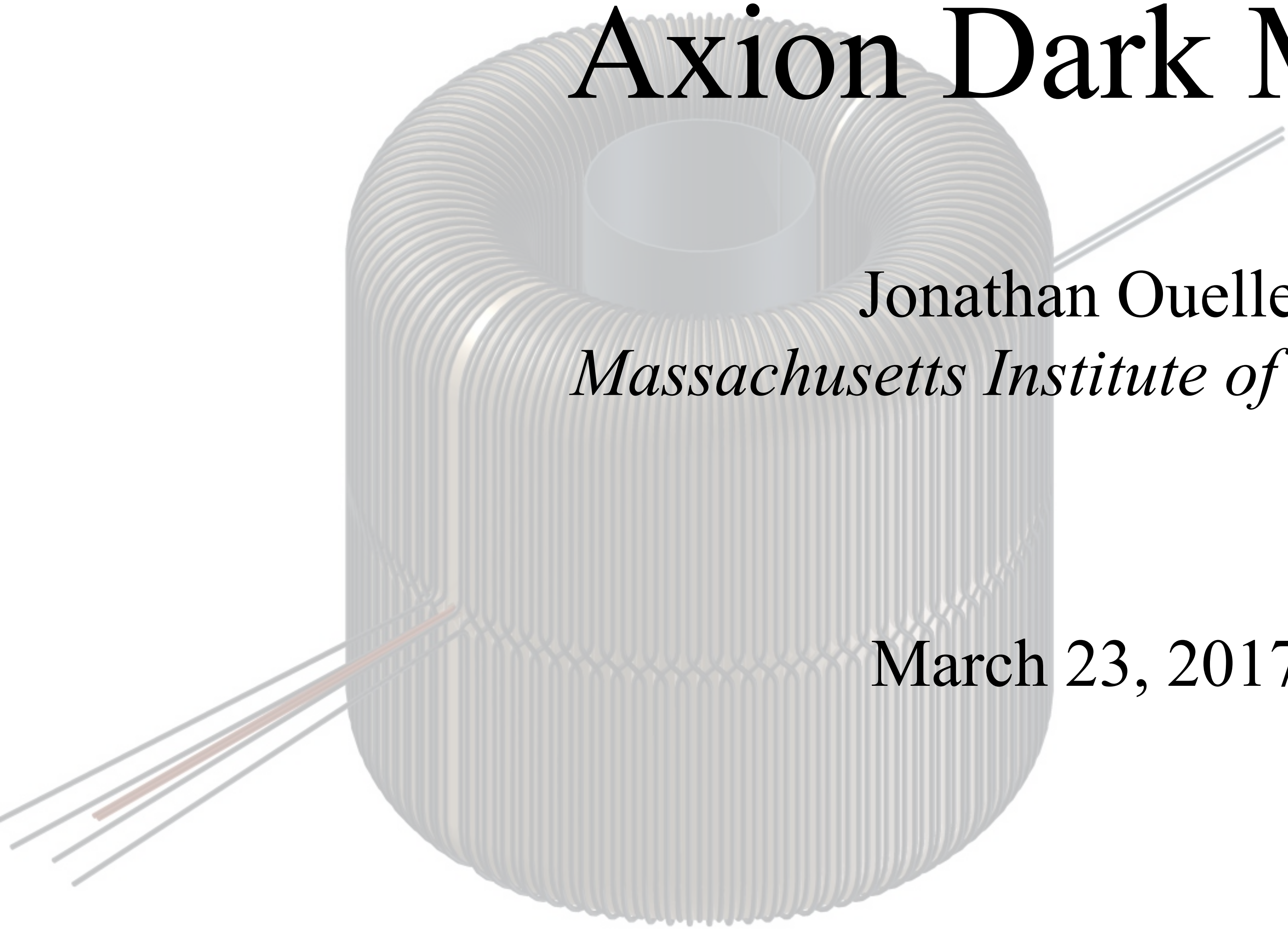
ABRACADABRA

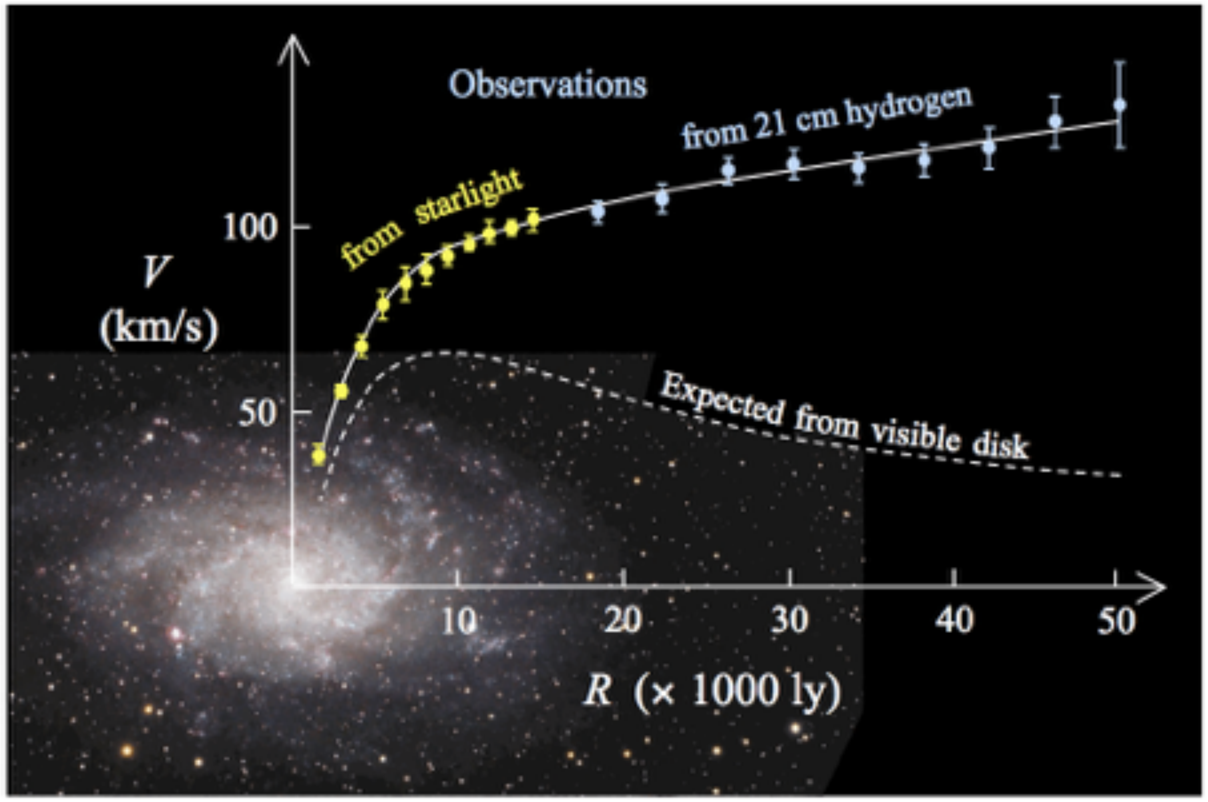
A Broadband Search for Axion Dark Matter



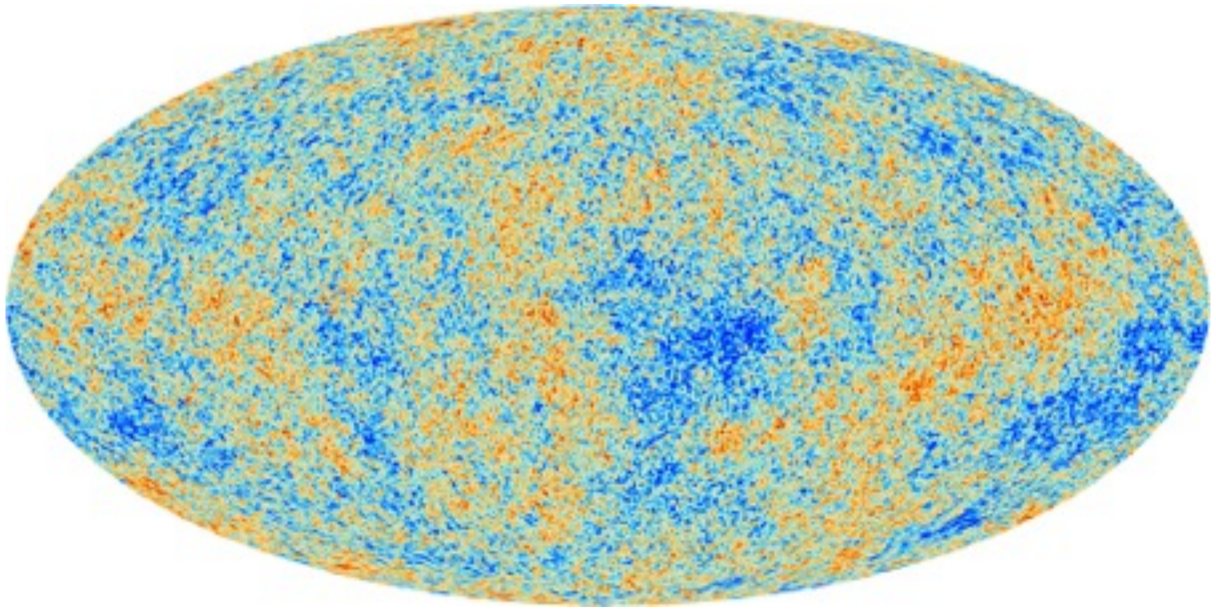
Jonathan Ouellet
Massachusetts Institute of Technology

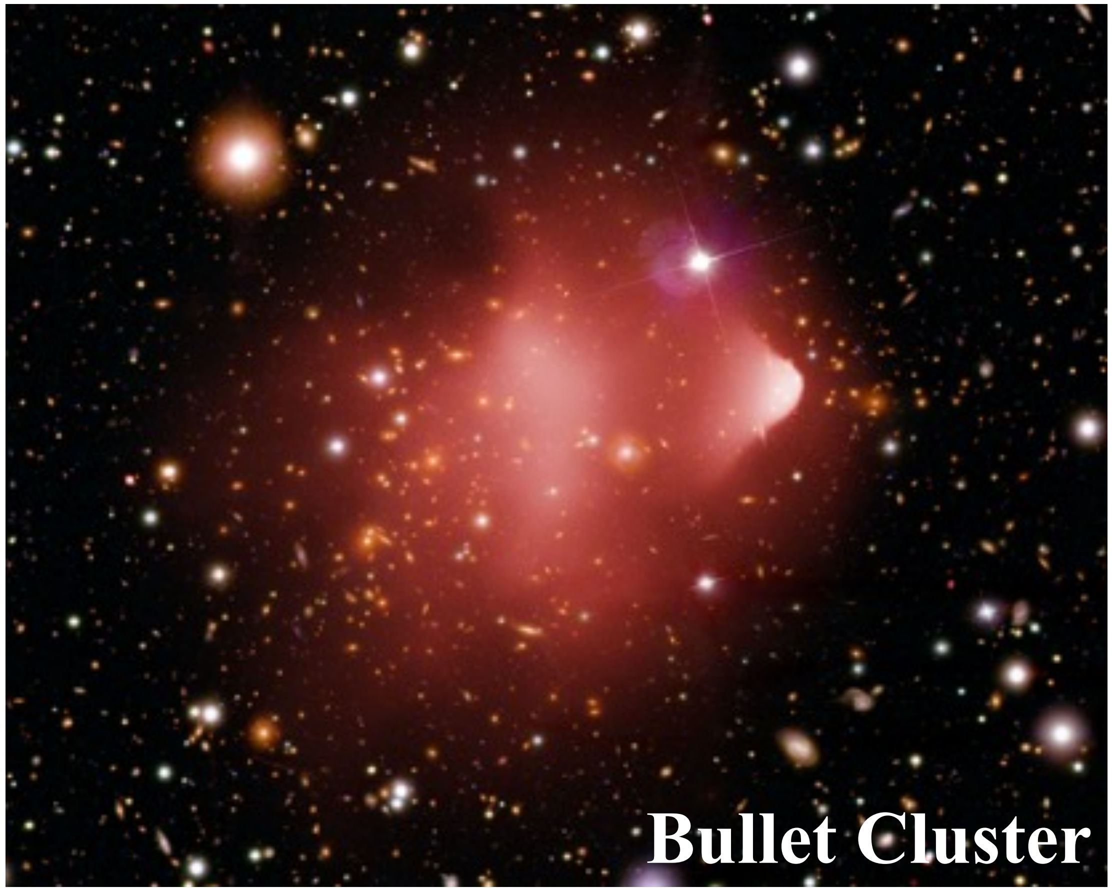
March 23, 2017

We can see there's something we can't see!



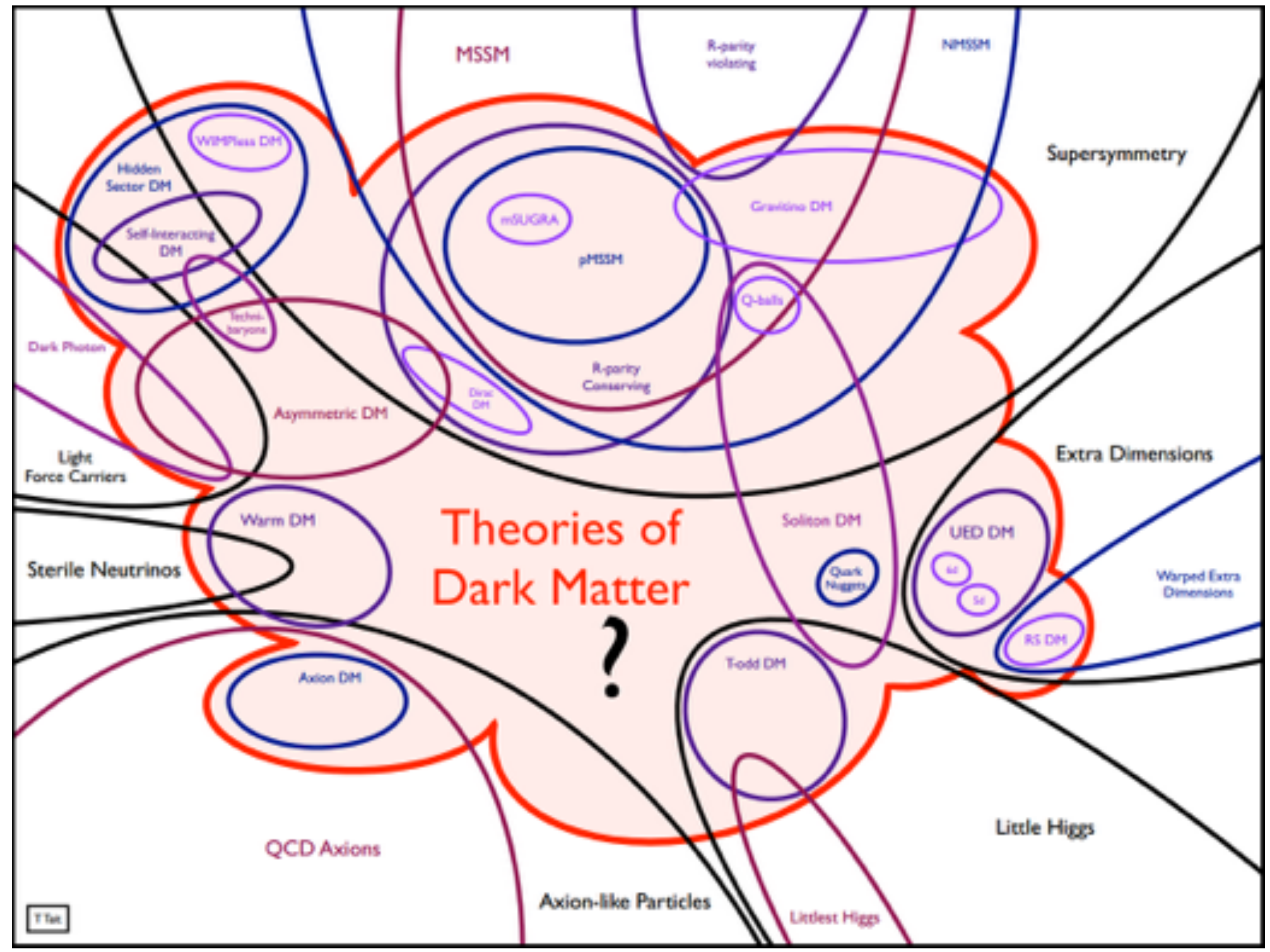
- Galaxies are spinning too fast, but not flying apart!
- There's a footprint in the CMB!
- Galaxy mergers



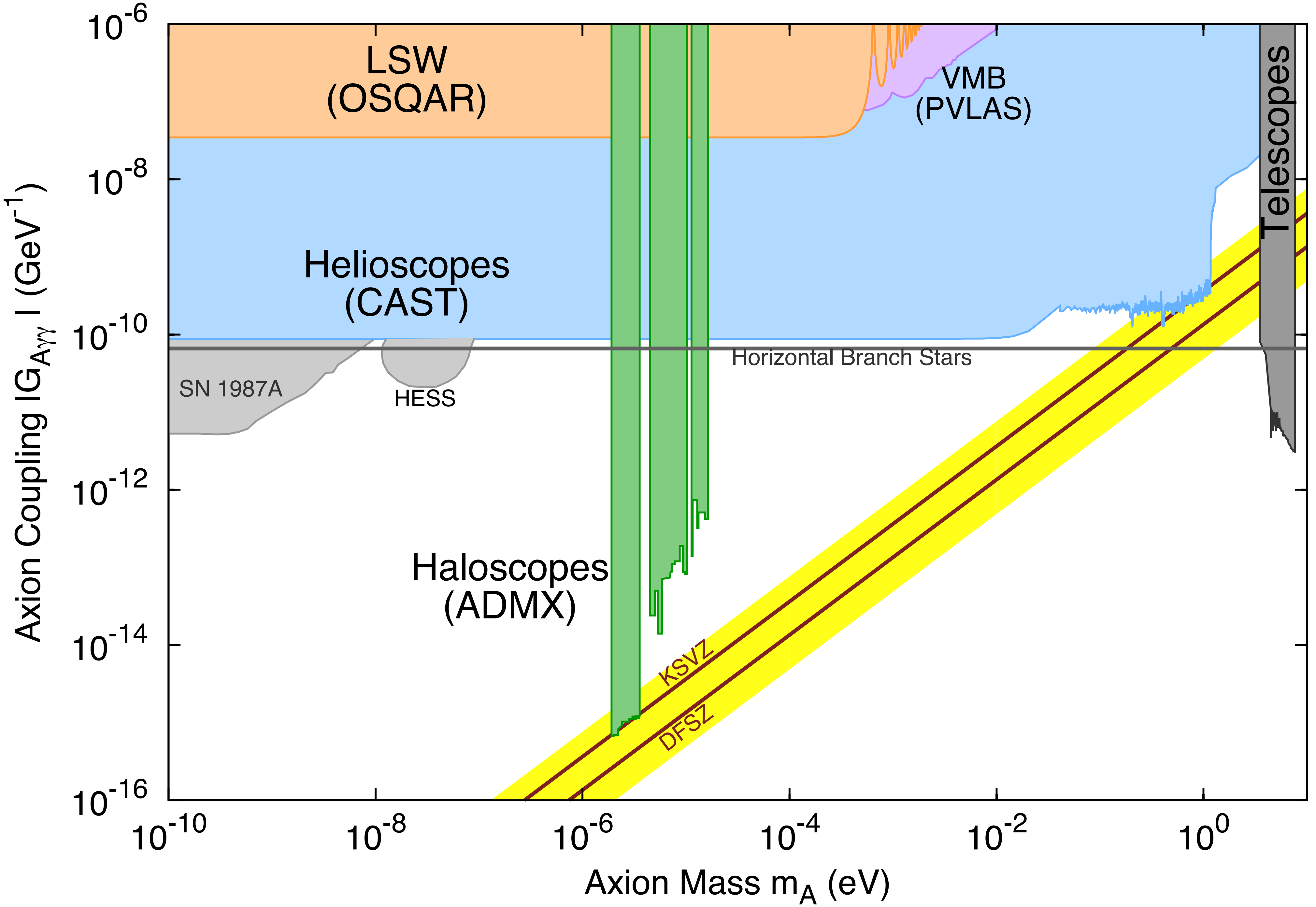


So, what is Dark Matter?

