(Future) Experimental Efforts to Search for Dark Matter Axions at Stockholm University

Junu Jeong (Jun-Woo Jeoung)

Department of Physics, Stockholm Univeristy

Partikeldagarna 2024, 21/10

Outline

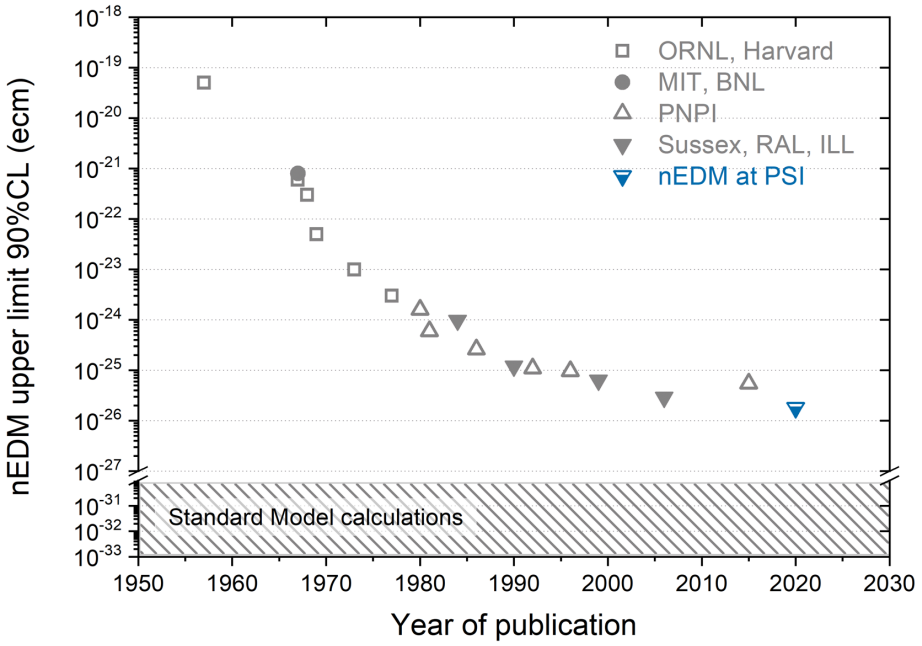
- Axion Overview
- Cavity Haloscope
- ALPHA Collaboration
- SU Group’s Objective
- Summary

Axion Overview

Strong CP Problem

Why the **CP** symmetry seems to be conserved in QCD?

$\theta_{\mathbf{CP}}^{\mathrm{th.}} \sim O(1)$ but $\theta_{\mathbf{CP}}^{\mathrm{exp.}} \leq 10^{-10}$



$$\left|\vec{d}_n\right| \sim 3\times10^{-16}\bar{\theta}\; e\cdot\mathrm{cm}$$

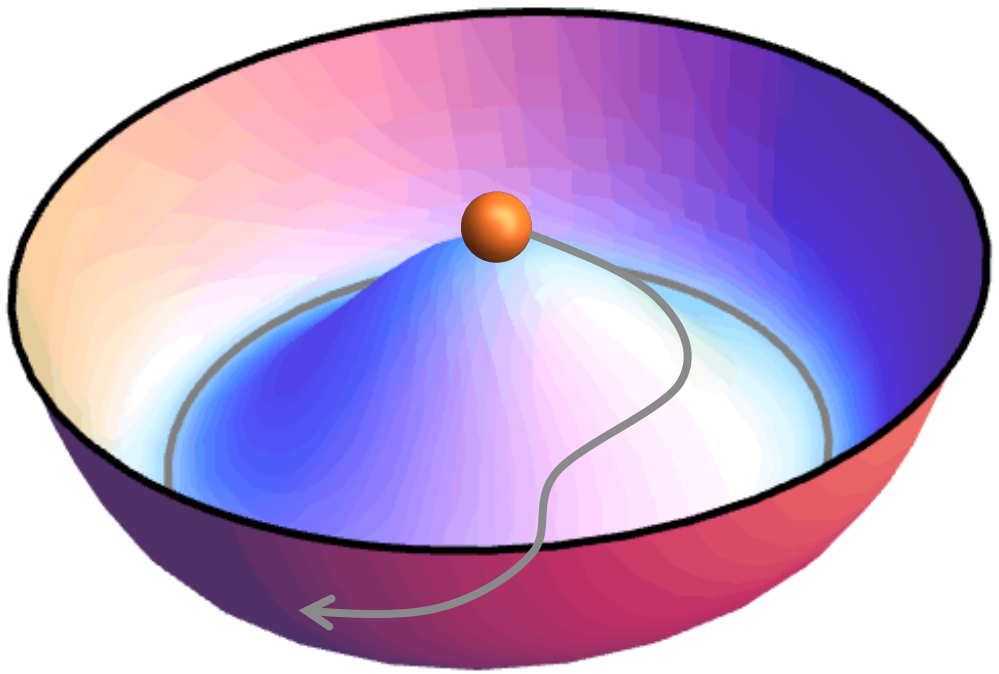
Axion Overview

Strong CP Problem

Why the **CP** symmetry seems to be conserved in QCD?

$\theta_{\mathbf{CP}}^{\mathrm{th.}} \sim O(1)$ but $\theta_{\mathbf{CP}}^{\mathrm{exp.}} \leq 10^{-10}$

Titled Mexican-Hat Potential



$\theta_{\mathbf{CP}} = \mathbf{0}$

Peccei-Quinn Mechanism

Prominent solution to the strong CP problem

S.S.B. of new global U(1) chiral symmetry

As the universe cools down, dynamically $\theta_{\mathbf{CP}} \rightarrow 0$

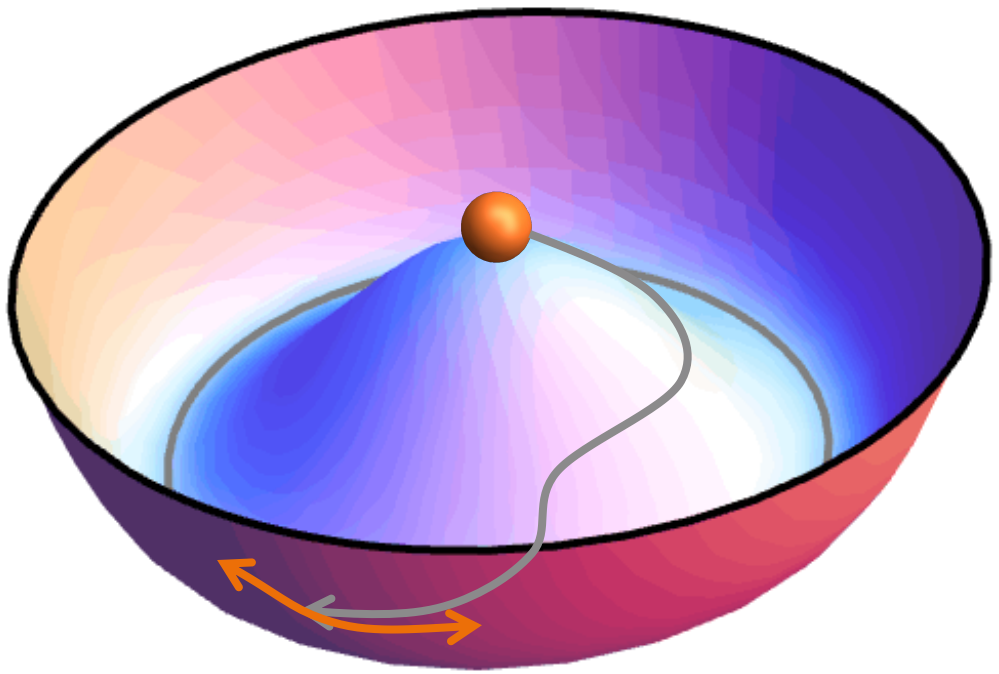
Axion Overview

Strong CP Problem

Why the **CP** symmetry seems to be conserved in QCD?

