Review on recent axion search and R&D toward higher mass region

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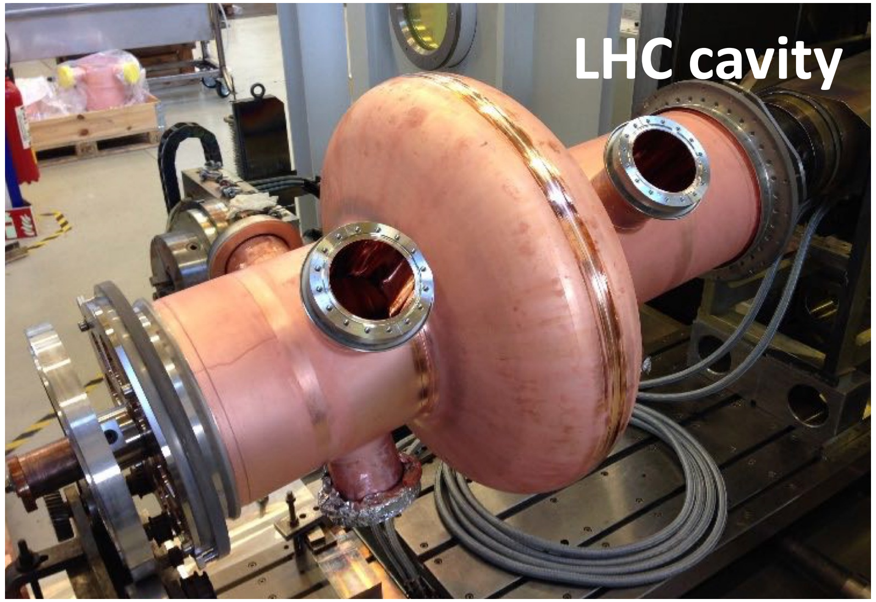
My main business: superconducting accelerators

Confine electromagnetic waves inside RF resonant cavities

Charged particles synchronized with RF can be accelerated

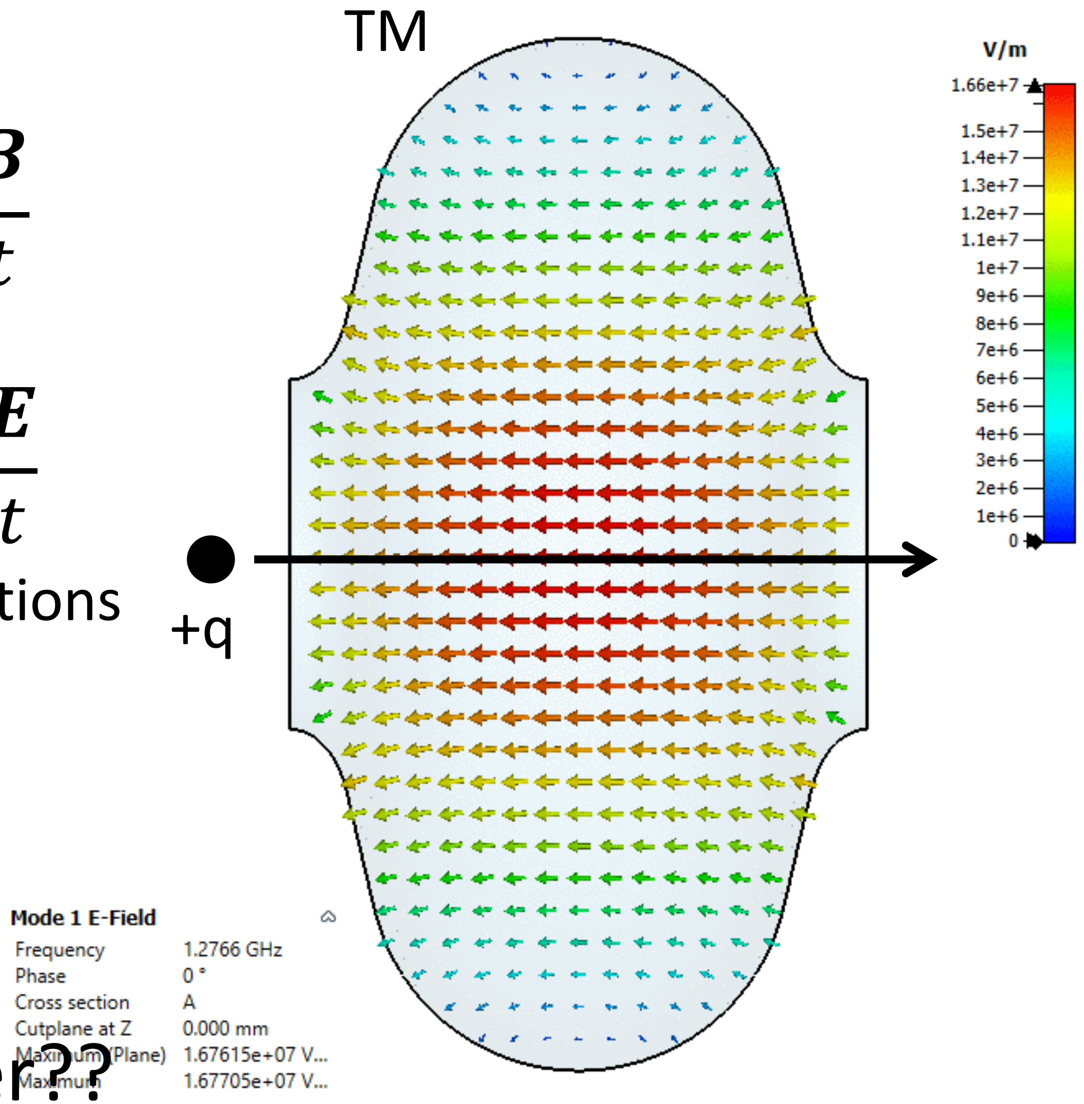


1 m ⟷

$$\begin{cases} \nabla \cdot \boldsymbol{E} = 0 \\ \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \cdot \boldsymbol{B} = 0 \\ \nabla \times \boldsymbol{B} = \dfrac{1}{c^2}\dfrac{\partial \boldsymbol{E}}{\partial t} \end{cases}$$

+ boundary conditions

$$\frac{d\boldsymbol{p}}{dt} = q\boldsymbol{E}$$



What is the relevance to the dark matter??

De Broglie wavelength λ_B of cold dark matter

We are moving in the **galaxy halo of dark matter** with speed of 220 km/s

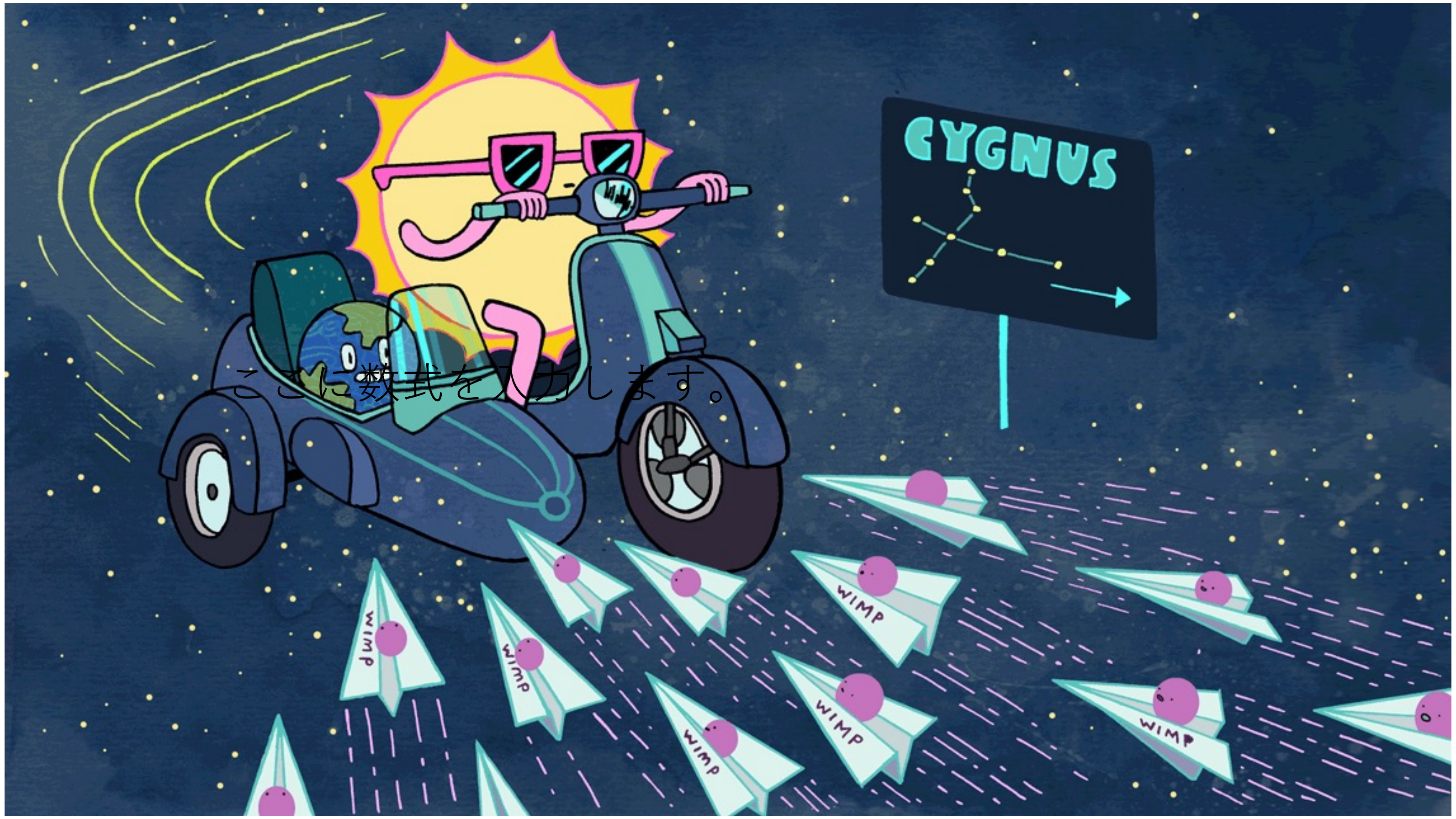
$$\frac{v}{c} \sim 0.07\%$$

Nonrelativistic

$$\lambda_B = \frac{196 \text{ MeVfm}}{mv}$$

SUSY: $m > 1$ TeV (?)

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

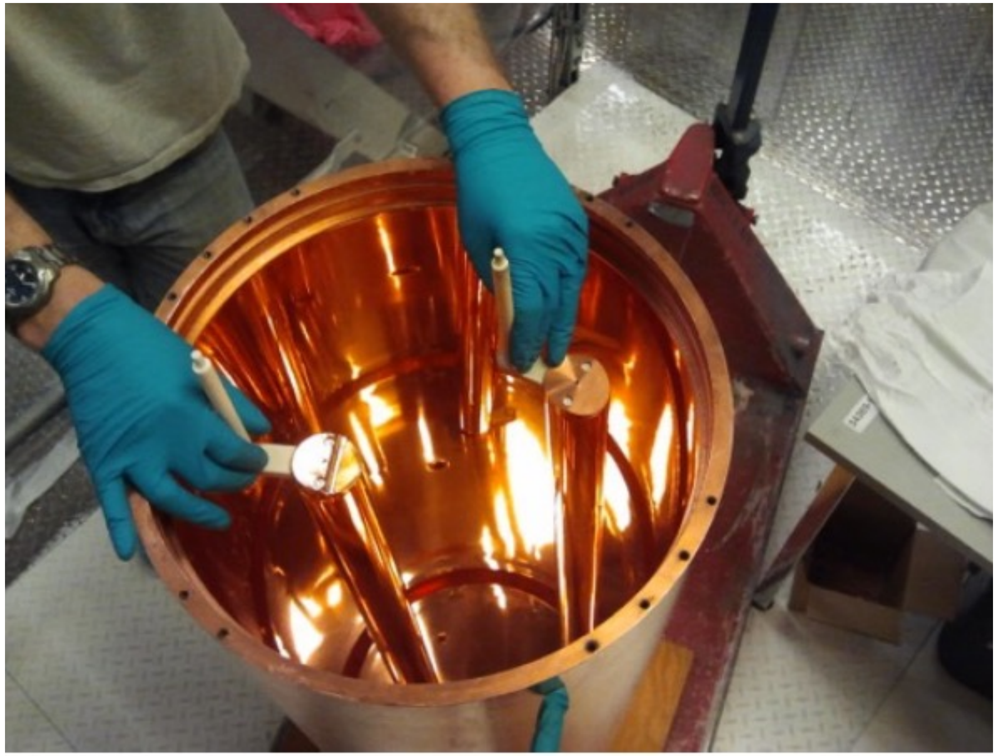


https://www.symmetrymagazine.org/article/wimps-in-the-dark-matter-wind
Artwork by Sandbox Studio, Chicago with Corinne Mucha

Nuclear recoil to detect it

Lighter dark matter candidates

If $m < 10\ \mu\text{eV}$ $\lambda_B > \dfrac{2\times 10^{-7}\ \text{eVm}}{0.07\%\times 10^{-5}\ \text{eV}} = 28\ \text{cm}$



This type of dark matter behaves like a ***wave*** in a laboratory-scale

→ Strong synergy with accelerator technology

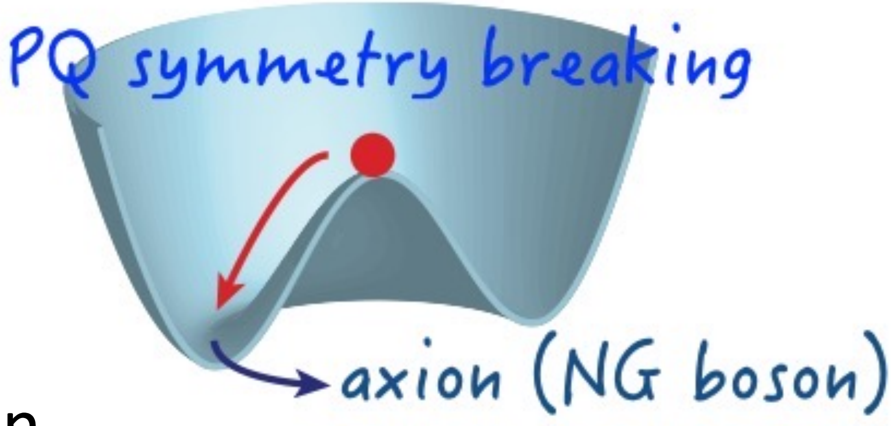
What to search? $\left\{\begin{array}{l}\textbf{Axions} \\ \text{(Dark photons)}\end{array}\right.$

Axions: a byproduct to cancel the strong CP

Quantum Chromodynamics (theory of strong force)

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

gluons

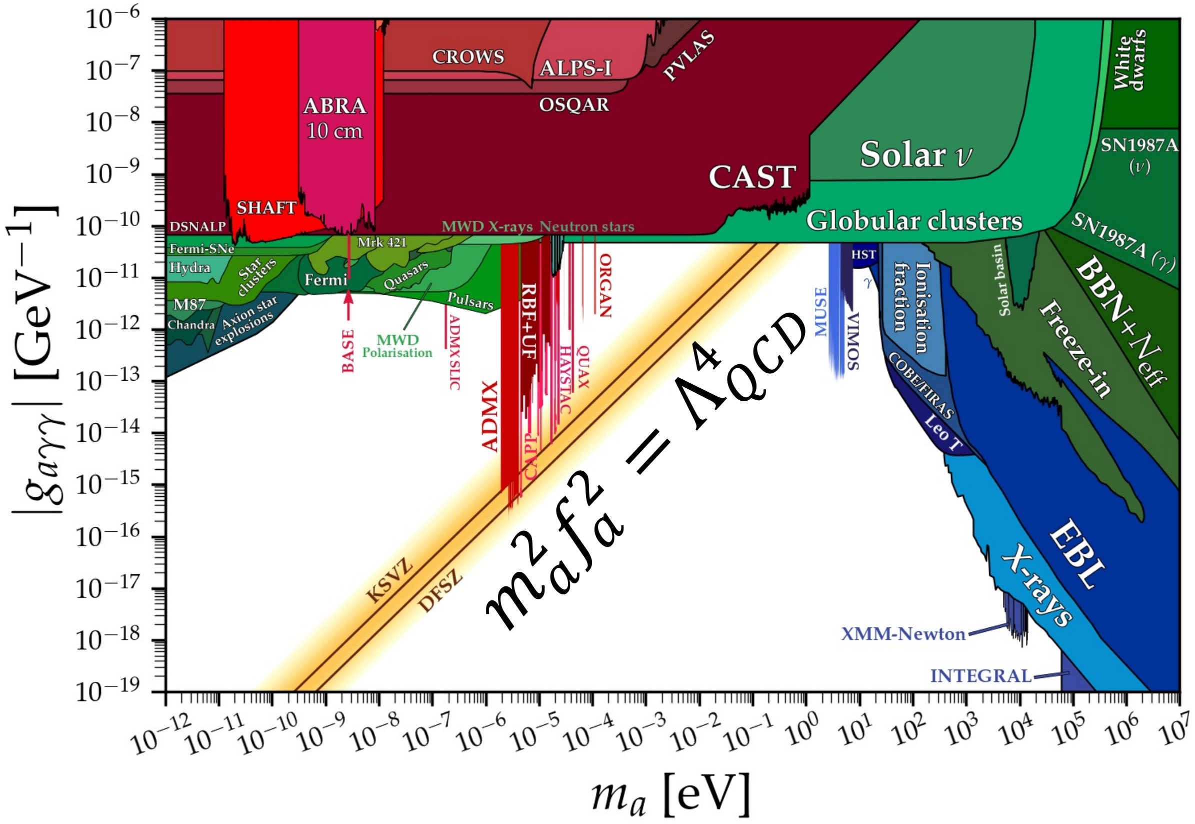


This term generates electric dipole moment in neutron

- Theory: $d_n \sim 4.5\times10^{-15}\boldsymbol{\theta}$ ecm
- Experiment: $|d_n| < 2.9\times10^{-29}$ ecm

$\rightarrow |\theta| < 0.7\times10^{-11} \ll 1$

Naturalness without anthropic solutions



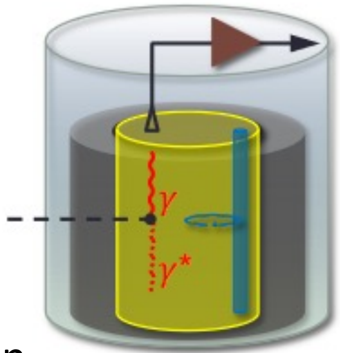
Introduce a new global chiral U(1) field a

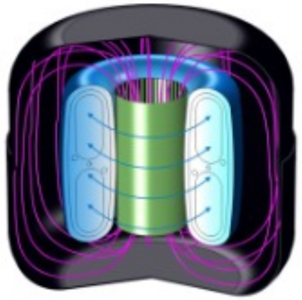
$$\frac{g_s^2}{32\pi^2}\left(\theta + \frac{\boldsymbol{a}}{F_a}\right)G^{a}_{\mu\nu}\tilde{G}^{\mu\nu a} \rightarrow 0 \text{ (after SSB)}$$

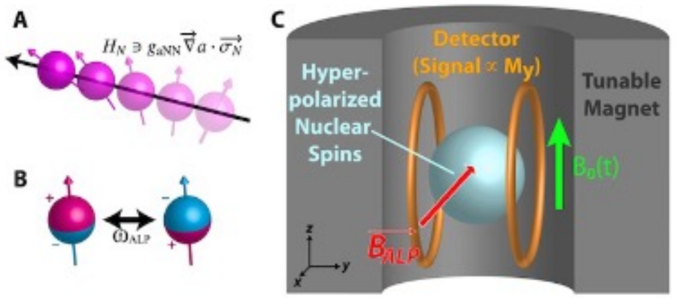
SSB → A pNG boson appears as byproduct

Various experimental searches

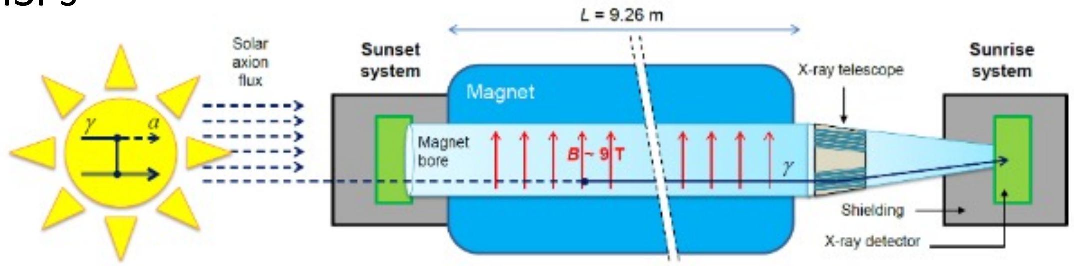
Source \ Coupling	Photons	Fermions	nEDMs
Dark matter	ADMX, CAPP, MADMAX, DM Radio, …	QUAX-ae, GNOME, CASPEr-wind, …	CASPEr-electric, srEDM, …
Solar	CAST, IAXO		
Laboratory	ALPS (II)	ARIADNE	

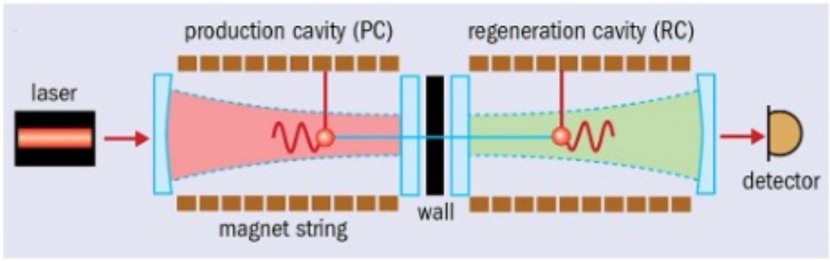






Courtesy: SungWoo Youn, "Axions and WISPs"





Quantum state of dark matter

Thermal equilibrium

The dark matter is cooled down by interaction with other field (eg radiation) in thermal equilibrium

