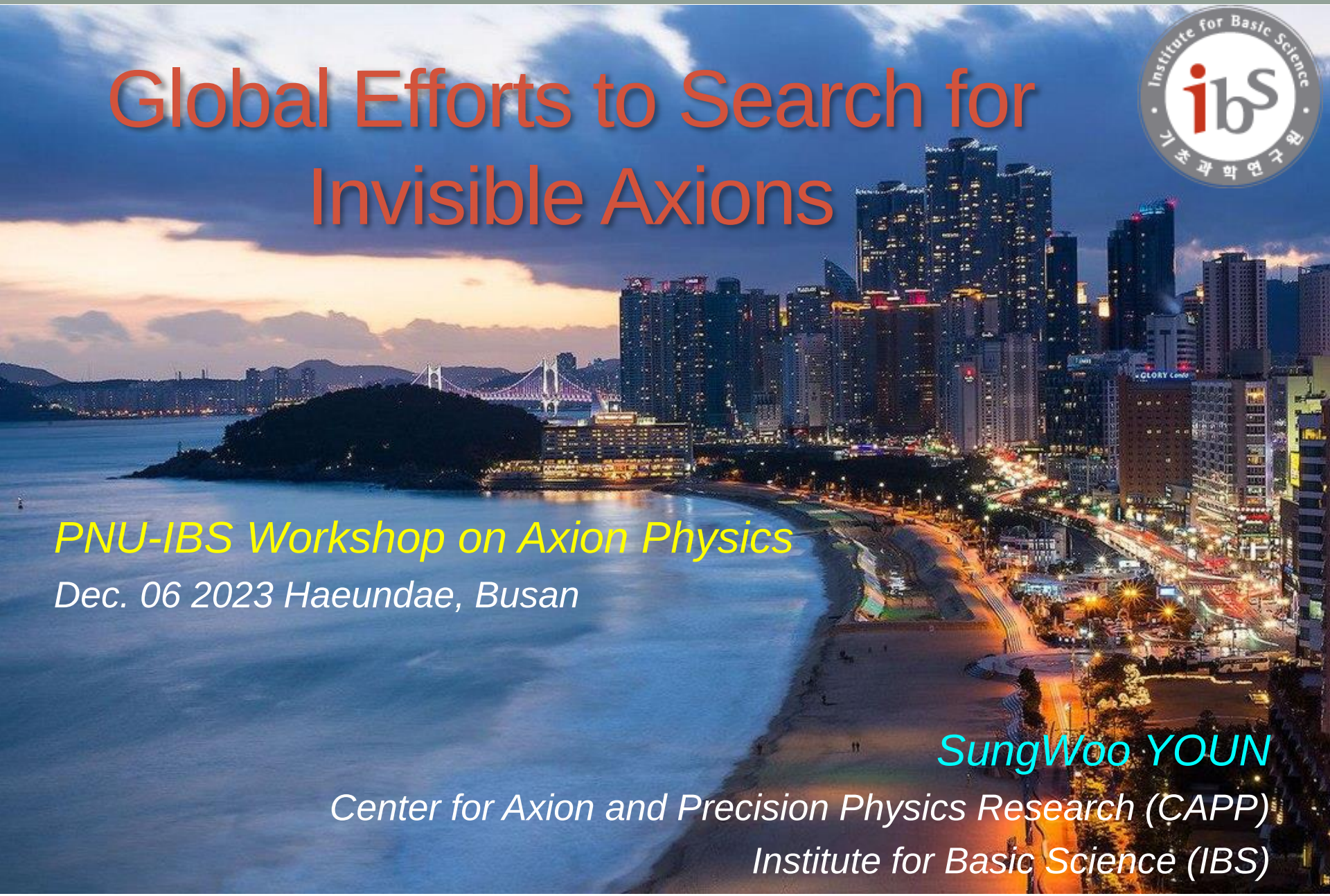


Global Efforts to Search for Invisible Axions

PNU-IBS Workshop on Axion Physics

Dec. 06 2023 Haeundae, Busan

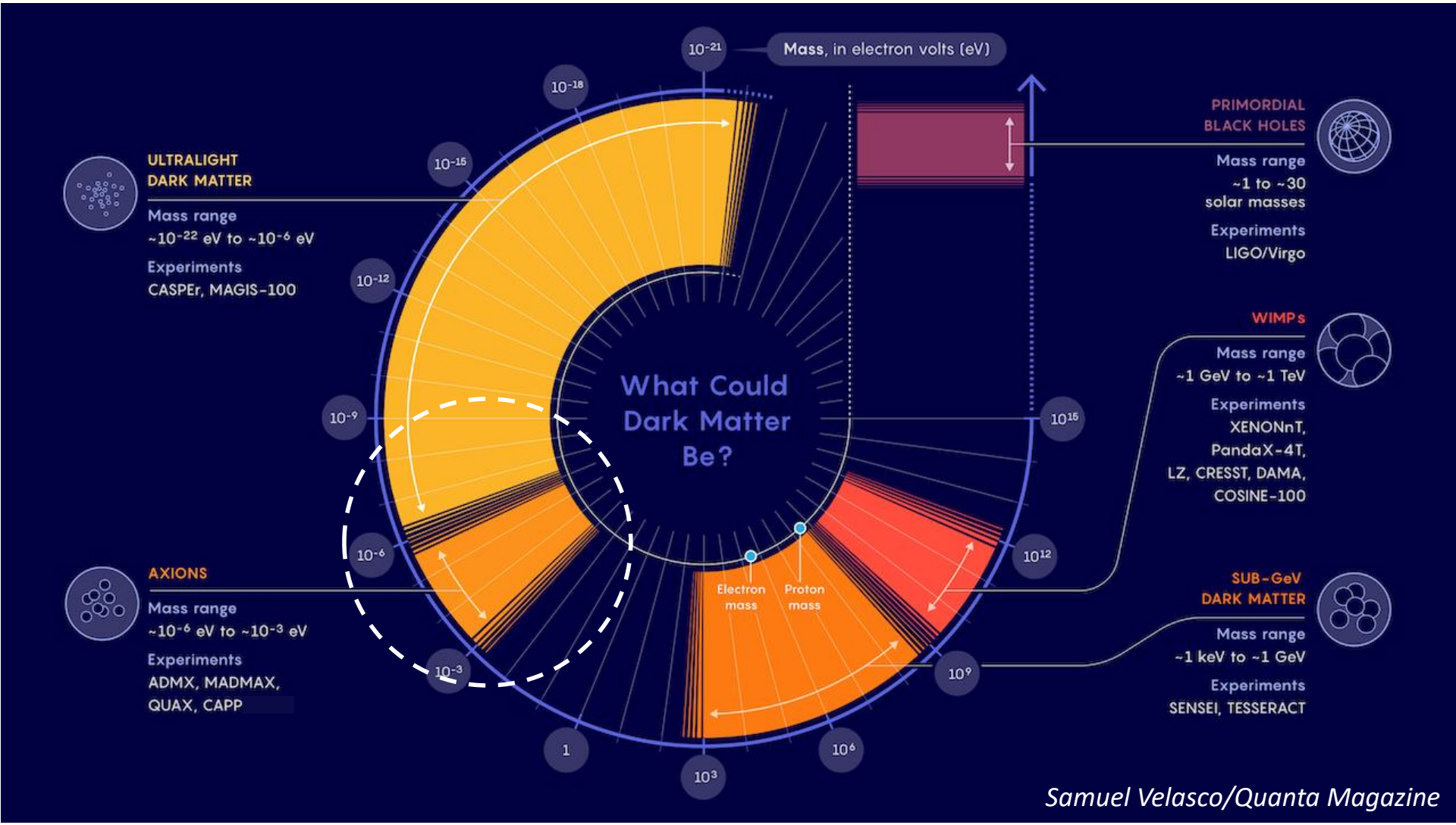
SungWoo YOUN

Center for Axion and Precision Physics Research (CAPP)

Institute for Basic Science (IBS)

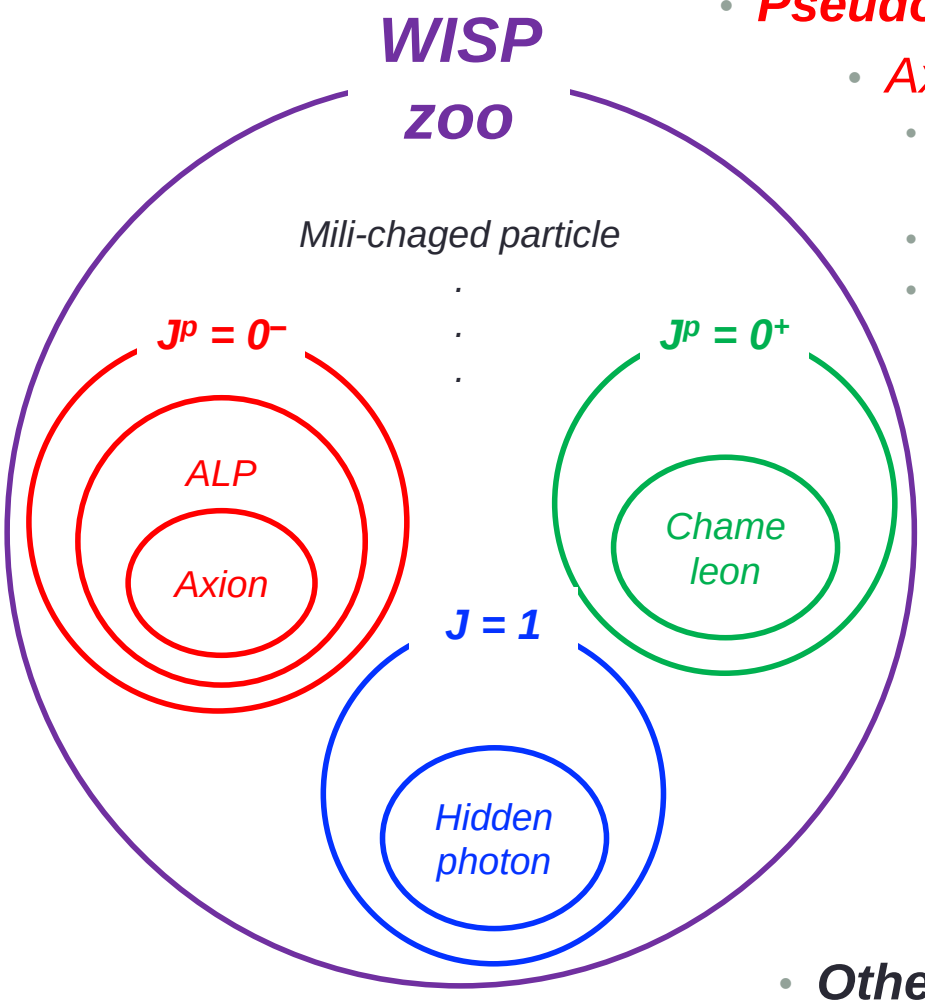
Dark Matter and Axion

Dark matter business expanding



Samuel Velasco/Quanta Magazine

Weakly Interacting Slim Particles



- ***Pseudo-scalar***
  - *Axion*
    - *PQ solution to strong CP problem (1977)*
      $m_a f_a \sim \Lambda_{QCD}$
    - *Invisible axion (1979)*
    - *Dark matter candidate (1983)*
  - *Axion-Like Particle (ALP)*
    - *Generic axion w/o solving the strong CP problem*
      $m_a f_a \nsim \Lambda_{QCD}$
  - ***Scalar***
    - *Chameleon (2003)*
    - *Dark energy candidate*
  - ***Vector***
    - *Hidden photon*
    - *Gauge field in hidden sector*
- ***Others***
  - *Mili-charged particle, …*

Axion couplings

- *SM particles and experimental signatures*

	Photons	Fermions	nEDMs
Hamiltonian	$g_{a\gamma\gamma} a\boldsymbol{E}\cdot\boldsymbol{B}$	$g_{aff}\boldsymbol{\nabla} a\cdot\widehat{\boldsymbol{S}}$	$g_{EDM} a\widehat{\boldsymbol{S}}\cdot\boldsymbol{E}$
Observable	Photon	Spin precession	Oscillating EDM
Detection method	Power spectrum, photon counter, …	Magnetometer, NMR, …	NMR, polarimeter, …

- *Sources and experiments*

Source	Photons	Fermions	nEDMs
Dark matter	***ADMX, CAPP, QUAX***, MADMAX, DM Radio, …	***QUAX-ae***, CASPEr-wind, ***GNOME***, …	CASPEr-electric, srEDM, …
Solar	***CAST***, IAXO		
Laboratory	***ALPS (II)***	ARIADNE	

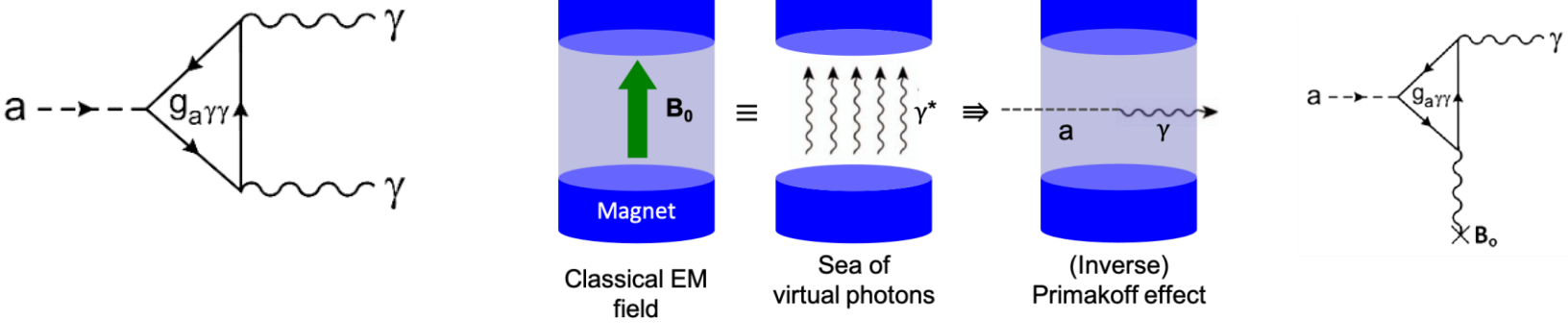
- *Many searches relies on photon couplings*

Models and detection

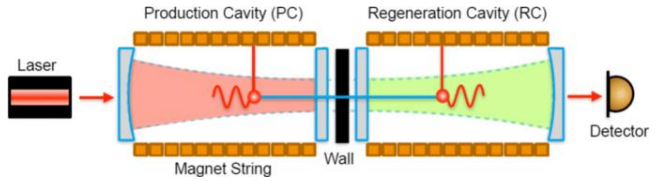
- *Axion models*

Model	PQWW	DFSZ	KSVZ
QCD anomaly	SM ferminons		BSM fermions
Spont. breaking	2 Higgs	2Higgs+singlet	Higgs+singlet
Nickname	Standard ($f_a \sim v_{EW}$)	Invisible ($f_a \gg v_{EW}$)	
Remark	Ruled out	Benchmark	