$\theta_{\mathbf{CP}}^{\mathrm{th.}} \sim O(1)$ but $\theta_{\mathbf{CP}}^{\mathrm{exp.}} \leq 10^{-10}$

Titled Mexican-Hat Potential



Axion

Peccei-Quinn Mechanism

Prominent solution to the strong CP problem

S.S.B. of new global U(1) chiral symmetry

As the universe cools down, dynamically $\theta_{\mathbf{CP}} \rightarrow 0$

Axion

Oscillation of $\theta_{\mathbf{CP}}$ (Pseudo-Goldstone Boson)

High energy scale of S.S.B. ⇒ light and invisible

Sufficient quantities in a non-relativistic state

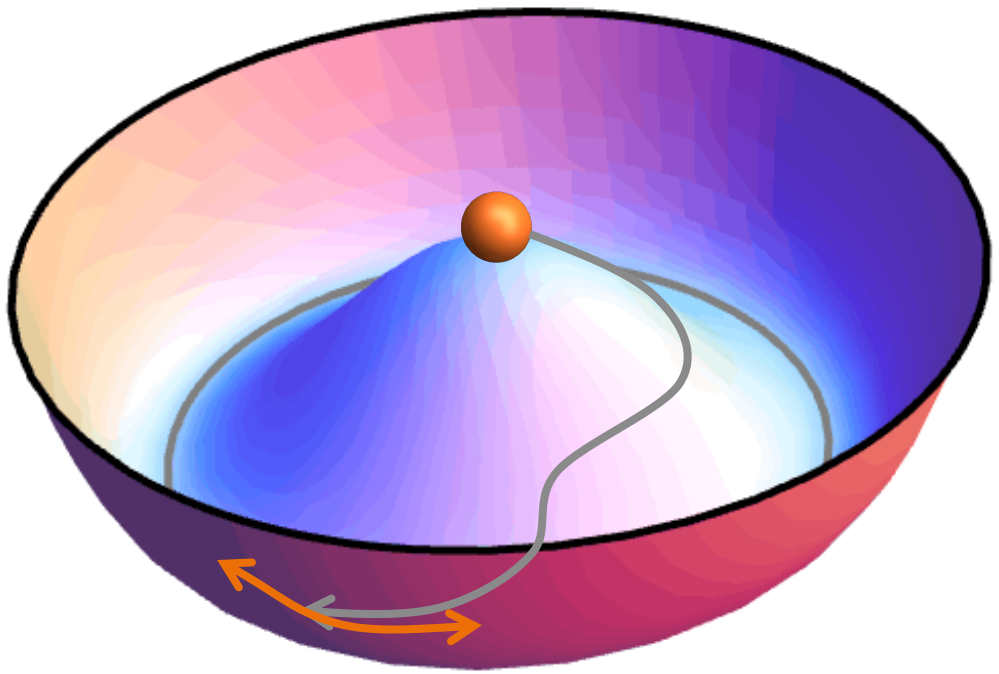
Axion Overview

Strong CP Problem

Why the **CP** symmetry seems to be conserved in QCD?

$\theta_{\mathbf{CP}}^{\mathrm{th.}} \sim O(1)$ but $\theta_{\mathbf{CP}}^{\mathrm{exp.}} \leq 10^{-10}$

Titled Mexican-Hat Potential



Axion

Peccei-Quinn Mechanism

Prominent solution to the strong CP problem

S.S.B. of new global U(1) chiral symmetry

As the universe cools down, dynamically $\theta_{\mathbf{CP}} \rightarrow 0$

Axion

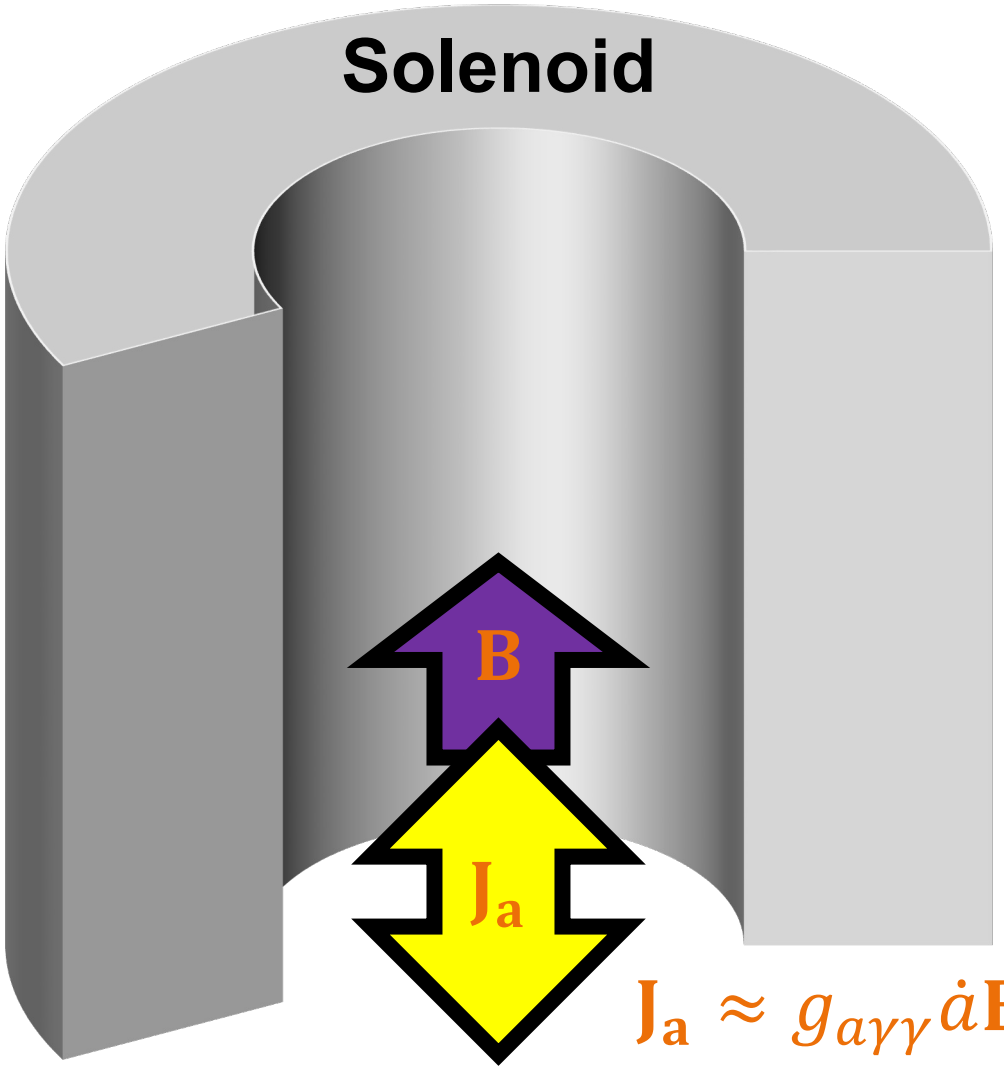
Oscillation of $\theta_{\mathbf{CP}}$ (Pseudo-Goldstone Boson)

