CAPP

Center for
Axion and Precision
Physics Research

The incredible journey of IBS-CAPP in South Korea towards DFSZ sensitivity in axion dark matter search

Yannis K. Semertzidis, IBS-CAPP & KAIST

Colloquium, Physics Dept., BNL, January 3, 2023

- South Korea, coming out of the war in the fifties, was a destroyed country
- Economically & technologically, it is now a modern/advanced country, member of G20 (2010)
- Q: Can S. Korea replicate the economic/technological miracle in the basic sciences as well?
- A: It will, IBS-CAPP demonstrated that it is possible.

Institute for Basic Science, 2011: Major Investment in Basic Sciences

- Economy is based on technology, exports
- They figured they need to invest in long term-basic science.
- Established the Institute for Basic Science, modeled after the Max Planck Institutes

- “Foreigners are welcome, opening up the society/economy, Institutes…”

KAIST in Daejeon

- Korea Advanced Institute of Science and Technology, >10,000 students
- “Foreigners are welcome…”
- All courses are taught in English
- KAIST’s 2015 target: 10% foreign faculty, 10% women faculty, 10% foreign students

Republic of Korea

Then: A satellite photo taken 20 years ago

Now

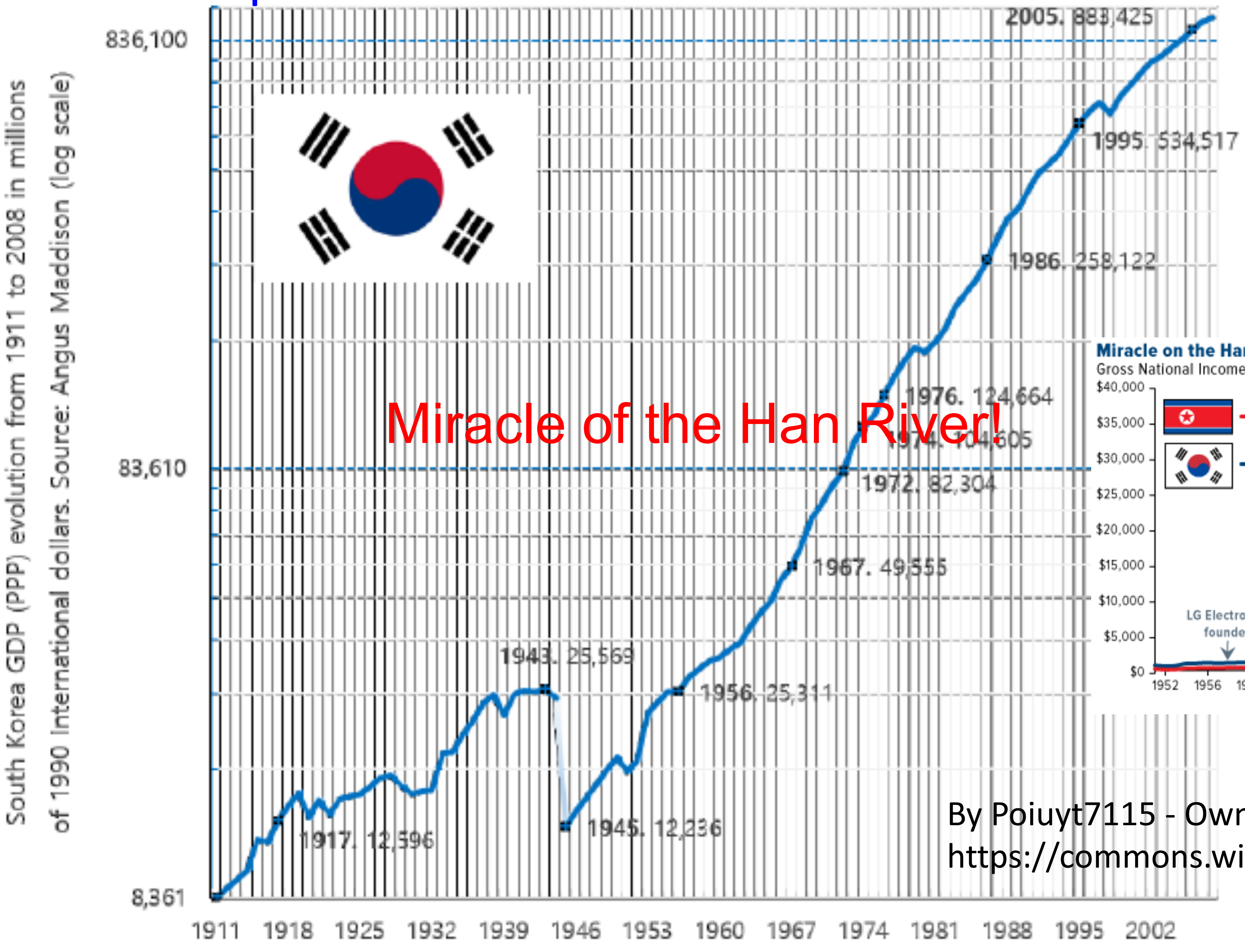
Center for Axion and Precision Physics
KAIST, Daejeon, Korea

Republic of Korea right after the war

Wonsan completely ruined

Republic of Korea

Republic of Korea



By Poiuyt7115 - Own work, CC BY-SA 4.0,
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What made modern Korea possible?

- Hard work, highest levels of competency, integrity
- Dedication, perseverance
- Mission
- Critical: The industry underwent a “Phase-transition” that changed everything! It worked.

Steve Jobs and apple

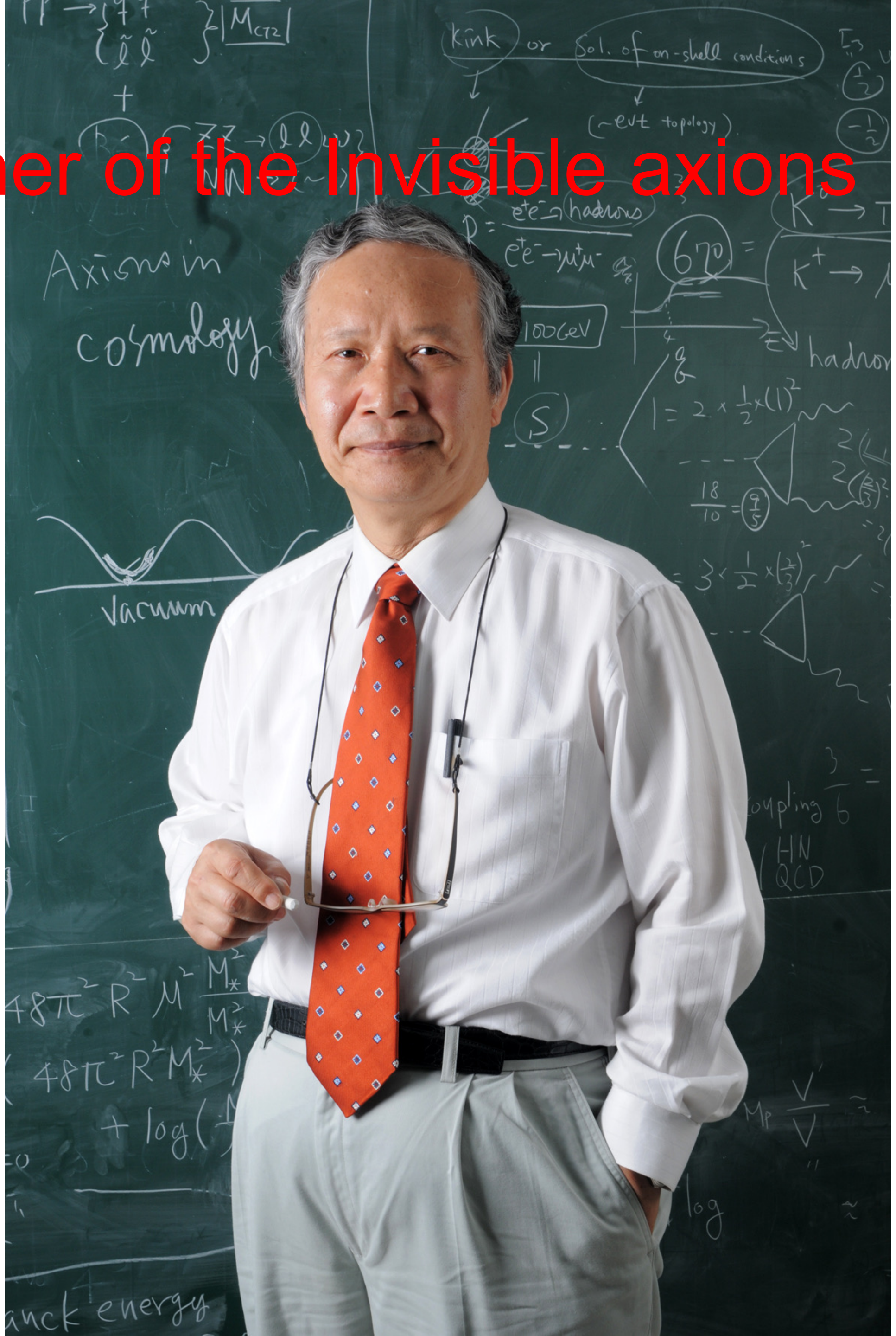
“When You Need A Miracle, Be Miracle”

“Don’t let the noise of others’ opinions drown out your own inner voice."

“I've been rejected, but I am still in love.”
– Steve Jobs

Professor Jihn E. Kim

Father of the Invisible axions



He worked hard to establish IBS-CAPP to make axions Visible

What made CAPP's position possible?

- Hard work, highest levels of competency, integrity

- Dedication, perseverance

- Mission

- Critical: We had to change everything! It worked.
- The question is whether it will last…

CAPP-Physics: strong CP-problem and axion dark matter

- Dark Matter and CP-violation are both on the top ten most important Particle Physics questions
- The axion coupling is feeble, it requires the effective application of latest state of the art technology and lots of ingenuity (high-risk, high-physics-potential)
- CAPP (est. October 16, 2013) has acquired the equipment and has developed the technology, know-how, and infra-structure to effectively probe the 1-8 GHz in the next five years at DFSZ sensitivity. CAPP is on the top of its field today.
- Projection: All the interesting axion frequencies will be probed globally in the next 10-20 years

Institute for Basic Science 기초과학연구원 ibs
CAPP
Center for Axion and Precision Physics Research

Dark Matter and Isaac Newton (1642-1726)

Isaac Newton unified the Physics phenomena: falling of an apple with the planet, moon, star, sattelite, comet motions, under Gravity!

He clarified the view of Heavens for Humanity!

He also gave us the ability to see what cannot be seen with ordinary methods. Looking from deviations from his rules we are able to sense the presence of Dark Matter.

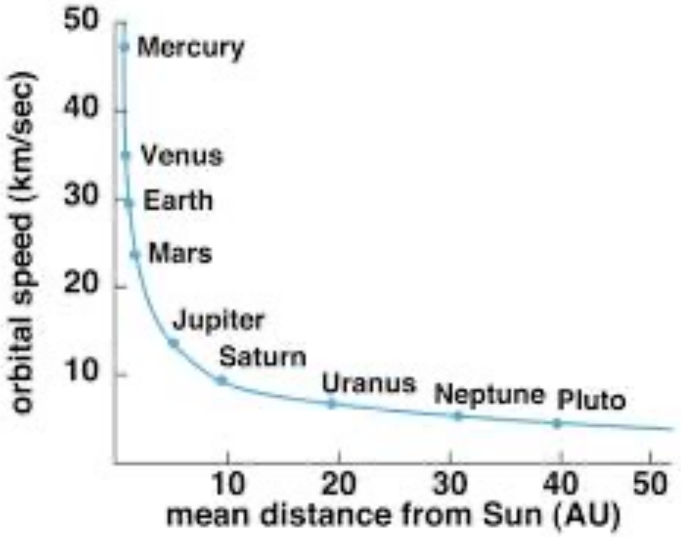
Newton's laws: "observing" the unseen

- Gravitational law applied to the planets: by measuring the planet velocity and its distance from the center, we can estimate the enclosed mass.

$$F = \frac{GM_{\odot}m}{r^2} = \frac{mv^2}{r}$$

$$v = \sqrt{\left(\frac{GM_{\odot}}{r}\right)}$$

1915, Einstein's General Relativity
Resolved the issue with Mercury's precession

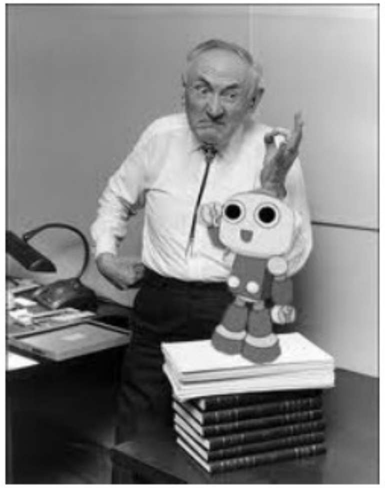


1846, Adams and Le Verrier suggested the existence of Neptune: First discovery of "Dark Matter"

For gravitational attraction, n equals −1 and the average kinetic energy equals half of the average negative potential energy

$$\langle T \rangle_\tau = -\frac{1}{2} \langle V_{\mathrm{TOT}} \rangle_\tau .$$

Origins of dark-matter: Zwicky (Coma cluster) & Smith (Virgo cluster)



Coma Cluster

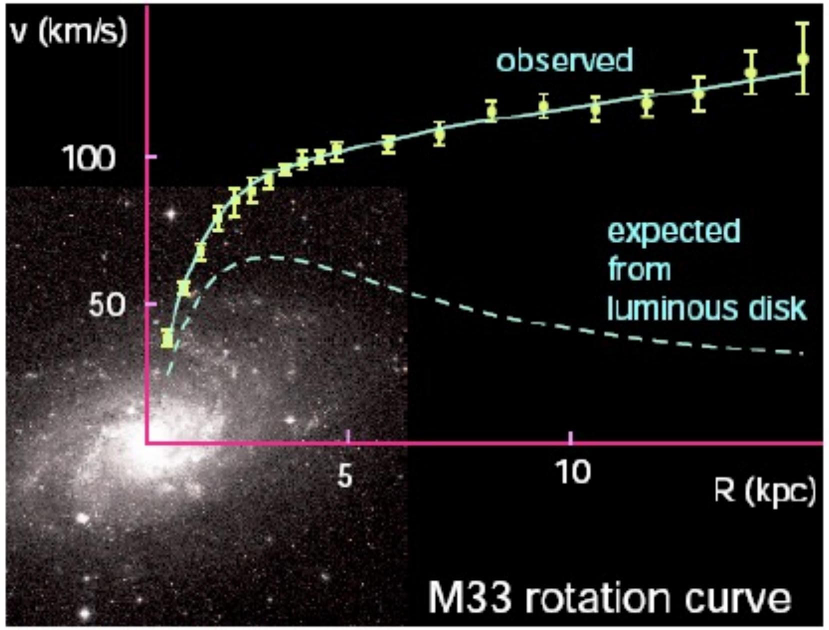
Virial motions within galaxy clusters:

"The difference between this result and Hubble's value for the average mass of a nebula must remain unexplained until further information becomes available."

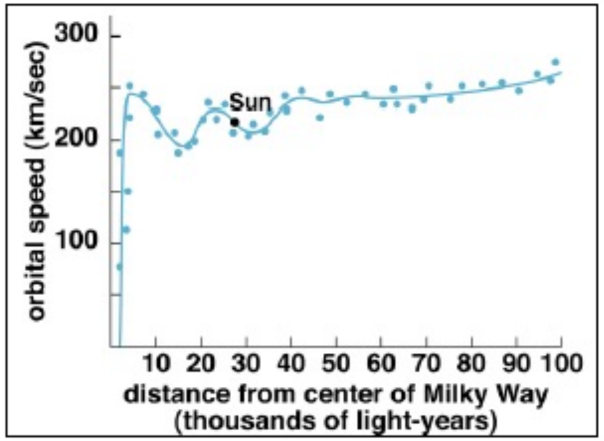
The "dunkelmaterie" of Zwicky 1936

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

Flat galactic rotation curves
Rubin, “1970’s: The decade of seeing is believing.”



Paolo Saluchi



Vera Rubin

- Her findings were cross checked and found to be correct.
- More galaxies were checked, most of them found to be part of extended halos
- Vera Rubin started a field in Astronomy that firmly established the idea of DM.

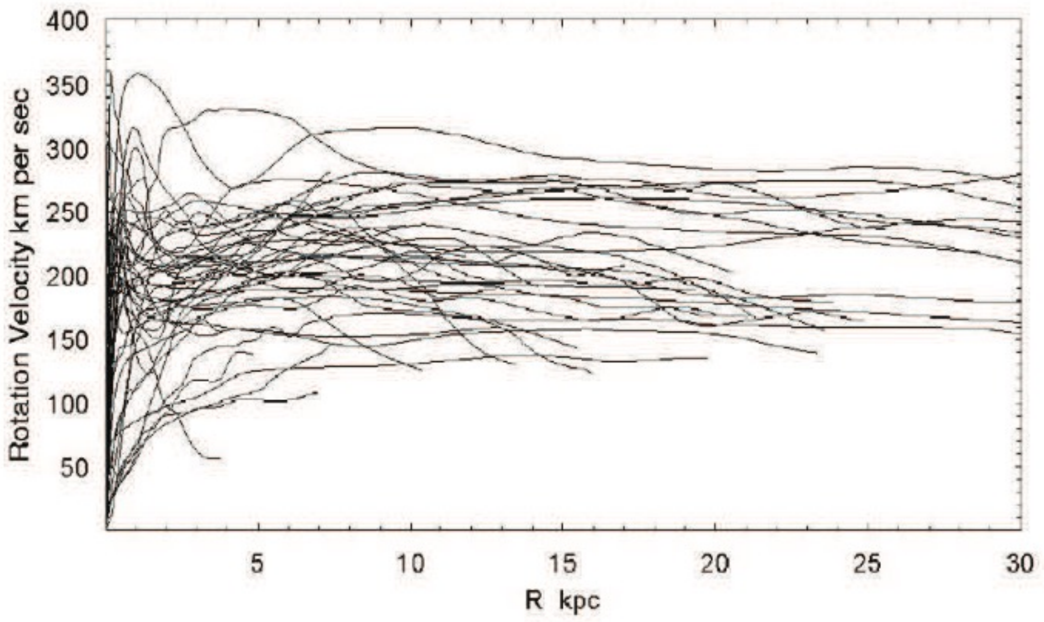


Figure 4: Rotation curves of spiral galaxies obtained by combining CO data for the central regions, optical for disks, and HI for outer disk and halo (Sofue et al. 1999).

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

A Galaxy without Dark Matter, effectively confirming Dark Matter!

A Galaxy Without Dark Matter

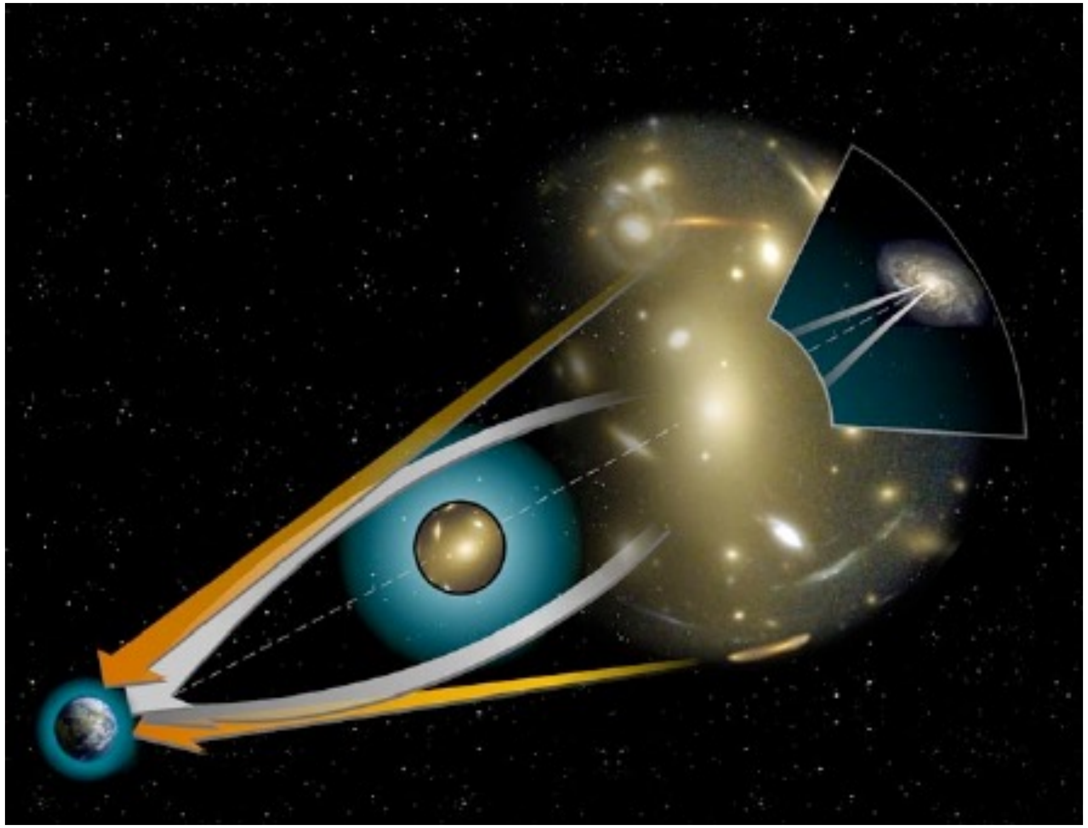
Press Release - Source: Yale University   Posted March 28, 2018 10:34 PM   0 Comments

NGC 1052-DF2   ©YALE/NASA

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.

Characteristics of Matter



- Gravitational lensing: The light path bends to the presence of ordinary and dark matter forming multiple images of the same subject, called Einstein's rings
- Clumps together: Coalesces to large structures
- In addition, ordinary matter interacts (friction)

Matter's characteristic

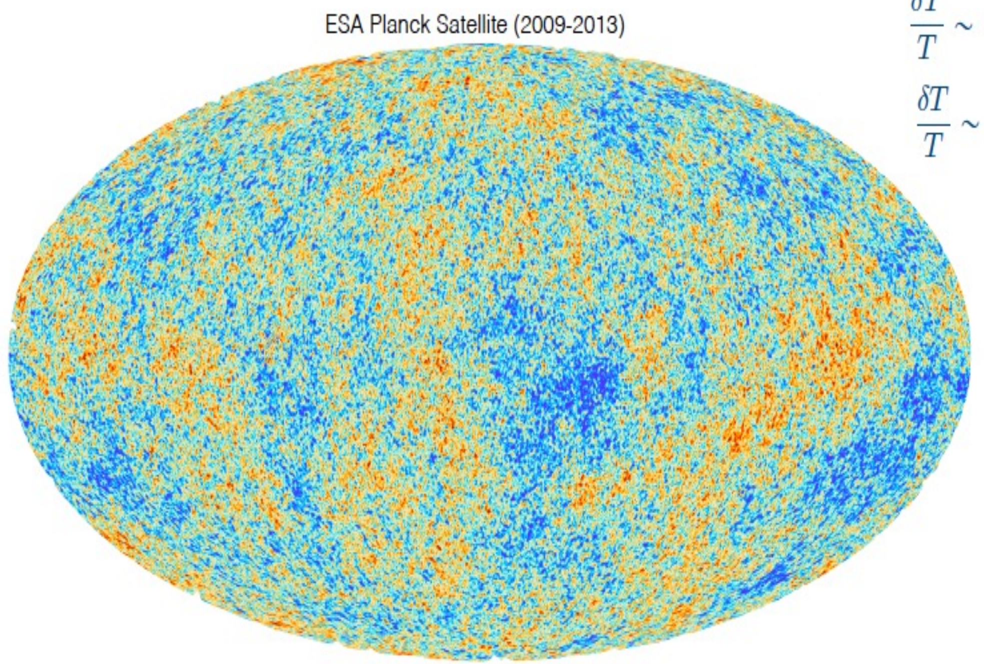
Is that it clumps together

shown here from the

Cosmic

Microwave

Background measurements



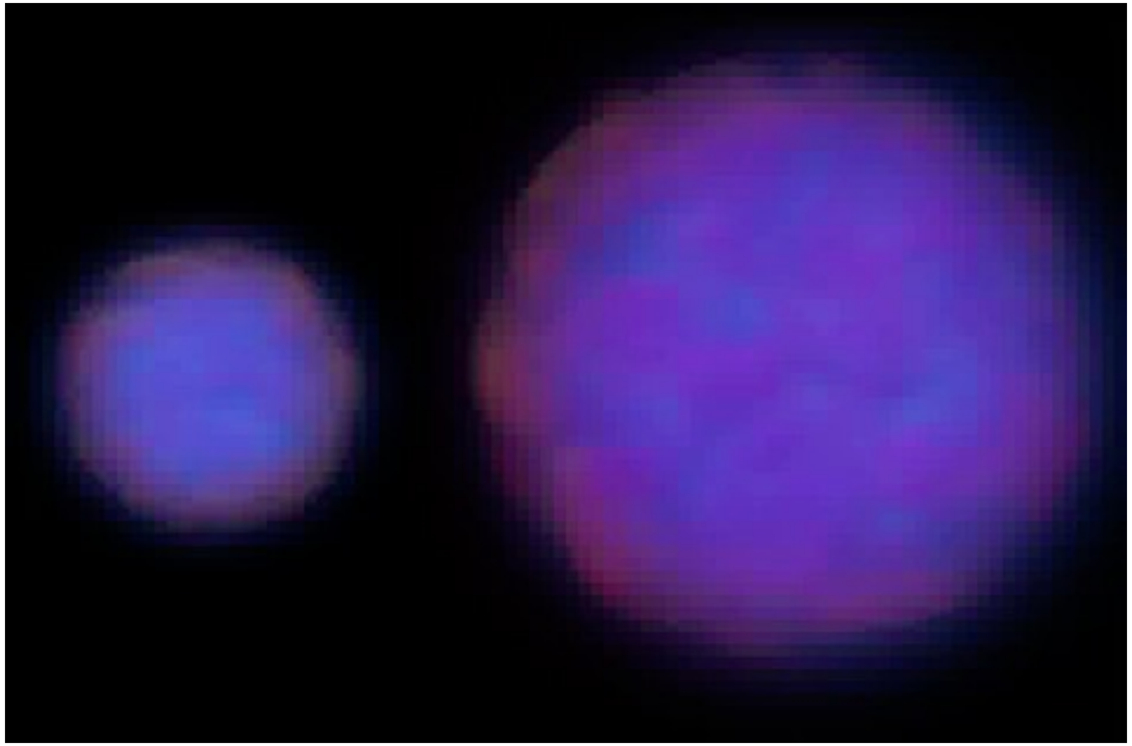
$$\frac{\delta T}{T} \sim 10^{-5}$$

$$\frac{\delta T}{T} \sim \frac{\delta \rho_b}{\rho_b}$$

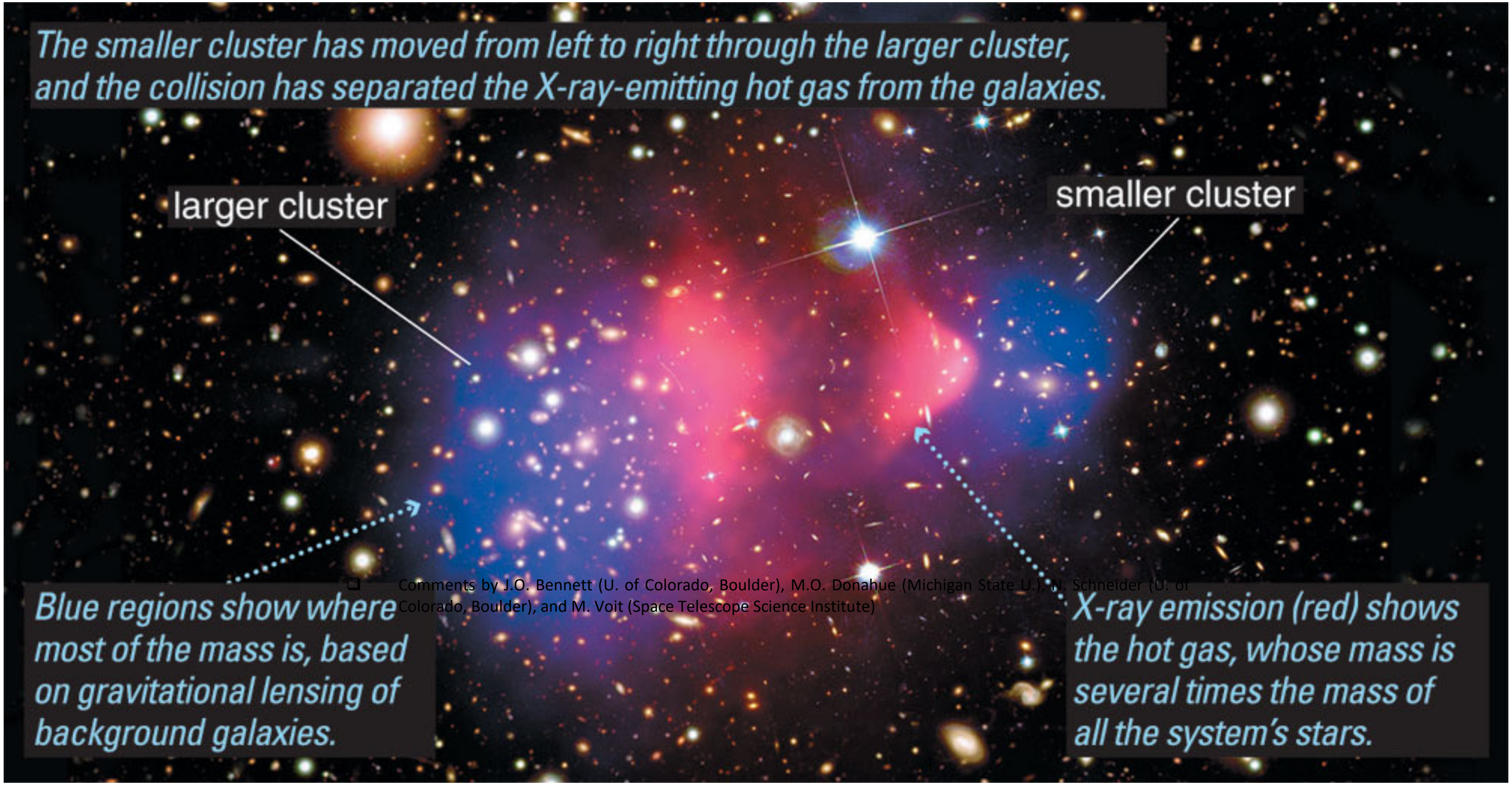
Ordinary matter doesn't have enough density to create the observed large-scale structure. Not enough time…, requiring Dark Matter!

Dark Matter's smoking gun

- Two cluster galaxies colliding
- The regular matter (red) interacts, i.e., collides (friction) with each other
- The dark matter (blue) moves unaffected…



Dark matter: the Bullet Cluster

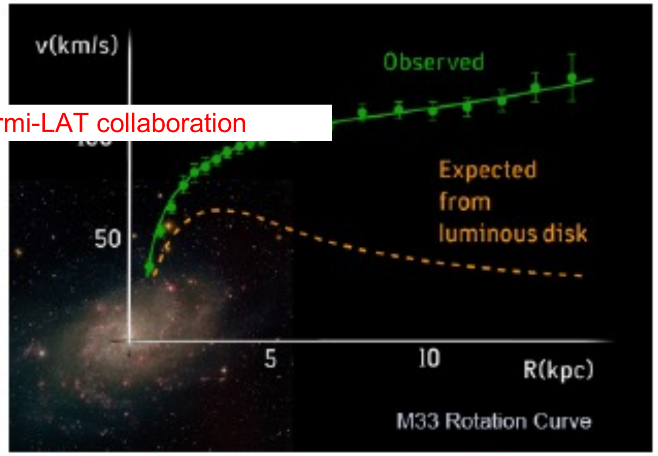


- Comments by J.O. Bennett (U. of Colorado, Boulder), M.O. Donahue (Michigan State U.), N. Schneider (U. of Colorado, Boulder), and M. Voit (Space Telescope Science Institute)

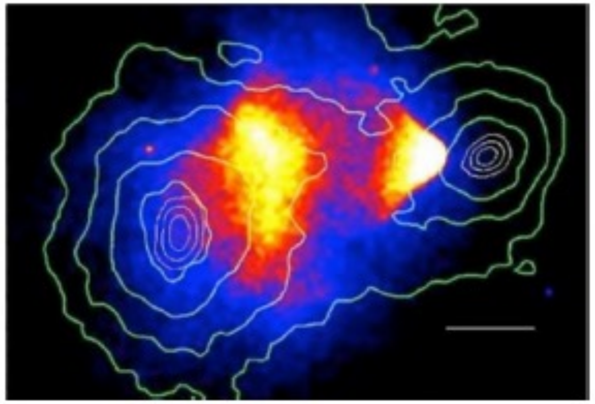
Evidence for / Salient Features of Dark Matter

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

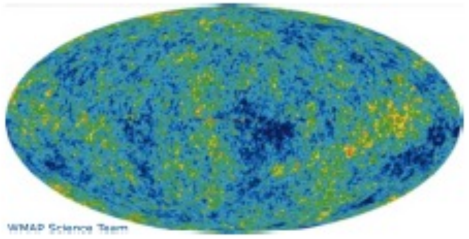
Eric Charles, Fermi-LAT collaboration

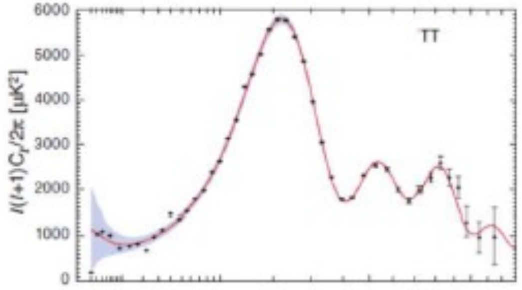


*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



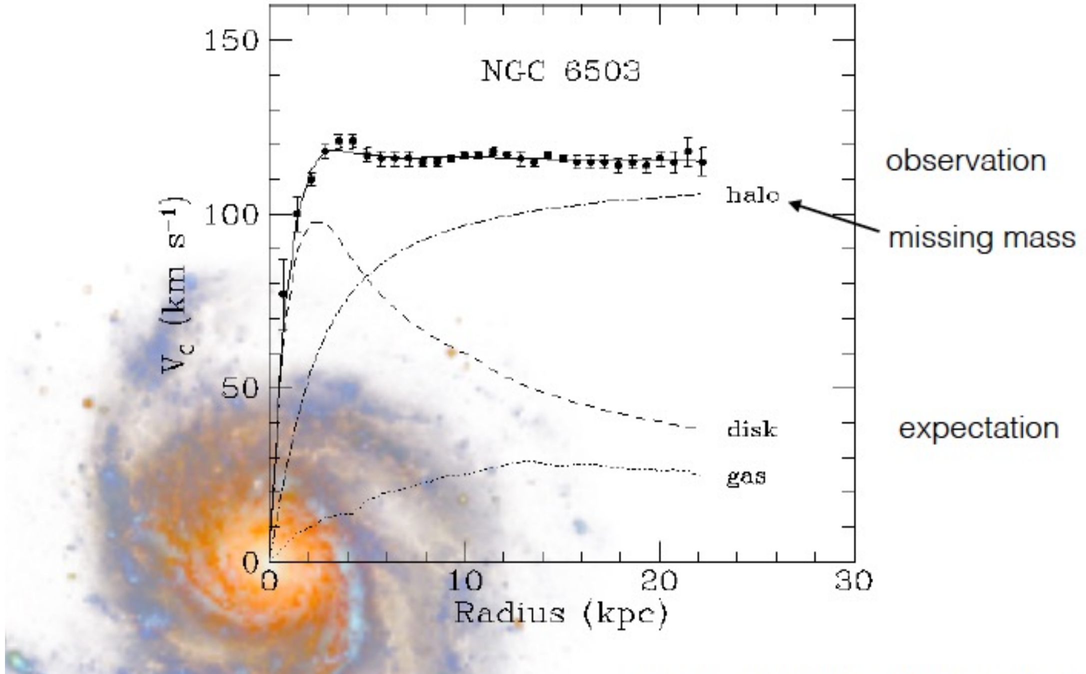
*Almost **collisionless***
Bullet Cluster
Clowe+(2006)





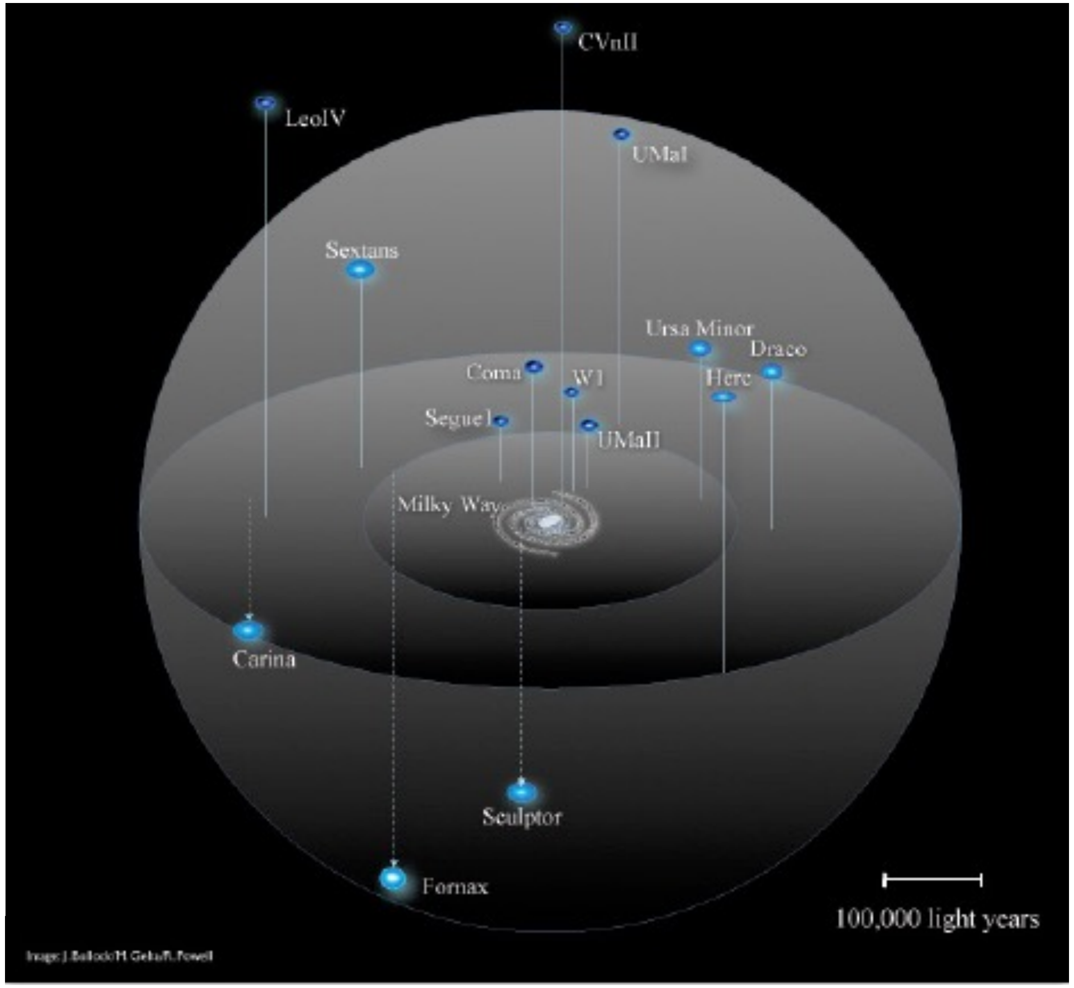
Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)

Rotation curves (10's kpc)

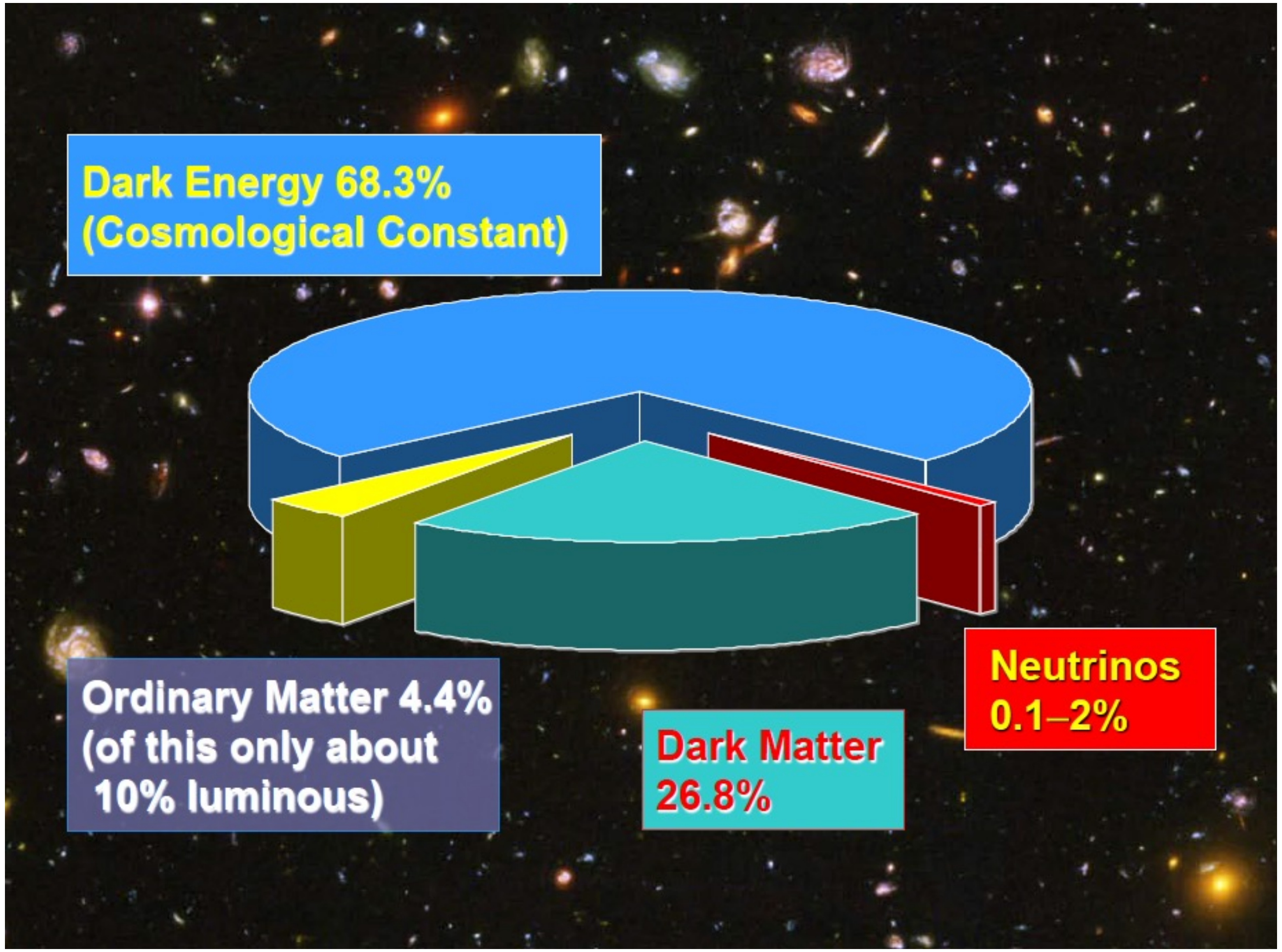


For the Milky Way fit yields at sun's position

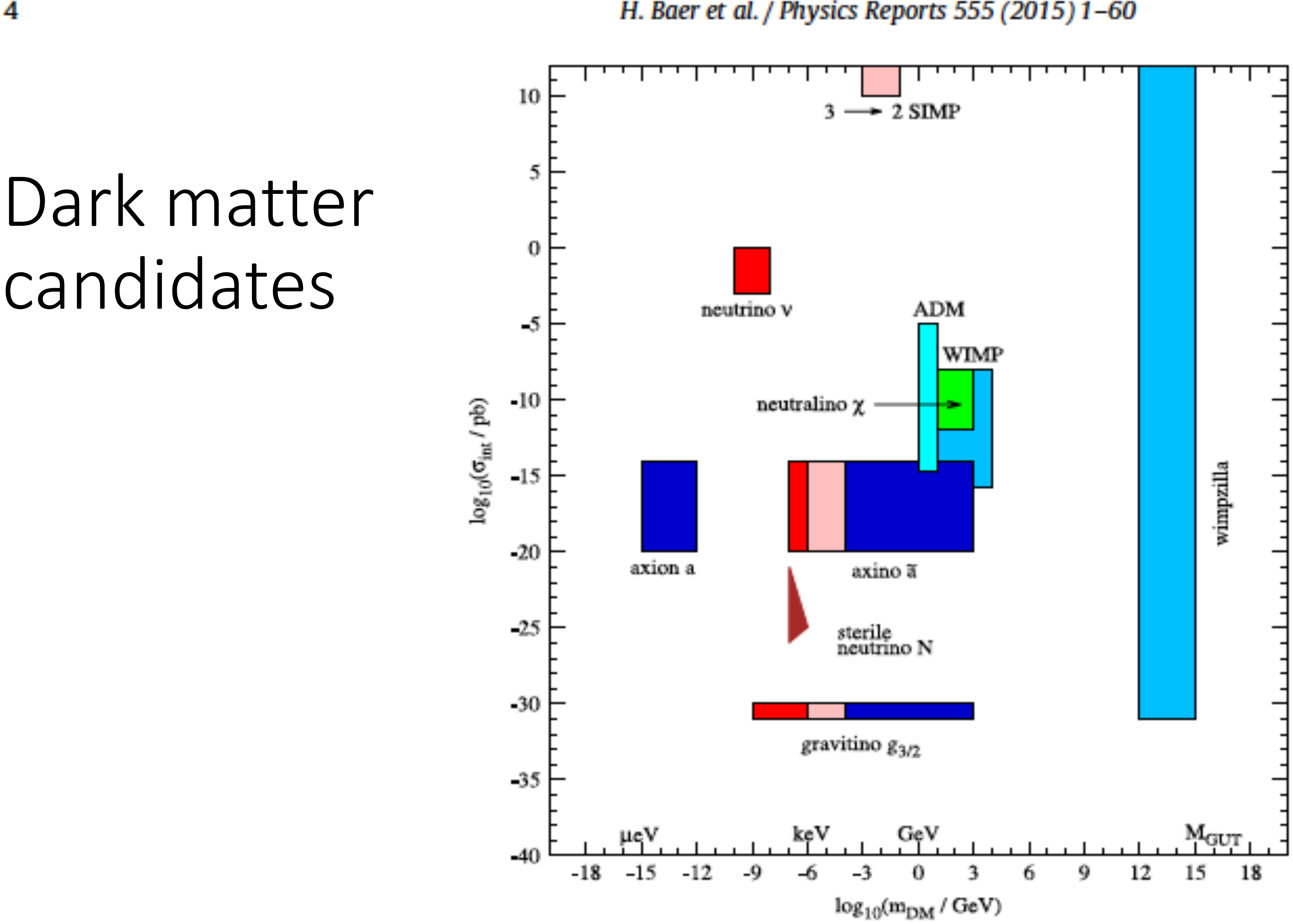
$$\rho_\odot \simeq (0.3 \pm 0.1)\,\mathrm{GeV/cm^3}$$

