CAPP

Center for
Axion and Precision
Physics Research

New technology and breakthroughs in axion dark matter search

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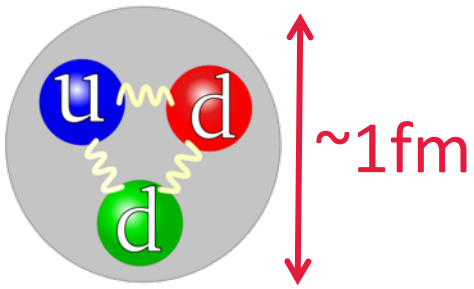
TIPP meeting (online), TRIUMF May 24-29, 2021

- CAPP is ready to take data with DFSZ sensitivity level in the 1-8 GHz frequency range
- This and other frequencies are also targeted for high sensitivity searches by CAPP, ADMX, HAYSTAC, MADMAX, IAXO, ARIADNE, Hadronic EDMs, DM-RADIO, CASPEr, etc.

Strong CP-problem and neutron EDM

$$L_{QCD,\bar{\theta}} = \bar{\theta}\,\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



Dimensional analysis (naïve) estimation of the neutron EDM:

$$d_n(\bar{\theta}) \sim \bar{\theta}\,\frac{e}{m_n}\,\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times10^{-17}\right)\mathrm{e}\cdot\mathrm{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

$$d_n(\bar{\theta}) \approx -d_p(\bar{\theta}) \approx 3.6\times10^{-16}\,\bar{\theta}\ \mathrm{e}\cdot\mathrm{cm}$$

M. Pospelov, A. Ritz, Ann. Phys. 318 (2005) 119.

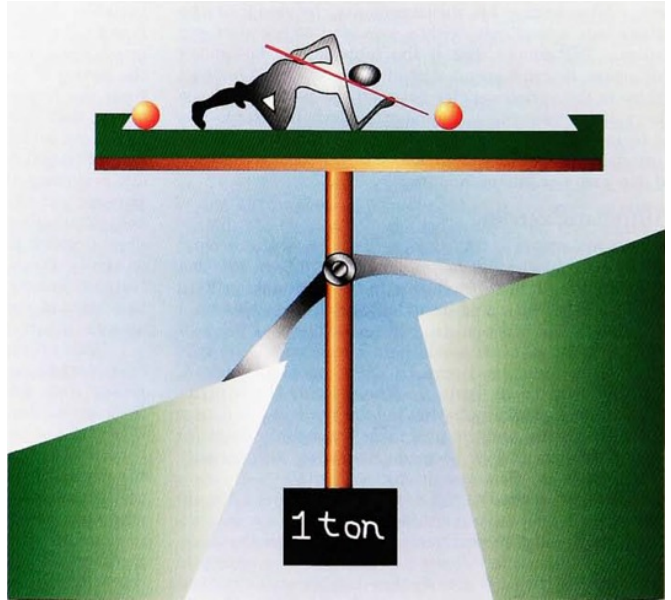
$$\text{Exp.:}\ d_n < 3\times10^{-26} e\cdot\mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$$

In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least ~9-10 orders of magnitude less! WHY?

Strong CP-problem

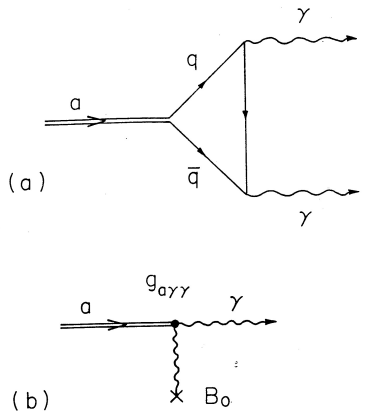
$$L_{QCD,\bar{\theta}} = \left(\bar{\theta} - \frac{a(x)}{f_a} \right) \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally



The Pool-Table Analogy with Axion Physics, Pierre Sikivie
Physics Today **49**(12), 22 (1996);
http://dx.doi.org/10.1063/1.881573

Axion Couplings



- Gauge fields:
  - Electromagnetic fields
  -
  - Gluon Fields (Oscillating EDM,…)

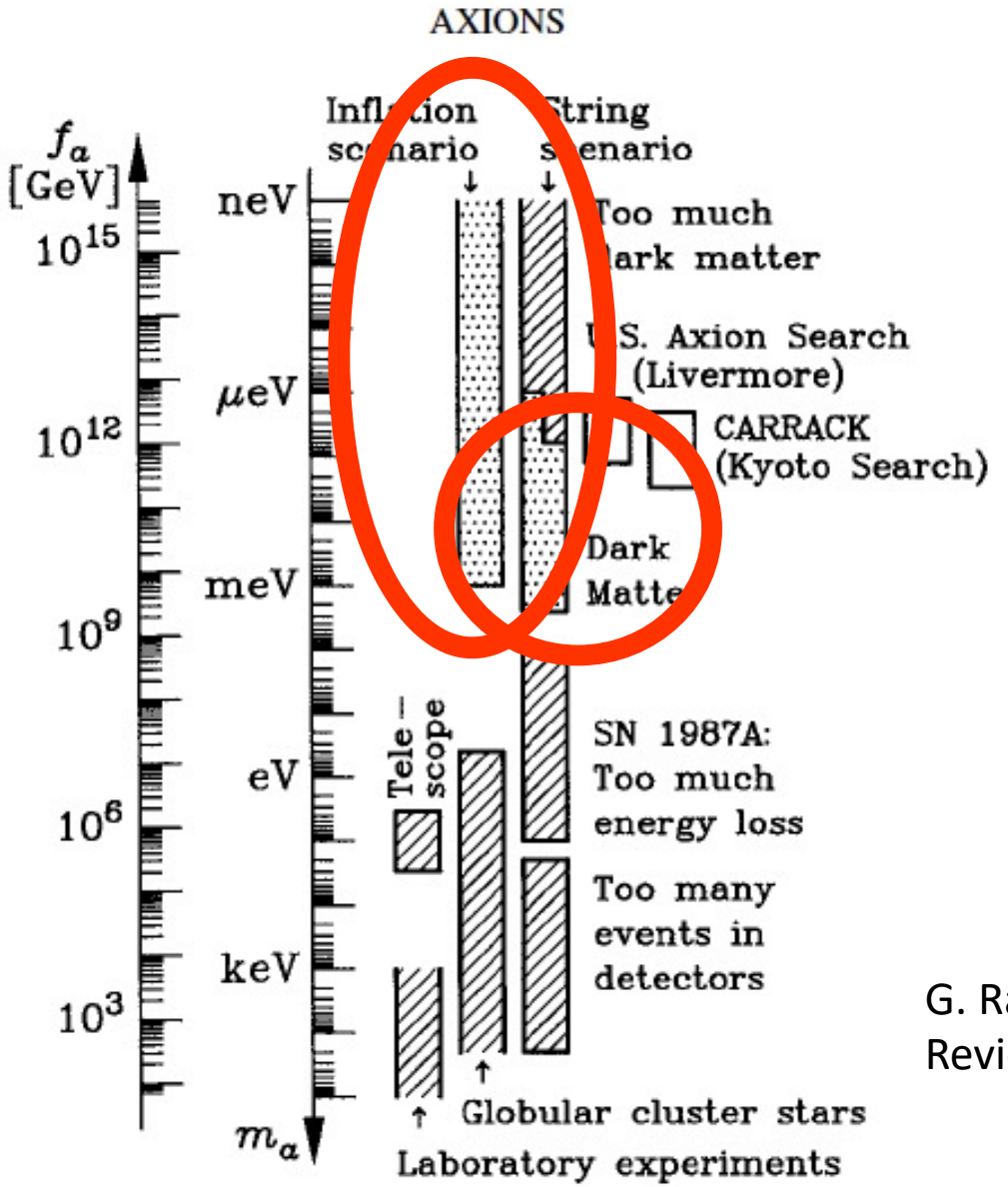
$$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

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

- Fermions (coupling with axion field gradient, pseudomagnetic field)

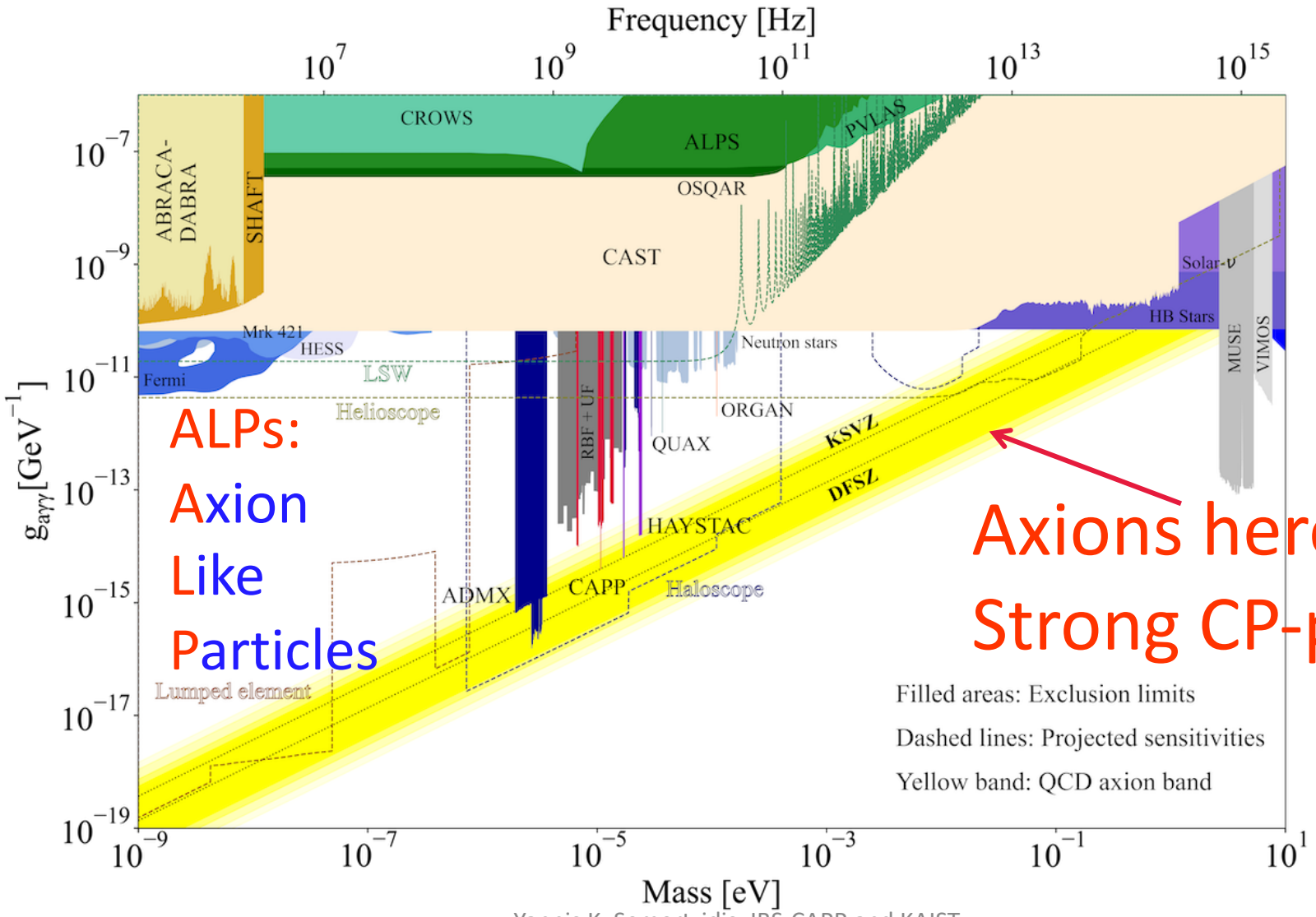
$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

Axion parameters range



G. Raffelt, Space Science Reviews **100**: 153-158, 2002

Axion coupling vs. axion mass



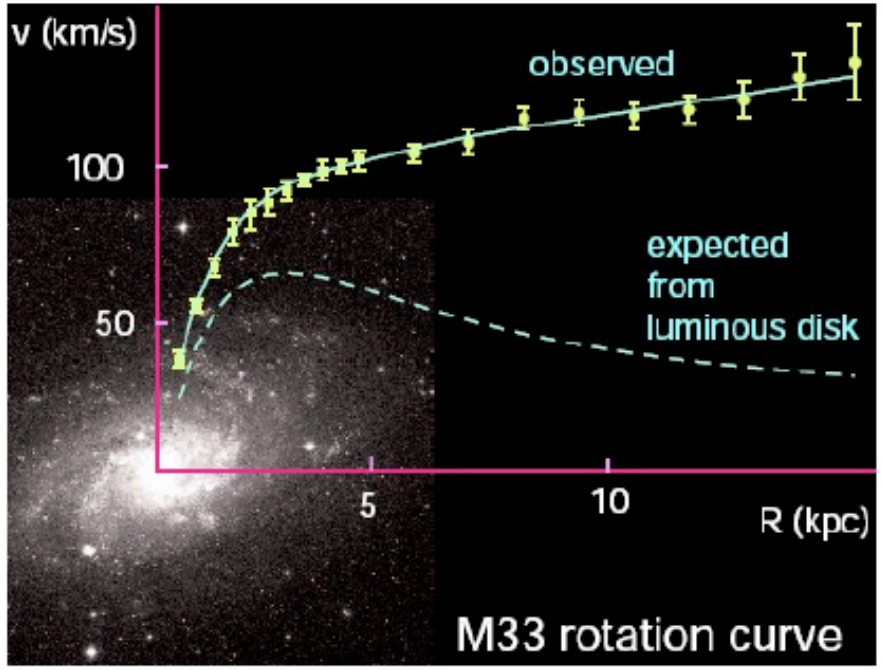
ALPs:
Axion
Like
Particles

Axions here solve the
Strong CP-problem

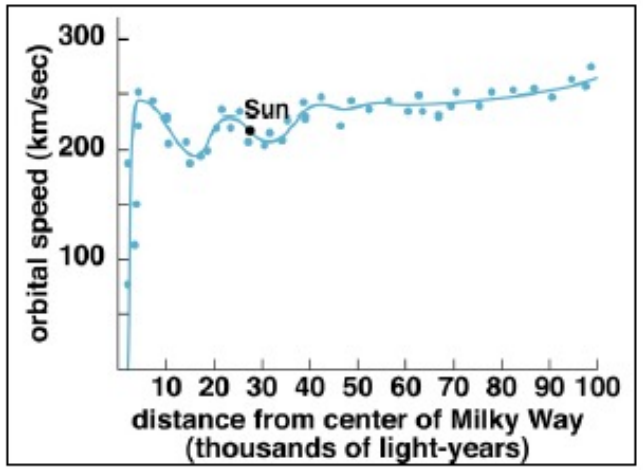
Dark Matter

Origins of dark matter: Rubin, Gallagher, Faber et al.

Flat galactic rotation curves
Rubin, "1970's: The decade of seeing is believing."