High energy scale of S.S.B. ⇒ light and invisible

Sufficient quantities in a non-relativistic state

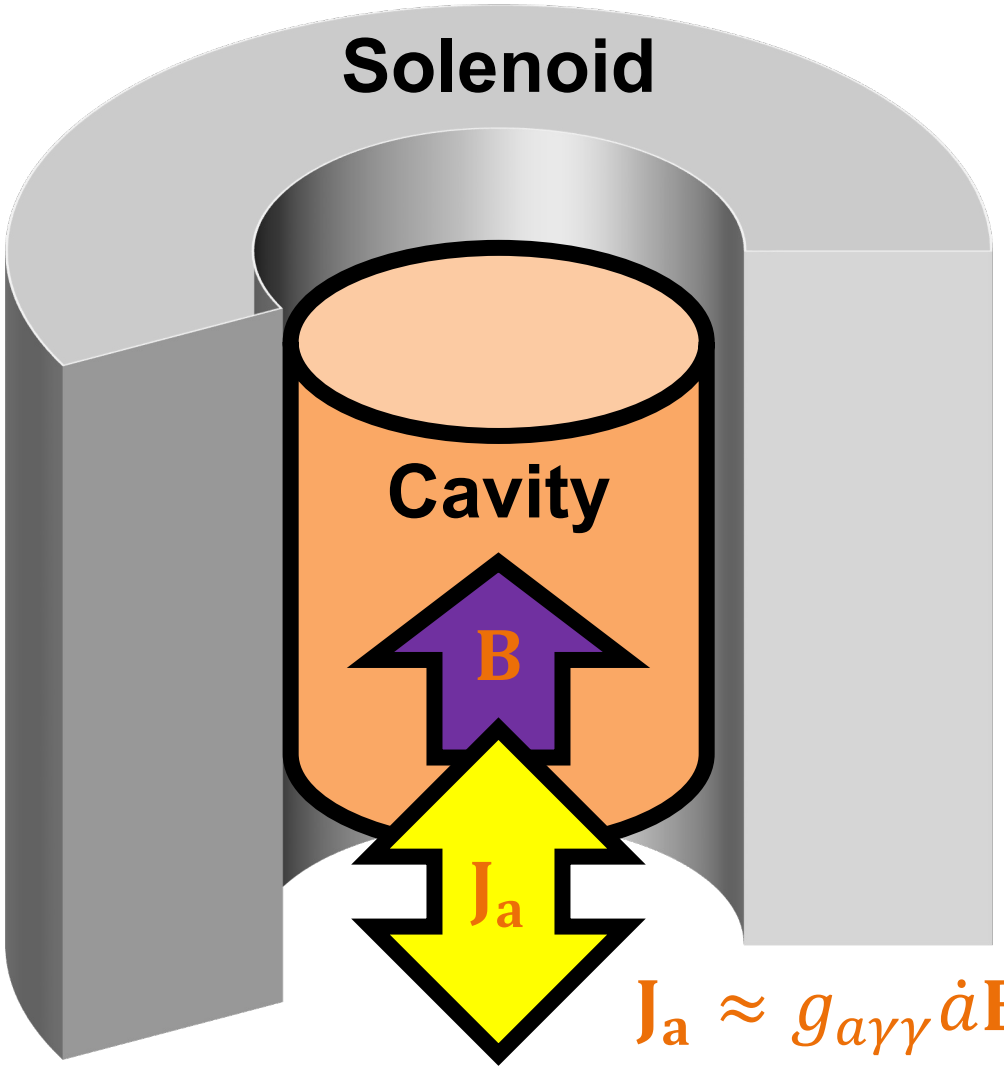
⇒ **Strong Dark Matter Candidate**

Cavity Haloscope



$$J_a \approx g_{a\gamma\gamma}\dot{a}B$$

Cavity Haloscope

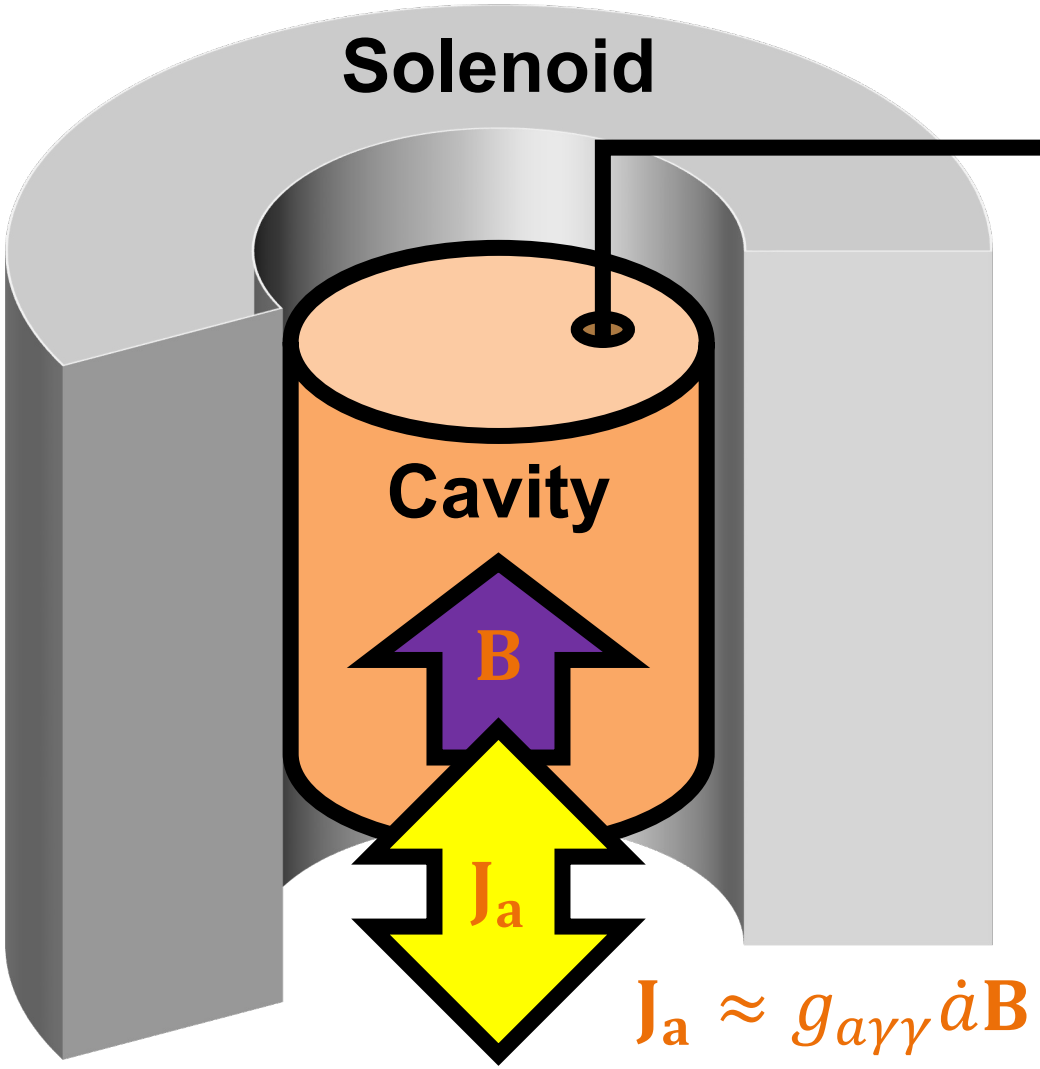


Axion-to-Photon Conversion

(when $\omega_a = \omega_c$)

$$P_{a\gamma\gamma} \approx \frac{g_{a\gamma\gamma}^2 \rho_a}{m_a} \langle B^2 \rangle V_c Q_c C \sim 10^{-23}\ \mathrm{W}$$

