CAPP

Center for
Axion and Precision
Physics Research

XXth RENCONTRES DU VIETNAM
Gặp gỡ Việt Nam lần thứ 20

International Centre for Interdisciplinary Science and Education

Introductory review on Axion Physics

Yannis K. Semertzidis, IBS-CAPP & KAIST

The Axion Quest, Quy Nhon, Vietnam, August 4-10, 2024

- Axion dark matter research has become:
- Main stream. Once thought impossible field, seems plausible to cover it within <2 decades
- Haloscopes: Conquering the 1-8 GHz region, expanding up to 25 GHz and down to ~100 MHz
- Great promise above 25 GHz and below ~100 MHz with new approaches

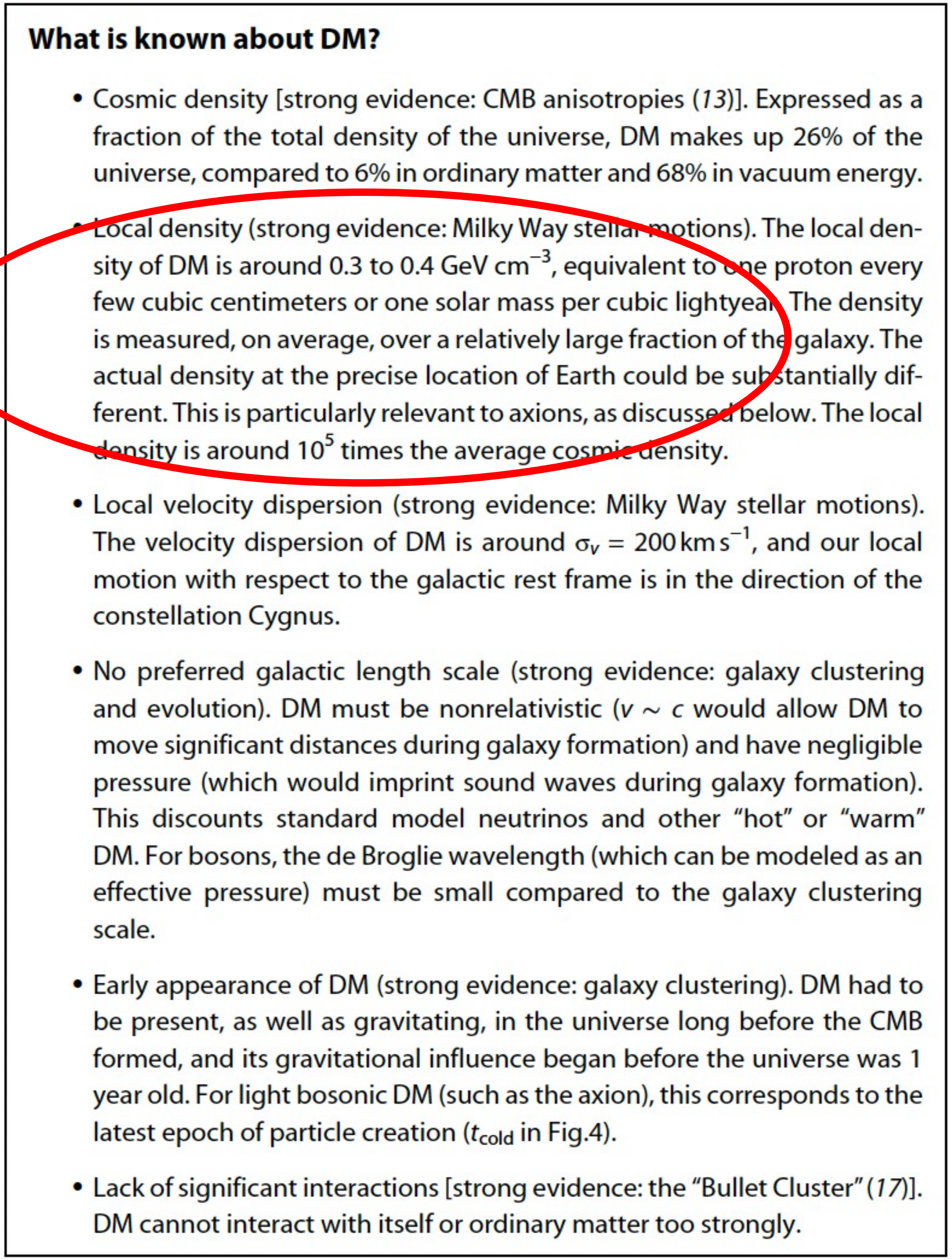
Axion dark matter review articles, theory and experiment

- Axion dark matter: What is it and why now?

By Francesca Chadha-Day, John Ellis, David J.E. Marsh, *Sci. Adv.* **8**, eabj3618 (2022)

- Axion dark matter: How to see it?

By YkS and SungWoo Youn, *Sci. Adv.* **8**, eabm9928 (2022)



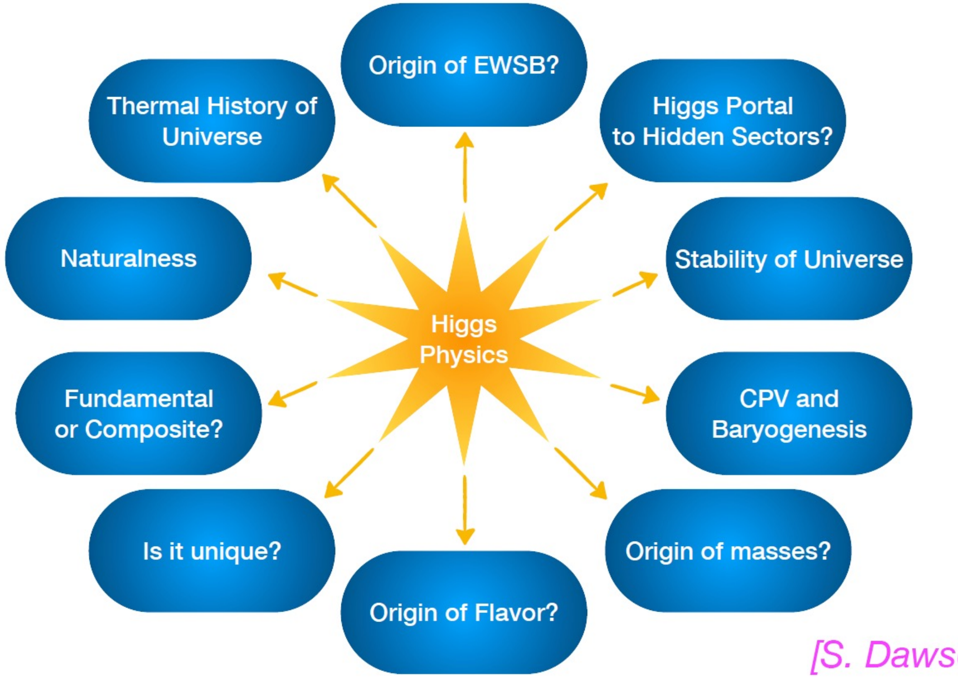
What is known about DM?

- Cosmic density [strong evidence: CMB anisotropies (*13*)]. Expressed as a fraction of the total density of the universe, DM makes up 26% of the universe, compared to 6% in ordinary matter and 68% in vacuum energy.
- Local density (strong evidence: Milky Way stellar motions). The local density of DM is around 0.3 to 0.4 GeV cm^{-3}, equivalent to one proton every few cubic centimeters or one solar mass per cubic lightyear. The density is measured, on average, over a relatively large fraction of the galaxy. The actual density at the precise location of Earth could be substantially different. This is particularly relevant to axions, as discussed below. The local density is around 10^5 times the average cosmic density.
- Local velocity dispersion (strong evidence: Milky Way stellar motions). The velocity dispersion of DM is around $\sigma_v = 200\,\mathrm{km\,s}^{-1}$, and our local motion with respect to the galactic rest frame is in the direction of the constellation Cygnus.
- No preferred galactic length scale (strong evidence: galaxy clustering and evolution). DM must be nonrelativistic ($v \sim c$ would allow DM to move significant distances during galaxy formation) and have negligible pressure (which would imprint sound waves during galaxy formation). This discounts standard model neutrinos and other "hot" or "warm" DM. For bosons, the de Broglie wavelength (which can be modeled as an effective pressure) must be small compared to the galaxy clustering scale.
- Early appearance of DM (strong evidence: galaxy clustering). DM had to be present, as well as gravitating, in the universe long before the CMB formed, and its gravitational influence began before the universe was 1 year old. For light bosonic DM (such as the axion), this corresponds to the latest epoch of particle creation (t_{cold} in Fig.4).
- Lack of significant interactions [strong evidence: the "Bullet Cluster" (*17*)]. DM cannot interact with itself or ordinary matter too strongly.

Higgs, the Standard Model, and SUSY

- The SM seems robust, though without answers to major problems yet
- Higgs: existence proof of scalar particles

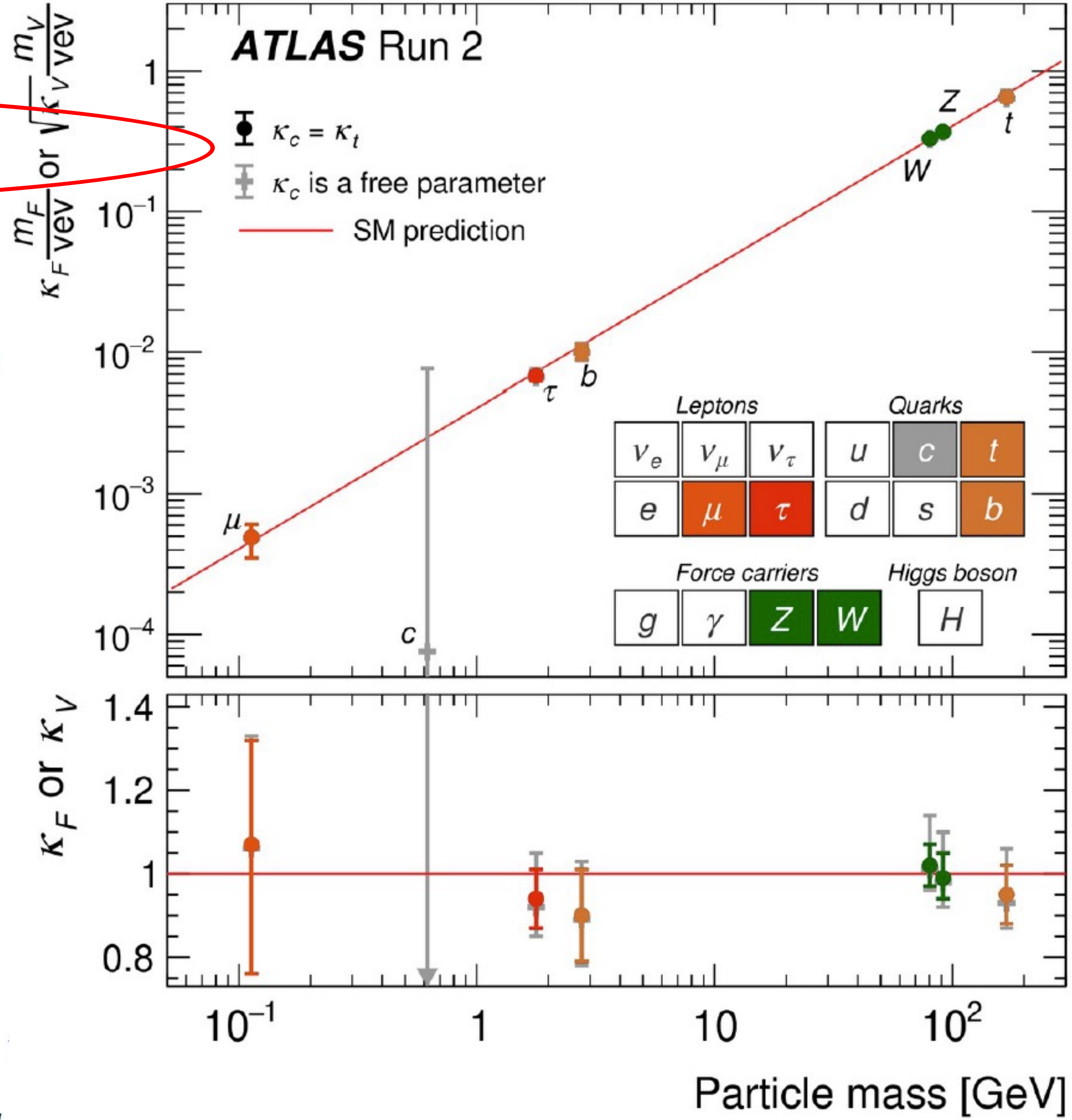
Most of the open questions of particle physics are directly related to Higgs physics and in particular to the Higgs potential



- Origin of EWSB?
- Higgs Portal to Hidden Sectors?
- Stability of Universe
- CPV and Baryogenesis
- Origin of masses?
- Origin of Flavor?
- Is it unique?
- Fundamental or Composite?
- Naturalness
- Thermal History of Universe

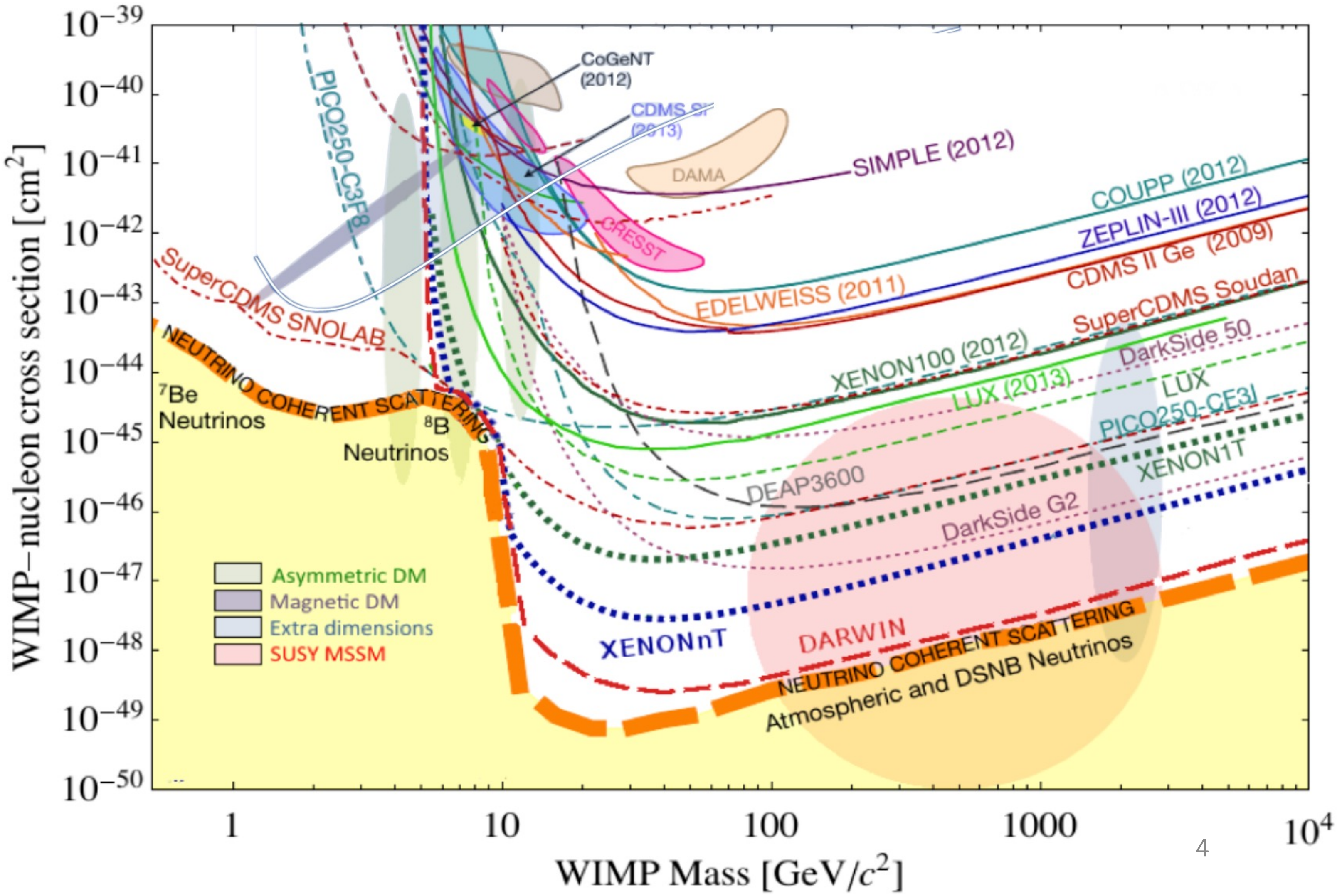
[S. Dawson et al.

Higgs physics at future colliders, Georg Weiglein, Workshop on Future Accelerators, Corfu, 05 / 2024



Higgs, the Standard Model, and SUSY

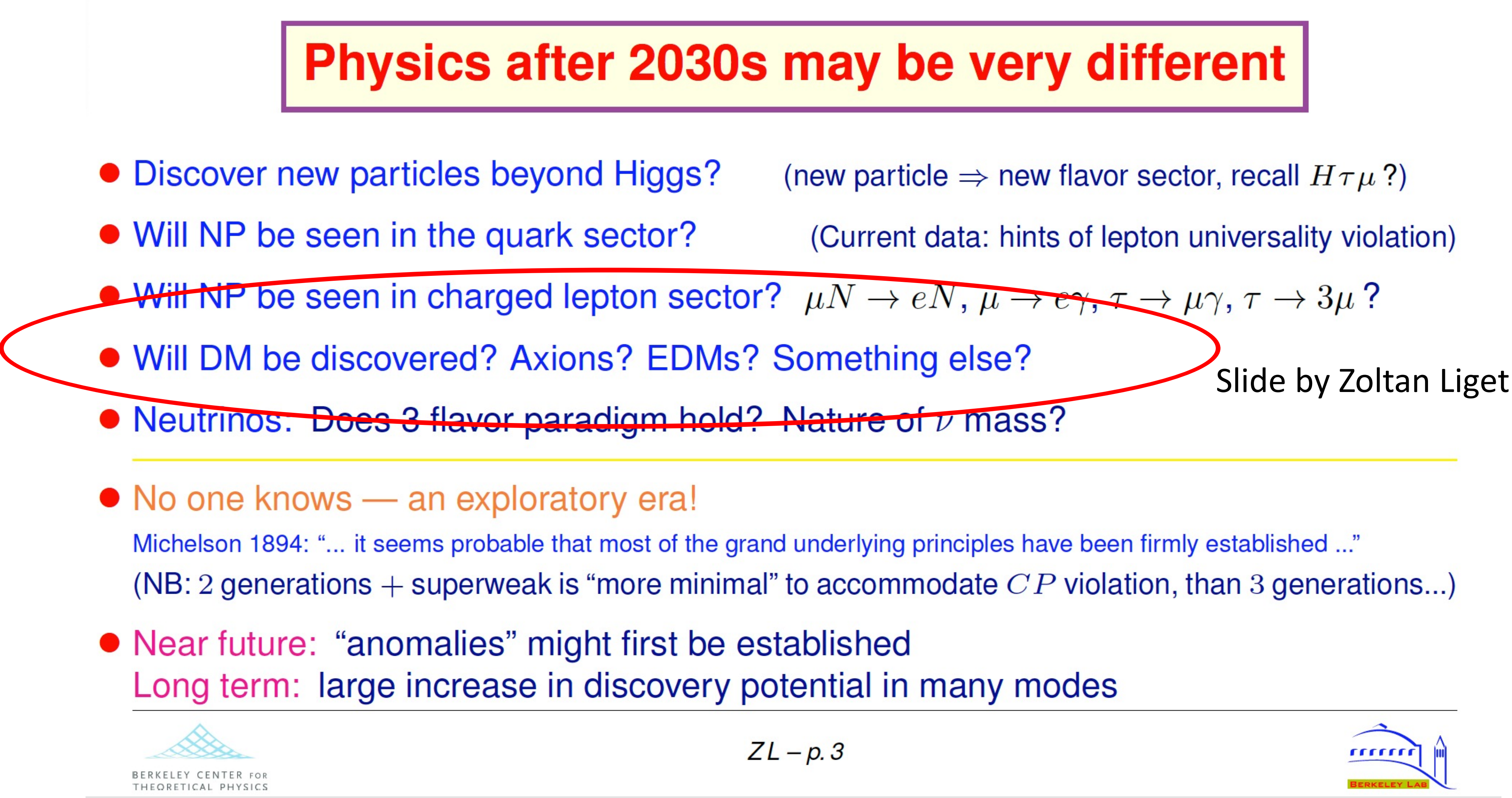
- Impressive WIMP search failed to give any positive evidence so far



Spin independent: Status

Looking beyond the Higgs

- The SM seems robust, without answering major problems yet, e.g., DM, Matter-Antimatter asymmetry mystery,…



Physics after 2030s may be very different

- Discover new particles beyond Higgs? (new particle ⇒ new flavor sector, recall $H\tau\mu$?)
- Will NP be seen in the quark sector? (Current data: hints of lepton universality violation)
- Will NP be seen in charged lepton sector? $\mu N \to eN$, $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to 3\mu$?
- Will DM be discovered? Axions? EDMs? Something else?
- Neutrinos: Does 3 flavor paradigm hold? Nature of ν mass?

- No one knows — an exploratory era!

  Michelson 1894: "... it seems probable that most of the grand underlying principles have been firmly established ..."

  (NB: 2 generations + superweak is "more minimal" to accommodate CP violation, than 3 generations...)

- Near future: "anomalies" might first be established
  Long term: large increase in discovery potential in many modes

ZL – p. 3

Slide by Zoltan Ligeti, Berkeley

Forces in Nature

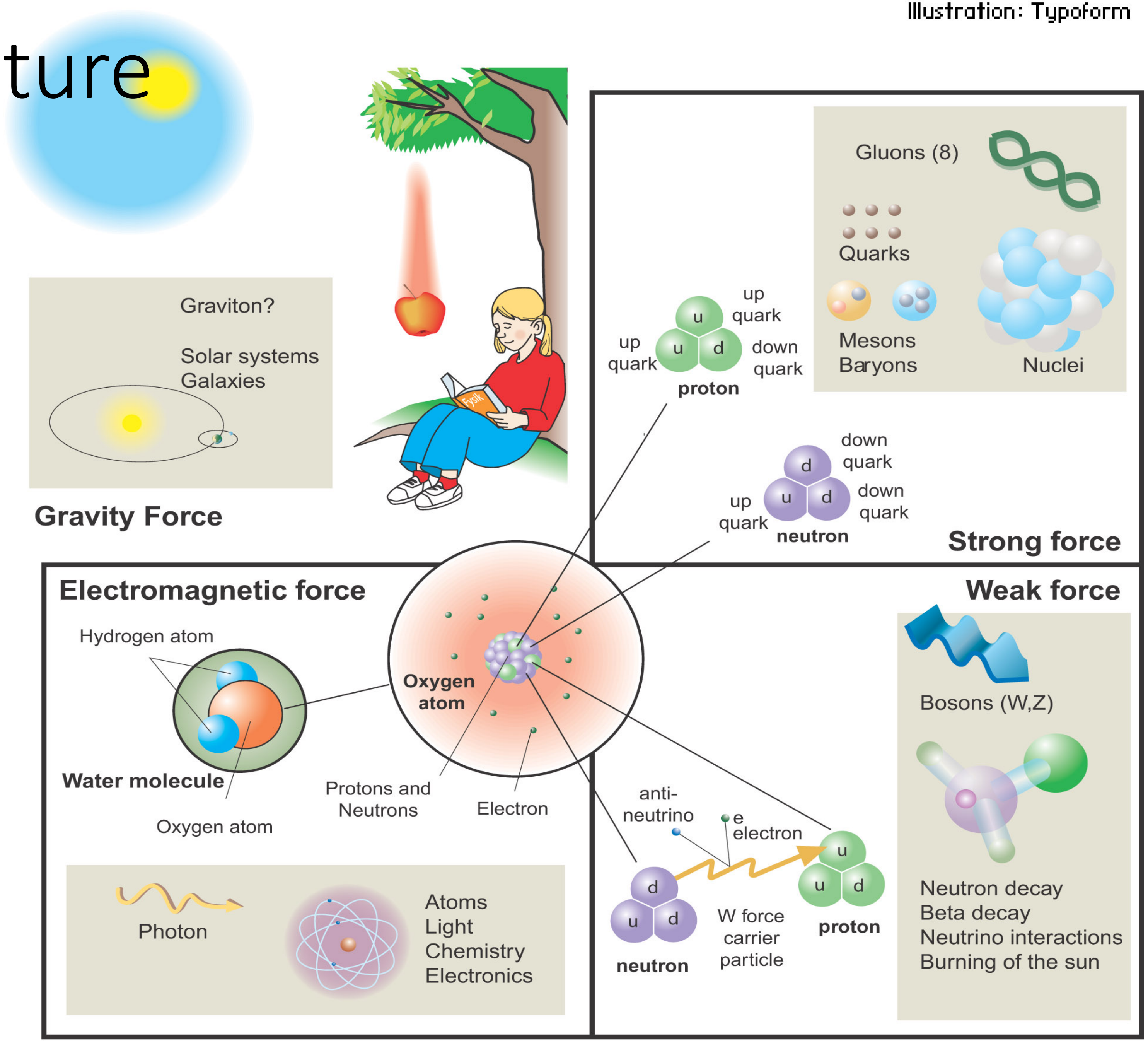


Illustration: Typoform

The Strong Force Explained!

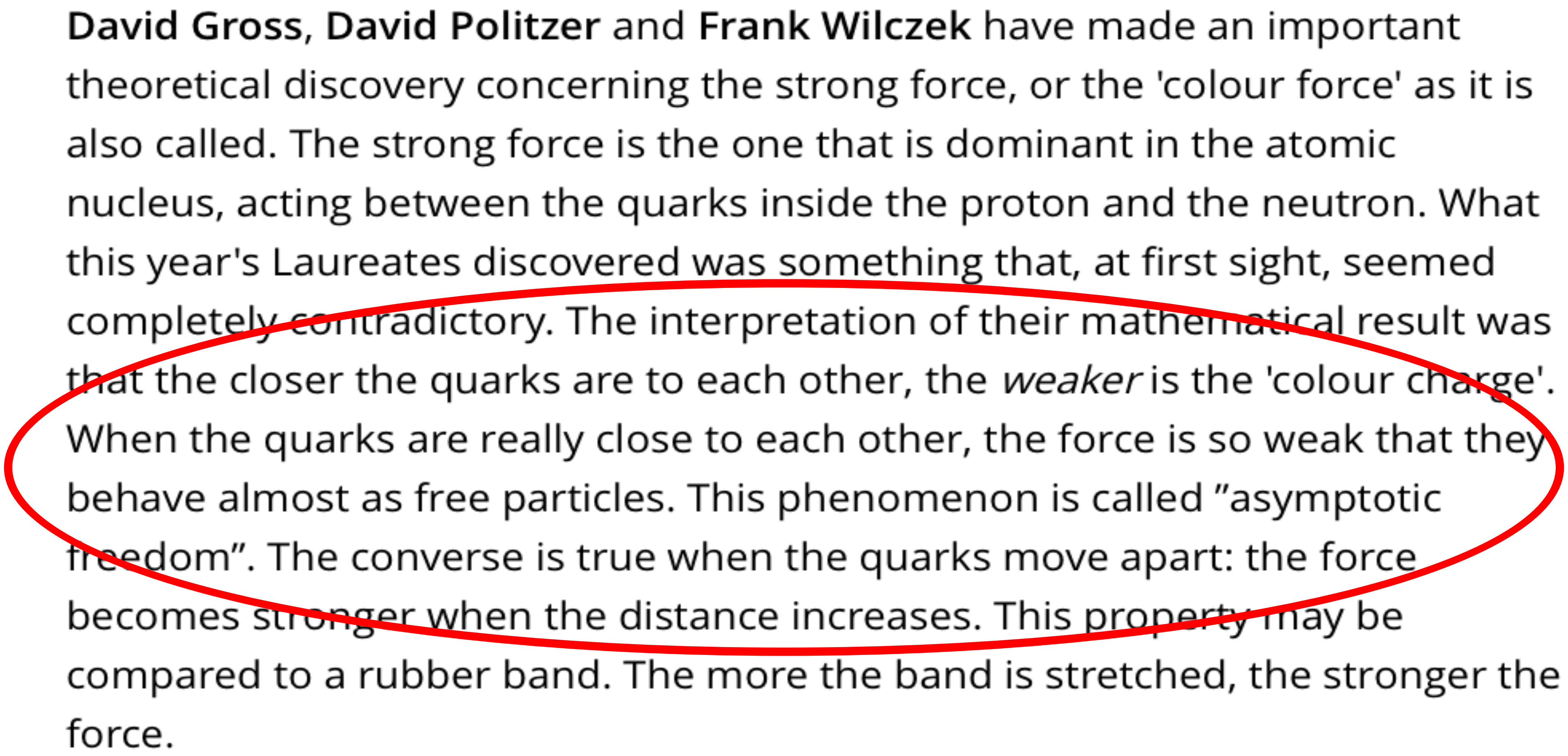
The Nobel Prize in Physics 2004

David J. Gross
Prize share: 1/3

H. David Politzer
Prize share: 1/3

Frank Wilczek
Prize share: 1/3

The Strong Force Explained!



David Gross, **David Politzer** and **Frank Wilczek** have made an important theoretical discovery concerning the strong force, or the 'colour force' as it is also called. The strong force is the one that is dominant in the atomic nucleus, acting between the quarks inside the proton and the neutron. What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called ”asymptotic freedom”. The converse is true when the quarks move apart: the force becomes stronger when the distance increases. This property may be compared to a rubber band. The more the band is stretched, the stronger the force.

The theory of Strong Force has a flaw!

It predicts Time reversal violation!

Frank Wilczek

"…Wouldn't it be great to be able to turn back the flow of time? To grow younger, for a change, instead of older? It's a long-standing fantasy, which has proved difficult to pull off in practice. But is there a fundamental barrier, rooted in the laws of physics?

For many centuries, the answer appeared to be "No". If you imagined taking a movie, and then reversing the order of its frames, the new movie would still depict (it seemed) a physically possible history of events. That assertion holds true in Newtonian mechanics, in Einstein's relativity, and in quantum electrodynamics, which governs, in the words of Paul Dirac, "all of chemistry and most of physics". Physicists elevated such time-reversibility to a fundamental principle, called time reversal invariance, or simply T."

Frank Wilczek

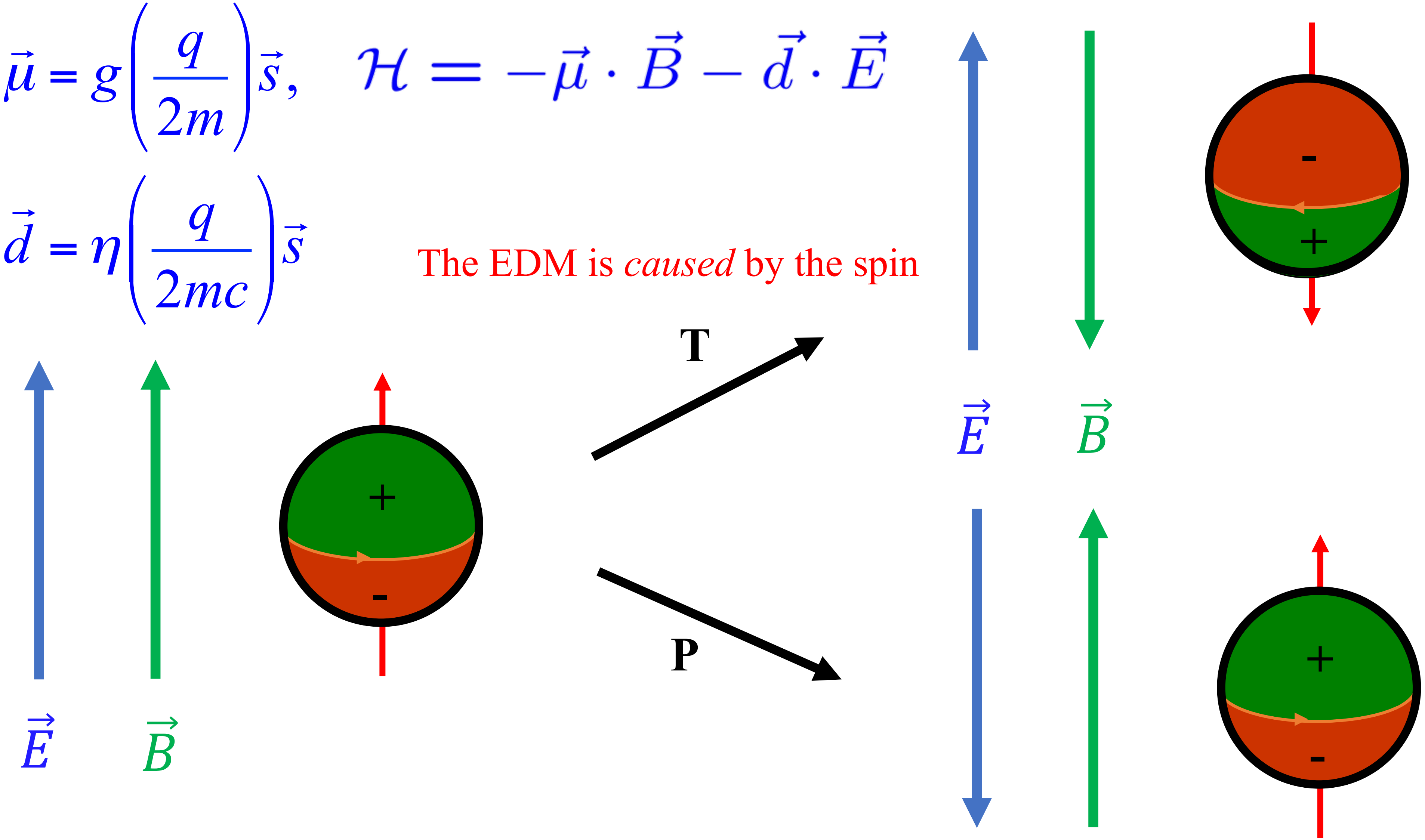
"…There is a term that leads to T violation in the strong forces among quarks and gluons, the particles that combine to make protons (and neutrons, and other atomic nuclei). It remains mysterious. For despite heroic efforts, no effect of this kind has ever been observed."

A Permanent EDM Violates both T & P Symmetries:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}, \quad \mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

The EDM is *caused* by the spin



Reminder: batteries are allowed in the SM!

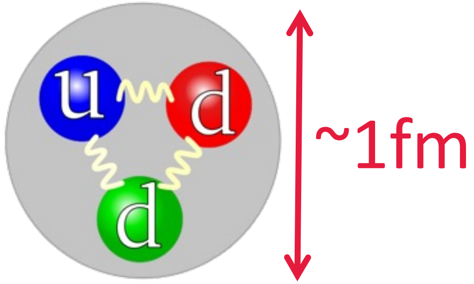
Purcell and Ramsey:

"The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle…becomes a purely experimental matter"

Phys. Rev. 78 (1950)

Strong CP-problem and neutron EDM

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



Dimensional analysis (naïve) estimation of the neutron EDM:

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

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

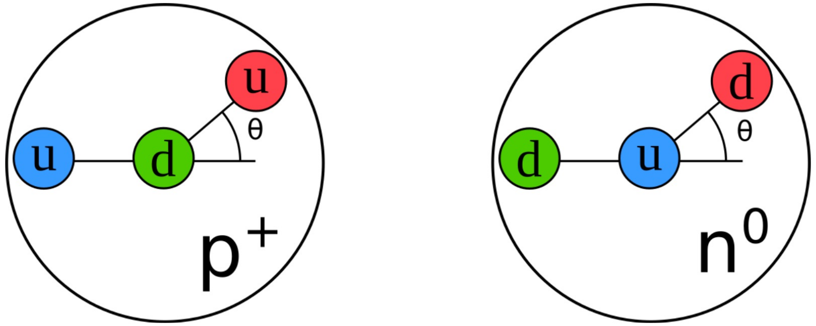
M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

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

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

Strong CP-problem: the neutron EDM is too small…

Roberto Peccei
(1942-2020)



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

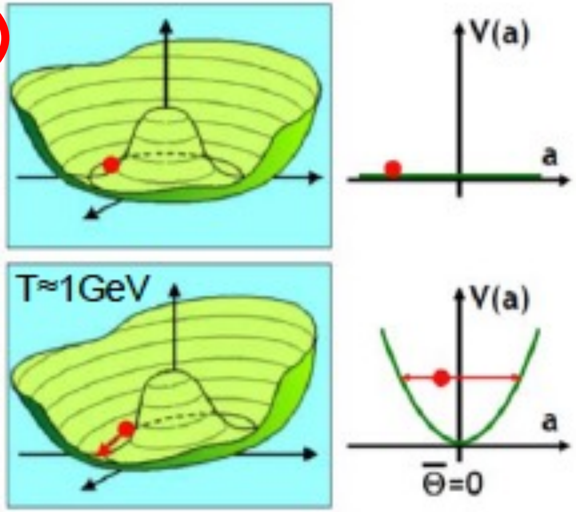
- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally.
- Weinberg and Wilczek pointed out that a new particle must exist, axion.

