SSI 2026: Quantum Probes for a Quantum Universe: Cavities & Experiments (a case study on the use of quantum enhancement)

Danielle H. Speller (Johns Hopkins University)

SLAC Summer Institute

August 10-14, 2026

Johns Hopkins University

Overview: Cavities and Experiments

- Context/Recap
- Cavities
- Highlight: Select quantum enhanced cavity searches
- Summary

Dark Matter

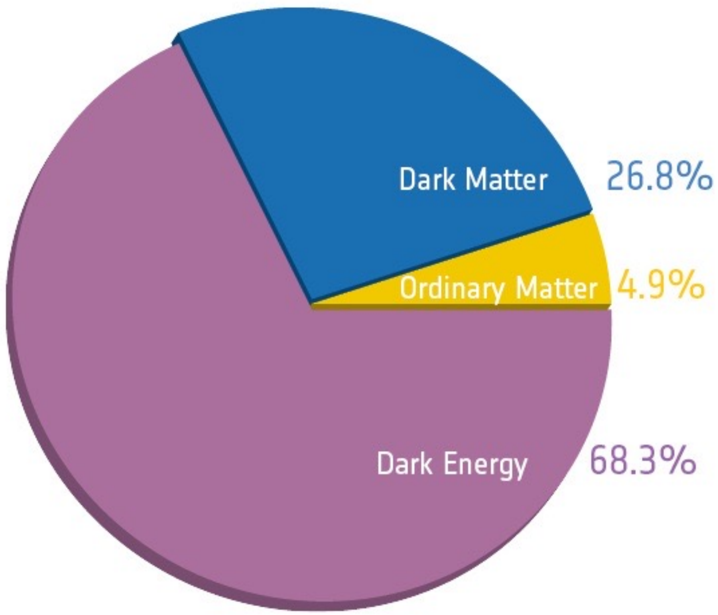


Image Credit: ESA/Planck

- Massive
- Abundant
- Stable
- Neutral
- Cold/non-relativistic
- Weakly/feebly interacting

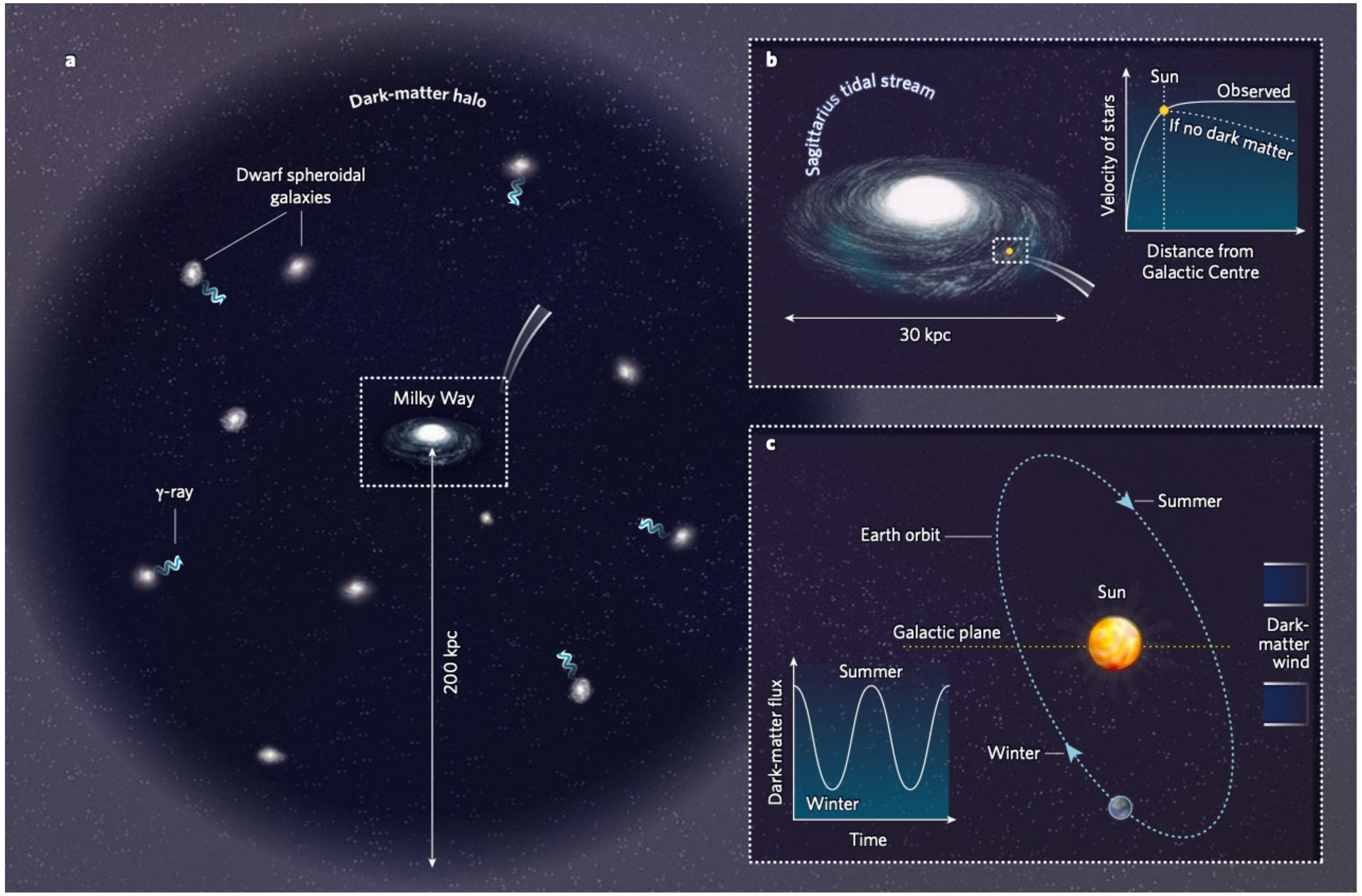


Image: Caldwell & Kamionkowski (2009)

... But what is it?

WIMPS, axions, and other possibilities

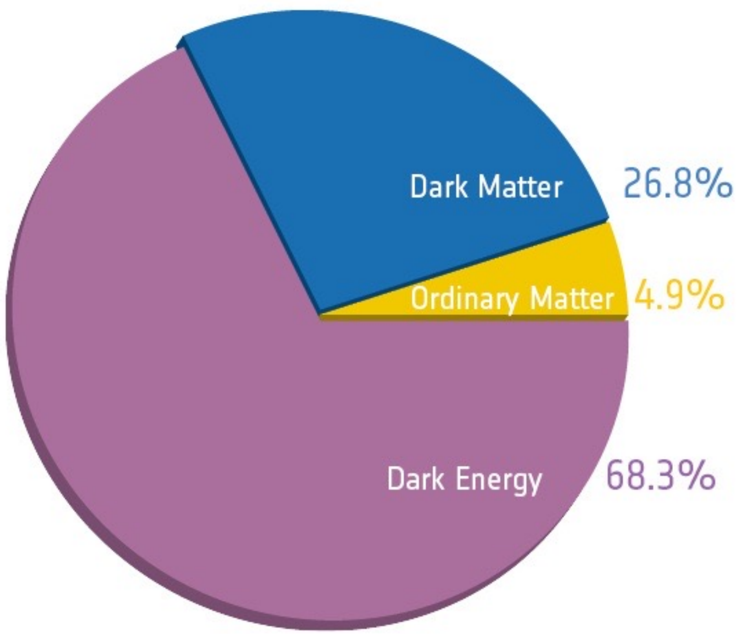


Image Credit: ESA/Planck

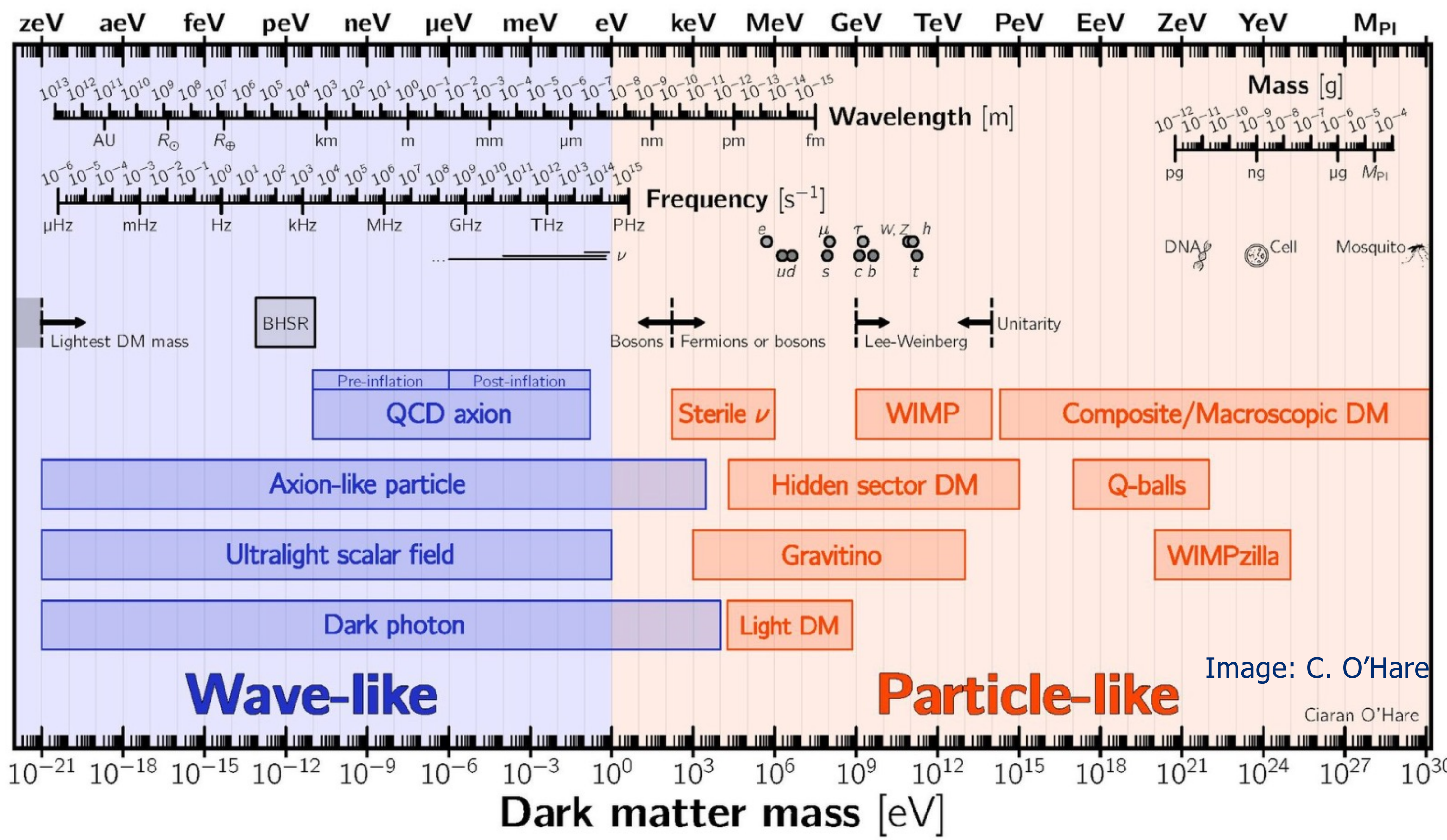


Image: C. O'Hare

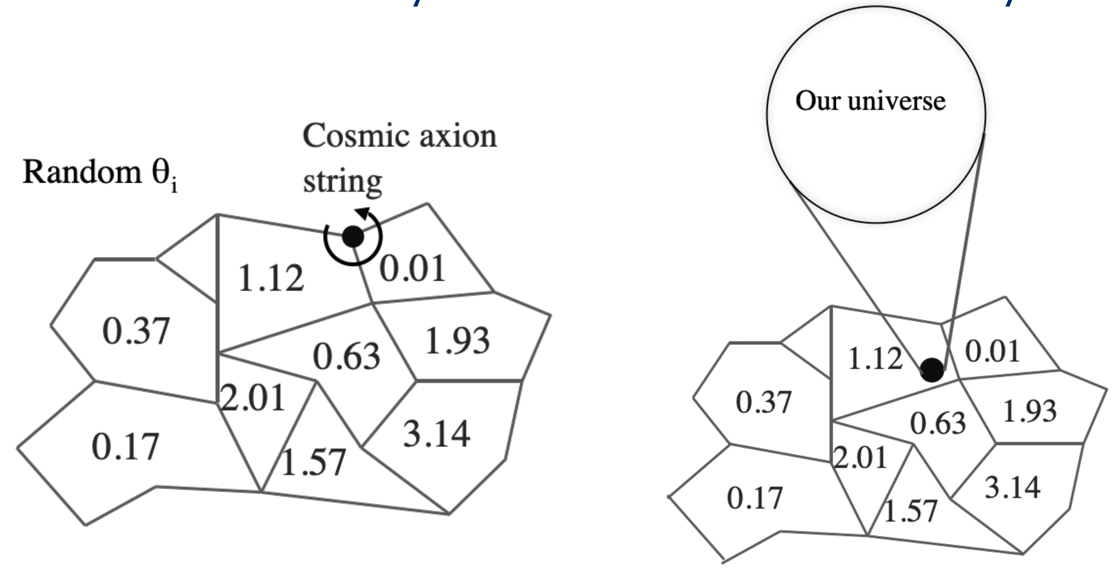
Low mass

High mass

Axions as Dark Matter

- Naturally produced in string theory descriptions of cosmology
- QCD Axion may simultaneously be dark matter and address the strong-CP problem
- If the axion is generated ***after*** inflation, There is a unique mass that gives mass to the observed dark matter abundance.
- **Pre-inflationary models** describe masses on the order of ≲ 1 μeV
- **Post-inflationary** axion models favor masses in the range **30-300 μeV**
- *The calculations are hard to do and the measurements are hard to make (*most QCD axion constraints are <20 μeV*)

Pre-inflationary Post-inflationary



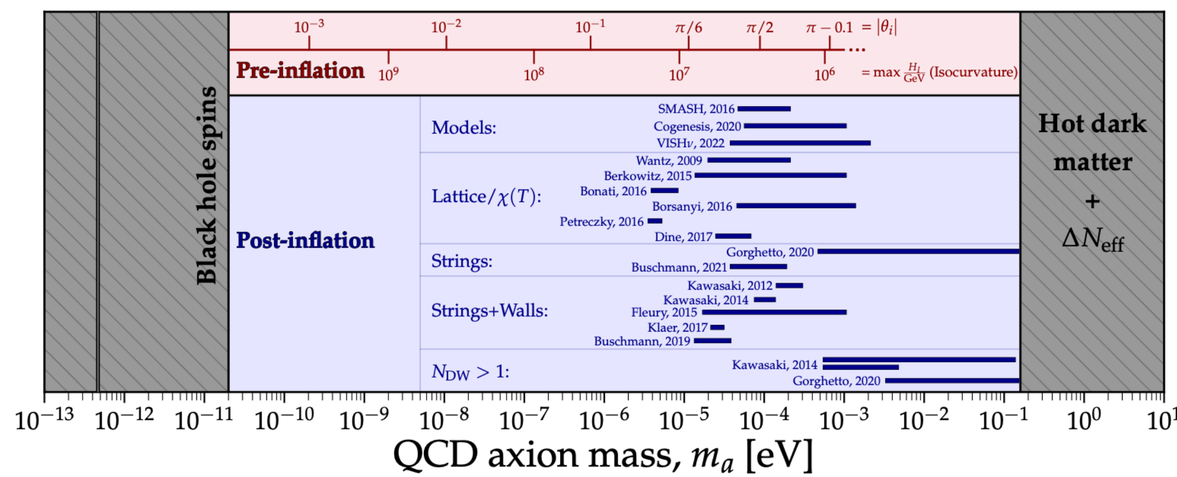


Image: PDG

Axion-Standard Model Interactions

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F_{\mu\nu} + g_{aNN} (\partial_\mu) \bar{N} \gamma^\mu \gamma_5 N + g_{aee} (\partial_\mu) \bar{e} \gamma^\mu \gamma_5 e$$

Coupling to Photons

(The approach of most cavity experiments)

Coupling to Nucleon EDM

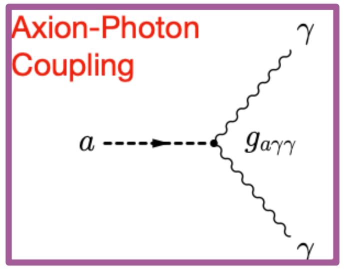
Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

Slide: adapted from L. Winslow, Y.Kahn. See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Axion mass and coupling

- The axion-photon-photon interaction term can be rewritten in terms of electric field ***E*** and magnetic field ***B*** :



$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

- **Brief note/reminder**: this can be written in terms of the symmetry breaking scale for the axion field, f_a:

$$\mathcal{L}_{a\gamma\gamma} = \frac{g_\gamma}{4} \frac{\alpha}{\pi} \frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

where g_γ is a dimensionless, model-dependent coupling factor and α is the fine structure constant. Consequently, $g_{a\gamma\gamma}$ is proportional to $1/f_a$ (and suppressed for large values):