Cavity Haloscope



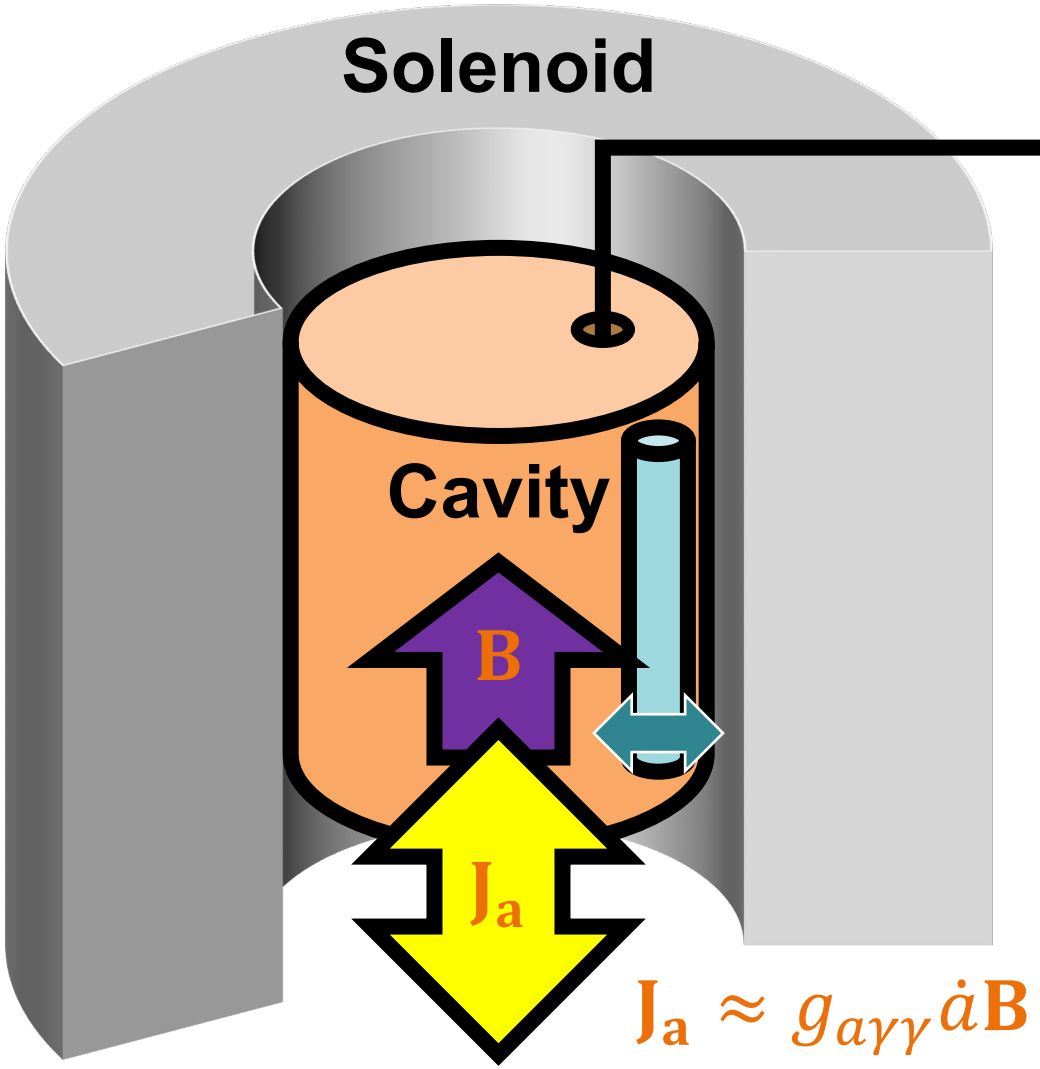
Readout electronics

Axion-to-Photon Conversion

(when $\omega_a = \omega_c$)

$$P_{a\gamma\gamma} \approx \frac{g_{a\gamma\gamma}^2 \rho_a}{m_a} \langle B^2 \rangle V_c Q_c C \sim 10^{-23}\ \mathrm{W}$$

Cavity Haloscope



Scanning rate

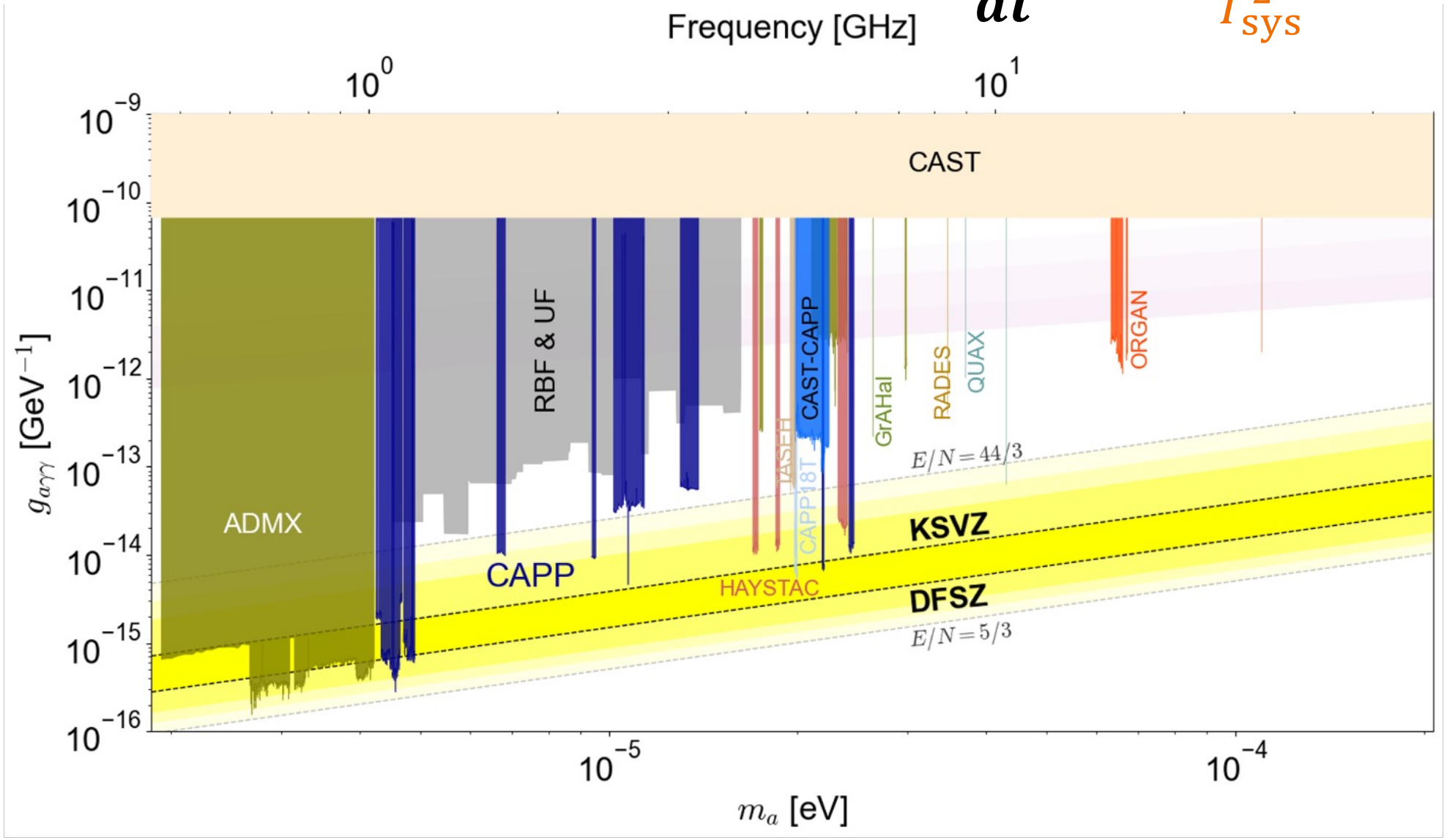
(ω_a is unknown *a priori*)

$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{\mathrm{sys}}^2}$$

- ***Strong and large magnet***
- ***High quality factor cavity***
- ***Clever design of cavity***
- ***Low system noise temperature***

