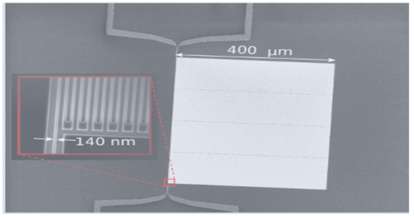
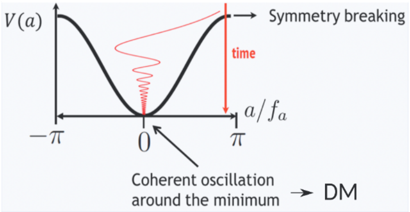
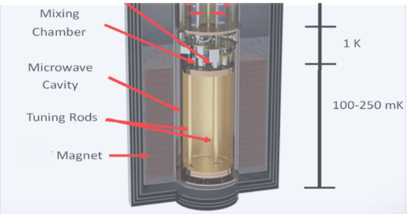
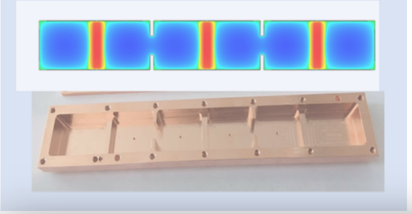
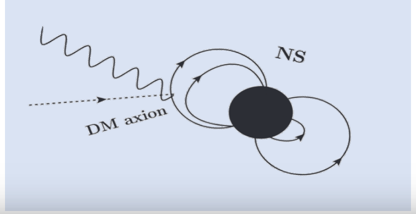
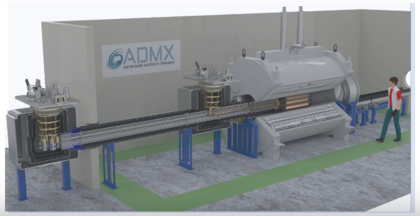






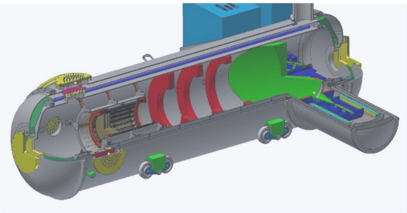



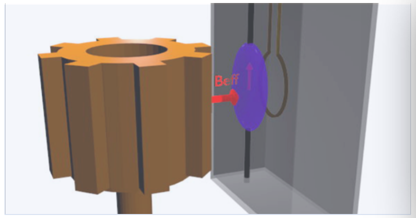
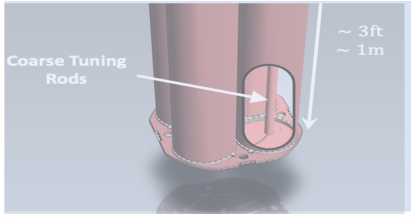


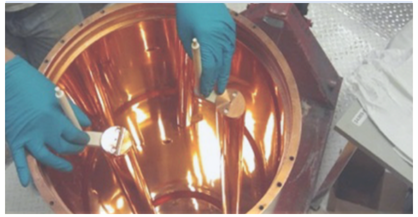
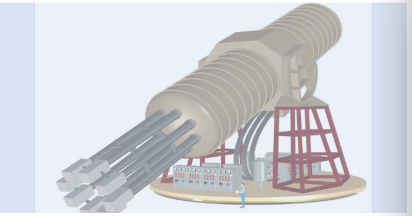
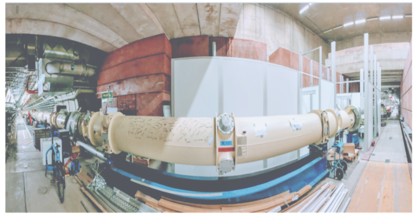
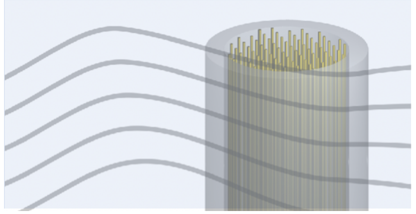

# Axion Searches

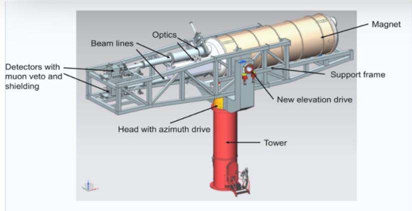
Stefan Knirck (knirck@fnal.gov)
Fermi National Accelerator Laboratory
Fermilab

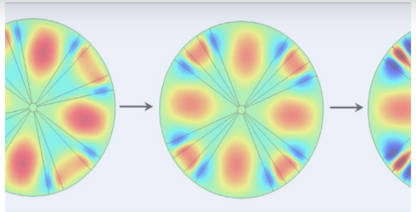
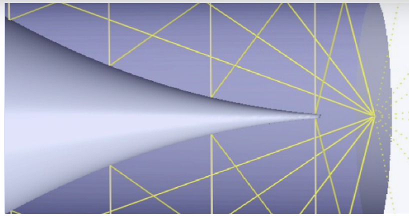
for the ADMX collaboration
ADMX AXION DARK MATTER EXPERIMENT





**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]
[Y. Semertzidis, S. Youn, arXiv:2104.14831]
[P. Sikivie, Rev. Mod. Phys.93, 015004 (2021)]



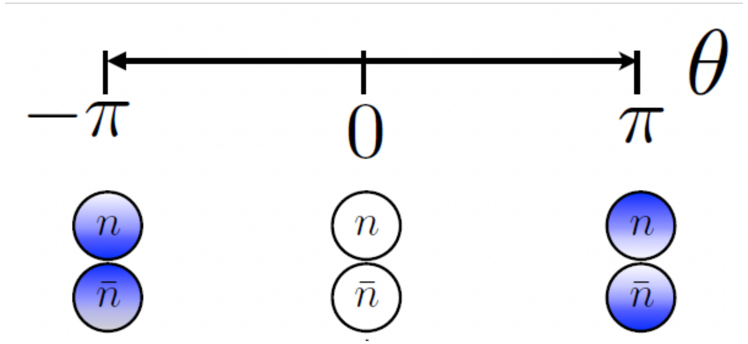
for image sources see slides of different experiments

# Why Axions? - The Strong CP Problem

QCD allows term:

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

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

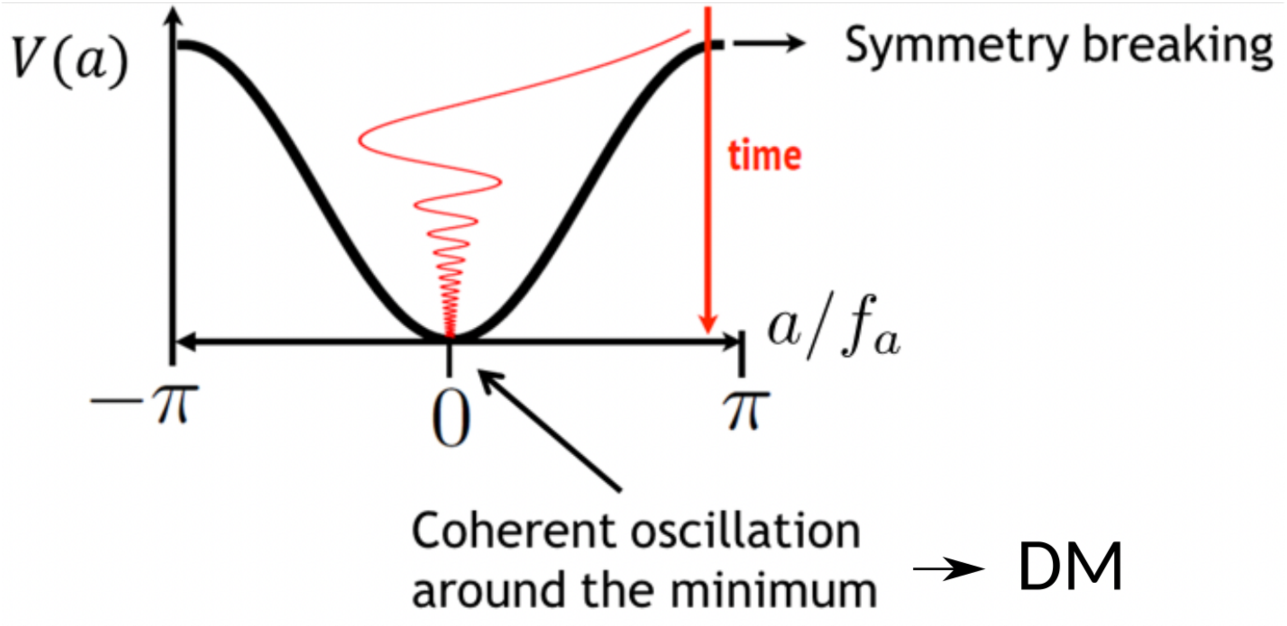


# Why Axions? - The Strong CP Problem

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

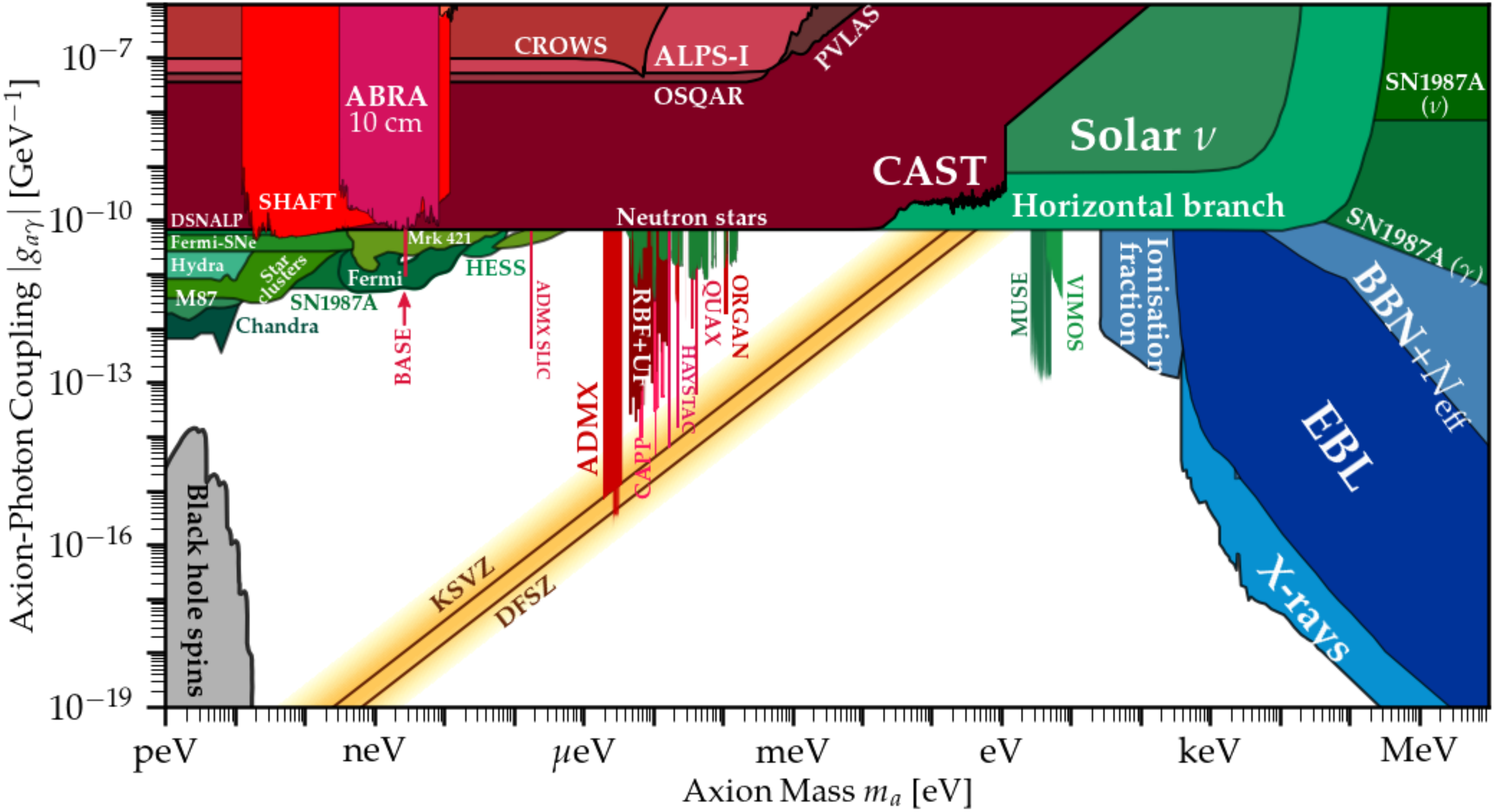
$$\mathcal{L} = -\frac{a}{f_a}\frac{g_S}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a + \frac{1}{2}\partial_\mu a\,\partial^\mu a$$

**Cosmology:** rolldown to CP conserving limit:



# Where to look?

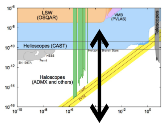
[adapted from cajohare.github.io/axionlimits]



# 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]

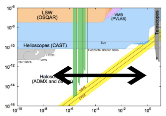
"KNP alignment"

[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

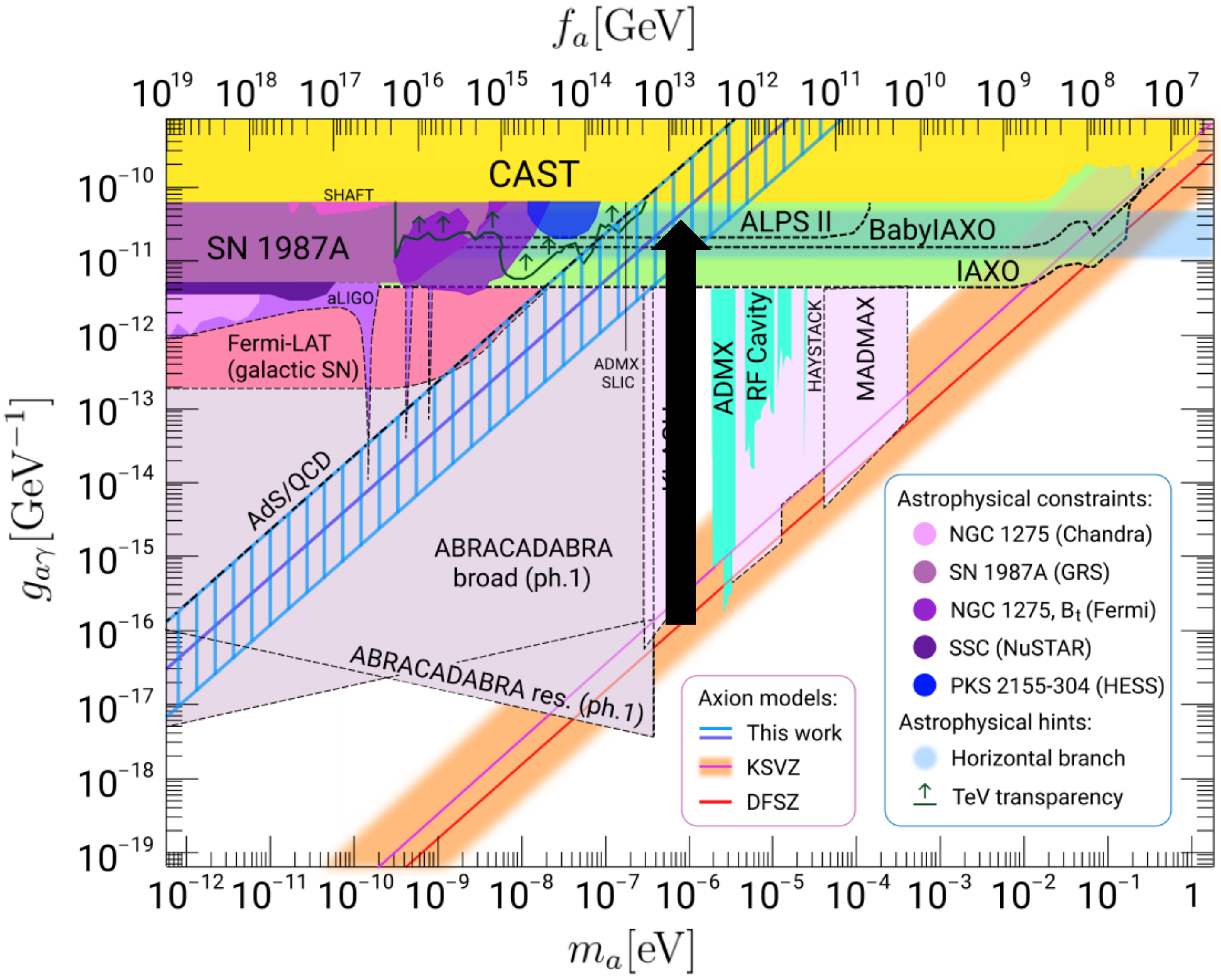
[Hook, 18]
[Luzio, Gavela, PQ, Ringwald, 21]
[Luzio, Gavela, PQ, Ringwald, 21]

# Where to look? - Models

## Recent Example:

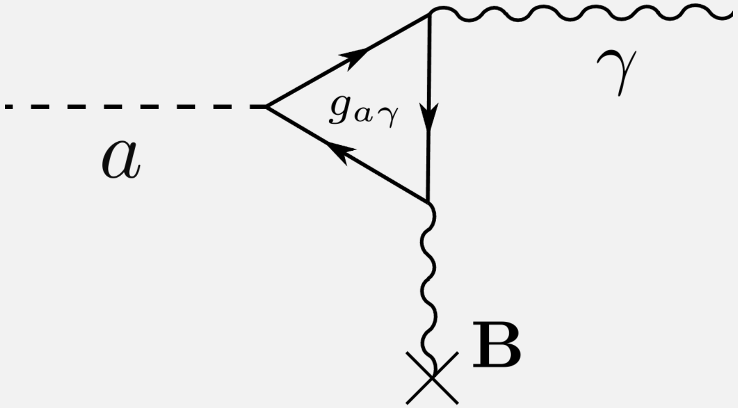
## **Photophilic Axion**

[Sokolov, Ringwald, 2104.02574]



# How to look?

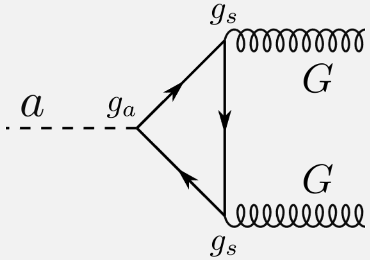
**Electro-Magnetic Coupling**



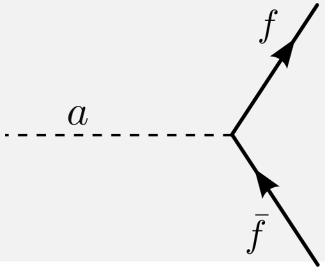

$$\sim a\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} \sim a\, \boldsymbol{E} \cdot \boldsymbol{B}$$

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

**Other Coupling**




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

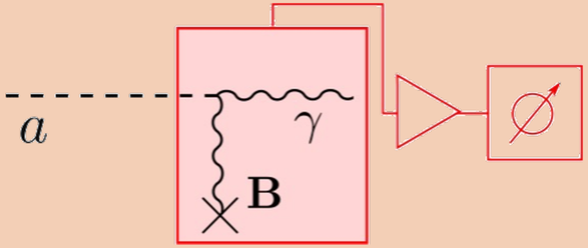



$$\sim \partial_\mu\, a\, \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

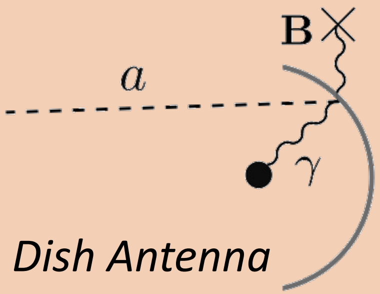
# How to look?

## Dark Matter *(Haloscopes)*

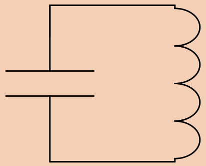
**Electro-Magnetic Coupling**




*Microwave Cavity*

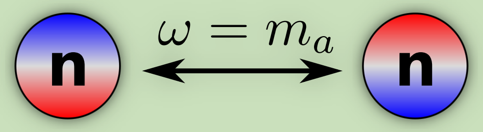



*Dish Antenna*



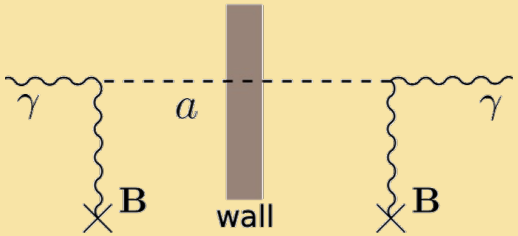
*LC Circuit*

**Other Coupling**




*Oscillating EDM*

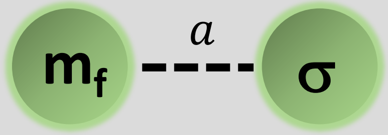
## Lab Axions




*Light-Shining-through-Wall*

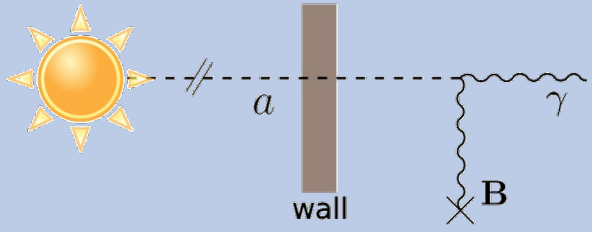
*Polarization/Birefringence*

*Collider*




*Firth Force, Collider*

## Sun & Astrophysics




*Helioscope*

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

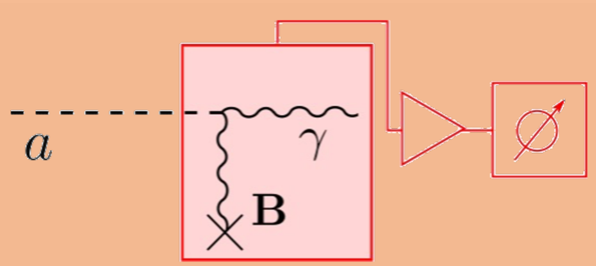
# How to look?