Strong CP-problem

- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally
- Wilczek and Weinberg: axion particle (1977)
- J.E. Kim: Hadronic axions (1979)

- Axions: pseudoscalars,

  light cousins of neutral pions



$$m_a \approx 6 \times 10^{-6}\ \text{eV}\ \frac{10^{12}\ \text{GeV}}{f_a}$$

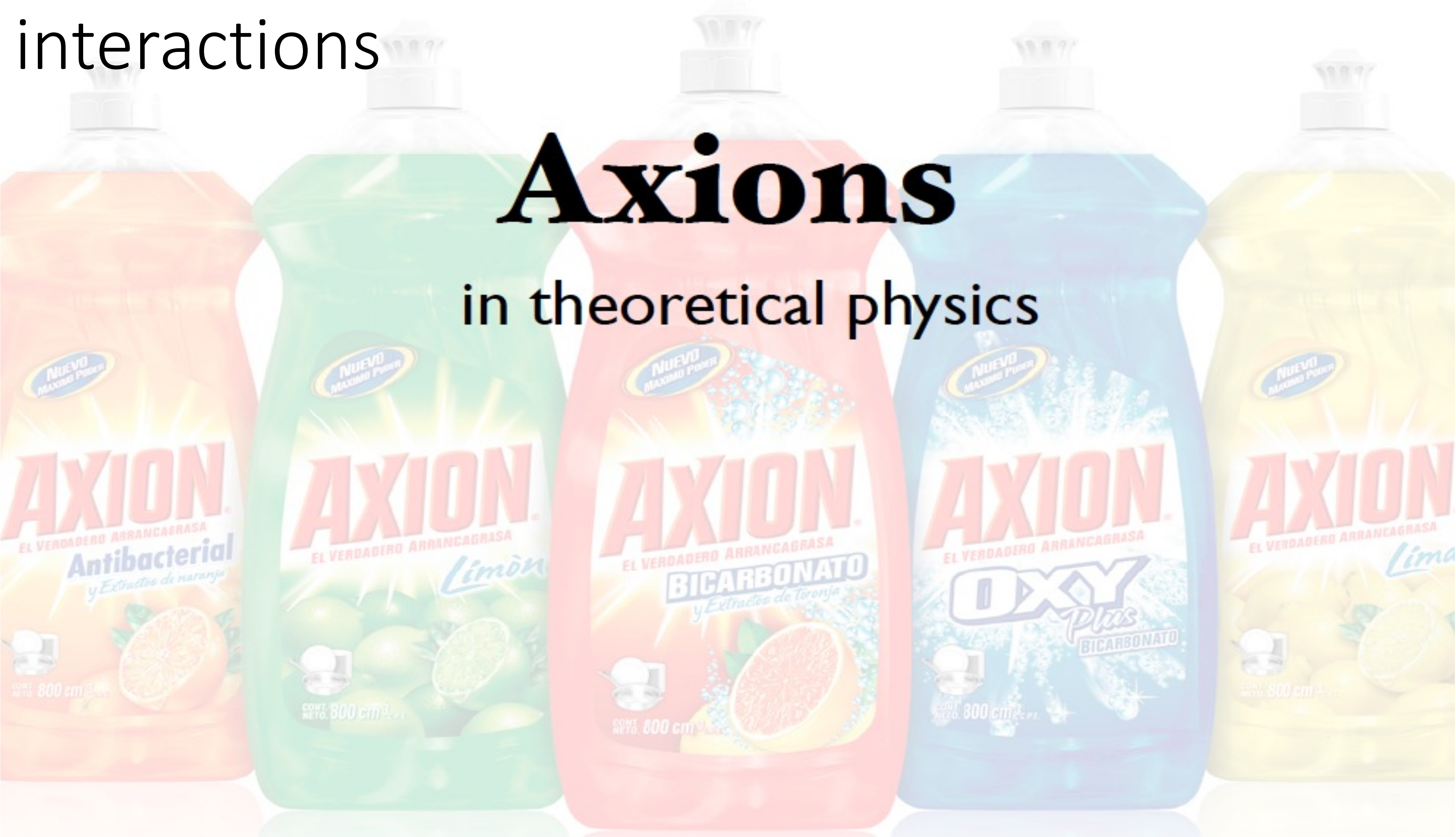
Strong CP-problem

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

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

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

Named by Frank Wilczek as axions "cleaned up" a mess in theoretical physics of the strong interactions



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.

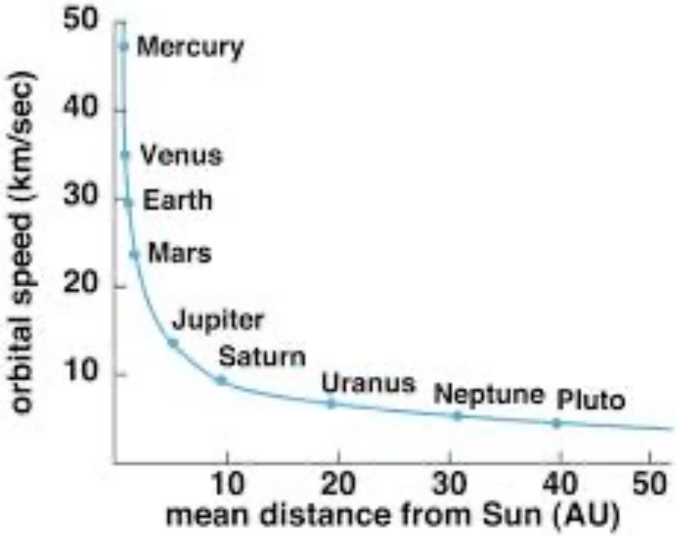
Newton’s laws: “observing” the unseen

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

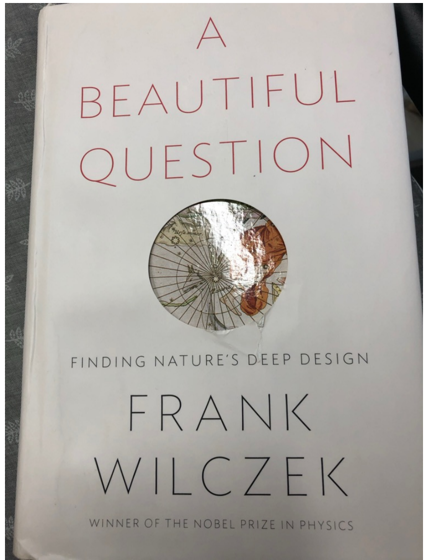
$$F = \frac{GM_{\odot}m}{r^2} = \frac{mv^2}{r}$$

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

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



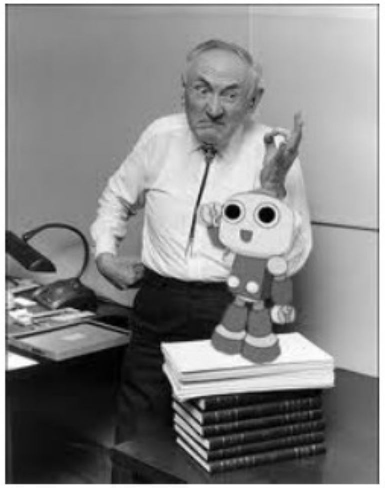
1846, Adams and Le Verrier suggested the existence of Neptune: First discovery of “Dark Matter”. Frank Wilczek in “A Beautiful Question”



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

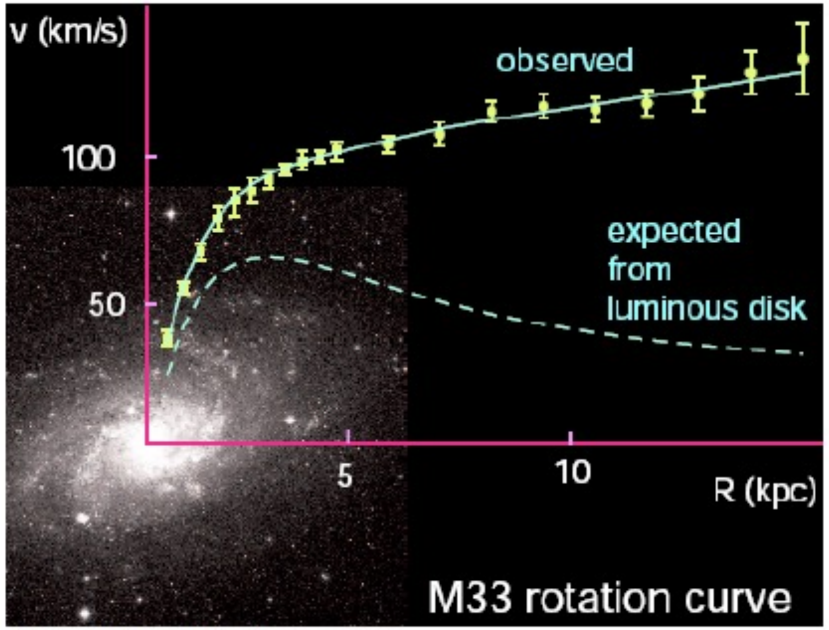
Virial motions within galaxy clusters:

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

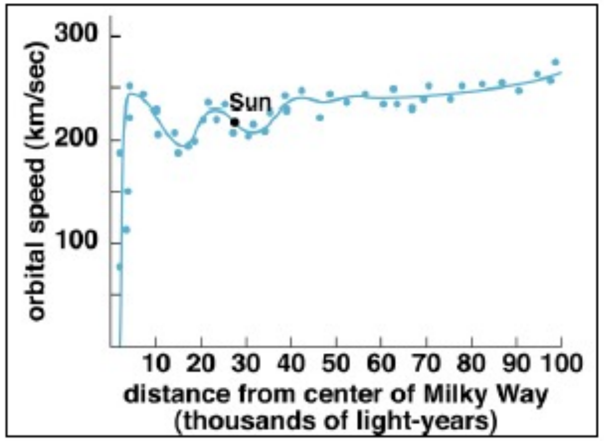
The "dunkelmaterie" of Zwicky 1936

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.

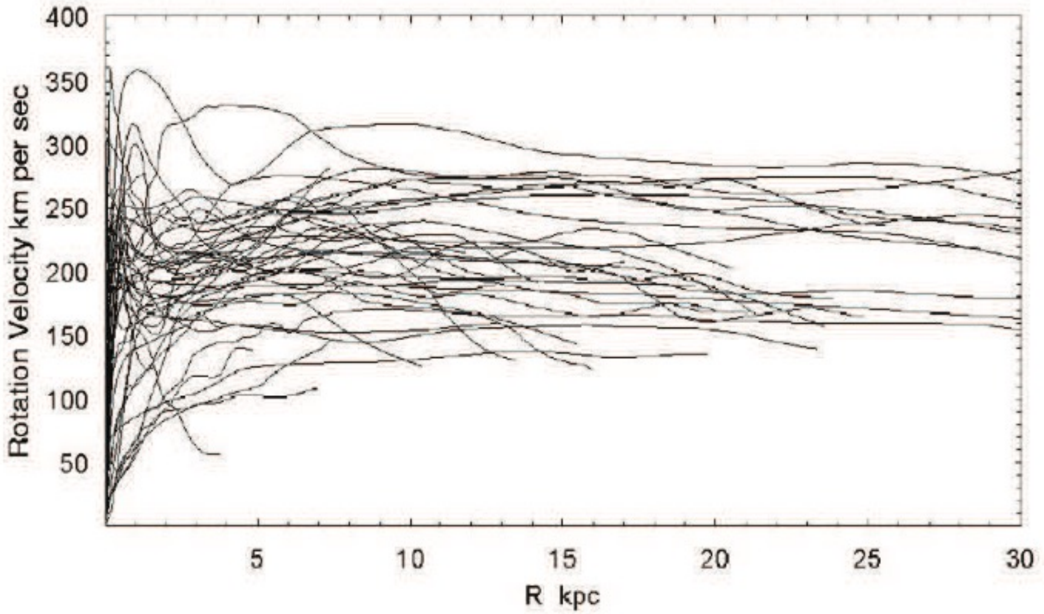


Figure 4: Rotation curves of spiral galaxies obtained by combining CO data for the central regions, optical for disks, and HI for outer disk and halo (Sofue et al. 1999).

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

A Galaxy without Dark Matter, effectively confirming Dark Matter!

(This “discovery” is critical to be confirmed!)

A Galaxy Without Dark Matter

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

NGC 1052-DF2

©YALE/NASA

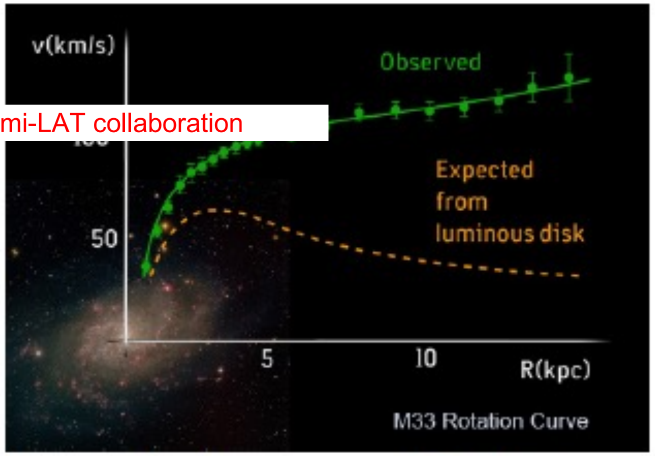
A Yale-led research team has discovered a galaxy that contains no dark matter -- a finding that confirms the possibility of dark matter as a separate material elsewhere in the universe.

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.

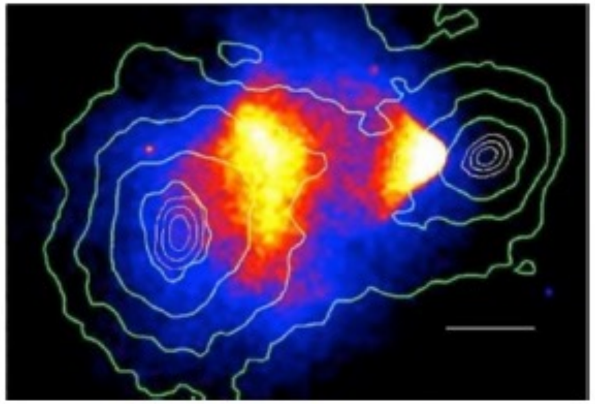
Evidence for / Salient Features of Dark Matter

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

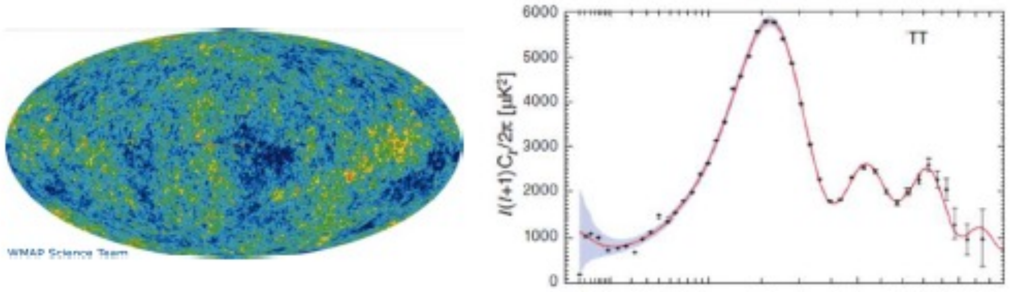
Eric Charles, Fermi-LAT collaboration



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

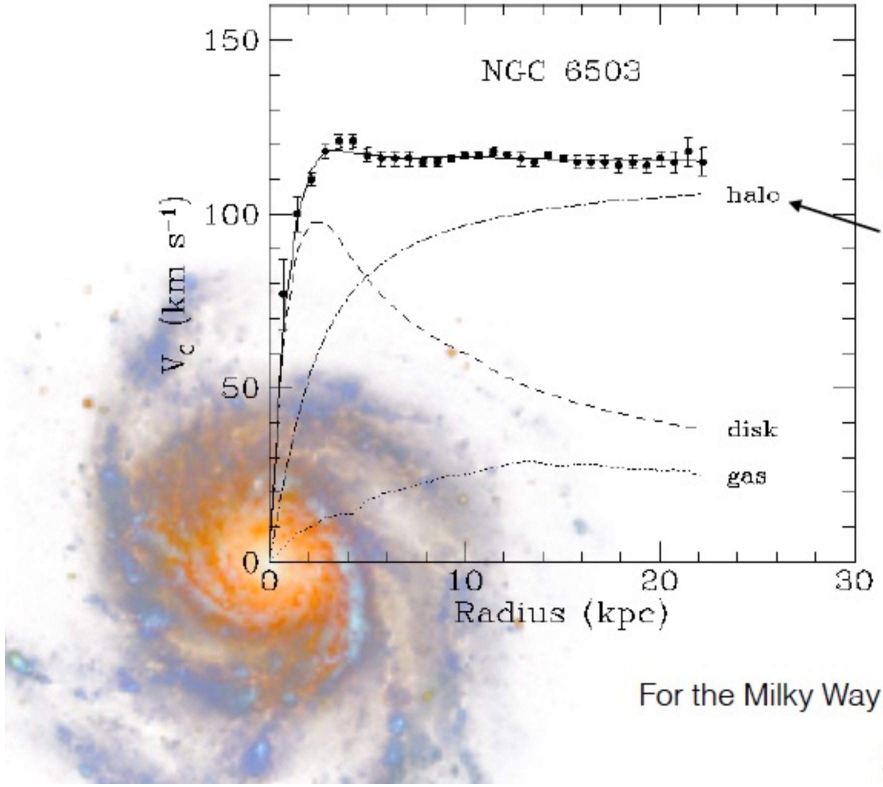


*Almost **collisionless***
Bullet Cluster
Clowe+(2006)



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

Rotation curves (10’s kpc)



observation

missing mass

expectation

For the Milky Way fit yields at sun’s position

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

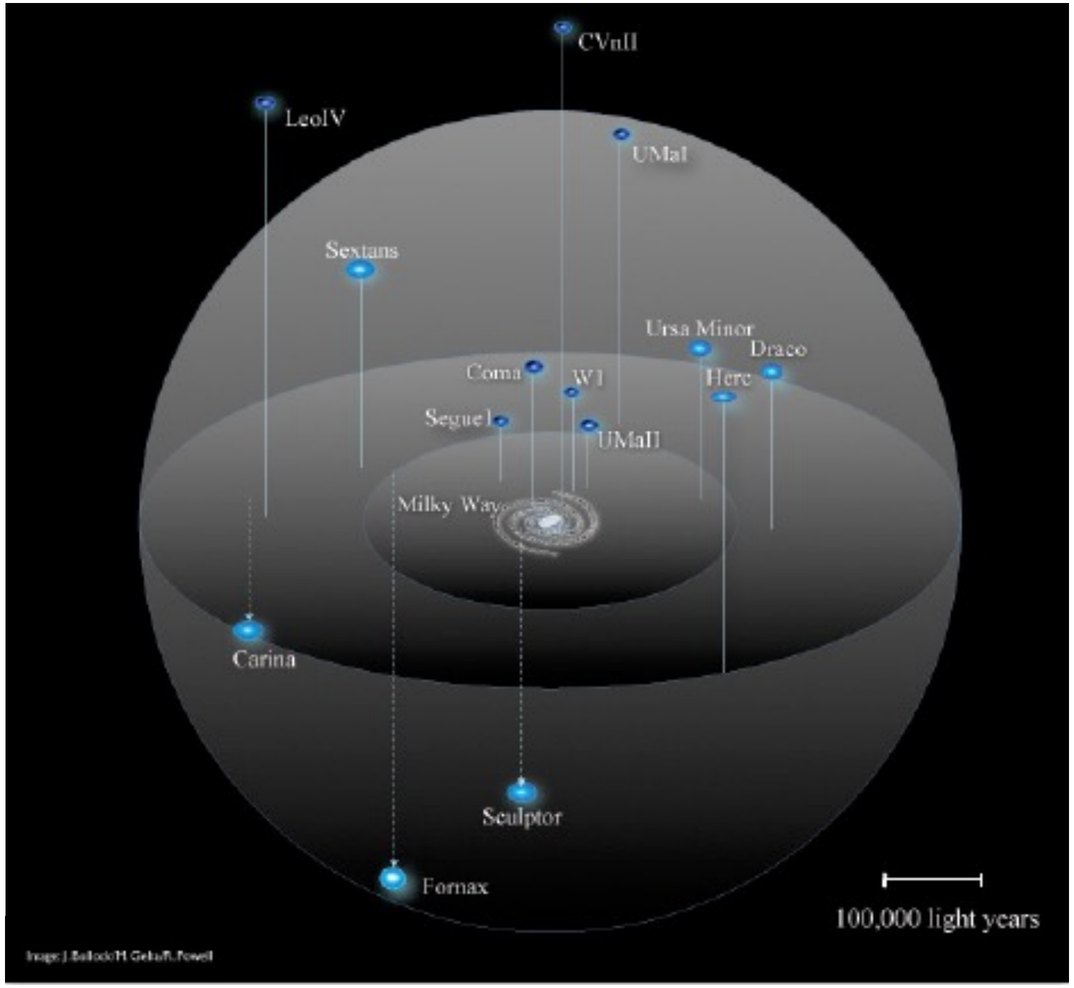
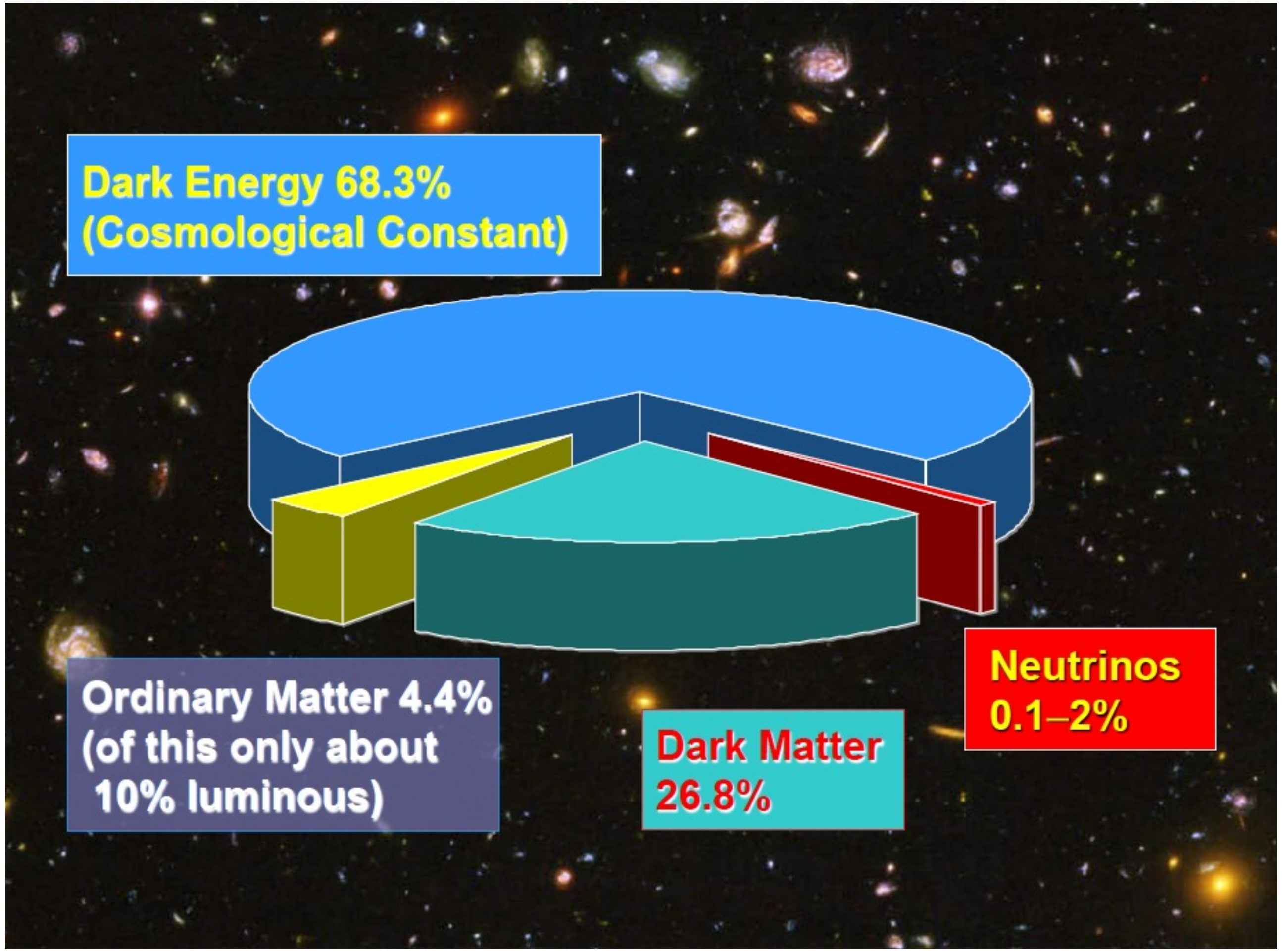


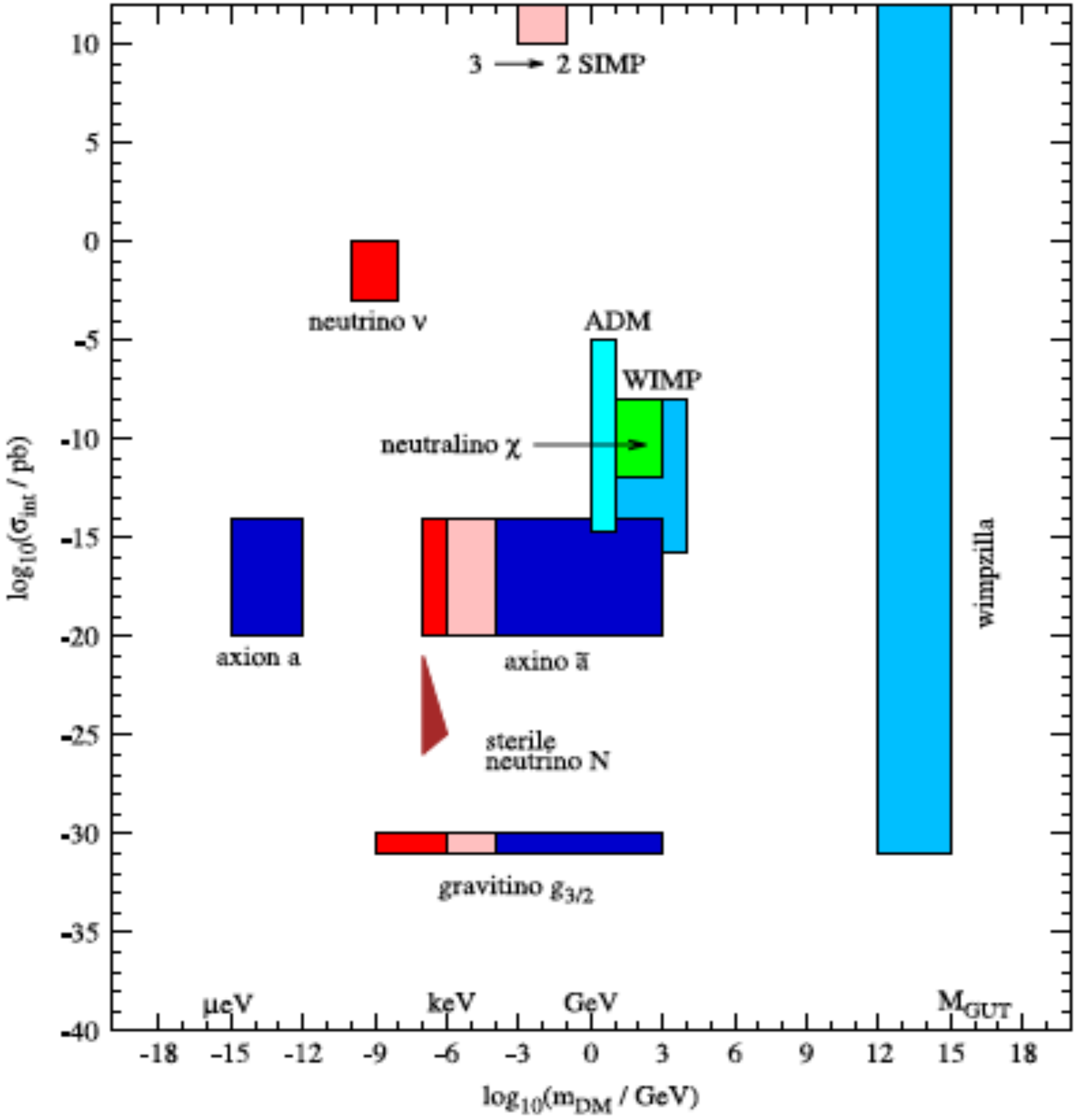
Image: J. Bullock/M. Geha/R. Powell

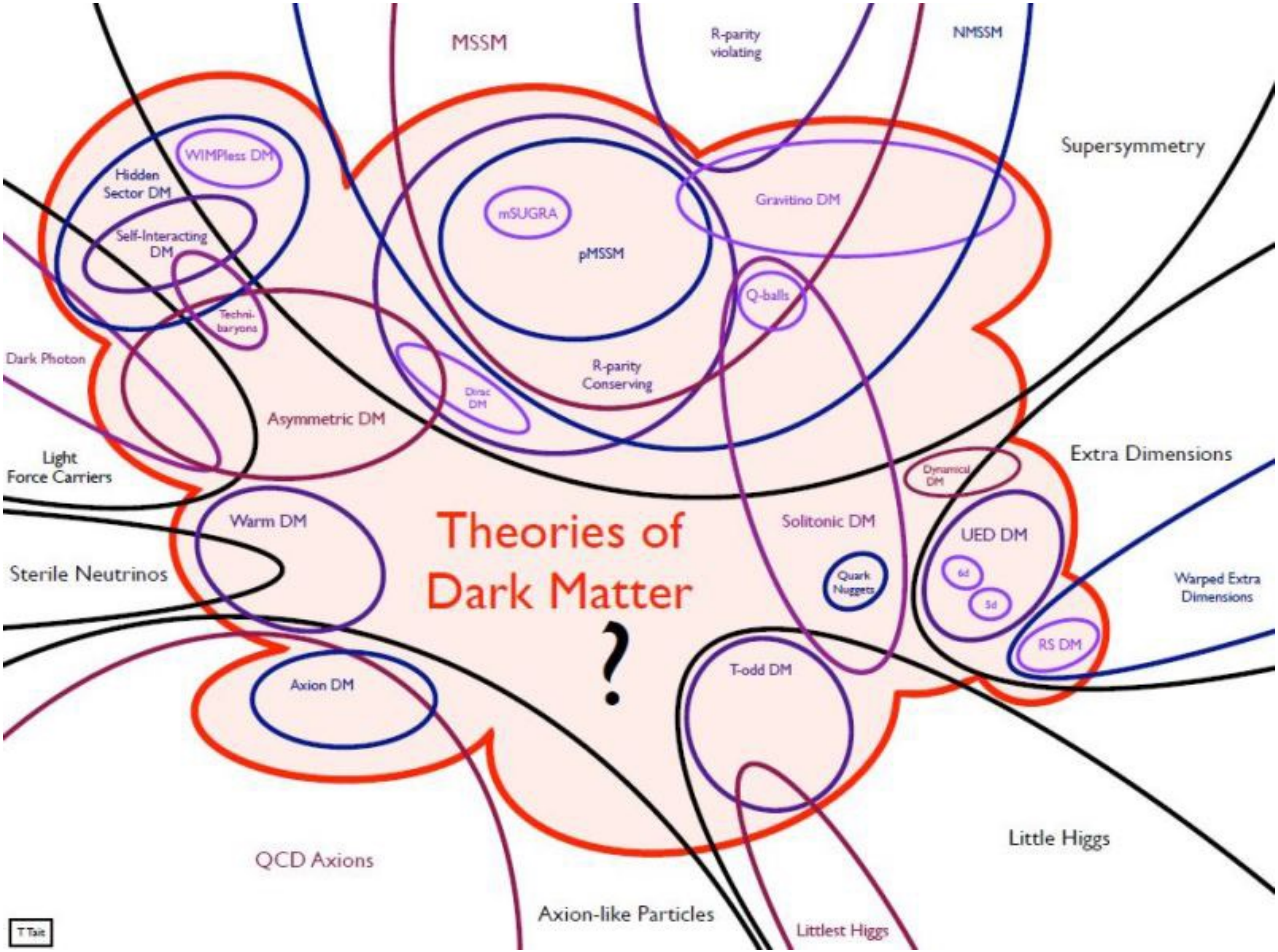
Cosmological inventory



Dark matter candidates

4 *H. Baer et al. / Physics Reports 555 (2015) 1–60*





Theories of Dark Matter

?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Dark Photon

Asymmetric DM

Light Force Carriers

Extra Dimensions

Dynamical DM

Warm DM

Solitonic DM

UED DM

6d

5d

Sterile Neutrinos

Quark Nuggets

Warped Extra Dimensions

RS DM

Axion DM

T-odd DM

Little Higgs

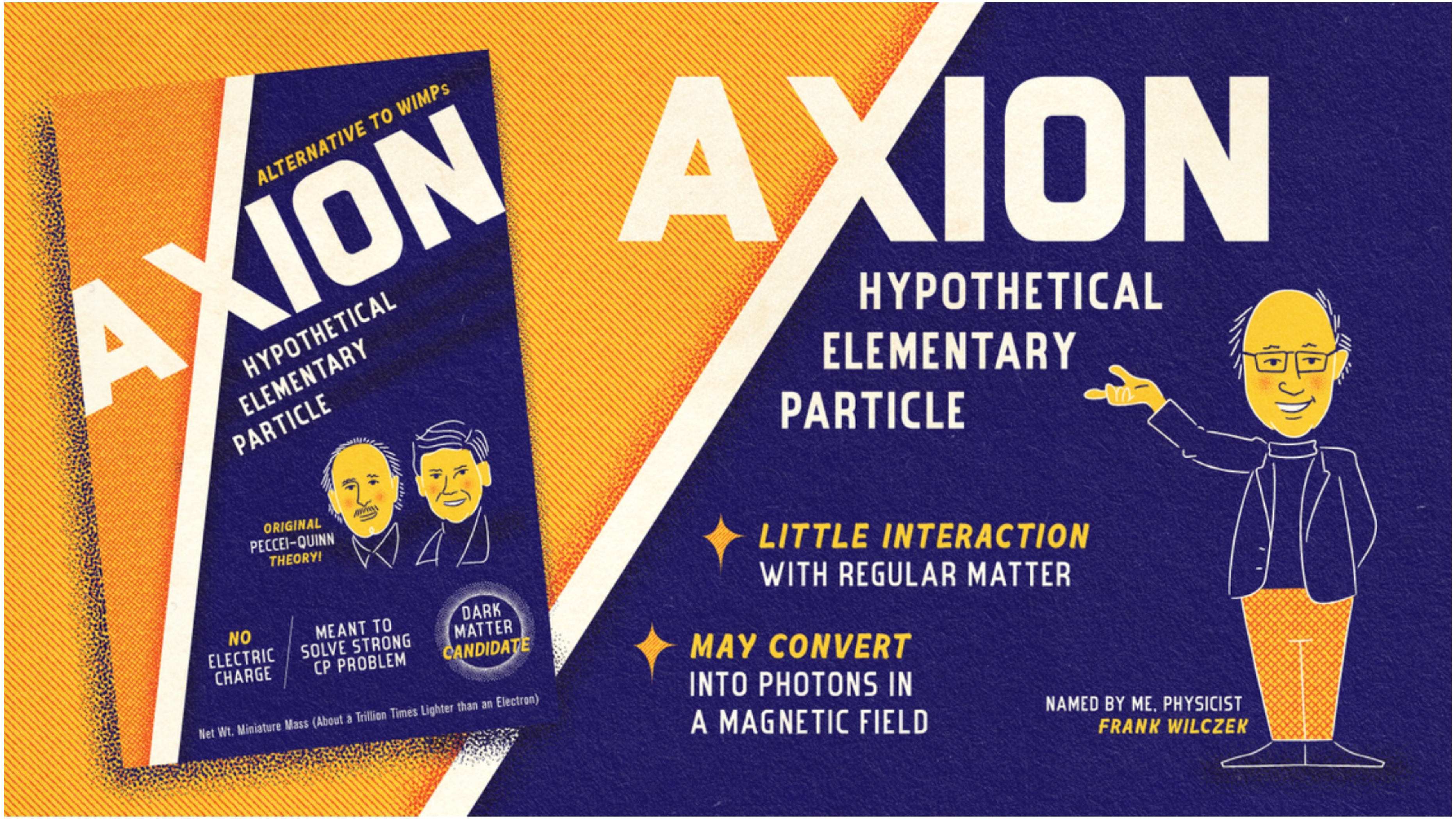
QCD Axions

Axion-like Particles

Littlest Higgs

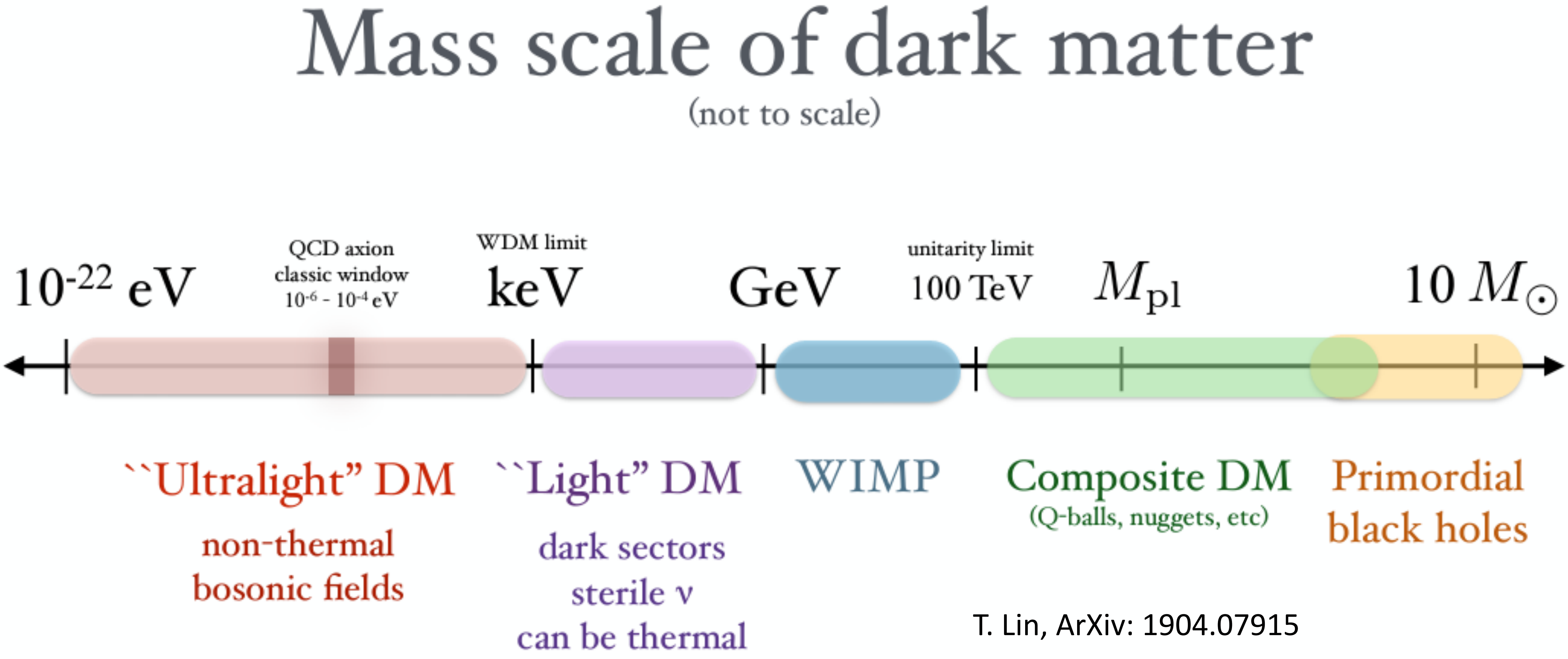
T Tait

Axions: A leading Dark Matter Candidate

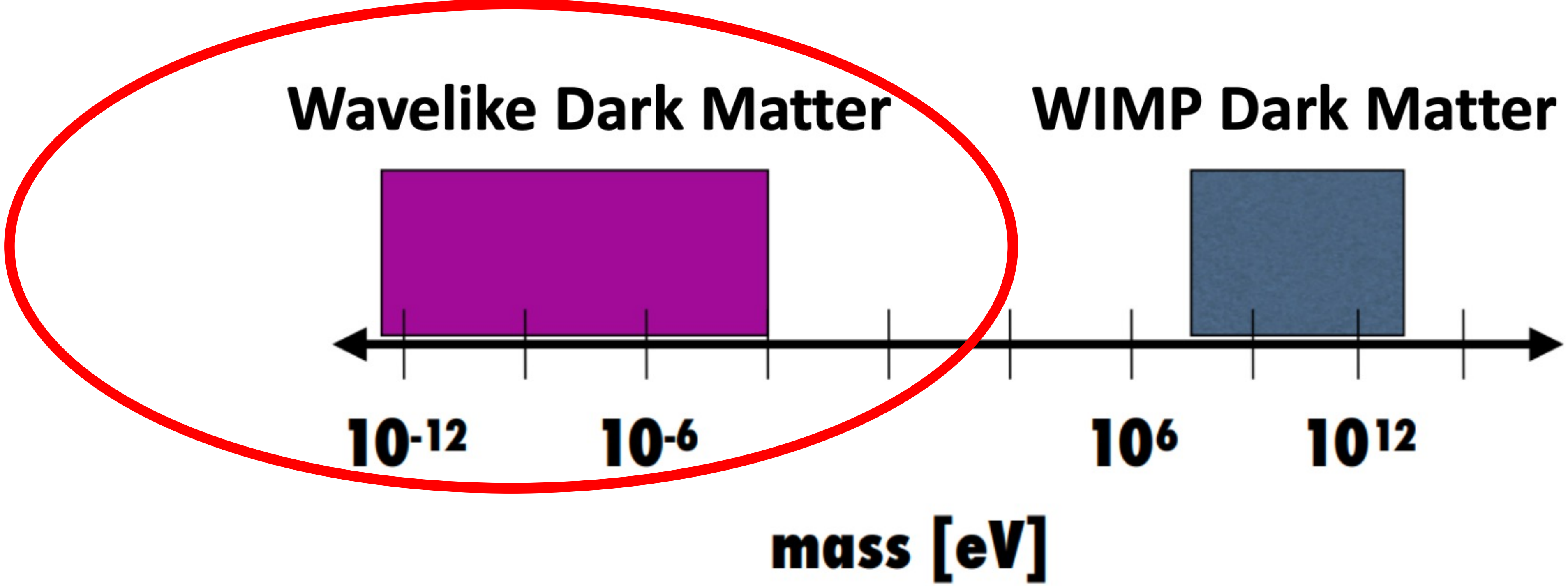


(https://www.symmetrymagazine.org/sites/default/files/images/standard/Inline_1_Axion.png)