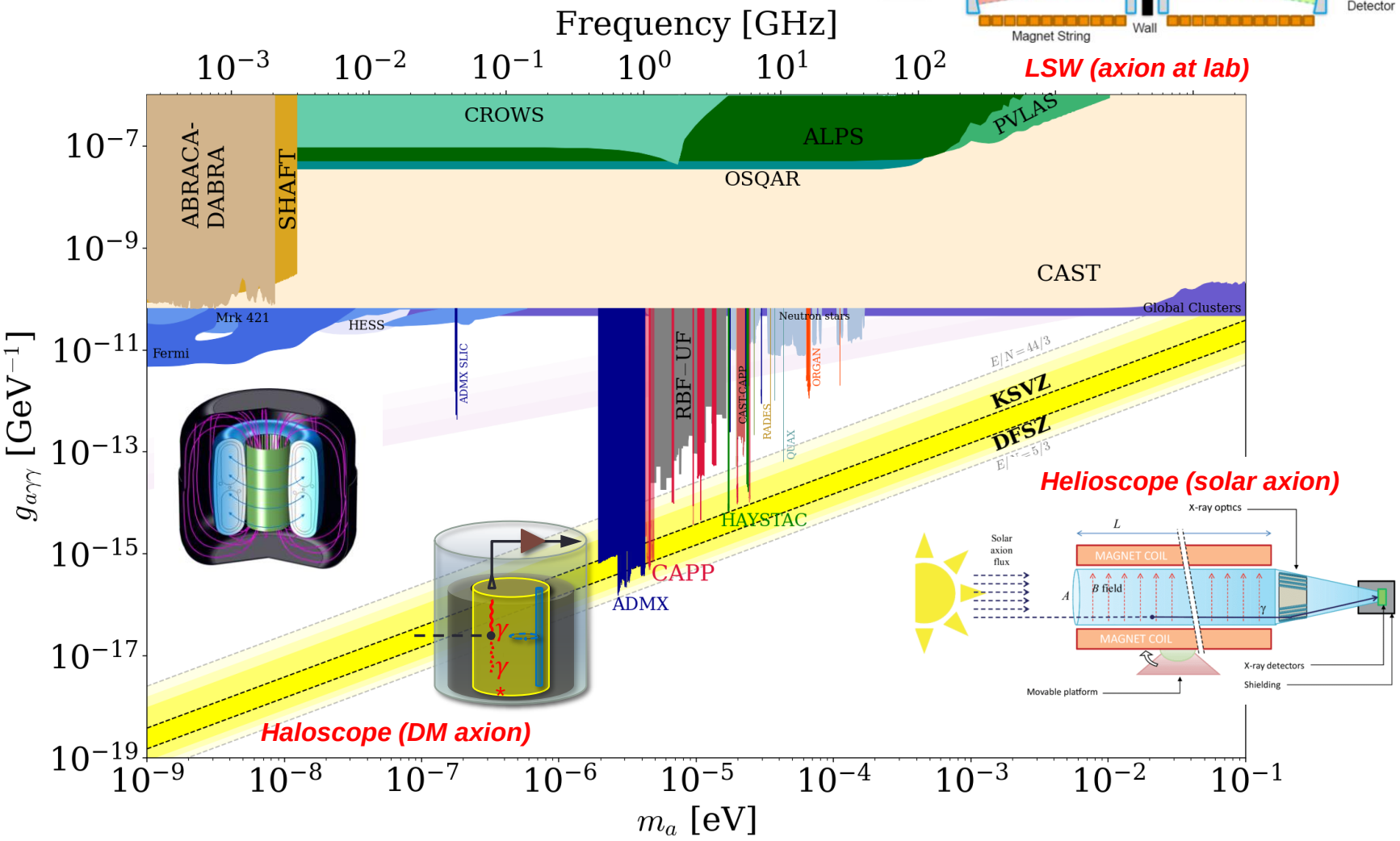
- *Detection principle*
  - *Sikivie effect (1983): macroscopic Primakoff effect*



Axion searches

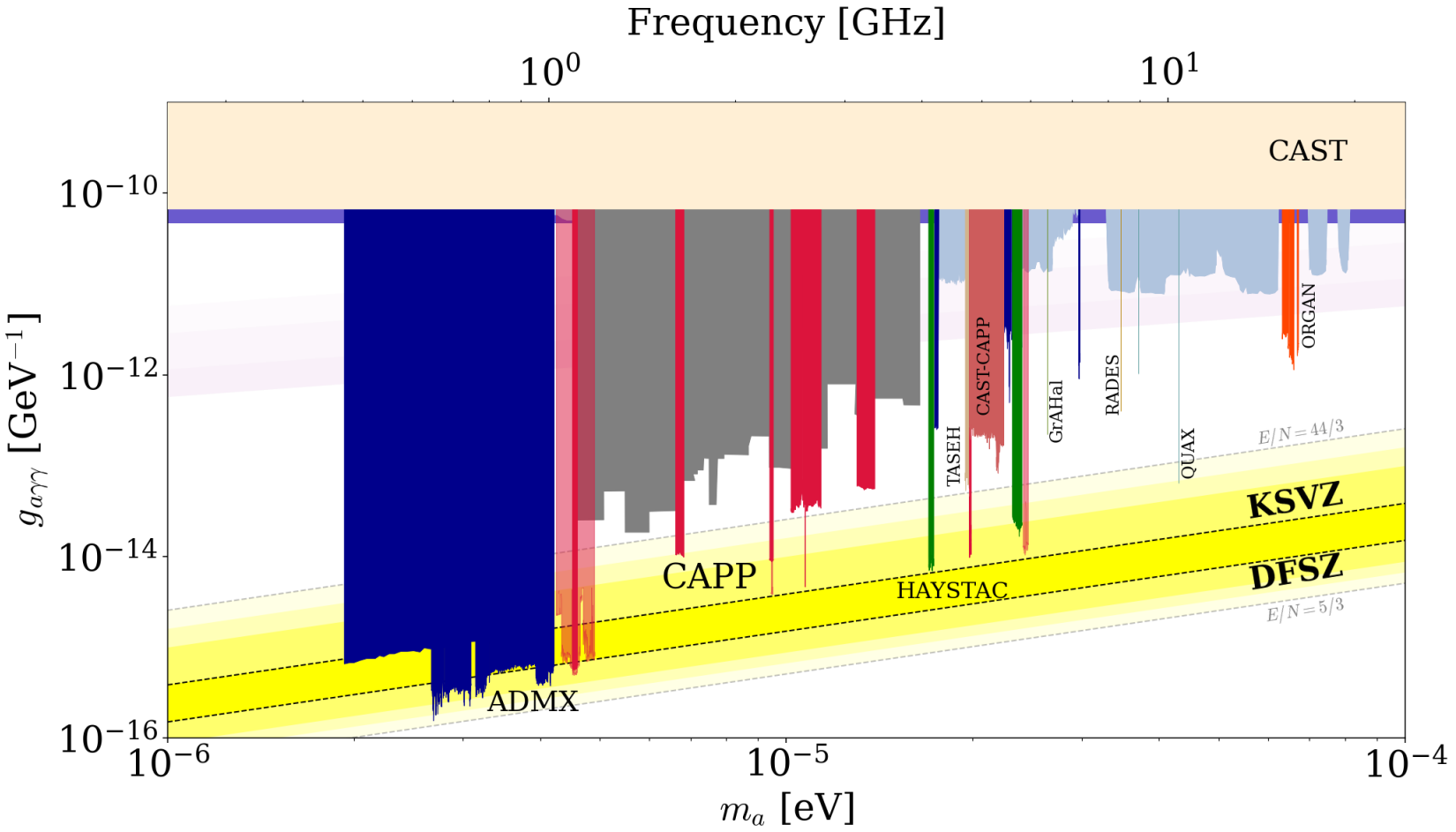


LSW (axion at lab)



Haloscope Searches

Haloscope searches



Detector of halo axions

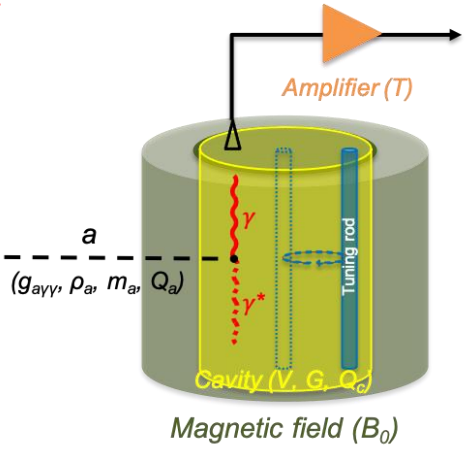
- *Most sensitive approach in μeV regime*
  - *Resonant enhancement of axion-induced photons*

- *Conversion signal power (a→γγ)*

- theoretical parameters
- experimental parameters

$$P_{a\to\gamma\gamma} = g^2_{a\gamma\gamma}\frac{\rho_a}{m_a}B^2 V C_{mnp}\min(Q_L, Q_a) \sim 10^{-21}\,W$$

Coupling constant
Axion number density
Magnetic field
Effective volume
Cavity Q factor
Axion Q factor



- *Signal-to-noise ratio (SNR)*

$$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}}\sqrt{\frac{t_{\rm int}}{\Delta f_a}}$$

Integration time
Axion bandwidth ($\sim 10^{-6} f$)
System noise temperature

- *Scanning rate (F.O.M.):*

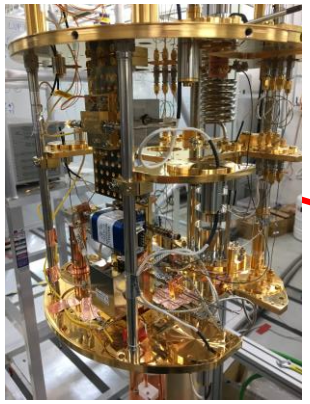
$$\frac{df}{dt} = \left(\frac{1}{SNR}\right)^2\left(\frac{P(f)}{k_B T_{syst}}\right)^2 \cdot \frac{Q_a}{Q_L} \propto B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cavity haloscope – in a nutshell

- *Enhancing the experimental performance*

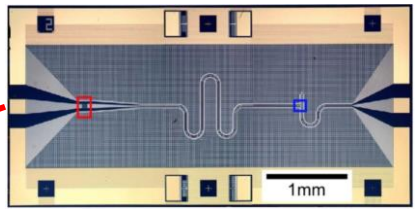
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics *T*

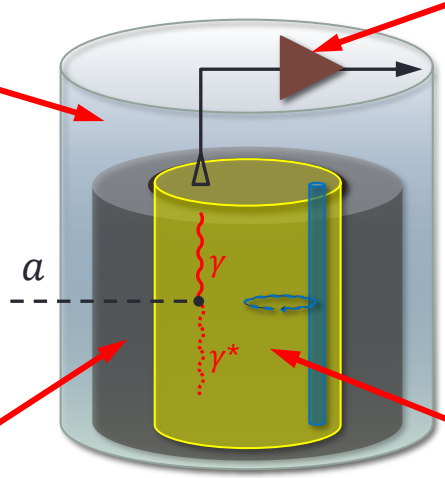


Lowering thermal noise

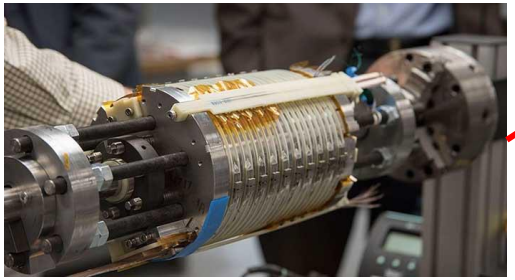
Quantum noise limited amplifier *T*



Signal amplification w/ minimal noise added



High field Magnet *B*



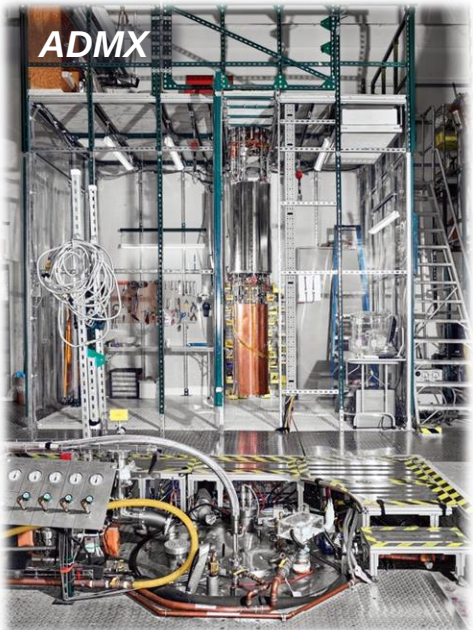
Boosting a→γγ conversion rate

Tunable High-Q resonator
V, Q, C, Δf

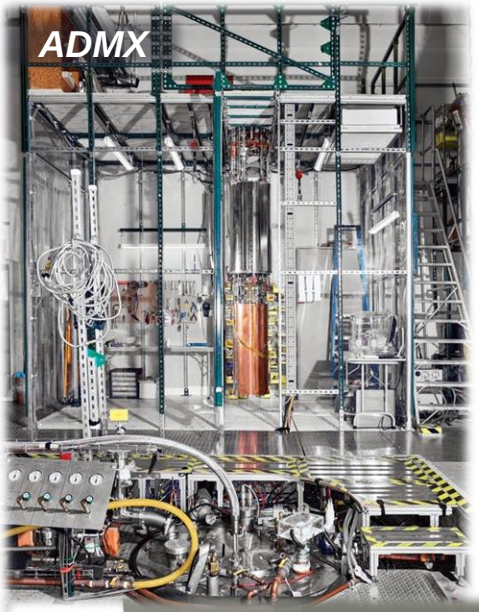
Resonant frequency tuning

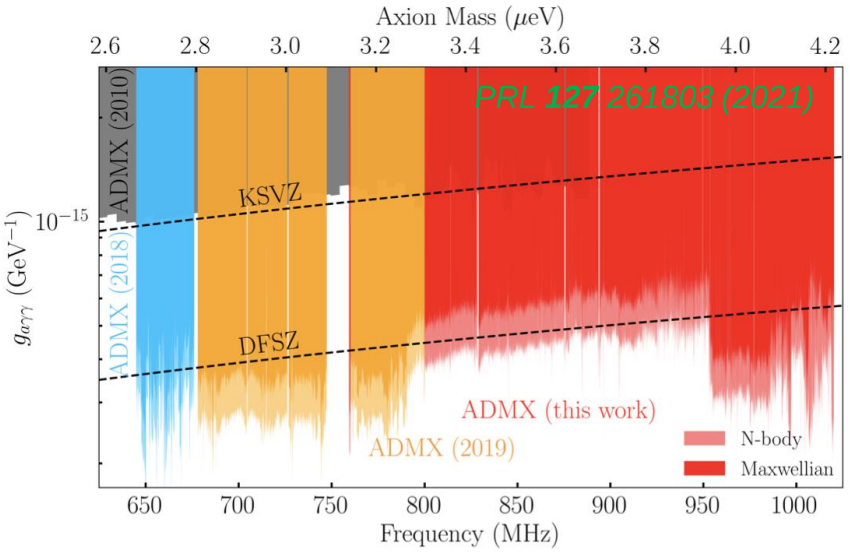
Small-scale experiments!