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

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

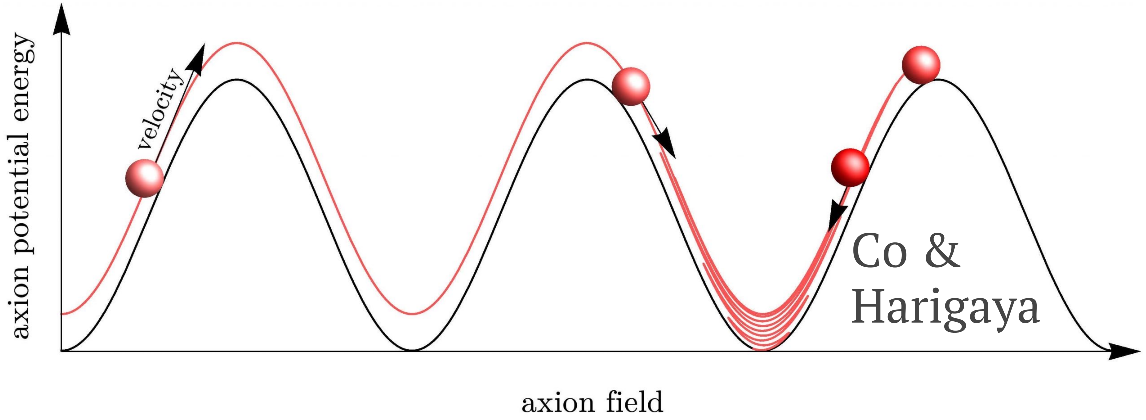
Density matric is diagonal → incoherent

Thermal axion cannot explain the abundance of dark matter

→ WIMP

Coherent state

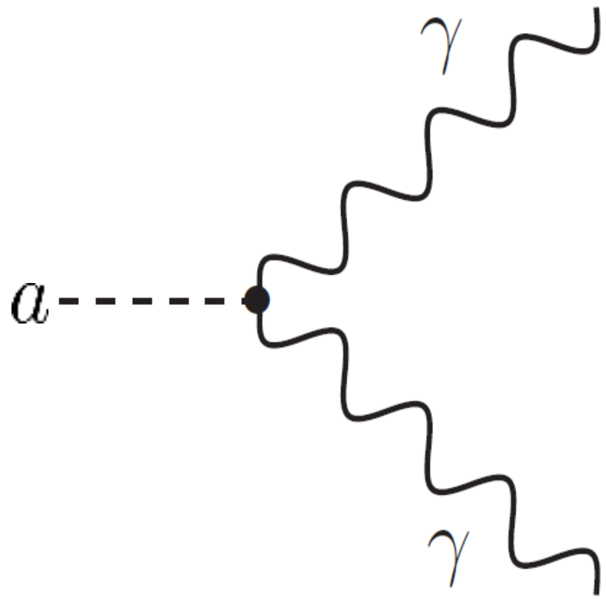
Axion loses kinetic energy non-thermally by damped coherent oscillation in the PQ potential



$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

→ axion

Coherent state → (semi-)classical waves



$$\begin{cases} \hat{\mathcal{E}}(\boldsymbol{r},t) = i\sqrt{\dfrac{\hbar\omega}{2\epsilon_0 V}}\left[\hat{a}e^{-i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})} - \hat{a}^\dagger e^{i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})}\right] \\ \hat{a}|\alpha\rangle = \alpha|\alpha\rangle \end{cases}$$

$|\alpha|^2$: mean # of photons in Poisson distribution

$$E \equiv \langle\alpha|\hat{\mathcal{E}}(\boldsymbol{r},t)|\alpha\rangle = i\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}\left[\alpha e^{-i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})} - \alpha^* e^{+i(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})}\right]$$

$$\rightarrow \left(\frac{\partial^2}{\partial t^2} - \nabla^2\right)E = 0$$

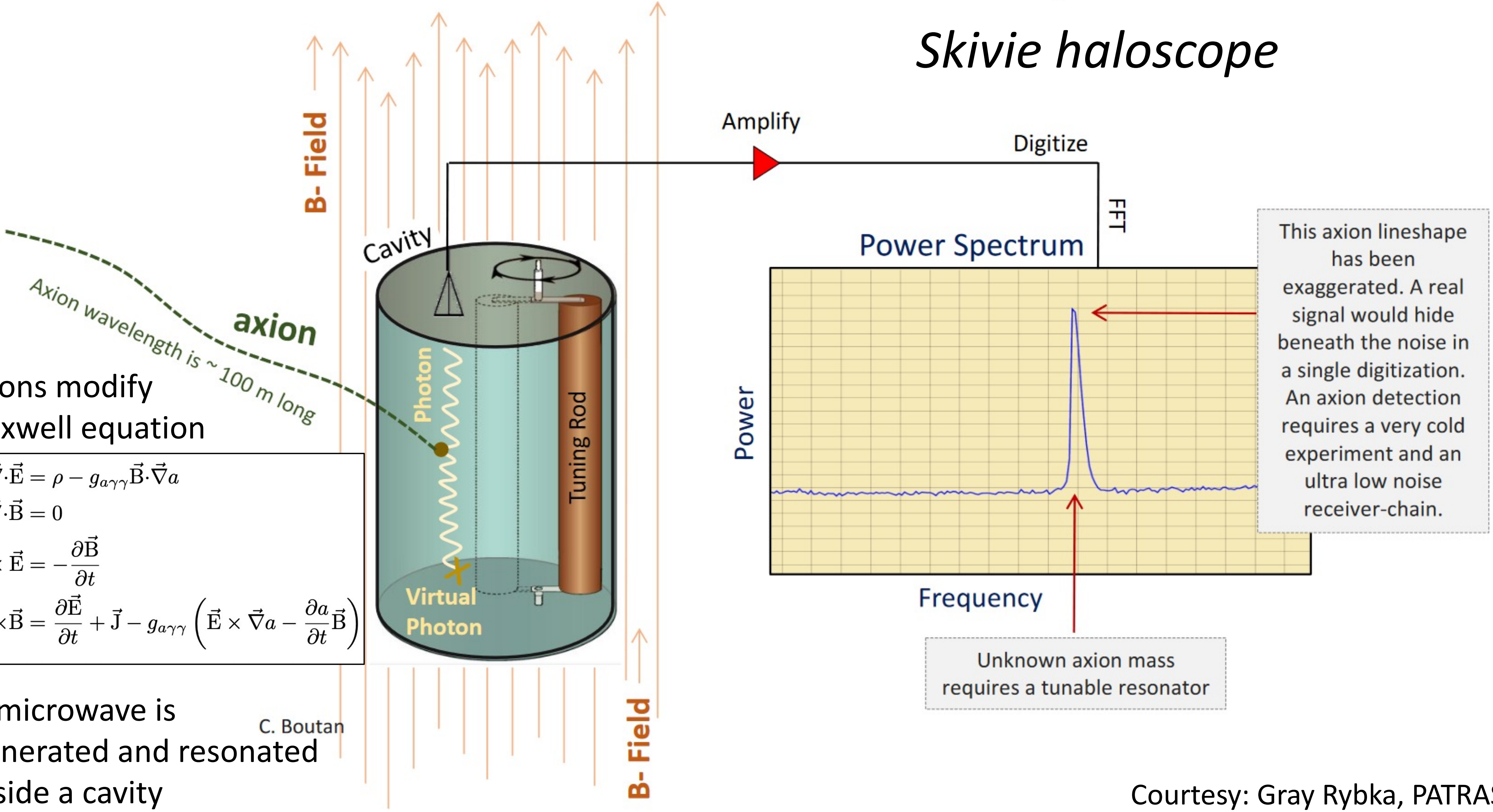
- The axion coherent state generates a coherent photon field inside a static magnetic field
- A coherent state is an eigenstate of the electric field operator

  → Expectation value of the electric field follows Maxwell equation

→ Dark matter axion search is a matter of classical microwave sensing

Classical electrodynamics is the mean to hunt axions

Skivie haloscope



Axions modify Maxwell equation

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

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

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

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

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

$$P_S = (1.0\times 10^{-22}\ \mathrm{W}) \times \left(\frac{V}{136\mathrm{L}}\right)\left(\frac{B}{6.8\mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g}{0.97}\right)^2\left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\left(\frac{Q}{50000}\right)$$

- Johnson Nyquist noise power

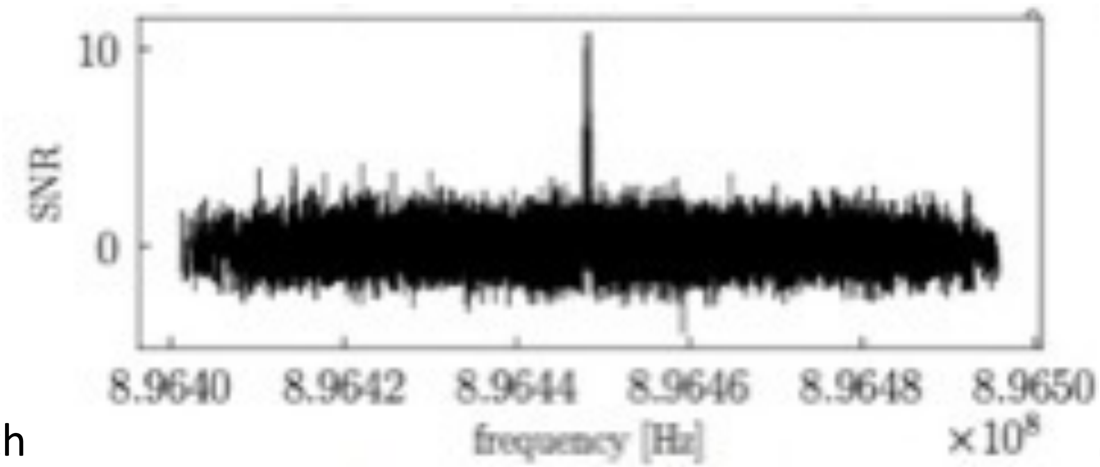
$$P_N = k_B T_s = 1.4\times 10^{-23}\left(\frac{T_s}{1\mathrm{K}}\right)\ \mathrm{W/Hz}$$

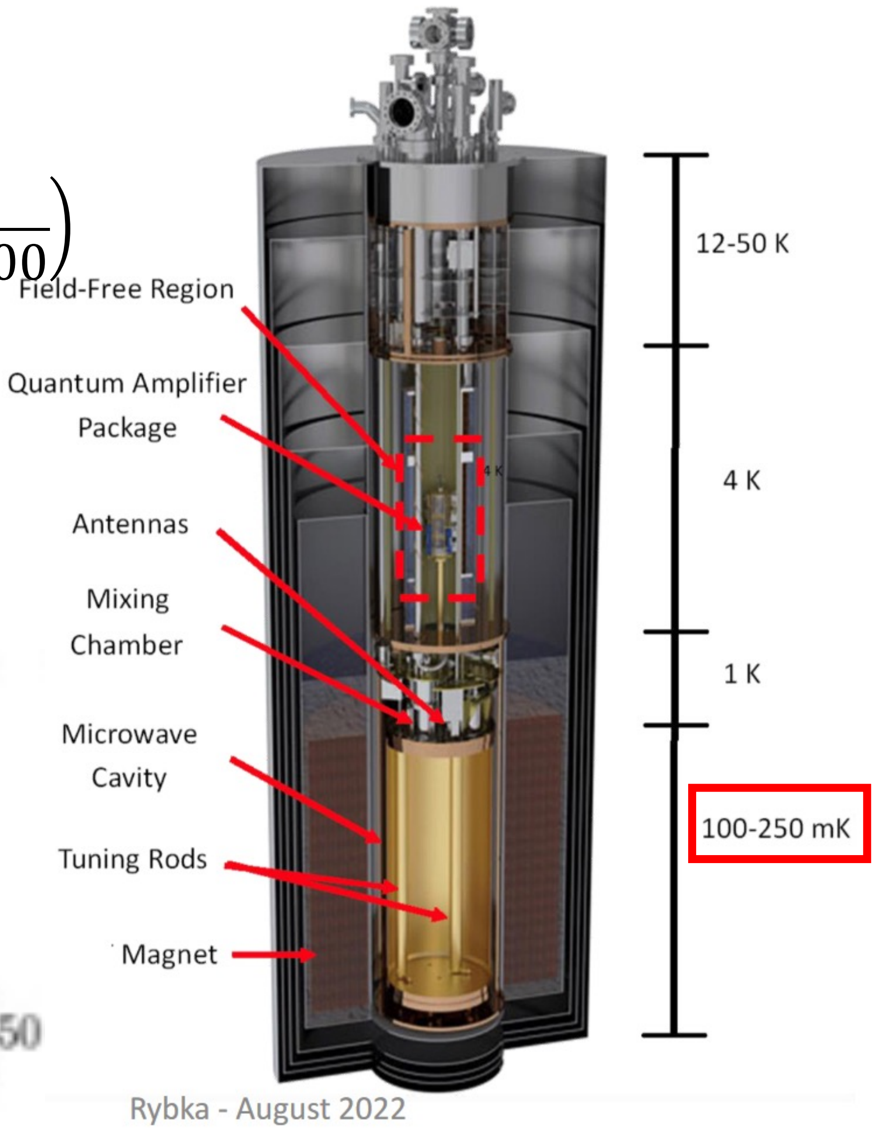
- Dicke's radiometer formula

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

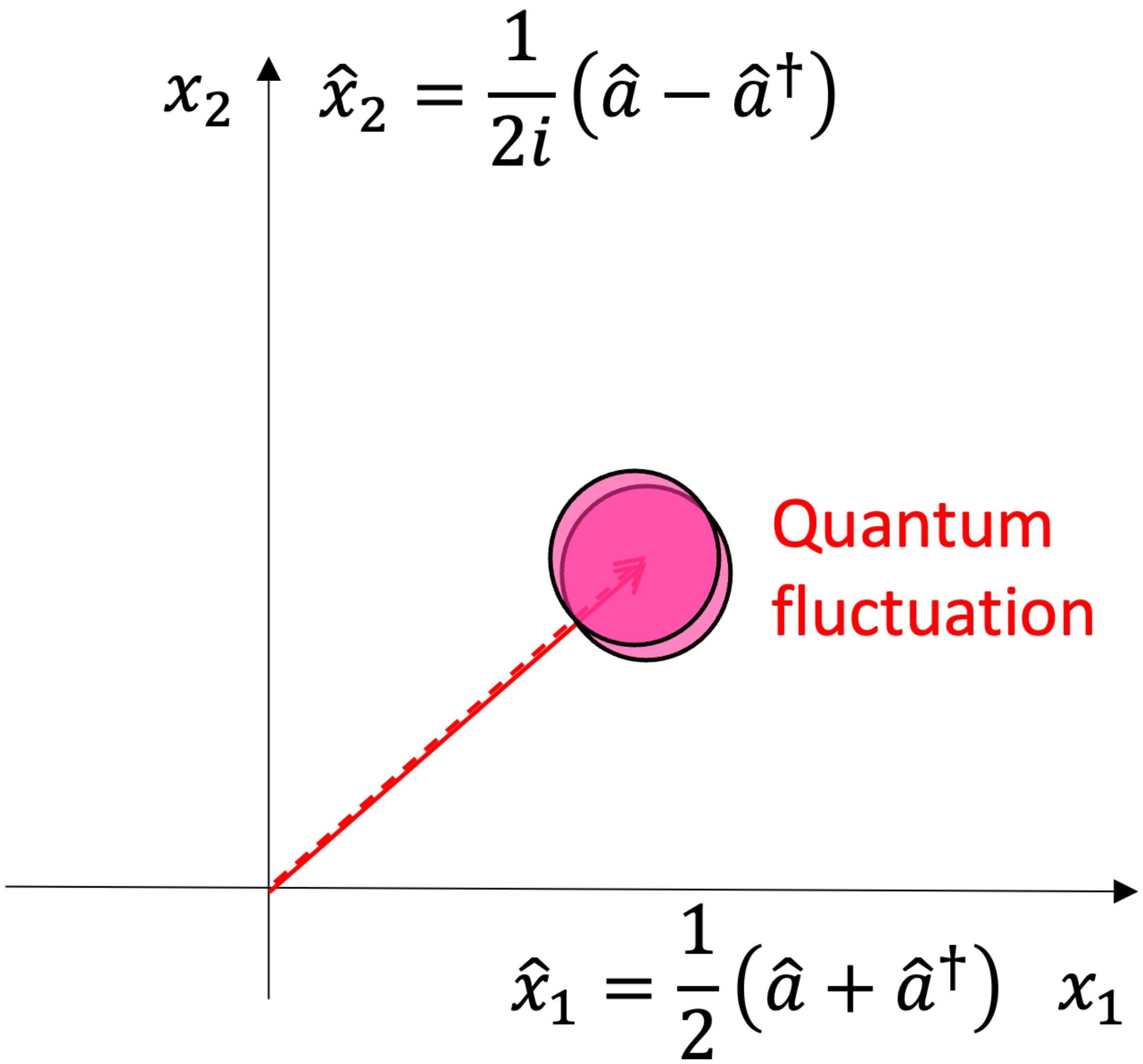
t: integration time

b: measurement bandwidth





Standard quantum limit of coherent state

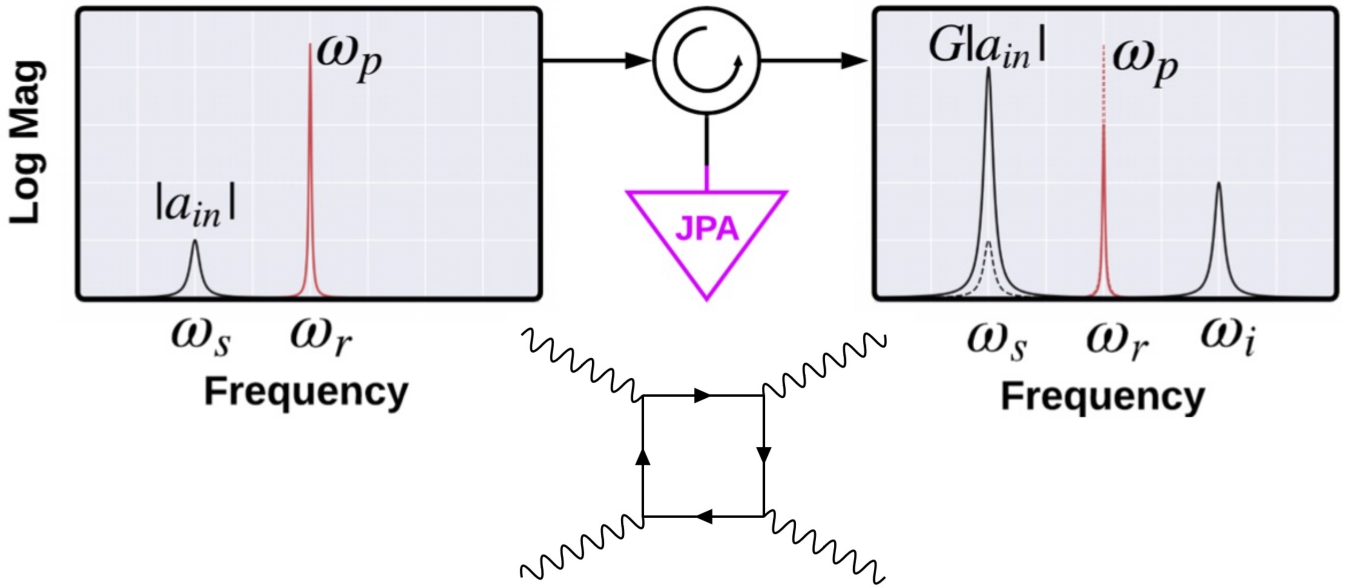


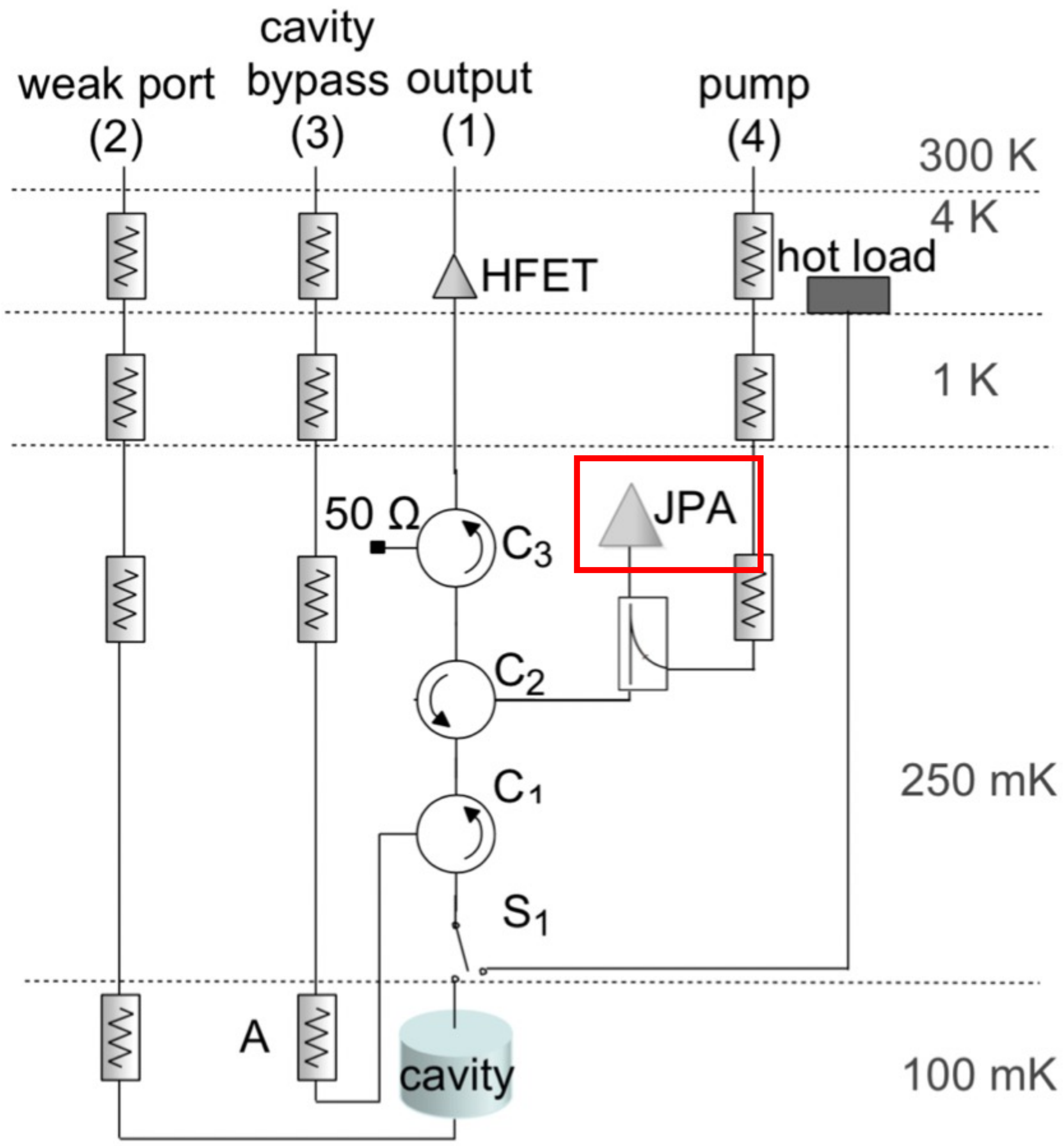
$$k_B T_S > h\nu$$

Cooling down does not help

arXiv:2010.00169

Semi-classical: Parametric Amplifier (in ADMX)



