October 8, 2021
Wave dark matter
Snowmass, community talk

Short and long-term axion dark matter searches

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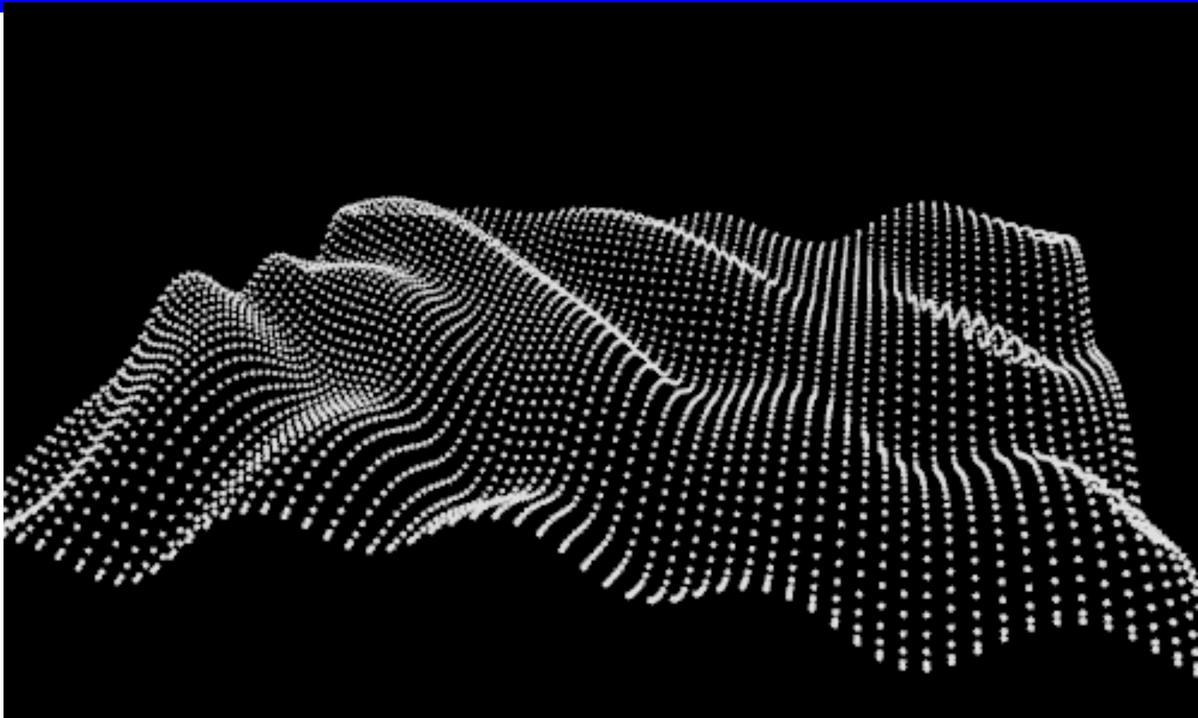
Weighing the vacuum using:

- High-field, high volume magnets; microwave cavities
- Low temperature (<50mK)
- High quality resonators, and
- Quantum-noise-limited RF amplifiers.

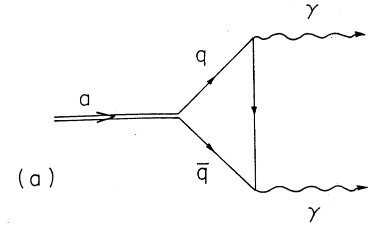
Axion dark matter search

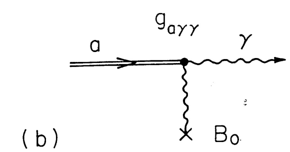
Axion Dark Matter: a Cosmic MASER

$$l_{DB} \approx 1\text{m} \times \left(\frac{1\text{meV}}{m_a} \right)$$



Axion Couplings





- Gauge fields:
  - Electromagnetic fields (cavities)

$$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

  -
  - Gluon Fields (Oscillating EDM; storage ring EDM)

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Fermions (coupling with axion field gradient, pseudomagnetic field, ARIADNE; GNOME)

$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

CAPP's magnets

- Establish a facility to take immediate advantage of currently available technology
  - HTS and
  - LTS (NbTi, and Nb_3Sn) magnets

- NI-HTS, 18T, 70mm diam. Delivered Summer 2017
- NI-HTS, 25T, 100mm diam. (funding limited). On hold.
- LTS (Nb_3Sn), 12T, 320mm diam. Delivered and commissioned in 2020. Currently operational.

