ABRACADABRA from axions to gravitational waves

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UHF GW Workshop
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Outline

ABRACADABRA and axions

The ABRA detector

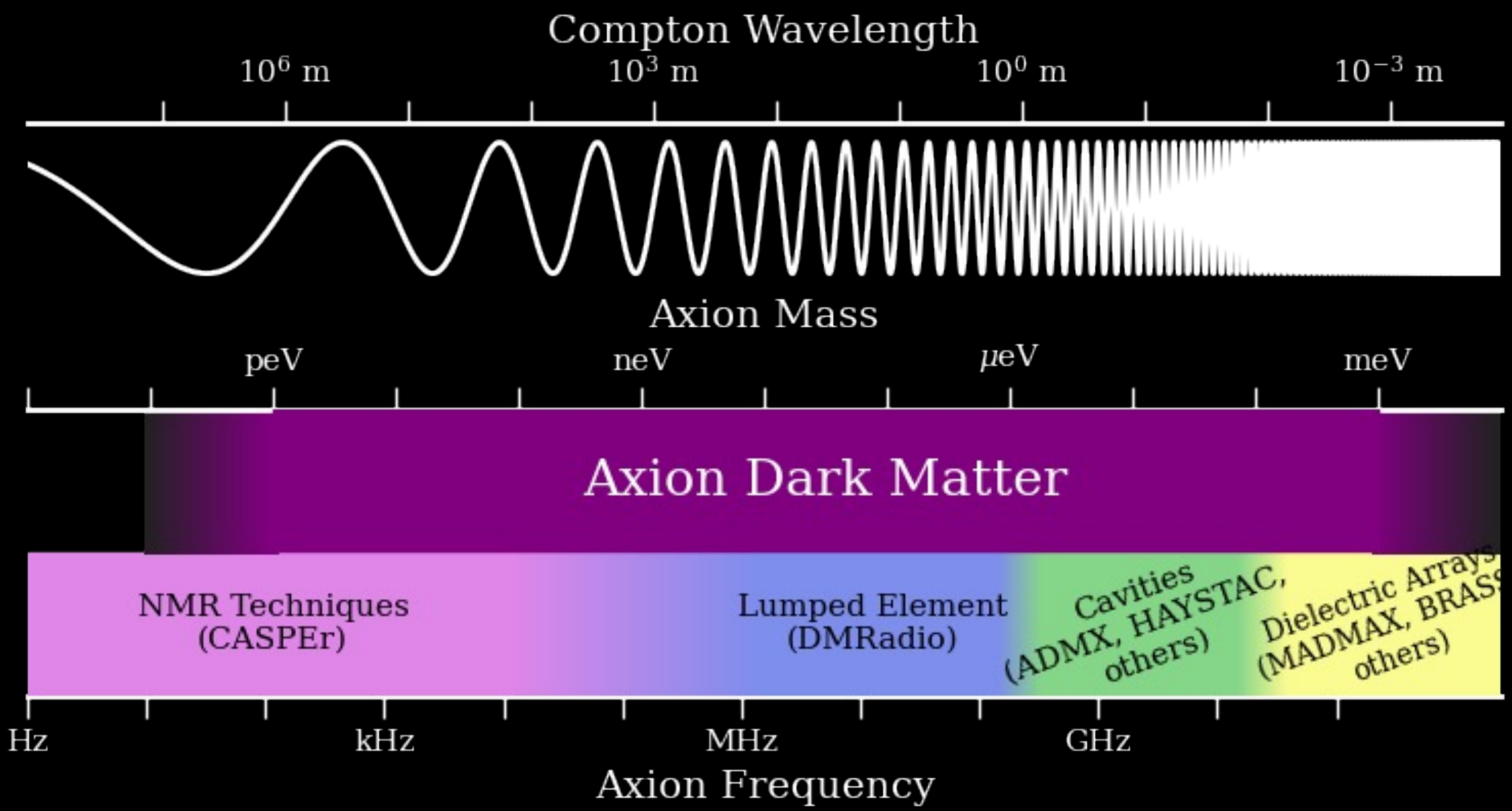
ABRA-grav

Calibrating ABRA

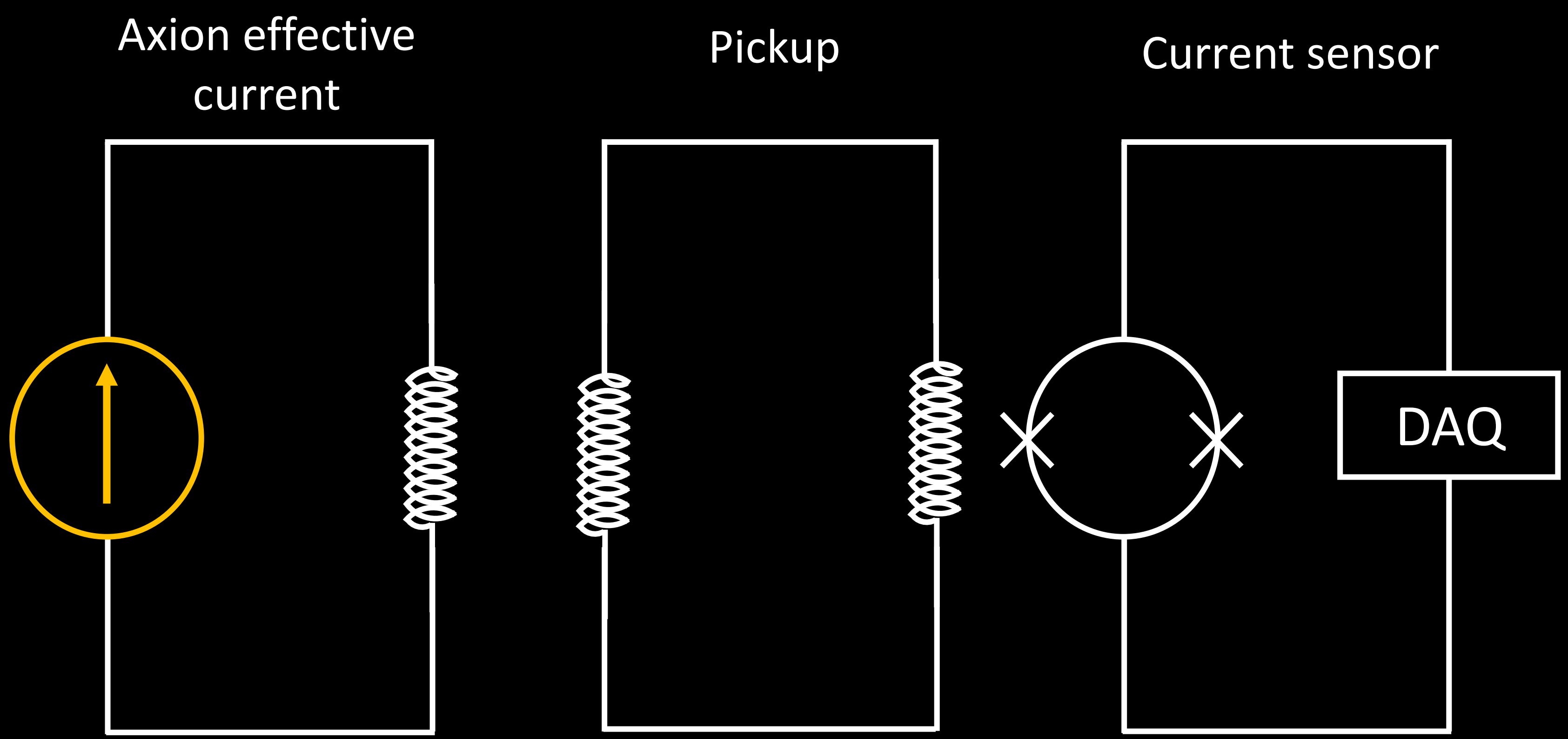
Signal modeling

ABRACADABRA and axions

Axion detection: axion mass and frequency



Lumped element searches



ABRACADABRA-10 cm

A Broadband/Resonance Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

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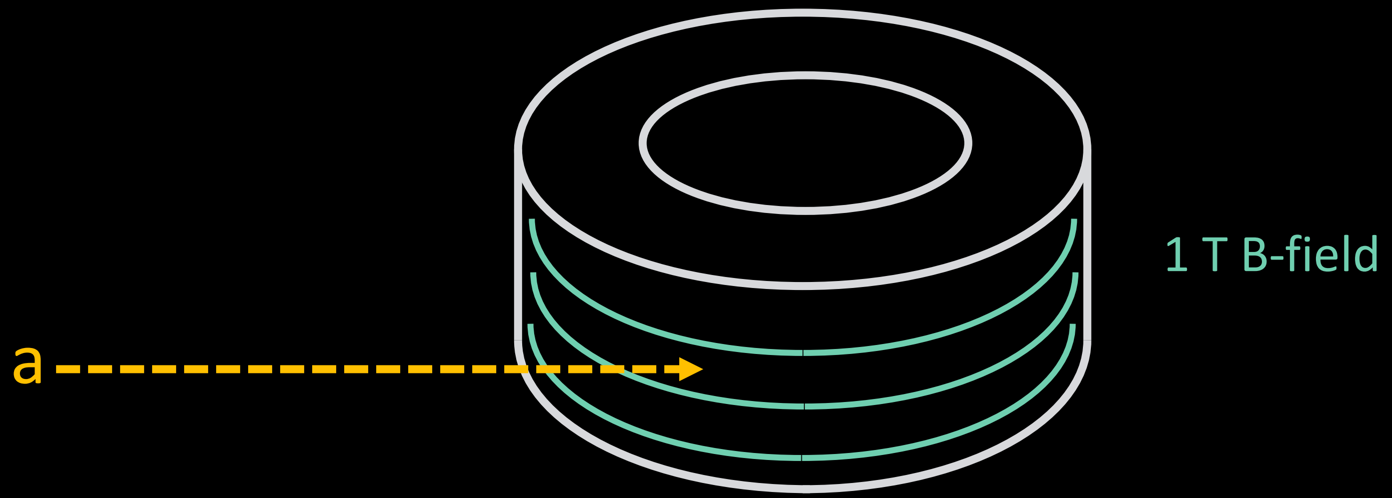
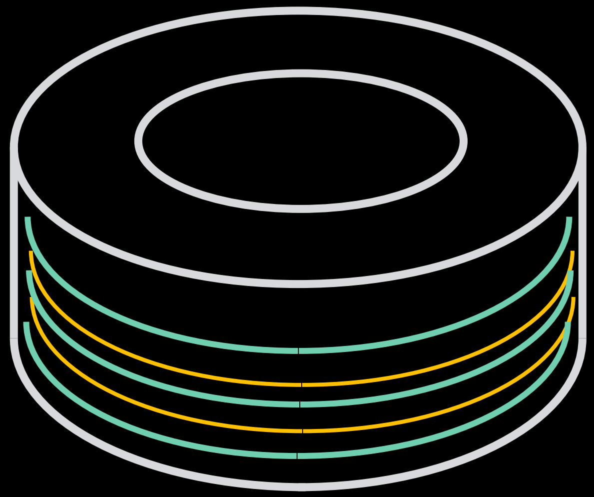
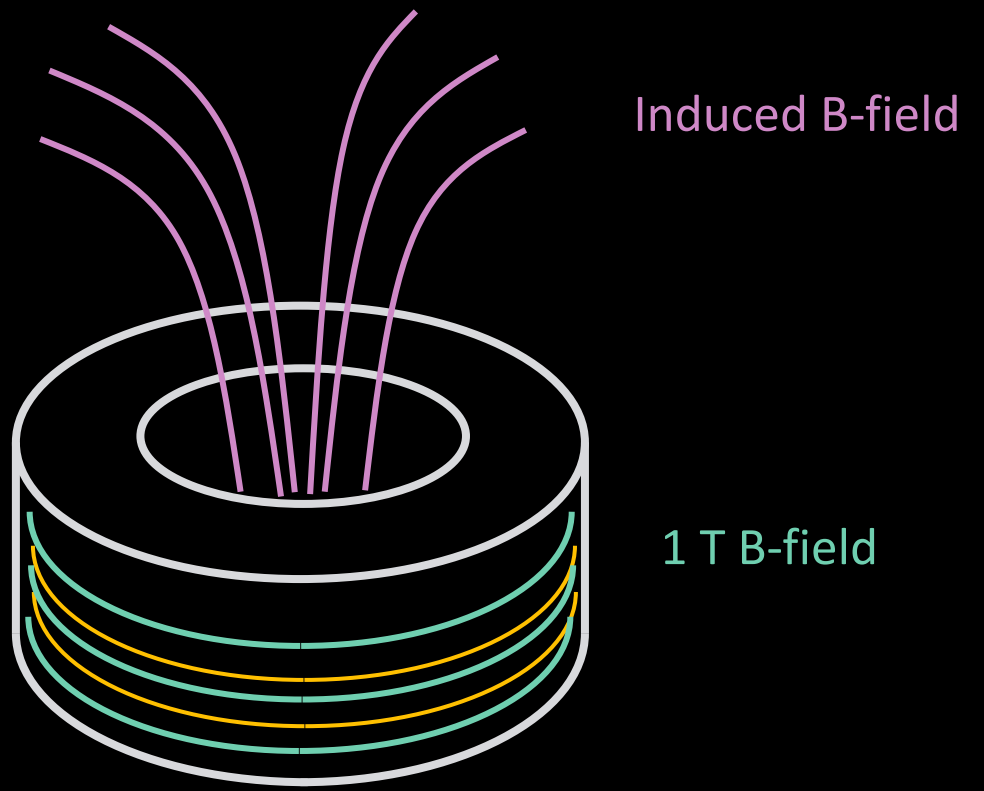


ABRACADABRA-10 cm



$J_{eff} = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\cos(m_a t)B$

ABRACADABRA-10 cm



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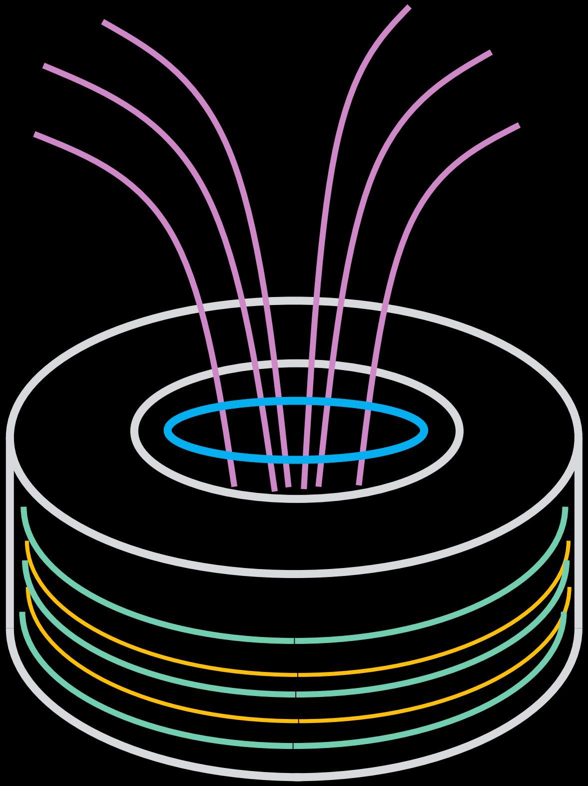
ABRACADABRA-10 cm



