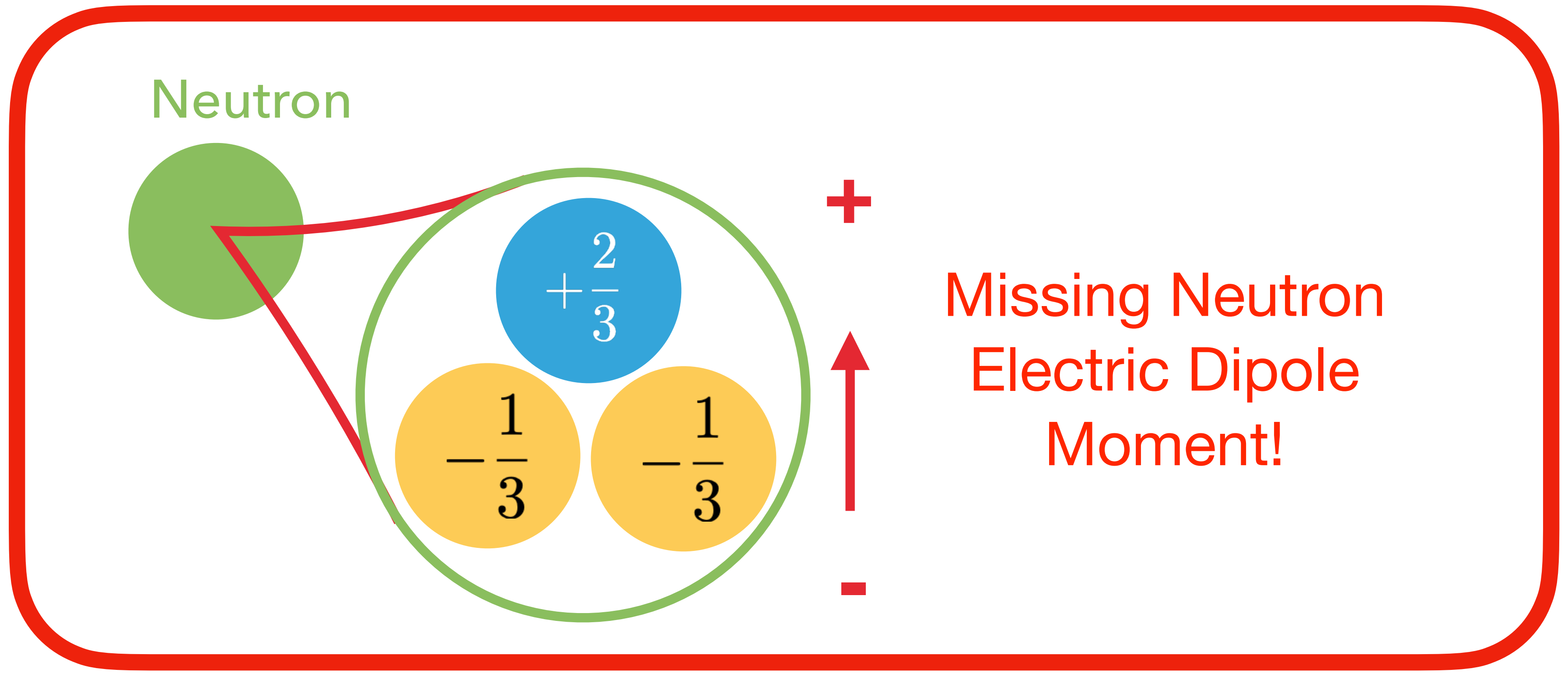
DMRadio: Searching for Axion Dark Matter Below 1 μeV

J. Ouellet ***for the DMRadio Collaboration***
Massachusetts Institute of Technology

Axion Dark Matter

An Introduction



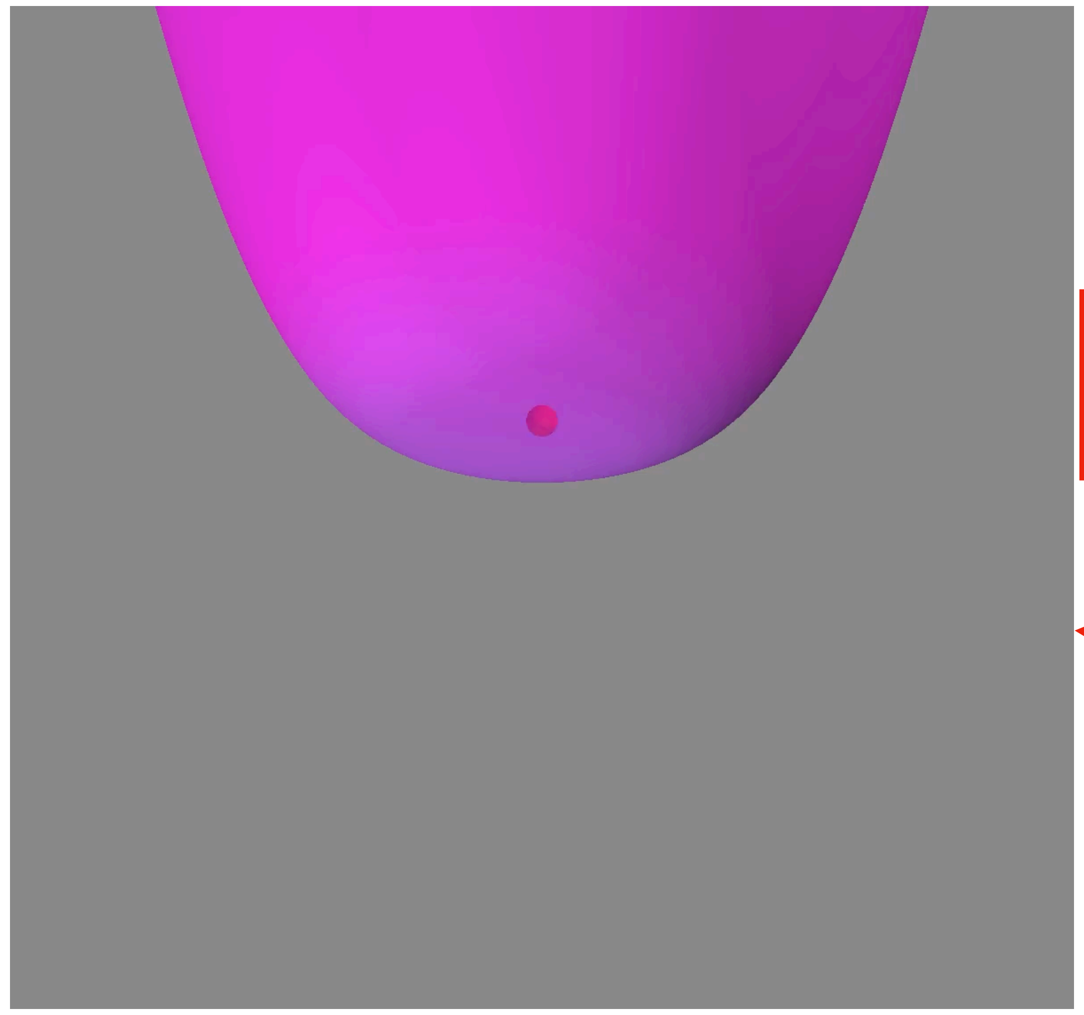
➡ **Axion is one of the most compelling candidates to explain the Dark Matter density**

- Originally proposed to solve the Strong CP problem (not Dark Matter!)
- Key axion facts:
  - … Very weakly coupled to SM particles
  - … Produced cold in the early universe via the misalignment mechanism
  - … Low energy relic of new physics at high energies
  - … Extremely light

