Towards search for 100 μeV axions and axion dark matter with high-frequency microwaves

Akira Miyazaki

Outline

- Introduction
  - New physics with microwaves
  - Axion and axion dark matter
  - Particle vs wave
- State of the art
  - ADMX experiment
  - Background noise and quantum limit
  - Squeezing (HAYSTAC) and photon counting
- New experiments
  - Challenge toward higher frequency
  - Dish antenna: signal from metal/vacuum interface
  - MADMAX: signal boost with dielectric disks
  - ALPHA: plasma haloscope with wire metamaterial
- Conclusion

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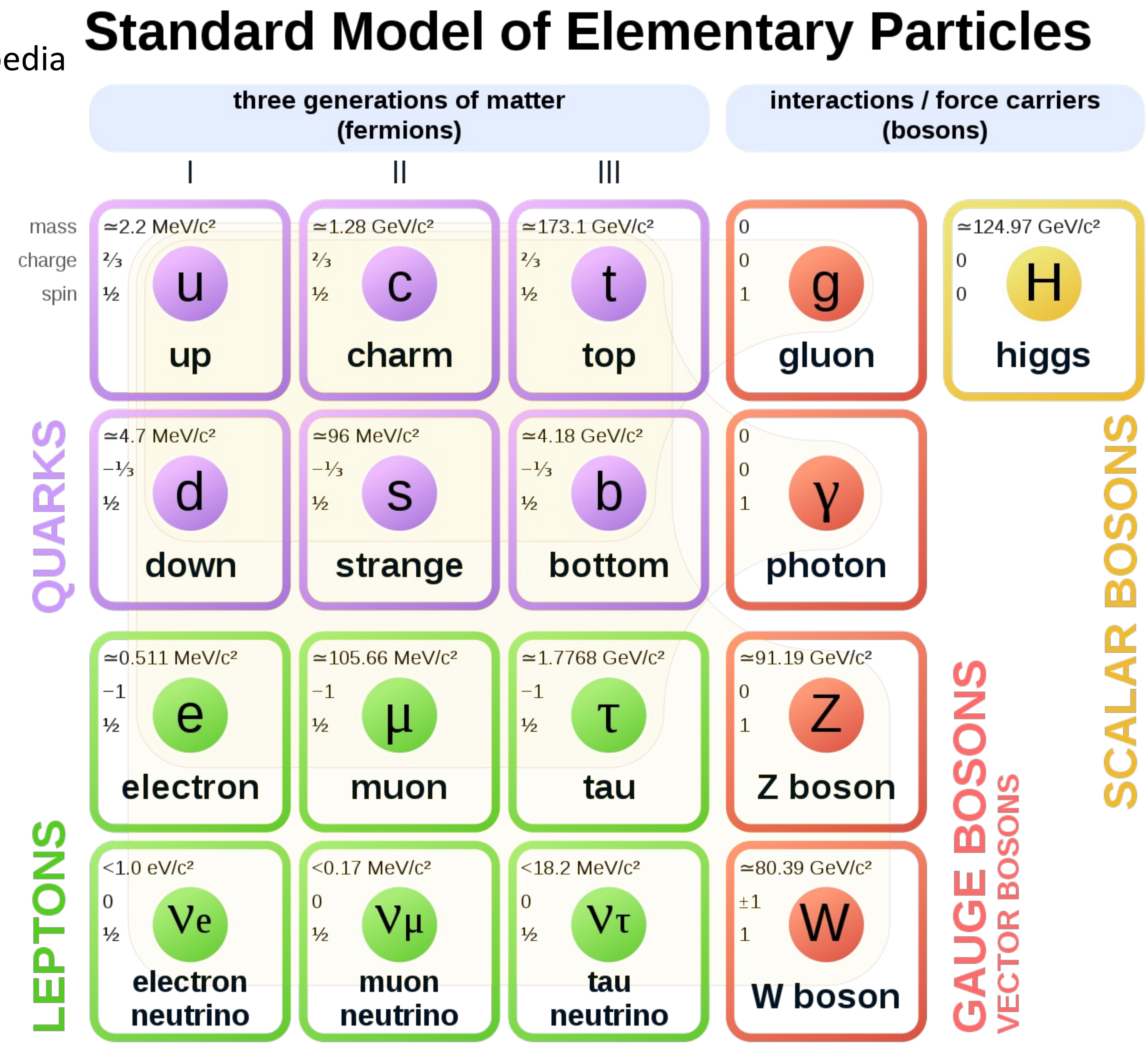
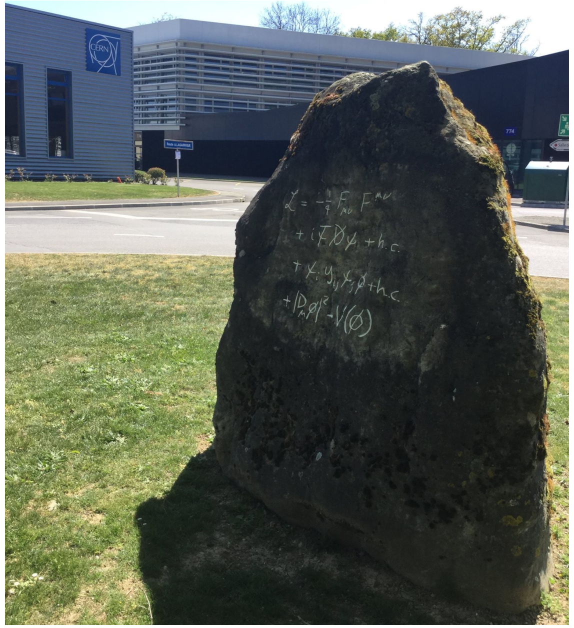
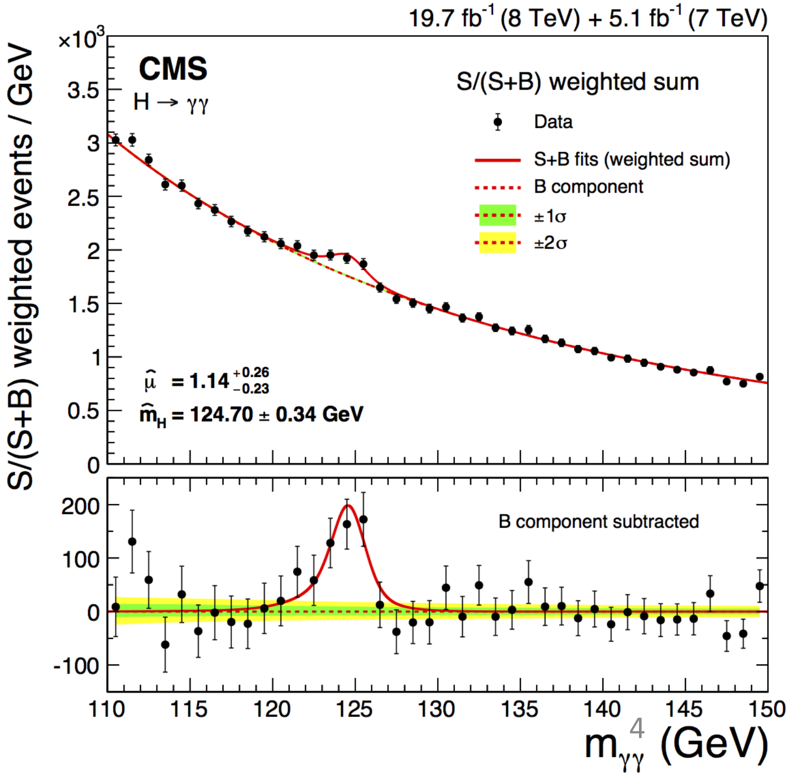
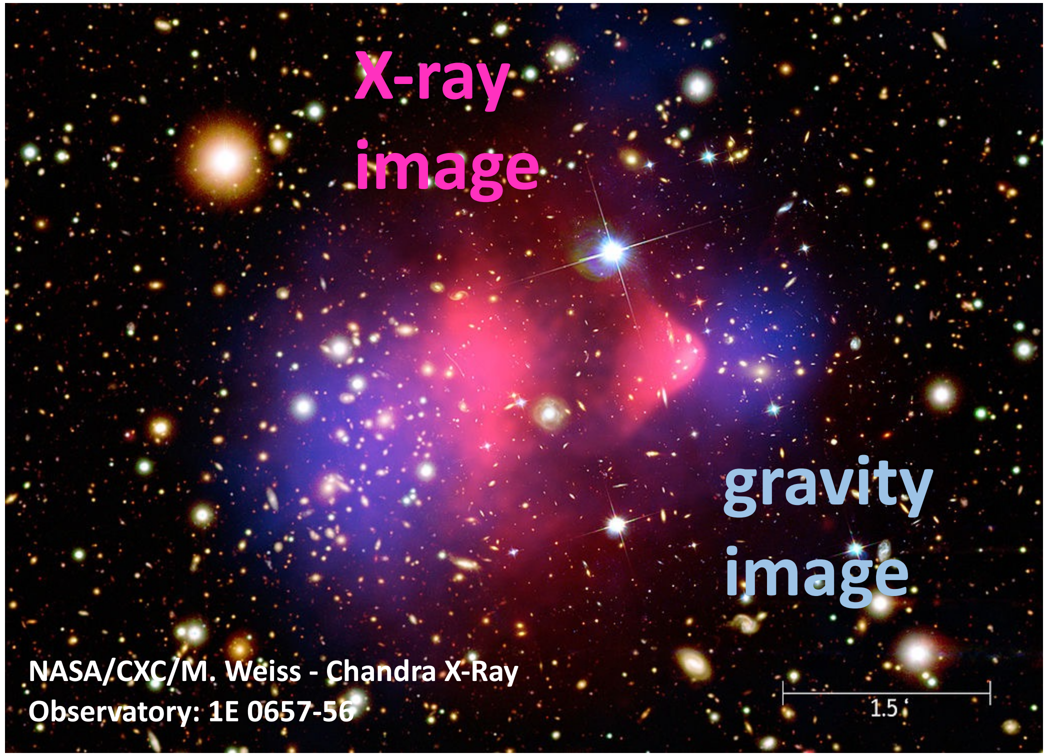
From wikipedia

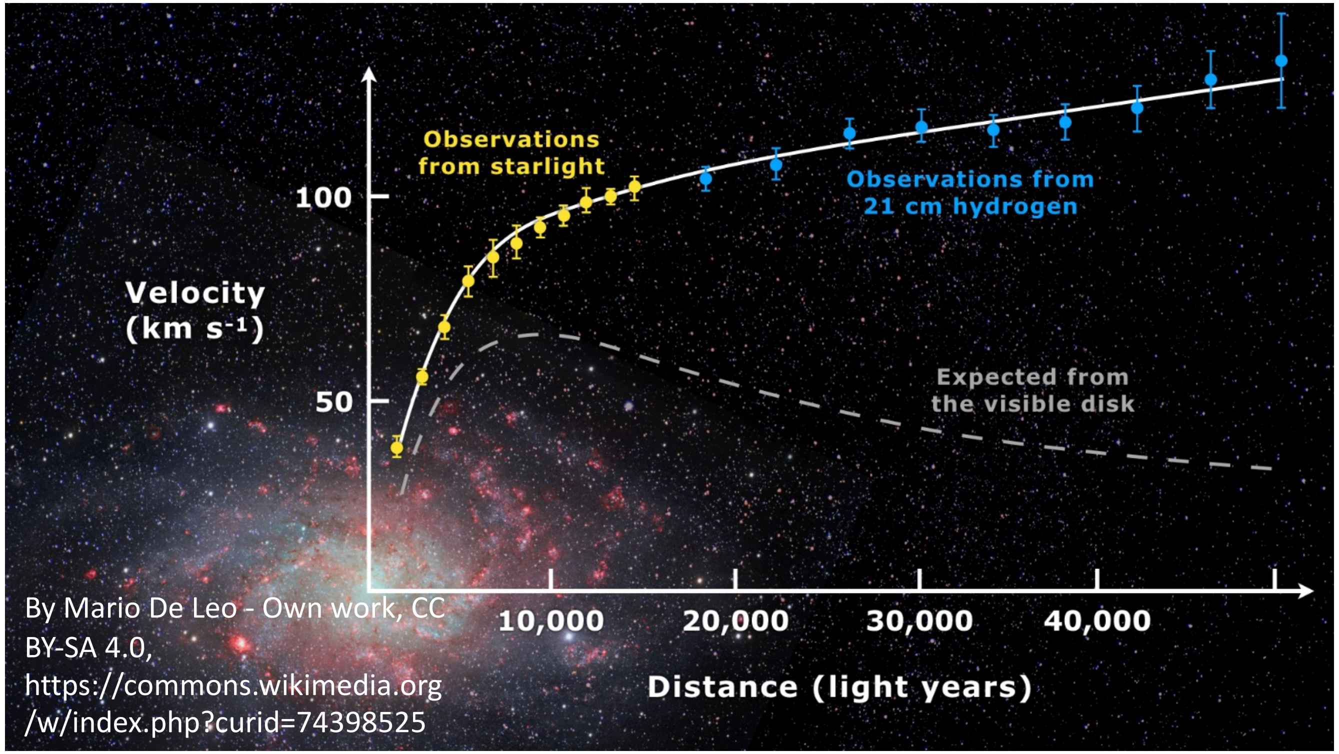






Clear need for new physics: e.g. Dark Matter (DM)

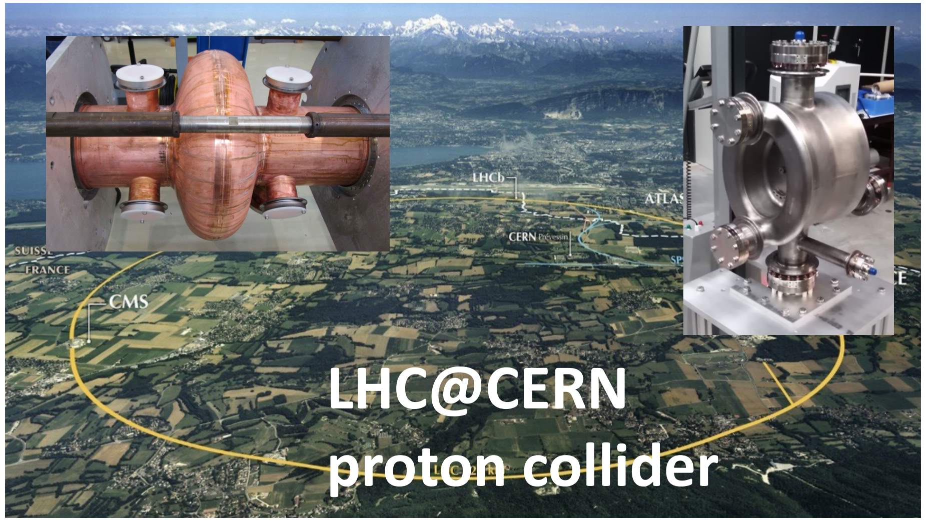


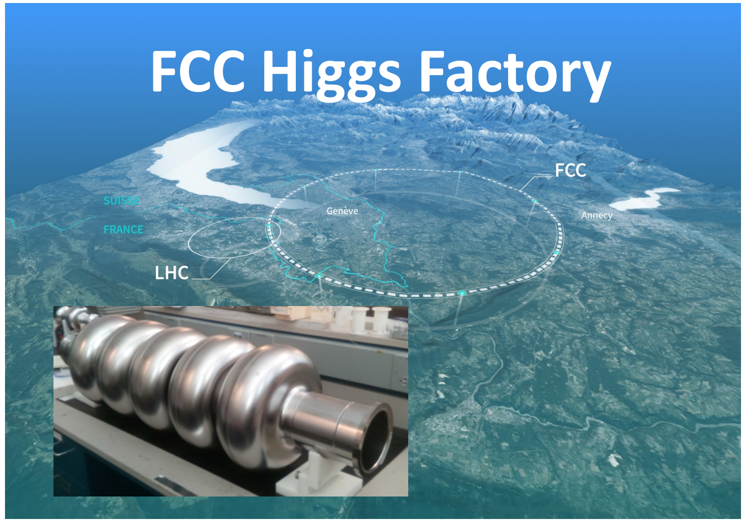


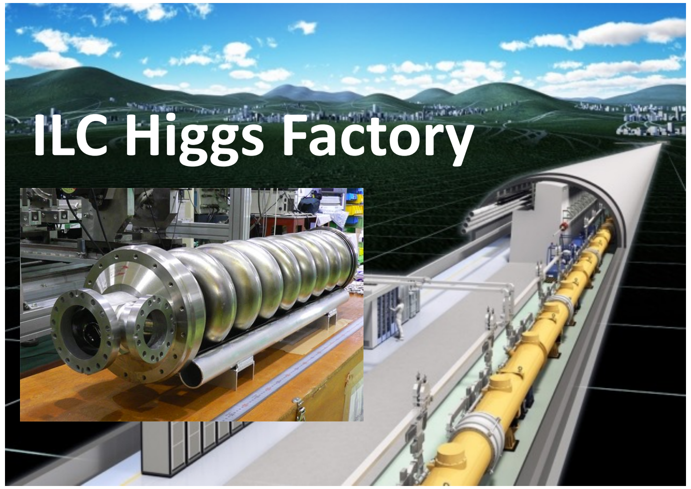
~~Neutrino~~?
~~Dark astrophysical objects~~?
~~Modified gravity~~? van Dokkum, *et al. Nature* **555,** 629–632 (2018)
Primordial black holes?

✓ Hypothetical new particles linked to intrinsic issues in the Standard Model?

My main business: Radio Frequency cavities for accelerators



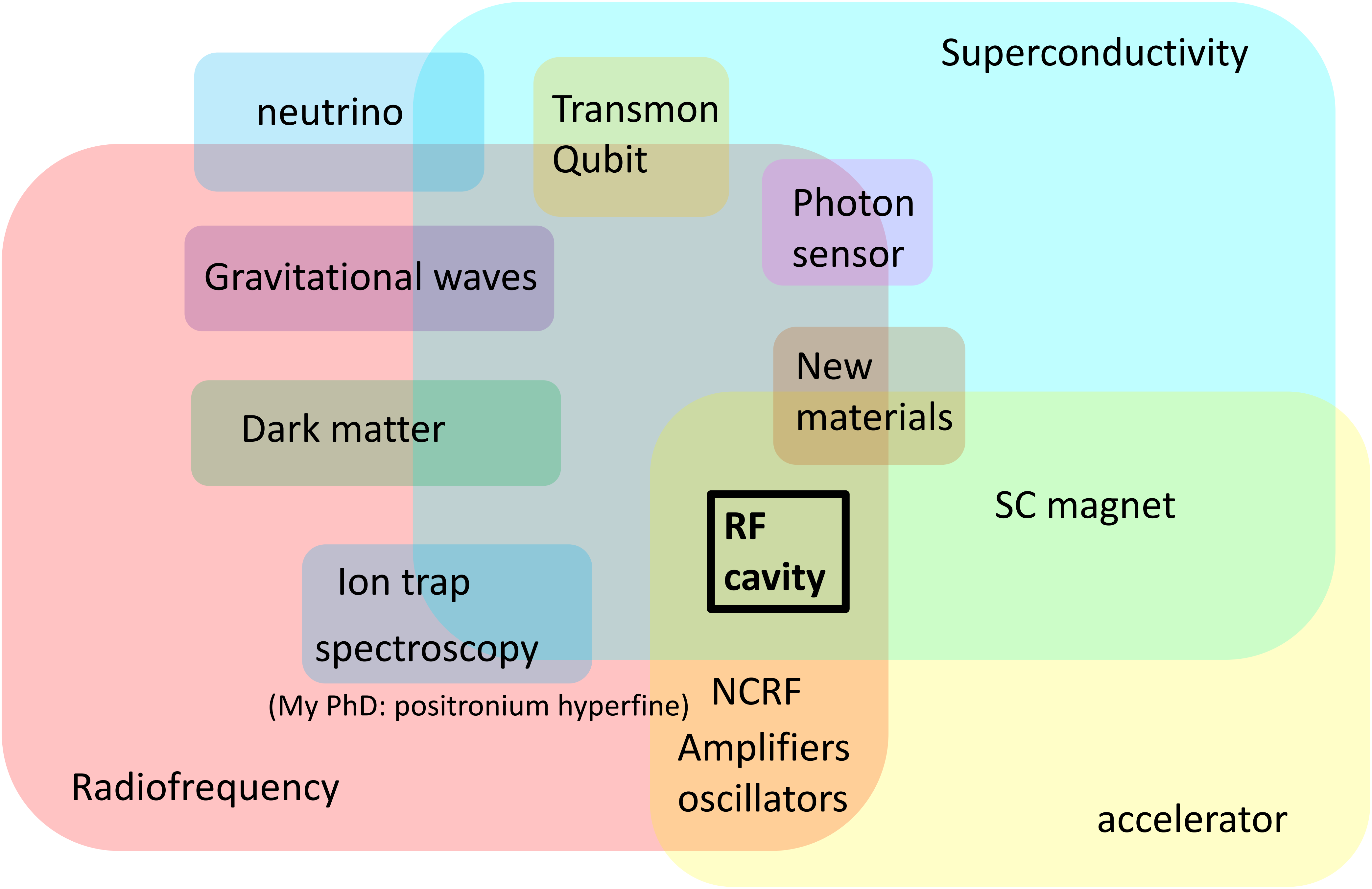




Pros: any present and future accelerators would include superconducting RF cavities

Cons: Timeline (decades?) costs (>>BEUR?) still no promise for ***new physics***

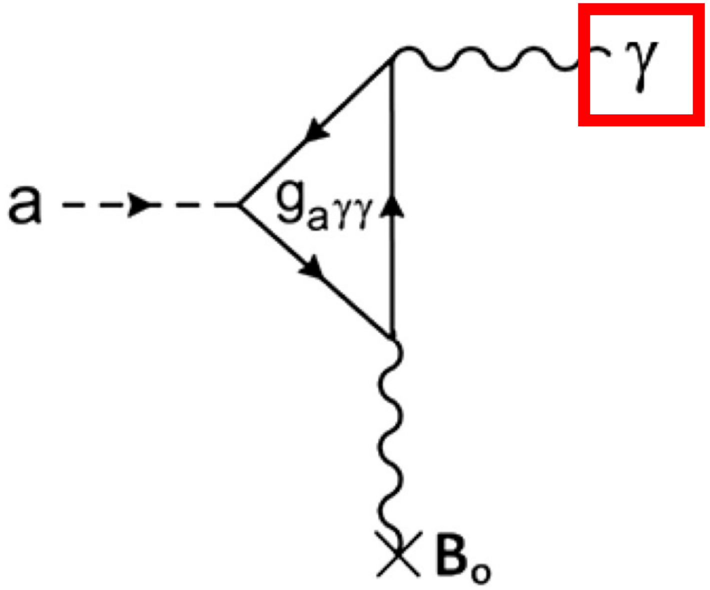
→ Can't we directly make use of RF for discovery?


Superconductivity
neutrino
Transmon Qubit
Photon sensor
Gravitational waves
New materials
Dark matter
SC magnet
RF cavity
Ion trap
spectroscopy
(My PhD: positronium hyperfine)
NCRF
Amplifiers
oscillators
Radiofrequency
accelerator

Microwave photons may address fundamental physics

Today's talk

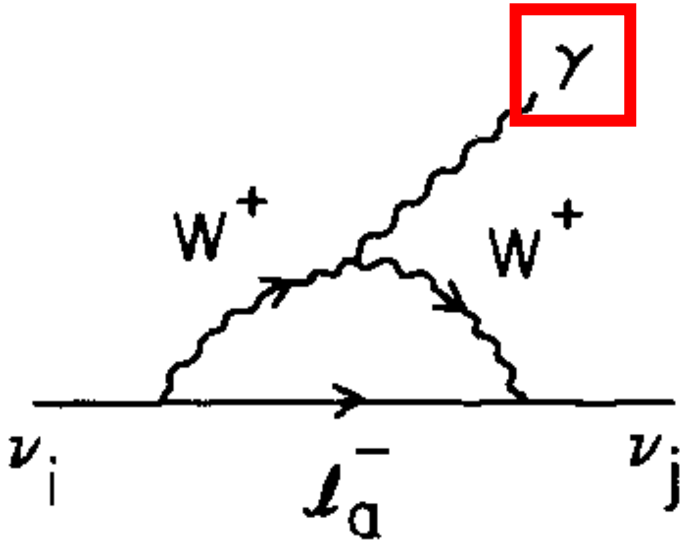
Axions



Inverse Primakoff effect

Minimal extension of SM

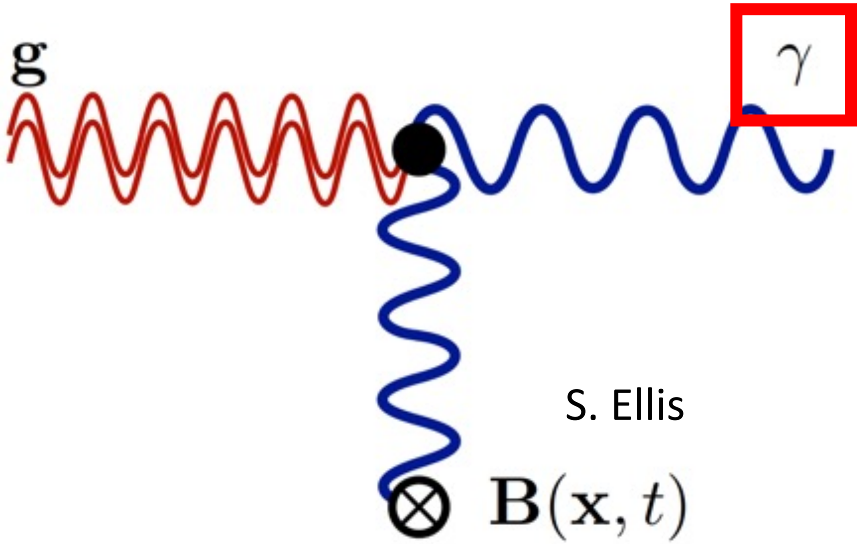
Neutrinos



Cosmic neutrino background

Extension of SM and/or SM

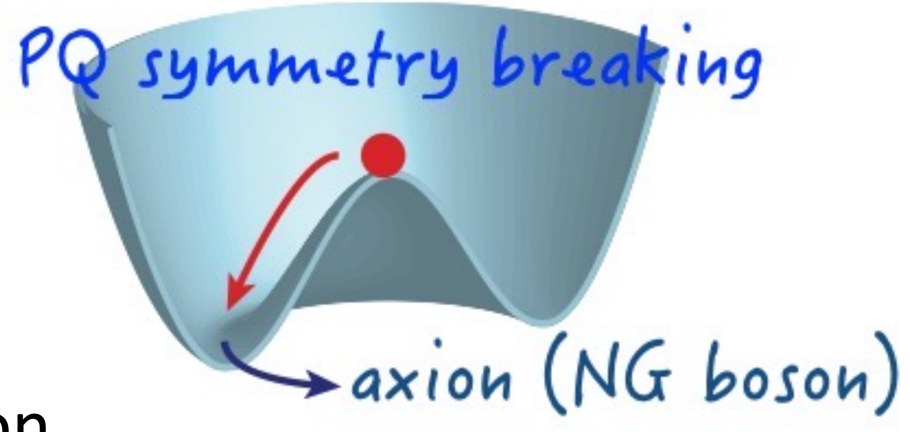
Gravitational waves



Inverse Gertsenshtein effect

Solution of general relativity

Axions: a byproduct to cancel the strong CP



Quantum Chromodynamics (theory of strong force)

$$L_{QCD} \supset -\frac{1}{4}\overset{\text{gluons}}{G^a_{\mu\nu}G^{\mu\nu a}} + \frac{g_s^2}{32\pi^2}\boldsymbol{\theta} G^a_{\mu\nu}\tilde{G}^{\mu\nu a}$$

This term generates electric dipole moment in neutron

- Theory: $d_n \sim 4.5\times 10^{-15}\boldsymbol{\theta}$ ecm
- Experiment: $|d_n| < 2.9\times 10^{-29}$ ecm

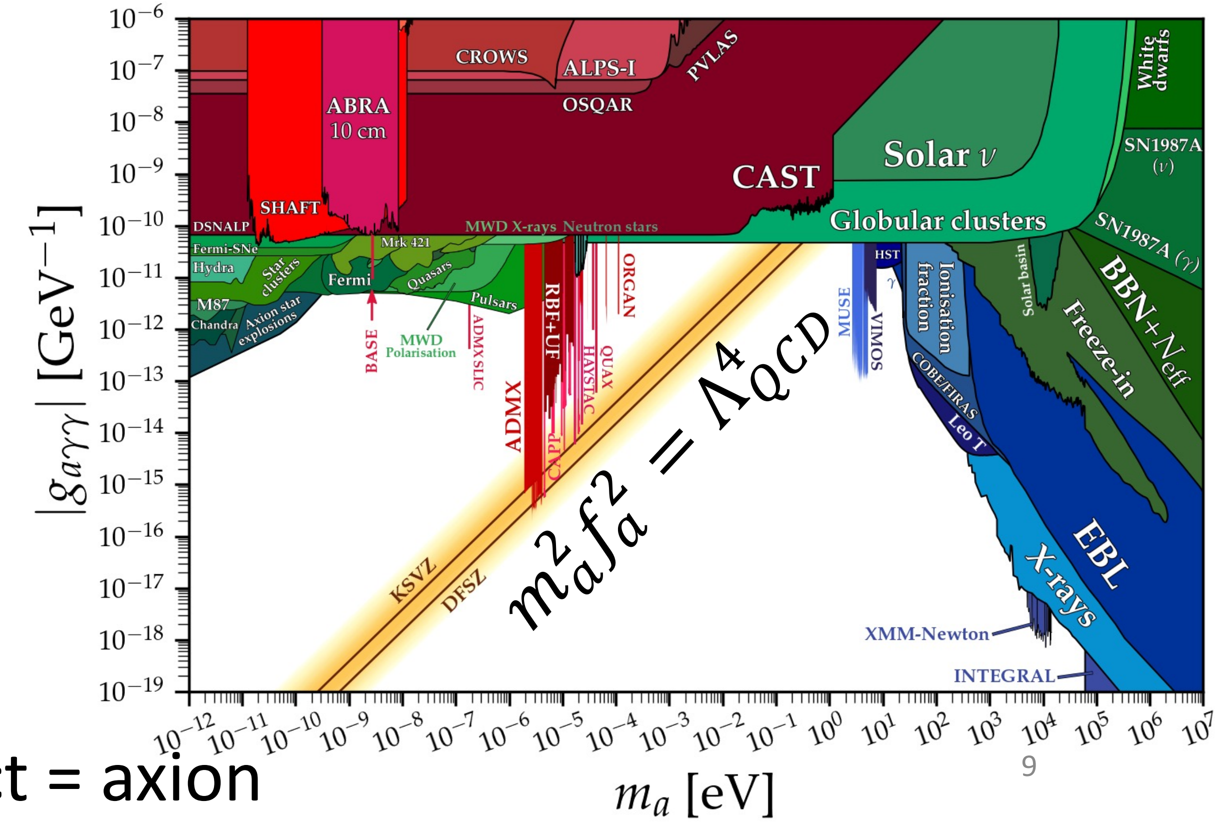
$\rightarrow |\theta| < 0.7\times 10^{-11} \ll 1$

