When the Darkness is Finally Dispelled …

…it's the

Axion

Embrace it.

Karl van Bibber
UC Berkeley
August 21, 2017

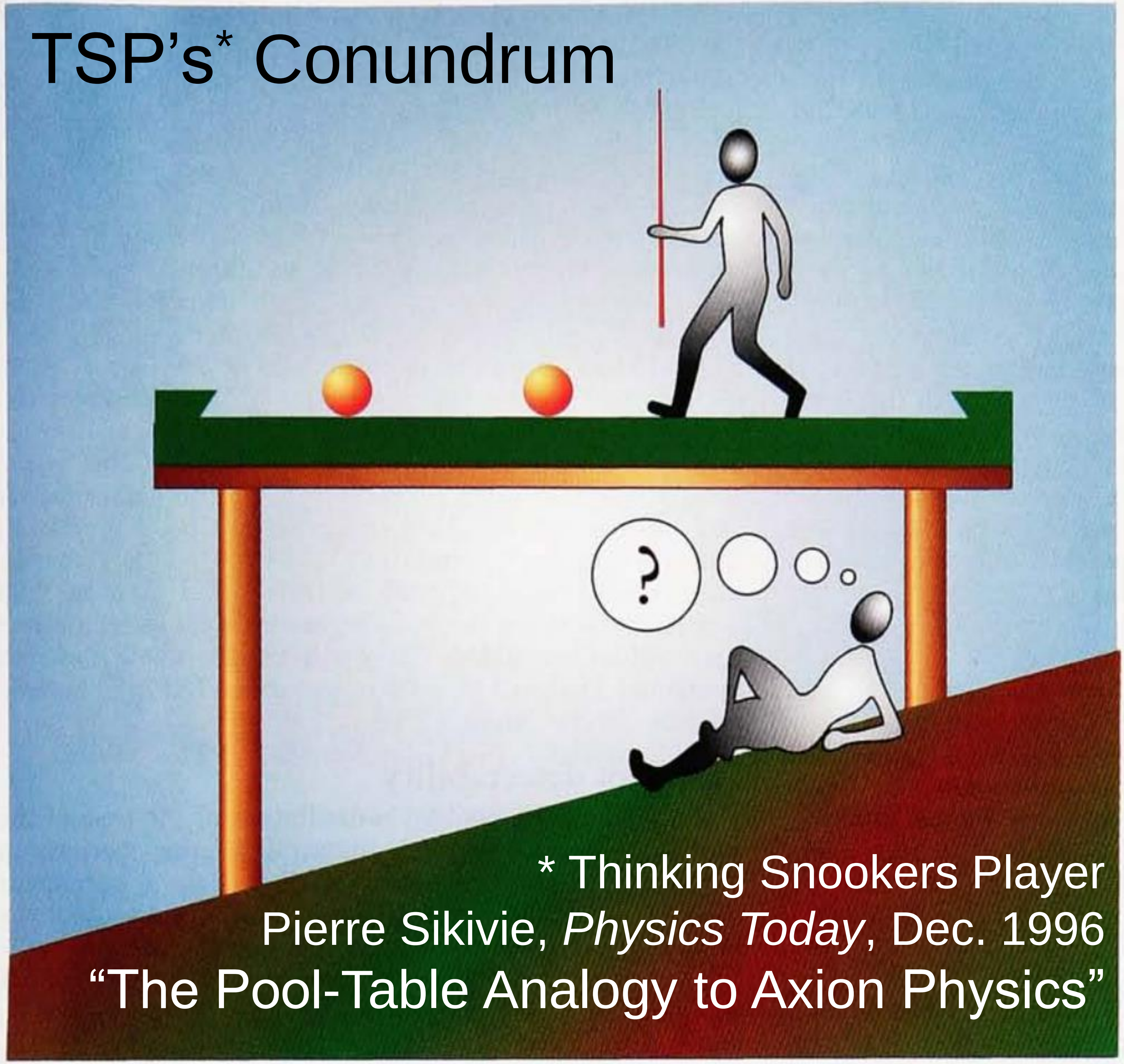
Outline

- Some basics on the axion & dark matter
- The microwave cavity search for axionic dark matter
- Where we are today – ADMX & HAYSTAC
- Towards improved sensitivity, higher & lower masses
- Other axion searches
- When will the axion be found, and what then?

See P.W. Graham, I.I. Irastorza, S.K. Lamoreaux, A. Lindner, K. A. van Bibber, Annual Reviews of Nuclear and Particle Science 65 (2015) 485

The Axion, Particle Physics & Cosmology

TSP's* Conundrum

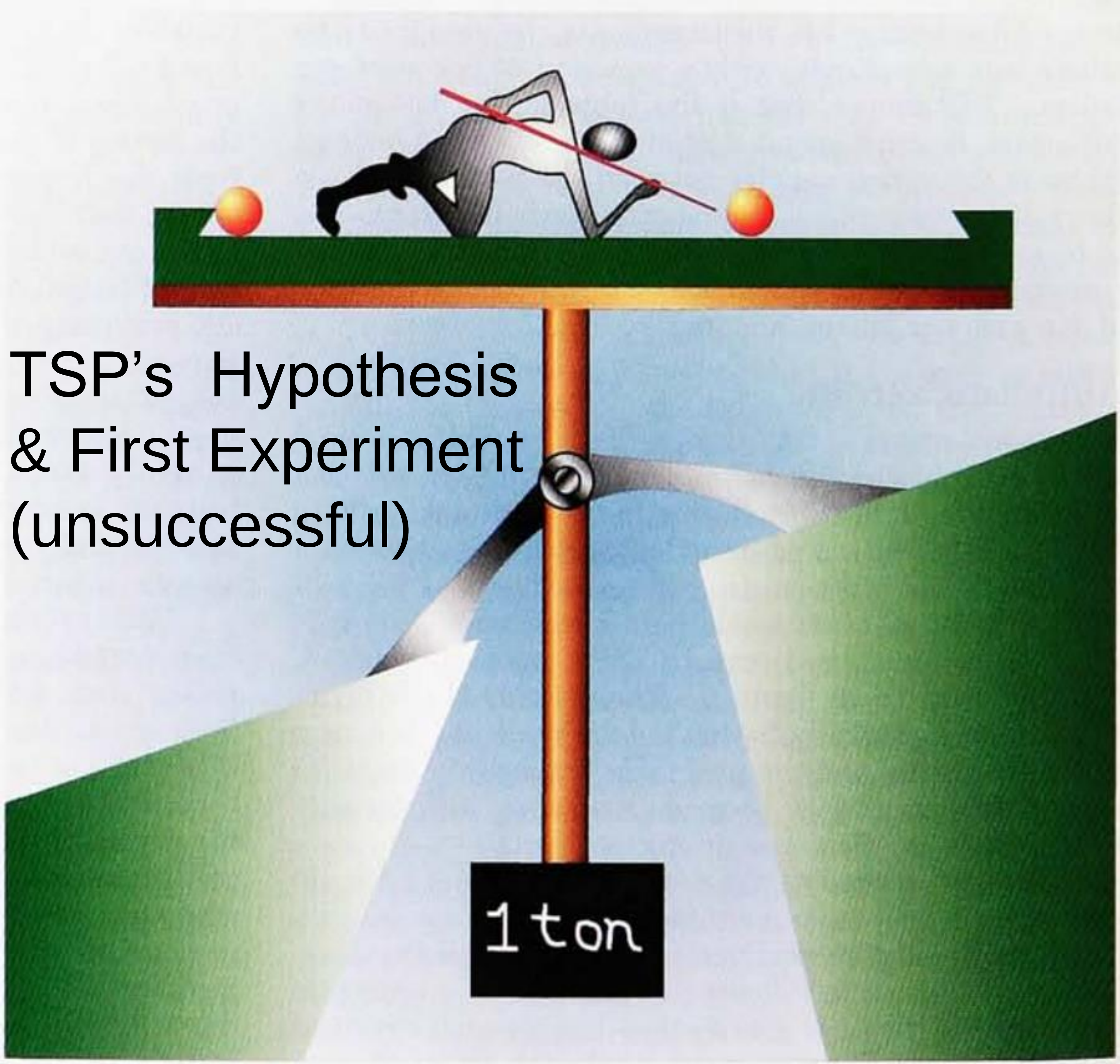


* Thinking Snookers Player

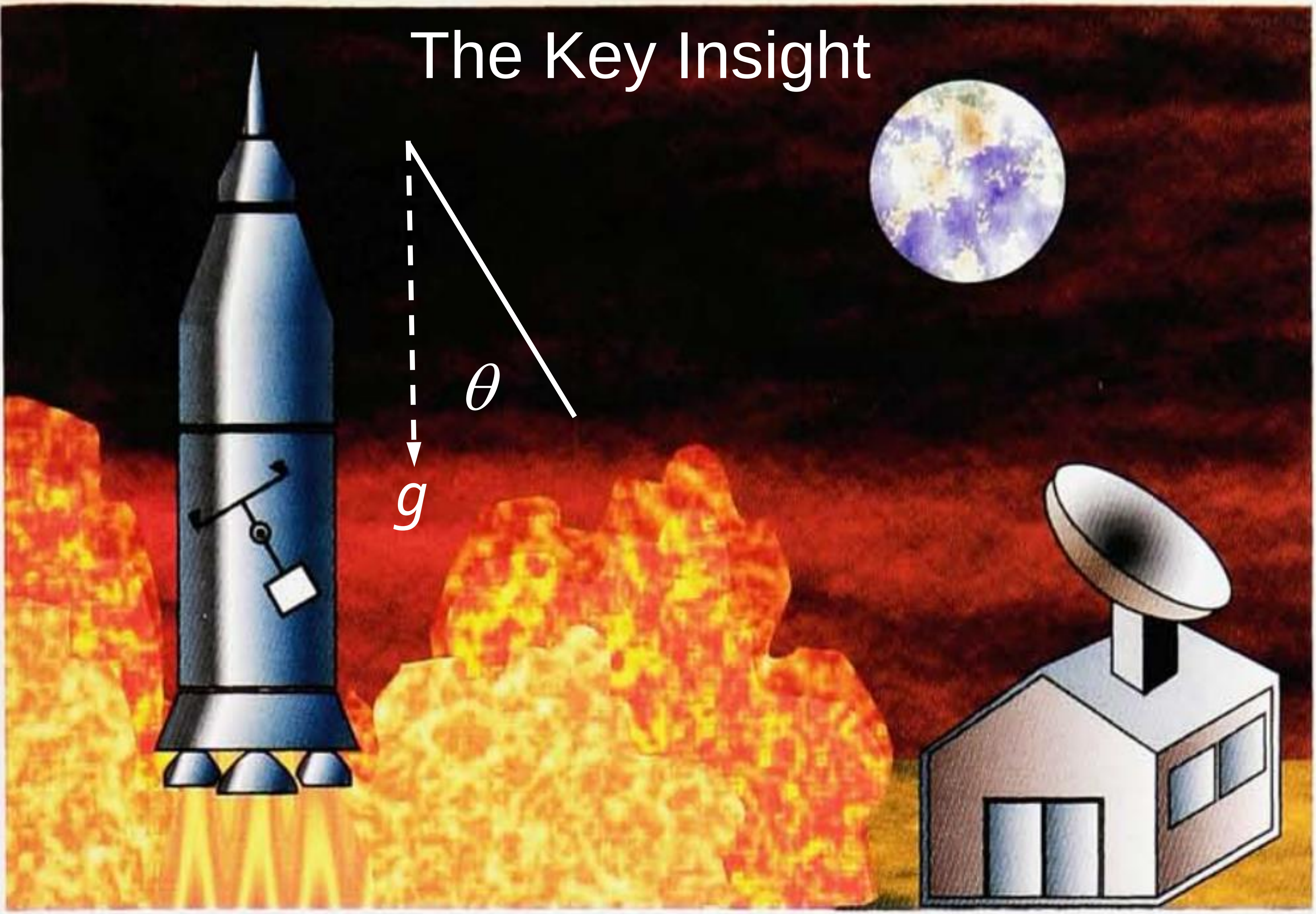
Pierre Sikivie, *Physics Today*, Dec. 1996

"The Pool-Table Analogy to Axion Physics"

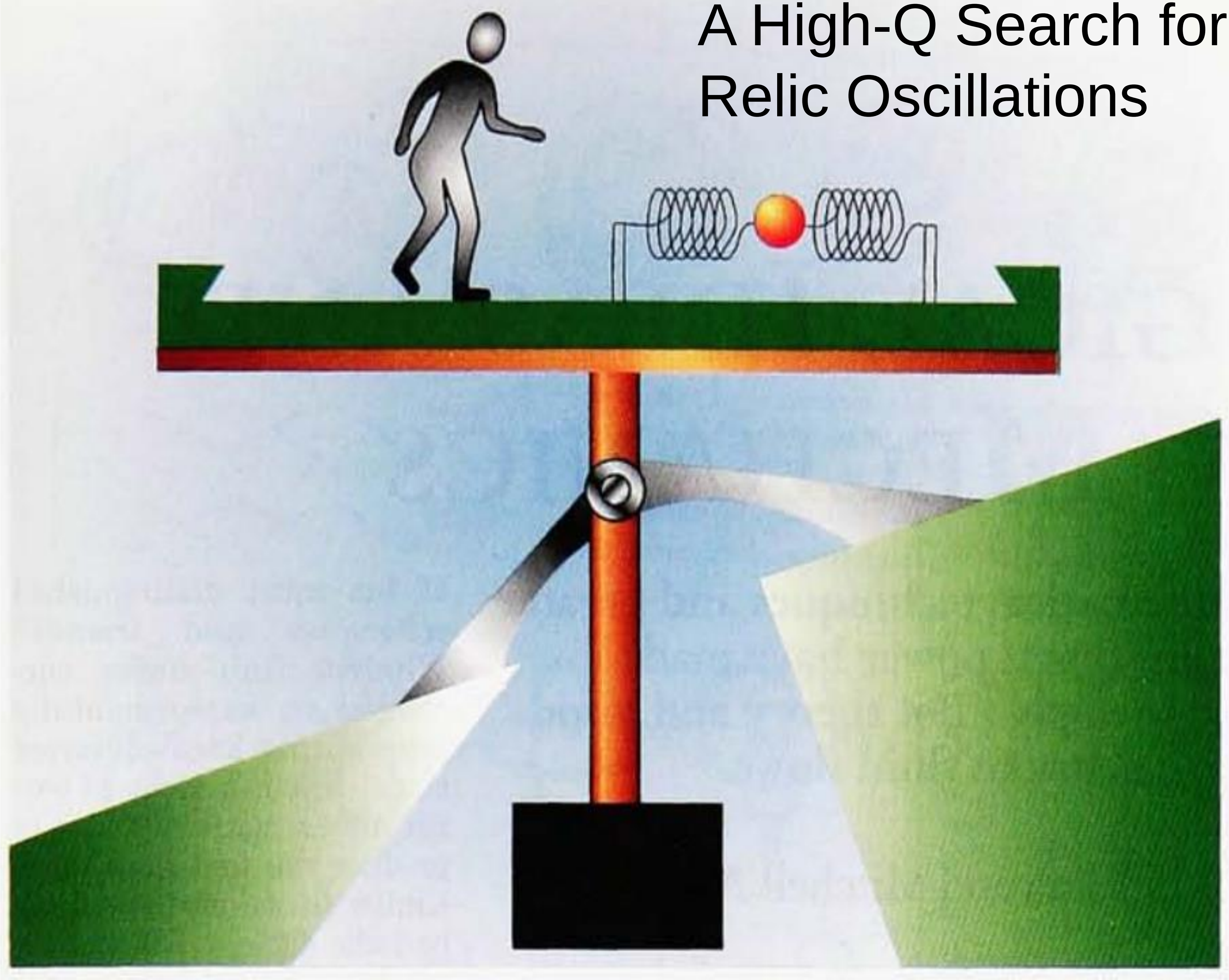
TSP’s Hypothesis & First Experiment (unsuccessful)



The Key Insight



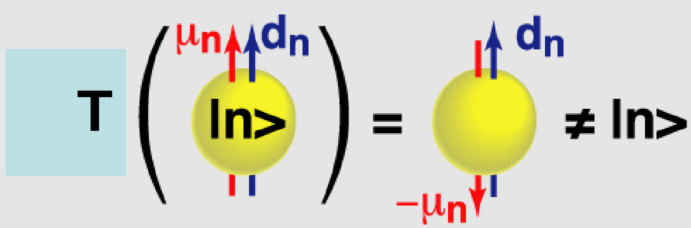
A High-Q Search for Relic Oscillations



The Axion

The Strong-CP Problem

- $\mathcal{L}_{QCD} = ... + \dfrac{\theta}{32\pi^2} G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e • cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving



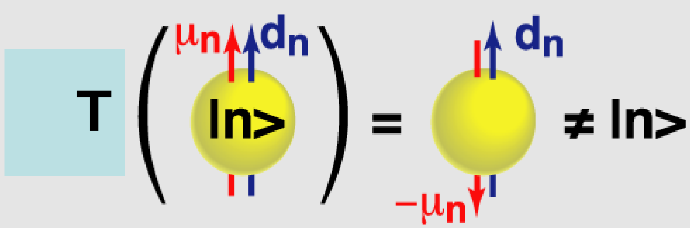
$\not{T} \longrightarrow \not{CP}$

- Why?

The Axion

The Strong-CP Problem

- $\mathscr{L}_{QCD} = \ldots + \frac{\theta}{32\pi^2} G\tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e • cm
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving

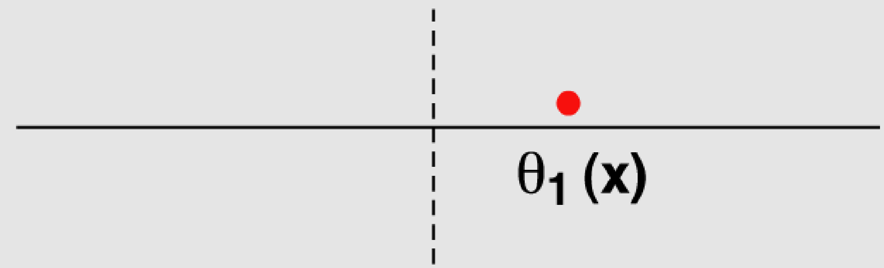


$\not{T} \longrightarrow \not{CP}$

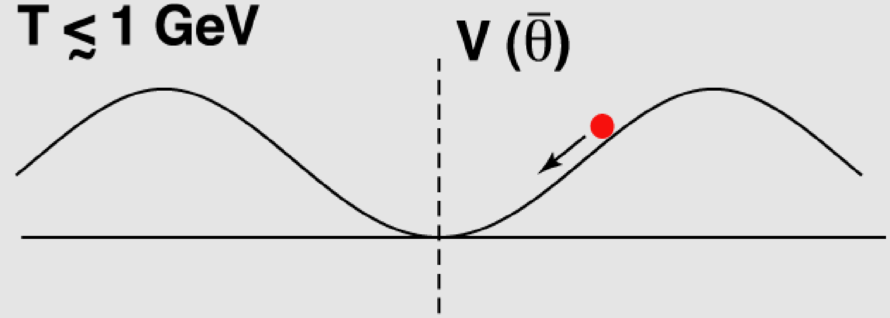
- Why?

Peccei-Quinn / Weinberg-Wilczek

- θ a dynamical variable
- $T = f_a$ spontaneous symmetry breaking

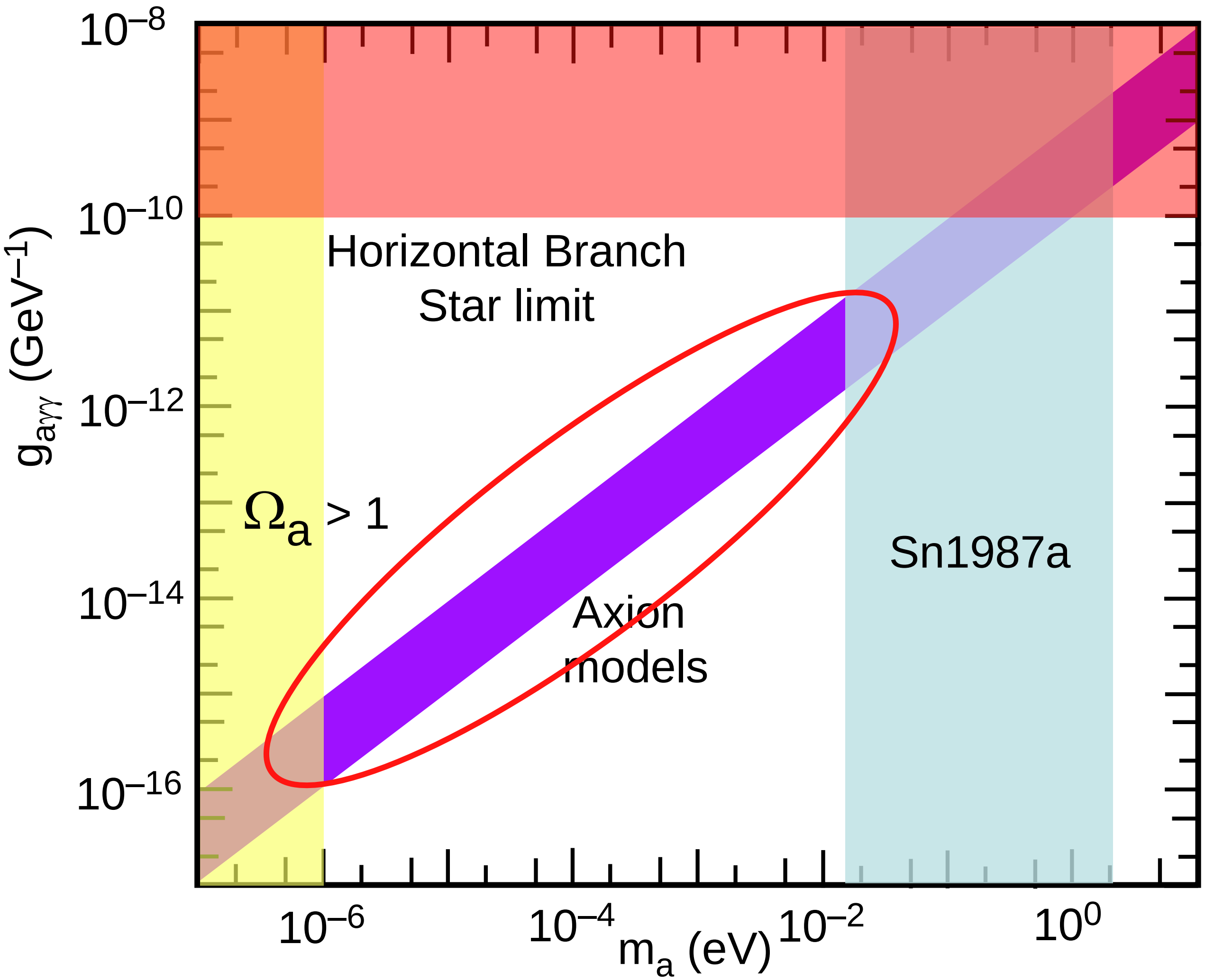


- $T \lesssim 1$ GeV

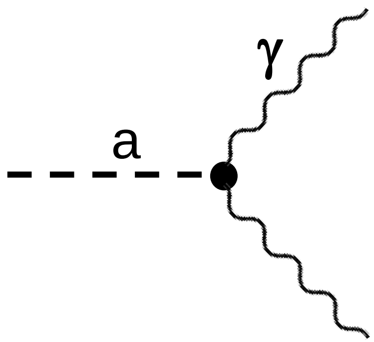


  - $\bar{\theta}$ dynamically $\rightarrow 0$
  - Remnant oscillation = Axion

Axion phenomenology & completing the pool-table analogy



Light cousin of π^0: $J^\pi = 0^-$



m_a , $g_{aii} \propto f_a^{-1}$ ∴ $g_{a\gamma\gamma} \propto m_a$

$\Omega_a \propto f_a^{7/6} \rightarrow m_a > 1\ \mu$eV

Sn1987a ν pulse precludes NN→NNa for m_a~$10^{-(3-0)}$ eV

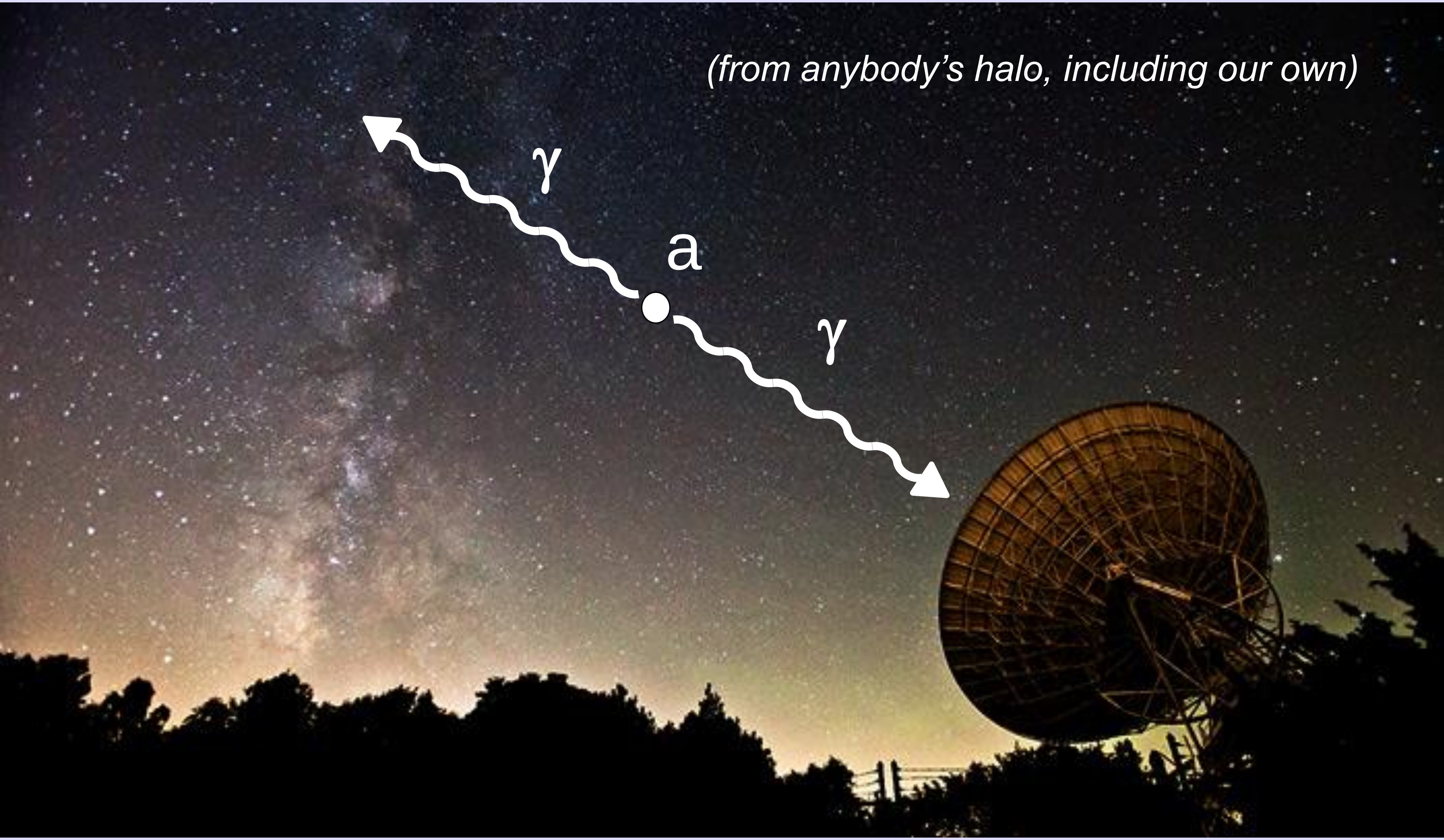
Horizontal Branch Stars preclude $g_{a\gamma\gamma} > 10^{-10}$ GeV^{-1}

G.G. Raffelt *"Stars as Laboratories for Fundamental Physics"* U. Chicago Press (1996)

Good news – Parameter space is bounded

Bad news – All couplings are *extraordinarily* weak

Why not just look for an unidentified radio line at which $E_\gamma = m_a / 2$?

