Detection of dark matter axions 1/3

from classical microwaves to quantised photons

Akira Miyazaki

CNRS/IN2P3/IJCLab Université Paris-Saclay

Who am I?

Prof. Koshiba
Nobel Prize 2002
“Neutrino from SN1987”

ICEPP
The University of Tokyo

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Prof Orito

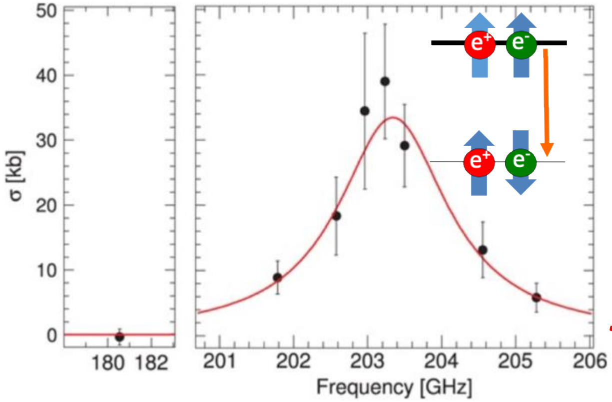
Prof Totsuka

KEK

Prof. Asai
KEK DG 2024-

SUSY
Guru

Prof. Kajita
Nobel Prize 2015
“Neutrino oscillation 1998”



PhD supervisor

PhD Thesis opponent

Microwaves for fundamental physics

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

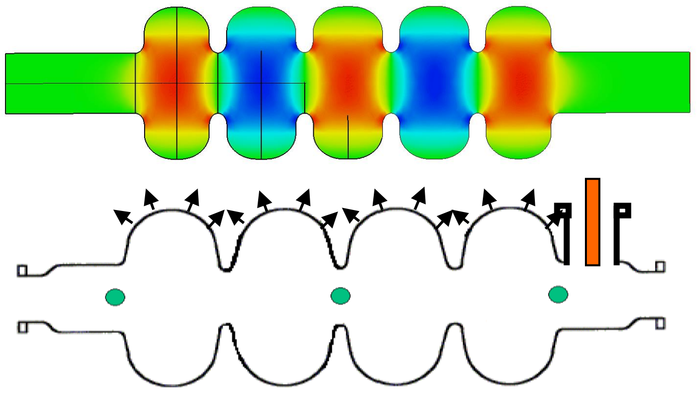
CERN

UPPSALA UNIVERSITET

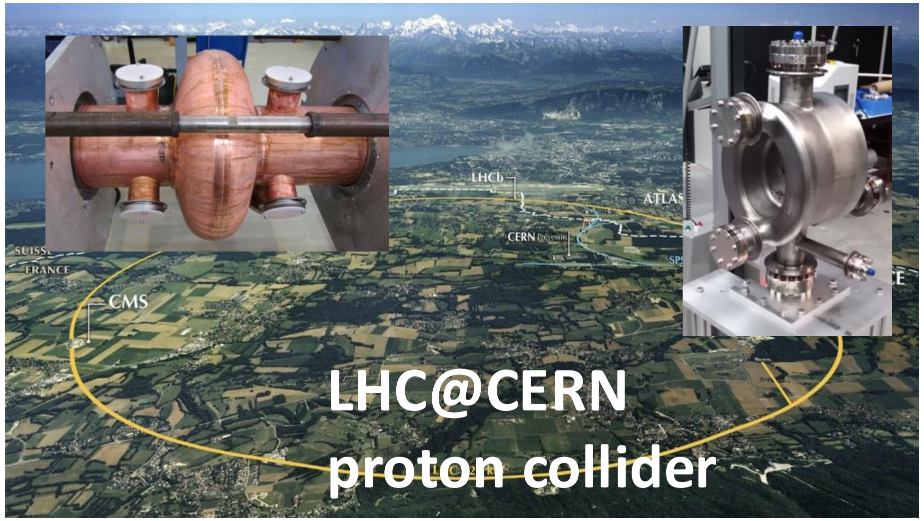
MANCHESTER 1824
The University of Manchester

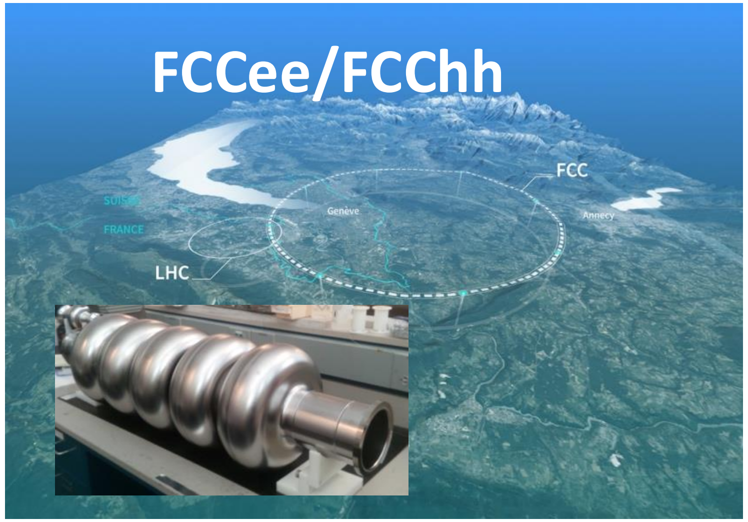
My main business: microwave cavities for Present/Future Accelerators

FCCee ttbar protoype



Courtesy: F. Bouly





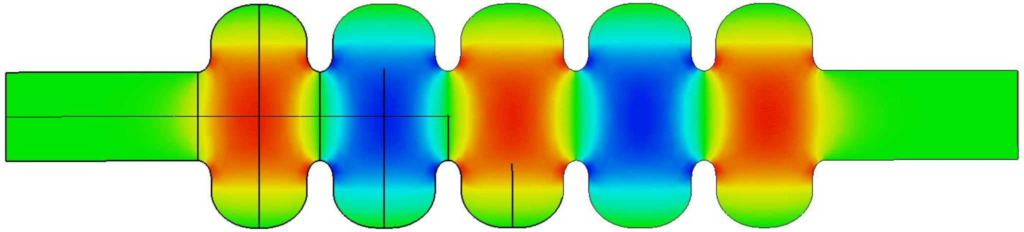
It will take time, very expensive, and very political ☹

→ **Can't we directly make use of microwaves (MW) for discovery?**

Wakefield links accelerators & ultralight dark matter detectors

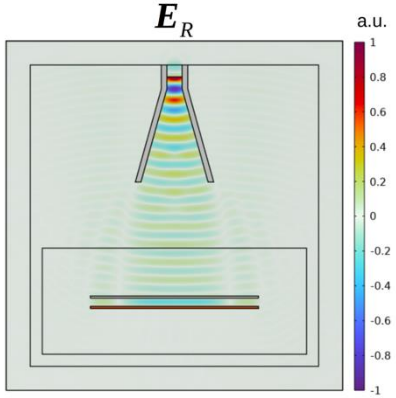
$$\begin{cases} \nabla \cdot \boldsymbol{D} = \rho(t,\boldsymbol{r}) \\ \nabla \times \boldsymbol{H} - \dot{\boldsymbol{D}} = \boldsymbol{J}(t,\boldsymbol{r}) \\ \nabla \cdot \boldsymbol{B} = 0 \\ \nabla \times \boldsymbol{E} + \dot{\boldsymbol{B}} = 0 \end{cases} \longrightarrow \begin{cases} \nabla \cdot \boldsymbol{D} = \cancel{\rho(t,\boldsymbol{r})} - g_{a\gamma}\boldsymbol{B}_e \cdot \nabla a \\ \nabla \times \boldsymbol{H} - \dot{\boldsymbol{D}} = \cancel{\boldsymbol{J}(t,\boldsymbol{r})} + g_{a\gamma}(\dot{a}\boldsymbol{B}_e - \boldsymbol{E}_e \times \nabla a) \\ \nabla \cdot \boldsymbol{B} = 0 \\ \nabla \times \boldsymbol{E} + \dot{\boldsymbol{B}} = 0 \end{cases}$$

Accelerator as a resonator



Driven by RF source via coupler

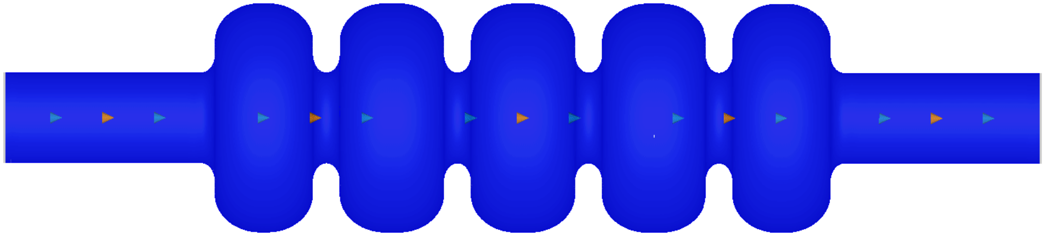
Detector as a resonator



Driven by MW source via antenna

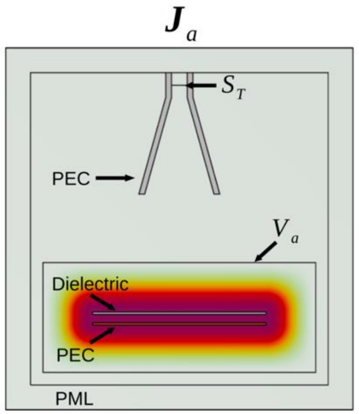
Jacob Egge PhD thesis

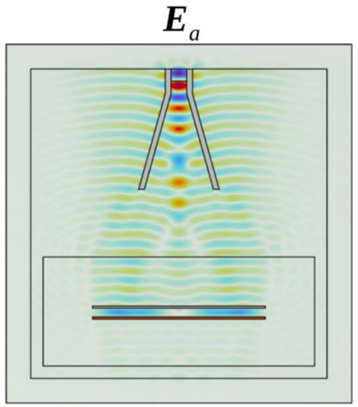
Accelerator as an oscillator



Wakefield by high current e-/e+ beam (crucial in FCCee collider)

detector as an oscillator

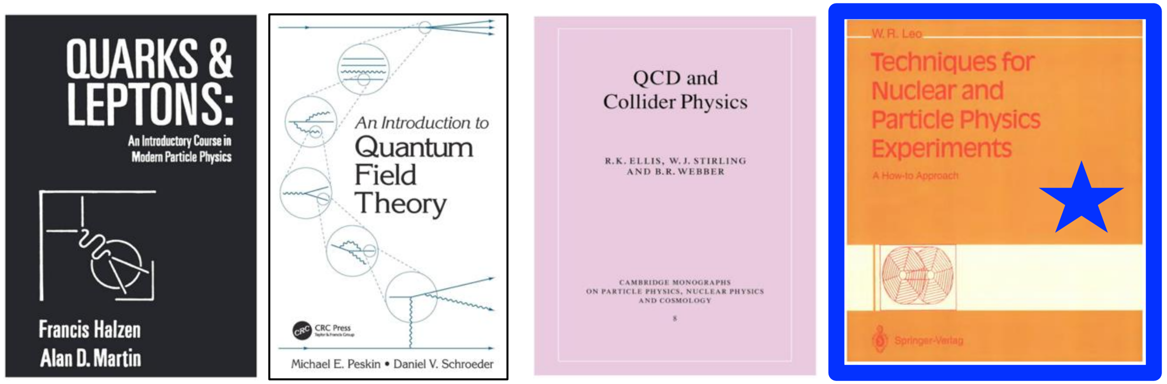




Wakefield by dark matter axions

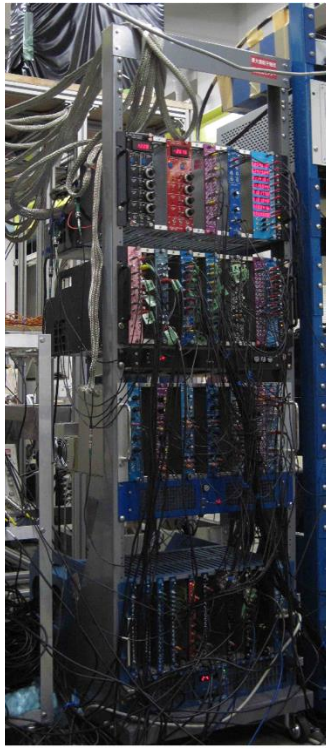
How to learn ultralight DM physics

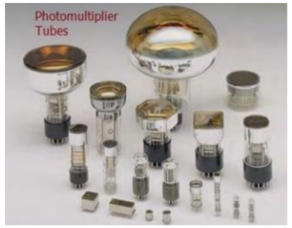
Conventional particle detectors



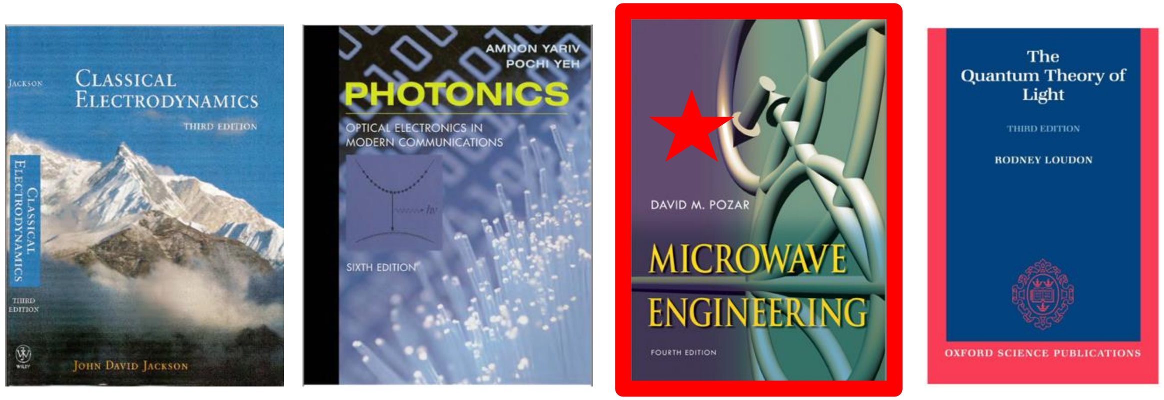
ROOT
Data Analysis Framework

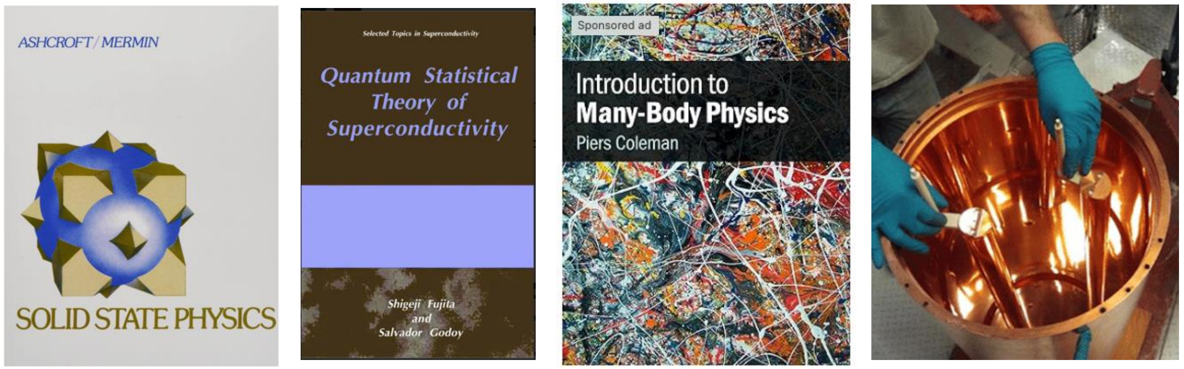
GEANT4
A SIMULATION TOOLKIT





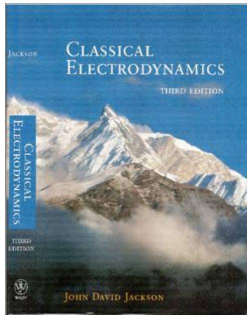
Ultralight DM axion detectors

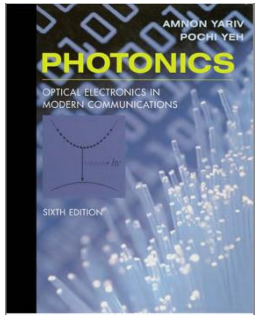


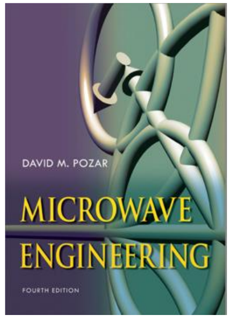


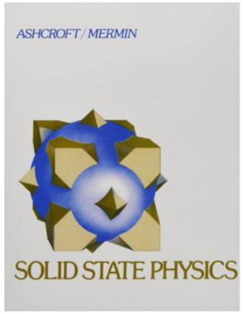
Outline of the lecture courses and textbooks

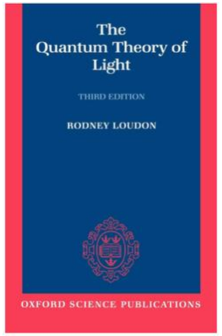
- Part 1: overview on axion searches
  - Axion vs WIMPs
  - Various experiments
  - Non-DM axions
- Part 2: classical detection scheme
  - Boundary conditions
  - Microwave resonators
  - Analog and digital system
  - Data processing and noise
- Part 3: quantum detection scheme
  - Quantum coherent states
  - Glauber’s theorem
  - Thermal noise and Standard Quantum Limit
  - Squeezing and photon counting

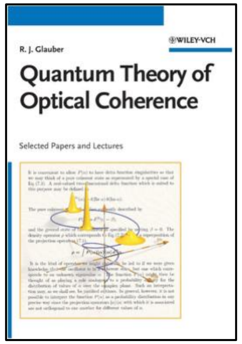












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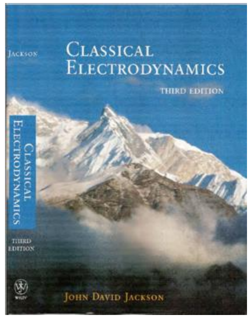

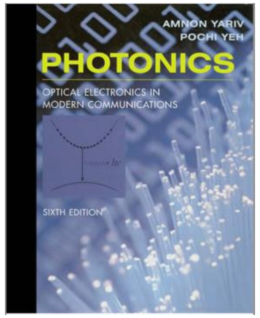

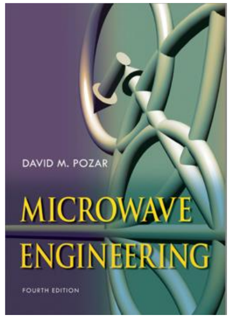

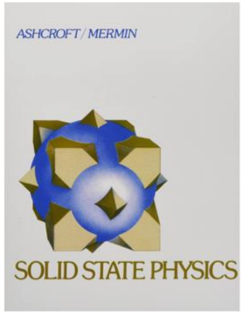

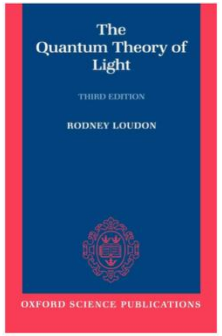

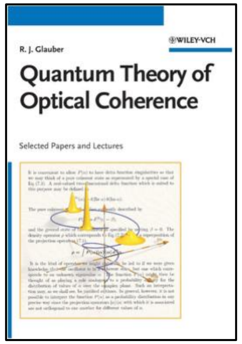

Part 1: overview on axion searches

- Axion vs WIMPs
  - WIMP: particle; axions: waves
  - Particle detection
  - Classical wave detection
- Various haloscope experiments
  - ADMX families
  - Lower masses
  - Higher masses
- Non-DM axions
  - Light-Shining-Through-a-wall
  - Solar axion helioscopes
- Conclusion of part 1

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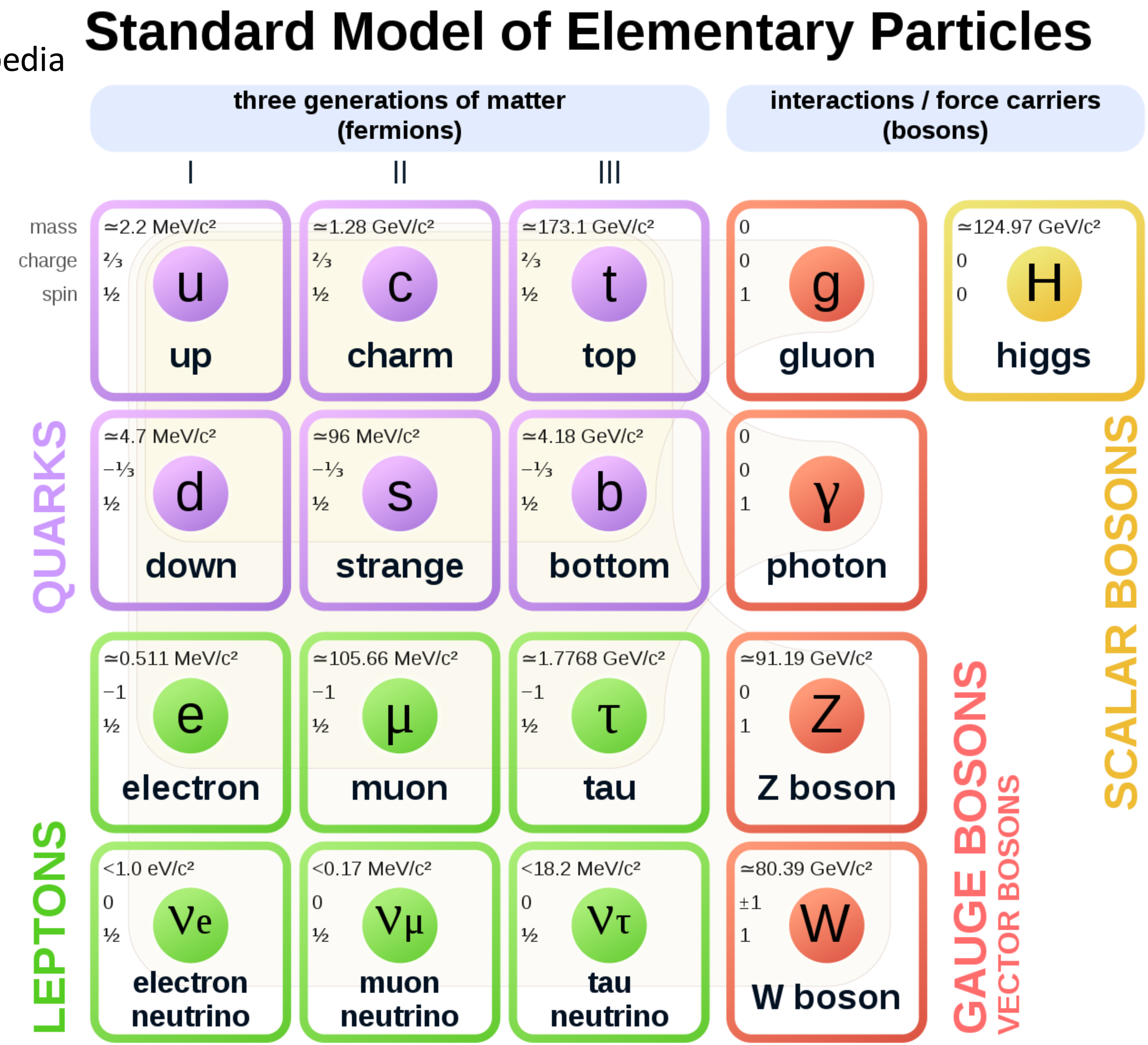
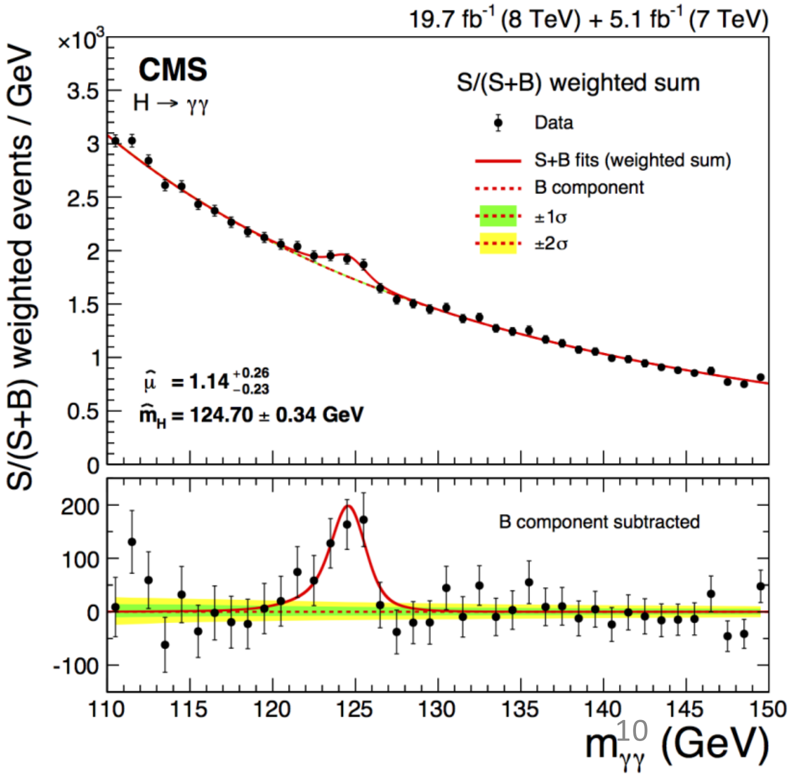
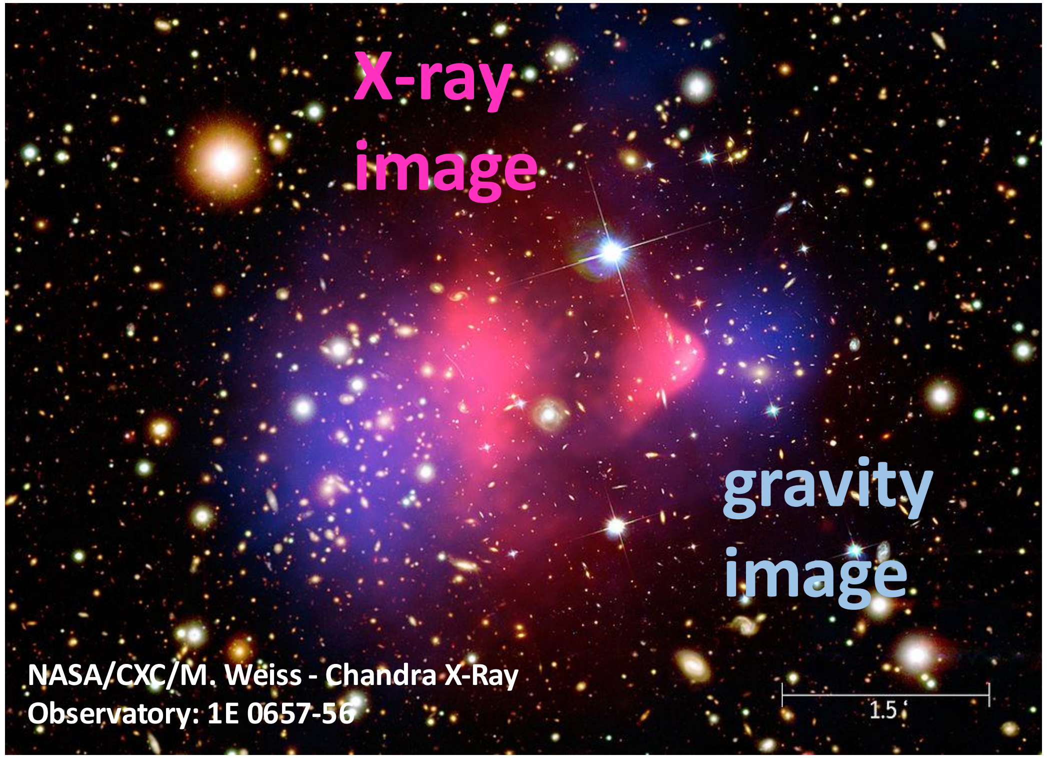
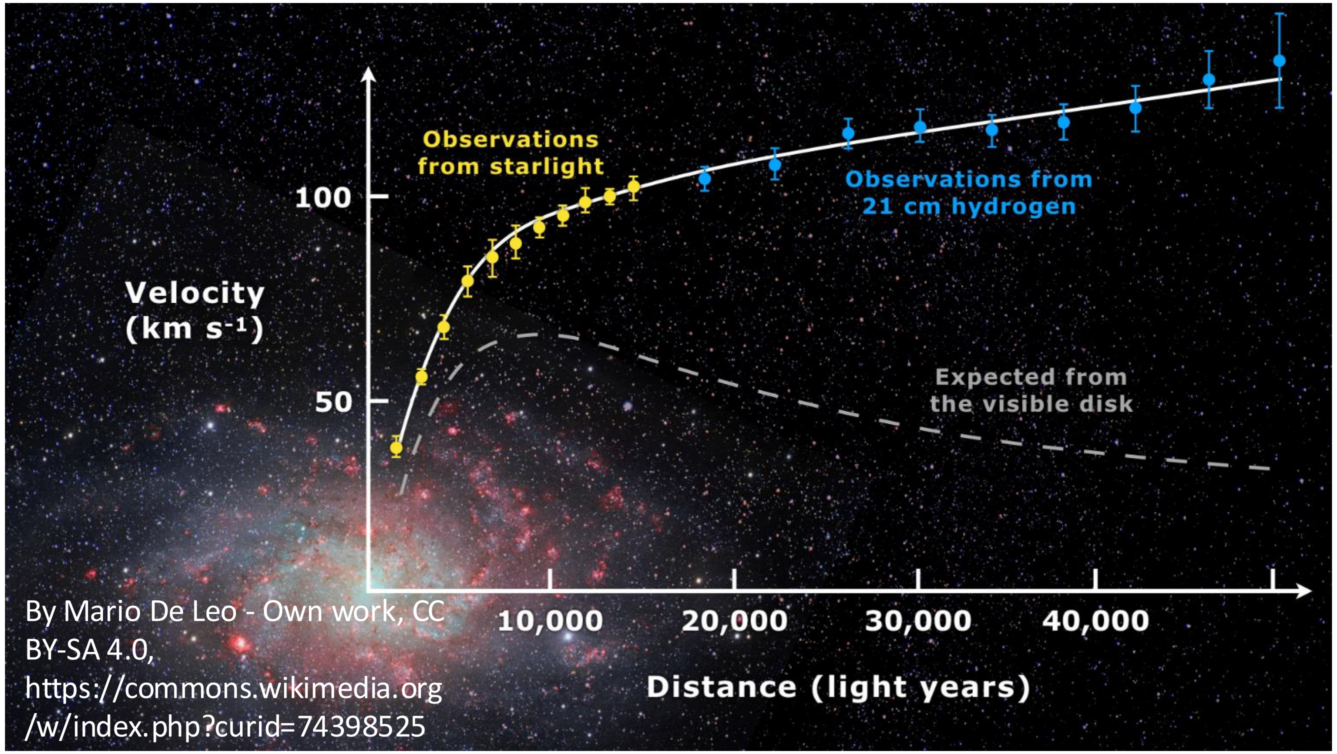
From wikipedia





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





~~Neutrino~~?

~~Modified gravity~~? van Dokkum, *et al. Nature* **555,** 629–632 (2018)

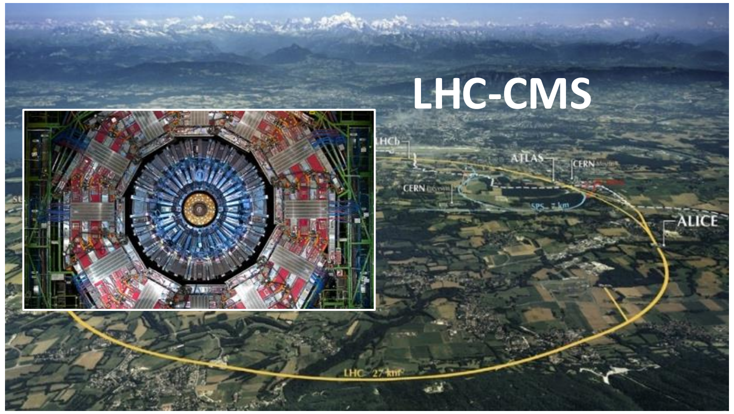
Primordial black holes?

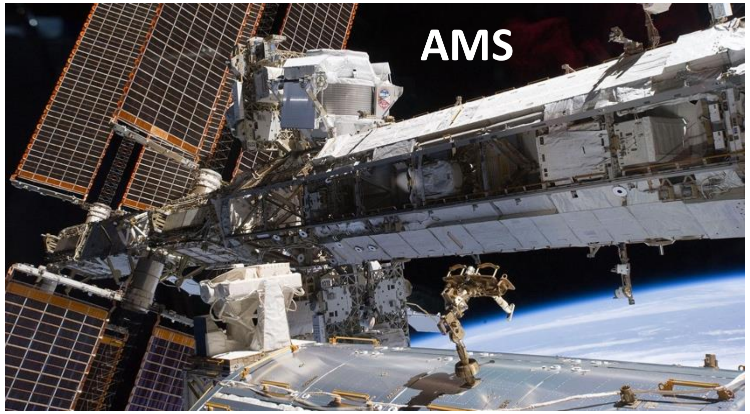
✓ Hypothetical new particles linked to intrinsic issues in the Standard Model?

