Axion Dark Matter

International Committee for Future Accelerator (ICFA)
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SungWoo YOUN
Young Scientist
Center for Axion and Precision Physics Research (CAPP)
Institute for Basic Science (IBS)

Outline

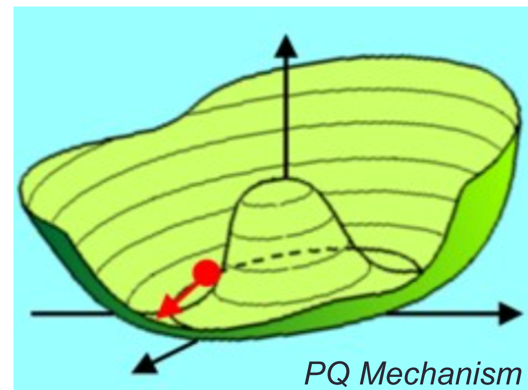
- *Introduction*
- *Axion Detection Philosophy*
- *Strategies for Axion Search*
  - *Laser searches*
  - *Solar axion searches*
  - *Cosmic axion searches*
- *Future Prospects*
- *Summary*

Introduction

- *Strong-CP problem*
  - *Lack of CP violation in strong interaction*
  - *nEDM ~ 10^{-26} ecm => θ_{QCD} ~10^{-10}*
- *Peccei-Quinn theory (1977)*
  - *Appealing solution to the strong CP problem*
  - *A new global symmetry, $U(1)_{PQ}$, with a scalar field permeating all space*
  - *Spontaneous (explicit) PQ symmetry breaking => new Goldstone boson: axion*
  - *Similar to Higgs mechanism*
- *Candidate for CDM (μeV~meV) – invisible*

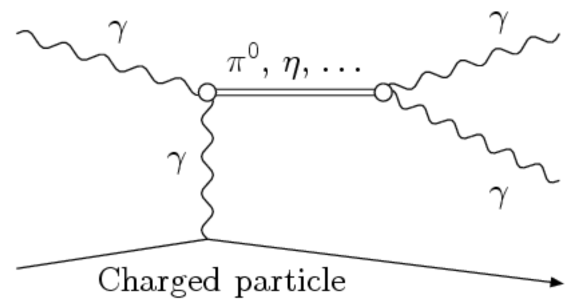
Axion properties			
Interaction	*Gravity, EM*	*Mass*	*μeV to eV*
C	*0*	ρ_{local}	*0.45 GeV/cm^3*
J^P	*0^-*	*β~10^{-3} → Q_a~10^6*	


Peccei and Quinn discussing their proposed symmetry with the aid of a sombrero.

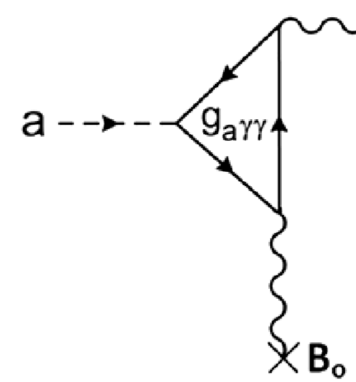


Detection Philosophy

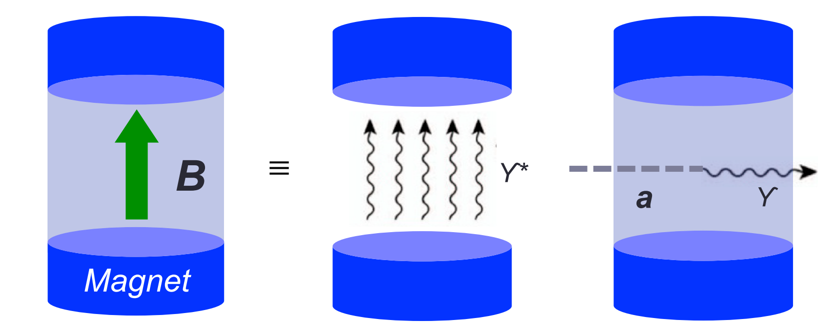
- *Primakoff effect*
  - *Pseudoscalar production by a photon scattering off EM fields*
  - $\gamma\gamma \to \pi^0, \eta, \ldots$



- *Reverse Primakoff effect*
  - *Conversion of axions into photons in the presence of magnetic fields*
    - $a \to \gamma\gamma$ (cf. $\pi^0 \to \gamma\gamma$)
  - *Most promising technique for the faintest axion-photon coupling*



- *P. Sikivie's method (1983)*
  - *Enhanced in a EM resonator*
  - *Principle of haloscope*