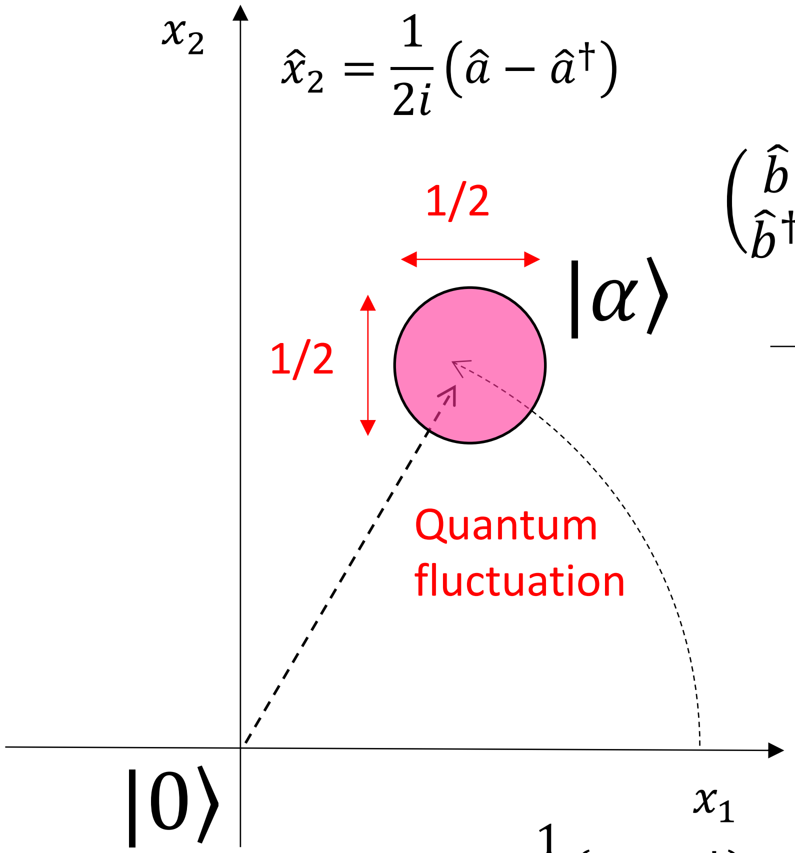


- Amplification of microwave signal at ω_s via pump microwaves at ω_p
- Nonlinear optics (Kerr effect) for frequency mixing
- No real electron/hole current
  → Free from the noise source of transistors
  → One can reach $k_B T_{SQL} = h\nu$ by cooling down

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

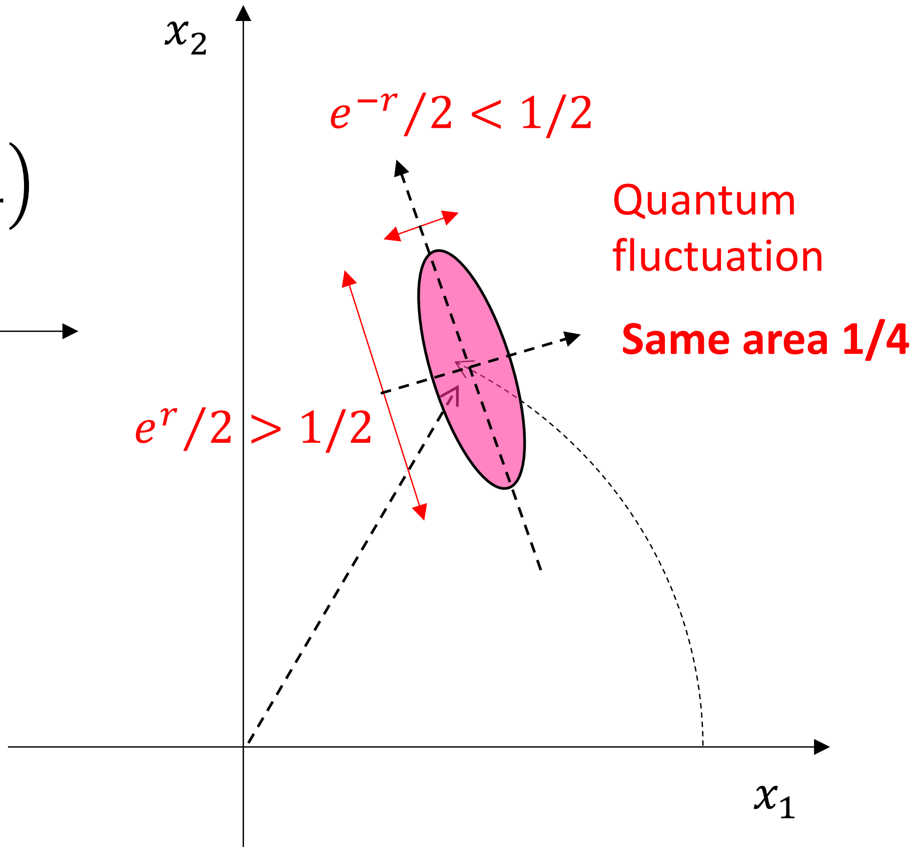


$$\hat{x}_1 = \frac{1}{2}(\hat{a} + \hat{a}^\dagger)$$

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

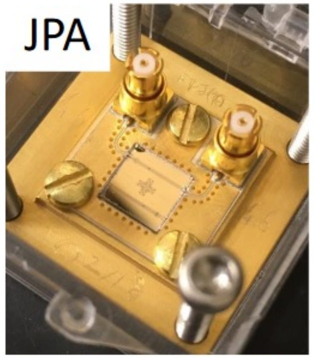
$$\hat{H} = \hbar\lambda \hat{b}^\dagger \hat{b} + \frac{\lambda - \omega}{2}$$

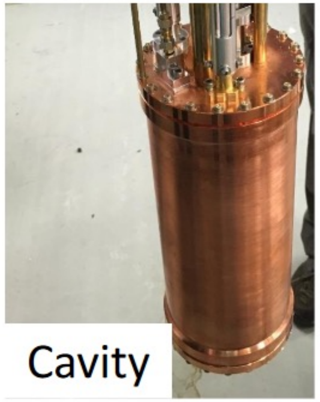
$$\begin{cases} \lambda = \sqrt{\omega^2 - |E|^2} \\ r = \frac{1}{2}\tanh^{-1}(|E|/\omega) \\ e^{2i\phi} = E/|E| \end{cases}$$



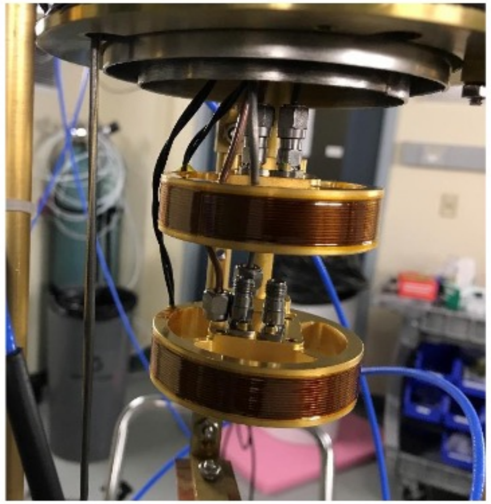
Axions search is entering a quantum regime

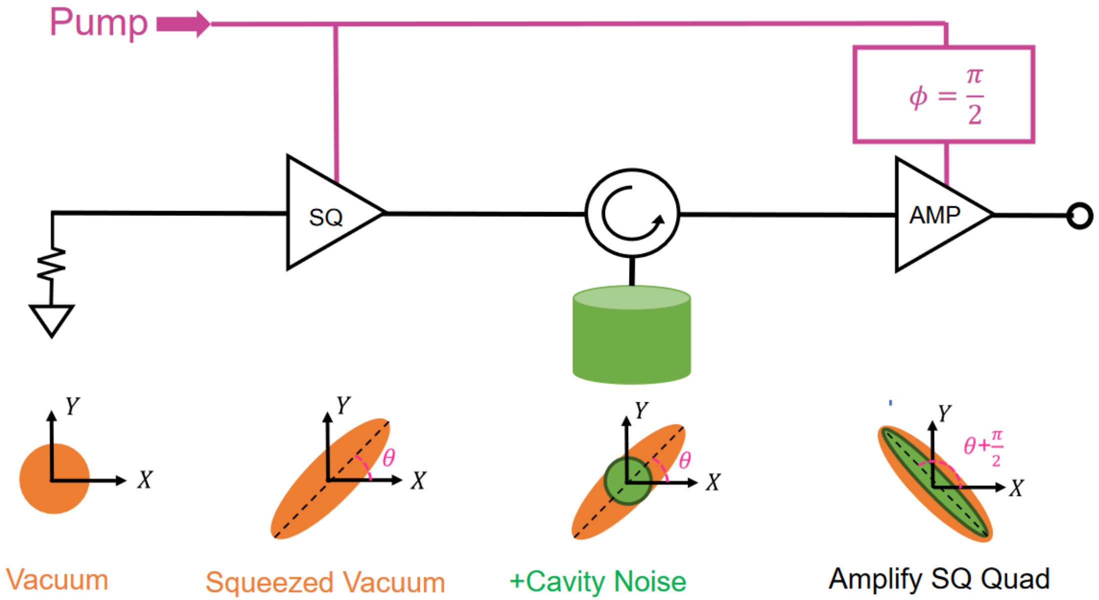
HAYSTAC (Yale University + Berkley)



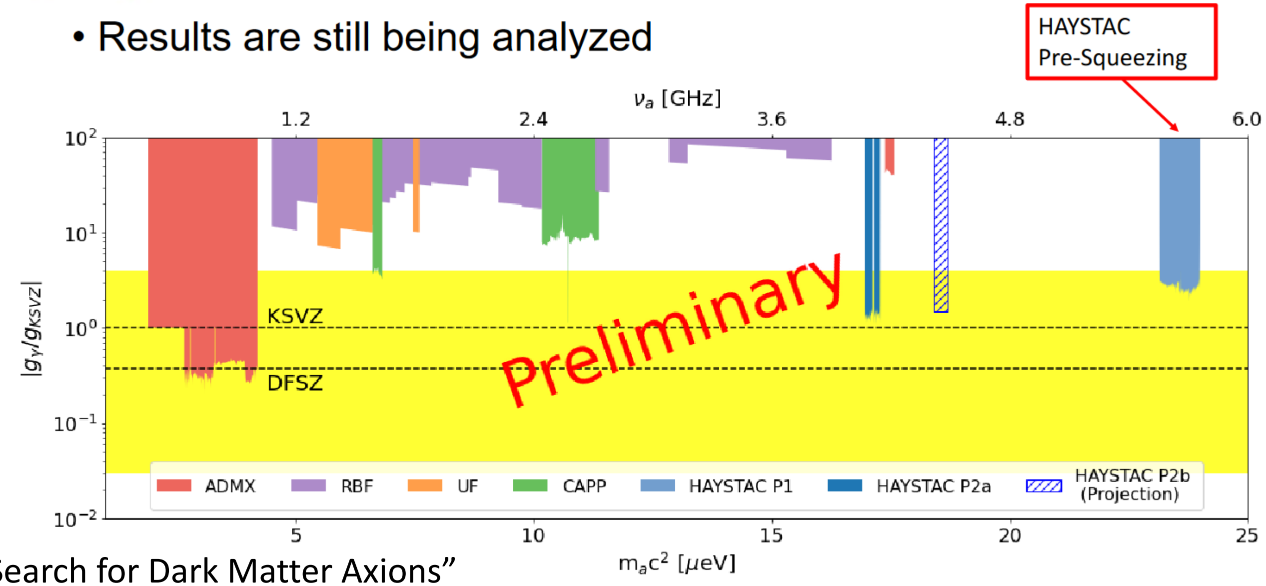


Squeezed State Receiver





- Results are still being analyzed

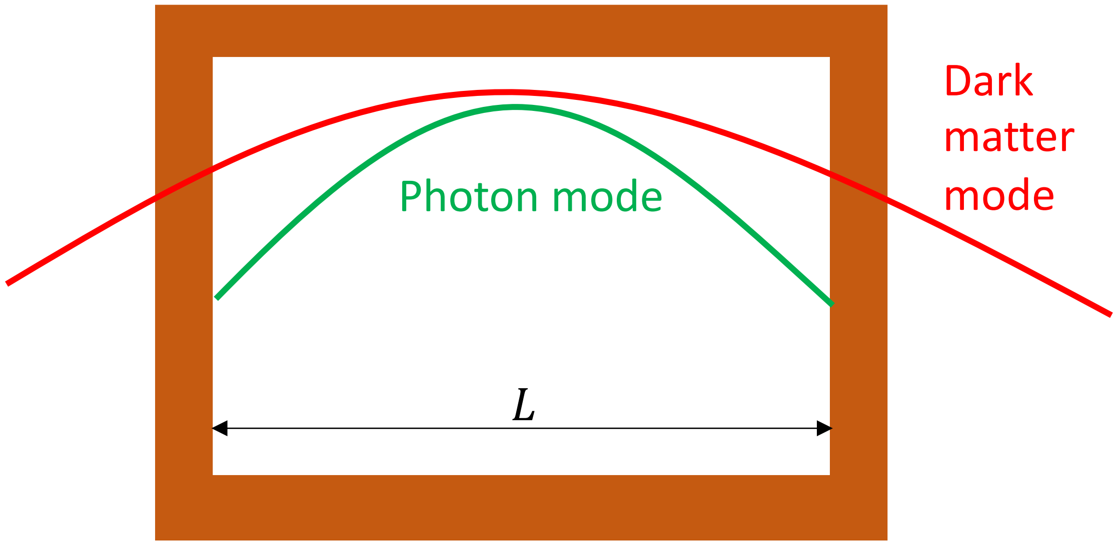


- JPAs achieve near SQL when Phase-Insensitive
- JPAs are Phase-Sensitive Amplifiers
- Each Phase alone is not limited by SQL
- Can produce "Squeezed" States
  - Dump all uncertainty/noise into a single quadrature

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

Issue of high-frequency resonators for dark matter search

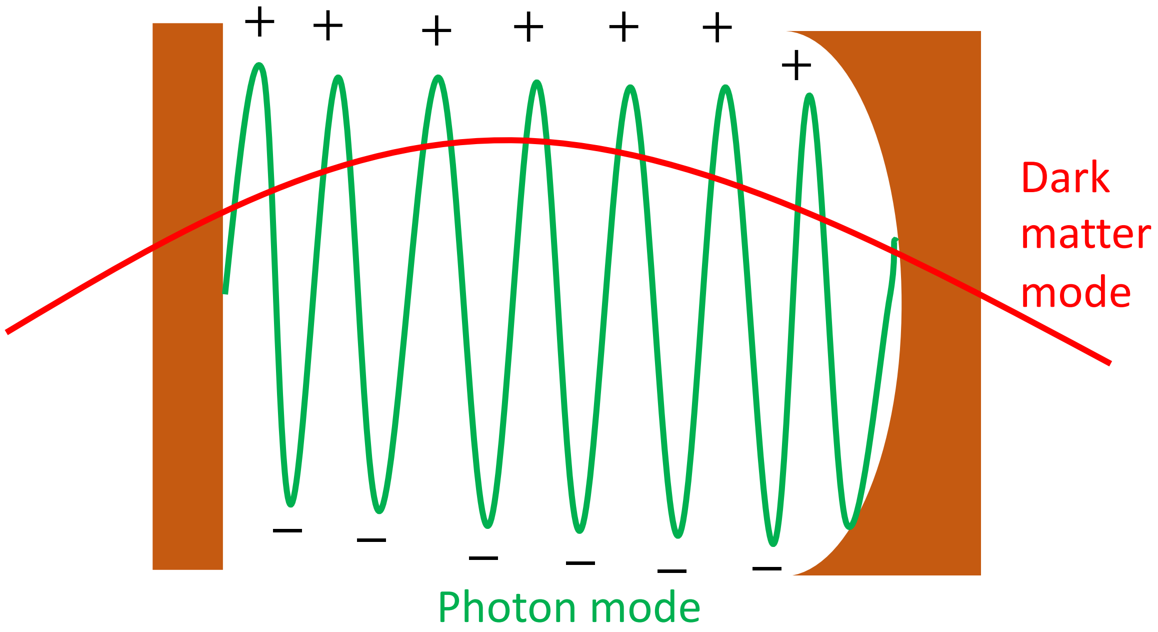
<u>An RF cavity (ADMX-type) becomes $V \sim f^{-3}$</u>



Signal: $\propto VQ$

The signal is lost by higher frequency

<u>An over-sized cavity cancels the signal</u>



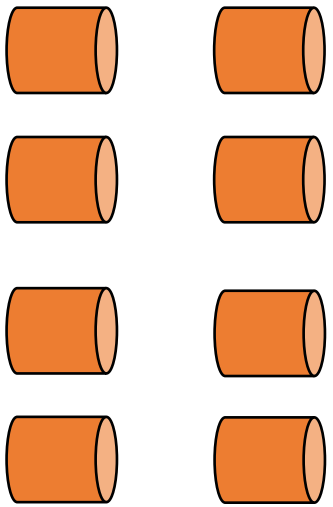
The dark matter is cold → De Broglie wavelength is long

Spatial integral is cancelled!

→ We needed an idea to keep the resonator size huge with high frequency without having phase shifts

