Theory Meets Experiments 2025:

Direct Detection across Dark Matter mass ranges

Wave Dark Matter Experiments

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Lecture 2: searches for low-mass axions

- Review + moved from yesterday:
  - dark matter signal
  - dark matter detection regimes
- Low mass motivation and background
- Lumped-element detection
- SRF cavity detection

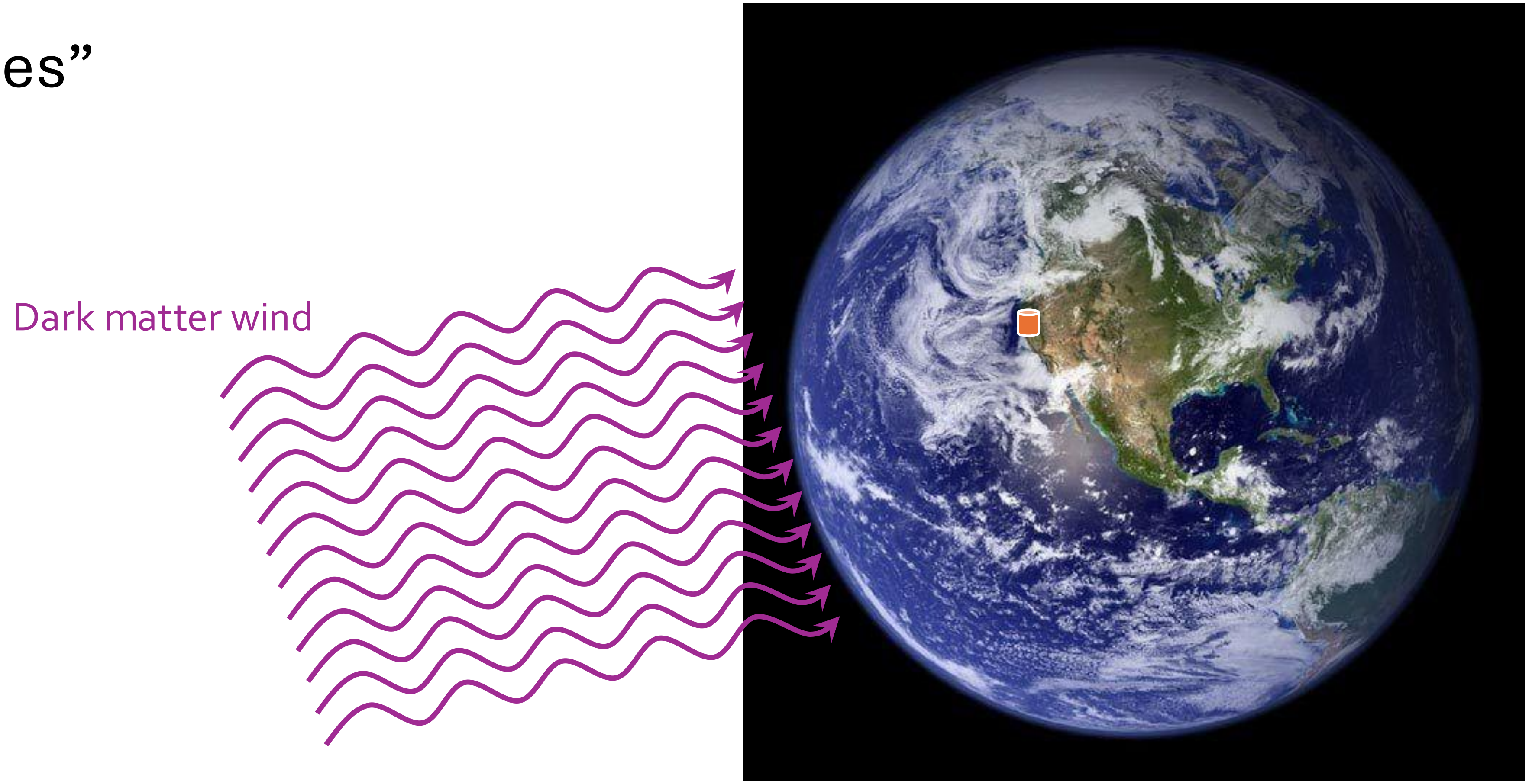
Axion-photon experiment ingredients

1. Strong magnetic field (axion-to-photon converter)
2. Coupling system (couple photons/EM signal into detector)
3. Very sensitive detector (amplify a tiny signal)

$$\mathbf{J}_{\rm eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

Sources of axions: dark matter

“Haloscopes”



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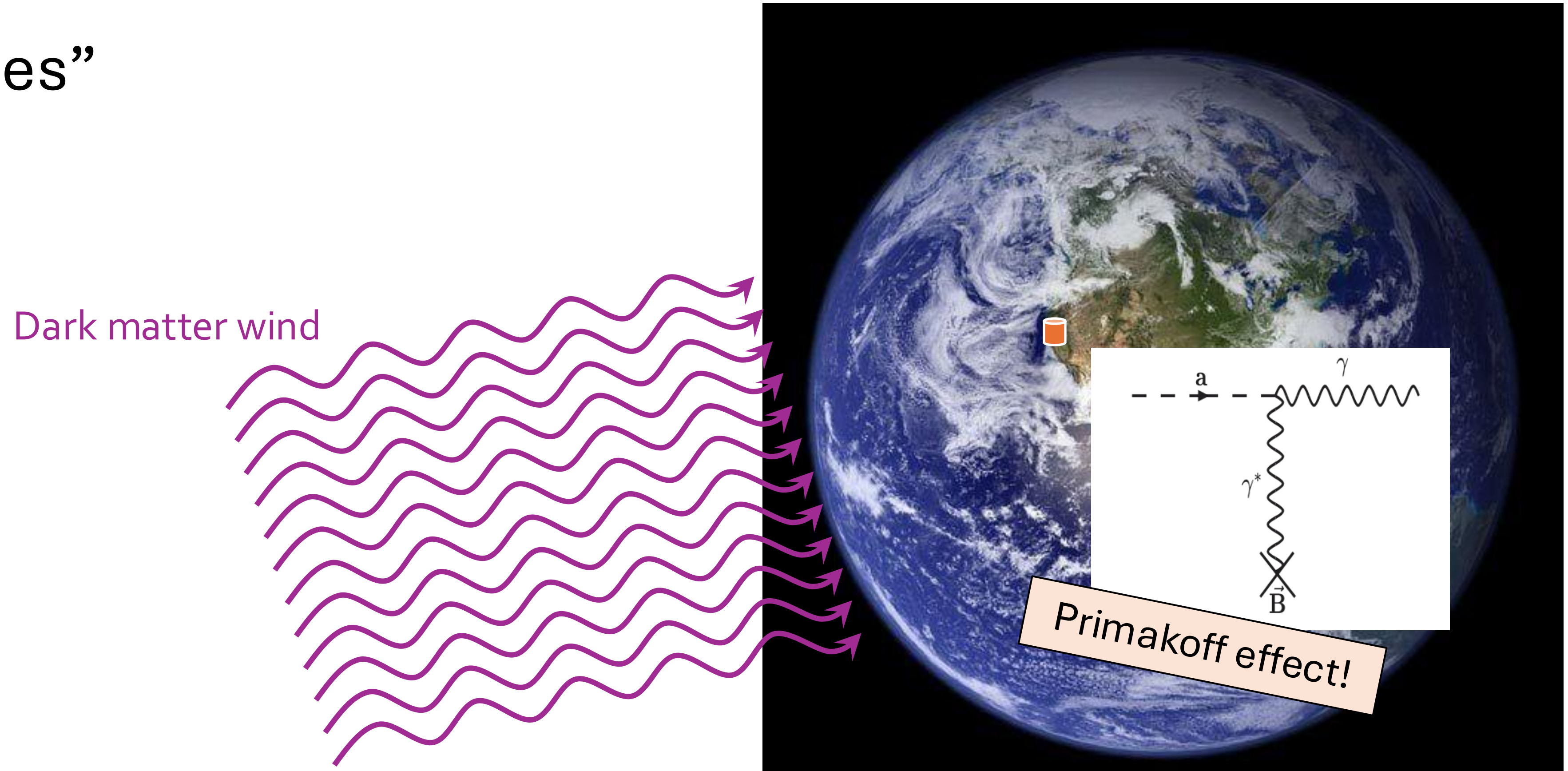

What does the dark matter signal look like?

- Approximately monochromatic sinusoidal signal

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Why only "approximately"?

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$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

- Virialized dark matter halo → distribution of velocities

$$\Delta v \sim 10^{-3}$$ ← 220 km/s (velocity dispersion)

$$v_{\text{obs}} \sim 10^{-3}$$ ← 232 km/s (sun's orbital velocity)

$$v_{\text{DM, max}} = v_{\text{esc}}$$ ← 550 km/s

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- Virialized dark matter halo → distribution of velocities

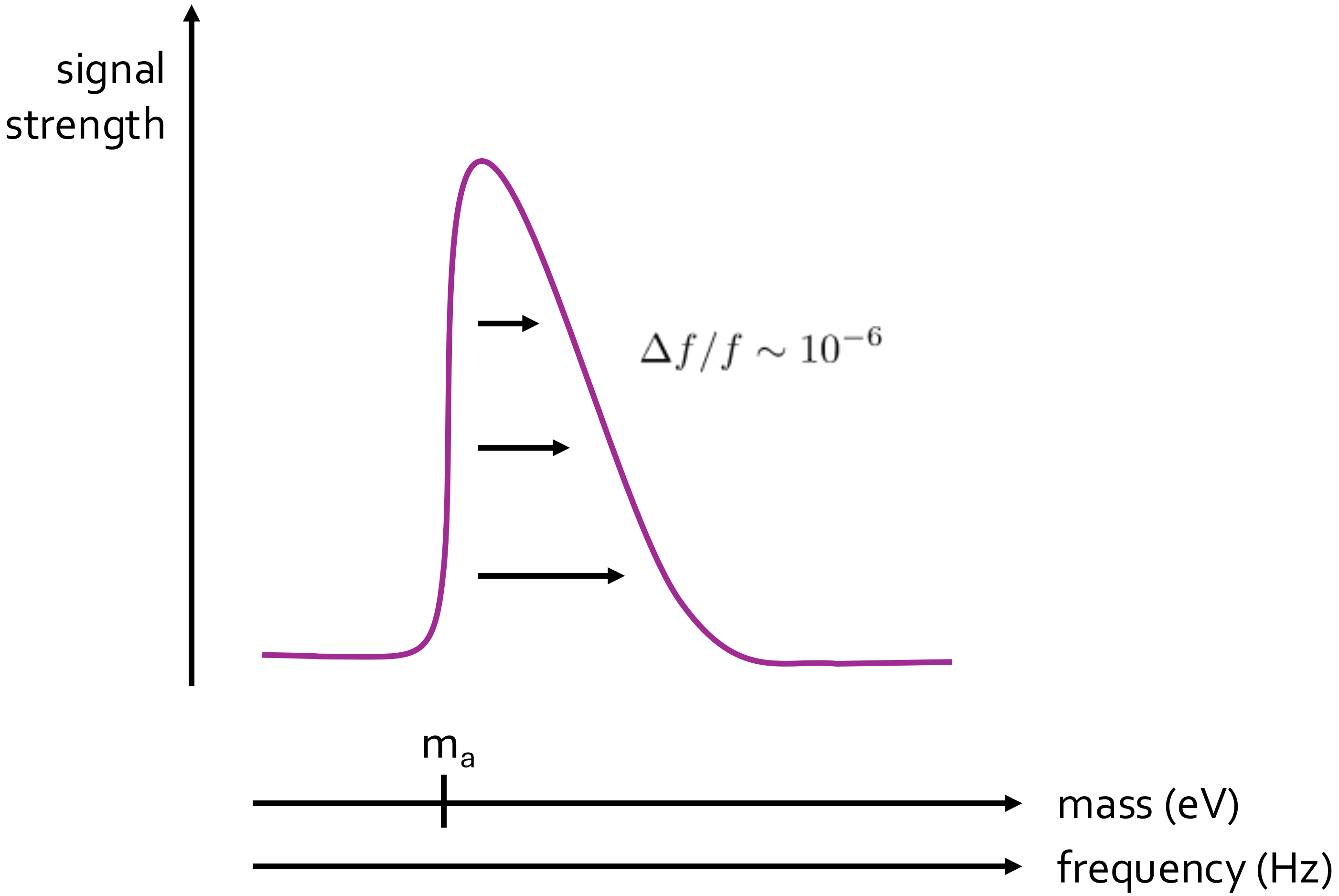
$$\Delta v \sim 10^{-3}$$

this low dispersion implies the axion field is coherent over:

$$\tau \sim 10^6 \times \frac{2\pi}{m_a}$$

How do we read out the dark matter signal?

- Take time series
- Fourier transform
- Search in frequency space for persistent signal



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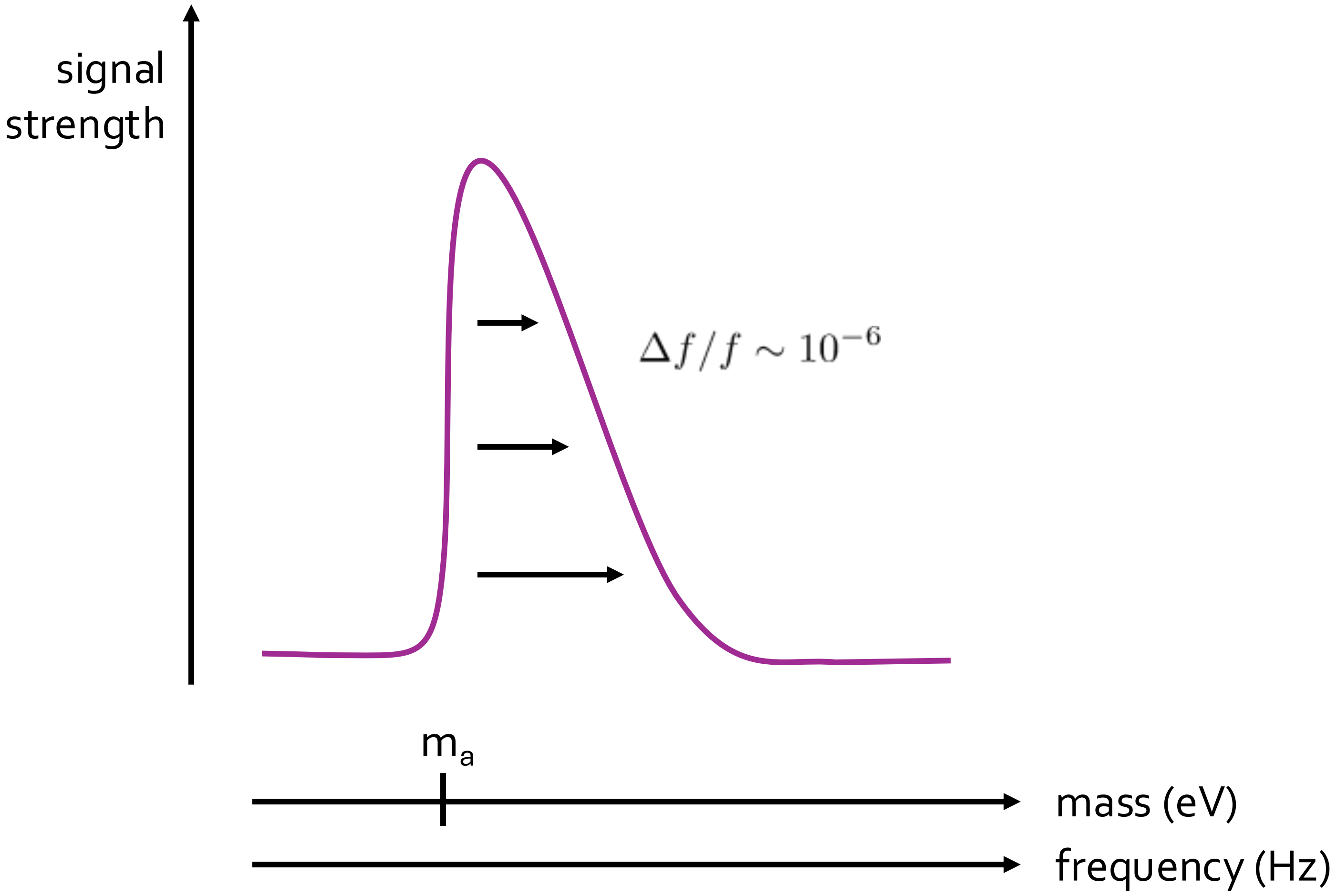
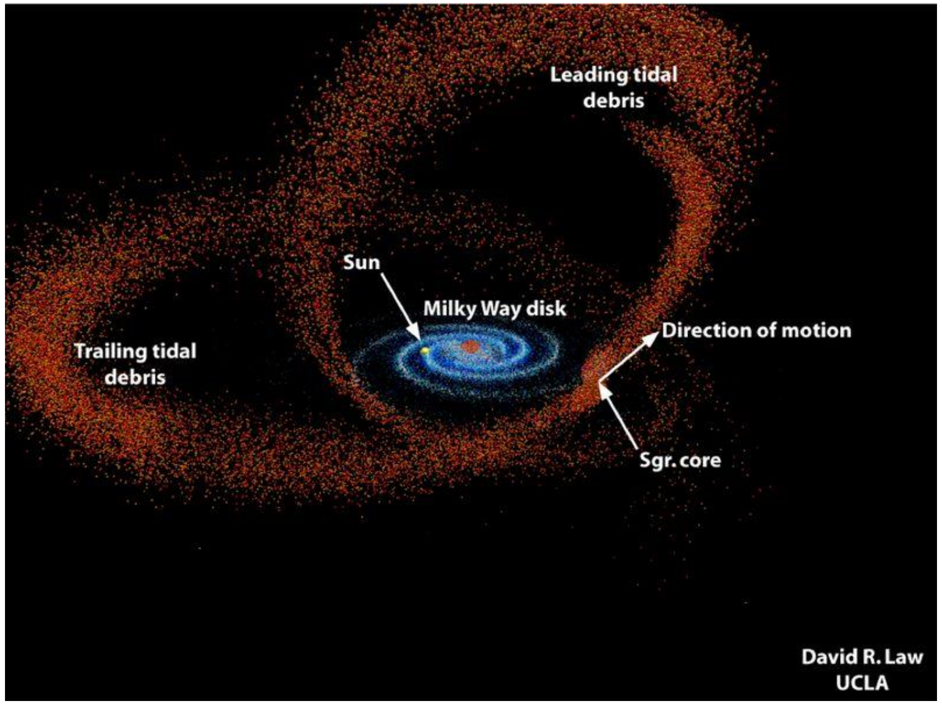
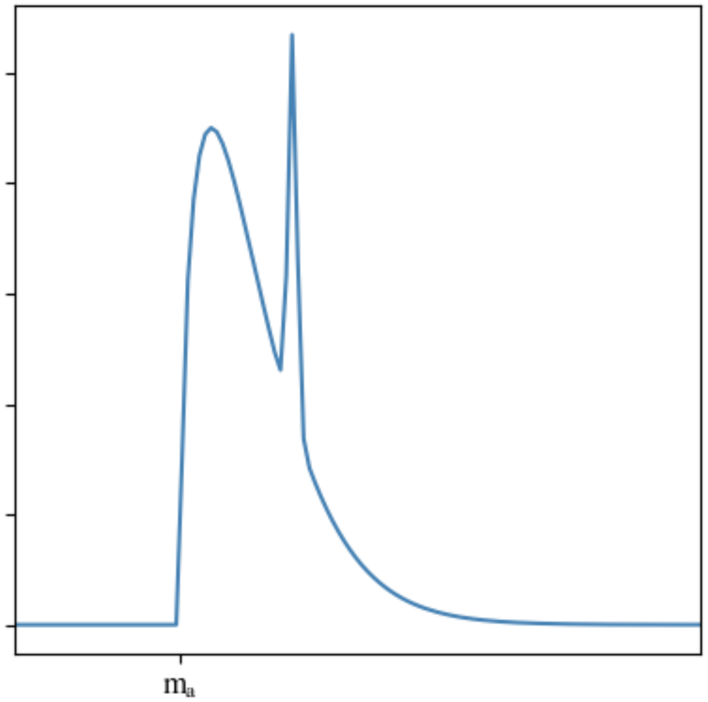
persistence assumption breaks down if axions are clumped



Variations to the Standard Halo Model

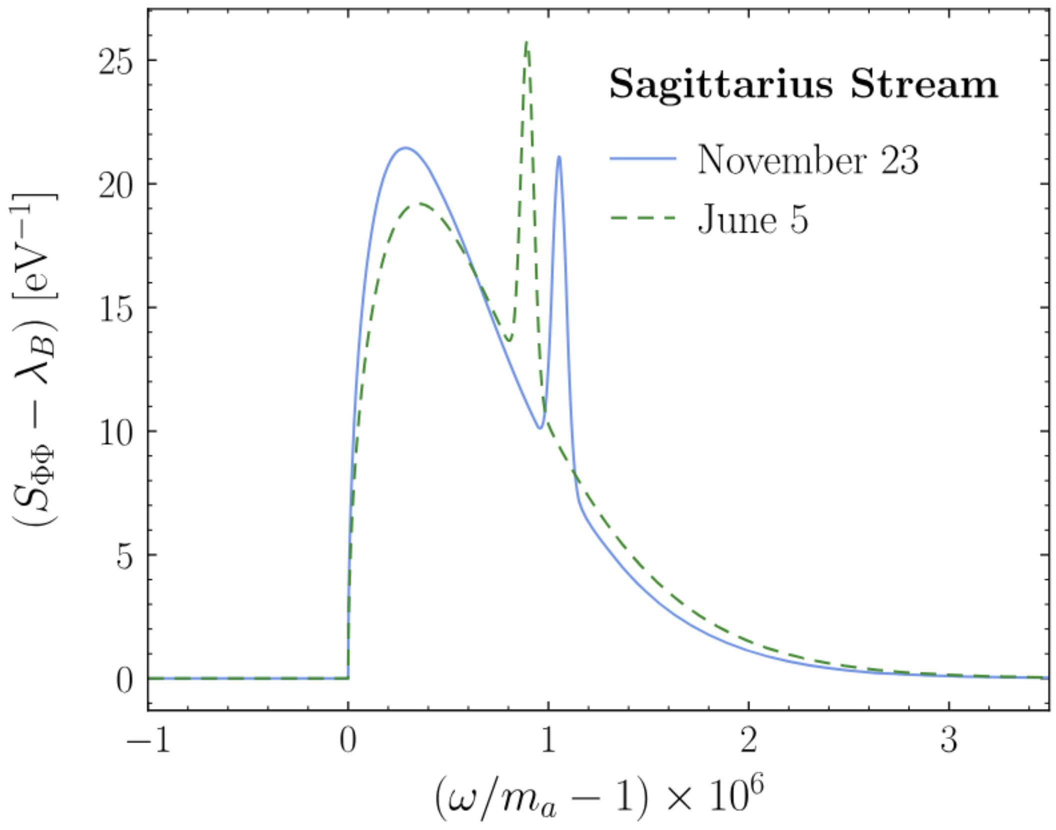
- Dark matter isn’t all virialized
- May have a more intense signal from dark matter streams
  - Lower velocity dispersion