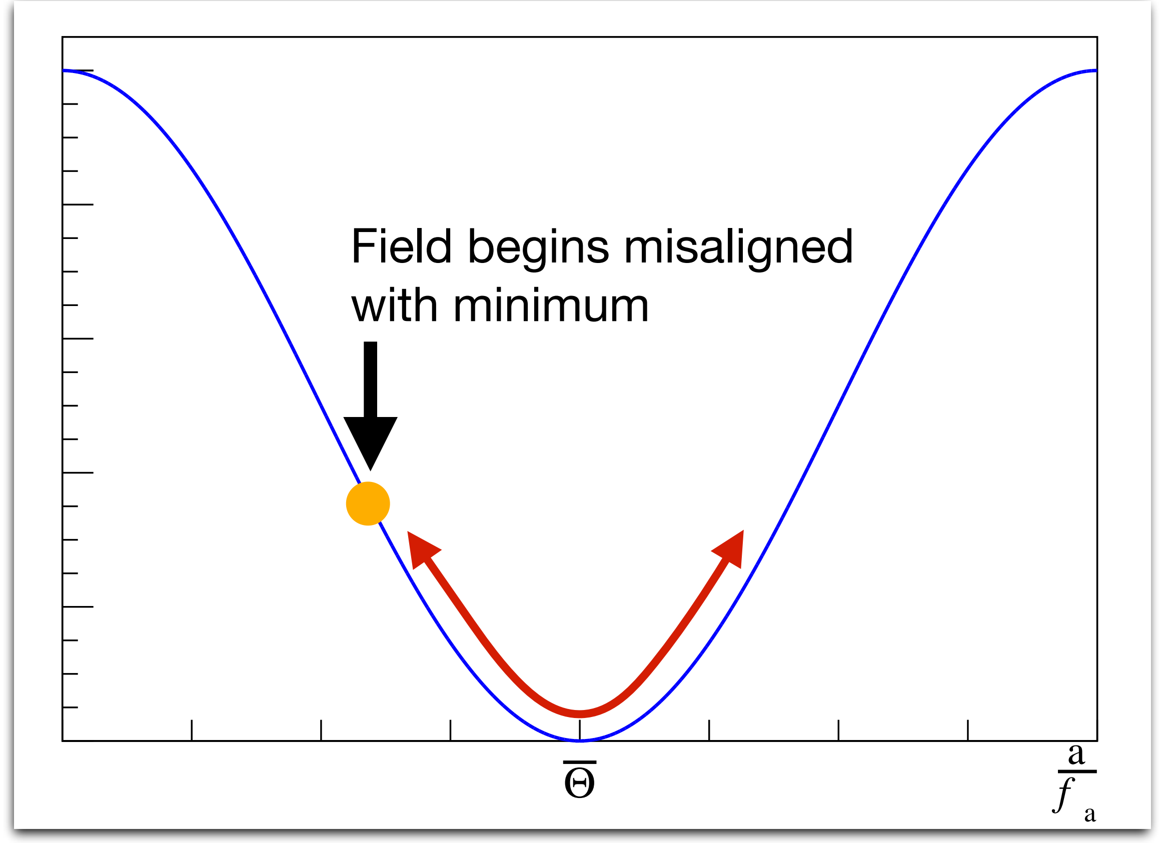
    $$m_a \ll 1\,\mathrm{eV}$$

  - … Today behaves like an oscillating field

    $$a(t) \approx a_0 \cos(m_a t)$$



Dark Matter from axion oscillating in its potential



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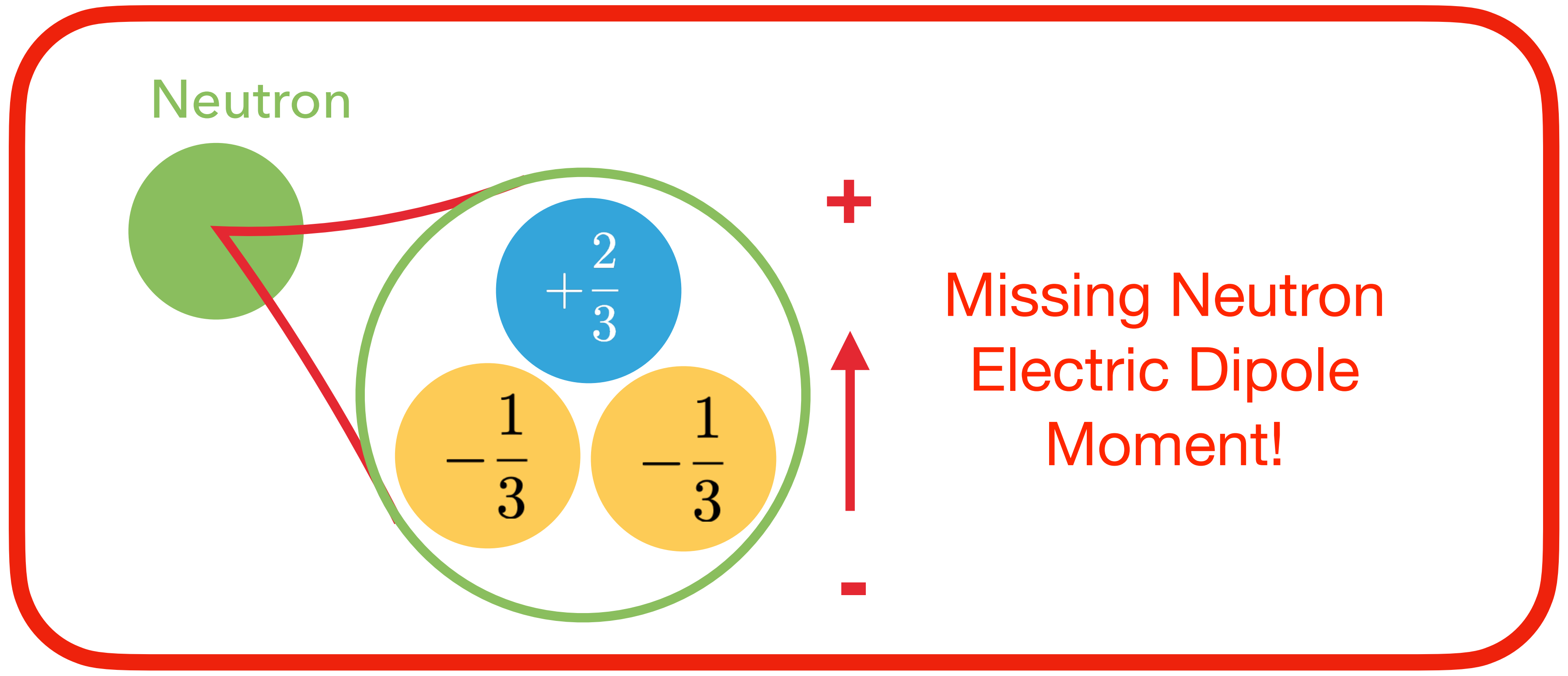