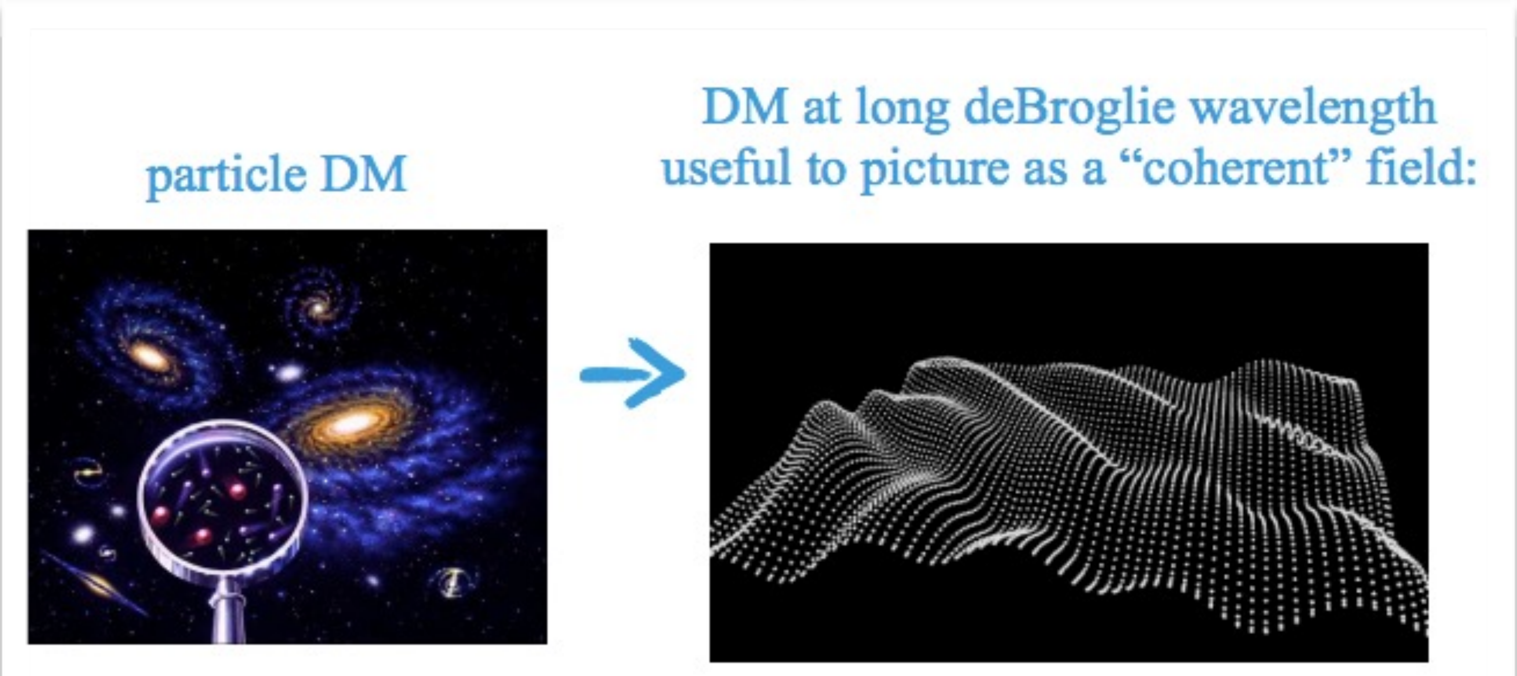
$$g_{a\gamma\gamma} = \frac{g_\gamma \alpha}{\pi f_a}$$

**One may find quantities expressed in terms of either coupling factor; this is the means of converting between them.*

For a nice overview, see Kimball & van Bibber, et. al, The Search for Ultralight Bosonic Dark Matter, *Springer (2021)*

Haloscopes: The Axion-Photon Coupling & the Primakoff Interaction

- For ultralight particles like nonrelativistic axions, the deBroglie wavelength is long – you can treat as a coherent field



P. Graham, UCLA Dark Matter (2018)

Haloscopes: The Axion-Photon Coupling & the Primakoff Interaction

- With a strong magnetic field acting as a sea of virtual photons, the axion-photon coupling can be used to convert axions (or axion-like particles, aka ALPs) into photons in the presence of the field. This is usually referred to as the “Inverse Primakoff Interaction”

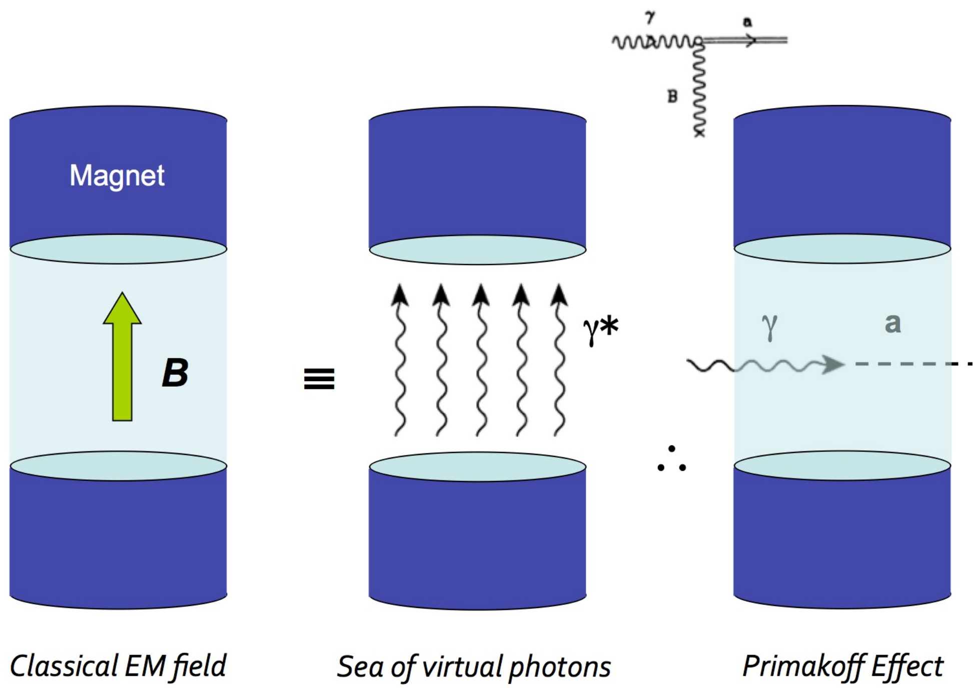
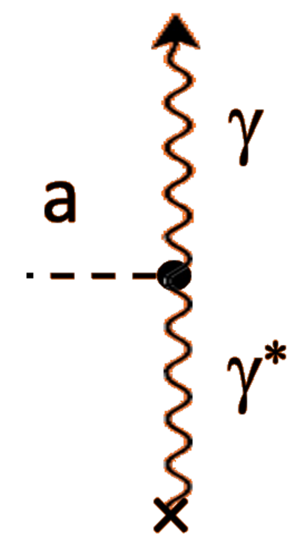


Figure: Semertzidis & Youn, Sci. Adv. 8 (2022)

Inverse Primakoff:



Haloscopes: The Axion-Photon Coupling & the Primakoff Interaction

- The oscillating E field (the proton produced in the interaction) can be detected. In traditional haloscopes, a microwave cavity is used to resonantly enhance the signal

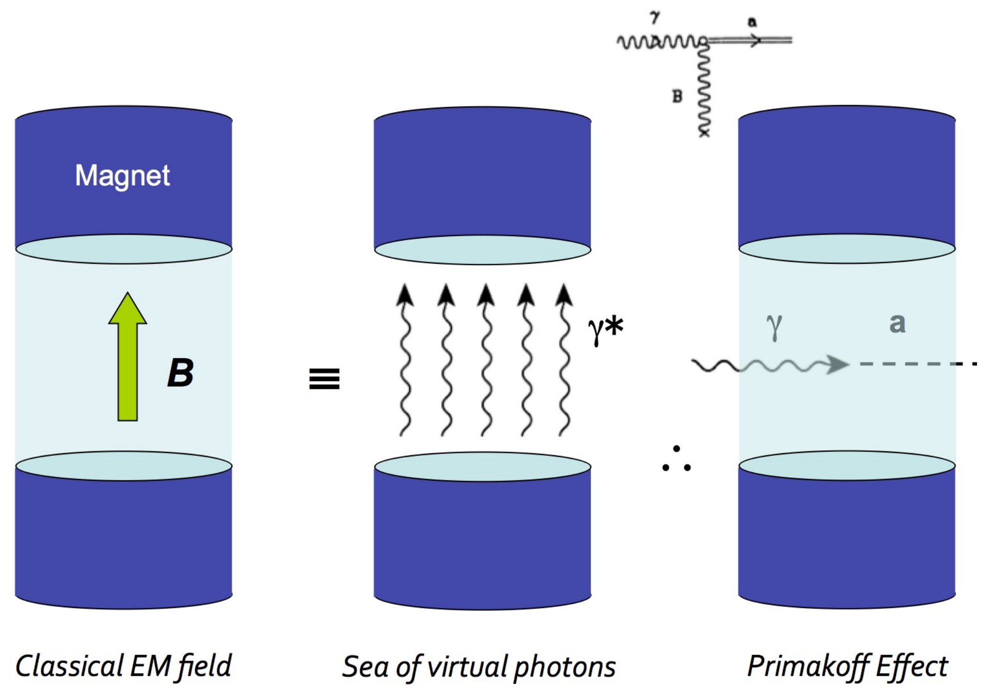
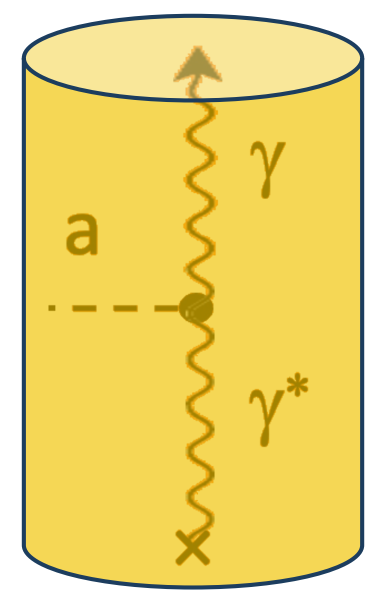


Figure: Semertzidis & Youn, Sci. Adv. 8 (2022)

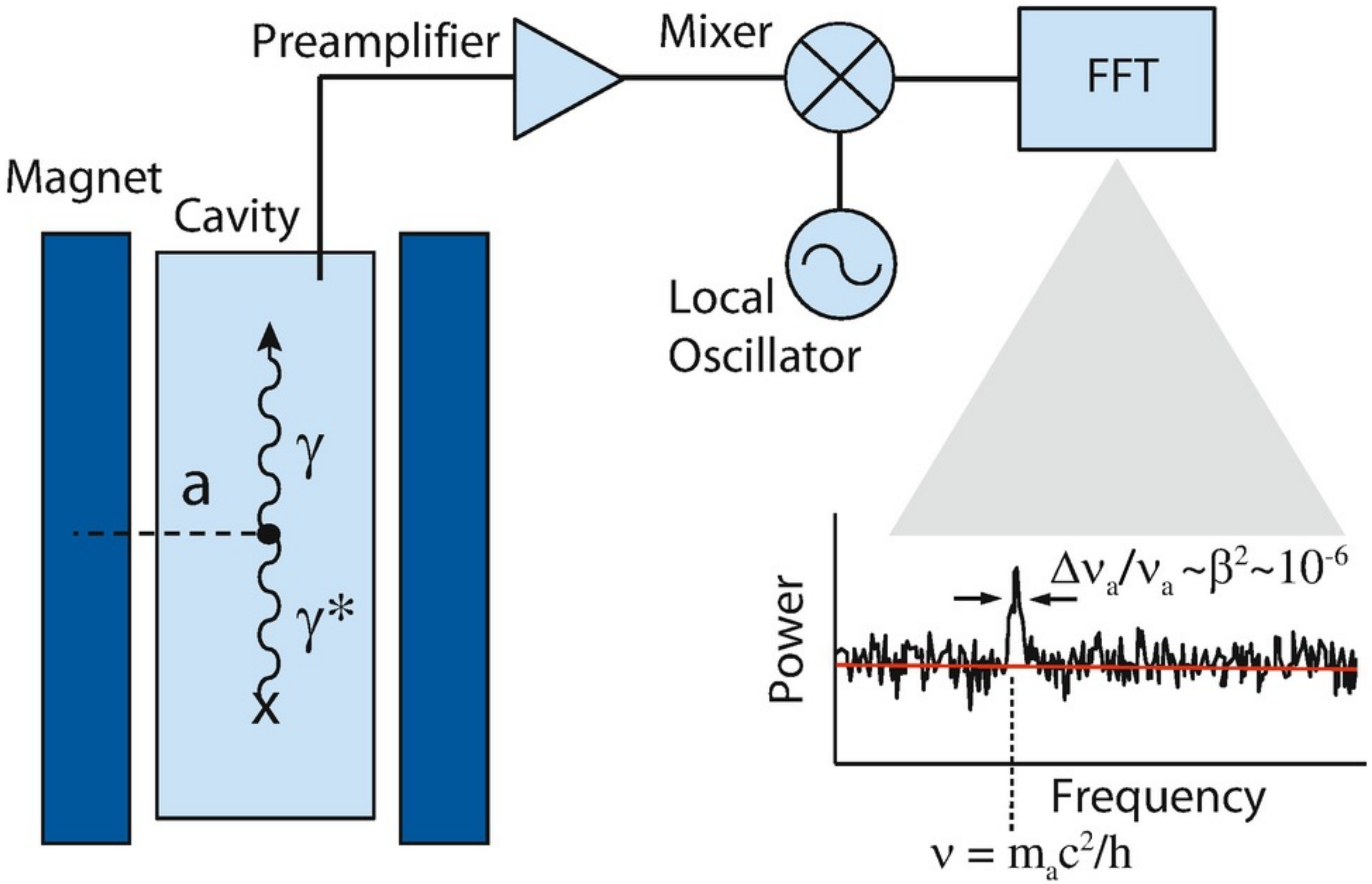
Inverse Primakoff:



$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

Searching for Axions: The Sikivie Haloscopes

Since axions are wave-like, we measure frequency!

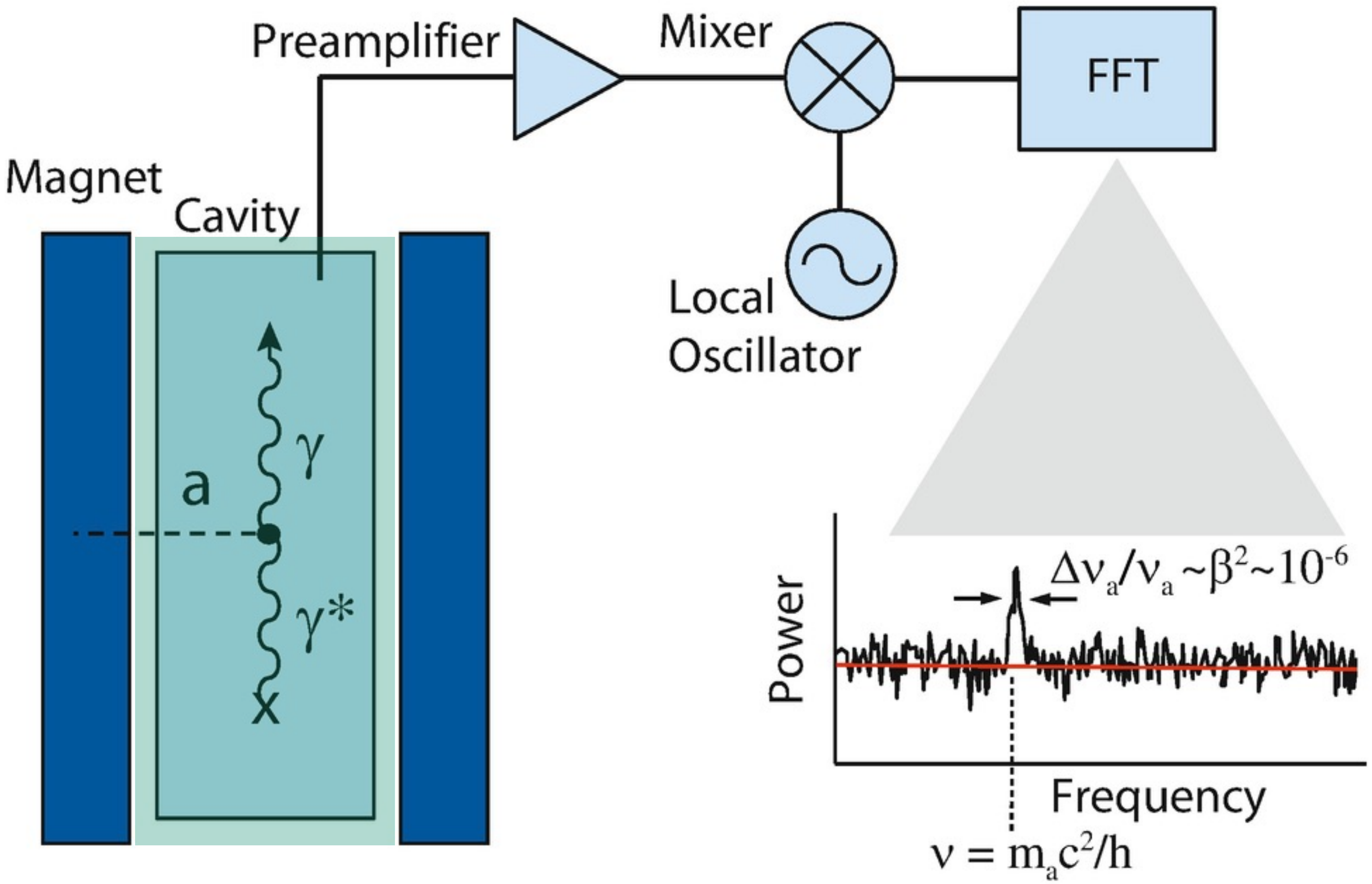


Microwave Cavities and Detectors for Axion Research pp 67-73 S. Lewis

Searching for Axions: The Sikivie Haloscopes

Since axions are wave-like, we measure frequency!