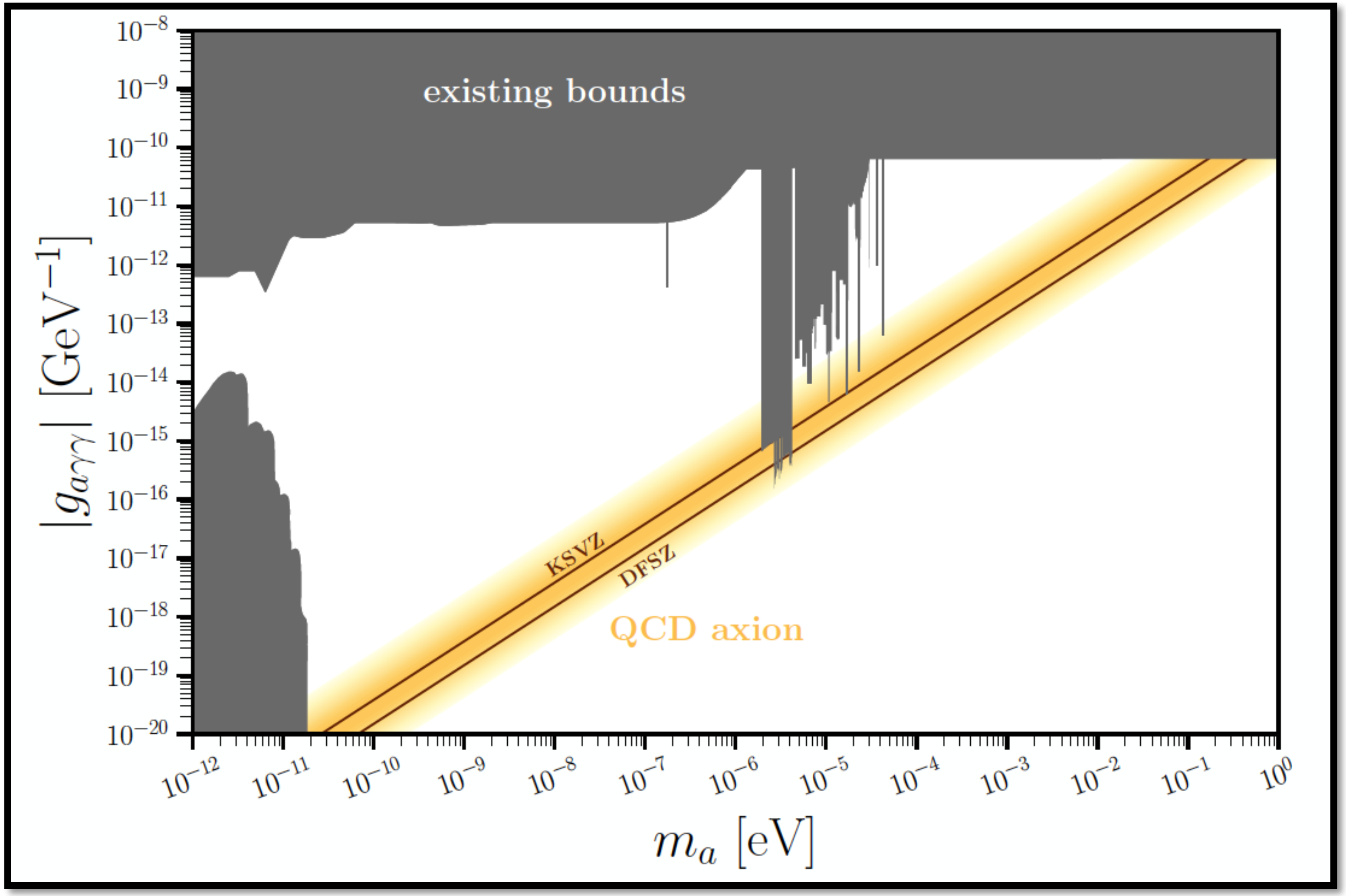
Time variation of signal

Daily and annual modulation expected



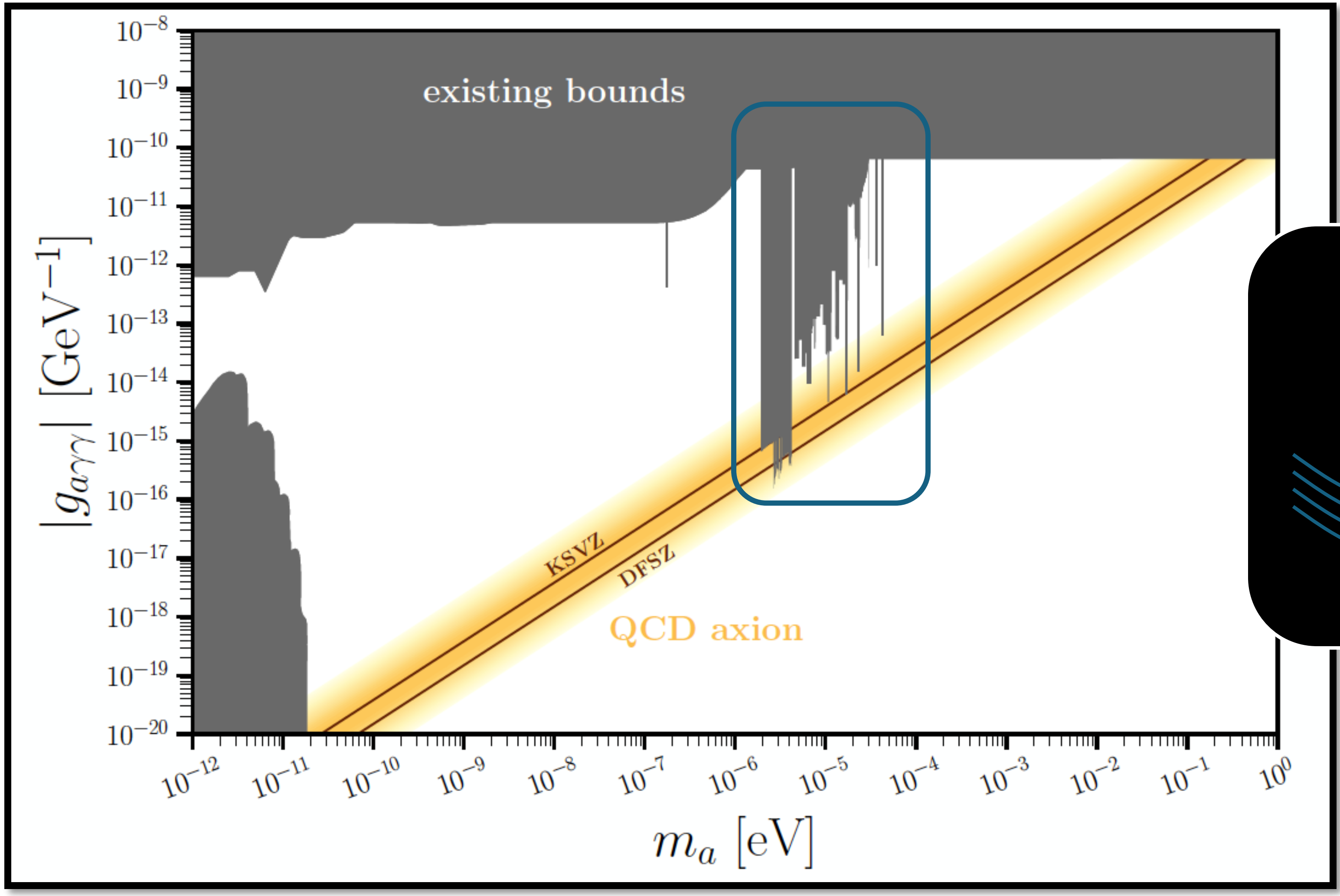
Foster, Rodd, Safdi 2018

Different wavy regimes



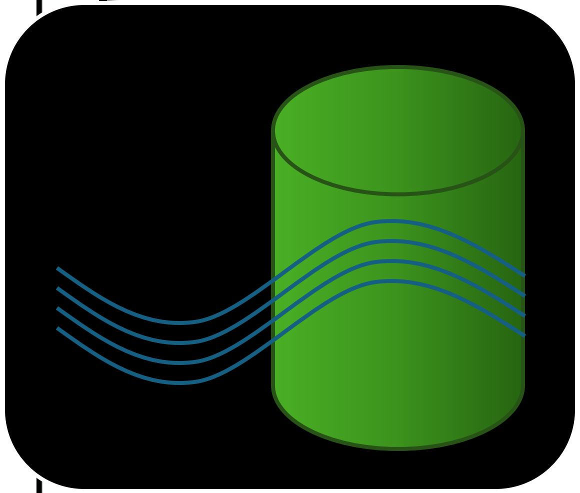
A. Berlin and others

Different wavy regimes: middle masses

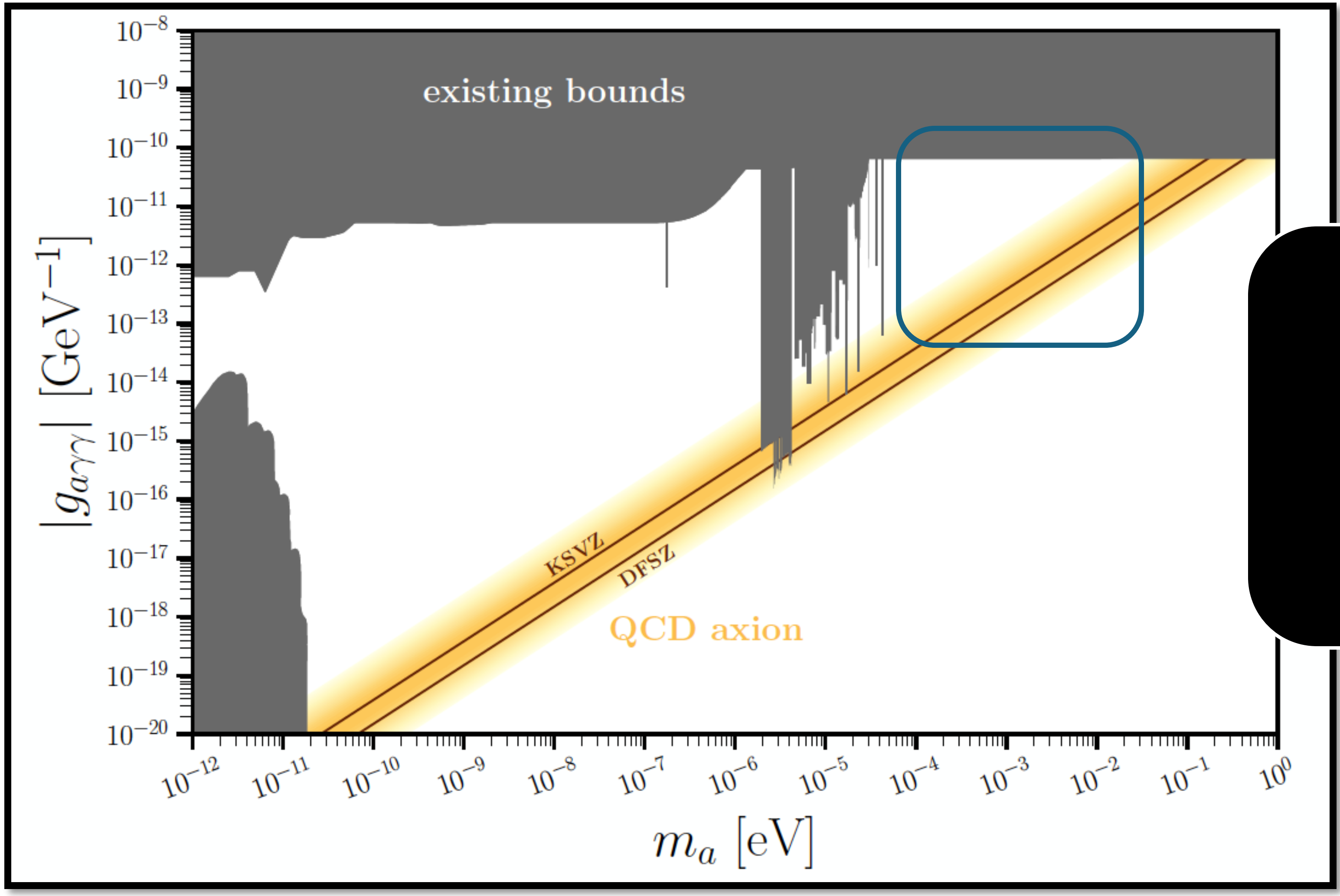


A. Berlin and others

cavities

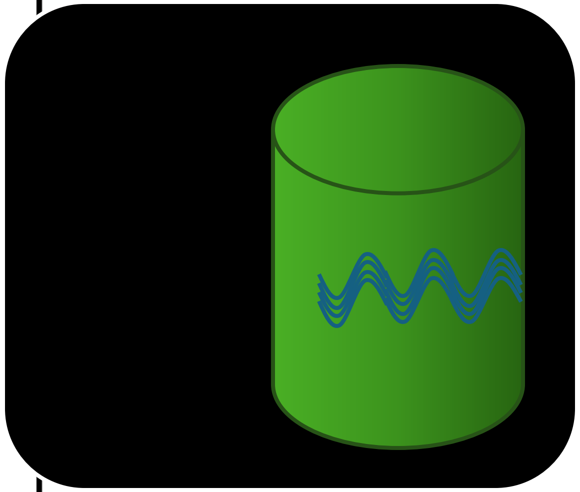


Different wavy regimes: high masses

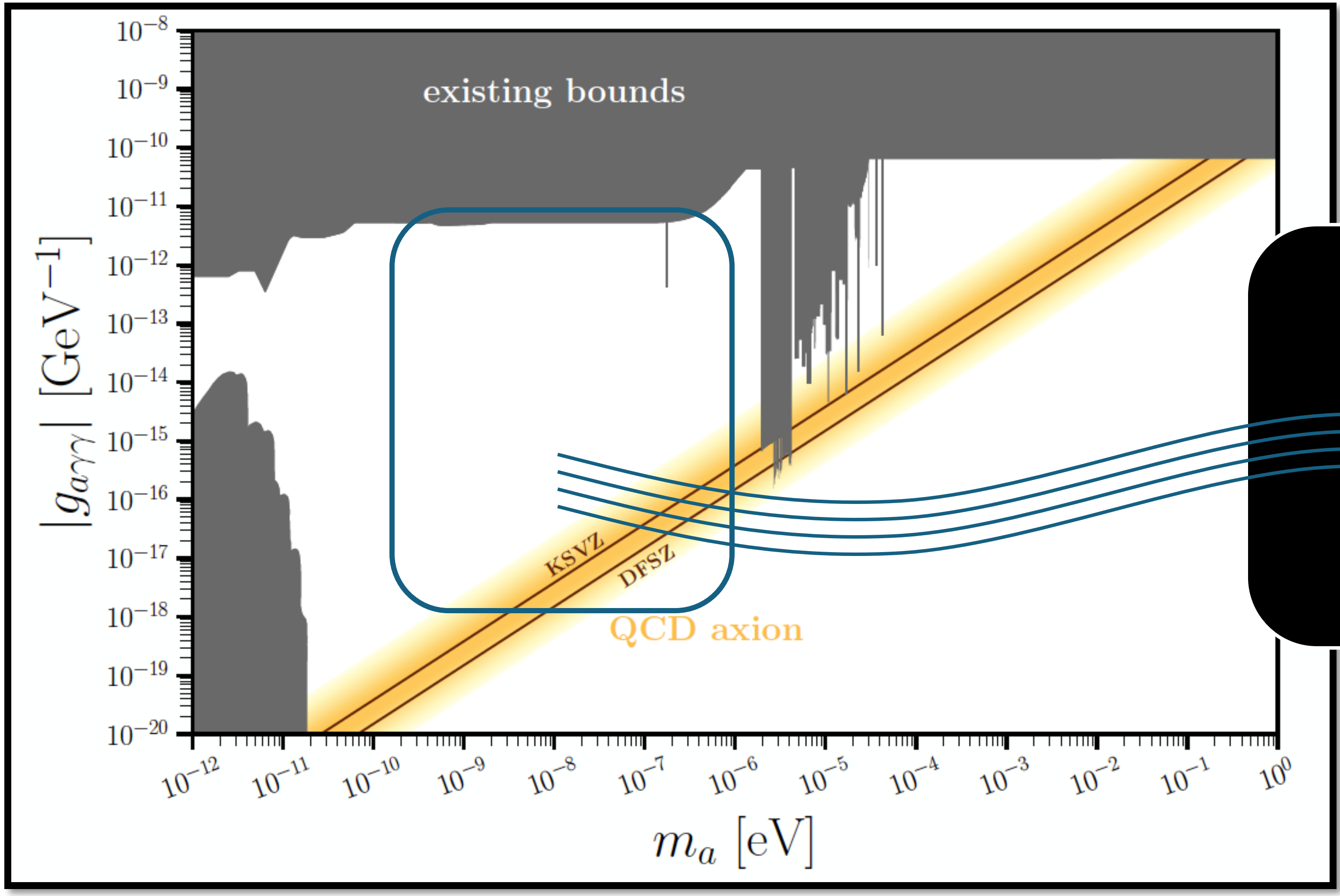


A. Berlin and others

reflectors,
dielectric stacks

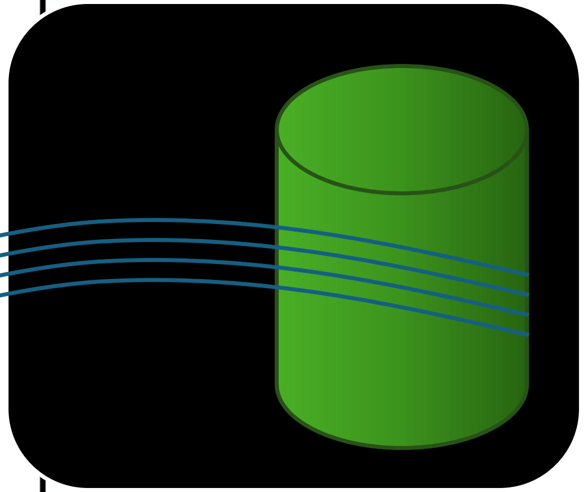


Different wavy regimes: low masses

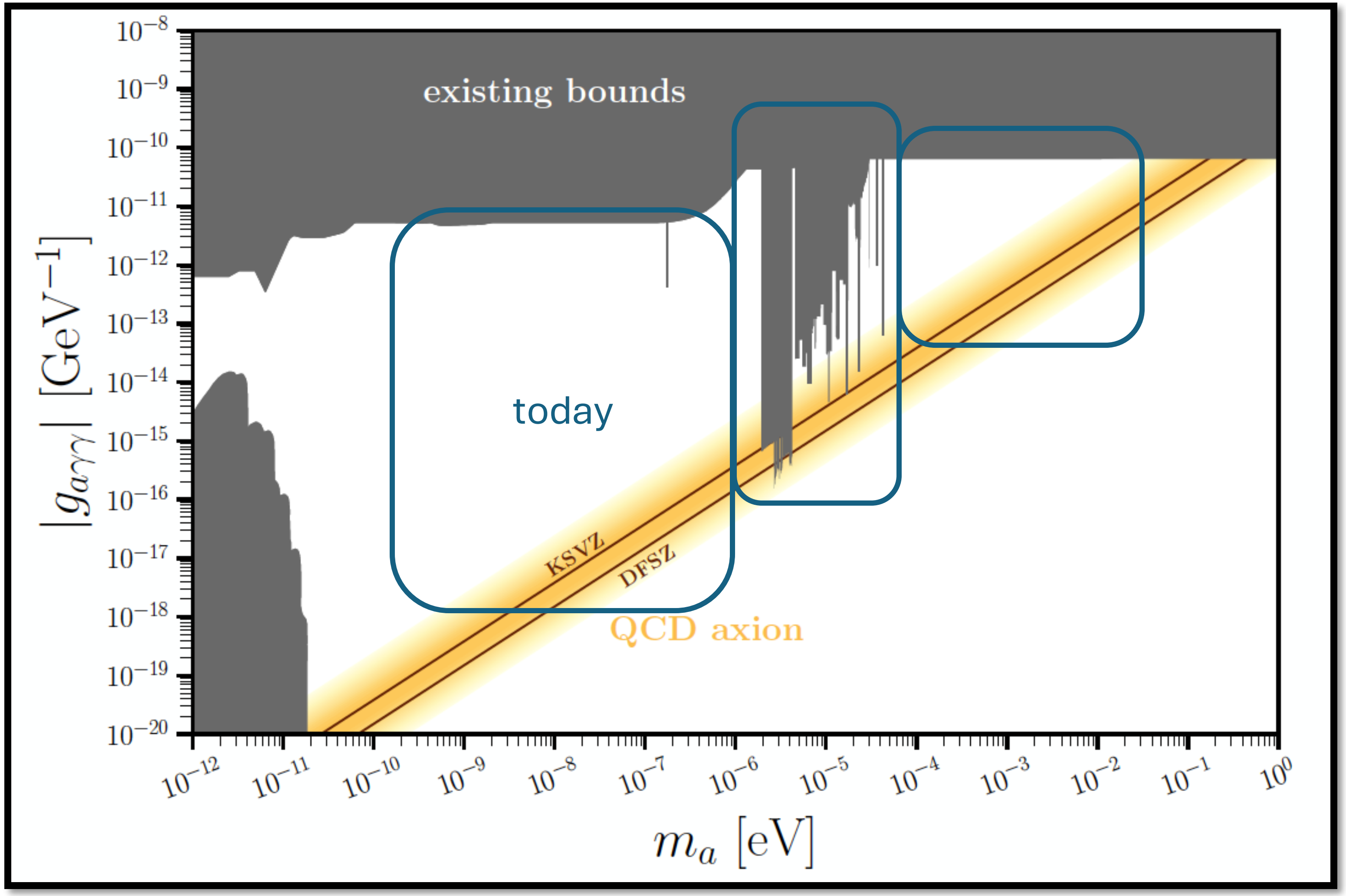


A. Berlin and others

lumped elements,
SRF cavities



You will hear about all of these this week!



A. Berlin and others

Other considerations for dark matter searches: Broadband vs. resonant

- **Broadband readout:**
  - Read out a wide range of frequencies all at once

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  - Axion signal rings up a resonator in narrow frequency band
  - Huge signal boost by quality factor of resonator

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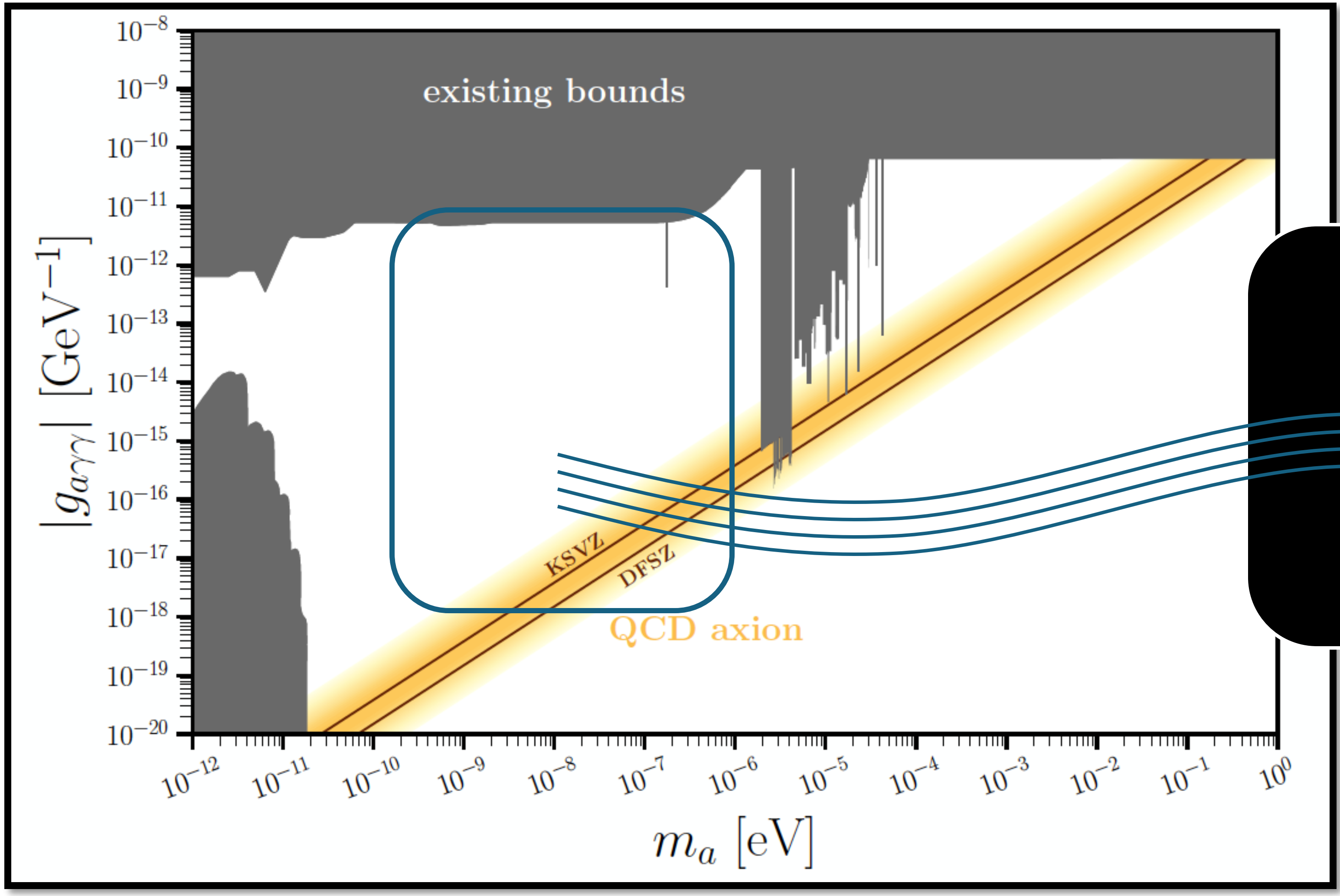
$$Q = 2\pi \frac{\text{energy stored}}{\text{energy dissipated per cycle}} \xleftrightarrow{\text{equivalent}} Q = \frac{f}{\Delta f}$$

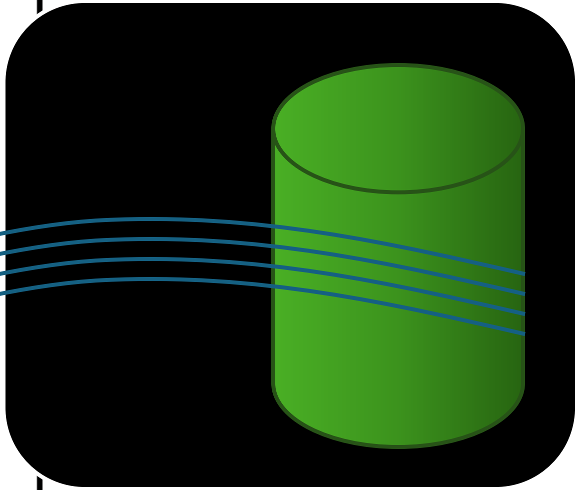
Which to pick—deep or broad?

- Most experiments opt for resonant
  - QCD axion band is reallllly low in coupling
- A boost for broadband experiments
  - In ALP space, we don't have a strong theoretical prior to go "deep"
  - Tuning is technically challenging
  - Clumpy dark matter is only accessible with a broadband experiment unless you get VERY lucky

Rest of today: long wavelength detection



A. Berlin and others



lumped elements,
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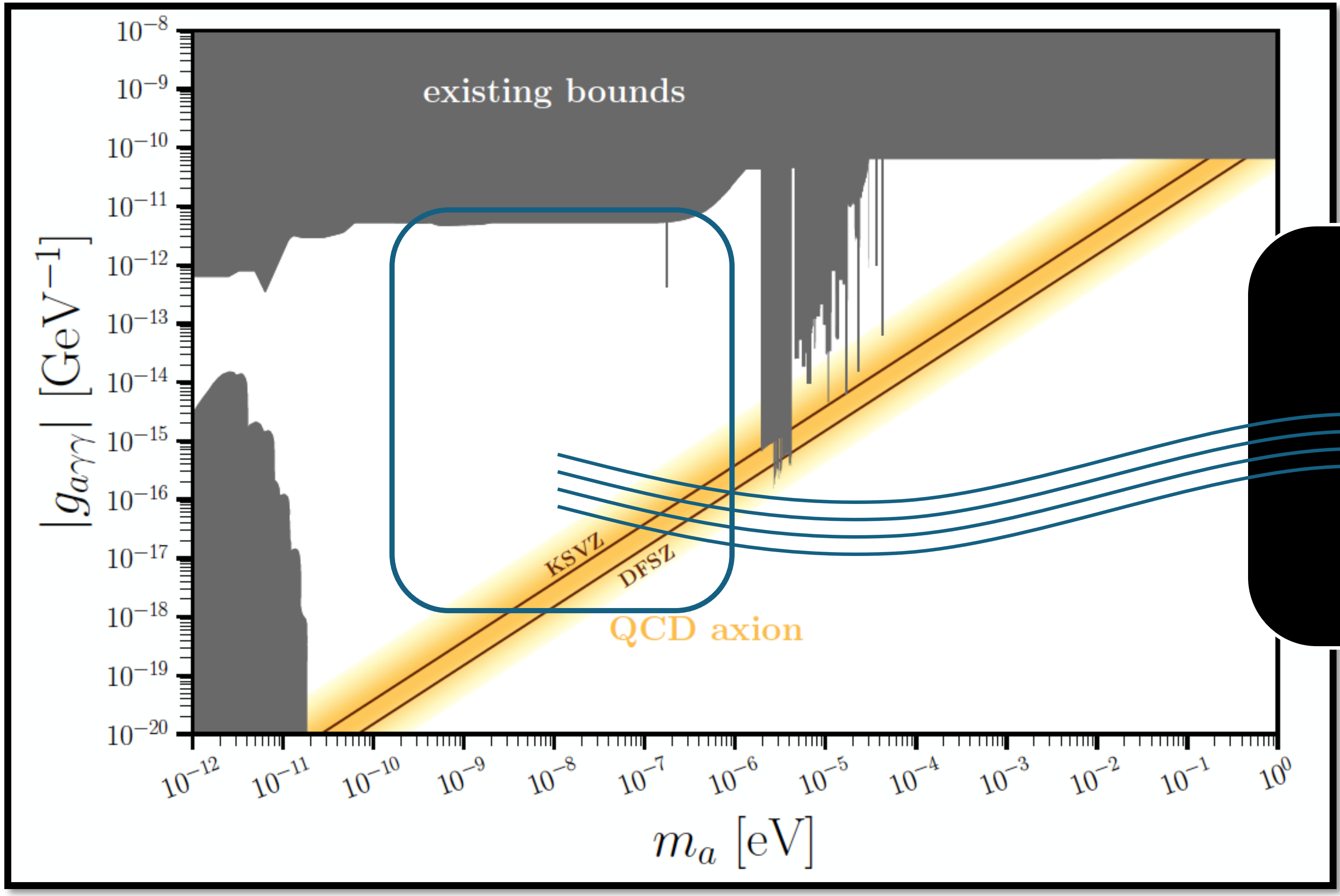

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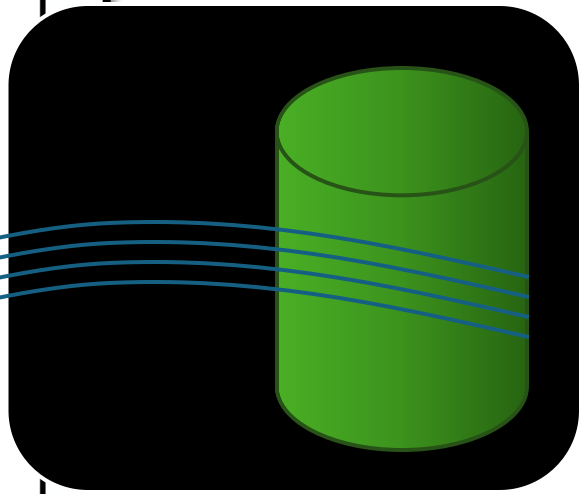
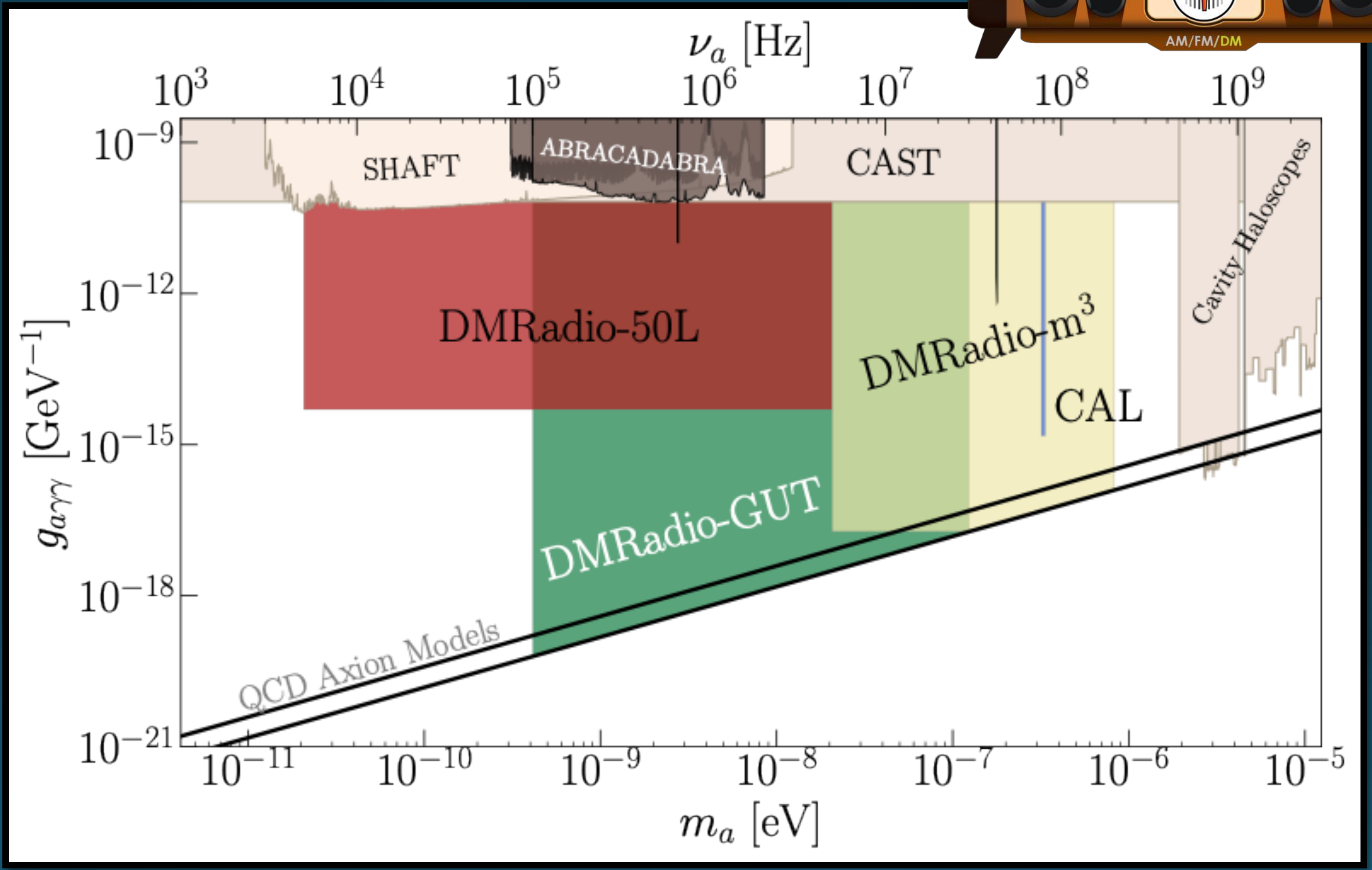


Low-mass axions are highly motivated

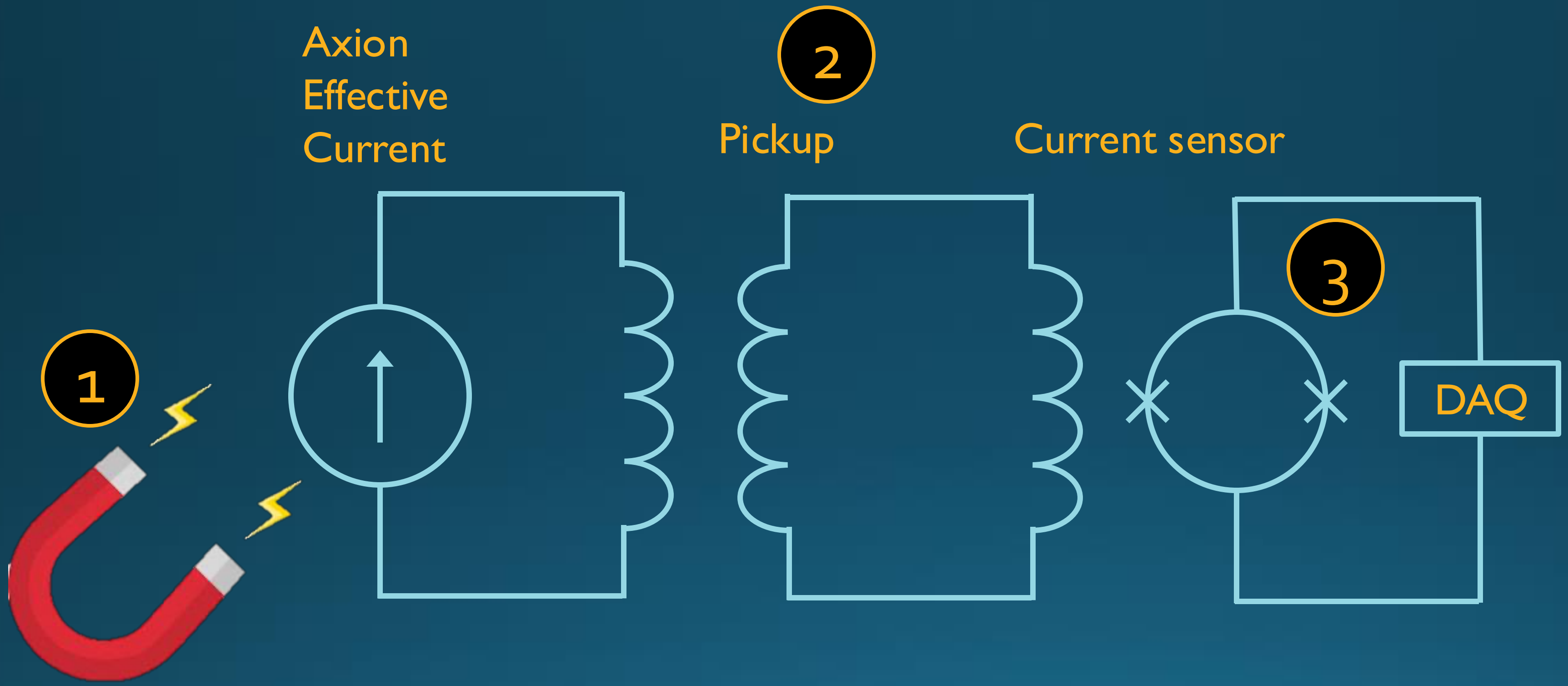
- **Field theory:** if you put f_a at the GUT scale, get ~neV axion
- **String theory:** universally predicts (one or more) low-mass axions
  - Model-independent axion ~0.5 neV
  - Low-mass axion experiments can constrain string models
- **Cosmology:** can naturally get correct dark matter abundance with a variety of inflation models (pre-inflationary PQ symmetry breaking)

M. Dine and W. Fischler, Phys. Lett. 120B, 137 (1983)
J. Preskill, M. Wise, and F. Wilczek, Phys. Lett. 120B, 127 (1983)
L. F. Abbott and P. Sikivie, Phys. Lett. 120B, 133 (1983)
M. Tegmark, A. Aguirre, M. Rees, and F. Wilczek, Phys. Rev. D 73, 023505 (2006)
M. P. Hertzberg, M. Tegmark, and F. Wilczek, Phys. Rev. D 78, 083507 (2008).
R. T. Co, F. D'Eramo, and L. J. Hall, Phys. Rev. D 94, 075001 (2016).
P. W. Graham and A. Scherlis, Phys. Rev. D 98, 035017 (2018)
F. Takahashi, W. Yin, and A. H. Guth, Phys. Rev. D 98, 015042 (2018)
J. Benabou, K. Fraser, M. Reig, B. Safdi, arxiv: 2505.15884
and many more!