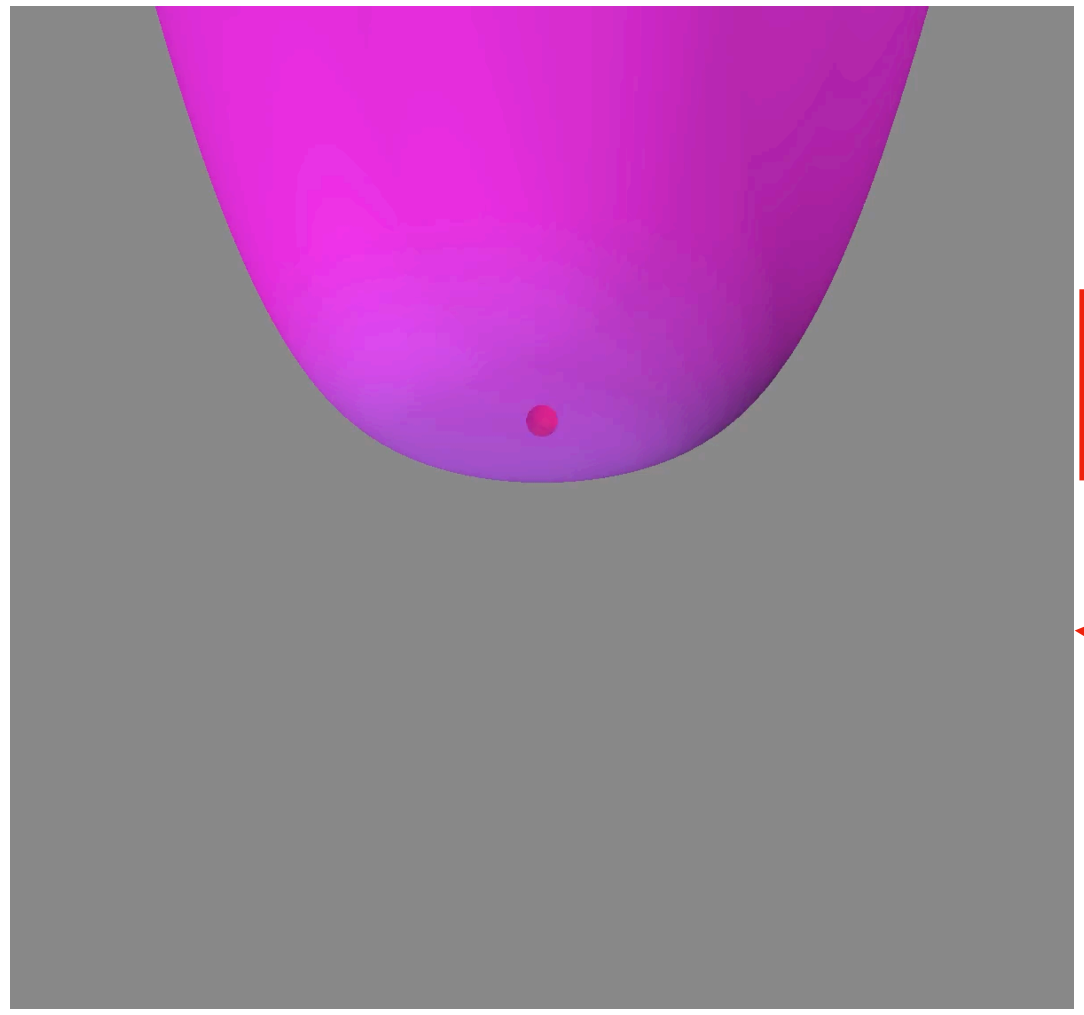

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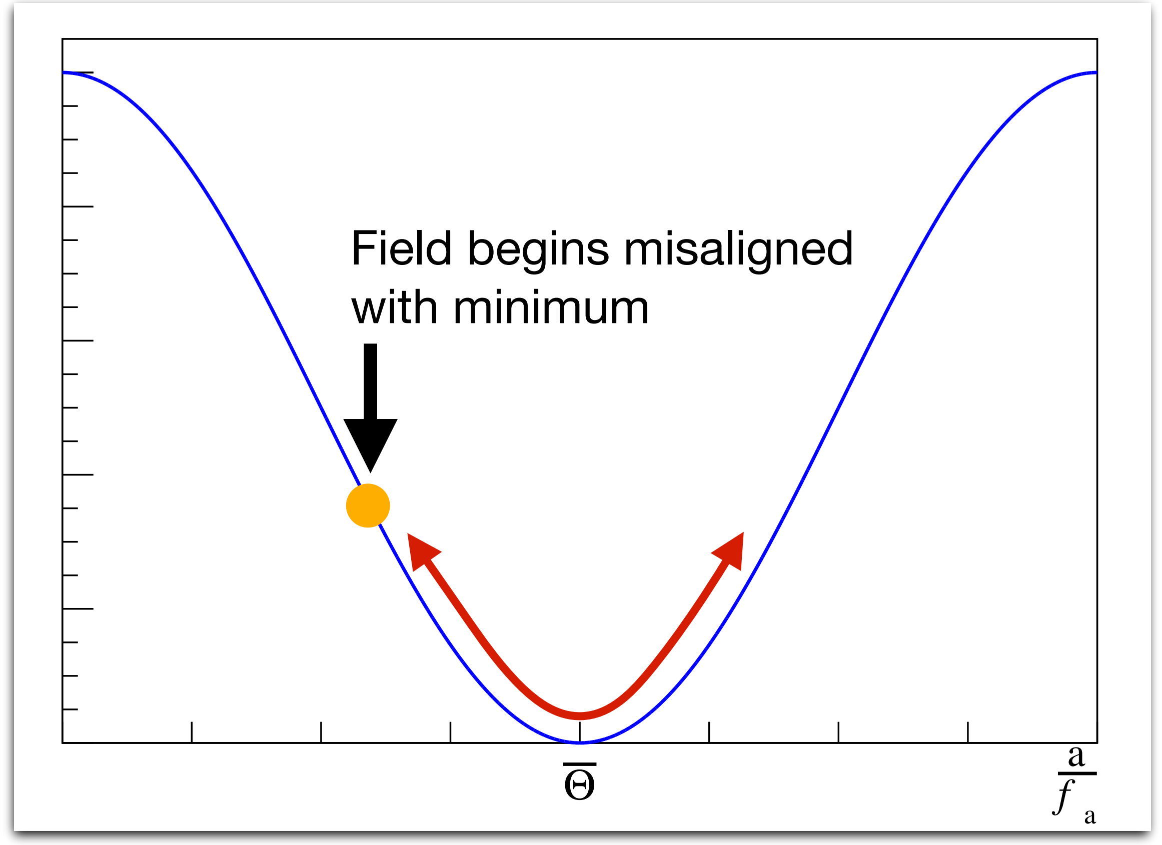
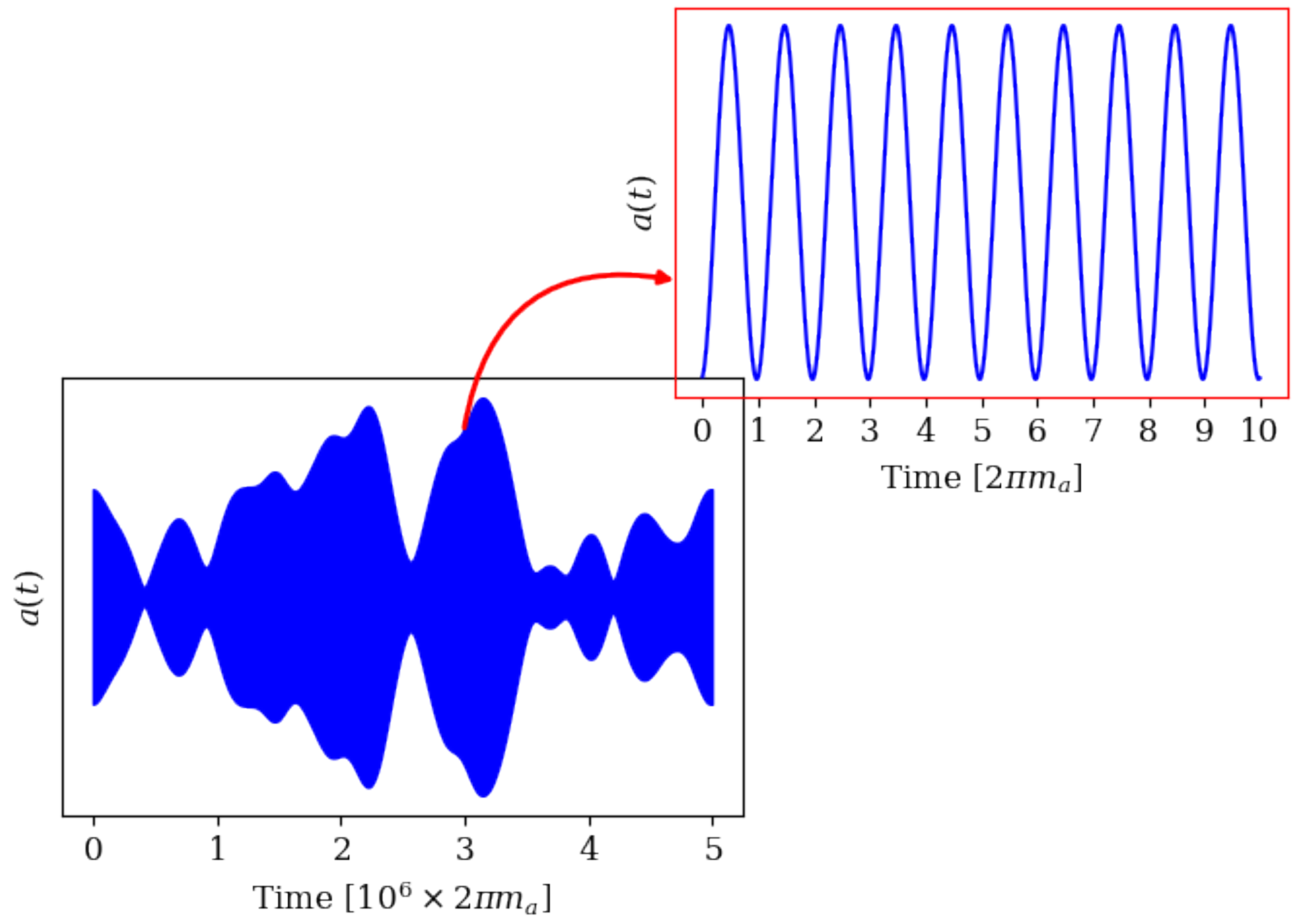


