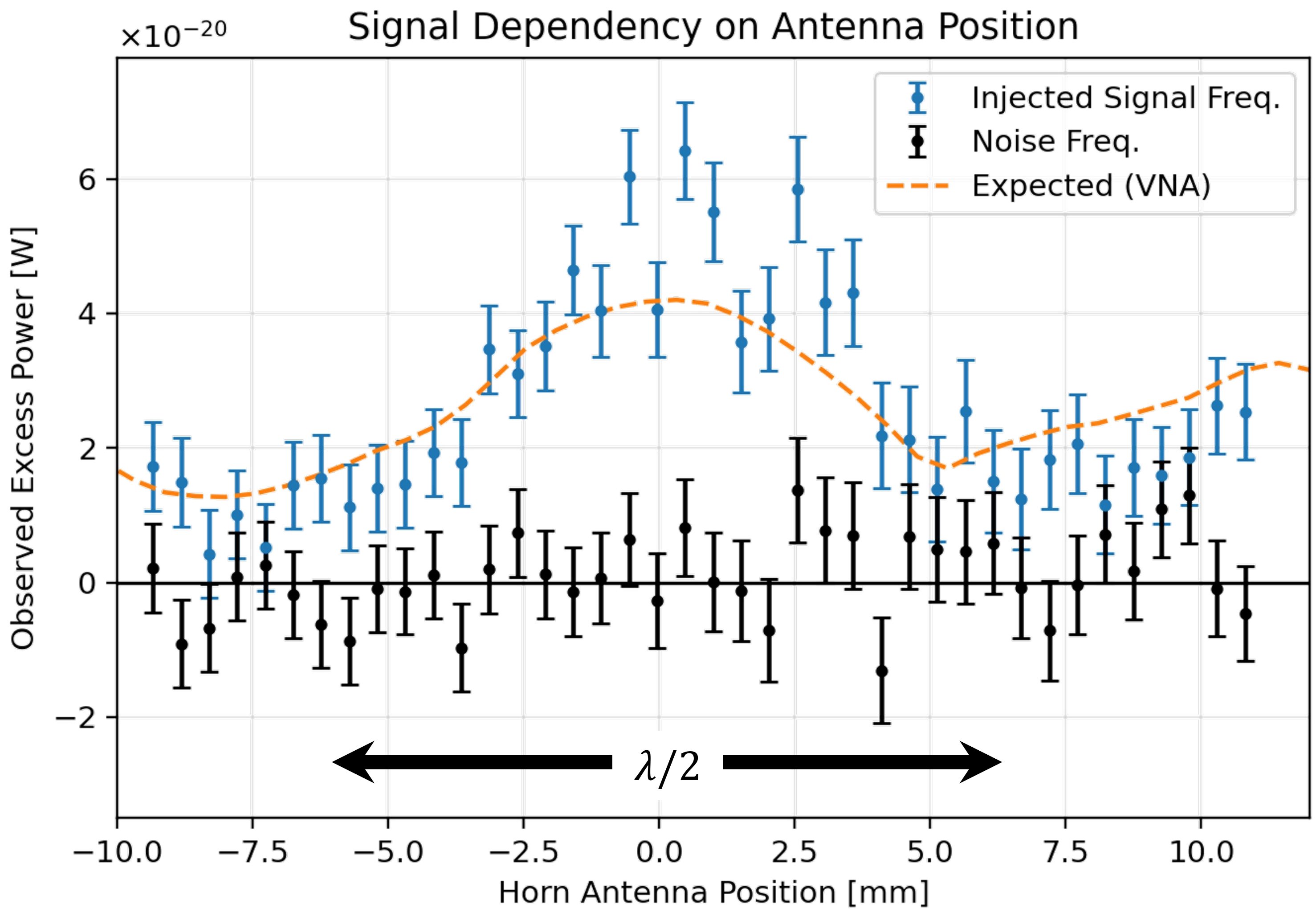


(controlled by DAQ board)



intrinsic RFI rejection with negligible impact on sensitivity

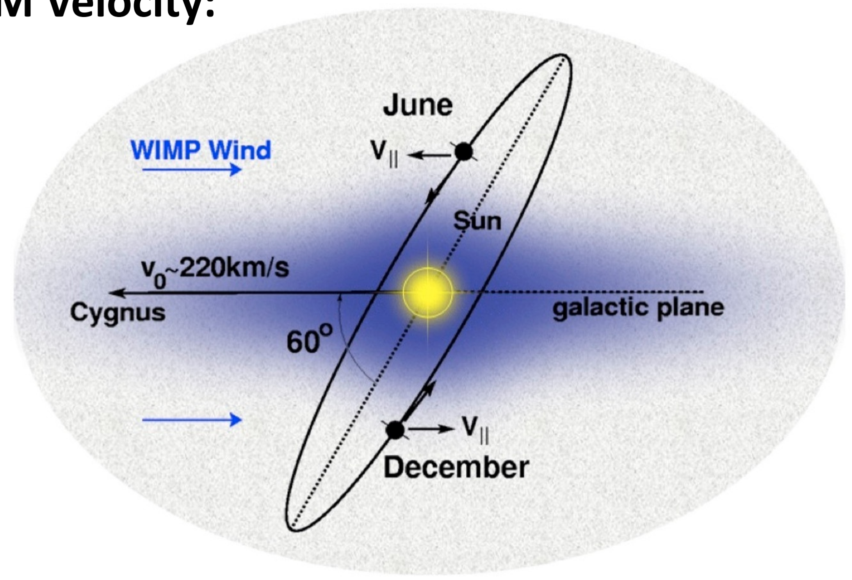
Result – Injected Signal



see expected resonant enhancement

InfraBREAD: Velocity Effects

CDM Velocity:



[https://www.hep.ucl.ac.uk/darkMatter/pictures/wind.jpg]

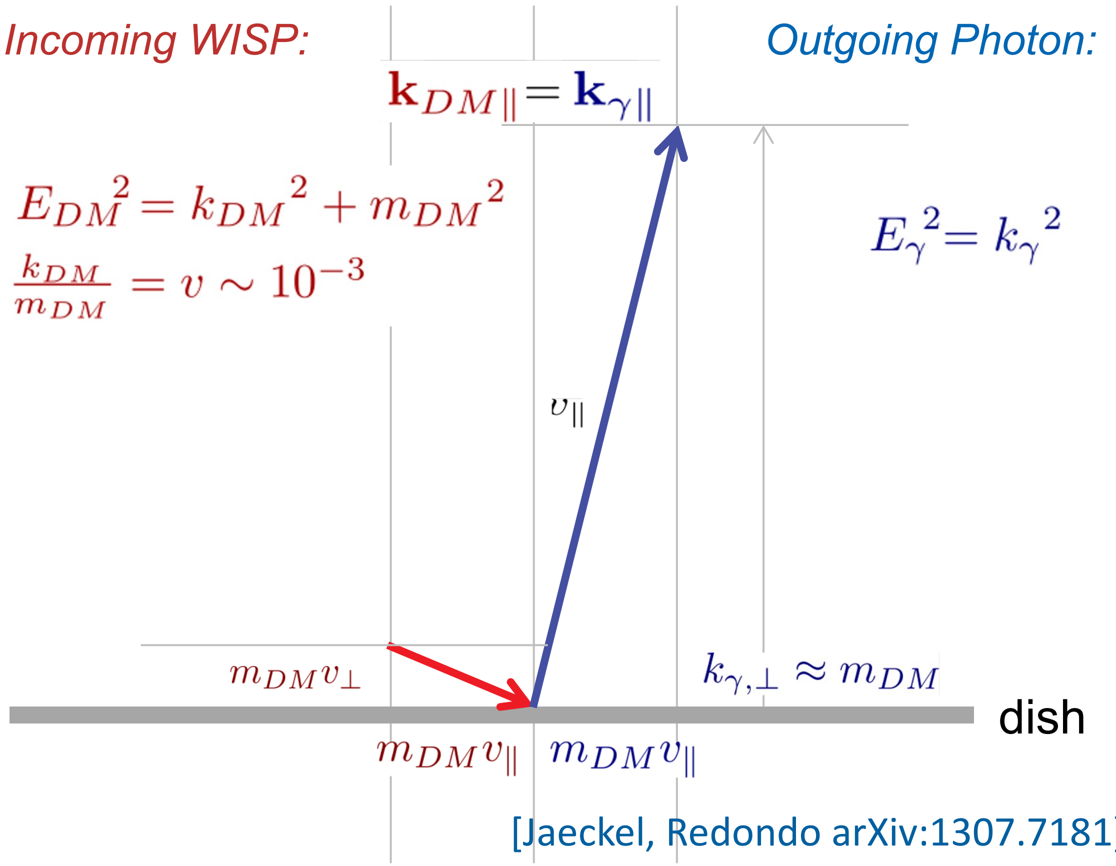
Standard Halo Model:

$$f(\boldsymbol{v}) = \frac{1}{(2\pi\sigma_v^2)^{3/2}} \exp\left(-\frac{|\boldsymbol{v} - \boldsymbol{v}_{\rm lab}|^2}{2\sigma_v^2}\right) \frac{\Theta\left(v_{\rm esc} - |\boldsymbol{v}|\right)}{N_{\rm esc}}$$

$$|\boldsymbol{v}_{\rm lab}| \sim 220\,{\rm km\,s^{-1}},\ \sigma_v \sim 156\,{\rm km\,s^{-1}}$$