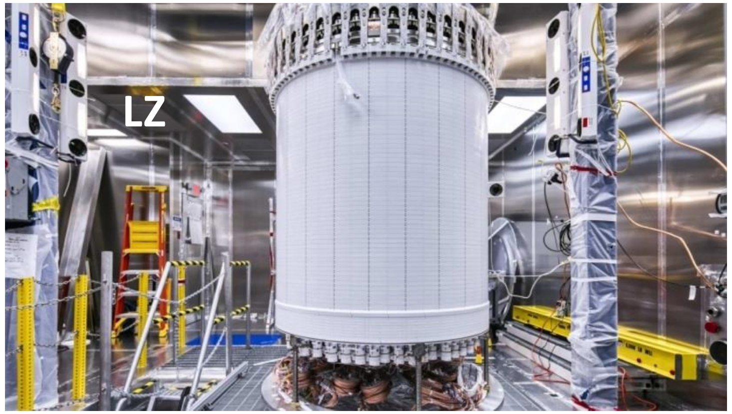
Three ways to study dark matter candidates

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

WIMP
SUSY
FIMP
DP

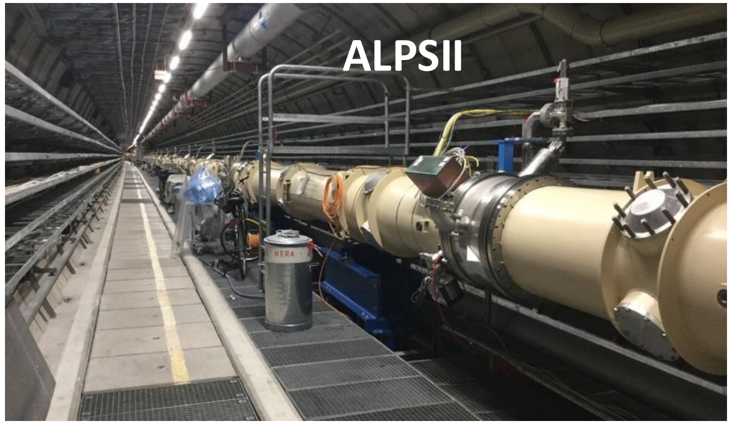






→ Common techniques: **particle** detection, reconstruction, PID, etc

WISP
Axions
ALP
DP

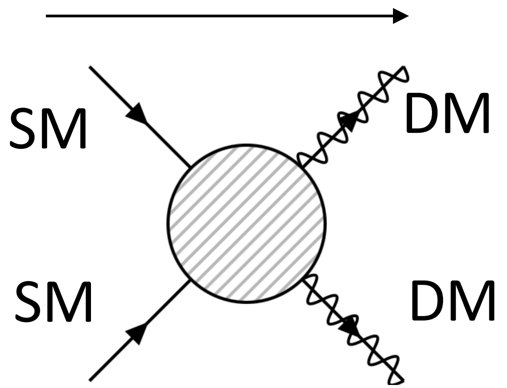


full knowledge in source | uncertainty in astrophysical models | Uncertainty in cosmological models

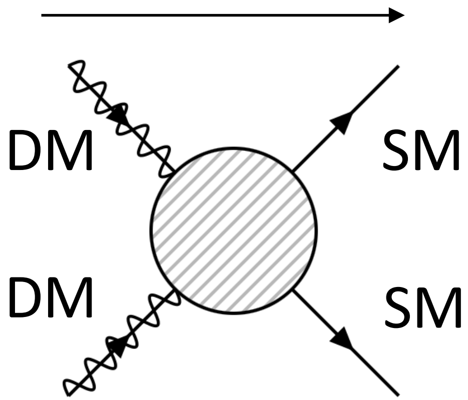
→ Common techniques: magnets & **photon or wave science**

Weakly Interacting Massive Particles (WIMPs)

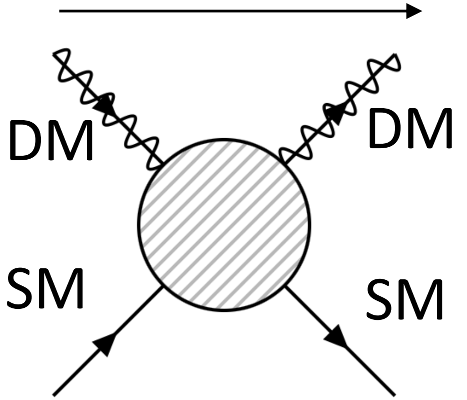
Accelerator production

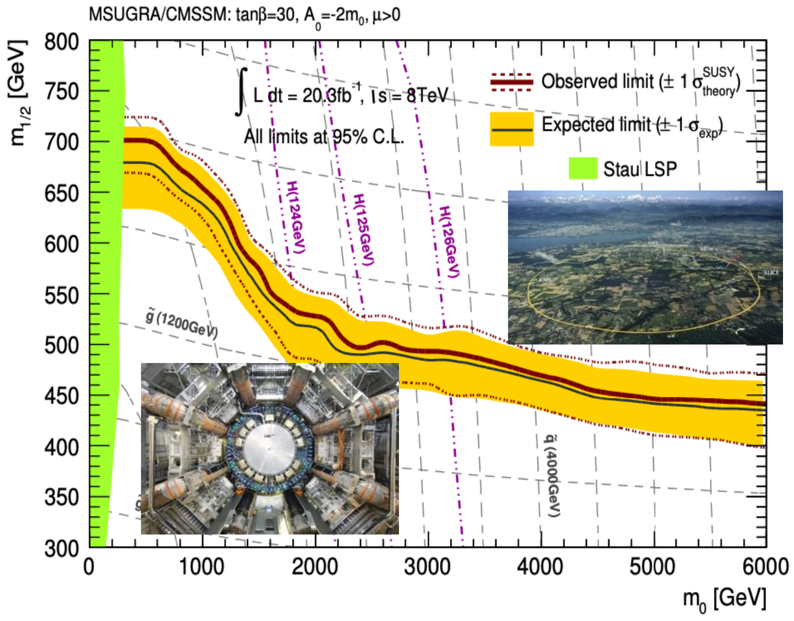


Indirect search

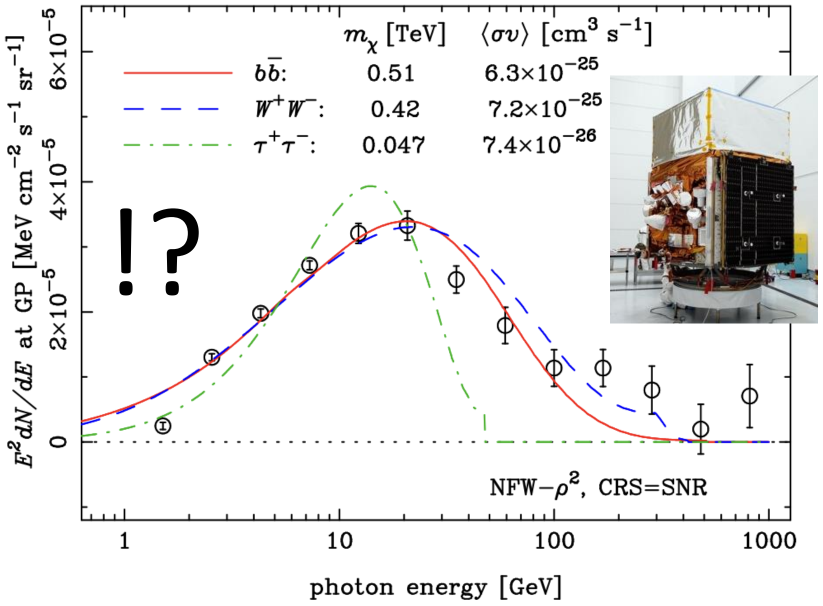


Direct search

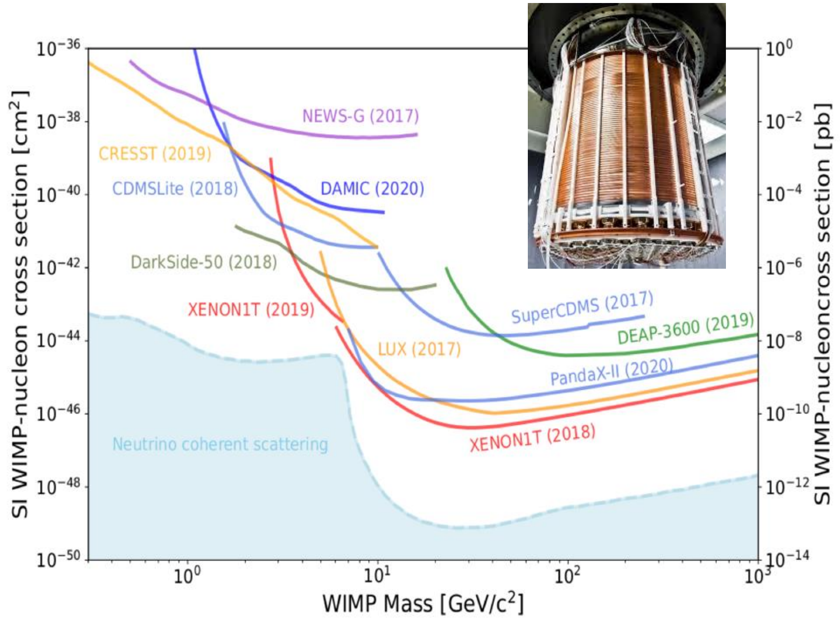




Y. Sasaki PhD thesis



T. Totani arXiv:2507.07209



PDG2022

Axions: a byproduct to cancel the strong CP

Quantum Chromodynamics includes

gluons

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

This term generates electric dipole moment in neutron

- Theory: $d_n \sim (2.4 \pm 1.0) \times 10^{-3} \boldsymbol{\theta}$ efm
- Experiment: $|d_n| < 1.8 \times 10^{-13}$ efm

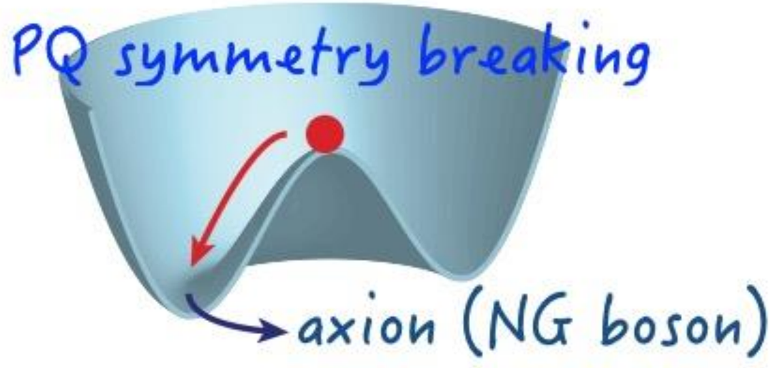
SciPost Phys. Lect. Notes 45 (2022)

$\rightarrow |\theta| < 0.8 \times 10^{-10} \ll 1$

Naturalness problem without anthropic solution

Introduce a new global chiral U(1) (PQ symmetry) field a

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



Spontaneous Symmetry Breaking

→ A Nambu-Goldston boson appears as a byproduct = **axion**

Axion after QCD phase transition $m_a f_a \sim m_\pi f_\pi$

F. Chadha-Day, J. Ellis, D. J. E. Marsh, "Axion Dark Matter: What is it and Why Now?" arXiv:2105.0140

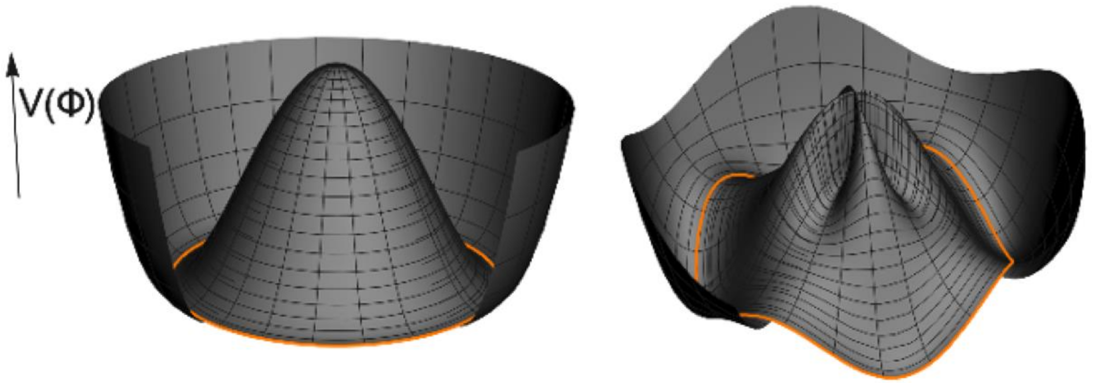
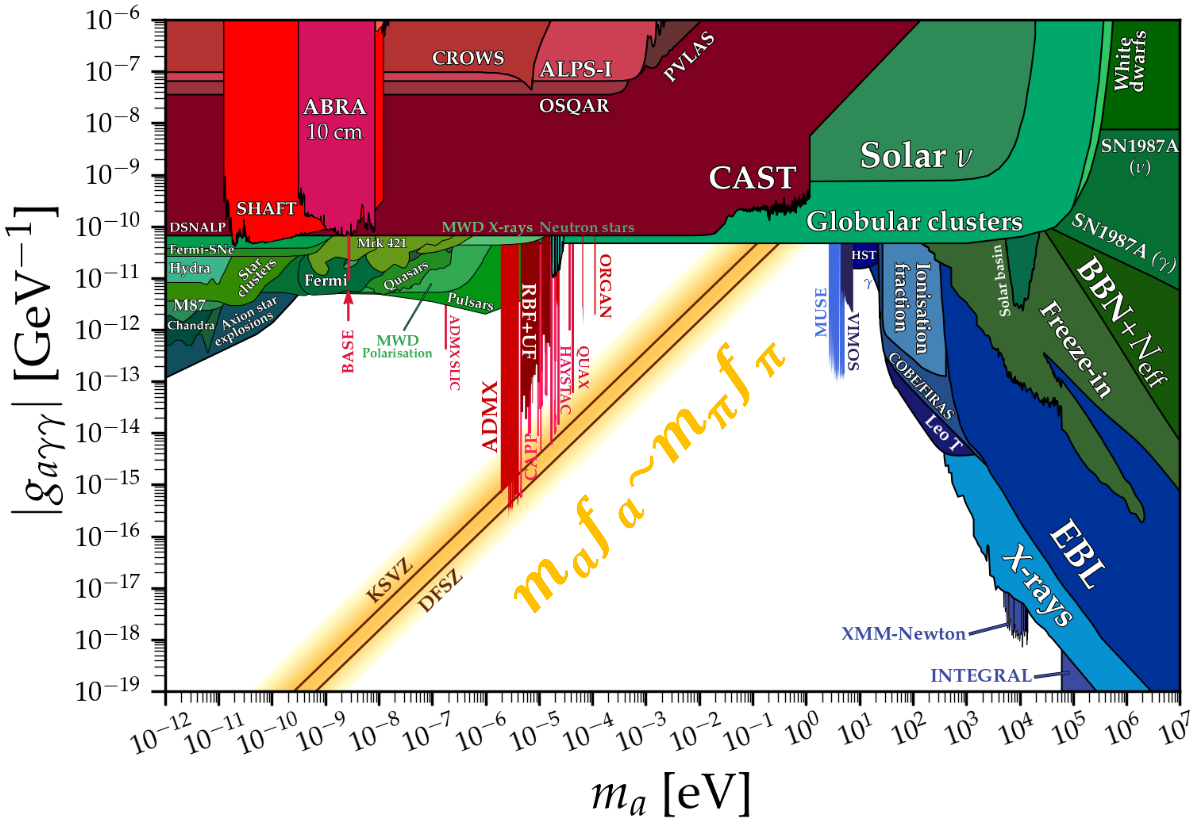
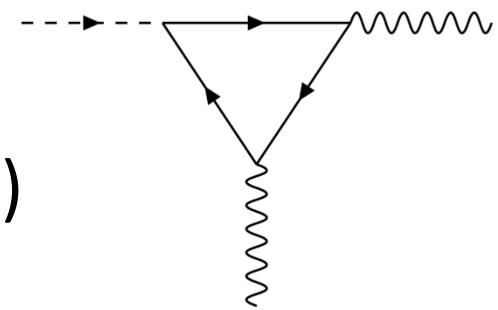


Figure 3: "Sombrero" potential of the Peccei-Quinn field Φ is shown schematically before (left) and after (right) the QCD phase transition. The axion corresponds to the angular direction of this potential, shown by the orange line. The state of the field is given by a point in the potential. Low energy configurations are favoured. For illustration, the potential on the right is shown for a scenario with a large amount of PQ symmetry breaking. More details are given in appendix A.2.

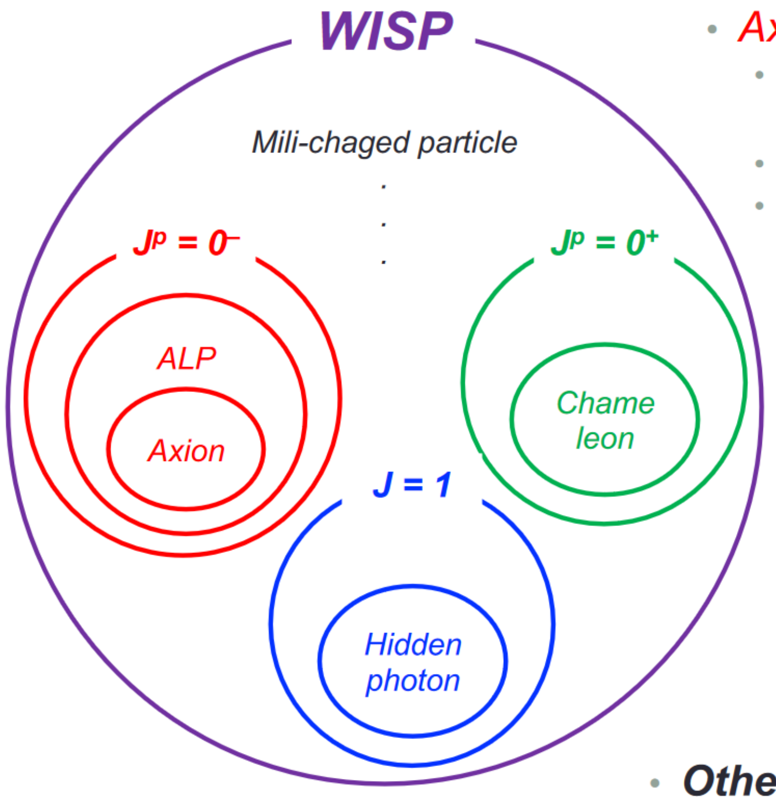


PQ Symmetry is explicitly broken
→ Axion gains (light) mass

Axion couples to two photons (Primakoff effect)
→ **RF/microwaves**



More than just an axion

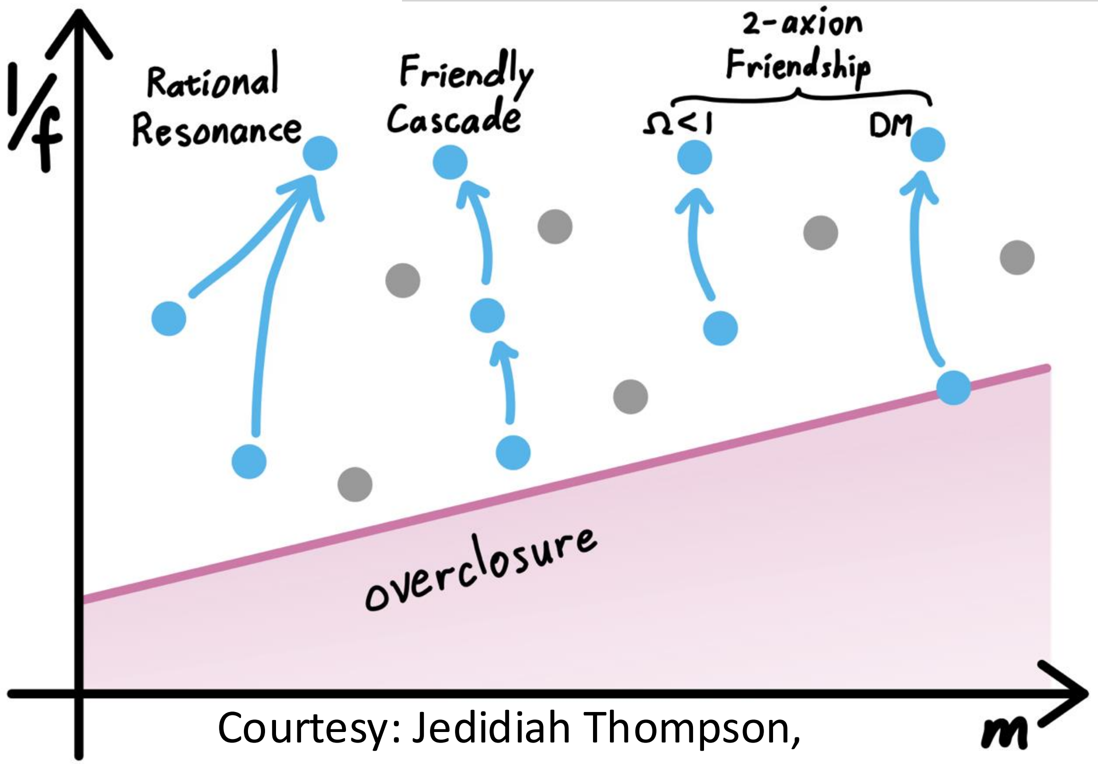


- ***Pseudo-scalar***
  - *Axion*
    - *PQ solution to strong CP problem (1977)*
      $m_a f_a \sim \Lambda_{QCD}$
    - *Invisible axion (1979)*
    - *Dark matter candidate (1983)*
  - *Axion-Like Particle (ALP)*
    - *Generic axion w/o solving the strong CP problem*
      $m_a f_a \nsim \Lambda_{QCD}$
- ***Scalar***
  - *Chameleon (2003)*
  - *Dark energy candidate*
- ***Vector***
  - *Hidden photon*
  - *Gauge field in hidden sector*
- ***Others***
  - *Mili-charged particle, …*

Courtesy: SungWoo Youn, "Axions and WISPs"

$$V(\phi) \simeq m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

For QCD axion: $m^2 f^2 = \Lambda_{QCD}^4$

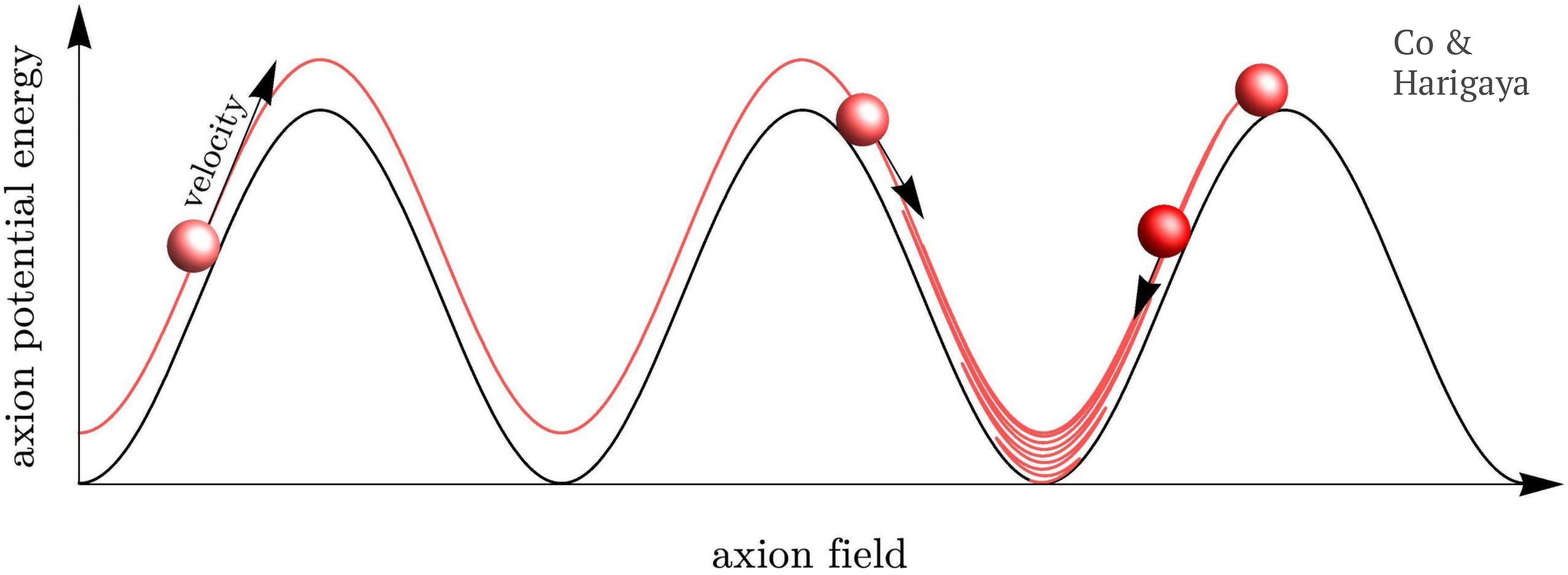


Courtesy: Jedidiah Thompson, "Friendship in the Axiverse"

- ***Anything may exist** anywhere while the **QCD axion is the most motivated** from the naturalness of strong QCD*
- ***Strong QCD naturalness problem cannot be solved by anthropic principle like gauge hierarchy***

Axion as dark matter (PQ scale > inflation)

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



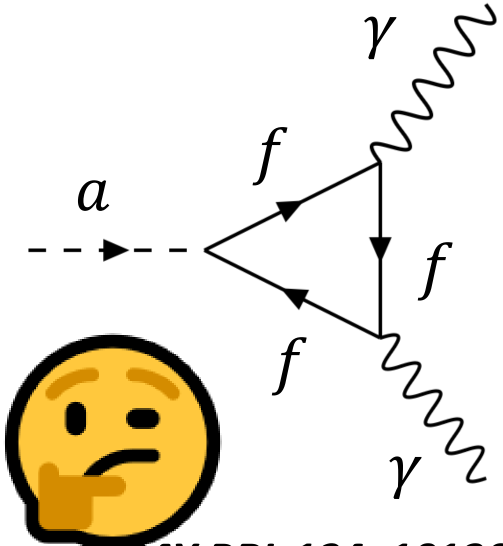
Misalignment mechanism

$$\frac{d^2a}{dt^2} + 3H(t)\frac{da}{dt} + m_a(T)^2 a = 0$$

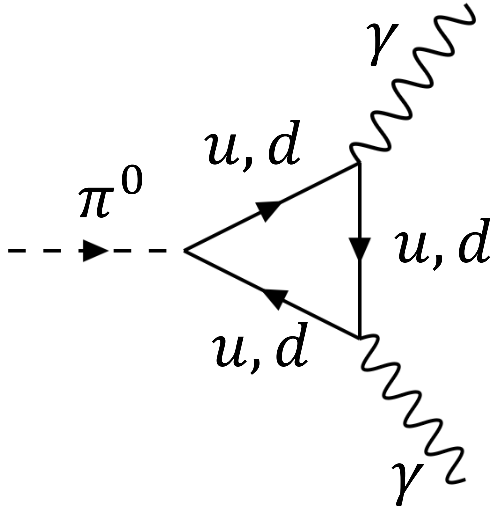
Hubble parameter: friction → "cooling" down

Axion, mesons to Higgs: (peudo-)scalars and photons…*same*?

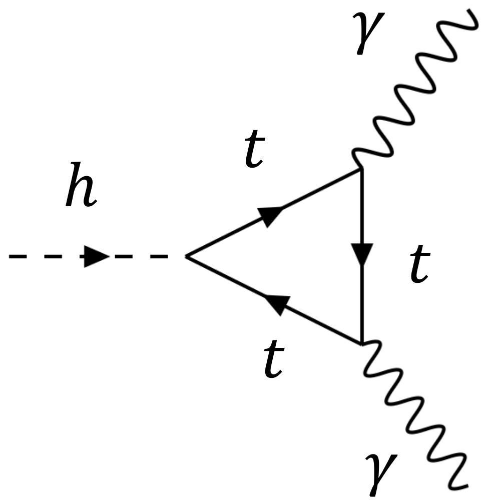
??? μeV

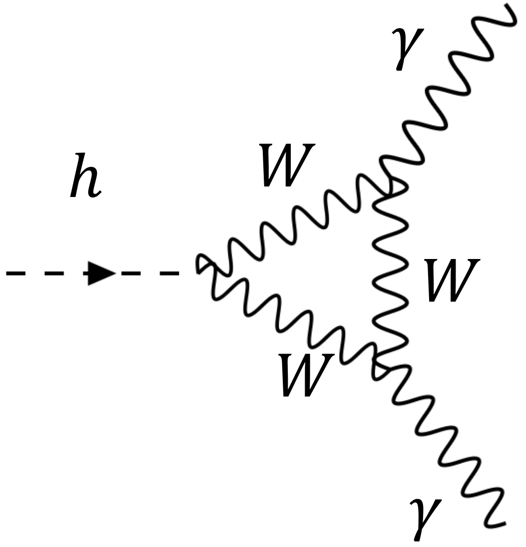


135 MeV

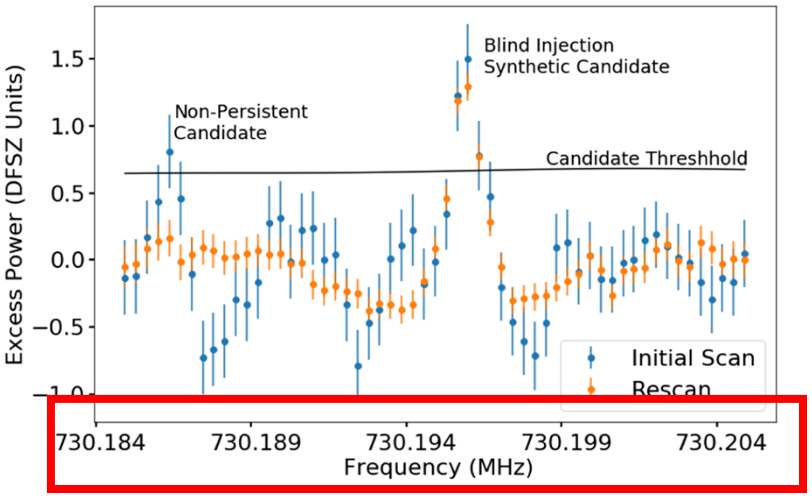


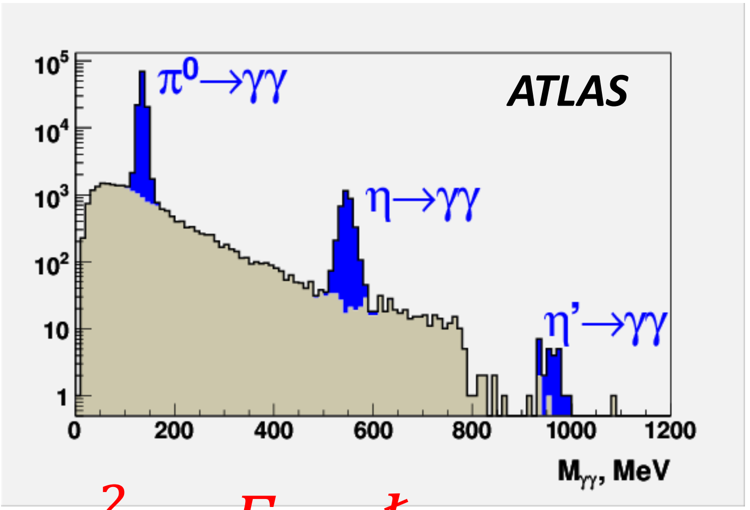
125 GeV

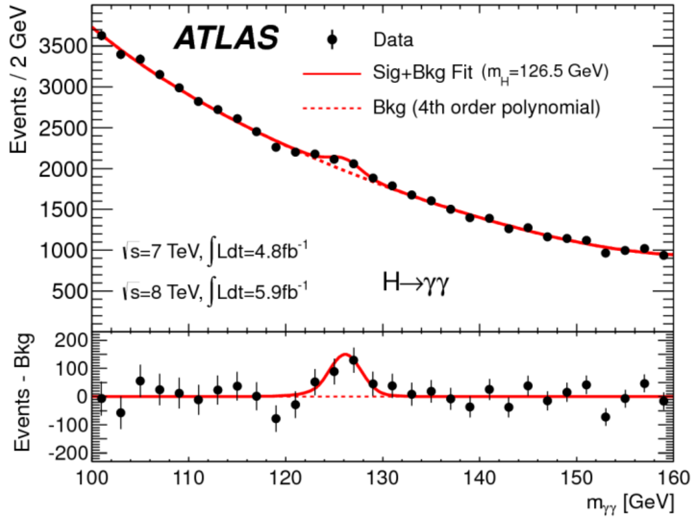




ADMX PRL 124, 101303 (2020)



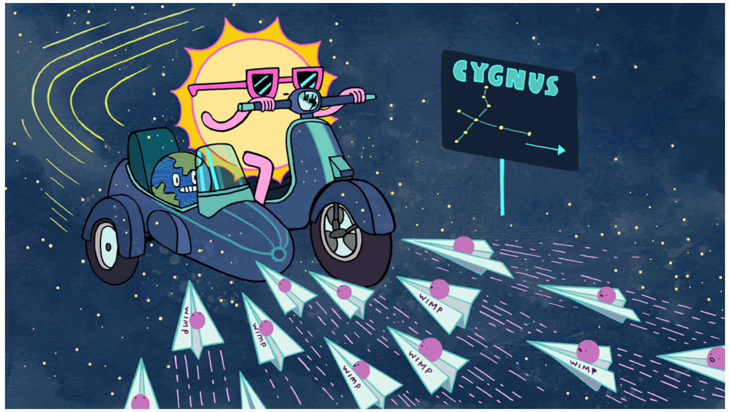




$mc^2 = E = \hbar\omega$

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

- 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** $\rho \sim 0.45\ \mathrm{GeV/cm^3}$



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

<u>WIMP: $m \sim 1\ \mathrm{TeV}$ (Higgsino/Wino)</u>

$$\lambda_B \sim \frac{2\pi \times 196\ \mathrm{MeVfm}}{0.07\% \times \color{red}{1\ \mathrm{TeV}}} = 1.8\ \mathrm{fm}$$

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

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

WIMP behaves as a **particle**

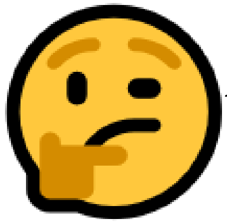
<u>Axions: $m \sim 10\ \mu\mathrm{eV}$</u>

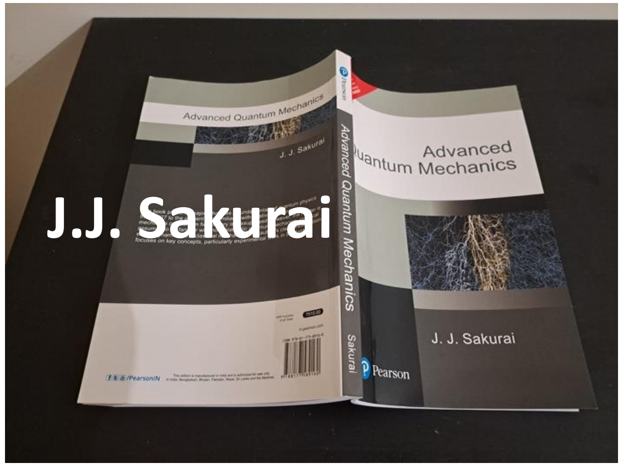
$$\lambda_B \sim \frac{2\pi \times 196\ \mathrm{MeVfm}}{0.07\% \times \color{red}{10\ \mu\mathrm{eV}}} = 176\ \mathrm{m}$$

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

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

DM Axions behave as a wave





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

> keV photon physics: γ-ray spectroscopy

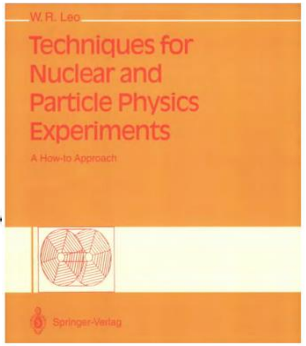
^{60}Co

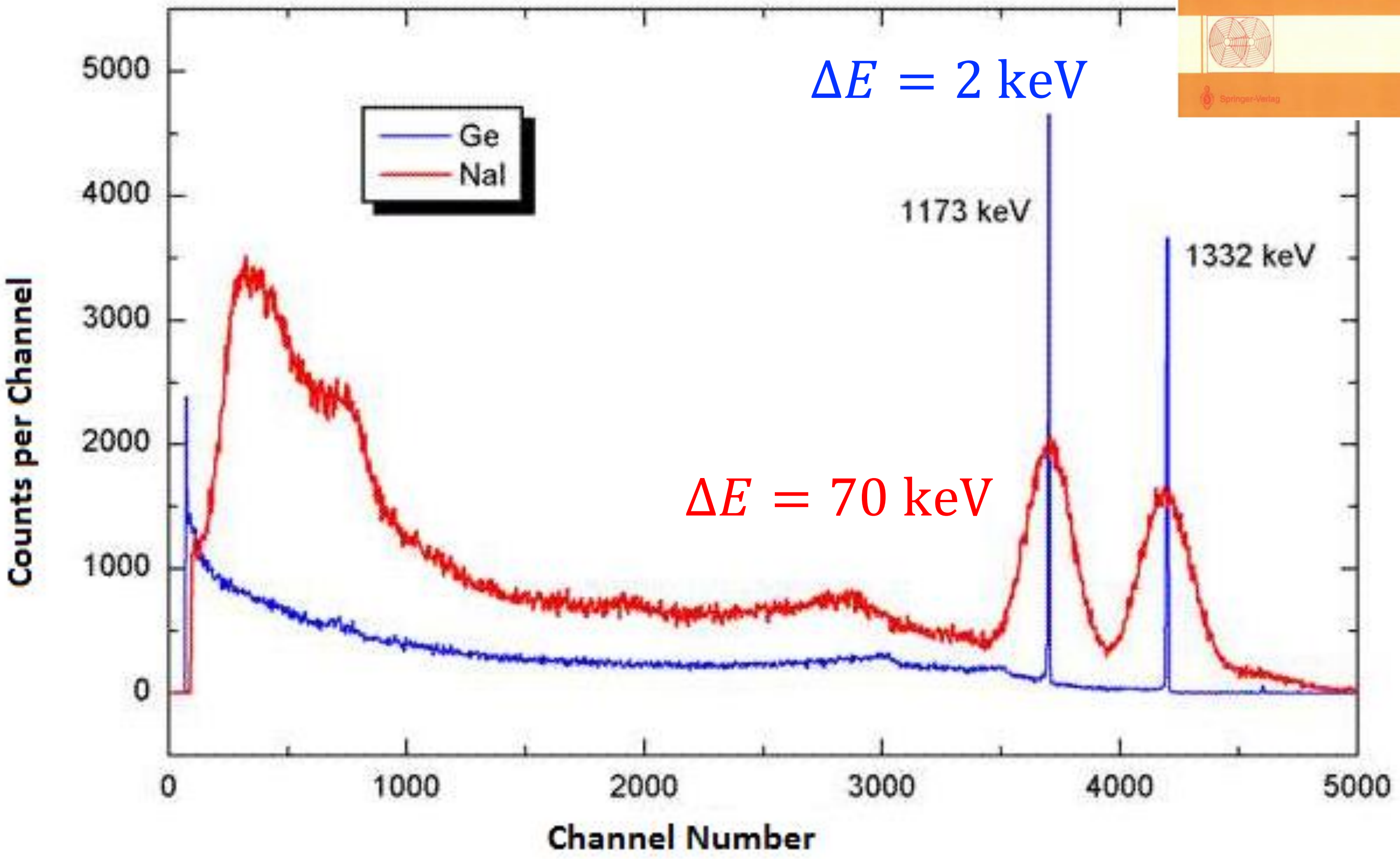
γ

NaI (Tl)
or Ge

DC amp.

qADC



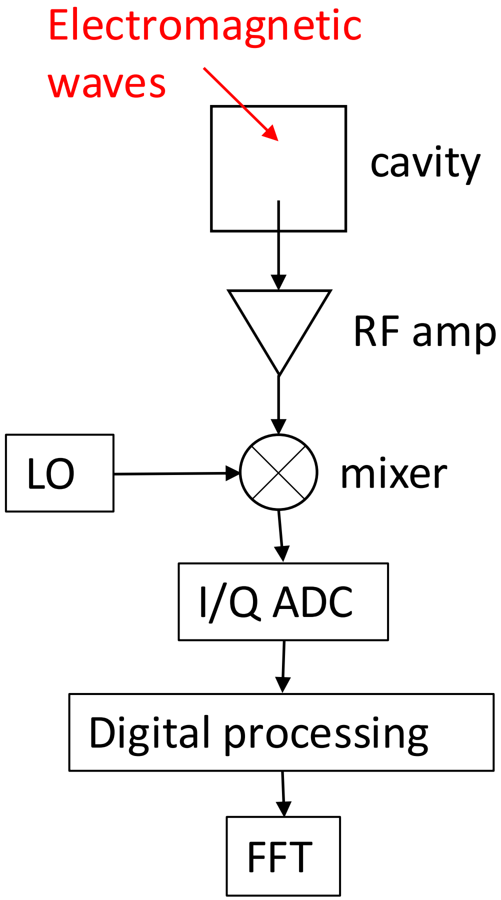


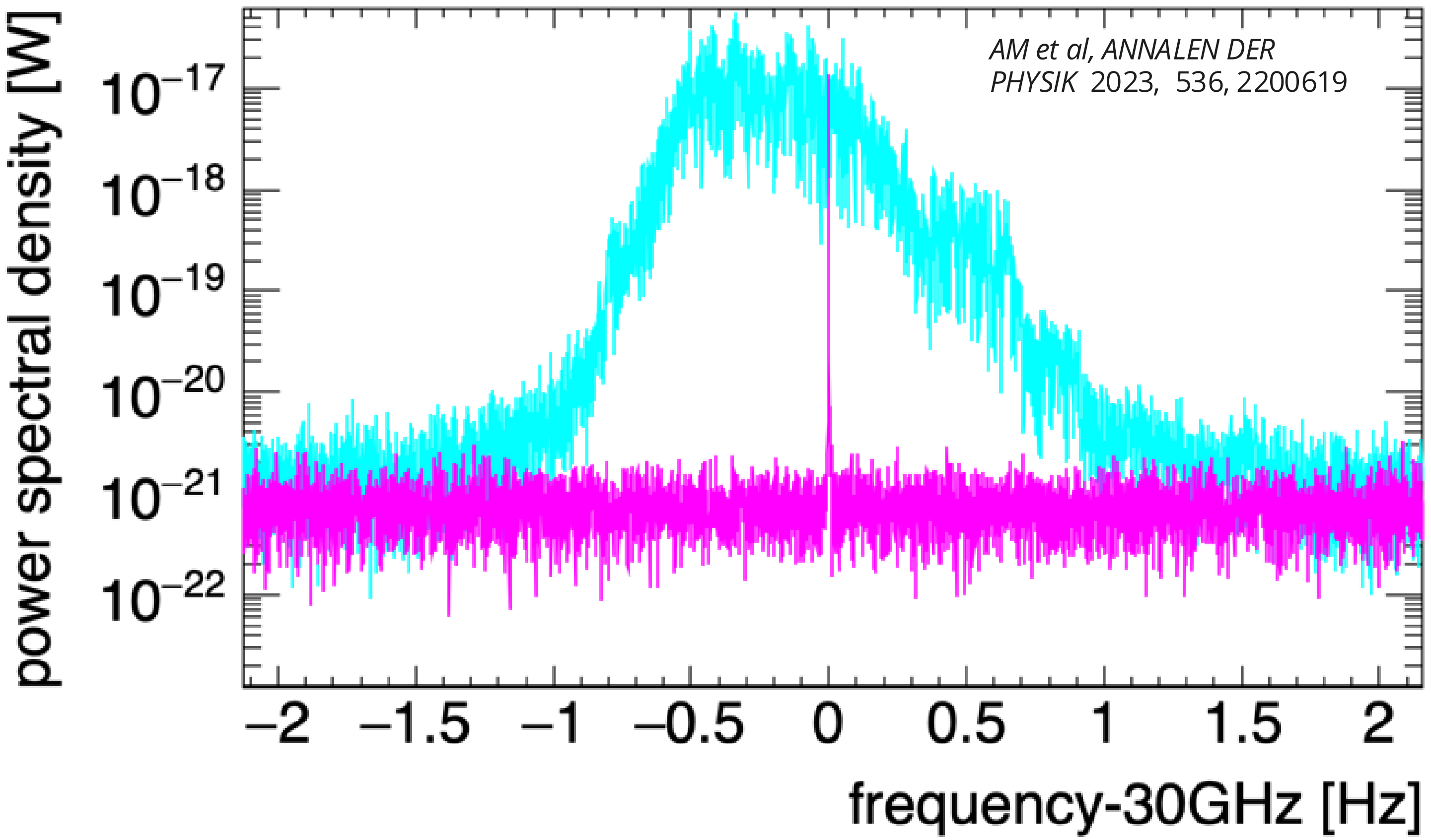
<u>Elementary process</u>

- Photoelectric effect
- Compton scattering
- Pair creation

Energy resolution via particles $E/\Delta E \sim 14 - 500$

Frequency (and phase) measurement





Energy resolution via frequency $E/\Delta E = \nu/\Delta\nu > 10^9$

<u>Elementary process</u>

- Voltage of the microwave moves electrons in the circuit

Is photon particle or wave?