Three ideas toward heavier axion dark matter

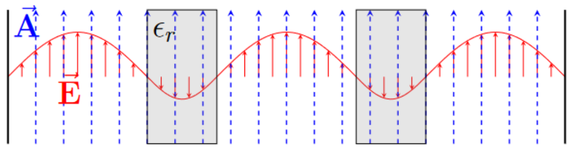
Multiple small cavities

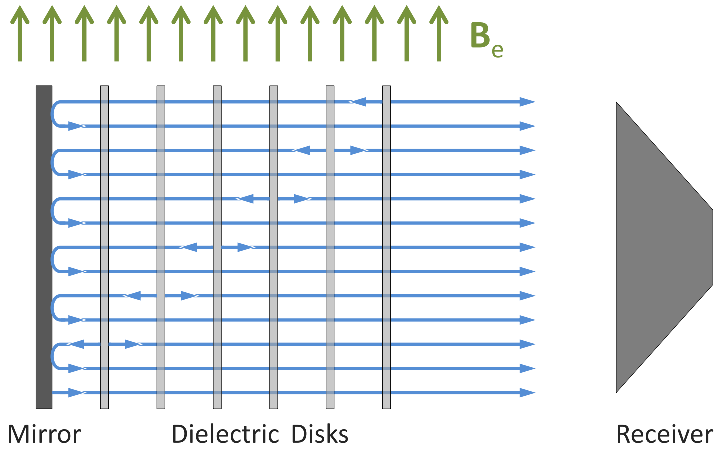


ADMX-EFR @ US

CAST-CAPP @ CERN

Dielectric disks



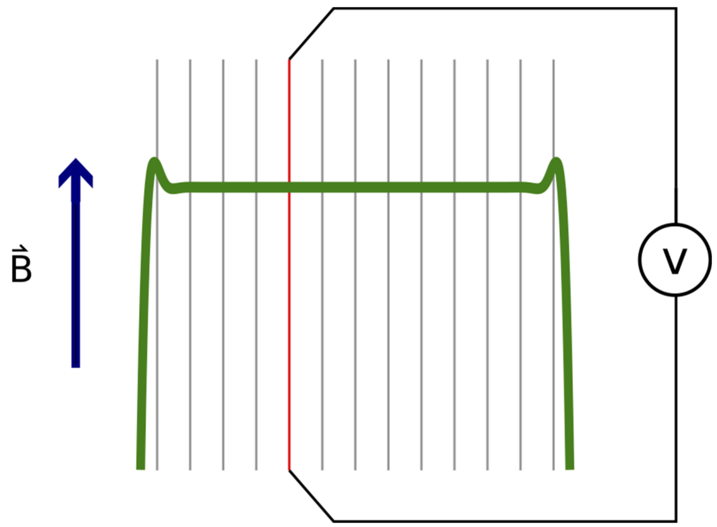


ORGAN @ Australia

ADMX-Orpheus @ US

MADMAX @ DESY

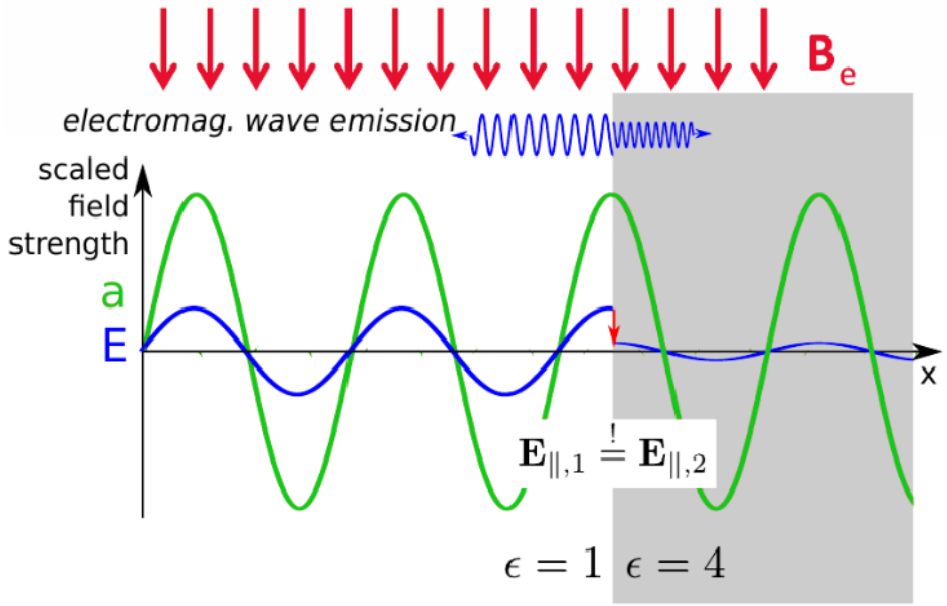
Effective plasma with metamaterial



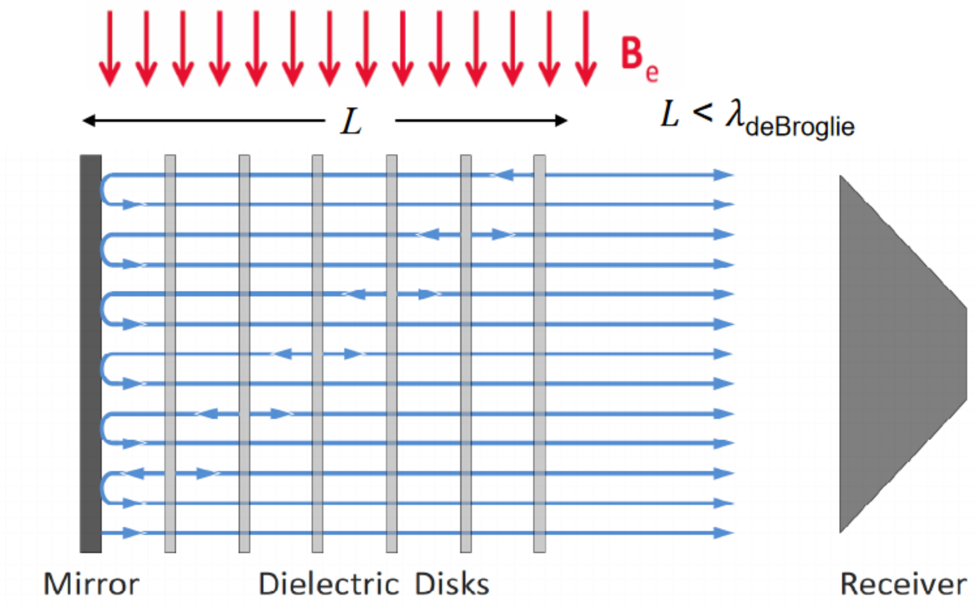
ALPHA @ SU

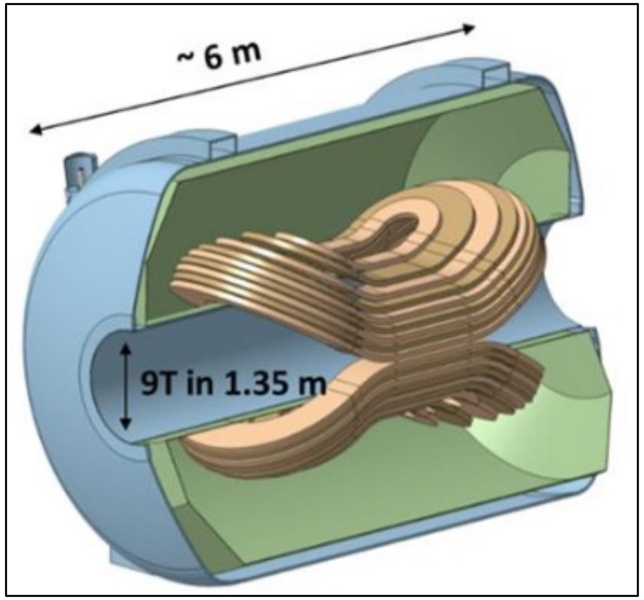
MADMAX (DESY)

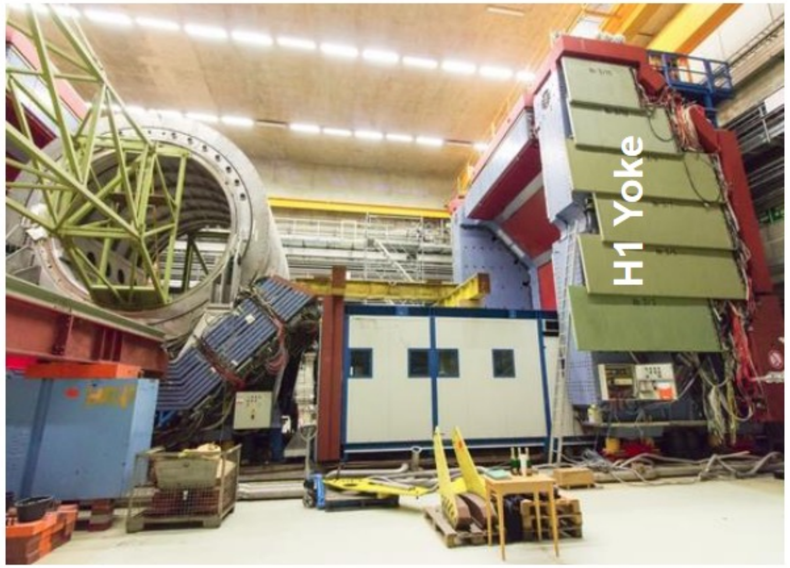
Courtesy: Antonios Gardikiotis, “Advances in searching for galactic axions with a Dielectric Haloscope”

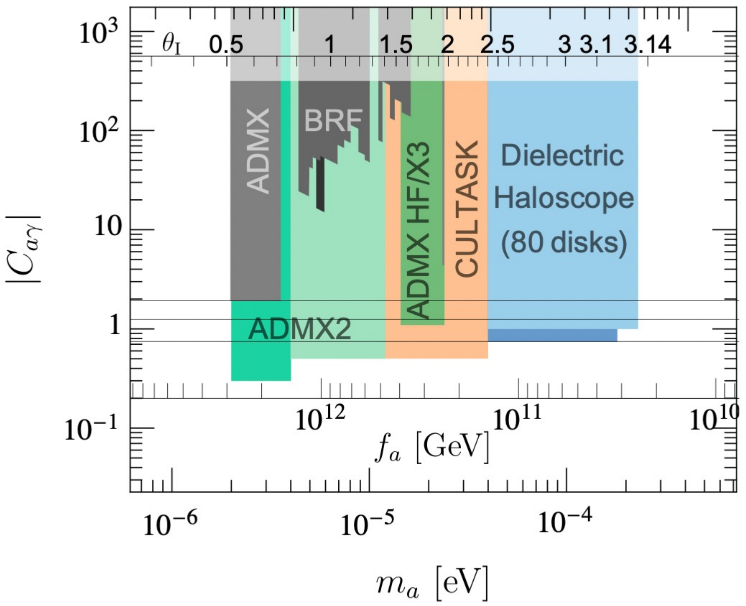


- Enhance the coherent microwave signal generated on the dielectric surface
- Dipole magnet









One technical challenge of dielectric-disk haloscope

higher Q!

Resonant cavity search including plasma haloscope

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

In-situ measurement observable

Dish antenna

Wider A!

$$P_S = (8.27\times10^{-26}\ \mathrm{W})\times\boxed{\left(\frac{A}{10\ \mathrm{m}^2}\right)}\left(\frac{B}{10\ \mathrm{T}}\right)^2\left(\frac{g_{a\gamma}}{3.92\times10^{-16}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{\rho}{0.3\ \ \mathrm{GeV/cm^3}}\right)\left(\frac{1\ \mu\mathrm{eV}}{m_a}\right)^2$$

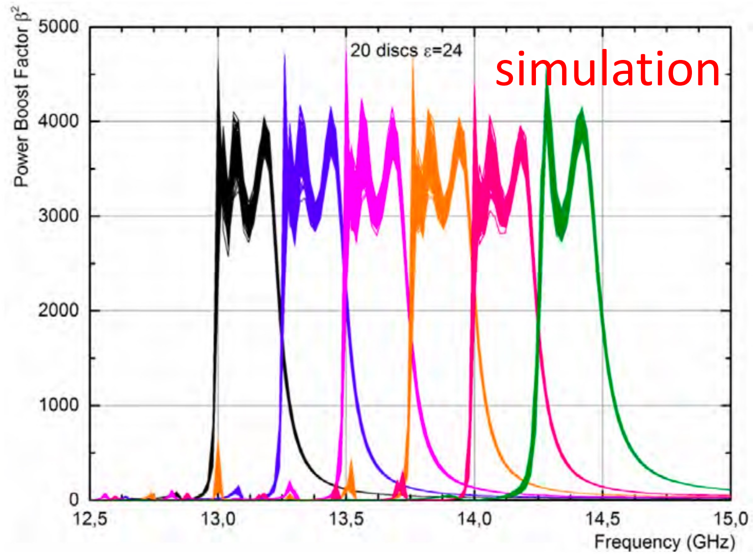
Fixed by mechanical design

Dielectric-disk haloscope:

Higher β!

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

How to measure β ??



→ Cavity-based search may be simpler to just measure Q

Axion-plasmon mixing in a cavity

$$\boxed{\epsilon}\boldsymbol{\nabla}\cdot\mathbf{E} = \rho - g_{a\gamma}\mathbf{B}_{\rm e}\cdot\boldsymbol{\nabla}a\,,$$
$$\boldsymbol{\nabla}\times\mathbf{H} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma}\mathbf{B}_{\rm e}\dot{a}\,,$$
$$\ddot{a} - \boldsymbol{\nabla}^2 a + m_a^2 a = g_{a\gamma}\mathbf{E}\cdot\mathbf{B}_{\rm e}\,,$$

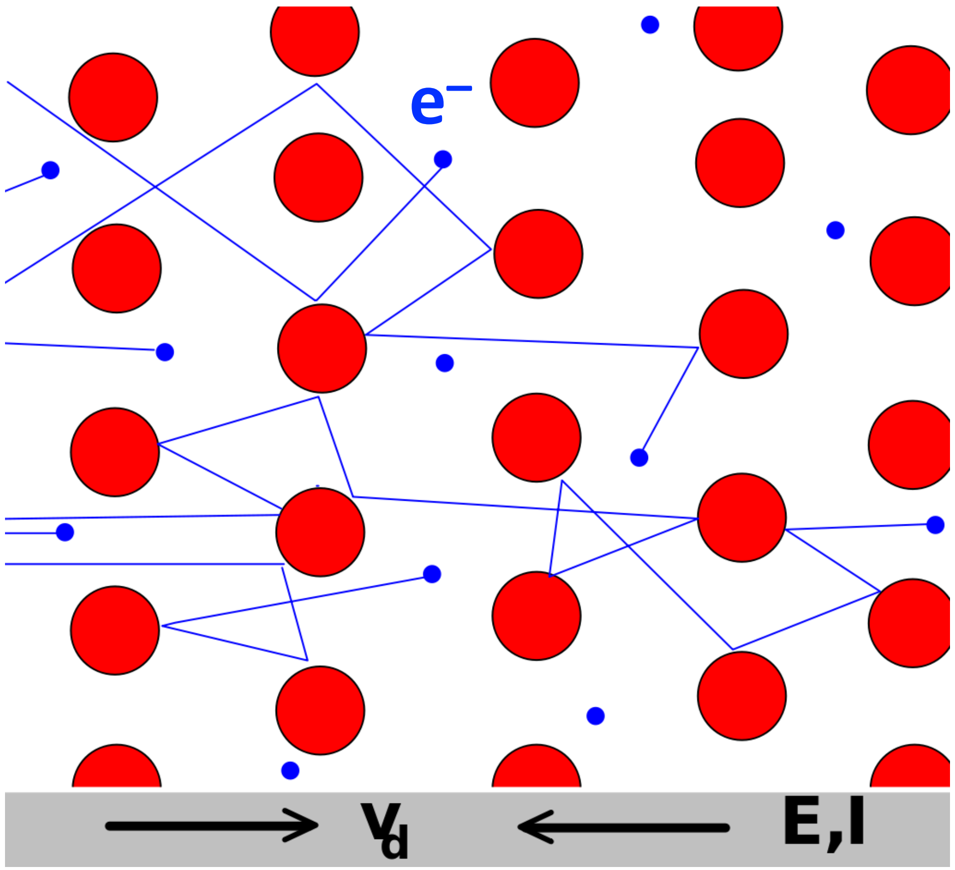
$\epsilon = 0$ gives and resonance inside a plasma

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

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



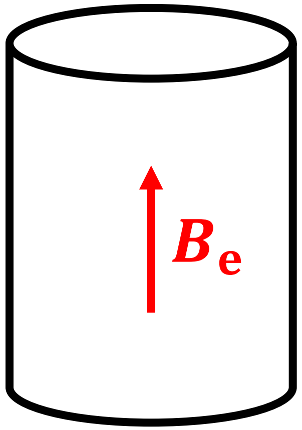
From wiki

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

Cavity filled with 1D wire metamaterial

Free electrons inside wires behave like 1D plasma

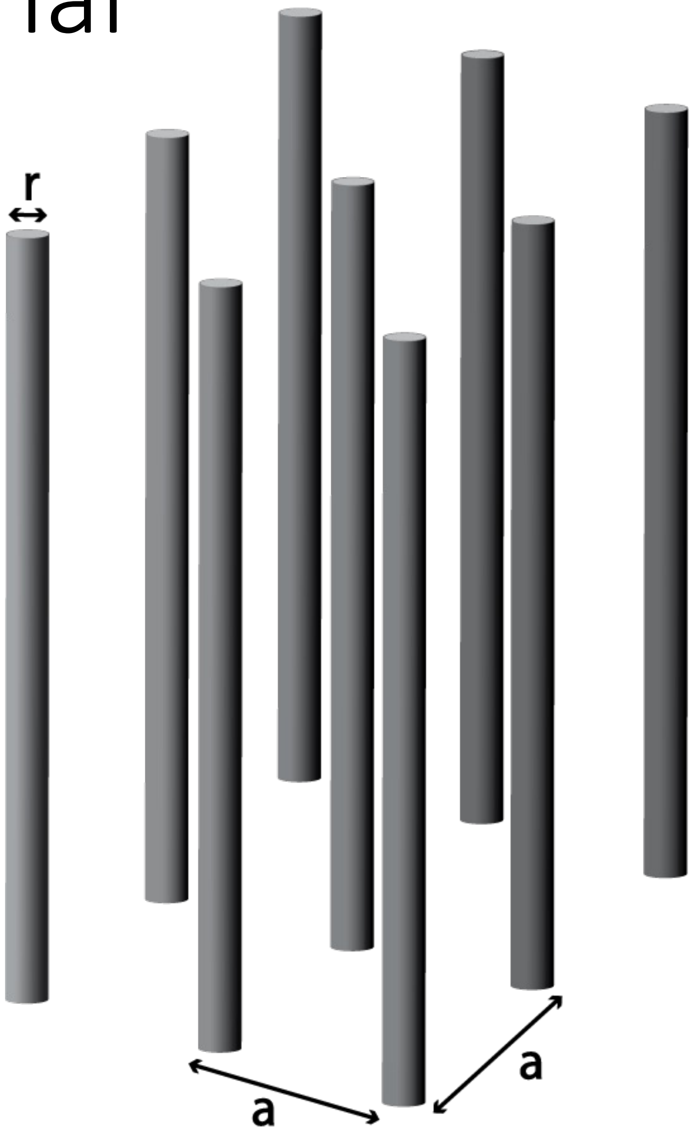
$$n_e = n\frac{\pi r^2}{a^2} \quad ; \quad m_{eff} = \frac{e^2 \pi r^2 n}{2\pi}\log\frac{a}{r},$$

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

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

$\omega_p/2\pi \sim 16\ \mathrm{GHz}$

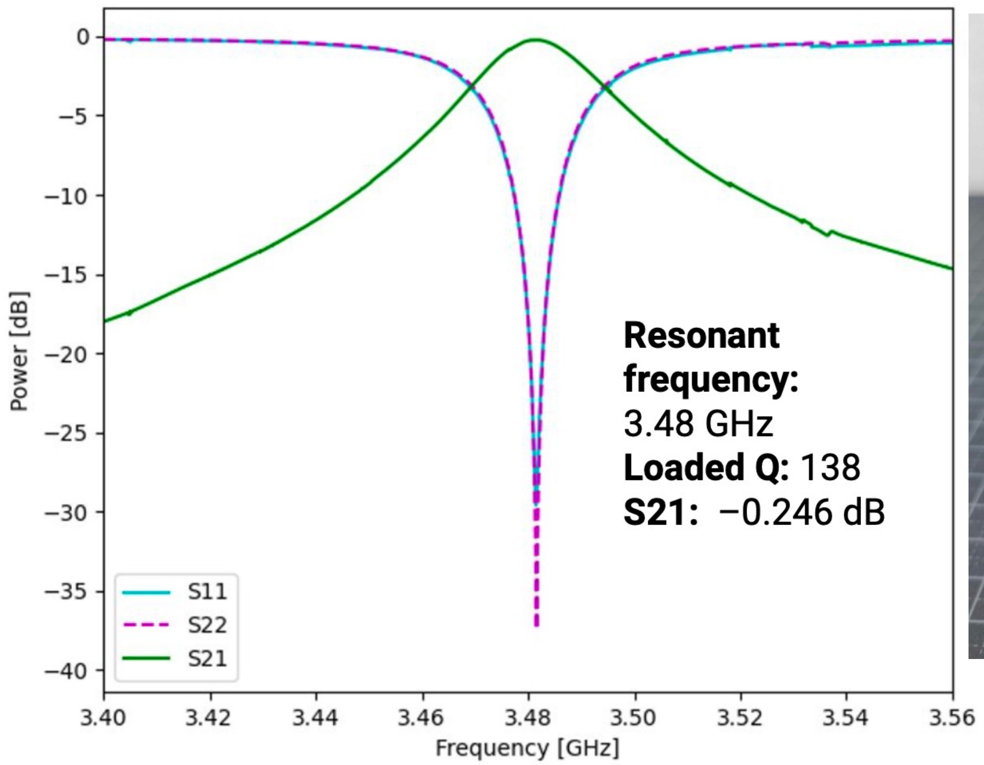
Free from the size of the cavity itself



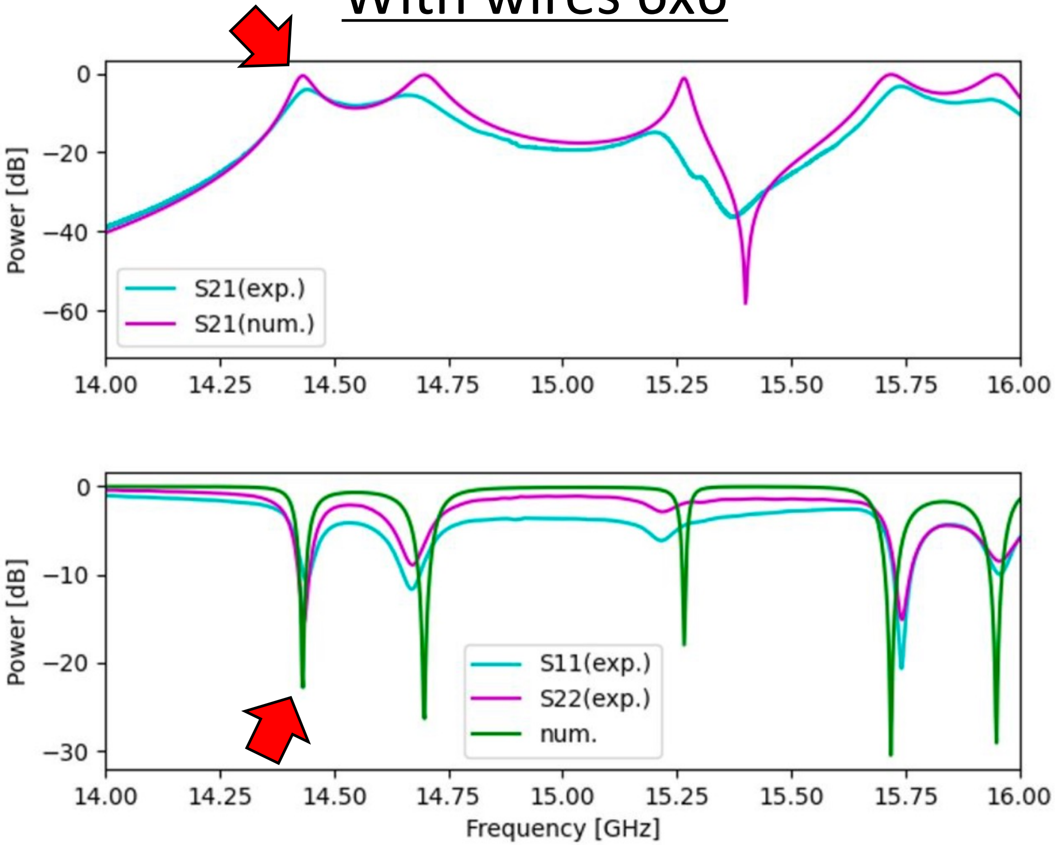
Changing the spacing a tunes the plasma frequency