High quality resonator

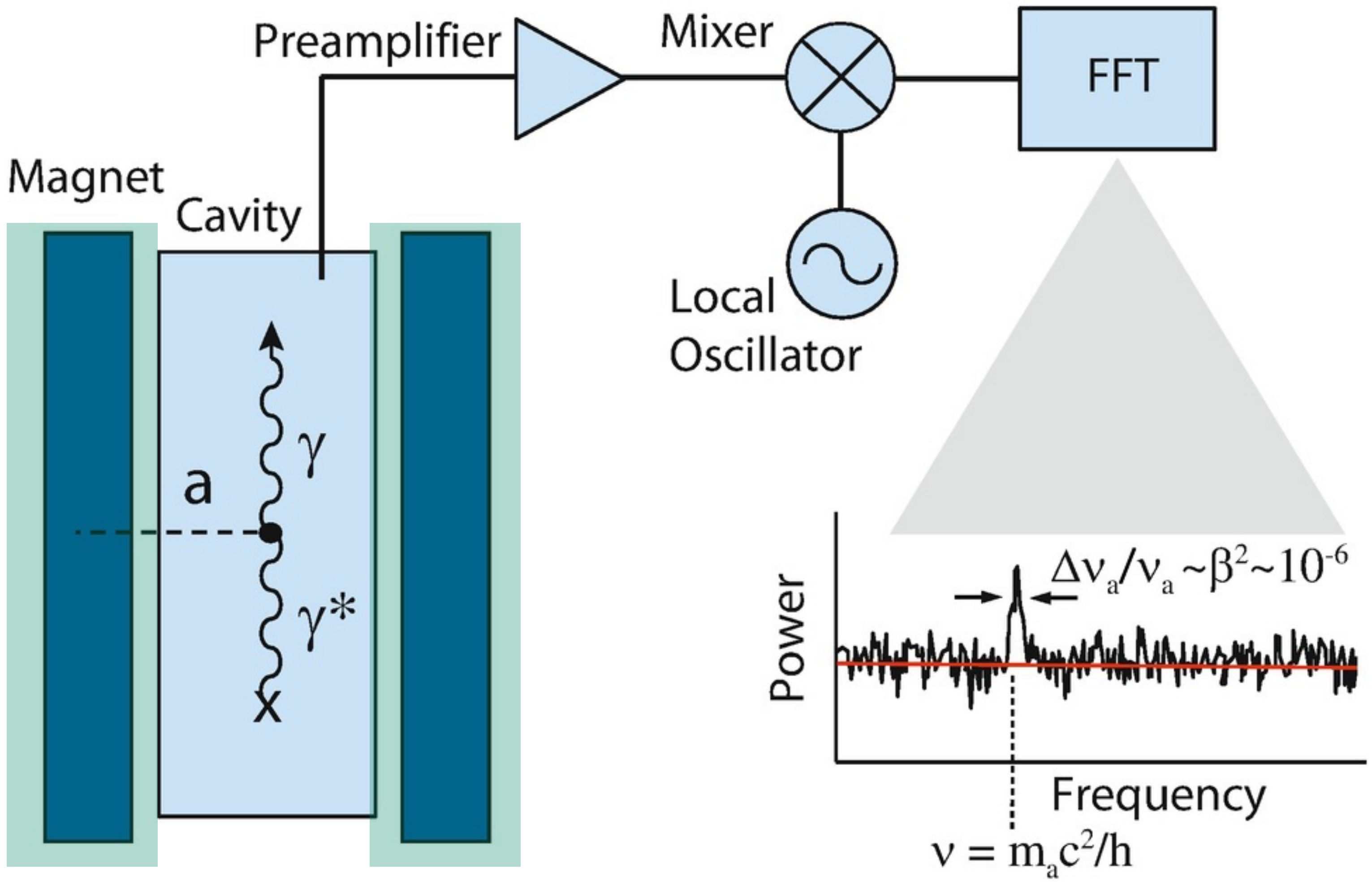


[Microwave Cavities and Detectors for Axion Research](#) pp 67-73 S. Lewis

Searching for Axions: The Sikivie Haloscopes

Since axions are wave-like, we measure frequency!

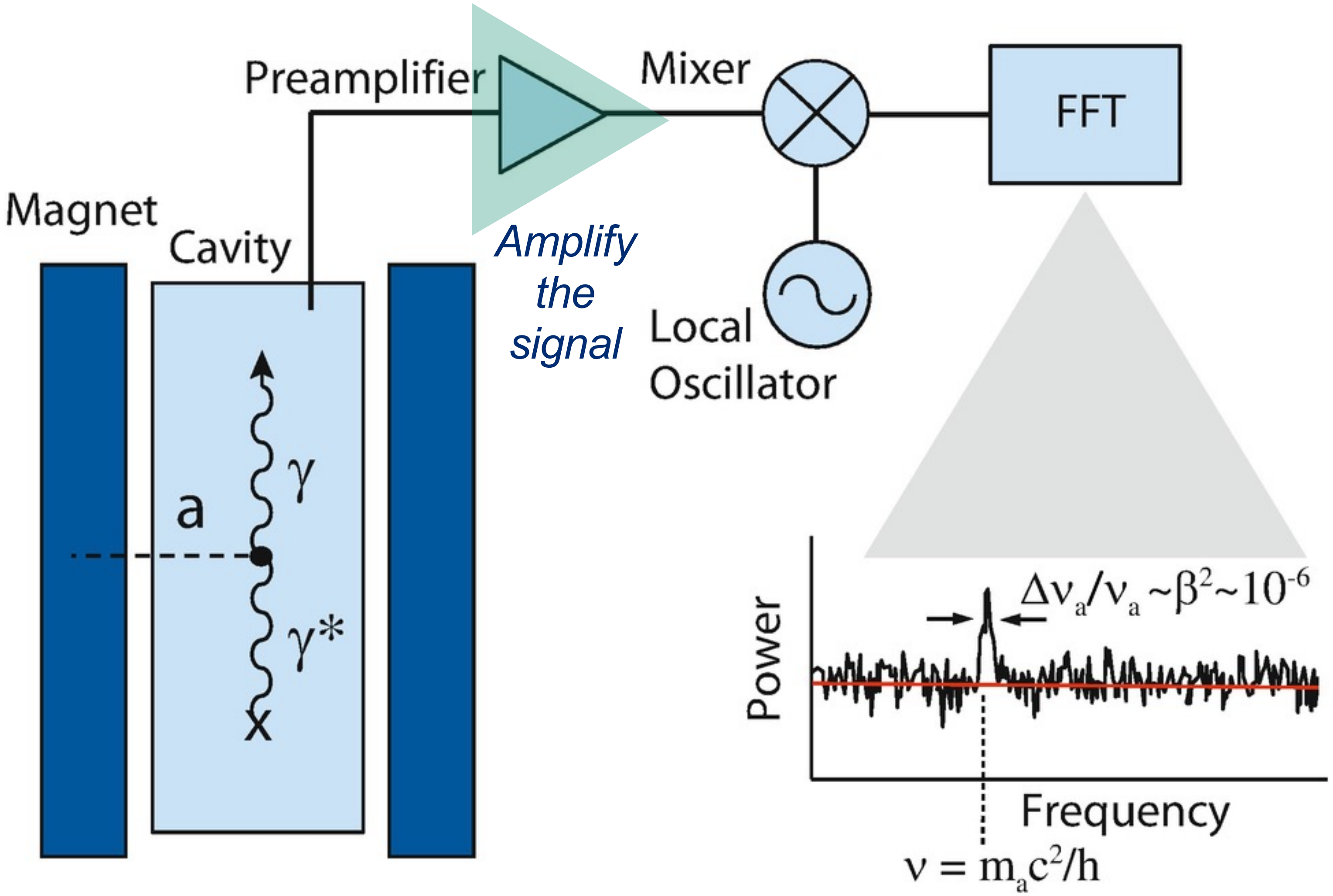
Strong external magnetic field



Microwave Cavities and Detectors for Axion Research pp 67-73 S. Lewis

Searching for Axions: The Sikivie Haloscopes

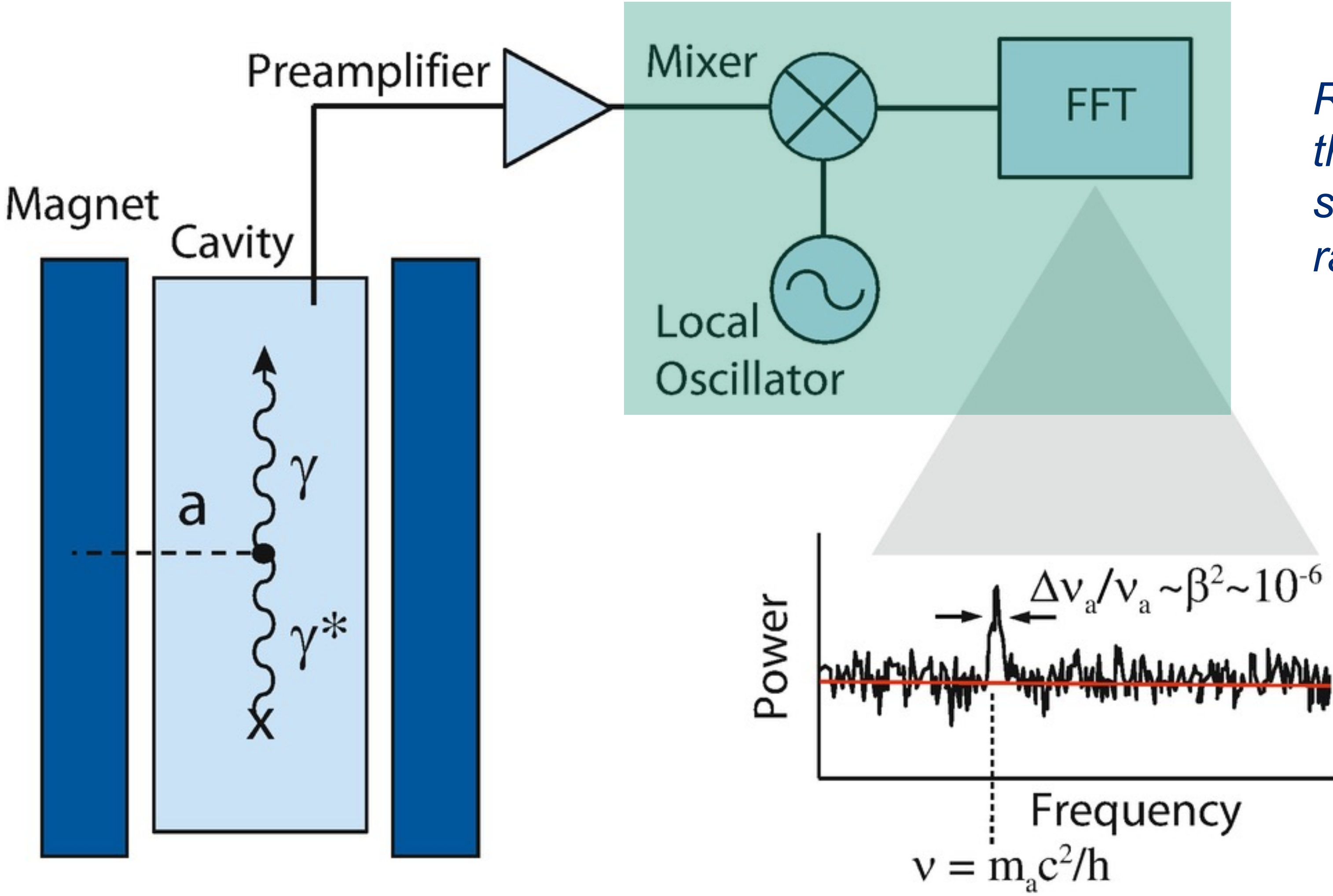
Since axions are wave-like, we measure frequency!



Microwave Cavities and Detectors for Axion Research pp 67-73 S. Lewis

Searching for Axions: The Sikivie Haloscopes

Since axions are wave-like, we measure frequency!

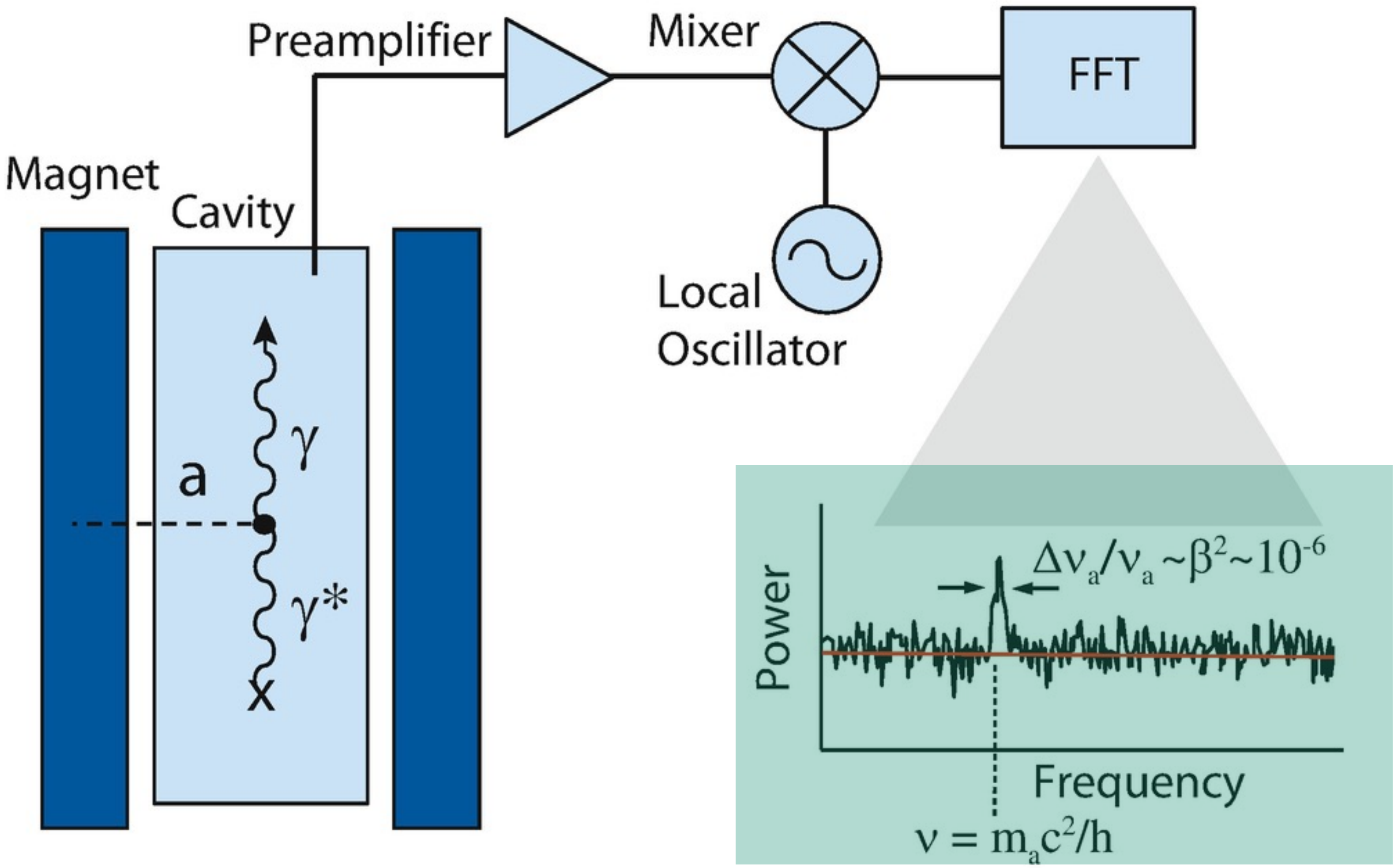


Reduce the sampling rate

Microwave Cavities and Detectors for Axion Research pp 67-73 S. Lewis

Searching for Axions: The Sikivie Haloscopes

Since axions are wave-like, we measure frequency!



Analyze the signal

Microwave Cavities and Detectors for Axion Research pp 67-73 S. Lewis

Traditional Cavity Experiments

The earliest haloscopes and the majority of operating cavity experiments rely on some variation of the traditional cylindrical conducting microwave cavity design.

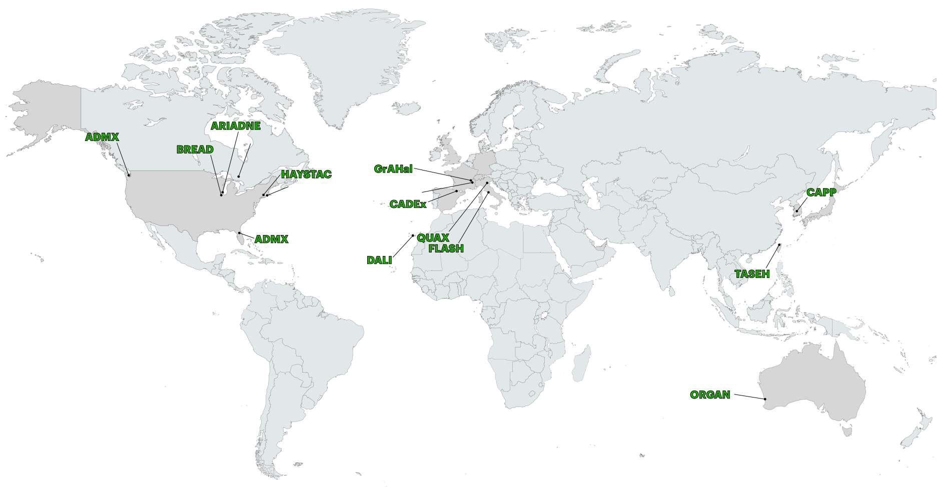


Image modifed from
https://cajohare.github.io/AxionLimits/

RBF (Rochester-Brookhaven-Fermilab)

UF (University of Florida)

ADMX (the Axion Dark Matter eXperiment)

HAYSTAC (the Haloscope at Yale Sensitive to Axion CDM)

CAPP (Center for Axion and Precision Physics Research) – e.g. CAPP-Max

QUAX-LNF (QUest for AXions – Laboratori Nazionali di Frascati)

GrAHal (Grenoble Axion Haloscope)

TASEH (Taiwan Axion Search Experiment with Haloscope)

CADEX (Canfranc Axion Detection Experiment)

FLASH (FINUDA magnet for Light Axion Search experiment) (proposed)

*not exclusive!

Traditional Cavity Experiments

The earliest haloscopes and the majority of operating cavity experiments rely on some variation of the traditional cylindrical conducting microwave cavity design.