Vast range



T. Lin, ArXiv: 1904.07915



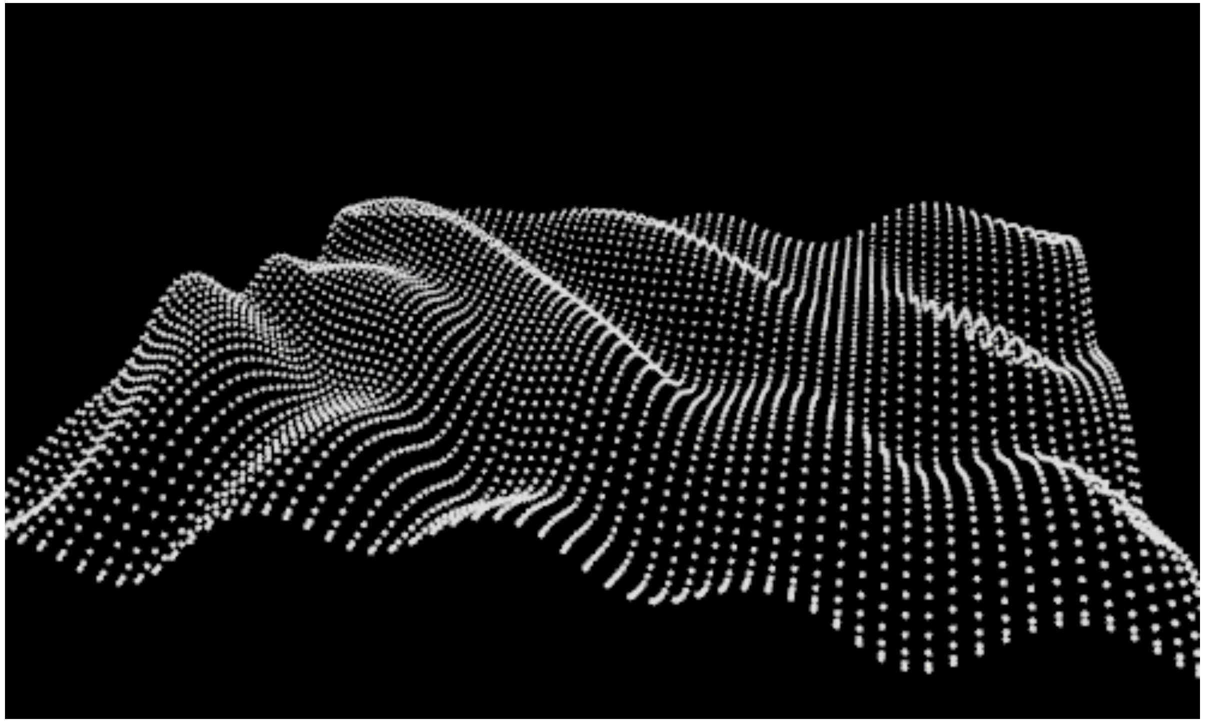
de Broglie Wavelength - $\lambda_{dB} \approx \frac{2\pi}{mv}$ Occupancy Number - $N \approx \frac{\rho_{DM}}{m}\lambda_{dB}^3$

- 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

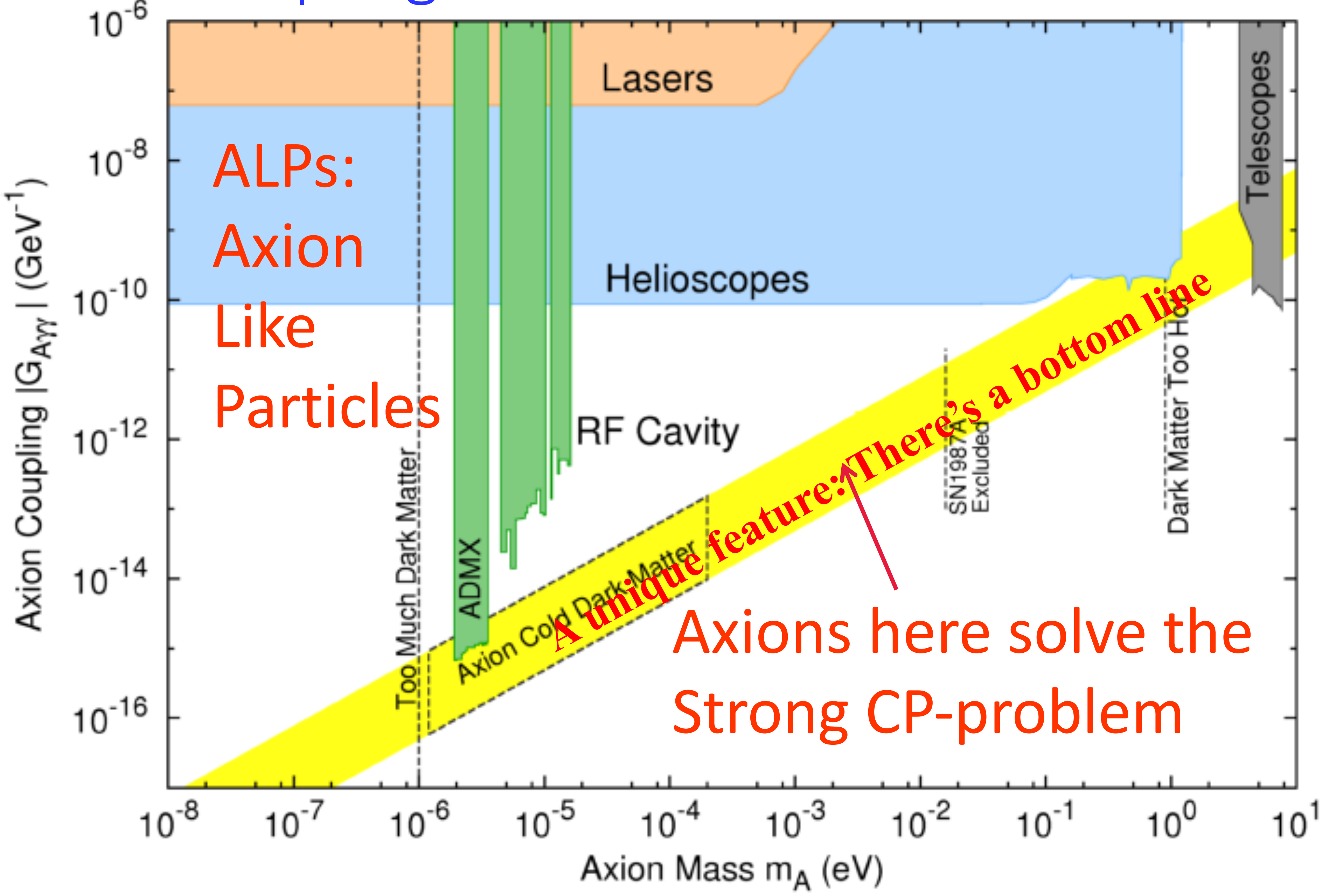
$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

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

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.

Axion coupling vs. axion mass



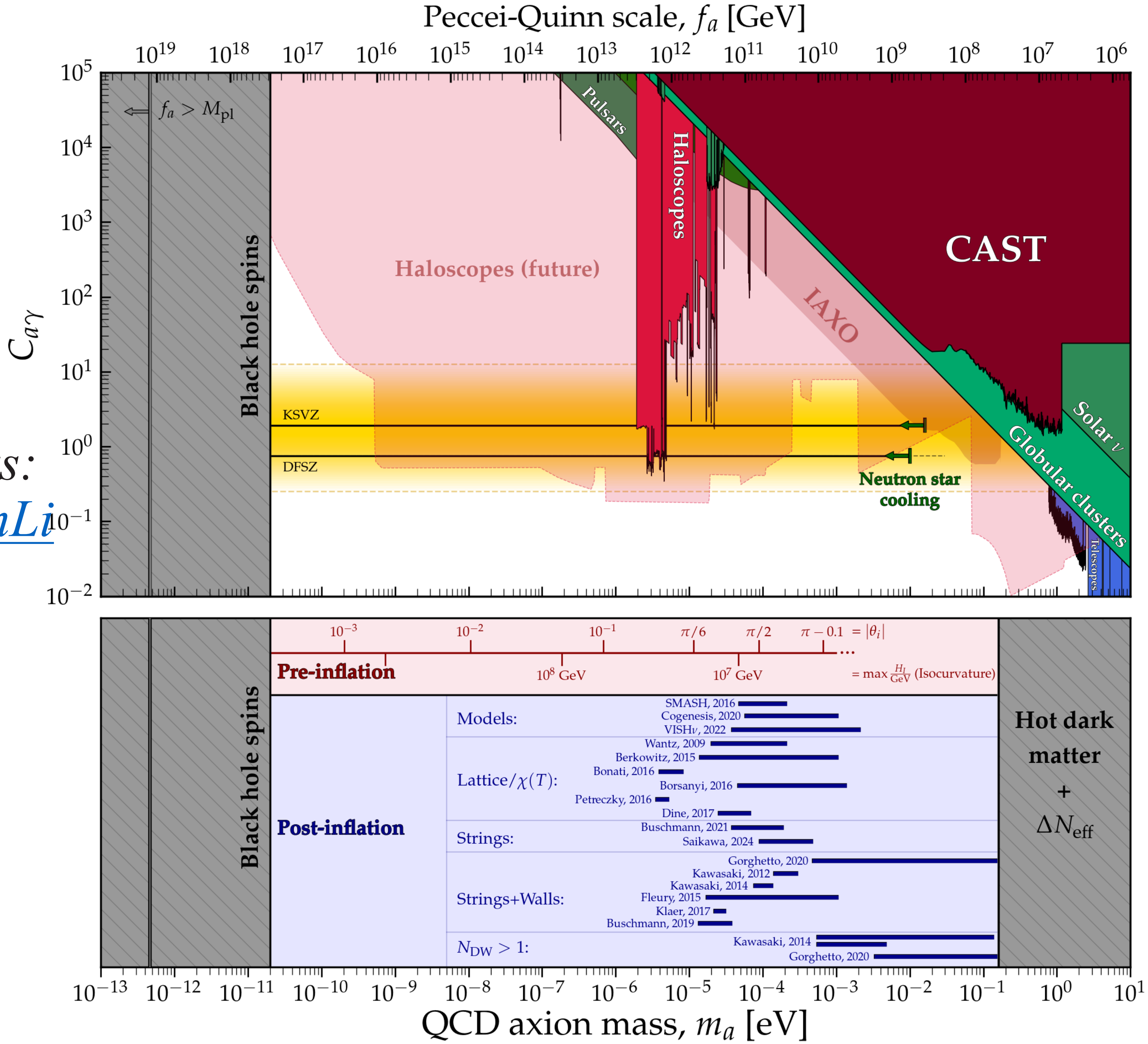
ALPs:
Axion
Like
Particles

A unique feature: There's a bottom line

Axions here solve the Strong CP-problem

Axion coupling vs. axion mass

C. O'Hare, cajohare/axionlimits: https://cajohare.github.io/AxionLimits/



World map of current experiments on wavy dark matter

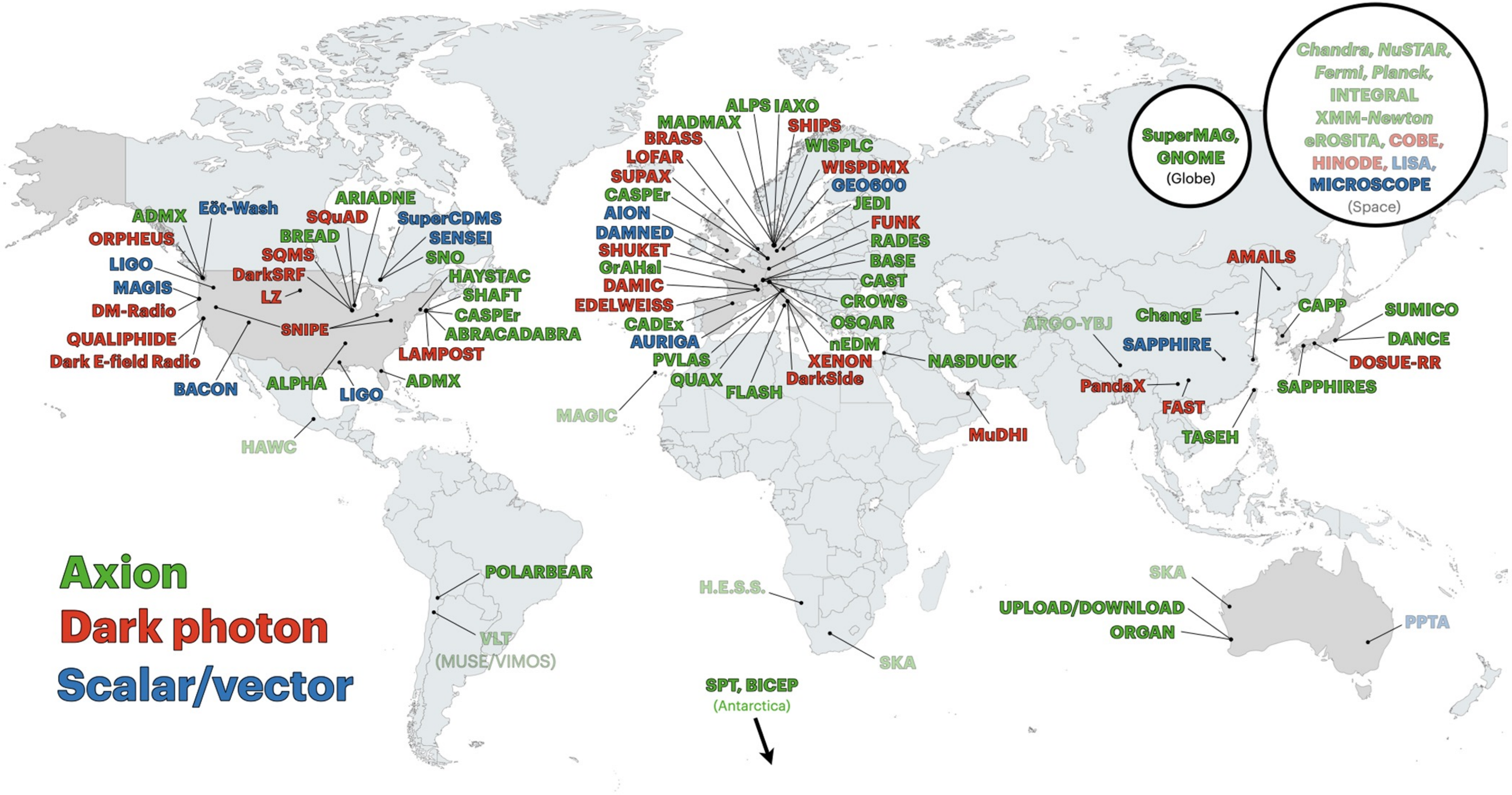
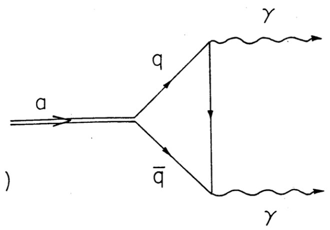
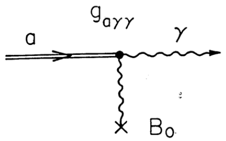


Figure 6: World map displaying current experiments searching for wavy dark matter [9].

Axion Couplings



(a)



(b)

- 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)

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

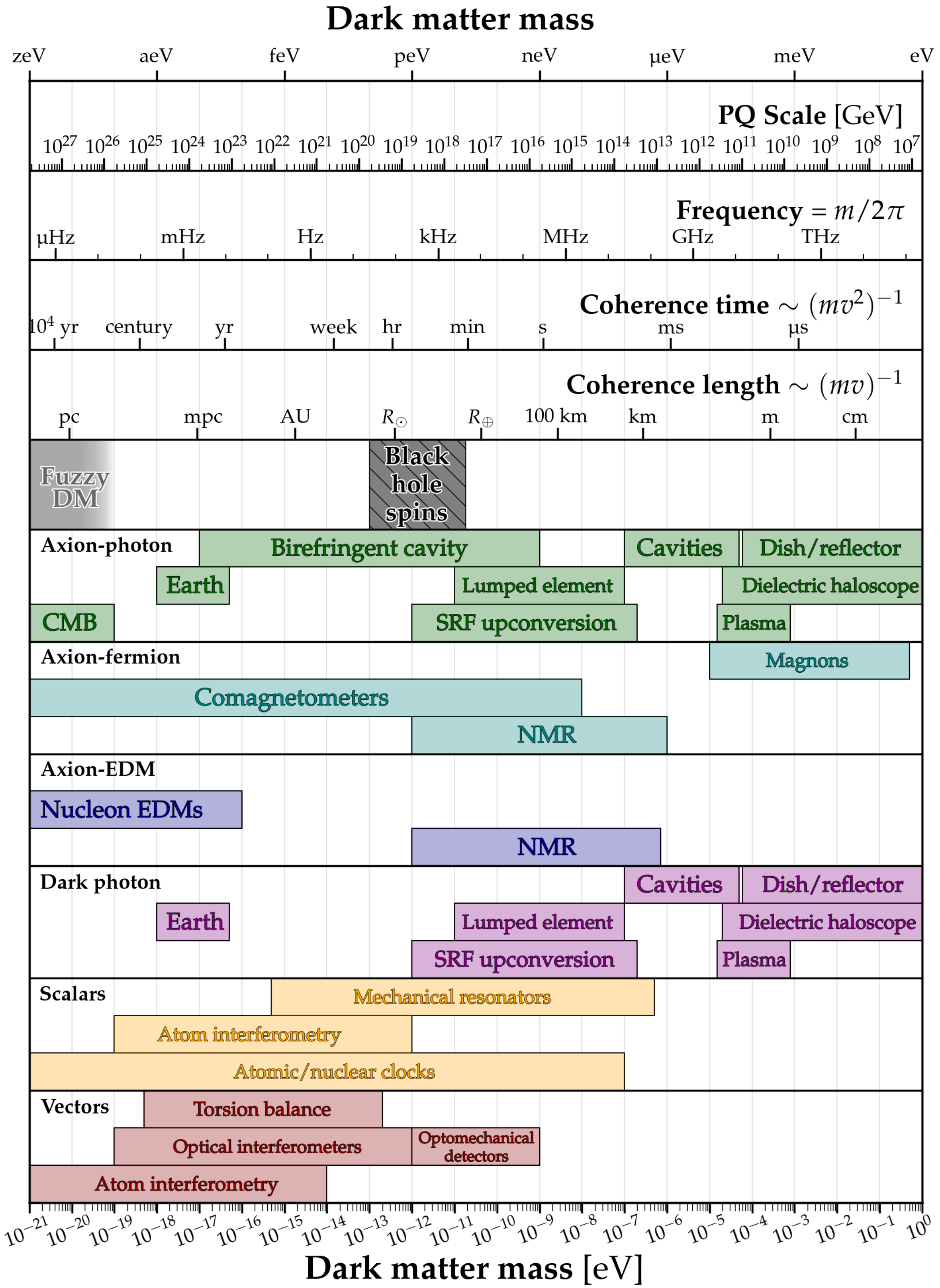
- Fermions (coupling with axion field gradient, pseudomagnetic field, CASPEr-Electric, ARIADNE; GNOME)

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

Axion Couplings

- Experiments for various couplings

- *C. O'Hare, cajohare/axionlimits:*
- [*https://cajohare.github.io/AxionLimits/*](https://cajohare.github.io/AxionLimits/)



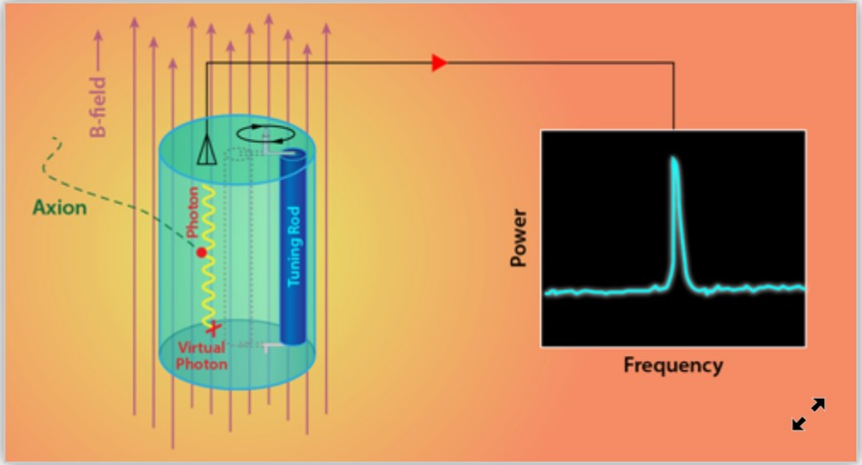
Axion Detection Scheme (Haloscope)

- 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

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

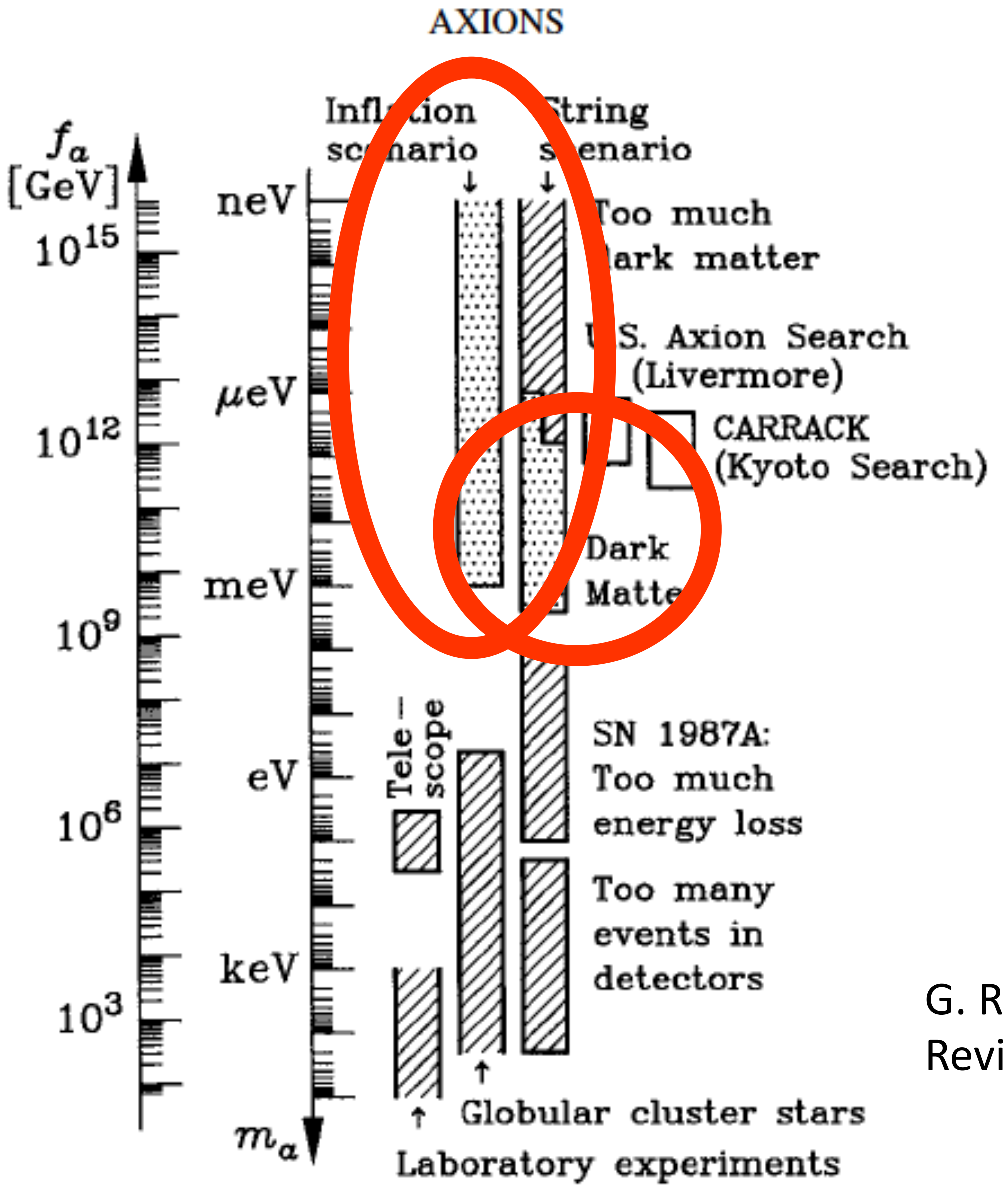


C. Boutan/Pacific Northwest National Laboratory; adapted by APS/**Alan Stonebraker**

Running Axion Experiments (Haloscope)

ADMX
HAYSTAC
CAPP

Axion parameters range



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

Axion Dark matter

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

Major activities

- ADMX (UW, microwave cavity)
- HAYSTAC (Yale, microwave cavity)
- IBS/CAPP (CULTASK, multiple microwave cavities)
- ORGAN (UWA, high frequency)
- KLASH (KLOE magnet in Frascati, microwave cavity)
- MADMAX (DESY, dielectric interfaces)
- ALPs (DESY, coupled FP resonators)
- CAST-CAPP (CERN, rectangular cavities-TE modes)
- Dark Matter RADIO

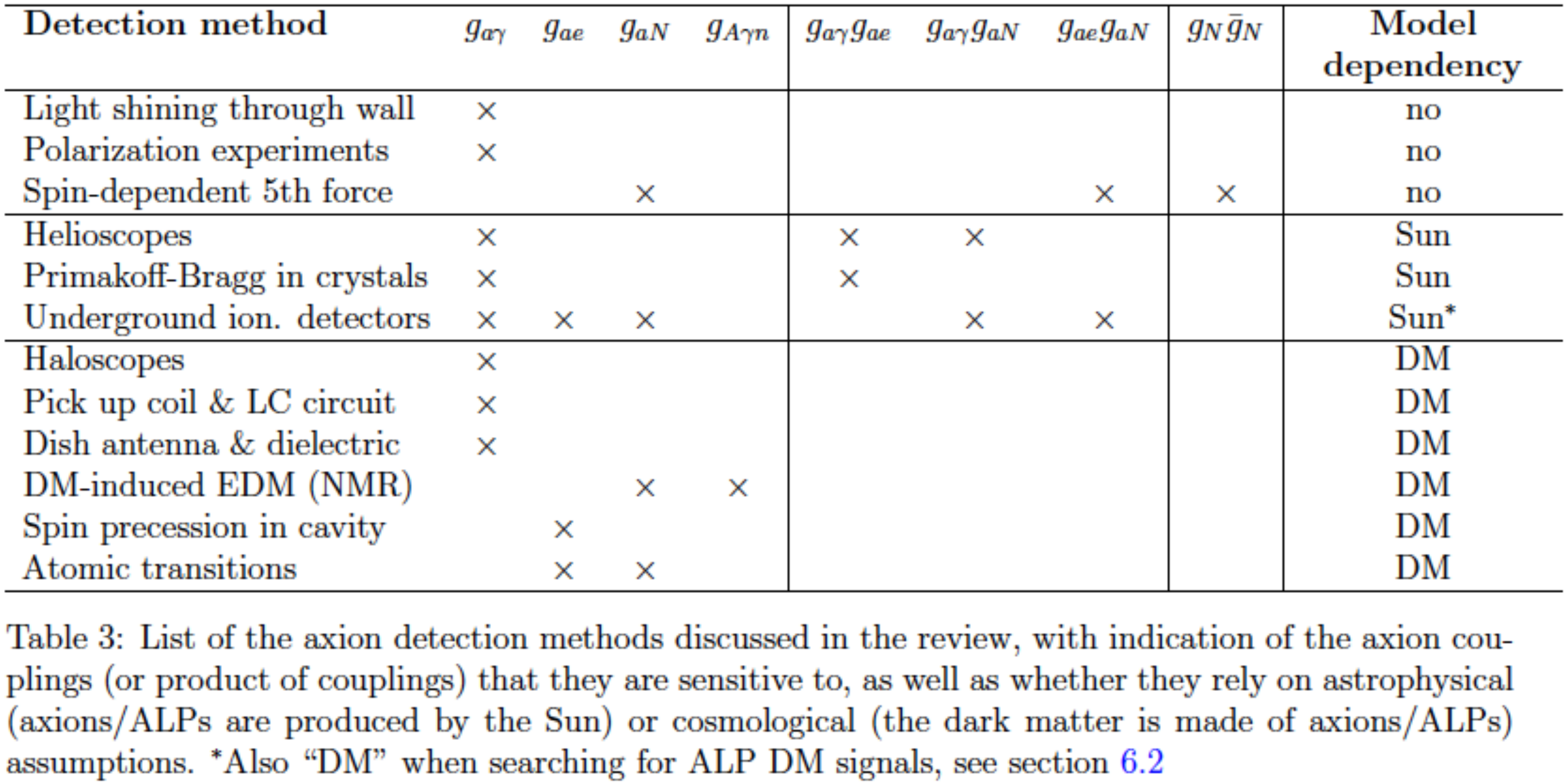
Major activities

- CASPEr electric (Boston Univ.)
- CASPEr axion-wind (MAINZ)
- Oscillating neutron-EDM (PSI)
- Axion-EDM (JEDI at Juelich)

Major activities

- GNOME (Axion domain walls, stars; International network)
- ARIADNE (Axion-mediated long-range forces; No dark matter needed)

Axion detection method



Detection method	$g_{a\gamma}$	g_{ae}	g_{aN}	$g_{A\gamma n}$	$g_{a\gamma}g_{ae}$	$g_{a\gamma}g_{aN}$	$g_{ae}g_{aN}$	$g_N\bar{g}_N$	Model dependency
Light shining through wall	×								no
Polarization experiments	×								no
Spin-dependent 5th force			×				×	×	no
Helioscopes	×				×	×			Sun
Primakoff-Bragg in crystals	×				×				Sun
Underground ion. detectors	×	×	×			×	×		Sun*
Haloscopes	×								DM
Pick up coil & LC circuit	×								DM
Dish antenna & dielectric	×								DM
DM-induced EDM (NMR)			×	×					DM
Spin precession in cavity		×							DM
Atomic transitions		×	×						DM

Table 3: List of the axion detection methods discussed in the review, with indication of the axion couplings (or product of couplings) that they are sensitive to, as well as whether they rely on astrophysical (axions/ALPs are produced by the Sun) or cosmological (the dark matter is made of axions/ALPs) assumptions. *Also "DM" when searching for ALP DM signals, see section 6.2

Nice overview: Irastorza, Redondo 1801.08127v2

Figure of merit in various experiments

R. Battesti *et al.*, Phys. Rep. (2018)

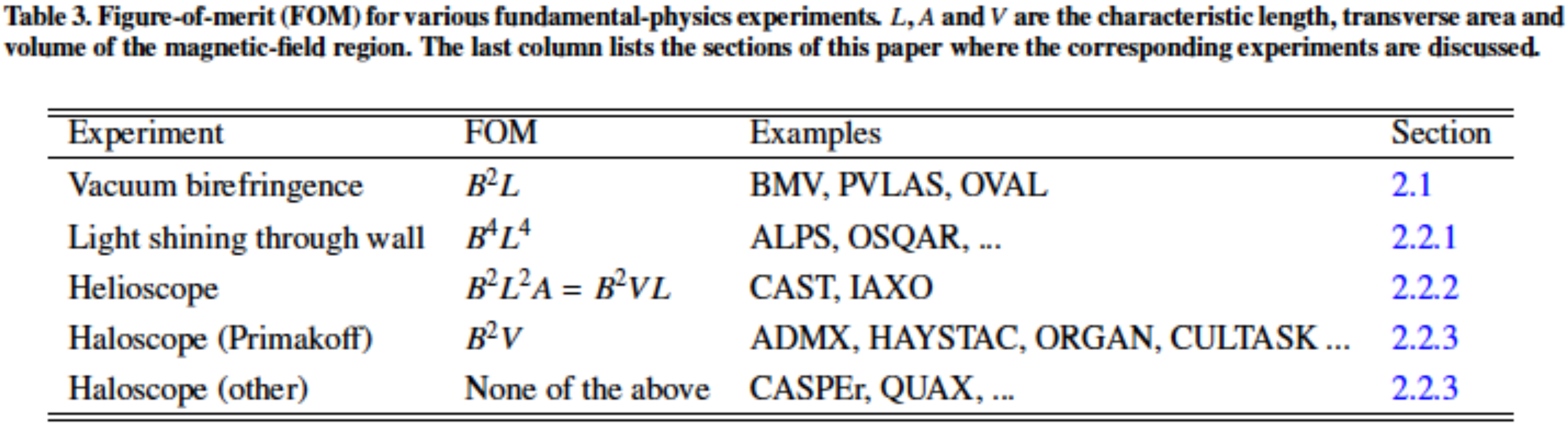


Table 3. Figure-of-merit (FOM) for various fundamental-physics experiments. L, A and V are the characteristic length, transverse area and volume of the magnetic-field region. The last column lists the sections of this paper where the corresponding experiments are discussed.