Prototype wire-filled cavities

<u>Same size, without wires</u>



<u>With wires 6x6</u>

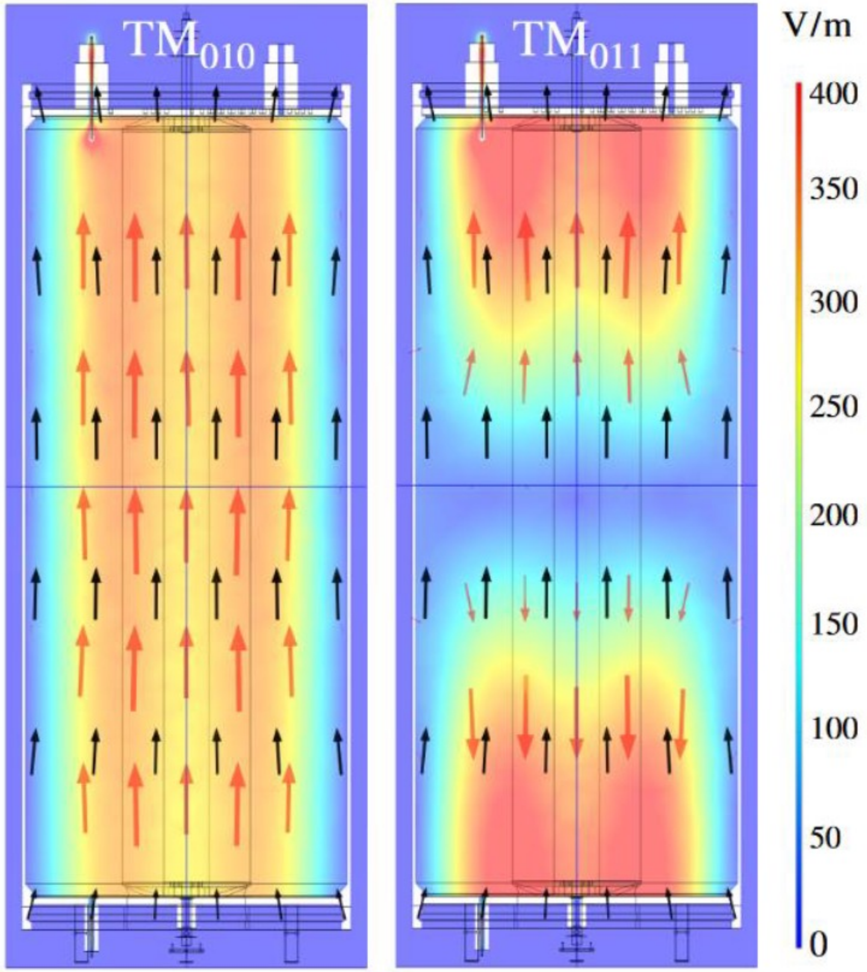


Resonance frequency of the lowest TM mode

3.48 GHz → 14.4 GHz

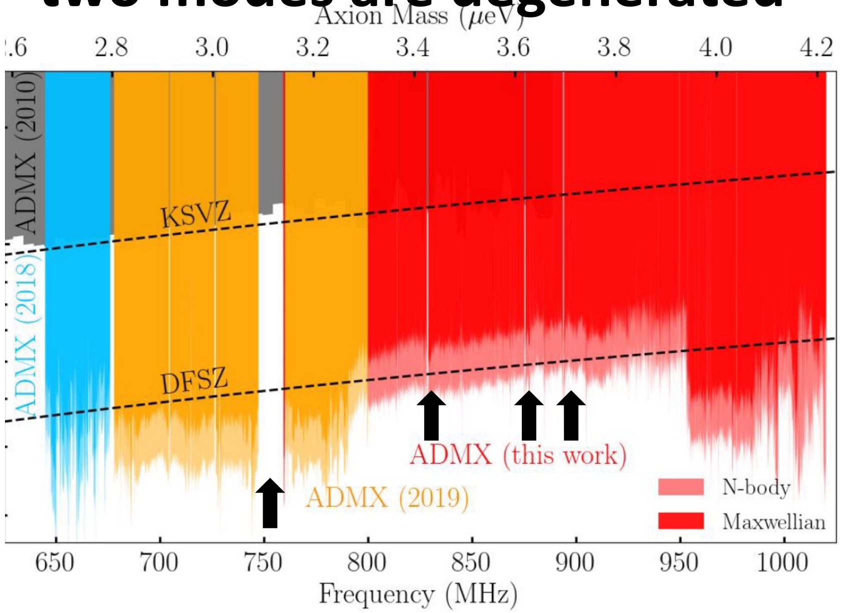
With the artificial plasma by the wire metamaterial

One important lesson from ADMX



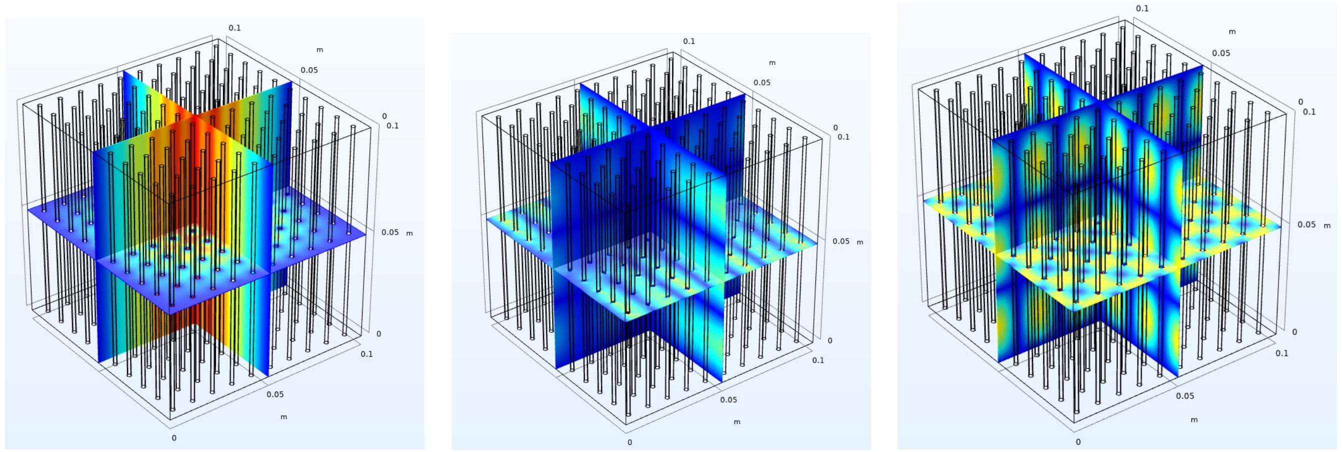
Courtesy: Gray Rybka, "Current Status and Future Plans of ADMX"

No limits in a frequency where two modes are degenerated



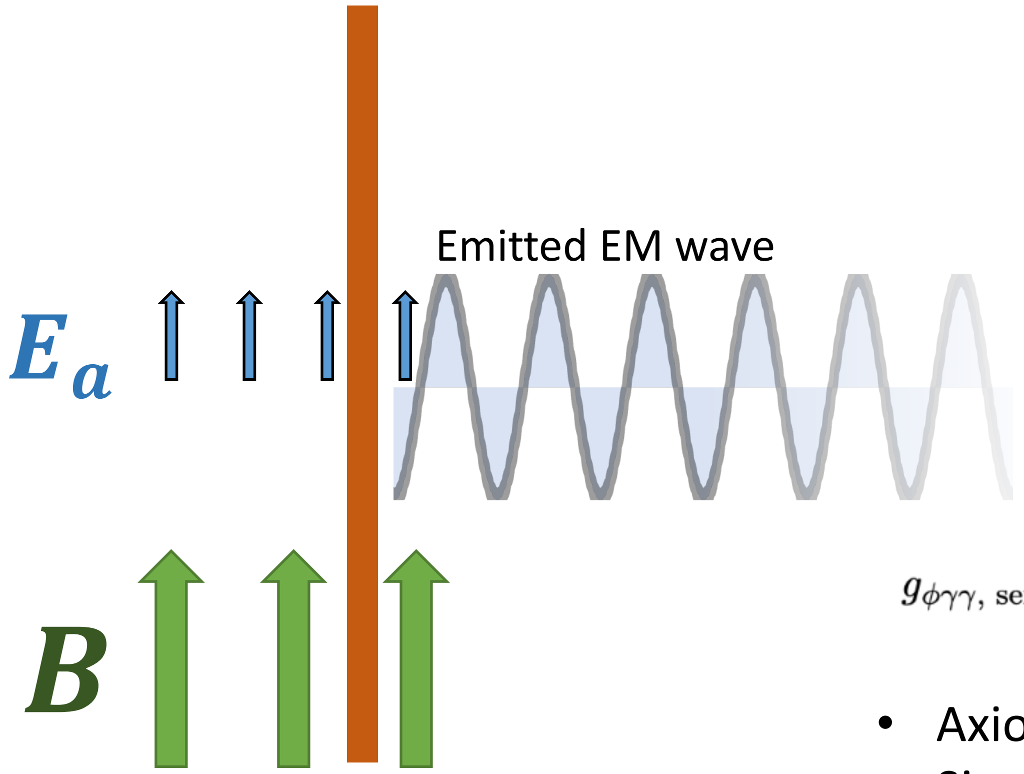
mode	f_0 [GHz]	Q_0
TE	11.347	20780
TE	11.347	20780
TE	11.359	20917
TM110	11.421	4152.6
TEM	11.502	5678.7
TEM	11.502	5293.8

The same and much severer issues in plasma haloscope

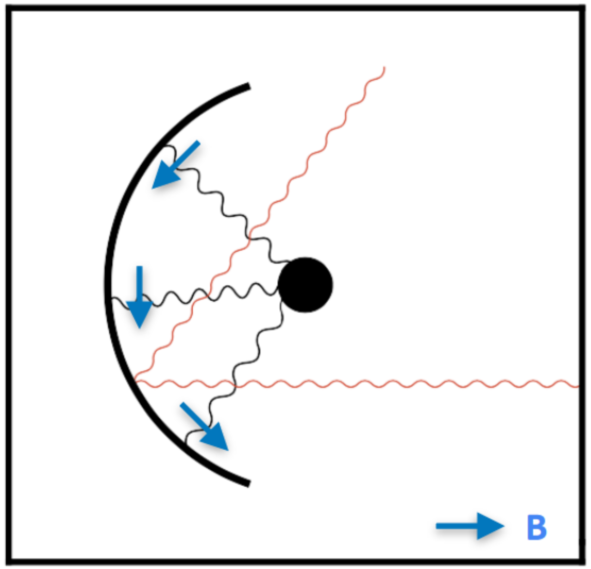


→ Photonic bandgap to avoid parasite mode during tuning (?)

Even higher frequency → Dish antenna



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



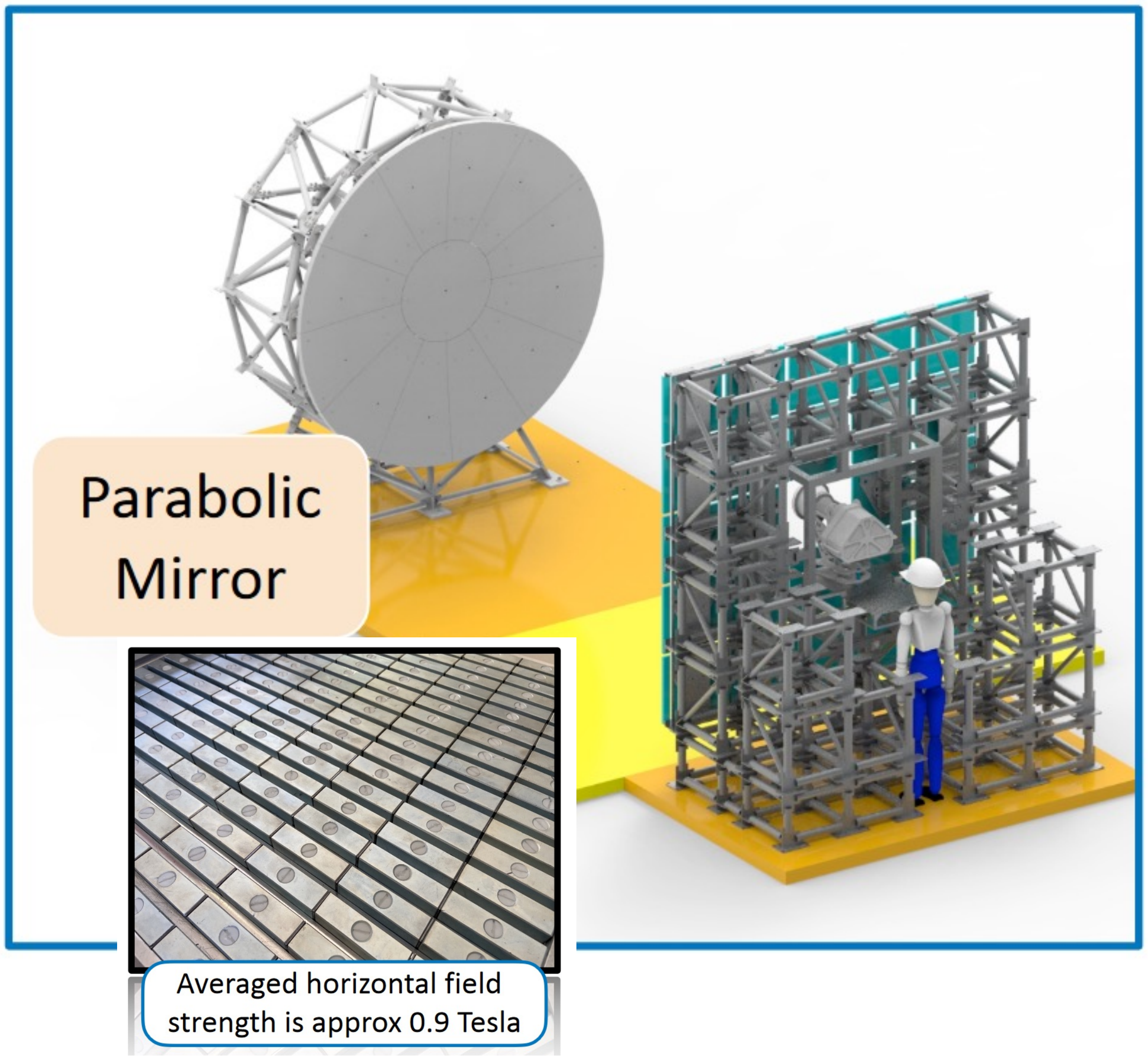
$$g_{\phi\gamma\gamma,\,\mathrm{sens}} = \frac{3.6\times10^{-8}}{\mathrm{GeV}}\left(\frac{5\,\mathrm{T}}{\sqrt{\langle|\mathbf{B}_{||}|^2\rangle}}\right)\left(\frac{P_{\mathrm{det}}}{10^{-23}\,\mathrm{W}}\right)^{\frac{1}{2}}\left(\frac{m_\phi}{\mathrm{eV}}\right)\left(\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_{\mathrm{DM,halo}}}\right)^{\frac{1}{2}}\left(\frac{1\,\mathrm{m}^2}{\boxed{A_{\mathrm{dish}}}}\right)^{\frac{1}{2}}$$

- Axion-photon conversion at the metal-vacuum interface
- Signal enhancement by larger area, neither cavity Q nor dielectric boosting factor

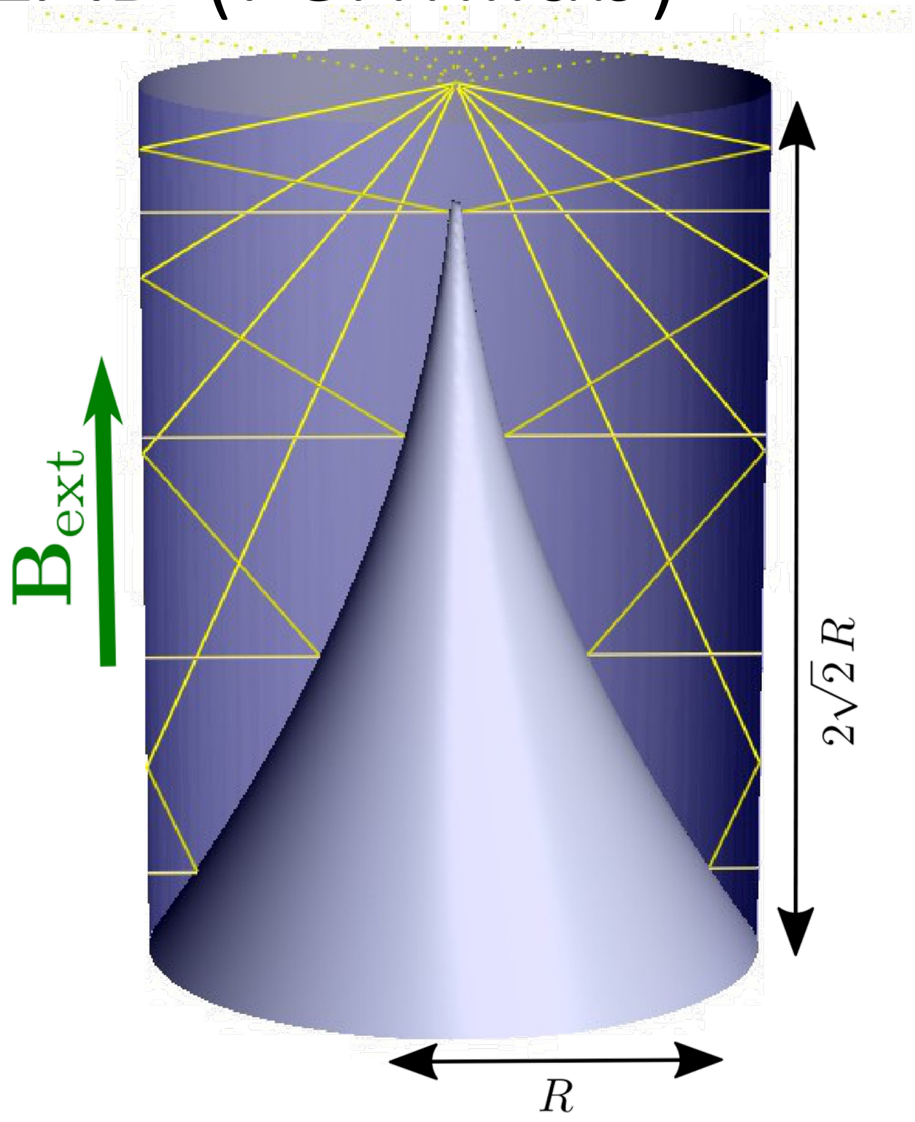
- Challenge: parallel B-field on the large area of a metal surface

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

PA may not be available at higher f→ single photon sensors

Noise power of wave detection

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

Noise power of photon detection

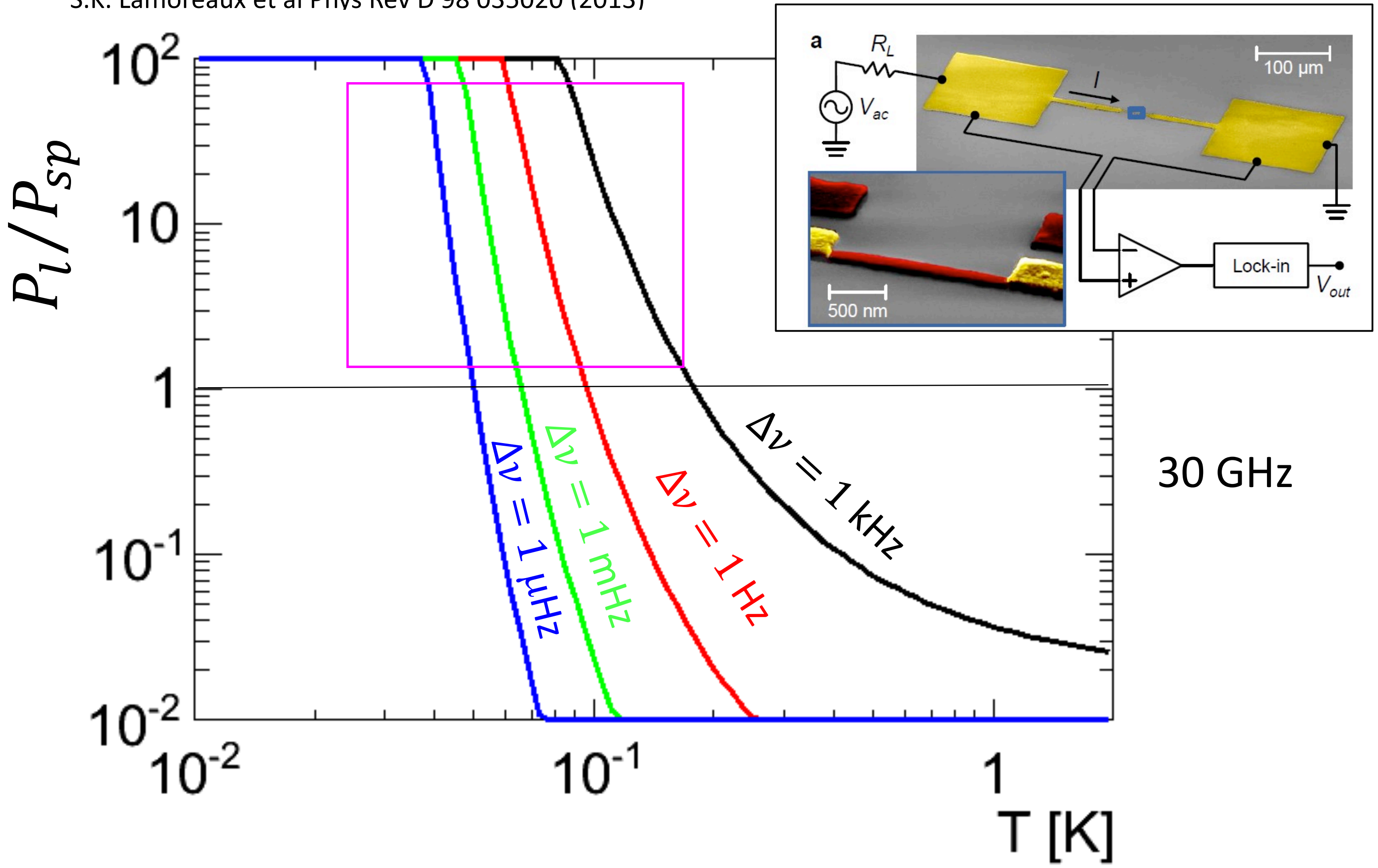
$$P_{sp} = h\nu\sqrt{\frac{\eta\bar{n}Q_c}{2\pi\nu t}}$$

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

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)



30 GHz

Superconducting single photon sensors may be a solution in the future
→ Although one loses phase information, zero background at cold may be better

Conclusion

- Axion dark matter behaves like coherent waves
  - Microwave technology developed in the particle accelerator community is a mean to address axions
- The axion search around 1 GHz is going to the quantum regime
  - The classical microwave technology is approaching the standard quantum limit and quantum optics is being implemented
- To address heavier axions, several methods have been proposed
  - Multiple cavities, dielectric disks, plasma haloscope, dish antenna
  - Plasma haloscope is being demonstrated
    - Tuning and mode mixing will be the next challenge
  - Different pros and cons in each idea
- Single photon sensors may be necessary for such heavier axions

backup

Dark photon: massive extra U(1) gauge bosons

Extra bosons are classic: Grand Unified theories

$$SU(5) \to SU(3)_C \times SU(2)_L \times U(1)_Y$$

QCD

Electroweak theory

SM

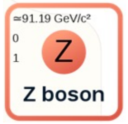
Higgs mechanism leaves one $U(1)_\gamma$ boson massless = photon γ