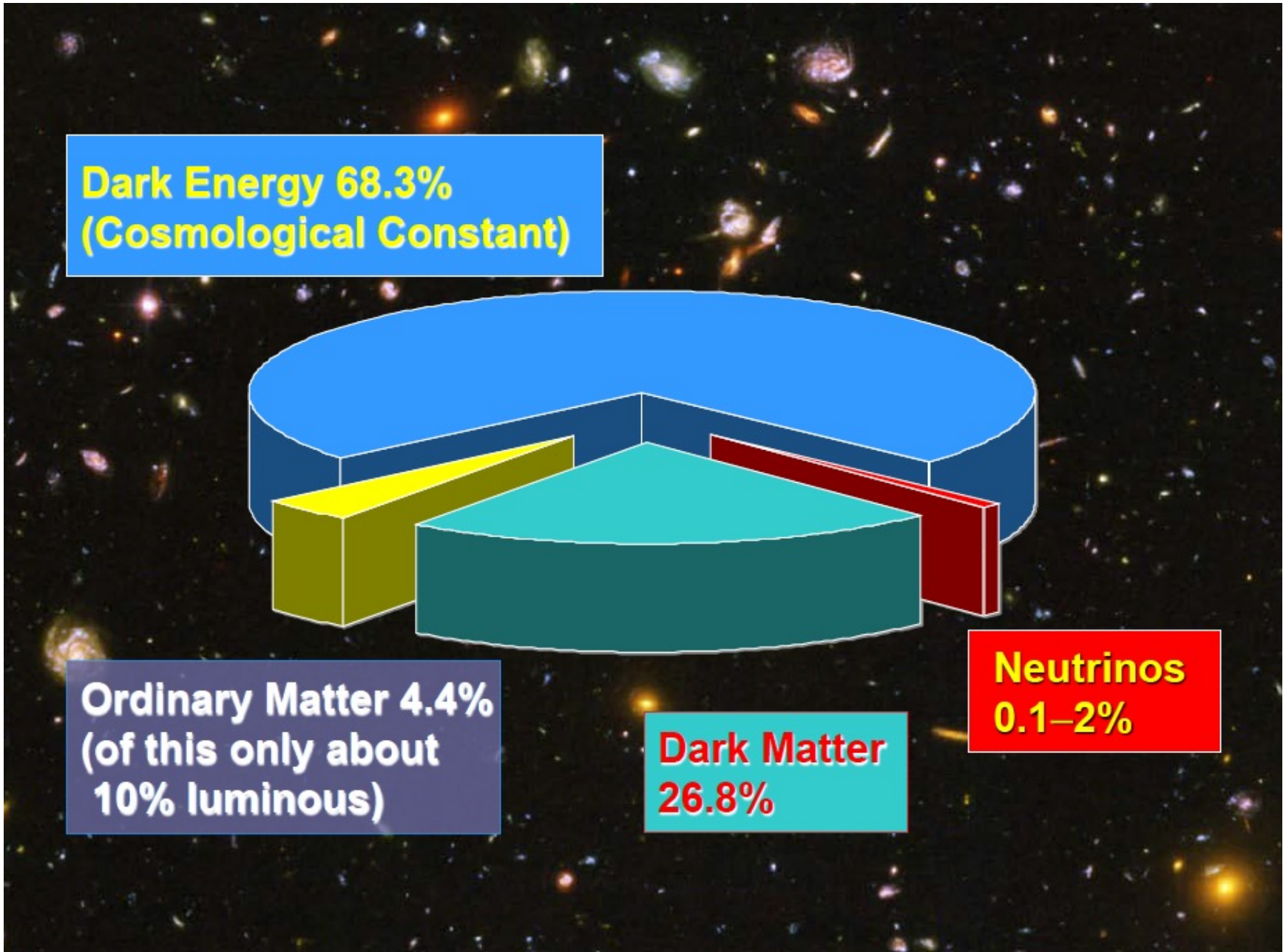


Paolo Saluchi



Professor Vera Rubin passed away 25th of December 2016 at 88. A true Pioneer!

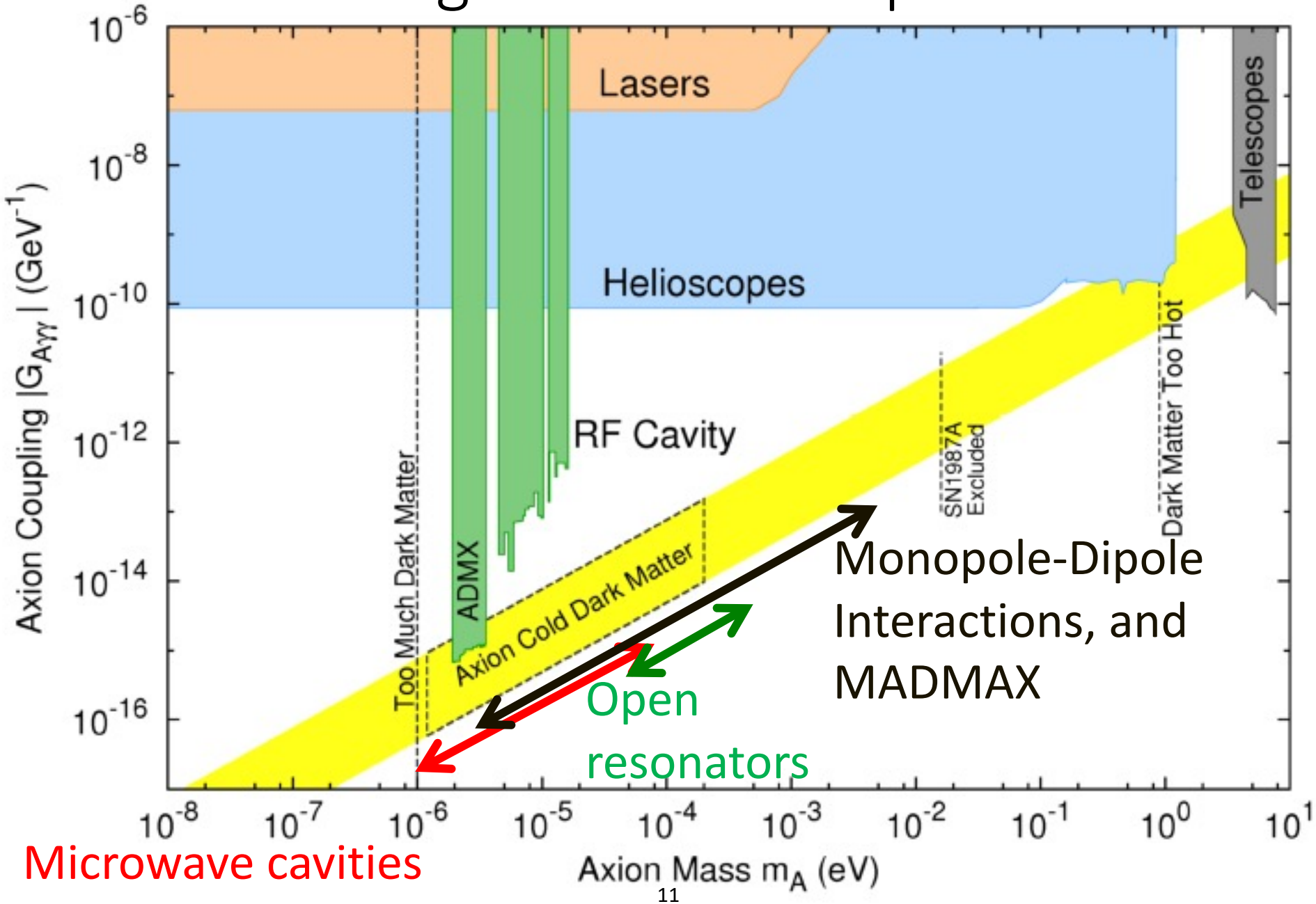
Cosmological inventory



Axion Dark matter

- Dark matter: 0.3-0.5 GeV/cm^3
- Axions in the 1-300μeV range: 10^{12}-10^{14}/cm^3, classical system.
- Lifetime ~7×10^{44}s (100μeV / m_a)^5
- Cold Dark Matter (v/c~10^{-3}), Kinetic energy ~$10^{-6}m_a$, very narrow line in spectrum.

Axion mass target and technique



ADMX, longest in the game

ADMX: Recent results at the DFSZ frontier

N. Du, N. Force, R. Khatiwada, E. Lentz, R. Ottens, L.J Rosenberg, and G. Rybka
University of Washington

G.P. Carosi, N Wollett,
Livermore

A.S. Chou, A. Sonnenschein, and W. Wester
FNAL

C. Boutan and N. Oblath
PNNL

John Clarke, S. O'Kelley, Karl van Bibber
UC Berkeley

Leanne Dufffy
Los Alamos

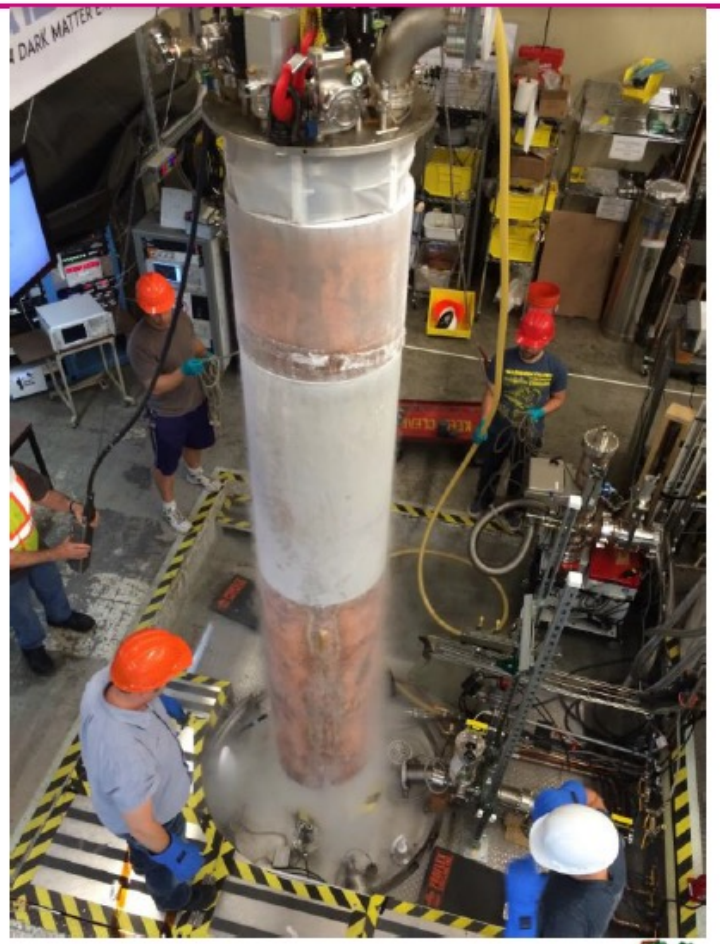
Richard Bradley
NRAO

Ed Daw
Sheffield

Nicole Crisosto, Jeff Hoskins, J. Gleason,

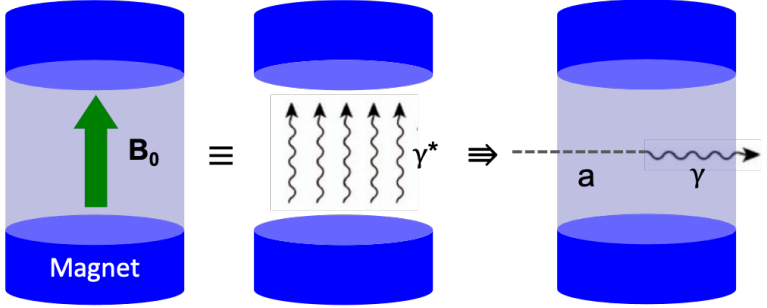
R. Jois, I. Stern, Jihee Yang,

Pierre Sikivie, Neil Sullivan, D.B.T.
University of Florida



ADMX is the Axion Dark Matter eXperiment

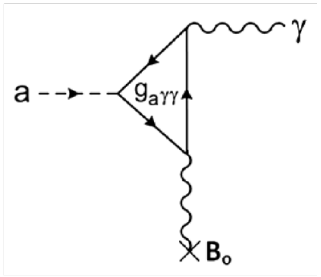
The full ADMX receiver

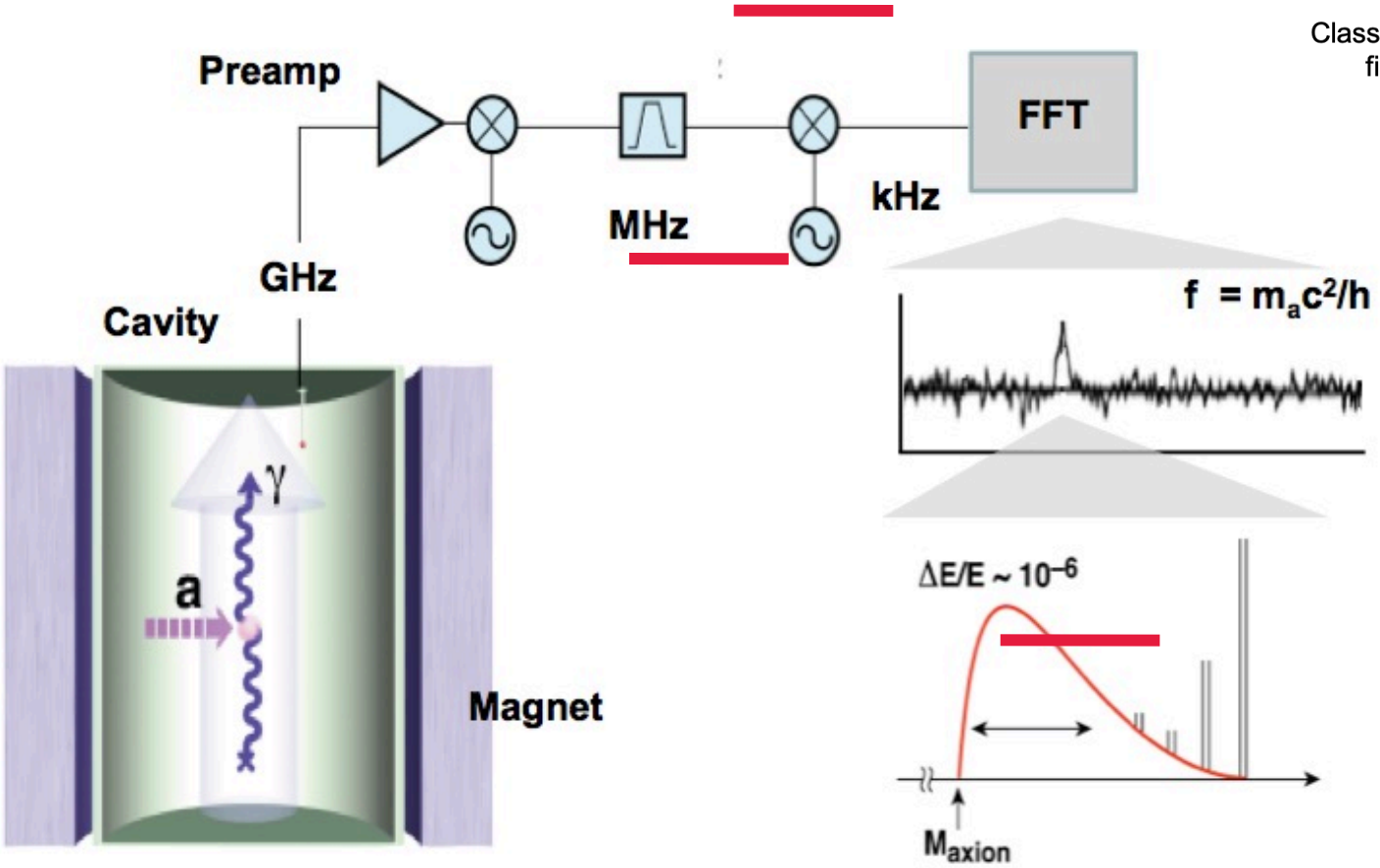


Classical EM field

Sea of virtual photons

(Inverse) Primakoff effect





$$P_{sig} \propto (B^2 V Q_{cav})(g^2 m_a \rho_a) \sim 10^{-23}\,W \qquad s/n = \frac{P_{sig}}{kT_{sys}}\sqrt{\frac{t}{\Delta\nu}}$$

Center for Axion and Precision Physics Research goals: Most advance at 1-8 and applicable up to 25 GHz

- Frequency: 1-8 GHz, CAPP will probe axions with DFSZ sensitivity within next five years. ADMX and HAYSTAC are also launching sensitive searches in this range.