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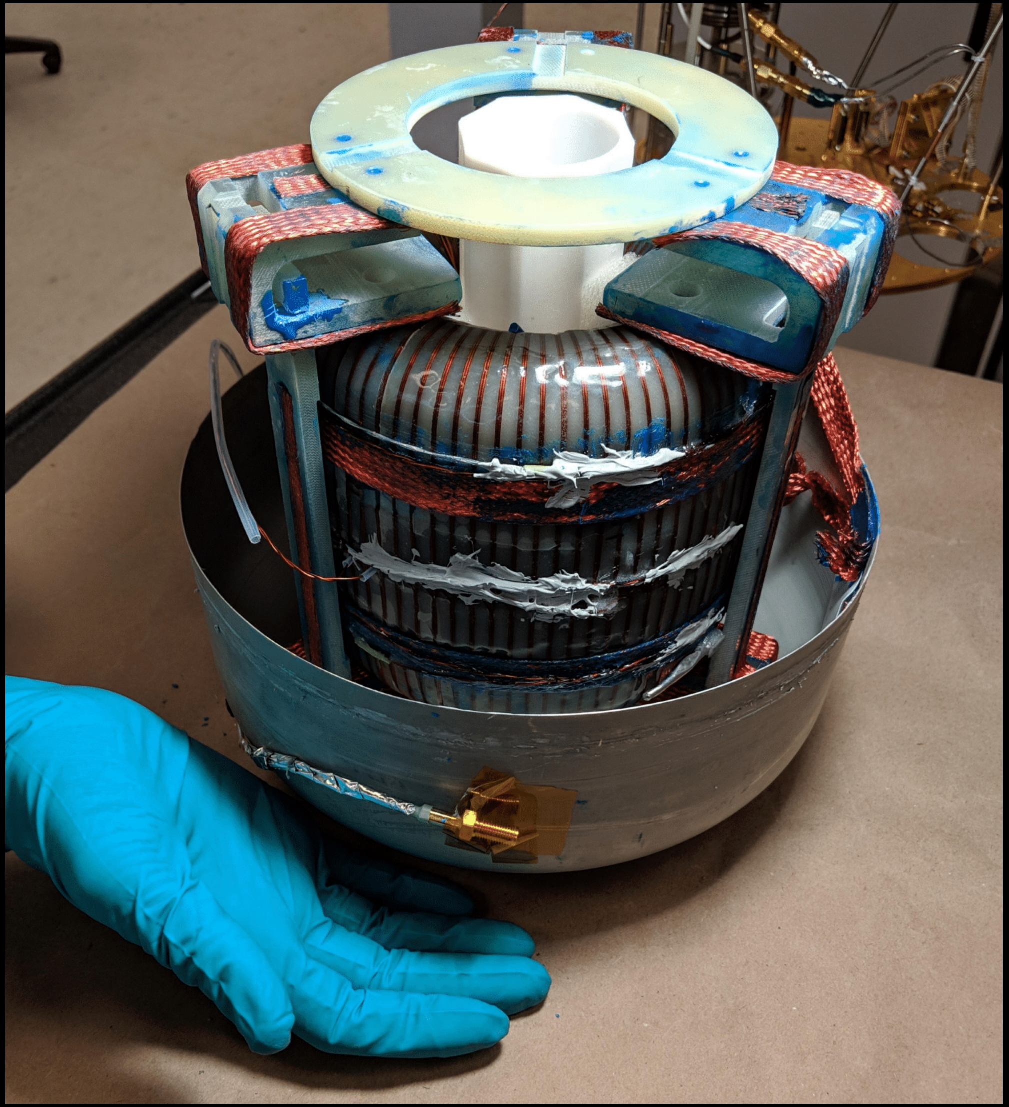
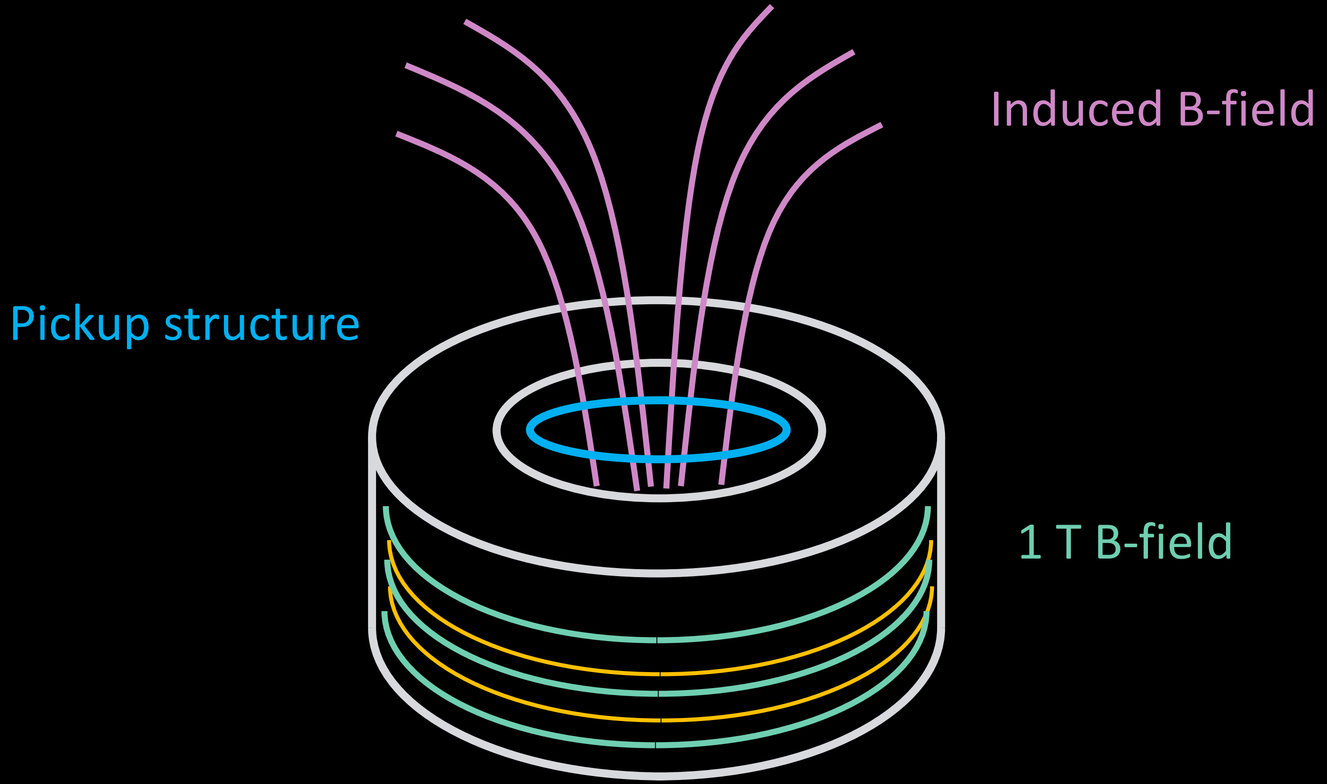
ABRACADABRA-10 cm



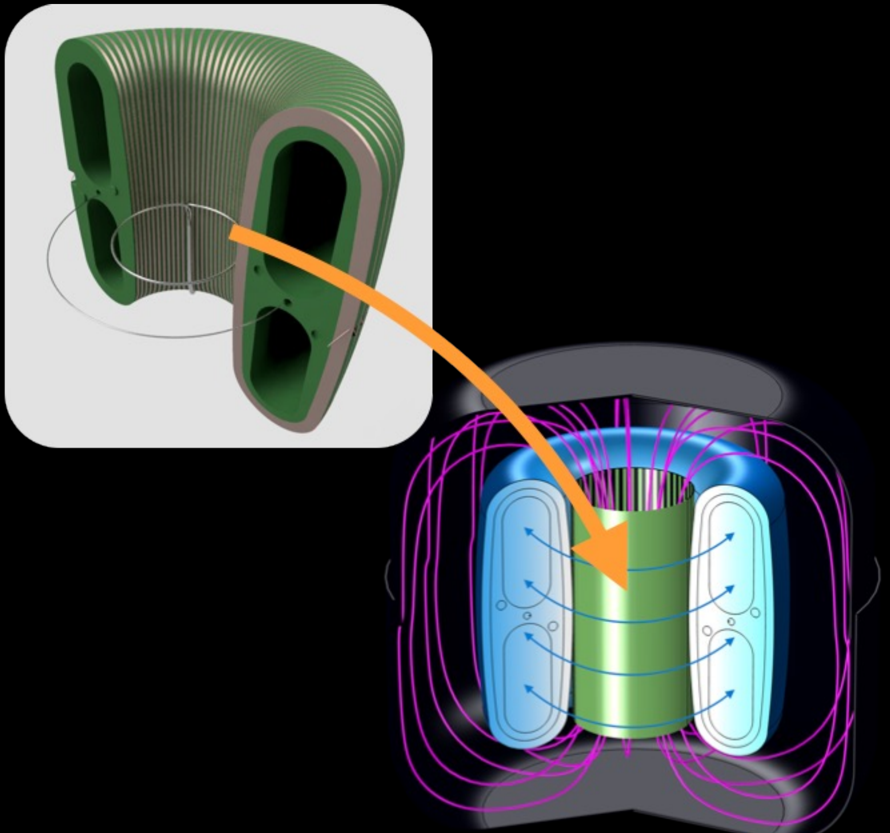


$$J_{eff} = g_{a\gamma\gamma}\sqrt{\rho_{DM}}\cos(m_a t)B$$

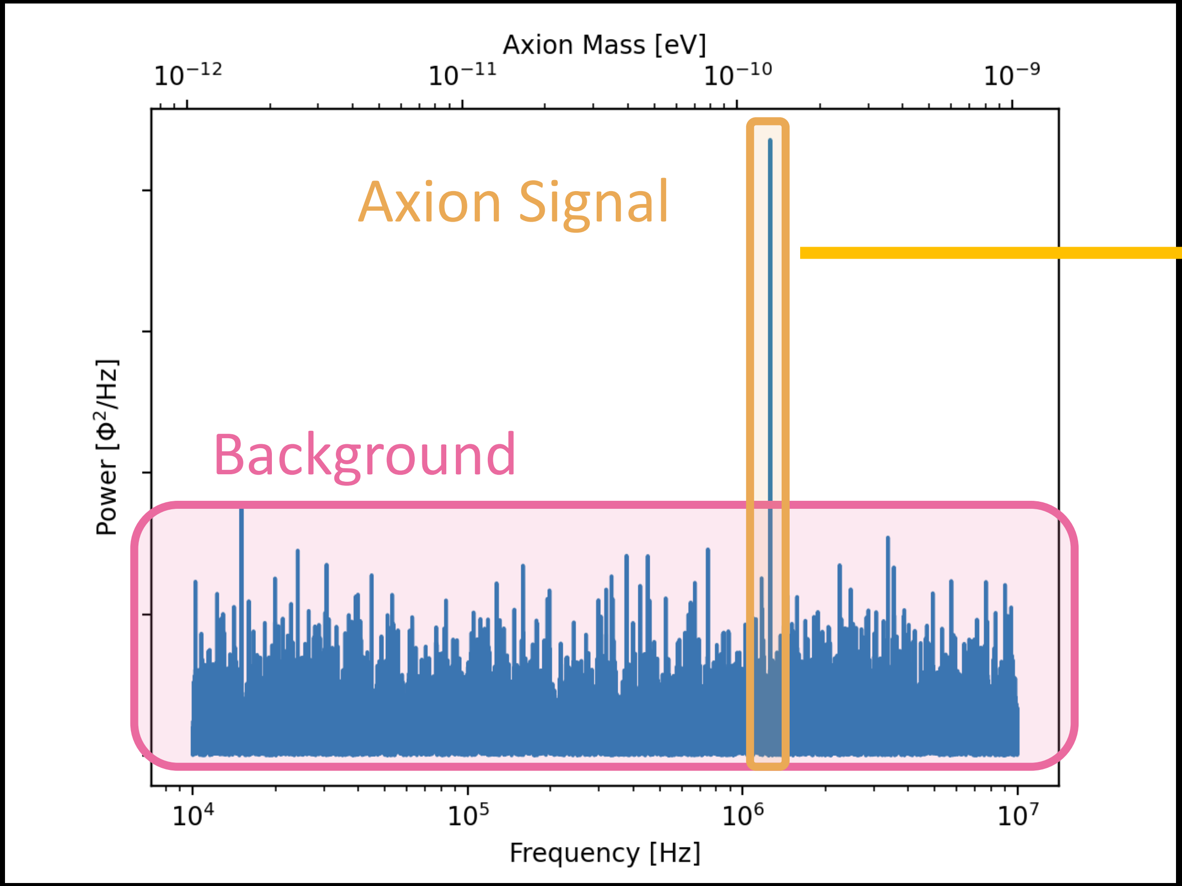
ABRACADABRA pickup update

Run 1

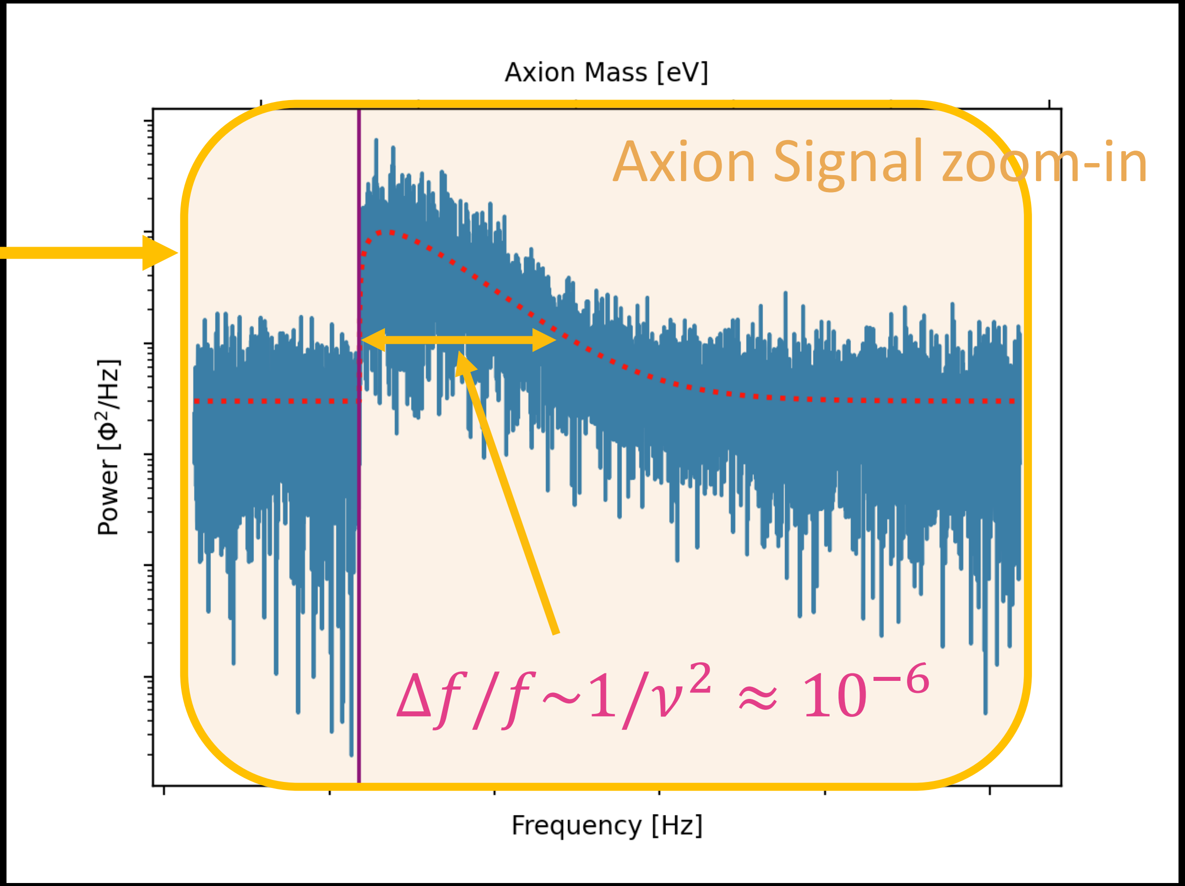
Runs 2 & 3



Axion Signal



Simulated Data



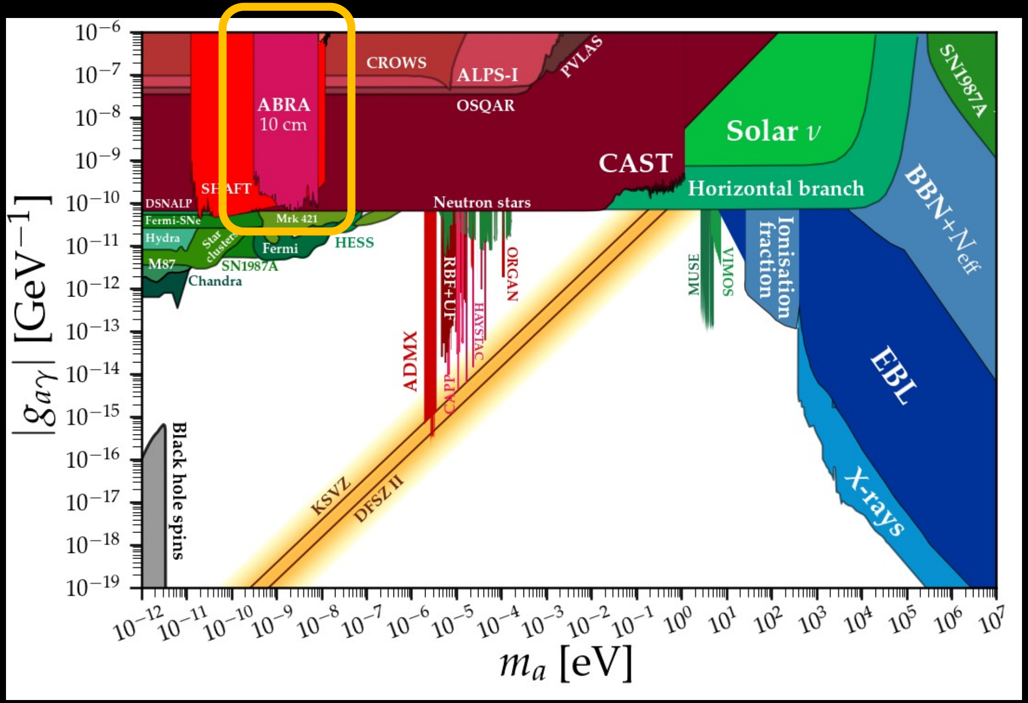
Standard Halo Model

ABRACADABRA-10 cm

ABRA searched for low-mass axions 0.31- 8.3 neV

Two published runs:

- Phys. Rev. Lett. 122, 121802 – Published 29 March 2019
    - Phys. Rev. D 99, 052012 – Published 29 March 2019
- Phys. Rev. Lett. 127, 081801 – Published 17 August 2021



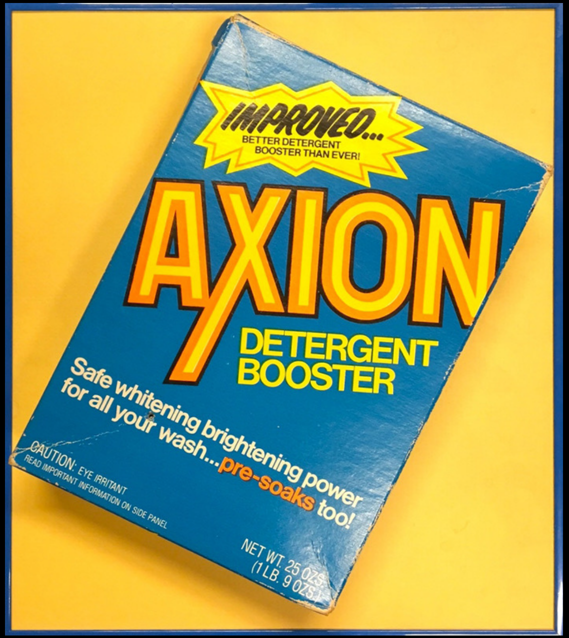
DOI: 10.5281/zenodo.3932430

ABRACADABRA-10 cm

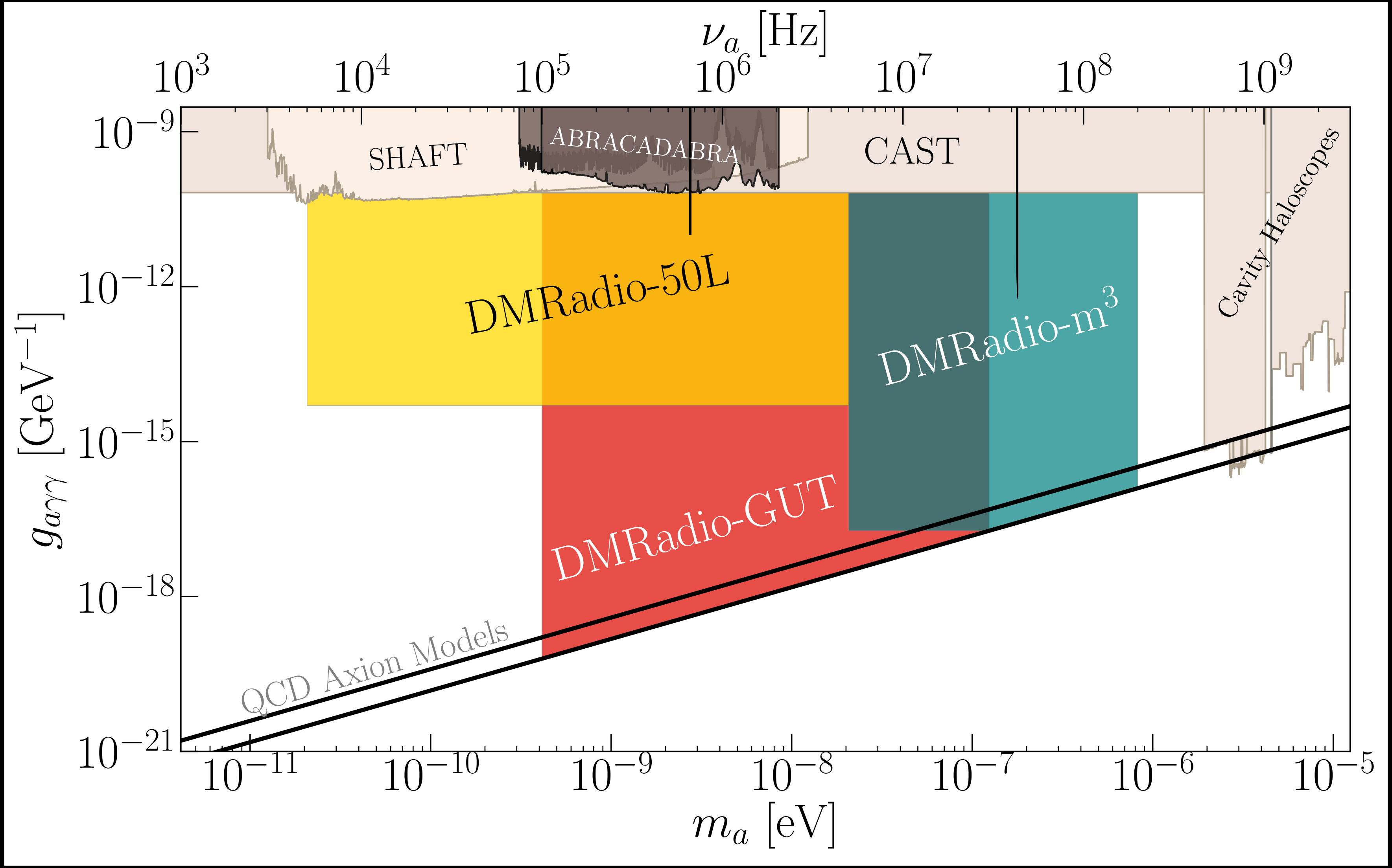
Next steps for lumped element axion searches:

- Larger magnet
- Resonant readout
- More sensitive pickup

  → DMRadio



DMRadio saga



ABRACADABRA-10 cm

New directions for ABRA-10cm detector:

- Exploring sensitivity to gravitational waves
  - Prove that we can search for UHFGWs using an axion detector while simultaneously searching for axions

ABRA-grav

Axion Signal

Gauss-Ampère law

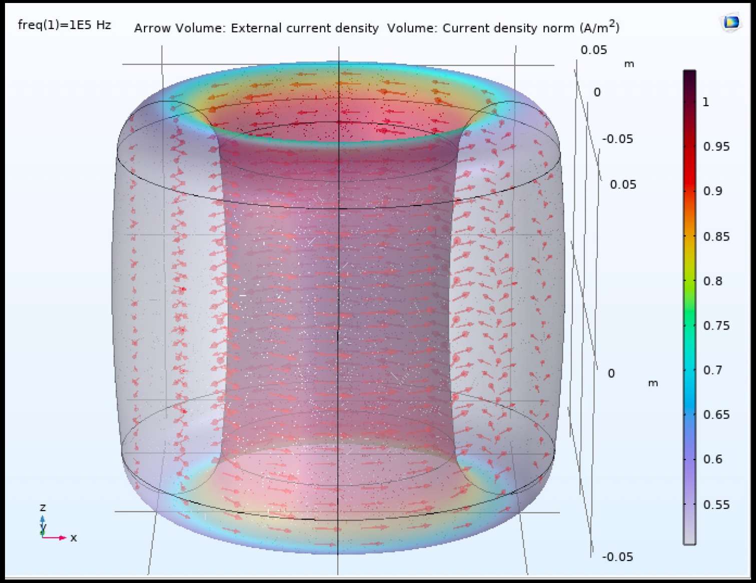
$$\partial_\nu F^{\mu\nu} = j^{\mu}_{eff}$$

Axions Modification:

$$j^{\mu}_{eff} = \partial_\nu \left(g_{a\gamma\gamma} a \tilde{F}^{\nu\mu} \right)$$

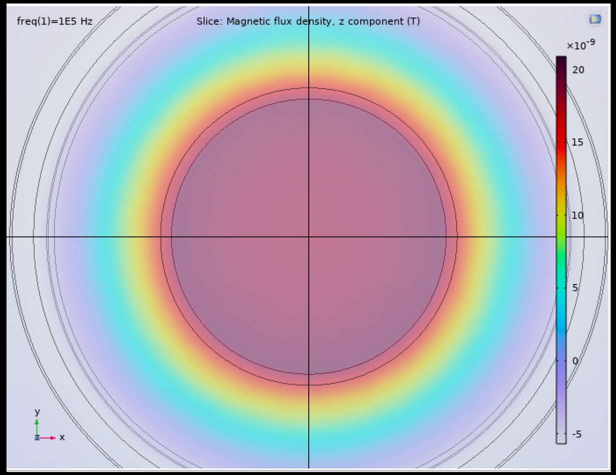
↓

$$J_{eff} = g_{a\gamma\gamma} \sqrt{\rho_{DM}} \cos(m_a t) B$$



Axion effective current in the ABRA magnetic volume

Axion Signal



The z-component of the magnetic field resulting from an axion effective current

Gauss-Ampère law

$$\partial_\nu F^{\mu\nu} = j^\mu_{eff}$$

Axions Modification:

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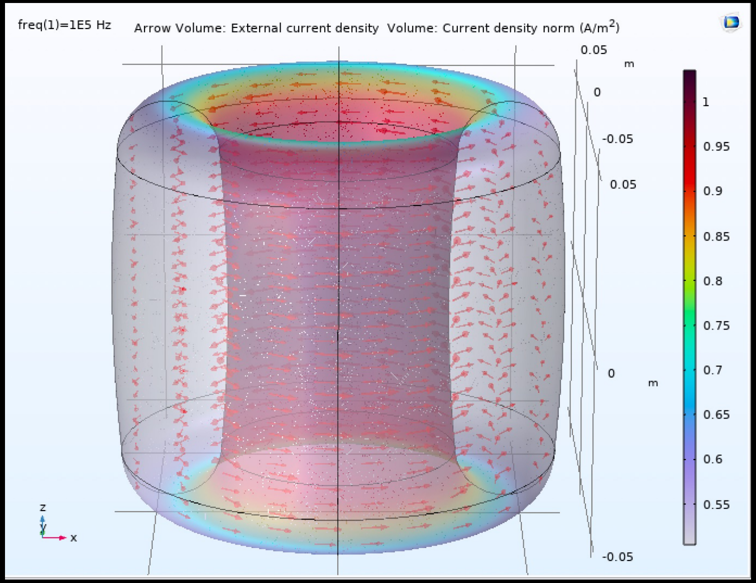

Axion effective current in the ABRA magnetic volume

Gravitational Wave Signal

Gauss-Ampère law

$$\partial_\nu F^{\mu\nu} = j^\mu_{eff}$$

Gravitational Wave Modification:

$$j^\mu_{eff} = \partial_\nu \left(-\frac{1}{2} h F^{\mu\nu} + F^{\mu\alpha} h^\nu_\alpha - F^{\mu\nu} h^\mu_\alpha \right)$$

Gravitational Wave Signal

Gauss-Ampère law

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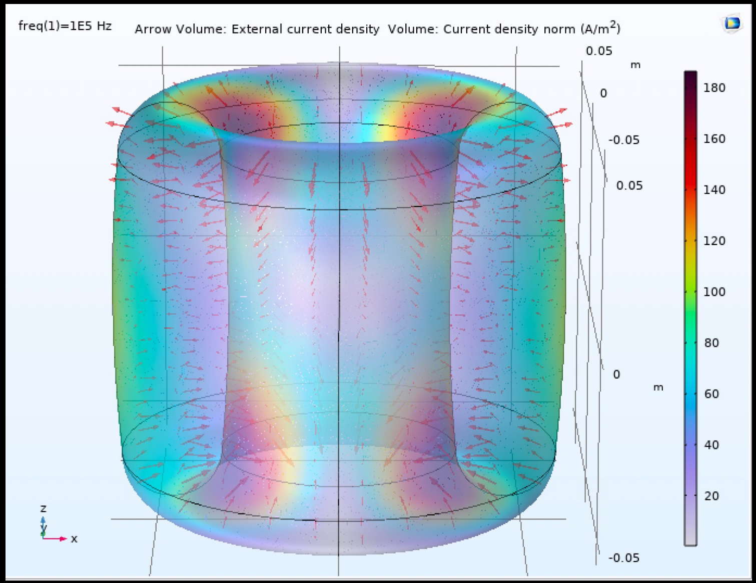
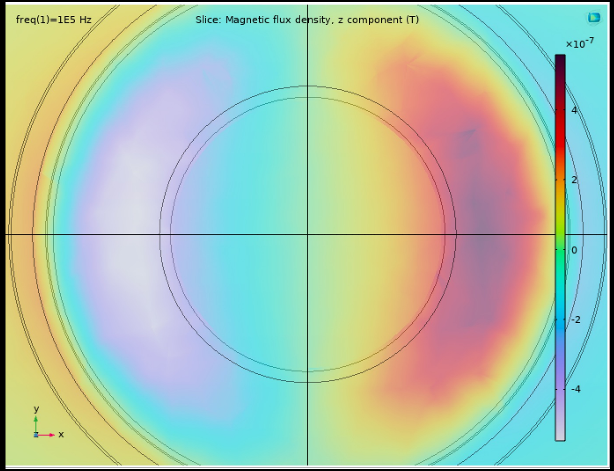


GW effective current in the ABRA magnetic volume

Gravitational Wave Signal



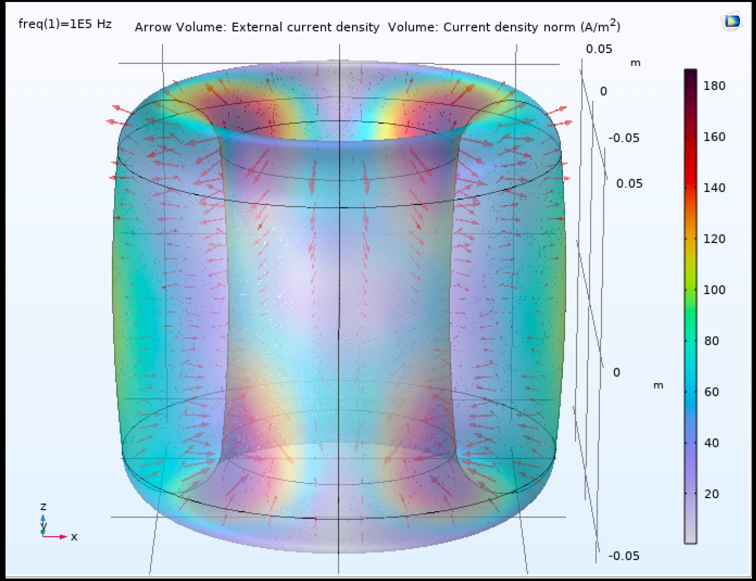
The z-component of the magnetic field resulting from a GW effective current

Gauss-Ampère law

$$\partial_\nu F^{\mu\nu} = j^\mu_{eff}$$

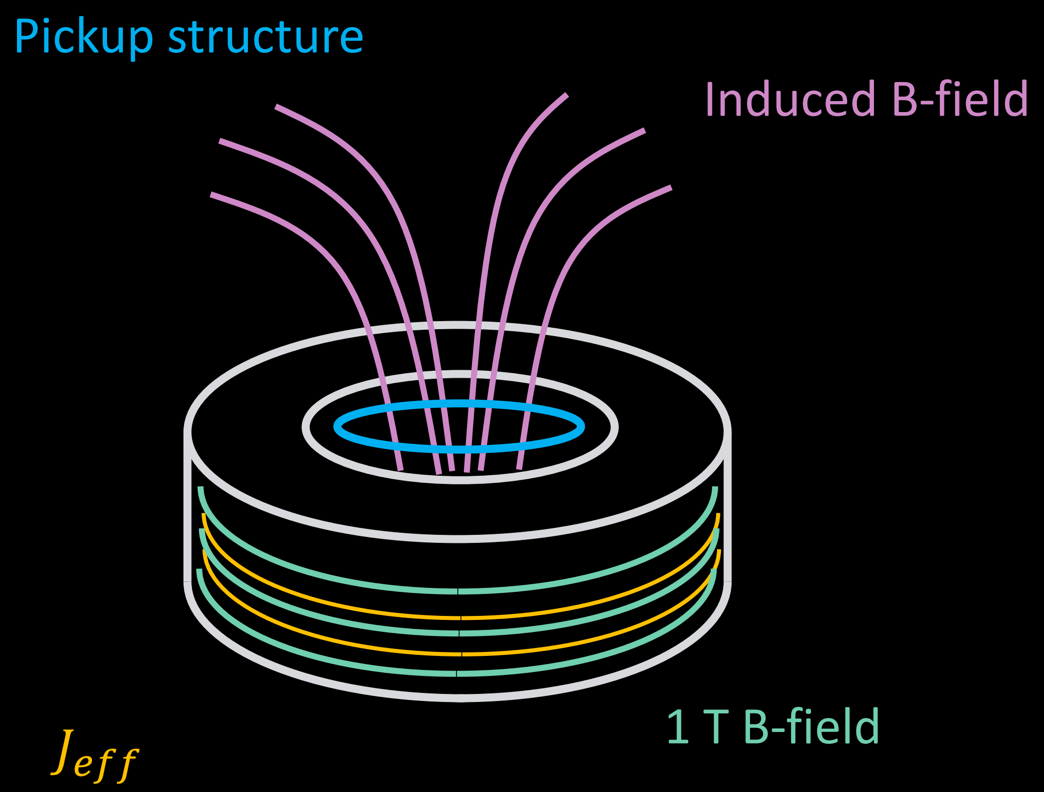
Gravitational Wave Modification:

$$j^\mu_{eff} = \partial_\nu \left(-\frac{1}{2} h F^{\mu\nu} + F^{\mu\alpha} h^\nu_\alpha - F^{\mu\nu} h^\mu_\alpha \right)$$

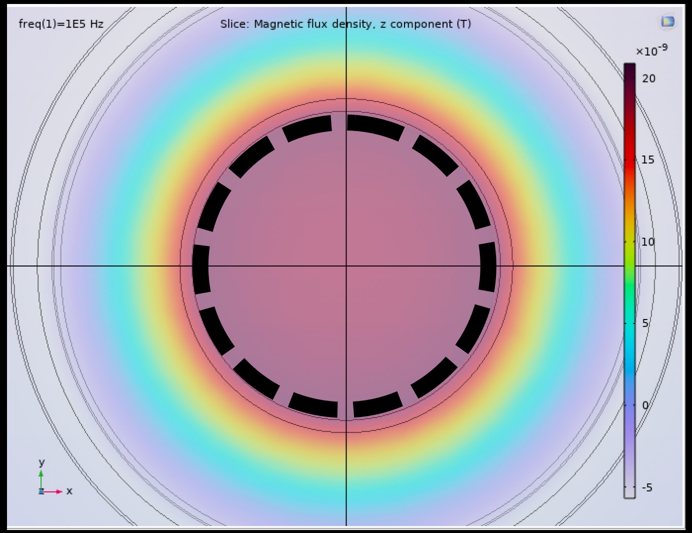


GW effective current in the ABRA magnetic volume

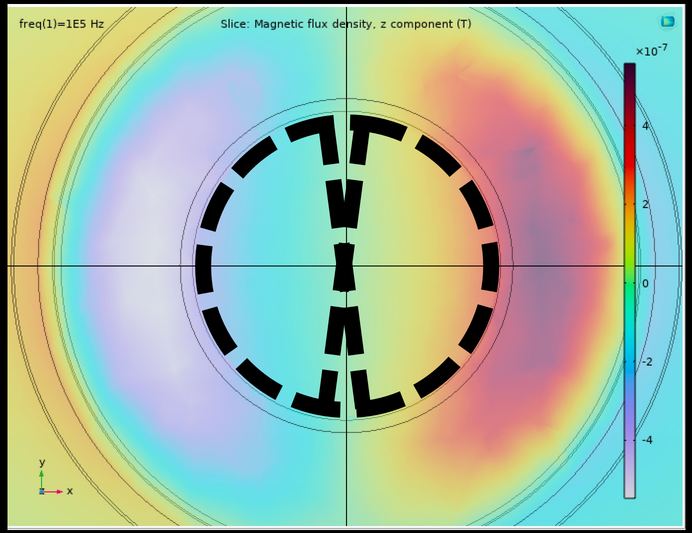
Experimental Setup



Top-down view



The z-component of the magnetic field resulting from an axion effective current



The z-component of the magnetic field resulting from a GW effective current

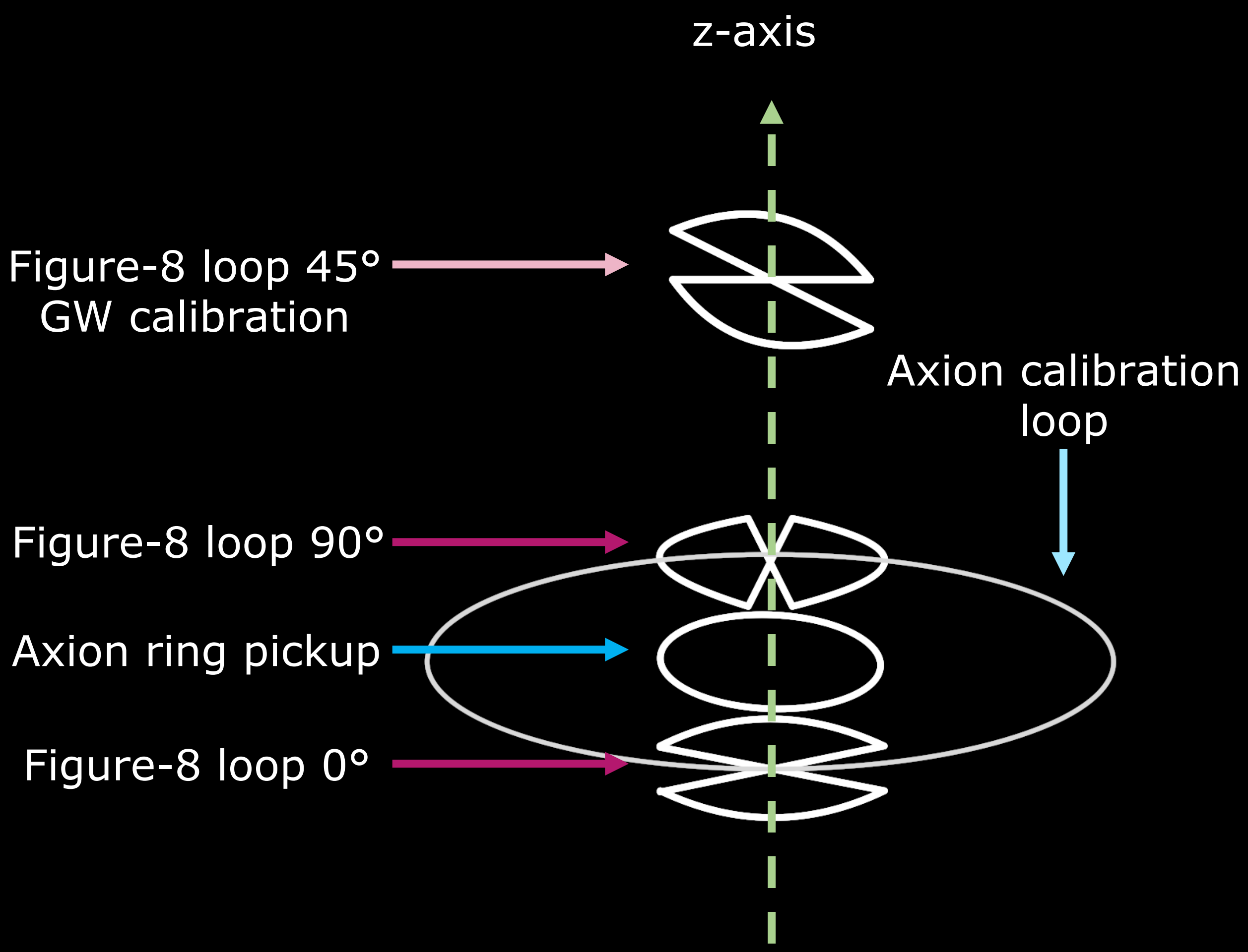
Experimental setups

We have tried two difference experimental setups:

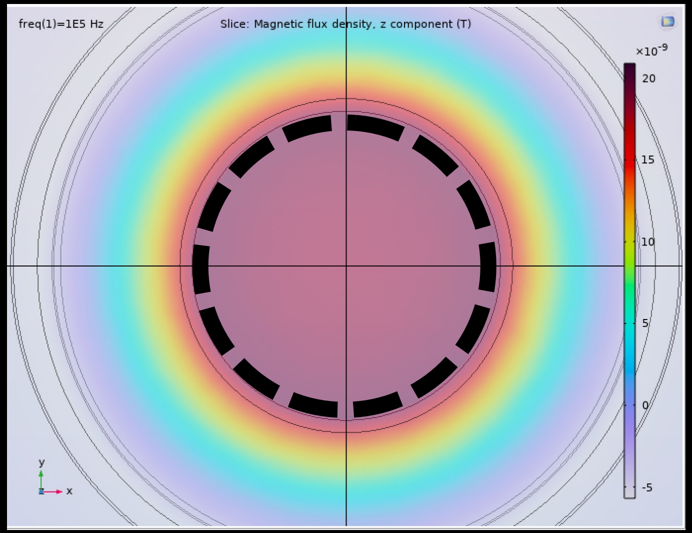
1. Axion-GW search with a directional two GW loop option
2. Axion-GW search simplified with single GW loop

Calibration

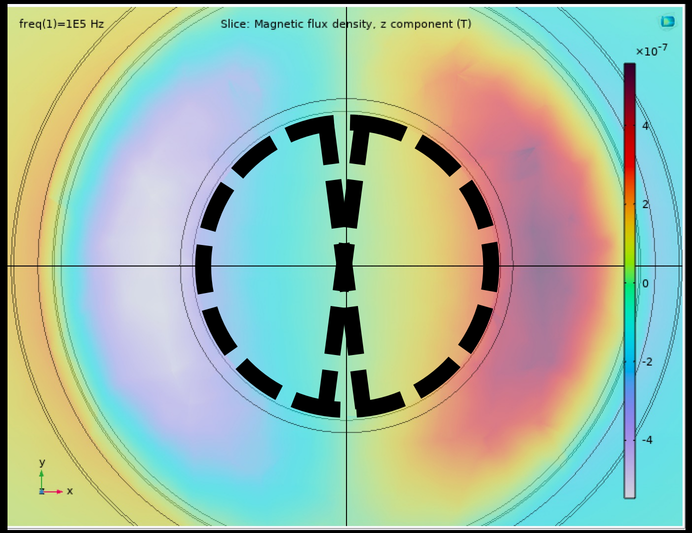
1. Directional search



The pickup structures and calibration structures that are used in the GW axion run



The z-component of the magnetic field resulting from an axion effective current



The z-component of the magnetic field resulting from a GW effective current

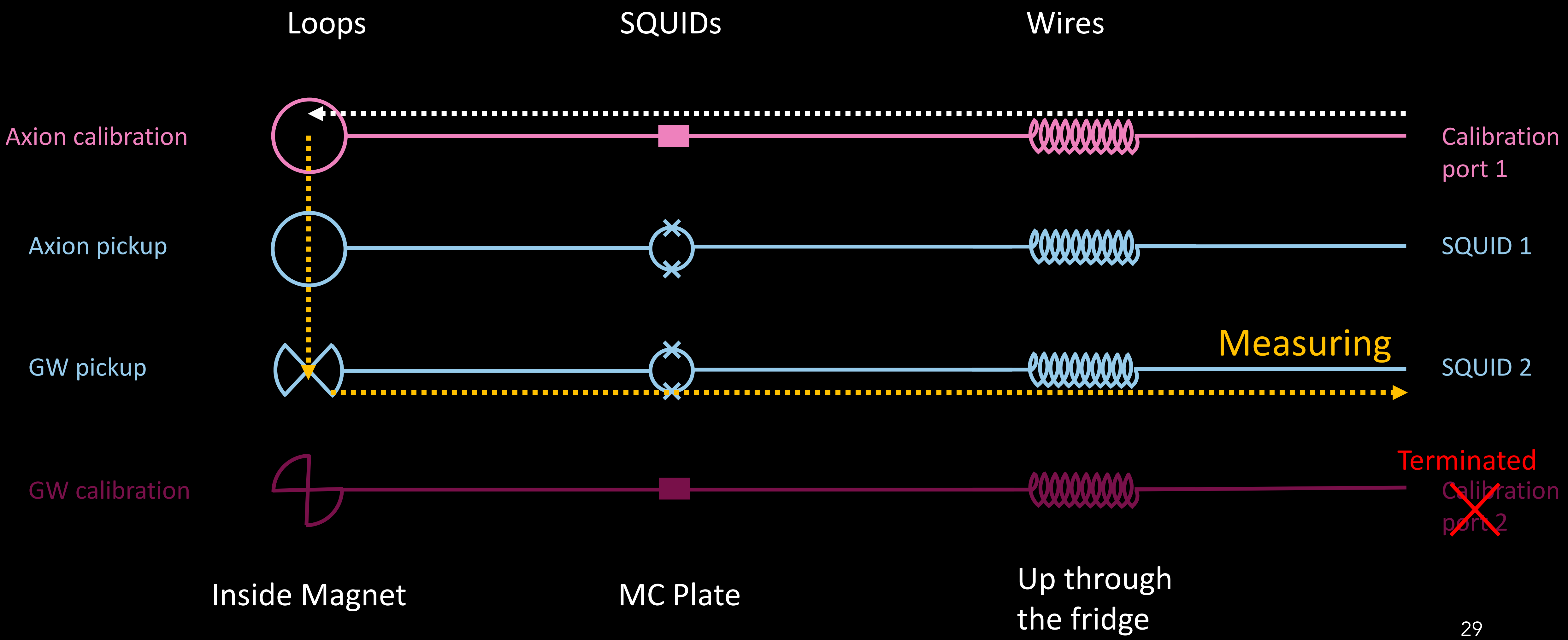
Calibration an axion-GW run

To prove we can run a simultaneous axion and GW run, we must demonstrate that the GW search and the axion search can be calibrated independently

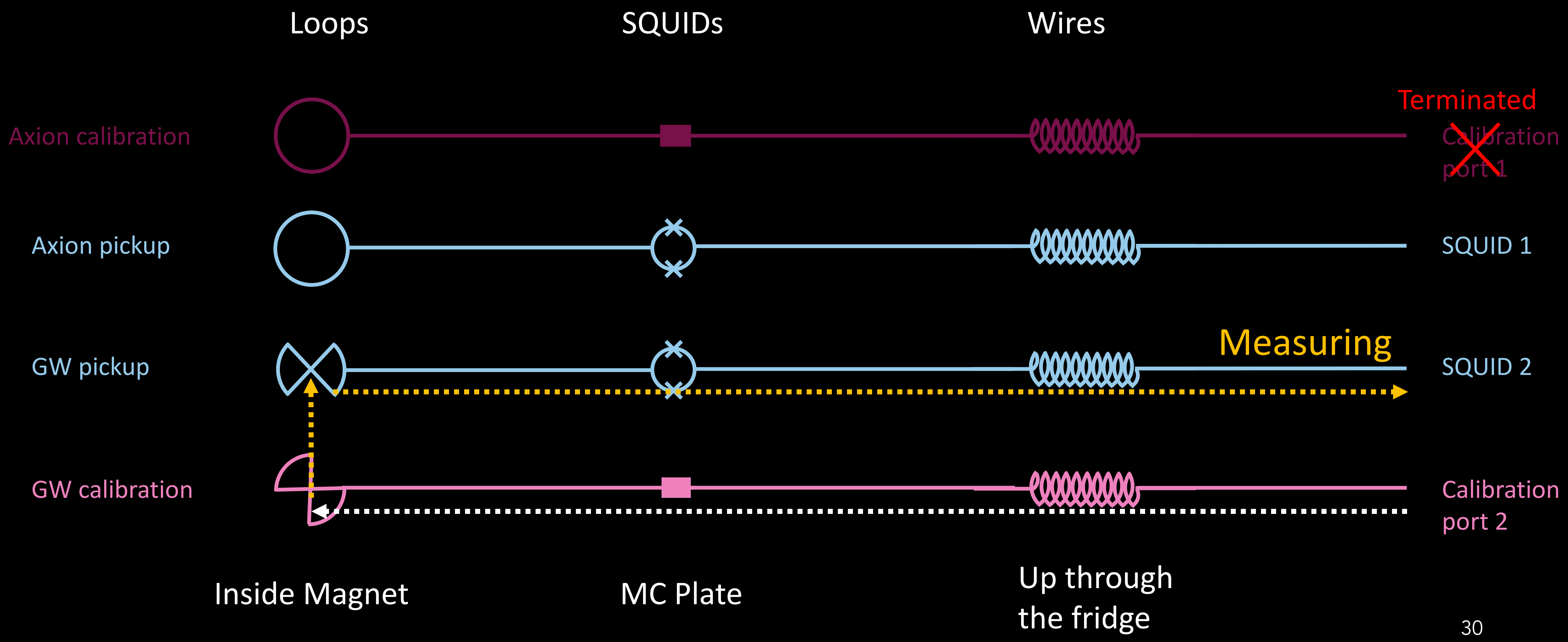
We have four calibrations:

1. GW pickup calibrated with GW signal (GW end-to-end)
2. Axion pickup calibrated with axion signal (axion end-to-end)
3. GW pickup calibrated with axion signal (GW cross calibration)
4. Axion pickup calibrated with GW signal (axion cross calibration)

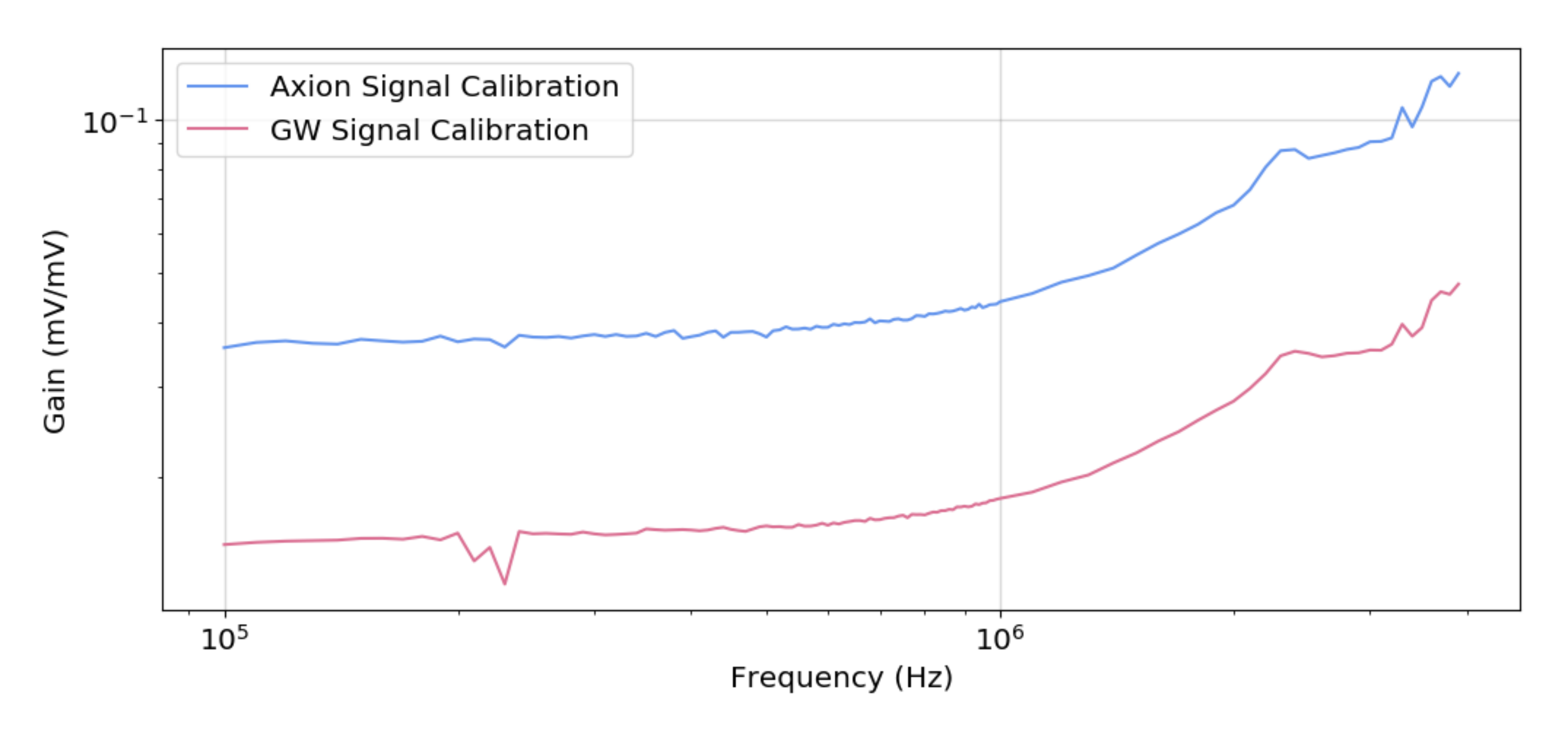
GW pickup: axion signal cross calibration



GW pickup: GW signal end-to-end calibration



Calibration on GW pickup

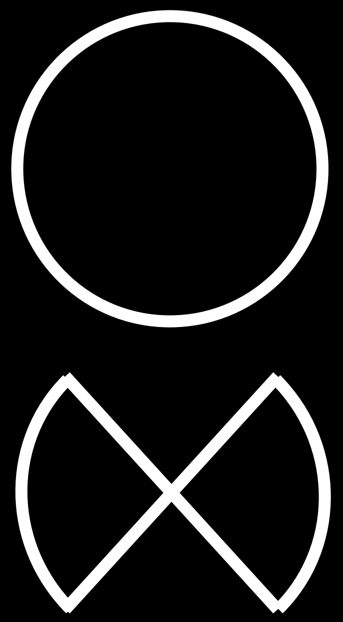


Axion to GW mutual inductance

We expect (to first order) zero mutual inductance between the figure-8 and the circle

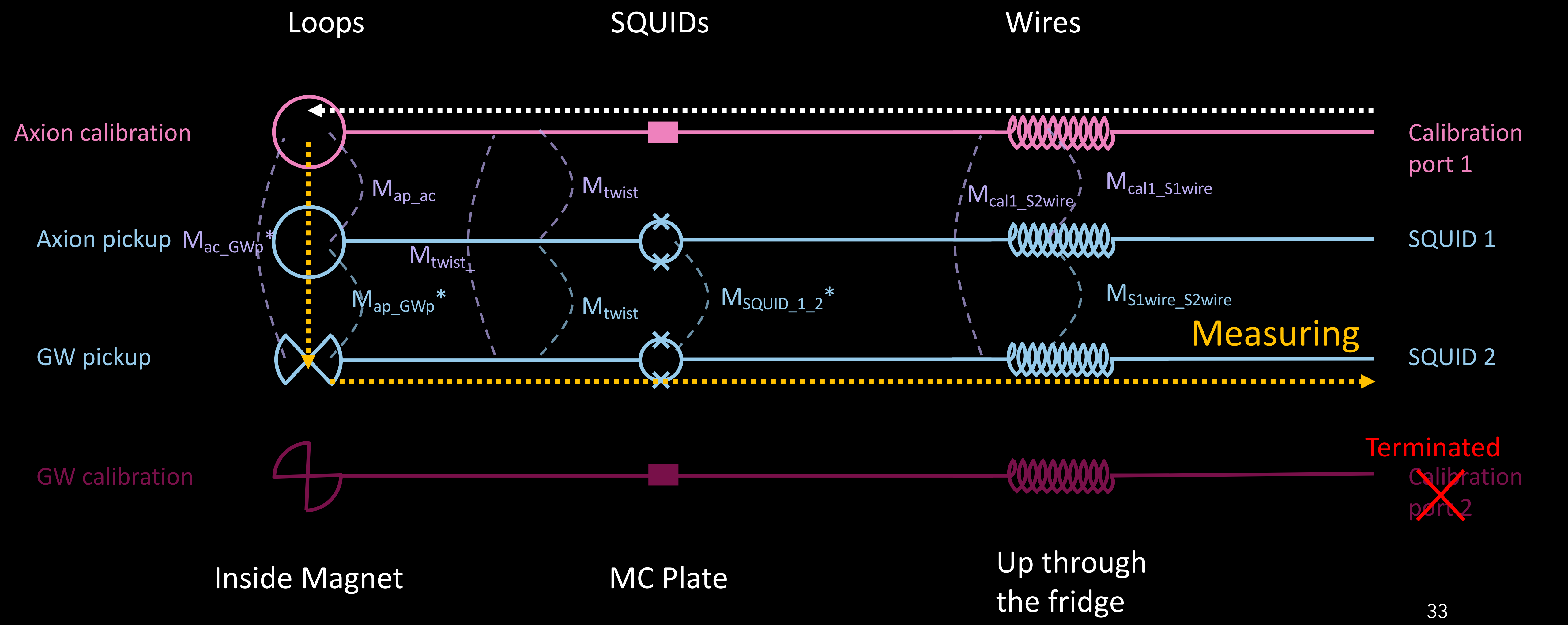
However, we see a high amount of correlation between the signals