- **We know what it's not:**
  - It is not normal matter
- **But we have no evidence about what it could be**
  - ~50 orders of magnitude in viable mass range
  - Little restriction on how it interacts (just feebly and gravitationally)
- **The best motivated theories simultaneously solve two problems:**
  - DM + Supersymmetry (WIMPs)
  - DM + BAU (~GeV Scale WIMPs)
  - DM + Strong CP problem (Axions)



Axion and ALP Parameter Landscape



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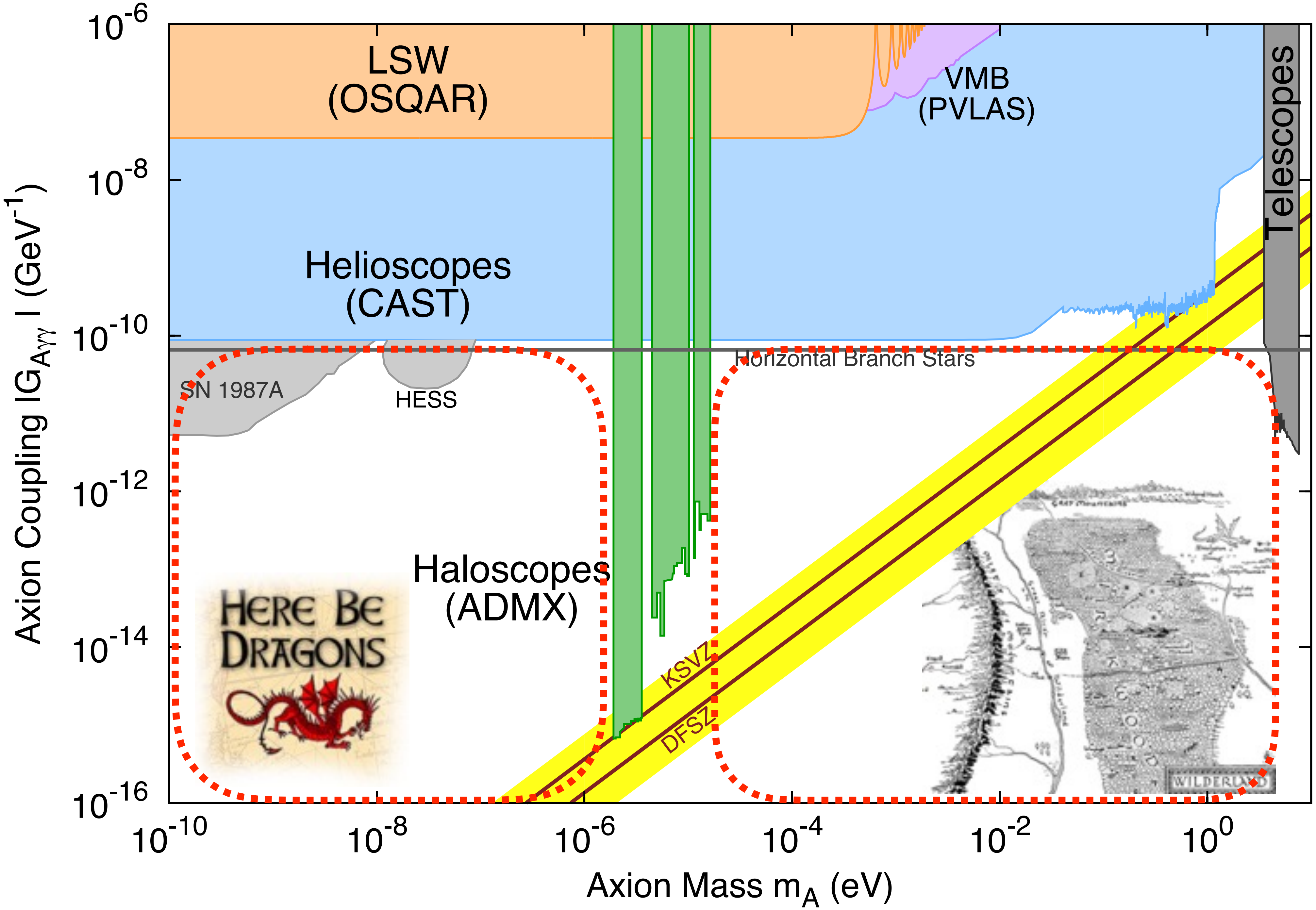
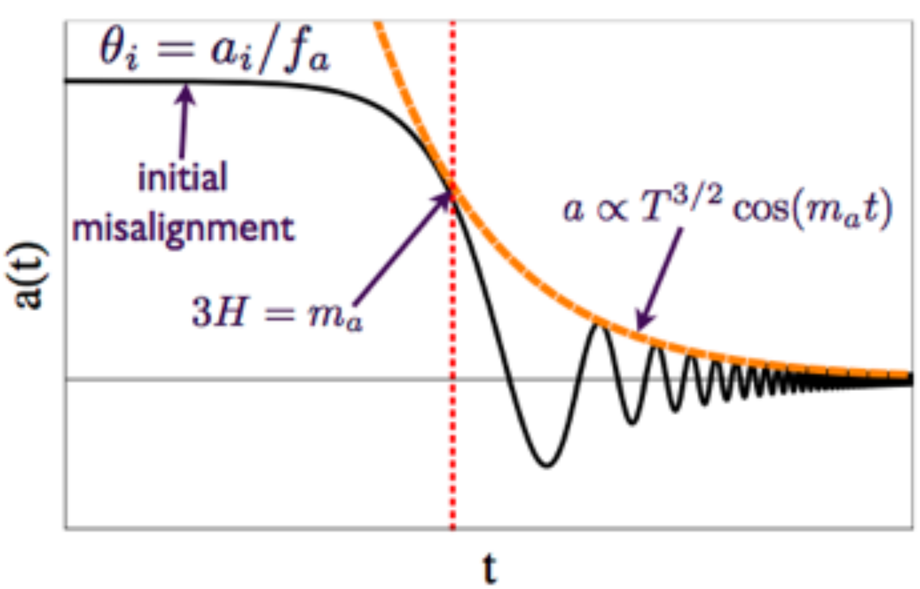
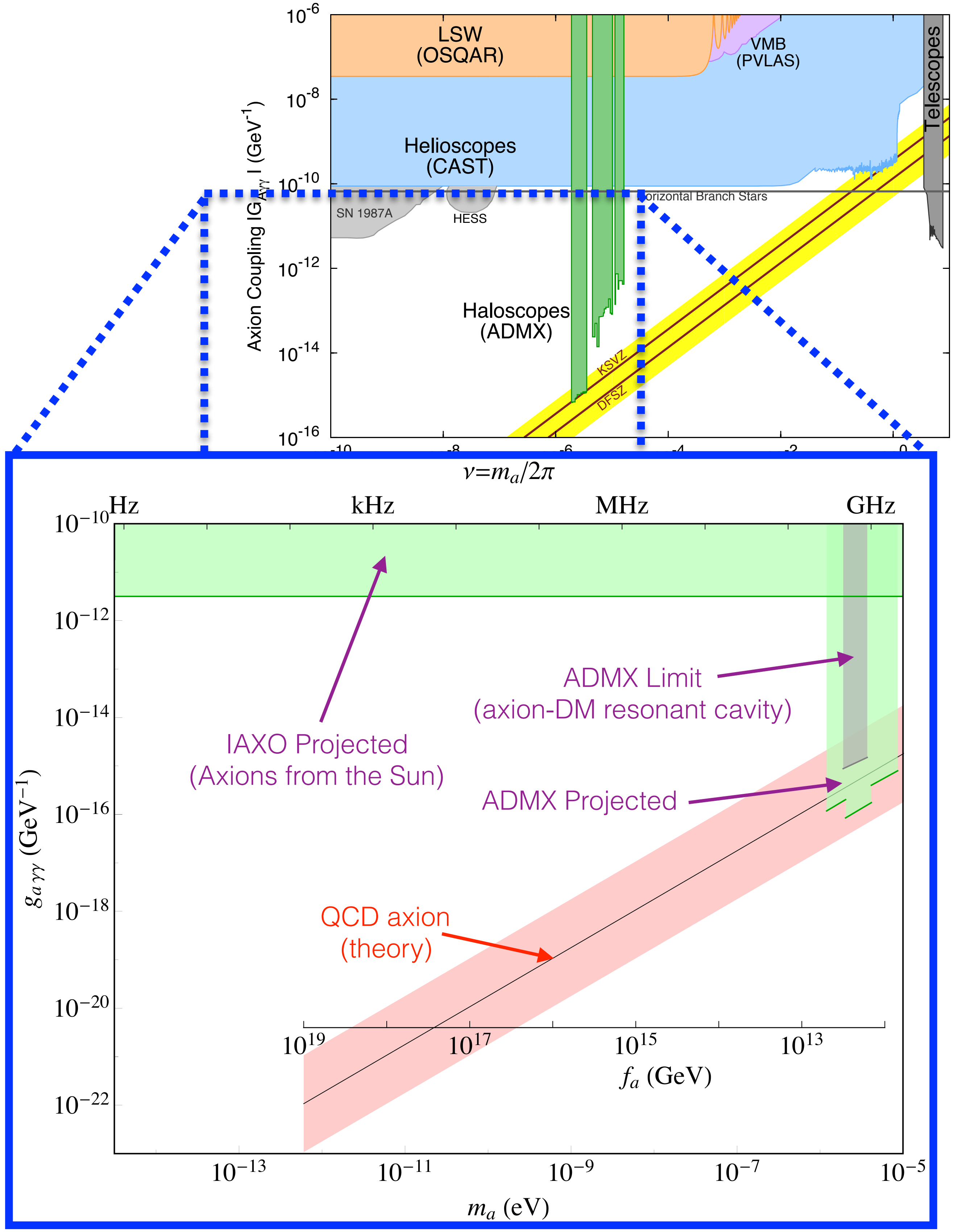


Axion and ALP Parameter Landscape

- Low mass ($m_a < 10^{-3}$ eV) Axion DM created through the realignment mechanism
- This parameter space was initially discounted on theoretical grounds
- Models require a pre-inflationary PQ transition, combined with a O(1%) tuning on the initial alignment angle.





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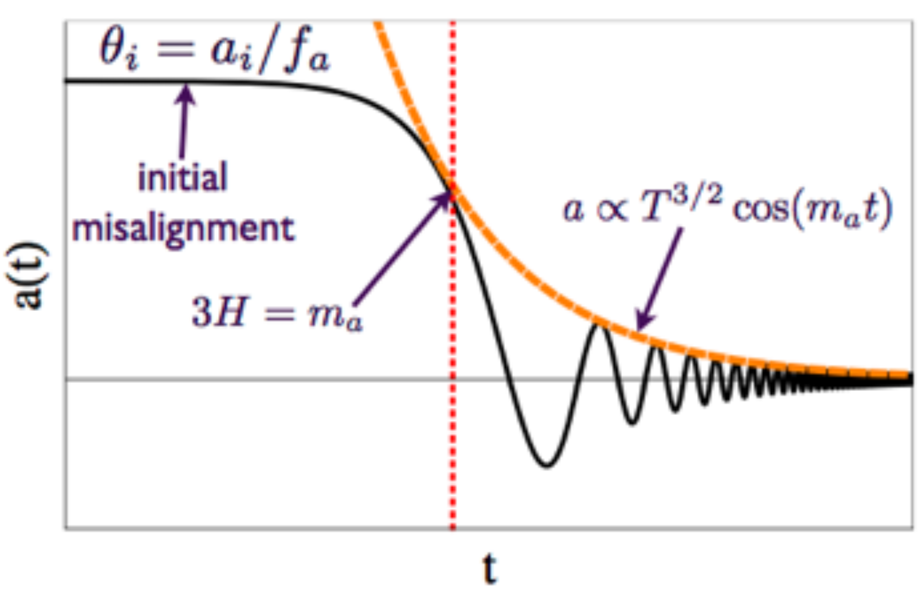

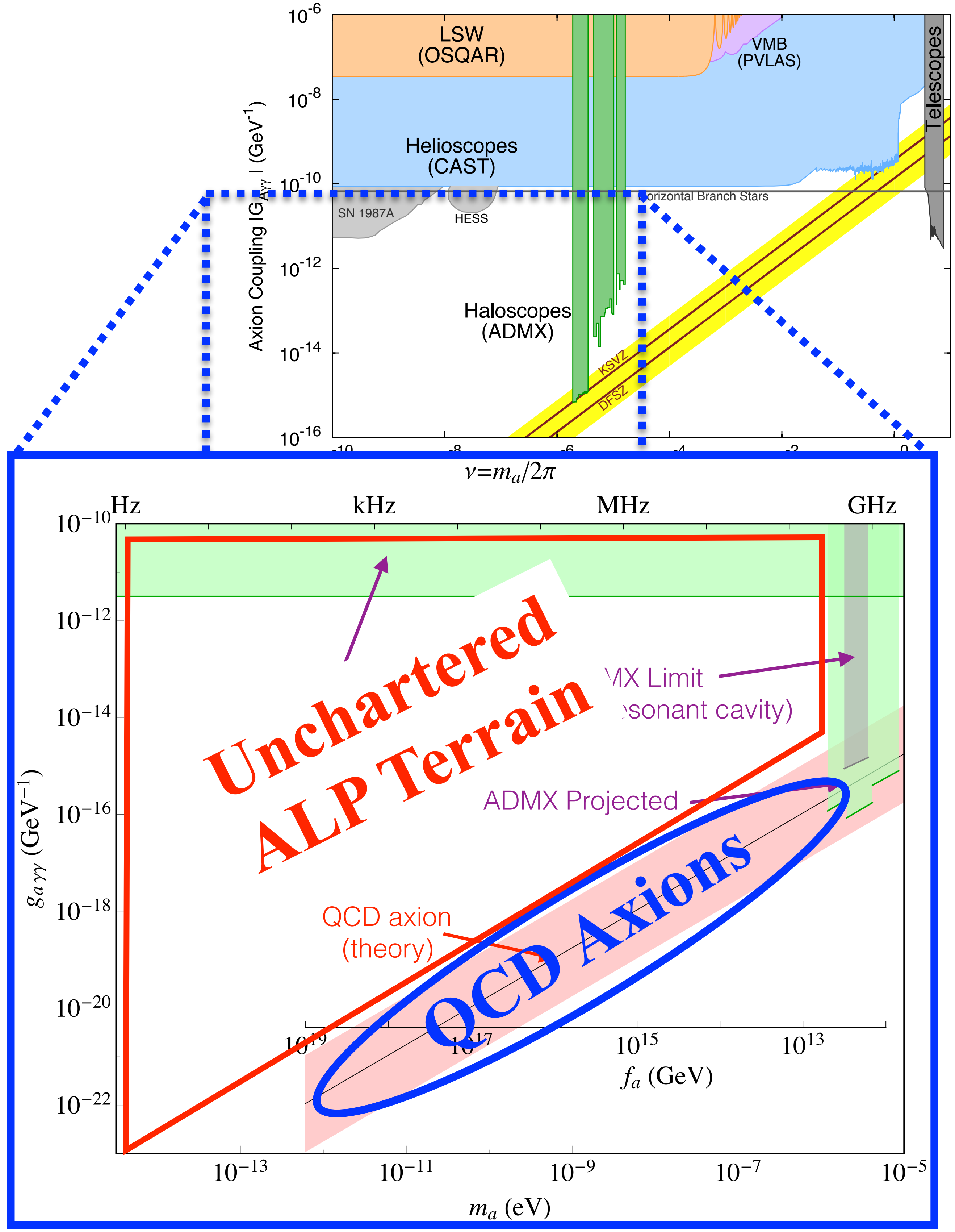

Axion Modifications to EM Lagrangian

New terms in the Lagrangian:

$$\mathcal{L}_{\text{aEM}} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Leads to modifications to Maxwell's Equations:

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

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0 0

λ≫Detector Scale

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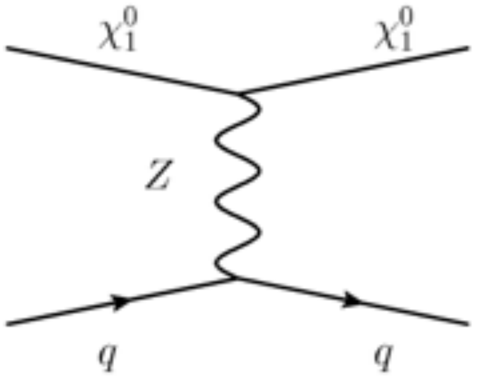
In the magneto-quasistatic limit, this behaves like an effective current parallel to the magnetic field

$$\nabla \times \mathbf{B} = g_{a\gamma\gamma} \mathbf{B} \frac{\partial a}{\partial t} \quad \Rightarrow \quad \mathbf{J}_{\mathrm{eff}} \equiv g_{a\gamma\gamma} \mathbf{B} \frac{\partial a}{\partial t}$$

Axion Modifications to EM

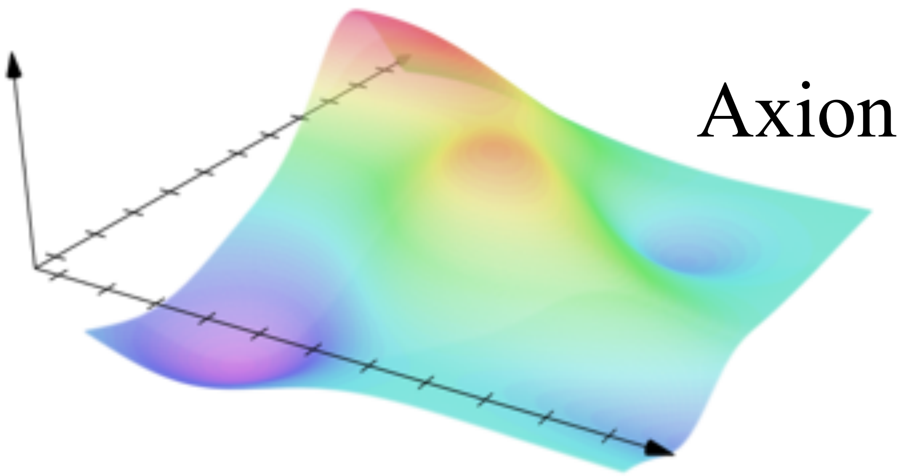
- Rather than being particles (e.g. WIMPs) floating around bumping into detector, they act as a coherent axion field (similar to an E&M field)

WIMP



- If the local DM density (~ 0.3 GeV/cm^3) is dominated by axions, the axion field oscillates in time

$$a(t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \sin(m_a t)$$



Axion

➡ **Constant magnetic field ⇒ effective AC current at a frequency of $f = m_a/2\pi$:**

$$\mathbf{J}_{\mathrm{eff}}(t) = g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{DM}}}\cos(m_a t)\mathbf{B_0}$$