Classical EM field *Sea of virtual photons* *Primakoff effect*

Haloscope in a Nutshell

Axion conversion power

$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} Q_L$$

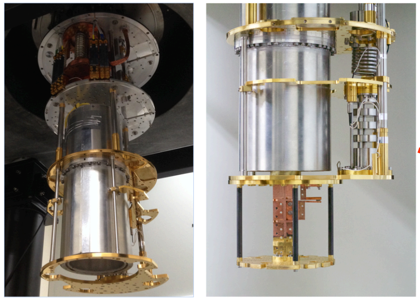
Signal-to-Noise Ratio

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

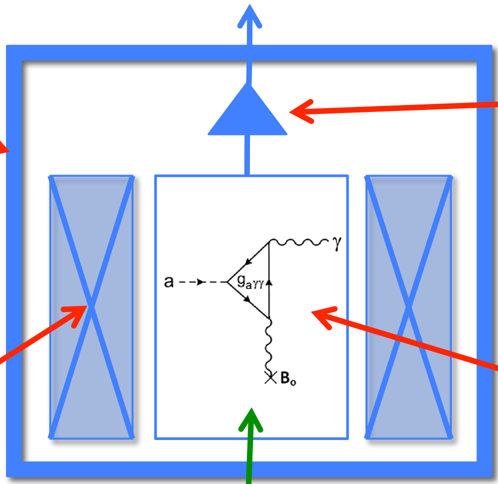
Scan Rate

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

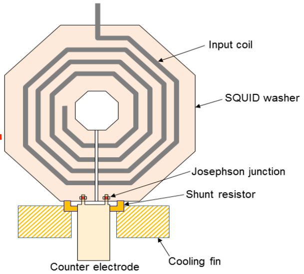
Cryogenics



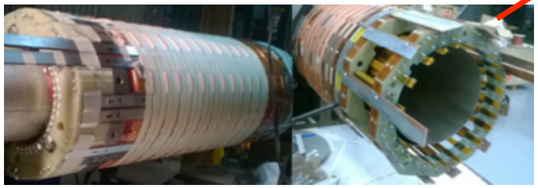
To RF Receiver



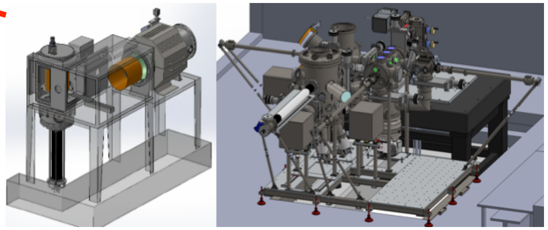
SQUID amplifier



High field SC magnet



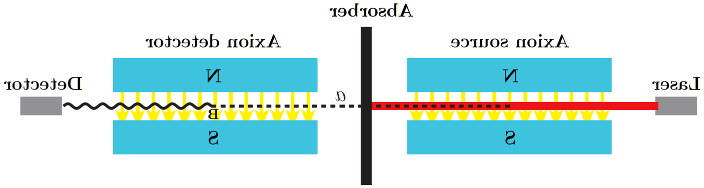
High Q tunable cavity



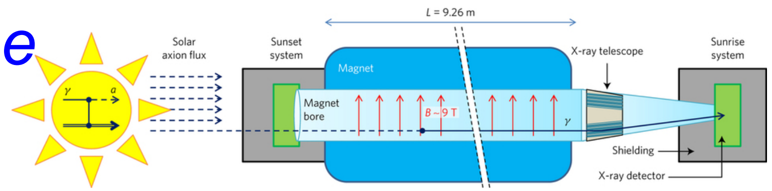
Primakoff Effect

Strategies for Axion Search

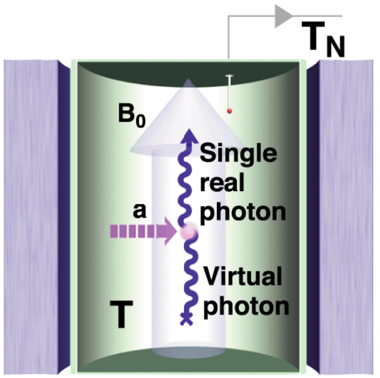
- *Laser searches*
  - *Magneto-optical vacuum effect*
    - *PVLAS (Italy) claimed signal in 2006*
  - *Light shining through walls*