DM velocity $\sim v \sim 10^{-3}c$

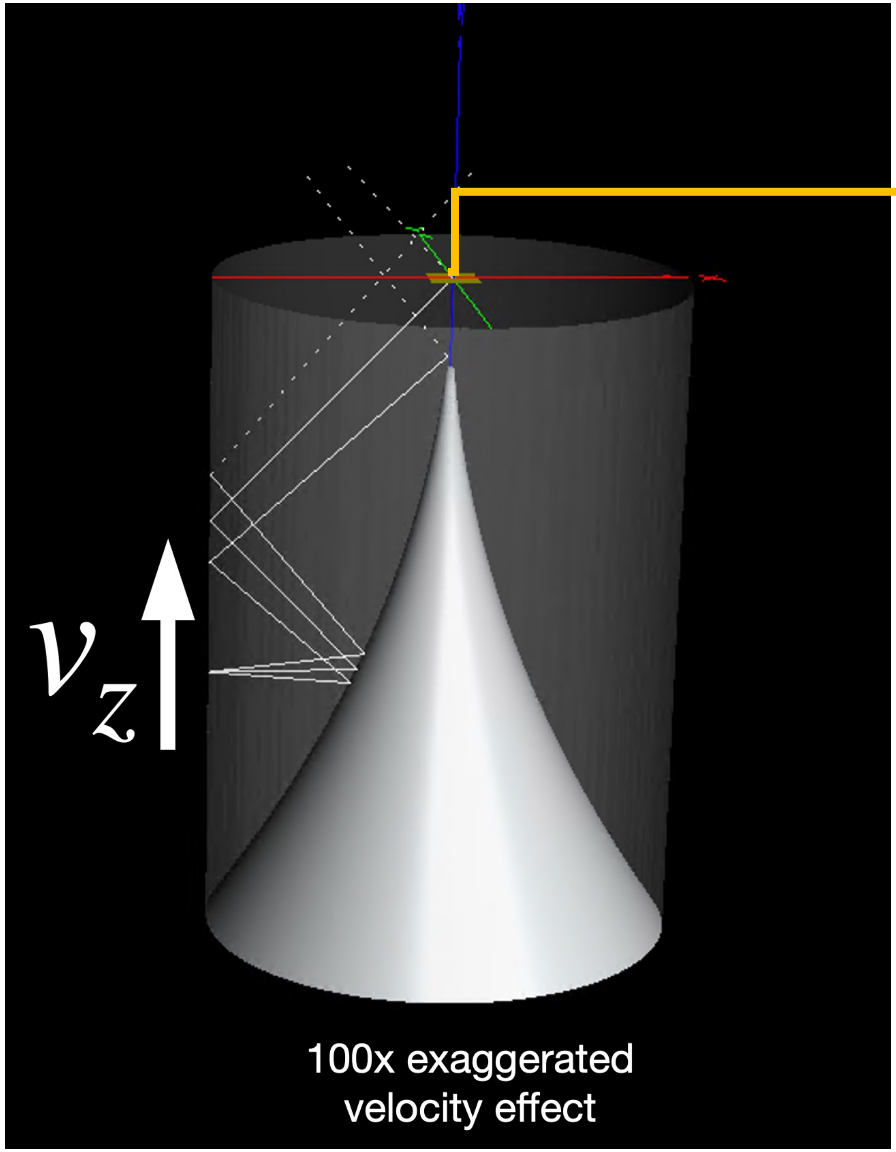
For Dish Antenna:

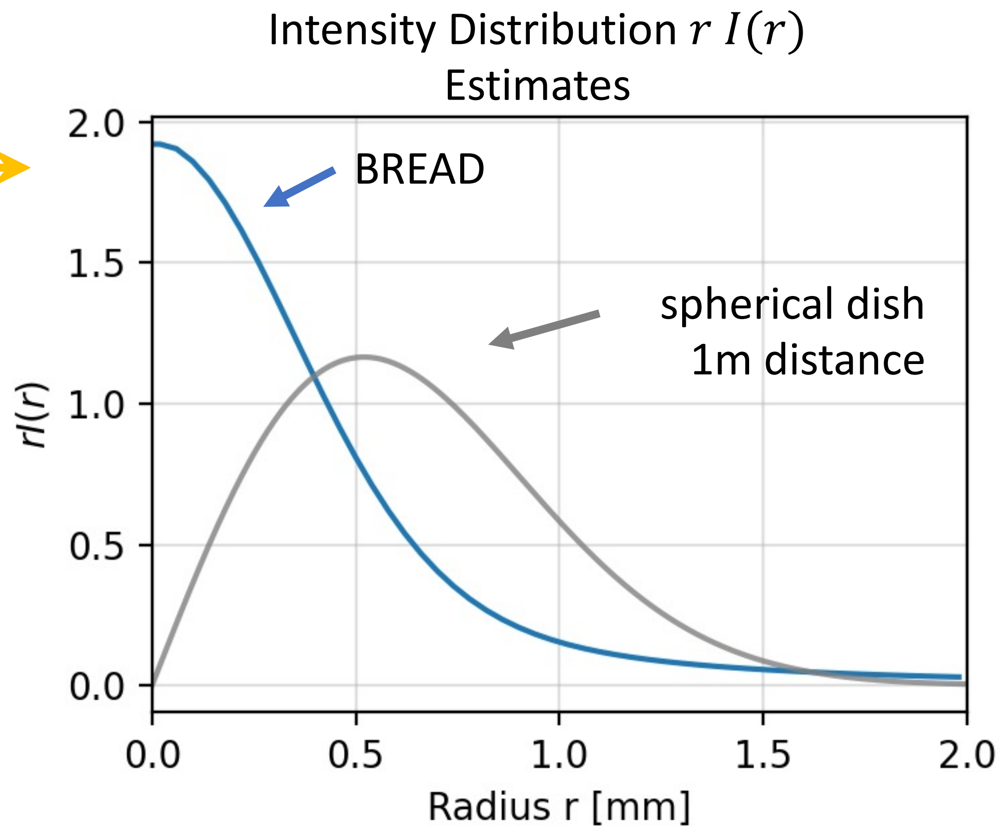


[Jaeckel, Redondo arXiv:1307.7181]
[Jaeckel, SK arXiv:1509.00371]

outgoing angle $\sim v \sim 10^{-3}c$

InfraBREAD: Velocity Effects





Radius:

$$R = 200\text{mm}$$

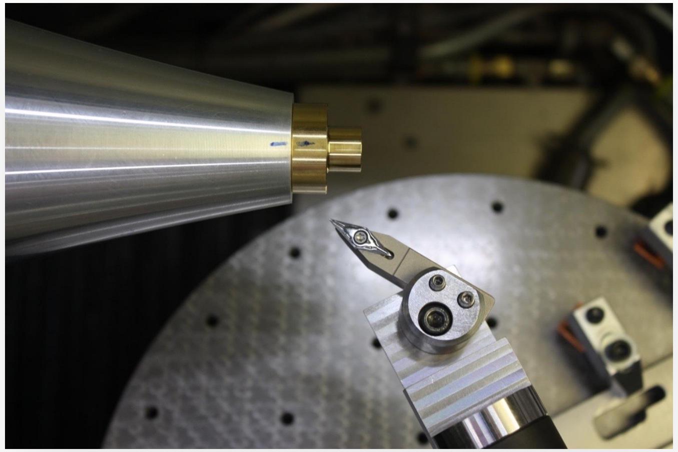
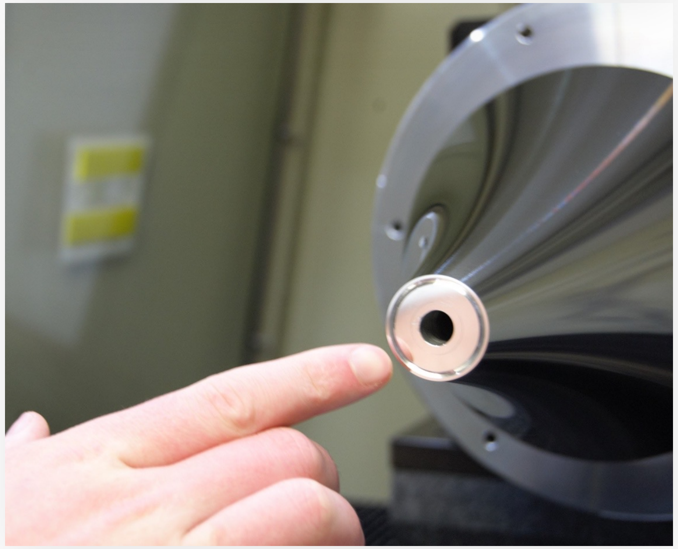
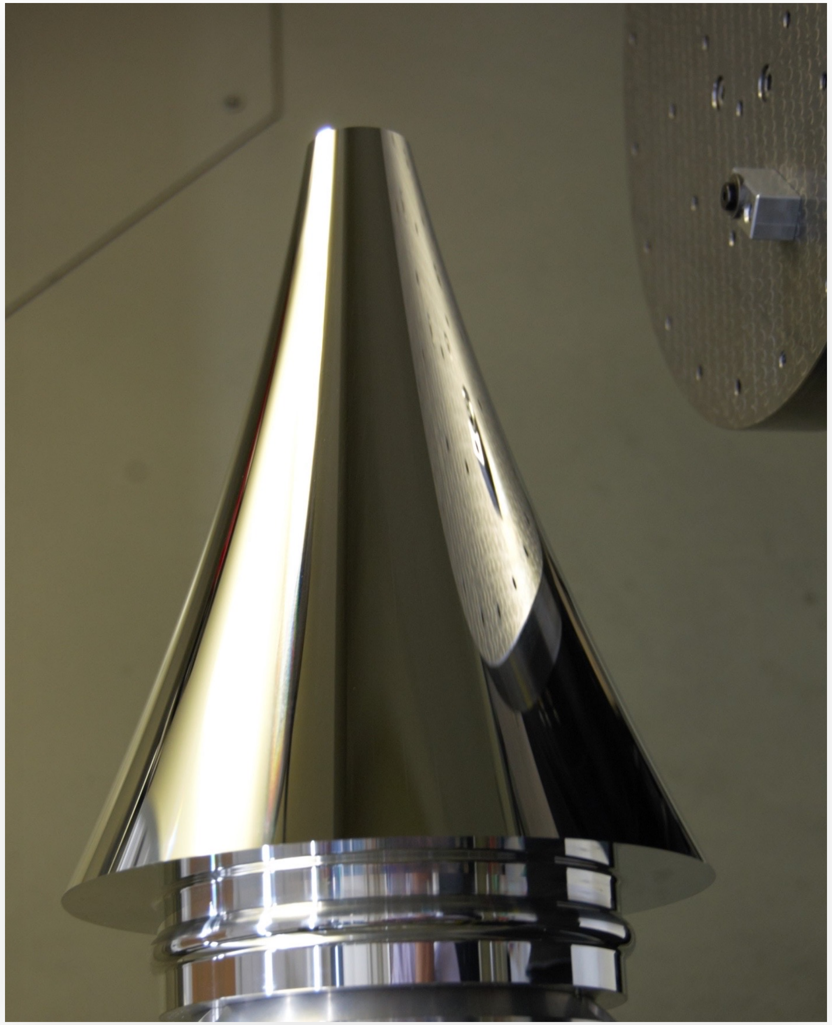
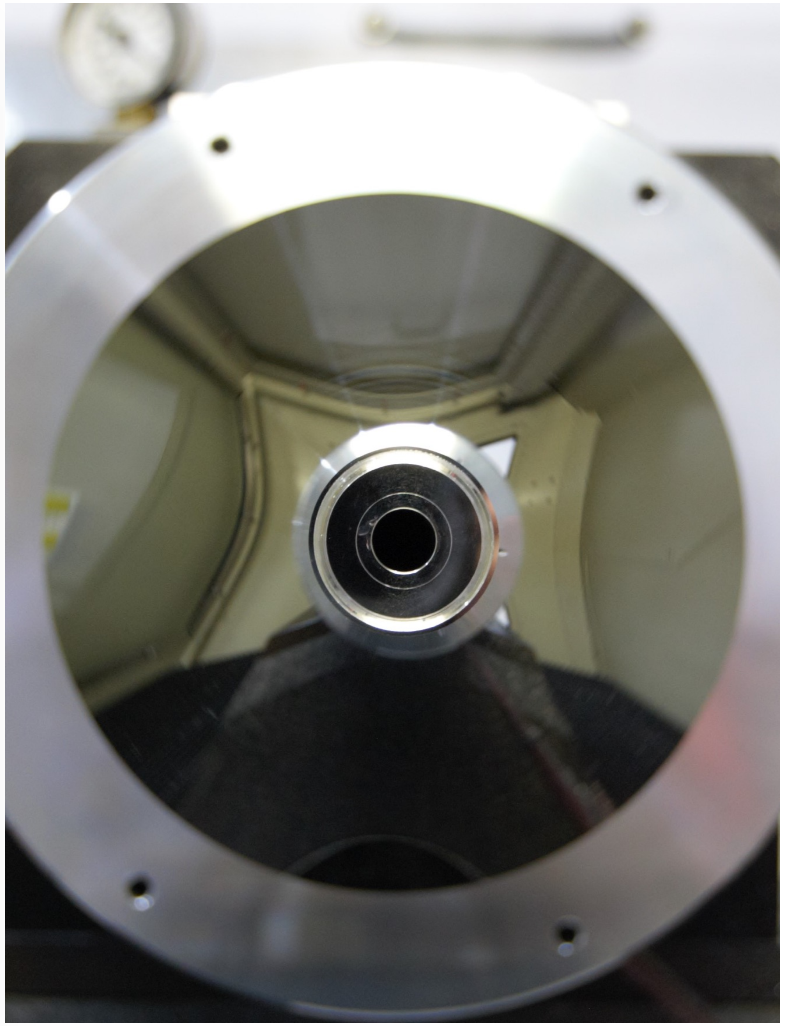
Dish Area:

$$A = 0.7\text{m}^2$$

(Pilot Experiment Dims.)