Naturalness without anthropic solution

Introduce a new global chiral U(1) field a

$$\frac{g_s^2}{32\pi^2}\left(\theta + \frac{\boldsymbol{a}}{F_a}\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu a} \rightarrow 0 \text{ (after SSB)}$$

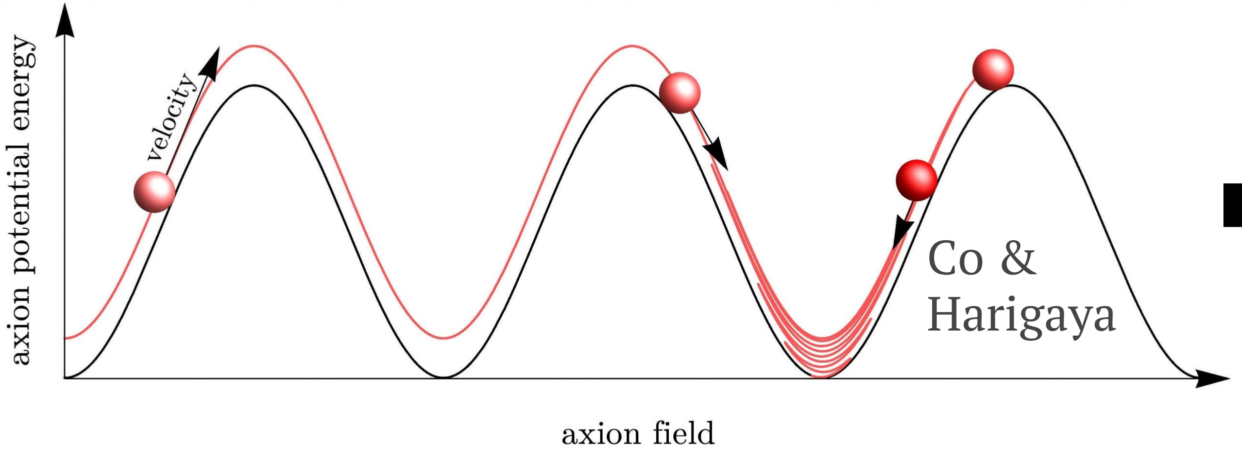
SSB→ A pNG boson appears as a byproduct = axion



Axion as dark matter

Axion loses kinetic energy ***non-thermally*** by coherent oscillation in the PQ potential

Misalignment mechanism

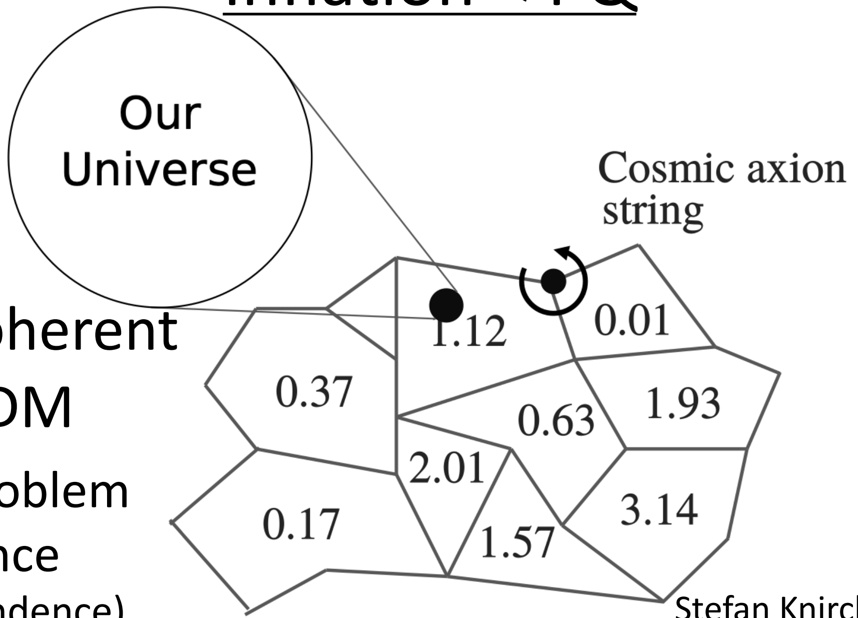


Two possible scenarios related to the energy scale of inflation

Inflation < PQ

Remaining coherent oscillation = DM

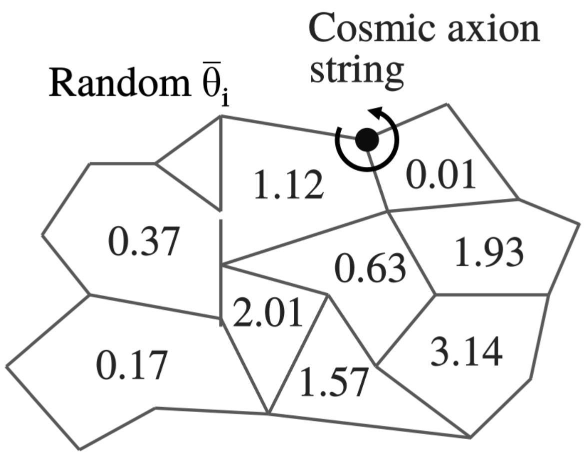
Naturalness problem in DM abundance (initial value dependence)



Stefan Knirck PhD thesis

Inflation > PQ

Our Universe:



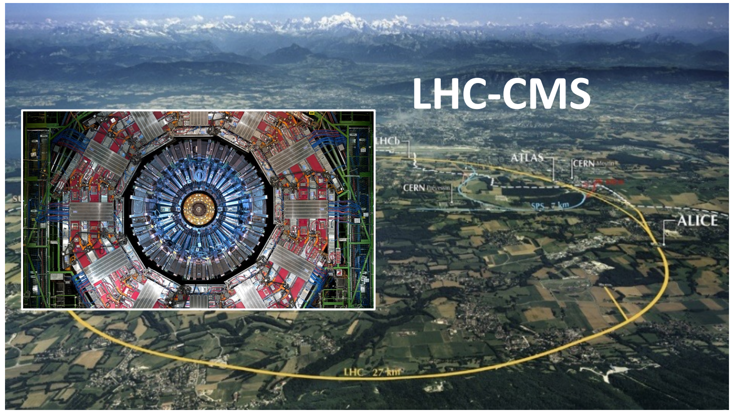
Annihilating axion string = DM

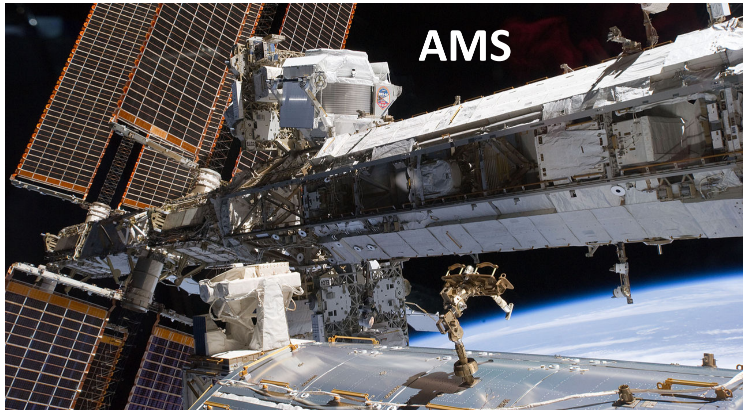
Natural solution to DM abundance

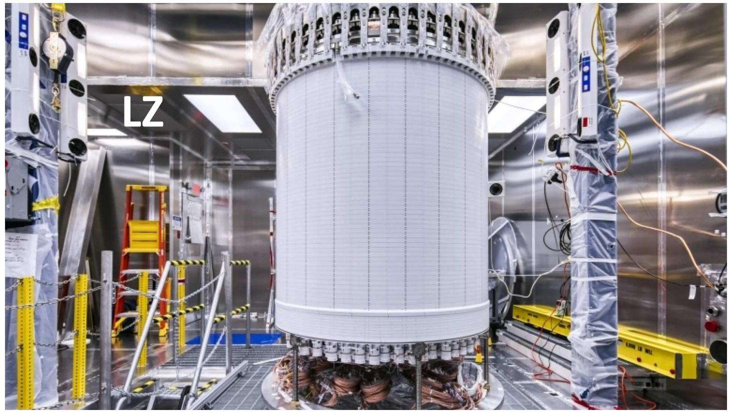
Three ways to study dark matter candidates

Production in lab | Signal from astrophysics | DM from galaxy halo

WIMP
SUSY

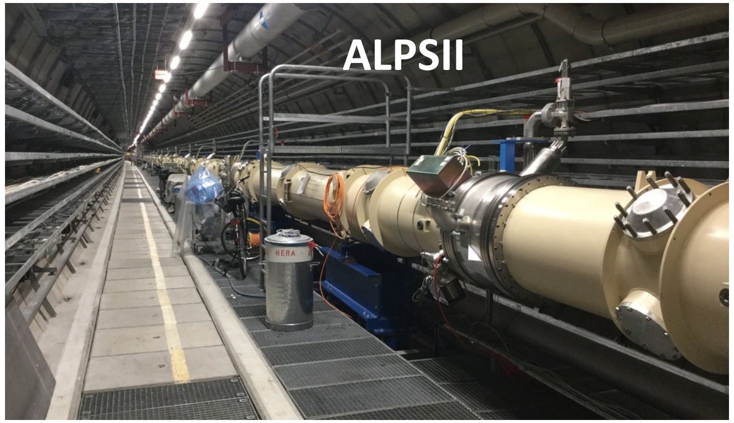






→ Common techniques: **particle** detection, reconstruction, PID, etc

WISP
axions



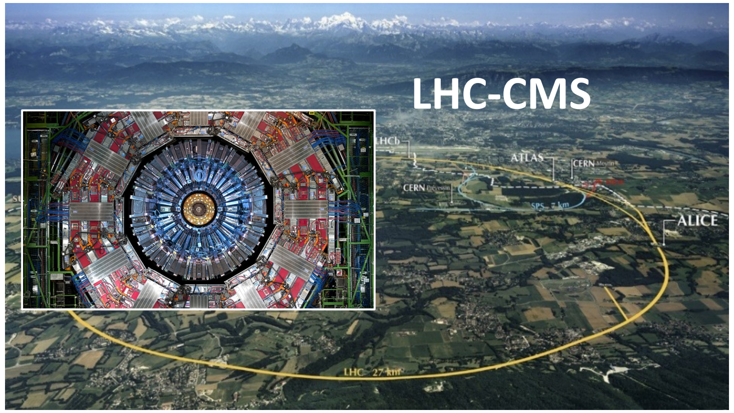
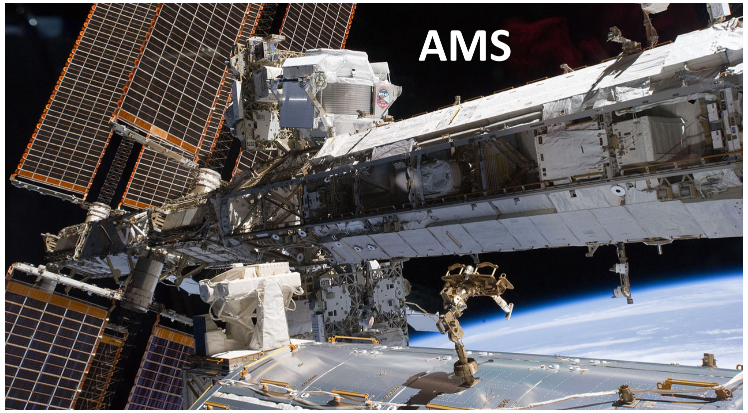
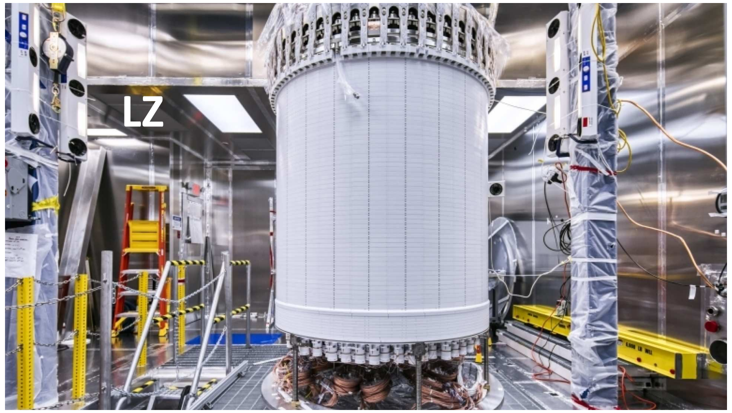
full knowledge in source

uncertainty in astrophysical models

Uncertainty in cosmological models

→ Common techniques: magnets & **photon science**

Three ways to study dark matter candidates

	Production in lab	Signal from astrophysics	DM from galaxy halo
WIMP SUSY			

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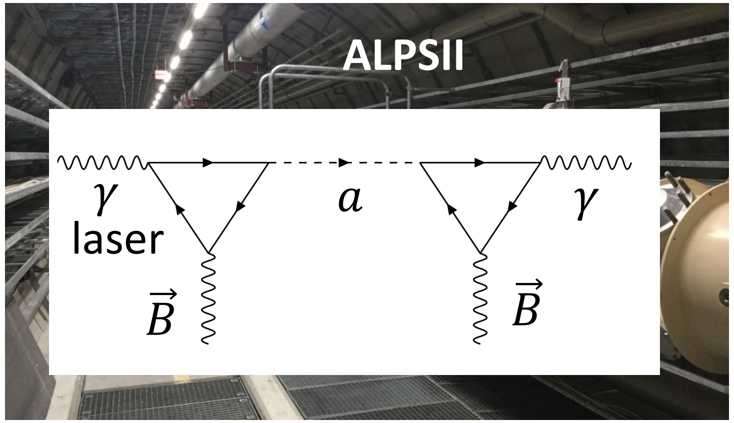
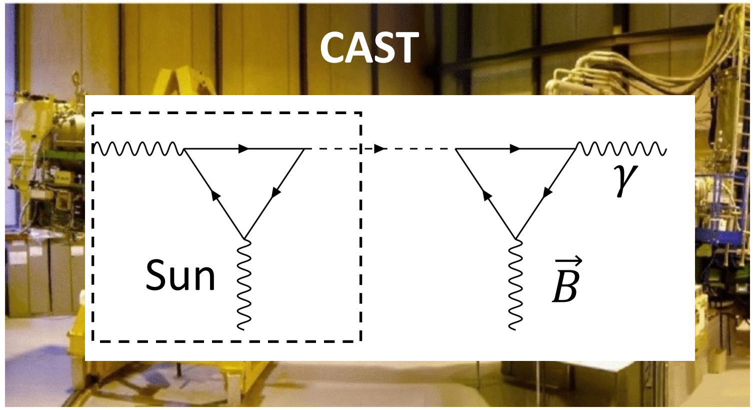
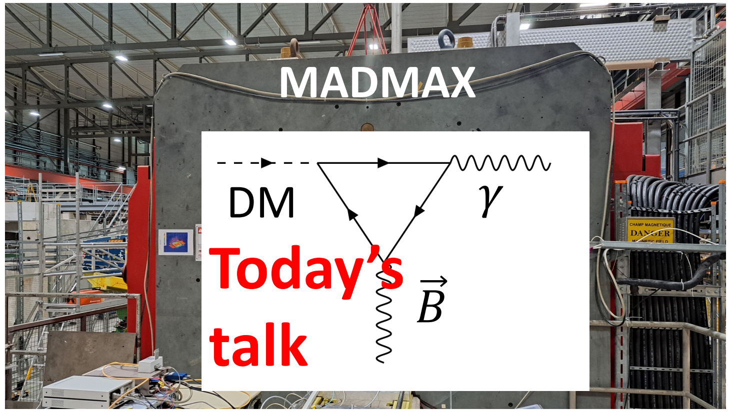
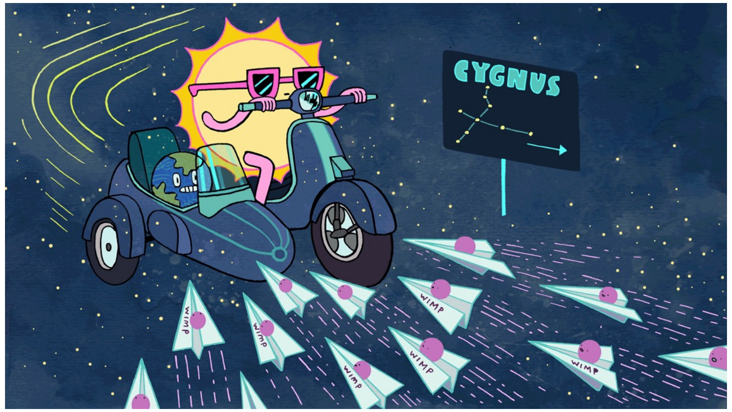
WISP axions			
	full knowledge in source	uncertainty in astrophysical models	Uncertainty in cosmological models

→ Common techniques: magnets & **photon science**

De Broglie wavelength λ_B vs density of DM $\bar{n}$



https://www.symmetrymagazine.org/article/wimps-in-the-dark-matter-wind Artwork by Sandbox Studio, Chicago with Corinne Mucha

- We are moving in the **galaxy halo of dark matter** with speed of 220 km/s → $\beta \sim 0.07\%$
- **Galaxy halo of dark matter density** $\rho \sim 0.45\ \text{GeV/cm}^3$

<u>WIMP: $m \sim 1$ TeV (?)</u>

$$\lambda_B \sim \frac{196\ \text{MeVfm}}{0.7\ \text{GeV}} = 0.3\ \text{fm}$$

$$\bar{n} \sim \frac{0.45\ \text{GeV/cm}^3}{1\ \text{TeV}} \sim 10^{-3}\ \text{cm}^{-3}$$

$$\rightarrow \bar{n} \ll \frac{1}{\lambda^3}$$

WIMP behaves as a particle

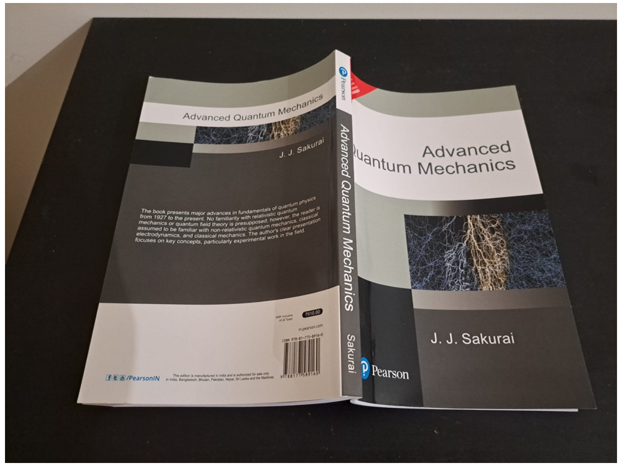
<u>Axions: $m \sim 10\ \mu\text{eV}$</u>

$$\lambda_B \sim \frac{2\times10^{-7}\ \text{eVm}}{7\ \text{neV}} = 28\ \text{cm}$$

$$\bar{n} \sim \frac{0.45\ \text{GeV/cm}^3}{10\ \mu\text{eV}} \sim 10^{13}\ \text{cm}^{-3}$$

$$\rightarrow \bar{n} \gg \frac{1}{\lambda^3}$$

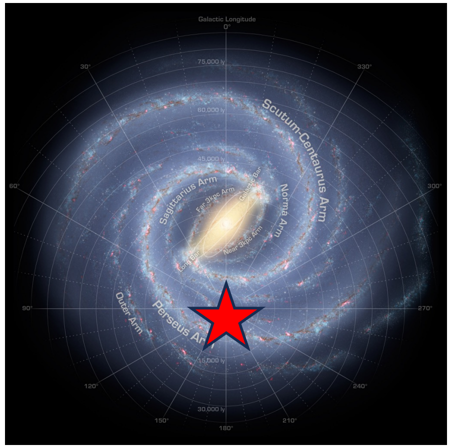
DM Axions behave as a wave

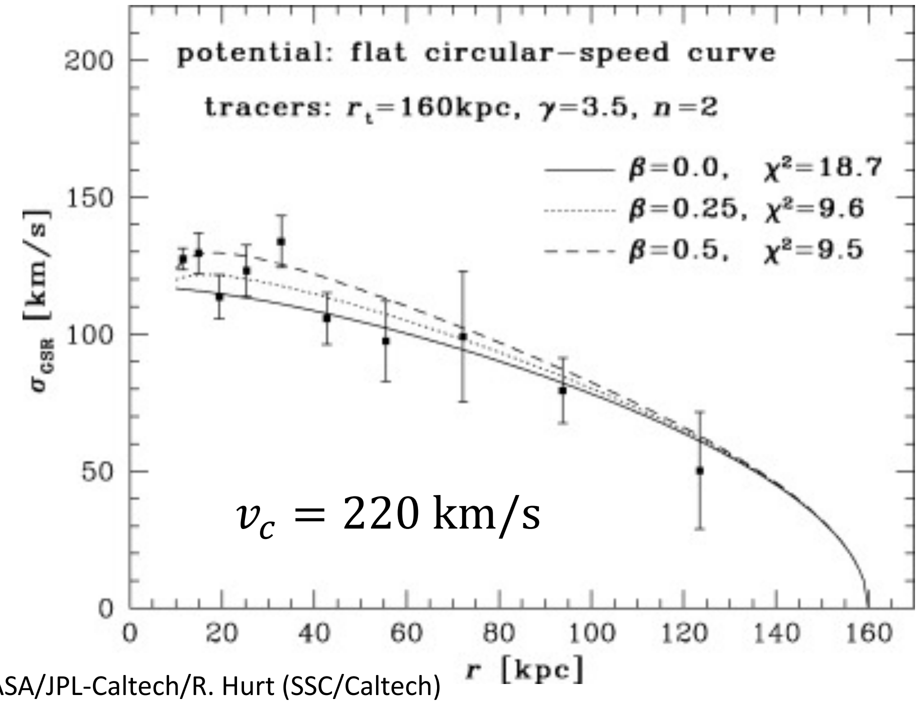


$$E_{cl}^2 = \frac{\bar{n}}{\lambda} \gg \frac{1}{\lambda^4} \sim \langle 0|\hat{E}\cdot\hat{E}|0\rangle$$

Standard model of dark matter axion distribution function

Velocity dispersion of Milky way Galaxy around



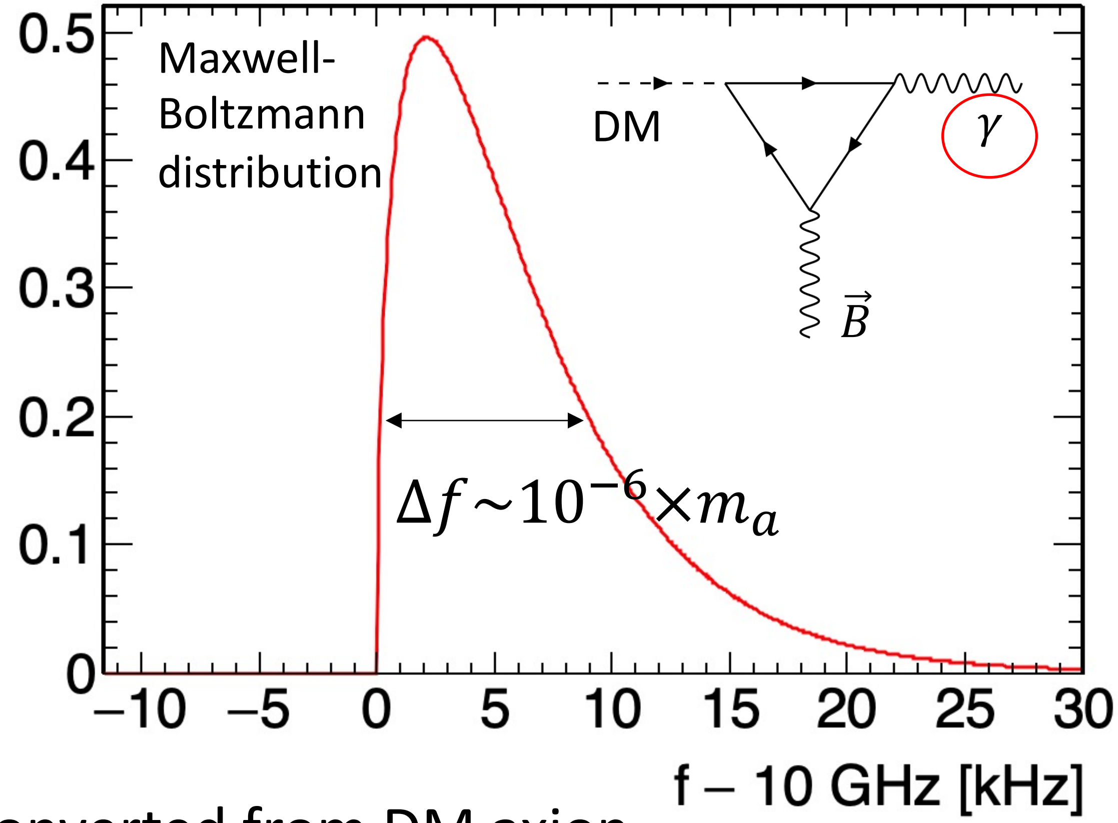


NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Mon Not R Astron Soc, Volume 369, Issue 4, July 2006, Pages 1688–1692,

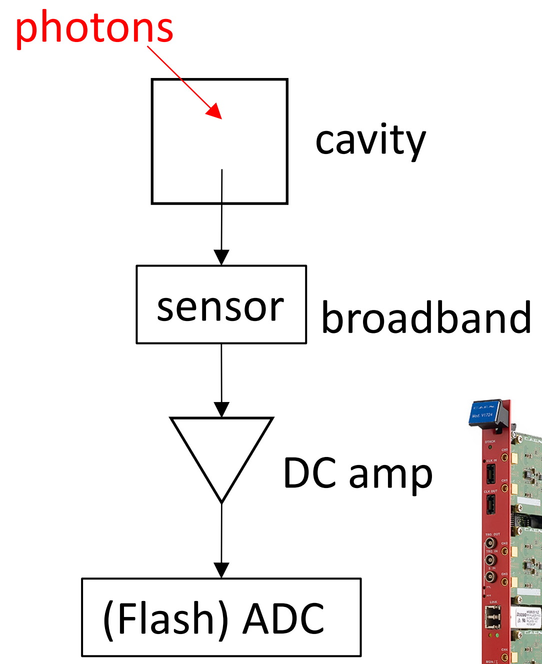
$$f(\omega) = P_0\theta(\omega - m_a)2\omega_0^{-\frac{3}{2}}\sqrt{\frac{\omega - m_a}{\pi}}\exp\left(-\frac{\omega - m_a}{\omega_0}\right)$$

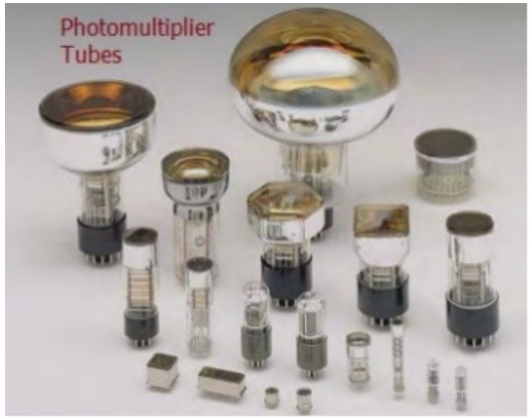
If $m_a = 10$ GHz

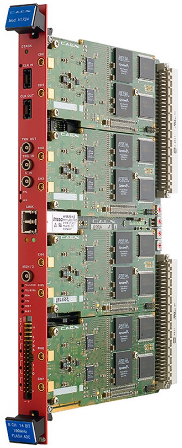


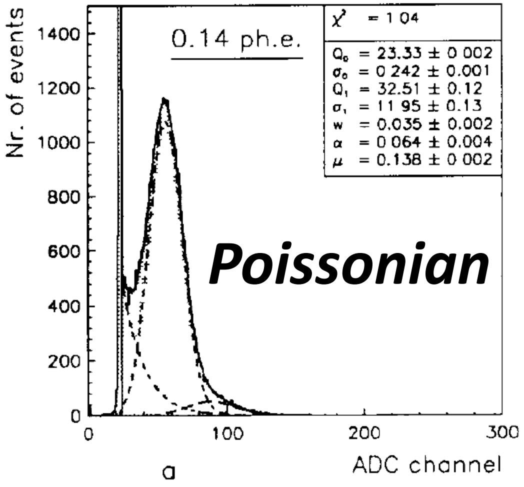
Microwaves converted from DM axion is very narrow band classical waves