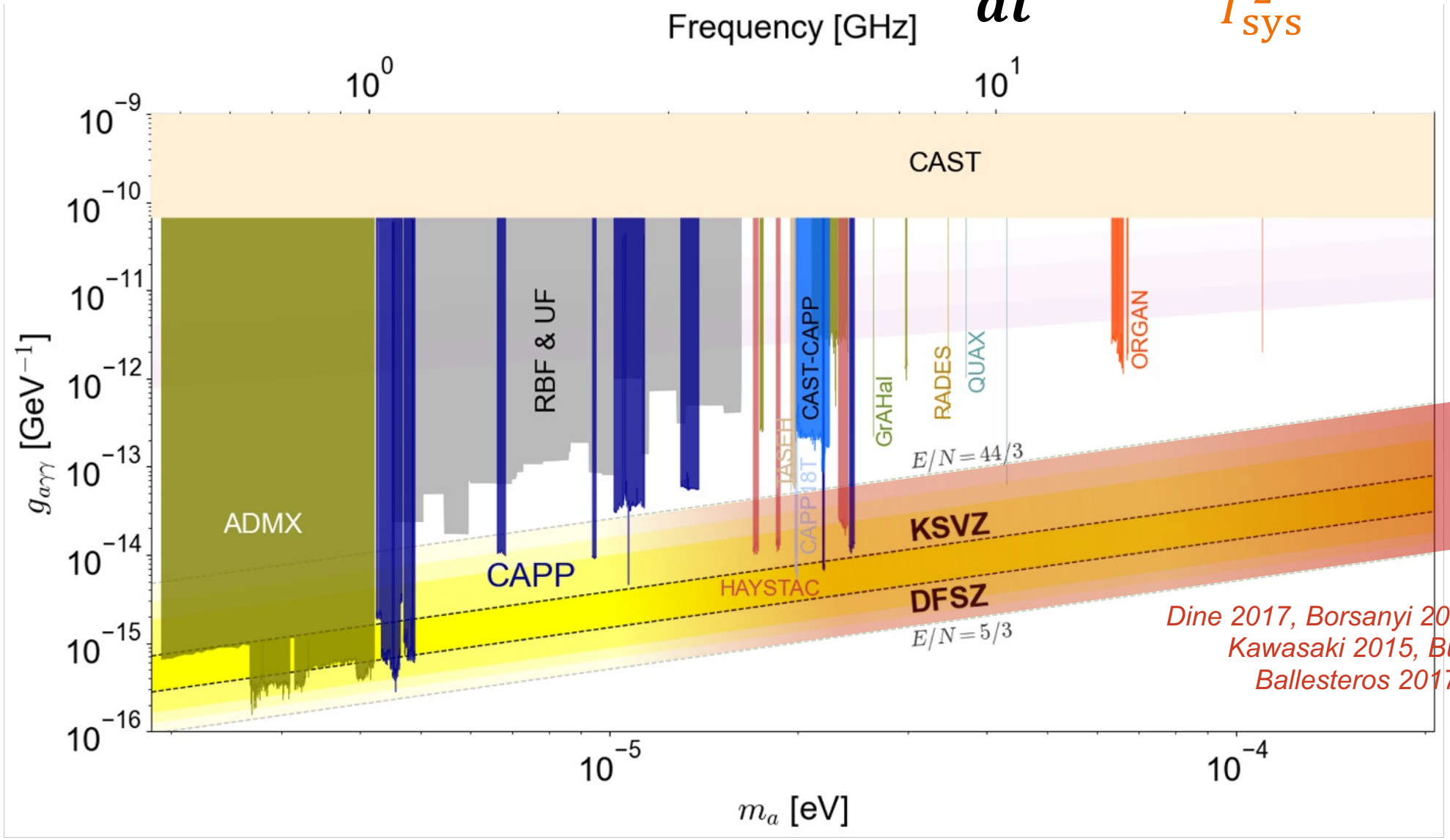
Cavity Haloscope

$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$



High-Mass Axion Search

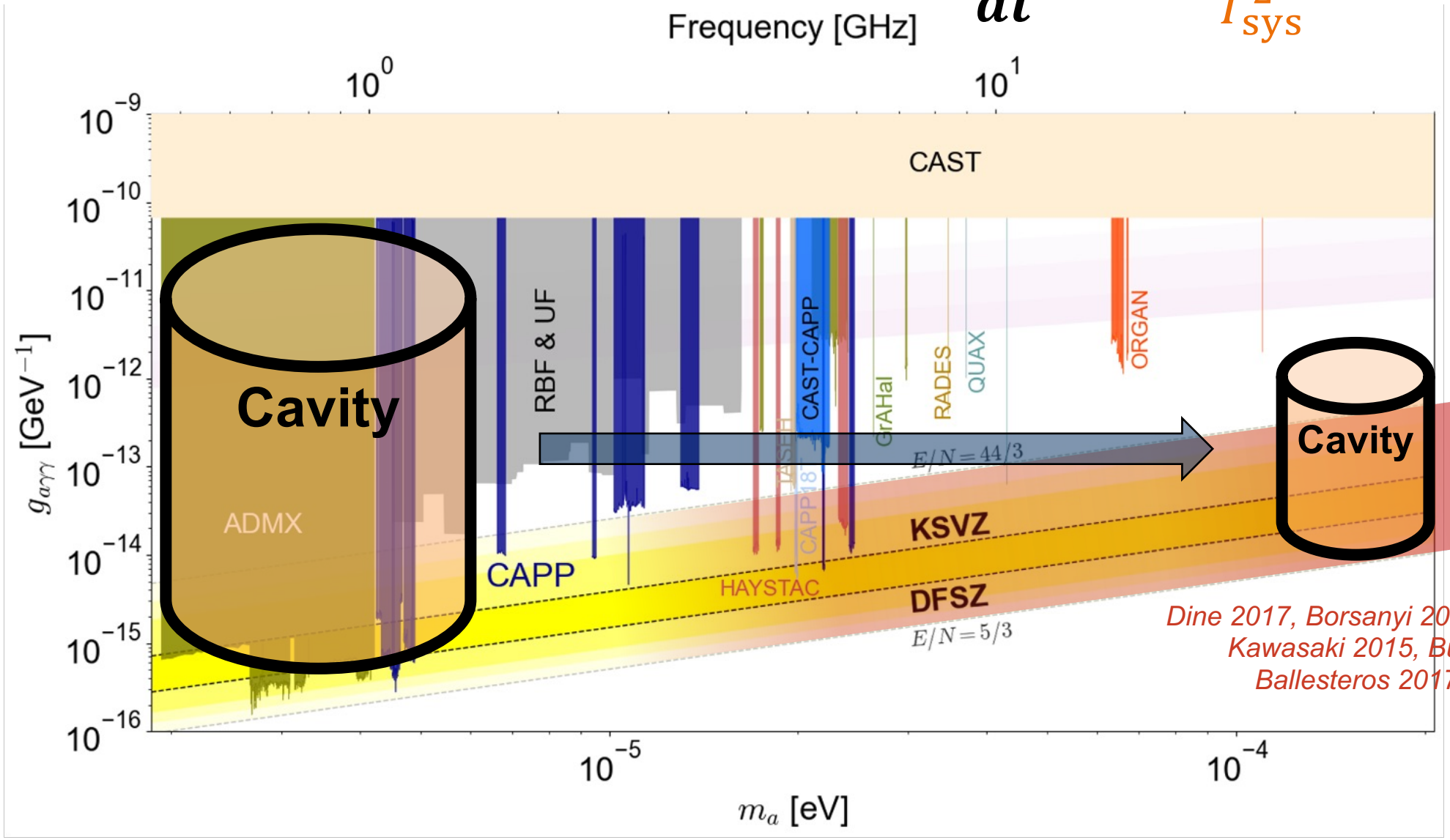
$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$



Dine 2017, Borsanyi 2016, Wantz 2010, Kawasaki 2015, Buschmann 2022, Ballesteros 2017, Klaer 2017, …

High-Mass Axion Search

$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{sys}^2} \propto f^{-20/3}$$



Dine 2017, Borsanyi 2016, Wantz 2010, Kawasaki 2015, Buschmann 2022, Ballesteros 2017, Klaer 2017, …

Plasma Haloscope

PHYSICAL REVIEW LETTERS **123,** 141802 (2019)

Editors' Suggestion | Featured in Physics

Tunable Axion Plasma Haloscopes

Matthew Lawson,[1,2] Alexander J. Millar,[1,2,*] Matteo Pancaldi,[3] Edoardo Vitagliano,[4] and Frank Wilczek[1,2,5,6,7,8]

[1]*The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, 10691 Stockholm, Sweden*

[2]*Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 10691 Stockholm, Sweden*

[3]*Department of Physics, Stockholm University, AlbaNova, 10691 Stockholm, Sweden*

[4]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*

[5]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[6]*T. D. Lee Institute, Shanghai 200240, China*

[7]*Wilczek Quantum Center, Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*

[8]*Department of Physics and Origins Project, Arizona State University, Tempe, Arizona 25287, USA*

(Received 30 April 2019; revised manuscript received 24 July 2019; published 1 October 2019)

$$\mathbf{J_a} \approx g_{a\gamma\gamma}\dot{a}\mathbf{B}$$

- ***Resonance occurs at the plasma frequency***

Plasma Haloscope

PHYSICAL REVIEW LETTERS **123,** 141802 (2019)