➡ **Signal is very coherent**

$$\frac{\Delta f}{f} \sim v^2 \sim 10^{-6}$$

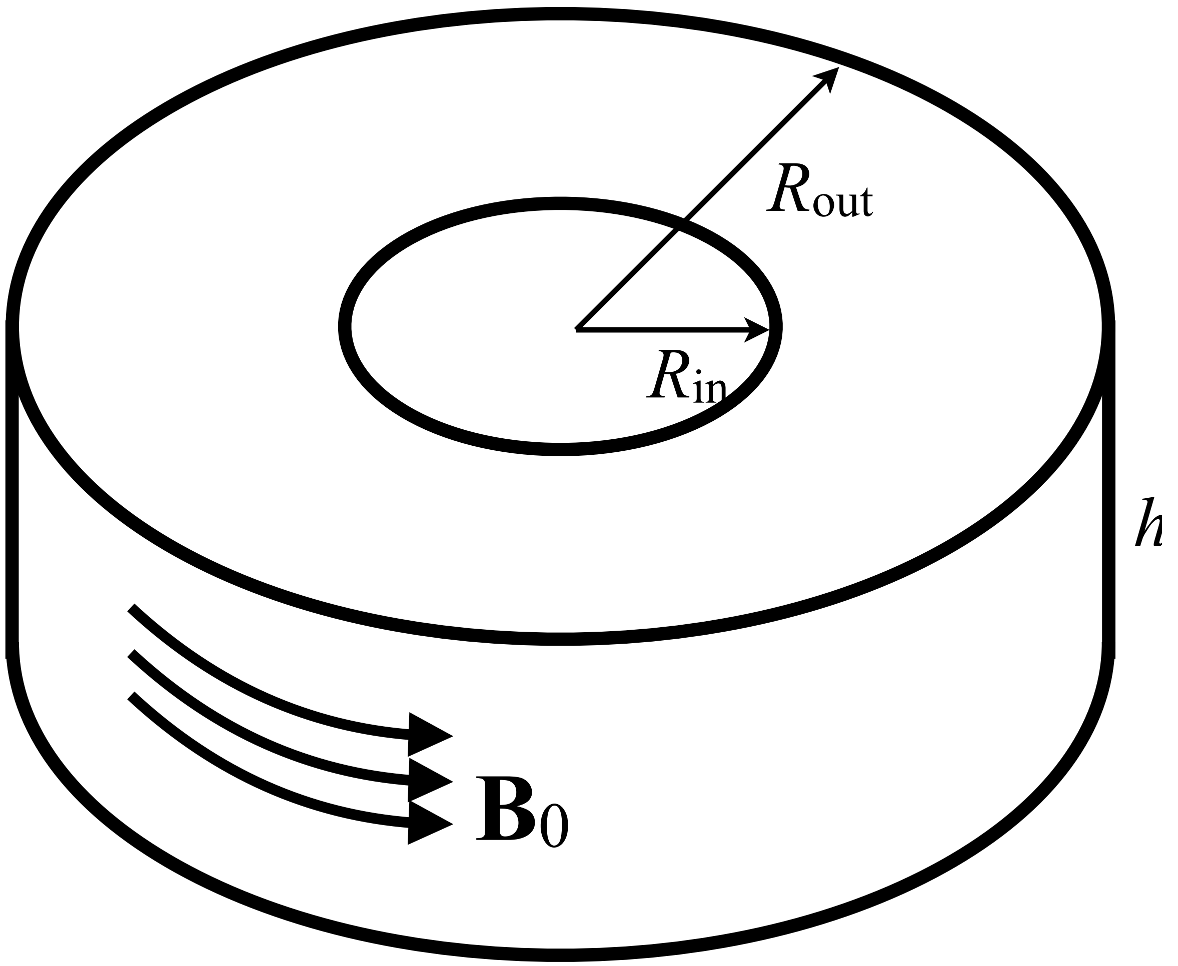
ABRACADABRA Search Principle

A Broadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

ABRACADABRA Search Principle

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

- Start with a toroidal magnet, with a fixed magnetic field, $\mathbf{B}_0$



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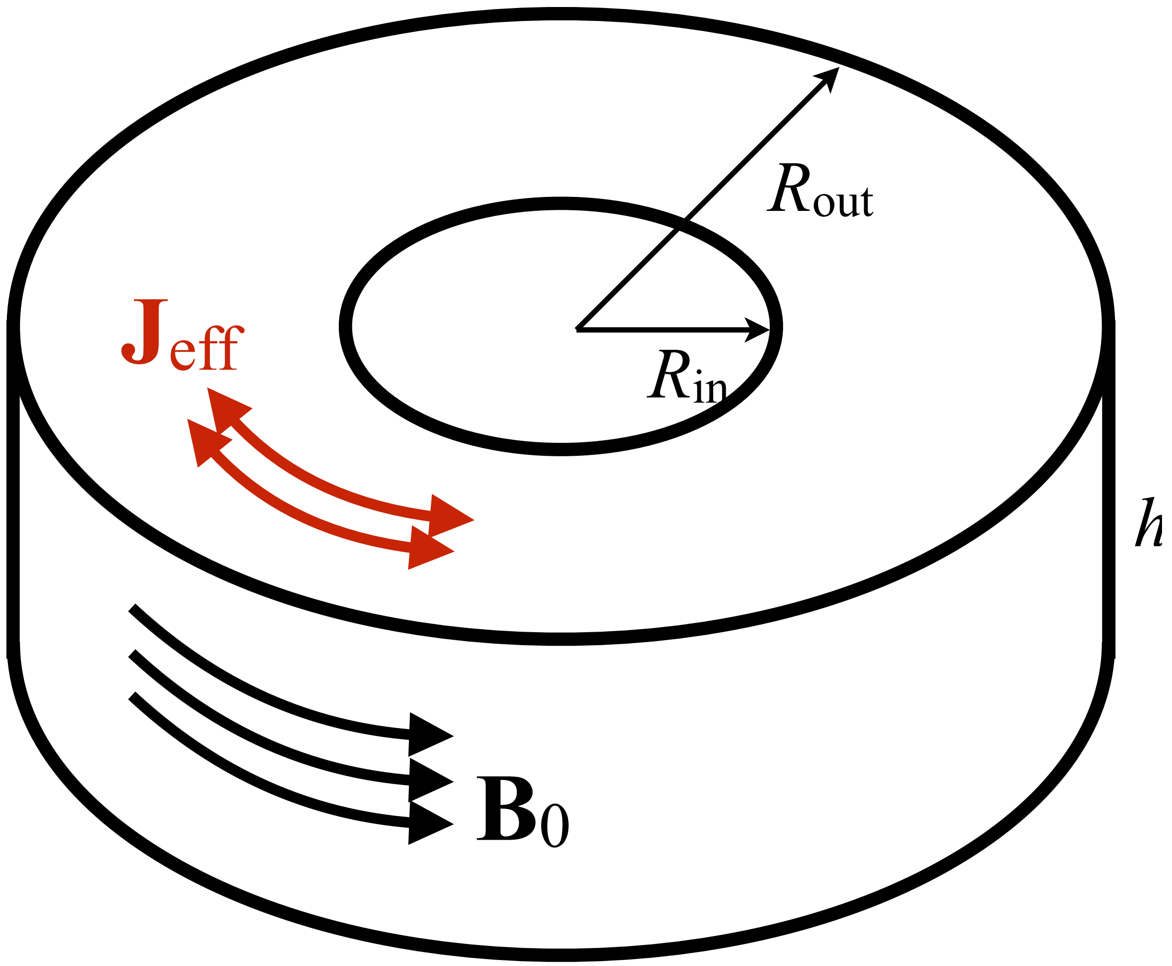

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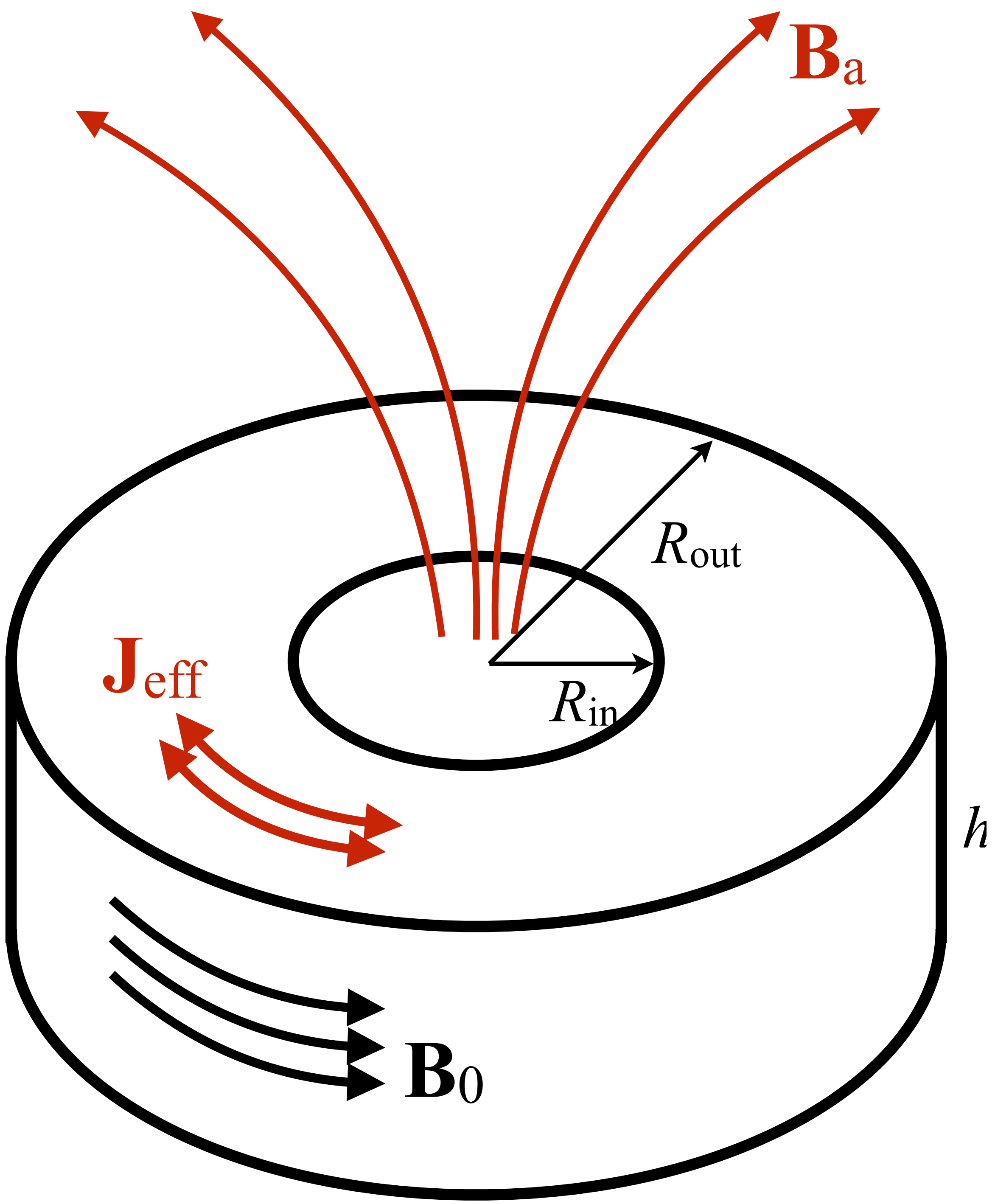
- … this generates an oscillating magnetic field through the center



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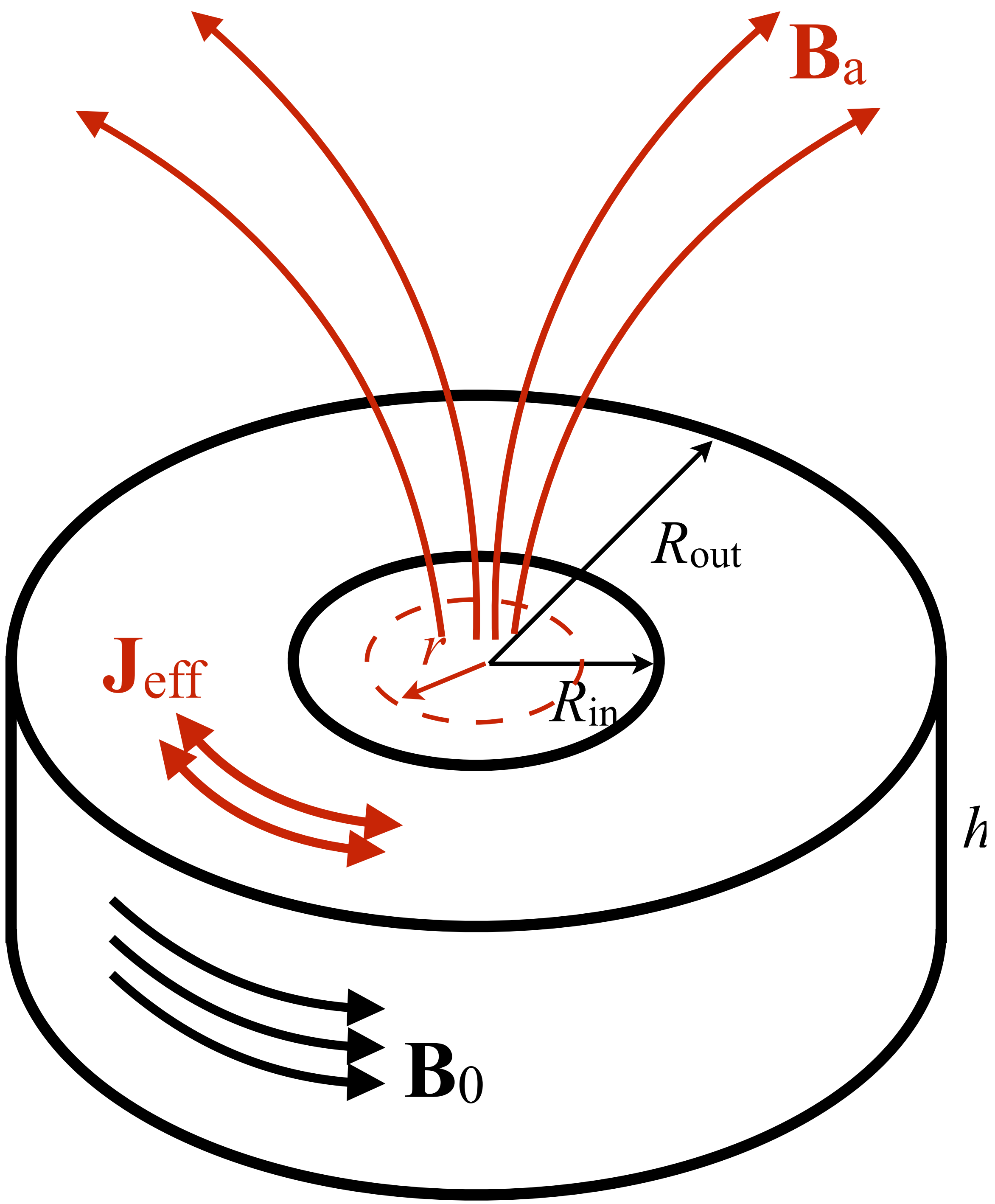
(MQS approx: $2\pi/m_a \gg R_{in}, R_{out}, h$)
- … this generates an oscillating magnetic field through the center
- Insert a pickup loop in the center of the toroid to detect the oscillating magnetic field

$$\Phi_a(t) = g_{a\gamma\gamma} B_{\max} \sqrt{2\rho_{\rm DM}} \cos(m_a t)\, \mathcal{G}_V V$$

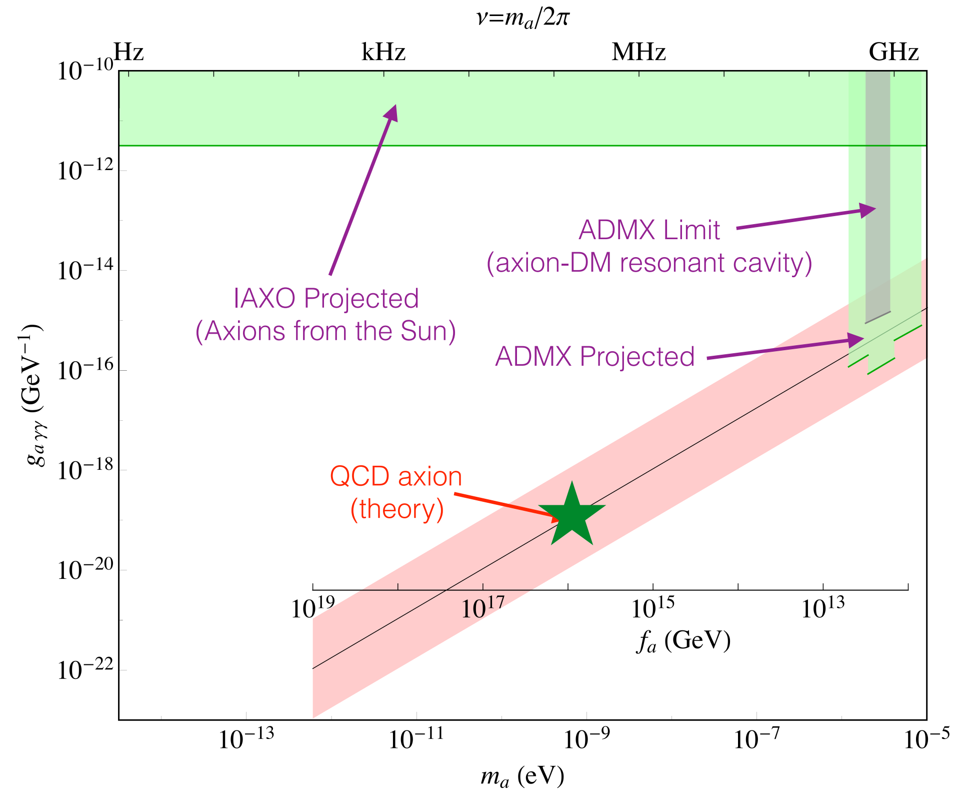
G_V: Geometric factor, depends on magnet geometry

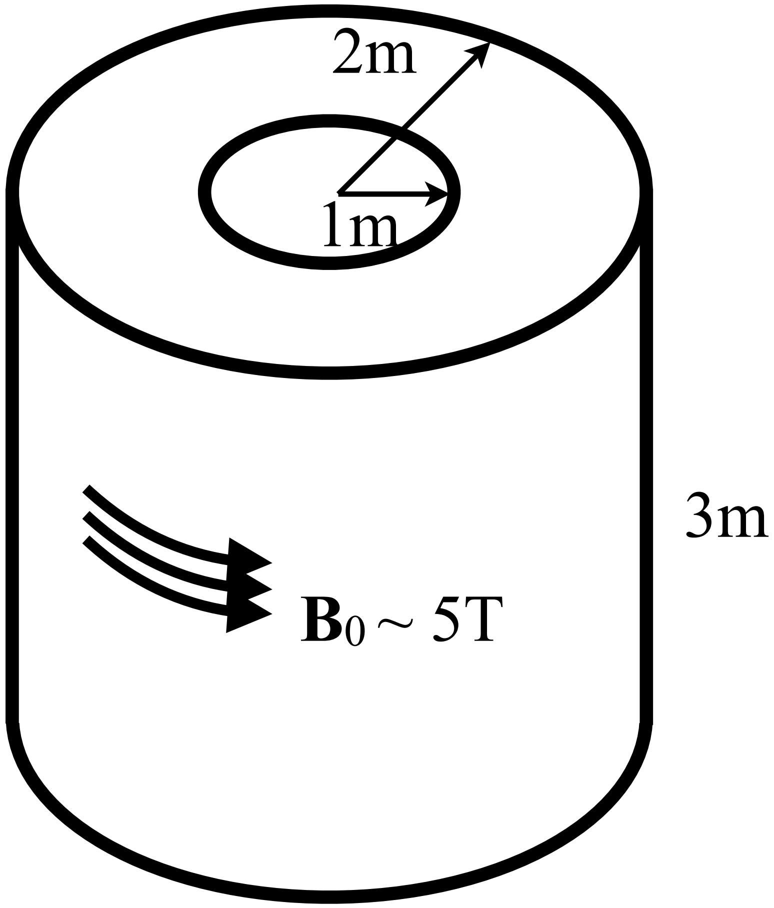


The Challenge

To get an idea of the size of the effect:

- Take as an example, the geometry $r = R_{in} = R_{out}/2 = h/3 = 1$ m, $B_{max} = 5$T
- For $f_a = 10^{16}$ GeV (m_a~1 neV), KSVZ





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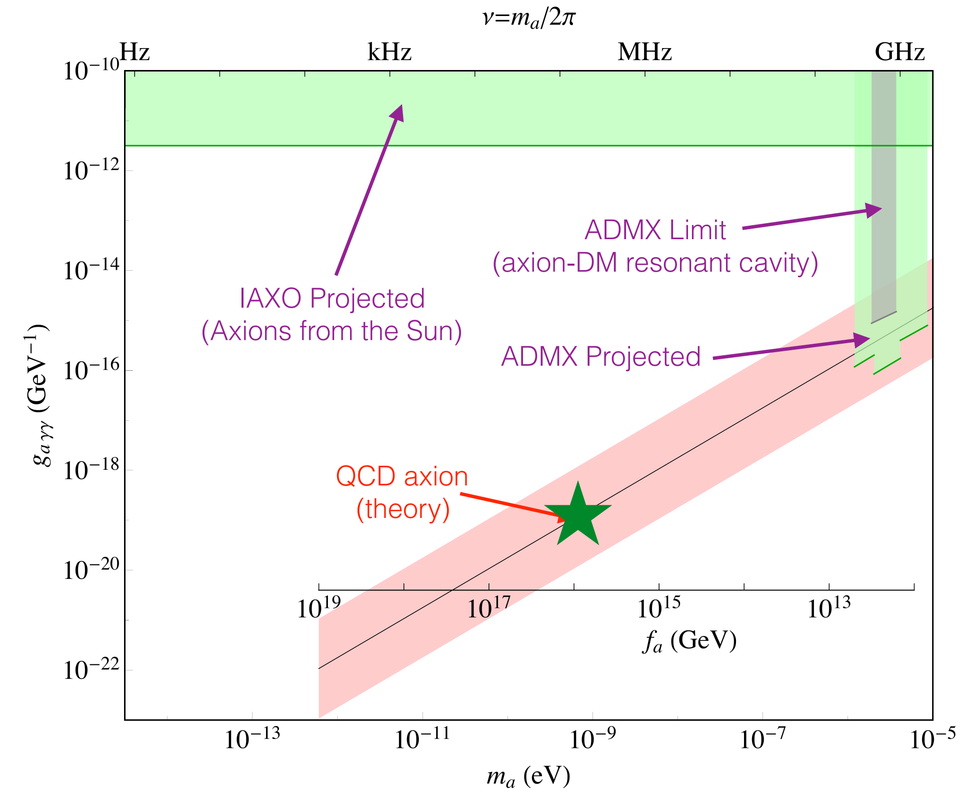
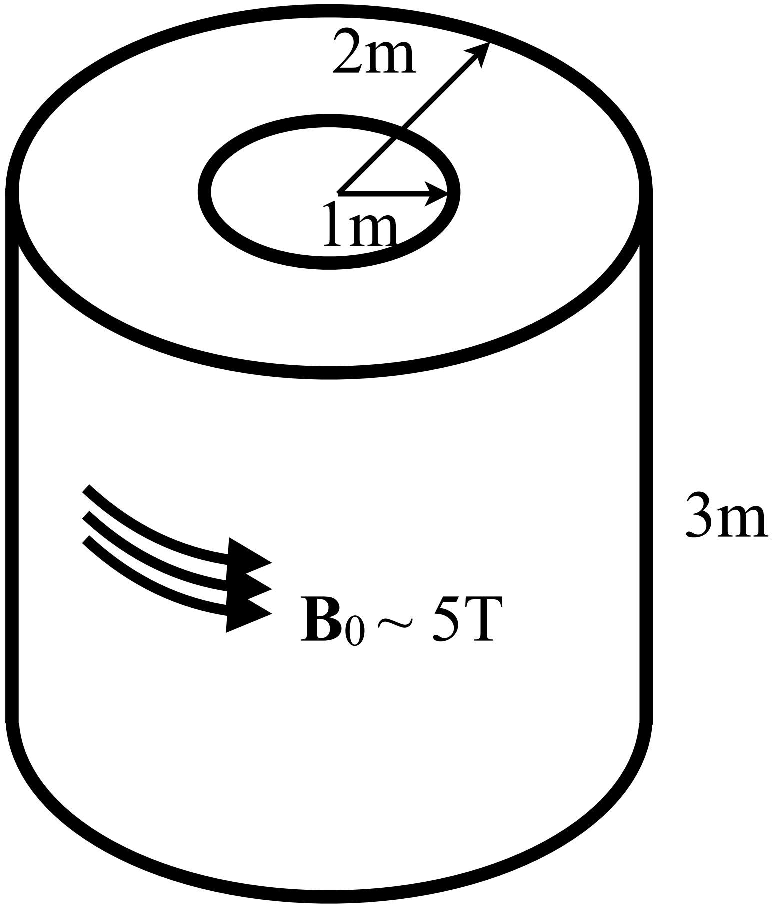
➡ B ~ 5×10^{-22} T @ $f = 240$ kHz, $\Delta f \sim 240$ mHz