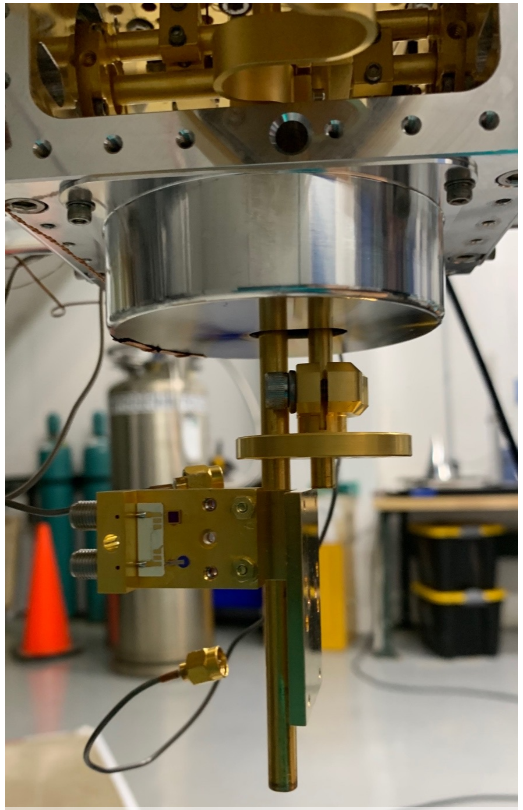
focusing velocity effect limited

InfraBREAD: Optical Grade Reflector from LLNL

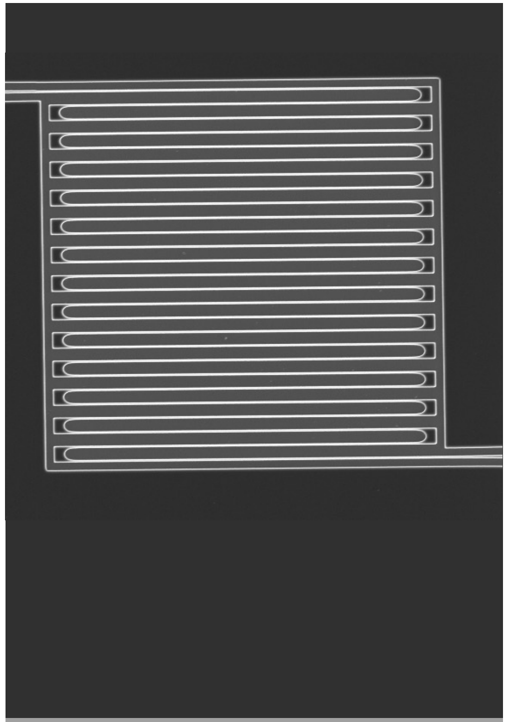





mirror-like finish, expected focal properties

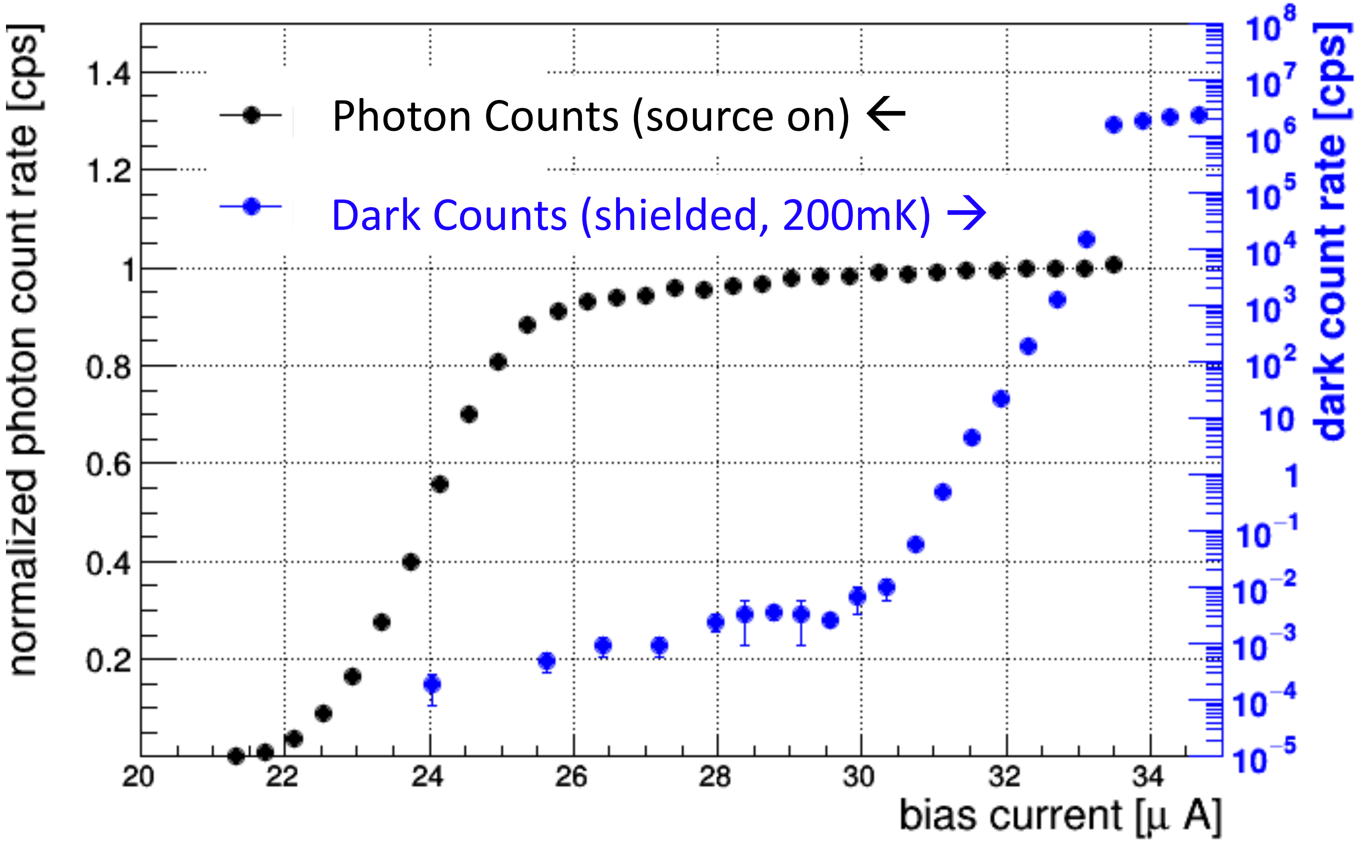
Infrared Sensors: Superconducting Nanowire Single Photon Detector (SNSPD)