**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.

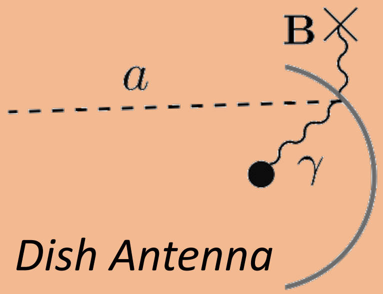
| | **Dark Matter** *(Haloscopes)* | **Lab Axions** | **Sun & Astrophysics** |
|---|---|---|---|
| **Electro-Magnetic Coupling** | ADMX, HAYSTAC, IBS/CAPP, CAST/CAPP, QUAX-a$\gamma$<br><br>RADES, ORGAN, MADMAX, DALI, ORPHEUS, ALPHA, SHUKET, BRASS, BREAD, TOORAD, LAMPOST, UPLOAD-DOWNLOAD<br><br>ABRACADABRA, ADMX-SLIC, SHAFT, DMRadio | ALPS, JURA, OSQAR, CROWS, STAX, JURA<br><br>DANCE<br><br>SAPPHIRES<br><br>Collider | CAST, IAXO, TASTE<br><br>Stellar Energy Loss, Microwave Background, Transparency; Neutron Stars, Black Hole Superradiance, … |
| **Other Coupling** | CASPER-electric,<br><br>CASPEr-gradient, GNOME, QUAX-ae | ARIADNE<br><br>Collider | |

# How to look?

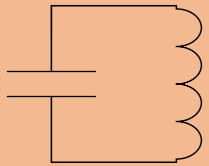
| | **Dark Matter** *(Haloscopes)* | **Lab Axions** | **Sun & Astrophysics** |
|---|---|---|---|
| **Electro-Magnetic Coupling** | *Microwave Cavity*, *Dish Antenna*, *LC Circuit* | *Light-Shining-through-Wall*, *Polarization/Birefringence*, *Collider* | *Helioscope* |
| **Other Coupling** | *Oscillating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



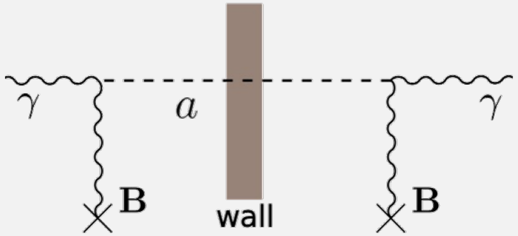

*Microwave Cavity*




*Dish Antenna*



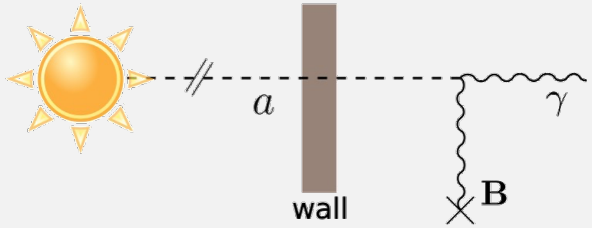
*LC Circuit*



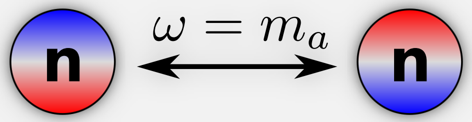

*Light-Shining-through-Wall*

*Polarization/Birefringence*

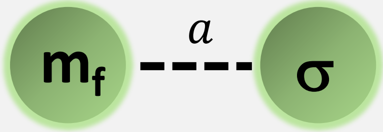
*Collider*




*Helioscope*




*Oscillating EDM*

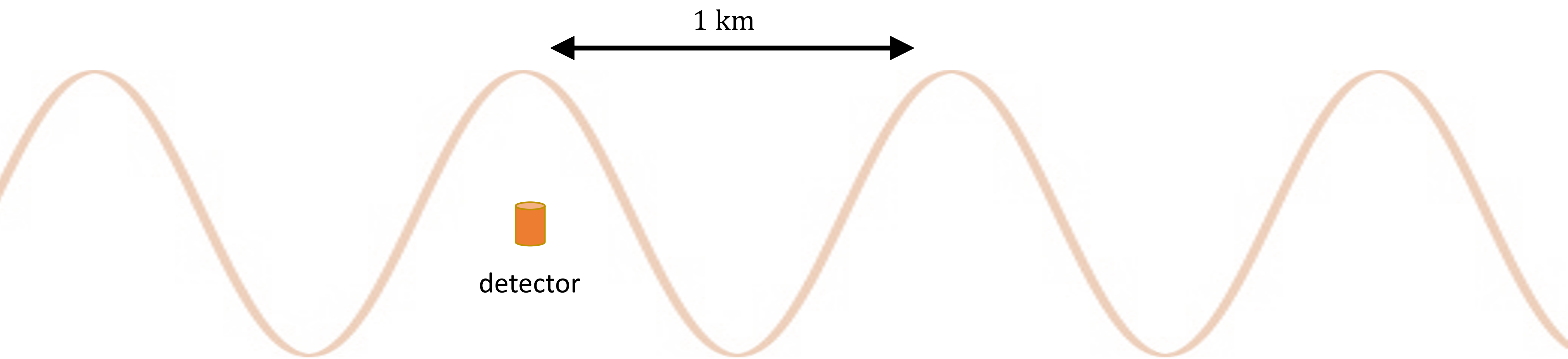



*Firth Force,*
*Collider*

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

# Wave-like Dark Matter

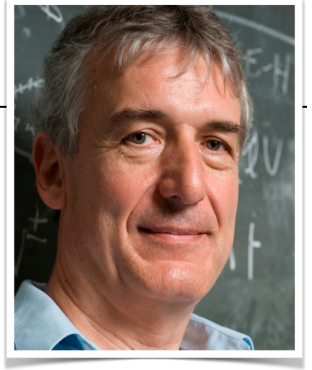
$$\rho_a \sim 0.45\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \qquad \lambda_{\mathrm{DB}} \sim \frac{2\pi}{m_a v} \sim 1\ \mathrm{km}\left(\frac{1\mu\mathrm{eV}}{m_a}\right) \quad \rightarrow \quad \frac{\#\mathrm{particles}}{\lambda_{\mathrm{DB}}^3} \sim 10^{30}\left(\frac{1\mu\mathrm{eV}}{m_a}\right)^4$$

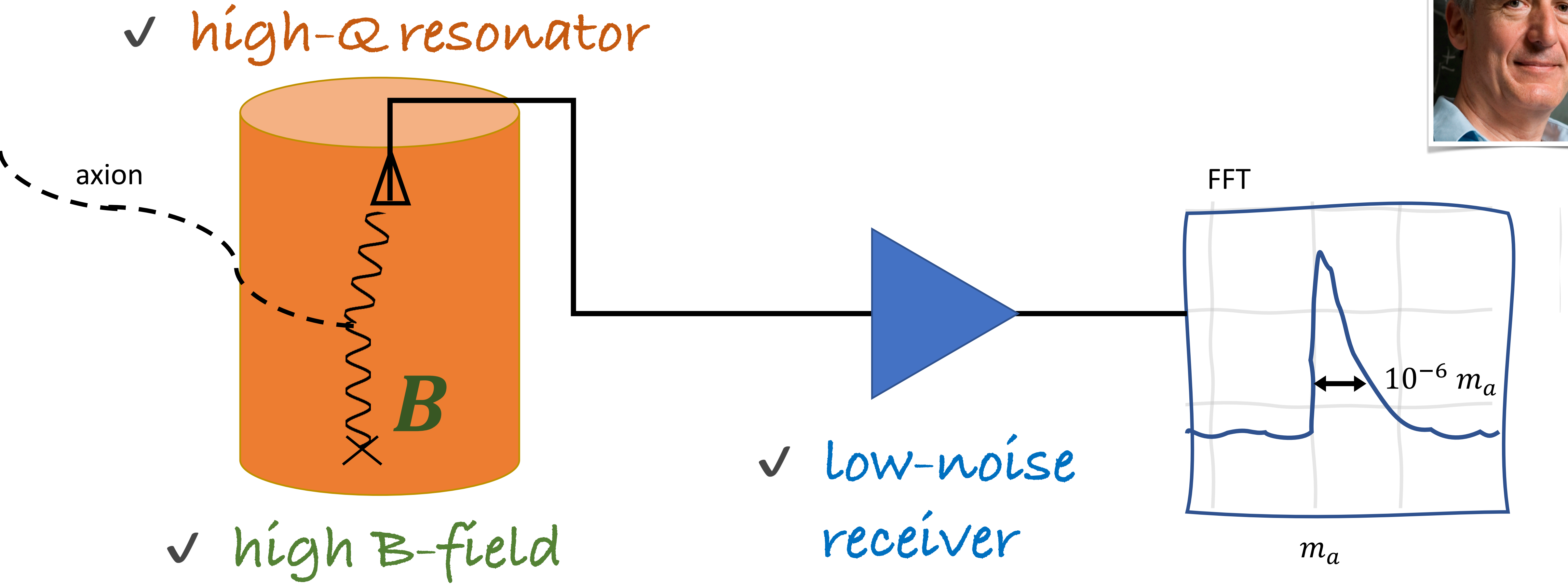



coherent detection

# The Resonant Cavity

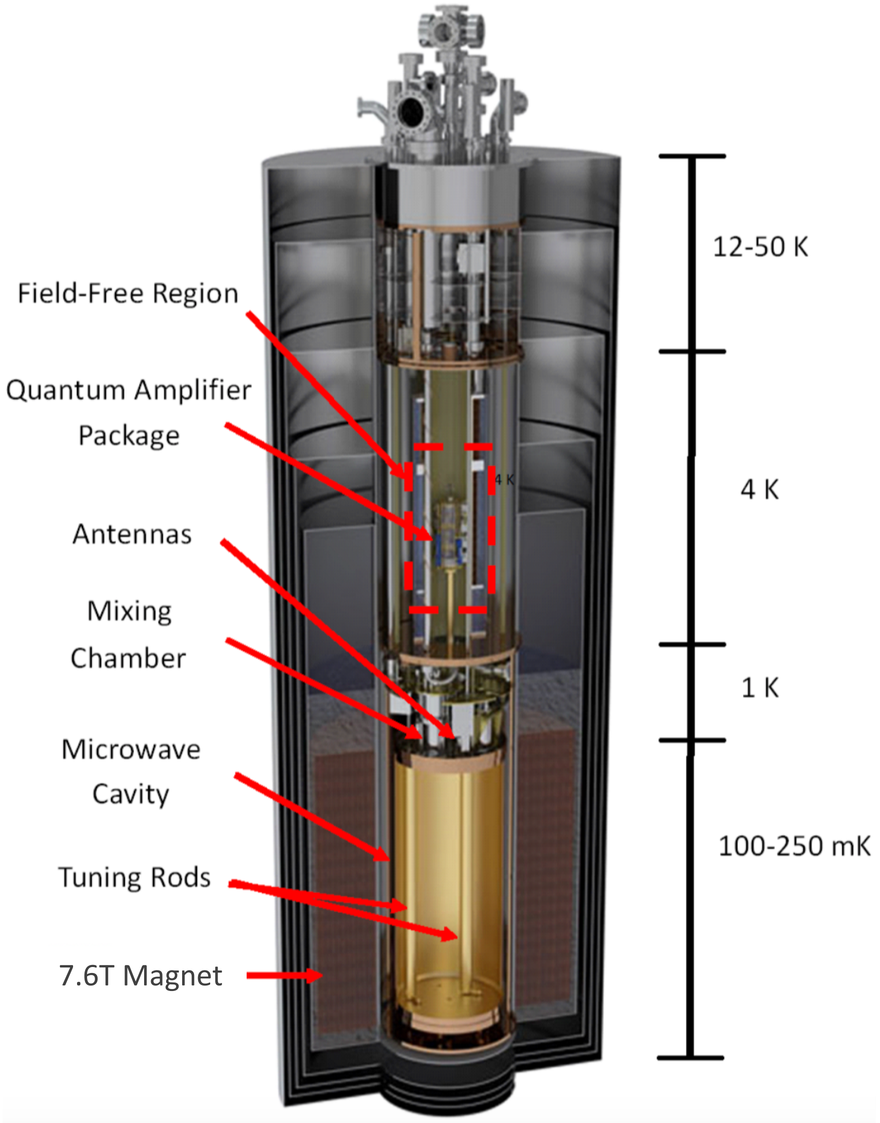
[P. Sikivie, PRL 51, 1415 (1983)]

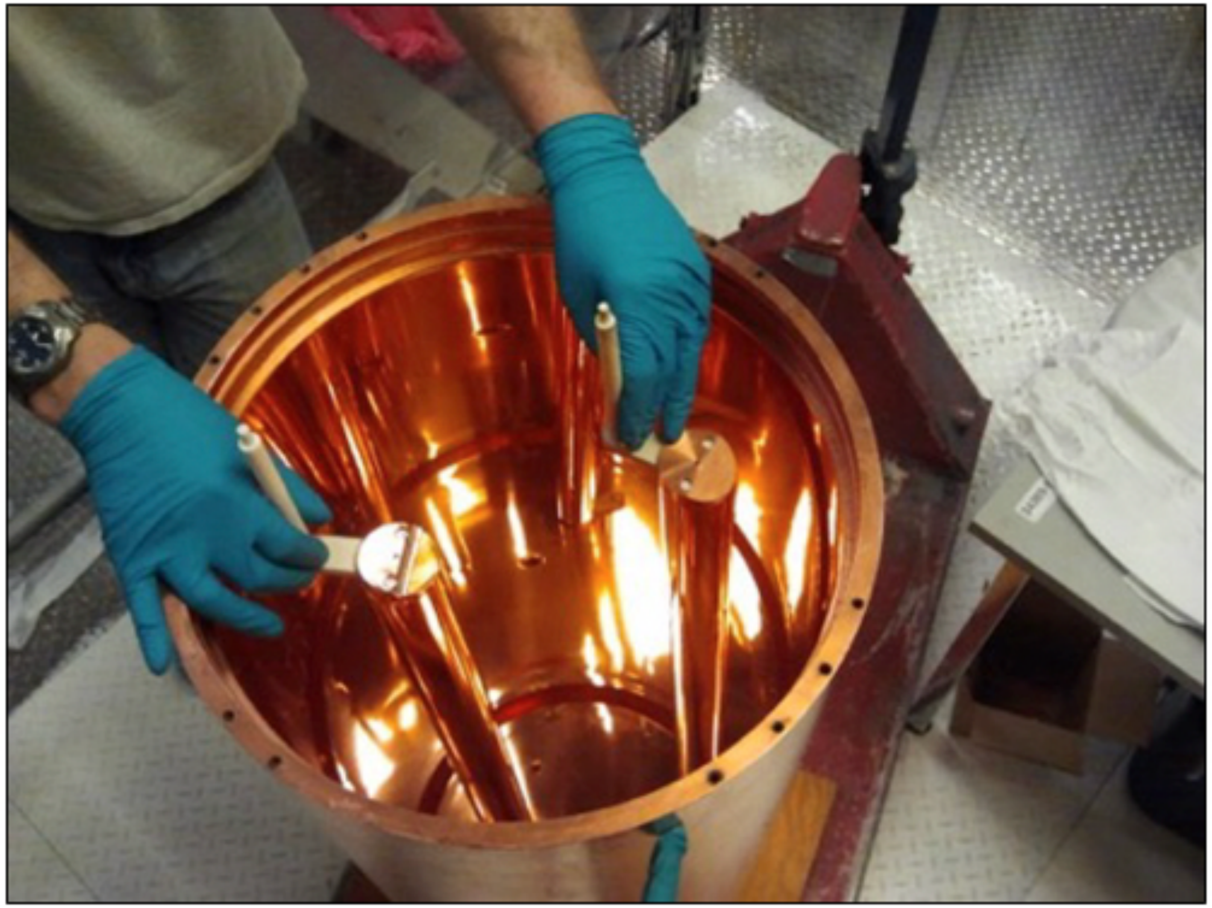





$$P_{\text{sig}} = 2 \cdot 10^{-23}\ \text{W} \cdot \left(\frac{B}{7.6\ \text{T}}\right)^2 \left(\frac{V}{136\ L}\right) \left(\frac{C}{0.4}\right) \left(\frac{Q}{30{,}000}\right) \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{m_a}{3\ \mu\text{eV}}\right) \left(\frac{\rho_{\text{DM}}}{0.45\ \text{GeV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

# ADMX: Axion Dark Matter eXperiment

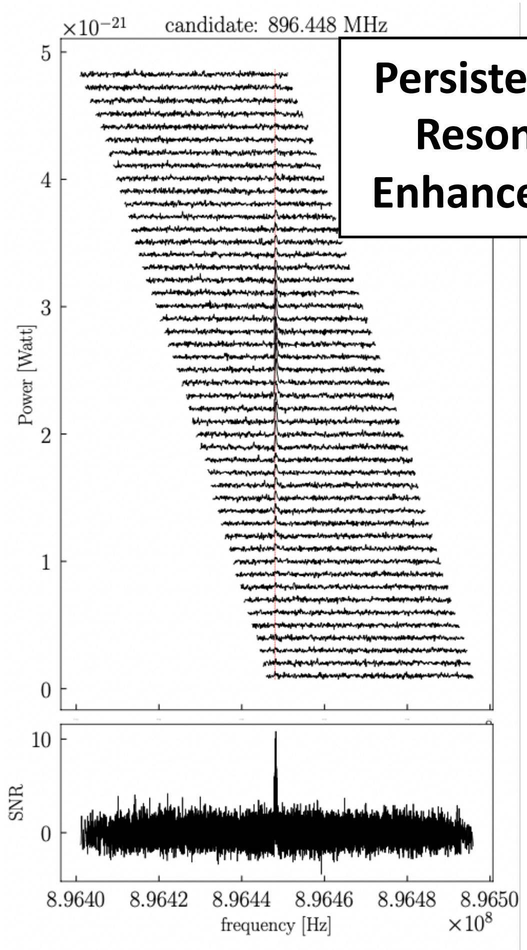


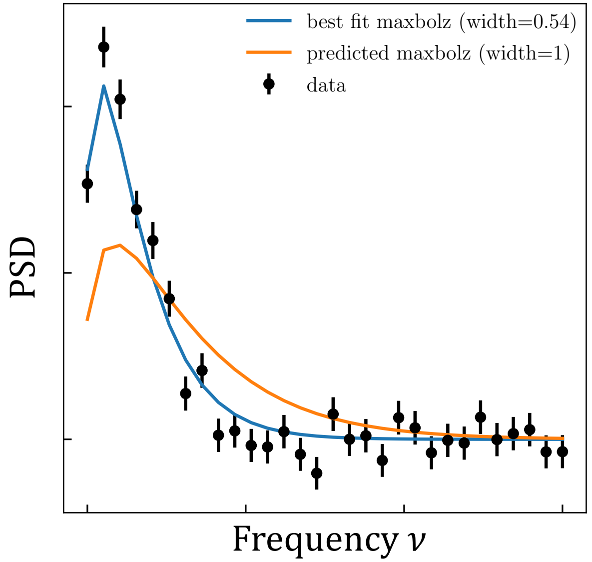
[T. Braine *et al* (ADMX collab.), PRL 124 (2020) 10, 101303]
[R. Khatiwada *et al* (ADMX collab.), RSI (accepted), arXiv:2010.00169]
[C. Bartram *et al* (ADMX collab.), PRD 103 (2021) 3, 032002]

# ADMX: Power of Candidate Exclusion Criteria

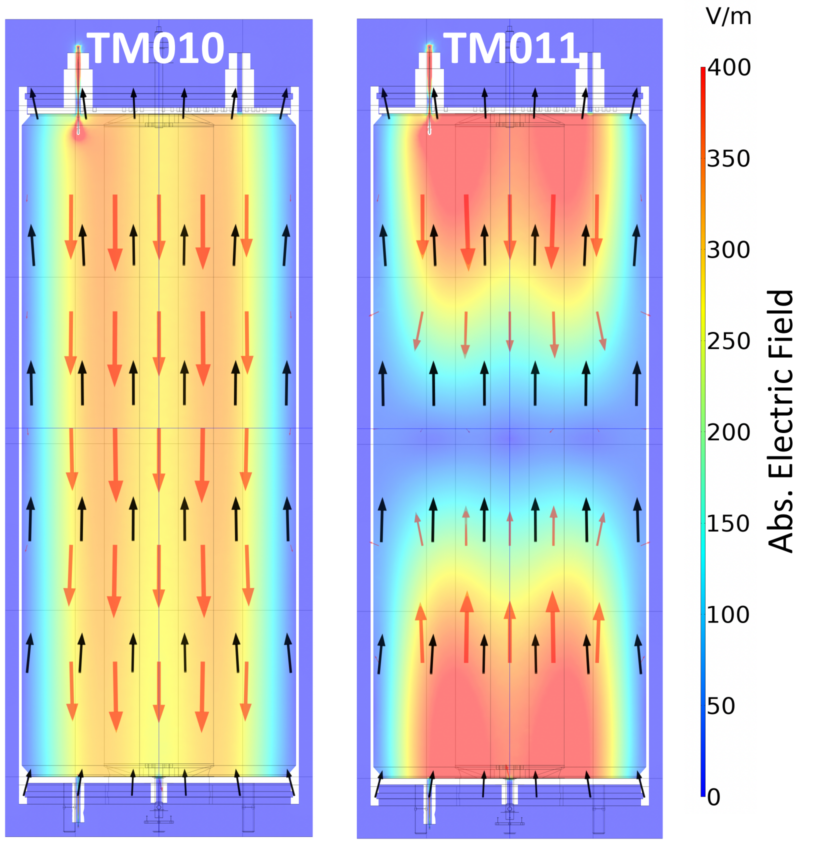
**Persistence & Resonant Enhancement**




**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**

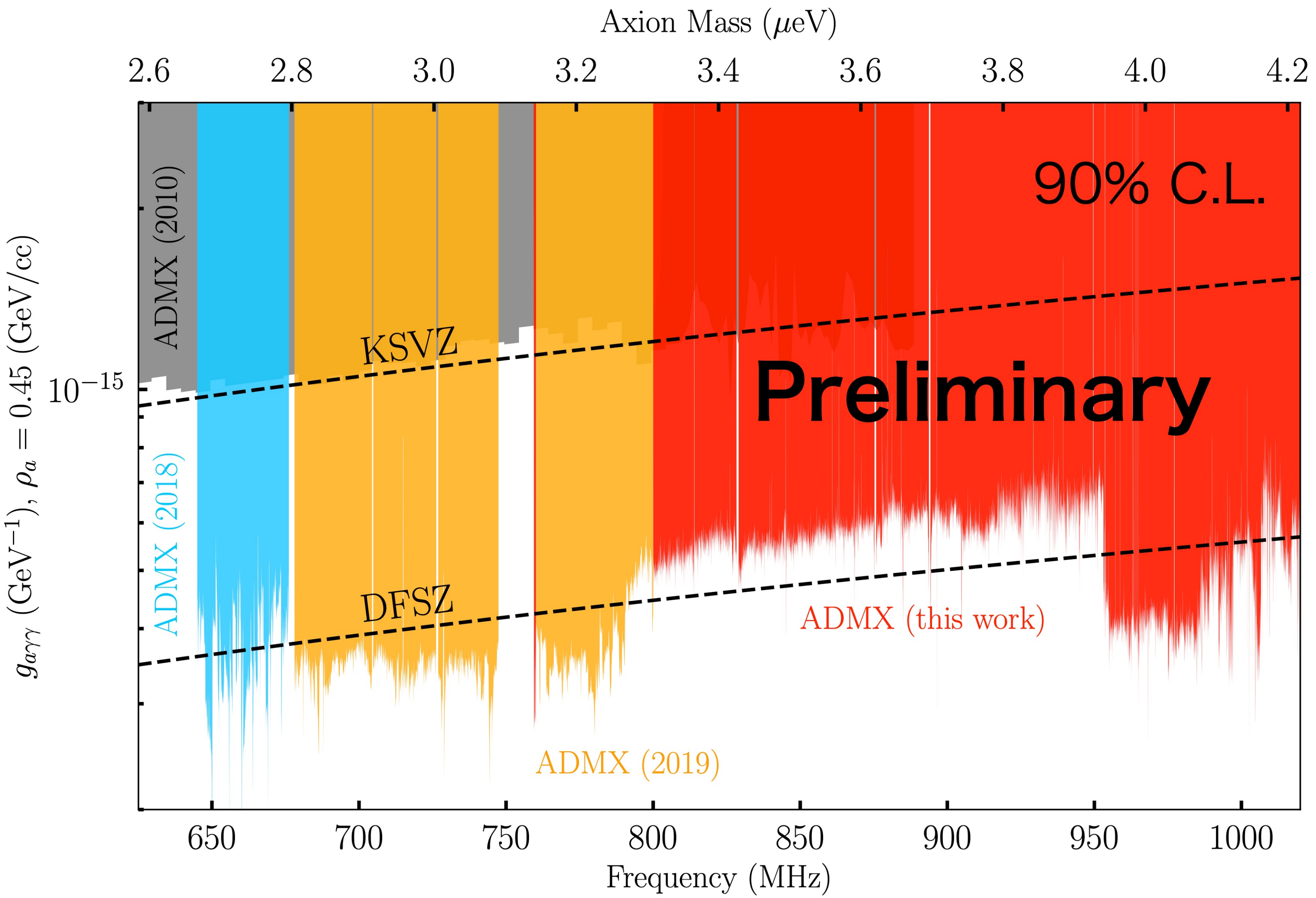
**Magnet Rampdown**
(last check, never happened for ADMX)

# ADMX Collaboration

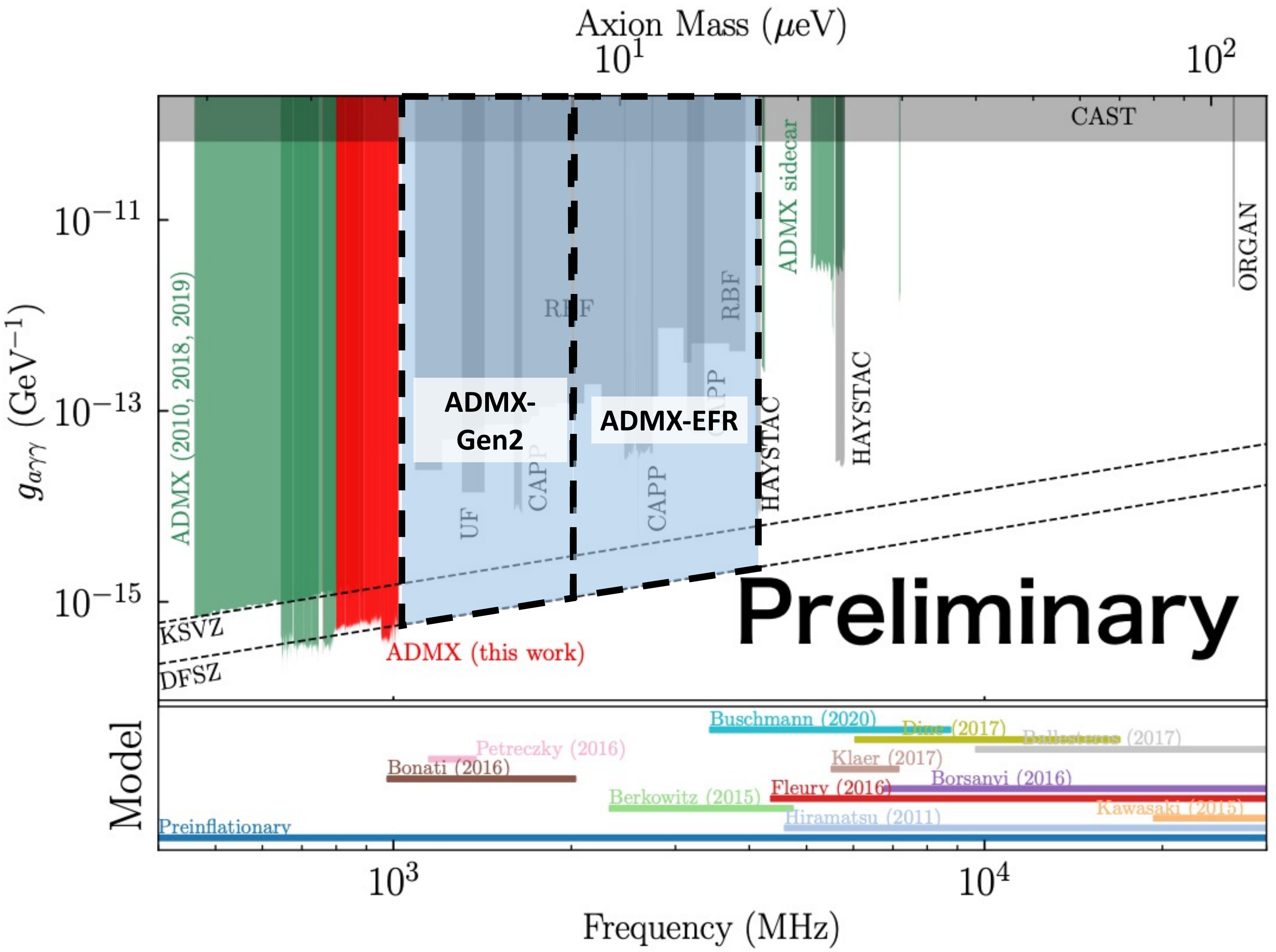

This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

# ADMX: Most Recent Results

[first presented at PATRAS2021]
[T. Nitta *et al.* (ADMX collab.), in prep.]