- Frequency: 1-25 GHz, CAPP will probe axions with DFSZ sensitivity within next ten years, even if axions are only 10% of the local dark matter density

Axion searches outside 1-25 GHz

- Above 25 GHz:
  - ARIADNE and hadronic EDM experiments can either detect it or exclude it.
  - MADMAX, using dielectric surfaces to probe high-frequency
  - IAXO, next generation axion helioscope

- At 0.1-1 GHz:
  - ADMX

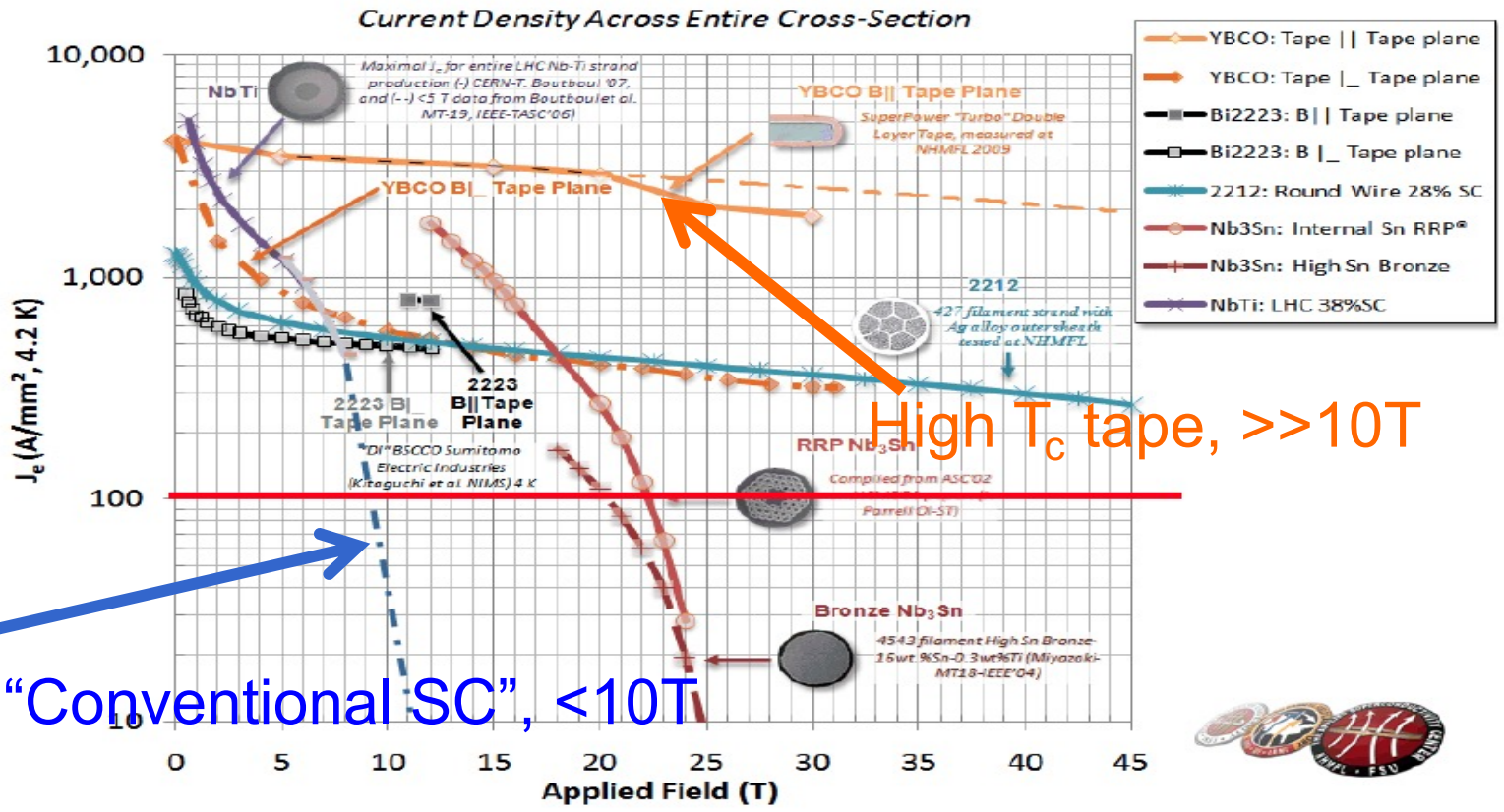
- Very light axions (<0.1 GHz):
  - ABRACADABRA, DM-RADIO (LCR-circuits)
  - CASPEr, based on spin resonance (NMR)

How CAPP is making a difference

- 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)
- LTS (Nb_3Sn), 12T, 320mm diam. Delivered and commissioned in 2020

Future Solenoids:
High- Temperature Superconductors



High T_c tape, >>10T

NbTi: "Conventional SC", <10T

Plot maintained by Peter Lee at: http://magnet.fsu.edu/~lee/plot/plot.htm

Center for Axion and Precision Physics Research (IBS-CAPP) at KAIST

- CAPP of Institute for Basic Science (IBS) at KAIST in Korea since October 2013.
- Projects : Axion dark matter, Storage ring proton EDM, Axion mediated long range forces

Created a state-of-the-art RF-lab at an existing bldg.

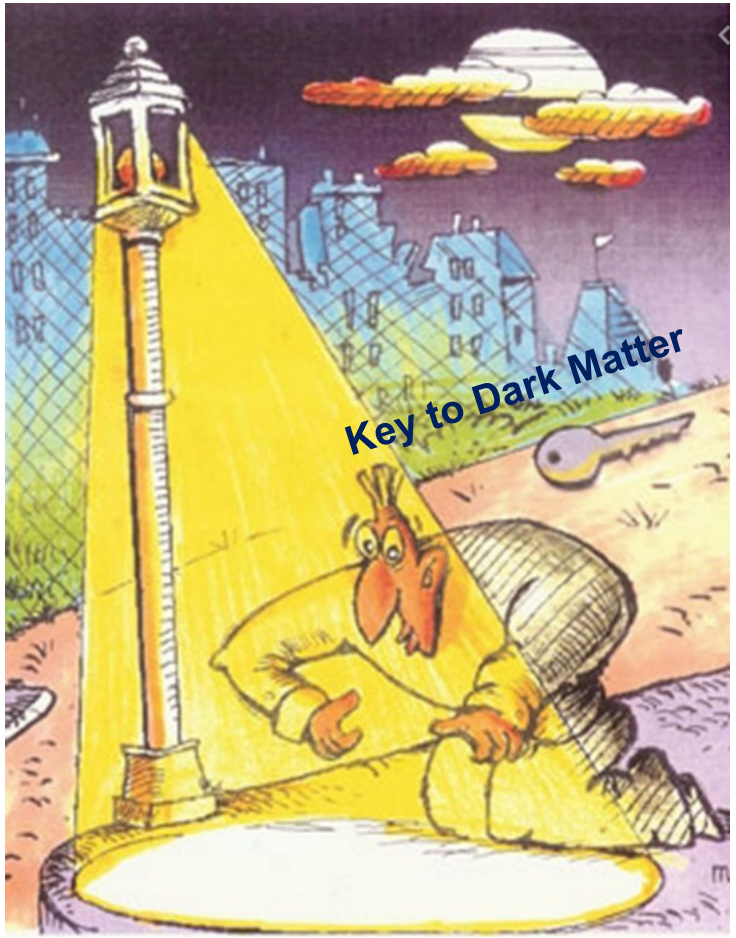
Operation model:

- Reward risk taking with high-physics potential R&D efforts
- Created a can-do environment with independent, competent and confident scientists.

State of the art infra-structure: 7 low vibration pads for parallel experiments; 6 cryo or dilution refrigerators; high B-field, high volume magnet: 12T, 5.6MJ. Flagship exp.

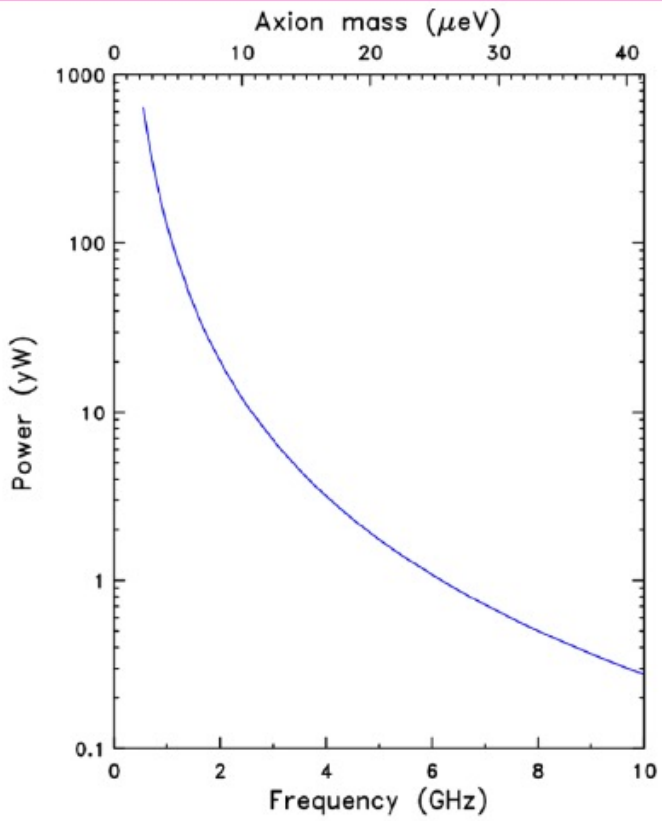
Where to look?

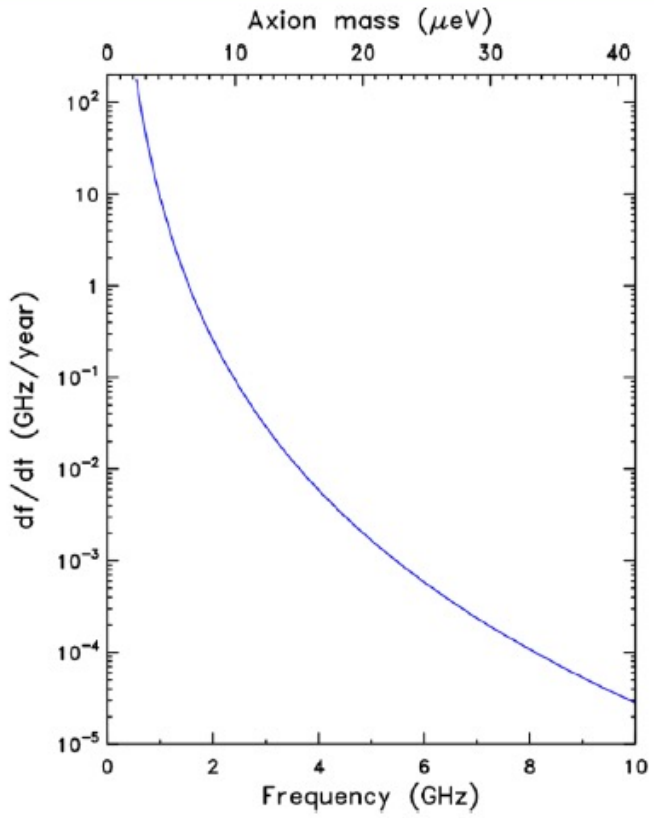
- Below 1 GHz there is a “sweet” spot chosen by ADMX:
- Large volume, with large B^2V including a low-cost low temperature superconducting (LTS) magnet.
- Low noise Microstrip SQUID Amplifier (MSA)
- Dilution refrigerators became readily available (reducing labor cost)



David Tanner, UF

Strawman 2: Single cavity





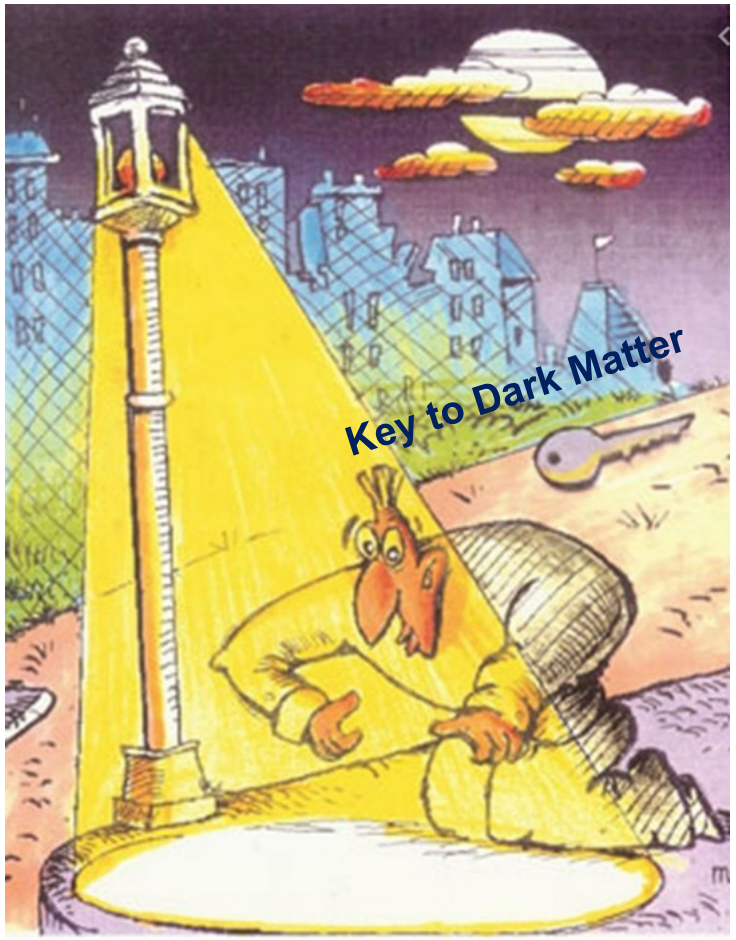
- Power and scan rate decrease as frequency goes up ☹
- Just the opposite of what we want.