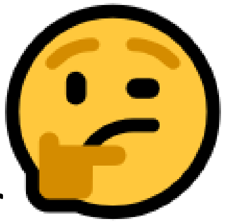
Revisit wave-particle duality (→ part 3)

Wave (field) states

$$\hat{\mathcal{E}} \sim \hat{a}\exp(+i\omega t) - \hat{a}^\dagger \exp(-i\omega t)$$

$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$$

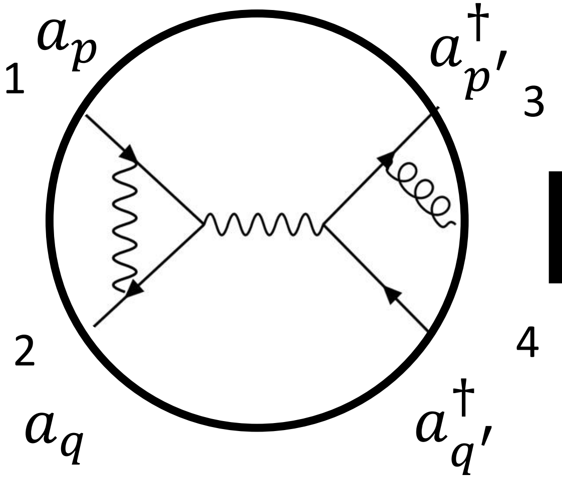
Eigenstate of the annihilation operator



$$\rho = \int d\alpha^2 P(\alpha)|\alpha\rangle\langle\alpha|$$

projection

Quantum field



ρ

projection

Number (energy) states

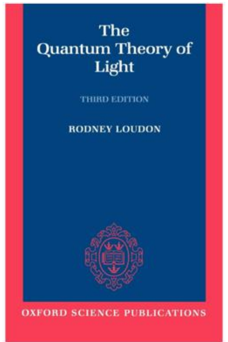
$$\hat{n} = \hat{a}^\dagger \hat{a}$$

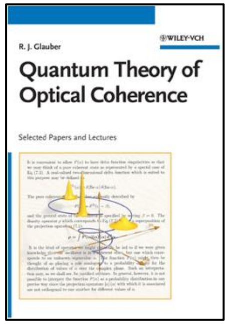
$$\hat{n}|n\rangle = n|n\rangle$$

Eigenstate of the number operator

$$\rho = \sum_n c_n |n\rangle\langle n|$$

- Typical particle physics focuses on number states
- We count numbers and measure energy NOT field
- We are not familiar with coherent states





Quantum to classical field: more detail

arXiv:2408.04696

$$\hat{\phi}(t,\mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^3}\frac{1}{\sqrt{2\omega_\mathbf{k}}}\left(\hat{a}_\mathbf{k} e^{-ik\cdot x} + \hat{a}^\dagger_\mathbf{k} e^{ik\cdot x}\right) \qquad [\hat{a}_\mathbf{k},\, \hat{a}^\dagger_\mathbf{q}] = (2\pi)^3\delta(\mathbf{k}-\mathbf{q}) \qquad \hat{a}|\alpha\rangle = \alpha|\alpha\rangle$$

Part 3 Coherent state

$$\hat{\rho}_{th} \equiv \frac{\exp\left(-\hat{H}_0/k_B T\right)}{Z} = \frac{1}{1+\bar{n}_{th}}\sum_{n=0}^{\infty}\left(\frac{\bar{n}_{th}}{1+\bar{n}_{th}}\right)^n |n\rangle\langle n| = \int d^2\alpha \frac{\exp\left(-|\alpha|^2/\bar{n}_{th}\right)}{\pi\bar{n}_{th}}|\alpha\rangle\langle\alpha|$$

→ Incoherent mixed state with max entropy (thermal equilibrium) → Stefan Boltzmann, Planck law

$$N \gg 1 \qquad \langle\hat{A}(\hat{a},\hat{a}^\dagger)\rangle = \int d\alpha\, P(\alpha)A(\alpha) + \mathcal{O}(1/N)$$

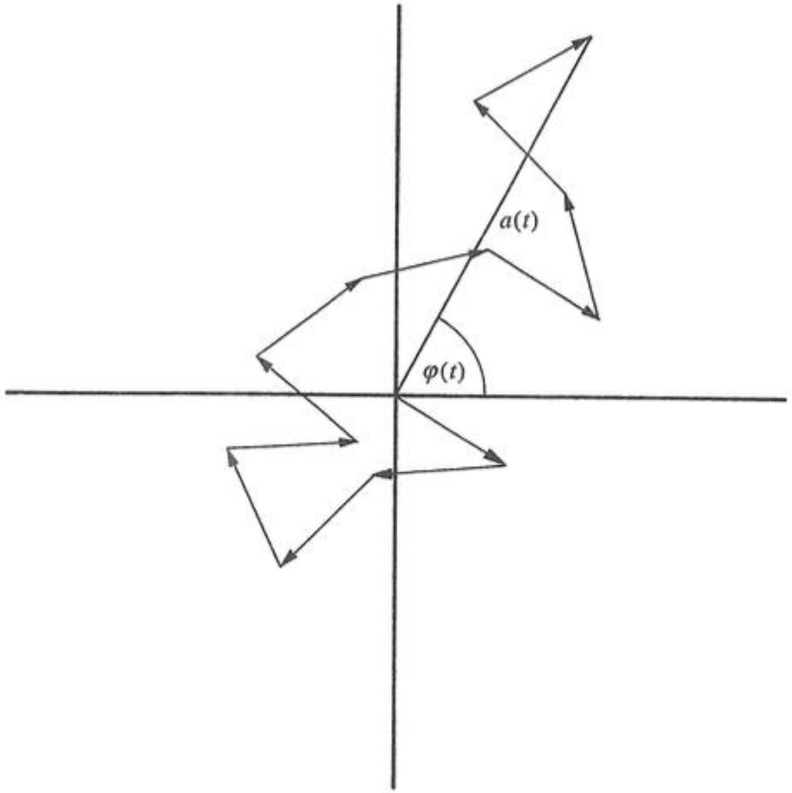
$$\hat{\phi}(t,\mathbf{x}) \simeq \phi(t,\mathbf{x}) = \sum_\mathbf{k}\sqrt{\frac{2}{V\omega_\mathbf{k}}}\,\mathrm{Re}\left[\alpha_\mathbf{k} e^{-ik\cdot x}\right] \longrightarrow \sum_\mathbf{k}\sqrt{\frac{2N_\mathbf{k}}{V\omega_\mathbf{k}}}\cos(\omega_\mathbf{k} t - \mathbf{k}\cdot\mathbf{x} + \varphi_\mathbf{k})$$

Quantum field — classical field

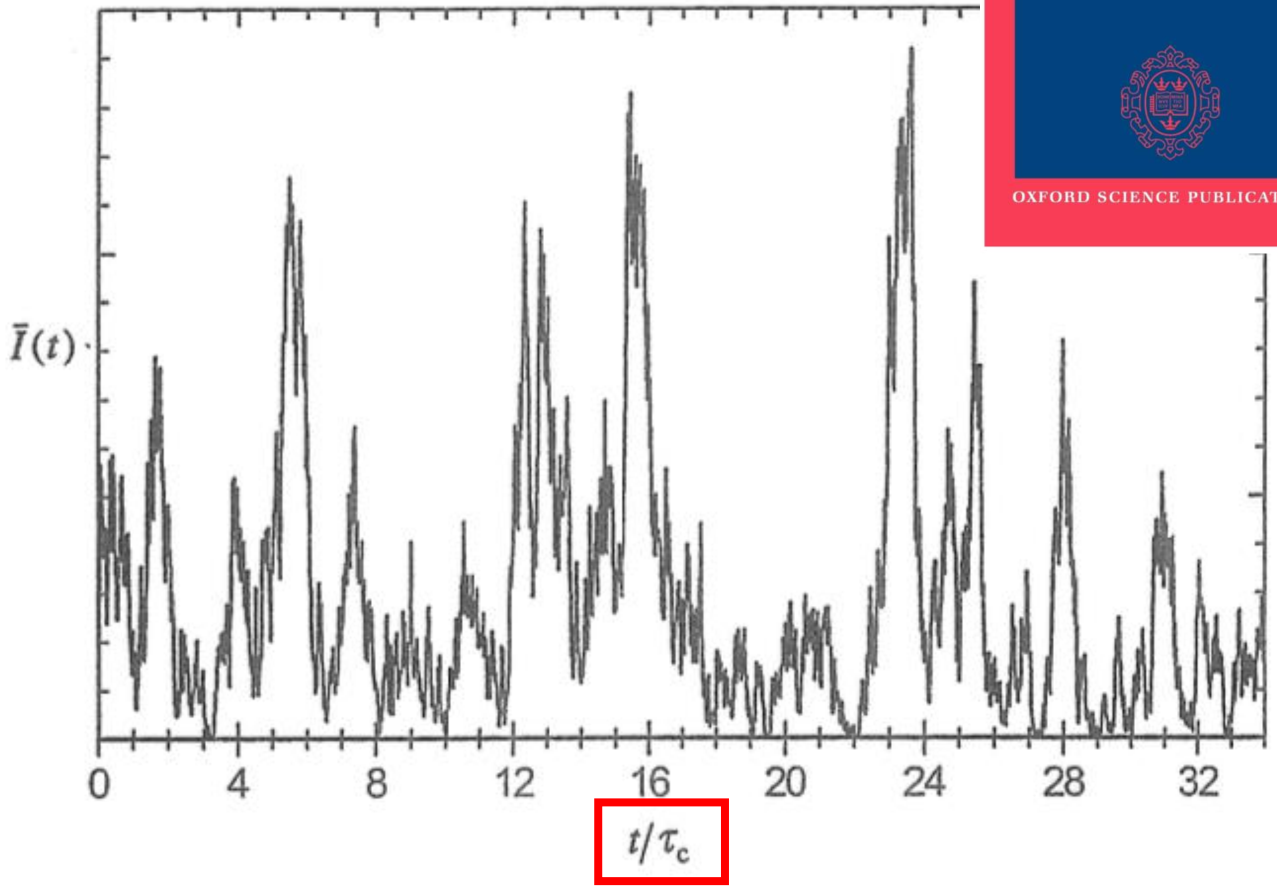
A bosonic field of a high occupation number becomes classical chaos field

Cf) classical chaos waves

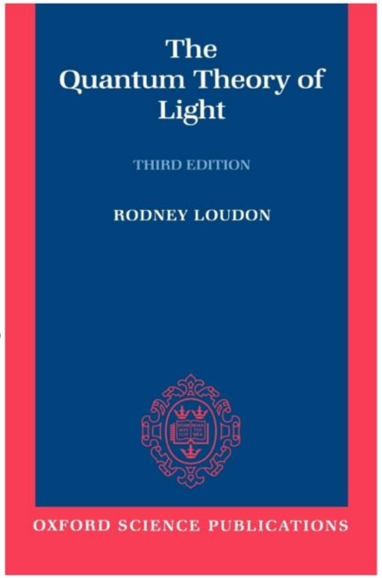
Key concept: classical coherence time τ_c



$$E(t) = E_1(t) + E_2(t) + \ldots + E_\nu(t)$$
$$= E_0 \exp(-i\omega_0 t)\{\exp(i\varphi_1(t)) + \exp(i\varphi_2(t)) + \ldots + \exp(i\varphi_\nu(t))\}$$
$$= E_0 \exp(-i\omega_0 t) a(t) \exp(i\varphi(t)),$$

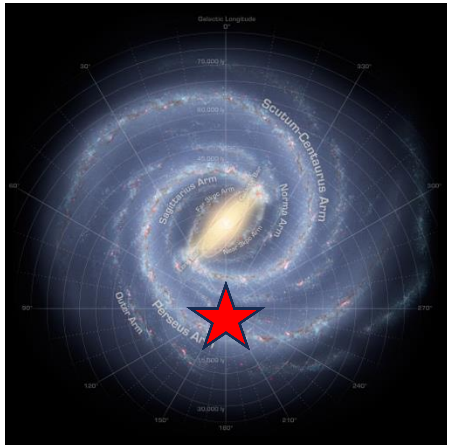


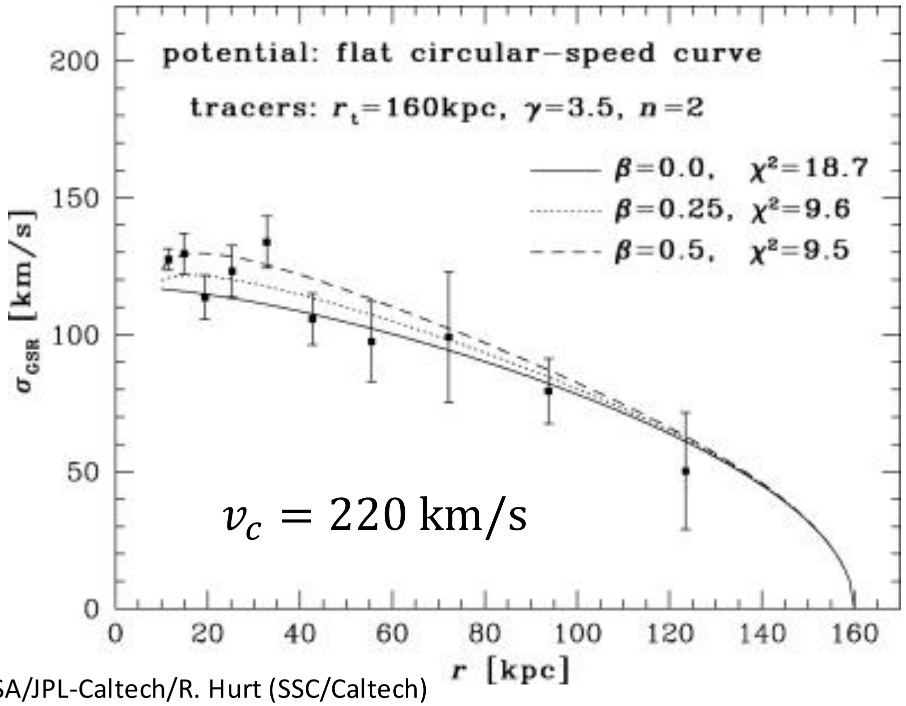
$$\bar{I}(t) = \frac{1}{2}\varepsilon_0 c|E(t)|^2 = \frac{1}{2}\varepsilon_0 c E_0^2 a(t)^2$$



DM axion distribution function and coherence time

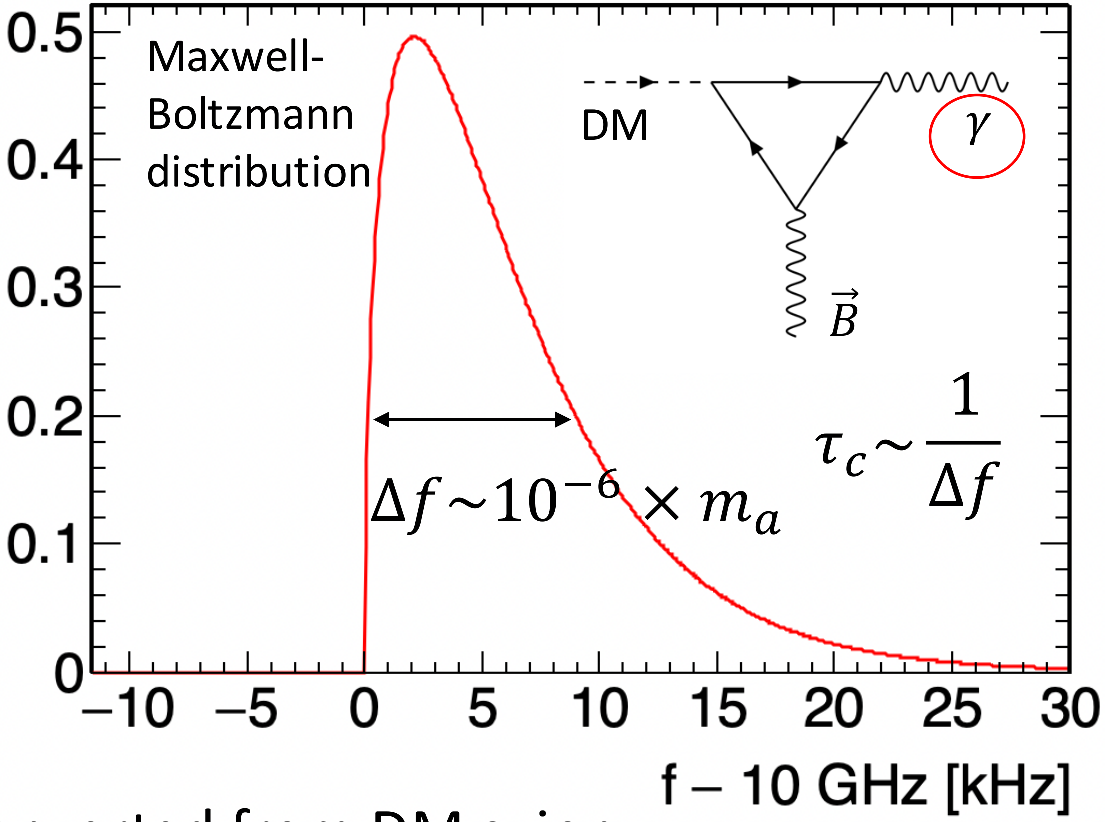
Velocity dispersion of Milky way Galaxy around





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

If $m_a = 10$ GHz



Microwaves converted from DM axion is very narrow band classical waves

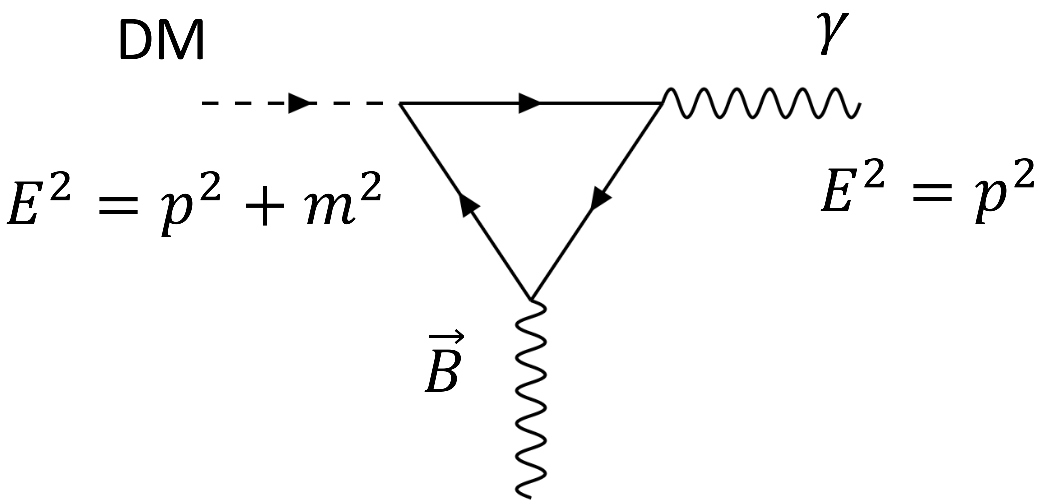
NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

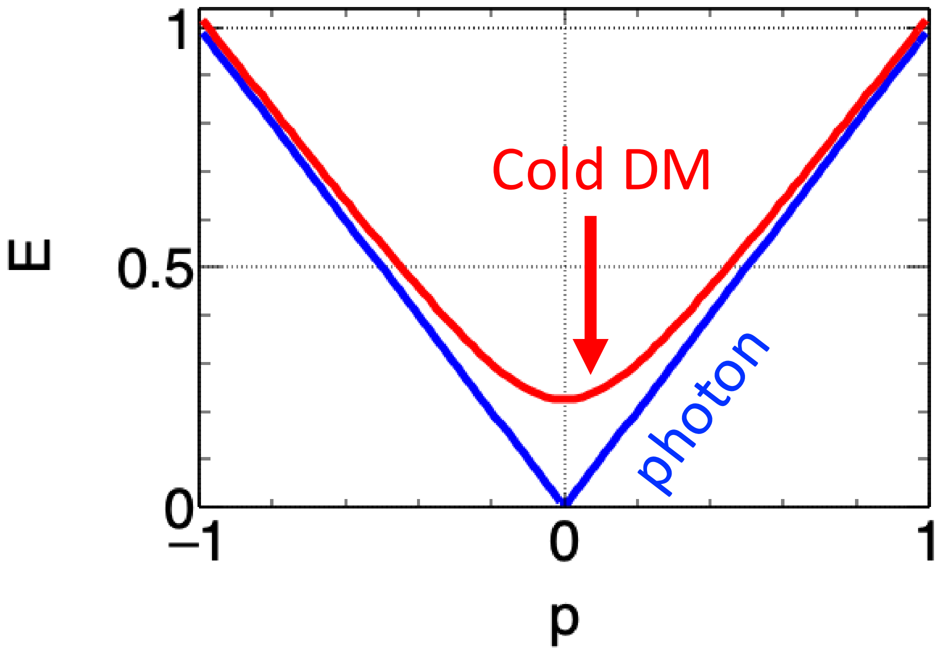
Mon Not R Astron Soc, Volume 369, Issue 4, July 2006, Pages 1688–1692,

Part 1: overview on axion searches

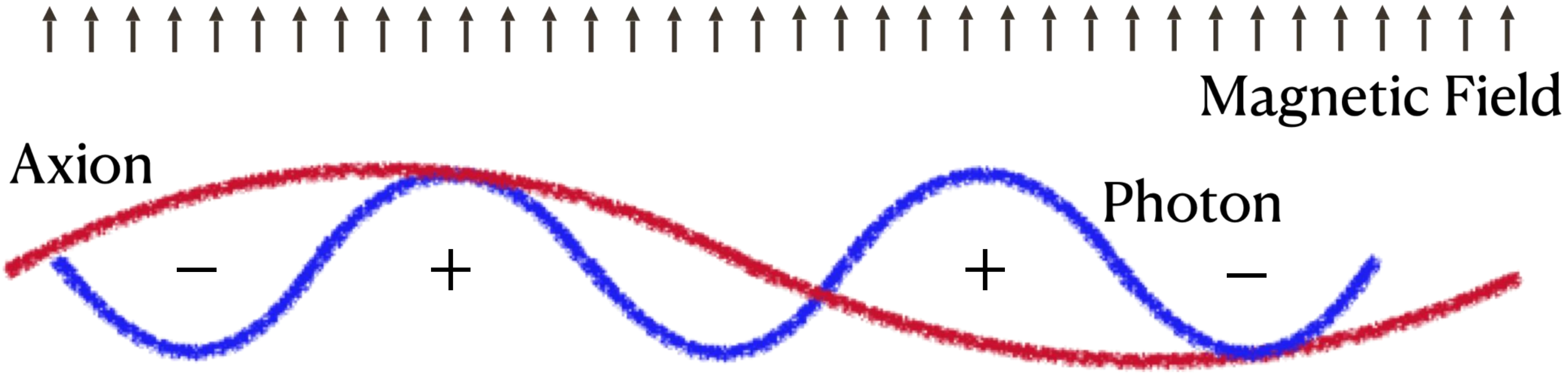
- Axion vs WIMPs
  - WIMP: particle; axions: waves
  - Particle detection
  - Classical wave detection
- Various haloscope experiments
  - ADMX families
  - Lower masses
  - Higher masses
- Non-DM axions
  - Light-Shining-Through-a-wall
  - Solar axion helioscopes
- Conclusion of part 1

Energy momentum *mismatch*



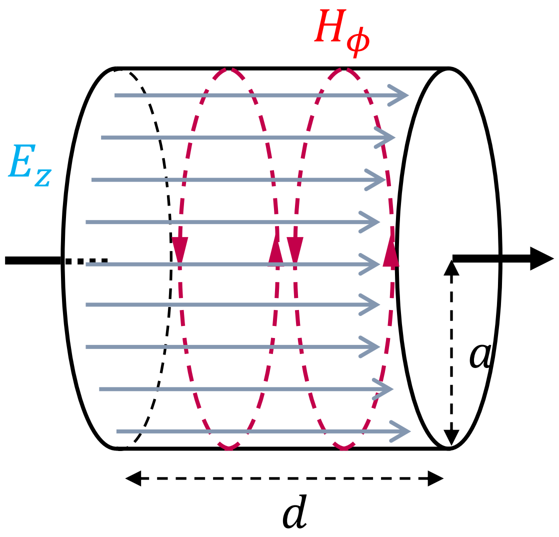


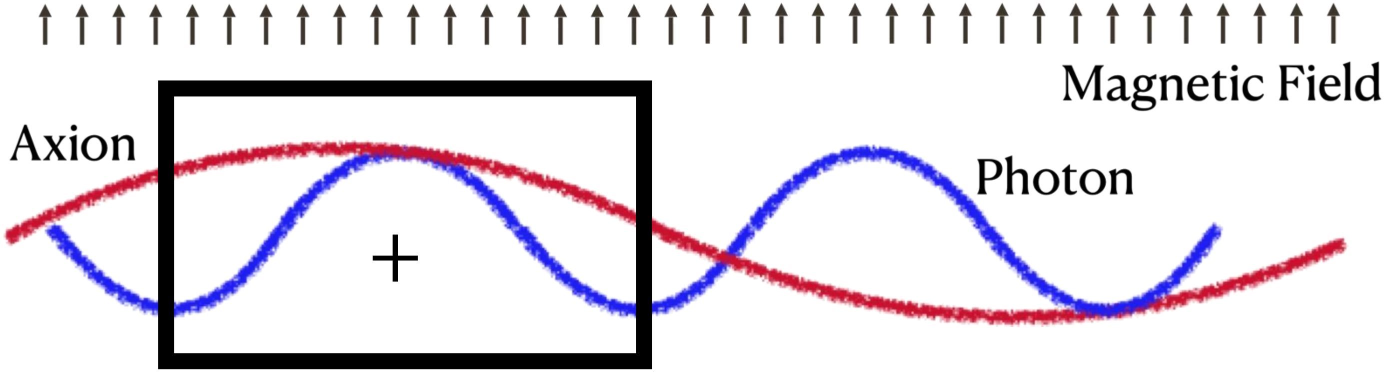
In real space: zero overlap integral



Courtesy of Alex Millar Jr.

A resonant cavity breaks translational symmetry





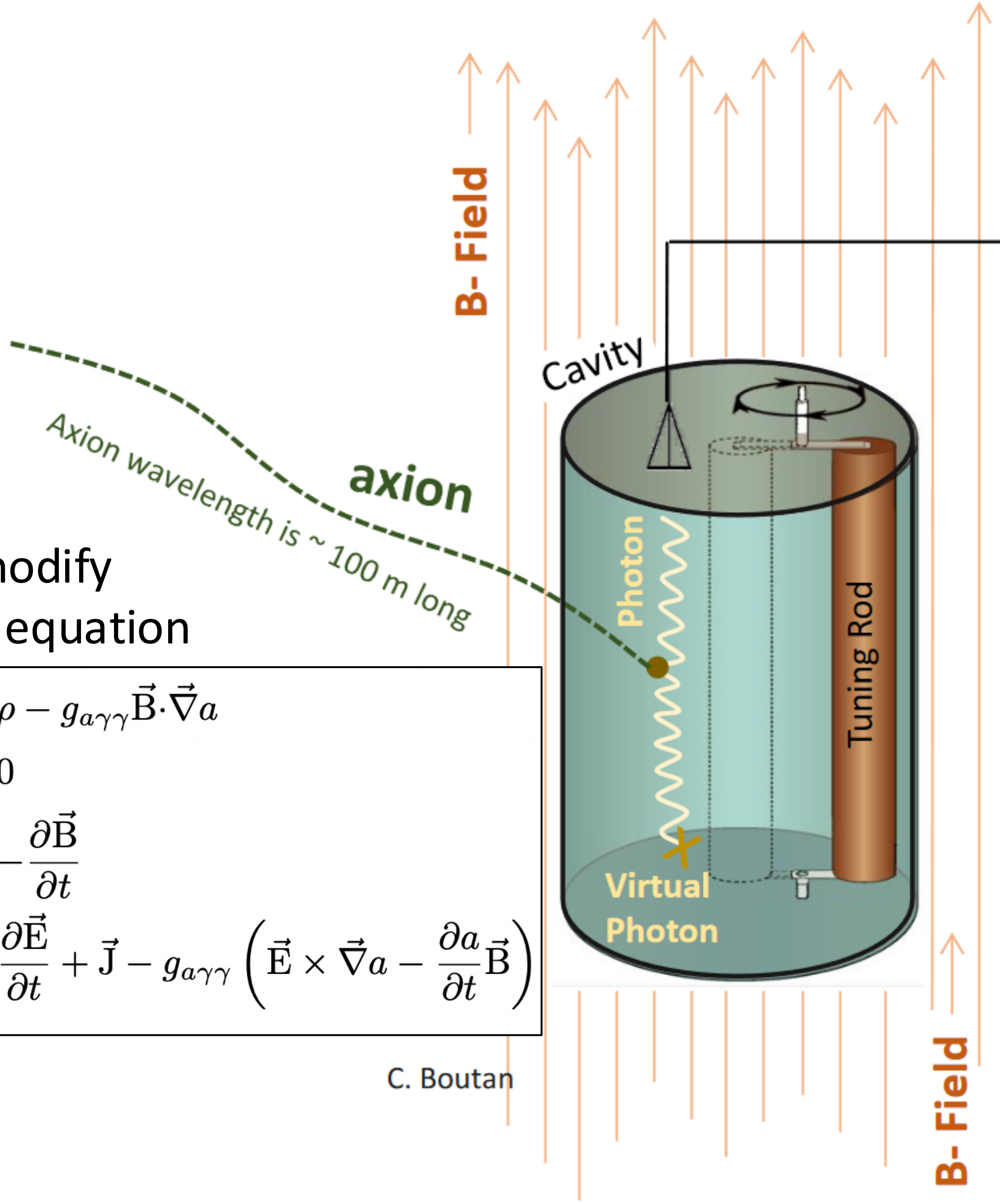
Microwave cavity

Resonant frequency of the fundamental mode TM_{010}

$$\hbar\omega_{010} = \frac{1}{\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{j_{01}}{a}\right)^2 + \left(\frac{0\cdot\pi}{d}\right)^2} \sim \frac{2.405}{a\sqrt{\mu\varepsilon}} \sim \frac{2.405}{a/c} \sim m_a c^2$$

Classical MW cavity is a mean to hunt DM axions

Skivie haloscope



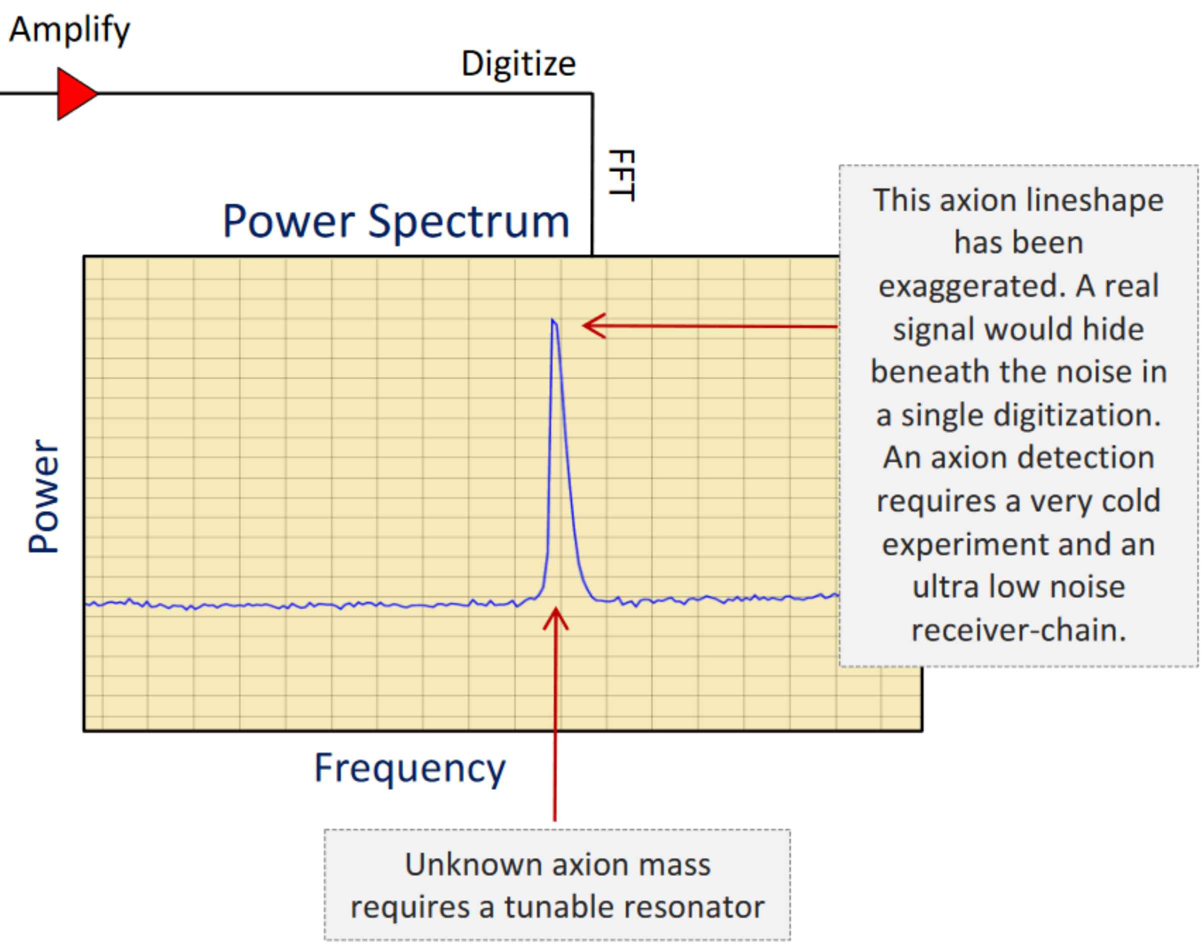
Axions modify Maxwell equation

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

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

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

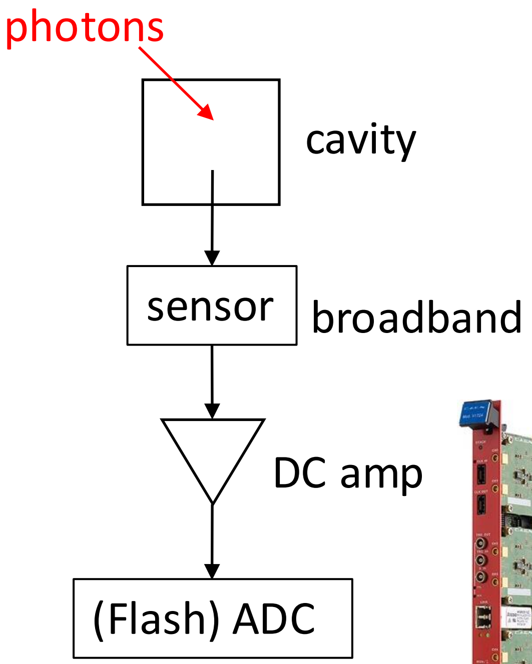
$$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + \vec{J} - g_{a\gamma\gamma}\left(\vec{E}\times\vec{\nabla}a - \frac{\partial a}{\partial t}\vec{B}\right)$$