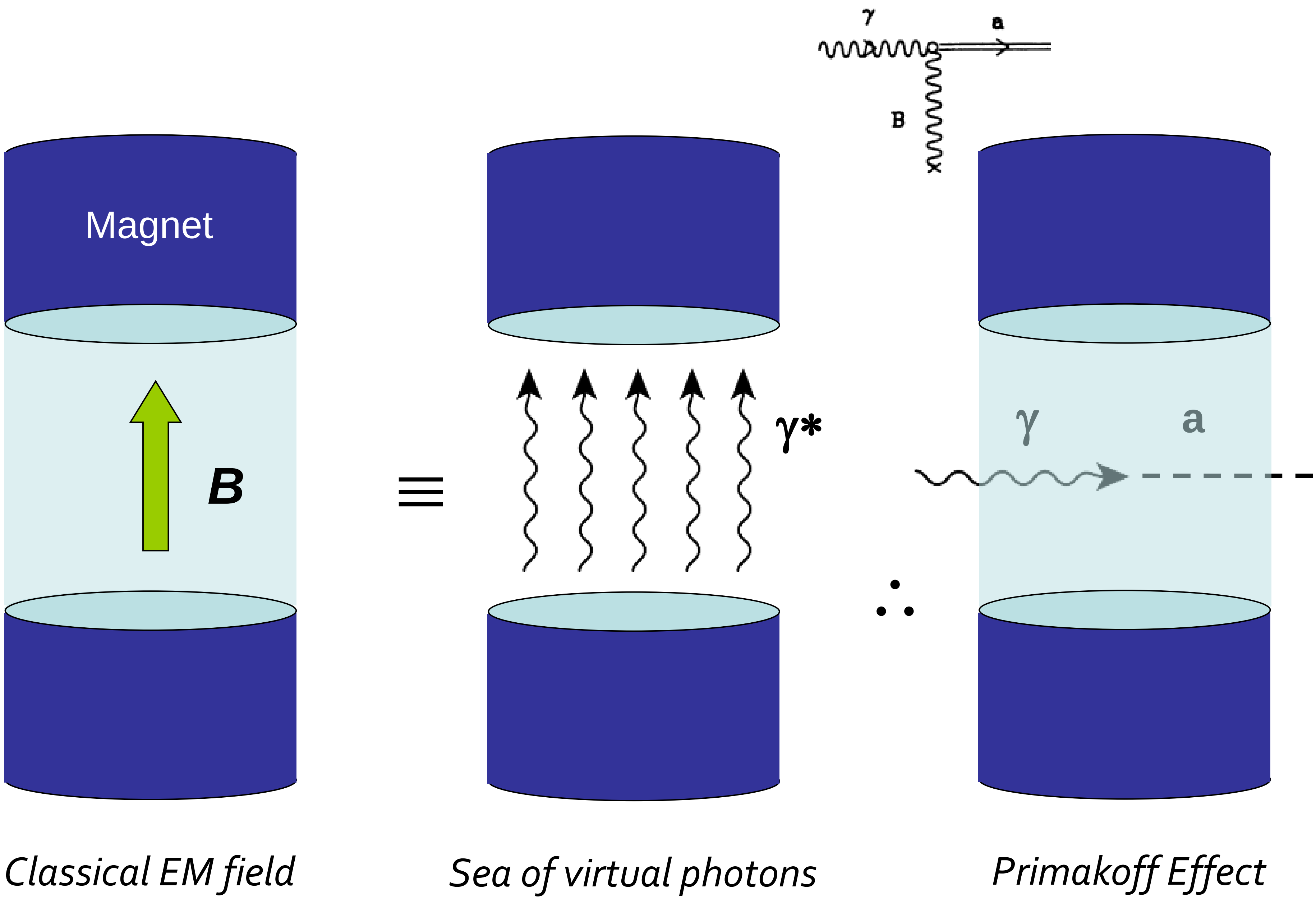


Problematically, the lifetime $\tau \sim 10^{60}$ sec for $m_a \sim \mu eV$

Microwave cavity searches for DM axions

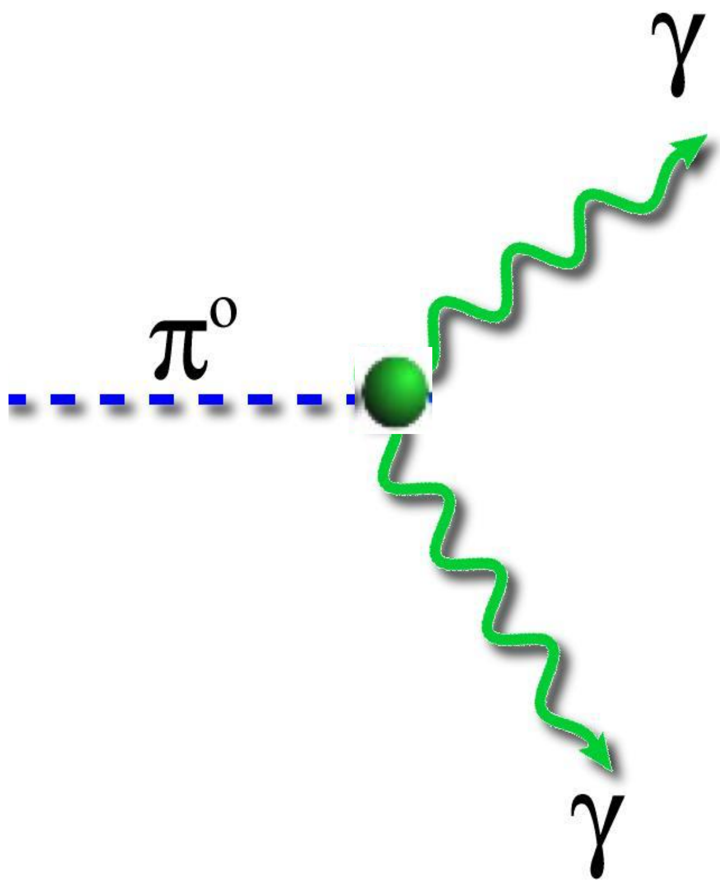
The Primakoff Effect

P. Sikivie, Phys. Rev. Lett. 51 (1983) 1415



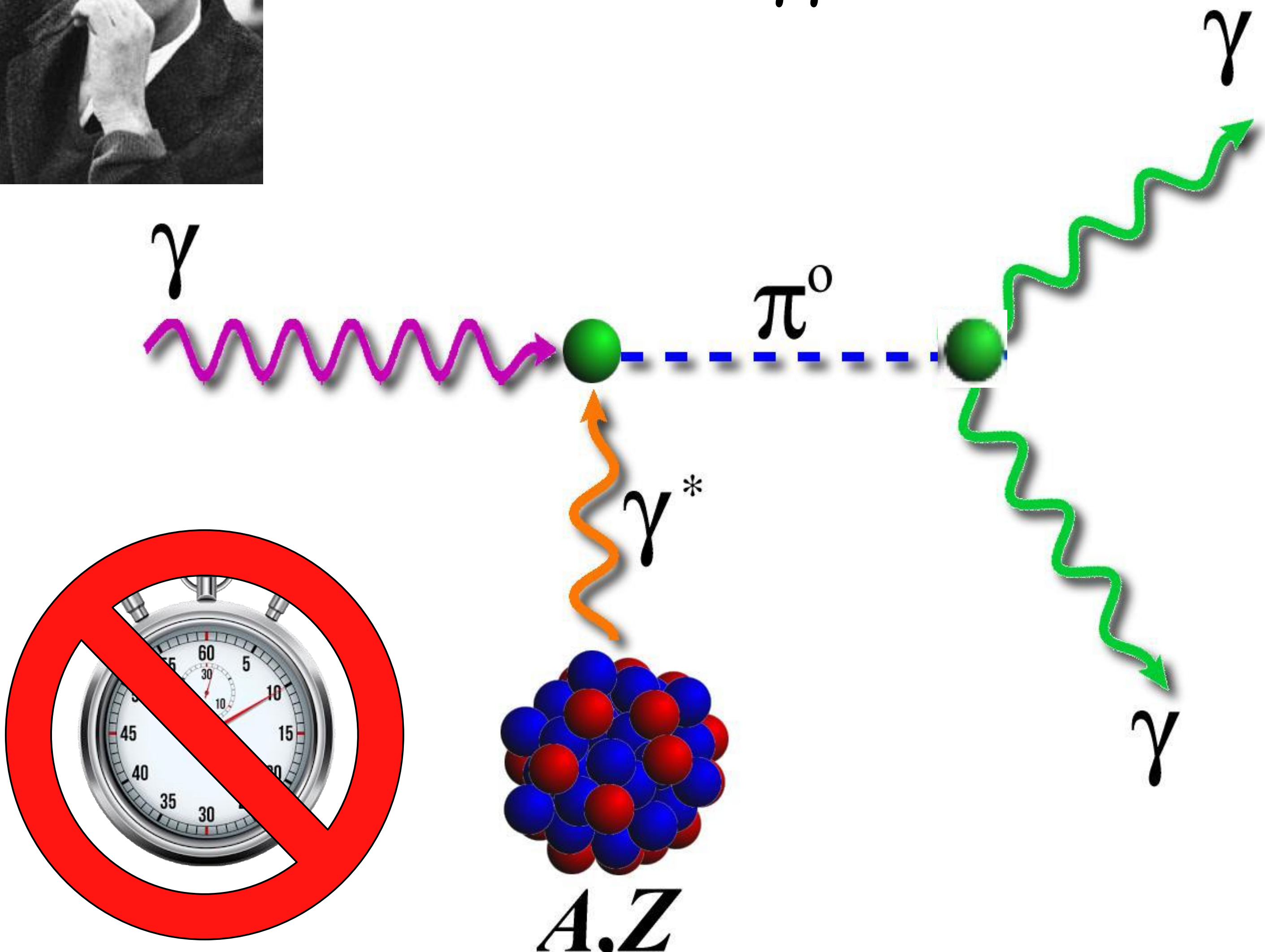
Primakoff effect (1951)

Problem: How to accurately measure the lifetime of the neutral pion, $\tau_{\pi o}$ which was known to be very short?



Primakoff – experiment (1965): $\tau \sim 8.7 \times 10^{-17}$ sec

$$\sigma \leftarrow g_{\pi\gamma\gamma} \rightarrow \tau$$

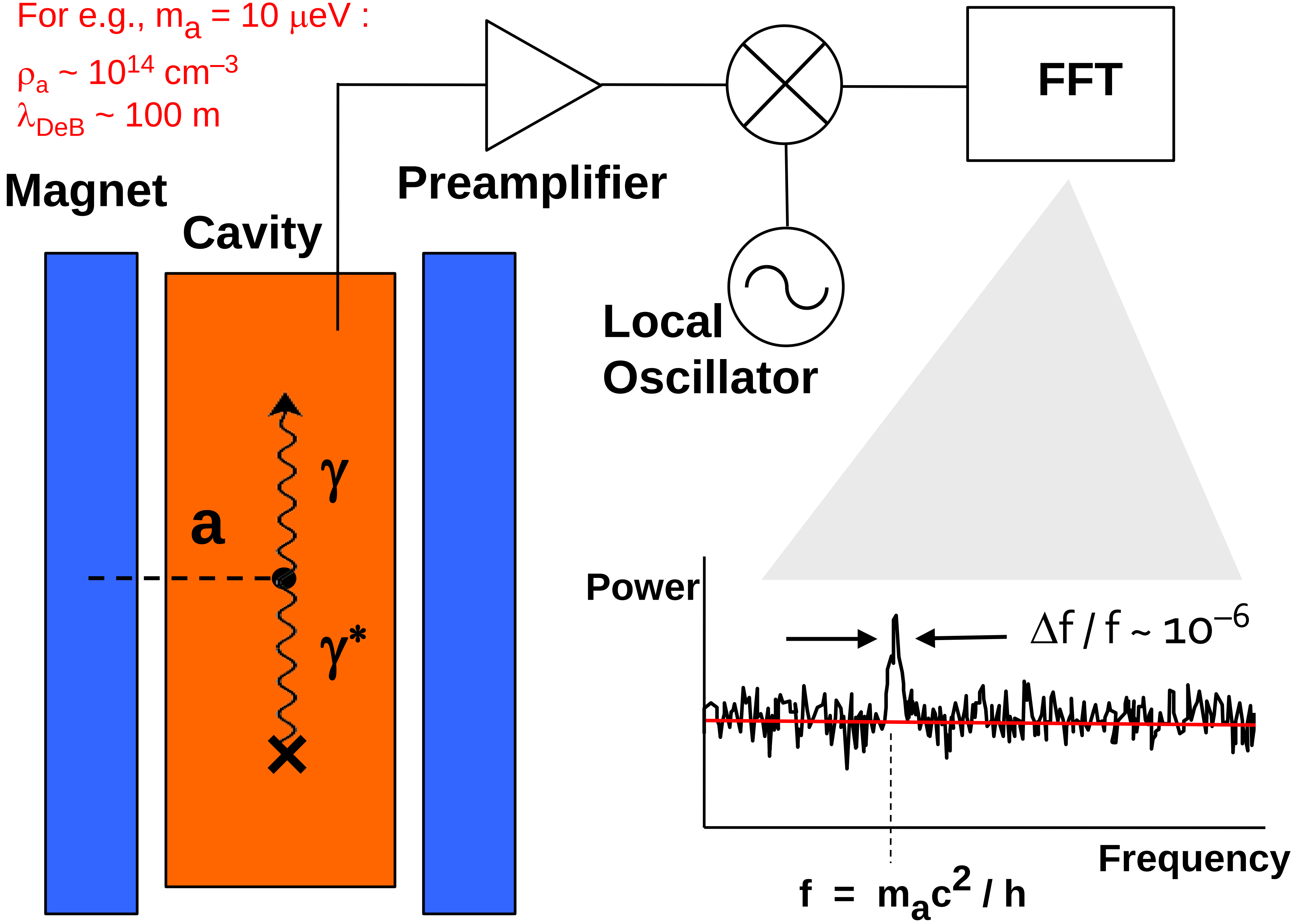


The microwave cavity axion search - Your car radio on steroids

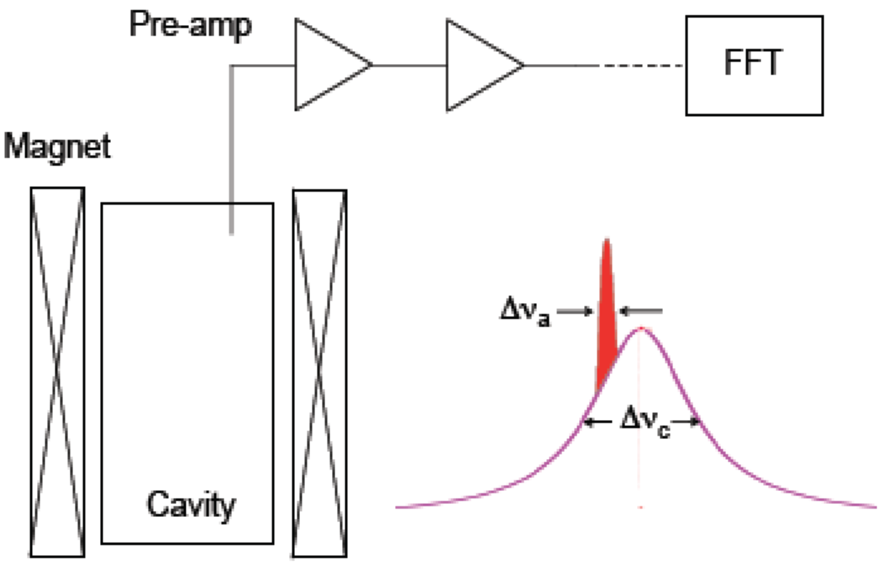
For e.g., $m_a = 10\ \mu eV$:

$\rho_a \sim 10^{14}\ cm^{-3}$

$\lambda_{DeB} \sim 100$ m



Signal to Noise & detectability



Cavity Bandwidth: $\Delta\nu_c / \nu_c = Q^{-1} \sim 10^{-4}$

Axion Bandwidth: $\Delta\nu_a / \nu_a \sim \beta^2 \sim 10^{-6}$

Conversion Power: $P \sim g_{a\gamma\gamma}^2 (\rho_a / m_a) B^2 Q_c V C_{nm\ell} \quad \sim 10^{-23}$ watt

Signal to Noise Ratio: $$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

System Noise Temperature: $$kT_S = h\nu\left(\frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2}\right) + kT_A$$

Note $T_S \approx T + T_A$, for $T >> h\nu$

Linear amplifiers are subject to the Standard Quantum Limit

$$T_N > T_{SQL} \quad \text{where} \quad k_B T_{SQL} = h\nu$$

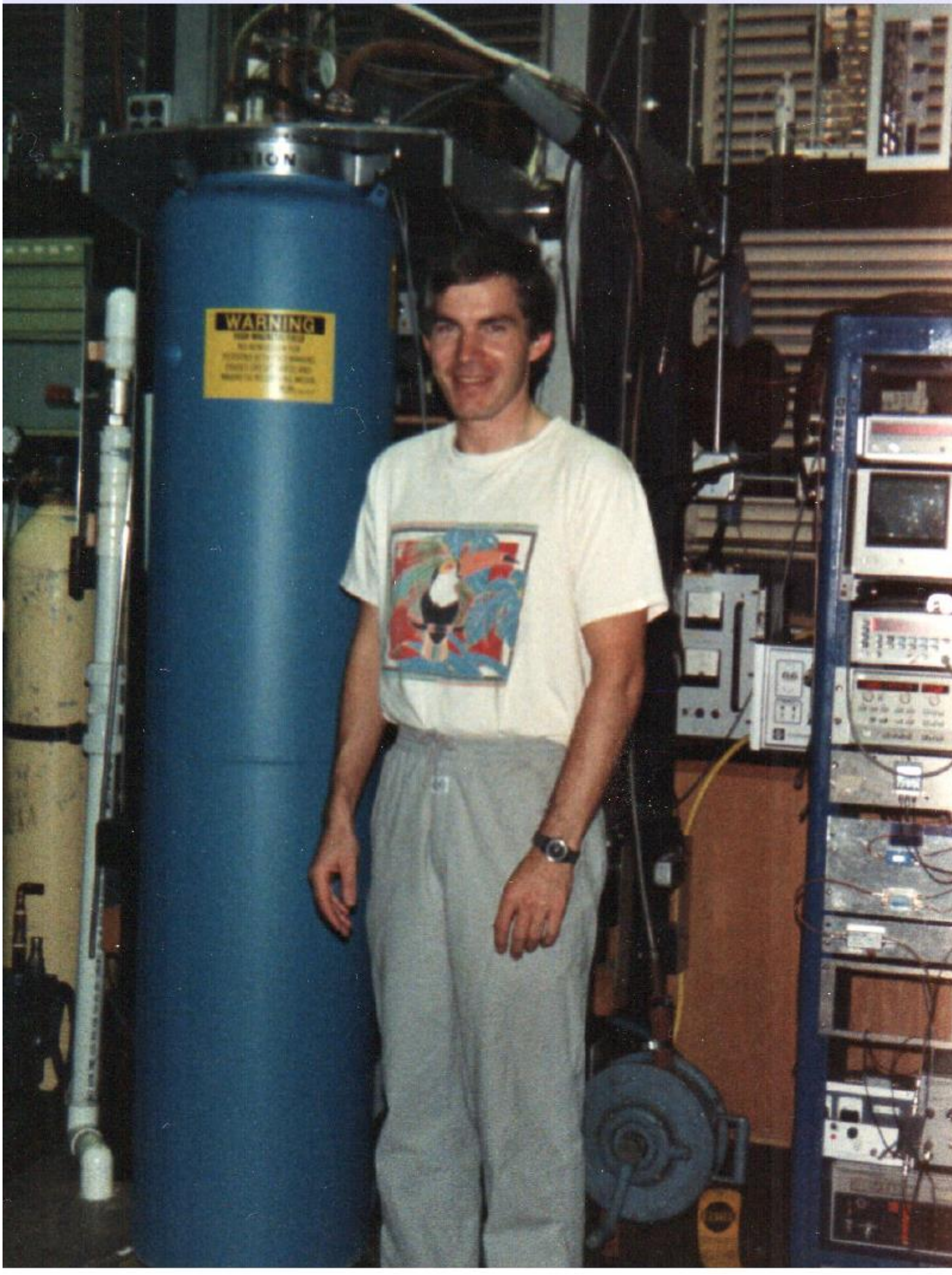
ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	20.7	240
20	82.8	960

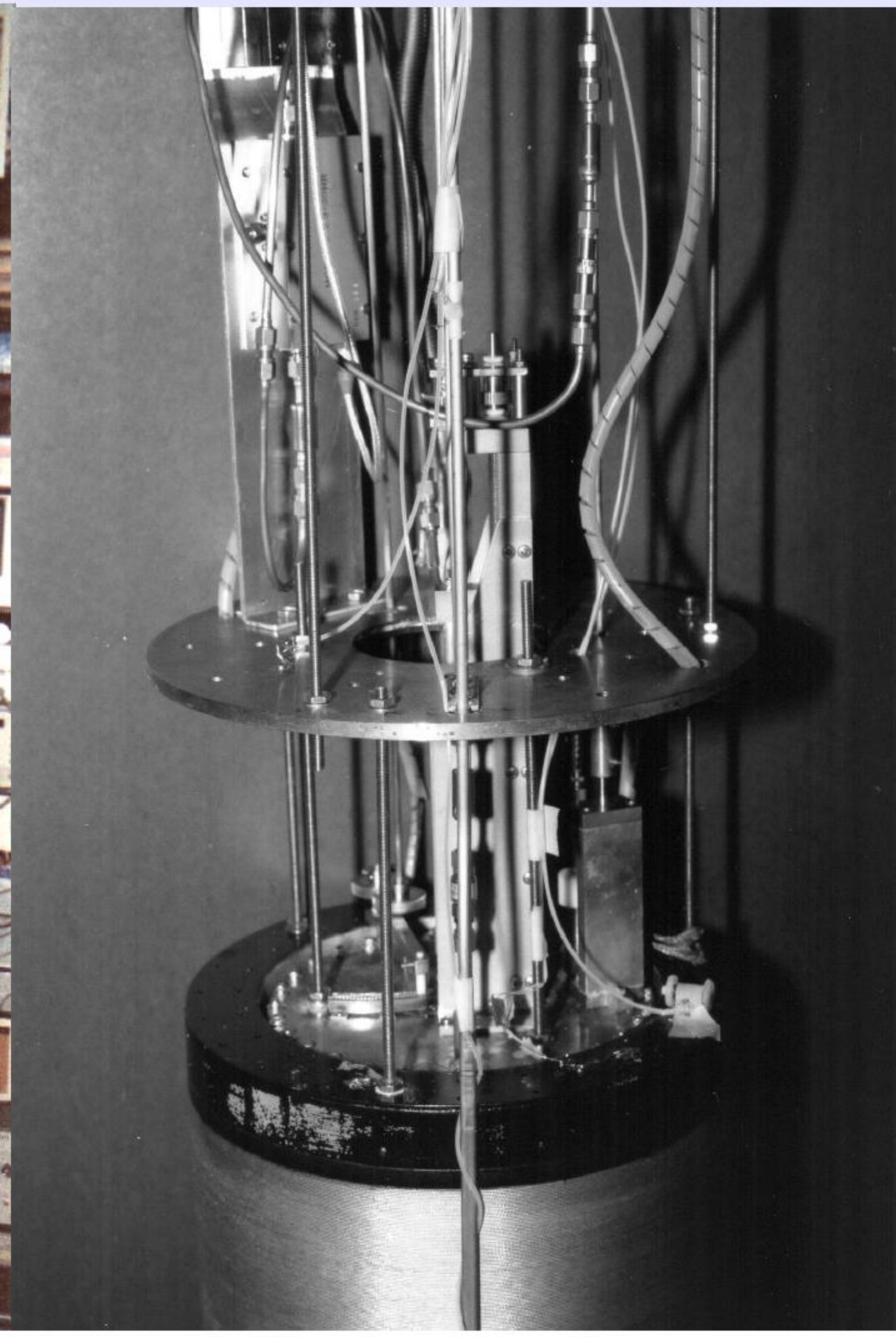
The SQL can be evaded by

- Squeezed-vacuum state receiver (e.g. GEO, LIGO)
- Single-photon detectors (e.g. qubits, bolometers)

The Prehistory c. 1989

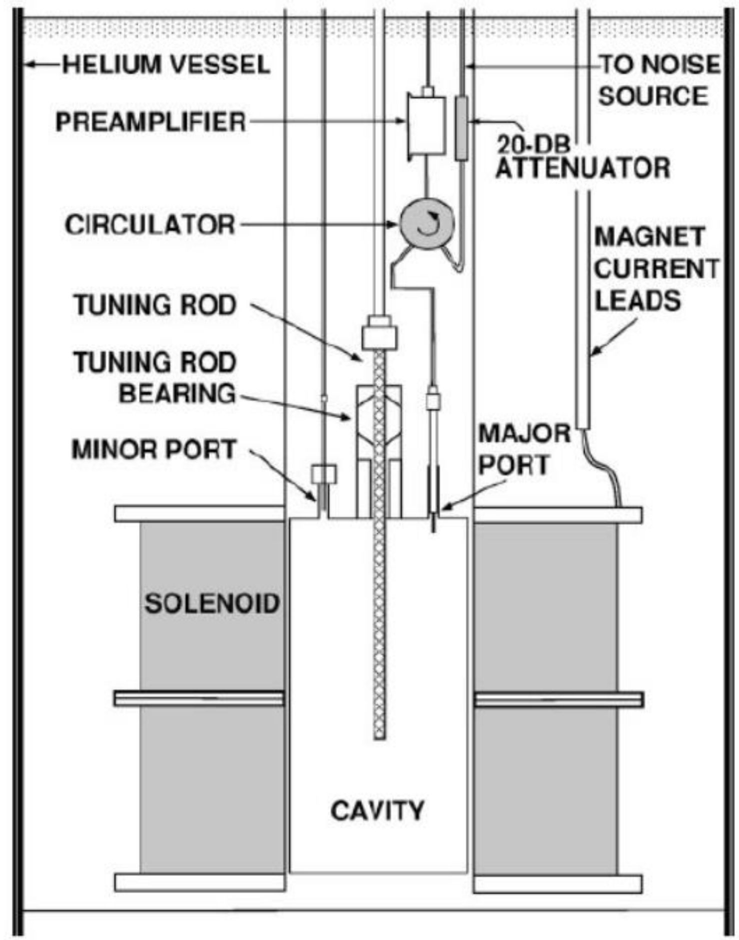
The Florida Experiment – Williamson Hall c. 1989





Rochester-Brookhaven-Fermilab Experiment

BNL Magnet Lab, Bldg. 903

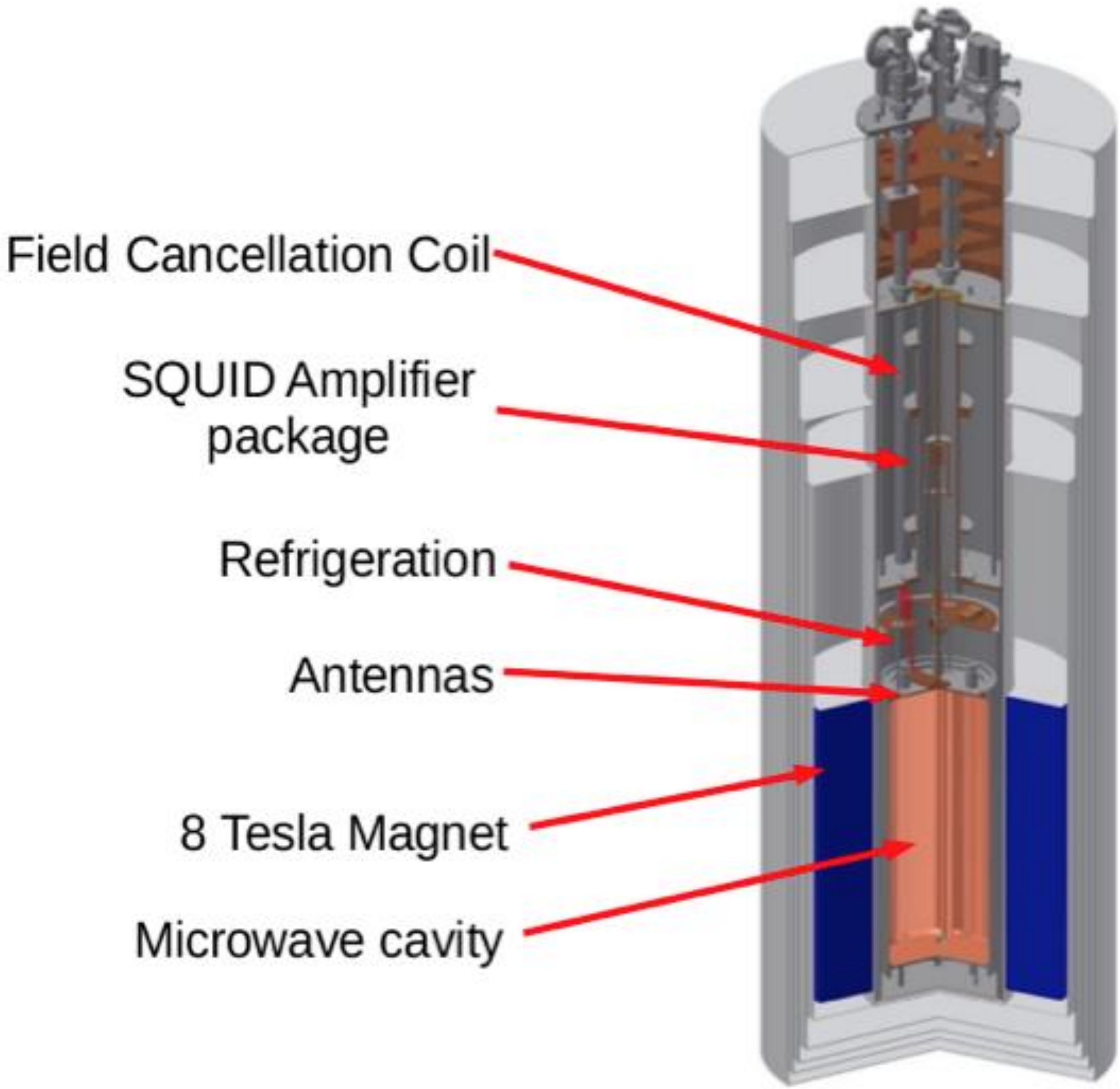


ADMX

&

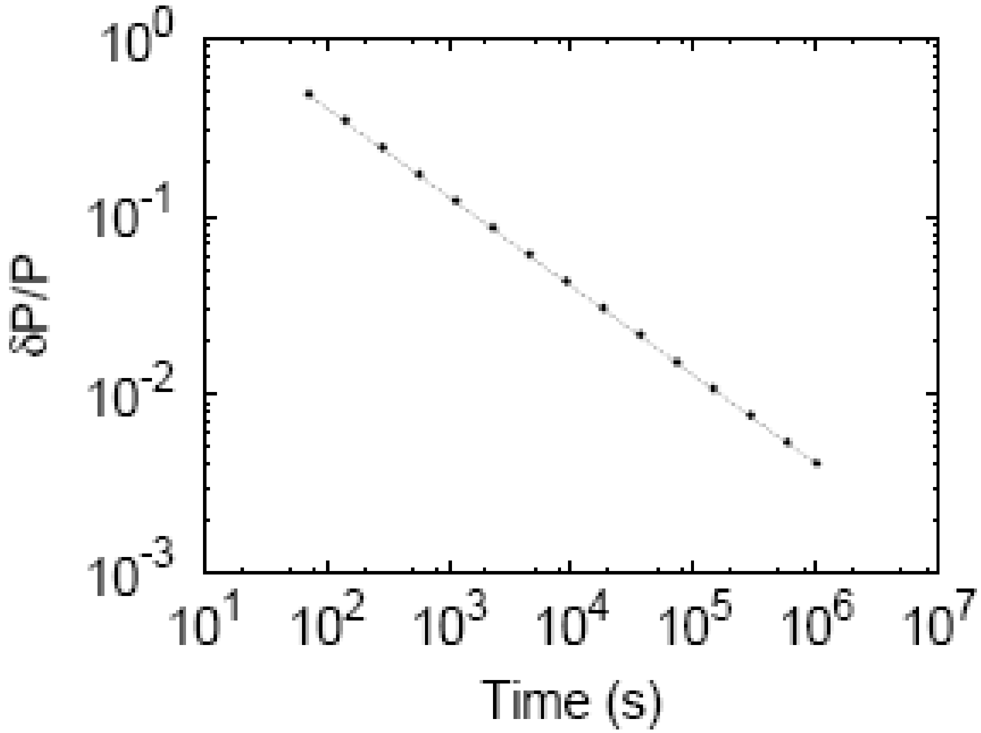
HAYSTAC

Axion Dark Matter eXperiment (ADMX)