Axion Dark Matter

Wavelike Dark Matter

- Axion dark matter behaves like a classical field!
  - Very high number density of $n_a \sim 10^{14} \left(\frac{\mu\text{eV}}{m_a} \right) \text{cm}^{-3}$
  - Extremely high quantum state occupation $\mathcal{N}_a \sim 10^{27} \left(\frac{1\ \mu\text{eV}}{m_a} \right)^4$
  - A detector interacts with an enormous number of axions at a time
- Axions are large and coherent
  - Compton wavelengths comparable in size to a detector
  - Correlated over distances larger than the detector
  - Coherent over millions of cycles → Can ring up resonators!



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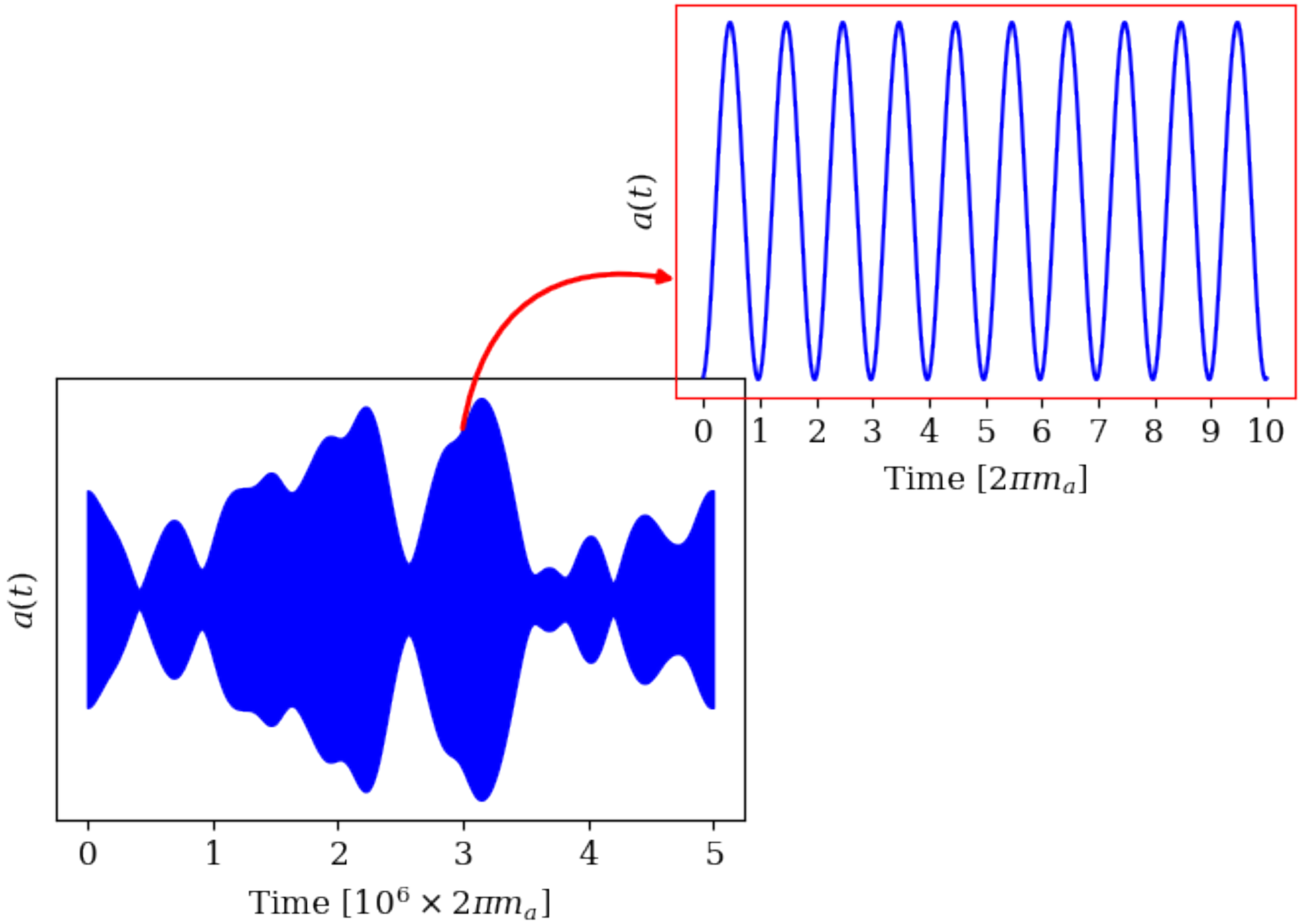