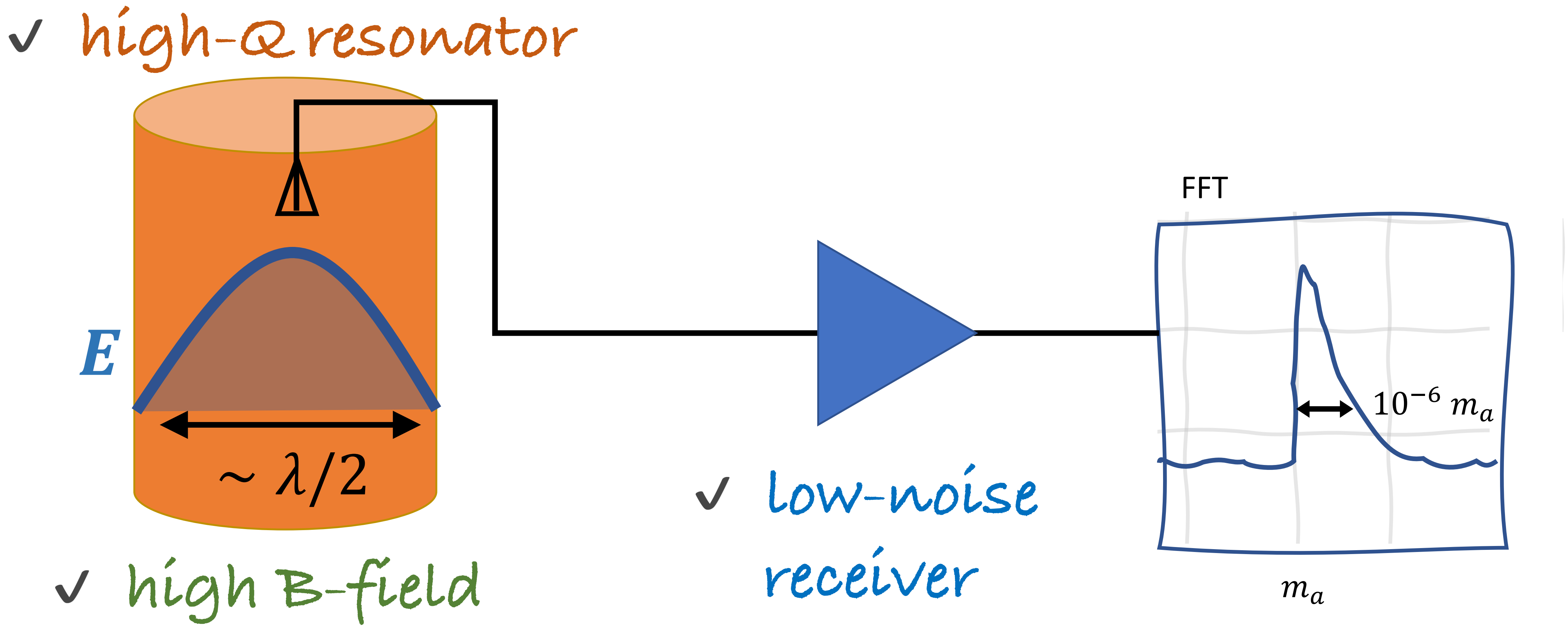
# Higher Mass Plans




*IBS/CAPP and others similar plans*

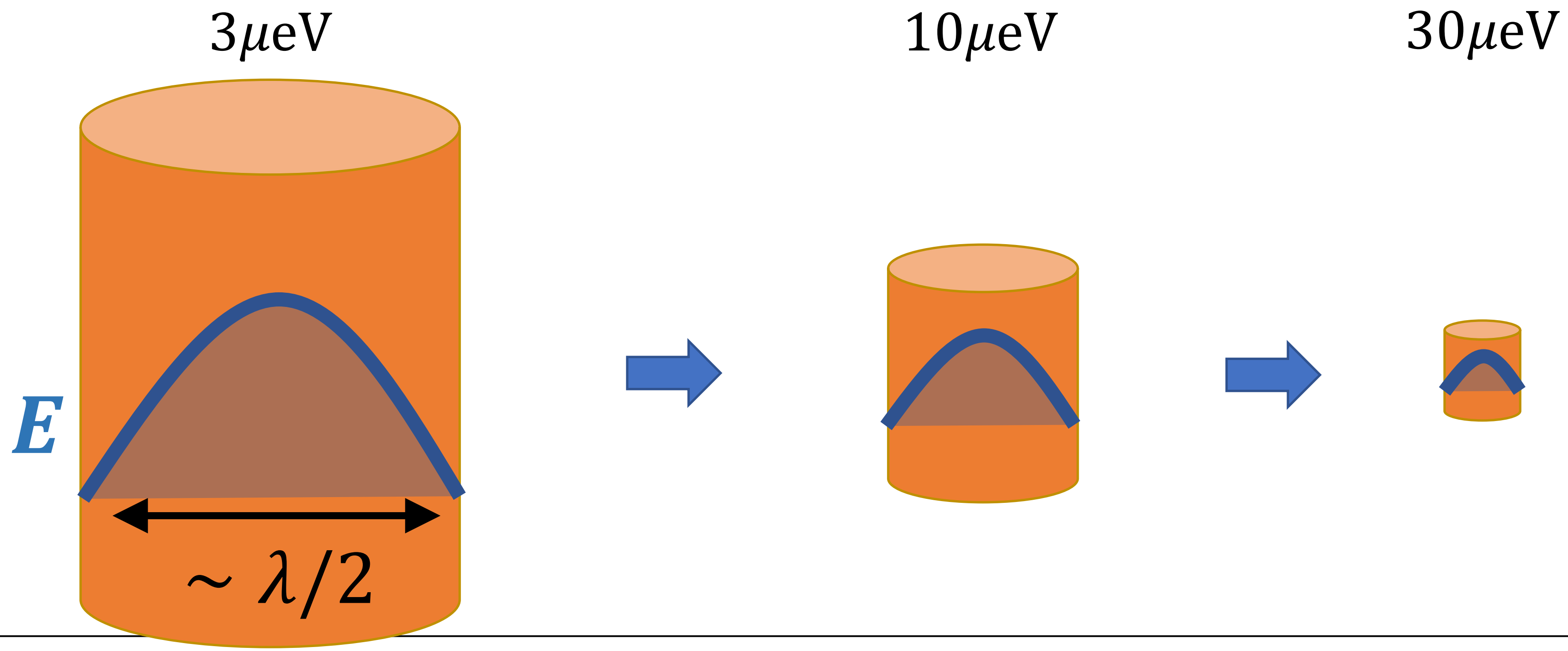
# The Resonant Cavity – High Masses

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




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

# The Resonant Cavity – High Masses

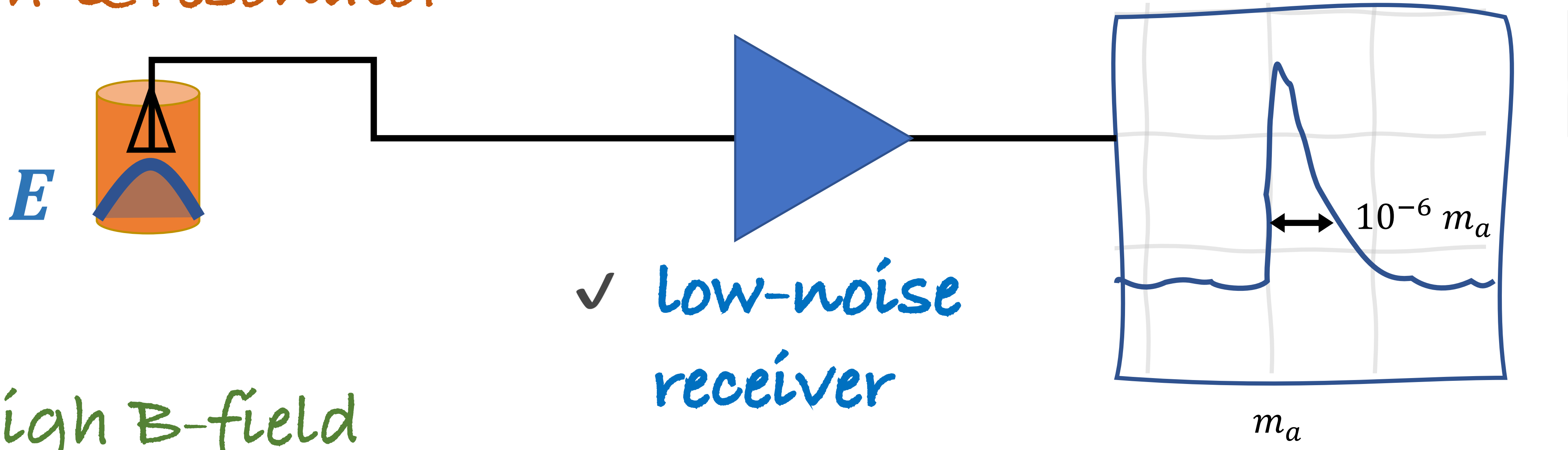



| | | | |
|---|---|---|---|
| $V$ | $100L$ | $3L$ | $0.1L$ |
| $Q \propto V/\delta V$ | 30,000 | 10,000 | 3,000 |

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

# High Mass Challenge – Lower Noise

✓ high-Q resonator




✓ low-noise receiver

Quantum Limit:

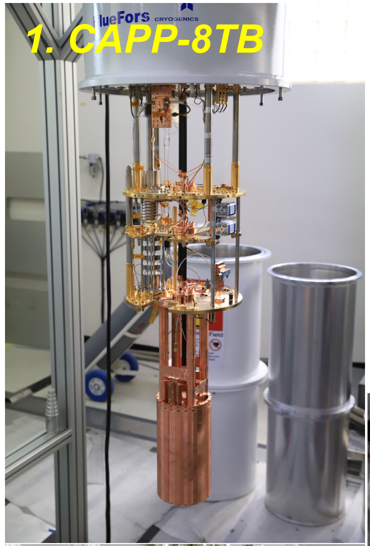
$$k_B T_{sys} = h\nu$$

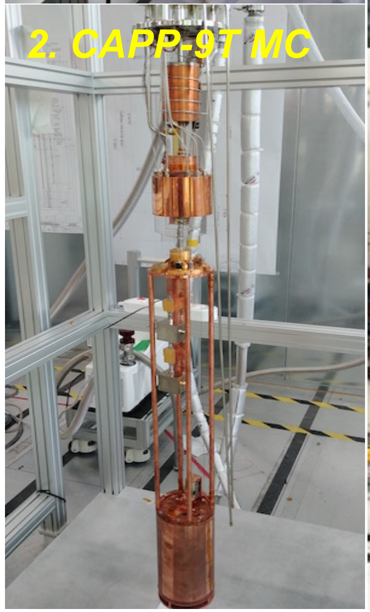
✓ high B-field

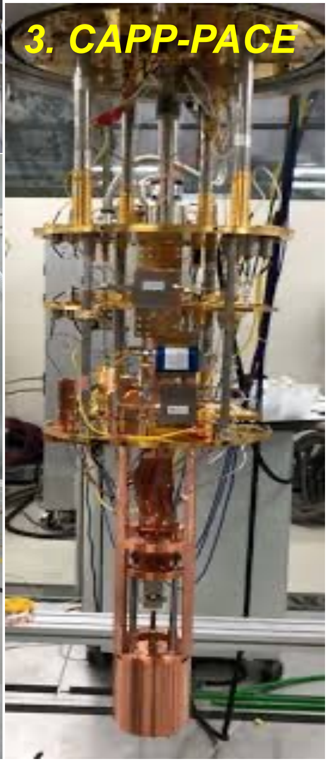
$$P_{\text{sig}} = 2 \cdot 10^{-23}\,\text{W} \cdot \left(\frac{B}{7.6\,\text{T}}\right)^2 \left(\frac{V}{136\,L}\right)\left(\frac{C}{0.4}\right)\left(\frac{Q}{30{,}000}\right)\left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{m_a}{3\,\mu\text{eV}}\right)\left(\frac{\rho_{\text{DM}}}{0.45\,\text{GeV cm}^{-3}}\right)$$

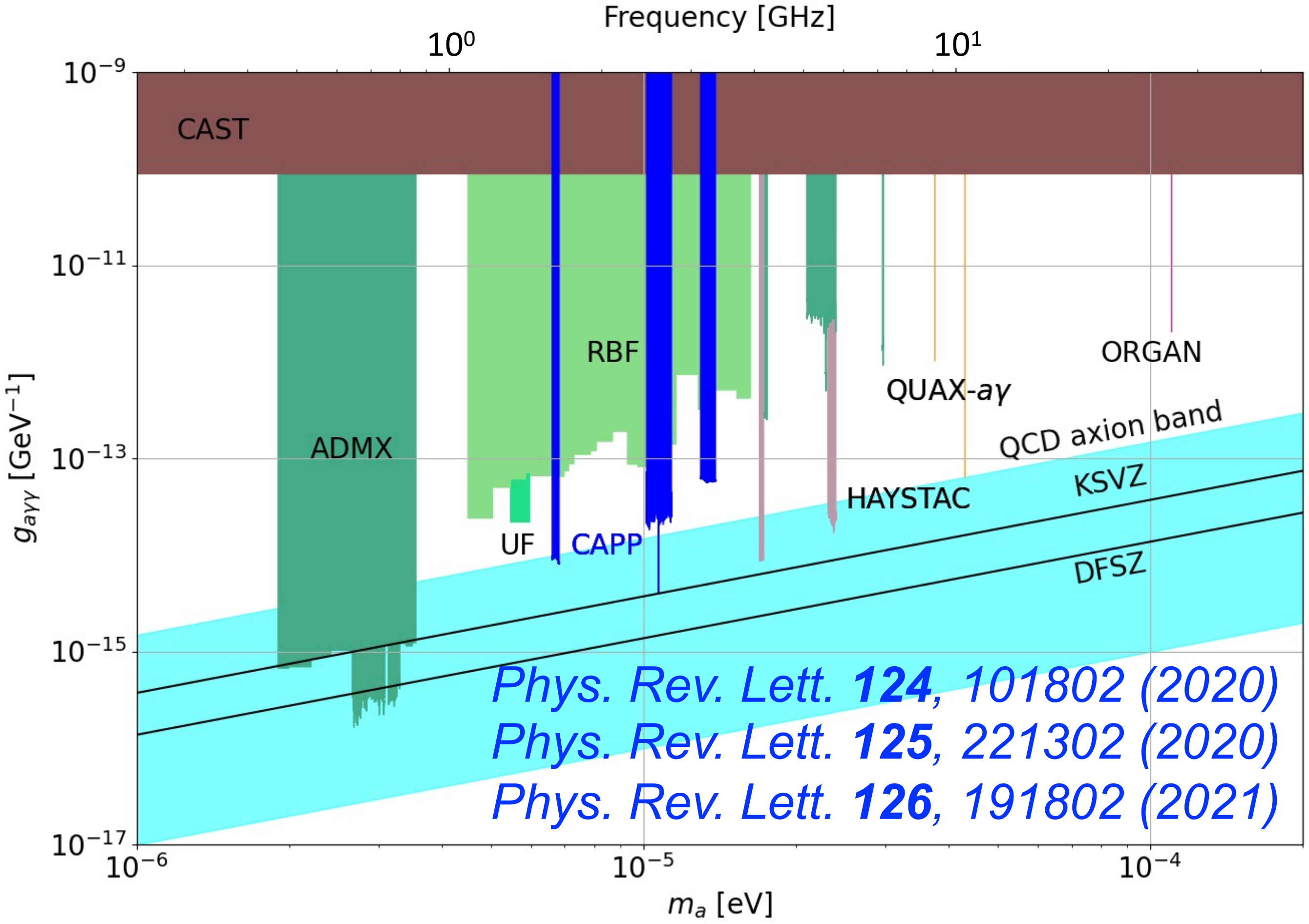
# IBS/CAPP Searches

**[based on slide from SungWoo YOUN, PATRAS2021]**




*Phys. Rev. Lett.* ***124***, *101802 (2020)*
*Phys. Rev. Lett.* ***125***, *221302 (2020)*
*Phys. Rev. Lett.* ***126***, *191802 (2021)*

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

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

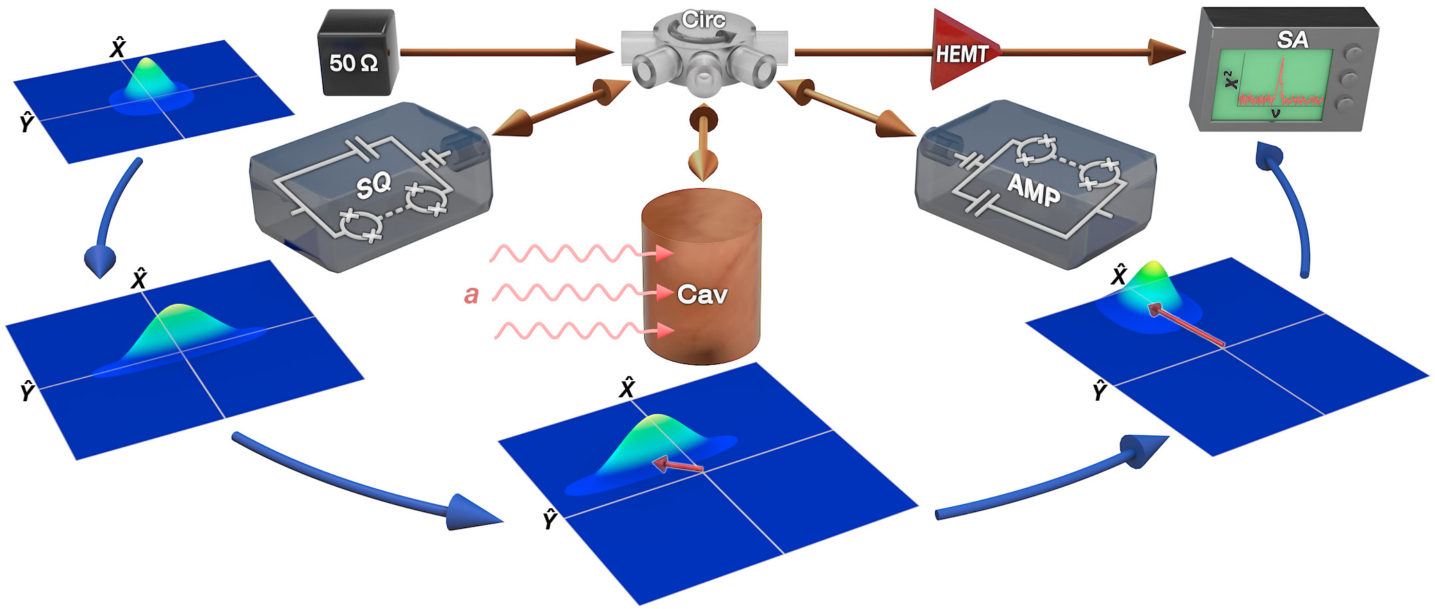
***2. CAPP-9T MC***
- *9T/127mm*
- *$T_{phy}$ ~ 2 K*
- *HEMT ~ 1.5 K*
- *> 3 GHz*
- *Pizza cavity*

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

# HAYSTAC: Haloscope At Yale Sensitive To Axion CDM

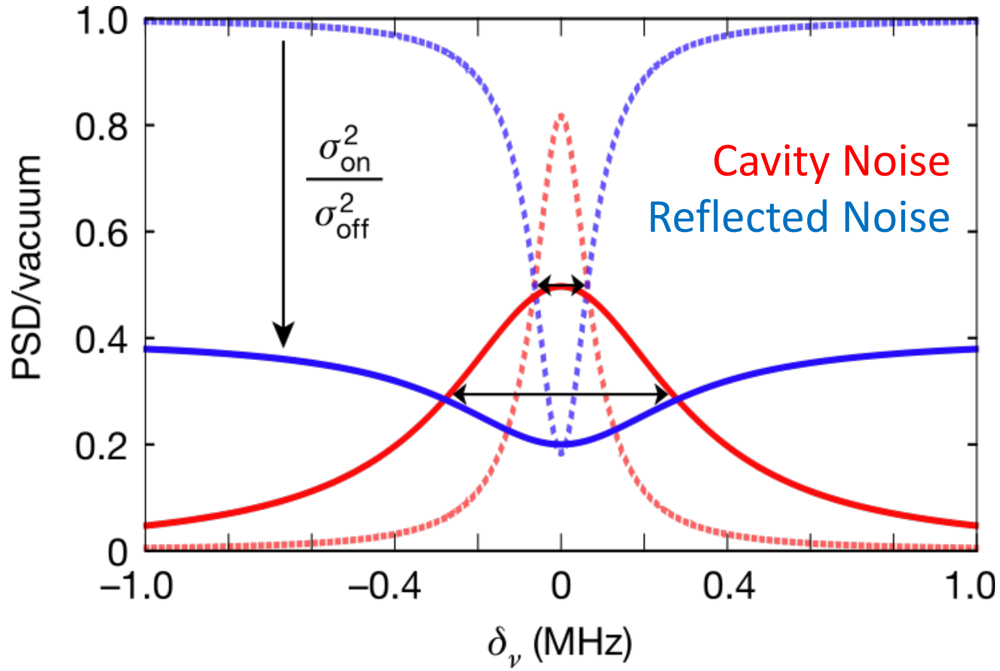
[Backes et al., Nature 590, 238–242 (2021)]

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




**Squeezing of Reflected Noise**

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

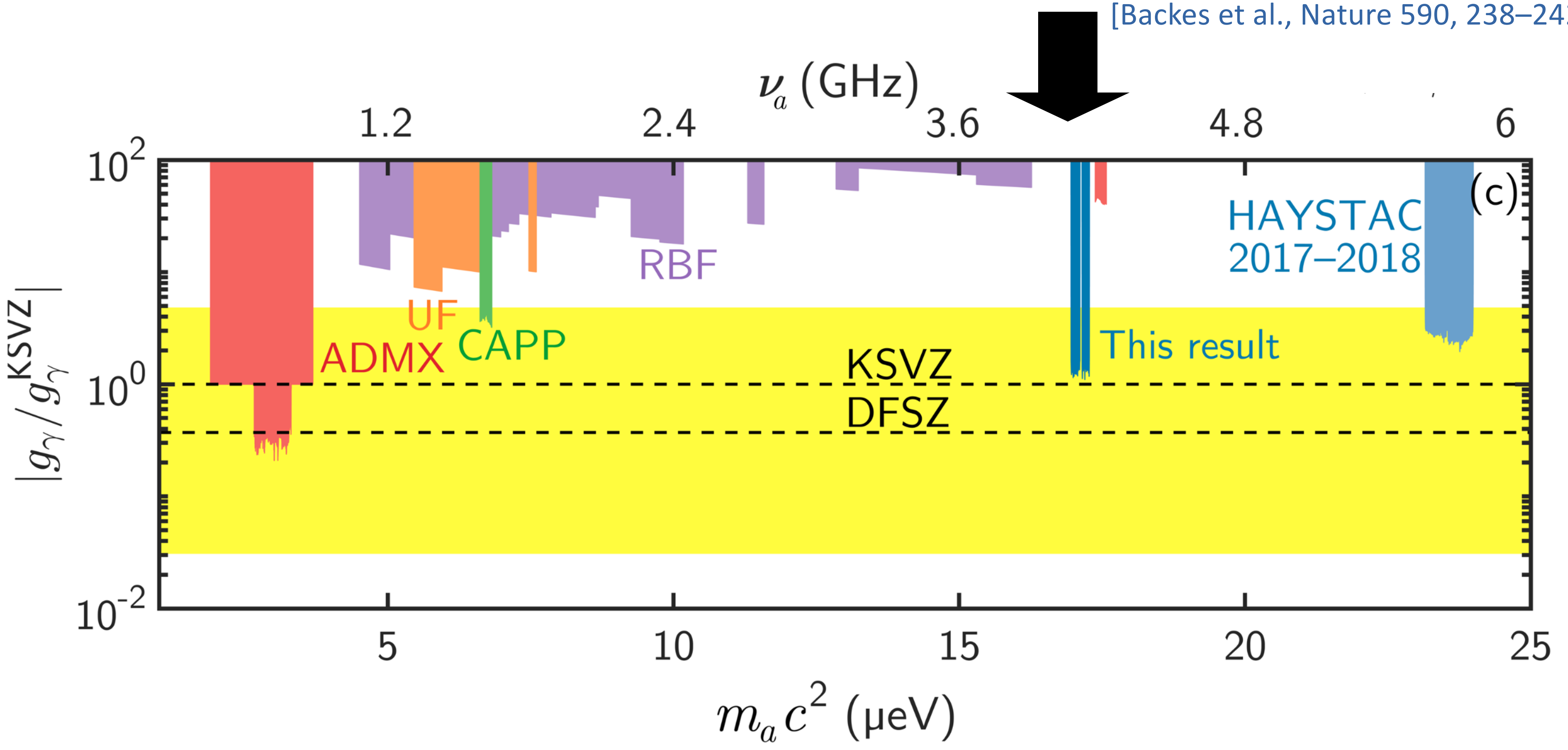



bandwidth increase
→ **double scan rate**

# HAYSTAC: First μeV Sub-Quantum Axion Search

HAYSTAC

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




Advanced Proposal using Cavity-State Swapping: CEASEFIRE [K. Wurtz *et al.*, arXiv:2107.04147]

# Single Photon Detection

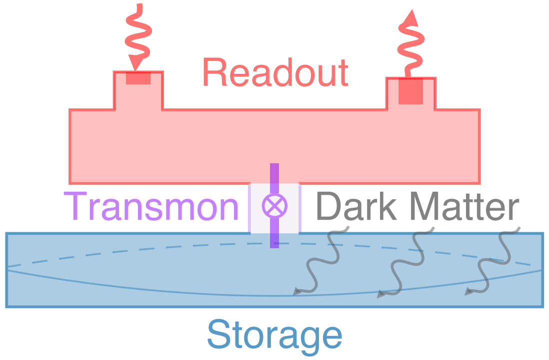
**Non-Destructive Qubit Readout:** [A. V. Dixit *et al*, PRL 126, 141302]

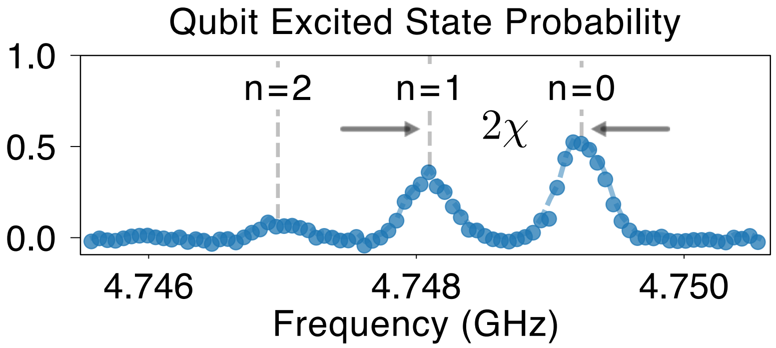
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

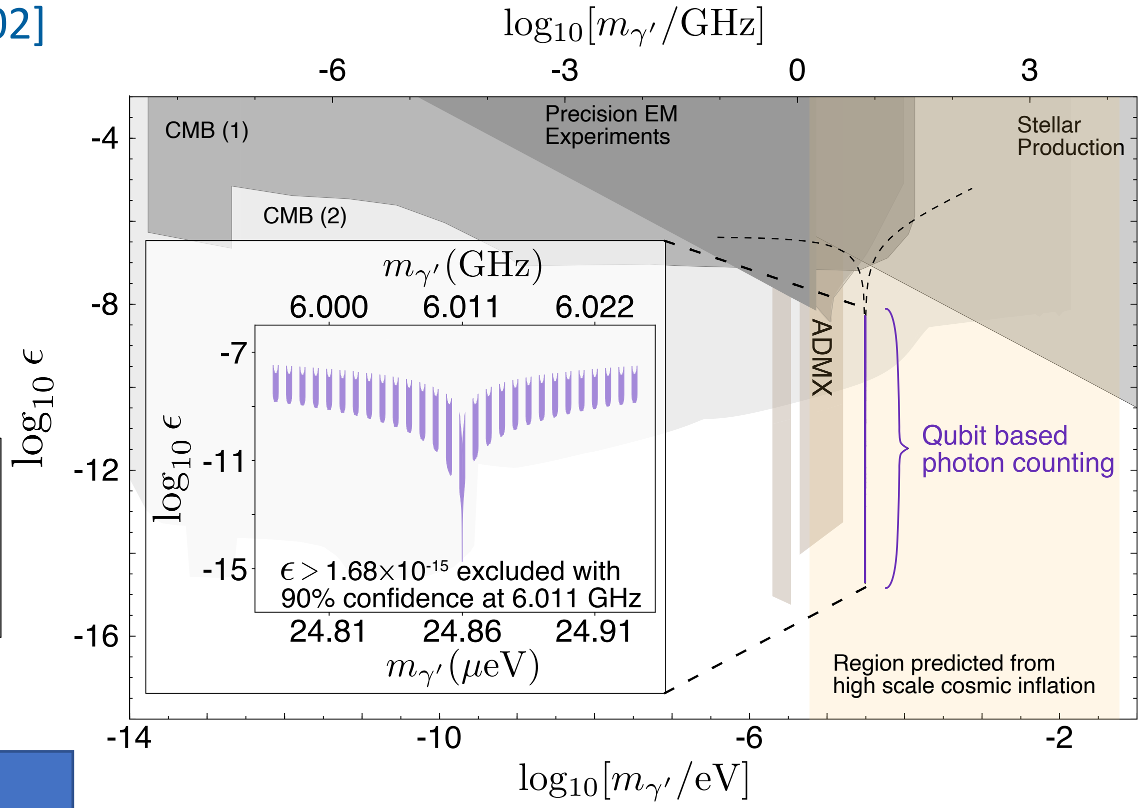
cavity

Qubit

Interaction (commutes with cavity/Qubit!)