Photon (energy) detection vs wave detection



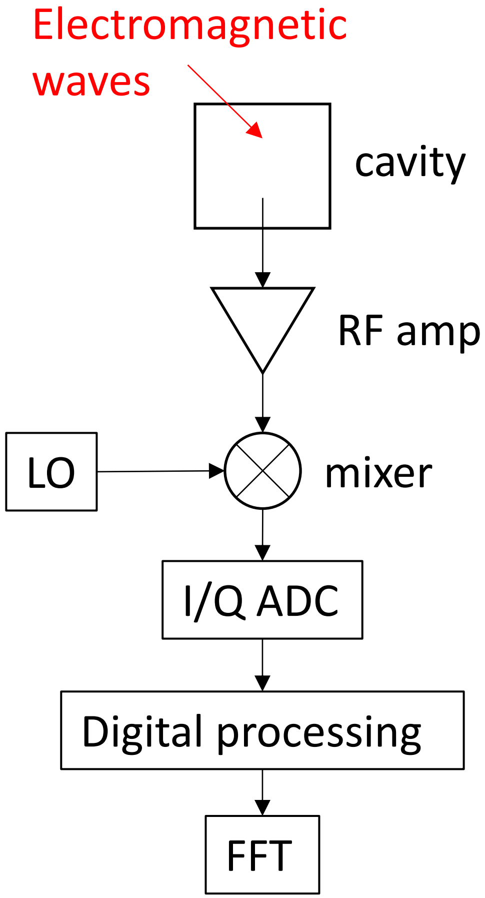


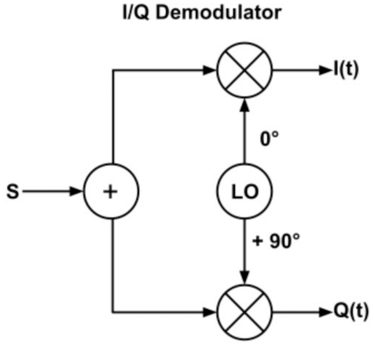




$$P(t) = n \times \hbar\omega \propto V_{ADC}\,(t)$$

$$\Delta\phi\Delta n > 0$$





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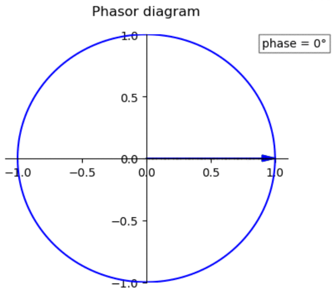
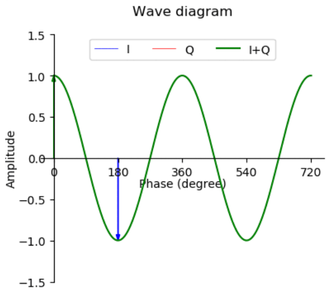
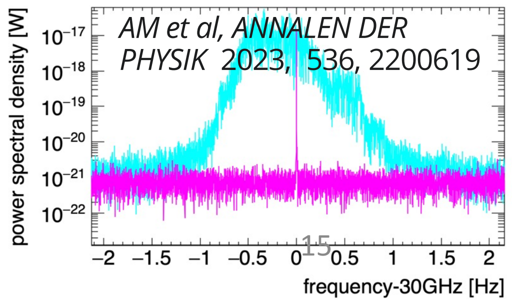




$$RF(t) = I(t)\cos(\omega t) + Q(t)\sin(\omega t)$$

$$\rightarrow P(\omega) = \tilde{I}^2(\omega) + \tilde{Q}^2(\omega)$$



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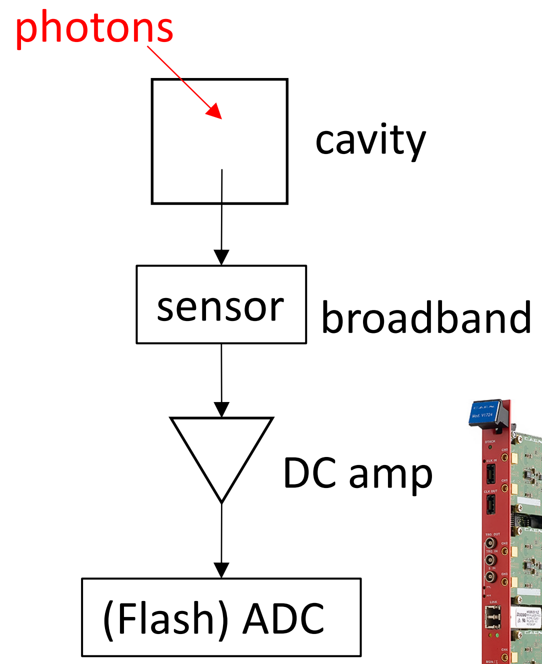

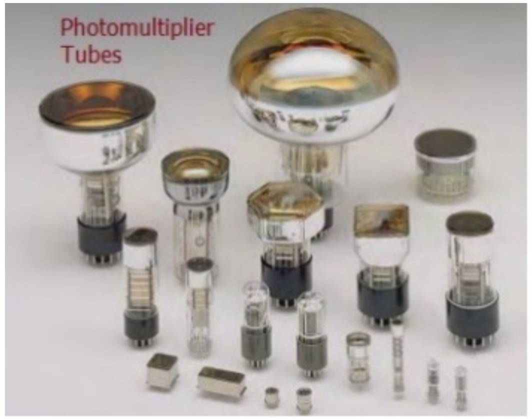

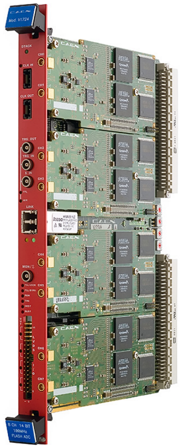

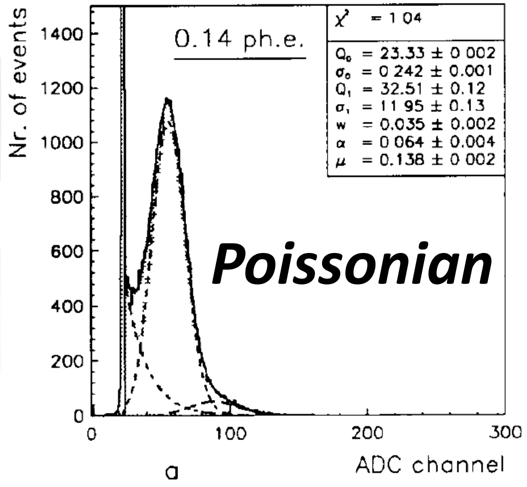

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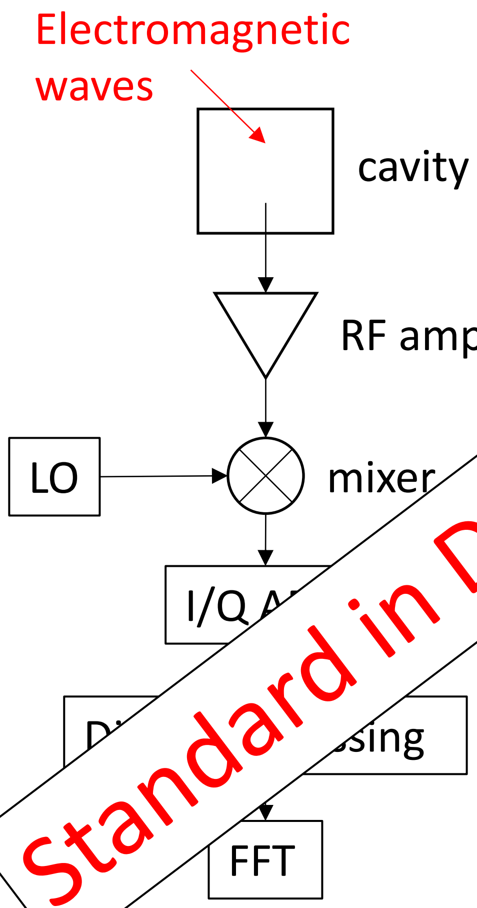

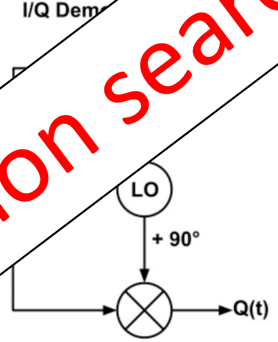

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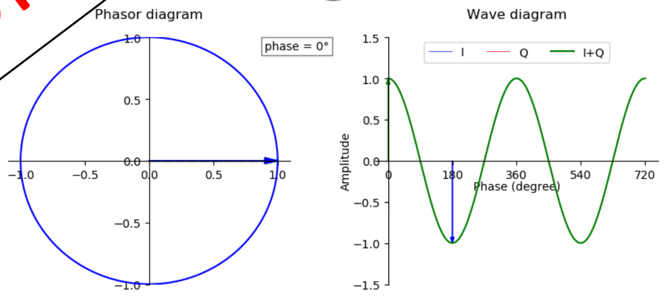
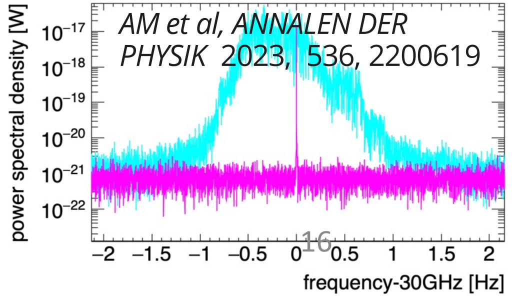


Standard in DM axion searches

$$RF(t) = I(t)\cos(\omega t) + Q(t)\sin(\omega t)$$

$$\rightarrow P(\omega) = \tilde{I}^2(\omega) + \tilde{Q}^2(\omega)$$



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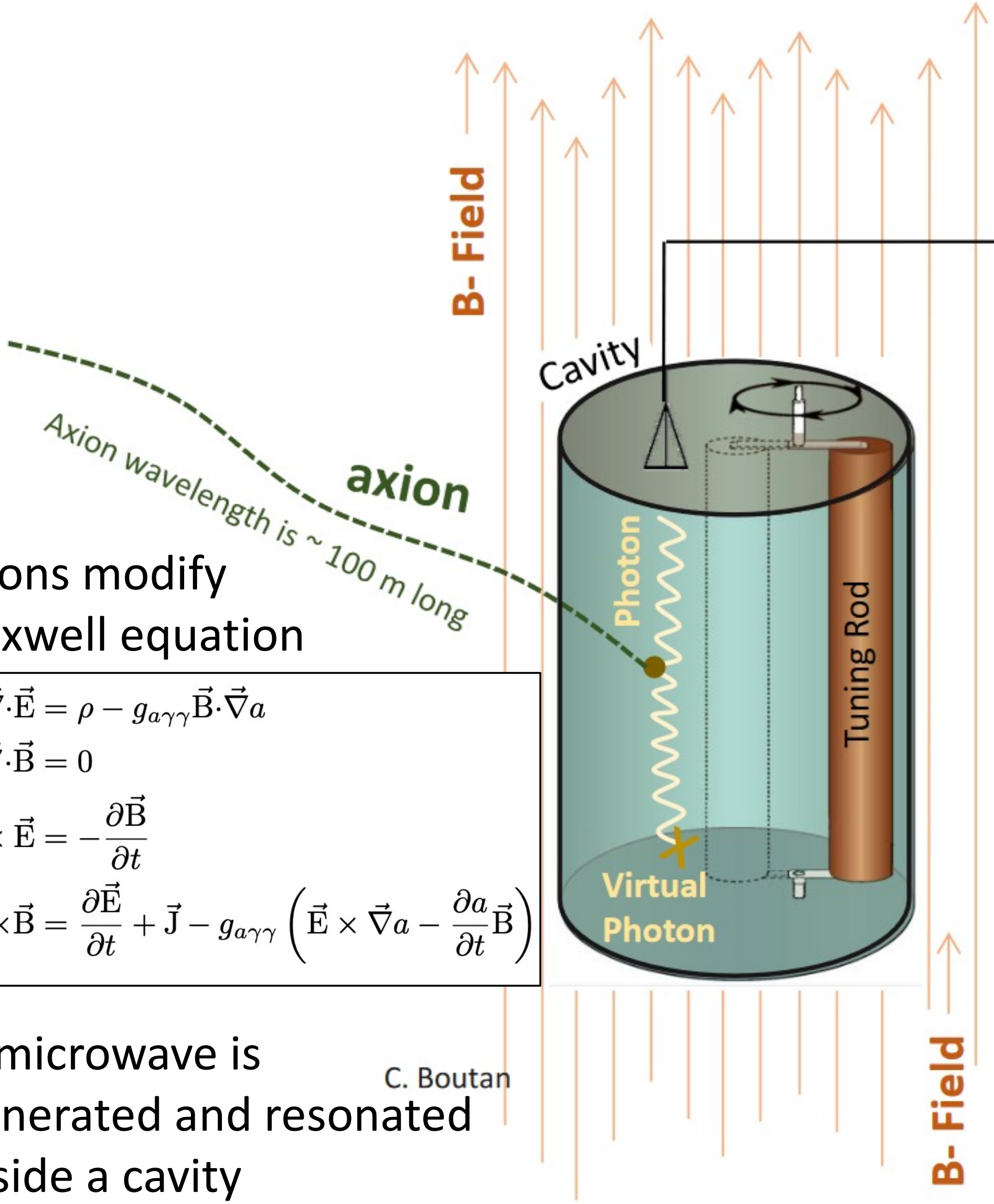
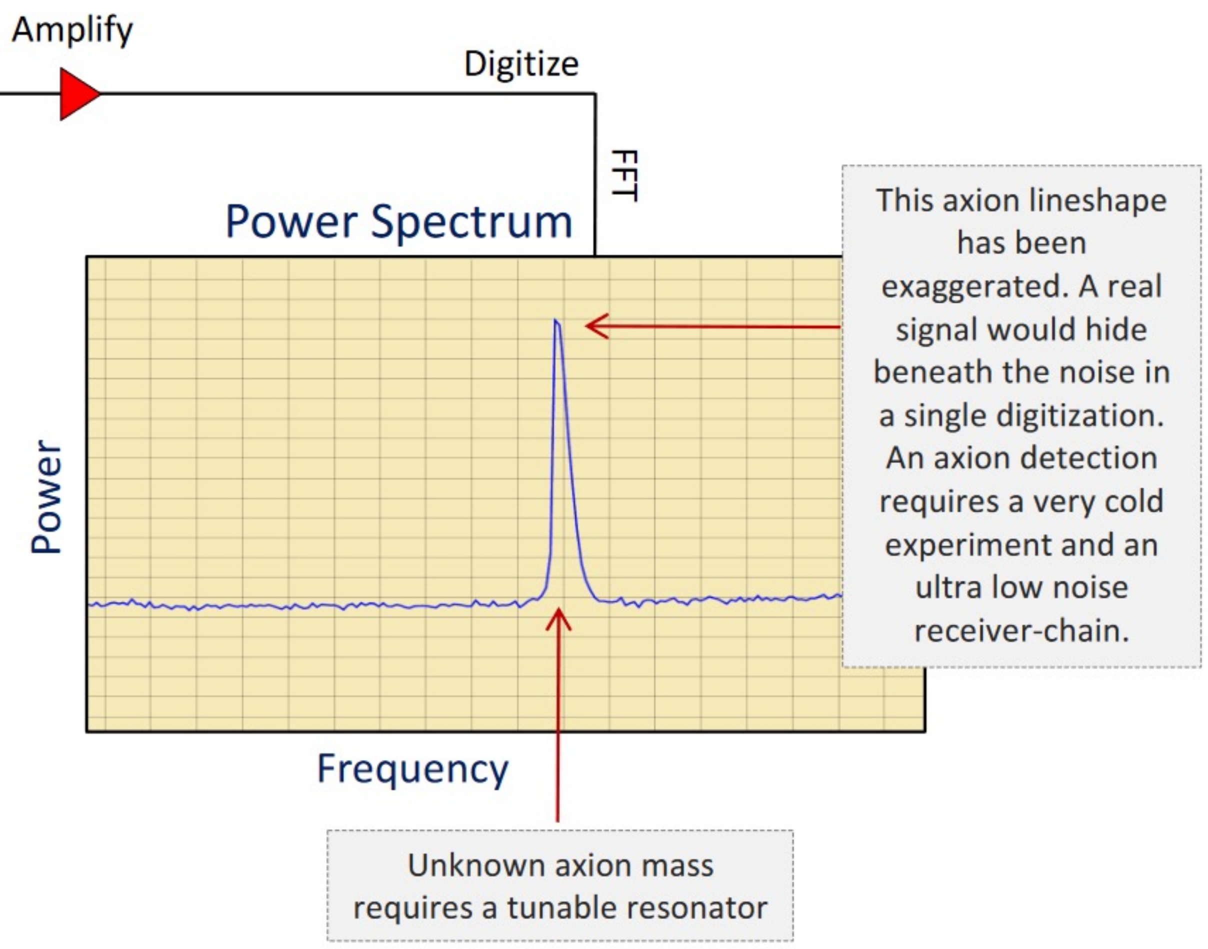
Classical electrodynamics is the mean to hunt axions

Skivie haloscope





Axions modify Maxwell equation

$$\vec{\nabla}\cdot\vec{E} = \rho - g_{a\gamma\gamma}\vec{B}\cdot\vec{\nabla}a$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + \vec{J} - g_{a\gamma\gamma}\left(\vec{E}\times\vec{\nabla}a - \frac{\partial a}{\partial t}\vec{B}\right)$$

A microwave is generated and resonated inside a cavity

Courtesy: Gray Rybka, PATRAS2022

Axion Dark Matter eXperiment (ADMX)

Signal to Noise Ratio is the key for discovery

arXiv:2010.00169

- Signal is a narrow peak ($f/\Delta f \sim 10^6$) from axion

$$P_S = (1.0\times10^{-22}\ \mathrm{W}) \times\left(\frac{V}{136\mathrm{L}}\right)\left(\frac{B}{6.8\mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g}{0.97}\right)^2\left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\left(\frac{Q}{50000}\right)$$

- Johnson Nyquist noise power

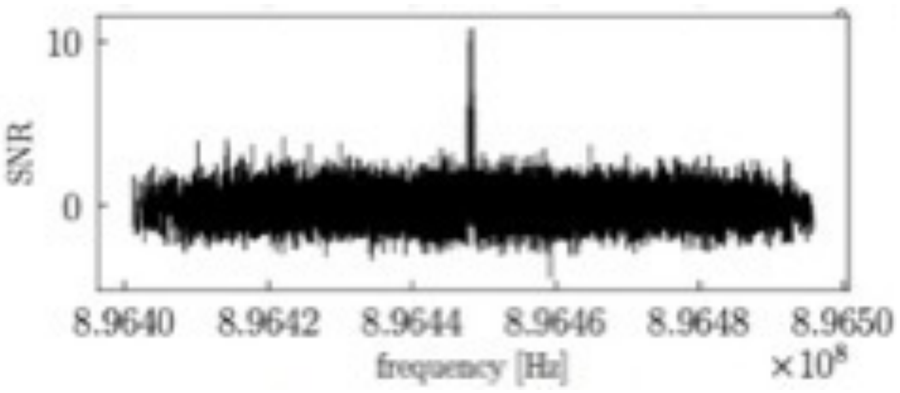
$$P_N = k_B T_s = 1.4\times10^{-23}\left(\frac{T_s}{1\mathrm{K}}\right)\ \mathrm{W/Hz}$$

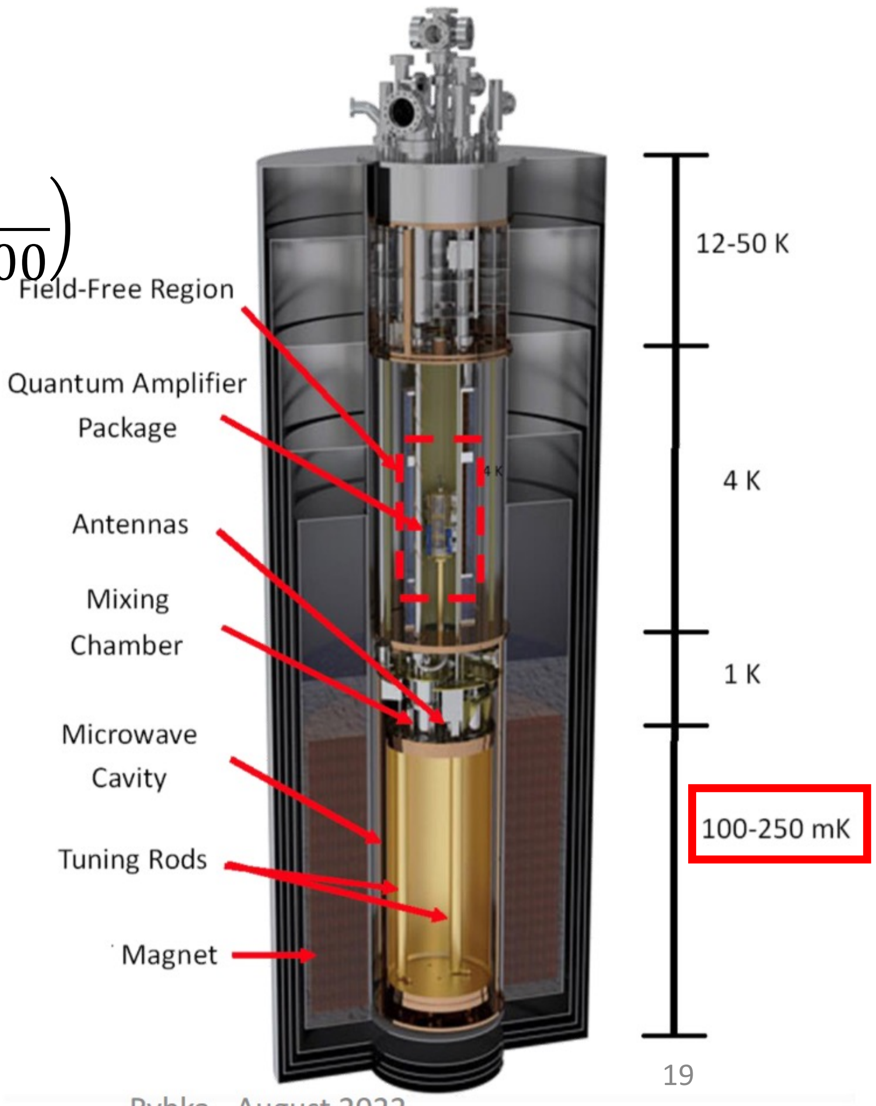
- Dicke's radiometer formula

$$S/_N = \frac{P_s}{P_N}\sqrt{\frac{t}{b}}$$

t: integration time

b: measurement bandwidth



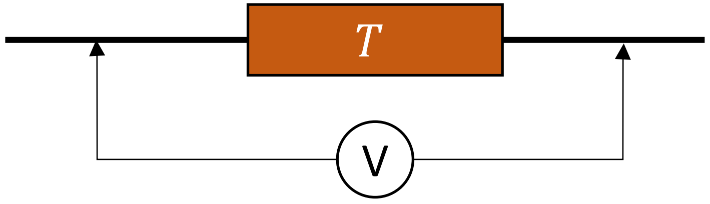


Jonsson Nyquist Noise

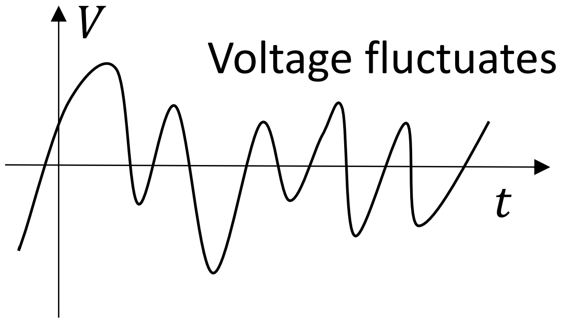
J. B. Johnson Phys Rev 32 97 (1928): Experimental discovery of the relation

H. Nyquist Phys Rev 32 110 (1928): Thermodynamics + statistical mechanics of **bosonic** modes

Any conductor at temperature T



$$\langle V^2\rangle \Delta\nu \sim 4R\Delta\nu \frac{h\nu}{e^{h\nu/k_BT}-1} \xrightarrow[\text{Rayleigh Jeans}]{h\nu \ll k_BT} 4Rk_BT\Delta\nu$$



$$P_N = \frac{\langle V^2\rangle}{4R}$$

Noise power spectral density $P_N = \dfrac{\langle V^2\rangle}{4R\Delta\nu} \sim k_BT$

→ "Blackbody radiation" of electromagnetic waves inside a 1D conductor

Quantum mechanical derivation H. B. Callen and T. A. Welton Phys Rev 1 34 (1951)

$$P_N = \left(\frac{h\nu}{2} + \frac{h\nu}{e^{h\nu/k_BT}-1}\right) \quad [\mathrm{W/Hz}]$$

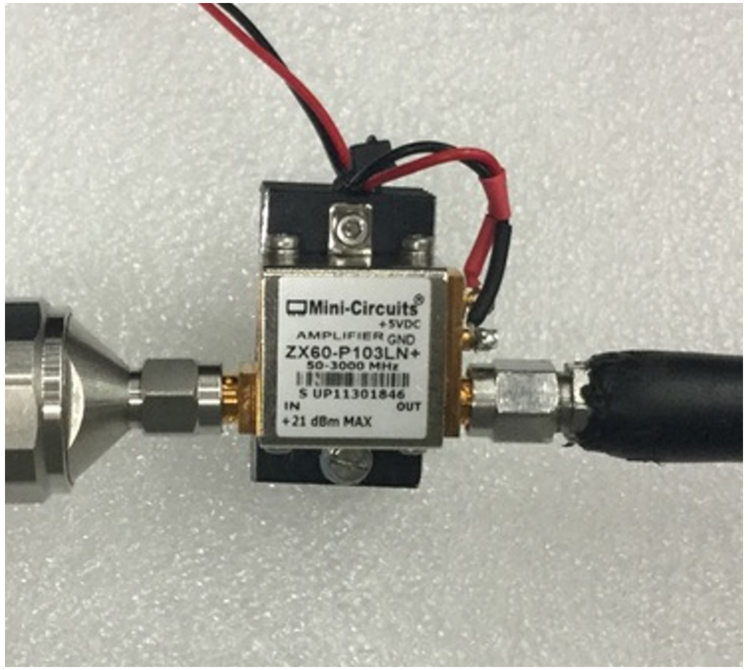
Zero-point energy

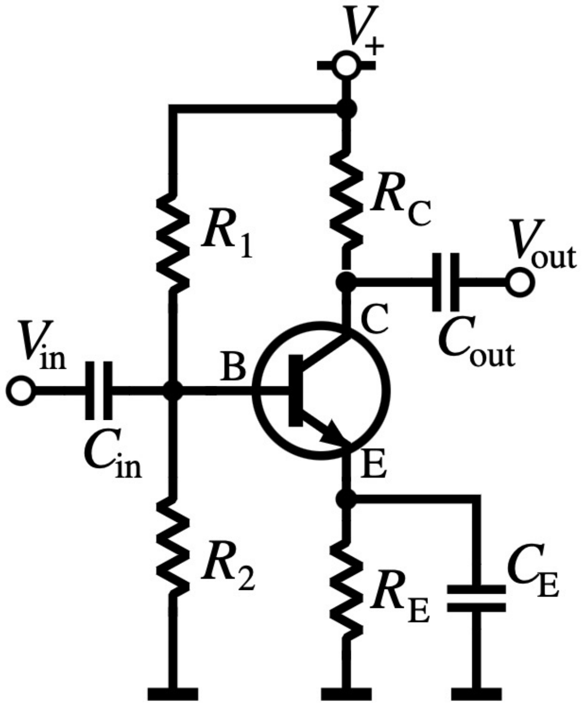
→ Cooling down reveals fundamental noise floor

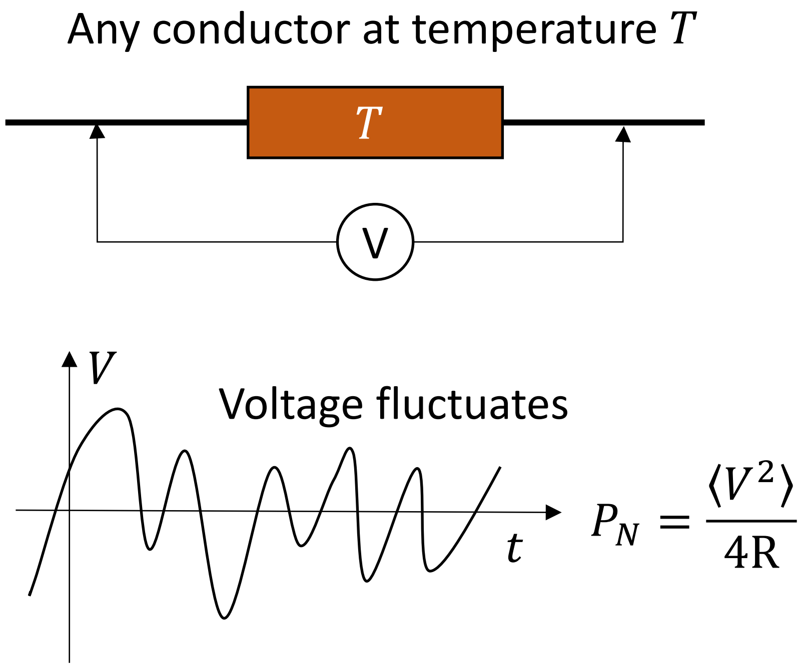
$P_{SQL} = h\nu$: standard quantum limit