Patras 18

CAPP: where to look?

- Create (a brighter) lamp-post:
  - New technology LTS, and HTS high-field magnets
  - Best, quantum-noise-limited RF-amplifiers

- Monopole-dipole interactions (ARIADNE)
  - 25 GHz - 2,500 GHz with International Collaboration
  - Together with the storage ring proton EDM it can detect or exclude axions in the 25 GHz to 2,500 GHz.



CAPP is creating an experimental lamp-post above 1GHz:

1. LTS, Nb_3Sn magnet: 1-8 GHz
2. HTS, ReBCO magnet: for 8-25 GHz

3. Quantum-noise-limited RF-amplifiers (JPA)
4. Super-conducting cavities in strong B-fields
5. “Pizza-cavities” and meta-materials, novel techniques for efficient volume utilization at high-frequencies
6. Phase-match several axion dark matter experiments

7. Novel ways of frequency tuning
8. Efficient and low dark count single photon detector

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: 30 liter cavity, <30mK

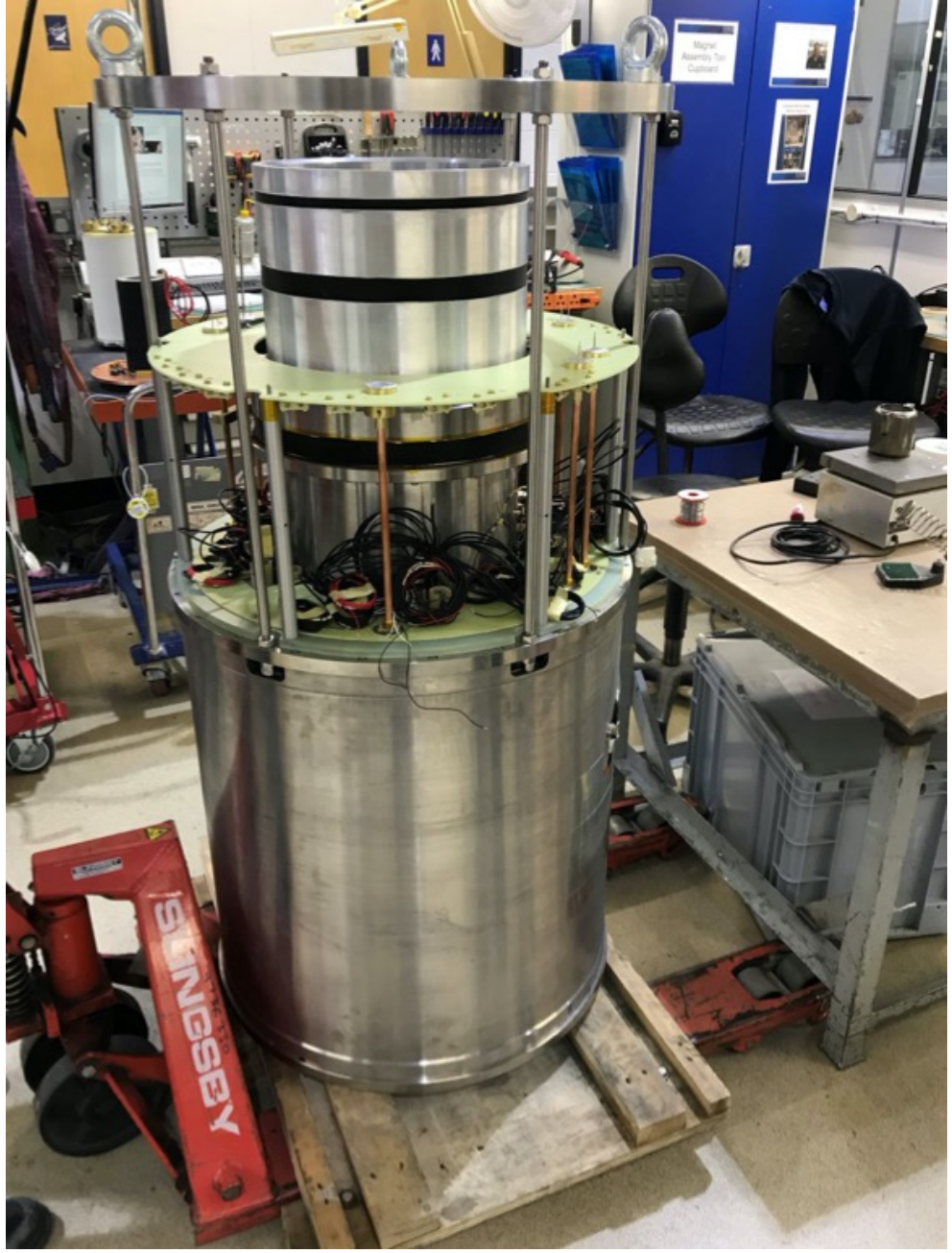
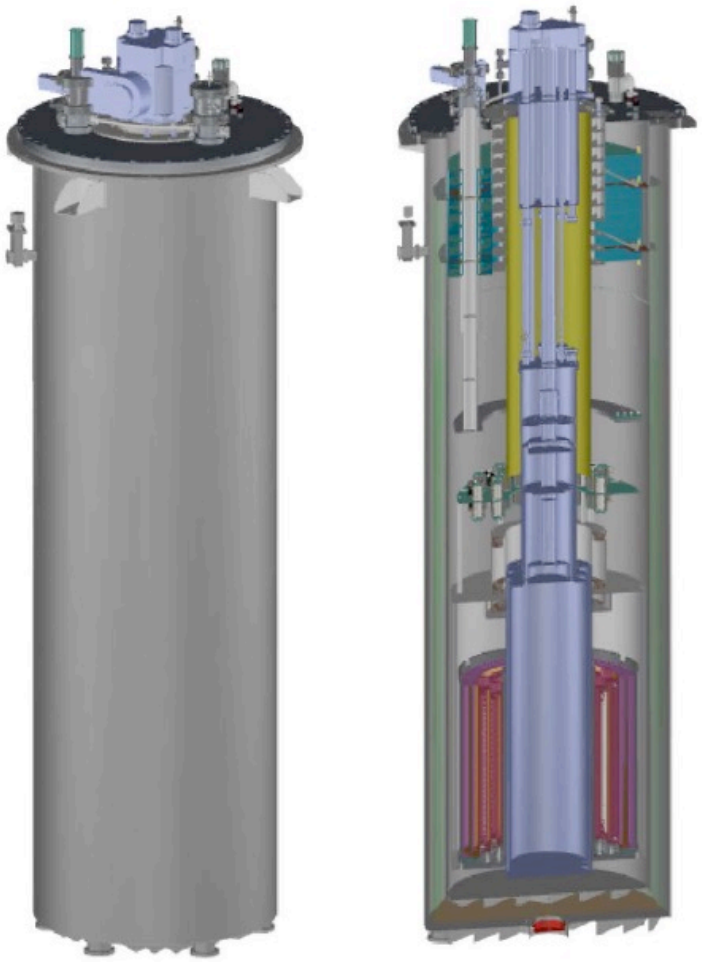
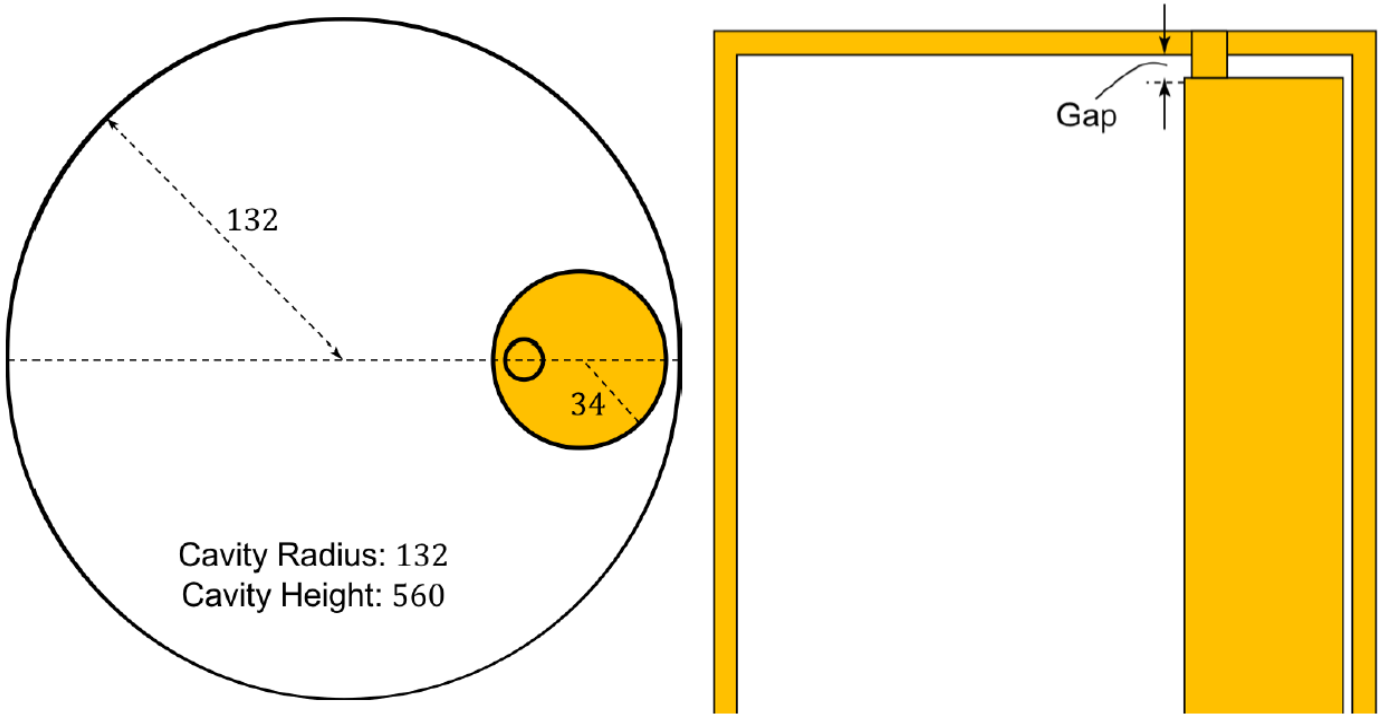


Figure 6. Recent picture of the LTS-12T/320mm magnet in its final form at the Oxford Instruments laboratory. Its total energy content is 5.652 MJ, a powerful magnet that requires respect and caution when energized. The system is to undergo its final tests before its scheduled shipment to IBS-CAPP by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

LTS-12T/320mm from Oxfrod Instruments

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





Left: The cryostat, and dilution refrigerator for the LTS-12T/320mm magnet based on Nb_3Sn from Oxford Instr. Right: Microwave cavity dimensions in mm.

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

The Josephson parametric amplifiers (JPA) from Tokyo/RIKEN are near-quantum-noise limited. They are the best in the world.

- Collaboration with University of Tokyo/RIKEN, providing us with the chips, while we provide feedback for noise improvement.

- Currently we have the lowest noise temperature JPAs at 1GHz, 2 GHz, and 6 GHz.

CAPP delegation visiting
Prof. Nakamura's Lab in Tokyo. Jan. 8, 2019

Superconducting cavity in large B-field!

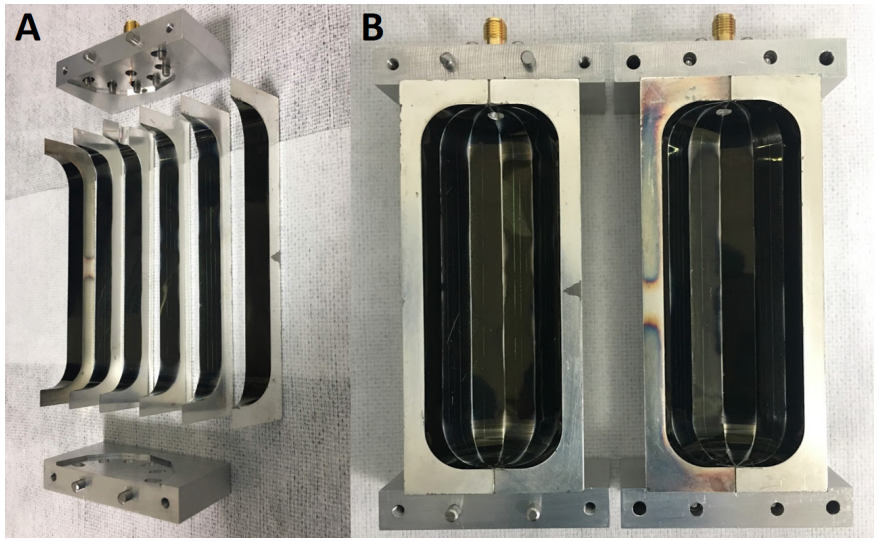
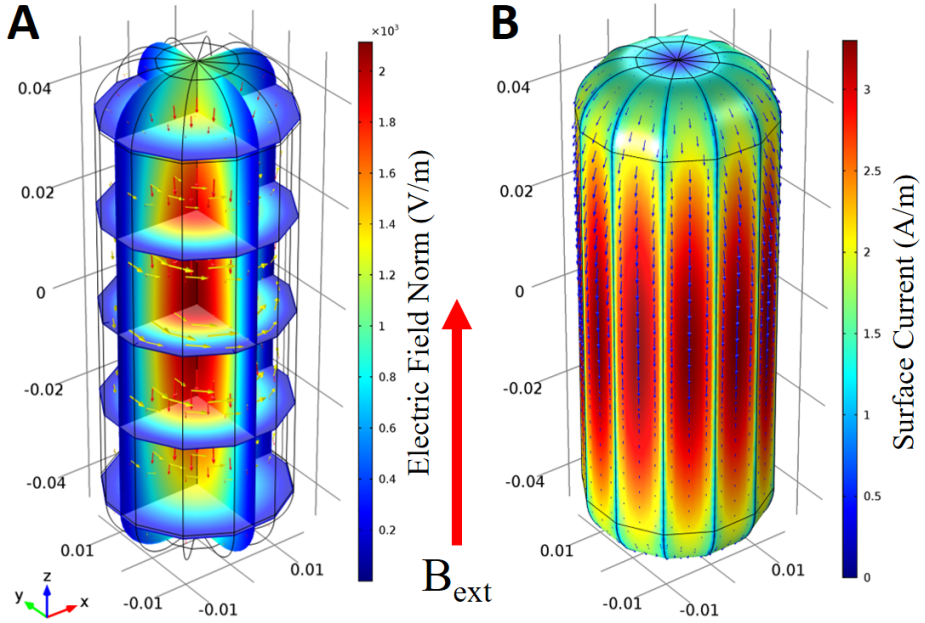