Editors' Suggestion | Featured in Physics

Tunable Axion Plasma Haloscopes

Matthew Lawson,[1,2] Alexander J. Millar,[1,2,*] Matteo Pancaldi,[3] Edoardo Vitagliano,[4] and Frank Wilczek[1,2,5,6,7,8]

[1]*The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, 10691 Stockholm, Sweden*

[2]*Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 10691 Stockholm, Sweden*

[3]*Department of Physics, Stockholm University, AlbaNova, 10691 Stockholm, Sweden*

[4]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*

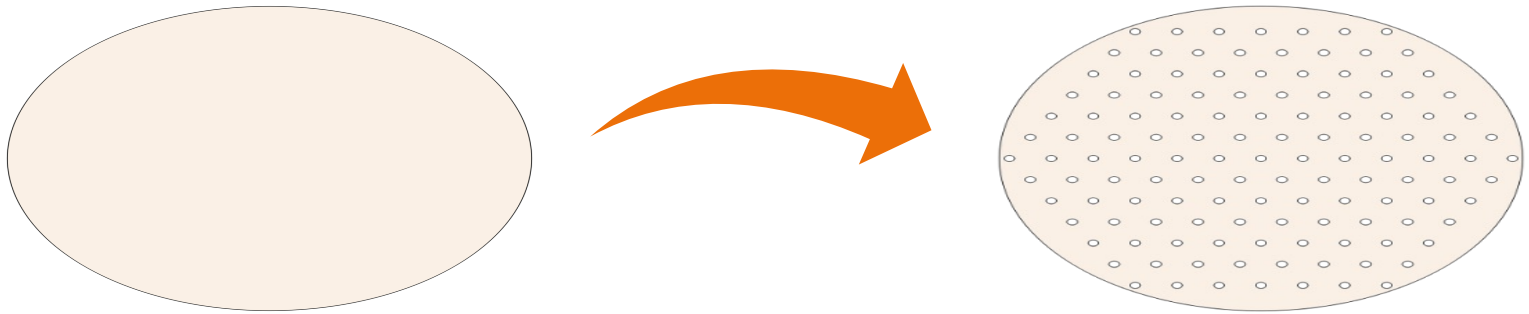
[5]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[6]*T. D. Lee Institute, Shanghai 200240, China*

[7]*Wilczek Quantum Center, Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*

[8]*Department of Physics and Origins Project, Arizona State University, Tempe, Arizona 25287, USA*

(Received 30 April 2019; revised manuscript received 24 July 2019; published 1 October 2019)



Cylindrical cavity **Array of conducting wires**

$$\mathbf{J_a} \approx g_{a\gamma\gamma}\dot{a}\mathbf{B}$$

- ***Resonance occurs at the plasma frequency***
- ***The wire array mimics a medium with a reduced plasma frequency***

Plasma Haloscope

PHYSICAL REVIEW LETTERS **123,** 141802 (2019)

Editors' Suggestion | Featured in Physics

Tunable Axion Plasma Haloscopes

Matthew Lawson,[1,2] Alexander J. Millar,[1,2,*] Matteo Pancaldi,[3] Edoardo Vitagliano,[4] and Frank Wilczek[1,2,5,6,7,8]

[1]*The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, 10691 Stockholm, Sweden*

[2]*Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 10691 Stockho Sweden*

[3]*Department of Physics, Stockholm University, AlbaNova, 10691 Stockho Sweden*

[4]*Max-Planc für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80*

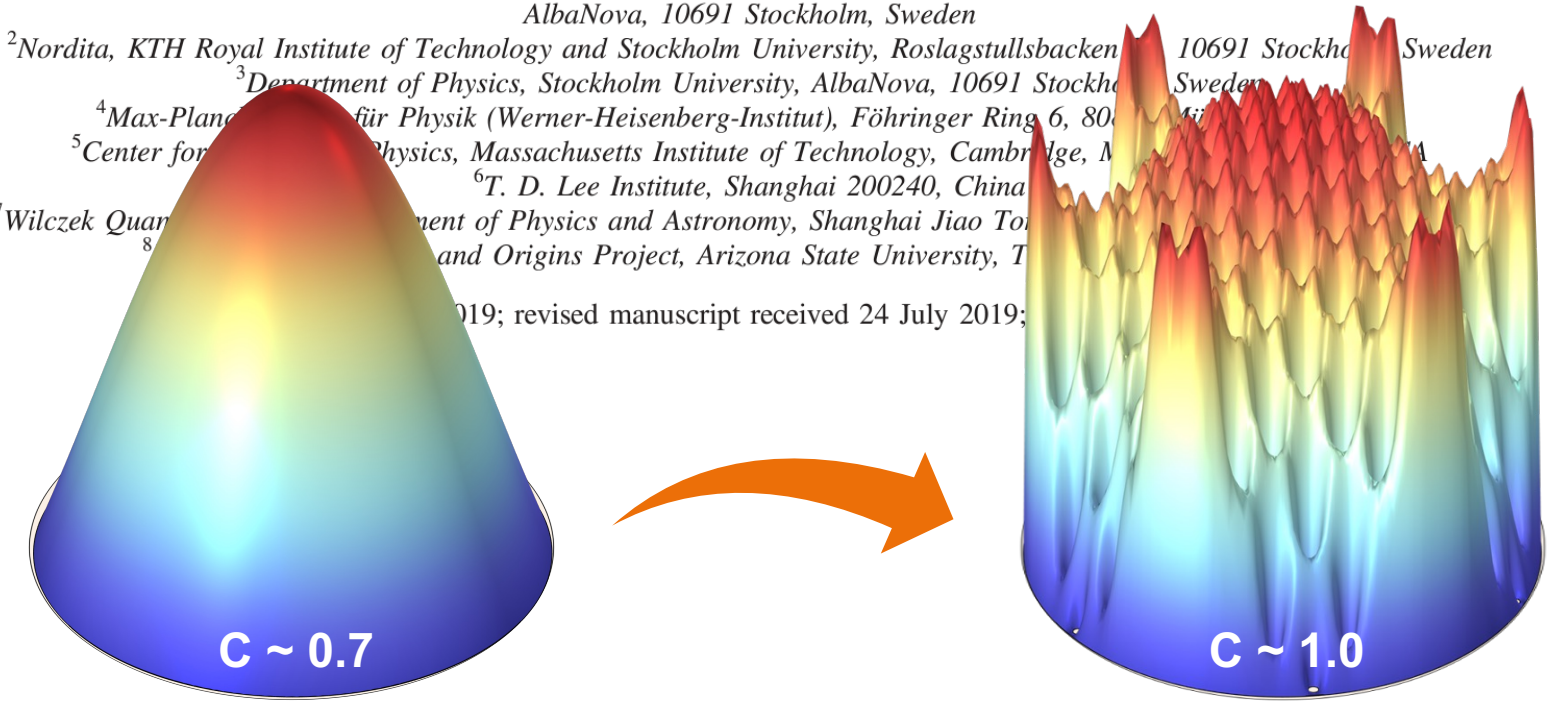
[5]*Center for hysics, Massachusetts Institute of Technology, Cambridge, M*

[6]*T. D. Lee Institute, Shanghai 200240, China*

[7]*Wilczek Quan nent of Physics and Astronomy, Shanghai Jiao To*

[8] *and Origins Project, Arizona State University, T*

019; revised manuscript received 24 July 2019;



