Canfranc Axion Detection Experiment (CADEx)

A novel haloscope search for Dark Matter axions in the mass range 330–460 μeV

Bradley J. Kavanagh
IFCA (UC-CSIC), Santander
On behalf of the **CADEx** Collaboration

13 September 2023

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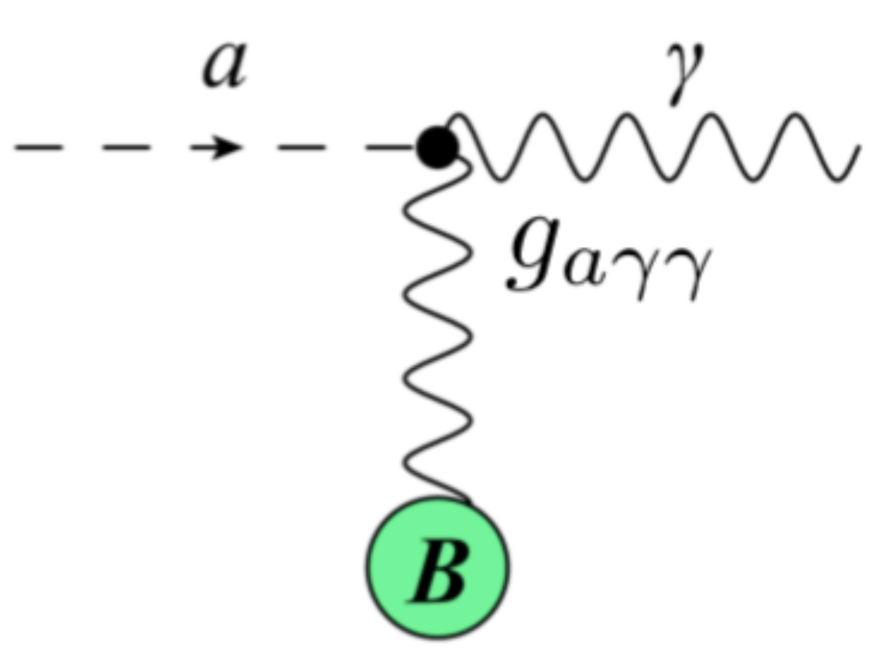
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
IFCA Instituto de Física de Cantabria
CSIC Consejo Superior de Investigaciones Científicas
50 UC Universidad de Cantabria
TeVPA 2023

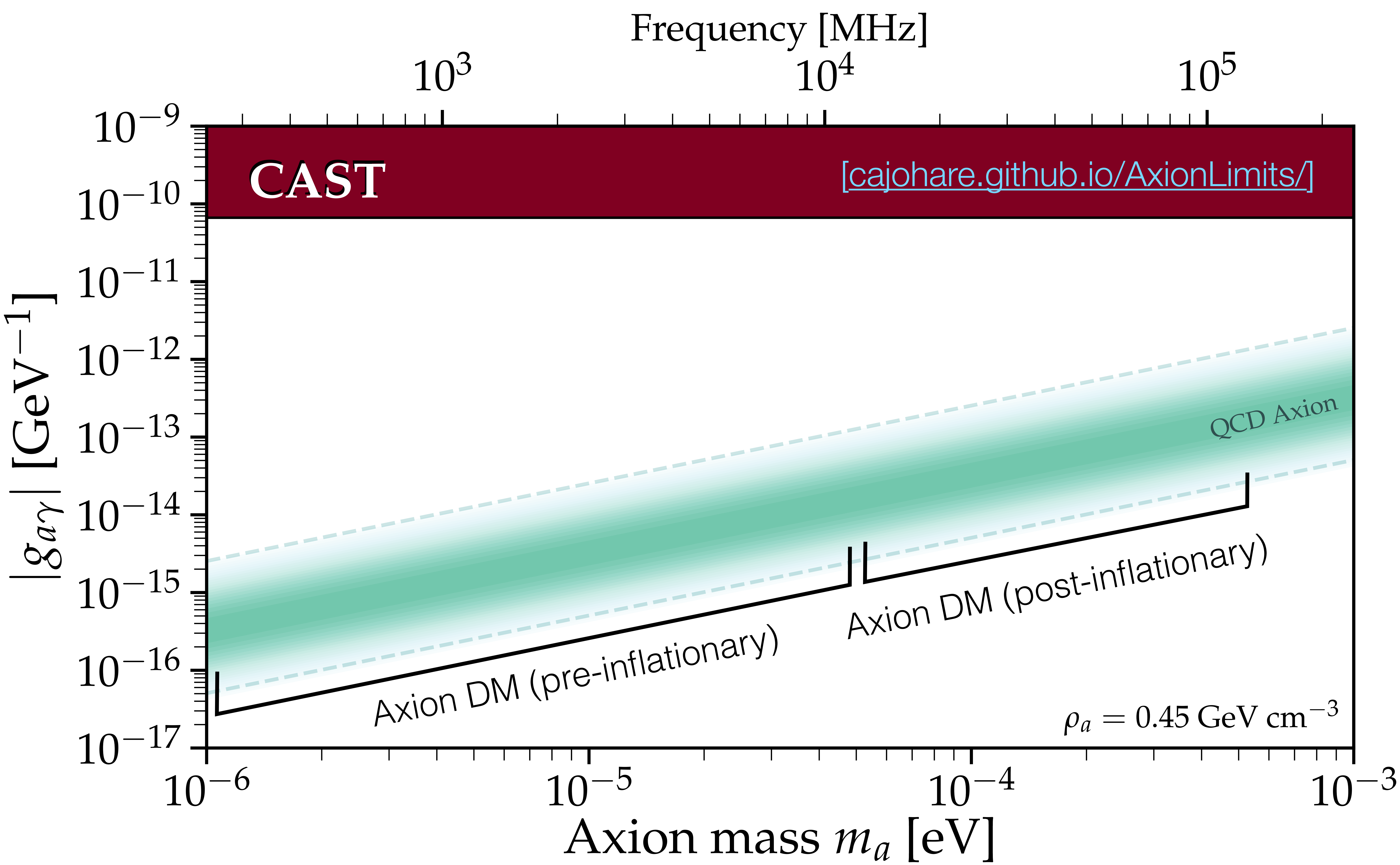
The QCD Axion

Axions, a, are light pseudo-scalar particles proposed to solve the Strong CP problem of QCD*. Also natural cold Dark Matter candidates!

*Why is Charge-Parity (CP) symmetry preserved by QCD
(or, why doesn't the neutron have an electric dipole moment?)

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





[See also Plenary Talk by Luca Visinelli on Thursday]

[Pre-inflationary axion abundance: e.g. 1810.07192, 2003.01100]

[Post-inflationary axion abundance: e.g. 1412.0789, 2108.05368,2007.04990]

The QCD Axion

Axions a are light pseudo-scalar particles proposed to solve the Strong CP

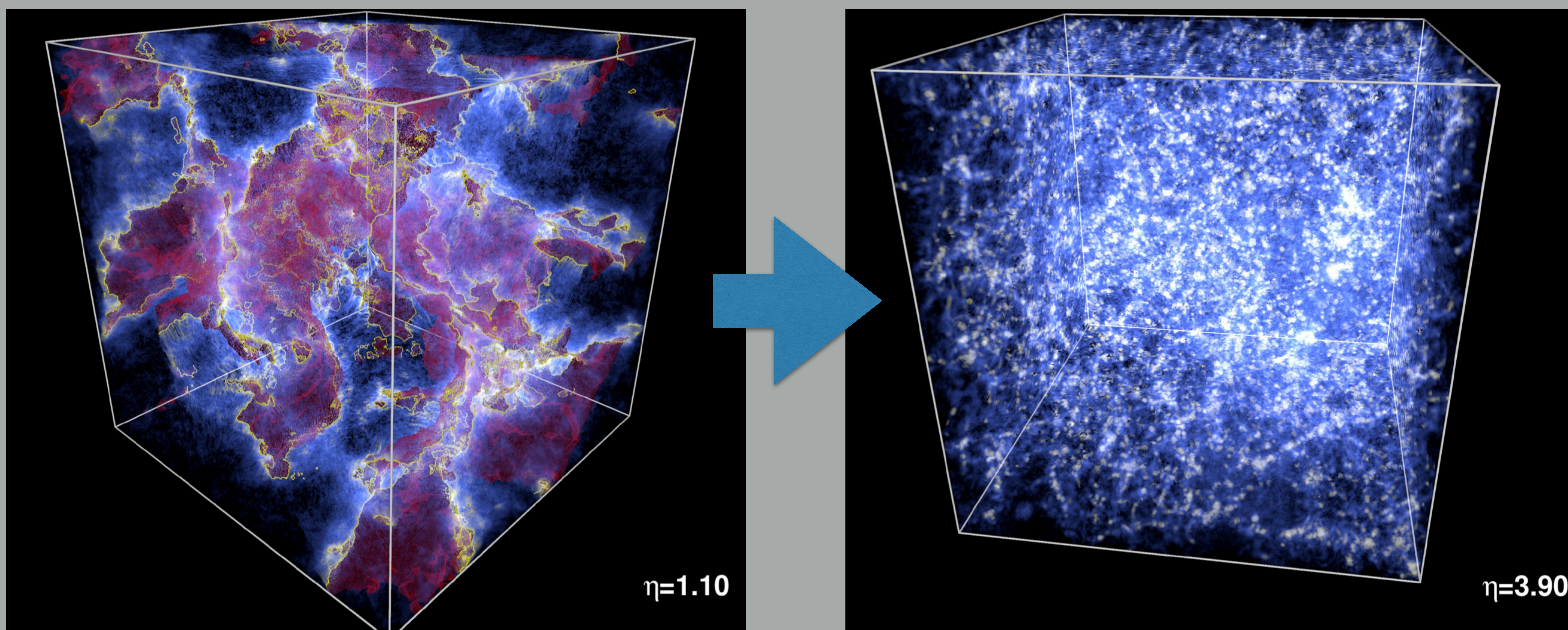
$\mathcal{L} \supset$

$=$

$- -$

-3

Complicated dynamics of the **axion field**, including **domain walls** and **strings**



[Buschmann, Foster & Safdi, 1906.00967]

[See als…
Luca Visinelli on Thursday]

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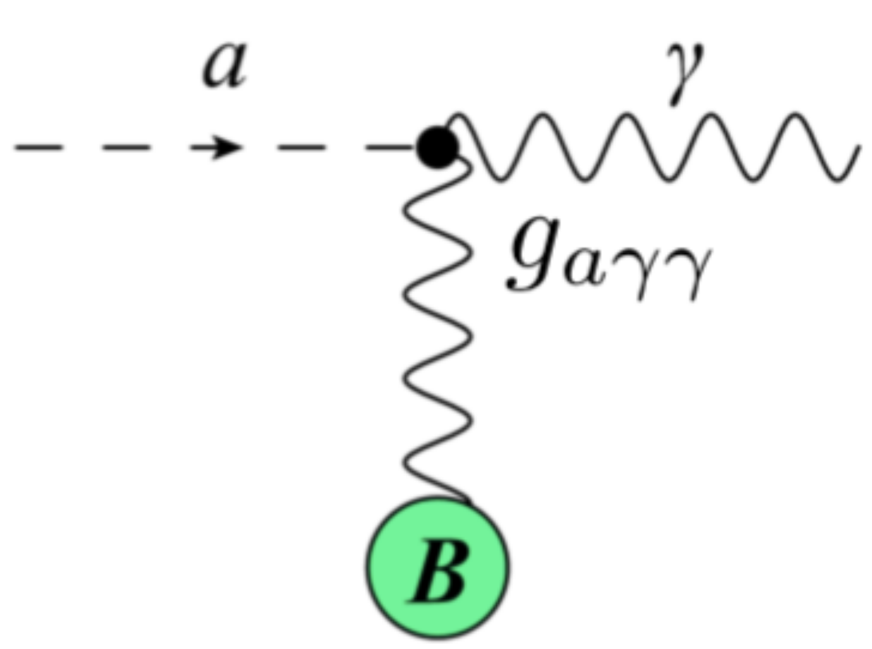