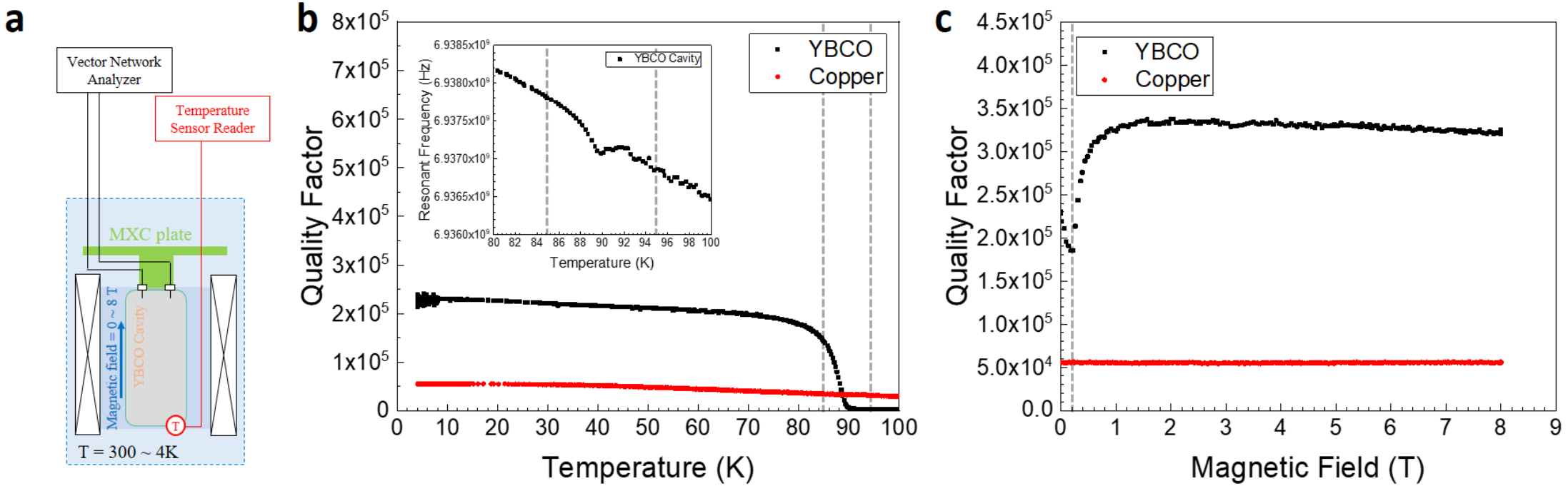
FIG. 1: Design of the YBCO polygon cavity. **(A)** Six aluminum cavity pieces to each of which a YBCO tape is attached. **(B)** Twelve pieces composing two cylinder halves are assembled to a whole cavity.

TM_{010} mode



YBCO tapes placed on cavity slices!

Superconducting cavity in large B-field!

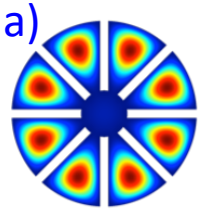


State of the art LTS magnet based on Nb_3Sn; CAPP-12TB, the flagship experiment of IBS-CAPP. Combined with CAPP's breakthrough achievements will place us to the top of our field internationally.

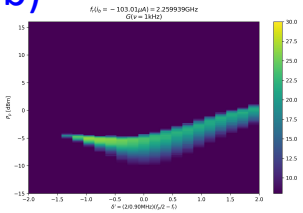
CAPP
Center for Axion and Precision Physics Research

- B-field at center: 12T at 4.2K
- Bore diameter: 320mm
- Max stored energy: 5.65MJ

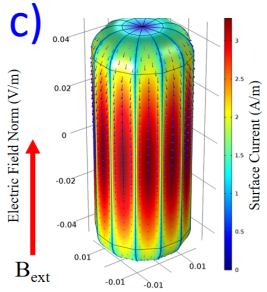
a)

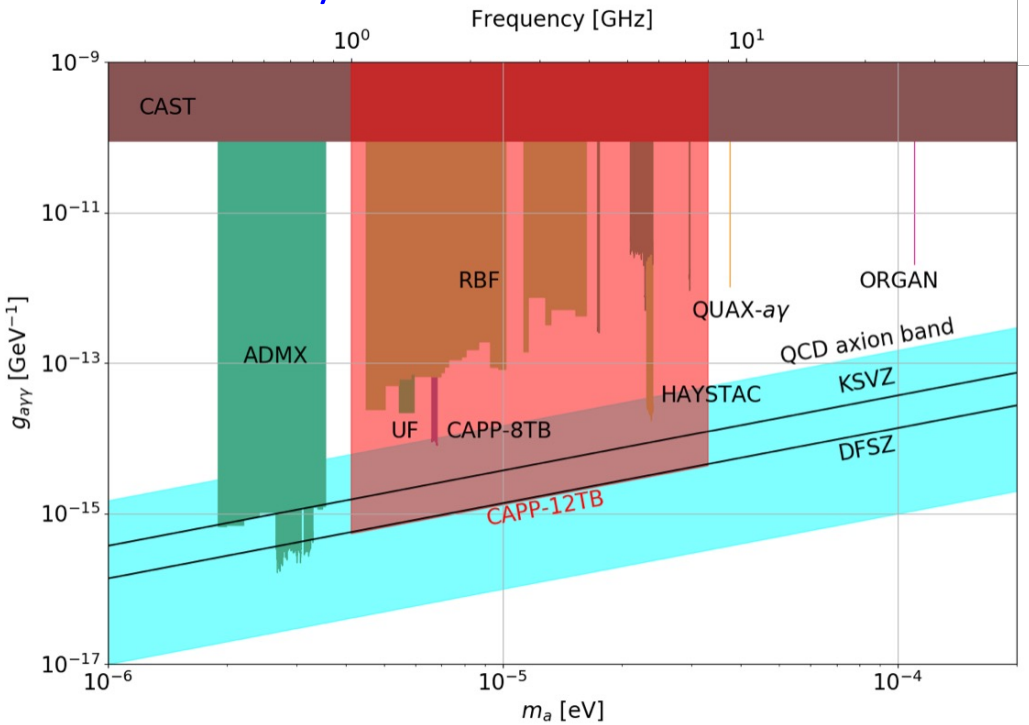


b)



c)





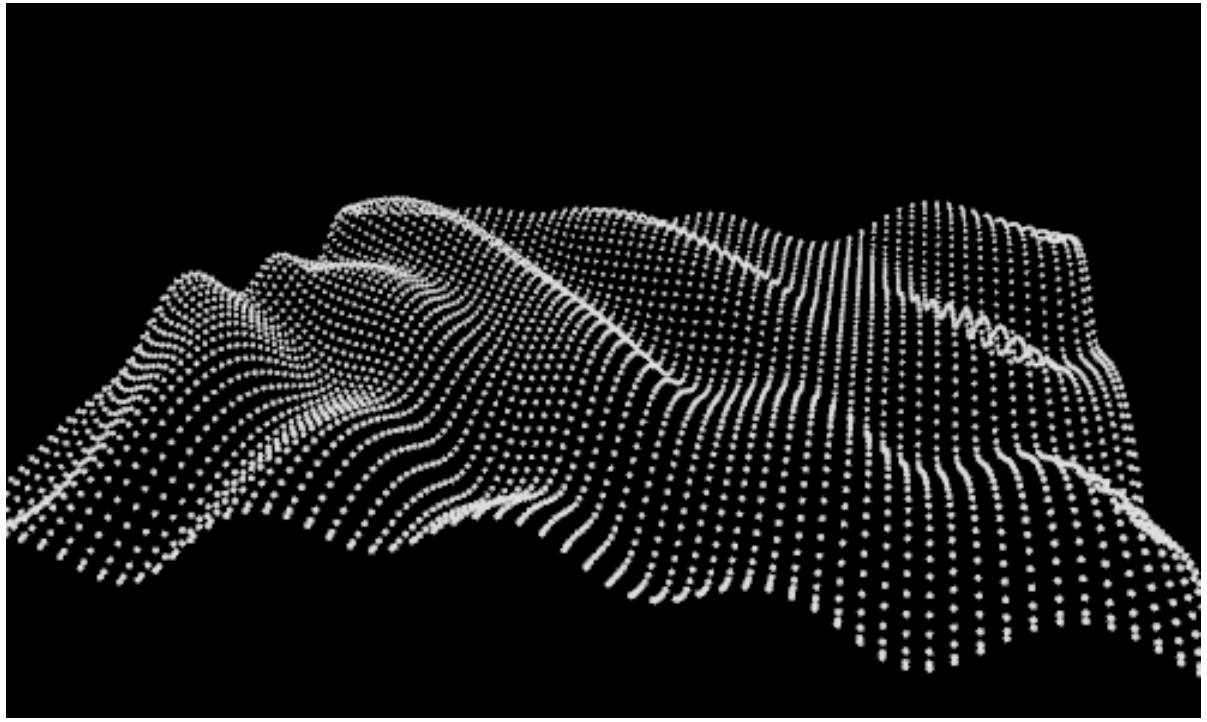
CAPP-12TB, 1-8 GHz axion-frequency projected sensitivity based on our achievements:

a) High-efficiency, high-frequency "Pizza-cavity";
b) Quantum-noise limited amplifiers;
c) Super-conducting cavities in strong magnetic fields!

Axion Dark matter, Phase Matching (PM) several experiments together to increase sensitivity

- Axions: A Cosmic MASER
- Axion coherence length (De Broglie wavelength):

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



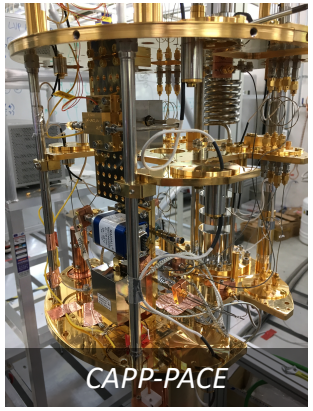
IBS/CAPP axion dark matter search timeline

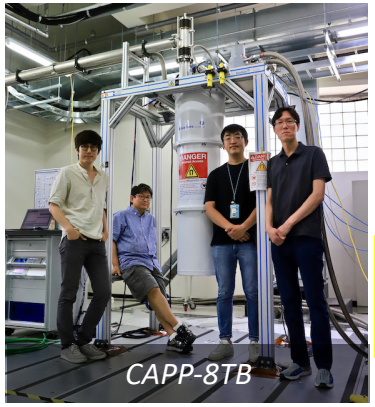
- Support for operations and the current R&D items is critical to keep the momentum
- We need support to finish the 25 T, HTS magnet ($1M to finish it)

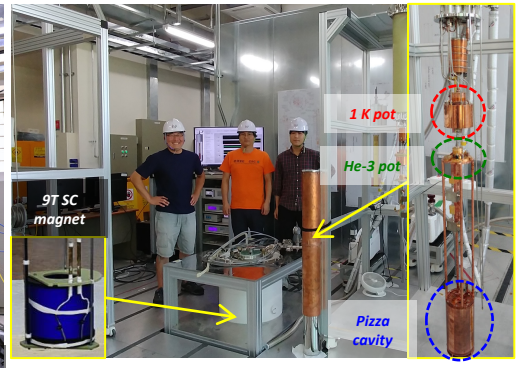
Table 1: IBS-CAPP R&D project timeline. The projects already completed or under development will set the Center to probe $1-8$ GHz at DFSZ sensitivity within the next five years. An integration of a HTS magnet, superconducting cavities, and a single photon detector (SPD) will enable the Center to reach high sensitivity in axion physics in the $1-25$ GHz range in the years after 2024.

Project	**Target frequency**	**Sensitivity level / frequency band**			
		2021	**2022**	**2023**	**2024**
CAPP-PACE (8T/2L)	2.3 & 6 GHz	KSVZ / 50 MHz	KSVZ / 1 GHz (PM)	DFSZ / 0.5 GHz (PM & SCR)	DFSZ / 1 GHz (PM & SCR)
CAPP-8T (8T/3.1L)	1.6 & 6 GHz	KSVZ / 200 MHz	KSVZ / 1 GHz (PM)	DFSZ / 0.5 GHz (PM & SCR)	DFSZ / 1 GHz (PM & SCR)
CAPP-MC (12T/1.5L)	$6-8$ GHz	KSVZ / 20 MHz	KSVZ / 1 GHz (PM)	DFSZ / 0.5 GHz (PM & SCR)	DFSZ / 1 GHz (PM & SCR)
CAPP-12T (12T/30L)	$1-8$ GHz	DFSZ / 100 MHz	DFSZ / $1-2$ GHz	DFSZ / $2-4$ GHz	DFSZ / $4-8$ GHz
HTS-25T magnet	$8-25$ GHz	Funding security	24 coils $(16+8)$	Additional 24 coils	Magnet complete. (2025: Test)
Superconducting resonator (SCR)	$1-25$ GHz	$Q = 10^6$	$Q = 2 \times 10^6$	$Q = 5 \times 10^6$	$Q = 10^7$
JPA (TWJPA) & SPD	$1-10$ GHz (JPA) $8-25$ GHz (SPD)	$1-3$ & $5-6$ GHz (JPA)	$1-8$ GHz (JPA & TWJPA)	$1-8$ GHz (JPA & TWJPA)	SPD first results