CAPP's plan

- High-frequency, high-efficiency microwave (pizza) cavities

- Low temperature, high quality resonators → Superconducting cavities (currently, Q near 1M)

- Quantum-noise limited RF-amplifiers (currently, JPAs near quantum noise level)

- Single photon RF-detectors (>8GHz), plan.

International collaborations

- GNOME (Axion domain walls, stars; International network)
- ARIADNE (Axion-mediated long-range forces; No dark matter needed. Probes high-mass axions.)
- Storage ring EDM for direct low mass axion-like exps., probing of theta_QCD with high-sensitivity

CAPP's International activities status

- GNOME (axion stars, domain walls,…). CAPP is operational and reporting.

- ARIADNE (axion mediated long-range monopole-dipole interactions). Funded by NSF, great technical progress.

- Storage ring proton electric dipole moment experiment (pEDM) Part of Snowmass process.

Refrigerators and Magnets at CAPP

Refrigerators				
Vendor	Model	Base T (mK)	Cooling power	Install
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016
BlueFors (BF4)	LD400	10	18μW@20 580μW@100	2016
Janis	HE3	300	25μW@300mK	2017
BlueFors (BF5)	**LD400**	**10**	18μW@20mK 580μW@100K	**2017**
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100K	2017
Oxford	Kelvinox	<30	400 @120mK	2017
Leiden	DRS1000	100	1mW @100mK	2019

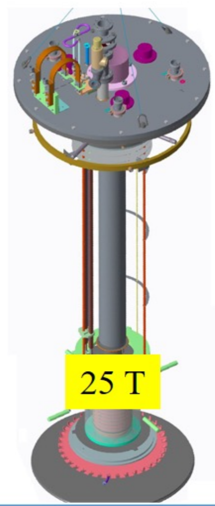
Magnets				
B field	Bore (cm)	Material	Vendor	Delivery
26T	3.5	HTS	SUNAM	2016
18T	7	HTS	SUNAM	2017
9T	12	NbTi	Cryo-Magnetics	2017
8T	**12**	**NbTi**	**AMI**	**2016**
8T	16.5	NbTi	AMI	2017
25T	**10**	**HTS**	**BNL/CAPP**	**2020**
12T	**32**	**Nb_3Sn**	**Oxford**	**2020**

EXP
BF3 & BF4 for testing RF, QA and cavities
CAPP-MC
CAPP-PACE
CAPP-8TB
CAPP-12TB and CAPP-25T

Woohyun Chung's slide

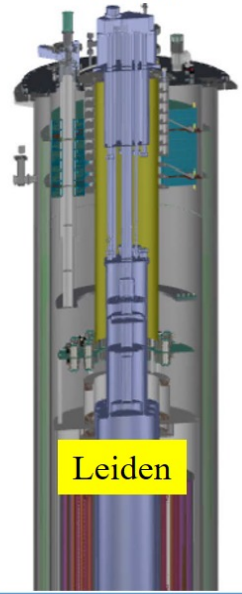
18 T HTS magnet

25 T
HTS magnet



Oxford
- kelvinox

Oxford
- Leiden



9 T
LTS, Janis

18 T	**25 T**	**9 T**	**12 T**	**9 T**
70 mm	100 mm	50 mm	320 mm	120 mm
4 K	4 K	30 mK	30 mK	300 mK
Working	2019	Testing	2018	Working

Liquid helium type superconducting magnet system at CAPP

LTS-12T/320mm from Oxfrod Instruments

- Based on Nb_3Sn and NbTi
- Persistent mode switch
- Delivered and commissioned in 2020
- The dilution fridge, >1mW at 120mK has been delivered and commissioned
- Low temp dil. fridge base 5.5mK
- Cavity: 37 liter cavity, <100mK