- Somewhere in our system there is an unknown high amount of parasitic induction
  - Pickups or twisted pairs
  - SQUIDs
  - Wires

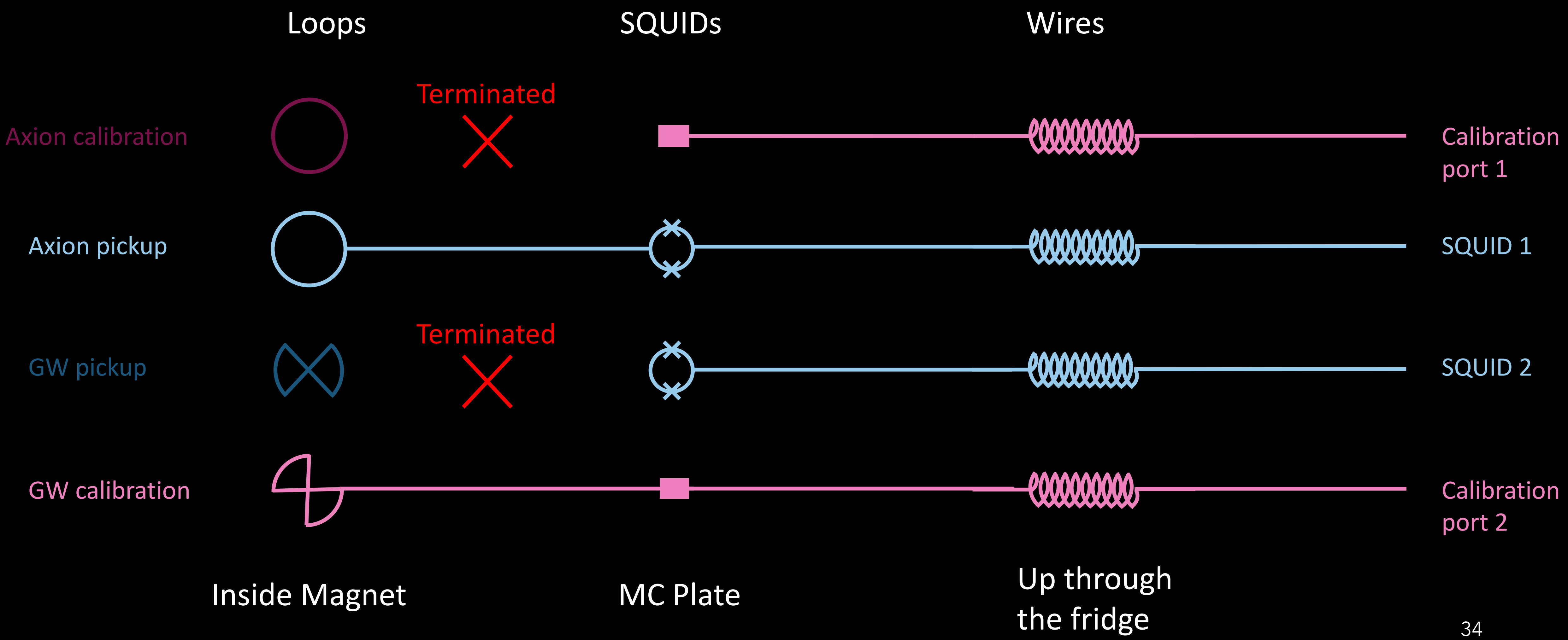


GW pickup: axion signal cross calibration

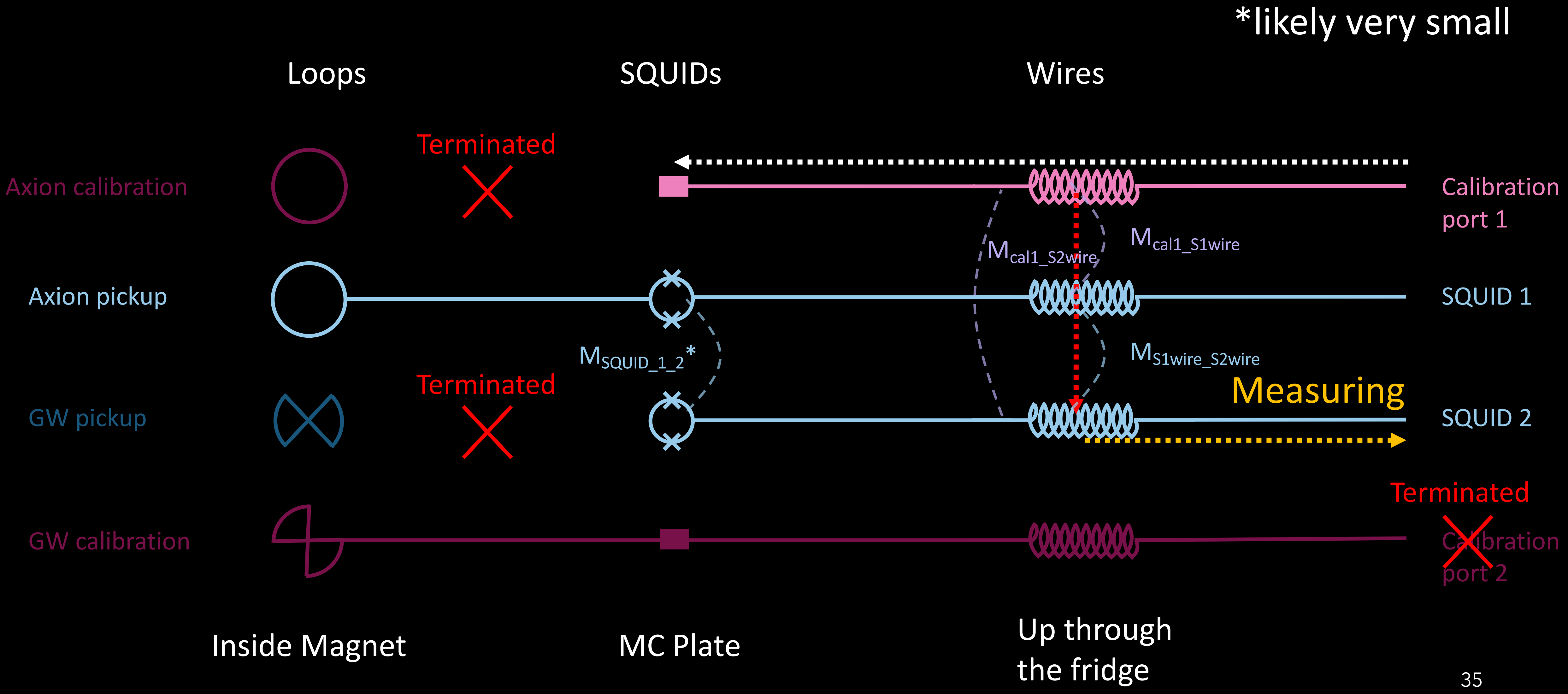
*likely very small



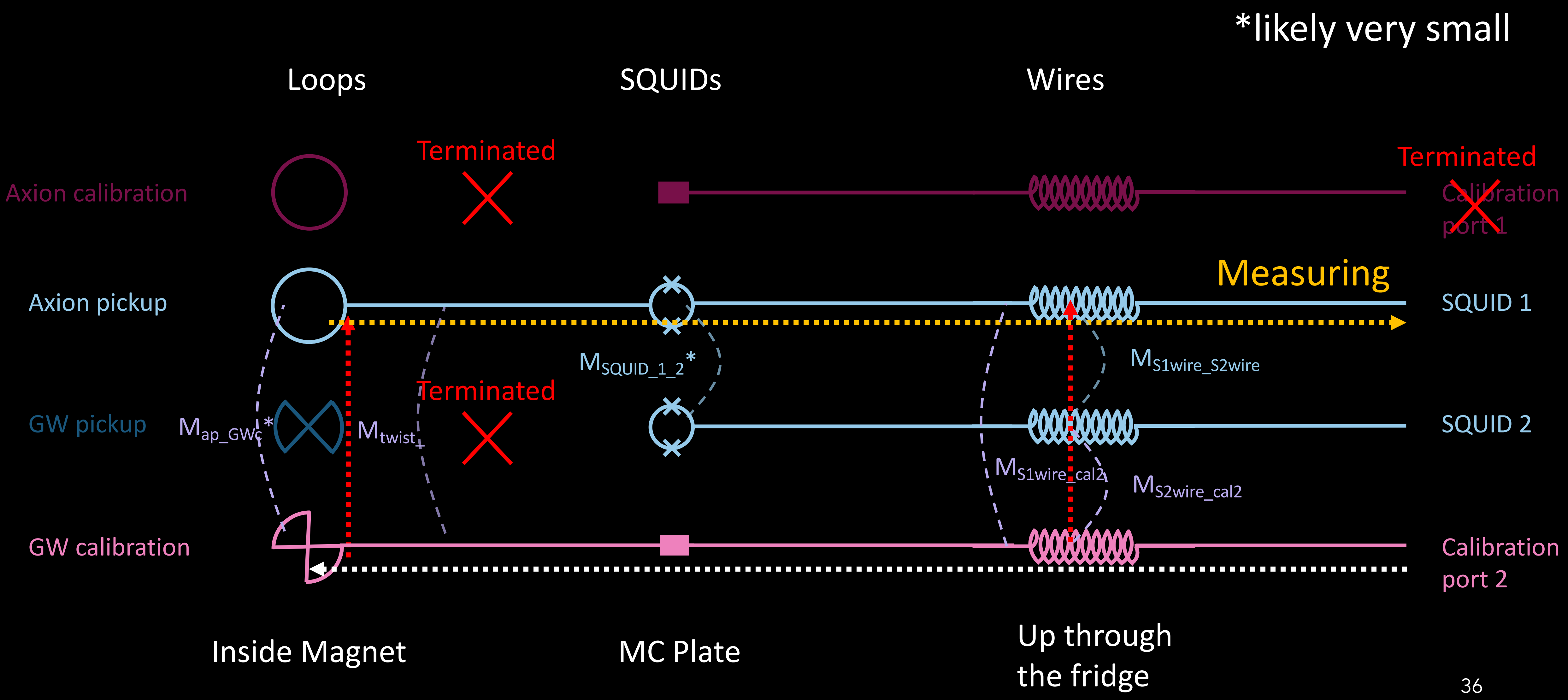
Parasitic inductance run



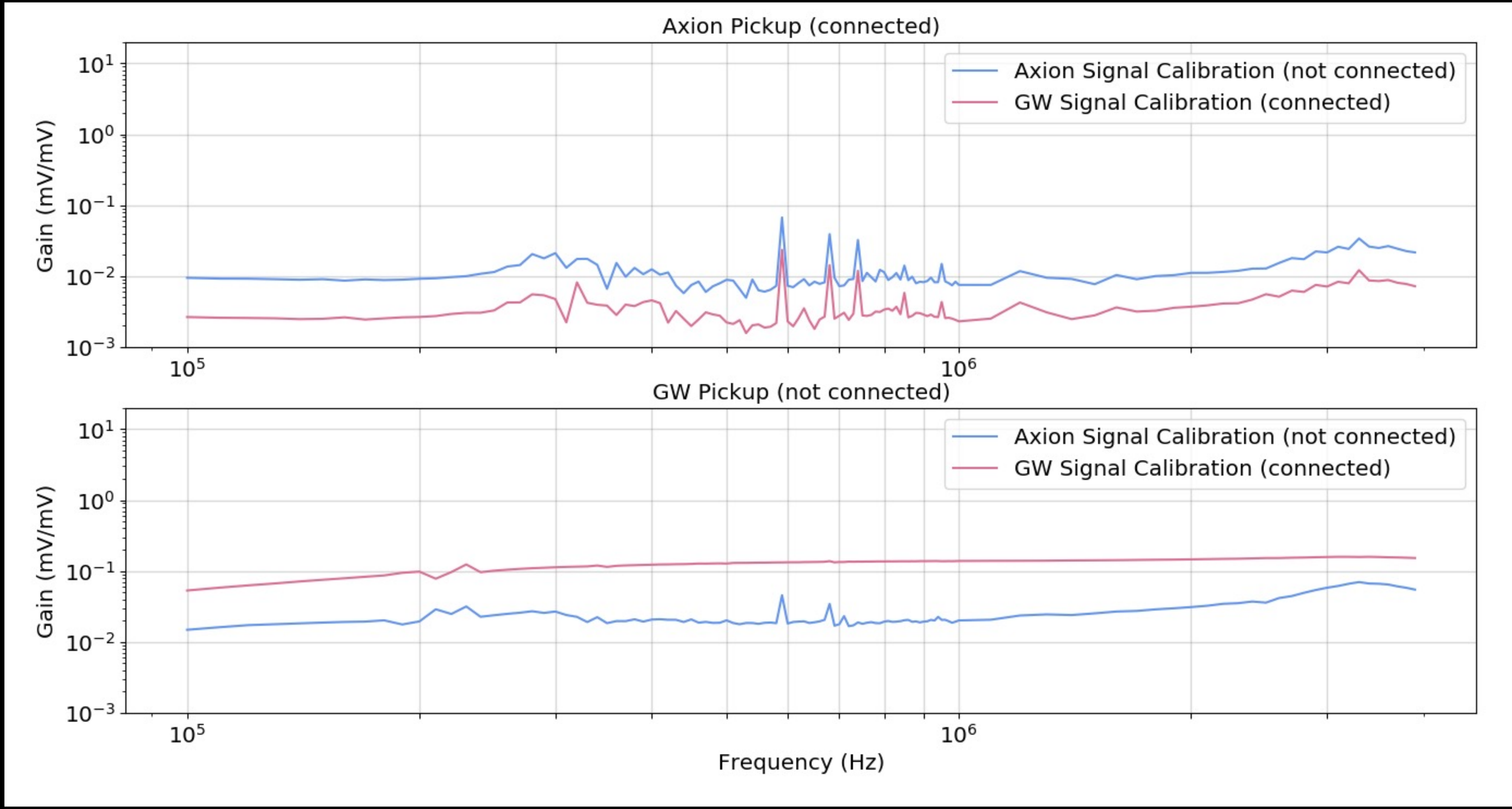
Disconnected cross calibration



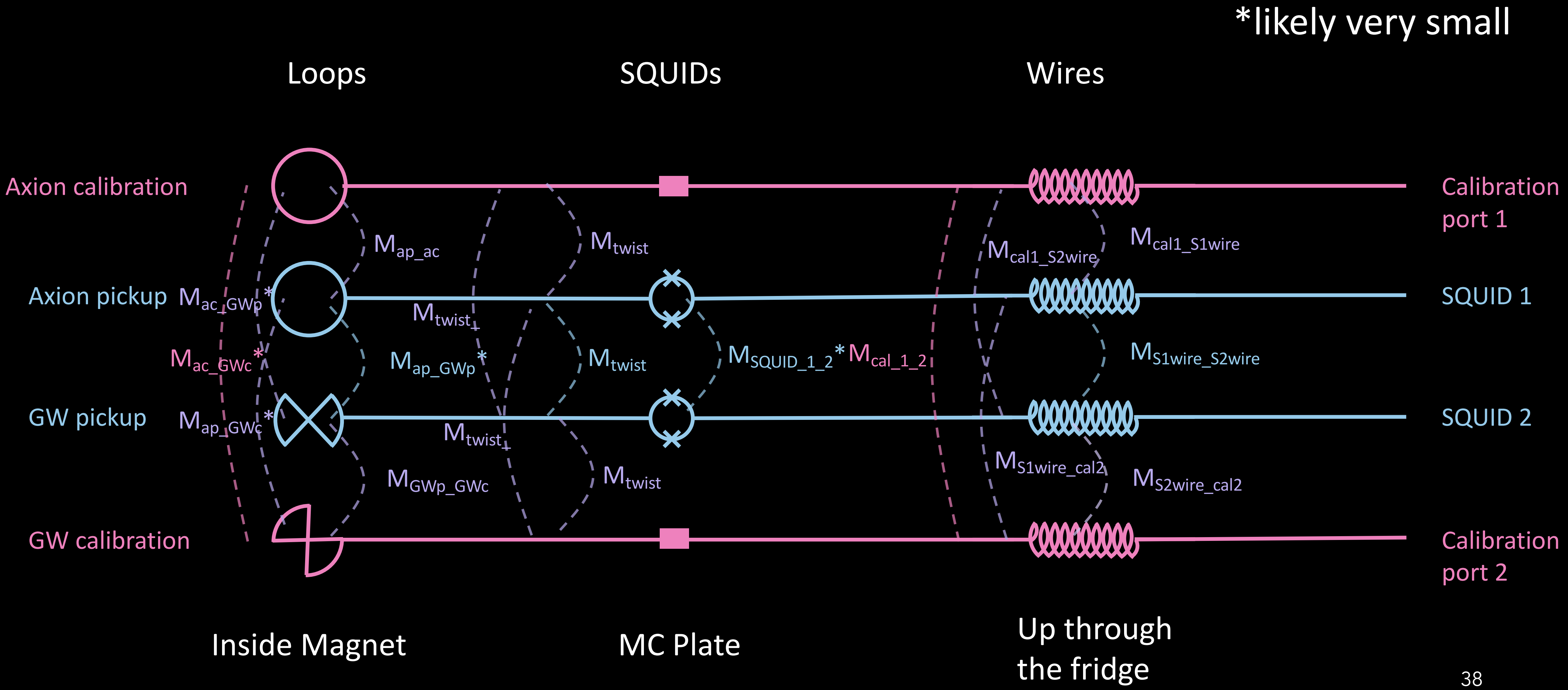
Connected cross calibration



Inductance run results

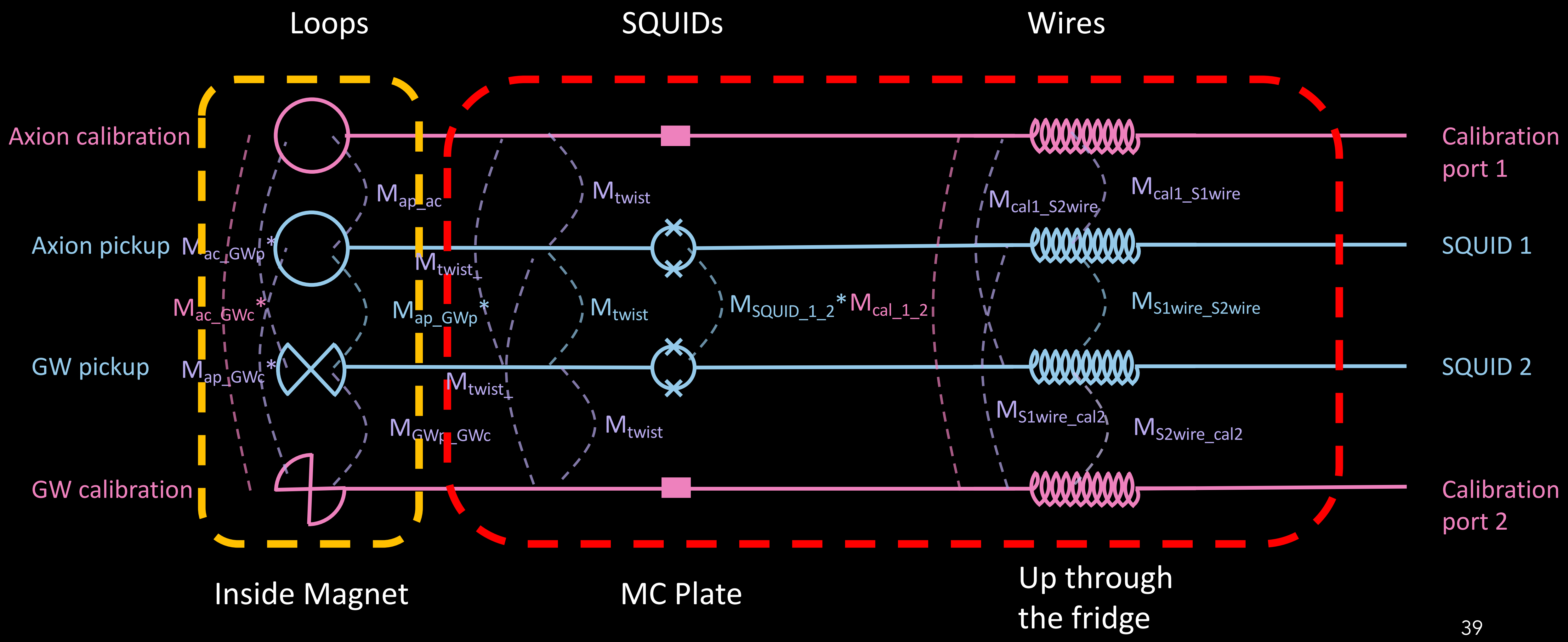


Inductance schema of all possible calibration inductances