UW, UF, LLNL, UCB, NRAO, Sheffield, FNAL, LANL, PNNL, …

Even at T_{SYS} ~ 3K ADMX was the world's quietest radio receiver

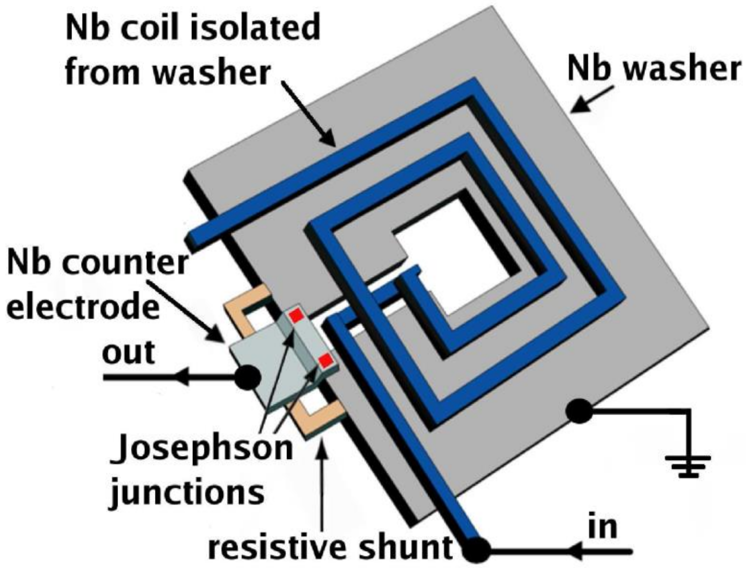


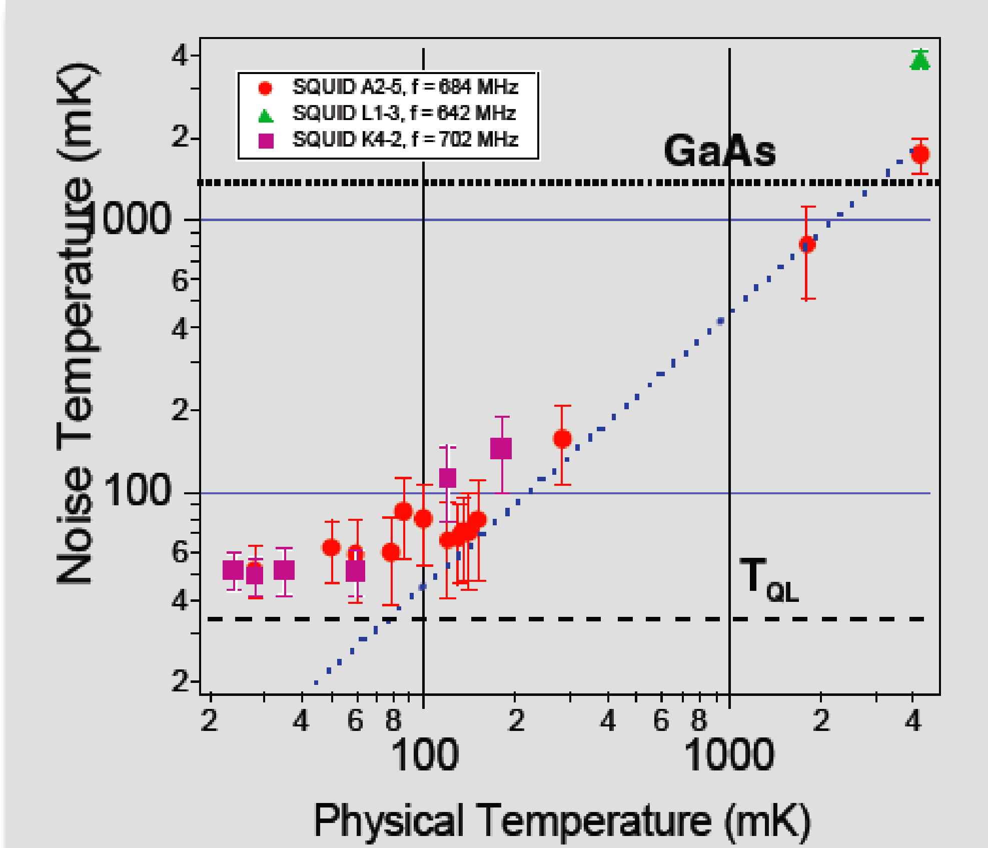
Dicke Radiometer equation:

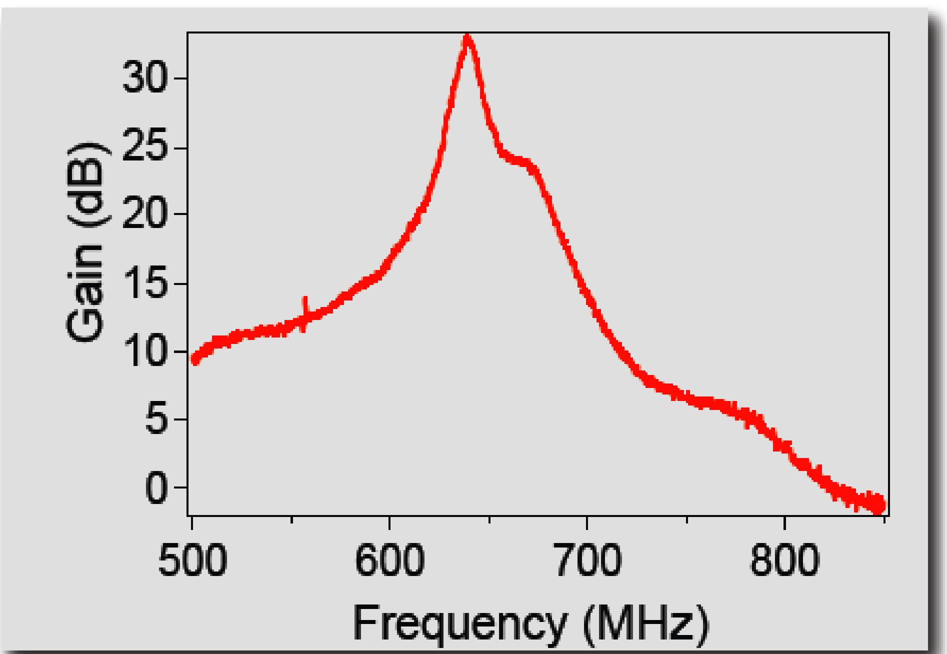
$$\frac{s}{n} = \frac{P_s}{kT_n}\sqrt{\frac{t}{\Delta \nu}}$$

Systematics-limited for signals of 10^{-26} W – 10^{-3} of DFSZ axion power.
Last signal received from Pioneer 10 (6 billion miles away) ~ 10^{-21} W.

In 1998 John Clarke saved the field – Microstrip SQUID amplifiers

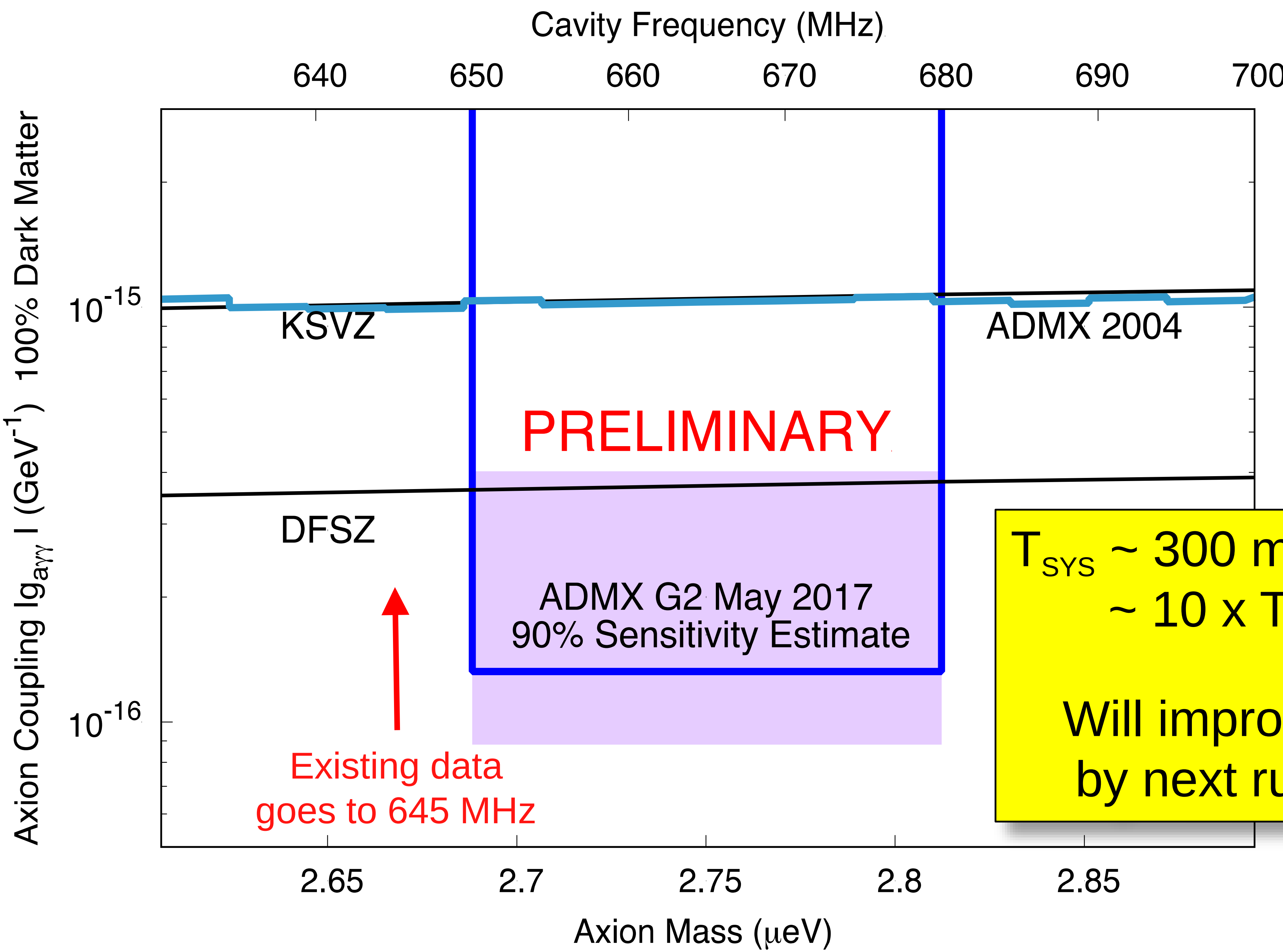






High frequency SQUID amplifiers have become a cornerstone of QI/QC

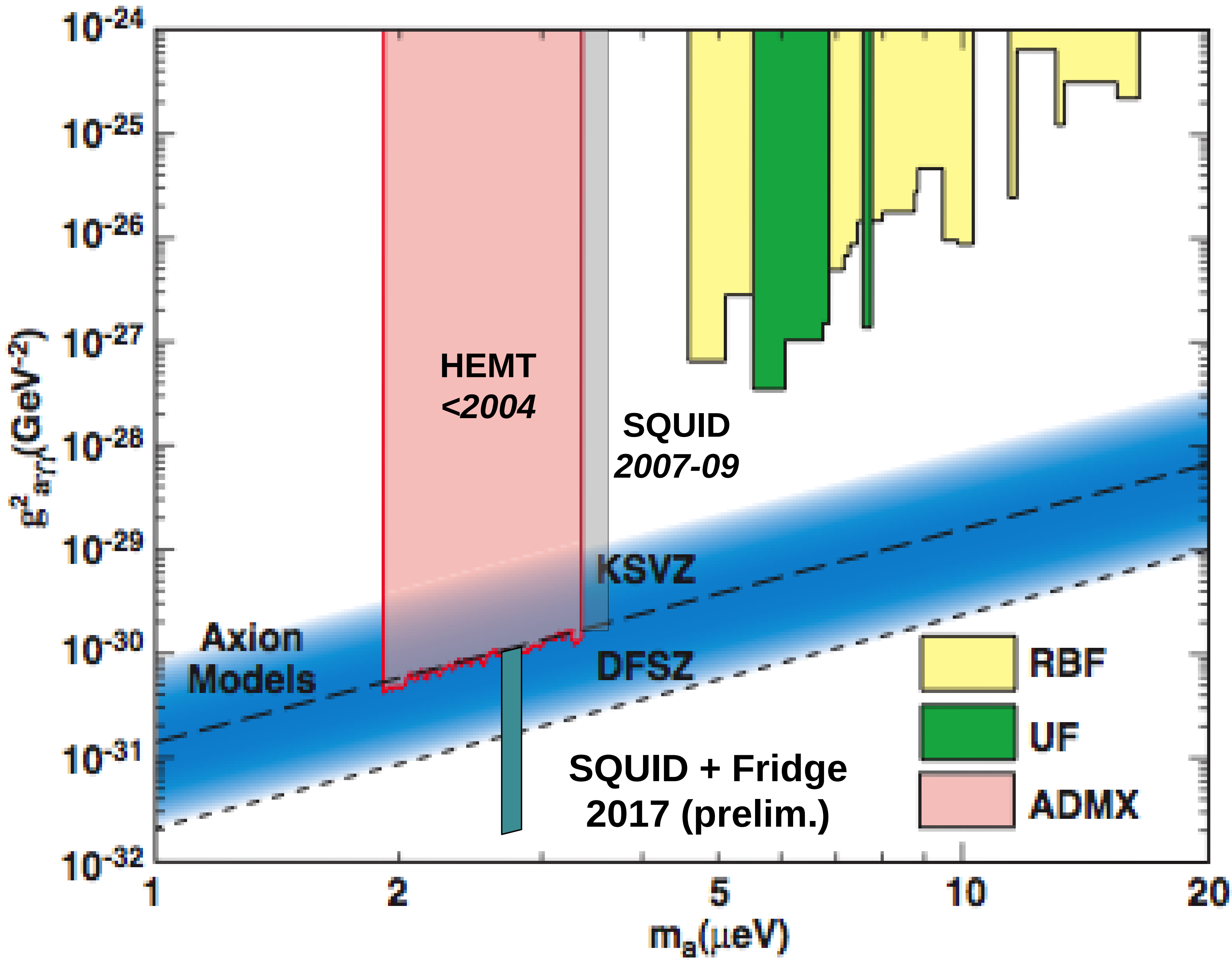
ADMX Gen.2 preliminary result – DFSZ reached!



T_{SYS} ~ 300 mK
~ 10 x T_{SQL}

Will improve
by next run

The situation 25 years later – We need to pick up the pace!



Motivation & philosophy

- **Concept born at Sikivie *festschrift* in 2010**
- **Serves both as *Data Pathfinder & Innovation Test-bed* in the 10-50 μeV mass range**
- **Develop new cavity & amplifier technologies in the 3-12 GHz range**
- **Small, agile platform that can be quickly reconfigured to try new things**
- **Work with the greatest degree of informality; no formal project management, etc.**

BTW, the drawing on Steve Lamoreaux's blackboard *was* our TDR !

The team

HAYSTAC

Yale University

Steve Lamoreaux, Yulia Gurevich, Ling Zhong, Ben Brubaker, Sid Cahn

UC Berkeley

Karl van Bibber, Maria Simanovskaia, Samantha Lewis, Jaben Root, Saad Al Kenany, Kelly Backes, Nicholas Rapidis, Isabella Urdinaran, Tim Shokair

CU Boulder/JILA

Konrad W. Lehnert, Daniel Palken, William F. Kindel, Maxime Malnou, M.A. Anil

Lawrence Livermore National Lab

Gianpaolo Carosi

NSF

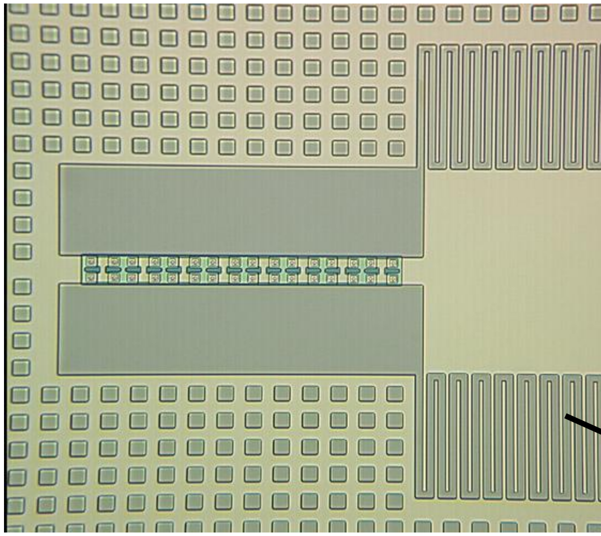
HEISING - SIMONS FOUNDATION

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

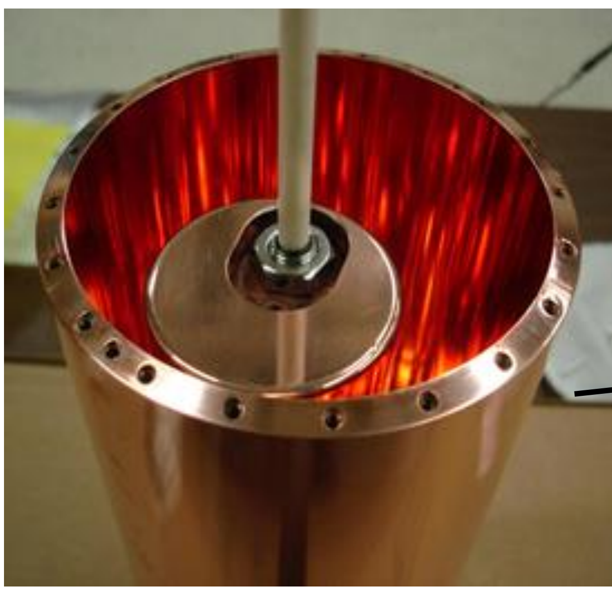
Integration at Yale

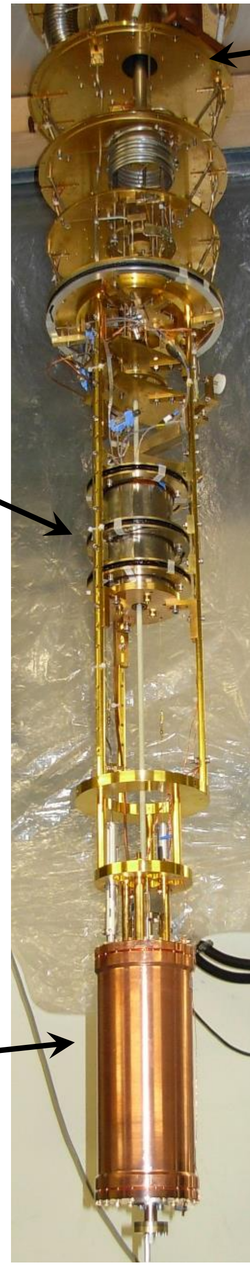
HAYSTAC

Josephson Parametric Amplifier



Microwave Cavity (copper)





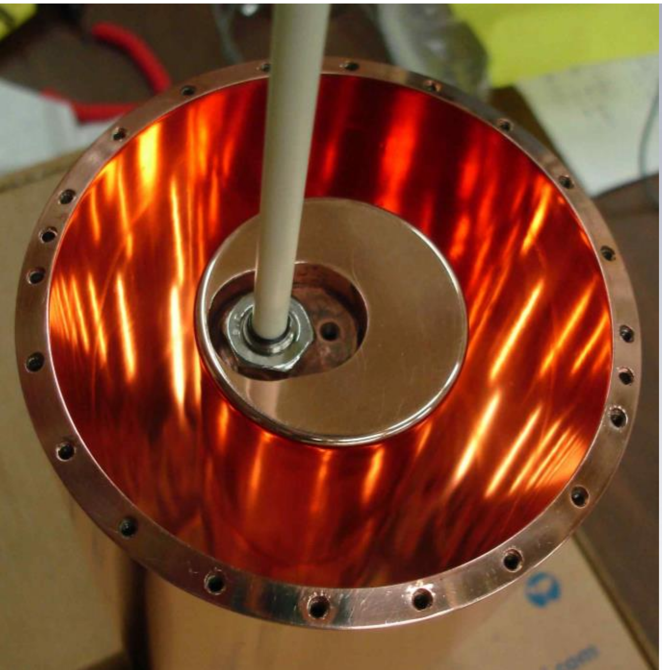
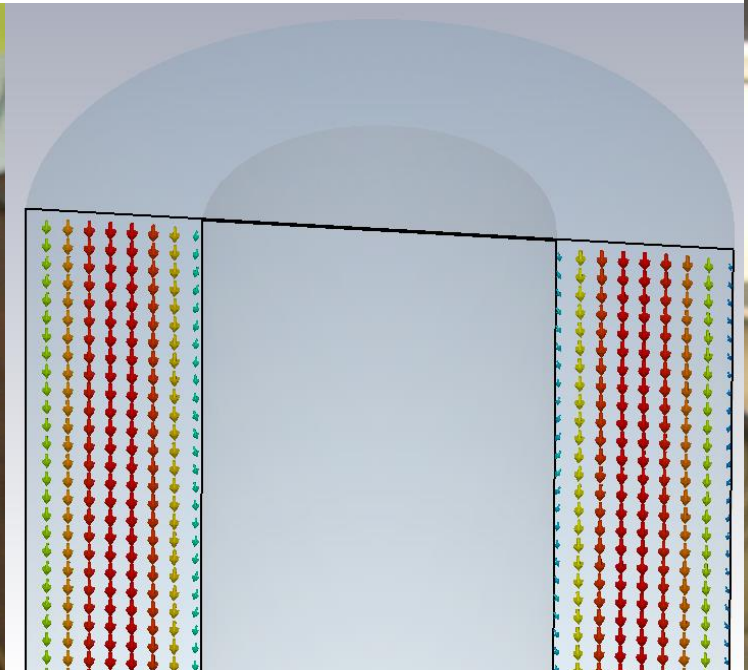
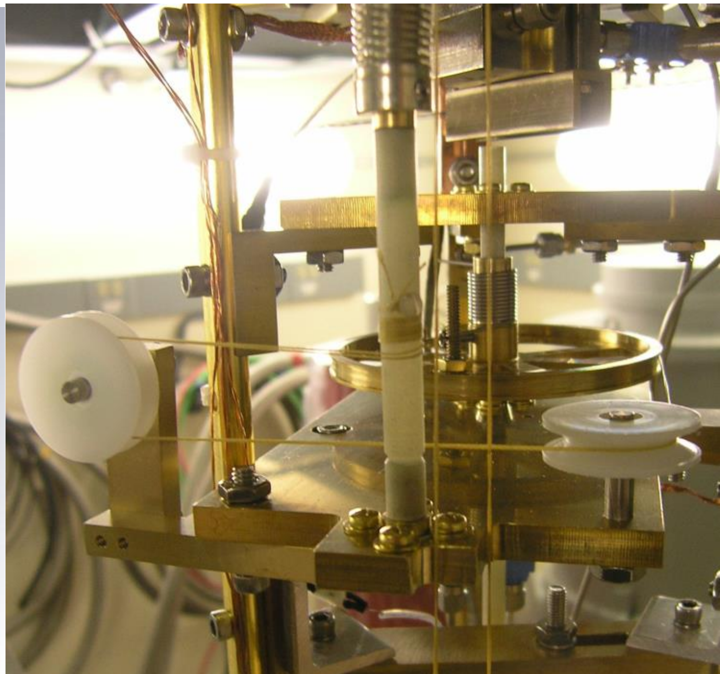
$^3He/^4He$ Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet

Microwave cavity (Berkeley/LLNL)

HAYSTAC

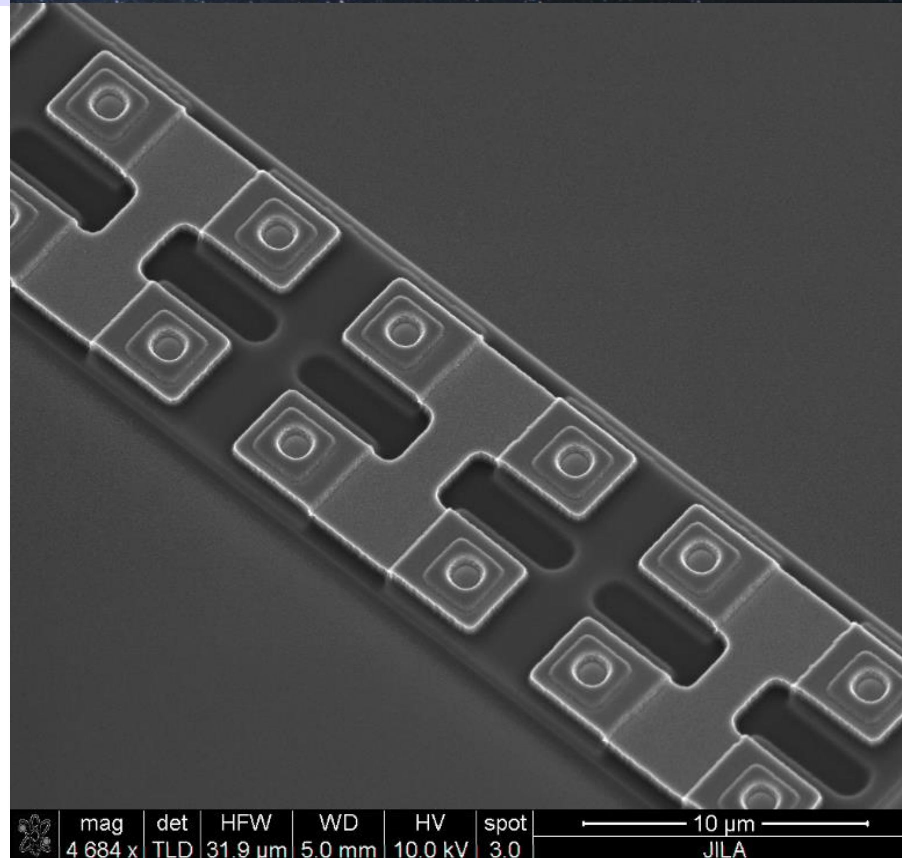
- **Cu body with off-axis tuning rod**
- **Tunable over 3.6 – 5.8 GHz**
- **Q_C ~ 20,000**
- **Stepping motors and Kevlar lines used for motion**

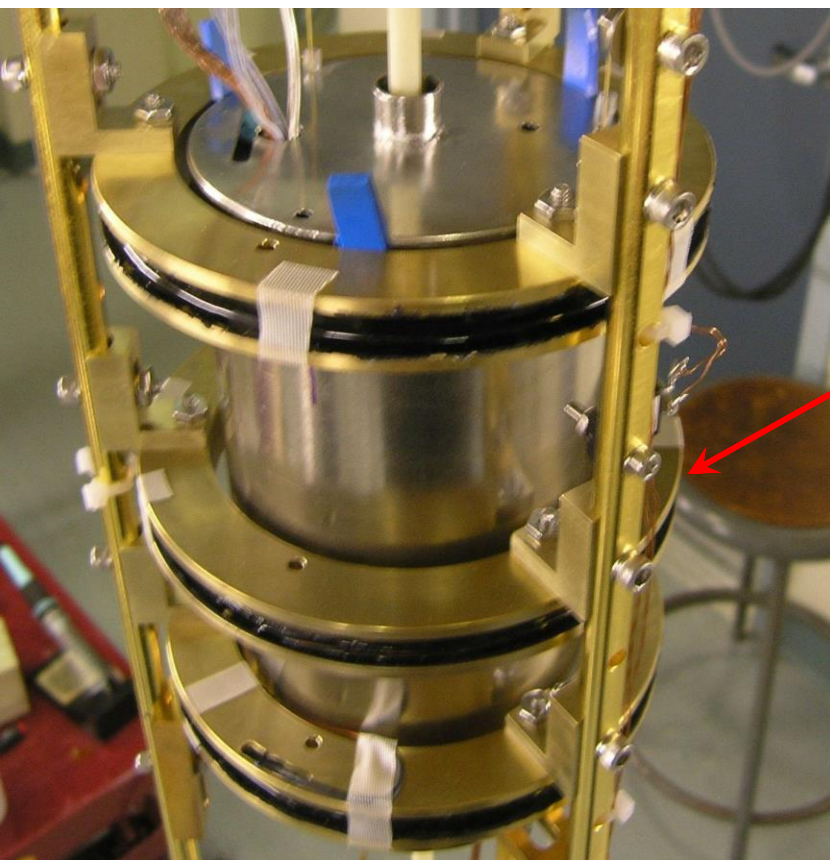




JPA (Colorado/JILA)