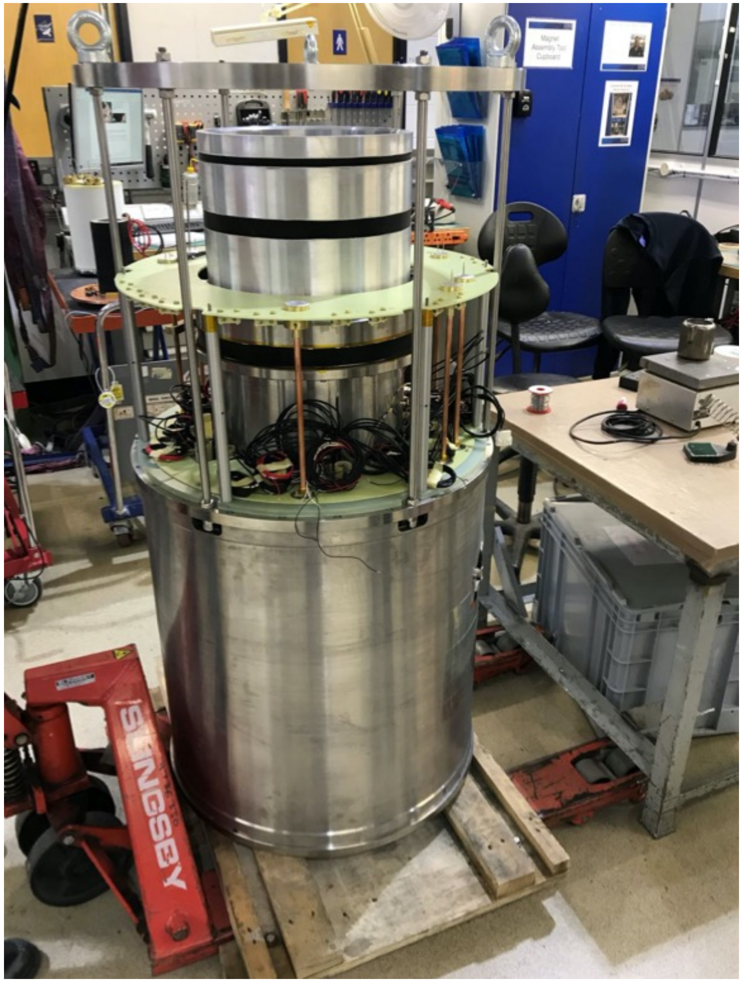


Figure 6. Recent picture of the LTS-12T/320mm magnet in its final form at the Oxford Instruments laboratory. Its total energy content is 5.652 MJ, a powerful magnet that requires respect and caution when energized. The system is to undergo its final tests before its scheduled shipment to IBS-CAPP by March 2020.

LTS-12T/320mm from Oxfrod Instruments

- Commissioned in 2020 delivering 12T max field (5.6MJ)

The CAPP-12TB, our flagship experiment

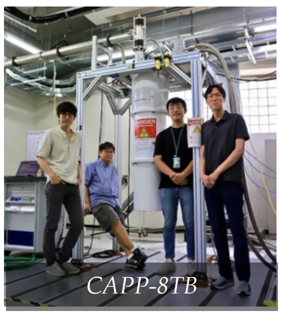
- Axion to photon conversion power at 1 GHz
  - KSVZ: 4.3×10^{-22} W or ~650 photons/s generated
  - DFSZ: 5.9×10^{-23} W or ~90photons/s generated
- With total system noise of 0.1K, $Q=10^5$
  - KSVZ: 100GHz/year
  - DFSZ: 2GHz/year
- With total system noise of 0.4K, $Q=10^5$
  - KSVZ: 7GHz/year
  - DFSZ: 0.15GHz/year
- With total system noise of 1.2K, $Q=10^5$
  - KSVZ: 0.7GHz/year
  - DFSZ: 0.015GHz/year

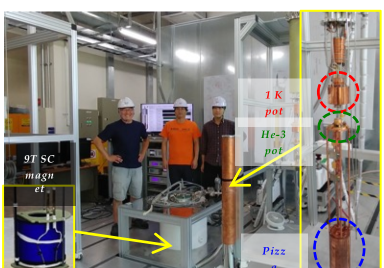
Short term goals (5 years)

- Prototype experiments running at KSVZ level sensitivity (currently two are running and two more are coming online soon)
- Flagship experiment at DFSZ level sensitivity with 12T, 37 liter-cavity
- Next five years: 1-8 GHz at DFSZ level.
- Subsequently: probe axions in the 1-8 GHz for 10% of axions as dark matter with SC cavities, better noise.