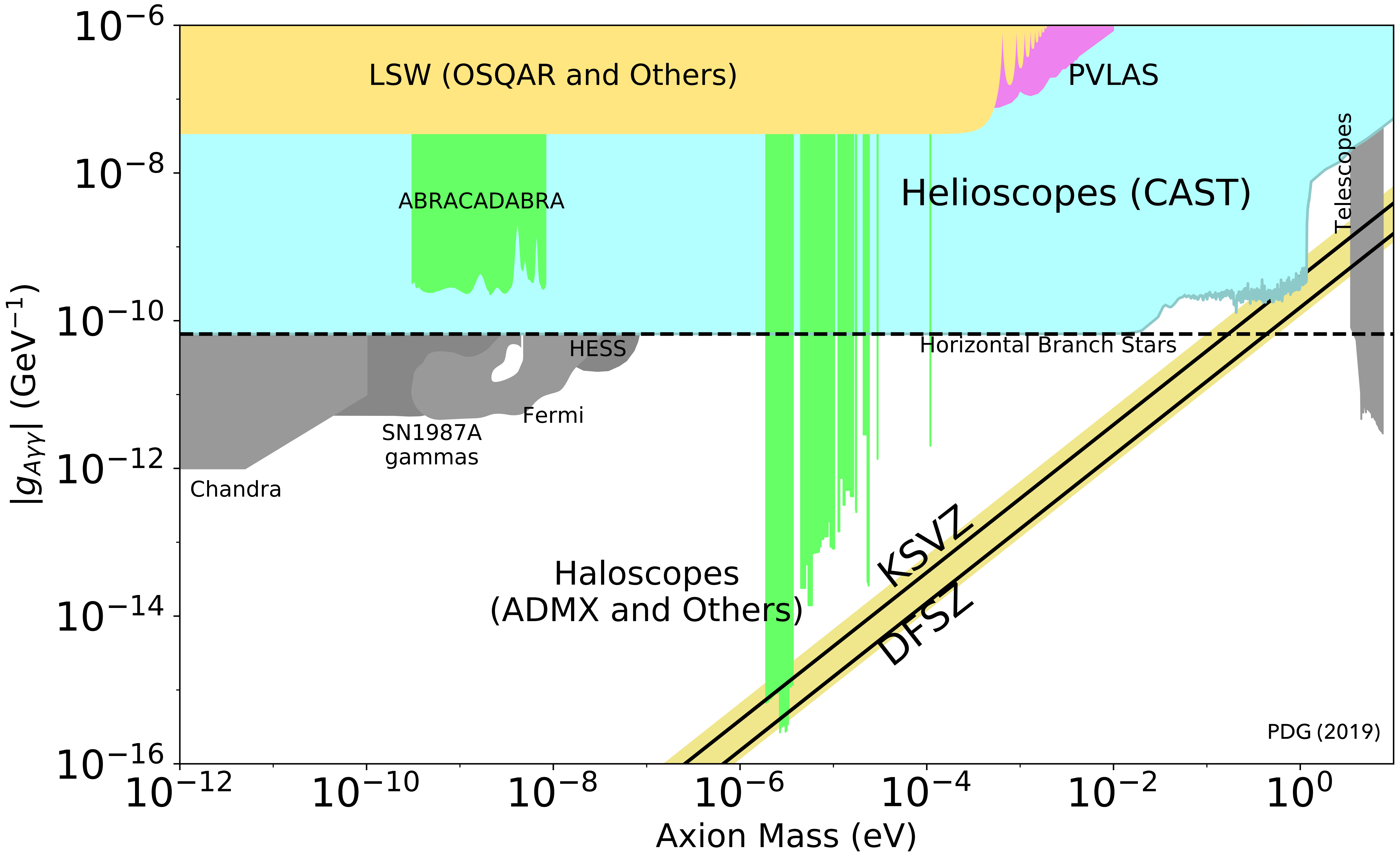
Axion Dark Matter

$a \leftrightarrow \gamma\gamma$ Parameter Space

Present day axion density

$$\Omega_a h^2 \approx 0.1 \left(\frac{10\,\mu\text{eV}}{m_a}\right)^{7/6} \langle \theta_i^2 \rangle$$

Initial misalignment



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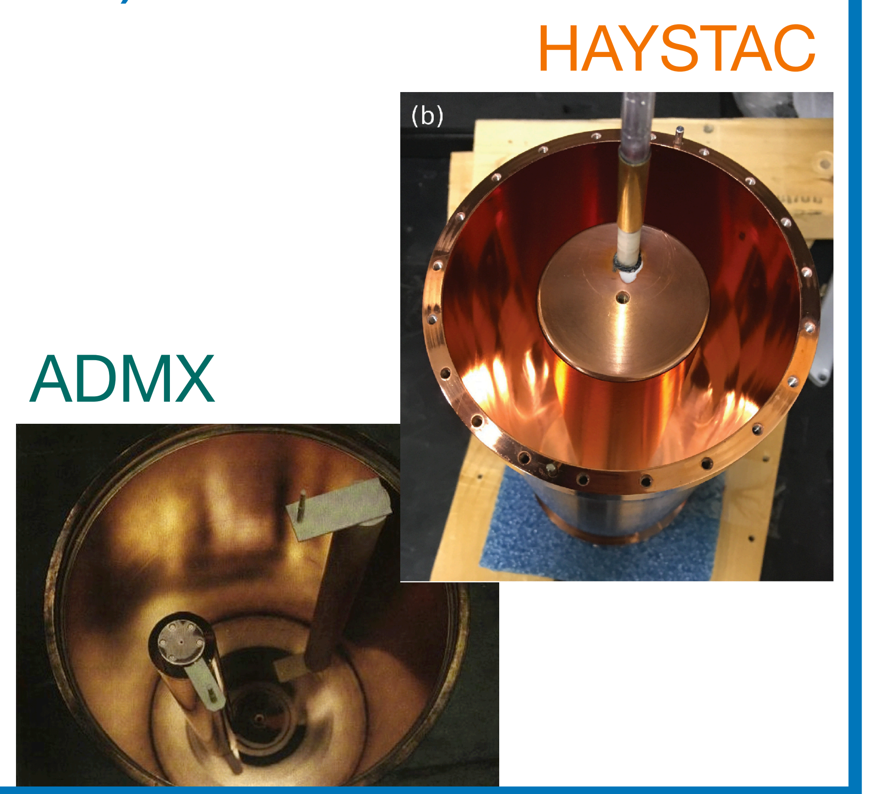
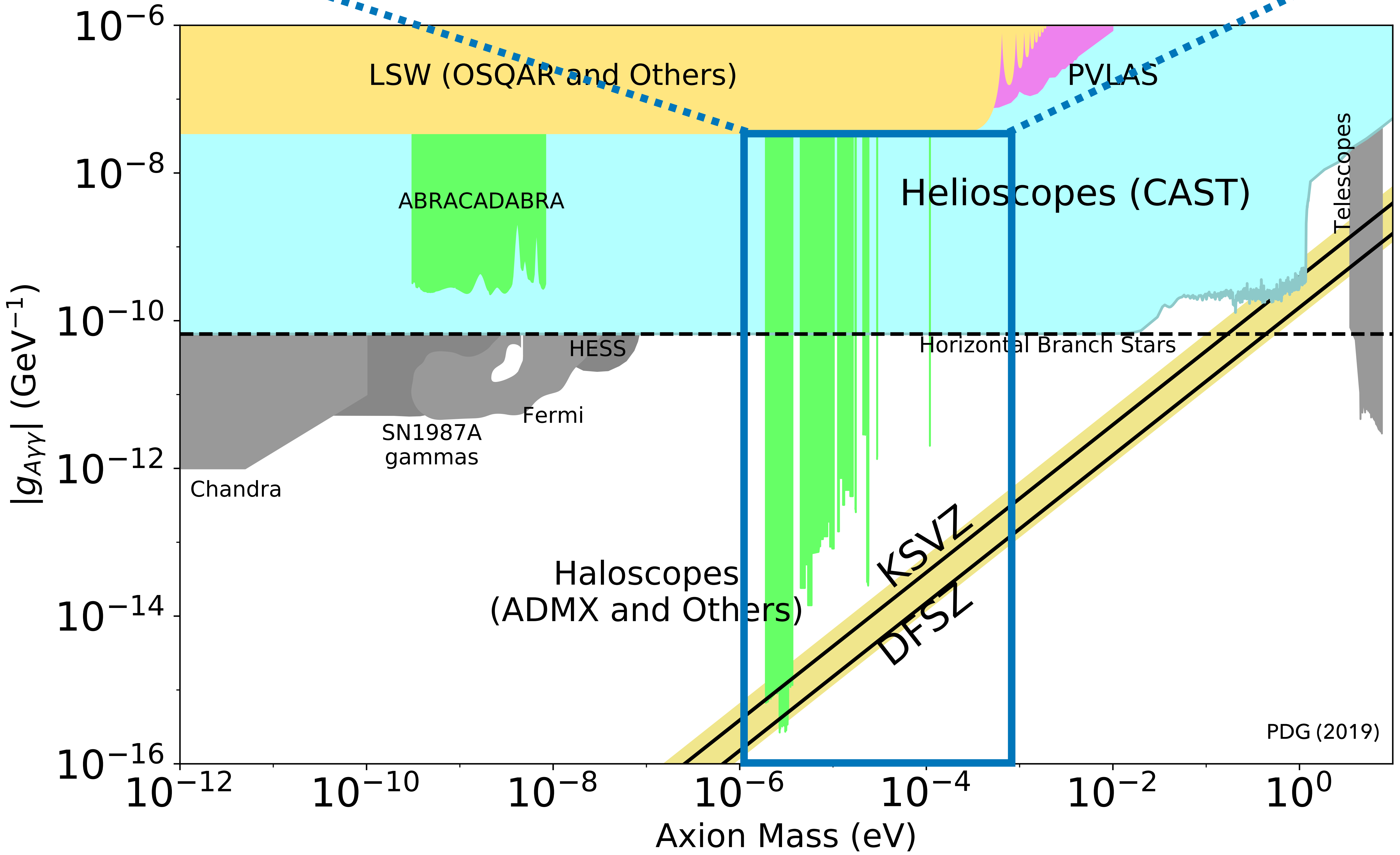
Initial misalignment

