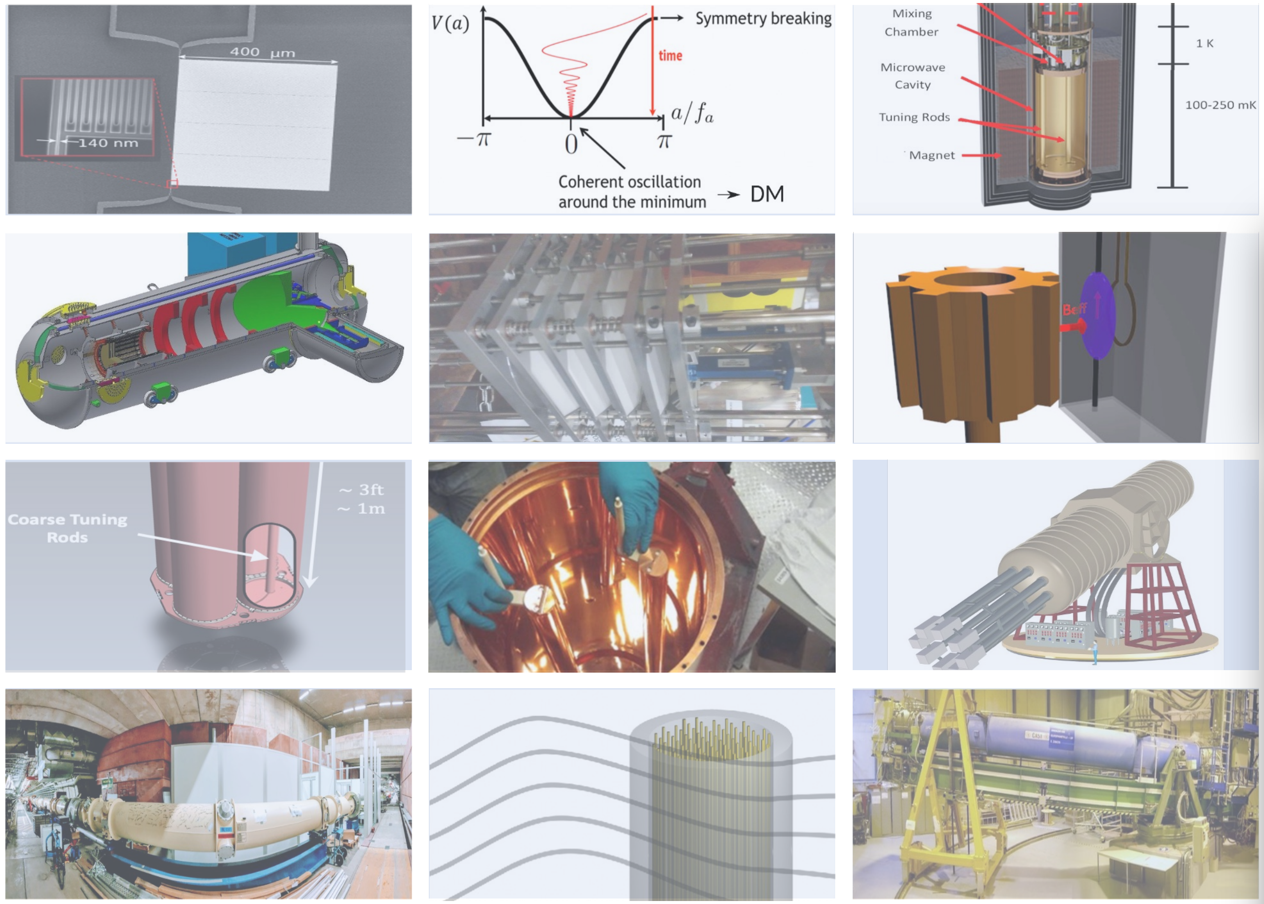
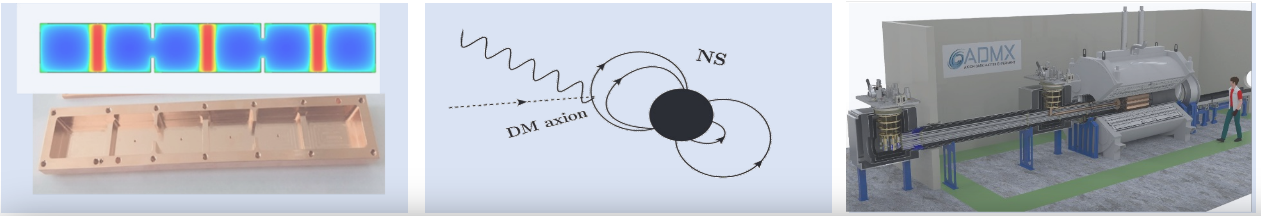




Axion Experiments

Stefan Knirck (knirck@fnal.gov)
Fermi National Accelerator Laboratory
Fermilab

member of ADMX and BREAD
ADMX AXION DARK MATTER EXPERIMENT
BREAD COLLABORATION

Selected Review Articles:

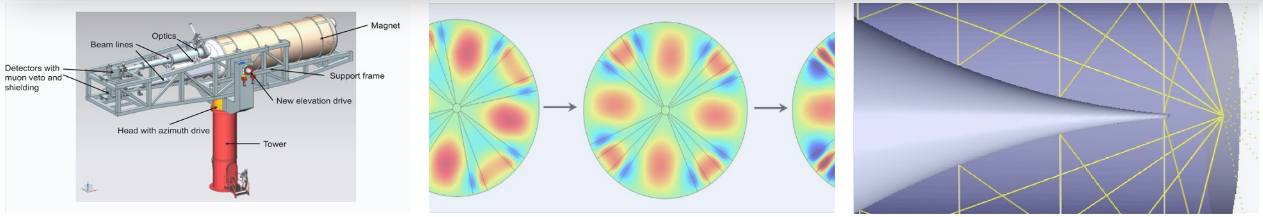
[P. Graham *et al*, Ann. Rev. Nucl. Part. Sci. 65 (2015) 485-514]

[I. Irastorza, R. Redondo, Prog.Part.Nucl.Phys. 102 (2018) 89-159]

[P. Sikivie, Rev. Mod. Phys. 93, 015004 (2021)]

[Y. Semertzidis, S. Youn, Sci. Adv. 8 (8) (2022)]

[C.B. Adams *et al*, Snowmass white paper, arXiv:2203.14923]

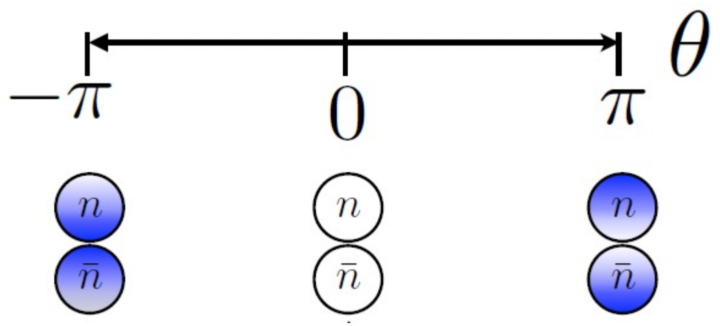


Why Axions? – The Strong CP Problem

QCD allows term:

$$\mathcal{L} = -\theta \frac{g_S}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a, \qquad \theta = -\pi \dots \pi$$

Experimentally: $|\theta| < 10^{-10}$ (neutron electric dipole moment)

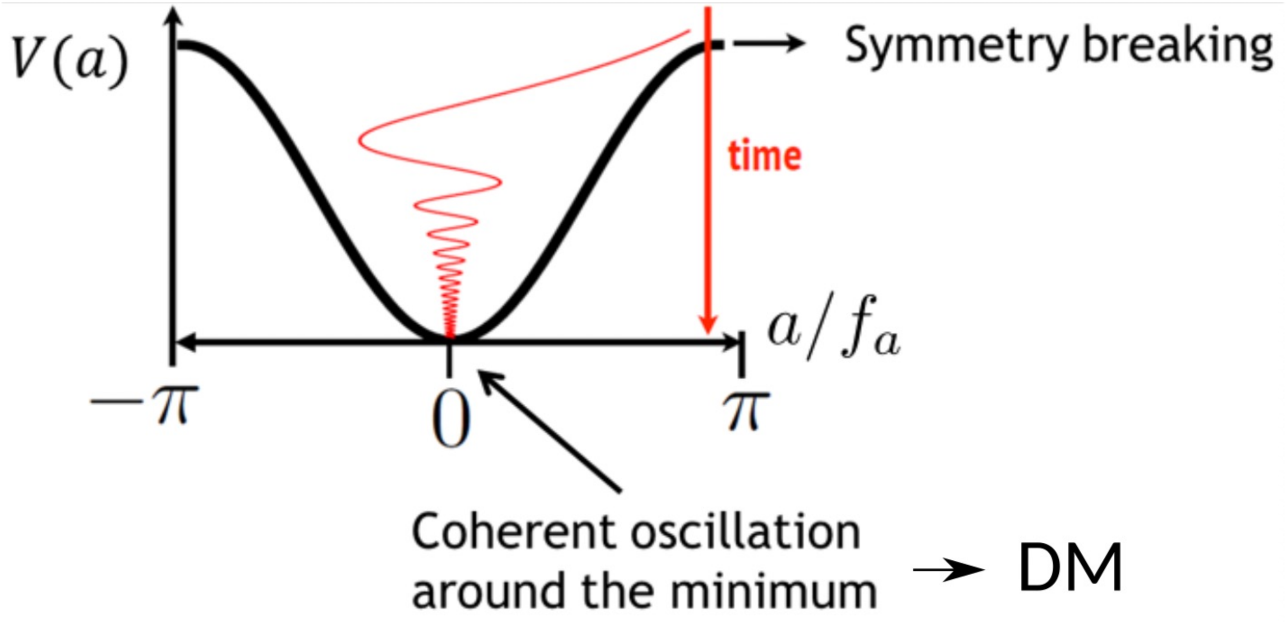


Why Axions? – The Strong CP Problem

make it a dynamic field: $\theta \to f_a^{-1} a(t; \boldsymbol{x})$ [Peccei, Quinn, 1977]

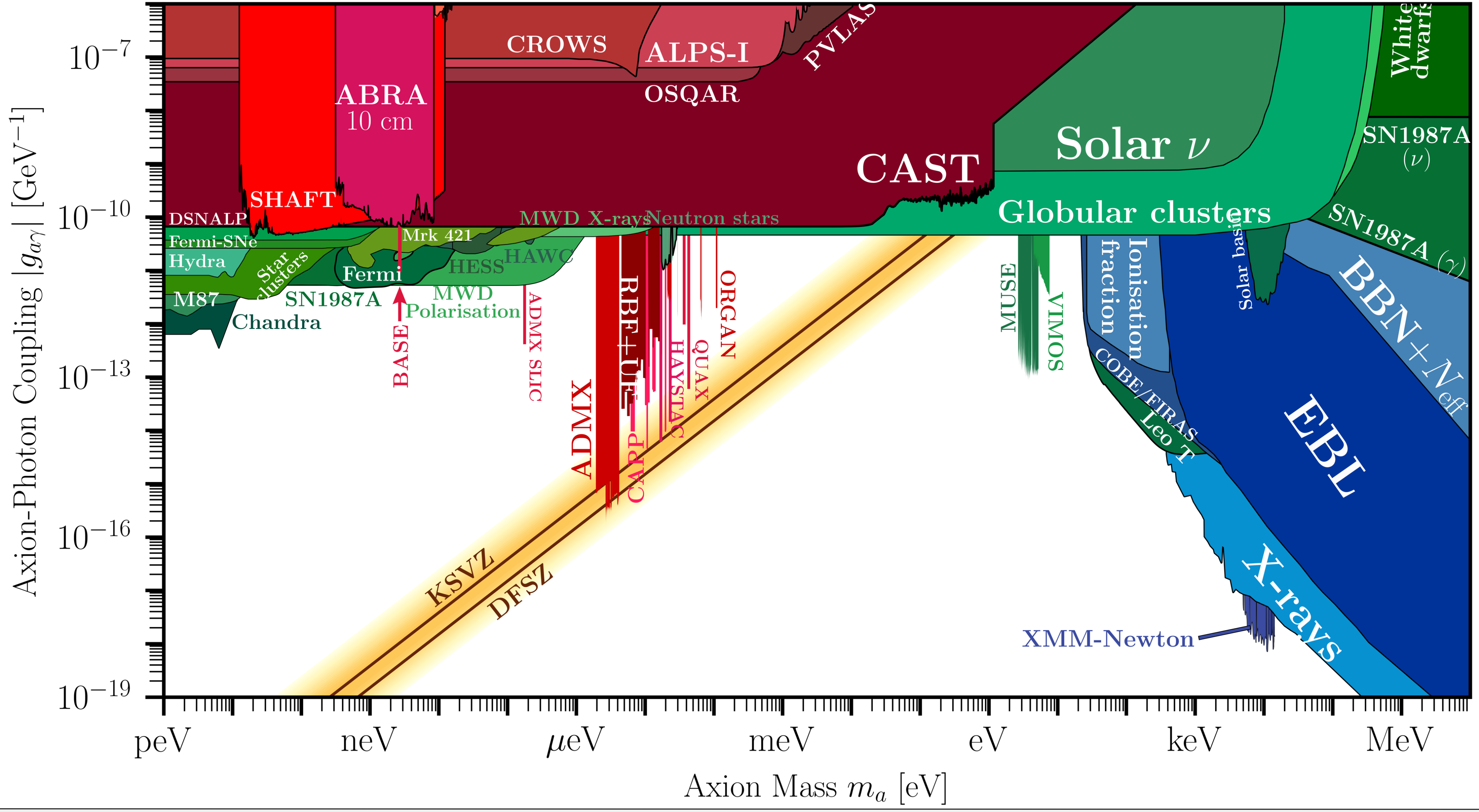
$$\mathcal{L} = -\frac{a}{f_a}\frac{g_S}{32\pi^2} G^a_{\mu\nu}\, \tilde{G}^{\mu\nu}_a \quad + \frac{1}{2}\partial_\mu a\, \partial^\mu a$$

Cosmology: rolldown to CP conserving limit:



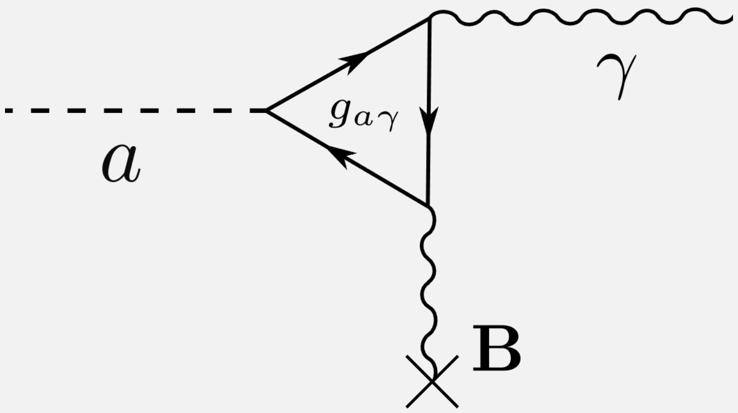
Where to look?

[adapted from cajohare.github.io/axionlimits]



How to look?

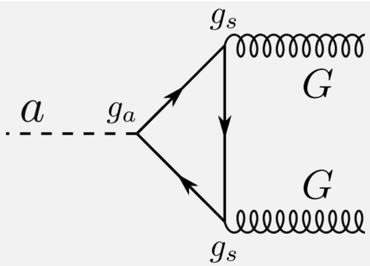
Electro-Magnetic Coupling



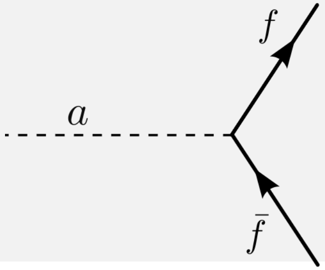
$$\sim a\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} \sim a\, \boldsymbol{E} \cdot \boldsymbol{B}$$

→ **Axion-Photon-Mixing under ext. B-field** (Primakoff effect)

Other Coupling

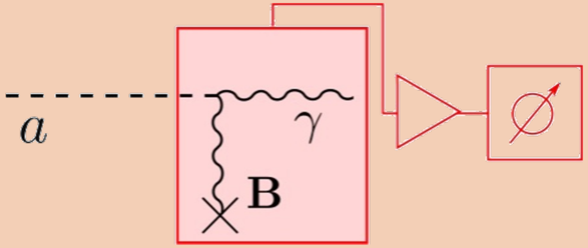
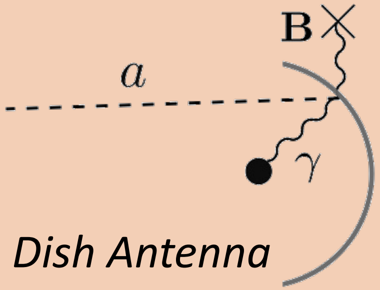
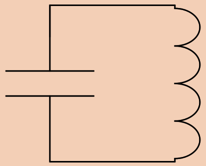
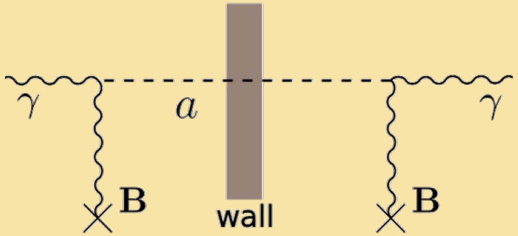
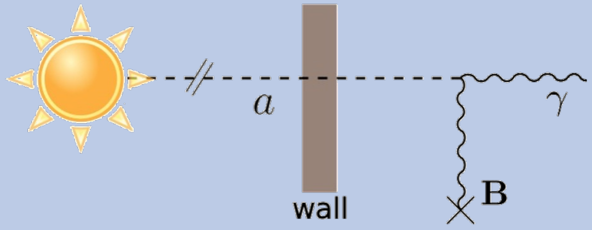
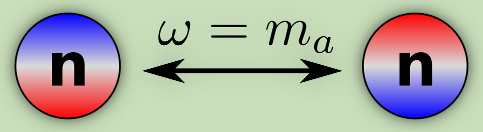
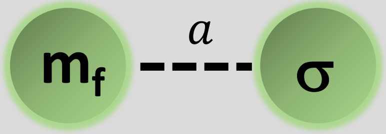


$$\sim a\, G^{a}_{\mu\nu}\, \tilde{G}^{\mu\nu}_{a}$$



$$\sim \partial_\mu\, a\, \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

How to look?

	Dark Matter *(Haloscopes)*	**Lab Axions**	**Sun & Astrophysics**
Electro-Magnetic Coupling	 *Microwave Cavity*  *Dish Antenna*  *LC Circuit*	 *Light-Shining-through-Wall* *Polarization/Birefringence* *Collider*	 *Helioscope* *Indirect Detection:* Stellar Energy Loss, Neutron Star Radio Emission, Galaxy Clusters, Black Hole Superradiance, …
Other Coupling	 *Oscillating EDM*	 *Firth Force, Collider*	

How to look?

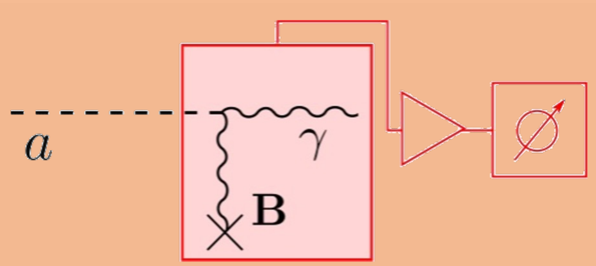
Disclaimer: This is just a selection. This talk is not intended to endorse or advertise any particular experiment or study, but rather wants to give a (necessarily incomplete) high-level overview over the field.

	Dark Matter *(Haloscopes)*	**Lab Axions**	**Sun & Astrophysics**
Electro-Magnetic Coupling	ADMX, HAYSTAC, IBS/CAPP, CAST/CAPP, GrAHal, TASEH, SUPAX, QUAX-aγ RADES, ORGAN, MADMAX, T-RAX, CADEx, DALI, ORPHEUS, MuDHI, ALPHA, SHUKET, BRASS, BREAD, TOORAD, LAMPOST, UPLOAD-DOWNLOAD ABRACADABRA, ADMX-SLIC, SHAFT, DMRadio, WISPLC	ALPS, JURA, OSQAR, CROWS, STAX, JURA WISPFI DANCE SAPPHIRES Collider	CAST, IAXO, TASTE Stellar Energy Loss, Microwave Background, Transparency; Neutron Stars, Black Hole Superradiance, …
Other Coupling	CASPER-electric, CASPEr-gradient, GNOME, QUAX-ae	ARIADNE Collider	

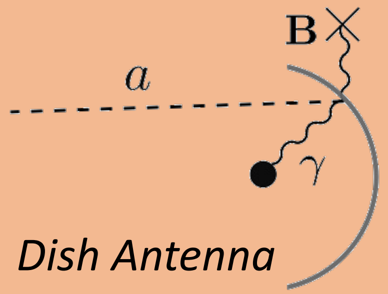
How to look?

Dark Matter *(Haloscopes)*

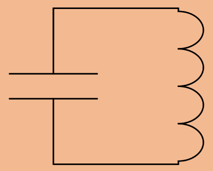
Electro-Magnetic Coupling



Microwave Cavity

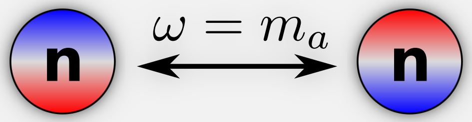


Dish Antenna



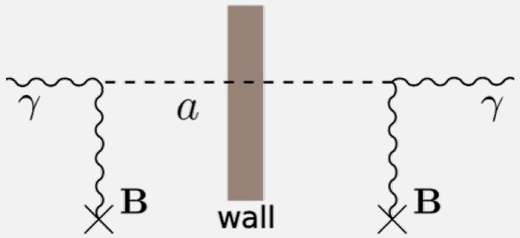
LC Circuit

Other Coupling



Oscillating EDM

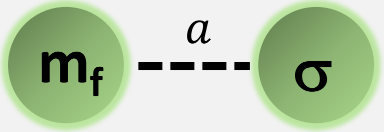
Lab Axions



Light-Shining-through-Wall

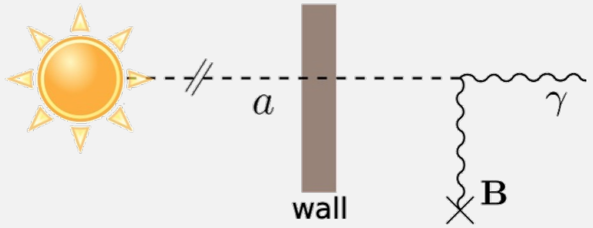
Polarization/Birefringence

Collider



Firth Force, Collider

Sun & Astrophysics

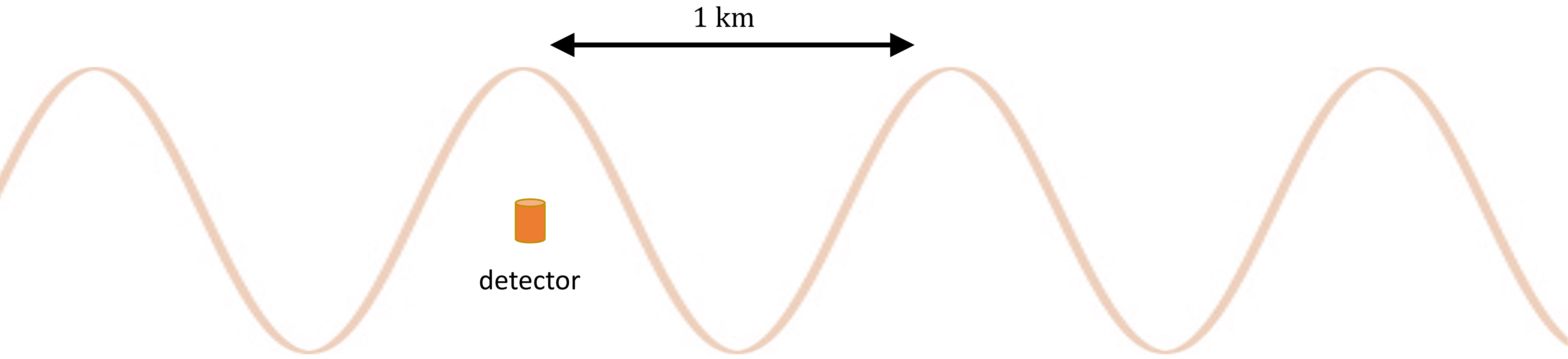


Helioscope

Indirect Detection:
Stellar Energy Loss, Neutron Star Radio Emission, Galaxy Clusters, Black Hole Superradiance, …

Wave-like Dark Matter

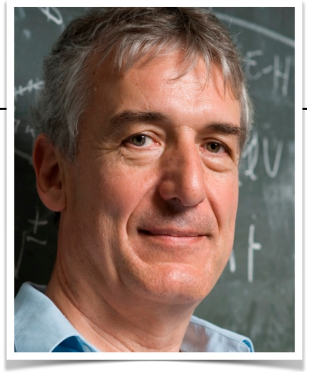
$\rho_a \sim 0.45\,\frac{\text{GeV}}{\text{cm}^3}$ $\lambda_{\text{DB}} \sim \frac{2\pi}{m_a v} \sim 1\text{ km}\left(\frac{1\mu\text{eV}}{m_a}\right)$ → $\frac{\#\text{particles}}{\lambda_{\text{DB}}^3} \sim 10^{30}\left(\frac{1\mu\text{eV}}{m_a}\right)^4$



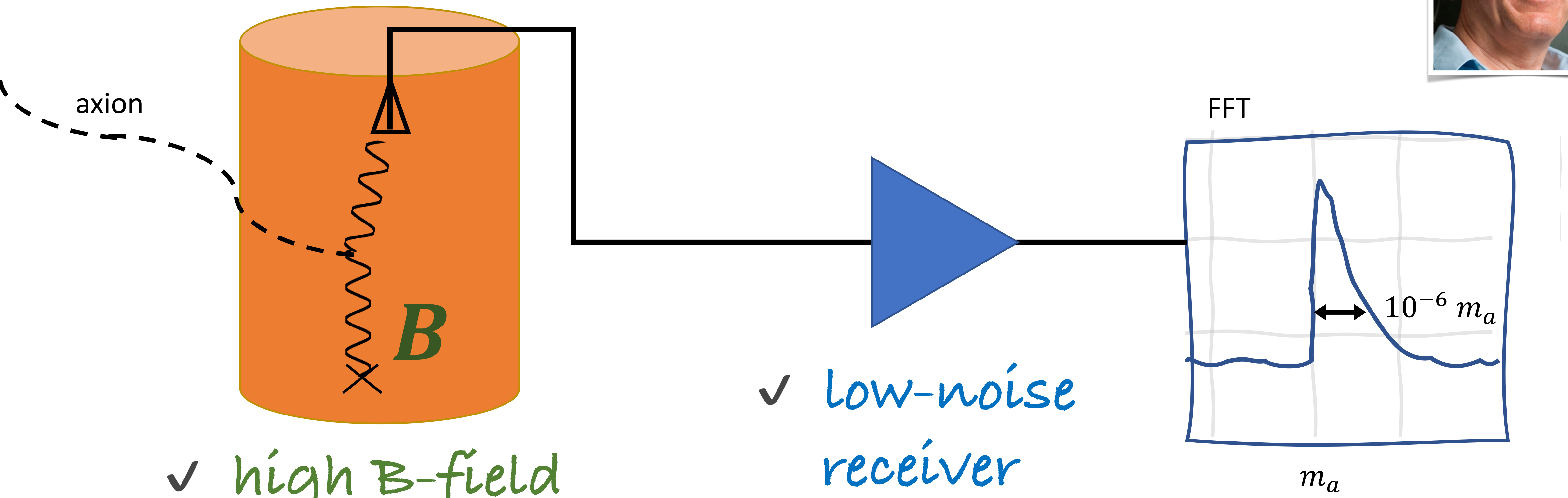
coherent detection

The Resonant Cavity

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



✓ high-Q resonator



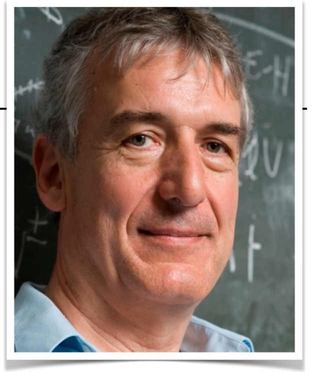
✓ high B-field

✓ low-noise receiver

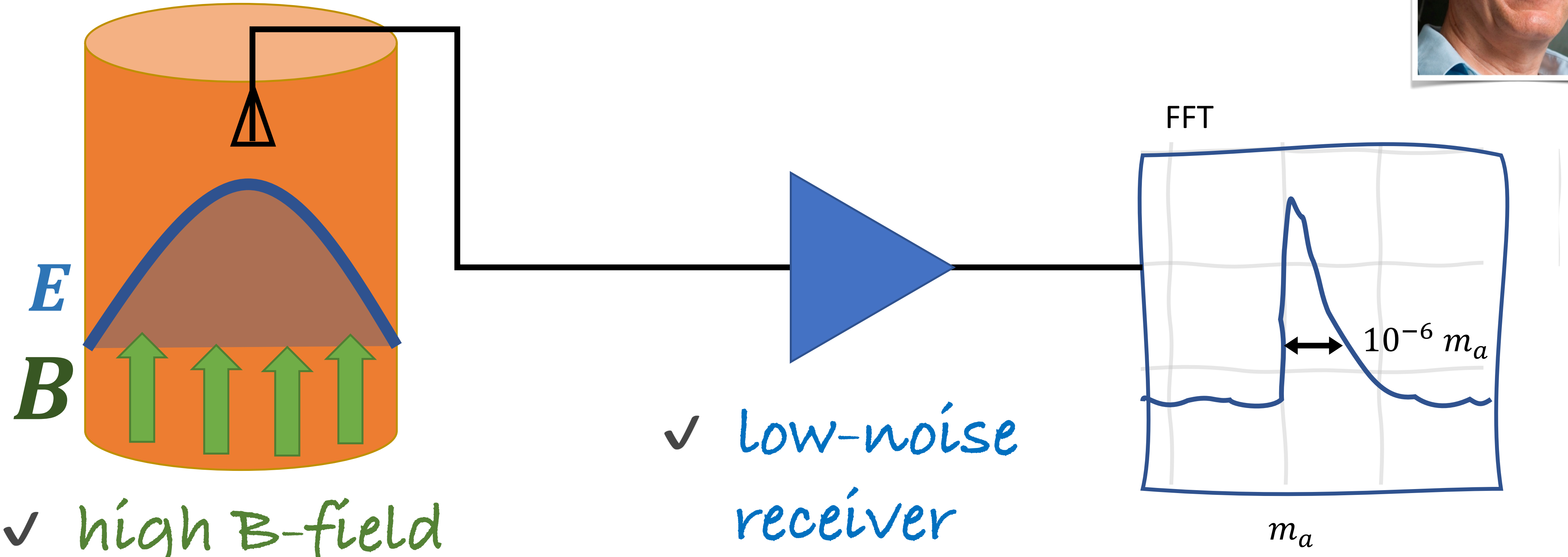
$$P_{\rm sig} = 2\cdot 10^{-23}\,{\rm W}\cdot\left(\frac{B}{7.6\ {\rm T}}\right)^2\left(\frac{V}{136\ L}\right)\left(\frac{C}{0.4}\right)\left(\frac{Q}{30{,}000}\right)\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{m_a}{3\ \mu{\rm eV}}\right)\left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeV\ cm^{-3}}}\right)$$

The Resonant Cavity

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



✓ high-Q resonator

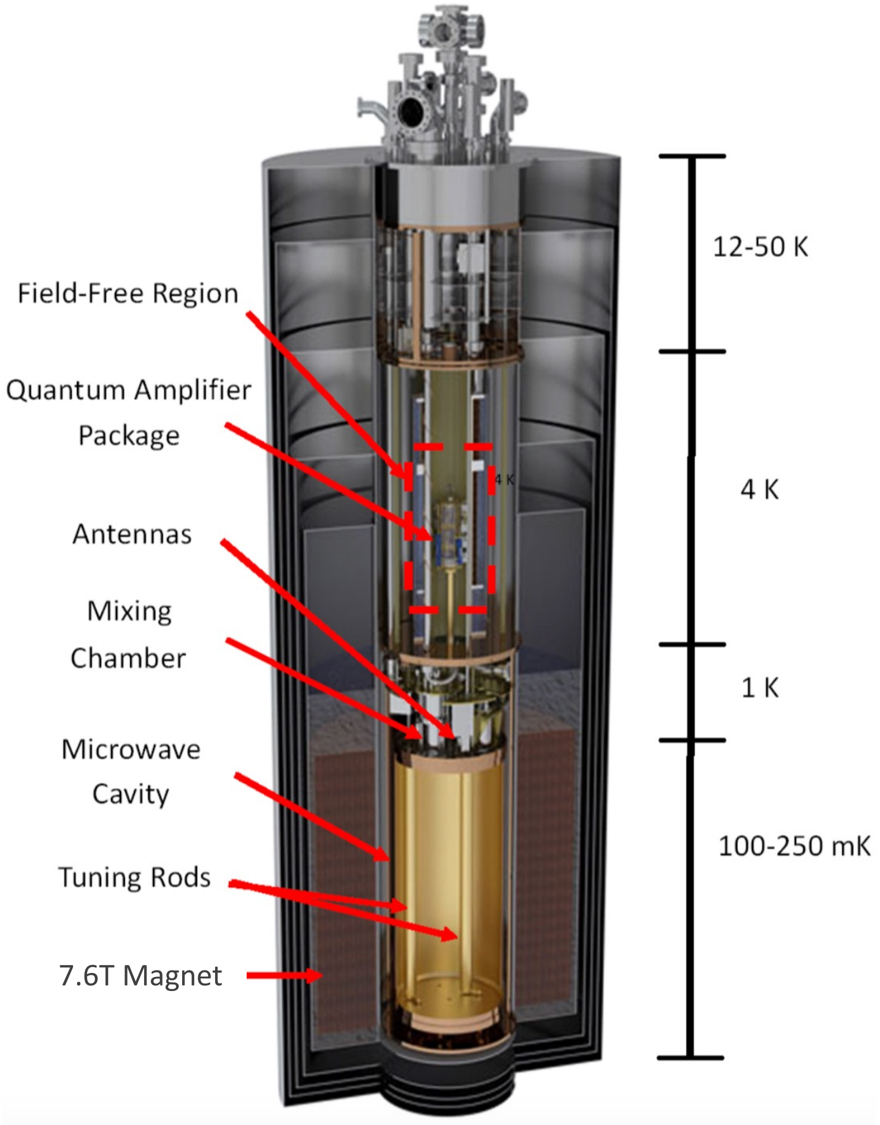


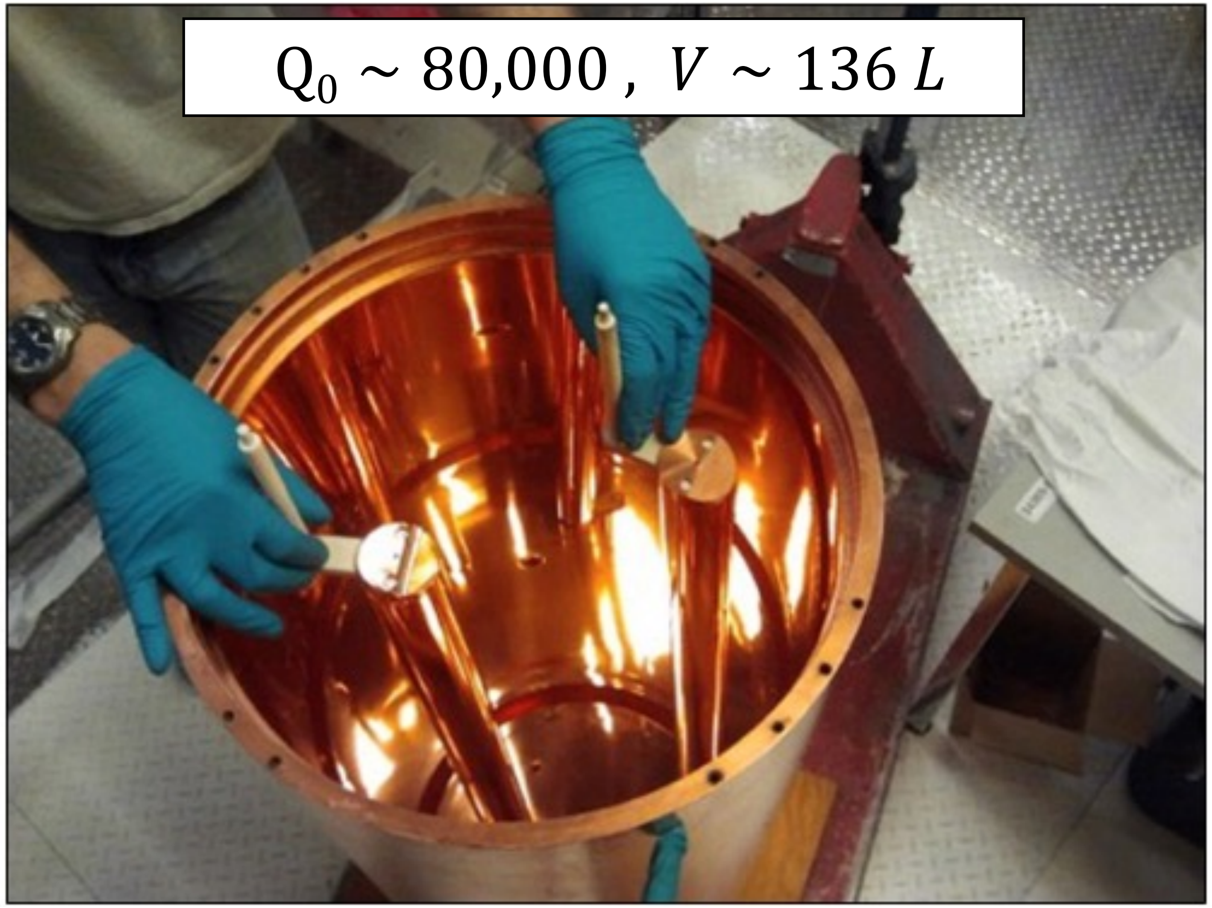
✓ high B-field

✓ low-noise receiver

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

ADMX: Axion Dark Matter eXperiment

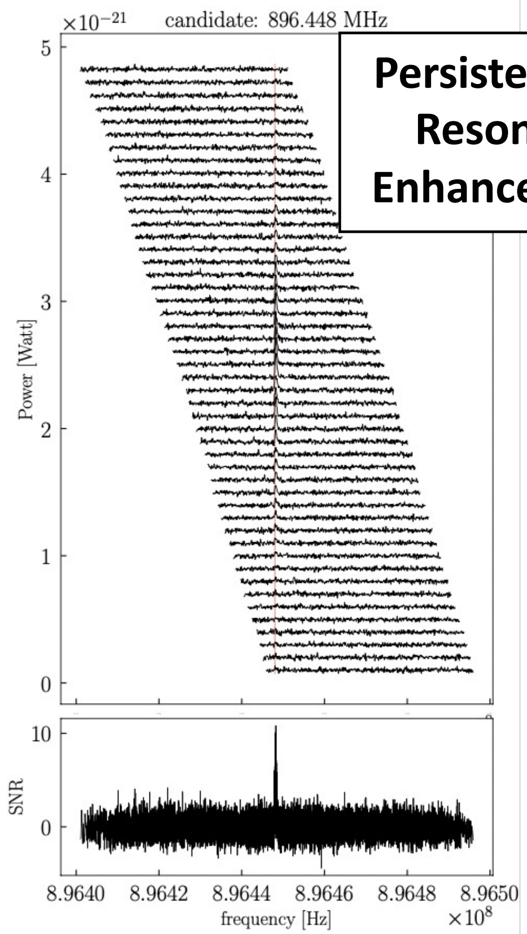




$$Q_0 \sim 80{,}000\,,\ V \sim 136\,L$$

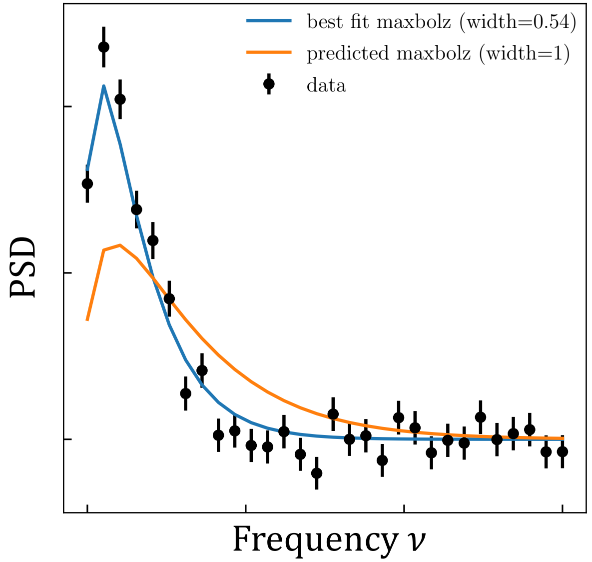
[T. Braine *et al* (ADMX collab.), PRL 124 (2020) 10, 101303]
[R. Khatiwada *et al* (ADMX collab.), RSI (accepted), arXiv:2010.00169]
[C. Bartram *et al* (ADMX collab.), PRD 103 (2021) 3, 032002]

ADMX: Power of Candidate Exclusion Criteria

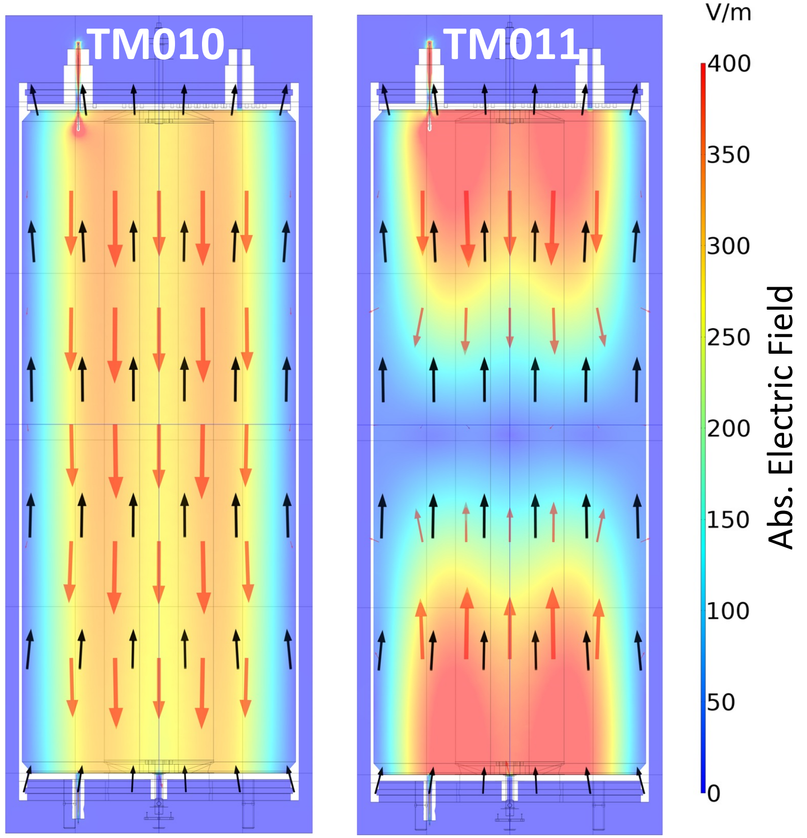


Persistence & Resonant Enhancement

Axion-Lineshape



$$h\nu = m_a c^2 + \frac{1}{2} m_a v_a^2$$



(No) Coupling to higher modes

Other Checks:

RF Sources Outside Cavity

Magnet Rampdown
(last check, never happened for ADMX)

ADMX Collaboration

ADMX
AXION DARK MATTER EXPERIMENT

University of Washington · Washington University in St. Louis · The University of Western Australia · Berkeley University of California · Georg-August-Universität Göttingen · UF University of Florida · The University Of Sheffield. · Lawrence Livermore National Laboratory · Los Alamos National Laboratory · Fermilab · Pacific Northwest National Laboratory

Heising - Simons Foundation

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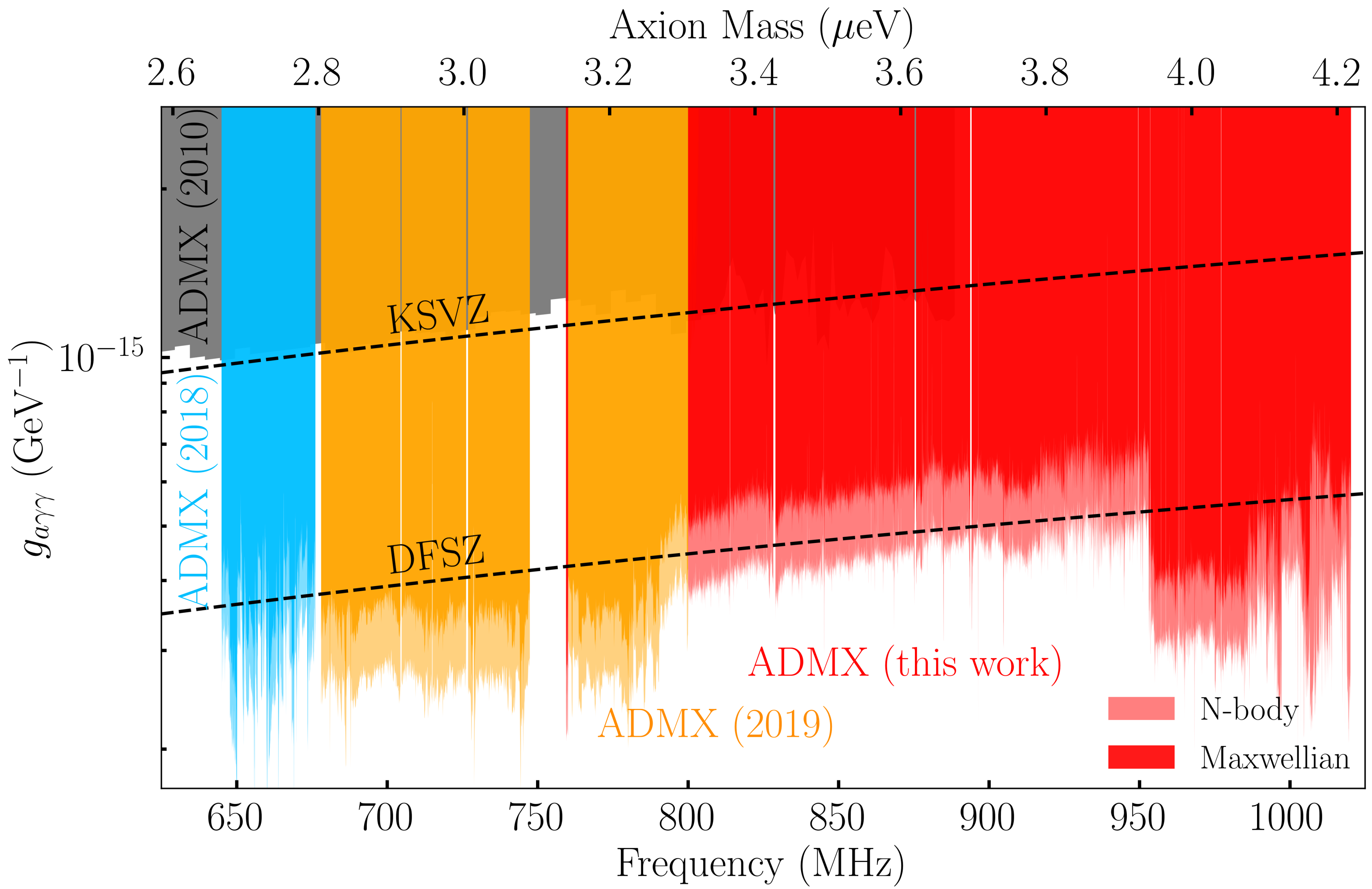
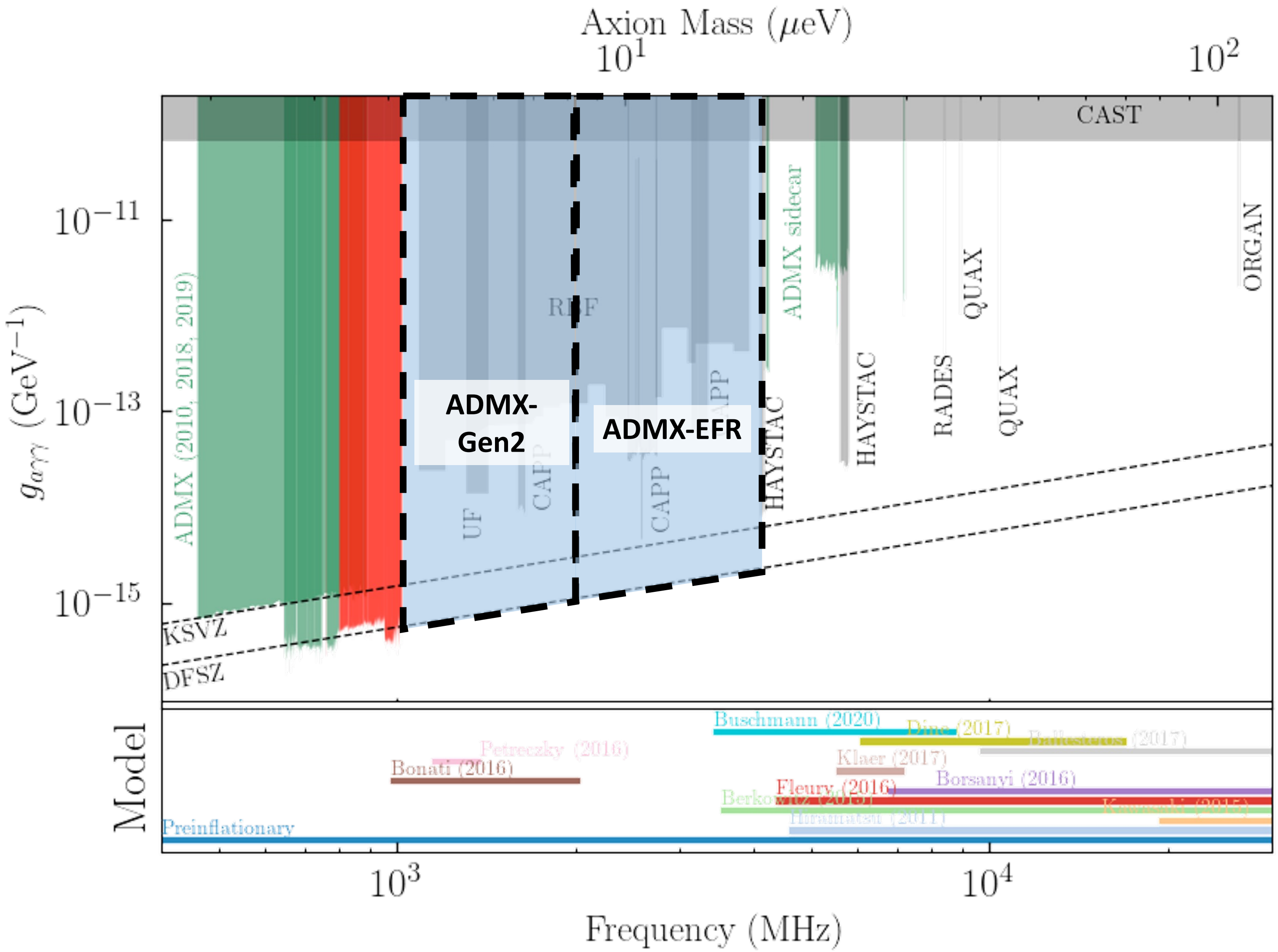
ADMX: Most Recent Results

[PRL 127, 261803 (2021)]



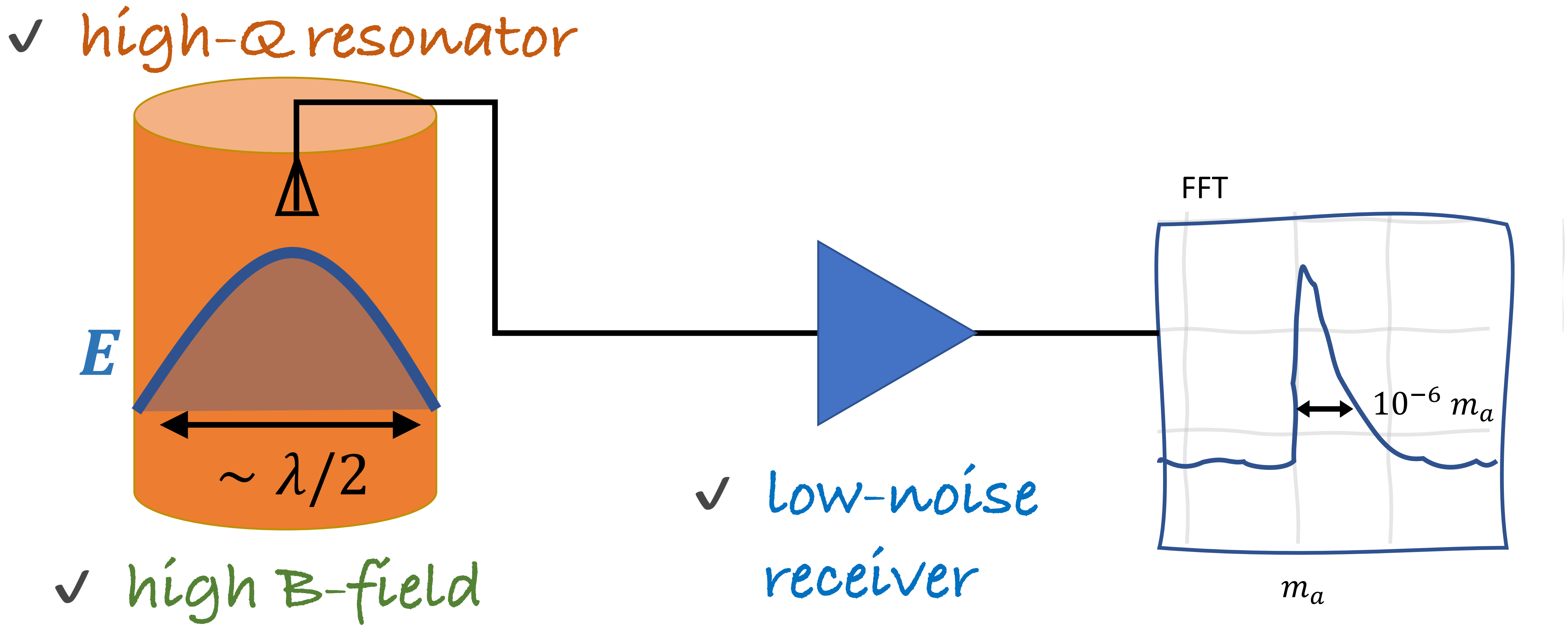
ADMX: Higher Mass Plans



IBS/CAPP and others similar plans

The Resonant Cavity – High Masses

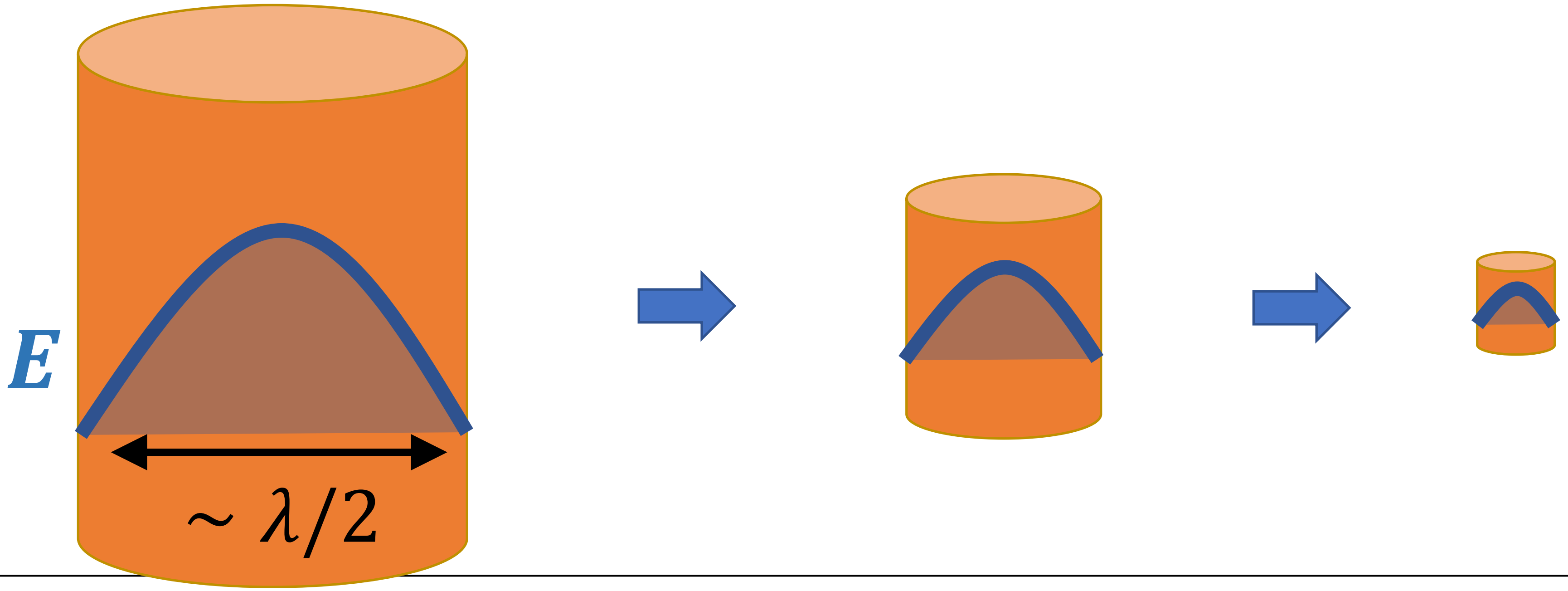
[P. Sikivie, PRL 51, 1415 (1983)]



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

The Resonant Cavity – High Masses

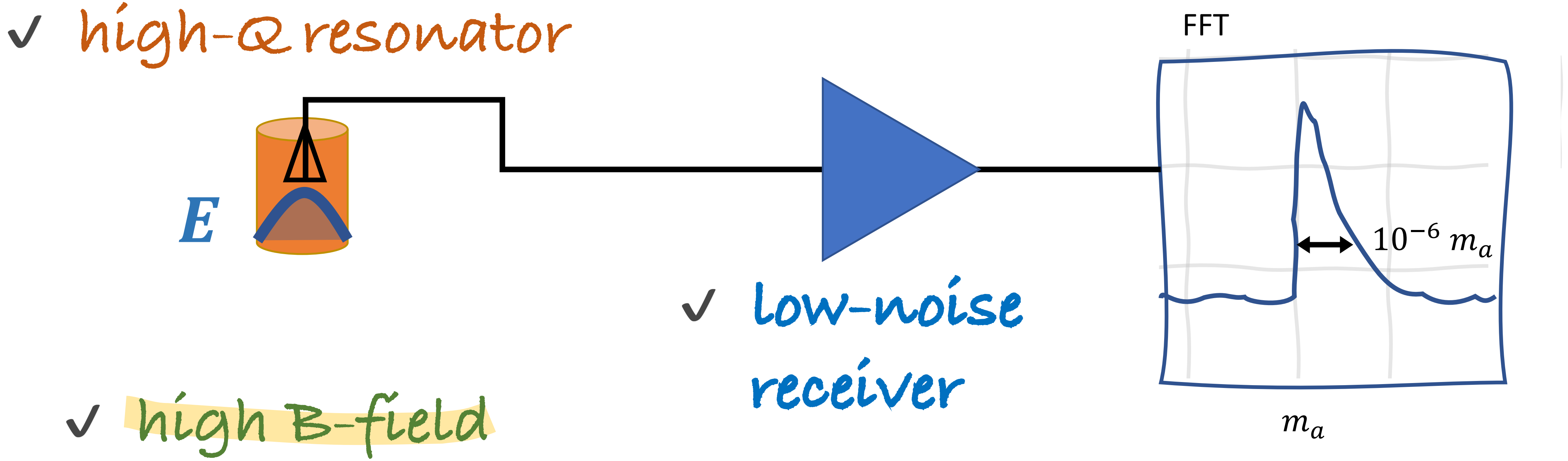
	3μeV	10μeV	30μeV



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

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

High Mass Challenge – Stronger Magnets

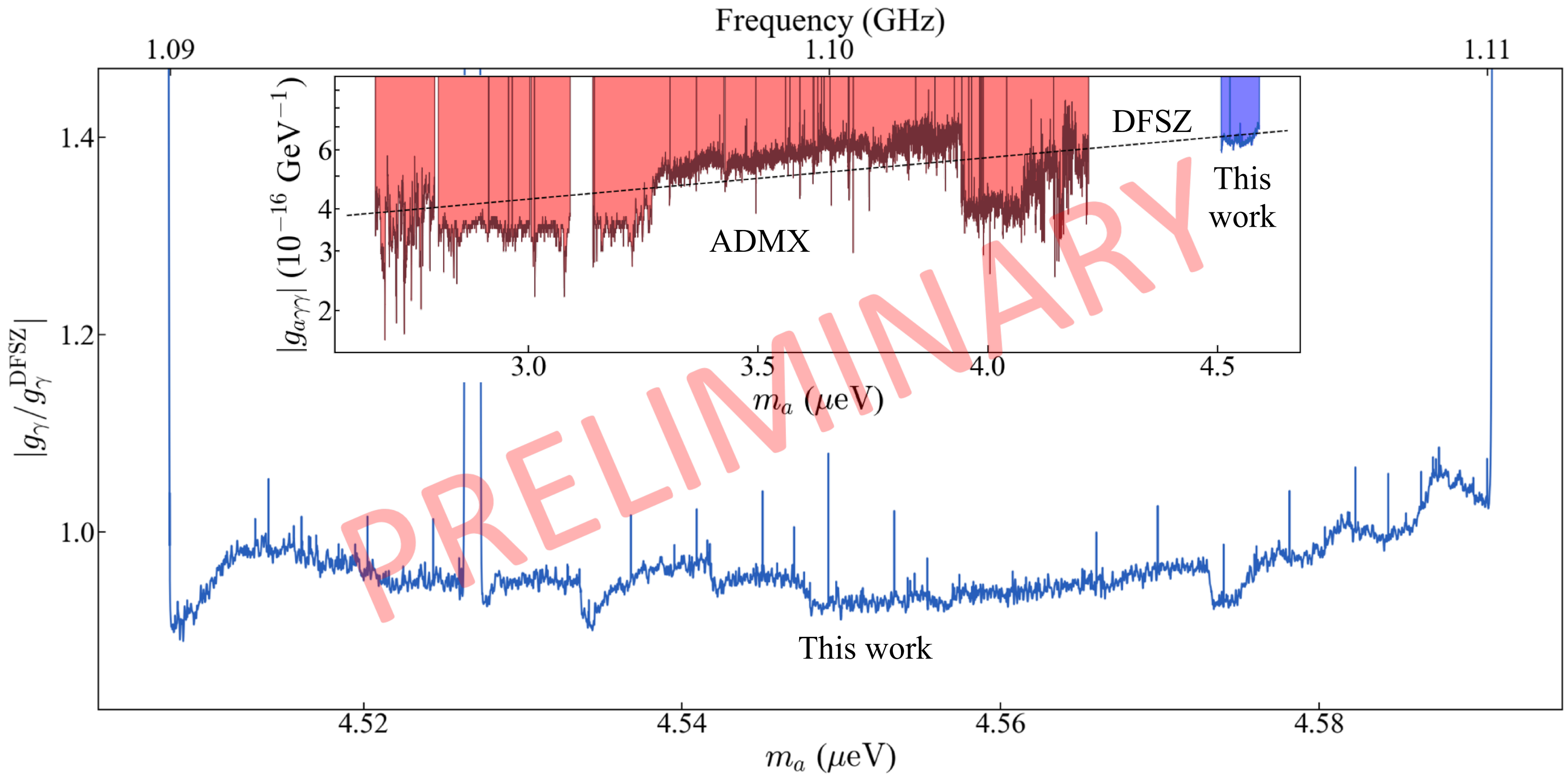


see e.g., [M. D. Bird, Springer Proc.Phys. 245 (2020) 9-16], [N. Bykovskiy *et al.*, IEEE Trans.Appl.Supercond. 31 (2021) 5, 4500305], …

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

IBS/CAPP: Center for Axion and Precision Physics Research

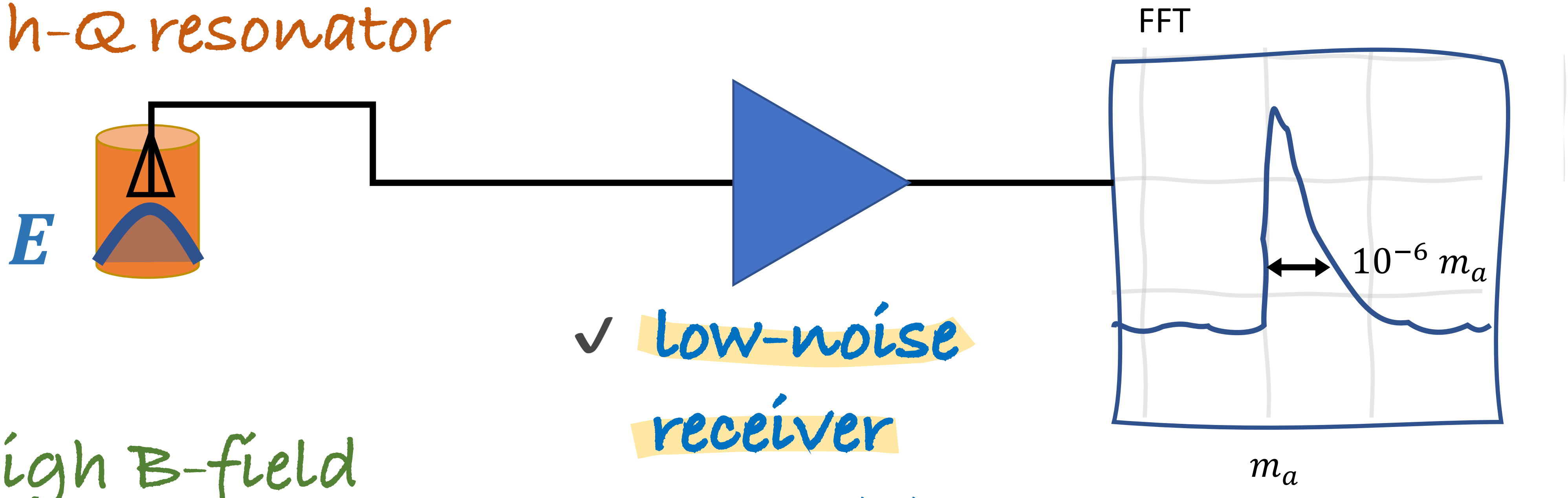
CAPP-12TB [A. K. YI, talk at PATRAS2022]



Other setups with results from IBS:	single cav., 8T magnet, 2.6GHz [PRL 126, 191802 (2021)]	supercond. cav., 8T, 2.3GHz [arXiv:2207.13597]	multicell, 8T, 3.2GHz [PRL 125, 221302 (2020)]	single cav., **18T magnet**, 4.8GHz [PRL 128 241805 (2022)]	…

High Mass Challenge – Lower Noise

✓ high-Q resonator



✓ low-noise receiver

✓ high B-field

Quantum Limit:

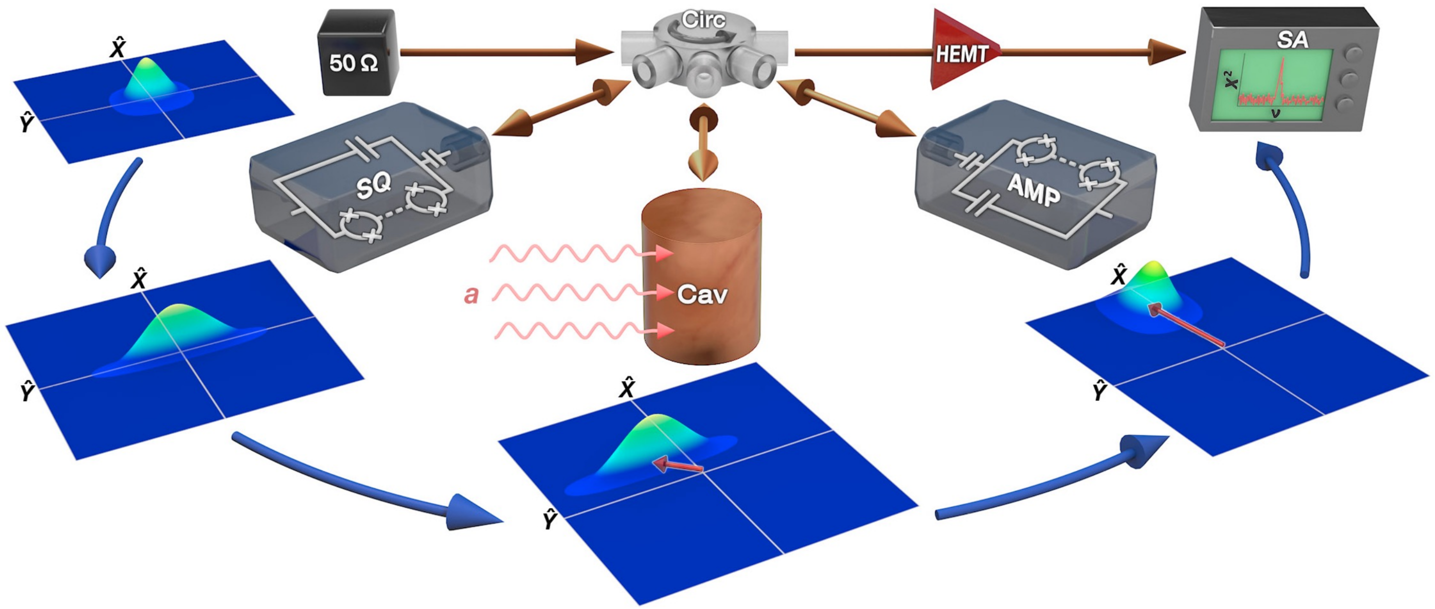
$$k_B T_{sys} = h\nu$$

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

HAYSTAC: Haloscope At Yale Sensitive To Axion CDM

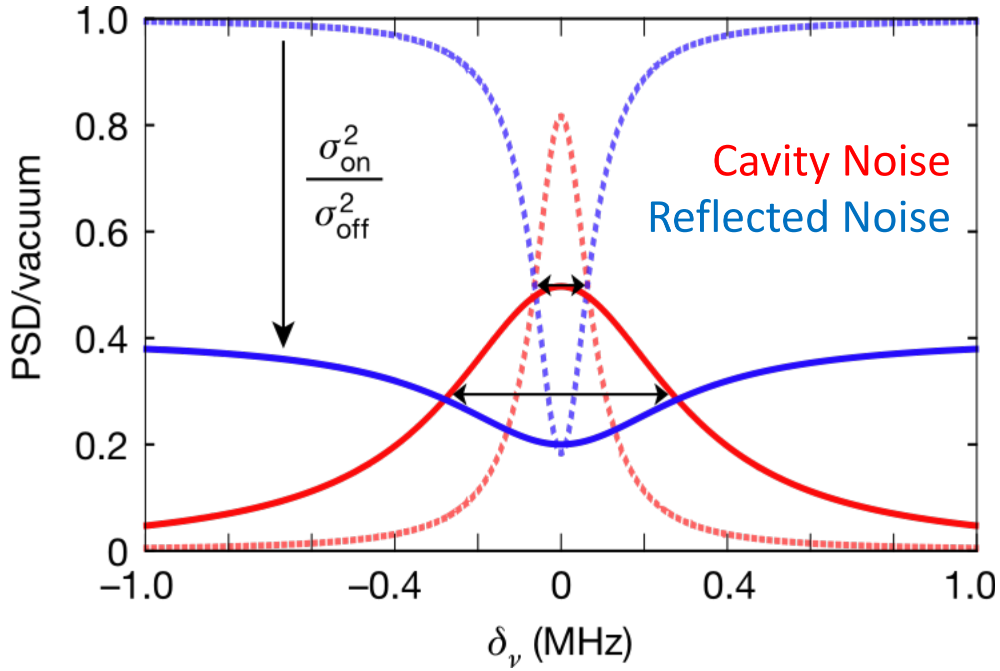
[Backes *et al*, Nature 590, 238–242 (2021)]

$$\hat{E} = E_0 \left[\cos(\omega t)\hat{X} + \sin(\omega t)\hat{Y} \right]$$



Squeezing of Reflected Noise

see also [Phys. Rev. X 9, 021023 (2019)]

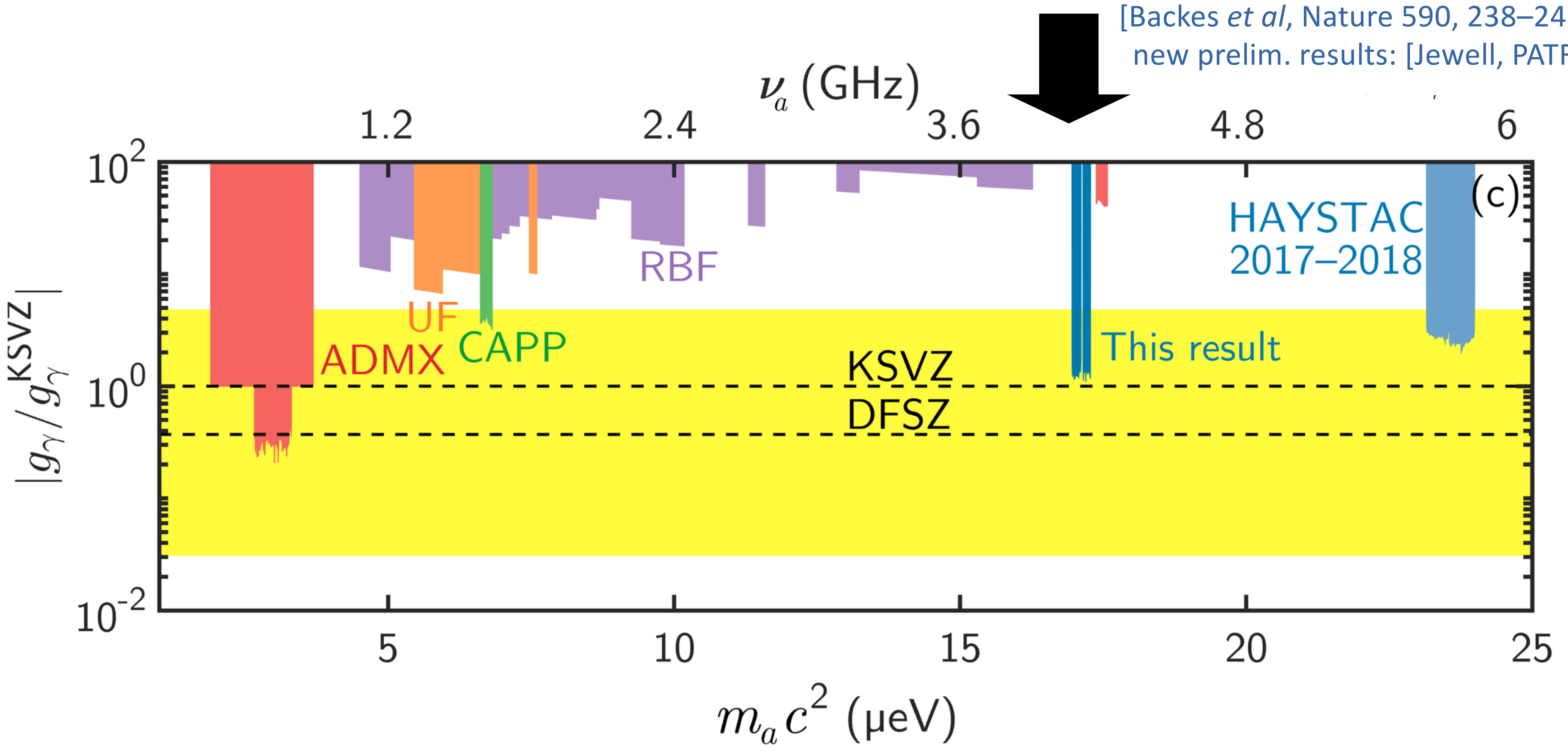


bandwidth increase
→ **double scan rate**

HAYSTAC: First μeV Sub-Quantum Axion Search

HAYSTAC

[Backes *et al*, Nature 590, 238–242 (2021)]
new prelim. results: [Jewell, PATRAS2022]



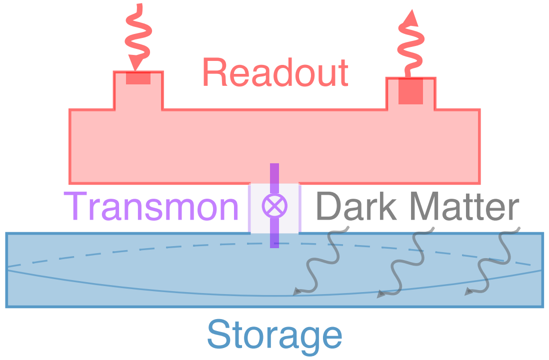
Advanced Proposal using Cavity-State Swapping: CEASEFIRE [K. Wurtz *et al*, PRX Quantum 2, 040350 (2021)]

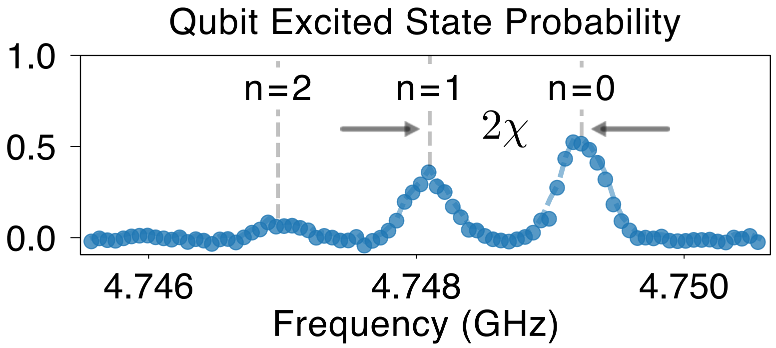
Single Photon Detection

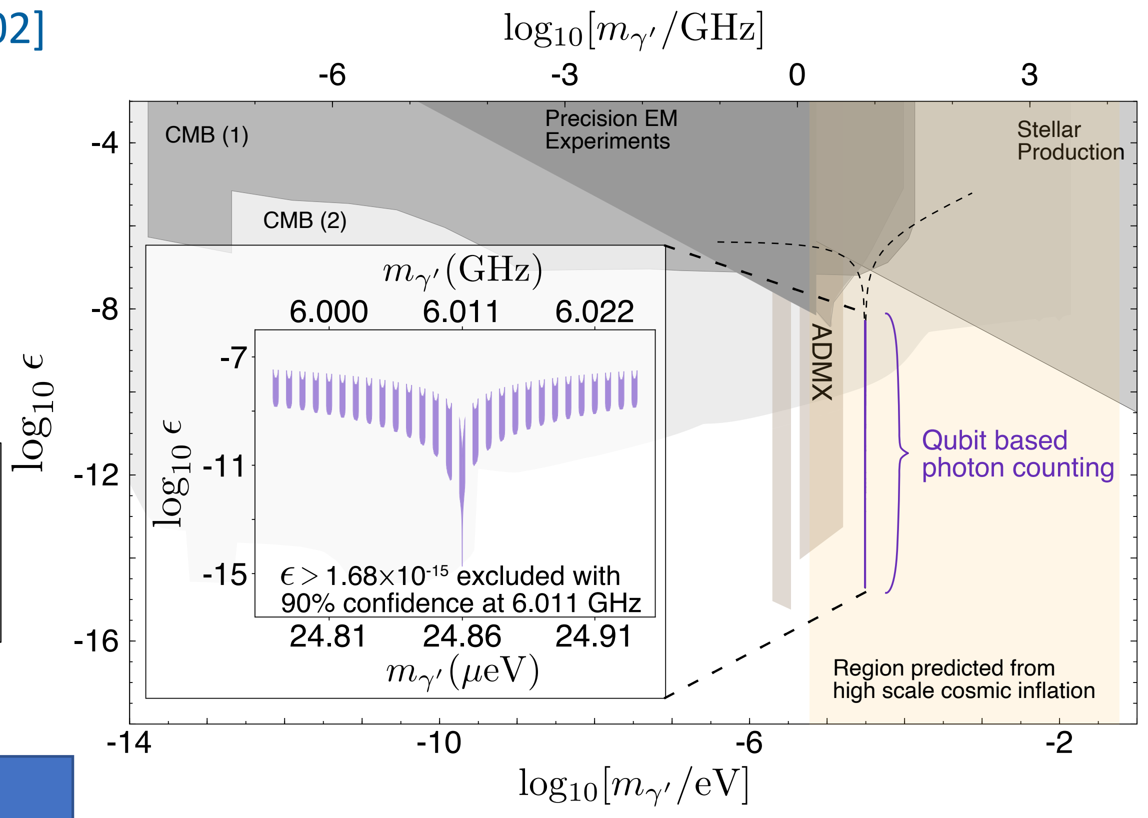
Non-Destructive Qubit Readout: [A. V. Dixit *et al*, PRL 126, 141302]

$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

cavity Qubit Interaction (commutes with cavity/Qubit!)