Ex) $h\times 1$ GHz $= 6.6\times 10^{-25}$ W/Hz

Classical: amplifier based on transistors







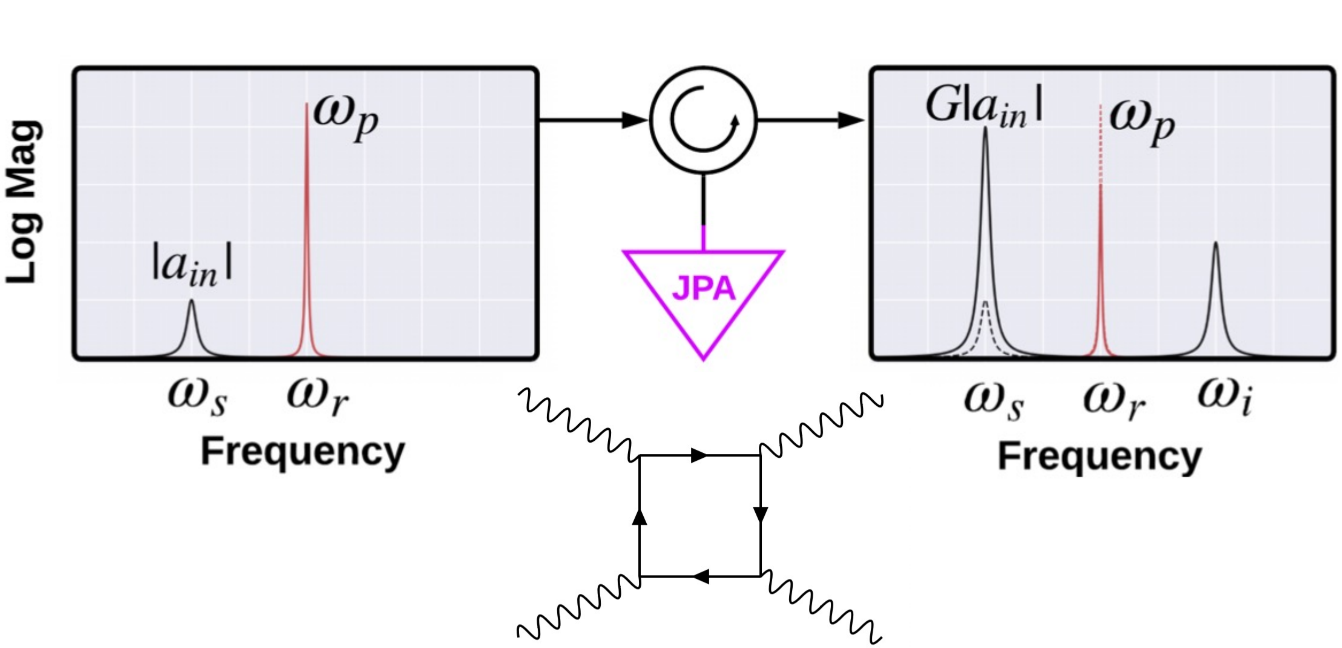
- Amplification of microwaves (typically $>\times 100$) via electron or hole current in the transistors
- Noise sources
  - Resistance' thermal noise
  - Shot noise of currents (dominating)

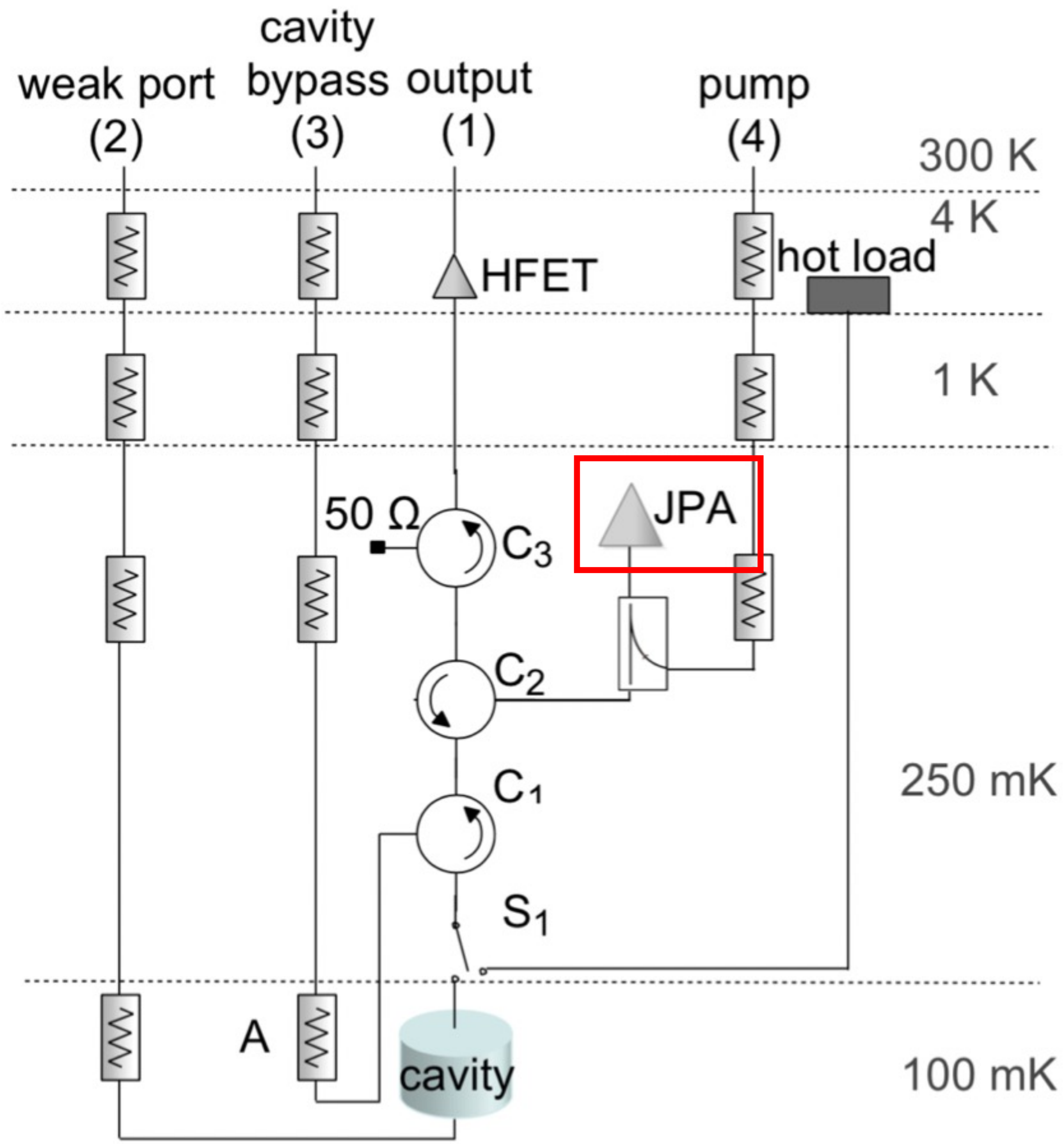
→ The effective noise temperature is always limited by a certain value

→ One cannot reach standard quantum limit by cooling down $k_B T_{SQL} = h\nu < k_B T_s$ ☹

arXiv:2010.00169

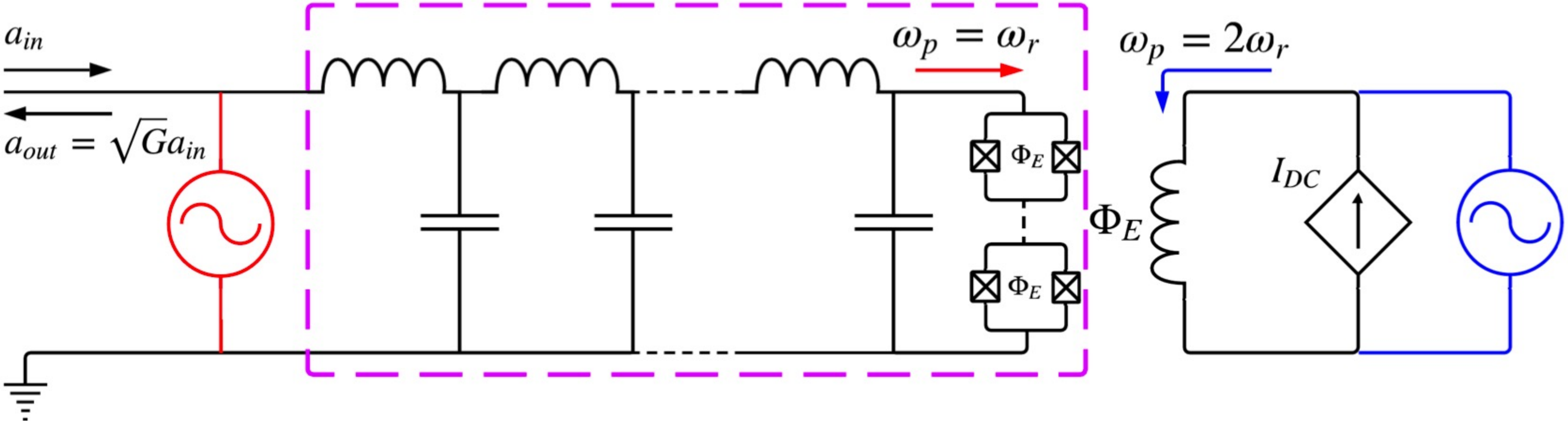
Semi-classical: Parametric Amplifier (in ADMX)



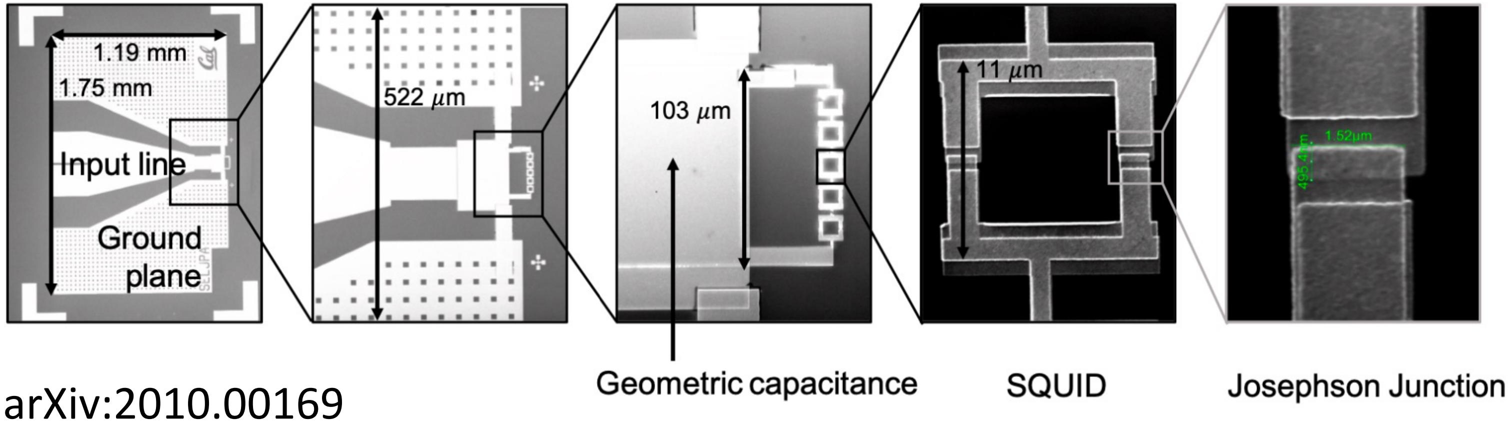


- Amplification of microwave signal at ω_s via pump microwaves at ω_p
- Nonlinear optics (Kerr effect) for frequency mixing
- No real electron/hole current
  → Free from the noise source of transistors
  → One can reach $k_B T_{SQL} = h\nu$ by cooling down

Implementation: Josephson Parametric Amplifier



$$L_J = \frac{L_{J0}}{\sqrt{1-(I/I_0)^2}} = L_{J0}\left(1 + \frac{1}{2}(I/I_0)^2 + \ldots\right)$$



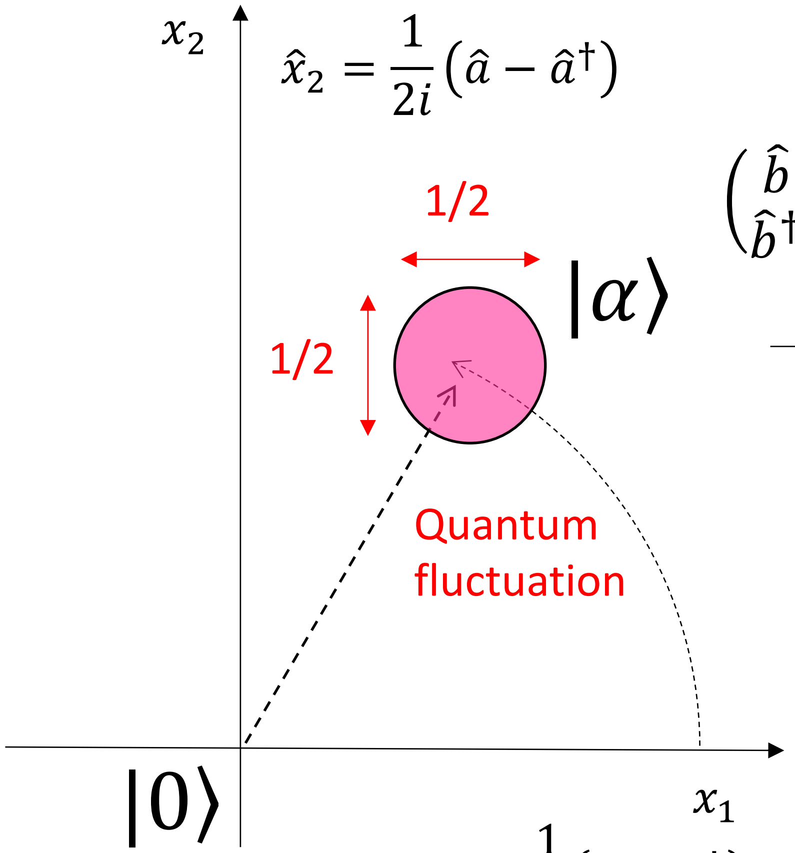
arXiv:2010.00169

- The nonlinearity is induced from Josephson junctions inside SQUID
- Although SQUID is a superconducting quantum device, **microwave's behavior is classical** (→ semi-classical)

Another use of JPA: Squeezed state (not in ADMX)

$$\hat{H} = \left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)\hbar\omega + \hbar\left(\frac{E^*}{2}\hat{a}^2 + \frac{E}{2}\hat{a}^{\dagger 2}\right)$$

Nonlinear term added by parametric oscillation

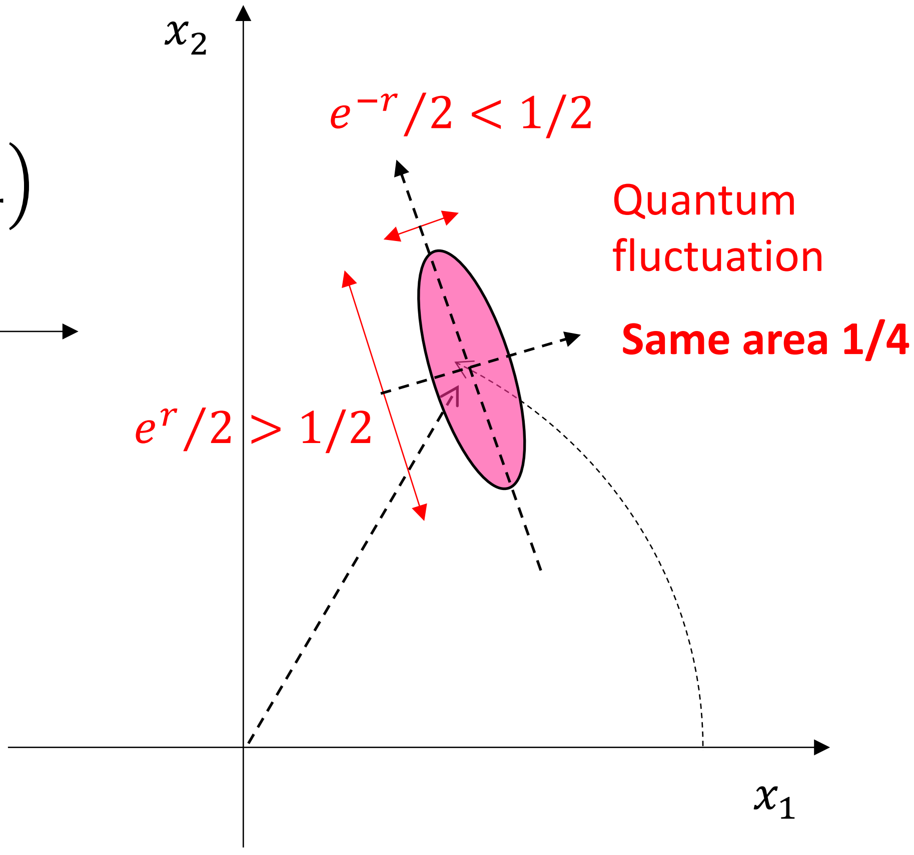


$\hat{x}_1 = \frac{1}{2}(\hat{a} + \hat{a}^\dagger)$

$$\begin{pmatrix}\hat{b}\\ \hat{b}^\dagger\end{pmatrix} = \begin{pmatrix}\cosh r & e^{2i\phi}\sinh r\\ e^{-2i\phi}\sinh r & \cosh r\end{pmatrix}\begin{pmatrix}\hat{a}\\ \hat{a}^\dagger\end{pmatrix}$$

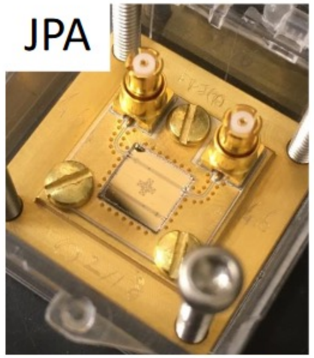
$$\hat{H} = \hbar\lambda\hat{b}^\dagger\hat{b} + \frac{\lambda - \omega}{2}$$

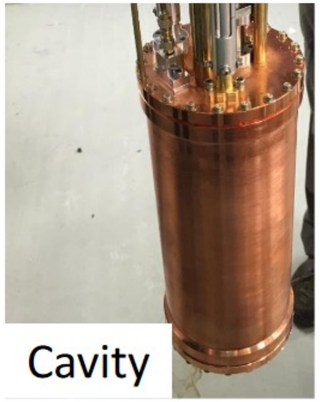
$$\begin{cases}\lambda = \sqrt{\omega^2 - |E|^2}\\ r = \frac{1}{2}\tanh^{-1}(|E|/\omega)\\ e^{2i\phi} = E/|E|\end{cases}$$



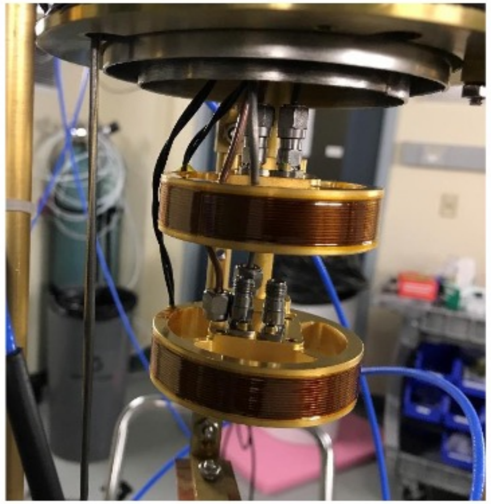
Axions search is entering a quantum regime

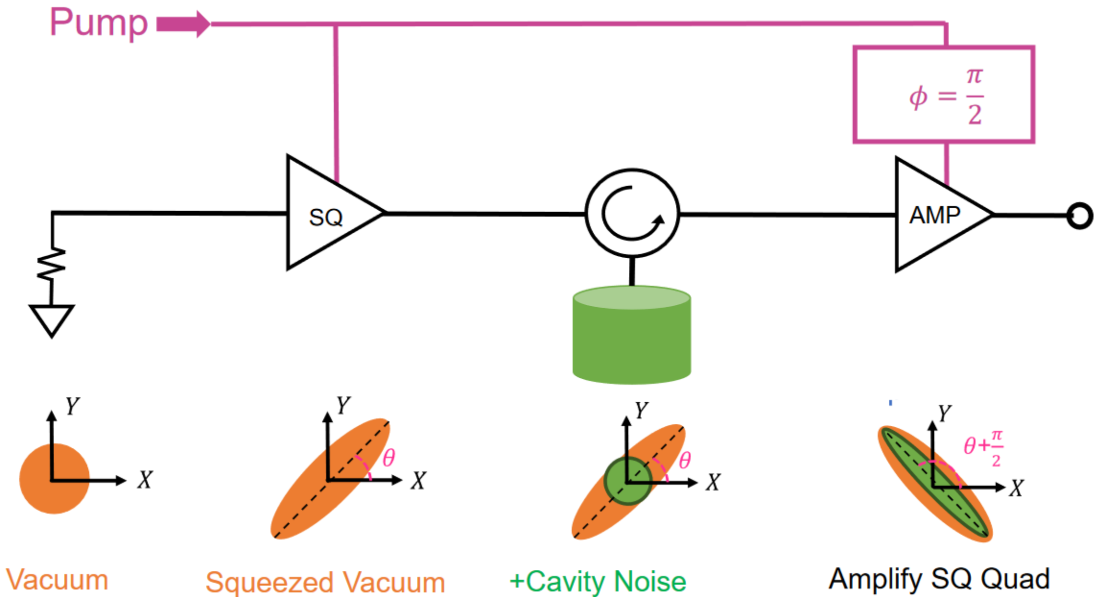
HAYSTAC reduces one of the noises via squeezing



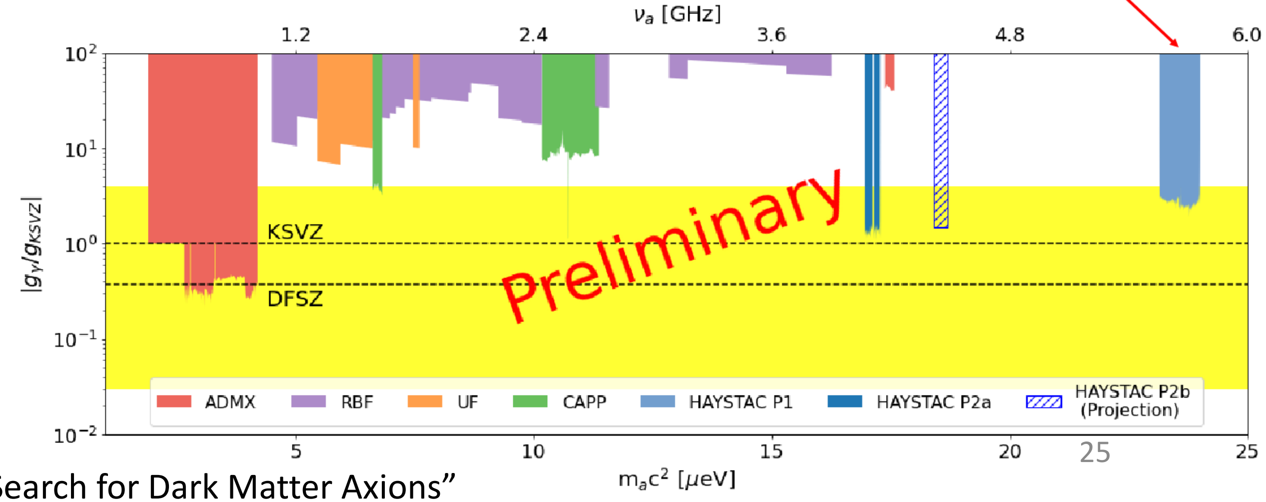


Squeezed State Receiver





- Results are still being analyzed



Single quadrature read-out & reduced external noise from squeezed read-out line

→ Currently ×2 (finite loss in circuit)

→ potentially >×20

Courtesy: Michael Jewell, "Updated Results from HAYSTAC's Quantum-Enhanced Search for Dark Matter Axions"

Single photon sensors (?)

Noise power of wave detection

$$P_l = h\nu(\bar{n}+1)\sqrt{\frac{\Delta\nu}{t}} \propto \nu$$

Noise power of photon detection

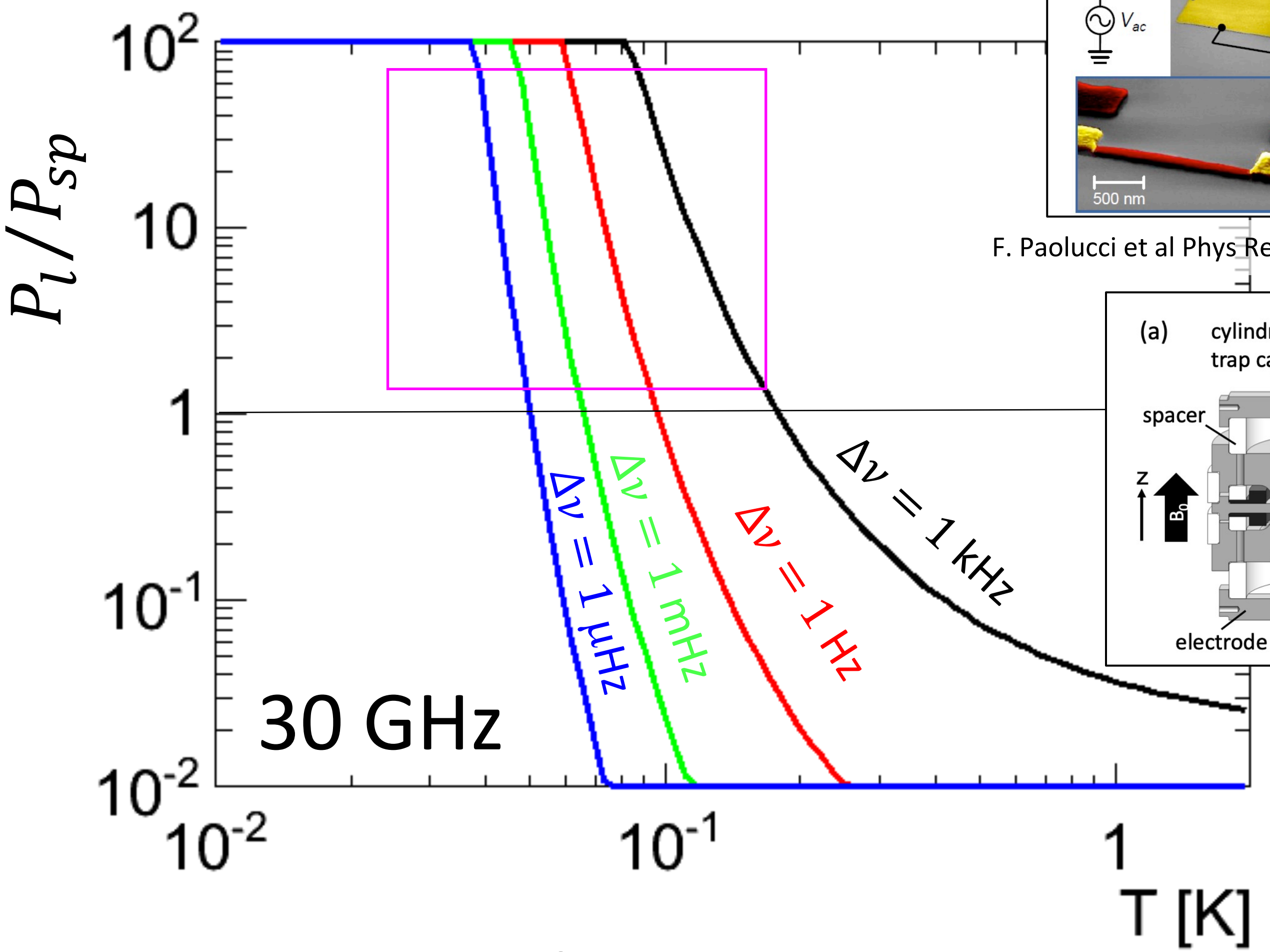
$$P_{sp} = h\nu\sqrt{\frac{\eta\bar{n}Q_c}{2\pi\nu t}} \propto \sqrt{\nu}$$

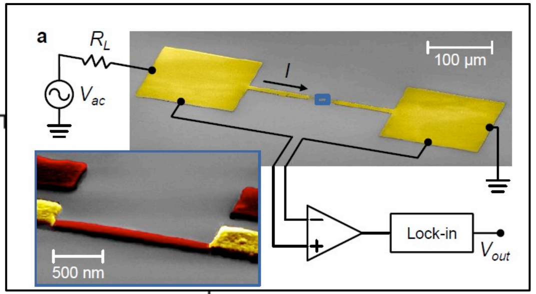
$$\bar{n} = \frac{1}{e^{h\nu/k_BT}-1}$$

Q_c: cavity quality factor

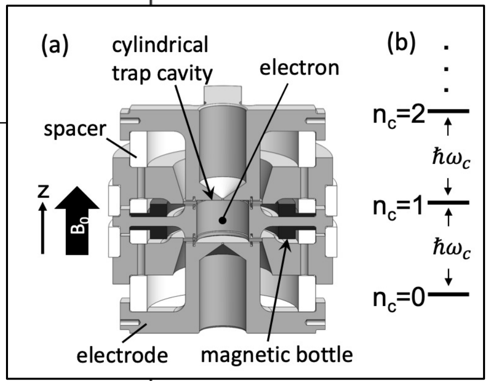
η: quantum efficiency of the sensor

S.K. Lamoreaux et al Phys Rev D 98 035020 (2013)





F. Paolucci et al Phys Rev Appl. 14 034055 (2020)



X. Fan et al, PRL129, 261801, 2022

Single photon sensors may be a solution in the future

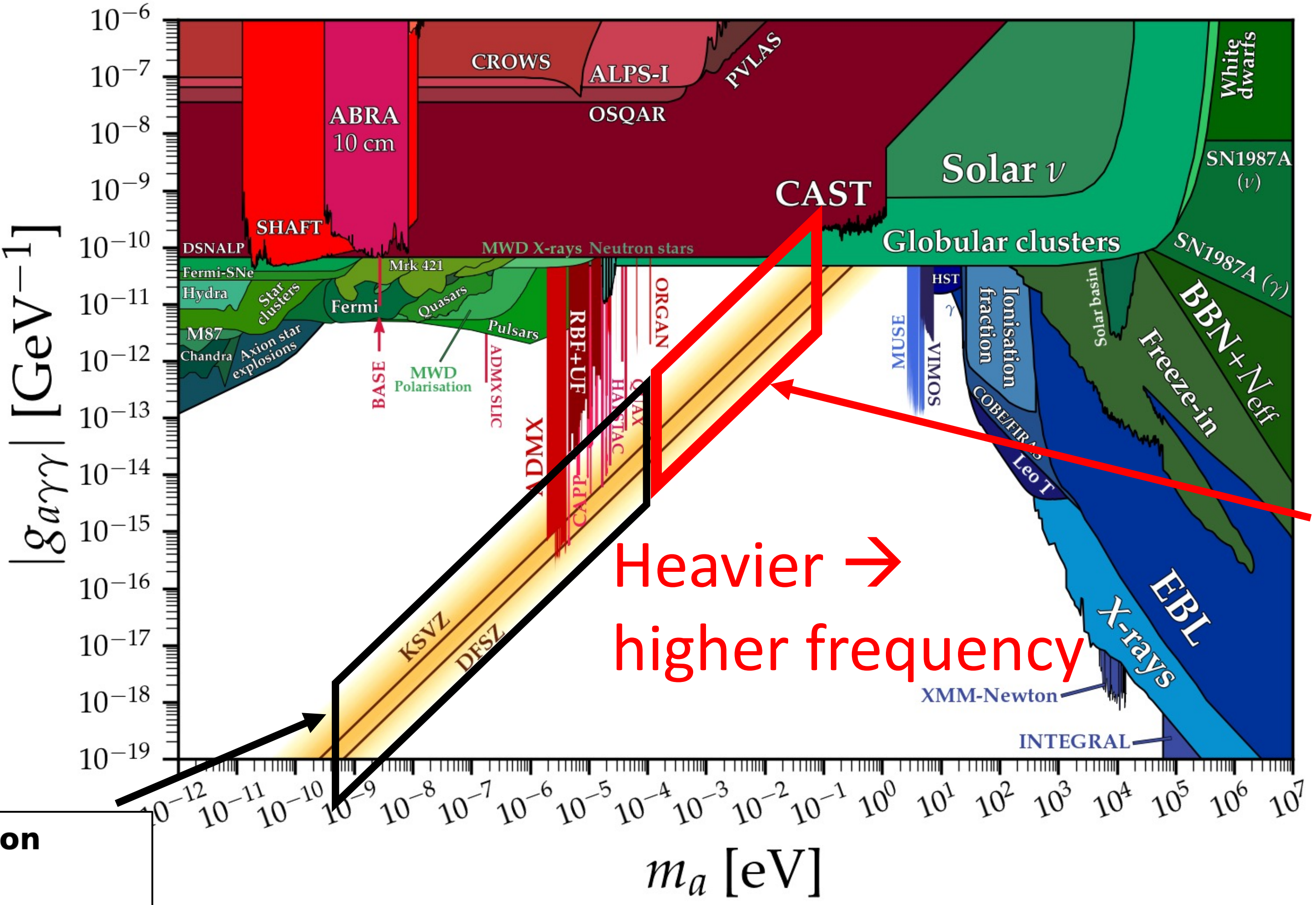
→ Although one loses phase information, zero background at cold may be better

→ Lower noise in **higher frequency** → where is the cross-over? 10 GHz? 100 GHz??