SNSPDs from JPL

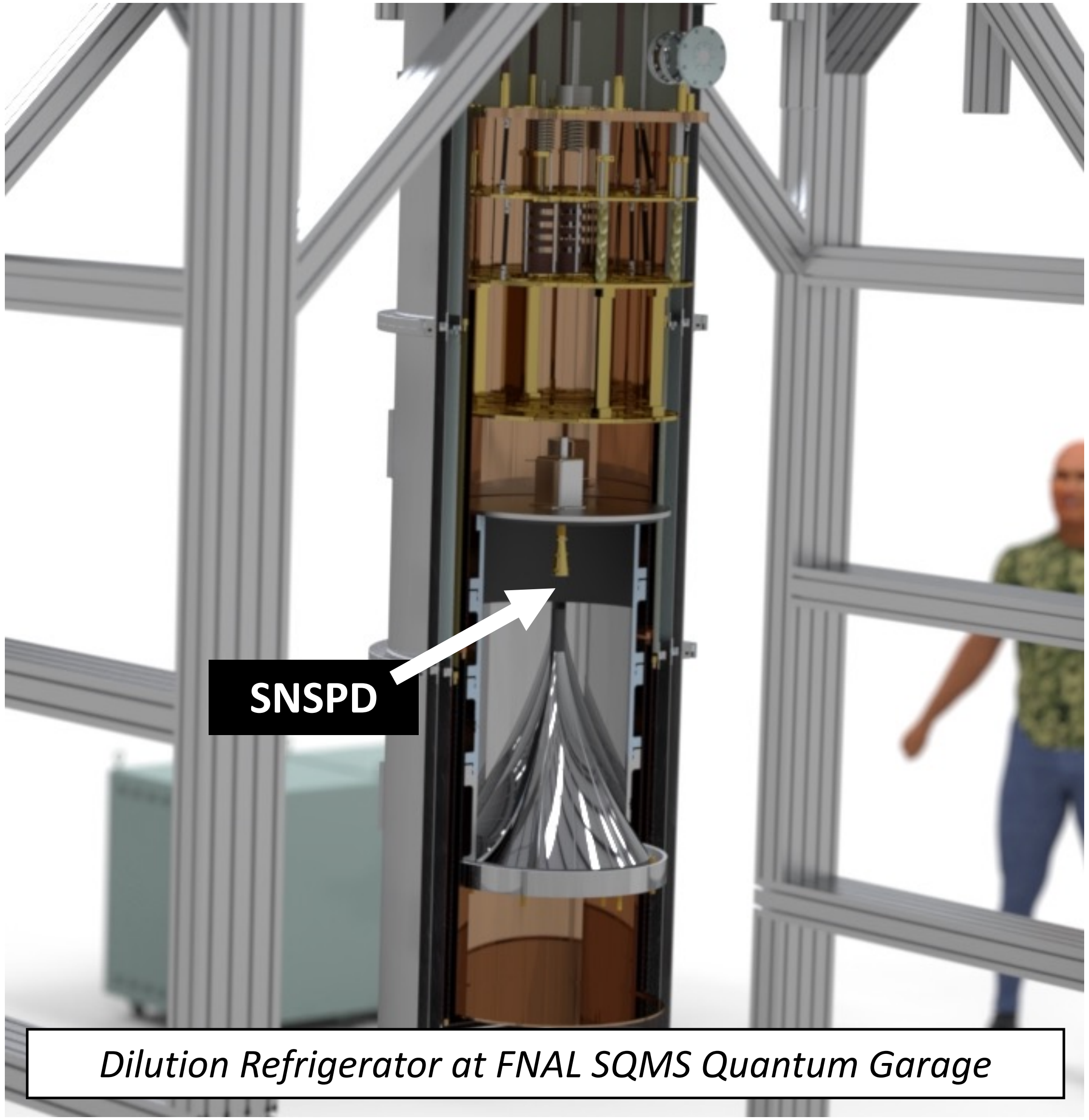


100nm wide nanowires in 15x15µm SNSPD from MIT



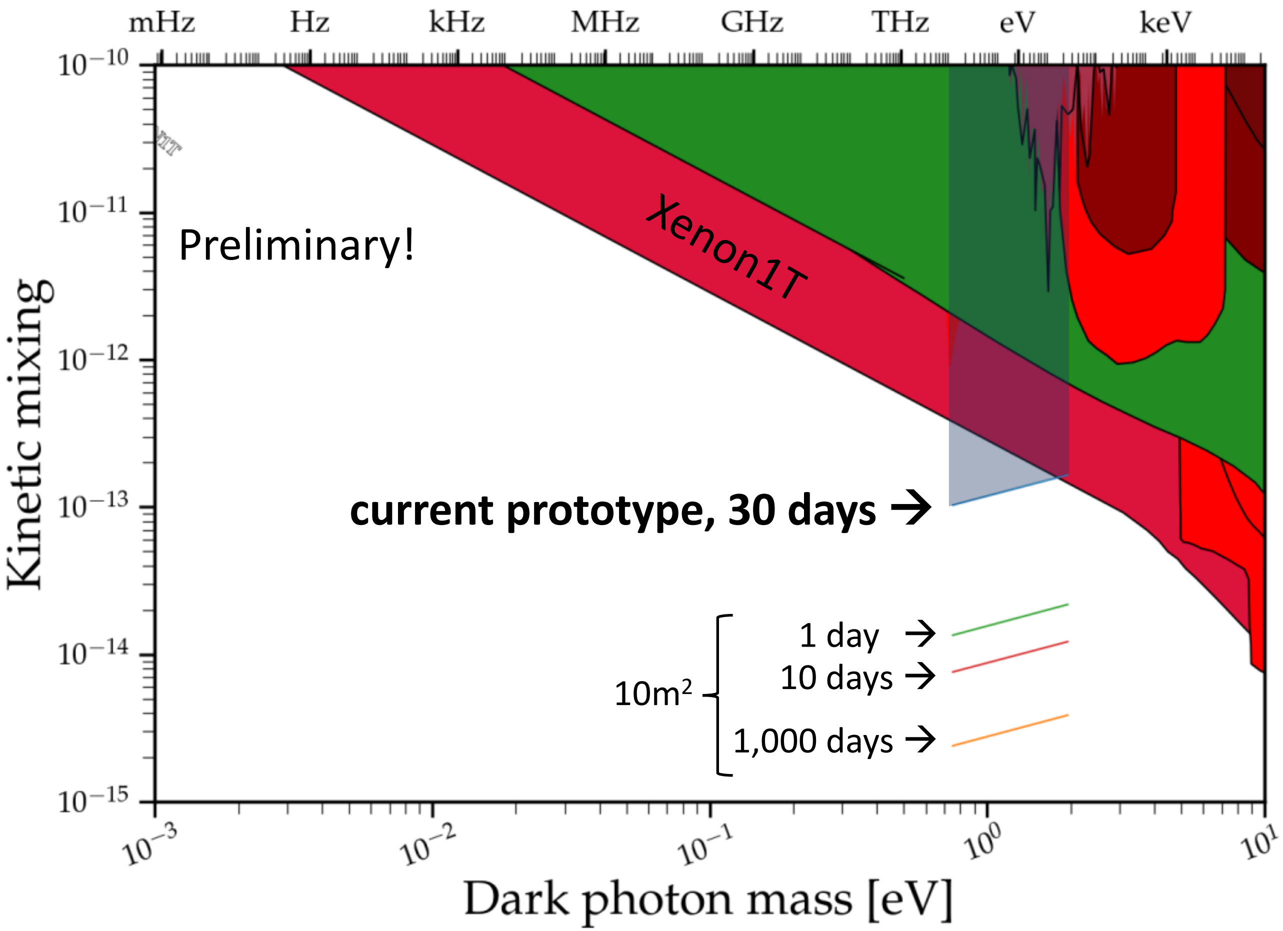
will enable cryogenic dark photon search at infrared (eV)

InfraBREAD Pilot Sensitivity

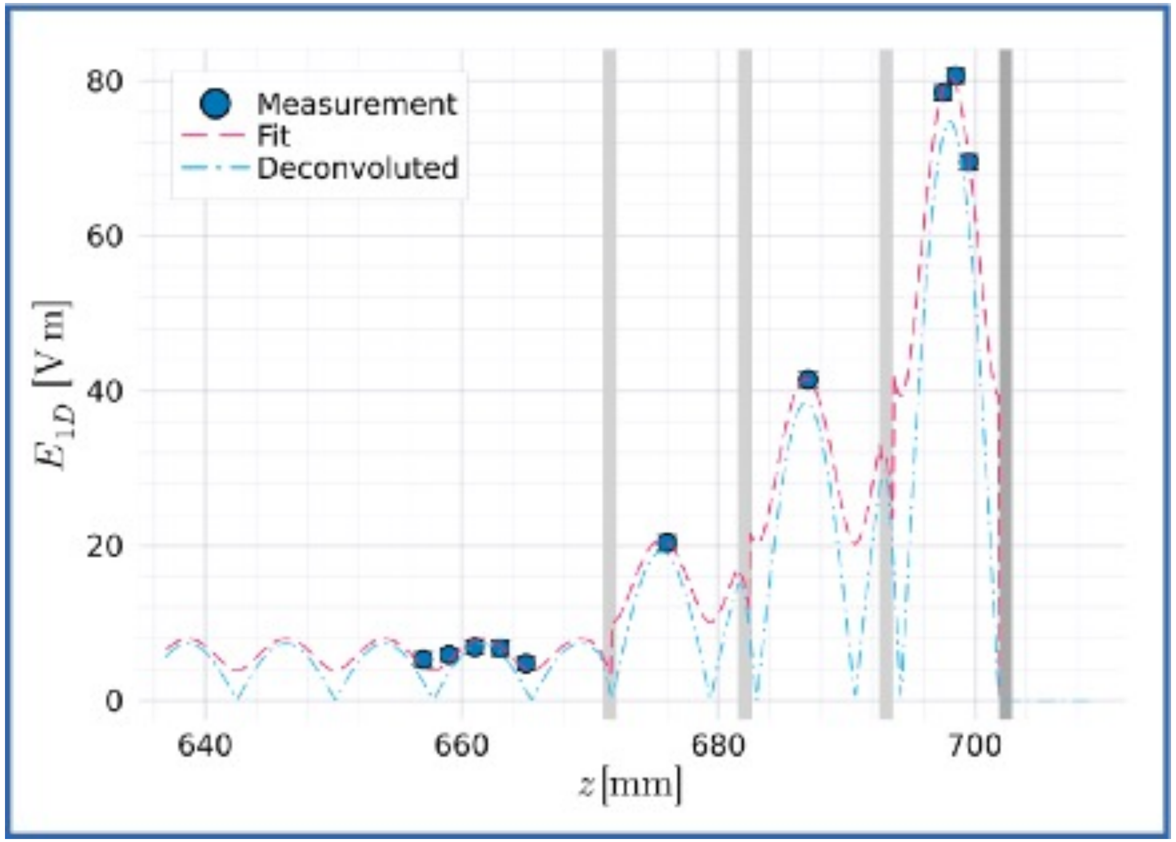


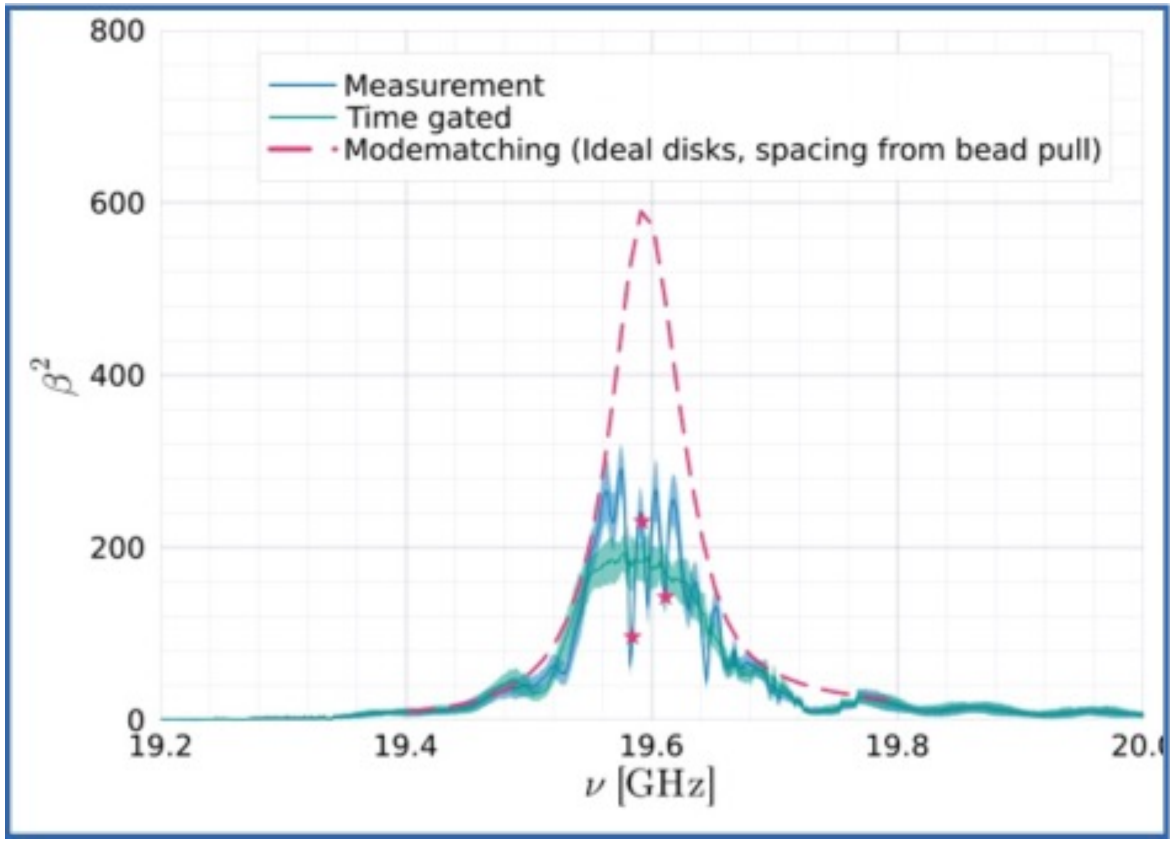
Dilution Refrigerator at FNAL SQMS Quantum Garage