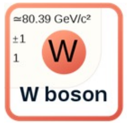
$B \in U(1)_Y$

$$\begin{pmatrix} A_\gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}$$

Maxwell equation for vector potential A_γ

$$W^\pm = \frac{W_1 \mp i W_2}{\sqrt{2}} \quad W_j \in SU(2)_L \quad \left(\frac{\partial^2}{\partial t^2} - \nabla^2\right) A_\gamma = 0$$



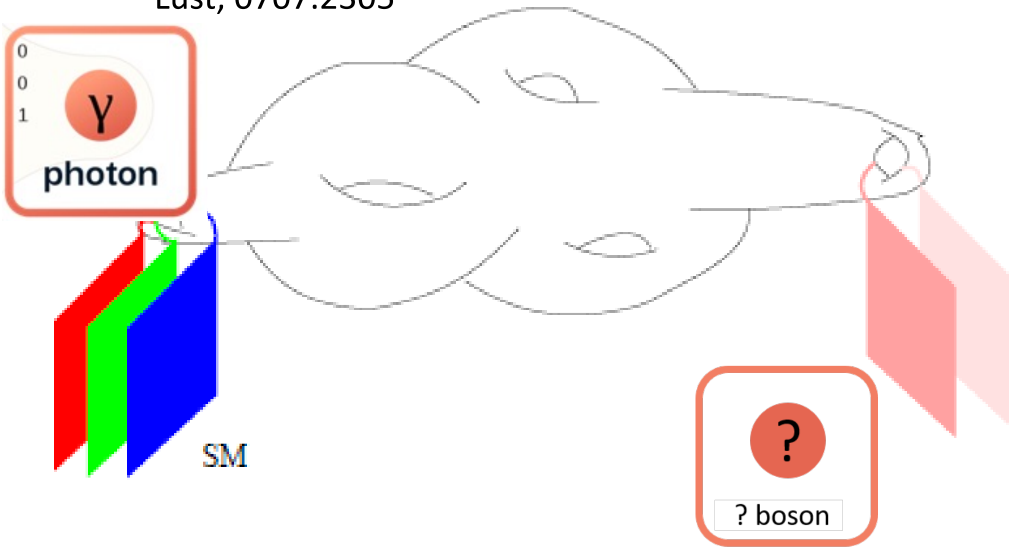


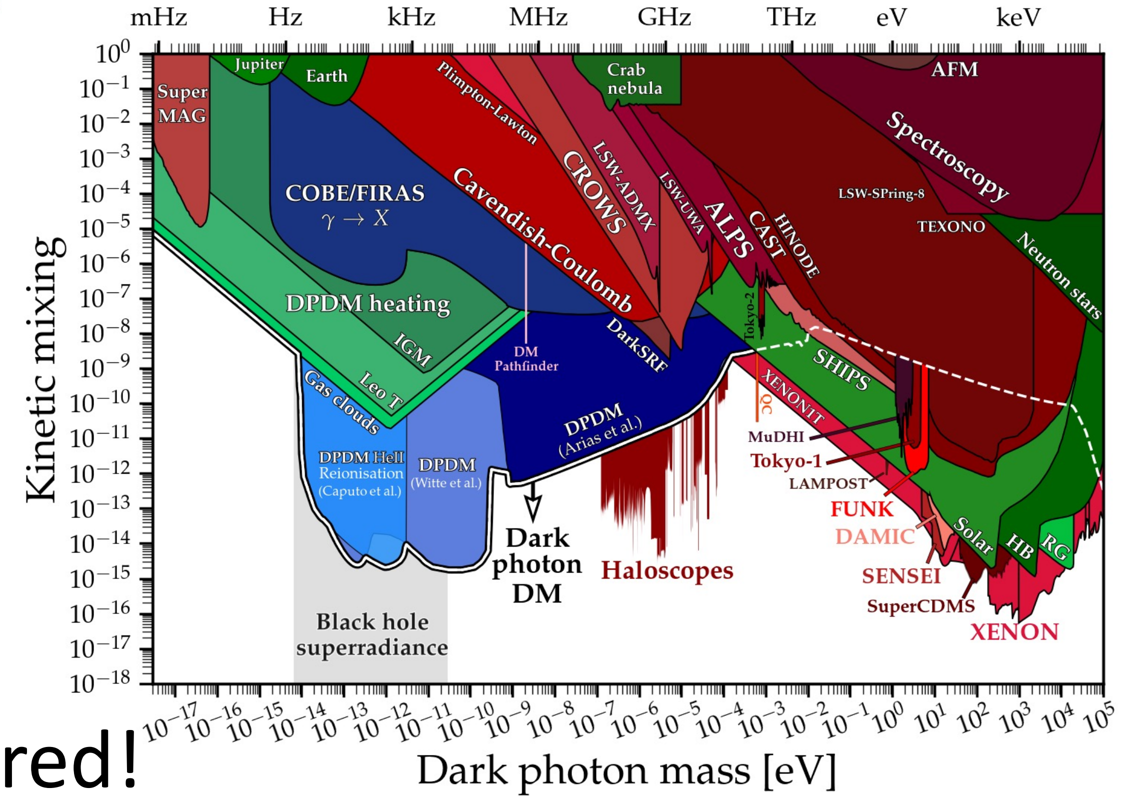
$$SO(10) \to SU(5) \times U(1)$$

$$E_6 \to SO(10) \times U(1)$$

Modern generalization from string theory

Lust, 0707.2305



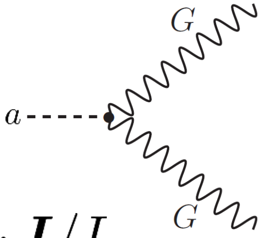


Yet to be discovered!

Axion: only 3 possible (non-gravitational) interactions with standard model particles

interaction with gluons:

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$



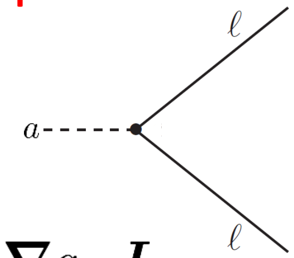
$$\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ nuclear spin interacts with an oscillating electric dipole moment (**EDM**) in presence of effective electric field.

defines QCD axion

interaction with leptons:

$$\frac{\partial_\mu a}{f_a} \bar{\psi}_\ell \gamma^\mu \gamma_5 \psi_\ell$$



$$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$$

→ nuclear spin interacts with an effective magnetic field

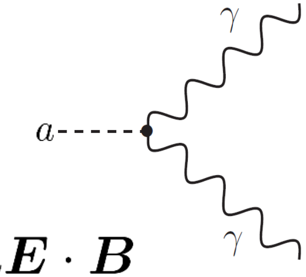
Spin precession

interaction with photons:

ALP field amplitude

symmetry breaking scale

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

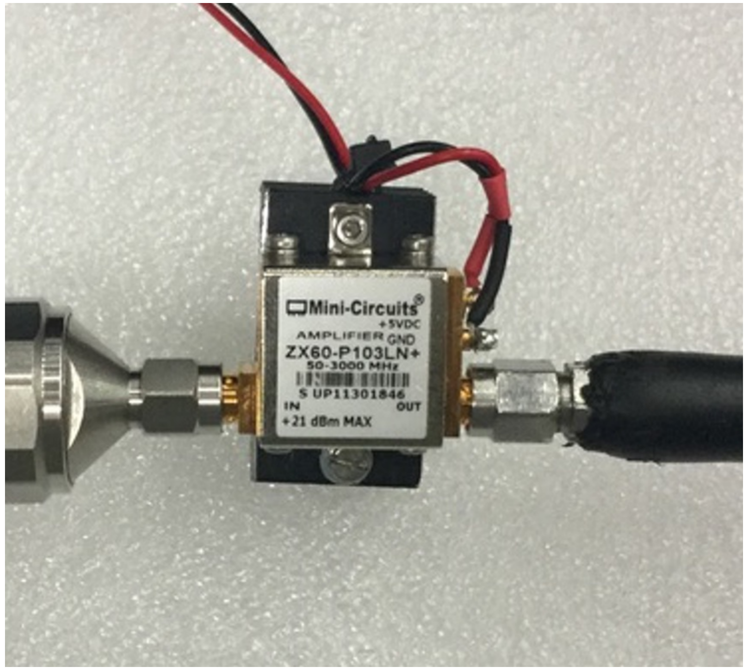
→ ALP ↔ photon conversion in a magnetic field
→ precision electromagnetic sensors

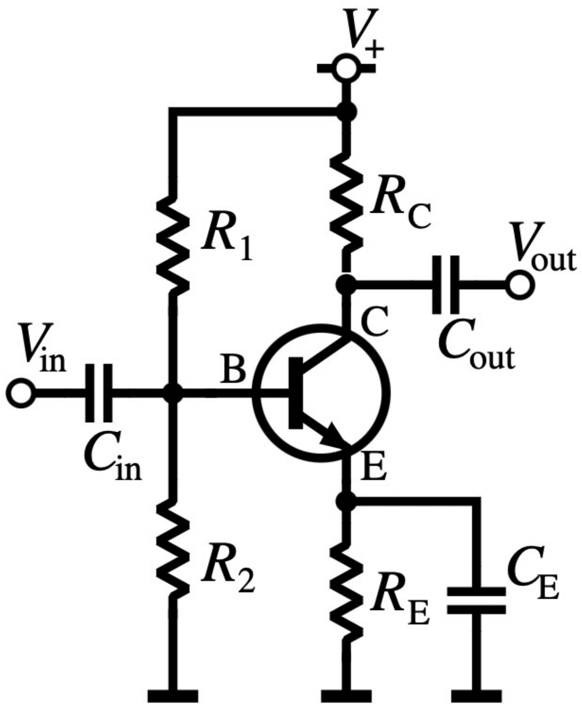
Primakov effect

Courtesy: Alex Sushkov "The quantum limits on magnetic resonance searches for axion-like dark matter"

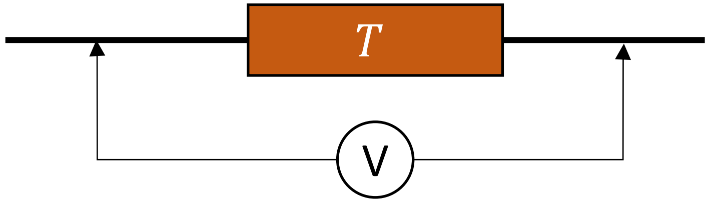
[*Rev. Mod. Phys.* ***93***, 015004 (2021)]
[*arXiv:2203.14923* (2022)]

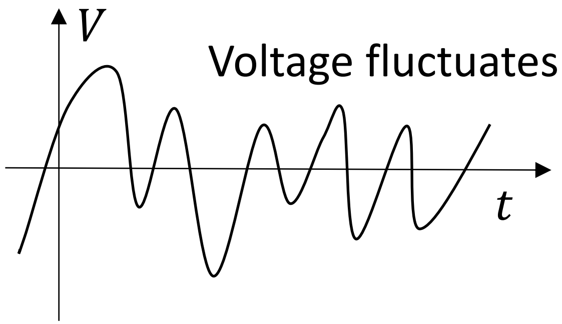
Classical: amplifier based on transistors





Any conductor at temperature T





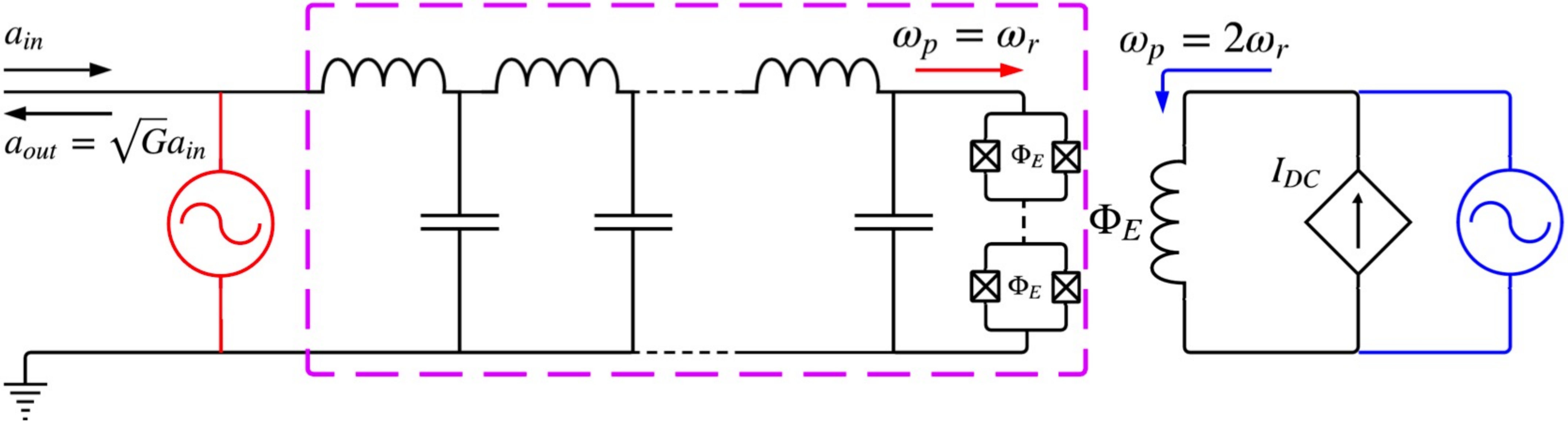
$$P_N = \frac{\langle V^2 \rangle}{4R}$$

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

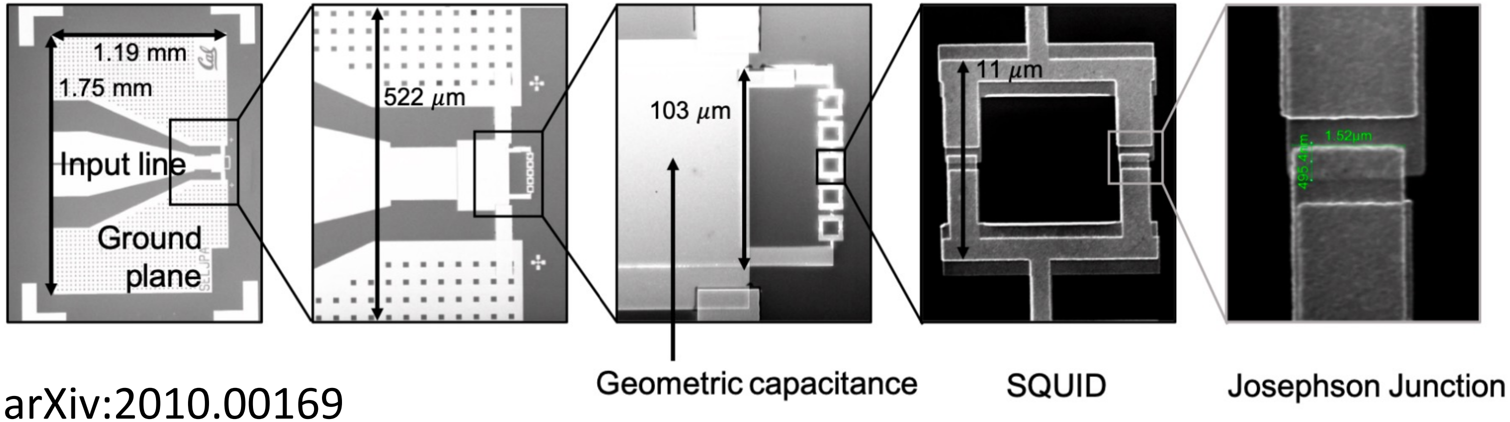
→ The effective noise temperature is always limited by a certain value

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

Implementation: Josephson Parametric Amplifier



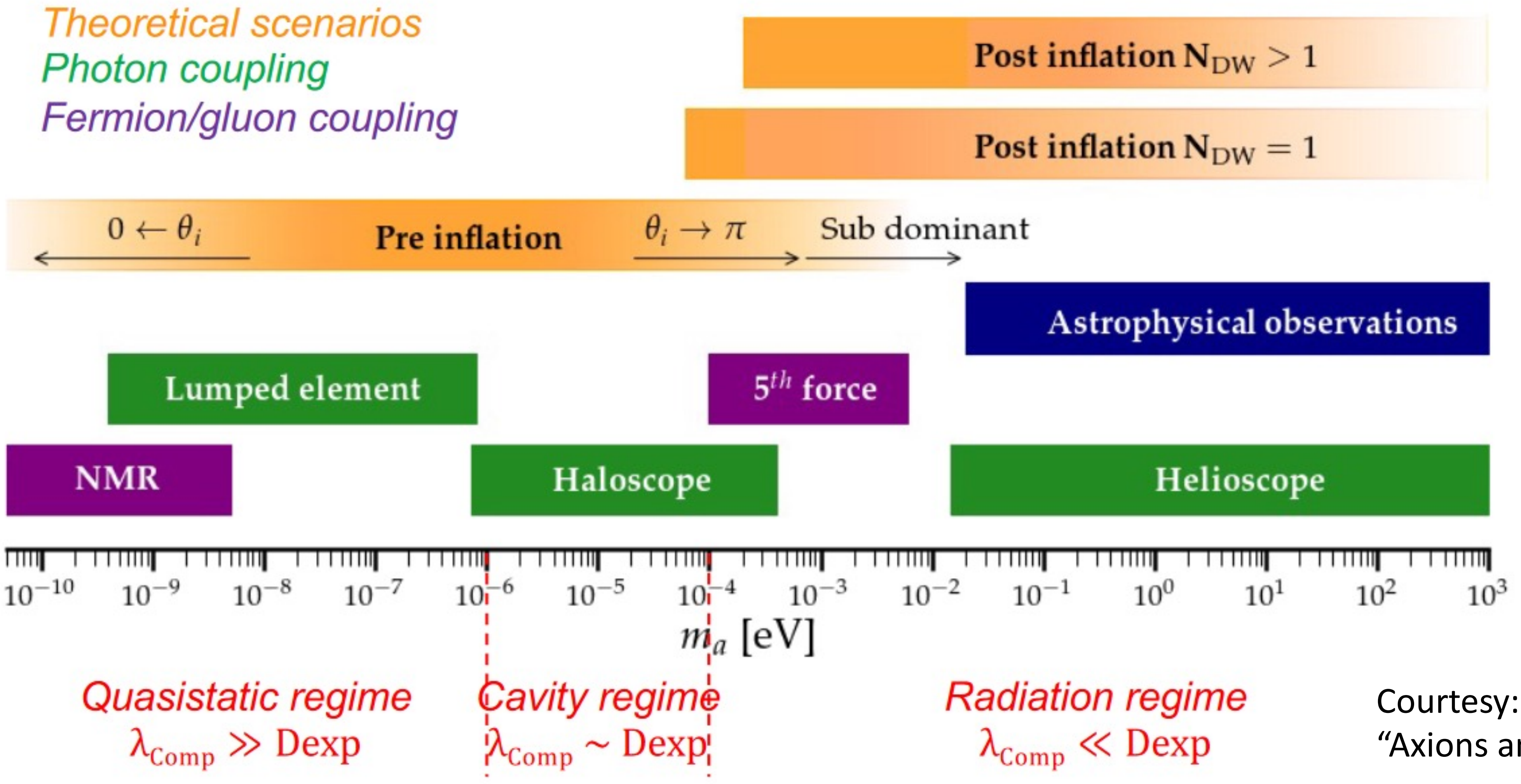
$$L_J = \frac{L_{J0}}{\sqrt{1-(I/I_0)^2}} = L_{J0}\left(1+\frac{1}{2}(I/I_0)^2+\ldots\right)$$



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)

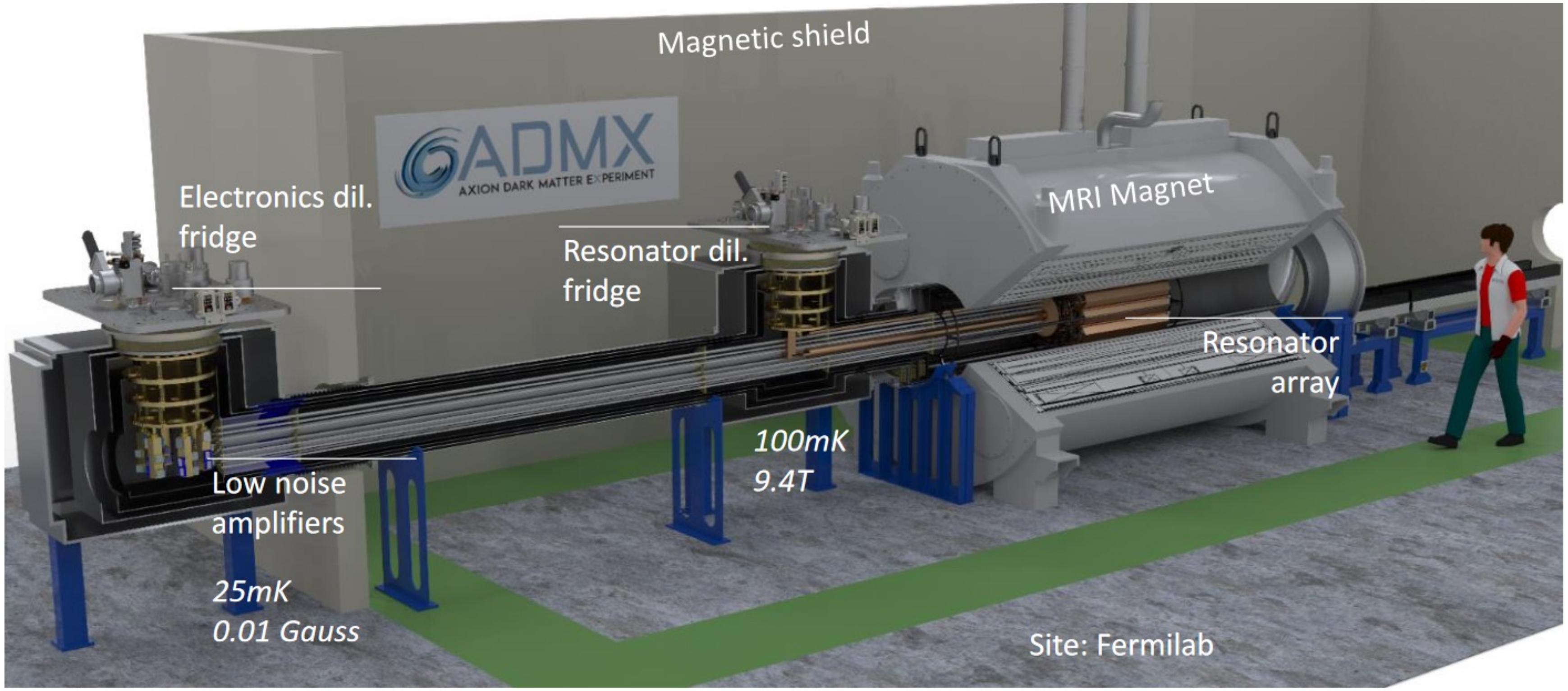
To be dark matter axions: before or after inflation



Courtesy: SungWoo Youn, "Axions and WISPs"

→ How to access heavier dark matter axions in the post inflationary scenario?