ABRACADABRA + DARK MATTER RADIO



Schematic of lumped-element detection



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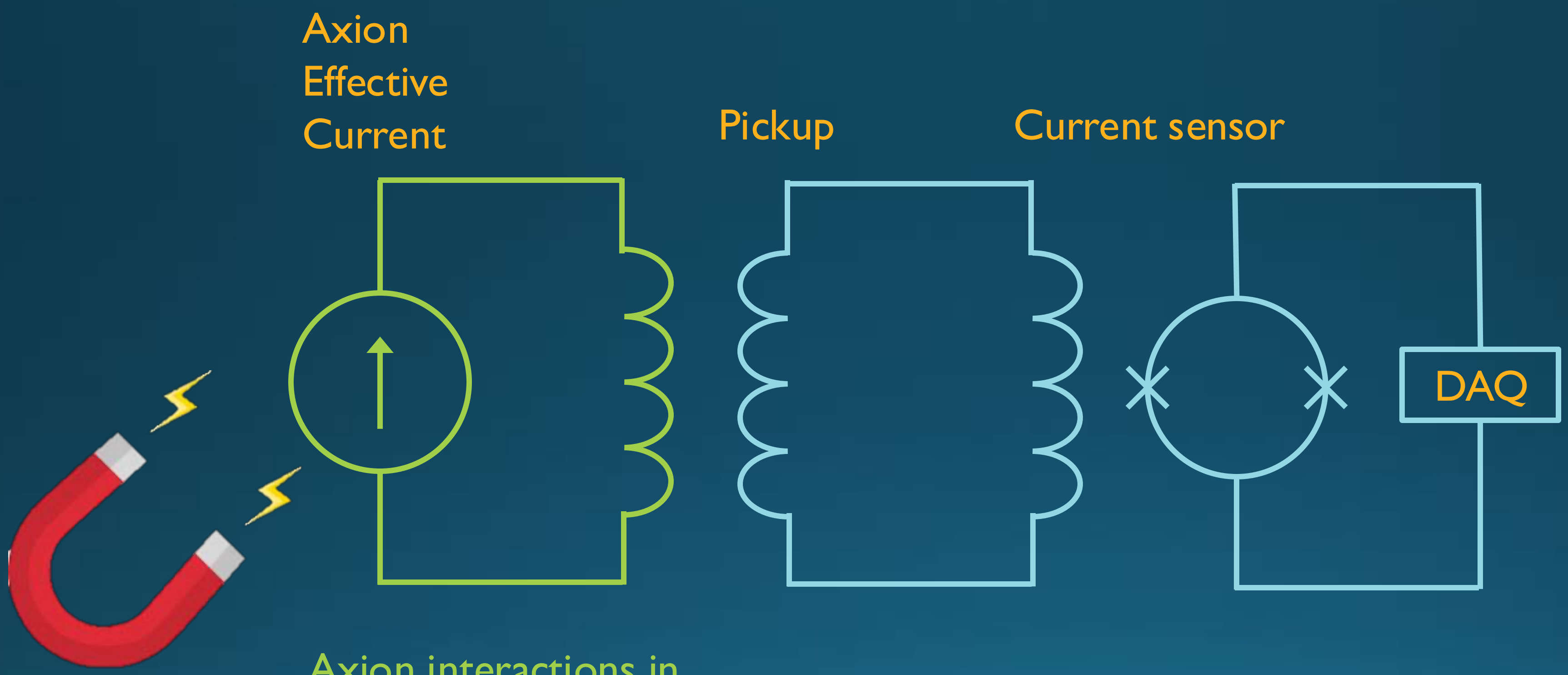

Axion interactions in magnetic field

$$\mathbf{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

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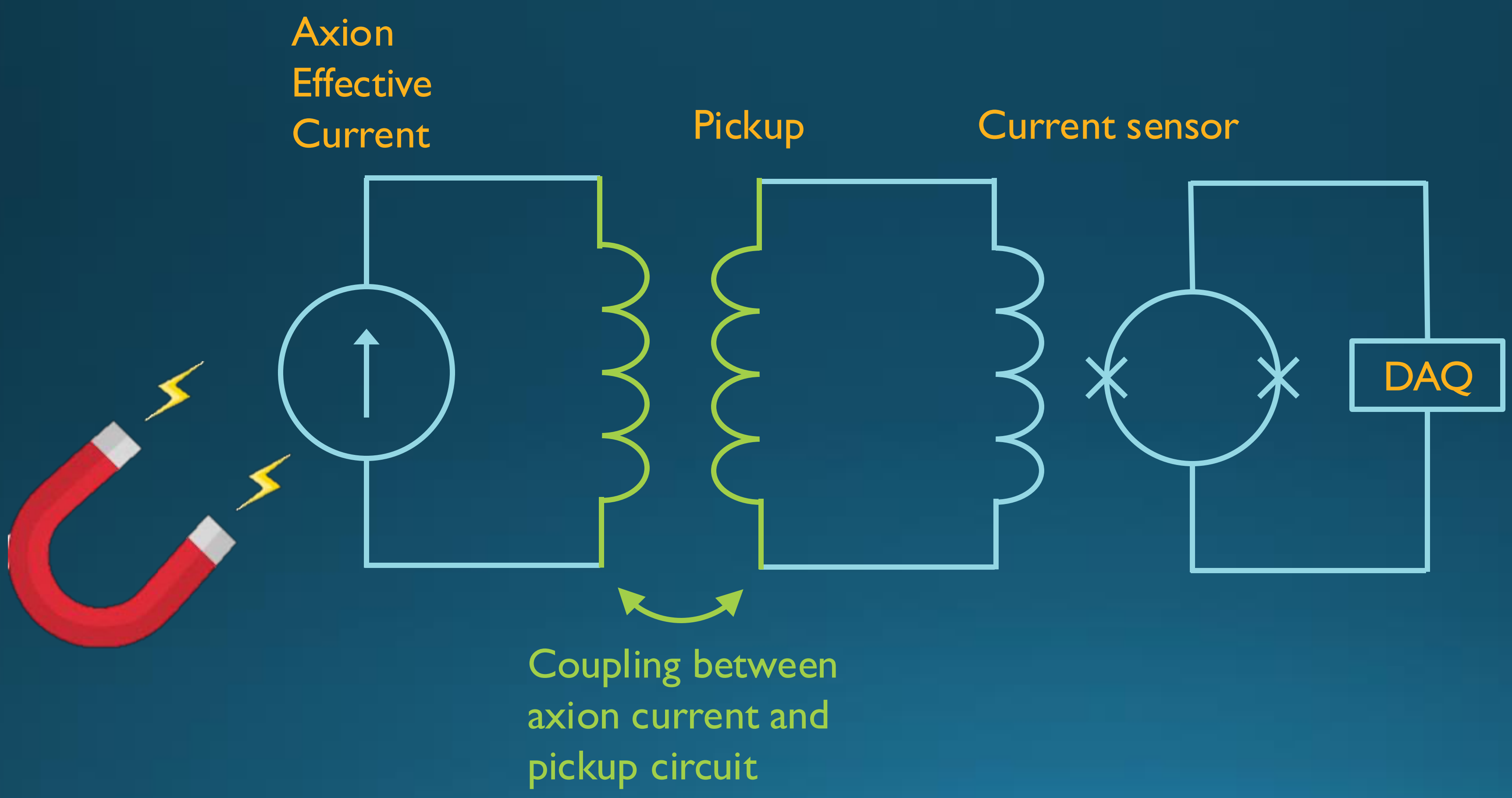

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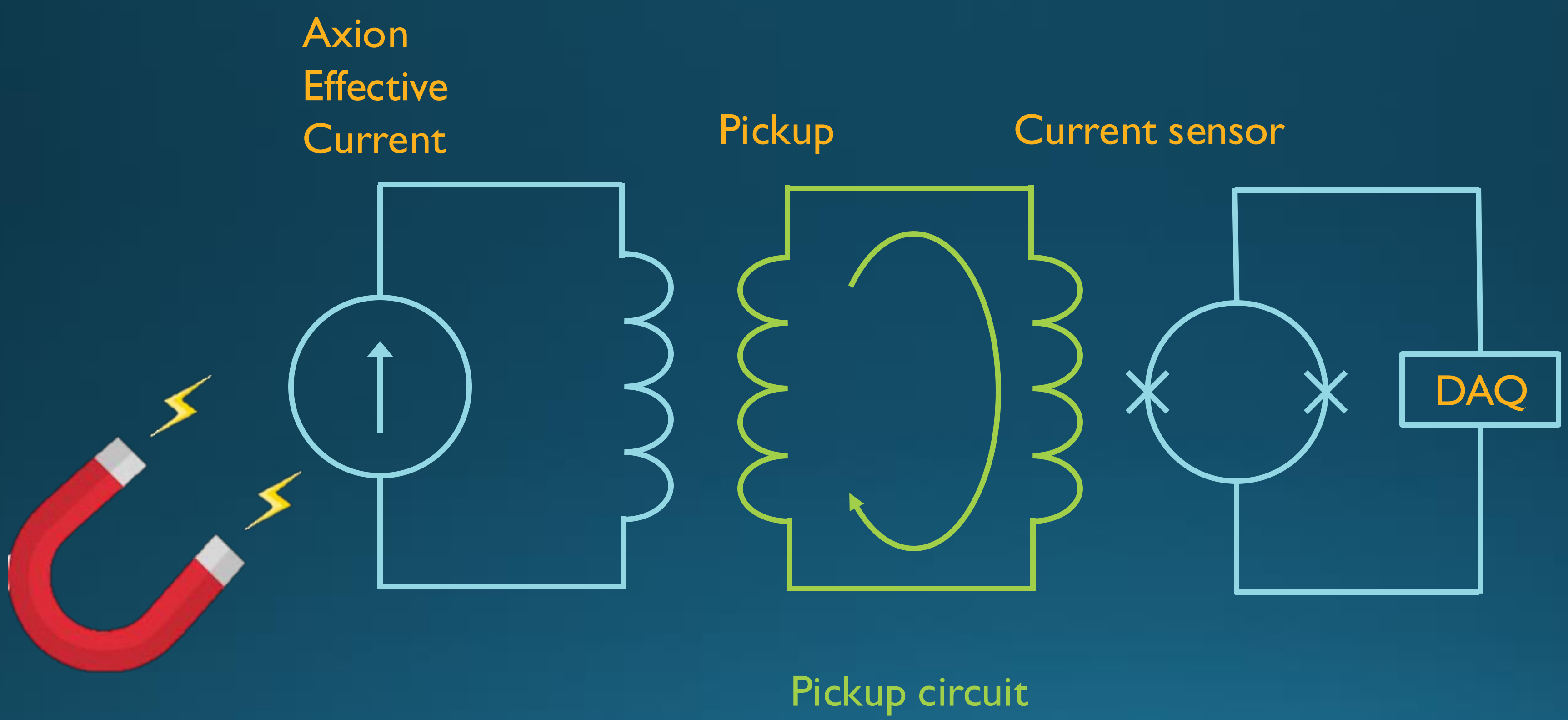

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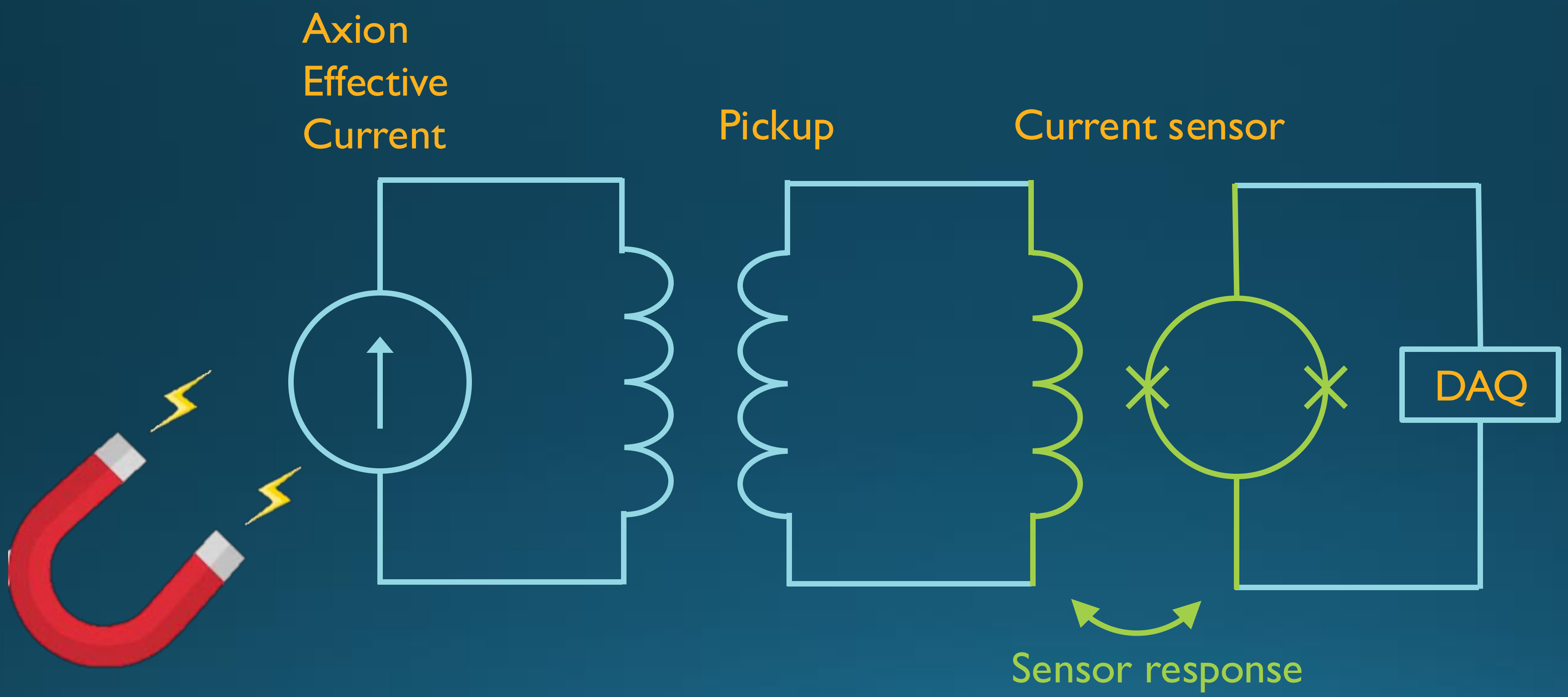

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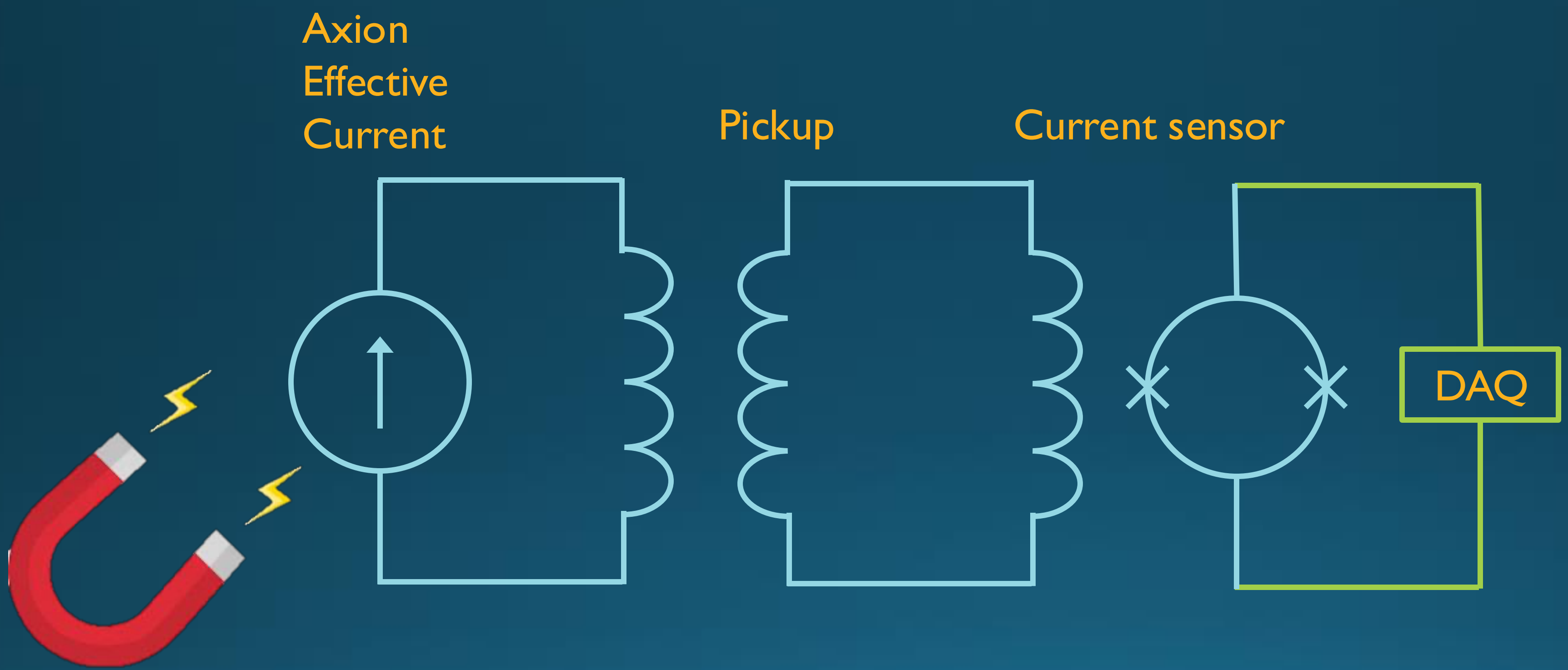
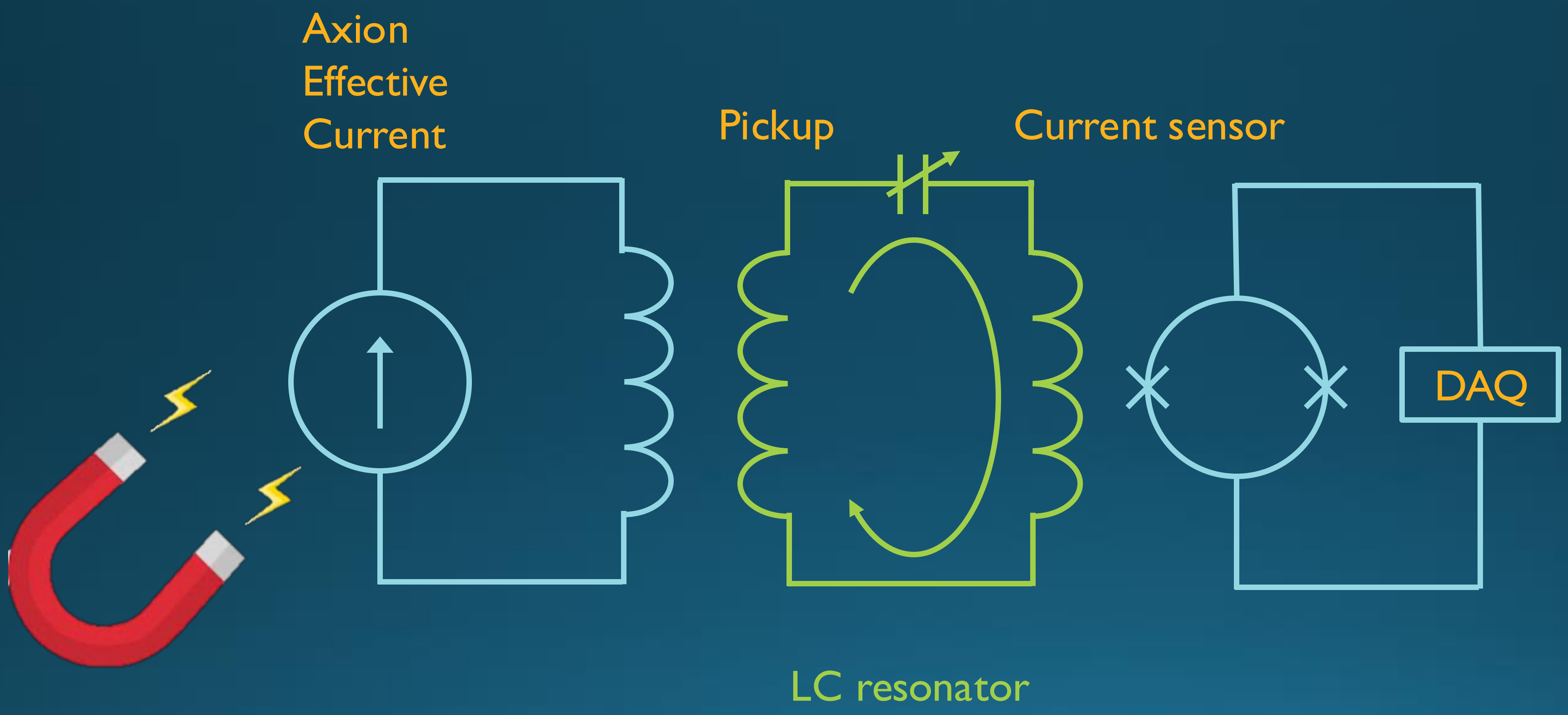


2

Schematic of lumped-element detection

Resonant readout



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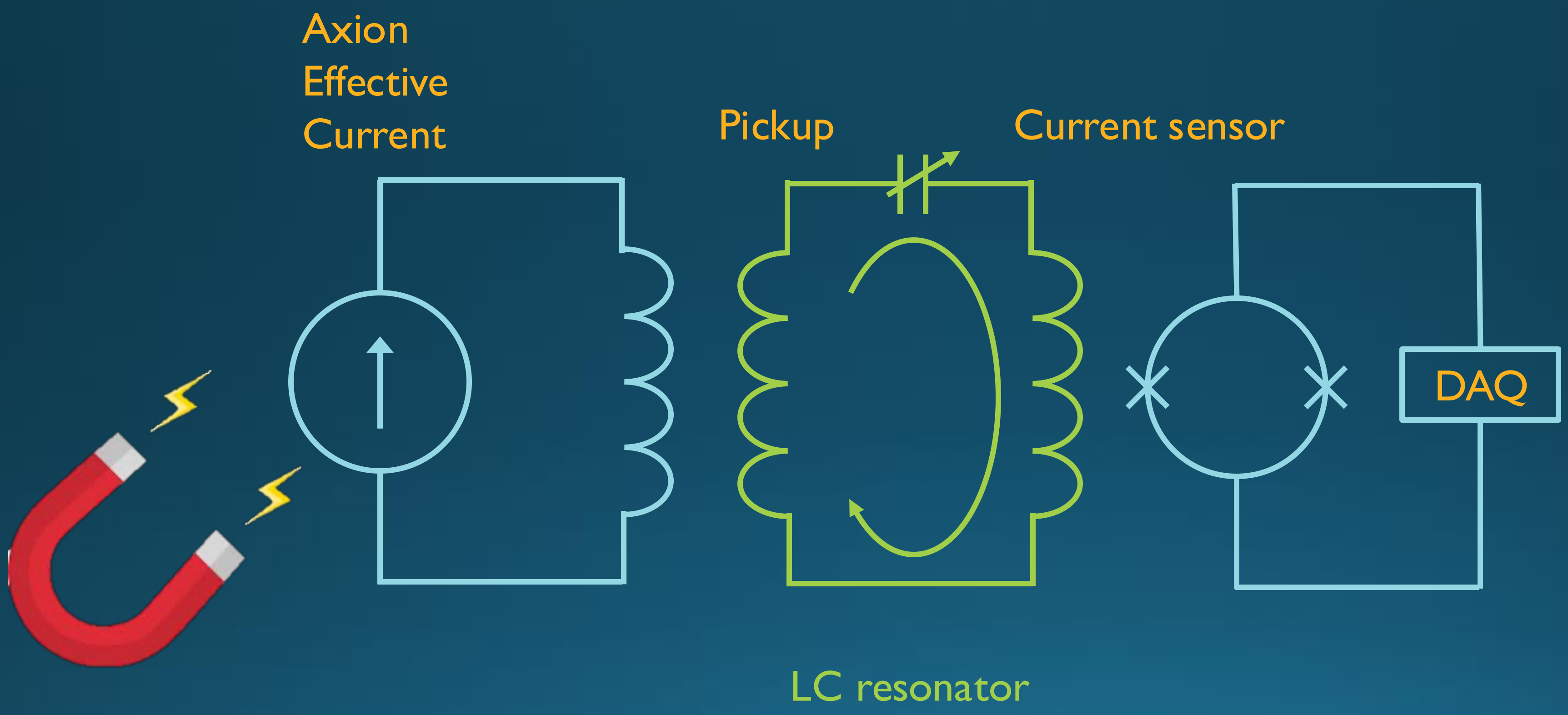
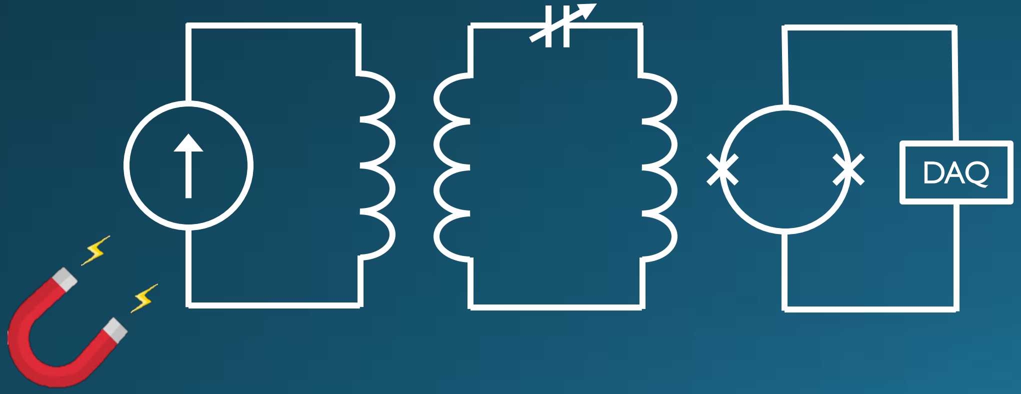