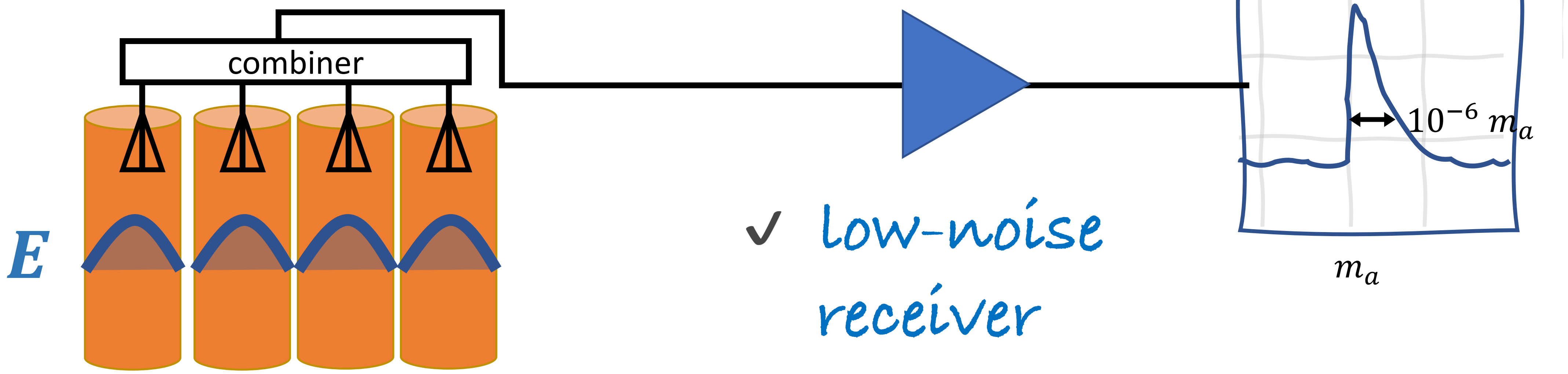

**15.7 dB** advantage over SQL

**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 – Combine Signals

✓ high-Q resonators

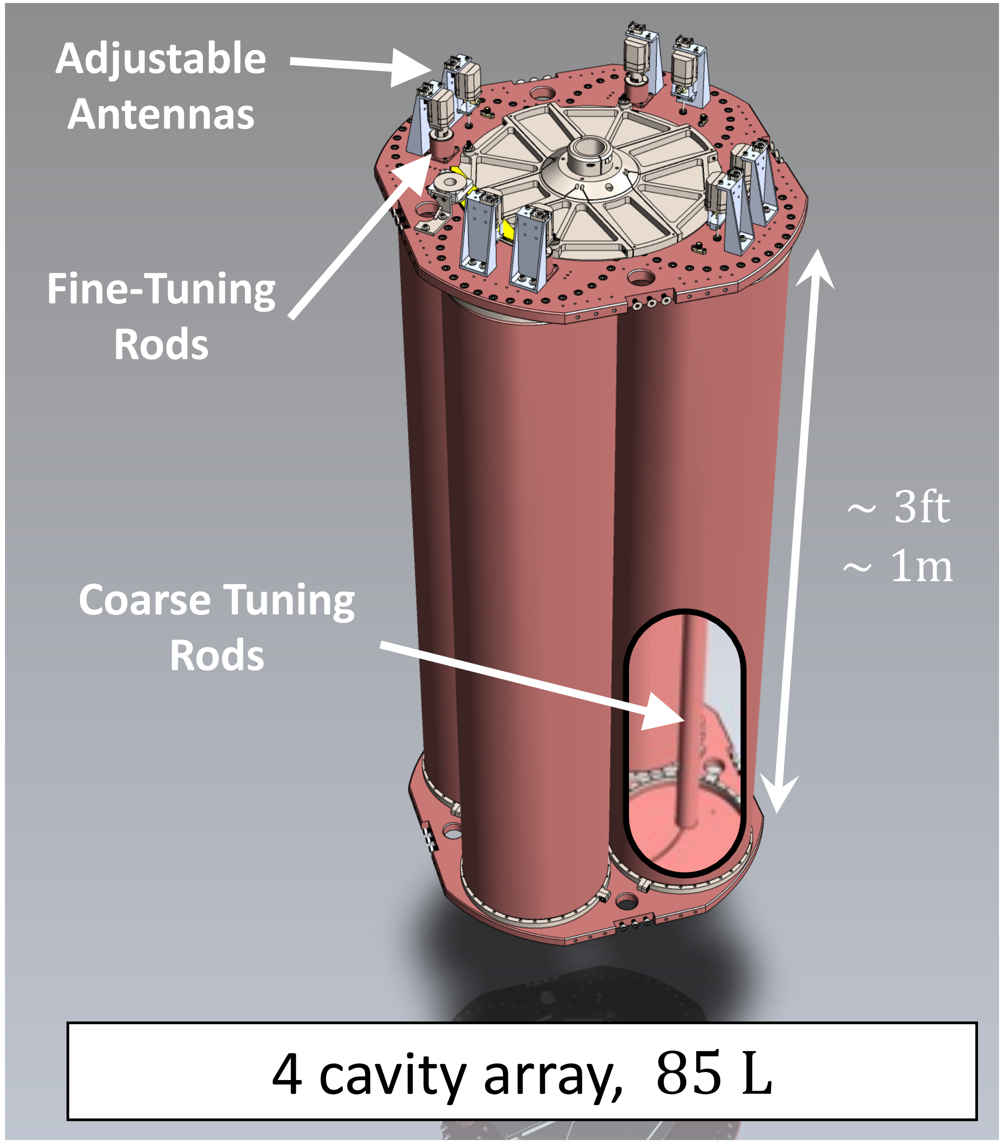



✓ low-noise receiver

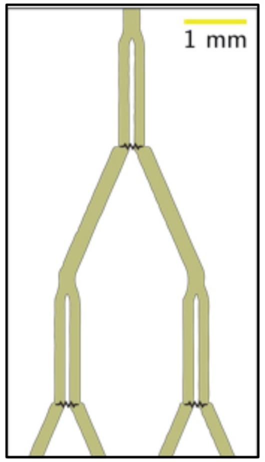
✓ high B-field

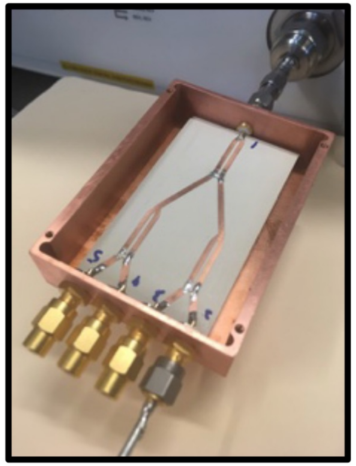
$$P_{\text{sig}} = 2\cdot 10^{-23}\ \text{W}\cdot\left(\frac{B}{7.6\ \text{T}}\right)^2\left(\frac{V}{136\ L}\right)\left(\frac{C}{0.4}\right)\left(\frac{Q}{30{,}000}\right)\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{m_a}{3\ \mu\text{eV}}\right)\left(\frac{\rho_{\text{DM}}}{0.45\ \text{GeV cm}^{-3}}\right)$$

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




4 cavity array, 85 L



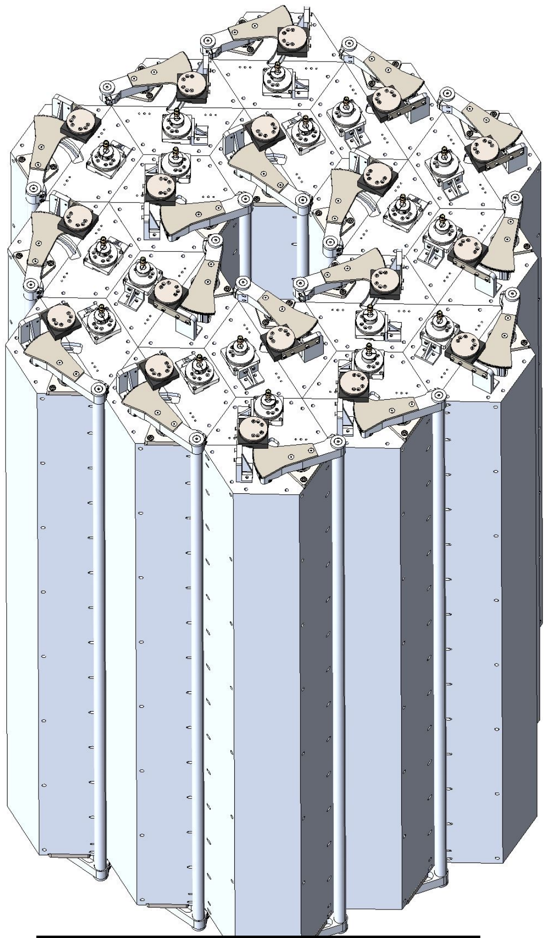



analog power combining

Site: Univ. Washington

Data Taking from 2023

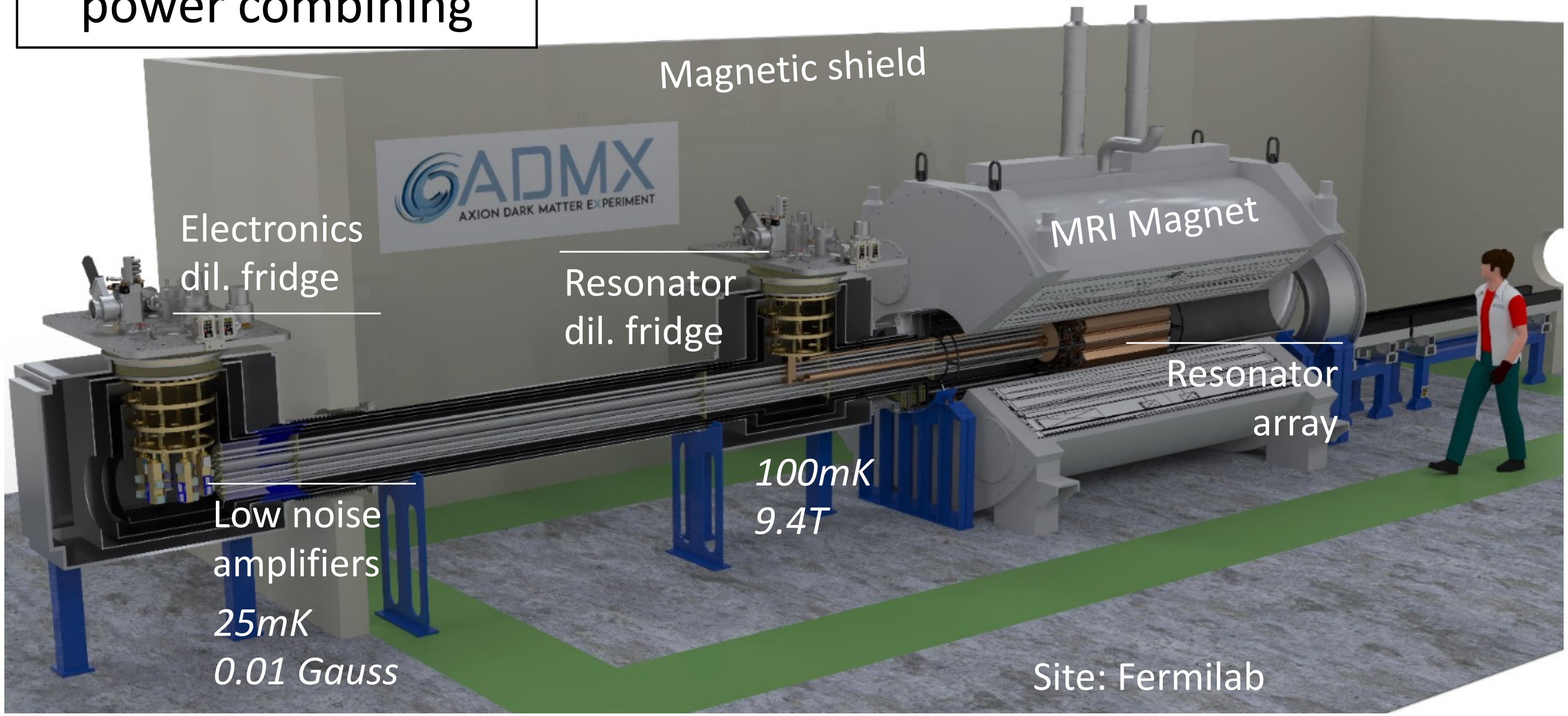
# ADMX-EFR (Extended Frequency Range): 2-4GHz



18 cavity array

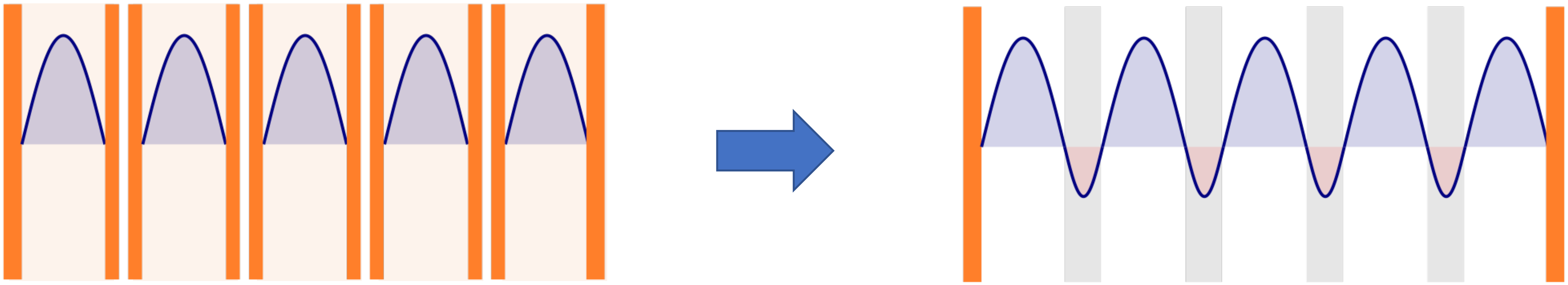
digital power combining

horizontal magnet: 9.4 T, 258 L

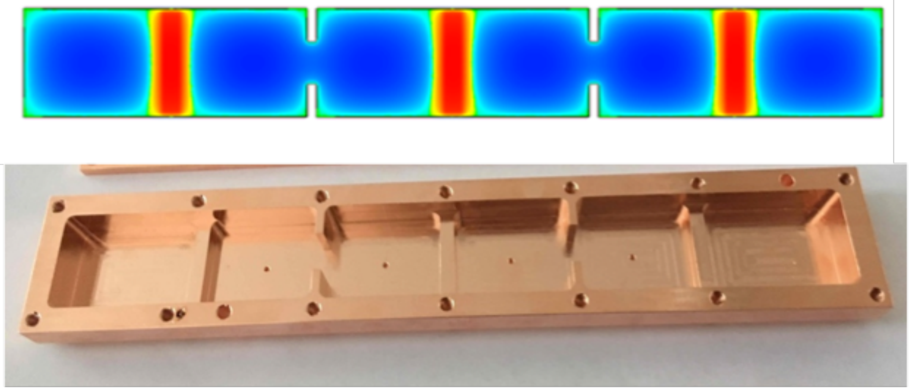



~ 10 × scan speed of current ADMX

# Other Multi-Cavity Searches



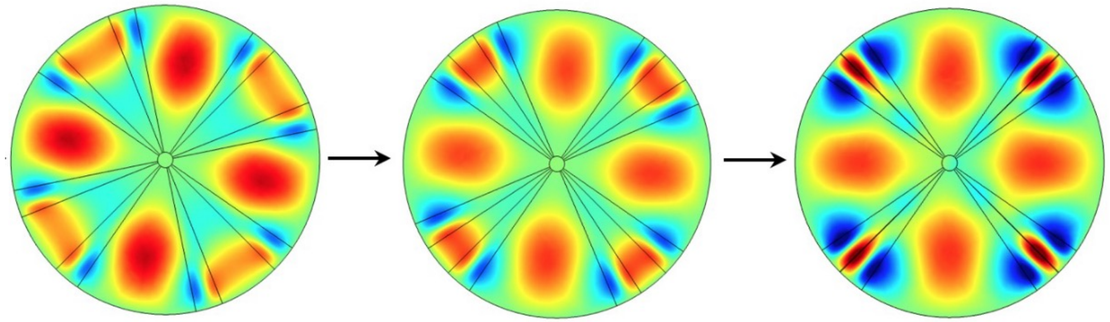
**RADES**



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

**QUAX-a$\gamma$:**
[D. Alesini, Nuc. Inst. and Meth. in Phys. Res. A, 985, 2021]

**Pizza / Wedge Cavities**

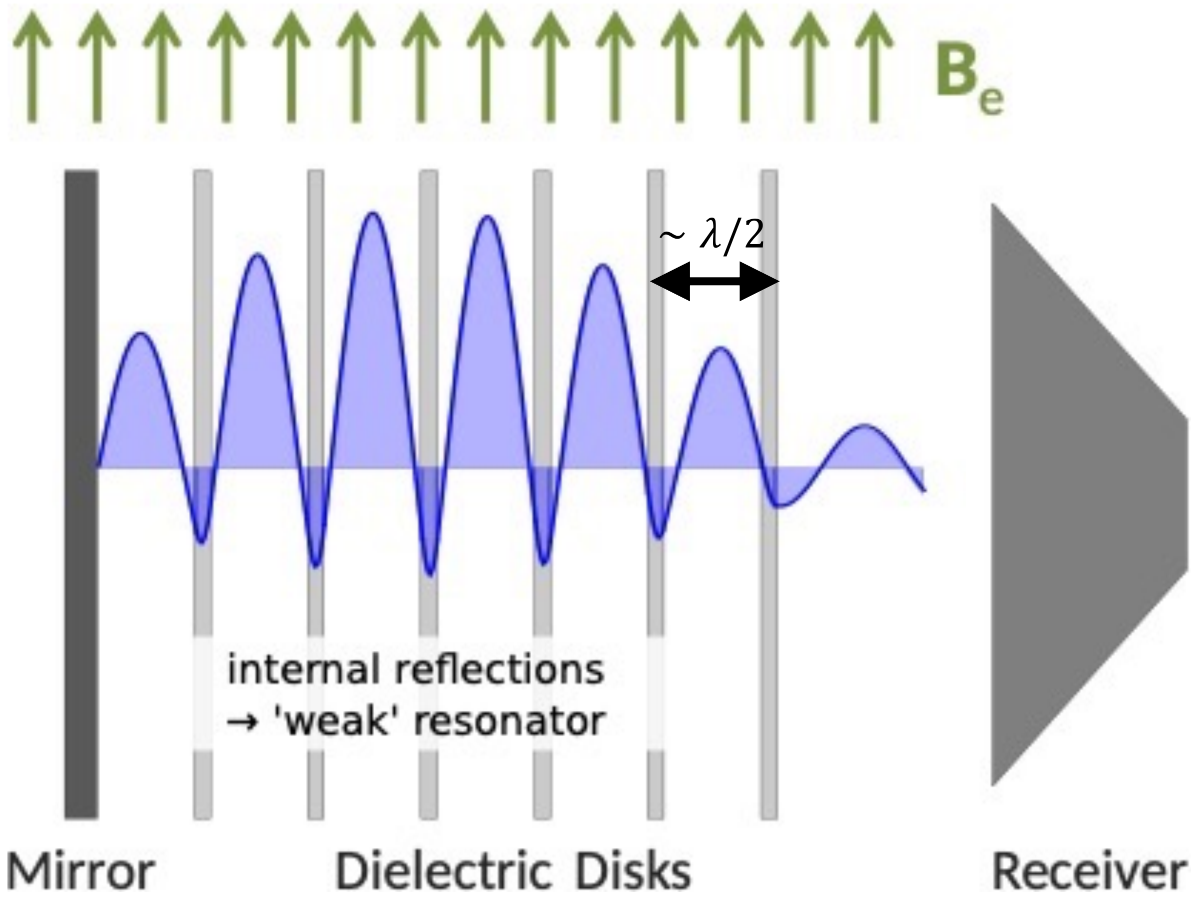


**ORGAN:** [Quiskamp *et al.*, Phys. Rev. Applied 14 (2020) 4]
[McAllister *et al.*, Springer Proc. Phys.245 (2020) 37-43]