Experiment	FOM	Examples	Section
Vacuum birefringence	B^2L	BMV, PVLAS, OVAL	2.1
Light shining through wall	B^4L^4	ALPS, OSQAR, ...	2.2.1
Helioscope	$B^2L^2A = B^2VL$	CAST, IAXO	2.2.2
Haloscope (Primakoff)	B^2V	ADMX, HAYSTAC, ORGAN, CULTASK ...	2.2.3
Haloscope (other)	None of the above	CASPEr, QUAX, ...	2.2.3

Axion haloscope method by Pierre Sikivie

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

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

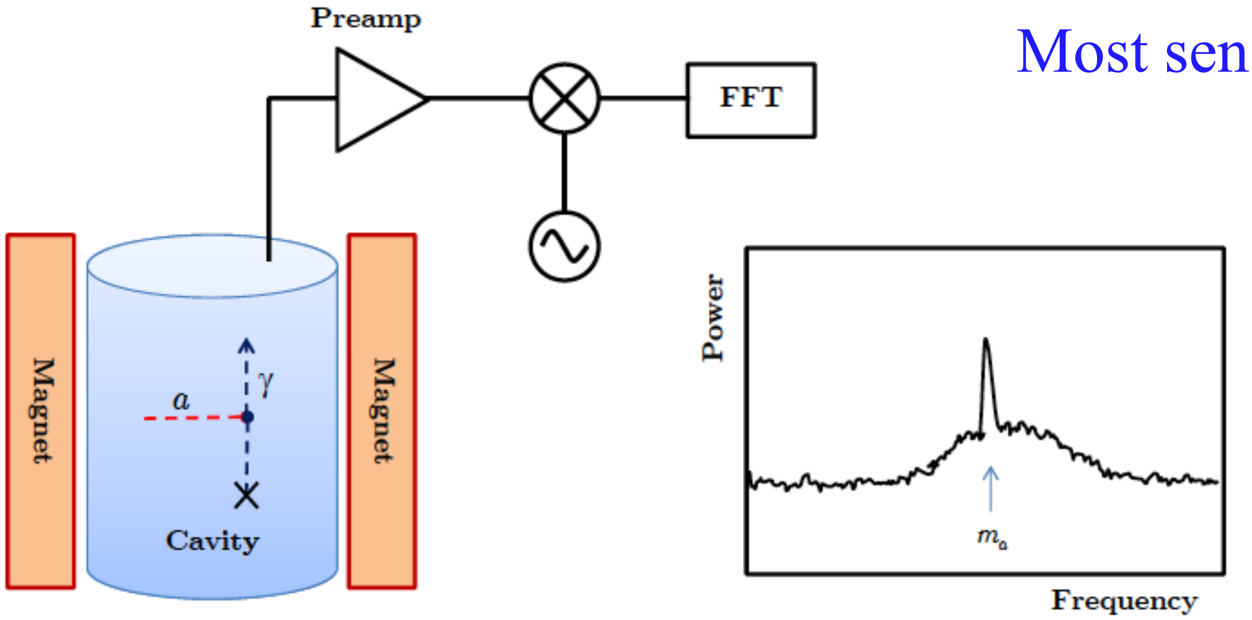


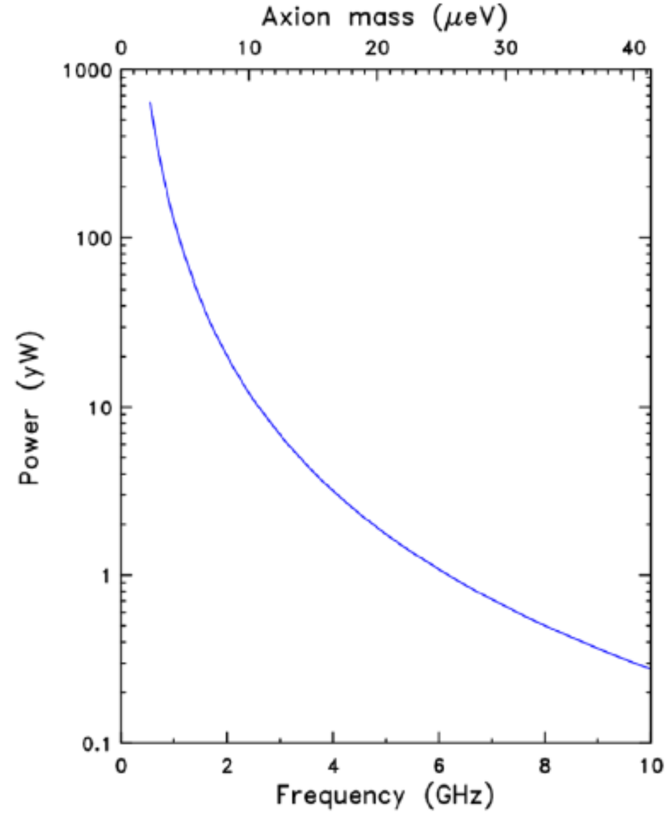
Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

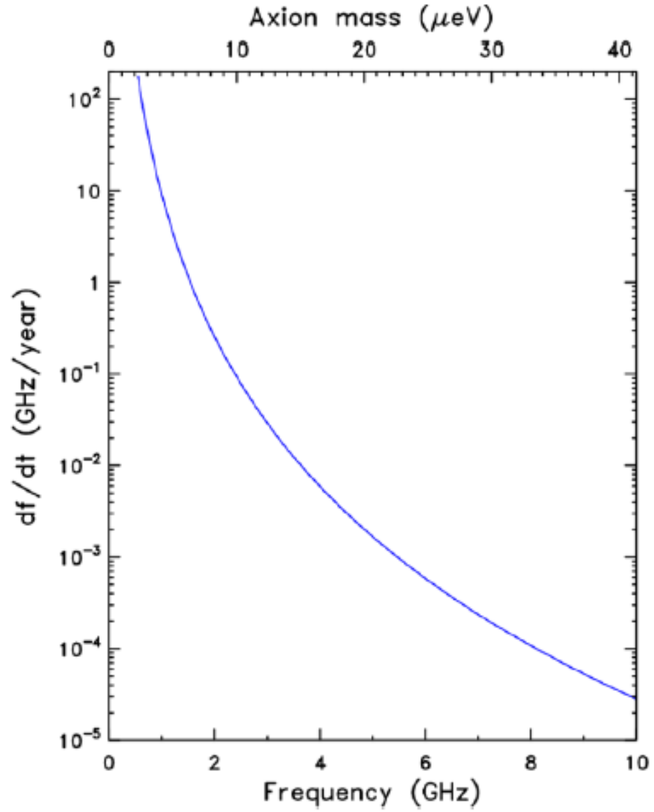
Most sensitive method

Running Haloscope Experiments:
CAPP
ADMX
HAYSTAC

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

Axion research is like a Marathon requiring hard work, high-risk, high-potential choices, and lots of patience

IBS President Oh, Se Jeong at my recruitment time (as first foreign-born IBS-Director): “Just show promise…”

CAPP was established October 16, 2013, first major investment on axion research and it has helped bring in the critical mass to the field.

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.)

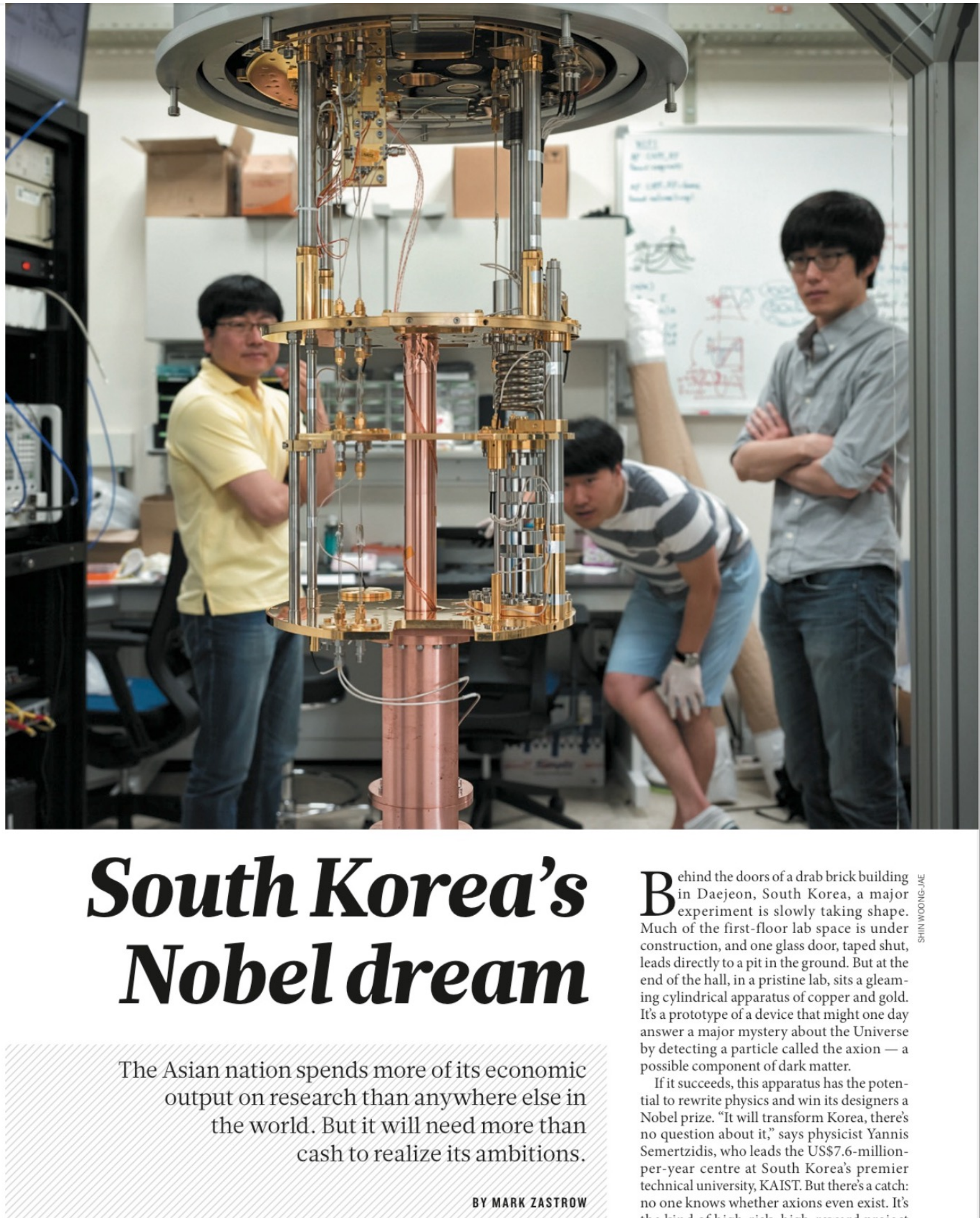
CERN Courier, Dec. 2013

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

Could CAPP produce a Nobel Prize opportunity for Korea?

Nature article about our CAPP/IBS center in Korea

Nature, V534, 2 June 2016



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.

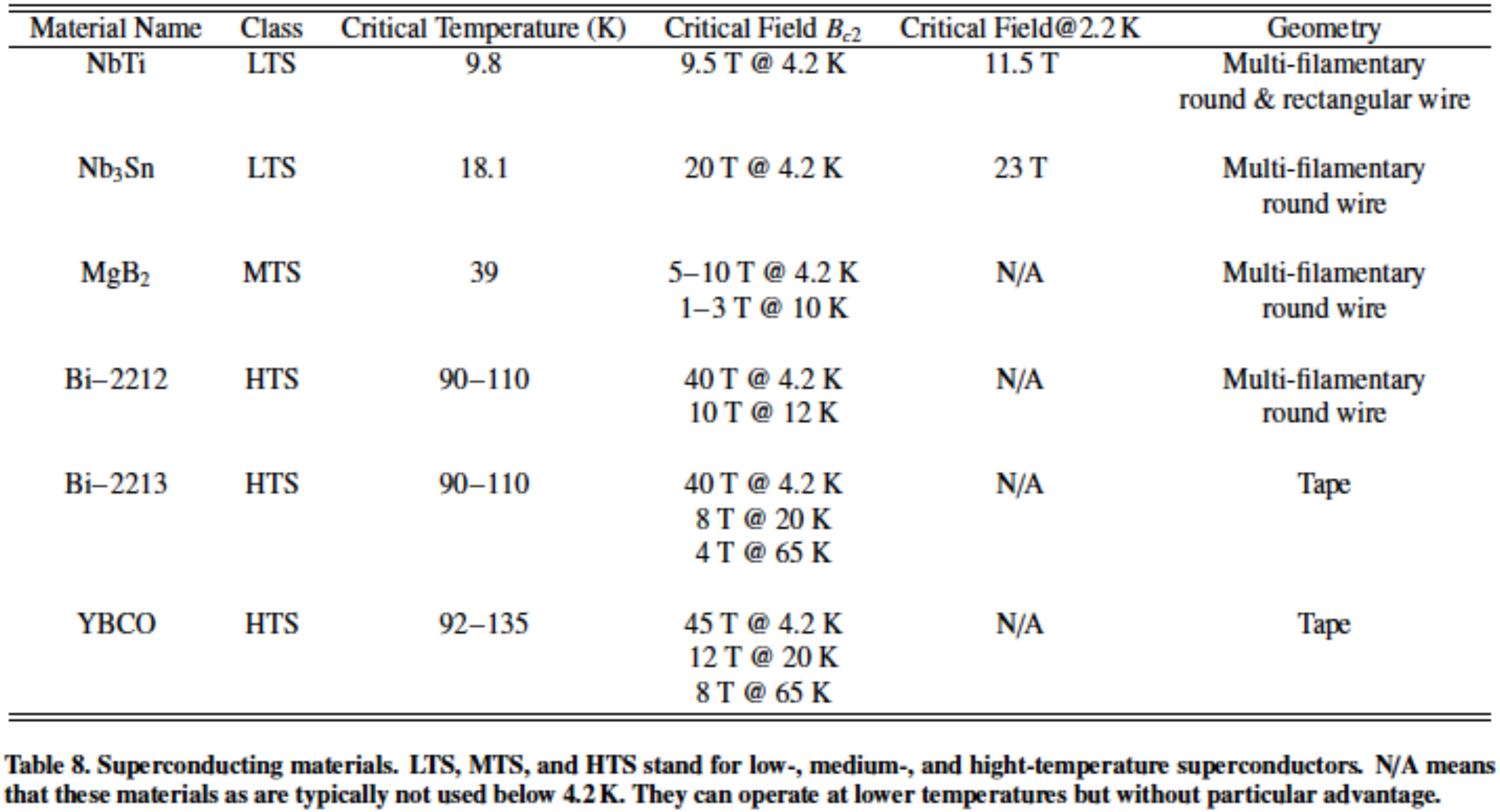
If it succeeds, this apparatus has the potential to rewrite physics and win its designers a Nobel prize. "It will transform Korea, there's no question about it," says physicist Yannis Semertzidis, who leads the US$7.6-million-per-year centre at South Korea's premier technical university, KAIST. But there's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

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, and 18T)
2. Cavity volume, *V*, especially for high-frequencies (37*l*,12T)
3. Cavity quality factor with HTS cavity 34*l*, Q_0 (10^6)
4. System noise temperature, *T* (~200 mK, 1.1 GHz)
5. Geometrical factor, *C* (keep it high >0.6 with special techniques)

Superconducting materials



Material Name	Class	Critical Temperature (K)	Critical Field B_{c2}	Critical Field@2.2 K	Geometry
NbTi	LTS	9.8	9.5 T @ 4.2 K	11.5 T	Multi-filamentary round & rectangular wire
Nb$_3$Sn	LTS	18.1	20 T @ 4.2 K	23 T	Multi-filamentary round wire
MgB$_2$	MTS	39	5–10 T @ 4.2 K 1–3 T @ 10 K	N/A	Multi-filamentary round wire
Bi–2212	HTS	90–110	40 T @ 4.2 K 10 T @ 12 K	N/A	Multi-filamentary round wire
Bi–2213	HTS	90–110	40 T @ 4.2 K 8 T @ 20 K 4 T @ 65 K	N/A	Tape
YBCO	HTS	92–135	45 T @ 4.2 K 12 T @ 20 K 8 T @ 65 K	N/A	Tape

Table 8. Superconducting materials. LTS, MTS, and HTS stand for low-, medium-, and hight-temperature superconductors. N/A means that these materials as are typically not used below 4.2 K. They can operate at lower temperatures but without particular advantage.

Superconducting materials

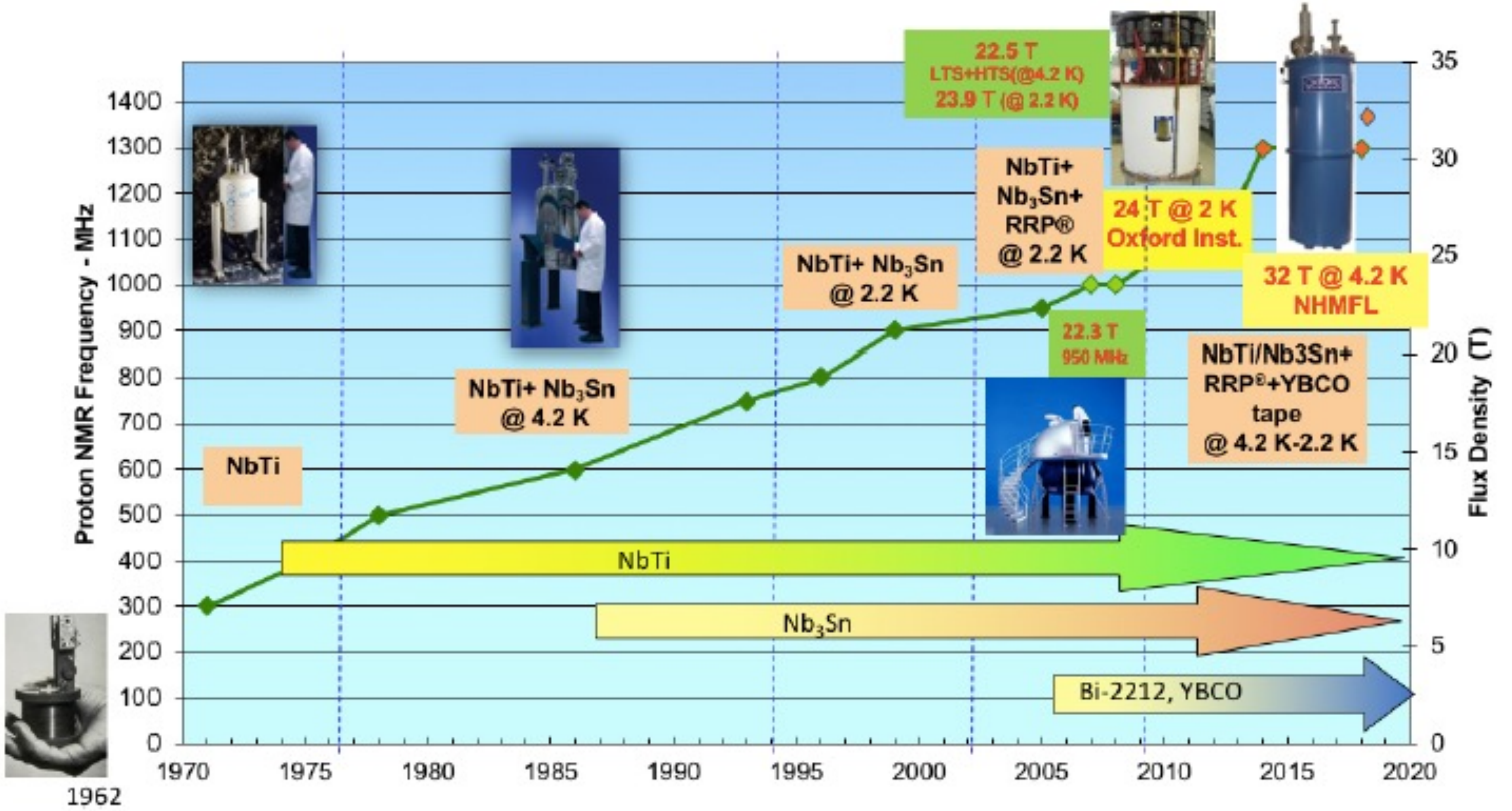


Fig. 22. Solenoid magnets for NMR as a representative example of the progress in magnet technology. NHMFL: National High Magnetic Field Laboratory, Tallahassee, Florida.

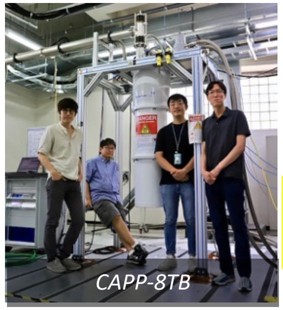
IBS-CAPP at eight-years and beyond

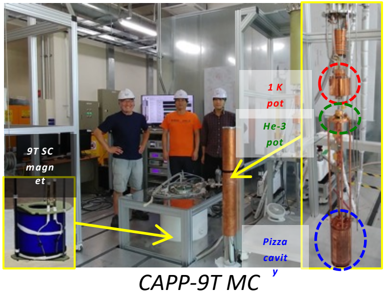
- S. Lee *et al.*, Phys. Rev. Lett. **124**, 101802 (2020)

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

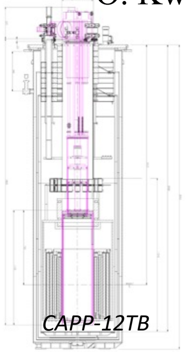
O. Kwon *et al.*, Phys. Rev. Lett. **126**, 191802 (2021)


CAPP-PACE

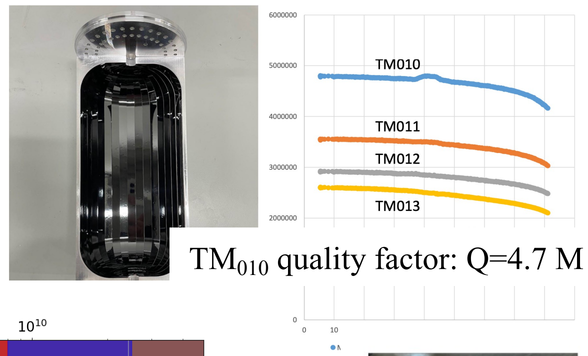

CAPP-8TB



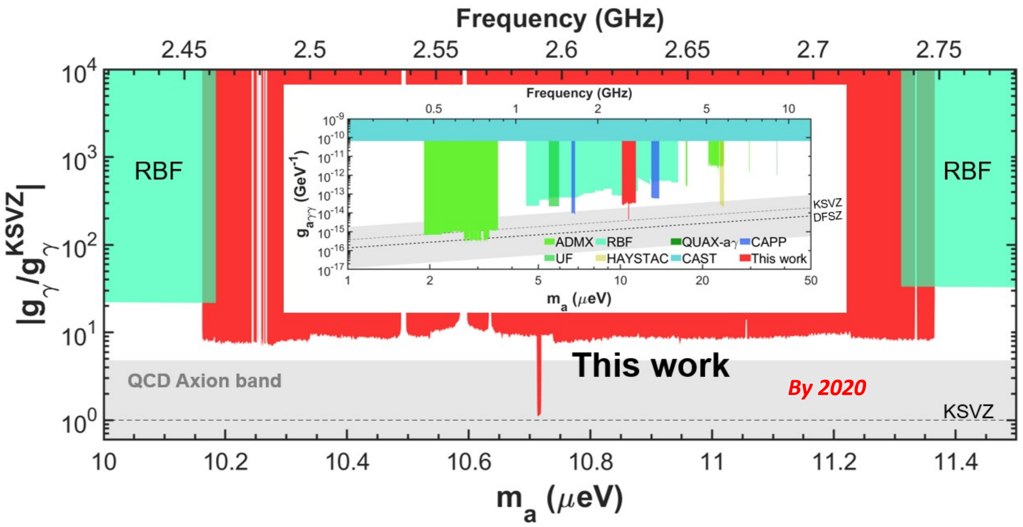
CAPP-9T MC

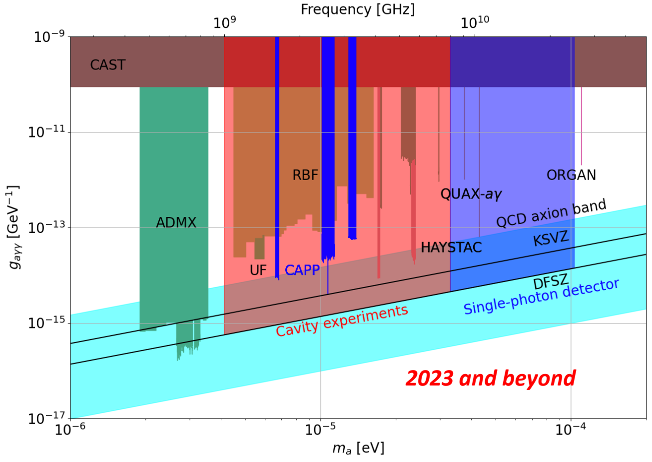

CAPP-12TB

Melon 34 Cavity Q Factor Measurement

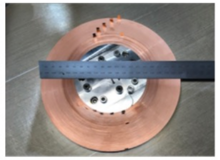


TM$_{010}$ quality factor: Q=4.7 M

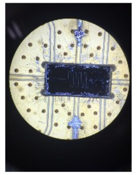




CAPP-25T



+



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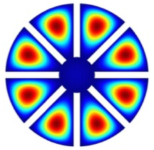


- *Cu cavities are assumed*
- *W/ SC cavities, down to 10% of axion dark matter content can be probed*

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.

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

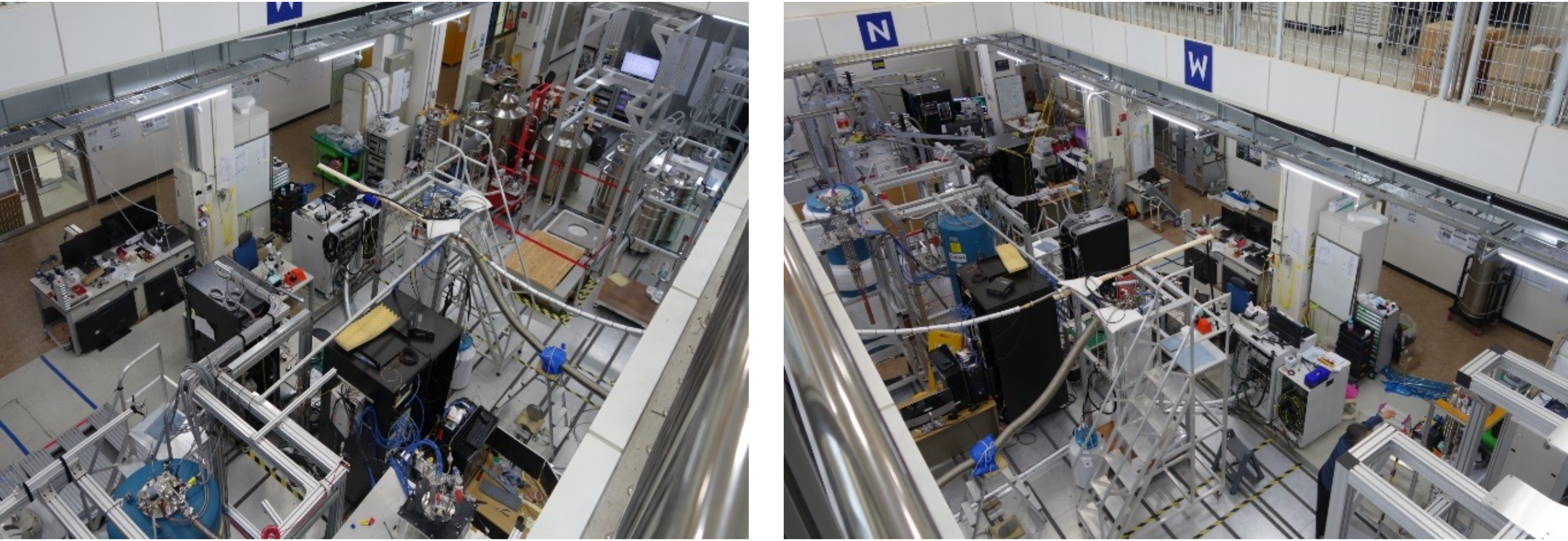
Operation model of parallel R&D

- Several experiments in parallel
- Nb_3Sn based magnet
- High-risk, high physics potential outcome

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

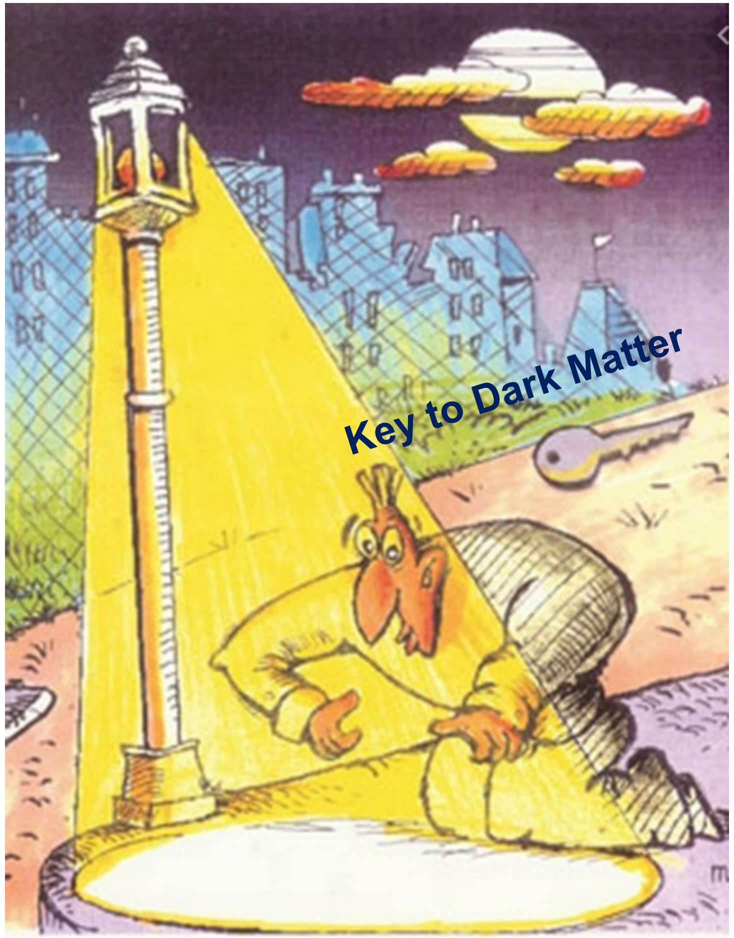
State of the art infra-structure: 7 low vibration pads for parallel experiments; 6 cryo or dilution refrigerators; high B-field, high volume magnet: 12T, 5.6MJ. Flagship exp.

CAPP experimental hall, top view



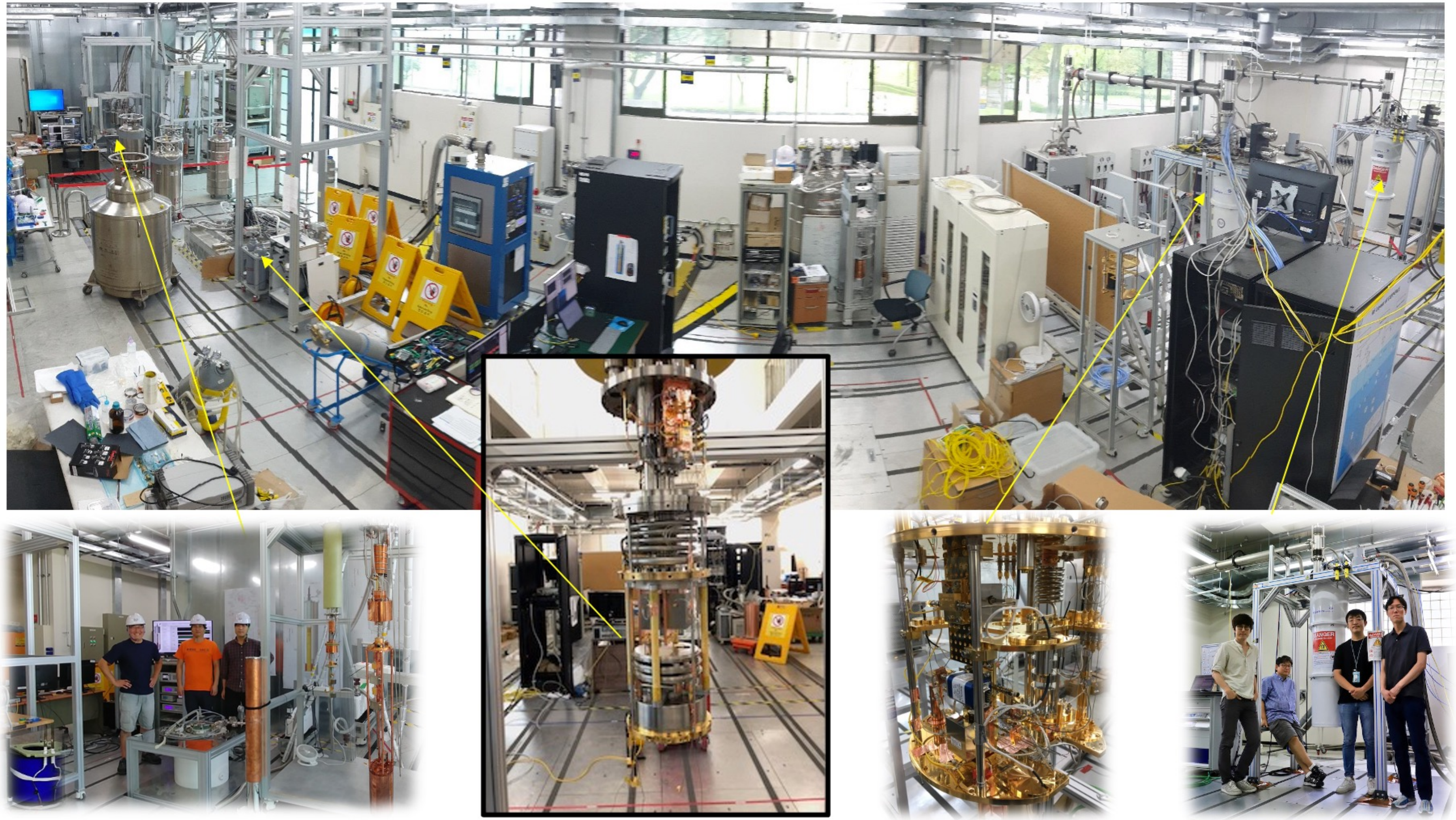
Strategy at CAPP: best infra-structure and know-how

- 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 Experimental Hall (LVP) in 2021



CAPP-HF

CAPP-12TB

CAPP-PACE

CAPP-8TB

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)

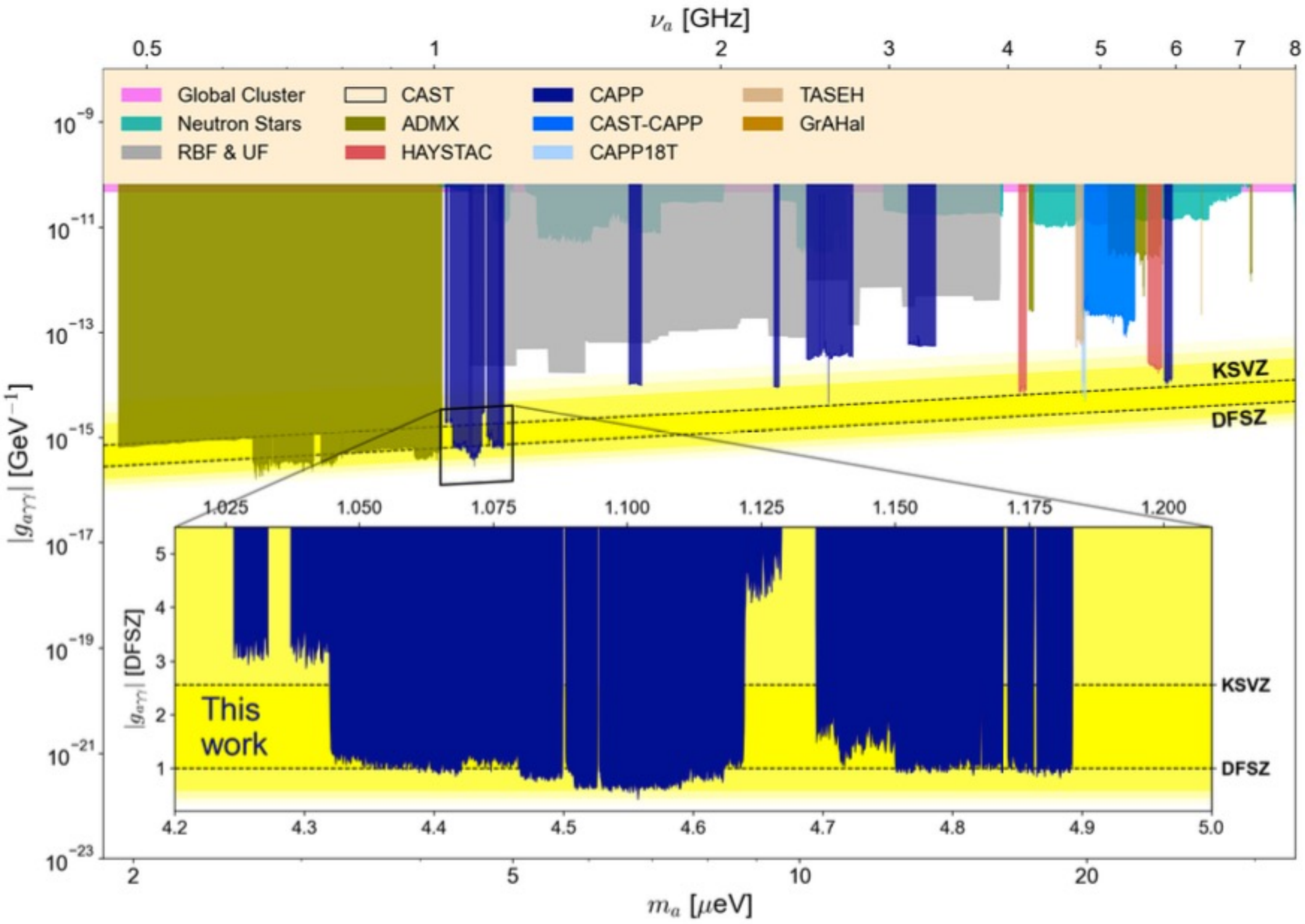
The CAPP-MAX, our flagship experiment

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)

IBS-CAPP at DFSZ sensitivity, scanning 1-8 GHz



S. Ahn et al., PRX (2024)

IBS-CAPP and collaborators

- First efficient high frequency scanning with “pizza” cavities, at KSVZ sensitivity at >5 GHz. New designs >10 GHz
- Low temperature (<40mK), with large volume ultra-light-cavity, reaching DFSZ sensitivity over 1 GHz and 3MHz/day.
- Best JPA performance for wide frequency cover (international collaboration with Tokyo/RIKEN)
- First HTS cavities with $Q>10^6$ in high magnetic field, projected to reach >10MHz/day at better than DFSZ

- Critical contributions to ARIADNE, GNOME (international collaborations)
- Active R&D on bolometer, single photon detectors, large volume magnets (international collaborations, Aalto, INFN, Grenoble)

The CAPP-MAX, 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
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  - 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 125mK, $Q_0=1\times10^6$
  - DFSZ: 1-2 GHz/year for 20% of dark matter as axions
  - DFSZ: 2-4 GHz/year, 4-8 GHz/year, 20% ADM

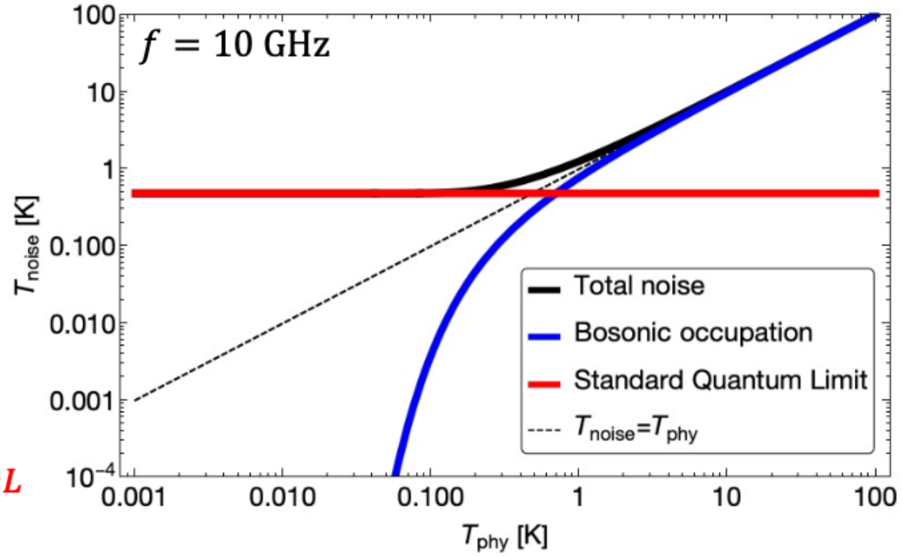
Equivalent noise temperature

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)

Single RF-photon detector!