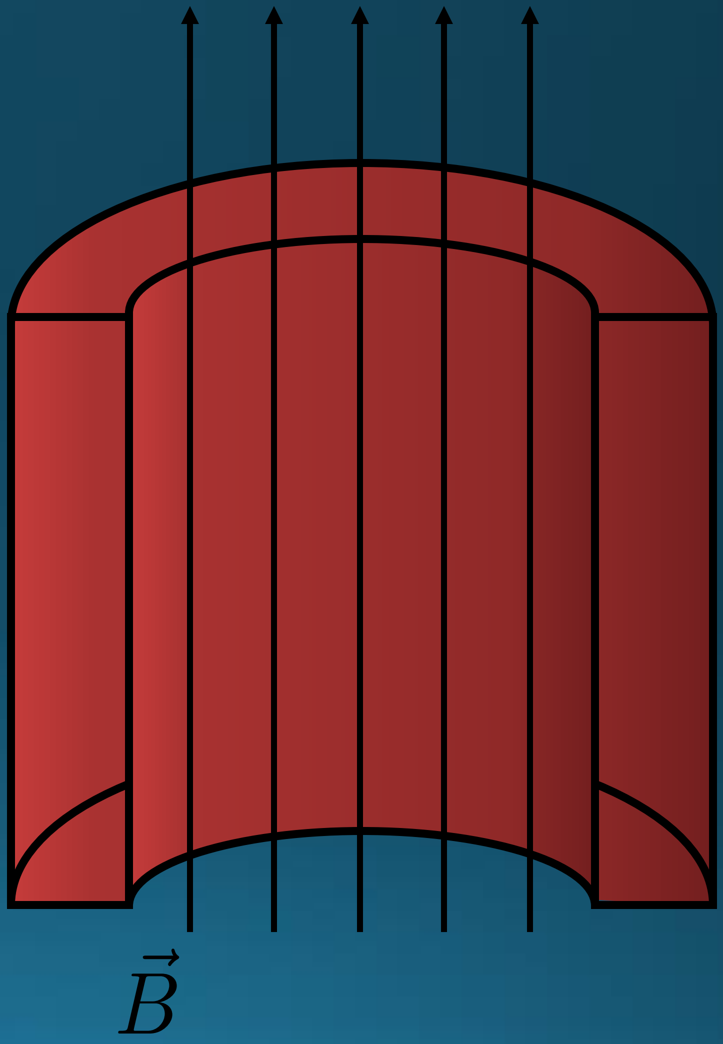
Can be achieved with multiple geometries

The CAL detector

1

Solenoidal superconducting magnet with fixed field, B_0

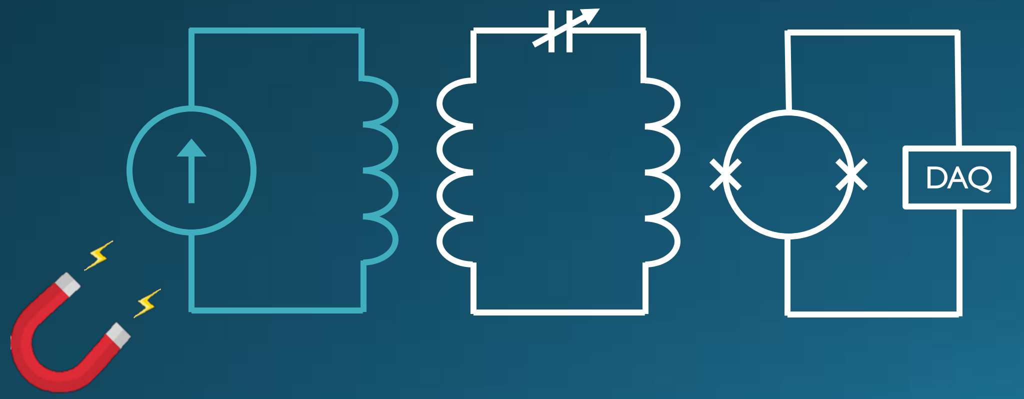


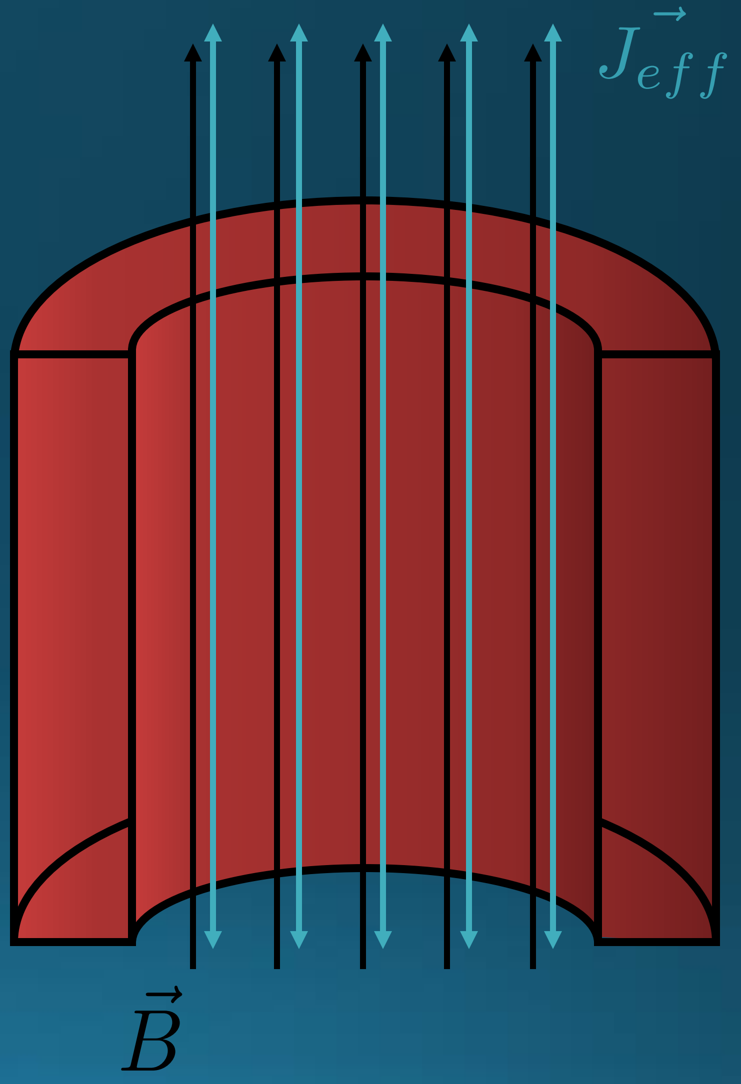


The CAL detector

Axion dark matter generates parallel oscillating effective current, J_{eff}

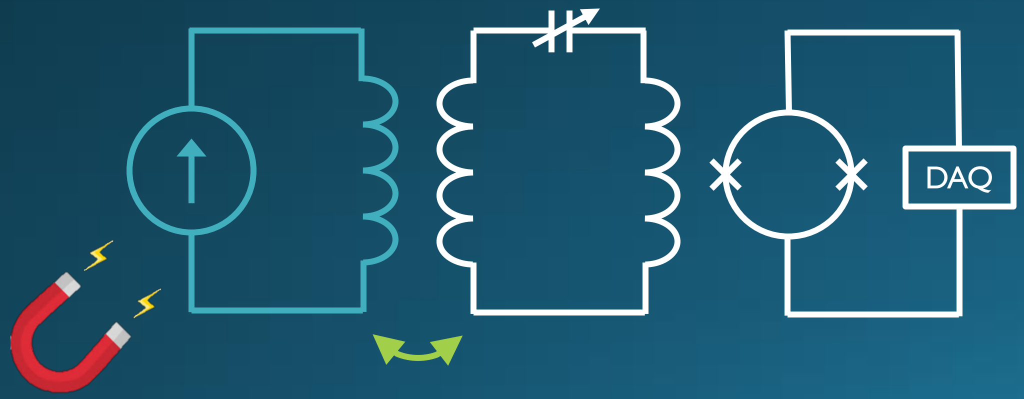
$$\vec{J}_{\text{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}}\cos(m_a t)\vec{B}_0$$

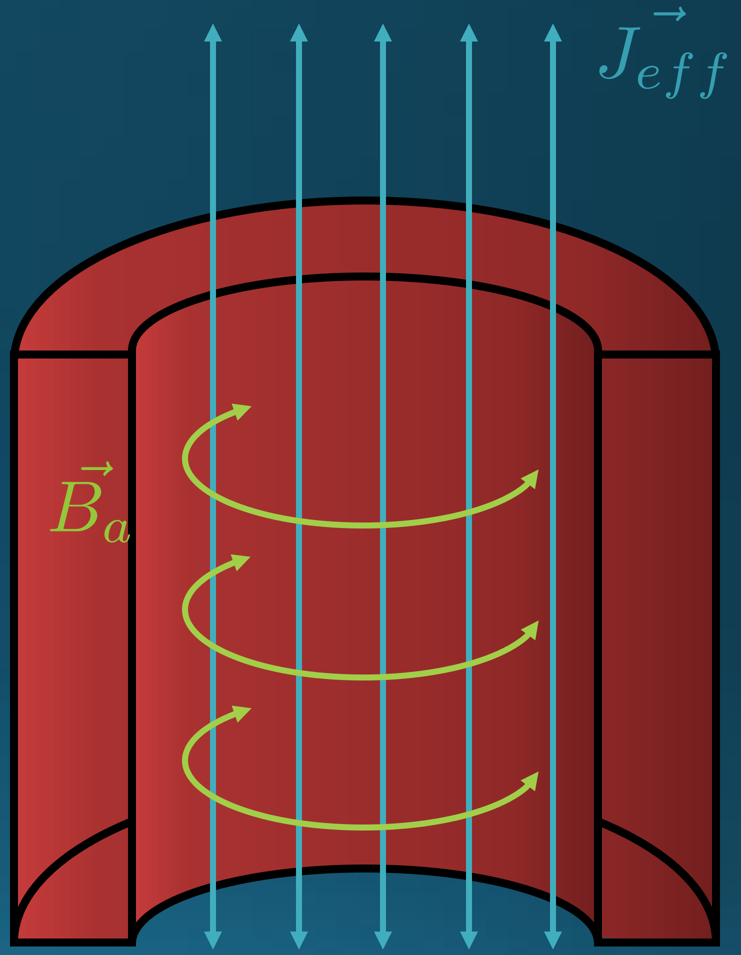




The CAL detector

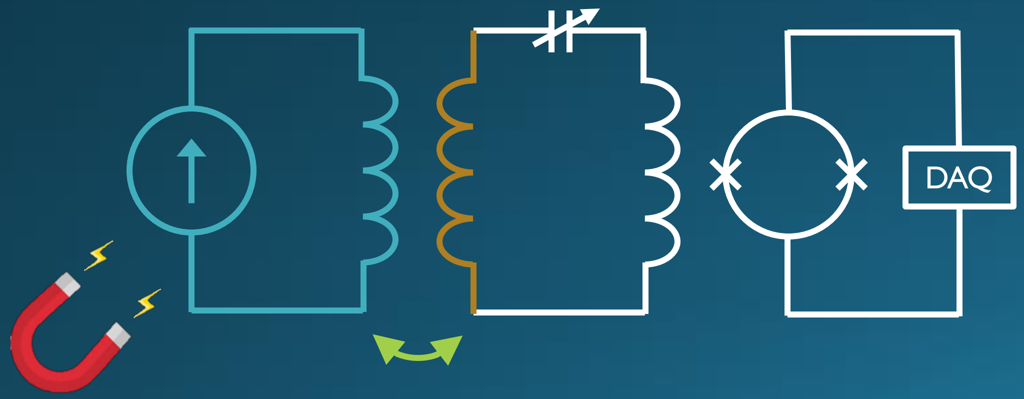
Axion dark matter generates parallel oscillating effective current, J_{eff}, which generates an oscillating magnetic field

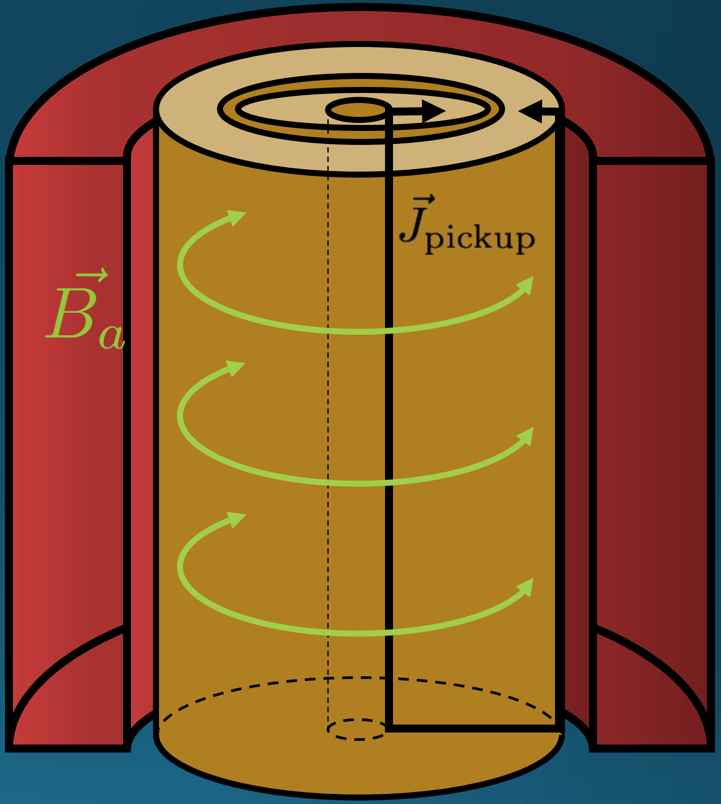




The CAL detector

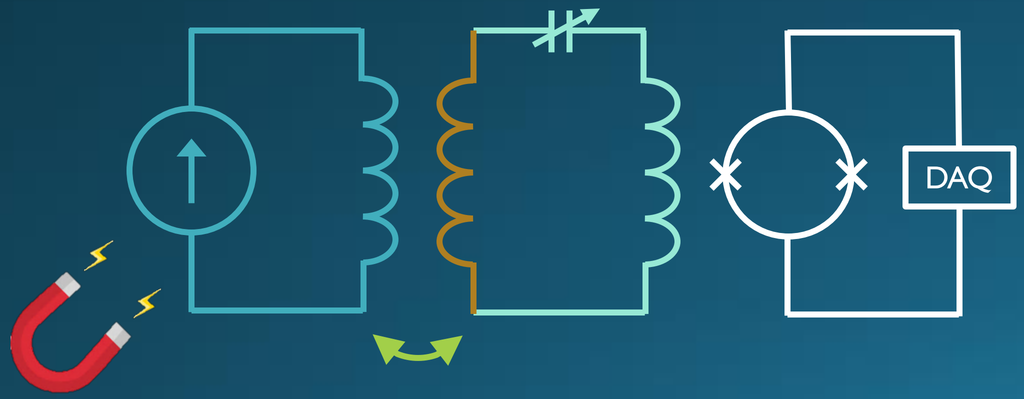
...inducing currents on the pickup coax

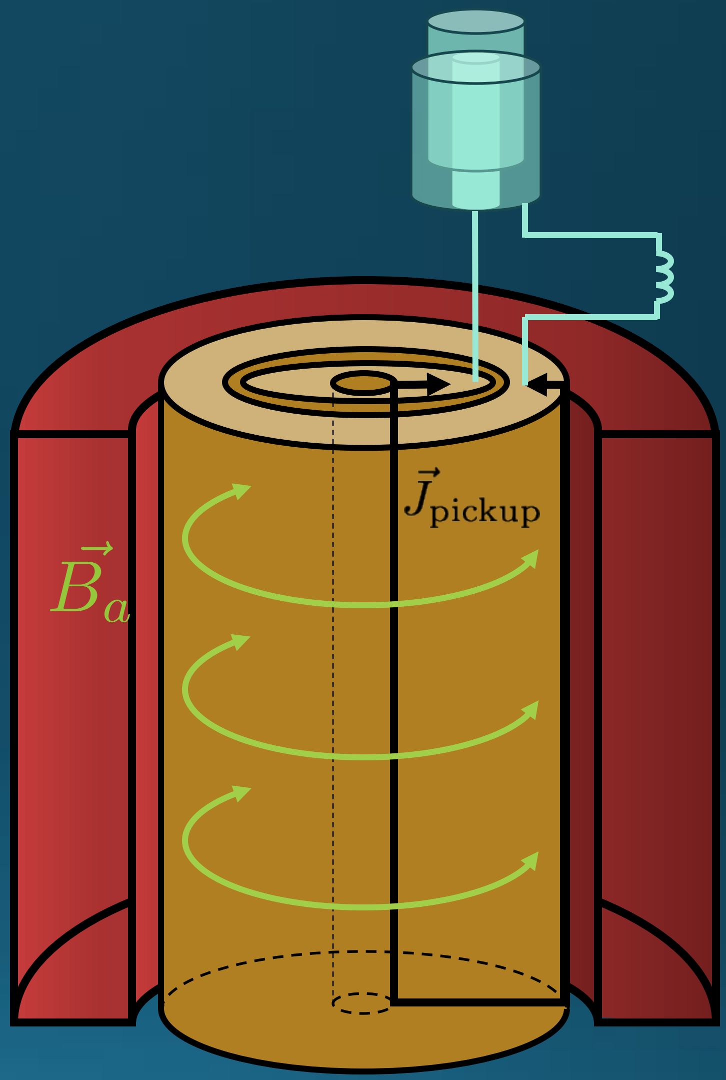




The CAL detector

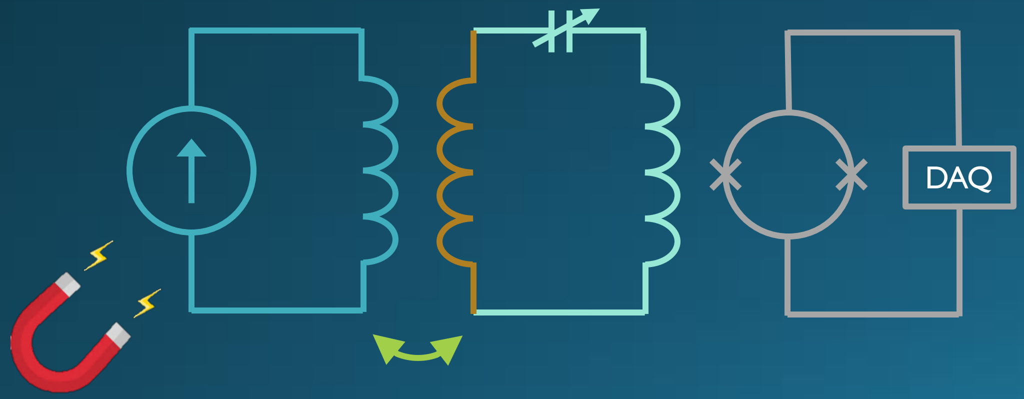
…inducing currents on the pickup coax and ringing up the tunable LC resonator

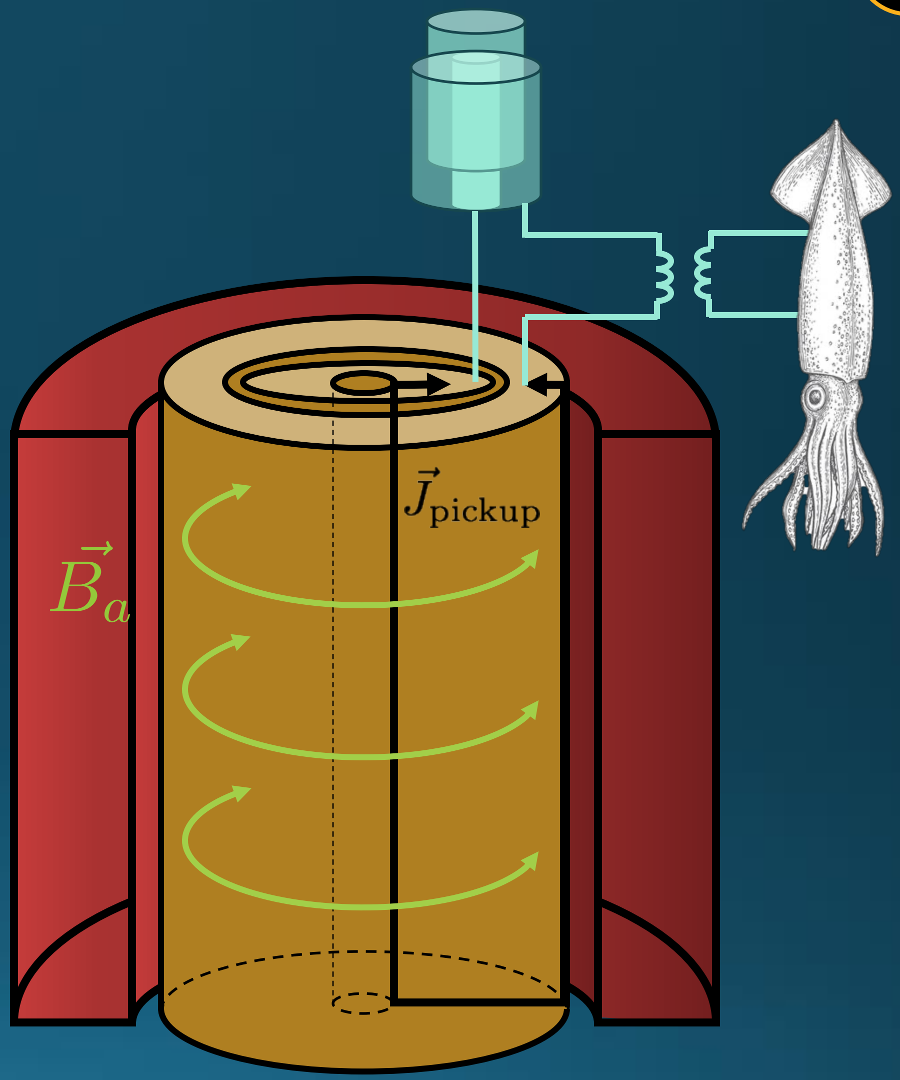




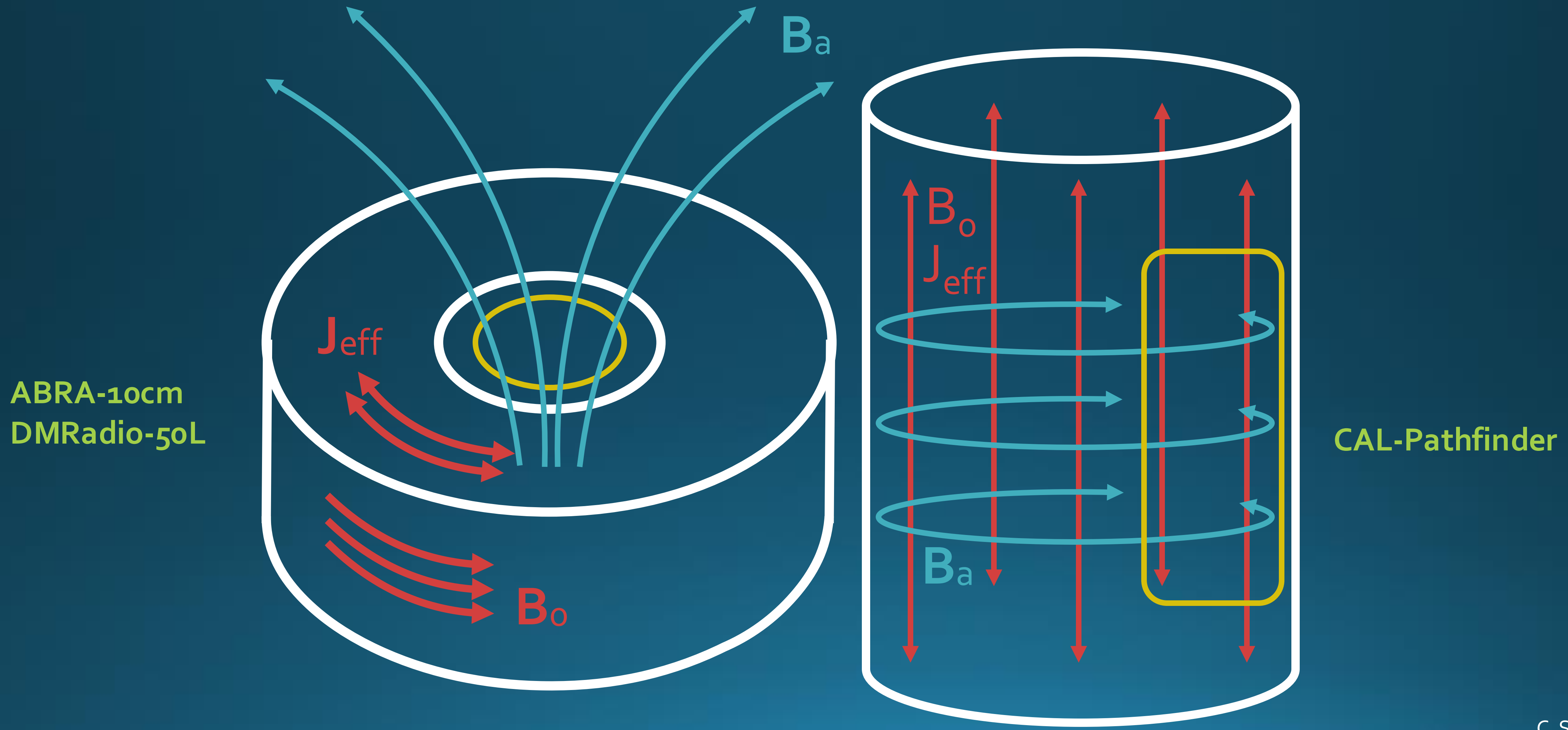
The CAL detector

This signal is read out and amplified using a SQUID current sensor





Detector geometry: toroid vs solenoid



Design considerations for different geometries

	Toroid	Solenoid
High quality factor	• Superconducting sheath shields lossy magnet materials • Pickup in field-free region: can use low T_c superconductors for resonator	• Current contained in coaxial pickup so naturally no access to lossy magnet materials • Pickup in high-field region: use high purity copper or high T_c superconductors

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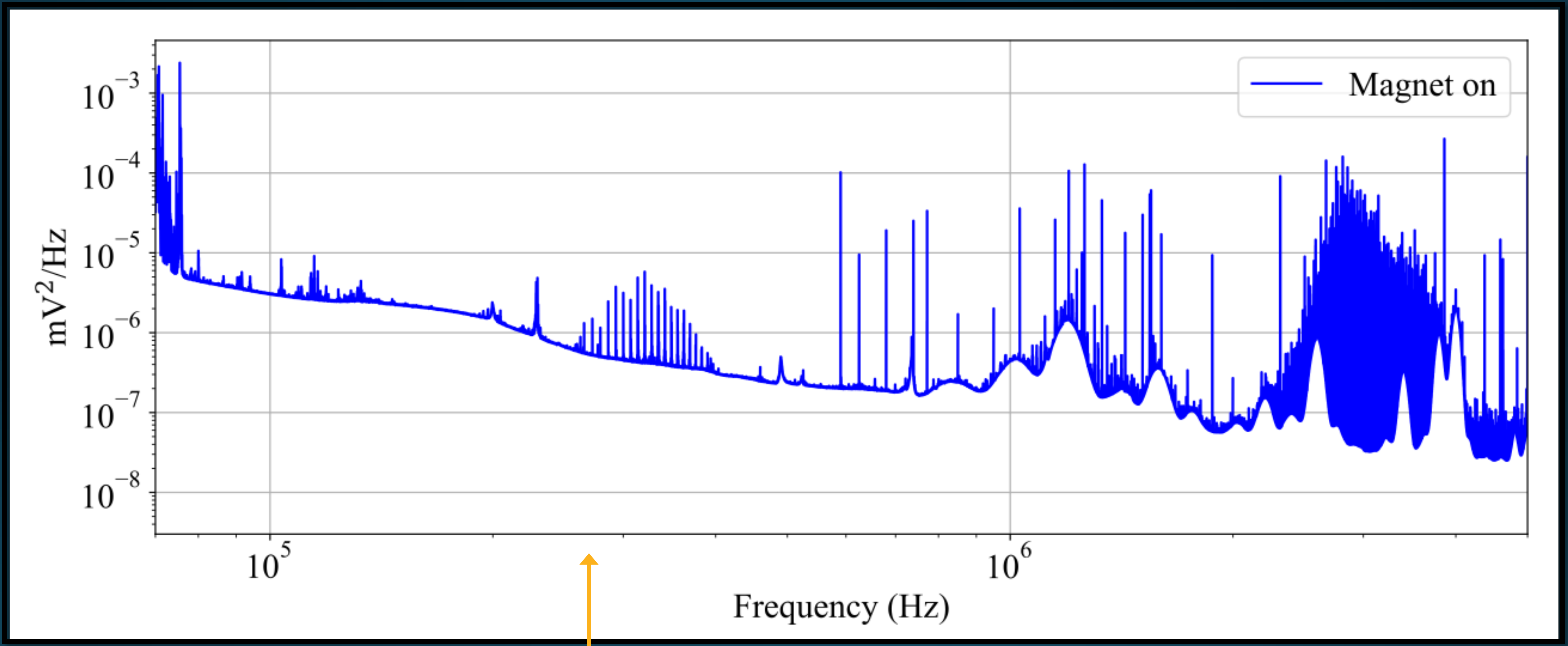
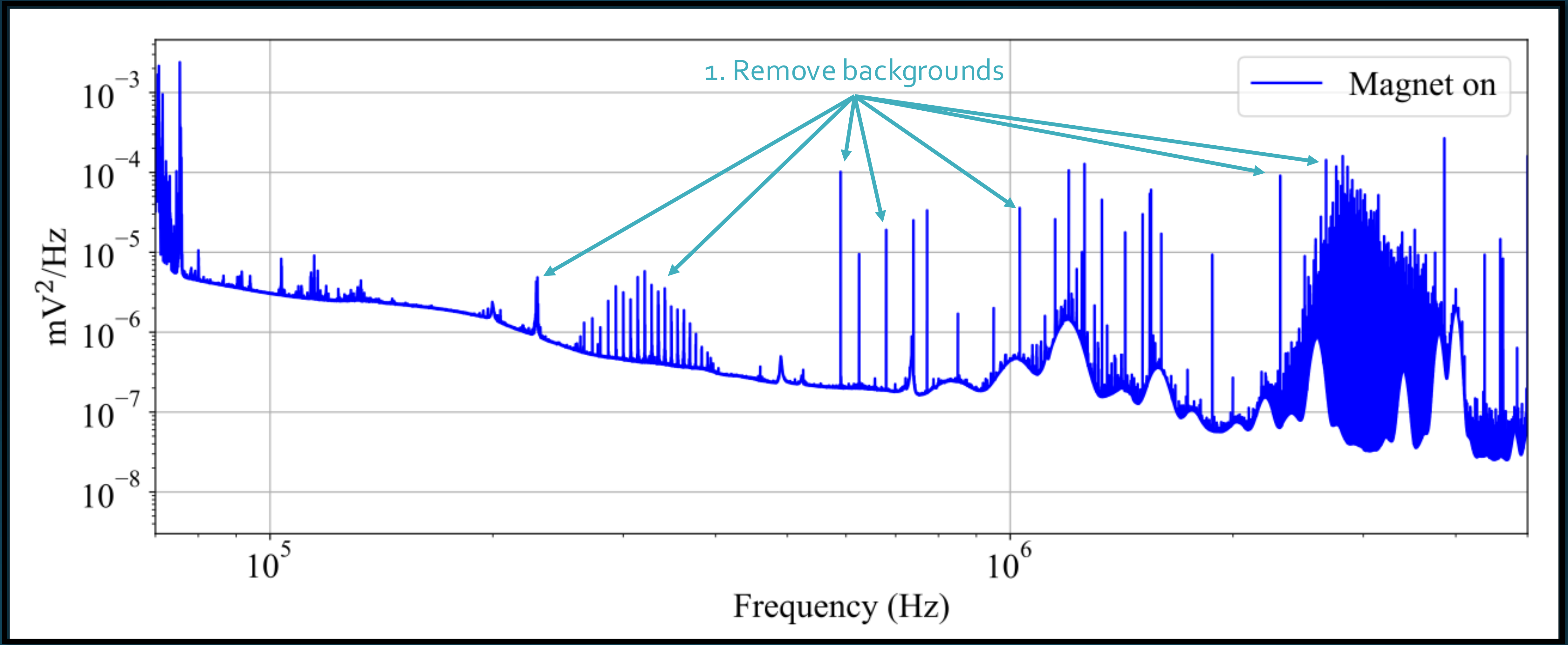
Can both of these geometries also be used to detect dark photons?