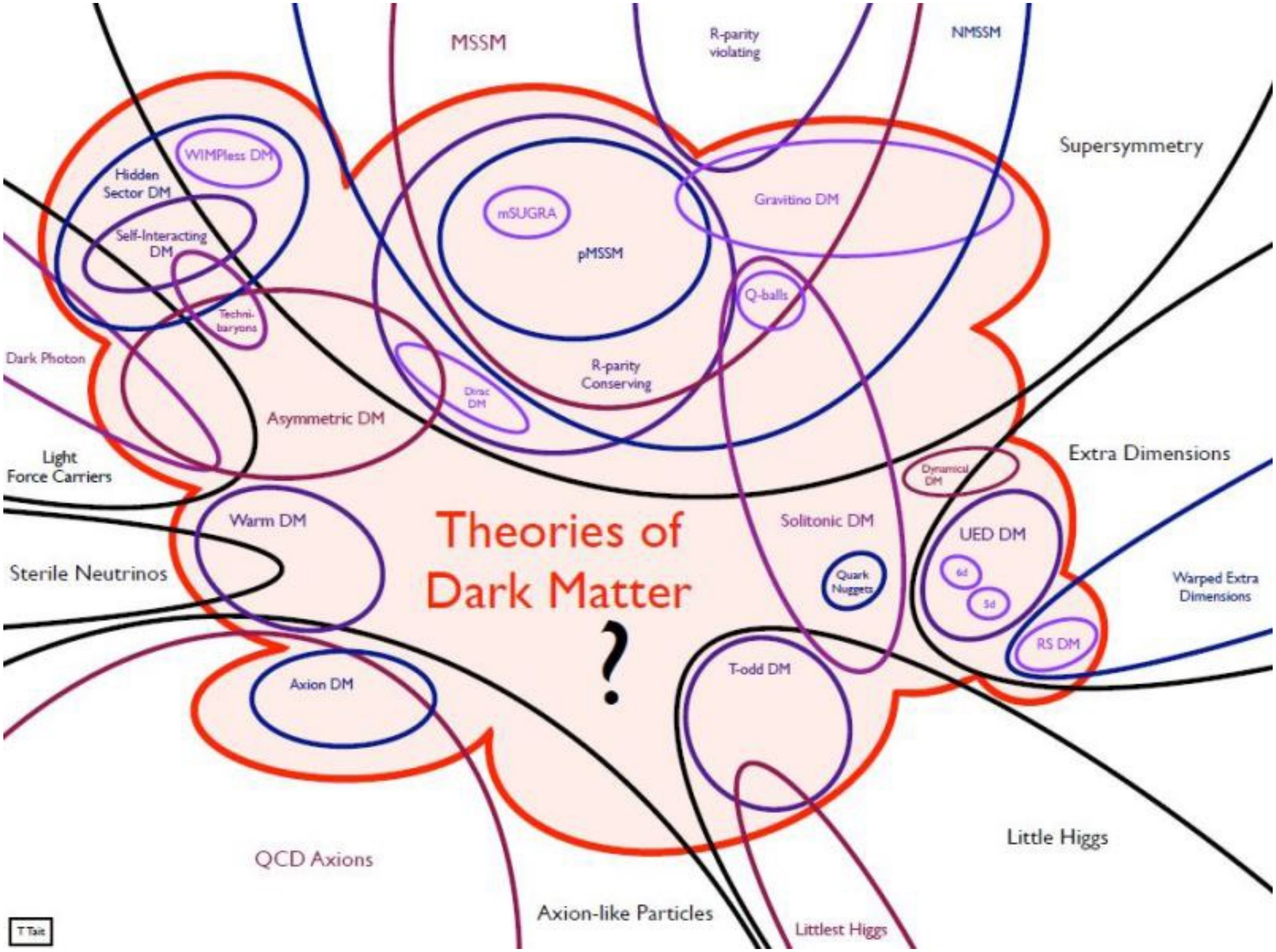


Cosmological inventory

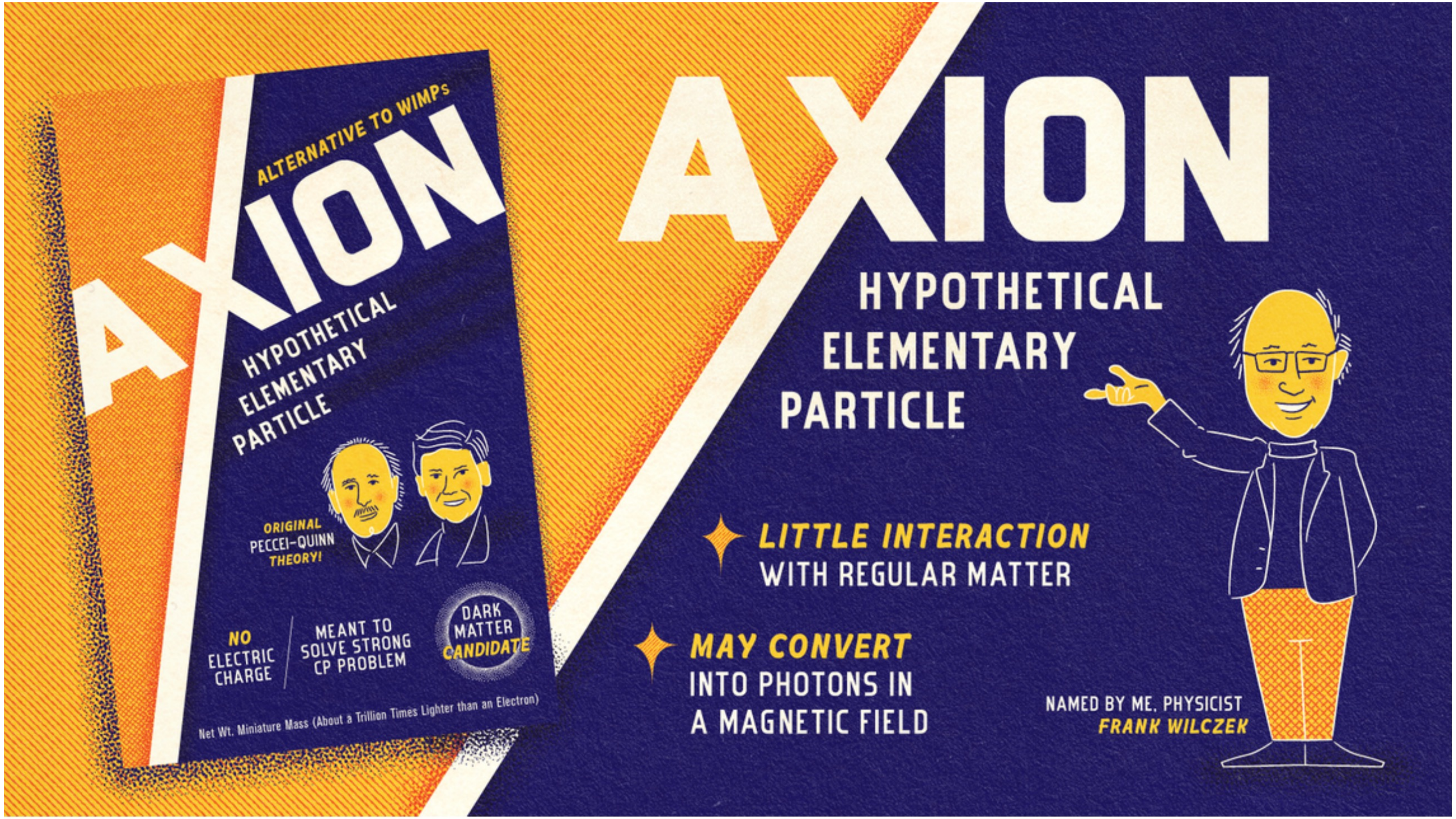


Dark matter candidates

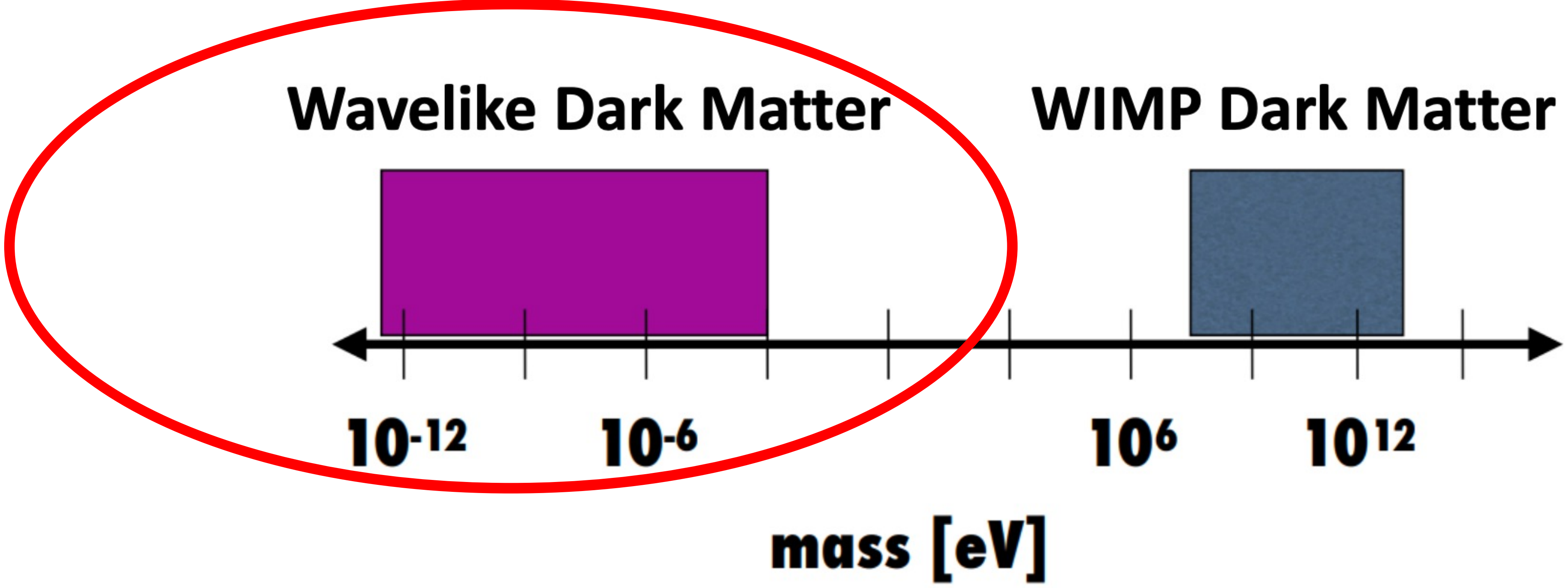



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Axions: A leading Dark Matter Candidate



(https://www.symmetrymagazine.org/sites/default/files/images/standard/Inline_1_Axion.png)



de Broglie Wavelength - $\lambda_{dB} \approx \frac{2\pi}{mv}$

Occupancy Number - $N \approx \frac{\rho_{DM}}{m}\lambda_{dB}^3$

- Axion ($m \sim 10^{-9}$ eV): $\lambda_{dB} \sim 10^4$ km with $N \sim 10^{44}$
- WIMP ($m \sim 100$ GeV): $\lambda_{dB} \sim 10^{-16}$ km with $N \sim 10^{-36}$

where $\rho_{DM} = 0.4$ GeV/cm^3

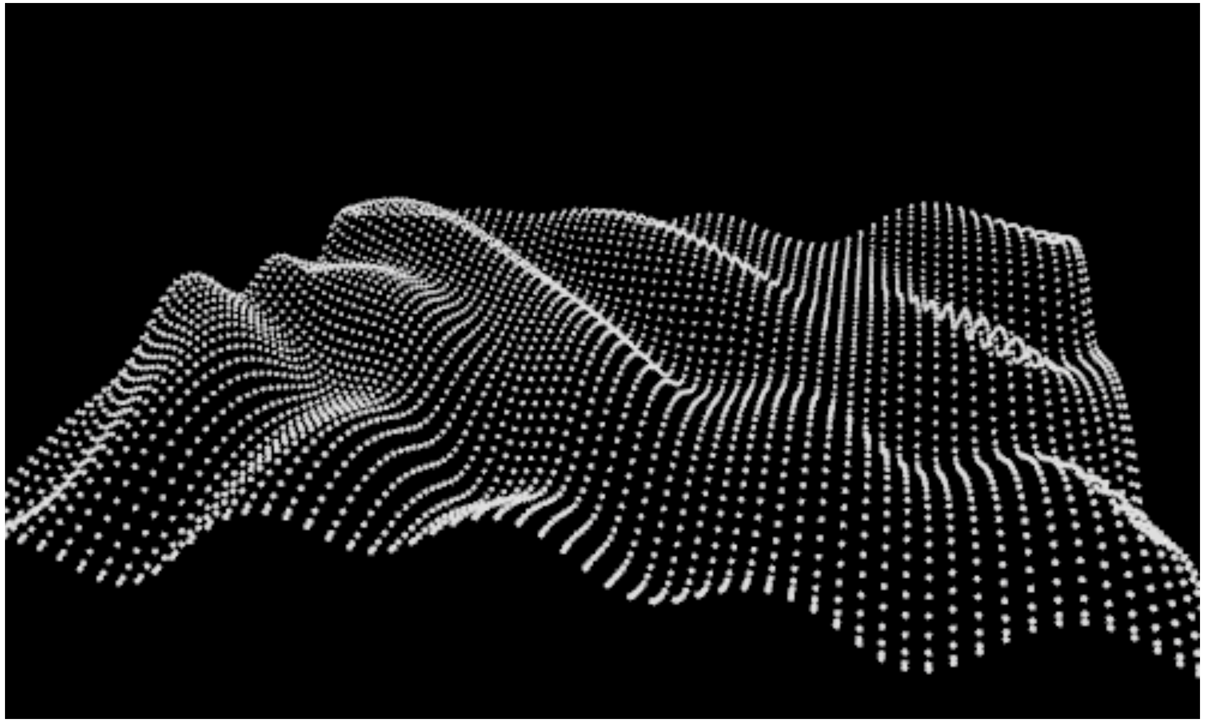
Adapted from B. Safdi

Axion Dark Matter: a Cosmic MASER

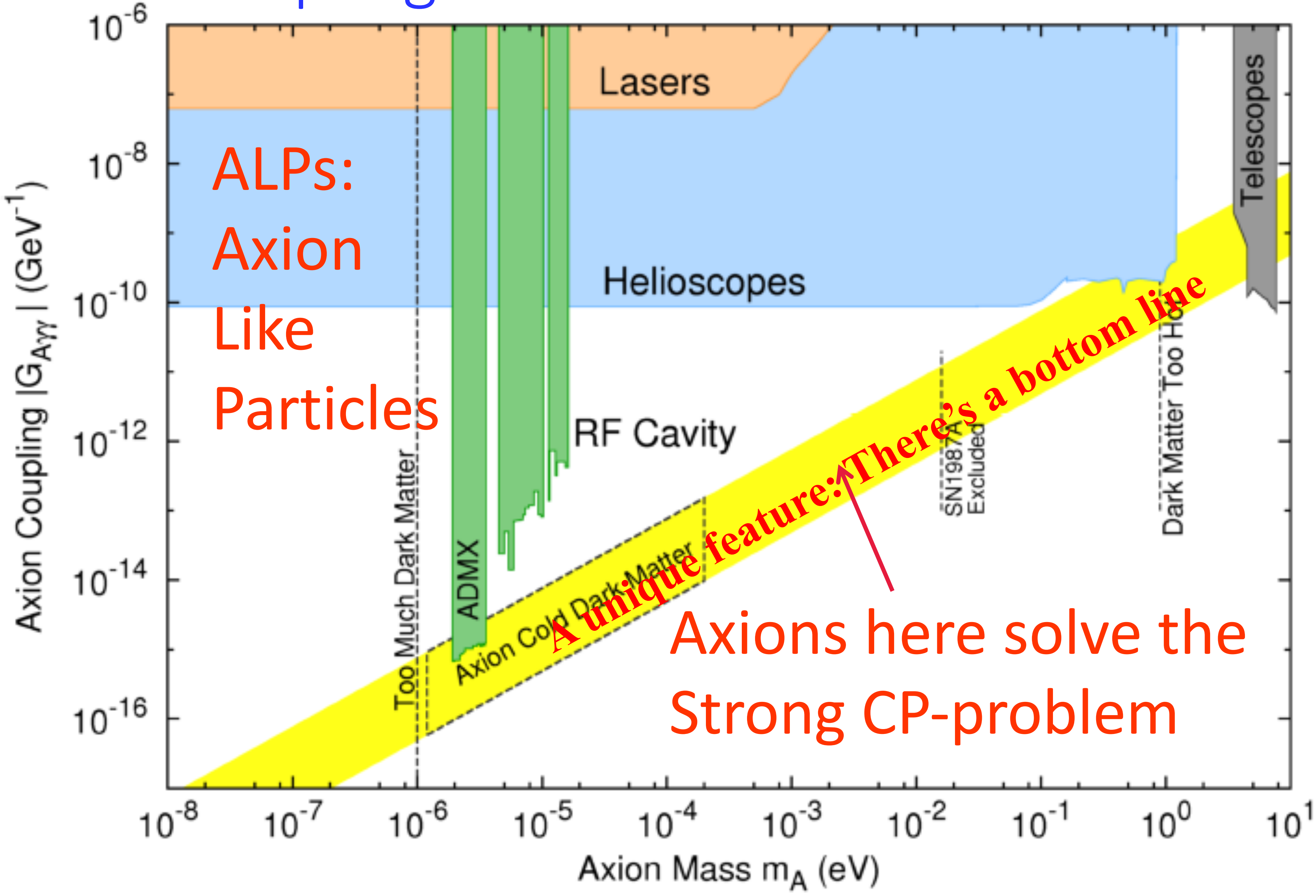
De Broglie wavelength of axions

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

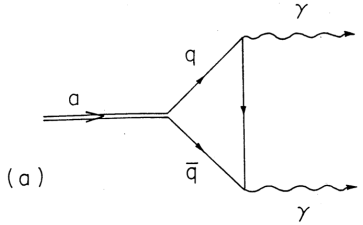
$$\lambda \approx 300\text{m} \times \left(\frac{1\mu\text{eV}}{m_a}\right)$$

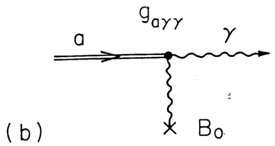


Axion coupling vs. axion mass



Axion Couplings





- Gauge fields:
  - Electromagnetic fields (microwave 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: CASPEr, 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, CASPEr-Electric, ARIADNE; GNOME)

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

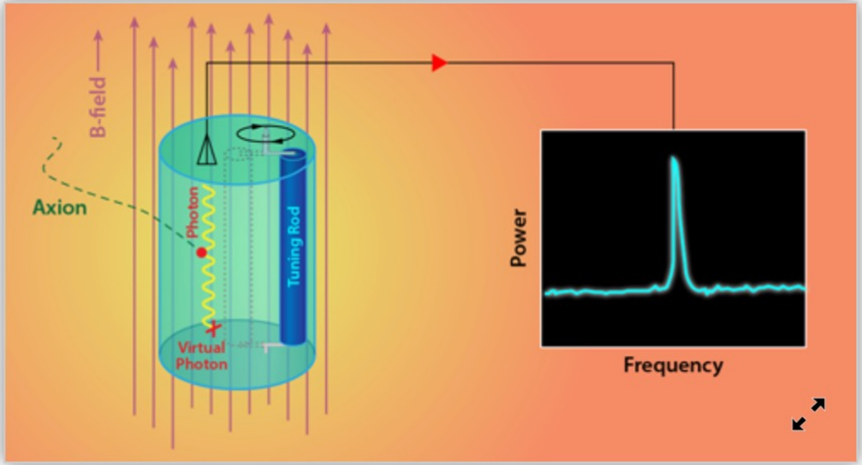
Axion Detection Scheme (Haloscope)

- Conventional axion haloscope technique consists of a high-Q microwave cavity inside a homogeneous magnetic field to trigger the conversion of DM axions into photons.

P. Sikivie, \Experimental tests of the invisible axion,"
Phys. Rev. Lett. 51 (1983) 1415 . 6 , 53 , 61 , 63

Woohyun Chung's slide

$$L_{a\gamma\gamma} = g_{\gamma} \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



C. Boutan/Pacific Northwest National Laboratory; adapted by APS/Alan Stonebraker

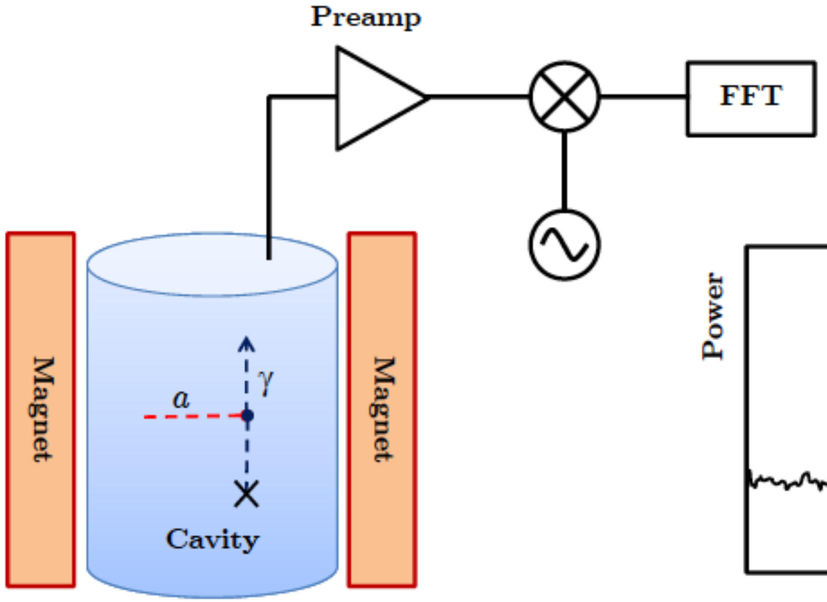
Running Axion Experiments (Haloscope)

ADMX
HAYSTAC
CAPP

Axion haloscope method by Pierre Sikivie

The ability to scan fast depends on B-field, Volume, Temperature, and Q_0

$$P_{\text{signal}} = 22.51\ \text{yW} \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{B_{\text{avg}}}{10.31\ \text{T}}\right)^2 \left(\frac{V}{36.85\ \text{L}}\right)\left(\frac{C}{0.6}\right)\left(\frac{Q_L}{35000}\right)\left(\frac{\nu}{1.1\ \text{GHz}}\right)\left(\frac{\rho_a}{0.45\ \text{GeV/cc}}\right)$$



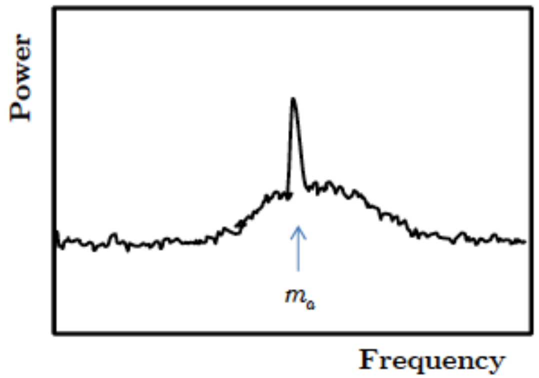


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

Most sensitive method

Running Haloscope Experiments:
CAPP
ADMX
HAYSTAC

IBS-CAPP looked at all possible parameters

$$\frac{df}{dt}=\frac{f}{Q}\frac{1}{t}\approx\left[\frac{1.5\text{ GHz}}{\text{year}}\right]\times\left[\frac{g_\gamma}{0.36}\right]^4\left[\frac{1.1\text{ GHz}}{\nu_a}\right]^2\left[\frac{3}{SNR}\right]^2\left[\frac{0.25\text{ K}}{T}\right]^2\left[\frac{B}{10.3\text{ T}}\right]^4\times$$
$$\left[\frac{C}{0.6}\right]^2\left[\frac{\rho_a}{0.45\text{ GeV/cc}}\right]^2\left[\frac{V}{37\,l}\right]^2\left[\frac{Q_0}{10^5}\right]\left[\frac{Q_a}{10^6}\right]\left[\frac{\beta}{1+\beta}\right]^2$$

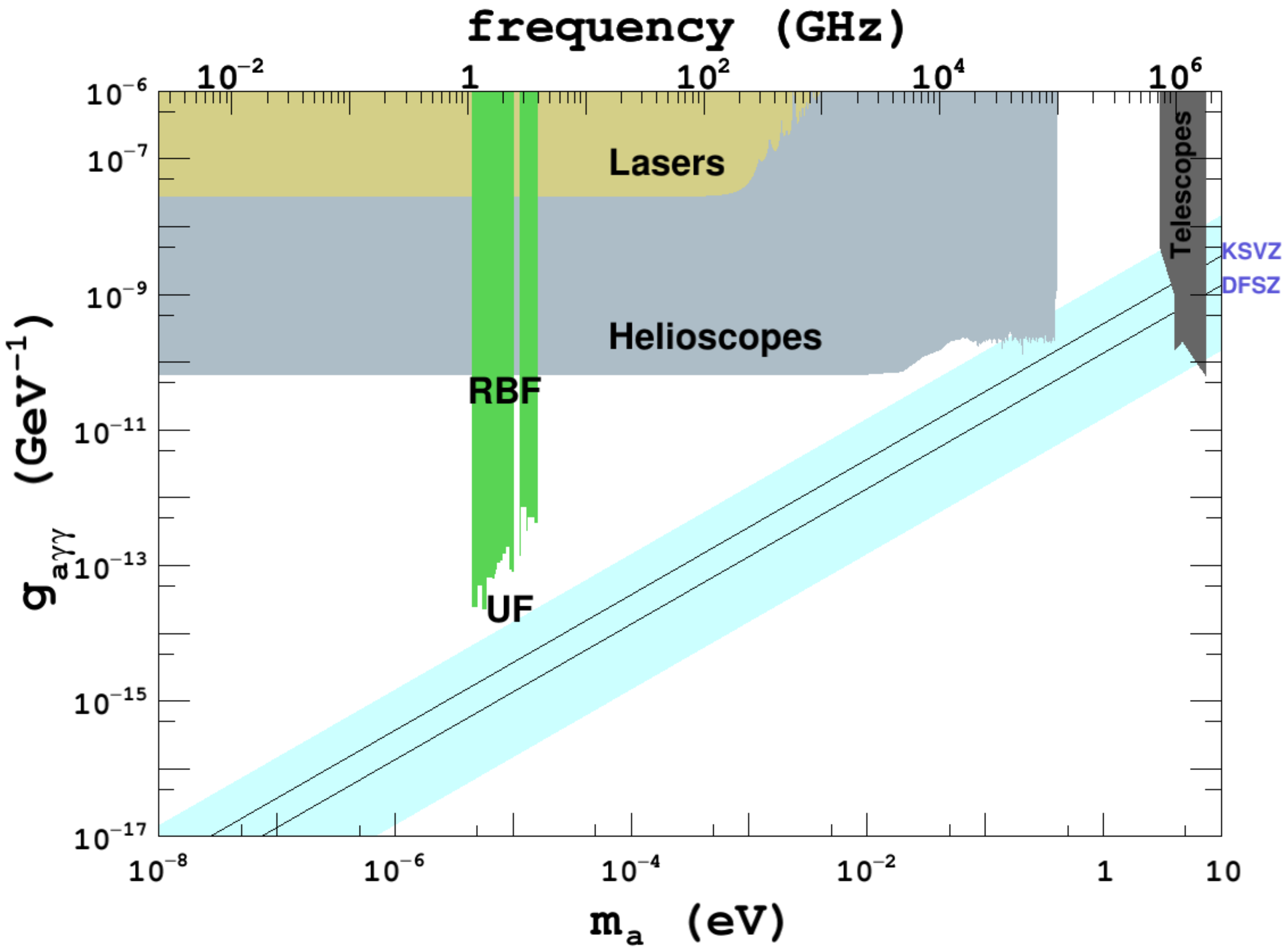
1. *B*-field, maximum value of magnetic field (8T, 9T, 12T, 18T, and perhaps up to 25T)
2. Cavity volume, *V*, especially for high-frequencies (37*l*,12T)
3. Cavity quality factor, Q_0 (4.5×10^6)
4. System noise temperature, *T* (~150 mK, 1.1 GHz)
5. Geometrical factor, *C* (keep it high >0.6 with special techniques)

Rochester Brookhaven Fermilab axion dark matter search

- The RBF-dark matter axion group, circa 1990
- Under the leadership of Adrian C. Melissinos (Rochester), 1929-2022, a daring pioneer, full of energy, a great teacher.

First haloscope limits:
Rochester,
Brookhaven,
Fermilab.

Then
University of
Florida



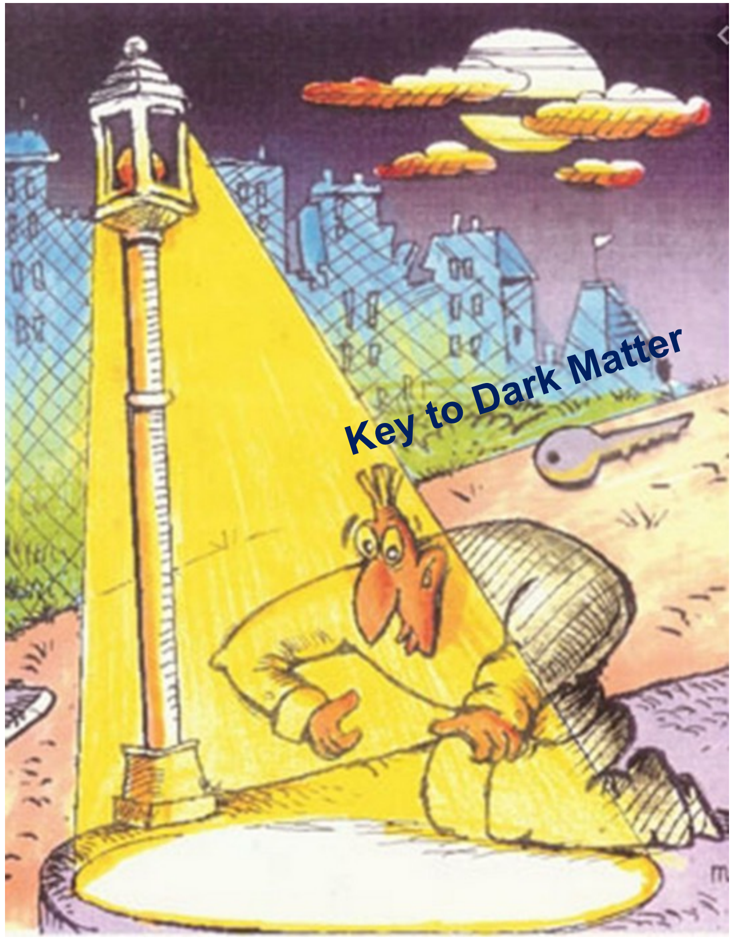
Where to look? ADMX established in 1990.

- 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.

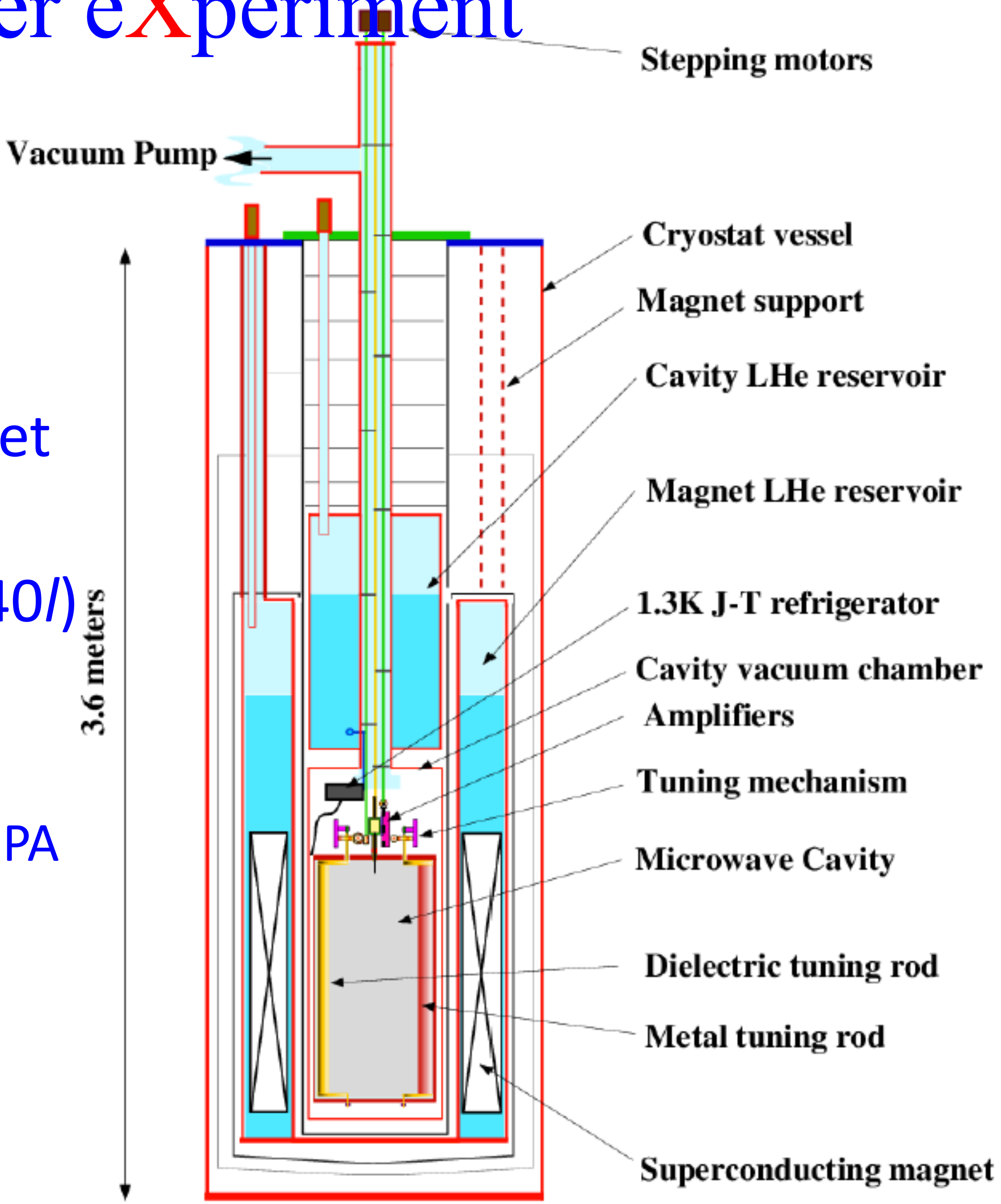
- Low noise Microstrip SQUID Amplifier (MSA)

- Dilution refrigerators became readily available (reducing labor cost)

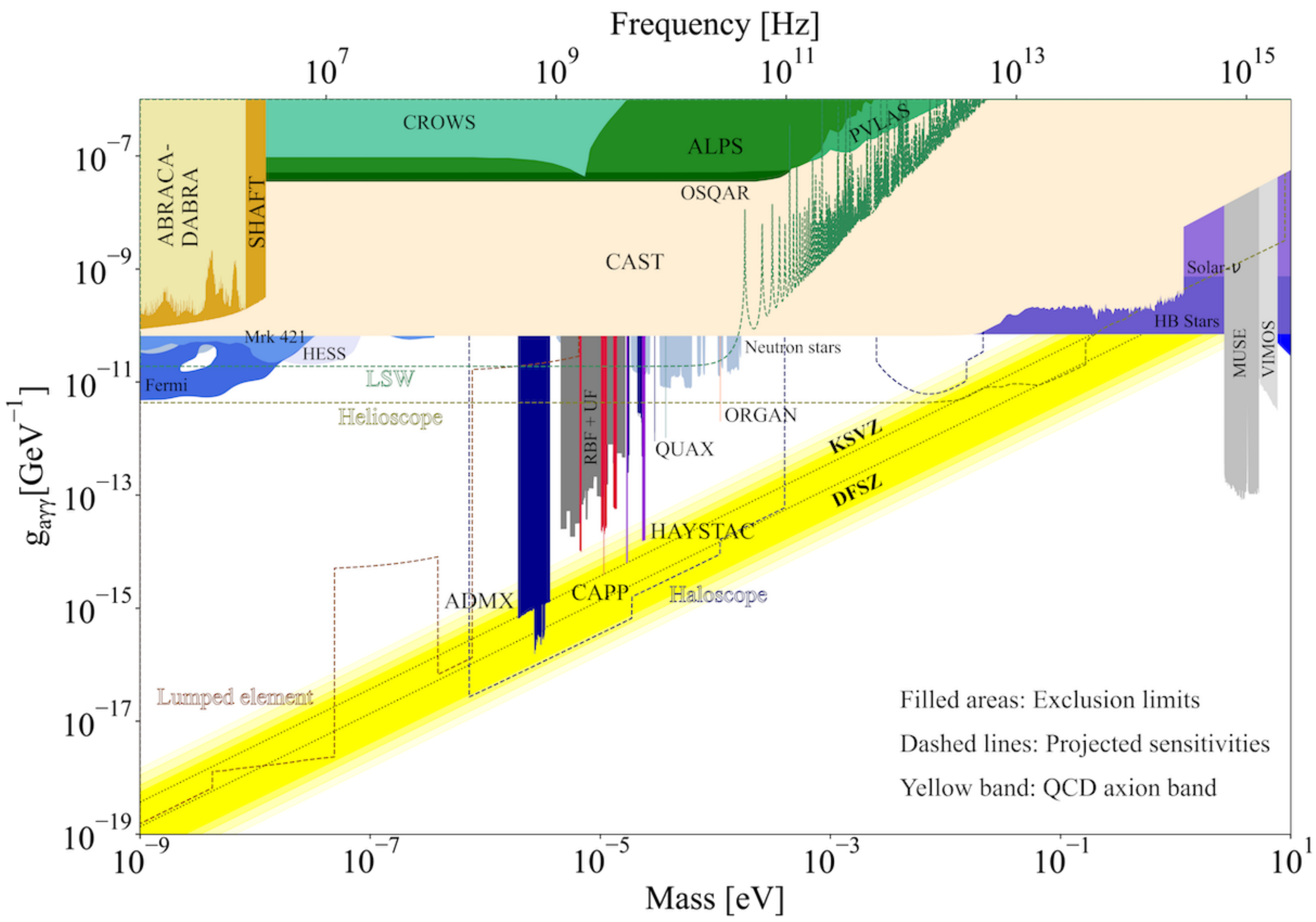


Axion Dark Matter eXperiment

- Cryogenics (0.1K)
- Superconducting magnet (>7.5 T)
- Large volume cavity (140*l*)
- Low noise amplifiers
  - From 12K to 1K
  - Currently SQUID and JPA (<1K)

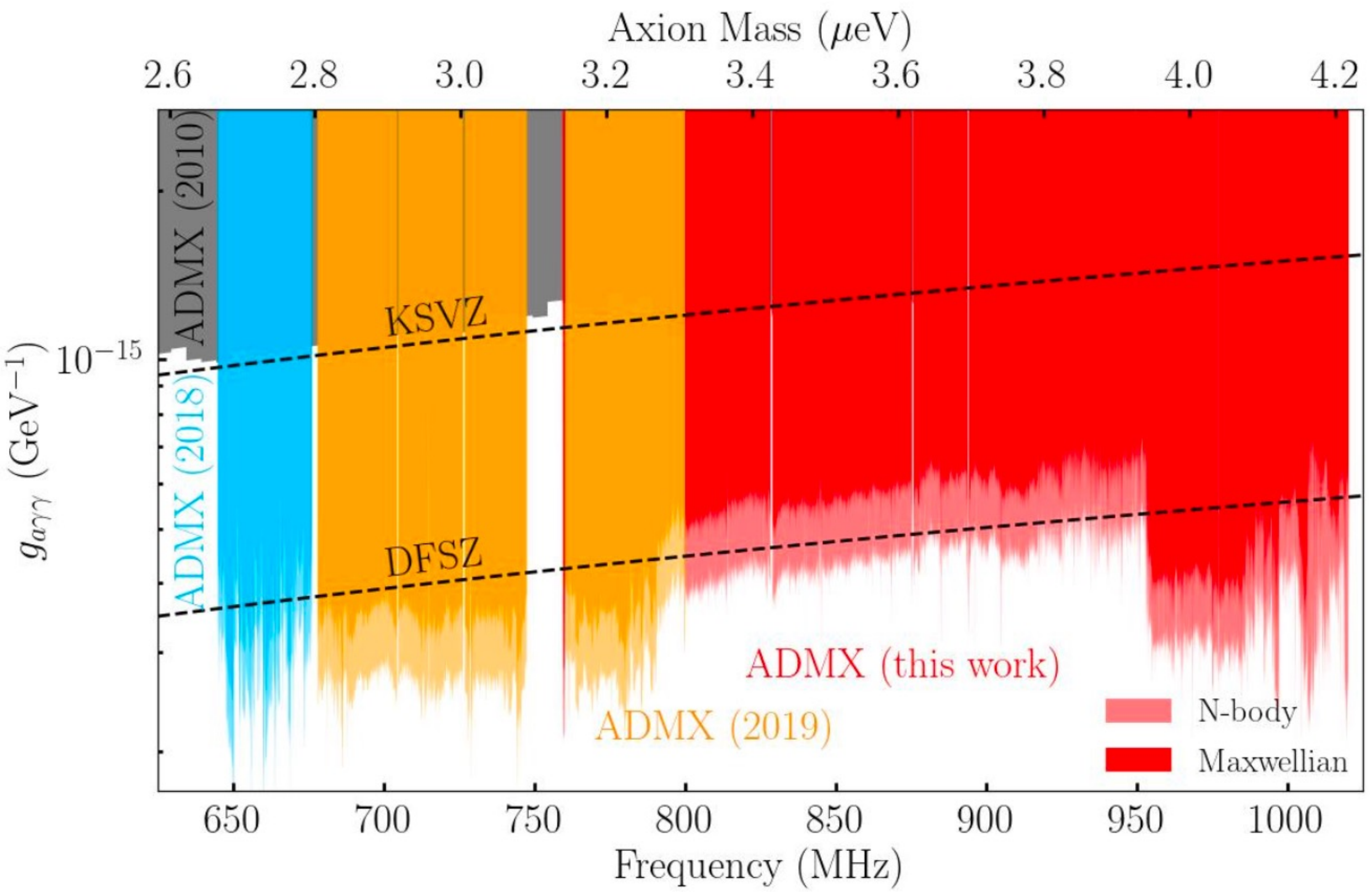


ADMX reached KSVZ sensitivity in 2010; DFSZ in 2018. Patience paid off



ADMX 2021 Exclusion

Gray Rybka’s slide



As we found no axion signals, we can exclude an even wider mass range.

PHYSICAL REVIEW LETTERS **127**, 261803 (2021)

Editors' Suggestion Featured in Physics

Search for Invisible Axion Dark Matter in the 3.3–4.2 μeV Mass Range

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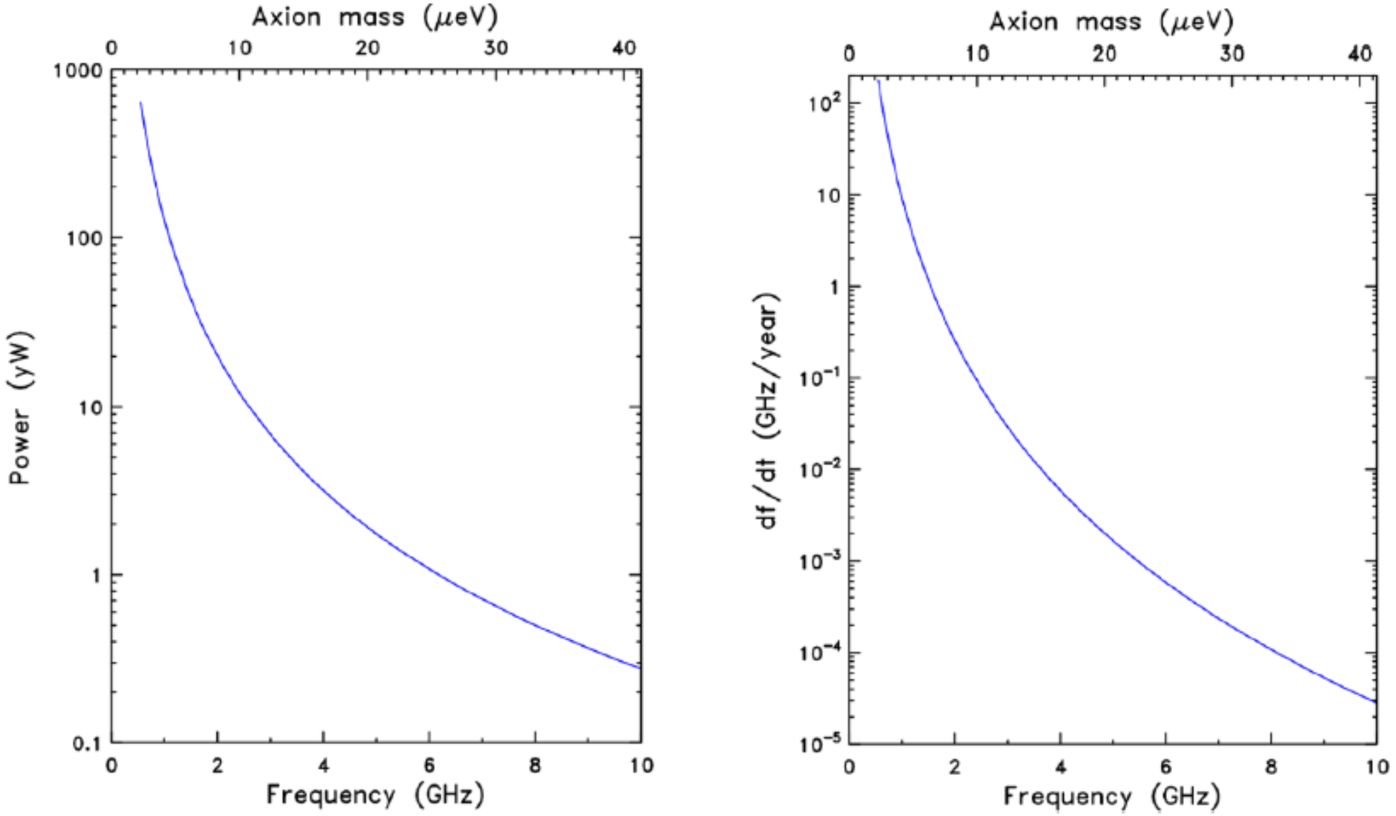
(ADMX Collaboration)

David Tanner, Univ. of Florida

Strawman 2: Single cavity



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

Patras 18

ADMX

IBS-CAPP recruitment time, making clear: Axion research is like a Marathon, not a short-term effort

IBS President Oh, Se Jeong at my recruitment time (I was the first foreign-born IBS-Director): "Just show promise…" when I stated 10-years as too short for axion dark matter research to leave my Senior-Scientist-Tenured position at BNL for it. He gave me a very supportive contract to enable the effective operation of the Center. CAPP was established October 16, 2013.

Center for Axion and Precision Physics Research: CAPP/IBS at KAIST, Korea

Se-Jung Oh (right), the president of the Institute for Basic Science (IBS) in Korea, and Yannis Semertzidis, after signing the first contract between IBS and a foreign-born IBS institute director. On 15 October, Semertzidis became the director of the Center for Axion and Precision Physics Research, which will be located at the Korea Advanced Institute of Science and Technology in Daejeon. The plan is to launch a competitive Axion Dark Matter Experiment in Korea, participate in state-of-the-art axion experiments around the world, play a leading role in the proposed proton electric-dipole-moment (EDM) experiment and take a significant role in storage-ring precision physics involving EDM and muon g-2 experiments. (Image credit: Ahram Kim IBS.)

CERN Courier, Dec. 2013

- Completely new (green-field) Center dedicated to Axion Dark Matter Research and Storage Ring EDMs/g-2. KAIST campus.

The process

- Spring 2012, I submitted a proposal to IBS to study the Strong-CP problem, axion dark matter and proton EDM

- The Selection and Evaluation Committee with Prof. Dr. Peter Fulde (Chairman of SEC, Max Planck Inst.) invited me to compete

The proposal to IBS

IBS-Seoul, 16 September 2012

Plan to build-up the Institute

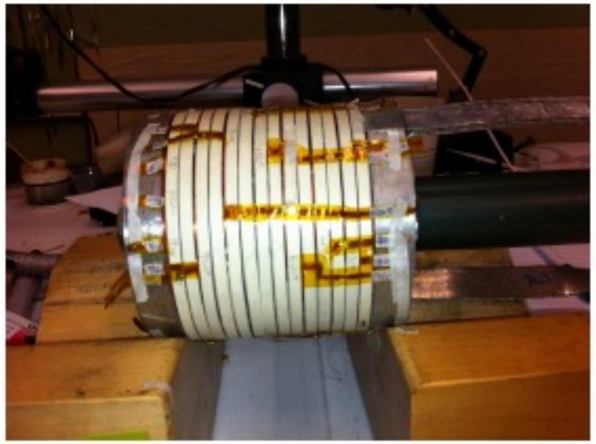
Yannis Semertzidis, BNL

- Goal: To establish a first rate axion dark matter research center at GIST.
- To play a critical role in the storage ring EDM experiments

From my presentation: HTS magnet

New record field, 16 T, for solenoid wound with YBCO High *Field* Superconductor

- High *Field* Superconductor =
  High Temperature Superconductor at 4 K (not 77 K)
- Previous record: 10 T
- YBCO tape: 0.1 mm x 4-12 mm
- OHEP SBIR with Particle Beam Lasers, BNL as subcontractor (2 Phase IIs, 1 Phase I) – YBCO vendor: SuperPower
- Full program: 3 nested coils, can test full set to ~ 40 T



I = 285 A
id = 25 mm, od 91 mm
700 m tape
Did not quench

R&D program at BNL, from P. Wanderer

Weighing the vacuum using

- Highest field magnets
  - LTS: NbTi 8 and 9T and Nb_3Sn 12T/320mm
  - HTS: 18T/70mm; 25T/100mm

- Lowest temp possible (<50mK)

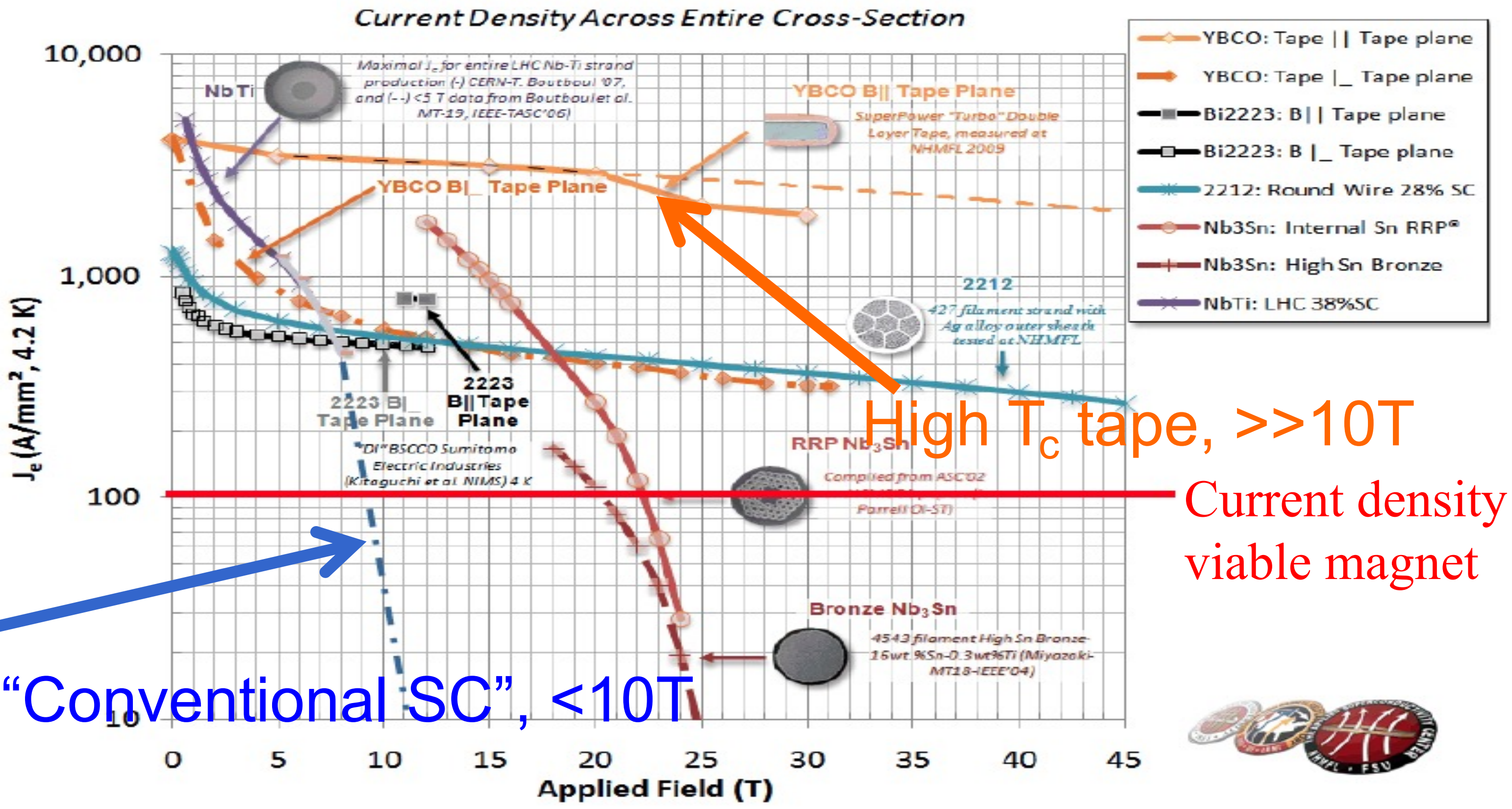
- Quantum-noise limited amplifiers SQUIDs and JPAs for <10GHz; Single photon detector for >10GHz

- High-quality factor microwave-resonators ($>10^6$)

- Particle physics approach of massive parallel R&D

Future Solenoids:

High- Temperature Superconductors



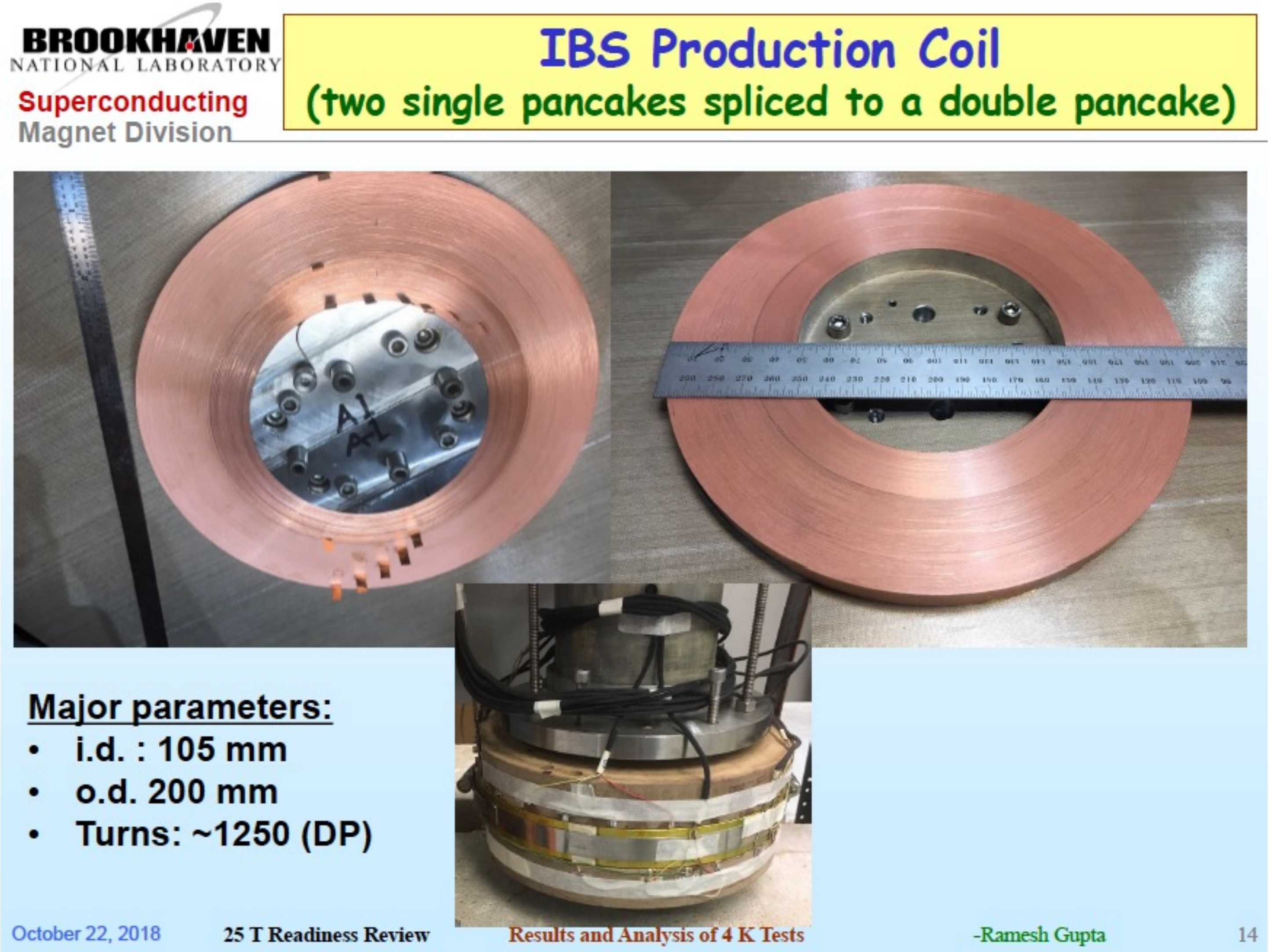
High T_c tape, >>10T

Current density threshold for viable magnet

NbTi: “Conventional SC”, <10T

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

Working with Ramesh Gupta of the BNL Magnet Division

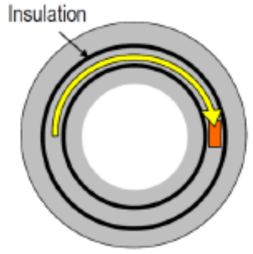


BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

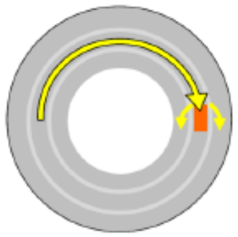
No Insulation Approach to Magnet Protection (slides courtesy S. Hahn)

No-Insulation HTS Winding Technique

INS: Difficulty in Protection



NI: "Quench Current Bypass"



- Slow normal zone propagation in HTS
  - ➔ Slow quench detection
- Larger enthalpy (stability margin) of HTS
  - ➔ Difficulty in "activate-heater" protection

- "Automatic bypass" of quench current through turn-to-turn contacts

REF: S. Hahn, D. Park, J. Bascuñán, and Y. Iwasa, "HTS Pancake Coil without Turn-to-Turn Insulation," *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 1592 – 1595, 2011.