IBS-CAPP up to now

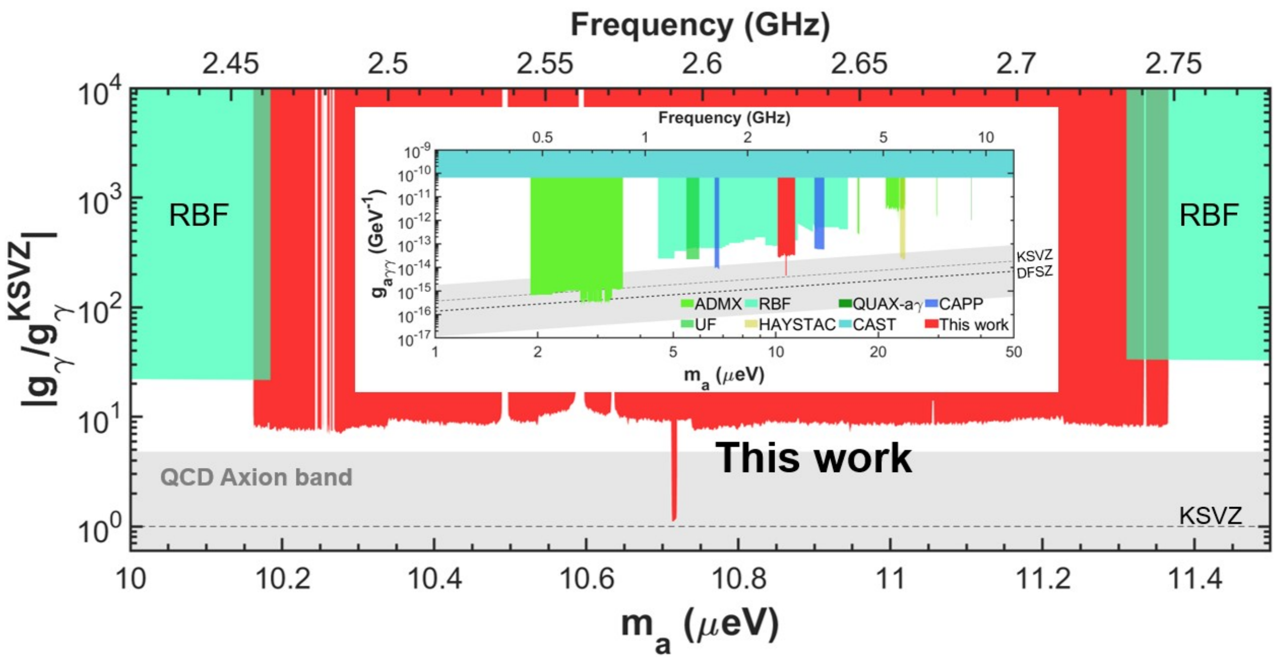

CAPP-PACE


CAPP-8TB



CAPP-9T MC

- S. Lee *et al.*, Phys. Rev. Lett. **124**, 101802 (2020)
  J. Jeong *et al.*, Phys. Rev. Lett. **125**, 221302 (2020).
  O. Kwon *et al.*, Phys. Rev. Lett. **126**, 191802 PRL (2021)