Post Inflationary PQ Breaking
($f_a \sim 10^{12}\,\text{GeV}$)

- Mass range 1 μeV ≲ m_a ≲ 1 meV
- Microwave Cavity regime
- Compton wavelength ~ 1m
- Frequencies ~ 1 GHz
- ADMX, HAYSTAC, CAPP-8TB, QUAX-aγ, ORGAN, others…





Axion Dark Matter

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Present day axion density

$$\Omega_a h^2 \approx 0.1 \left(\frac{10\,\mu\text{eV}}{m_a}\right)^{7/6} \langle\theta_i^2\rangle$$

Initial misalignment

Pre-Inflationary PQ Breaking
(f_a near GUT scale)

- Mass range 20 peV ≲ m_a ≲ 1 μeV
- "GUT-scale" axion (f_a ~ 10^{17} GeV)
- Long Compton wavelength regime (Magneto quasistatic regime)
- Lumped element detectors

Post Inflationary PQ Breaking
($f_a \sim 10^{12}$ GeV)

- Mass range 1 μeV ≲ m_a ≲ 1 meV
- Microwave Cavity regime
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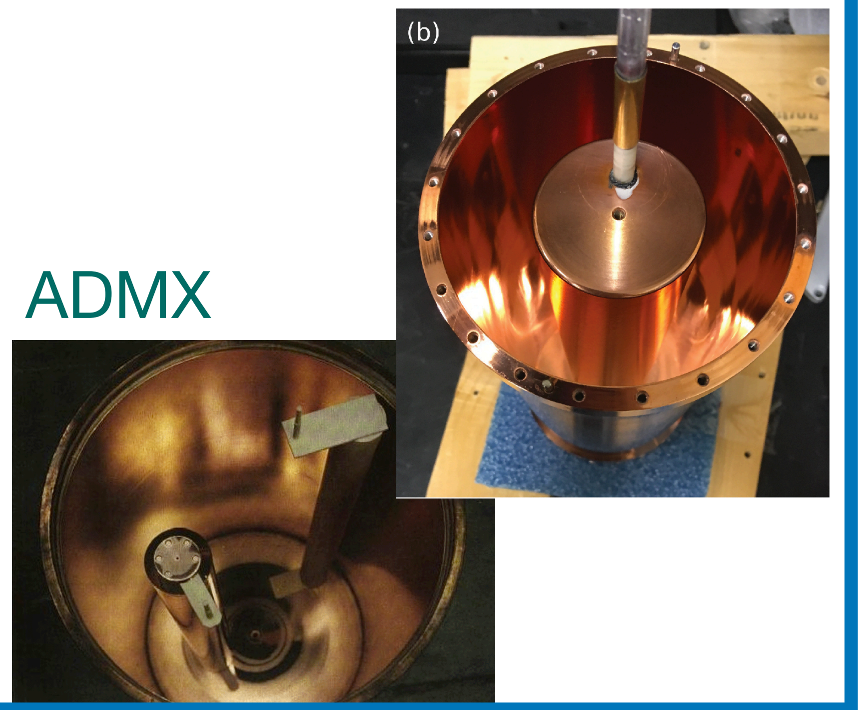
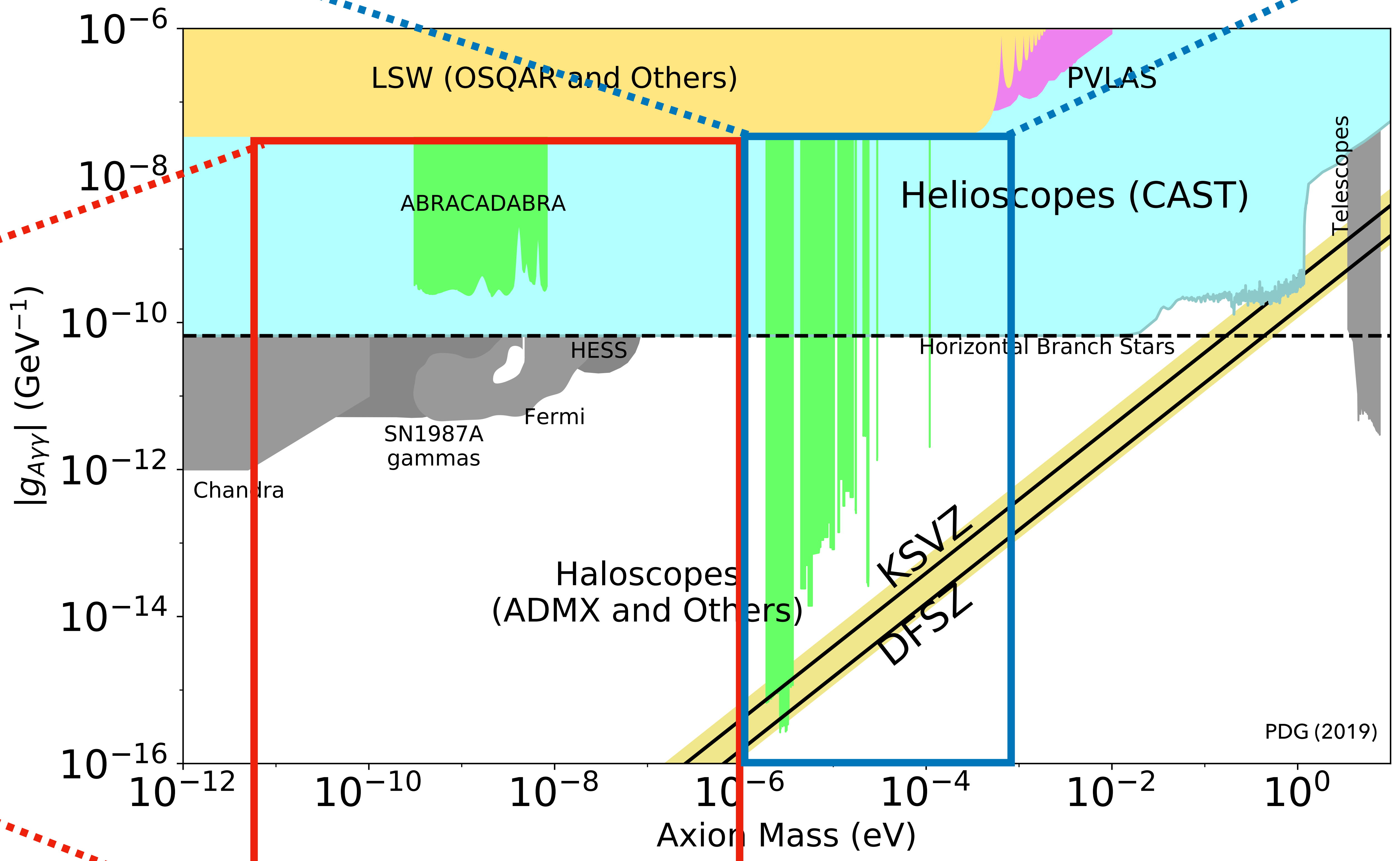
HAYSTAC