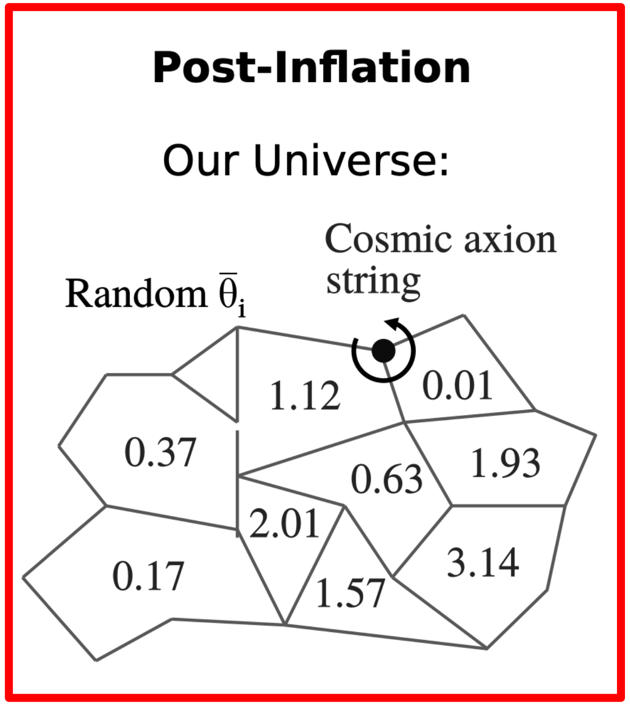
Outline

- Introduction
  - New physics with microwaves
  - Axion and axion dark matter
  - Particle vs wave
- State of the art
  - ADMX experiment
  - Background noise and quantum limit
  - Squeezing (HAYSTAC) and photon counting
- New experiments
  - Challenge toward higher frequency
  - Dish antenna: signal from metal/vacuum interface
  - MADMAX: signal boost with dielectric disks
  - ALPHA: plasma haloscope with wire metamaterial
- Conclusion

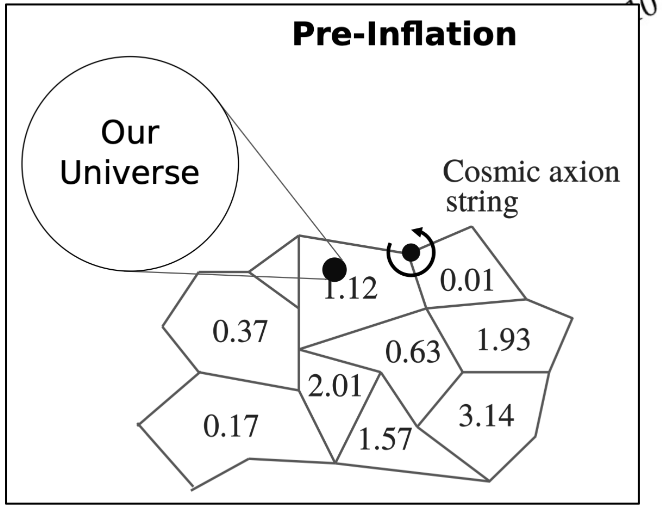
From now

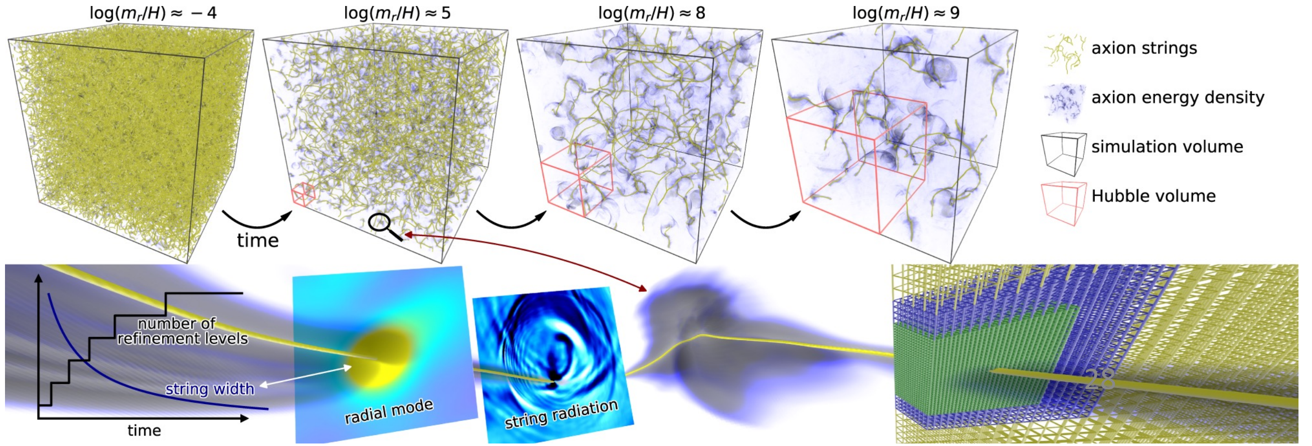


Heavier → higher frequency



So far

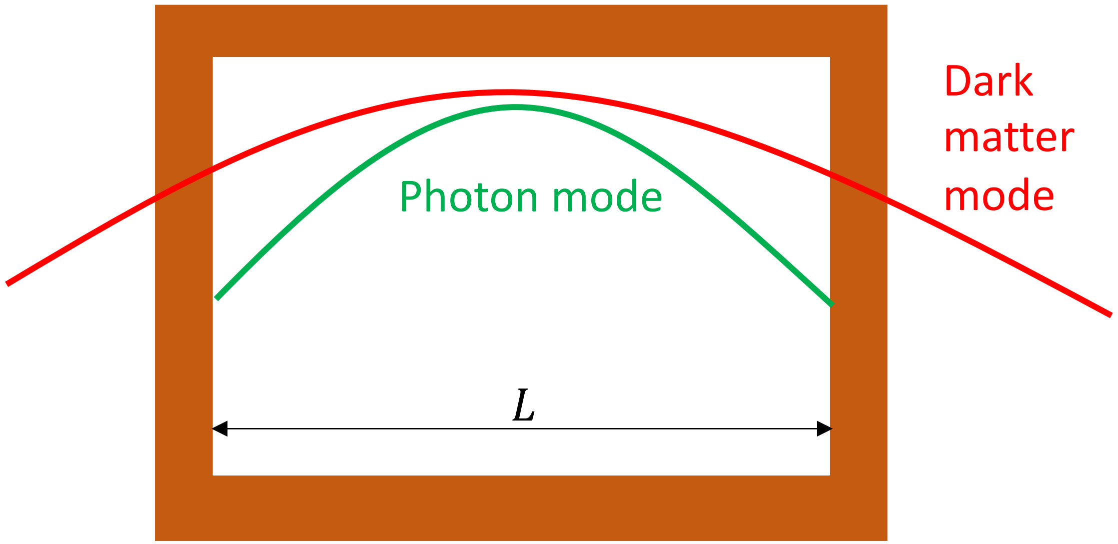




Buschmann, *et al. Nat Commun* **13**, 1049 (2022)

Issue of high-frequency resonators for dark matter search

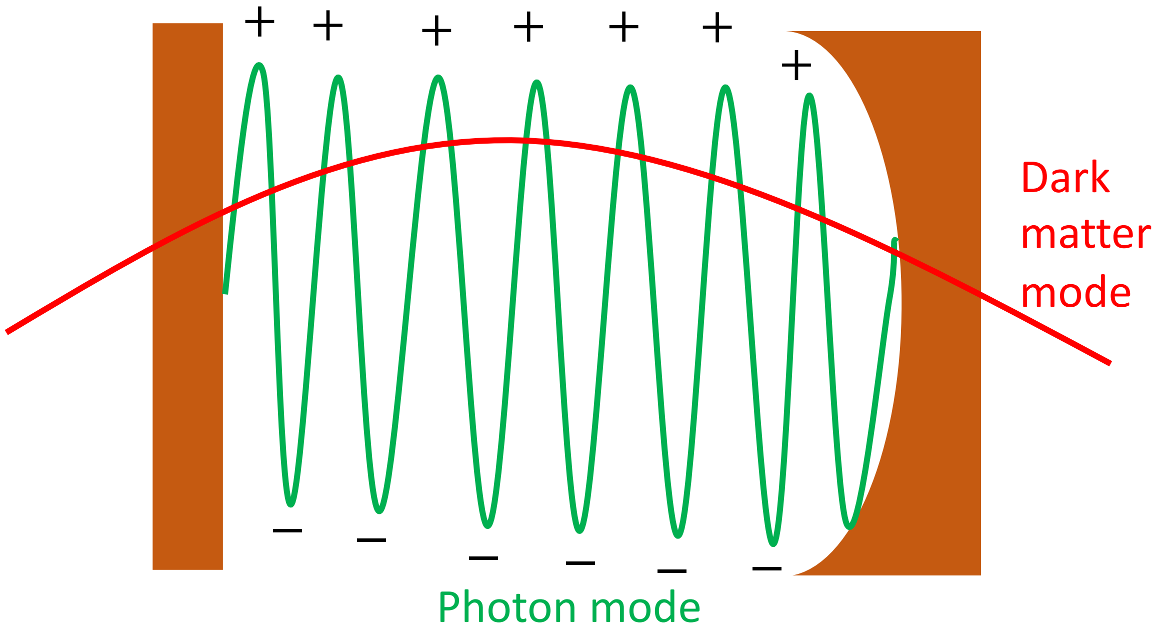
An RF cavity (ADMX-type) becomes $V \sim f^{-3}$



Signal: $\propto VQ$

The signal is lost by higher frequency

An over-sized cavity cancels the signal



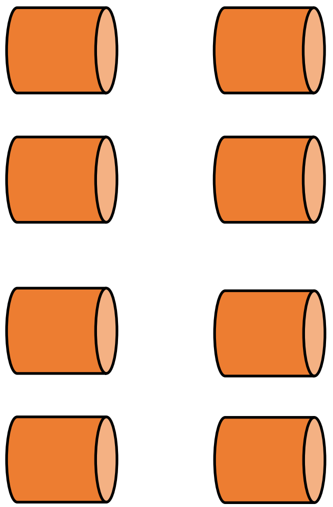
The dark matter is cold → De Broglie wavelength is long

Spatial integral is cancelled!

→ We have needed an idea to keep the resonator size reasonable with high frequency without having polarity changes

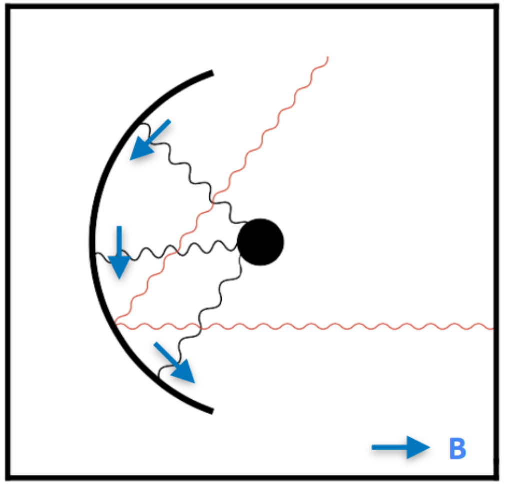
Four ideas toward heavier axion dark matter

Multiple small cavities



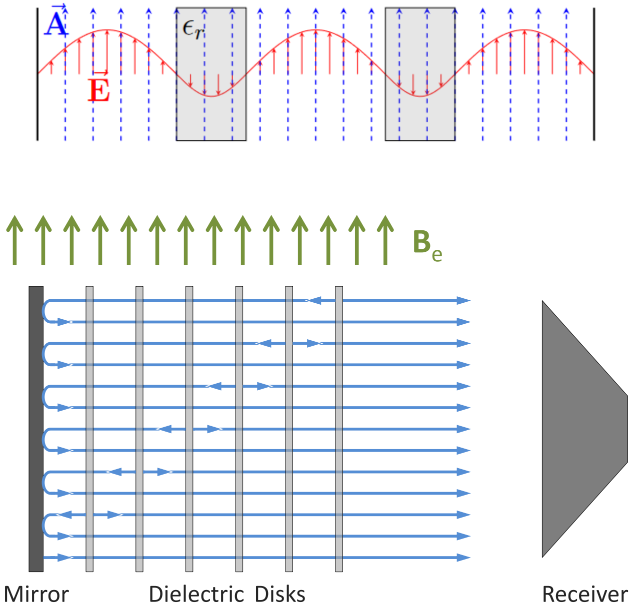
ADMX-EFR @ US
CAST-CAPP @ CERN

Dish antenna



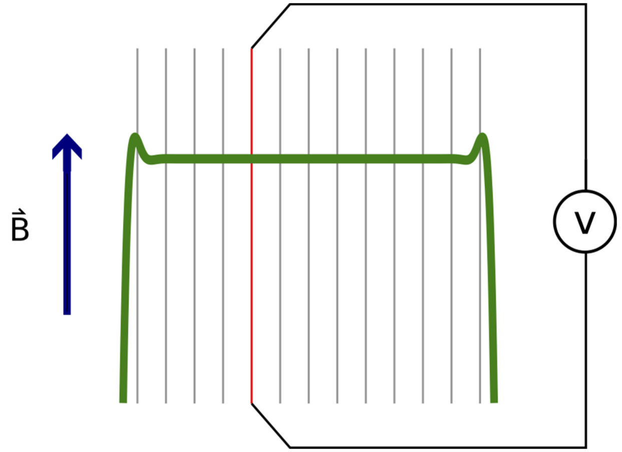
BRASS @ DESY
BREAD @ US

Dielectric disks



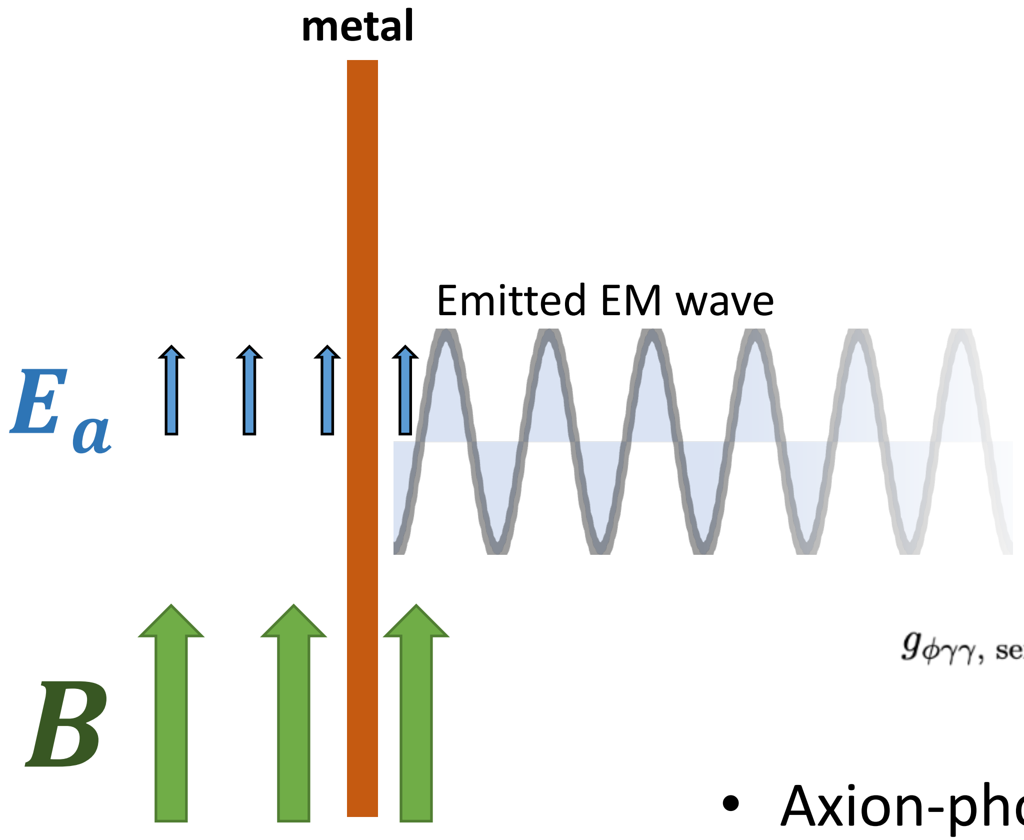
ORGAN @ Australia
ADMX-Orpheus @ US
MADMAX @ DESY

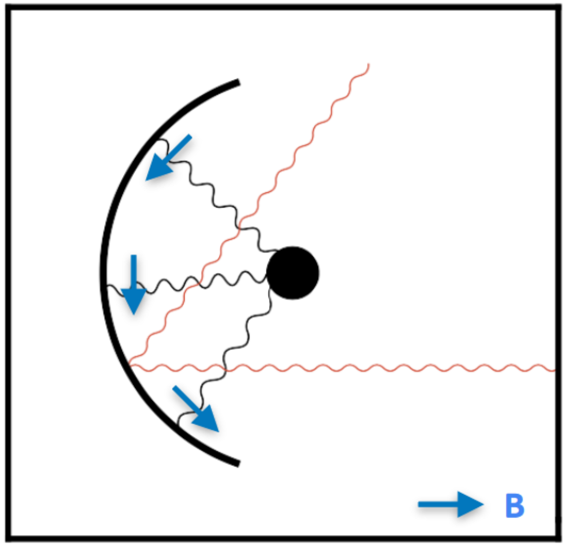
Wire metamaterial



ALPHA @ SU
New projects rising

Dish antenna: mismatch between metal and vacuum





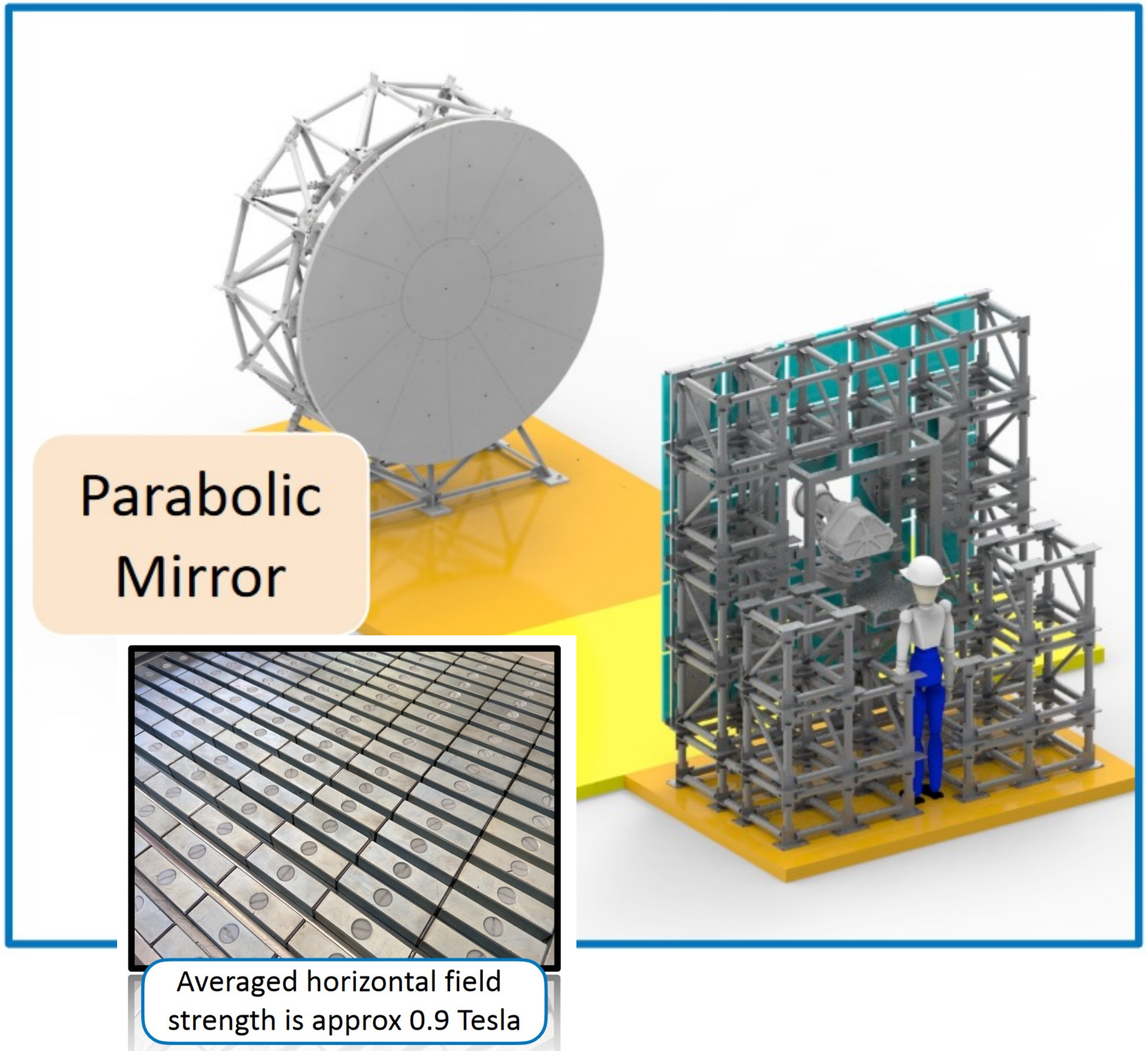
$$g_{\phi\gamma\gamma,\,\mathrm{sens}} = \frac{3.6\times 10^{-8}}{\mathrm{GeV}} \left(\frac{5\,\mathrm{T}}{\sqrt{\langle |\mathbf{B}_{||}|^2\rangle}}\right) \left(\frac{P_{\mathrm{det}}}{10^{-23}\,\mathrm{W}}\right)^{\frac{1}{2}} \left(\frac{m_\phi}{\mathrm{eV}}\right) \left(\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_{\mathrm{DM,halo}}}\right)^{\frac{1}{2}} \left(\frac{1\,\mathrm{m}^2}{A_{\mathrm{dish}}}\right)^{\frac{1}{2}}$$

Horns et al, arXiv:1212.2970, JCAP04(2013)016

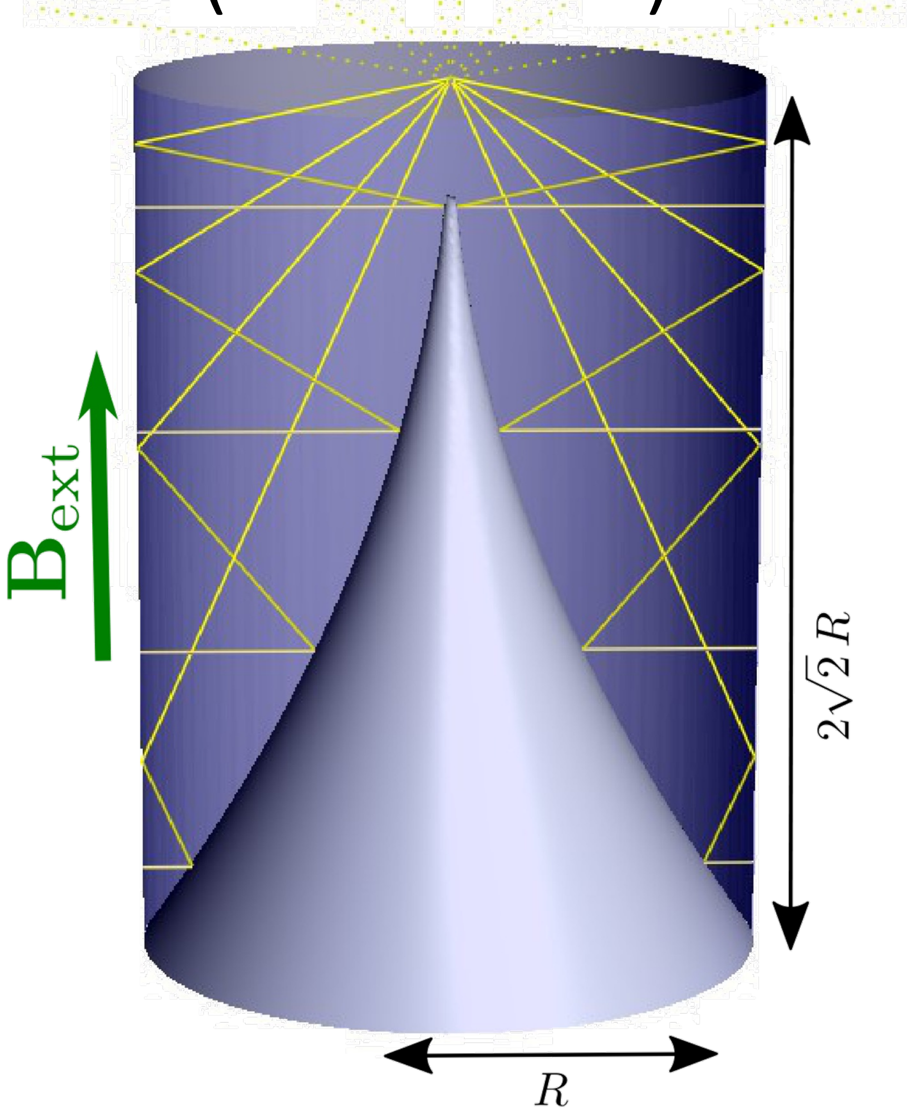
- Axion-photon conversion at the metal-vacuum interface
- Signal enhancement by **larger area**
- Challenge: parallel B-field on the large area of a metal surface