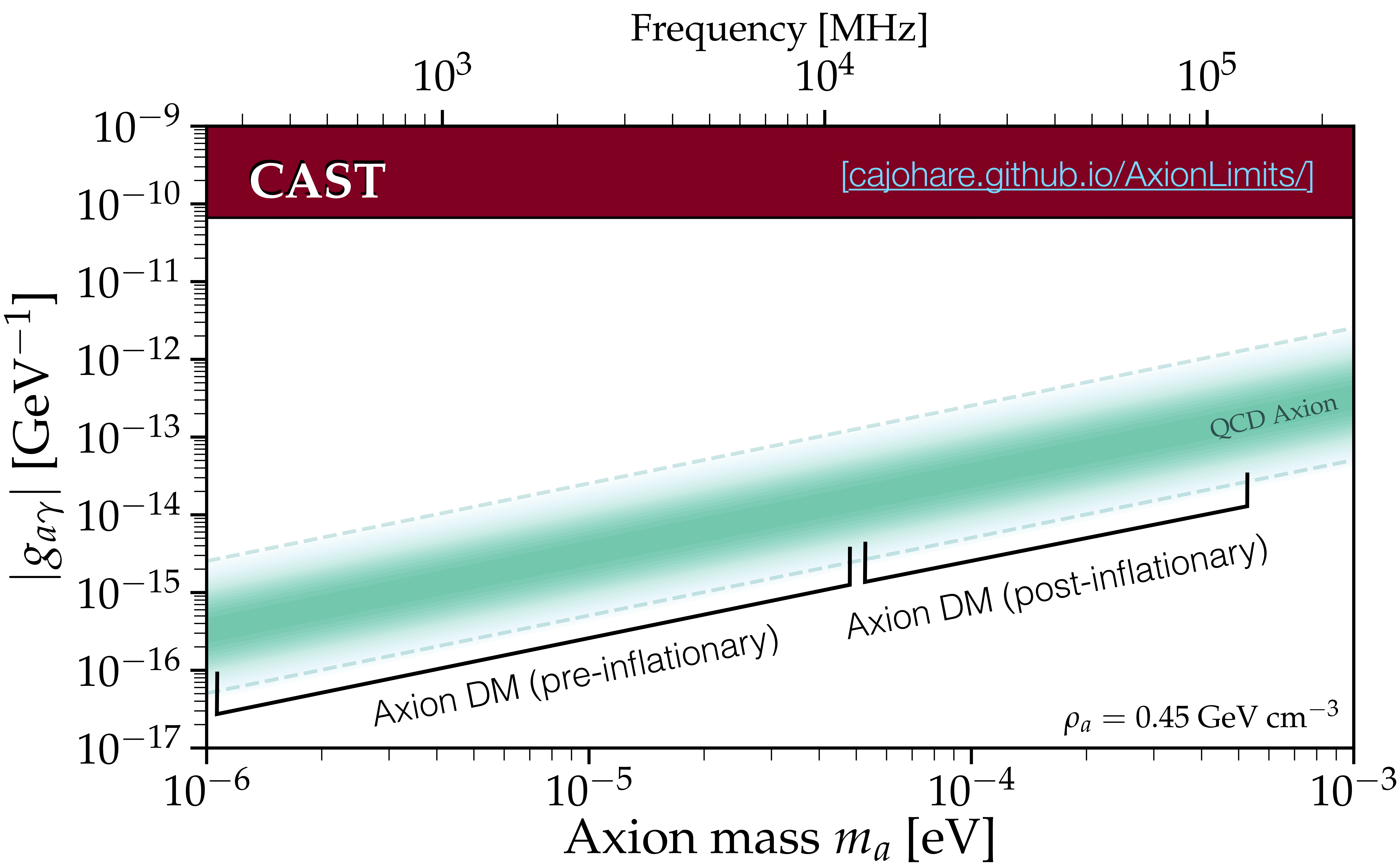

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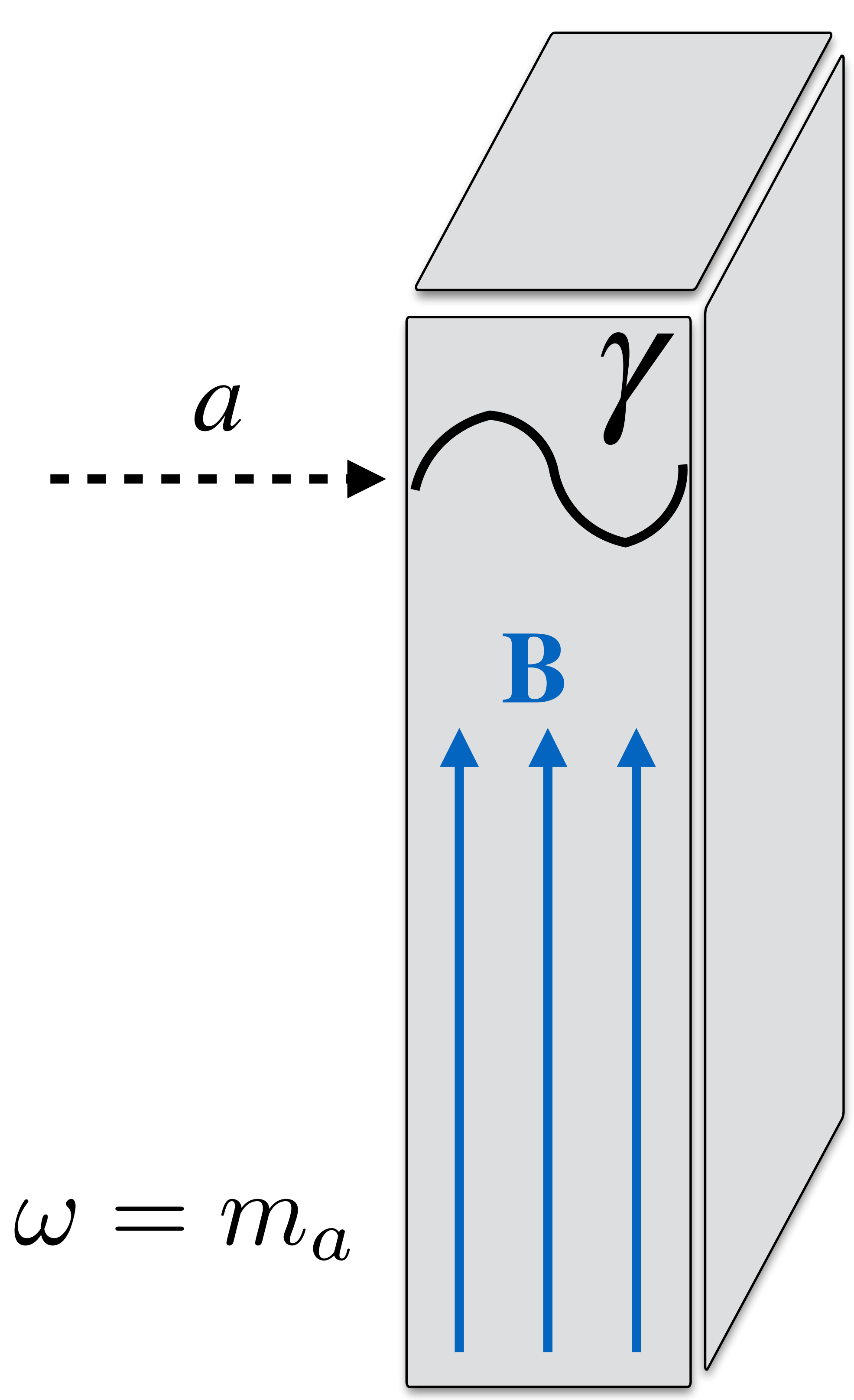
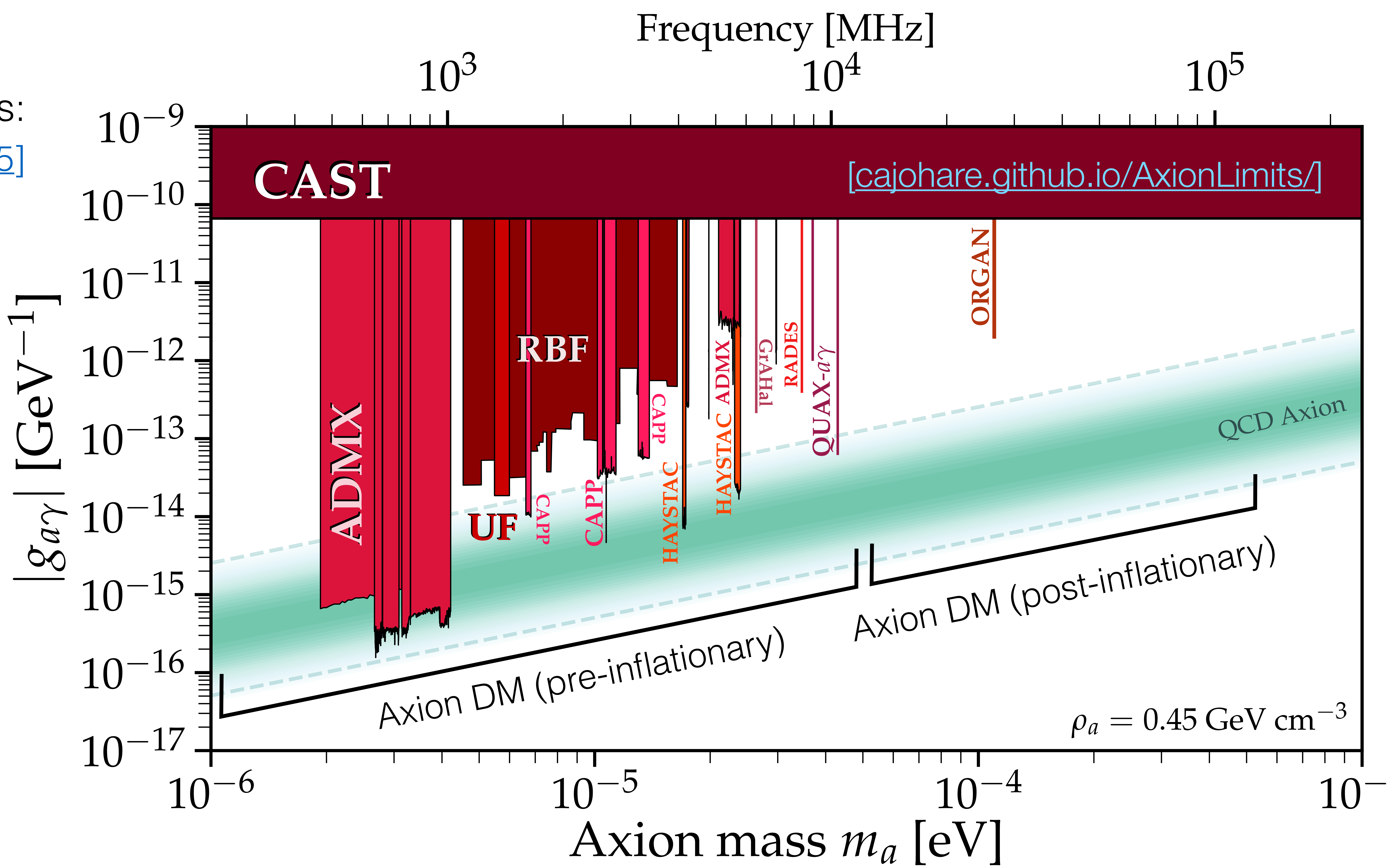
Microwave cavity or "**Haloscope**" Searches:
[2003.02206, 2105.04565]





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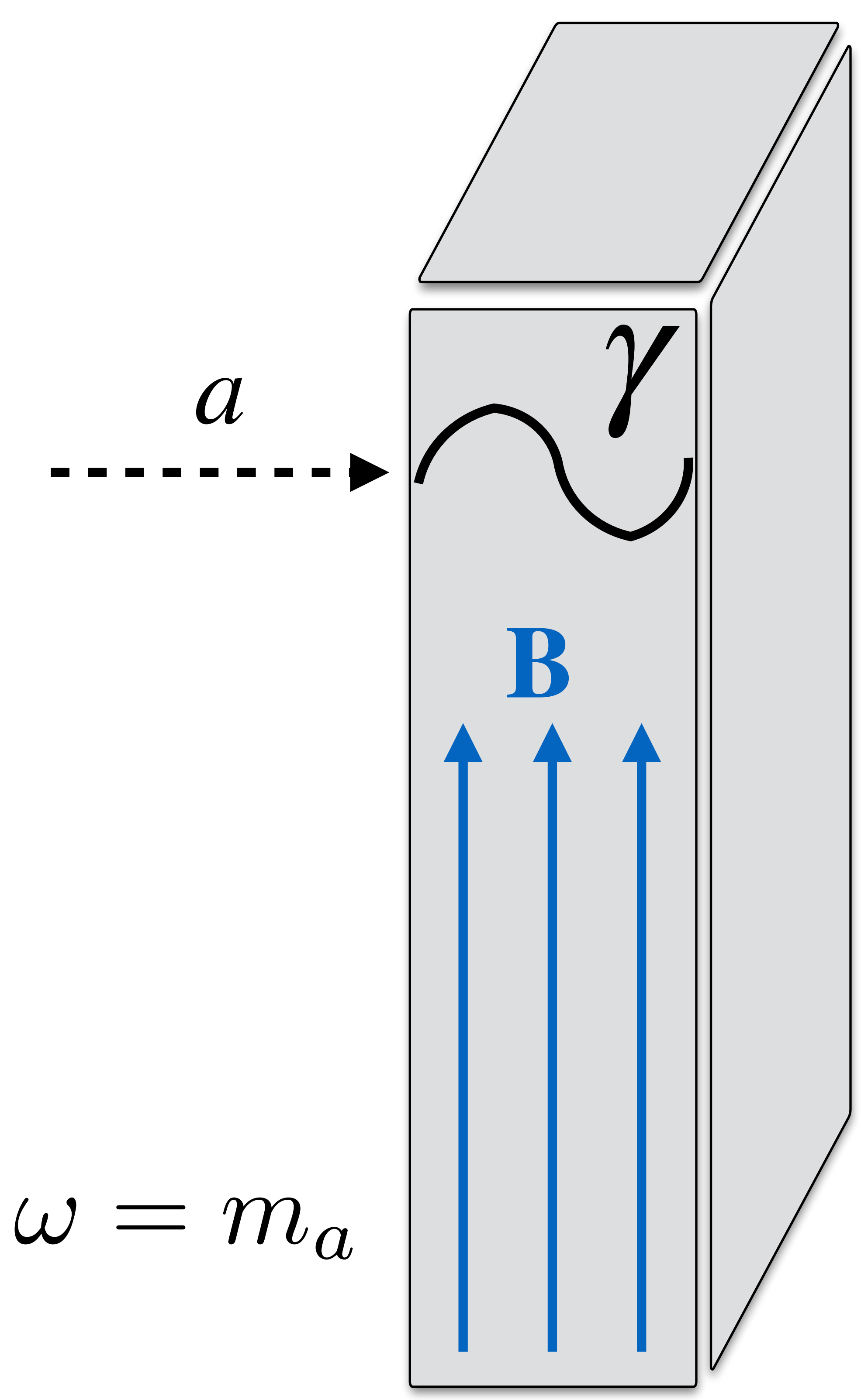

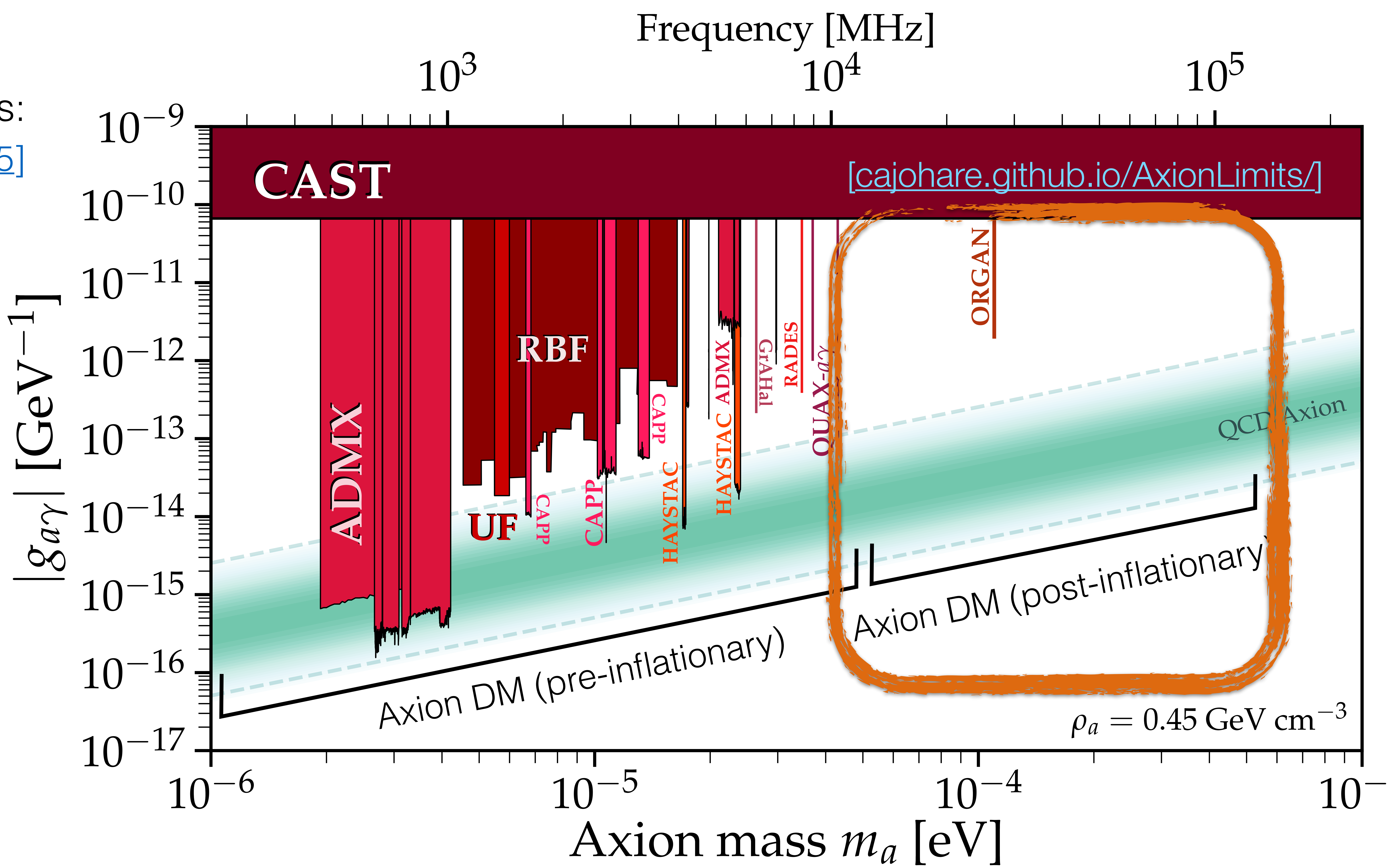

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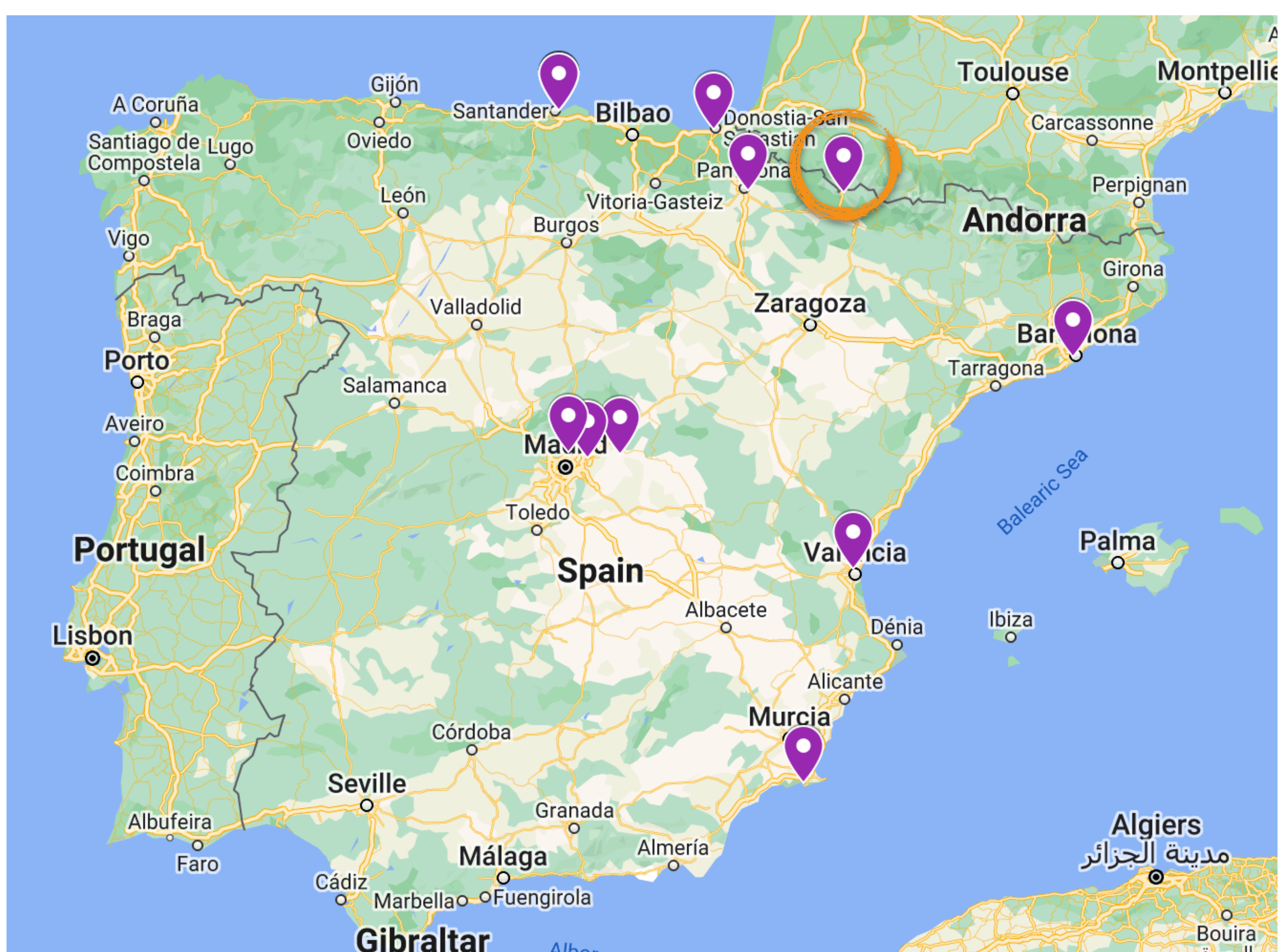
The Canfranc Axion Detection Experiment (CADEx): search for axions at 90 GHz with Kinetic Inductance Detectors