Example data: ABRA-10cm



$m_a \sim 1$ neV (GUT-scale)

ABRA-10cm data processing



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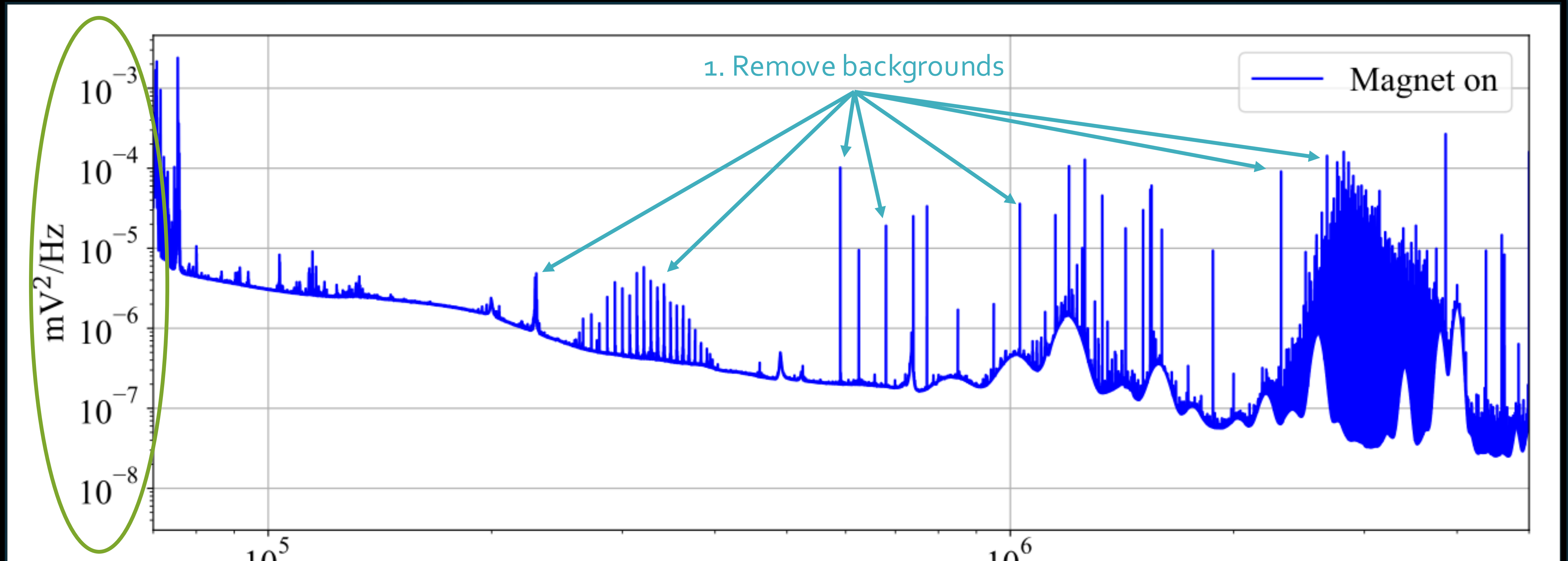
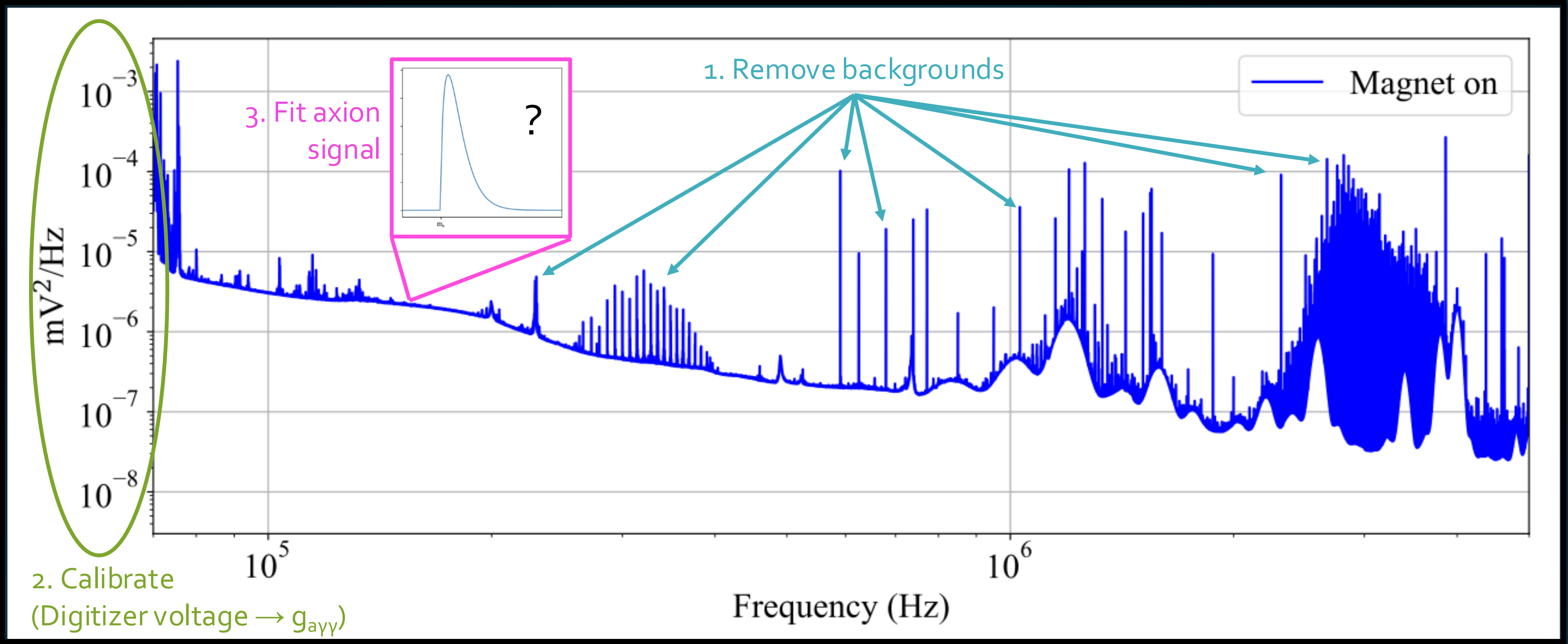


2. Calibrate
(Digitizer voltage $\longrightarrow g_{a\gamma\gamma}$)

ABRA-10cm data processing



Calibrating lumped-element detectors

- Info we need:
  - **DAQ voltage $\rightarrow$ $g_{a\gamma\gamma}$ conversion**
  - Resonance frequency
  - Q
  - System gain
  - Readout gain

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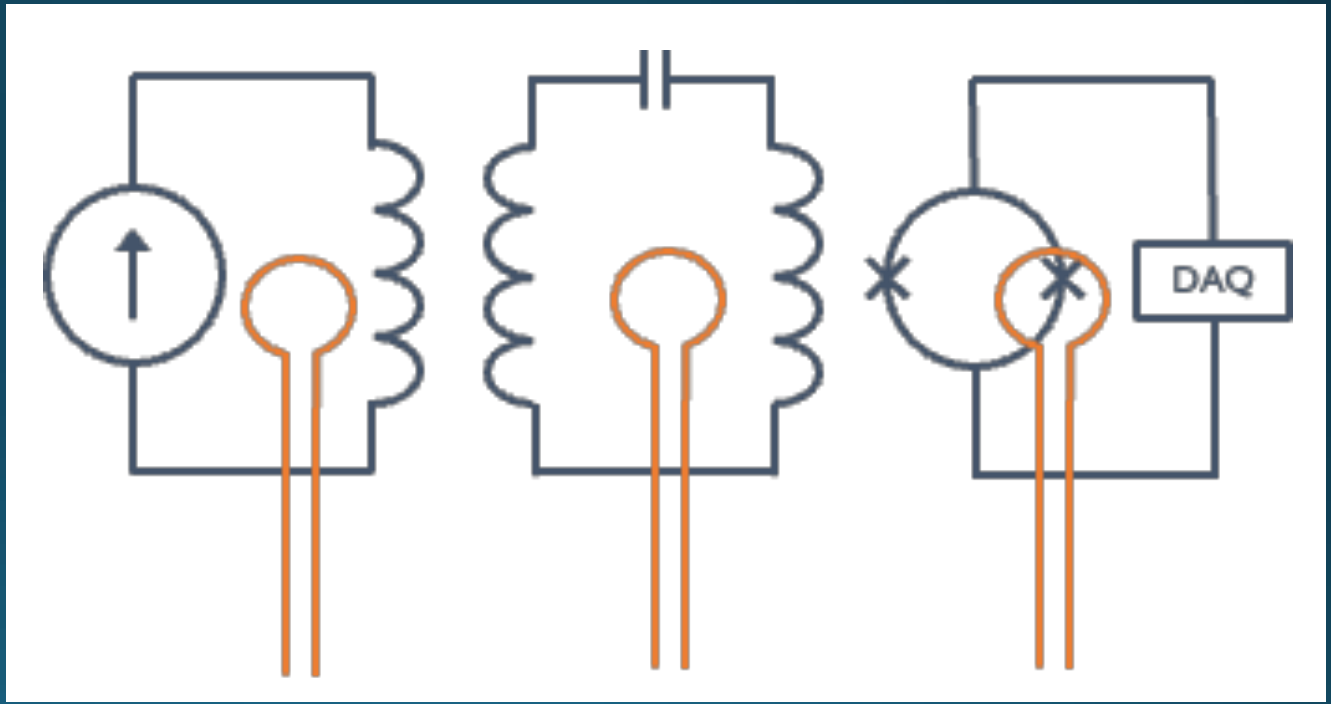
- Info we need:
  - **DAQ voltage → $g_{a\gamma\gamma}$ conversion**
  - Resonance frequency
  - Q
  - System gain
  - Readout gain
- Consider:
  - Where to inject calibration signal
  - What frequency(ies) to inject at
  - What 'shape' signal to inject

Where to inject calibration signals

- Mimetic axion loop
- Loop into resonator
- Directly into SQUID



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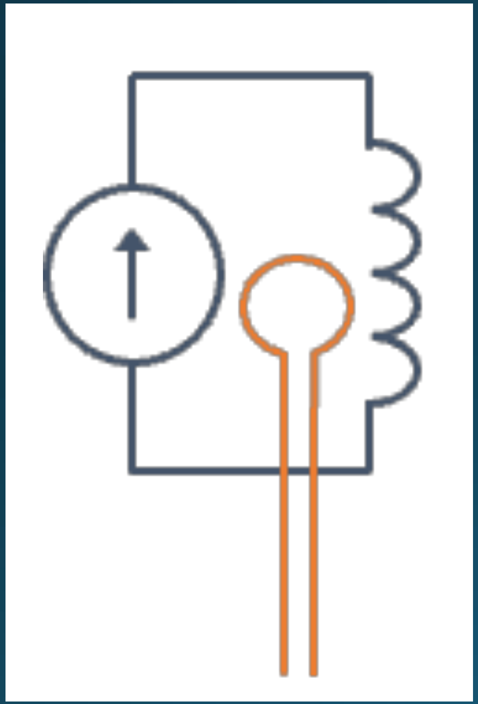
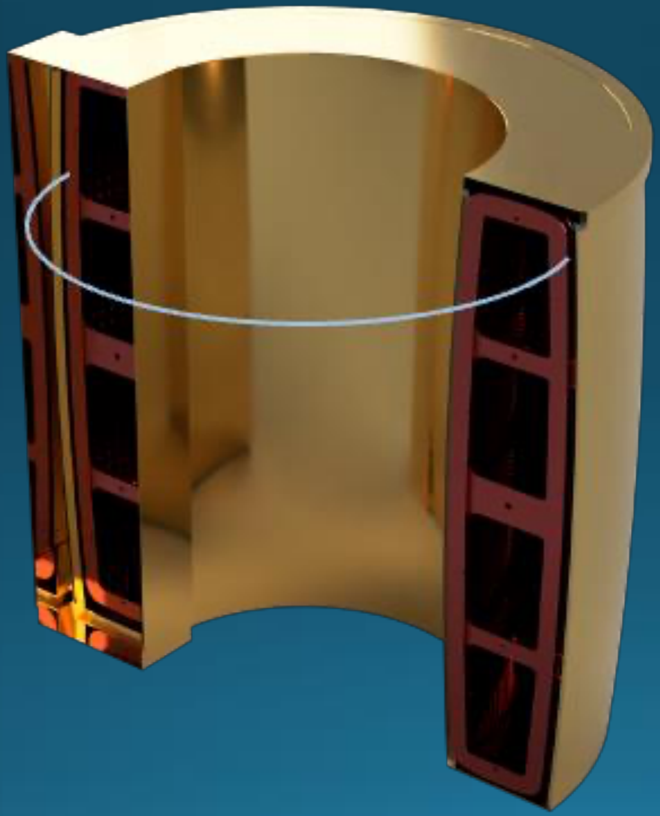
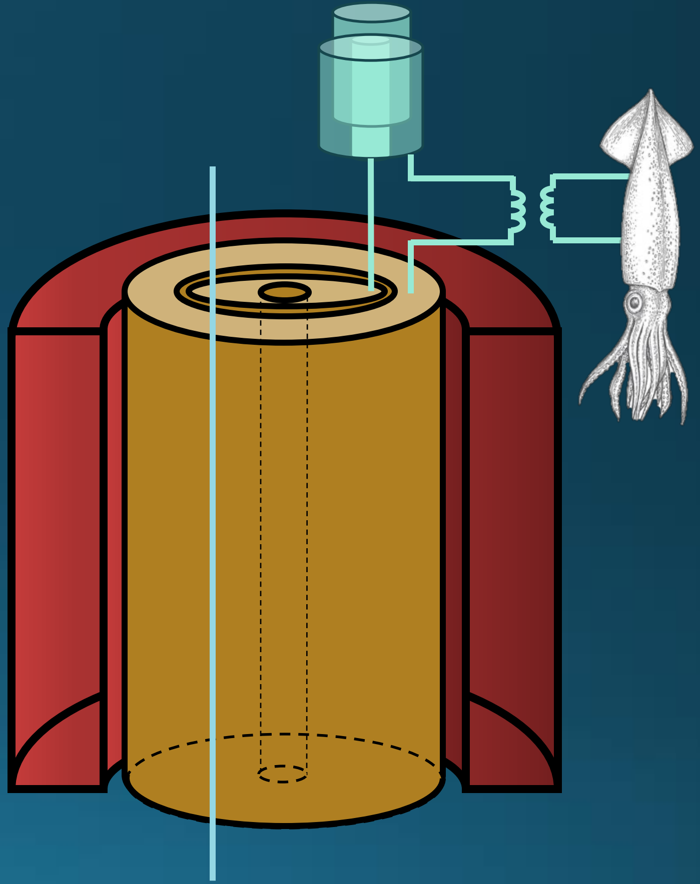
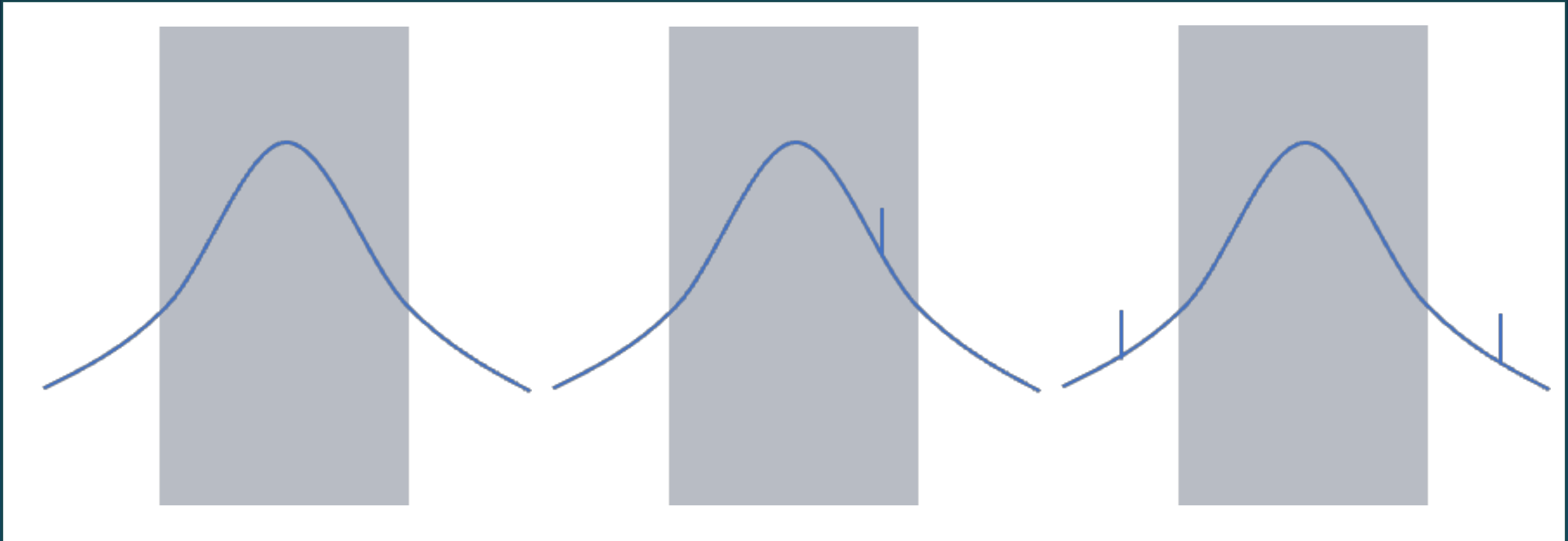


Mimetic axion





What frequencies to inject



no injection;
read out noise only

in-band injection

sideband injection

What signature to inject

- Monochromatic tones:
  - Scan across resonance
  - Sidebands
- Ringdown:
  - Single monochromatic injection over time Δt near resonance
  - Measure resonator decay over Δt'
- Synthetic axion signal:
  - Non-trivial frequency distribution (more useful for blinding)

A brief note on background rejection

- Axion signal…

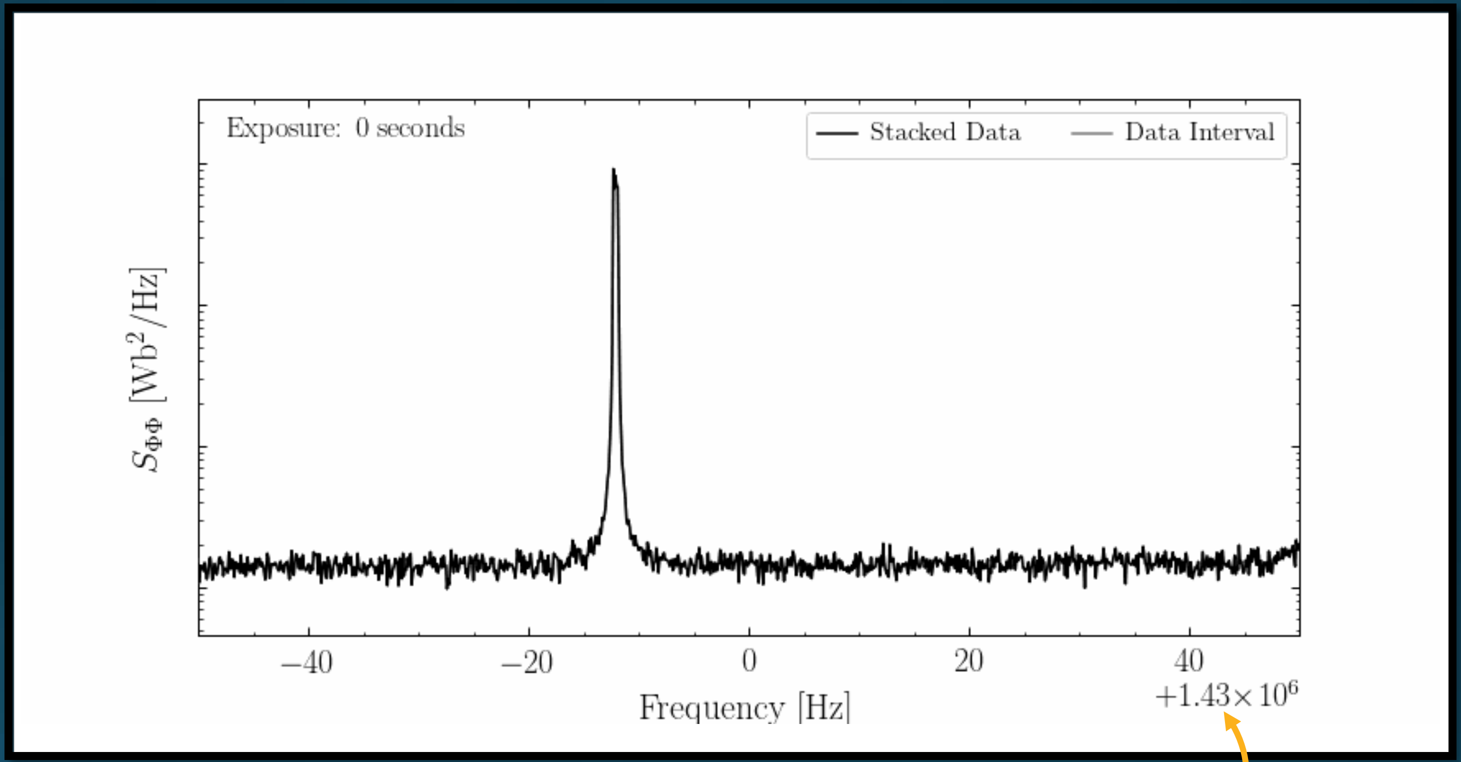
What is different about the
axion signal from
background sources?

A brief note on background rejection

- Axion signal…
  - has an expected lineshape
  - is persistent over time in amplitude and frequency, even on a rescan
  - rolls off with the resonance
  - scales with B field strength
  - modulates daily and annually

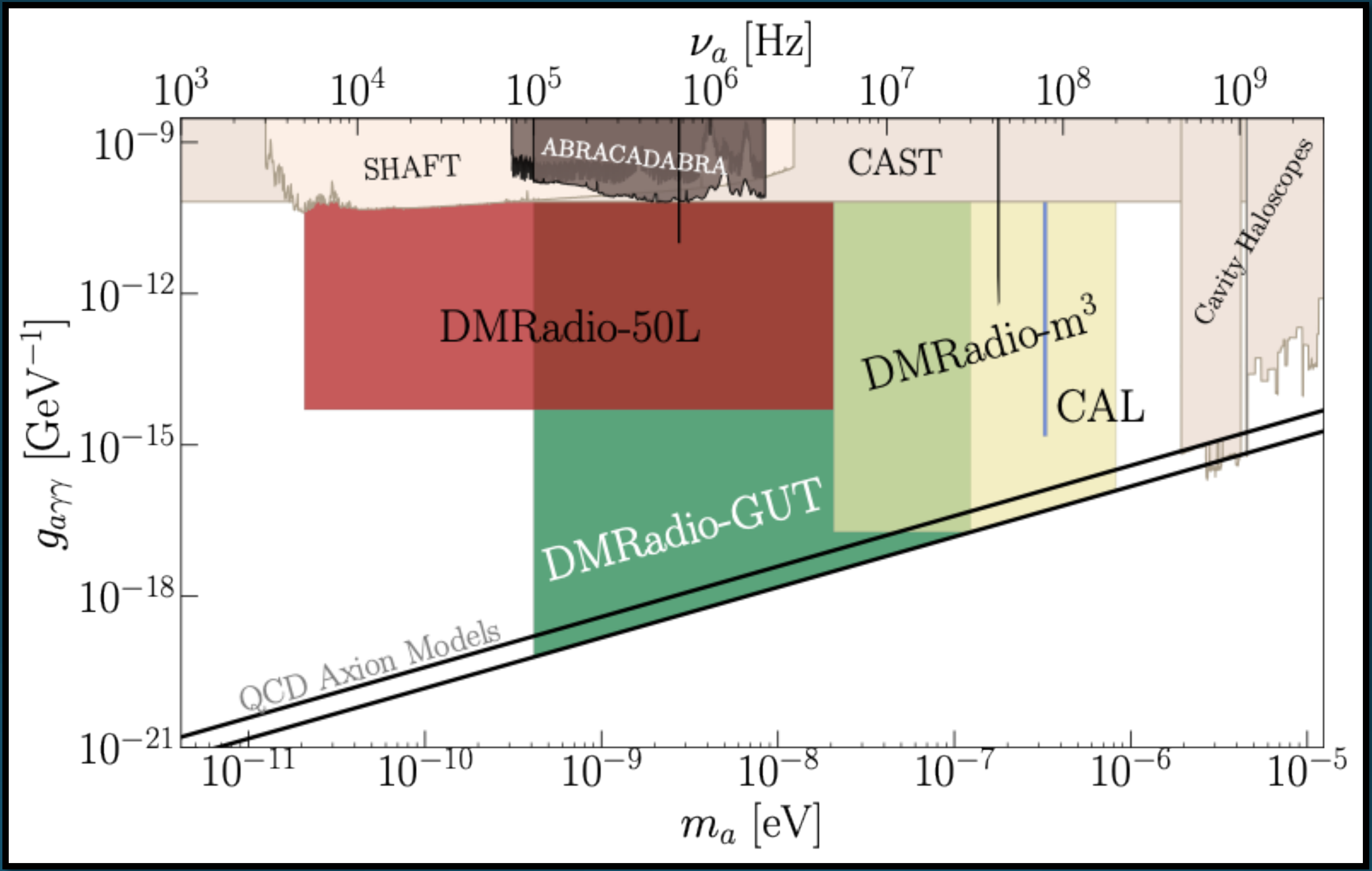
hard to think of any backgrounds that obey all of these criteria

My favorite ABRA-10cm background



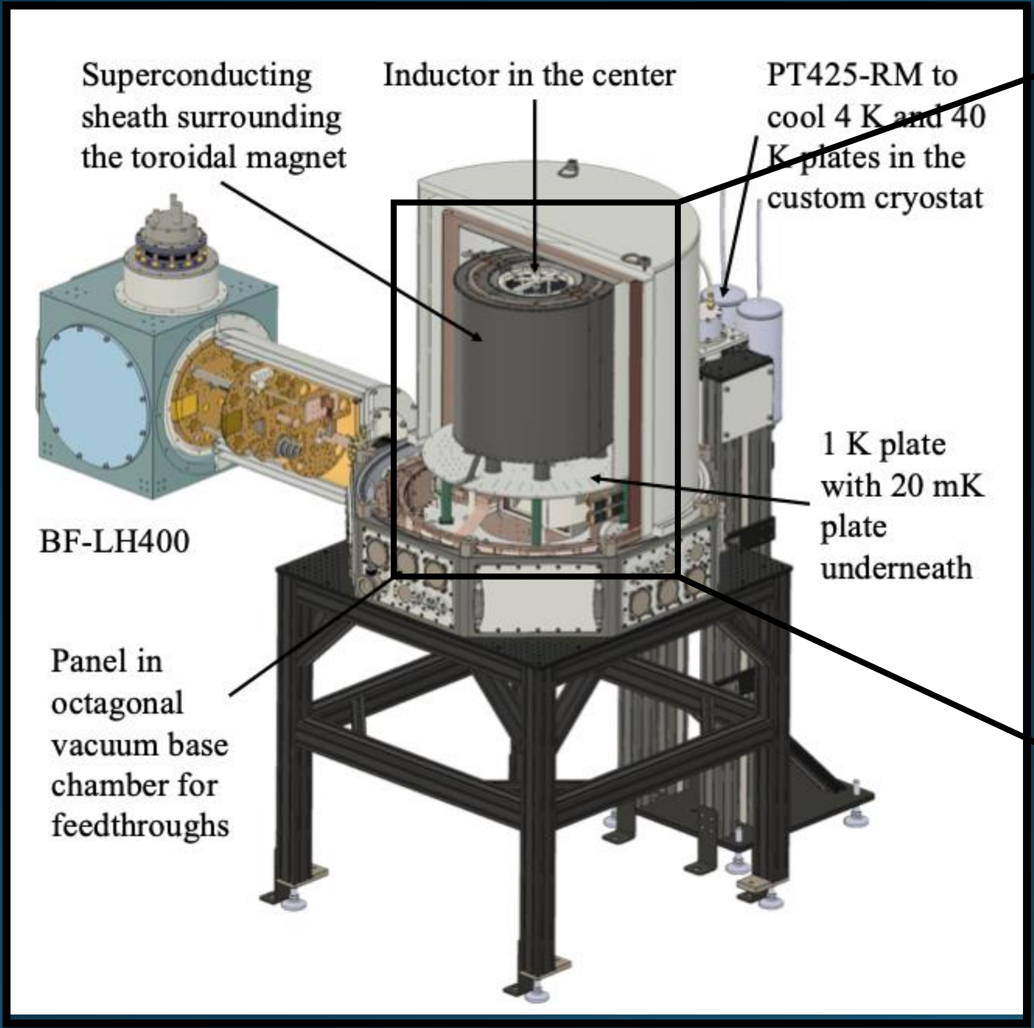
J. Foster

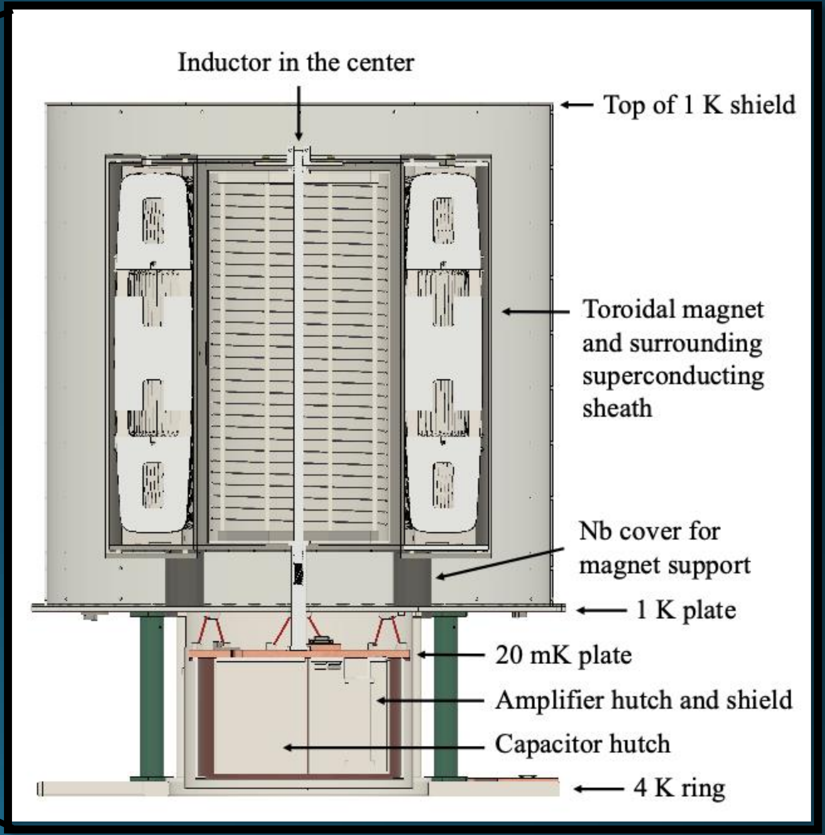
Why so many experiments?