Courtesy: Le Hoang Nguyen, "Development, Calibration and Current Status of the BRASS-p Experiment"
Courtesy: Stefan Knirck, "BREAD: Broadband Reflector Experiment for Axion Detection"

BRASS-p (DESY) & BREAD (Fermilab)



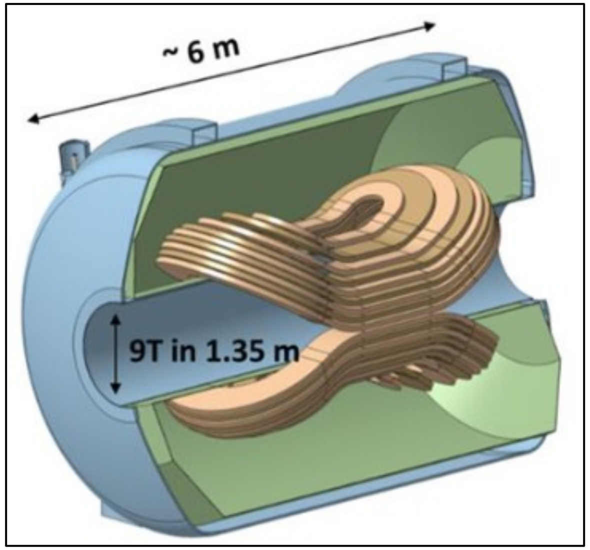
Courtesy: Le Hoang Nguyen, “Development, Calibration and Current Status of the BRASS-p Experiment” PATRAS2022

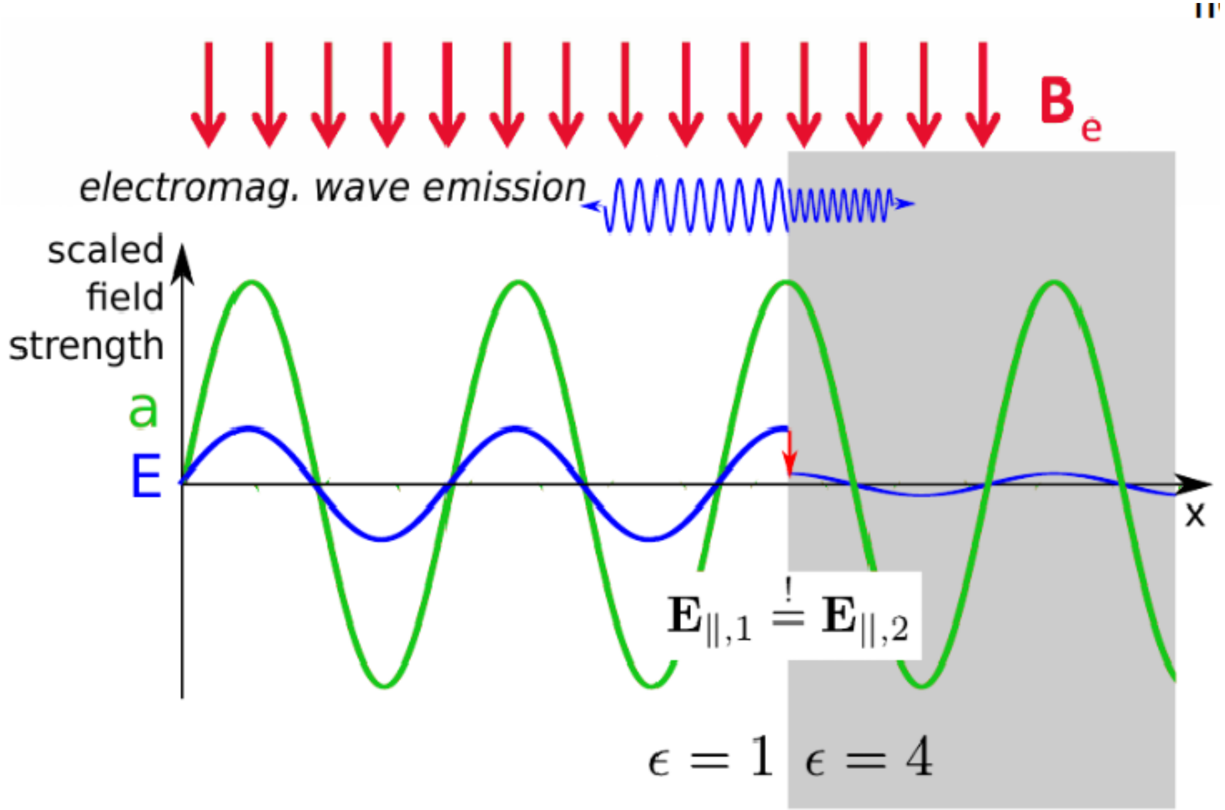


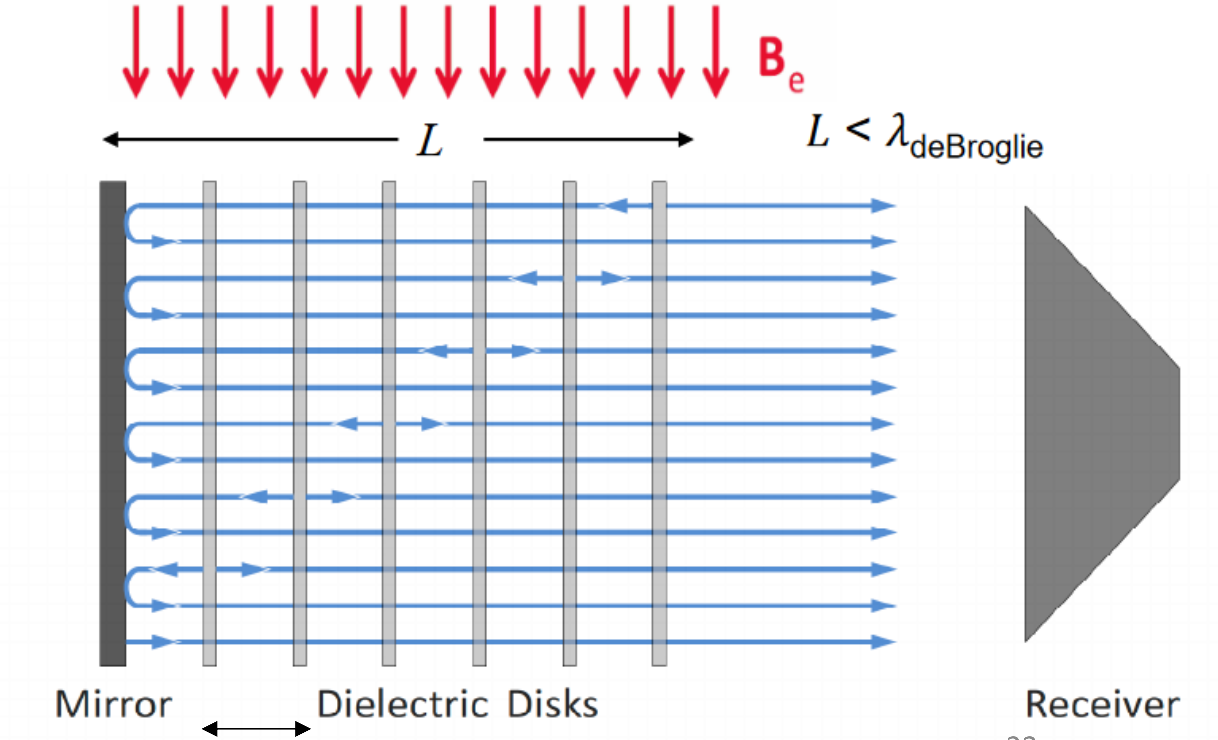
Courtesy: Stefan Knirck, “BREAD: Broadband Reflector Experiment for Axion Detection” PATRAS2022

MADMAX: multiple dielectric dishes

- Enhance the coherent microwave signal generated at the dielectric-vacuum surface (**transparent dish antenna**)
- Many disks to ***boost*** the signal
- Dipole magnet is mandatory

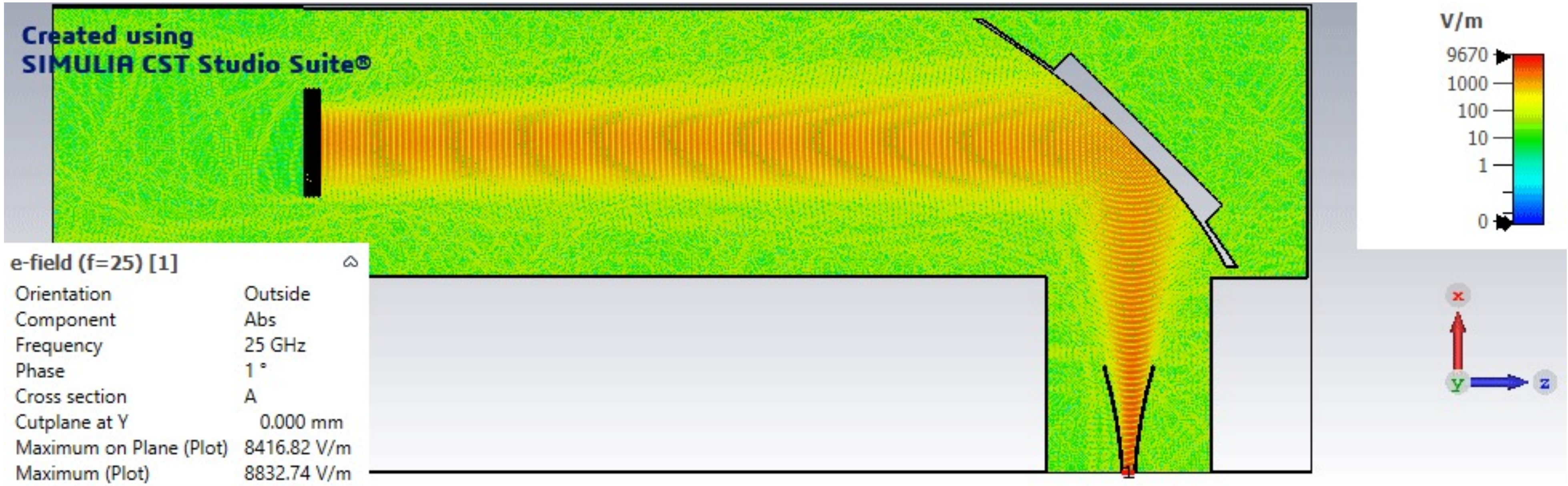


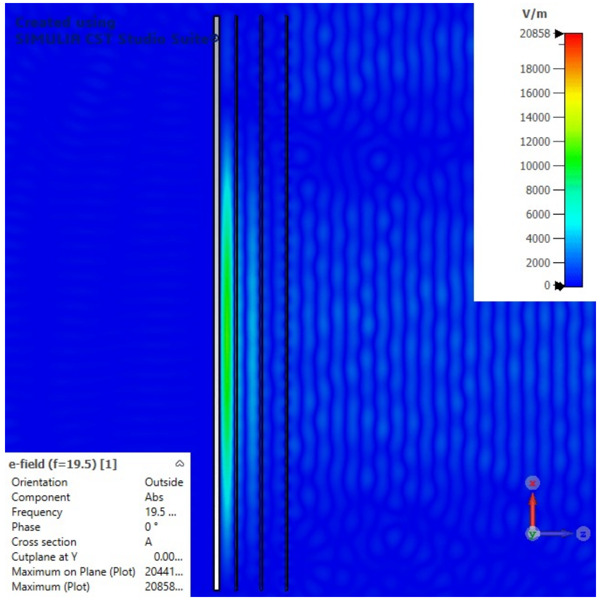




Frequency tuning by moving disks with piezo

Booster resonance + whole standing wave





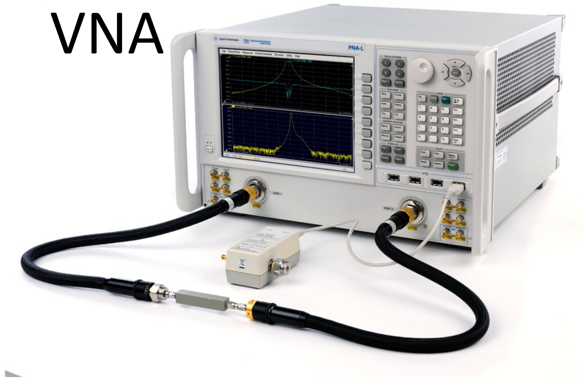
- The resonance inside the booster
- Standing-wave in the whole structure
- White noise resonates (Rayleigh Jeans)
  - Interference to the booster peak
- Very challenging subject in microwave engineering!
  - Enormous mesh in FEM (scale >>>> wavelength)

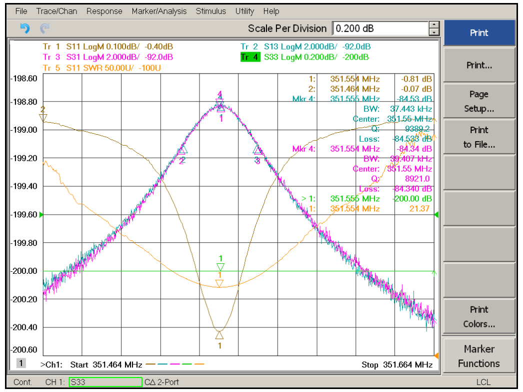
Boost β in dielectric disks ≠ resonance Q in a cavity

Resonant cavity search including plasma haloscope

$$P_S = (1.0\times10^{-22}\ \mathrm{W})\times\left(\frac{V}{136\mathrm{L}}\right)\left(\frac{B}{6.8\mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g_{a\gamma}}{0.97}\right)^2\left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\boxed{\left(\frac{Q}{50000}\right)}$$

VNA





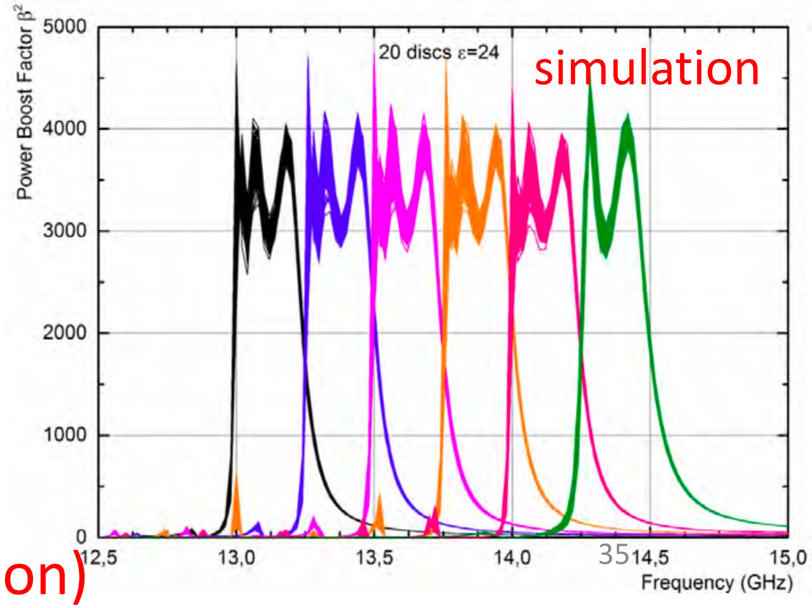
Q: microwave propery in a cavity
→ In-situ measurement observable

Dielectric-disk haloscope:

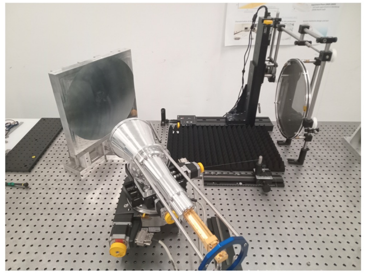
$$P_S = (2.2\times10^{-27}\ \mathrm{W})\times\left(\frac{A}{1\ \mathrm{m^2}}\right)\boxed{\beta^2}\left(\frac{B}{10\ \mathrm{T}}\right)^2 C_{a\gamma}^2$$

β is defined uniquely for axion interaction not for microwaves
→ Not a direct observable of microwave measurement

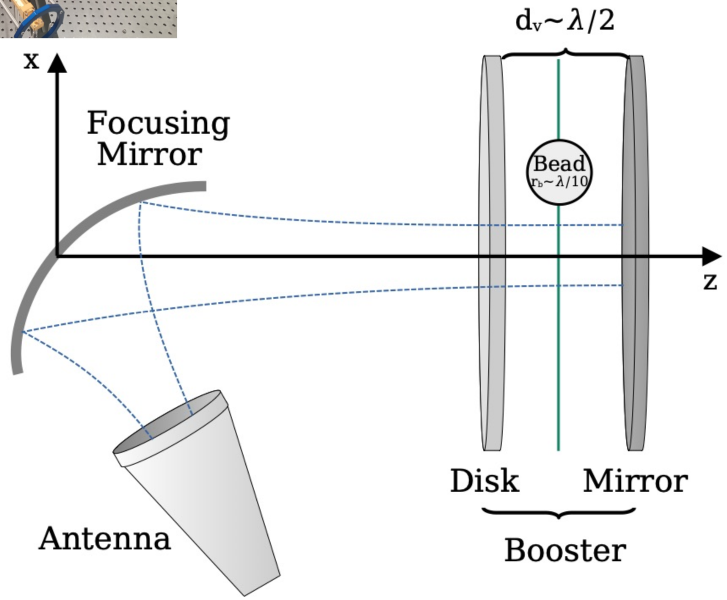
→ Indirect calibration and reconstruction via microwave measurements and noise resonance (fitting data with simulation)



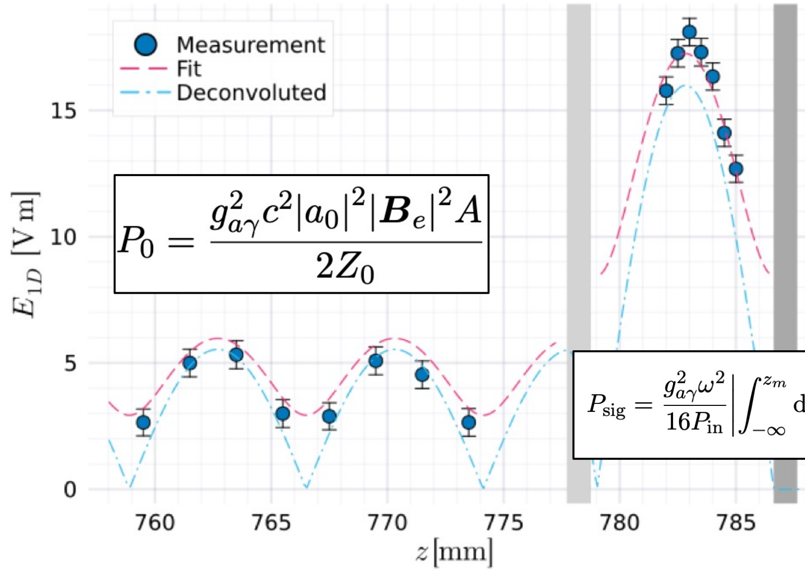
Direct measurement of boost factor



JCAP04(2024)005



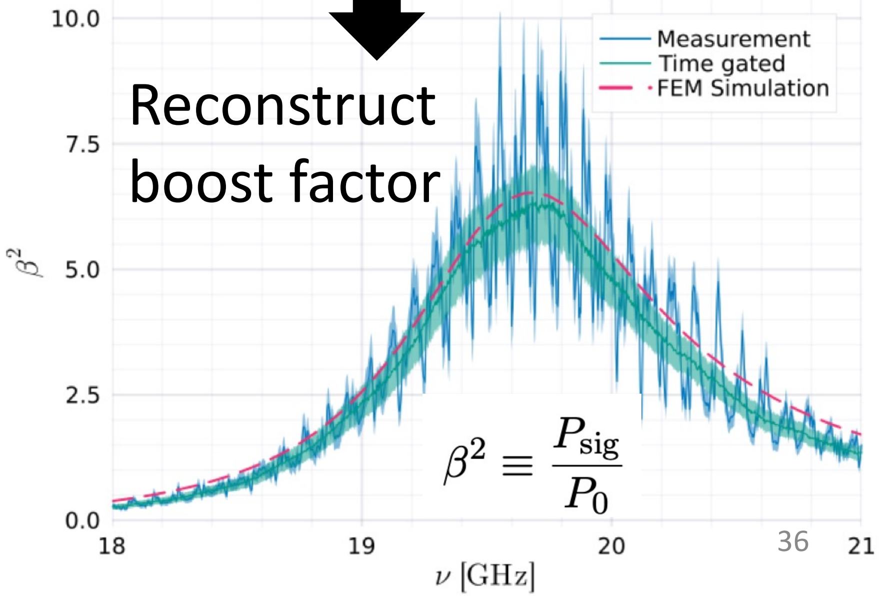
Measuring field distribution via bead-pull method



$$P_0 = \frac{g_{a\gamma}^2 c^2 |a_0|^2 |\boldsymbol{B}_e|^2 A}{2Z_0}$$

$$P_{\text{sig}} = \frac{g_{a\gamma}^2 \omega^2}{16 P_{\text{in}}} \left| \int_{-\infty}^{z_m} \mathrm{d}z\, E_{1D} a B_e \right|^2 .$$

Reconstruct boost factor



$$\beta^2 \equiv \frac{P_{\text{sig}}}{P_0}$$

- Direct measurement of microwave field distributions gave consistent results with simulations (Lorentz reciprocity)
- Calibration of boost factor for physics run (to be published):
  - Modeling the system with parameters
  - Fitting reflection data and noise resonance to determine parameters
  - Calculate boost factor (model dependent)
  - was confirmed with this bead-pull method

Prototype experiment at CERN NA

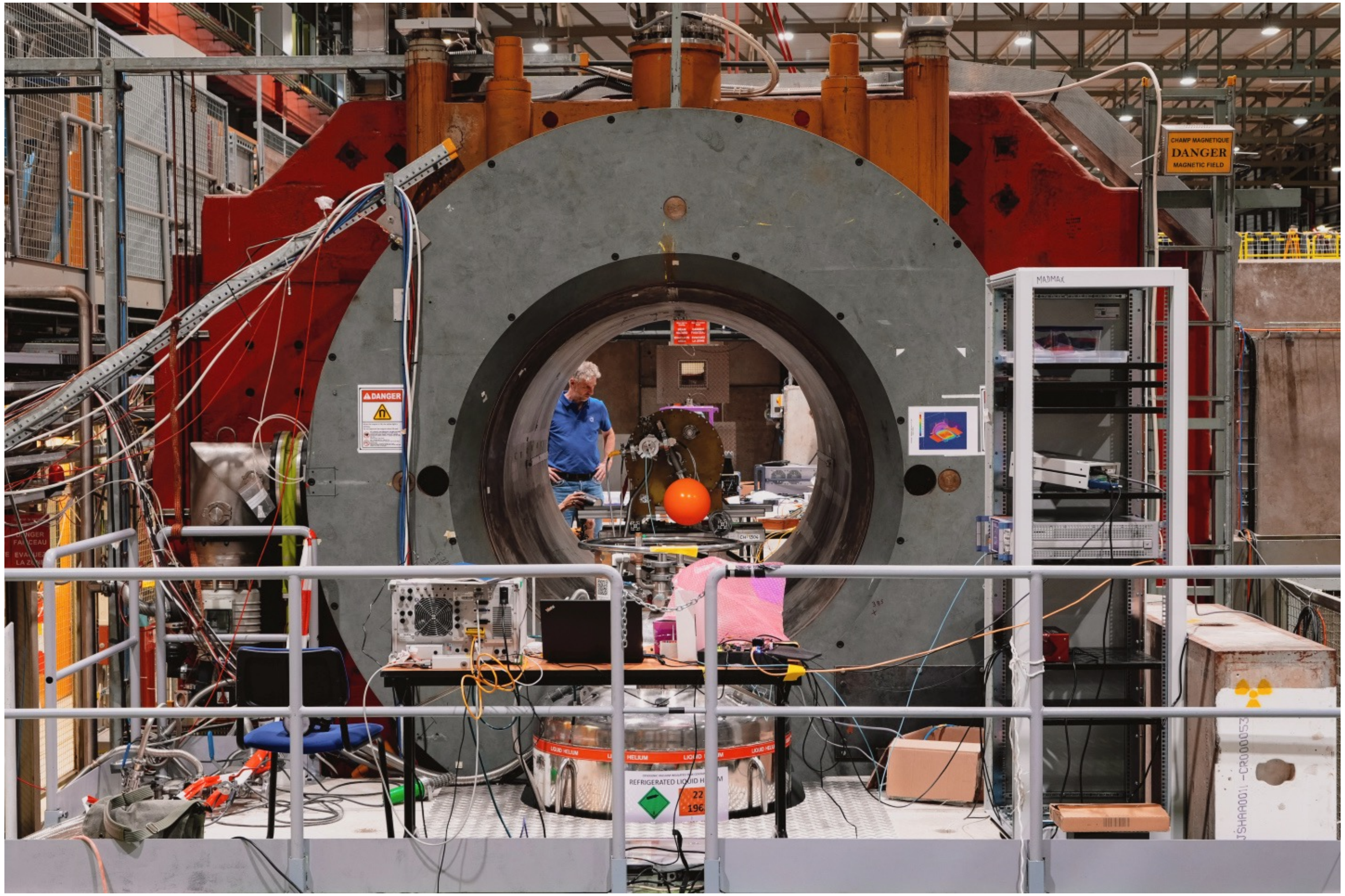
MADMAX at the forefront of the search for axions

The MADMAX experiment at CERN's North Area probes dark matter candidates with two new prototypes

13 MAY, 2024 | By Chetna Krishna

https://home.cern/news/news/experiments/madmax-forefront-search-axions

- First physics papers are being prepared
- Dark photon at room temperature, dark photon at cold, axion at room temperature, axion at cold, …



Stay tuned :-)

Another approach: axion-plasmon mixing in a cavity

$$\epsilon \boldsymbol{\nabla} \cdot \mathbf{E} = \rho - g_{a\gamma} \mathbf{B}_{\mathrm{e}} \cdot \boldsymbol{\nabla} a \,,$$

$$\boldsymbol{\nabla} \times \mathbf{H} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma} \mathbf{B}_{\mathrm{e}} \dot{a} \,,$$

$$\ddot{a} - \boldsymbol{\nabla}^2 a + m_a^2 a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}_{\mathrm{e}} \,,$$

$\epsilon = 0$ gives and resonance inside a plasma

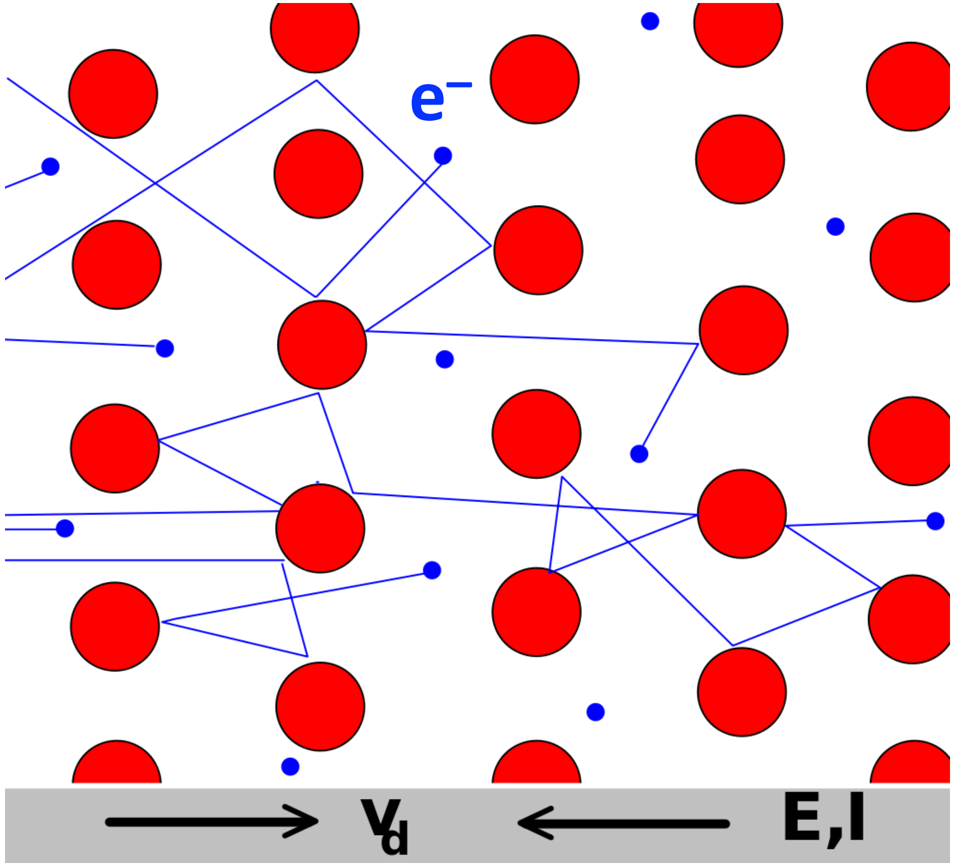
$$\mathbf{E} = -\frac{g_{a\gamma} \mathbf{B}_{\mathrm{e}} a}{\epsilon} = -g_{a\gamma} \mathbf{B}_{\mathrm{e}} a \left(1 - \frac{\omega_p^2}{\omega_a^2 - i\omega_a \Gamma}\right)^{-1}$$