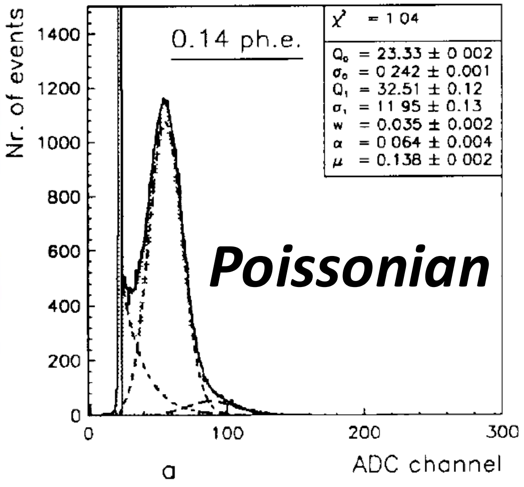


Courtesy: Gray Rybka, PATRAS2022

Photon (energy) detection vs wave detection

Part 3

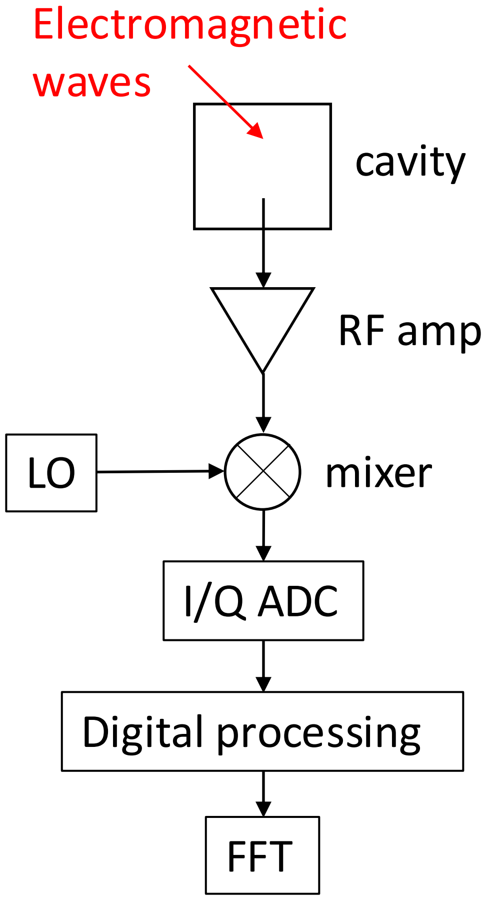


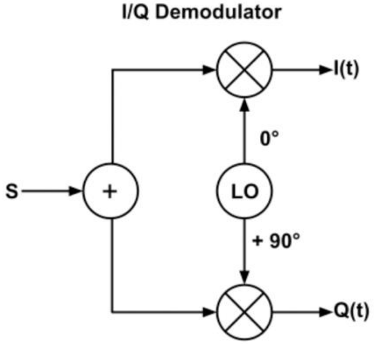


$$P(t) = n \times \hbar\omega \propto V_{ADC}\,(t)$$

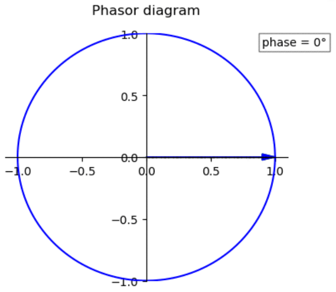
$$\Delta\phi\Delta n > 1$$

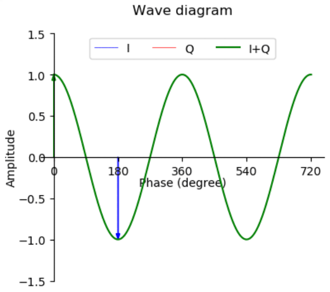
Part 2





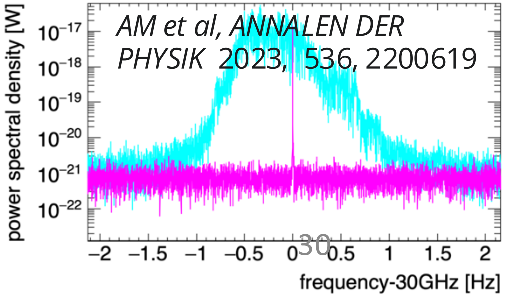
From wikipedia





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

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



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

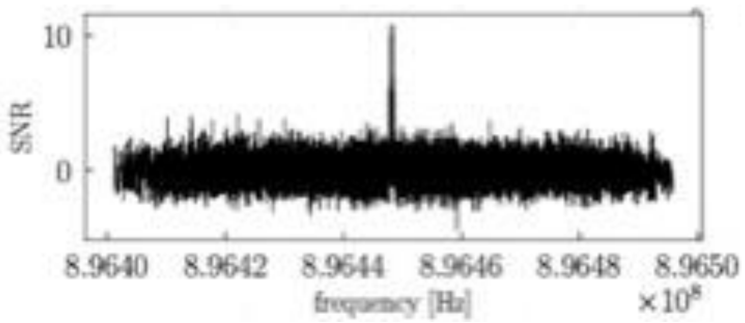
$$P_N = k_B T_s = 1.4 \times 10^{-23}\left(\frac{T_s}{1\mathrm{K}}\right)\ \mathrm{W/Hz}$$

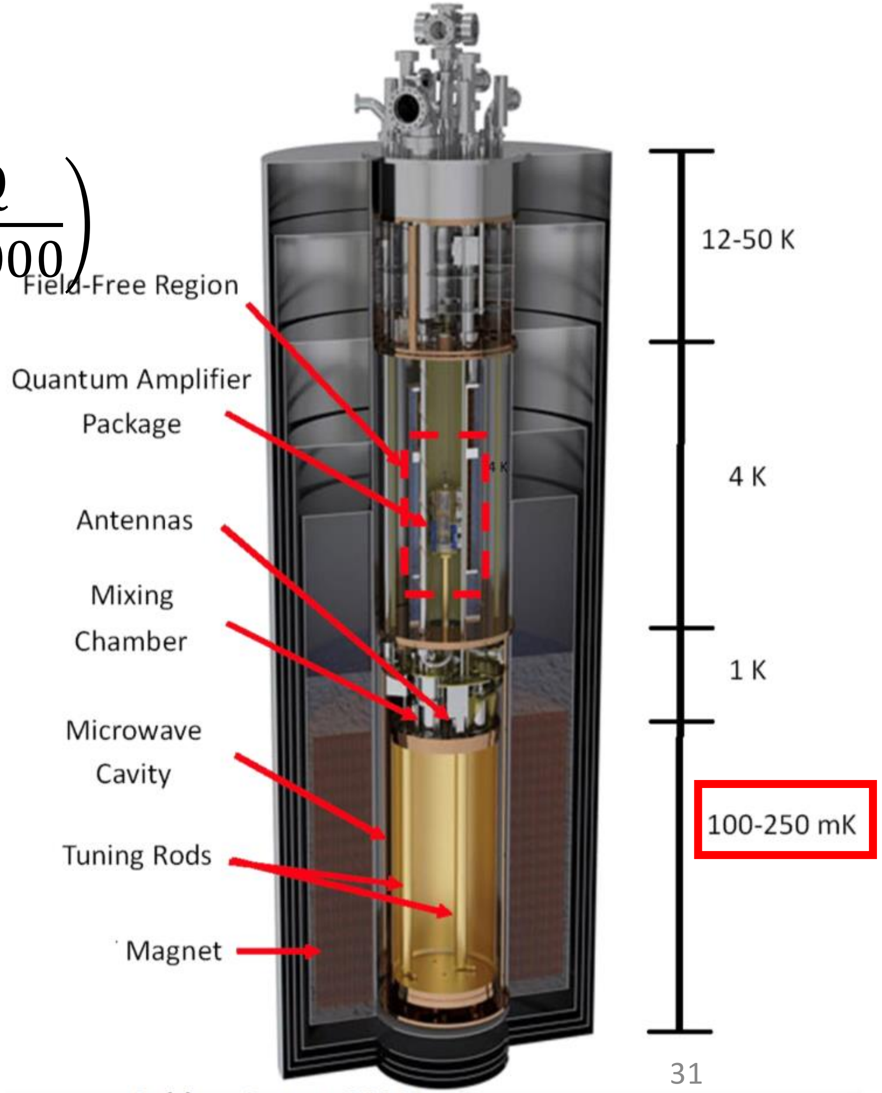
- Dicke's radiometer formula

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

t: integration time
b: measurement bandwidth

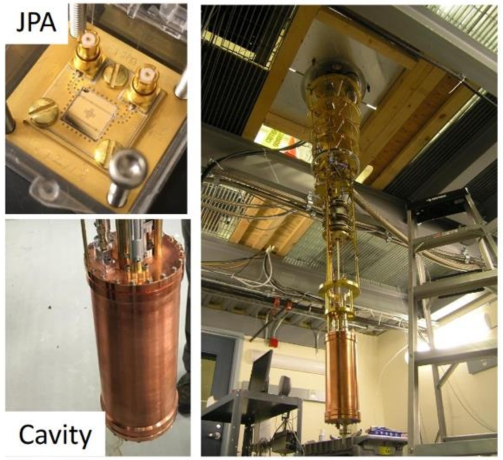
Fake signal





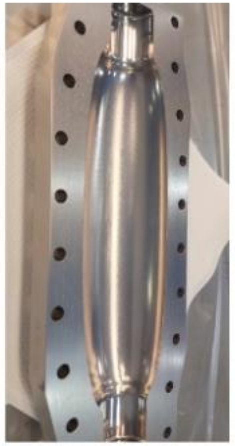
Conventional resonant cavity-based experiments (not all...)

HAYSTAC



QUAX

darkSRF

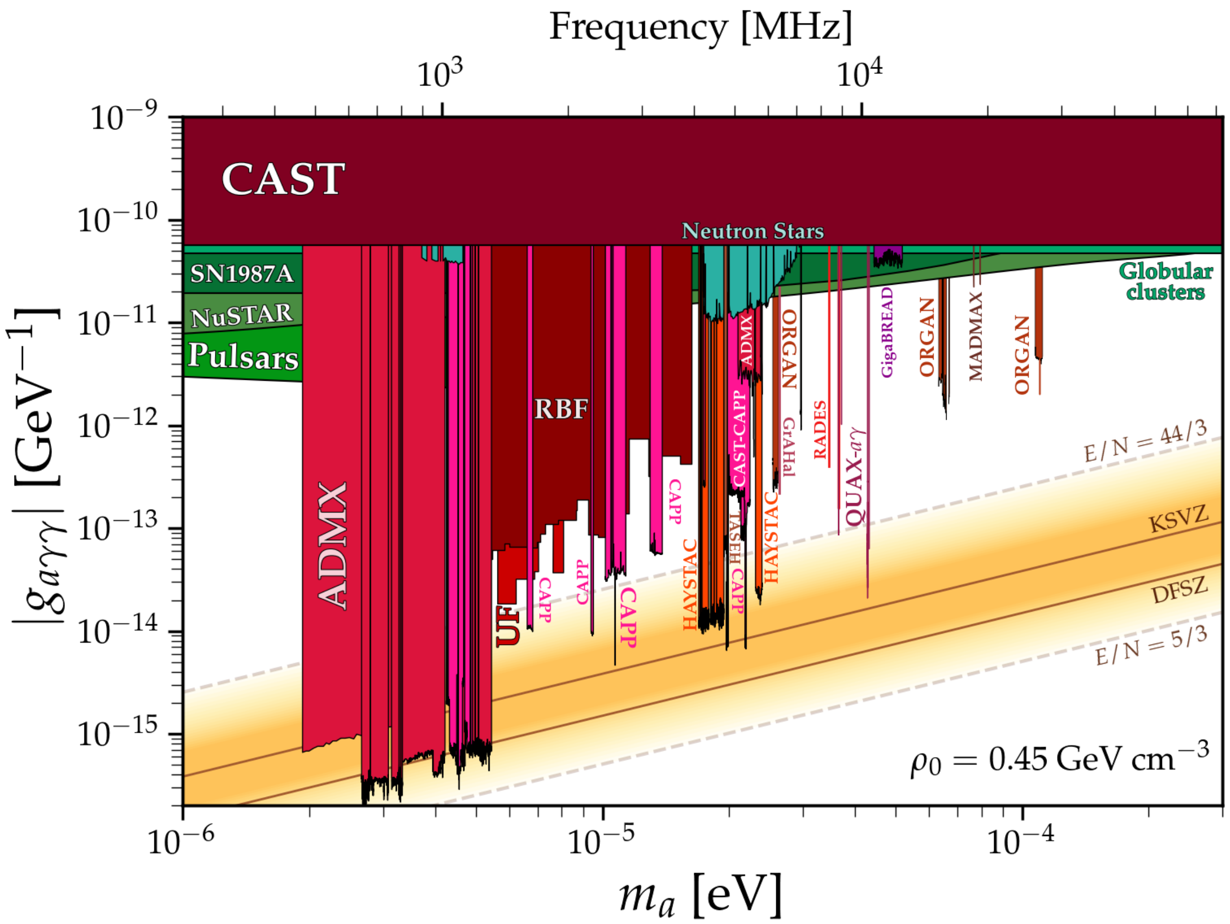


RADES

KAIST/CAPP

ORGAN

And others!

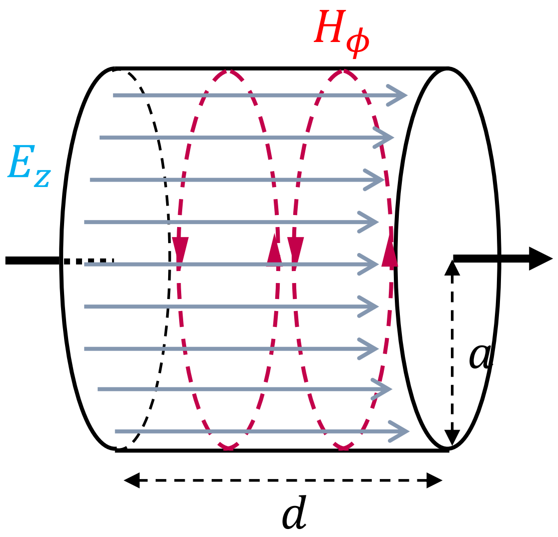


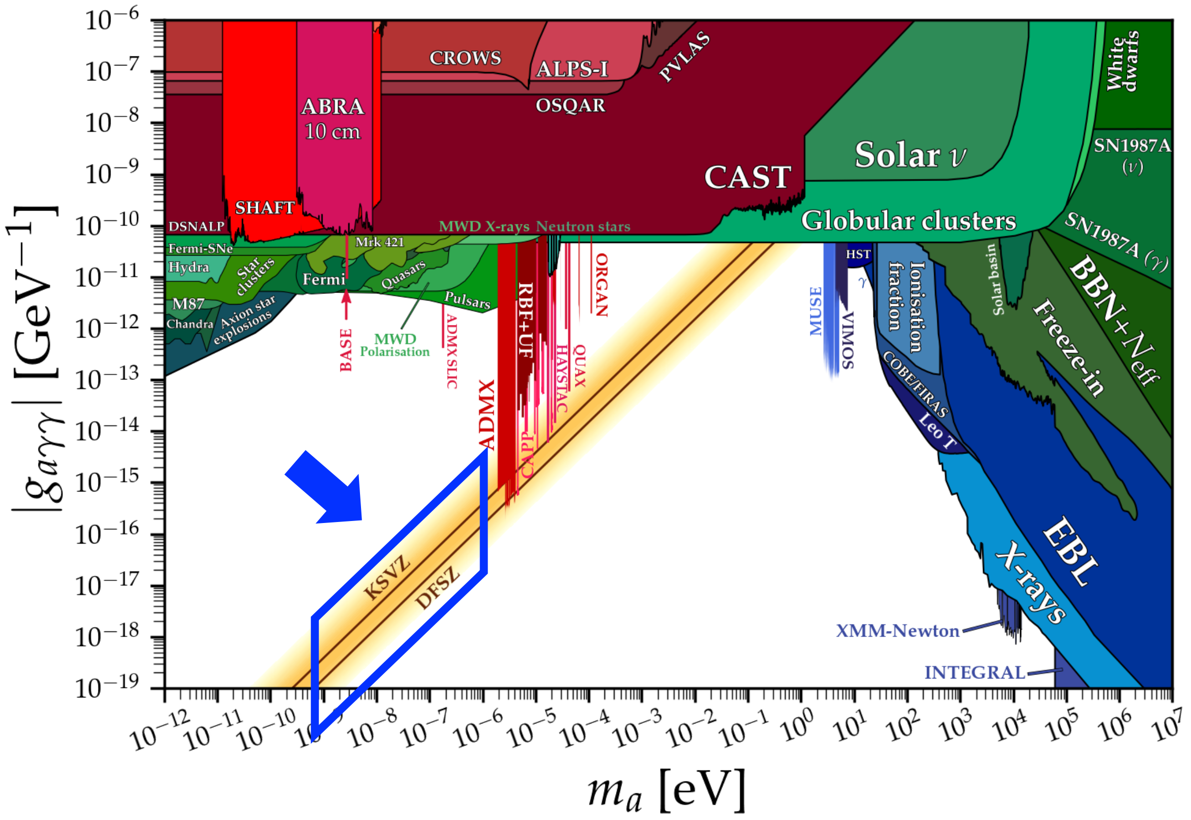
- Resonator concepts are similar but different materials (normal conducting, superconducting, dielectric) → Part 2
- Installation of quantum detection scheme → Part 3

Lower masses?

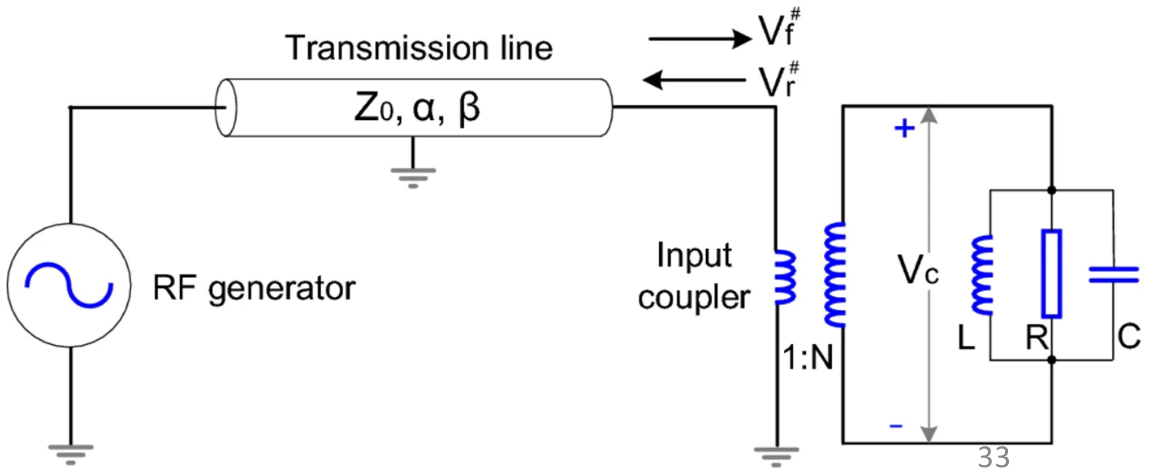
- Axion mass lower than ADMX (700 MHz) is motivated from the mis-alignment mechanism

$$\hbar\omega_{010} = \frac{2.405}{a/c} \sim m_a c^2$$

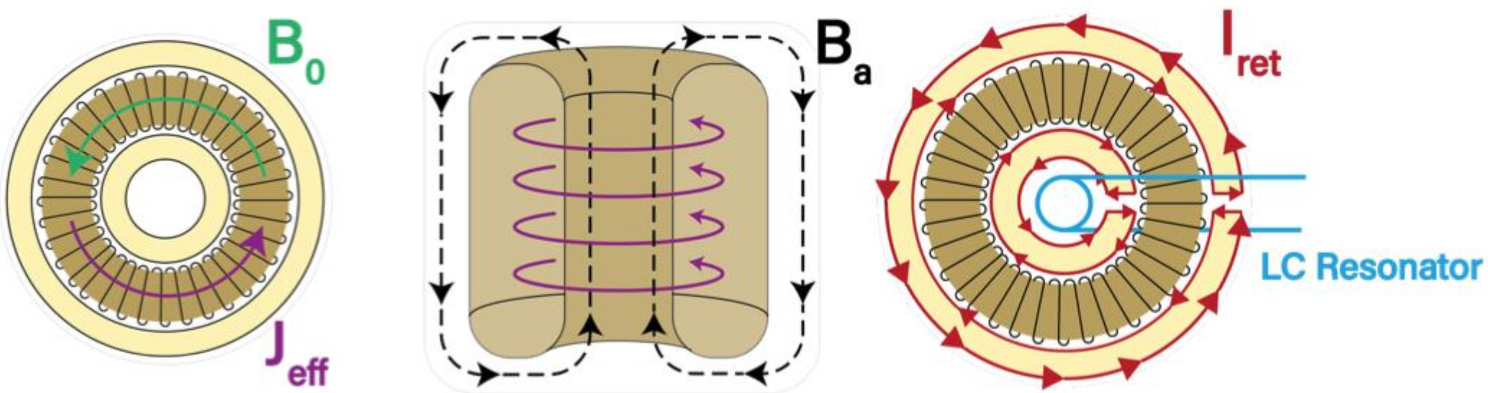


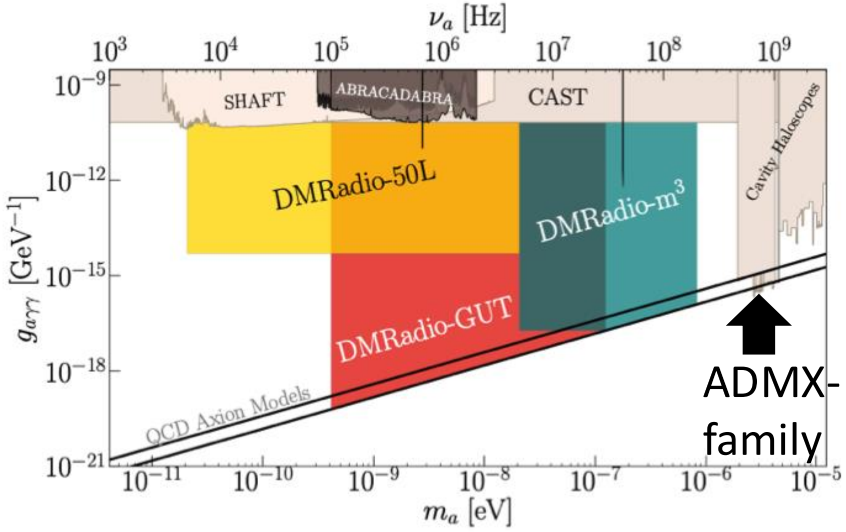


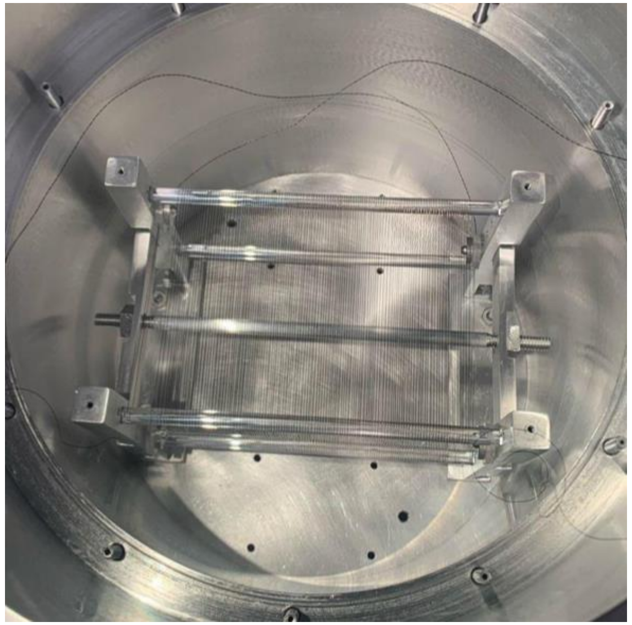
- A resonant cavity becomes impractically huge (>> 1 m) below 100 MHz not to fit any magnets
- RF resonators can be expressed as a LC equivalent circuit
  → Why not simply use LC real circuit

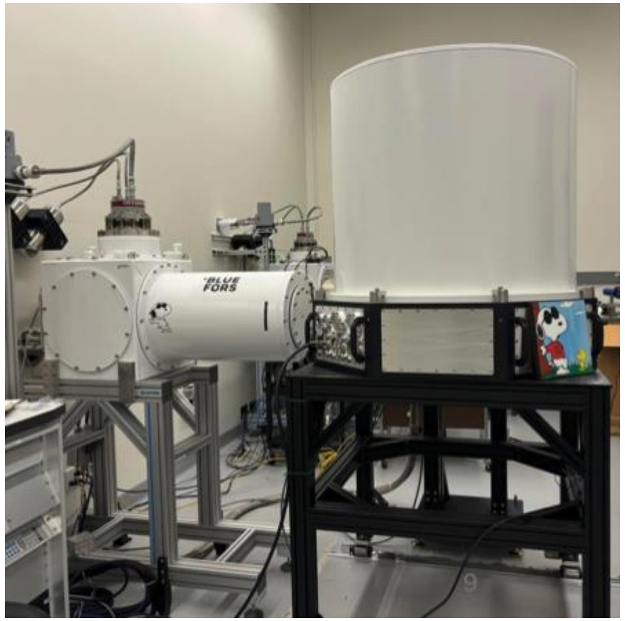


LC-circuit approach: DMRadio





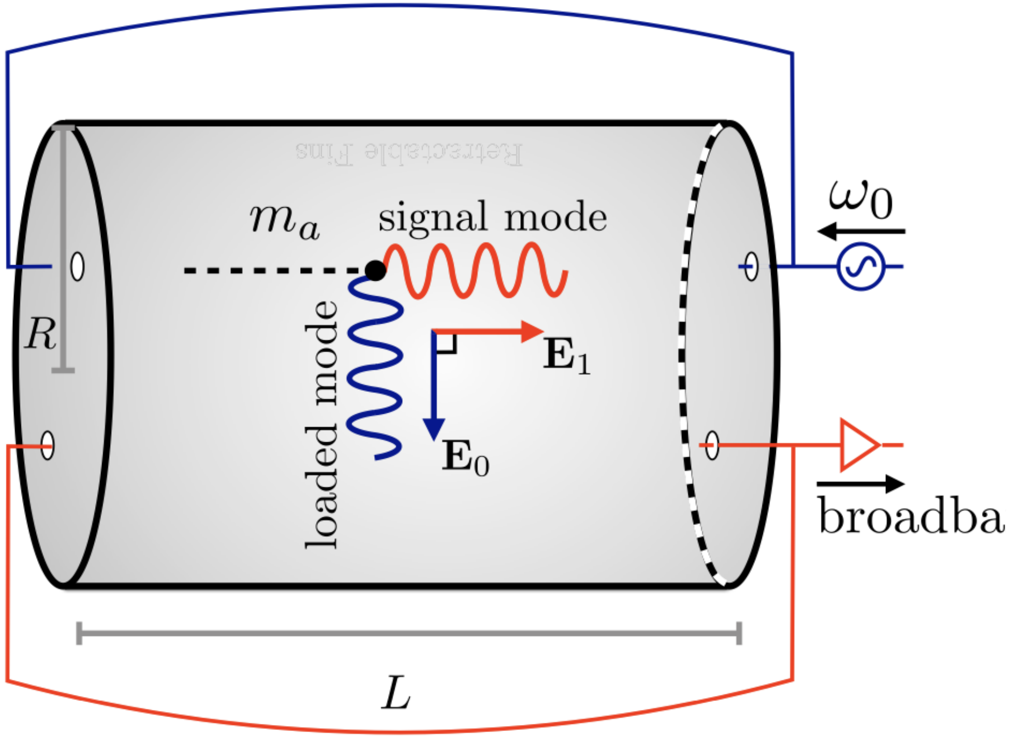




Courtesy:
Jessica Fry,
Patras2025

Axion heterodyne: ~~magnetic field~~ → pump MW

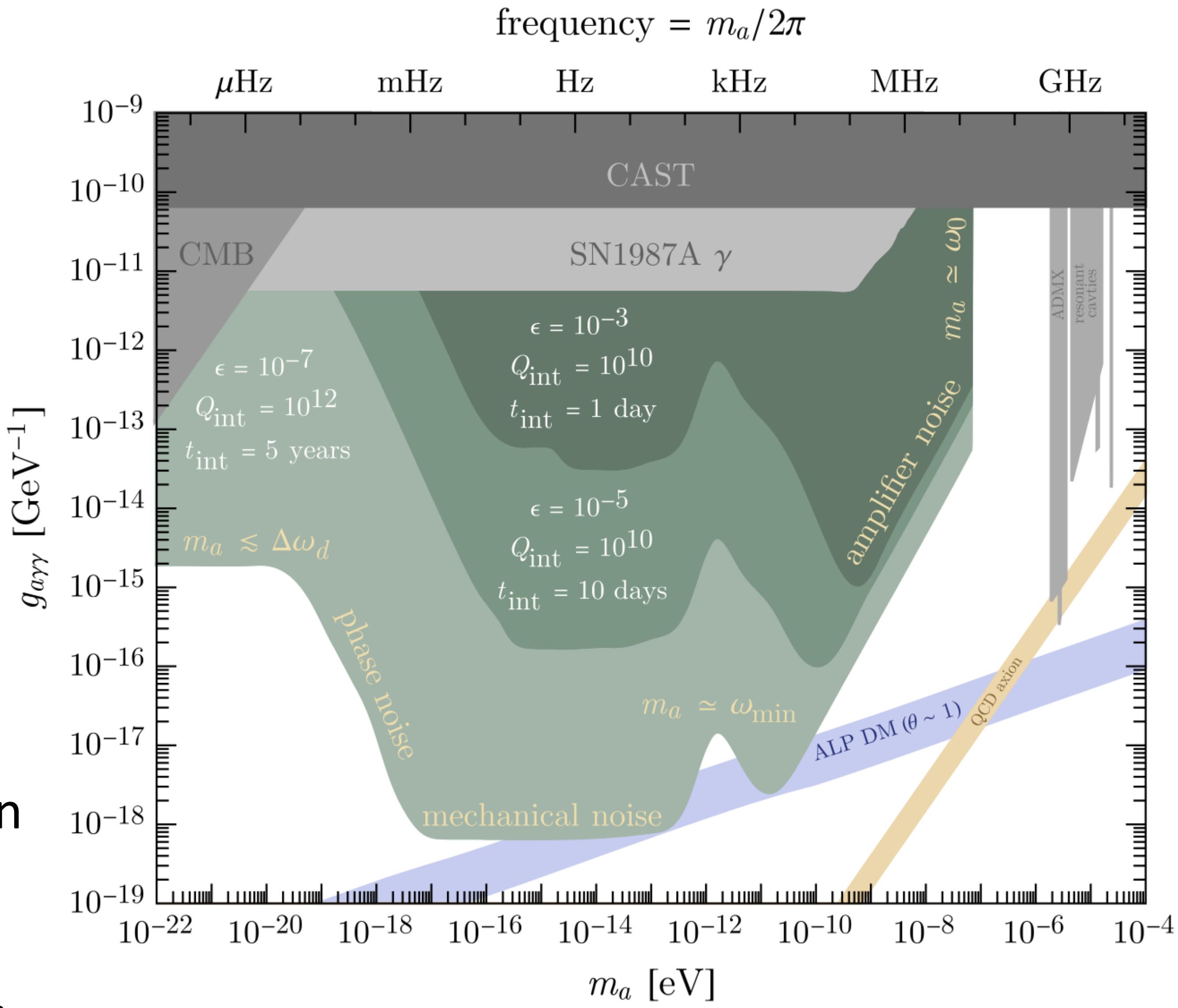
A. Berlin et al. PRD 104 L111701 (2021)



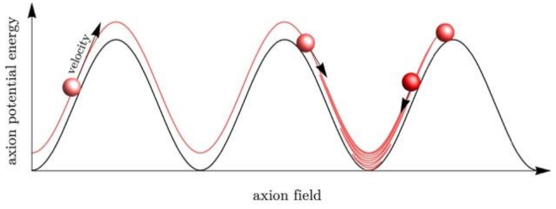
NC cavity at SLAC

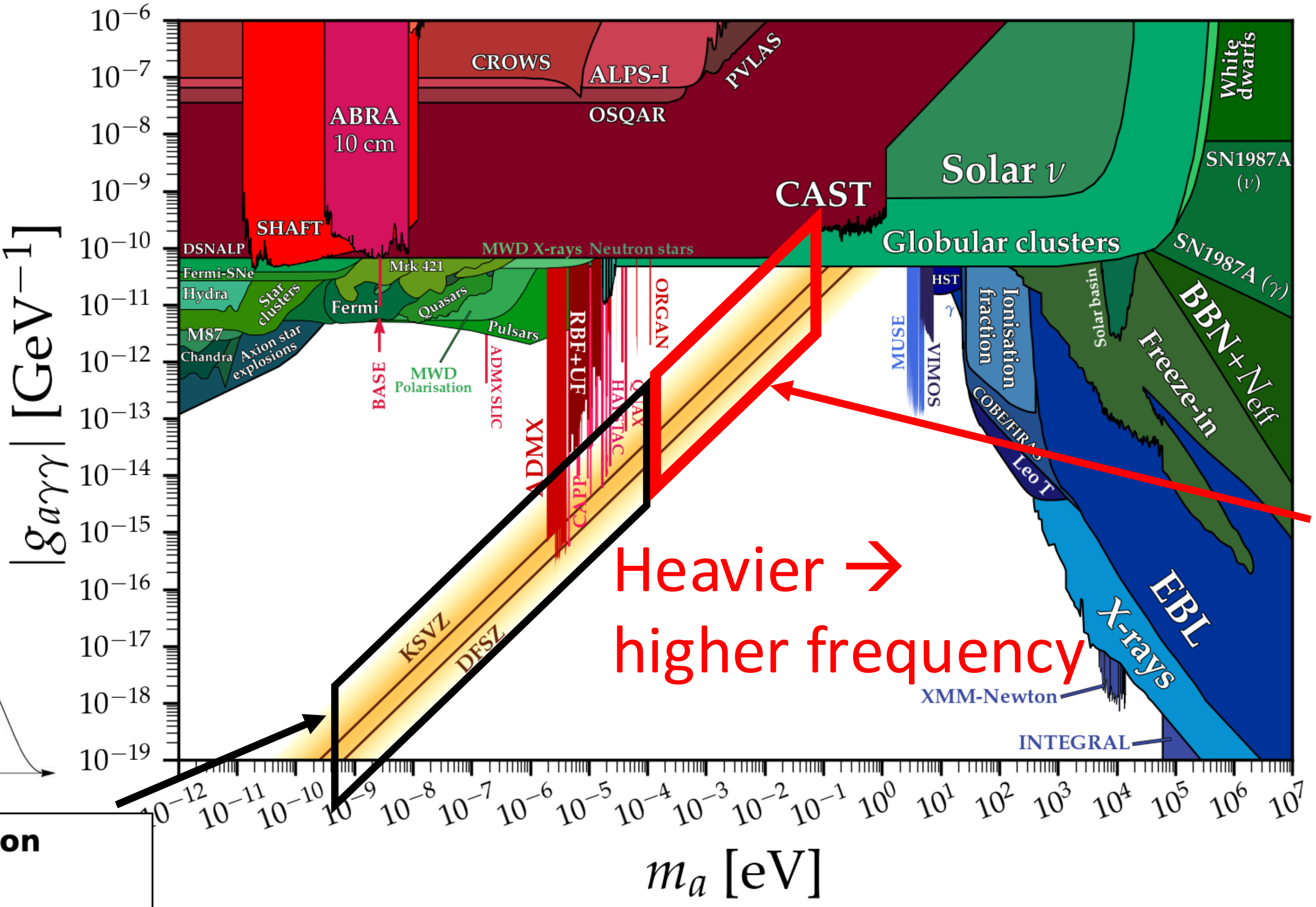
arXiv:2507.0773

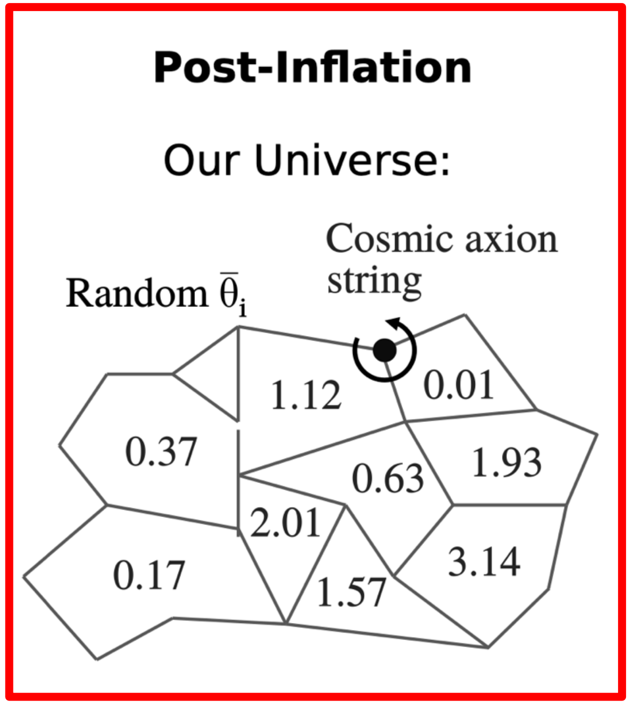
Initiative in CERN and FNAL with SC cavities