- *Solar axion searches: helioscope*
  - *CAST*

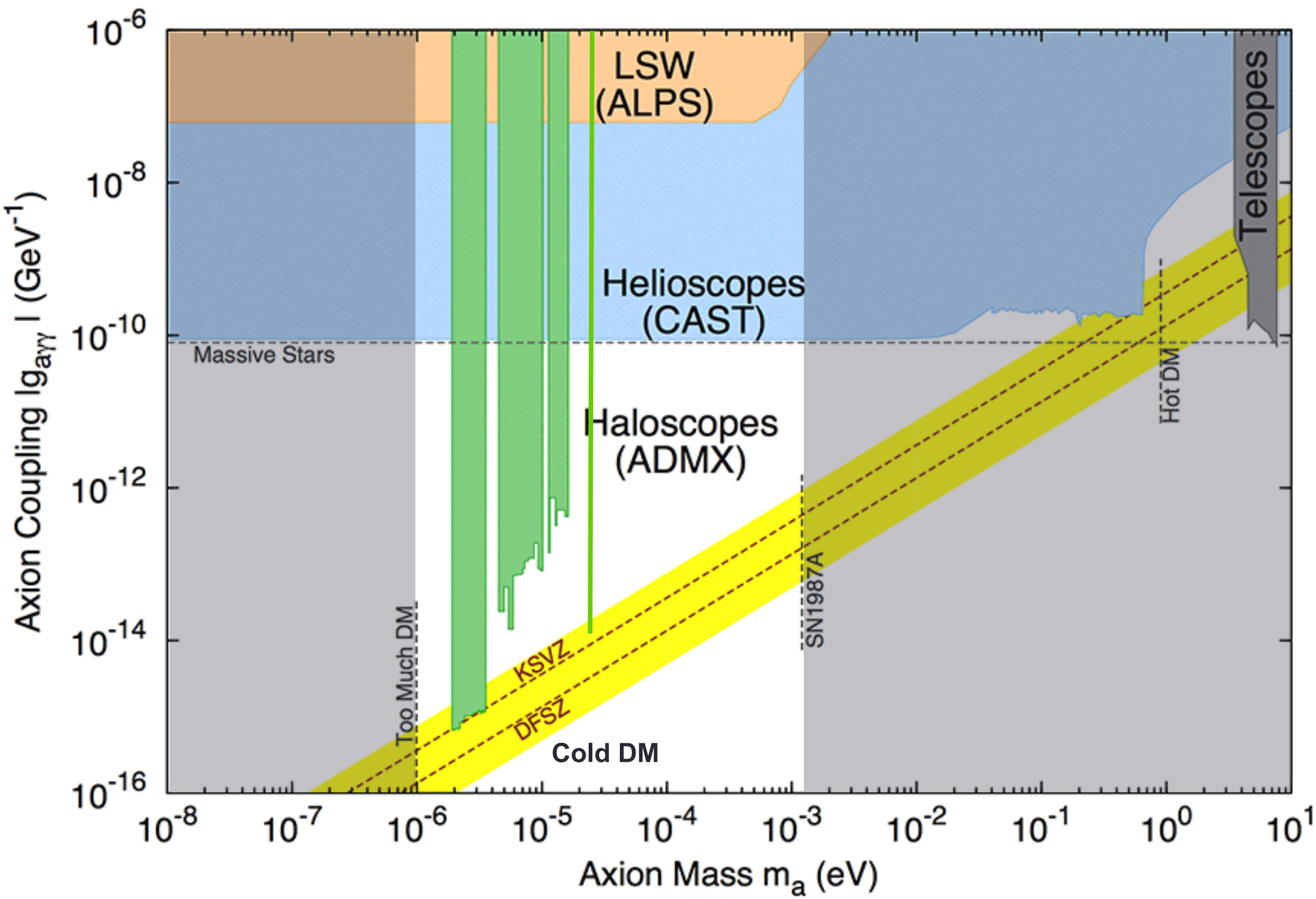


- *Cosmic axion searches: haloscope*
  - *ADMX, HAYSTAC, CULTASK, …*

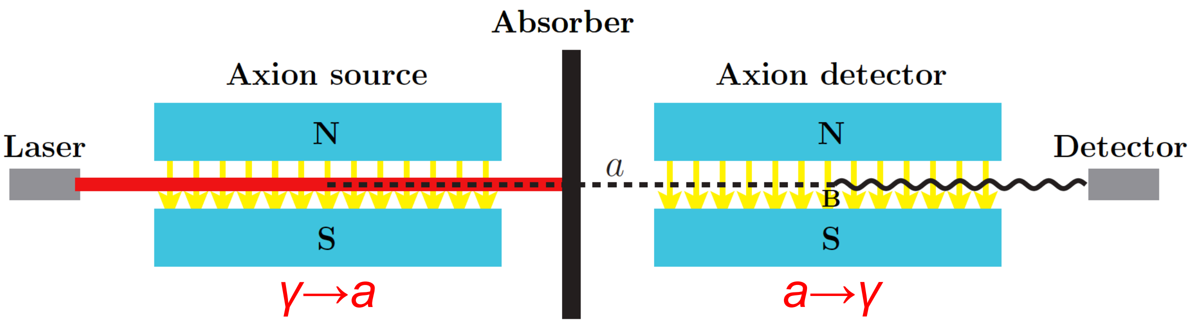


- *Others*
  - *Spin precession*
    - *GNOME, ARIADNE (NMR)*

Current Experimental Status



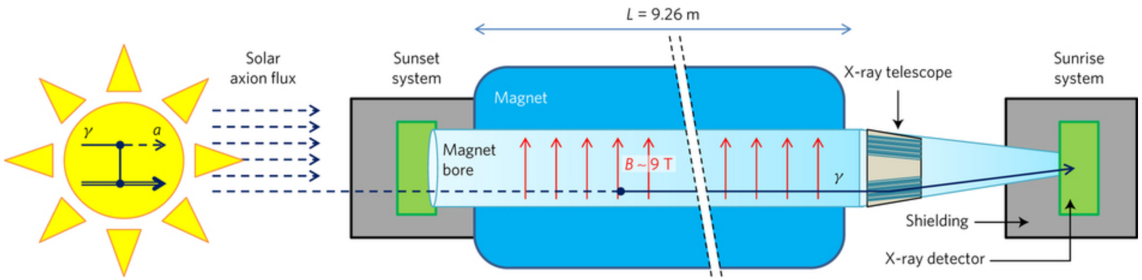
Light Shining through Walls



$$P_{\gamma\to a} \propto \frac{1}{4}\left(\frac{\alpha c_{a\gamma\gamma}}{2\pi f_a} BL\right)^2 \frac{1-\cos(qL)}{(qL)^2}$$

- *GammeV (FNAL)*
  - *Saw no events in 2008*
- *Any Light Particle Search (DESY)*
  - *ALPS I set constraints in 2010*
  - *ALPS II upgrade*
    - *F-P optical resonators / longer detectors / Hera dipole magnets*
- *Optical Search for QED vacuum birefringence Axion photon Regeneration (CERN)*
  - *Found no signal (2014) and continue to run*
- *Search for wide range sub-eV particles*

Solar Axion Search

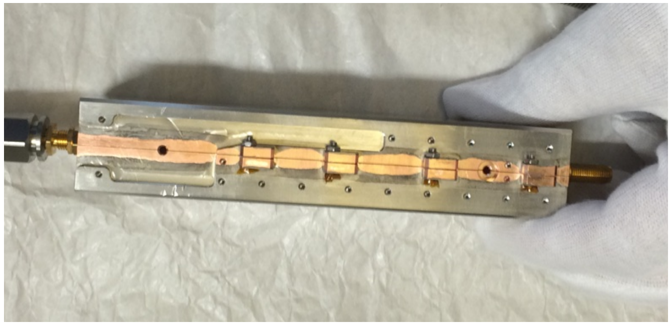


$$P_{a\to\gamma} = \left(g_{a\gamma} B \frac{\sin(qL/2)}{q} \right)^2$$

X-ray to axion in the Sun's core *Axion to X-ray in a magnetic field*

- *CERN Axion Solar Telescope*
  - *Searching for solar axion (X-ray)*
    - *9 m / 9 T LHC prototype dipole magnet*
  - *Final result in 2017*
    - *Nature Physics **13** 584*

- *CAST-CAPP*
  - *CAST helioscope to axion haloscope*
  - *QCD axion with rectangular cavities*
  - *Target axion mass 20~30 μeV*



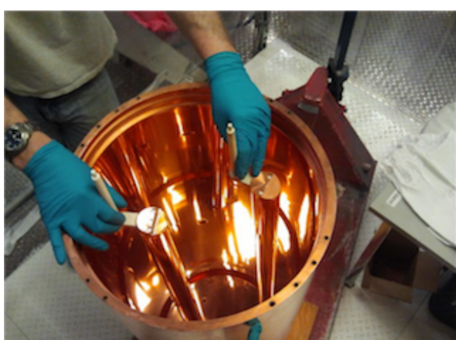
Cosmic Axion Searches

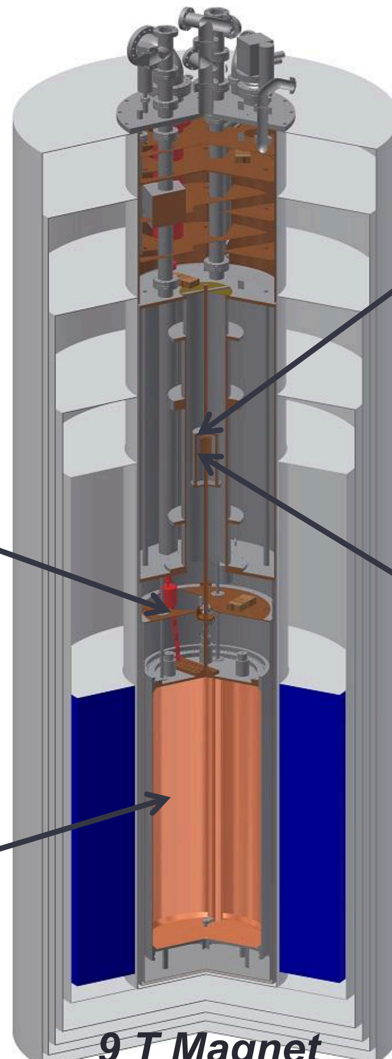
- *Axion Dark Matter eXperiment*
  - *30 years of history (UW)*
  - *9 T magnet / 200 L cavity*
  - *Gen 2 – sensitive to DSVZ at 1~40 μeV*
- *Haloscope At Yale Sensitive To Axion Cold dark matter*
  - *ADMX-HF (Yale)*
  - *9 T magnet / 2 L cavity / JPA*
  - *Recent results at 24 μeV*
- *CAPP Ultra Low Temperature Axion Search in Korea*
  - *Axion research program in Korea*
  - *Six (5+1) dilution refrigerators*
  - *Two 8 T (5”, 6”) magnets / one 18 T (3”) magnet in hand*
  - *25 T (4”) magnet / 12 T (12.5”) magnet in 2 years*
  - *Simultaneous runs at different frequencies*