S. Hahn <shahn@fsu.edu> | No-Insulation HTS Magnet WAMHTS-3, Lyon, France (September 11, 2015) | 5/18

No Protection Device: No-Insulation HTS Magnets

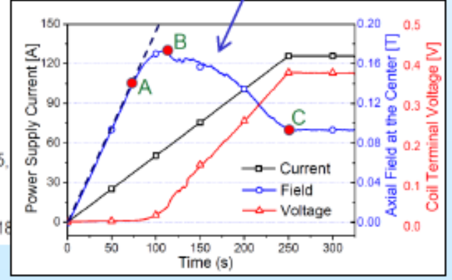
Seungyong Hahn

Applied Superconductivity Center
National High Magnetic Field Laboratory
Department of Mechanical Engineering
Florida State University

WAMHTS-3
Lyon, France

September 11, 2015

A decrease in field implies that more and more turns are getting shorted

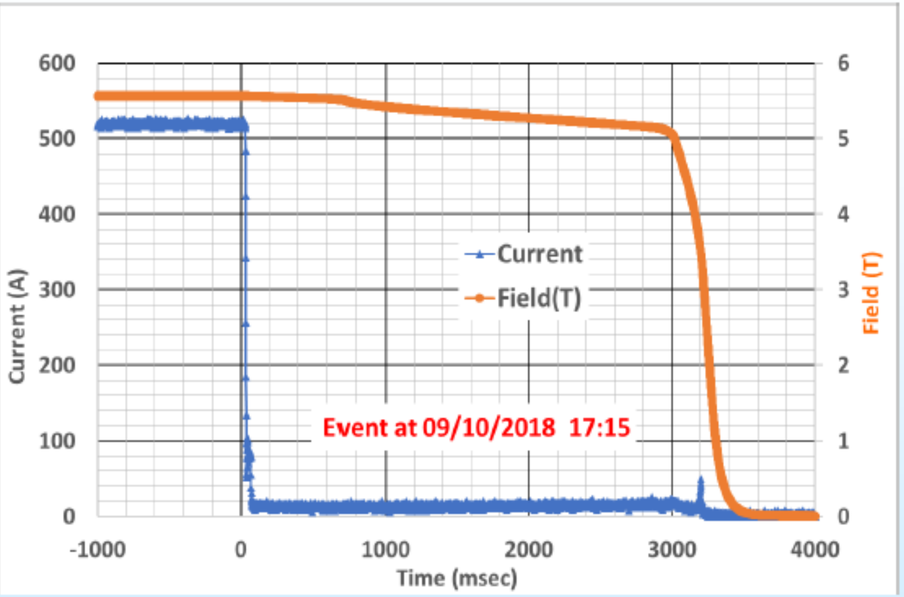


Successfully demonstrated to work in small coils, but not yet in big coils at 4K

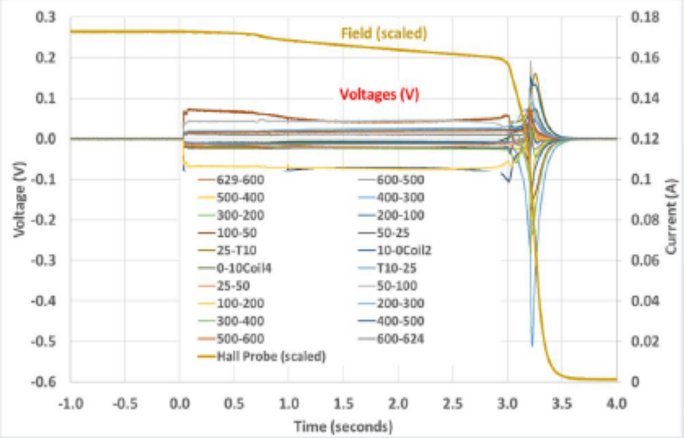
Part of review presentations, Ramesh Gupta

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

Shut-off Tests in No-insulation Coils (an example @550 A, operating current 450 A)



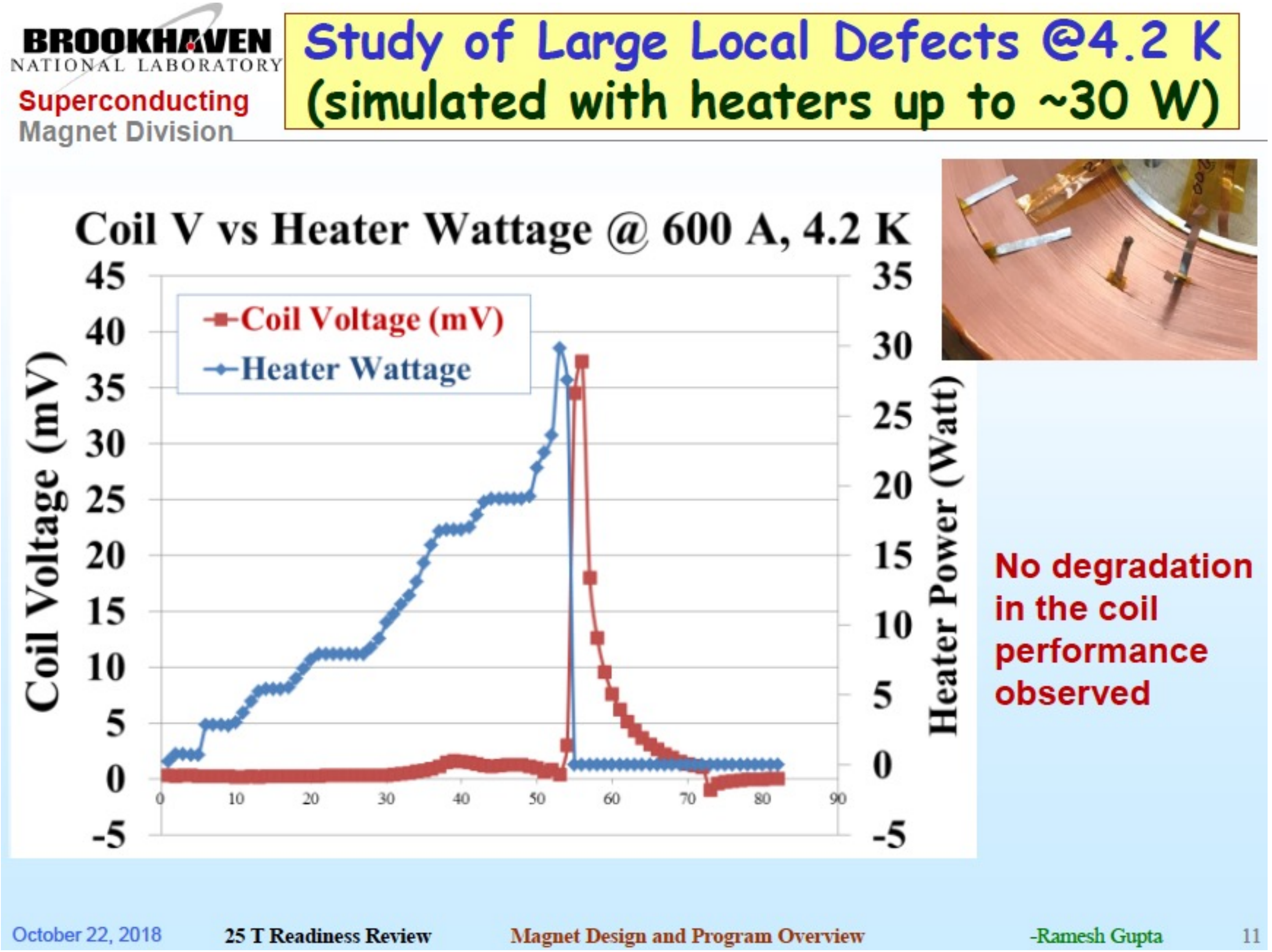
- No significant energy is extracted during shut-offs or quenches in the no-insulation coils
- Energy is dumped/distributed inside the whole coil with contact resistance between the turns
- Whether coil recovers or runs away depends on how far away it is from critical surface
- Crucial test of inter-connect when it runs-away



550 A example (operating current 450 A):
- Slow internal deposition of energy (3 sec)
- Fast run-away (<0.5 sec), once triggered

This coil recovered (no runaway) up to 400 A

Punishing tests



Axion dark matter HTS magnet specs

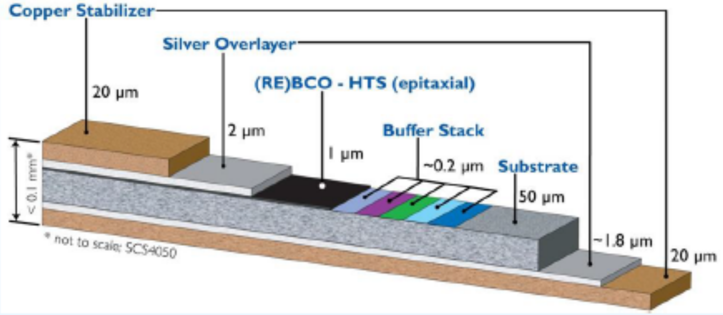
- No Insulation quenches the magnet fast!
- Quenches safely. (Further tests with 3DP, 7DP, 14DP)
- What's next? Material strength…

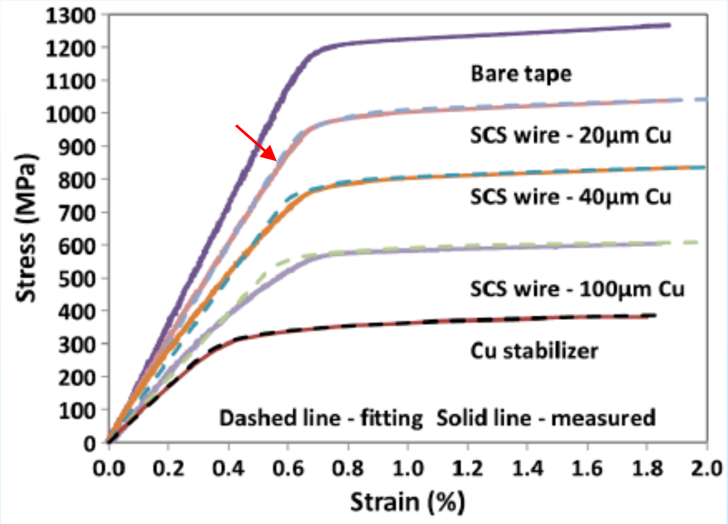
>50% margins, R&D worked!

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Choice of Conductor





- Removing insulation increases the current densities in coils
- This creates higher stresses within the coil
- Reducing amount of copper allows us to deal with the higher stresses
- Copper reduced from 40/ 65 microns in SMES to 20 microns in IBS solenoid while keeping the Hastelloy same (50 microns)
- This choice offers >50% margin on hoop stresses

Landscape

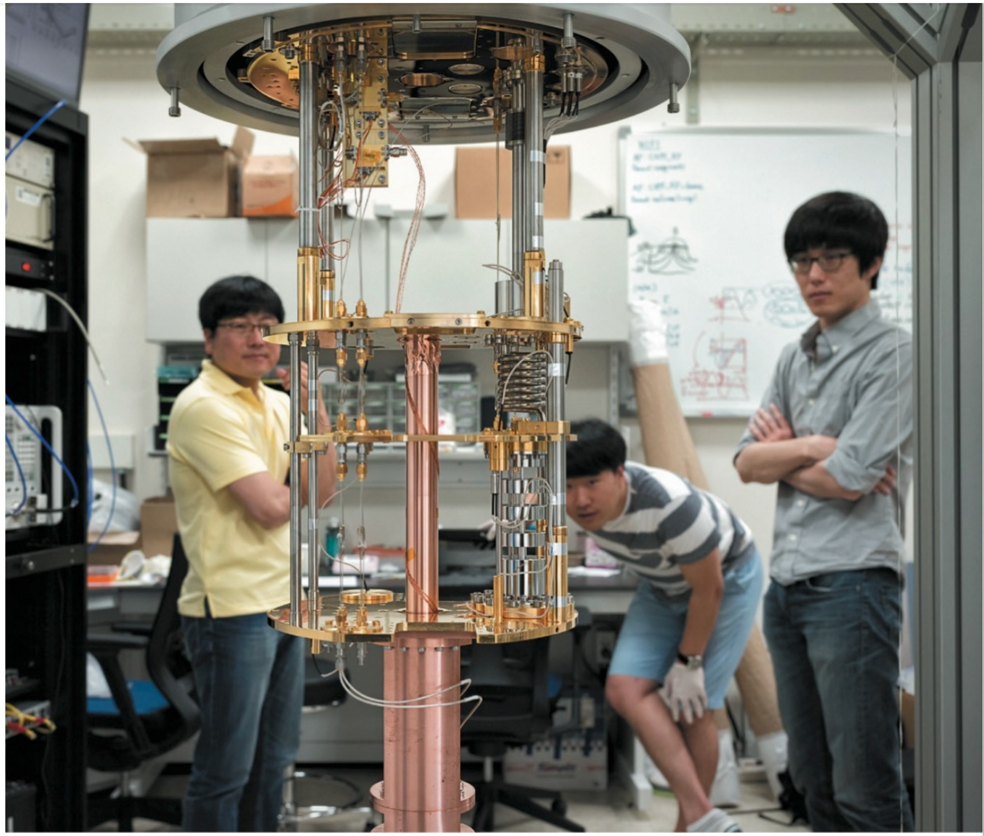
- October 16, 2013 CAPP is established. No particle or nuclear exp. physics present at KAIST
- 2014-2017. Setting up infrastructure, purchasing expensive equipment. Started hiring "high-energy", dynamic people.
- 2017-2020. Set R&D goals, work in parallel to achieve results fast. First setup and runs of prototype experiments.
- 2020-present. Combine achievements to create competitive axion dark matter experiments

Some points to consider:

1. No axion dark matter experimental activity in Korea prior to CAPP.
2. The prospects of reaching theoretically interesting sensitivities above 1 GHz seemed remote.
3. IBS established in 2011. Not long Basic Science tradition in Korea. Nonetheless, it was possible to make it happen since Korea learns fast.

Could CAPP produce a Nobel Prize opportunity for Korea?

Nature article about our CAPP/IBS center in Korea



SHIN WOONG-JAE

South Korea's Nobel dream

The Asian nation spends more of its economic output on research than anywhere else in the world. But it will need more than cash to realize its ambitions.

BY MARK ZASTROW

Behind the doors of a drab brick building in Daejeon, South Korea, a major experiment is slowly taking shape. Much of the first-floor lab space is under construction, and one glass door, taped shut, leads directly to a pit in the ground. But at the end of the hall, in a pristine lab, sits a gleaming cylindrical apparatus of copper and gold. It's a prototype of a device that might one day answer a major mystery about the Universe by detecting a particle called the axion — a possible component of dark matter.

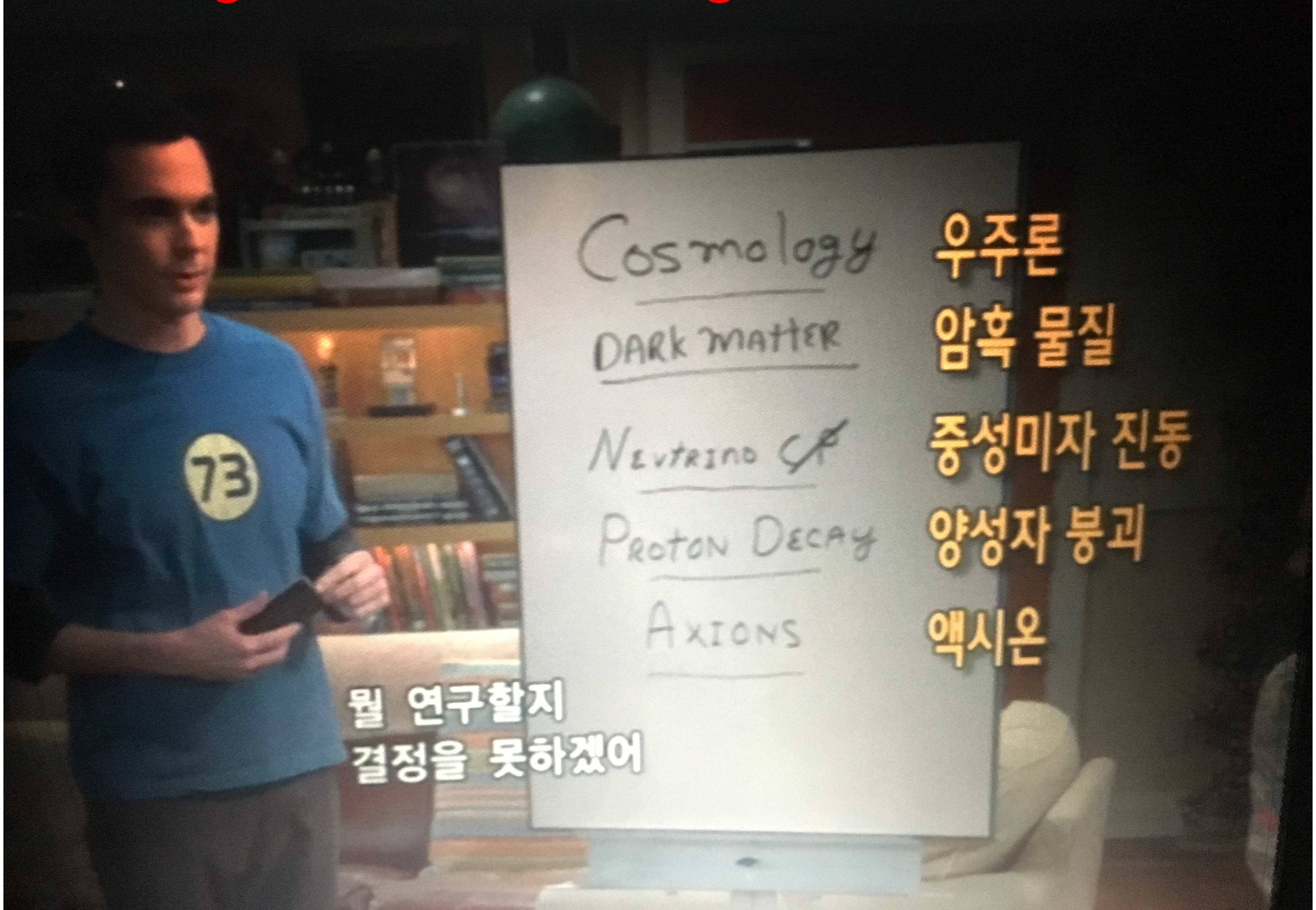
If it succeeds, this apparatus has the potential to rewrite physics and win its designers a Nobel prize. "It will transform Korea, there's no question about it," says physicist Yannis Semertzidis, who leads the US$7.6-million-per-year centre at South Korea's premier technical university, KAIST. But there's a catch: no one knows whether axions even exist. It's

Nature, V534, 2 June 2016

IBS/CAPP

- 2014 and 2015 was major recruitment time.
- Traveled to major labs/Universities around the world.
- Absolutely exhausting!

Learning Korean with in-flight entertainment!



IBS-CAPP period timeline, established Oct. 16, 2013

- 2013-2015, intense recruitment effort, not a single "axion expert" came to Korea. We needed to develop all expertise in-house. A time of great growth and infra-structure setup.

- 2016-2019, turbulent period for IBS, budget was drastically reduced. All my contract provisions were fully ignored by the second IBS administration. Building up of CAPP prototype experiments and developing know-how.

- 2020-May 2022, returned to stability with thriving innovation period. Breakthrough results from CAPP pouring out. New government change…

BNL 25T/10cm, HTS magnet review

October 22, 2018

- Magnet construction plan with single layer is sound
- Magnet design with No Insulation making it safe from quenches and structural integrity
- >50% margins in critical current and stresses
- 16 out of 28 pancakes constructed.

Canceled by IBS-HQ when IBS's budget was reduced

Figure 2.67: Manufacturing process (10 HTS coils).

IBS-HQ, improvising mode

- 2016, after the government changed, funding was cut, the strict regulations were enforced. IBS-HQ set priorities to protect the "important" centers.

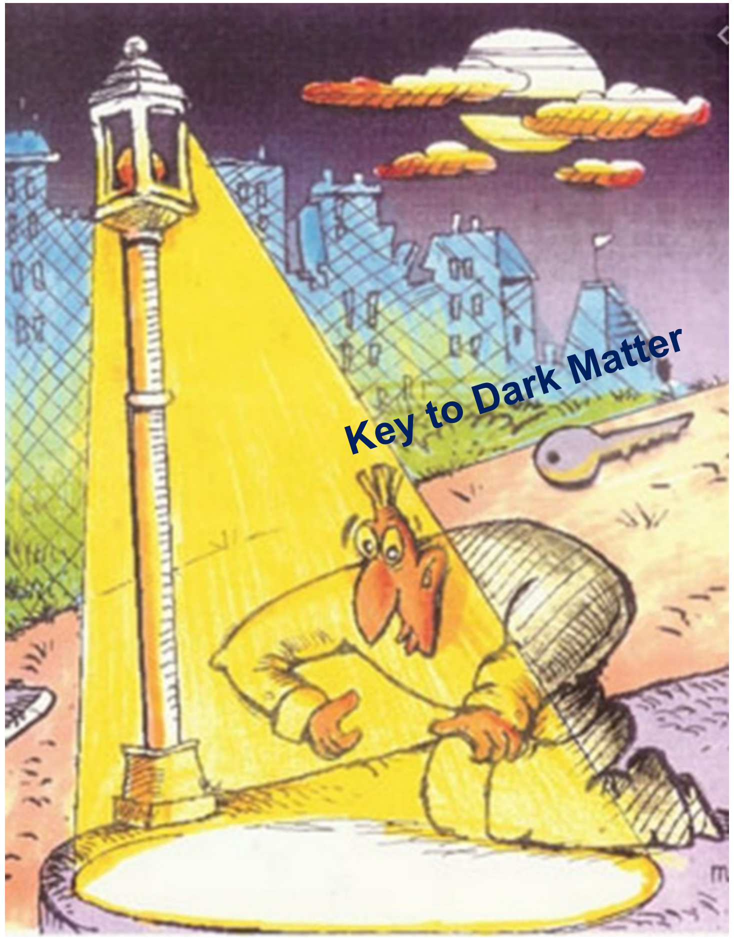
- IBS-HQ had intervened and dismounted my Korean collaborations with KAIST (super-conducting cavities) and KIST (NIST equivalent) on quantum noise limited RF-amplifiers

- Set a priority on different type of centers, moving the funding around, changing regulations seemingly constantly. End of 2018 the HTS magnet was cancelled using non-kosher arguments.

IBS's original character did not survive the change of government

Strategy at CAPP: best infra-structure and know-how

- Under (a brighter) lamp-post with microwave resonators
  - LTS-12T/320mm, Nb_3Sn magnet: for 1-8 GHz
  - 12T for large volume 37 liters



- Powerful dilution refrigerator: ~5mK base temp.
  - 25mK for the top plate of the 37 liter cavity

- State of the art quantum amplifiers (JPAs)
  - Best noise for wide frequencies: 1-6 GHz

- High-frequency, efficient, high-Q microwave cavities (best in the world)

CAPP started from scratch in 2013.
Lab space at KAIST, 2014

Another room at KAIST.
We had to buy even screwdrivers.

CAPP had to create a miracle

Had to change everything:

- Several parallel R&D efforts. High-risk projects, high-potential payout.

- Established decision making process

- Seniority based on age was eliminated. Young people could be correct.

- High safety standards and transparency in transactions were implemented. Benefited from BNL experience.

- Developing state of the art infrastructure at the same time.

Main CAPP tactics, targeting axions of 1-10 GHz

- Develop infra-structure
- Develop in-house expertise
- Collaborate with the best around the world on amplifiers (long lead-time) and others as needed

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

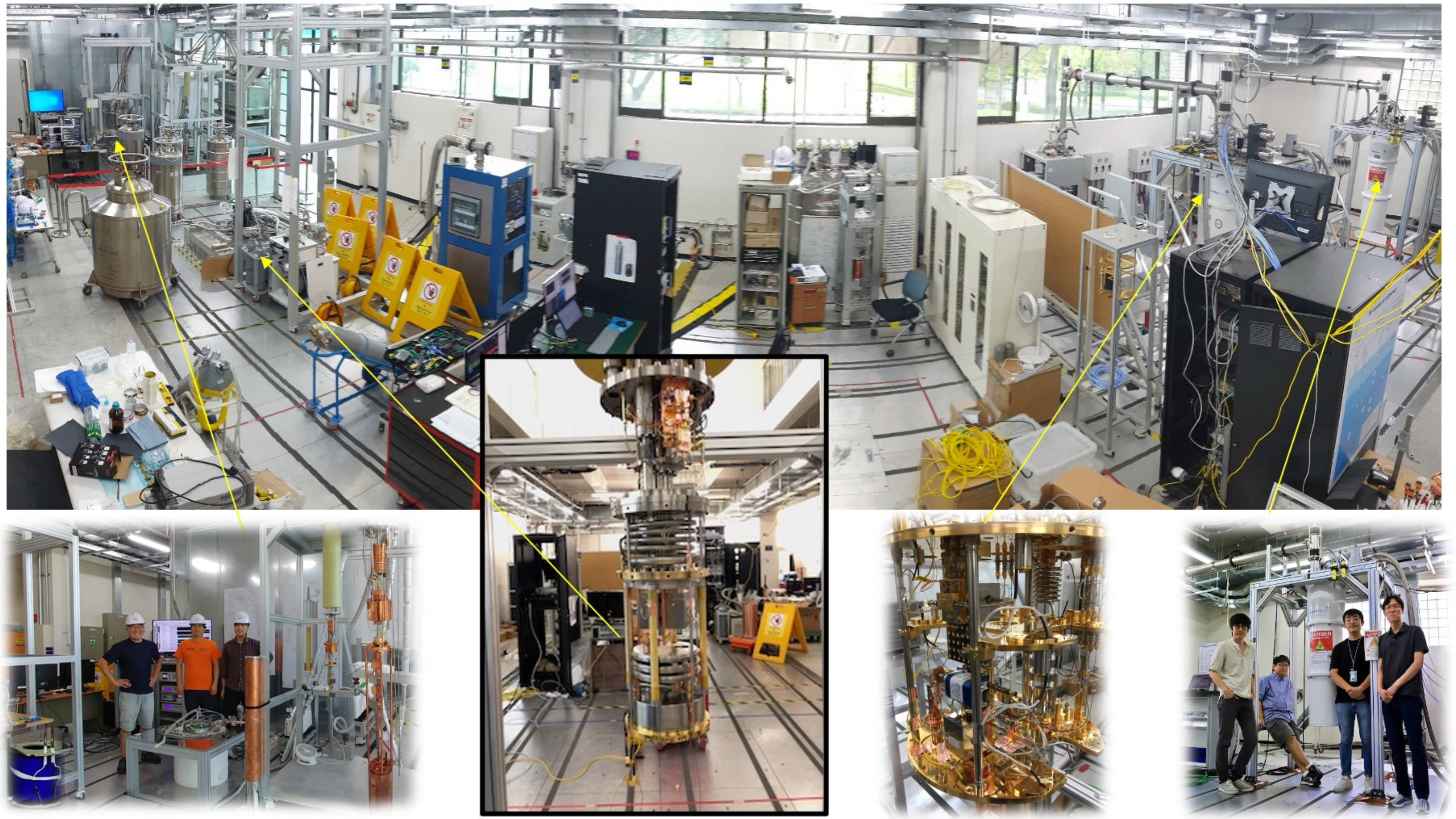
Operation model:

- Reward risk taking with high-physics potential R&D efforts
- Created a can-do environment with competent and confident scientists.
- Fast pace, the Korean clock running three times faster than regular clocks!

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

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.

CAPP Experimental Hall (LVP) in 2021



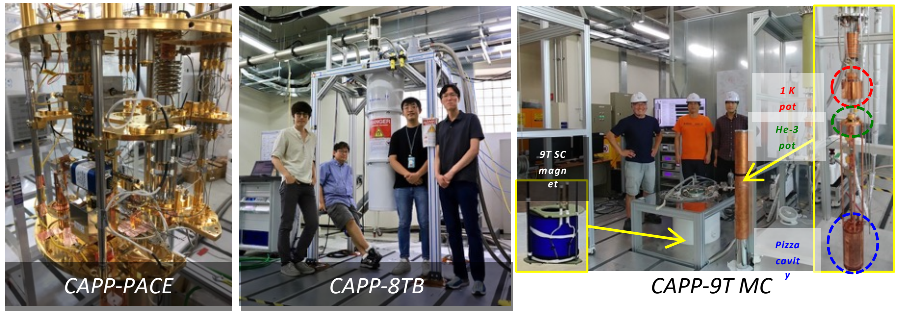
CAPP-HF CAPP-12TB CAPP-PACE CAPP-8TB

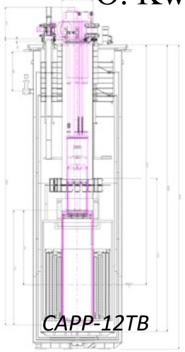
IBS-CAPP at eight-years and beyond

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

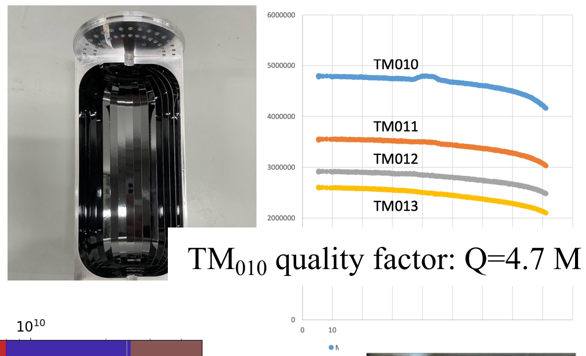
J. Jeong *et al.*, Phys. Rev. Lett. **125**, 221302 (2020).

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

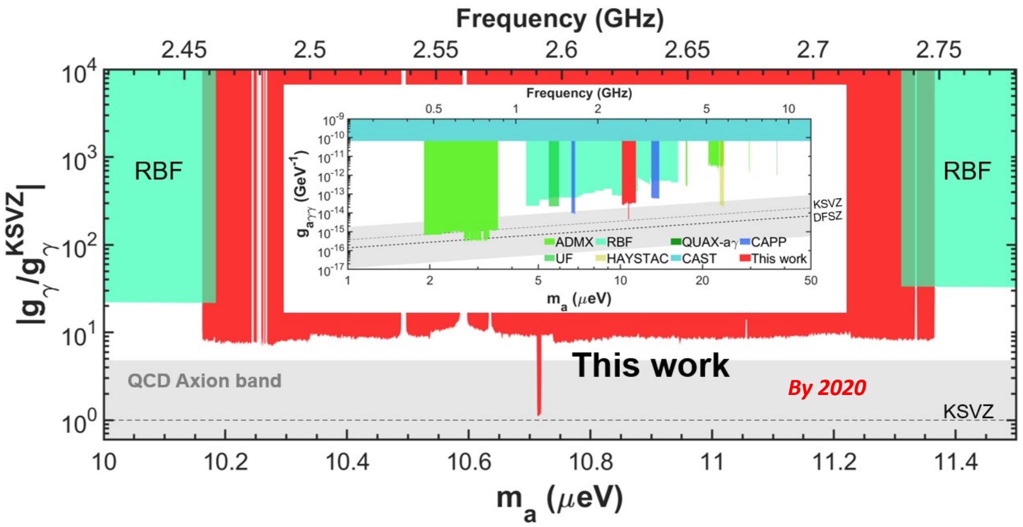


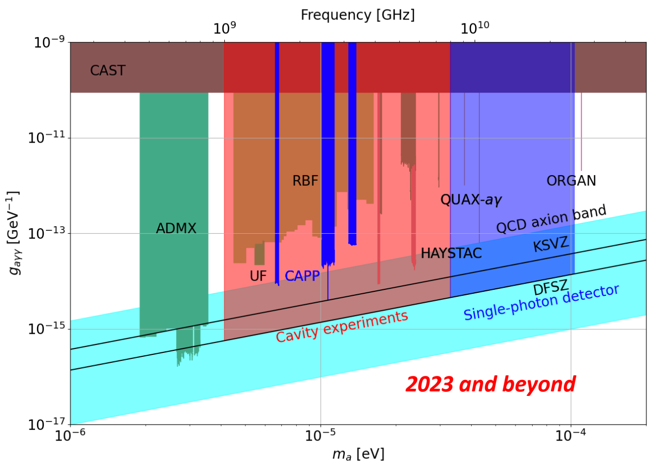


Melon 34 Cavity Q Factor Measurement

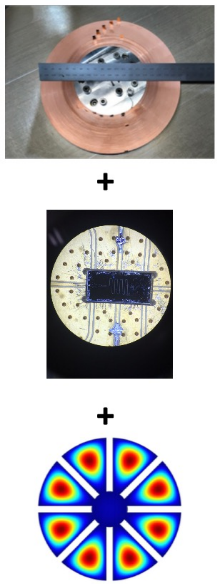


TM_{010} quality factor: Q=4.7 M





CAPP-25T



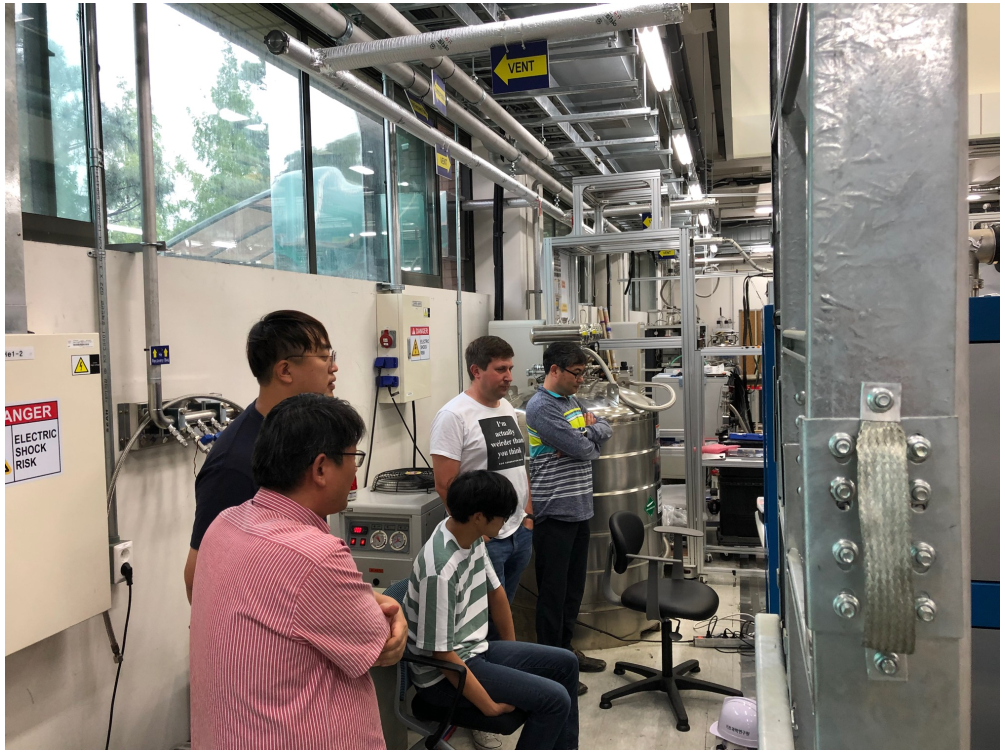
- *Cu cavities are assumed*
- *W/ SC cavities, down to 10% of axion dark matter content can be probed*

We expect to reach DFSZ sensitivity even for a fraction of axion content in the local dark matter halo. Target sensitivity: 10% axions in DM halo.

LTS-12T/320mm from Oxford Instruments

- ByeongRok Ko, Team leader of CAPP-12TB including the Nb_3Sn, LTS-12T/320mm magnet. Here, with his team testing the Leiden system.

Saturday, September 21, 2019



LTS-12T/320mm magnet (12TB experiment)

- Nb_3Sn + NbTi, LTS-12T/320mm from Oxford Instr., delivered March 2020, commissioned in August-December 2020.

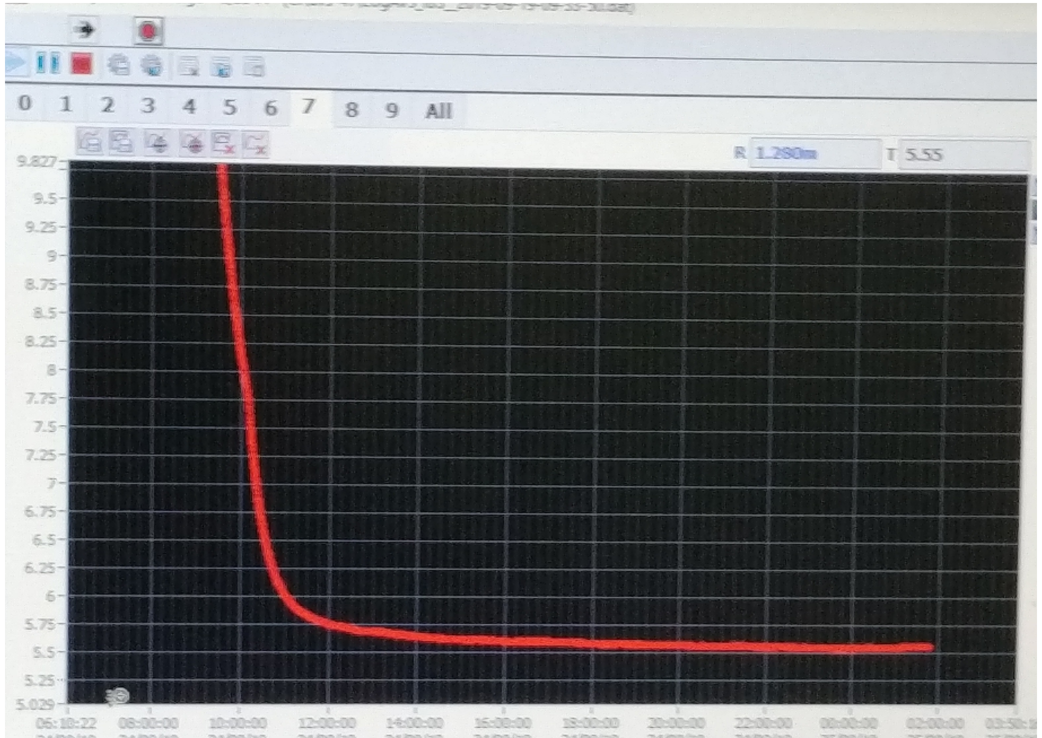
- This system can reach DFSZ level sensitivity in the 1-8 GHz, with present technology. Using SC cavities probe more…

- Wet system,

  Leiden dilution system:

  1.3mW at 120mK,

  achieved 5.6mK.



LTS-12T/320mm from Oxfrod Instruments

- Based on Nb_3Sn and NbTi, new challenging technology, 12T. Persistent mode switch
- The dilution fridge, 1mW at 120mK

  was delivered and commissioned in 2019
- Lowest temp dil. fridge base 5.5mK
- Cavity: ~37 liter, ultra-light cavity, <30mK

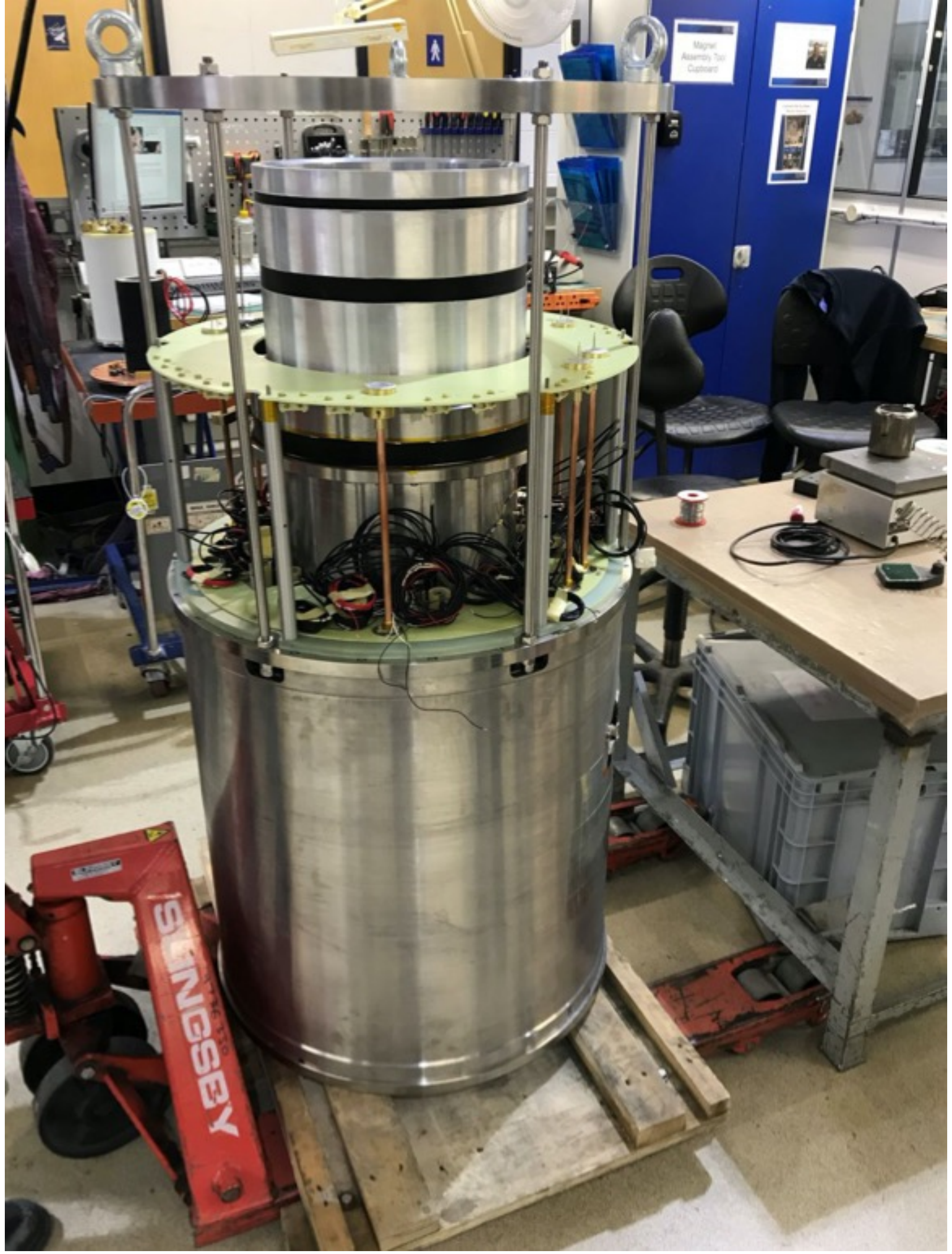


Figure 6. Recent picture of the LTS-12T/320mm magnet in its final form at the Oxford Instruments laboratory. Its total energy content is 5.652 MJ, a powerful magnet that requires respect and caution when energized. The system is to undergo its final tests before its scheduled shipment to IBS-CAPP by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

LTS-12T/320mm from Oxfrod Instruments

Magnet delivered early
March 2020 but couldn't be
comissioned due to COVID-19

- Fully commissioned end of 2020 delivering 12T max field (5.6MJ)

The CAPP-12TB, our flagship experiment

based on the LTS-12T/320mm magnet

- Axion to photon conversion power at 1.15 GHz
  - KSVZ: 6.2×10^{-22} W or ~10^3 photons/s generated
  - DFSZ: 0.9×10^{-22} W or ~10^2 photons/s generated

- With total system noise of 300mK, $Q_0=10^5$, eff. = 0.80
  - KSVZ: 25 GHz/year
  - DFSZ: 0.5 GHz/year
- With total system noise of 200mK (250mK), $Q_0=10^5$
  - KSVZ: 50 GHz/year (35 GHz/year)
  - DFSZ: 1 GHz/year (0.64 GHz/year)
- With total system noise of 100mK (150mK), $Q_0=10^5$
  - KSVZ: 200 GHz/year (90 GHz/year)
  - DFSZ: 4 GHz/year (1.7 GHz/year)

The Josephson parametric amplifiers (JPA) from Tokyo/RIKEN are quantum-noise limited. Best integrated system 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 in the world at:

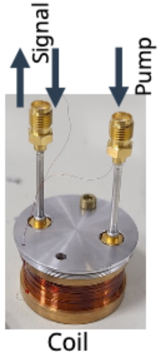
  1GHz, 2 GHz, and 6 GHz.