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

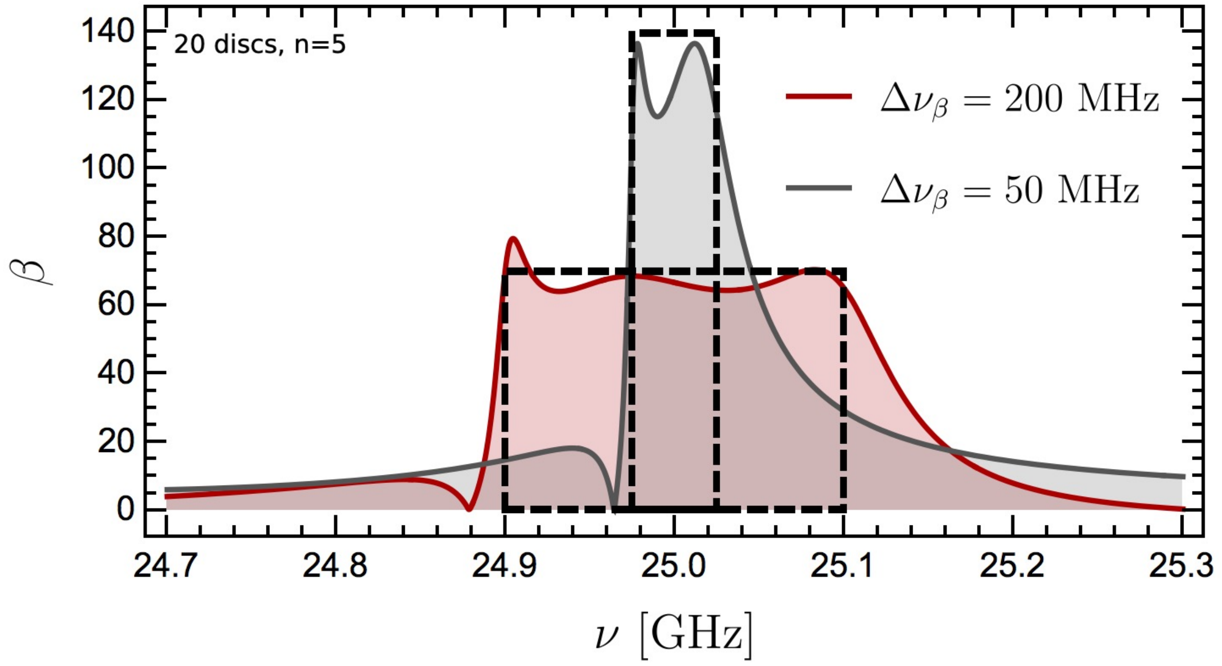
# Open Resonators: Dielectric Haloscope

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




**Power ∝ Boost Factor $\beta^2$**

tunable via disk positions




**ORPHEUS** (15-18GHz)
[Cervantes *et al.*, Springer Proc.Phys. 245 (2020) 169-175]

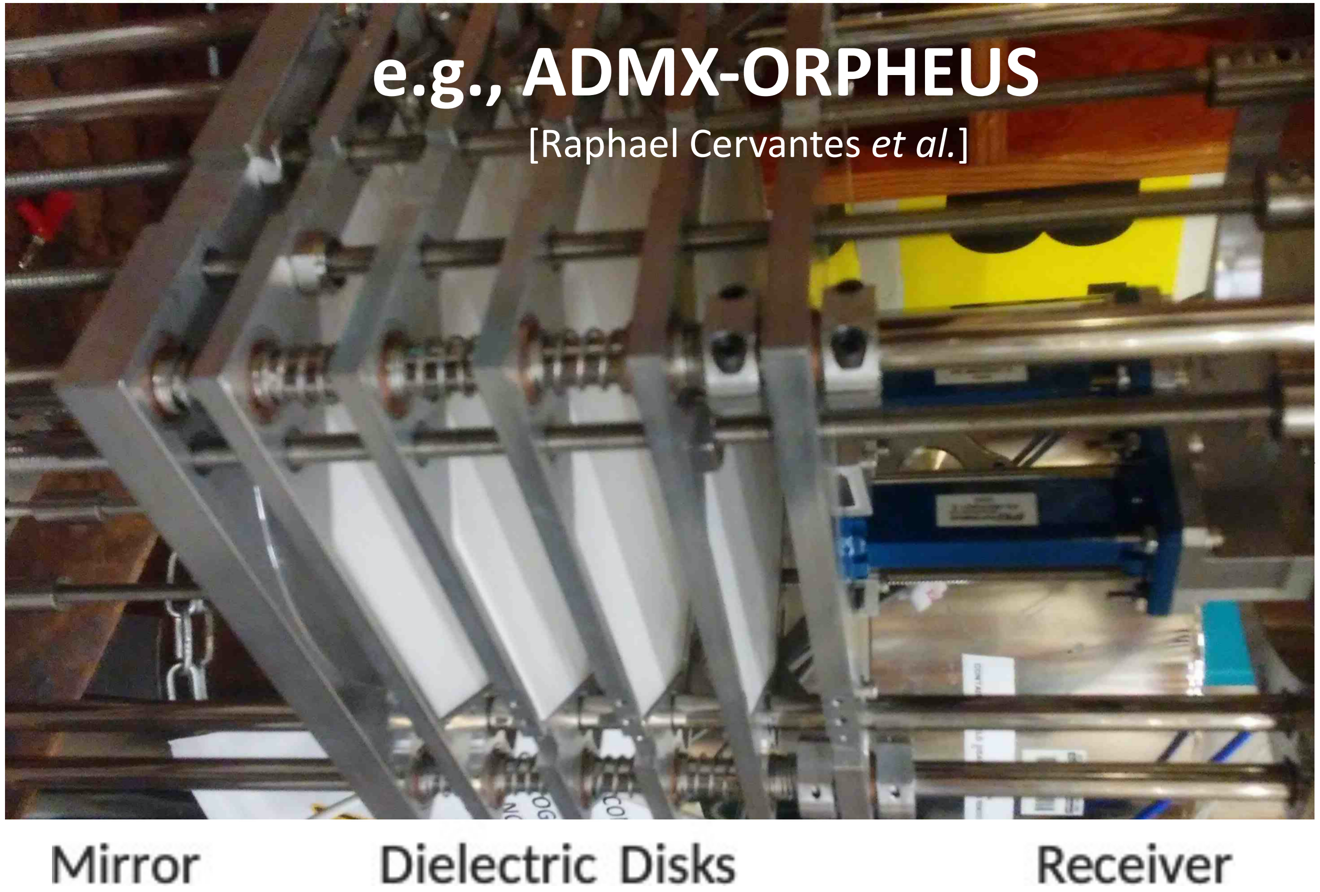
**MADMAX** (10-100GHz)
[P. Brun *et al.*, Eur. Phys. J. C (2019) 79: 186]

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

**LAMPOST** (optical)
[M. Baryakhtar *et al.*, PRD 98 (2018) 3]

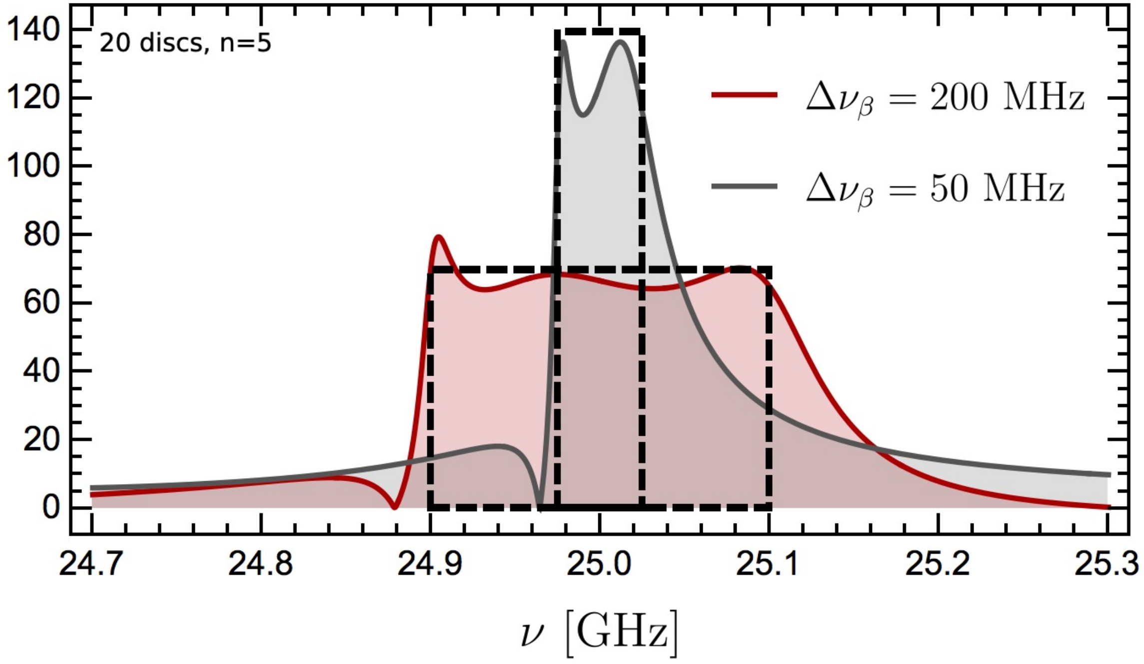
# Open Resonators: Dielectric Haloscope

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




**Power ∝ Boost Factor $\beta^2$**

tunable via disk positions

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[Cervantes *et al.*, Springer Proc.Phys. 245 (2020) 169-175]

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[P. Brun *et al.*, Eur. Phys. J. C (2019) 79: 186]

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

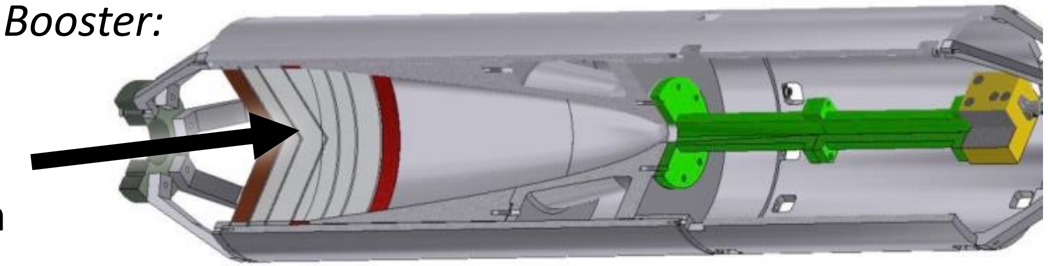
**LAMPOST** (optical)
[M. Baryakhtar *et al.*, PRD 98 (2018) 3]

# MADMAX: MAgnetized Disk and Mirror Axion eXperiment

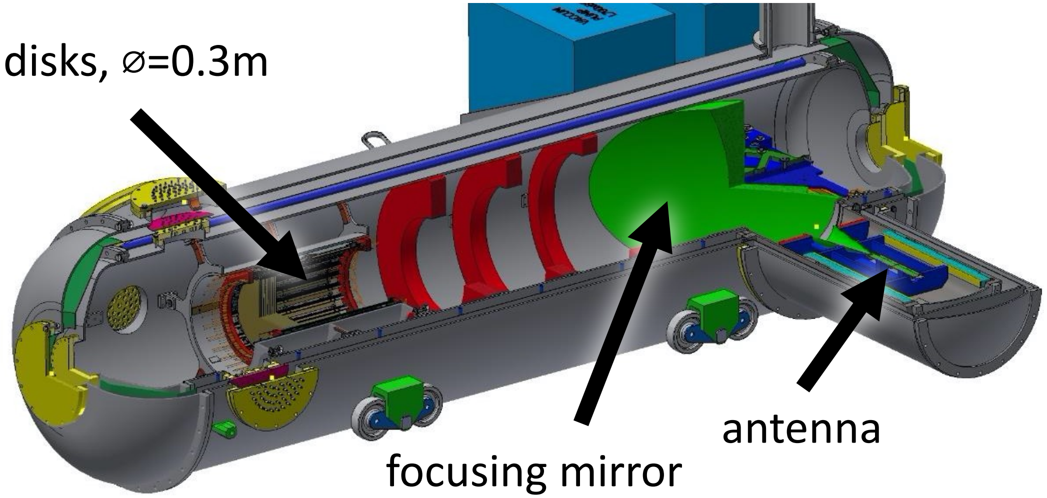
### Proof-of-Principle R&D

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

*Closed Booster:*

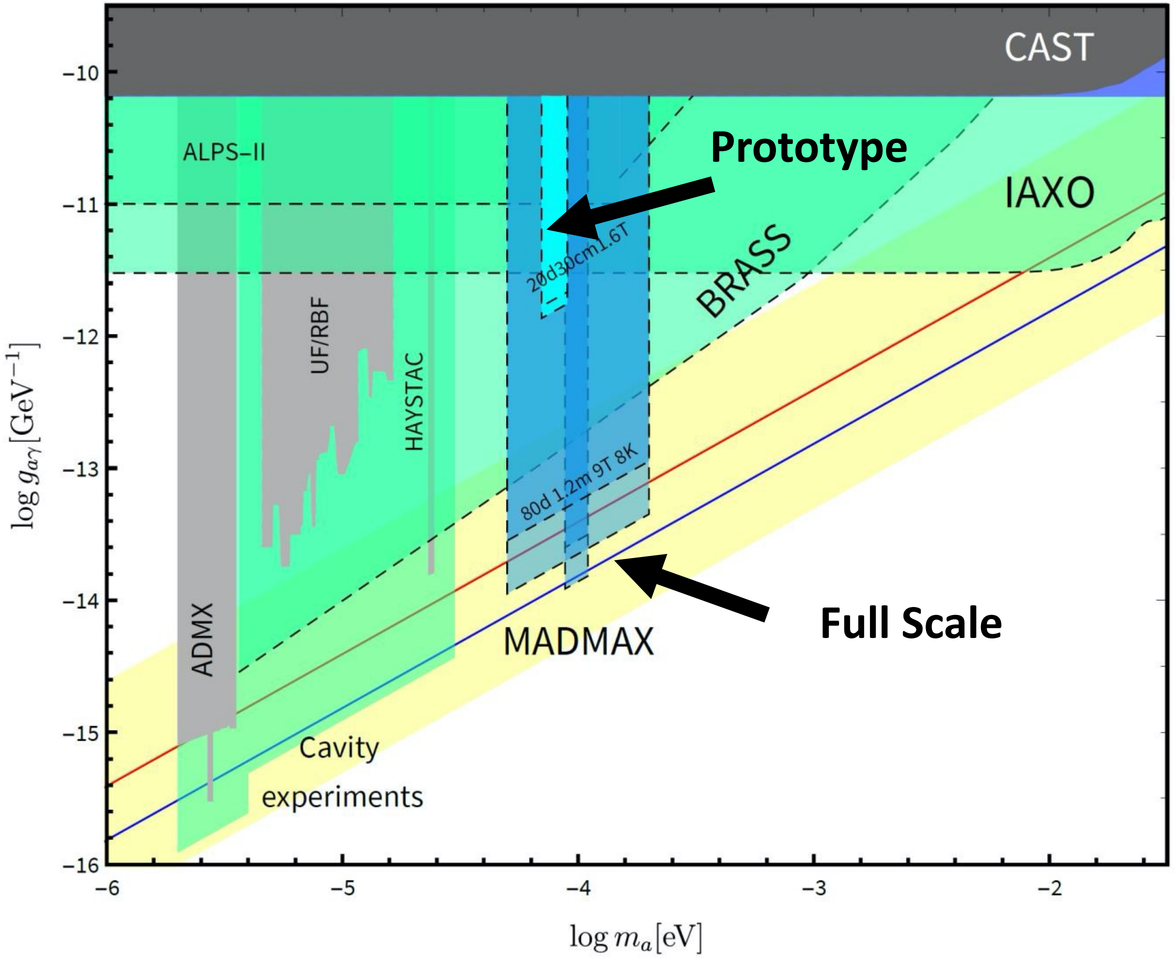



### Prototype @ CERN MORPURGO (1.6T)




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

### Projected Sensitivities



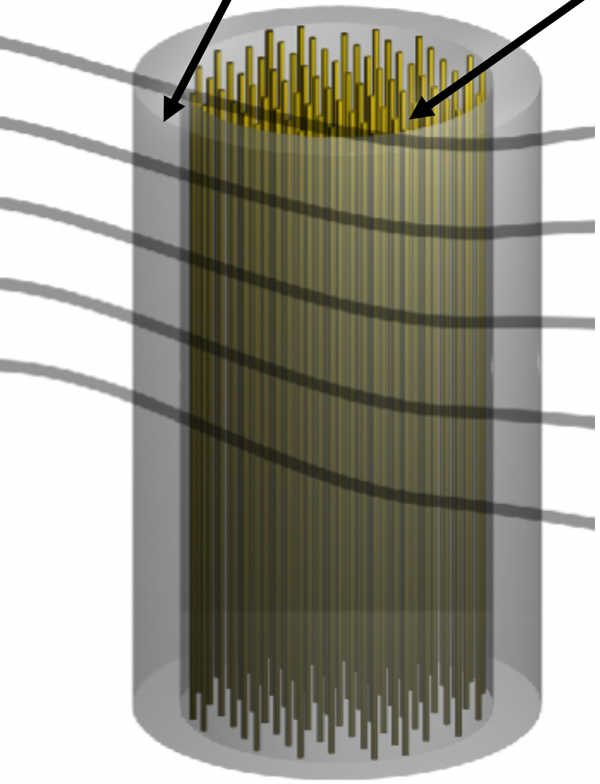

[S. Beurthey *et al.*, arXiv:2003.10894]

# ALPHA: Axion Longitudinal Plasma HAloscope

alpha

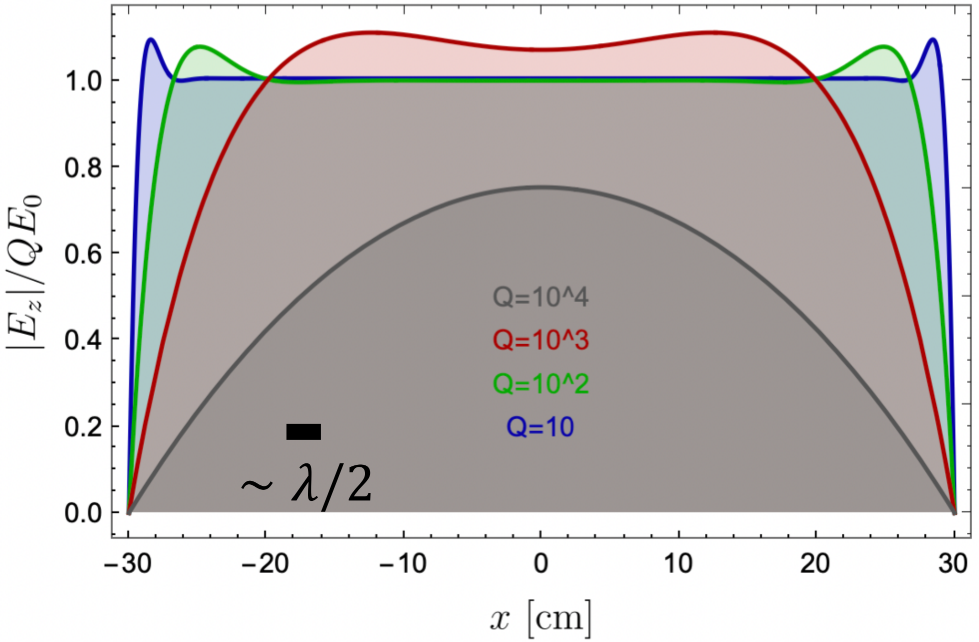
**Solenoid Magnet**

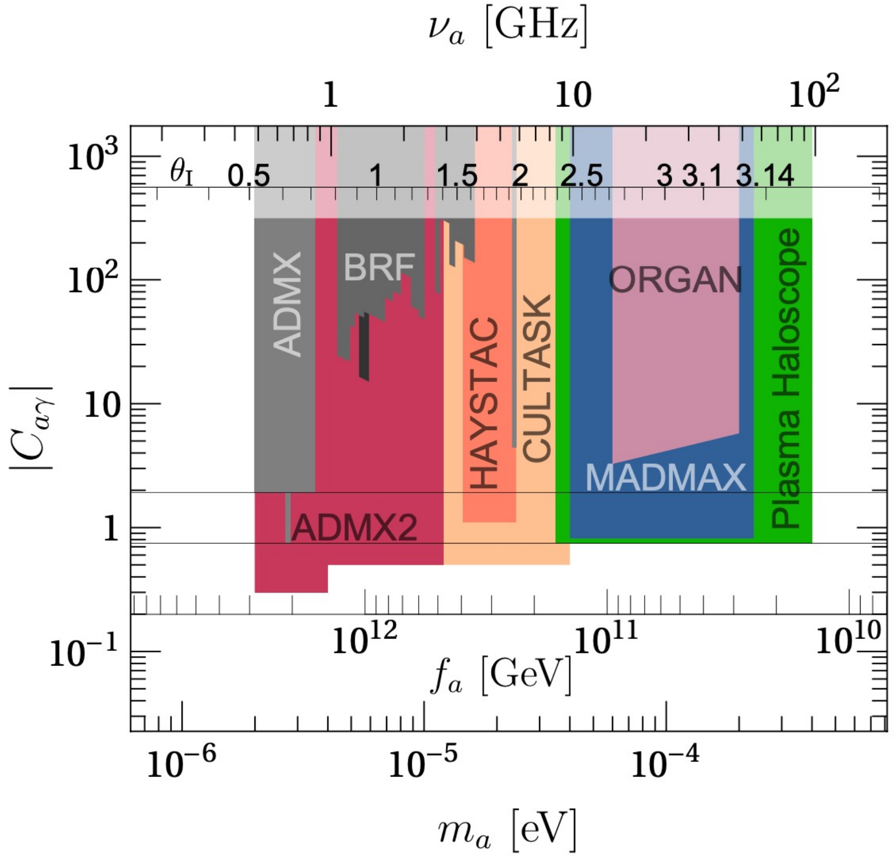
**Wire Metamaterial**



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

**Coherent Plasmon Modes:**



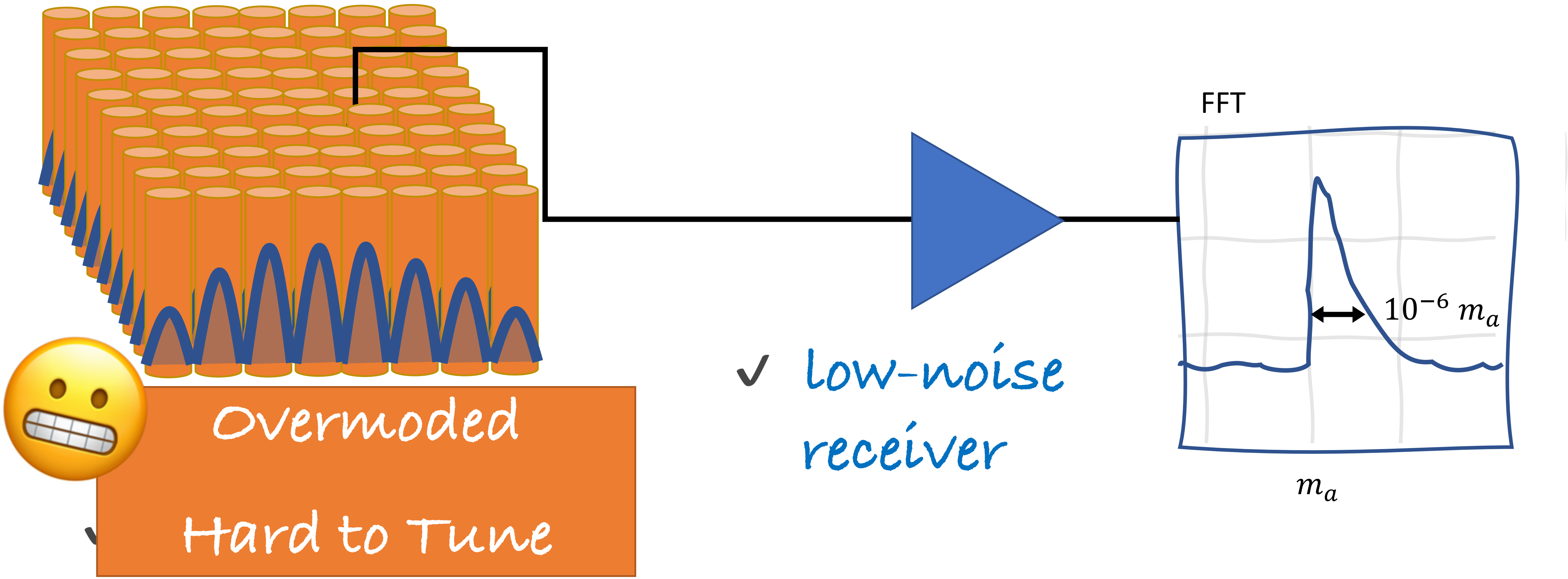

first proof of principle existing

[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~~

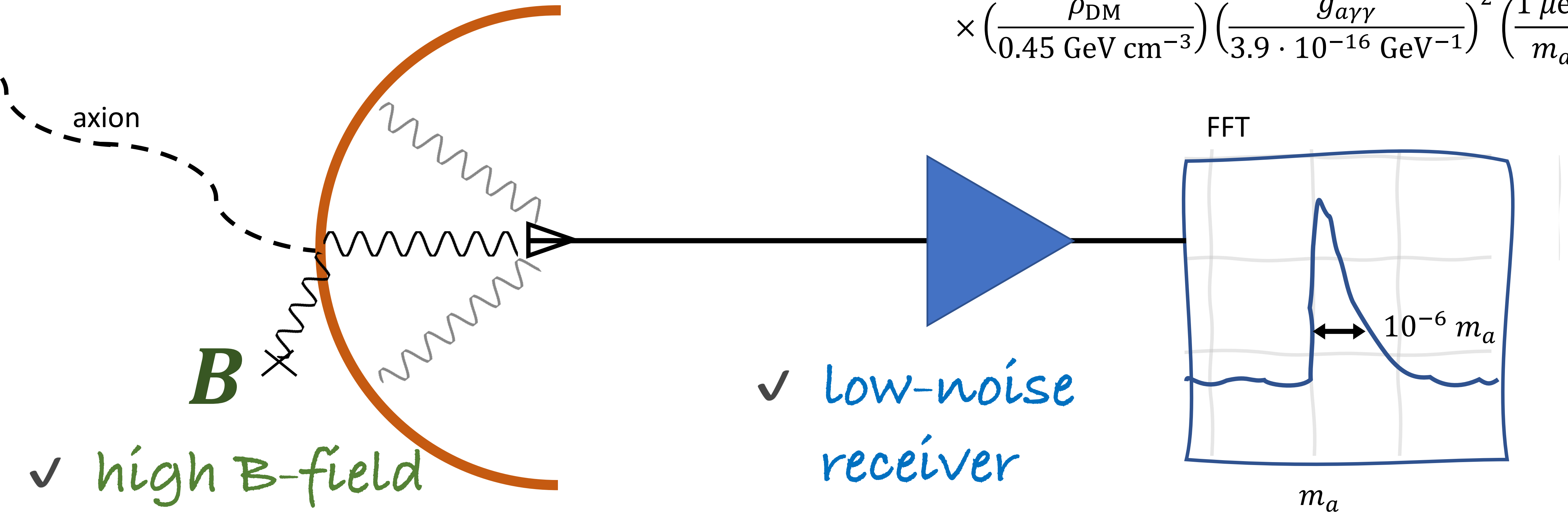
[https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-IF1_IF0_Aaron_Chou-175.pdf]