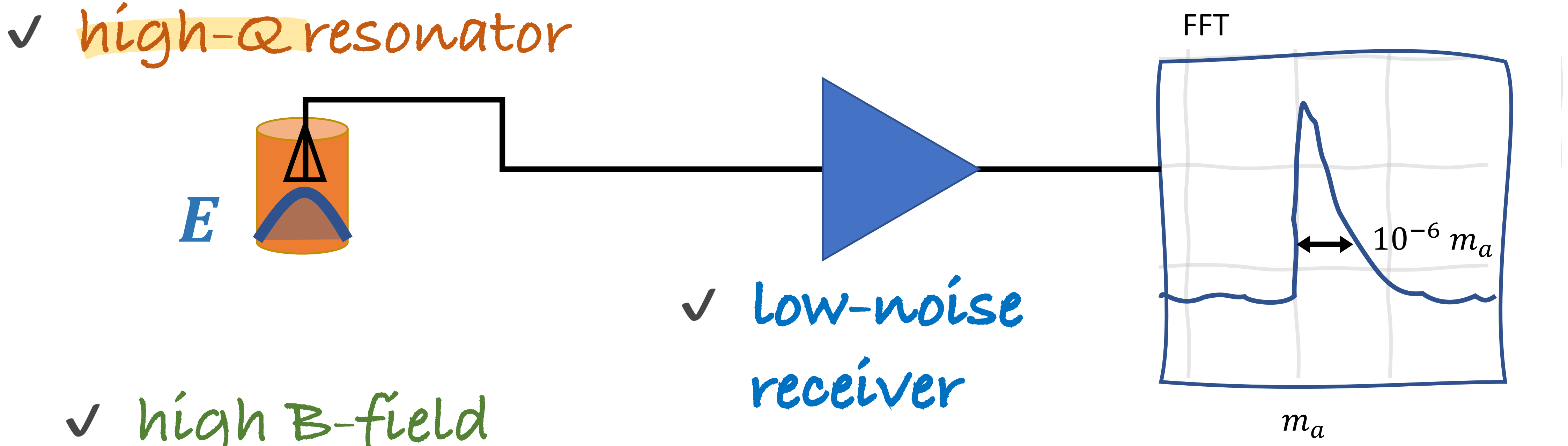
15.7 dB advantage over SQL

Other Recent low GHz Single Photon Detectors:

14 GHz photon counting with current-biased Josephson junction
[Kuzmin *et al*, *IEEE Trans. Appl. Super.* 28 7 (2018)]

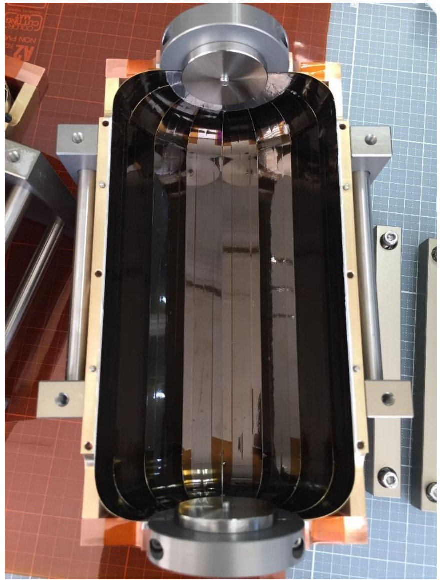
…

High Mass Challenge – Better Cavities



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

Superconducting Cavities

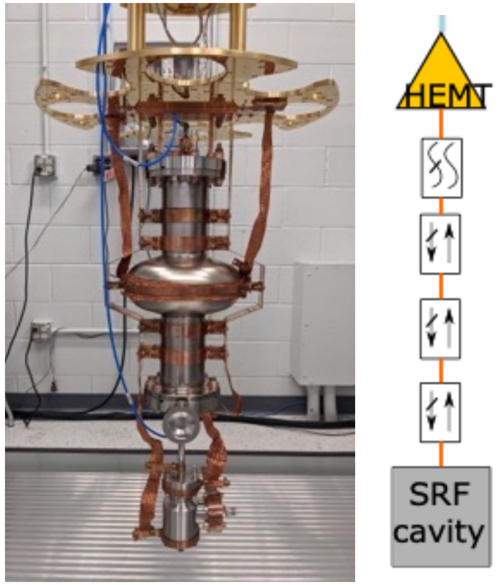


GdBCO, $Q \sim 5{\times}10^5$ $(\mathrm{B} = 8\mathrm{T})$

KSVZ-sensitive Search @2.3GHz:
[D. Ahn, PATRAS2022],
[J. Kim *et al*, arXiv:2207.13597]

NbTi, $Q \sim 10^6$ $(\mathrm{B} = 0\mathrm{T})$

Surface Contribution Analysis:
[T. Braine *et al*, arXiv:2208.11799]



Niobium, $Q \sim 10^{10}$ $(\mathrm{B} = 0\mathrm{T})$

DP Search:
[R. Cervantes *et al*, arXiv:2208.03183]

Nb_3Sn, $Q \sim 10^6$ $(\mathrm{B} \sim 6\mathrm{T})$

[S. Posen *et al*, arXiv:2201.10733]

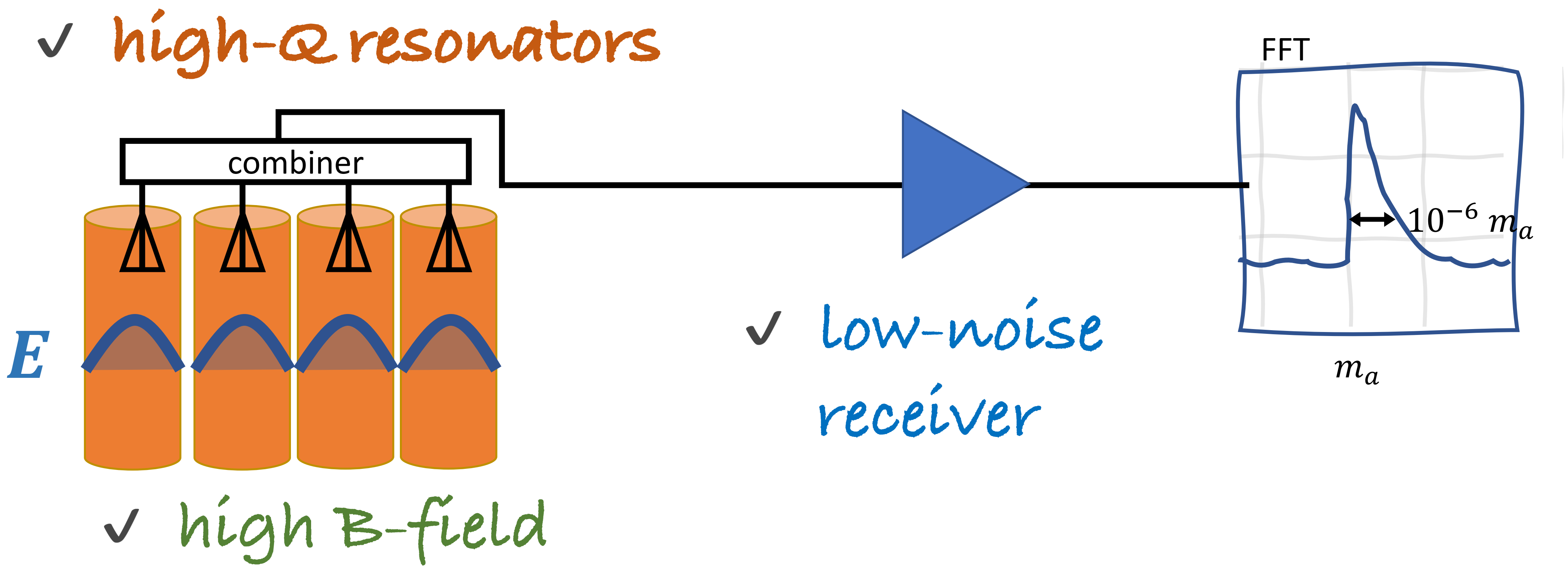
Other Efforts:

QUAX-aγ, 9GHz, $Q \sim 3{\times}10^5$, $B \sim 5\mathrm{T}$
[PRD 99 101101 (2019)]

RADES, 9GHz, $Q \sim 10^5$, $B \sim 11\mathrm{T}$
[IEEE Trans. on Appl. Supercond. (2022)]

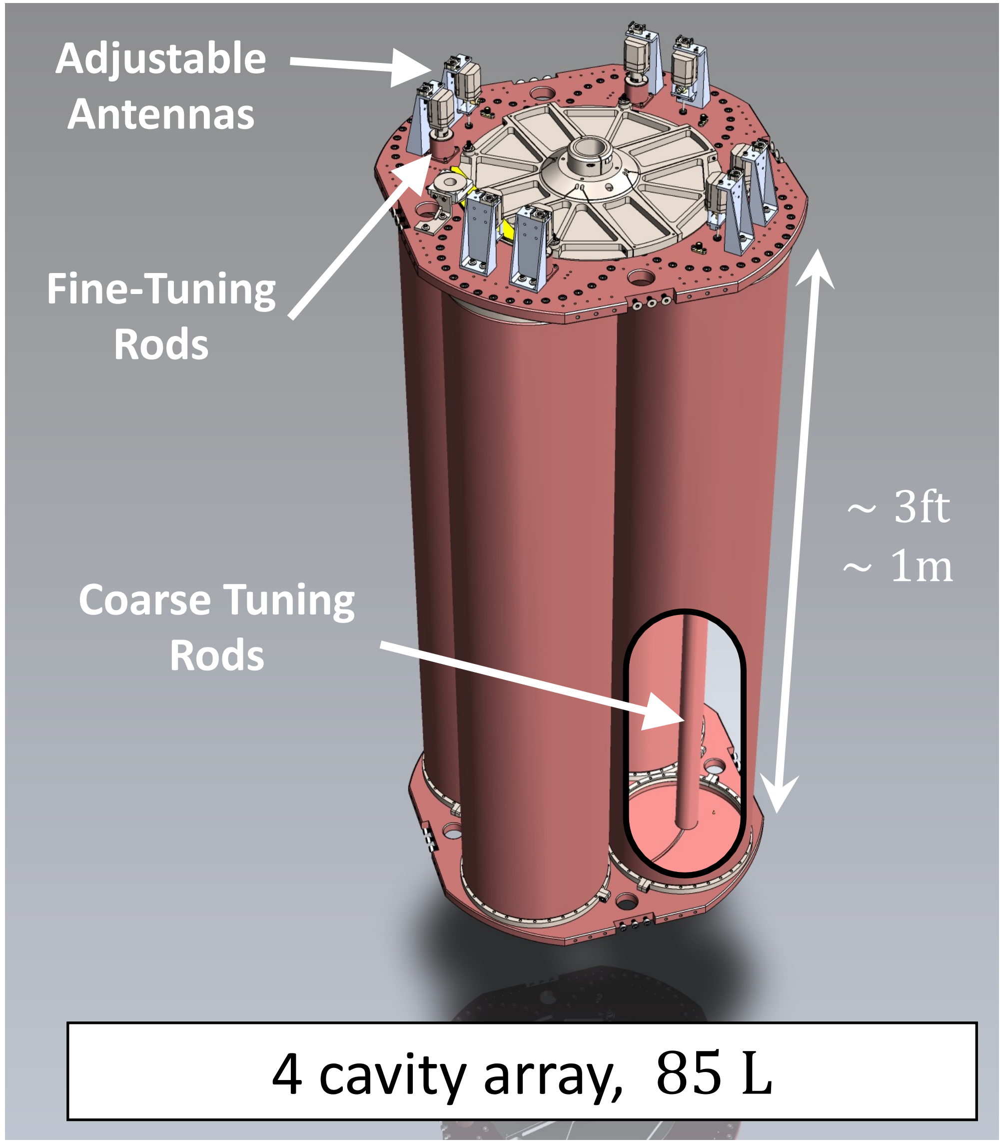
SUPAX …

High Mass Challenge – Combine Signals

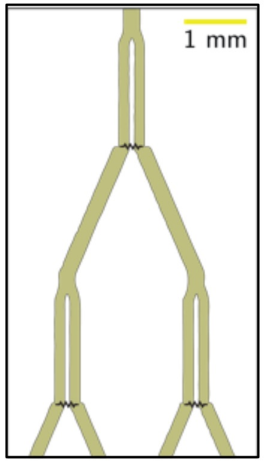


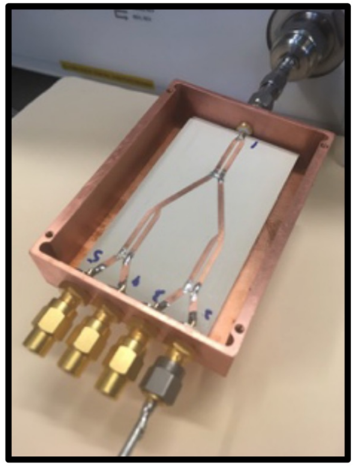
$$P_{\mathrm{sig}} = 2 \cdot 10^{-23}\ \mathrm{W} \cdot \left(\frac{B}{7.6\ \mathrm{T}}\right)^2 \left(\frac{V}{136\ L}\right) \left(\frac{C}{0.4}\right) \left(\frac{Q}{30{,}000}\right) \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{m_a}{3\ \mu\mathrm{eV}}\right) \left(\frac{\rho_{\mathrm{DM}}}{0.45\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

Next ADMX Gen-2: (1.4 - 2.2) GHz



4 cavity array, 85 L





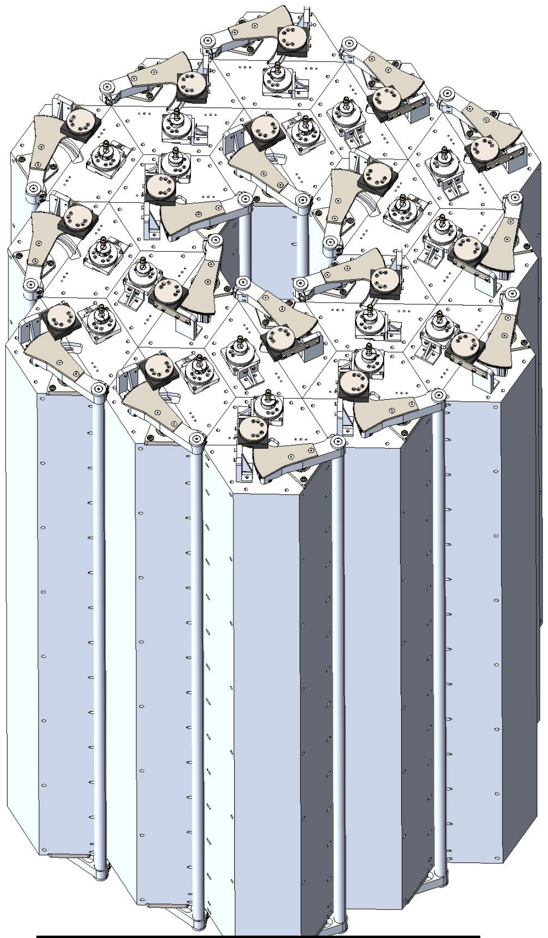
analog power combining

Site: Univ. Washington

Data Taking from 2023/24

ADMX-EFR (Extended Frequency Range): 2-4GHz

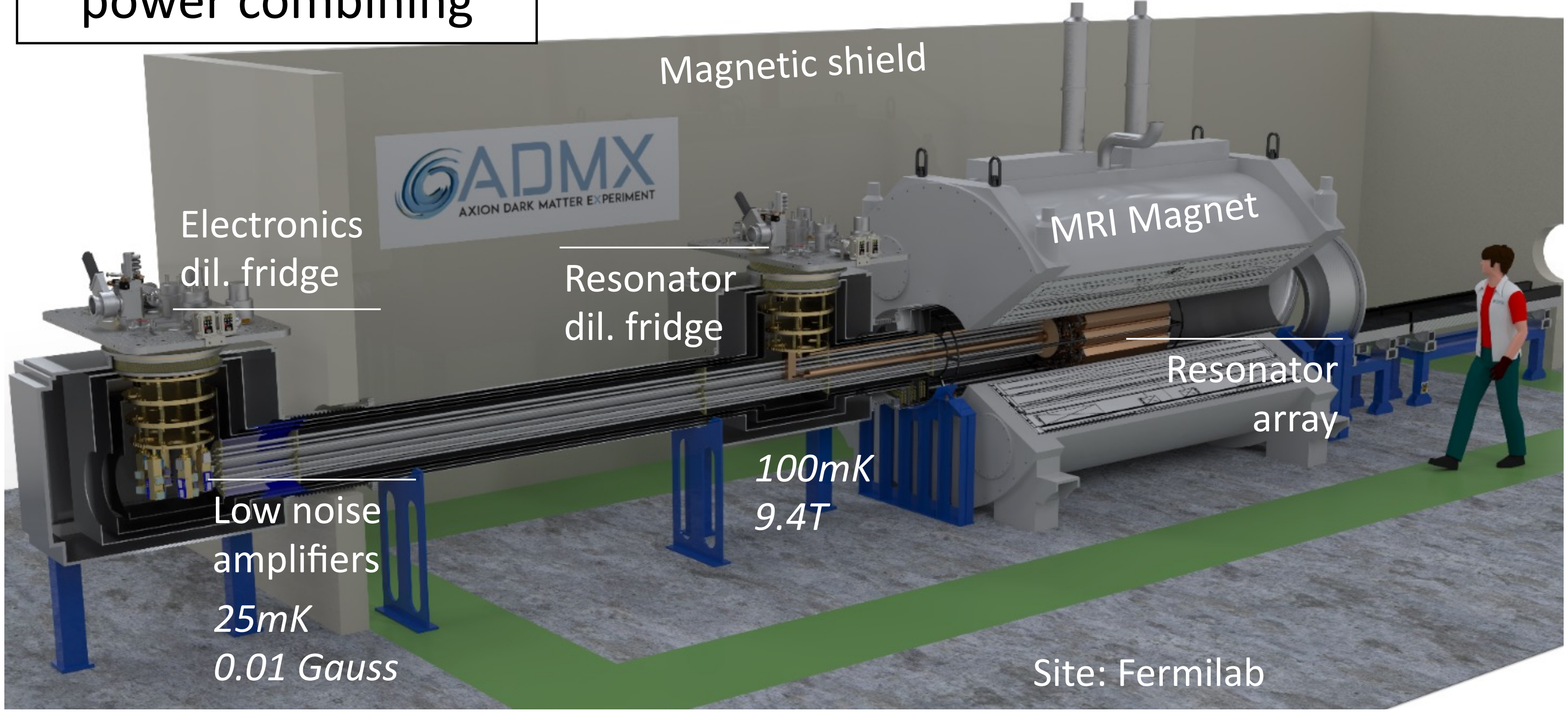
ADMX AXION DARK MATTER EXPERIMENT



18 cavity array

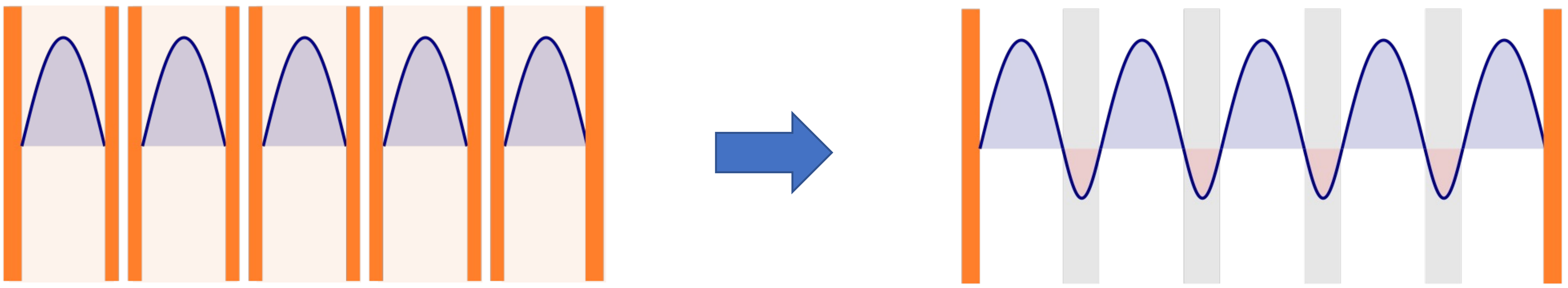
digital power combining

horizontal magnet: 9.4 T, 258 L

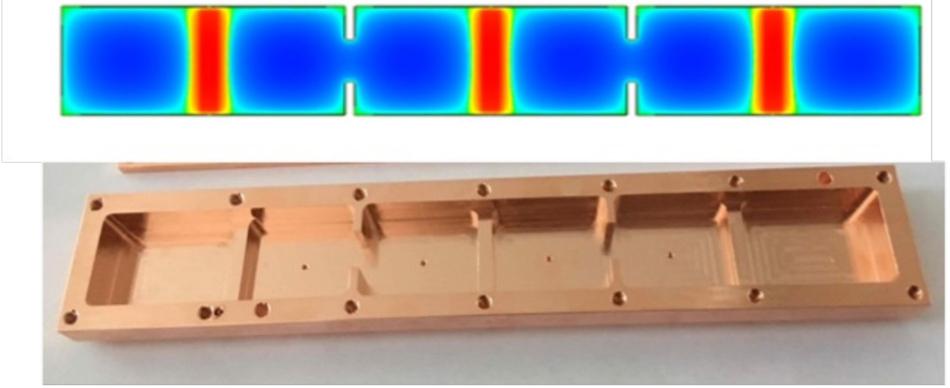


Goal: Search 2-4GHz @ DFSZ sensitivity in 3 years scan time

Multi-Cavity and Multi-Cell



RADES

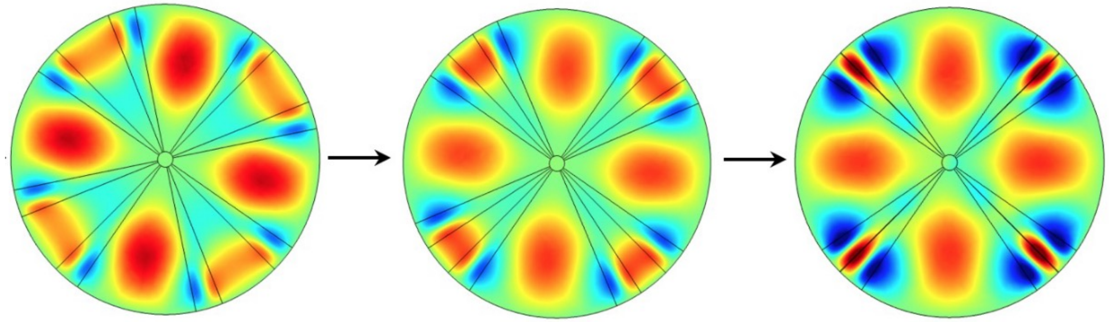


[Döbrich *et al.*, JHEP 07 (2020) 084]

QUAX-aγ: [PRD 103 102004 (2021)]
[D. Alesini, Nuc. Inst. and Meth. in Phys. Res. A, 985, 2021]

CAST-CAPP: [M. Maroudas, PATRAS2022]

Pizza / Wedge Cavities

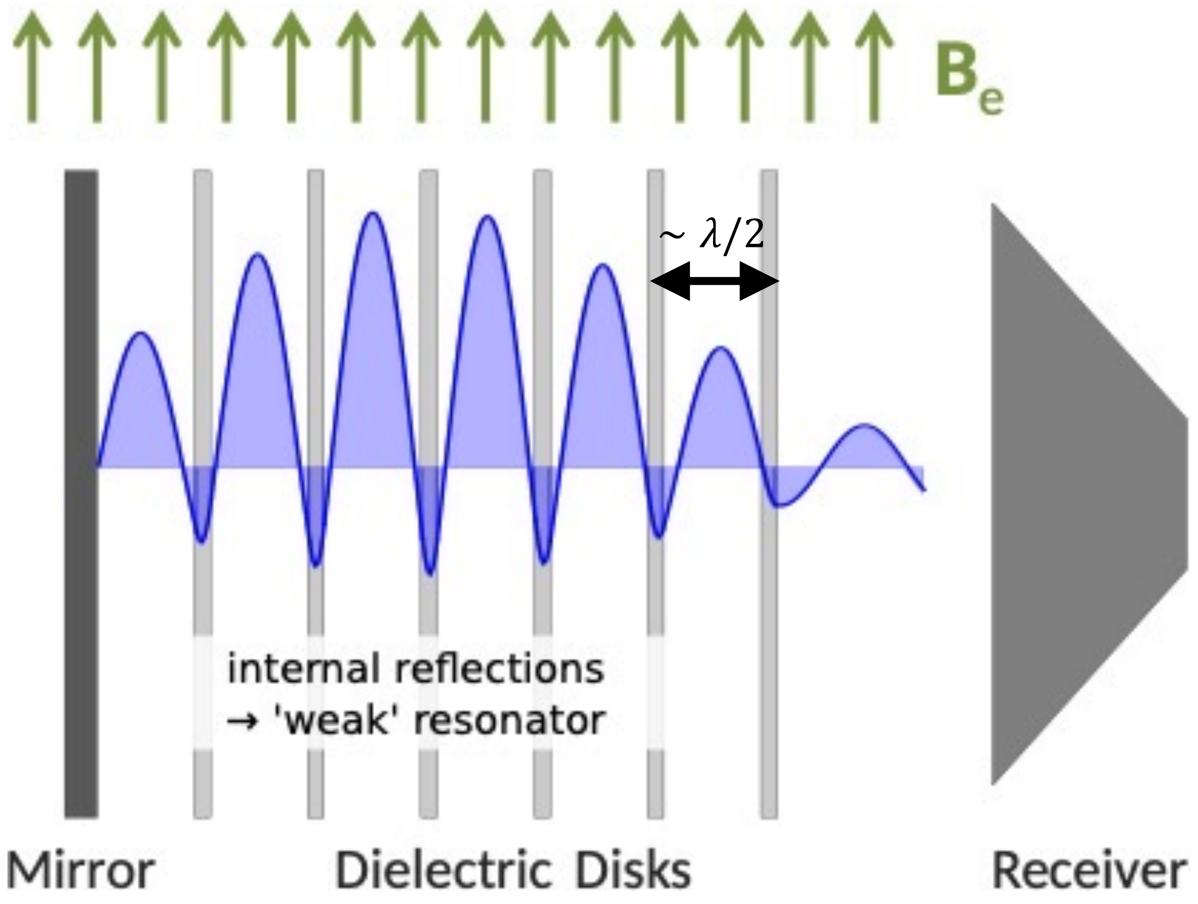


ORGAN: [Quiskamp *et al.*, Phys. Rev. Applied 14 (2020) 4]
[McAllister *et al.*, Springer Proc. Phys.245 (2020) 37-43]

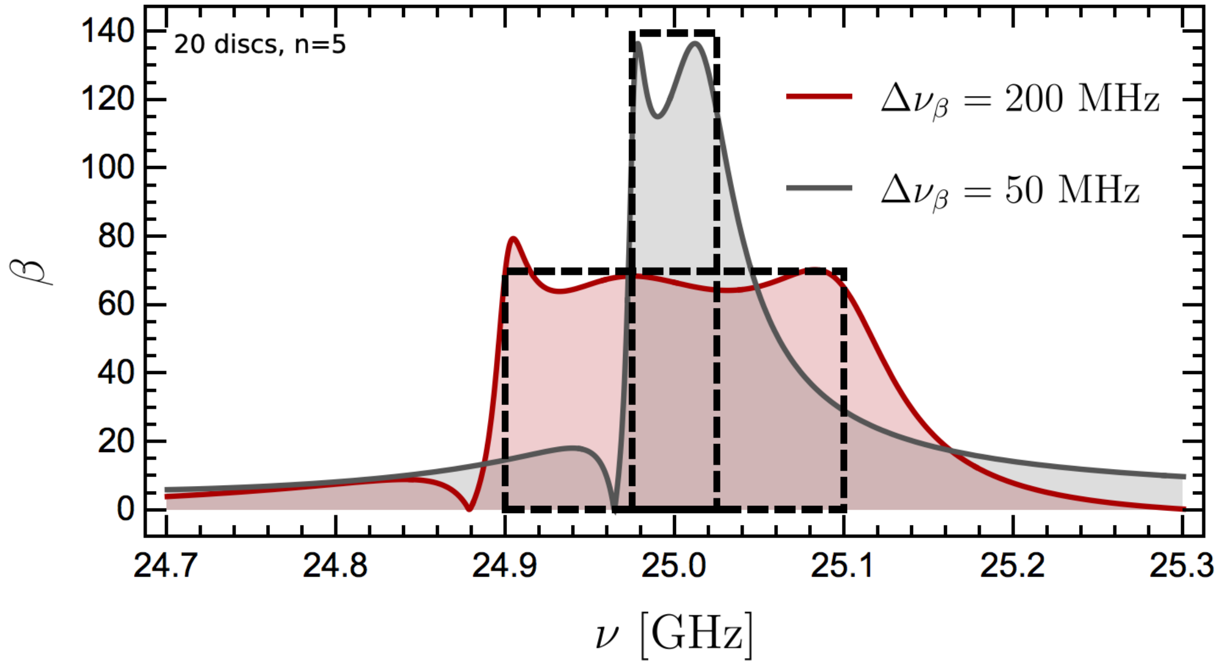
IBS/CAPP: [Youn *et al.*, Phys. Lett. B 777 (2018) 412-419]
[Youn *et al.*, Phys. Rev. Lett. 125, 221302]

Open Resonators: Dielectric Haloscope

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



Power ∝ Boost Factor β^2
tunable via disk positions



ORPHEUS (15-18GHz)
[Cervantes *et al.*, arXiv:2204.09475]

MADMAX (10-100GHz)
[P. Brun *et al.*, Eur. Phys. J. C (2019) 79: 186]

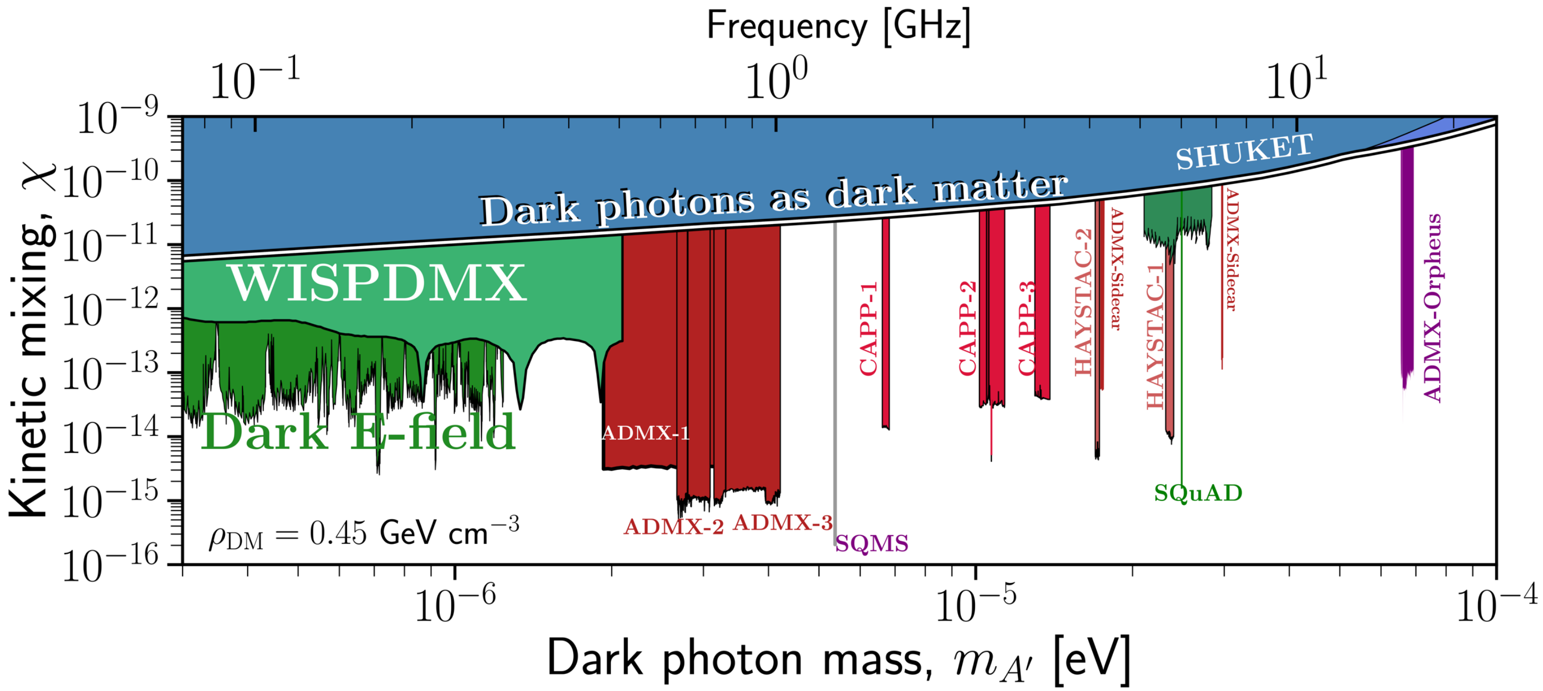
DALI (6-60GHz)
[J. De Miguel, JCAP 04(2021)075]

LAMPOST (infrared)
[J. Chiles *et al.*, PRL 128, 231802]

MuDHI (infrared)
[L. Manenti *et al.*, PRD 105, 052010]

Open Resonators: Dielectric Haloscope

ADMX-ORPHEUS



[R. Cervantes *et al.*, arXiv:2112.04542, arXiv:2204.09475]

ORPHEUS (15-18GHz) [Cervantes *et al.*, arXiv:2204.09475]

MADMAX (10-100GHz) [P. Brun *et al.*, Eur. Phys. J. C (2019) 79: 186]

DALI (6-60GHz) [J. De Miguel, JCAP 04(2021)075]

LAMPOST (infrared) [J. Chiles *et al.*, PRL 128, 231802]

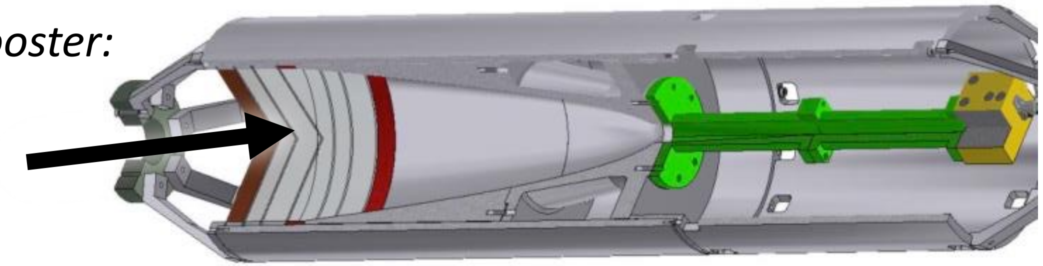
MuDHI (infrared) [L. Manenti et al., PRD 105, 052010]

MADMAX: MAgnetized Disk and Mirror Axion eXperiment

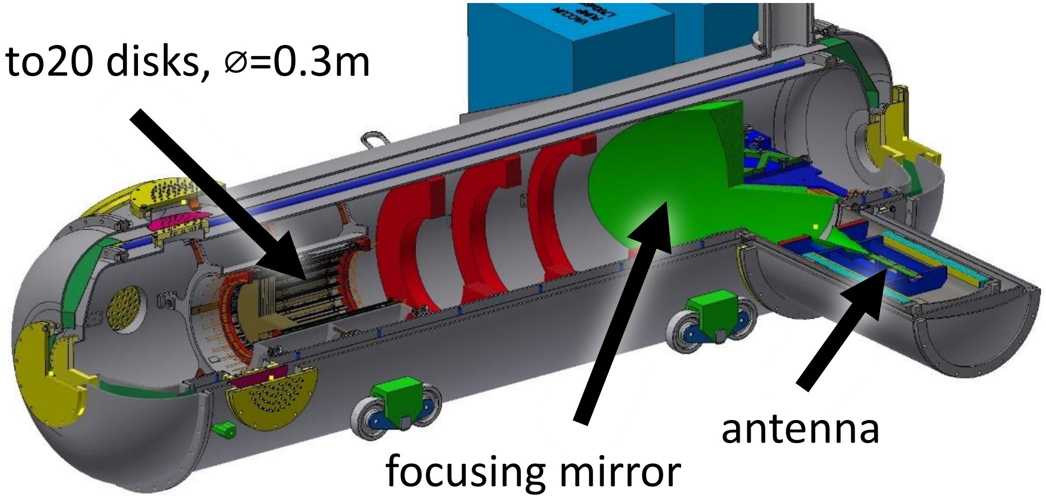
Proof-of-Principle R&D:

Open Booster (5 disks, ⌀=20cm): [J. Egge *et al.*, EPJC80 (2020) 392]

Closed Booster:

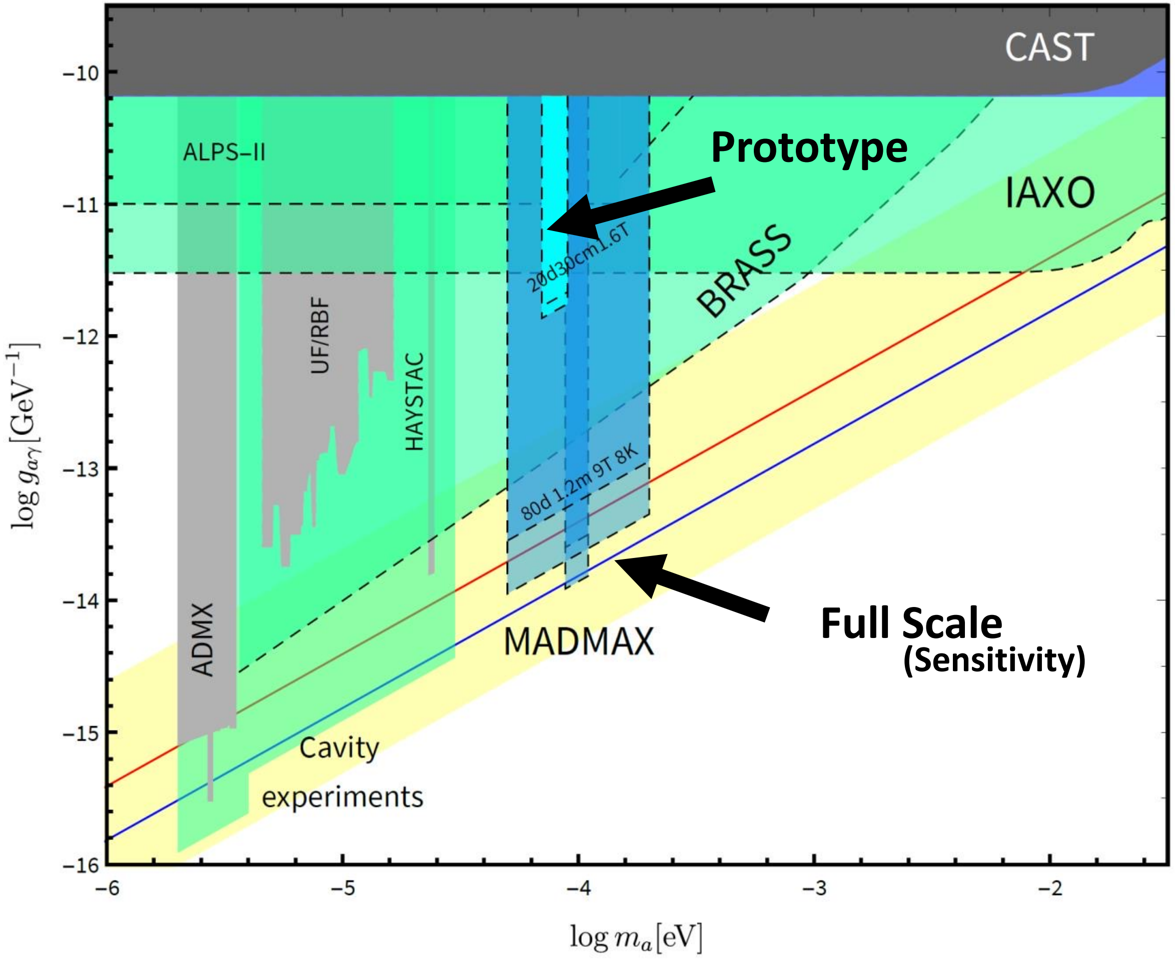


Prototype @ CERN MORPURGO (1.6T)



Full Scale (80 disks, ⌀=1.2m, 9T dipole magnet)

Projected Sensitivities



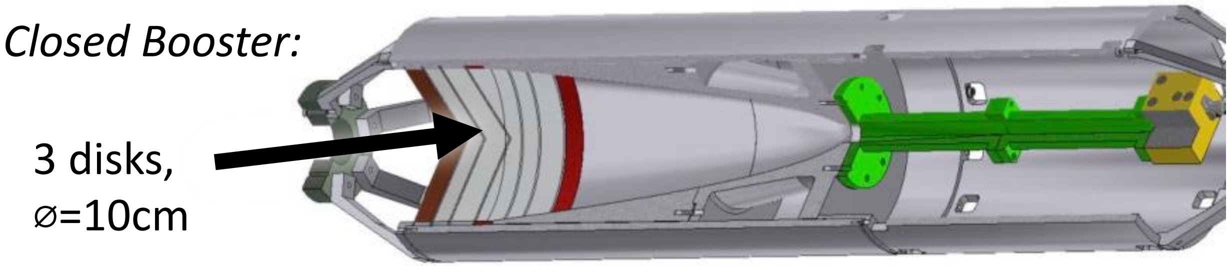
[S. Beurthey *et al.*, arXiv:2003.10894]

MADMAX: MAgnetized Disk and Mirror Axion eXperiment

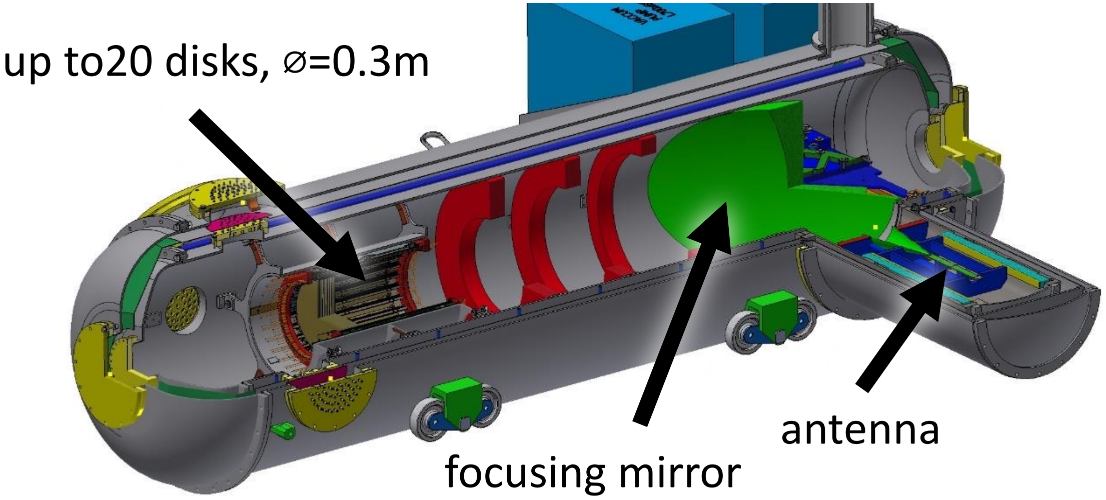
Proof-of-Principle R&D:

Open Booster (5 disks, ⌀=20cm): [J. Egge *et al.*, EPJC80 (2020) 392]

Closed Booster:

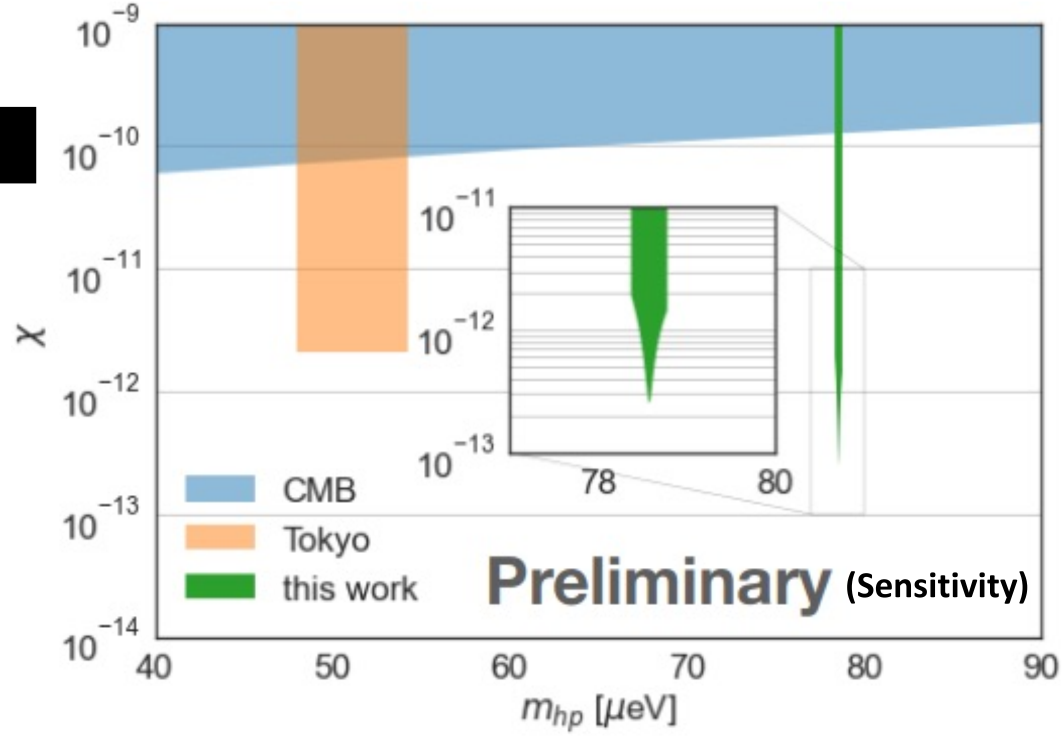


Prototype @ CERN MORPURGO (1.6T)



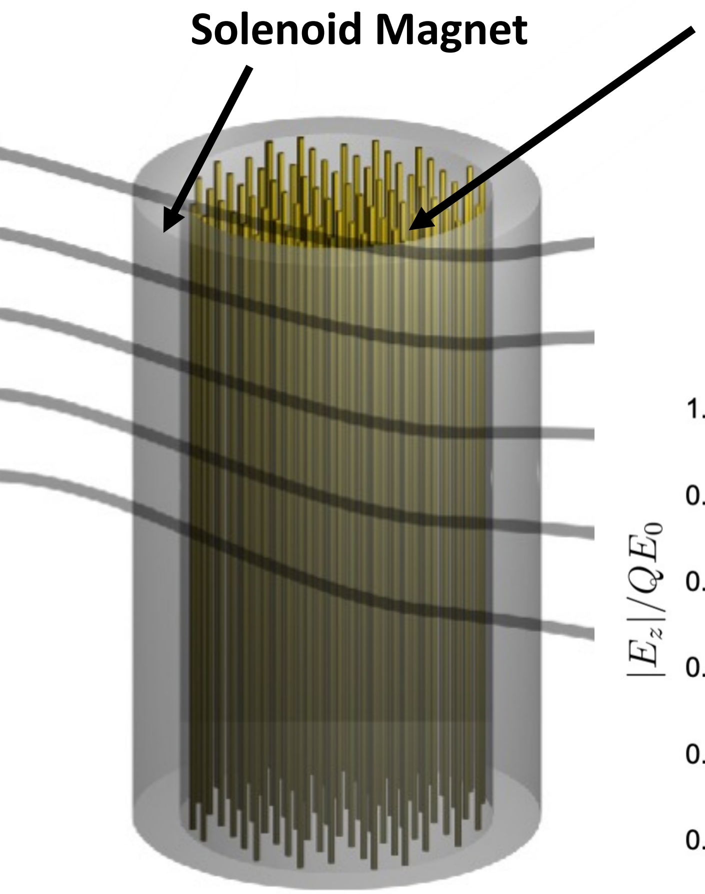
Full Scale (80 disks, ⌀=1.2m, 9T dipole magnet)

First Dark Photon Results with *Closed Booster R&D Setup*:



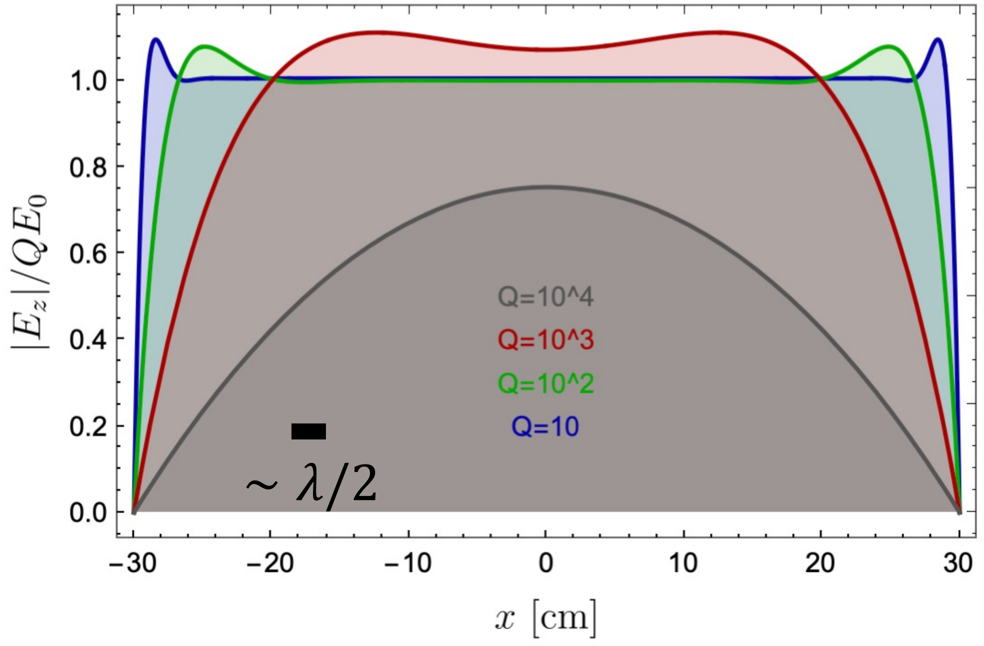
[A. Gardikiotis, PATRAS2022]

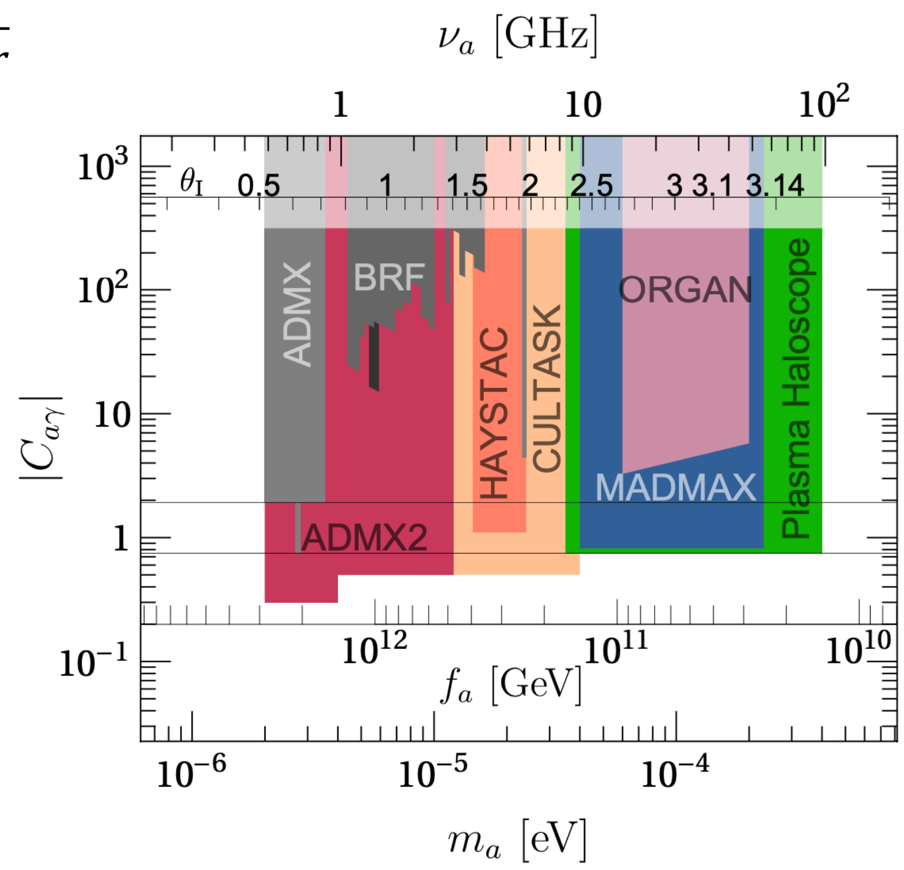
ALPHA: Axion Longitudinal Plasma HAloscope



$$\varepsilon_z = 1 - \frac{\omega_p}{\omega^2 - k_z^2 - i\omega\Gamma} \qquad \omega_p = \frac{2\pi}{a^2 \log a/r}$$

Coherent Plasmon Modes:





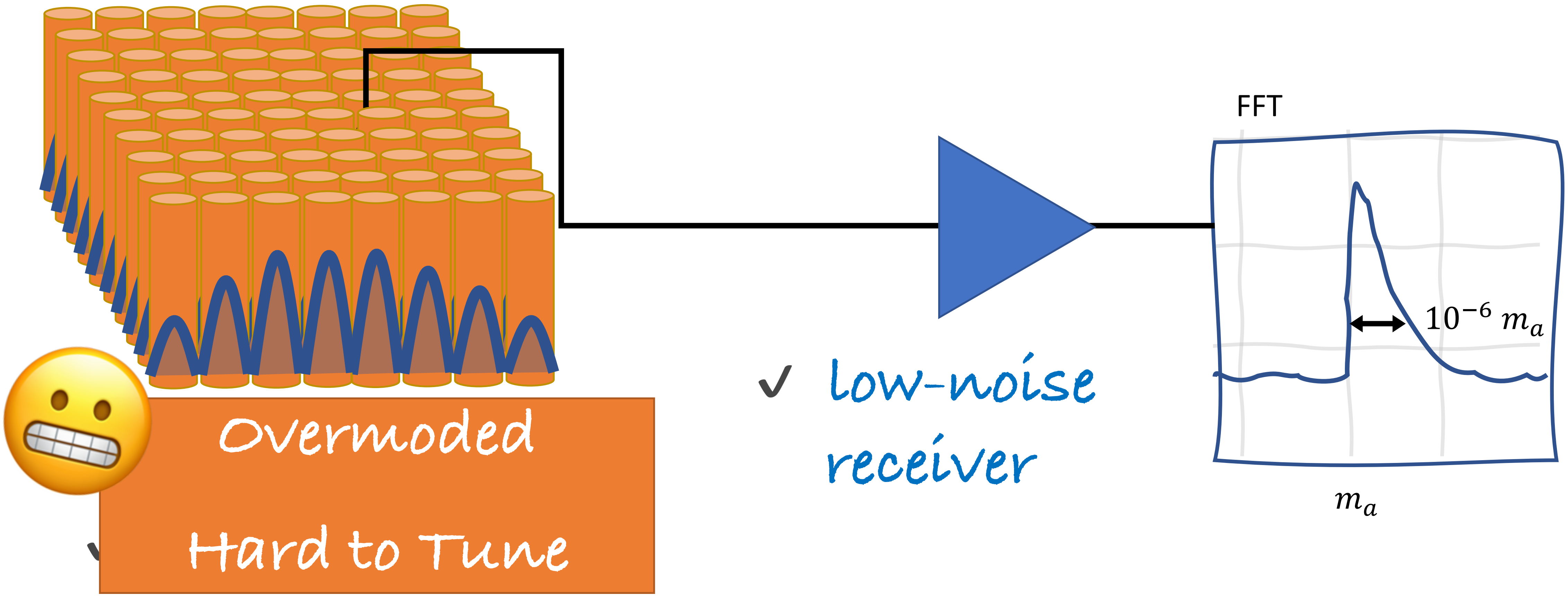
first proof of principles existing

[M. Lawson *et al.*, PRL 123 (2019) 14]
[A. J. Millar, S. Al Kenany *et al.*, talks at APS April Meeting 2021]
[M. Lawson *et al*, talk at PATRAS2021]

Dish Antenna

✓ ~~high-Q resonance~~

[https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-IF1_IF0_Aaron_Chou-175.pdf]

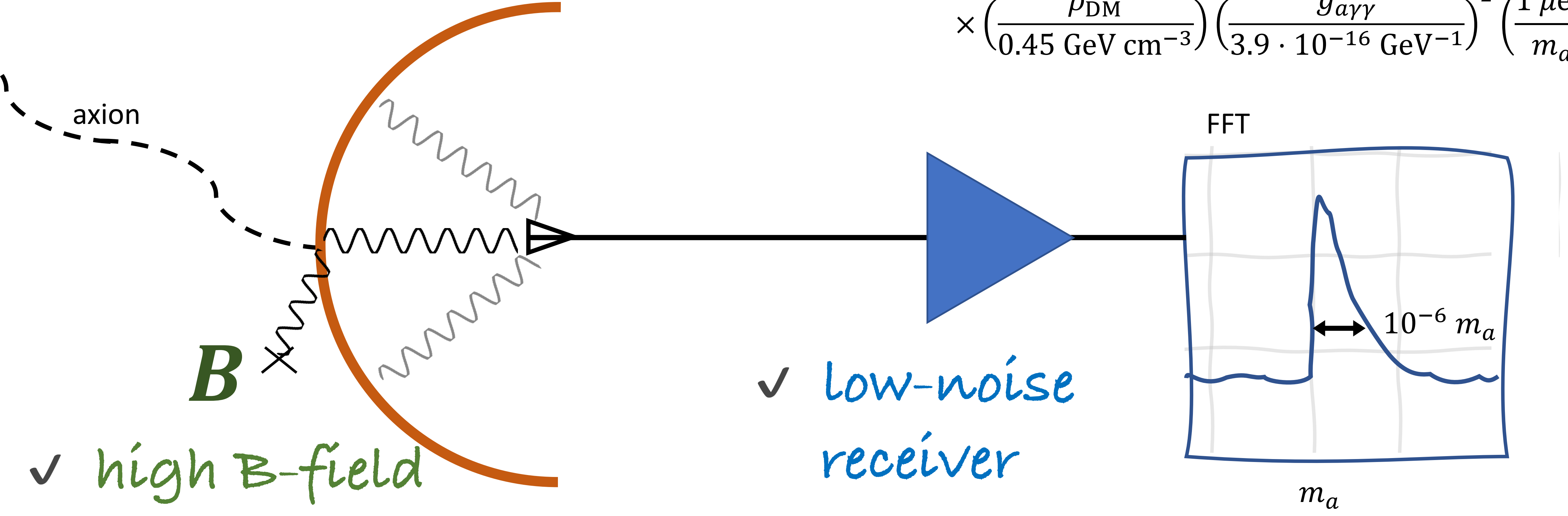


✓ low-noise receiver

Dish Antenna

✔ "dish antenna"
[Horns *et al.*, JCAP 04 (2013) 016]

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

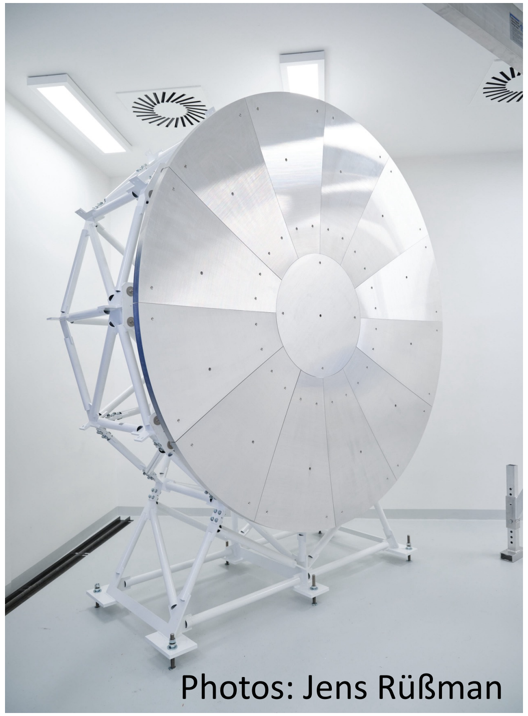


✔ high B-field

✔ low-noise receiver

Dish Antenna – Results for Dark Photons

BRASS-p (12-18GHz) [Le Hoang Nguyen, PATRAS2022]

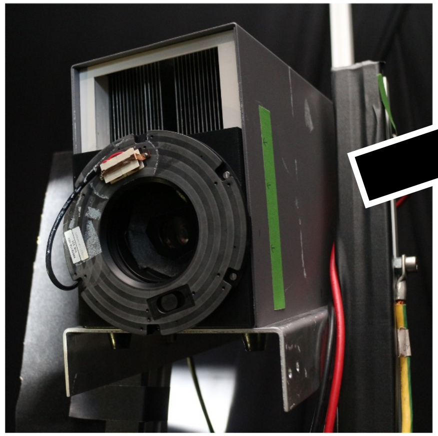


$D \sim 2.5m, f \sim 4.8\mathrm{m}$ $\quad A \sim 2\mathrm{m}^2$

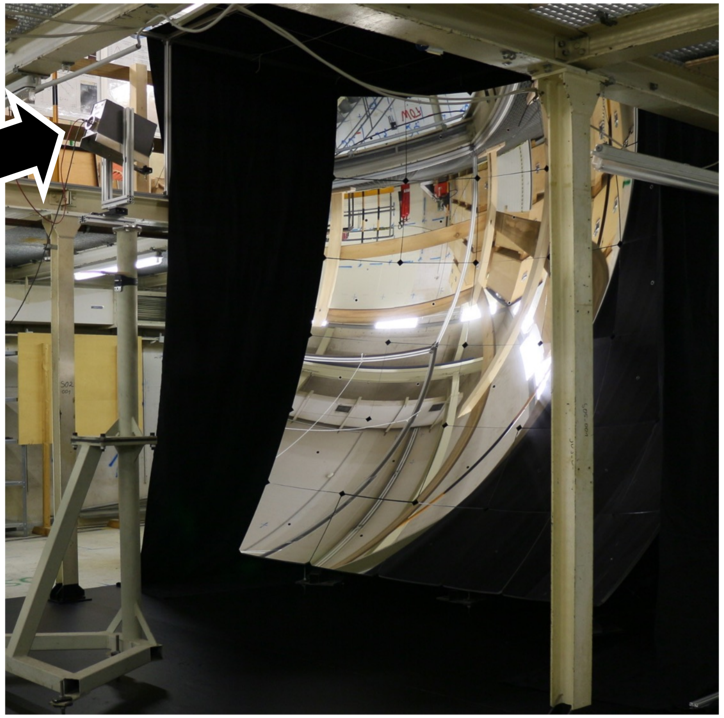
plans to magnetize surface $B \sim 1\mathrm{T}$

see also [http://wwwiexp.desy.de/groups/astroparticle/brass/brassweb.htm]

FUNK (optical) [PRD 102, 042001 (2020)]



PMT (housing)



$A \sim 13\mathrm{m}^2$

SHUKET (5-6GHz)
[P. Brun *et al.*, PRL 122 (2019) 20]

DOSUE (18-26GHz)
[Kotaka *et al*, arXiv: 2205.03679]

Tokyo (28GHz)
[N. Tomita *et al*, JCAP 09 (2020) 012]

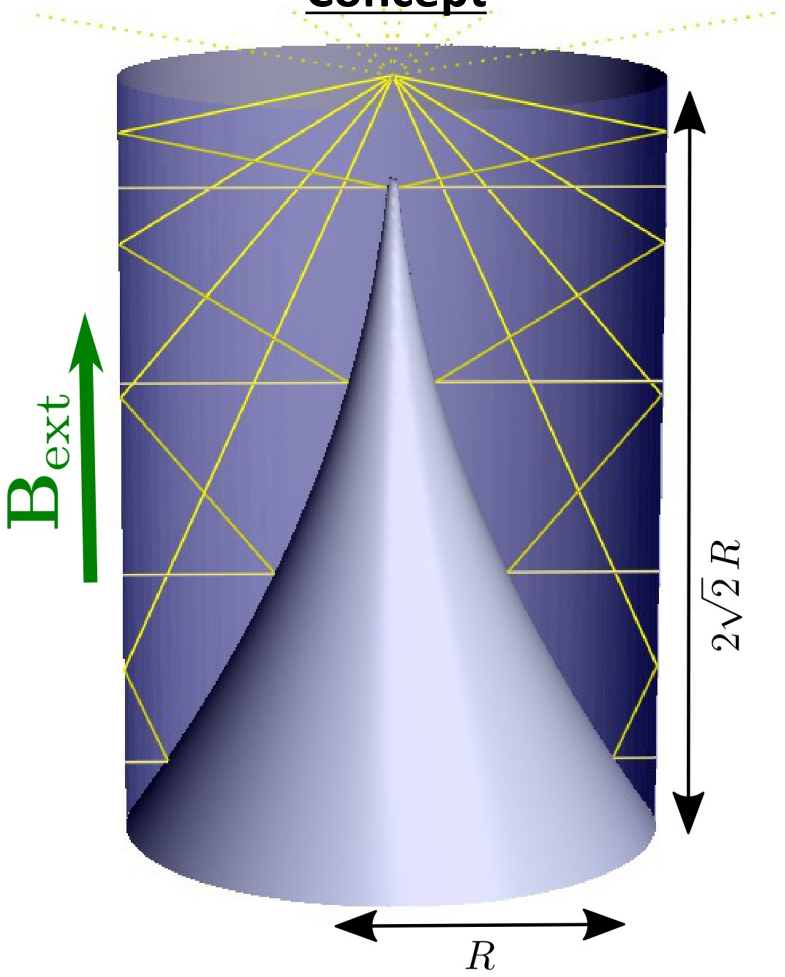
Tokyo (160-220GHz)
[SK *et al*, JCAP 11 (2018) 031]

Tokyo (optical)
[J. Suzuki et al., *JCAP* 09 (2015) 042]

BREAD: Broadband Reflector Experiment for Axion Detection

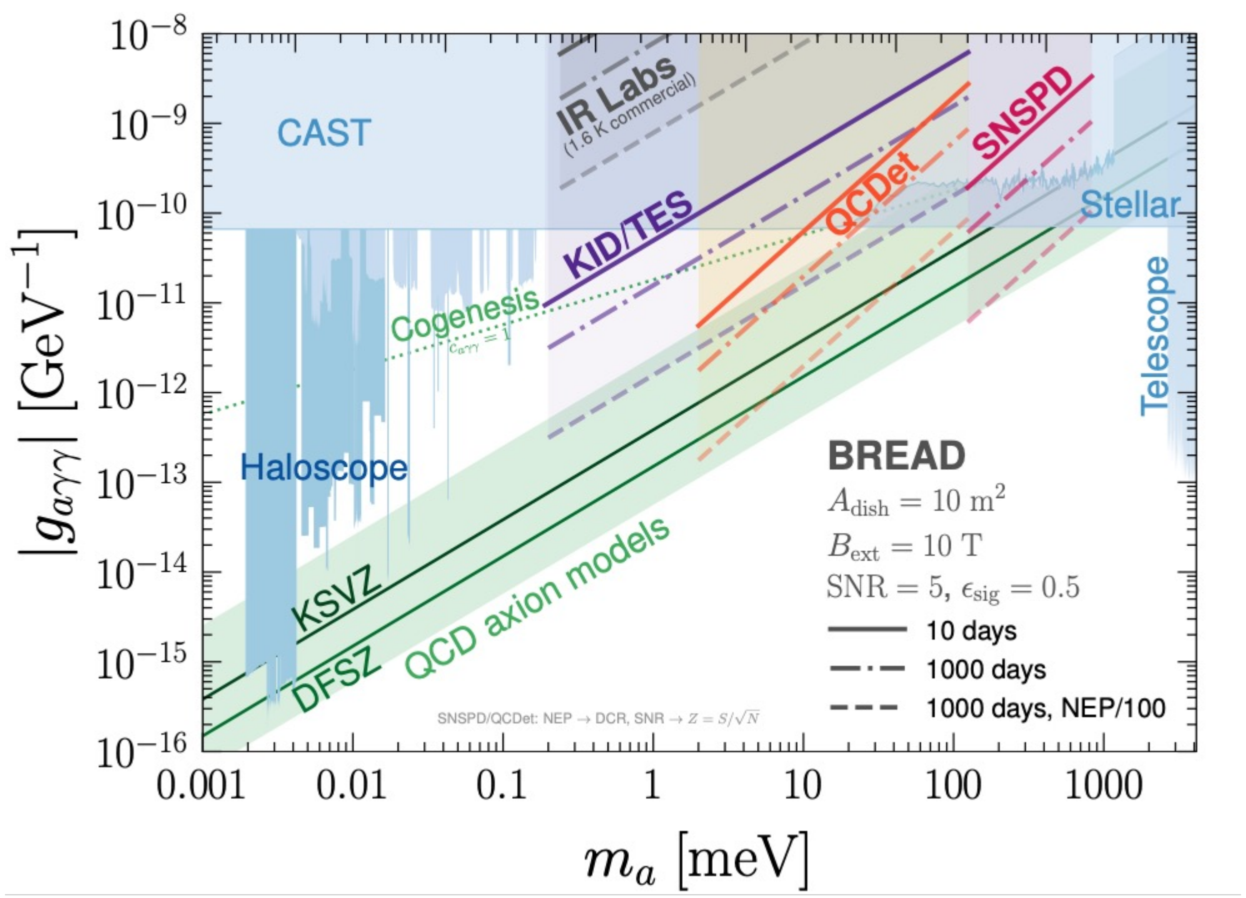
BREAD COLLABORATION

Concept



use solenoid magnet

Projections with Detector Technologies

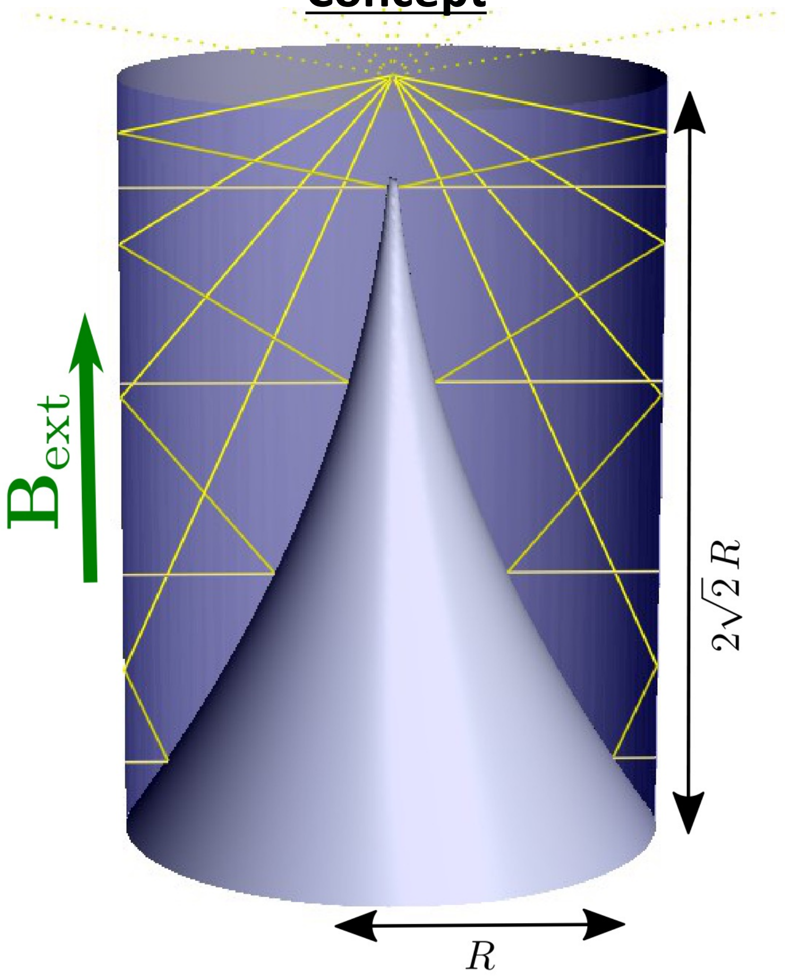


[PRL 128 (2022) 131801]

BREAD: Broadband Reflector Experiment for Axion Detection

BREAD COLLABORATION

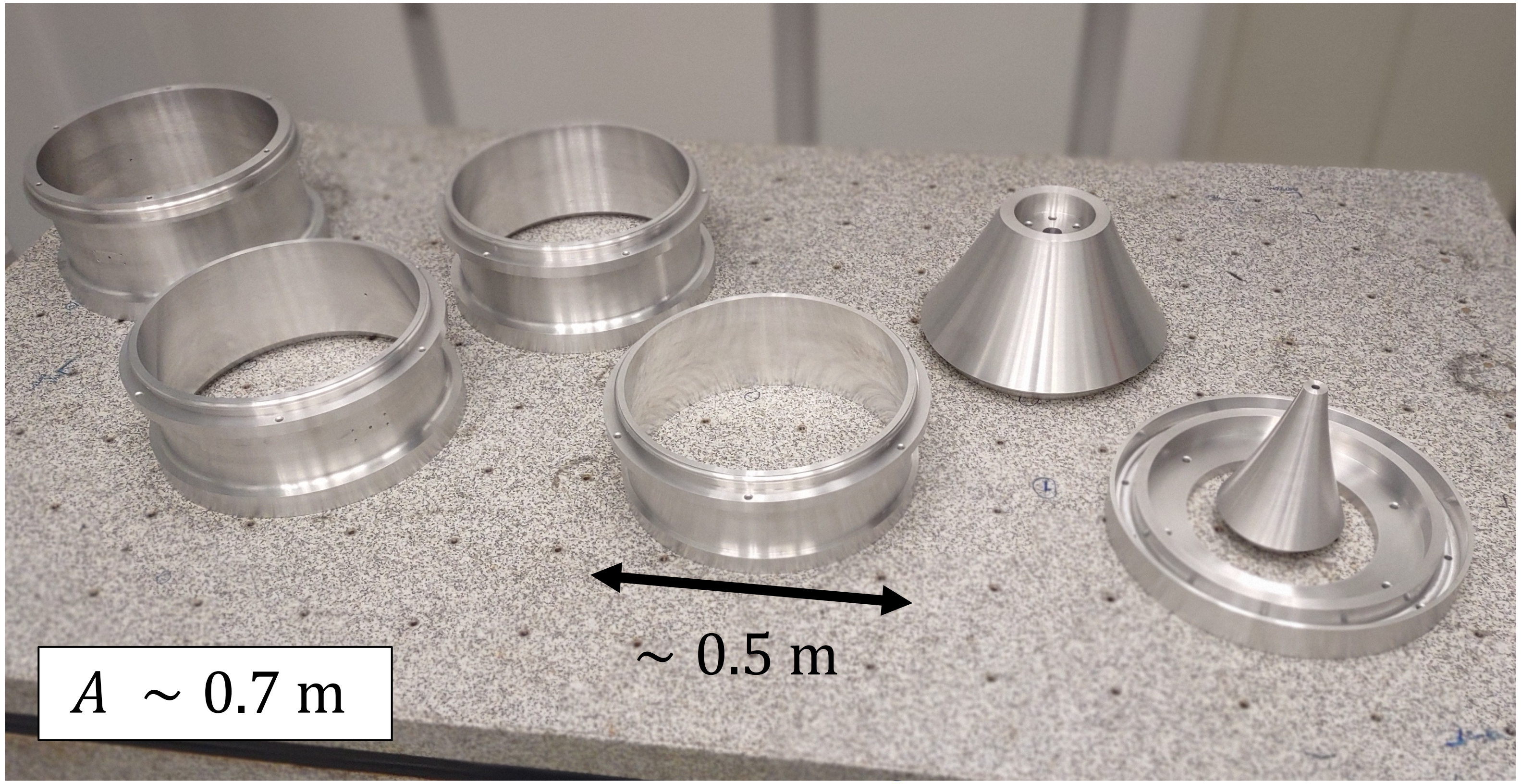
Concept



use solenoid magnet

Upcoming Pilot Experiments

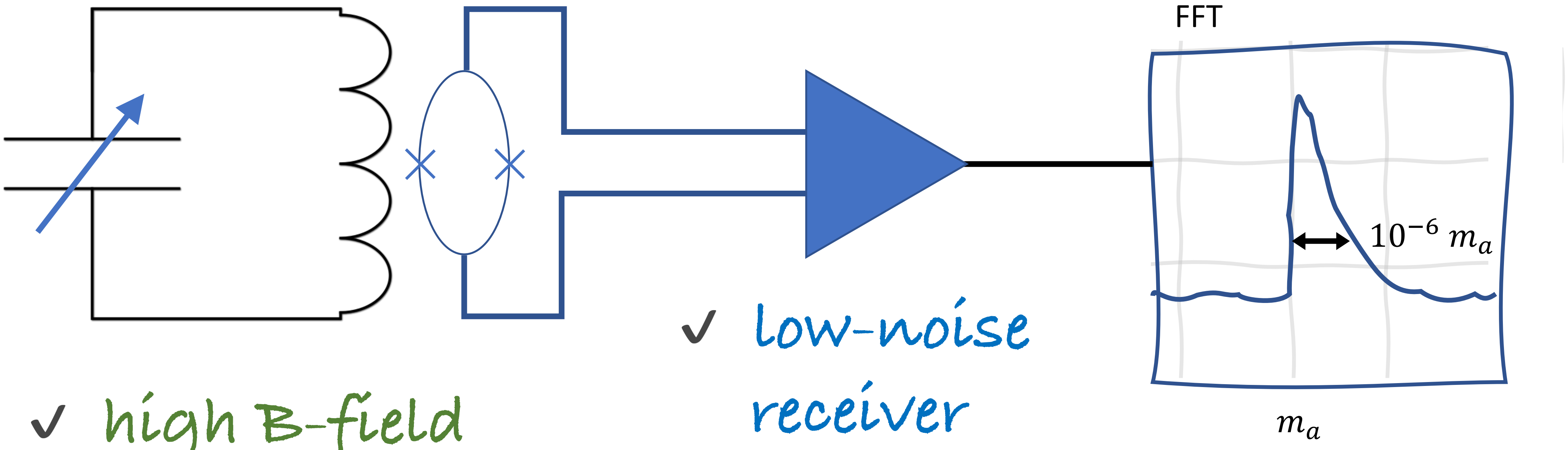
GigaBREAD *InfraBREAD*



Lumped Element Resonator

[Tuned LC Circuit Readout: Cabrera, Thomas (2010)]
[P. Sikivie, N. Sullivan, D. B. Tanner, PRL 112, 131301 (2014)]

✓ high-Q resonator



✓ high B-field

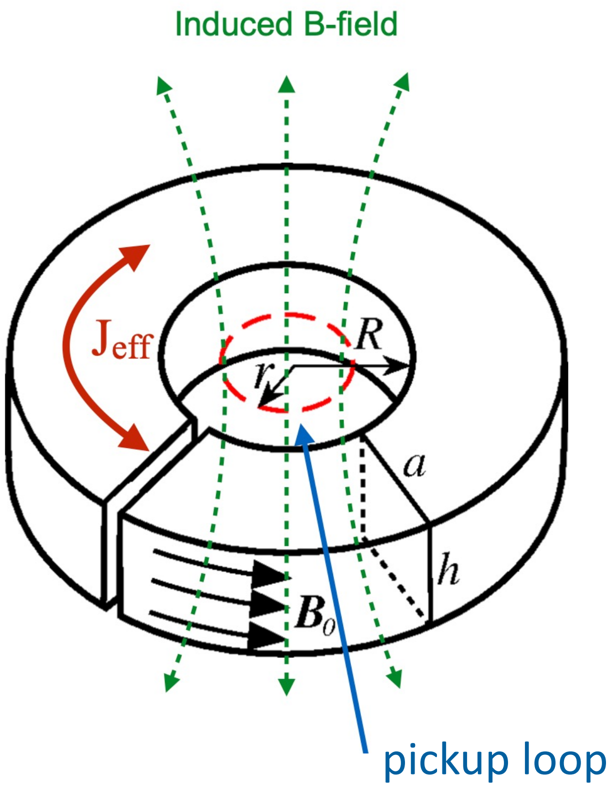
✓ low-noise receiver

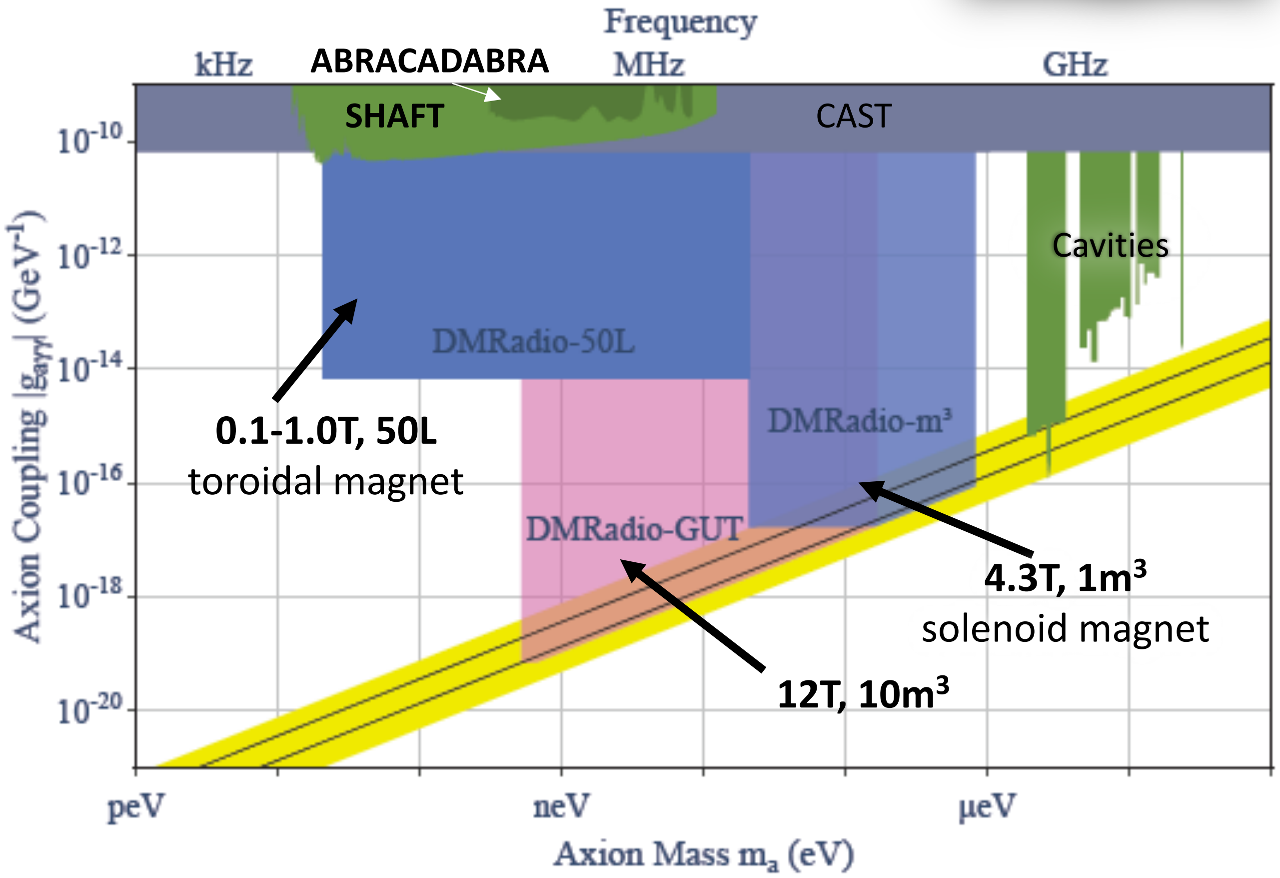
tunable via lumped elements

DMRadio

[R. Henning, talk at PATRAS2021]
[S. Chaudhuri *et al.*, arXiv:1803.01627]

ABRACADABRA:
[PRL 127 (2021) 081801]





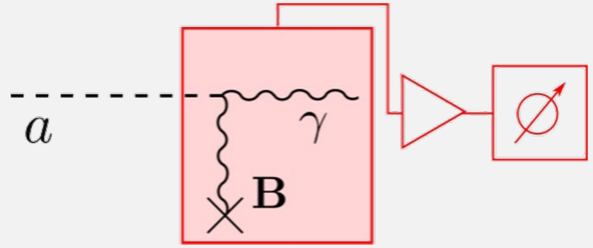
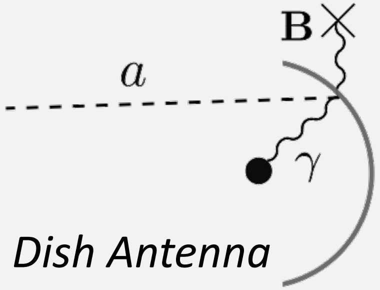
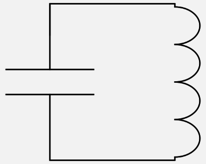
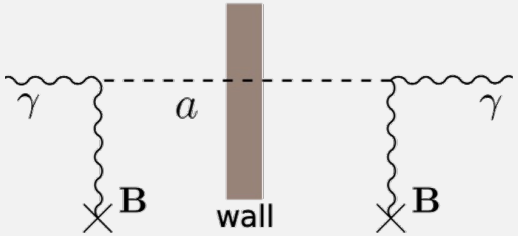
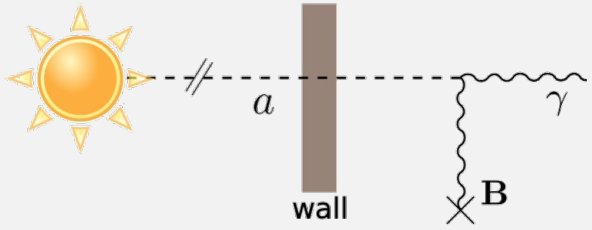
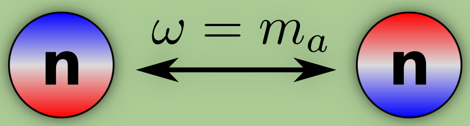
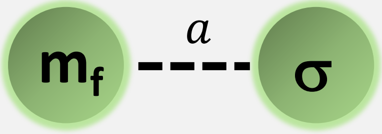
Other efforts:

ADMX-SLIC
[PRL 124, 241101 (2020)]

SHAFT
[Nature Phys. 17, 79–84 (2021)]

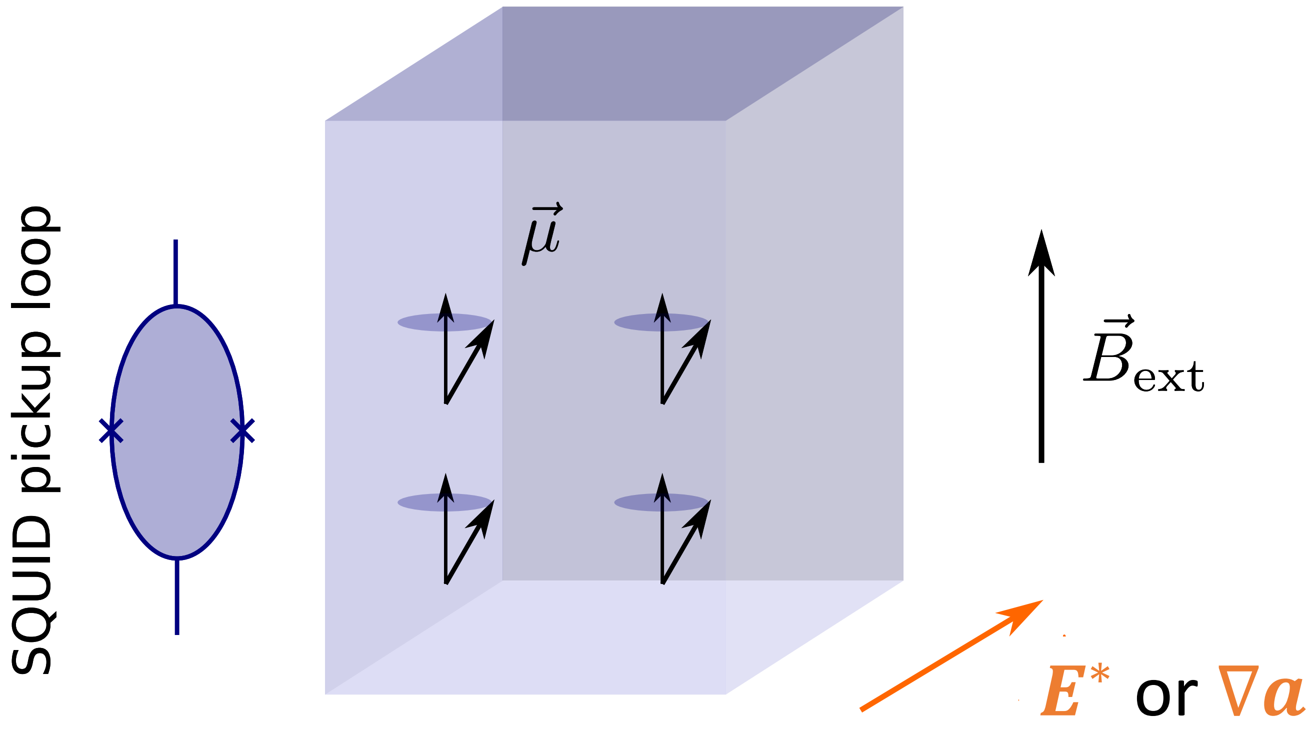
WISPLC
[PRD 106, 023003 (2022)]

How to look?