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

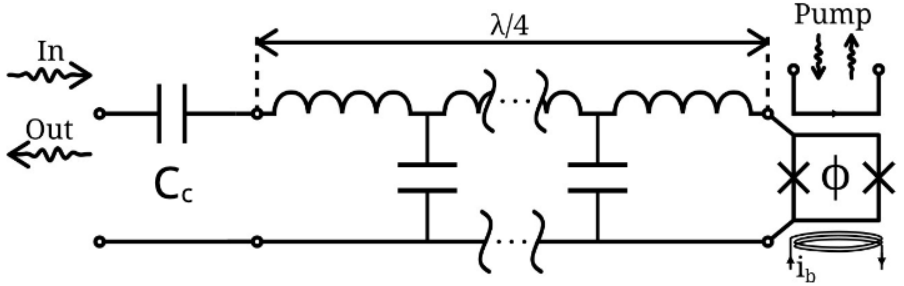
JPA Principle

(no resistors)

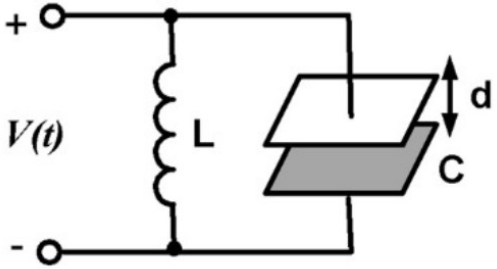
JPA Principle
(Caglar Kutlu's slide)



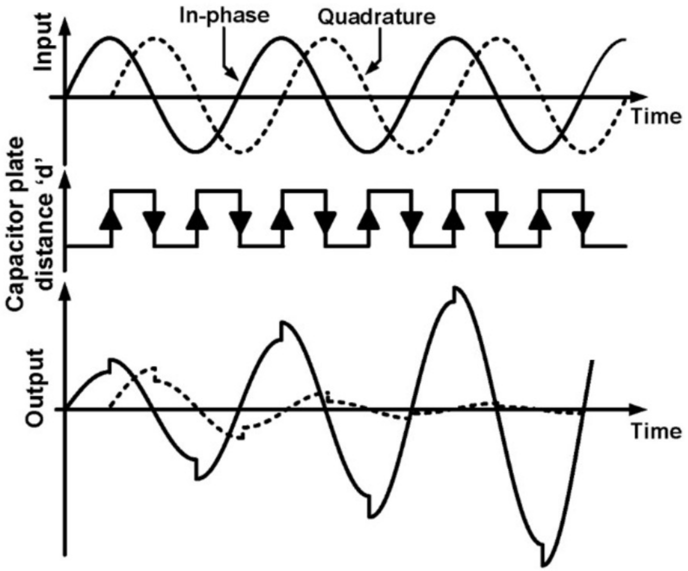
Flux-driven Josephson Parametric Amplifier

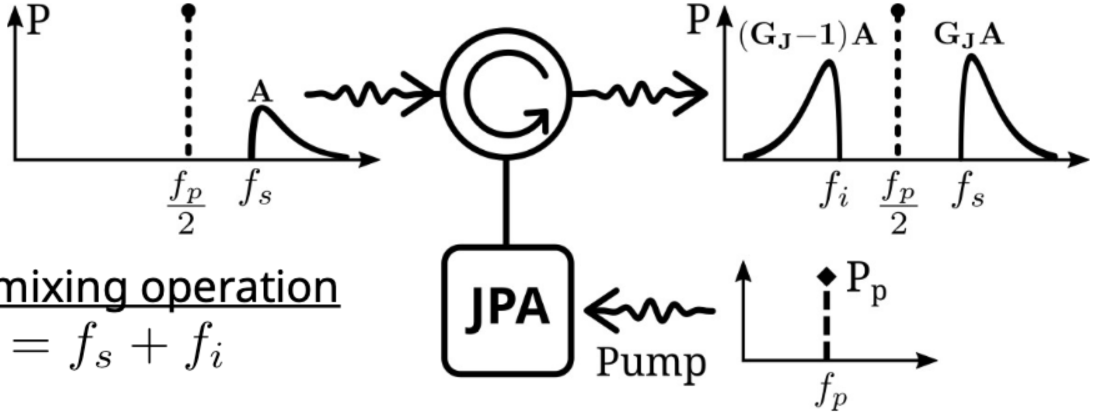


$$L_s = \frac{\Phi_0}{2\pi I_c}\frac{1}{\left|\cos\left(\pi\frac{\Phi}{\Phi_0}\right)\right|}$$



- The "parameter" is the effective inductance of the SQUID.
- With $\phi = \phi_{DC}(i_b) + \phi_{AC}(P_p, f_p)$, the ϕ_{DC} controls bare resonance frequency f_r.
- When the pump tone is present, its amplitude P_p, and frequency f_p determine the dynamics of the system for a certain f_r.





3 wave mixing operation

$$f_p = f_s + f_i$$

[1] W. Lee and E. Afshari, "A CMOS Noise-Squeezing Amplifier," in IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 2, pp. 329-339, Feb. 2012

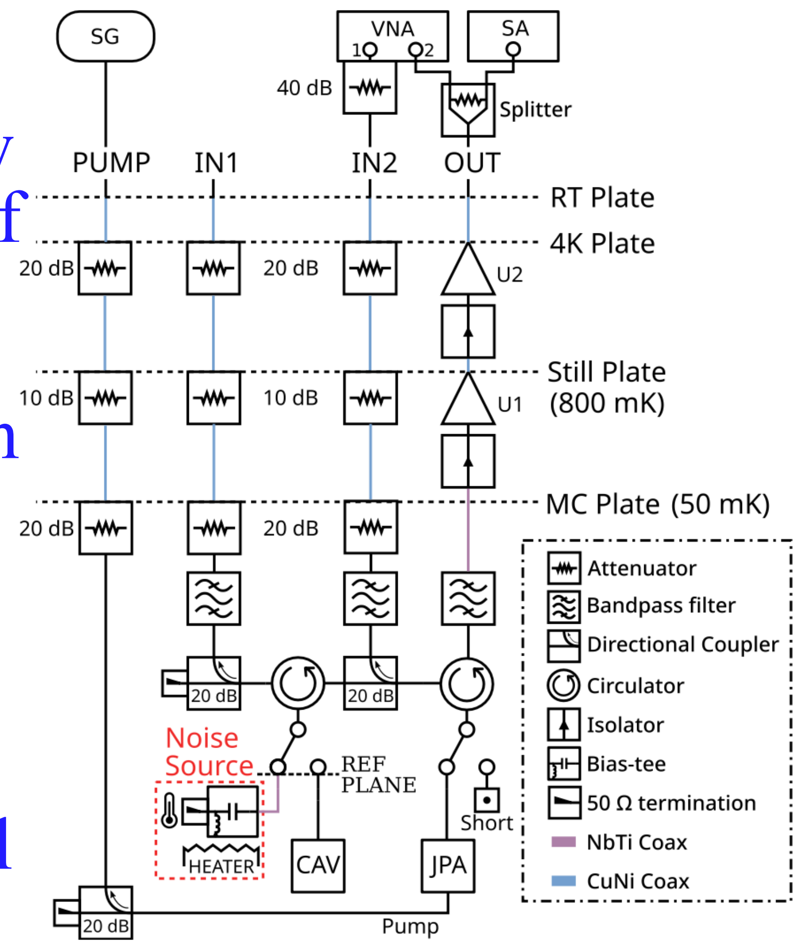
Cryogenics, RF-chain & JPAs

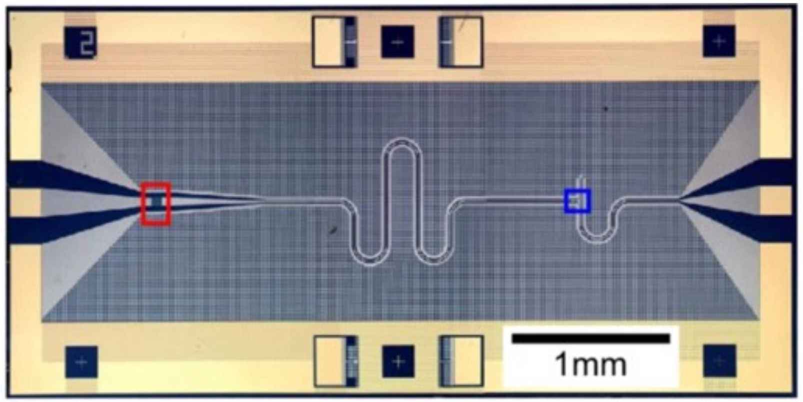
- Caglar Kutlu, JinMyeong Kim, Saebyeok Ahn, Andrew Yi, … KAIST graduate students under the leadership of Sergey Uchaikin on JPAs created the best performing quantum-noise-limited amplifiers. Chips/expertise from RIKEN/Univ. of Tokyo, Prof. Y. Nakamura, Arjan F van Loo.

- Ultra-light-cavity (37 liter) and cryogenics, OhJoon Kwon, Woohyun Chang, Heesu Byun, Sergey Uchaikin, Boris Ivanov achieved 25mK cavity physical temperature. The best in the world.

- Total system noise <200mK, measured with Noise Source at 1 GHz. Best in the world.

Ç Kutlu *et al*

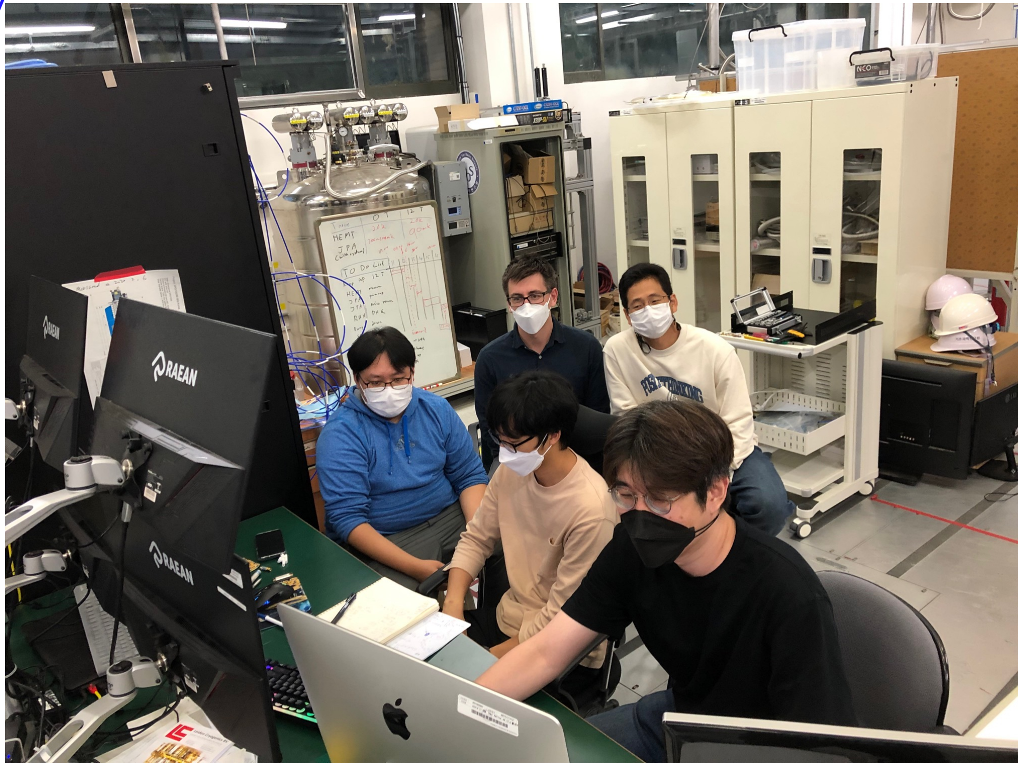




CAPP status in spring 2022

- We have two small systems taking data at KSVZ sensitivity:
  - BF6: Around 5.8 GHz, ~1 MHz/day, scanned: ~100 MHz, “Pizza” cavity, first and still best in the world
  - BF5: Around 2.3 GHz, ~1 MHz/day, first goal: 25 MHz, superconducting cavity, first and still best in the world

- LTS-12T/320mm, after the heroic job by so many
  - Taking axion dark matter data at DFSZ sensitivity at 1.1 GHz with ~1.4 MHz/day

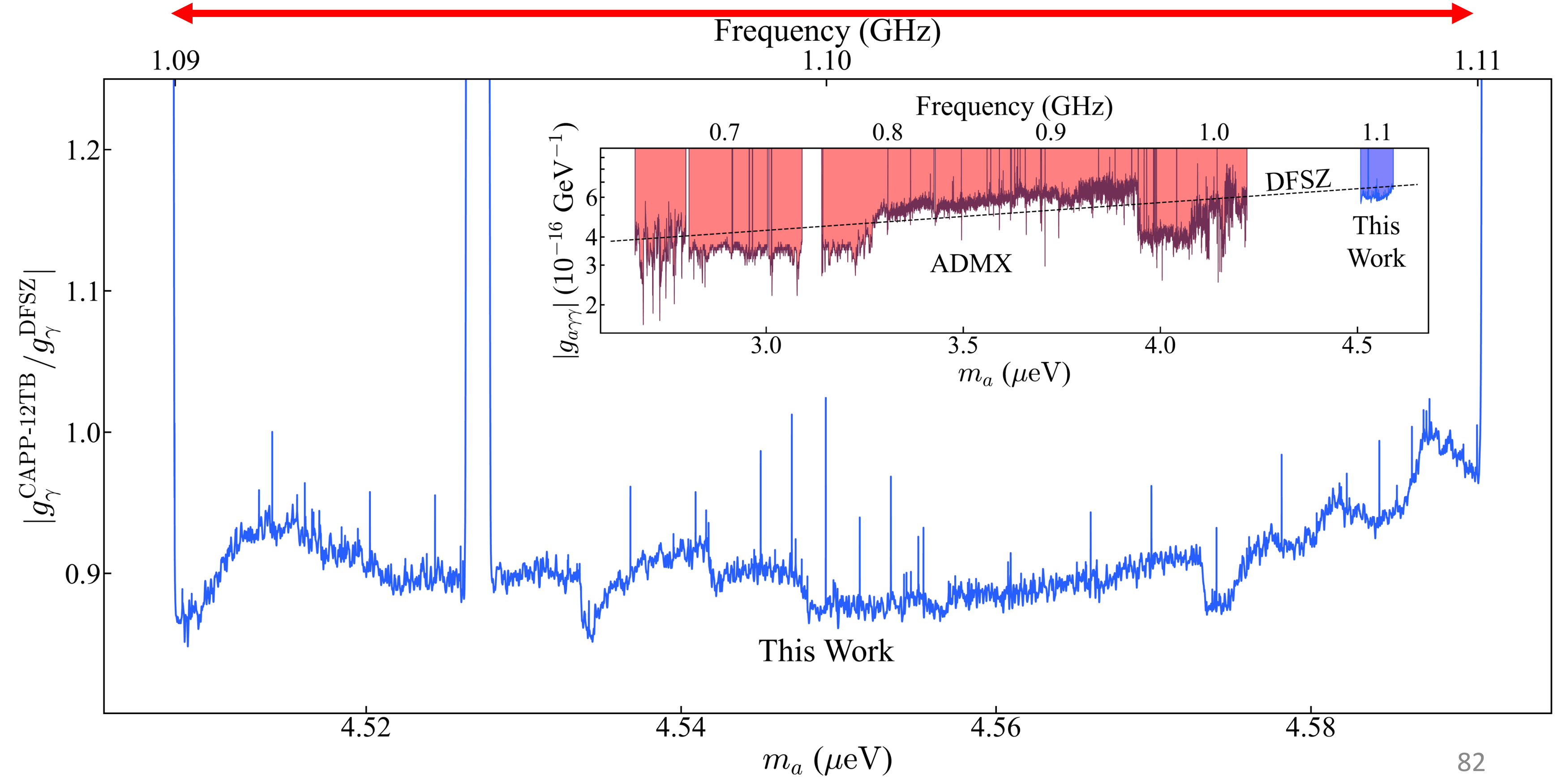


- In preparation:
- HTS-18T/70mm, with SC cavity, 6 GHz
- BF3, at 7 GHz
- JANIS high Freq. at ~10 GHz

CAPP-12TB RUN4, engineering run, spring 2022

CAPP in the DFSZ club. Axion search around 4.55 μeV (1.09 – 1.11 GHz) with DFSZ sensitivity, scanning at 1.4MHz/day

20 MHz



CAPP-12TB RUN4, engineering run, spring 2022

Andrew. Y. et al, Submitted to PRL

DFSZ Axion Dark Matter Search around 4.55 μeV

Andrew K. Yi,[1,2] Saebyeok Ahn,[1,2] Çağlar Kutlu,[1,2] JinMyeong Kim,[1,2] Byeong Rok Ko,[2,*] Boris I. Ivanov,[2] HeeSu Byun,[2] Arjan F. van Loo,[3,4] SeongTae Park,[2] Junu Jeong,[2] Ohjoon Kwon,[2] Yasunobu Nakamura,[3,4] Sergey V. Uchaikin,[2] Jihoon Choi,[2,†] Soohyung Lee,[2] MyeongJae Lee,[2,‡] Yun Chang Shin,[2] Jinsu Kim,[1,2] Doyu Lee,[2,§] Danho Ahn,[1,2] SungJae Bae,[1,2] Jiwon Lee,[1,2] Younggeun Kim,[2] Violeta Gkika,[2] Ki Woong Lee,[2] Seonjeong Oh,[2] Taehyeon Seong,[2] DongMin Kim,[2] Woohyun Chung,[2] Andrei Matlashov,[2] SungWoo Youn,[2] and Yannis K. Semertzidis[2,1]

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[4]*Dept. of Applied Physics, Graduate School of Engineering,*
The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan

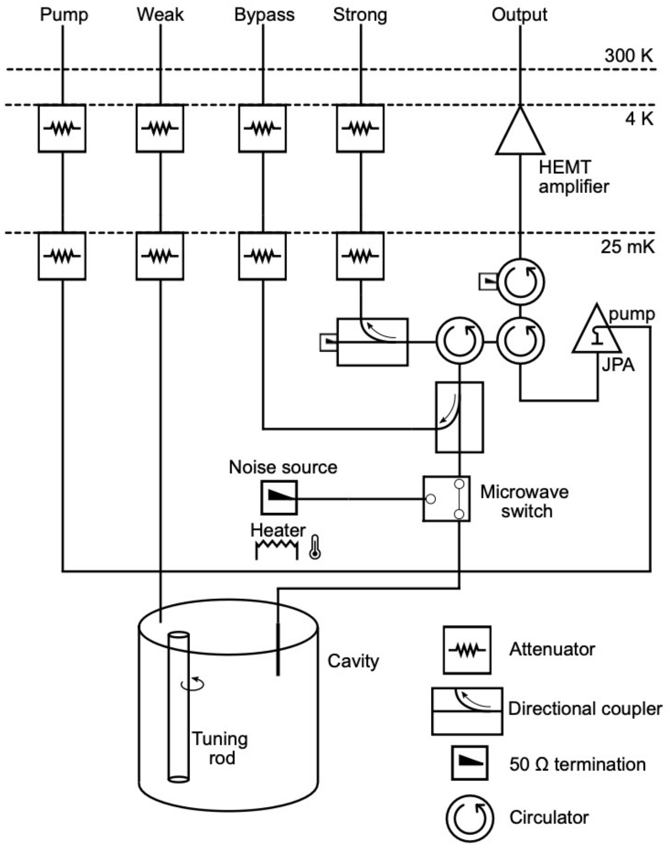
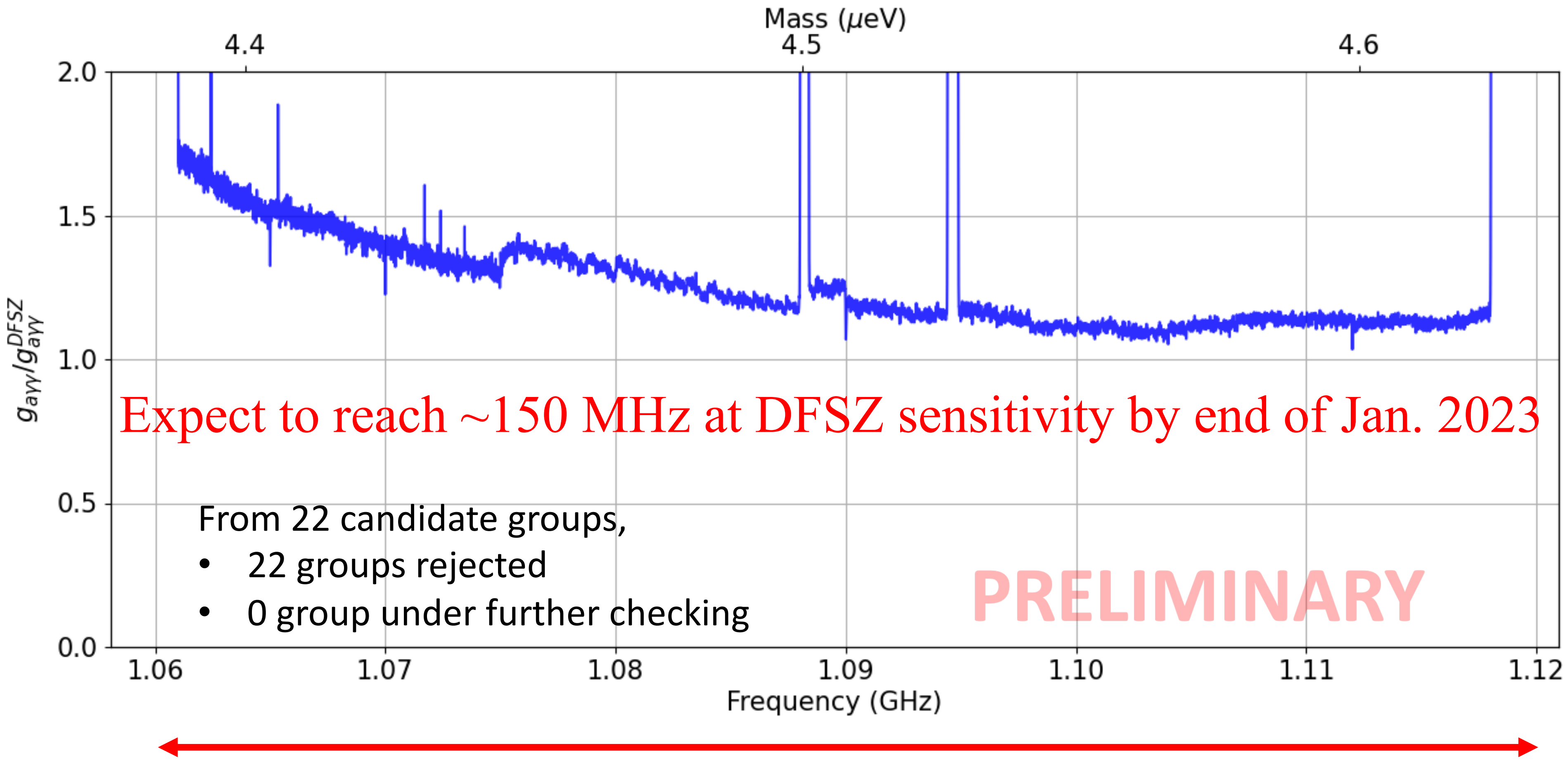


FIG. 2: CAPP-12TB receiver diagram.

New data: CAPP-12TB RUN5C, since September 2022

Achieved already sensitivity (preliminary), scanning at 4MHz/day



60 MHz

The CAPP-12TB, our flagship experiment

based on the LTS-12T/320mm magnet

- Axion to photon conversion power at 1.15 GHz
  - KSVZ: 6.2×10^{-22} W or ~10^3 photons/s generated
  - DFSZ: 0.9×10^{-22} W or ~10^2 photons/s generated

- With total system noise of 300mK, $Q_0=10^5$, eff. = 0.80
  - KSVZ: 25 GHz/year
  - DFSZ: 0.5 GHz/year
- With total system noise of 200mK (250mK), $Q_0=10^5$
  - KSVZ: 50 GHz/year (35 GHz/year)
  - DFSZ: 1 GHz/year (0.64 GHz/year)
- With total system noise of 100mK, $Q_0=2\times10^6$
  - DFSZ: 2 GHz/year for 20% of dark matter as axions

HTS superconducting cavity in large B-field!

arXiv:2002.08769v1 [physics.app-ph] 19 Feb 2020

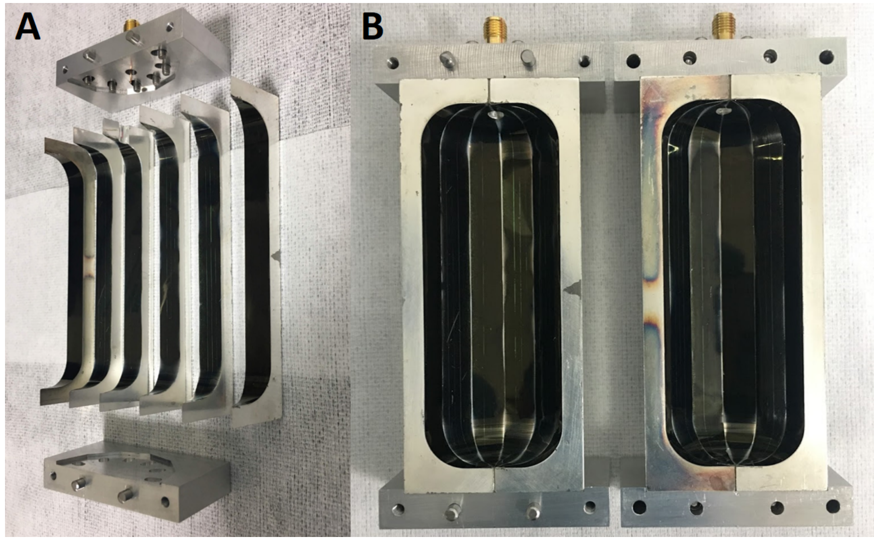
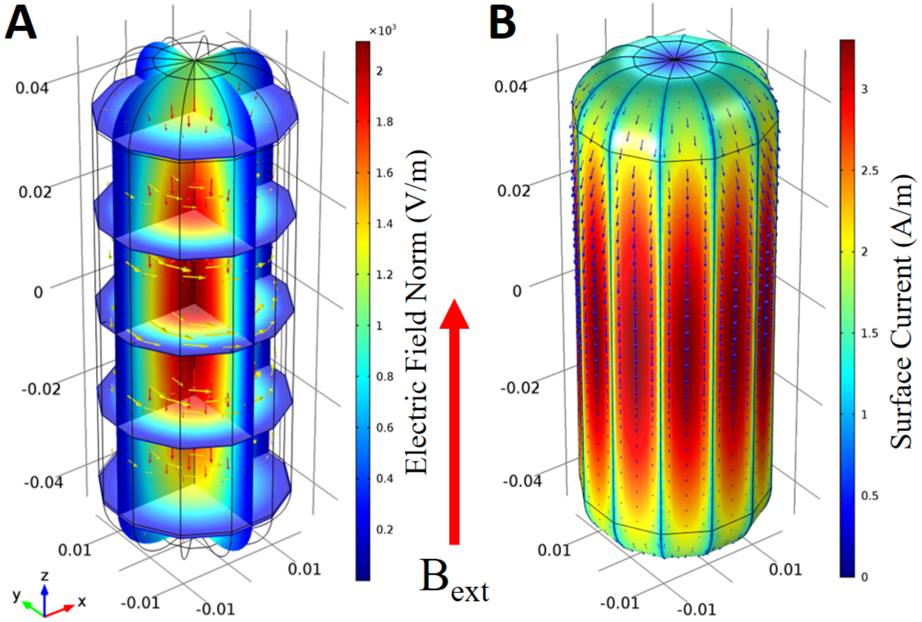


FIG. 1: Design of the YBCO polygon cavity. **(A)** Six aluminum cavity pieces to each of which a YBCO tape is attached. **(B)** Twelve pieces composing two cylinder halves are assembled to a whole cavity.

TM_{010} mode

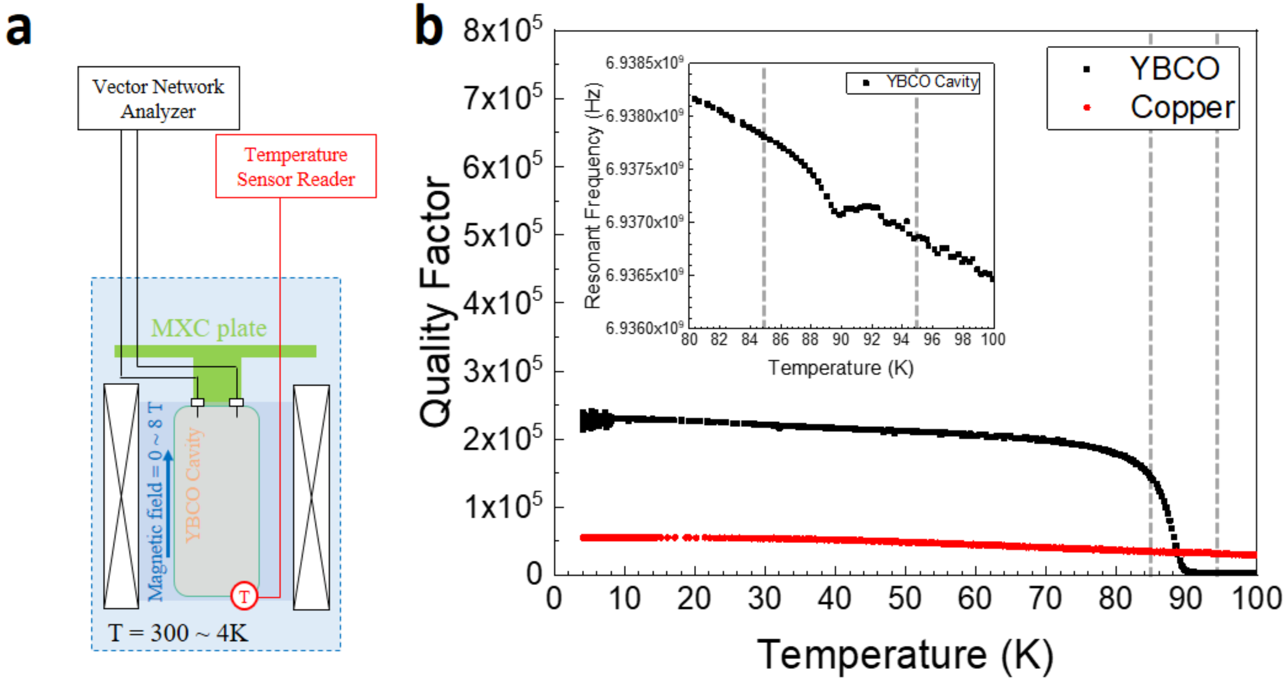


YBCO tapes on cavity walls

Phys. Rev. Applied **17**, L061005 – Published 28 June 2022

HTS superconducting cavity in large B-field!

arXiv:2002.08769v1 [physics.app-ph] 19 Feb 2020

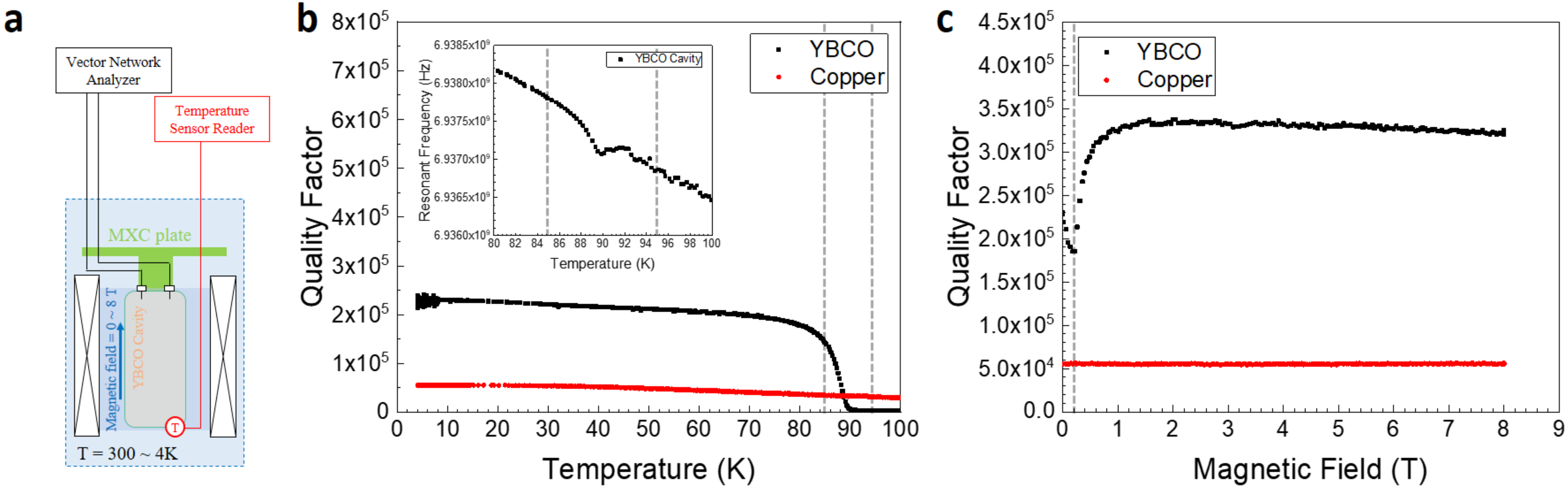


First and best in the world!

Phys. Rev. Applied **17**, L061005 – Published 28 June 2022

HTS superconducting cavity in large B-field!

arXiv:2002.08769v1 [physics.app-ph] 19 Feb 2020



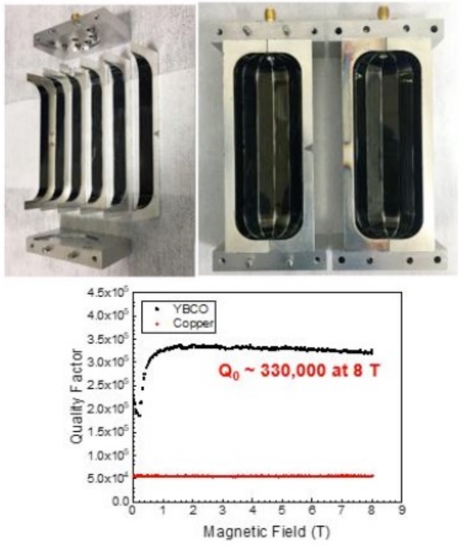
First and best in the world!

Phys. Rev. Applied **17**, L061005 – Published 28 June 2022

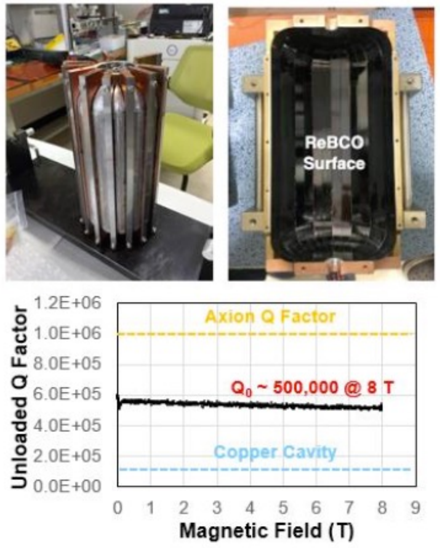
HTS tapes: Superconducting cavities in large B-field for first time.

History of HTS Cavity Development @ CAPP

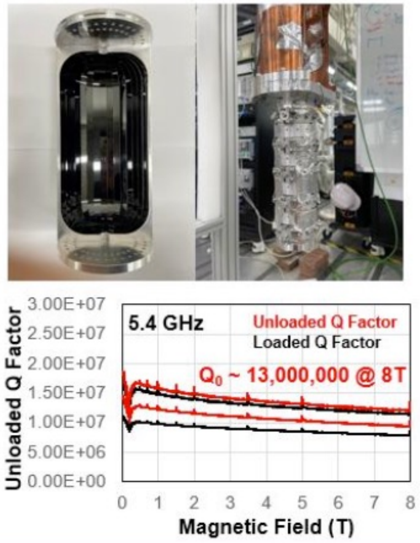
First Gen. (6.9 GHz)



Second Gen. (2.3 GHz)



Third Gen. (2.2 GHz & 5.4 GHz)

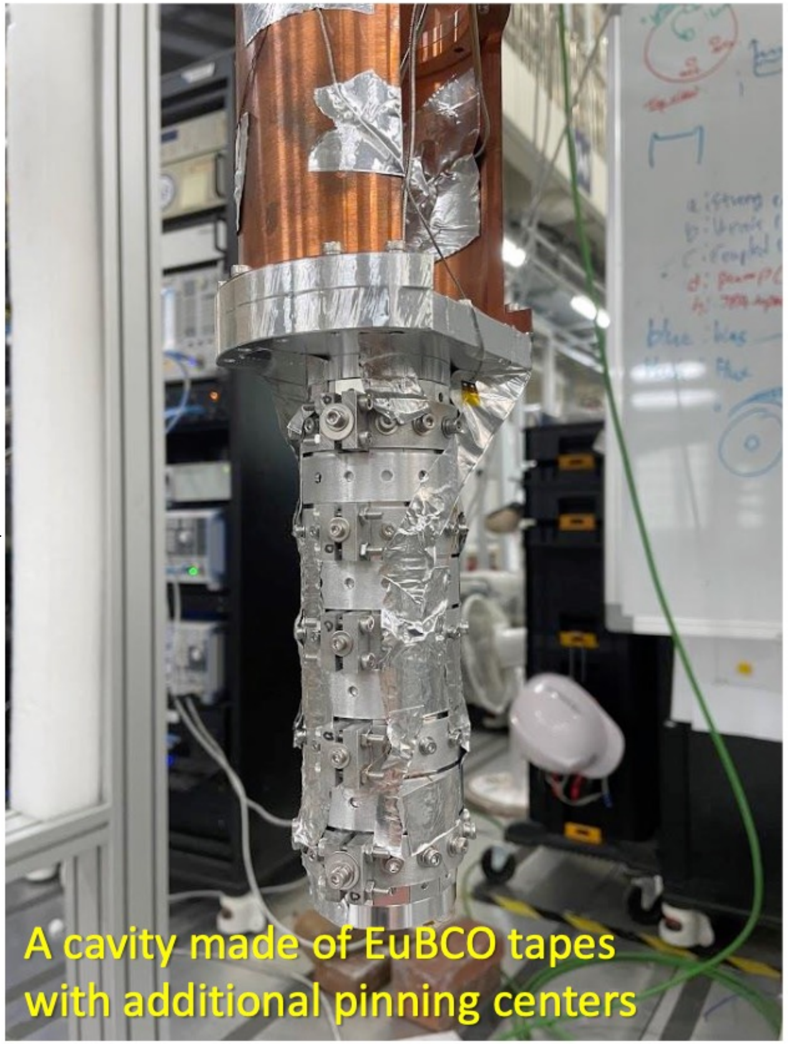


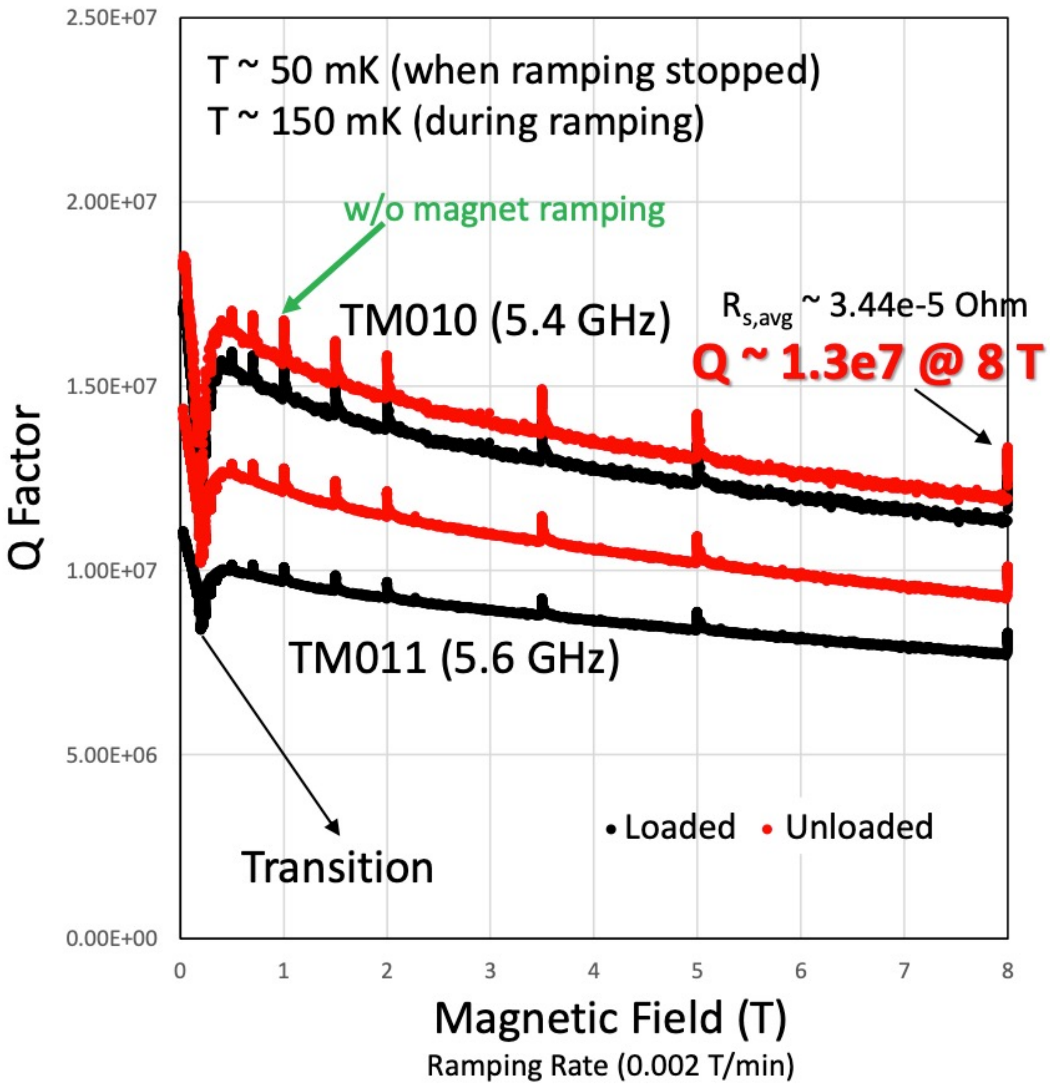
Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T 330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	~ 500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	1.5	2.2	4,500,000 @ 0 T Waiting for Magnet Test
	EuBCO + APC	Hastelloy	0.2	5.4	~ 13,000,000 @ 8 T

Superconducting cavity with Q=13M in large B-field!

3rd Generation Cavity using EuBCO Tapes

CAPP plans to make a 36-liter HTS cavity for CAPP-12TB



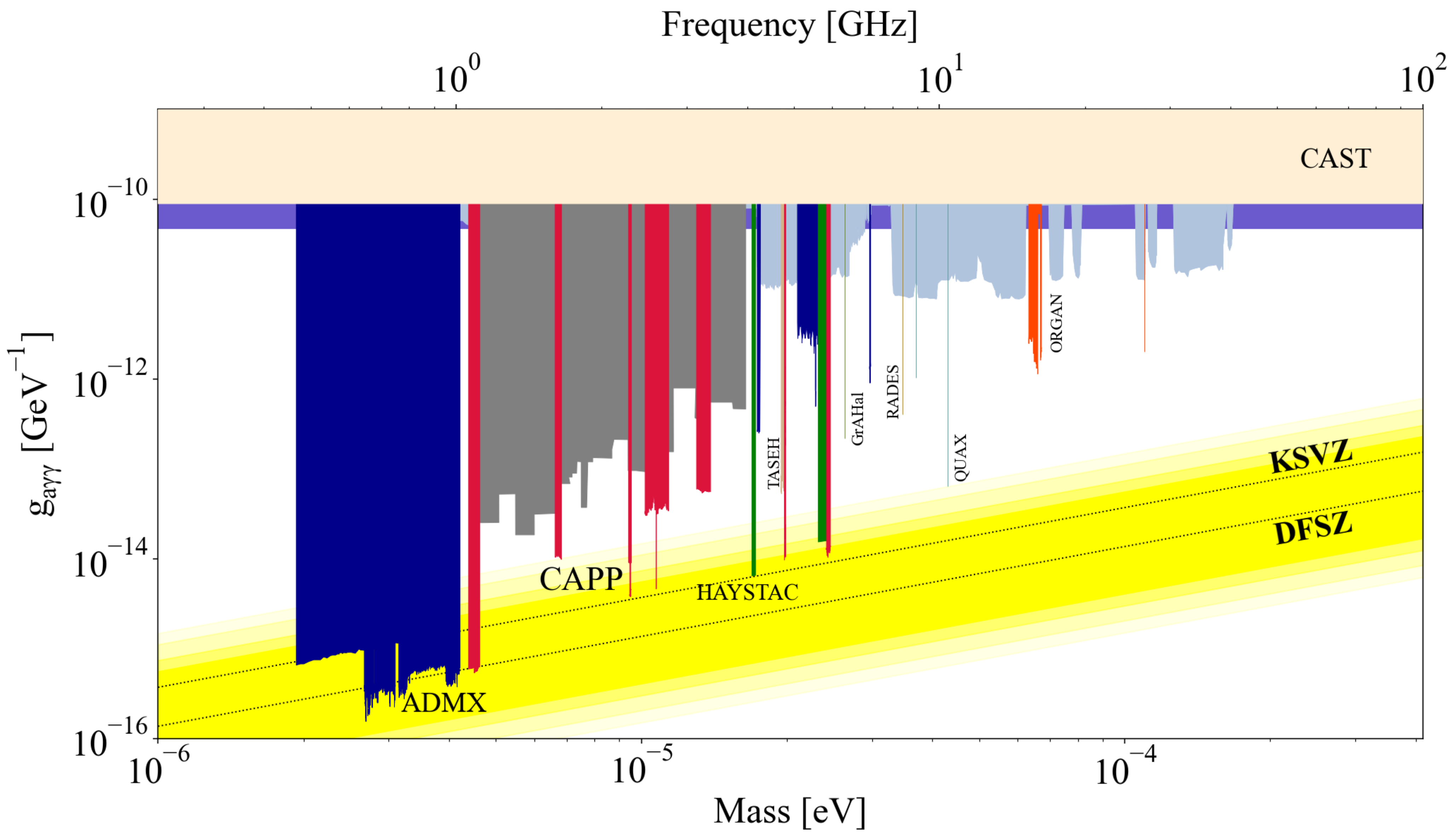


CAPP-PACE Detector

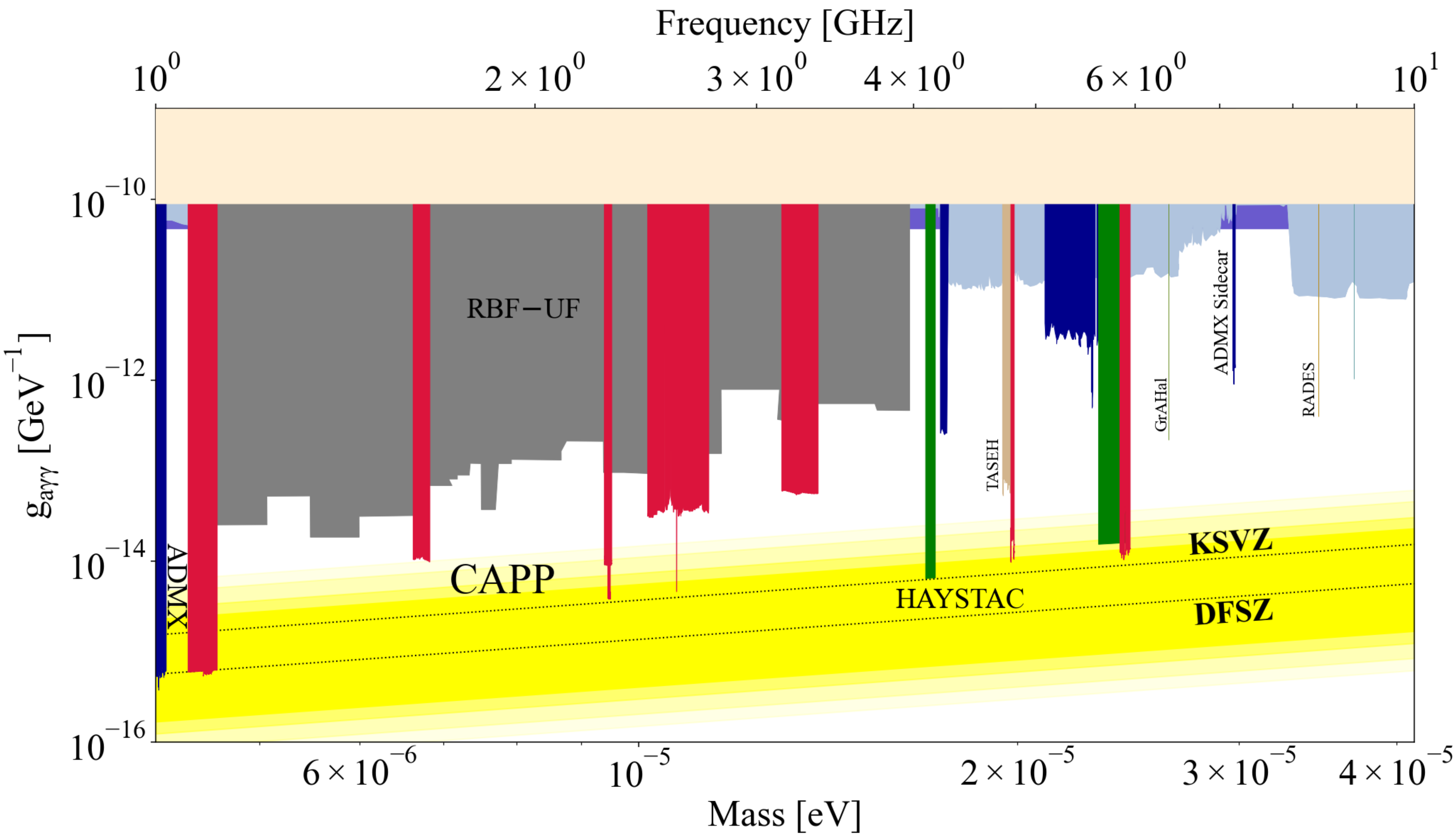
HTS cavities speed up scanning rates

	HEMT Run Phys. Rev. Lett. 126 (2021)	**JPA Run** arXiv:2207.13597, PRL (in process) (Mr. Jinsu Kim *et al.*)	**SC Run** In process
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T	7.2 T	6.95 T
Volume (V)	1.12 L	1.12 L	**1.5 L**
Quality Factor (Q_0)	100,000	100,000	**500,000**
Geometrical Factor (C)	0.51 – 0.66	0.45	0.51 – 0.65
System Noise (T_{sys})	~ 1.1 K	**~ 200 mK**	**~ 180 mK**
Scan Rate (Norm.) $\propto B^4V^2C^2Q_0/T_{sys}^2$	**1**	**18**	**310**

Our place in the world, CAPP in red, now



Our place in the world, CAPP in red, now

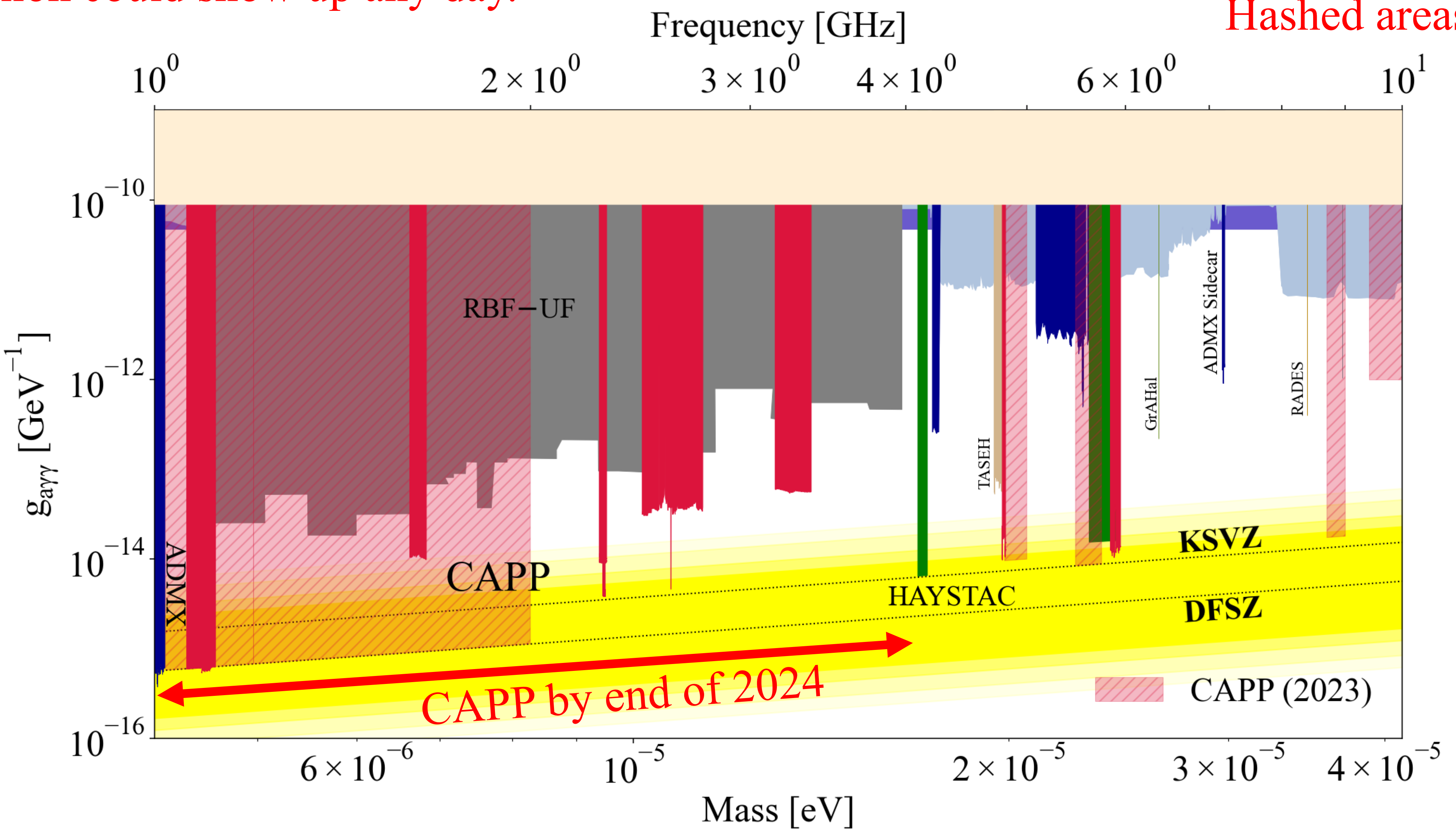


Near future

CAPP's target for 2023, 1-10 GHz

The axion could show up any day.