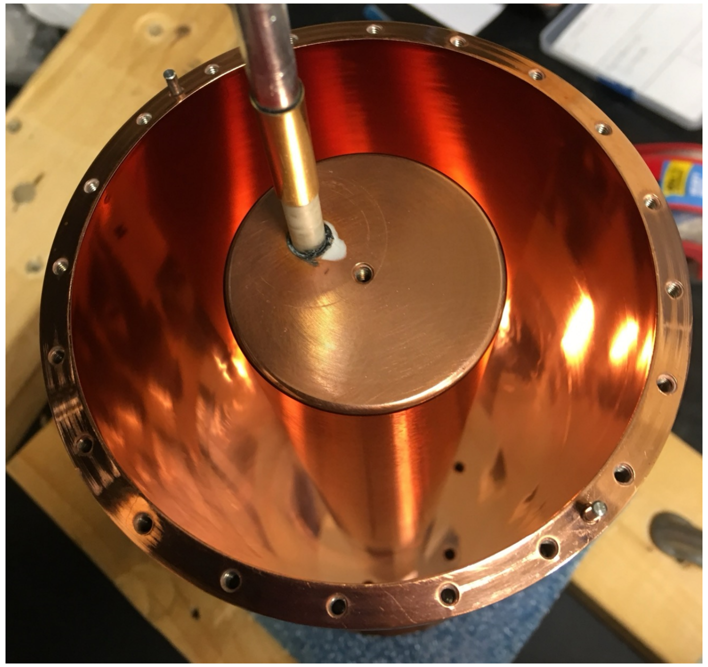


Image: the HAYSTAC Collaboration

RBF (Rochester-Brookhaven-Fermilab)

UF (University of Florida)

ADMX (the Axion Dark Matter eXperiment)

HAYSTAC (the Haloscope at Yale Sensitive to Axion CDM)

CAPP (Center for Axion and Precision Physics Research) – e.g. CAPP-Max

QUAX-LNF (QUest for AXions – Laboratori Nazionali di Frascati)

GrAHal (Grenoble Axion Haloscope)

TASEH (Taiwan Axion Search Experiment with Haloscope)

CADEX (Canfranc Axion Detection Experiment)

FLASH (FINUDA magnet for Light Axion Search experiment) (proposed)

Conversion power

- Recall…

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

- When an appropriate cavity mode frequency ω equals the mass of an axion, the axion can convert to the excitations (photons) of that cavity mode (with some linewidth corresp. to energy spread).

Velocity of galactic halo axions

$$v \sim 10^{-3} c \rightarrow \text{energy} \propto \frac{v^2}{c^2} \sim 10^{-6}$$

Energy spread of axion→ linewidth

- For a resonator of volume *V* permeated by a static magnetic field (the external $\mathbf{B}_0$ pointing in the z-direction) and the axion field, we're interested in the coupling of the axion field to a given cavity mode. The coupling for a given mode of frequency ω is roughly

factors

$$[g_{a\gamma\gamma}] a B_0 \int_V d^3x E_\omega(\vec{x}, t) \cdot \hat{z}$$

The magnetic field strength

Integrate over the cavity volume

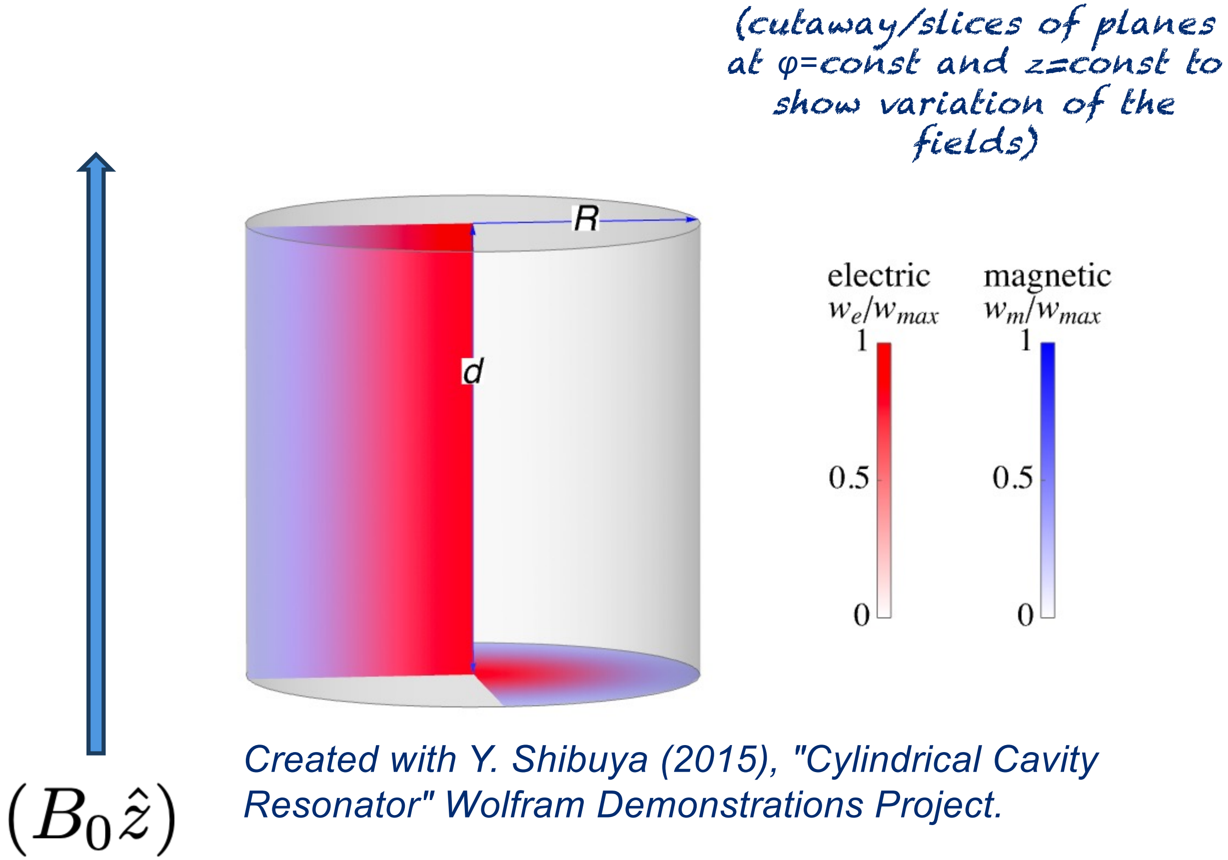
P. Sikivie, PRD 32, 11, p2988-2991 (1985)
P. Sikivie, RevModPhys.93.015004

Conversion Power

- The modes into which the halo axions can convert energy are the TM_{nl0} modes (with $\boldsymbol{E}_\omega$ along the z-direction)

- The mode to which the coupling is strongest is the **TM_{010}** mode*, corresponding to an axion-induced ***E*** field along the axis (parallel to $\boldsymbol{B}_{0,ext}$) and a transverse magnetic field component.

- This is the mode targeted by most traditional cavity experiments. The coupling is ultimately encoded in the "form factor", C_{mnl}



Created with Y. Shibuya (2015), "Cylindrical Cavity Resonator" Wolfram Demonstrations Project.

$$C \equiv \frac{1}{B_0^2 V} \frac{\left[\int_V d^3x \vec{B}_0(\vec{x}) \cdot \vec{E}_\alpha(\vec{x})\right]}{\int_V d^3x \epsilon(\vec{x}) \vec{E}_\alpha(\vec{x}) \cdot \vec{E}_\alpha(\vec{x})}$$

With tuning rods, the cavity is "TM_{010}-like" (mode is affected)

**C is typically estimated/numerically evaluated*

Conversion Power

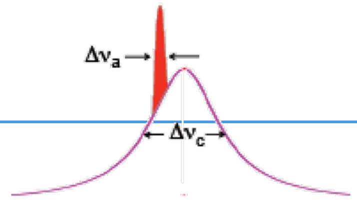
- From the coupling of the axion field to the cavity mode, one can obtain the power on resonance from the axion to photon conversion. For a cylindrical cavity,

$$P \sim g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B^2 Q_C V C_{nml}$$

where ρ_a and m_a are the local dark matter density and axion mass, respectively, and where Q_C is the quality factor of the cavity.

P. Sikivie, PRD 32, 11, p2988-2991 (1985)
P. Sikivie, RevModPhys.93.015004

Detecting the Axion

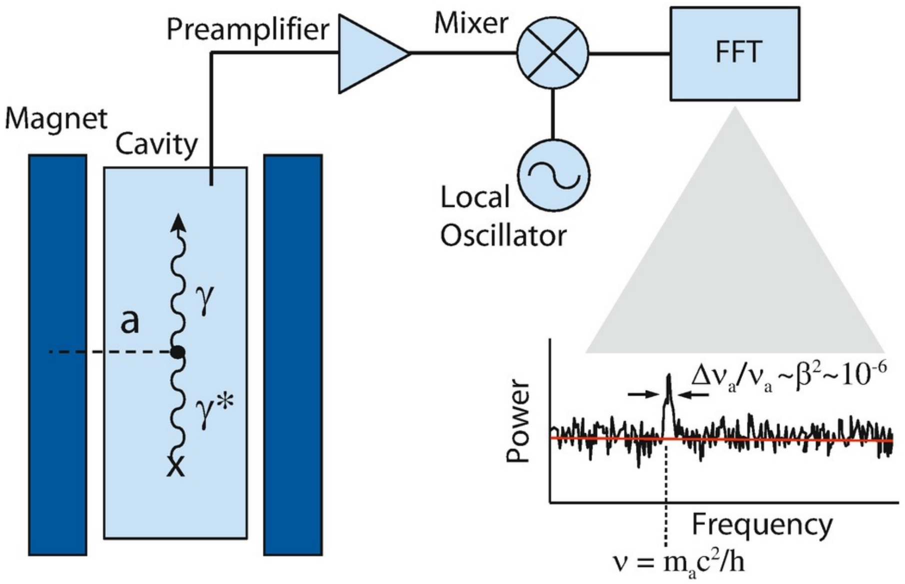


The Dicke Radiometer Equation:

$$SNR = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

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

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



$$P \sim g^2_{a\gamma\gamma}\left(\frac{\rho_a}{m_a}\right)B^2 Q_C V C_{nml}$$

Sikivie's Haloscope

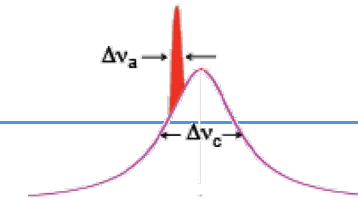
$$kT_S = h\nu\left(\frac{1}{e^{h\nu/kT}-1} + \frac{1}{2}\right) + kT_A$$

$$(T_S \approx T + T_A, \text{for } T >> h\nu)$$

System Noise Temperature

P. Sikivie, PRD 32, 11, p2988-2991 (1985)
P. Sikivie, RevModPhys.93.015004

Detecting the Axion

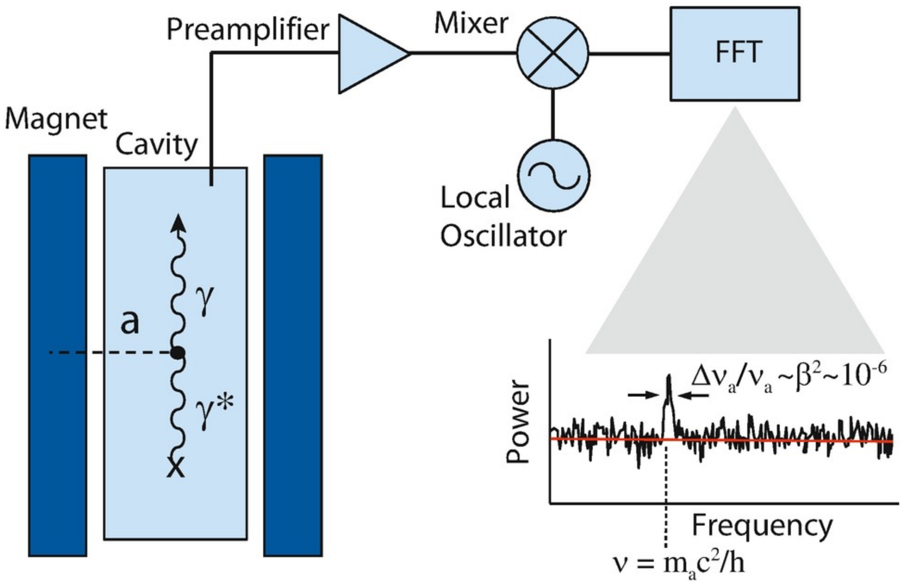


The Dicke Radiometer Equation:

$$SNR = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

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

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



$$P \sim g_{a\gamma\gamma}^2\left(\frac{\rho_a}{m_a}\right)B^2 Q_C V C_{nml}$$

Sikivie's Haloscope

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

System Noise Temperature

$$(T_S \approx T + T_A, \text{for } T >> h\nu)$$

The Goal:

- *Optimize the conversion power*
- *Minimize the system noise temperature***

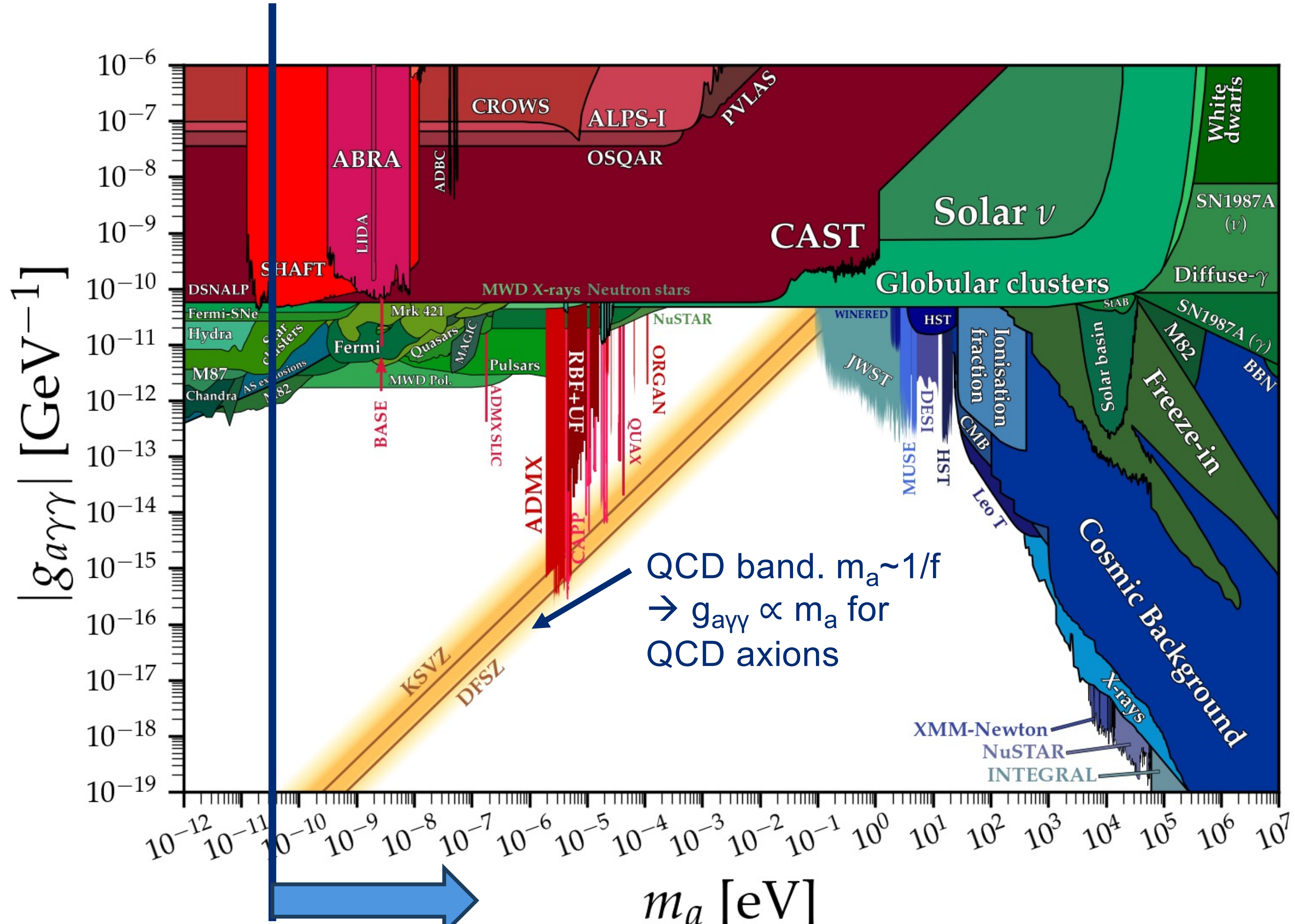
P. Sikivie, PRD 32, 11, p2988-2991 (1985)
P. Sikivie, RevModPhys.93.015004

Detecting the Axion

- We don't actually know the mass: Need to scan through parameter space
- Requires:
  - Tunability
  - Efficient scan rate
- **Figure of merit**: Scan Rate

$$\frac{d\nu}{dt} \propto (\mathrm{SNR})^2$$

Smaller coupling → smaller power, better SNR required



Unknown axion mass → requires ability to tune & scan

Image: adapted from C. O'Hare

Detecting the Axion

- For a given SNR, the scan rate corresponding to the minimum integration time needed per cavity bandwidth can be given as:

Scan Rate:
$$\frac{d\nu}{dt} \propto \left(\frac{g_\gamma^4}{SNR'^2}\right)\left(\frac{\rho_a^2 Q_a}{\Lambda^8}\right)\left(\frac{B_0^4 V^2 C_{nml}^2 Q_0}{T_S^2}\right) \propto g_\gamma^4 \frac{\nu^2}{T_S^2} B^4 Q_C^2 V^2 C_{nml}^2$$

- Ongoing R&D to optimize the field, volume, quality factor, cooling, etc.