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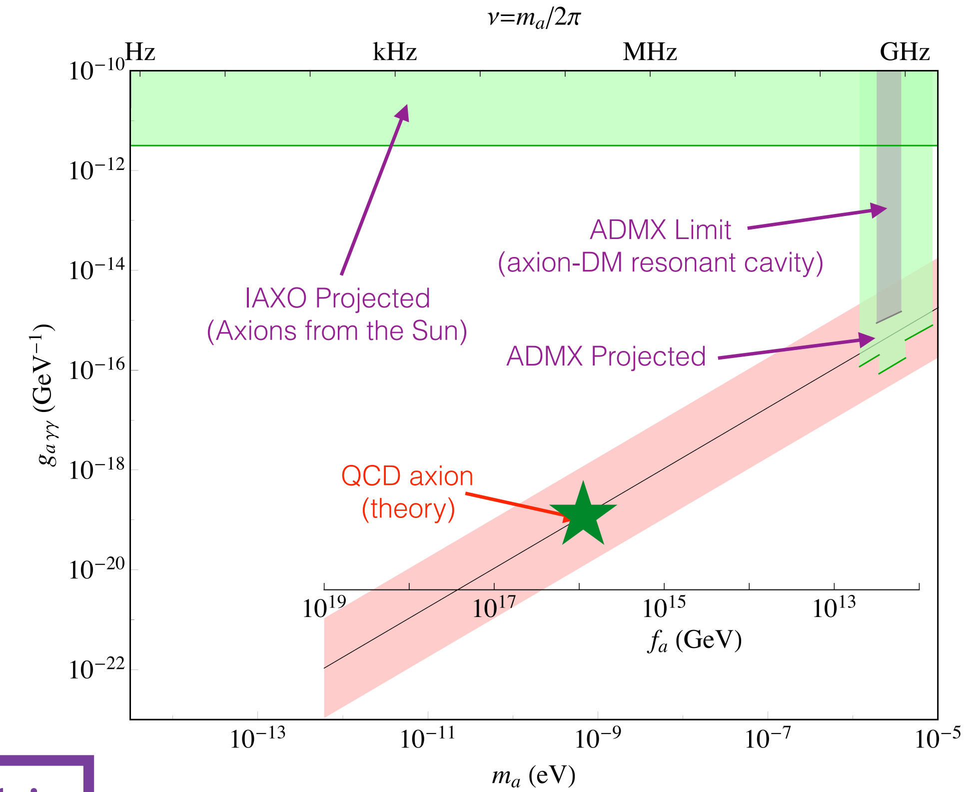
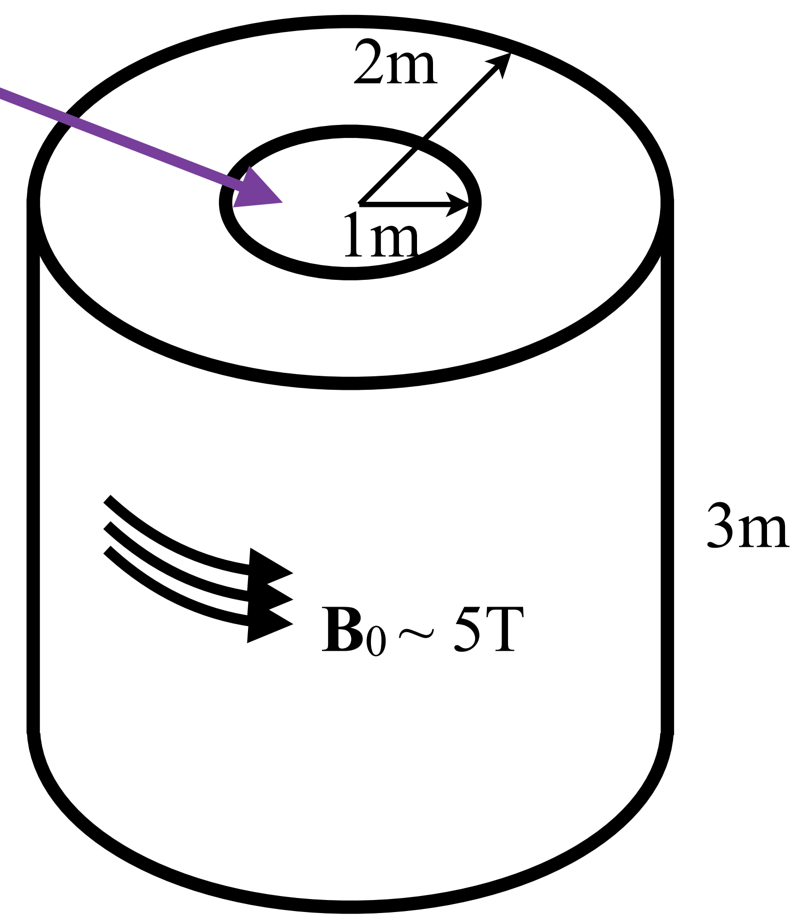
➡ B ~ 5×10^{-22} T @ f = 240 kHz,
Δf ~ 240 mHz



In the absence of a(t), this is a zero field region!



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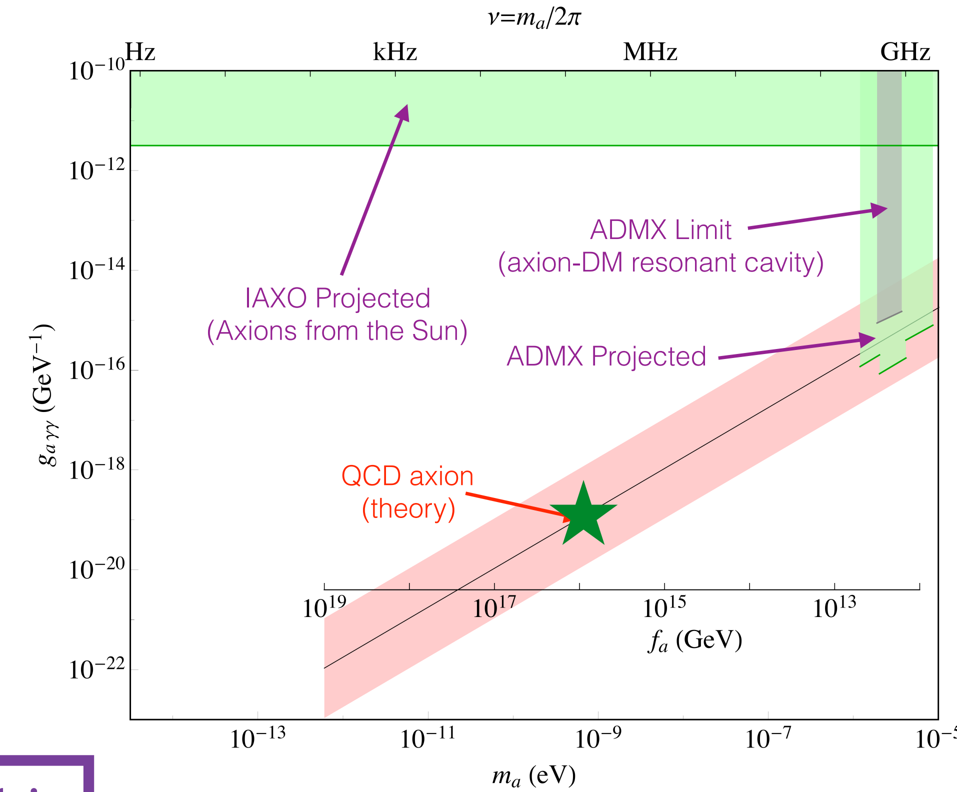

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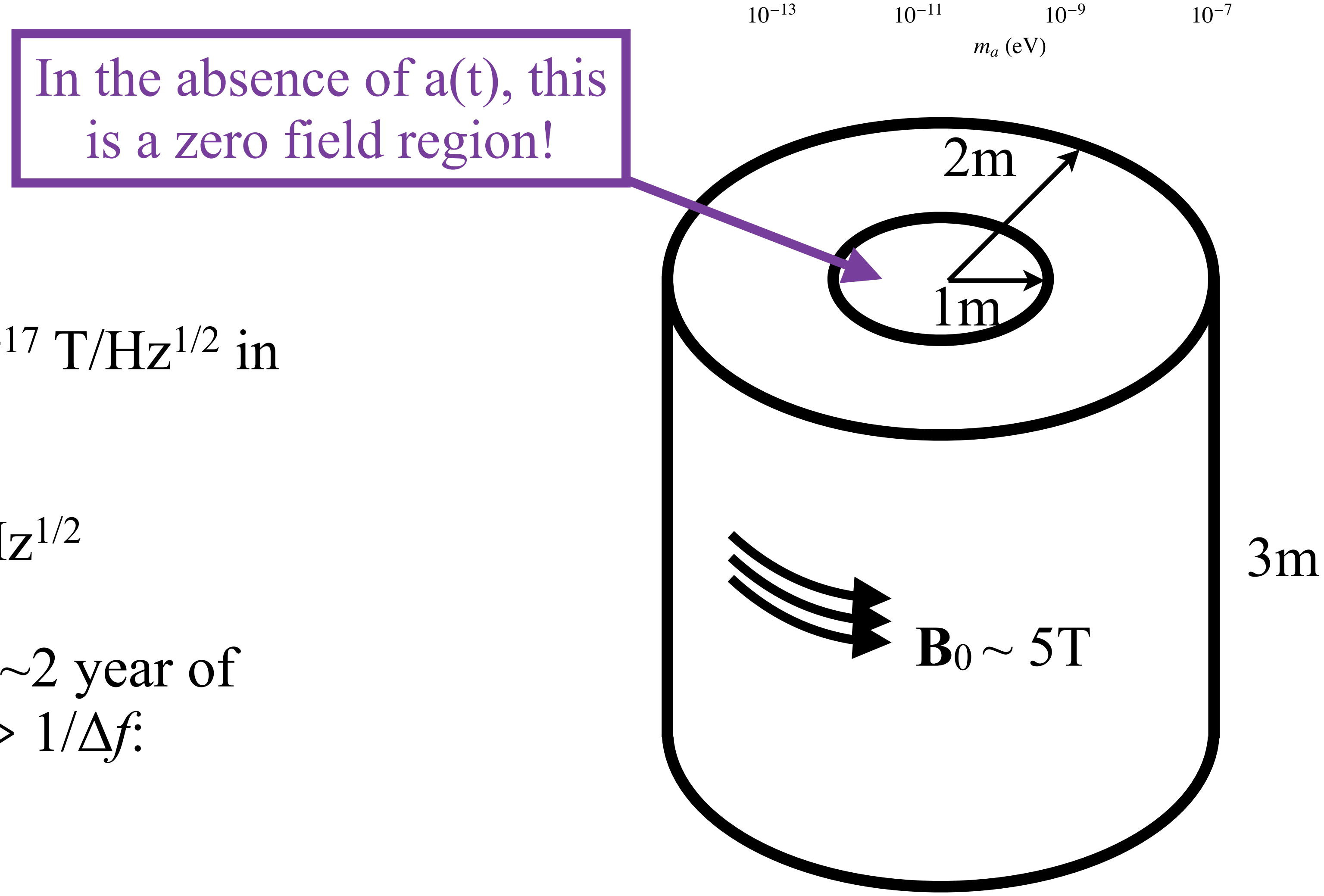


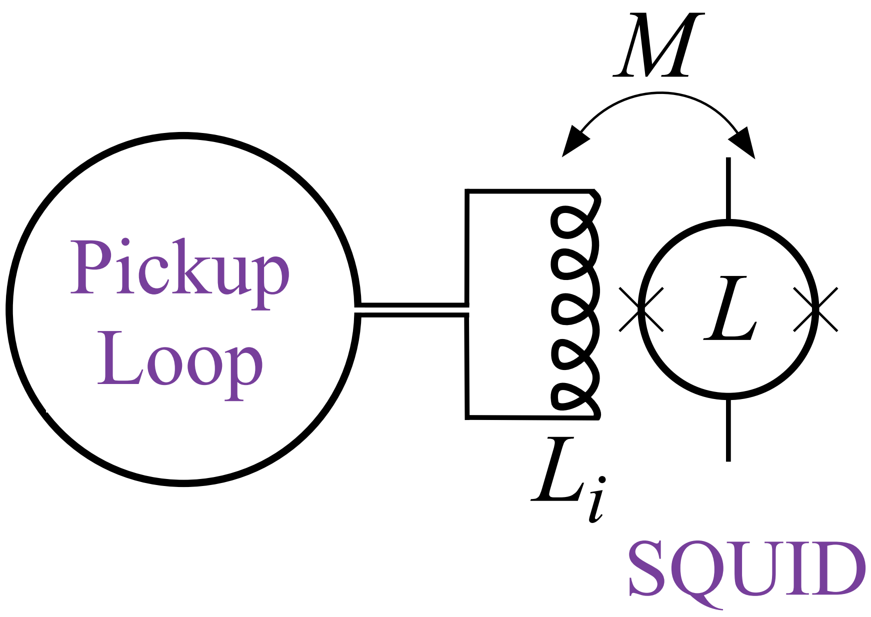
Example from MRI:

- Demonstrated sensitivity $S_B \sim 10^{-17}$ T/Hz$^{1/2}$ in SQUID R ~ 3.3 cm
- Scaling to R = 1m, $S_B \sim 10^{-20}$ T/Hz$^{1/2}$
- Access to QCD axion scale after ~2 year of scan (when integration time ≫ $1/\Delta f$: $g_{a\gamma\gamma} \sim S_B(t/\Delta f)^{1/4}$)

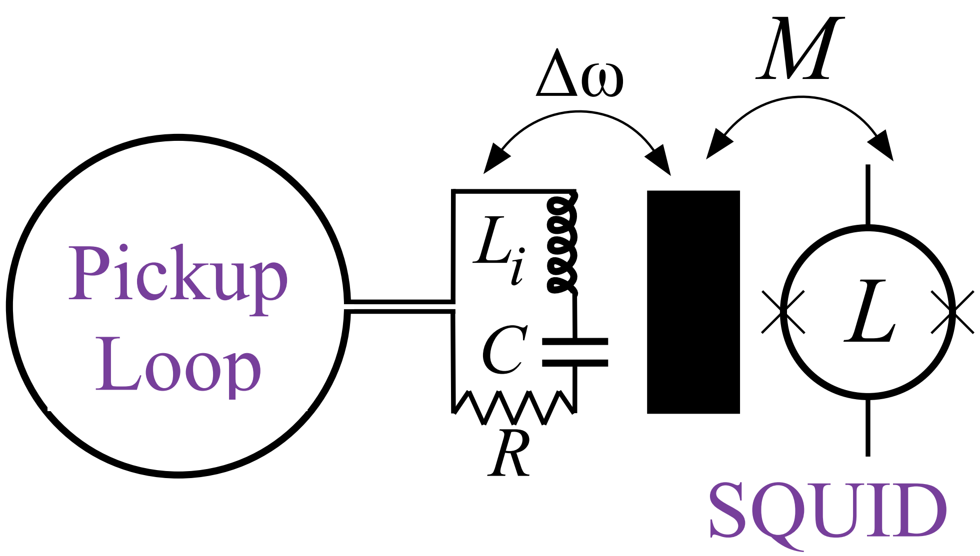
Two Readout Approaches

Exploring two SQUID based readout approaches:

- **A broadband approach**
  - Scan the full frequency range in “one” measurement
  - No resonance amplification



- **A resonance amplification approach**
  - Resonance circuit can enhance signal by $Q_0 \gtrsim 10^6$
  - “Narrow” but tunable frequency line slowly scans through the full frequency range

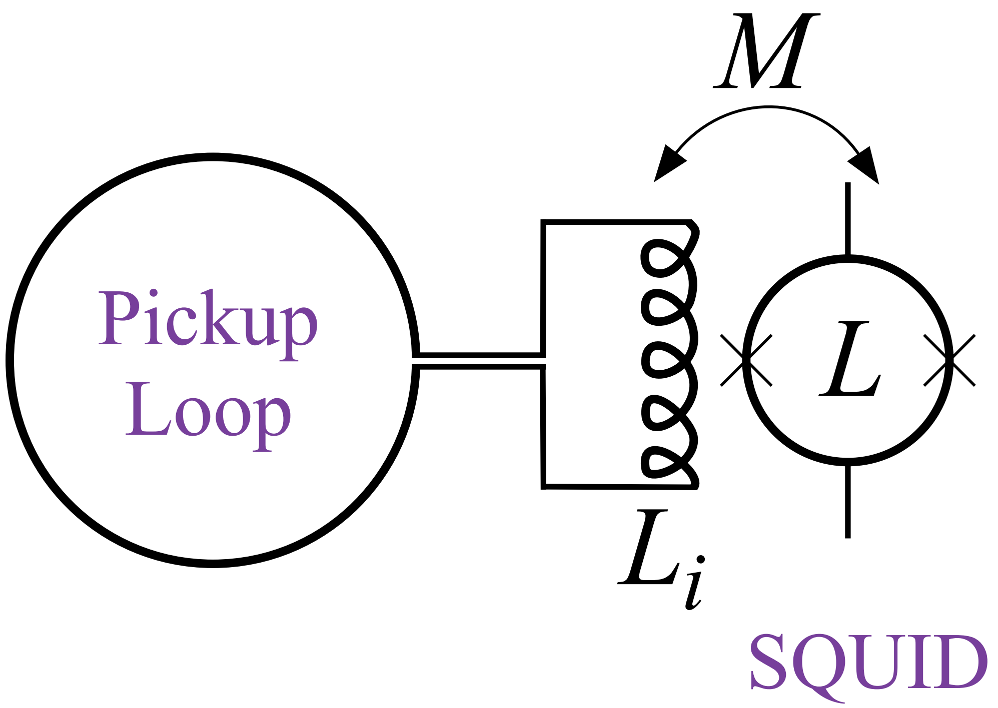


Broadband Axion Search

- SQUID readout systems can measure very small AC currents coming out of the pickup loop
- Over ~5 — 50 Hz, the primary noise source is flux noise from the SQUID
  - Typical noise level is

$$S_{\Phi,0}^{1/2} \sim 10^{-6}\Phi_0/\sqrt{\mathrm{Hz}}$$

- Below ~5 — 50 Hz, $1/f$ noise takes over and becomes dominant
- Cannot resolve thermal noise floor, so somewhat insensitive to temperature
- Broadband only sensitivity:

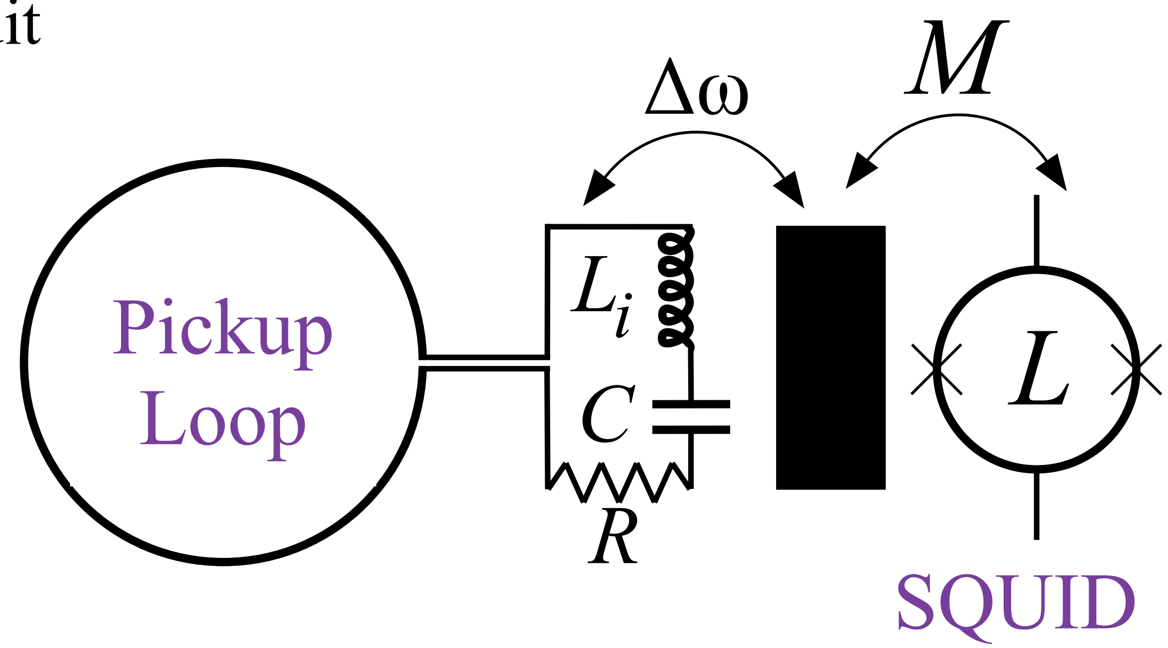


$$t \gg \frac{1}{\Delta\nu}$$

$$g_{a\gamma\gamma} \propto \left(\frac{m_a}{t}\right)^{\frac{1}{4}} \frac{1}{B_{\mathrm{max}}} \frac{1}{\mathcal{G}_V V} \frac{1}{\sqrt{\rho_{\mathrm{DM}}}} S_{\Phi,0}^{1/2}$$