Beatriz Aja,[a] Sergio Arguedas Cuendis,[b] Ivan Arregui,[c] Eduardo Artal,[a] R. Belén Barreiro,[d] Francisco J. Casas,[d] Marina C. de Ory,[e] Alejandro Díaz-Morcillo,[f] Luisa de la Fuente,[a] Juan Daniel Gallego,[g] Jose María García-Barceló,[f] Benito Gimeno,[h] Alicia Gomez,[e] Daniel Granados,[i] Bradley J. Kavanagh,[d] Miguel A.G. Laso,[c] Txema Lopetegi,[c] Antonio José Lozano-Guerrero,[f] Maria T. Magaz,[e] Jesús Martín-Pintado,[e,*] Enrique Martínez-González,[d] Jordi Miralda-Escudé,[b,j] Juan Monzó-Cabrera,[f] Francisco Najarro de la Parra,[e] Jose R. Navarro-Madrid,[f] Ana B. Nuñez Chico,[k] Juan Pablo Pascual,[a] Jorge Pelegrin,[k] Carlos Peña Garay,[k] David Rodriguez,[e] Juan M. Socuéllamos,[d] Fernando Teberio,[l] Jorge Teniente,[c] Patricio Vielva,[d] Iván Vila,[d] Rocío Vilar[d] and Enrique Villa[e]

[JCAP 11 (2022) 044, arXiv:2206.02980]



Science
- Instituto de Ciencias del Cosmos de la Universidad de Barcelona
- Donostia International Physics Center
- Laboratorio Subterráneo de Canfranc
- Instituto de Física de Cantabria (CSIC-UC)

Haloscope
- Universidad Politécnica de Cartagena
- Instituto de Física Corpuscular (Universidad de Valencia, CSIC)

Optics
- Universidad Pública de Navarra
- Anteral S.L.

Detectors: Heterodyne & KIDs
- Observatorio de Yebes (IGN)
- Centro de Astrobiología (CSIC-INTA)
- Universidad de Cantabria
- Instituto de Física de Cantabria (CSIC-UC)
- Instituto Madrileño de Estudios Avanzados en Nanociencia
- Instituto de Ciencias del Cosmos de la Universidad de Barcelona

Calibration & data reduction
- Instituto de Ciencias del Cosmos de la Universidad de Barcelona
- Donostia International Physics Center
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- Instituto de Física de Cantabria (CSIC-UC)
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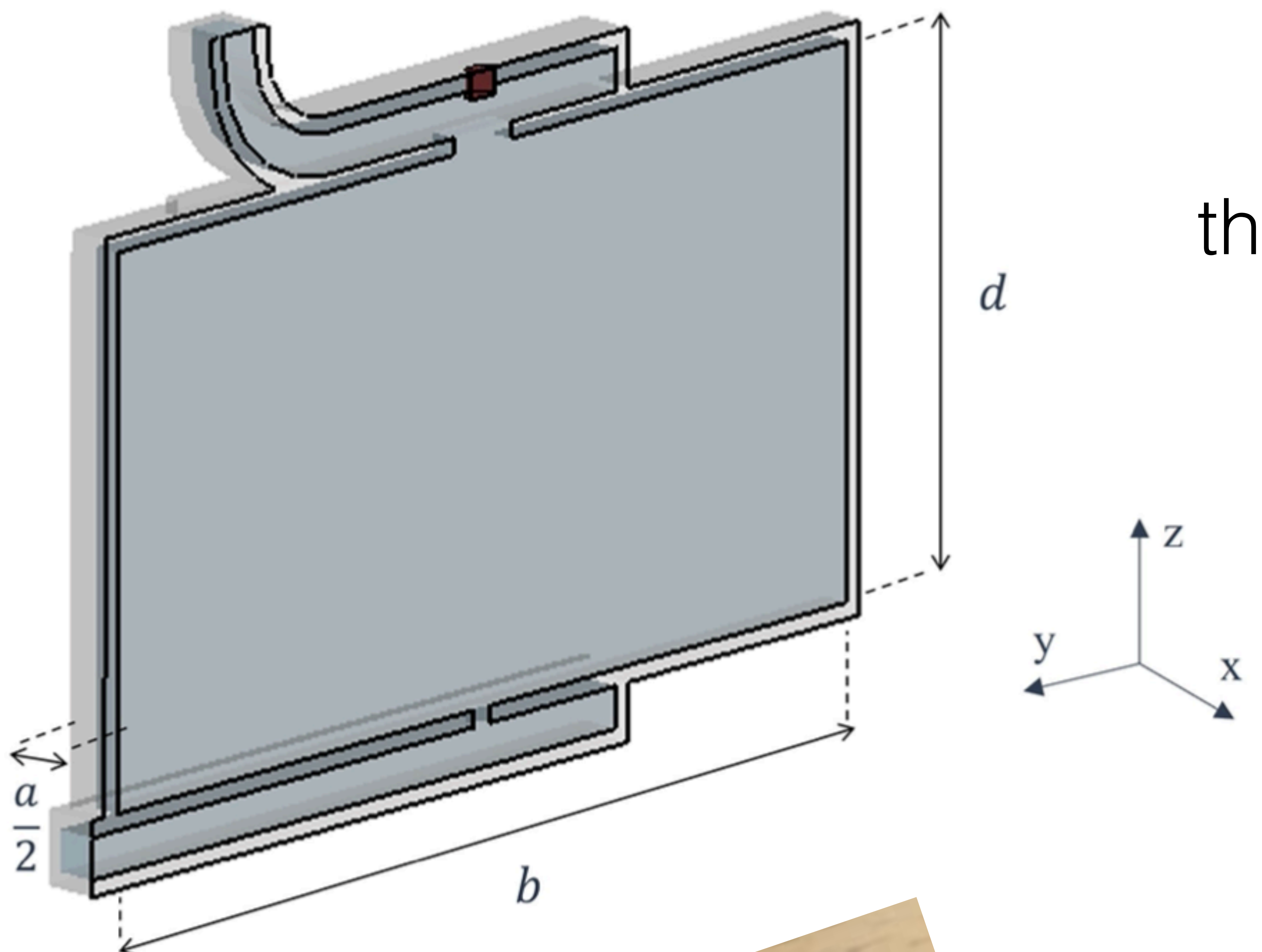
Haloscope

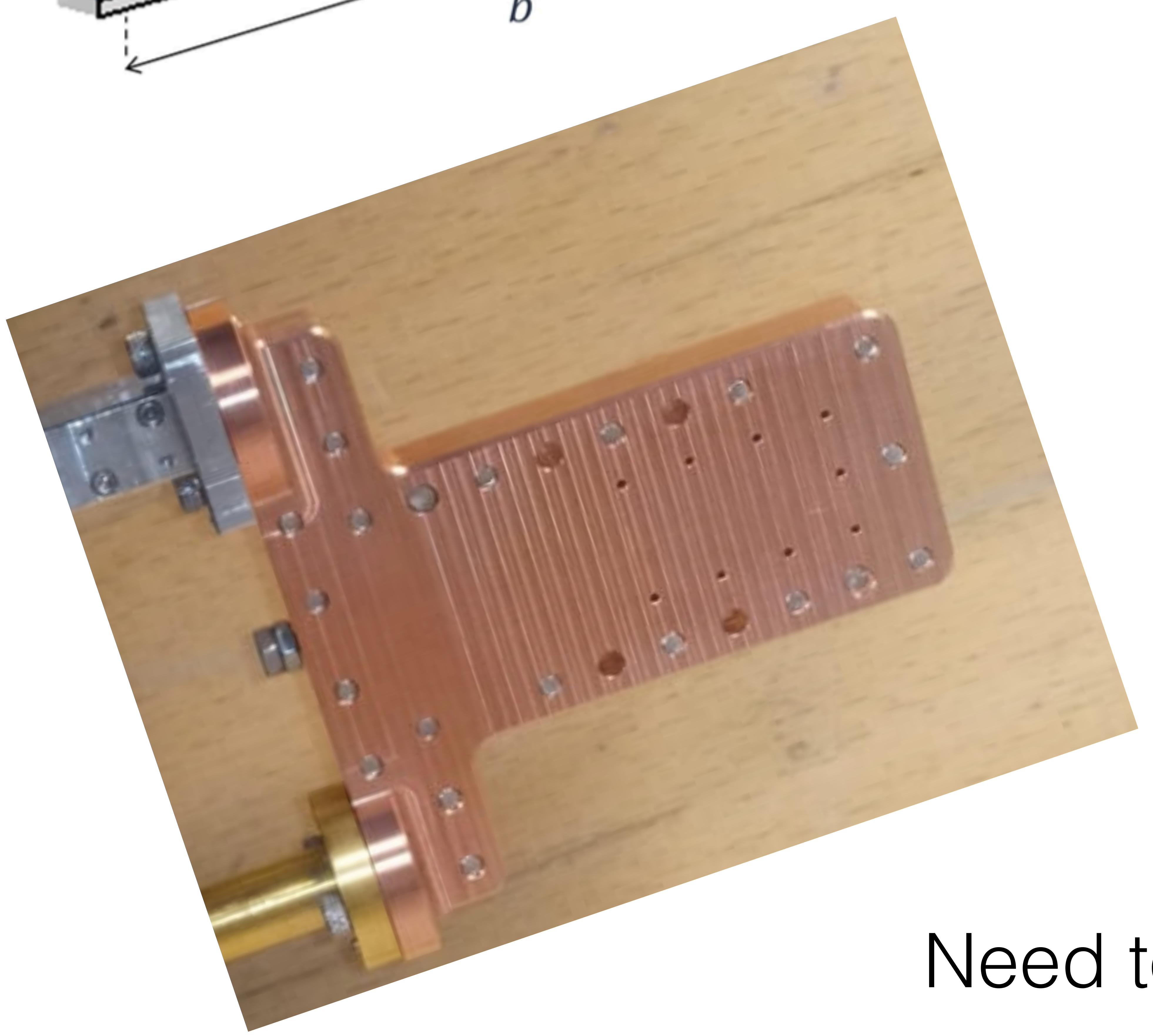
Detectable axion mass set by resonant frequency of the haloscope cavity.

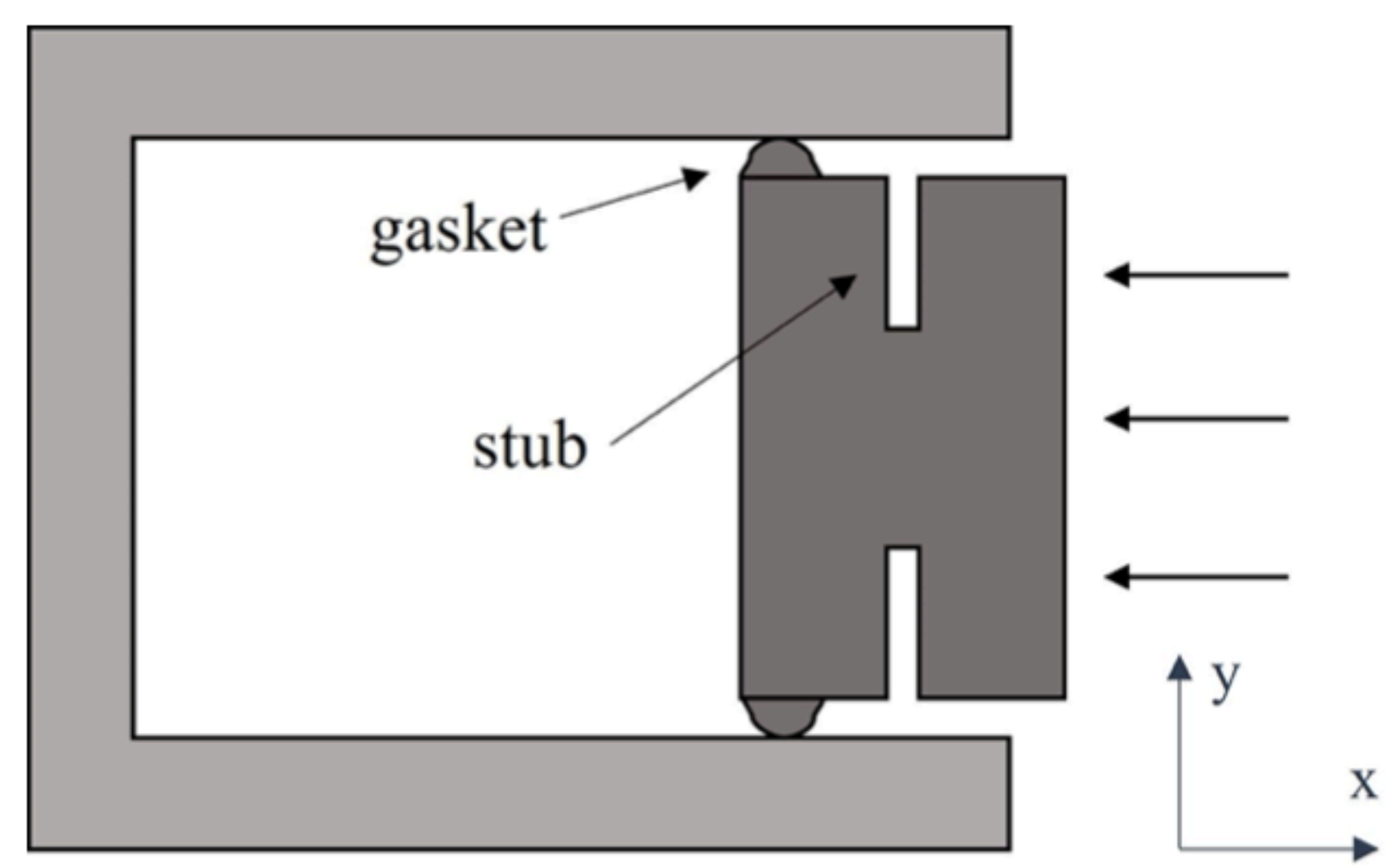
For the TM_{110} mode, the resonant frequency is: $$f_r = \frac{c}{2}\sqrt{\frac{1}{a^2} + \frac{1}{b^2}}$$

Dimensions $a \approx 1.7\,\mathrm{mm}$ and $b = 40\,a$ gives a resonance frequency of $f_r = 90\,\mathrm{GHz}$

Develop **tunable cavities** to scan frequency range $f_r \in [86, 111]\,\mathrm{GHz}$