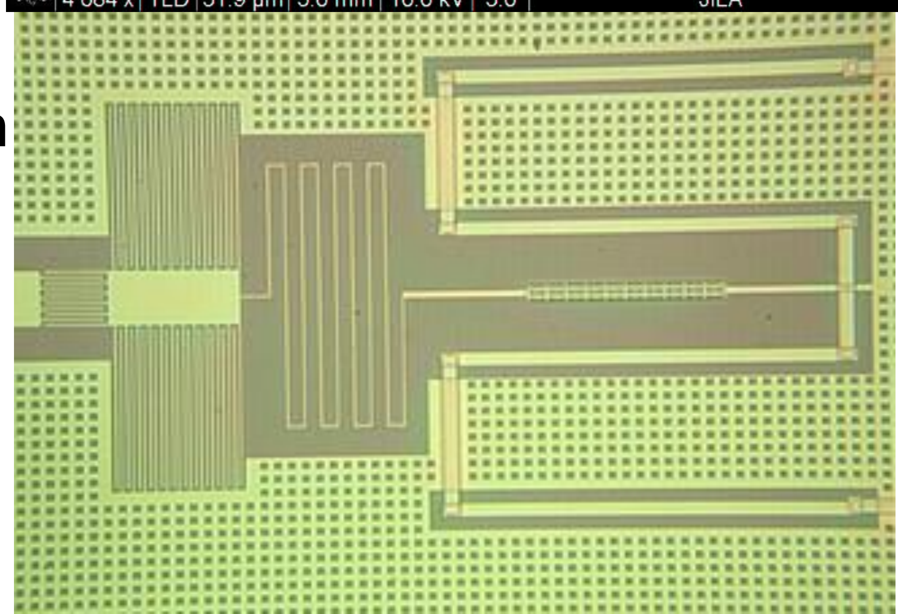
HAYSTAC

- **Josephson Parametric Amplifier composed of SQUIDs**
- **Tunable from 4.4-6.5 GHz with 20 dB of gain**



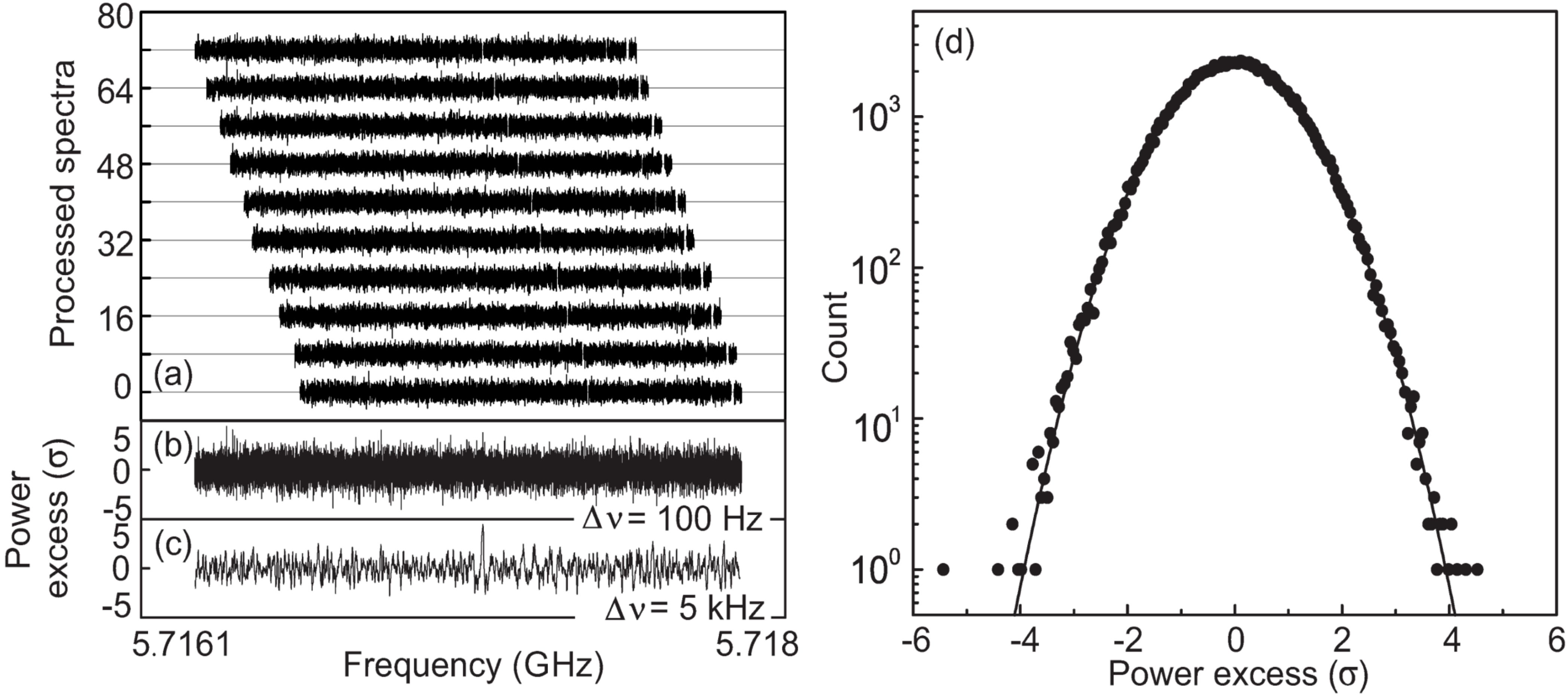


Persistent coils for cancellation of fringe fields



What the data looks like

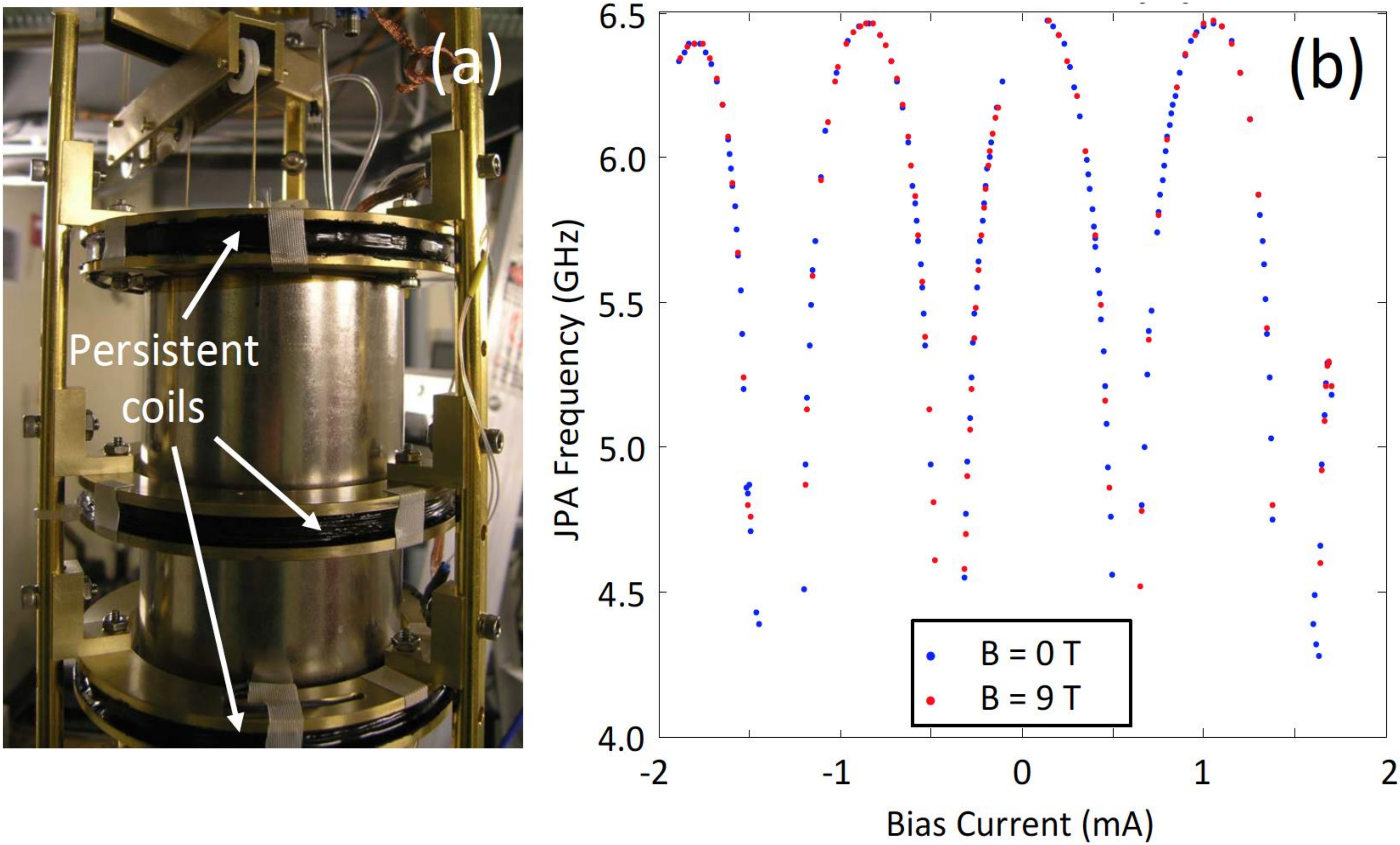
HAYSTAC



T_{SYS}~ 3 x T_{SQL} for first run; ‘hot rod’ implicated, thermal link improved

T_{SYS}~ 2 x T_{SQL} for second run recently concluded

One of the myriad of challenges: Magnetic shielding of the JPA



“It takes a licking & keeps on ticking!
(Timex watch commercial, 1950’s)

HAYSTAC

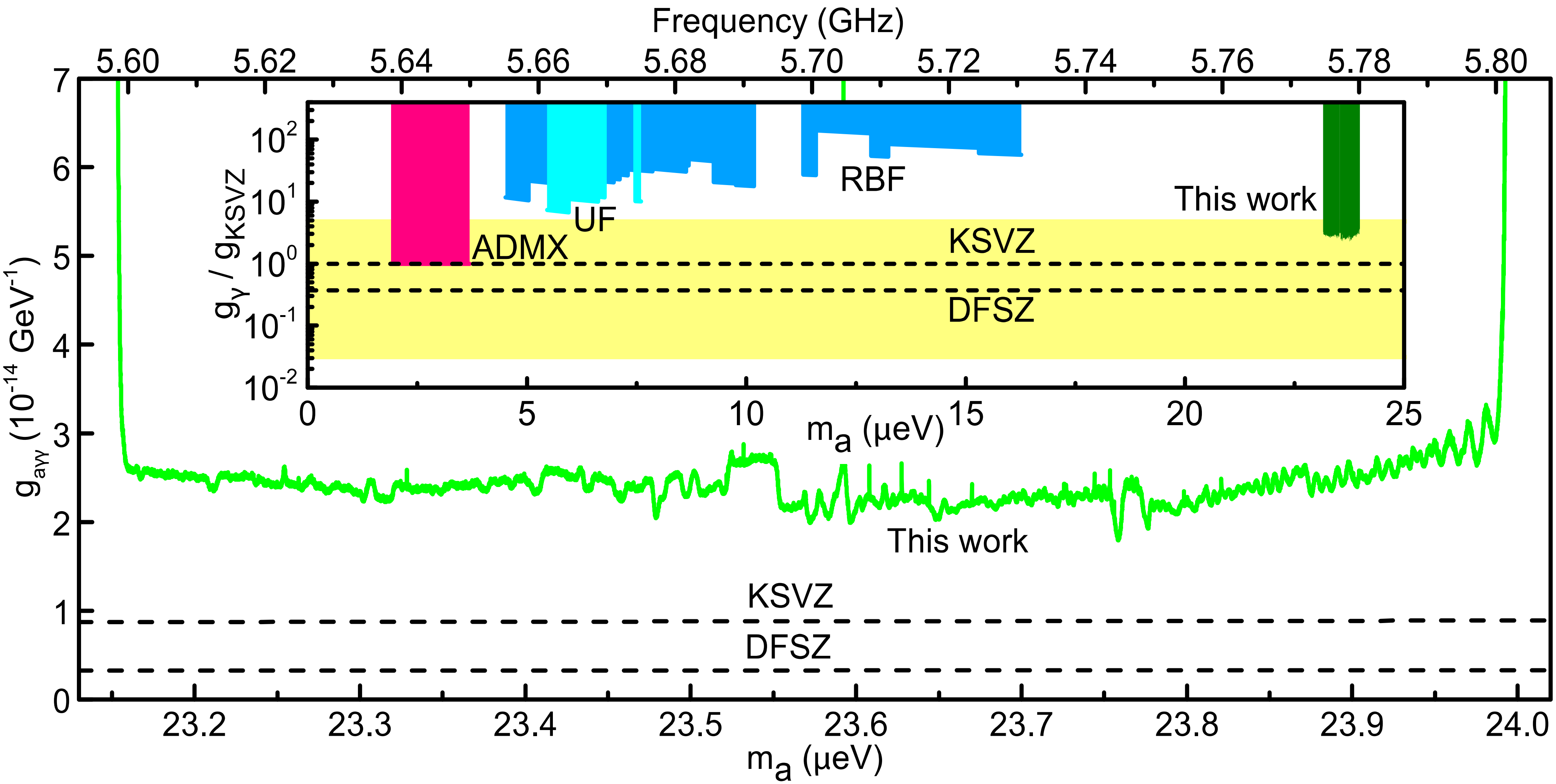
- Experienced a magnet quench in early March 2016
- Surprisingly little damage
- Repairs completed, experiment back in operation by May

Experiment rebuilt with much less mass of copper

Results from 2016-17 run

B. Brubaker et al., Phys. Rev. Lett. 118 (2017) 061302

HAYSTAC



PRL Editor's Suggestion & APS Highlight

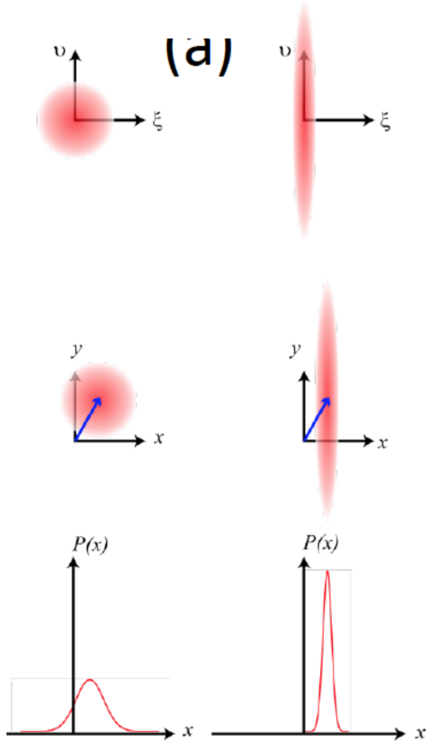
Innovations: Deeper, Higher, Lower

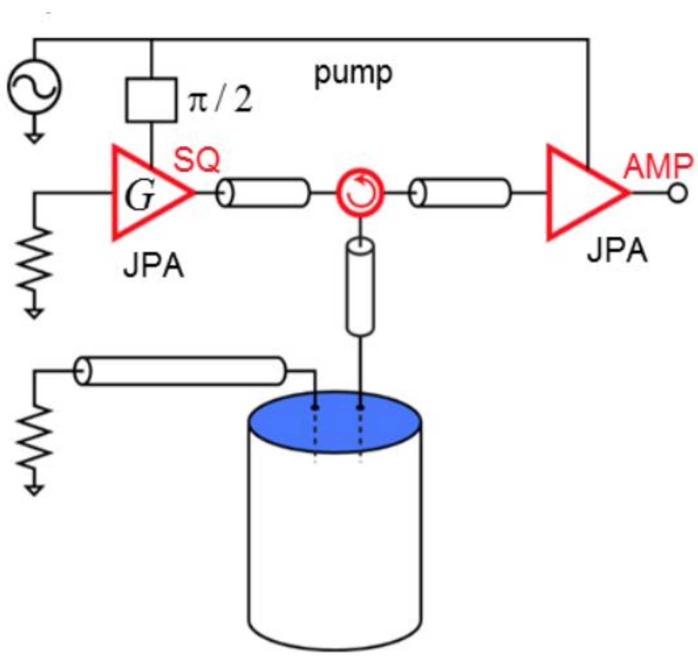
Squeezed-vacuum state receiver

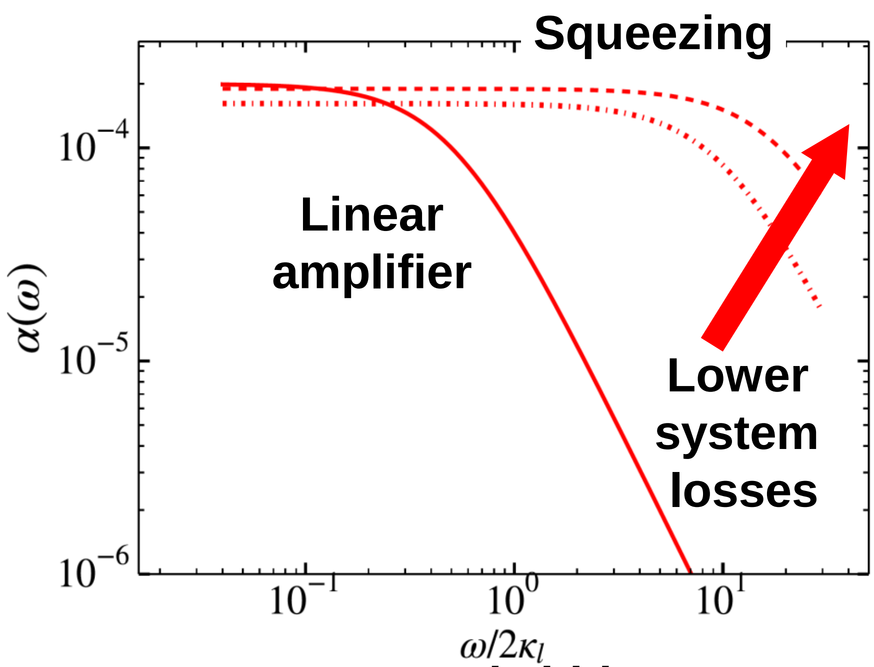
HAYSTAC

"Accelerating dark-matter axion searches with quantum information technology"
(S. Girvin, K. Lehnert & students), arXiv:1607.02529v1

Evading the Standard Quantum Limit $kT_S = h\nu\left(\frac{1}{e^{h\nu/kT}-1}+\frac{1}{2}\right)+kT_A$



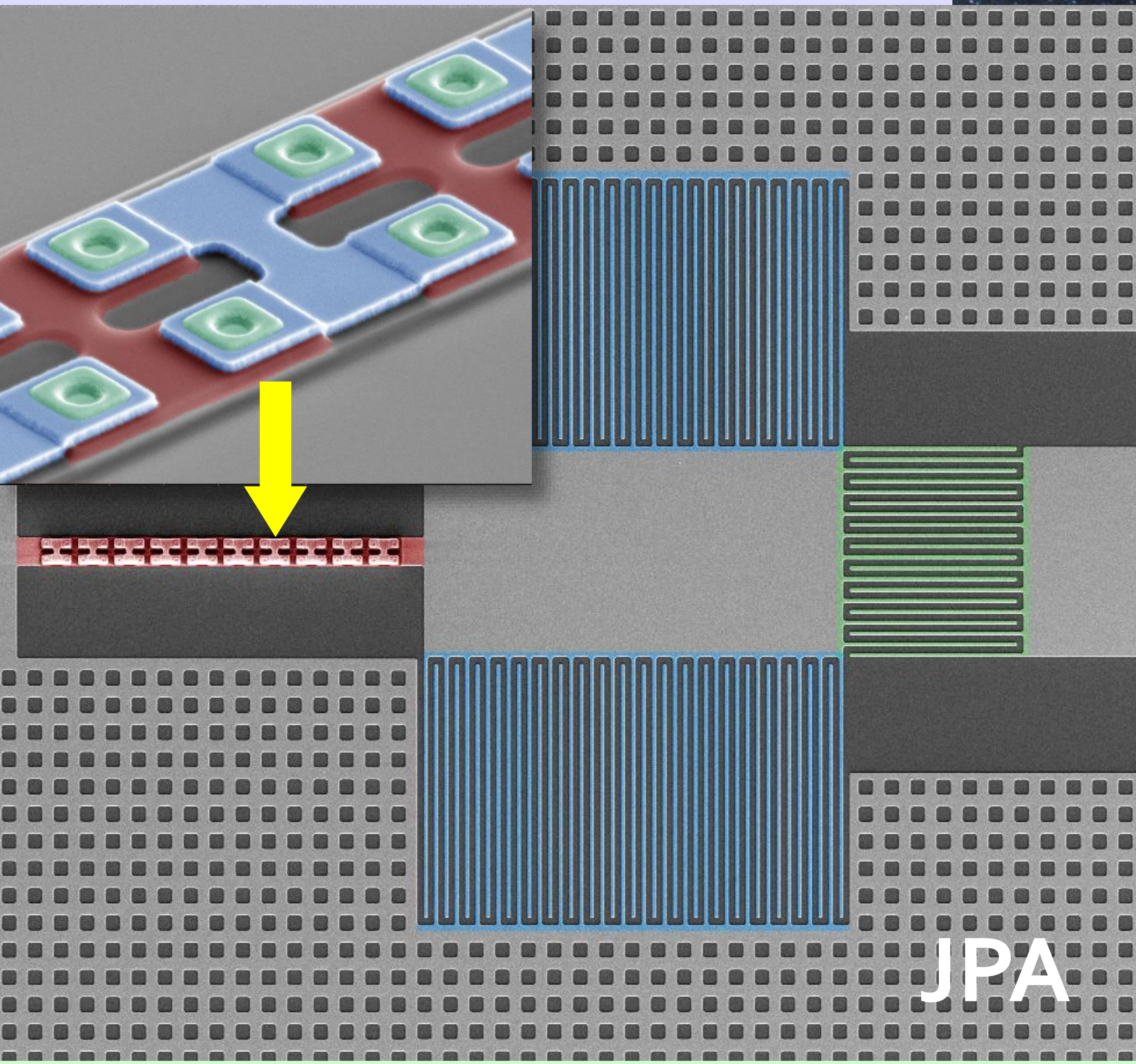


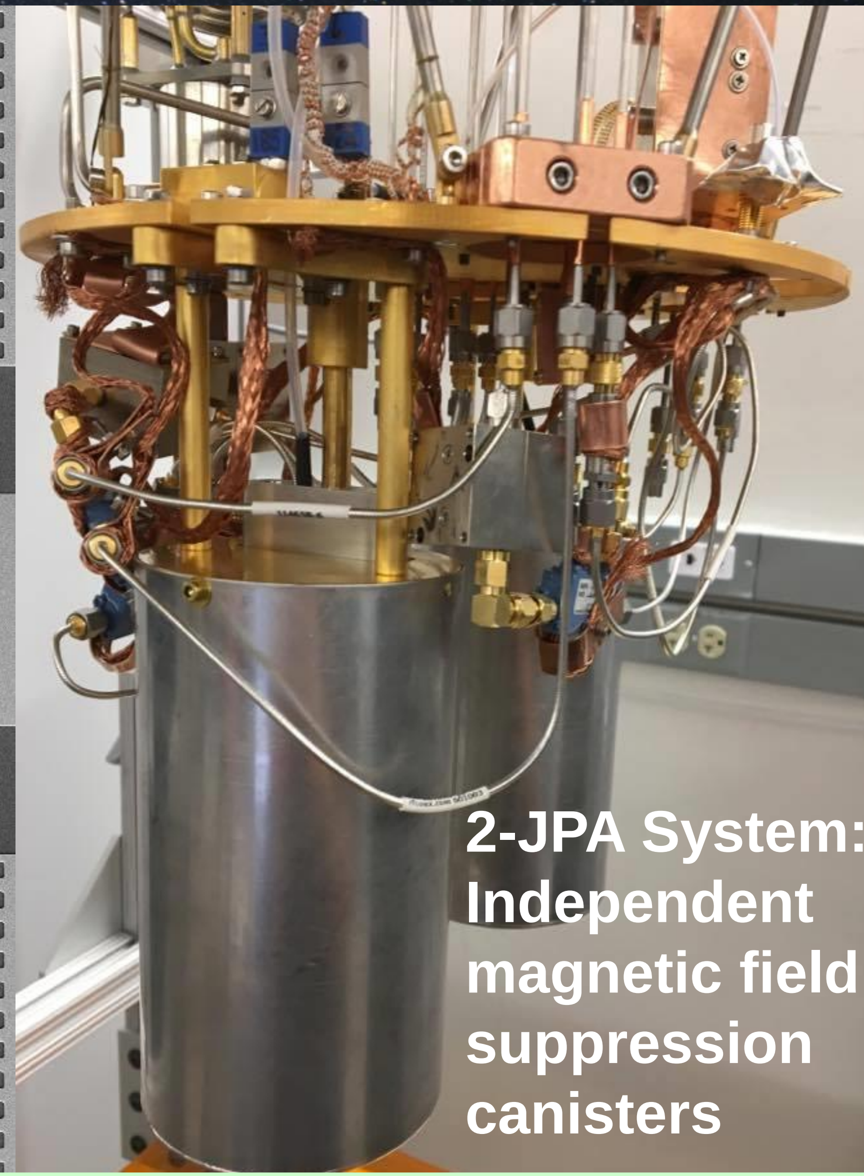


As one reduces losses in the system, the sensitivity optimizes for overcoupling the cavity, thus broadening the bandwidth & increasing the scan rate.

Squeezed-state receiver being prepared at JILA

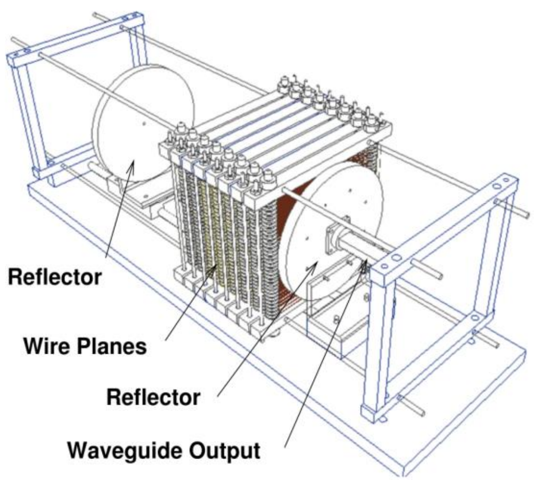
HAYSTAC

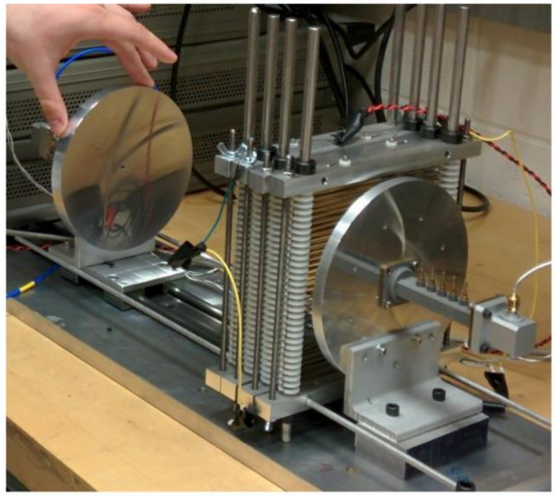


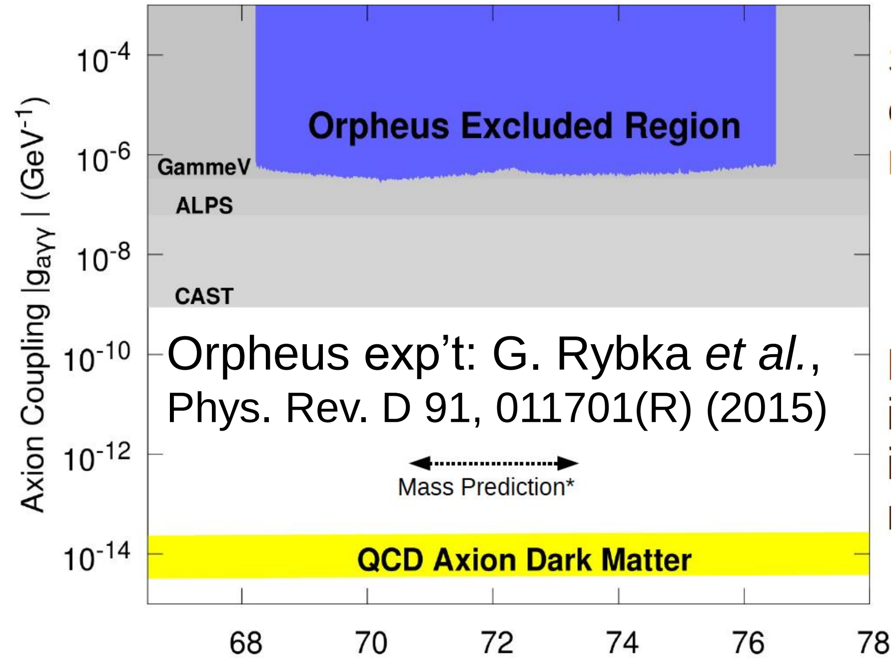


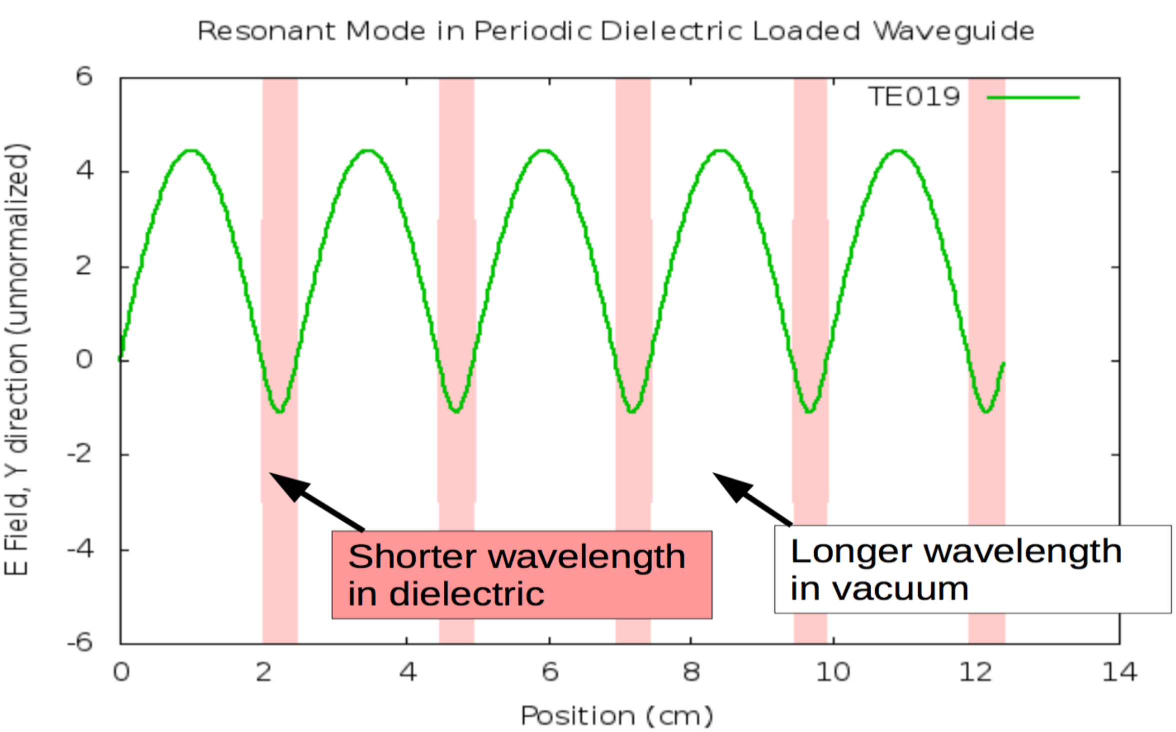
Lehnert group has built squeezed-state receivers; achieved $T_{SYS} \sim ¼\ T_{SQL}$ [F. Mallet *et al.*, PRL 106 (2011) 220502]. Integration in HAYSTAC this year.