A Resonance Enhanced Search

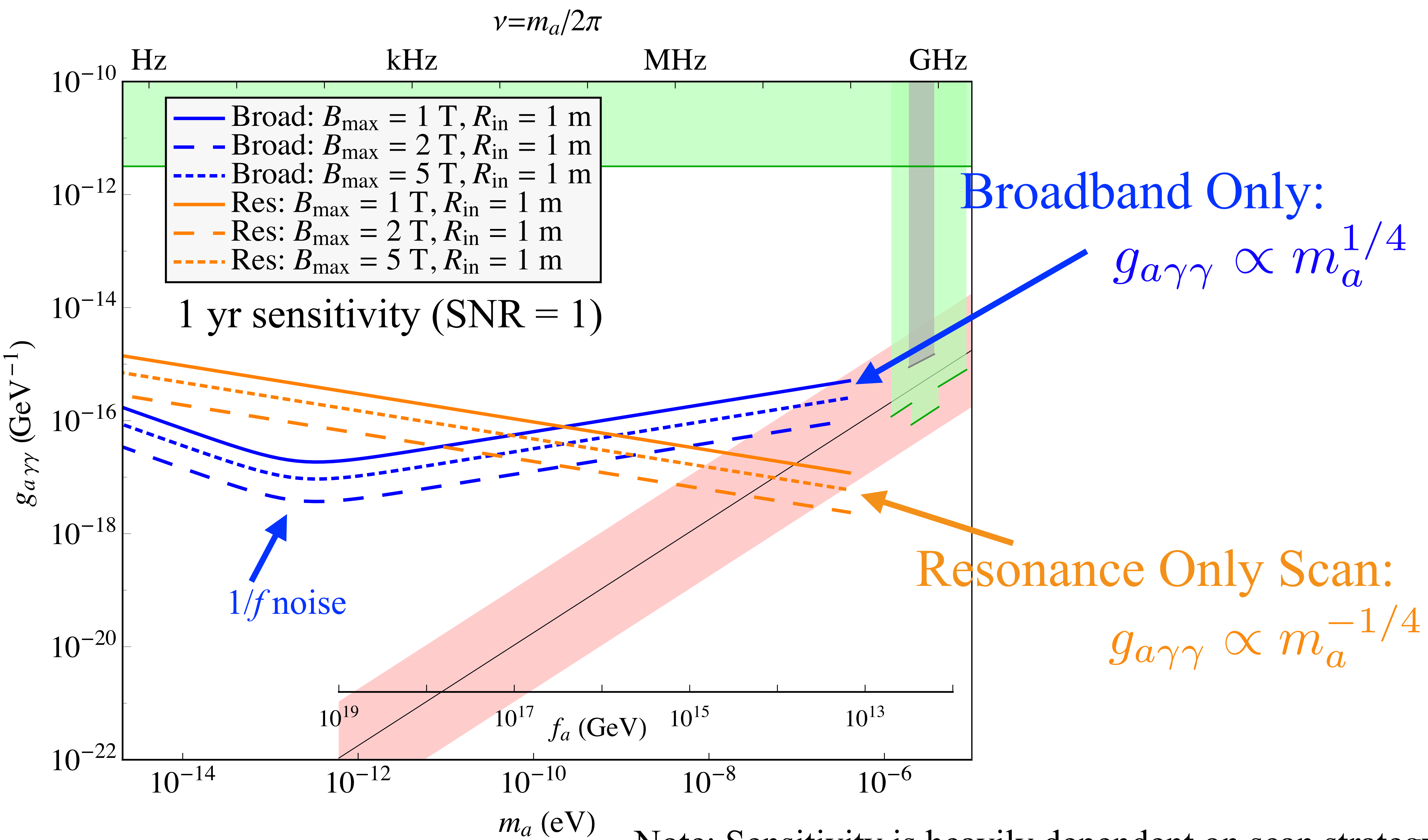
- We can enhance the signal in a narrow frequency window by adding a capacitor to create a RLC circuit
- This can amplify the signal by Q_0, in a narrow bandwidth, $\Delta\omega = \omega/Q_0$
  - Resonators with $Q_0 \sim 10^6$ are achievable
- Dominant noise source becomes dissipation in the oscillator circuit ⇒ temperature dependent
- Benchmark at operating temperature of 100mK
- Naive resonance scan sensitivity:



$$t \gg \frac{1}{\Delta\nu}$$

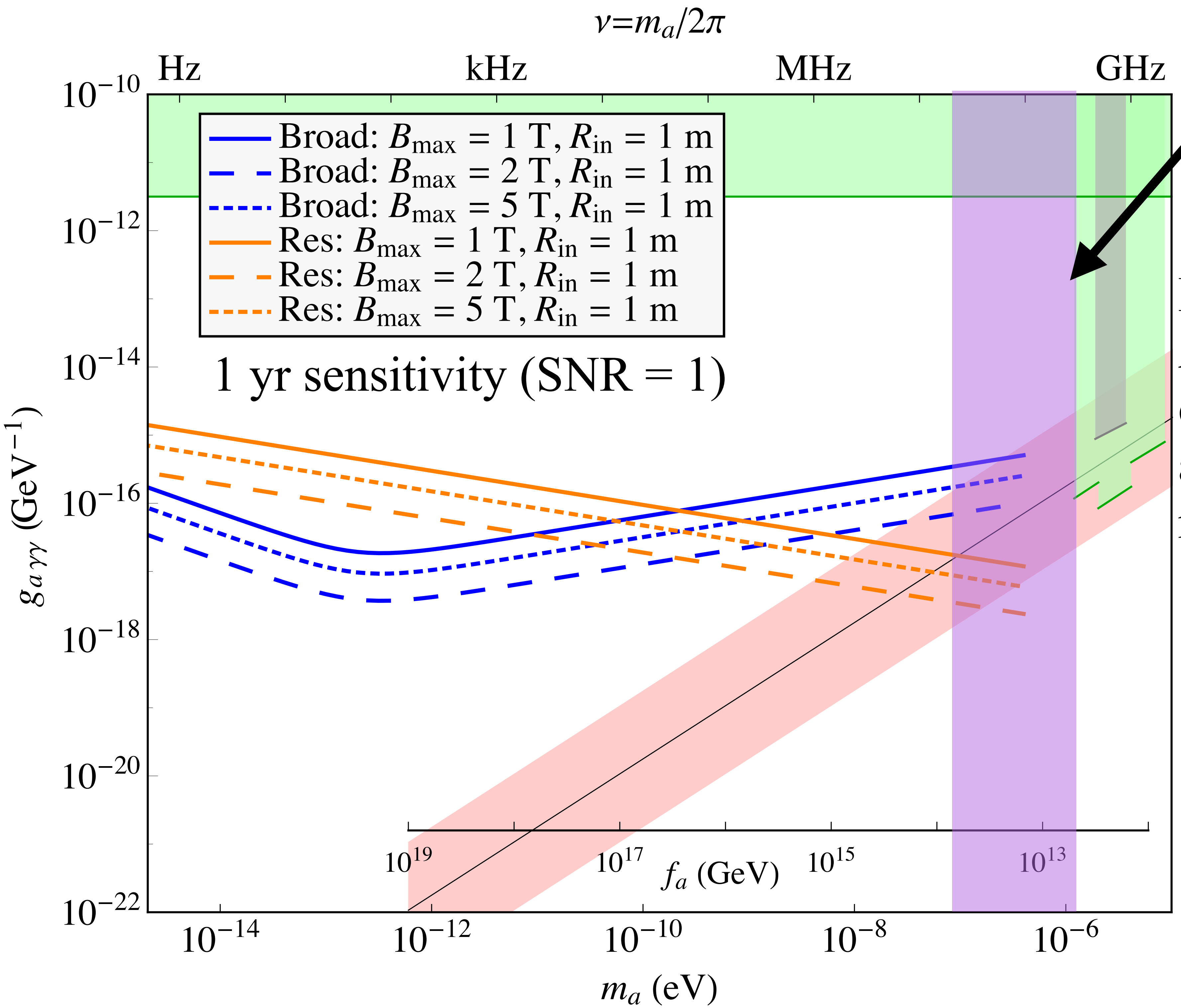
$$g_{a\gamma\gamma} \propto \sqrt{L_T}\left(\frac{1}{m_a t_{\mathrm{scan}}}\right)^{\frac{1}{4}} \frac{1}{B_{\max}} \frac{1}{\mathcal{G}_V V} \sqrt{\frac{1}{\rho_{\mathrm{DM}}} \frac{k_B T}{Q_0}}$$

Broadband Axion Search Sensitivity



Note: Sensitivity is heavily dependent on scan strategy! These curves are not optimal. In discussions with K. Irwin's group about a more optimal scan strategy.

Broadband Axion Search Sensitivity

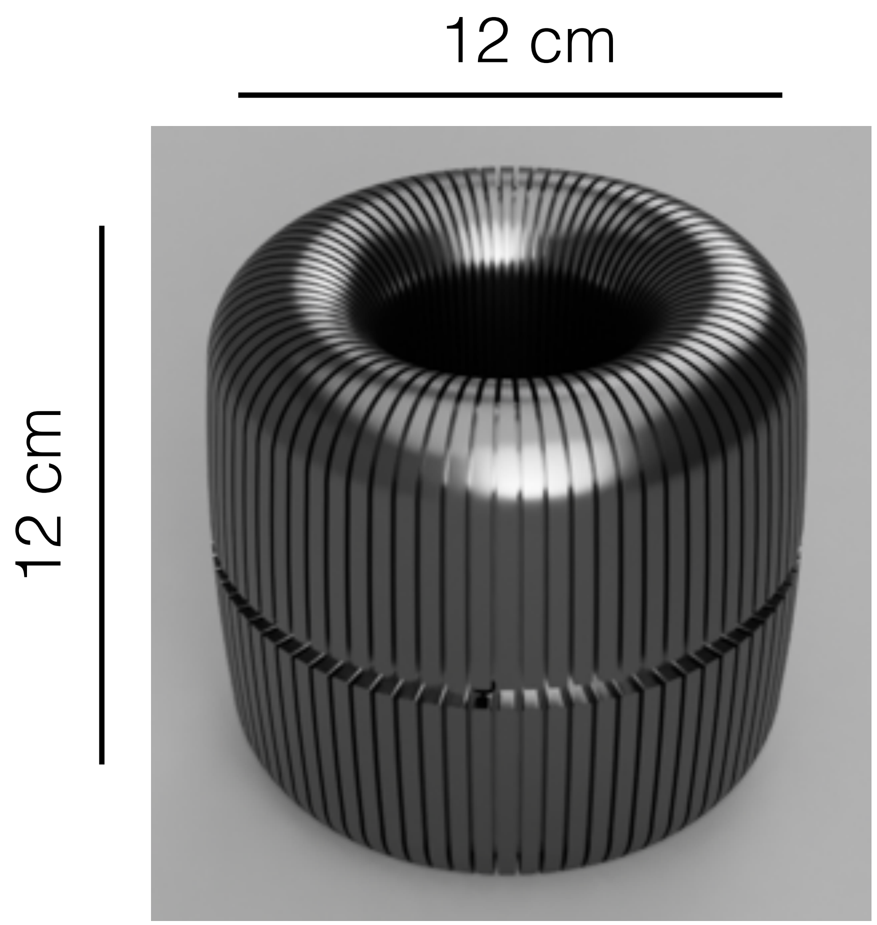


The MQS approximation breaks down ($2\pi/m_a \sim R_{in}$)

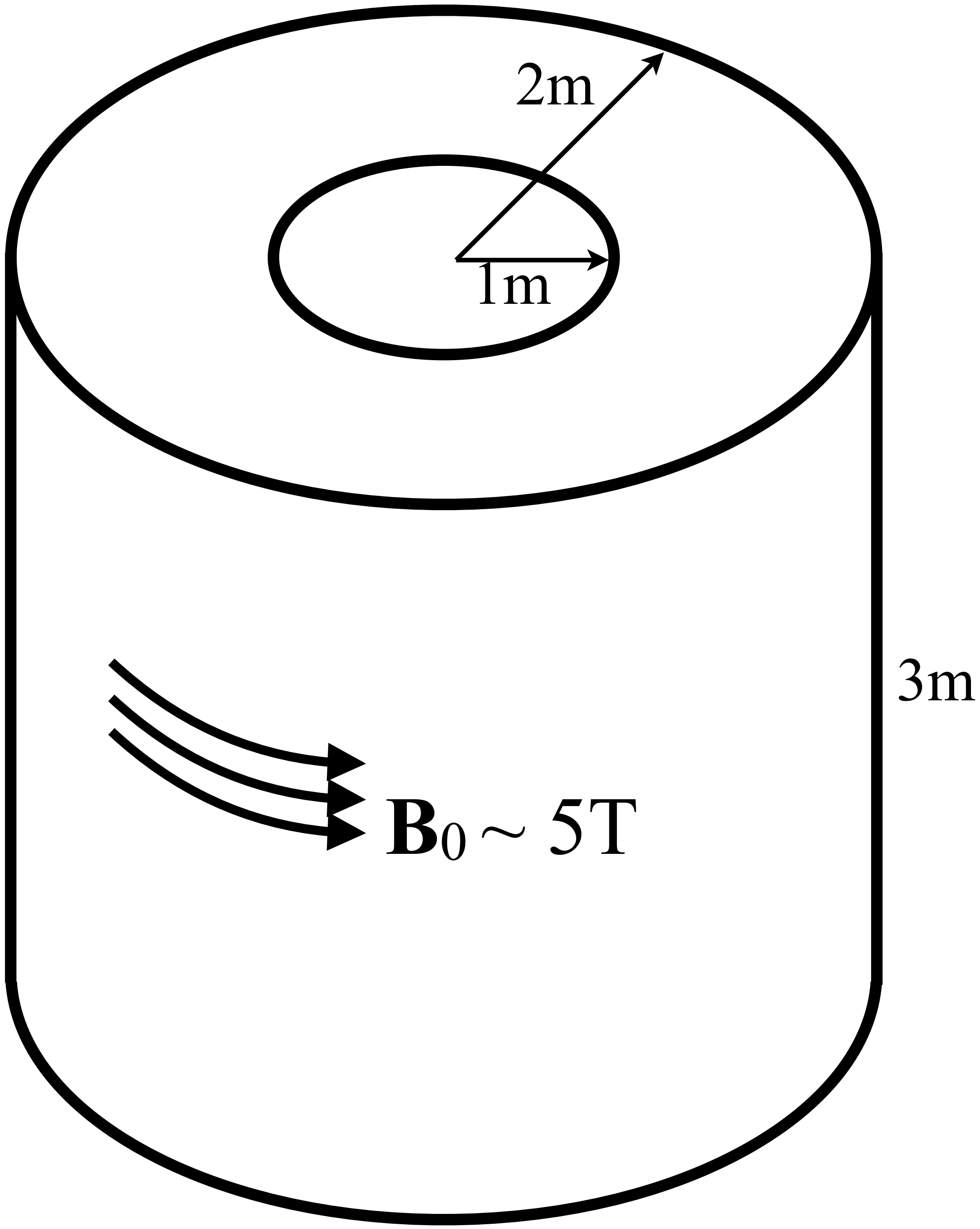
Broadband search and ADMX make complimentary assumptions, and so probe complimentary ranges!

We have some interesting calculations to do to understand what happens in this regime

ABRACADABRA Program



ABRACADABRA 10cm

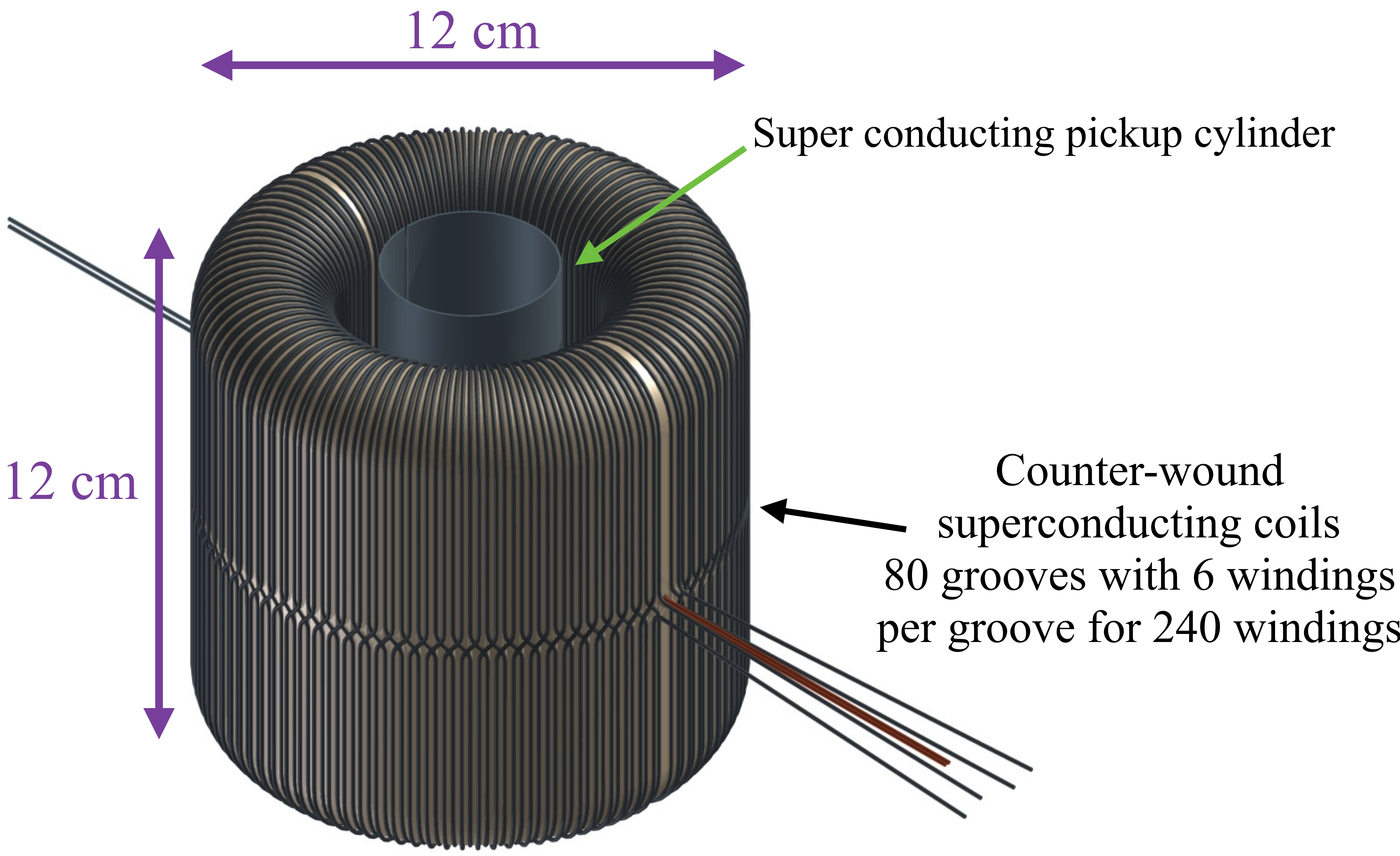


ABRACADABRA

ABRACADABRA-10 cm

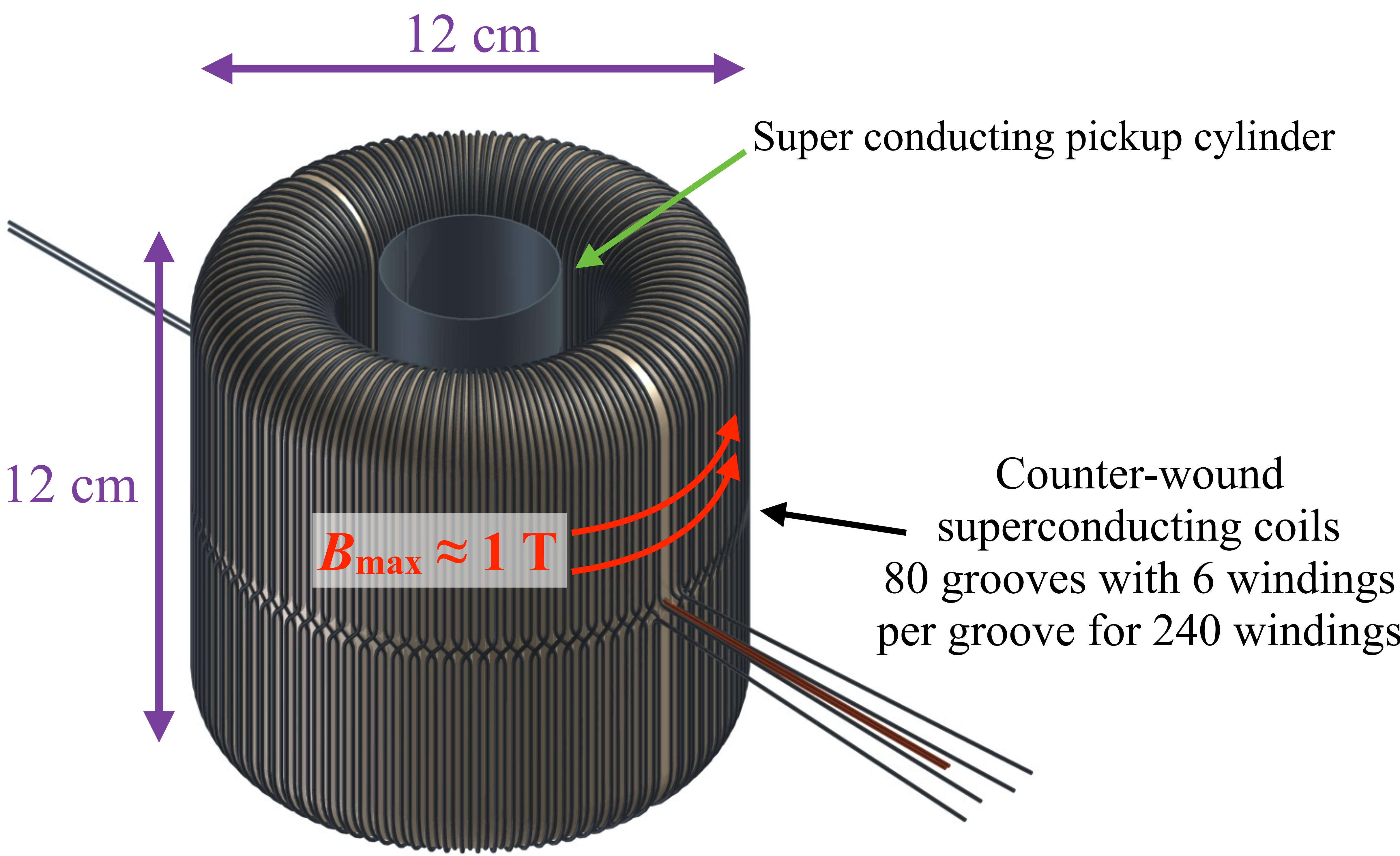
- We are building a 10 cm scale prototype version at MIT
- **Dimensions:** R_{in} = 3 cm, R_{out} = 6 cm, h = 12 cm. $G_V \sim 5\%$. B_{max} = 1 T.
- **People:** Janet Conrad, Joe Formaggio, Sarah Heine, Reyco Henning (UNC), Yoni Kahn (Princeton), Joe Minervini, Jonathan Ouellet, Kerstin Perez, Alexey Radovinsky, Ben Safdi, Jesse Thaler, Daniel Winklehner, Lindley Winslow
- Funded by an $80k NSF grant
  - Expected magnet delivery in May
  - Hope to have first results before the end of 2017, though we will spend quite a bit of time investigating different data taking configurations.