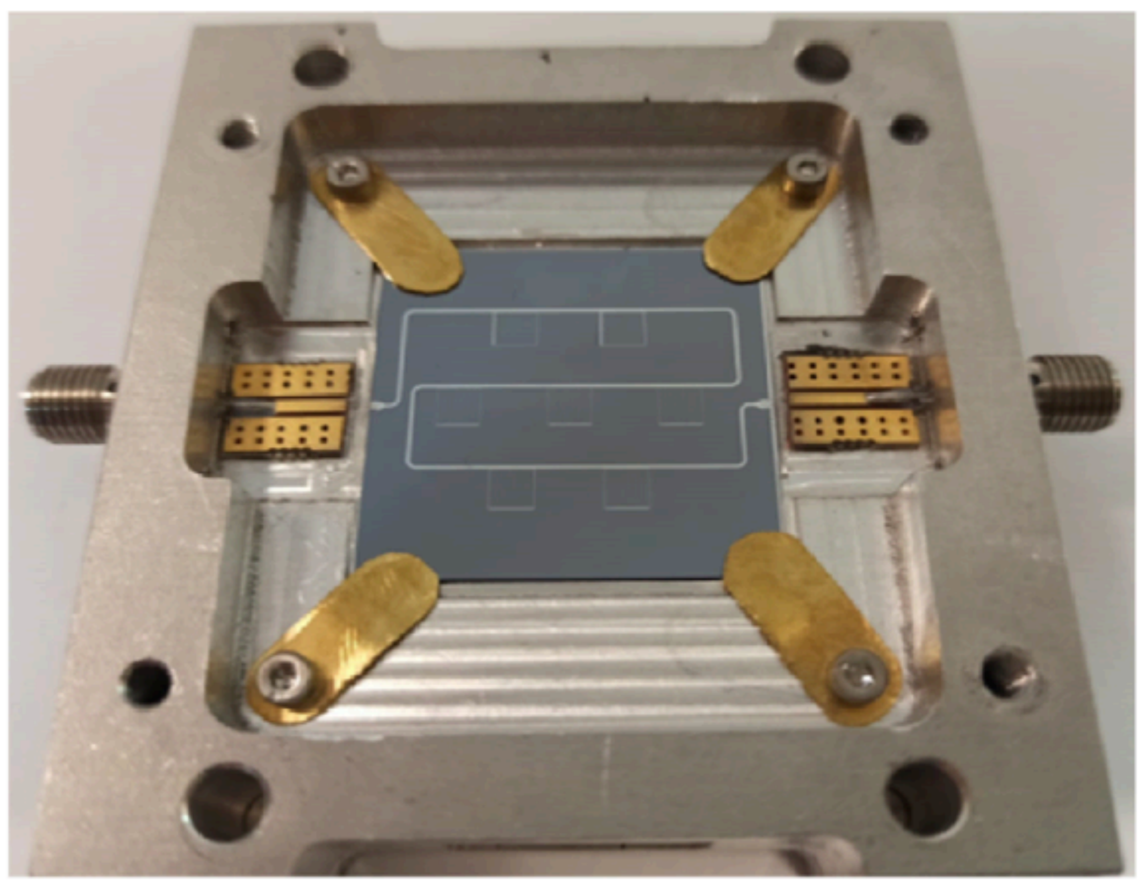


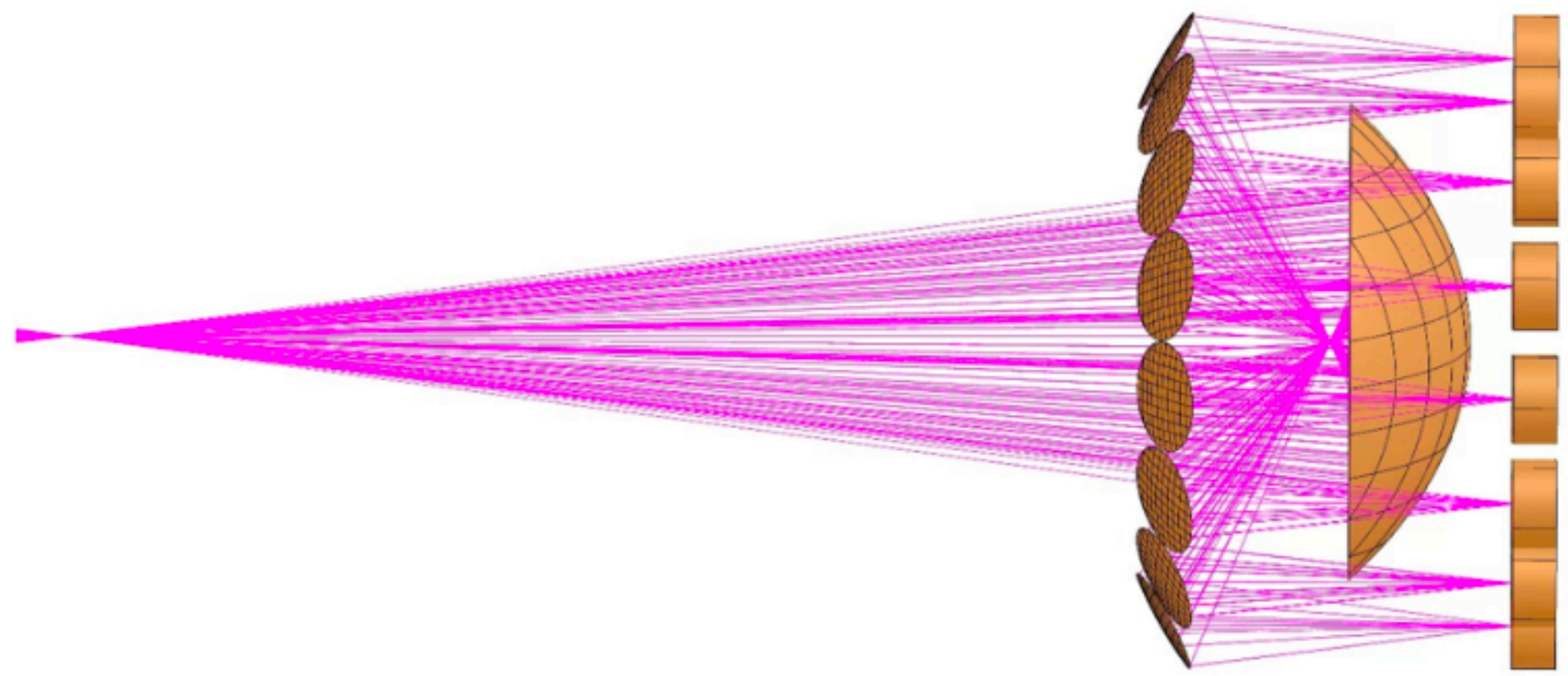


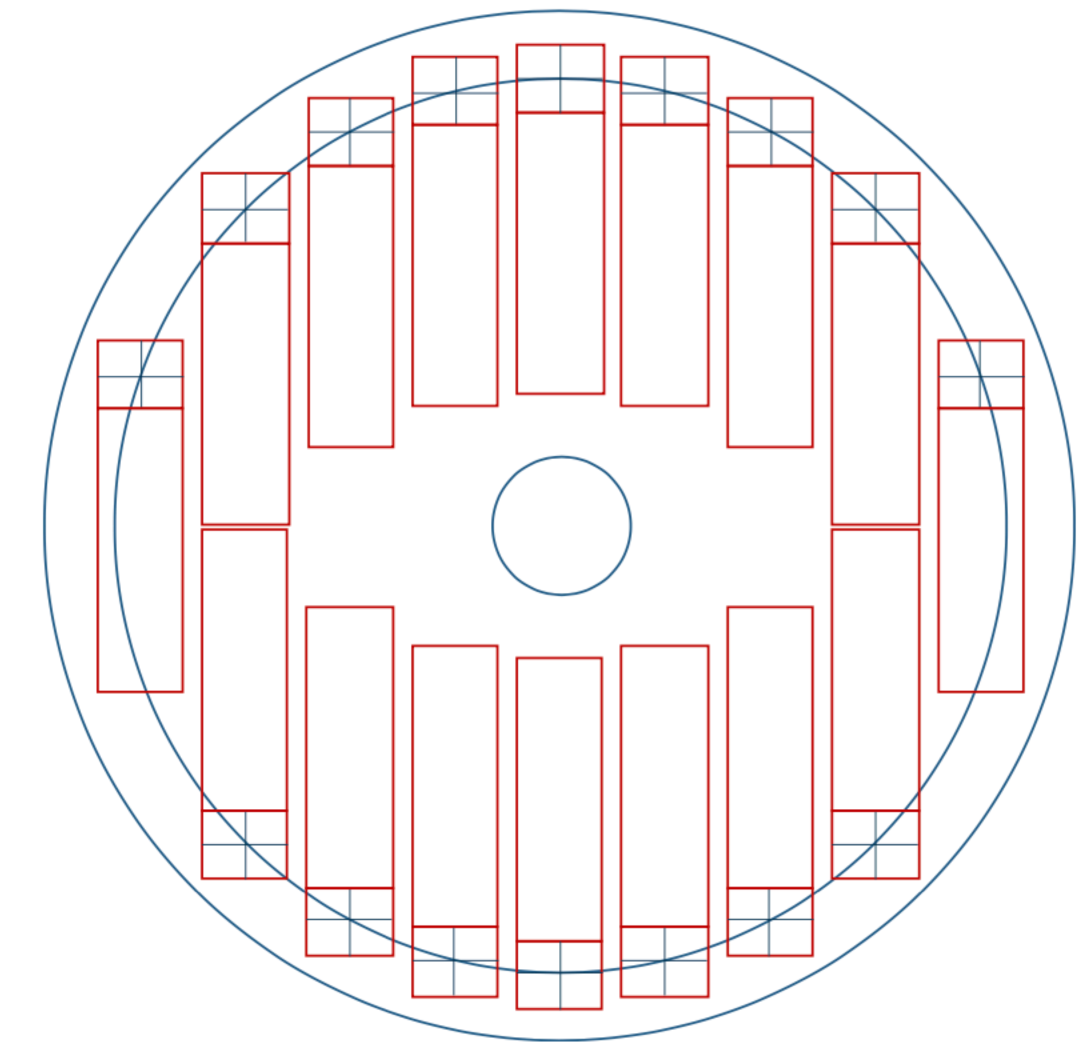
Need to maximize volume to increase the sensitivity → **Parallelized haloscope of 16 cavities**

Detection: KIDs

Quasi-optical system of16 horns + mirrors focuses signal on broadband **Kinetic Inductance Detector (KID)** sensors





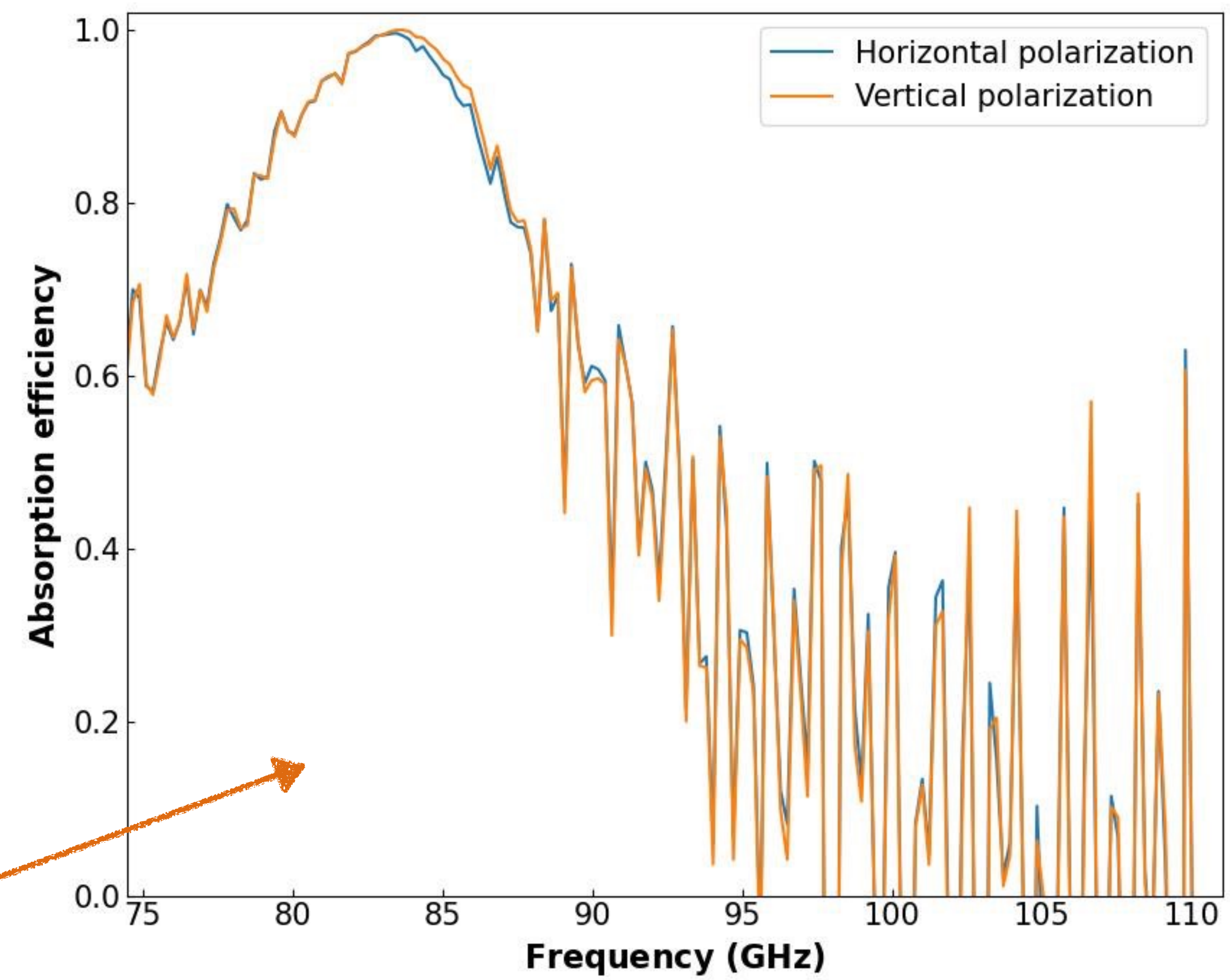


KIDs sensitivity characterized by Noise Equivalent Power (NEP); values of $3.8 \times 10^{-19}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ have been achieved.

Aim to reduce NEP by a factor of 4-10.