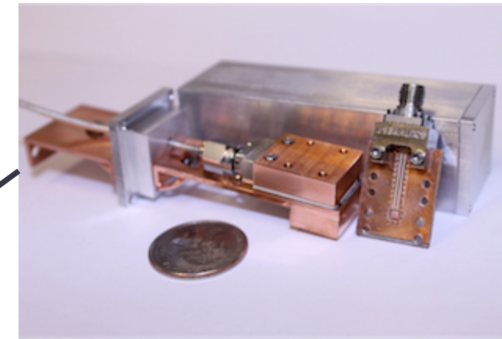
ADMX

Side car
(higher mass)

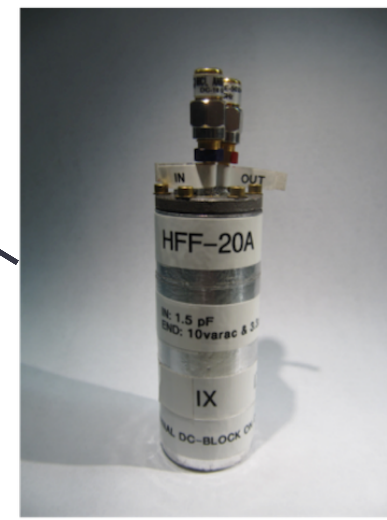
Main cavity (200 L)
Two copper rods







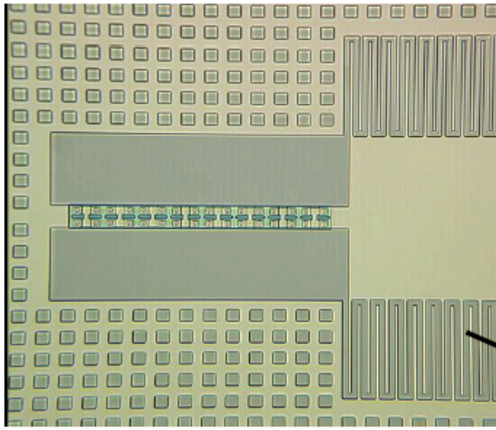
Josephson Parametric Amplifier



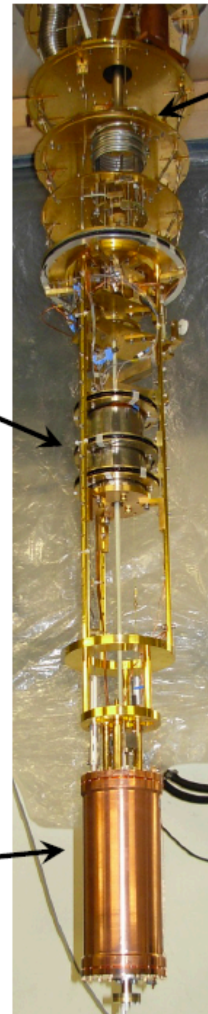
SQUID

HAYSTAC

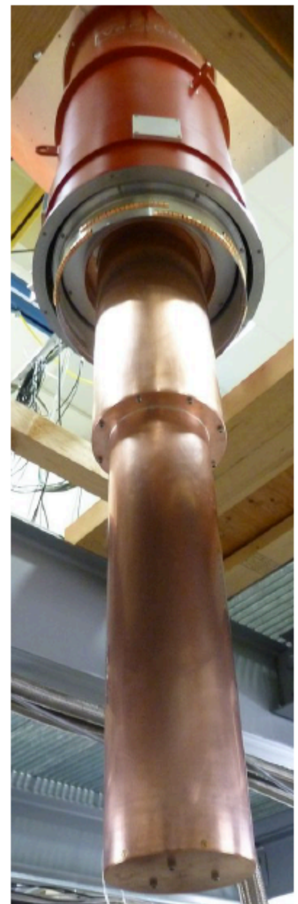
Josephson Parametric Amplifier



Microwave Cavity (copper)



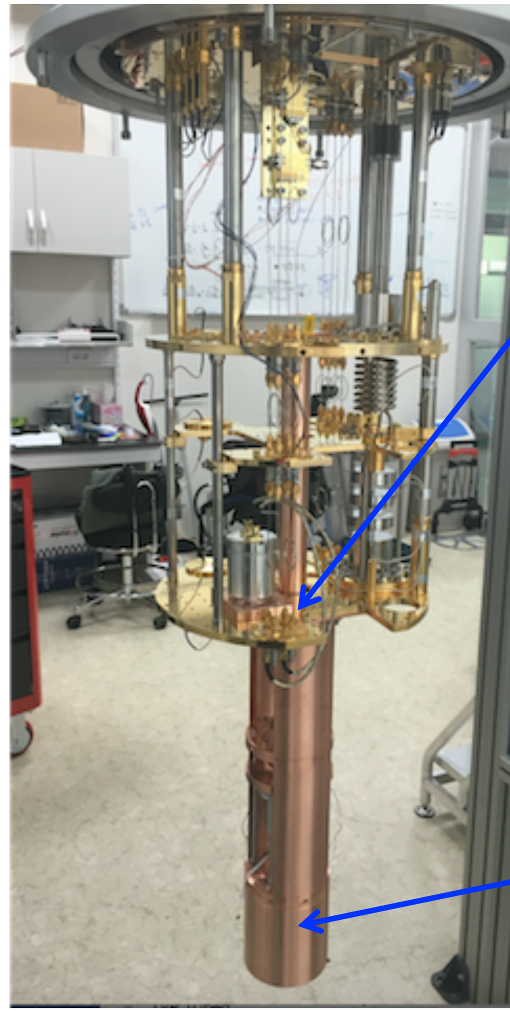
^{3}He/^{4}He Dilution Refrigerator



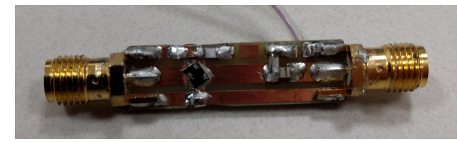
9.4 Tesla, 10 Liter Magnet

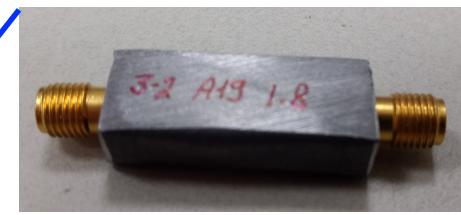
First result from a microwave cavity axion search at 24 μeV