The 50L detector (next physics data)

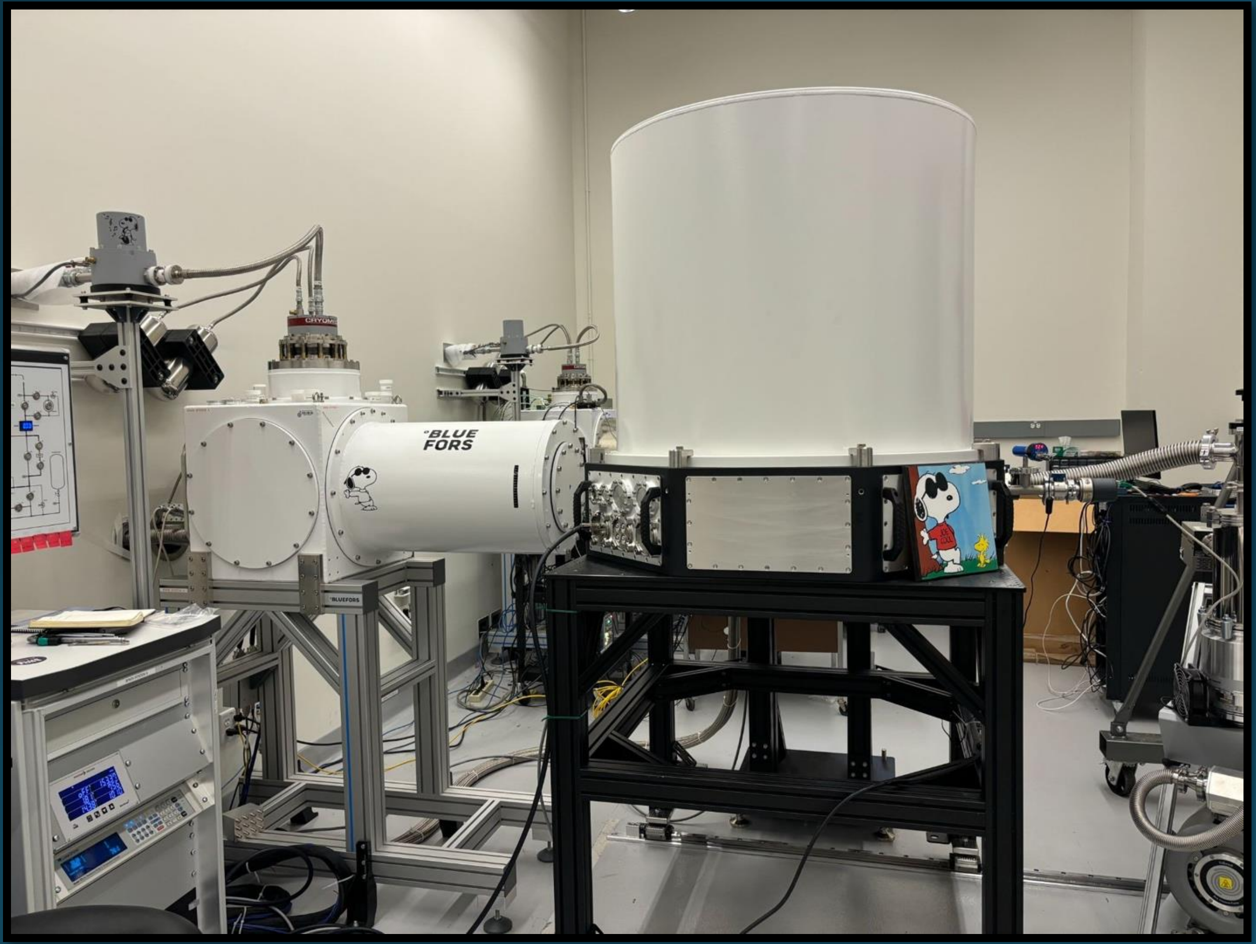
from design…





The 50L detector (next physics data)

from design… to reality



A note on the challenge of low frequencies

- Lowest nominal DMRadio-GUT frequency: 100 kHz
  - 10^6 cycles at 100 kHz is 10 s
  - Bandwidth for Q = 10^6 at 100 kHz is 0.1 Hz
  - Scan rate is then 0.1 Hz/10 s = 10^{-2} Hz/s
- Highest nominal DMRadio-GUT frequency: ~10 MHz
  - 10^6 cycles at 10 MHz is 0.1 s
  - Bandwidth for Q = 10^6 at 10 MHz is 10 Hz
  - Scan rate is then 10 Hz/0.1 s = 10^2 Hz/s
- Total scan time is dominated by scanning lowest frequencies

Scanning and dead time

- At low frequencies, it takes a long time to ring up the resonator
- At high frequencies, scan time can begin to be dominated by tuning and calibration in between frequency steps

Lumped-element scan rate

$$\frac{d\nu}{dt} \approx \frac{1}{\mathrm{SNR}^2} \underbrace{\left(g_{a\gamma\gamma}^4 \rho_{\mathrm{DM}}^2 Q_a \nu\right)}_{\text{axion physics}} \underbrace{\left(c_{\mathrm{PU}}^4 \frac{Q B_0^4 V^{10/3}}{k_B T \eta}\right)}_{\text{detector}}$$

ν : resonator frequency

Q : resonator quality factor

B_0 : peak magnetic field

T : system effective temperature

Q_a : axion quality factor

c_{PU} : pickup coupling

V : pickup volume

η : amplifier noise

Funny exponents

$$\frac{d\nu}{dt} \propto c_{\mathrm{PU}}^4 \frac{Q\boxed{B_0^4 V^{10/3}}}{k_B T \eta}$$

$$\boxed{\left(\underbrace{B_0^2 V}_{\text{magnet stored energy}} \cdot \underbrace{V^{2/3}}_{\text{inductor area: } L \propto A}\right)^2}$$

Lots of pieces to work on

maximize magnet stored energy

reduce resonator loss

maximize axion-coupled inductance

$$\frac{d\nu}{dt} \propto c_{\mathrm{PU}}^4 \frac{Q\left(B_0^2 V \cdot V^{2/3}\right)^2}{k_B T \eta}$$

get as cold as possible

efficient axion-detector and internal transformer couplings

beyond SQL amplifiers

Technology 0: Cryogenics

$$\frac{d\nu}{dt} \propto c_{\mathrm{PU}}^4 \frac{Q\left(B_0^2 V \cdot V^{2/3}\right)^2}{\underbrace{k_B T}_{\text{get as cold as possible}}\eta}$$

Low temperatures are required

- Superconductors must be cooled below their transition temperature
  - Needed for low loss
  - Nb ~ 9K, Al ~ 1K
  - Generally want to cool well below this point

Low temperatures are required

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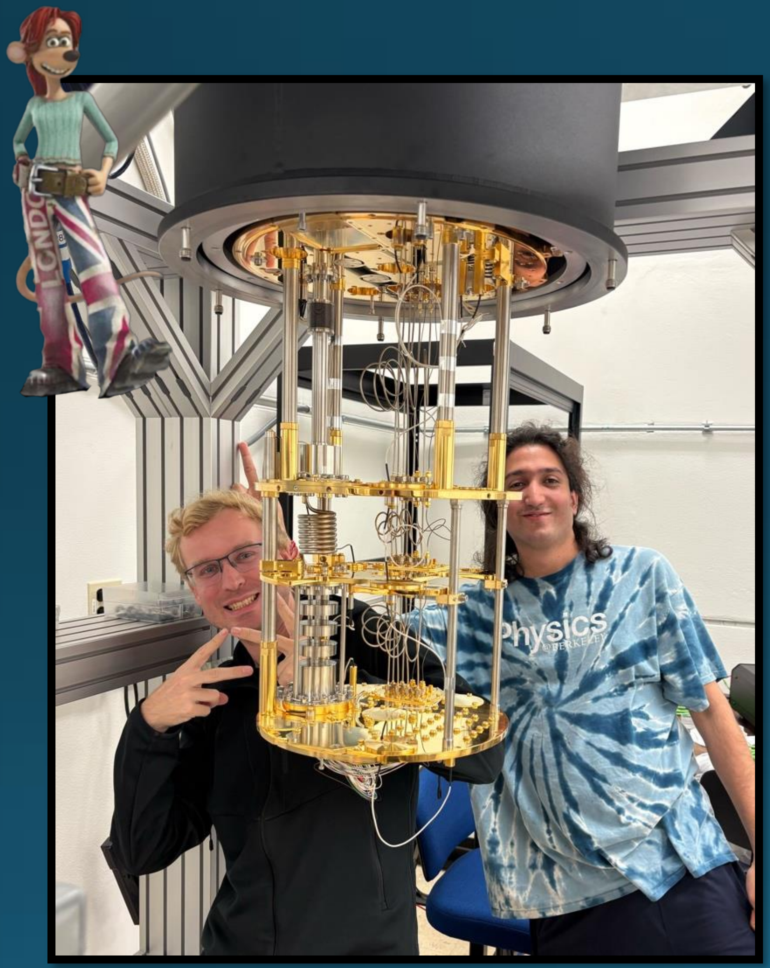
Why is this true?

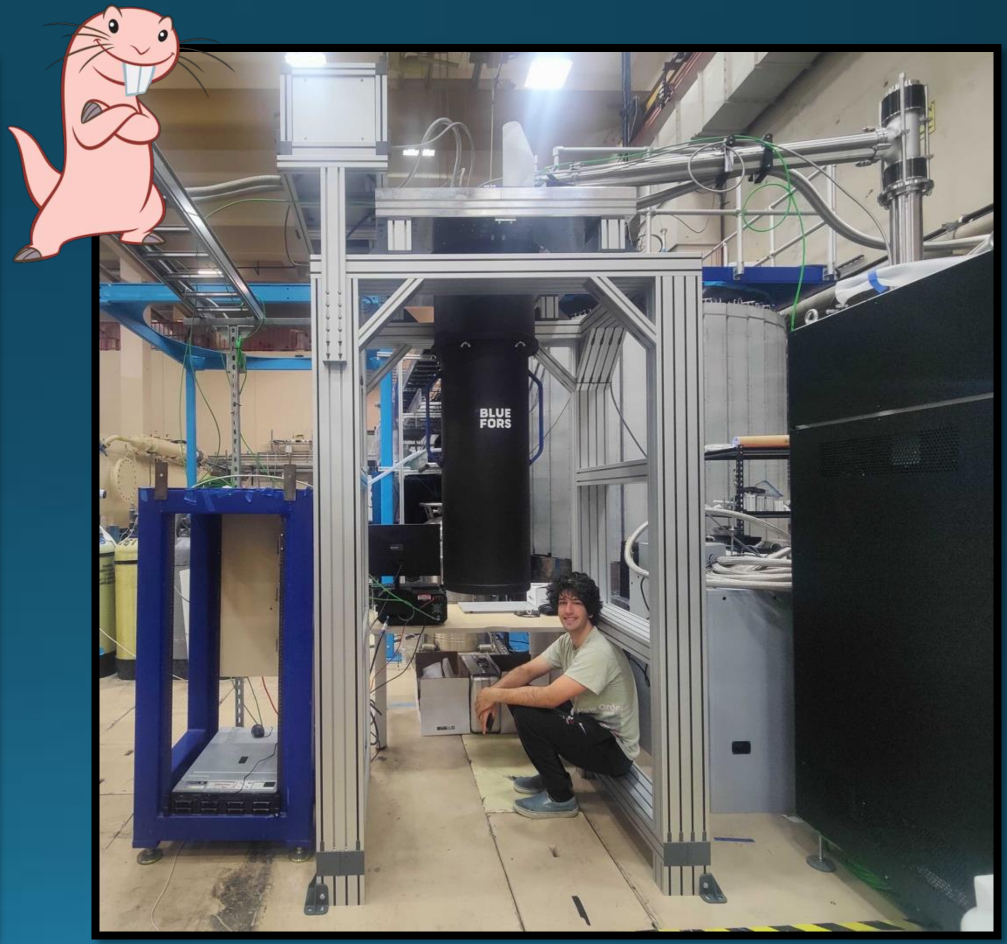
Low temperatures are required

- Superconductors must be cooled below their transition temperature
  - Needed for low loss
  - Nb ~ 9K, Al ~ 1K
  - Generally want to cool well below this point
- Thermal noise is the fundamental limitation at low frequencies*
  - Cool as low as possible!

*will revisit this in more detail tomorrow

Achieve mK temperatures with dilution refrigerators





Technology 1: Magnets

maximize magnet
stored energy

$$\frac{d\nu}{dt} \propto c_{\mathrm{PU}}^4 \frac{Q\left(\overline{B_0^2 V} \cdot V^{2/3}\right)^2}{k_B T \eta}$$

What do we want
from our magnets?

Magnet requirements

- High field
- High volume
- Stable, known field pattern
- Toroid or solenoid
- Low-field region for superconducting sensors

Magnet considerations

- Forces
  - GUT magnet: $B^2V/(2\mu_0) \approx 1$ GJ (almost a quarter of a ton of TNT)
- Quench protection
- How strong/large you can reach is material-dependent
  - Critical temperature: T_c
  - Critical field: H_{c1}
  - Critical current density
- Cost: magnet often is ~half the price of an axion experiment

Magnet materials (Iron)

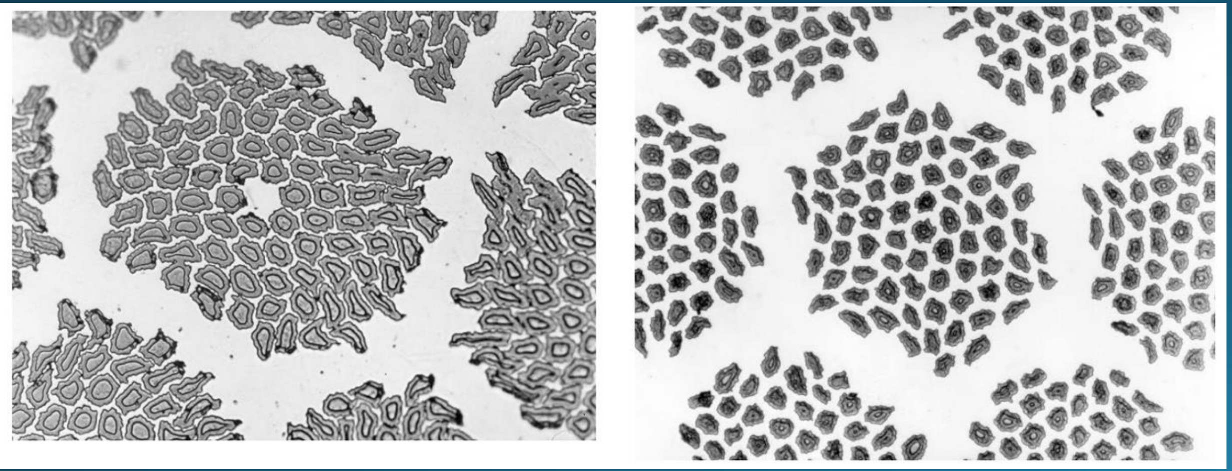
- low saturation (~1-2T)
- permanent (or semi-permanent with a coil)
- too much mass to cool down effectively, so must be larger to accommodate cryostat infrastructure inside

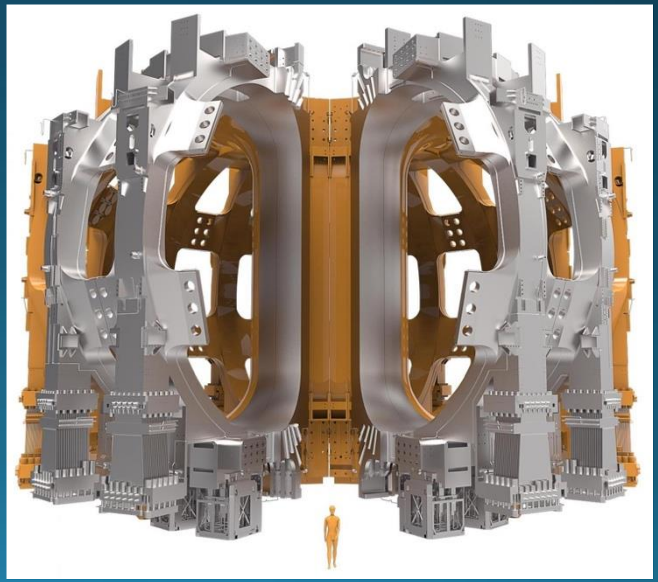
Magnet materials (NbTi)

- traditional superconducting magnet wire material
- easy to make into flexible cabling for winding
- typically have multiple strands of NbTi in a copper matrix for thermalization and quench protection
- critical field ~ 15T; in practice magnets max field ~9-10T
- most existing axion experiments

Magnet materials (Nb_3Sn)

- can reach higher fields (critical field ~30T, max practical ~16-20T)
- very brittle – challenging to work with and cannot pull into wires
- how to form?
  - make composite wire of Nb filaments in Cu+Sn (bronze) matrix
  - wind your magnet
  - bake @ 650-700C to react Nb + Sn

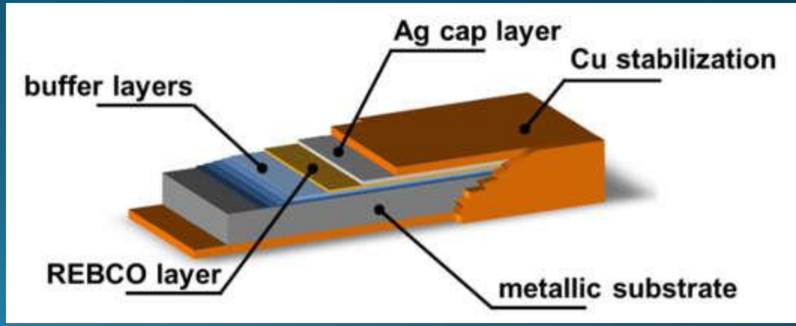




ITER tokomak uses Nb3Sn

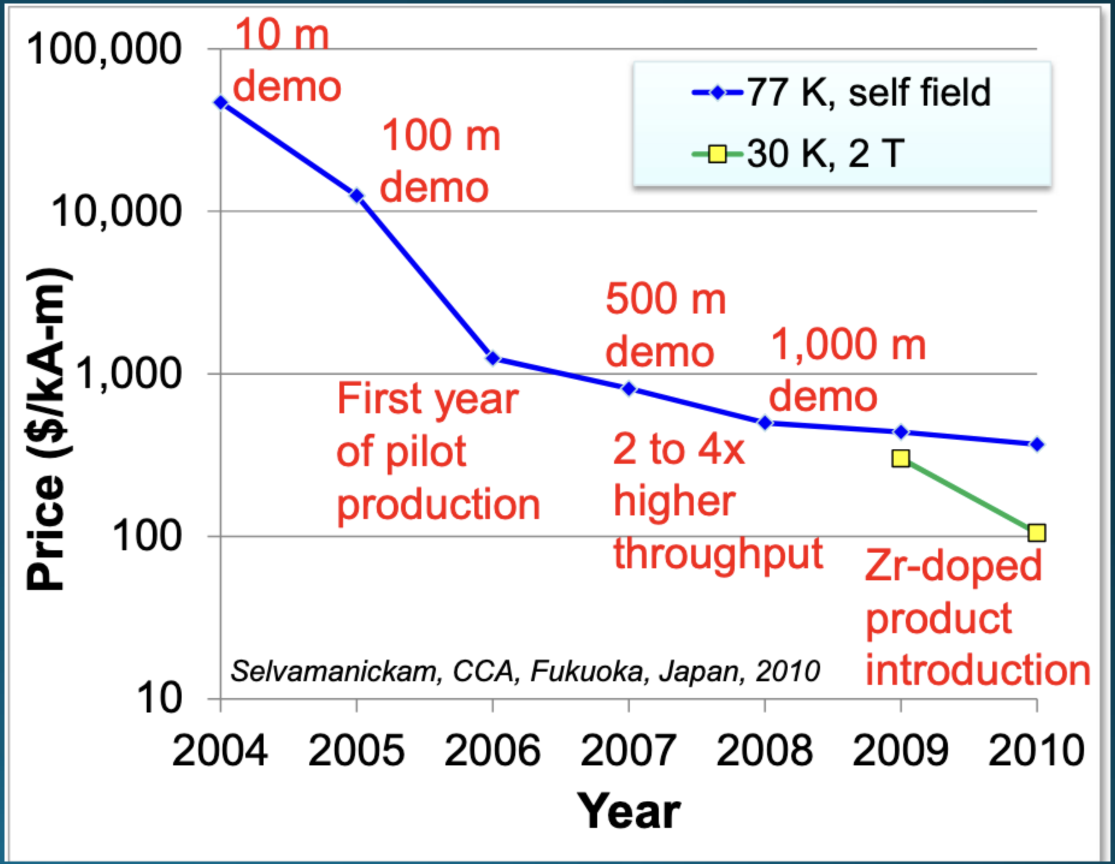
Magnet materials (HTS)

- Rare Earth Barium Copper Oxide
  - e.g. BSCCO, YBCO
- can reach much higher fields (record: 48.7 T from Florida Mag Lab)
- can also operate at higher temperatures (e.g. operate with LN_2)
  - can cool more to have higher current densities
- exist as tapes rather than wires – need different winding methods
- quenches are less well understood
- $$$ (although prices are dropping!)