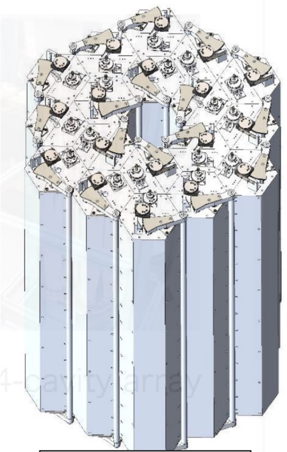
ADMX (Washington University → Fermilab)



~ 5 × scan speed of current ADMX

<u>ADMX-EFR</u>

Multiple cavities to address heavier axions



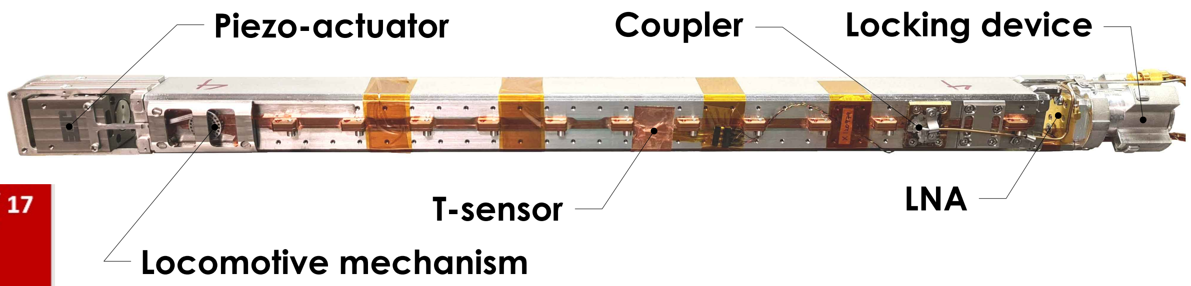
18 cavity array

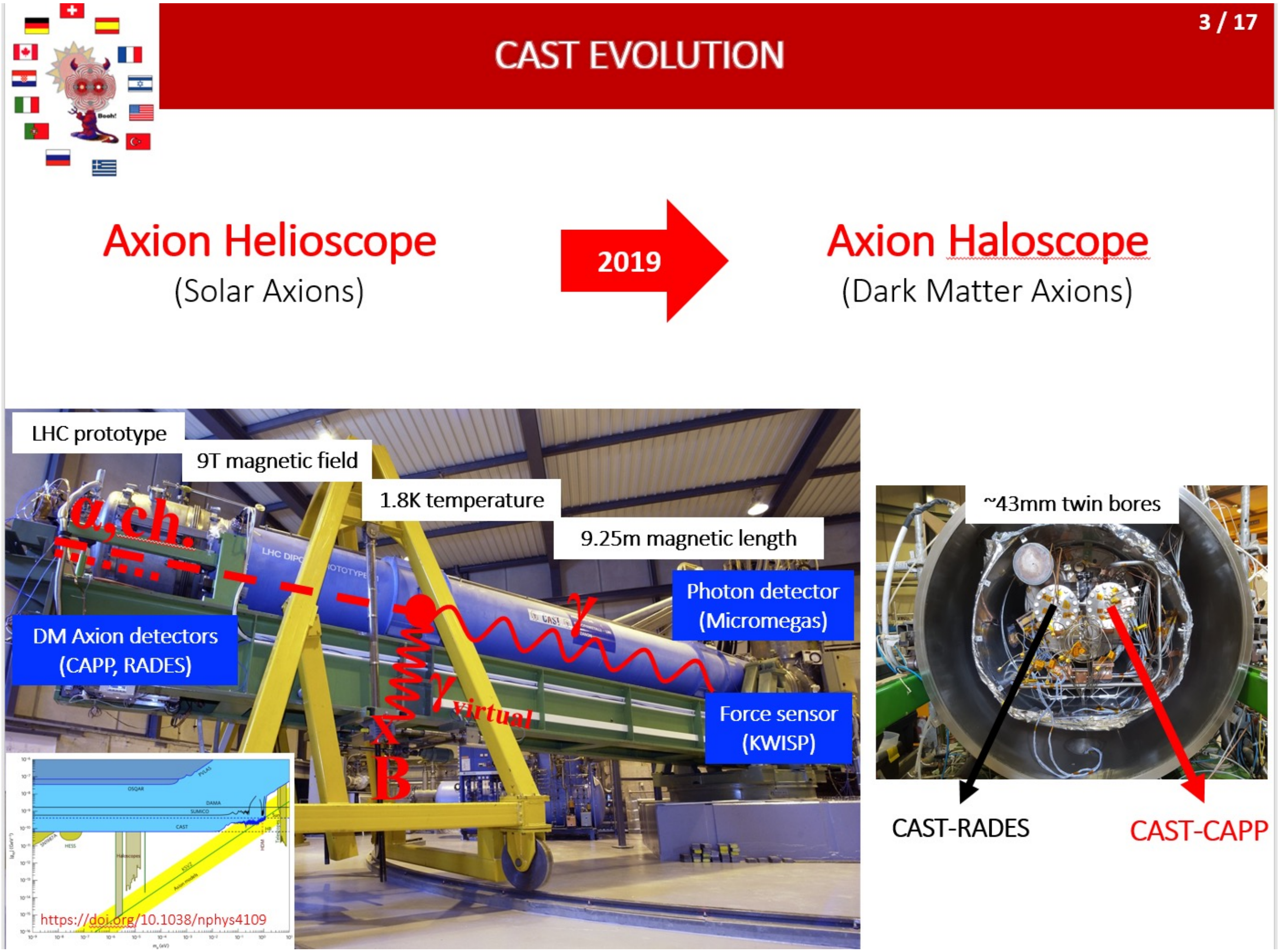
~ 80 cm warm bore | $B \approx 9.4$ T

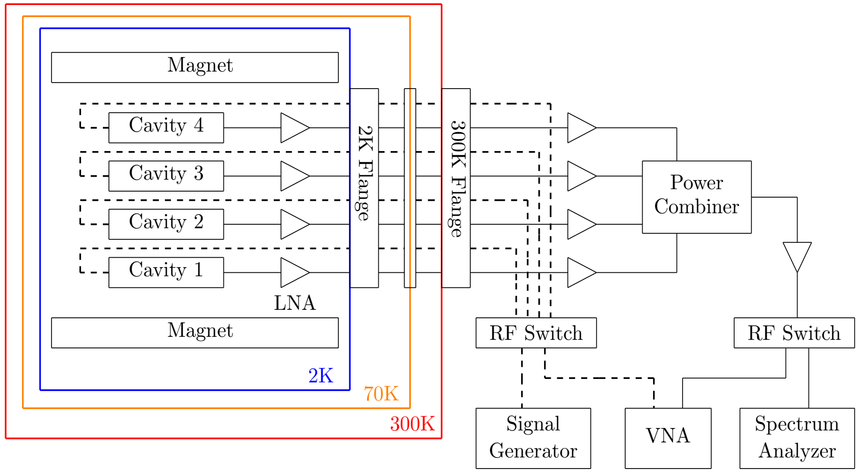
Challenge: phase lock of all the cavities (S. Knirck)

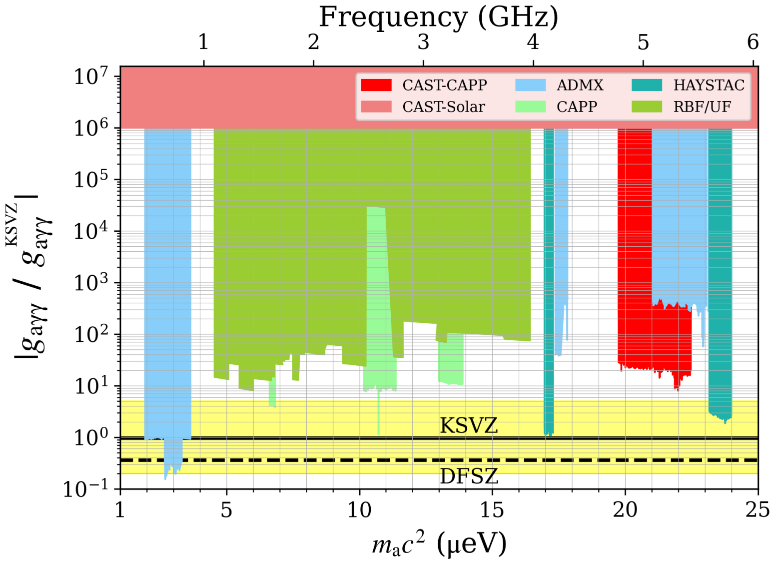
Courtesy: Gray Rybka, "Current Status and Future Plans of ADMX"

CAST-CAPP @ CERN









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

→ Multiple cavity option with a recycled magnet

Cavity filled with 1D wire metamaterial

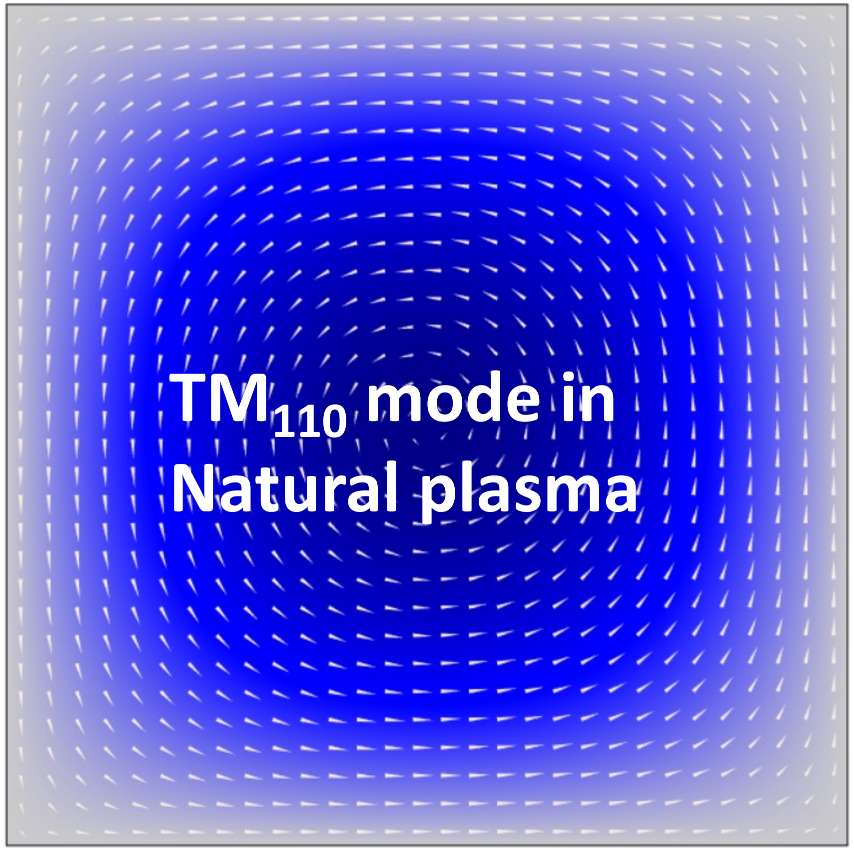
Free e… as 1D plasma

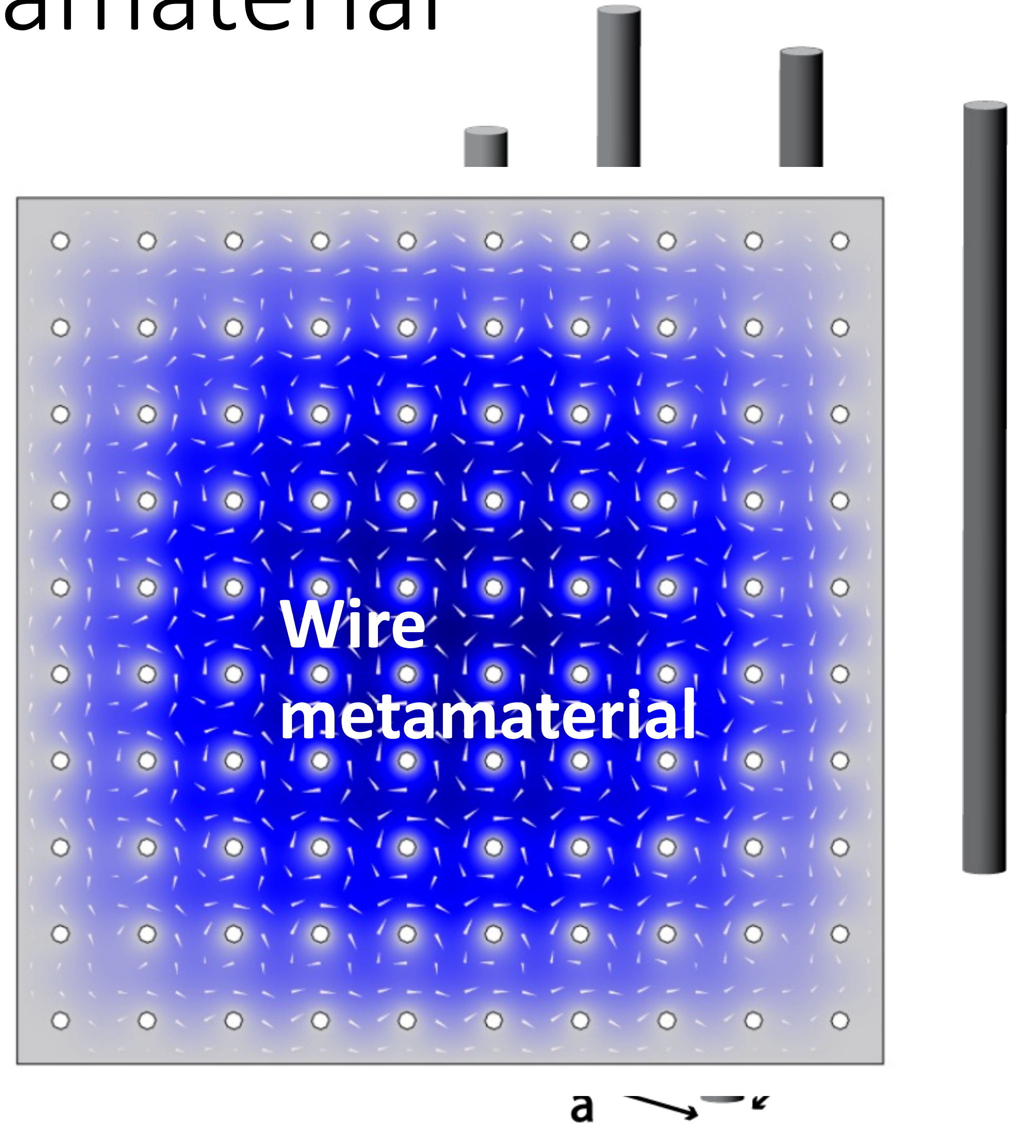
n_e … $\frac{\pi r^2 n}{2\pi} \log \frac{a}{r}$

ω_p^2 … .