	Dark Matter *(Haloscopes)*	**Lab Axions**	**Sun & Astrophysics**
Electro-Magnetic Coupling	 *Microwave Cavity*  *Dish Antenna*  *LC Circuit*	 *Light-Shining-through-Wall* *Polarization/Birefringence* *Collider*	 *Helioscope* *Indirect Detection:* Stellar Energy Loss, Neutron Star Radio Emission, Galaxy Clusters, Black Hole Superradiance, …
Other Coupling	 *Oscillating EDM*	 *Firth Force, Collider*	

CASPEr: Cosmic Axion Spin Precession Experiment

e.g., [Kimball *et al.*, Springer Proc.Phys. 245 (2020) 105-121]



$$H = -\mu_n \, \boldsymbol{B} \cdot \hat{\boldsymbol{S}} \; - d_n \, \boldsymbol{E}^* \cdot \hat{\boldsymbol{S}}$$

Pseudo-B-field: $\boldsymbol{B}_{\mathbf{ALP}} = g_{aNN} \, \nabla a$

$\sim \partial_\mu \, a \, \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$

Nucleon EDM $\propto a$

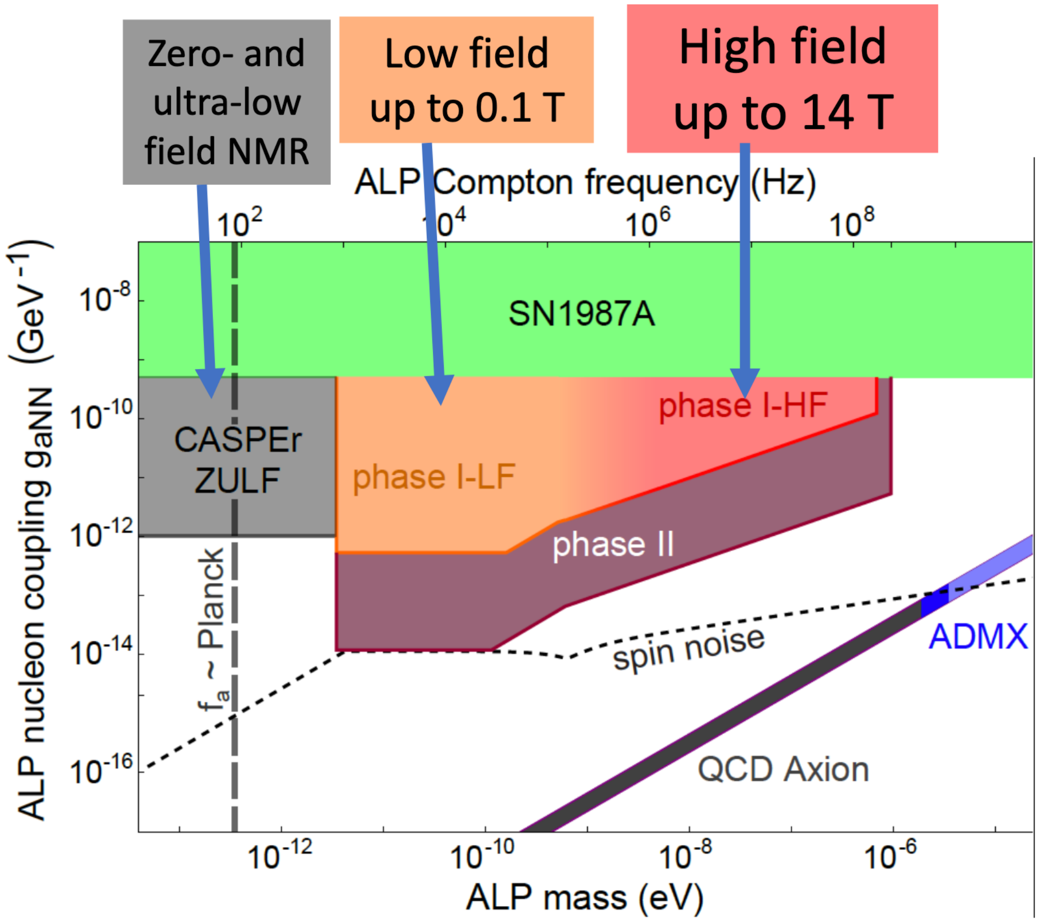
$\sim a \, G^a_{\mu\nu} \, \tilde{G}^{\mu\nu}_a$

Resonance if: $\omega_L = 2\,\mu\, B_{\text{ext}} = \omega \; = m_a$ **→ tunable via $\boldsymbol{B_{ext}}$**

Similar concept using electrons: **QUAX-ae** [PRL 124 (2020) 17, 171801]

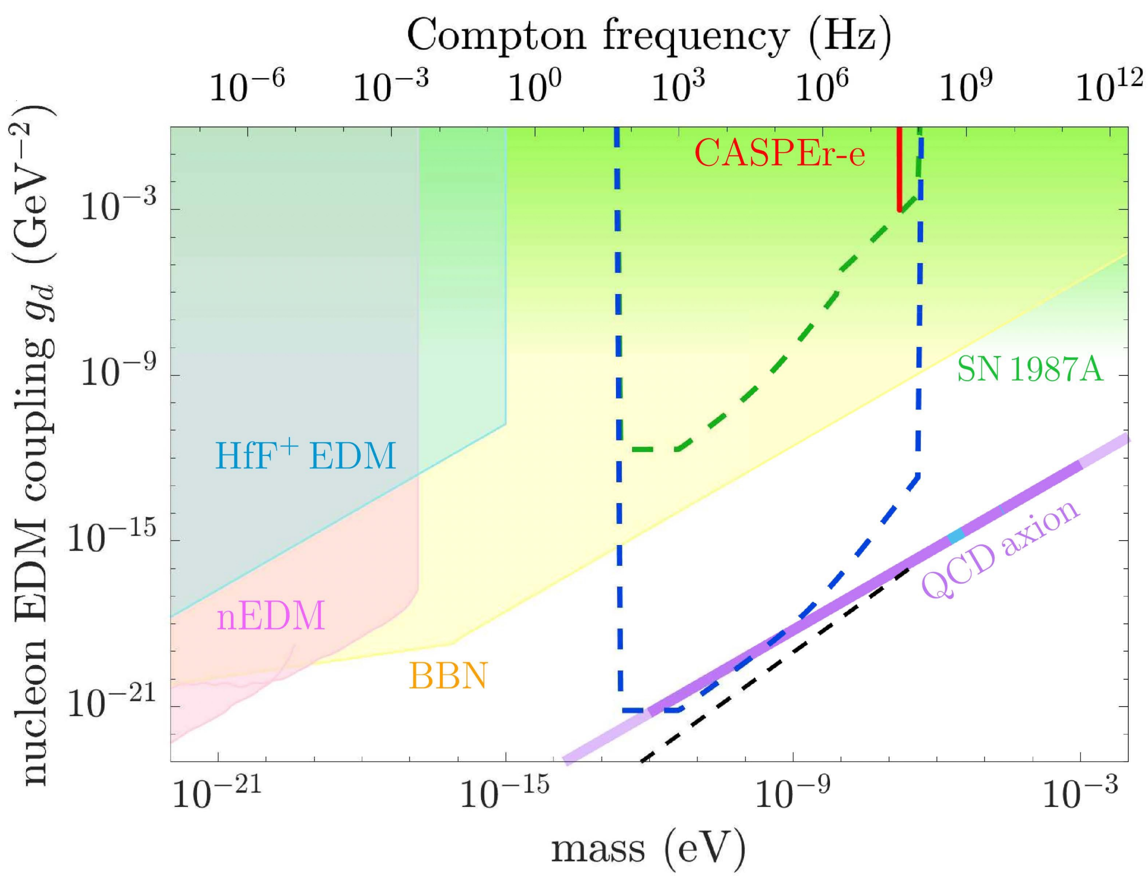
CASPEr: Cosmic Axion Spin Precession Experiment- Sensitivities

CASPEr-gradient



[Y. Zhang, H. Bekker, A. Wickenbrock, talks at PATRAS2022]

CASPEr-electric

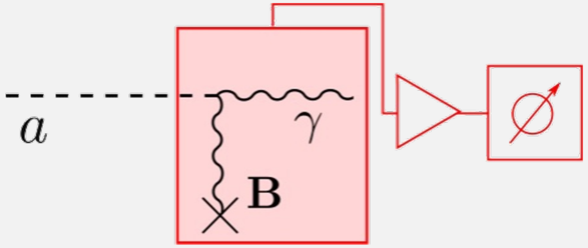


[D. Aybas, talk at PATRAS2021]
[D. Aybas et al., PRL 126, 141802 (2021)]

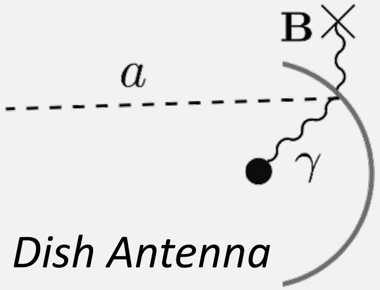
How to look?

Dark Matter *(Haloscopes)* | **Lab Axions** | **Sun & Astrophysics**

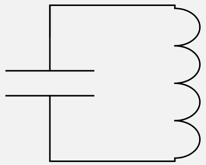
Electro-Magnetic Coupling



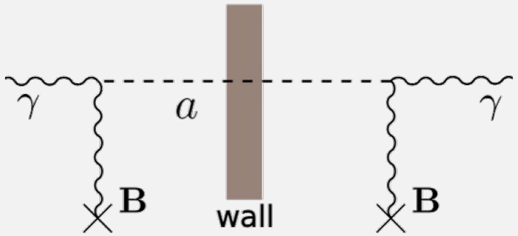
Microwave Cavity



Dish Antenna



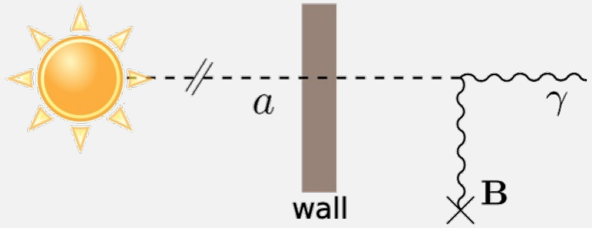
LC Circuit



Light-Shining-through-Wall

Polarization/Birefringence

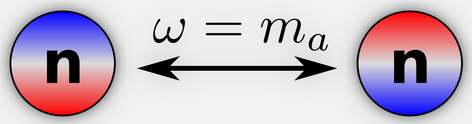
Collider



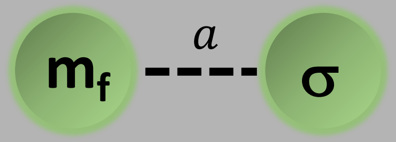
Helioscope

Indirect Detection:
Stellar Energy Loss, Neutron Star Radio Emission, Galaxy Clusters, Black Hole Superradiance, …

Other Coupling



Oscillating EDM

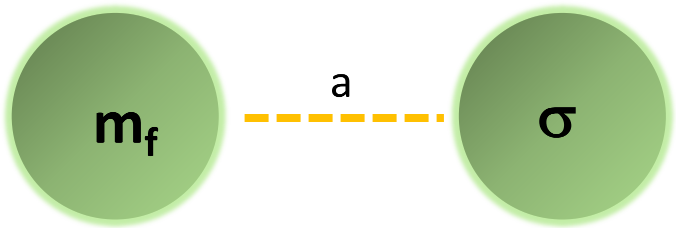


Firth Force, Collider

ARIADNE: Axion Resonant InterAction DetectioN Experiment

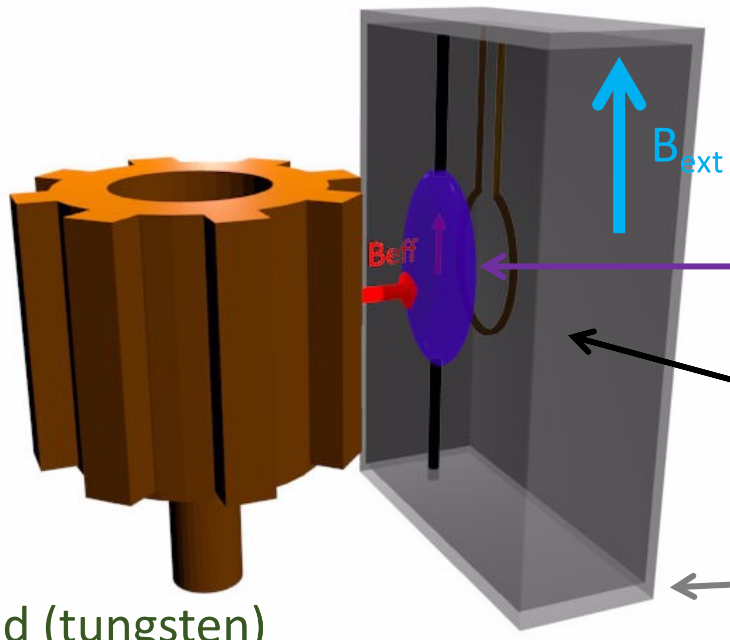
[A. Geraci, talk at PATRAS2021]

Monopole-Dipole axion exchange



$$U(r) = \frac{\hbar^2 g_s^N g_p^N}{8\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right) e^{-r/\lambda_a} (\hat{\sigma}\cdot\hat{r}) \equiv \mu \cdot B_{\mathrm{ALP}}$$

$m_a < 6$ meV → $\lambda_a > 30$ μm

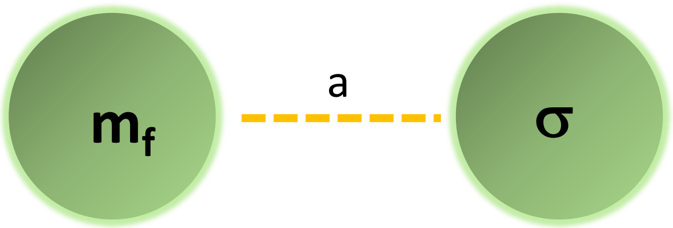


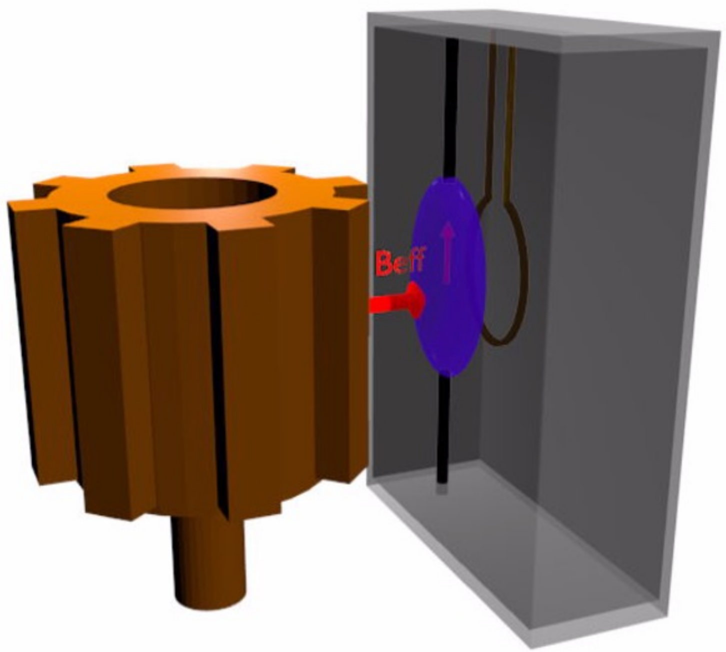
ω known → no tuning needed!

ARIADNE: Axion Resonant InterAction DetectioN Experiment

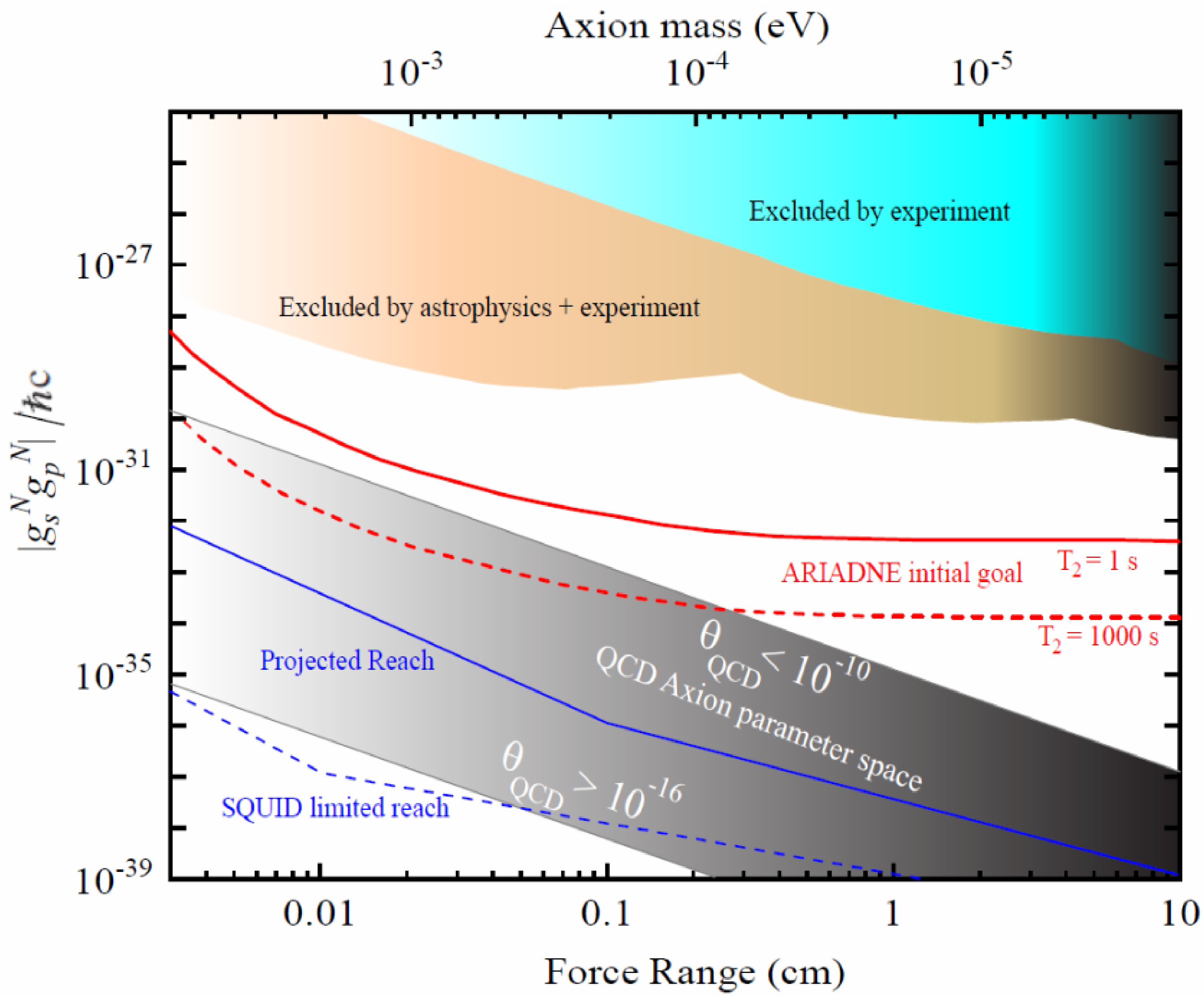
[A. Geraci, talk at PATRAS2022]

Monopole-Dipole axion exchange





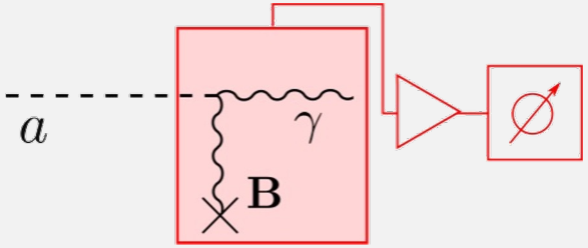
[A. Arvanitaki, A. Geraci, PRL 113,161801 (2014)]



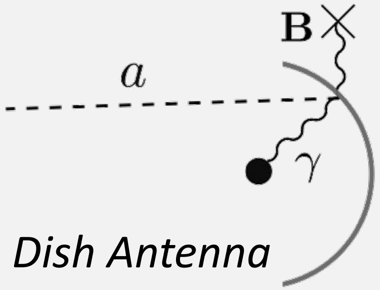
How to look?

Dark Matter *(Haloscopes)* | **Lab Axions** | **Sun & Astrophysics**

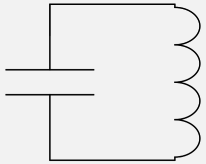
Electro-Magnetic Coupling



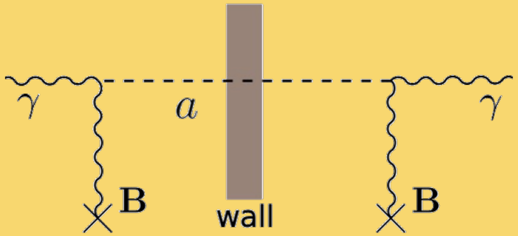
Microwave Cavity



Dish Antenna



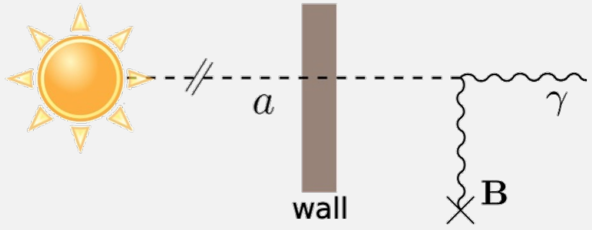
LC Circuit



Light-Shining-through-Wall

Polarization/Birefringence

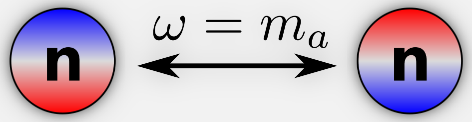
Collider



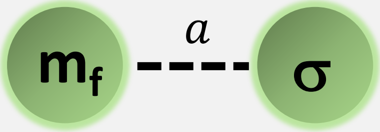
Helioscope

Indirect Detection:
Stellar Energy Loss, Neutron Star Radio Emission, Galaxy Clusters, Black Hole Superradiance, …

Other Coupling



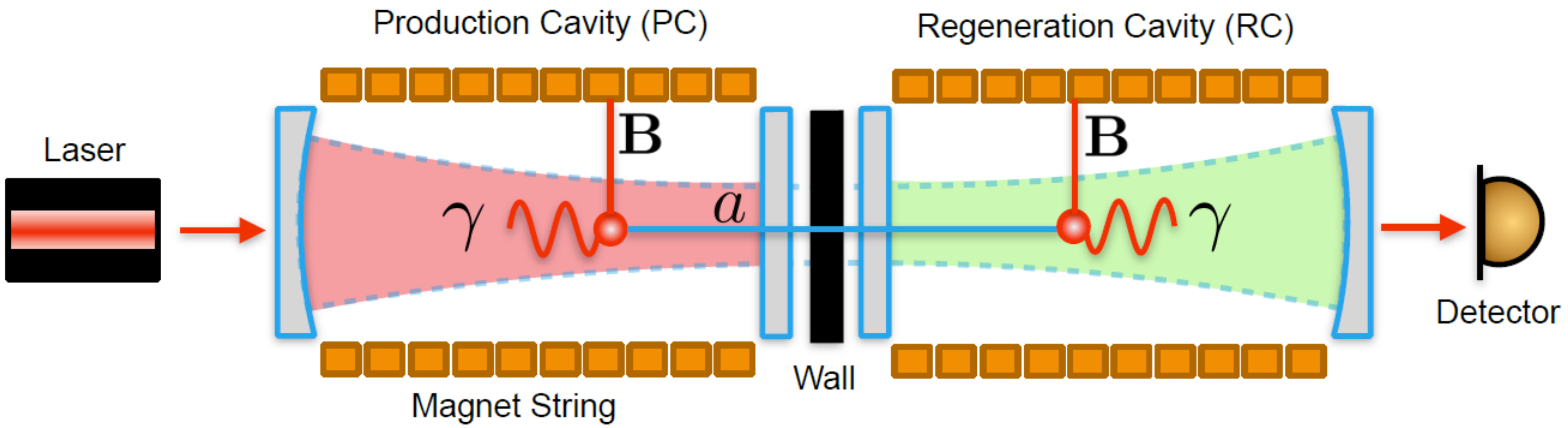
Oscillating EDM



Firth Force, Collider

LSW: Light-Shining-Through-Wall

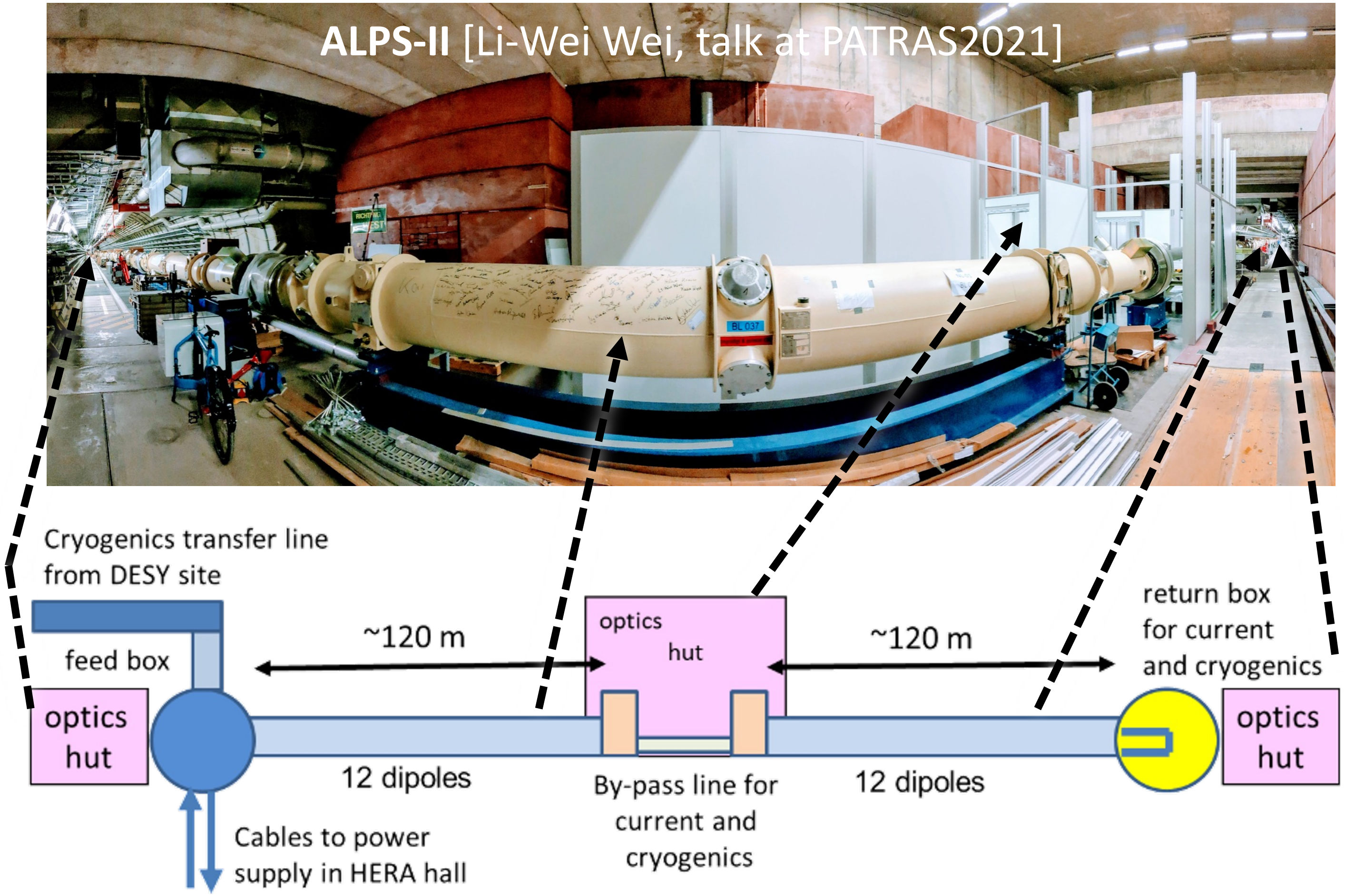
e.g., [G. Mueller, et al., PRD80 (2009) 072004]
[Fig.: ALPS collaboration]



$$P_{\gamma\to a\to\gamma} = 6\times 10^{-38}\,\mathcal{F}_{\rm PC}\,\mathcal{F}_{\rm RC}\left(\frac{B}{1\rm T}\right)^4\left(\frac{L}{10\rm m}\right)^4\left(\frac{g_{a\gamma\gamma}}{10^{-10}{\rm GeV}^{-1}}\right)^4$$

OSQAR	STAX	CROWS	ALPS	...
[PRD 92, 092002 (2015)]	[L. Capparelli *et al.*, Phys. Dark Univ. 12, 37 (2016)]	[M. Betz *et al.*, PRD 88, 075014 (2013)]	[next slide]	

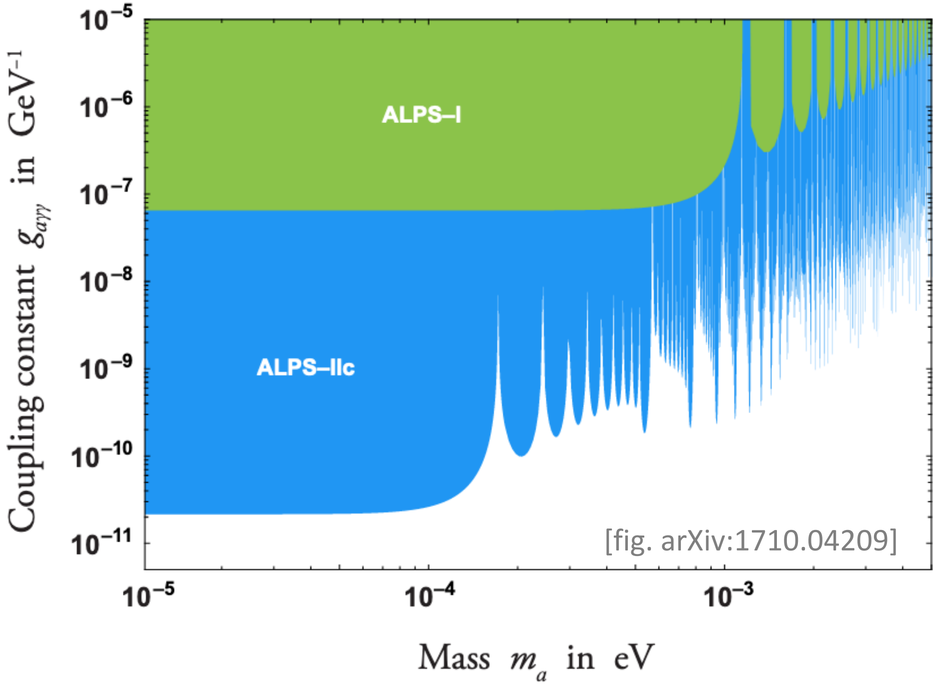
ALPS: Any Light Particle Search



$$L \sim 100\text{m}, B \sim 5\text{T}, \mathcal{F}_P \sim 5{,}000,\ \mathcal{F}_R \sim 40{,}000$$

first physics run expected end 2022

Sensitivity Estimate (ALPS-IIc):



[Z. R. Bush *et al*, PRD 99 (2019) 2]

see also [G. Othman, PATRAS2022]

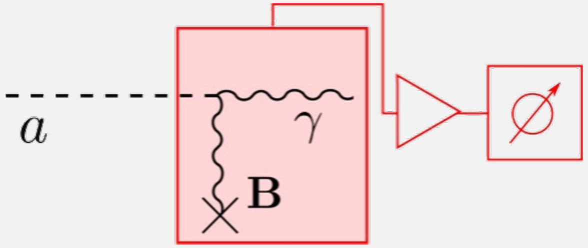
How to look?

Dark Matter *(Haloscopes)*

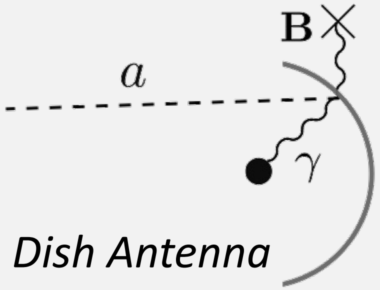
Lab Axions

Sun & Astrophysics

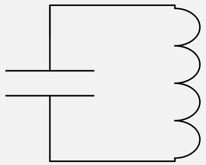
Electro-Magnetic Coupling



Microwave Cavity



Dish Antenna



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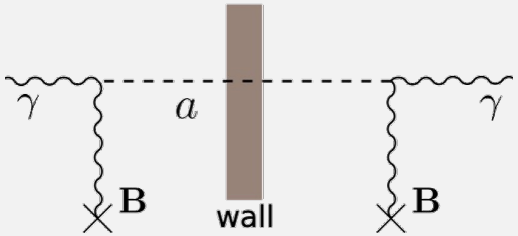

Light-Shining-through-Wall

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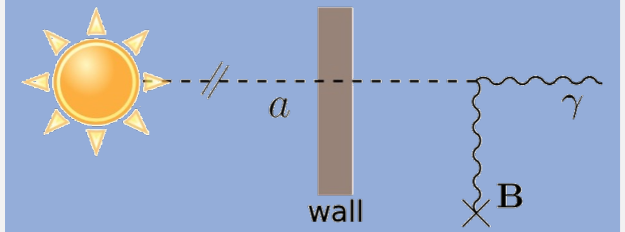
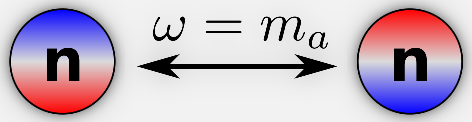


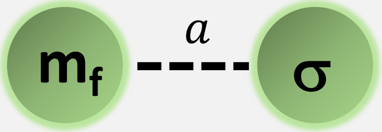
Helioscope

Indirect Detection:
Stellar Energy Loss, Neutron Star Radio Emission, Galaxy Clusters, Black Hole Superradiance, …

Other Coupling



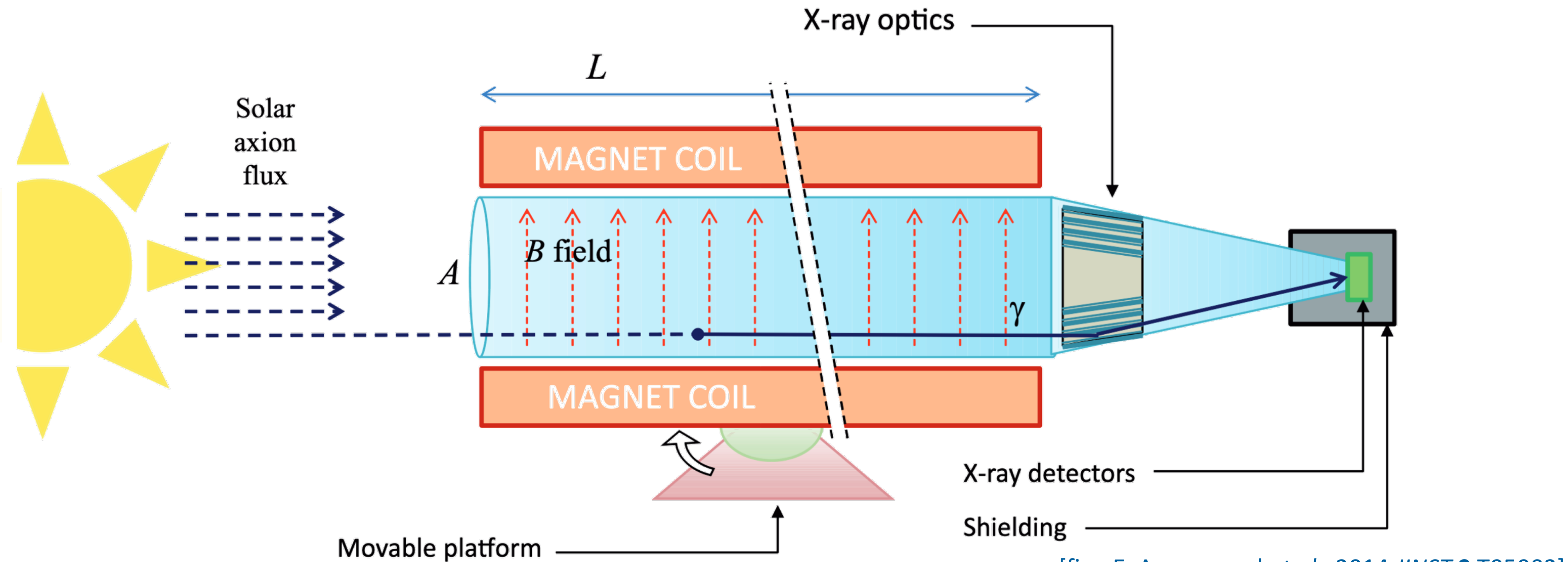
Oscillating EDM



Firth Force, Collider

Helioscopes

e.g., [JCAP 0704 (2007) 010]



[fig.: E. Armengaud *et al.*, 2014 *JINST* **9** T05002]

$$P_{a\to\gamma} = 1.7 \times 10^{-17} \left(\frac{B}{9\mathrm{T}}\right)^2 \left(\frac{L}{9.3\mathrm{m}}\right)^2 \left(\frac{g_{a\gamma\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2$$

CAST, IAXO: [next slide]

TASTE: [JINST 12 (2017) 11, P11019]

Helioscopes

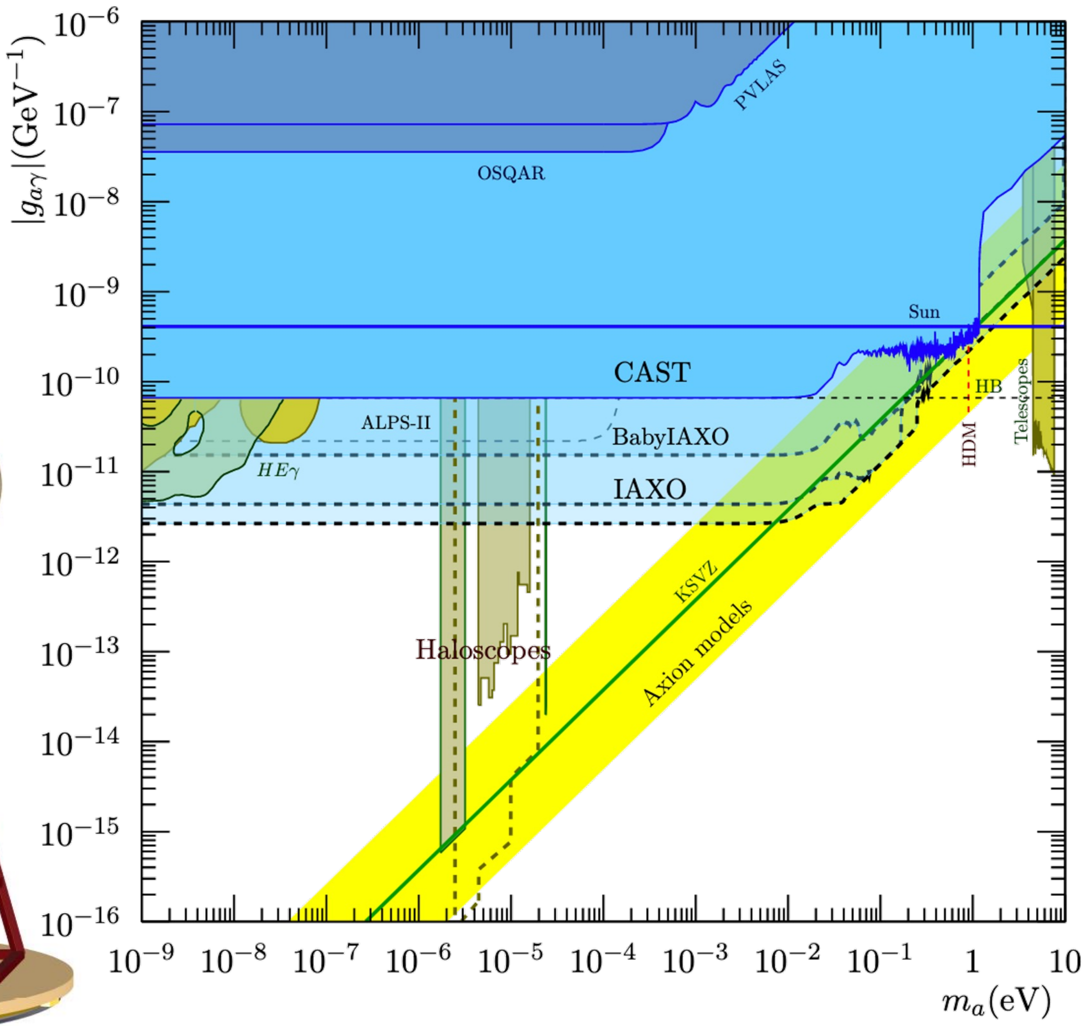
State-of-the-art: **CAST** [Nature Phys. 13 (2017) 584-590]

LHC magnet

$B = 9\,\mathrm{T}$

$L = 9.3\mathrm{m}$

$\varnothing = 2\times 15\mathrm{cm}^3$



Next Generation: **IAXO**

[E. Armengaud *et al.*, JCAP06(2019)047]

$B = 2.5\,\mathrm{T}$

$L = 20\mathrm{m}$

$\varnothing = 8\times 0.3\mathrm{m}^3$

Prototype: **BabyIAXO**

Constr. Start 2021

[JHEP05(2021)137]

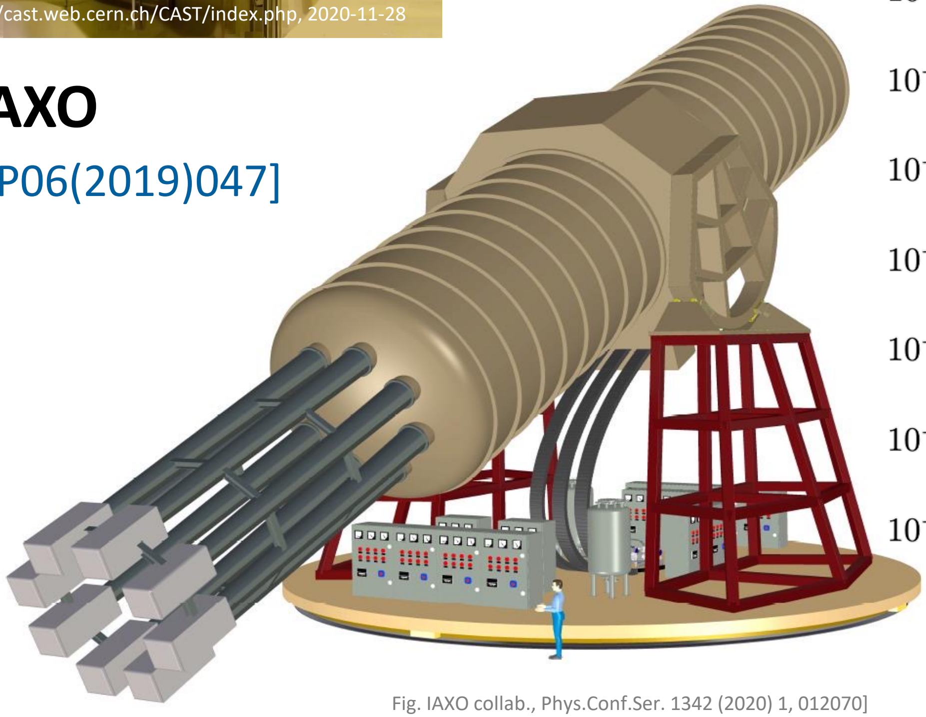


Fig. IAXO collab., Phys.Conf.Ser. 1342 (2020) 1, 012070]

Indirect Detection (Examples)

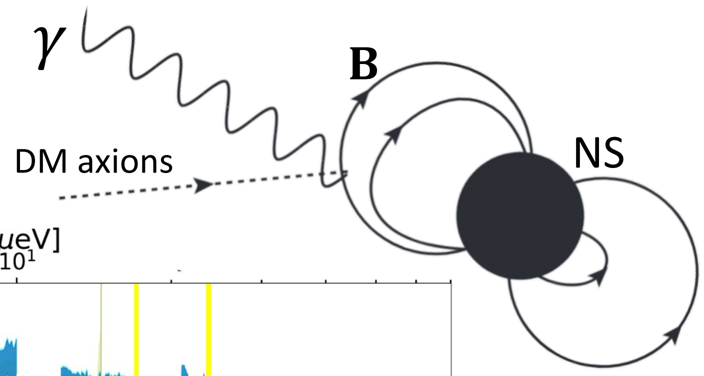
Black Hole Superradiance

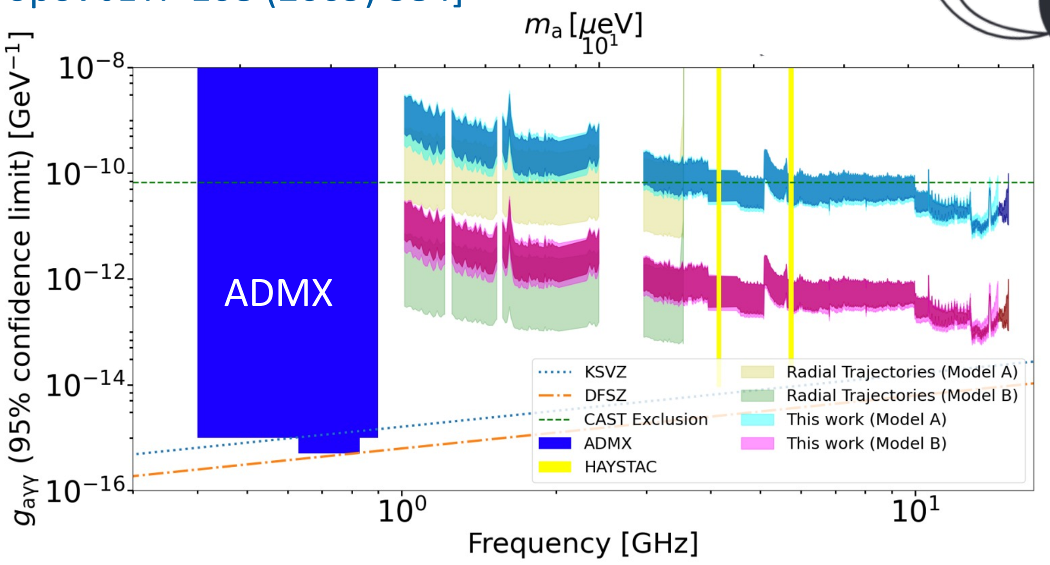
Excludes $10^{-12}\mathrm{eV} \lesssim m_a \lesssim 10^{-11}\mathrm{eV}$

e.g., [A. Arvanitaki *et al.*, PRD 91, 084011 (2015)]
[V. Cardoso *et al.*, JCAP 03 (2018) 043]
[M. Baryakhtar *et al.*, PRD 103, 095019 (2021)]

Neutron Star Radio Emission

e.g., [M.S. Pshirkov, S.B. Popov JETP 108 (2009) 384]





[R. A. Battye *et al.*, arXiv: 2107.01225]

others: [Foster *et al*, PRL125, 171301 (2020) & arXiv:2202.08274][J. Darlin, arXiv:2008.11188]

DM Density & Magnetosphere: systematic uncertainty

Other 'classics':

HB Stars (Energy Loss)
$g_{a\gamma} < 6.6\times10^{-11}\ \mathrm{GeV}^{-1}$
[A. Ayala *et al.*, PRL 113, 19, 191302 (2014)]

Abell Galaxy Clusters (2γ Decay)
$g_{a\gamma} < 10^{-11}\ \mathrm{GeV}^{-1}$ @ $m_a = 5\ldots7$ eV
[D. Grin *et al.*, PRD 75, 105018 (2007)]

SN1987A (Gamma Rays)
$g_{a\gamma} < 6\times10^{-12}\ \mathrm{GeV}^{-1}$ @ $m_a < 4\times10^{-10}$ eV
[A. Payez *et al.*, JCAP 1502 (2015) 006]

…

So Much More...