Hidden Photon Sensitivity Projection

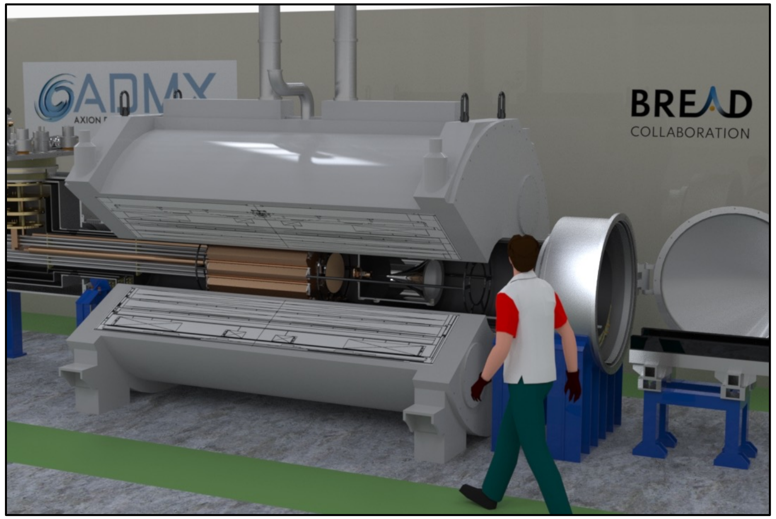
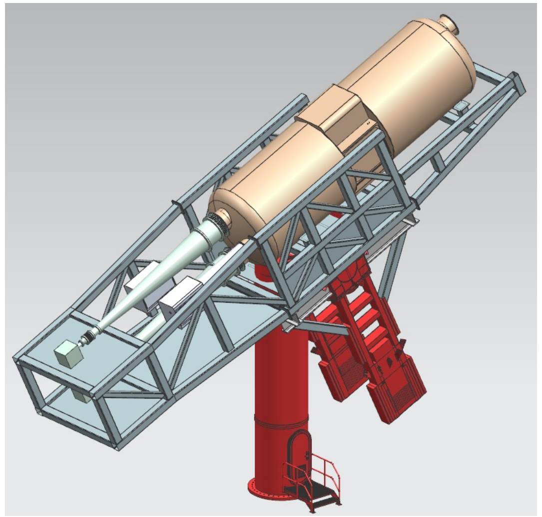
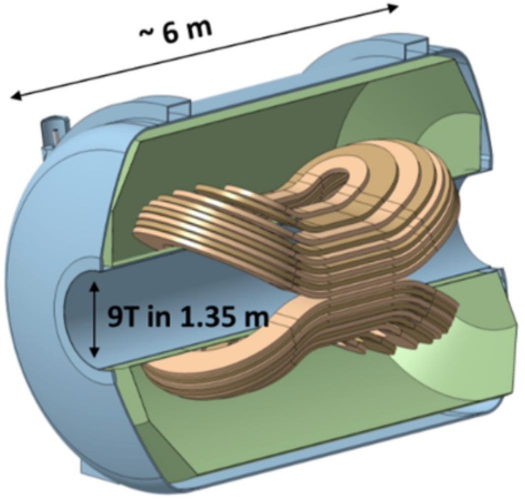