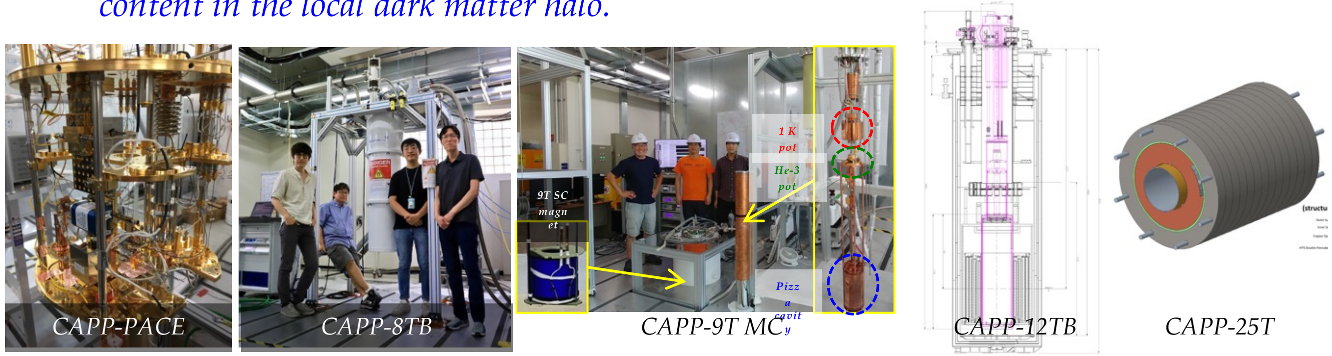
IBS/CAPP Prospects

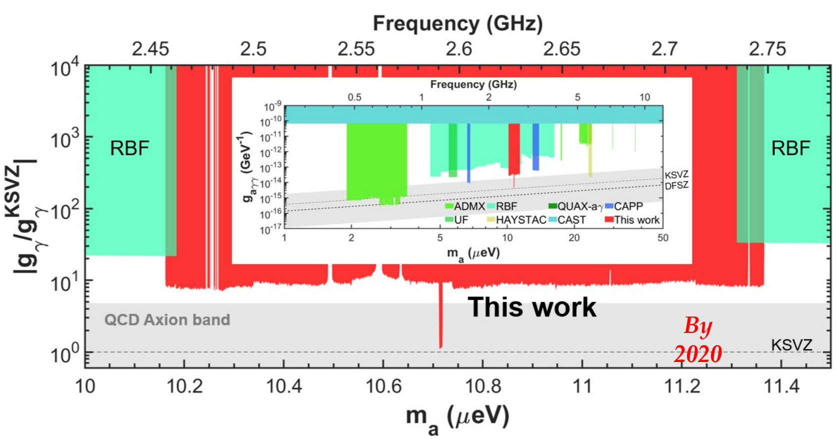
- S. Lee *et al.*, Phys. Rev. Lett. **124**, 101802 (2020)

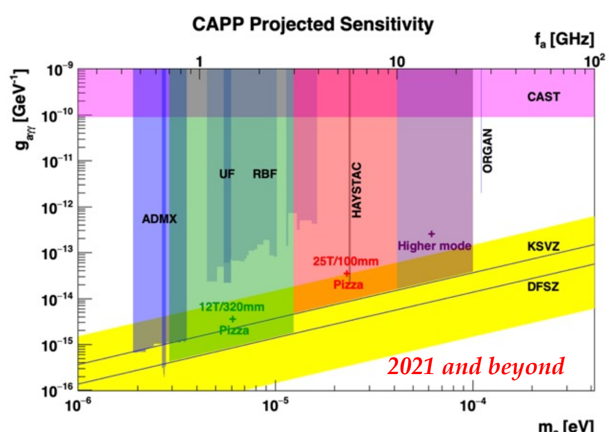
J. Jeong *et al.*, Phys. Rev. Lett. **125**, 221302 (2020).

O. Kwon *et al.*, Phys. Rev. Lett. **126**, 191802 PRL (2021)

- *All the ingredients together, we will reach the DFSZ sensitivity even for 10% axion content in the local dark matter halo.*







- *Cu cavities are assumed*
- *W/ SC cavities, down to 10% of axion dark matter content can be probed*

Long term goals (~10 years)

- Single photon detector, 8-25 GHz with micr. cavities

- ARIADNE, could provide axion evidence for higher mass

- Storage ring EDM with 10^{-29} *e*-cm sensitivity. Three orders of magnitude in theta_QCD improvement

- Storage ring EDM direct search for low mass axion-like experiments.

Summary

- Axion-dark-matter efforts are becoming interesting: High field magnets, High volume-high frequency sensitivity, quantum-noise limited detectors, SC cavities,…