ADMX





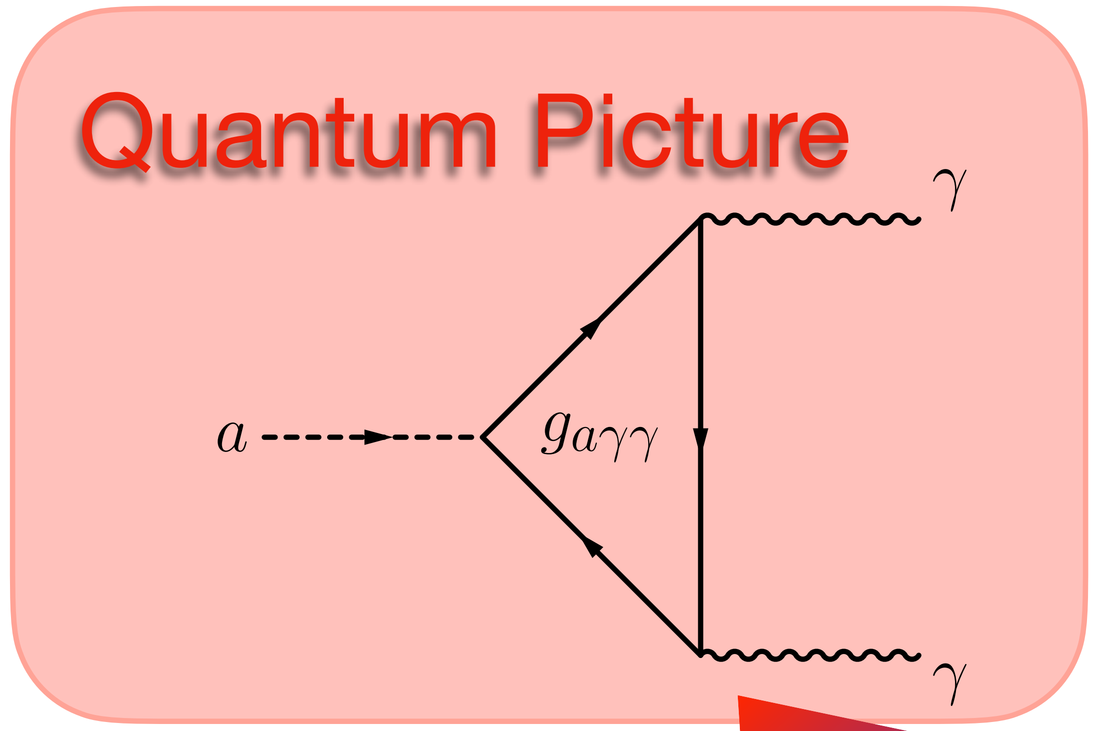
Axion Dark Matter

Axion Electrodynamics

- Axions can couple directly to many SM particles, but in this talk we focus on the a↔γγ coupling
  - In the quantum picture, this coupling is known as the (Inverse) Primakoff conversion
  - In the classical picture, this leads to modifications to Maxwell's Equations
- Additional terms in Maxwell's Equations
  - Axions can be thought of as generating an effective current in the presence of a magnetic field

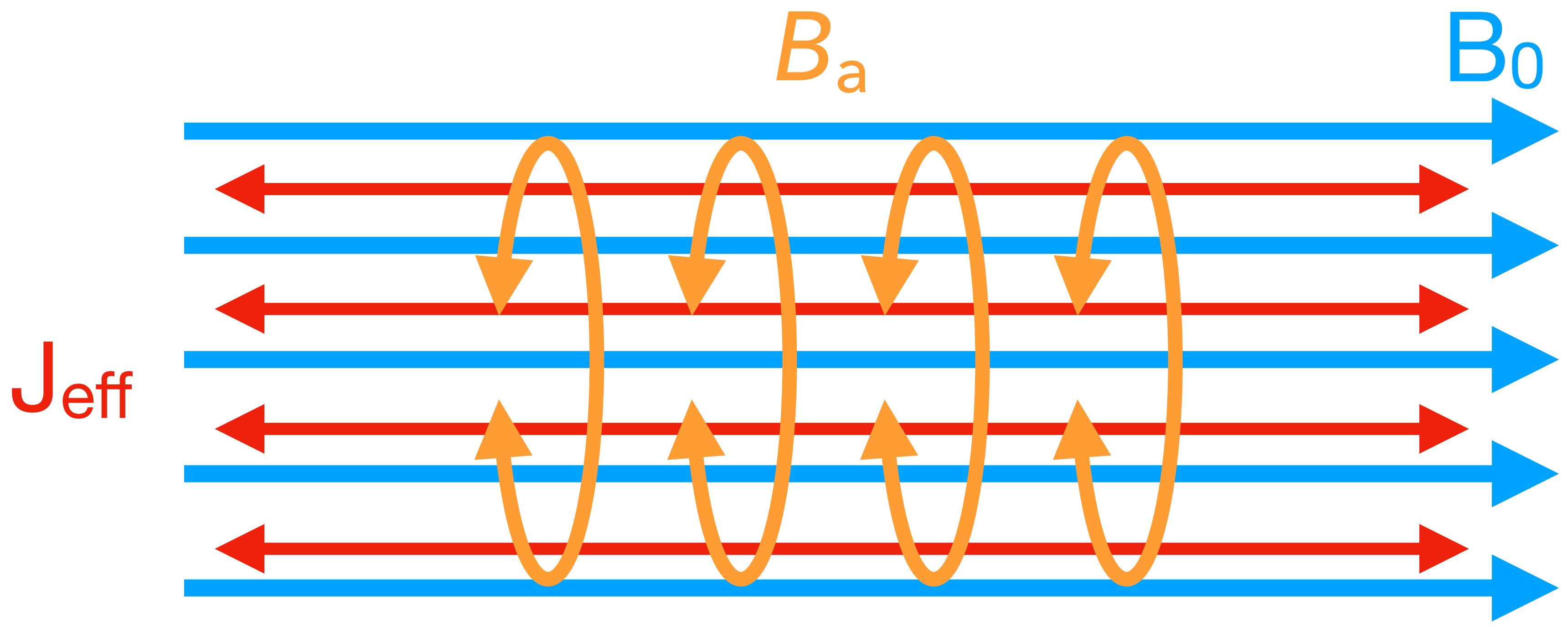
$$J_{\text{eff}} = g_{a\gamma\gamma}\partial_t a \mathbf{B} \approx g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}}\cos(m_a t)\mathbf{B}$$

  - We search for axion dark matter by looking for the induced **E** and **B** fields from this current
- There are of course, many ways to search for ADM!