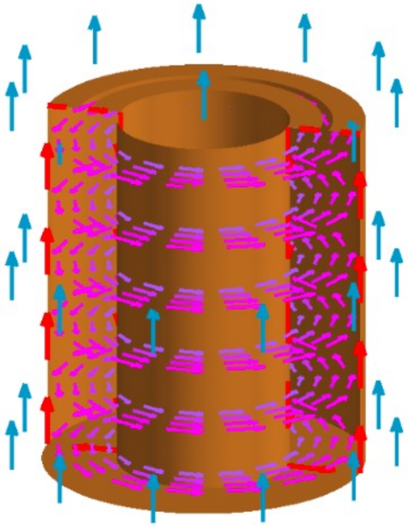
- A dream come true:
  - Lescanne et al., PRX (2020)
  - Albertinale et al., Nature (2021)
  - Wang et al., Nature (2023)

- Qubits or bolometers combined with HTS cavities pave the path to the high frequency. It’s getting very close to a major running system.

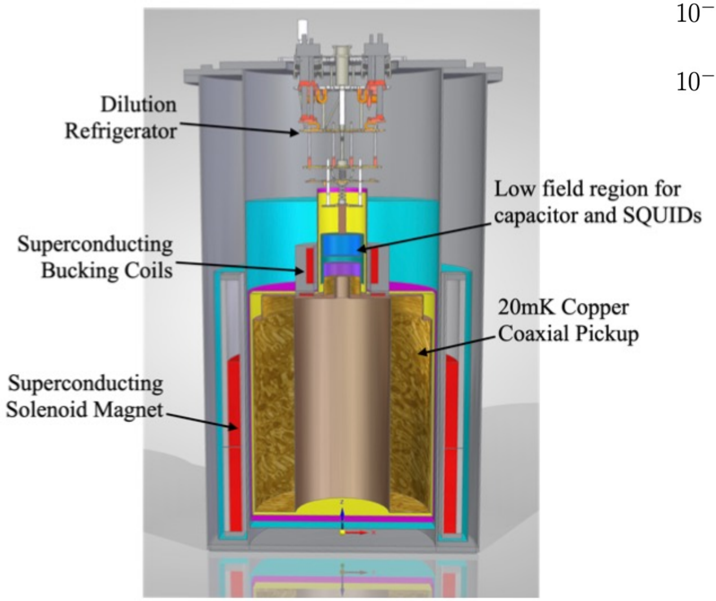
The low-frequency domain

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

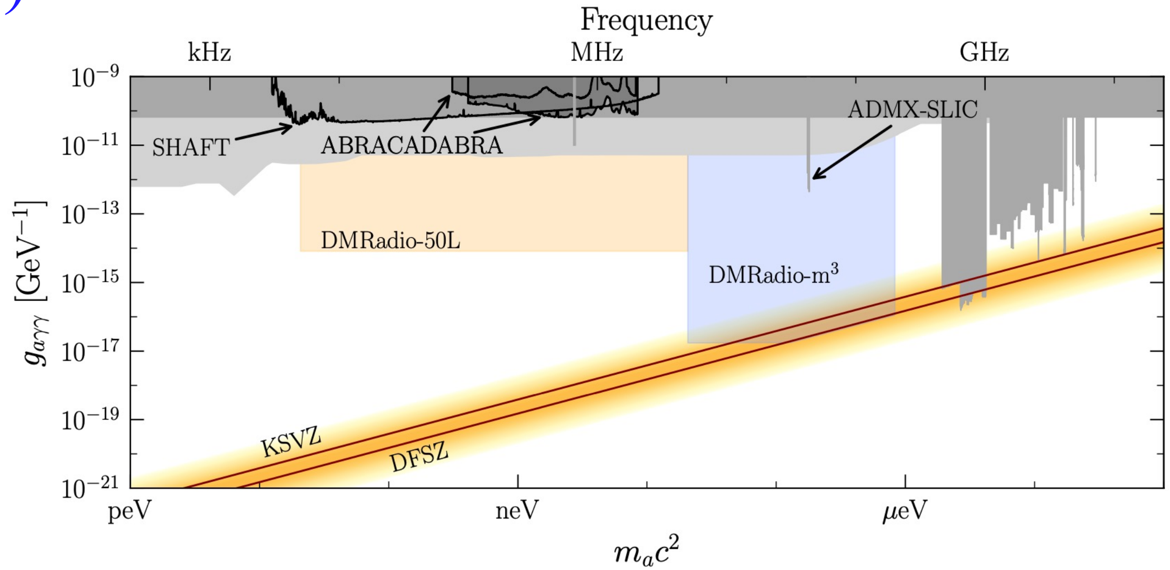
Low frequencies (long Compton wavelength) favor induction coil detection



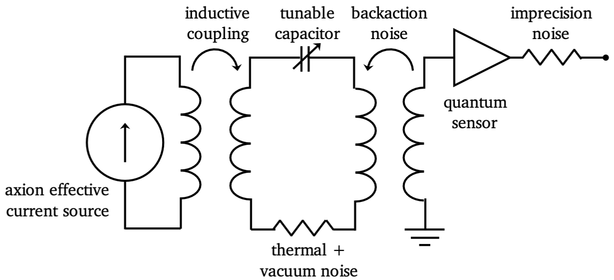
(a)



(b)



Dark Matter Radio, 2203.11246



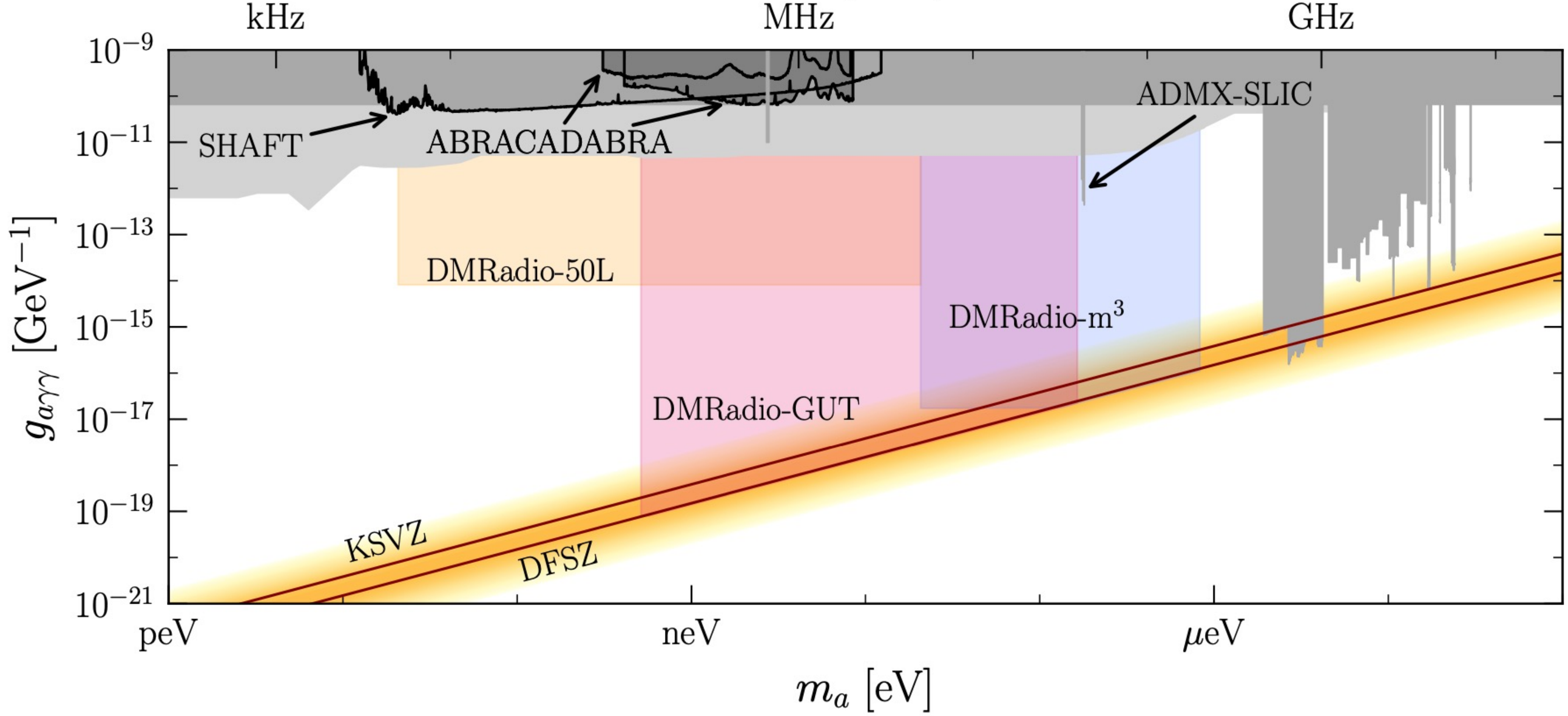
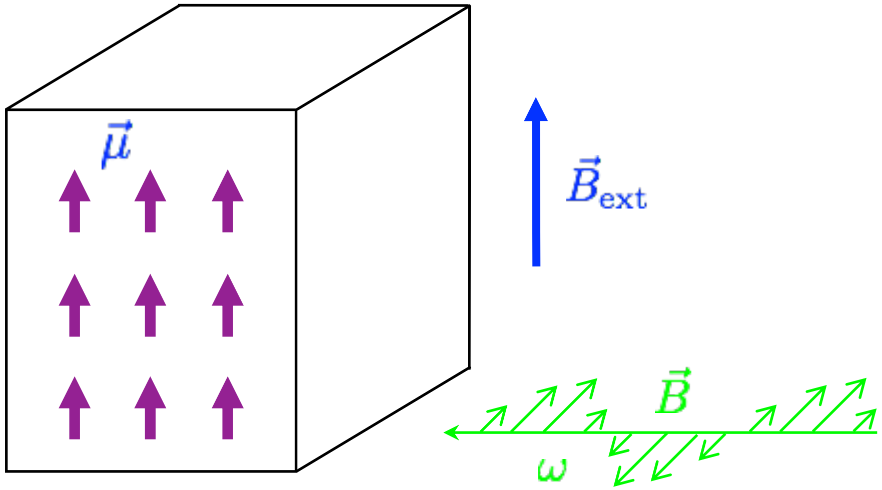


FIG. 4. Projected sensitivity for DMRadio-GUT in pink. The total scan time to cover this reach is ∼ 6 years, depending on R&D outcomes. Various scenarios are outlined in Table II. Existing limits are shown in grey.

Haloscopes using spins

Dima Budker, CASPEr

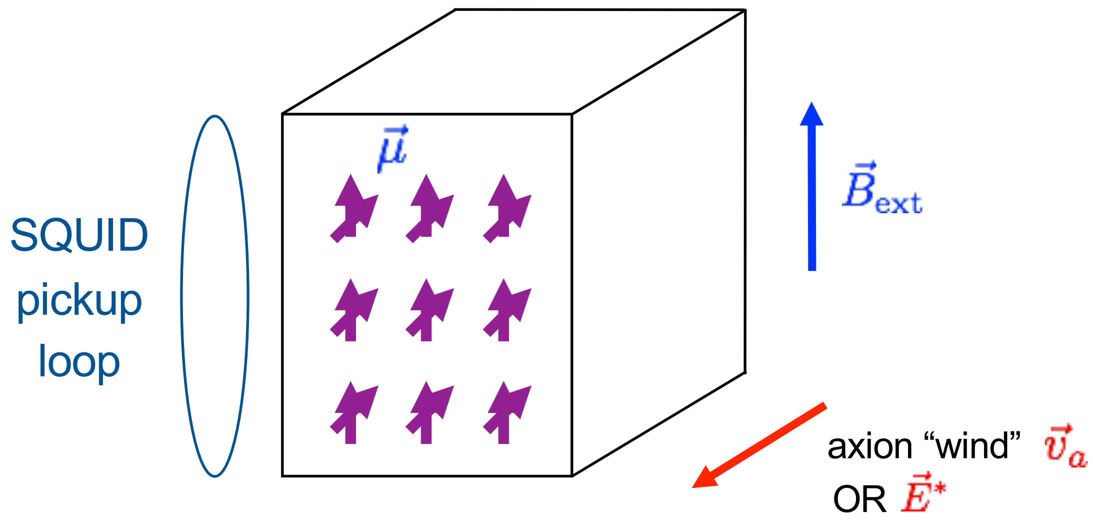
Nuclear Magnetic Resonance (NMR)



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

Dima Budker

CASPEr

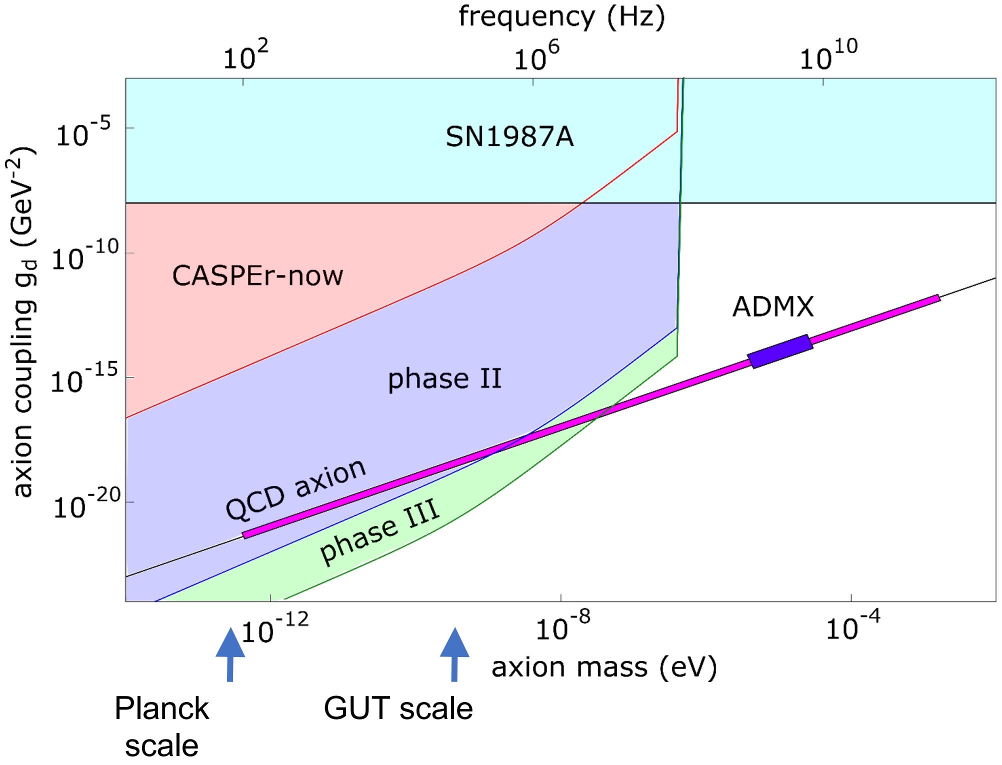


Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

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

The experimental reach of CASPEr



<u>CASPEr-now</u> at BU:

- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- broadband SQUID detection

HEISING - SIMONS FOUNDATION

SIMONS FOUNDATION

<u>phase II</u>:

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

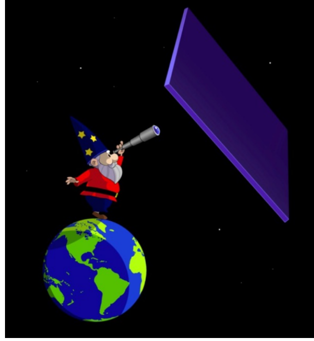
<u>phase III</u>:

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

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

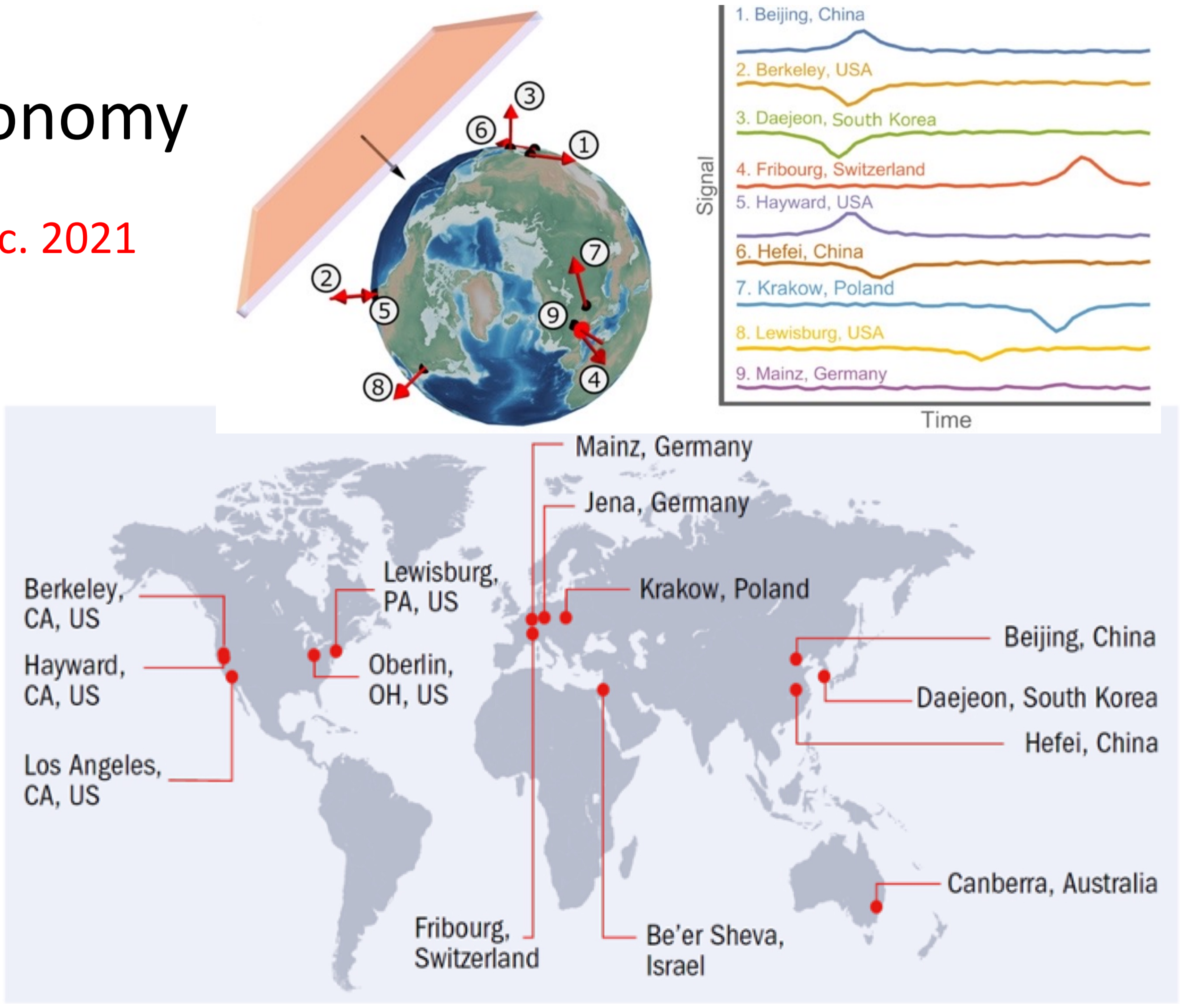
Slide by Alex Suskov (adapted)

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



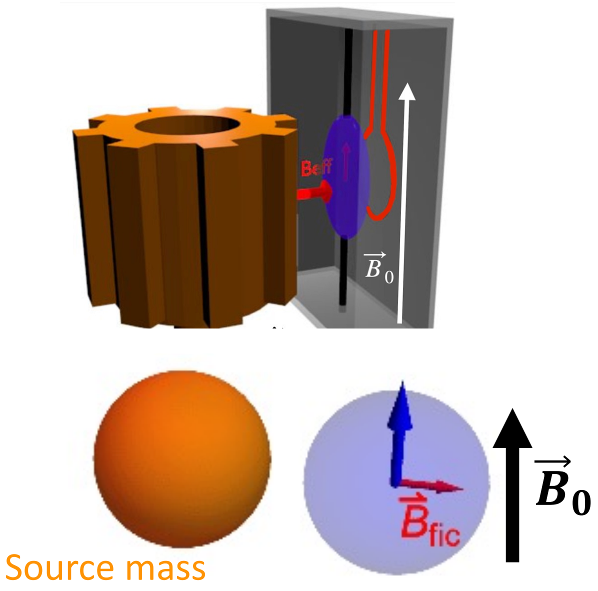
- Fictitious magnetic field B_{fic}:

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

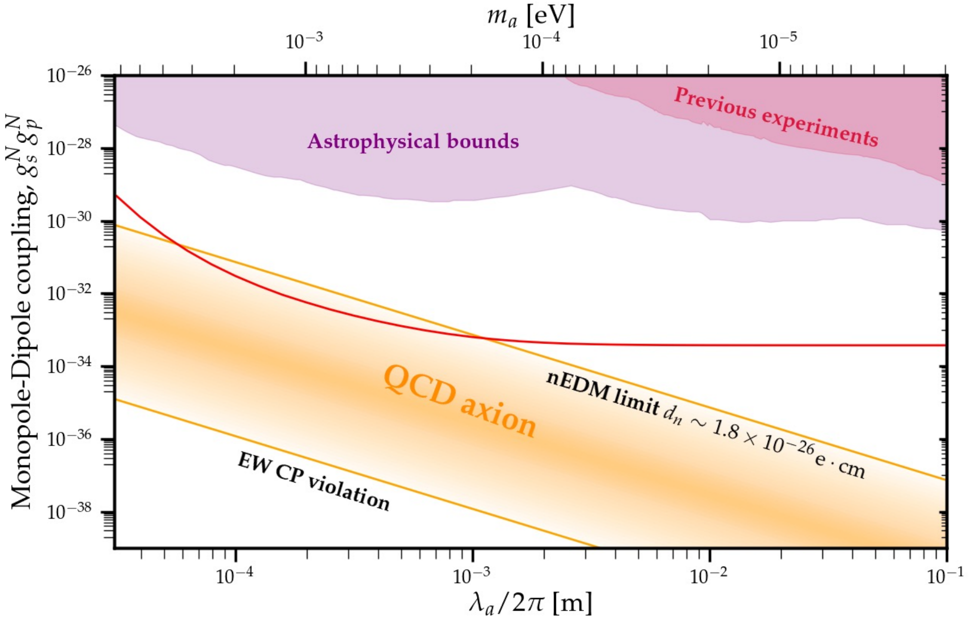
- Optically pumped atomic magnetometer detects B_{fic}
- Direct detection of local dark matter with network detector

ARIADNE

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



Experimental scheme



Projected Sensitivity (first phase)

- Fictitious magnetic field B$_{\text{fic}}$:

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

- Spin system resonantly enhance B$_{\text{fic}}$
- 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

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

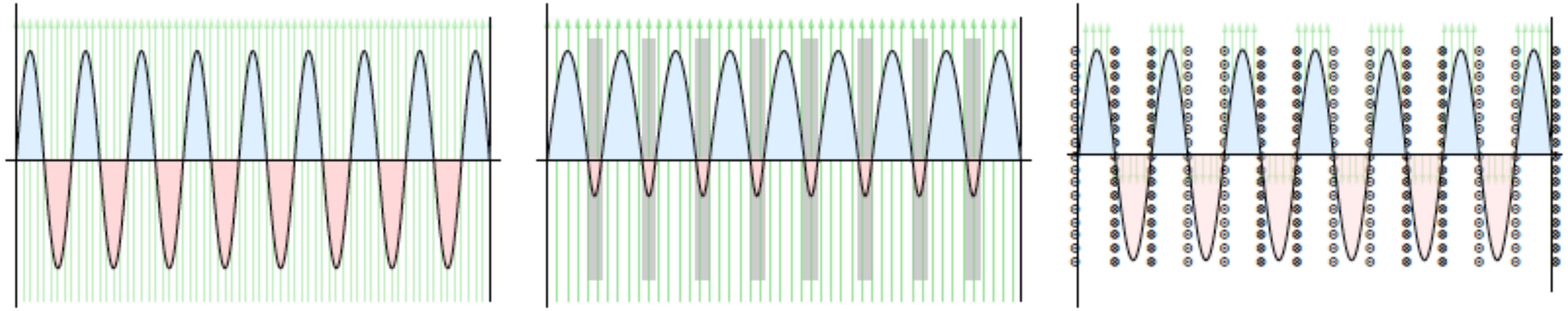
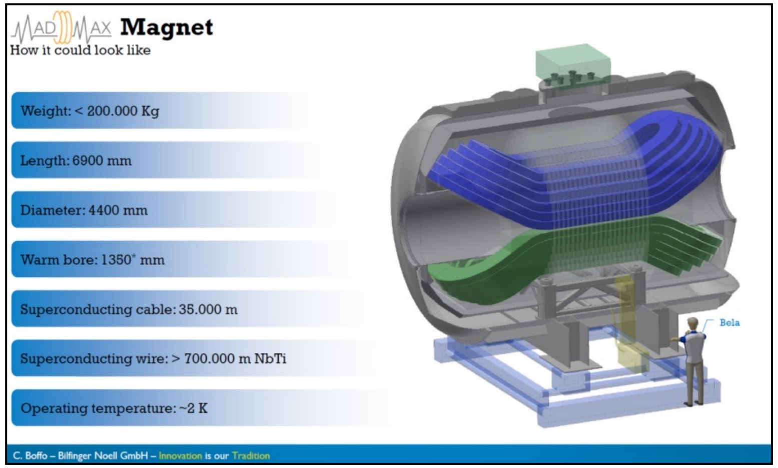


Figure 19: The geometric factor of an ideal 1D cavity in a homogeneous B-field (green arrows) cancels between crests and valleys of a high mode (left). The cancellation can be avoided by placing high-n dielectrics –grey regions– in the valleys (centre) or by alternating the polarity of the external B_e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

MADMAX: Physics at the interface

MADMAX – search for dark matter axions



MADMAX Magnet

How it could look like

Weight: < 200.000 Kg

Length: 6900 mm

Diameter: 4400 mm

Warm bore: 1350^{*} mm

Superconducting cable: 35.000 m

Superconducting wire: > 700.000 m NbTi

Operating temperature: ~2 K

C. Boffo – Bilfinger Noell GmbH – Innovation is our Tradition

MADMAX (dark matter)

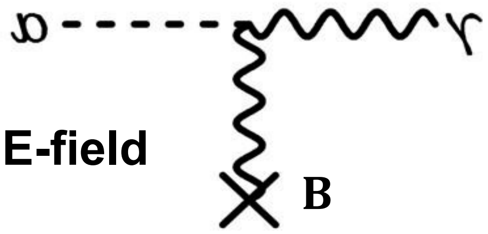
- Site in HERA hall north being prepared
- Magnet studies by Bilfinger-Noell and CEA Saclay, aim for magnet decision in late 2018

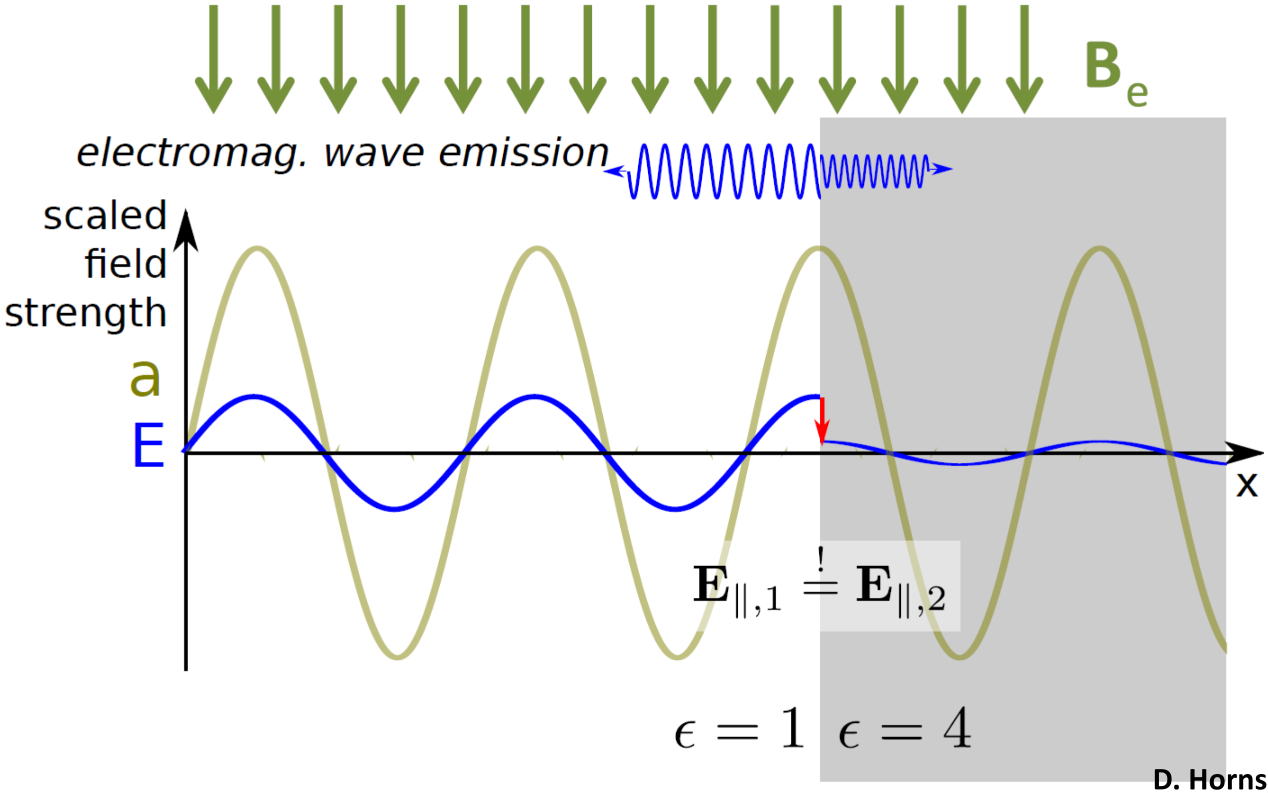
MADMAX collaboration

- Founded at DESY in 2017

Experimental approaches: Effect of Dielectric

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





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

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

Axion dark matter: MADMAX

1801.08127v2

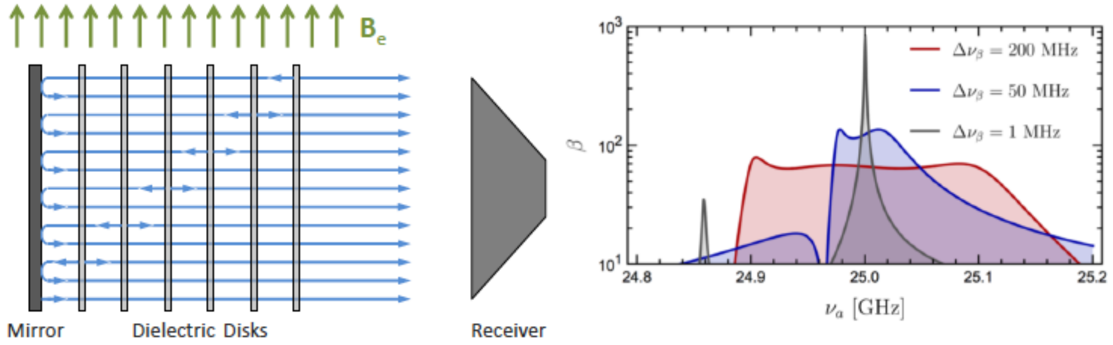


Figure 21: Left: sketch of the dielectric haloscope experiment. Photons in the B_e field are emitted from the dielectric surfaces and reflected in the leftmost mirror and other surfaces to be measured coherently by a receiver, from [585]. Right: Adjusting the distances between the layers, the frequency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

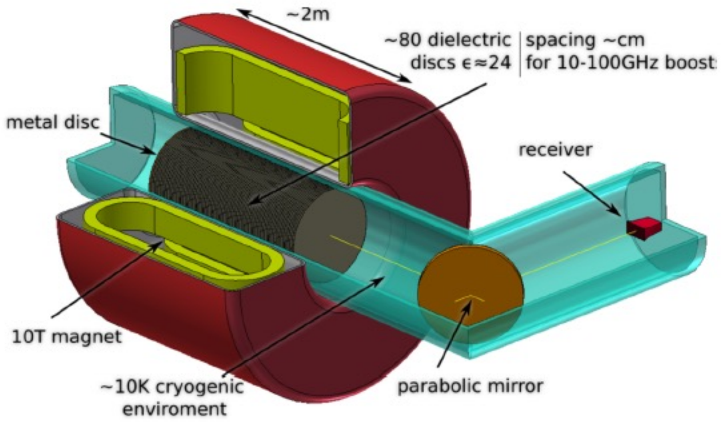
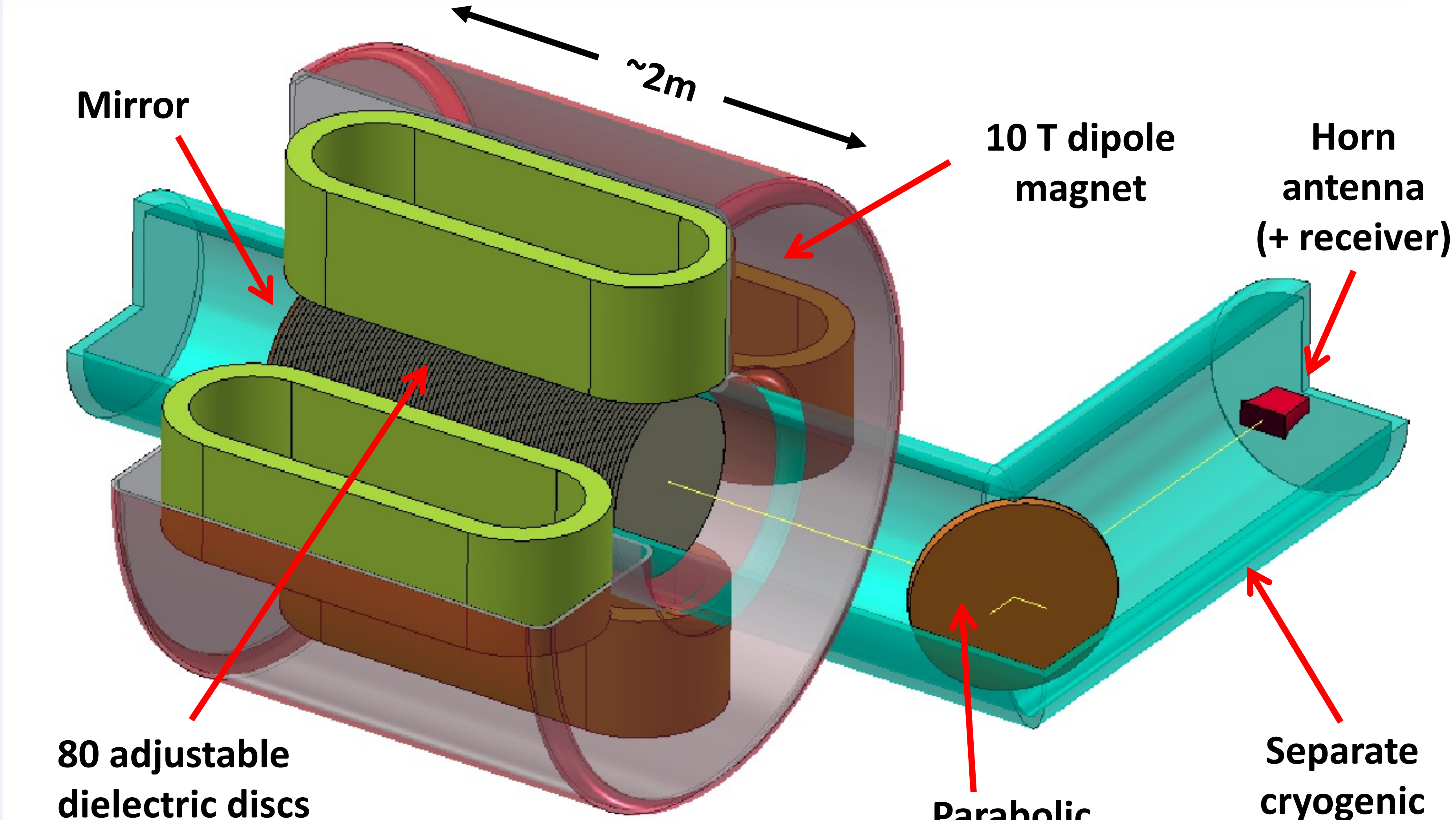


Figure 22: The concept of the MADMAX experiment, see text for details. From [590].