MADMAX Bead Pull Calibration



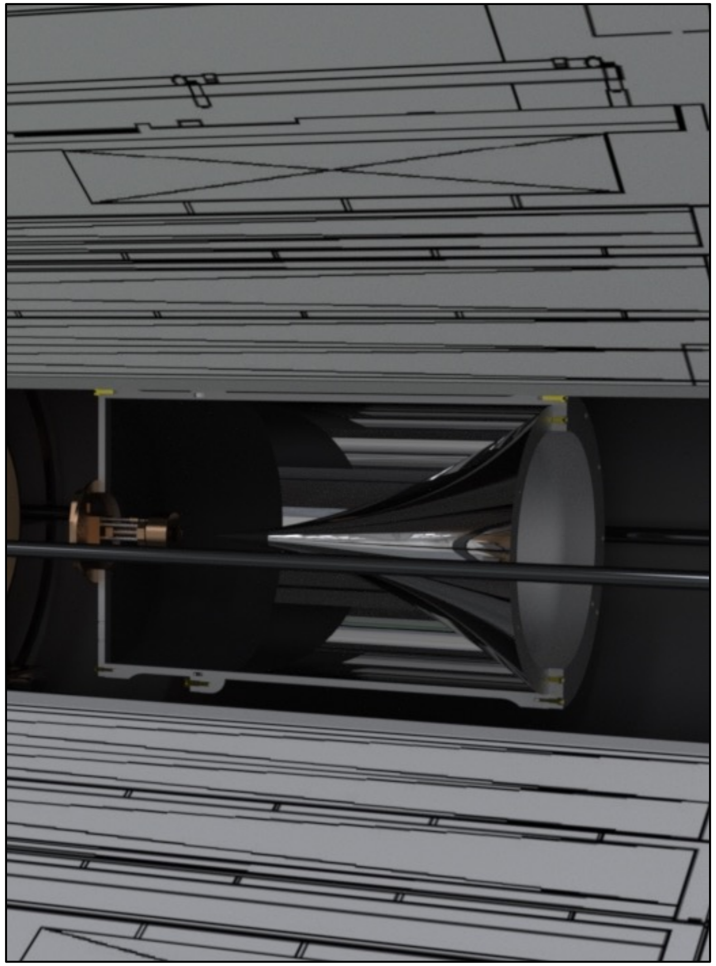


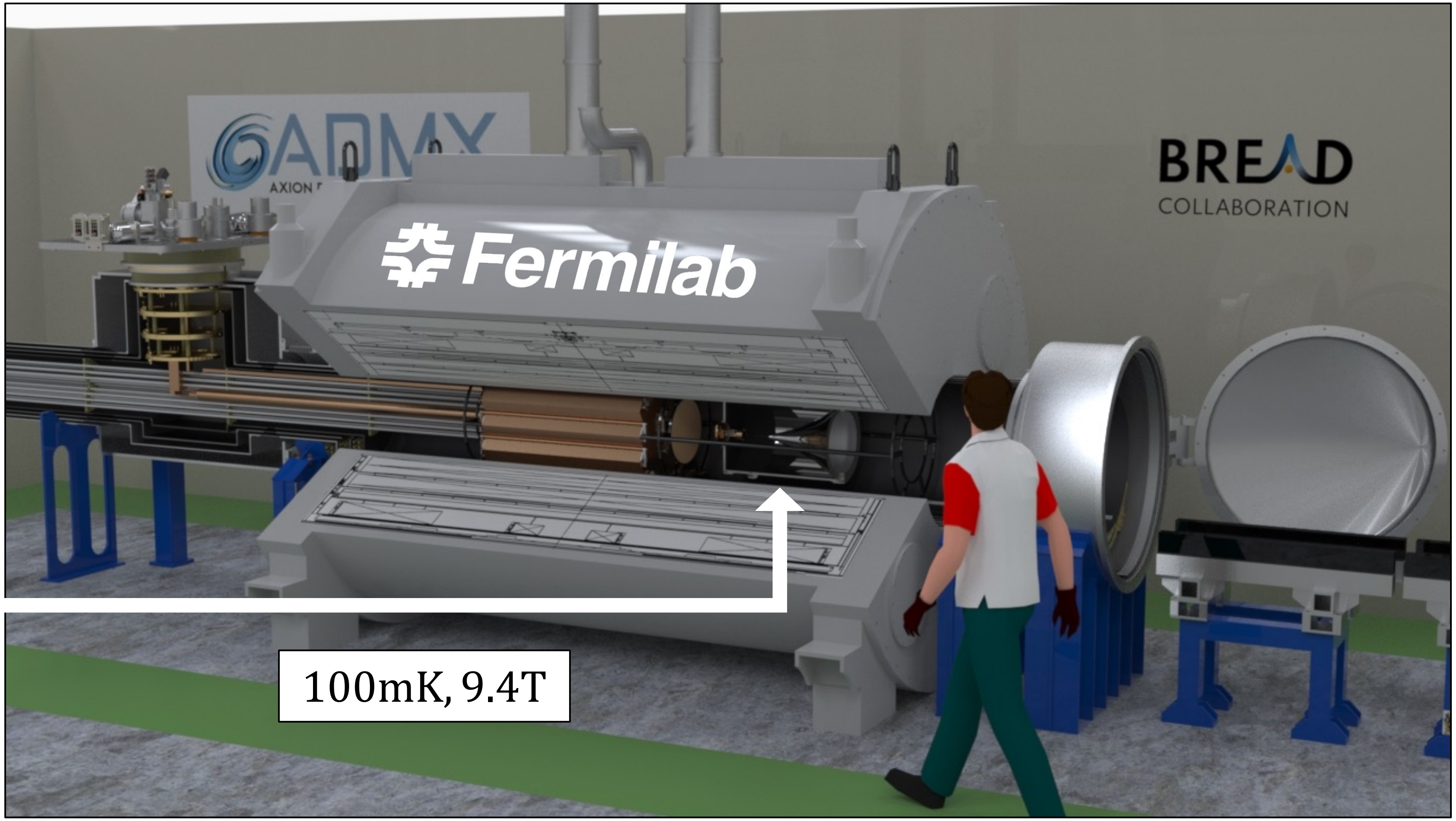
Scaling up: Some Large Magnets

Fermilab **ADMX-EFR magnet**	CERN **MORPURGO**	**BabyIAXO**	DESY **MADMAX**
			
$9.4\ \mathrm{T}, 80\mathrm{cm}$ bore	$1.4\ \mathrm{T}, 1.6\mathrm{m}$	$2\ \mathrm{T}, 0.7\mathrm{m}$	$9\ \mathrm{T}, 1.35\mathrm{m}$
solenoid	dipole		
available from ~ 2025	available	~ 2029	> 2030?

will enable mid-scale ALP searches → need for international collaboration

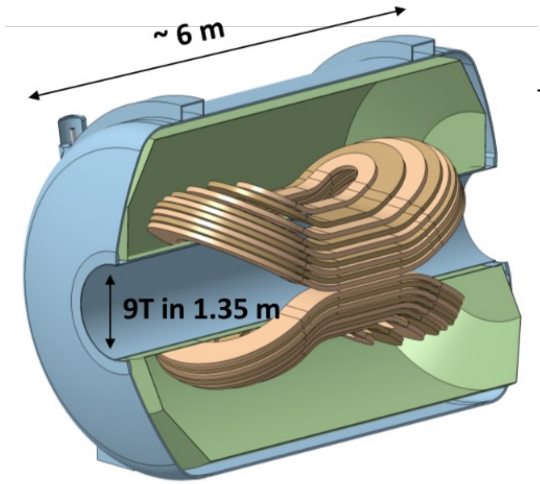
Axion Facility: Dark Wave Laboratory (DWL)





leverage Fermilab infrastructure for broadband axion physics program

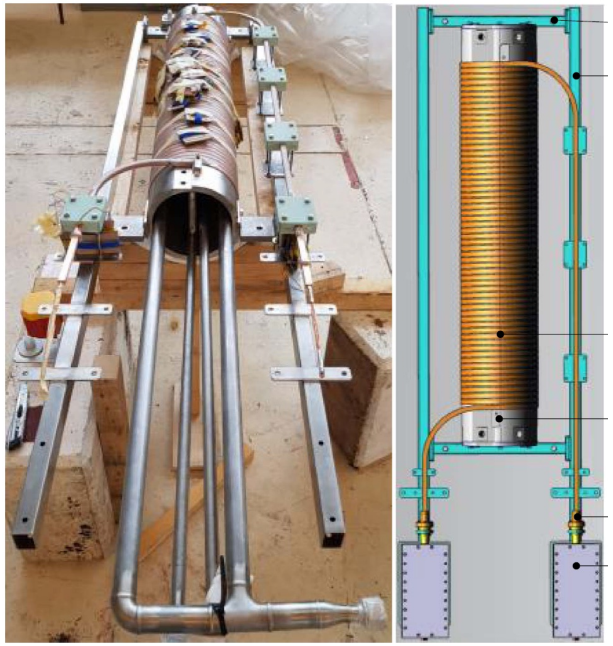
MADMAX magnet status

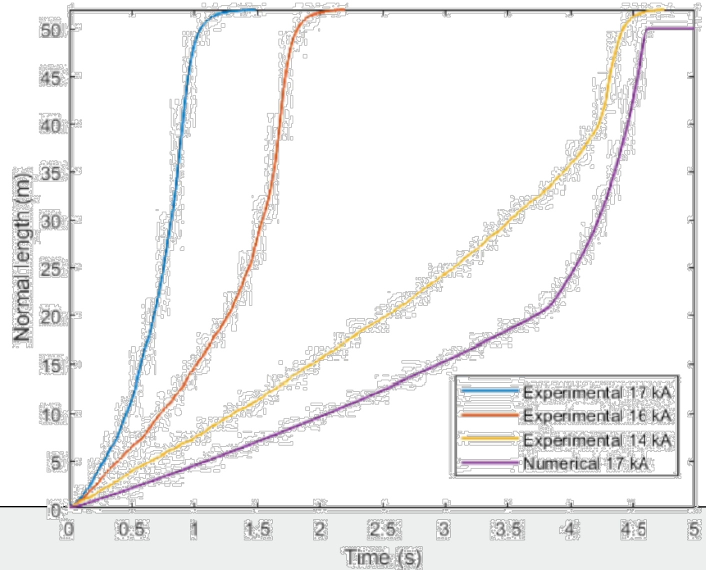


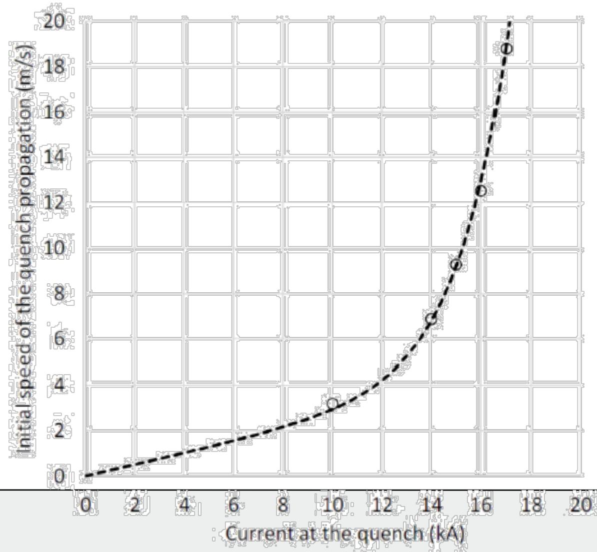
- Design study within innovation partnership finished:
  → 9.1 T dipole with 1.35 m warm bore feasible
- First important R&D results
  - Conductor based on CICC can be produced:
    Suppliers for conductor available
  - Copper yield strength ok after compaction
  - Quench protection feasible (propagation velocity)
  - Cooling concept of conductor

All results in special MADMAX issue IEEE Transactions on Applied Superconductivity, 33(7):1–11, 2023.