CULTASK

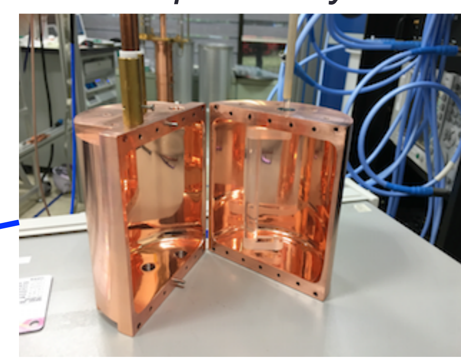


SQUID / MSA



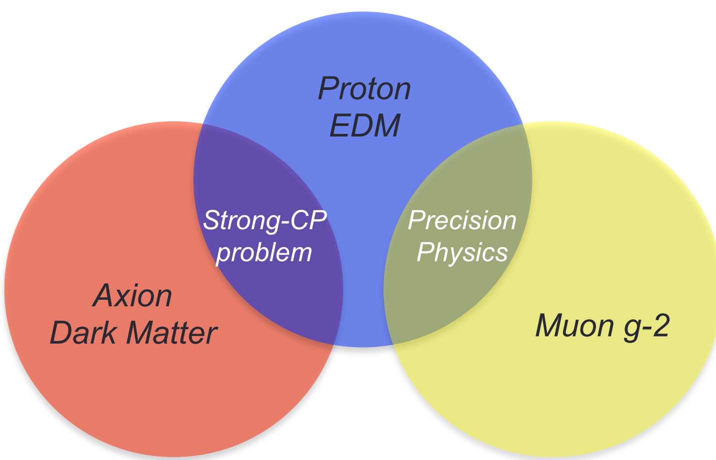


Split cavity



IBS-CAPP

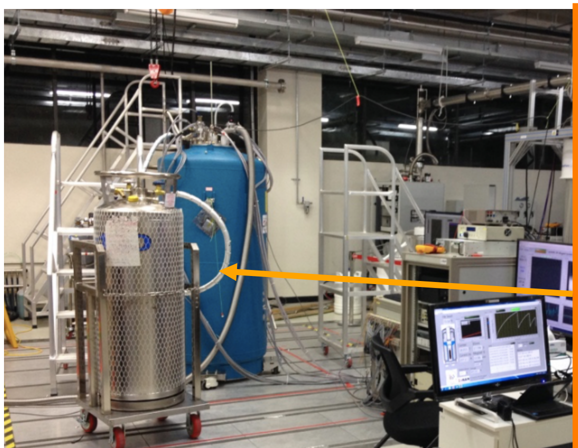
- Center for Axion and Precision Physics Research
  - Launched in 2013 / inauguration in 2017 (last week)
- Various programs for fundamental physics
  - Axion experiments
    - CULTASK
    - CAST-CAPP
    - GNOME / ARIADNE
  - Precision physics
    - pEDM / g-2 experiments



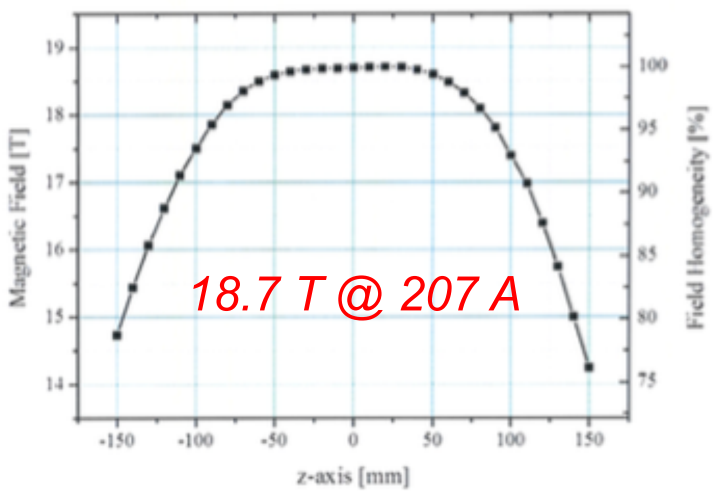
CAPP Inauguration

IBS conference on Dark World

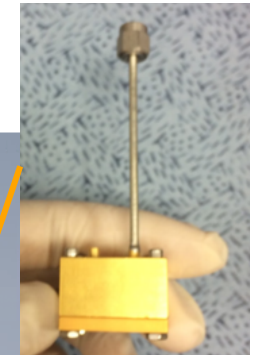
CAPP 18T / 70mm



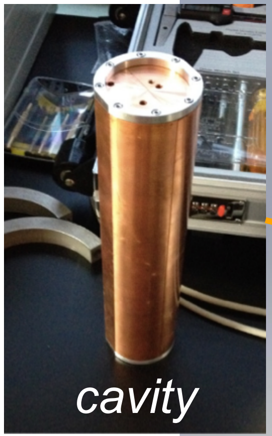
Magnet delivered in Aug. 2017



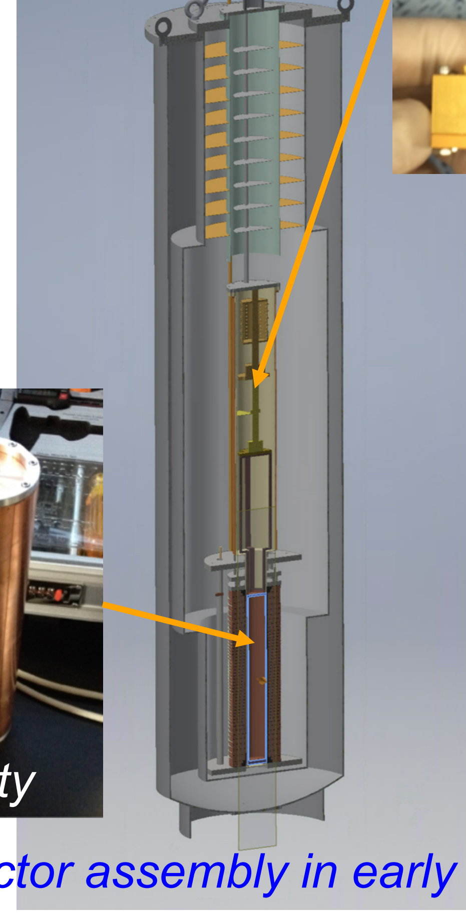
- *GdBCo HTS*
- *No-insulation*
- *Multi-width*