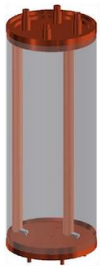
Cavity haloscopes



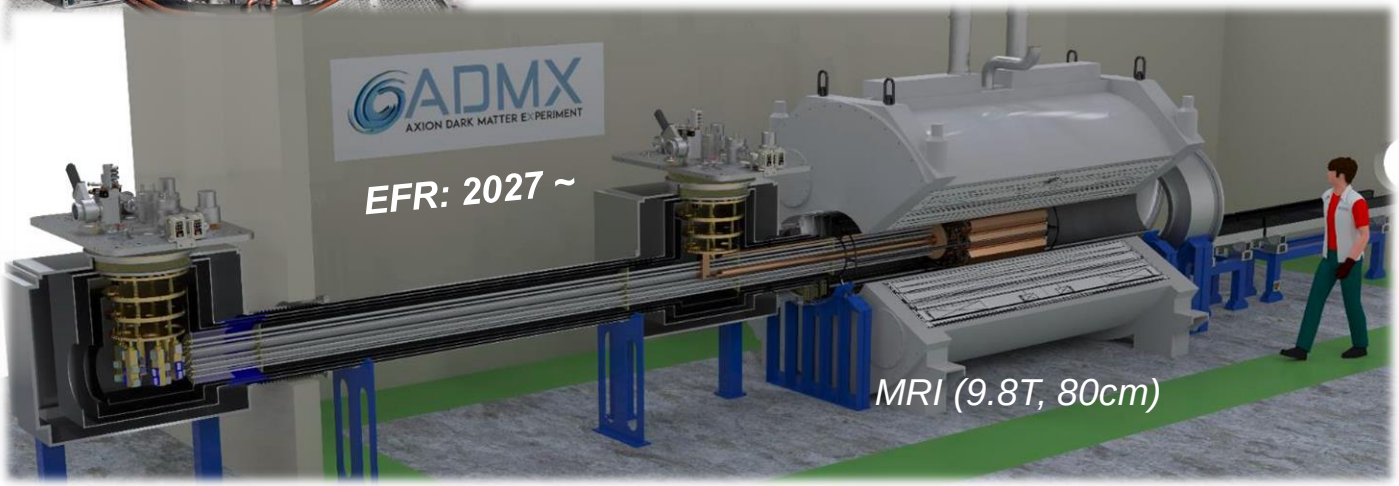
ADMX

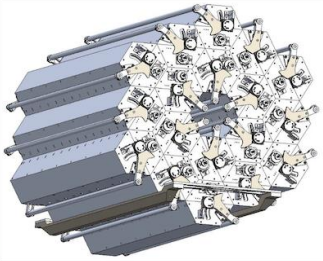





Run 1A-C

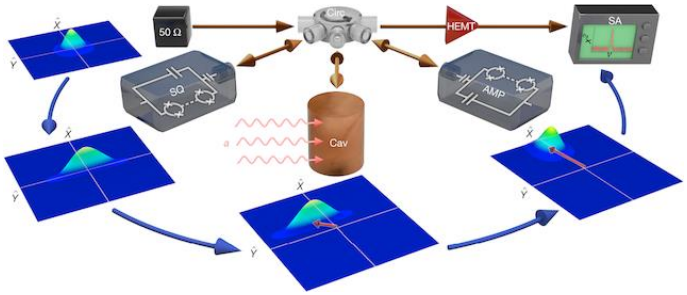

Run 2




EFR

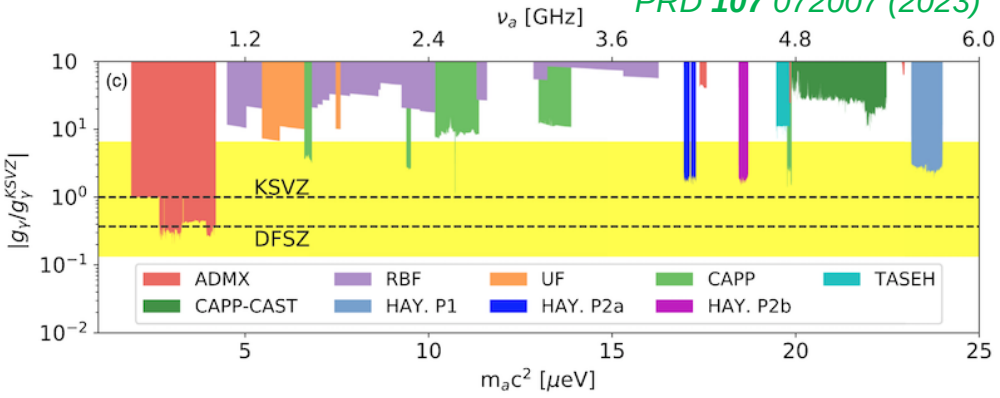
HAYSTAC

*Nature **590** 238 (2021)*

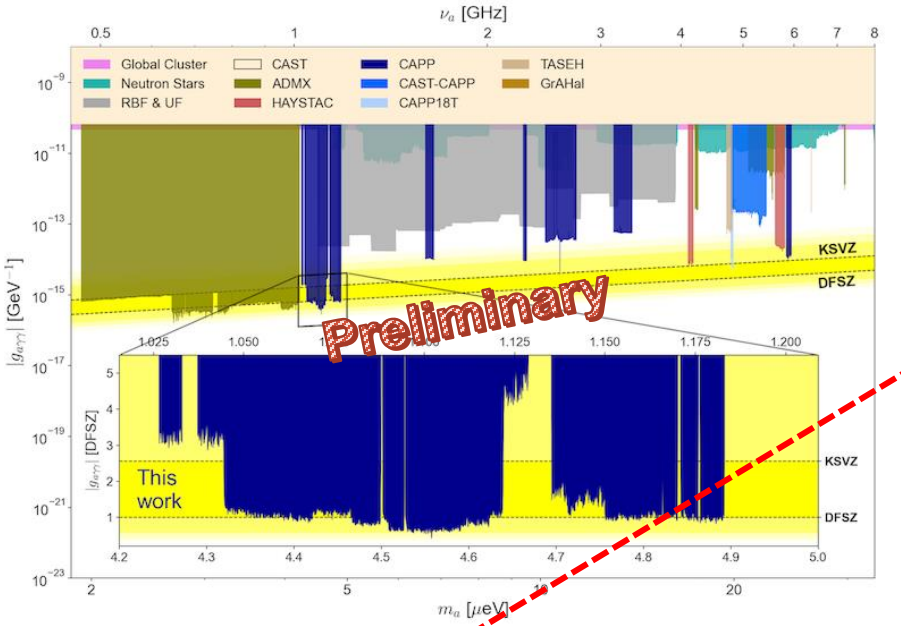


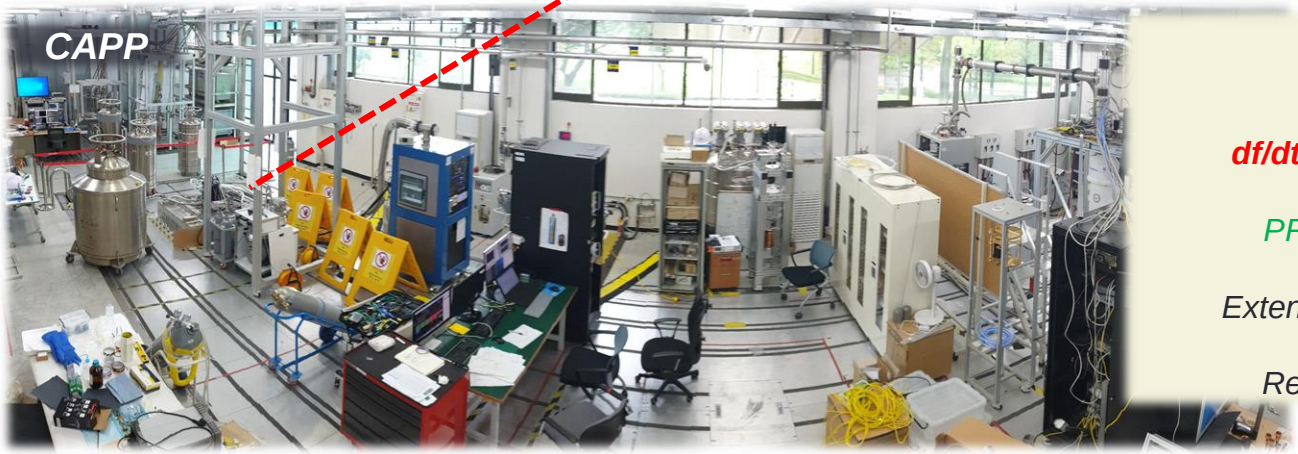
Quantum squeezing ($T_N < T_{SQL}$)

*PRD **107** 072007 (2023)*



CAPP





CAPP-12TB

(12T/320mm)

T_{sys} < 250 mK

df/dt~1.5 MHz/day @ DFSZ

DFSZ club!

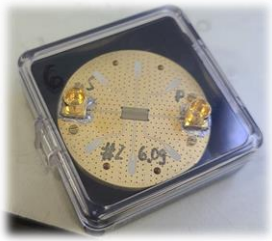
PRL 130 071002 (2023)

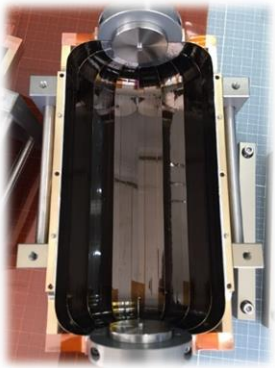
Extended scan (Δf~120 MHz)

to be published

Ready for up to 1.5 GHz

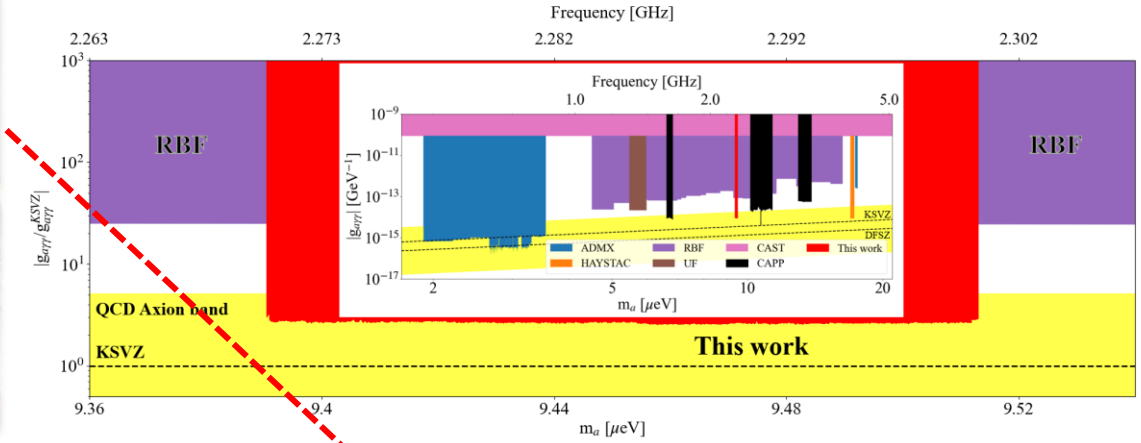
CAPP

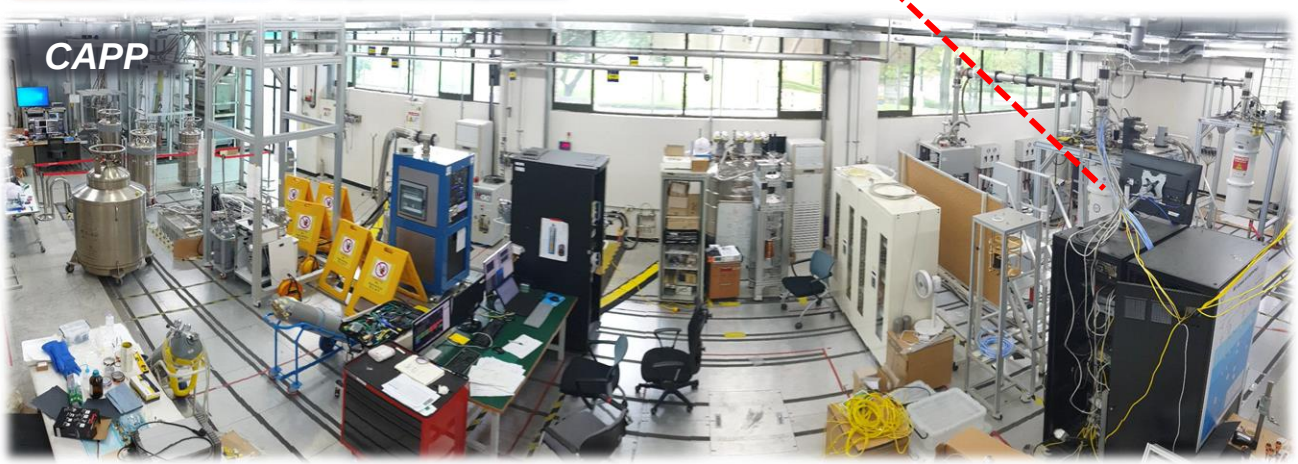




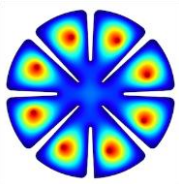
CAPP-PACE
(8T/125mm)
JPA (T_{sys} ~ 200 mK)
PRL 130 091602 (2023)

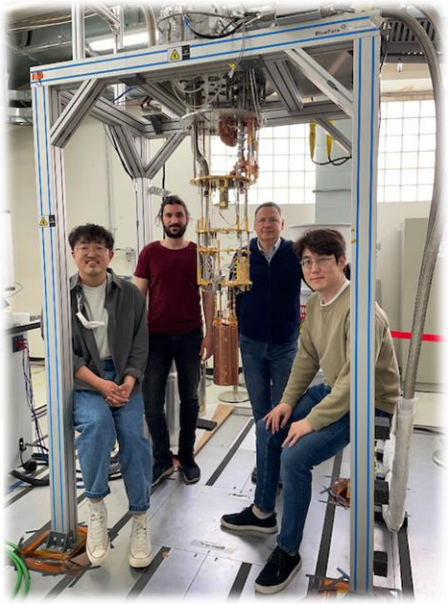
HTS SC cavity *(Q ~ 0.5 M)*
KSVZ
To be published



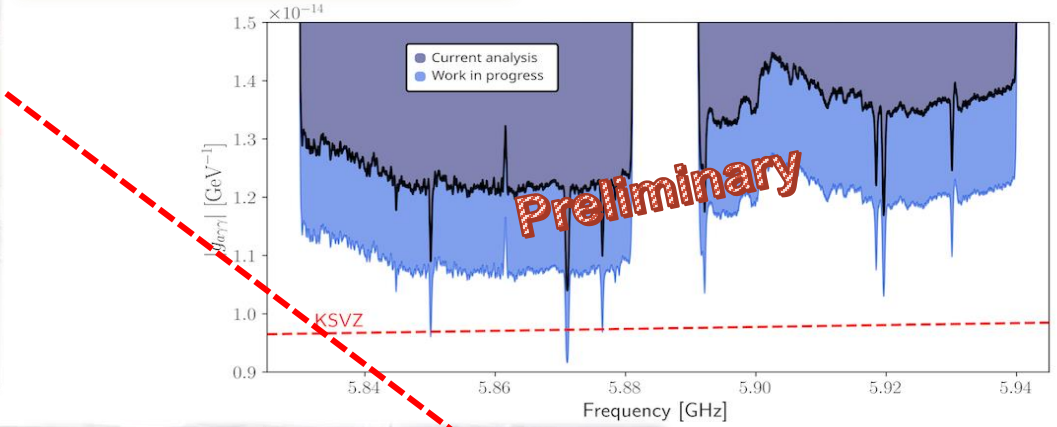


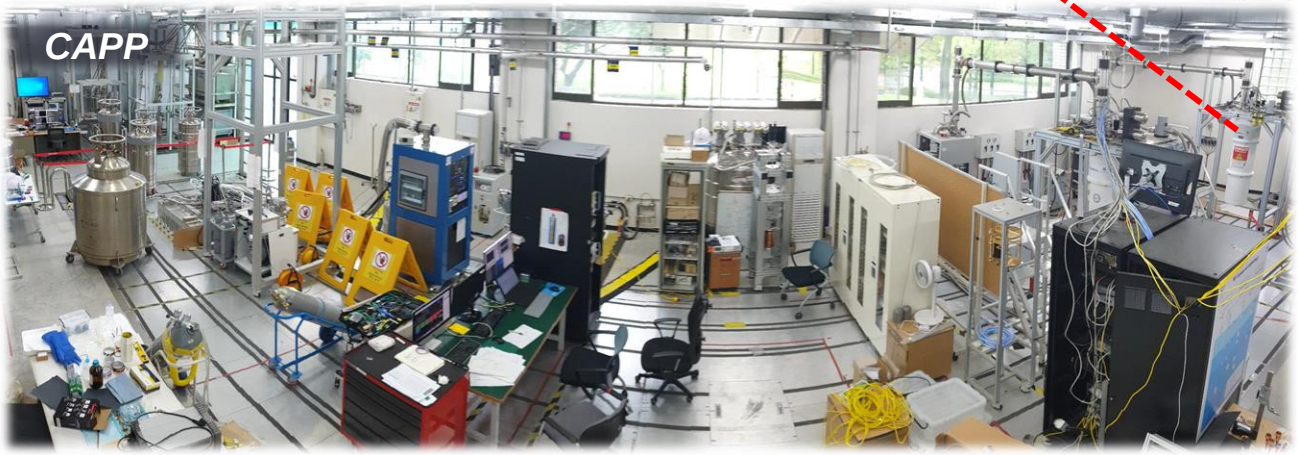
CAPP





CAPP-8TB
(8T/165mm)
8-cell pizza cavity
T_{sys} ~ 400 mK, KSVZ @ 6 GHz
To be published