ABRACADABRA-10 cm



Will be operated as a persistent superconducting magnet

ABRACADABRA-10 cm



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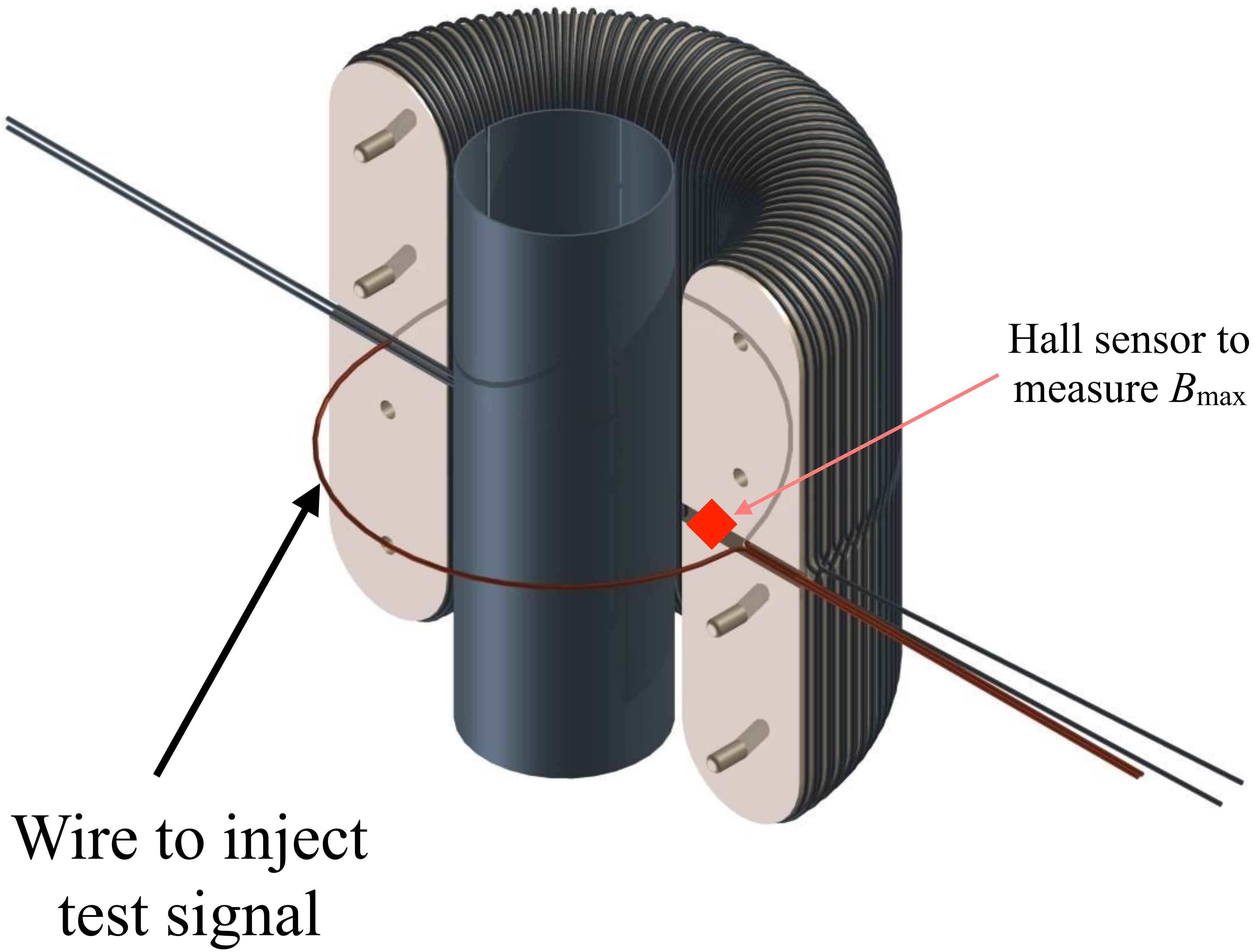
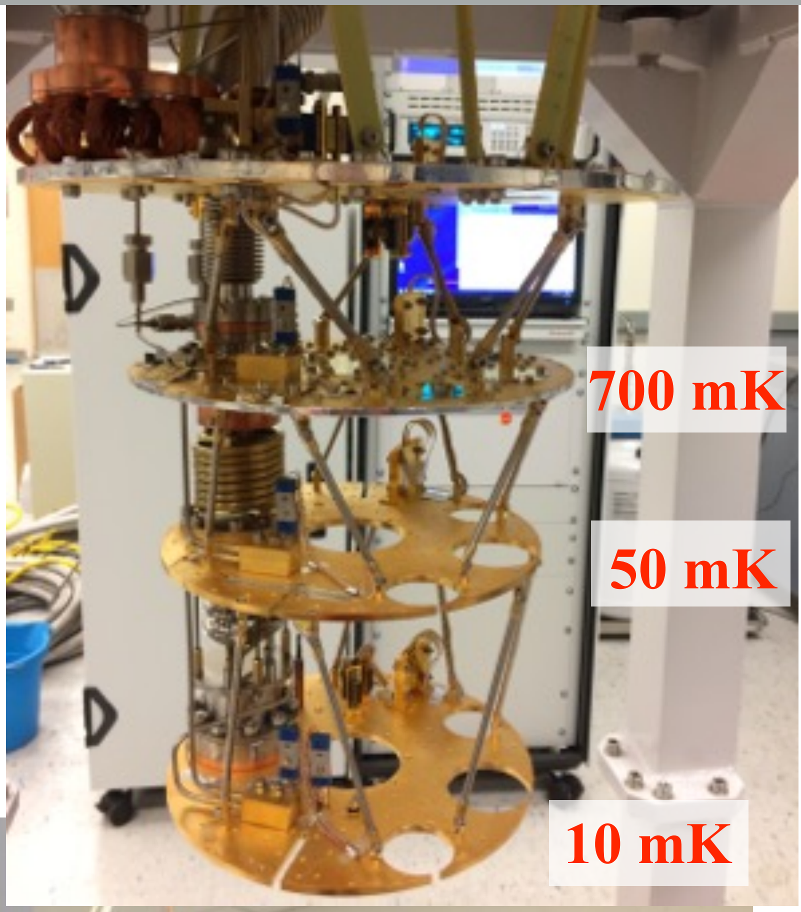
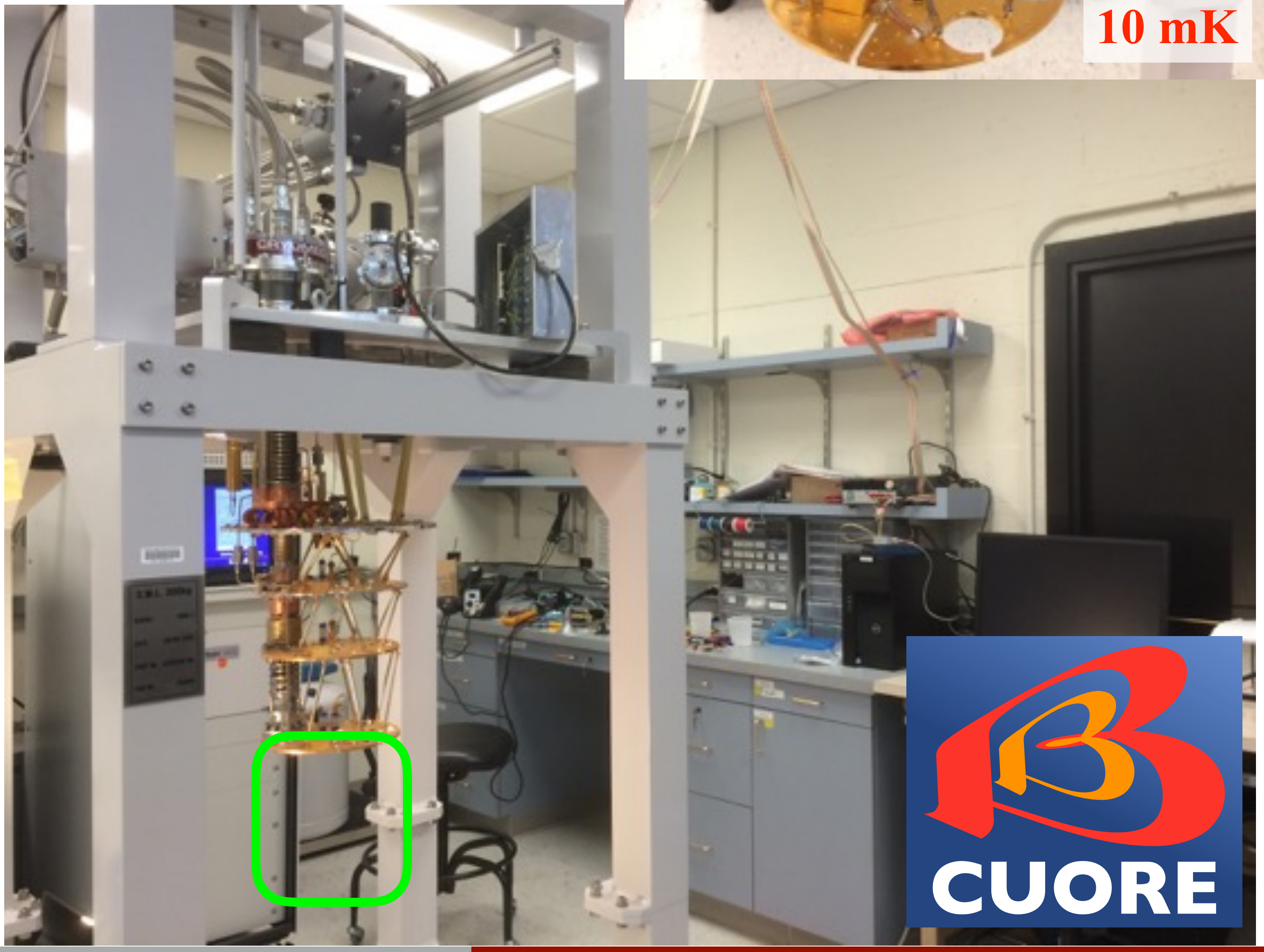
ABRACADABRA-10 cm



Lab At MIT

- We have an Oxford Instruments Triton 400 dilution refrigerator
- Normally used for R&D for CUORE/CUPID $0\nu\beta\beta$
- Capable of a base temperature of <10 mK
- Working volume of ~12 L
  - ~25 cm diameter by ~24 cm height
- Cryogen free, so does not require He refilling
- Can run ~2 weeks unattended

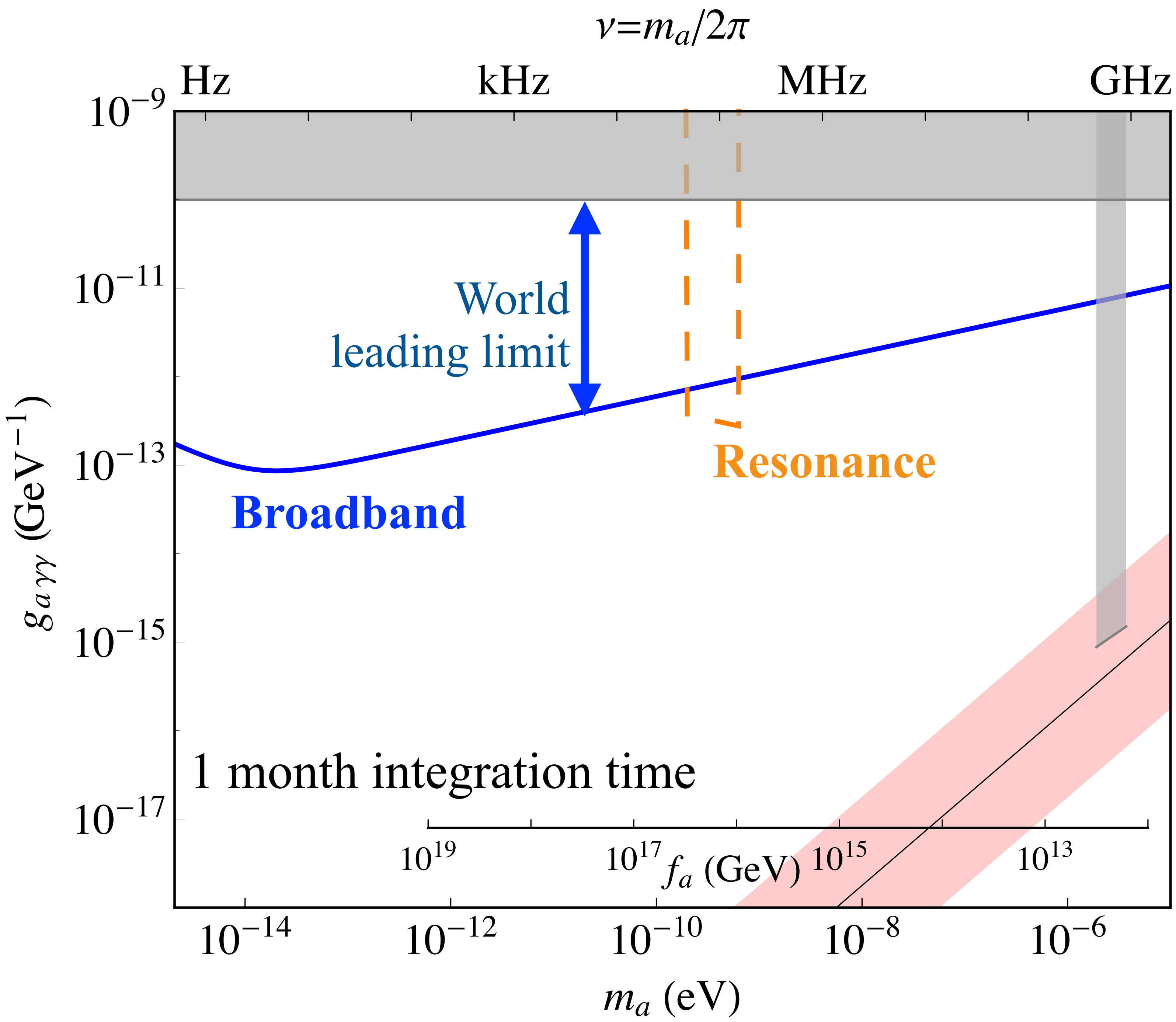




SQUIDs and SQUID Arrays

- We currently have a set of Magnicon SQUID amplifier arrays
  - These will act as a second stage amplification to a first stage SQUID
- We are looking to purchase a Magnicon SQUID current sensor
  - Typical noise @ 4K: $1.2 \times 10^{-6}\ \Phi_0/(\mathrm{Hz})^{1/2}$, with $1/f$ corner at 3 Hz
  - Bandwidth of 6MHz
  - Might be able to do slightly better with SQUID amplifiers or at lower temperatures.

ABRACADABRA-10 cm



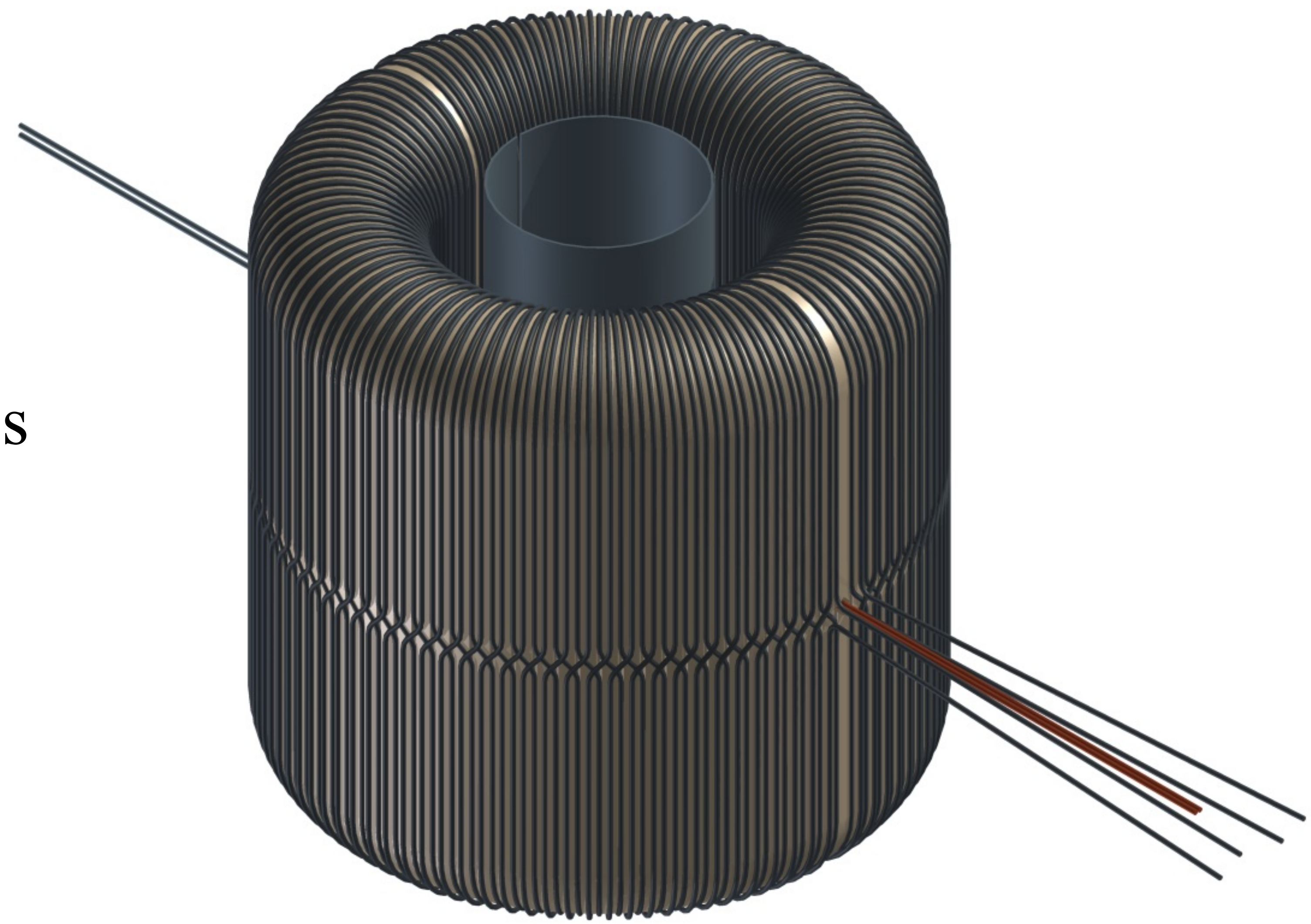
World leading limit after 1 month of data!