CAPP's scans in solid red
Hashed areas within 2023



Heterodyne-variance method, 2209.07022

Can always reach QNL performance even when the power detectors (bolometers) are noisy

Variance statistics

Junu Jeong's slide

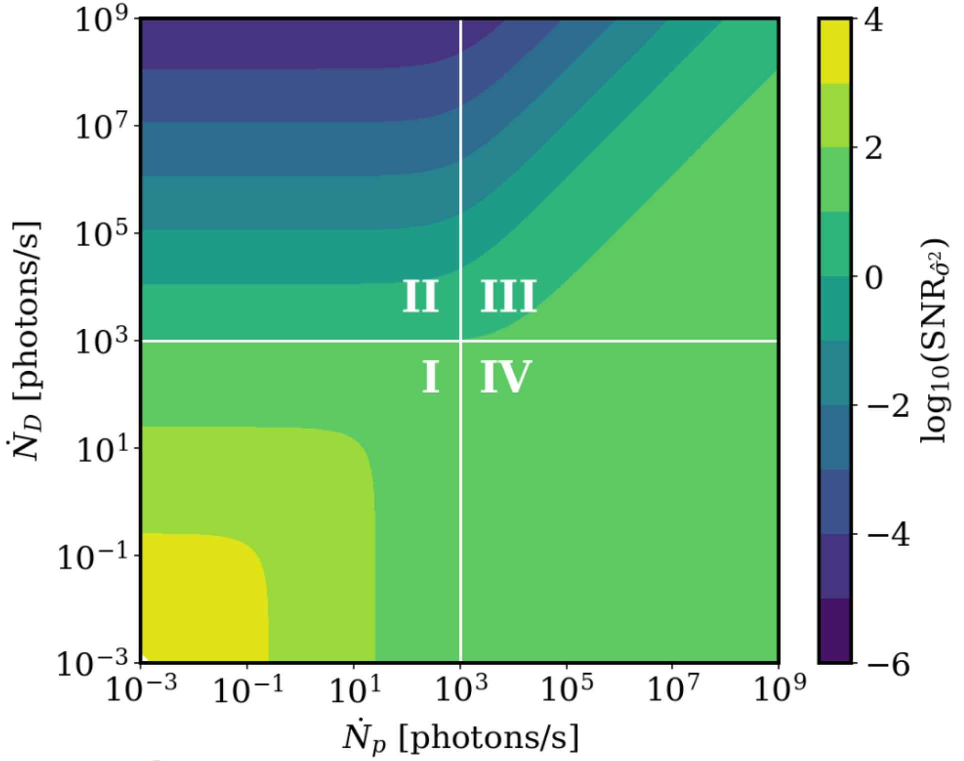
- **SNR of the variance estimator**

  Detector sampling rate: f_s

  Photon rate: $\dot{N} \equiv N \times f_s$

$$\mathrm{S/N}_{\sigma^2} \approx \frac{\dot{N}_s(1+\dot{N}_p/f_s)\sqrt{f_s \Delta t}}{(\dot{N}_D+\dot{N}_p)\sqrt{2+f_s/(\dot{N}_D+\dot{N}_p)}} \rightarrow \frac{\dot{N}_s}{\sqrt{2 f_s}}\sqrt{\Delta t}$$

$\dot{N}_p \gg f_s$



- **Region I:** $\dot{N}_D < f_s,\ \dot{N}_p < f_s$
- **Region II:** $\dot{N}_D > f_s,\ \dot{N}_p < f_s$
- **Region III:** $\dot{N}_D > f_s,\ \dot{N}_p > f_s$

  Injecting probe increases the SNR, converging to $\dot{N}_D|_{eff} \rightarrow 2f_s$
- **Region IV:** $\dot{N}_D < f_s,\ \dot{N}_p > f_s$

  Injecting prboe reduces the SNR

CAPP’s timeline

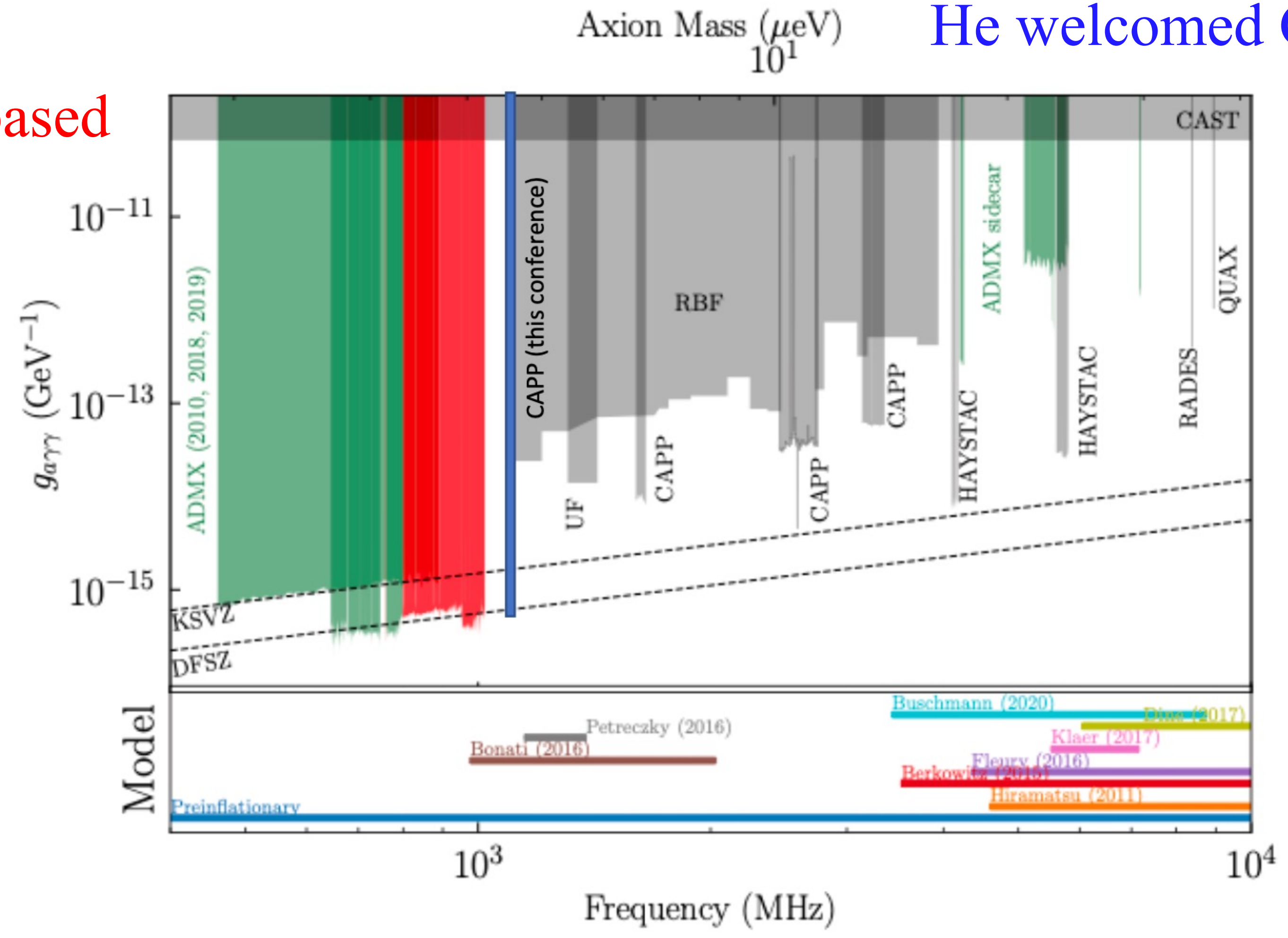
Goal	Sensitivity	Axion fraction of dark matter, assumption	Timeline	Readiness; systems developed or issues under development
Scan 1-2 GHz	Better than 1.5 × DFSZ	100%	By end of 2023, CAPP-MAX	On going; JPAs, cavities
Scan 2-4 GHz	Better than 1.5 × DFSZ	100%	By end of 2024, CAPP-MAX	Preparing; JPAs, cavities
Scan part of 4-8 GHz	KSVZ level	100%	By end of 2024, Smaller systems	Ongoing and Preparing; HTS cavities, metamaterials
Scan part of 8-25 GHz	Few × KSVZ	100%	By end of 2024, Smaller systems	Preparing; Metamaterials, single photon detector
Scan 1-8 GHz	DFSZ	100%	By end of 2027, CAPP-MAX	Preparing; Variance method
Scan 8-25 GHz	KSVZ	100%	By end of 2027, Smaller systems	Developing; Single photon det.
Scan 1-25 GHz	DFSZ	20%	By end of 2032, CAPP-MAX	Developing; Variance method, HTS cavities, single photon det.

Rybka's slide from Patras, August 2022

ADMX 2021 Exclusion - Context

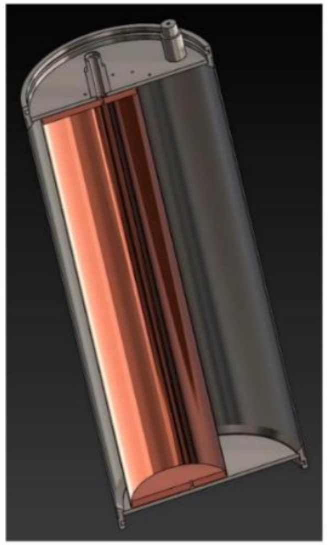
He welcomed CAPP to the DFSZ club!

ADMX: USA-based

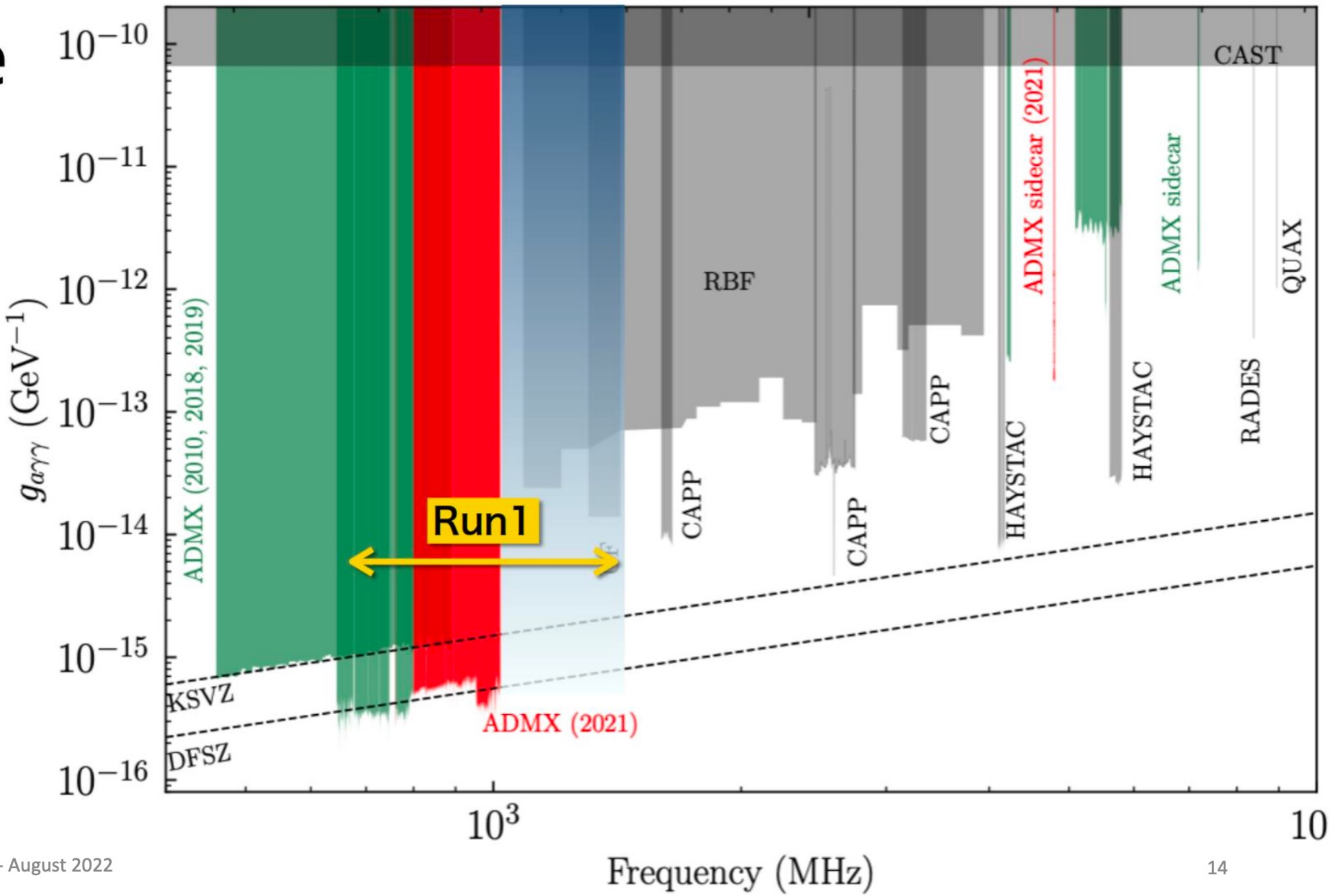


ADMX: Rybka, August 2022

Future Plans



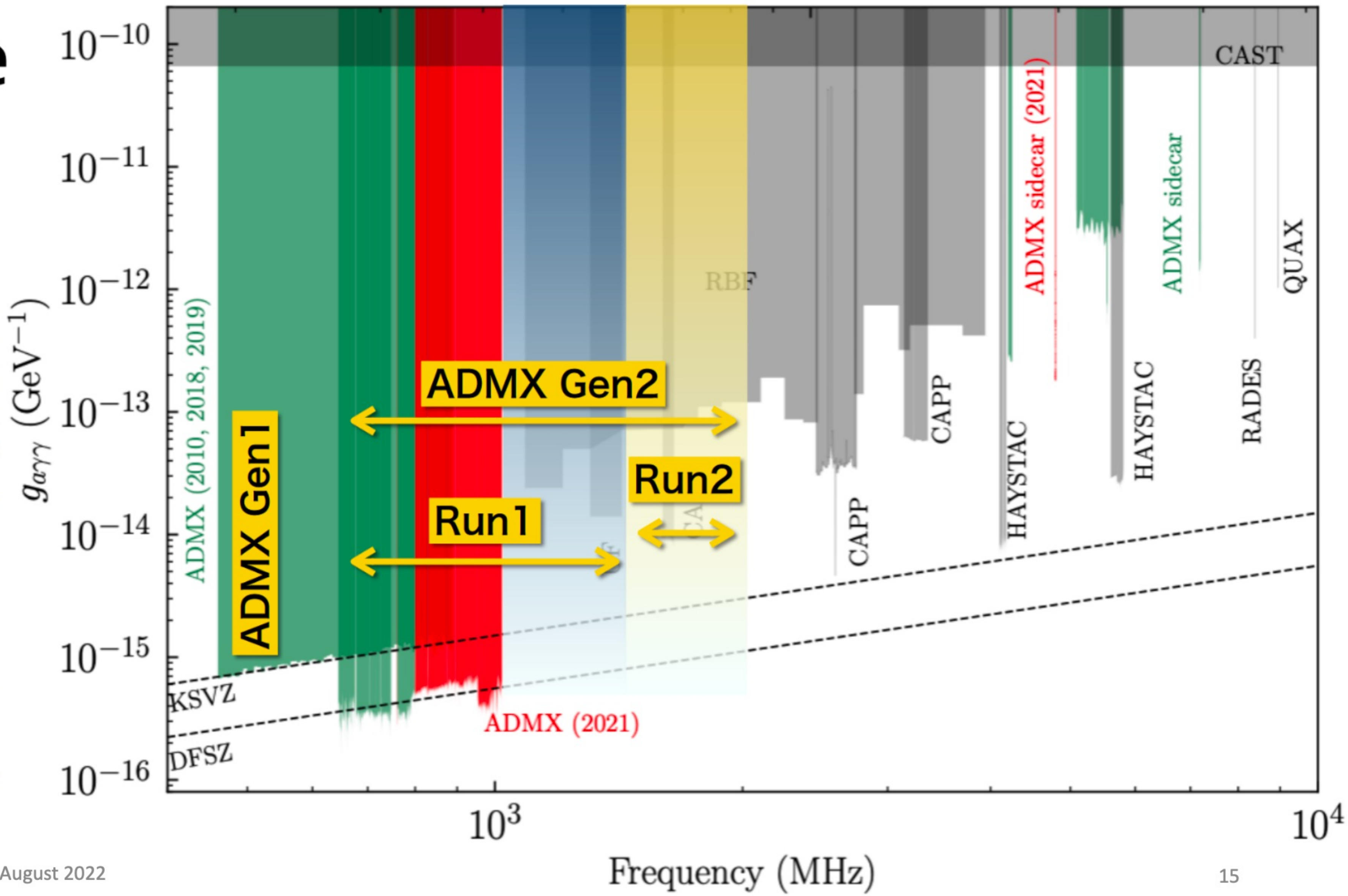
Bigger tuning rod



ADMX: Rybka, August 2022

Future Plans

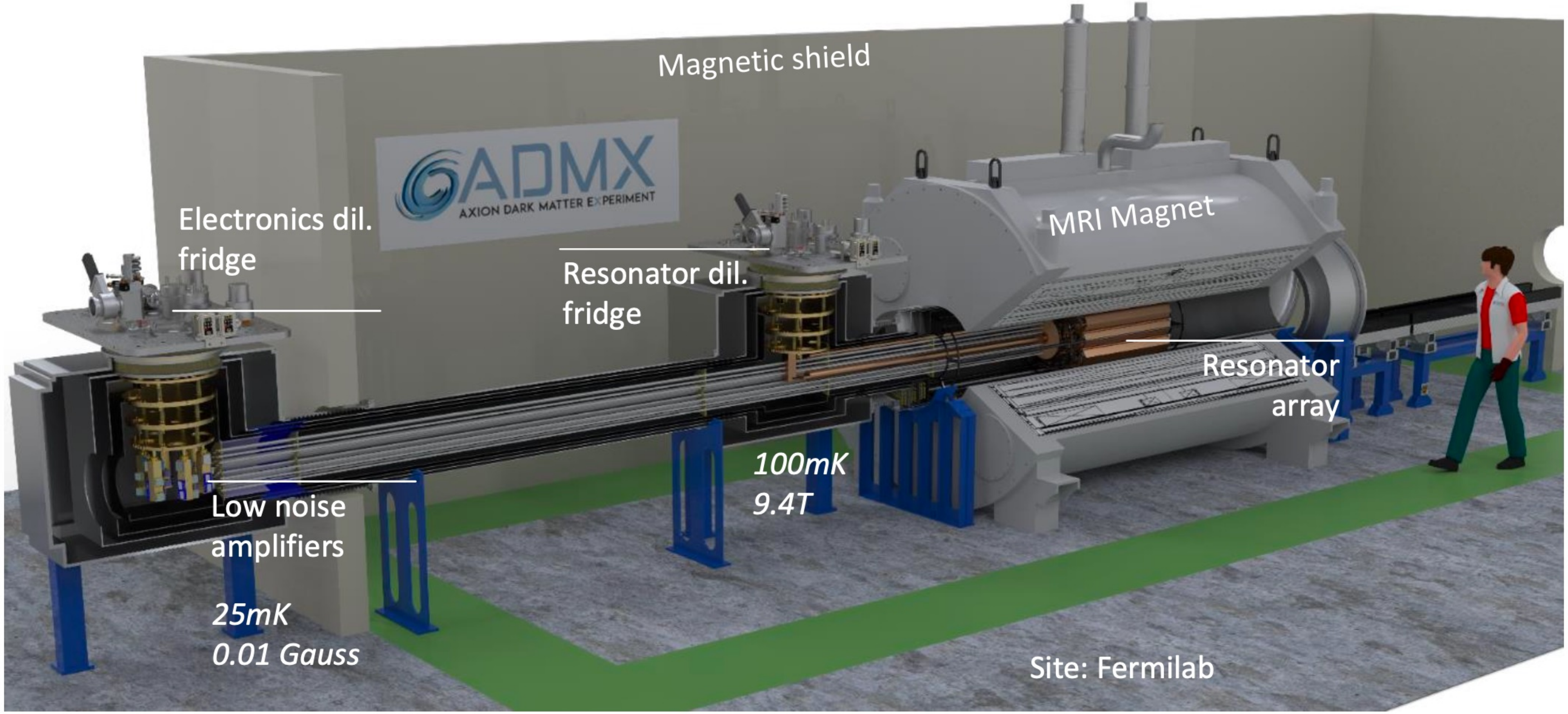
4-cavity array



ADMX: Rybka, August 2022

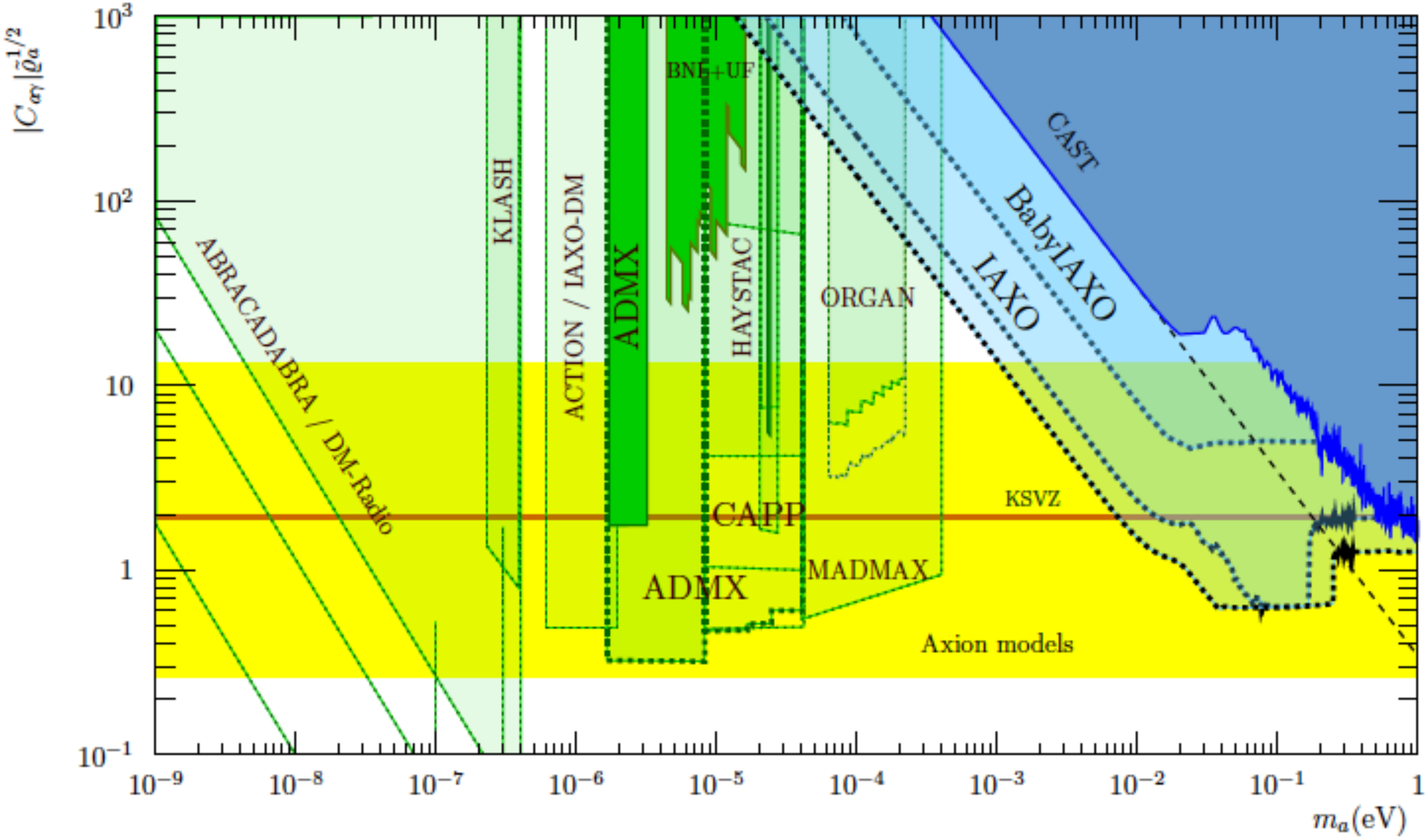
Proposal to DOE

ADMX-EFR – Design Overview



~ 5 × scan speed of current ADMX

Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

>>100 participants, 12th Patras Workshop on AXIONs, WIMPs, and WISPs, Jeju Island/Korea, 20-24 June 2016.

>150 participants, 17th Patras Workshop on AXIONs, WIMPs, and WISPs, Mainz, Germany, 8-12 August 2022.

Accelerator based Precision physics research

- Muon g-2, good physics and training ground

- Storage ring electric dipole moment (srEDM) experiment development

Selcuk Haciomeroglu, CAPP.
Currently at Istinye University, Istanbul

On Kim, PhD from KAIST, Post doc

Zhanibek Omarov, PhD from KAIST

Muon g-2 announcement, what does it mean?

- Physics: >8500 participants dialed in on “zoom” and YouTube channel during the announcement. It was estimated that the muon g-2 news reached >2.7B people.

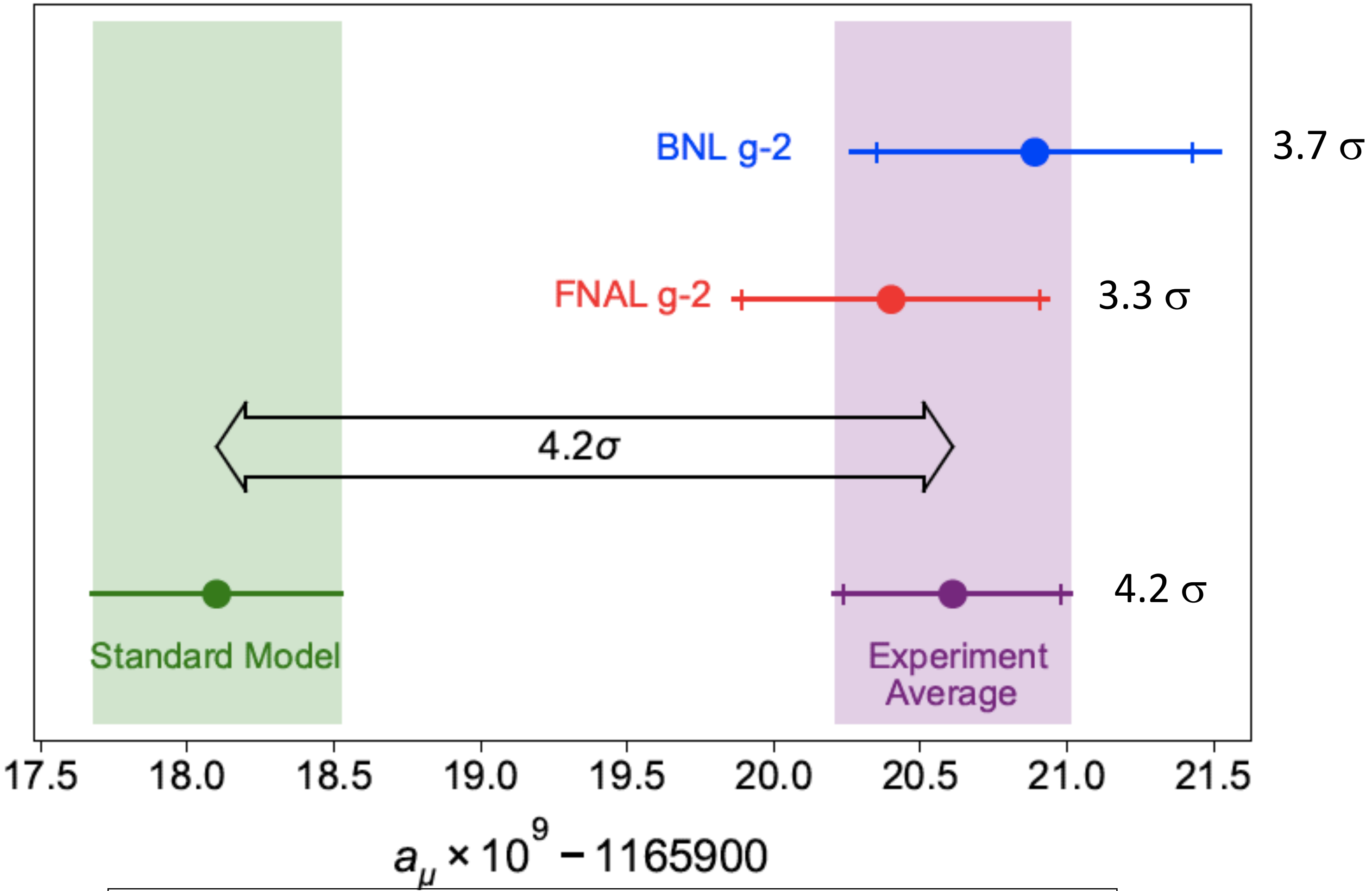
- Blind analysis, meaning the frequency has a constant offset, so you don’t know the result when analyzing. The offset was set by Fermilab people outside the collaboration.

- The result is right on with the BNL experimental value.

- The theory on hadronic contribution based on e^+e^- and lattice are at odds. There’s significant work towards the theory value.

Experiment and theory 4.2 sigma (theory based on e^+e^- data)

$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm})$$

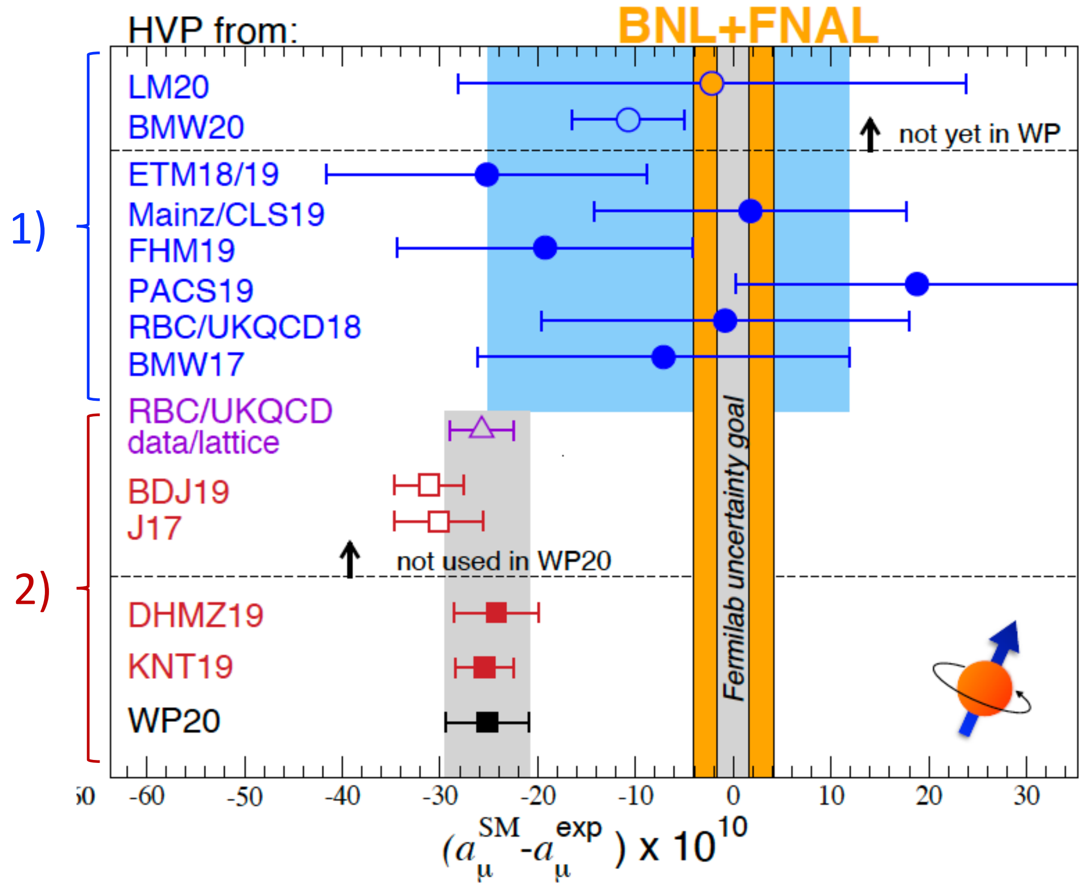


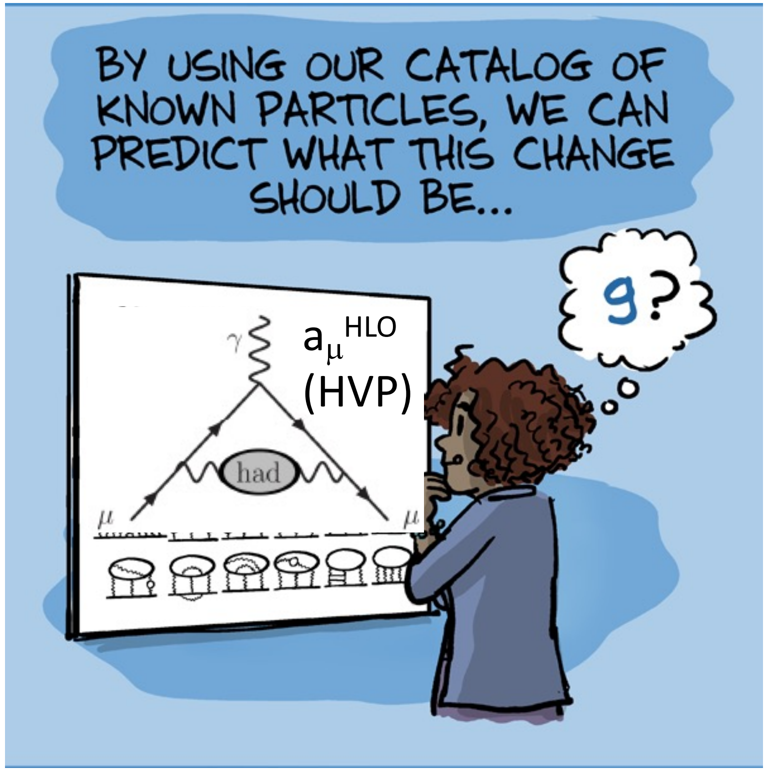
$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

Is the SM calculation “correct”?

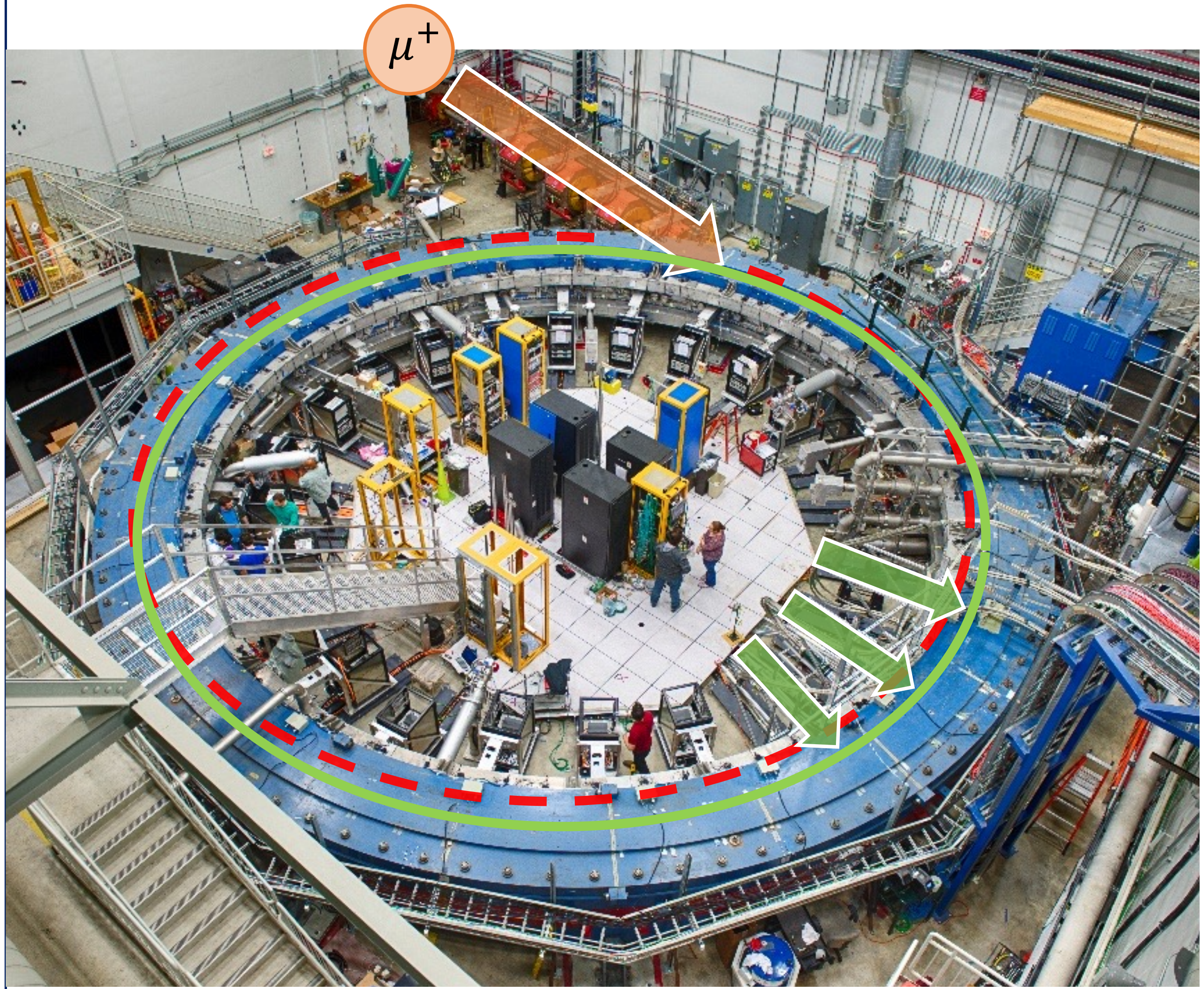
- The contribution from the strong interaction (Hadronic Vacuum Polarization, **HVP**) is challenging
- Tension between two different methods: 1) “lattice calculation”; 2) “dispersive approach”
- Ongoing work to clarify the tension

Graziano Venanzoni’s slide, Liverpool, Nov. 2022



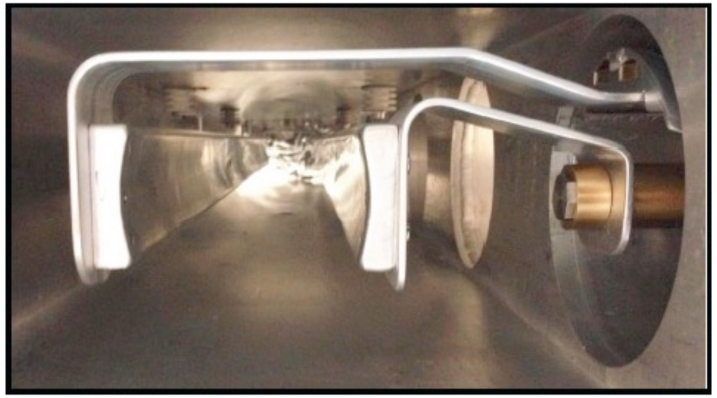


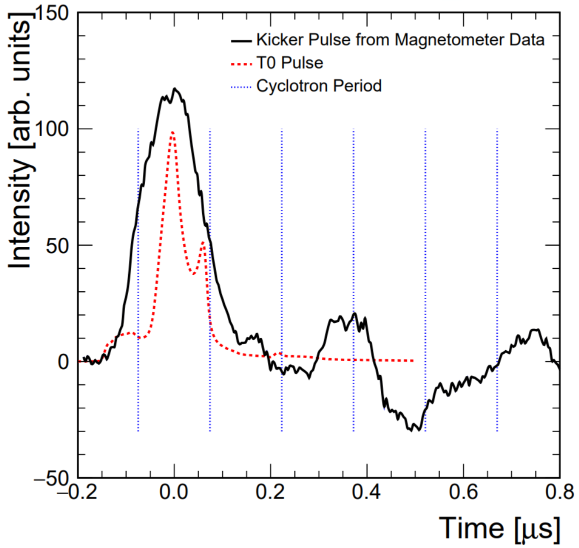
Overview of Muon $g-2$ Experiment at Fermilab (E989)



▶ Kick

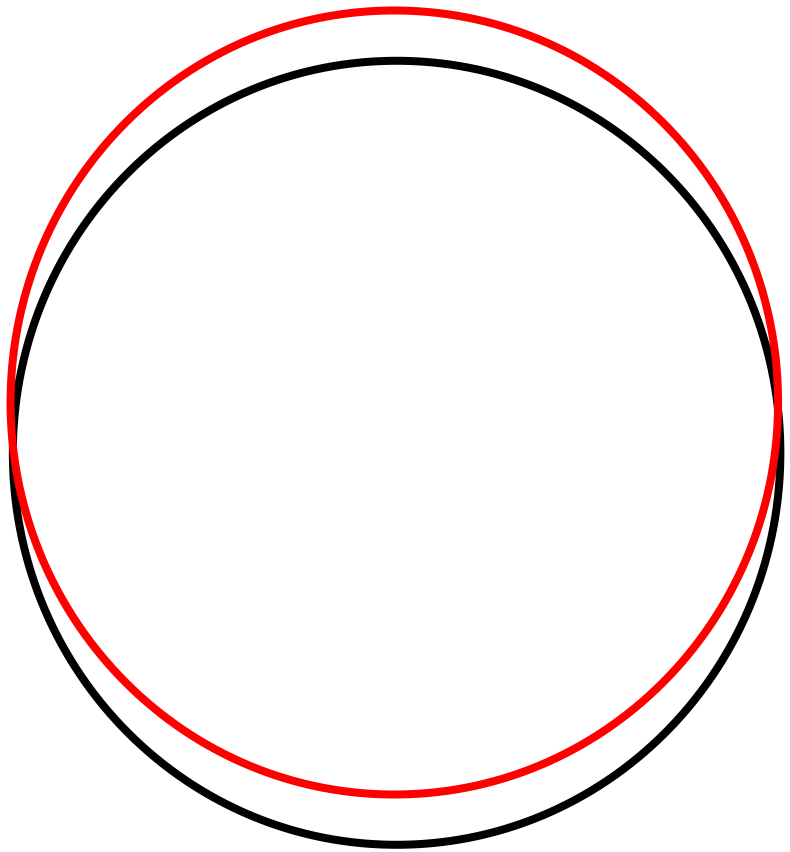
- Muons are kicked onto the design orbit by the fast non-ferric **kicker magnet** system.





Coherent betatron oscillations influence the g-2 phase

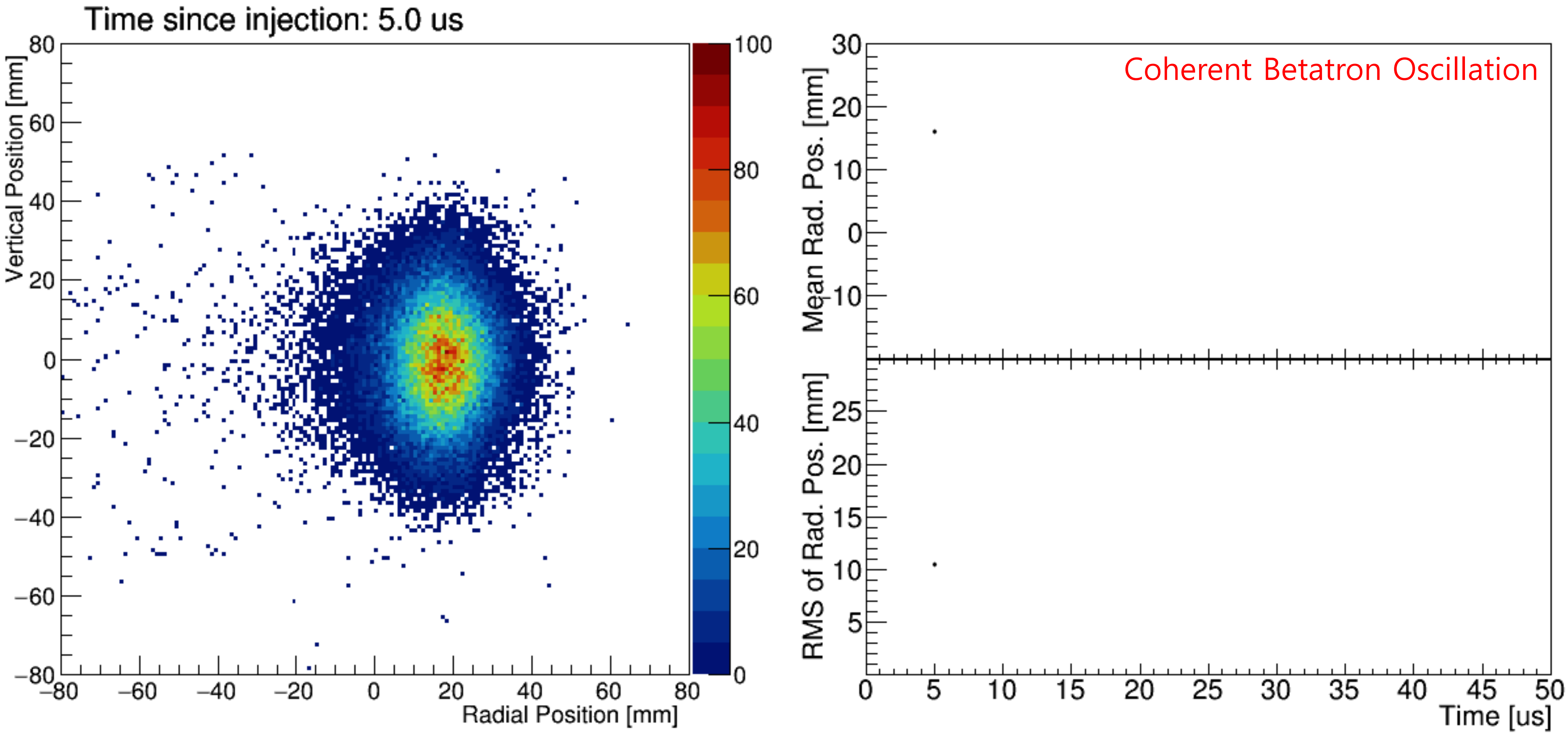
- CBO frequency $f_{cbo} = f_c\left(1 - \sqrt{1-n}\right)$. Radial oscillations, through aliasing, became a problem
- A very high-frequency, cascaded through various effects down to g-2 frequency



Straw trackers

▶ Straw trackers

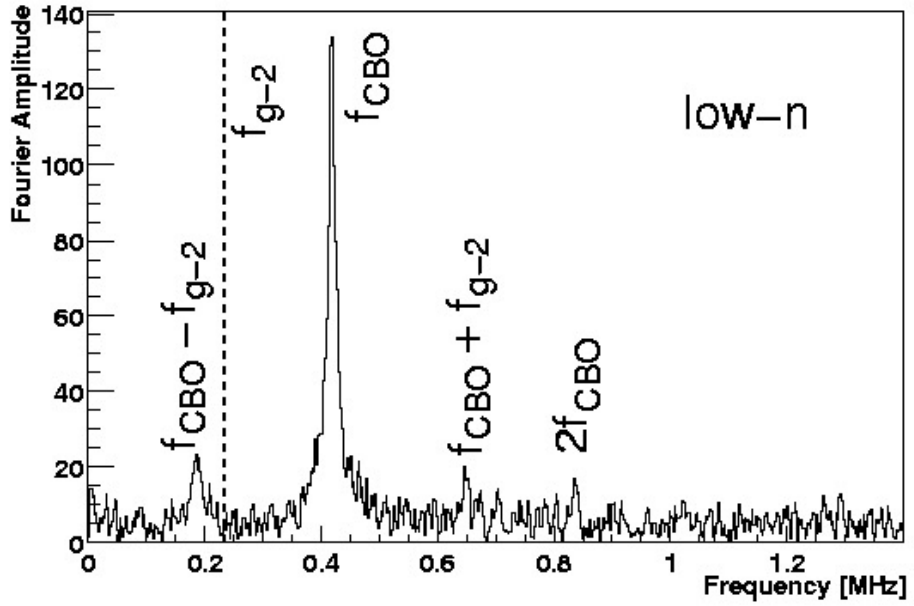
- Measures trajectories of the decay positrons and extrapolates to find the muon distribution.