# Dish Antenna

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

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




✔ high B-field

✔ low-noise receiver

**FUNK**
[A. Andrianavalomahefa *et al.*, *PRD* 102 (2020)]

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

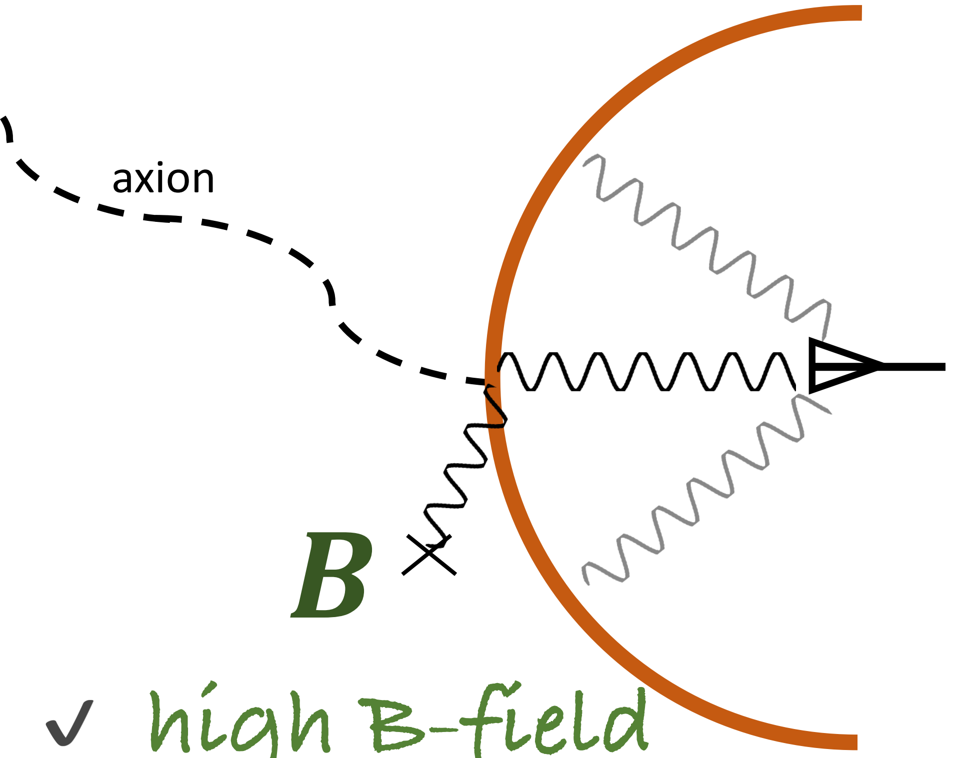
**SHUKET**
[P. Brun *et al.*, PRL 122 (2019) 20]

**BRASS**
[http://wwwiexp.desy.de/groups/astrop article/brass/brassweb.htm]

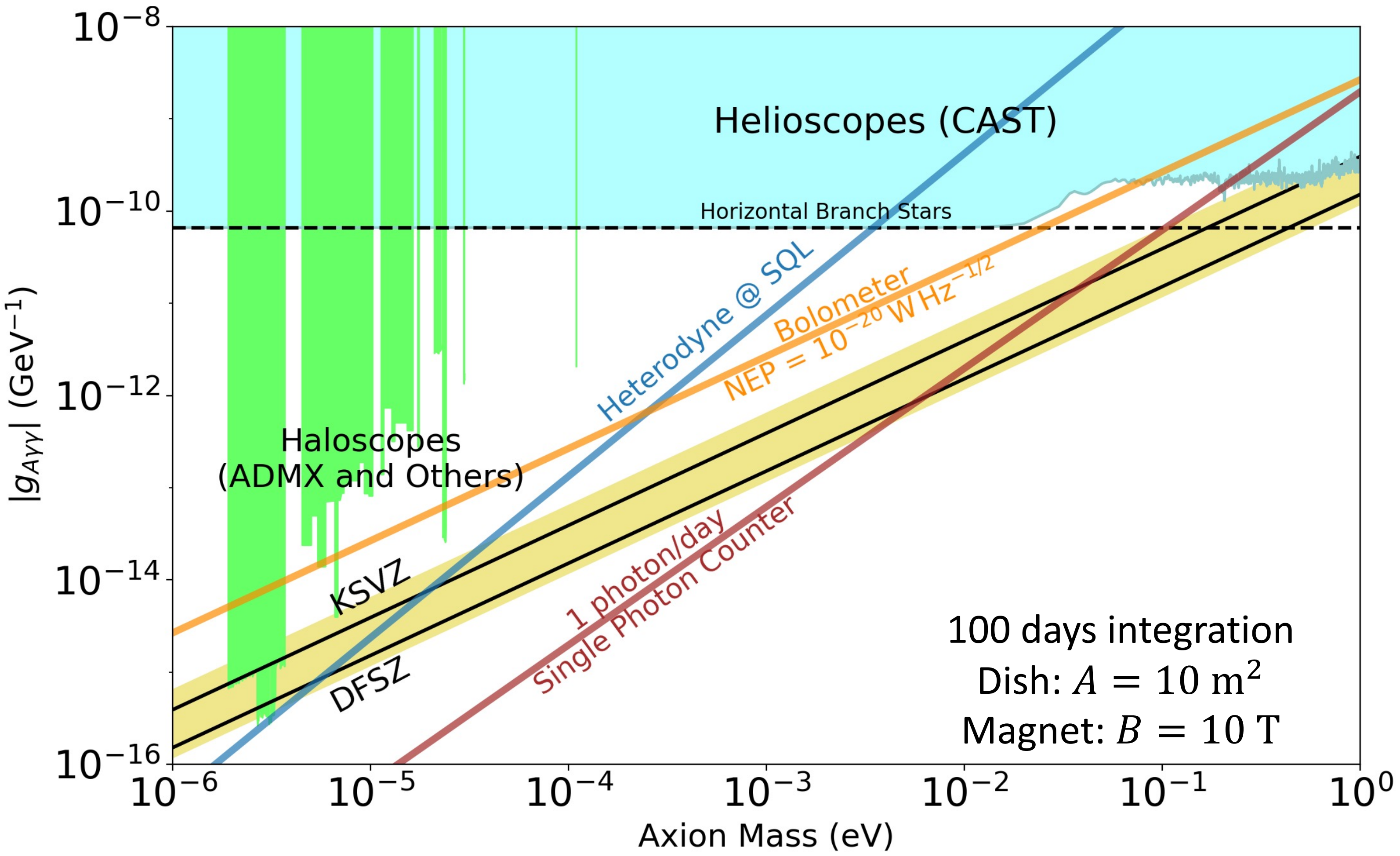
**BREAD**
[talk at PATRAS2021]

# Dish Antenna

✓ "dish antenna"
[Horns *et al.*, JCAP 04 (2013) 01




✓ high B-field

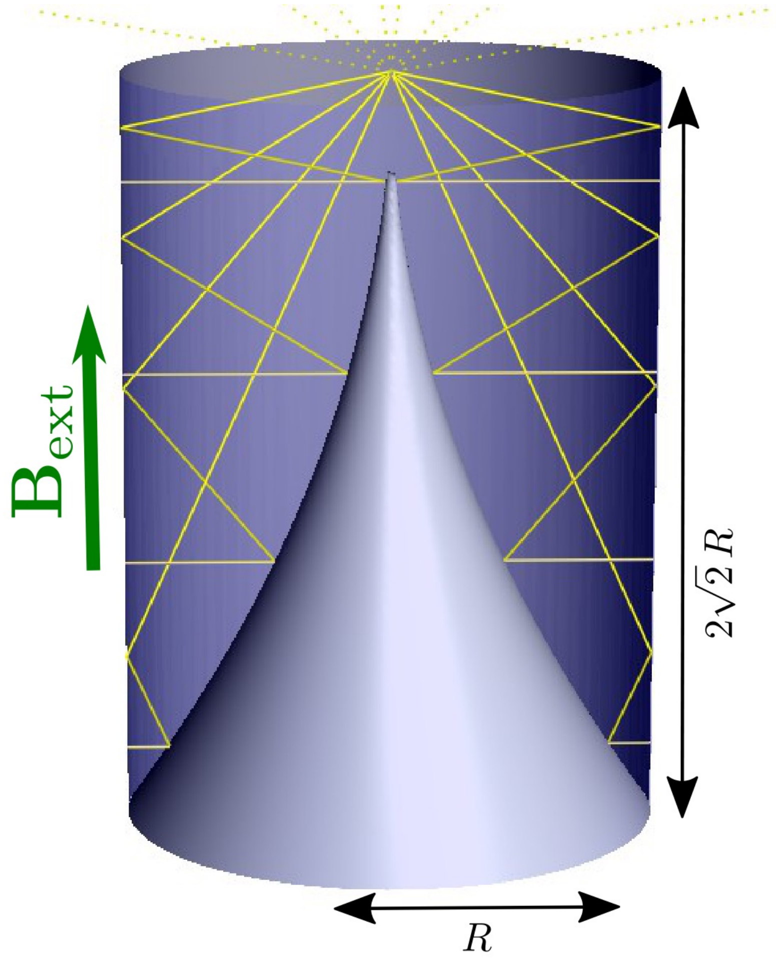



| FUNK | Tokyo | SHUKET | BRASS | BREAD |
|---|---|---|---|---|
| [A. Andrianavalomahefa *et al.*, *PRD* 102 (2020)] | e.g., [J. Suzuki et al., *JCAP* 09 (2015) 042] | [P. Brun *et al.*, PRL 122 (2019) 20] | [http://wwwiexp.desy.de/groups/astrop article/brass/brassweb.htm] | [talk at PATRAS2021] |

# BREAD: Broadband Reflector Experiment for Axion Detection

[SK, talk at PATRAS2021]

## Concept

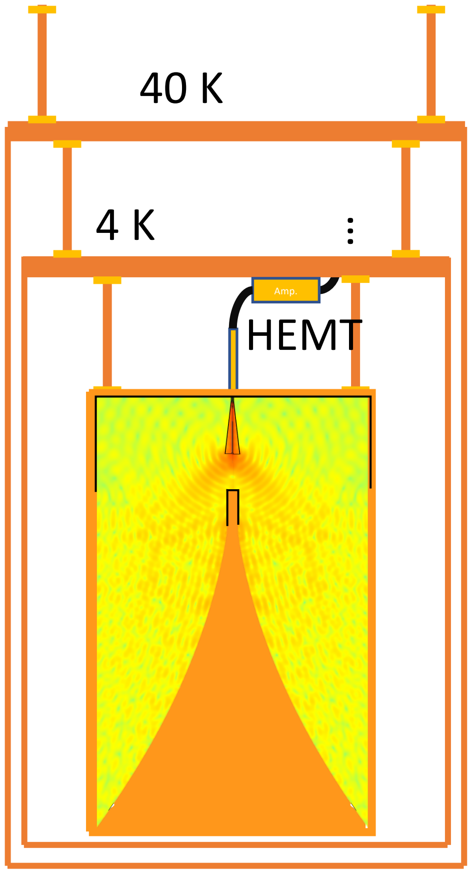



use solenoid magnet

## Pilot Experiments

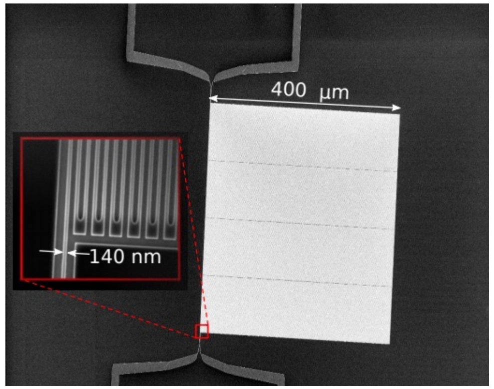
### *Giga-BREAD*

**coaxial horn antenna**




$R \sim 200\text{mm}$

### *Infra-BREAD*




NIST/MIT SNSPD

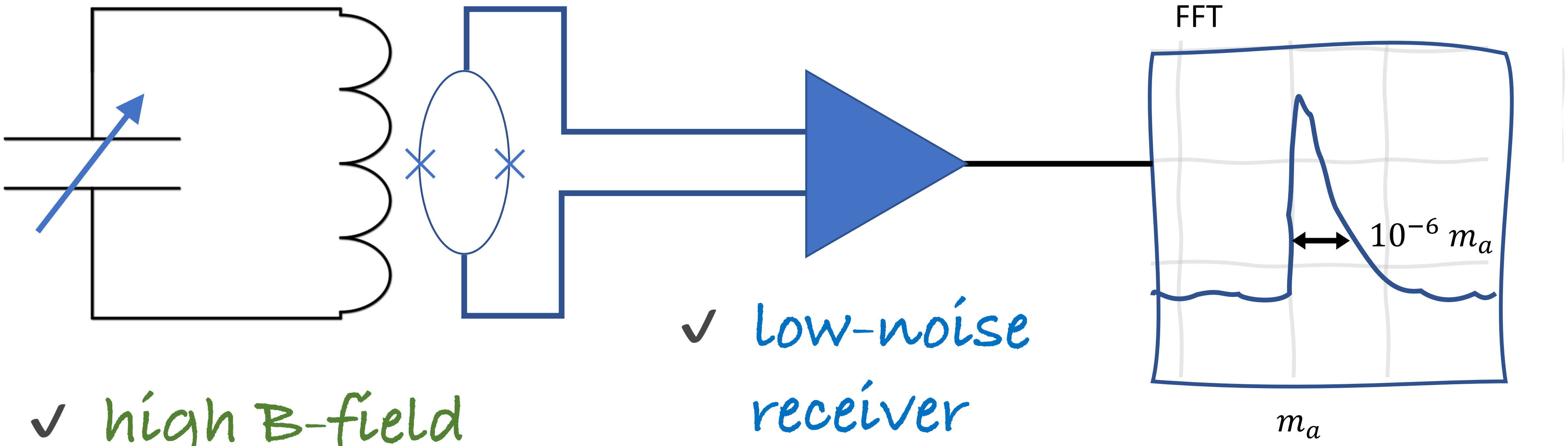
**1 photon/day dark rate**

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

# Lumped Element Resonator

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

✓ high-Q resonator




✓ low-noise receiver

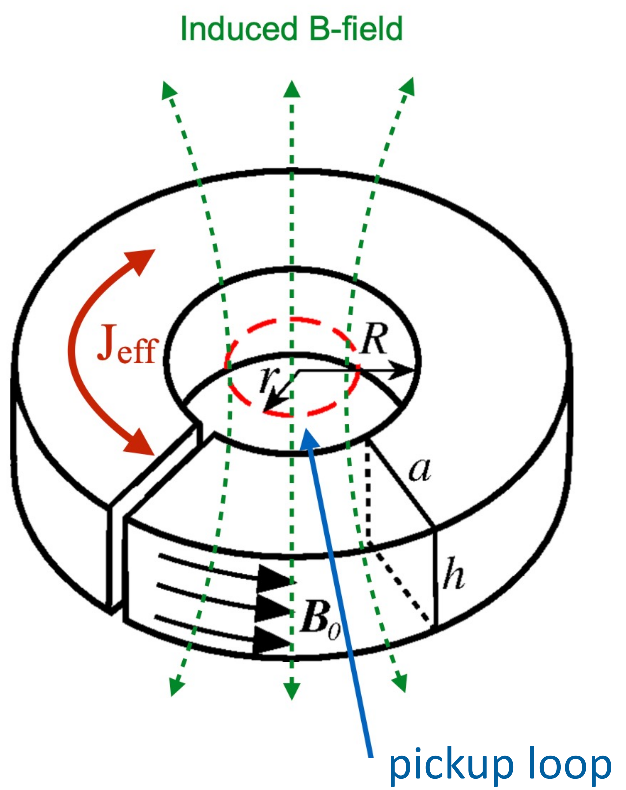
✓ high B-field

tunable via lumped elements

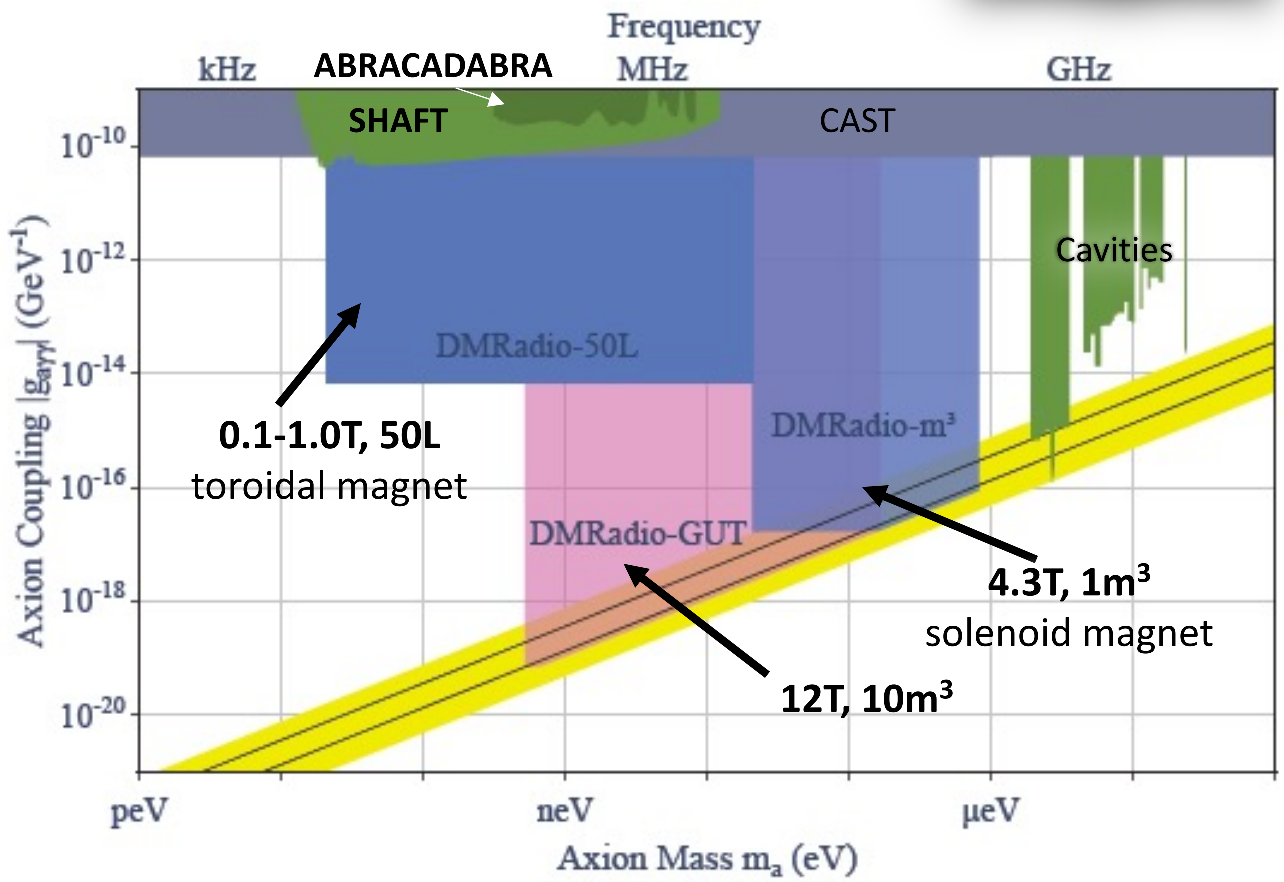
# DMRadio

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


**ABRACADABRA:**
[PRL 127 (2021) 081801]




Different collaboration:
**SHAFT**
[Nature Phys. 17, 79–84 (2021)]

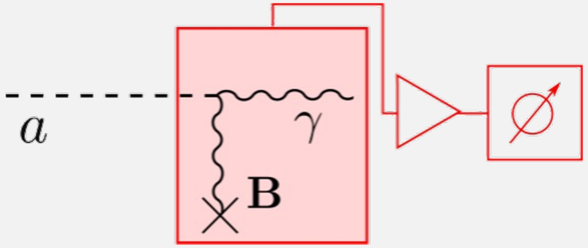



broadband readout possible

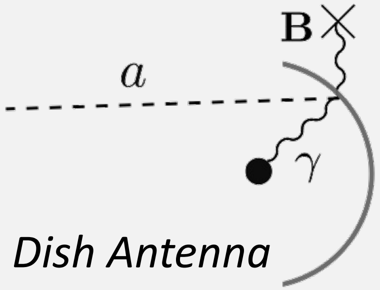
# How to look?

## Electro-Magnetic Coupling

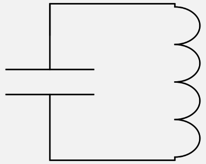
### Dark Matter *(Haloscopes)*




*Microwave Cavity*

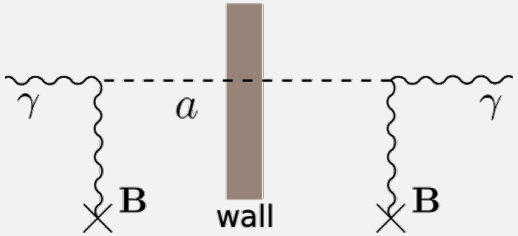



*Dish Antenna*



*LC Circuit*

### Lab Axions

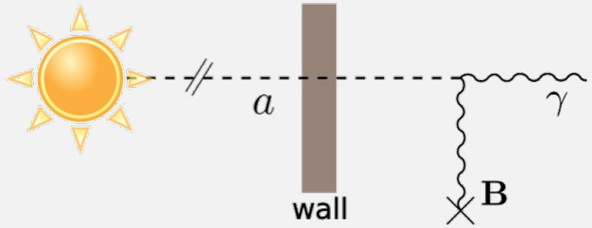



*Light-Shining-through-Wall*

*Polarization/Birefringence*

*Collider*

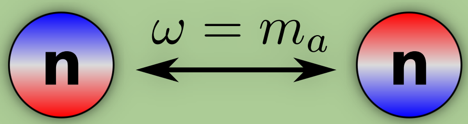
### Sun & Astrophysics



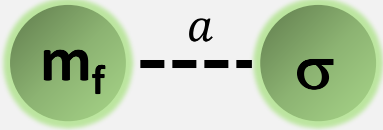

*Helioscope*

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

## Other Coupling



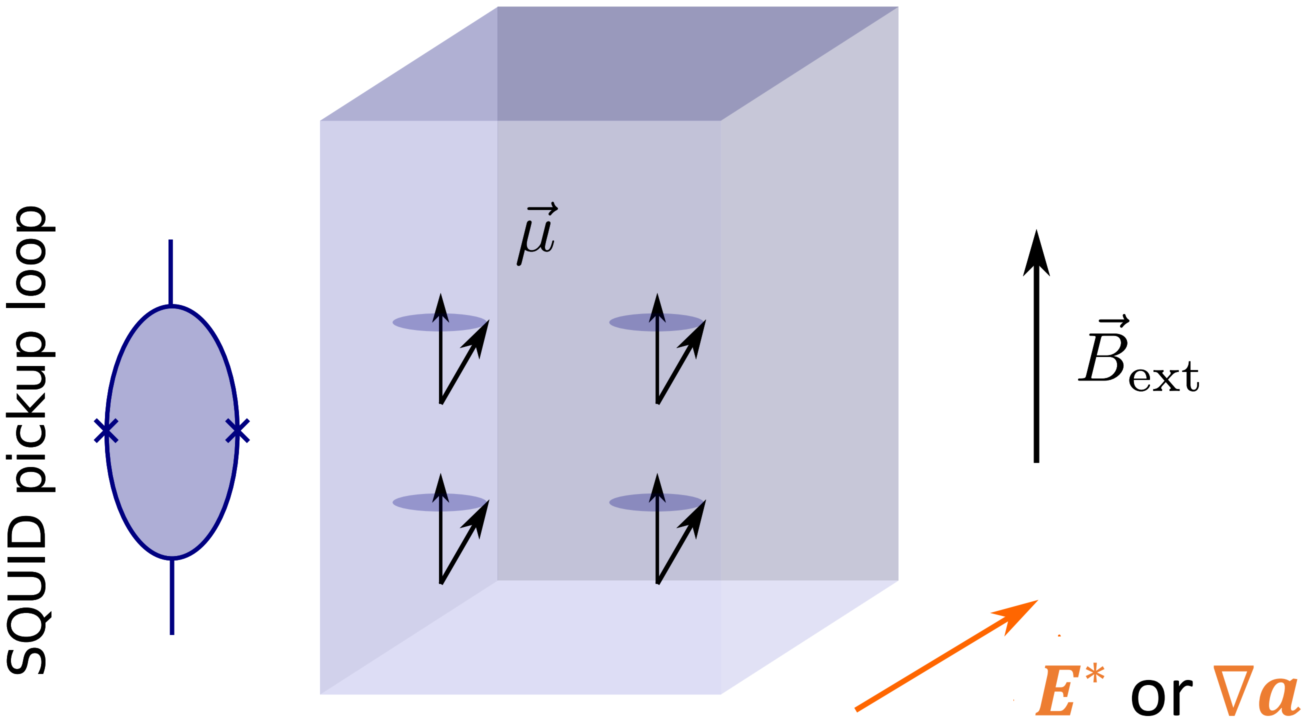

*Oscillating EDM*




*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: $\boldsymbol{B}_{\mathbf{ALP}} = g_{aNN} \boldsymbol{\nabla} a$