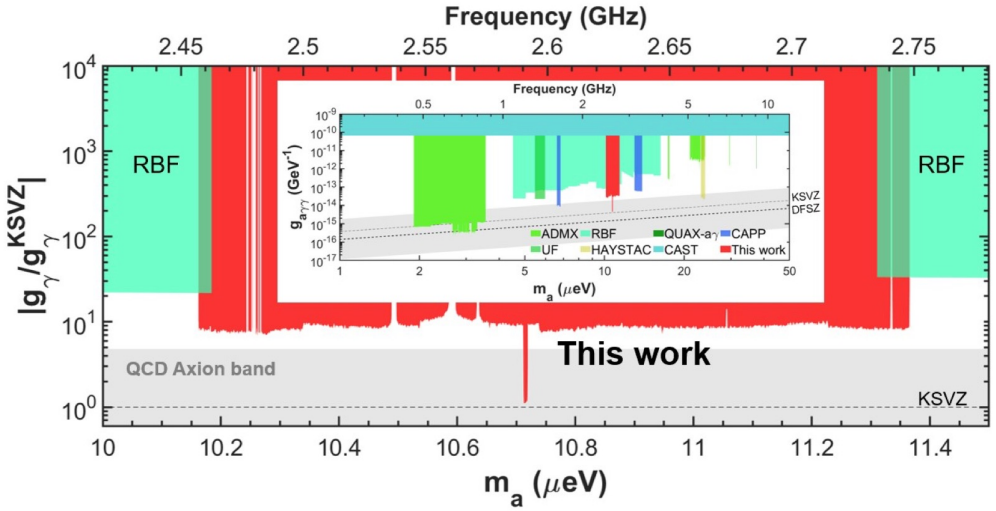
IBS/CAPP axion dark matter search

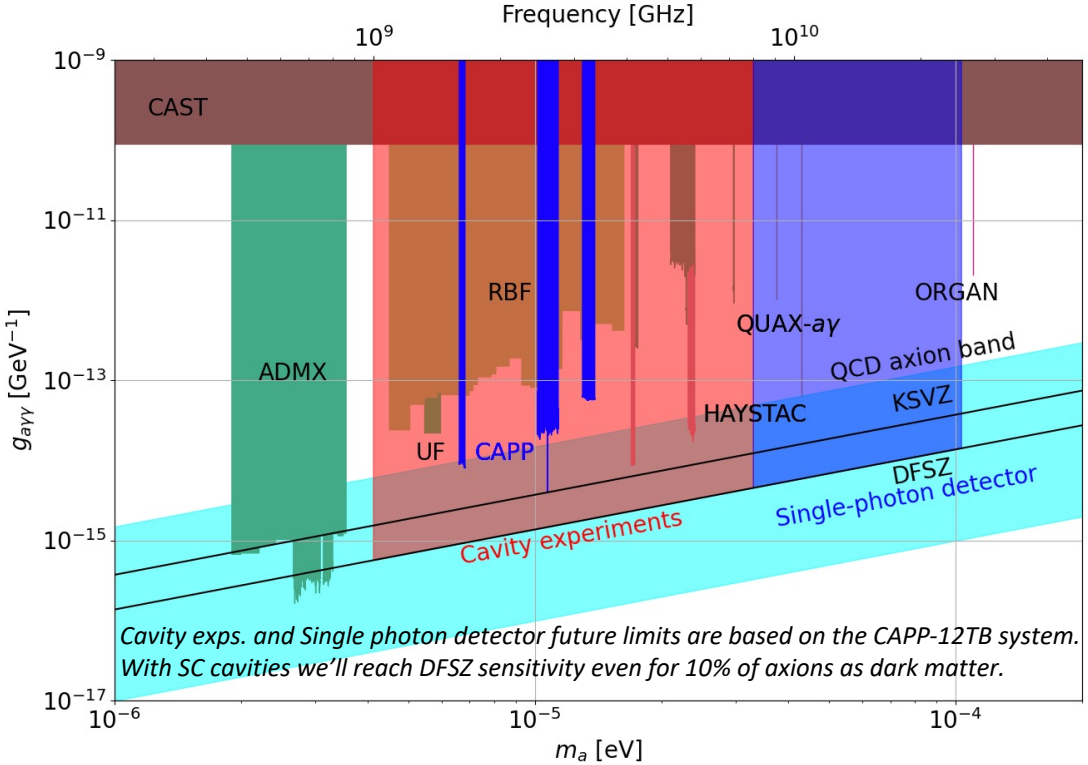






CAPP-9T MC





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

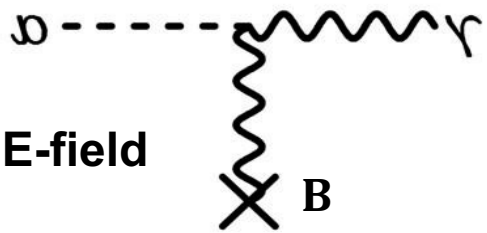
Other Haloscopes, Helioscopes, ALPs

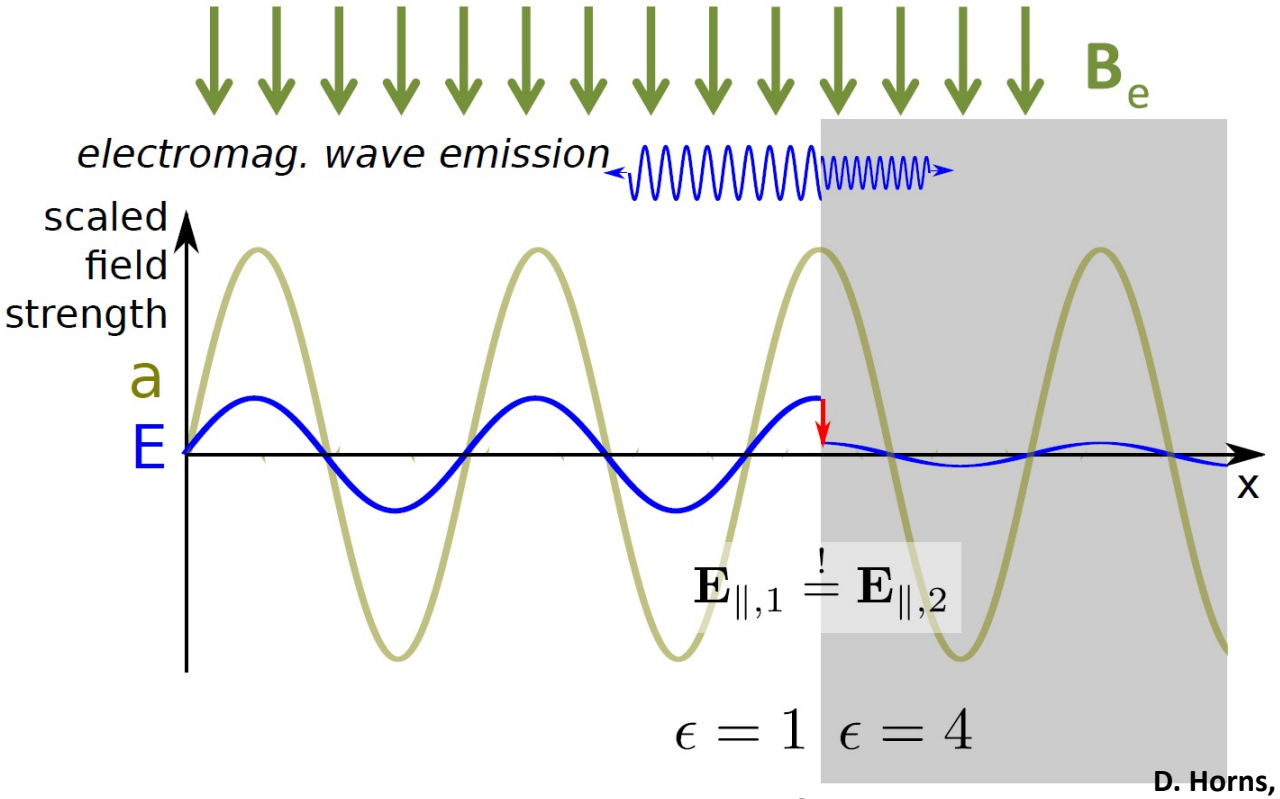
MADMAX

B. Majorovits

Experimental approaches: Effect of Dielectric

Mixing of axion with photon in extrenal B-field
→ Sources oscillating E-field
At surfaces with transition of ε: Discontinuity of E-field
→ Emission of photons





$$\left(\frac{P}{A}\right)_{mirror} \sim 2 \cdot 10^{-27} \frac{W}{m^2} \left(\frac{B_{||}}{10\ T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2$$

D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald JCAP 1304 (2013) 016 [arXiv:1212.2970].

Axion dark matter: MADMAX

1801.08127v2

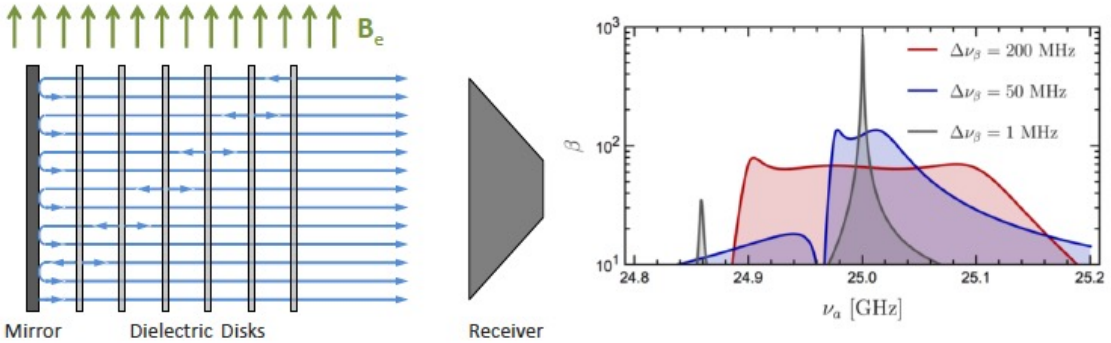


Figure 21: Left: sketch of the dielectric haloscope experiment. Photons in the B_e field are emitted from the dielectric surfaces and reflected in the leftmost mirror and other surfaces to be measured coherently by a receiver, from [585]. Right: Adjusting the distances between the layers, the frequency dependence of the boosted sensitivity can be adjusted to different bandwidths, from [590].

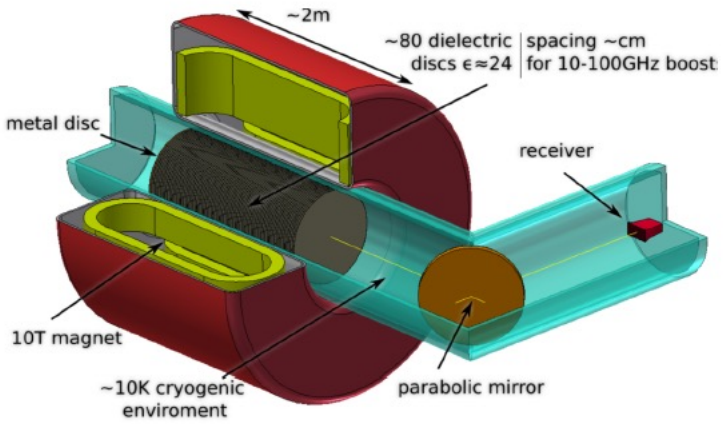
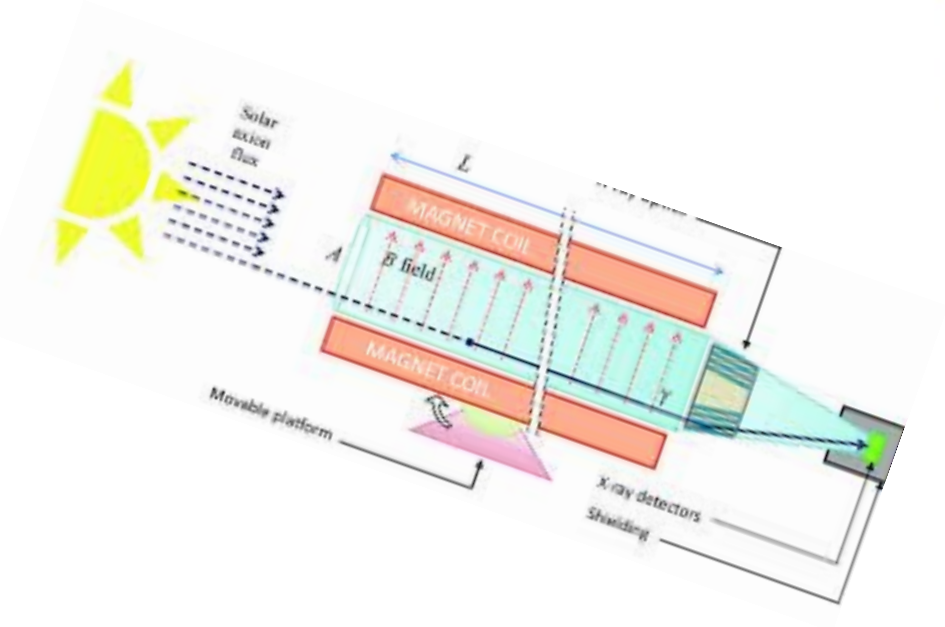
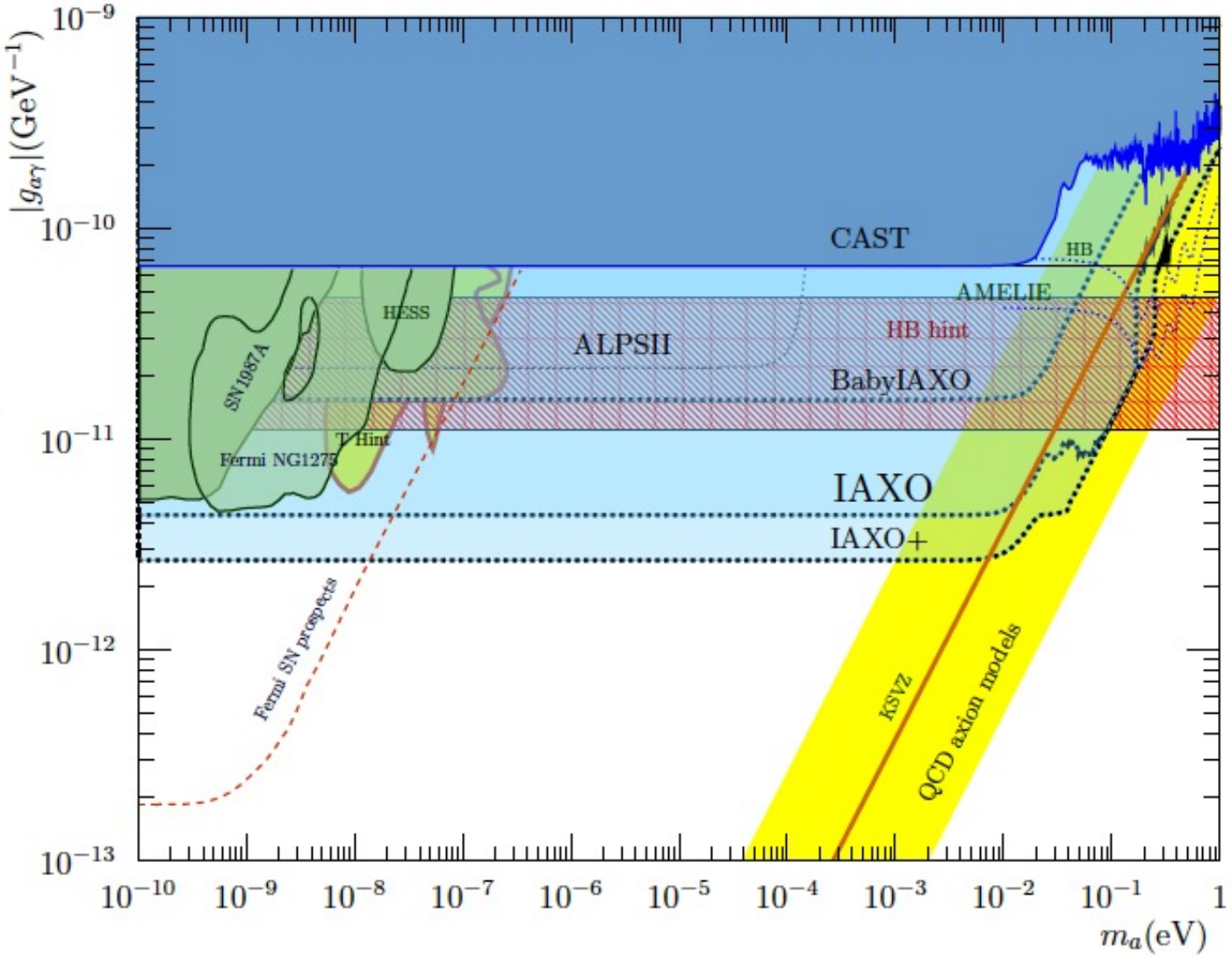


Figure 22: The concept of the MADMAX experiment, see text for details. From [590].