Cylindrical cavity **Array of conducting wires**

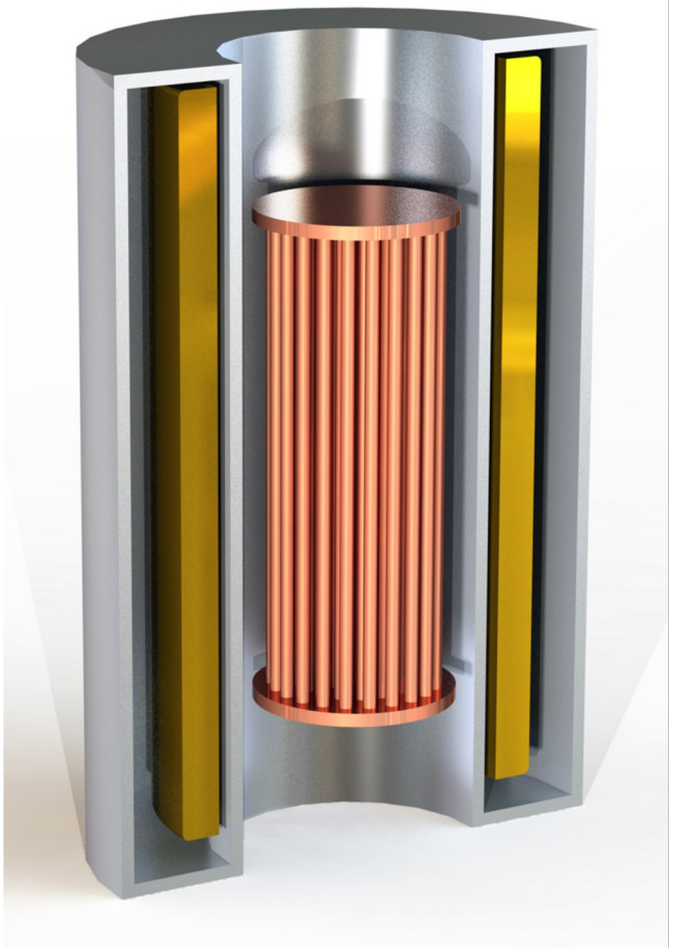
$$\mathbf{J_a} \approx g_{a\gamma\gamma}\dot{a}\mathbf{B}$$

- ***Resonance occurs at the plasma frequency***
- ***The wire array mimics a medium with a reduced plasma frequency***

- ***The cavity frequency is independent of its size***
- ***A wire spacing of 1 cm results in a frequency of approximately 10 GHz***

Axion Longitudinal Plasma HAloscope

alpha



Support is gratefully acknowledged from:

JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

SIMONS FOUNDATION

Knut and Alice Wallenberg Foundation

Swedish Research Council

OLLE ENGKVISTS STIFTELSE

Collaboration Institutions:

Yale University (Host)
Arizona State University
University of California Berkeley
University of Cambridge
Colorado University
Iceland University
ITMO University
Johns Hopkins University
Massachusetts Institute of Technology
Oak Ridge National Laboratory
Stockholm University
Wellesley College

Project Scientist:

F. Wilczek (MIT/Stockholm University)

Project PI:

K. van Bibber (Berkeley)

Project Technical Director:

M. Jewell (Yale)

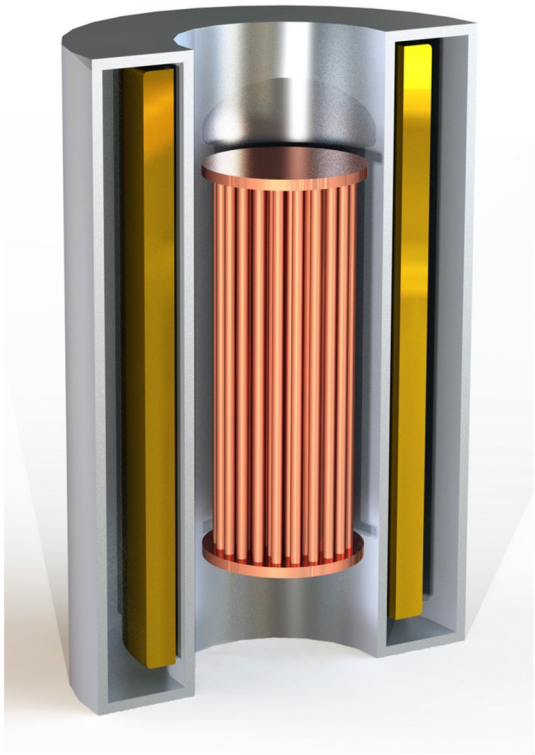
Spokes / deputy persons:

J. Gudmundsson (Stockholm University)
R. Maruyama (Yale)

Axion Longitudinal Plasma HAloscope

The 1st ALPHA Collaboration Meeting

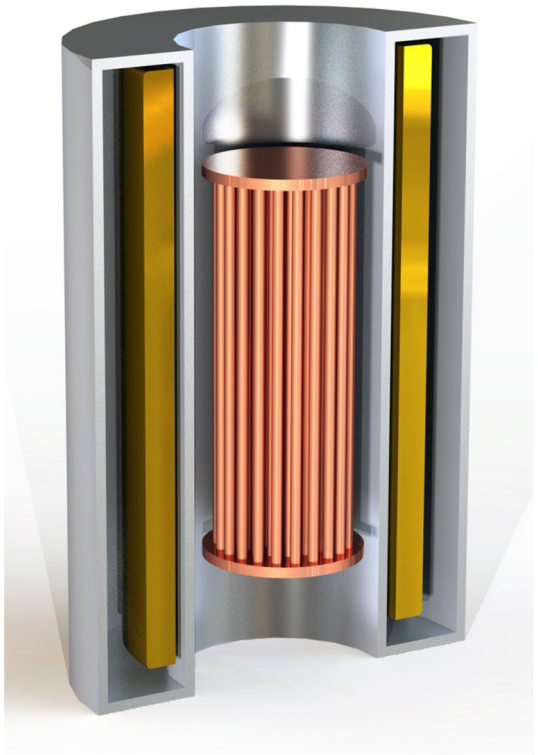
SU Group's Objective



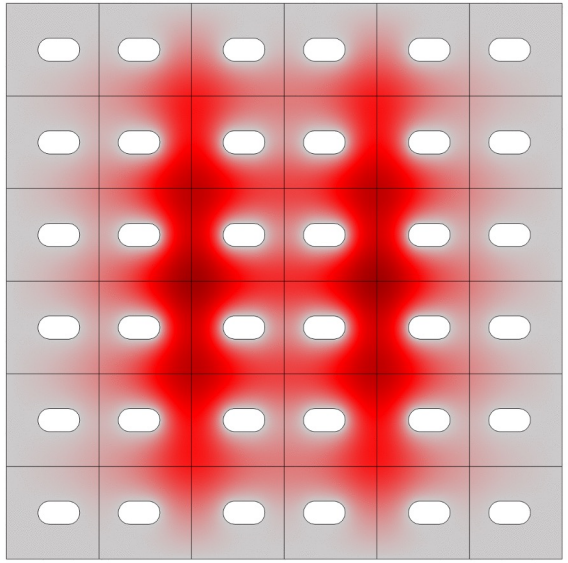
$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$

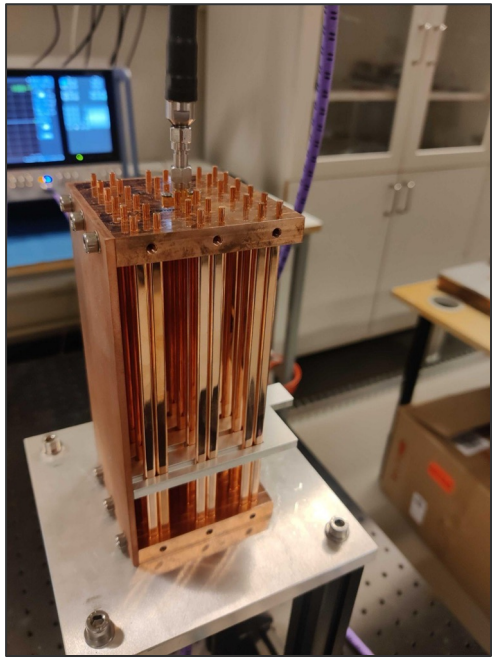
- ***Strong and large magnet***
- ***High quality factor cavity***
- ***Clever design of cavity***
- ***Low system noise temperature***