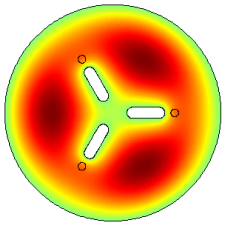


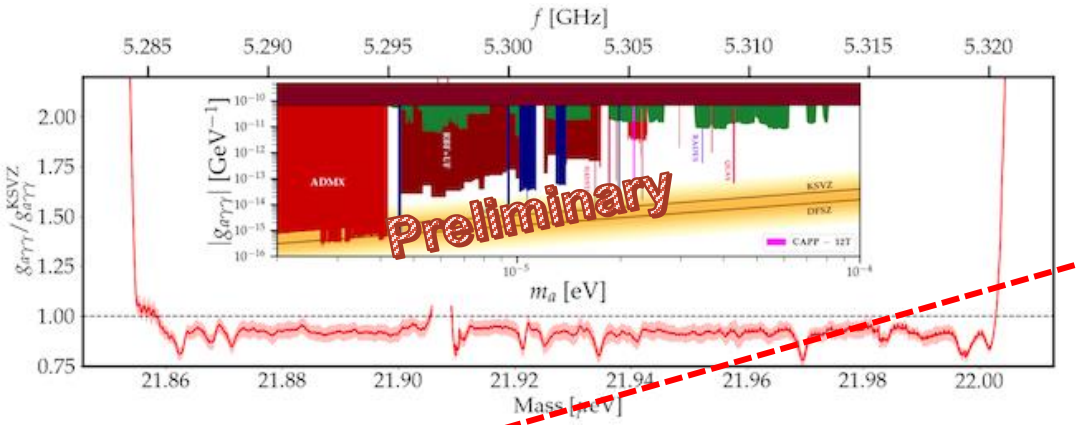


CAPP

Photonic crystal (f~10 GHz)
Physics run this Fall

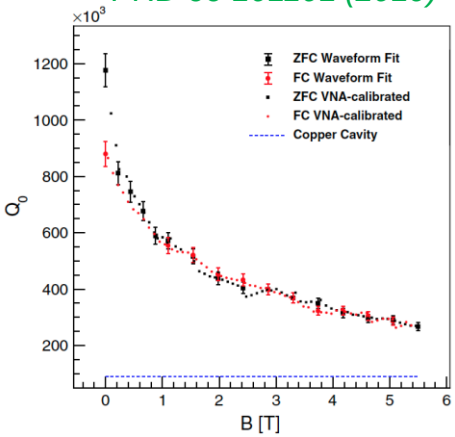
CAPP-12T & 9T
(12T/96mm & 9T/127mm)
3-cell pizza cavity
KSVZ run just decommisioned



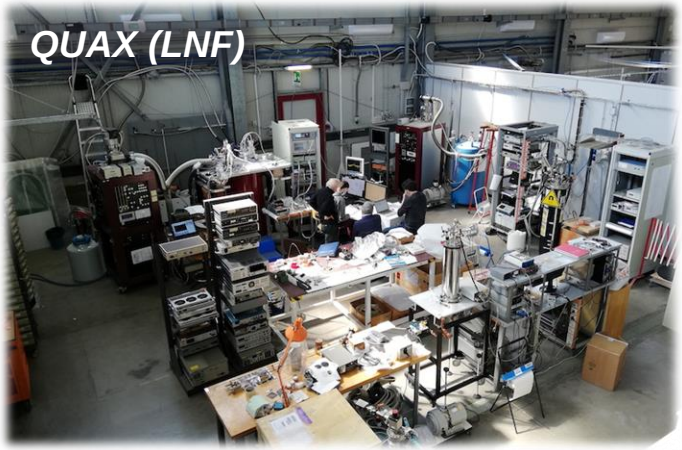


QUAX

PRD **99** 101101 (2019)

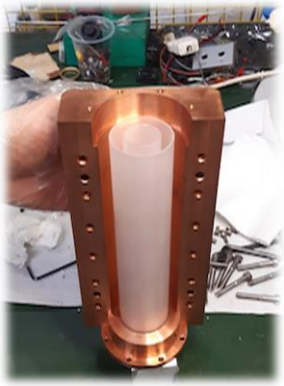


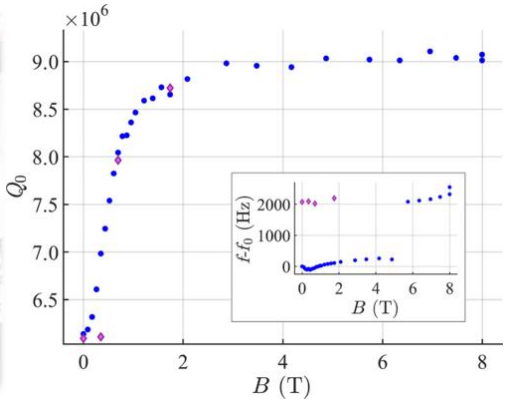
SC (NbTi) cavity

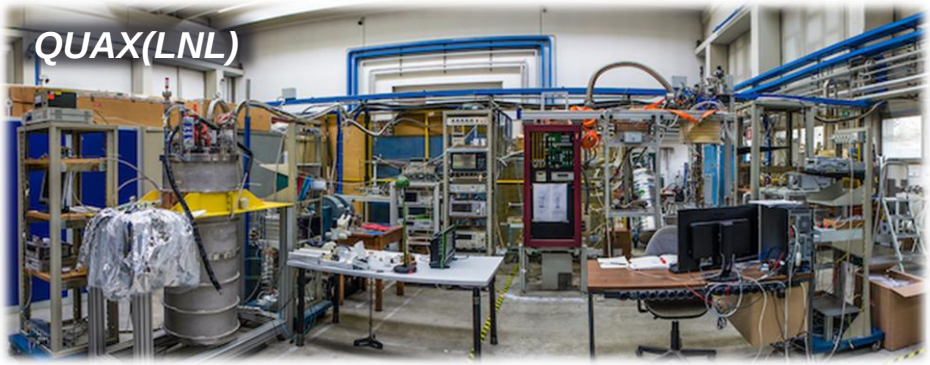


Dielectric cavity

PRApplied **17** 054013 (2022)







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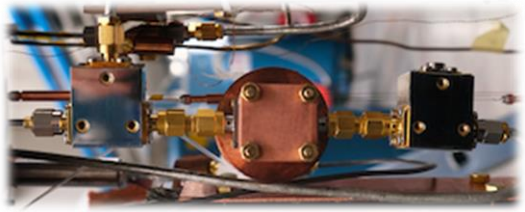
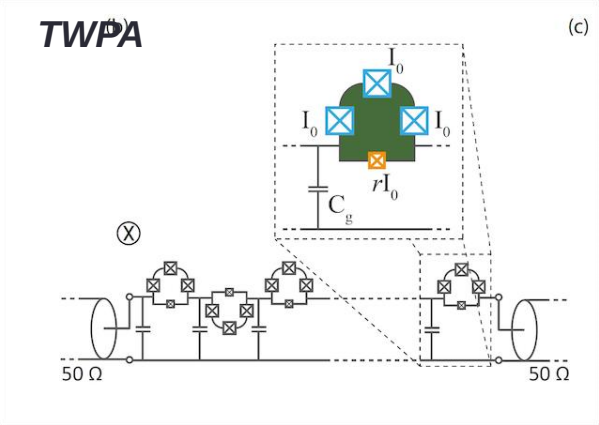
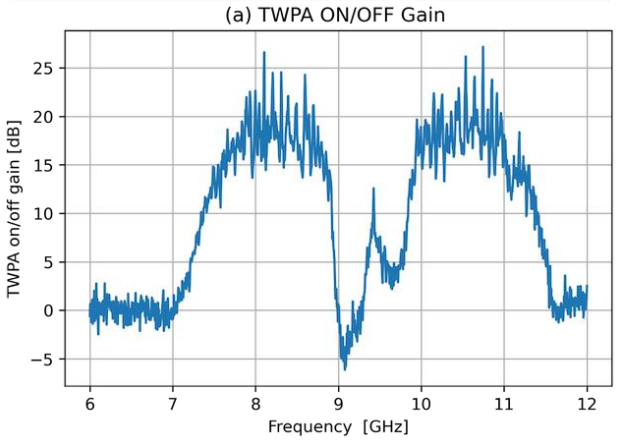
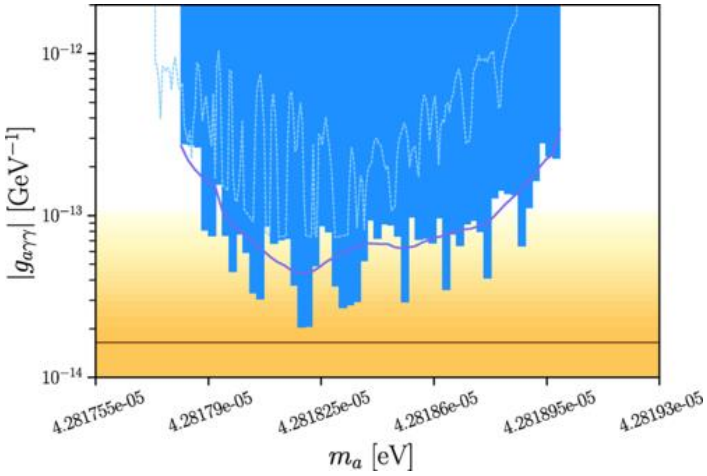
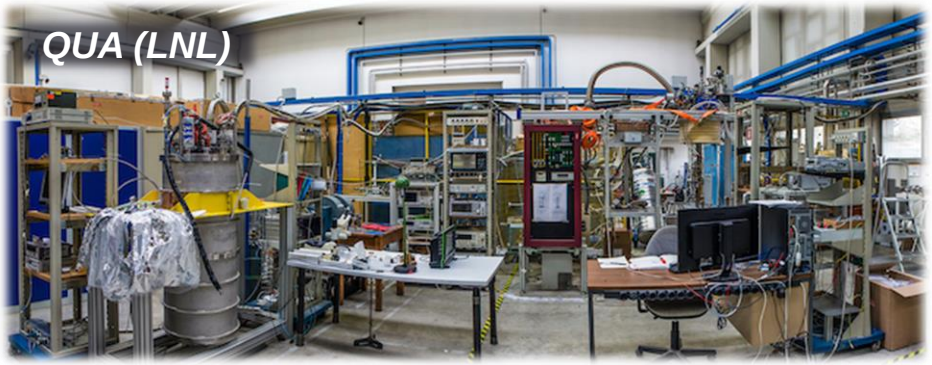






*PRD **108** 062005 (2023)*





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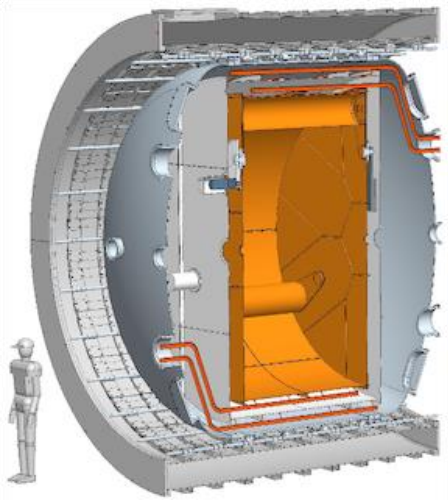
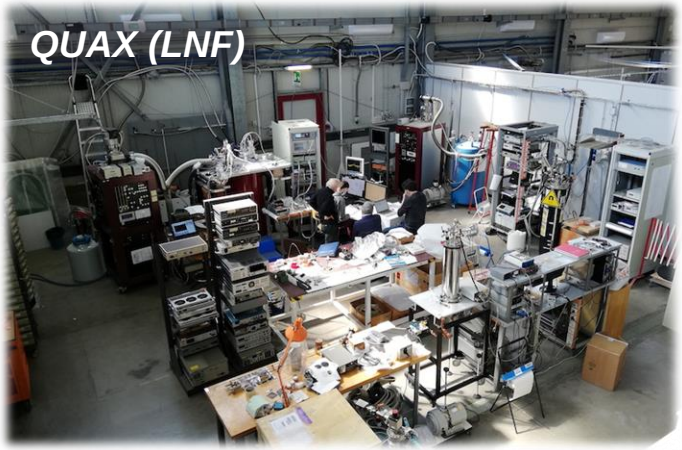


KLASH to FLASH



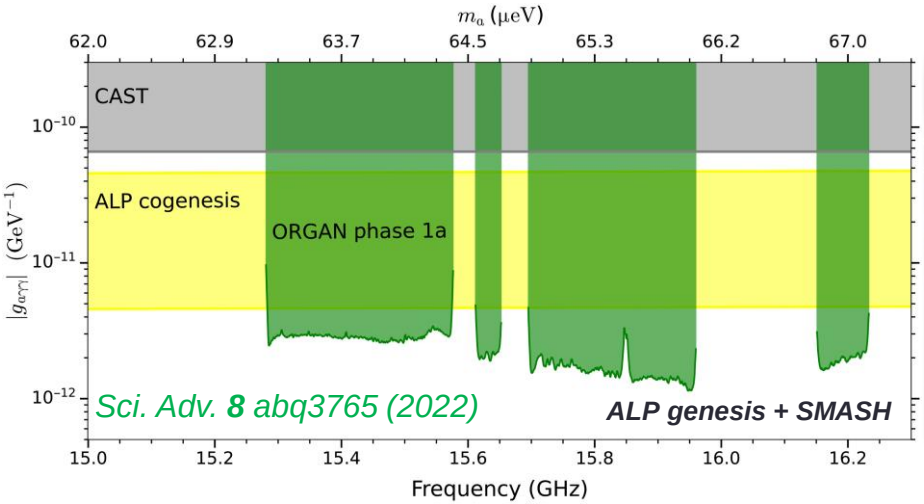
KLOE magnet
B = 0.6 T
R = 2.4 m

⇓

DUNE
(near detector)

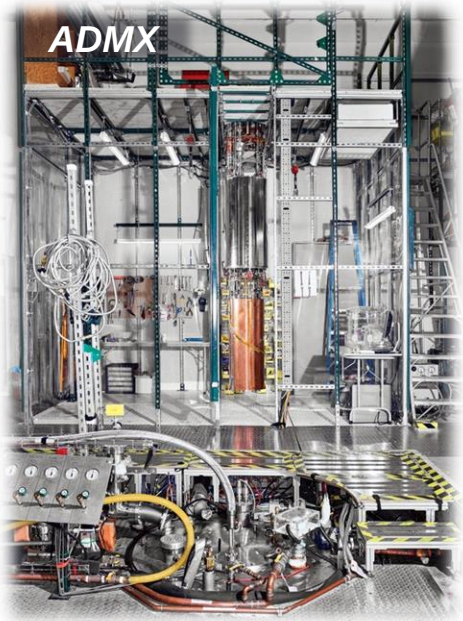
FINUDA magnet
B = 1.1 T
R = 1.4 m

ORGAN


m_a (μeV)
62.0
62.9
63.7
64.5
65.3
66.2
67.0
CAST
ALP cogenesis
ORGAN phase 1a
10^{-10}
10^{-11}
10^{-12}
$|g_{a\gamma\gamma}|$ (GeV^{-1})
Sci. Adv. 8 abq3765 (2022)
ALP genesis + SMASH
15.0
15.2
15.4
15.6
15.8
16.0
16.2
Frequency (GHz)