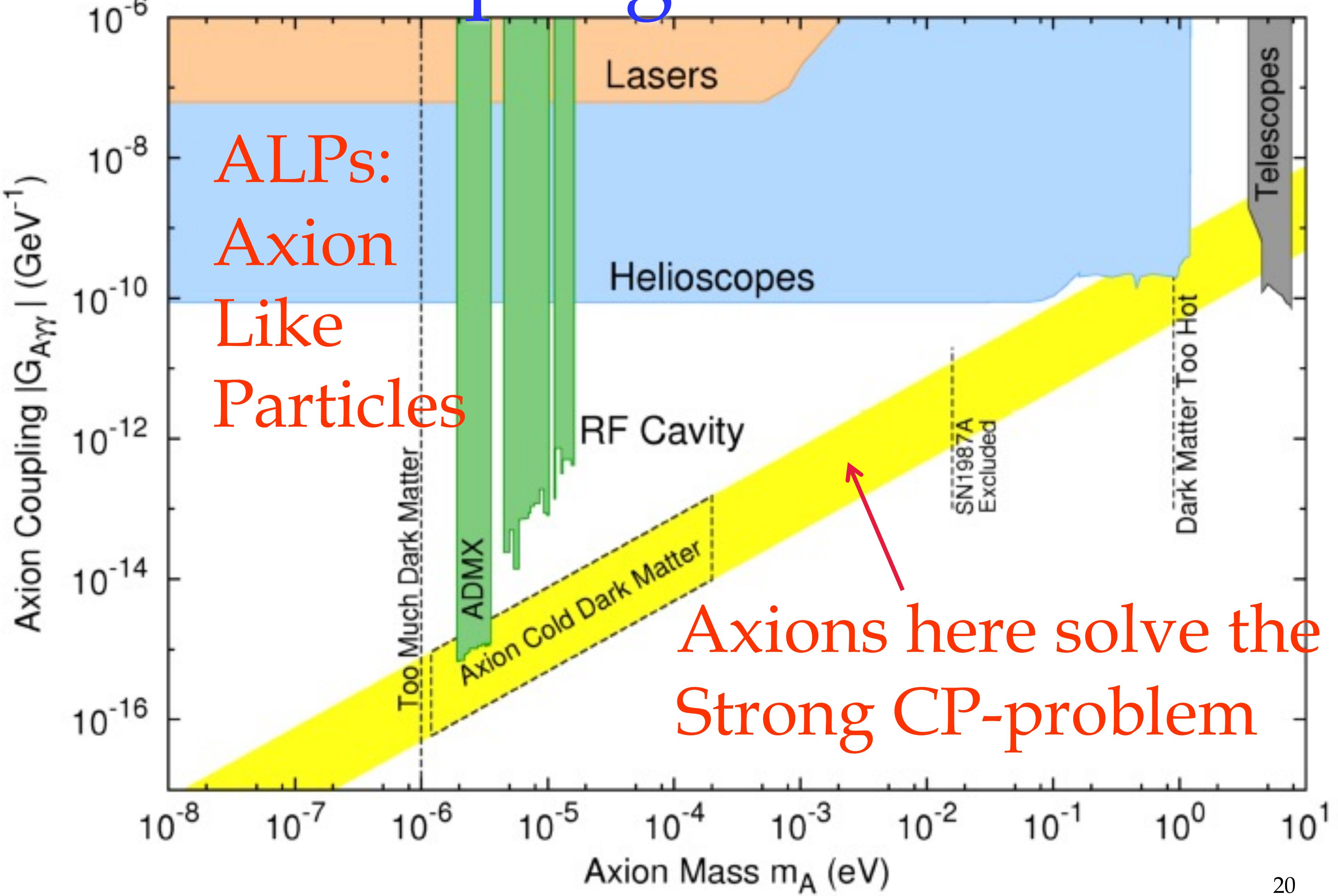
- We have accomplished all R&D goals. All efforts on data taking mode.

- Aiming for <10% axion dark matter sensitivity with a ten-year time-span, possibly shorter.

- 1-8 GHz (five years, 100% ADM) and 1-25 GHz (ten years, 10%ADM)

Extra Slides

Axion coupling vs. axion mass



Yannis K. Semertzidis, IBS & KAIST

If you don't know the axion mass need to tune

Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \mathrm{GHz}}{\mathrm{year}}\left(g_{a\gamma\gamma}10^{15}\mathrm{GeV}\right)^4\left(\frac{5\ \mathrm{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\ \mathrm{K}}{T}\right)^2$$

$$\times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$

$$T = T_{\mathrm{N}} + T_{\mathrm{ph}}$$

Axion dark matter search

- The axion mass is unknow … ne book. The way we look for it:

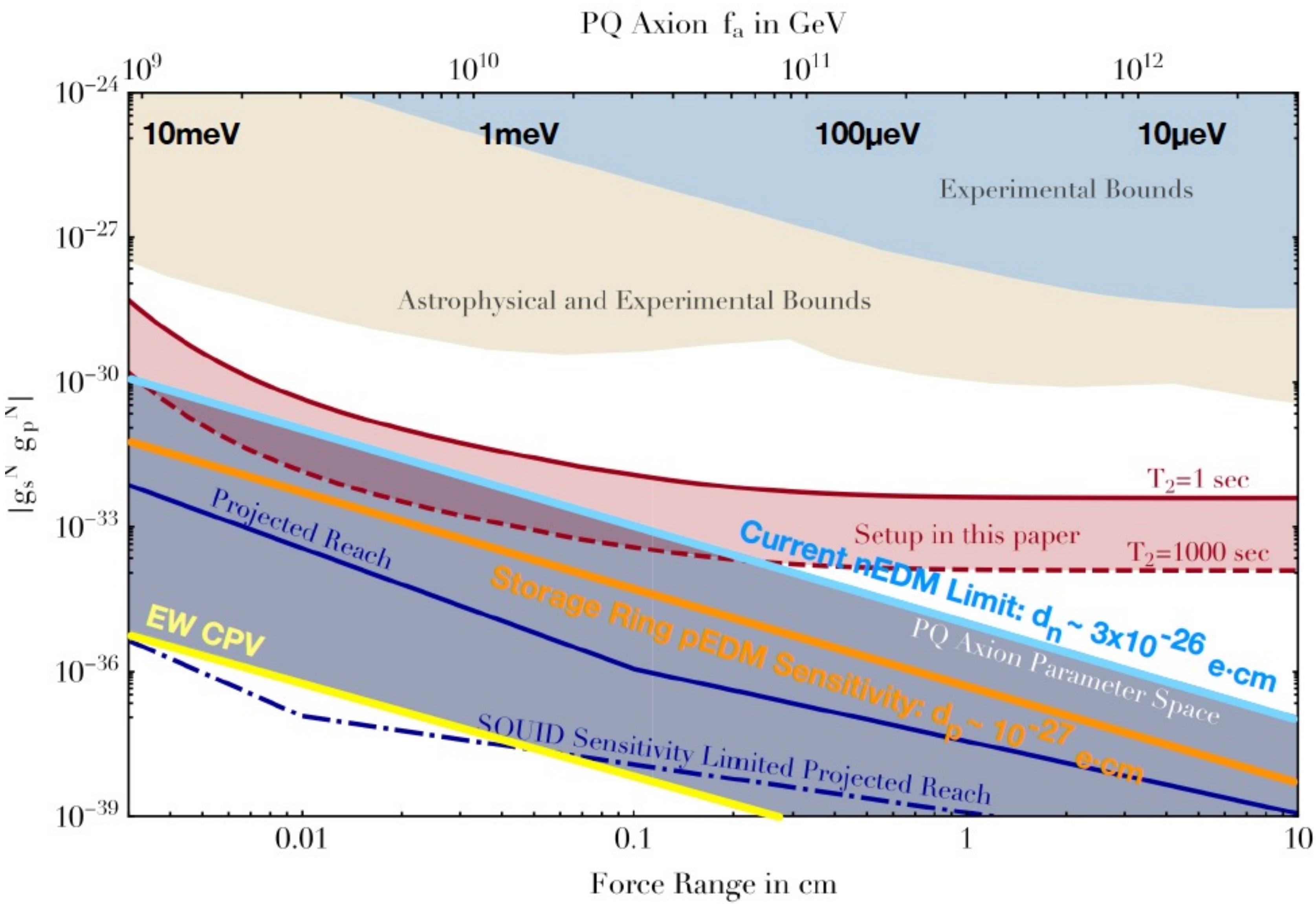
- Once it’s discovered, … dial in… and talk to it.

Can we experimentally check the axion physics?

Yes, with ARIADNE:
Axion Resonant InterAction DetectioN Experiment

and proton/neutron EDM!

Unique: probing axion physics with ARIADNE and p/nEDM



David Tanner

Strawman: Single cavity

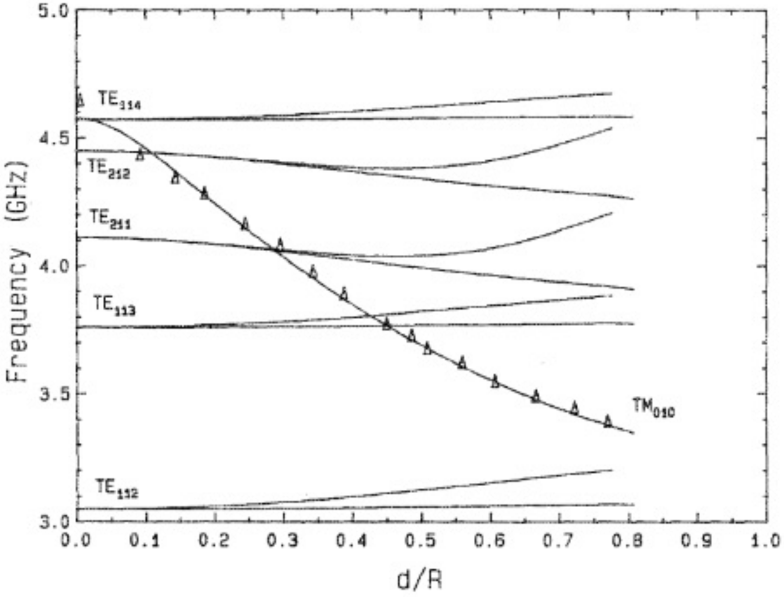
- Single cylinder, 8 T field; change size to resonate at search frequency

$$P = 130 \text{ yW} \left(\frac{1 \text{ GHz}}{f}\right)^{2.67}$$

- Volume decreases as f^{-3}, the Q decreases as $f^{-2/3}$ while the mass increases as f