- Other new Detection Ideas, e.g.,

  axion "echo" [Arza *et al*, arXiv:2108.00195]

  UPLOAD-DOWNLOAD [C. A. Thomson *et al*, PRL 126, 081803 (2021)],
  heterodyne axion detection [A. Berlin *et al*, PRD 104, L111701 (2021)]

  Möbius-ring resonator [Bourhill et al, arXiv:2208.01640]

  Piezoaxionic effect [Arvanitaki, Madden, Tilburg, arXiv:2112.11466]

  Axion Quasiparticles in Topological Insulators [Schütte-Engel *et al*, JCAP 08 (2021) 066]

  Effects of Local DM Halo Properties/Substructure [SK *et al*, JCAP11(2018)051], Caputo *et al*, PRD104, 095029(2021)], [Chakrabarty *et al*, arXiv:2007.10509], [O'Hare *et al*, 1701.03118], …

- Other WISPS

  Chameleons [PRD 69 044026 (2004)], [PRD 69 044026 (2004)], [Phys. Dark Univ. 26 100367 (2019)] …

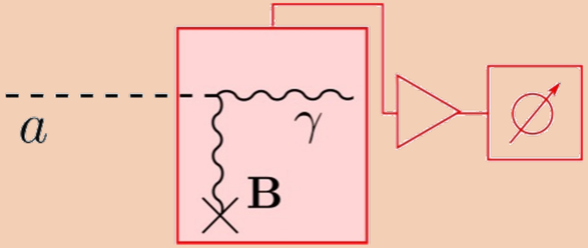
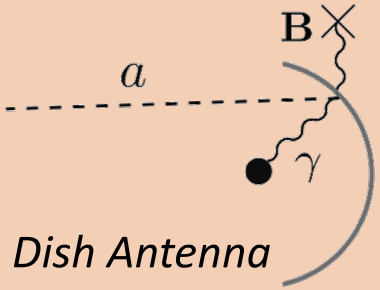
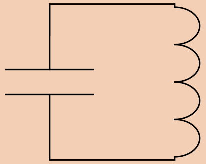
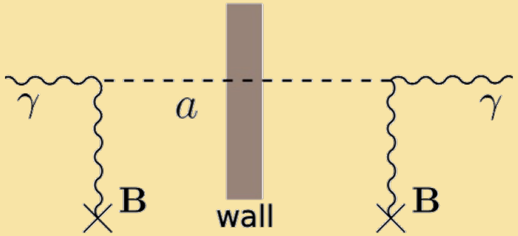
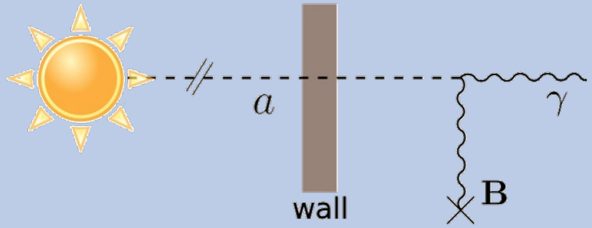
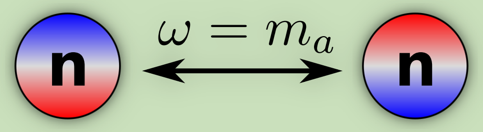
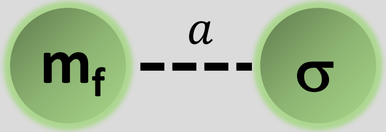
  Other Scalar and Vector Ultralight Dark Matter
  [D. Antypas *et al*, Snowmass white paper, arXiv: 2203.14915]

- Axion Experiments sensitive to HF Gravity Waves

  [A. Berlin *et al*, PRD105 (2022) 11, 116011, 2112.11465] …

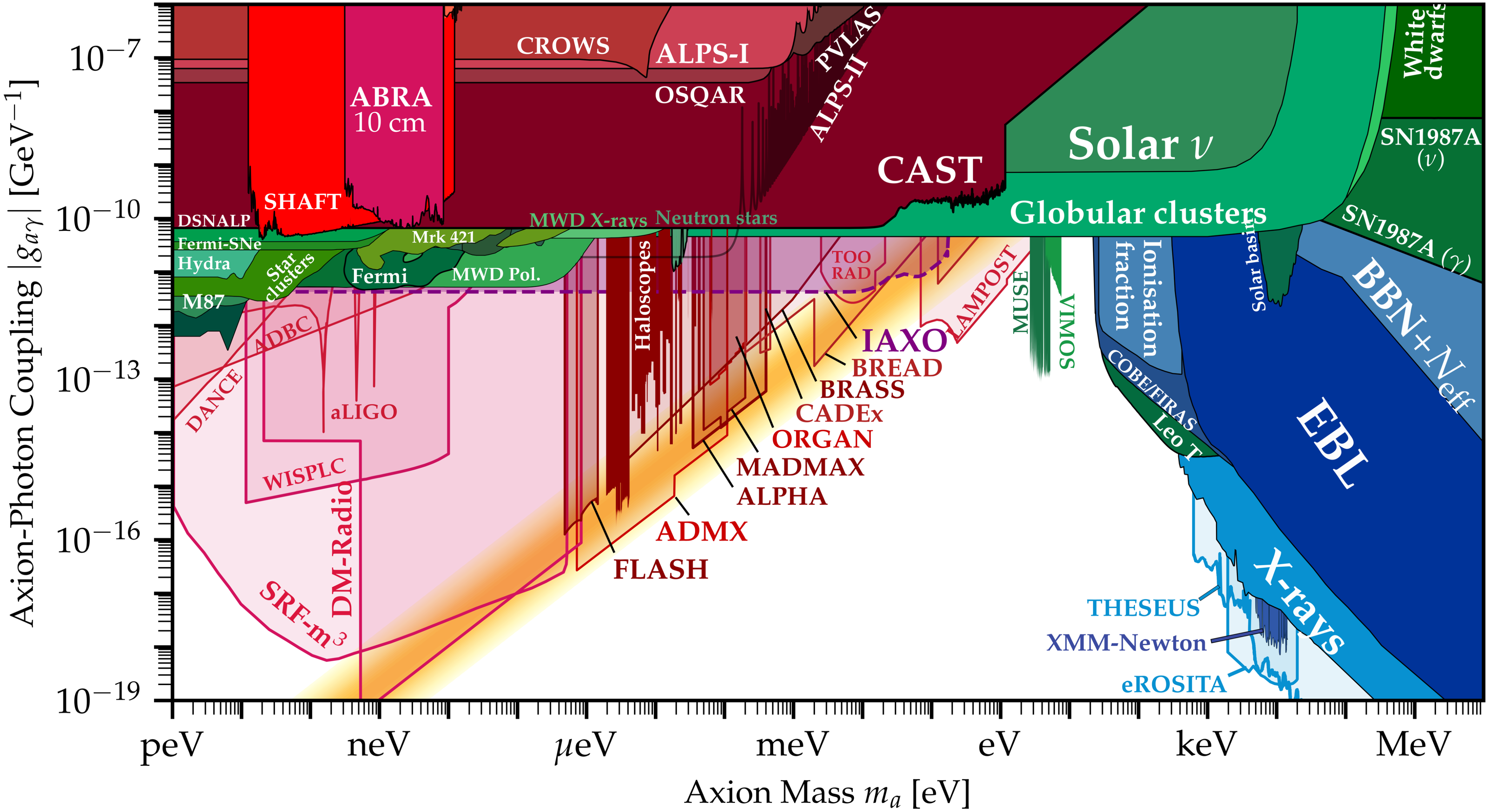
…

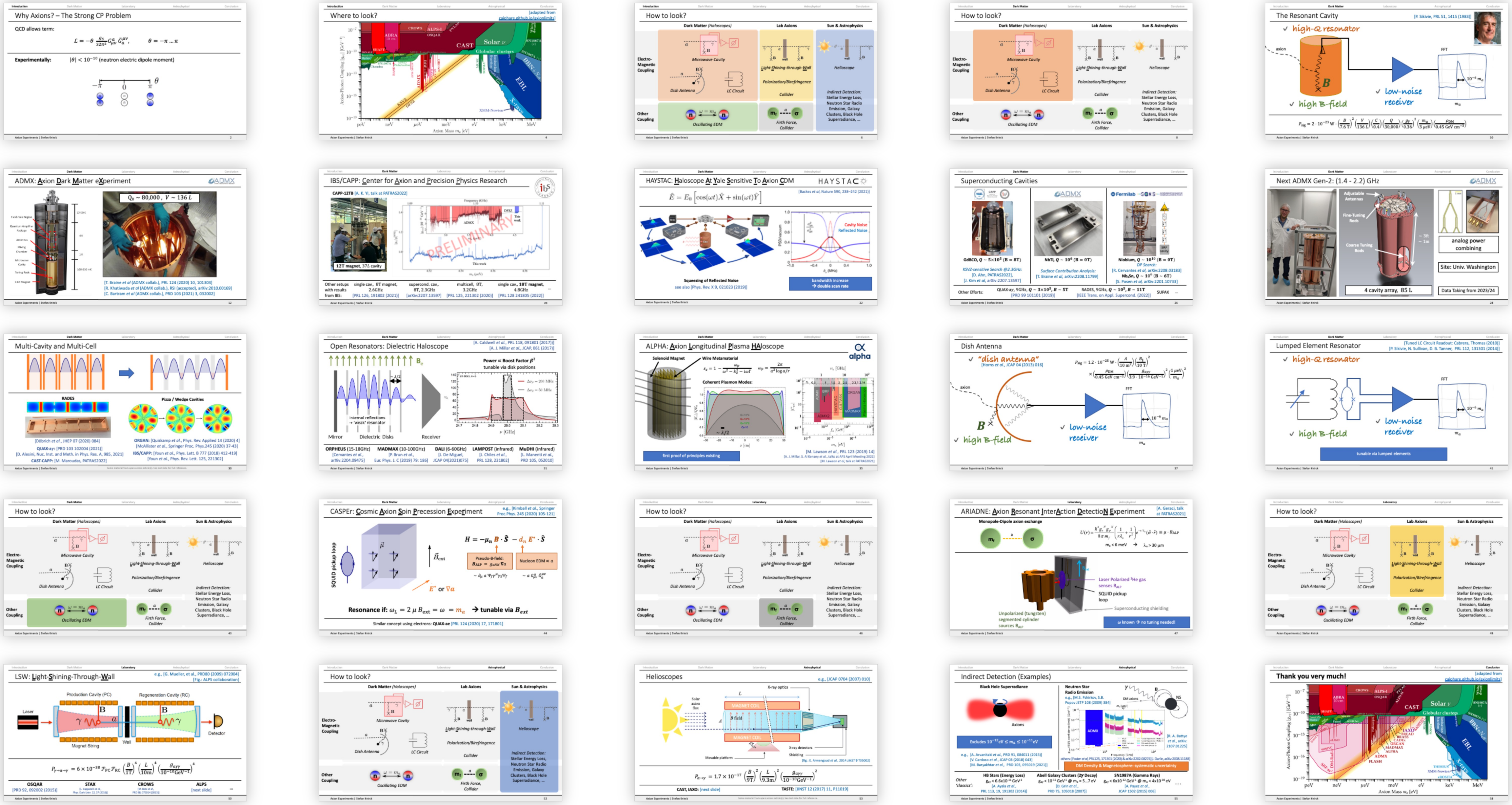
How to look?

	Dark Matter *(Haloscopes)*	**Lab Axions**	**Sun & Astrophysics**
Electro-Magnetic Coupling	 *Microwave Cavity*  *Dish Antenna*  *LC Circuit*	 *Light-Shining-through-Wall* *Polarization/Birefringence* *Collider*	 *Helioscope* *Indirect Detection:* Stellar Energy Loss, Neutron Star Radio Emission, Galaxy Clusters, Black Hole Superradiance, …
Other Coupling	 *Oscillating EDM*	 *Firth Force,* *Collider*	

Thank you very much!

[adapted from cajohare.github.io/axionlimits]

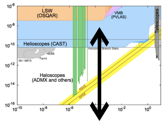



Why Axions? – The Strong CP Problem
Where to look?
How to look?
How to look?
The Resonant Cavity
ADMX: Axion Dark Matter eXperiment
IBS/CAPP: Center for Axion and Precision Physics Research
HAYSTAC: Haloscope At Yale Sensitive To Axion CDM
Superconducting Cavities
Next ADMX Gen-2: (1.4 - 2.2) GHz
Multi-Cavity and Multi-Cell
Open Resonators: Dielectric Haloscope
ALPHA: Axion Longitudinal Plasma HAloscope
Dish Antenna
Lumped Element Resonator
How to look?
CASPEr: Cosmic Axion Spin Precession Experiment
How to look?
ARIADNE: Axion Resonant InterAction DetectioN Experiment
How to look?
LSW: Light-Shining-Through-Wall
How to look?
Helioscopes
Indirect Detection (Examples)
Thank you very much!

Where to look? - Models

[Slide from Pablo Quílez Lasanta, PATRAS2021]

$g_{a\gamma}$



A) Photophilic/photophobic axions

1. Single scalar: Playing with fermionic representations

“Preferred axion window”

[Di Luzio, Mescia, Nardi, 16]
[Di Luzio, Mescia, Nardi, 18]

“Axion from monopoles”

[Sokolov, Ringwald, 21]

2. Multiple scalars: Alignment in field space

“Clockwork axion”

[Farina et al, 17]
[Coy, Frigerio, 17]
[Kim et al, 04]
[Choi et al, 14 and 16]
[Kaplan et al 16]
[Giudice et al 16]

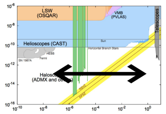
“KNP alignment”

[Agrawal et al 17]
[Kim et al, 04]
+ Refs in FIPs report [2102.12143]

“Multi-higgs models”

[Di Luzio, Mescia, Nardi, 17]
[Di Luzio, Giannotti, Nardi, Visinelli, 16]
[Darmé, Di Luzio, Giannotti, Nardi, 20]

m_a



B) Heavy/even lighter axions

1. Heavy axions: extra instantons

[Rubakov, 97]
[Berezhiani et al ,01]
[Fukuda et al, 01]
[Hsu et al, 04]
[Gianotti, 05]
[Hook et al, 14]
[Chiang et al, 16]
[Khobadize et al,]
[Dimopoulos et al, 16]
[Gherghetta et al, 16]
[Agrawal et al, 17]
[Gaillard, Gavela, Houtz, Rey PQ, 18]
[Fuentes-Martin et al, 19]
[Csaki et al, 19]
[Gherghetta et al, 20]

2. Even lighter QCD axion

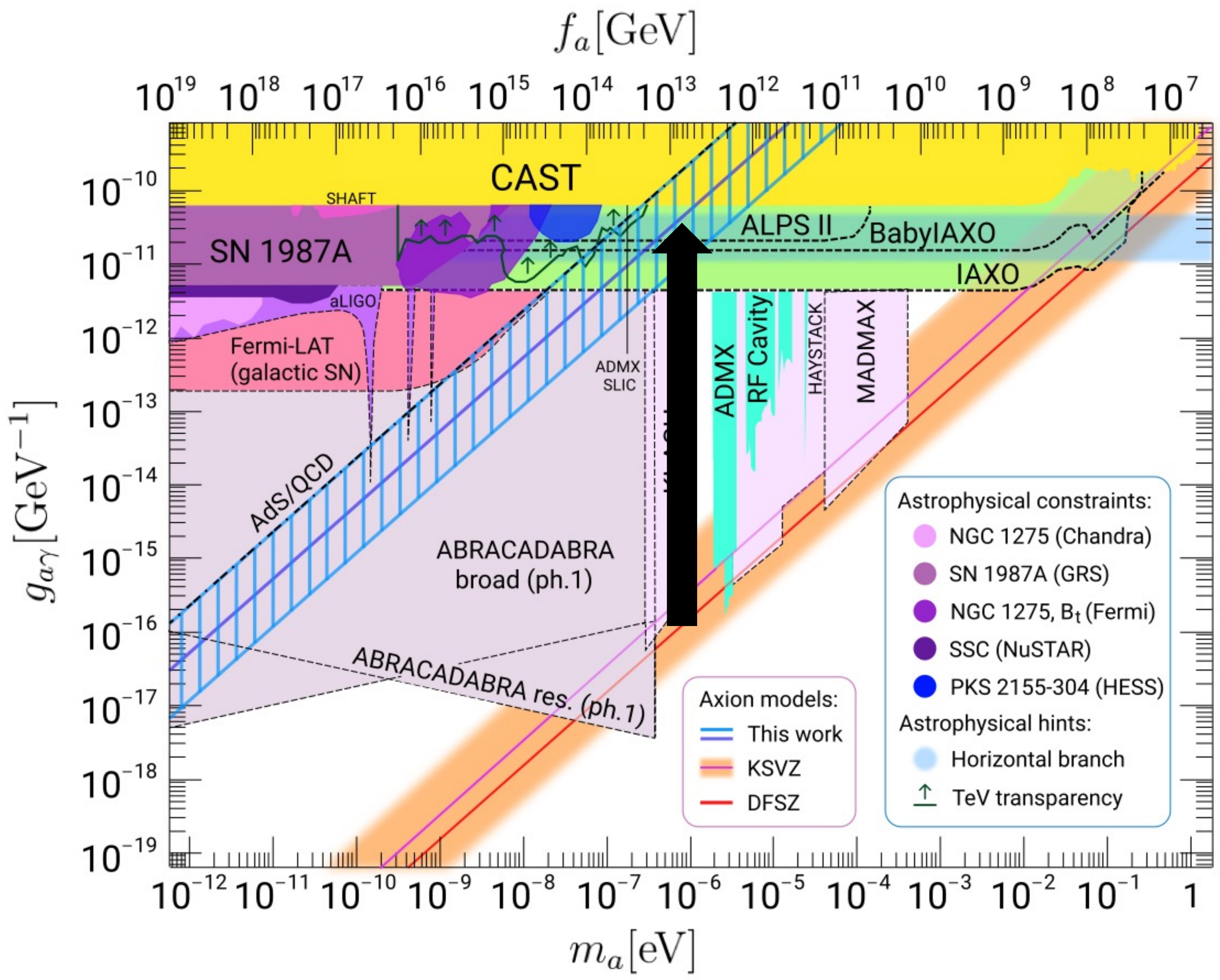
[Hook, 18]
[Luzio, Gavela, PQ, Ringwald, 21]
[Luzio, Gavela, PQ, Ringwald, 21]

Where to look?- Models

Recent Example:

Photophilic Axion

[Sokolov, Ringwald, 2104.02574]



Axion-Electrodynamics

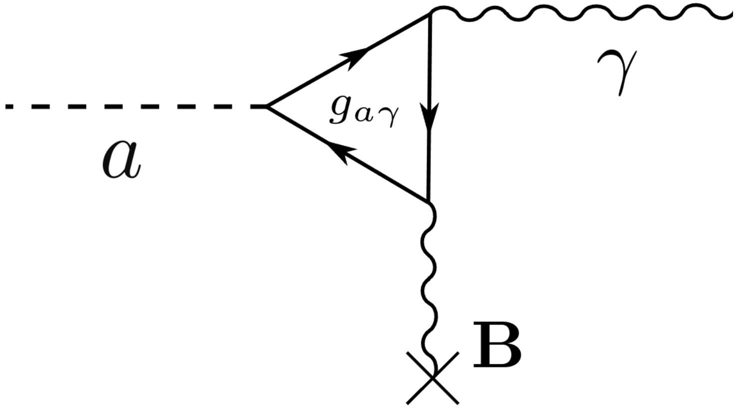
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - j^\mu A_\mu + \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Solve EOM under external magnetic field $\boldsymbol{B_e}$:

$$\varepsilon\, \nabla \cdot \boldsymbol{E} = \rho - g_{a\gamma\gamma}\, \boldsymbol{B_e} \cdot \nabla a$$

$$\nabla \times \boldsymbol{H} - \dot{\boldsymbol{E}} = J + g_{a\gamma\gamma}(\boldsymbol{B_e}\, \dot{a} + \boldsymbol{E} \times \nabla a)$$

$$\ddot{a} - \nabla^2 a + m_a^2 a = g_{a\gamma\gamma}\, \boldsymbol{E} \cdot \boldsymbol{B_e}$$

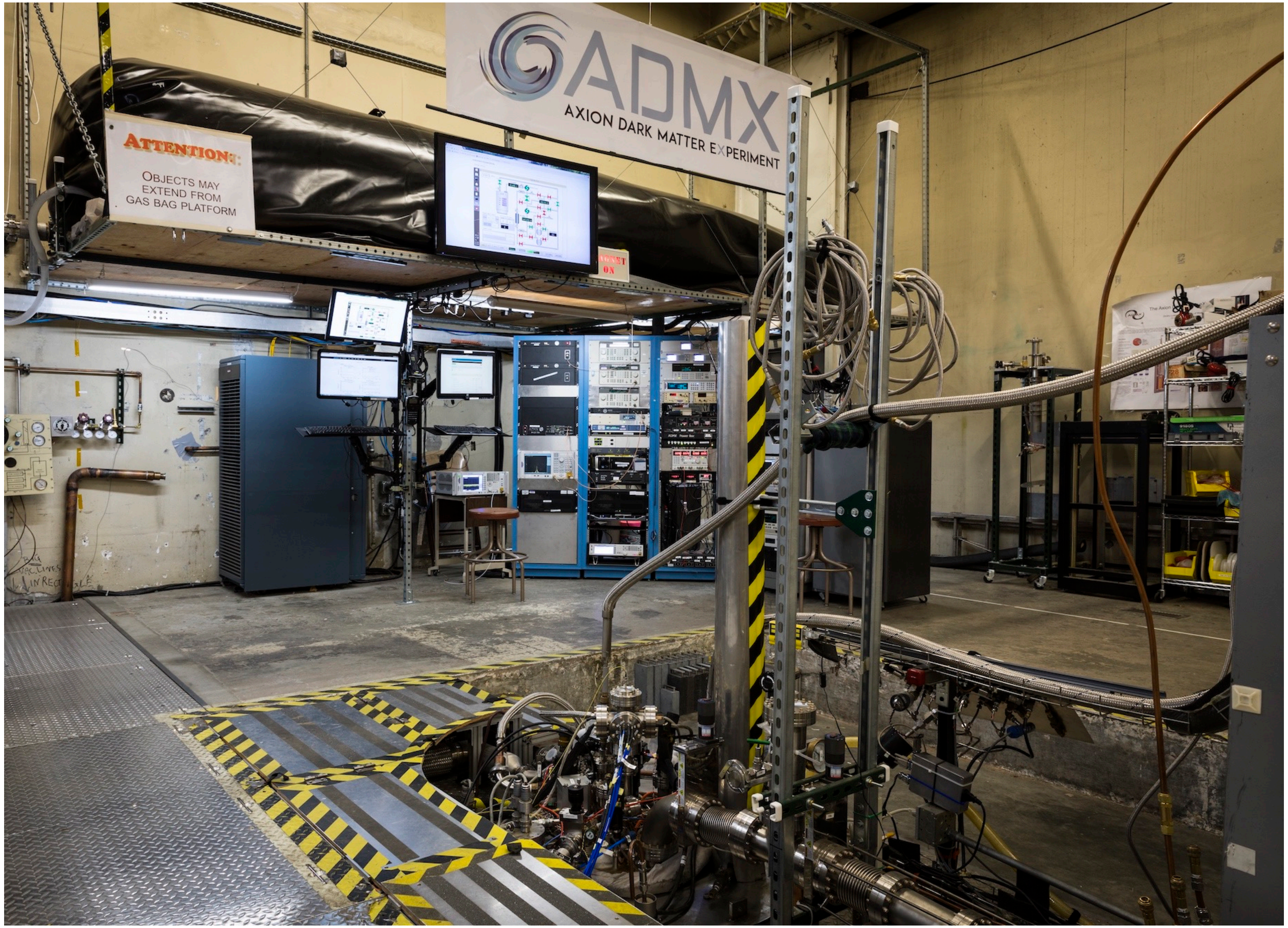


Primakoff effect

Axion-induced electric field (QCD axion dark matter):

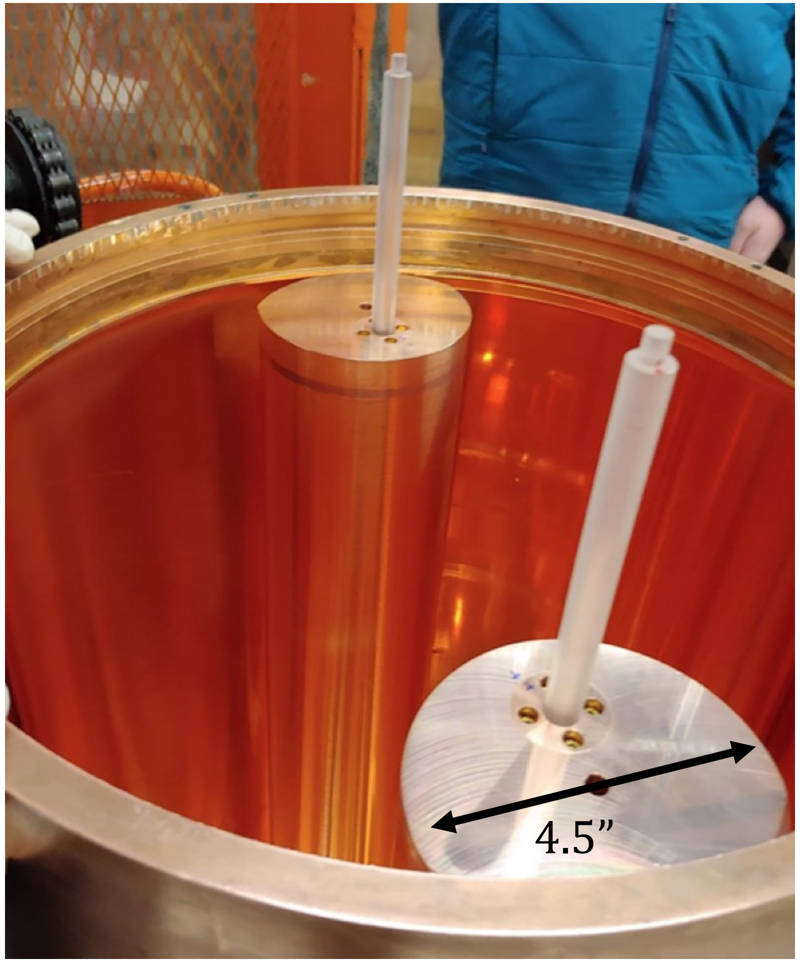
$$\boldsymbol{E_a} = -\varepsilon^{-1} g_{a\gamma\gamma}\, \boldsymbol{B_e}\, a \sim 1 \times 10^{-12}\ \mathrm{V\,m^{-1}} \left(\frac{B_e}{10\ \mathrm{T}}\right)\left(\frac{1}{\varepsilon}\right)\left(\frac{\rho_a}{0.45\ \mathrm{GeV\,cm^{-3}}}\right) \cos m_a t$$

The ADMX Setup

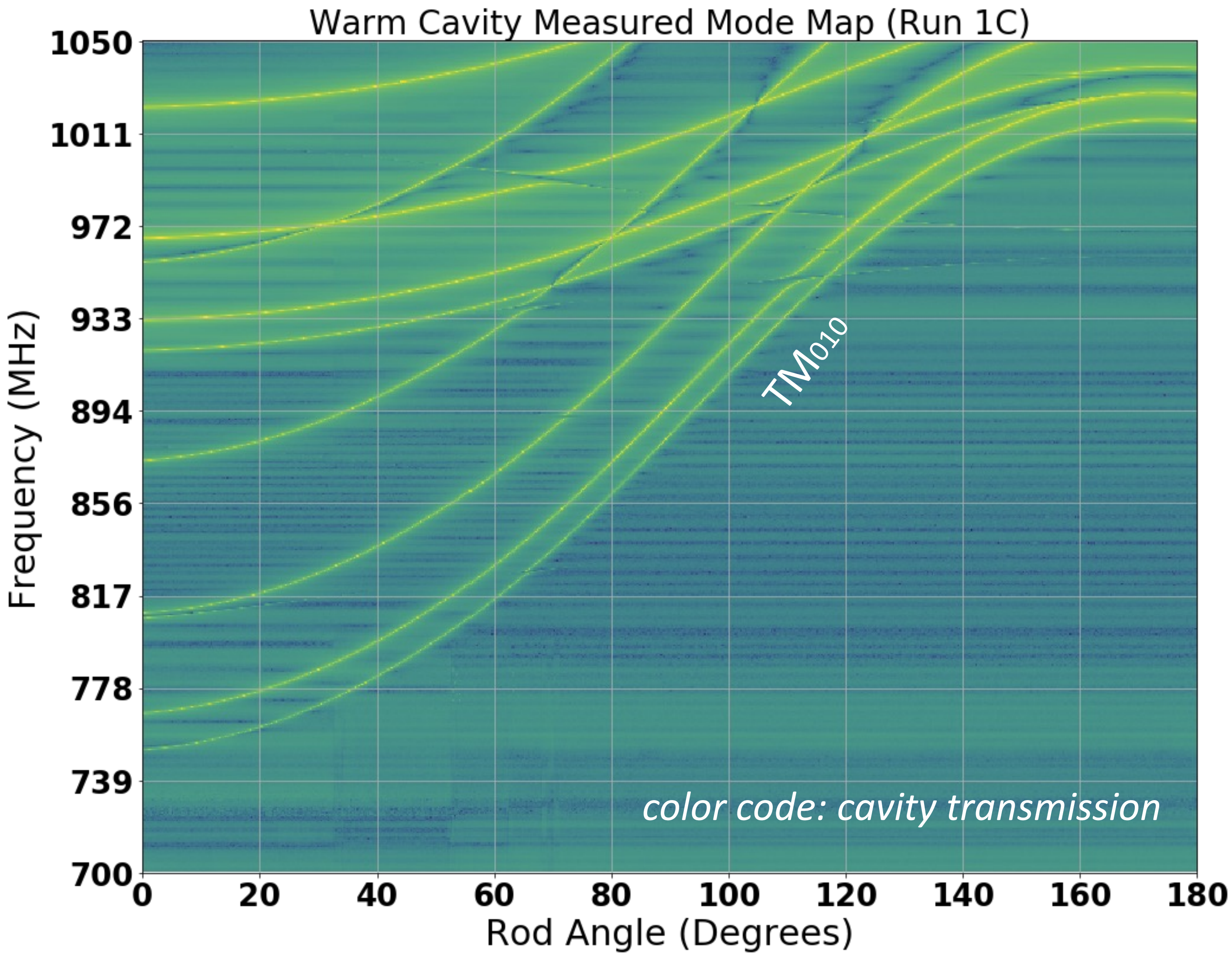


The ADMX Cavity - Tuning

✓ *high-Q resonator*

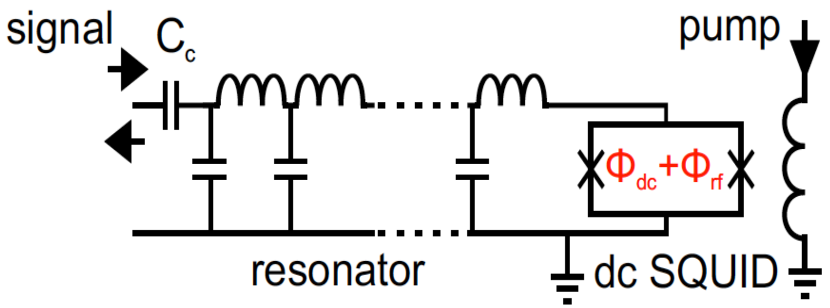


$V \sim 136\ \ell$

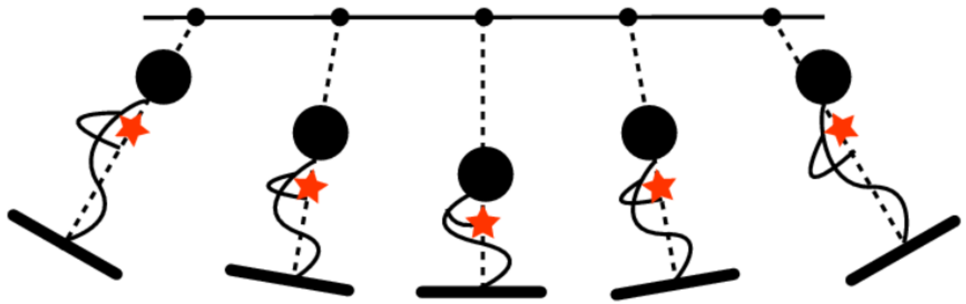


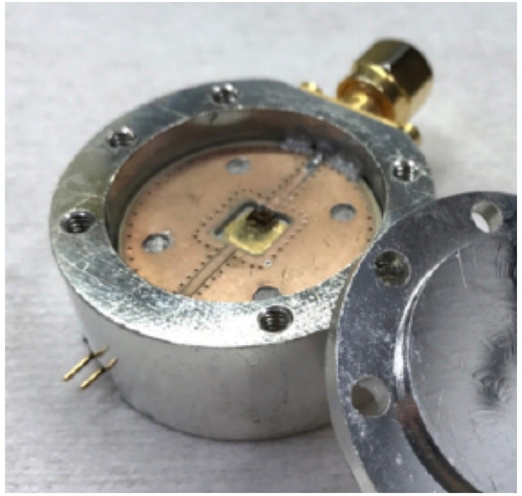
Josephson Parametric Amplifier (JPA)

✓ *low-noise receiver*

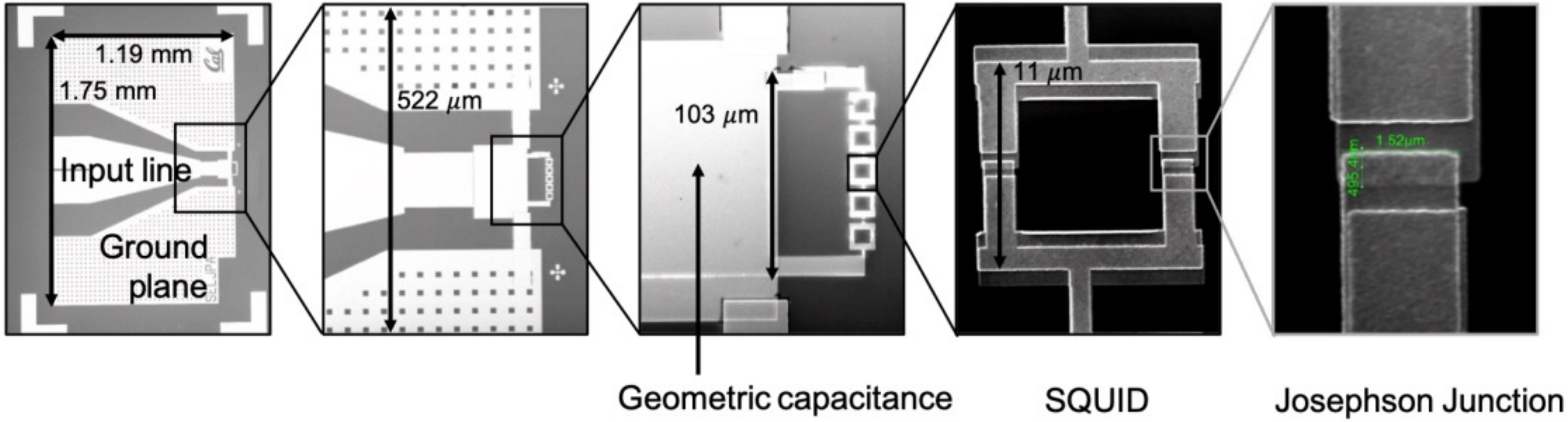


Modulate Frequency via SQUID Inductance
→ Parametric Amplification





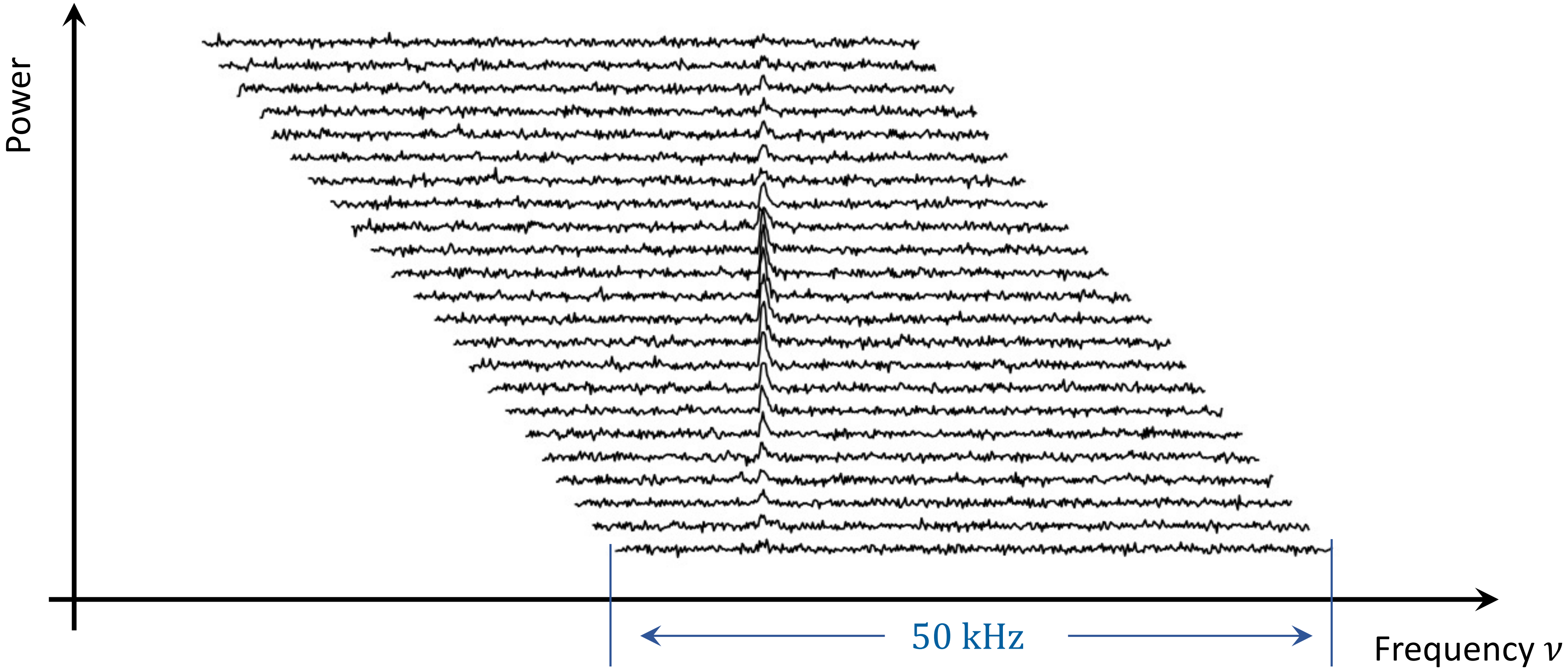
JPA provided by
Siddiq Group at UC Berkeley

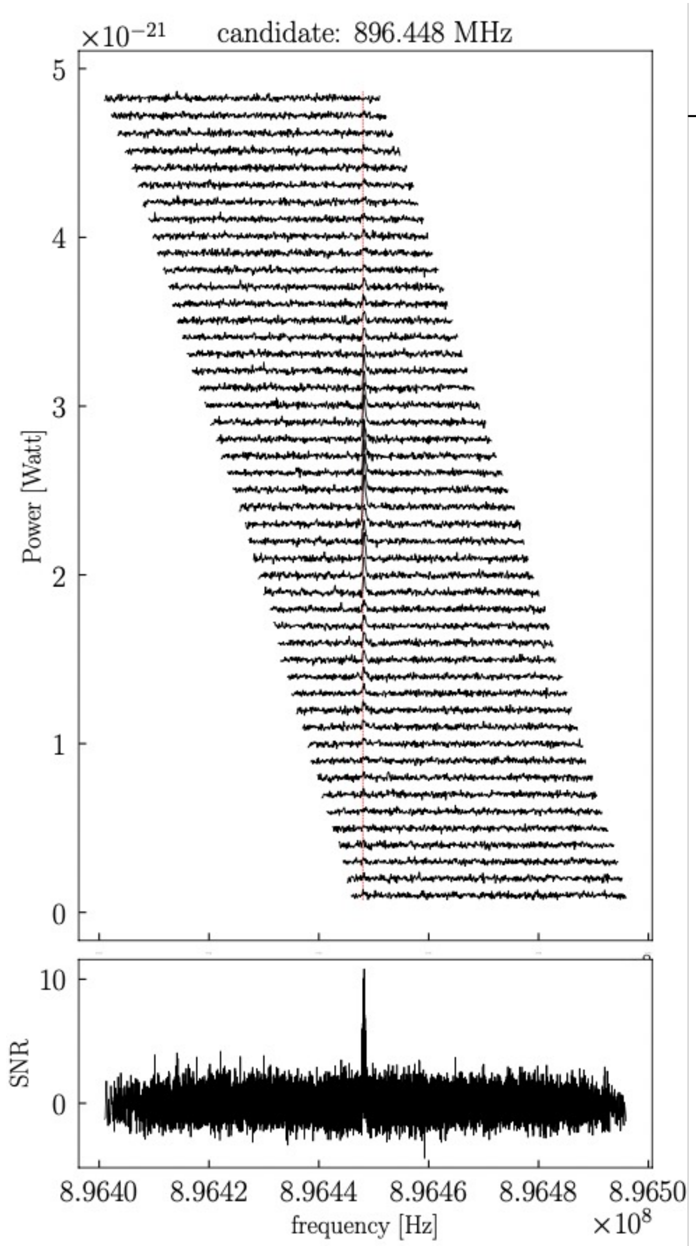


JPA noise ~100mK (Quantum Limit ~50mK) (@1GHz)