- *Making T_S as small as possible is one of the critical motivations for incorporation of quantum enhanced sensing – improvement in signal visibility directly contributes to increased scan rate*

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

B. Brubaker, Thesis, 2018
D. Palken, Thesis, 2020
P. Sikivie, RevModPhys.93.015004

Detecting the Axion

- Linear amplifiers are subject to the Standard Quantum Limit (SQL):

$$T_{\text{noise}} > T_{\text{SQL}}$$

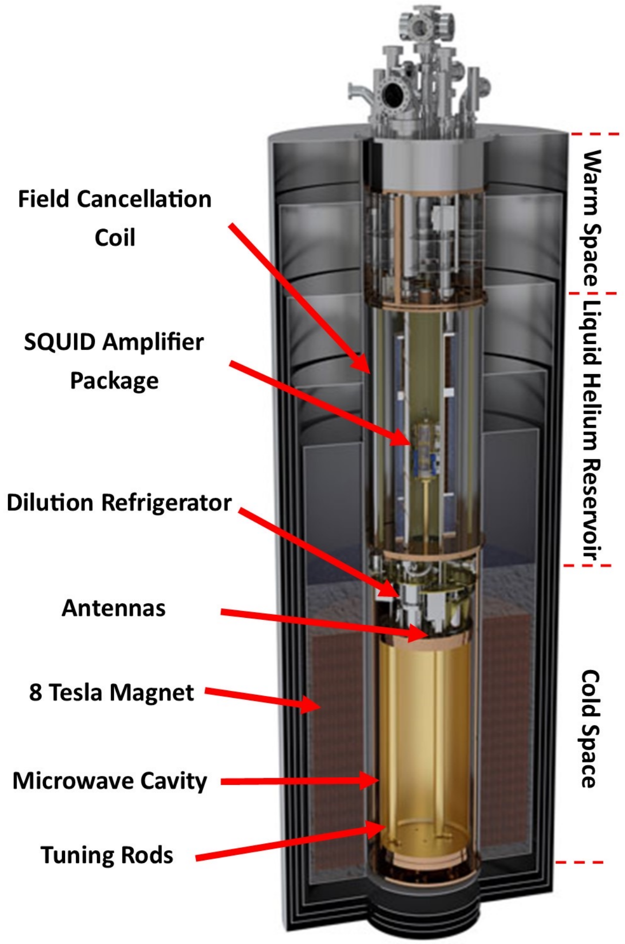
  where

$$k_B T_{\text{SQL}} = h\nu$$

- **Note that this also makes it more difficult to go to higher frequencies (from multiple dependencies, scan rate ultimately scales as $\frac{dv}{dt} \propto v^{-14/3}$)

- Earliest cavity experiments were operating in the regime T >> hv; major improvements by cryogenic cooling & moving to quantum-limited amplifiers

Spotlight: ADMX and HAYSTAC



ADMX

C. Bartram et al., *Phys. Rev. Lett.* 127, 261803, 2021

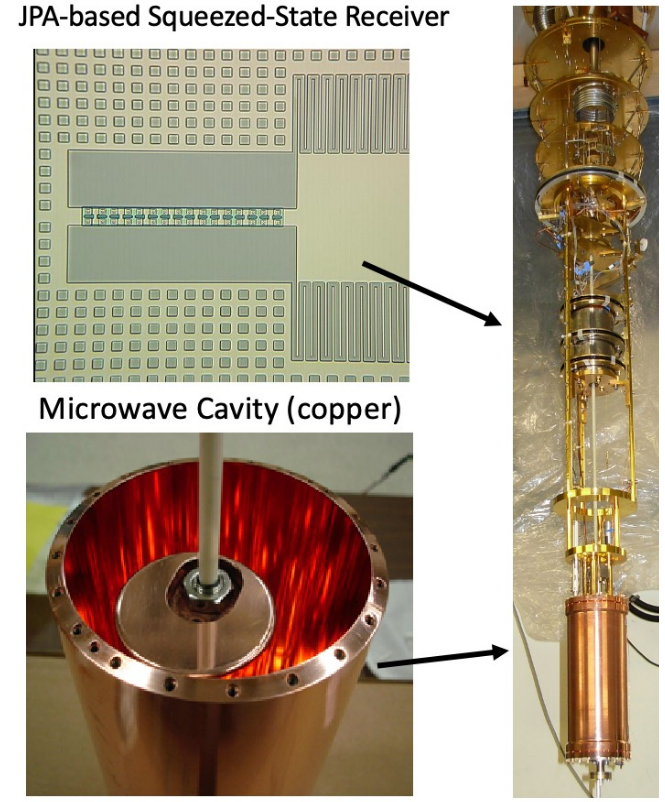
Expected Power (order of magnitude), (e.g. ADMX)

$$P = 5.0 \times 10^{-23}\mathrm{W}\left(\frac{g_\gamma}{0.75}\right)^2\left(\frac{\rho_a}{0.45\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right)\left(\frac{\nu_a}{1\mathrm{GHz}}\right)\left(\frac{B_0}{10\mathrm{T}}\right)^2\left(\frac{V}{30\mathrm{liters}}\right)\left(\frac{G}{0.5}\right)\left(\frac{Q_c}{10^5}\right)$$

Misc. experiments

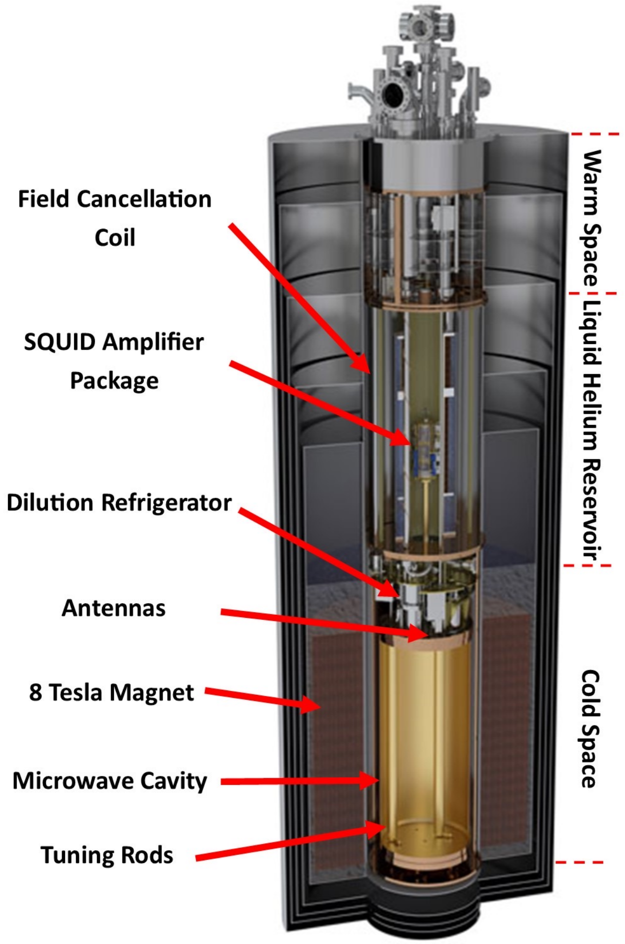
Experiment	Time	Frequency	Volume	Amplifier	Magnet	T_{SYS}/T_{SQL}
RBF [7]/UF [34]	1985–1990	2.5 GHz	5 L	HEMT	6 T/8 T	100–200
ADMX @ LLNL [35]	1995–2010	0.6 GHz	200 L	HEMT, SQUID	7.6 T	50–100
ADMX @ UW [36]	2016-present	0.8 GHz	150 L	SQUID, JPA	7.6 T	10
CAPP [37]	2019-present	1.6 GHz	3.5 L	HEMT	8 T	12
HAYSTAC I [38]	2015–2018	6 GHz	1.5 L	JPA	9 T	2
HAYSTAC II [28]	2019-present	4 GHz	1.5 L	SSR	8 T	<1

Simanovskaia et al (2021)



HAYSTAC

Spotlight: ADMX and HAYSTAC



ADMX

C. Bartram et al., *Phys. Rev. Lett.* 127, 261803, 2021

Expected Power (order of magnitude), (e.g. ADMX)

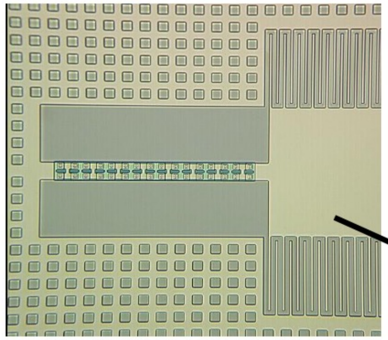
$$P = 5.0 \times 10^{-23}\mathrm{W}\left(\frac{g_\gamma}{0.75}\right)^2\left(\frac{\rho_a}{0.45\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right)\left(\frac{\nu_a}{1\mathrm{GHz}}\right)\left(\frac{B_0}{10\mathrm{T}}\right)^2\left(\frac{V}{30\mathrm{liters}}\right)\left(\frac{G}{0.5}\right)\left(\frac{Q_c}{10^5}\right)$$

Misc. experiments

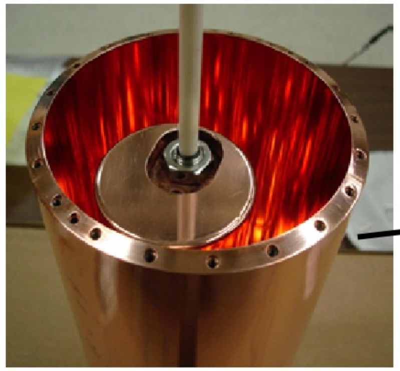
Experiment	Time	Frequency	Volume	Amplifier	Magnet	T_{SYS}/T_{SQL}
RBF [7]/UF [34]	1985–1990	2.5 GHz	5 L	HEMT	6 T/8 T	100–200
ADMX @ LLNL [35]	1995–2010	0.6 GHz	200 L	HEMT, SQUID	7.6 T	50–100
ADMX @ UW [36]	2016-present	0.8 GHz	150 L	SQUID, JPA	7.6 T	10
CAPP [37]	2019-present	1.6 GHz	3.5 L	HEMT	8 T	12
HAYSTAC I [38]	2015–2018	6 GHz	1.5 L	JPA	9 T	2
HAYSTAC II [28]	2019-present	4 GHz	1.5 L	SSR	8 T	<1

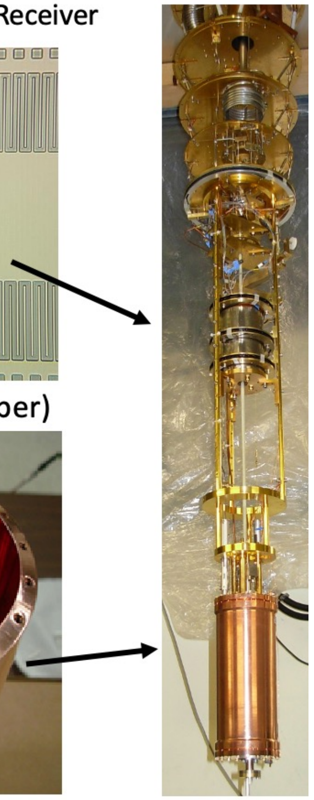
Simanovskaia et al (2021)

JPA-based Squeezed-State Receiver



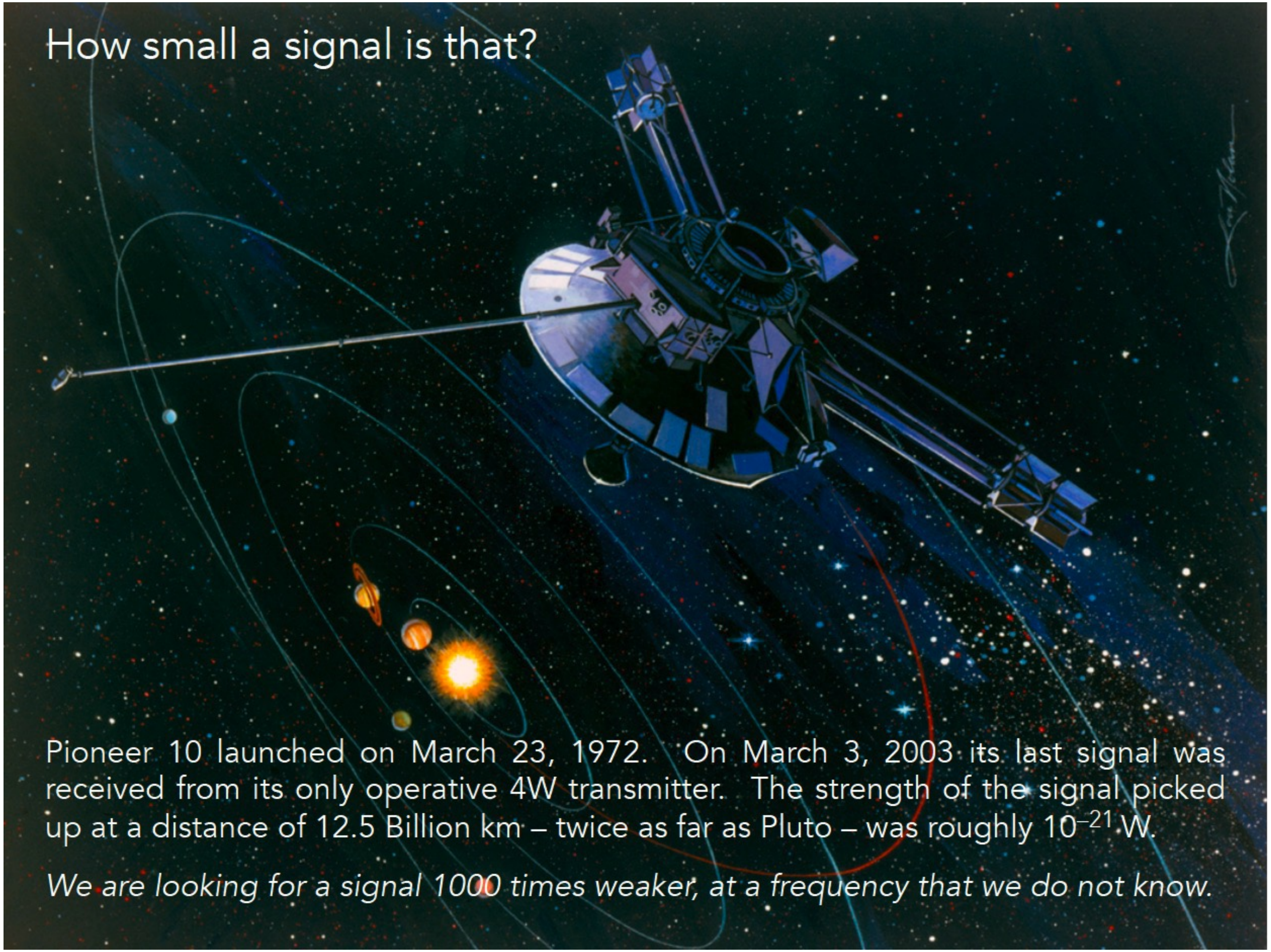
Microwave Cavity (copper)





HAYSTAC

How small a signal is that?

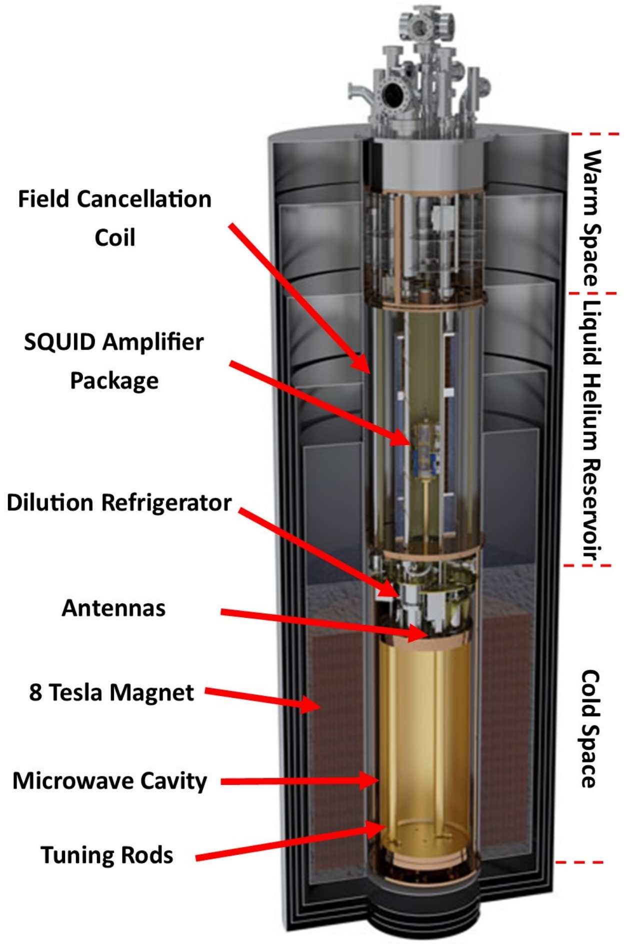


Pioneer 10 launched on March 23, 1972. On March 3, 2003 its last signal was received from its only operative 4W transmitter. The strength of the signal picked up at a distance of 12.5 Billion km – twice as far as Pluto – was roughly 10^{-21} W.

We are looking for a signal 1000 times weaker, at a frequency that we do not know.