ORGAN

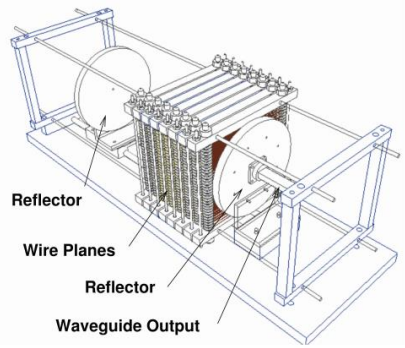
Cavity haloscopes



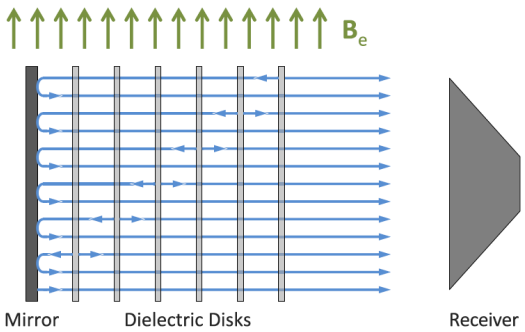
$$1 \lesssim f_a \lesssim 10\ GHz$$

High frequency searches

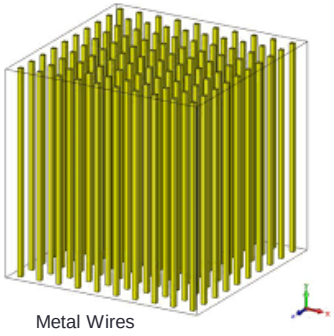
- *Periodic array of dielectric or metal*
  - *Search frequency*
    - *Depending on **interspace***
    - *Independent of detector size*
  - *Large conversion volume*



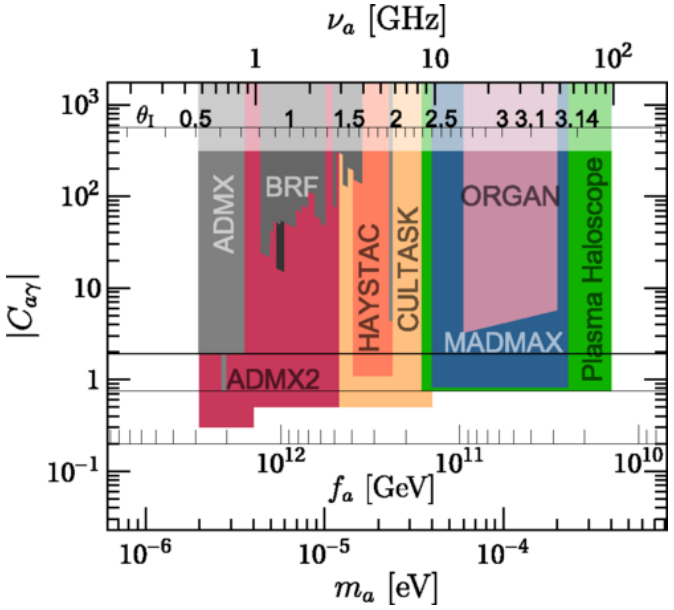
ORPHEUS *PRD **91** 011701 (2015)*



MADMAX
*JCAP **04** 016 (2013)*



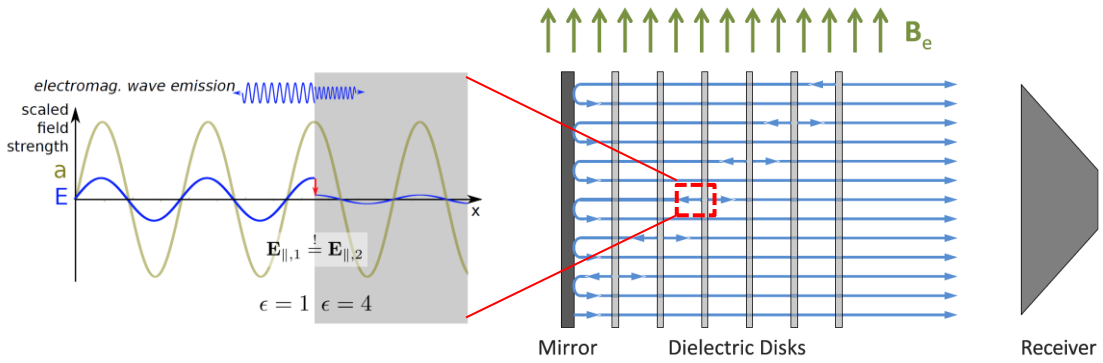
ALPHA
*PRL **123** 141802 (2019)*



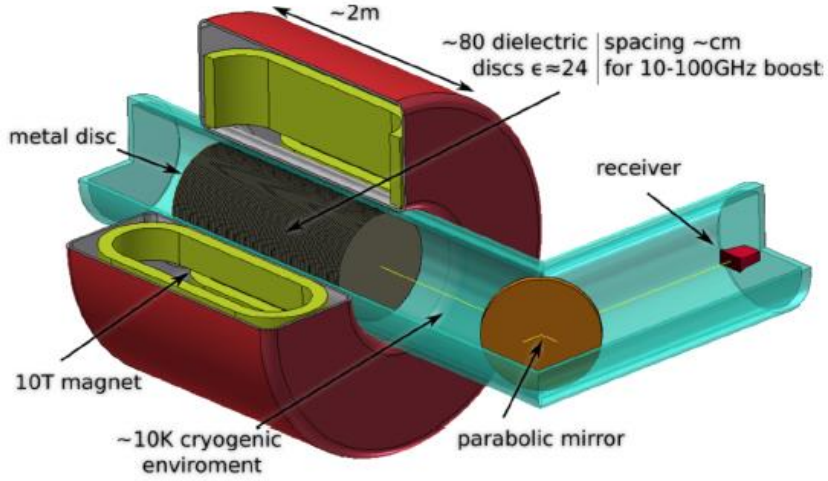
Suitable for post-inflation scenario (10–100 GHz)

MADMAX

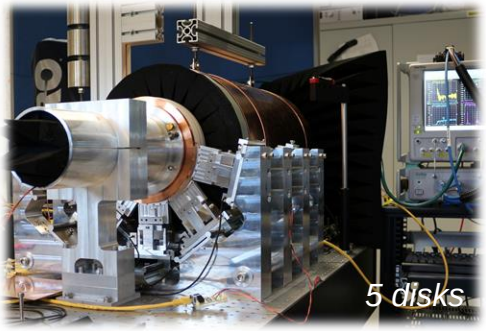
- *Dielectric power booster*



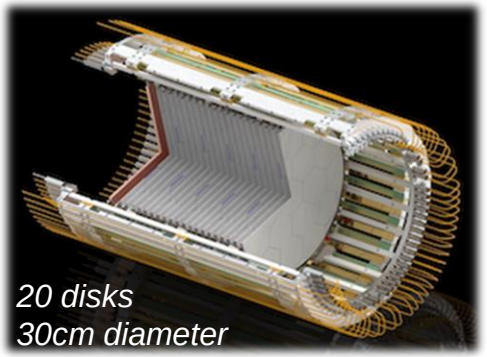
Full scale experiment

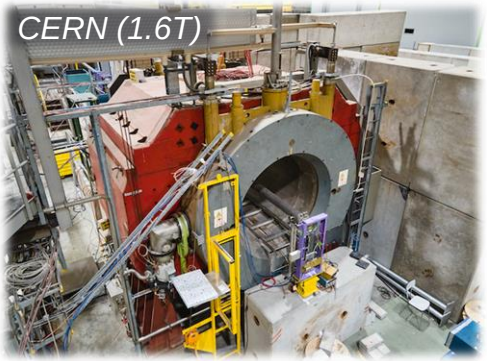


Proof-of-concept



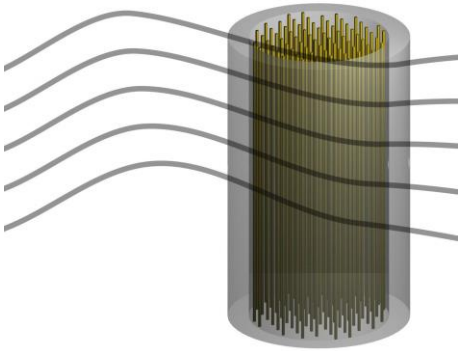
Prototype (2024)





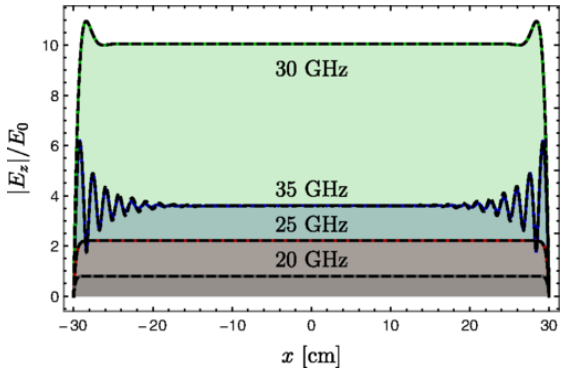
ALPHA

- *Plasma haloscope*

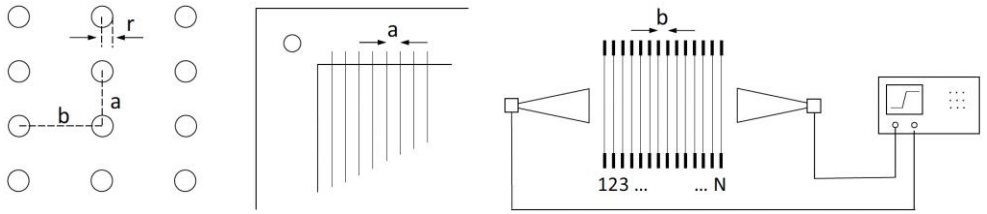


Axion-plasmon interaction

Periodic structure ⟹ Meta-material
Wire array ⟹ bulk plasmon

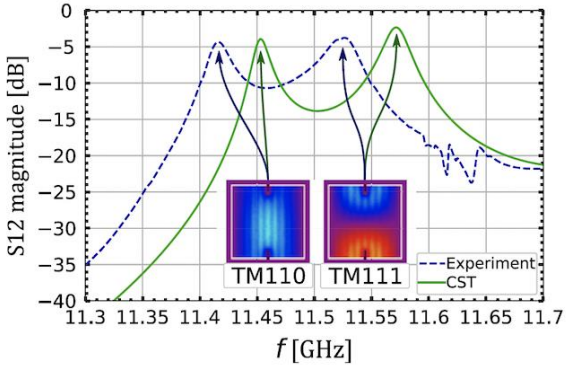


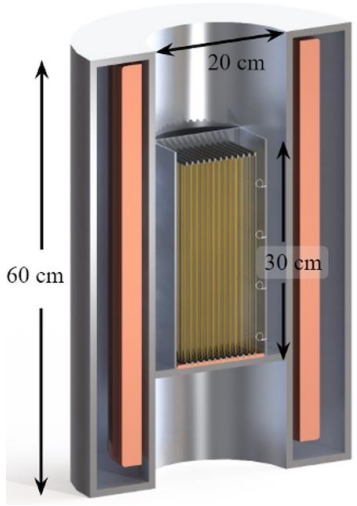
Frequency tunable



$$\omega_p^2 = \frac{n_e e^2}{m_e} = \frac{2\pi}{b^2 \log(\frac{b}{r})}$$

*PRD **107** 055013 (2023)*





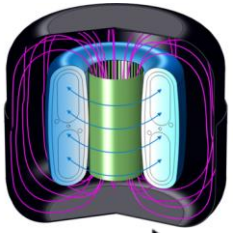
Physics data in 2026

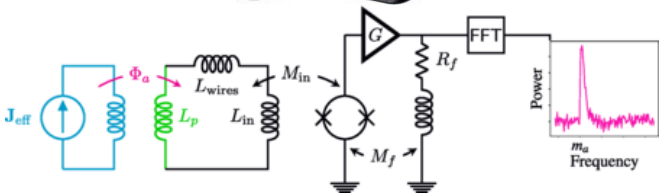
Lumped element haloscope

- *Broadband low mass search (< 1 ueV)*
  - *Sensitive to pre-inflation axions*

ABRACADABRA-10cm

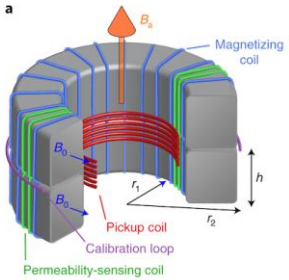
*PRL **127** 081801 (2021)*

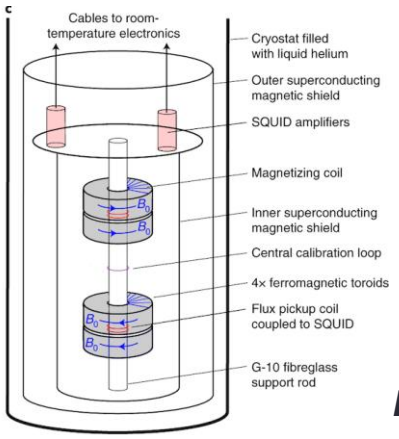




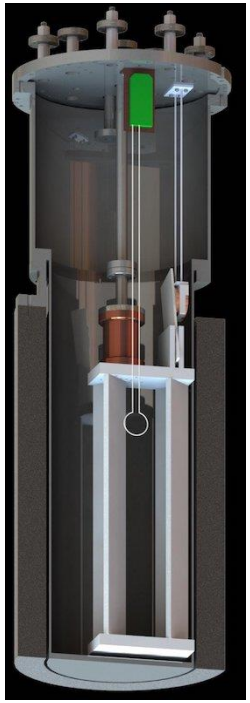
SHAFT

Nature Phys. 17, 79 (2021)



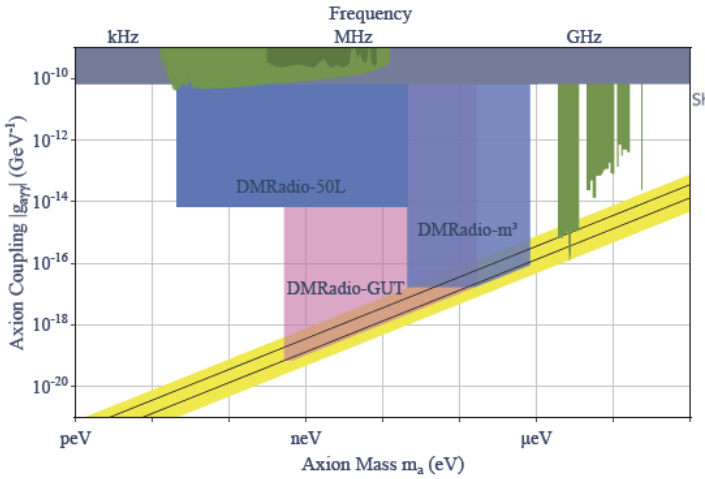


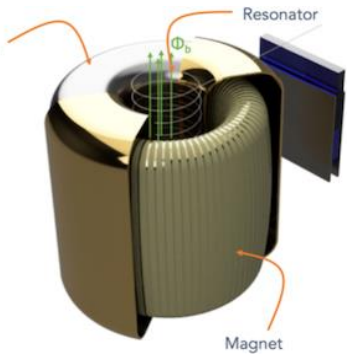
ADMX SLIC



PRL124, 241101 (2020)