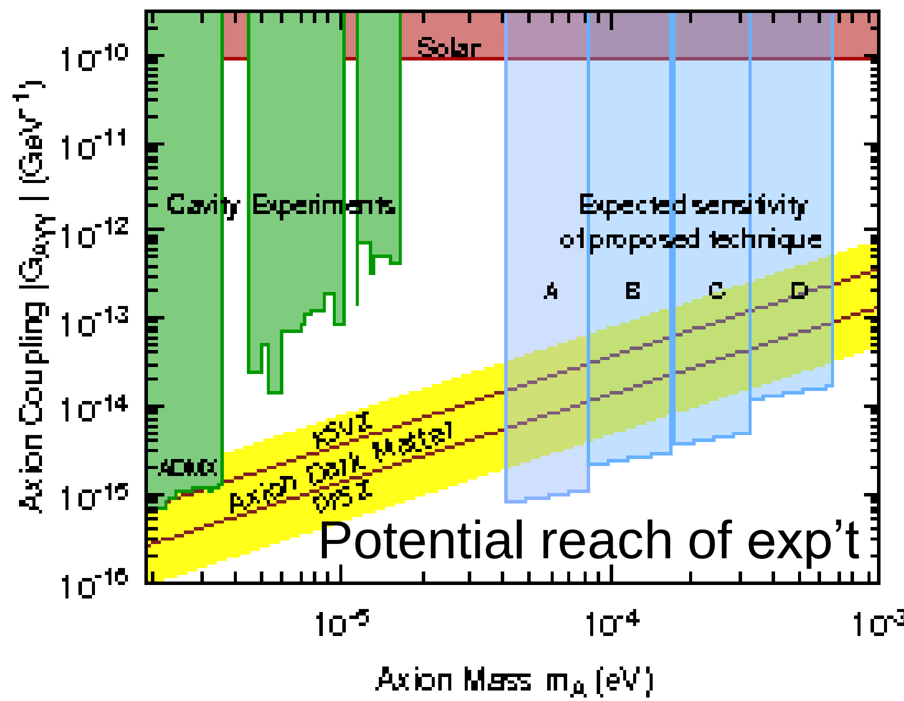
Higher Frequencies – Open Resonators (Orpheus, MADMAX)



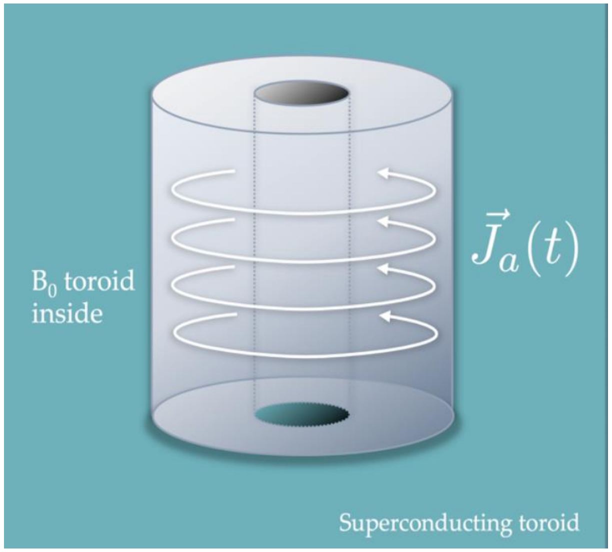


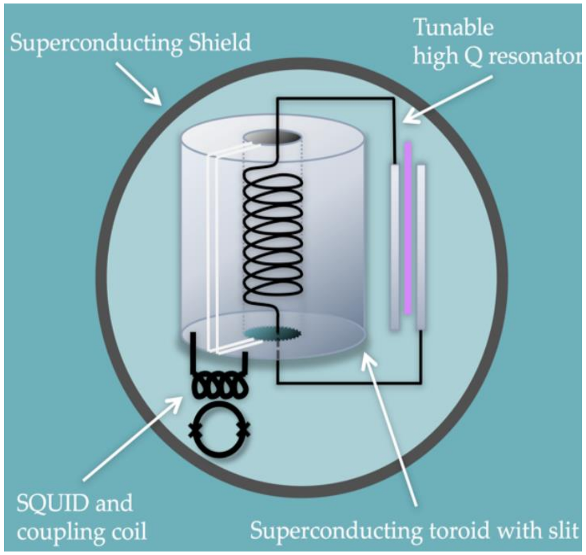






Lower Frequencies – Lumped Parameter Oscillators
(See Peter Graham's talk tomorrow)



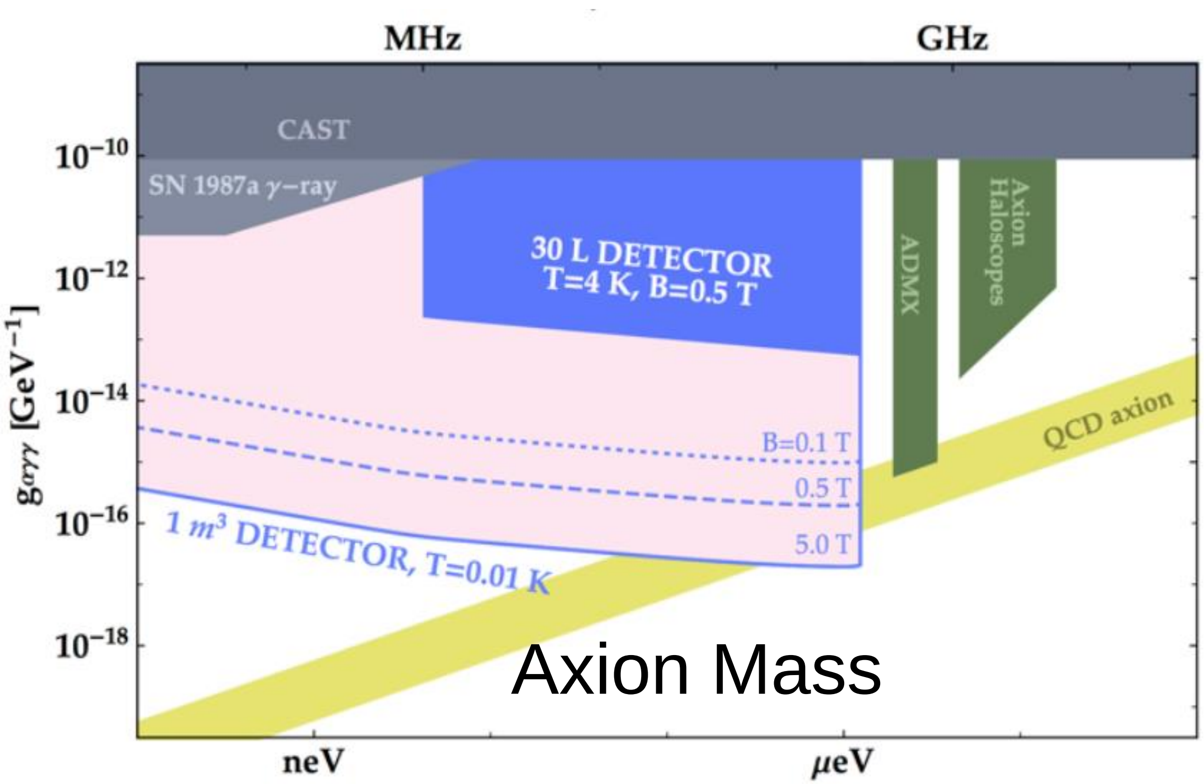


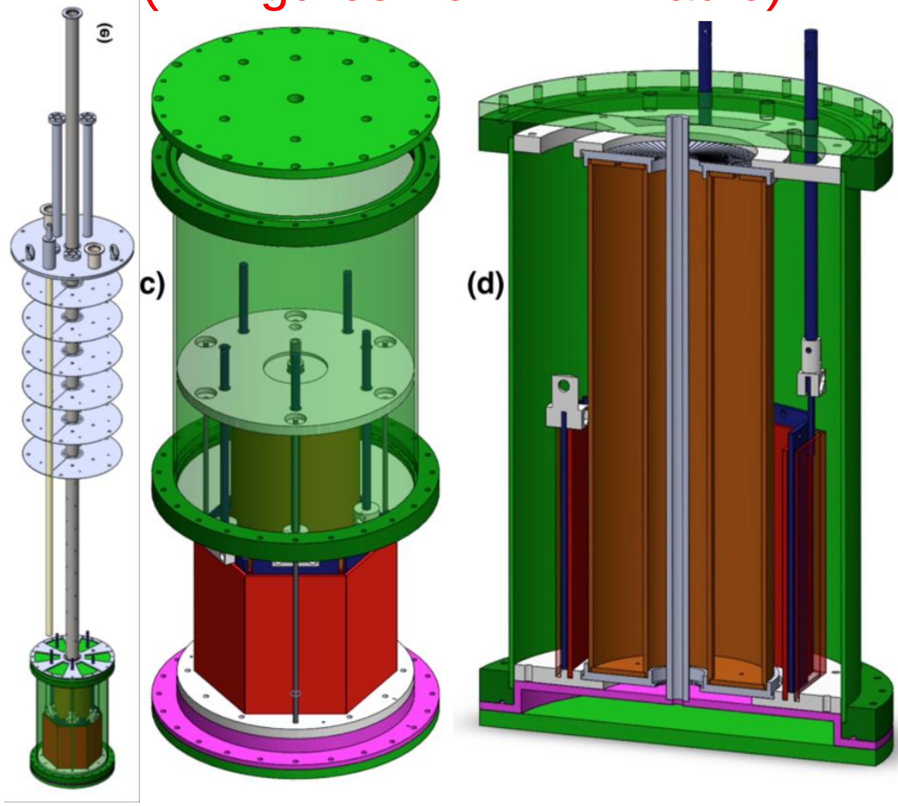
In a nutshell – Break the relationship between cavity diameter & frequency.

LC project *(U. Florida): Sikivie et al., Phys. Rev. Lett. 112, 131301 (2014)*

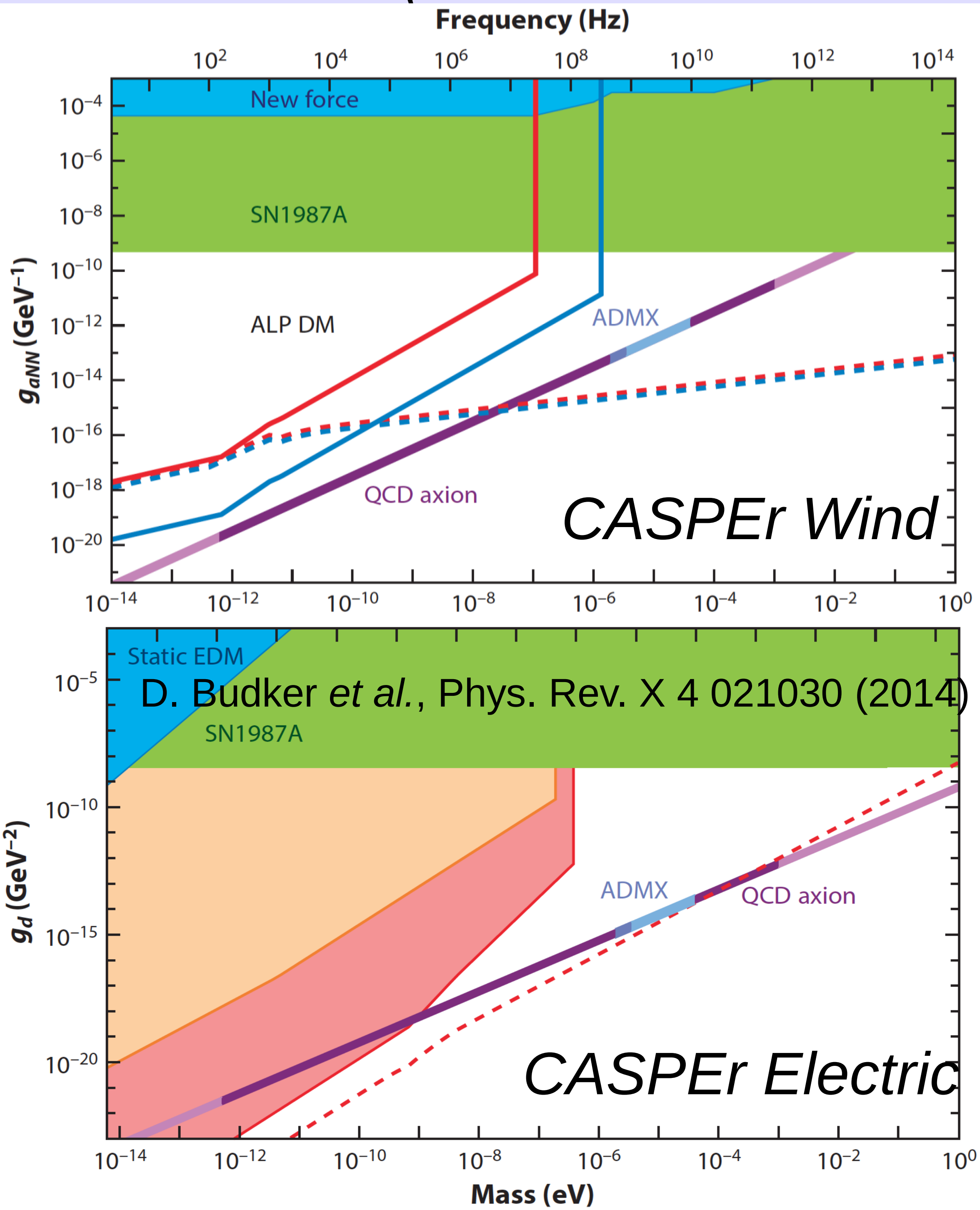
DM Radio *(SLAC): Chaudhuri et al., Phys. Rev. D 92:075012. (2015)*

(All figures from DM Radio)





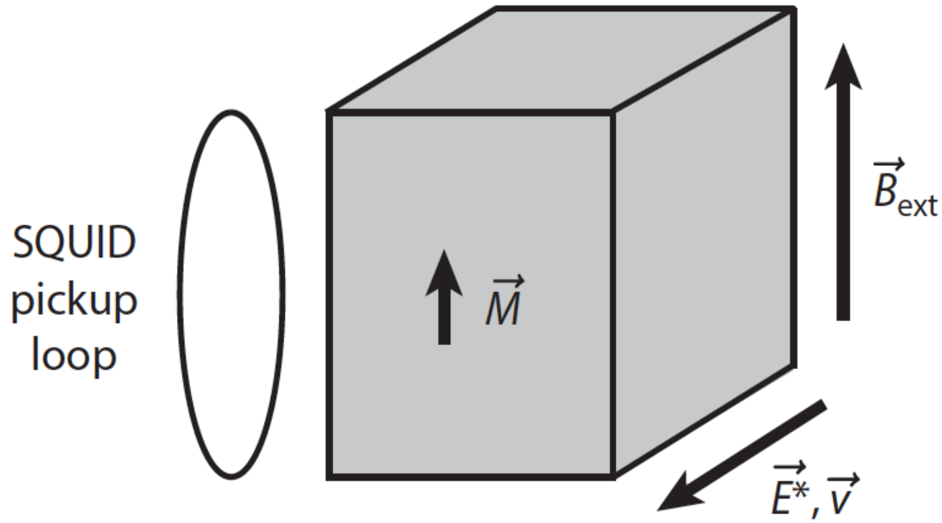
NMR-based search for dark matter axions: CASPEr
(See Peter Graham's talk tomorrow)



D. Budker *et al.*, Phys. Rev. X 4 021030 (2014)

CASPEr Wind: Direct coupling of axions to the nucleus; look for spin precession around spatial gradient of the axion field.

$$\mathcal{L} = \ldots + g_{aNN}(\partial_\mu a)\bar{N}\gamma^\mu\gamma_5 N$$



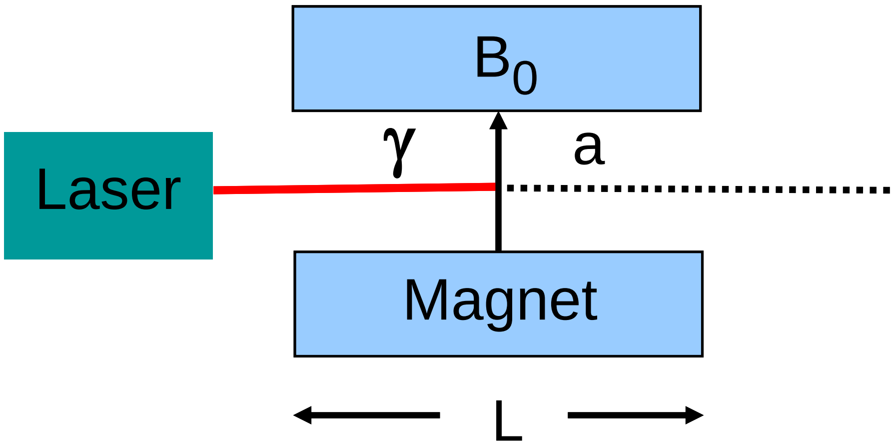
CASPEr Electric: Look for time-varying EDM due to coupling of axion to the nucleon; requires an external E-field.

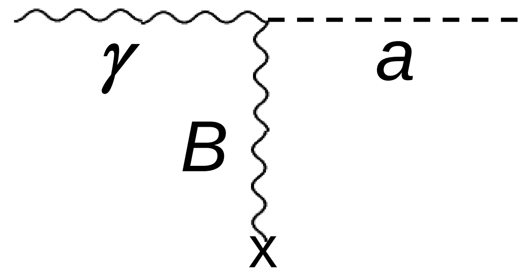
$$\mathcal{L} = \ldots - \frac{i}{2} g_d\, a\, \bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu}$$

Laboratory searches

Axion-photon mixing in a transverse magnetic field

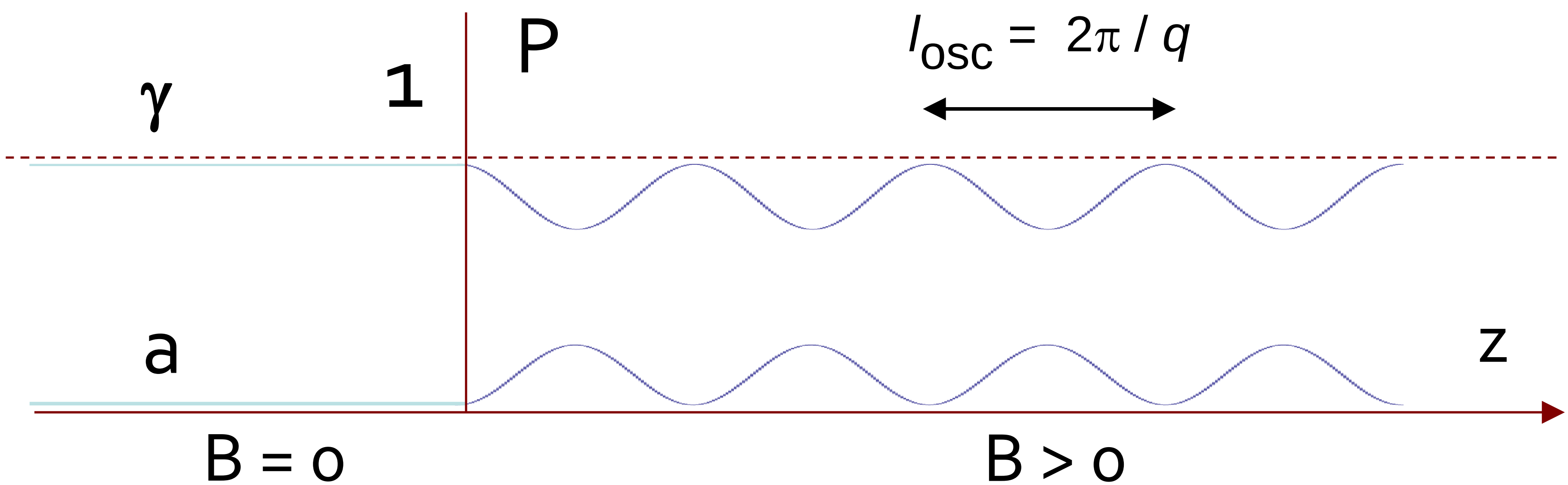
Raffelt & Stodolsky, Phys. Rev. D37 (1988) 1237





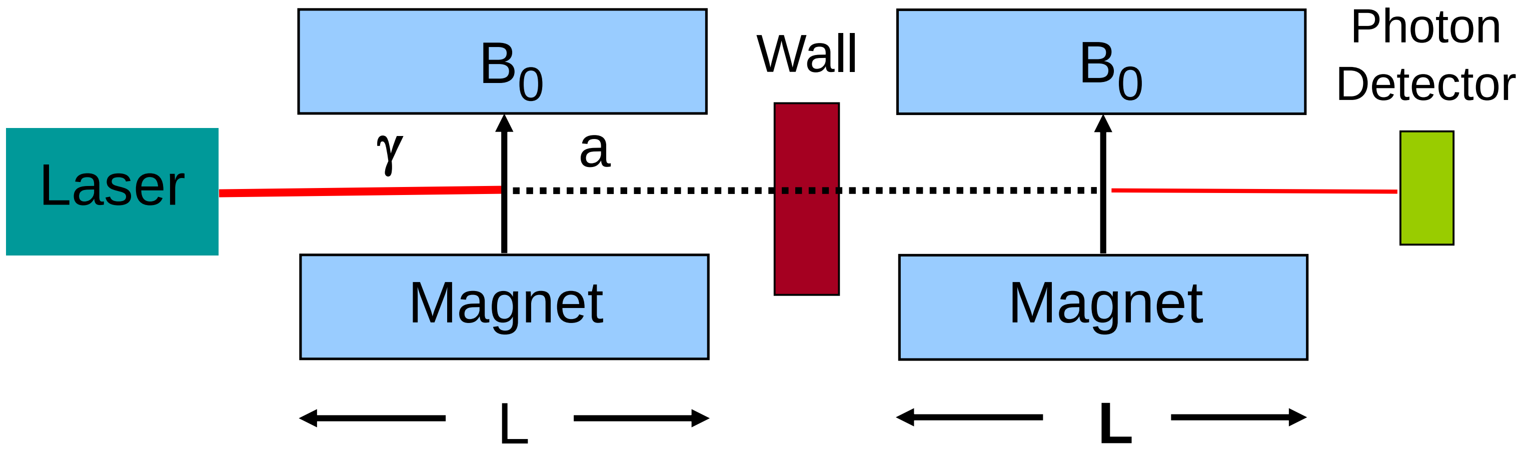
$$P(\gamma \rightarrow a) = \Pi = 1/4\,(gB_0L)^2\,|F(q)|^2$$

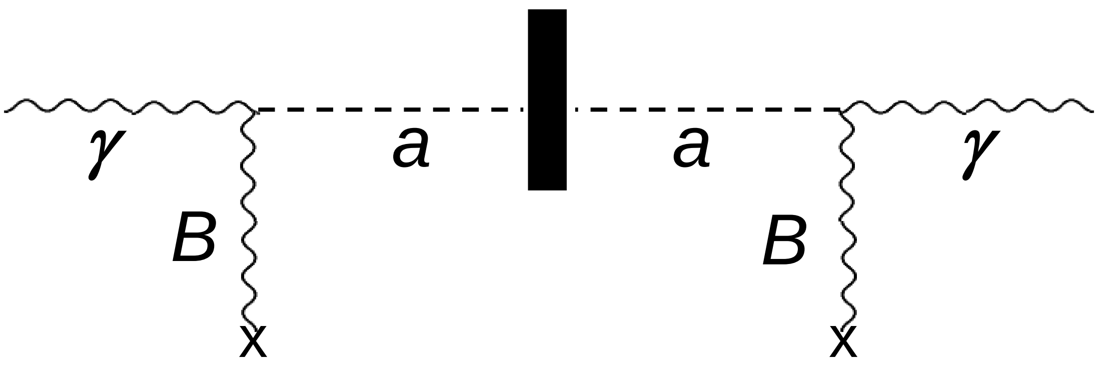
$$F(q) = \frac{Sin(qL/2)}{(qL/2)},\quad F(0) = 1 \qquad \text{where} \qquad q = k_\gamma - k_a \approx m_a^{\,2}/2\omega$$

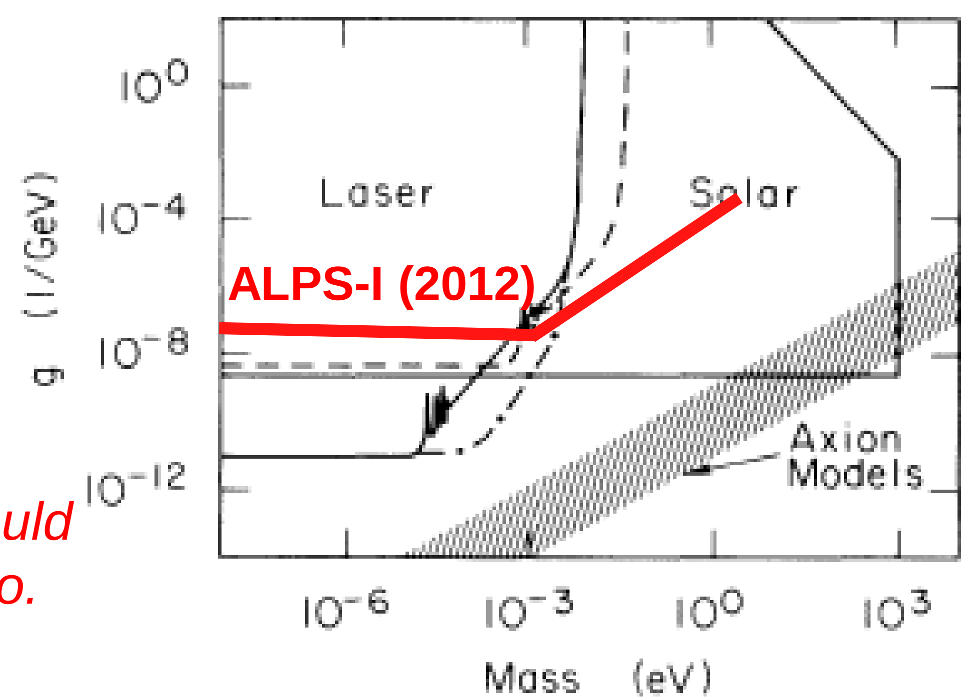


Photon Regeneration – “Shining Light through Walls”

KvB, Koonin, Kerman, Nelson, Dagdevirin, PRL 59 (1987) 759





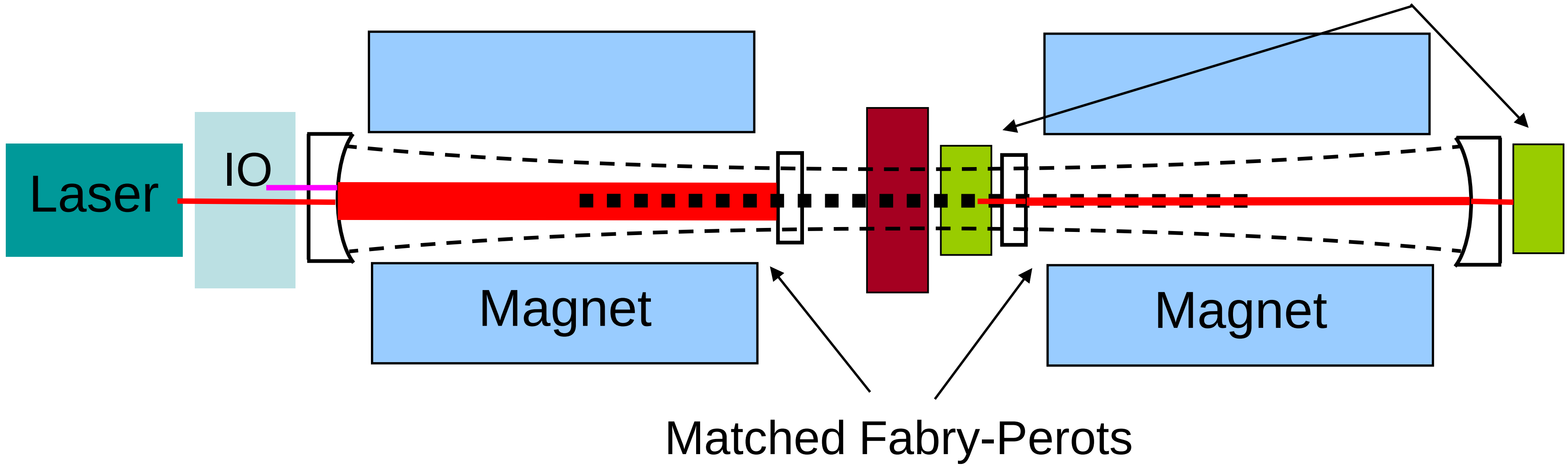


$$P(\gamma \rightarrow a \rightarrow \gamma) = \Pi^2 = 1/16\,(gB_0L)^4\,|F(q)|^4$$

Where we projected the laser experiments would get to, and about where they actually did get to. The g^4 scaling makes this very hard to push.