SU Group's Ongoing Contribution



Development of Tuning system





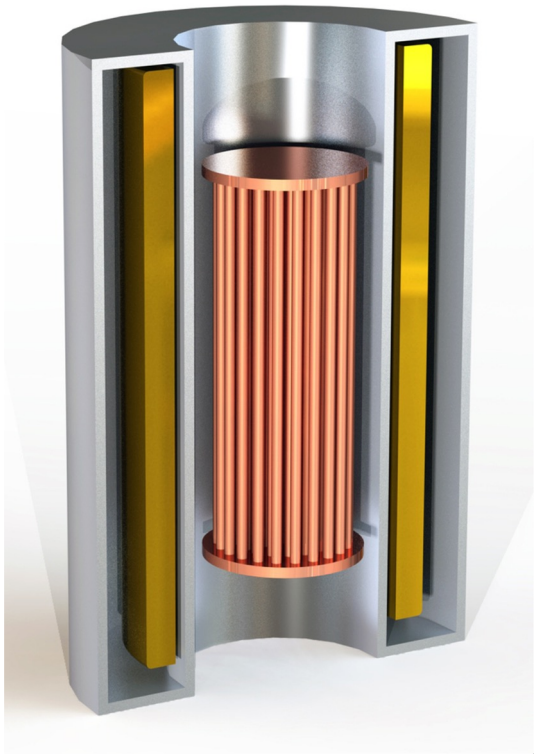
Gagandeep Kaur

Rustam Balafendiev

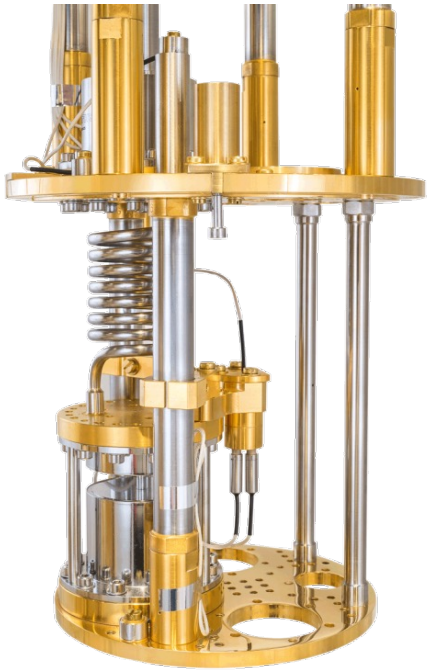
$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$

- ***Strong and large magnet***
- ***High quality factor cavity***
- ***Clever design of cavity***
- ***Low system noise temperature***

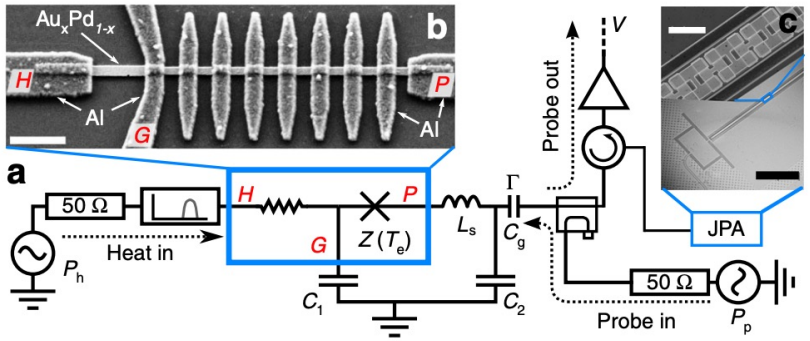
SU Group's Future Plan



Weak RF Photon Detection System



e.g.



[R. Kokkoniemi et al., Comm. Phys. **2**, 124 (2019)]

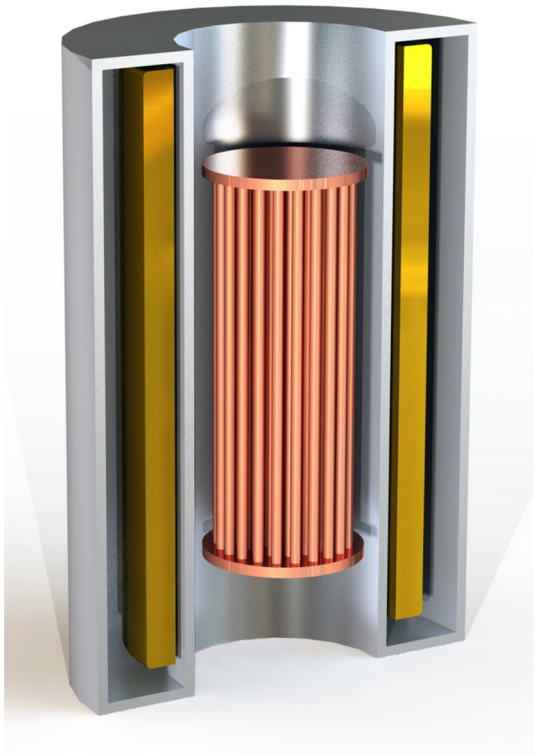
In the process of procuring DR

- **Single photon detection**
- **Microwave Interferometer**

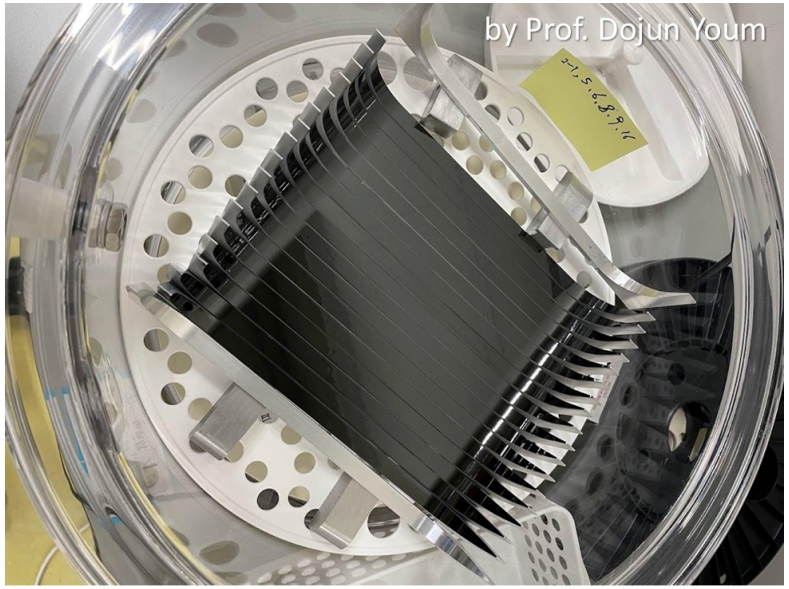
$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$

- ***Strong and large magnet***
- ***High quality factor cavity***
- ***Clever design of cavity***
- ***Low system noise temperature***

SU Group's Future Plan



Superconducting Cavity



[D. Ahn, 18th PATRAS]

$$\frac{df}{dt} \propto \frac{\langle B^2 \rangle^2 V_c^2 Q_c C^2}{T_{sys}^2}$$

- ***Strong and large magnet***
- ***High quality factor cavity***
- ***Clever design of cavity***
- ***Low system noise temperature***

Advertisement

https://www.su.se/department-of-physics/about-the-department/work-with-us

Two Postdoctoral Fellows in Axion Searches with Metamaterials

PhD Student in Physics for Axion Searches with Metamaterials

Summary

- The **axion** is a theoretically well-motivated particle that resolves the strong CP problem and also provides a compelling solution to the dark matter mystery.
- The **cavity haloscope** is the most sensitive method for searching for dark matter axions in the GHz range.
  - High-mass axions are theoretically preferred, but the scanning rate significantly decreases at higher masses.
- The **plasma haloscope** is an innovative approach to efficiently search for high-mass dark matter axions.
- The **ALPHA collaboration** is an international initiative focused on the plasma haloscope.
- **Stockholm University** is a core member of the ALPHA collaboration.
  - We are contributing to the development of tunable wire-metamaterial cavities.
  - We are planning to contribute to the development of a weak microwave photon detection system and superconducting wire-metamaterial cavities.

Rustam Balafendiev

Gagandeep Kaur