Slide: K. van Bibber, *Quantum Connections* (2024)

Spotlight: ADMX and HAYSTAC



ADMX

C. Bartram et al., *Phys. Rev. Lett.* 127, 261803, 2021

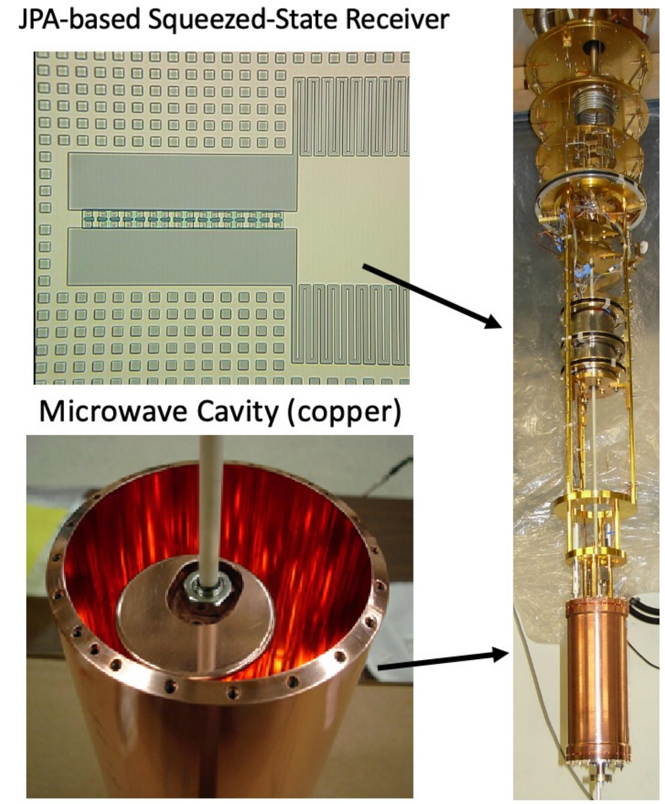
Expected Power (order of magnitude), (e.g. ADMX)

$$P = 5.0 \times 10^{-23}\mathrm{W}\left(\frac{g_\gamma}{0.75}\right)^2\left(\frac{\rho_a}{0.45\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right)\left(\frac{\nu_a}{1\mathrm{GHz}}\right)\left(\frac{B_0}{10\mathrm{T}}\right)^2\left(\frac{V}{30\mathrm{liters}}\right)\left(\frac{G}{0.5}\right)\left(\frac{Q_c}{10^5}\right)$$

Misc. experiments

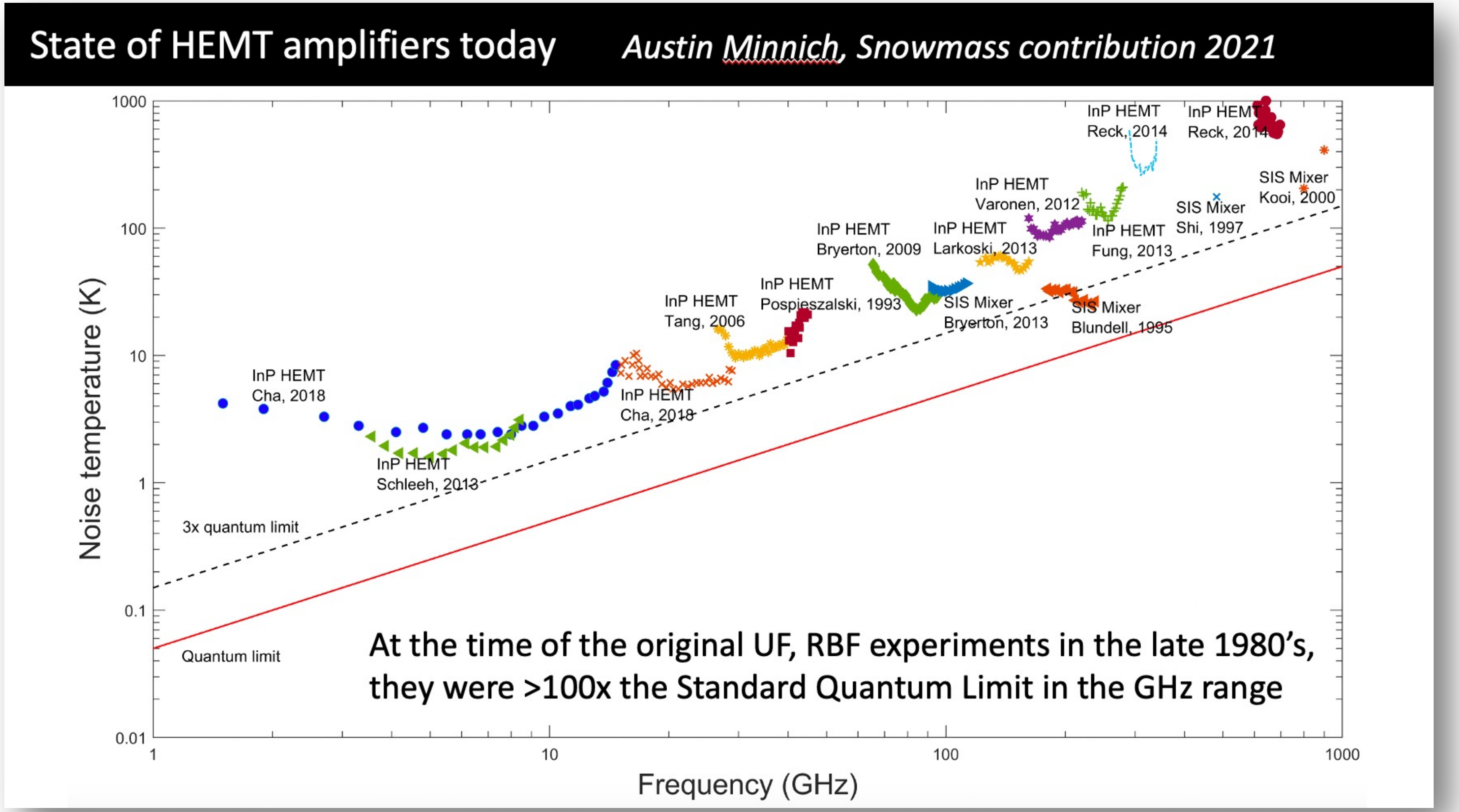
Experiment	Time	Frequency	Volum	Amplifier	Magnet	T_{SYS}/T_{SQL}
RBF [7]/UF [34]	1985–1990	2.5 GHz	5 L	HEMT	6 T/8 T	100–200
ADMX @ LLNL [35]	1995–2010	0.6 GHz	200 L	HEMT, SQUID	7.6 T	50–100
ADMX @ UW [36]	2016-present	0.8 GHz	150 L	SQUID, JPA	7.6 T	10
CAPP [37]	2019-present	1.6 GHz	3.5 L	HEMT	8 T	12
HAYSTAC I [38]	2015–2018	6 GHz	1.5 L	JPA	9 T	2
HAYSTAC II [28]	2019-present	4 GHz	1.5 L	SSR	8 T	<1

Simanovskaia et al (2021)



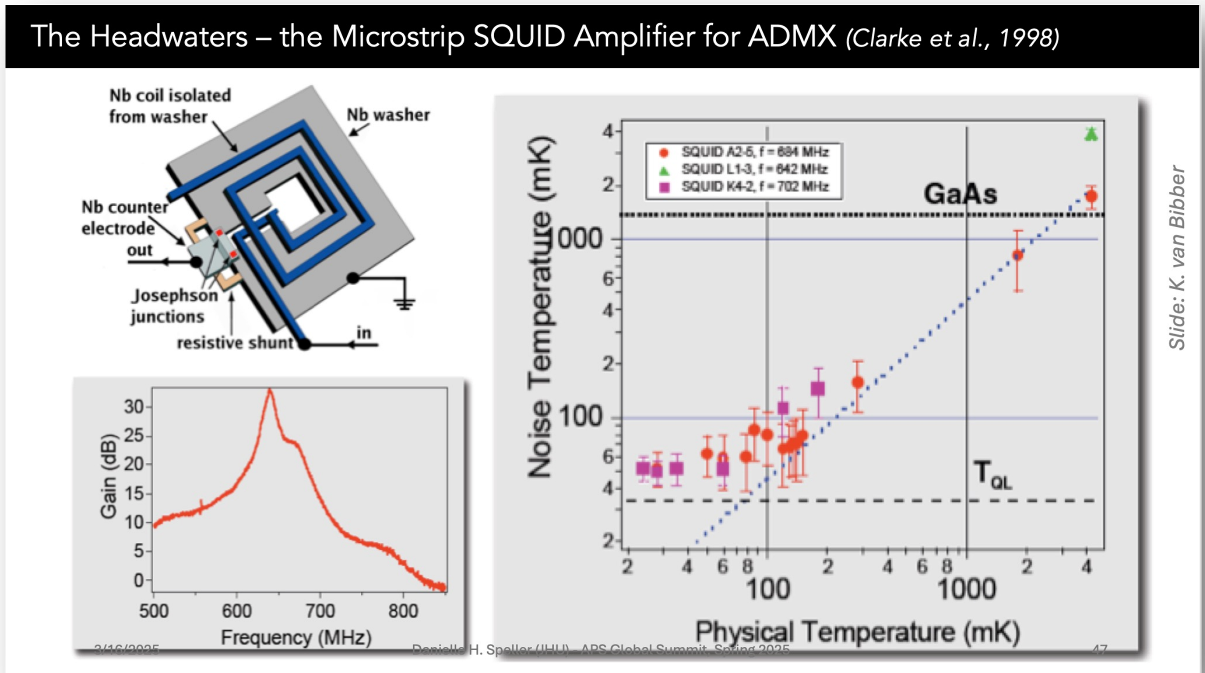
HAYSTAC

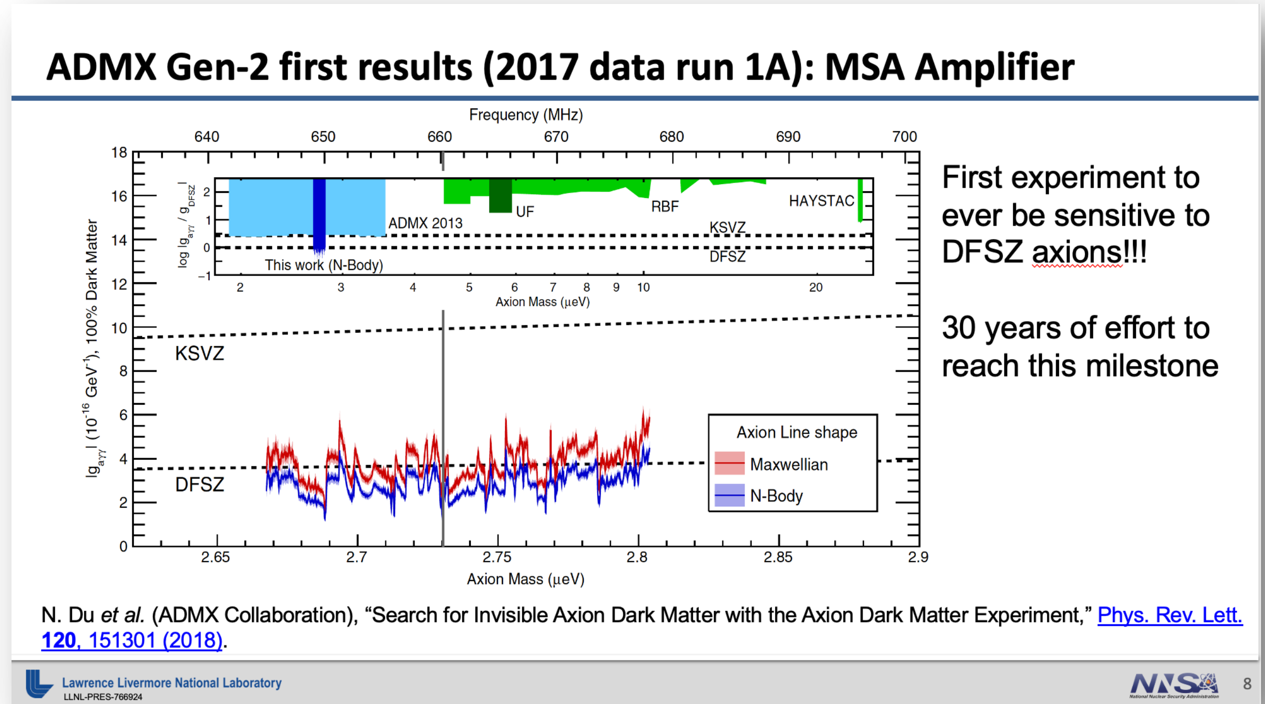
High Electron Mobility Transistors



Slide: K. van Bibber

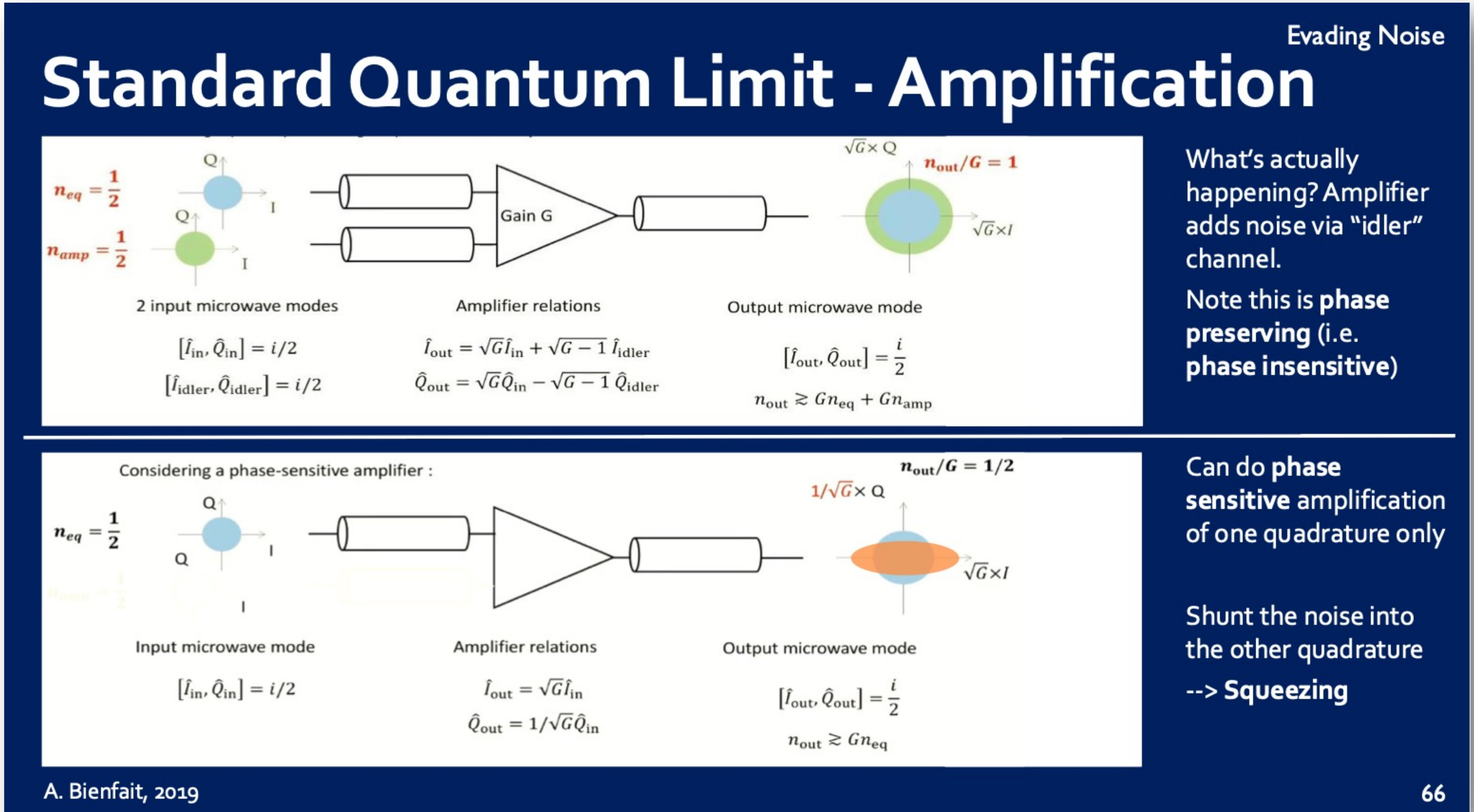
Next step: ADMX's Microstrip SQUID Amplifier





First to reach DFSZ with quantum enhancement

Moving to JPA amplifiers



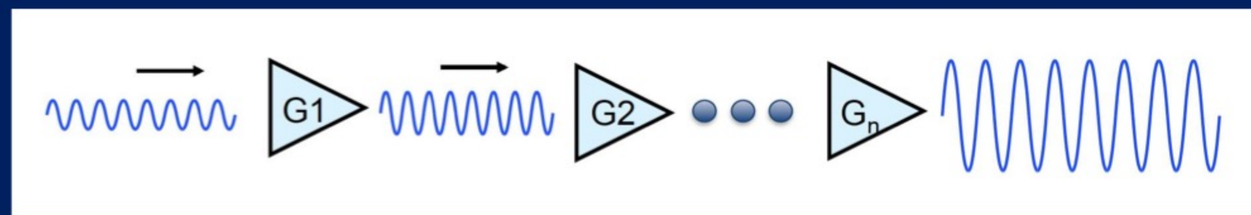
Slide: K. Ramanathan, SSI 2026 (Monday)

Amplification

Evading Noise

Why does this matter?

Multi-stage amplification:



Noise propagates as:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

Noise often set by the very first loss/amplification element after your detector!