MACQU test solenoid





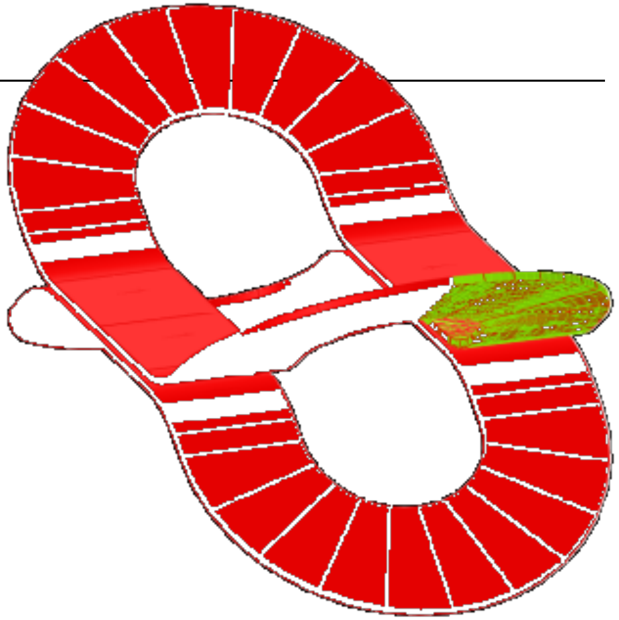


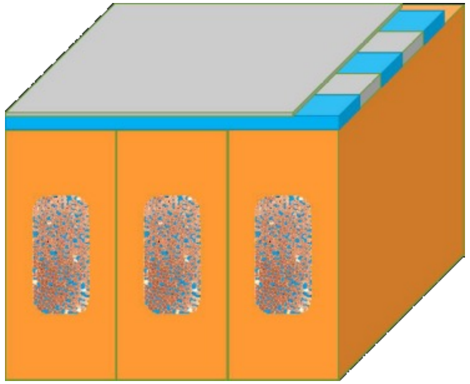
magnetpath forward

Path forward: Design, build and test demonstrator coils

- **Stick slip heat deposition**
- **Extraction of heat after stick slip**
- **Develop conductor termination**

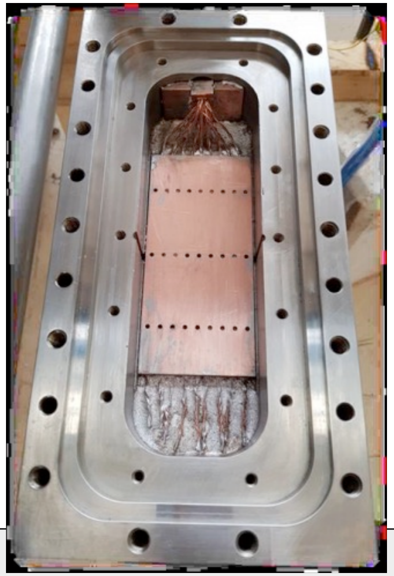
→ Mitigate underperformance risk





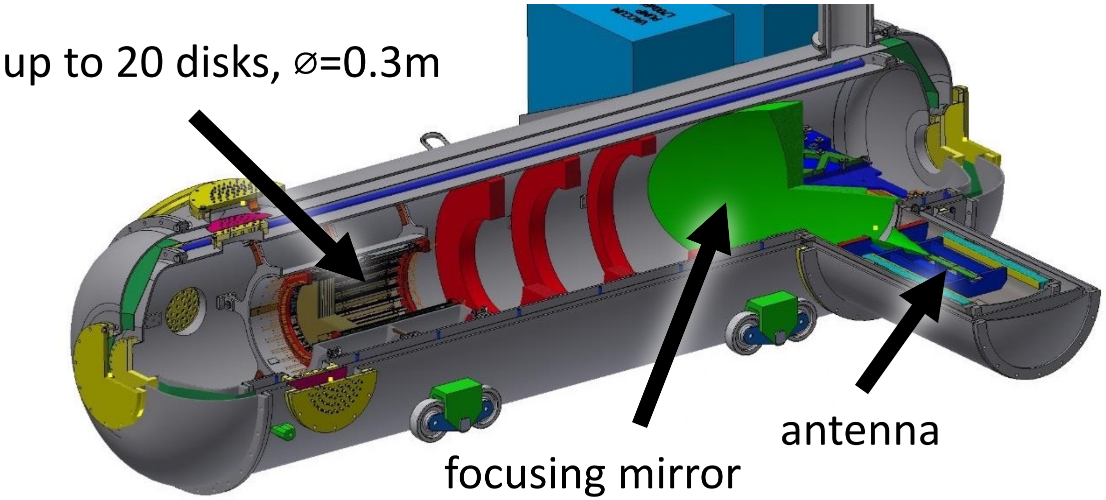
Test and understand conductor production, bending, impregnation…

→ Verify production sequence

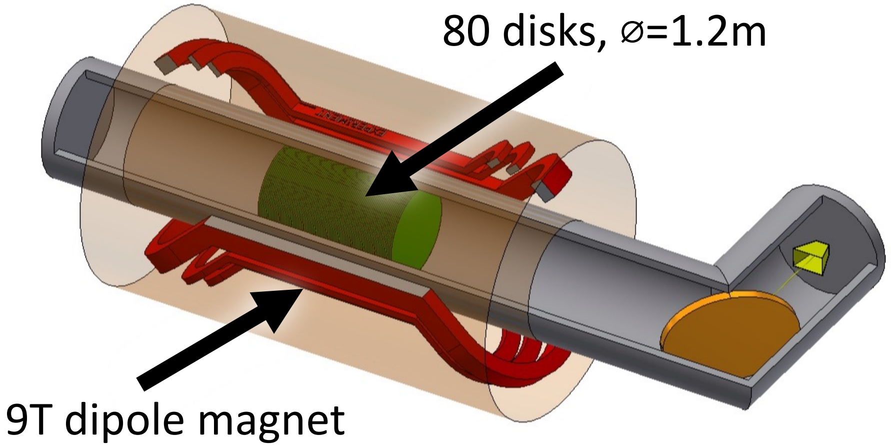


Next Big Steps

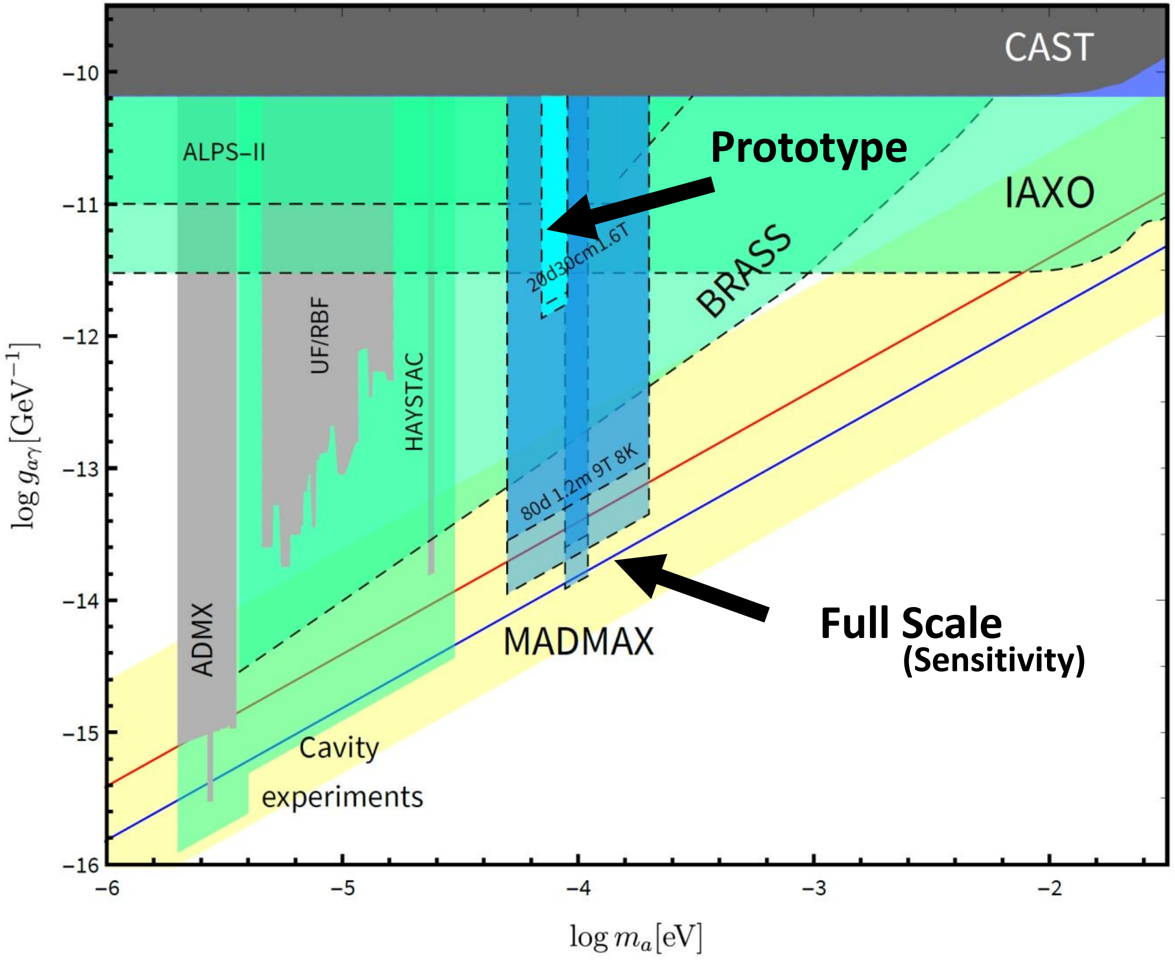
Prototype @ CERN MORPURGO (1.6T)



Full Scale @ DESY



Projected Sensitivities (10 - 100GHz)



[S. Beurthey *et al.*, arXiv:2003.10894]