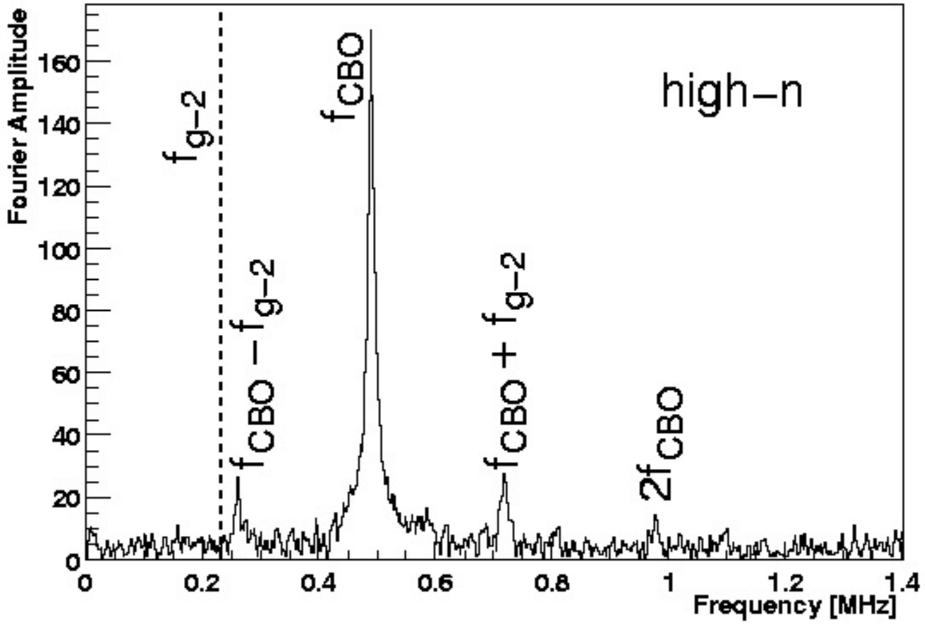


CBO in the 2001 Data Set

$$f(t) = N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

Residuals from fitting with the 5-parameter function





CBO in the Data Set

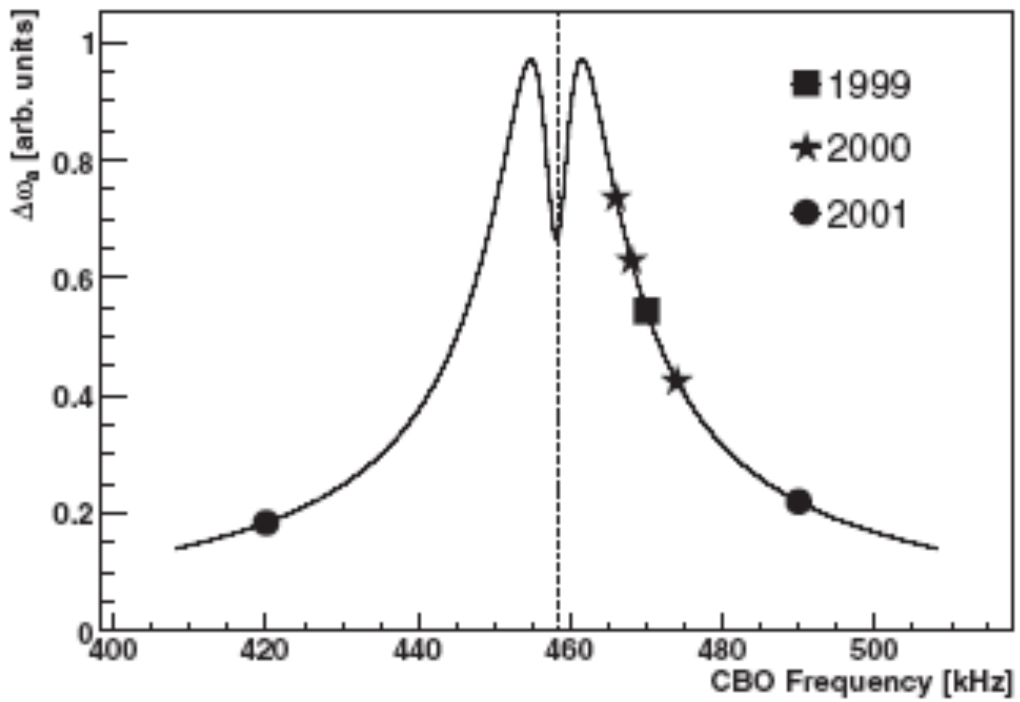
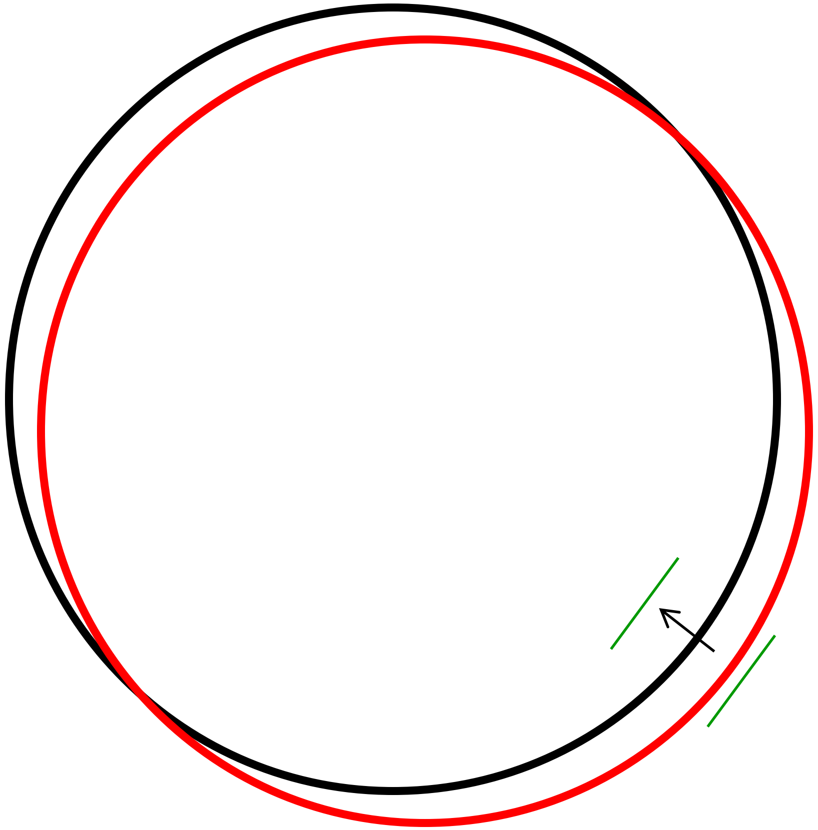


FIG. 36. The relative pull ($\Delta\omega$) versus the CBO modulation frequency *if not* addressed by the fitting function. A typical full vertical scale is several ppm; the actual scale depends on the specifics of the fit and the data set used. The R00 data were acquired under run conditions in which ω_a was very sensitive to CBO. This sensitivity was minimized in the R01 period where low- and high-n subperiods, each having CBO frequencies well below or above twice the $(g-2)$ frequency, were employed.

The effect depends on the CBO frequency

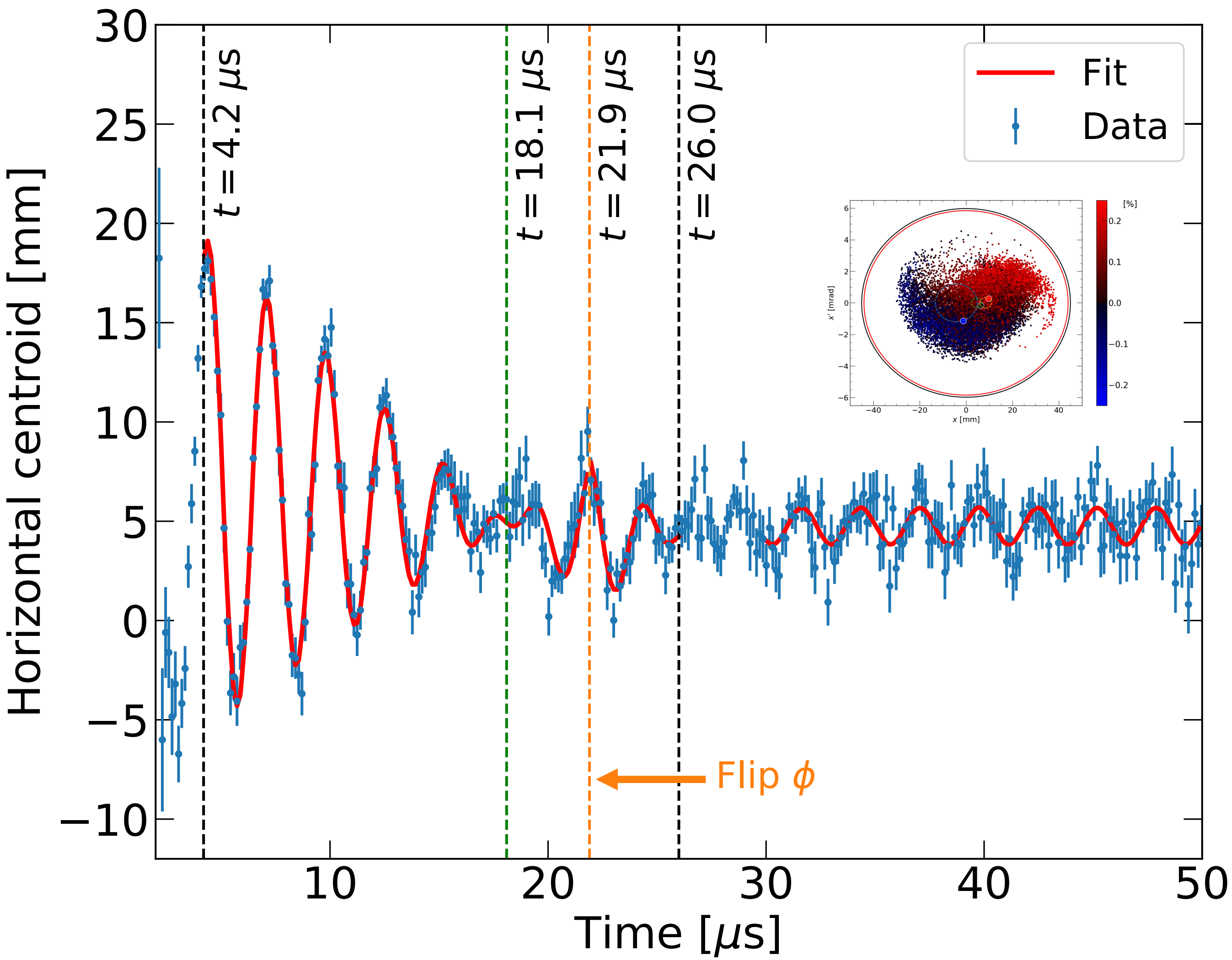
Frequency pull cancels integrating all detectors around the ring (assuming perfect symmetry)

Yuri Orlov suggested to fix it by applying RF: same frequency as CBO but opposite phase: We applied his method at Fermilab; it worked.



PE plates are 1m long
Apply rf E-field 470KHz

RF CBO amplitude reduction (data from muon g-2 experiment)

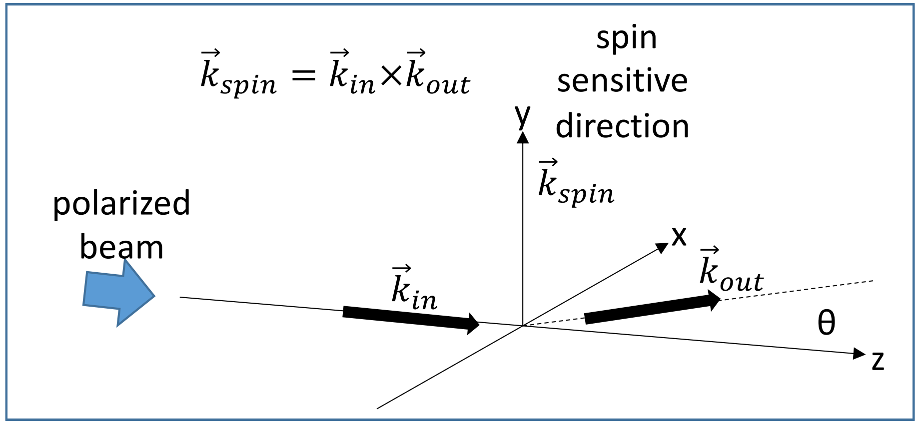


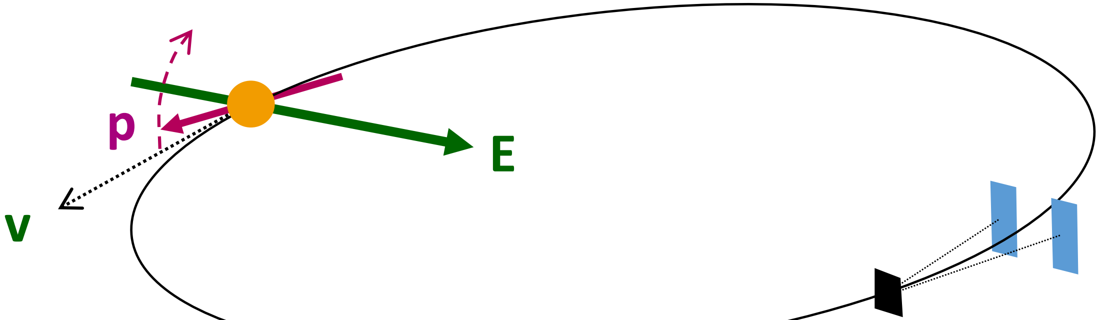
On Kim *et al*, New J. Phys. **22** (2020) 063002

Reduced CBO by an order of magnitude and muon losses by a factor of five

Applied in Run 5 and 6 (current)

Storage ring Electric Dipole Moments



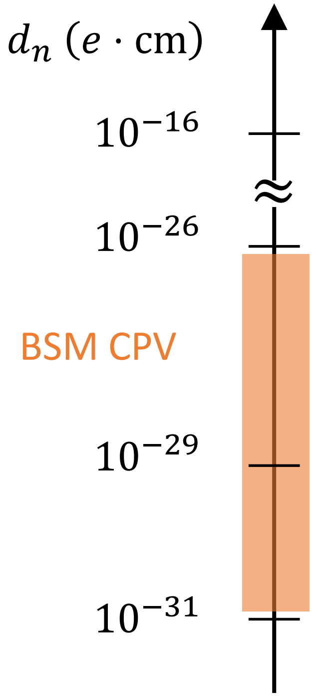


Frozen spin method:

- Spin aligned with the momentum vector
- Radial E-field precesses EDM/spin vertically
- Monitoring the spin using a polarimeter

Physics motivation

- Big question: Is there BSM CPV?



"Natural" order from Strong CPV $\bar{\theta} \approx \mathcal{O}(1)$

Experimental upper limit ⇒ Strong CP problem: $\bar{\theta} \lesssim 10^{-10}$

Projected pEDM sensitivity.

Physics reach of $d_p \approx \mathcal{O}(10^{-29})\ e \cdot \mathrm{cm}$:

1. Three orders of magnitude improvement in $\bar{\theta}$.
2. Sensitive to $M_{\mathrm{NP}} \approx \mathcal{O}(10^{1-3})$ TeV.
3. Baryogenesis ($\approx 10^{-28}\ e \cdot \mathrm{cm}$ expected in MSSM).
4. Two-loop Higgs coupling: $\tan \phi_{\mathrm{NP}} \approx \mathcal{O}(10^{-4})$.

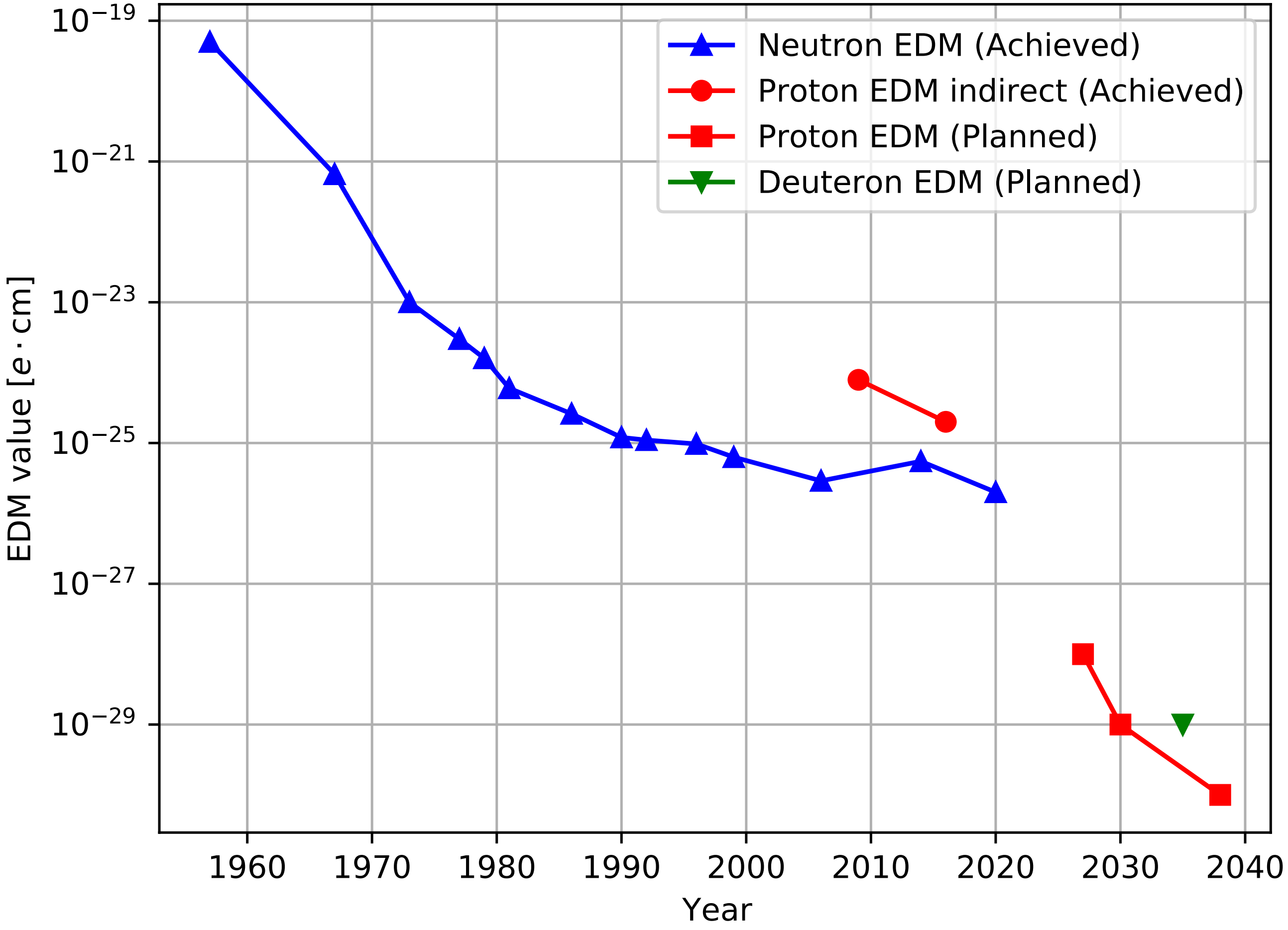
Upper bound from the SM expectation (Weak CPV: CKM & PMNS)

- Storage ring pEDM experiment
  - First "direct" measurement/constraint of d_p with improvement by 10^3 from the best current d_n limit.
  - Complementary to atomic & molecular EDM experiments.
  - Dedicated ALP/vector dark matter or dark energy search.

John Benante, Bill Morse in AGS tunnel, plenty of room for the EDM ring.

Timeline

- Snowmass/white paper. BNL & srEDM to produce a technically advanced proposal. P5
- CDR, proposal/TDR, prototype/string-test, ring construction (3-5 years), storage (2-3 years) to first publication
- Effort scale similar to muon g-2 experiments. Interesting results within a decade.



So, what works?

- IBS-CAPP has achieved greatness in less than 10 years operation. What's the recipe? Combine young people's innovation with older people's experience…

- Have a great research subject with high physics potential. Lots of patience.
- Challenging (important to set a successful path with small steps-celebrate success)
- Adequate funding (challenging R&D fails most of the time…!)
- Provide ownership, favor independence, confidence building measures, while protecting them from failures. Establish decision making process, stick with it!
- Checks and balances, without burdening them with reviews, exclude gossip.
- Prepare for reviews with simple/few messages (understand your reviewers' level, a reviewer from an irrelevant field or no experience can do immense damage).
- Regular communication with the leadership of your institution, work as a team.
- The political parties need to declare cease fire and work together

Summary

- IBS-CAPP has achieved all its R&D goals and now could cover
  - 1-4 GHz axion freq. in the next 2-years (DFSZ)
  - 4-8 GHz within the next 5-years (DFSZ)
  - 1-25 GHz within the next 10 years, even for 20% of axions as dark matter

- HTS-based cavities and single photon detectors can bring a phase-transition in high-frequency axion cavity searches. Heterodyne-variance method is a bridge…
- Large volume dielectric/metamaterial microwave cavities are sensitive and able to reach the high frequency axions
- The international effort is intensified, promising to cover all the available axion dark matter parameter space within the next 10-20 years.
- Storage ring EDM has excellent prospects, completed a comprehensive systematic errors study, Snowmass req. for a strong proposal at BNL, now at P5

Extra slides

Axion dark matter results using an LHC dipole magnet at CERN

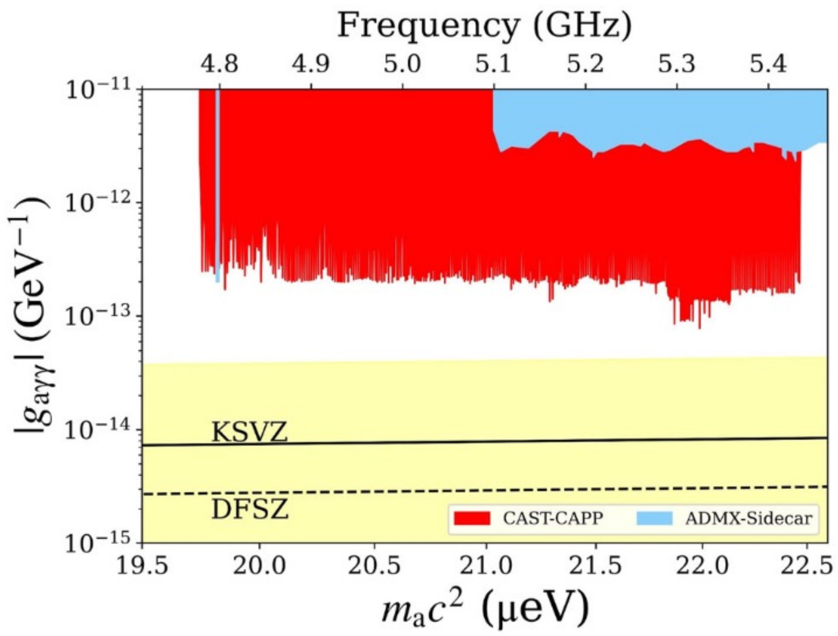


Fig. 5 | CAST-CAPP exclusion limit on the axion-photon coupling as a function of axion mass at 90% confidence level (left), and compared to other axion search results[10,25,30,34–41] within the mass range 1–25 μeV (right). The higher

nature communications

Article https://doi.org/10.1038/s41467-022-33913-6

Search for Dark Matter Axions with CAST-CAPP

Published online: 19 October 2022

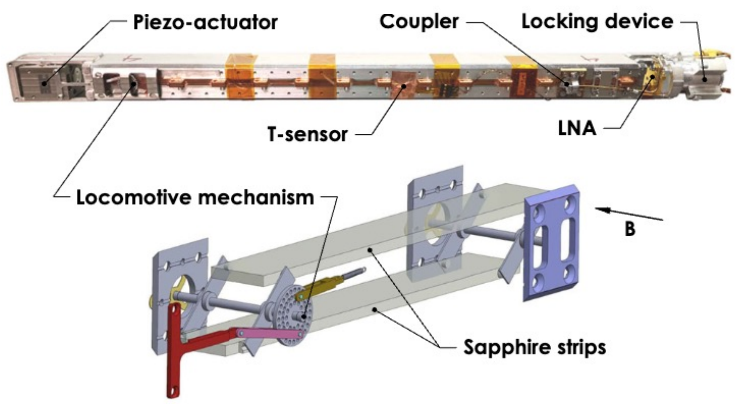
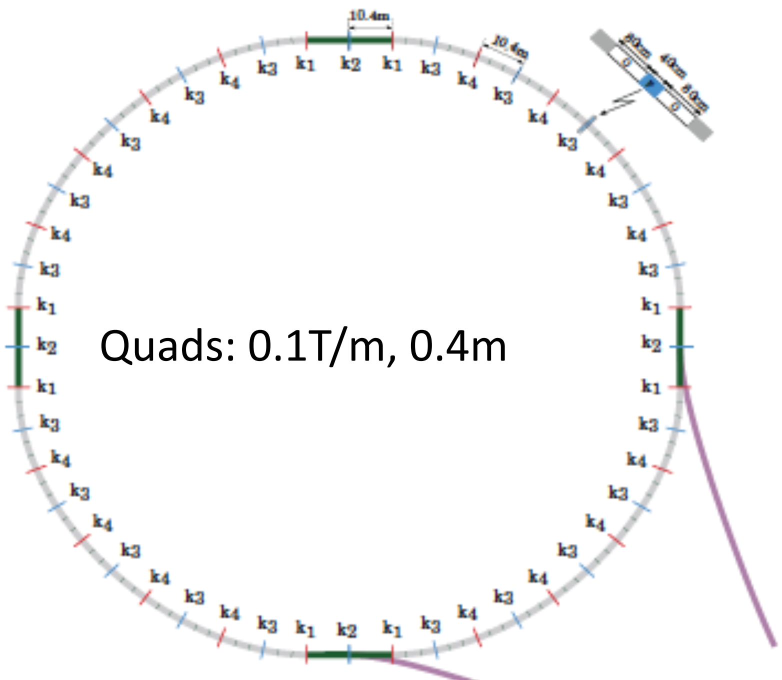
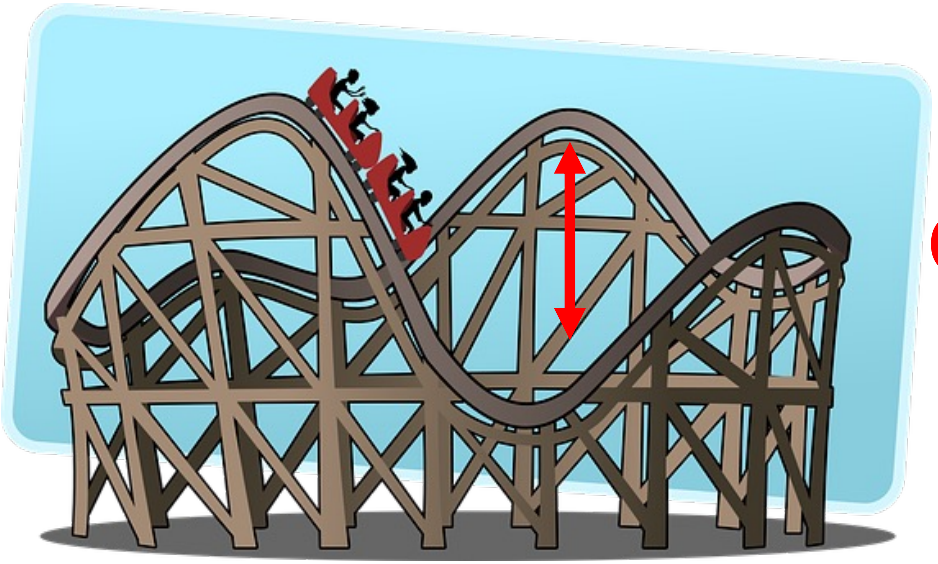


Fig. 1 | A photograph of the elements of a single cavity assembly (top) and a technical drawing of CAST-CAPP tuning mechanism with the two sapphire strips (bottom). The static B-field is shown by the arrow and is parallel to the two axes of the tuning mechanism.

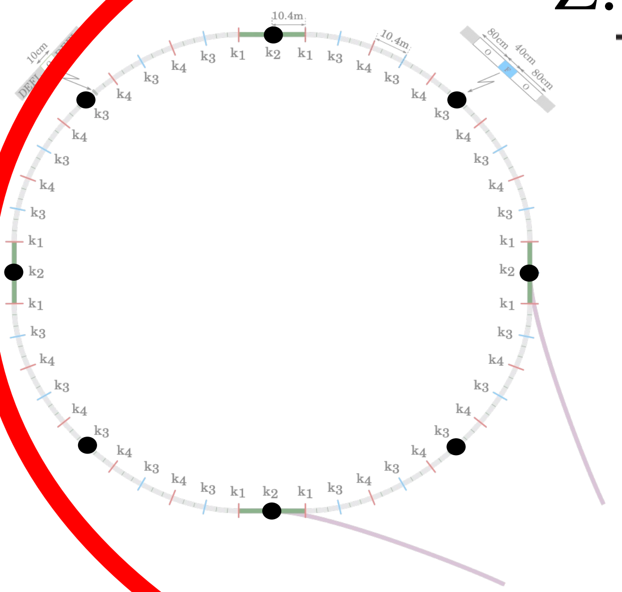
Ring planarity:
The average vertical speed in deflectors needs to be zero!

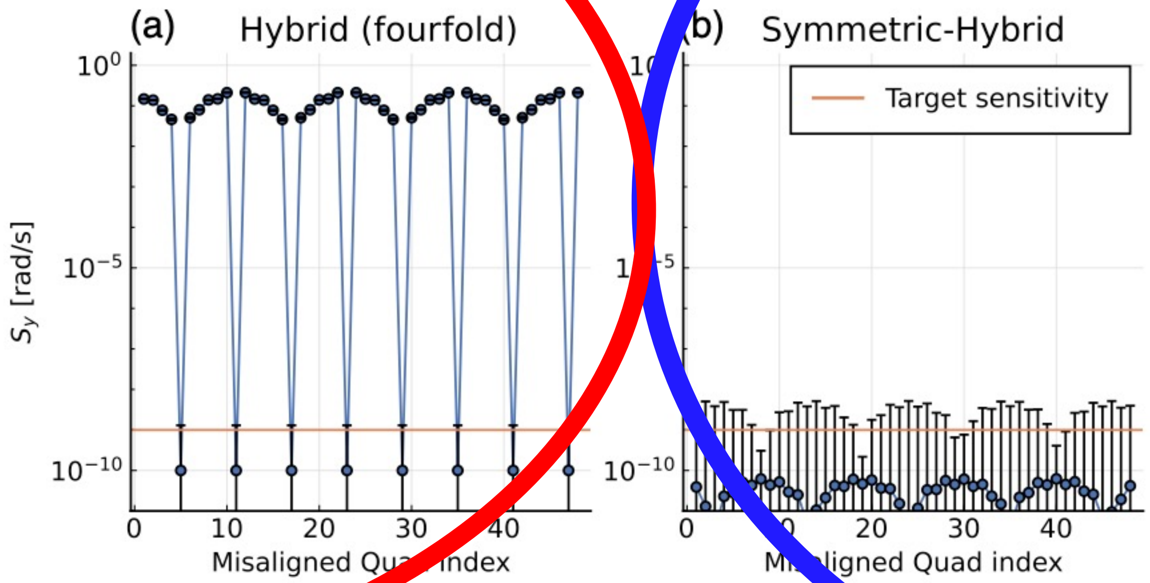


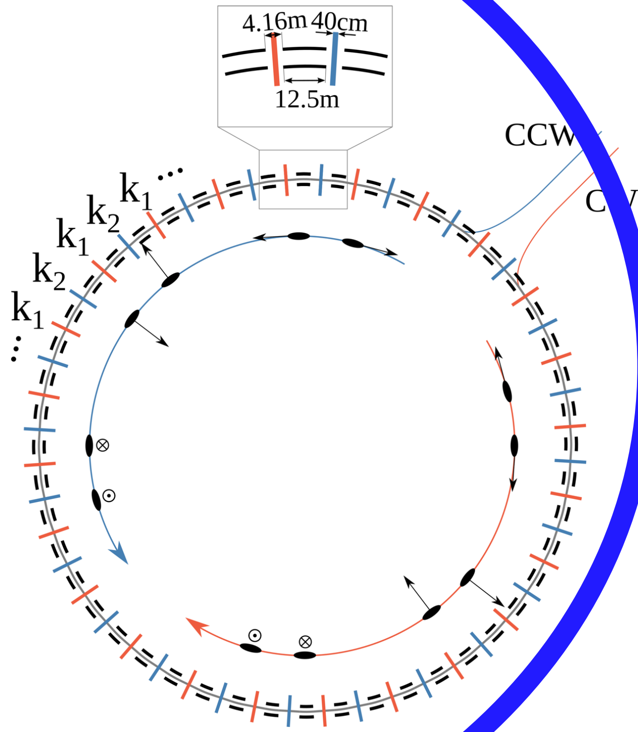


Hybrid, symmetric lattice storage ring. Great for systematic error reduction.

Z. Omarov *et al.*, PHYS. REV. D **105**, 032001 (2022)







Sensitivity of radially polarized beam (sensitive to V. Dark Matter/Dark Energy, P. Graham *et al.*, PRD, 055 010, 2021), most sensitive to vertical velocity problem

Effect as a function of azimuthal harmonic N

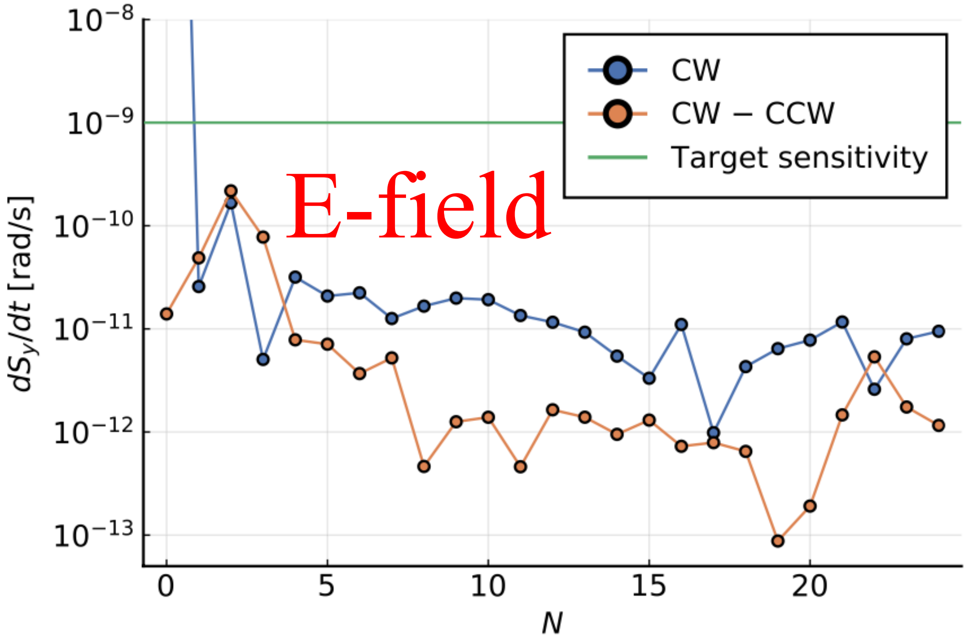


FIG. 7. *Longitudinal polarization case* $S_s = 1$, sensitive to EDM. Vertical spin precession rate vs $E_y = 10$ V/m field N harmonic around the ring azimuth. For $N = 0$, the precession rate for the CW (or CCW) beam is around 5 rad/s. The difference of the precession rates for CR beams (orange) is below the target sensitivity for all N. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

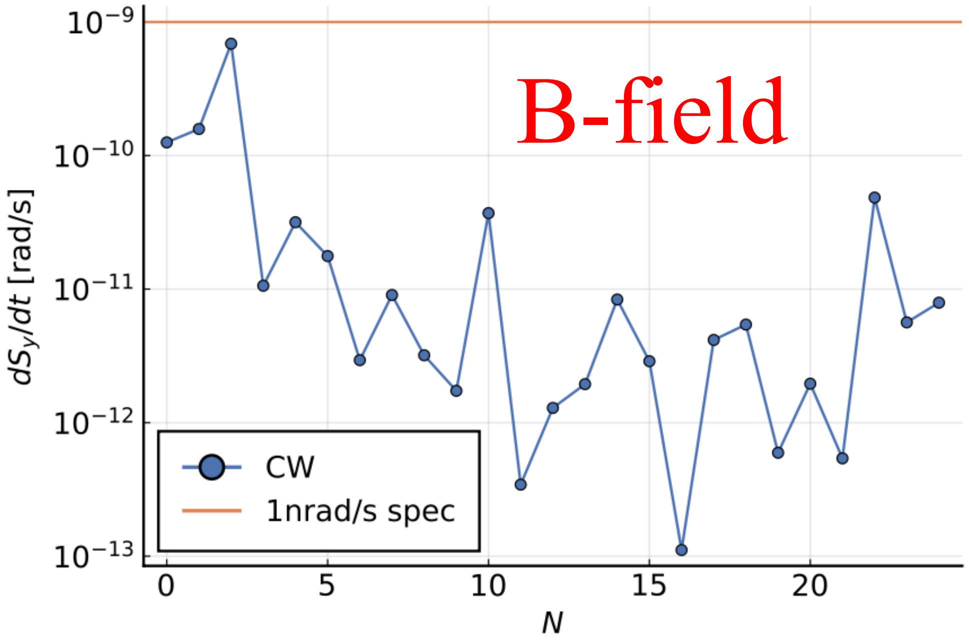


FIG. 8. *Longitudinal polarization case* $S_s = 1$, *CW beam only.* Vertical spin precession rate vs $B_x = 1$ nT field N harmonic around the ring azimuth. The magnetic field amplitude is chosen to be similar to beam separation requirements in Sec. IV A, and more than $B_x = 1$ nT splits the CR beams too much. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

CAPP's flagship experiment status and plans

- In spring 2022, covered 20MHz at DFSZ sensitivity, scanning rate at 1.4 MHz/day @ 1.1 GHz with our LTS-12T/320mm magnet from Oxford Instr.
- Covered ~60MHz at DFSZ sensitivity in September 2022, scanning at 4 MHz/day
- Target 1-2 GHz by the end of 2023 at 3 MHz/day.
- Target to cover 1-4 GHz within the next two years at DFSZ sensitivity.

Is the axion quality factor (10^6) the limit?

It depends on the noise temperature. For high-frequency, single photon detection is everything!

Revisiting the detection rate for axion haloscopes

To cite this article: Dongok Kim *et al* JCAP03(2020)066

Is the axion quality factor (10^6) the limit?

It depends on the noise parameter: $\lambda \equiv T_{\mathrm{add}}/T_{\mathrm{eff}}$

Single photon detector wins big!

Dongok Kim *et al* JCAP03(2020)066

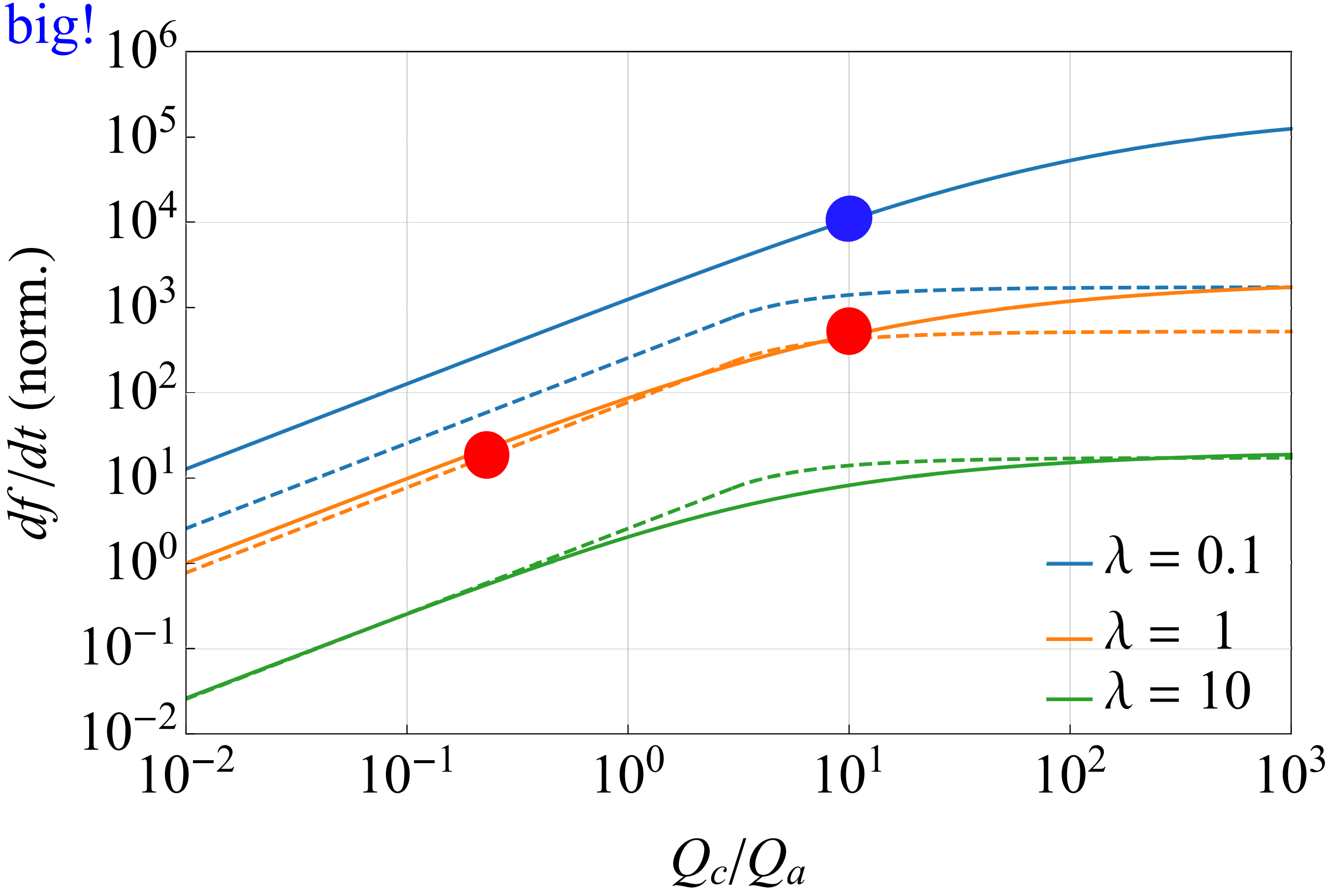


Figure 6. Comparison of the scanning rate between the original (eq. (1.4)) and revised (eq. (5.2)) calculations as a function of normalized cavity quality factor, Q_c/Q_a, for three different values of λ, the relative noise contribution. The former and the latter estimations are represented by dashed and solid lines, respectively.

Heterodyne-variance method, Omarov, Jeong, YkS, 2209.07022

Injecting photons into the microwave cavity can enhance the axion detection rate

System Noise Temperature

Adapted from Junu Jeong's slides

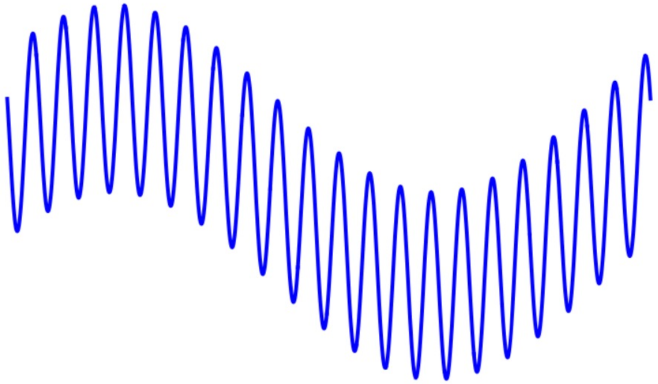
- **Noise Sources**

$$T_{\text{sys}} = \boxed{T_{\text{thermal}}} + \boxed{T_{\text{amplifier}}} = \frac{hf}{k_B}\left(\frac{1}{\exp[hf/k_B T_{\text{phy}}]-1}+\frac{1}{2}\right) + T_{\text{amplifier}}$$

Shot noise (Randomness of Amplification)

Bosonic statistics + Zero-point fluctuation

Dilution Refrigerator sufficiently reduces T_{thermal} *down to the limit* $(0.5\,hf)$



- **Amplifier Noise** [1]

$$T_{\text{amplifier}}^{\text{current best}} \approx 1.2\,hf, \quad T_{\text{amplifier}}^{\text{limit}} = 0.5\,hf$$

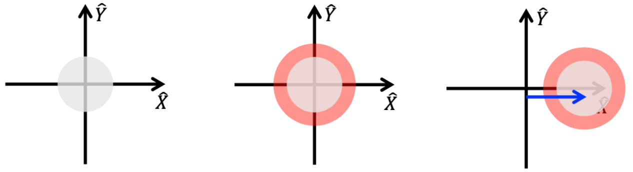
- **Heterodyne**

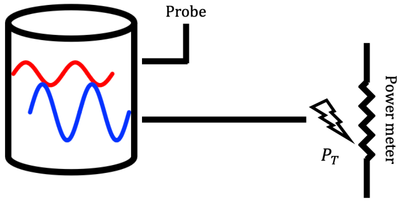
Mixing two frequencies

$$\propto \frac{1}{2}E_{\text{sig}}^2 + \frac{1}{2}E_{\text{LO}}^2 + 2E_{\text{sig}}E_{\text{LO}}\cos(\omega_{\text{sig}}t+\varphi)\cos(\omega_{\text{LO}}t)$$

Heterodyne haloscope

- **Assuming the axion and the probe are *the same frequency but random phase***
  - Thermal noise + Axion + Probe





⇒ Injecting the probe simply shifts the signal in IQ plane

⇒ It does not change the signal-to-noise ratio in IQ plane

Heterodyne-variance method, 2209.07022

Intermediate method before low-noise single photon detection

Comparisons

Junu Jeong's slide

- **SNR comparison with Single Photon Detector**

$$\mathrm{S/N}_{\sigma^2} \approx \frac{\dot{N}_s}{\sqrt{2f_s}}\sqrt{\Delta t} \qquad \mathrm{S/N}_{\mu} \approx \frac{\dot{N}_s}{\sqrt{\dot{N}_{\mathrm{th.}} + \dot{N}_D}}\sqrt{\Delta t}$$

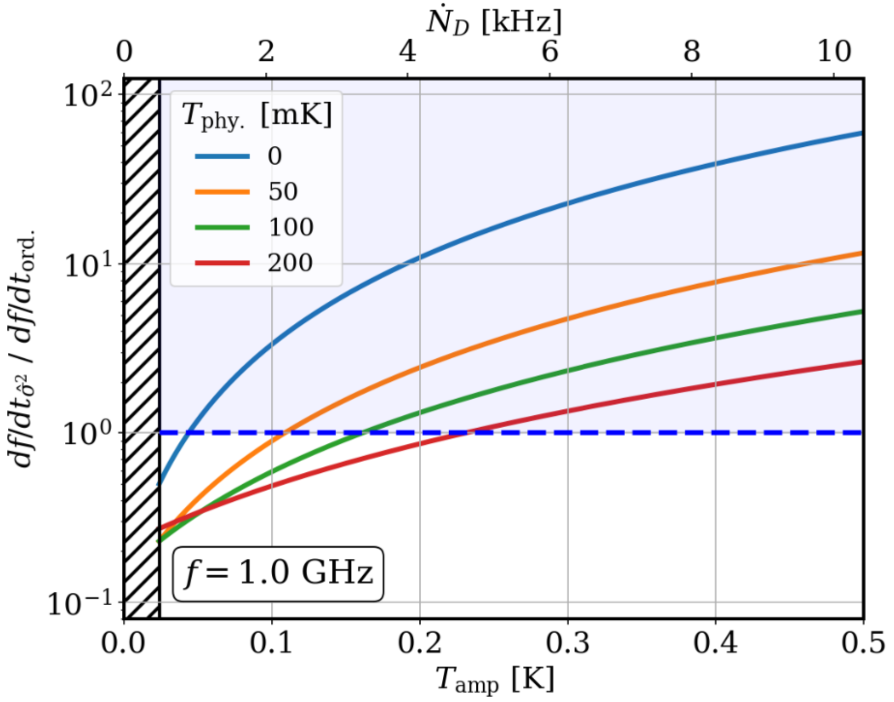
  - The denominator changes from $\sqrt{2f_s}$ to $\sqrt{\dot{N}_{\mathrm{th.}} + \dot{N}_D}$
  - In the case that $\dot{N}_D > 2f_s$, $\mathrm{S/N}_{\sigma^2} > \mathrm{S/N}_{\mu}$

- **Scan rate comparison with Ordinary Method**

$$\left.\frac{df}{dt}\right|_{\sigma^2} \approx \frac{\Delta f_c}{\Delta t} = \frac{\dot{N}_s^2}{\mathrm{S/N}_{\sigma^2}}\frac{\Delta f_c}{2\Delta f_a}$$

$$\left.\frac{df}{dt}\right|_{\mathrm{ord}} \approx \frac{\Delta f_c}{\Delta t} = \frac{1}{\mathrm{S/N}_{\mu}}\left(\frac{P_s}{k_B T}\right)^2 \frac{Q_a}{Q_l}$$

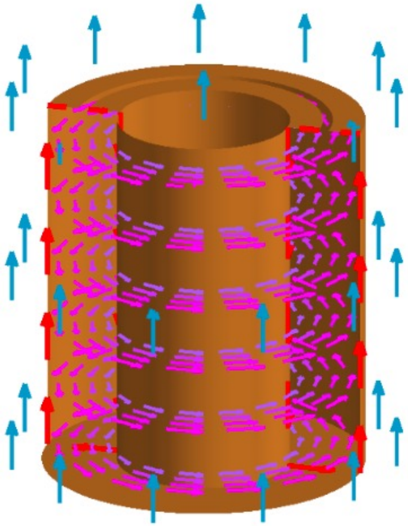
- $T_{\mathrm{amp}} \sim T_{\mathrm{QL}} = hf$: Ordinary method is fast
- $T_{\mathrm{amp}} \gtrsim 2T_{\mathrm{QL}} = 2hf$: Variance method is fast