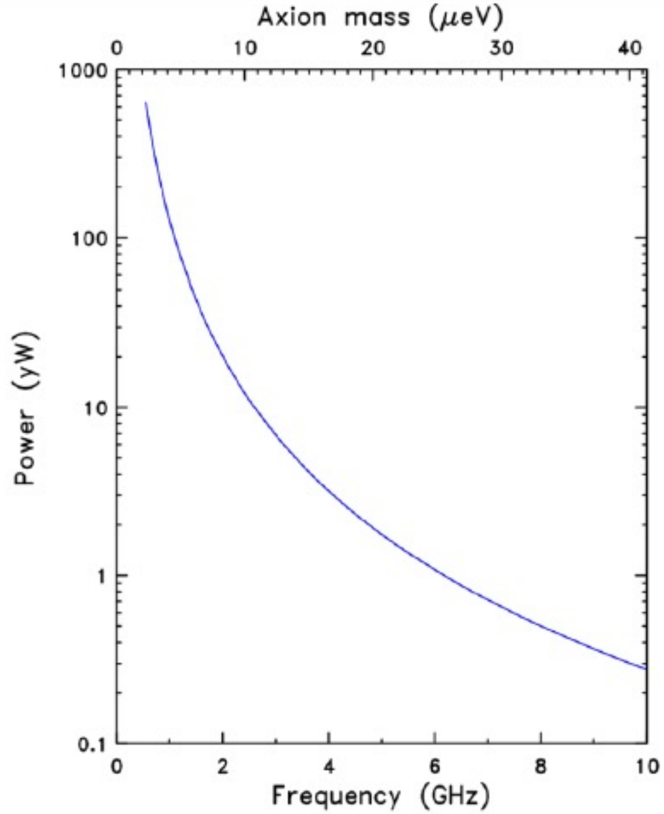
- Length as well as diameter changes because the cavity cannot get too long
  - The longer the cavity, the more TE/TEM modes there are
  - Typically:

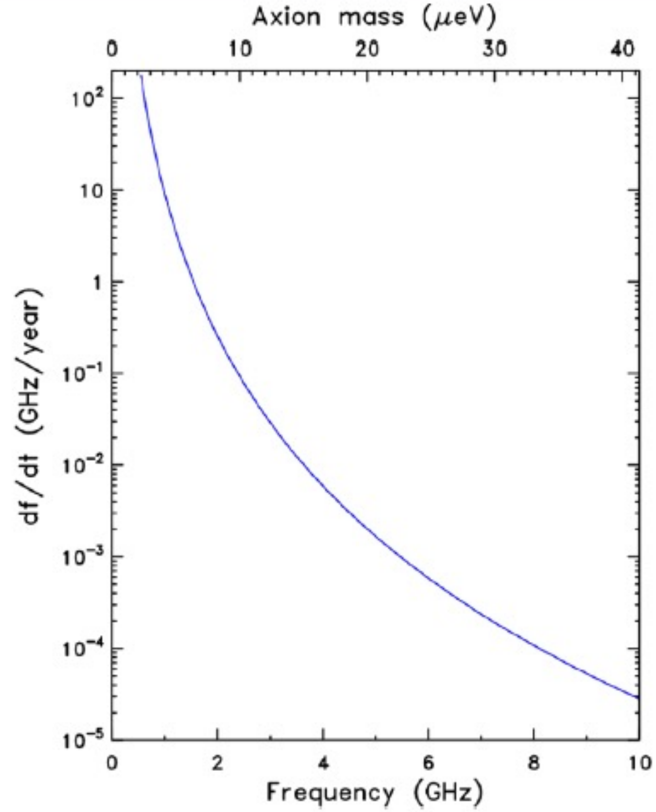
    $L \sim 4.4r$



David Tanner

Strawman 2: Single cavity





- Power and scan rate decrease as frequency goes up ☹
- Just the opposite of what we want.