Data Taking Cadence

14 “nibbles” = $\sim$ 10 MHz sweeps   single scans: **range:** 50 kHz, **resolution:** 100Hz, **integration time:** 100s



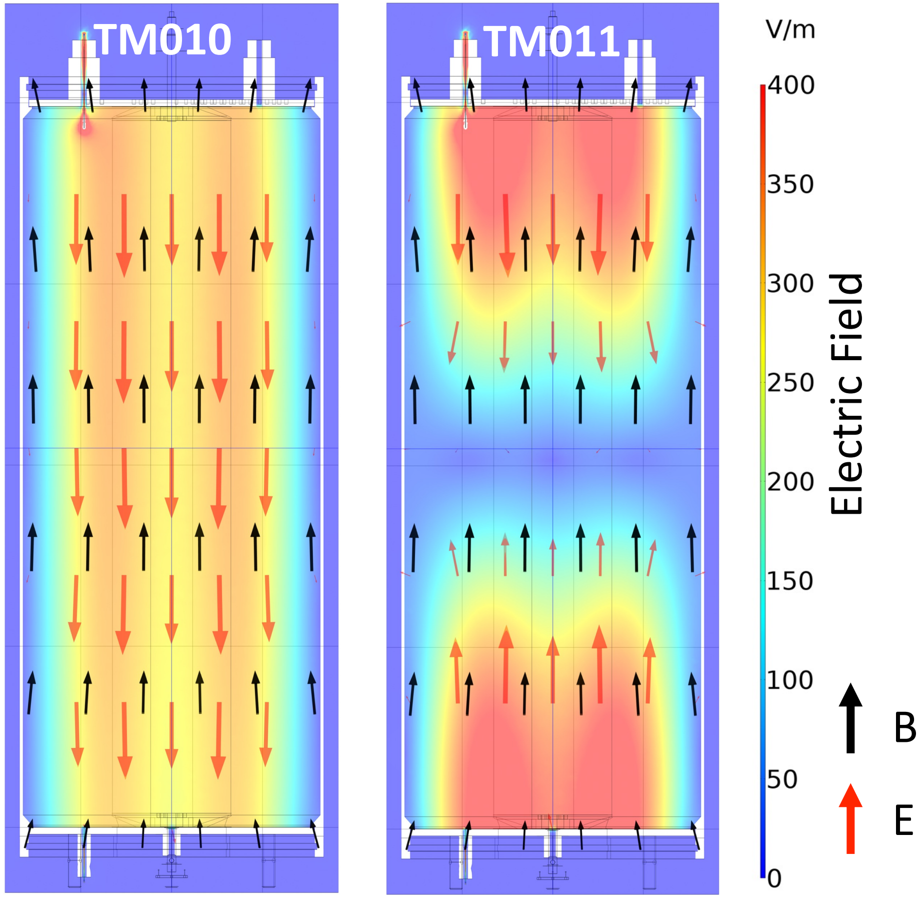


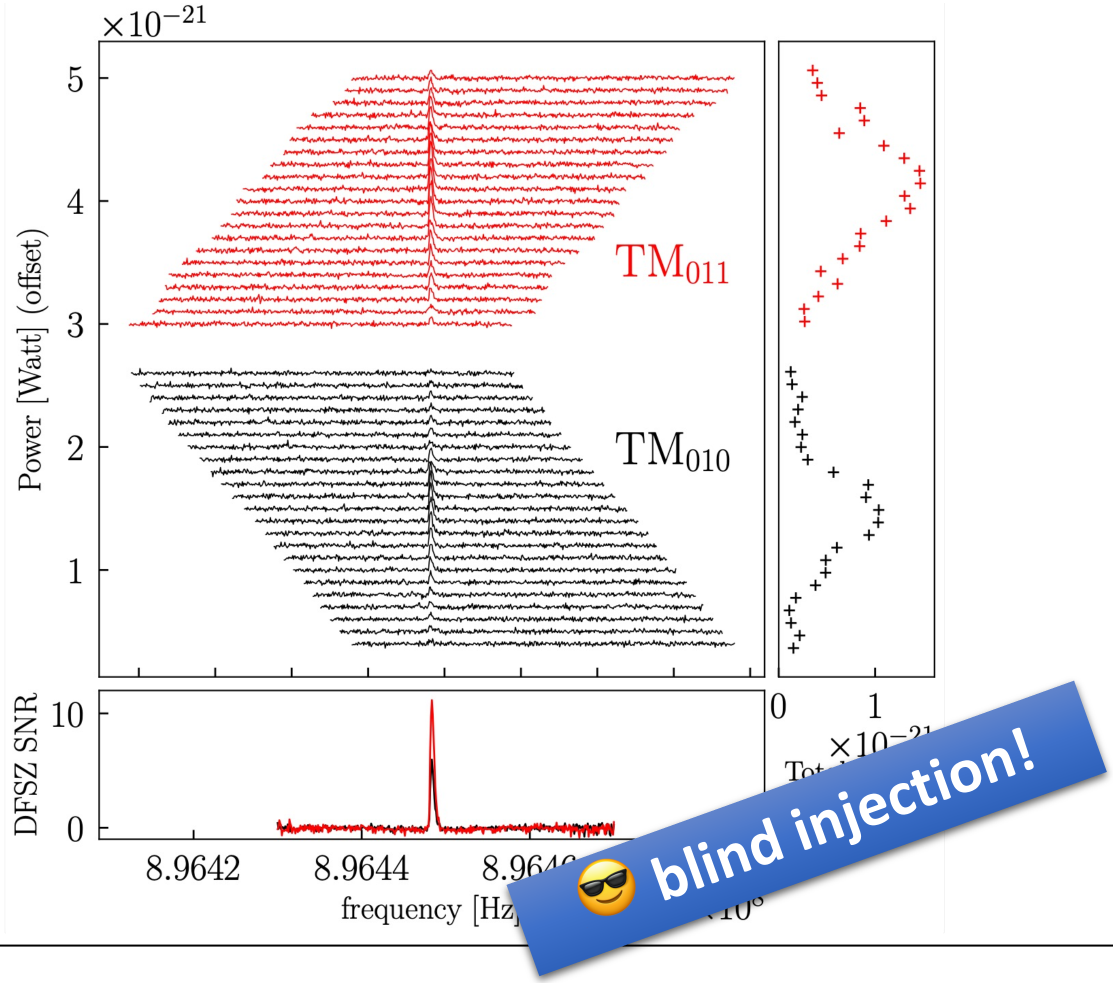
Observed Excesses

Candidates: **Tests:**

Frequency [MHz]	Persistence	At Same Frequency	Not in Air	Enhanced on Resonance
839.669	✓	×	✓	×
840.268	✓	✓	✓	×
860.000	✓	✓	×	×
891.070	✓	✓	✓	×
896.448	✓	✓	✓	✓
974.989	×	✓	✓	×
974.999	×	✓	✓	×
960.000	✓	✓	×	×
980.000	✓	✓	×	×
990.000	✓	✓	×	×
990.031	×	✓	✓	×
1000.000	✓	✓	×	×
1000.013	×	✓	✓	×
1010.000	✓	✓	×	×
1020.000	✓	✓	×	×

Cavity-Response Tests: Higher Modes





Form Factor: $C = \frac{\left(\int dV\, \boldsymbol{E}\cdot\boldsymbol{B}\right)^2}{V\, B^2 \int dV\, \varepsilon_r\, |E|^2}$

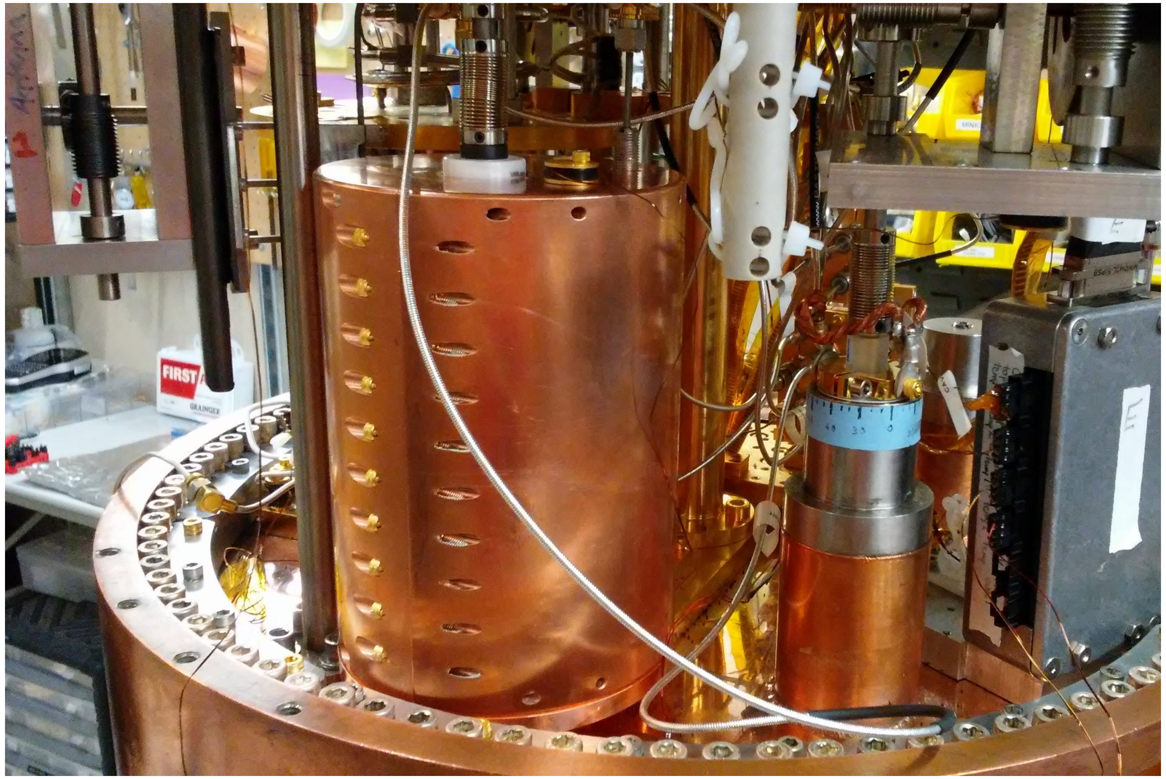
$C_{\mathrm{TM010}} \approx 0.455$ $C_{\mathrm{TM011}} < 0.001$

General R&D: ADMX-Sidecar

[arXiv: 2110.10262]

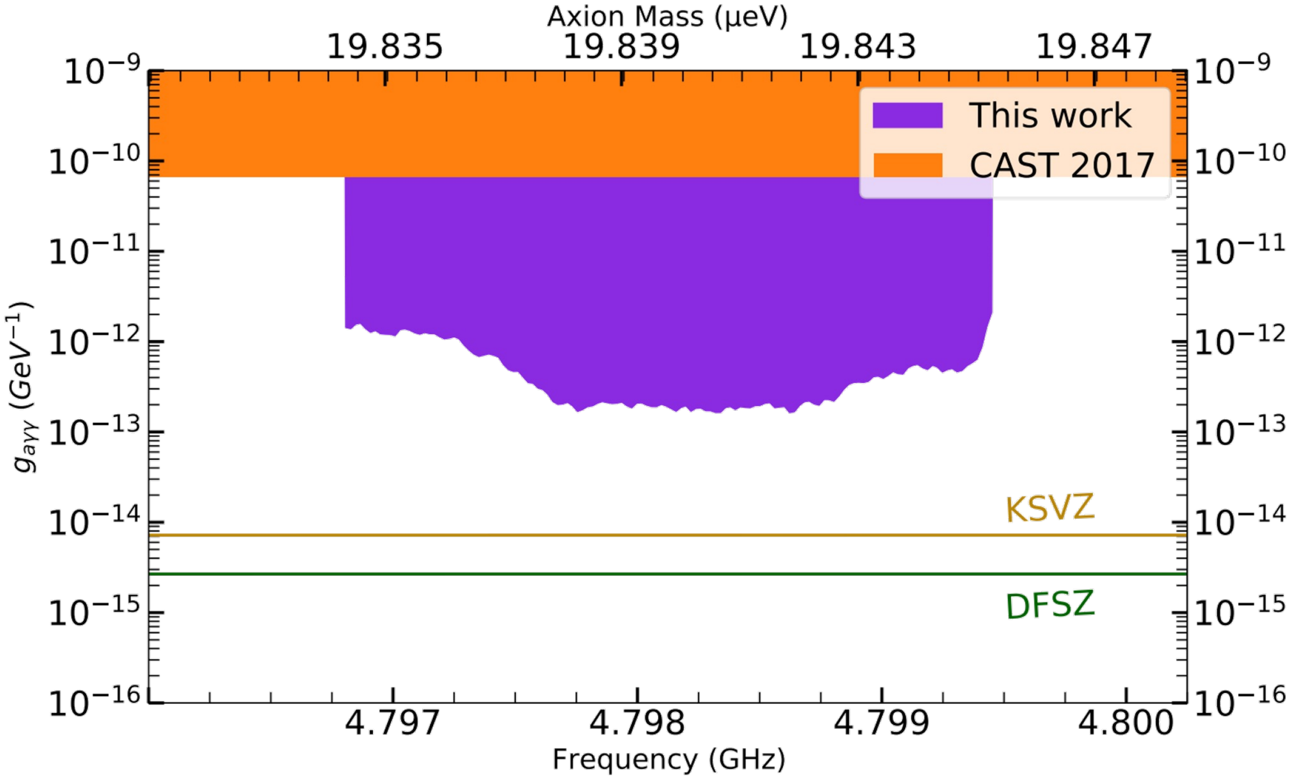
Cavity:

Testbed for High-Frequency Searches

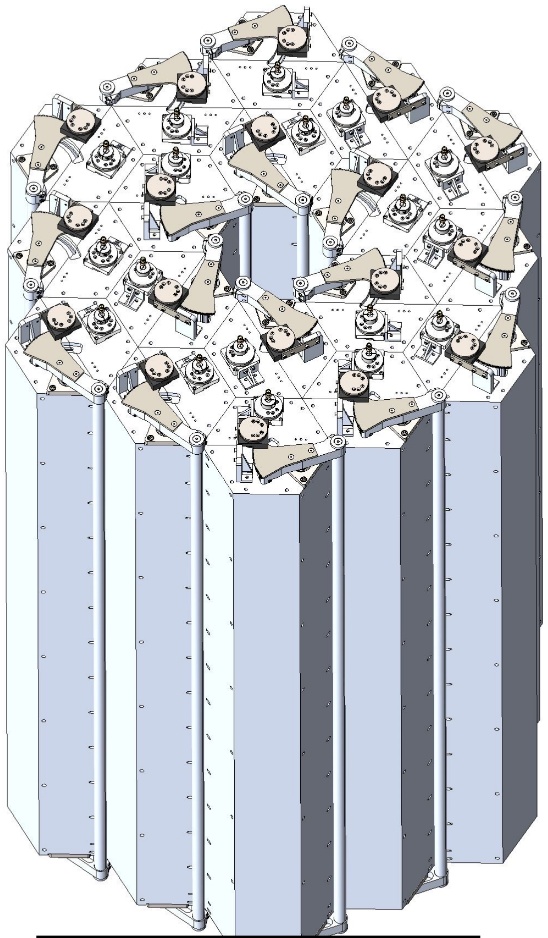


Cavity: Clamshell Design,
Tuning with Piezo Actuators, TWPA, …

Recent Result

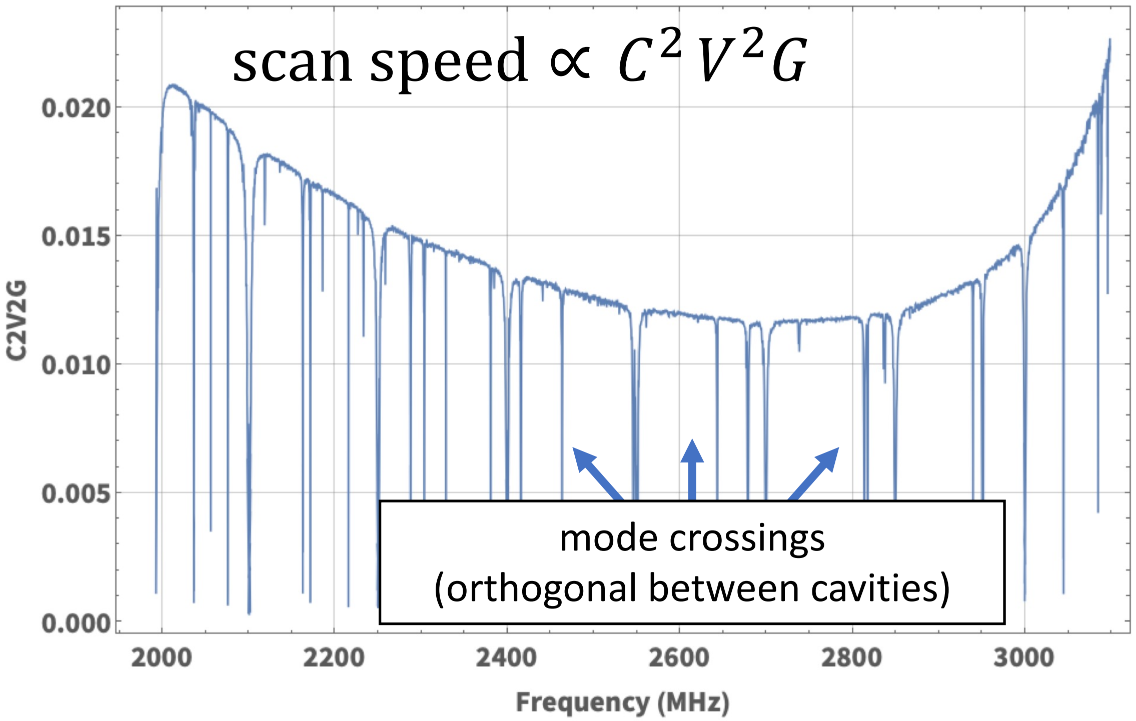


ADMX-EFR: More Cavities



18 cavity array

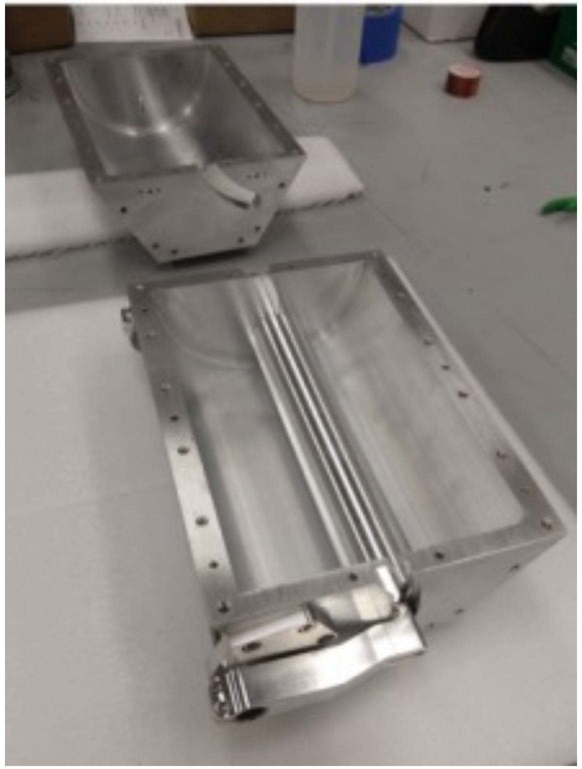
Simulations:



$Q_0 \sim 60{,}000$ (predicted, cryogenic)

$V \sim 250\,L$

First Prototypes:



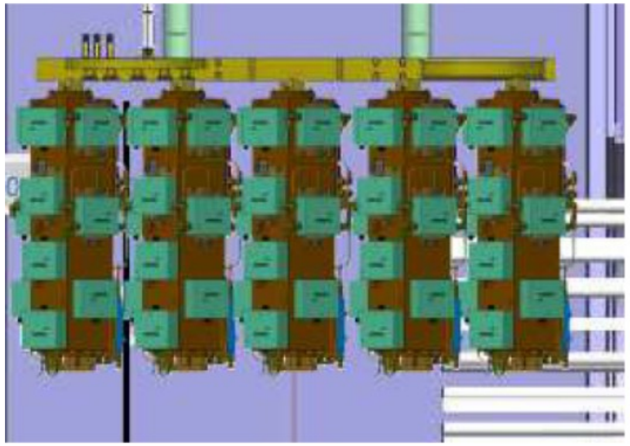
Actuators:
investigating feasibility
different companies
(Attocube, JPE, PI, …)

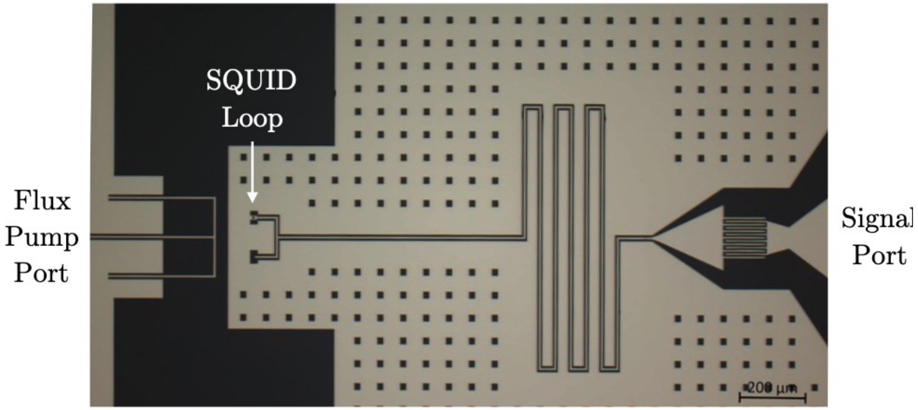
ADMX-EFR: Readout

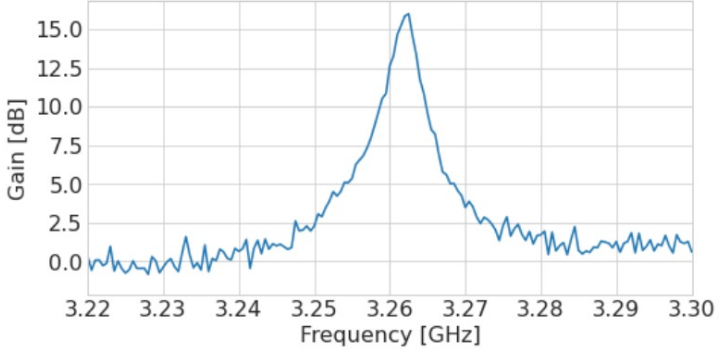
~ 5m signal transmission cavity → JPA

require: loss: $\mathcal{O}(0.5\text{dB})$ candidate: air cell cable [Kurpiers *et al. EPJ QT.* 4, 8 (2017)]

18 JPAs





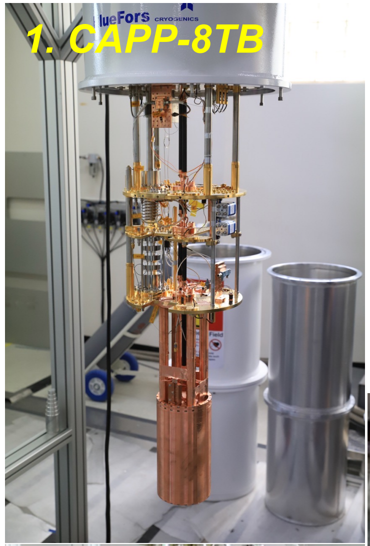


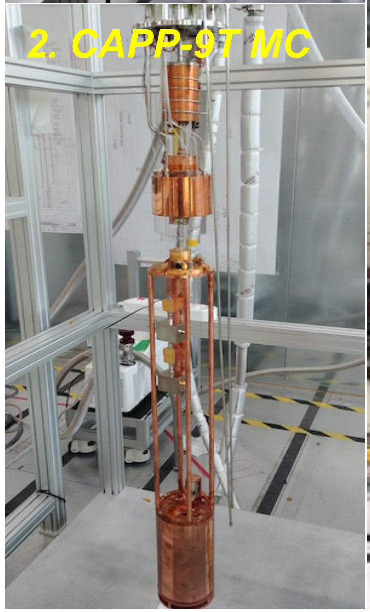
Prototype from Wash U.

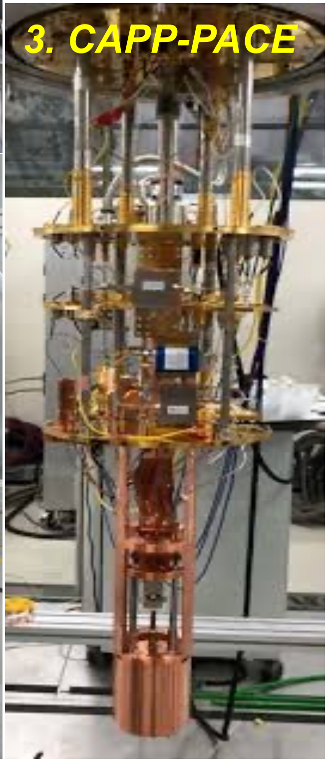
Digital Coherent Power Combining (FPGA based)

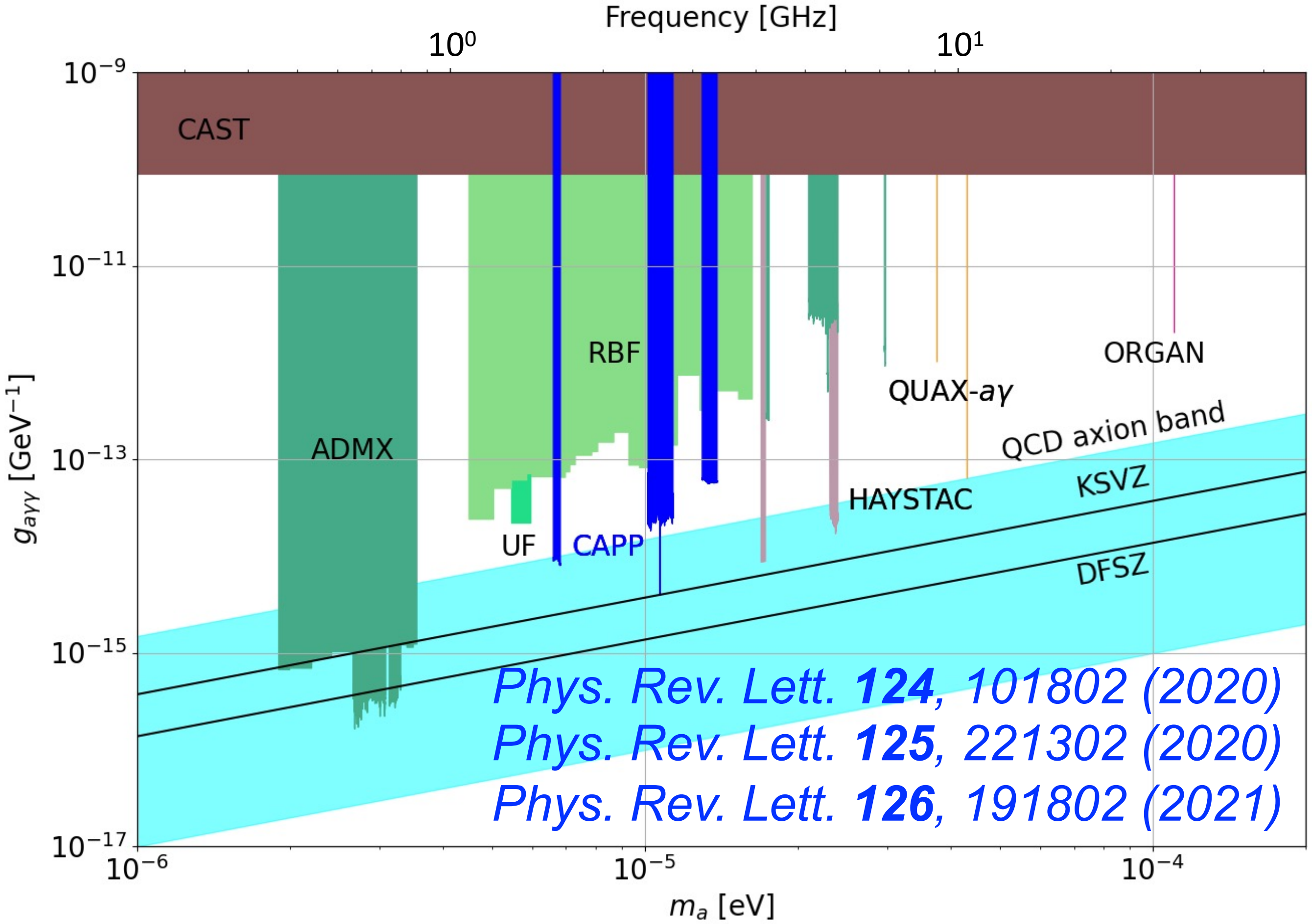
IBS/CAPP Searches

[based on slide from SungWoo YOUN, PATRAS2021]









1. CAPP-8TB
- 8T/165mm
- T_{phy} ~ 50 mK
- HEMT ~ 1 K
- 1.6 GHz
- First result

2. CAPP-9T MC
- 9T/127mm
- T_{phy} ~ 2 K
- HEMT ~ 1.5 K
- > 3 GHz
- Pizza cavity

3. CAPP-PACE
- 8T/127mm
- T_{phy} ~ 40 mK
- HEMT ~ 1 K
- 2.5 GHz
- ~300 MHz

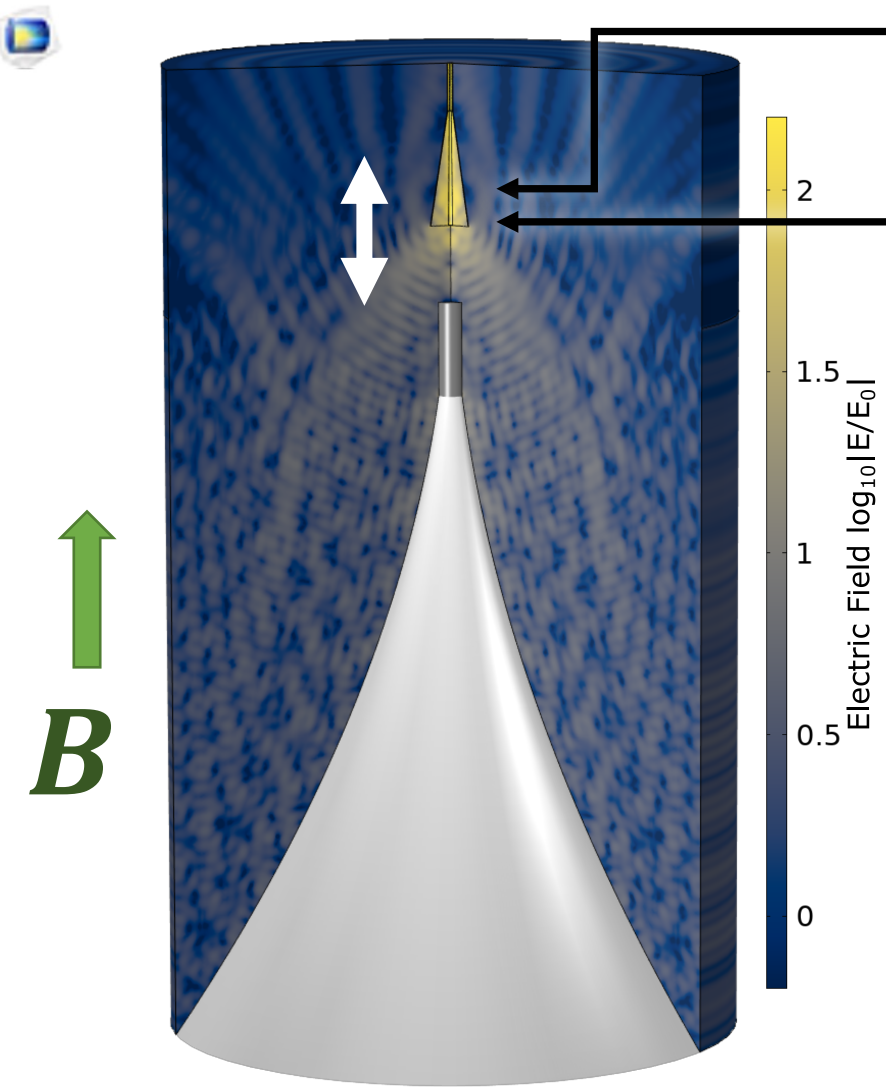
in preparation: **CAPP-12TB:** start data taking this year
[A. K. YI, PATRAS2021]

THz Sensors in Literature

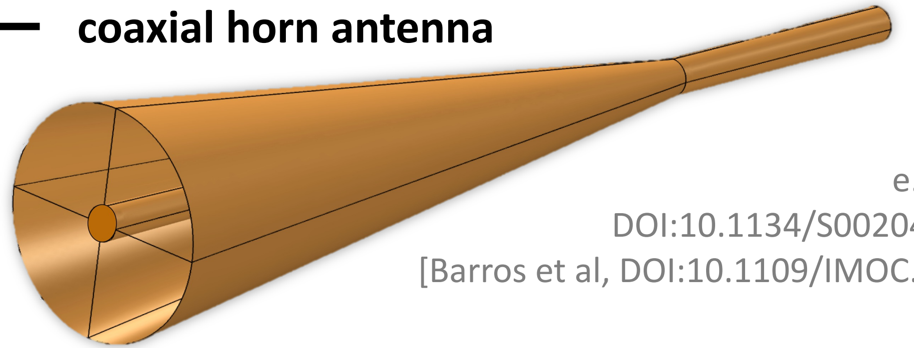
[Liu *et al*, BREAD collab., arXiv:2111.12103, PRL 128 (2022) 131801]

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)]

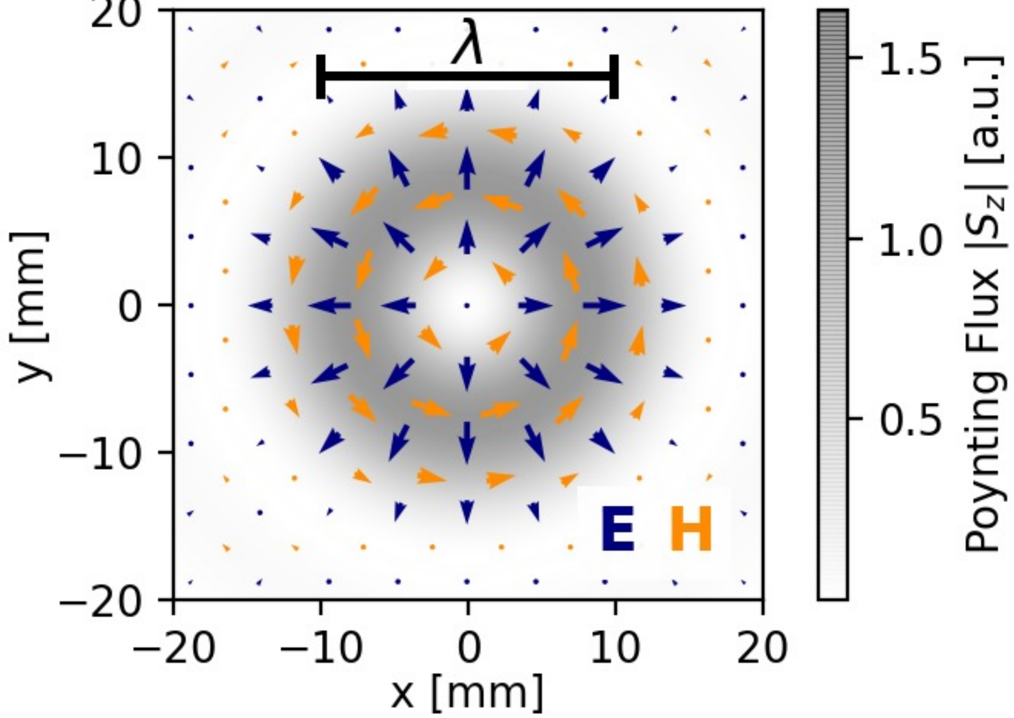
GigaBREAD: RF Simulation



coaxial horn antenna



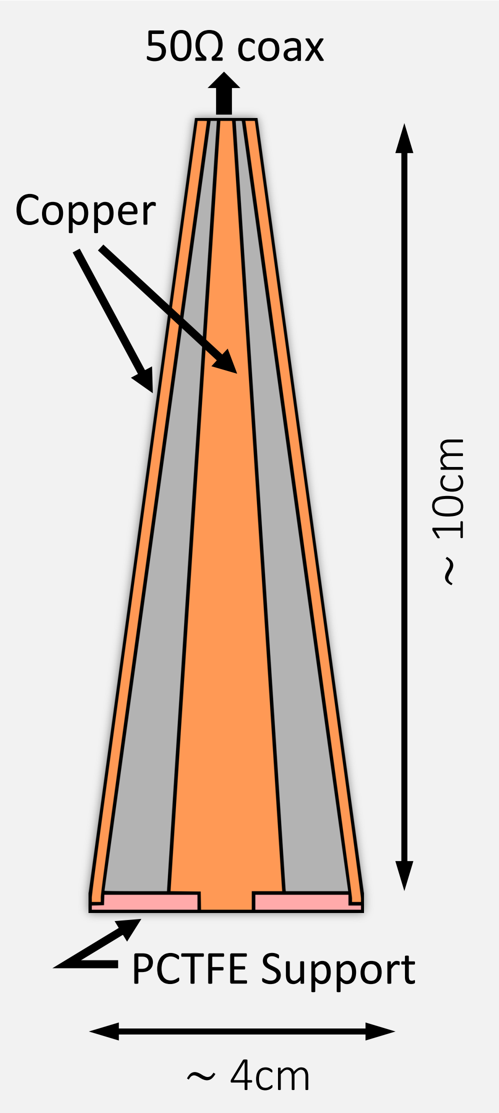
e.g. [Bykov et al, DOI:10.1134/S0020441208050126]
[Barros et al, DOI:10.1109/IMOC.2013.6646569]



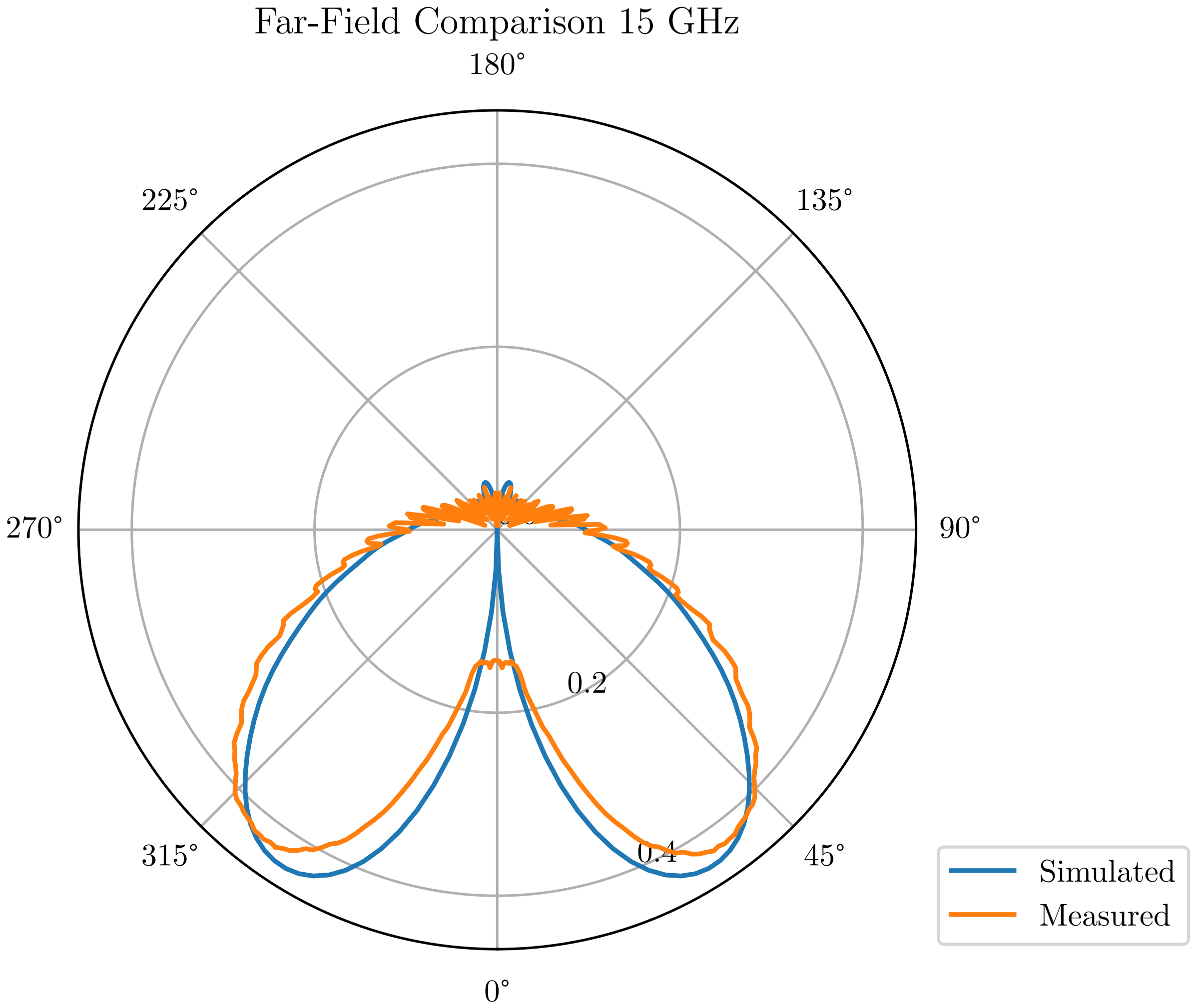
GigaBREAD: Coaxial Horn







GigaBREAD: Horn Characterization

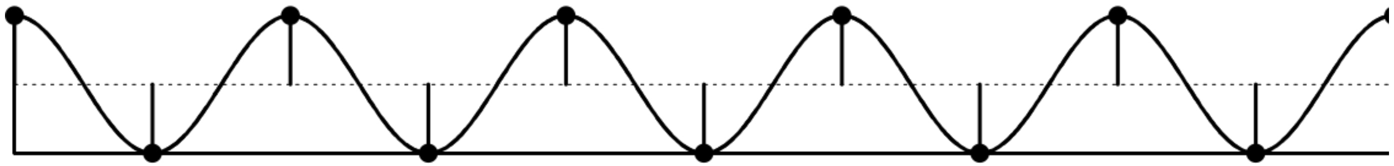


horns show close to expected performance

GigaBREAD: Large Bandwidth DAQ Architecture

Gustavo Cancelo
Leo Stefanazzi

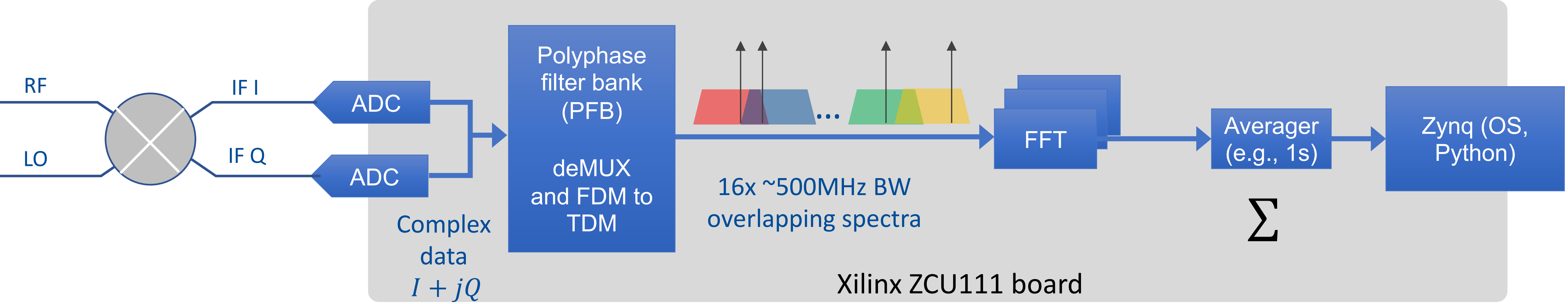
Nyquist: Min. Sample Rate = 2 × Bandwidth