DM Radio





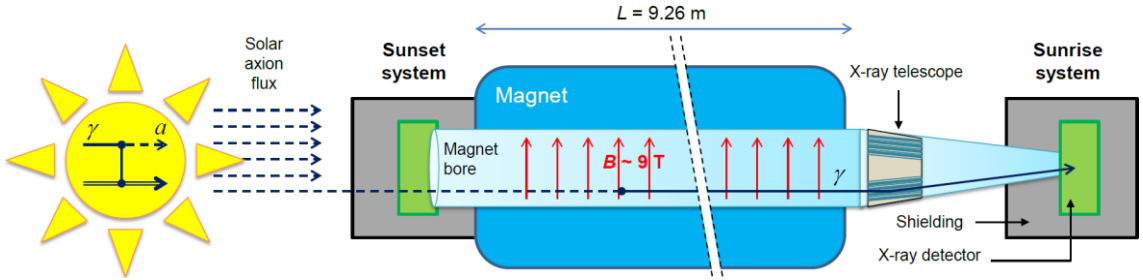
Other haloscopes

- *Recent*
  - *CAST-CAPP: phase-matched cavities, ~20 ueV* — Nat. Comm. **13**, 6180 (2022)
  - *RADES: microwave fiber, ~34 ueV* — JHEP **2021** 75 (2021)
  - *Grenoble Axion Haloscope* — arXiv:2110.14406
    - *14T/52mm magnet, ~26 ueV*
  - *Taiwan Axion Search Experiment with Haloscope* — PRL **129** 111802 (2022)
    - *4.7 GHz, 11 x* g_{arr}^{KSVZ}
  - *Superconducting axion search*
    - *SC cavity, 14T, 8.4 GHz (under construction)*
- *Proposed*
  - *Broadband Reflector Experiment for Axion Detection* — PRL 128 131801 (2022)
    - *Parabolic reflector, THz region*
  - *Canfranc Axion Detection Experiment* — JCAP **11** 044 (2022)
    - *90 GHz (W-band), Kinetic Induction Detectors*

Helioscope Searches

Helioscope

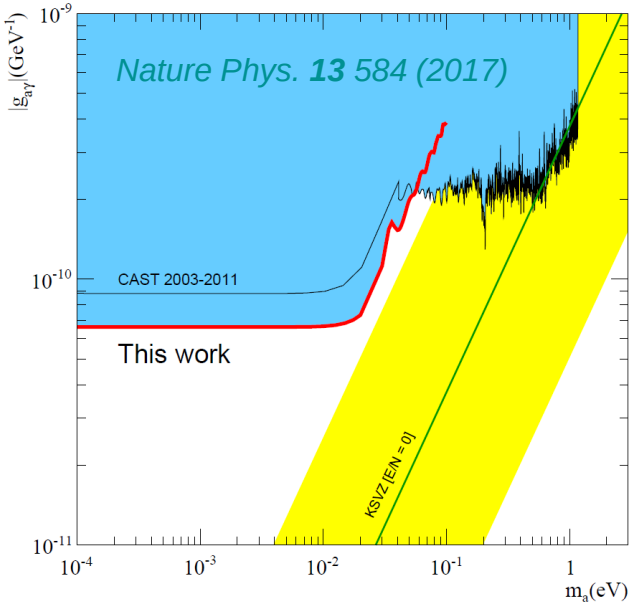
- *Solar axion telescope*



Black-body photons (keV) to axions in dense stellar plasma

Reconversion into photons (X-ray) in laboratory magnetic fields

$$\mathcal{P}_{a\to\gamma} \sim \left(\frac{g_{a\gamma\gamma}B_0}{q}\right)\sin\left(\frac{qL}{2}\right), \qquad q \equiv \frac{m_a^2}{2E_a}$$

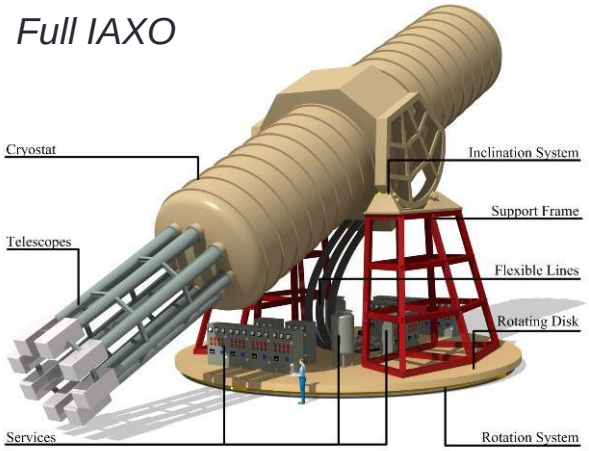


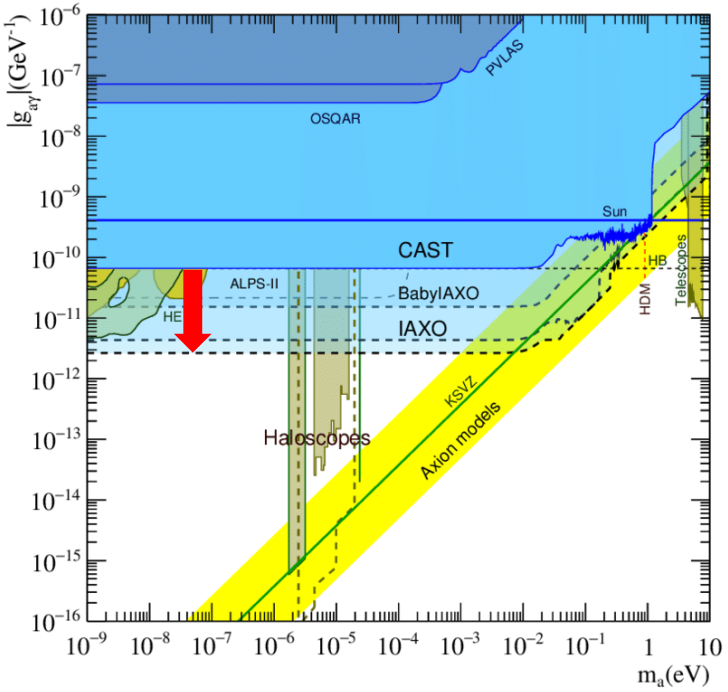
- *History*
  - *BNL, JAPAN*
  - *CAST completed in 2015*
  - *IAXO in plan*

IAXO

- *International AXion Observatory*
  - *Large toroidal helioscope*
    - *8 dipoles (5.4 T, 20 m, 600 mm)*
  - *Diverse physics over wide range*
    - *QCD axions / ALP miracle (DM & inflation)*
    - *Astrophysical hints*
  - *Goal :* $g_{a\gamma} \sim 10^{-12}\ GeV^{-1}$

Full IAXO



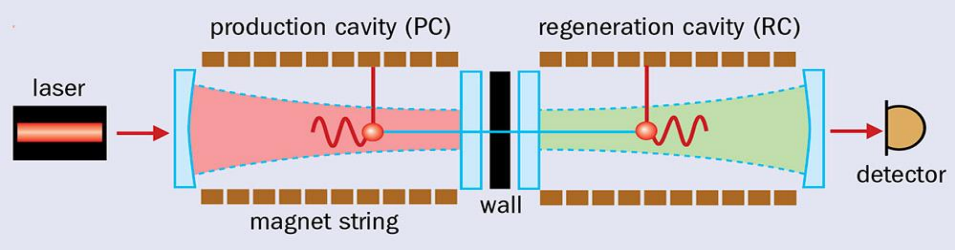


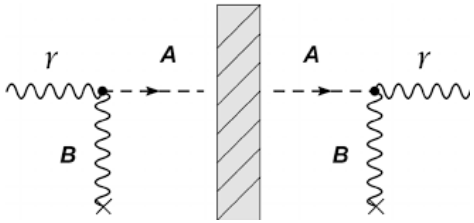
- *Baby-IAXO*
  - *Approved in 2020 (DESY)*
  - *First step towards full IAXO*
    - *4 T / 10 m long => 10 x CAST*

Laboratory Searches

Light shining through a wall

- *Axion production at laboratory*

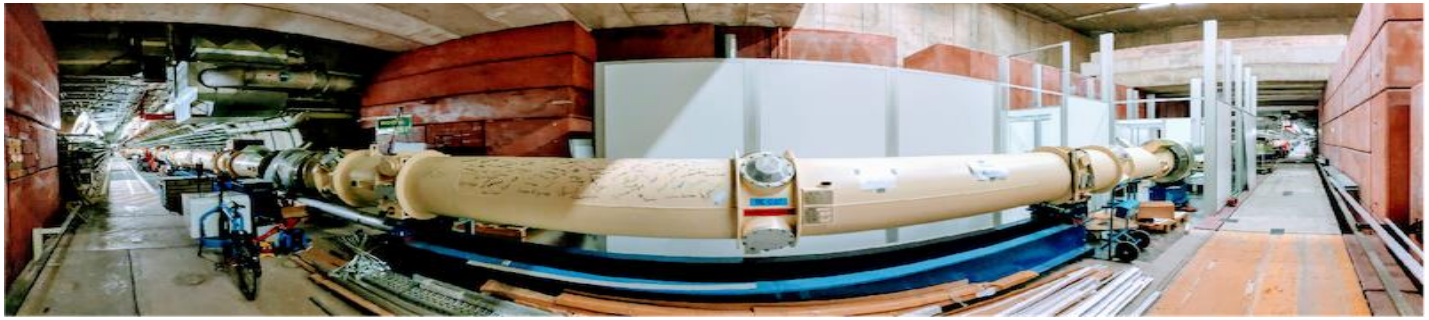




Two vertices => fourth power of coupling

  - *Model independent search*
    - *No need of cosmo./astrophys. source*
    - *cf. halo(helio)scope search needs density(flux)*

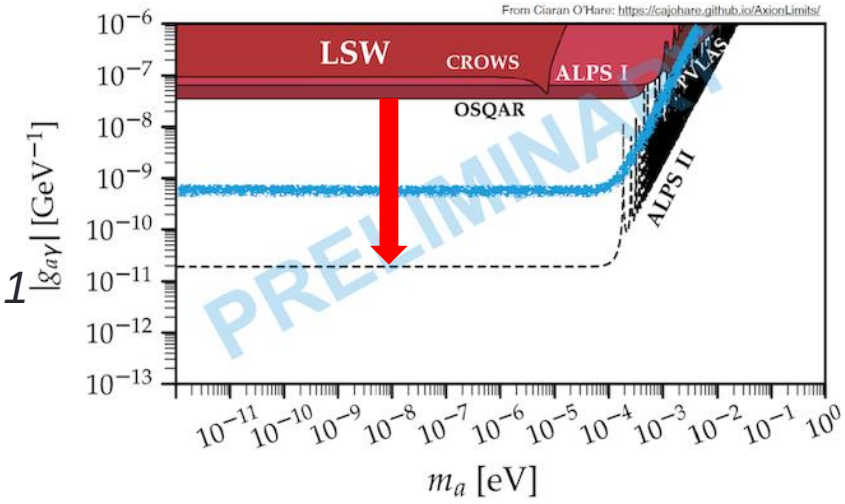
- *History*
  - *BFRT (Brookhaven-Fermilab-Rochester-Trieste)*
  - *OSQAR (LHC dipole at CERN) – most stringent limit*
  - *ALPS (HERA dipole at DESY)*



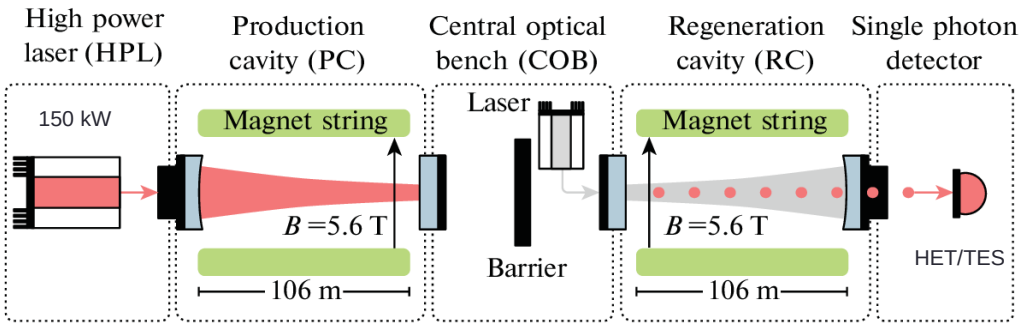
ALPS II

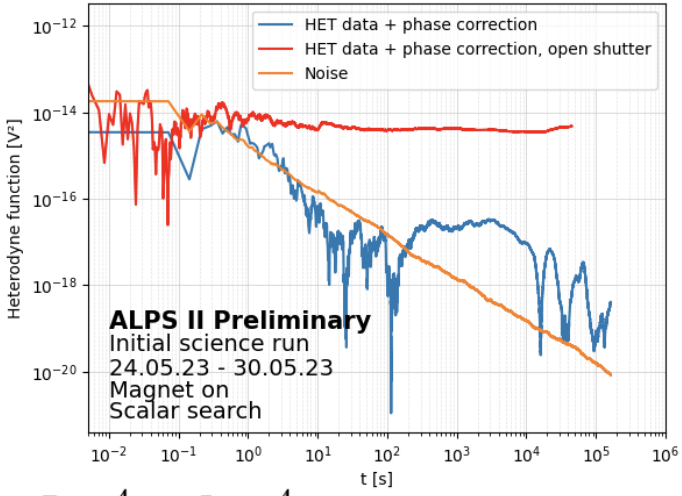
Early science run
(May 23rd t0 31st)

- *Any Light Particle Search II*
  - *2 x 12 Hera dipoles (8.8 m & 5.3 T)*
  - *High power laser system*
  - *Dual high-finesse optical cavities*
  - *Photon detector: HET/TES*
  - *Final goal: $g_{a\gamma\gamma} \sim 10^{-11}\ GeV^{-1}$ below 0.1*
    - *Three orders of magnitude of ALPS*



- *Early science run*
  - *May 23rd t0 31st (45 hours data)*
  - *No PC: 30 x ALPS*