Cost comparison…

- Cost given as USD/kA*m
- Analysis from 1998
- 4K materials:
  - NbTi: $1/(kA*m)
  - Nb3Sn: $8/(kA*m)
- HTS:
  - ~$800-1200/(kA*m)
  - This analysis says that costs need to drop to ~$10/(kA*m) to be widely adopted



Grant, Sheahan arxiv: cond-mat/0202386

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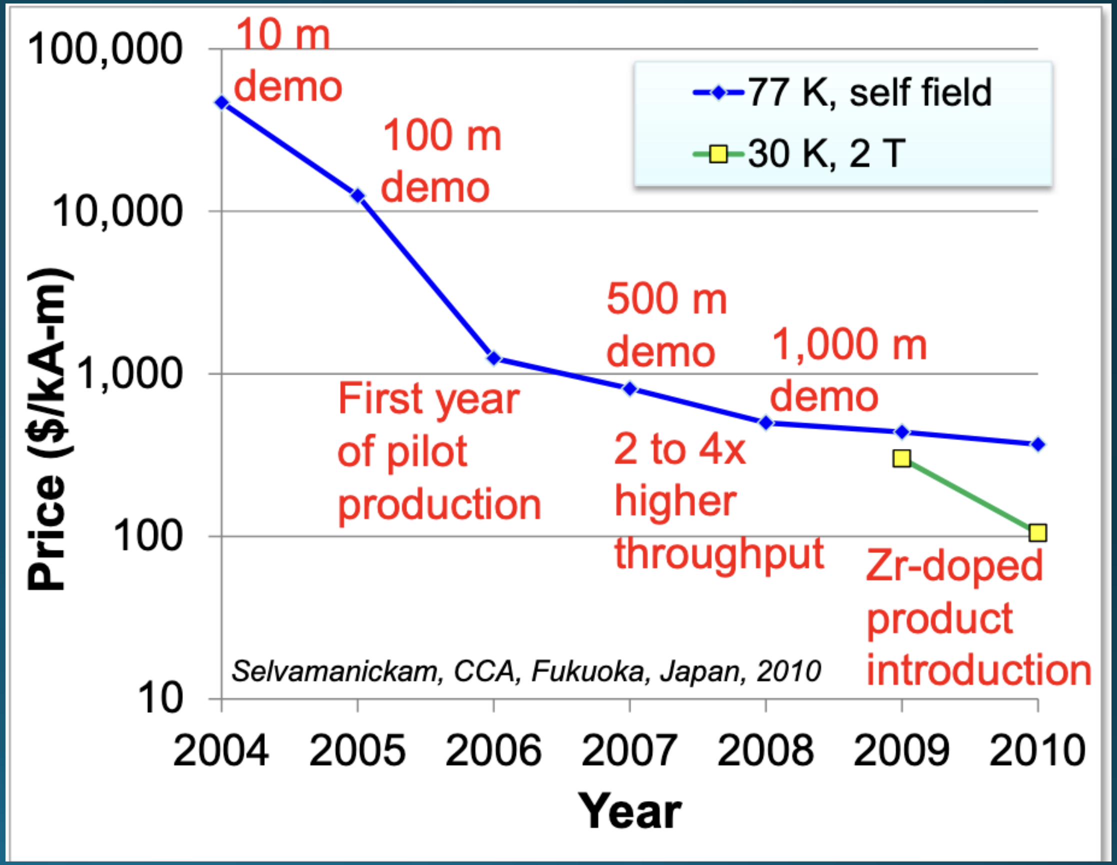

2010 prediction for 2021: $35/(kA*m)
actual 2021: $200/(kA*m)

Grant, Sheahan arxiv: cond-mat/0202386

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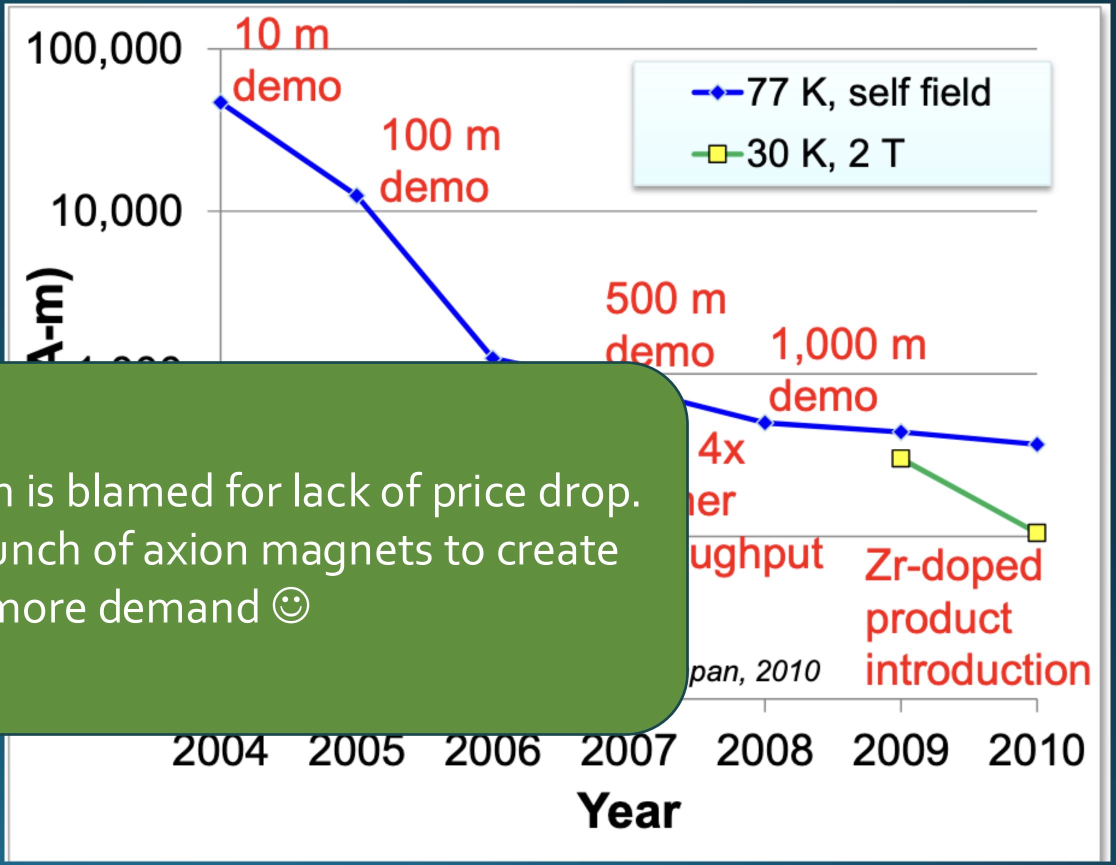


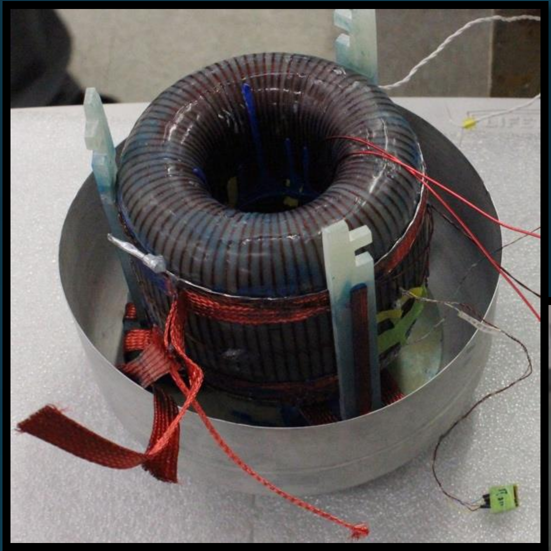
limited production is blamed for lack of price drop.
→ let's build a bunch of axion magnets to create more demand ☺

2010 prediction for 2021: $35/(kA*m)
actual 2021: $200/(kA*m)

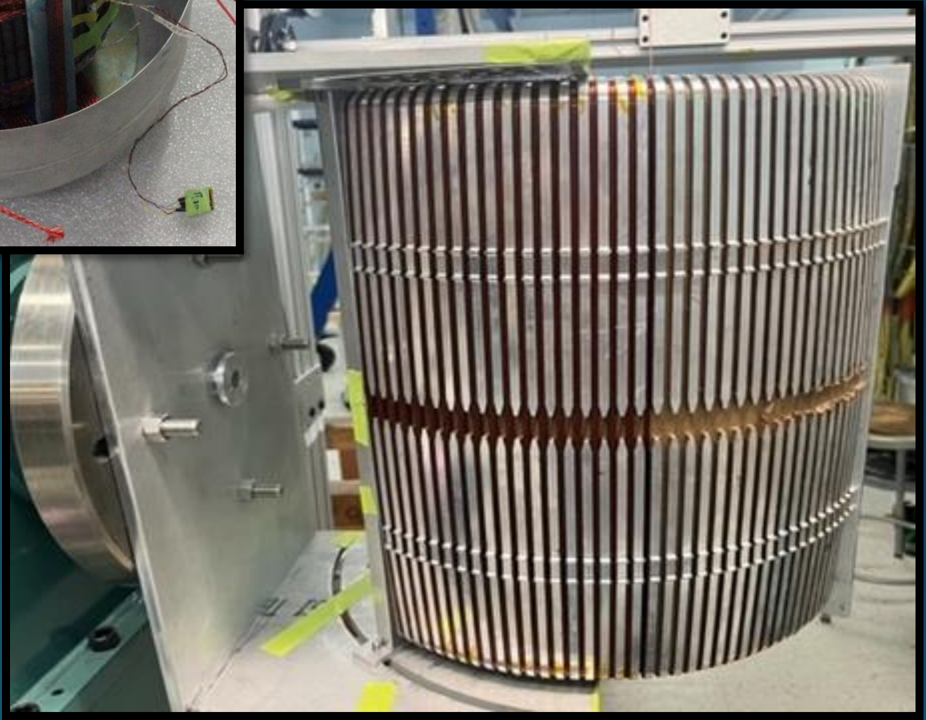
Grant, Sheahan arxiv: cond-mat/0202386

DMRadio program NbTi magnets

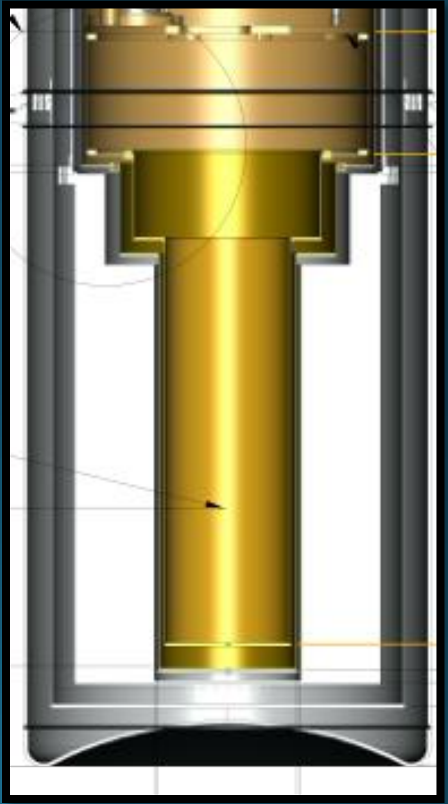
ABRA-10cm
1 T, 0.5 L toroid



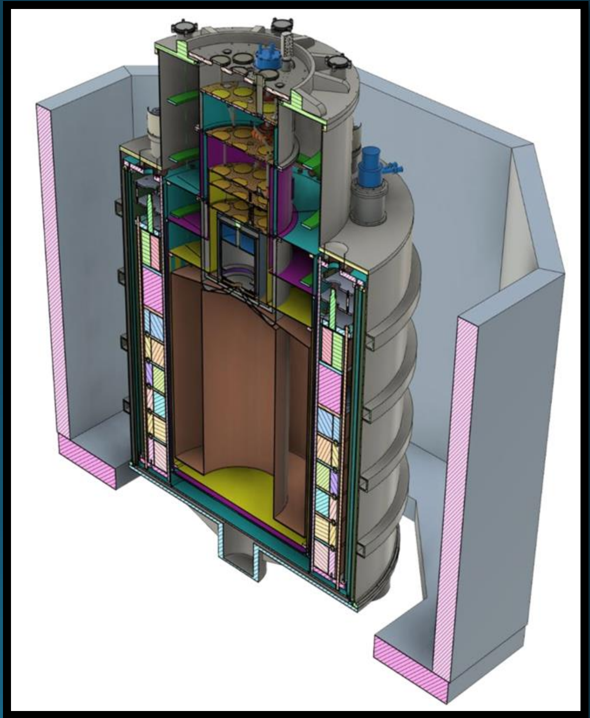
DMRadio-50L
1 T, 50 L toroid



CAL
9T, 10 L solenoid



DMRadio-m³
~5T, 1000 L solenoid



DMRadio-GUT magnet needs

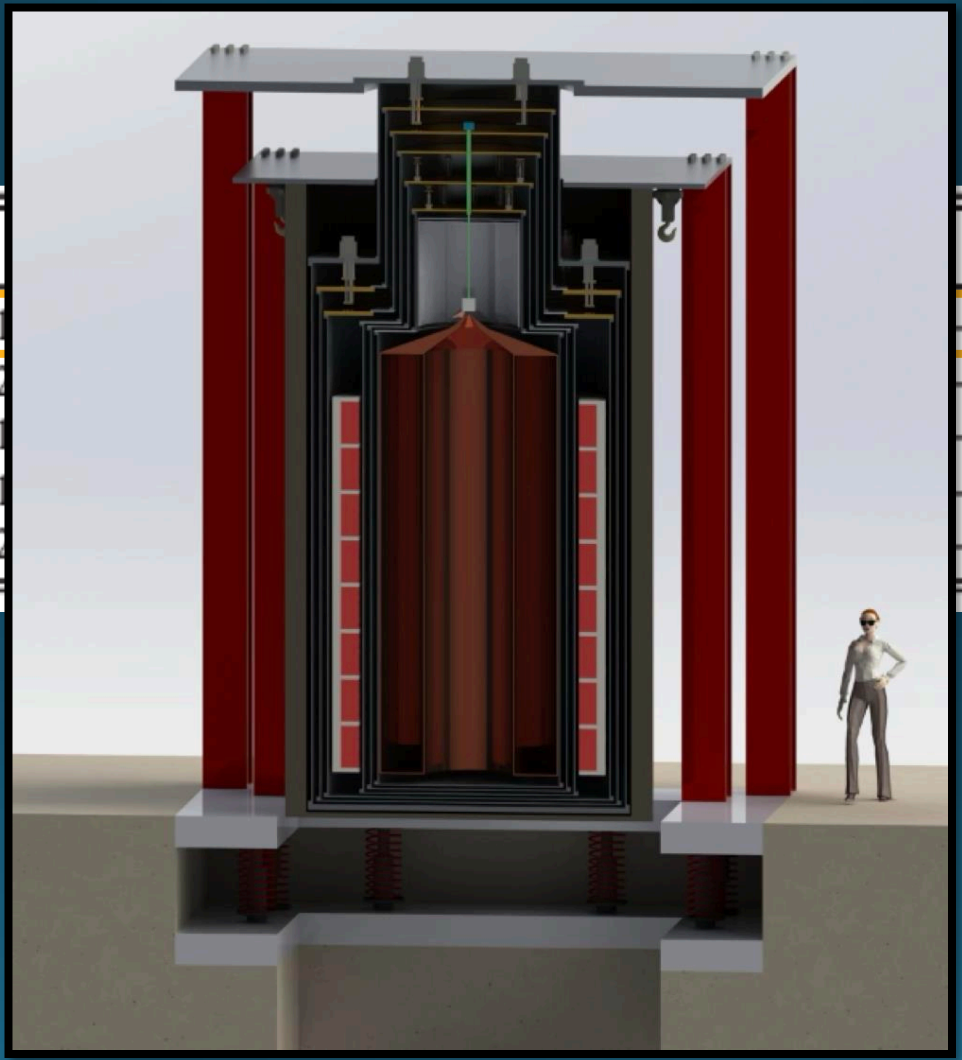
Scenario	B_0	V	c_{PU}	Q	η_A	T	*Scan time*
Baseline	16 T*	10 m^3	0.1	20×10^6	−20 dB	10 mK	6.2 years
Stronger magnet + higher noise	29 T	10 m^3	0.1	20×10^6	−5 dB	10 mK	3.2 years
Lower noise + lower volume	16 T	8 m^3	0.1	20×10^6	−25 dB	10 mK	7.3 years
Higher volume + lower Q	16 T	17 m^3	0.1	2×10^6	−20 dB	10 mK	10.6 years
Stronger magnet + lower Q	26 T	10 m^3	0.1	2×10^6	−20 dB	10 mK	8.9 years

Brouwer et al. Phys.Rev.D, 2022b

*16 T peak/12 T RMS

DMRadio-GUT magnet needs

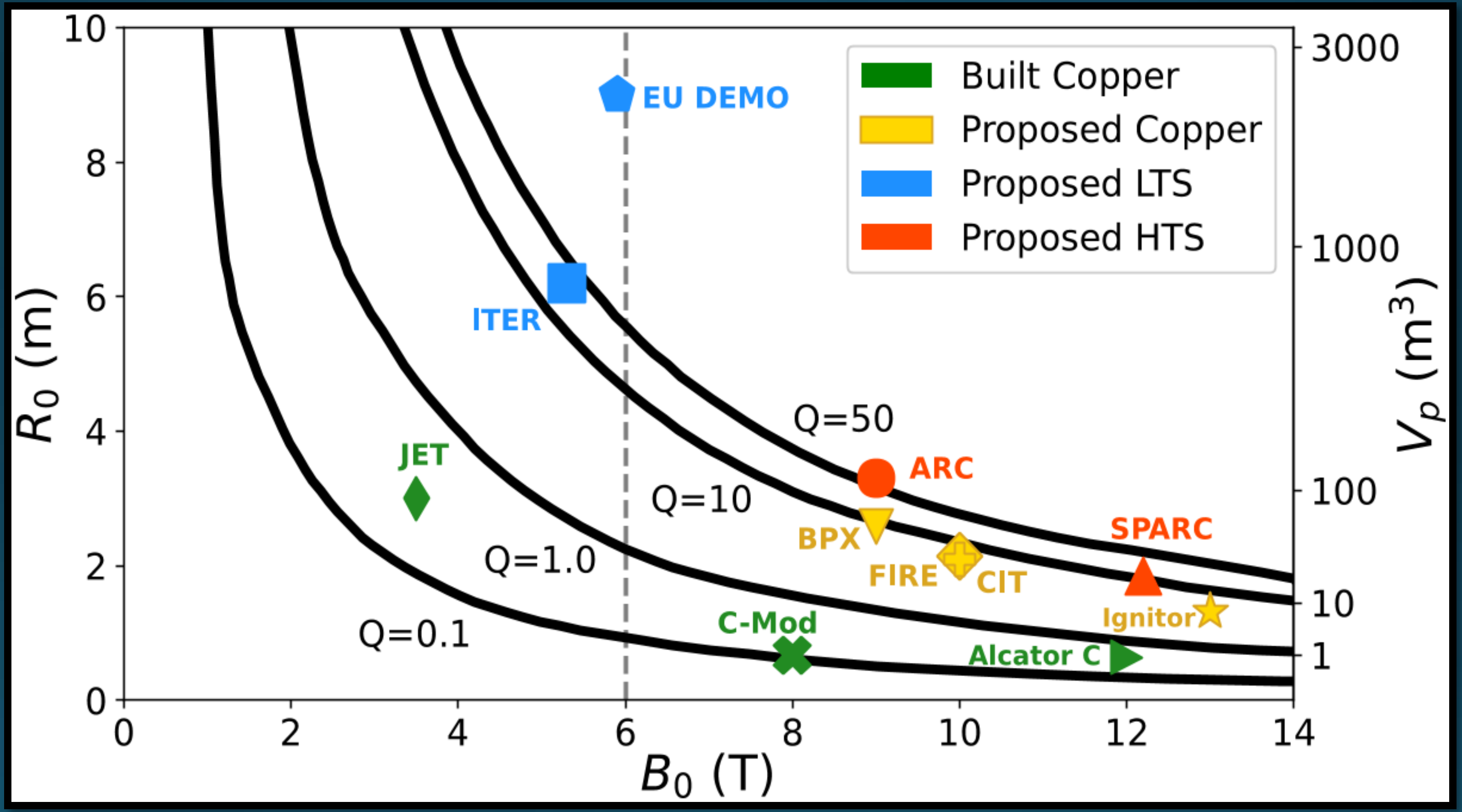
Scenario	η_A	T	Scan time
Baseline	−20 dB	10 mK	6.2 years
Stronger magnet + higher noise	−5 dB	10 mK	3.2 years
Lower noise + lower volume	−25 dB	10 mK	7.3 years
Higher volume + lower Q	−20 dB	10 mK	10.6 years
Stronger magnet + lower Q	−20 dB	10 mK	8.9 years



Brouwer et al. Phys.Rev.D, 2022b

*16 T peak/12 T RMS

R&D for large scale magnets is synergistic with fusion



Comparison to fusion magnets
Creely et al. (SPARC)

Technology 2: Tunable low-frequency resonators

$$\underbrace{\overset{\text{reduce resonator loss}}{\overbrace{Q}}}\,$$

reduce resonator loss

maximize axion-coupled inductance

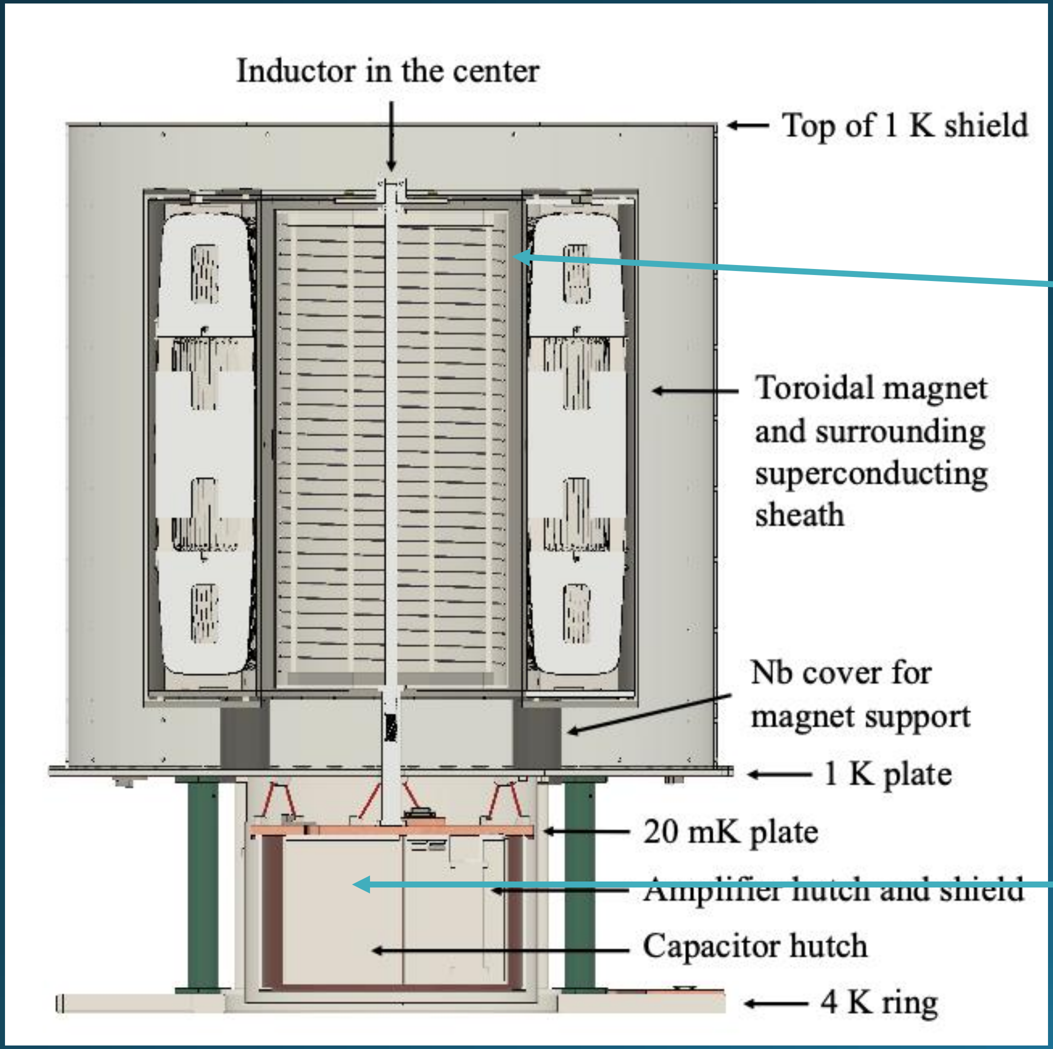
$$\frac{d\nu}{dt} \propto \underbrace{c_{\mathrm{PU}}^{4}}_{\text{efficient axion-detector and internal transformer couplings}} \frac{\overbrace{Q}^{\text{reduce resonator loss}}\left(B_0^2 V \cdot \overbrace{V^{2/3}}^{\text{maximize axion-coupled inductance}}\right)^2}{k_B T \eta}$$

Resonator needs

- Low loss/high Q
  - Best = superconducting (but unhappy* in B fields)
  - Requires fastidious separation from outside environment
- Tunable
  - We need orders of magnitude in frequency—require multiple resonators and/or tuning elements
- Different geometry for pickup and tuning elements depending on magnet geometry

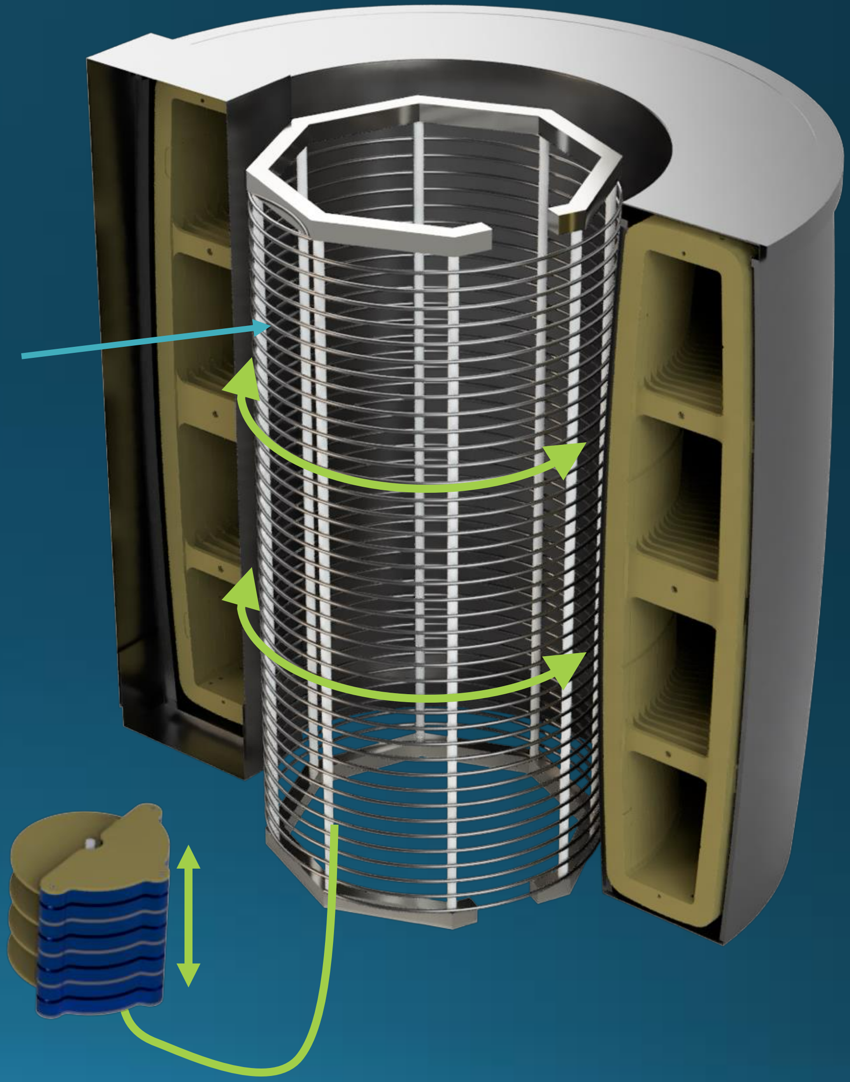
*strength of tolerable B field depends on material

Resonator for toroid



NbTi wound-wire inductor

tunable butterfly capacitor

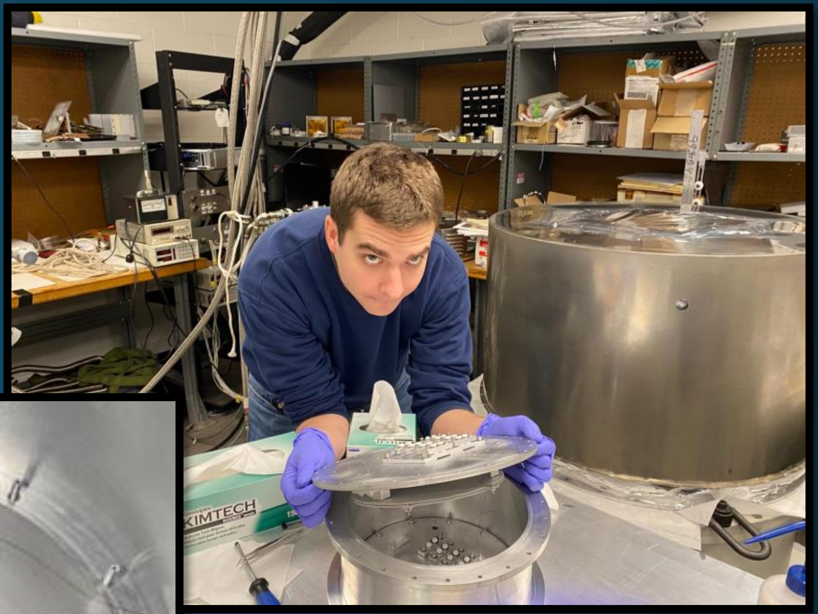


Challenge: reducing thermal load while maintaining high Q

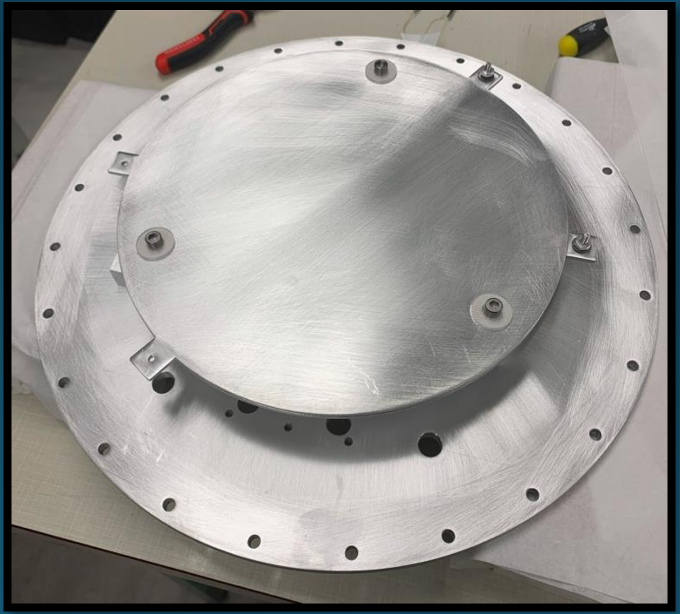
- Materials
  - Low tan(δ) dielectrics: sapphire ~ 2e-5, alumina ~1e-4
  - Low participation
  - Eliminate wire insulation where possible
- Connections
  - Screw terminals for better superconducting connections
  - Reduce connections where possible
- Cool well below T_c to avoid quasiparticles
  - Indium at aluminum-sapphire interfaces for better thermalization
- Motion
  - Reduce friction at interfaces (materials choices, ball bearings)

Very high-Q fixed-frequency resonator demonstration

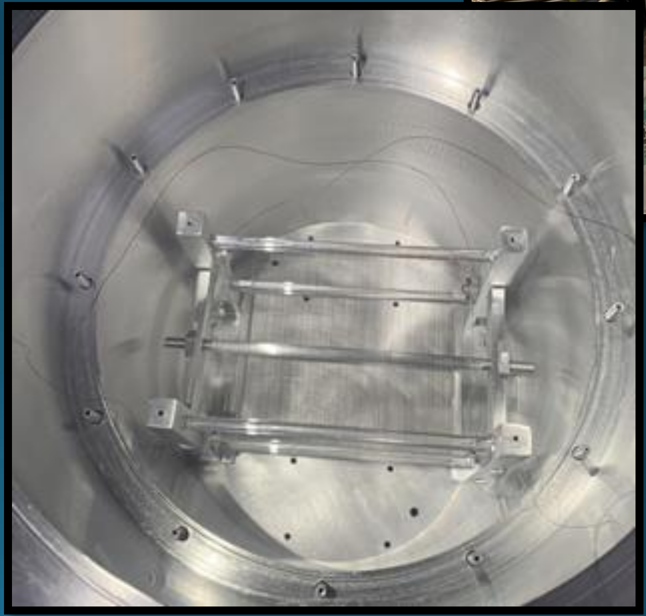
Q ~ 2 million at 254 kHz achieved at Princeton test stand