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

Nucleon EDM $\propto a$

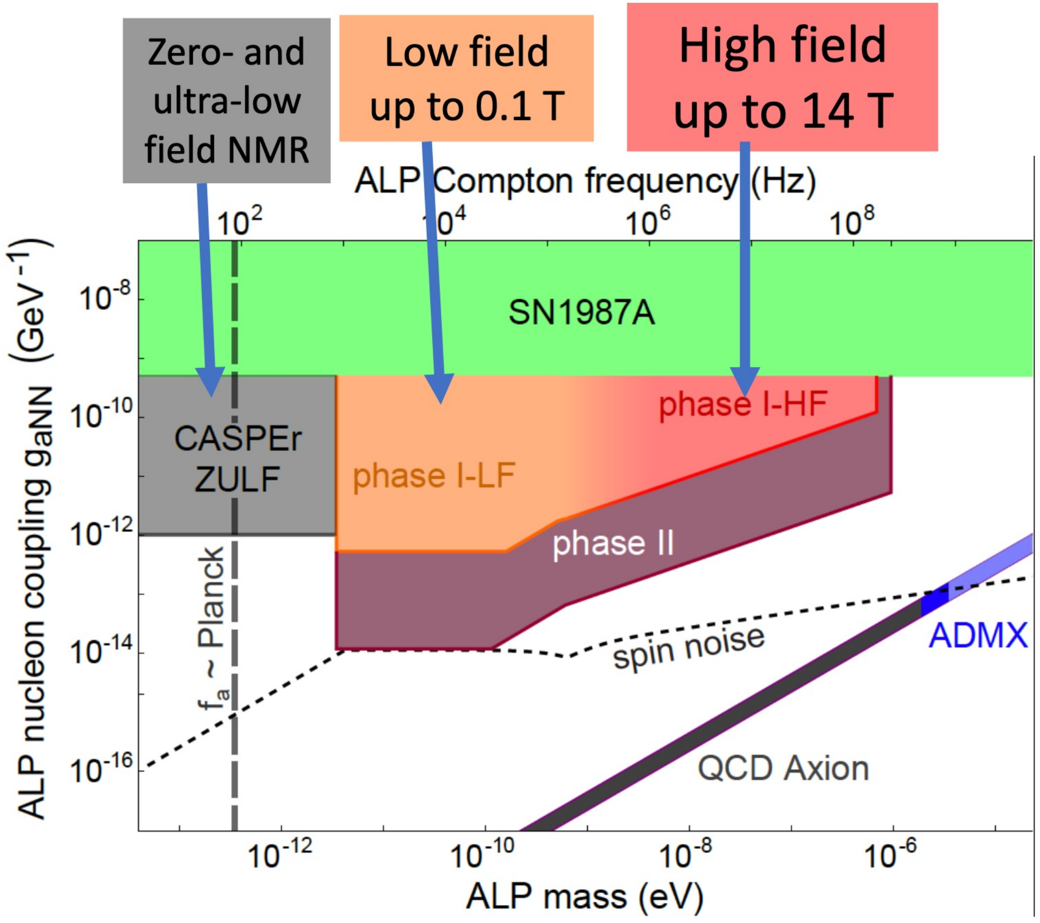
$\sim a \, G^a_{\mu\nu} \, \tilde{G}^{\mu\nu}_a$

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

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

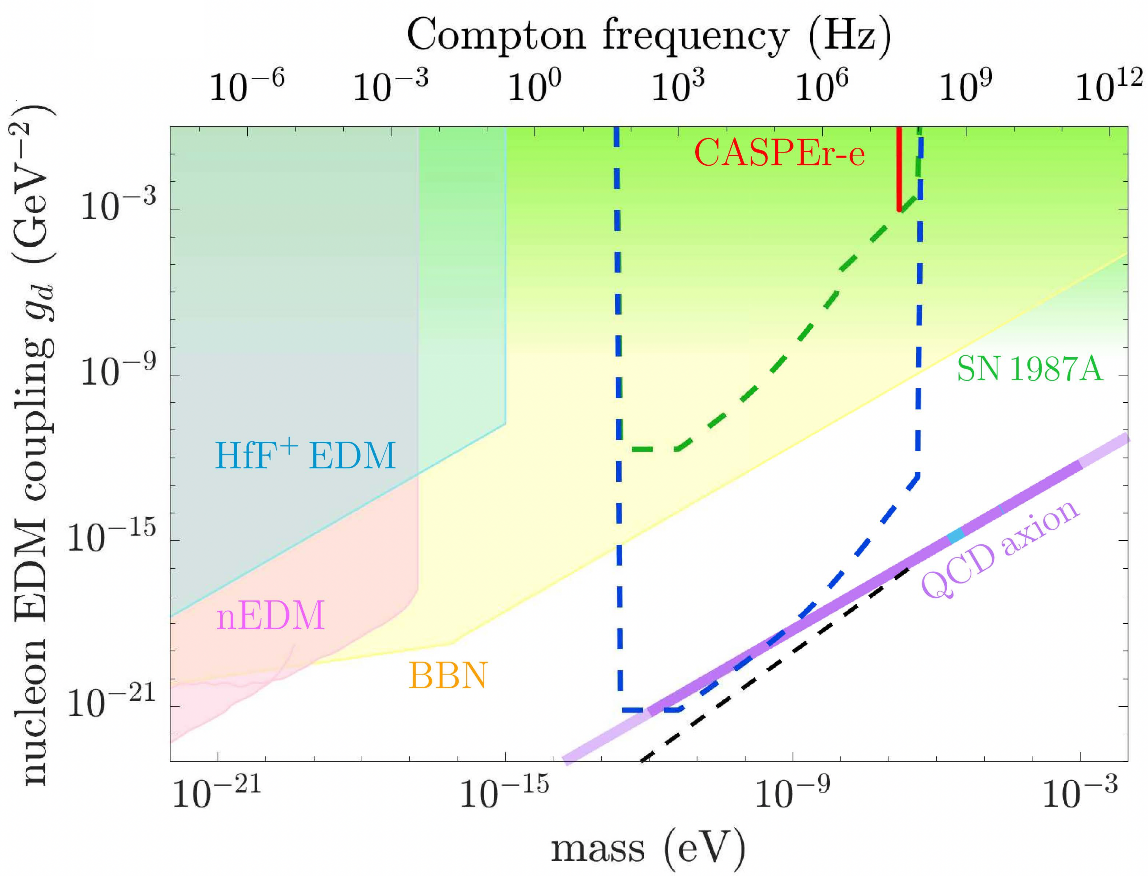
# CASPEr: Cosmic Axion Spin Precession Experiment - Sensitivities

## CASPEr-gradient




[Y. Zhang, H. Bekker, A. Wickenbrock, talks at PATRAS2021]

## CASPEr-electric




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

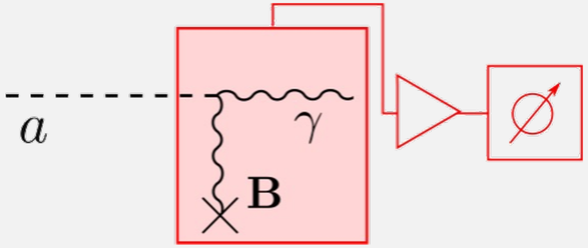
# How to look?

## Dark Matter *(Haloscopes)*

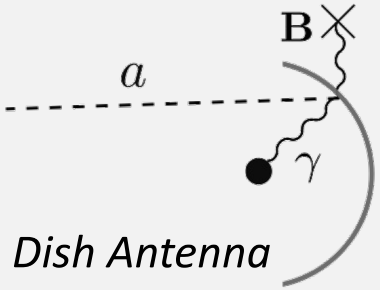
## Lab Axions

## Sun & Astrophysics

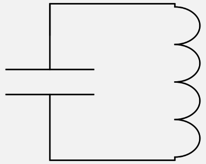
**Electro-Magnetic Coupling**



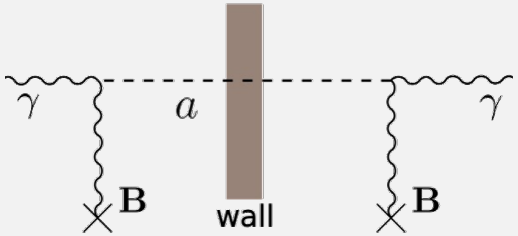

*Microwave Cavity*




*Dish Antenna*



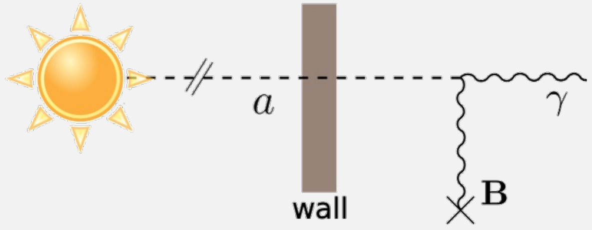
*LC Circuit*




*Light-Shining-through-Wall*

*Polarization/Birefringence*

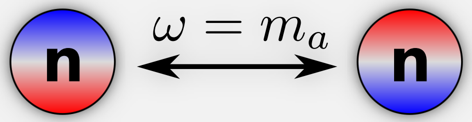
*Collider*



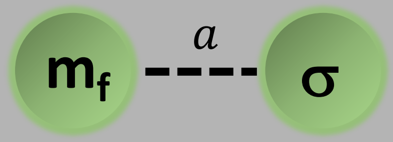

*Helioscope*

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

**Other Coupling**




*Oscillating EDM*

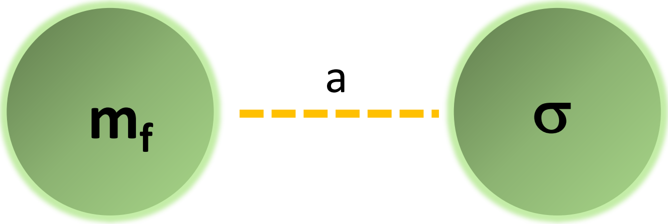



*Firth Force, Collider*

# ARIADNE: Axion Resonant InterAction DetectioN Experiment

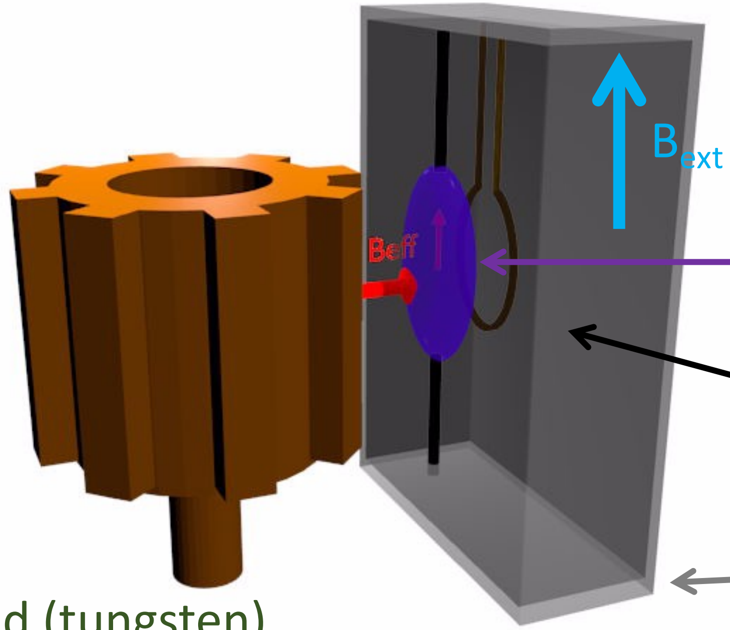
[A. Geraci, talk at PATRAS2021]

**Monopole-Dipole axion exchange**




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

$m_a < 6$ meV → $\lambda_a > 30$ μm




Laser Polarized $^3$He gas senses $B_{ALP}$

SQUID pickup loop

Superconducting shielding

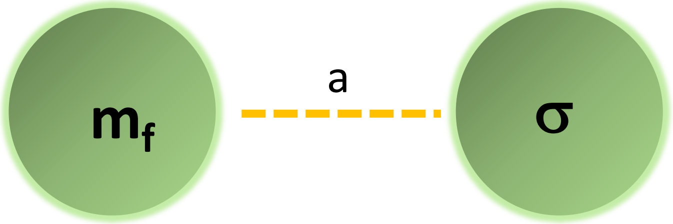
Unpolarized (tungsten) segmented cylinder sources $B_{ALP}$

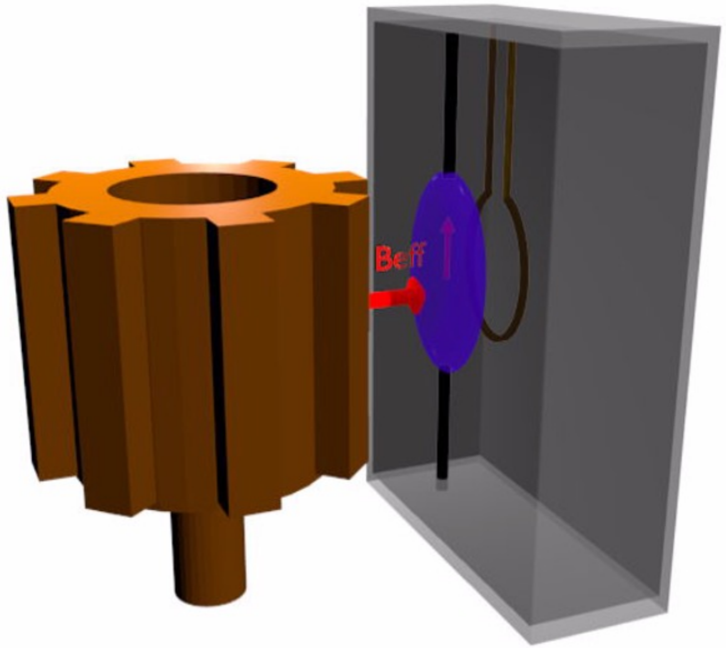
$\omega$ known → no tuning needed!

# ARIADNE: Axion Resonant InterAction DetectioN Experiment

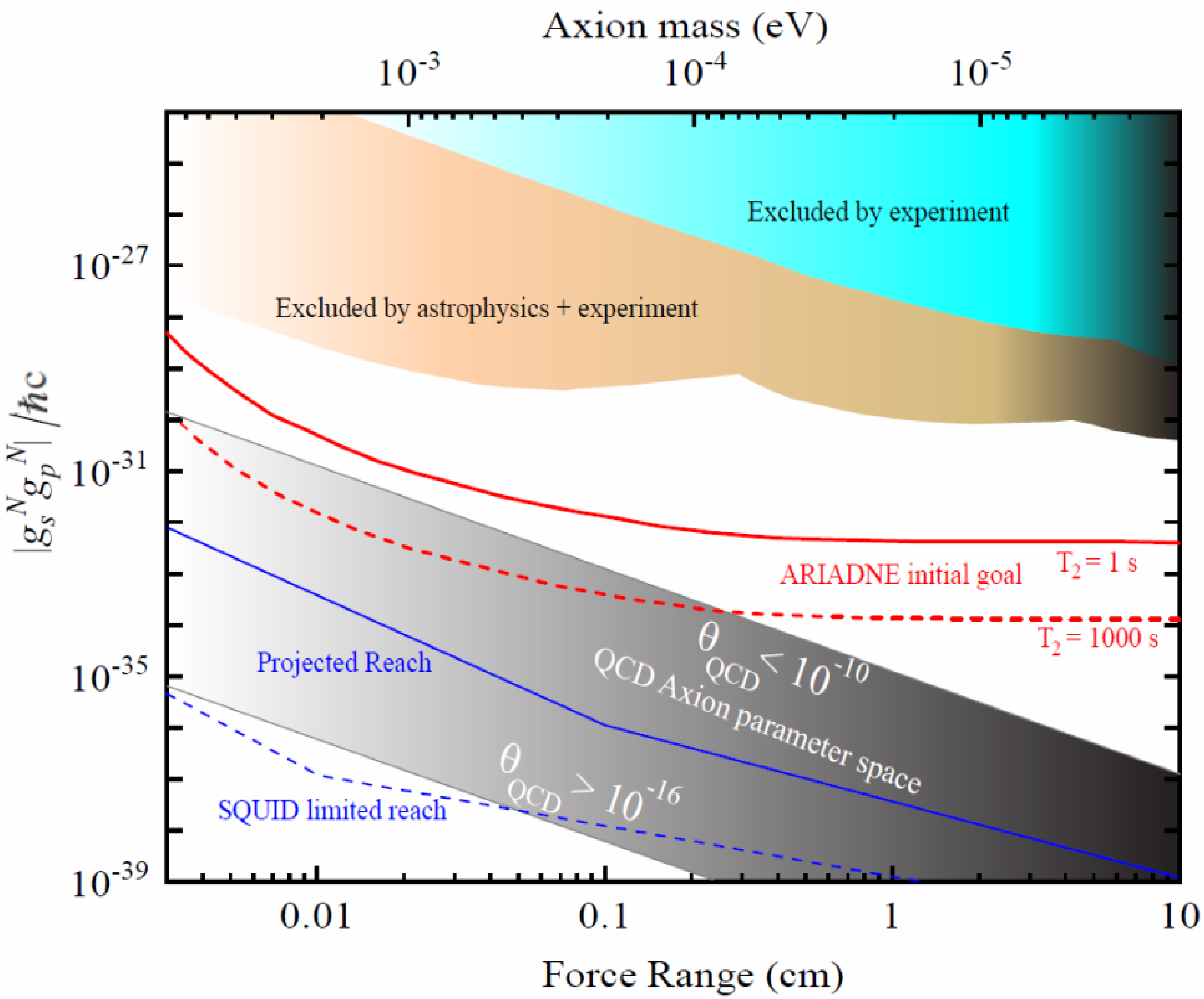
[A. Geraci, talk at PATRAS2021]

**Monopole-Dipole axion exchange**

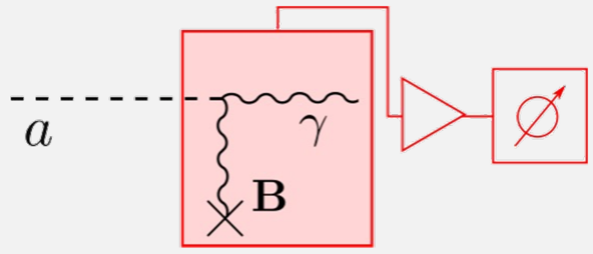
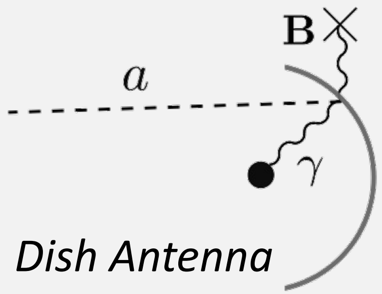
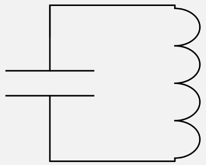
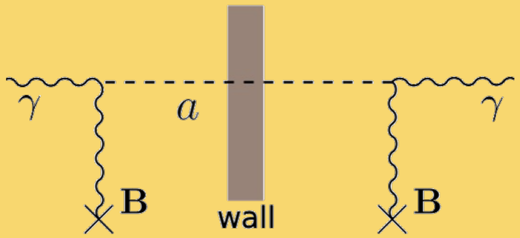
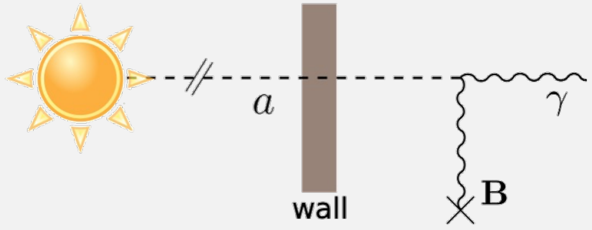
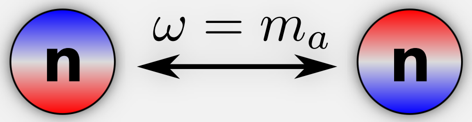
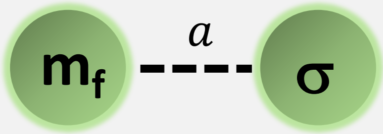



[A. Arvanitaki, A. Geraci, PRL 113,161801 (2014)]

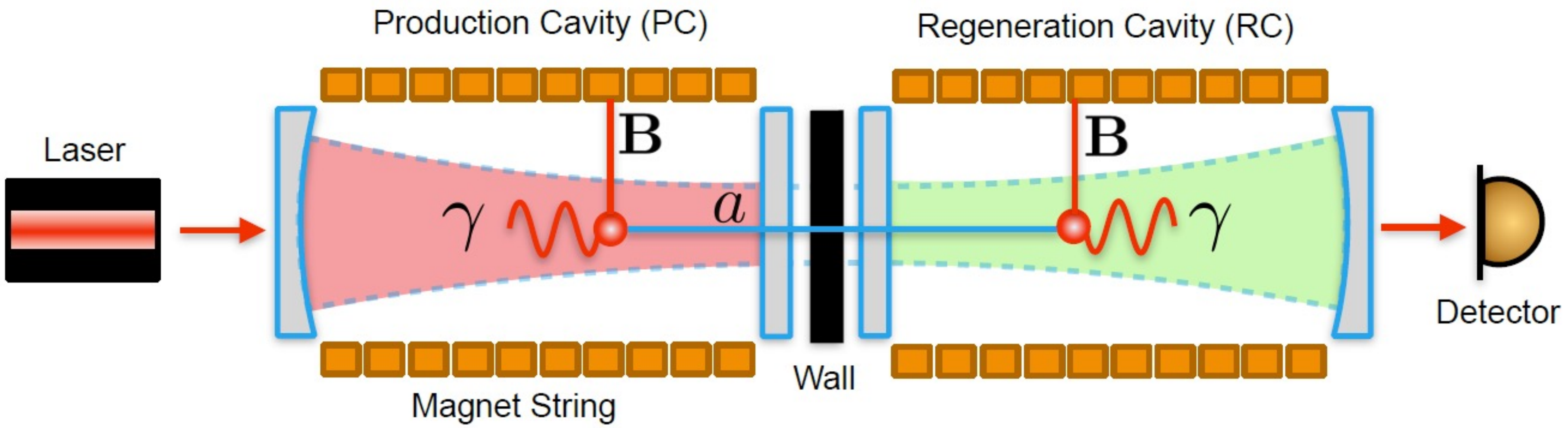


# How to look?

| | **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

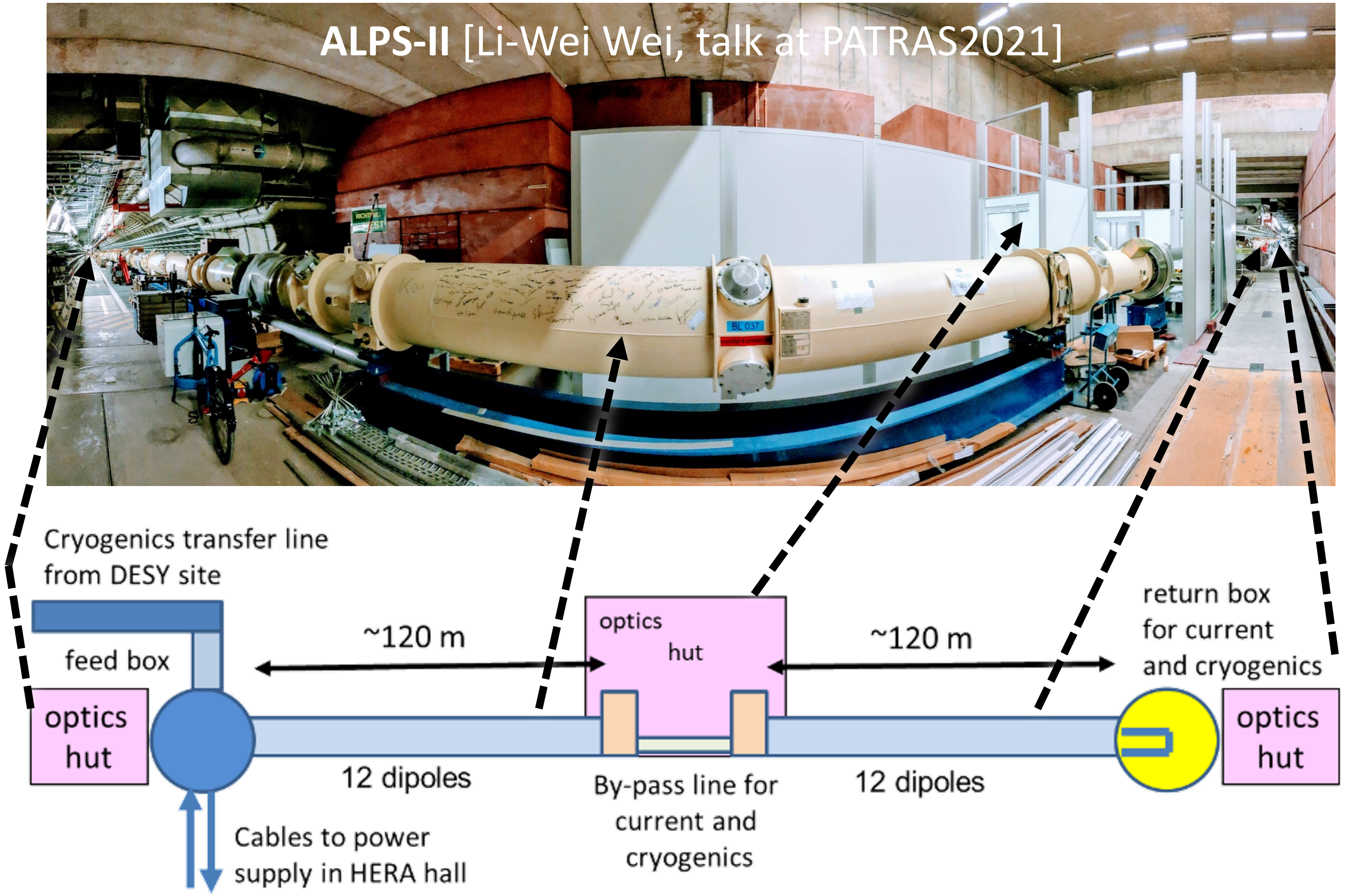
e.g., [G. Mueller, et al., PRD80 (2009) 072004]
[Fig.: ALPS collaboration]




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

| 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] | … |

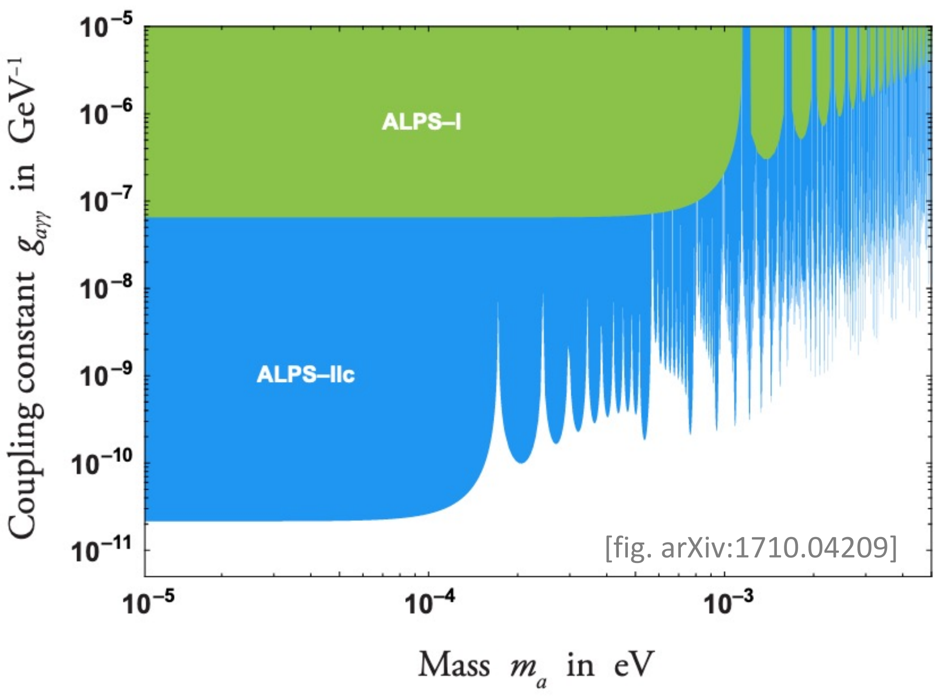
# ALPS: Any Light Particle Search




$\mathrm{L} \sim 100\mathrm{m}, B \sim 5\mathrm{T}, \mathcal{F} \sim 16{,}000$

first physics run expected early 2022

**Sensitivity Estimate (ALPS-IIc):**

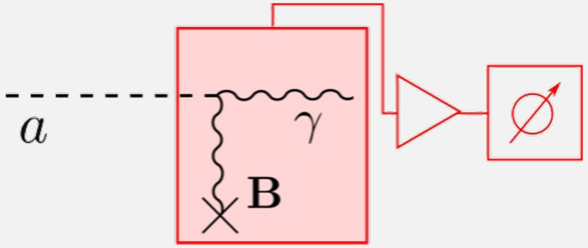



[Z. R. Bush *et al.*, PRD 99 (2019) 2]

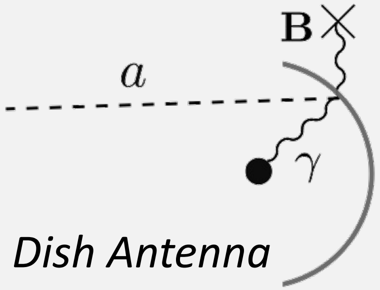
# How to look?