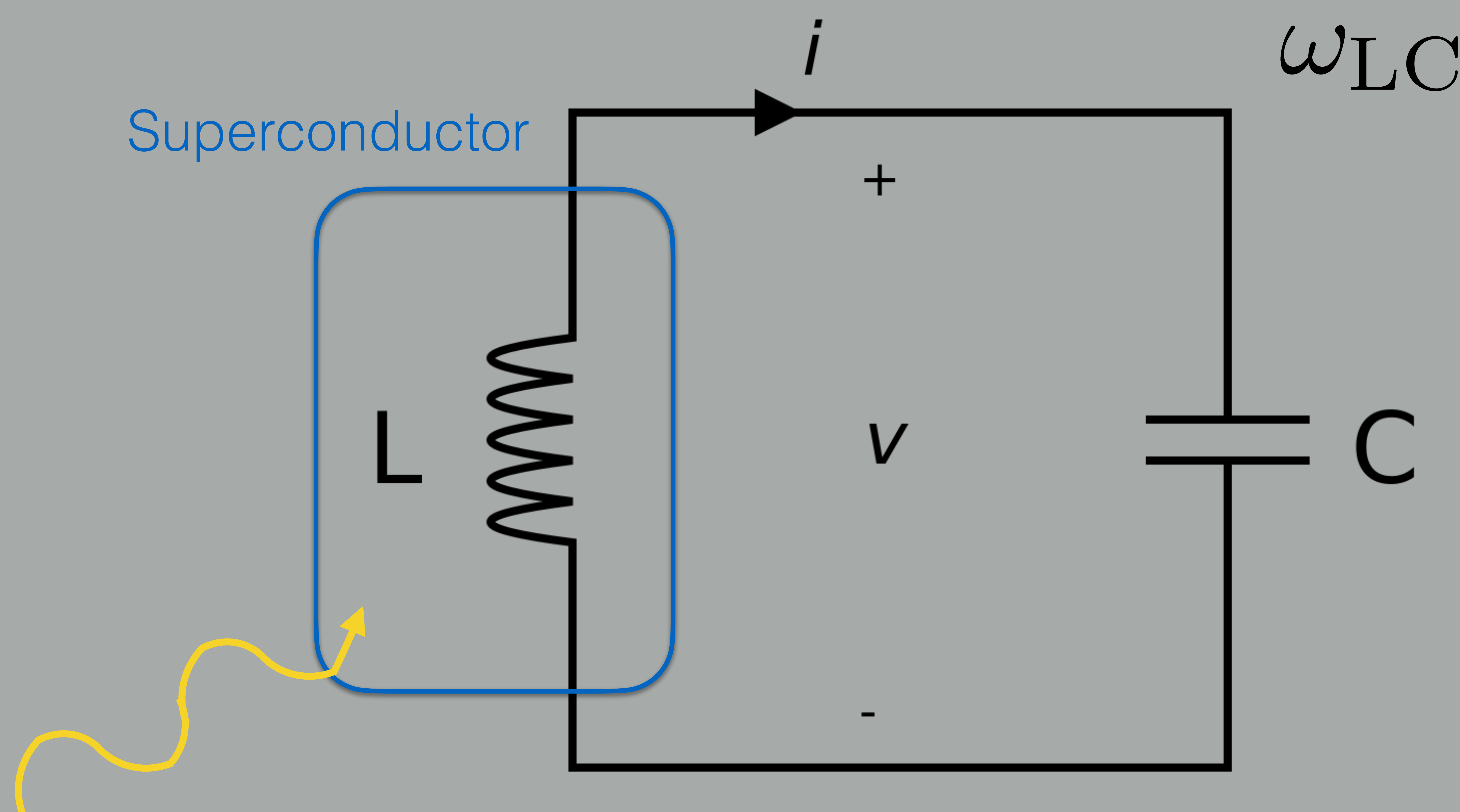
[1306.4238, S. Hailey-Dunsheath et al. (2021)]

Characterization of prototype KIDs sensors ongoing



Detection: KIDs

Kinetic Inductance Detectors (KIDs)



Photon absorbed by superconductor reduces kinetic inductance, altering the resonant frequency of the LC circuit

sensors ongoing

105 110
Frequency (GHz)

Detection: KIDs

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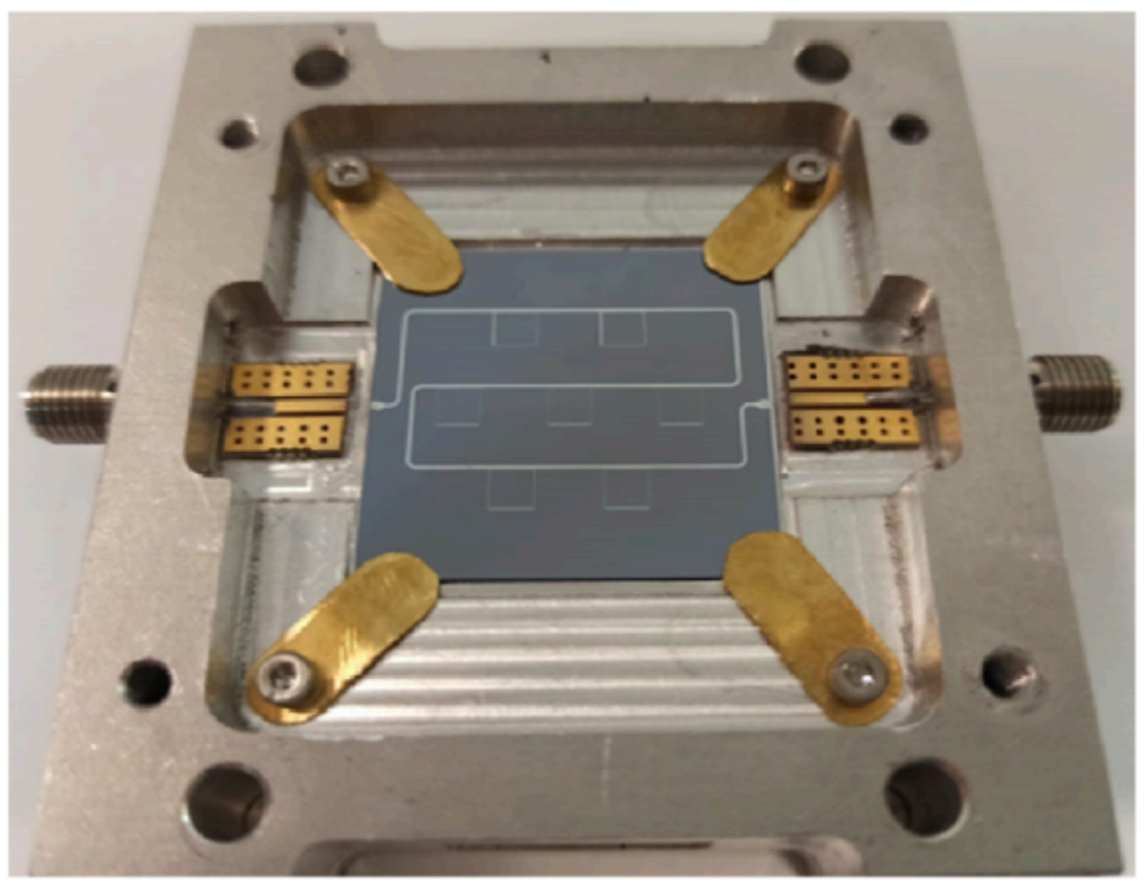

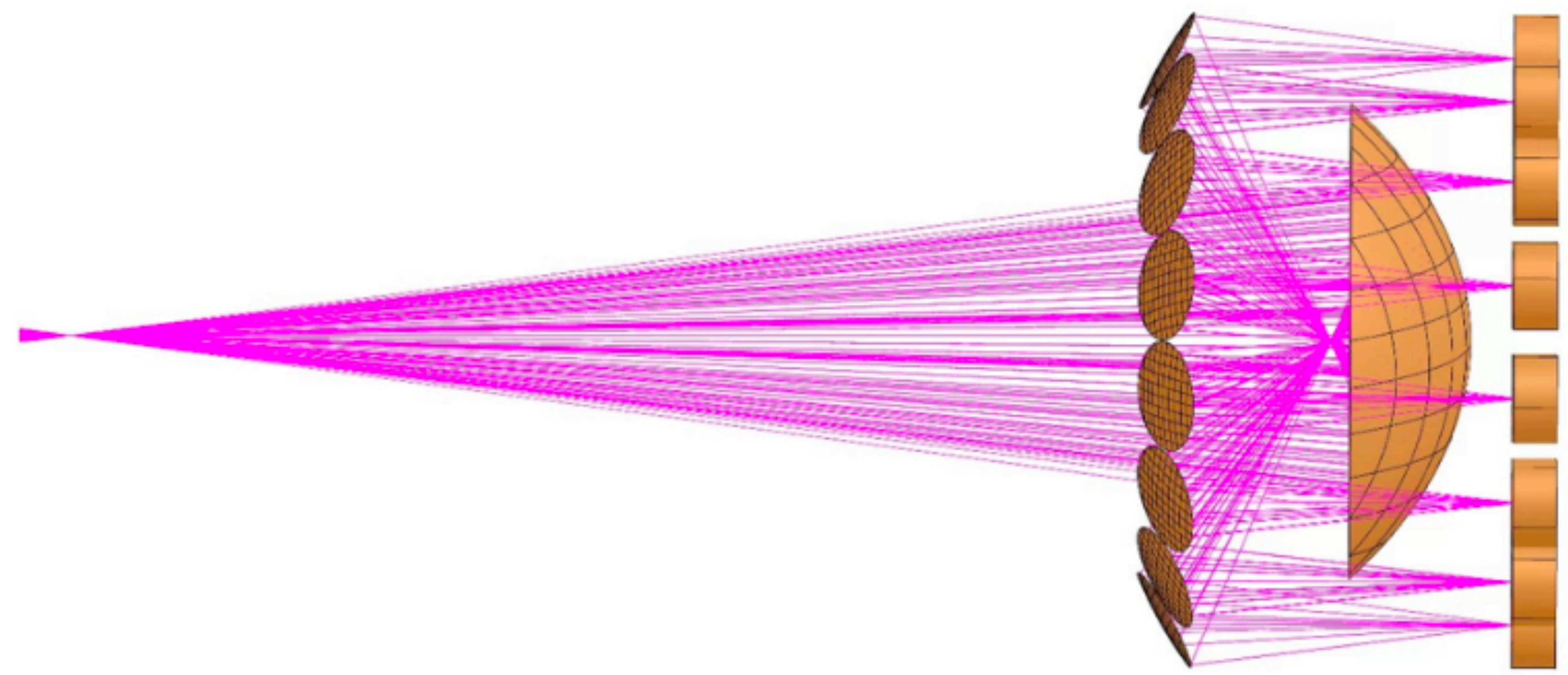

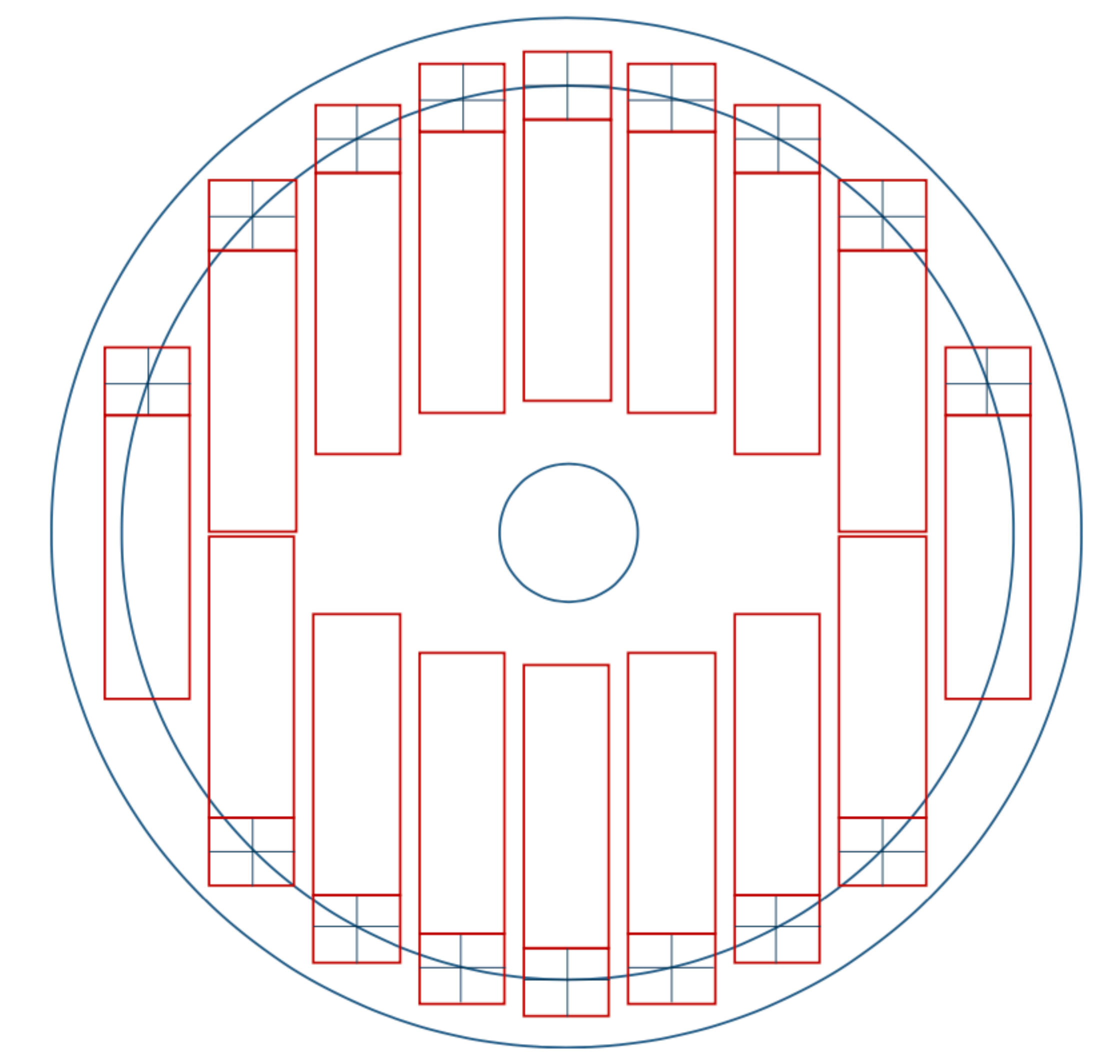

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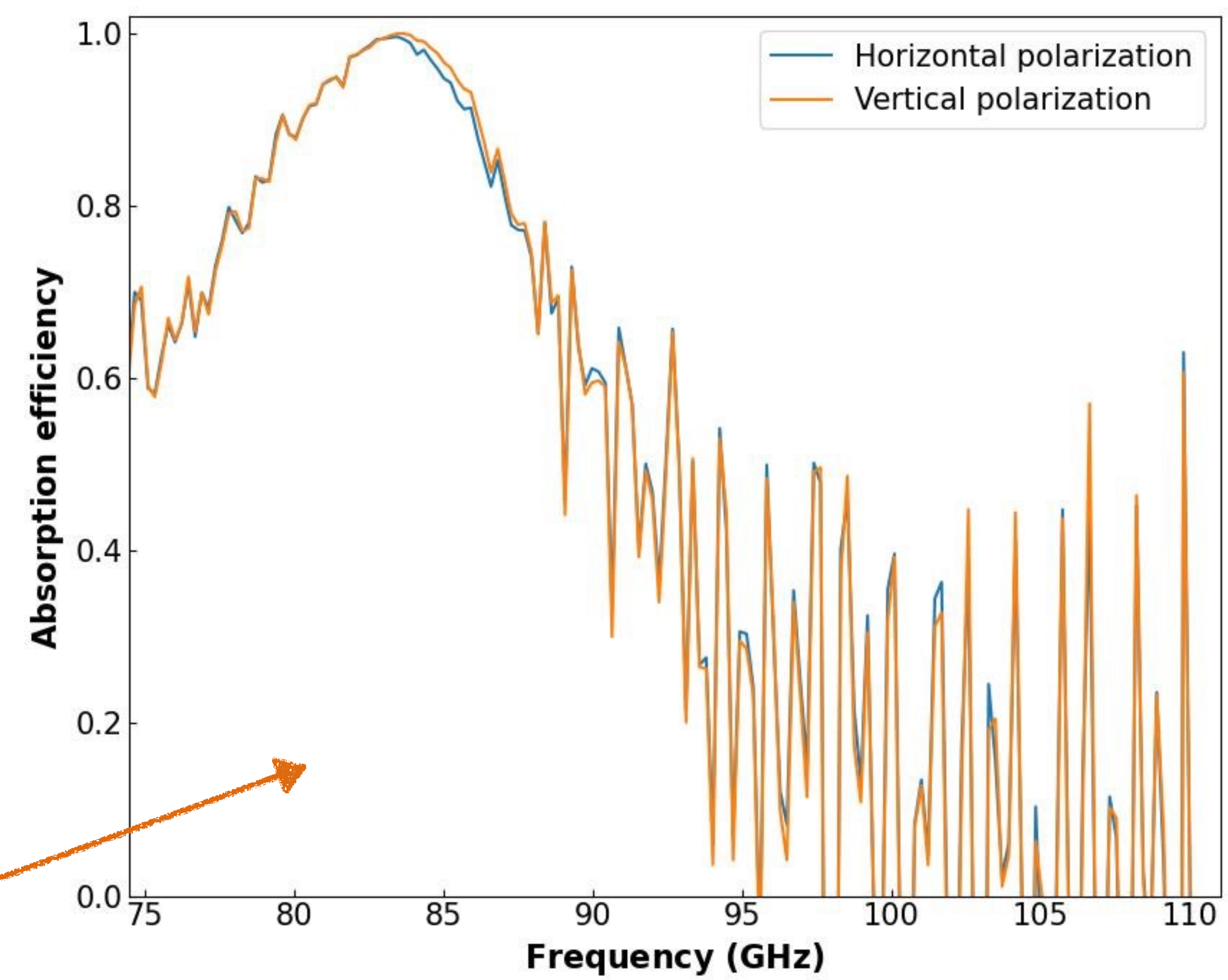
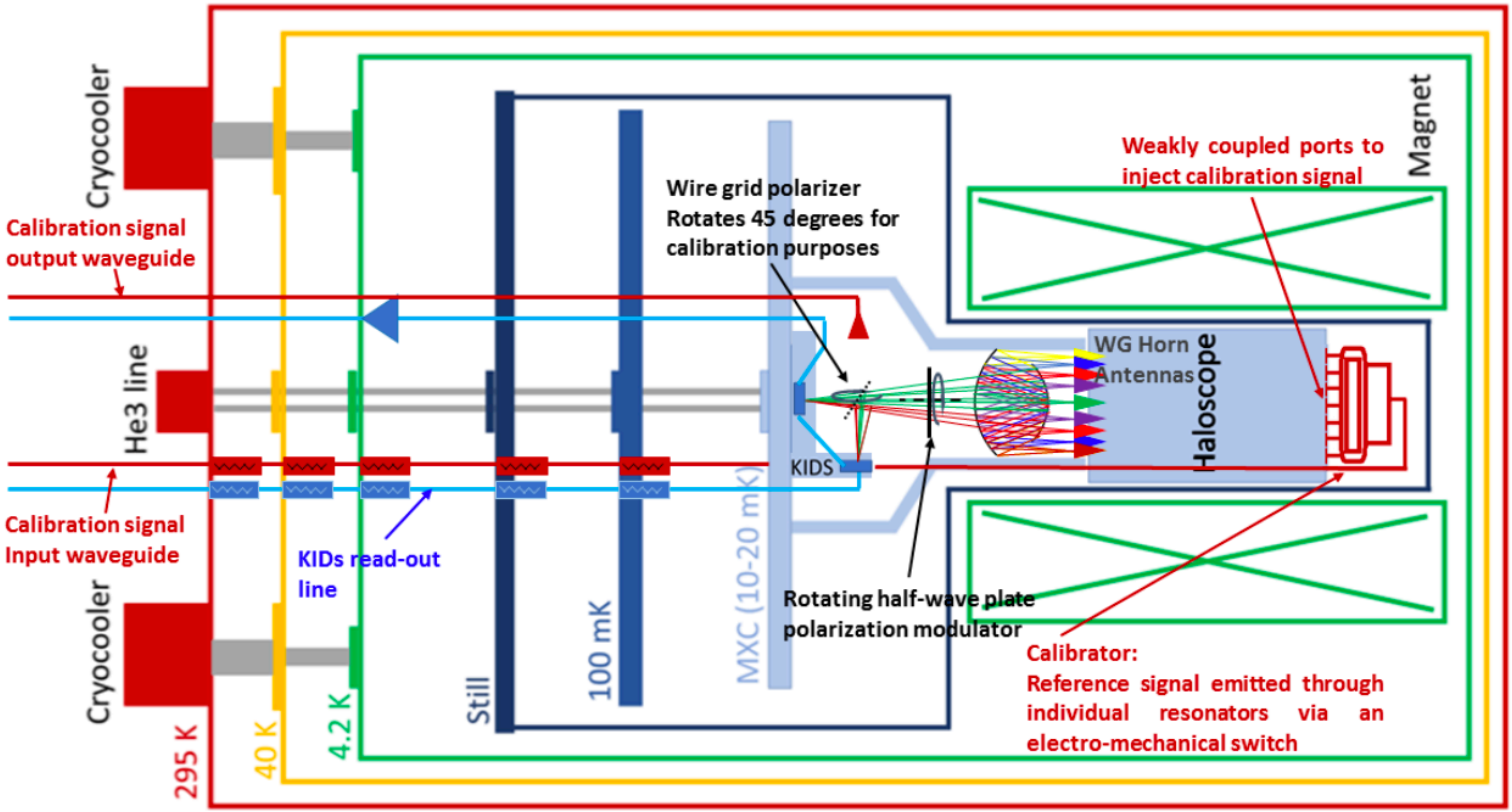