JPA



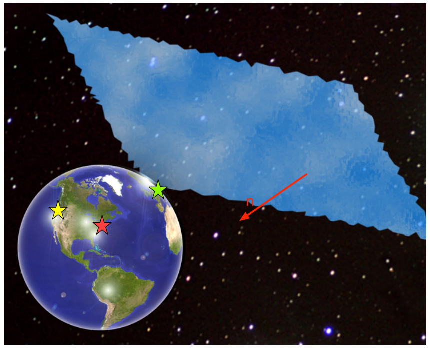
cavity



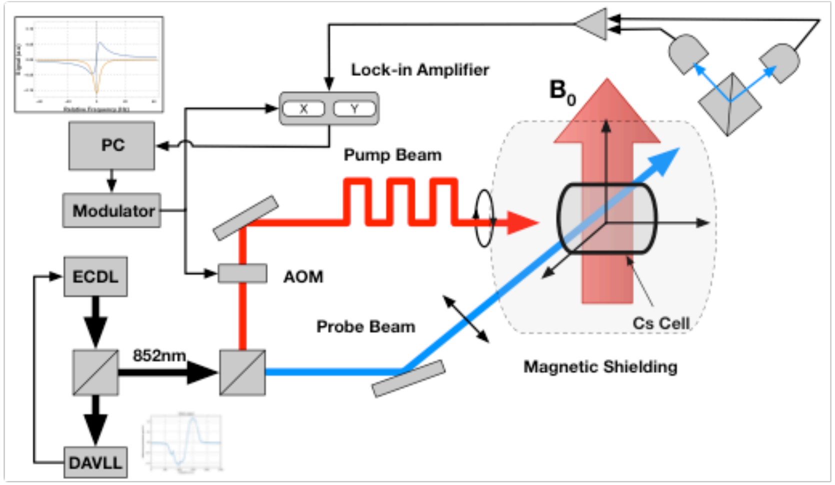
Detector assembly in early 2018

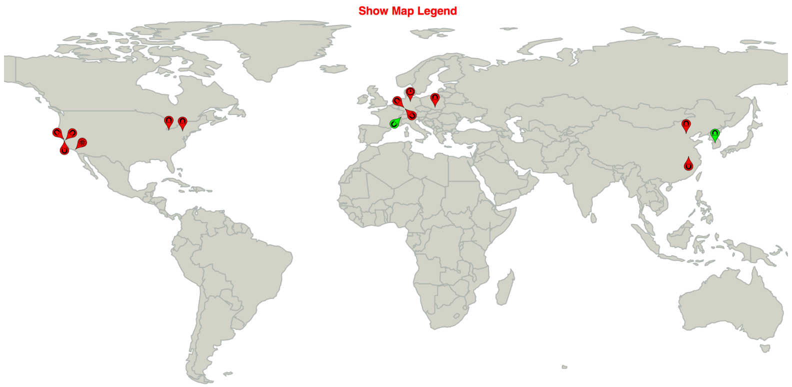
GNOME

- *Global Network of Optical Magnetometers for Exotic physics*
  - *Scalar field potential gradient induces domain walls*
  - *Interaction with atomic spin to exert brief torque*



$$H_a = \frac{\hbar}{c}\vec{s}\cdot\nabla a(\vec{r})$$





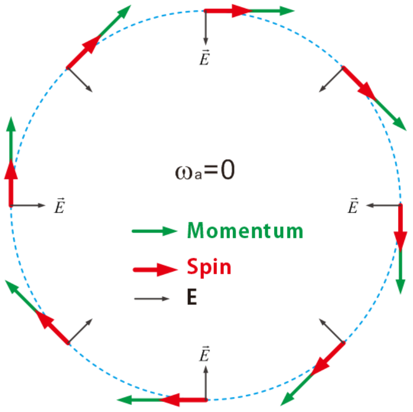
- *Optical magnetometers*
  - *Cs, Rb, He gas*
  - *Pol. AM pump beam / probe beam*
  - *Sensitivity: ~ 100 fT/√Hz*
- *Global network*
  - *14 stations*
  - *GPS time synchronization*
  - *First science network run in Nov. 2017*

Axion with srEDM

- *Proposal of storage ring pEDM experiment at CERN*

$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E} = \vec{s}\times(\vec{\omega}_{g-2} + \vec{\omega}_{edm})$$

$$\vec{\omega}_{g-2} = -\frac{e}{m}\left[a\vec{B} - \left(a - \left(\frac{m}{p}\right)^2\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \quad \vec{\omega}_{edm} = -\frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

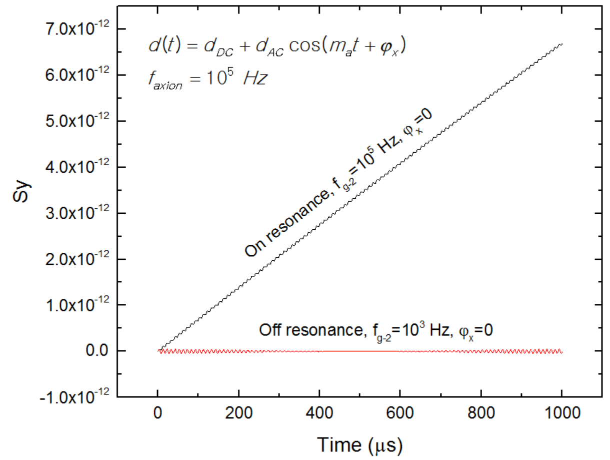


  - *At p=m/√a (magic momentum), spin freezes to the momentum*
  - *pEDM ~ 10^{-29} ecm (cf. nEDM ~ 10^{-26} ecm)*

- *Axion coupling with gluons induces oscillating EDM in nucleons*

$$a(t) = a_0\cos(\omega_a t) \;\Rightarrow\; d(t) = d_{DC} + d_{AC}\cos(\omega_a t + \phi_x)$$

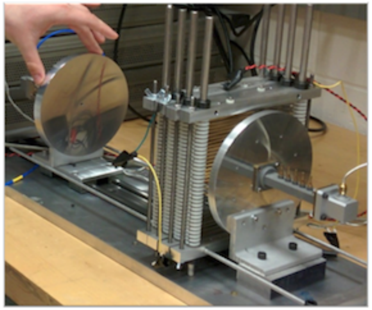
- *Resonance at $\omega_{g\text{-}2} = \omega_a$*
- *Amplitude stacks up with time*
- *Deutron (E field) and proton (B field)*
- *Sensitive to pEDM ~ 10^{-31} ecm*
- *Probe axion frequency 0.1 kHz ~100 MHz*