Resonantly-enhanced Photon Regeneration

Sikivie, Tanner, KvB, PRL 98 (2007) 172002; Hoogeveen & Ziegenhagen, Nucl. Phys. B358 (1991) 3

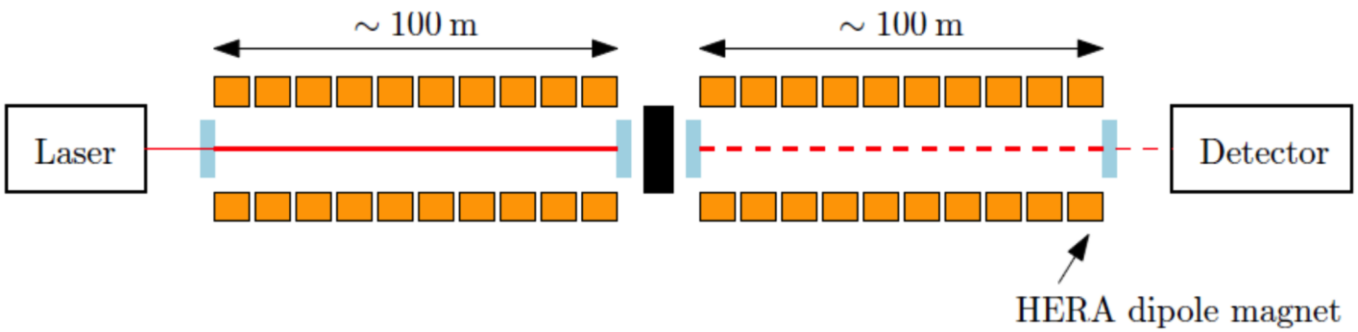


$$P^{Resonant}(\gamma \to a \to \gamma) = \frac{2}{\eta\eta'} \cdot P^{Simple}(\gamma \to a \to \gamma) = \frac{2}{\pi^2} FF' \cdot P^{Simple}(\gamma \to a \to \gamma)$$

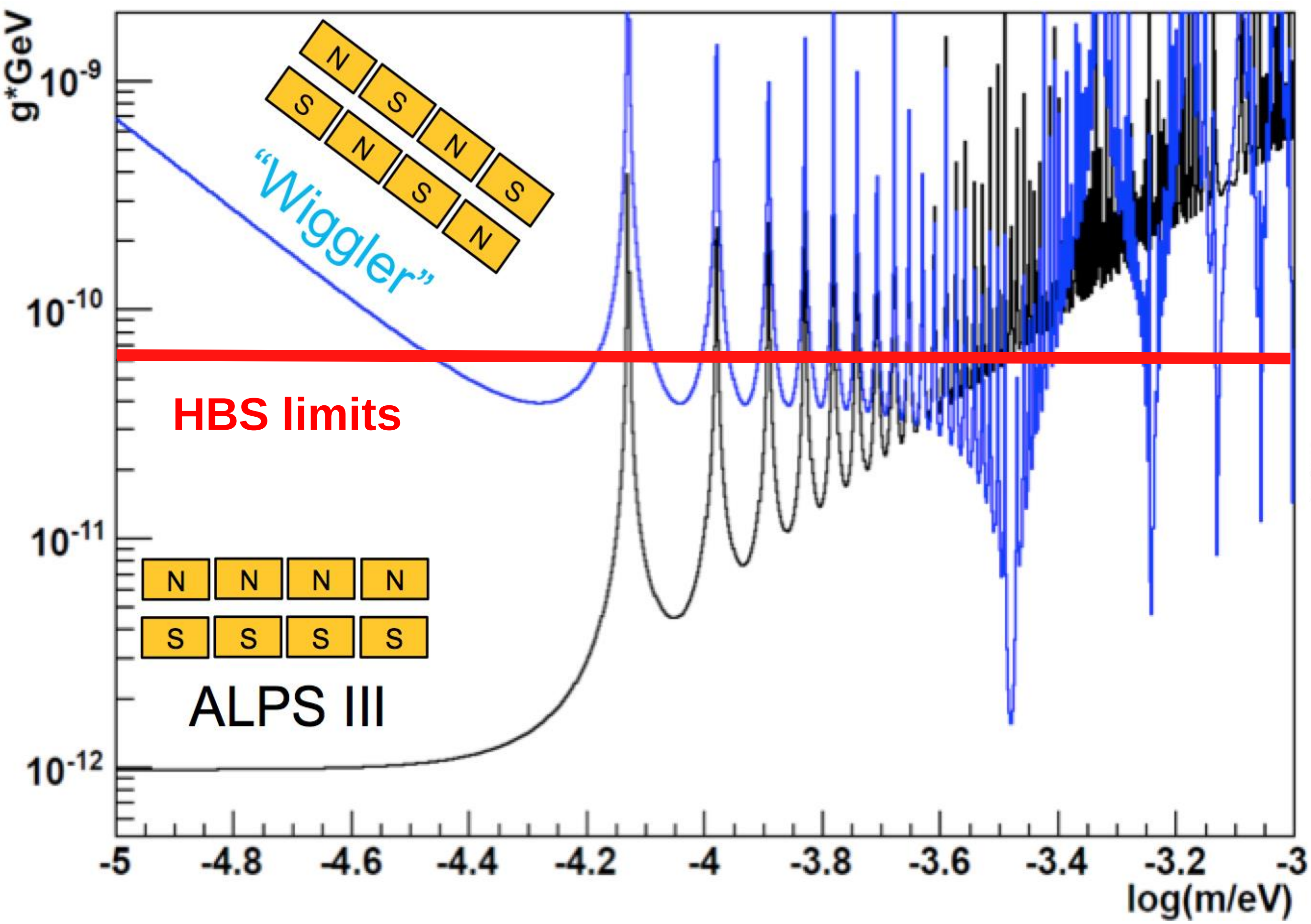
where η, η' are the mirror transmissivities & F, F' are the finesses of the cavities

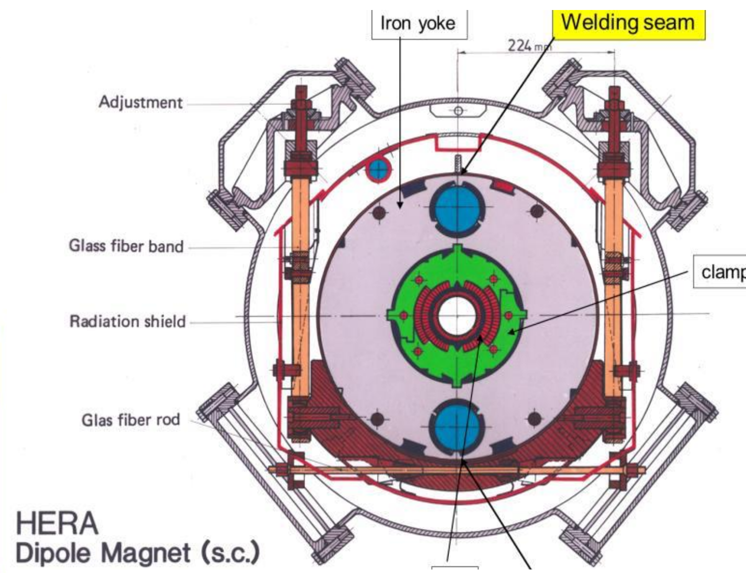
With $F \sim 10^{(5\text{-}6)}$, gains of $10^{(10\text{-}12)}$ in probability, and $10^{(2.5\text{-}3)}$ in coupling constant are possible

ALPS-II & III (DESY, Florida, Hannover, Mainz, Hamburg)

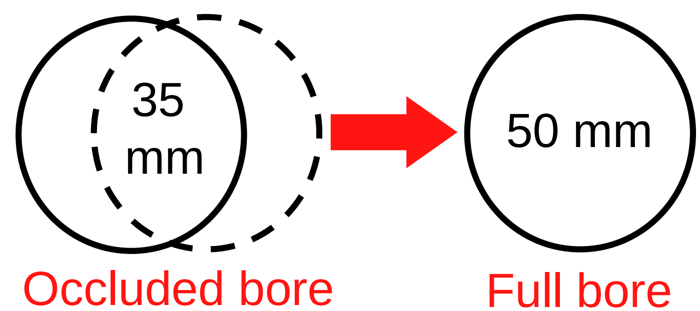


10+10 HERA dipoles
8.8 m, 5.4 T, 50 mm bore
LIGO optics
Pound-Drever-Hall locking



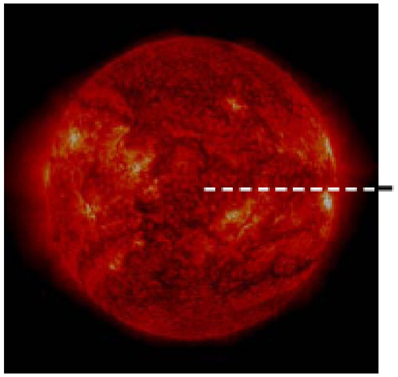


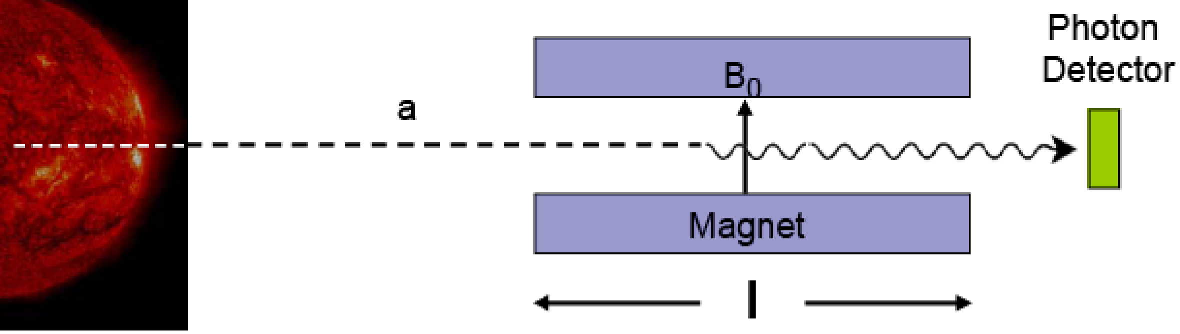
Removing the 15 mm Sagitta

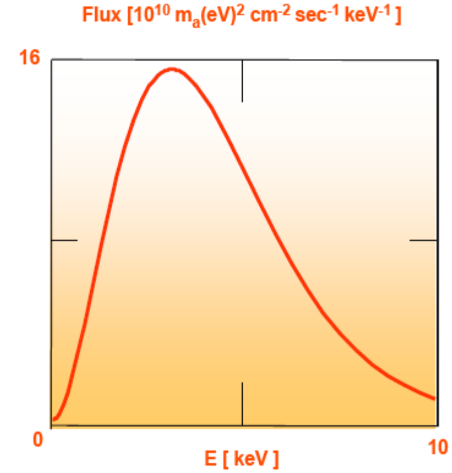


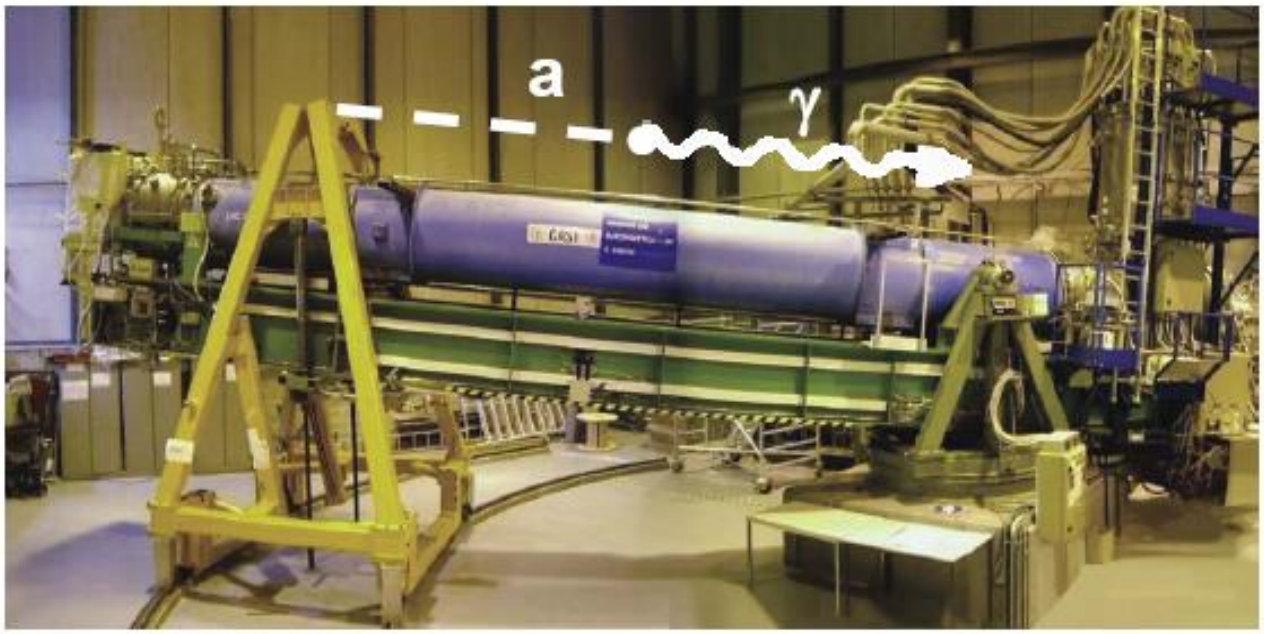
Solar axion searches

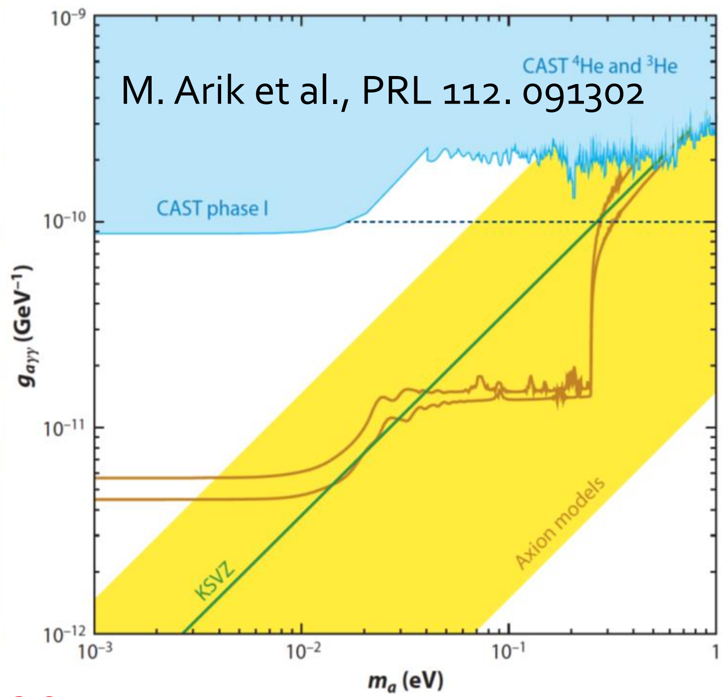
Axion Helioscope: The CERN Axion Solar Telescope (CAST)







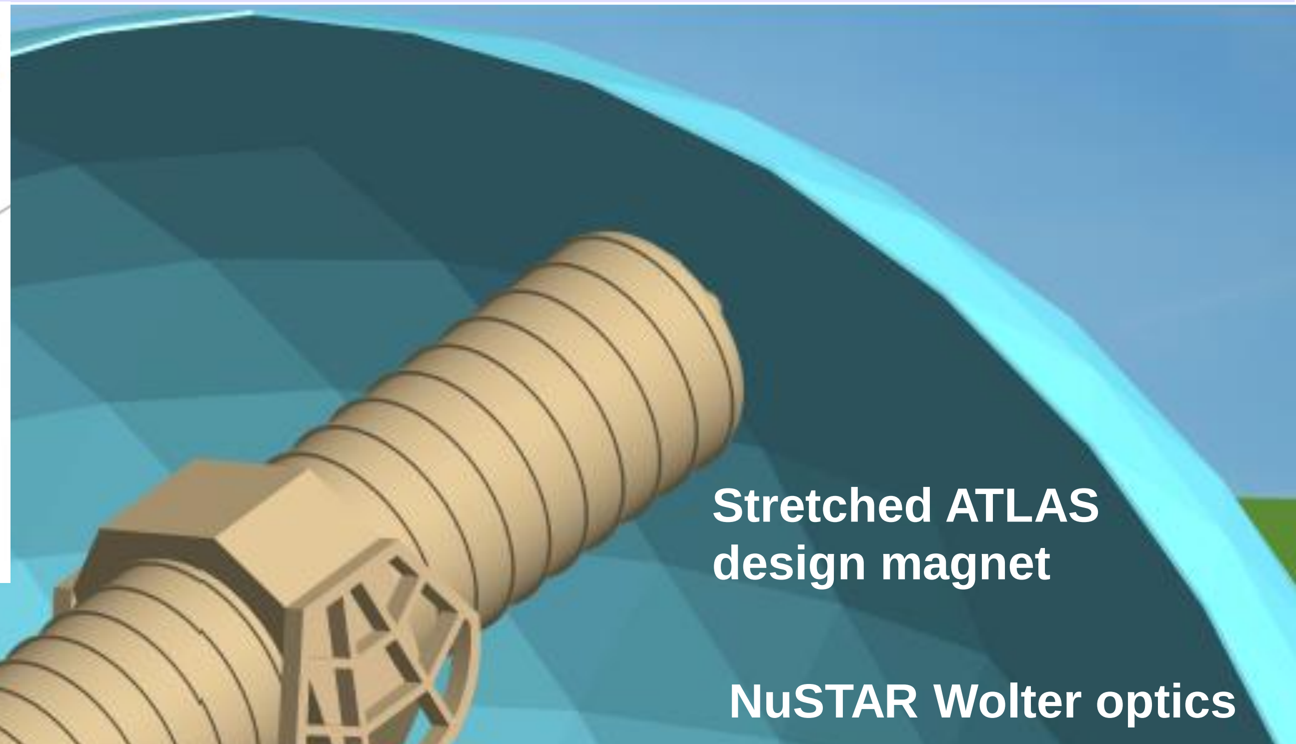


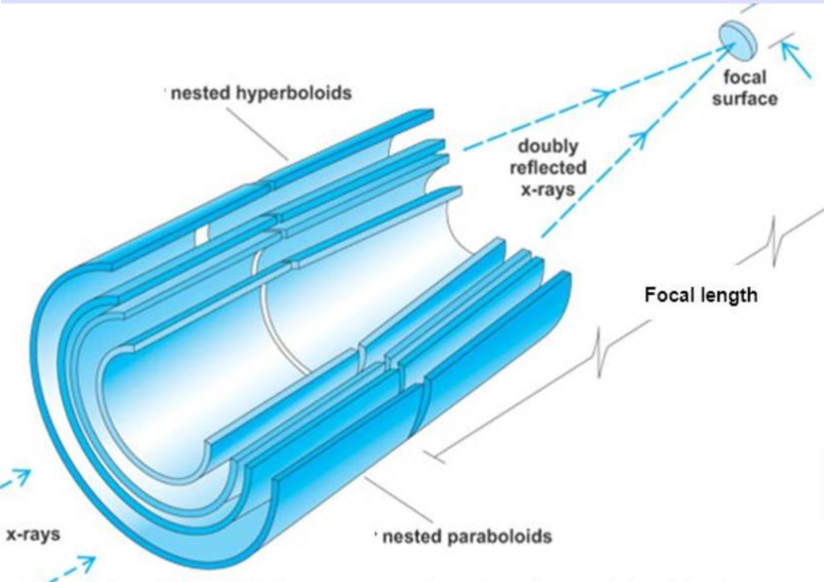


Filling the magnet bore with a gas (H, He) endows the photon with an effective mass, restoring full coherence at one axion mass; tune the pressure: $\omega_p = (4\pi\alpha N_e/m_e)^{1/2} \equiv m_\gamma$

KvB, McIntyre, Morris, Raffelt, Phys. Rev. D 39 (1989) 2089

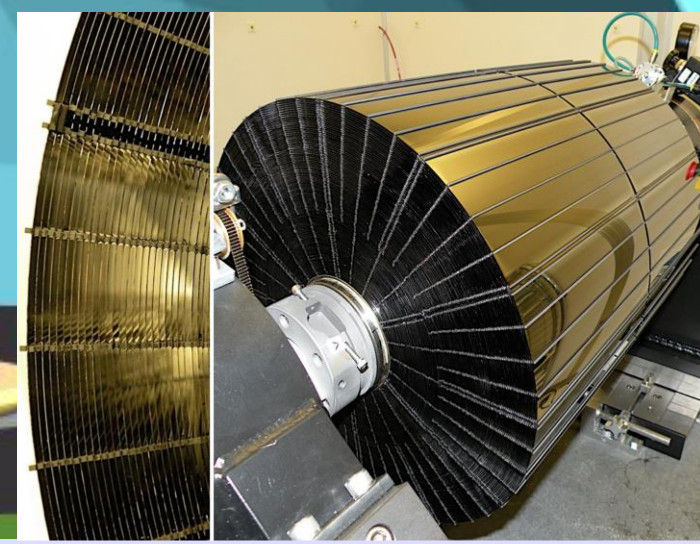
The International Axion Observatory (IAXO)





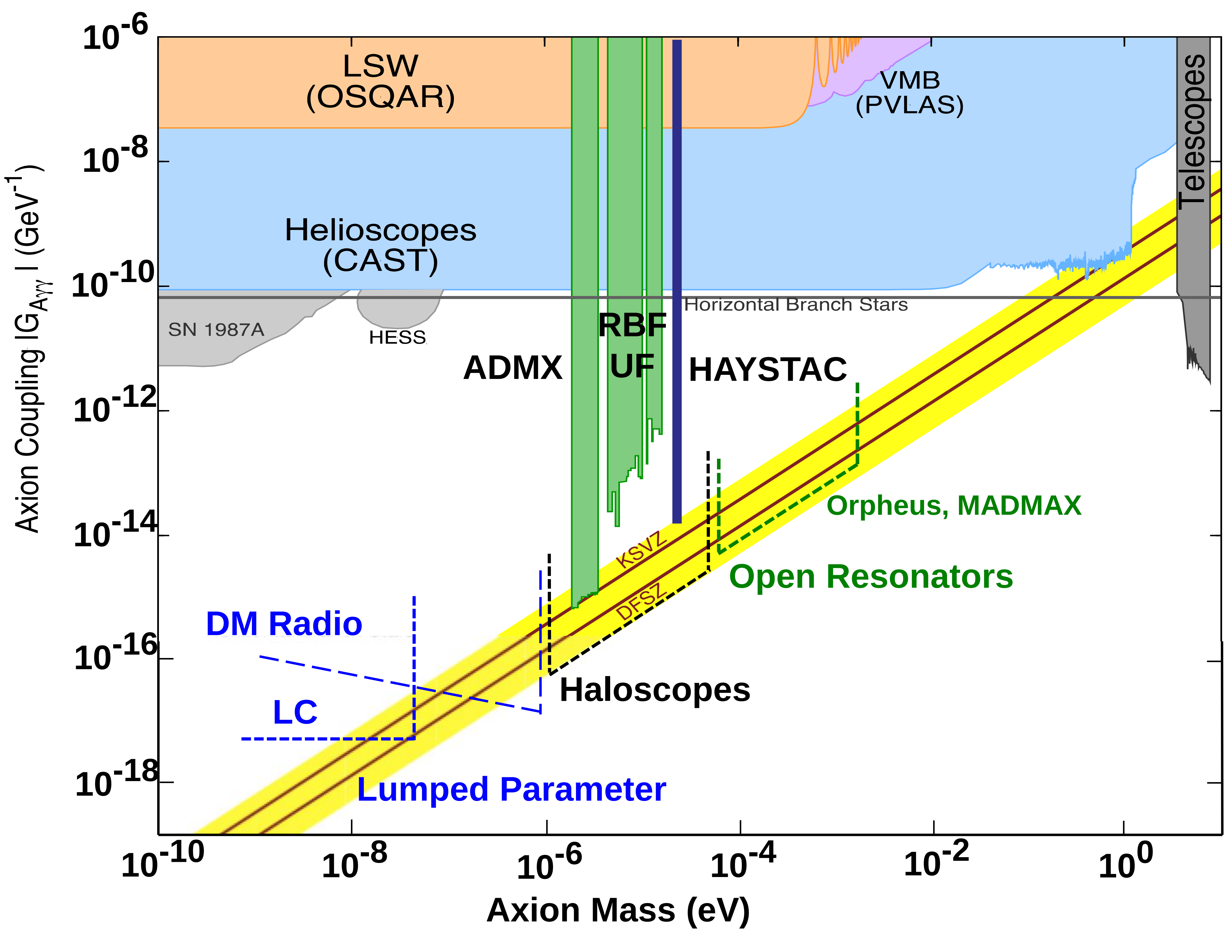
Proposed US contribution
NuSTAR design focusing
X-Ray optics (Wolter)
MIT, Columbia LLNL

NuSTAR Wolter optics



E. Armengaud *et al.*, Letter of Intent to the CERN SPC, August 7, 2013

Excluded $g_{A\gamma\gamma}$ vs. m_A with all experimental & observational constraints

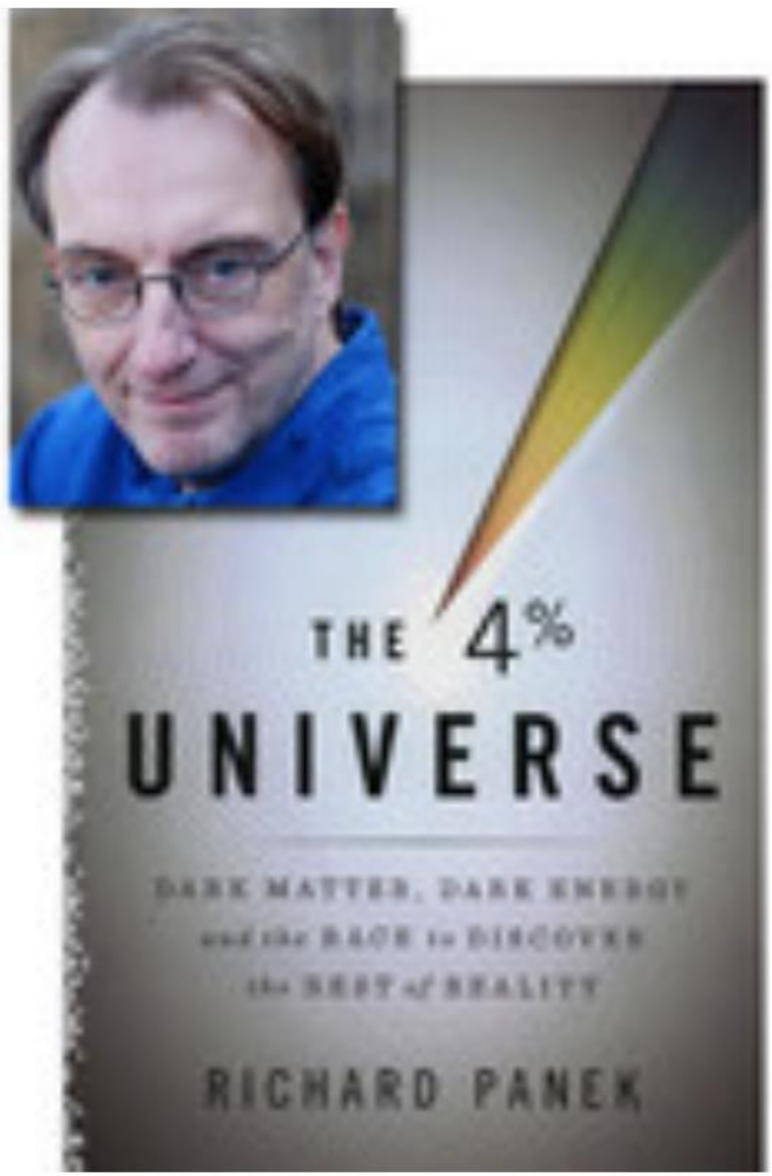


LSW
(OSQAR)
VMB
(PVLAS)
Telescopes
Helioscopes
(CAST)
Horizontal Branch Stars
SN 1987A
HESS
RBF
UF
ADMX
HAYSTAC
Orpheus, MADMAX
KSVZ
DFSZ
Open Resonators
DM Radio
Haloscopes
LC
Lumped Parameter
Axion Coupling $|G_{A\gamma\gamma}|$ (GeV^{-1})
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
Axion Mass (eV)

When shall the axion be found?

And then what?