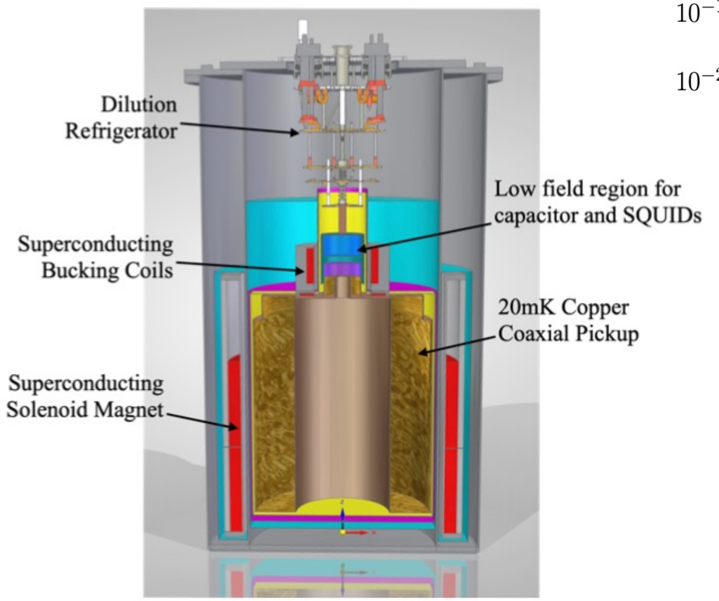


The low-frequency domain

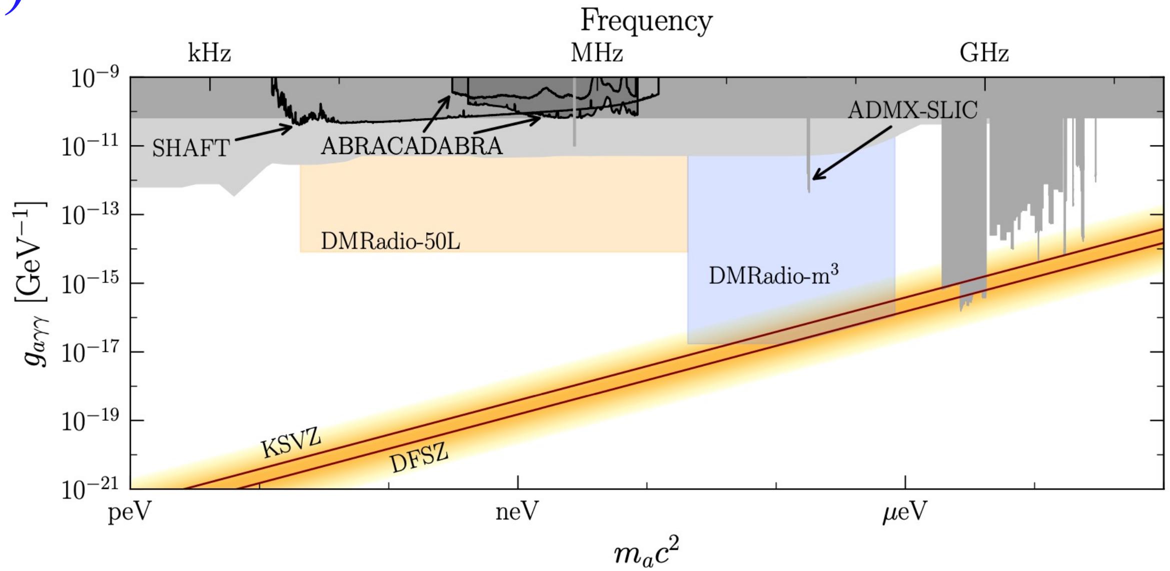
Dark-Matter Radio, probing the low frequency axions at SLAC/USA

Low frequencies (long Compton wavelength) favor induction coil detection

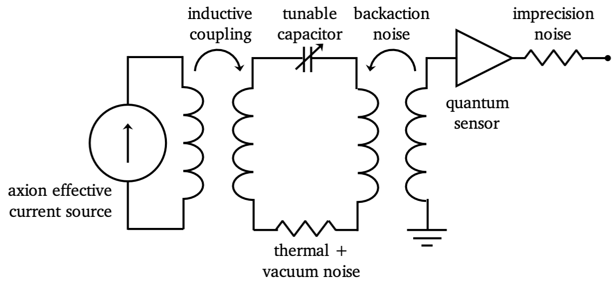




(a) (b)



Dark Matter Radio, 2203.11246



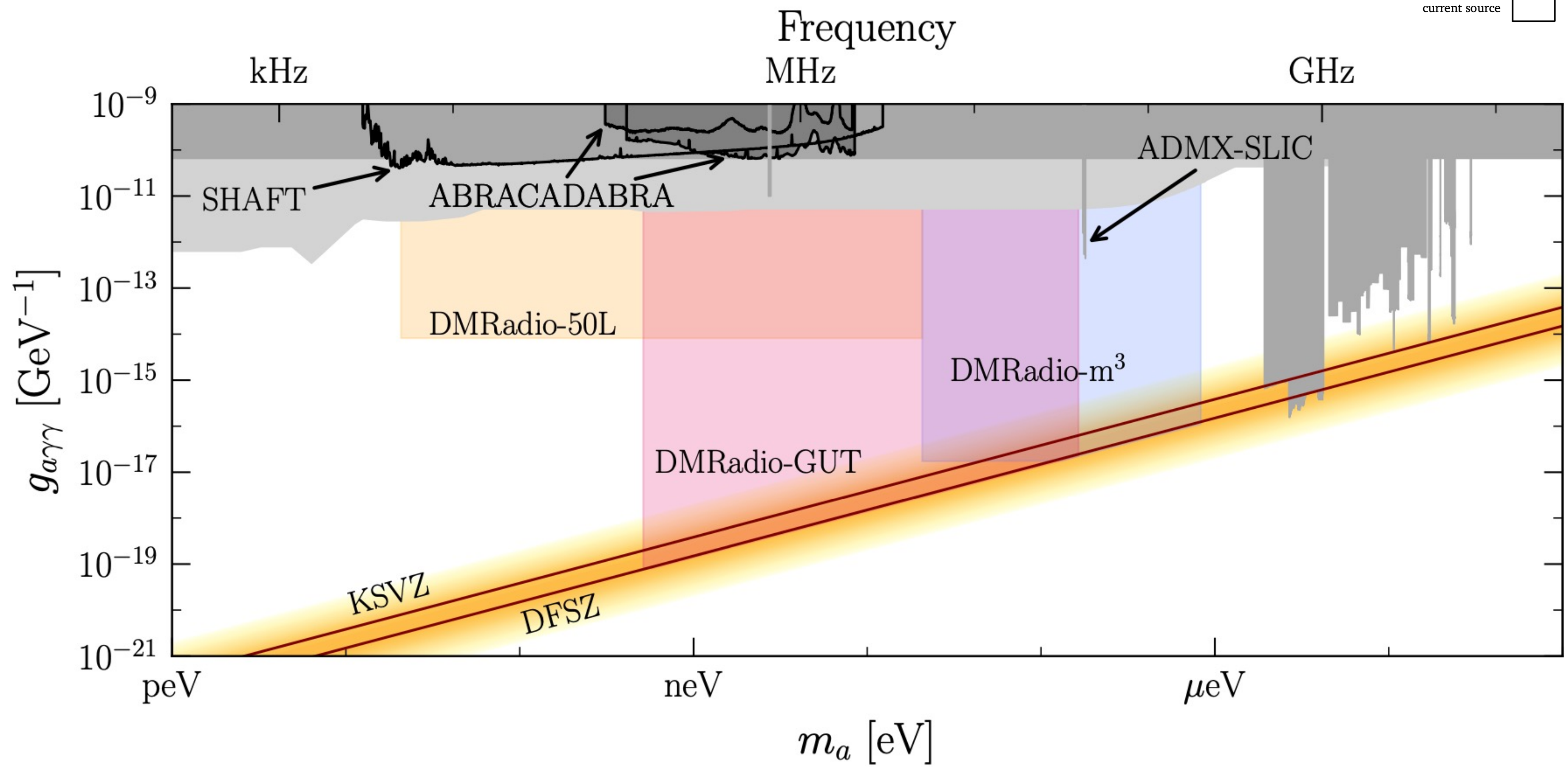
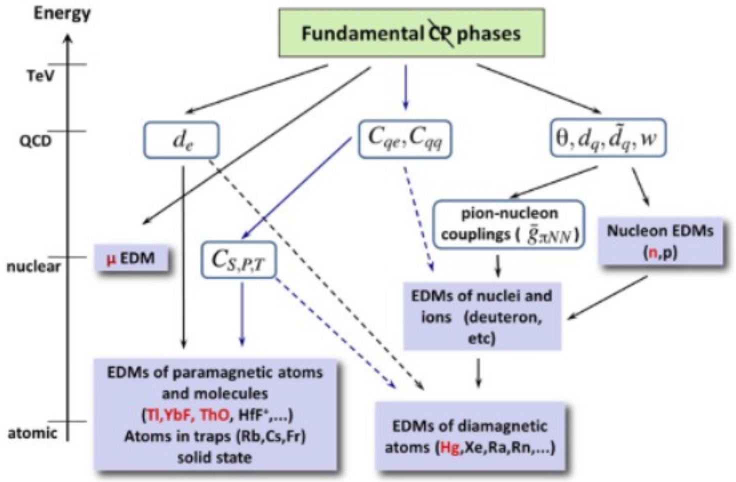
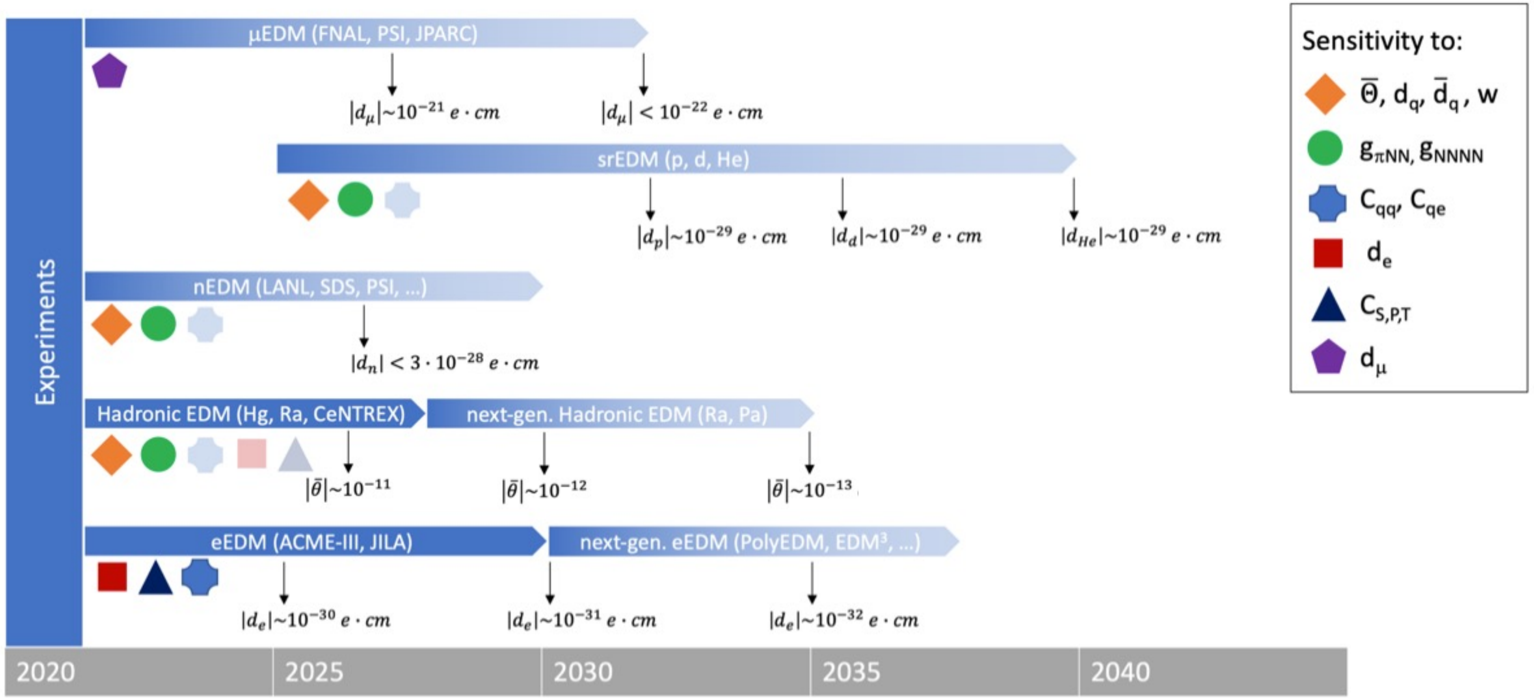


FIG. 4. Projected sensitivity for DMRadio-GUT in pink. The total scan time to cover this reach is ∼ 6 years, depending on R&D outcomes. Various scenarios are outlined in Table II. Existing limits are shown in grey.

Electric Dipole Moments

They set the current limits on SUSY-like New-Physics

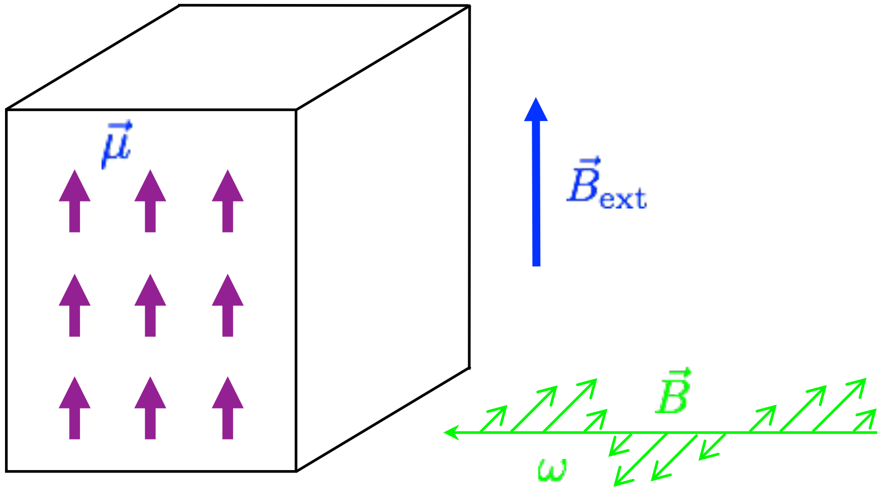




Haloscopes using spins

Dima Budker, CASPEr

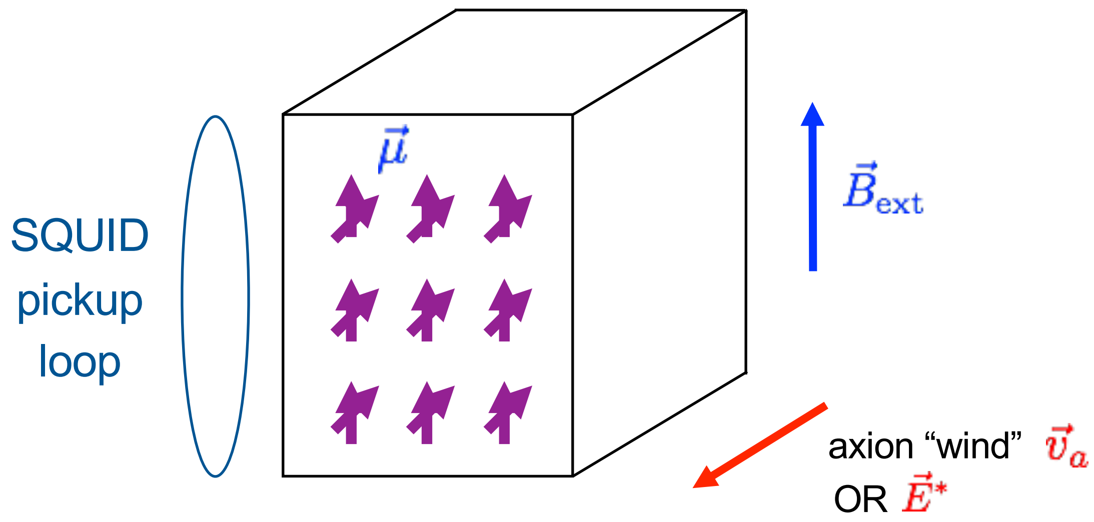
Nuclear Magnetic Resonance (NMR)



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

Dima Budker

CASPEr



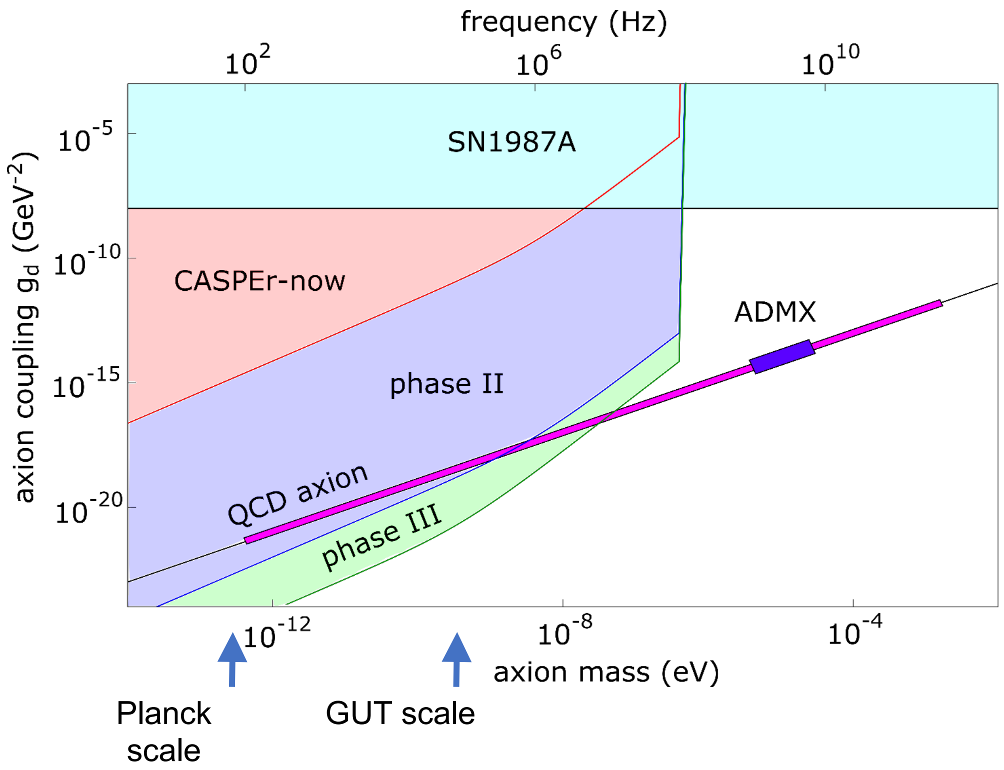
Larmor frequency = axion mass ➔ resonant enhancement

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

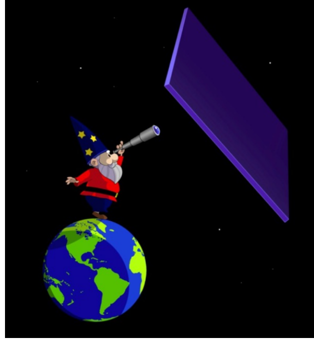
phase II:
- optically enhanced spin polarization
- 5 cm sample size,
- 14T magnet, homogeneity 100 ppm
- tuned SQUID circuit?

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

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

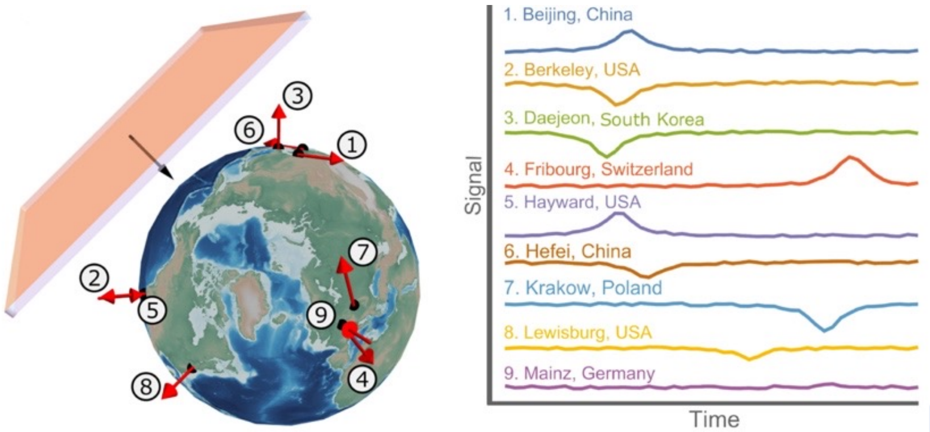
Slide by Alex Suskov (adapted)

GNOME



- Global network of GPS-synchronized optical magnetometers
- Sensitive to localized dark matter: domain walls, axion stars, …
- Multi-messenger astronomy

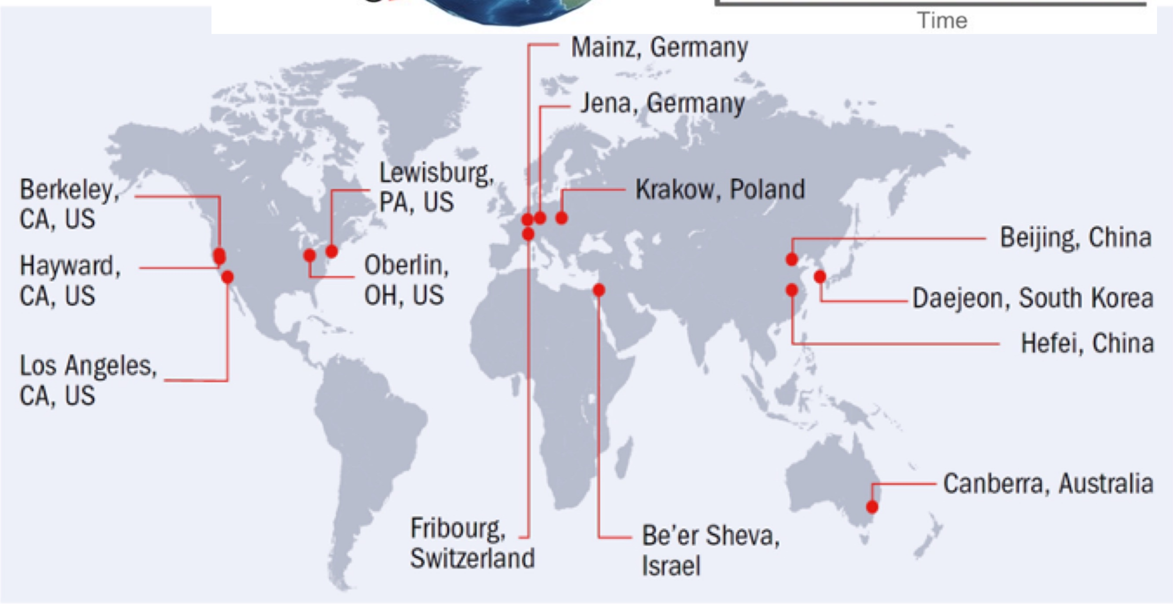
Nature Physics, V. 17, 1396-1401, Dec. 2021



- Fictitious magnetic field B_{fic}:

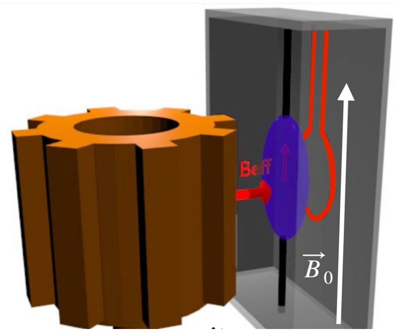
$$\vec{B}_{\text{fic}} = \frac{4}{\mu_B}\frac{f_{\text{SB}}}{f_{\text{int}}} m_a c^2 \frac{\sigma_s}{g_{F,s}} \cos\psi_s$$

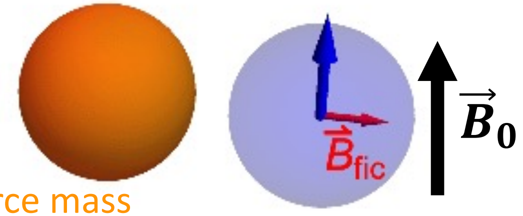
- Optically pumped atomic magnetometer detects B_{fic}
- Direct detection of local dark matter with network detector



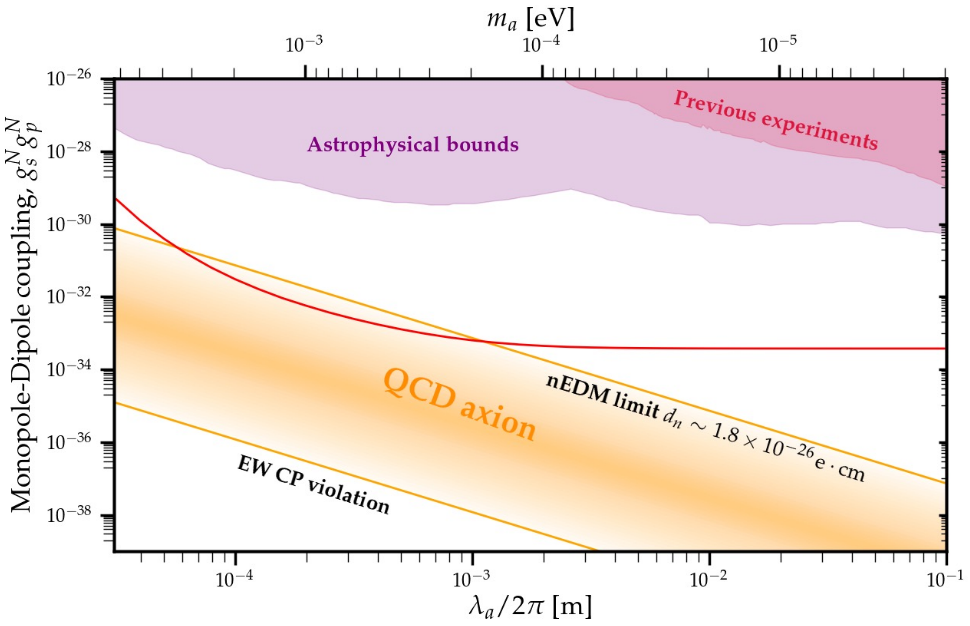
ARIADNE

Axion source: nuclear mass. The axion field gradient acts on fermion spins





Experimental scheme



Projected Sensitivity (first phase)

- Fictitious magnetic field B_{fic}:

$$\vec{B}_{fic} = \frac{\hbar g_s g_p}{8\pi\gamma_p M_p}(\vec{\sigma}\cdot\hat{r})\left(\frac{2\pi}{\lambda_a r}+\frac{1}{r^2}\right)e^{-2\pi r/\lambda_a}\hat{r}$$

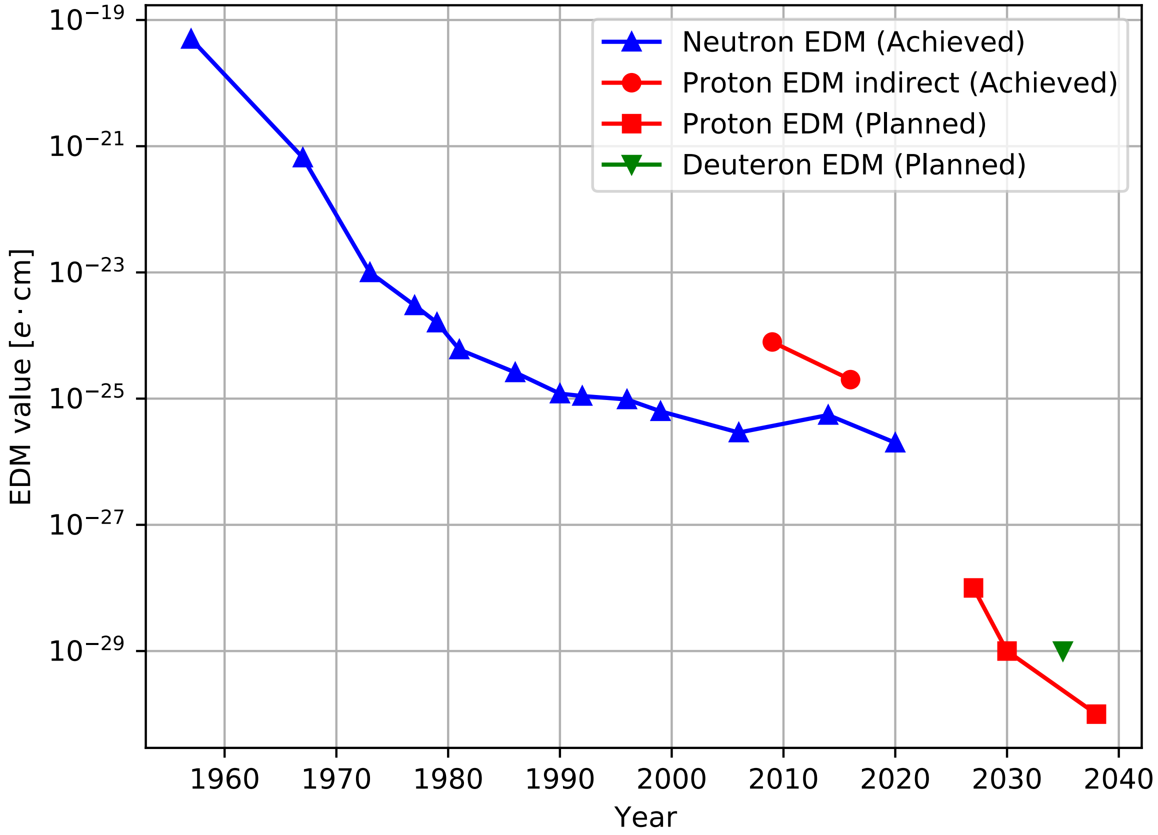
- Spin system resonantly enhance B_{fic}
- Scan broad axion mass range from one measurement.

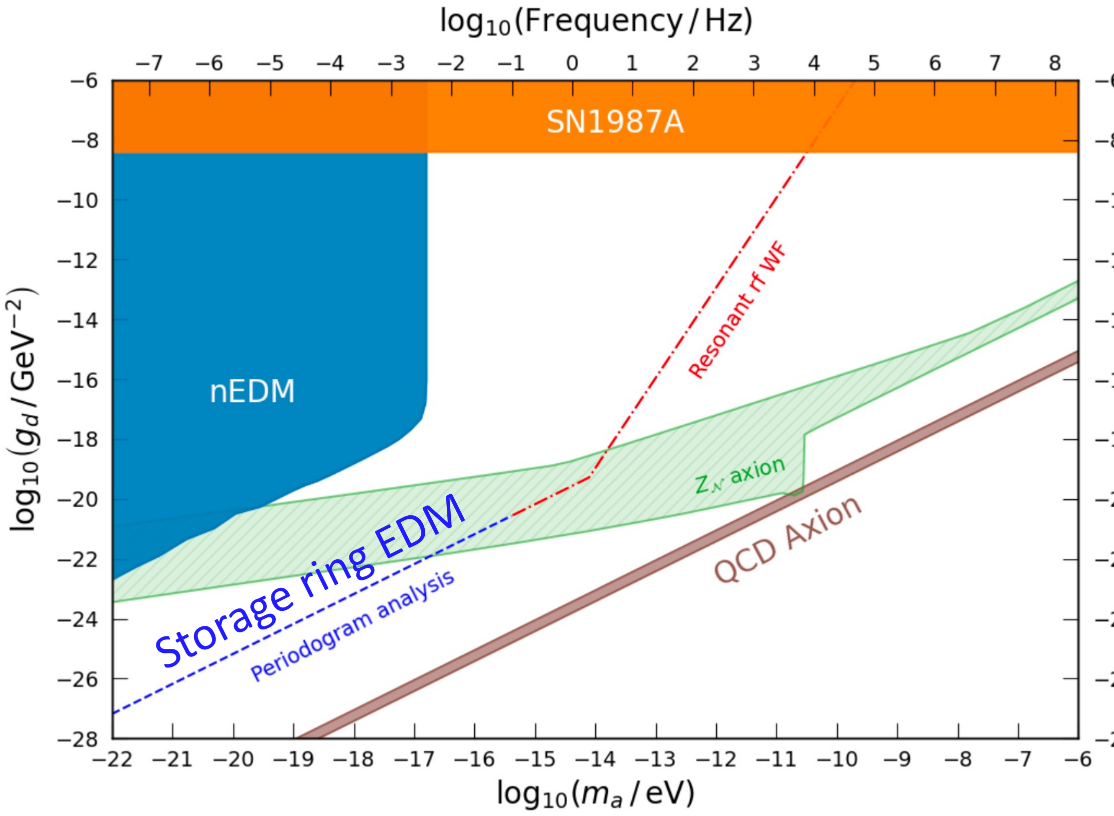
Plan

- Now in R&D of sub-components
- First Prototype measurement in 2022
- Full scale exp. In 2024

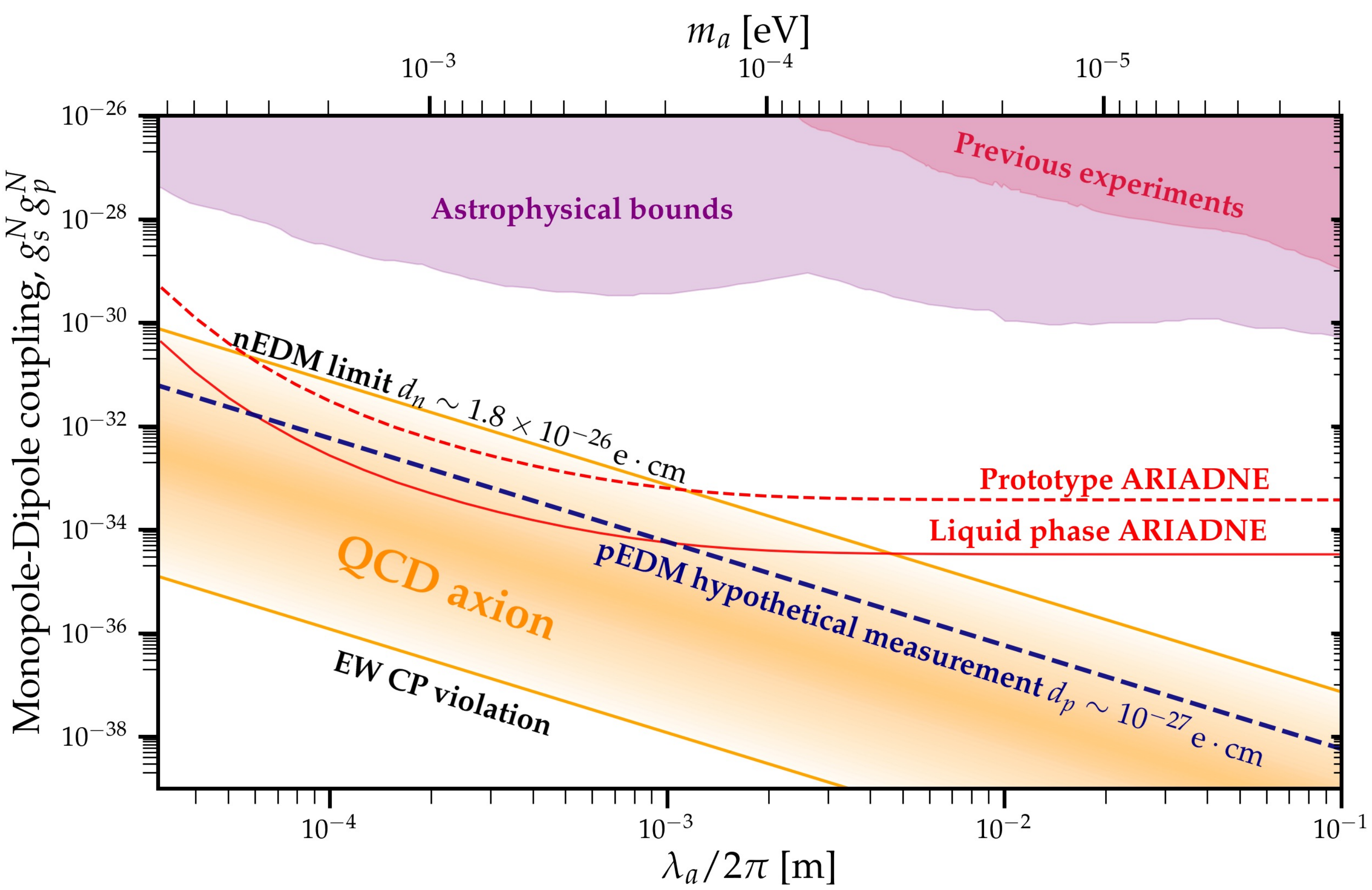
Storage ring proton EDM at 10^{-29} e-cm: Timeline, physics reach

- In progress or still ahead: Snowmass, CDR, proposal/TDR, ring construction, injection, storage.
- Experience with muon g-2 experiment; possible to have interesting results within the decade.
- Competitive EDM sensitivity:
  - New-Physics reach at 10^3 TeV.
  - Best probe on Higgs CPV, Marciano: proton is better than $H \rightarrow \gamma\gamma$, and 30x more sensitive than electron with same EDM.
  - Three orders of magnitude improvement in θ_{QCD} sensitivity.
  - Direct axion dark matter reach (best exp. sensitivity at very low frequencies).





ARIADNE and nucleon EDMs



- Combine with ARIADNE and nucleon EDM provides decisive information
- Scenario:
  - ARIADNE: Null axion
  - pEDM measure: $d_p \sim 10^{-27}\mathrm{e}\cdot\mathrm{cm}$
  - Exclude QCD axion independent of axion DM:

$$0.2\ \mathrm{meV} \lesssim m_a \lesssim 3\mathrm{meV}$$

Y. K. Semertzidis and S. Youn. , 2104.14831

Dipole-monopole interactions for the storage ring experiments

arXiv:2210.17547v1 [hep-ph] 31 Oct 2022

Axion field acting on muon (g-2) and proton EDM

CW vs. CCW beam storage?

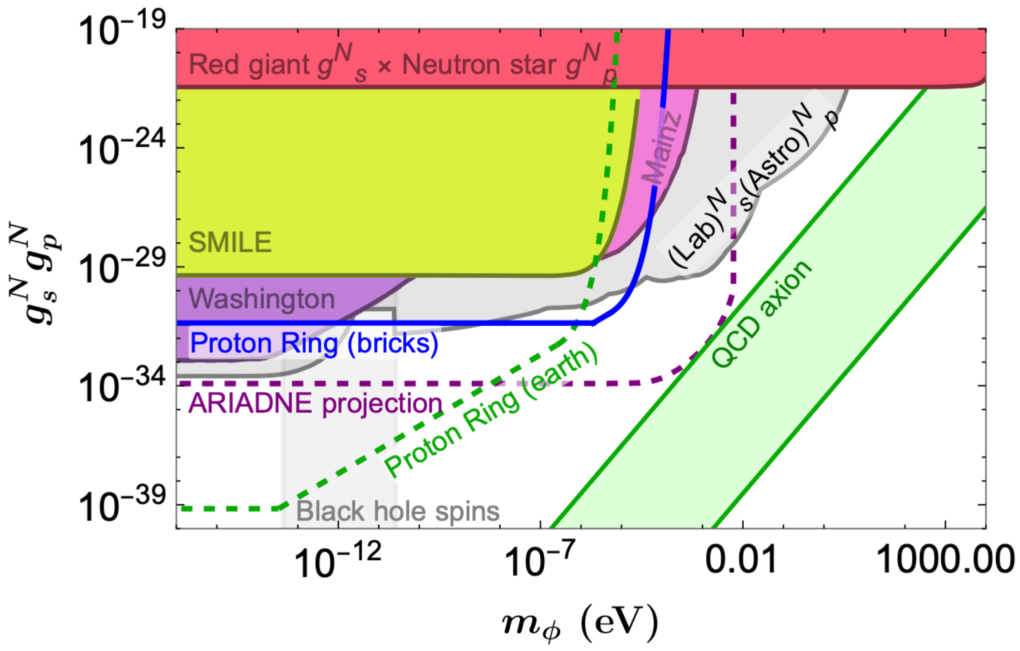


Figure 2. Expected sensitivity to axion forces in the proton storage ring experiment. The blue line corresponds to cubic lead bricks of 10cm size around the ring at a distance around 10cm from the beams generating spin precession out of the plane (EDM-like signature). We consider the conservative case of covering only $O(10\%)$ of the ring with bricks. This fraction is an important parameter, as the reach increases linearly with it. The green dashed line corresponds to the limits due to the axion field from the ground nucleons (spin precession on the ring plane). It is assumed that the ring is located around 150 cm above the ground. Combination of both configurations gives the strongest bounds to monopole-dipole forces on nucleons, beating astrophysics and existing laboratory bounds for any mass below $m_\phi = 10^{-5}$ eV. Bounds adapted from [30].

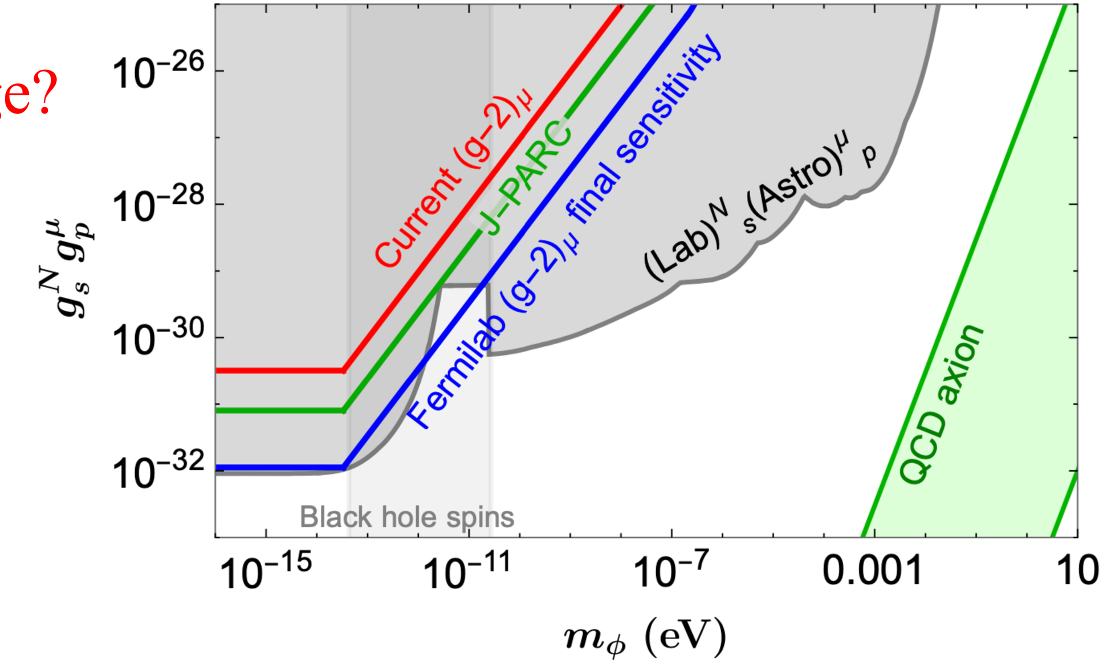


Figure 1. Axion-mediated monopole-dipole forces on muons. The red line corresponds to the values required to explain the $(g-2)_\mu$ anomaly at Fermilab and BNL assuming a signal at the level $\delta\omega_a \approx 4$ rad/s. Bounds from astrophysics are shown in gray. The anomaly can be more easily explained in the region around $m_\phi \sim 10^{-12}$ eV, where the new force limits are the weakest. This is still in slight conflict with SN bounds. Note that the stronger bound on a new force with $m_\phi \sim 10^{-11}$ eV would also apply at $m_\phi \sim 10^{-12}$ eV if the force violated the EP maximally. Thus, for this relaxation of limits, we require the new force to obey the EP at the ~ 1 percent level, which is reasonable in many models (*e.g.* mediation via the higgs). The green line corresponds to the expected sensitivity at J-PARC, which will reach the 0.45 ppm level of precision. The final sensitivity of Fermilab $(g-2)_\mu$, at the 0.1ppm level which corresponds to $\delta w_a = O(0.1)$ rad/s, is in blue.

Haloscopes with dielectrics

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

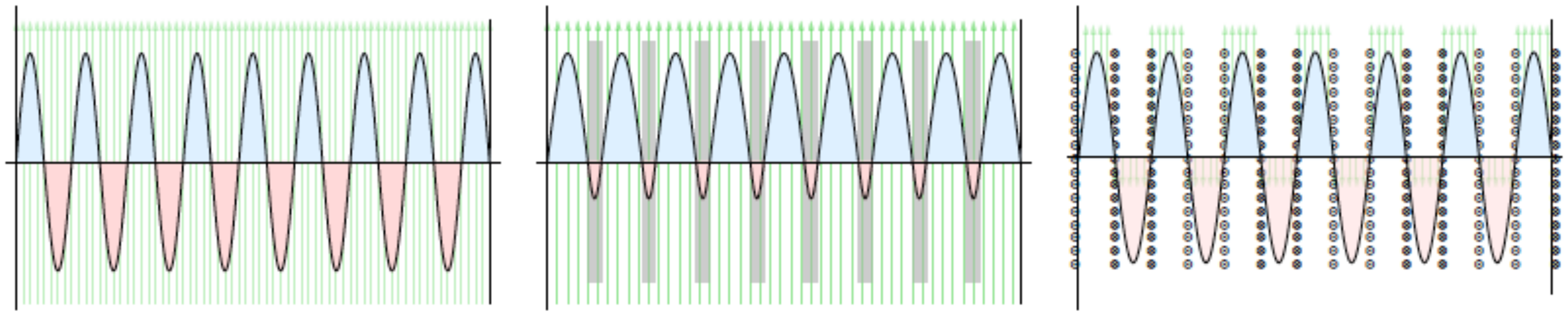
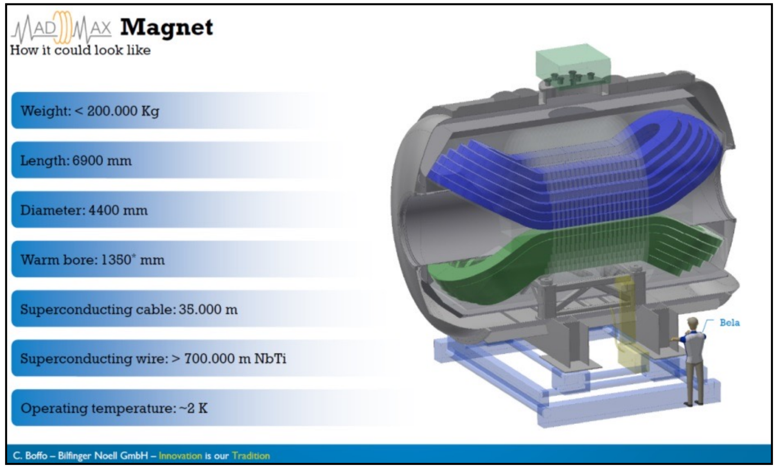


Figure 19: The geometric factor of an ideal 1D cavity in a homogeneous B-field (green arrows) cancels between crests and valleys of a high mode (left). The cancellation can be avoided by placing high-n dielectrics –grey regions– in the valleys (centre) or by alternating the polarity of the external B_e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

MADMAX – search for dark matter axions

MADMAX: Physics at the interface



MADMAX (dark matter)

- Site in HERA hall north being prepared
- Magnet studies by Bilfinger-Noell and CEA Saclay, aim for magnet decision in late 2018

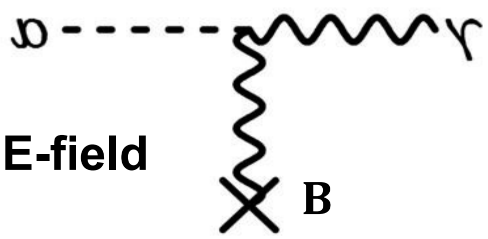
MADMAX collaboration

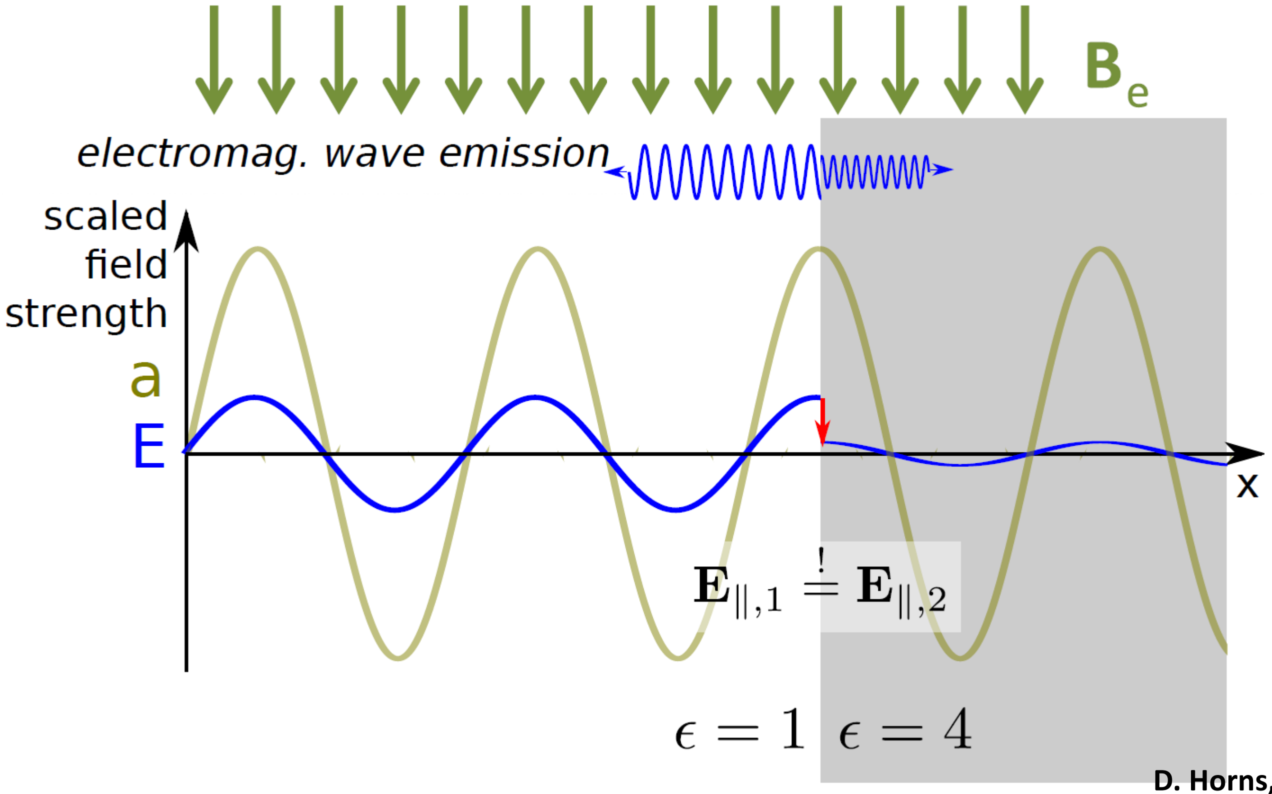
- Founded at DESY in 2017

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





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

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

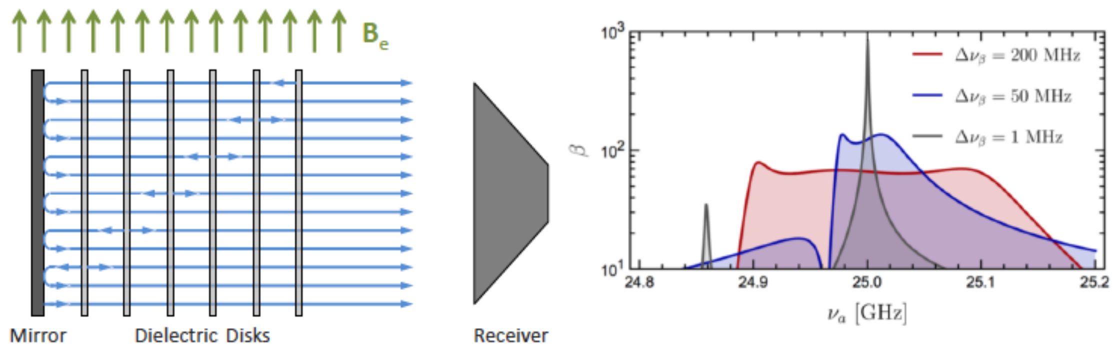


Figure 21: Left: sketch of the dielectric haloscope experiment. Photons in the B_e field are emitted from the dielectric surfaces and reflected in the leftmost mirror and other surfaces to be measured coherently by a receiver, from [585]. Right: Adjusting the distances between the layers, the frequency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

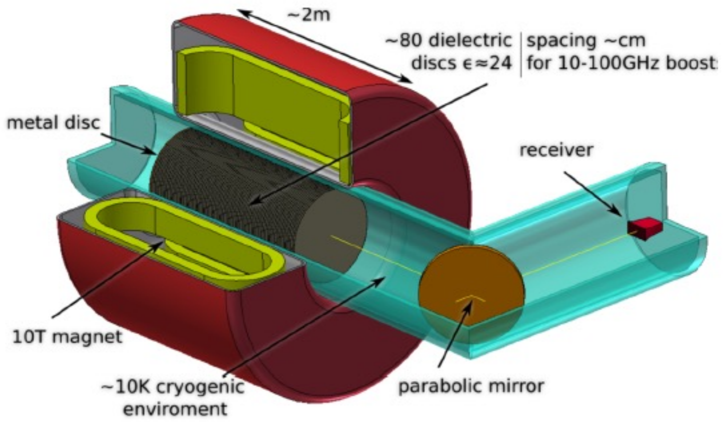
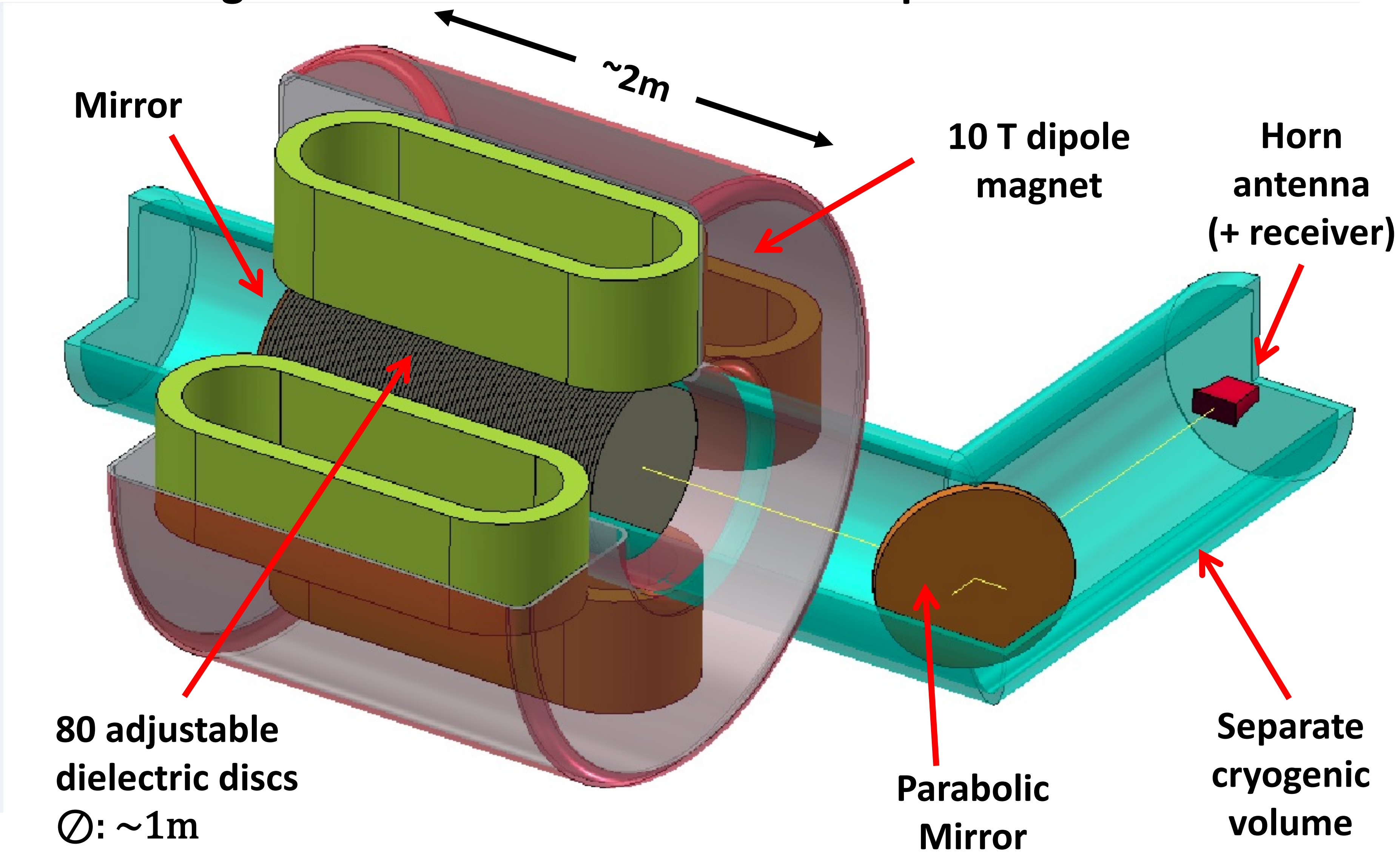


Figure 22: The concept of the MADMAX experiment, see text for details. From [590].