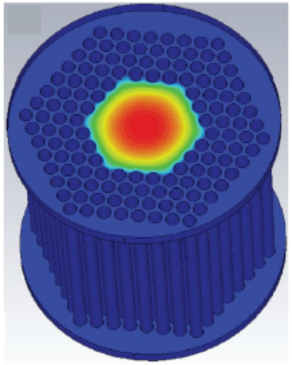
arXiv:1710.05271

Future R&D

- *Design for high frequency*
  - *Higher resonant modes*
    - *ex) distributed bragg reflector cavities*
  - *Single mode isolation*
    - *ex) photonic band gap*



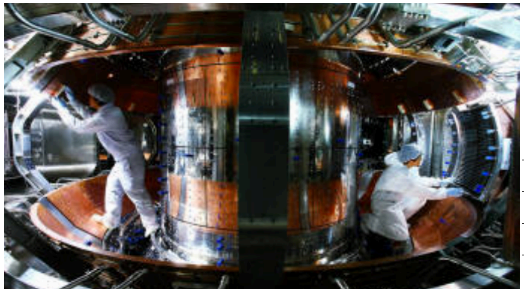
Open resonator



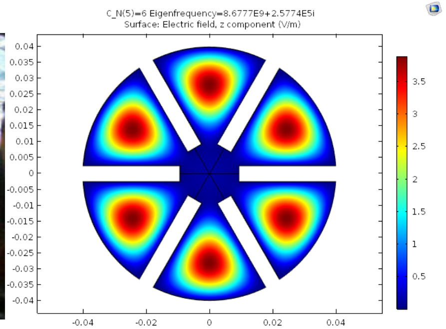
Photonic band gap

- *Design for large volume*
  - *Toroidal geometry*
  - *Multiple-cavity detector*

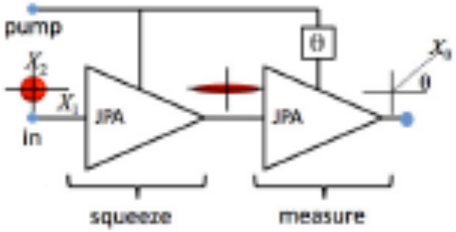
- *Noise reduction*
  - *Squeezed state receiver*
  - *Single photon detection*



Tokamak



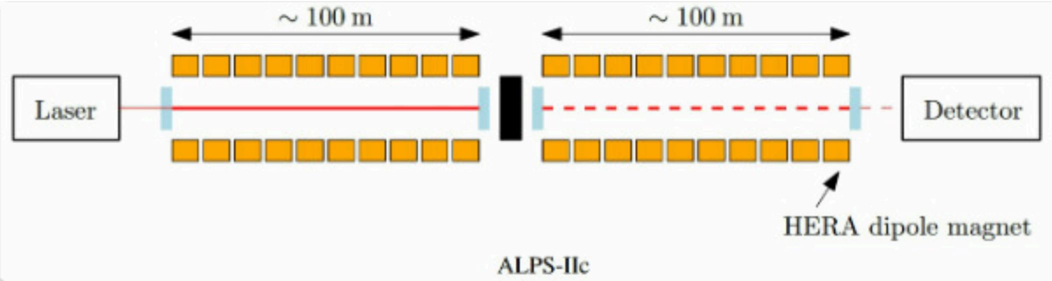
Pizza cavity



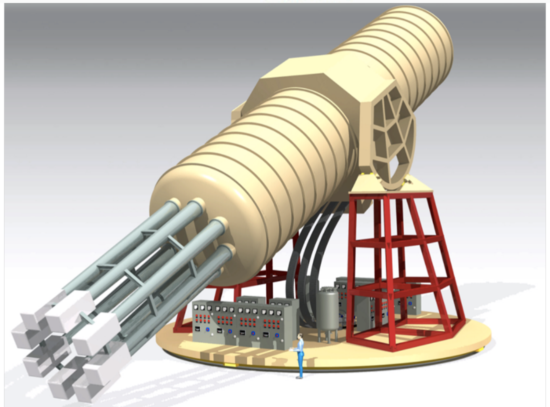
Quantum squeezing

Continuing / New Experiments

- *Laser searches*
  - *ALPS II with upgrades*



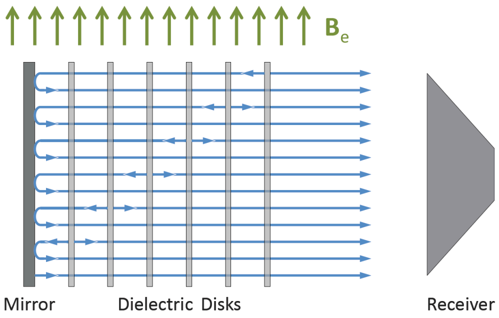
- *Solar axion searches*
  - *International AXion Observatory*
    - *Extension of CAST philosophy*