Characterization of prototype KIDs sensors ongoing

CADEx Conceptual Design

- Magnetic field + haloscope: < 0.1 K
- Optics : <0.1 K
- Superconducting detector system: mK
- Calibration system : injection signal



Immerse haloscope array in high static magnetic field of B = 8-10 T

Aim to **discriminate polarized axion-photon conversion signal** from unpolarized background.

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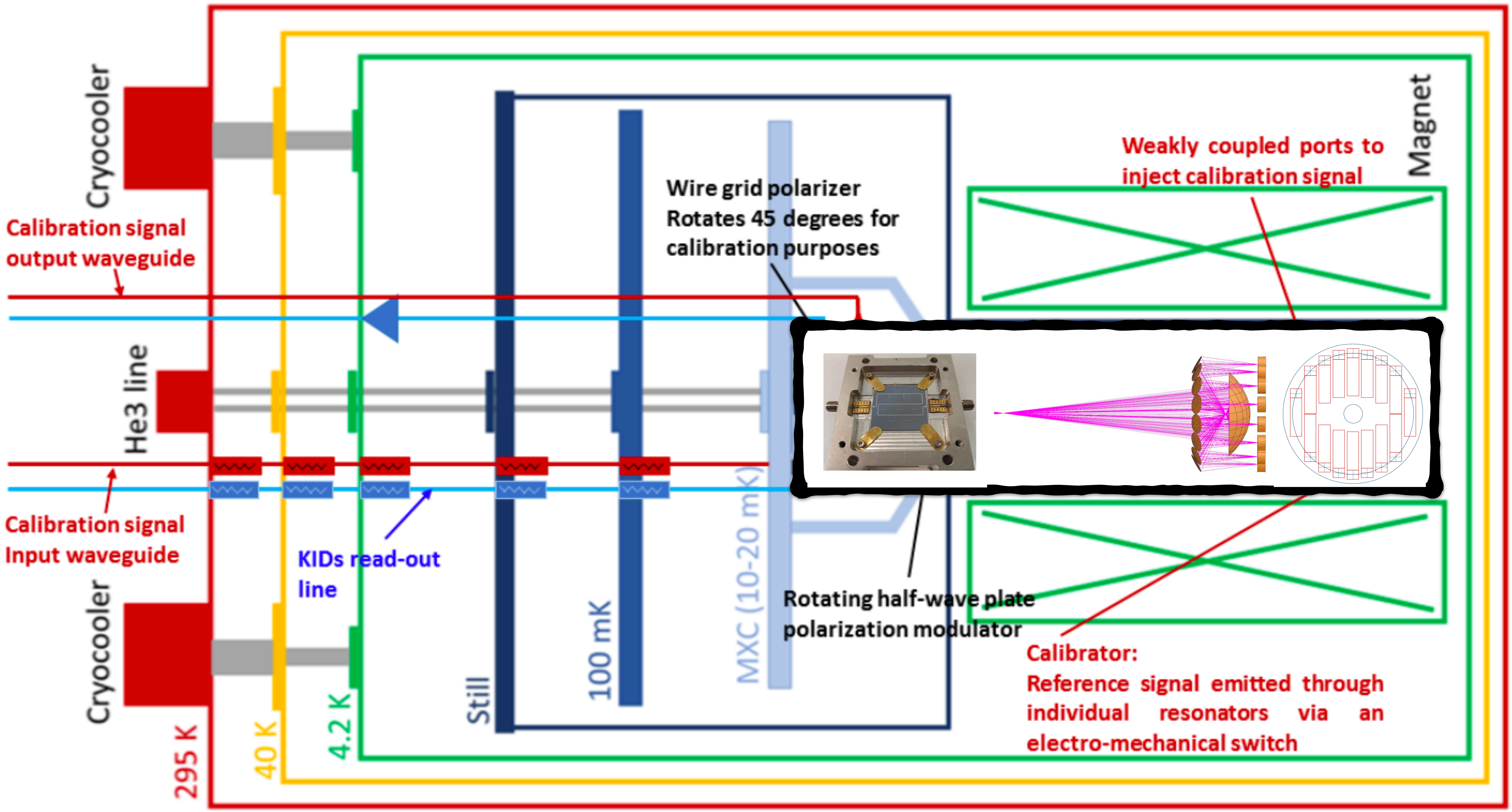

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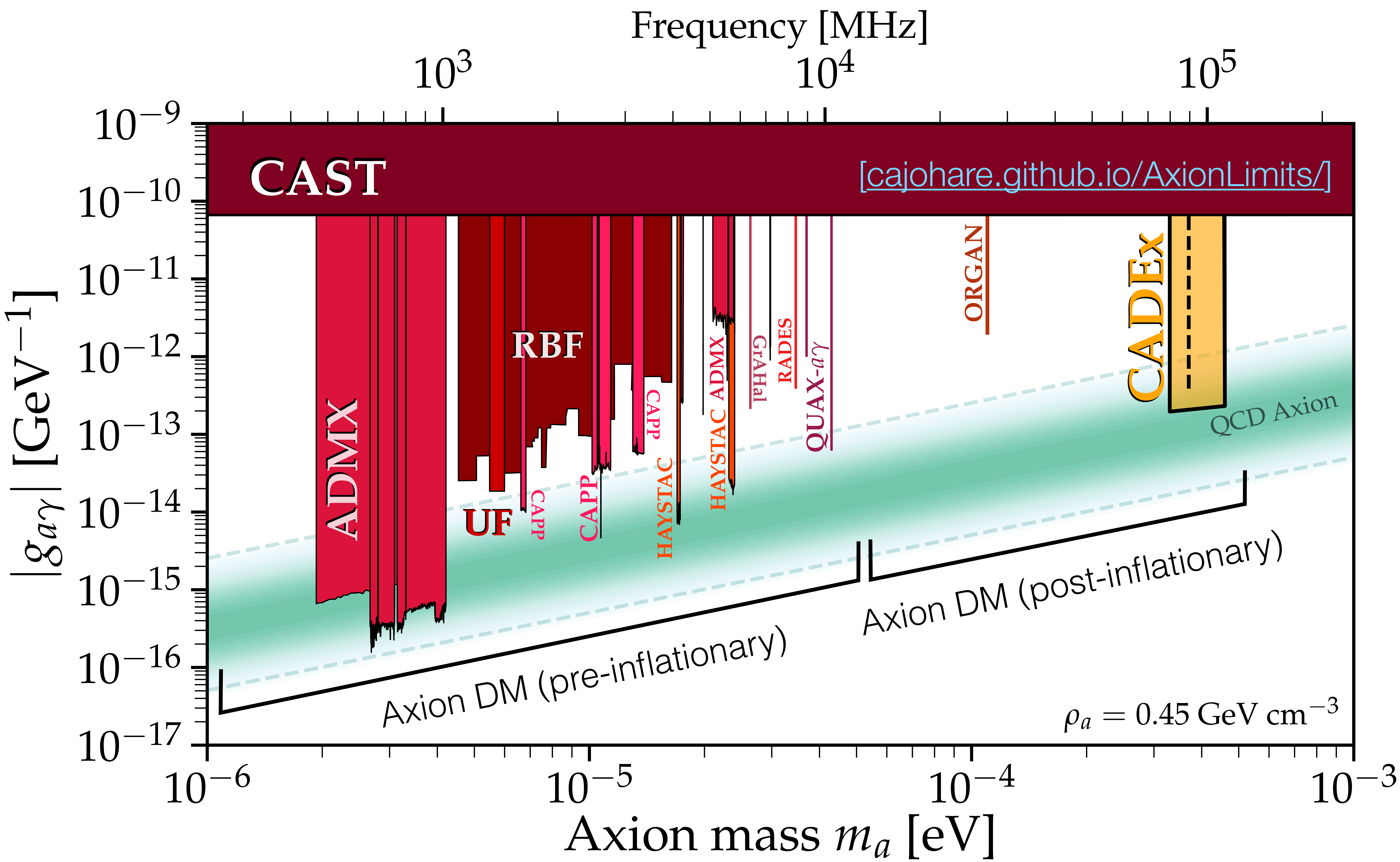
CADEx Axion Sensitivity

Axion-photon conversion power: $P_d \propto g_{a\gamma}^2 \frac{\rho_a}{m_a} B^2 V Q_0$



Estimate 5σ sensitivity assuming:

Magnetic field: $B = 8\,\mathrm{T}$
Total cavity volume: $V = 0.2\,\mathrm{L}$
Cavity quality factor: $Q_0 = 2 \times 10^4$

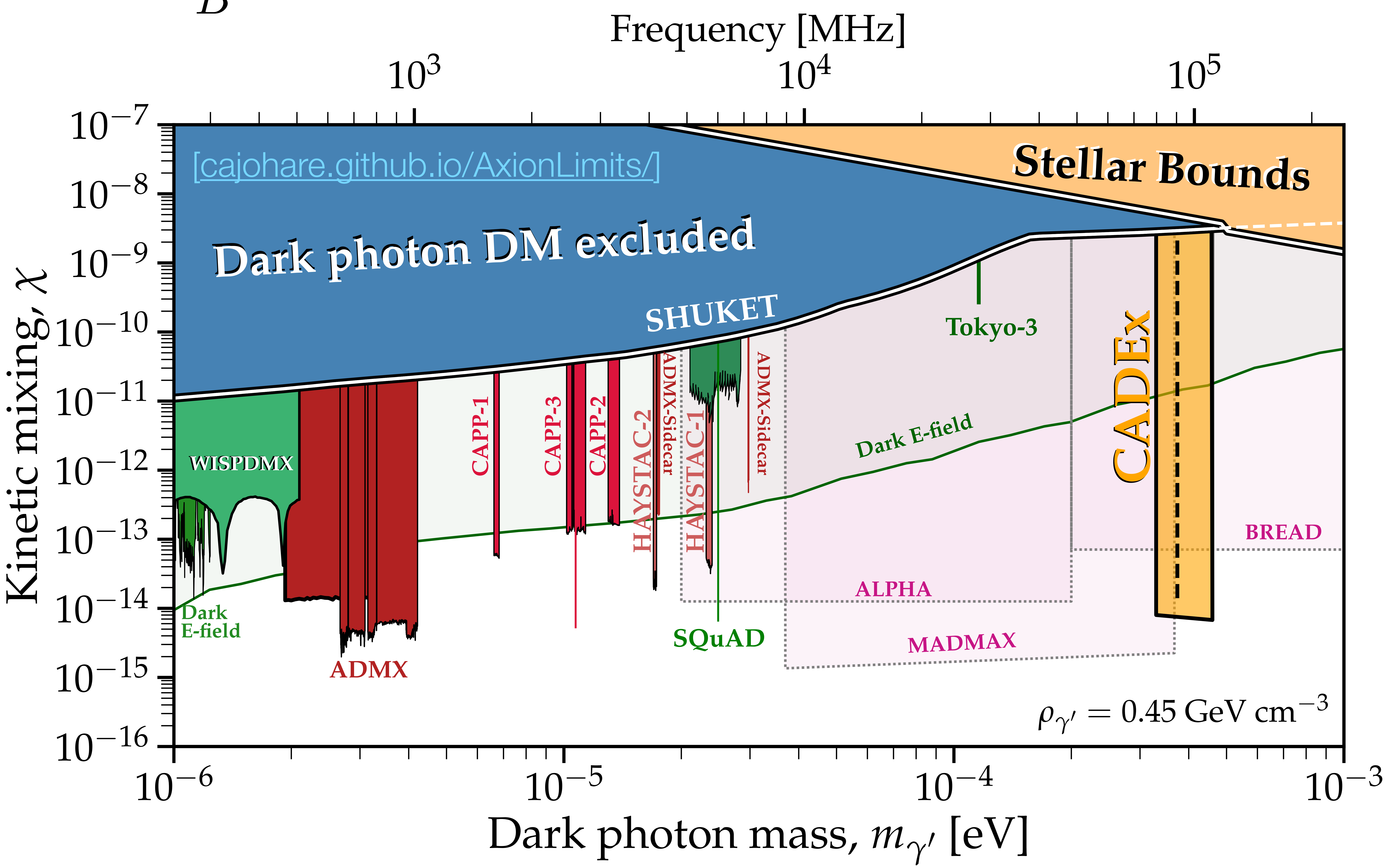
- - - - - - 3 month exposure with NEP = 10^{-19} $\mathrm{W}/\sqrt{\mathrm{Hz}}$

——— 8 year scan with NEP = 3×10^{-20} $\mathrm{W}/\sqrt{\mathrm{Hz}}$

Dark Photon Sensitivity

CADEx is sensitive to conversion of photons to **Dark Photon γ'** even without a magnetic field

$$g_{a\gamma} \to \frac{\chi m_{\gamma'} \sqrt{\cos^2 \theta_{\text{pol}}}}{B}$$



Other possibilities too:
e.g. GHz Gravitational Waves

- - - - - - 3 month exposure with NEP = 10^{-19} W/$\sqrt{\text{Hz}}$

——— 8 year scan with NEP = 3×10^{-20} W/$\sqrt{\text{Hz}}$

CADEx Timeline

CADEx already accepted by Canfranc Underground Laboratory (LSC) under EoI-31-2021

Design and Demonstration phase (2 years)

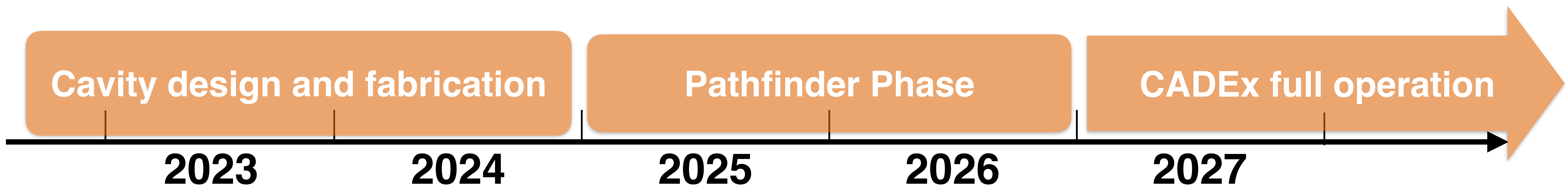
Cryostat acquisition, installation and operation. Design and fabrication of cavities. Demonstration of key technology (haloscope, detectors, etc.) in the lab.