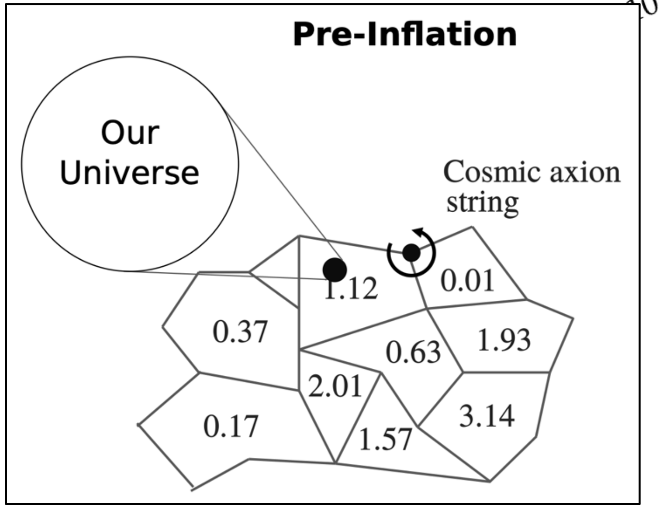


Higher masses

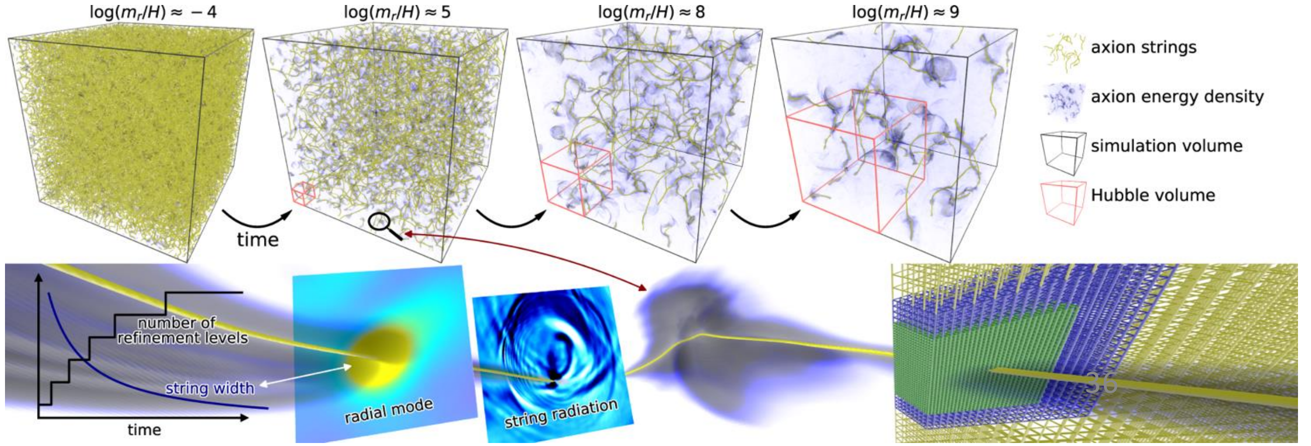






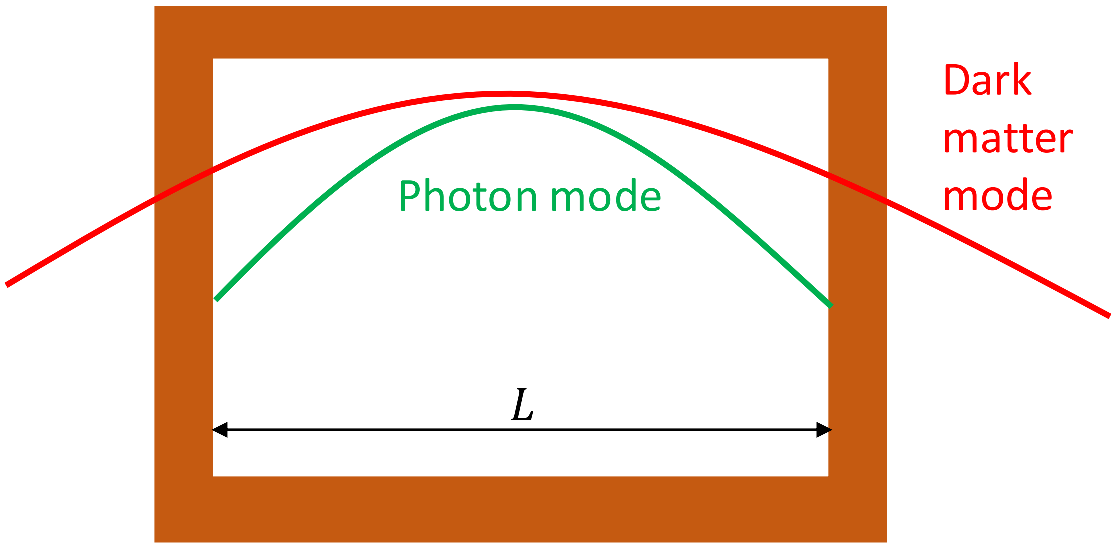


Buschmann, *et al. Nat Commun* **13**, 1049 (2022)



Issue of high-frequency resonators for dark matter search

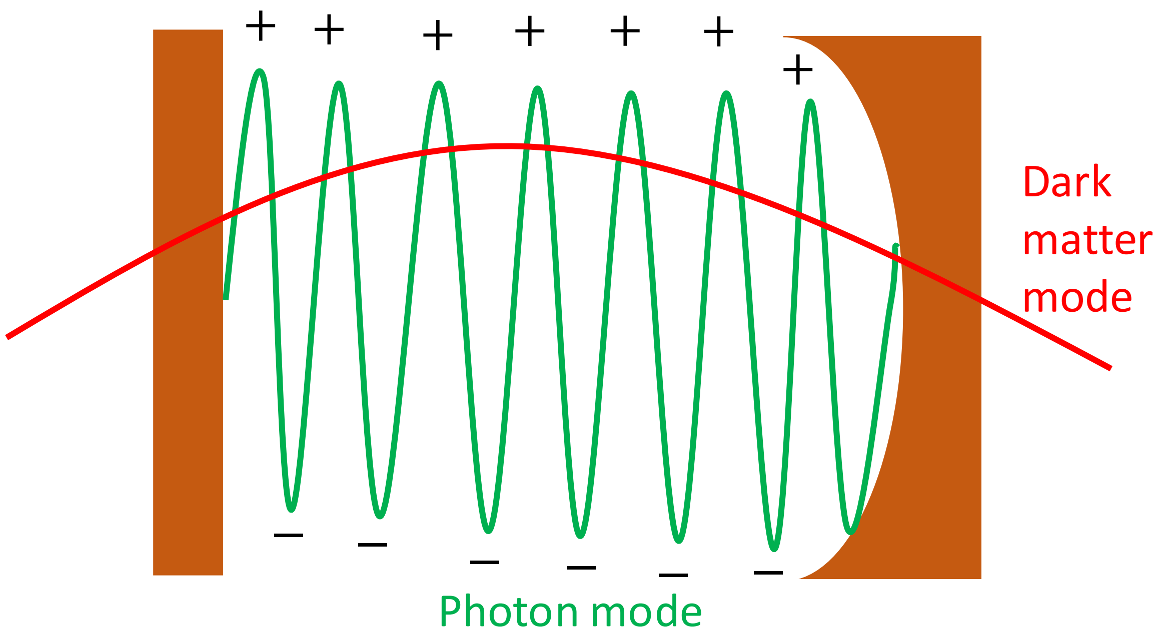
<u>An RF cavity (ADMX-type) becomes $V \sim f^{-3}$</u>



Signal: $\propto VQ$

The signal is lost by higher frequency

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



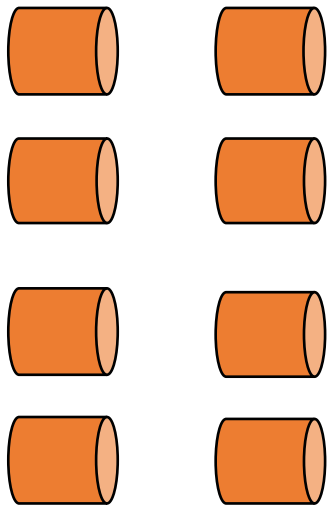
The dark matter is cold → De Broglie wavelength is long

Spatial integral is cancelled!

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

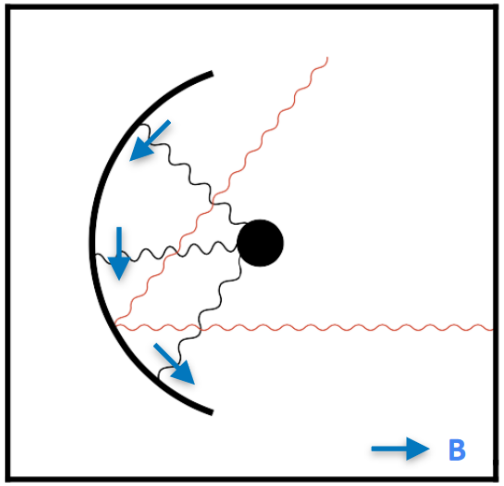
Four ideas to address heavier axion dark matter

Multiple small cavities



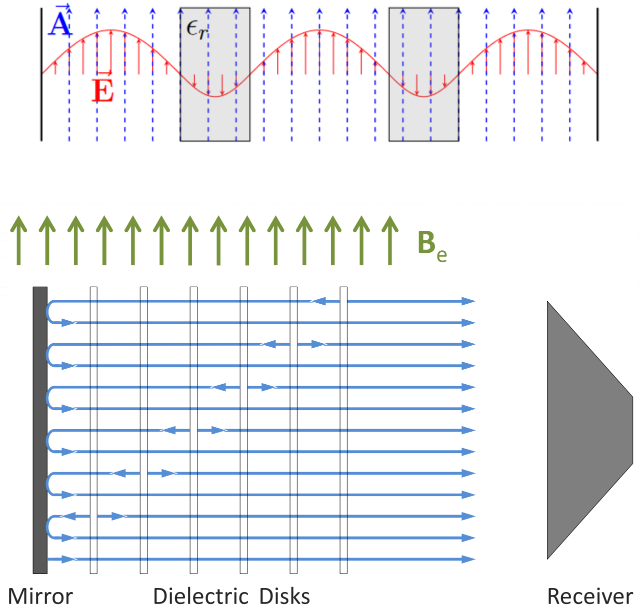
ADMX-EFR @ FNAL
CAST-CAPP @ CERN

Dish antenna



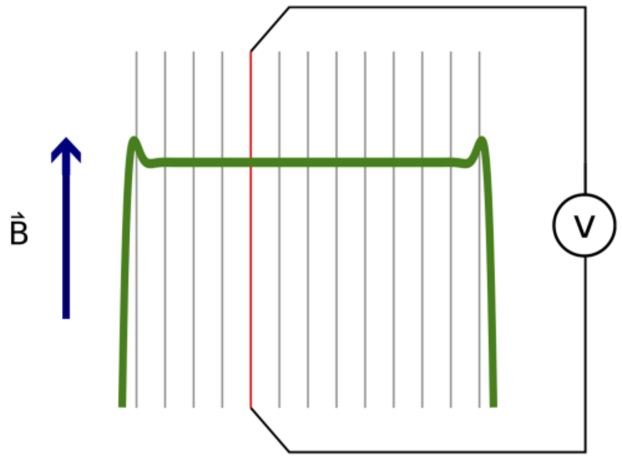
BRASS @ DESY
BREAD @ UChicago
DAWA@CEA
FUNK, DOSUE (DP)

Dielectric disks



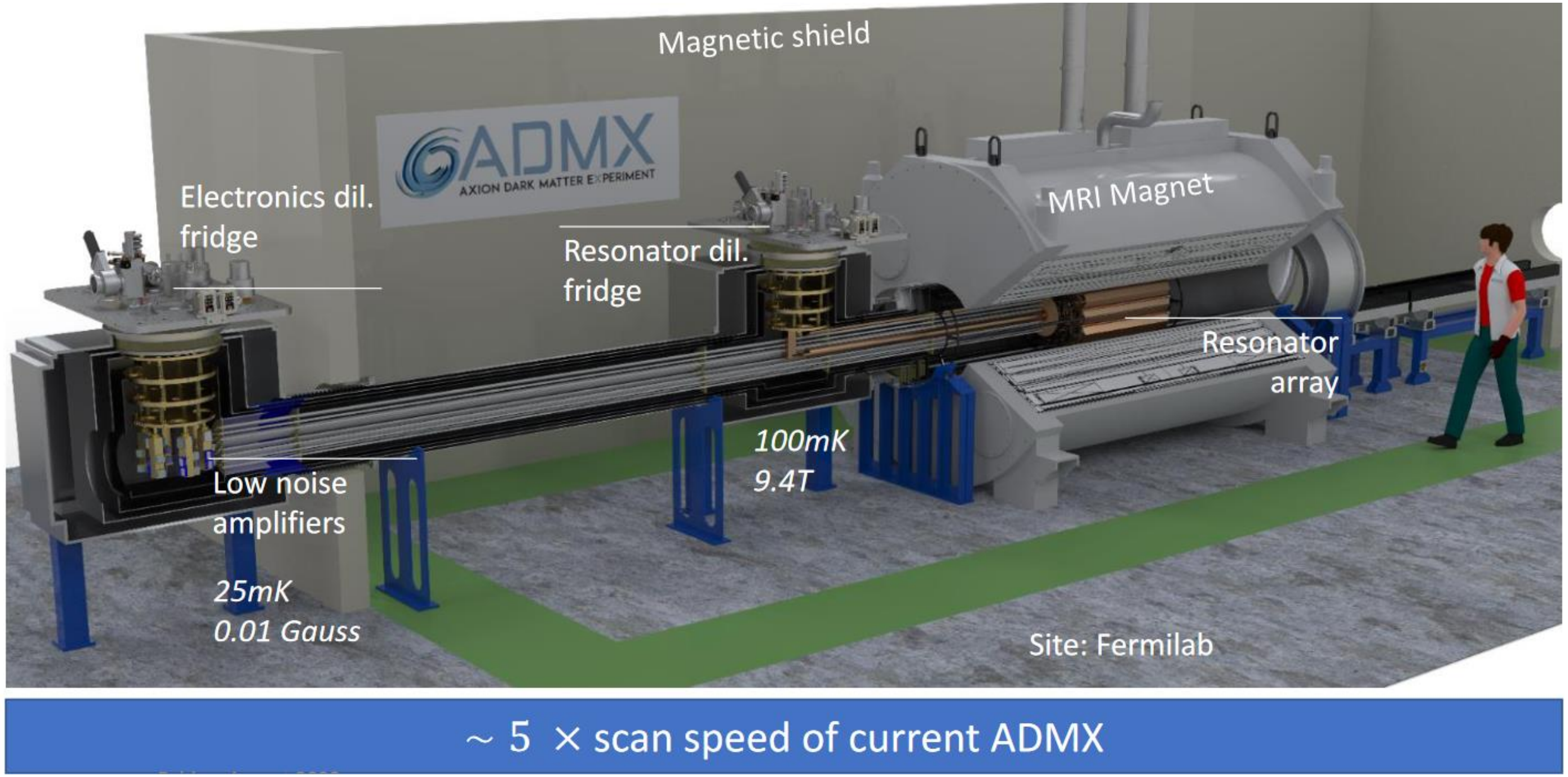
ORGAN @ Australia
ADMX-Orpheus @ US
MADMAX @ DESY

Wire metamaterial



ALPHA @ SU+Ylae+UCB
New projects rising

ADMX (Washington University → Fermilab)



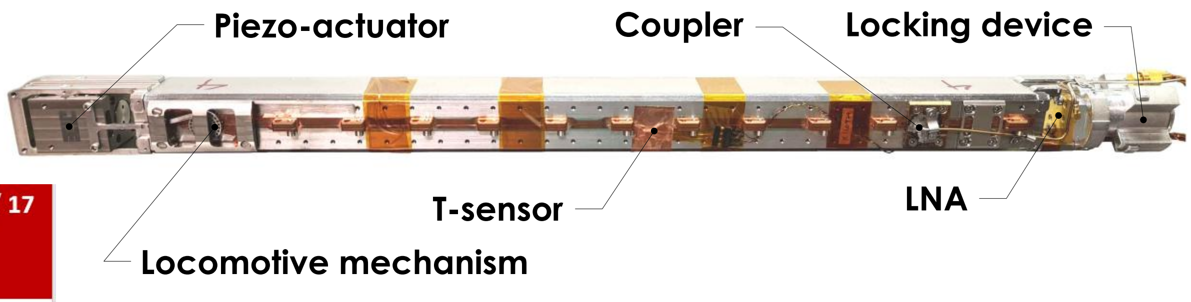
ADMX-EFR

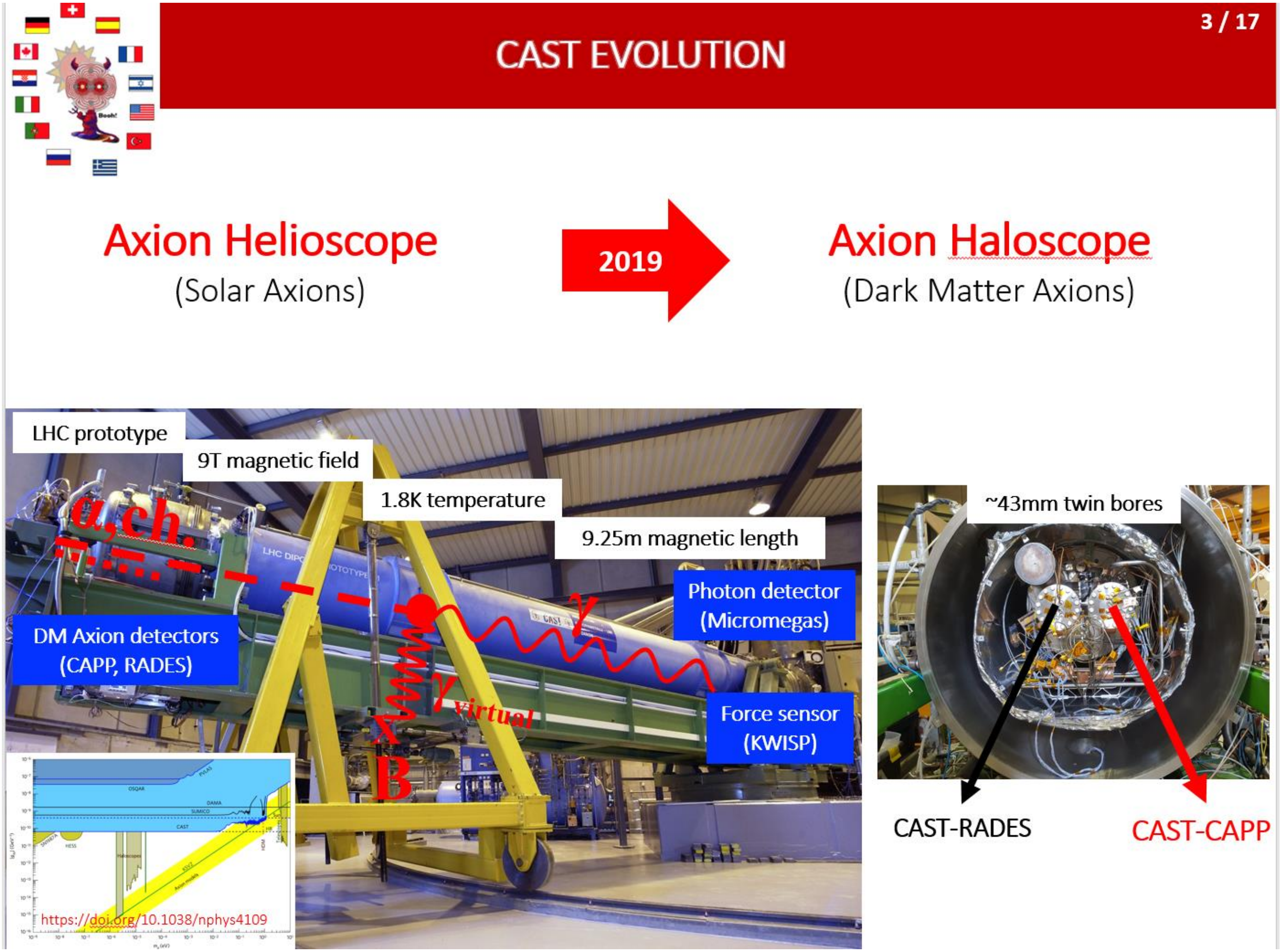
Multiple cavities to address heavier axions

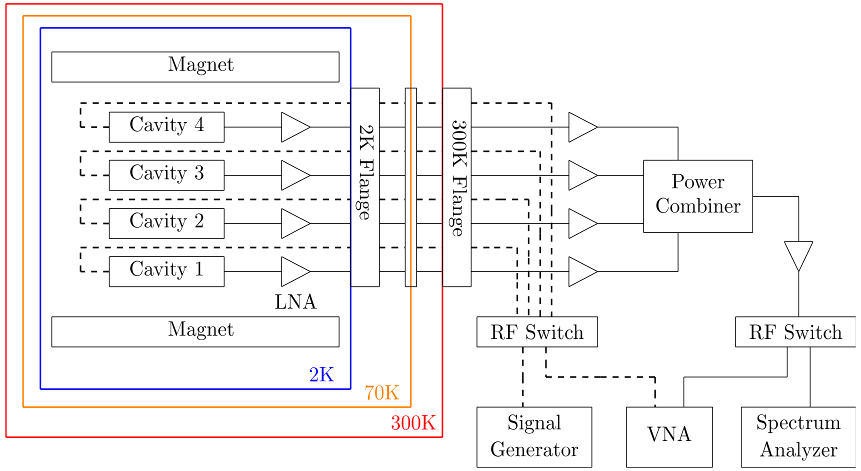
Challenge: phase lock of all the cavities (S. Knirck)

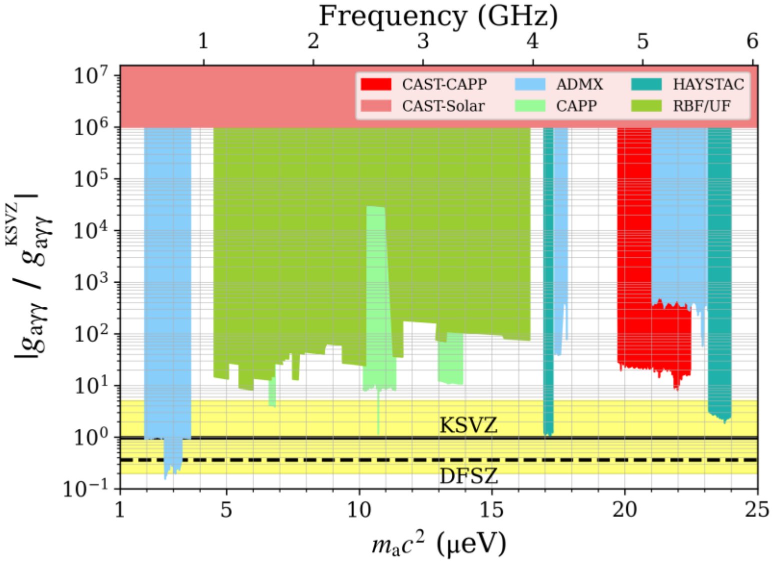
Courtesy: Gray Rybka, “Current Status and Future Plans of ADMX”

CAST-CAPP @ CERN





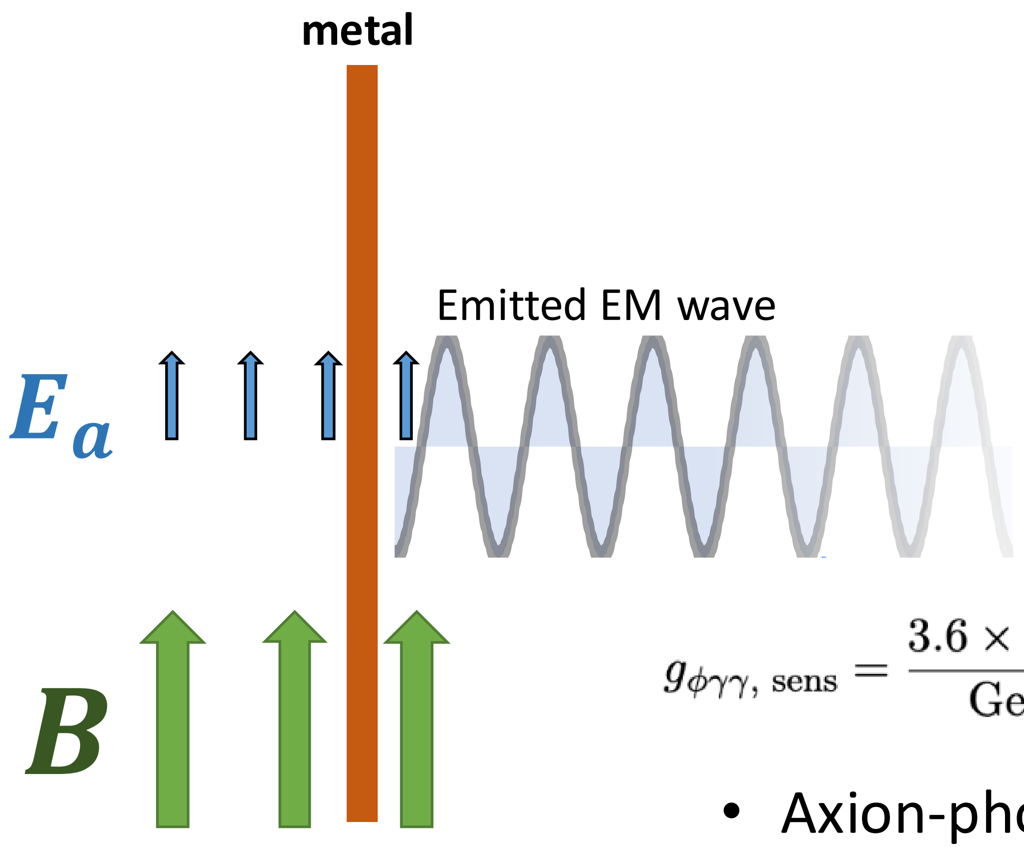


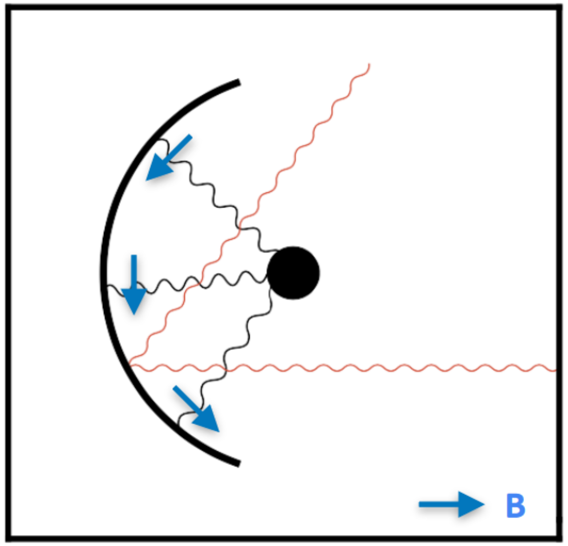


Courtesy: Marios Maroudas, "LATEST RESULTS ON DARK MATTER AXIONS WITH CAST-CAPP"

→ Multiple cavity option with a recycled magnet

Dish antenna: mismatch between metal and vacuum





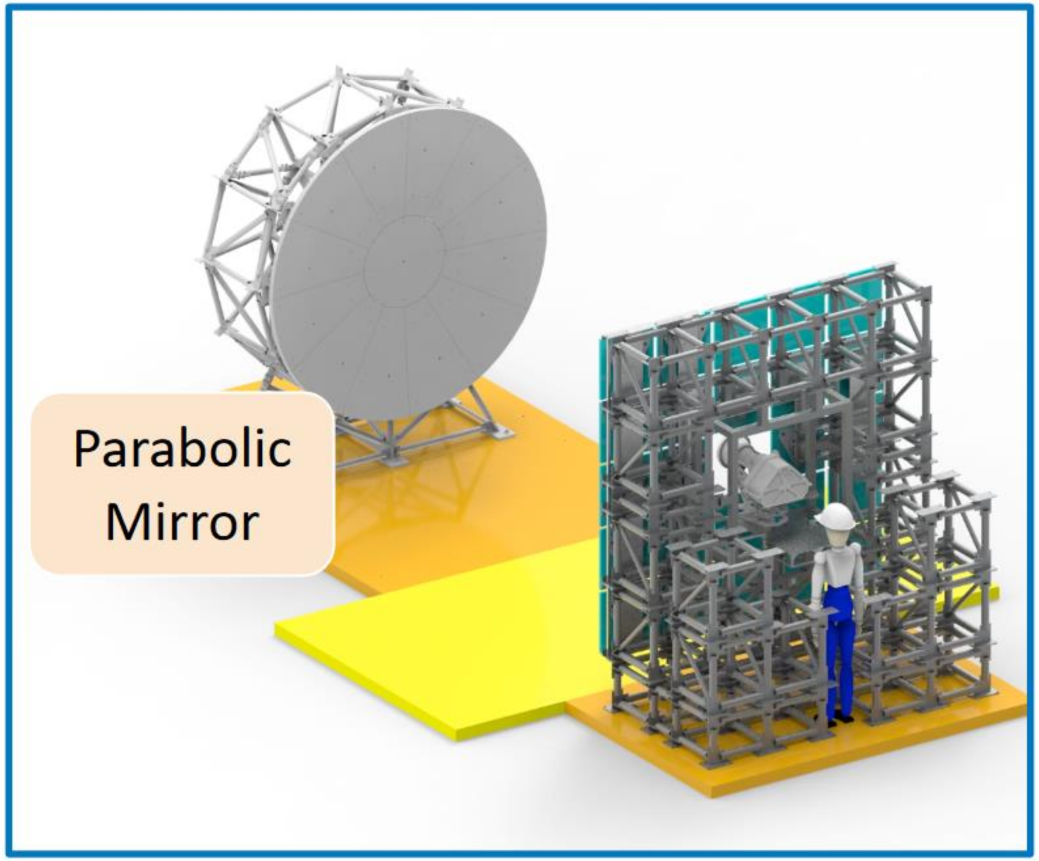
$$g_{\phi\gamma\gamma,\,\mathrm{sens}} = \frac{3.6\times10^{-8}}{\mathrm{GeV}}\left(\frac{5\,\mathrm{T}}{\sqrt{\langle|\mathbf{B}_{||}|^2\rangle}}\right)\left(\frac{P_{\mathrm{det}}}{10^{-23}\,\mathrm{W}}\right)^{\frac{1}{2}}\left(\frac{m_\phi}{\mathrm{eV}}\right)\left(\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_{\mathrm{DM,halo}}}\right)^{\frac{1}{2}}\left(\frac{1\,\mat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

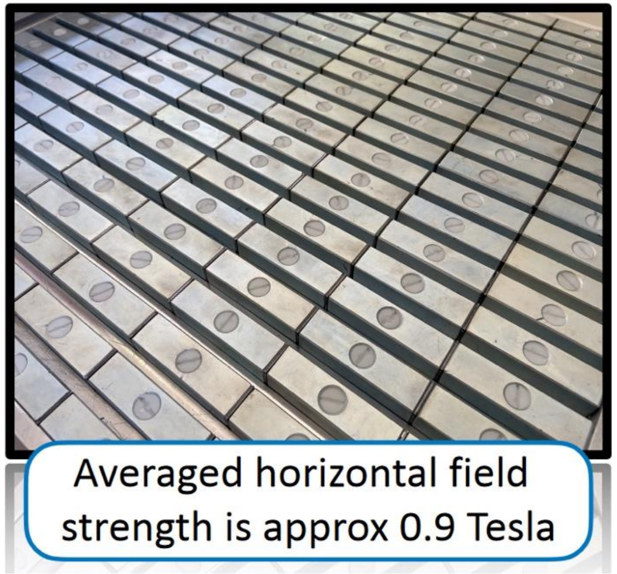
- Axion-photon conversion at the metal-vacuum interface
- Signal enhancement by **larger area**
- Challenge: parallel B-field on the large area of a metal surface

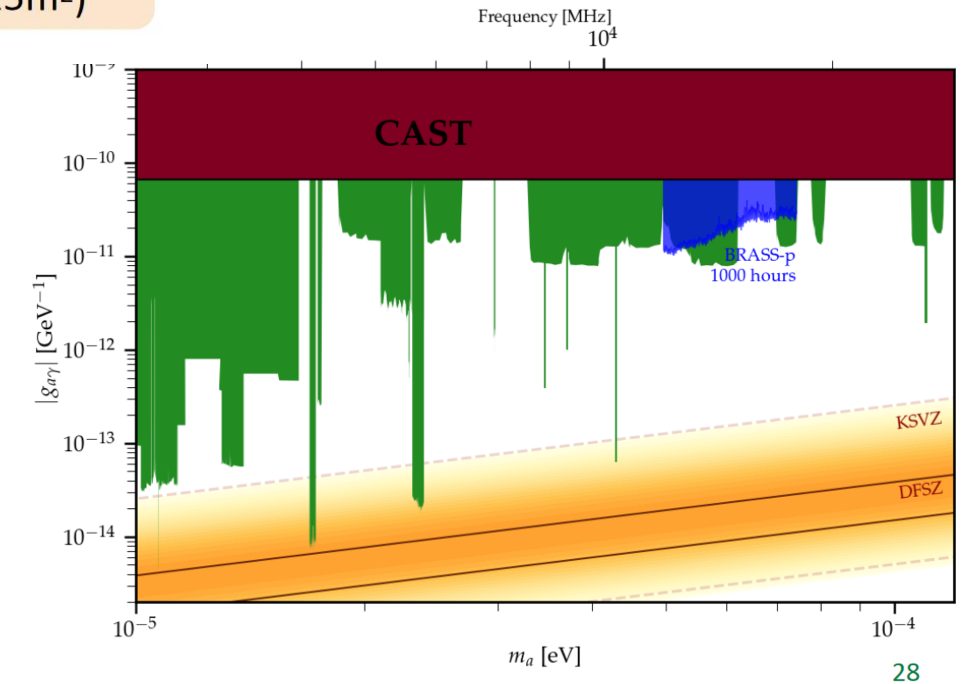
Horns et al, arXiv:1212.2970, JCAP04(2013)016

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)





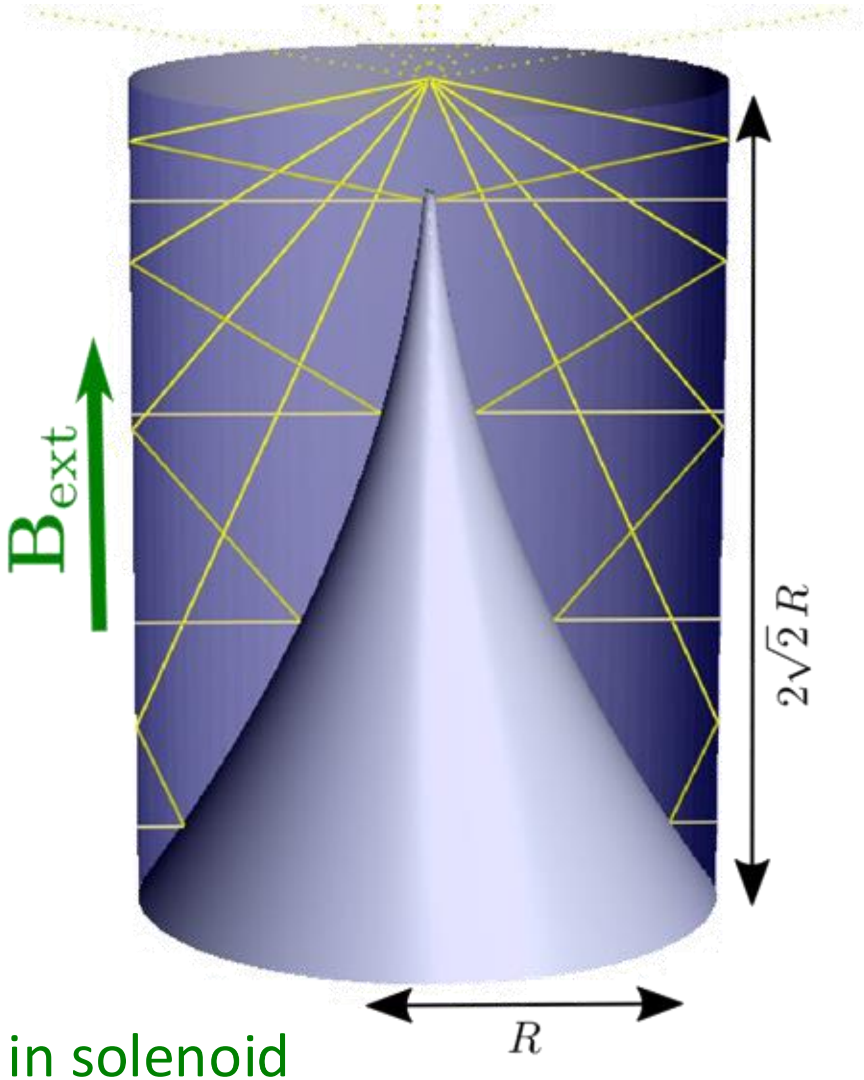


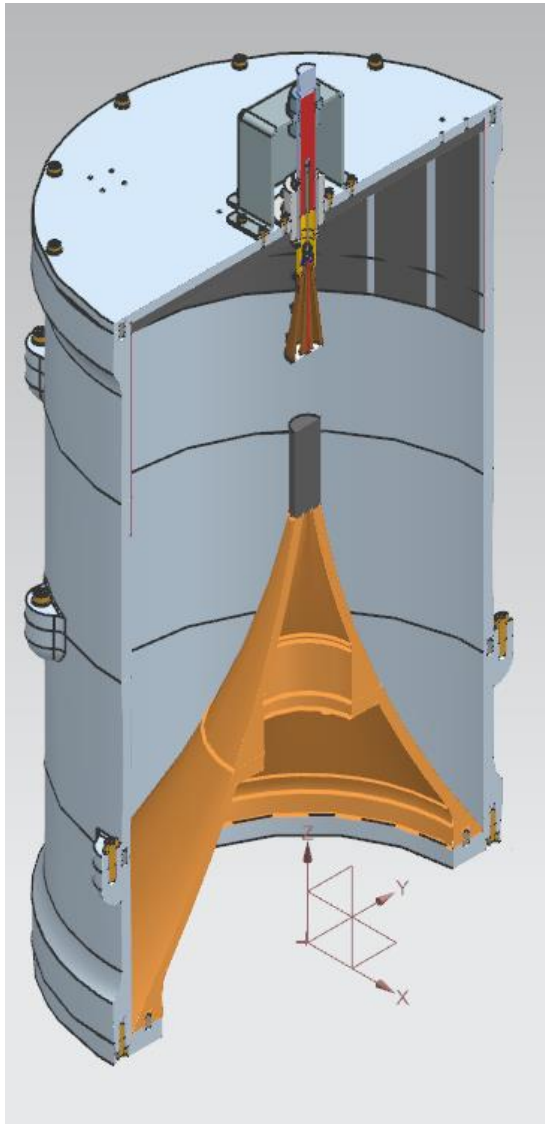
Array of permanent magnets to make effective parallel B-field on the conversion panel