CAST and planned axion Helioscopes





ALPS (Axion Like Particles)

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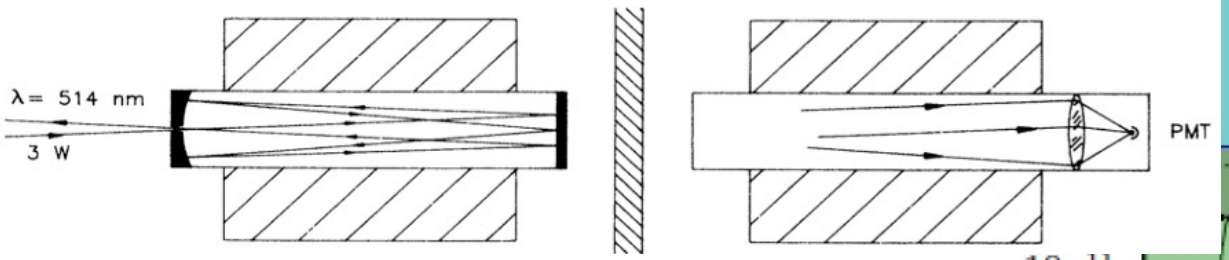
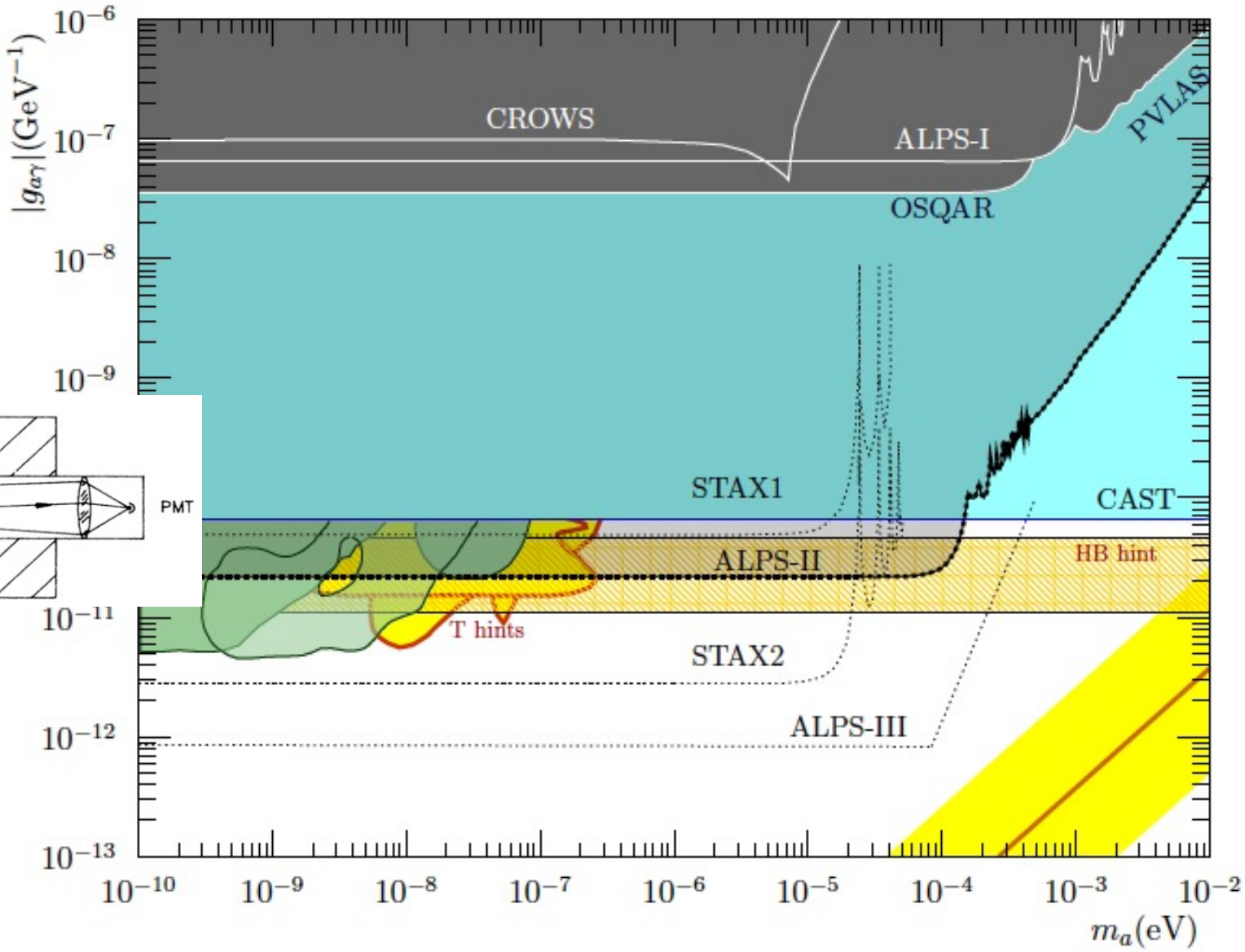
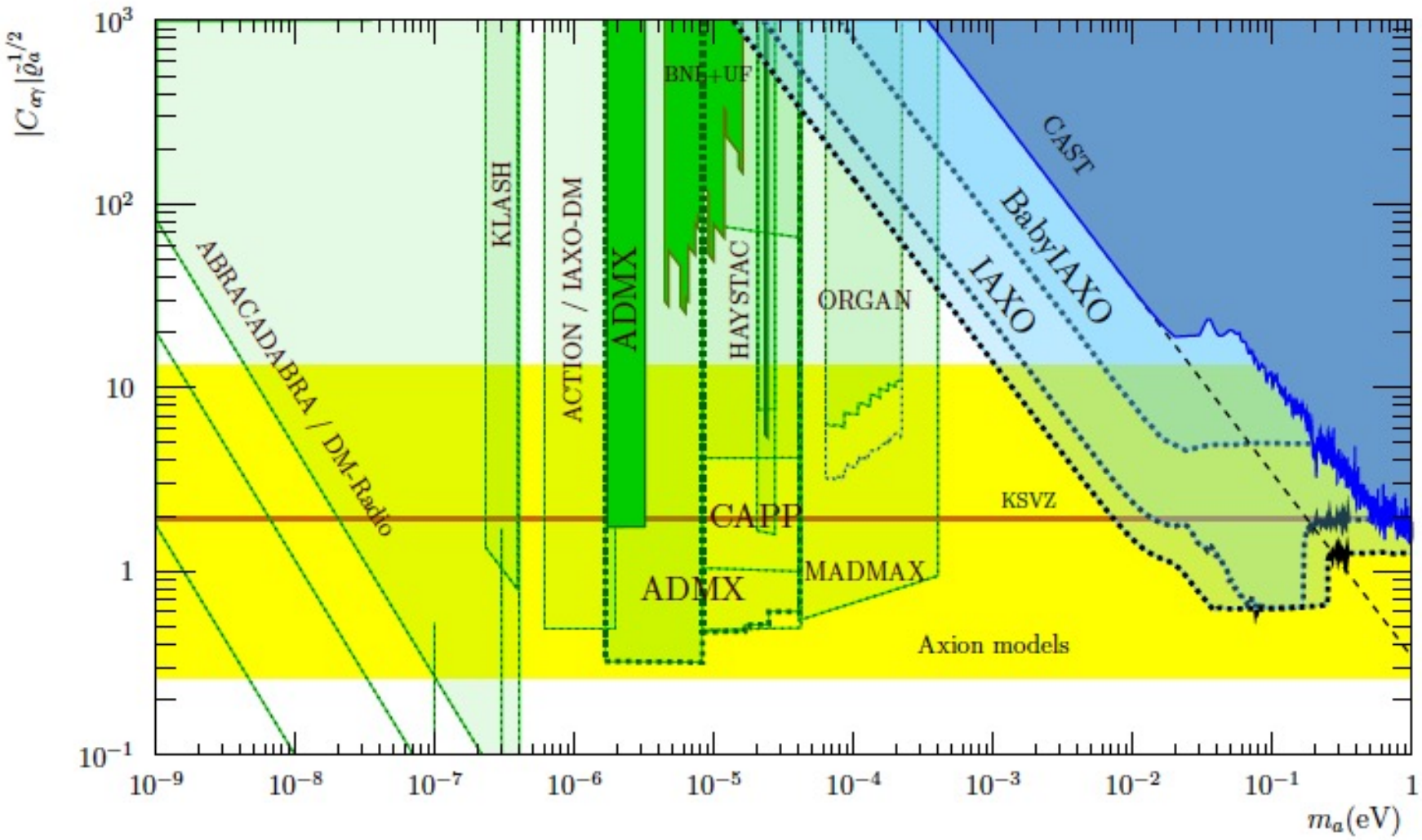
- Light shining through the wall





Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

Summary

- Within the next five years we will probe 1-8 GHz with DFSZ sensitivity assuming axions as 100% of the local dark matter density.
- Within the next ten years we will probe 1-25 GHz with DFSZ sensitivity even if axions are only 10% of the local density.
- ARIADNE and storage ring proton EDM will probe axions in the >25GHz range
- CASPEr, DM-RADIO, ABRACADABRA, etc., will probe the low frequency range, below 0.1 GHz with high sensitivity.
- The next ten years are very exciting!

Extra slides

Haloscopes using spins!

Axion and EDM: Proton and Deuteron

- Spin generates a magnetic dipole moment
- If it also generates an electric dipole moment: it violates both P&T, through CPT cons.→CP violation

$$L_{\cancel{CP}} = \bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$$

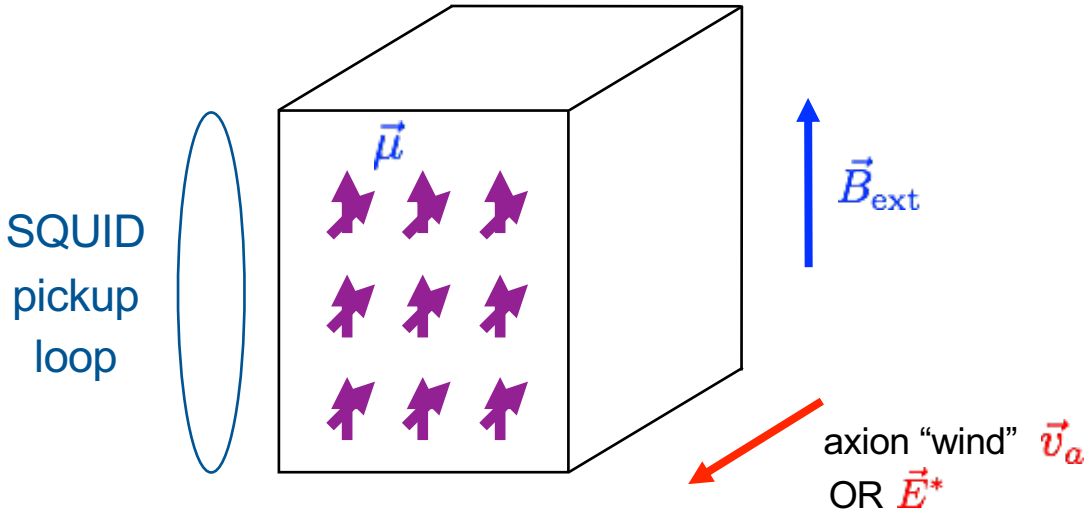
$$d_n\left(\bar{\theta}\right) \approx -d_p\left(\bar{\theta}\right) \approx 3.6\times10^{-16}\bar{\theta}\ \mathrm{e}\cdot\mathrm{cm}$$

M. Pospelov, A. Ritz, Ann. Phys. 318 (2005) 119.

$$\text{Exp.:}\ d_n < 3\times10^{-26} e\cdot\ \mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$$

Dima Budker

CASPEr



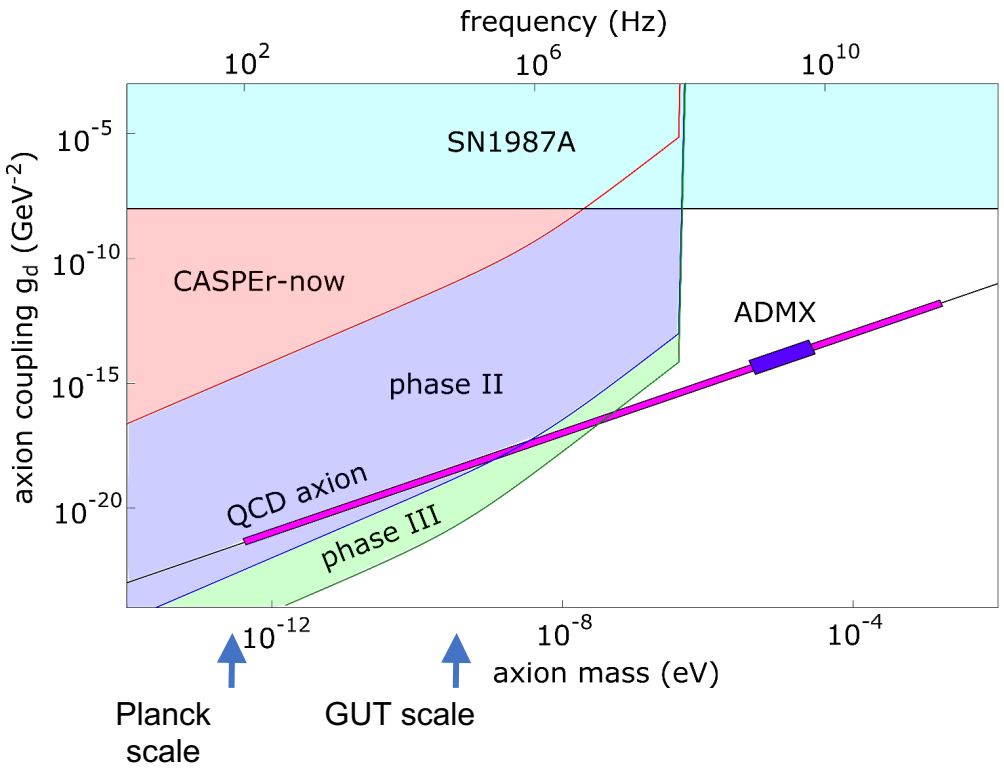
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

Example materials: liquid ^{129}Xe, ferroelectric $PbTiO_3$

Dima Budker

The experimental reach of CASPEr



CASPEr-now at BU:
- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- broadband SQUID detection

phase II:
- optically enhanced spin polarization
- 5 cm sample size,
- 14T magnet, homogeneity 100 ppm
- tuned SQUID circuit?

phase III:
- hyperpolarization by optical pumping
- 10 cm sample size,
- 14T magnet, homogeneity 10 ppm
- tuned SQUID circuit?

[*Phys. Rev. X* **4**, 021030 (2014)]

Slide by Alex Suskov (adapted)

Axion and EDM: Proton and Deuteron

- Storage ring p,d EDMs @ $<10^{-29}$ *e*-cm level, ~10^3TeV physics reach.
- Probing DC (permanent) EDM
- For axion dark matter, we need to detect an oscillating EDM!

[https://www.nature.com/articles/nature25767].

A Galaxy without Dark Matter,

effectively confirming

Dark Matter!