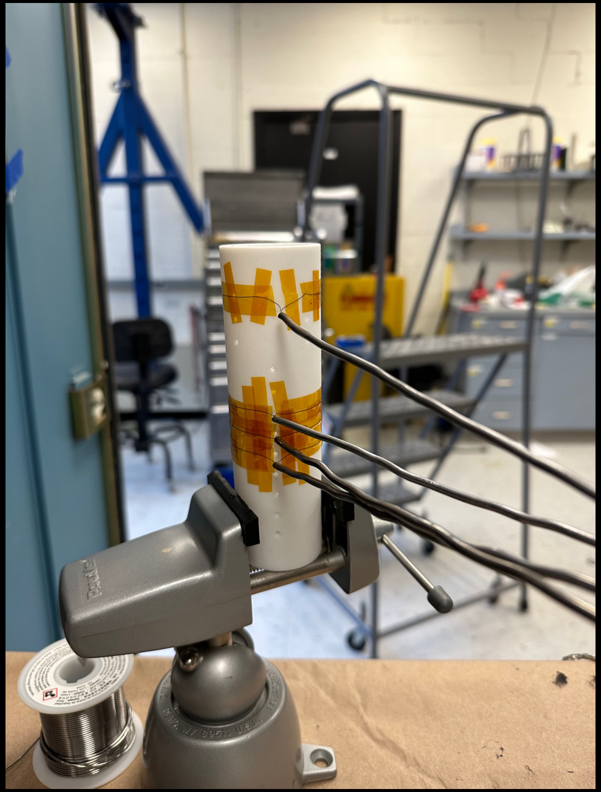
Inductance schema of all possible calibration inductances

*likely very small

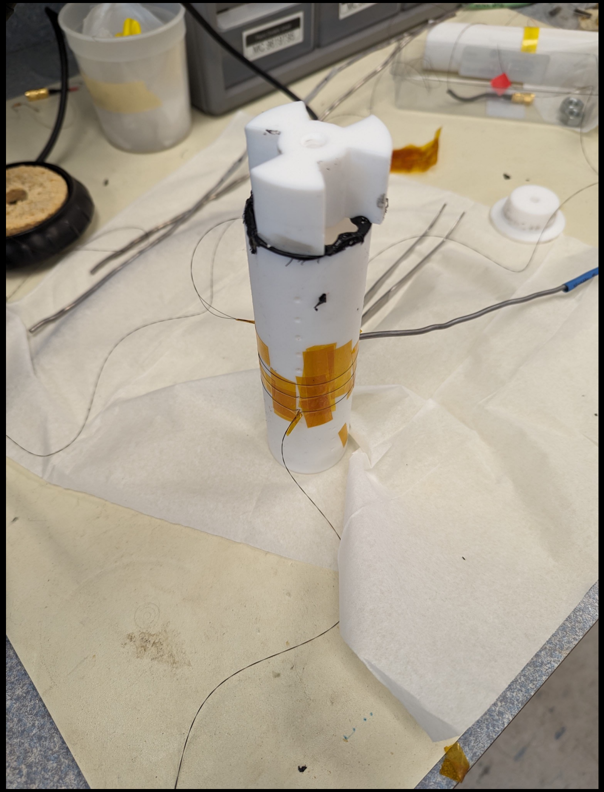


Changes made

- Loops were reduced



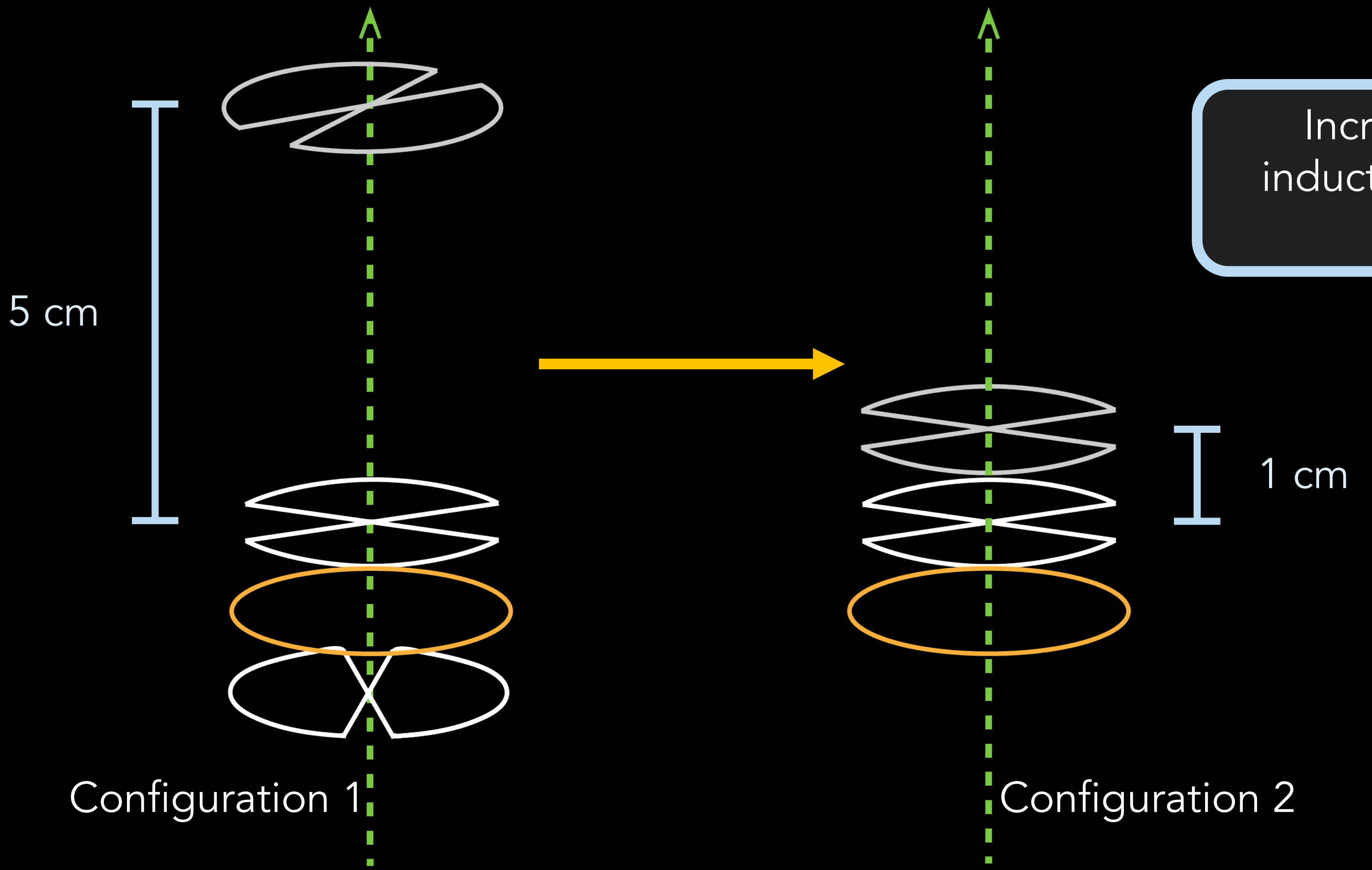
Configuration 1



Configuration 2

Changes made

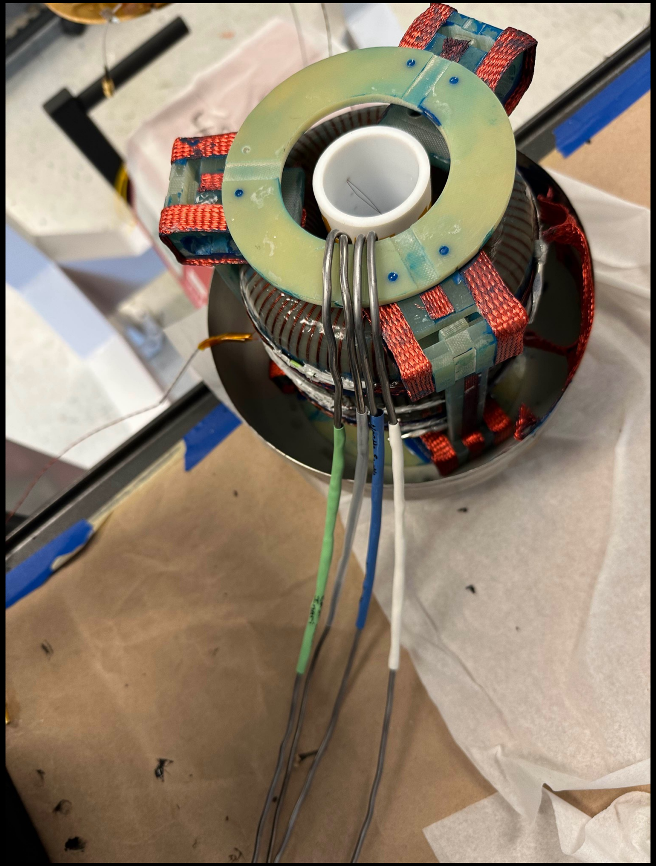
- GW calibration loop moved closer to GW pickup



Increased our mutual inductance by 2 orders of magnitude

Changes made

- Twisted pairs distanced



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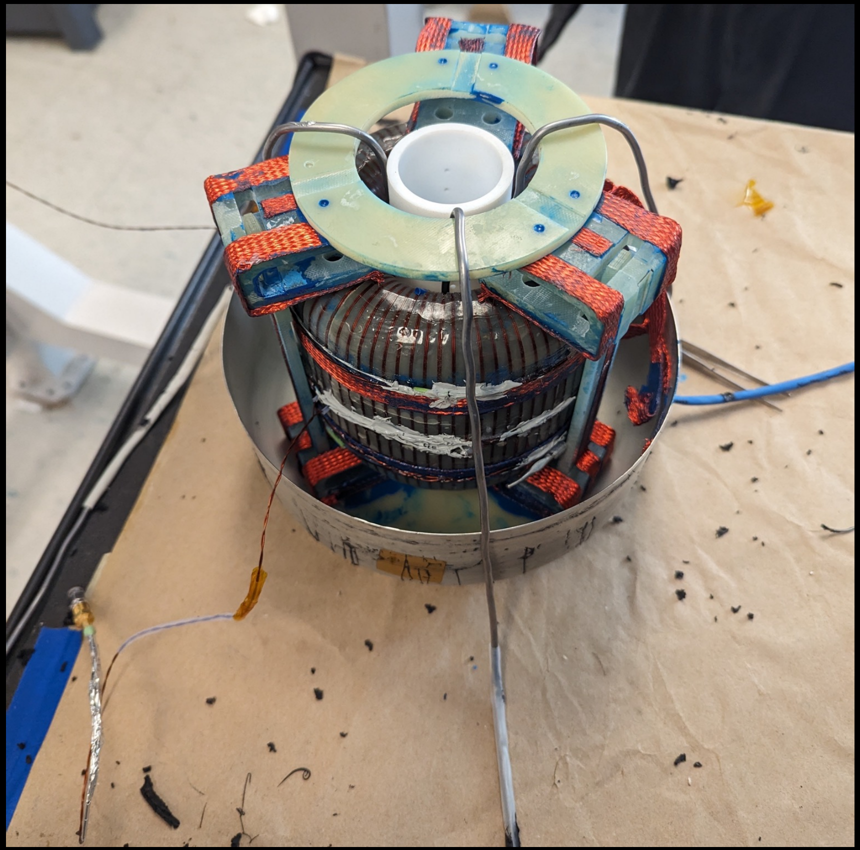
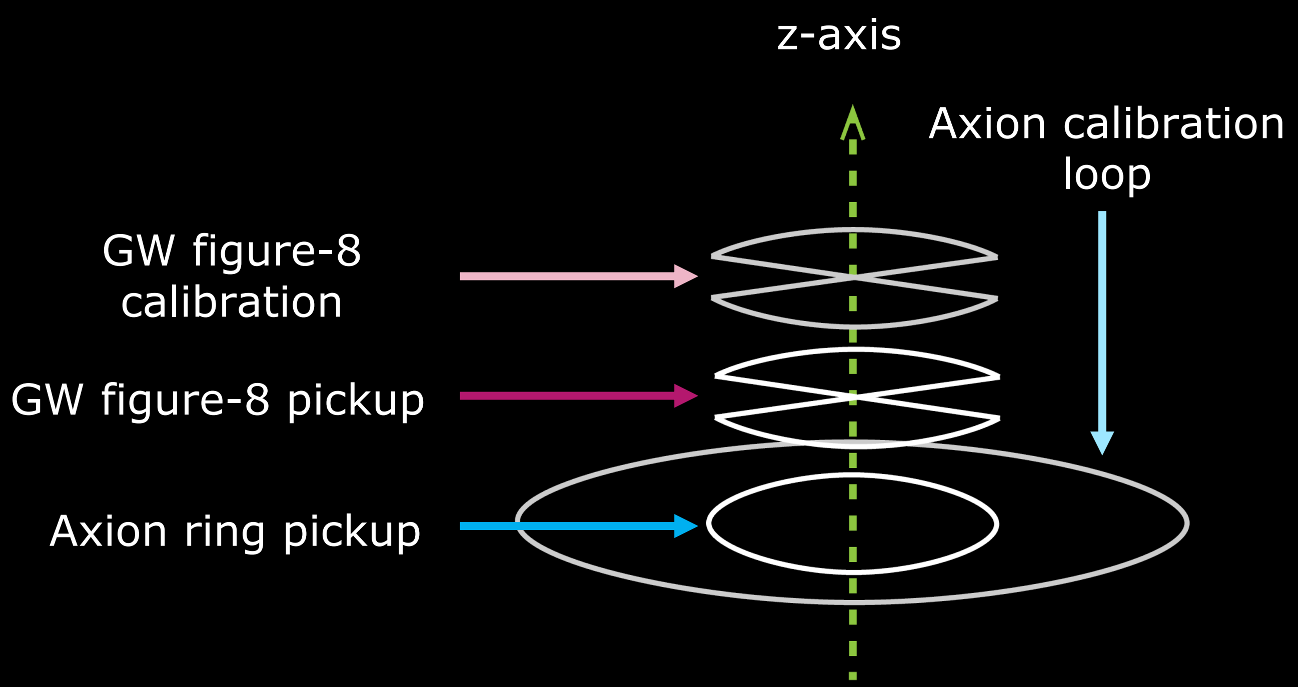