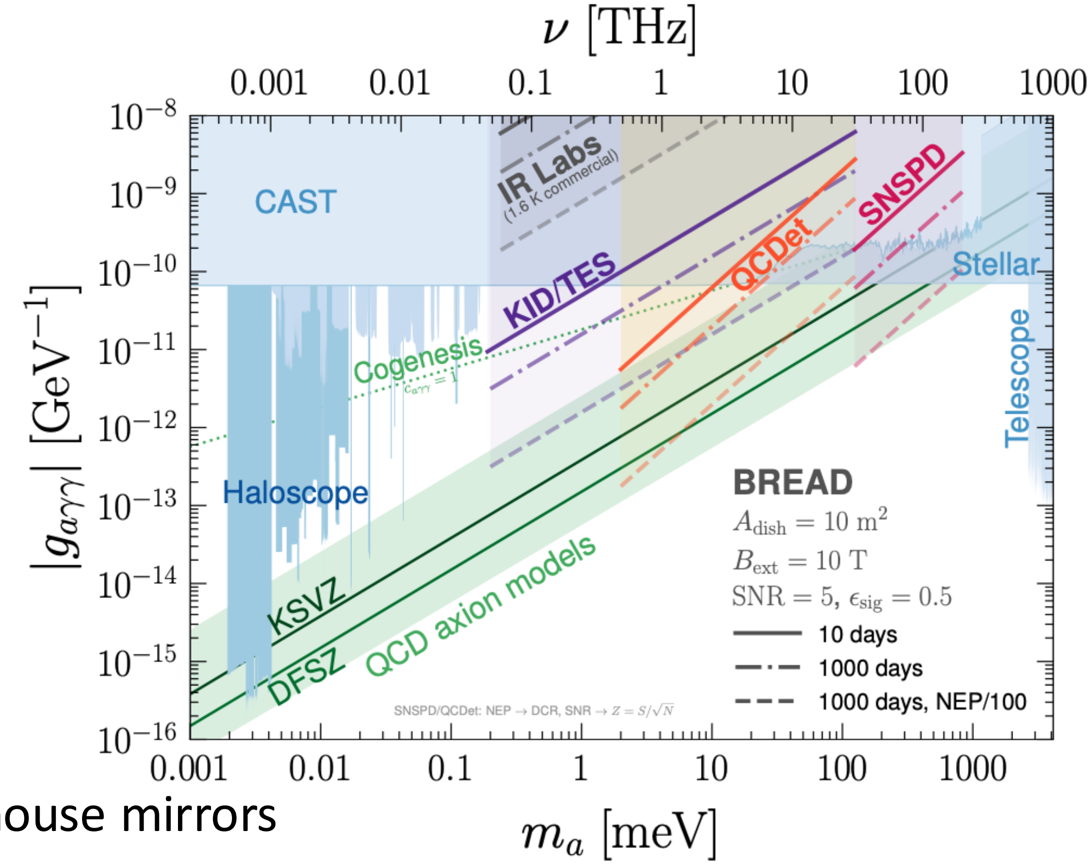
Courtesy: Le Hoang Nguyen, “Development, Calibration and Current Status of the BRASS-p Experiment”

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

Dielectric disks concept

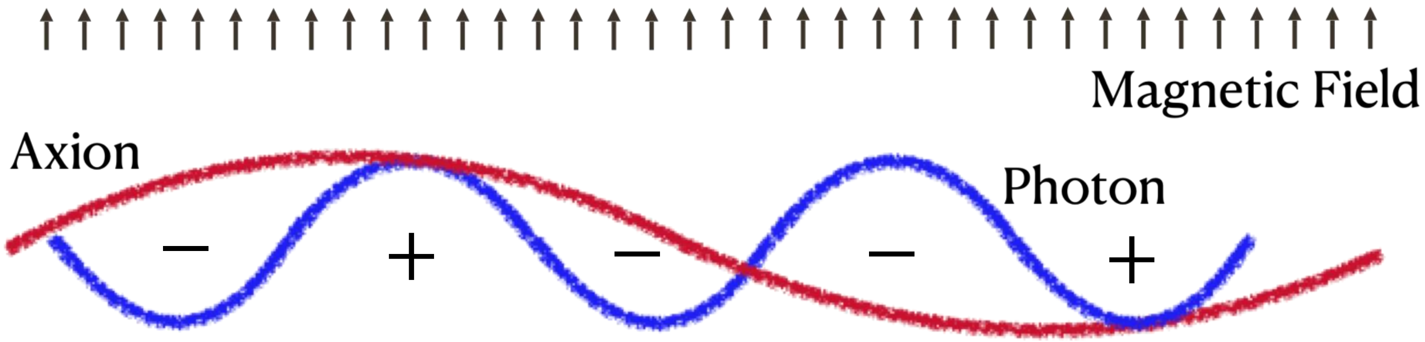
$m_a > 40\ \mu\text{eV}\ (10\ \text{GHz})$ is motivated (post-inflationary scenario, kinetic misalignment, etc) **but…**

Mismatch in wavelength! $\rightarrow \lambda_\gamma = 1.5\ \text{cm} \ll \lambda_B = 22\ \text{m}$

$$P_S \propto \left(\frac{V}{136\text{L}}\right)\left(\frac{B}{6.8\text{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{\text{Q}}{50000}\right)$$

Rev. Sci. Instrum. 92 124502 (2021)

Challenging to keep overlap integral C nonzero while keeping the detector size V large



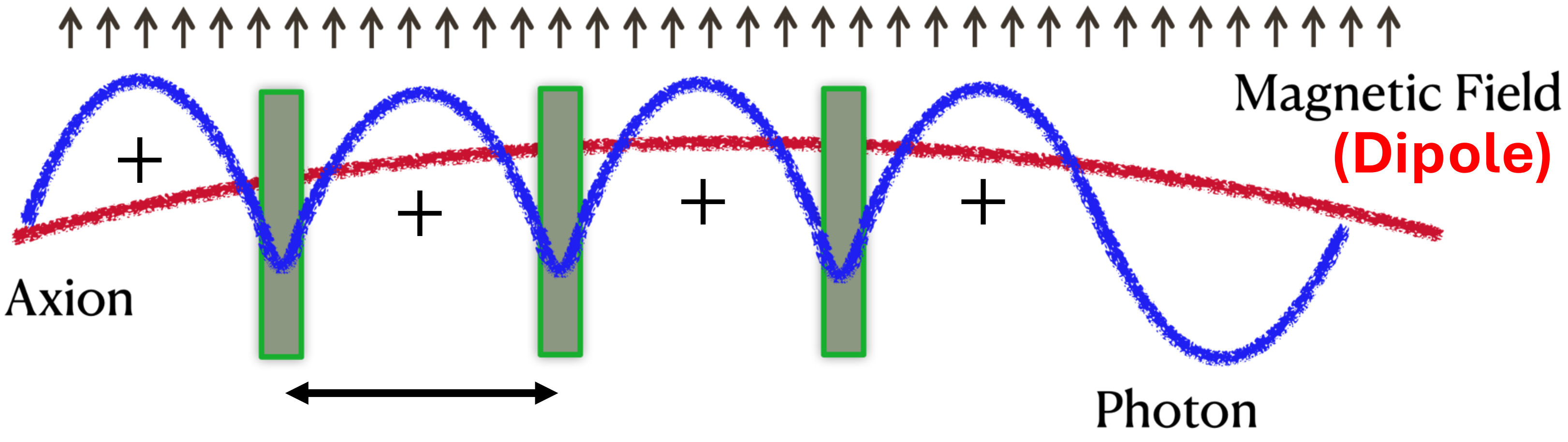
Courtesy of Alex Millar Jr.

→ Insert dielectric disks to cancel the negative overlaps!

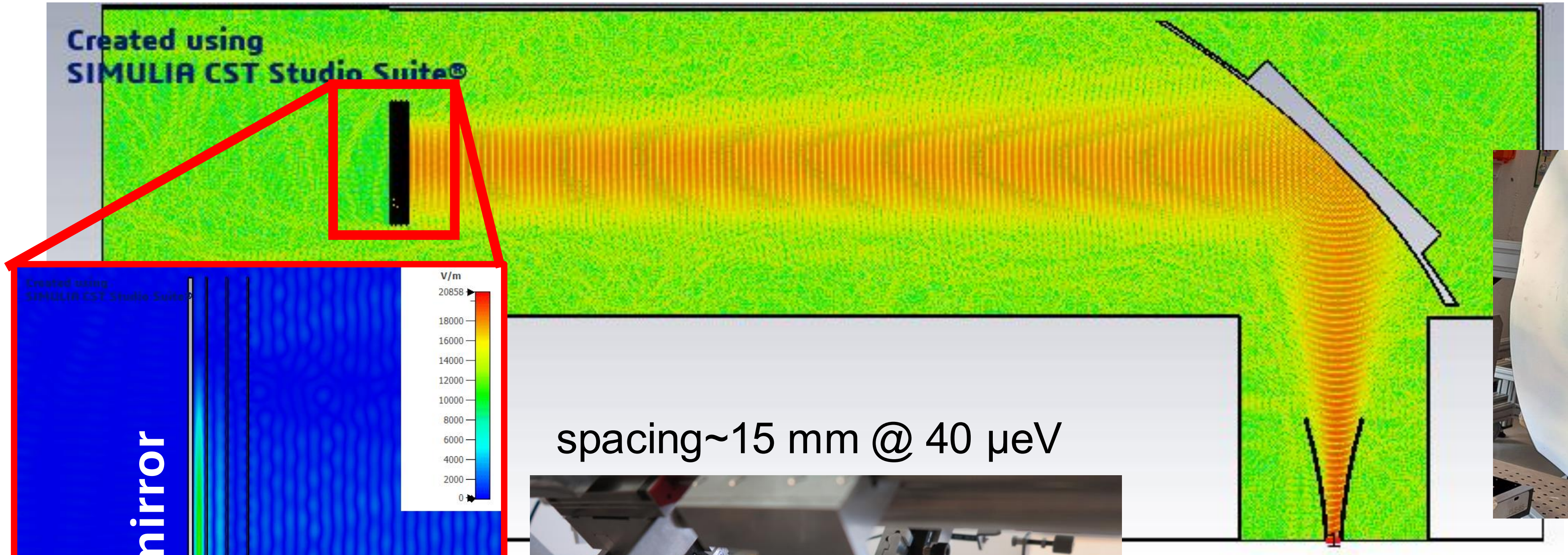
$$P_S \propto \left(\frac{A}{1\ \text{m}^2}\right)\left(\frac{B}{10\ \text{T}}\right)^2\left(\frac{\beta^2}{50000}\right)$$

MADMAX

Caldwell et al., PRL 118, 091801 (2017)



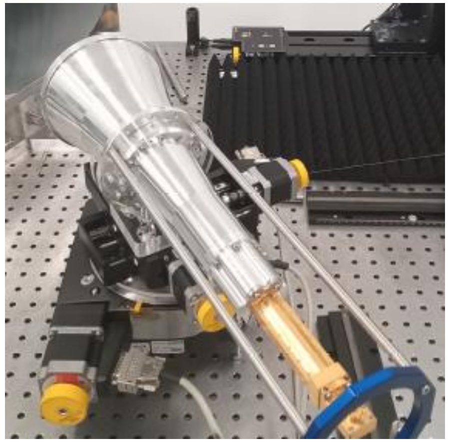
MADMAX overview (my current project)



Ellipsoidal mirror to focus MW

spacing~15 mm @ 40 μeV

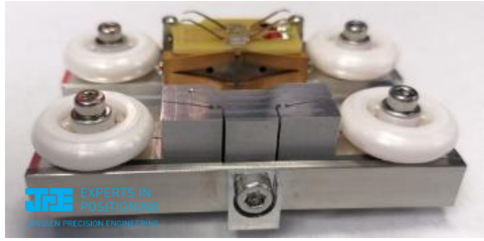
Horn antenna to collect MW

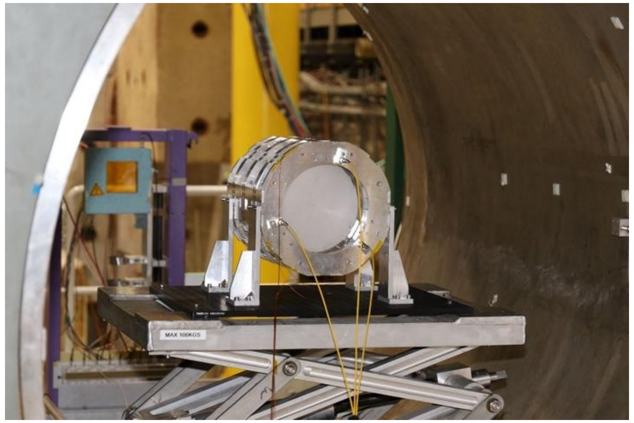


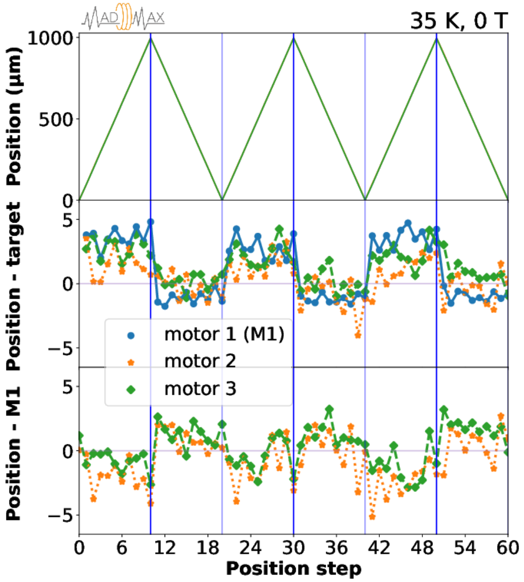
Resonance inside the dielectric disks

Technical milestones

- ✓ Piezo worked at 5 K + 5.3 T
- ✓ Disk motion with piezo-motor was successfully tested at 4K or 1.6 T

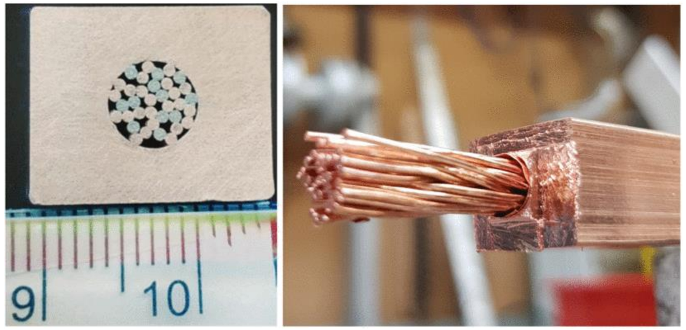




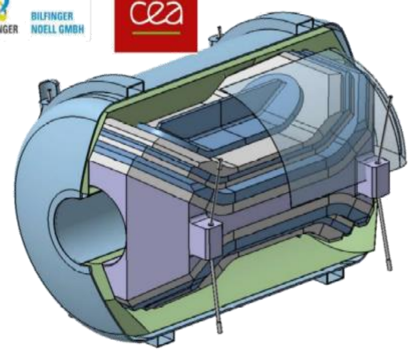


[MADMAX collaboration, 2024 JINST 19 T11002]

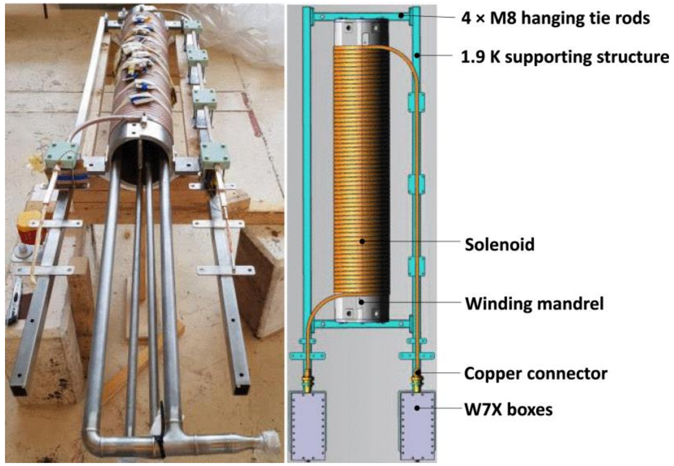
- ✓ Cable-in-Conduit Conductor
- ✓ MACQU Demo Coil
- ✓ Dipole feasible!
- ➢ Fabrication ($$$)



[NbTi with Cu jacket @ 1.8K]



[Lorin et al., IEEE TAS 33 (2023) 1]



Boost factor $\beta^2 \neq$ cavity Q → before large scale experiments…small setups!

✓ Boost factor determination & first physics runs without piezo-tuning & existing dipole

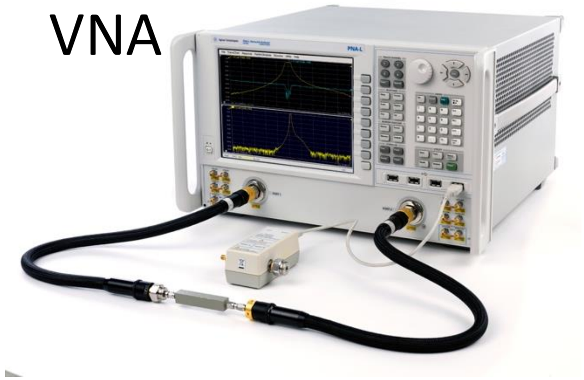
Boost β in dielectric disks ≠ resonance Q in a cavity

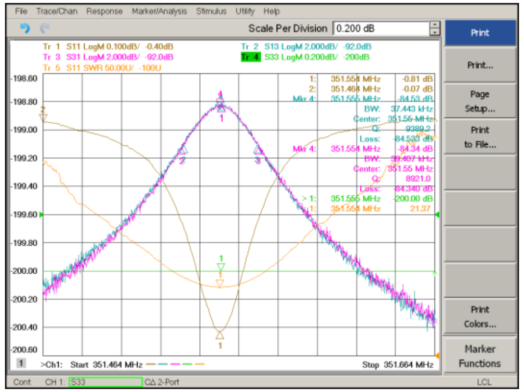
Resonant cavity search including plasma haloscope

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

Part 2

VNA





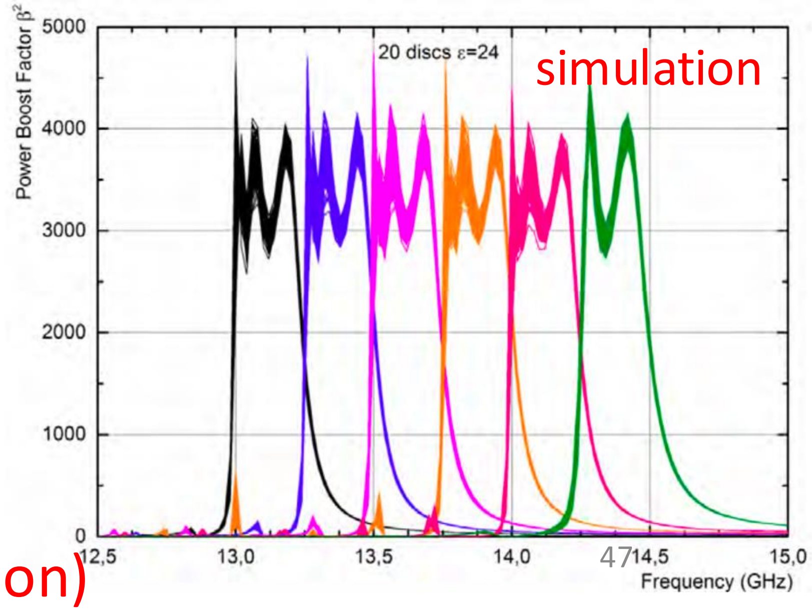
Q: microwave property in a cavity
→ In-situ measurement observable

Dielectric-disk haloscope:

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

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)



β^2 determination in close booster setup

Model-based approach

Modelling the TE_{11} booster with free parameters (ε, thickness, spacing, mismatch, etc)

1) Fit to determine parameters

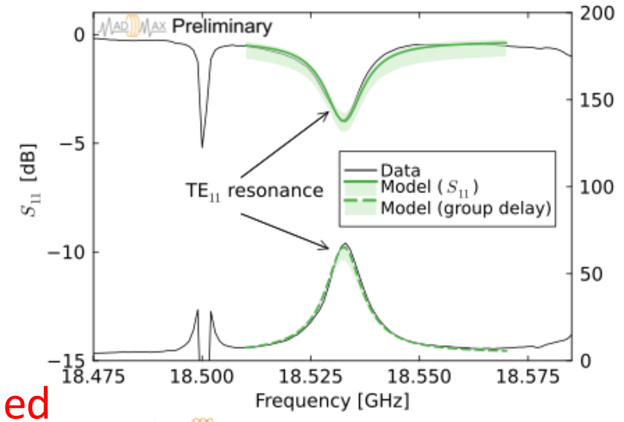
2) Calculation with determined parameters

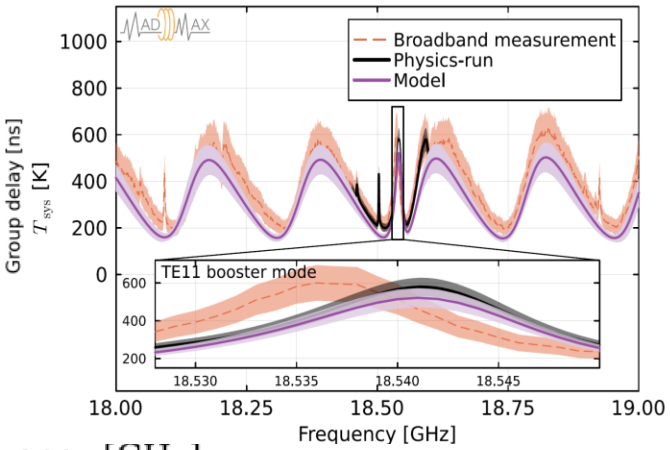
MW measurement data
- Reflection data
- Noise power resonance

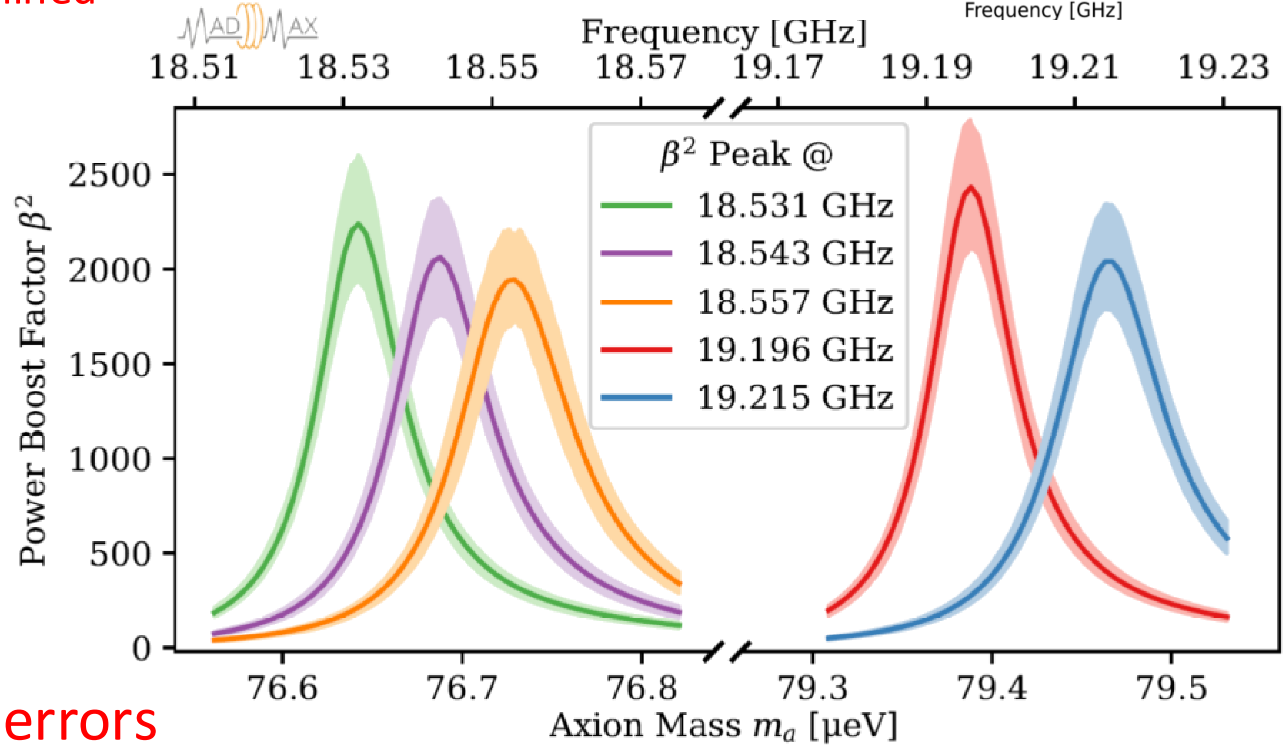
boost factor β^2

- Monte-Carlo approach to propagate the errors in parameters
- Limitation of the modelling (3D effect, etc) well included in the uncertainty
- In-situ monitoring of the booster resonance during physics run via noise power

→ β^2 determined with ~15% errors







$\boldsymbol{\beta^2}$ determination in open booster setup

<u>Lorentz reciprocity approach</u>

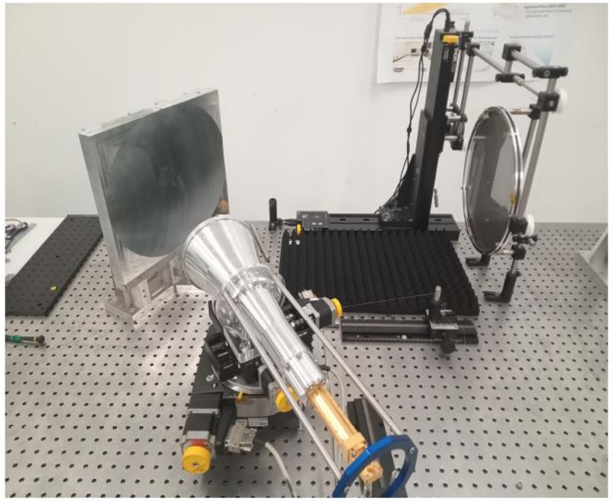
$$P_{sig} = \frac{1}{2}\mathrm{Re}\int_S (\boldsymbol{E}_a \times \boldsymbol{H}_a^*) \cdot dS \propto \left|\int_V (\boldsymbol{E}_R \cdot \boldsymbol{B}_0) dV\right|^2$$

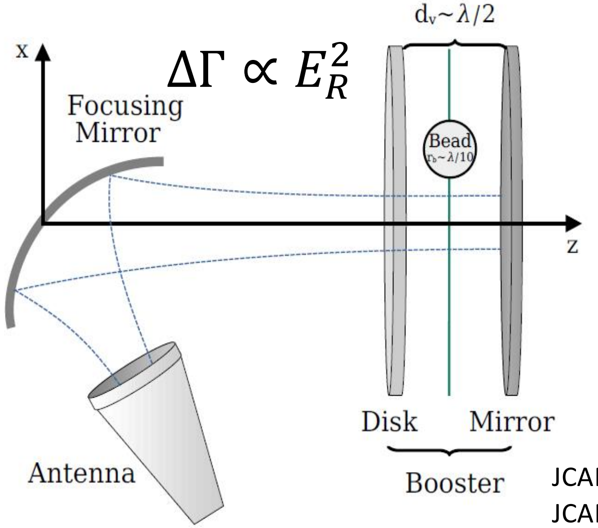
Unknown axion fields ↑ Measurement observable!

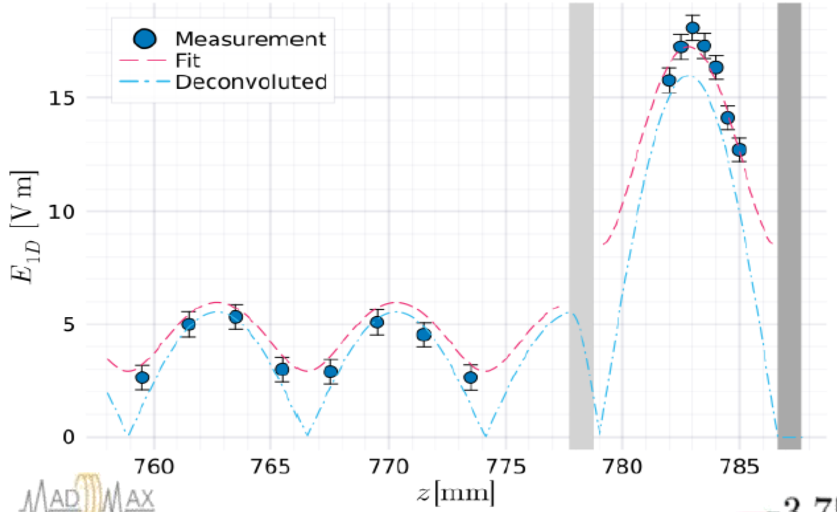
Boost factor can be determined via electric field of MW excited from outside

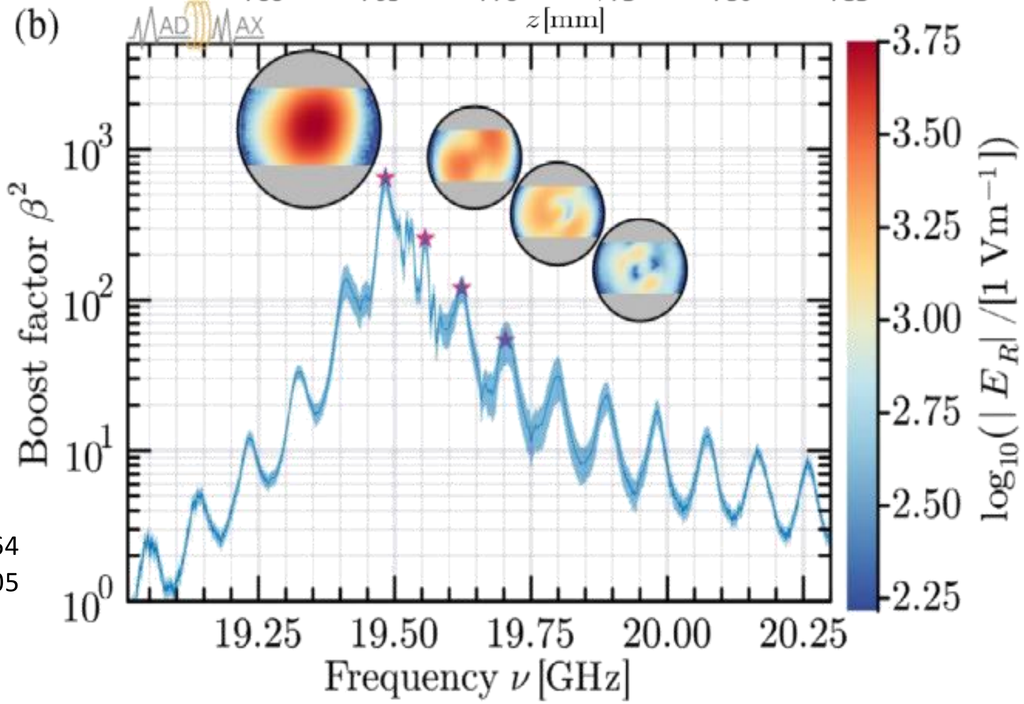
$$\beta^2 = \frac{P_{sig}}{P_0} \propto \left|\int_V E_R dV\right|^2$$

Electric field can be obtained through the beads-pulling method









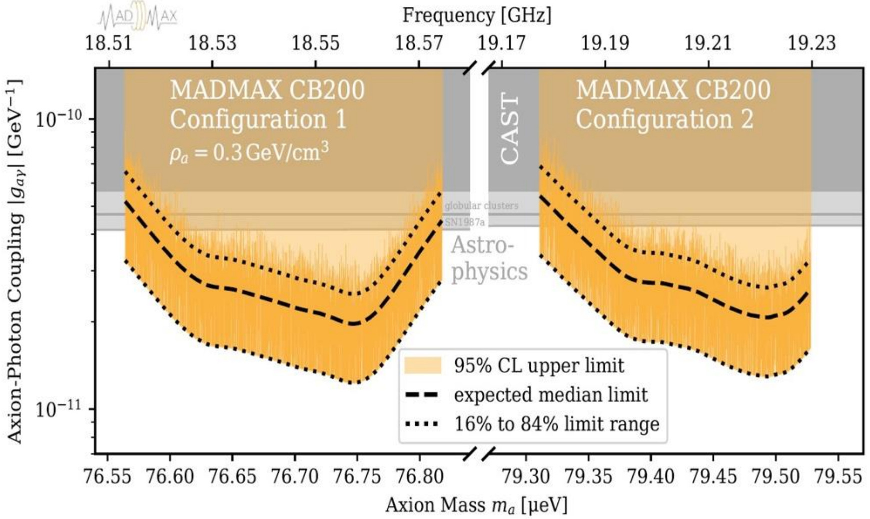
JCAP 04 (2023) 064
JCAP 04 (2024) 005

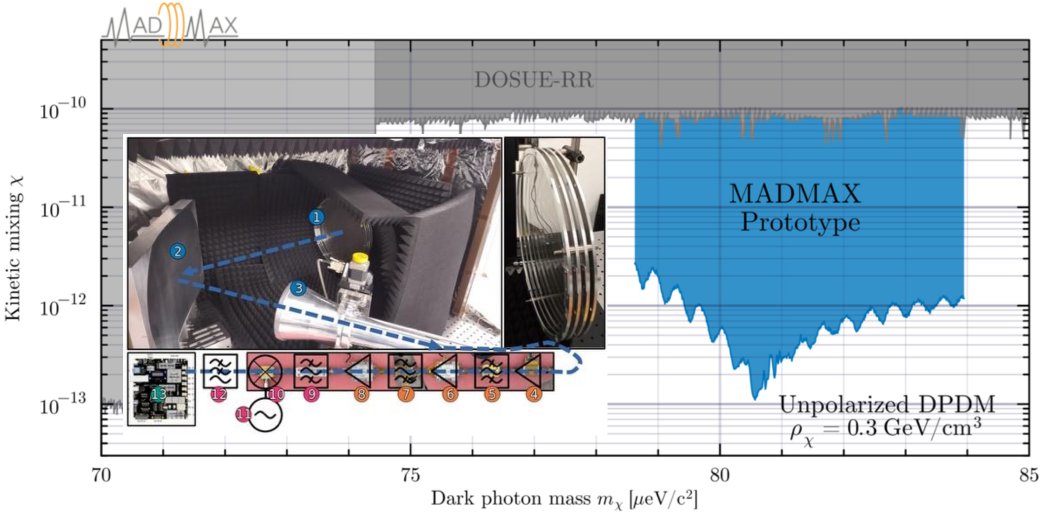
→ β^2 determined with ~15% errors

Current status and prospect of MADMAX

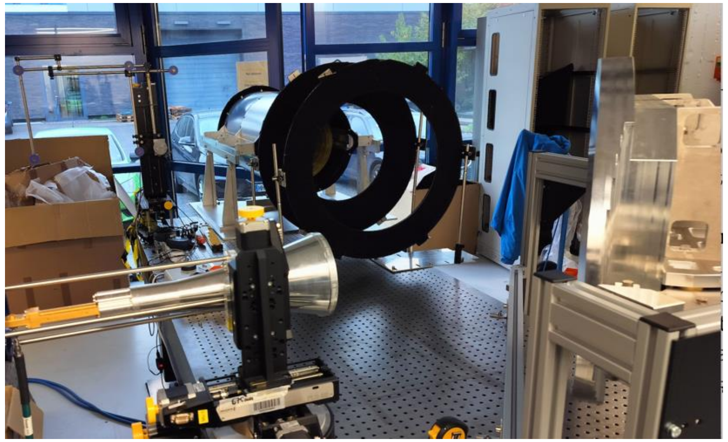
MADMAX collaboration, PRL 135, 041001 (2025)

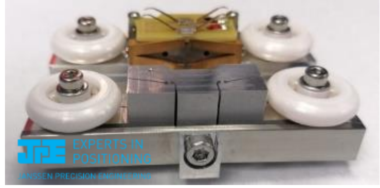
MADMAX collaboration, PRL 134, 15, 151004 (2025)

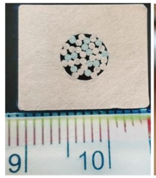


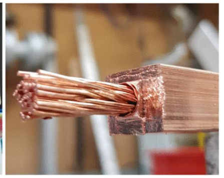


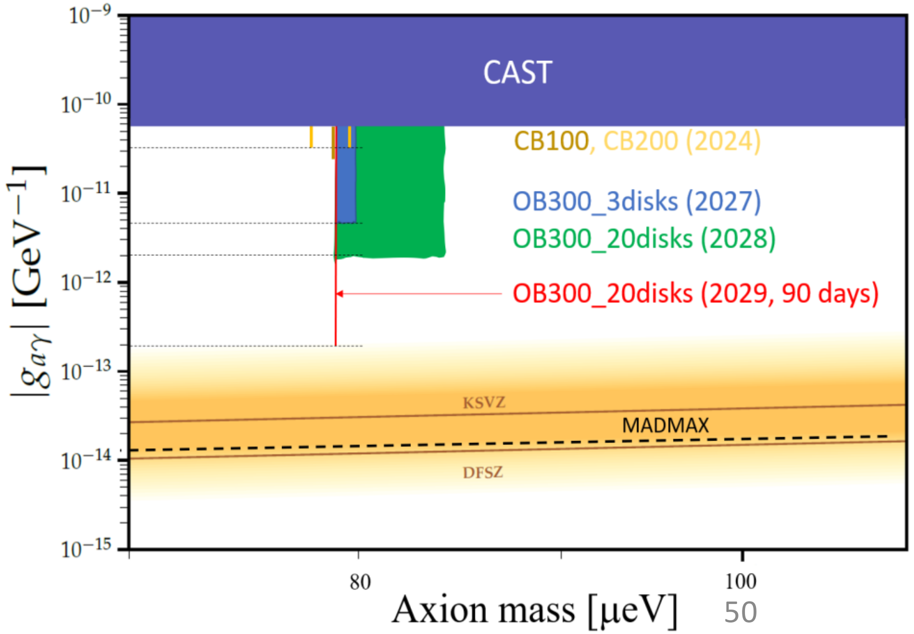
Scaling up





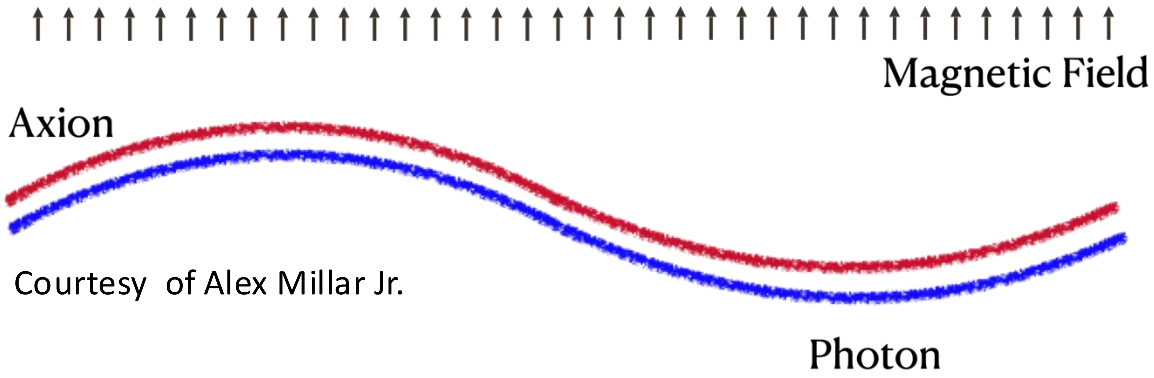




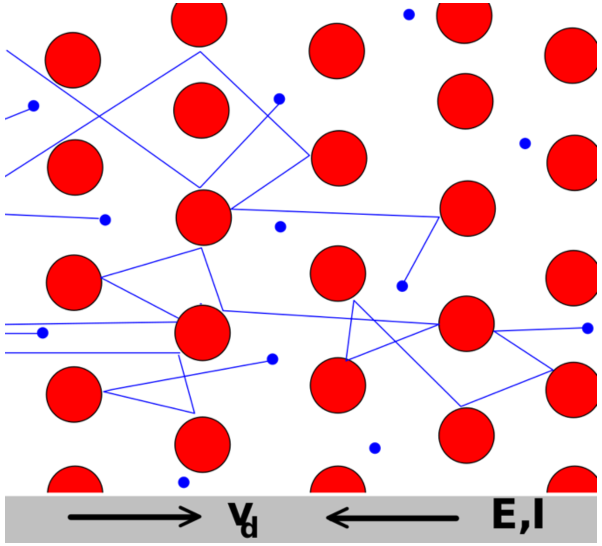


Axion-plasmon mixing in a cavity (my former project)

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



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



Photon gains effective mass in plasma (plasmon)
→ momentum mismatch is solved!