- SNR=1
- Assumes flux limited background
- $1/f$ corner between ~3Hz — 50Hz
- Bandwidth of ~6MHz

ABRACADABRA 10cm Prototype Goals

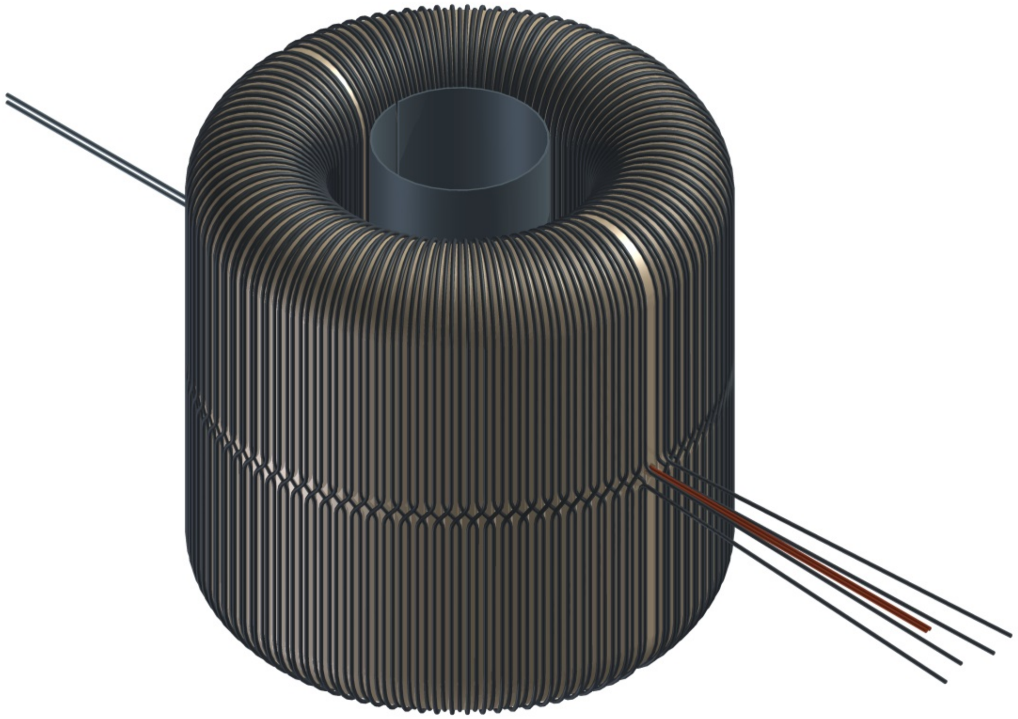
Questions we hope to address with the prototype:

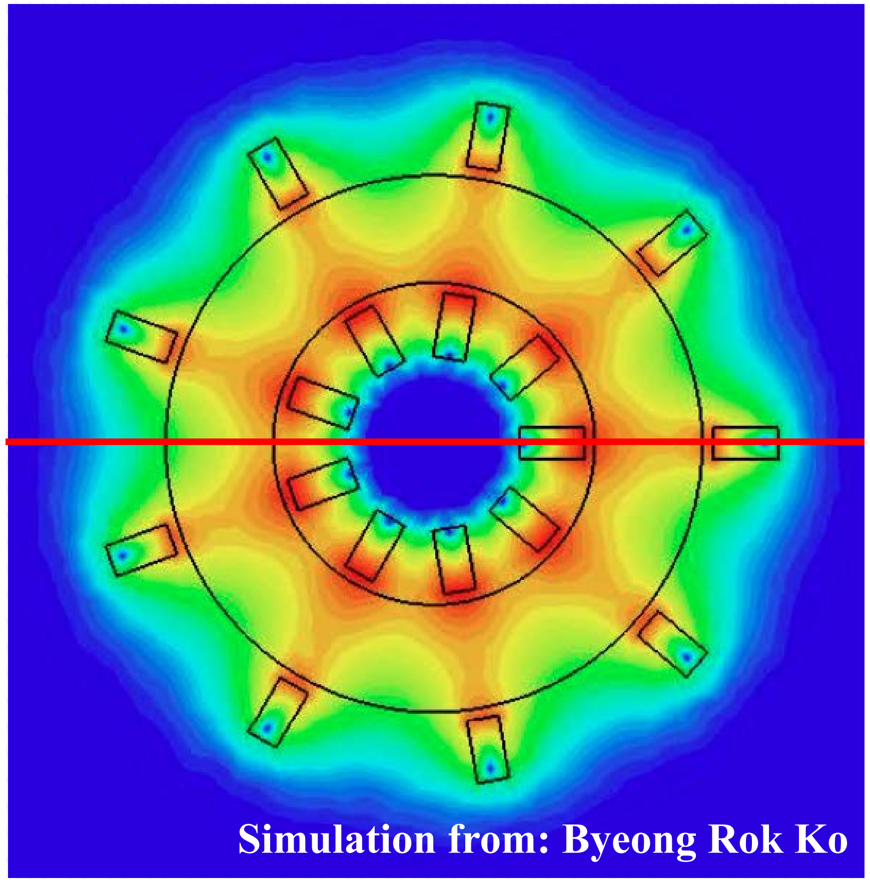
1. Stray fields
2. Shielding
3. Pickup loop geometry
4. Temperature
5. Vibration
6. Decoherence and Scan Strategies



Stray Fields And Toroid Construction

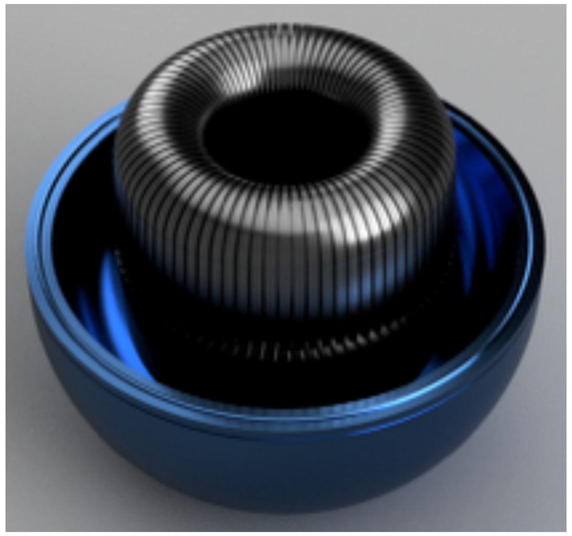
- The advantage of this approach is that we are searching for a signal in a **zero field** region
  - 4 orders of magnitude for free!
  - Need to minimize the stray fields in the center of the toroid
  - Want to keep wiring out of the center of the toroid
  - Persistent superconducting magnet to minimize noise in the coils
- Possibly investigate a segmented toroidal magnet
  - Easier to scale up in size
  - Possibly more stray fields
  - Worse geometric factor, G_V

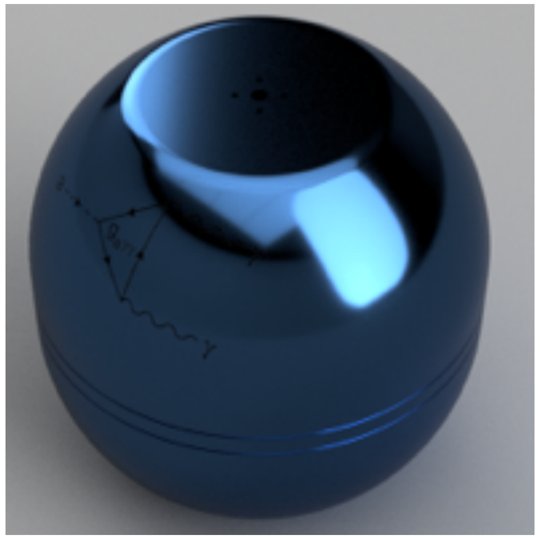




Magnetic Shielding

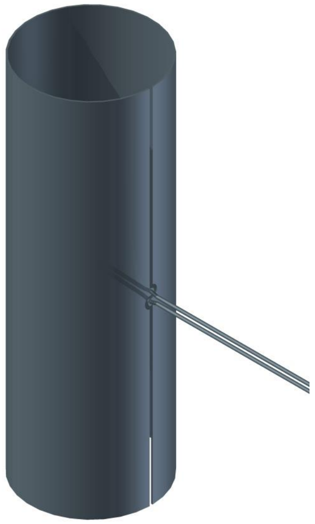
- Also need to have significant shielding of environmental magnetic fields
  - Looking into encapsulating toroid in a superconducting shield
- Johnson noise in normal conducting metals generates magnetic field noise
  - All materials must be superconducting or insulators (or outside)
- Exploring setting up Helmholtz coils to cancel Earth field during cool down.





Pickup Cylinder

- A pickup cylinder (rather than a simple wire) reduces the inductance
- Need to design detector to be disassembled and reassembled with different pickup configurations



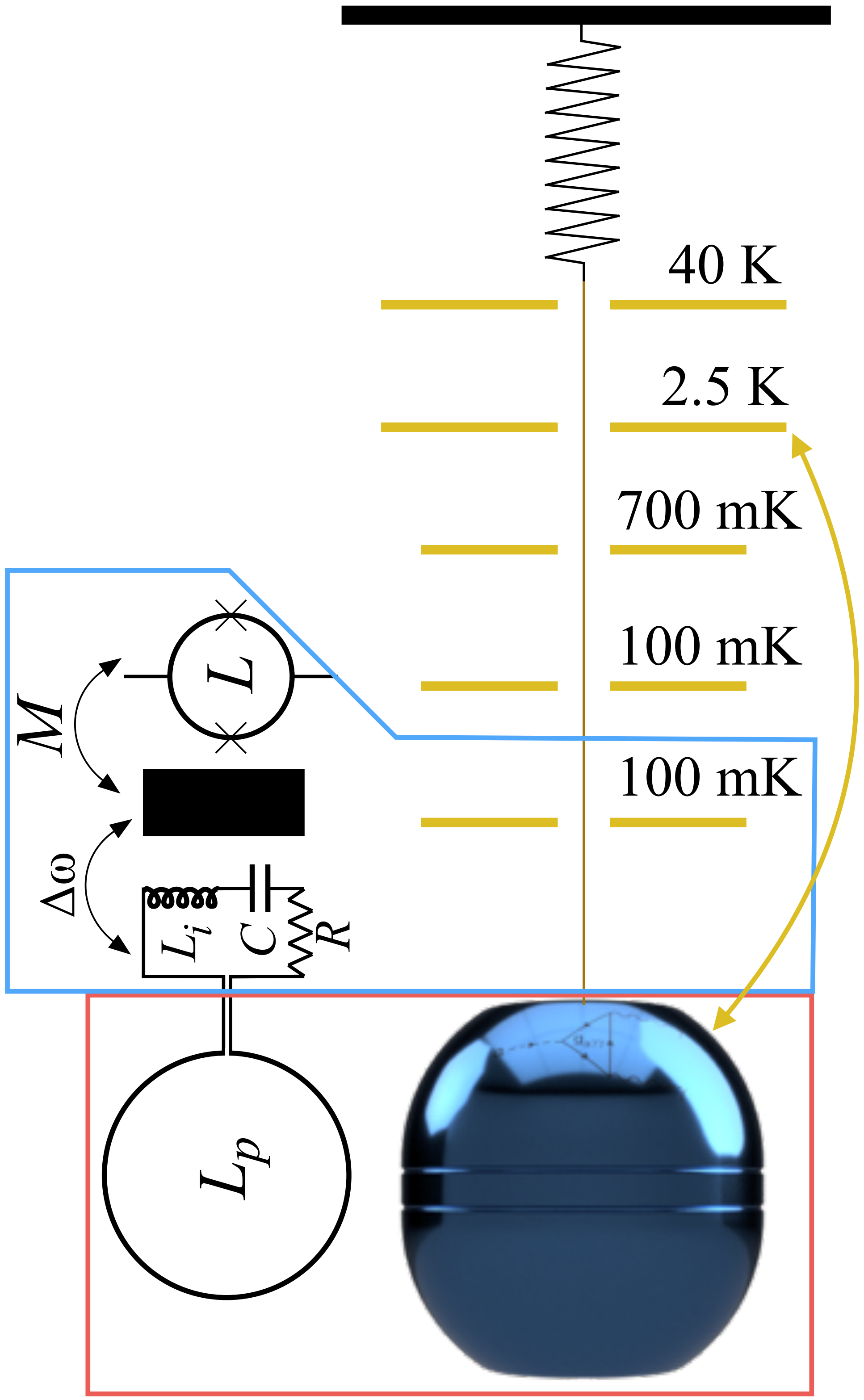
Operating Temperature and Vibration Isolation

The operating temperature is a big question

- The toroid and shield need to be superconducting, ≲ 1 - 4 K (depending on material, field, etc)
- The SQUIDs can operate between ~100mK and 4K, but do not need to be the same temperature as the toroid and shield
- The only temperature dependence is the resonant circuit
- Lower temperature reduces Johnson noise, but raises 1/*f* corner
- Does black body radiation induce noise?

Of course vibration can induce incoherent noise

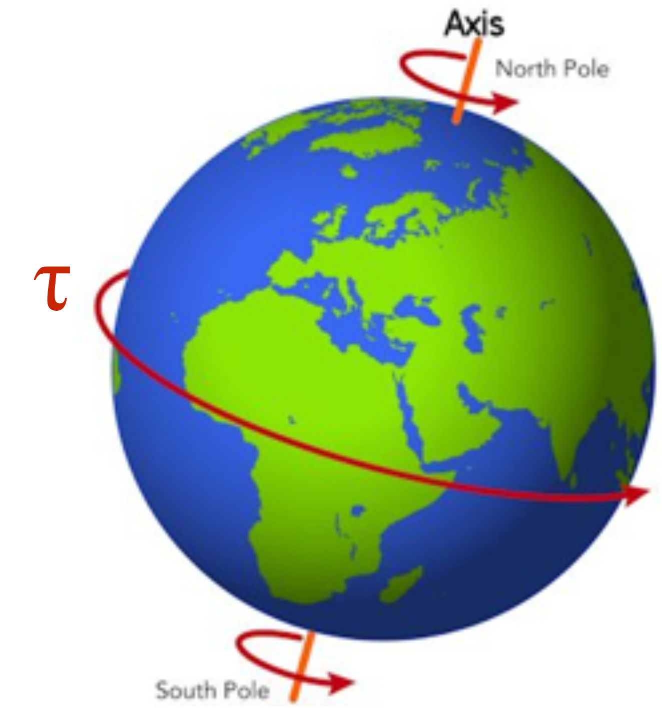
- Microphonic noise pickup creating a noise background
- Vibration of pickup relative to toroid ⇒ stray DC B-fields into AC B-fields



Data Taking and Scan Strategies

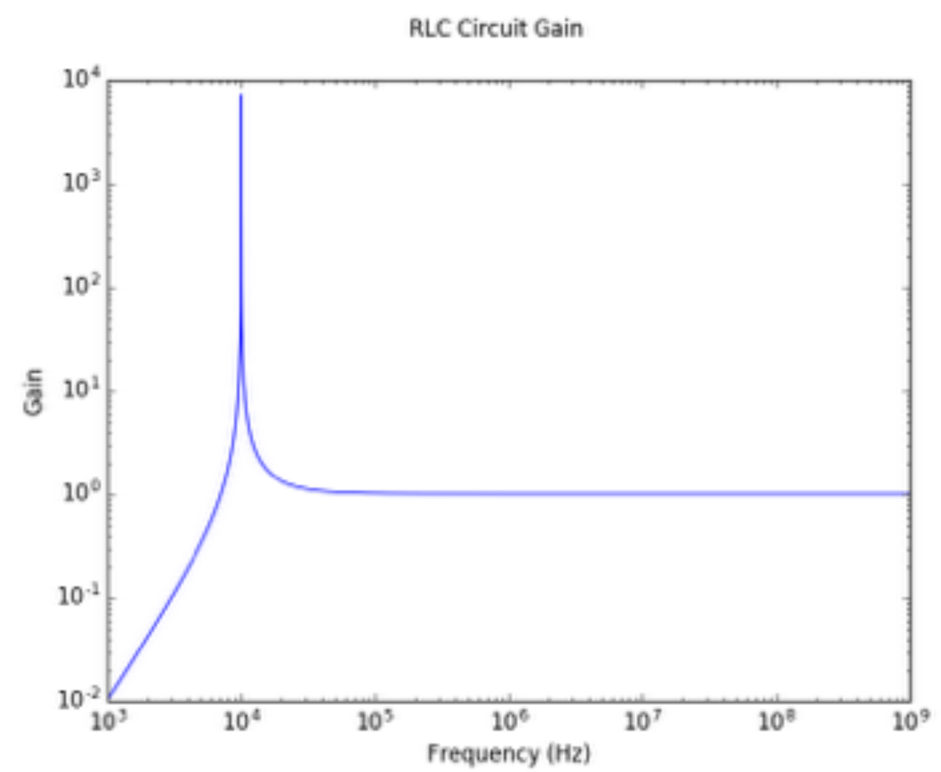
Decoherence can broaden a signal line and reduce sensitivity

- On board timing resolution of the digitizer
  - High precision clock?
- How high of a data rate can we handle?
- At very low frequency, correcting for Earth's motion



An optimal scan strategy can significantly improve sensitivity

- K. Irwin has pointed out that broadband data can be collected simultaneously with resonance data
- Currently studying optimal scan approaches



ABRACADABRA Budget Estimates

ABRACADABRA-10cm		
Dilution Refrigerator		✓
SQUID Readout System		✓
Magnet		$80k
Shielding		
ABRACADABRA 1m		
Cooling System:		
	Dilution refrigerator systems	O(≲$1M)
	Larger system to cool the toroid	
SQUID Readout Systems		
	Custom system with larger bandwidth and resonator	O(≲$1M)
Shielding		
	To be determined	
Magnet		
	Typical scaling number (cost driver)	$250k/MJ
	R_{min}=1m, R_{max} = 2m, h = 3m, B_{max} = 1T	$1.2M
	R_{min}=2.2m, R_{max} = 4.5m, h = 6.7m, B_{max} = 1T	$6M
	R_{min}=1m, R_{max} = 2m, h = 3m, B_{max} = 5T	$30M

*All numbers are ballpark estimates

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Same Sensitivity

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Summary

- Axions are interesting candidates for both Dark Matter and explaining the strong CP problem
- A broadband search using a toroidal magnet geometry has the potential to quickly probe into previously untested regions of parameter space
- Long term, this type of search could hope to probe down into the QCD axion regime
- At MIT, we are building a prototype called ABRACADABRA-10 cm with the goal of scaling this up to a 1 m scale experiment
- We are aiming to have early results by the end of 2017

Summary

- Axions are interesting candidates for both Dark Matter and explaining the strong CP problem
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Thank you for you attention!

Backup Slides

Broadband Sensitivity

Our benchmark geometry $R_{\text{in}} = R_{\text{out}}/2 = r = h/3$:

- The S/N ratio depends on the coherence time, τ

$$S/N \sim |\Phi_a| \, (t\tau)^{1/4} / S_{\Phi,0}^{1/2}$$

- The coherence time is given by

$$\tau \sim \frac{2\pi}{m_a v^2} \approx 3 \times 10^4 \, \text{s} \left(\frac{10^{-12} \, \text{eV}}{m_a} \right)$$

- The sensitivity goes as (depends strongly on scan strategy):

$$g_{a\gamma\gamma} > 6.3 \times 10^{-18} \, \text{GeV}^{-1} \left(\frac{m_a}{10^{-12} \, \text{eV}} \frac{1 \, \text{year}}{t} \right)^{1/4} \frac{5 \, \text{T}}{B_{\text{max}}} \times \left(\frac{0.85 \, \text{m}}{R} \right)^{5/2} \sqrt{\frac{0.3 \, \text{GeV/cm}^3}{\rho_{\text{DM}}}} \frac{S_{\Phi,0}^{1/2}}{10^{-6} \Phi_0 / \sqrt{\text{Hz}}}$$

Resonance Sensitivity

Our benchmark geometry $R_{in} = R_{out}/2 = r = h/3$:

- The signal and noise power goes as

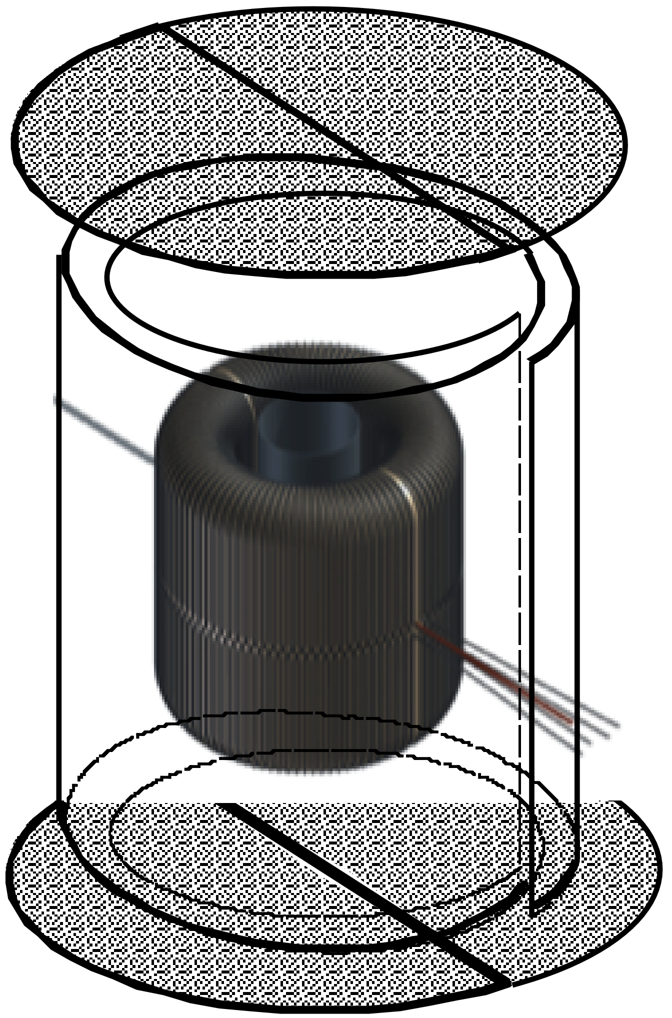
$$P_S = Q_0 \frac{m_a \Phi_a^2}{2L_T} \qquad P_N = k_B T \sqrt{\frac{m_a}{2\pi t_{\mathrm{e-fold}}}}$$