IAXO

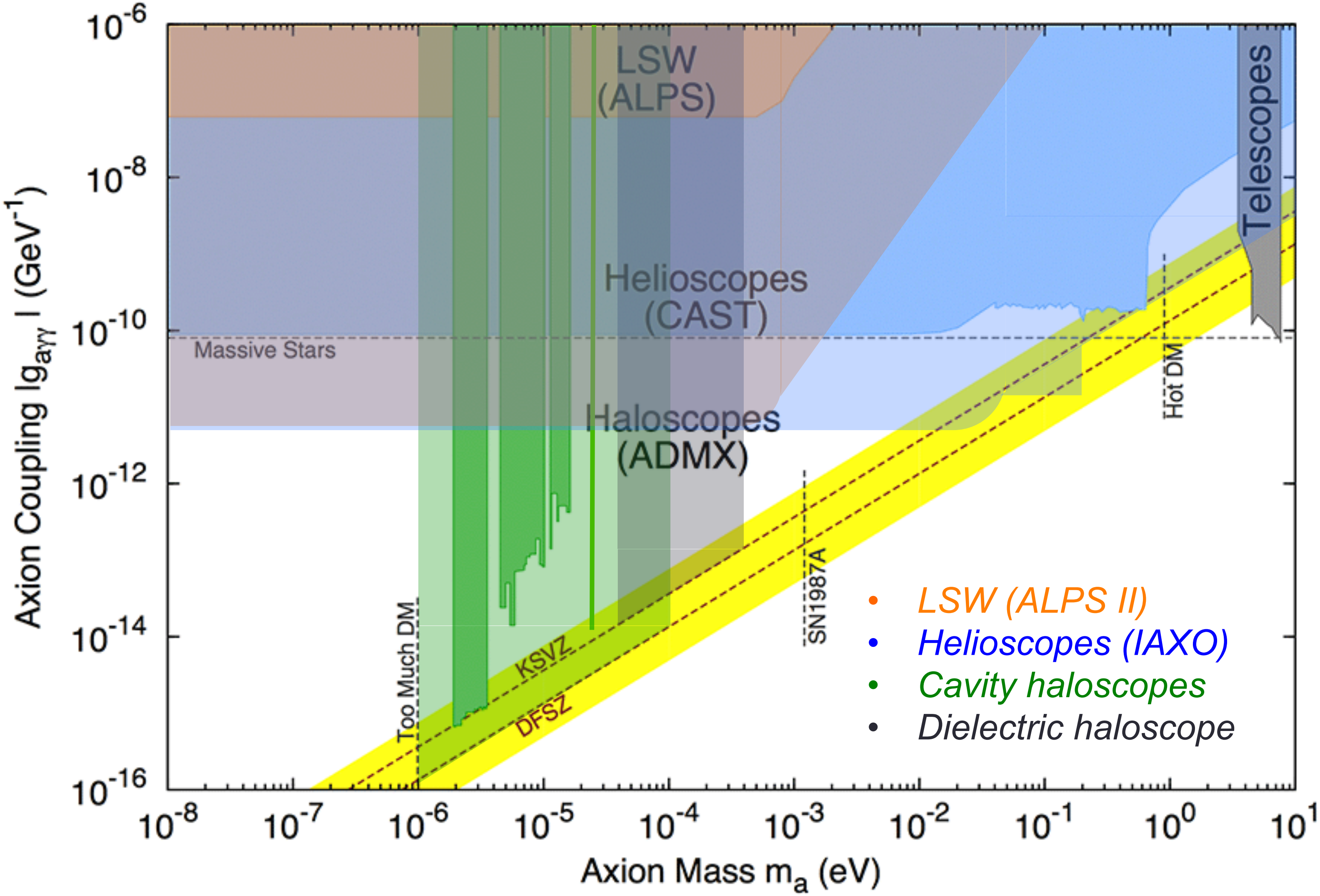
- *Cosmic axion searches*
  - *ADMX, HAYSTAC, CULTASK*
    - *Probing 1~40 μeV down to DSVZ*
  - *MADMAX*
    - *High mass region (up to 400 μeV)*

MADMAX



- *Others*
  - *Spin precession: GNOME, ARIADNE, CASPER*
  - *Storage ring, …*

Future Prospective



Summary

- *Axion is a highly-motivated solution to the long-lasting puzzles in HEP and cosmology*
  - *Strong-CP problem / dark matter*
- *Plenty of excellent project proposals and technical ideas*
  - *To cover large mass ranges and increase sensitivity*
- *Future plans require*
  - *Interdisciplinary R&D activities*
  - *Table-top experiments to large scale experiments*
  - *Collaborative works become more crucial*
- *Significant progresses expected in the near future*

Backups

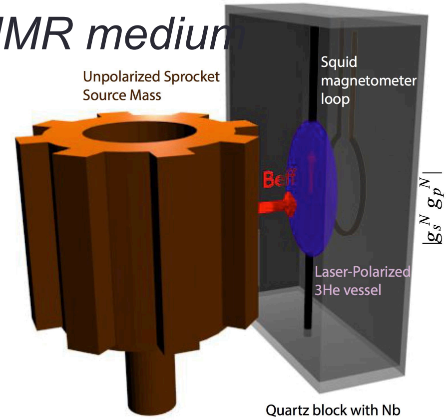
IBS-CAPP (T and B)

Refrigerators						Magnets			
Manufacturer	Model	Installation	Usage	Location		Strength & Bore size	Material	Manufacturer	Delivery
BlueFors (BF3)	LD400	2016	RF and Cavity test	RF room					
BlueFors (BF4)	LD400	2016	JPA & RF chain test	RF room					
Janis	HE3	2017	Magnet test	LVP 4		9T 12 cm	NbTi	Cryo-Magnetics	2017
BlueFors (BF5)	LD400	2017	Axion Exp DAQ & RF	LVP 6		8T 16.5 cm	NbTi	AMI	2016
BlueFors (BF6)	LD400	2017	Axion Exp Large bore	LVP 7		8T 12 cm	NbTi	AMI	2017
Leiden	DRS1000	2017	Axion Exp	LVP 3		25T 10 cm	HTS	BNL/CAPP	2019
Oxford	Kelvinox	2017	Axion Exp	LVP2		12T 32 cm	NbSn	Oxford	2019

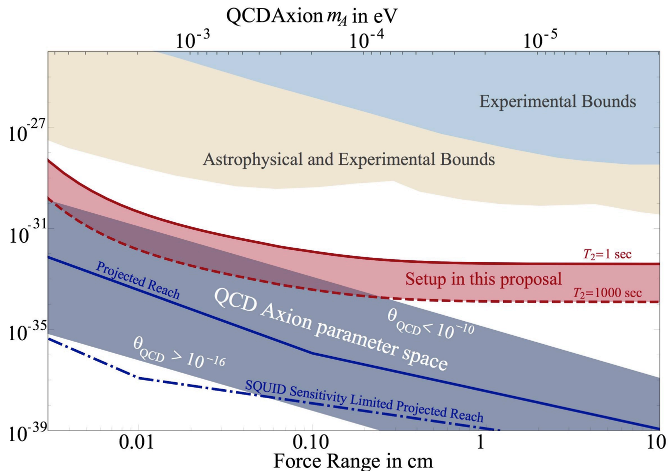
ARIADNE

- *Axion Resonant InterAction Detection Experiment*
  - *Axion-mediated spin-dependent force using NMR*
    - *Segmented rotating mass (W) sources axion field gradient*
    - *Effective magnetic field driving spin precession in the NMR medium (polarized He_3)*

$$U_{sp}(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f}\left(\frac{1}{\lambda_a r} + \frac{1}{r^2}\right) e^{-\frac{r}{\lambda_a}} (\hat{\sigma}\cdot\hat{r})$$



- *Collaborative work*
  - *IN/NV (US) & CAPP (Korea)*



- *Probing wide range QCD axion*
  - *1 μeV ~ 10 meV*
  - *Independent of cosmological assumptions*
- *Experimental challenges*
  - *SC magnetic shield (B~10^{-19} T)*