Natural plasma is too hot (10,000 K) → thermal noise, non-tunable plasma density, etc

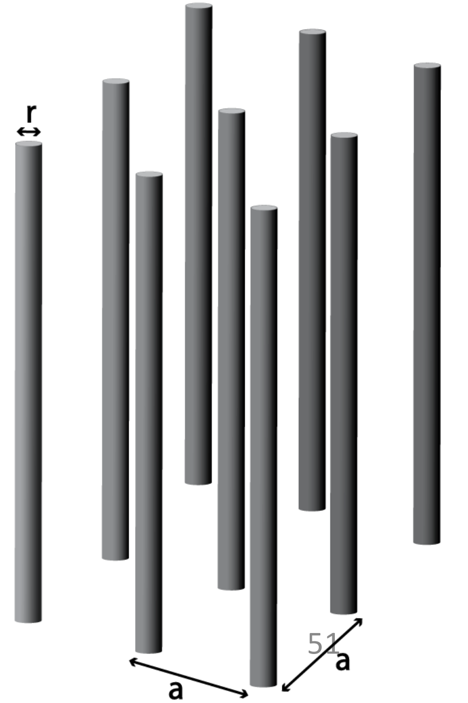
✓ Wire metamaterial plasma provides effective 1D plasma along the wire

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

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

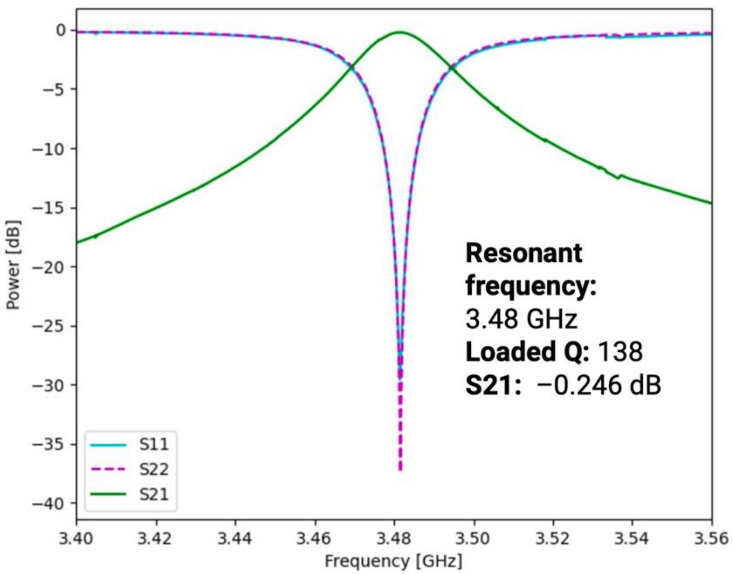
Free from the size of the cavity itself

$$\omega_p^2 = \frac{2\pi}{a^2 \log(a/r)}$$

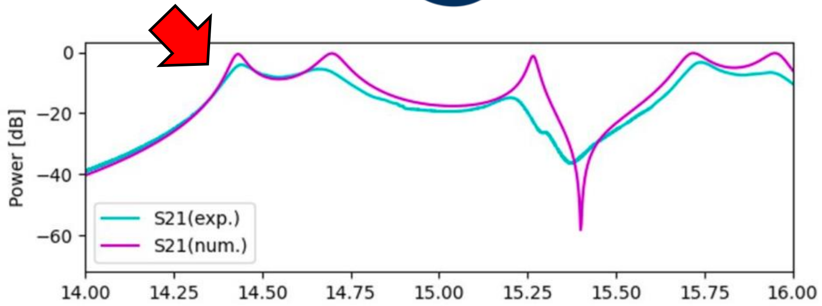


In reality, this is similar to drift chambers

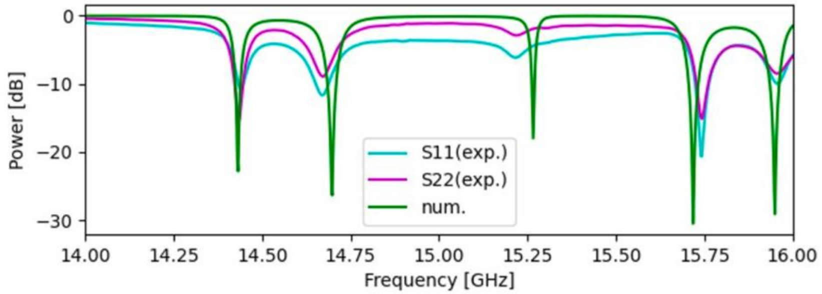
Status and prospect of



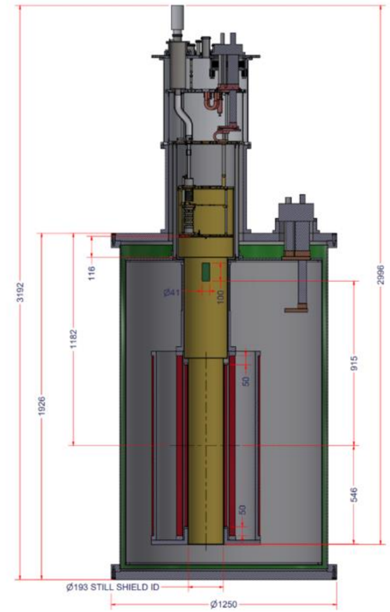
With wires 6x6

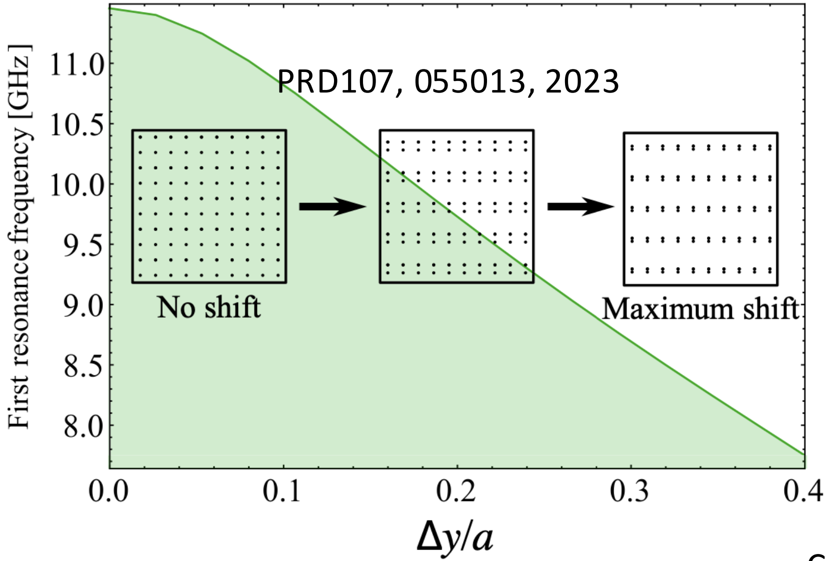


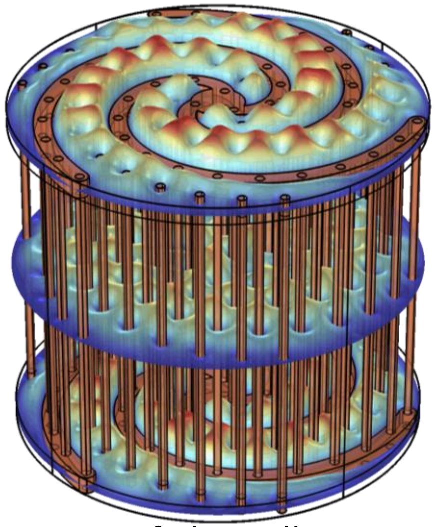
Courtesy of Gagandeep Kaur



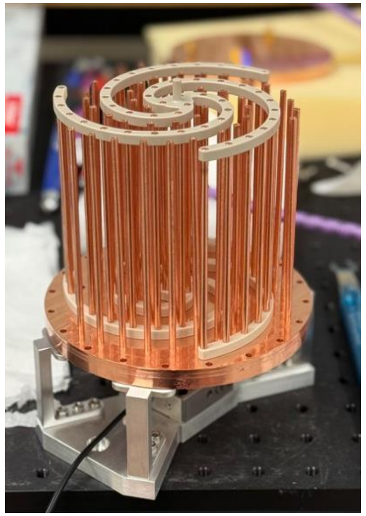
9T ϕ20 cm

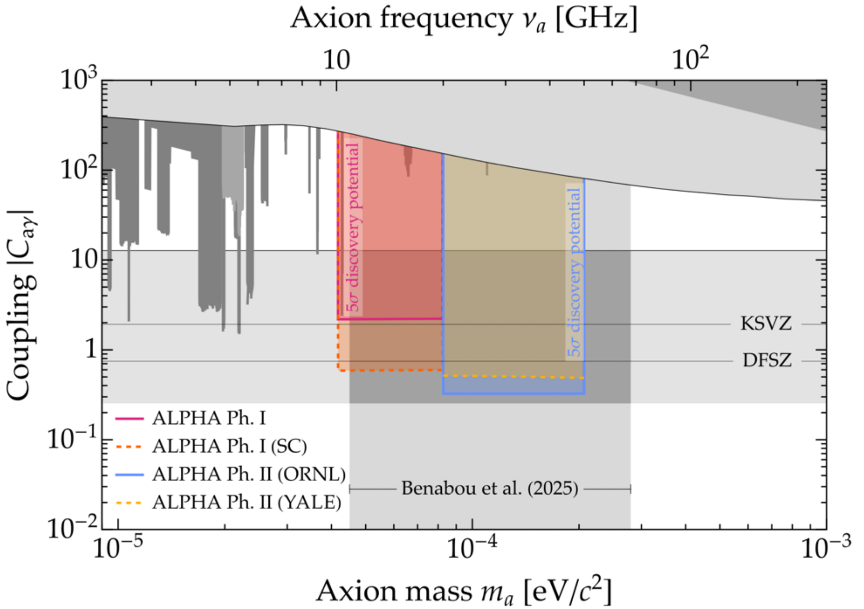






Courtesy of Alex Millar Jr.

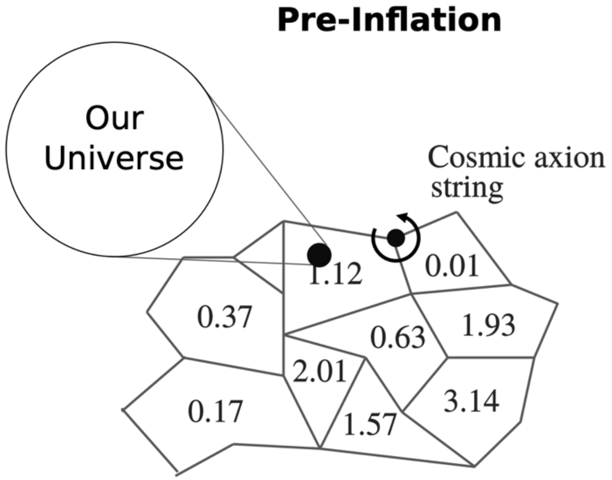




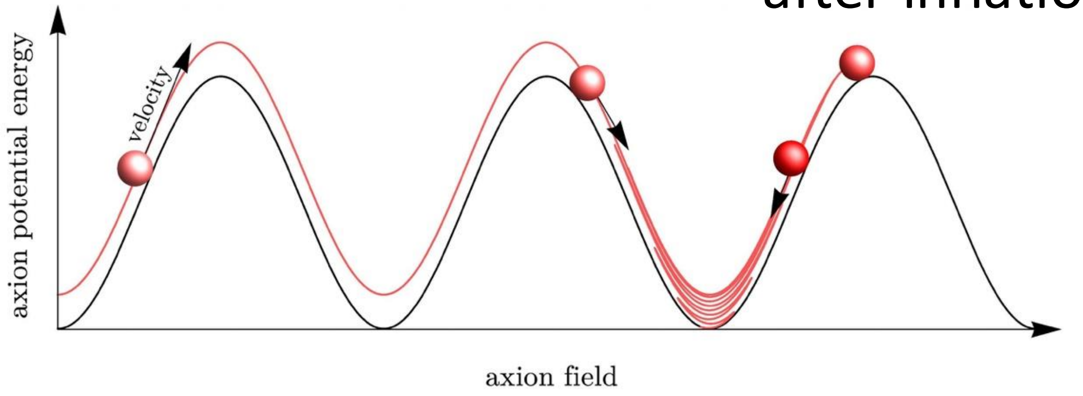
Part 1: overview on axion searches

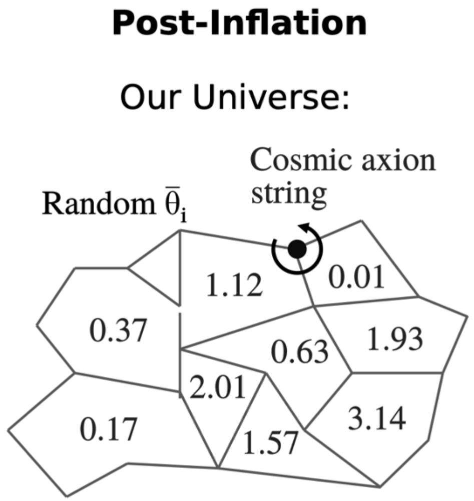
- Axion vs WIMPs
  - WIMP: particle; axions: waves
  - Particle detection
  - Classical wave detection
- Various haloscope experiments
  - ADMX families
  - Lower masses
  - Higher masses
- Non-DM axions
  - Light-Shining-Through-a-wall
  - Solar axion helioscopes
- Conclusion of part 1

DM axion is strongly model dependent

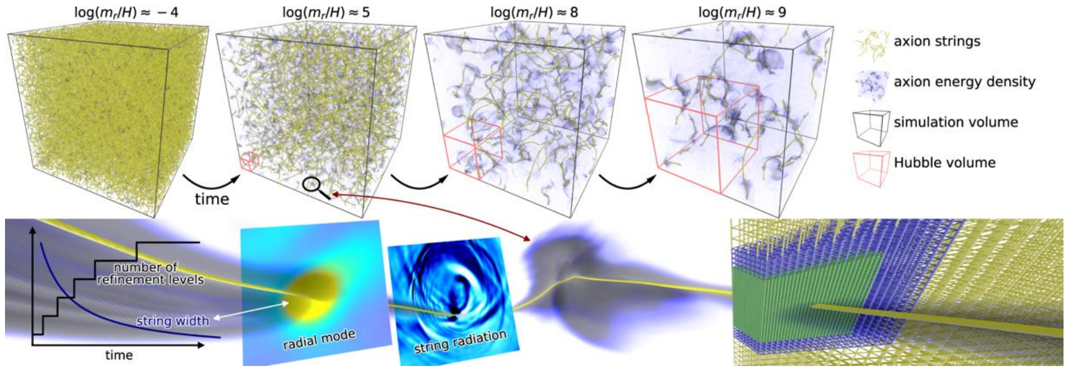


- Isocurvature problem
- Naturalness problem in DM abundance
- PQ restoration after inflation





- Domain wall problem
- Over-abundance



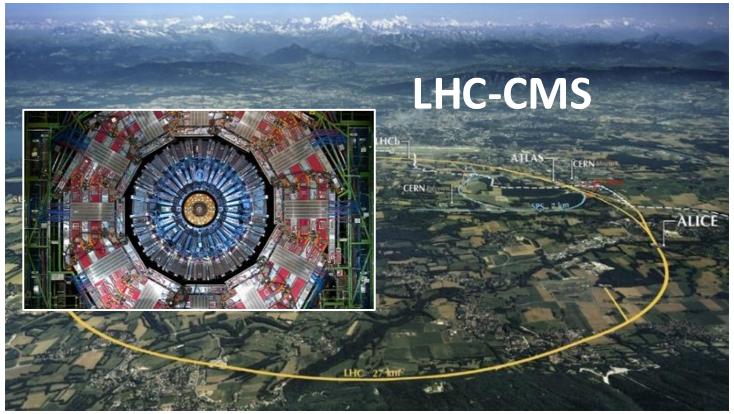
- Even the local DM density $\rho_{DM} = 0.3 - 0.45\ \mathrm{GeV/cm^3}$ is uncertain
- Axion is anyway motivated as a solution of strong CP problem

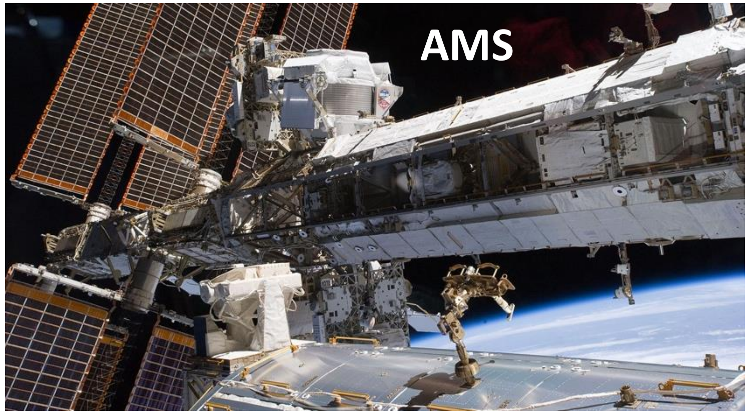
  → Non-DM axion search is also motivated

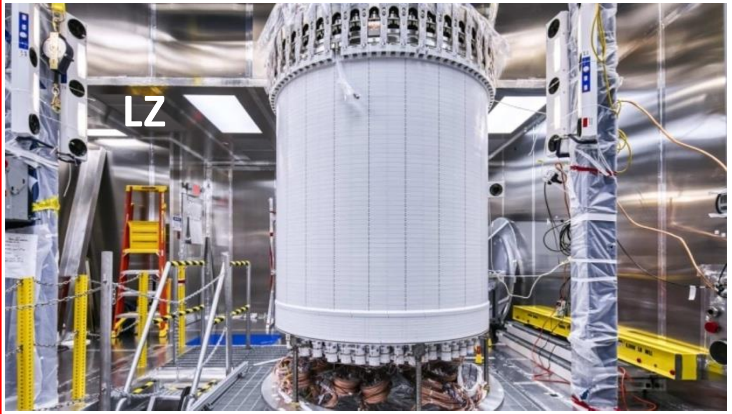
Three ways to study dark matter candidates

	Production in lab	Signal from astrophysics	DM from galaxy halo

WIMP
SUSY

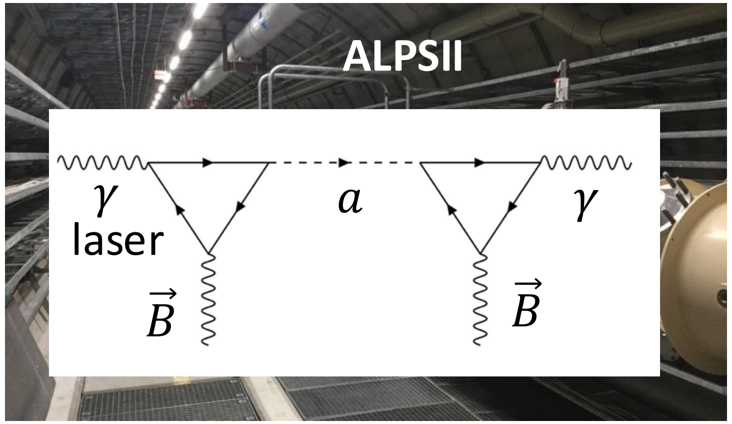


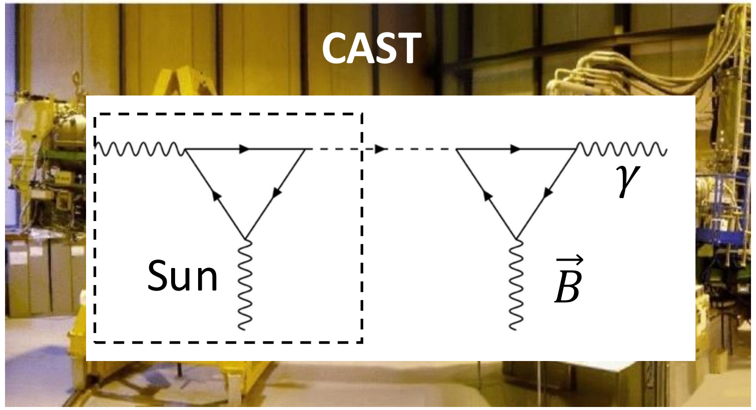


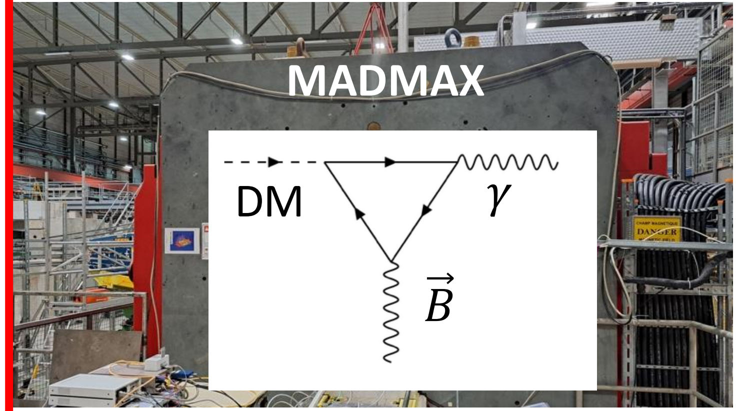


→ Common techniques: **particle** detection, reconstruction, PID, etc

WISP
axions







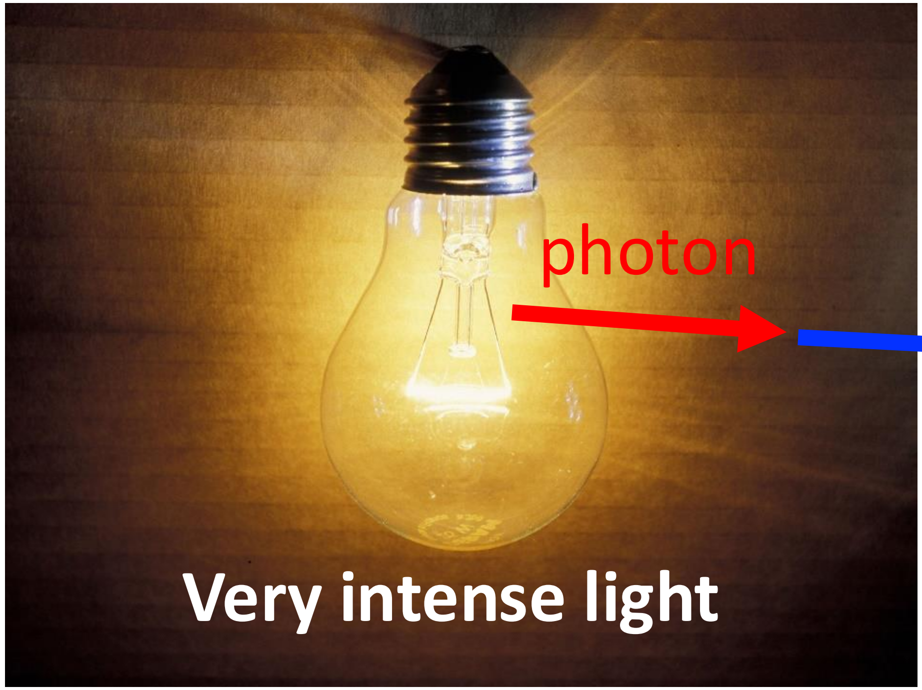
full knowledge in source

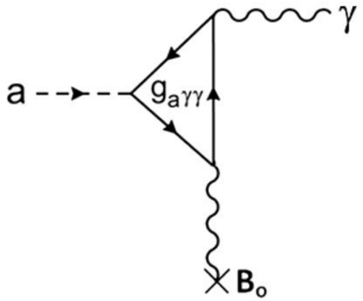
uncertainty in astrophysical models

Uncertainty in cosmological models

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

Experiment purely on the earth to be free from DM models

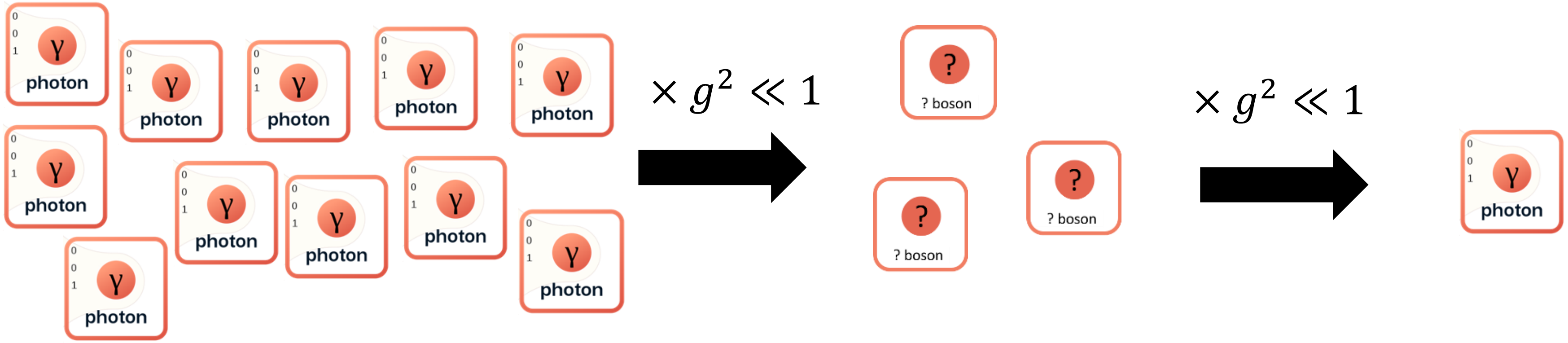




axion

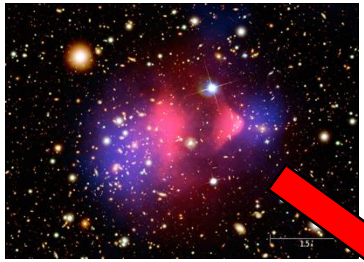
https://www.independent.co.uk/news/science/old-fashioned-light-bulbs-could-be-set-comeback-after-light-recycling-breakthrough-a6806446.html

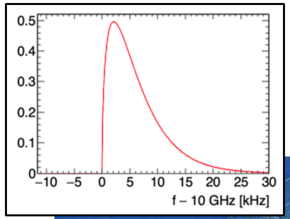
https://tomroyreleased.files.wordpress.com/2016/12/wp-1481922375633.jpeg

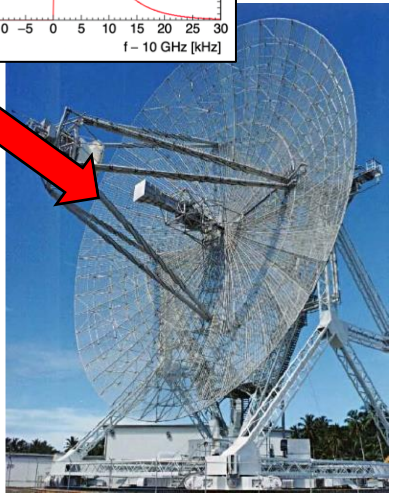


Major difference from DM: $\Delta\nu_a$ is under control

Dark matter: Passive detection

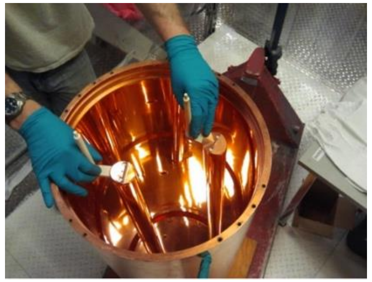






The galaxy determines $\Delta\nu_a \sim 10^{-6}\nu$

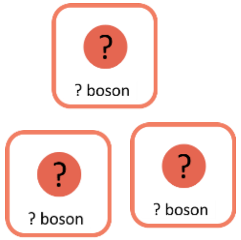
ADMX is this type



$$S/N = \frac{P_{sig}}{k_B T}\sqrt{\frac{\Delta t}{\Delta\nu_a}}$$

No way to control $\Delta\nu_a$ itself

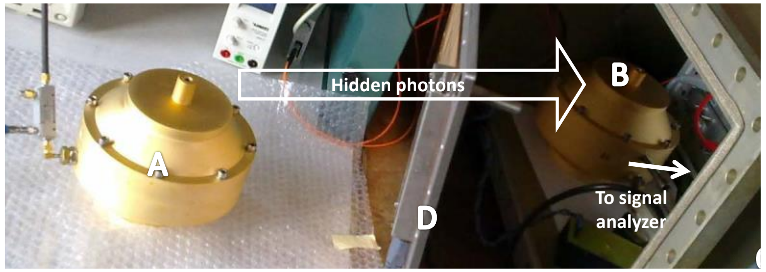
LSW: Active detection



Purely coherent axions $\sim\delta(\omega - m_a)$

Lock-in

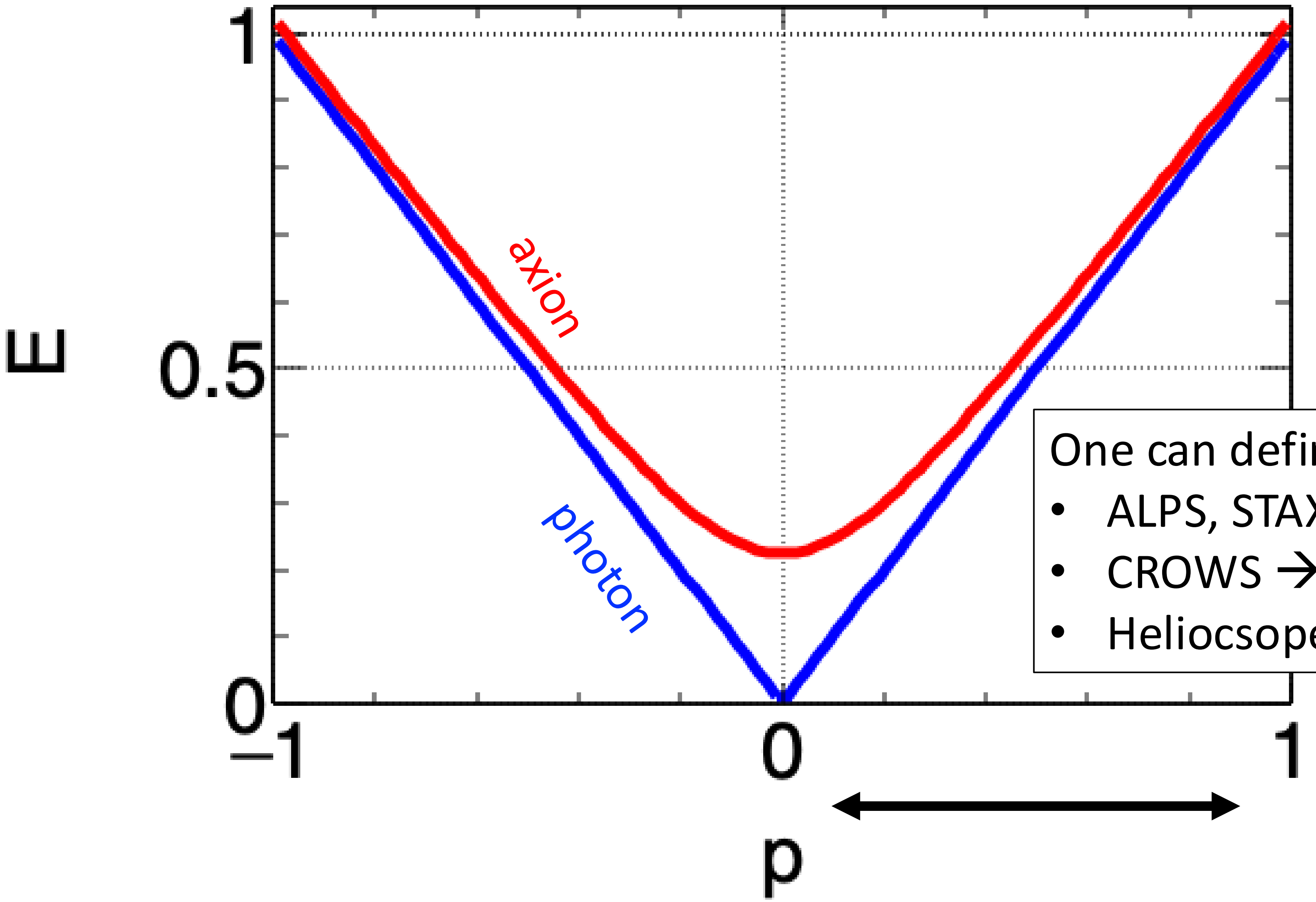
LSW can be this type if we can lock-in the signal



$$S/N = \frac{P_{sig}}{k_B T}\sqrt{\frac{\Delta t}{\Delta\nu_r}} = \frac{P_{sig}}{k_B T}\Delta t$$

The sensitivity can be increased over the coherence time

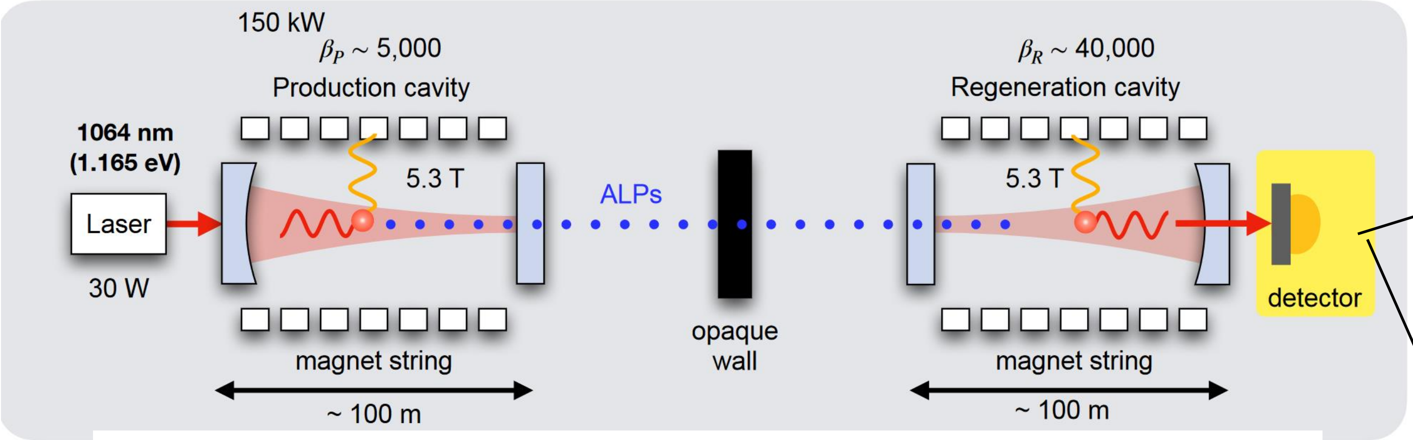
Another physical difference from DM axion