Pathfinder phase (2 years)

Development of first prototype of CADEx and installation in the LSC facility in the first year (haloscope + KIDs + calibration). During the second year, the pathfinder experiment will be carried out.

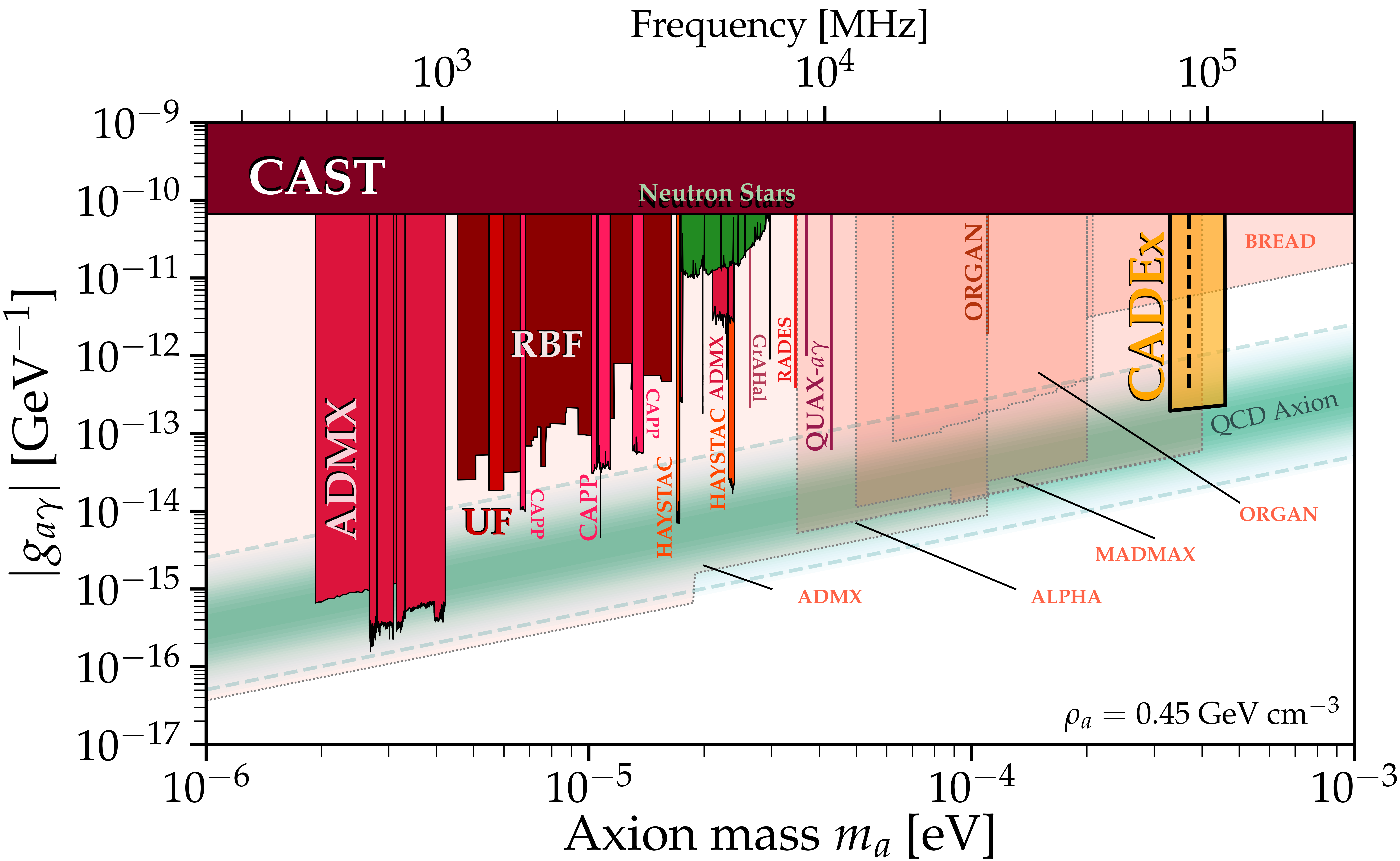
Operation phase (8 years)

Upgrade the experiment to improve the sensitivity & efficient non-resonant waveguide haloscope. Installation & Commissioning. Full Operation to cover mass range $m_a \in [330, 460]\,\mu\mathrm{eV}$



Outlook and Landscape

CADEx: a novel haloscope search for Dark Matter axions in the mass range 330–460 µeV (86–111 GHz)



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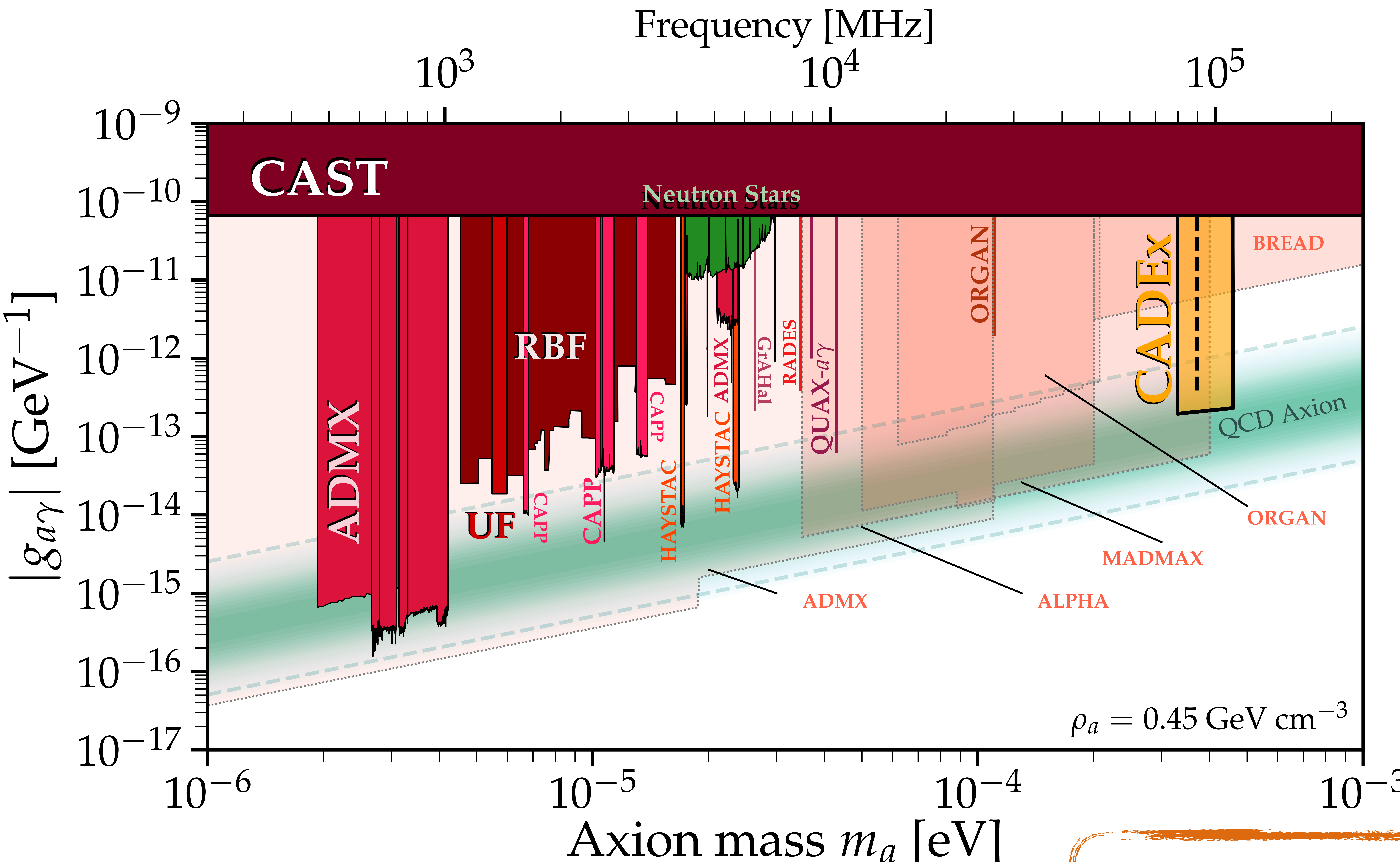
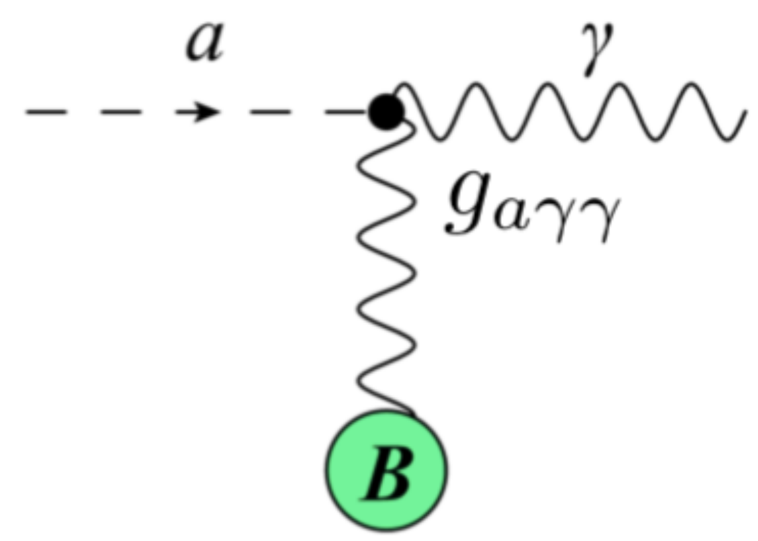


Thank you!

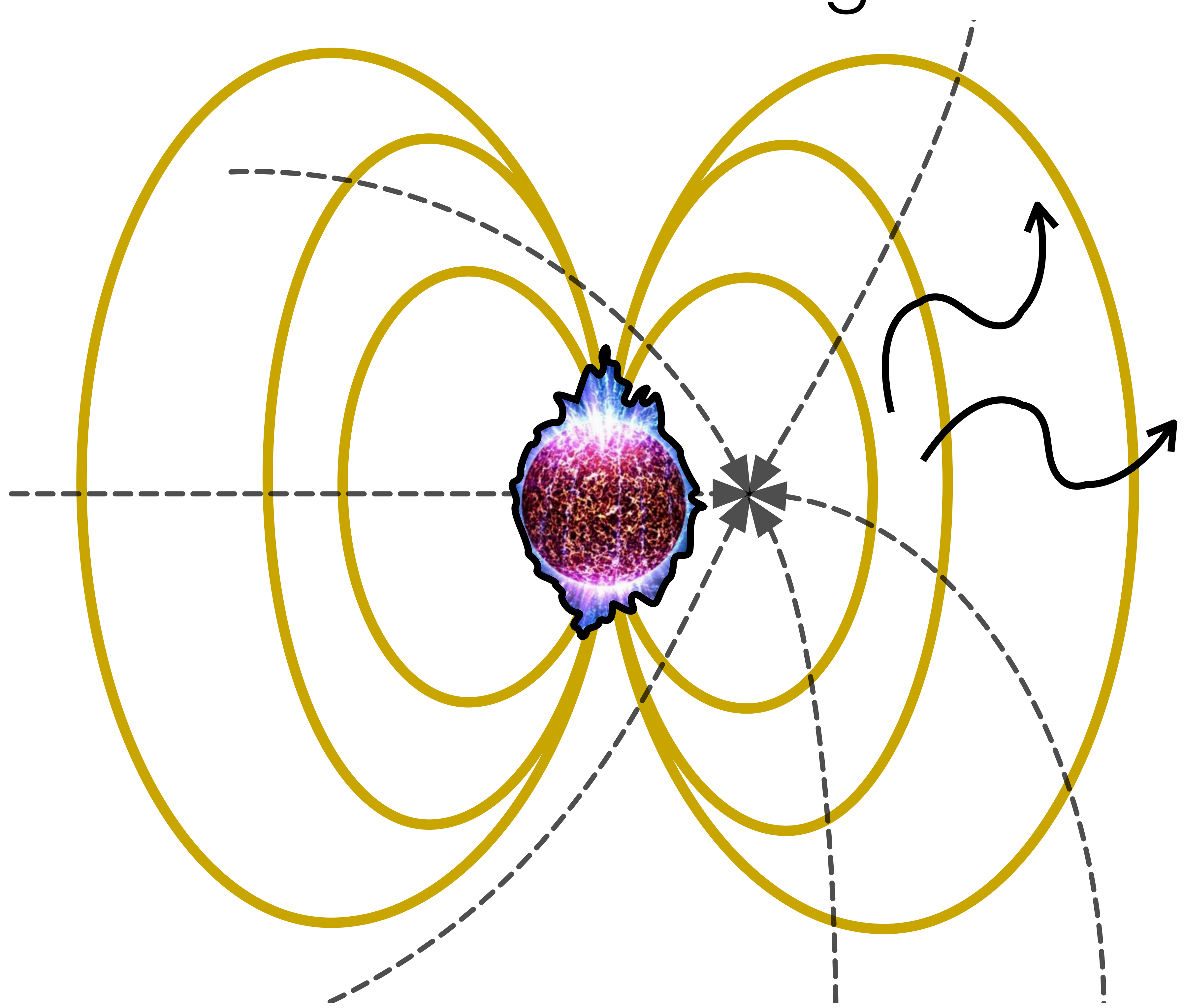
Additional Slides

Complementarity



NS surrounded by a dense plasma which allows 'resonant' conversion, **when axion mass matches plasma mass**: $\omega_p(B_0, P) = m_a/2\pi$

Axion-photon conversio
can lead to detectable
radio signals

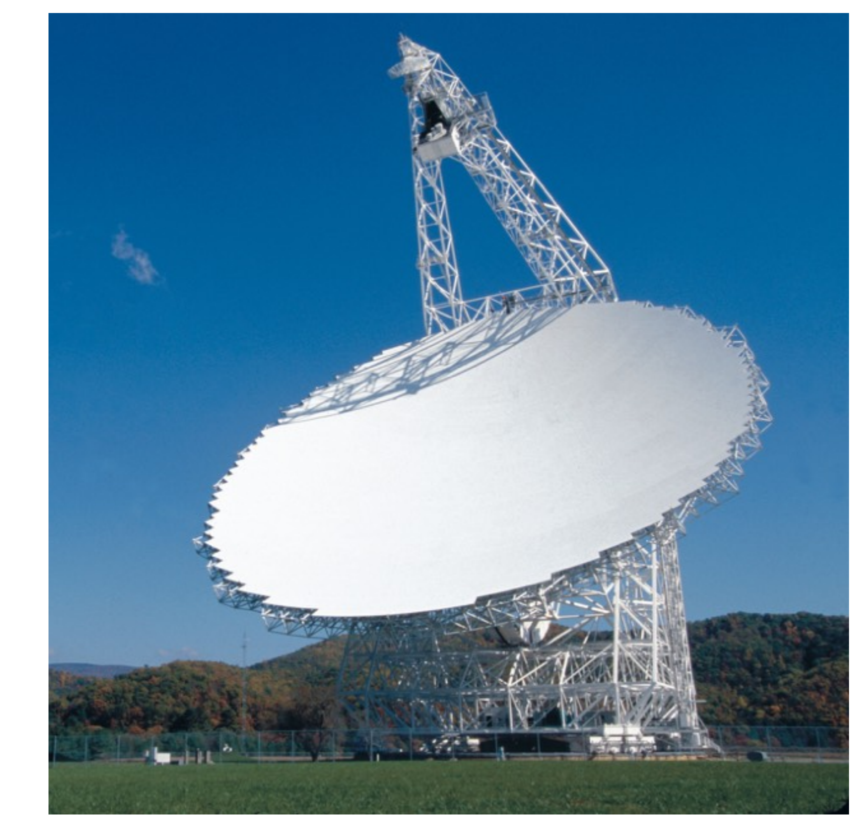


→ An axion haloscope!