For ex… nm gives

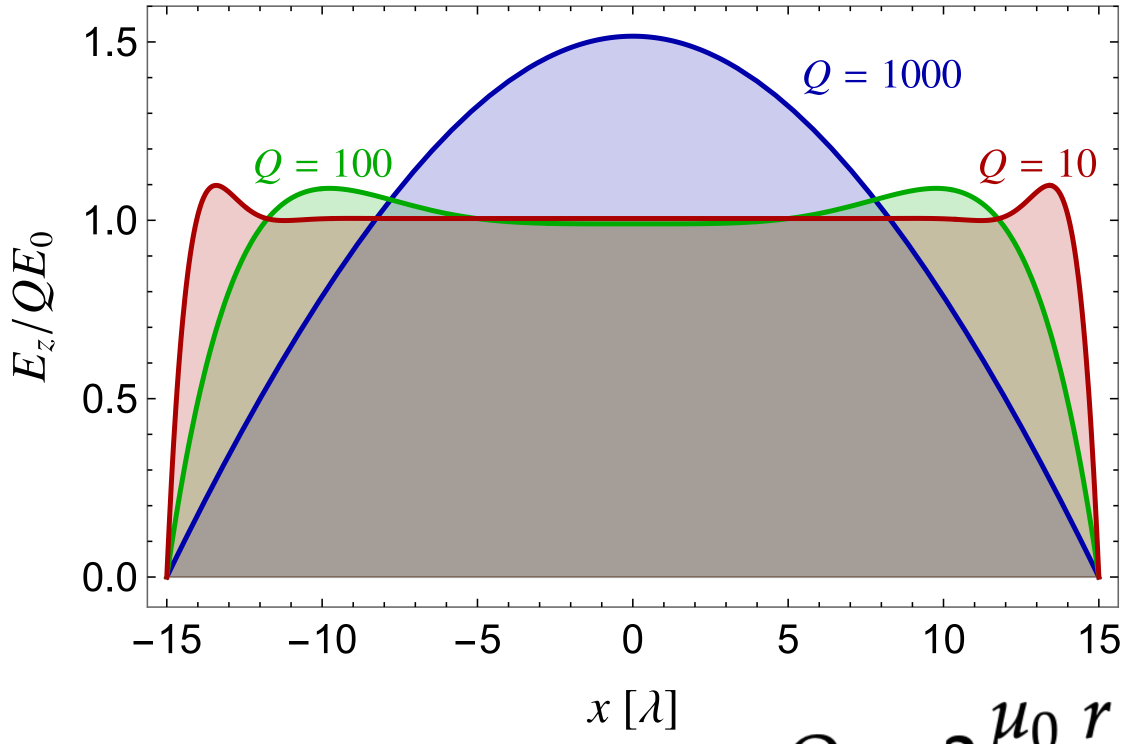
Free f… elf

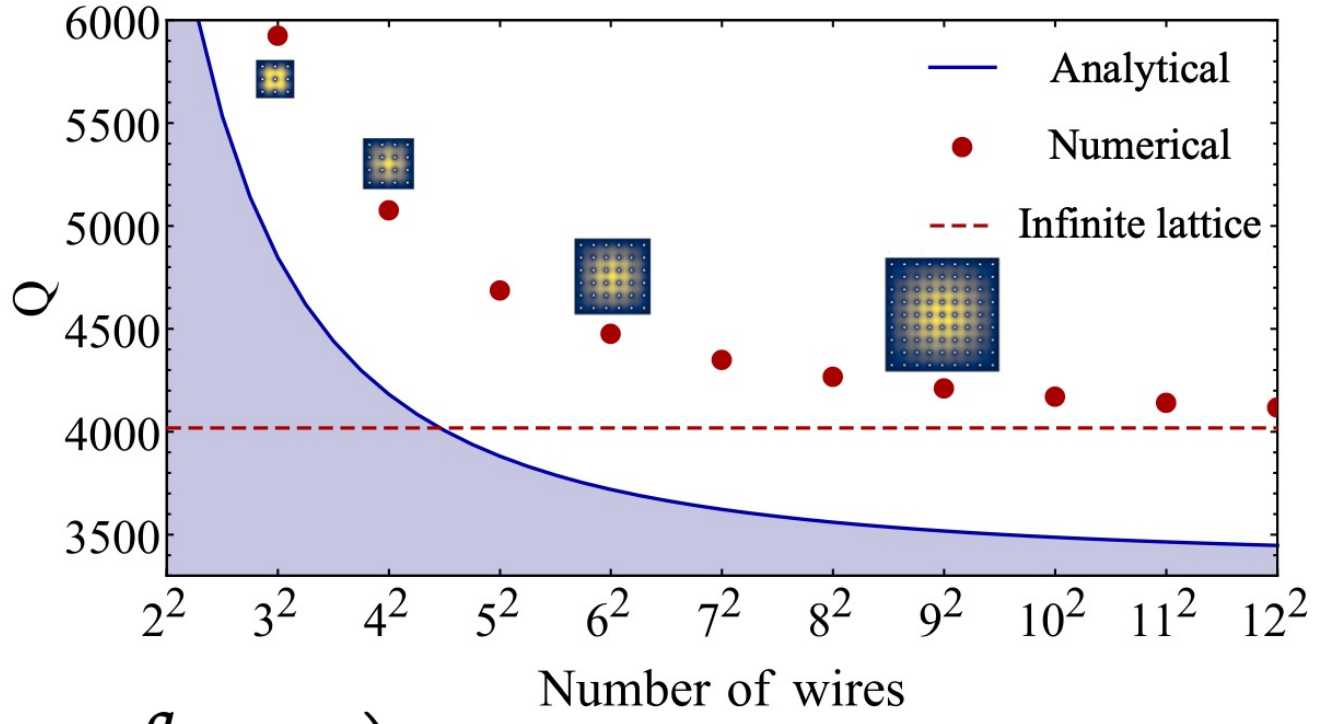




Changing the spacing a tunes the plasma frequency

Influence of cavity quality factor



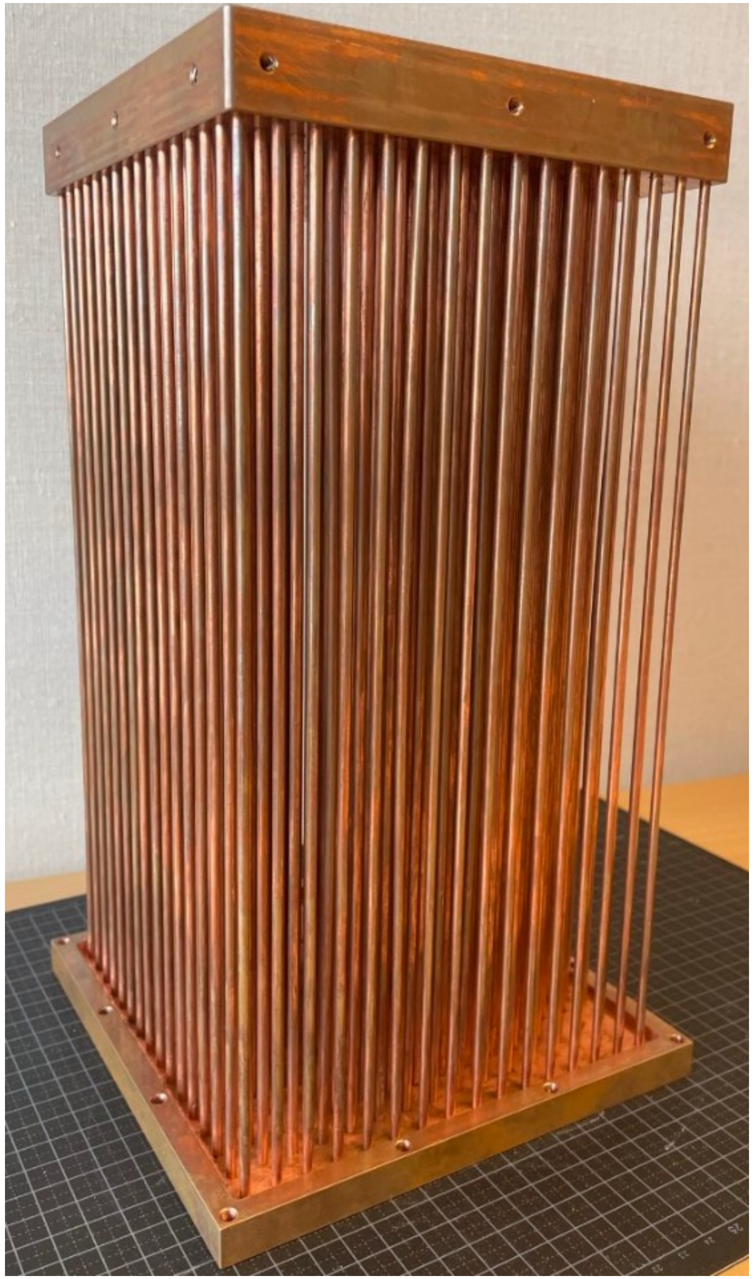


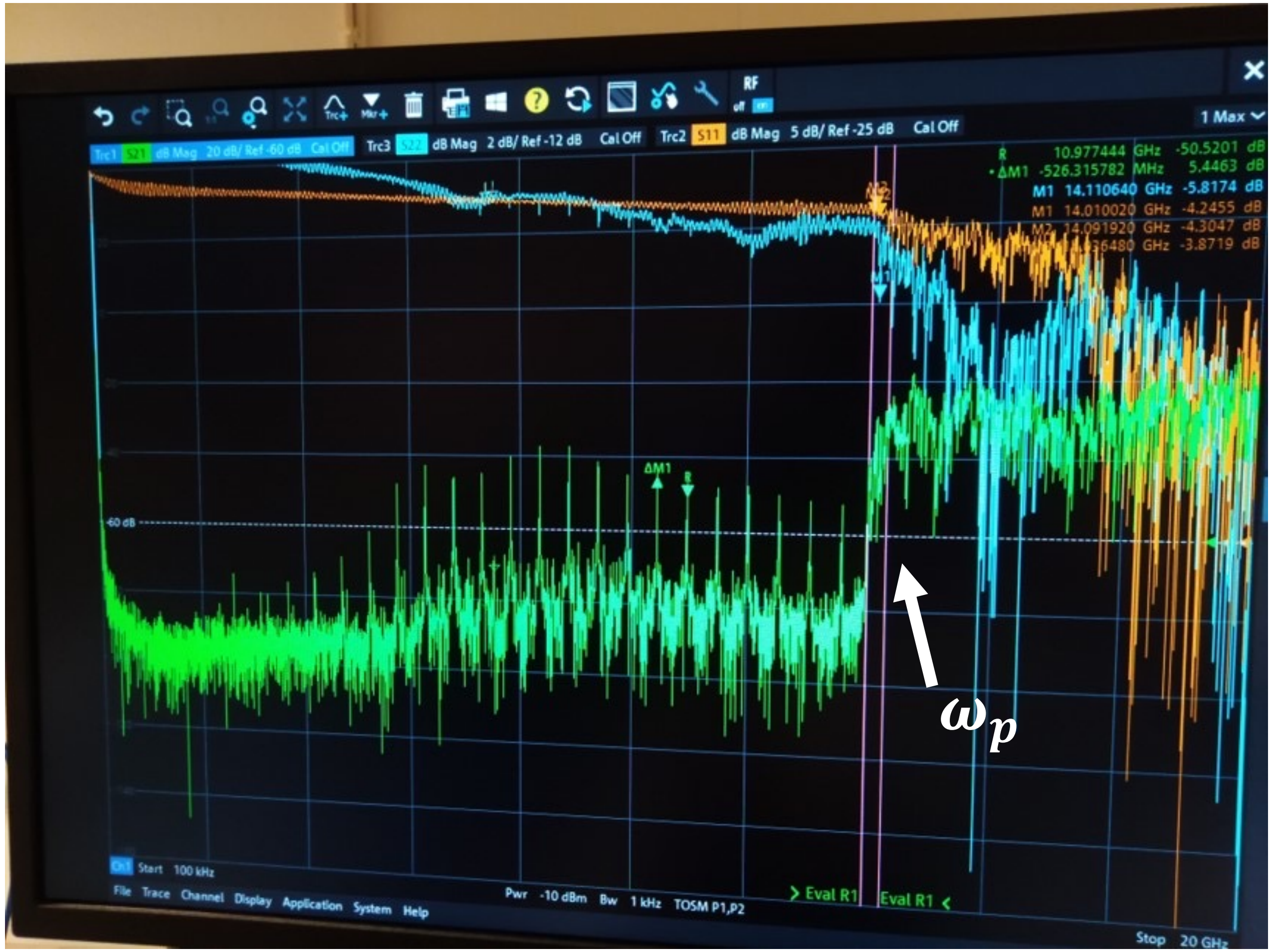
$$Q \simeq 2\frac{\mu_0}{\mu}\frac{r}{\boxed{\delta}}\left(\log\frac{a}{2\pi r} + F\right)$$

Skin depth

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

Prototype wire-filled cavities (2/2)

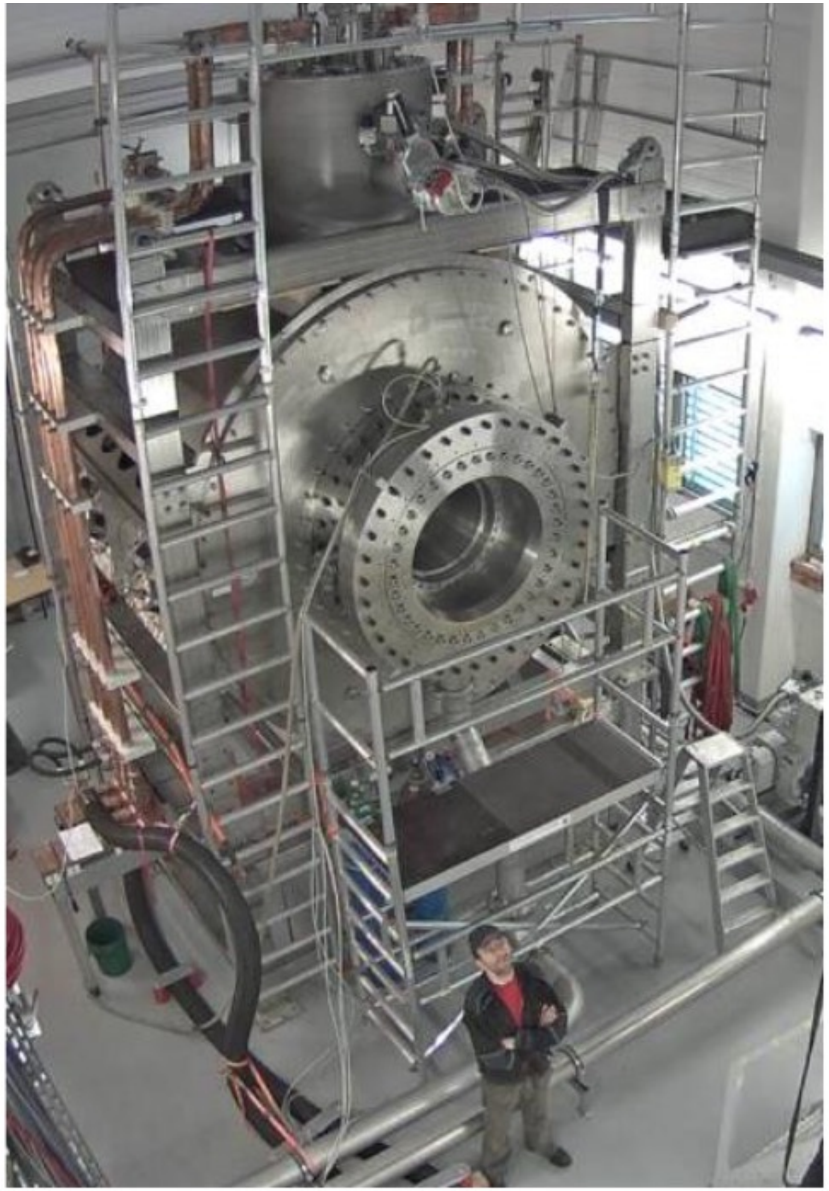


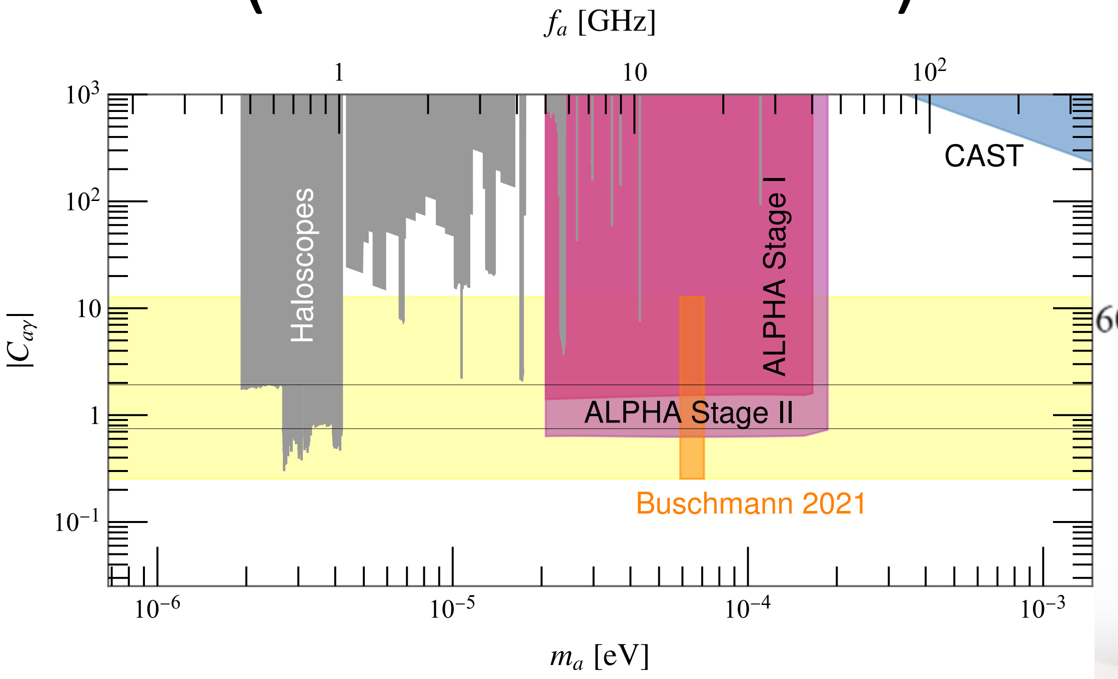


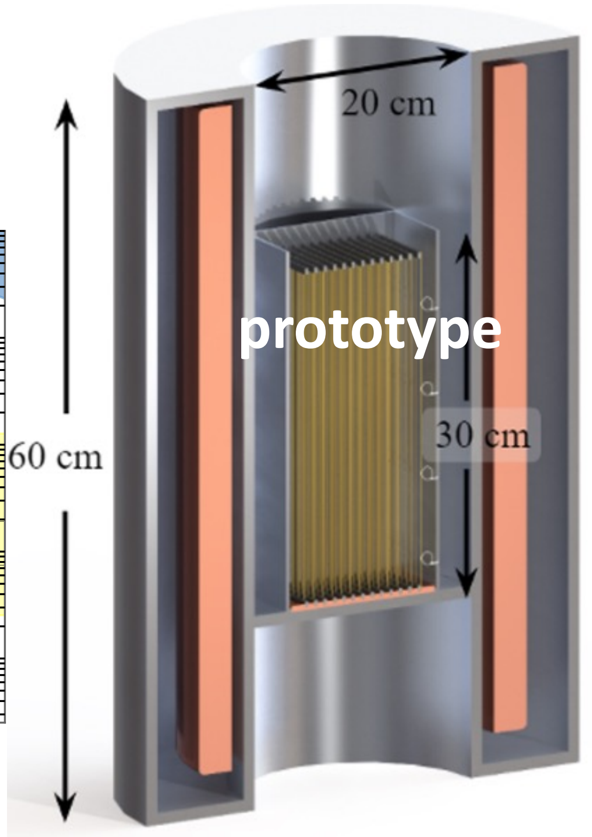
✓ Plasma-like phenomenon (cut-off) was observed

- Challenge in parasite modes
  - Mechanical tolerance, antenna design, electrical contacts of wires

Outlook: solenoid (HZB → ORNL)





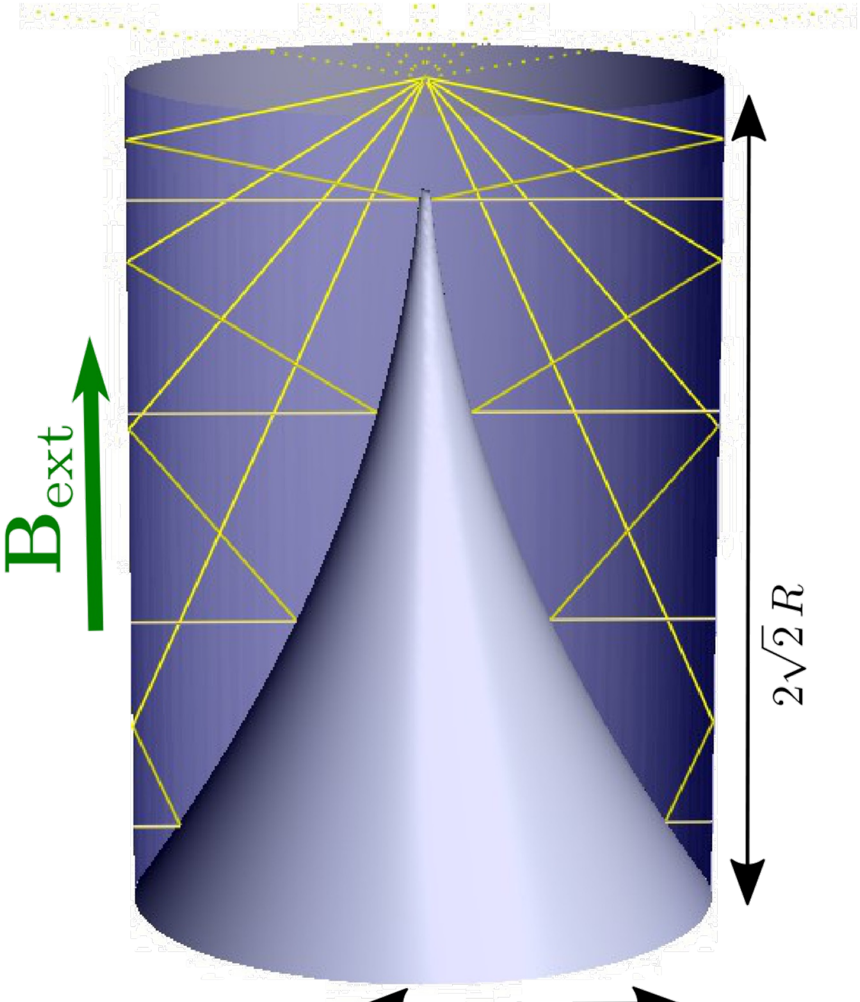


- 13 T ϕ50cm solenoid for ***neutron scattering facility*** at Helmholtz Zentrum Berlin (closed down)
- Donated to another neutron scattering facility (Spallation Neutron Source) in Oak Ridge National Laboratory
- Axion search before the beginning of neutron experiments

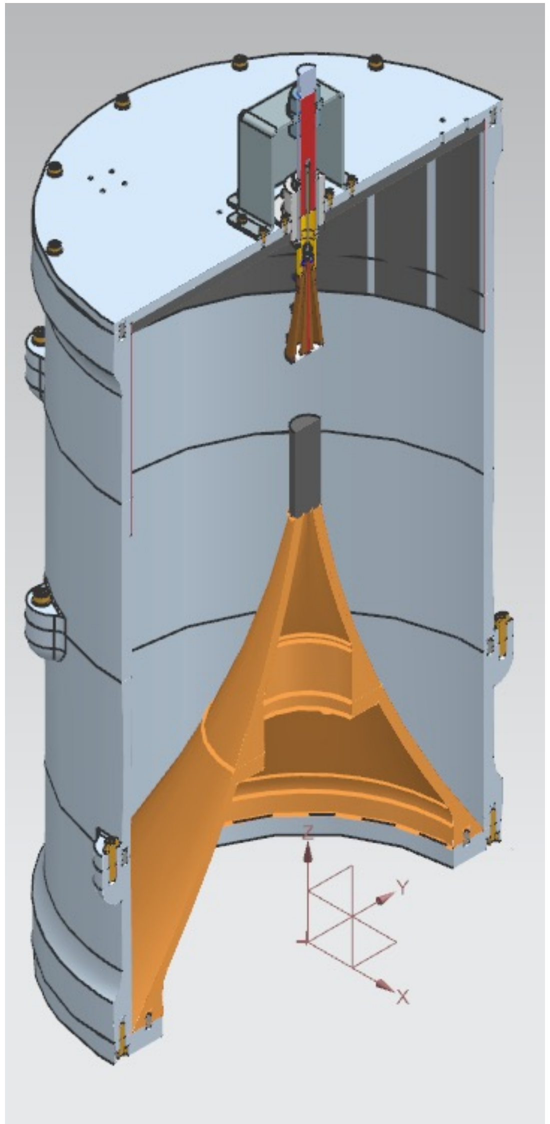
- To do: establish tuning mechanism

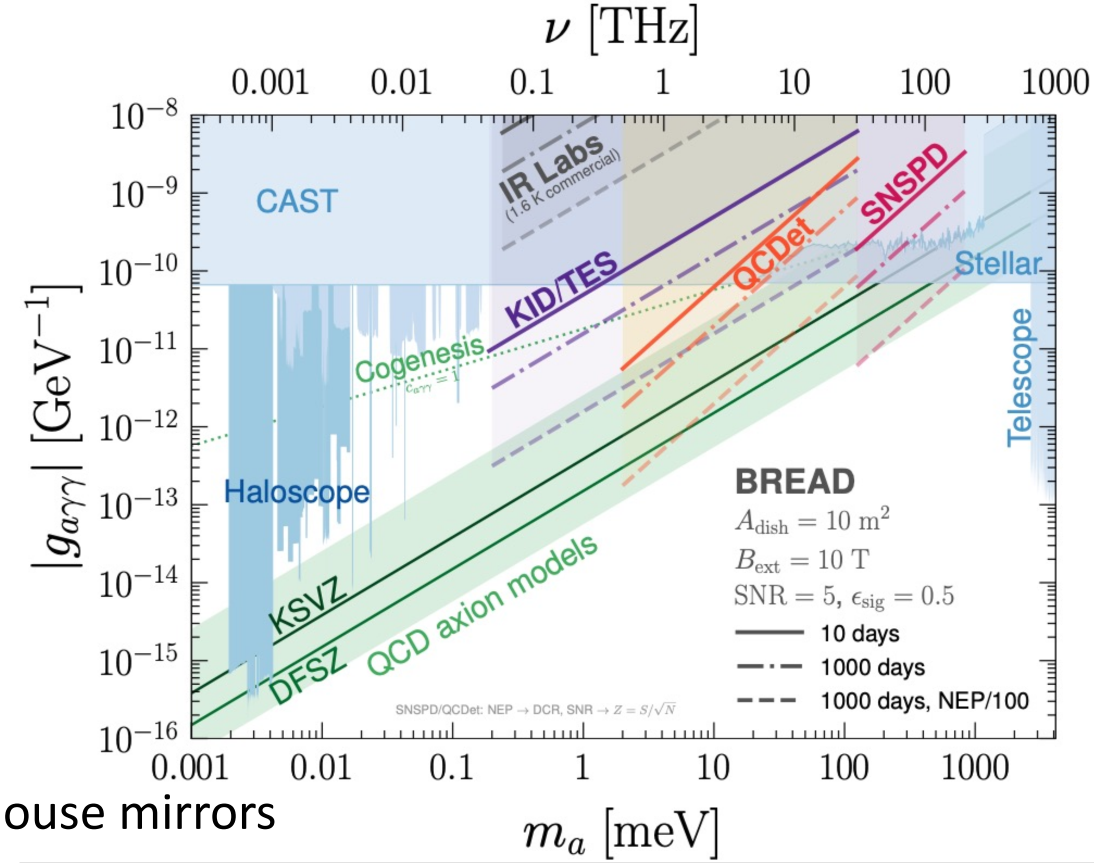
Courtesy: Stefan Knirck, “BREAD: Broadband Reflector Experiment for Axion Detection”

BREAD (Fermilab)



in solenoid magnet (e.g., MRI)





Innovative antenna design inspired by lighthouse mirrors