Scheduled for DESY (approved), using large-volume magnet at CERN (Morpurgo magnet) taking preliminary data

MAgnetized Disc and Mirror Axion eXperiment



~2m

Mirror

10 T dipole magnet

Horn antenna (+ receiver)

80 adjustable dielectric discs
∅: ~1m

Parabolic Mirror

Separate cryogenic volume

Solar axions

Solar Axions

R. Battesti *et al.*, Phys. Rep. (2018)

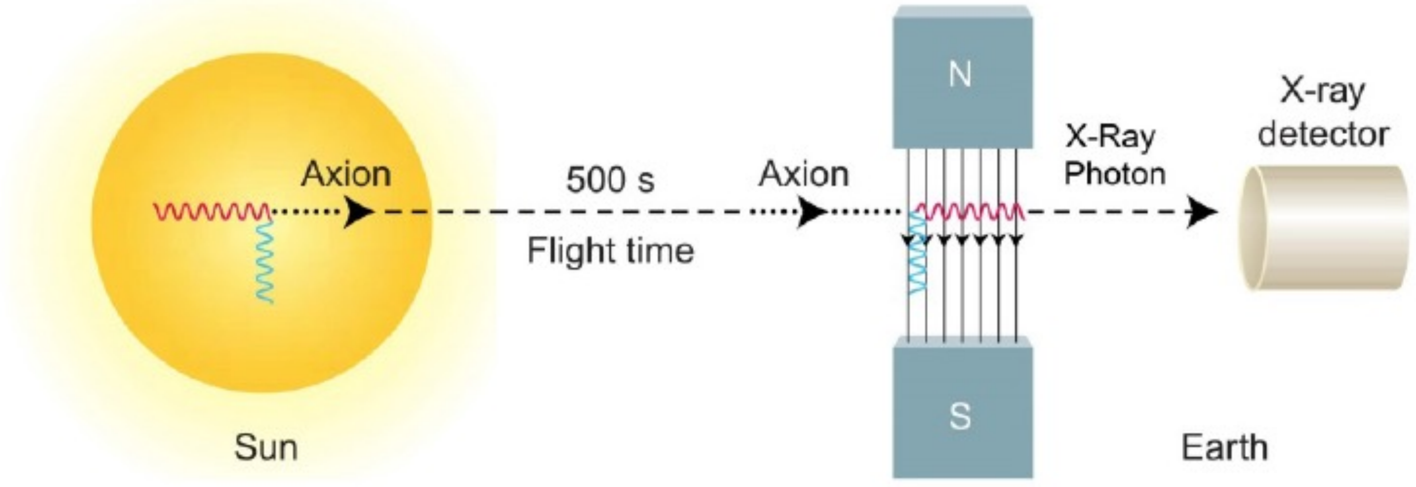
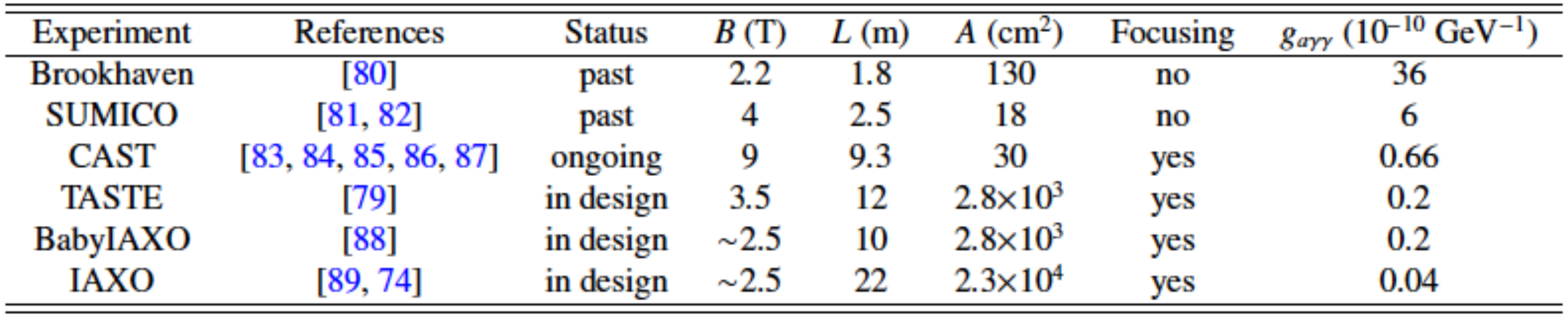


Fig. 9. The axion-helioscope concept. Axions are produced in the sun and travel towards the earth. In the presence of a transverse magnetic field in the haloscope (corresponding to the blue photon in the figure), the axions are converted into x-ray photons and detected. The energy spectrum of the x-ray photons corresponds to that of the axions produced in the sun.



Experiment	References	Status	B (T)	L (m)	A (cm^2)	Focusing	$g_{a\gamma\gamma}$ (10^{-10} GeV^{-1})
Brookhaven	[80]	past	2.2	1.8	130	no	36
SUMICO	[81, 82]	past	4	2.5	18	no	6
CAST	[83, 84, 85, 86, 87]	ongoing	9	9.3	30	yes	0.66
TASTE	[79]	in design	3.5	12	2.8×10^3	yes	0.2
BabyIAXO	[88]	in design	~2.5	10	2.8×10^3	yes	0.2
IAXO	[89, 74]	in design	~2.5	22	2.3×10^4	yes	0.04

Solar axion spectrum

1801.08127v2

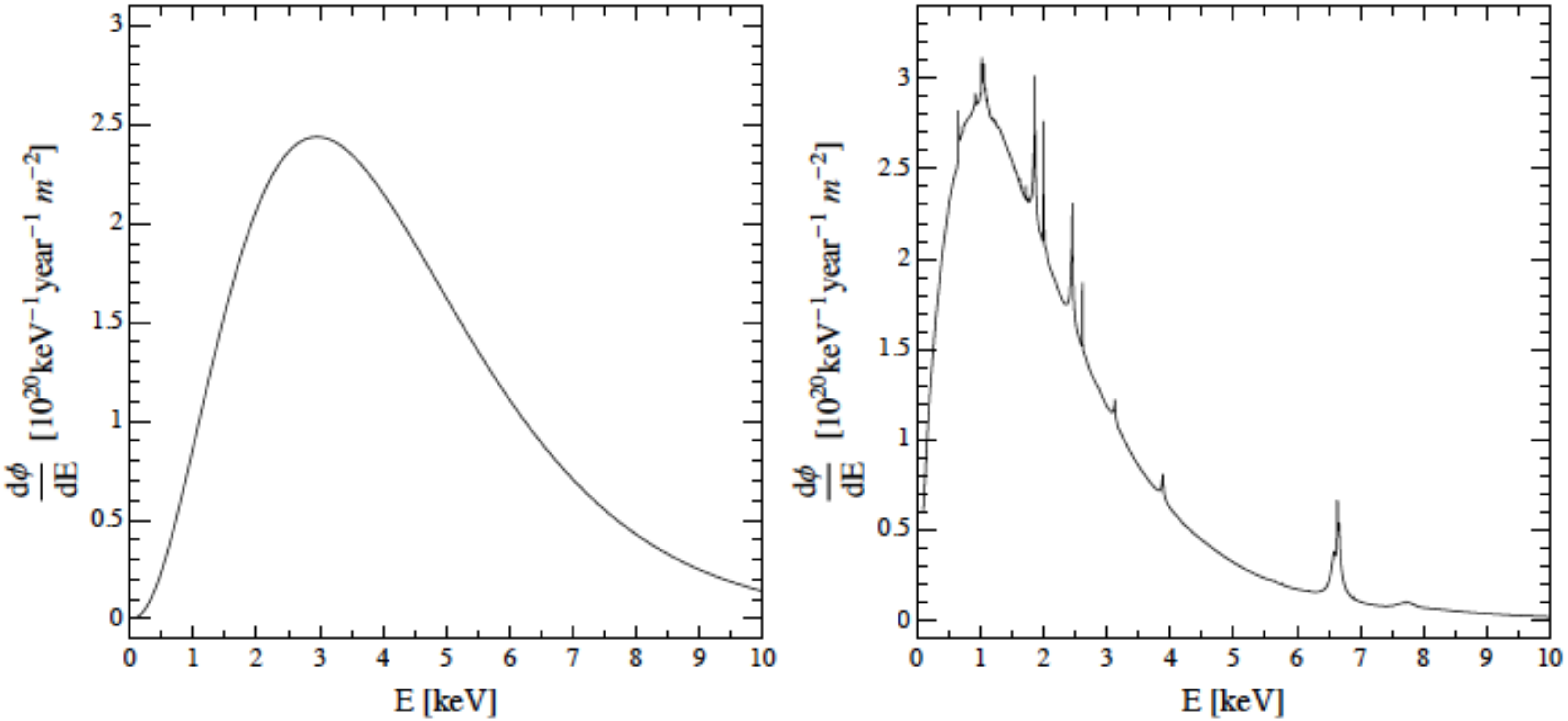
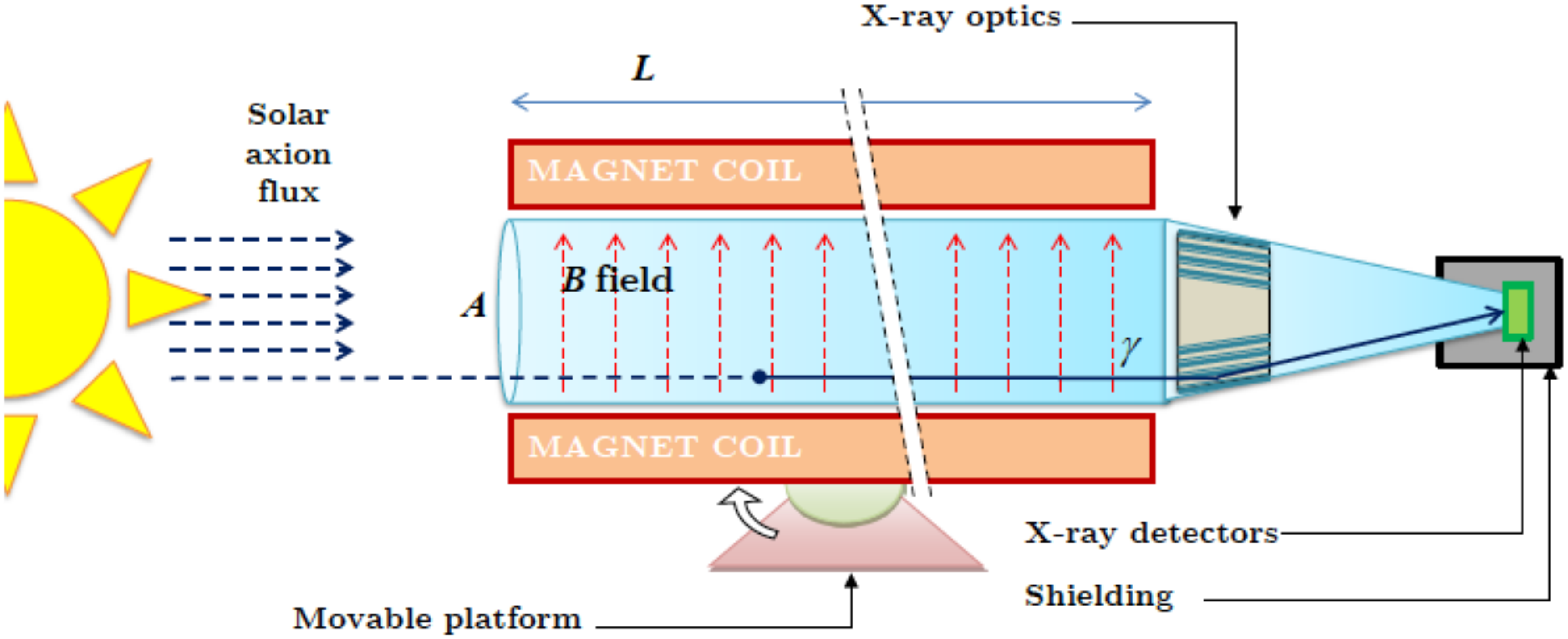


Figure 9: Solar axion flux spectra at Earth by different production mechanisms. On the left, the most generic situation in which only the Primakoff conversion of plasma photons into axions is assumed. On the right the spectrum originating from processes involving electrons, bremsstrahlung, Compton and axio-recombination [323, 395]. The illustrative values of the coupling constants chosen are $g_{a\gamma} = 10^{-12}$ GeV^{-1} and $g_{ae} = 10^{-13}$. Plots from [480].

Solar Axions

$\text{FOM} = B^2 l^2 A = B^2 V l$ 1801.08127v2



Solar Axions

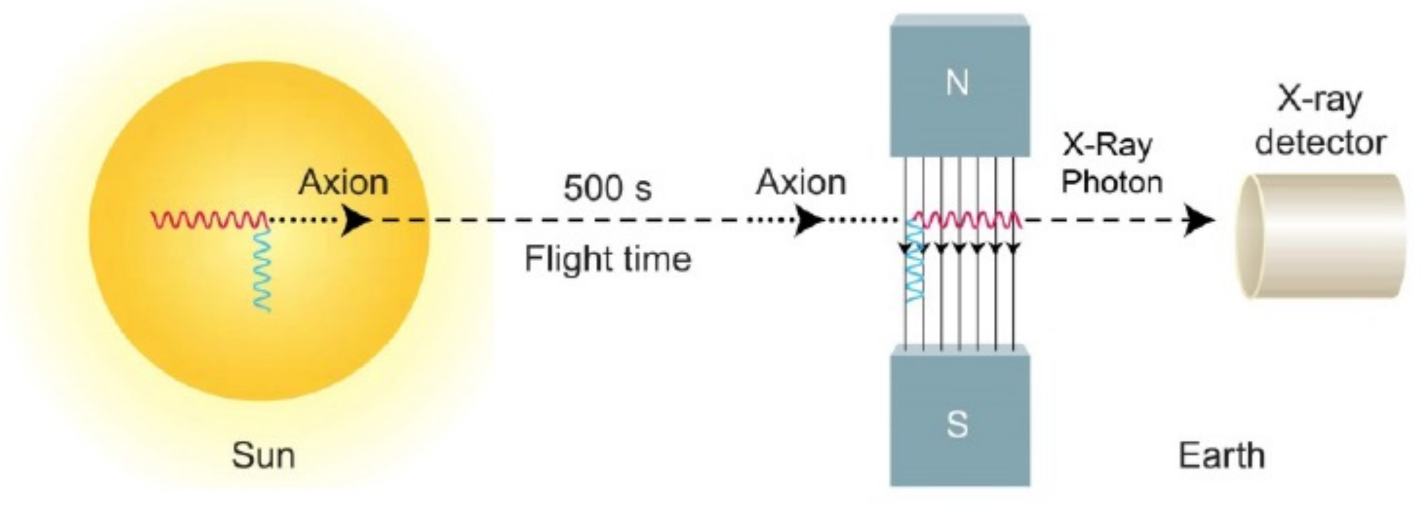


Fig. 9. The axion-helioscope concept. Axions are produced in the sun and travel towards the earth. In the presence of a transverse magnetic field in the haloscope (corresponding to the blue photon in the figure), the axions are converted into x-ray photons and detected. The energy spectrum of the x-ray photons corresponds to that of the axions produced in the sun.

CAST: LHC prototype magnet

Solar Axions

Baby-IAXO approved at DESY
Magnet design in progress

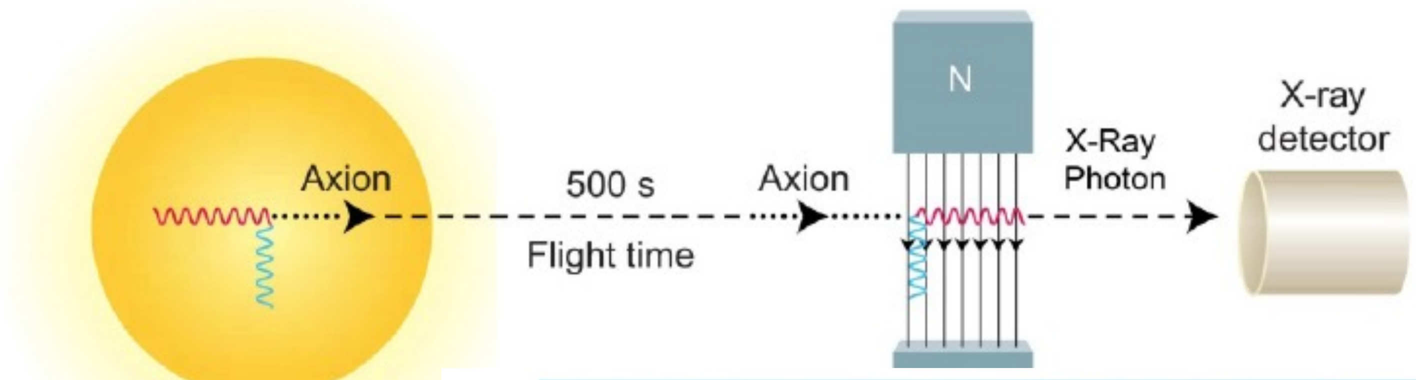


Fig. 9. The axion-helioscope concept. Axions a
field in the haloscope (corresponding to the blu
spectrum of the x-ray photons corresponds to

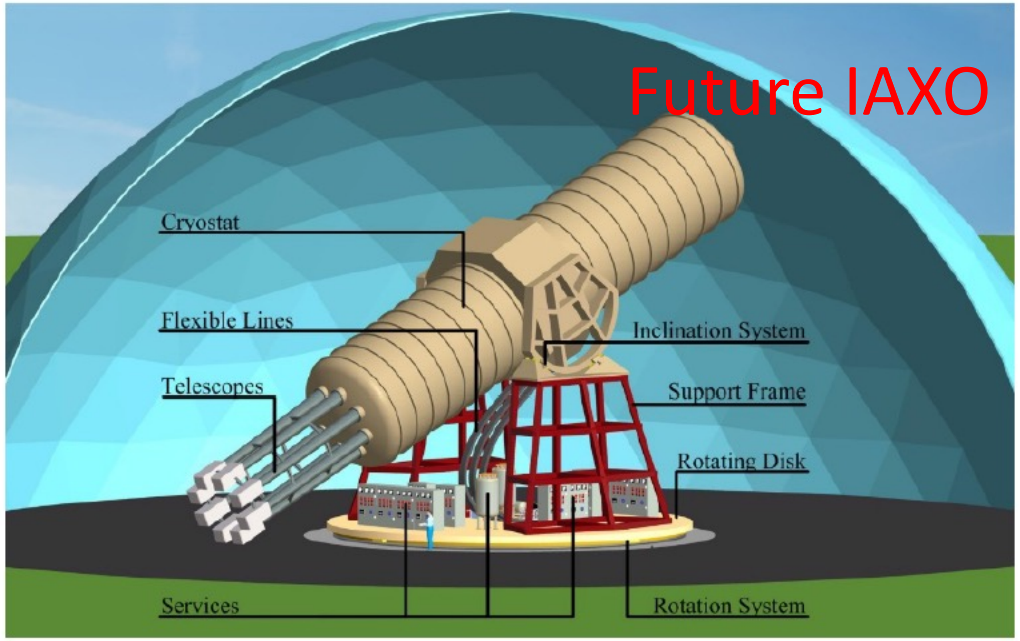
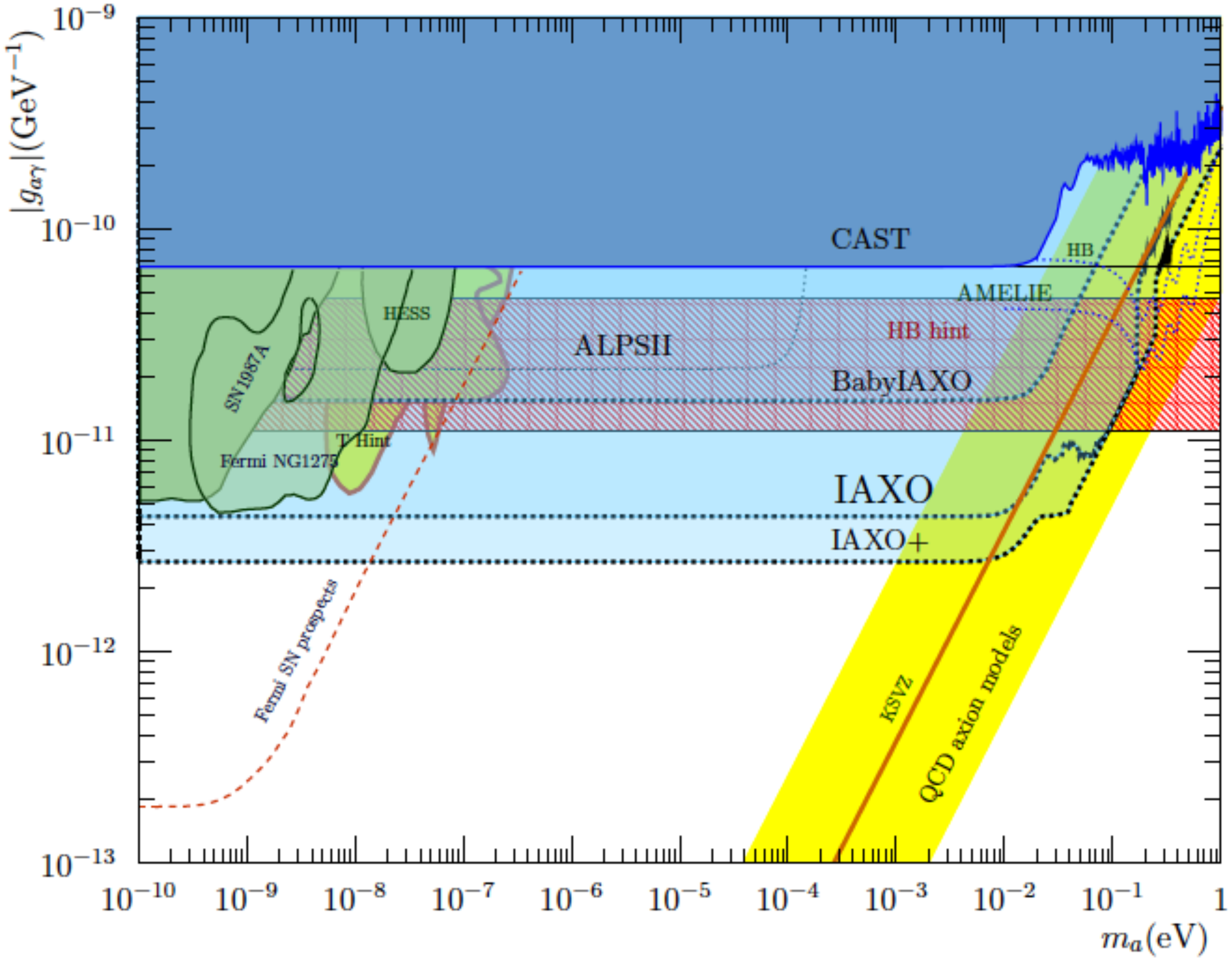


Fig. 10. General view of the IAXO design whose key part is a 22 m long eight-coil toroidal magnet enclosed in a 25 m long cryostat. Figure from [74].

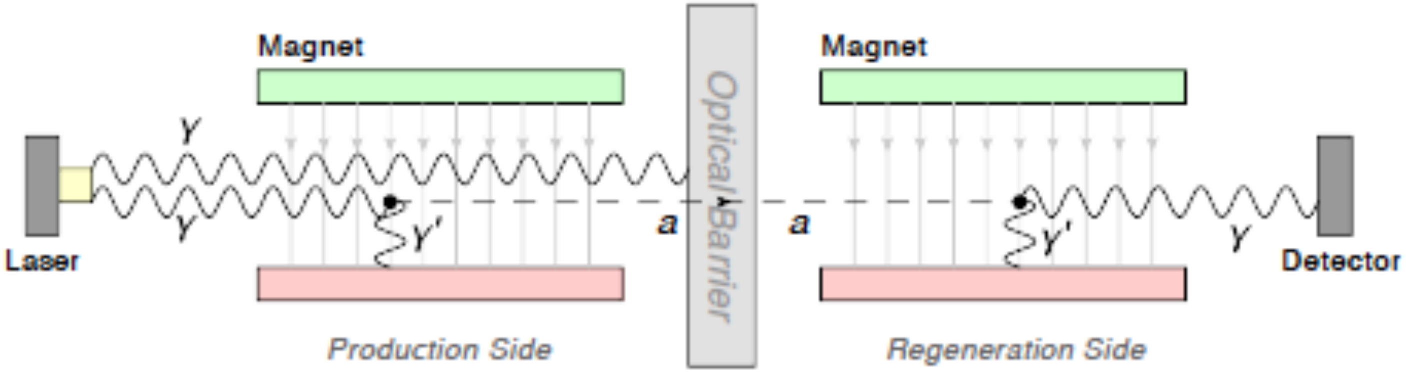
CAST and planned axion Helioscopes



Shining through the wall using axions

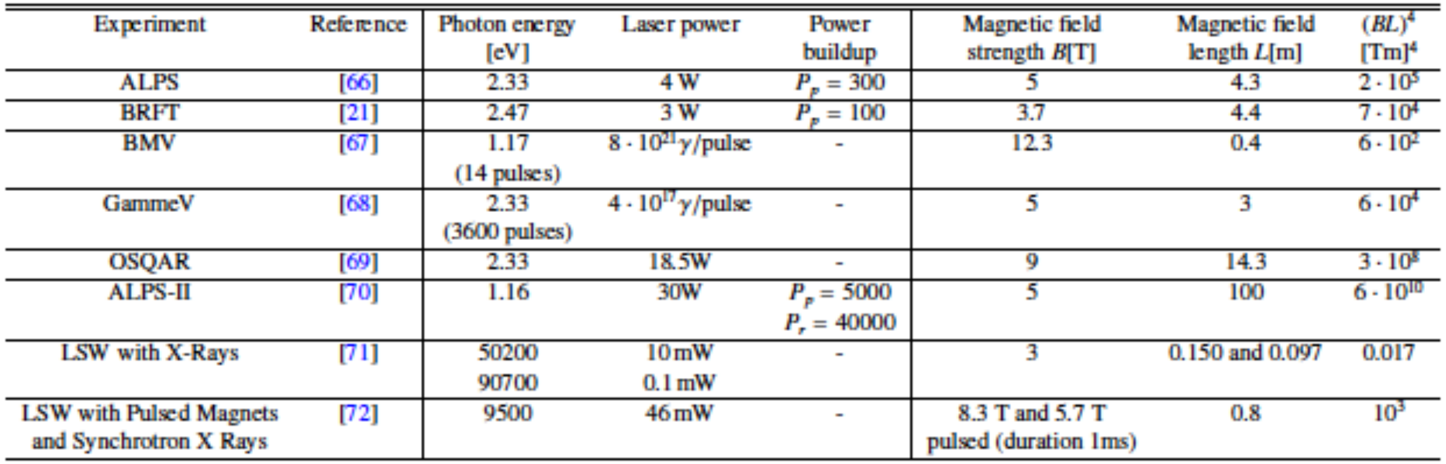
ALPS

ALPSII is running at DESY



$$P_{\gamma\to a\to\gamma} = \frac{1}{16}(g_{a\gamma\gamma}BL)^4 = 6\cdot 10^{-38}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\frac{B}{1\ \mathrm{T}}\frac{L}{10\ \mathrm{m}}\right)^4,$$

For sufficiently small axion mass

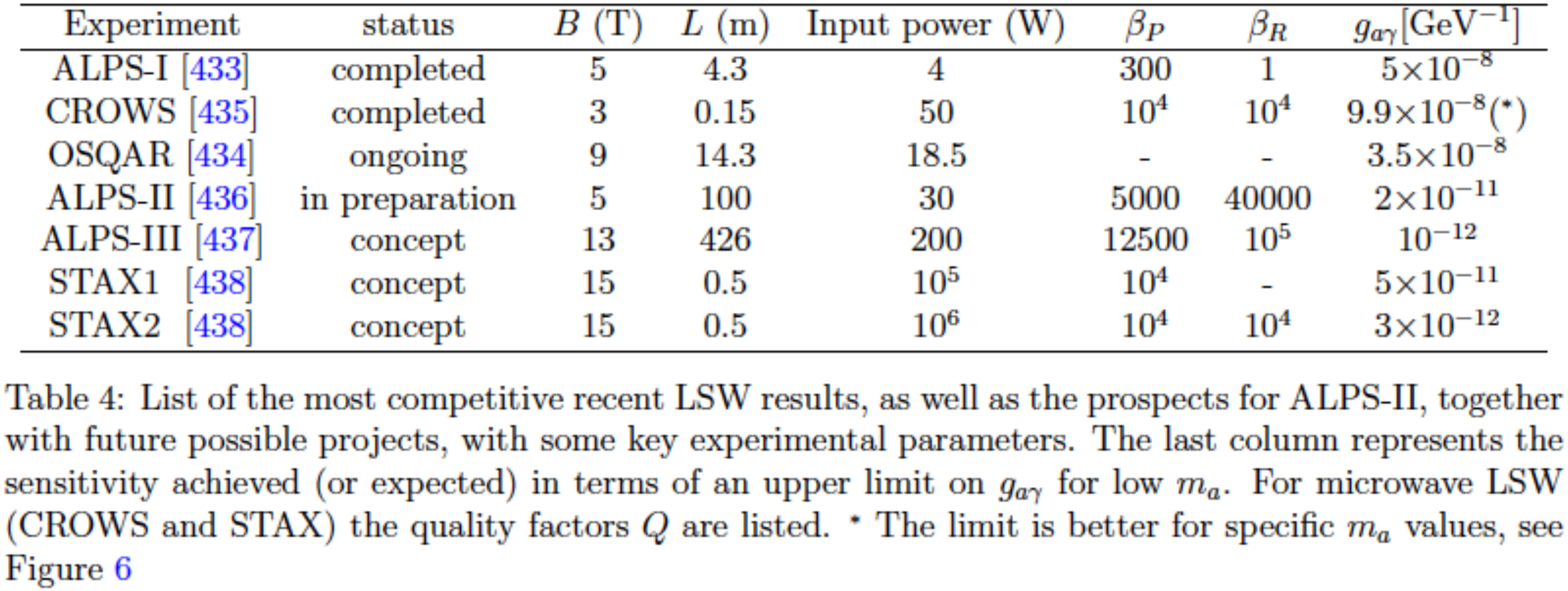


Experiment	Reference	Photon energy [eV]	Laser power	Power buildup	Magnetic field strength B[T]	Magnetic field length L[m]	$(BL)^4$ $[\mathrm{Tm}]^4$
ALPS	[66]	2.33	4 W	$P_p = 300$	5	4.3	$2\cdot 10^5$
BRFT	[21]	2.47	3 W	$P_p = 100$	3.7	4.4	$7\cdot 10^4$
BMV	[67]	1.17 (14 pulses)	$8\cdot 10^{21}\,\gamma$/pulse	-	12.3	0.4	$6\cdot 10^2$
GammeV	[68]	2.33 (3600 pulses)	$4\cdot 10^{17}\,\gamma$/pulse	-	5	3	$6\cdot 10^4$
OSQAR	[69]	2.33	18.5W	-	9	14.3	$3\cdot 10^8$
ALPS-II	[70]	1.16	30W	$P_p = 5000$ $P_r = 40000$	5	100	$6\cdot 10^{10}$
LSW with X-Rays	[71]	50200 90700	10 mW 0.1 mW	-	3	0.150 and 0.097	0.017
LSW with Pulsed Magnets and Synchrotron X Rays	[72]	9500	46 mW	-	8.3 T and 5.7 T pulsed (duration 1ms)	0.8	10^3

Table 5. Overview of experimental parameters of previous and future LSW experiments: the photon energy, the initial laser power, the power-buildup in the production and regeneration side (P_p and P_r), as well as the magnetic field strength and length in production and regeneration sides (B_P, B_R, L_P, L_R). For all the cases, $B = B_p = B_r$ and $L = L_p = L_r$.