Neutron stars benefit from enhanced DM density (strong gravitational field) and large magnetic fields ($B \gtrsim 10^{10}\,\mathrm{T}$)

[Originally proposed by Ben Safdi and collaborators, e.g. 1804.03145]

100 GHz Radio Searches
(same process…)

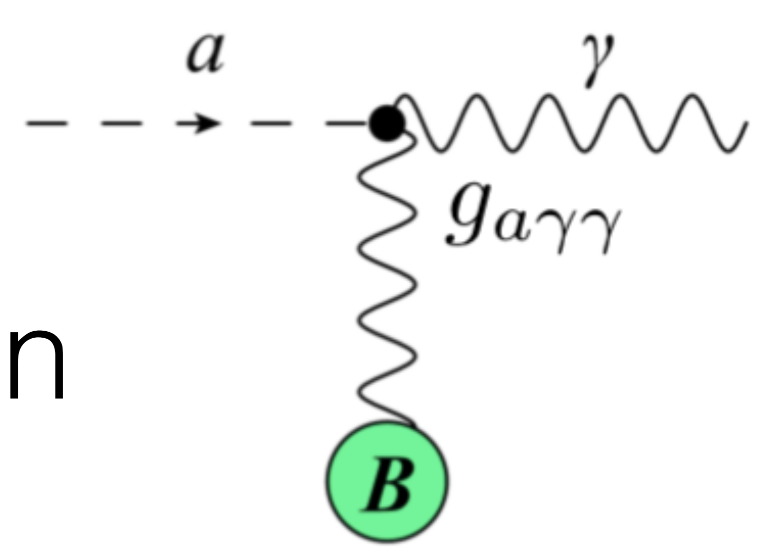


A new search strategy with much to do:

- Develop an **end-to-end signal modeling** pipeline (axion minicluster disruption, axion-photon conversion, radio detection)
- **Comprehensive exploration** of most promising targets (Andromeda? Milky Way? Elsewhere?)
- Explore a wide range of radio frequencies (and therefore a **wide range of axion masses**!)

[See e.g. 1910.11907, 2104.08290; 1912.08815, 2202.08274]

Complementarity



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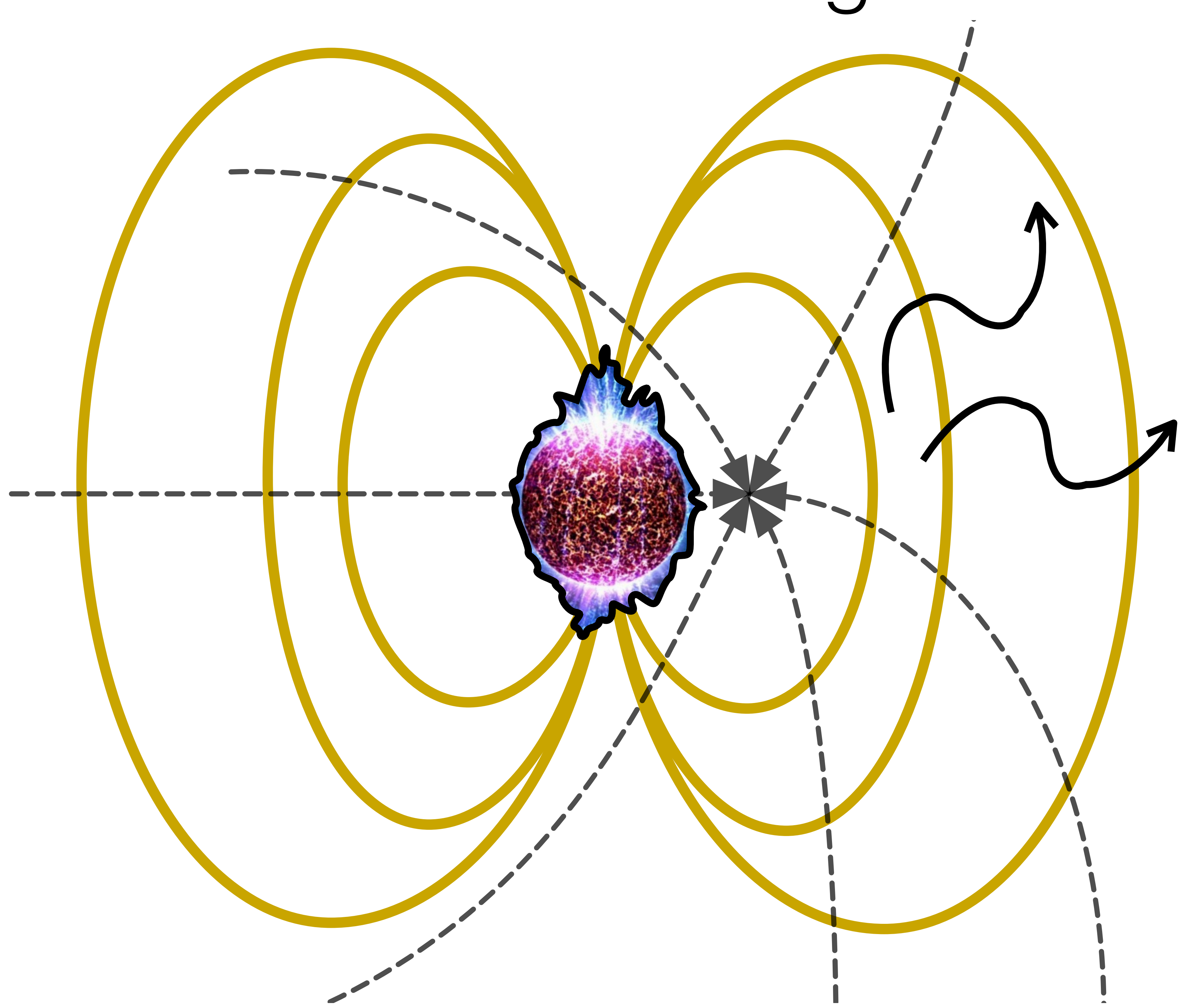

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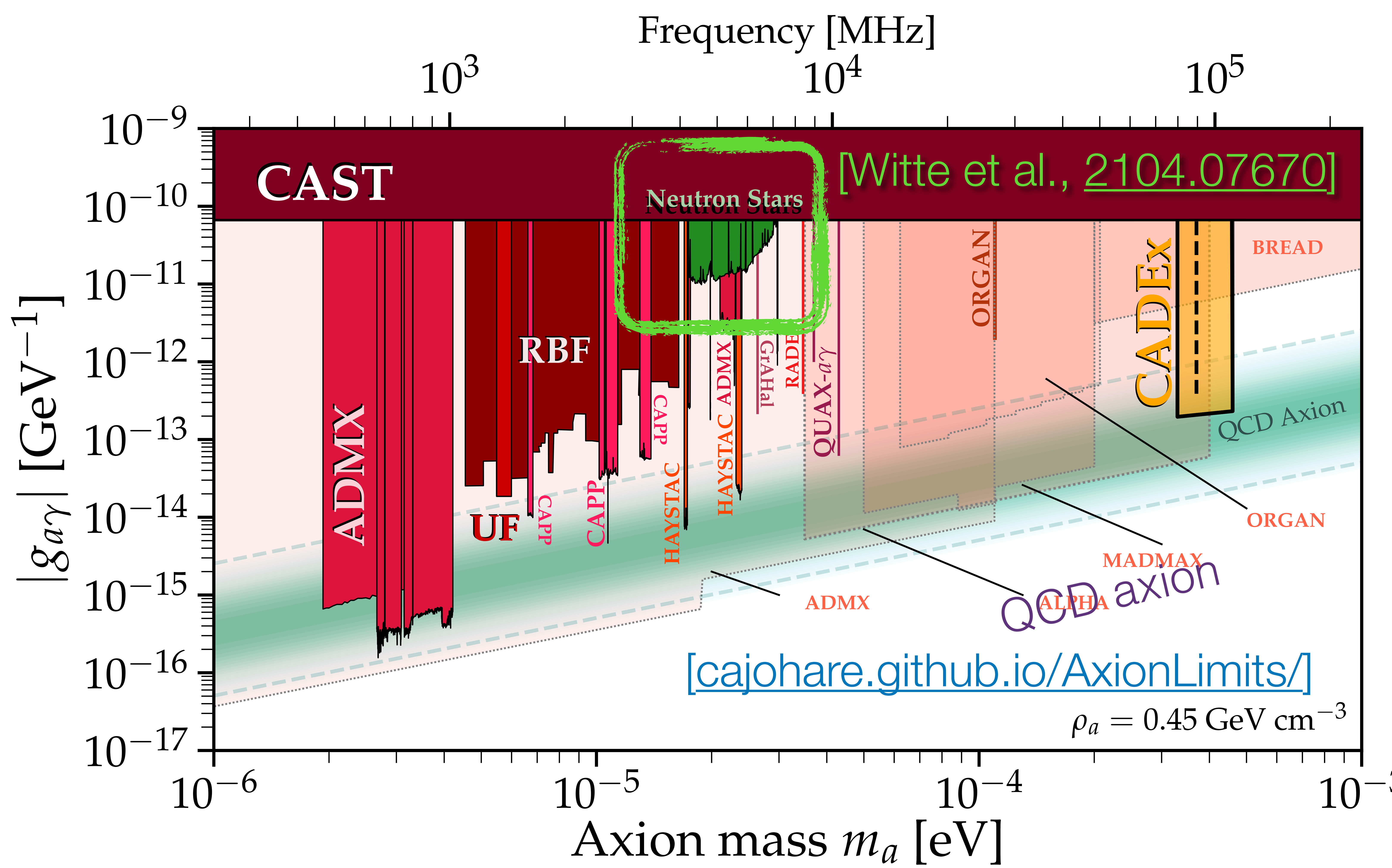


Can also look for transient radio signatures from encounters of neutron stars and **axion miniclusters**

[e.g. 2011.05377, 2011.05378]

Sensitivity Estimates

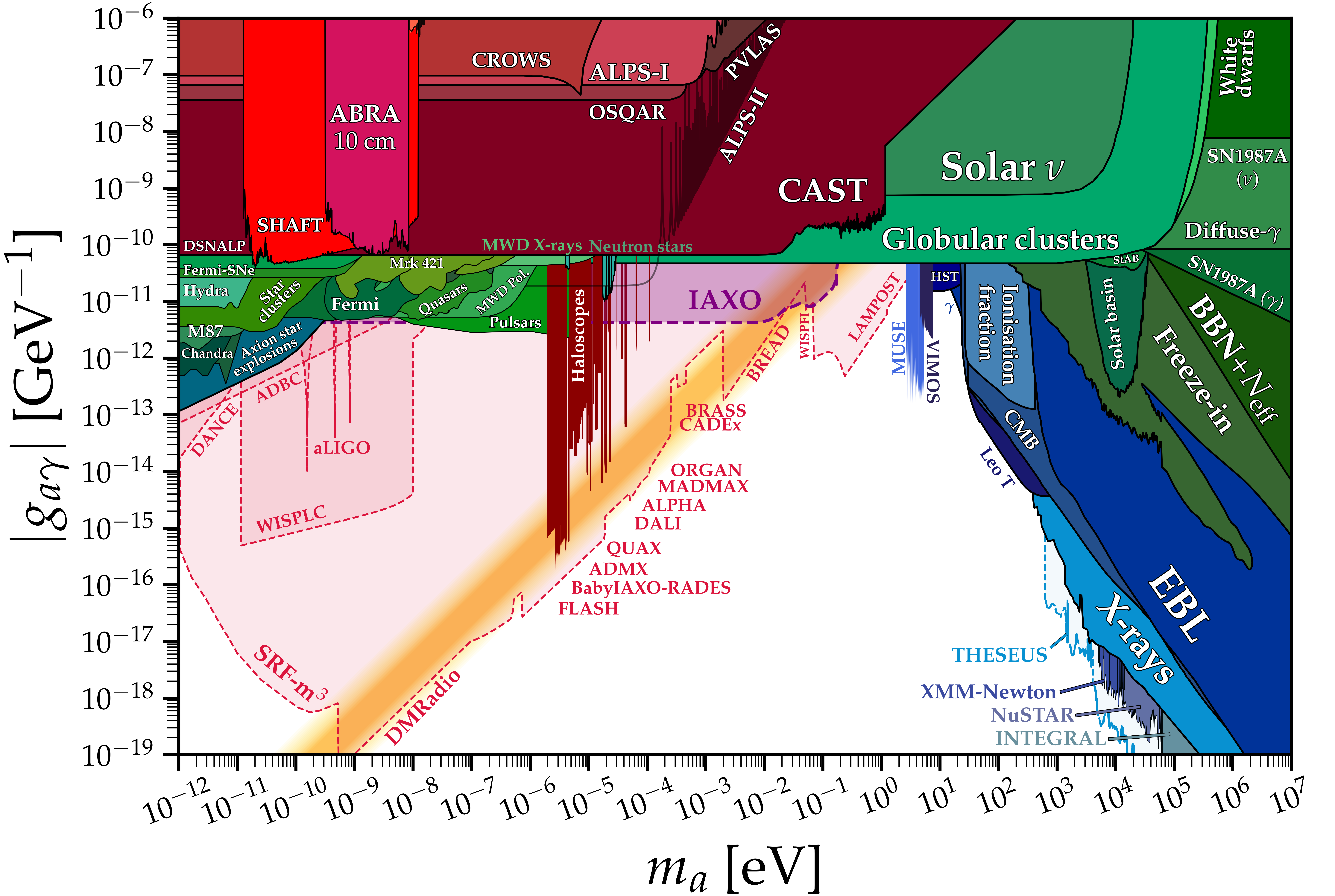
Parameter	Symbol	Value
Axion DM Density	ρ_a	$0.45\,\mathrm{GeV\,cm^{-3}}$
Total cavity volume	V	$0.2\,\mathrm{L}$
Magnetic field	B	8–10 T
Unloaded quality factor	Q_0	2×10^4
Coupling factor	β	1
Form factor	C	0.66
Axion mass	m_a	330–460 µeV
Noise equivalent power	NEP	1×10^{-19} (3×10^{-20}) $\mathrm{W}/\sqrt{\mathrm{Hz}}$

Detected axion-photon conversion power:

$$P_d = \frac{\beta}{(1+\beta)^2} g_{a\gamma}^2 \frac{\rho_a}{m_a} B^2 C V Q_0$$

$$\begin{aligned} g_{a\gamma}[\mathrm{GeV}^{-1}] &= \left(\frac{3.88 \times 10^2}{B[\mathrm{T}]}\right) \sqrt{\frac{(1+\beta)^2}{\beta}} \sqrt{\frac{\mathrm{SNR}\, m_a[\mathrm{eV}]\, \mathrm{NEP}[\mathrm{W}/\sqrt{\mathrm{Hz}}]}{V[\mathrm{L}]\, Q_0\, t[\mathrm{s}]^{\frac{1}{2}}\, C}} \\ &= 3.88 \times 10^{-13} \mathrm{GeV}^{-1} \\ &\times \left(\frac{10\mathrm{T}}{B}\right) \left(\frac{0.25}{\frac{\beta}{(1+\beta)^2}}\right)^{\frac{1}{2}} \left(\frac{\mathrm{SNR}}{5}\right)^{\frac{1}{2}} \left(\frac{m_a}{3.7 \times 10^{-4}\,\mathrm{eV}}\right)^{\frac{1}{2}} \\ &\times \left(\frac{\mathrm{NEP}}{1 \times 10^{-19}\,\mathrm{W}/\sqrt{\mathrm{Hz}}}\right)^{\frac{1}{2}} \left(\frac{0.2\mathrm{L}}{V}\right)^{\frac{1}{2}} \left(\frac{2 \times 10^4}{Q_0}\right)^{\frac{1}{2}} \left(\frac{3\ \mathrm{months}}{t}\right)^{\frac{1}{4}} \\ &\times \left(\frac{0.66}{C}\right)^{\frac{1}{2}}. \end{aligned}$$

The Wider Picture



The Wider Picture

[cajohare.github.io/AxionLimits/]