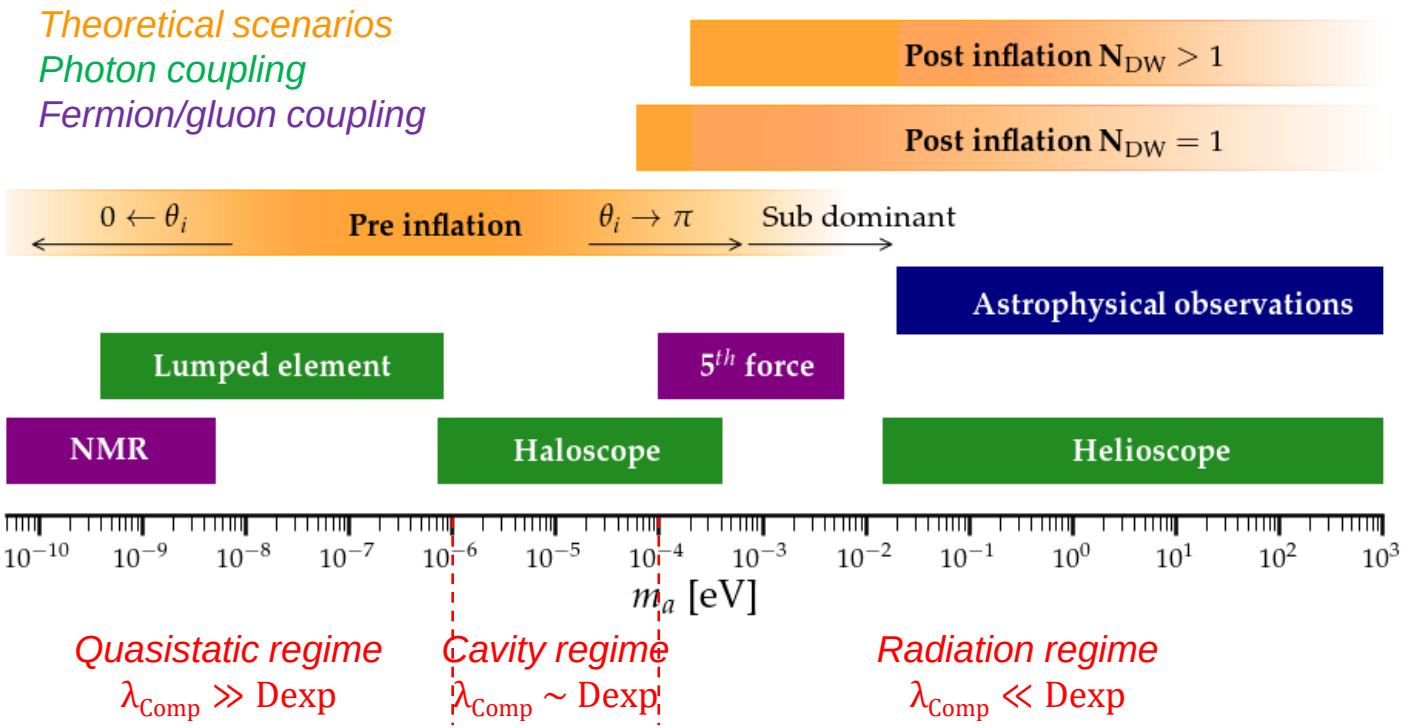
$$n_{\text{signal}} \approx \frac{1 \text{ photon}}{37 \text{ hours}} \cdot \left(\frac{P_{\text{PC}}}{150 \text{ kW}}\right)\left(\frac{\beta_{\text{RC}}}{10{,}000}\right)\left(\frac{\eta}{0.9}\right)\left(\frac{g_{a\gamma\gamma}}{2\times10^{-11} \text{ GeV}^{-1}}\right)^4\left(\frac{B}{5.3 \text{ T}}\right)^4\left(\frac{L}{106 \text{ m}}\right)^4$$

Summary

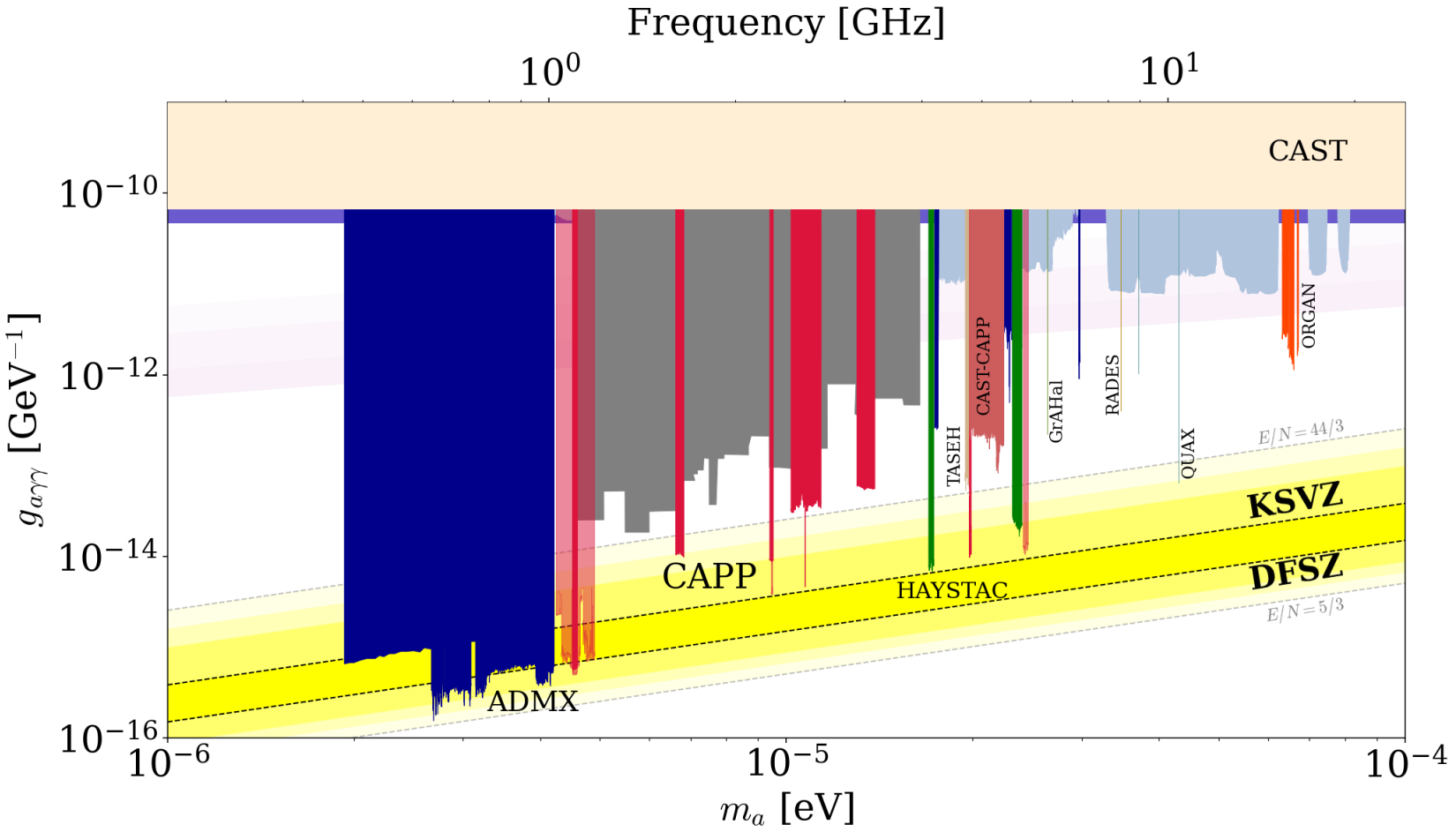
- *Axions address two fundamental questions*
  - *Strong CP problem & dark matter mystery*
- *Theoretically well motivated but experimentally challenging*
  - *Weak coupling and unknown mass*
- *Tremendous search efforts*
  - *Different technologies targeting at different mass ranges*
- *Axion community is getting larger*
  - *New results, new groups and new ideas (during the workshop)*
- *Next a couple of decades must be critical/exciting*
  - *Covering a substantial portion of the parameter space*
  - *Uncovering the nature of dark matter*

Where are dark matter axions?

- *Different PQ breaking scenarios*
  => Different mass ranges
  => Different search strategies
  (Depending on λ_{Comp} w.r.t. D_{exp})



Haloscope searches

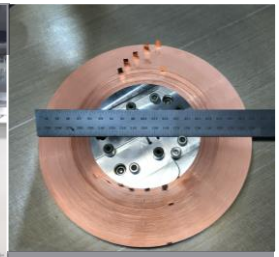


Magnet


ADMX (8T/600mm)

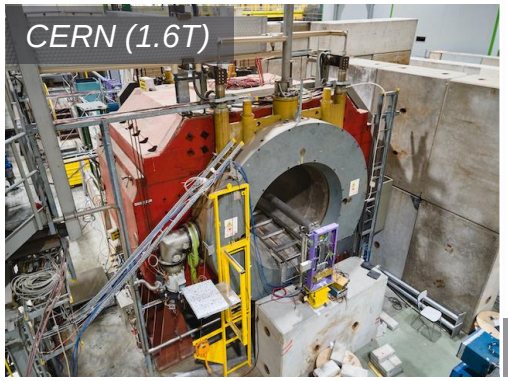

CAPP (12T/320mm)

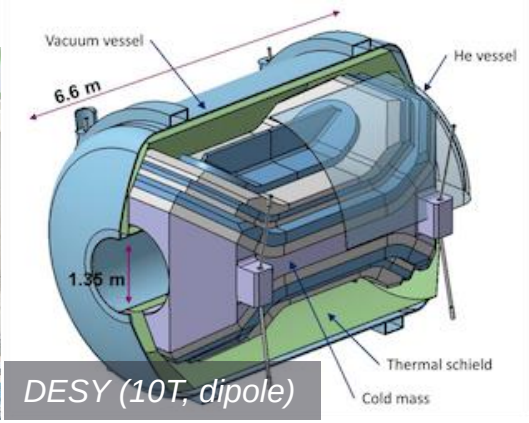

CAPP (18T/70mm)


YBCO pancakes

Grenoble (43T/34mm)

UIC (9.4T/800mm)

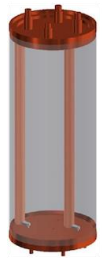

CERN (1.6T)



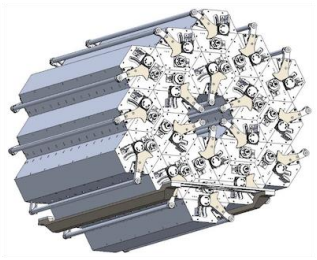
DESY (10T, dipole)

Cavity

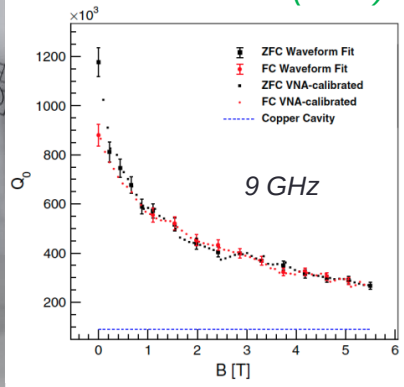
arXiv: 2203.14923


Run 1A-C

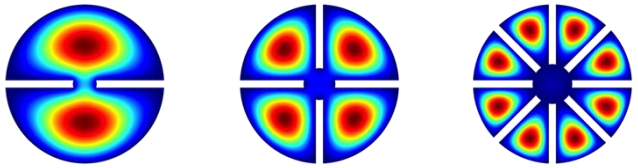

Run 2


EFR

*PRD **99** 101101 (2019)*

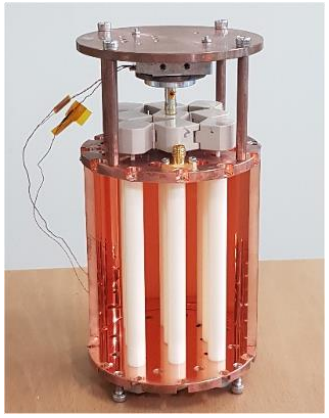


*PRL **125** 221302 (2020)*

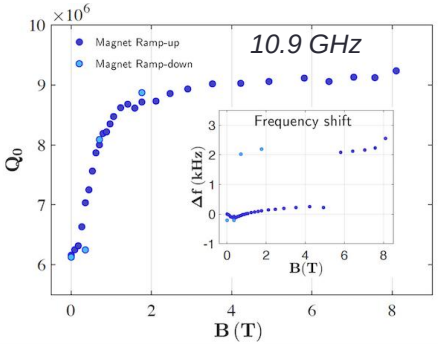


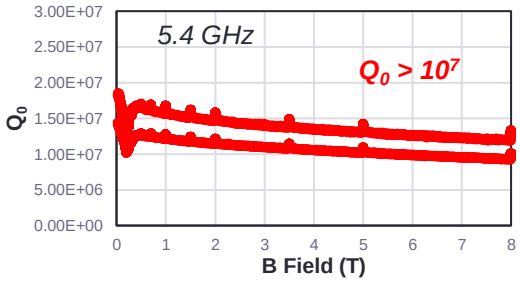
D. Ahn (Tue)

arXiv: 2205.08885



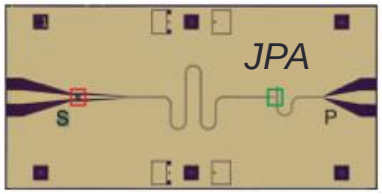
*NIM **985** 164641 (2021)*





Microwave photon detector

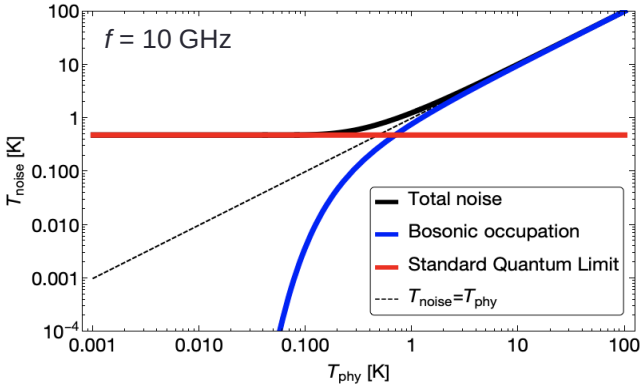
Transistor-based
(T_N ~ K)



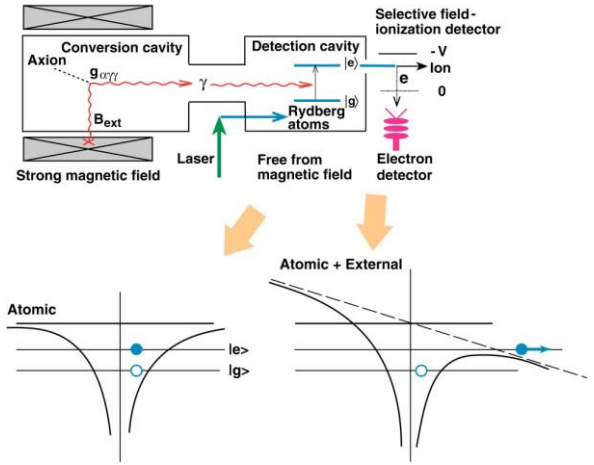
Quantum limited
(T_{SQL} ~ 50 mK x f [GHz])

Power detection vs. photon counting

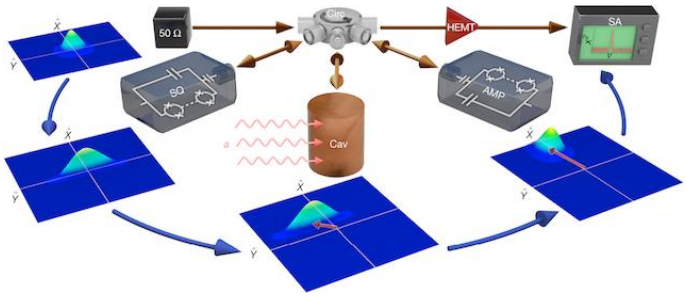
(w/ amplifiers) *(w/ single photon detector)*



Game changer
at high freq. and low temp.