One can define your operating momentum

- ALPS, STAX → relativistic
- CROWS → nonrelativistic (evanescence)
- Heliocsope → relativistic

Present flagship of LSW: ALPS-II (DESY)

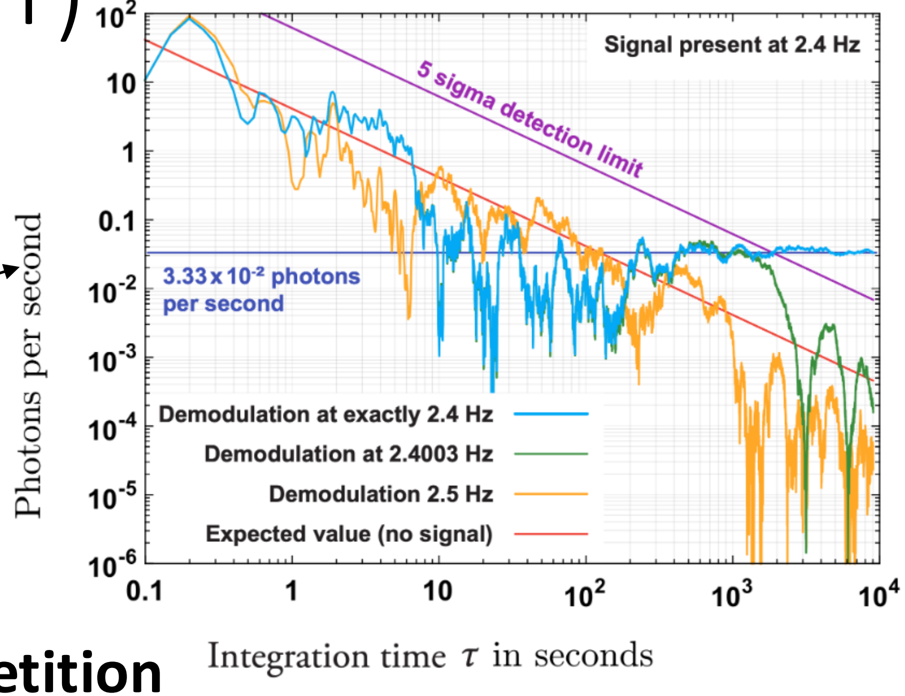


150 kW → 10^{-24} W (~1 photon/day)

- 24 HERA dipole magnets
- October 2020: Magnets installed and aligned
- March 2022: Magnet strings run successfully at full current
  - 5.7 kA, 5.3 T

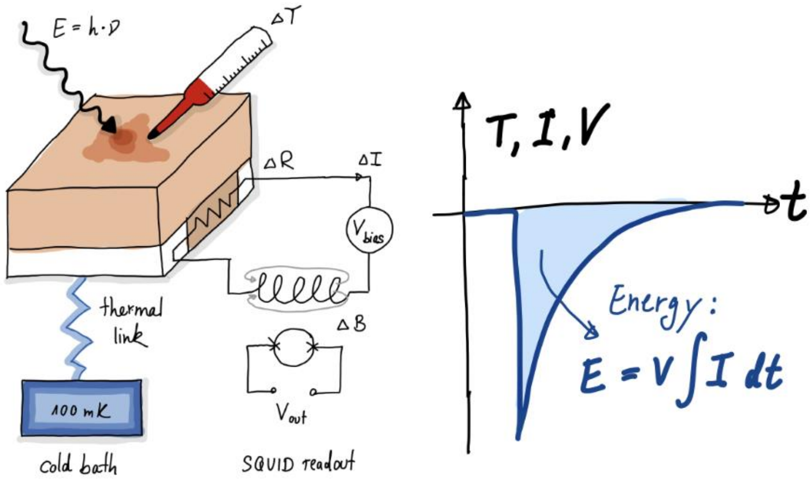
Courtesy: Gulden (Joule) Othman, "Status of the ALPS II Experiment"

Optical heterodyne



In competition

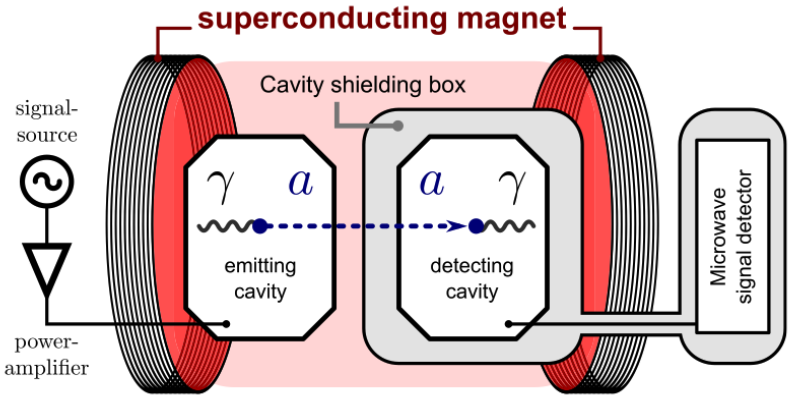
Transition Edge Sensor

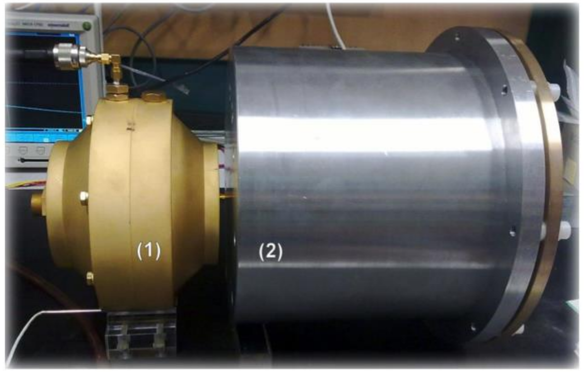


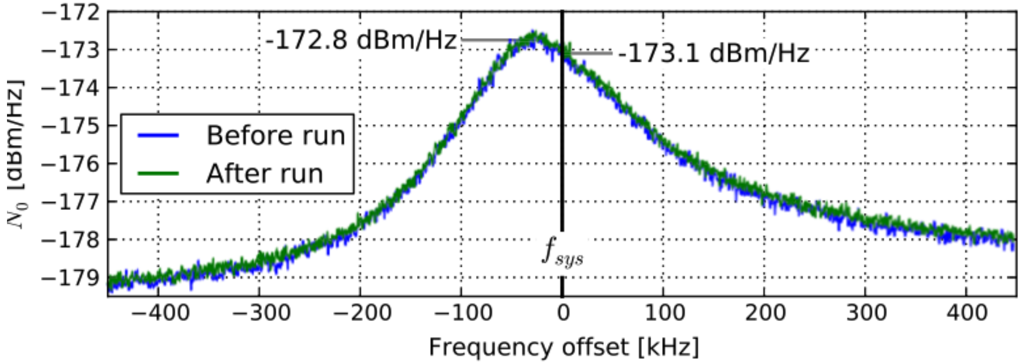
CROWS: GHz-based LSW

TABLE IV. Parameters of the ALPs run in June 2013.

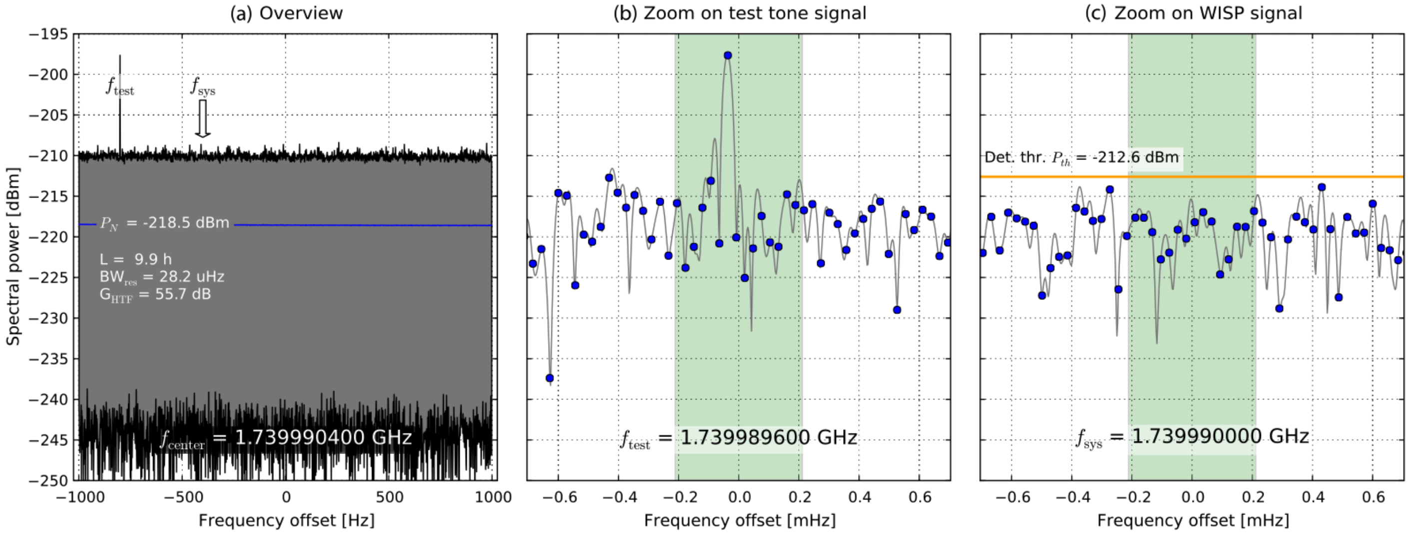
$f_{sys} = 1.739990$ GHz	$Q = 11392, 12151$	$B = 2.88$ T
$P_{sig} = 9.8 \times 10^{-25}$ W	$P_{em} = 47.9$ W	$\lvert G \rvert_{max} = 0.94$

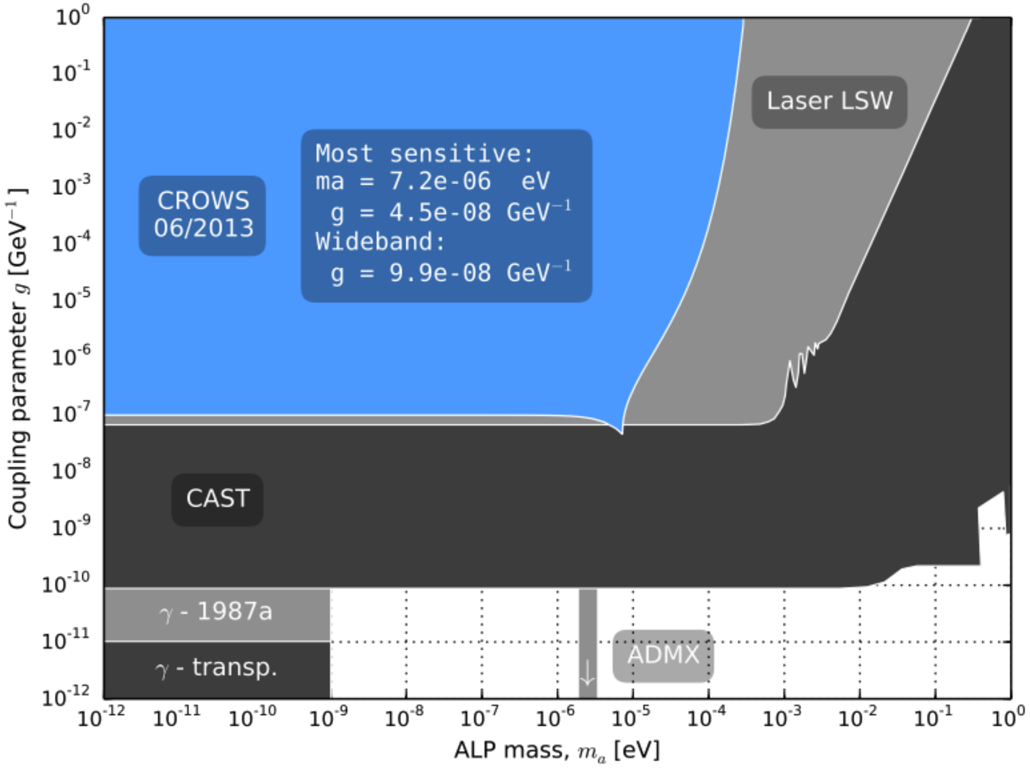






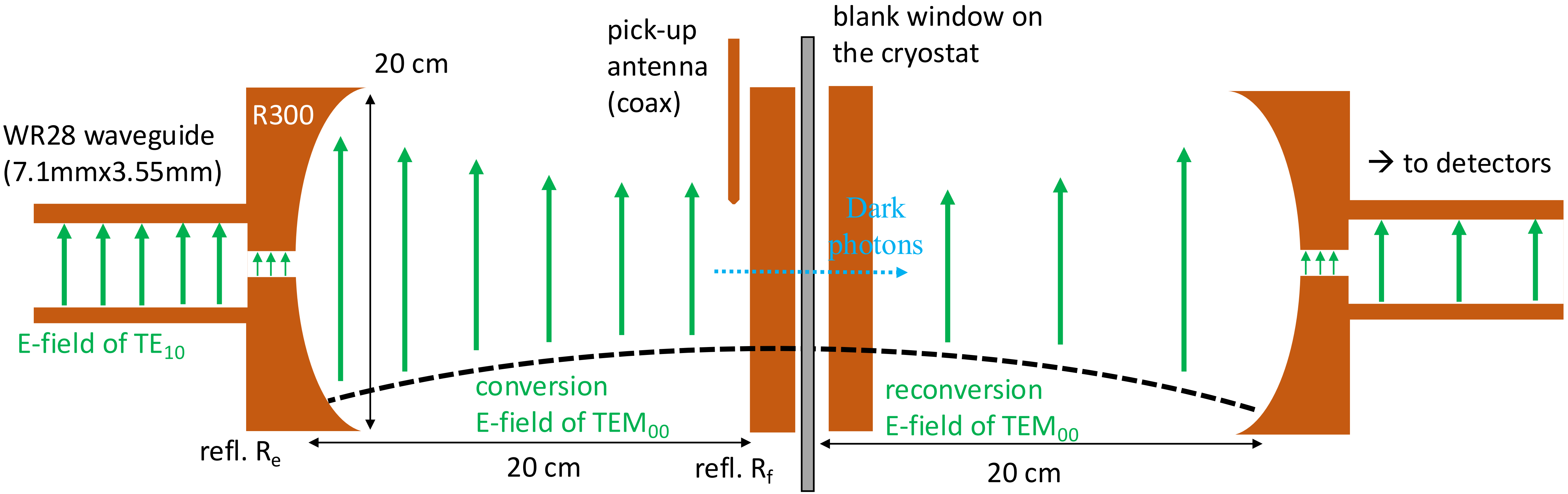
M. Betz, et al. PRD 88 075014 (2013)

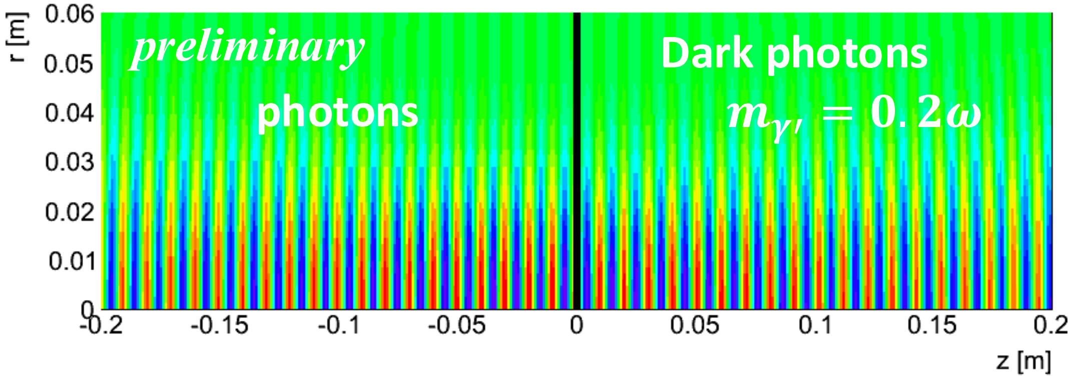




Superconducting version
→ darkSRF for dark photons A. Romanenko et al PRL 130 261801 2023

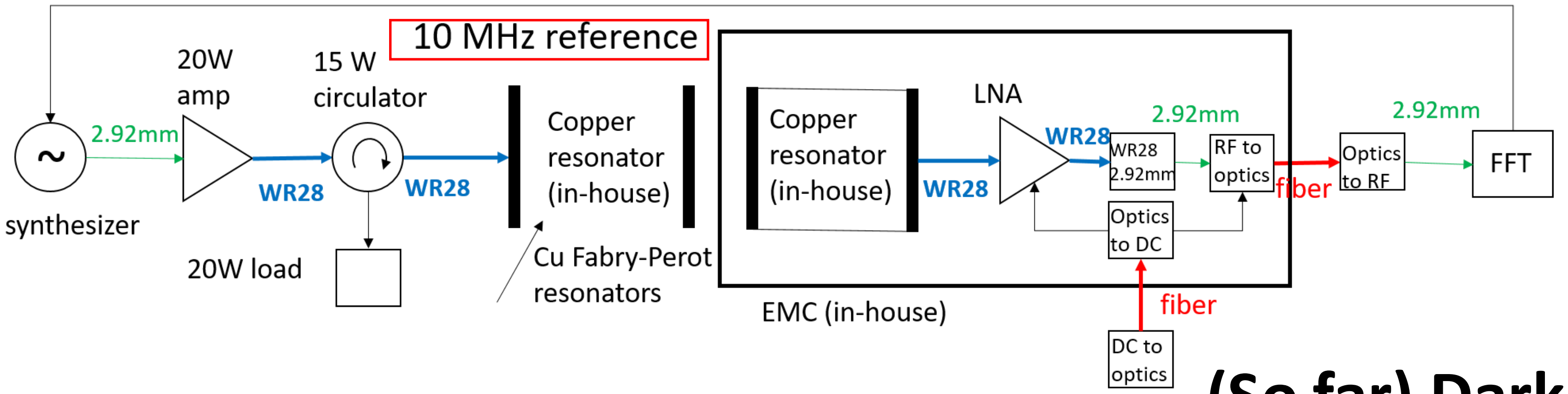
STAX: LSW at even higher frequency (my own project)

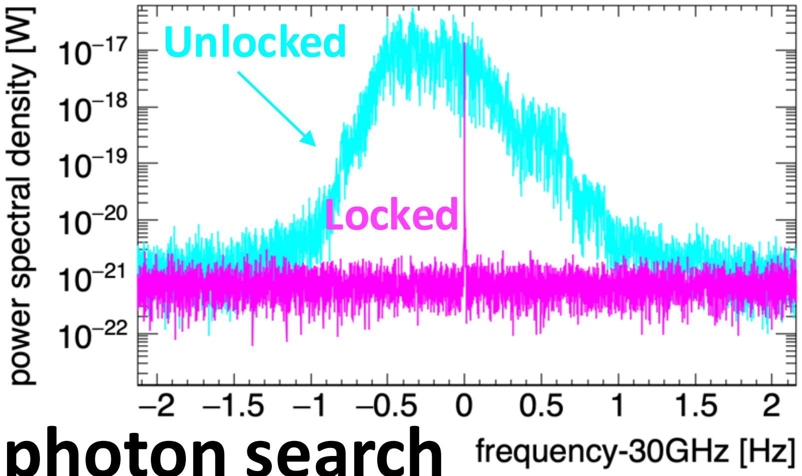


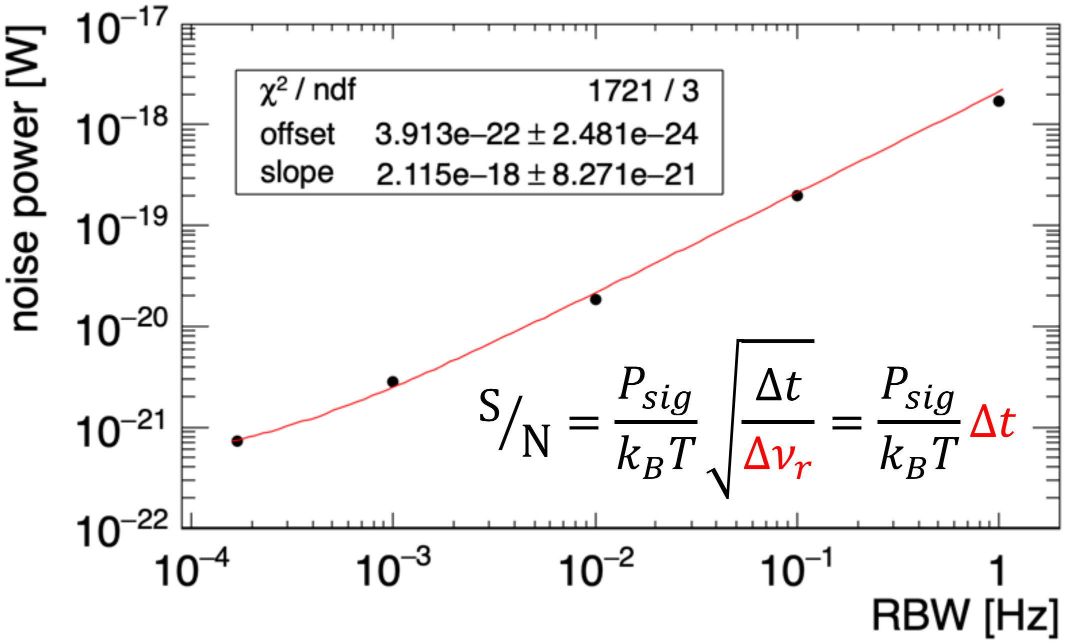


- Finesse $\mathcal{F} = 2\pi/(1 - R_e R_f) = 3300$
- Loaded Q $Q_L = \mathcal{F} \times L/\lambda = 6.6 \times 10^4$
- Band-width of the cavities: $BW = f/Q_L = 0.45$ MHz
- Spatial resonance width: $\delta L = \lambda/2\mathcal{F} = 1.5$ µm

Lock-in amplifier method in Light-Shining-Through-a-Wall

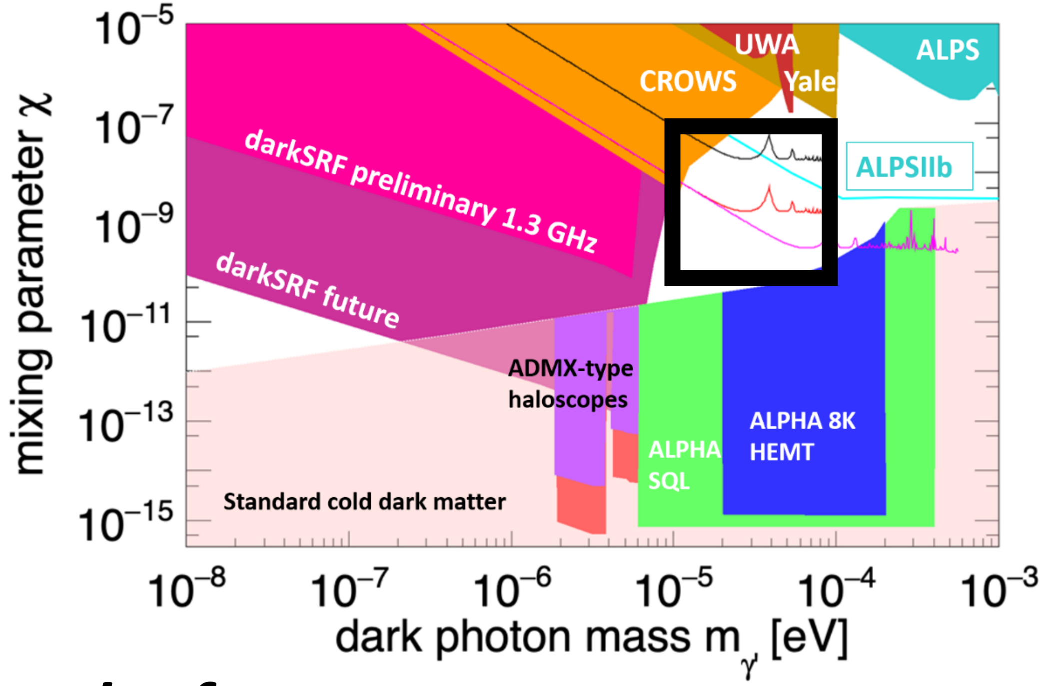






$$S/N = \frac{P_{sig}}{k_B T}\sqrt{\frac{\Delta t}{\Delta \nu_r}} = \frac{P_{sig}}{k_B T}\Delta t$$

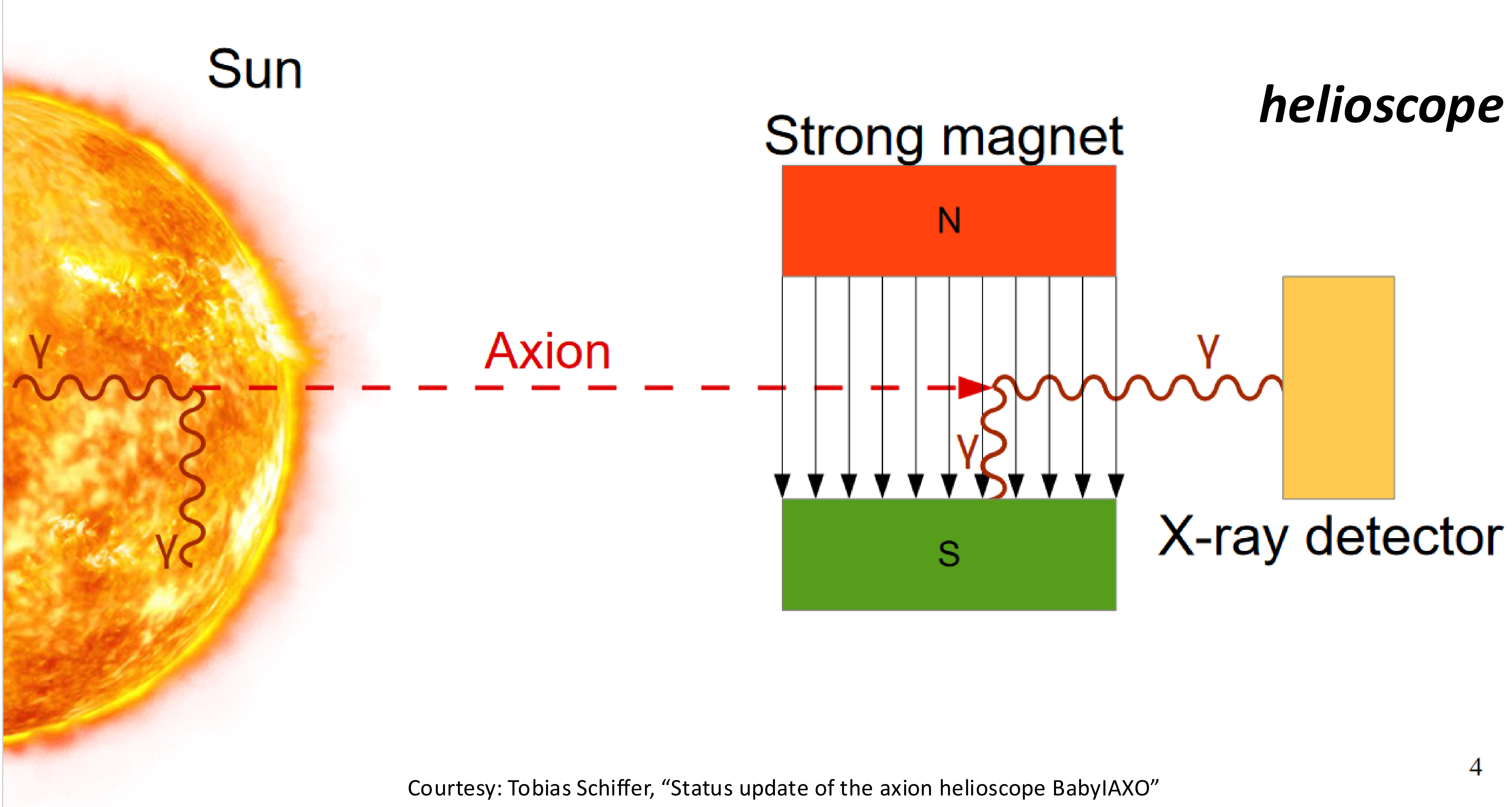
(So far) Dark photon search



A. Miyazaki et alCERN-ACC-NOTE-2021-0032
F. Caspers, S. Federmann, and D. Seebacher, CERN-BE-Note-2009-026
F. Caspers, J. Jaeckel, and R. Ringwald, arXiv:0908.0759, published in JINST

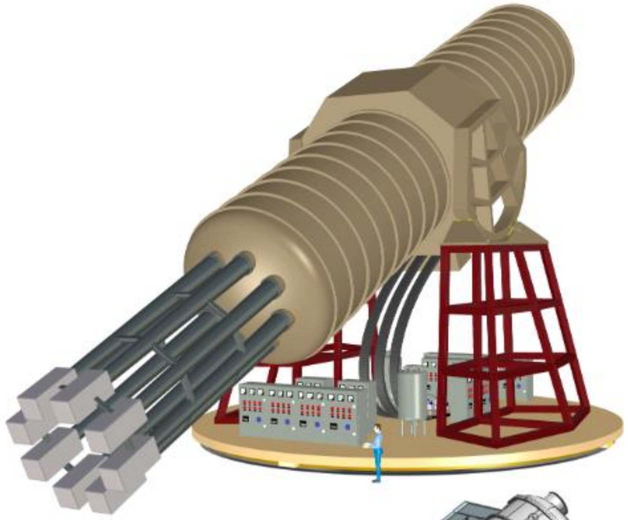
Opportunity for the future

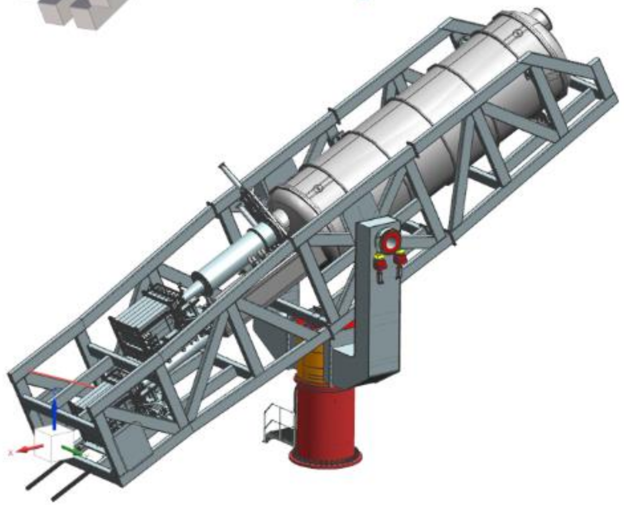
The sun can generate axions (astrophysical LSW)



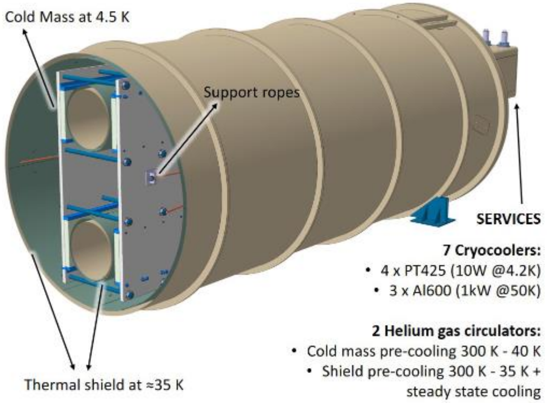
Courtesy: Tobias Schiffer, “Status update of the axion helioscope BabyIAXO”

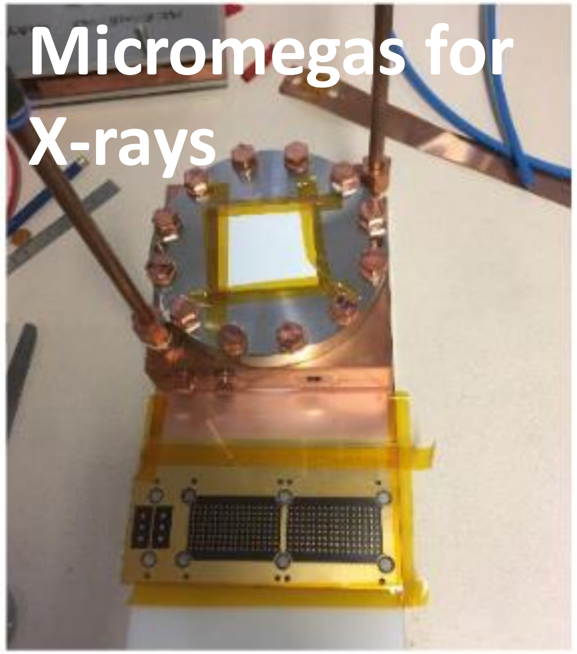
CAST (CERN) → BabyIAXO (DESY) → IAXO (?)



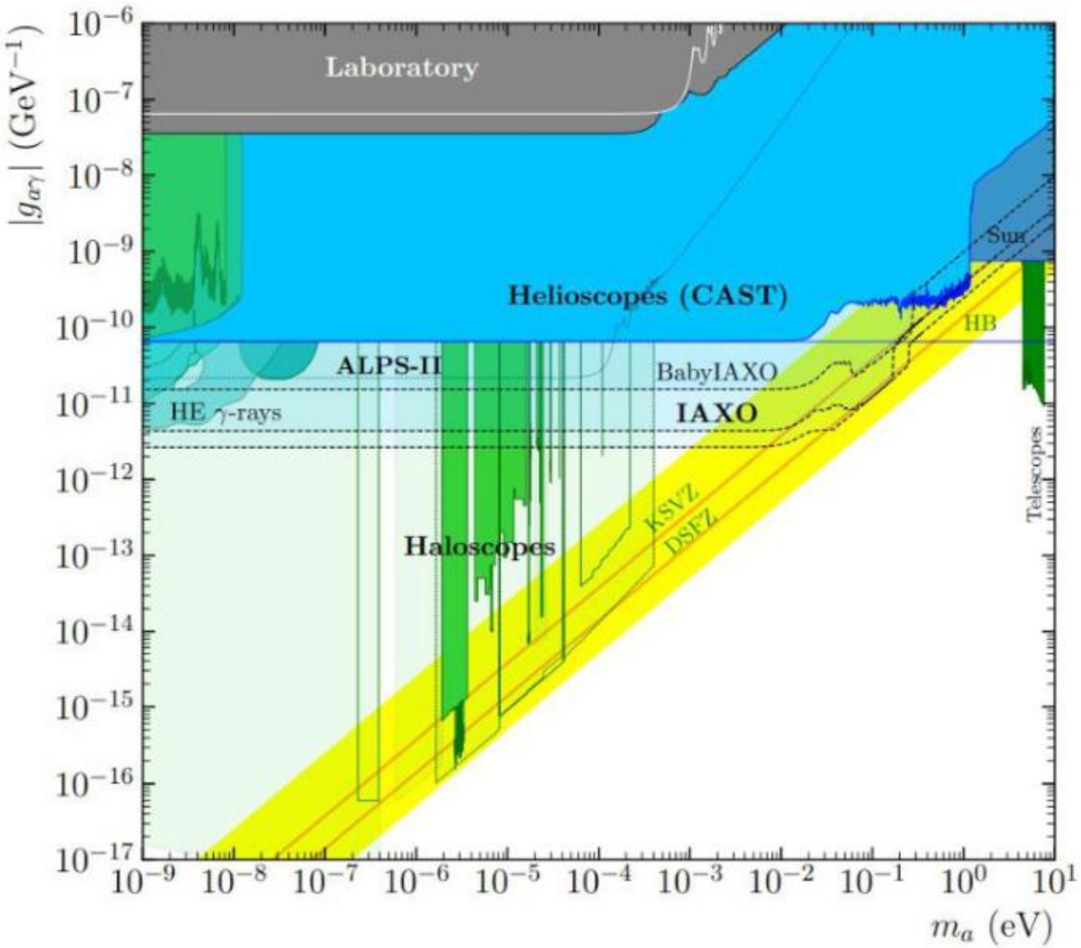


magnet





Courtesy: Tobias Schiffer, "Status update of the axion helioscope BabyIAXO"



Part 1: overview on axion searches

- Axion vs WIMPs
  - WIMP: particle; axions: waves
  - Particle detection
  - Classical wave detection
- Various experiments
  - ADMX families
  - Lower masses
  - Higher masses
- Non-DM axions
  - Solar axions
  - Light-Shining-Through-a-wall
- Conclusion of part 1

Conclusion of part 1

- Axion vs WIMPs
  - Axion is a solution of strong CP problem (SM model of particle physics) and dark matter puzzle (mystery in cosmology and astronomy)
  - Unlike WIMPs/FIMPs, axion dark matter behaves like a wave due to its long de Broglie wavelength and large occupancy
  - Inverse Primakoff effect converts axions into ***photon*** inside a static magnetic field but naïve thought on ***photon detection*** is a trap!
  - The DM-axion-induced photons are supposed to be ***classical microwaves*** with a finite coherent time due to the motion of the Milky Way Galaxy
- Various haloscope experiments
  - One needs to resolve the energy-momentum mismatch → translational symmetry
  - ADMX and similar experiments (HAYSTAC, QUAX, RADES, KAIST/CAPP, darkSRF, etc) established RF-cavity based search around 1 GHz
  - Cavity-based approach is not suitable for lower masses → LC-circuit approach (DMRadio)
  - Higher masses → multiple cavities (ADMX-EFR, CAST-CAPP), dish antenna (BRASS, BREAD), dielectric disks (MADMAX), wire metamaterial (ALPHA)
- Non-DM axions
  - DM axions are strongly model dependent but non-DM axions are also motivated
  - Light-Shining-Through-a-wall: ALPS for IR 1000 nm (photon vs waves), CROWS for 1 GHZ, STAS for > 10 GHz
  - Solar axion helioscopes: CAST, (baby-)IAXO for X-rays from the Sun, here is really ***photons***