At the plasma frequency $\omega_p = \omega_a$

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

In the Drude model

Drude model



From wiki

Cavity filled with 1D wire metamaterial

Free electrons inside wires behave as 1D plasma

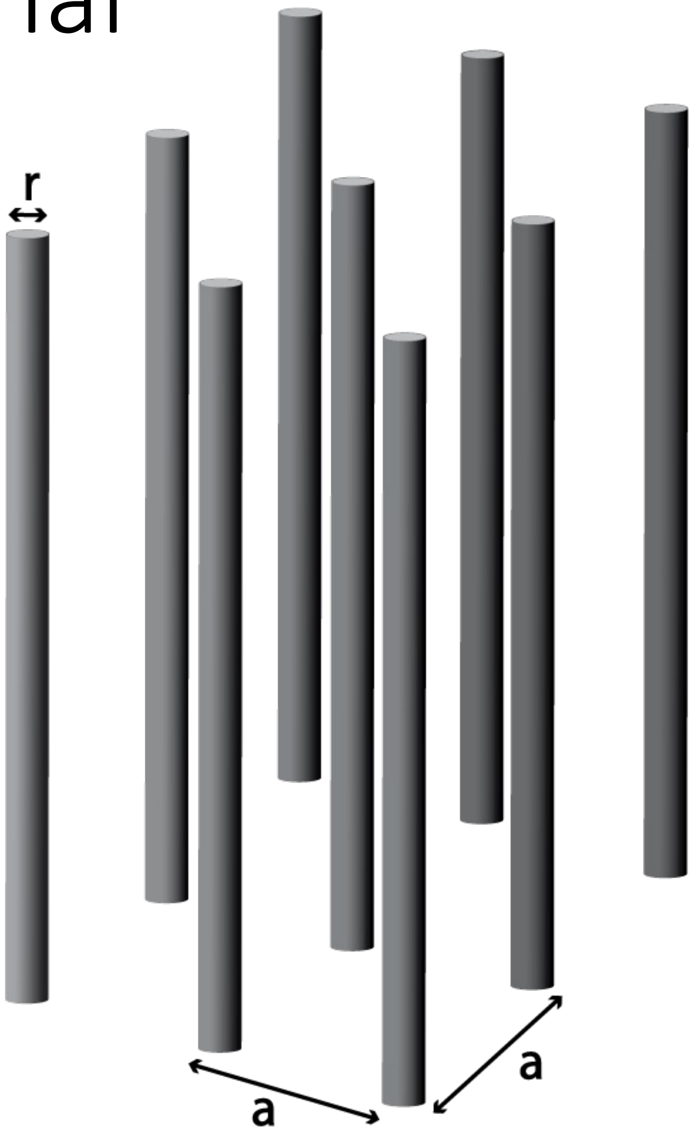
$$n_e = n\frac{\pi r^2}{a^2} \quad ; \quad m_{eff} = \frac{e^2\pi r^2 n}{2\pi}\log\frac{a}{r} ,$$

$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{a^2\log(a/r)} .$$

For example, $r = 0.5$ mm, $a = 5$ mm gives

$\omega_p/2\pi \sim 16$ GHz

Free from the size of the cavity itself



Changing the spacing a tunes the plasma frequency

Cavity filled with 1D wire metamaterial

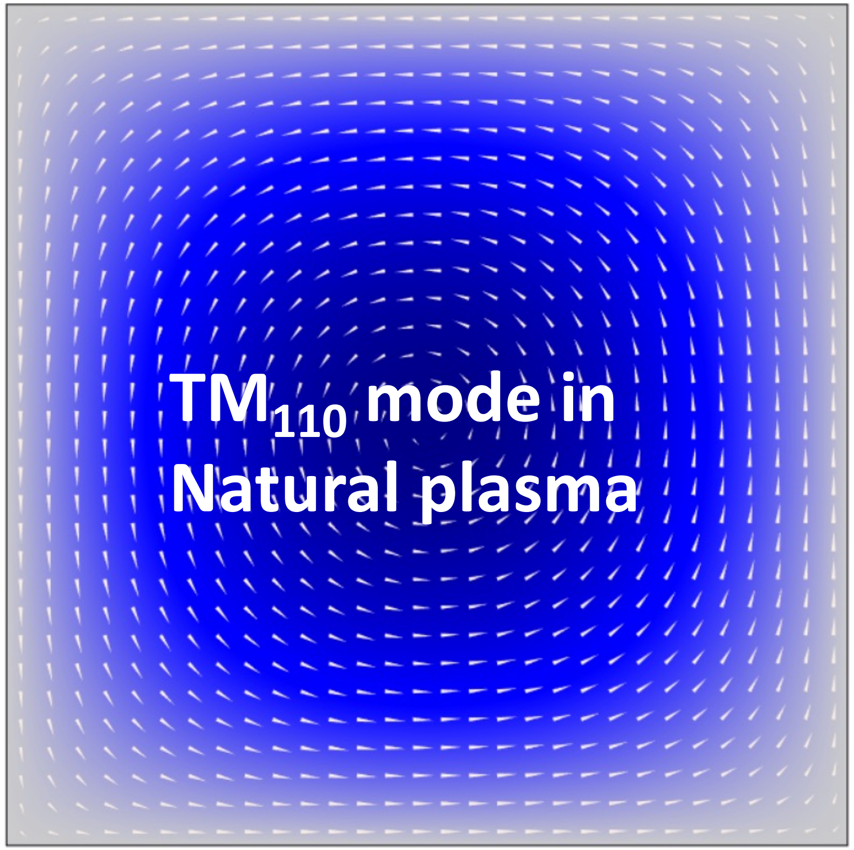
Free e… as 1D plasma

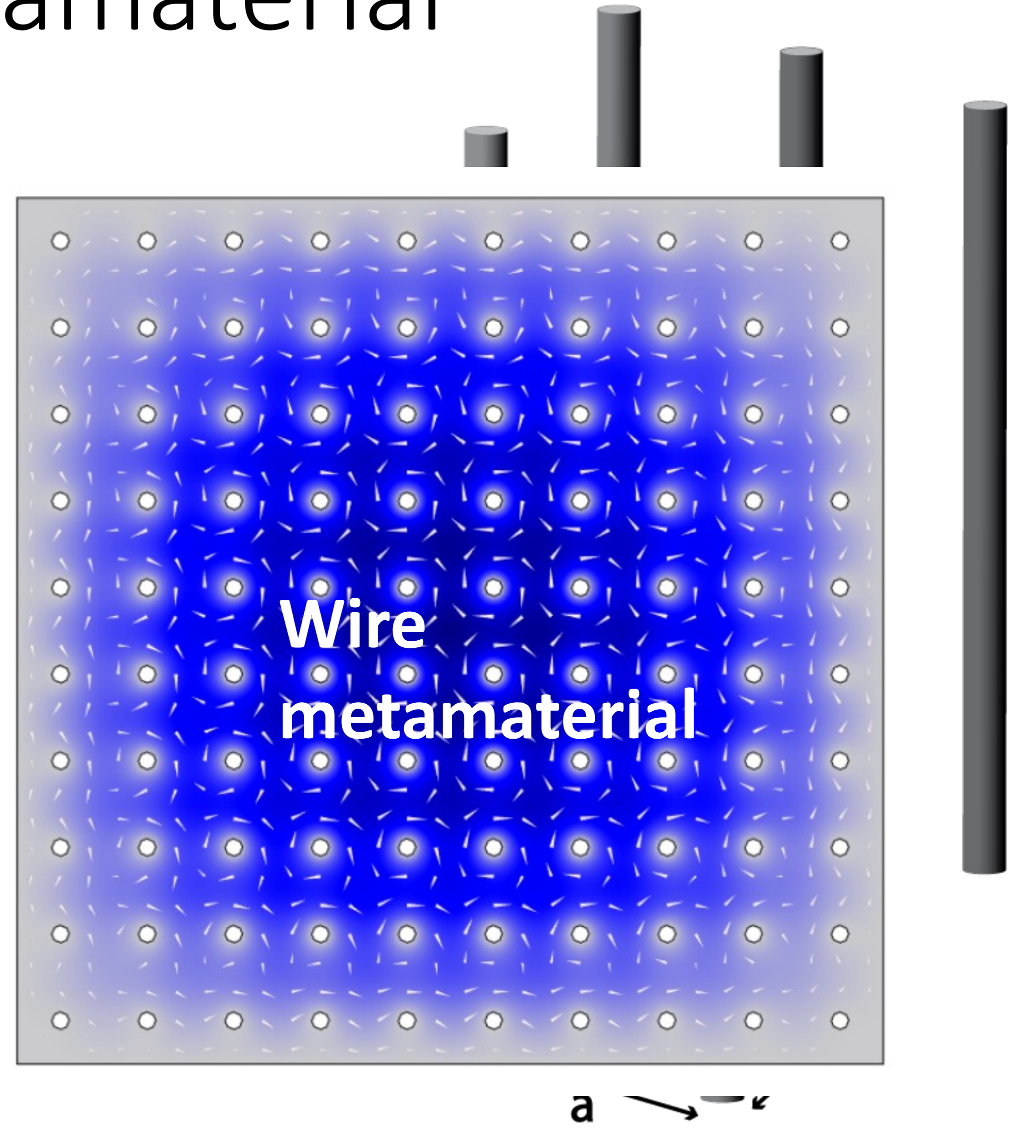
n_e … $\frac{\pi r^2 n}{2\pi} \log \frac{a}{r}$

ω_p^2 … .

For ex… nm gives

Free f… elf

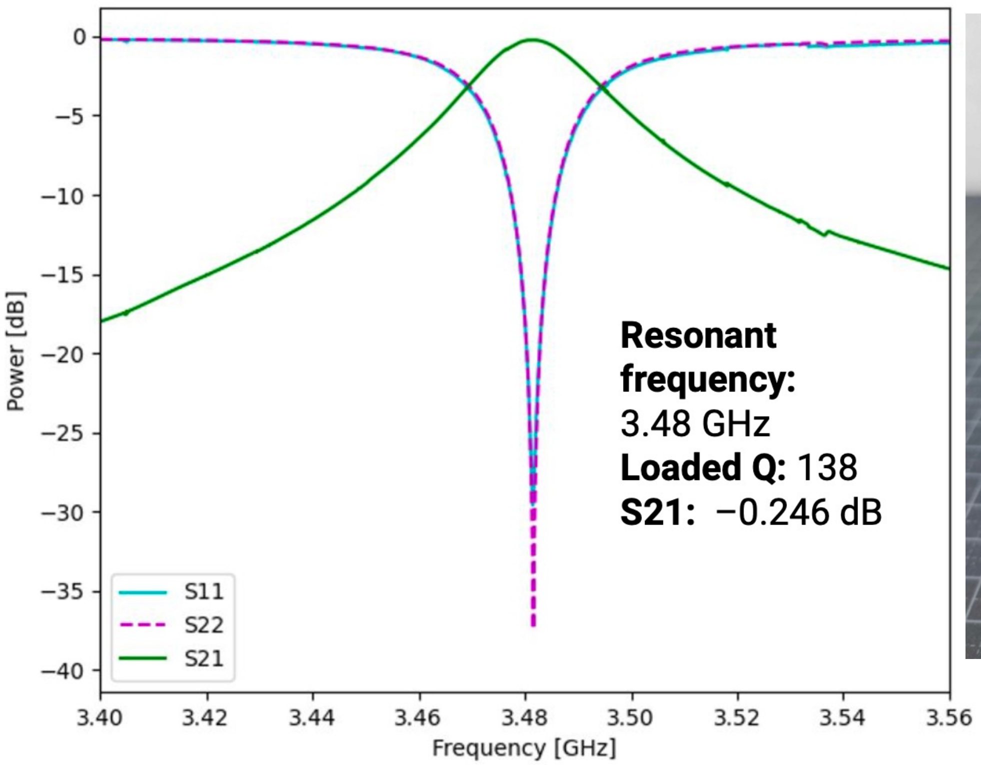




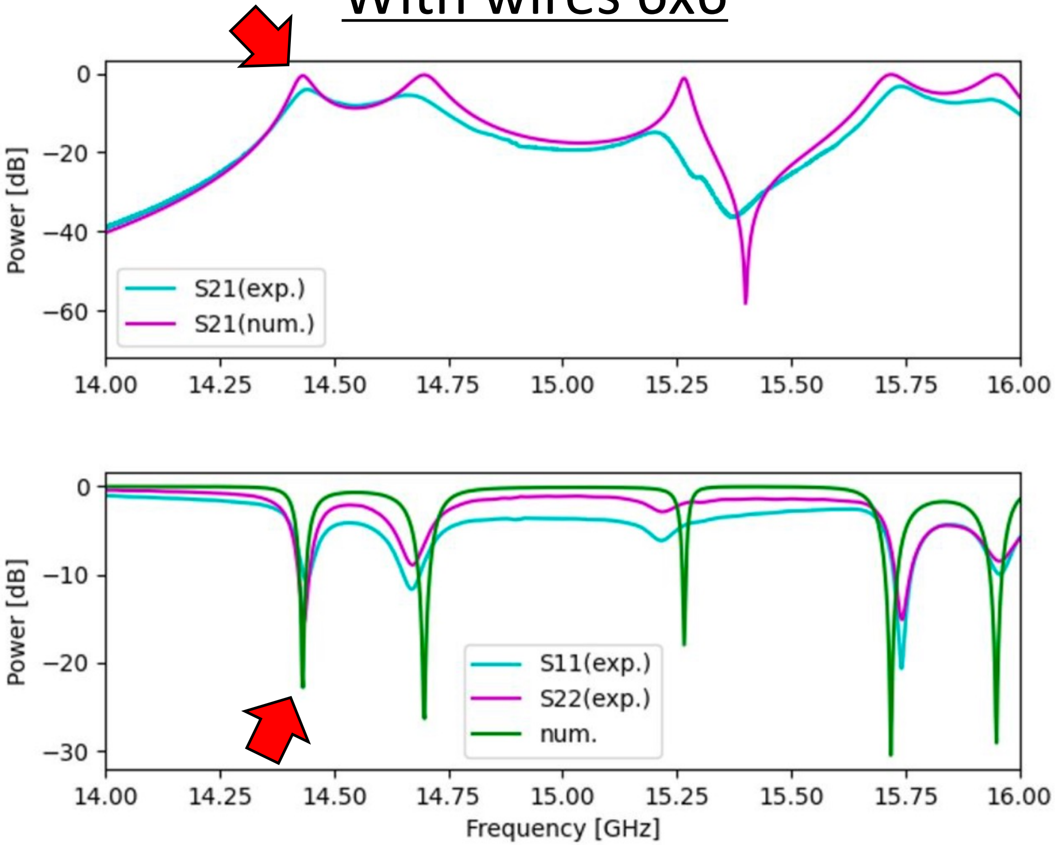
Changing the spacing a tunes the plasma frequency

Prototype wire-filled cavities

Same size, without wires



With wires 6x6



Courtesy of Gagandeep Kaur

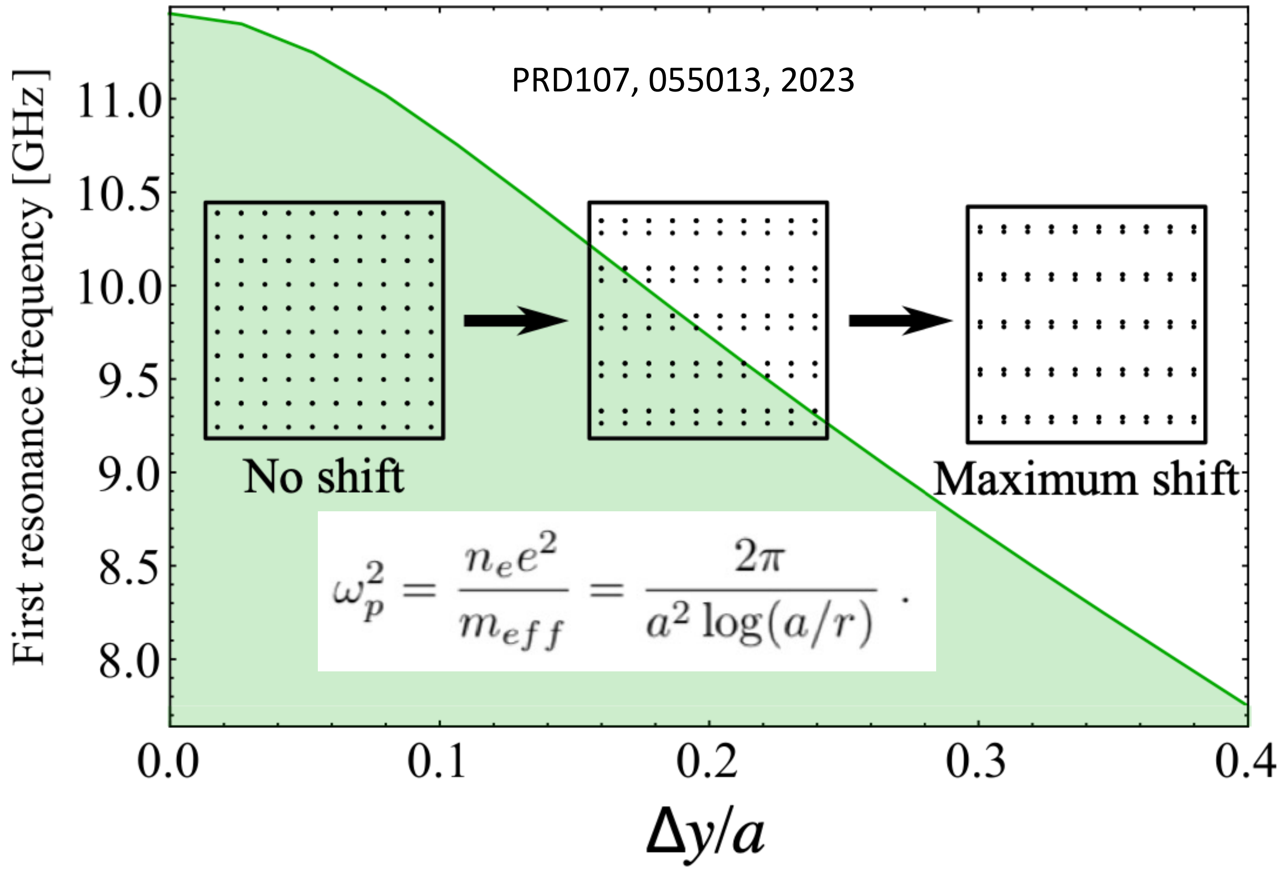
Resonance frequency of the lowest TM mode

3.48 GHz → 14.4 GHz

With the artificial plasma by the wire metamaterial

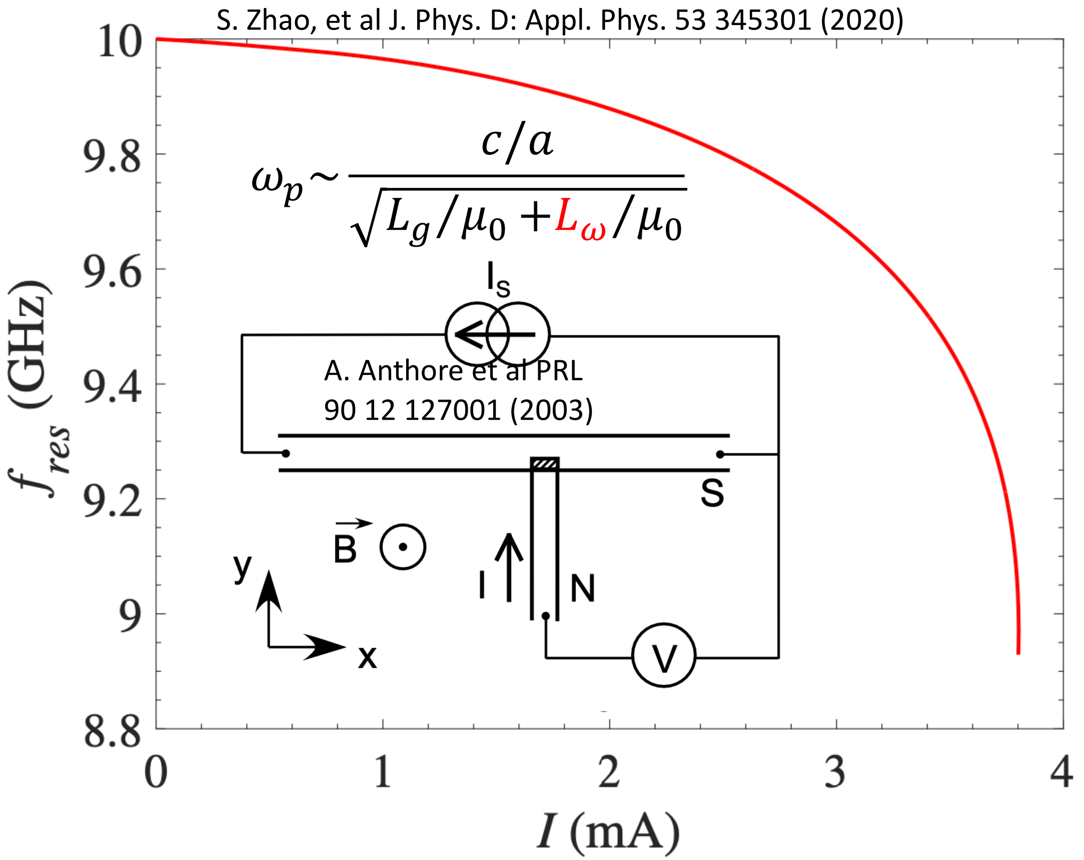
Frequency tuning

Baseline: mechanical tuning



- Copper wires
- Prototyping phase
- First physics run in a few years

Non-mechanical tuning via kinetic inductance



- Superconducting wires + DC current
- Basic R&D for proof-of-principle
- Preliminary studies to be published

Outline

- Introduction
  - New physics with microwaves
  - Axion and axion dark matter
  - Particle vs wave
- State of the art
  - ADMX experiment
  - Background noise and quantum limit
  - Squeezing (HAYSTAC) and photon counting
- New experiments
  - Challenge toward higher frequency
  - Dish antenna: signal from metal/vacuum interface
  - MADMAX: signal boost with dielectric disks
  - ALPHA: plasma haloscope with wire metamaterial
- Conclusion

Conclusion

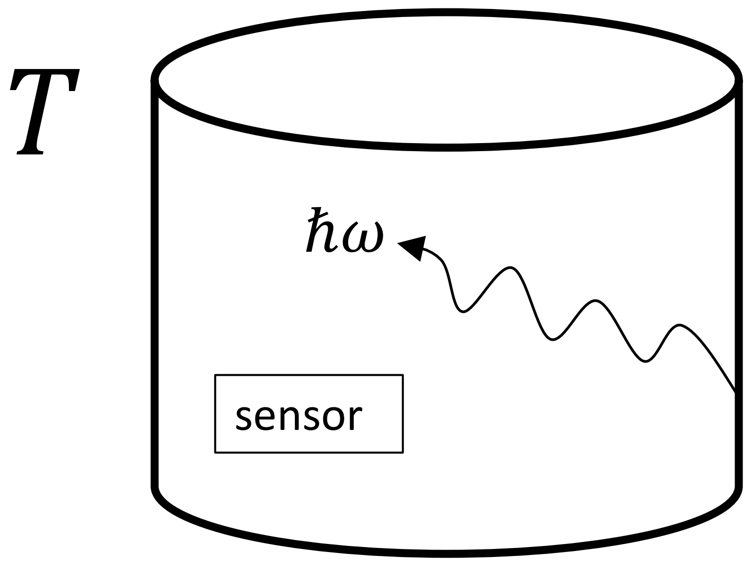
- Microwaves are alternative mean to address new physics
  - Scientific complementarity and technical synergy with accelerator-driven experiments
  - Axion can solve both strong CP problem and dark matter mystery
  - Relatively high-mass dark matter axions may be free from naturalness problems
  - Dark matter axions are treated as classical waves not particles
- Recent dark matter axions searches (< 10 GHz) profit from state-of-the-art microwave detector technology
  - ADMX reached SQL via JPA
  - HAYSTAC introduced phase-sensitive operation of JPA to overcome SQL via squeezing
  - Potential in single photon counting (wave → particle)
- One research direction is toward higher frequency
  - Challenge in keeping volume constant while increasing the frequency
  - BRASS/BREAD gives sensitivity proportional to surface area
  - MADMAX boosts the sensitivity via dielectric disks; 1st physics results to be published
  - ALPHA employs artificial plasma frequency via wire metamaterial; R&D on-going towards physics run

backup

Blackbody radiation

$$\bar{n} = \frac{1}{\exp(\hbar\omega/k_B T) - 1}$$

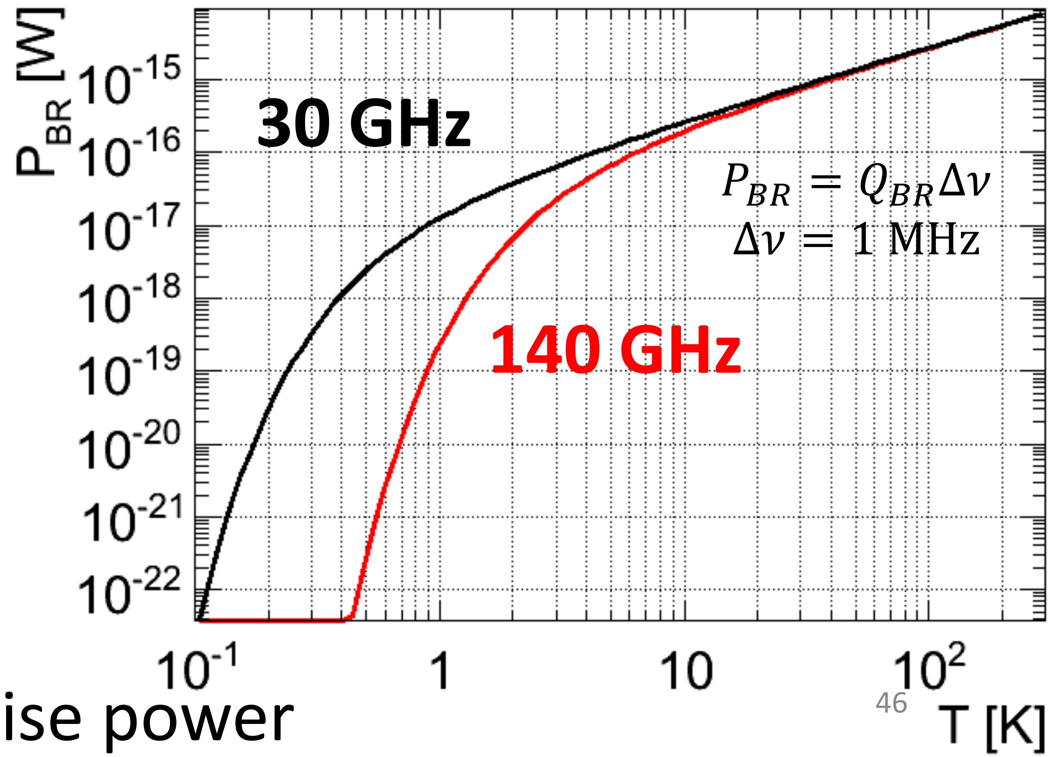
$$\hat{\rho}_{th} = \frac{1}{1+\bar{n}} \sum_{n=0}^{\infty} \left(\frac{\bar{n}}{1+\bar{n}}\right)^n |n\rangle\langle n|$$



Noise power spectral density

$$Q_{BR} = \frac{1}{2}\Omega A \frac{2h\nu^3}{\exp\left(\frac{h\nu}{k_B T}\right) - 1} \text{ [W/Hz]}$$