Configuration 2

Experimental Setup



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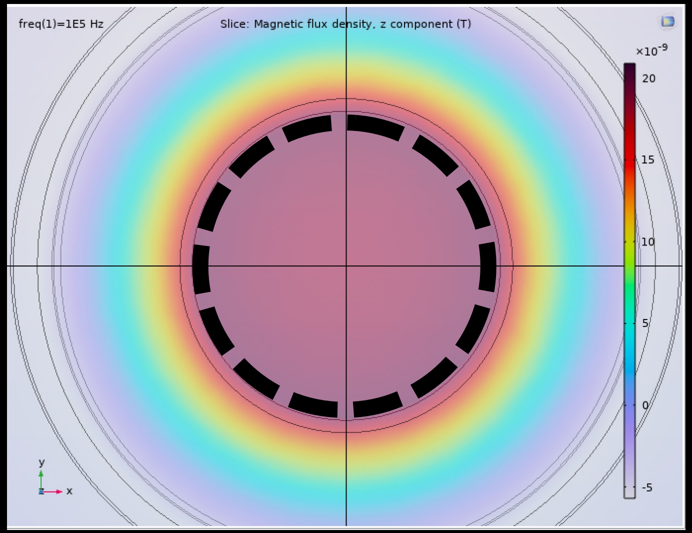
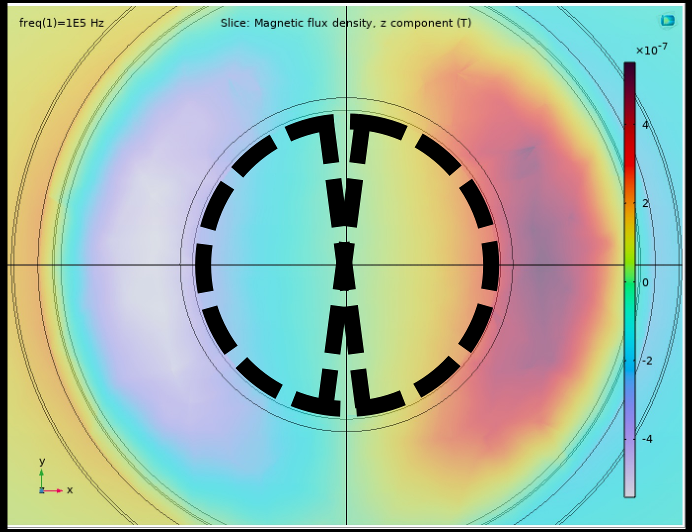
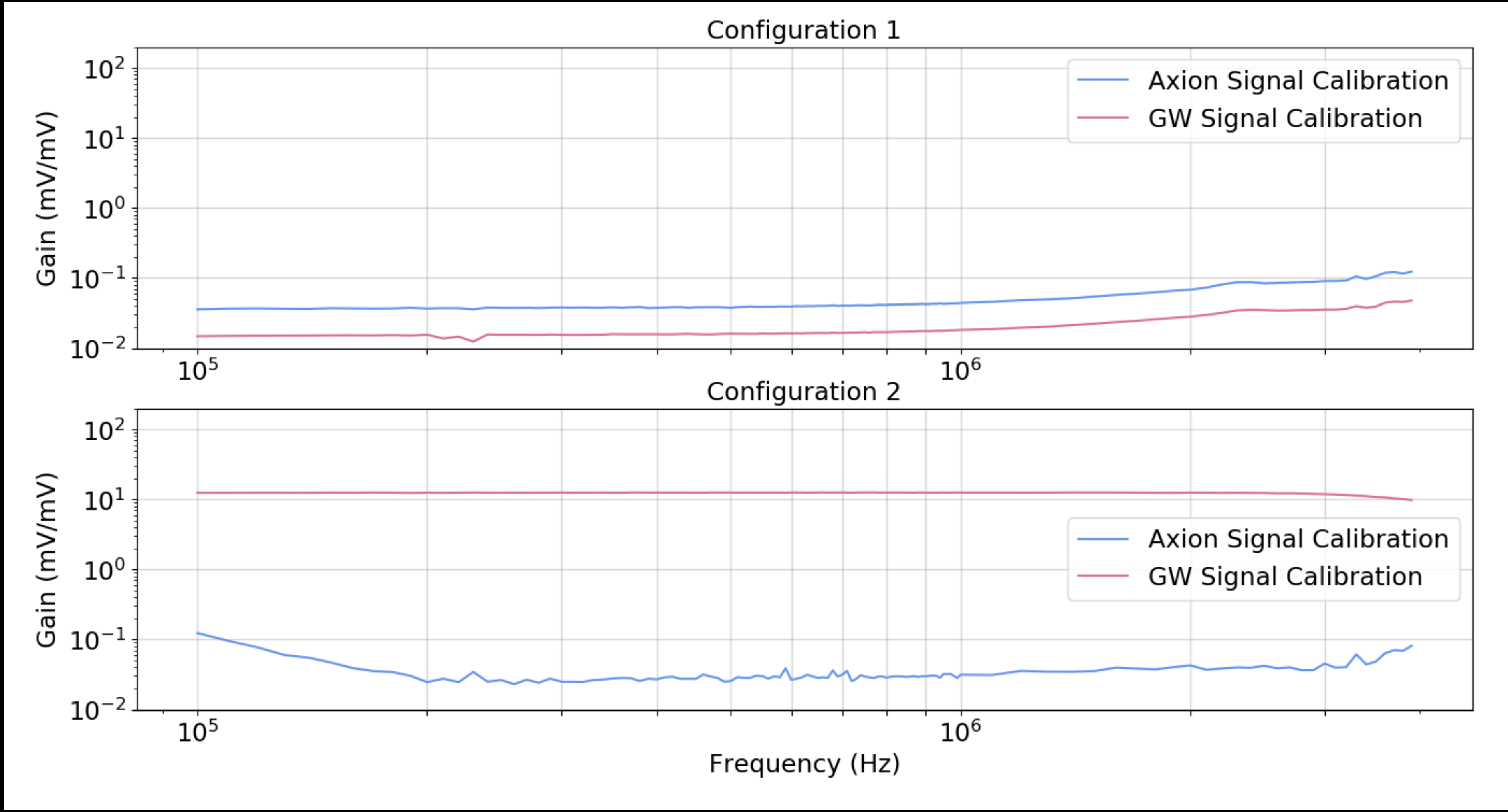


The z-component of the magnetic field resulting from an axion effective current

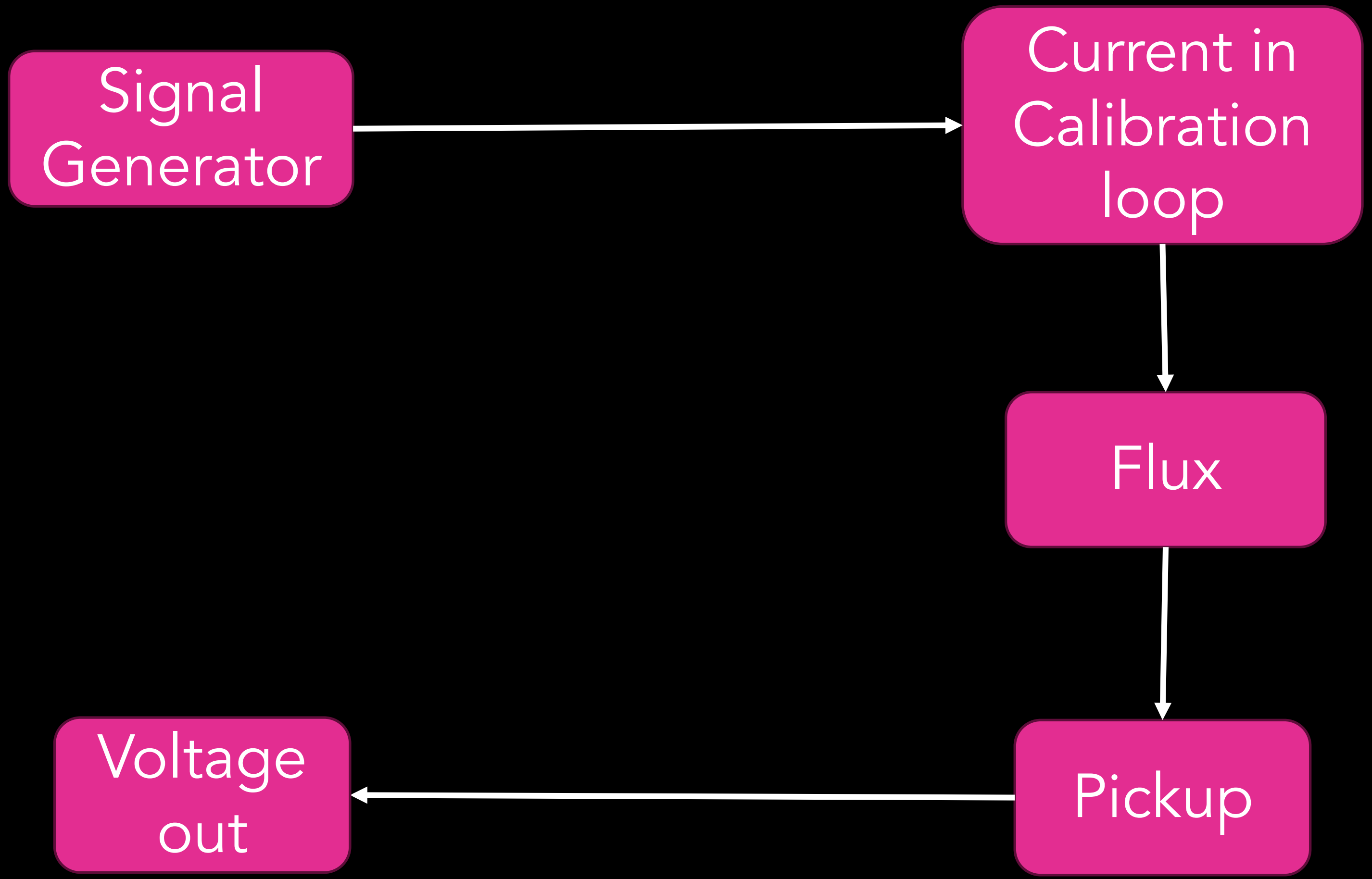


The z-component of the magnetic field resulting from a GW effective current

GW pickup calibration results from configurations 1 & 2



GW data and signal



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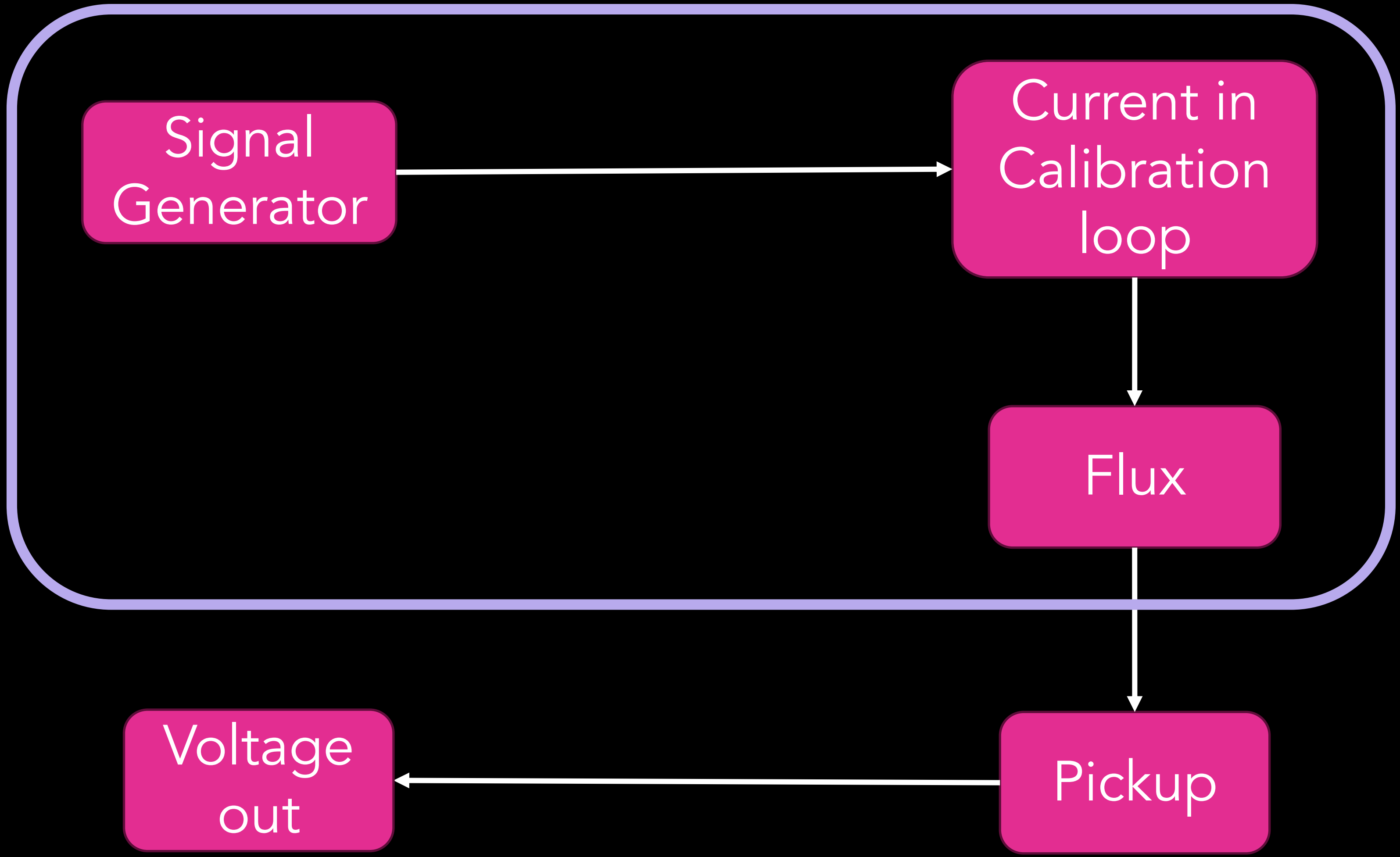

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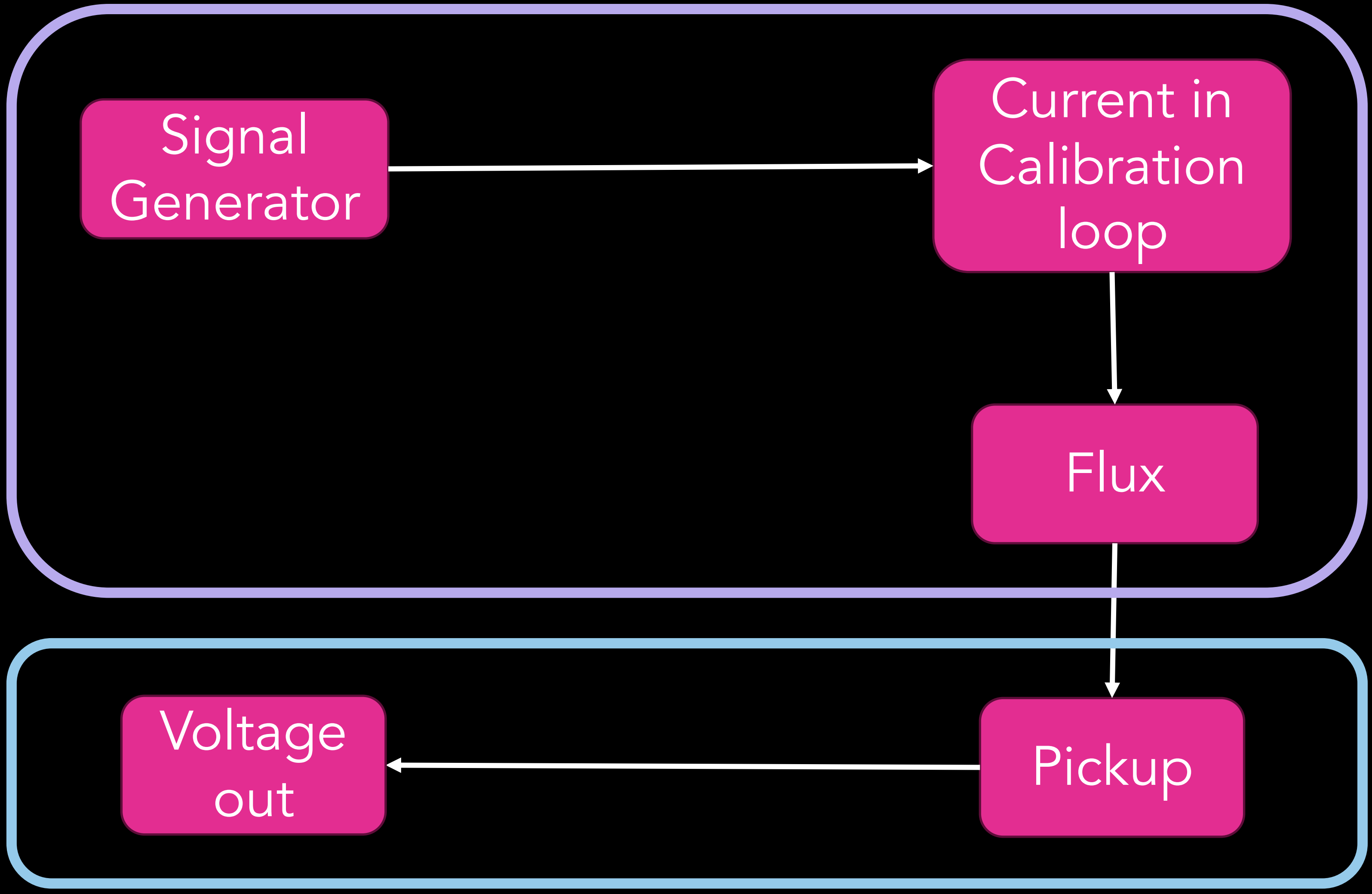
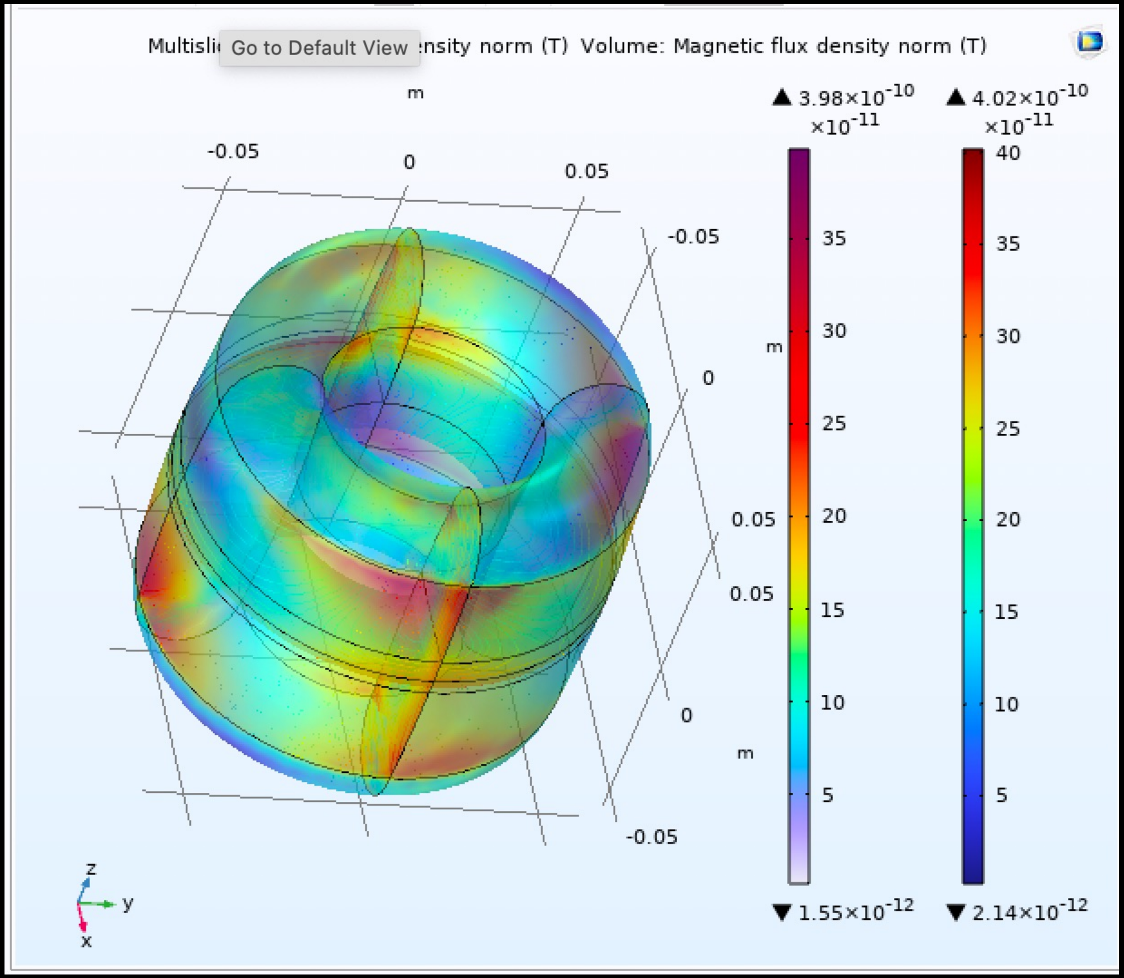