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

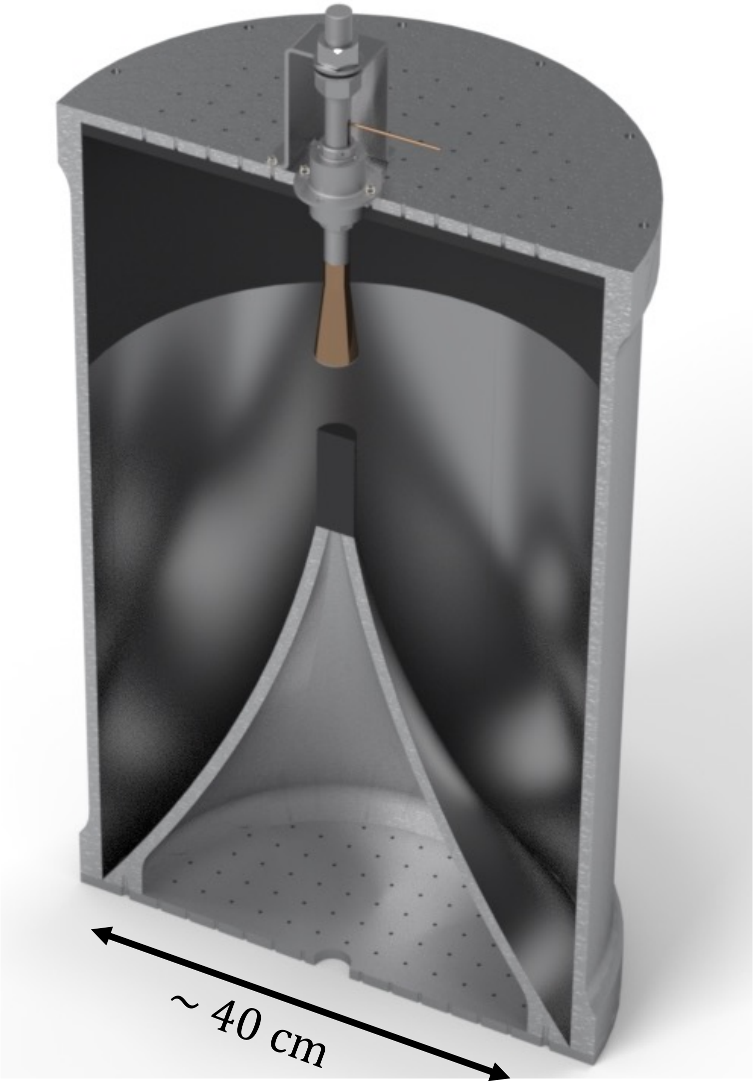
~ 4 GHz bandwidth → 8 GB/s

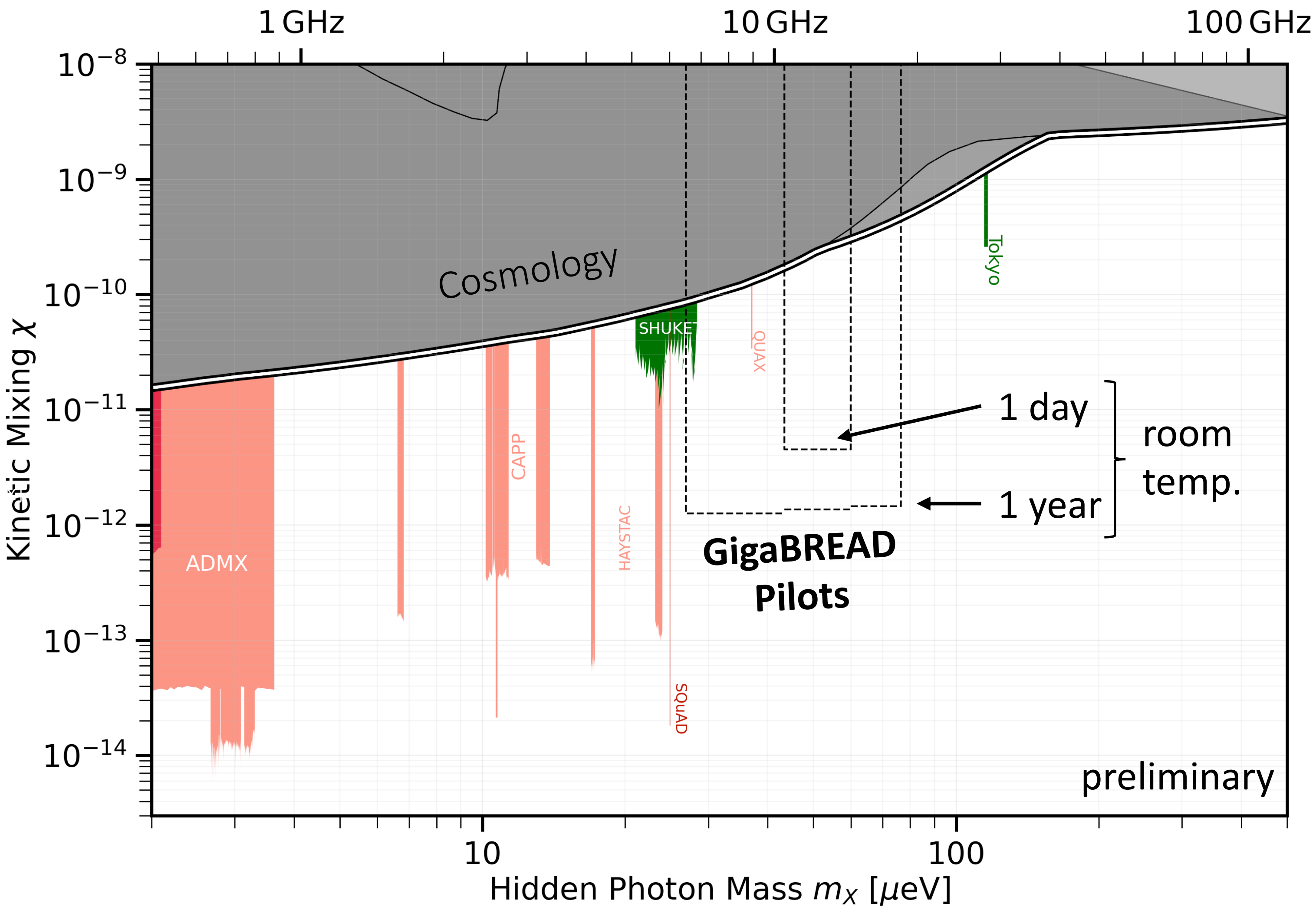
Challenge: Real-Time Data Reduction



16x 250MHz parallel FFT + Averaging in real time

GigaBREAD: Pilot Sensitivity – Hidden Photons

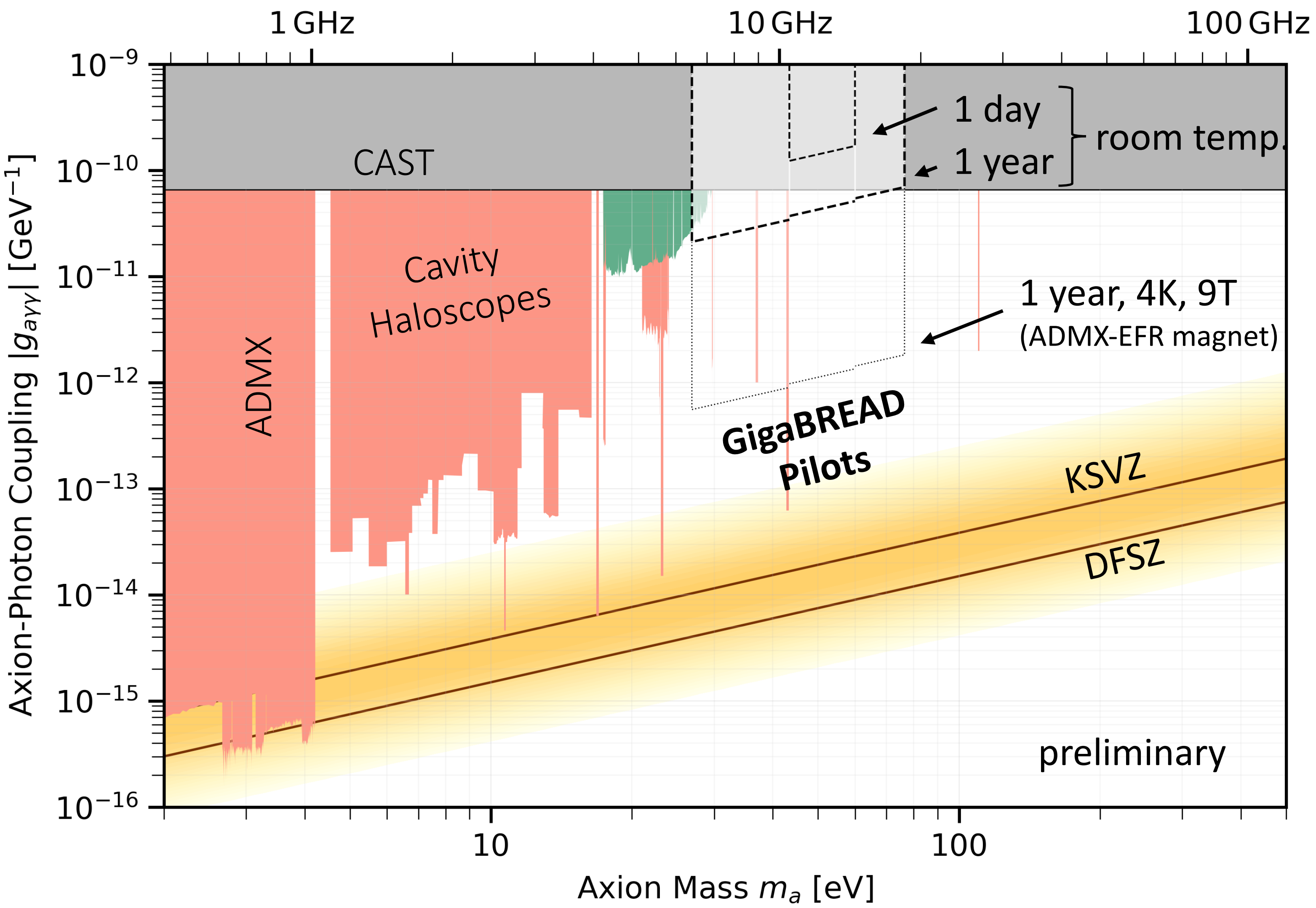




[limit plot adapted from cajohare.github.io/axionlimits]

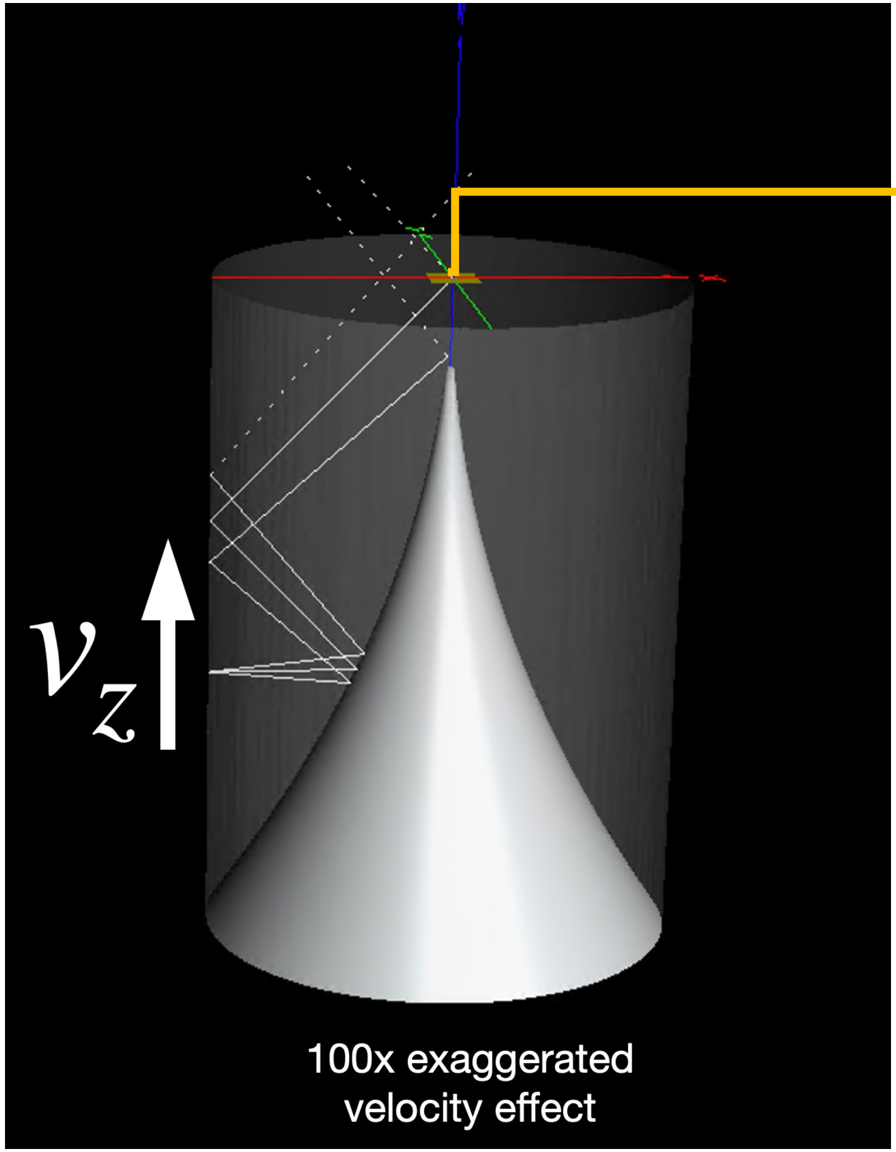
GigaBREAD: Pilot Sensitivity – Axions

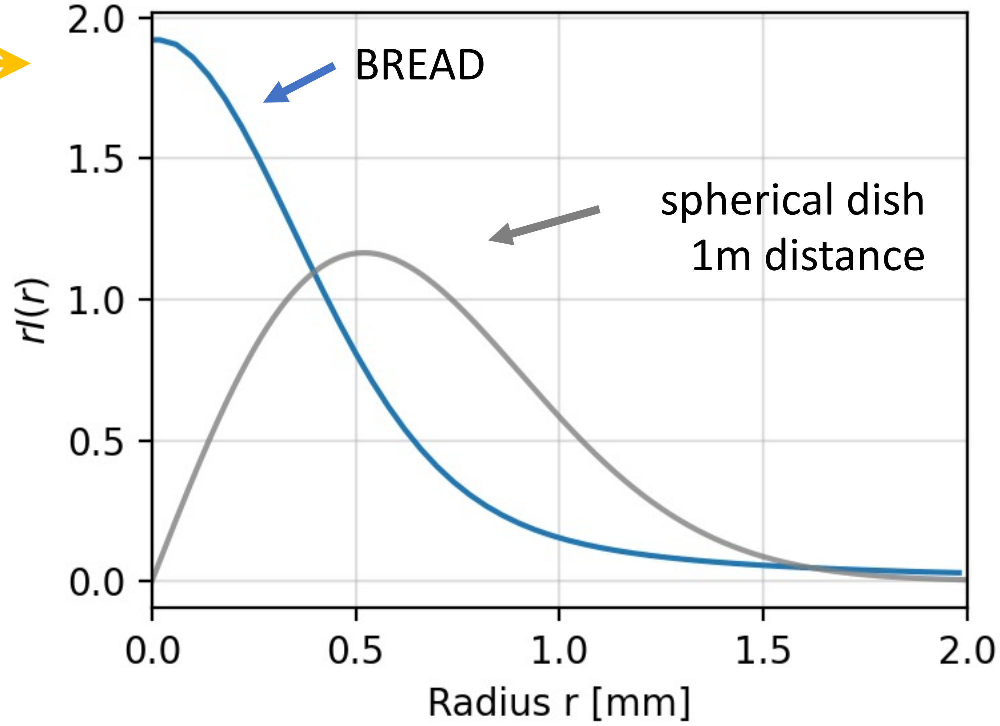
4 T MRI magnet at Argonne



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

InfraBREAD: Incoherent Detection - Velocity Effects





Radius:

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

Dish Area:

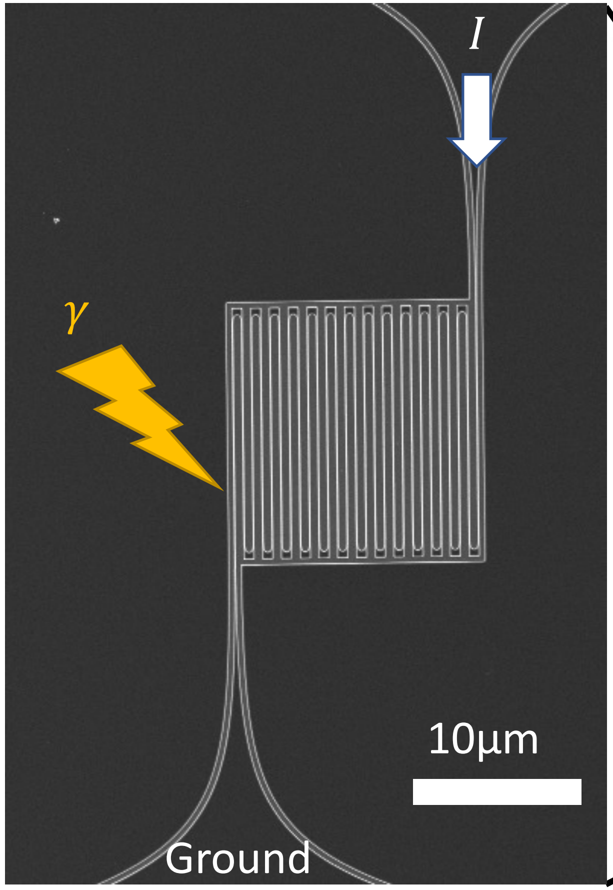
$$A = 0.7\text{m}^2$$

(Pilot Experiment Dims.)

focusing velocity effect limited

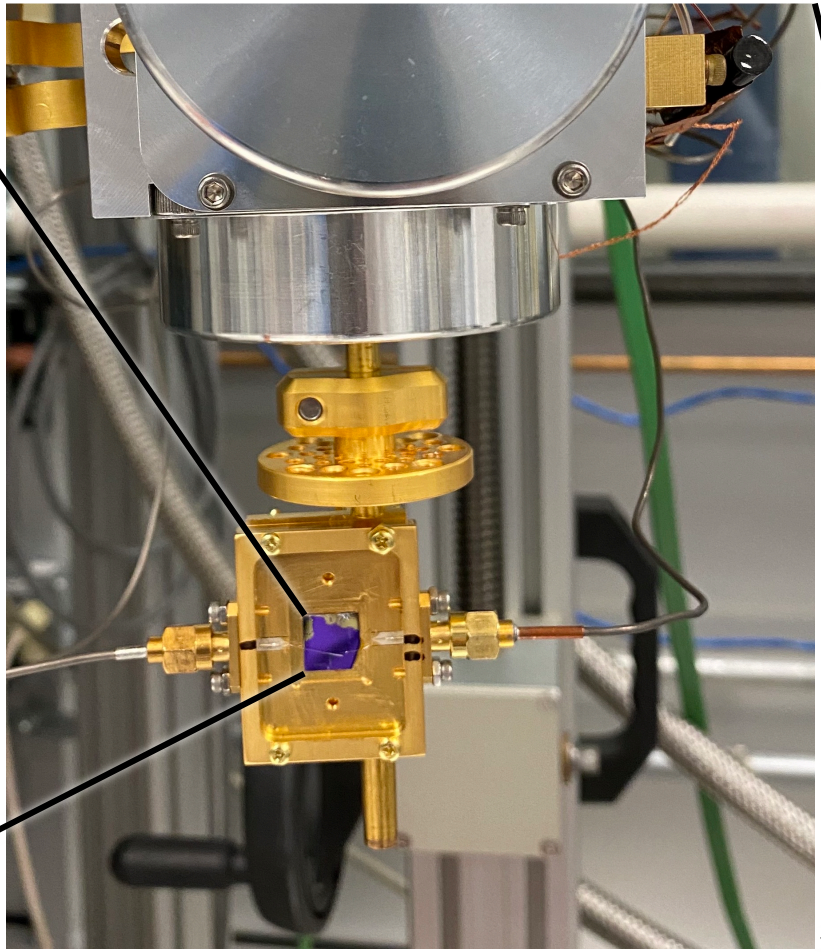
InfraBREAD: Superconducting Nanowire Single Photon Detector (SNSPD)

SNSPD from MIT



γ breaks I

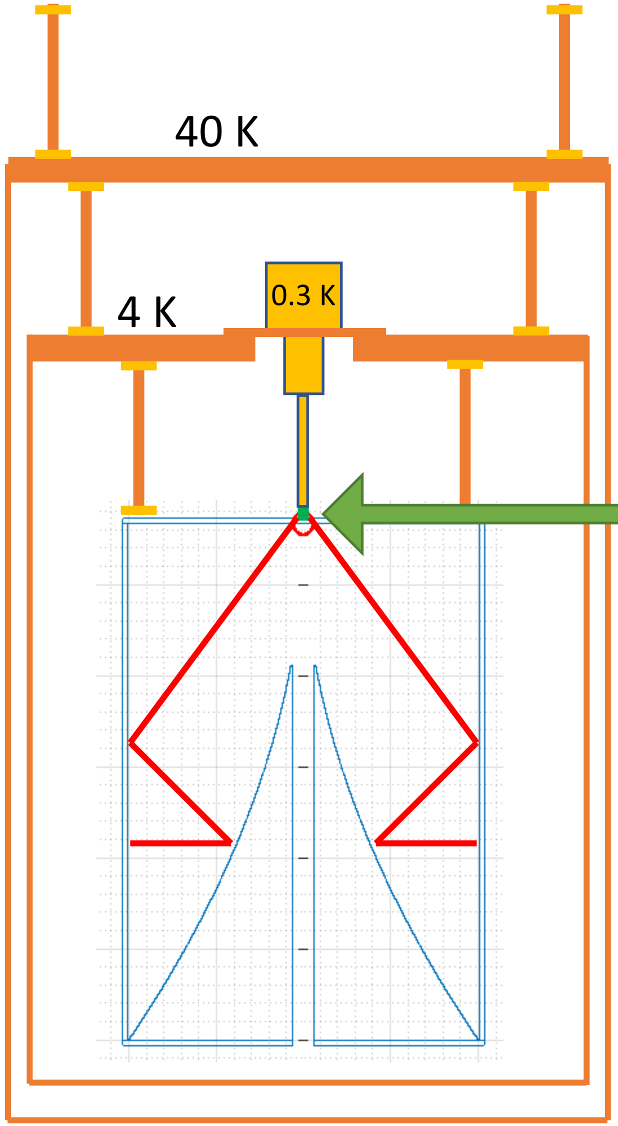
Mount



Adiabatic Demagnetization Refrigerator (ADR)

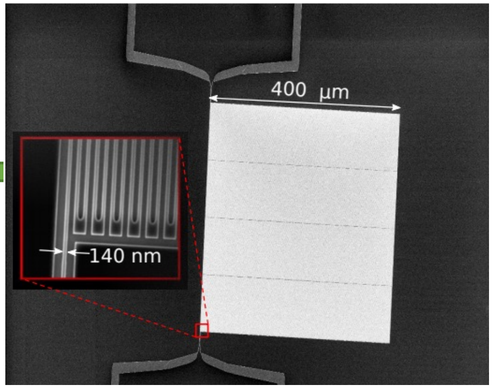
Window Flange for Laser Beam Injection

InfraBREAD Pilot Sensitivity



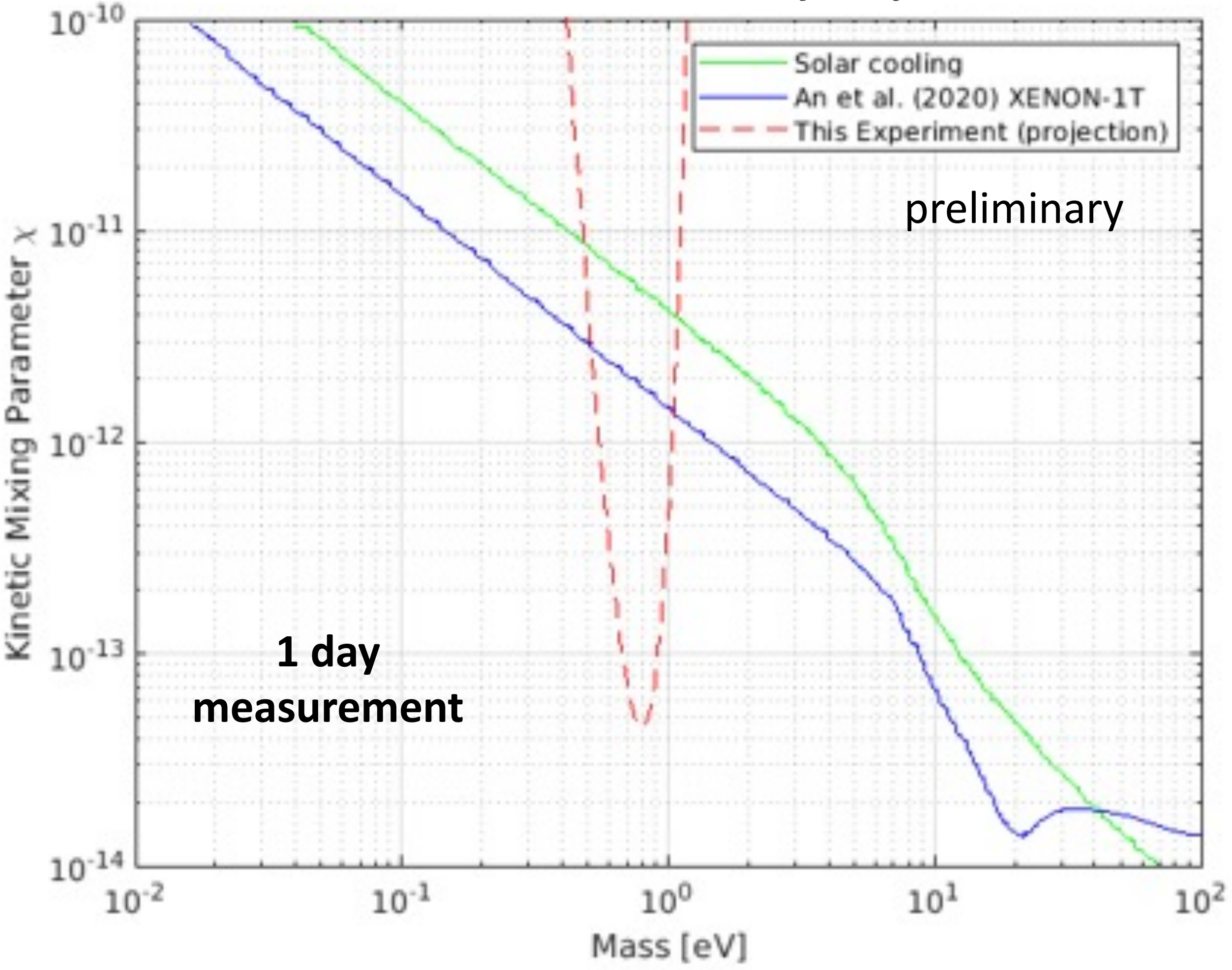
MIT SNSPD

1 photon/day dark rate



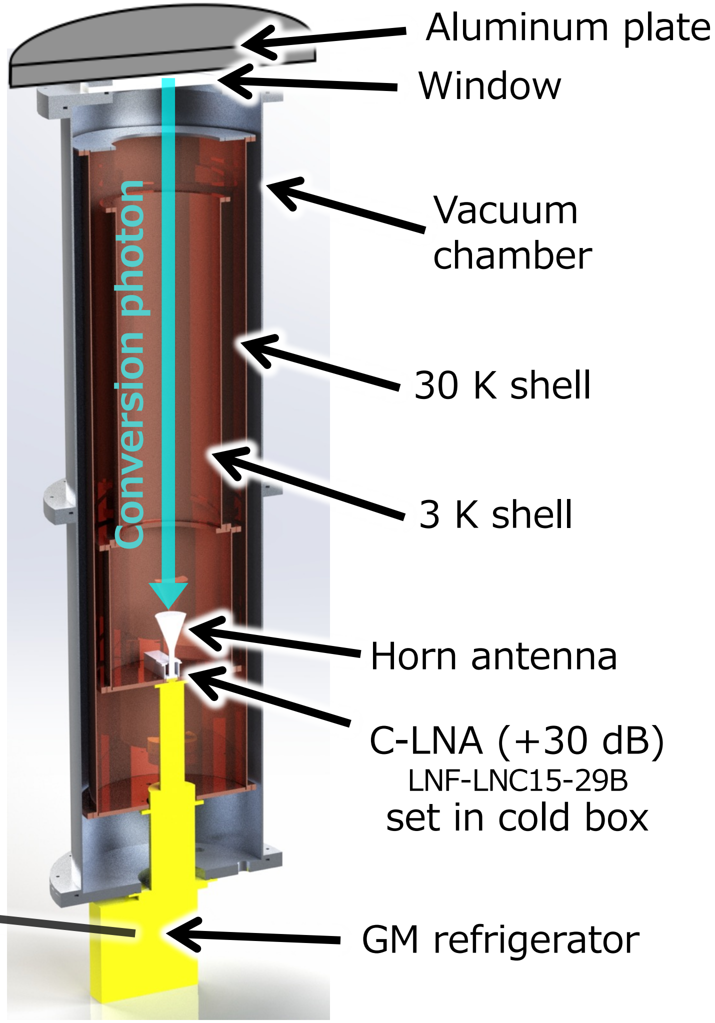
[Hochberg *et al.*, PRL 123 (2019)]

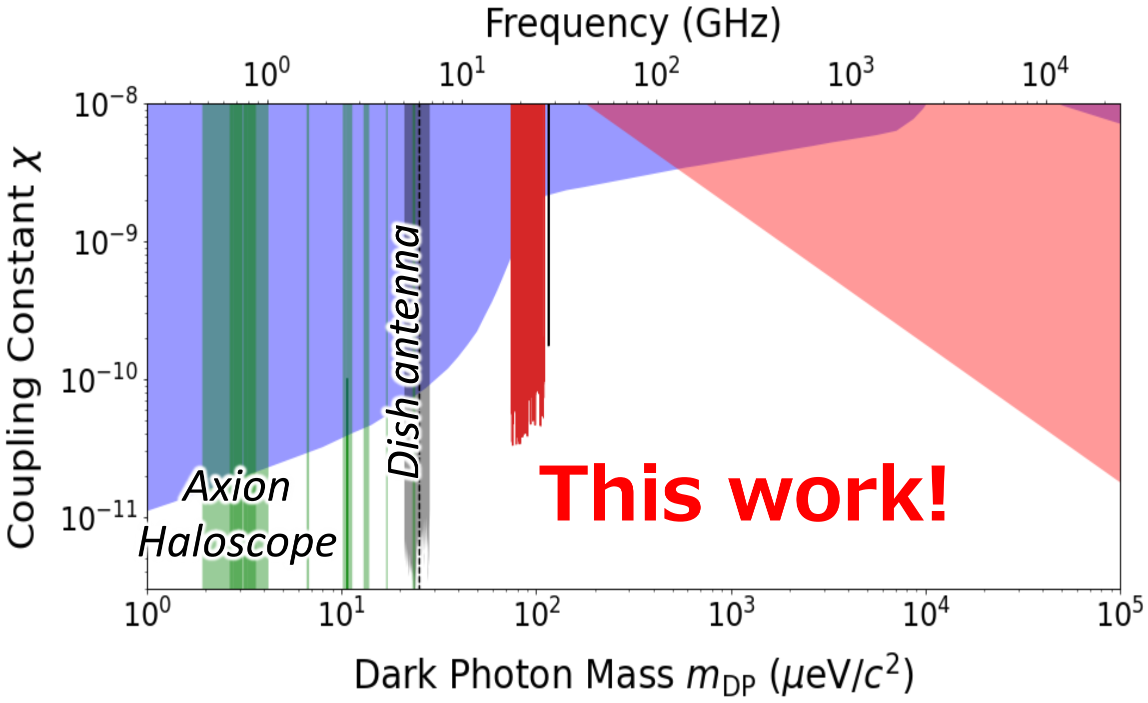
Hidden Photon Sensitivity Projection



DOSUE-RR: “どすえ” Dark-photon/dark-matter Observing System for Un-Explored Radio-Range

18-26.5GHz | **~30K noise temp.** | **no magnet**

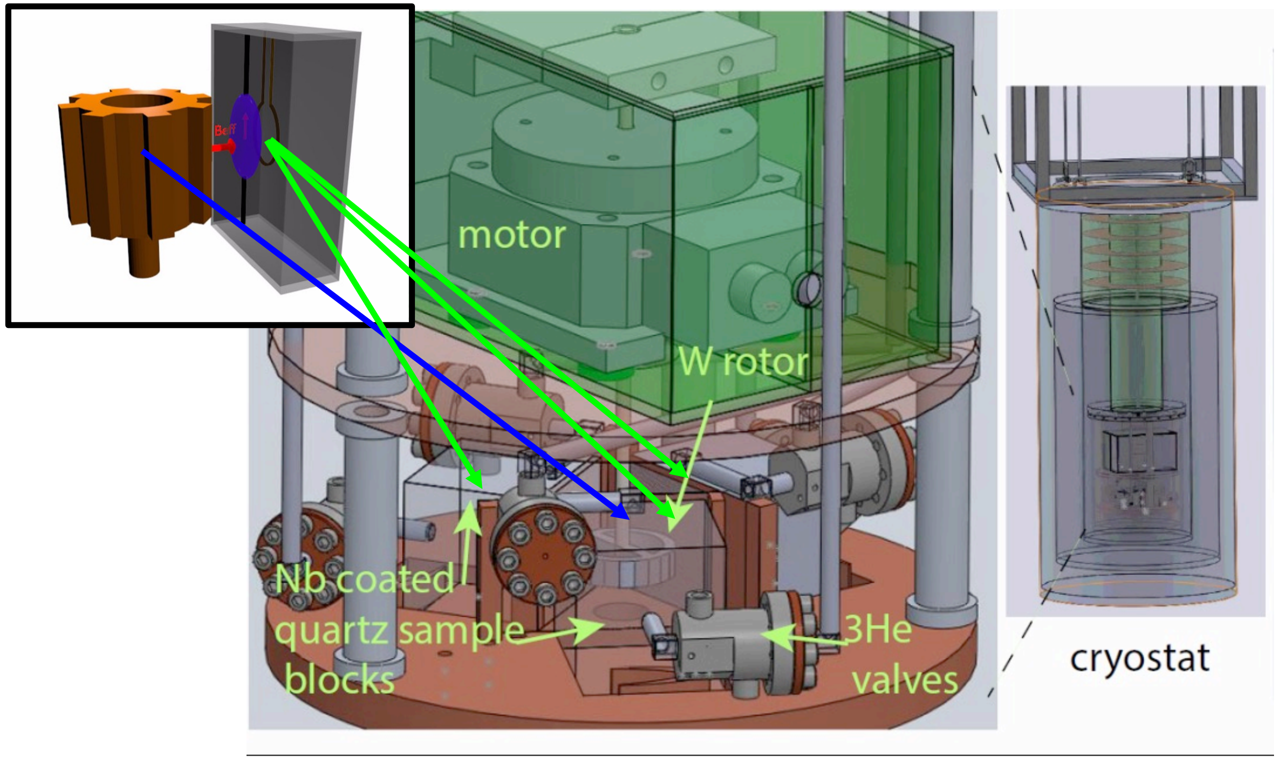


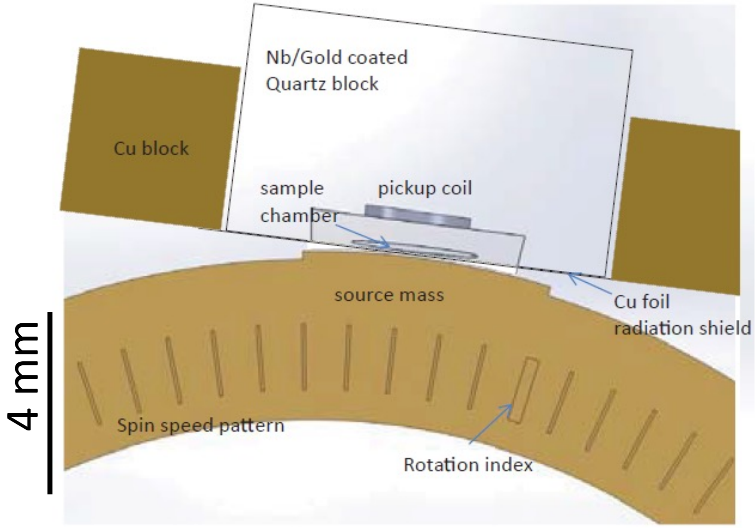


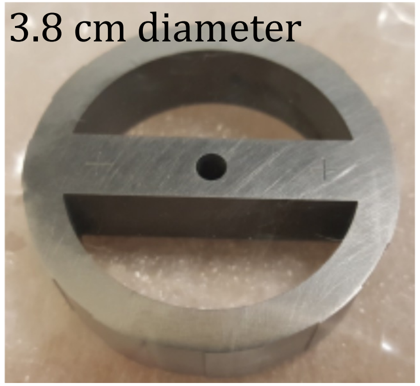
[O. Tajima, PATRAS2022]
[Kotaka, Adachi *et al*, arXiv: 2205.03679]

ARIADNE: Experimental setup

[slide taken from A. Geraci, talk at PATRAS 2021]

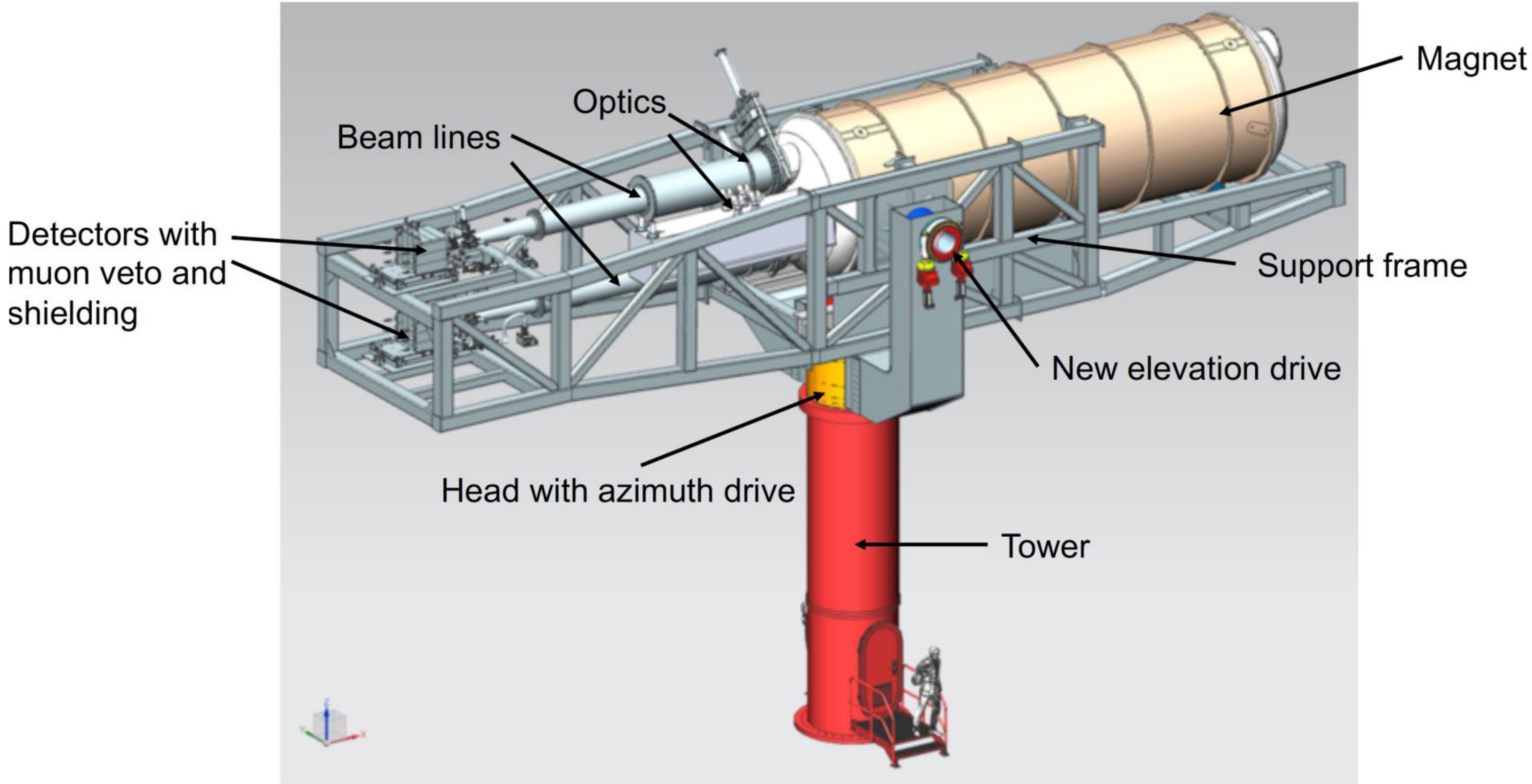






Tungsten source mass (high nucleon density)
11 segments
100 Hz nuclear spin precession frequency
2 x 10^{21} / cc ^{3}He density
3 mm x 3 mm x 150 µm volume
Separation ~200 µm

BabyIAXO



Magnet
Optics
Beam lines
Detectors with muon veto and shielding
Support frame
New elevation drive
Head with azimuth drive
Tower

Copyright Information / Detailed References

ADMX, BREAD, Assembly of Review:

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.