Solid angle Ω [st]
Sensor area A $[m^2]$
→ Usually, $\Omega A \sim \lambda^2$



Cooling down the system can decrease the noise power

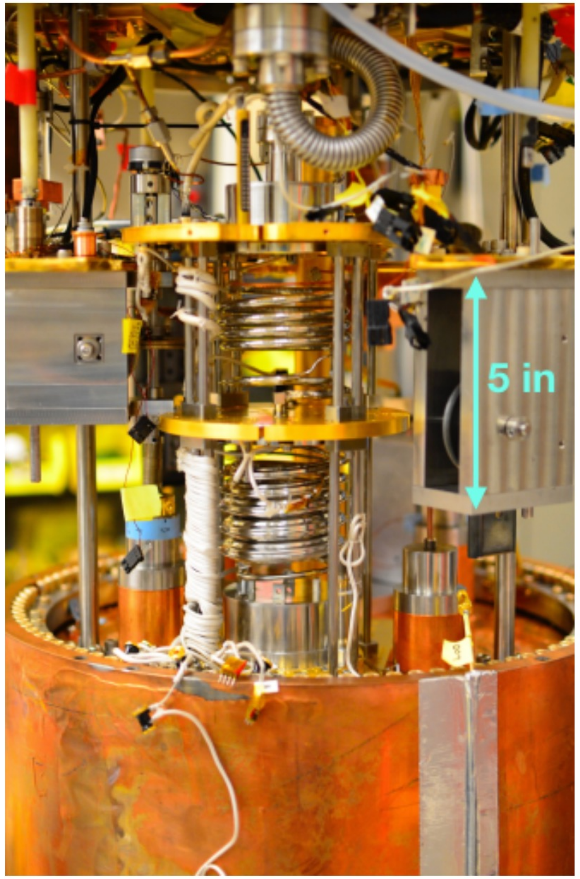
arXiv:2010.00169

ADMX again: $T_{SQL} = h\nu/k_B \sim 40\ \mathrm{mK}$

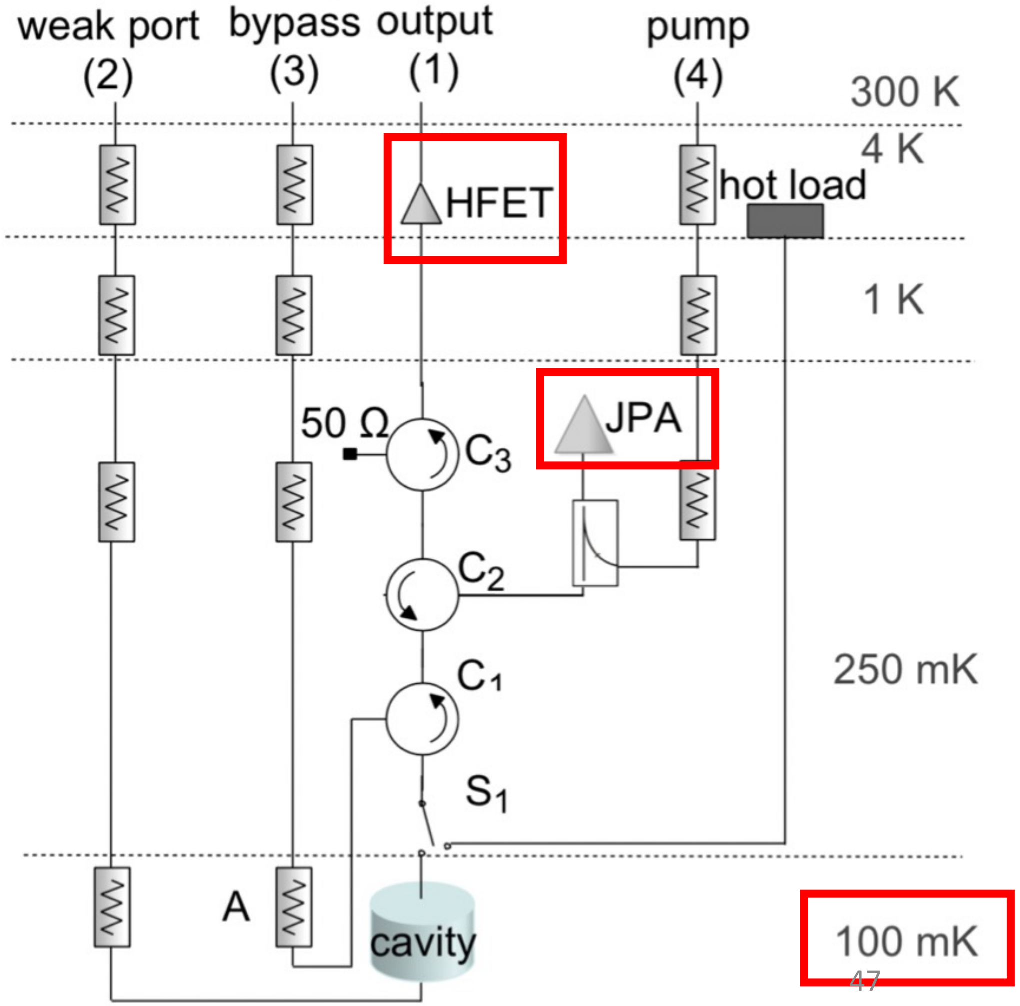
With a dilution refrigerator, the noise level is approaching to the quantum limit

→ Quantum devices have been developed and implemented

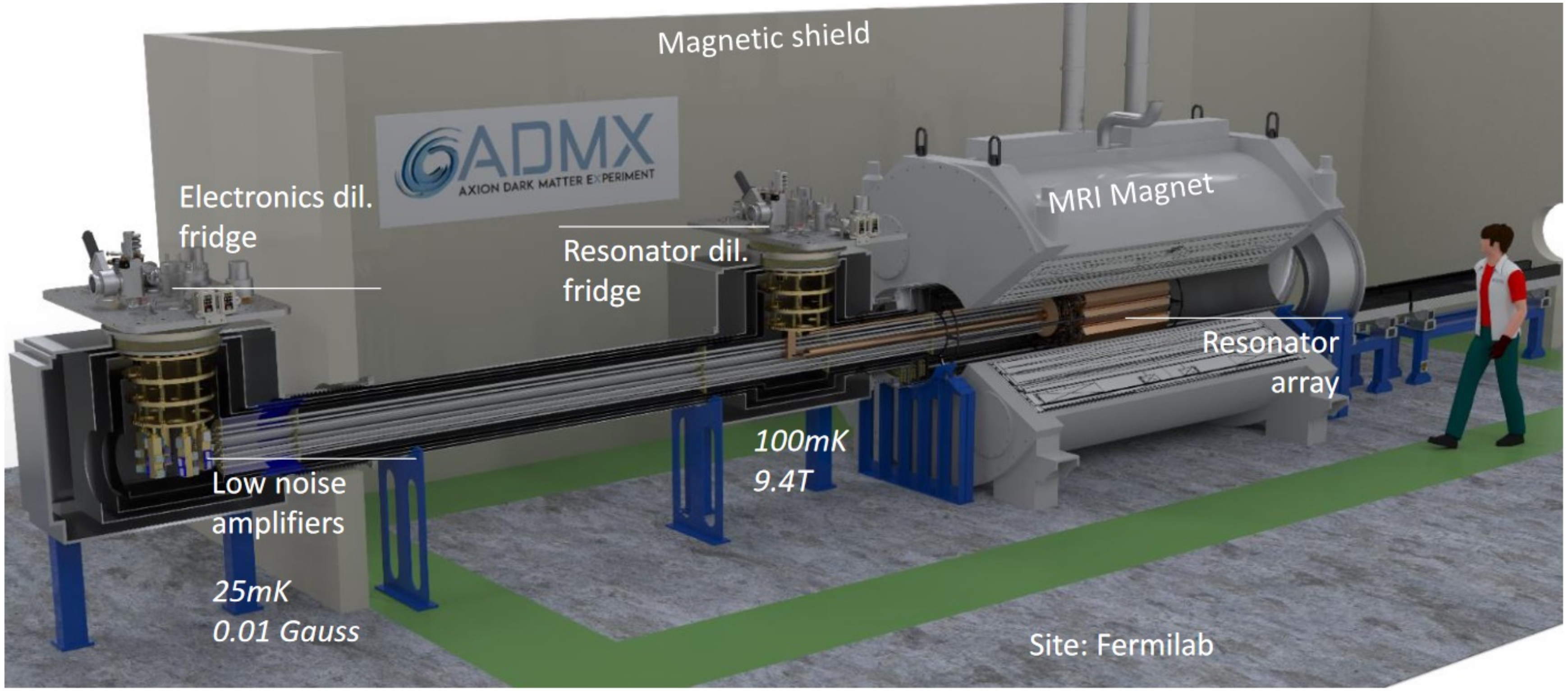
→ Toward quantum microwave optics of coherent signals



Run 1B



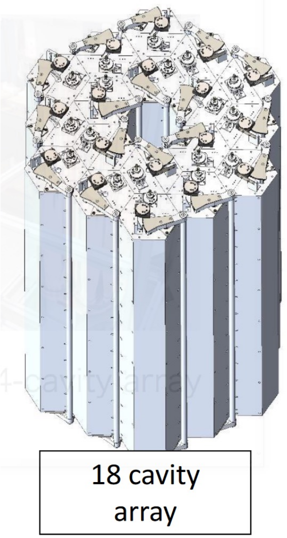
ADMX (Washington University → Fermilab)



~ 5 × scan speed of current ADMX

ADMX-EFR

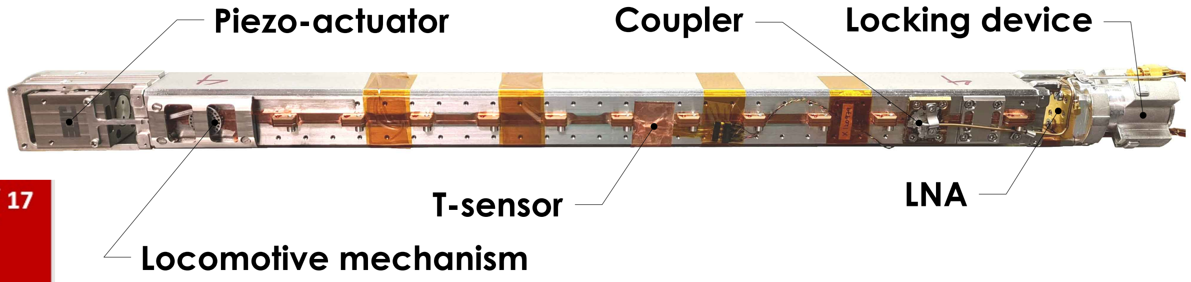
Multiple cavities to address heavier axions

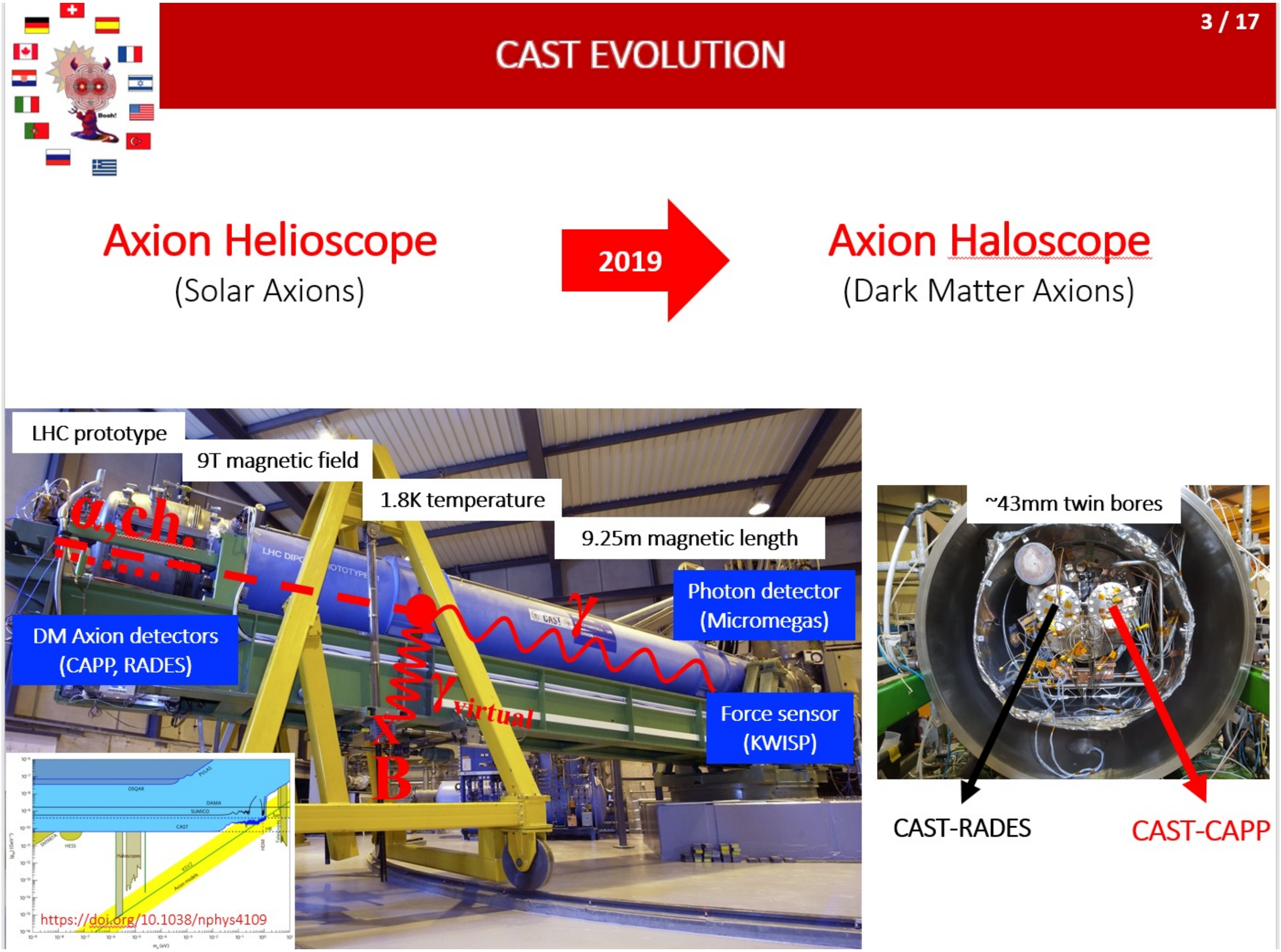


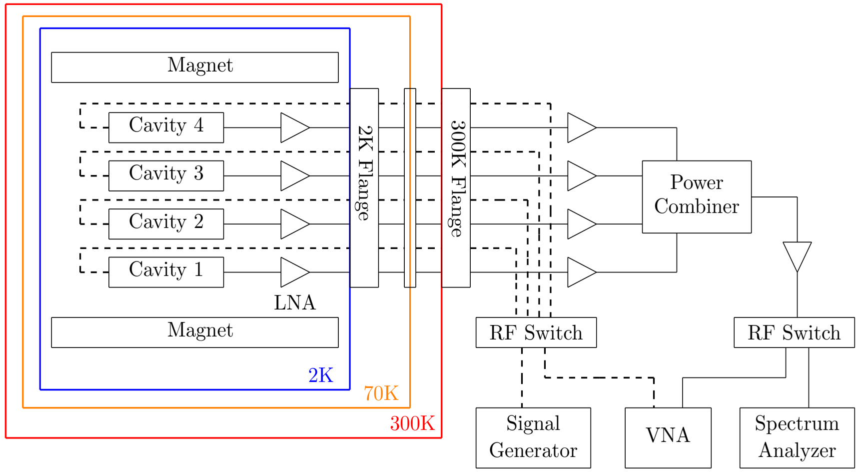
Challenge: phase lock of all the cavities (S. Knirck)

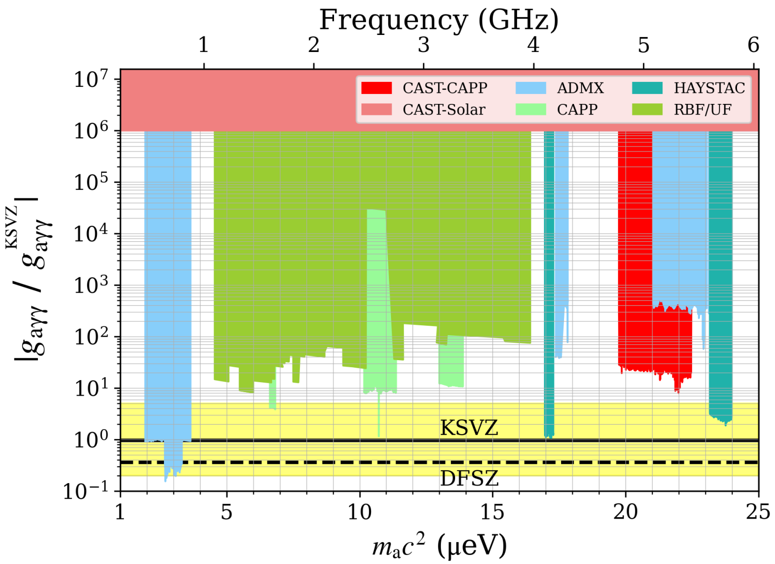
Courtesy: Gray Rybka, “Current Status and Future Plans of ADMX”

CAST-CAPP @ CERN









Courtesy: Marios Maroudas, “LATEST RESULTS ON DARK MATTER AXIONS WITH CAST-CAPP”

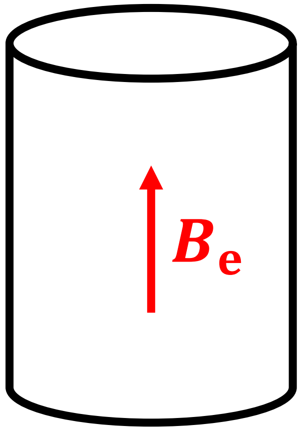
→ Multiple cavity option with a recycled magnet

Natural plasma (ionized gas, free e⁻ in metal, etc) in a cylinder

$$\mathbf{B} = \mathbf{B}_t + B_z\hat{\mathbf{z}}\,; \quad \mathbf{E} = \mathbf{E}_t + E_z\hat{\mathbf{z}}\,; \quad \mathbf{B}_\mathrm{e} = B_\mathrm{e}\hat{\mathbf{z}}\,,$$

$$\left(\boldsymbol{\nabla}_t + \frac{\partial}{\partial z}\hat{\mathbf{z}}\right) \times (\mathbf{B}_t + B_z\hat{\mathbf{z}}) = -i\omega\,(\mathbf{E}_t + \boxed{\epsilon_z} E_z\hat{\mathbf{z}}) - i\omega g_{a\gamma} a B_\mathrm{e}\hat{\mathbf{z}}\,,$$

$$\left(\boldsymbol{\nabla}_t + \frac{\partial}{\partial z}\hat{\mathbf{z}}\right) \times (\mathbf{E}_t + E_z\hat{\mathbf{z}}) = i\omega\,(\mathbf{B}_t + B_z\hat{\mathbf{z}})\,.$$



$$\longrightarrow \quad \frac{\omega^2}{\omega^2 - k^2}\left(r^2\frac{\partial^2 E_z}{\partial^2 r} + r\frac{\partial E_z}{\partial r}\right) + r^2\omega^2 \boxed{\epsilon_z} E_z + r^2\omega^2 g_{a\gamma} B_\mathrm{e} a = 0\,,$$

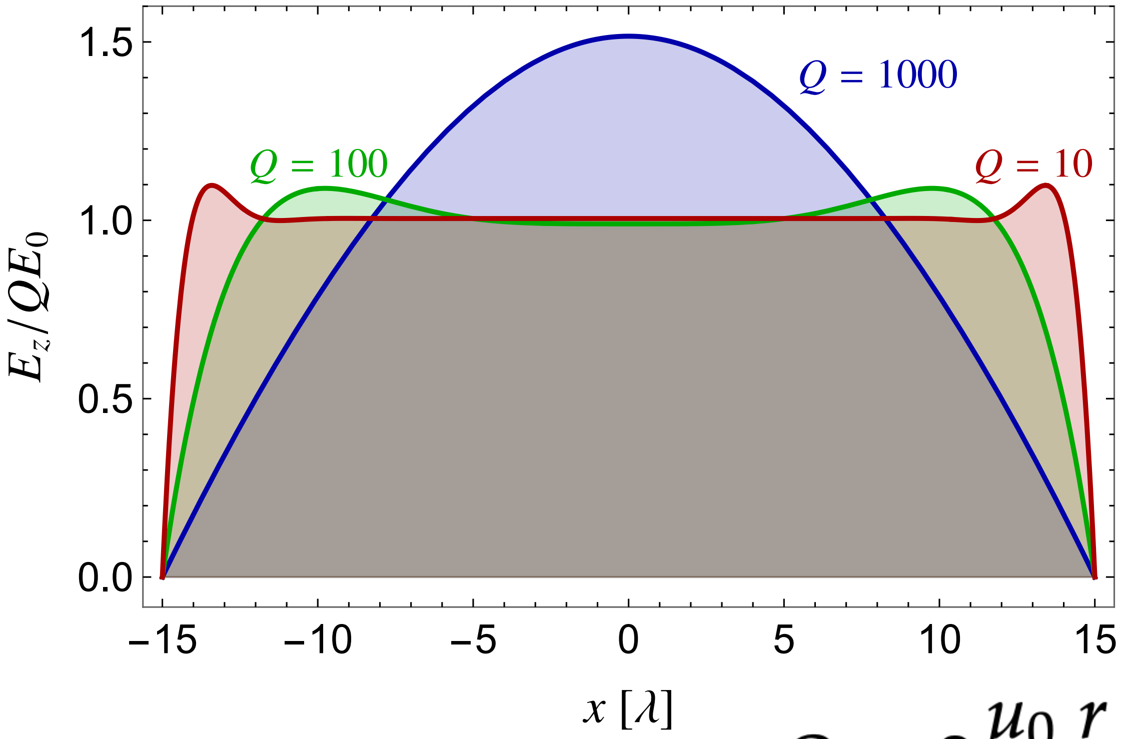
<u>Transverse magnetic mode (TM modes) couples to axions at higher frequency</u>

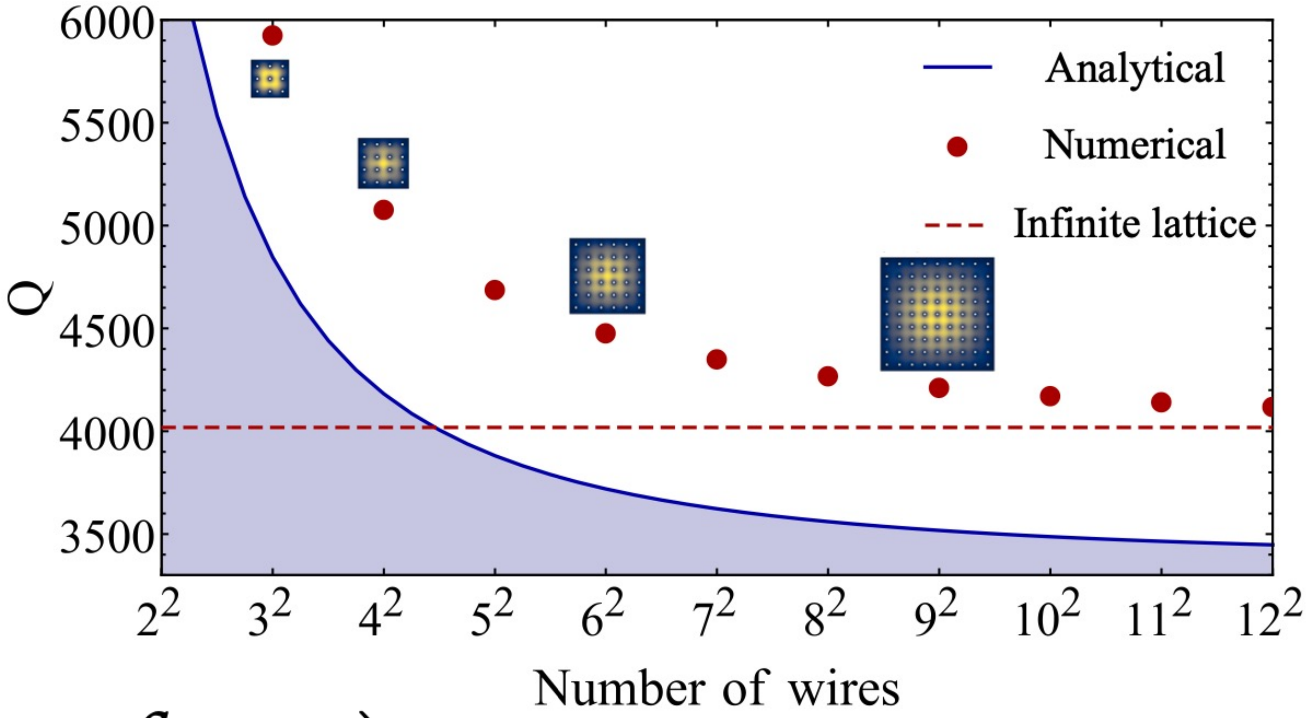
However, ***natural*** plasma is

- Not suitable in a cryogenic environment
- ω_p is not tunable to scan m_a

→ ***Artificial*** plasma by metamaterial

Influence of cavity quality factor



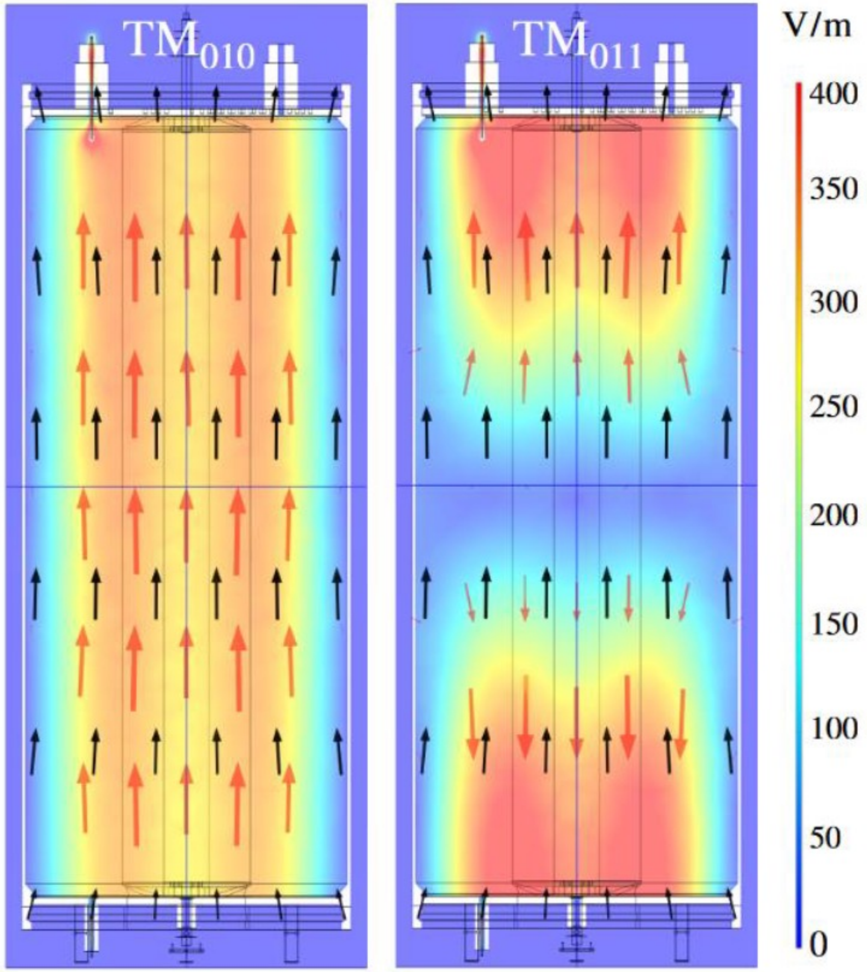


$$Q \simeq 2\frac{\mu_0}{\mu}\frac{r}{\delta}\left(\log\frac{a}{2\pi r}+F\right)$$

Skin depth

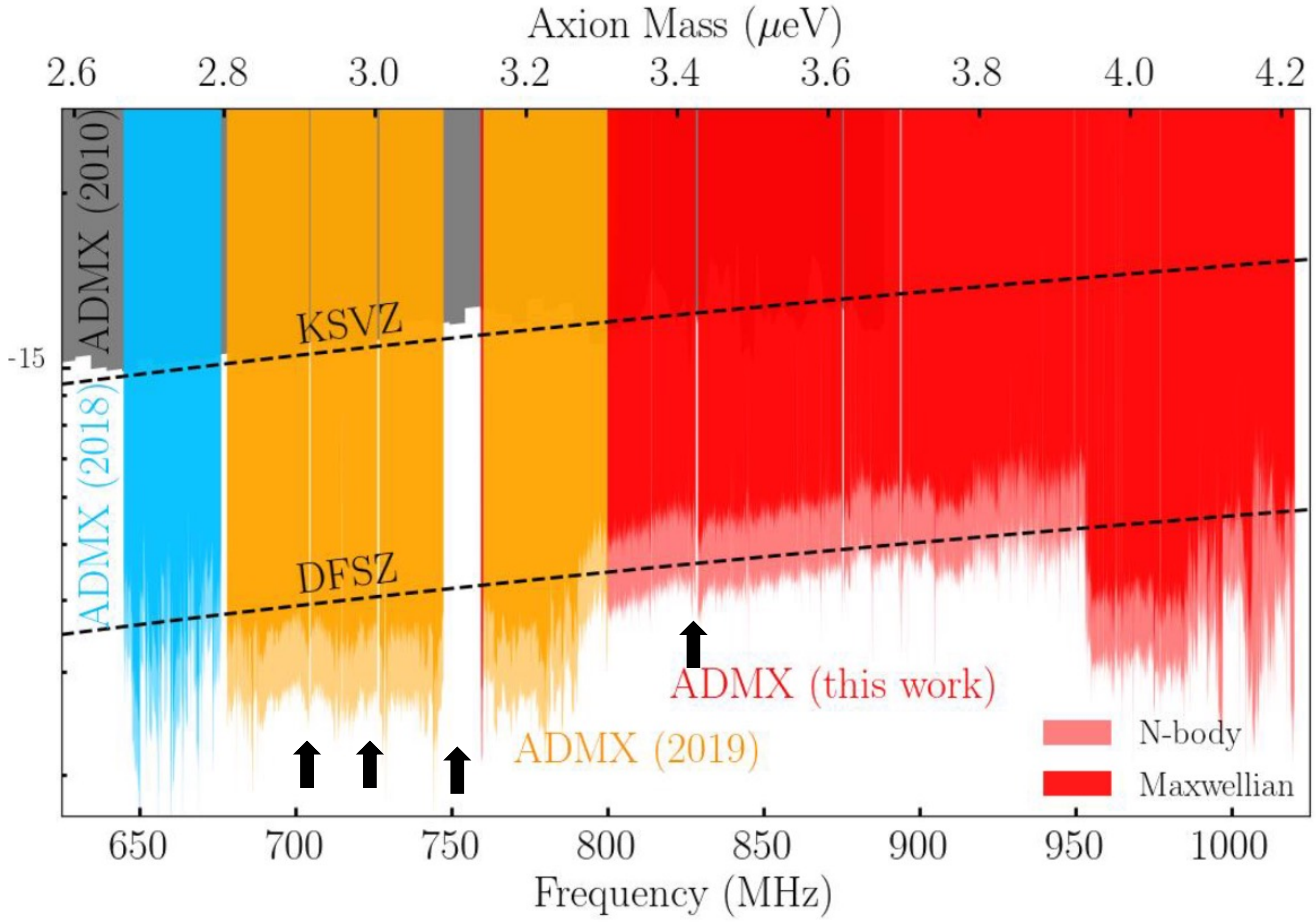
- Denser wires → Lower Q dominated by wire loss → uniform distribution
- Higher Q → Simpler cavity like behavior

One important lesson from ADMX



Courtesy: Gray Rybka, “Current Status and Future Plans of ADMX”

No limits in a frequency where two modes are degenerated



The same and much severer issues in plasma haloscope