Roman Kolevatov closing up LC resonator apparatus



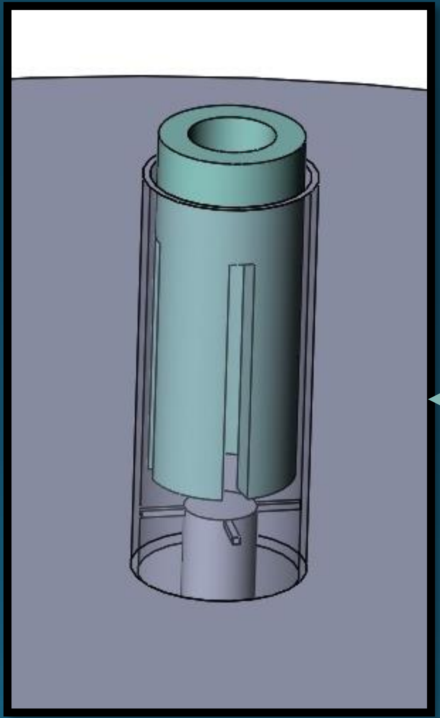
Al 1100 parallel-plate capacitor



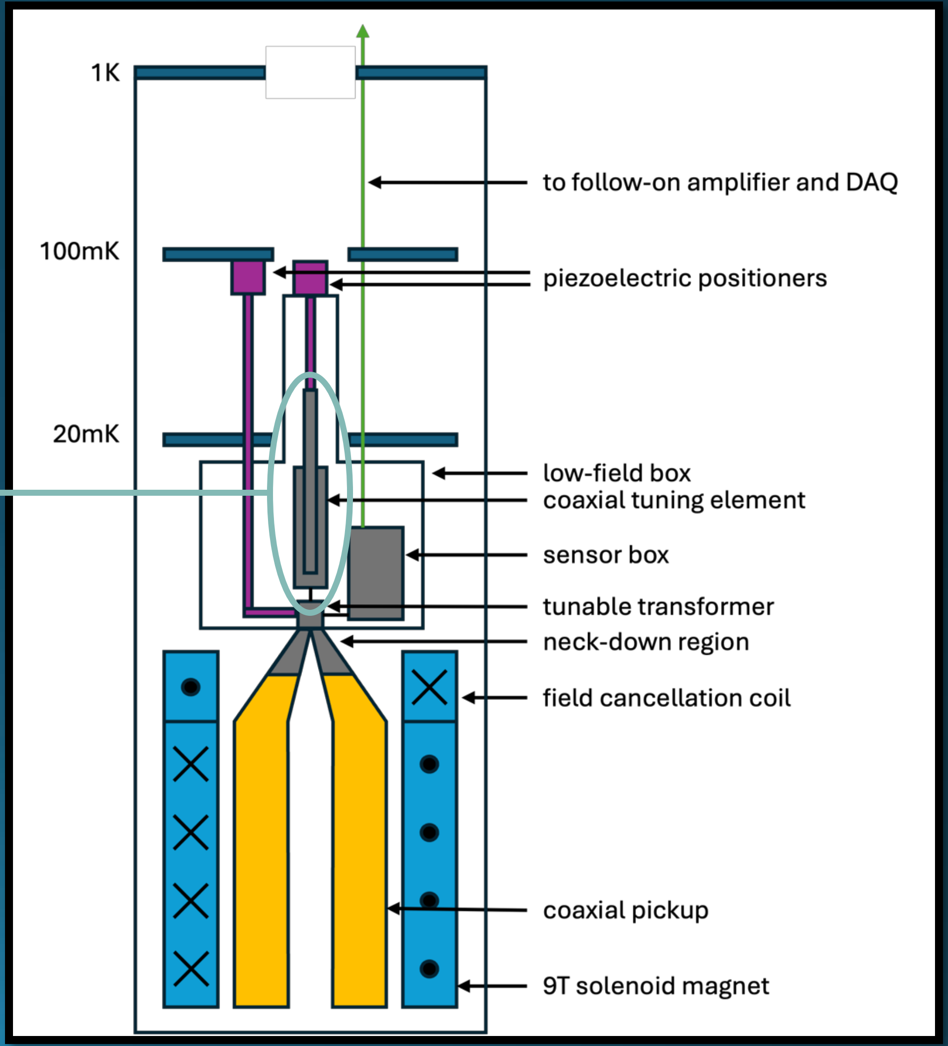
Tensioned NbTi wire on sapphire rods

Resonator for solenoid

- At high frequencies, a little bit of parasitic L or C can kill your sensitivity!
- Solution: coaxial pickup and tuning
  - Currents are fully enclosed – less loss
  - Analytically calculable impedance
- Similar thermal and Q considerations



Coaxial tuner concept



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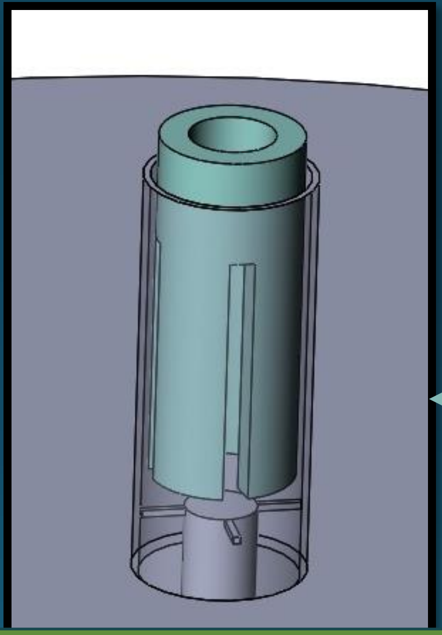
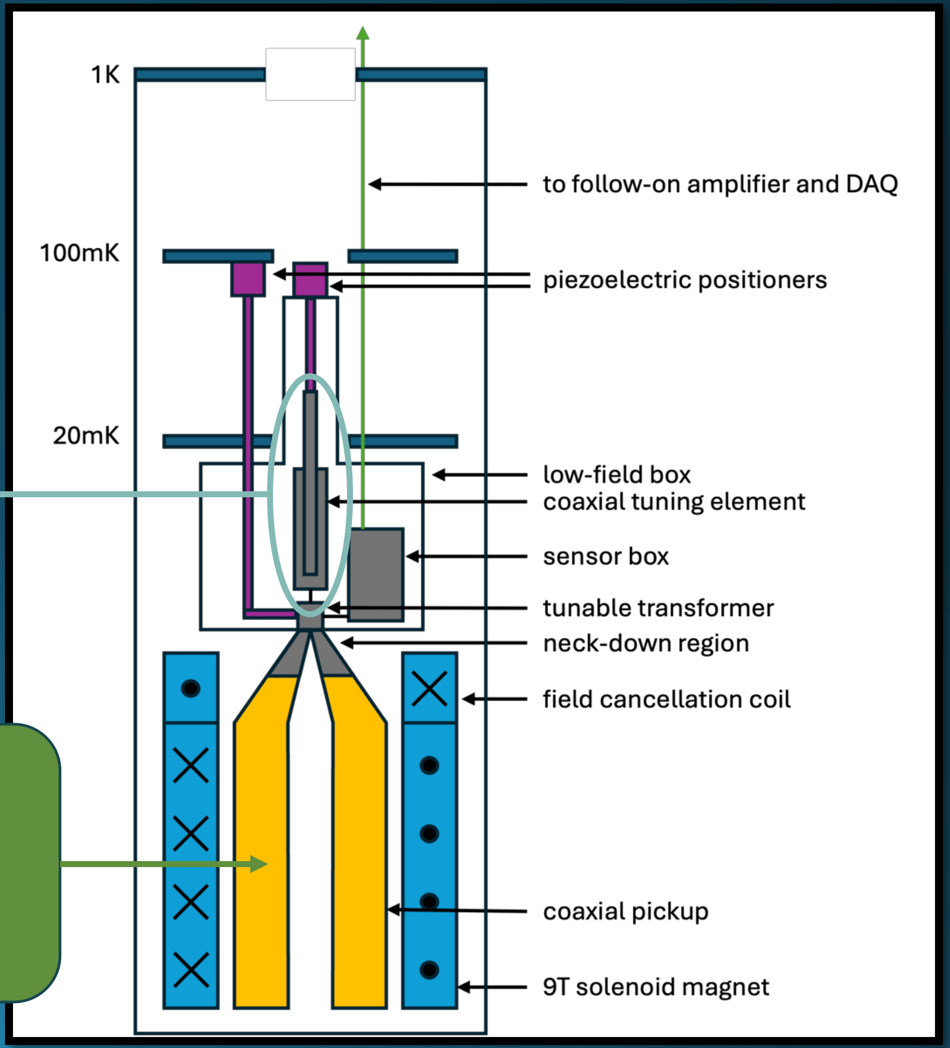




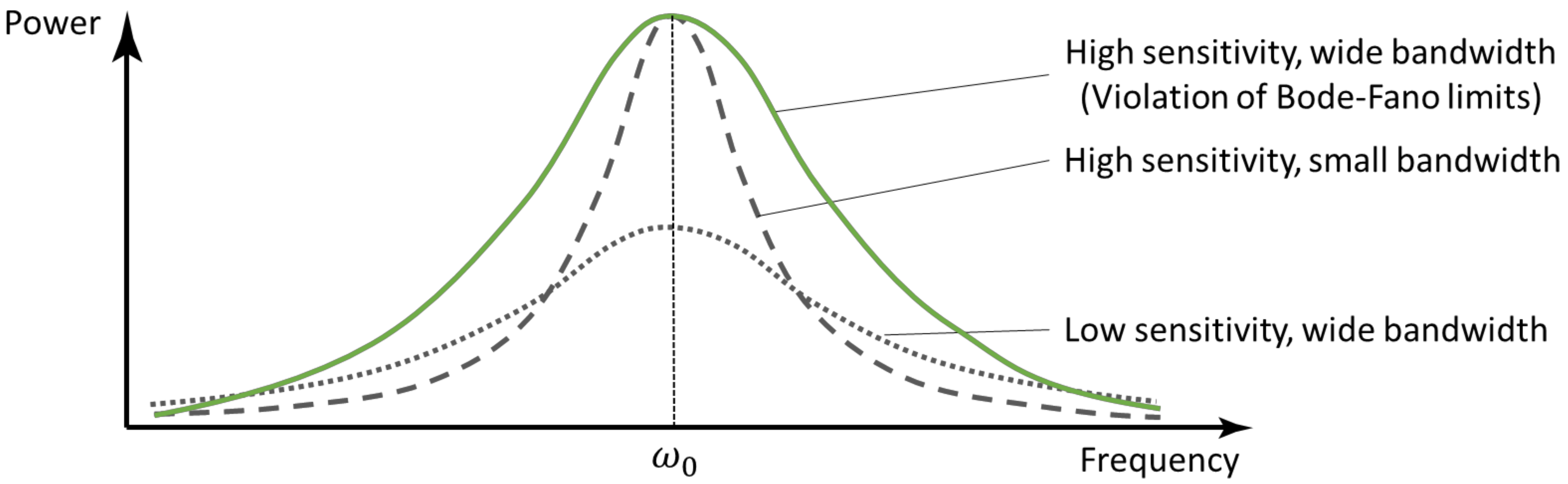
Baseline material: high purity copper
Possible upgrade: HTS MgB_2
$H_{c2}(T=0K) \sim 13\text{-}18\,T$
$H_{c1}(T=0K) \sim 0.03T$

Ambitious ideas: Bode-Fano evasion

Bode-Fano Limits

- Bode-Fano limit: A complex load having energy storage elements limits the bandwidth of the match achieved by a matching network
- Criteria (assumptions): Passivity, Linearity, Time Invariance

Removing some of these assumptions could bypass the Bode-Fano limits



Technology 3:
Low-frequency quantum sensors

$$\frac{d\nu}{dt} \propto c_{\mathrm{PU}}^4 \frac{Q\left(B_0^2 V \cdot V^{2/3}\right)^2}{k_B T \underbrace{\eta}_{\text{beyond SQL amplifiers}}}$$

Technology 3: Low-frequency quantum sensors

$$\frac{d\nu}{dt} \propto c_{\mathrm{PU}}^4 \frac{Q\left(B_0^2 V \cdot V^{2/3}\right)^2}{k_B T \eta}$$

beyond SQL
amplifiers

Next lecture!

An alternative low-mass technique: Superconducting Radio-Frequency (SRF) cavities

- Accelerator cavities can get Q factors ~10^{11}

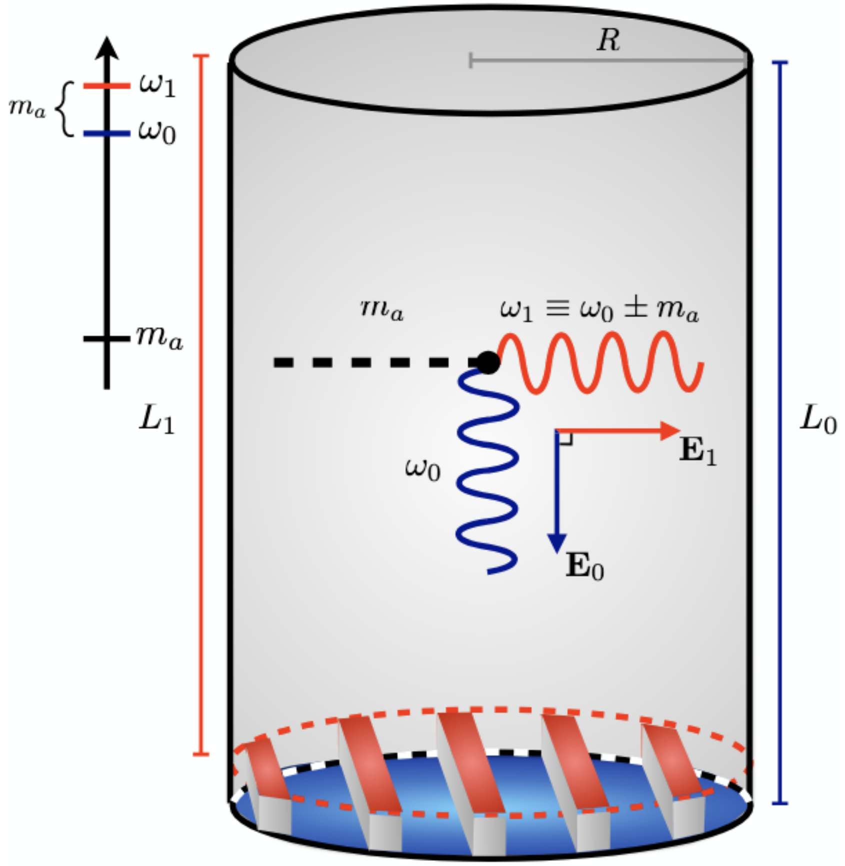
"Impressive! What can we do with that?"

*a few ideas of how to use these – I will only talk about one, heterodyne detection

An alternative low-mass technique: Superconducting Radio-Frequency (SRF) cavities

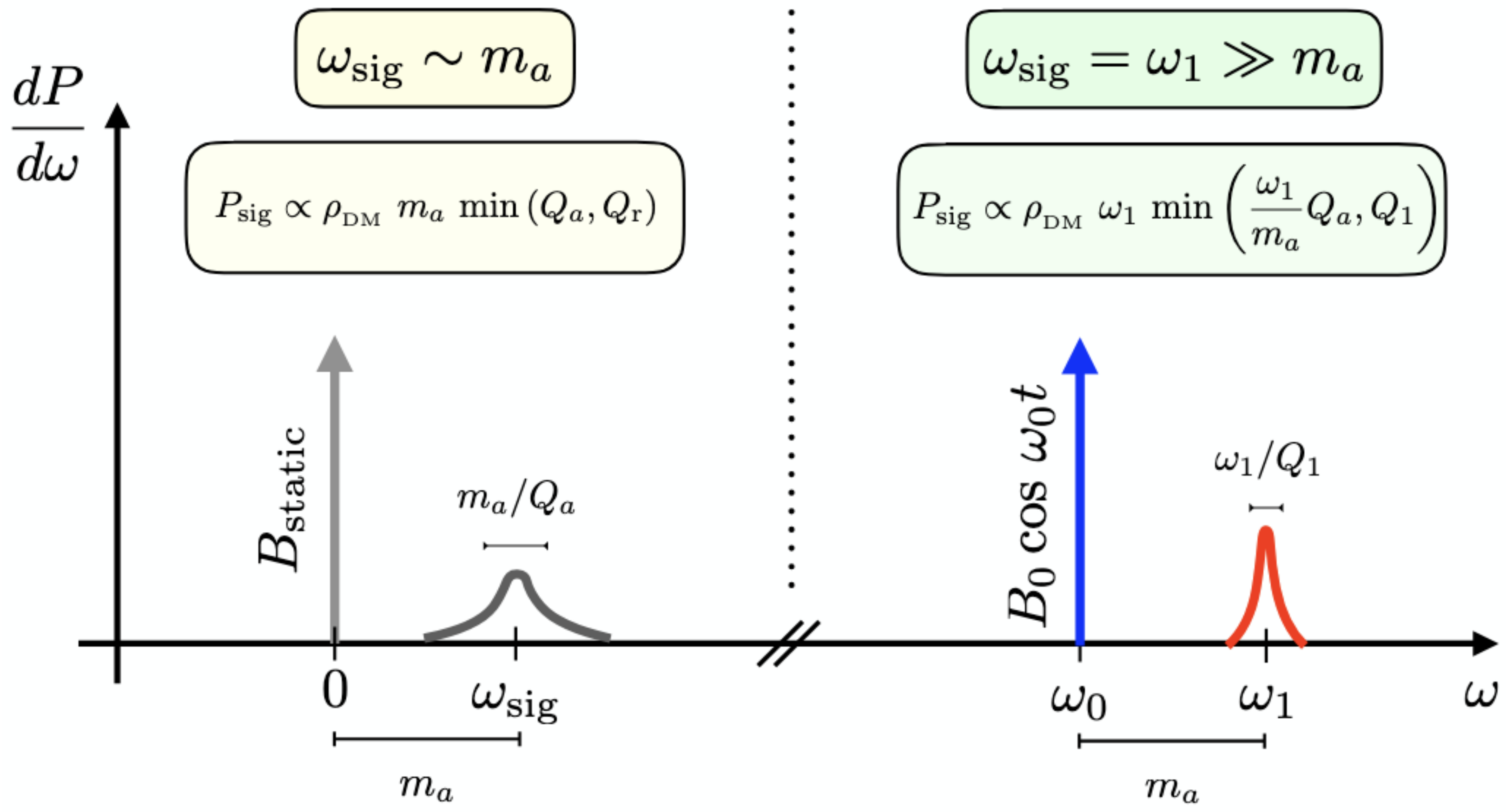
- Accelerator cavities can get Q factors ~10^{11}
- Heterodyne approach
  - Drive GHz cavity mode, ω_0
  - Axion interacts, driving signal mode

$$\omega_1 = \omega_0 \pm m_a$$



Berlin et al. 2020

Method comparison



Berlin et al. 2020

SRF signal

$$P_{\text{sig}} \sim (g_{a\gamma\gamma}^2 \rho_{\text{DM}})\,(B_0^2 V)\,(Q_1/\omega_1)$$

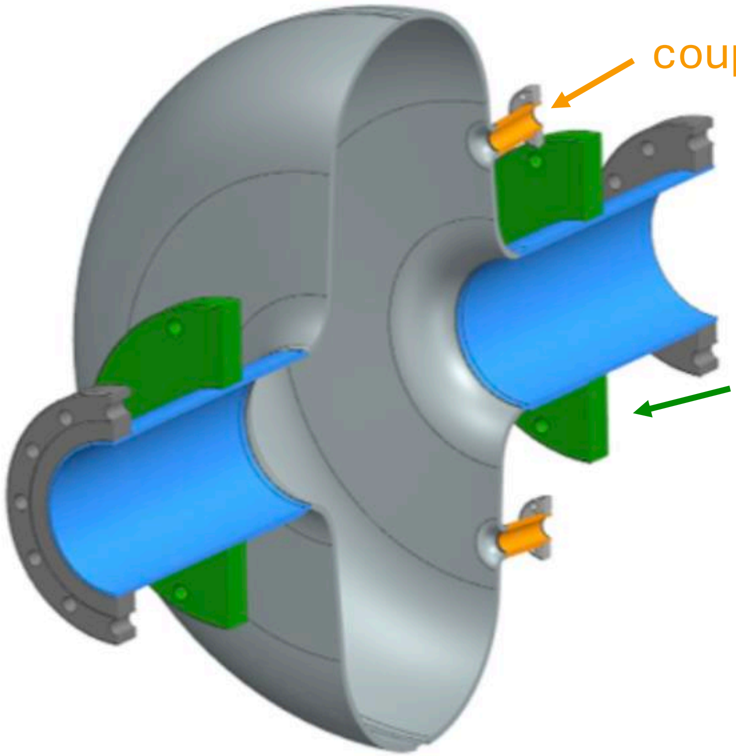
energy stored in driven mode

decay time of signal mode

Lower B_0, higher Q than lumped-element experiments

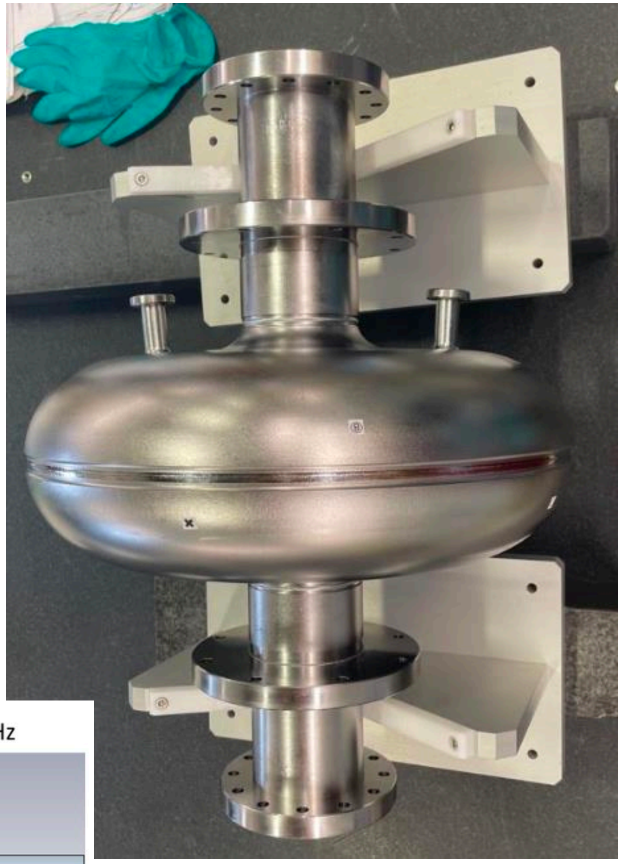
In real life

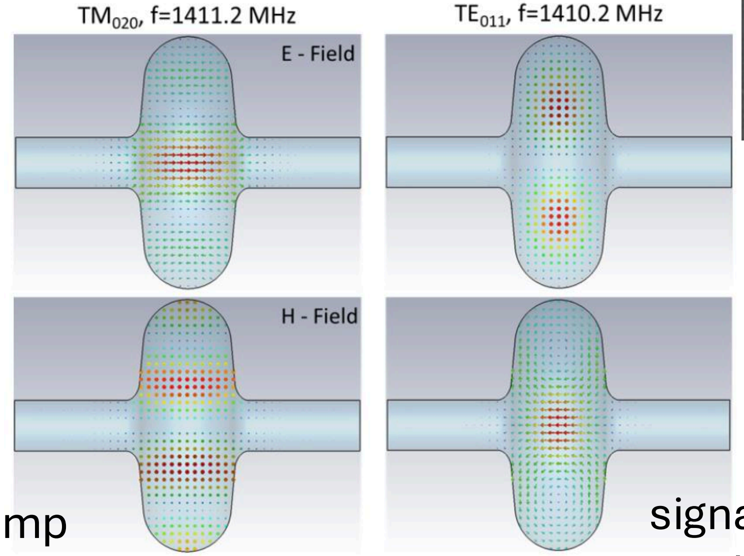
SHADE (Superconducting Heterodyne Axion Dark matter Experiment)



coupler ports

mechanically squeeze to tune the mode splitting





pump mode

signal mode

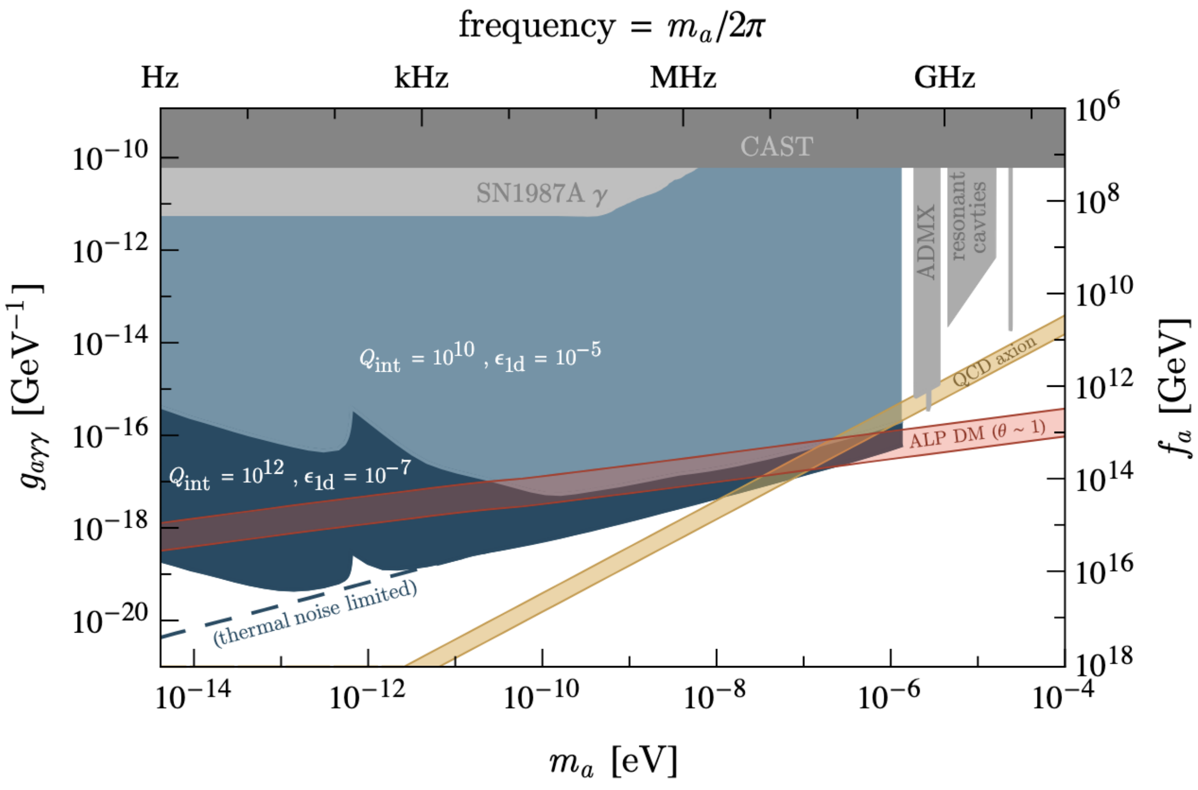
Giaccone et al. 2022

Challenges

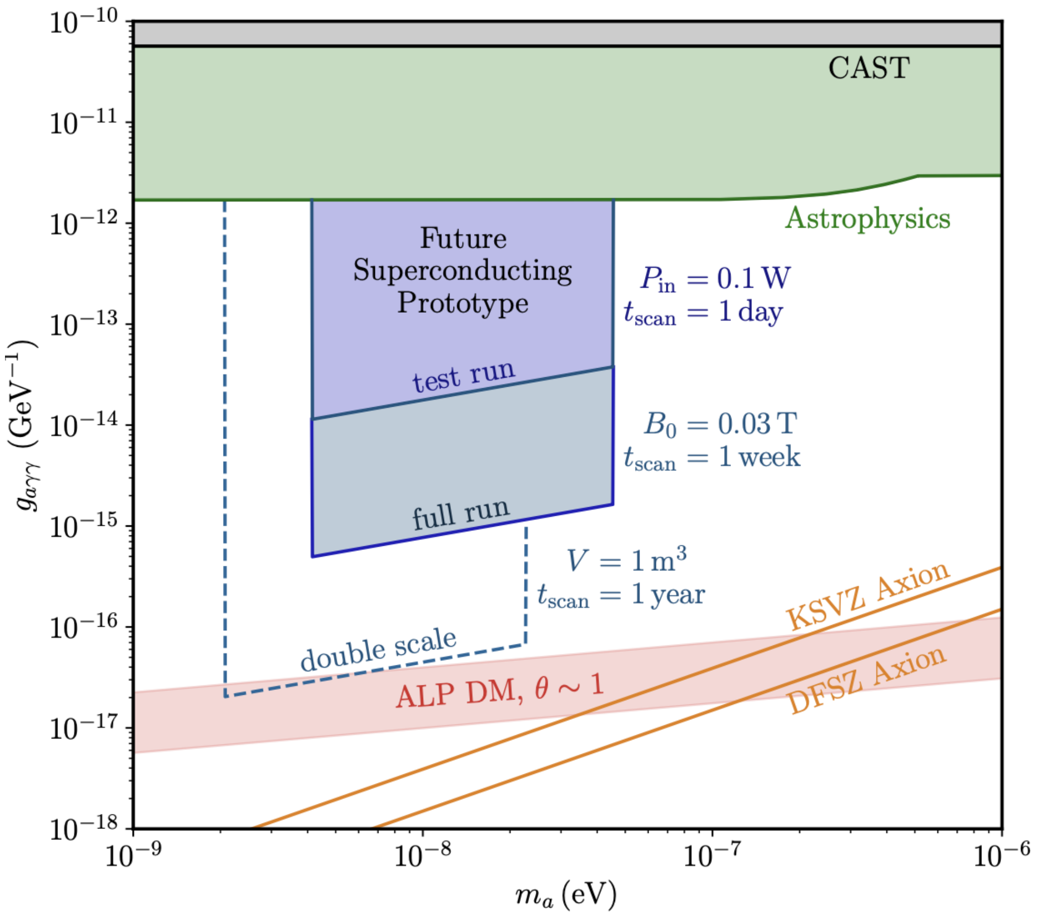
- Tuning reliability and calibration
- Mode leakage
- Vibrations/microphonics

Reach

Initial theorist reach: *Berlin et al. 2020*



Updated experimentalist reach: *Li et al. 2025*



Review of today

- Dark matter axion expected signal and detection regimes
- Low mass axion motivation
- Lumped-element detection with LC circuits
- Technology development for QCD axion reach with DMRadio
- Alternative low-mass method with SRF cavities