MAgnetized Disc and Mirror Axion eXperiment



David Tanner

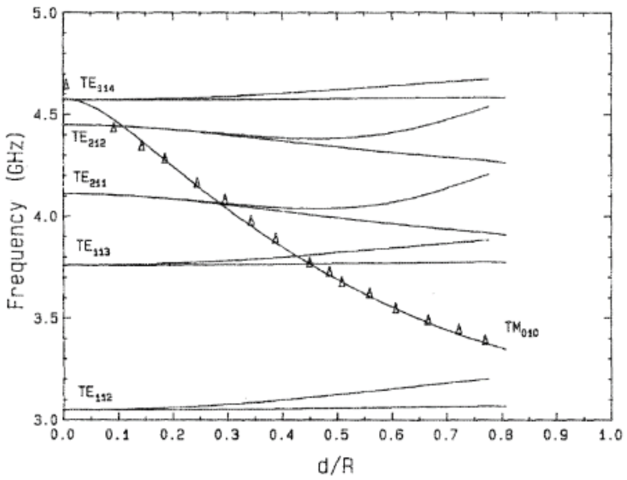
Strawman: Single cavity

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

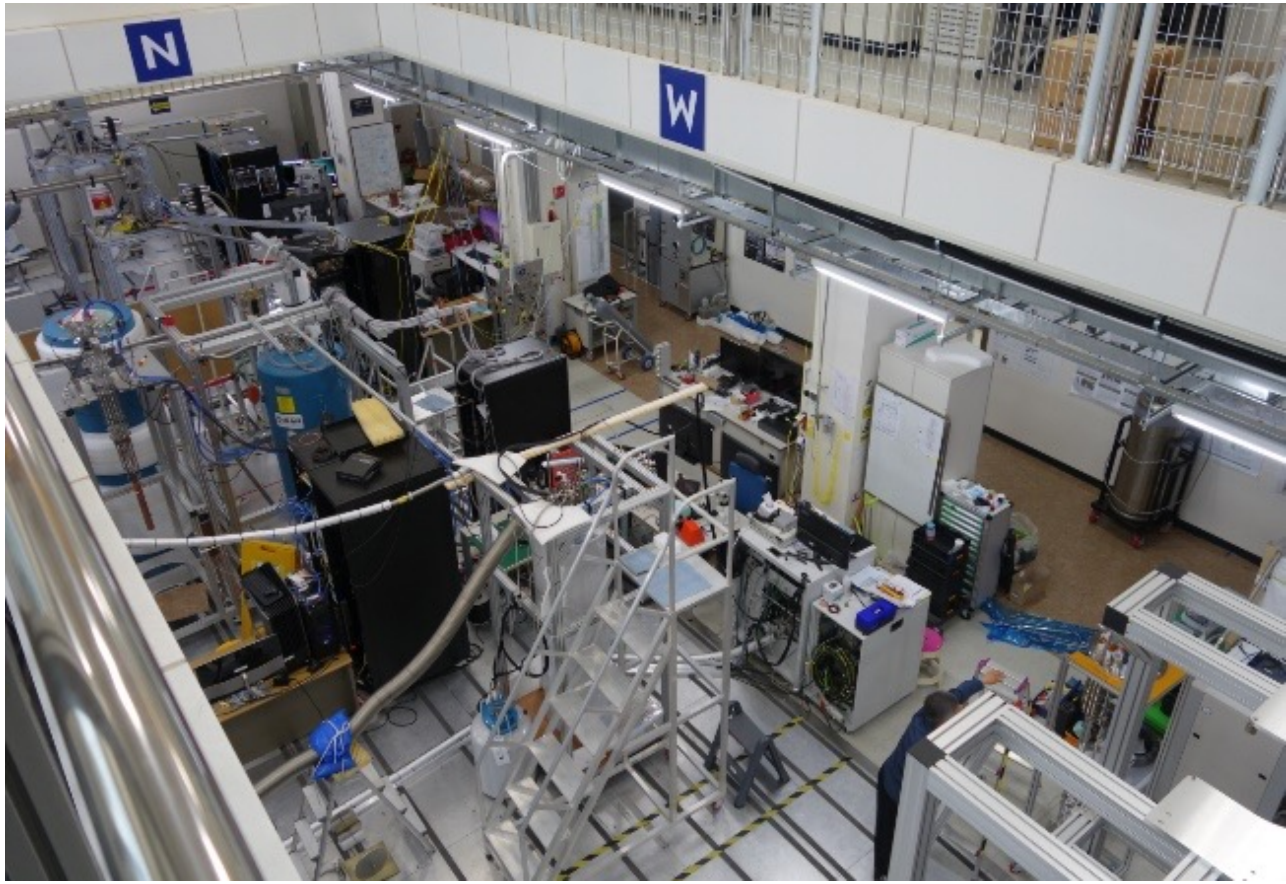
$$P = 130 \text{ yW} \left(\frac{1 \text{ GHz}}{f}\right)^{2.67}$$

- 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:

$$L \sim 4.4r$$



CAPP experimental hall, top view



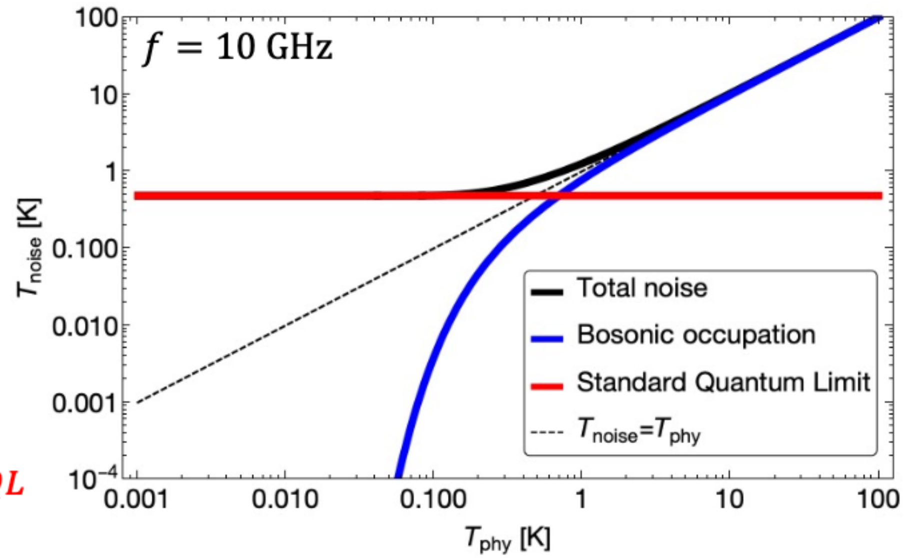
Equivalent noise temperature

Slide by SungWoo Youn

Noise contributions

$$T_{sys} = \frac{hf}{k_B}\left(\frac{1}{\exp\left[\frac{hf}{k_B T_{phy}}\right]-1} + \frac{1}{2} + \frac{G^2-1}{2G^2}\right)$$

- Thermal noise: bosonic occupation
- Zero-point fluctuations
- Minimum added noise



Standard quantum limit (SQL)

- Unavoidable limit by linear amplifiers

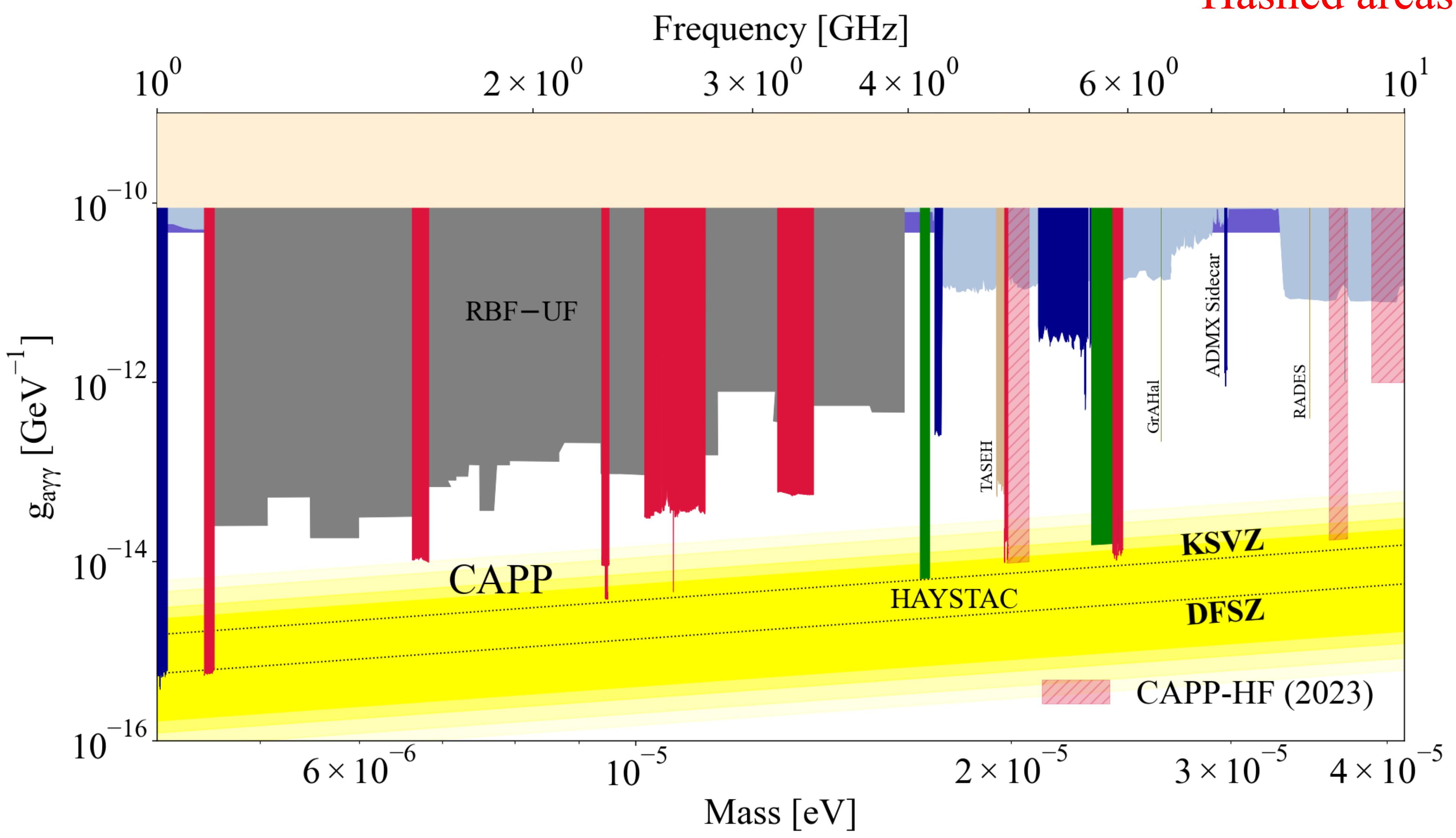
$$T_{sys} \geq \frac{hf}{k_B}\left(\frac{1}{2} + \frac{G^2-1}{2G^2}\right) \gtrsim \frac{hf}{k_B} \equiv T_{SQL}$$

- Predominant at high frequencies

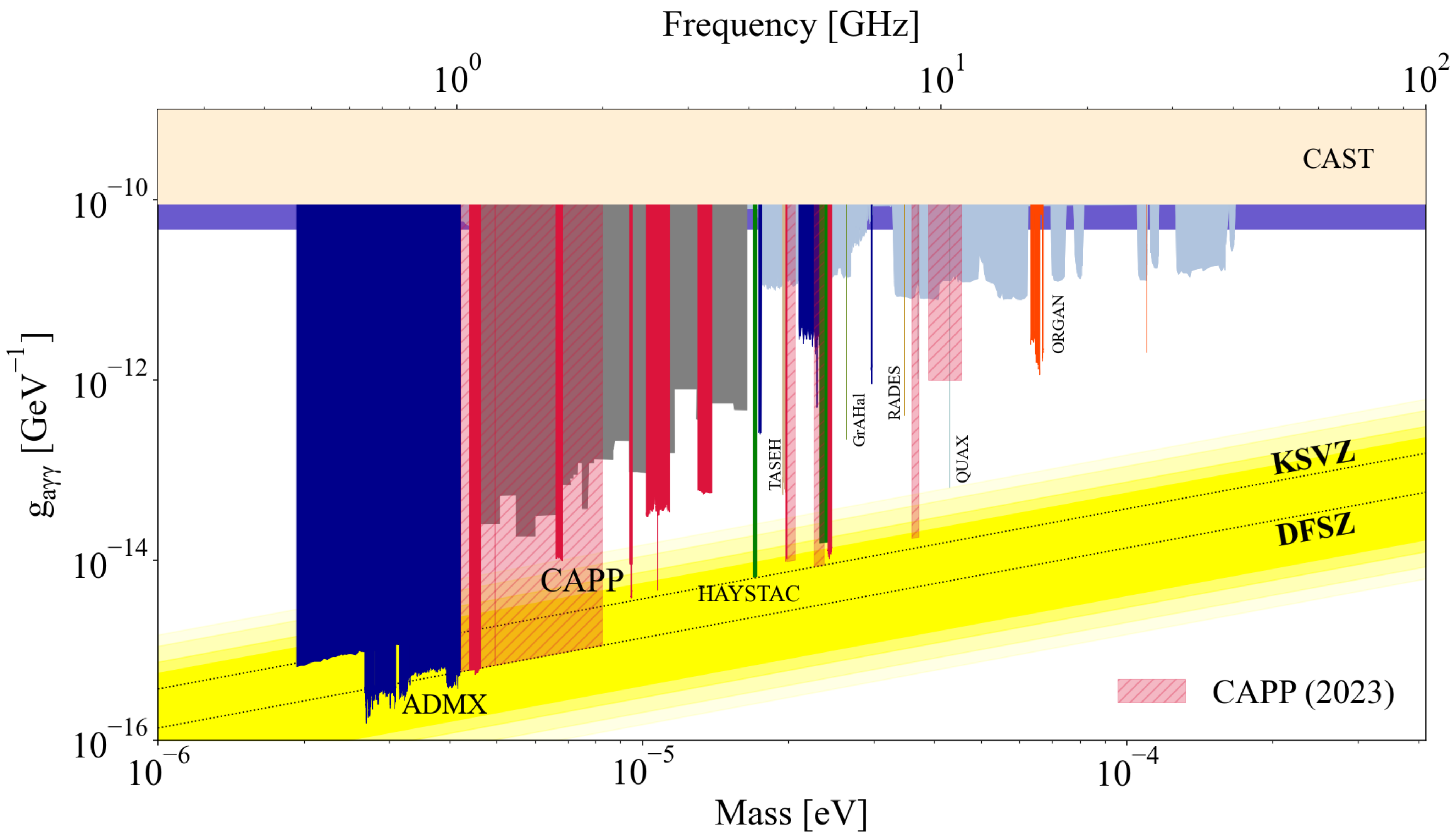
1. The uncertainty principle limits the lowest equivalent electronic noise of the system (quantum noise limited amplifiers)

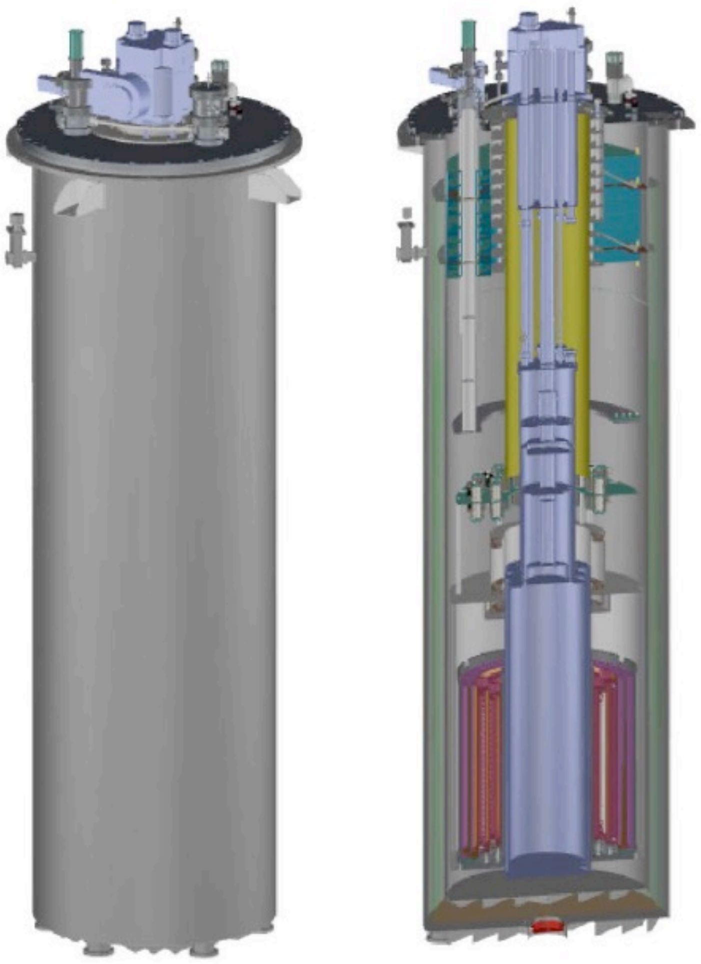
CAPP-HF's target for 2023

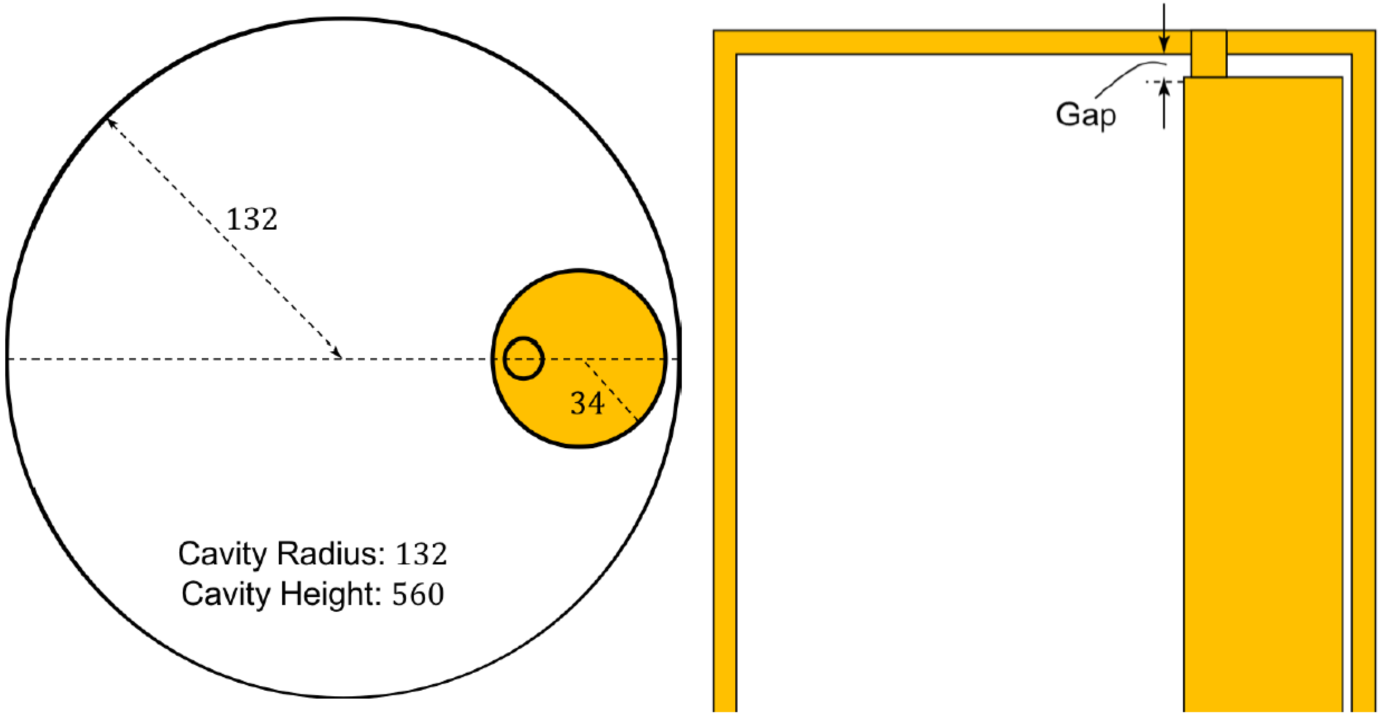
CAPP's scans in solid red
Hashed areas within 2023



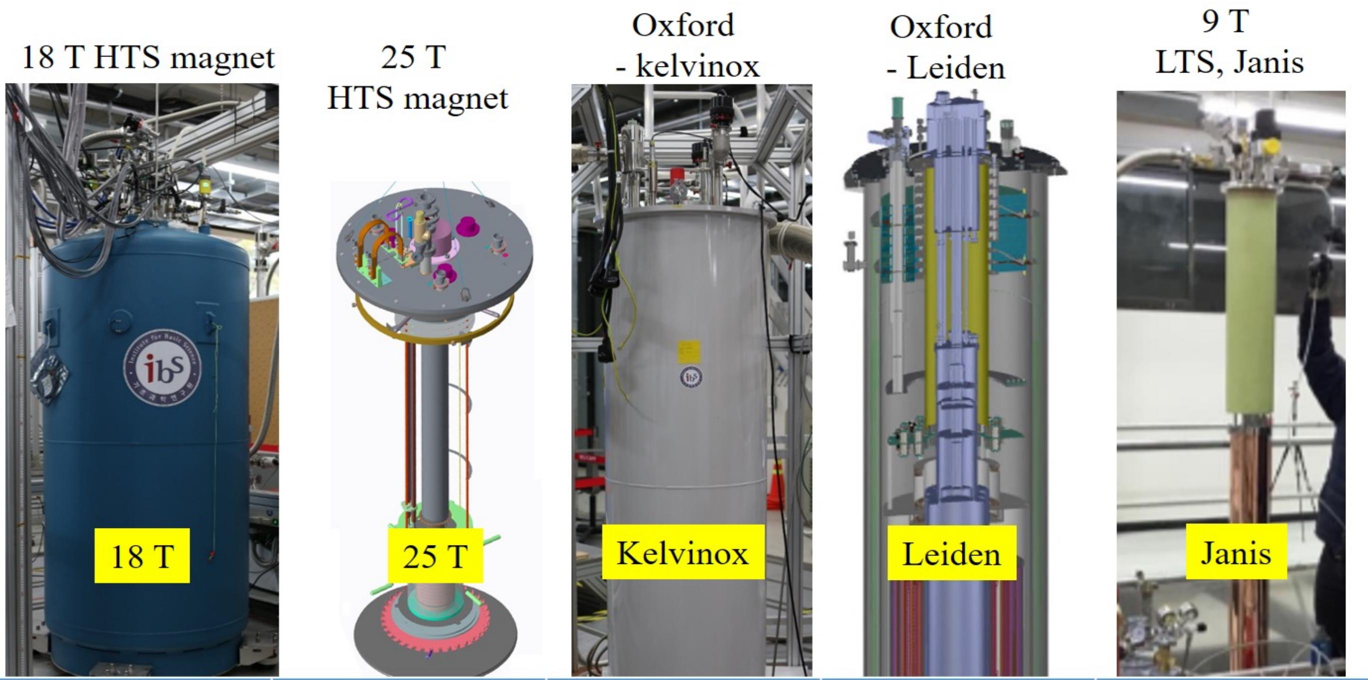
Our place in the world, CAPP in red







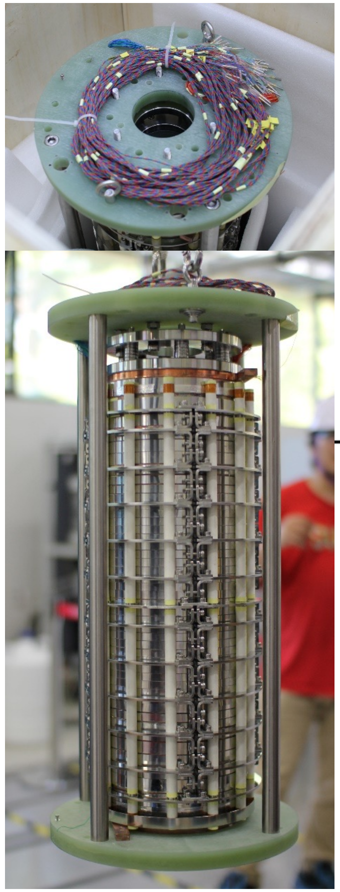
Left: The cryostat, and dilution refrigerator for the LTS-12T/320mm magnet based on Nb_3Sn from Oxford Instr. Right: Microwave cavity dimensions in mm.



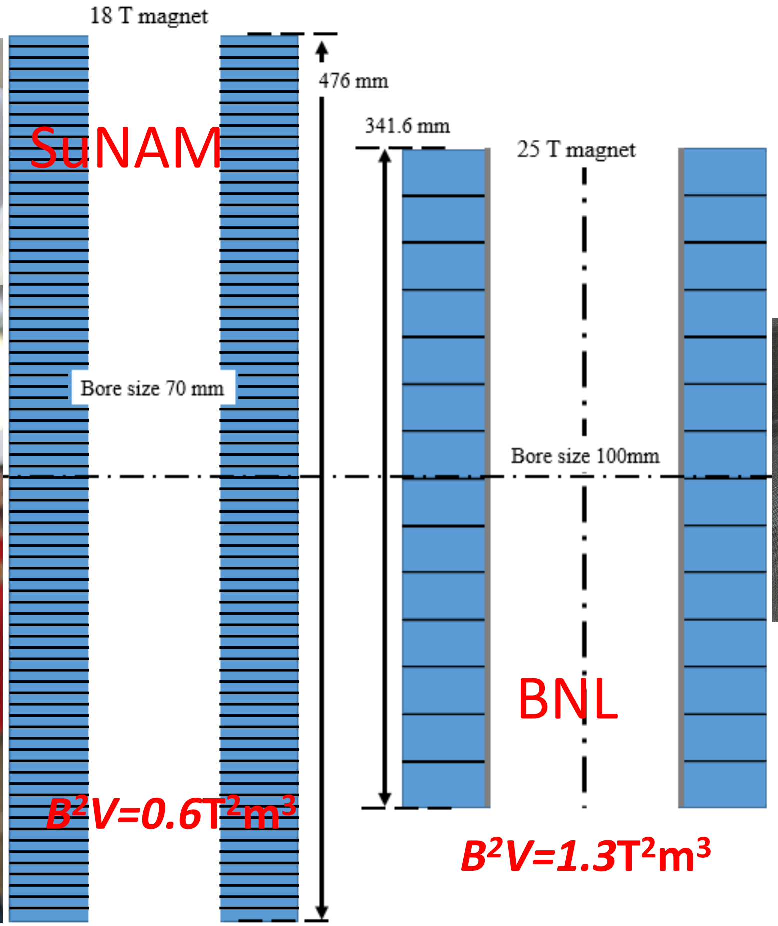
18 T	25 T	9 T	12 T	9 T
70 mm	100 mm	50 mm	320 mm	120 mm
4 K	4 K	30 mK	30 mK	300 mK
Working	2019	Testing	2018	Working

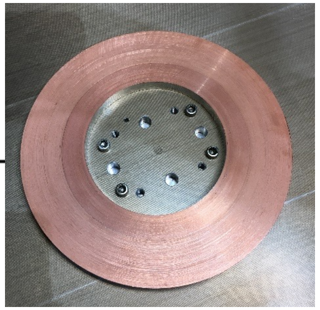
Liquid helium type superconducting magnet system at CAPP

18 T no insulation magnet



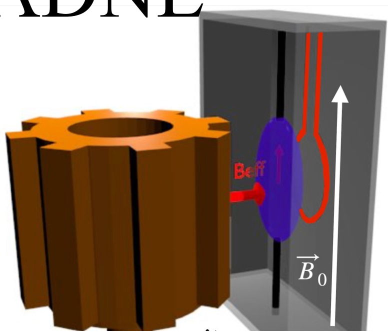
44 double pancake coils



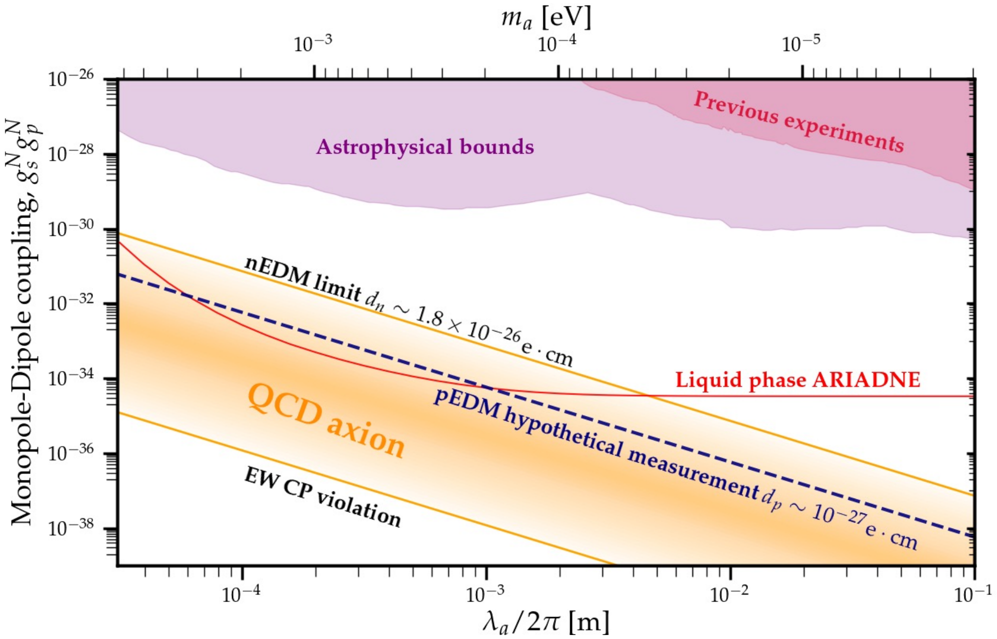


1st coil
for 25 T magnet
1/28

ARIADNE



Projected Sensitivity



IBS-CAPP main contributions that improve sensitivity

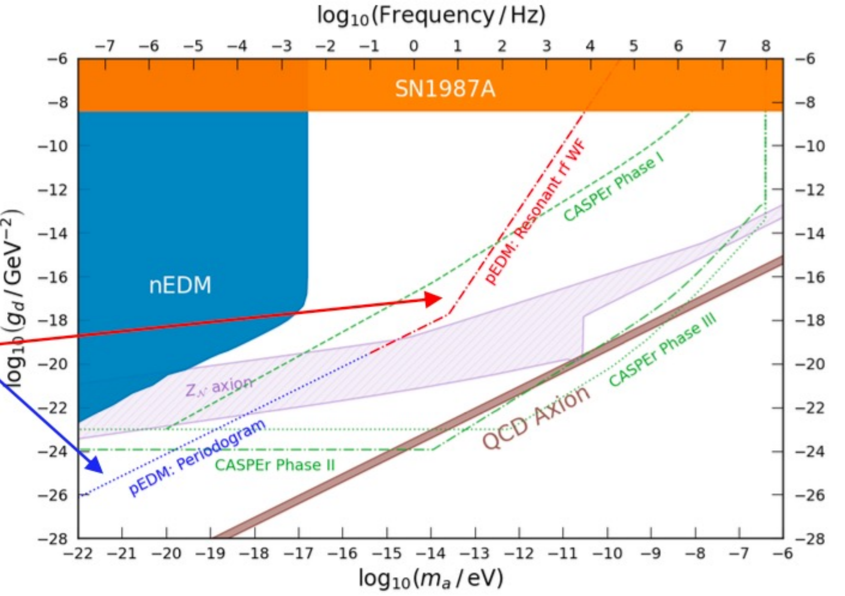
1. Low noise SQUID based second order coaxial planar gradiometer
2. Superconducting thin film shield
3. Source mass geometry optimization

Snowmass paper on pEDM

ALP-EDM coupling

Signature Vertical rotation of polarization.
Setup Longitudinal initial polarization.
Sensitivity

Storage ring pEDM



P. Graham and S. Rajendran, PRD 88, 035023 (2013)
S. Chang *et al.*, PRD 99, 083002 (2019)
On Kim and Y. Semertzidis, PRD 104, 096006 (2021)

The storage ring proton EDM experiment

arXiv:2205.00830v1 [hep-ph] 25 Apr 2022

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis *[6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

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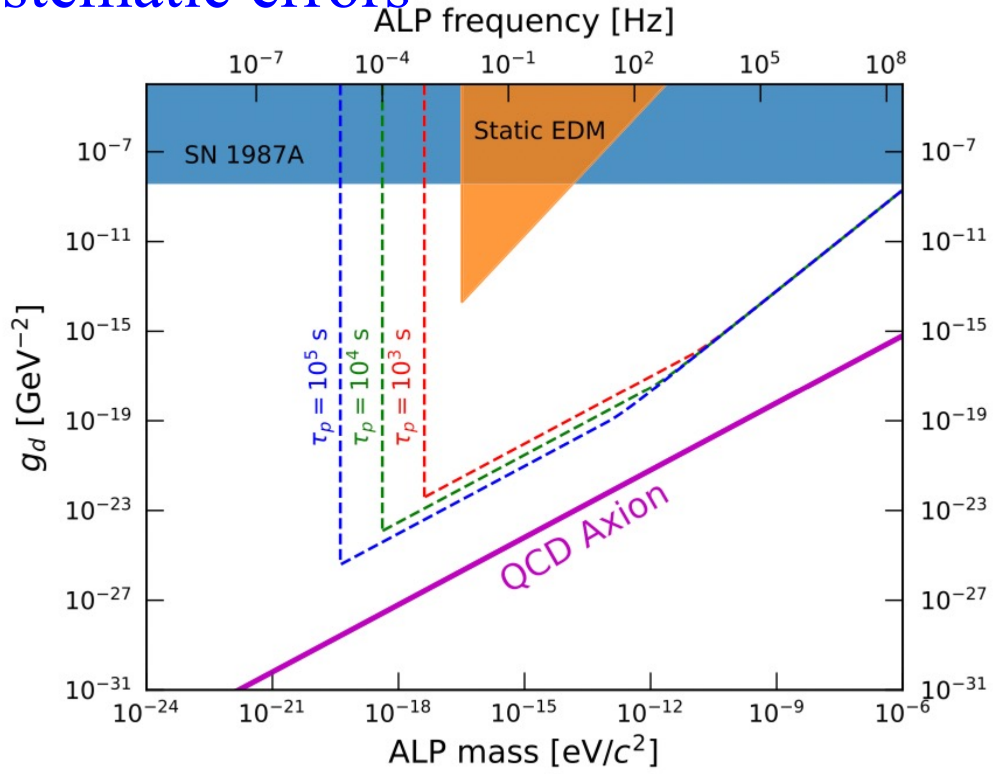
Storage ring proton/deuteron EDM

- Oscillating EDMs, Graham & Rajendran, PRD88, 035023, 2013
- Resonance: axion dark matter and g-2 frequencies (PRD99, 083002, 2019 and EPJ C80, 107, 2020). First run spring 2019 at COSY/Juelich/Germany.
- Storage ring probe of DM and DE (PRD103, 055010, 2021)
- New method with RF-Wien…, On Kim (PRD104, 096006, 2021), great advantage on systematic errors

The RF-Wien filter is NOT operating at the g-2 frequency, avoiding spin dynamics systematic error!

It can be fully implemented in the present muon g-2 ring by injecting polarized protons and/or deuterons



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2. On Kim *et al.,* New method of probing an oscillating EDM induced by axionlike dark matter…, Phys. Rev. D 104 (9), 096006 (2021)
3. P.W. Graham *et al.,* Storage ring Probes for Dark Matter and Dark Energy, Phys. Rev. D 103 (5), 055010 (2021)
4. S. Haciomeroglu and Y.K. Semertzidis, Hybrid ring design in the storage-ring proton EDM experiment, Phys. Rev. Accel. Beams 22 (3), 034001 (2019)
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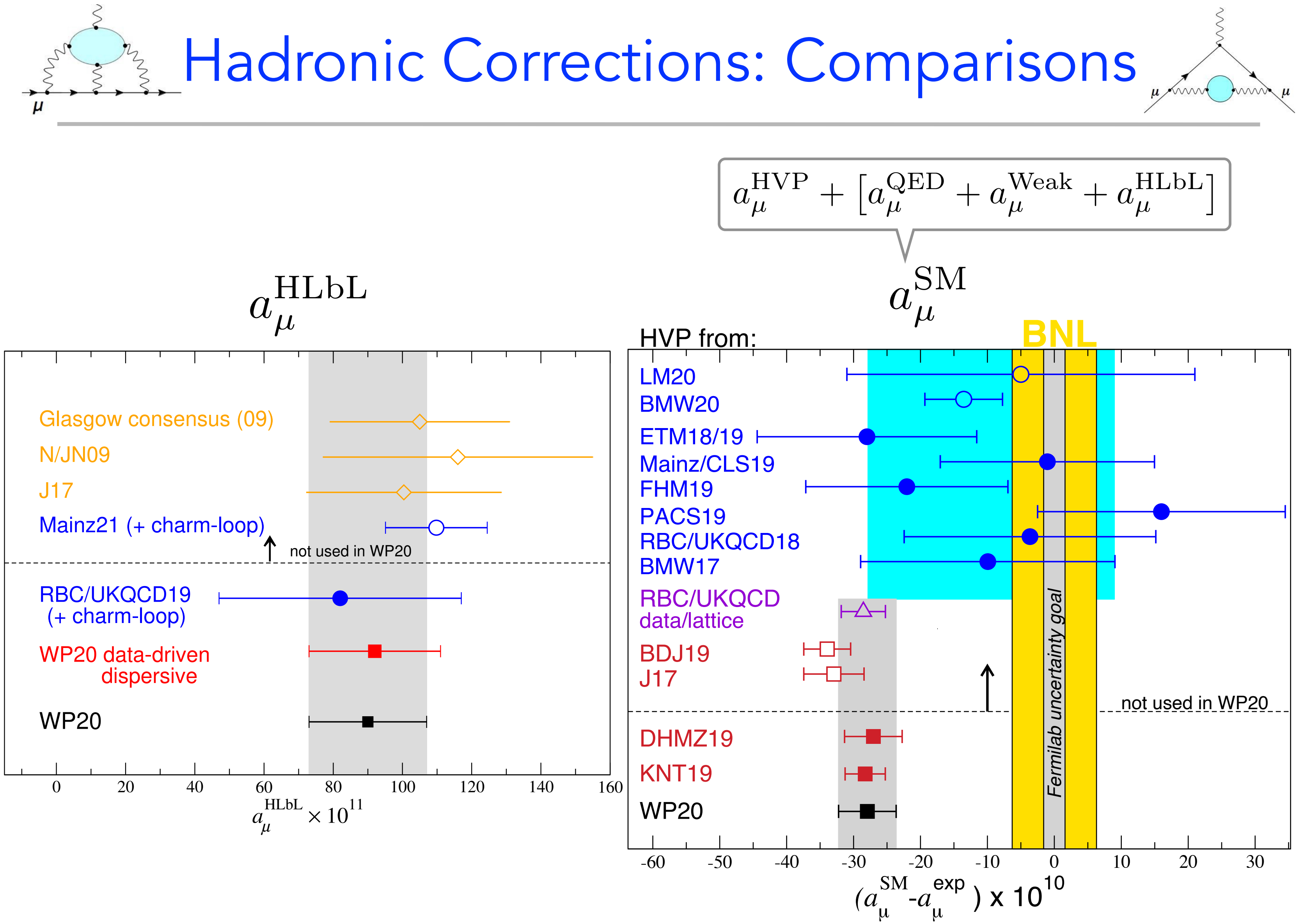
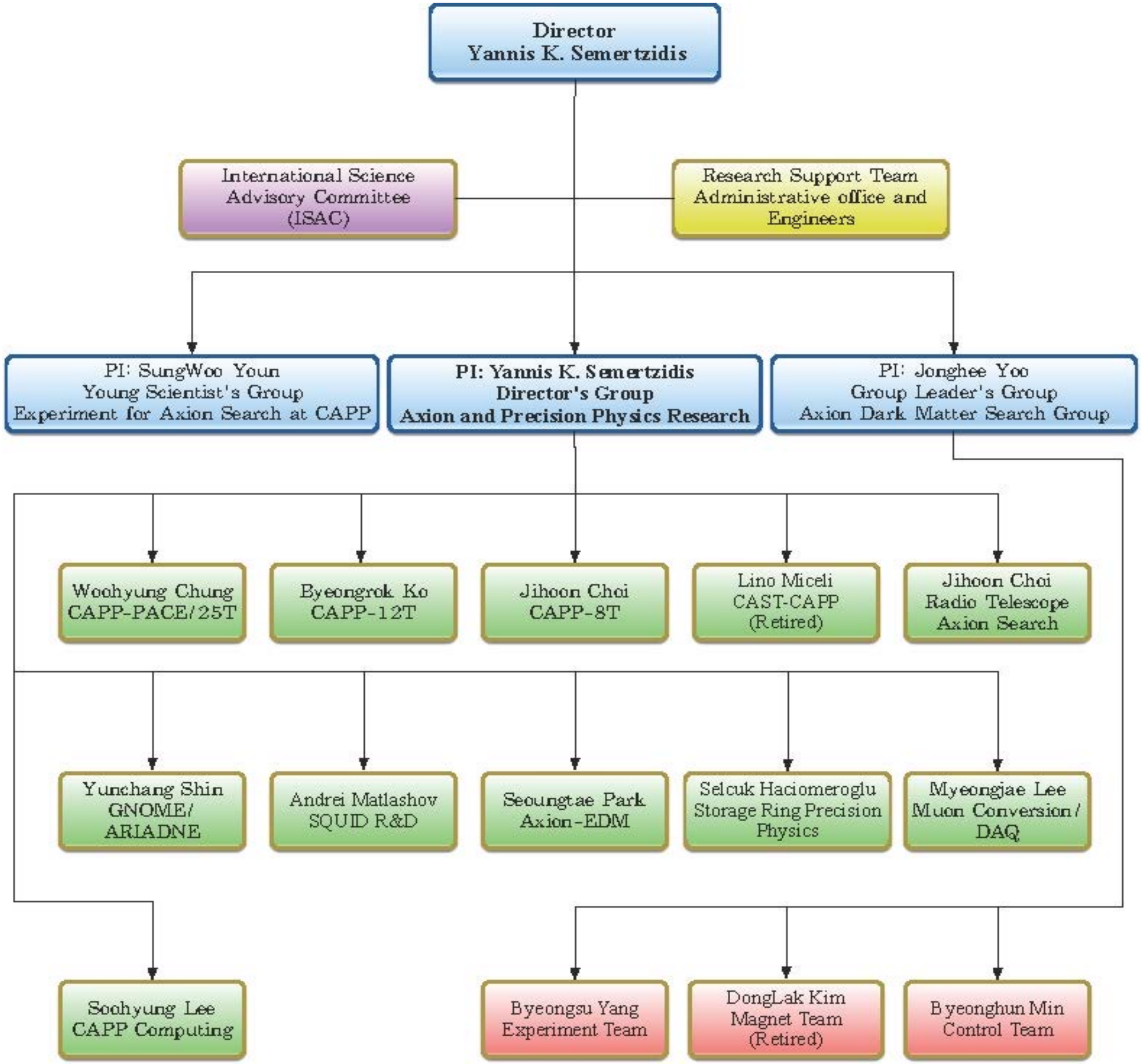
15. F.J.M. Farley *et al.,* A new method of measuring electric dipole moments in storage rings, Phys. Rev. Lett. 93, 052001 (2004)
16. …

Muon g-2 announcement, theory vs. theory

- Theory :



IBS/CAPP Structure and Teams



International Science Advisory Committee

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- ✓Prof. Naohito Saito, Director of J-PARC
- ✓Prof. Javier Redondo, Max Planck Munich, MADMAX
- ✓Prof. Pierre Sikivie, University of Florida

From the ISAC report

- CAPP has made tremendous progress and has arrived within five years becoming a serious player in a field that was dominated by others for more than twenty-five years. The projects are well-balanced and wise choices made.
- Our LTS-12T/320mm magnet from Oxford Instruments and the HTS-25T/100mm magnet from BNL have the highest priority and their delivery should not be delayed at any cost.
- The funding support needs to continue at the promised level, while micro-management can severely adversely affect the quality of the Center.