Modeling

Signal modeling in detector

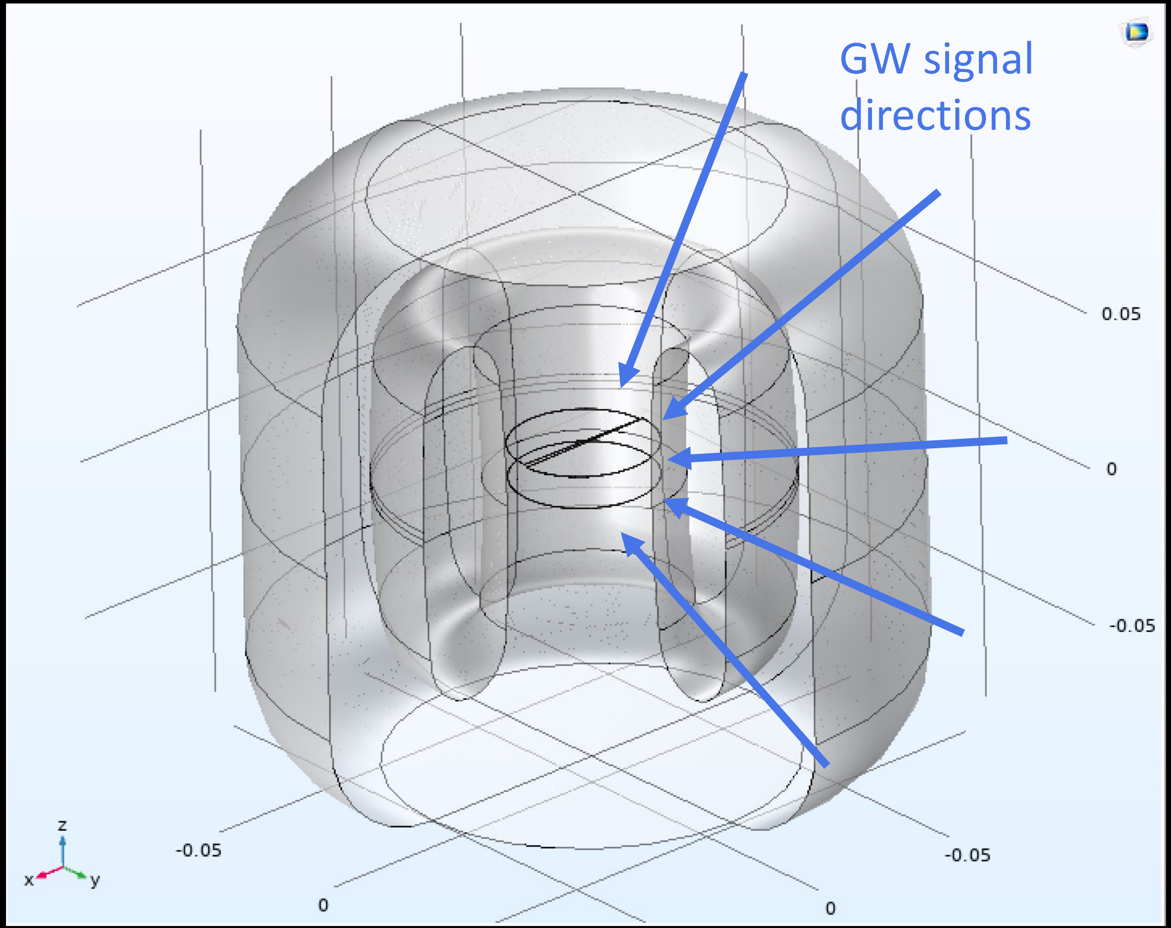


COMSOL is used to model the signal in the ABRA magnetic volume

Using the equations from Valerie Domcke, Camilo Garcia-Cely, Sung Mook Lee, Nicholas L. Rodd 2306.03125

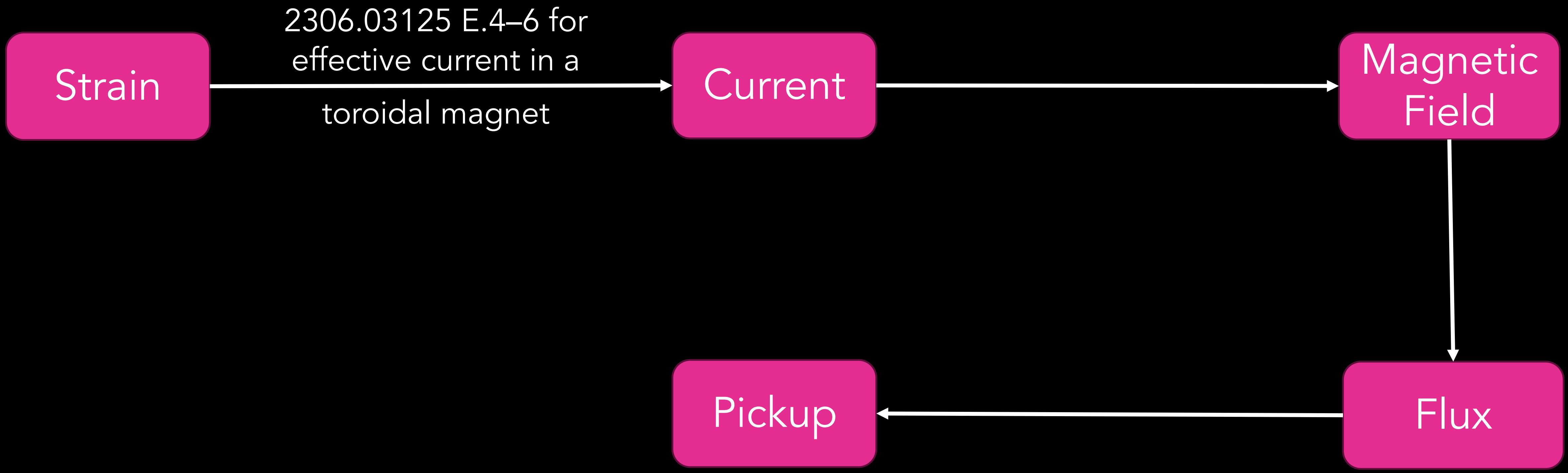
- Equations E.4–6 for effective current in a toroidal magnet

Signal modeling in detector

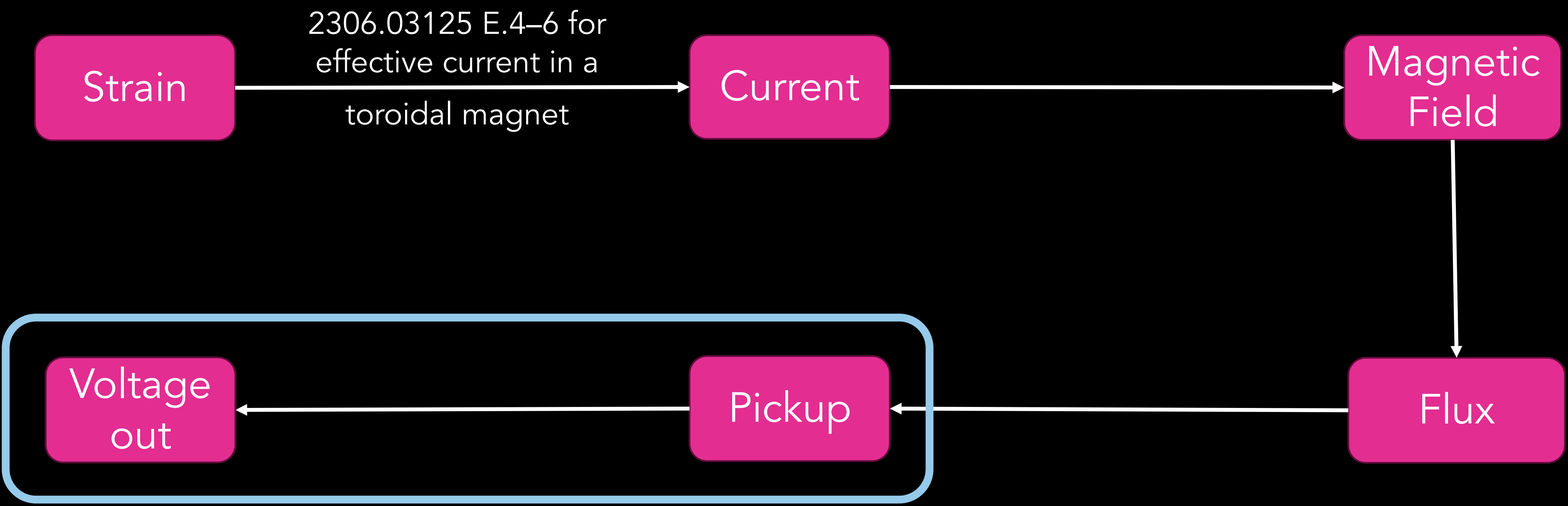


Taking advantage of symmetry, the GW loop only needs to be simulated with angles ranging over a quarter the sphere.

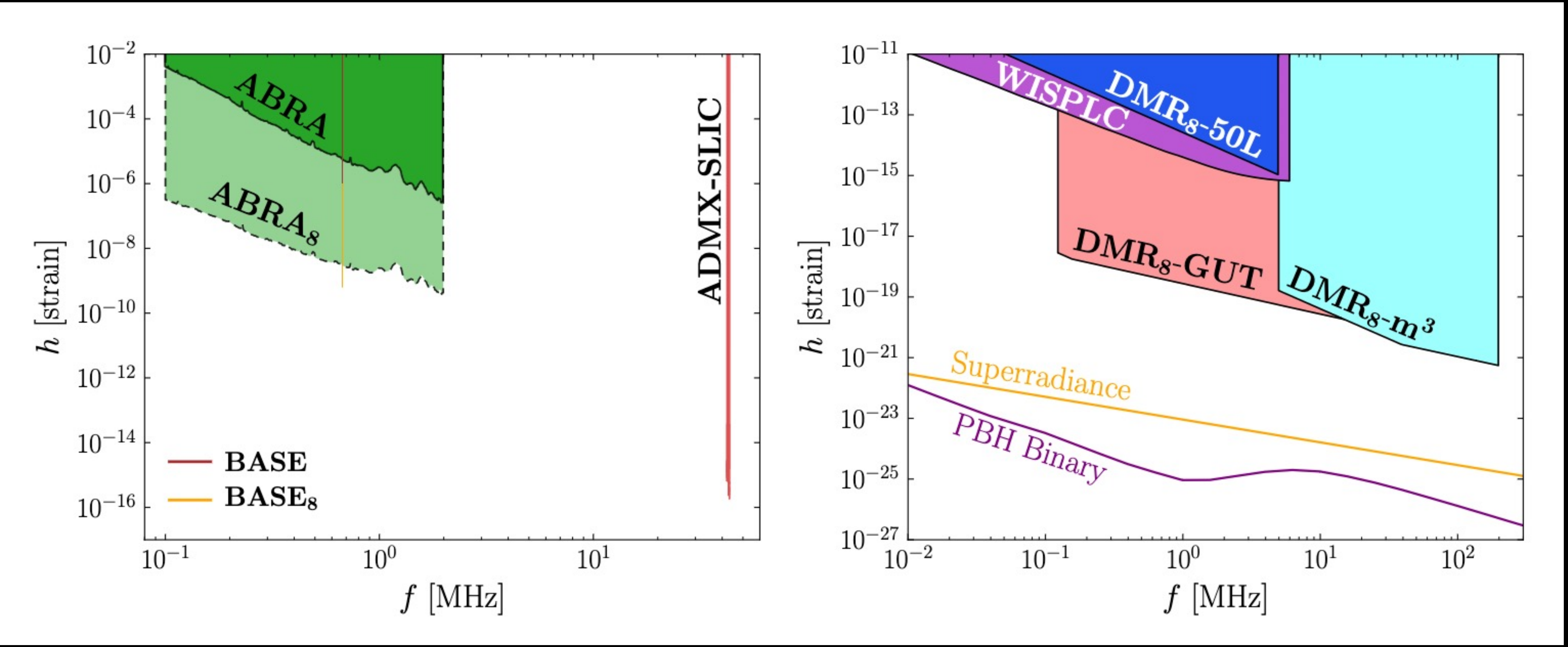
Signal modeling in detector



Signal modeling in detector + calibration



Projected sensitivity

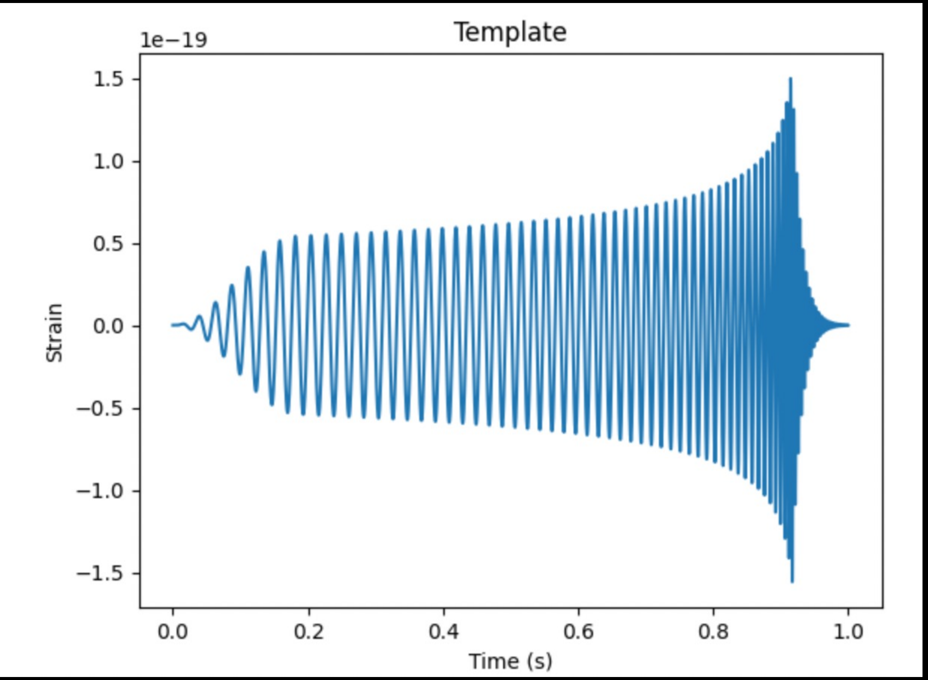


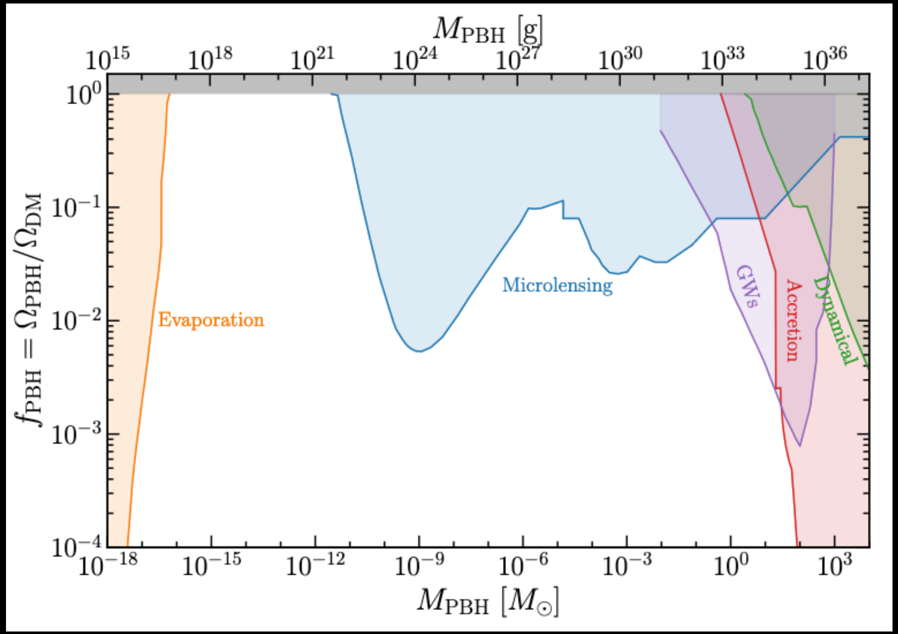
arXiv:2306.03125

The signal

Our frequency range: 10 kHz – 5 MHz *

We will use primordial black hole mergers as our signal template





https://arxiv.org/pdf/2205.14722.pdf

*Subject to noise

GW data

Taking time-series data on two channels, needs to be compressed

Templates are created using the Ripple code base

- Frequency range limits possible masses
- Sensitivity limits distance to source

Chirp search → no averaging

Time domain search

In-spiral only → less sensitive

Frequency domain (with averaging)

ABRA-grav current status

We've done all eight calibrations (magnet on and off)

Currently collecting data!

→ We will collect for a week