## Electro-Magnetic Coupling

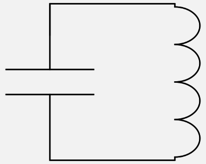
### Dark Matter *(Haloscopes)*




*Microwave Cavity*

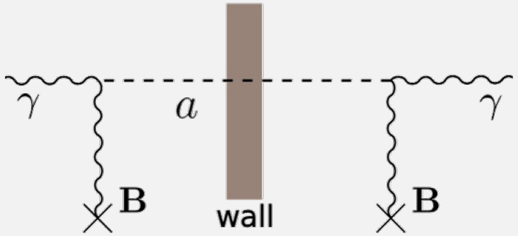



*Dish Antenna*



*LC Circuit*

### Lab Axions

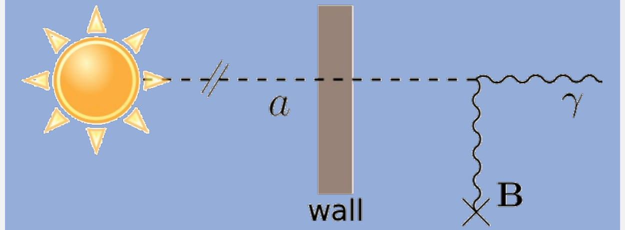



*Light-Shining-through-Wall*

*Polarization/Birefringence*

*Collider*

### Sun & Astrophysics

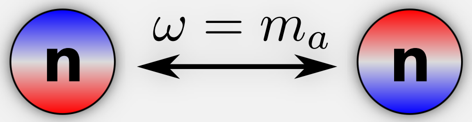



*Helioscope*

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

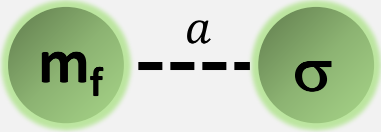
## Other Coupling

### Dark Matter *(Haloscopes)*




*Oscillating EDM*

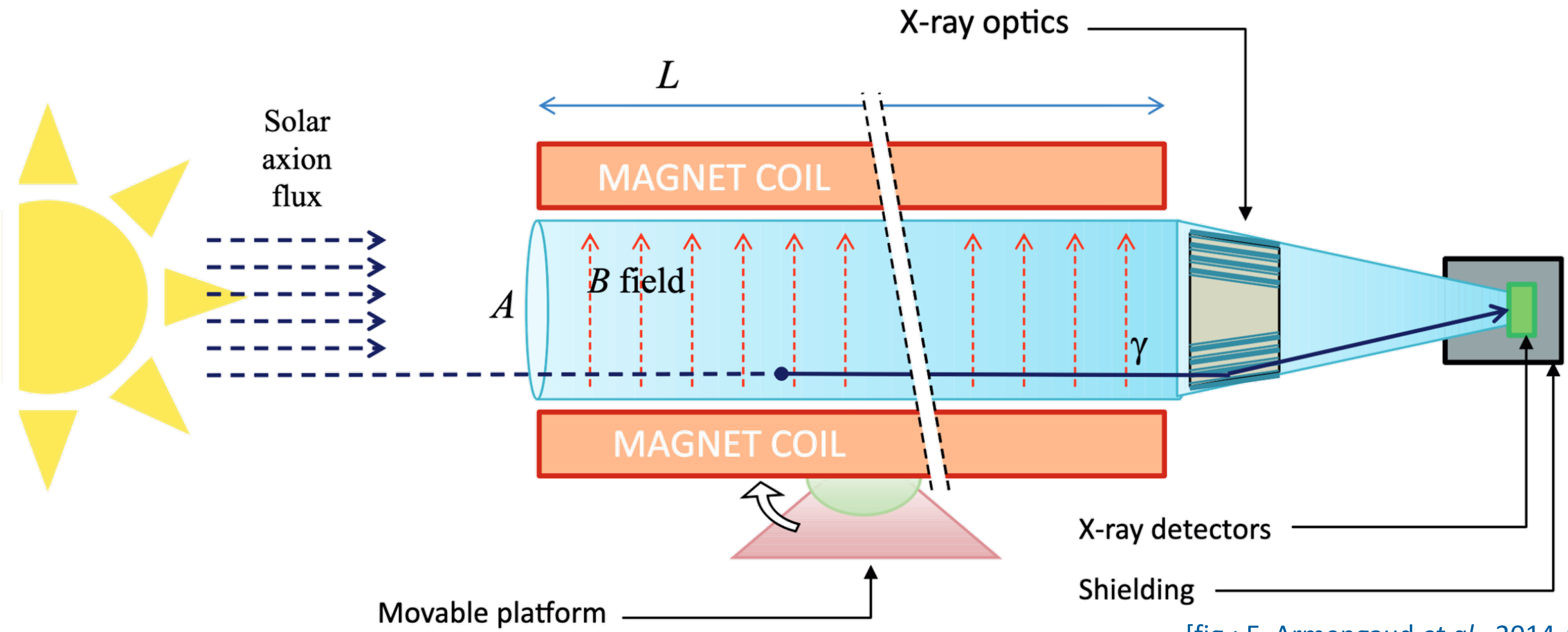
### Lab Axions




*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]

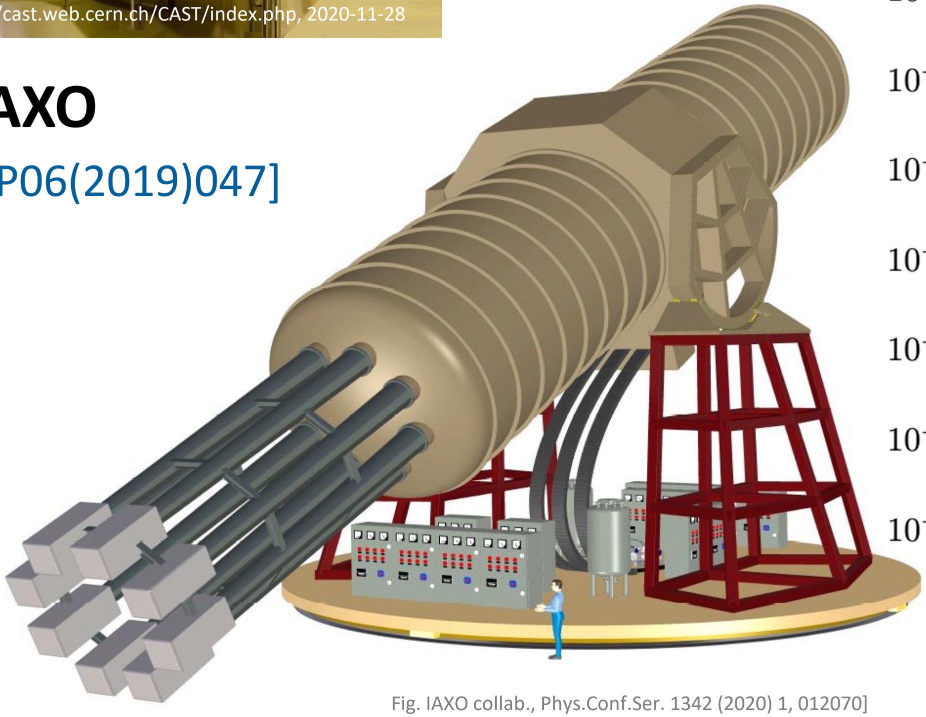
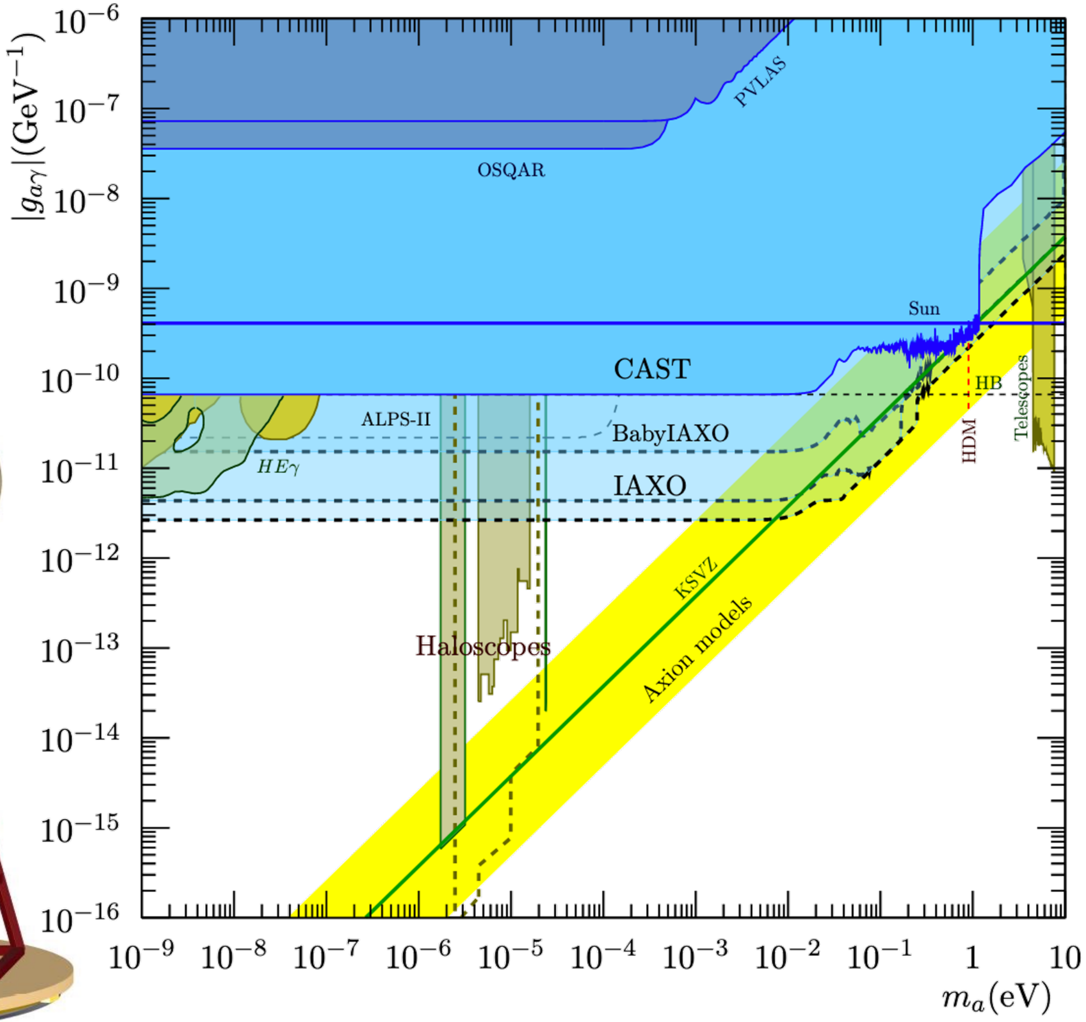
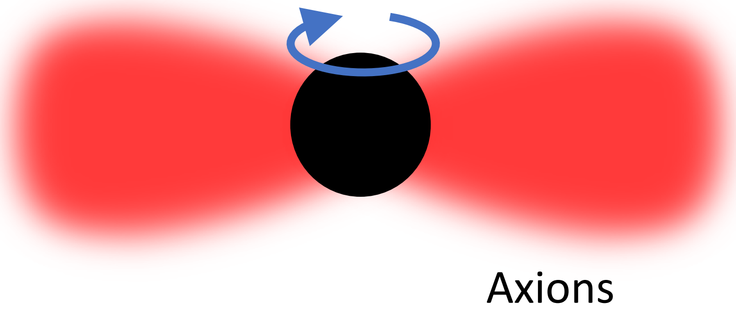


Fig. IAXO collab., Phys.Conf.Ser. 1342 (2020) 1, 012070]



# Indirect Detection (Recent Examples)

## Black Hole Superradiance

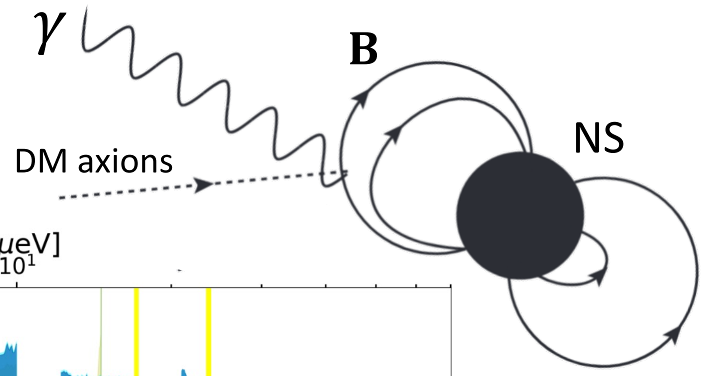


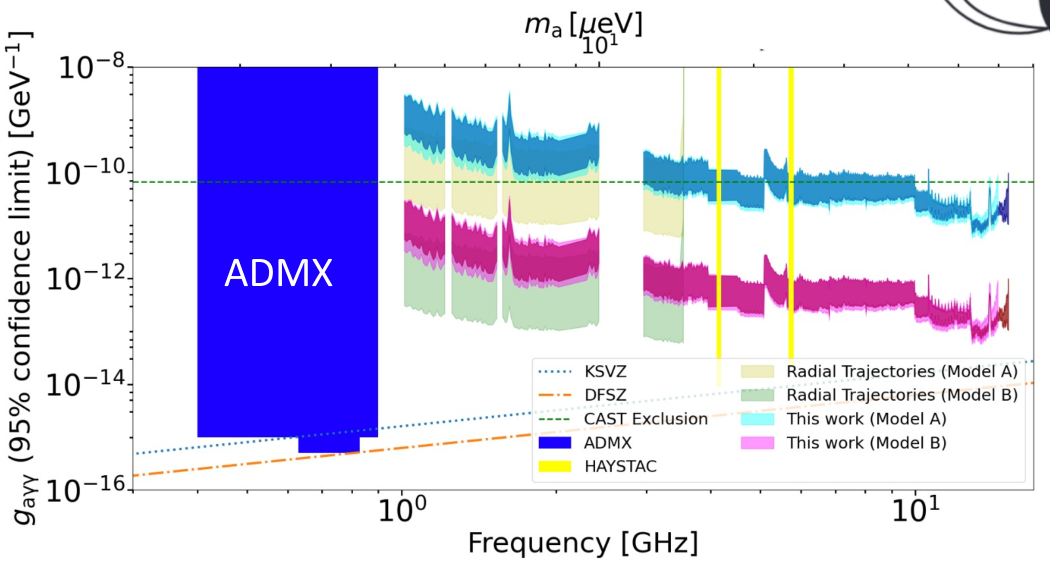

Excludes $10^{-12}\text{eV} \lesssim m_a \lesssim 10^{-11}\text{eV}$

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]

DM Density & Magnetosphere: systematic uncertainty

*Other 'classics':*

**HB Stars (Energy Loss)**
$g_{a\gamma} < 6.6\text{x}10^{-11}\ \text{GeV}^{-1}$
[A. Ayala *et al.*, PRL 113, 19, 191302 (2014)]

**Abell Galaxy Clusters (2γ Decay)**
$g_{a\gamma} < 10^{-11}\ \text{GeV}^{-1}$ @ $m_a$ = 5…7 eV
[D. Grin *et al.*, PRD 75, 105018 (2007)]

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

…

# So Much More...

## Theory

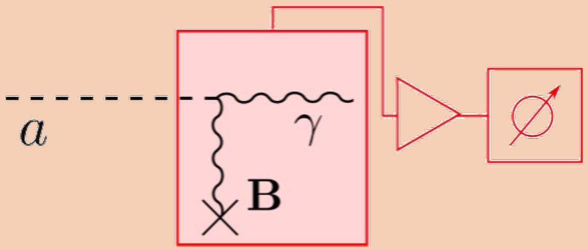
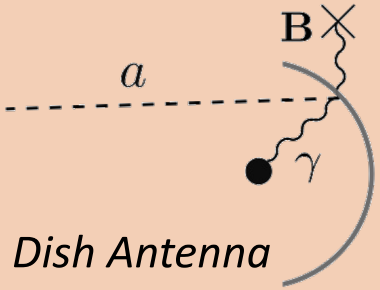
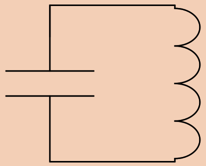
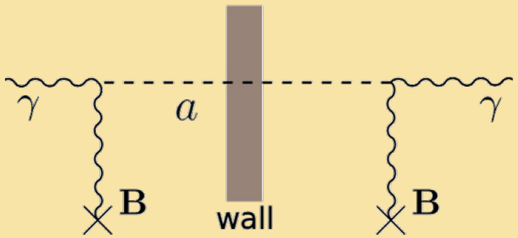
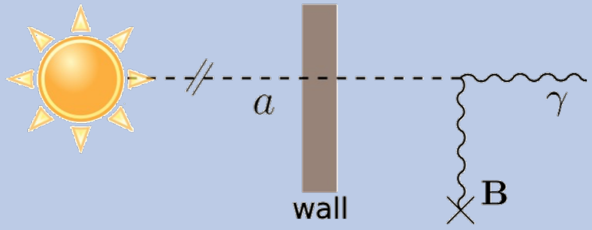
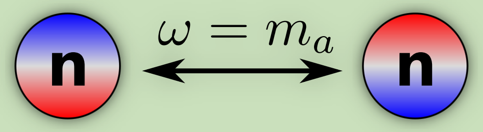
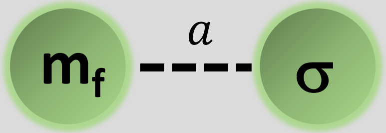
- Axion Mass-Predictions and Axion Cosmology
  e.g., [V. B. Klaer and G. D. Moore, JCAP 11, 049 (2017)], [A. Vaquero, J. Redondo, and J. Stadler, JCAP 04, 012 (2019)], [M. Buschmann *et al.*, arXiv:2108.05368], [IAXO collab., JCAP 06 (2019) 047], …
- Non-Standard-Halo-Models, Substructure
  e.g., [S. S. Chakrabarty *et al.*, Phys. Dark Univ., 33 (2021) 100838], [C. A.J. O'Hare, PRD98 (2018) 10, 103006], …

## Experiments

- High-Field Magnets
  e.g., [M. D. Bird, Springer Proc.Phys. 245 (2020) 9-16], [N. Bykovskiy *et al.*, IEEE Trans.Appl.Supercond. 31 (2021) 5, 4500305], …
- Superconducting Cavities
  e.g., [D. Alesini *et al.*, Phys. Rev. D 99, 101101 (2019)], [D. Ahn *et al.*, arXiv:1904.05111], …
- XENON1T Result
  e.g., [Phys. Rev. D 102, 072004 (2020)]
- 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., arXiv:2007.15656]
- Indirect Detection
  e.g., [Raffelt, Day, McDonald, Sigl, talks at MIAPP2020], …

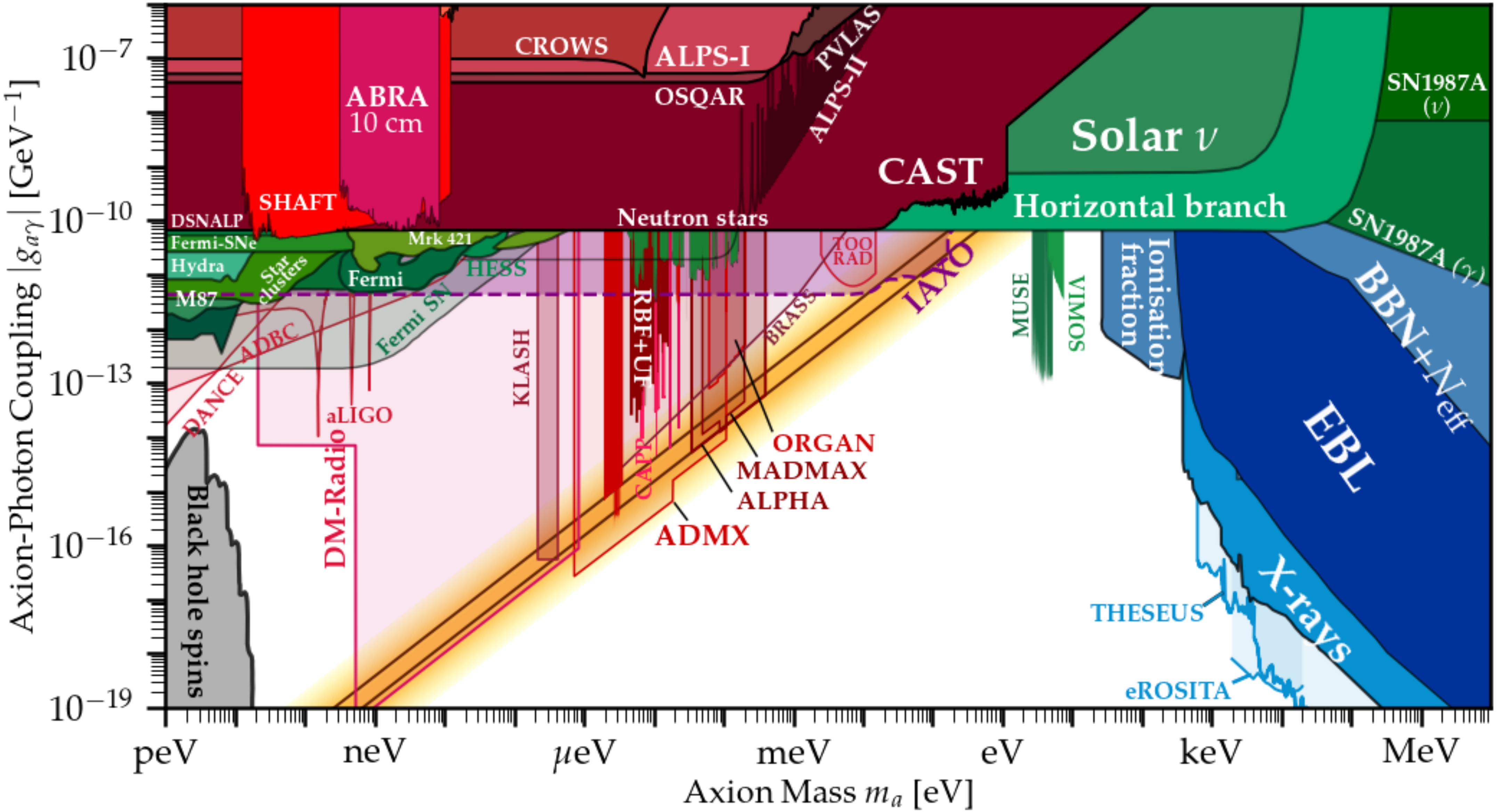
…

# 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* | |

# Vielen Dank nach Aachen!

[adapted from cajohare.github.io/axionlimits]



S. 28:
[Döbrich *et al.*, JHEP 07 (2020) 084]
**Scalable haloscopes for axion dark matter detection in the 30$\mu$eV range with RADES**
A. Álvarez Melcón (Cartagena Politecnica U.), S. Arguedas Cuendis (CERN), C. Cogollos (ICC, Barcelona U.), A. Díaz-Morcillo (Cartagena Politecnica U.), B. Döbrich (CERN) et al.
e-Print: 2002.07639 [hep-ex]
DOI: 10.1007/JHEP07(2020)084
Published in: JHEP 07 (2020), 084

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