Rémy Battesti *et al.*/ Physics Reports (2018)

Light shining through walls

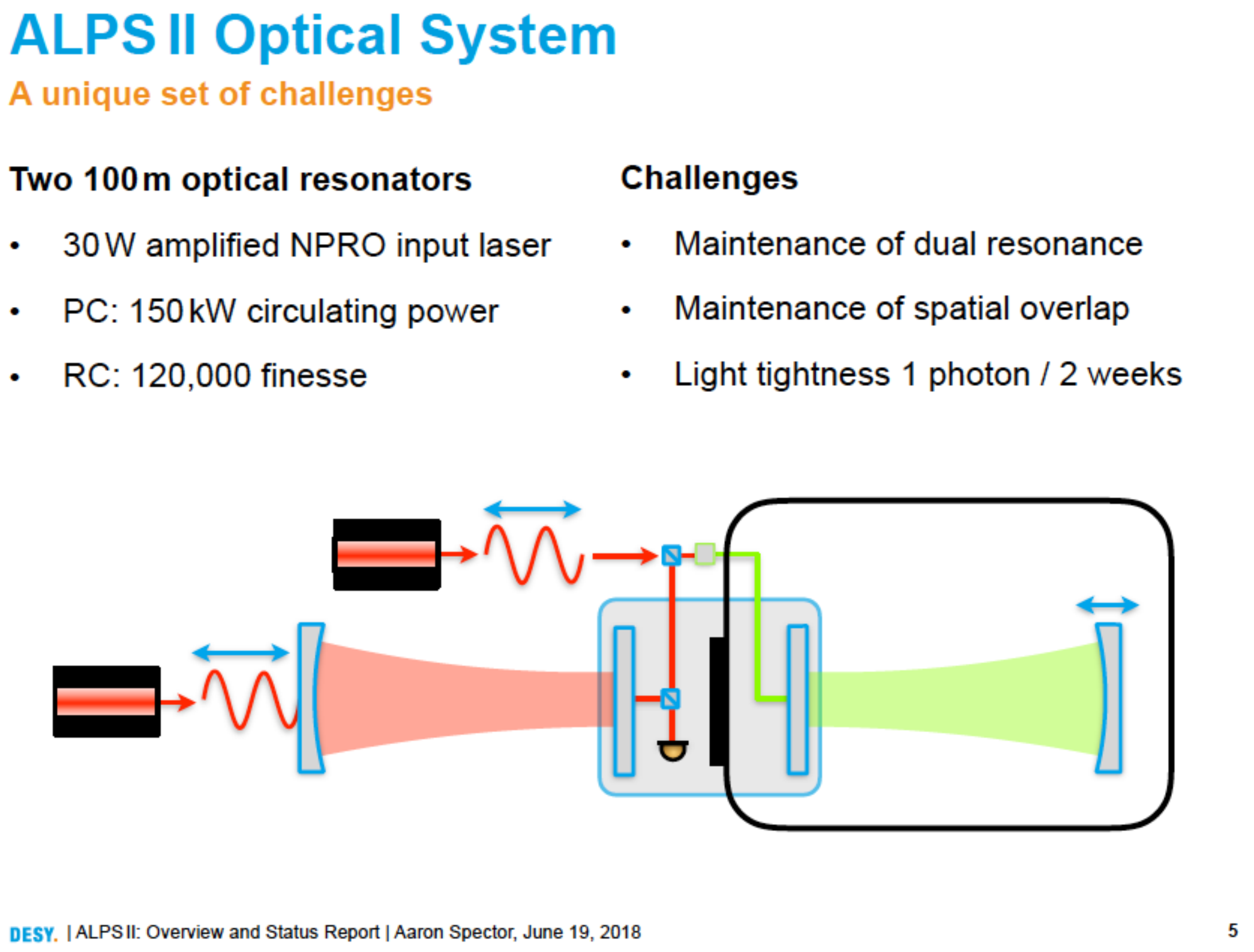


Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}$[GeV^{-1}]
ALPS-I [433]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [435]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [434]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [436]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [437]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [438]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [438]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

Table 4: List of the most competitive recent LSW results, as well as the prospects for ALPS-II, together with future possible projects, with some key experimental parameters. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g_{a\gamma}$ for low m_a. For microwave LSW (CROWS and STAX) the quality factors Q are listed. * The limit is better for specific m_a values, see Figure 6

Irastorza, Redondo 1801.08127v2

ALPS II at DESY, Started data taking with production cavity



ALPS II Optical System

A unique set of challenges

Two 100 m optical resonators

- 30 W amplified NPRO input laser
- PC: 150 kW circulating power
- RC: 120,000 finesse

Challenges

- Maintenance of dual resonance
- Maintenance of spatial overlap
- Light tightness 1 photon / 2 weeks

ALPS

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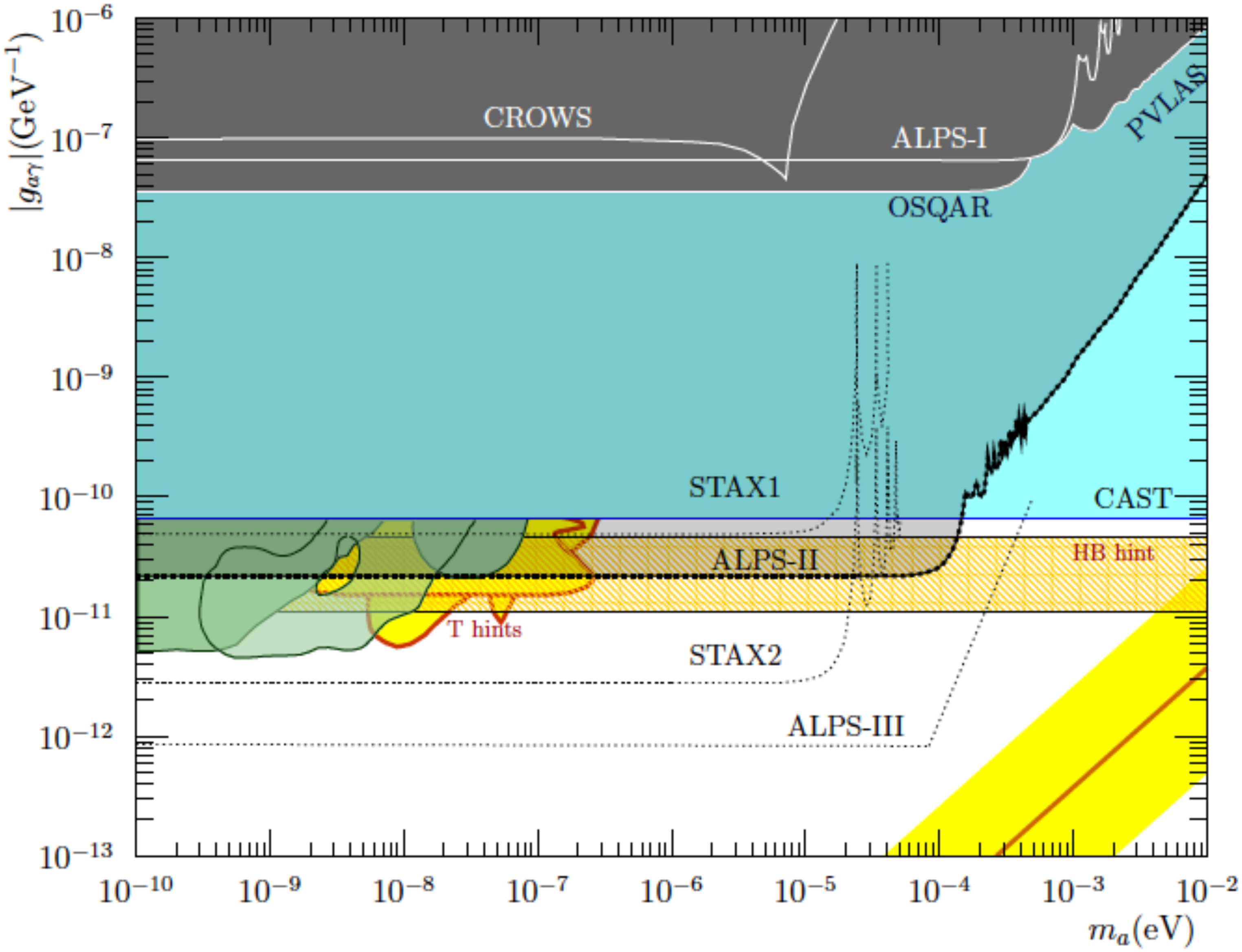
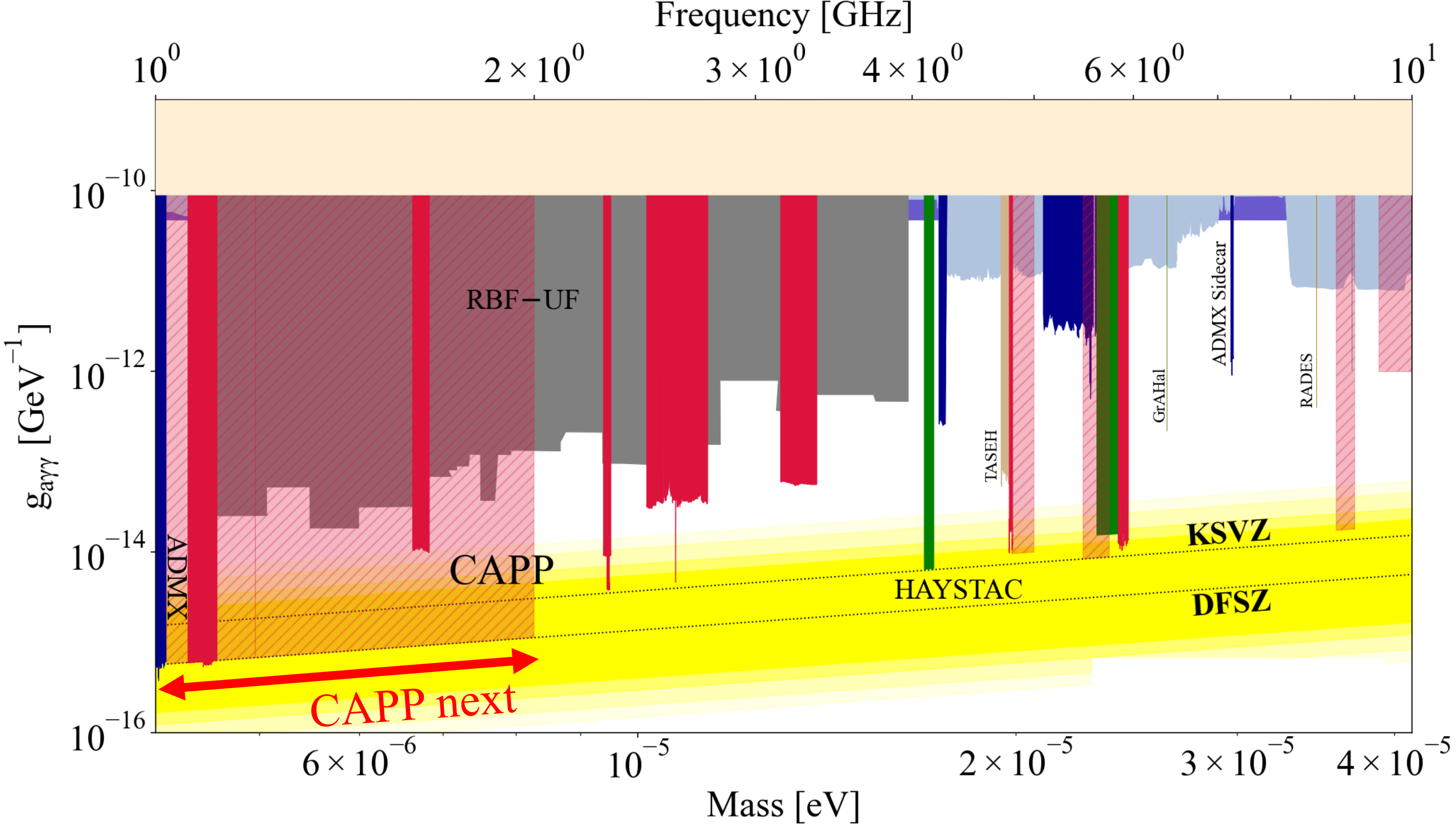


Near future

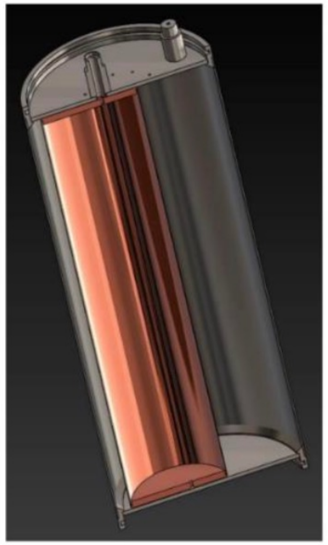
CAPP's immediate target 1-2 GHz

The axion could show up any day.

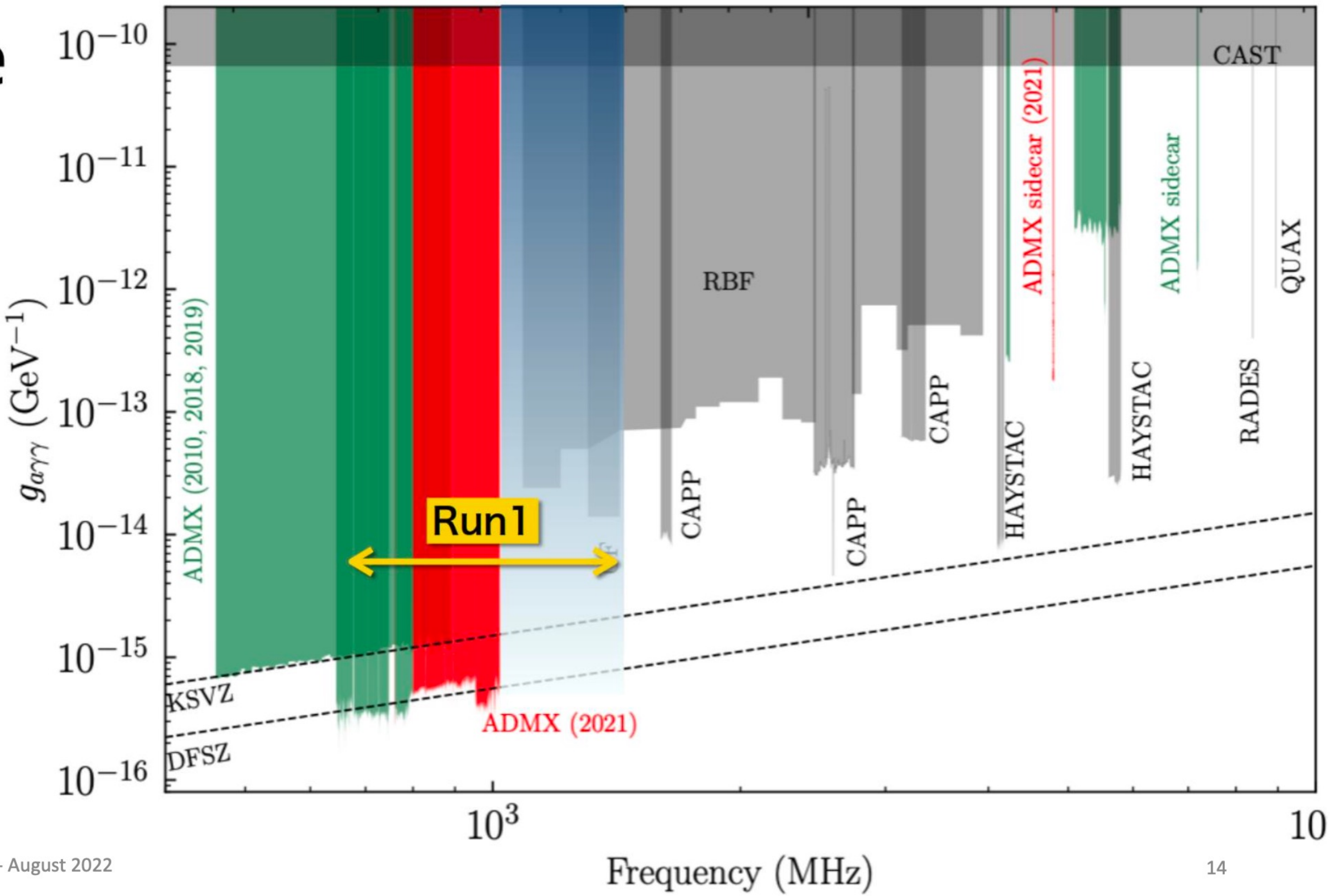


ADMX plan

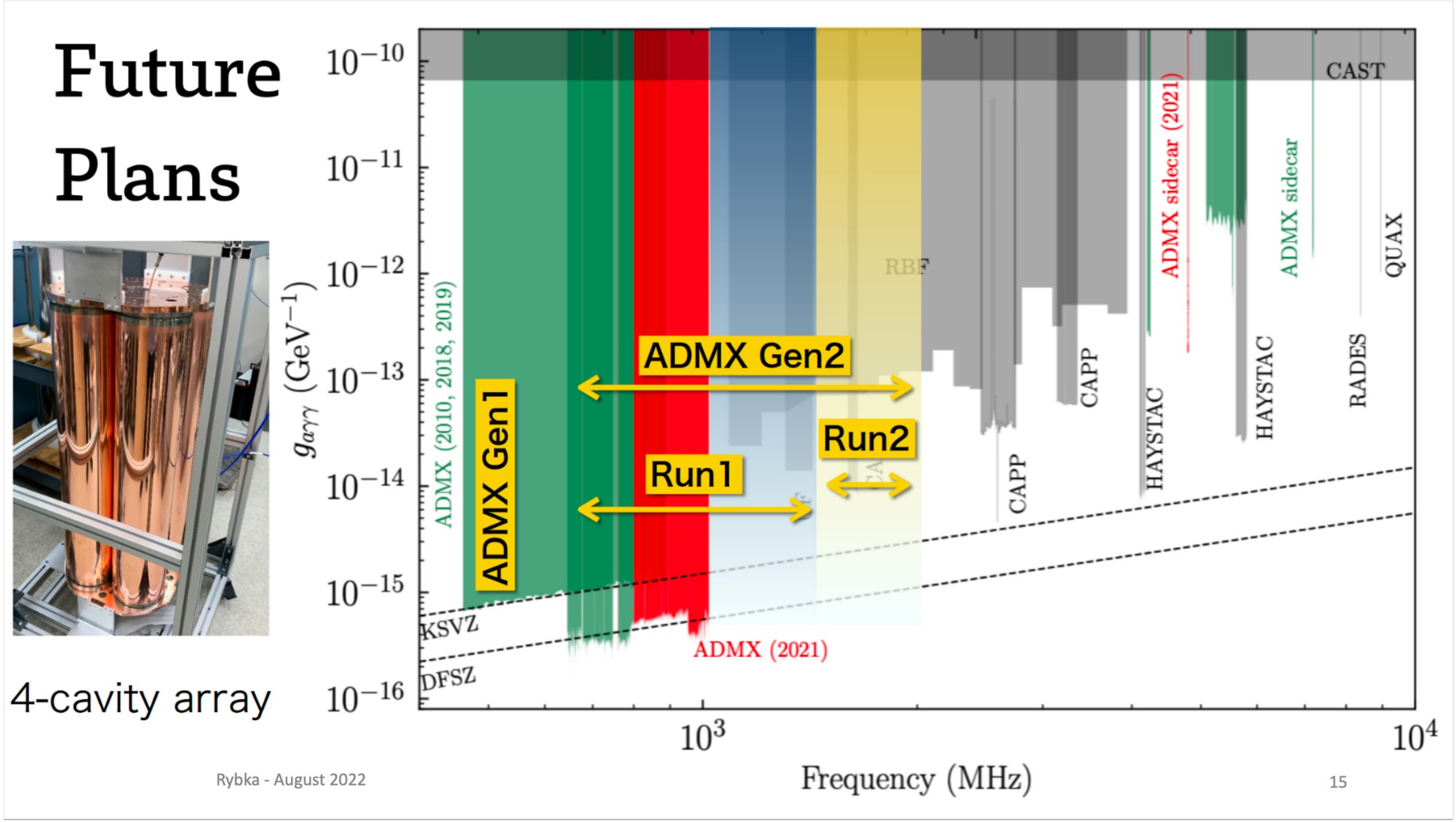
Future Plans



Bigger tuning rod



ADMX plan



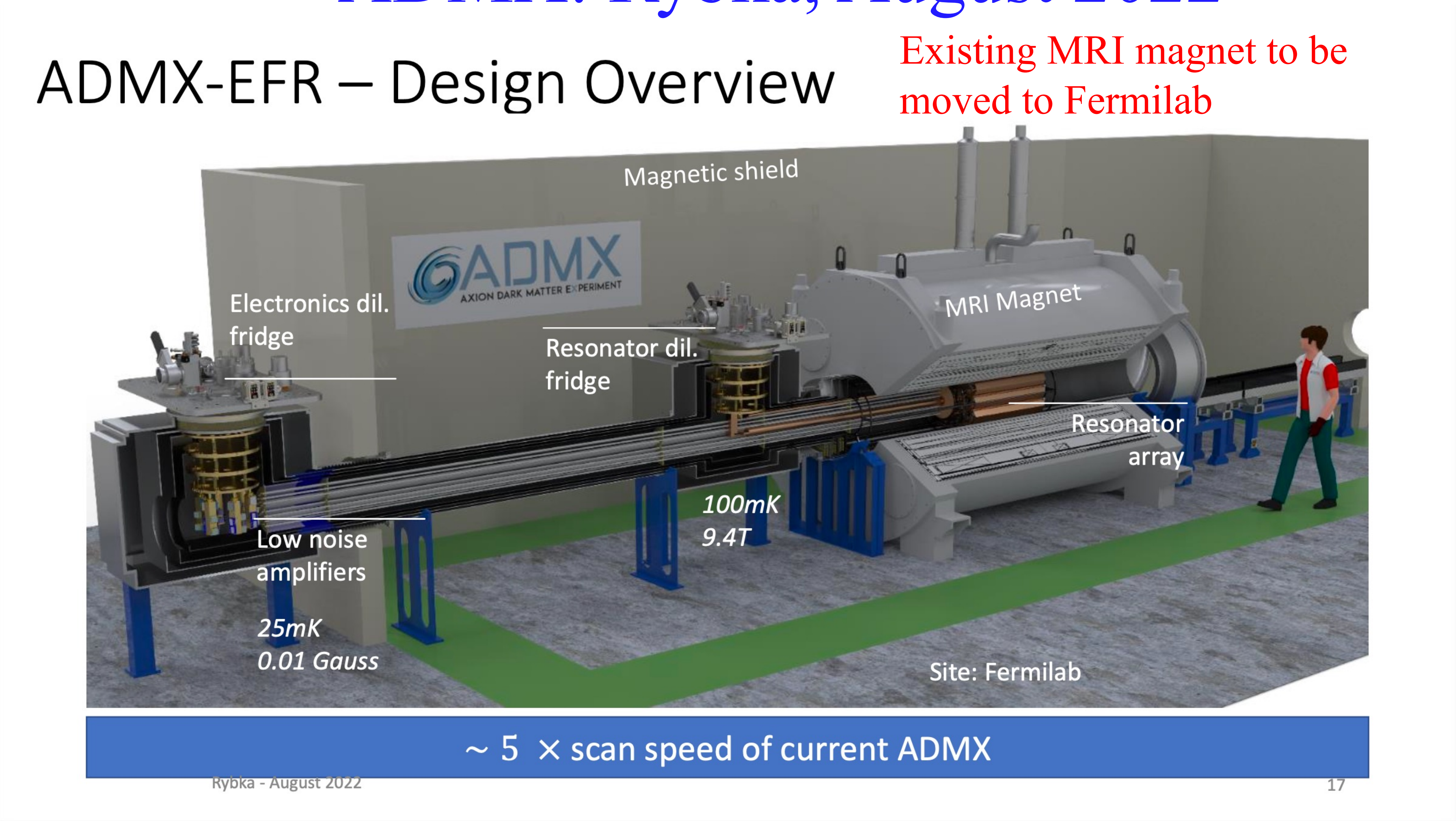
Future Plans

4-cavity array

Rybka - August 2022

15

ADMX: Rybka, August 2022



ADMX-EFR – Design Overview

Existing MRI magnet to be moved to Fermilab

~ 5 × scan speed of current ADMX

A new haloscope at Grenoble: GrAHal

New experimental effort!

B^2V wins (GrAHal-CAPP plans to scan 0.2-0.6 GHz at better than DFSZ)

9 T in 810 mm warm bore

$\langle B^2V \rangle$ at 9 T central field	Q at 4.4 K	C_{010}	Noise T	$g_{A\gamma\gamma}$
34.4 T^2m^3	1-2 10^5	0.63-0.69	1.6 K	DFSZ

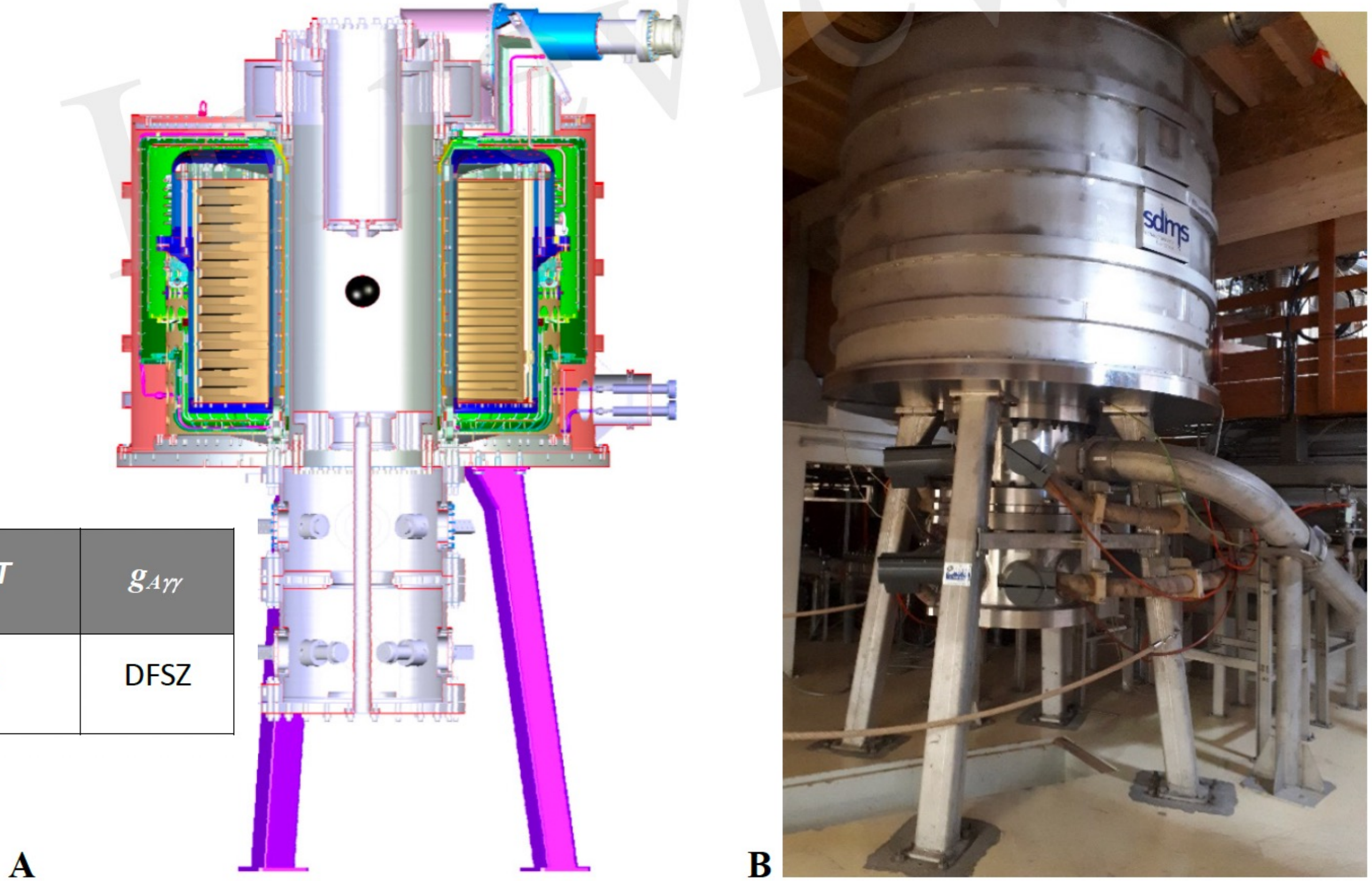


FIGURE 1

A) Cut view of the cryostat and large bore superconducting outsert of the Grenoble hybrid magnet.
B) The magnet as built in operation at LNCMI-Grenoble. The total height is about 5.4 m for a total weight of about 52 tons. Mechanical structures above and below the magnet aperture are water cooling boxes for the 24 MW resistive inserts used to reach higher magnetic fields. They will not be used for the GrAHal-CAPP haloscope described in this article.

Axion-photon with projections

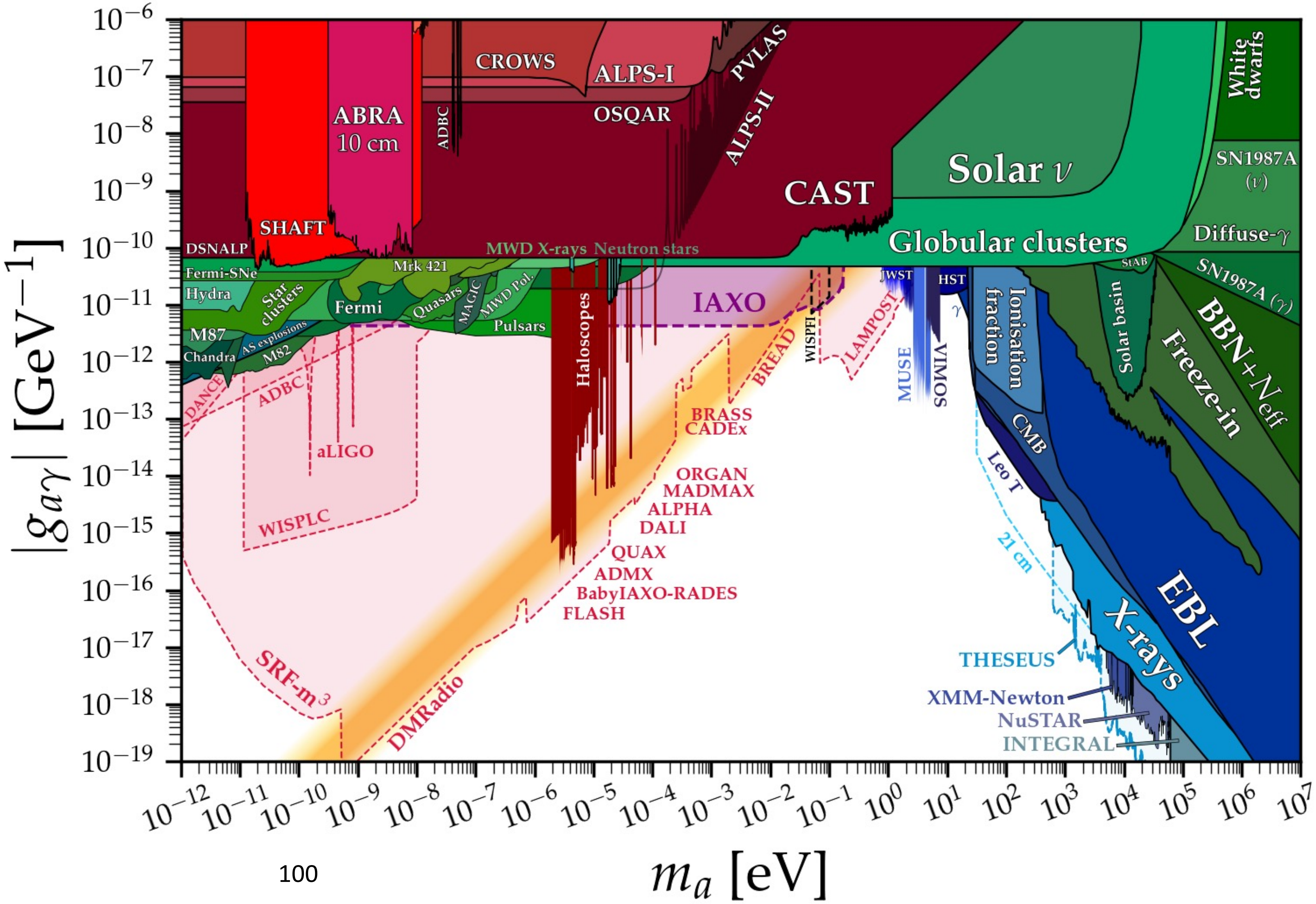
C. O'Hare, cajohare/axionlimits:
https://cajohare.github.io/AxionLimits/

CAPP plans to scan 1-8 GHz at better than DFSZ

GrAHal-CAPP plans to scan 0.2-0.6 GHz at better than DFSZ

Using existing magnets, know-how

Collaborating to reach our goals faster



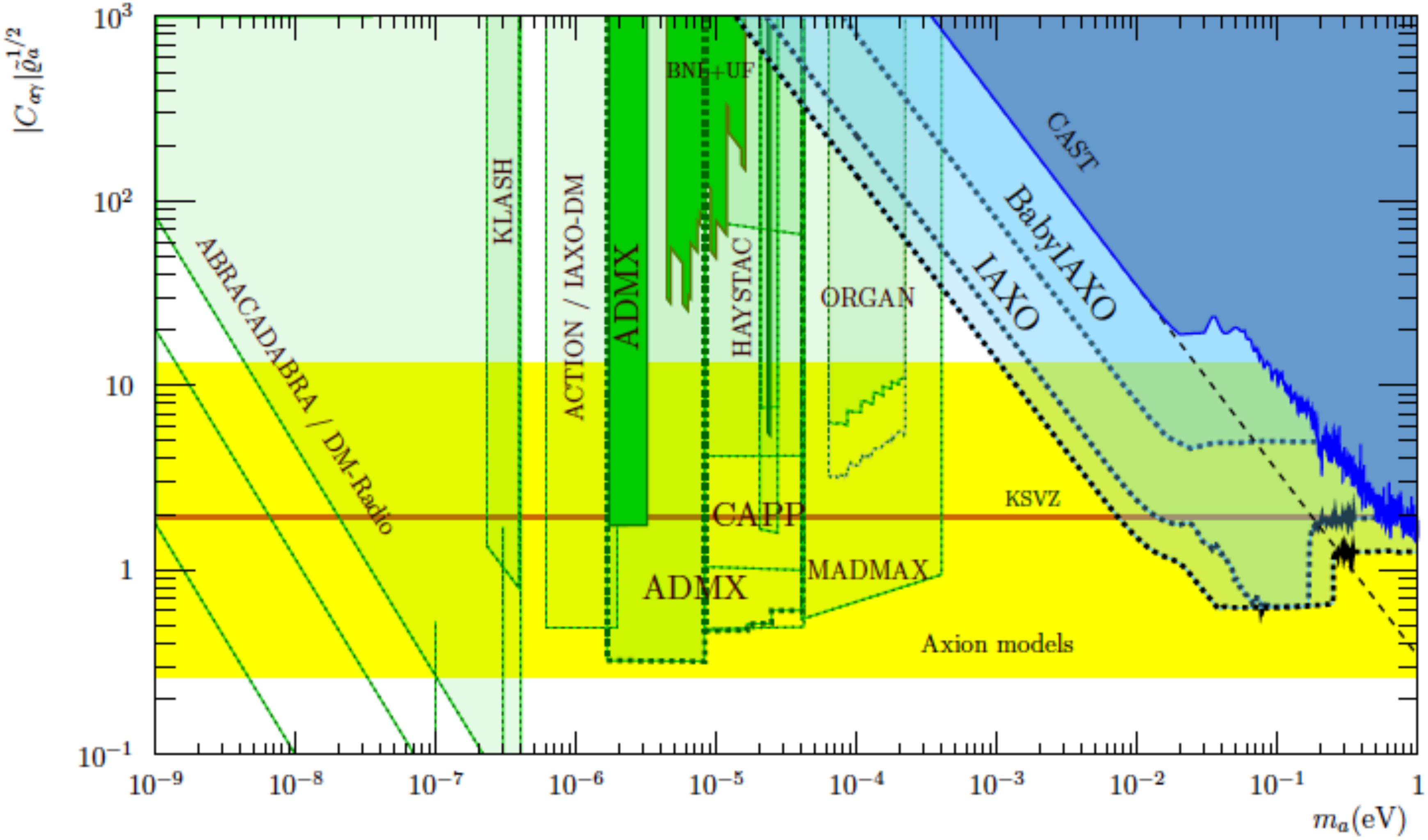
Summary

- ADMX, CAPP, GrAHal, HAYSTAC,… now could cover:
    - 0.2-4 GHz axion freq. in the next 2-years (DFSZ)
    - 4-8 GHz within the next 5-years (DFSZ)
    - 0.2-25 GHz within the next 10-20 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.
- The low frequency (<0.1 GHz), with DM-Radio and CASPER is on path to great success, the high frequency (>25 GHz) started developing sensitive experiments

Extra slides

Actively planned axion exps.



Irastorza, Redondo 1801.08127v2

Axion dark matter results using an LHC dipole magnet at CERN

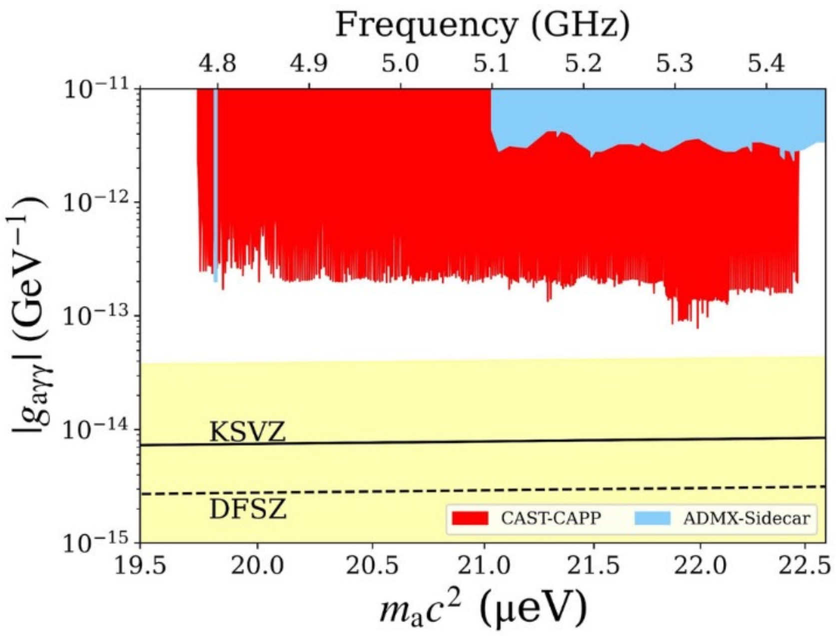


Fig. 5 | CAST-CAPP exclusion limit on the axion-photon coupling as a function of axion mass at 90% confidence level (left), and compared to other axion search results[10,25,30,34–41] **within the mass range 1–25 μeV (right).** The higher

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Nature Communications | (2022)13:6180

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nature communications

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

Search for Dark Matter Axions with CAST-CAPP

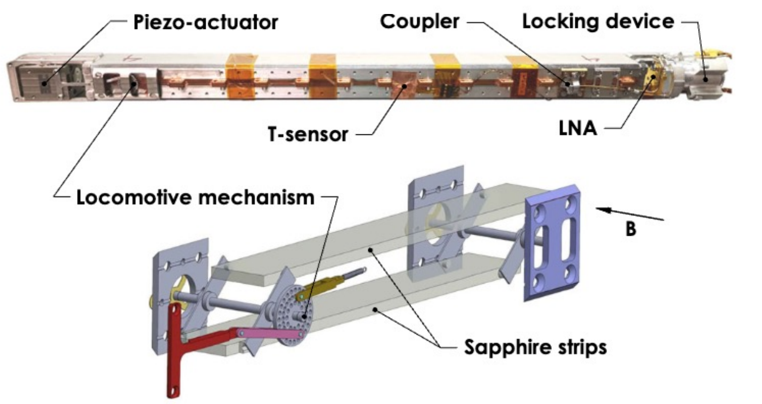


Fig. 1 | A photograph of the elements of a single cavity assembly (top) and a technical drawing of CAST-CAPP tuning mechanism with the two sapphire strips (bottom). The static B-field is shown by the arrow and is parallel to the two axes of the tuning mechanism.