“All real axion hunters are Red Sox fans.
It prepares you for life” *Richard Panek*



The 4% Universe

Dark Matter, Dark Energy & the Race to Discover the Rest of Reality

Harcourt, Houghton & Mifflin, 2010

Richard Panek

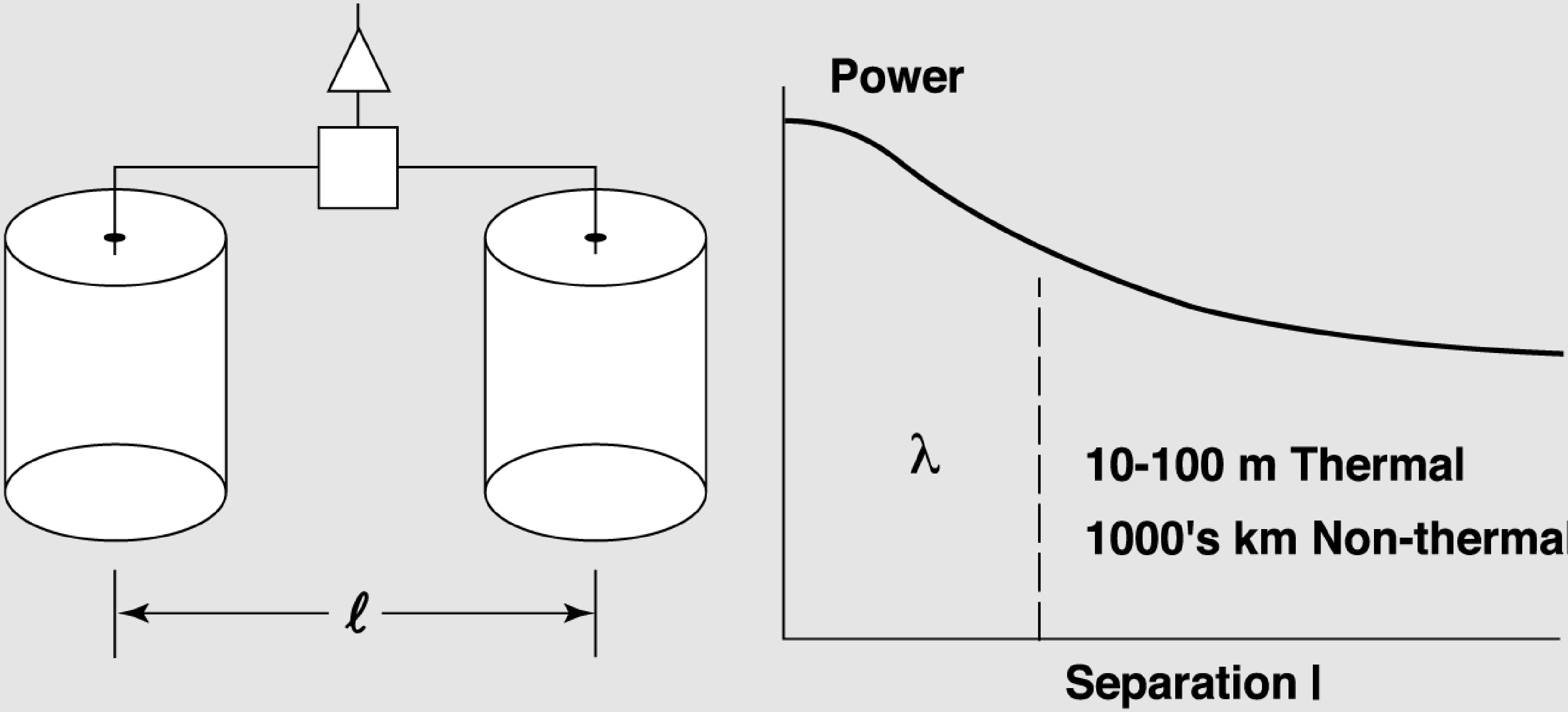
(See the chapter “The Curse of the Bambino”, about ADMX)

Forget Solar Eclipses – Lunar is the real deal

And if you thought it was just a coincidence…

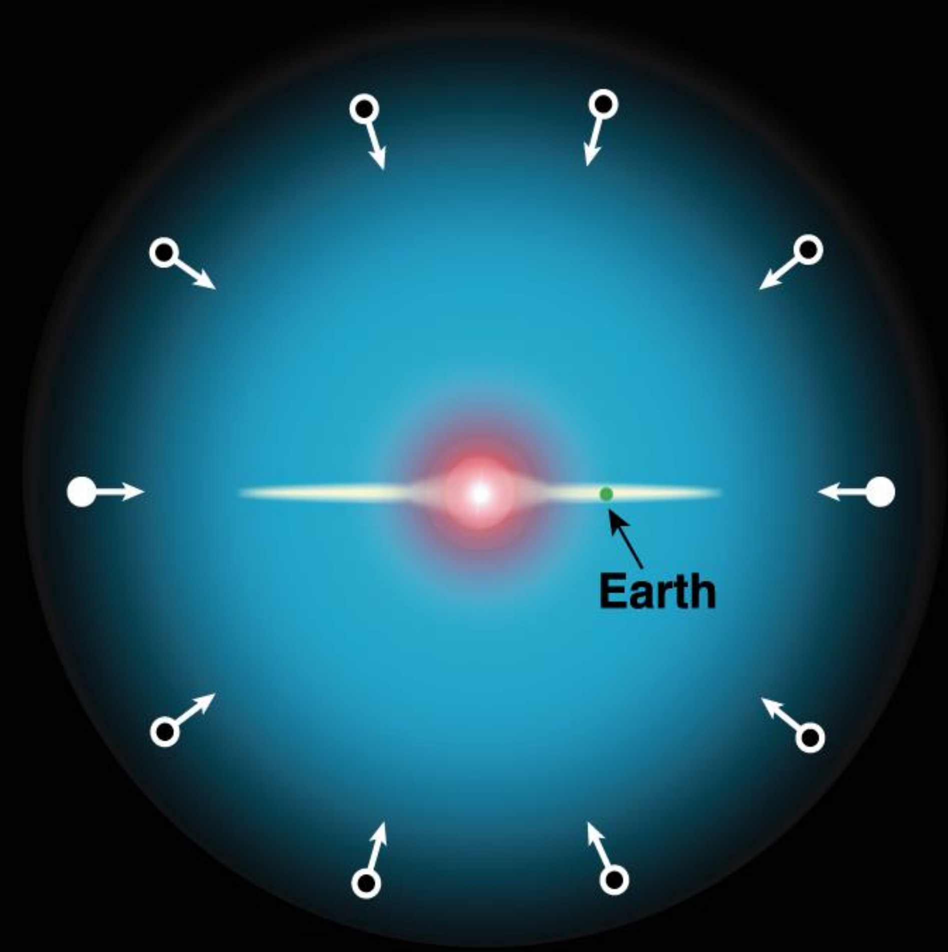
The Boston Bruins won their first Stanley Cup in 39 years, on June 15, 2011, under a blood red lunar eclipse

The Study of Unique Quantum System



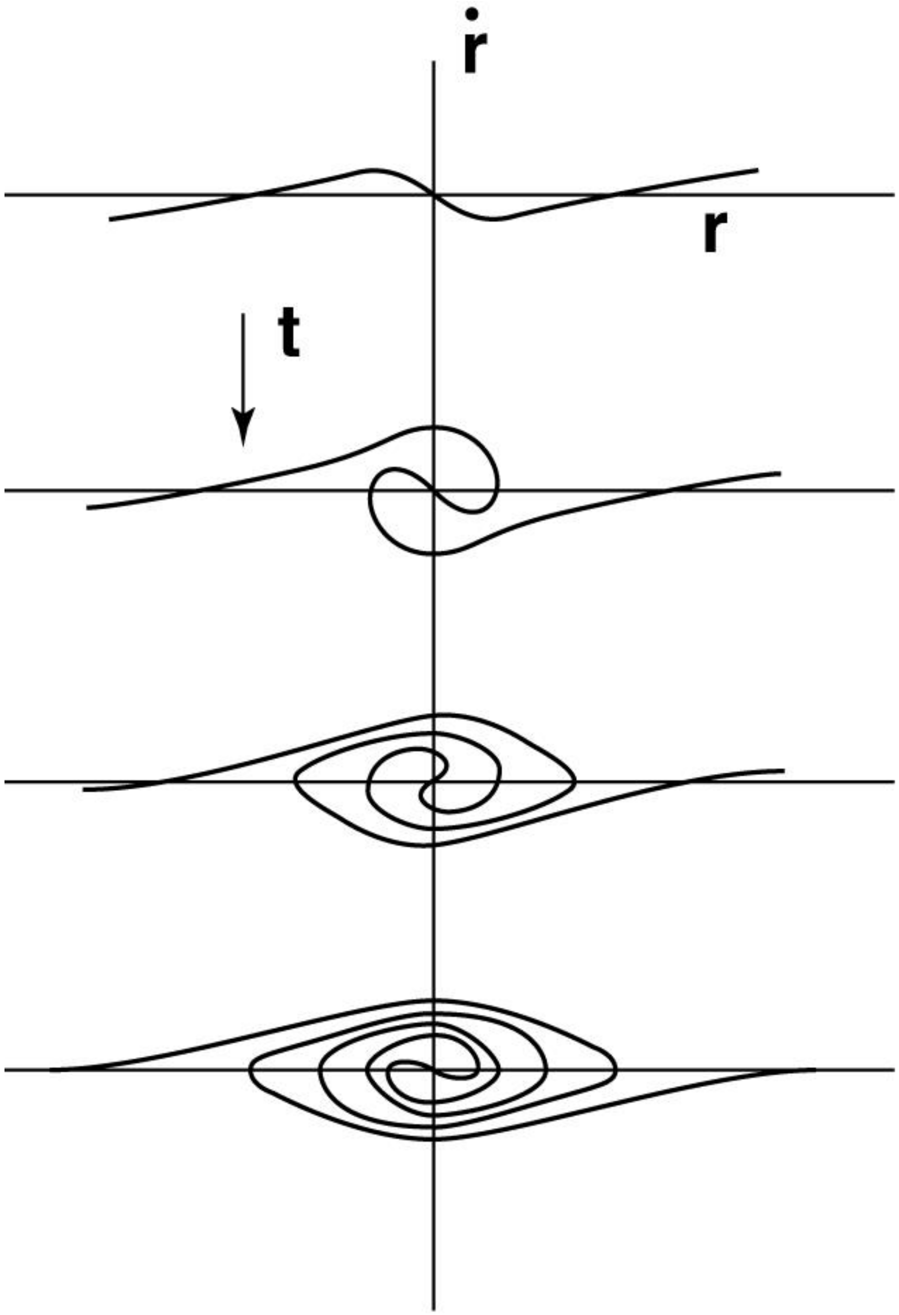
And should the axion posses fine-structure, it would constitute a "movie" of the formation of our Milky Way galaxy

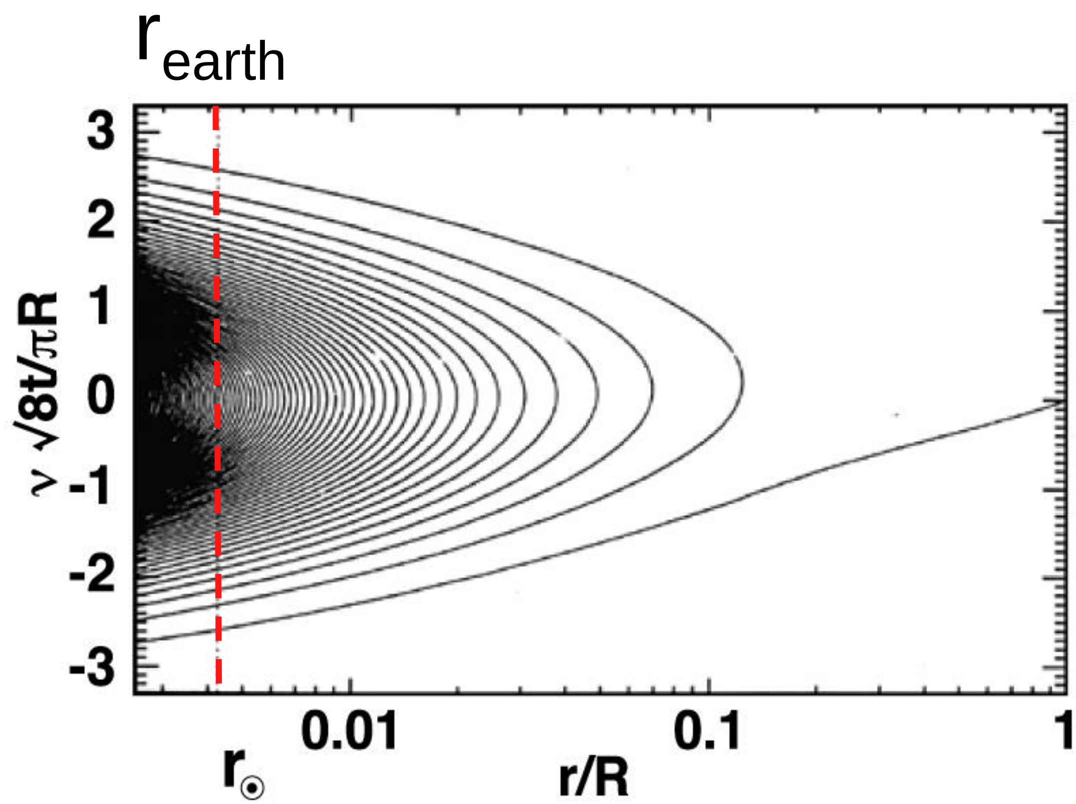
Modulation of fine structure may enable precision geolocation without GPS



Late-infall axions pass through our position with specific velocities

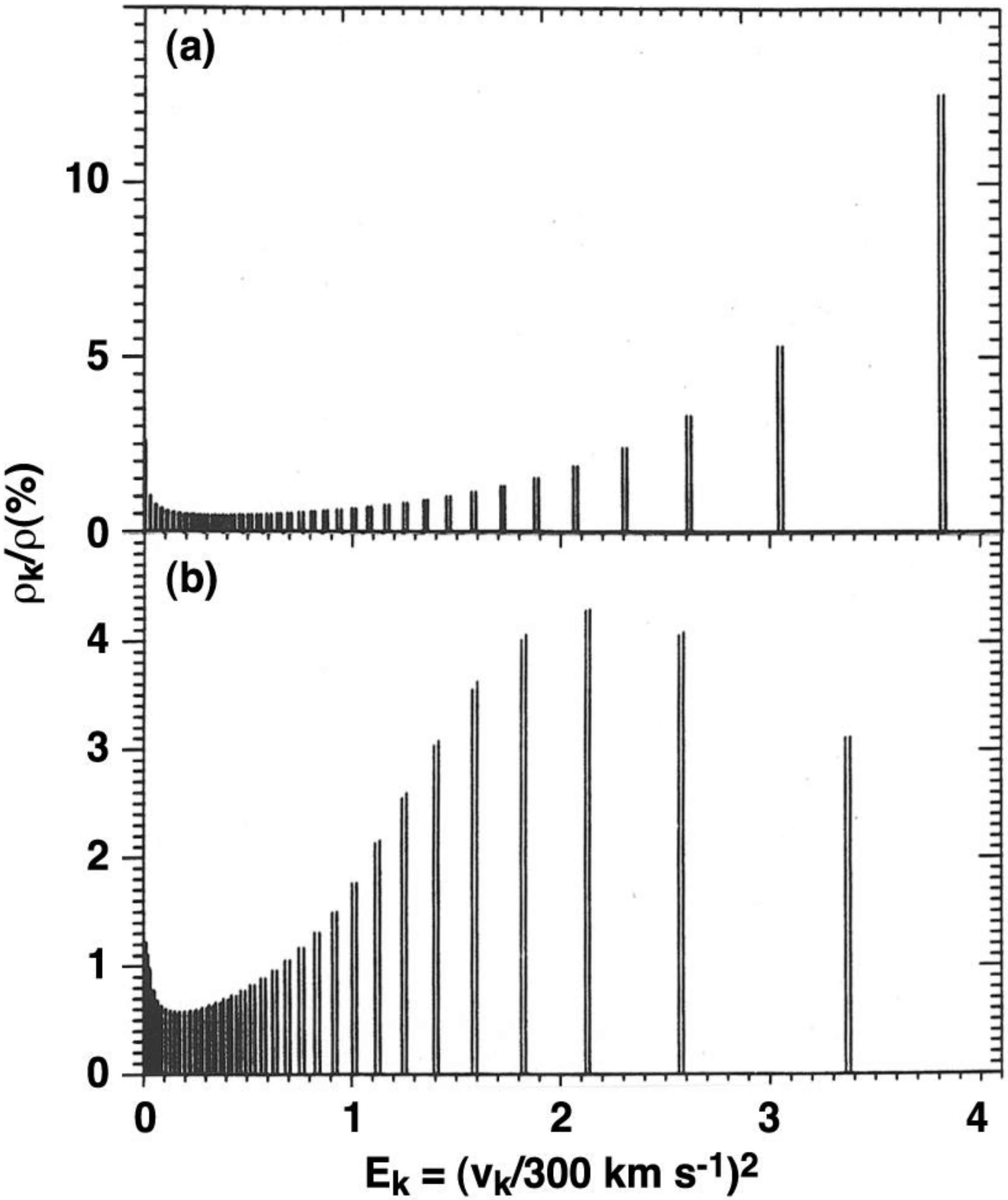
Axionic phase space in a Sikivie infall model





- Model begins with
  - Zero Temperature CDM
  - Hubble expansion
  - Initial density perturbation r = o
- Grows self-consistent potential

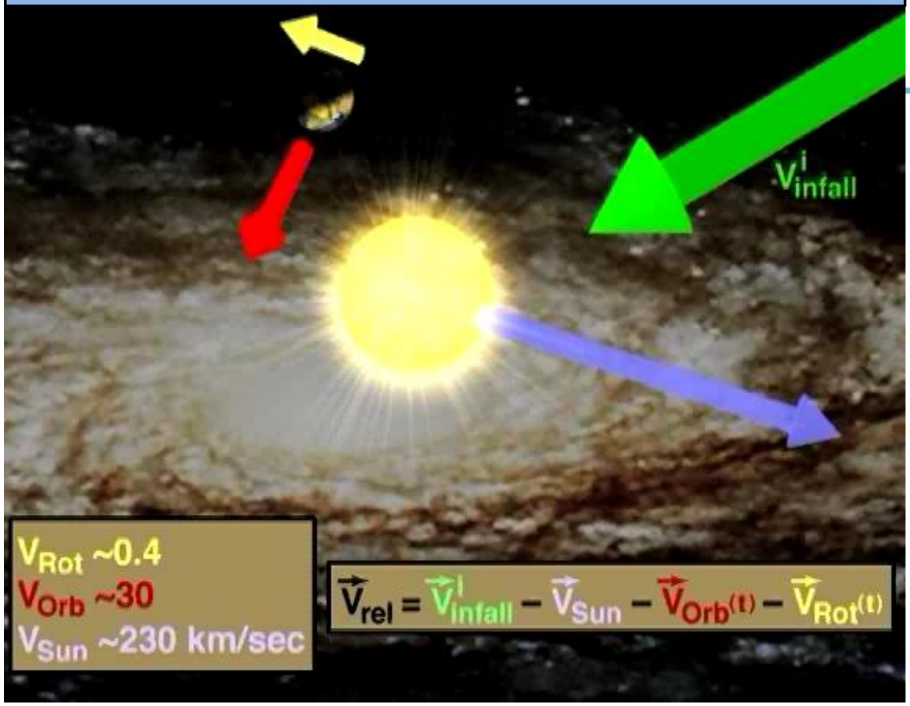
Sikivie infall model (II)



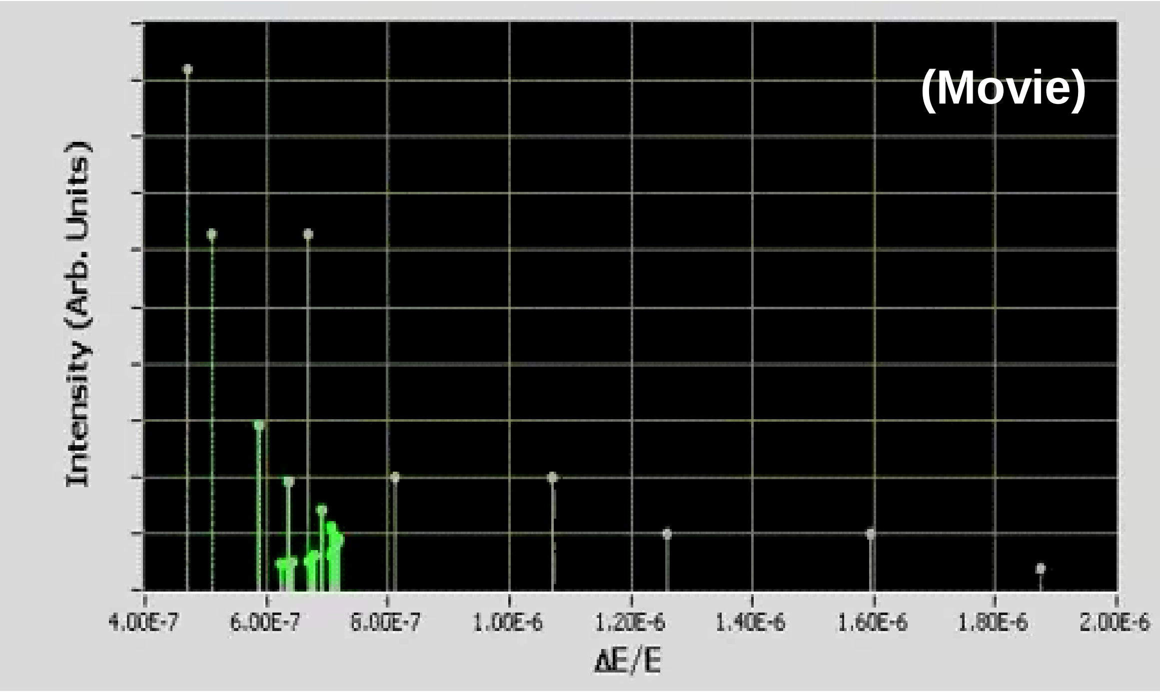
(a) No angular momentum

(b) Finite angular momentum

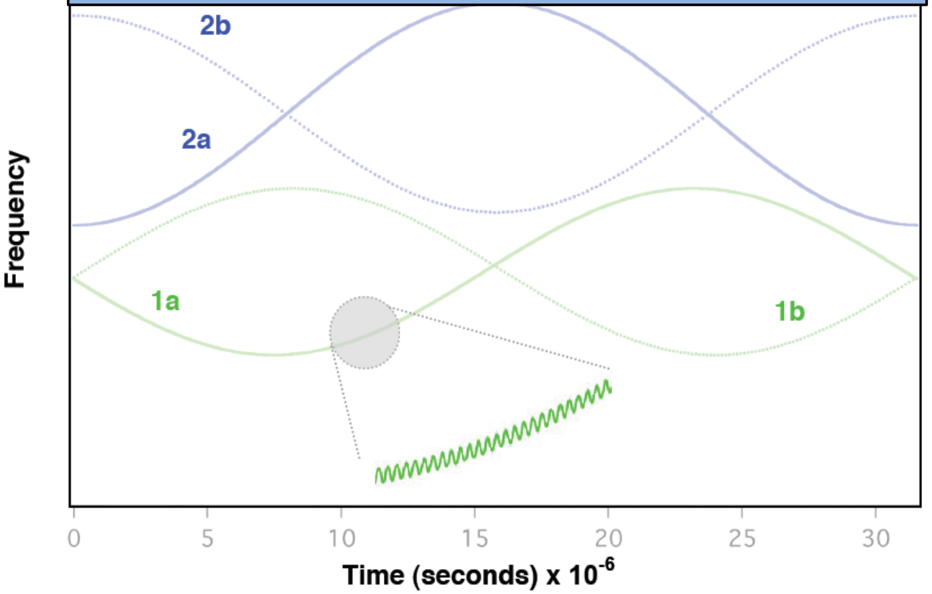
Modulation of one infall line



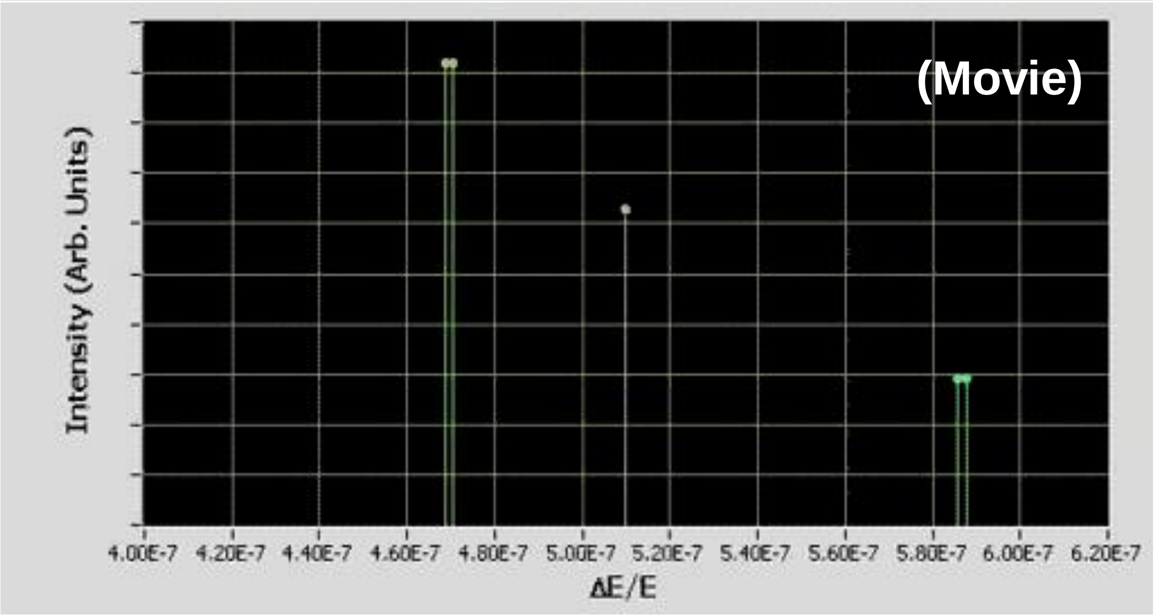
Annual Modulation: Earth's orbit around Sun



Vector DM Flow is uniquely determined



Daily Modulation: Earth's spin on its axis



Final thoughts

- Progress over the past quarter-century has been solid.
- The axion search is the one experiment where sensitivity is *not* the problem, but mass coverage – both in extent and in speed – continues to be. We have not turned the corner yet.
- The goal posts have moved; we have much more ground to cover than we thought a decade ago: at least neV to meV.
- The state of R&D is excellent; there is now a critical mass community to tackle the problems, and the agencies are to be thanked for their increased support.
- But new ideas are needed – join us!

See Peter Graham's talk tomorrow at 10:30!