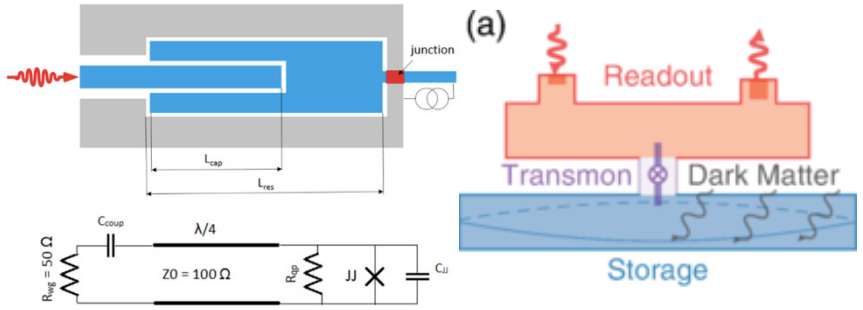


*Nature **590** 238 (2021)*



Quantum squeezing ($T_N < T_{SQL}$)

IEEE TASC 2850019 (2018) *PRL **126** 141302 (2021)*

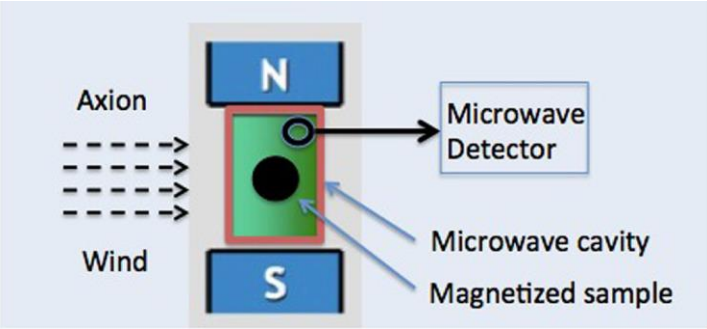


Single photon counting ($T_N << T_{SQL}$)

Fermion coupling

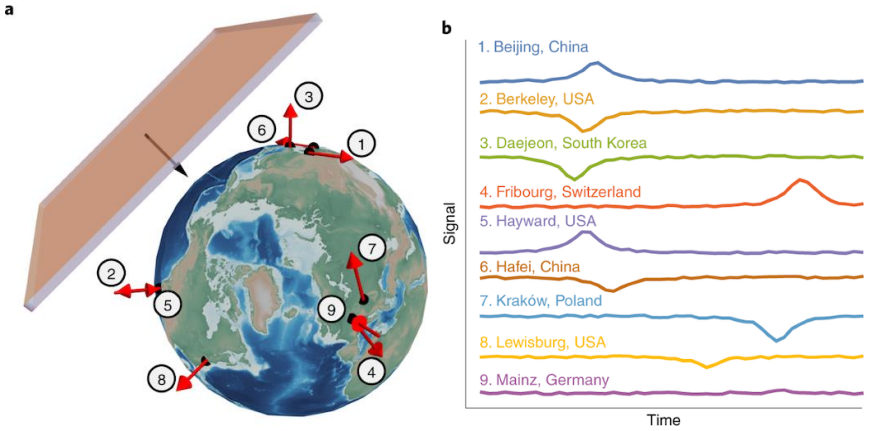
- *QUAX-ae*
  - *Ferromagnetic haloscope*
    - *Axion-electron spin*
  - *Photon-magnon system*
    - *Series of YIG spheres*
    - *TM_{110} of a cylindrical cavity*
  - *Upgraded with JPA*
  - *Best limit near $m_a \sim 43\ \mu eV$*

*PRL **124** 171801 (2020)*



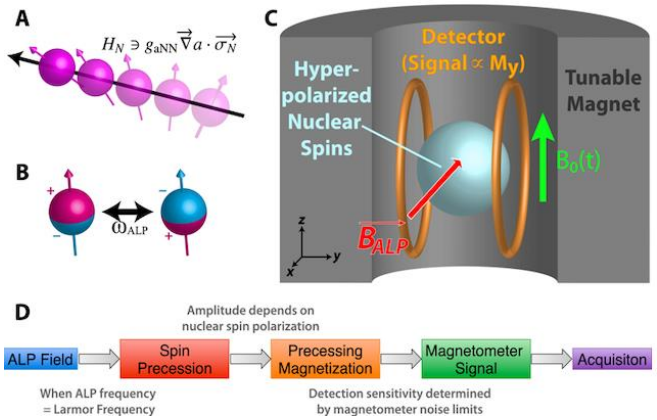
- *LACME*
  - *Low temperature Axion Chiral Magnetic Effect*
    - *Axion-electron coupling, axion as chemical potential for electron* *arXiv:2207.06884*
    - *Correlated signal*

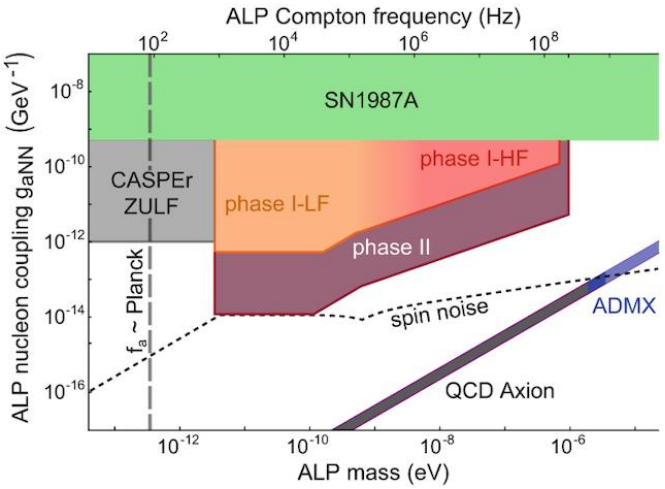
*Nature Phys. **17** 1396 (2021)*

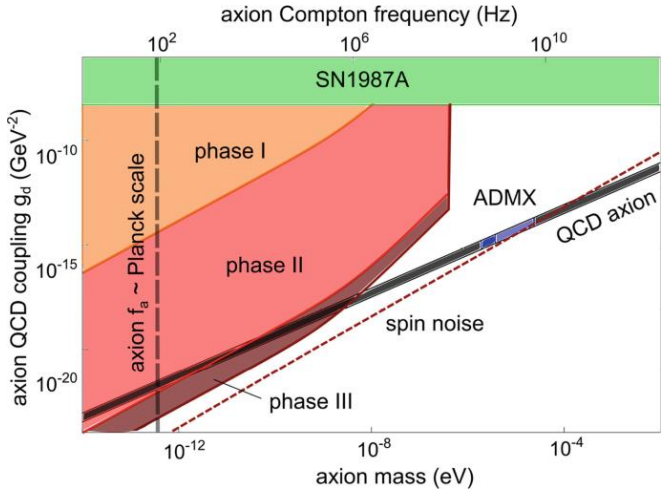


Fermion/EDM coupling

- *Cosmic Axion Spin Precession Experiment* — *H. Bekker, Thu*
  - *CASPEr-wind(gradient)*
    - *Axion-nuclear spin (axion wind)*
  - *CASPEr-electric*
    - *Axion-nEDM (electric field)*
    - *Probe for $aG\tilde{G}$ (QCD axion?)*
  - *Nuclear magnetic resonance*
    - $\omega_L(\propto B_0) = m_a$
    - *Highly sensitive to $m_a < 10^{-8}$ eV*







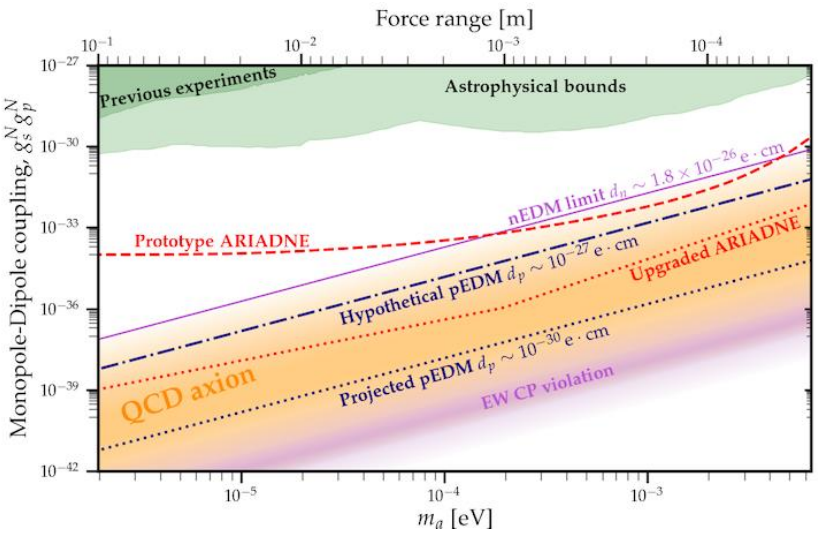
CPV and EDM

- *CPV in QCD*
  - $\theta_{eff} \equiv \theta_{QCD} - \frac{a}{f_a} = 0$
  - *QCD axion => EDM = 0*

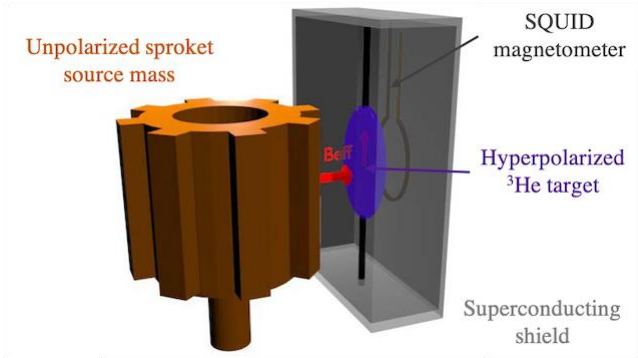
vs.

- *Additional CPV in nature*
  - $\theta_{eff} \equiv \theta_{QCD} - \frac{a}{f_a} + \ ... \neq 0$
  - *EDM ≠ 0 => non-QCD axion field?*

- *Storage ring proton beam*
  - *Direct probe for pEDM*
  - *Sensitivity improvement*
    - *pEDM ~10^{-29} $e \cdot cm$*



- *ARIADNE* *A. Geraci (Thu)*
  - *Nucleon-nucleon interactions*
    - *5th force mediator*
  - *No cosmological assumptions*

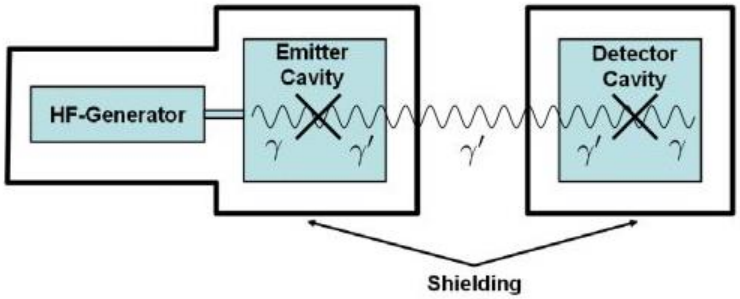


- *Decisive exclusion*
  - *Negative results from the two independent experiments*
  - *0.1 meV < m_a < 10 meV*

Hidden photon

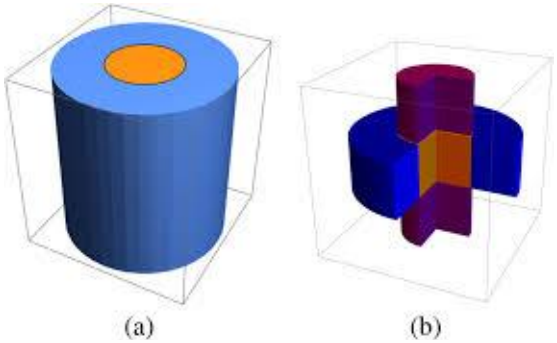
- *Vector field*
  - *Gauge boson in hidden sector + dark matter*
  - *Kinetic mixing with SM gauge fields*

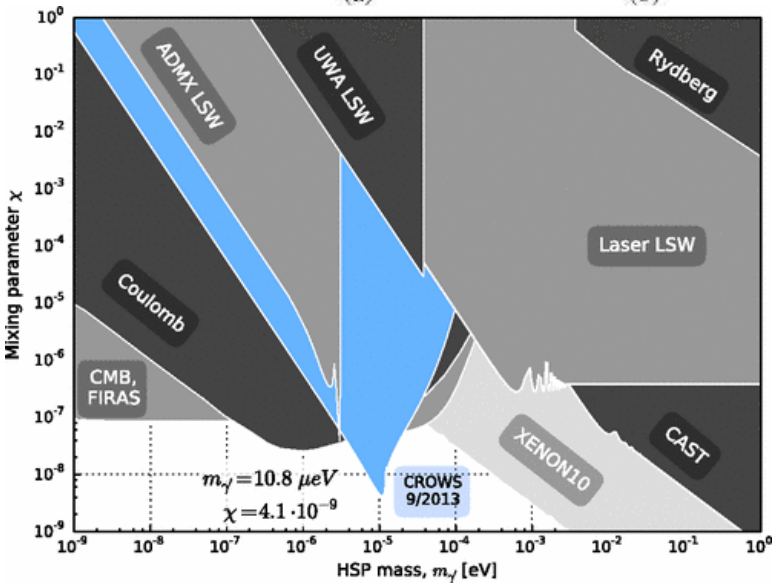
- *LSW-type w/ no magnets* PLB **659** 509 (2008)



- *Cavity searches*
  - *ADMX* PRL **105** 171801 (2010)
  - *UWA* PRD **82** 052003 (2010)
  - *CROW* PRD **88** 075014 (2013)
  - *SC cavities and …*
  - *New ideas* R. Cervantes, O. Tajima (Thu)

PRD **103** 055004 (2021)





Chameleon

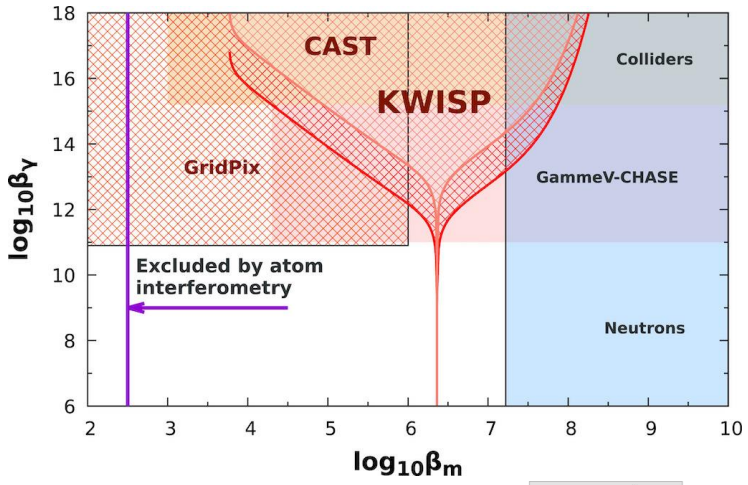
- *Scalar field*
  - *Dark energy candidate* PRD 69 044026 (2004)
- *Effective potential dependent on ambient matter / EM field*

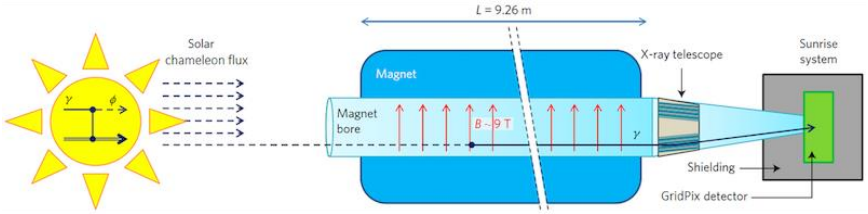
$$V_{eff}(\phi,\vec{r}) = \Lambda^4 e^{\frac{\Lambda^n}{\phi^n}} + e^{\frac{\beta_m}{M_{Pl}}\phi}\rho_m(\vec{r}) + e^{\frac{\beta_\gamma}{M_{Pl}}\phi}\rho_\gamma(\vec{r})$$

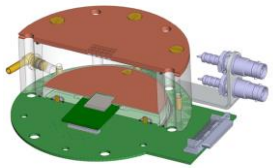
Matter coupling Photon coupling

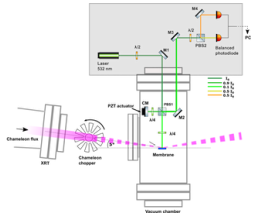
- *Searches*
  - *Afterglow effect*
    - *GammeV, CHASE, ADMX, …*
  - *Solar chameleon*
    - *Similar to solar axion search*
    - *CAST ($\phi-\gamma$) and KWISP ($\phi-m$)*
    - $P_{\phi\to\gamma,m} \propto \beta_{\gamma,m}^2 B^2 L^2$

Phys. Dark Univ. 26 100367 (2019)









Axion searches – future