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 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

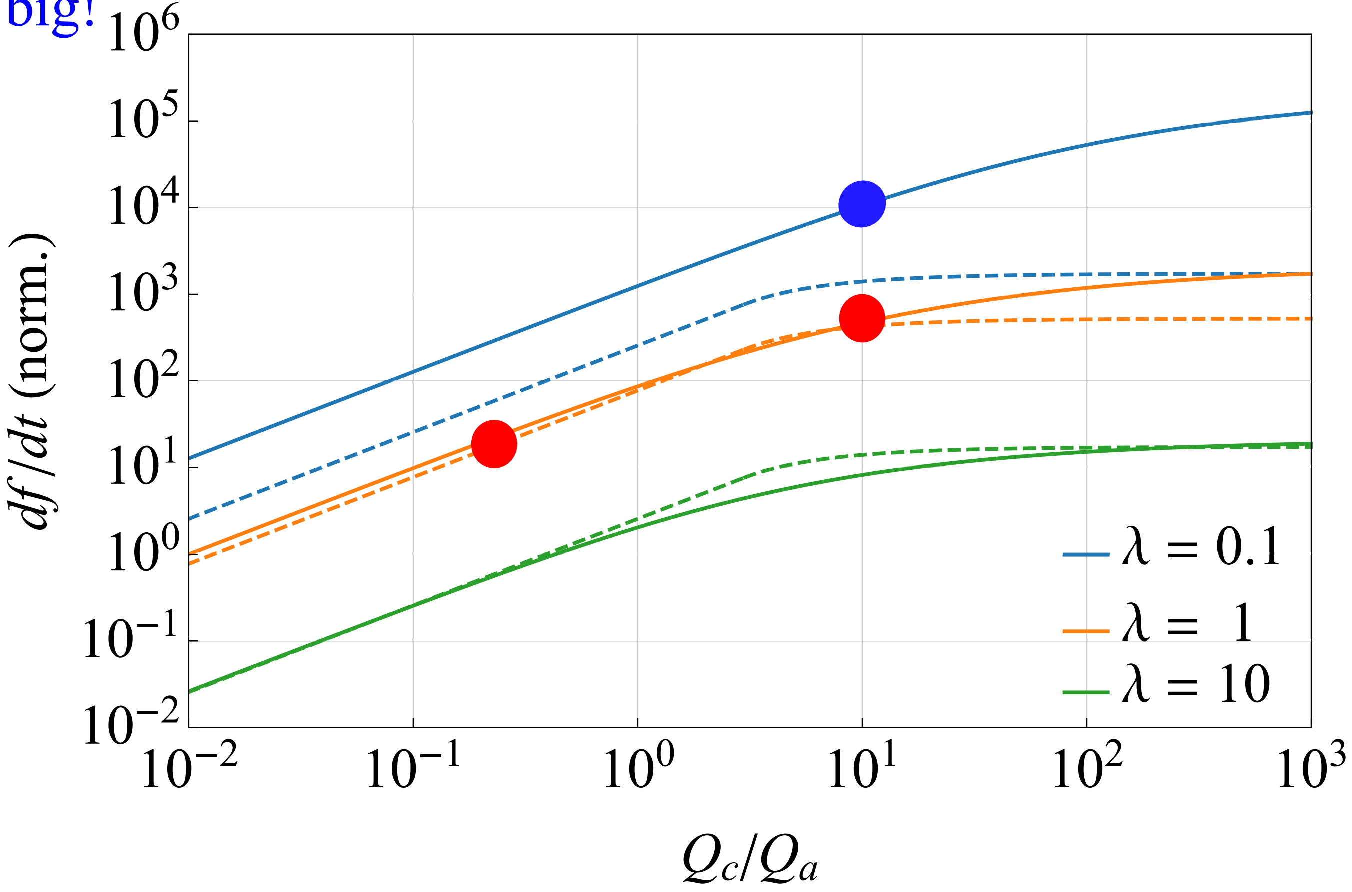


Figure 6. Comparison of the scanning rate between the original (eq. (1.4)) and revised (eq. (5.2)) calculations as a function of normalized cavity quality factor, Q_c/Q_a, for three different values of λ, the relative noise contribution. The former and the latter estimations are represented by dashed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

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

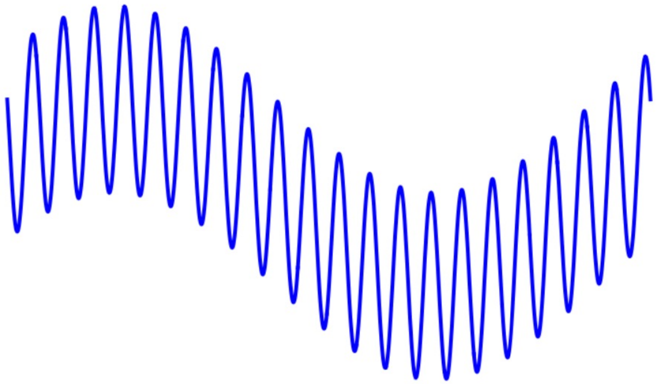
Shot noise (Randomness of Amplification)

Bosonic statistics + Zero-point fluctuation

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

- **Amplifier Noise** [1]

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



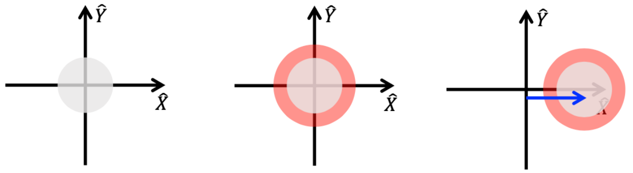
- **Heterodyne**

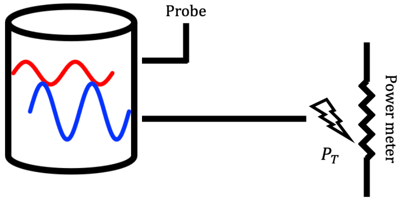
Mixing two frequencies

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

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

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

Variance statistics

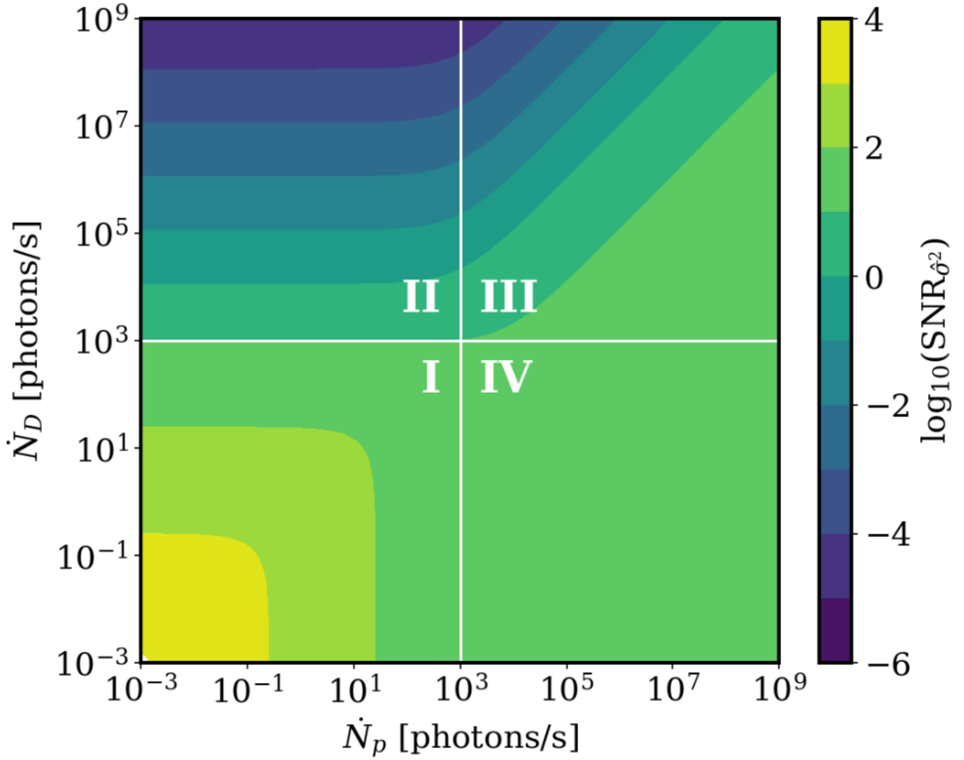
- **SNR of the variance estimator**

Detector sampling rate: f_s

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

$$\mathrm{S/N}_{\sigma^2} \approx \frac{\dot{N}_s(1+\dot{N}_p/f_s)\sqrt{f_s\Delta t}}{(\dot{N}_D+\dot{N}_p)\sqrt{2+f_s/(\dot{N}_D+\dot{N}_p)}} \xrightarrow[\uparrow\,\boxed{\dot{N}_p \gg f_s}]{} \frac{\dot{N}_s}{\sqrt{2f_s}}\sqrt{\Delta t}$$

Junu Jeong's slide



- **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 $\dot{N}_D|_{eff} \to 2f_s$
- **Region IV:** $\dot{N}_D < f_s,\ \dot{N}_p > f_s$

  Injecting prboe reduces the SNR

Heterodyne-variance method, 2209.07022

Intermediate method before low-noise single photon detection

Comparisons

Junu Jeong’s slide

- **SNR comparison with Single Photon Detector**

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

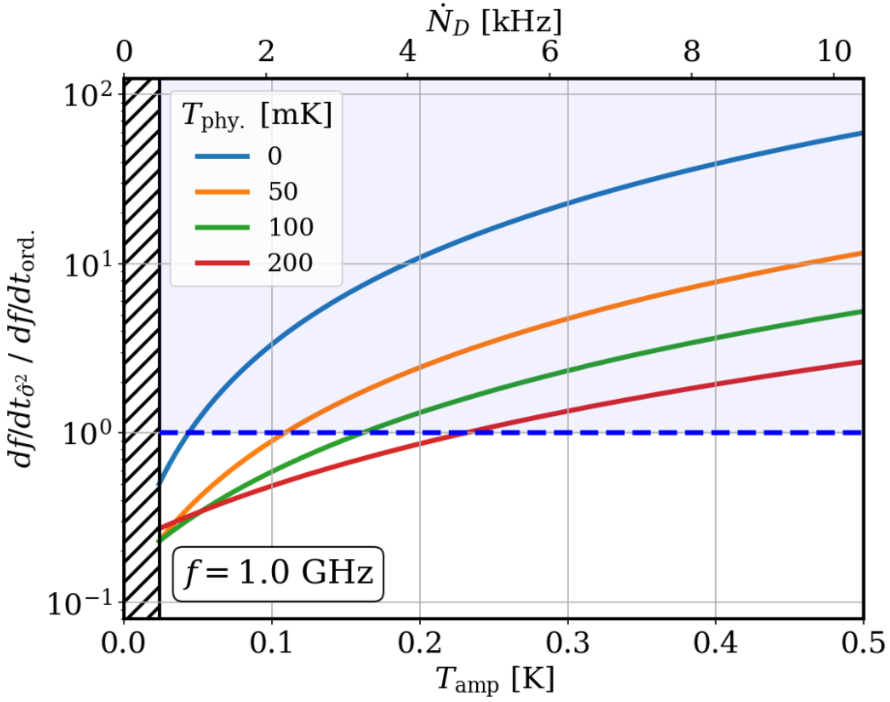
  - The denominator changes from $\sqrt{2 f_s}$ to $\sqrt{\dot{N}_{\mathrm{th.}} + \dot{N}_D}$
  - In the case that $\dot{N}_D > 2 f_s$, $\mathrm{S/N}_{\sigma^2} > \mathrm{S/N}_{\mu}$

- **Scan rate comparison with Ordinary Method**

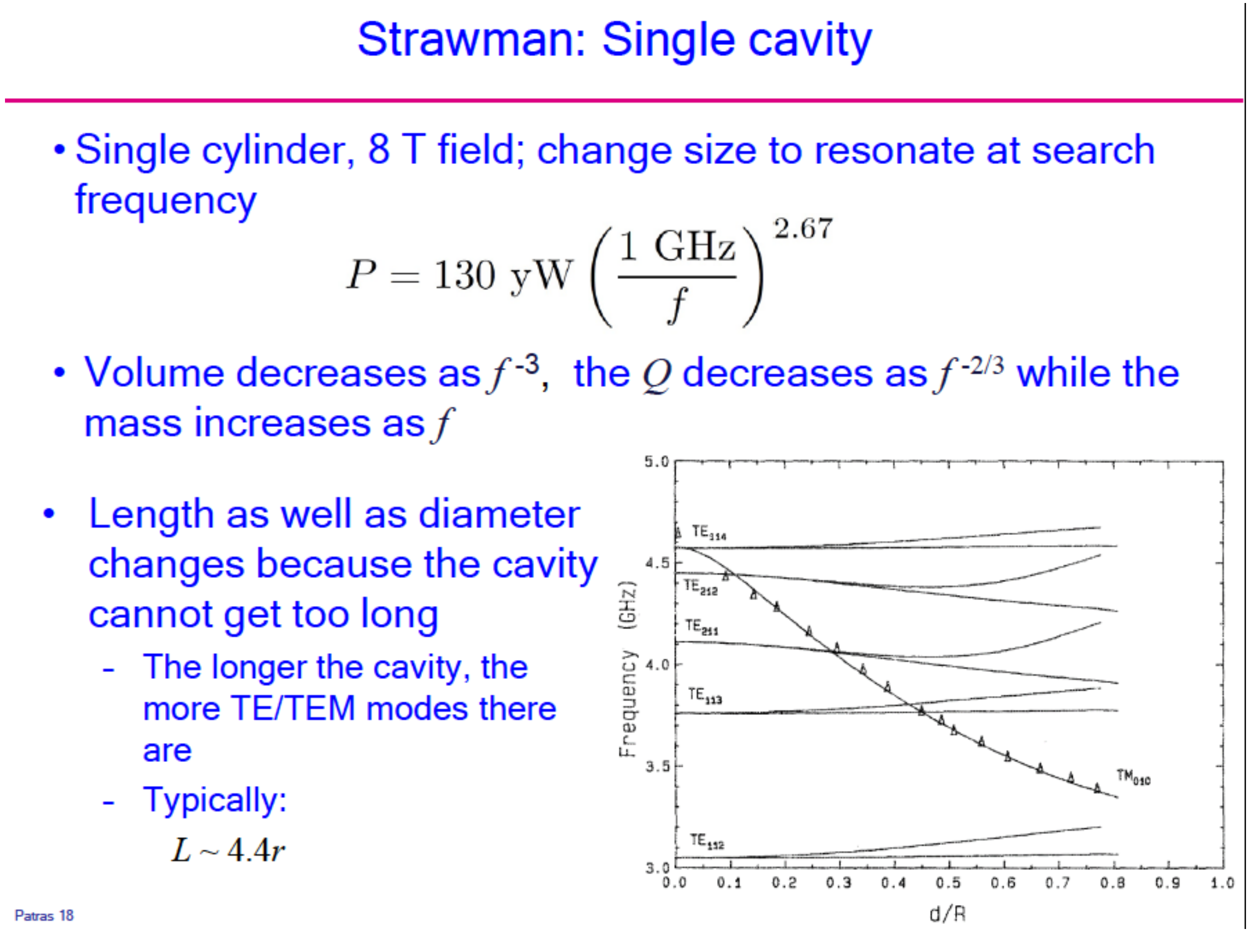
$$\left.\frac{df}{dt}\right|_{\sigma^2} \approx \frac{\Delta f_c}{\Delta t} = \frac{\dot{N}_s^2}{\mathrm{S/N}_{\sigma^2}} \frac{\Delta f_c}{2\Delta f_a}$$

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

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



David Tanner



Strawman: Single cavity

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

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

- 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:

$$L \sim 4.4r$$

HTS superconducting cavity in large B-field!

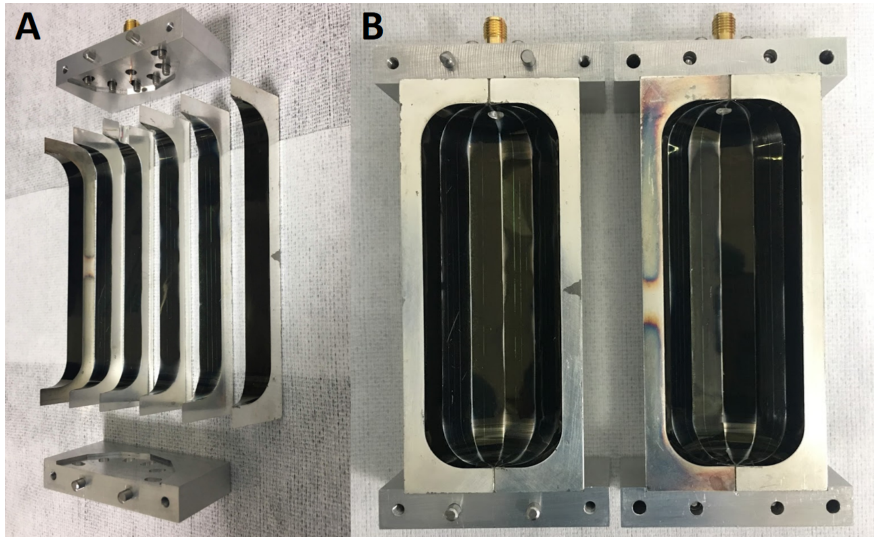
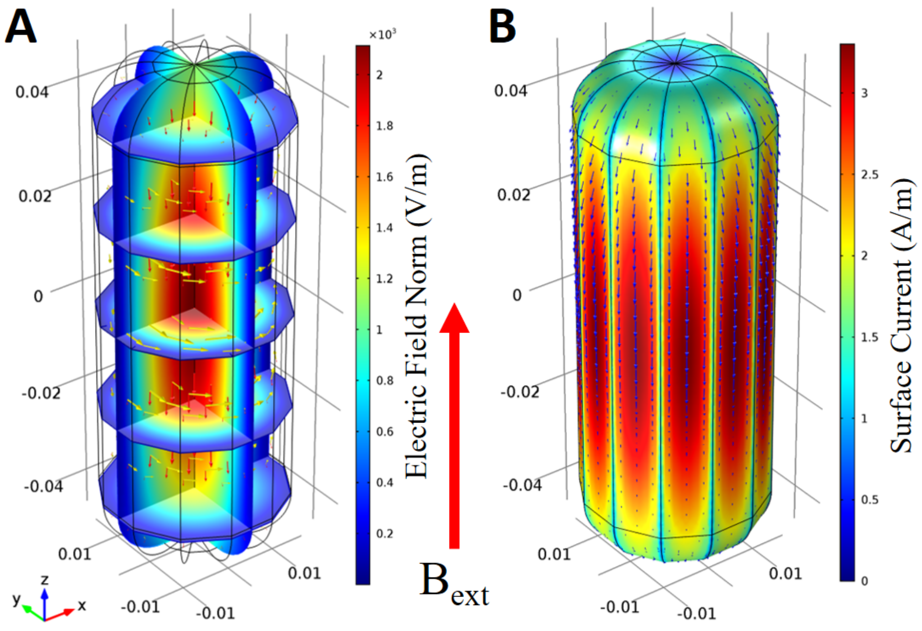


FIG. 1: Design of the YBCO polygon cavity. **(A)** Six aluminum cavity pieces to each of which a YBCO tape is attached. **(B)** Twelve pieces composing two cylinder halves are assembled to a whole cavity.

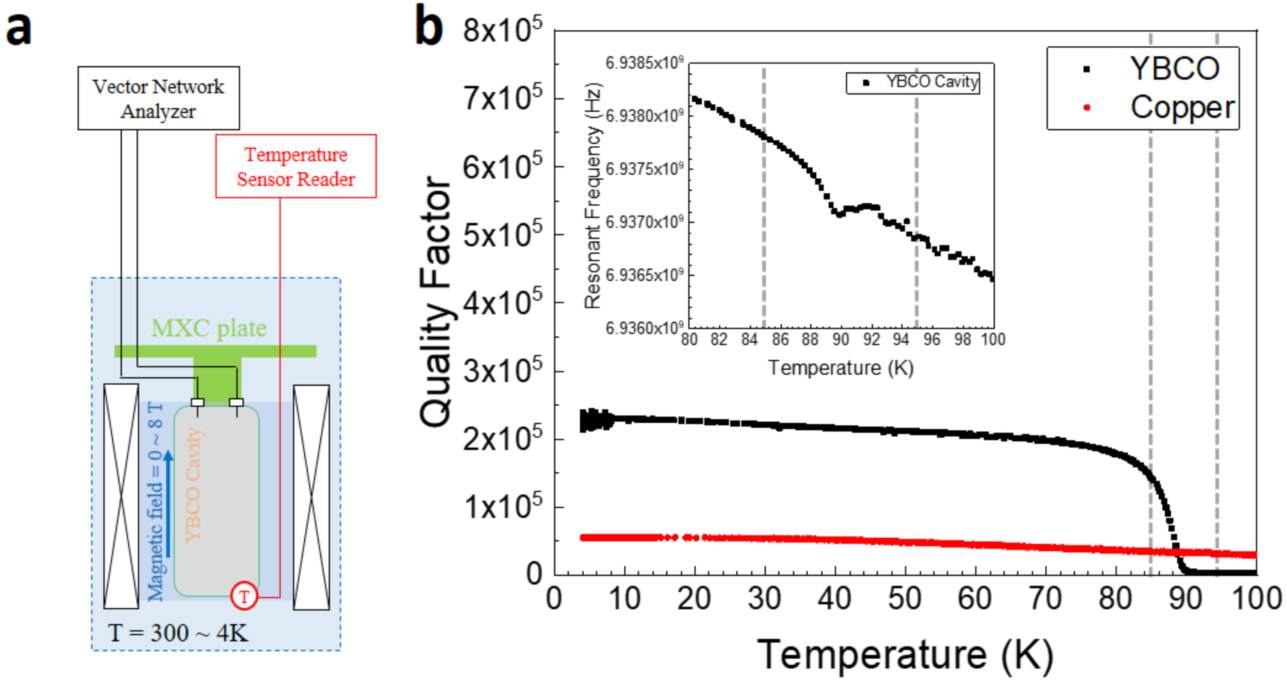
TM_{010} mode



YBCO tapes on cavity walls

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

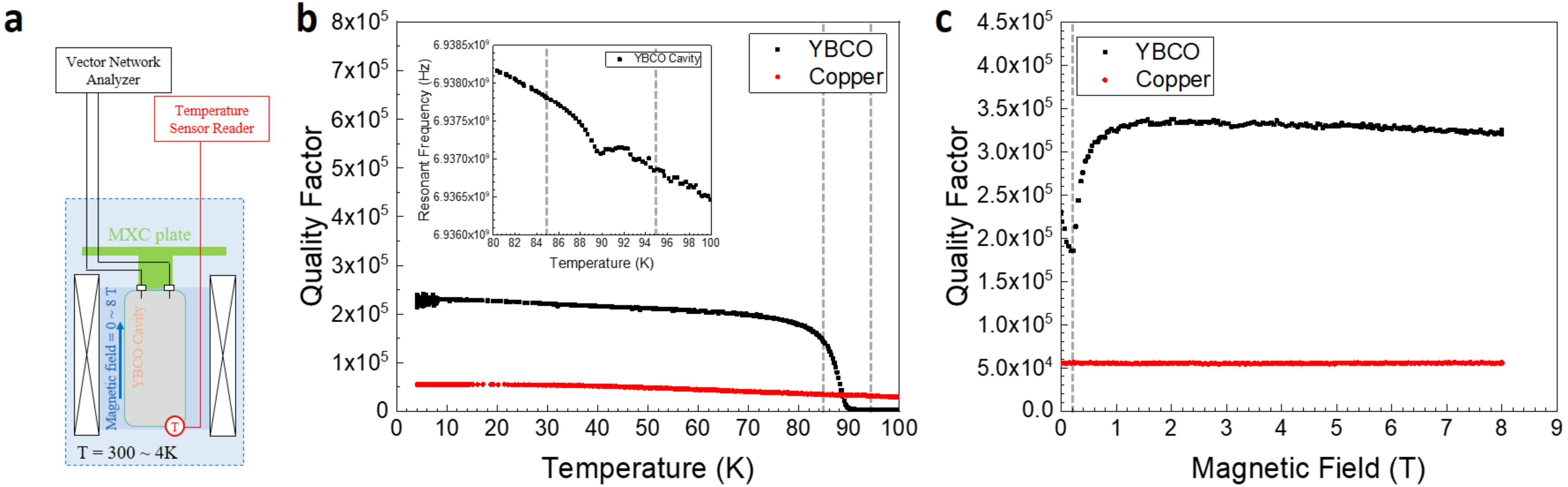
HTS superconducting cavity in large B-field!



First and best in the world!

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

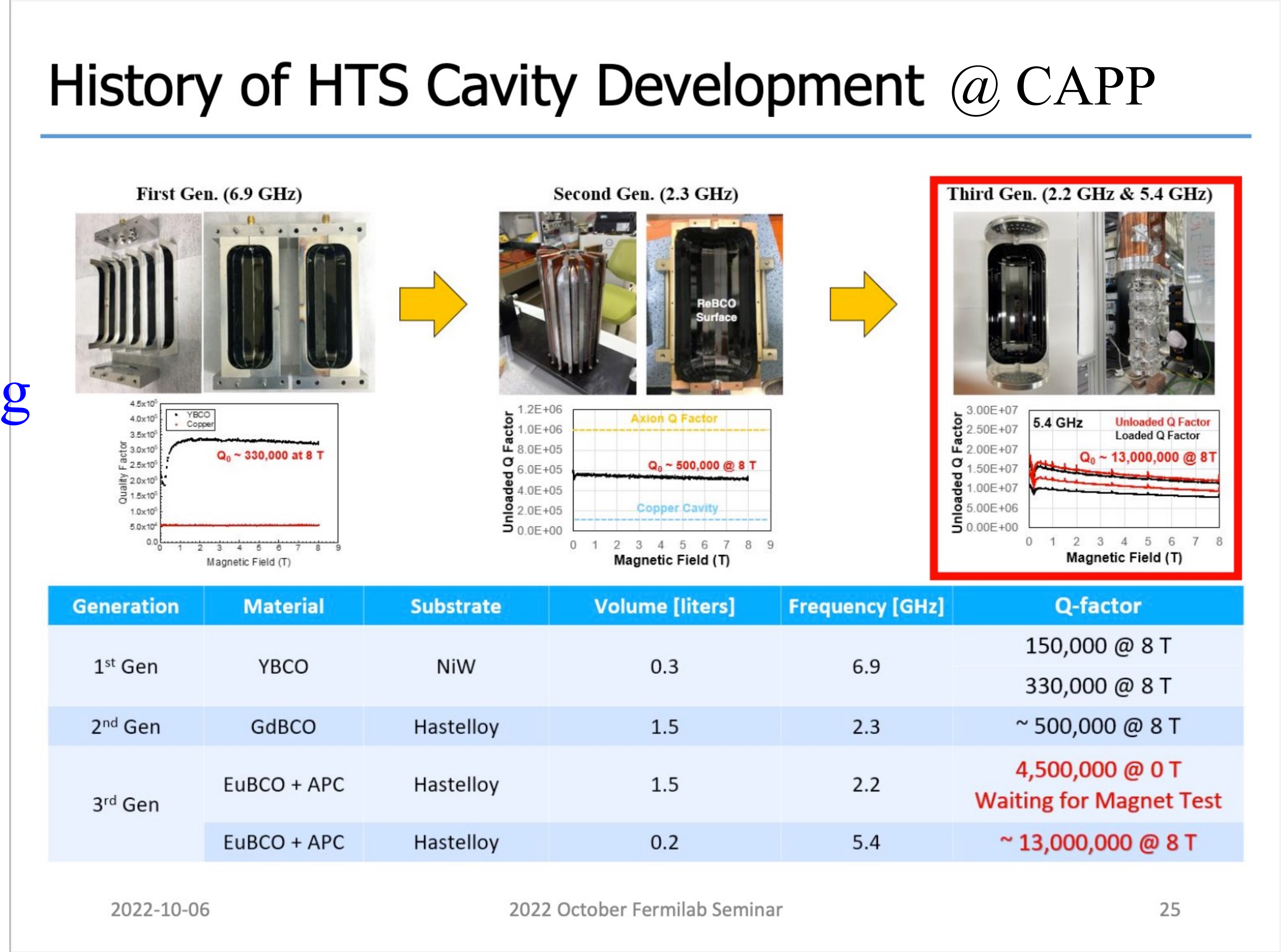
HTS superconducting cavity in large B-field!



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)

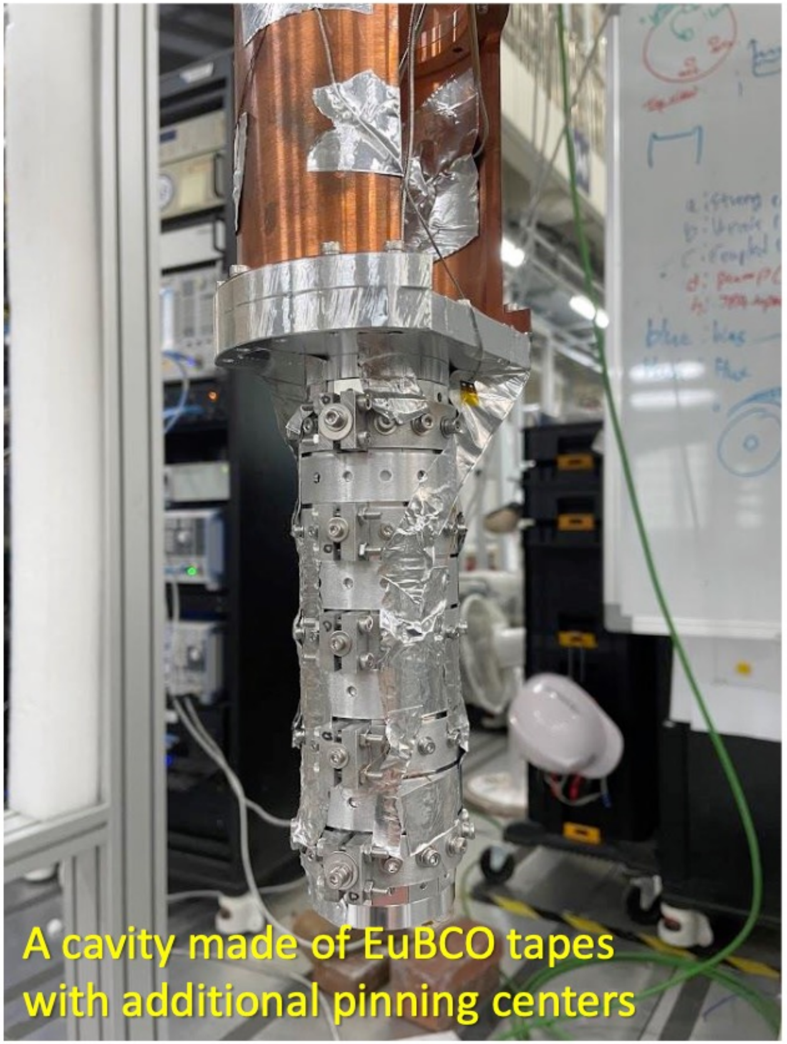
Third Gen. (2.2 GHz & 5.4 GHz)

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

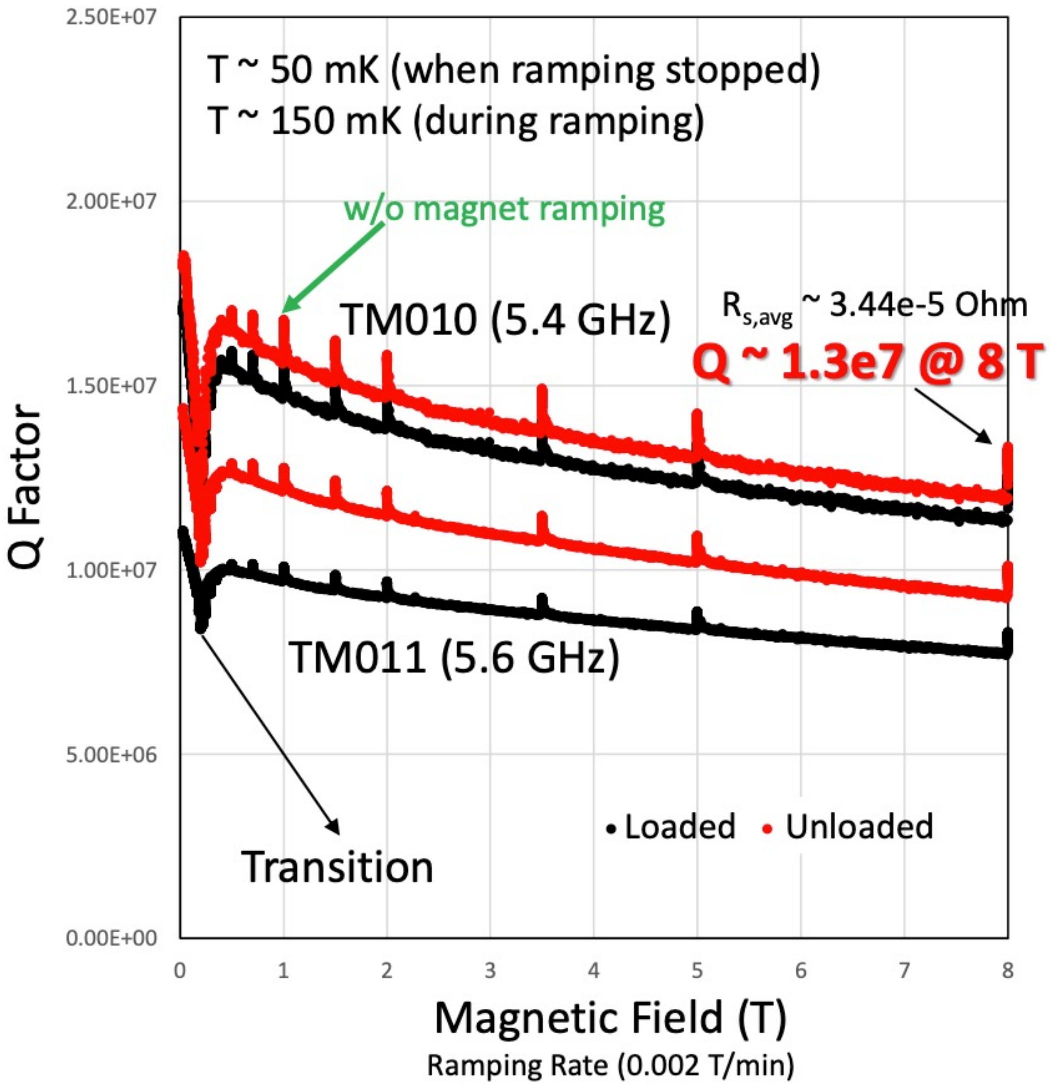
3rd Generation Cavity using EuBCO Tapes

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

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



A cavity made of EuBCO tapes with additional pinning centers

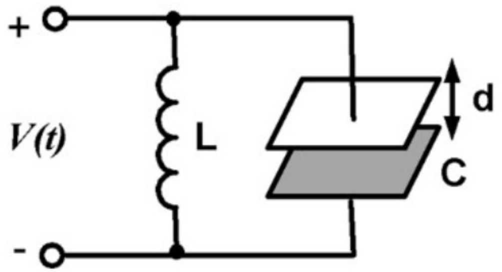


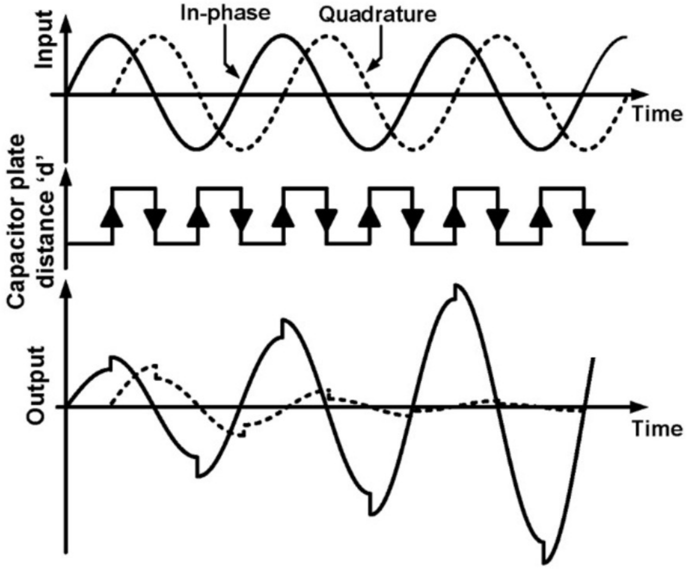
CAPP-PACE Detector

HTS cavities speed up scanning rates

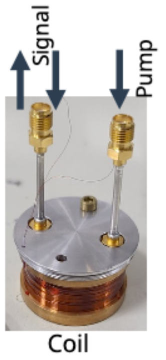
	HEMT Run Phys. Rev. Lett. 126 (2021)	**JPA Run** arXiv:2207.13597, PRL (in process) (Mr. Jinsu Kim *et al.*)	**SC Run** In process
Frequency Range	2.457 – 2.749 GHz	2.27 – 2.30 GHz	2.273 – 2.295 GHz
Magnetic Field (B)	7.2 T	7.2 T	6.95 T
Volume (V)	1.12 L	1.12 L	**1.5 L**
Quality Factor (Q_0)	100,000	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**

JPA Principle
(Caglar Kutlu's slide)

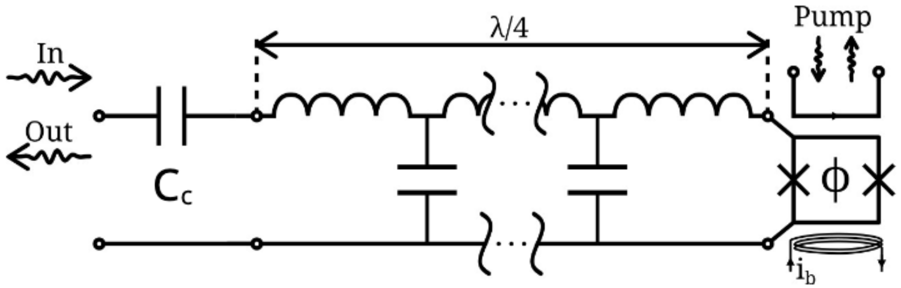




JPA Principle
(no resistors)

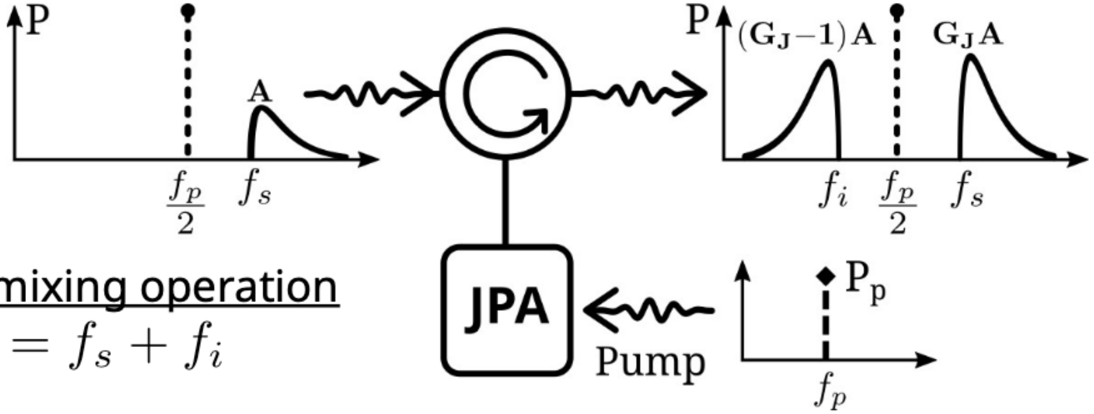


Flux-driven Josephson Parametric Amplifier



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

- 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

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