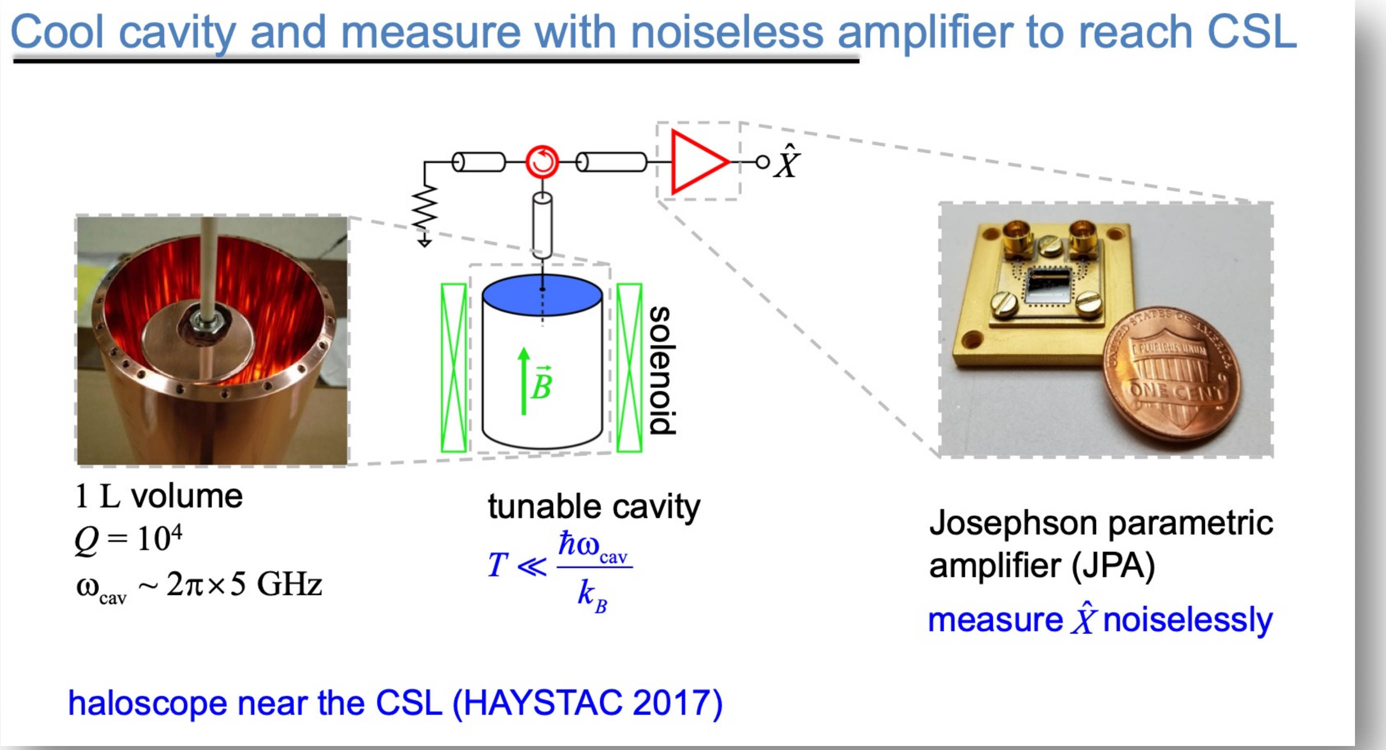
Qiu, 2017

67

Slide: K. Ramanathan, SSI 2026 (Monday)

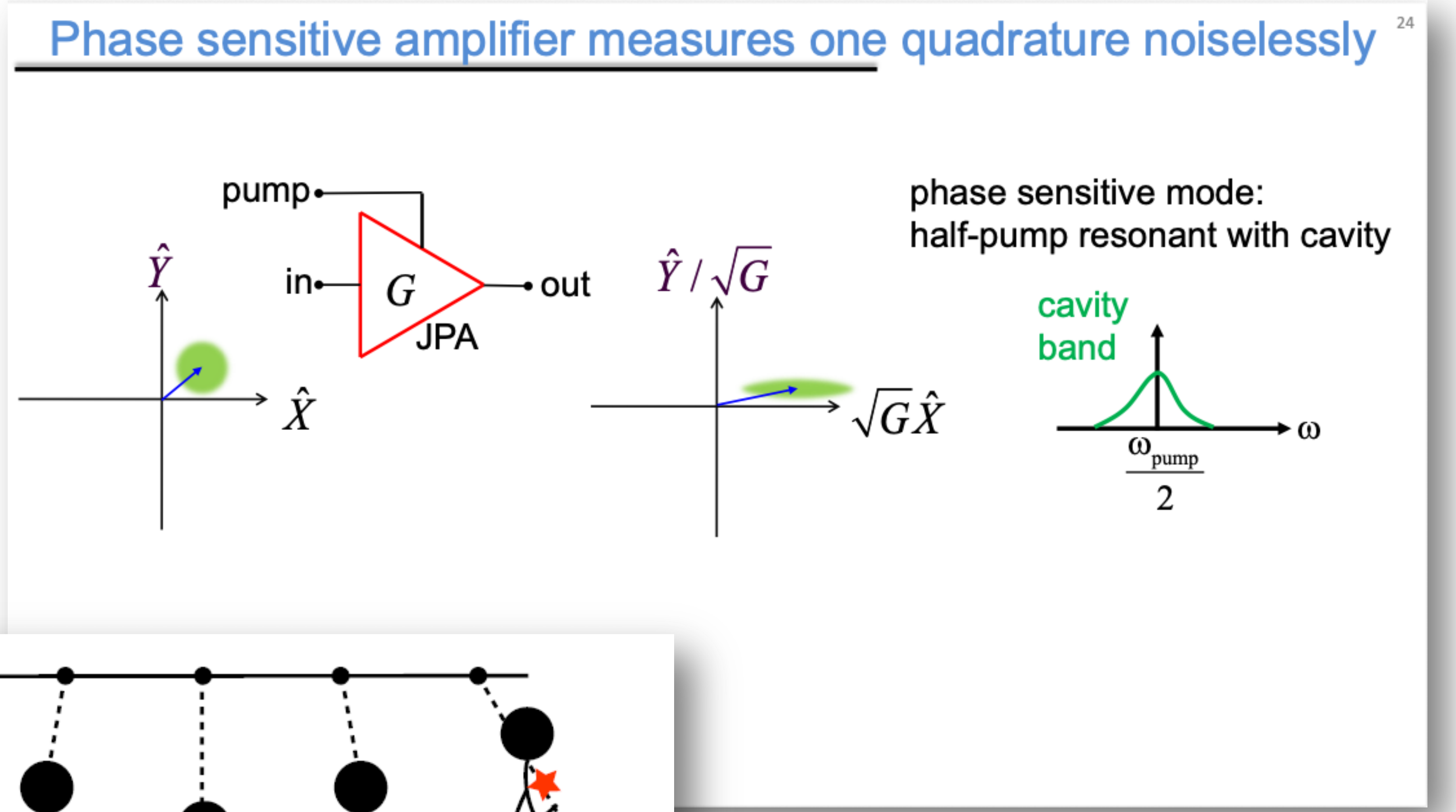
Below Standard Quantum Limit (BSQL)

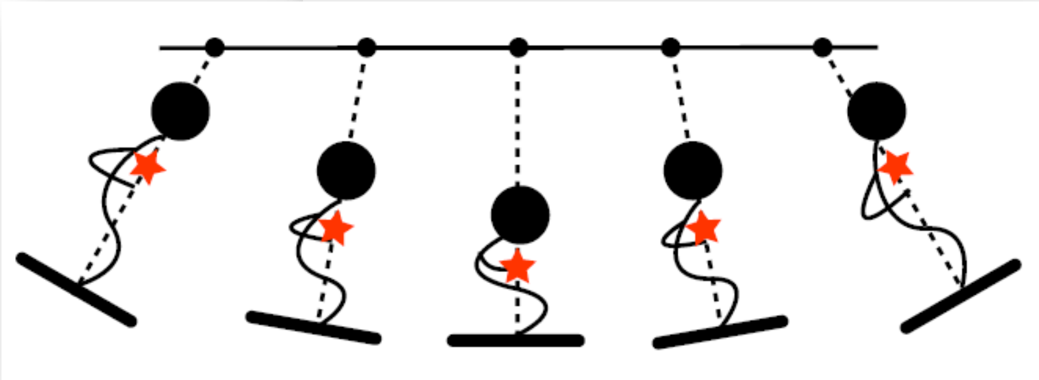
- The standard quantum limit can be evaded by e.g. squeezing or single photon detection (these are the two major thrusts to date).
- The HAYSTAC experiment achieved a ~2x increase in scan rate through the employment of squeezing



Slide: K. Lenhert, SSI 2026 (Monday)

Squeezing Vacuum



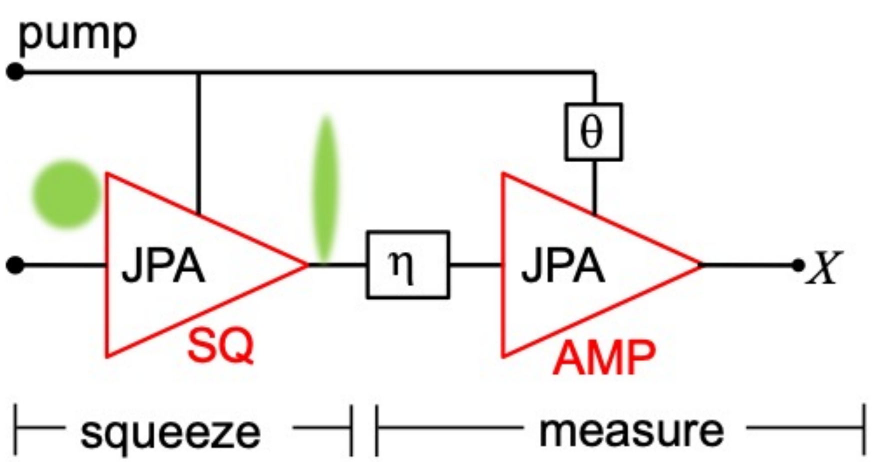


P.D. Nation, Rev.Mod.Phys. 84 (2012)

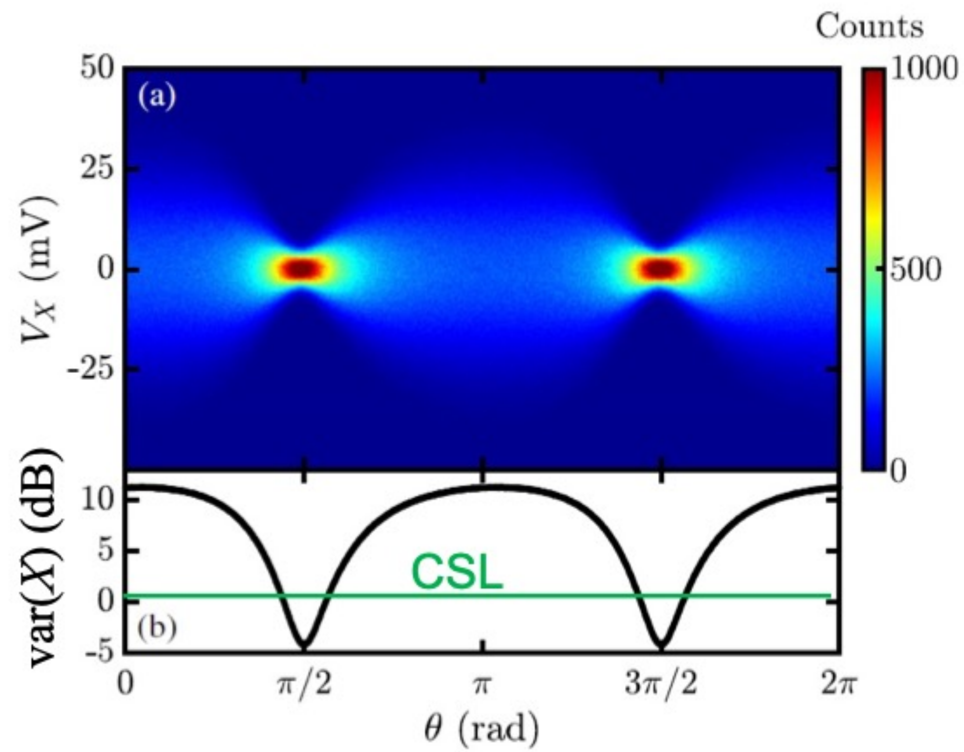
Slide: K. Lenhert, SSI 2026 (Monday)

Squeezing Vacuum

Demonstration of squeezing and determination of loss: second JPA analyzes squeezed state created by first



phase θ chooses measured quadrature relative to squeezed quadrature

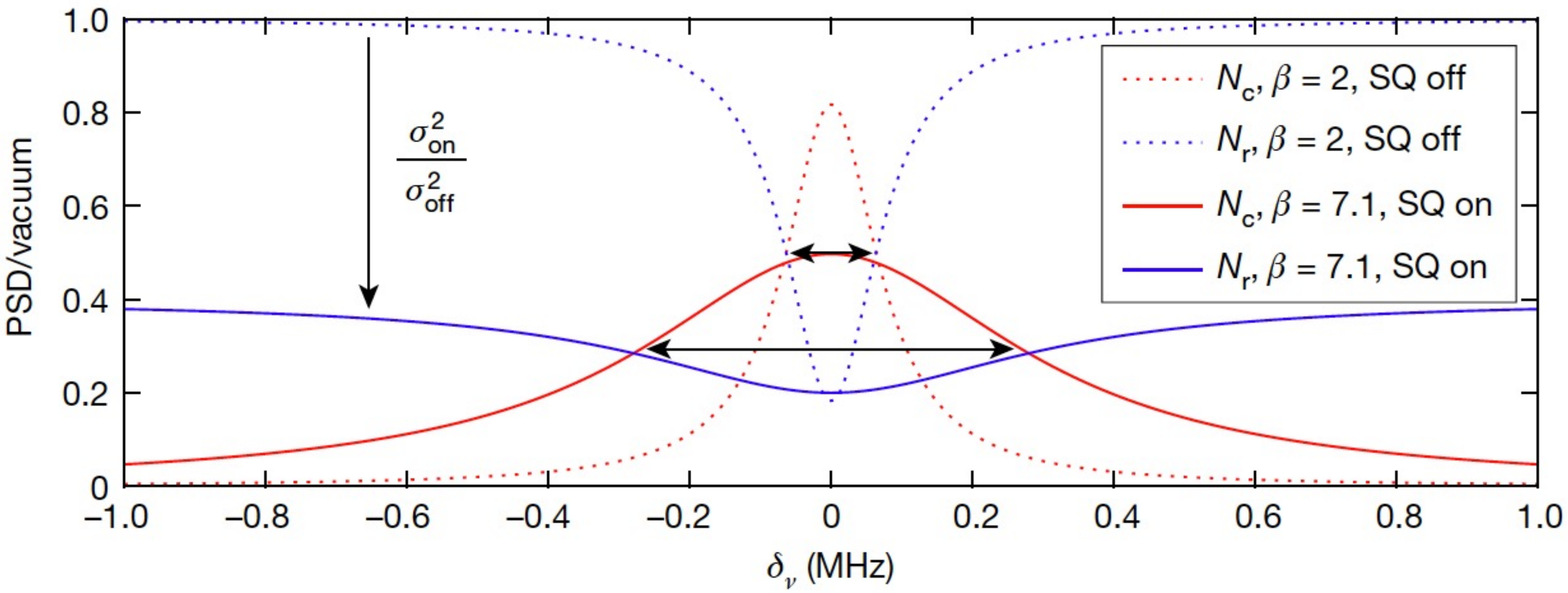


loss η: 1.63 dB

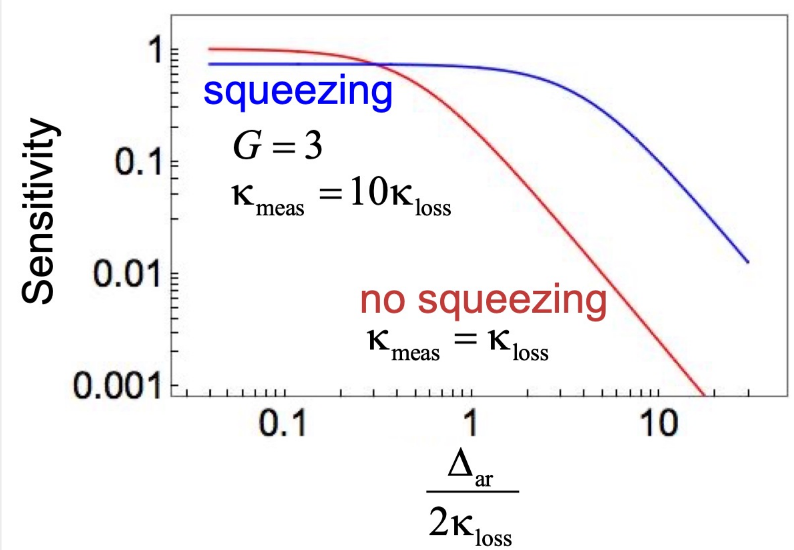
JILA

Slide: K. Lenhert, SSI 2026 (Monday)

Squeezing Vacuum



K. Lenhert/HAYSTAC



slight reduction in sensitivity
much larger bandwidth

- Over 4 dB squeezing → 2x scan rate improvement

Slide: K. Lenhert, SSI 2026 (Monday)

Squeezing Vacuum

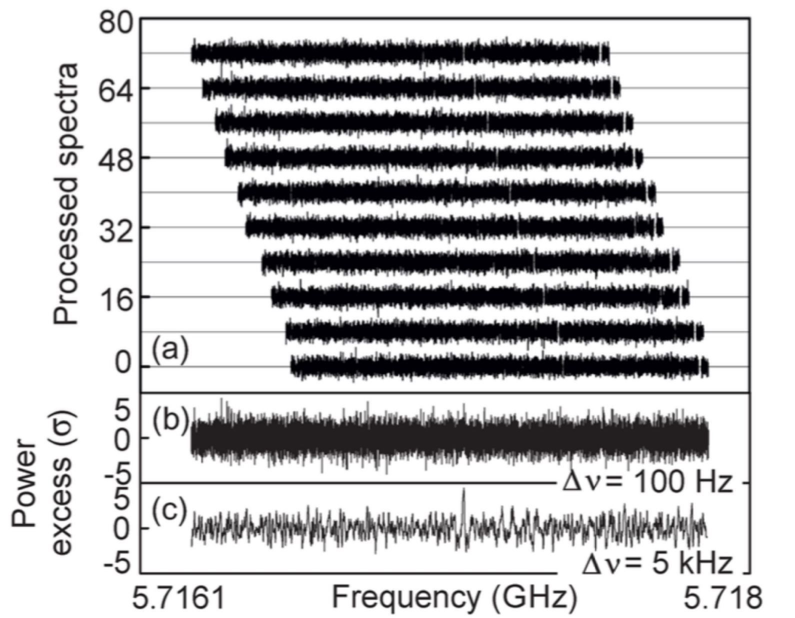
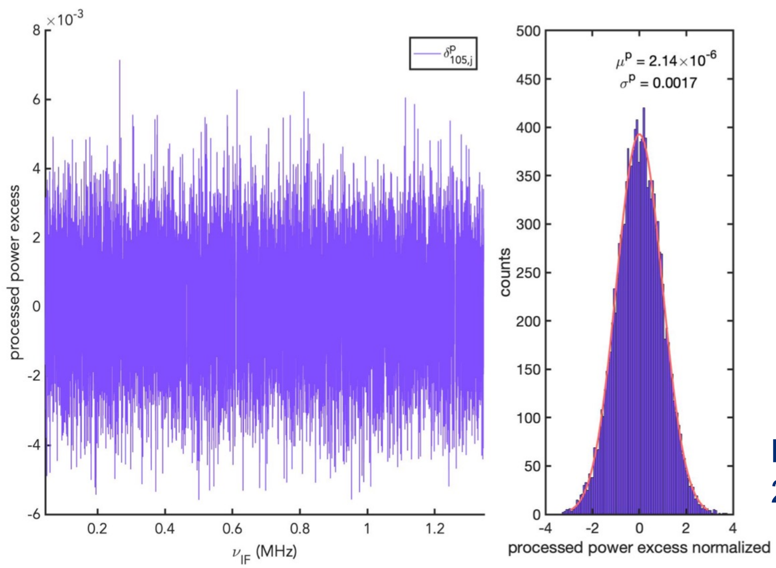
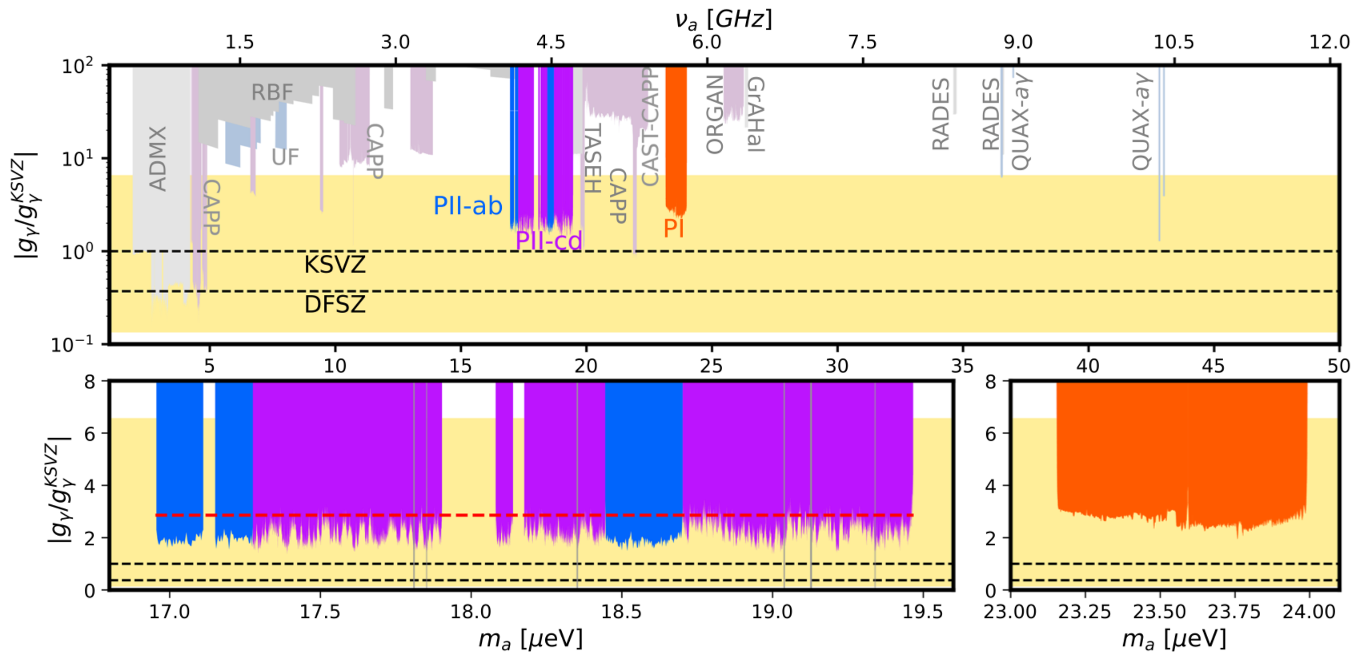