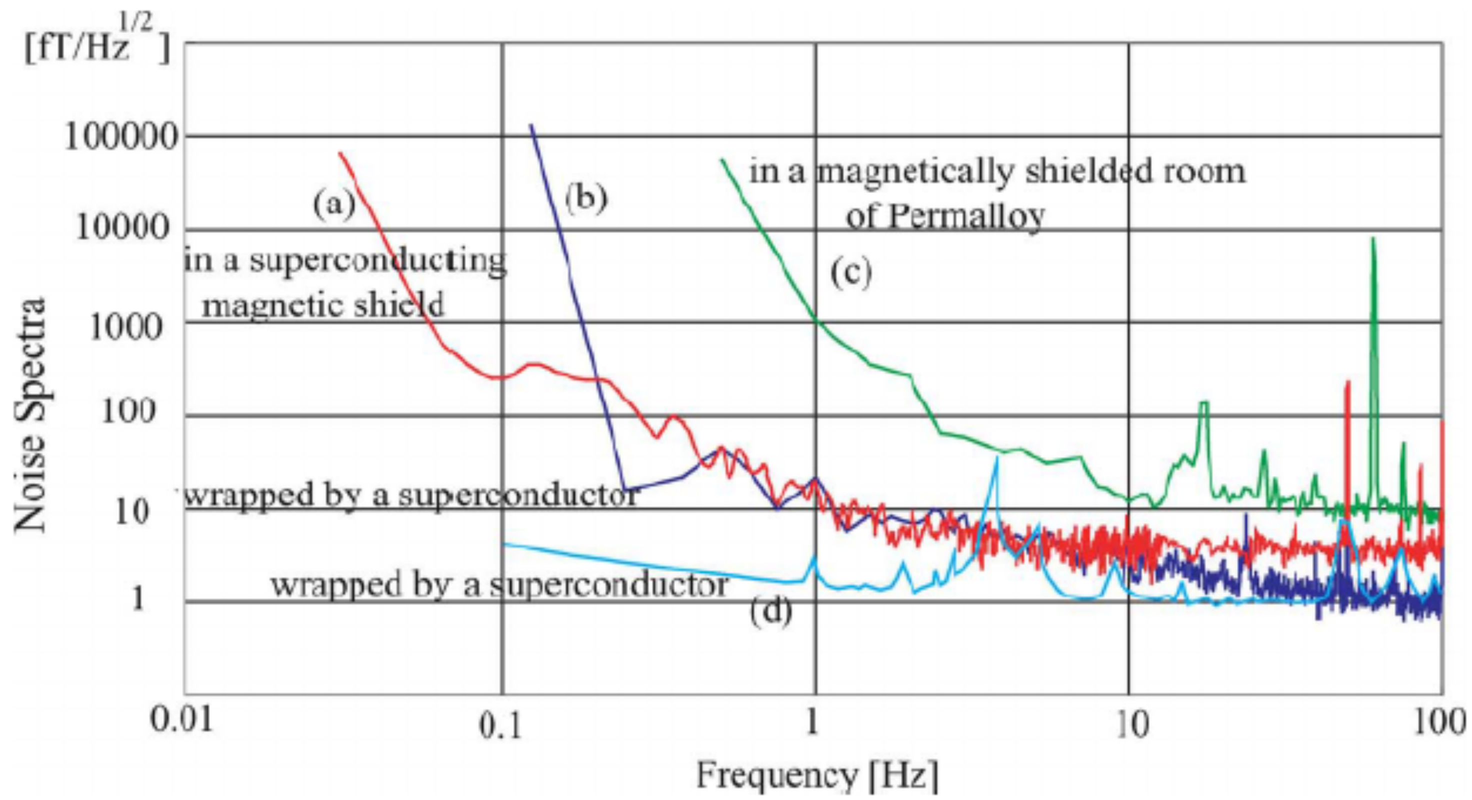
- The sensitivity goes as

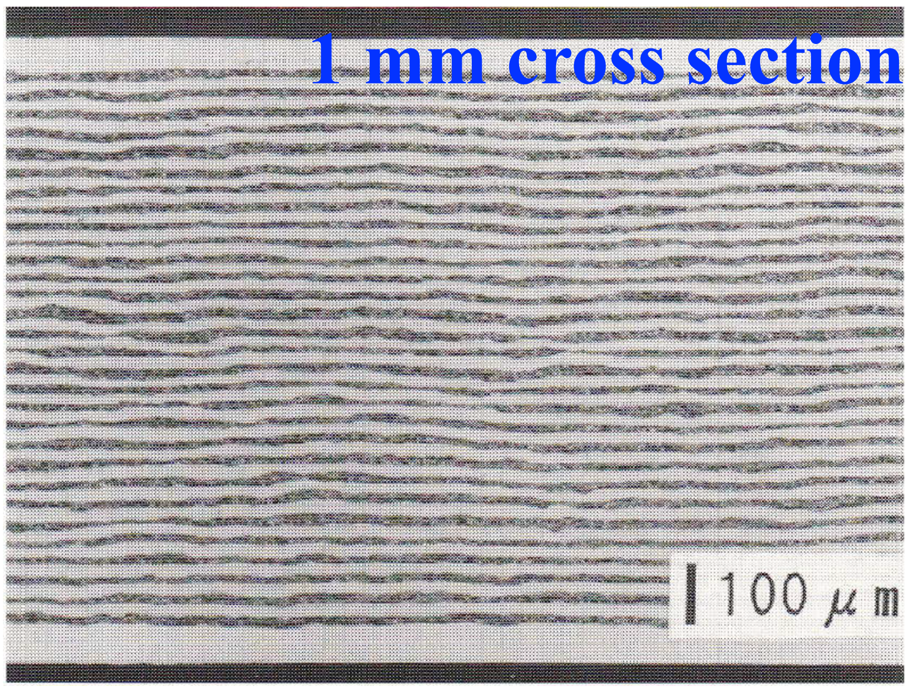
$$g_{a\gamma\gamma} > 9.0 \times 10^{-17} \mathrm{GeV}^{-1} \left(\frac{10^{-12}\,\mathrm{eV}}{m_a} \frac{20\,\mathrm{days}}{t_{\mathrm{e-fold}}} \right)^{1/4}$$
$$\times \frac{5\,T}{B_{\max}} \left(\frac{0.85\,m}{R} \right)^{5/2} \sqrt{\frac{0.3\,\mathrm{GeV/cm}^3}{\rho_{\mathrm{DM}}} \frac{10^6}{Q0} \frac{T}{0.1\,K}}$$

Magnetic Shielding

- We will need to shield the toroid from environmental magnetic noise
- Ideally, use a superconducting shield
- Looking into this NbTi/Nb/Cu multilayer sheet
  - Achieve ~fT/(Hz)$^{1/2}$ noise levels in SQUID magnetometers







Axion Dark Matter Density

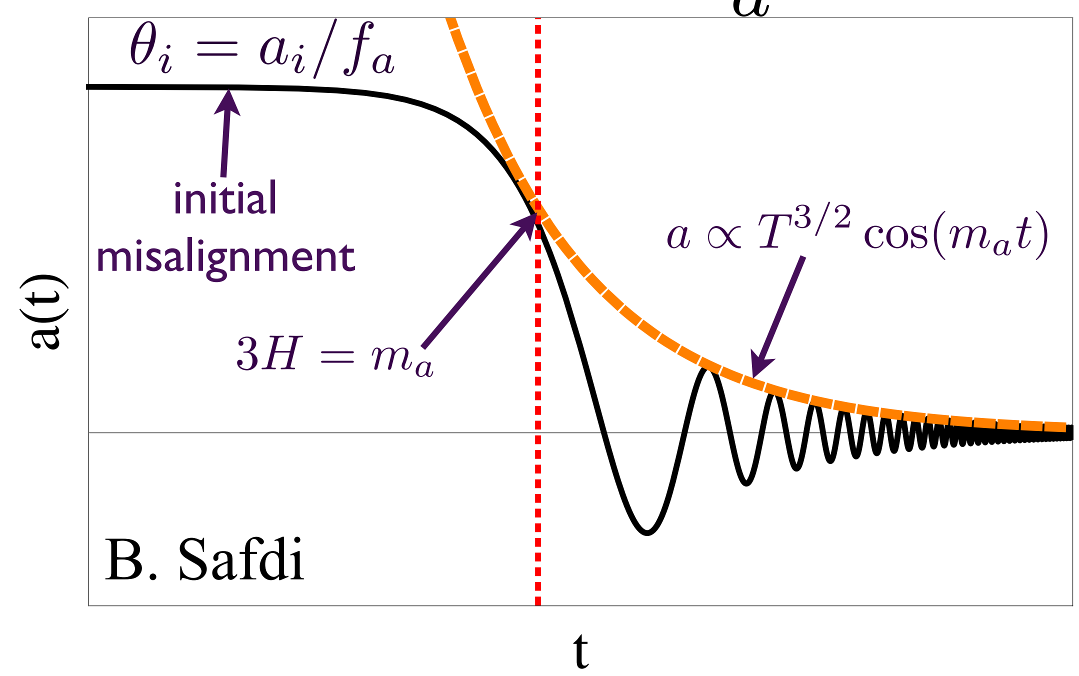
- The axion energy matter density today is given by

$$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \theta_i^2$$

- For $f_a = 10^{16}$ GeV ⇒ $|\theta_i| \lesssim 10^{-3} - 10^{-2}$

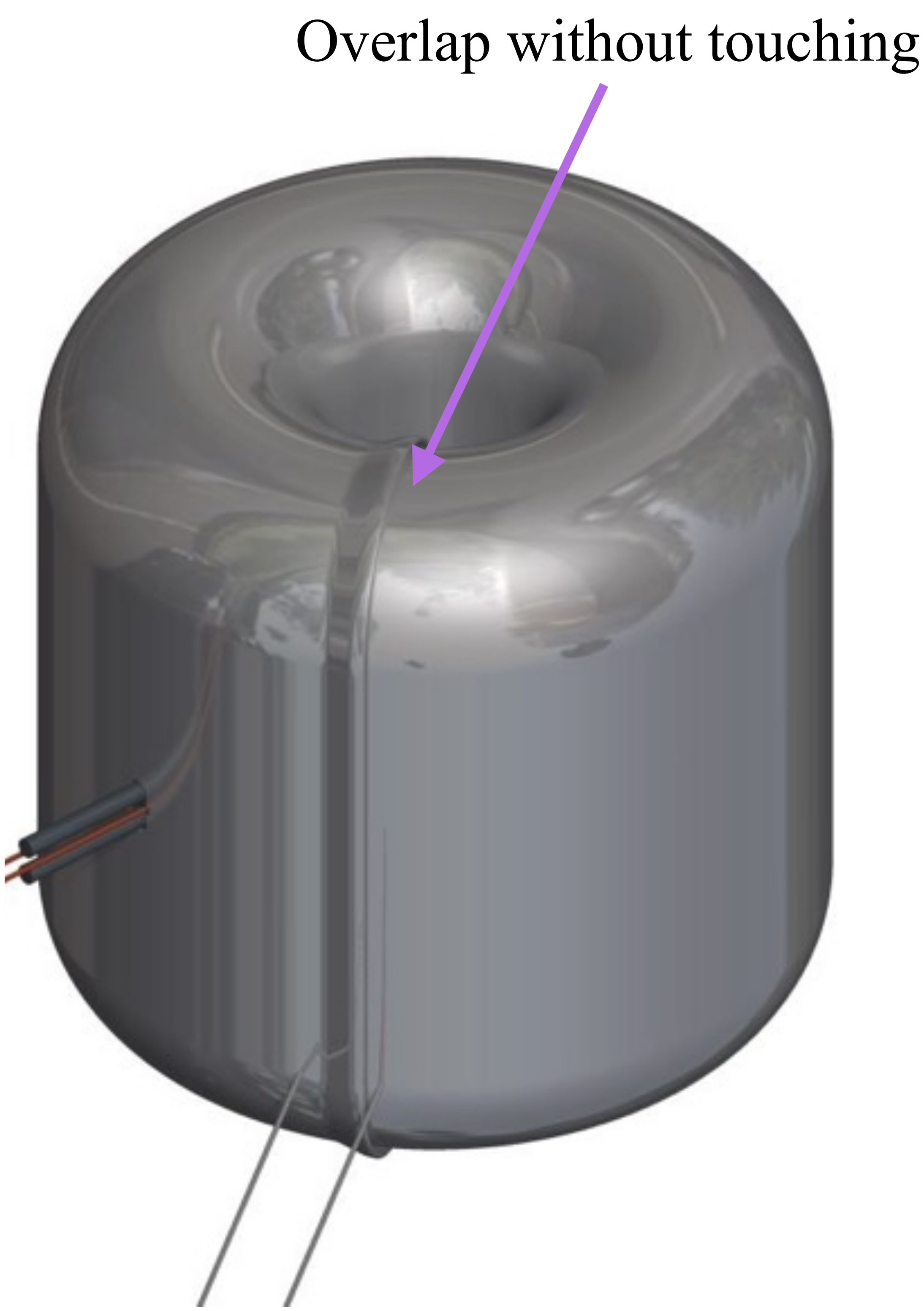
- Alternatively, we can also begin with a larger misalignment angle, and suppress the energy density by dumping entropy into the universe after $3H{=}m_a(T)$ but before BBN.

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



Future Directions?

- We have also considered surrounding the toroid in a non-overlapping superconducting shield
  - The axion induced B-field is trapped inside, and the FULL axion current returns through the SC shield!



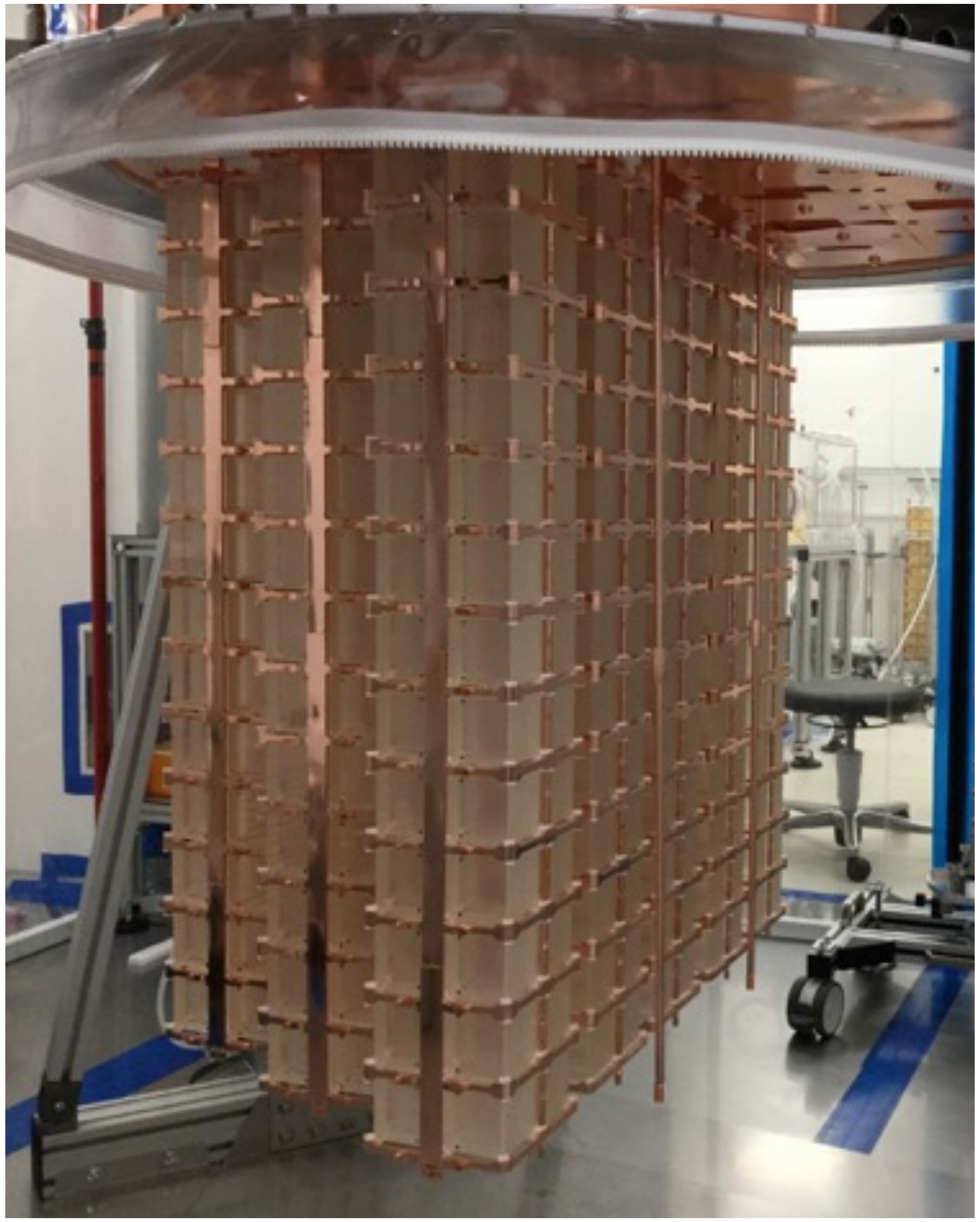
Large Cold Detectors

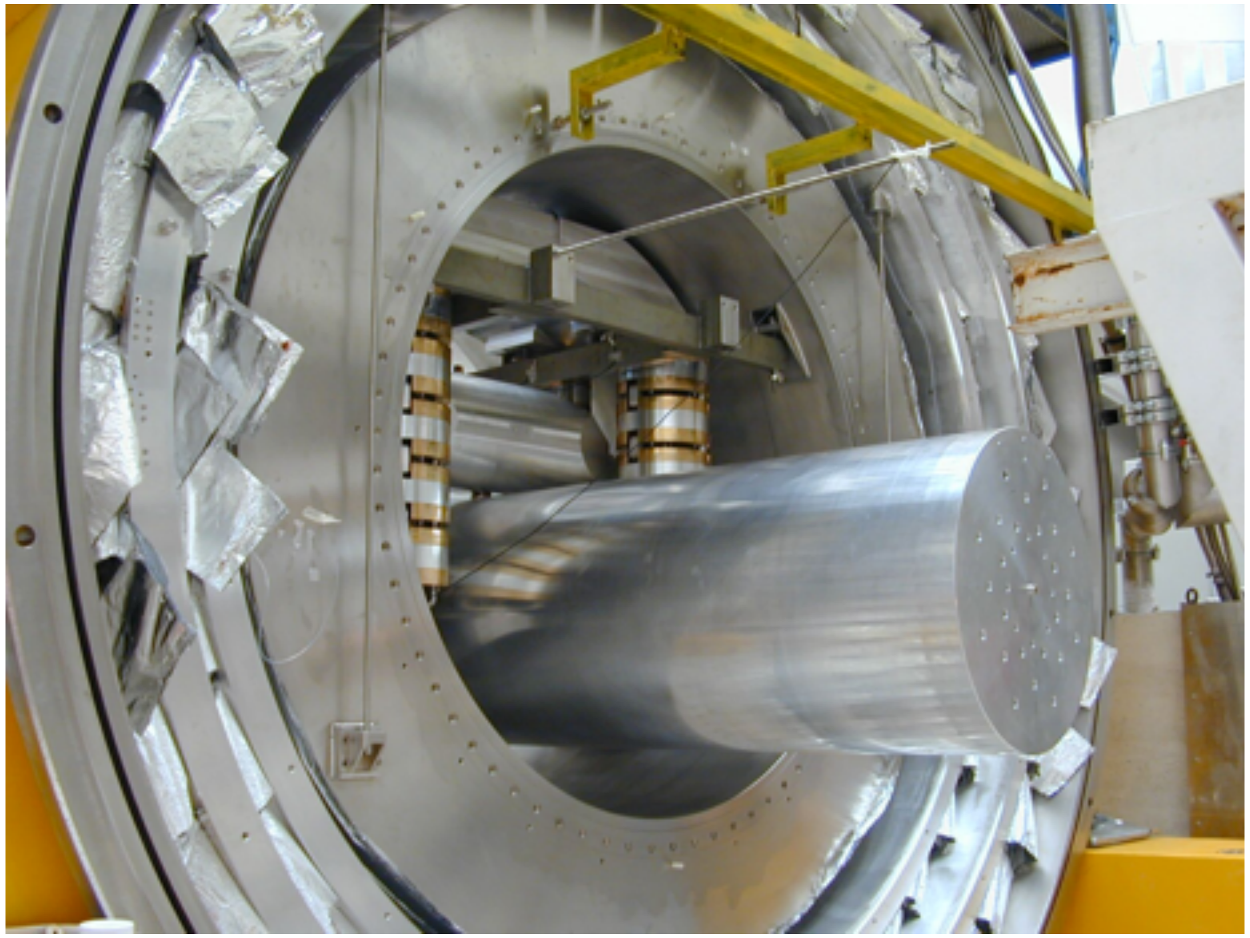
- Can we really cool down something that big??

Large Cold Detectors

- Can we really cool down something that big??

➡ ***Yes!***





AURIGA: 60 cm x 3 m
Cryogenic gravitational wave antenna

CUORE: 1.5 t of material at 10 mK
Coldest Cubic Meter in the Universe!