A Galaxy Without Dark Matter

Press Release - Source: Yale University Posted March 28, 2018 10:34 PM 0 Comments

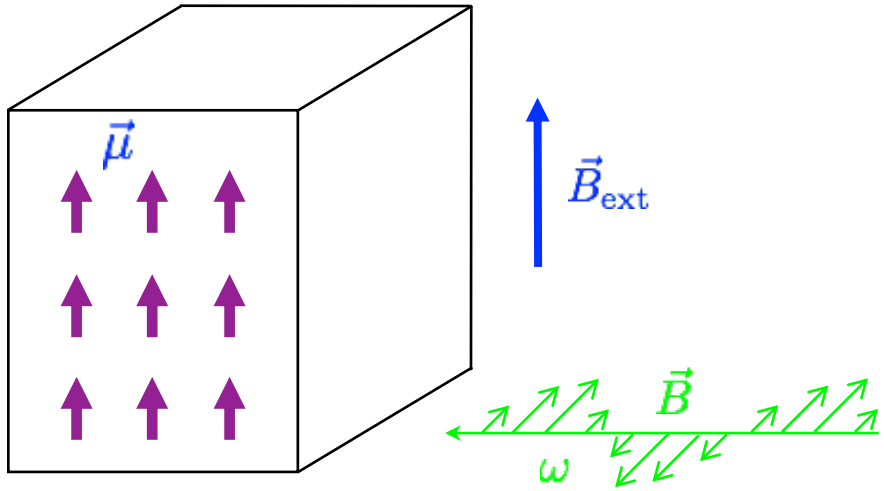
NGC 1052-DF2

A Yale-led research team has discovered a galaxy that contains no dark matter -- a finding that confirms the possibility of dark matter as a separate material elsewhere in the universe.

The discovery has broad implications for astrophysics, the researchers said. It shows for the first time that dark matter is not always associated with traditional matter on a galactic scale, ruling out several current theories that dark matter is not a substance but merely a manifestation of the laws of gravity on cosmic scales.

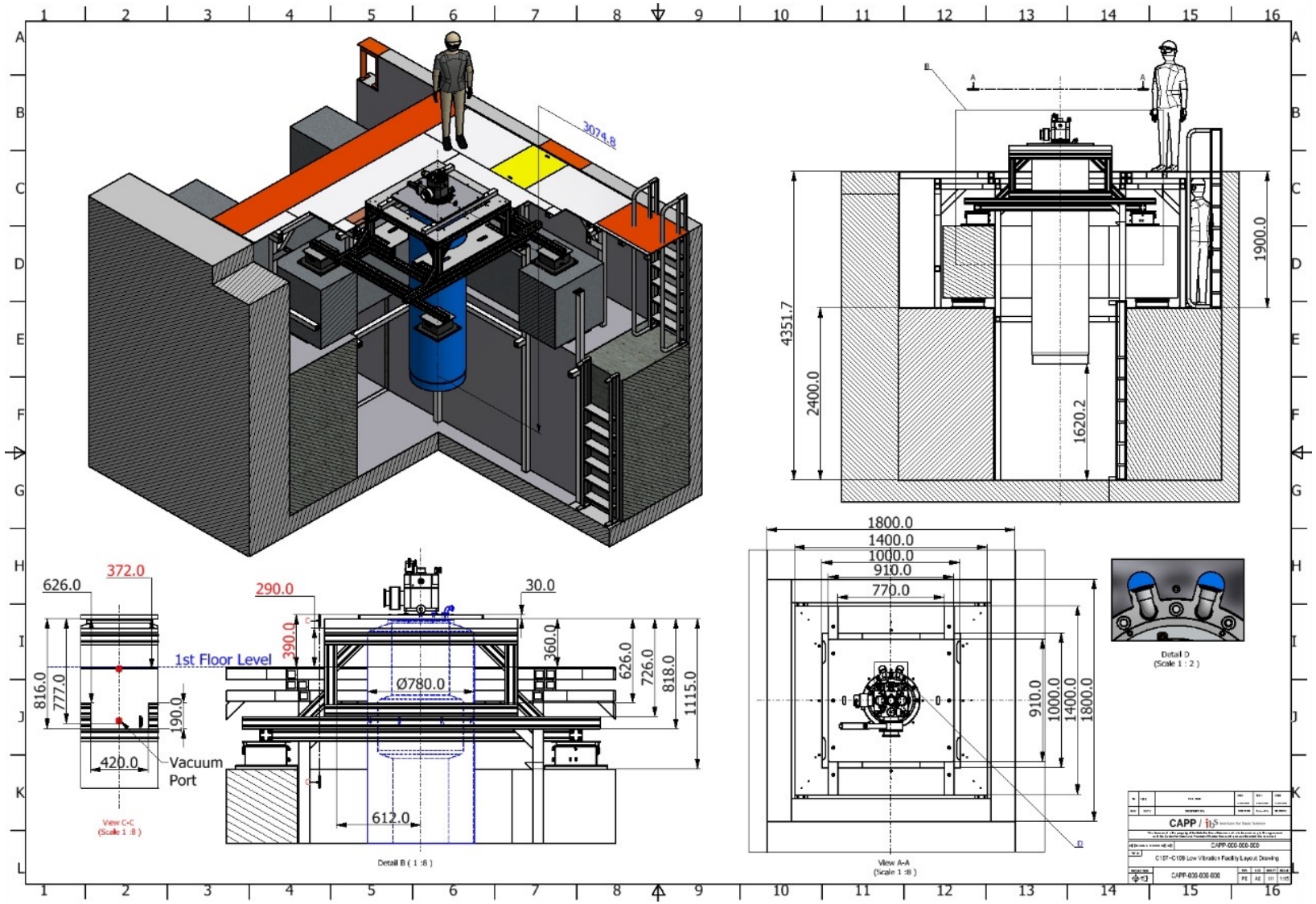
Dima Budker, CASPEr

Nuclear Magnetic Resonance (NMR)



Resonance: $2\mu B_{\text{ext}} = \omega$

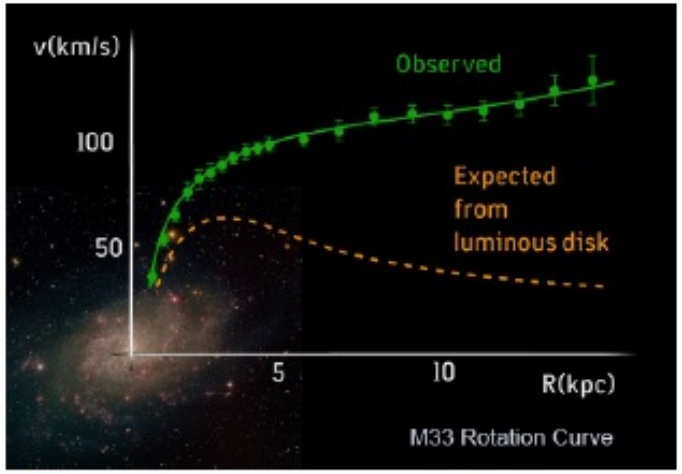
- Low vibration pad installation



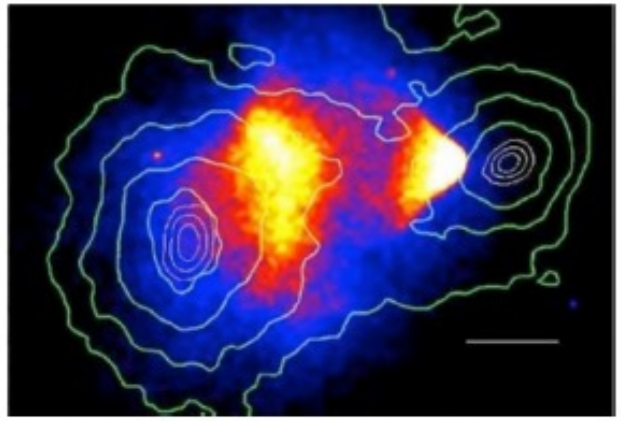
Eric Charles, Fermi-LAT collaboration

Evidence for / Salient Features of Dark Matter

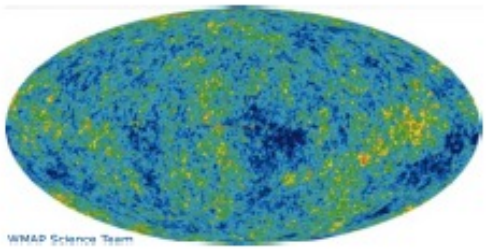
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)

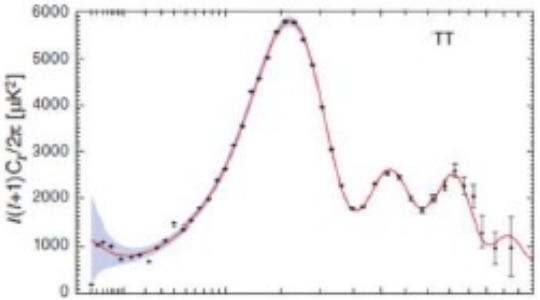


*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



*Almost **collisionless***
Bullet Cluster
Clowe+(2006)





Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)

Axion Dark matter

- Velocity range: $<10^{-3}c$ (bound in galaxies)
- Mass range: $>10^{-22}$eV (size of galaxies)
- Coherence length (De Broglie wavelength):

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

Axion dark matter: open resonators, MADMAX

1801.08127v2

Dielectrics for high frequency-short wavelength

Dielectrics to suppress negative E-field

Reverse direction of B-field

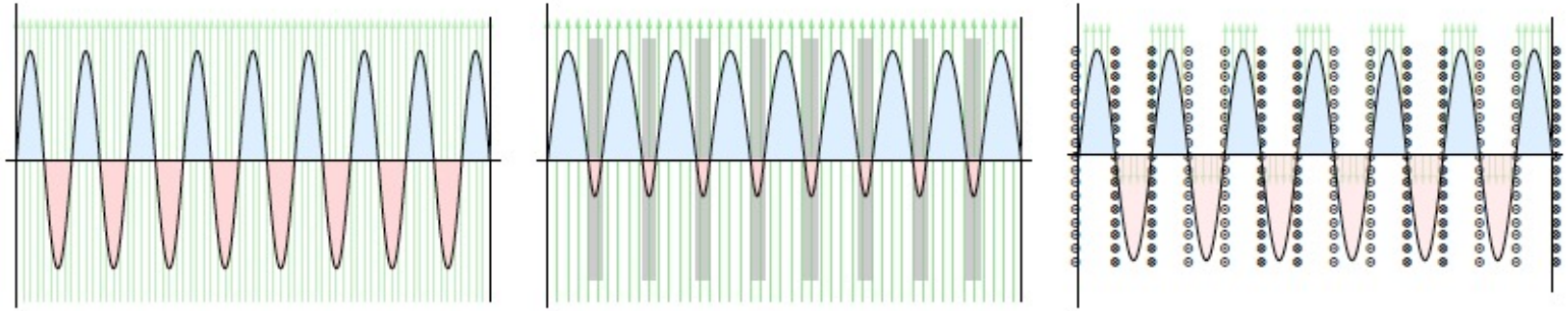
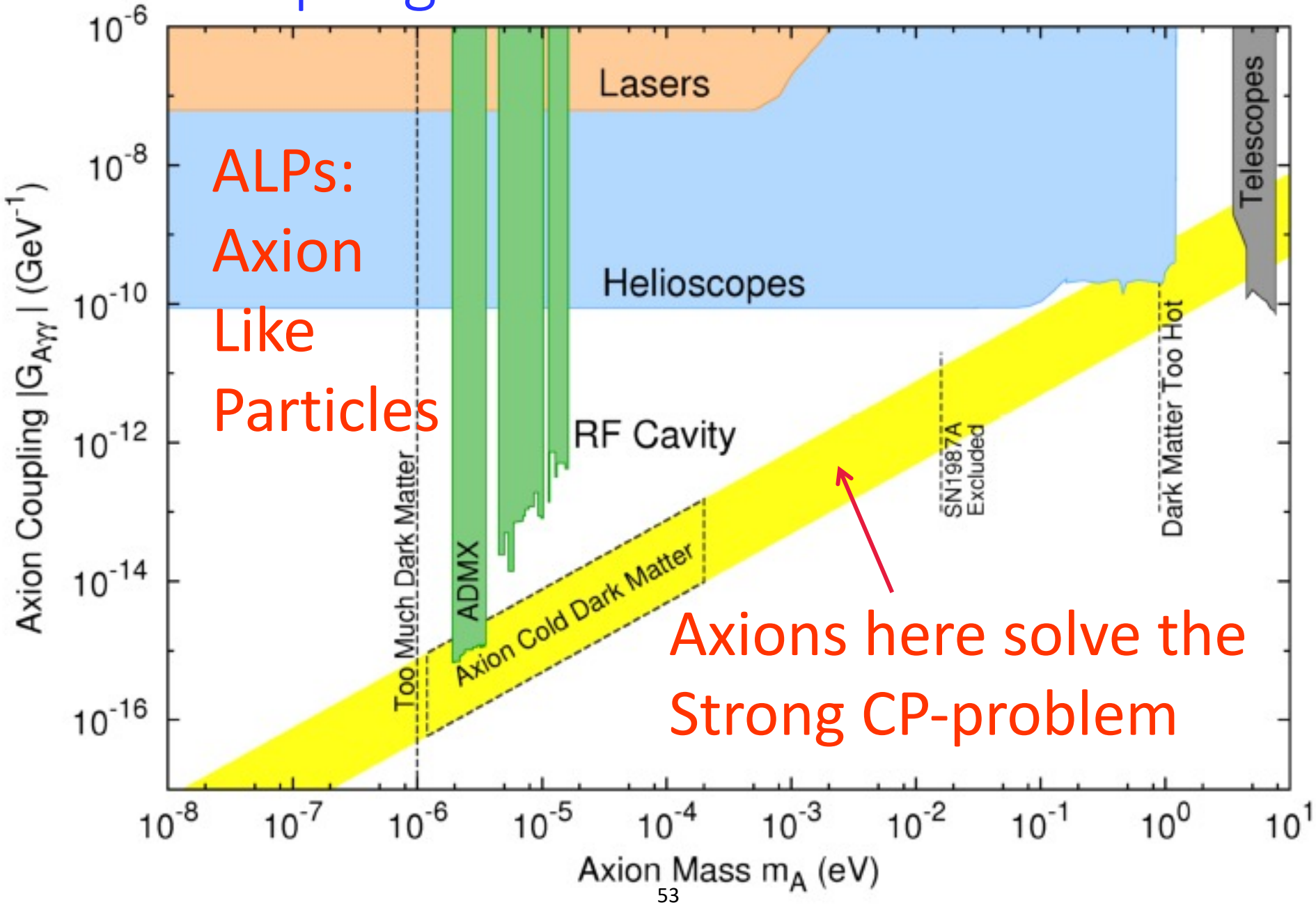


Figure 19: The geometric factor of an ideal 1D cavity in a homogeneous B-field (green arrows) cancels between crests and valleys of a high mode (left). The cancellation can be avoided by placing high-n dielectrics –grey regions– in the valleys (centre) or by alternating the polarity of the external B_e field to track the mode variations (right). This case can be done by introducing wire planes with suitable currents [563].

Axion coupling vs. axion mass



ALPs: Axion Like Particles

Axions here solve the Strong CP-problem