And profound gratitude to our sponsors

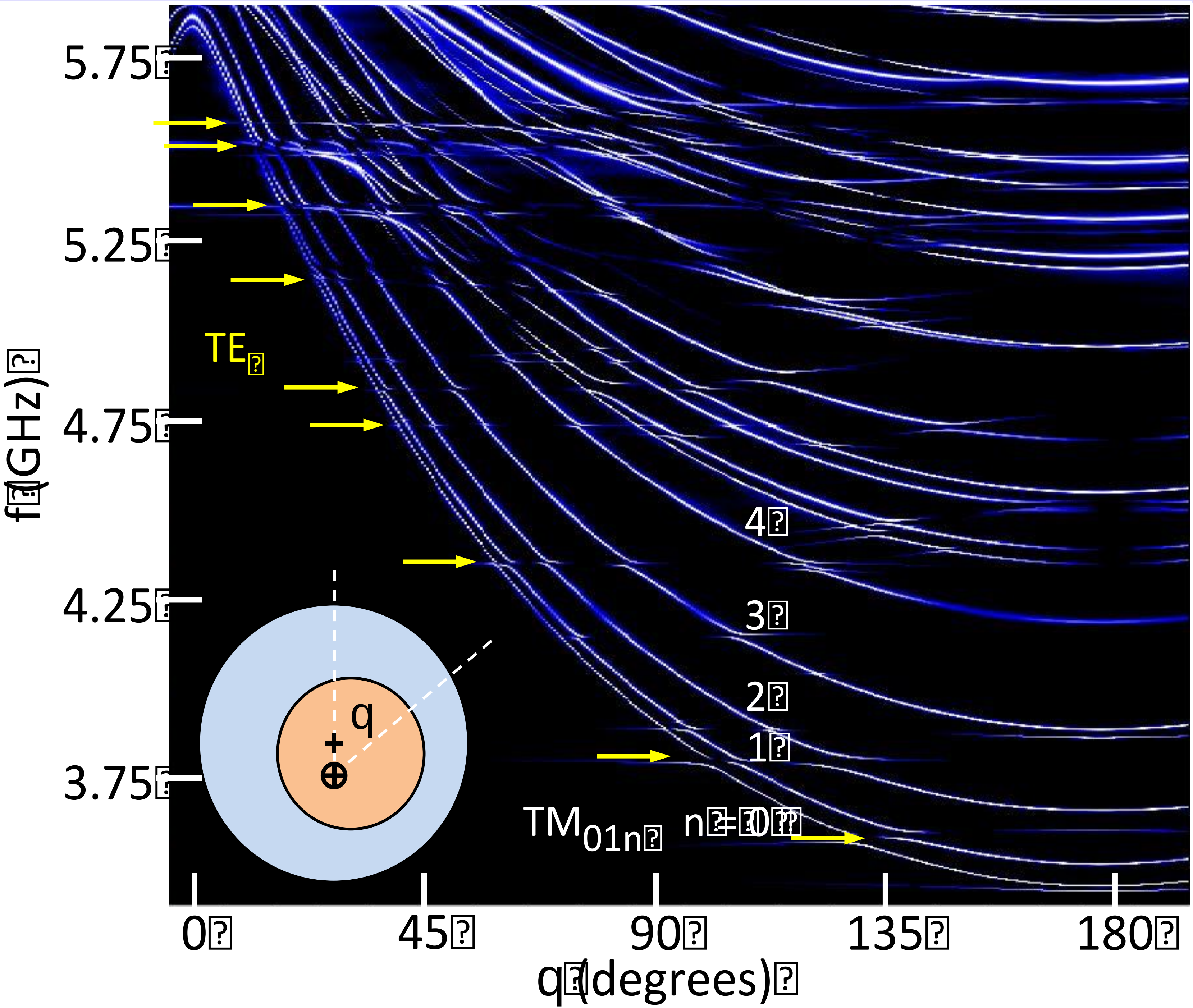
The National Science Foundation

The US Department of Energy

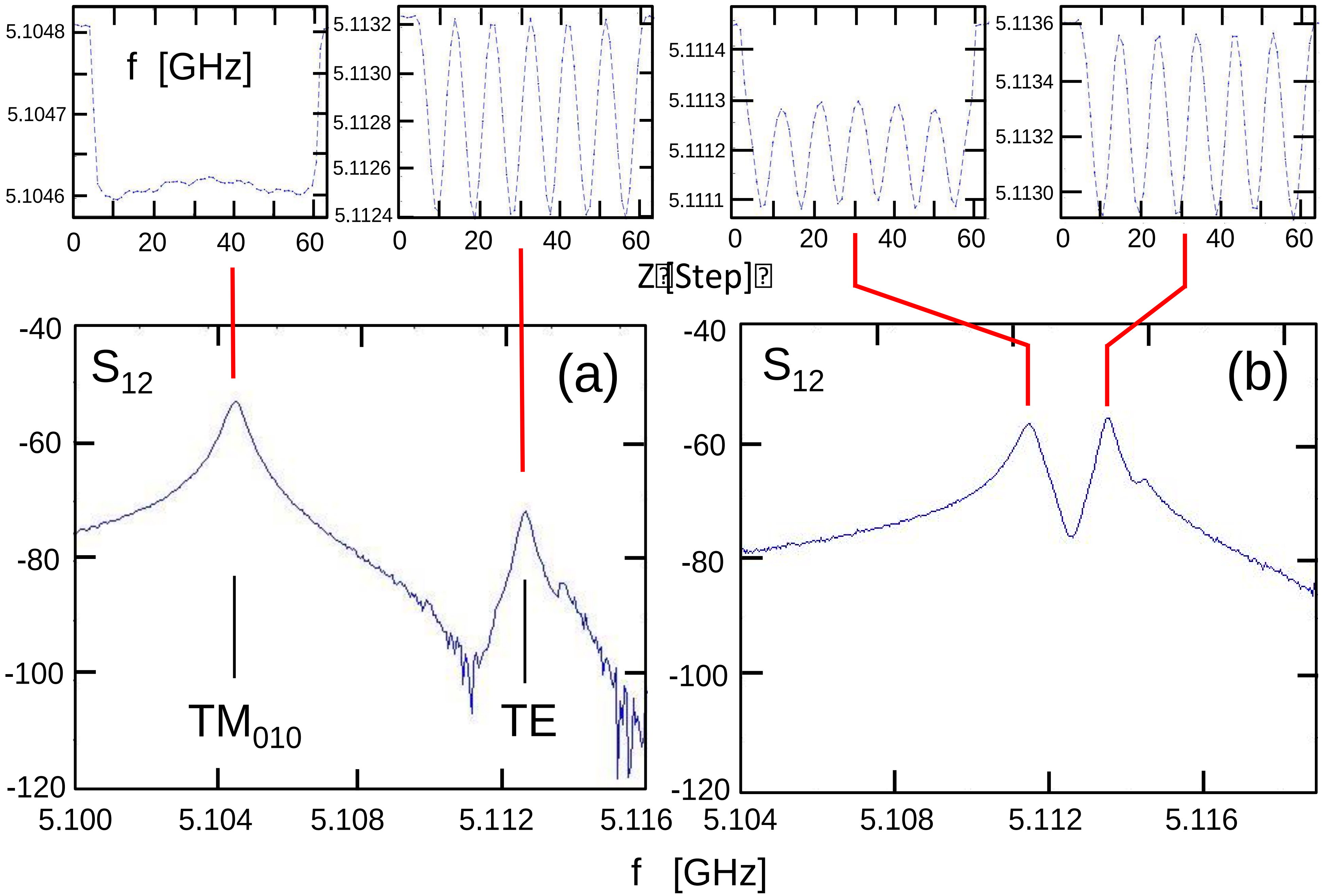
The Heising-Simons Foundation

Backup Slides

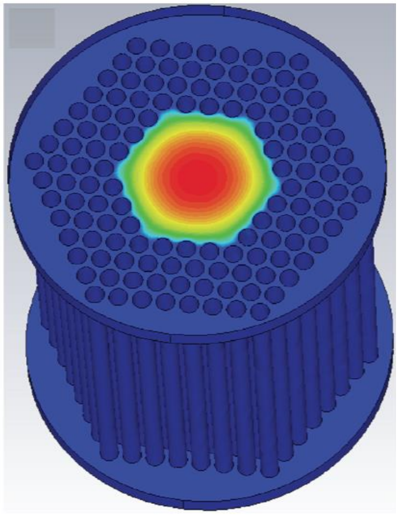
Bane of the search – thicket of TE-TM_{010} mode crossings

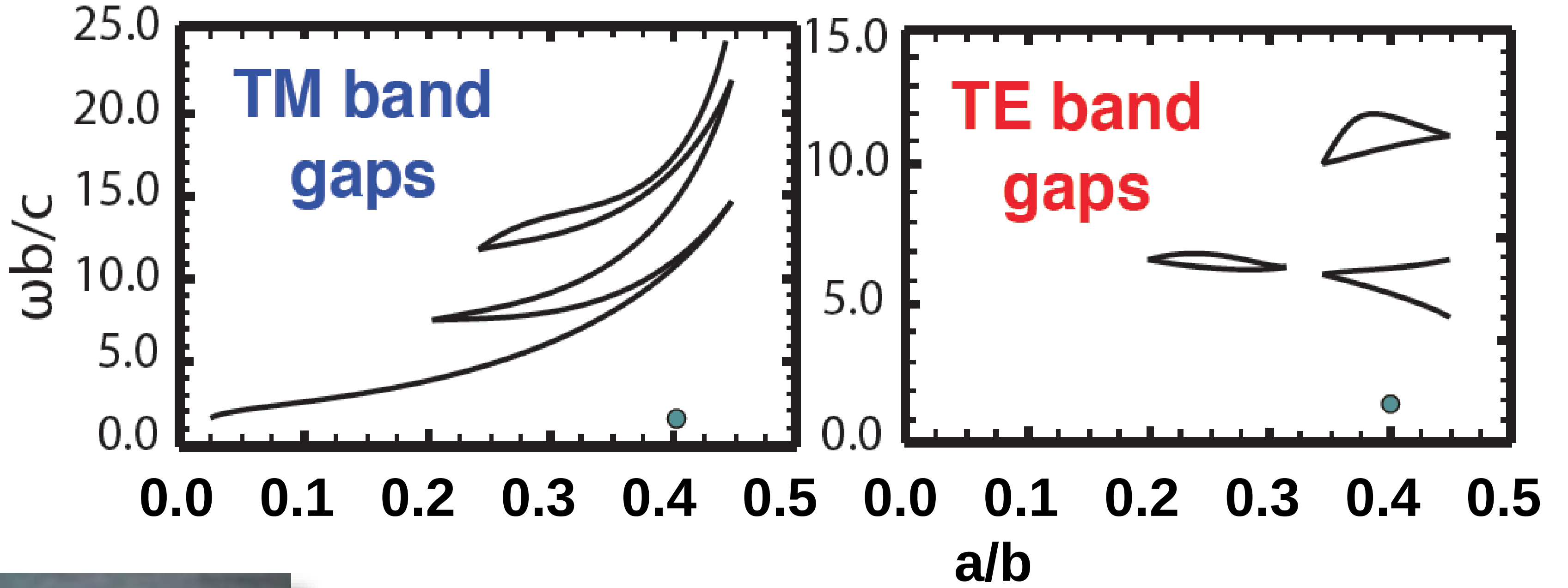


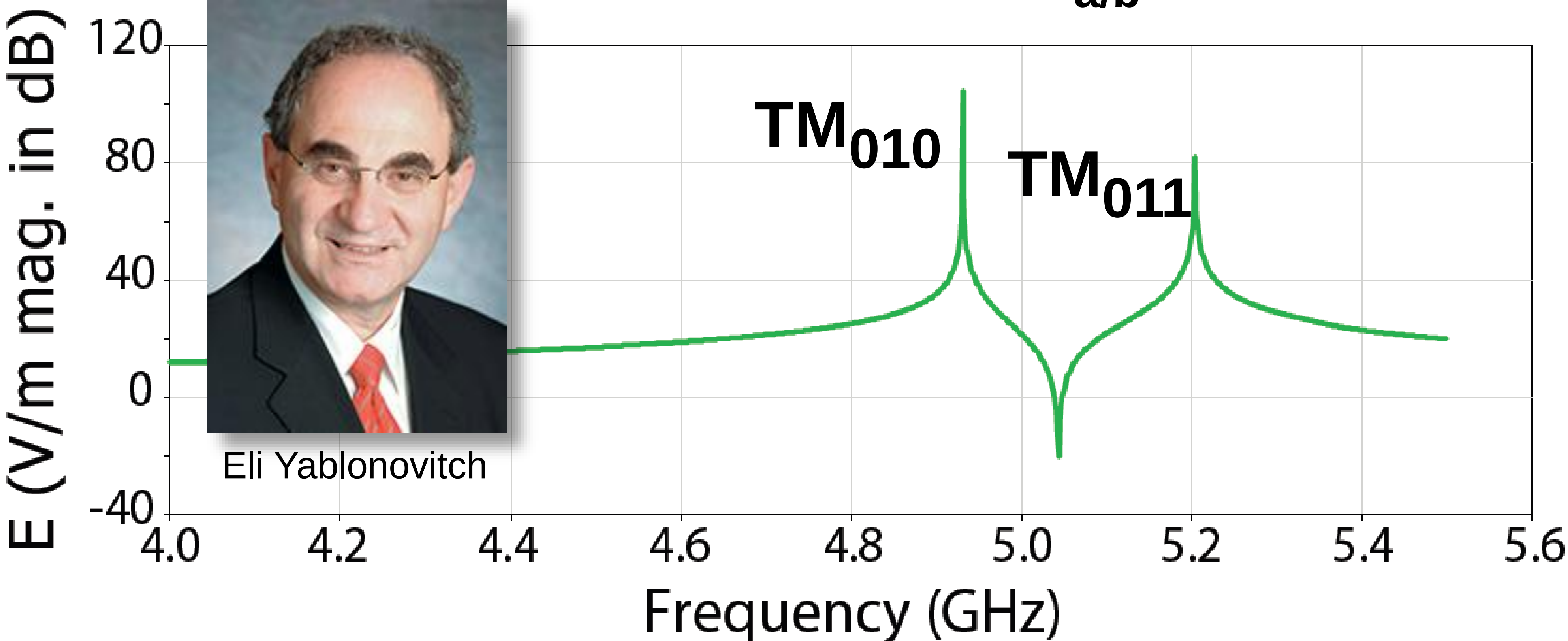
Two-level mixing of TM_{010} & TE modes



Cutting down the forest: Photonic Band Gap resonators

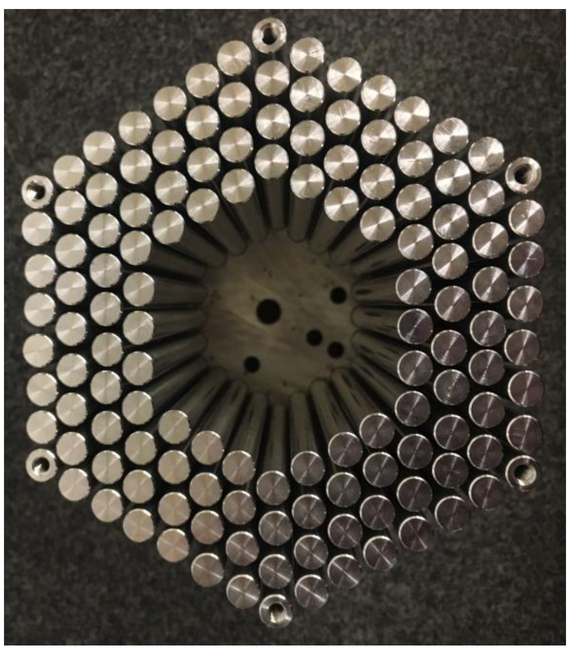




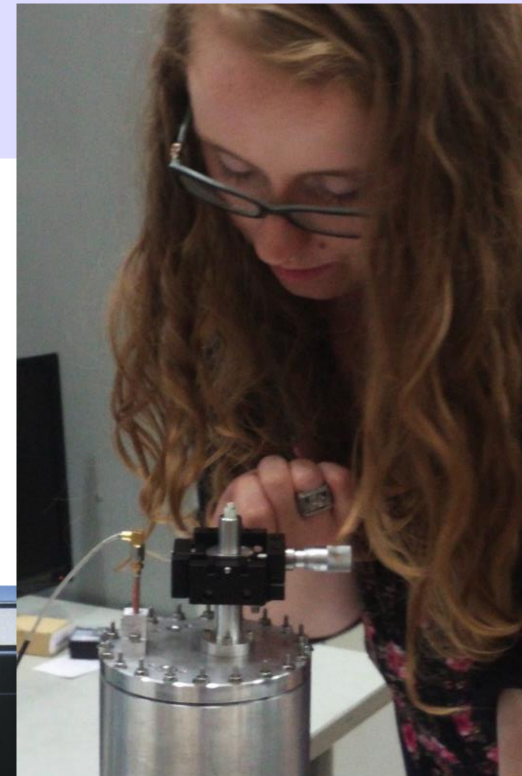


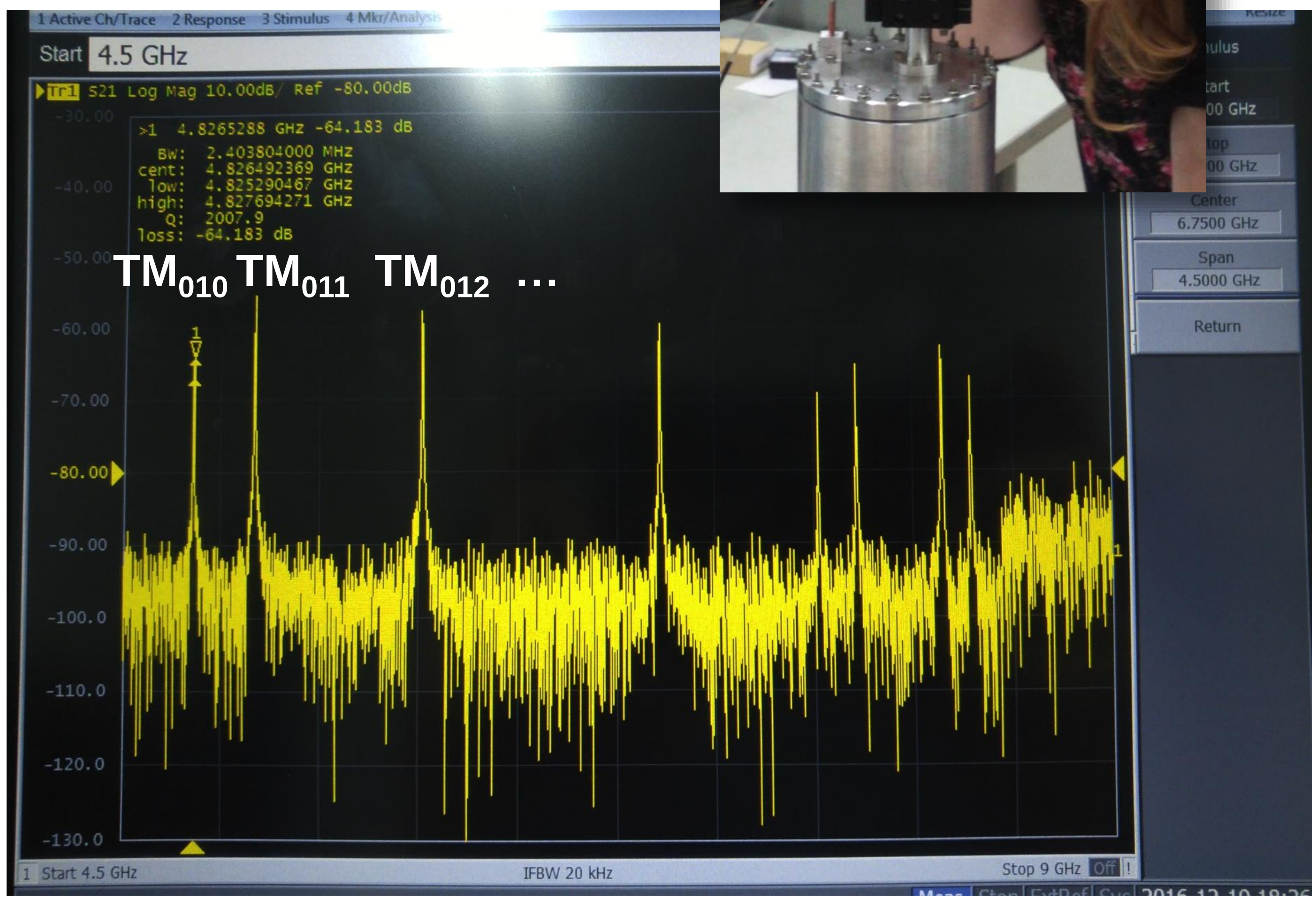
Eli Yablonovitch

Photonic Band Gap resonators (II)

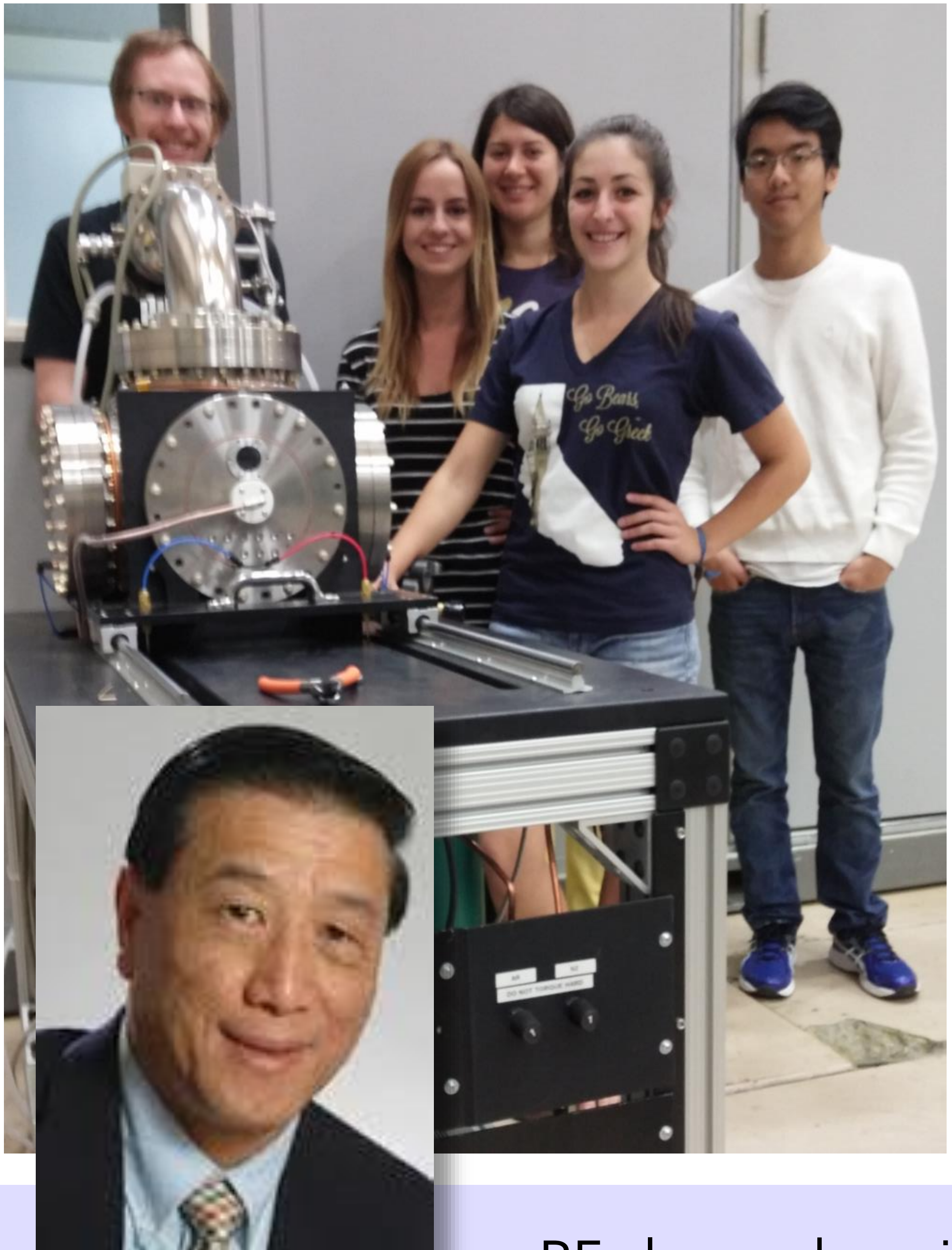


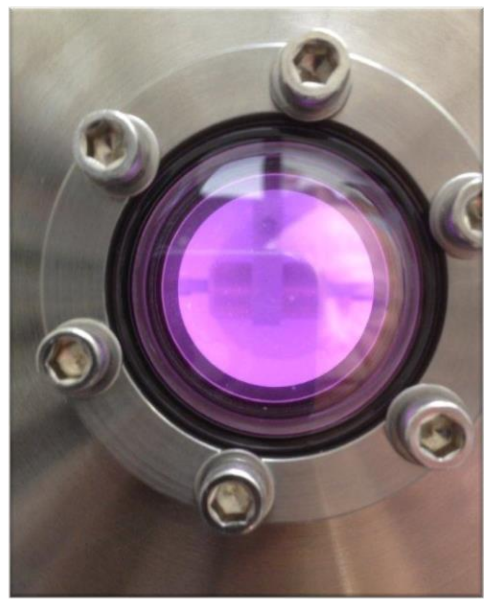
No TE modes in evidence, but more studies being done; next step is to make the resonator tunable





Development of cavities with thin film coatings of Type-II superconductors, e.g. $Nb_xTi_{1-x}N$ by RF plasma deposition

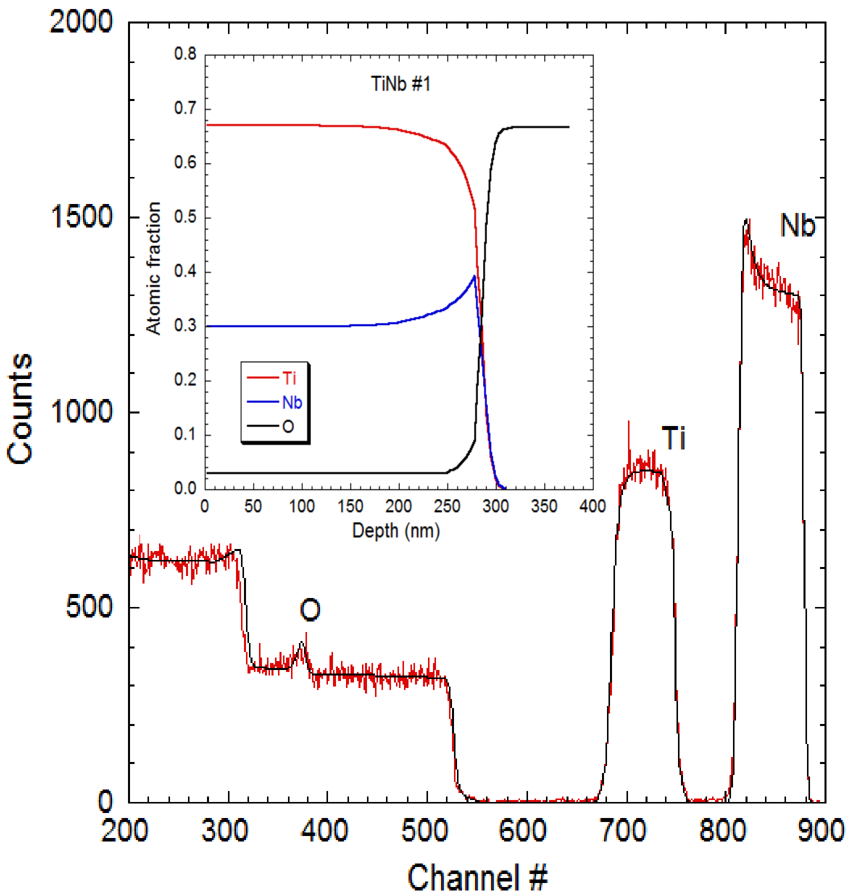


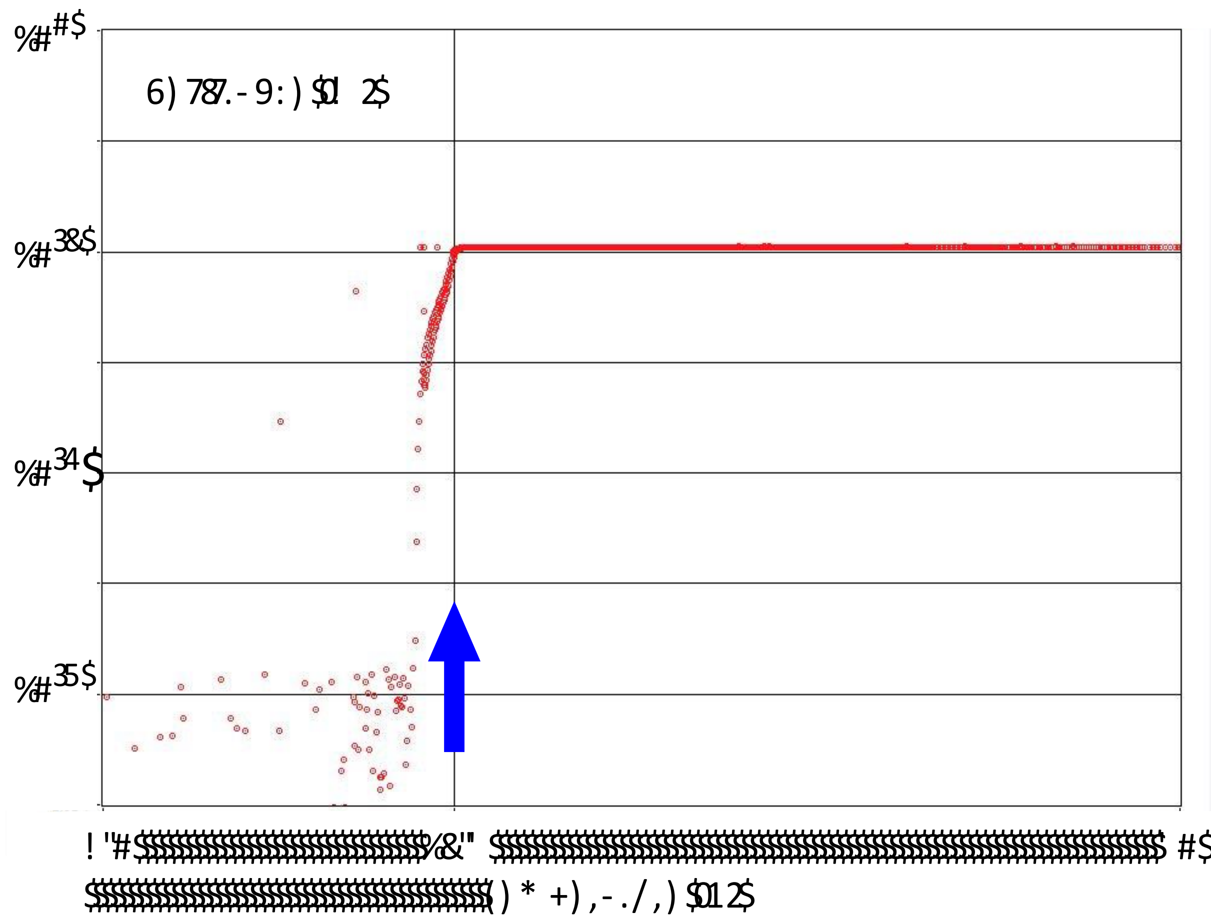


RF plasma deposition technology pioneered by Ka-Ngo Leung

Thin films of the desired stoichiometry, thickness and transition temperature have been successfully made – RF cavity prototype is next

$Nb_{0.30}Ti_{0.67}O_{0.03}$: 280 nm

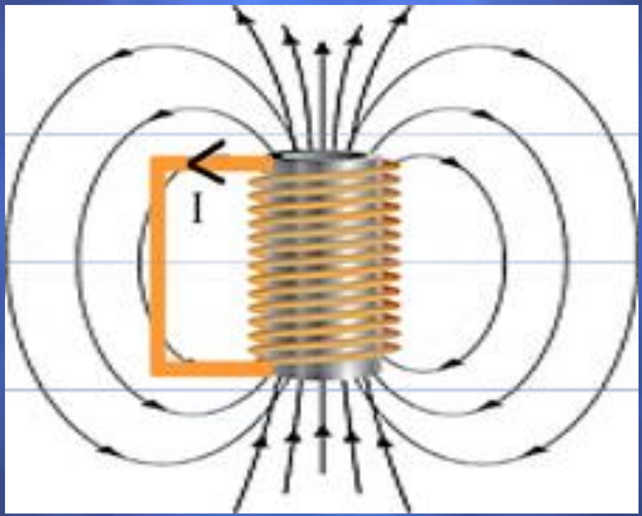




Final provocative thought (*"Throw deep, Mr. President"**)

Imagine you continuously convert all the dark matter within the de Broglie wavelength of your detector into RF power.

$\lambda_{\text{de Broglie}}$



Persistent superconducting magnet

$V_{virial} \sim 10^{-3}\,c$

It's about a Megawatt. Now there's a challenge worthy of our brilliant Berkeley NE students !

* Ken Stabler, when asked by President Ronald Reagan whether the US should build the SSC