Fig: B.Brubaker (2017)

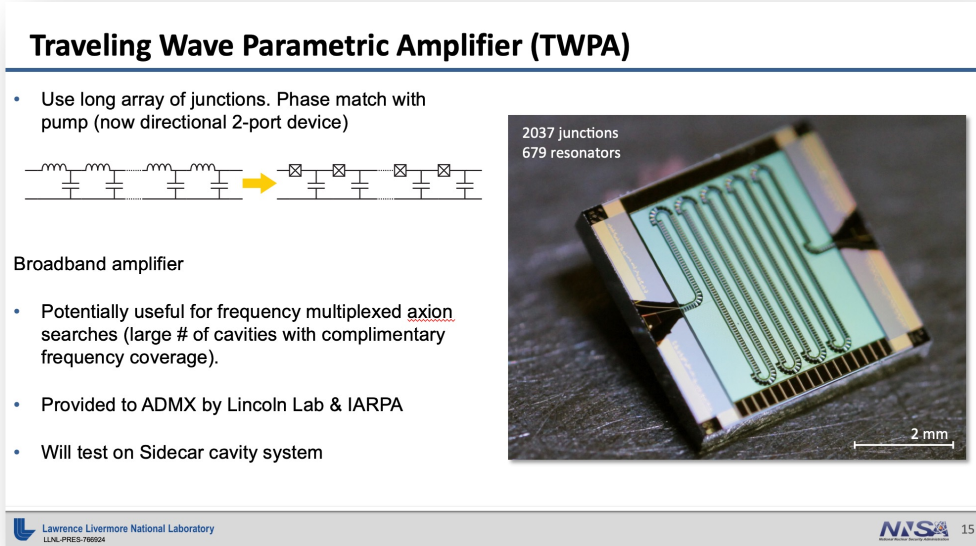


K. Backes 2021

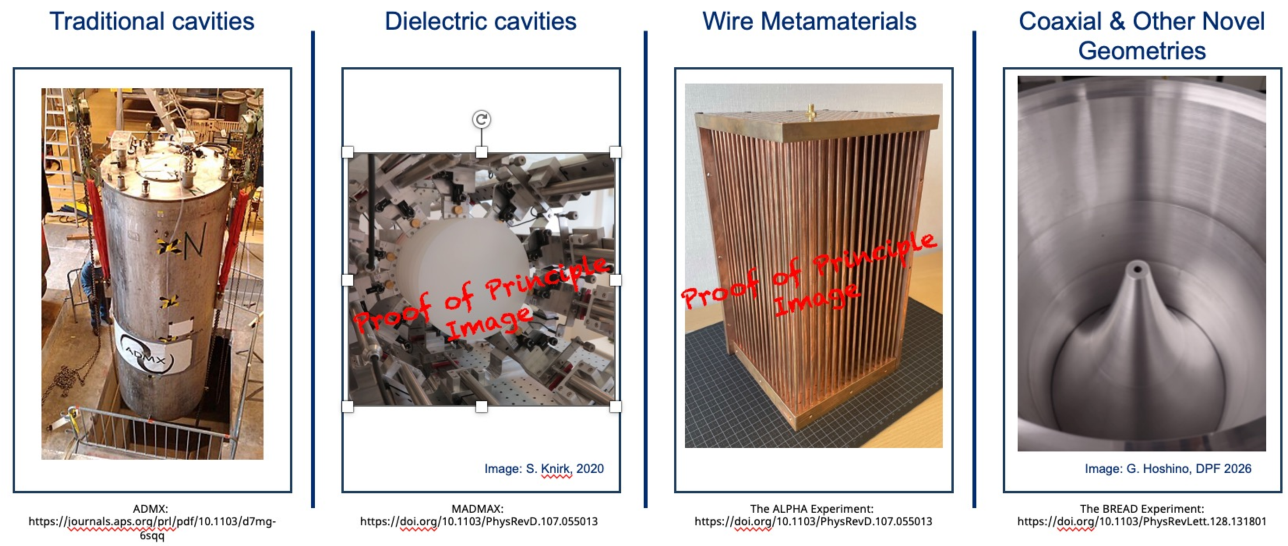


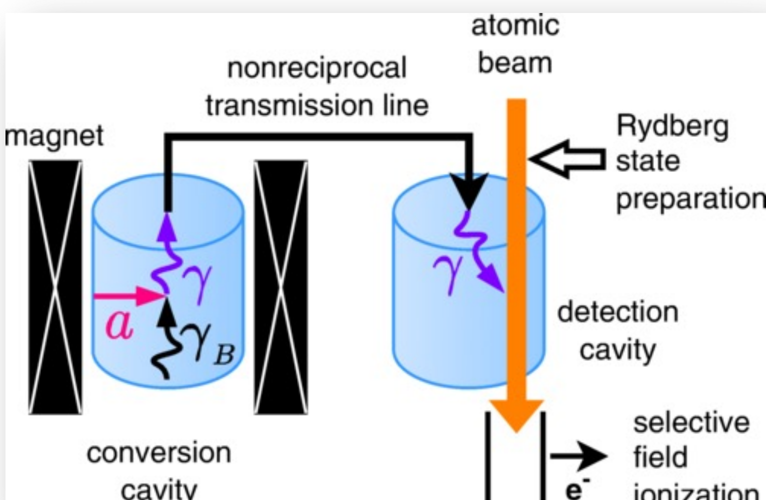
PhysRevLett.134.151006

Multiple Avenues

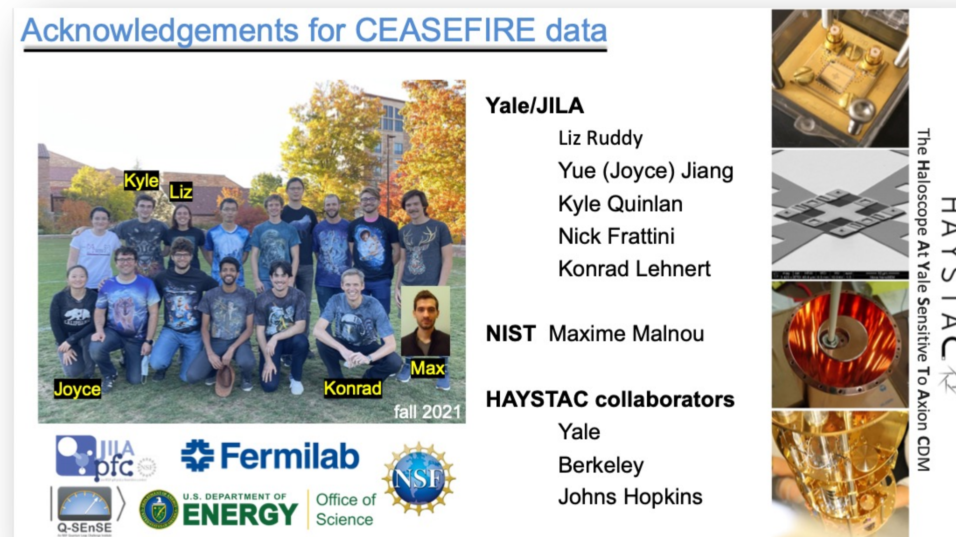


Slide: G. P. Carosi





RAY: Single Photon Detection



PhysRevD.109.032009

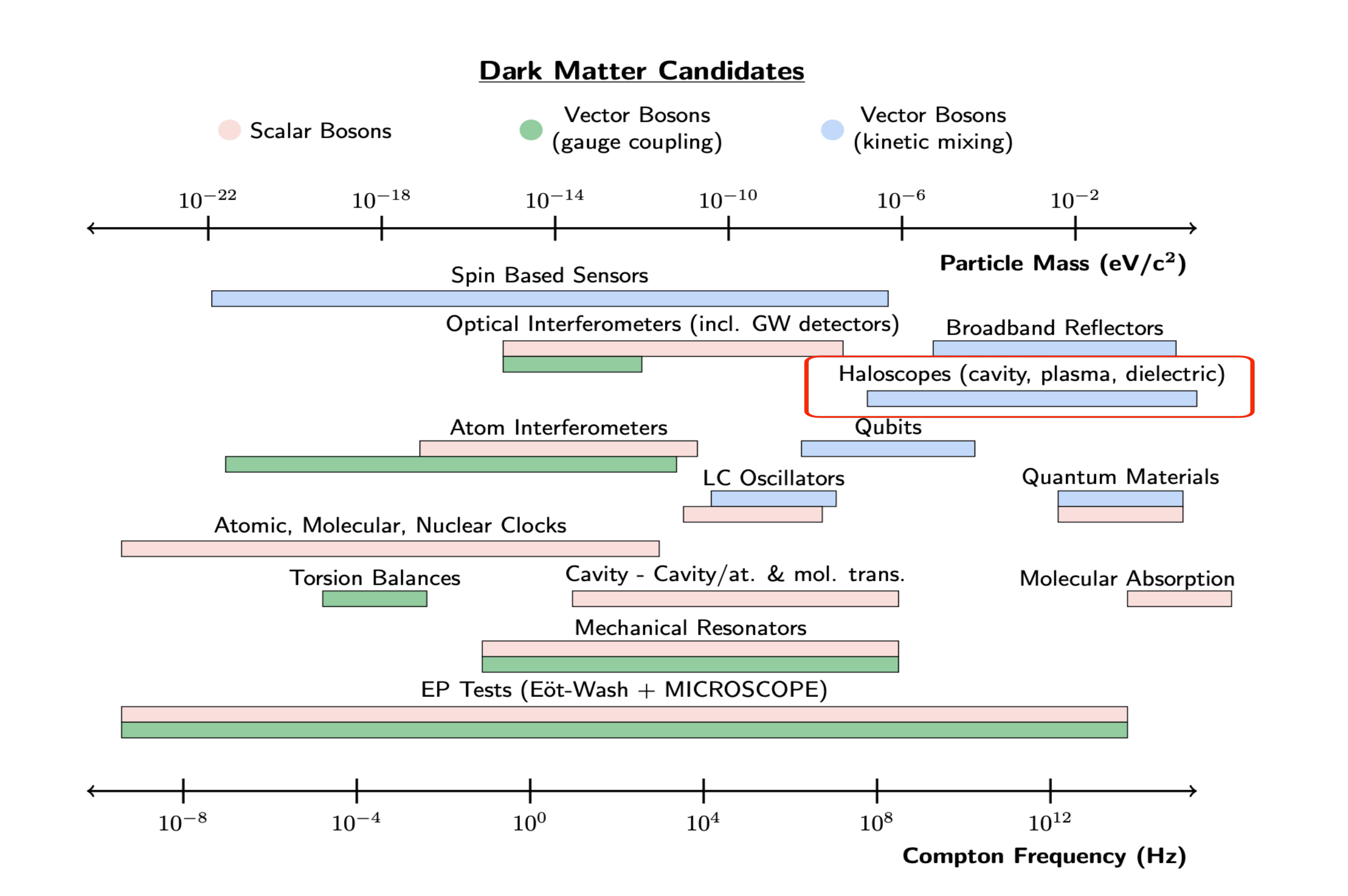
Slide: K. Lehnert

Summary

- Quantum enhancement has accelerated the search for ultra light dark matter

- Many new and emerging technologies for quantum enhancement beyond cavities & receivers, most not covered today (!)

- Advancement in cavity-based experiments are a prime example of the progress



https://arxiv.org/pdf/2203.14915

Acceleration in the field, but more progress to be made

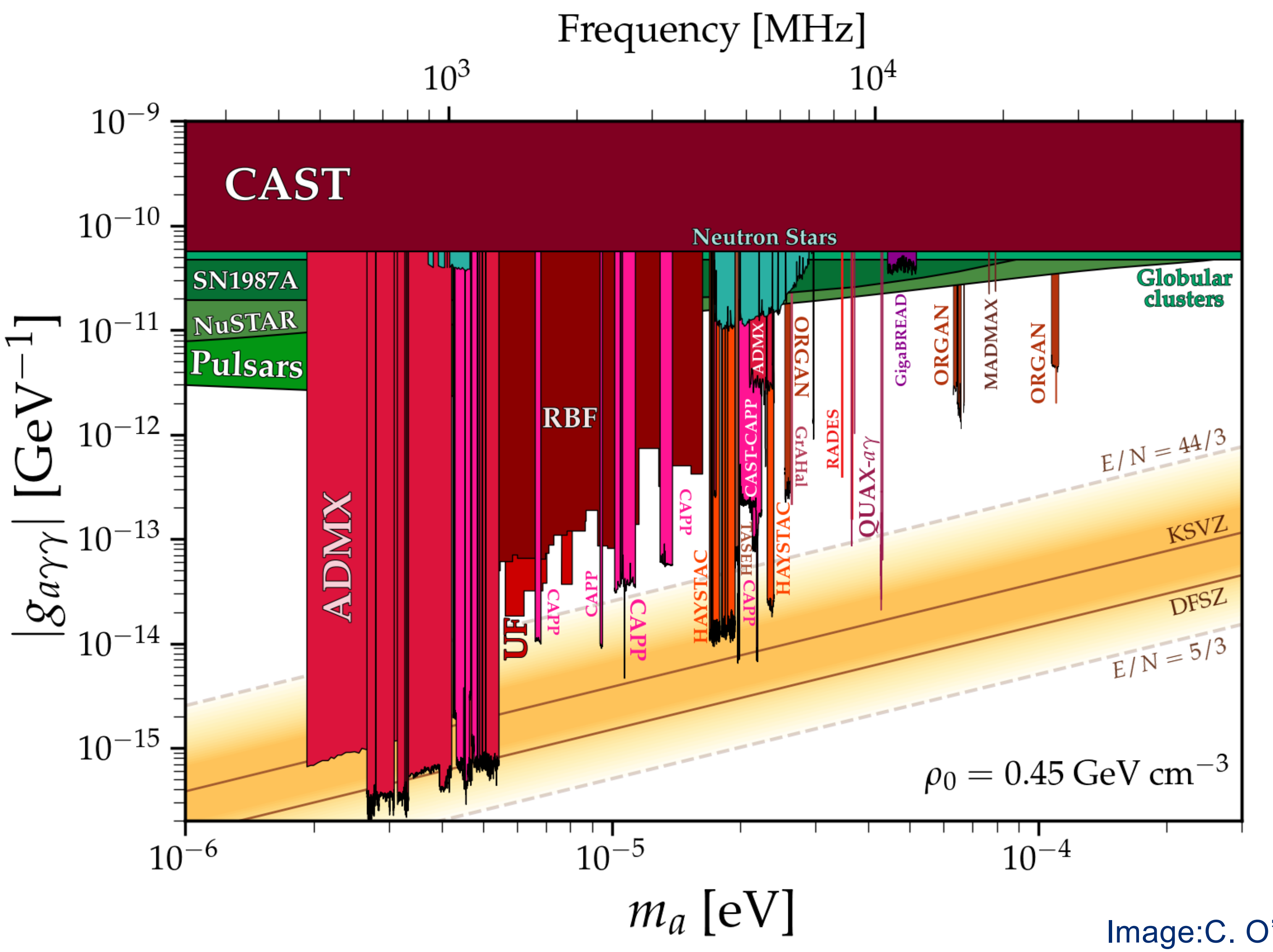


Image:C. O'Hare

Thanks

JOHNS HOPKINS
UNIVERSITY