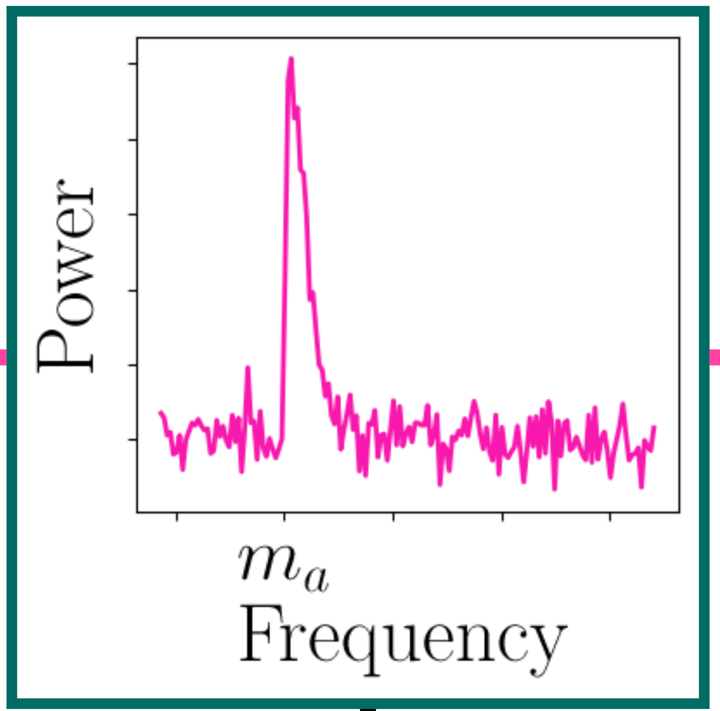


Classical Picture

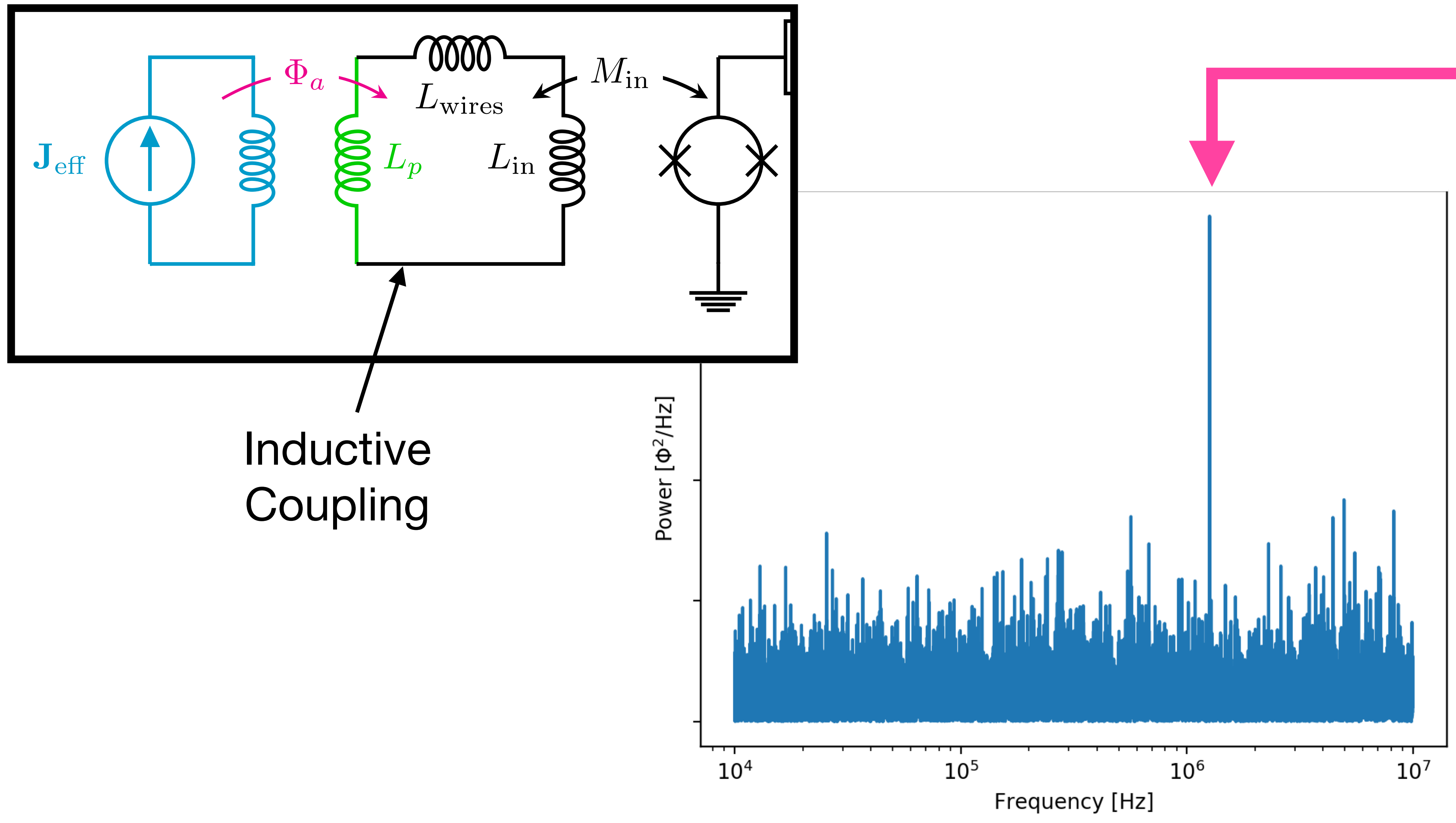
$$\nabla \cdot \mathbf{E} = -g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E}\times\nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$



From Broadband To Resonant



Broadband



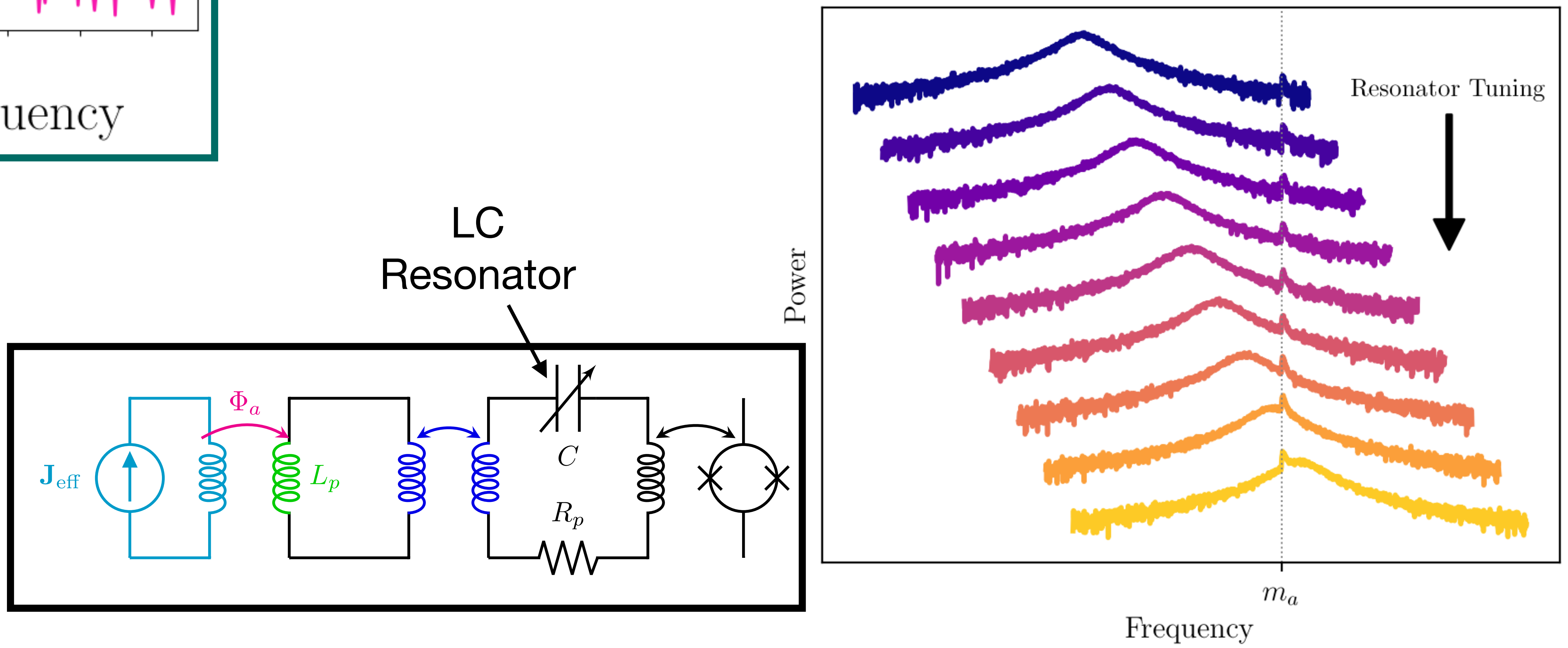
- E.g. ABRACADABRA, SHAFT

✓ Searches all frequencies simultaneously, no tuning

✓ Easier detector setup

✗ Higher noise, less sensitive

Resonant



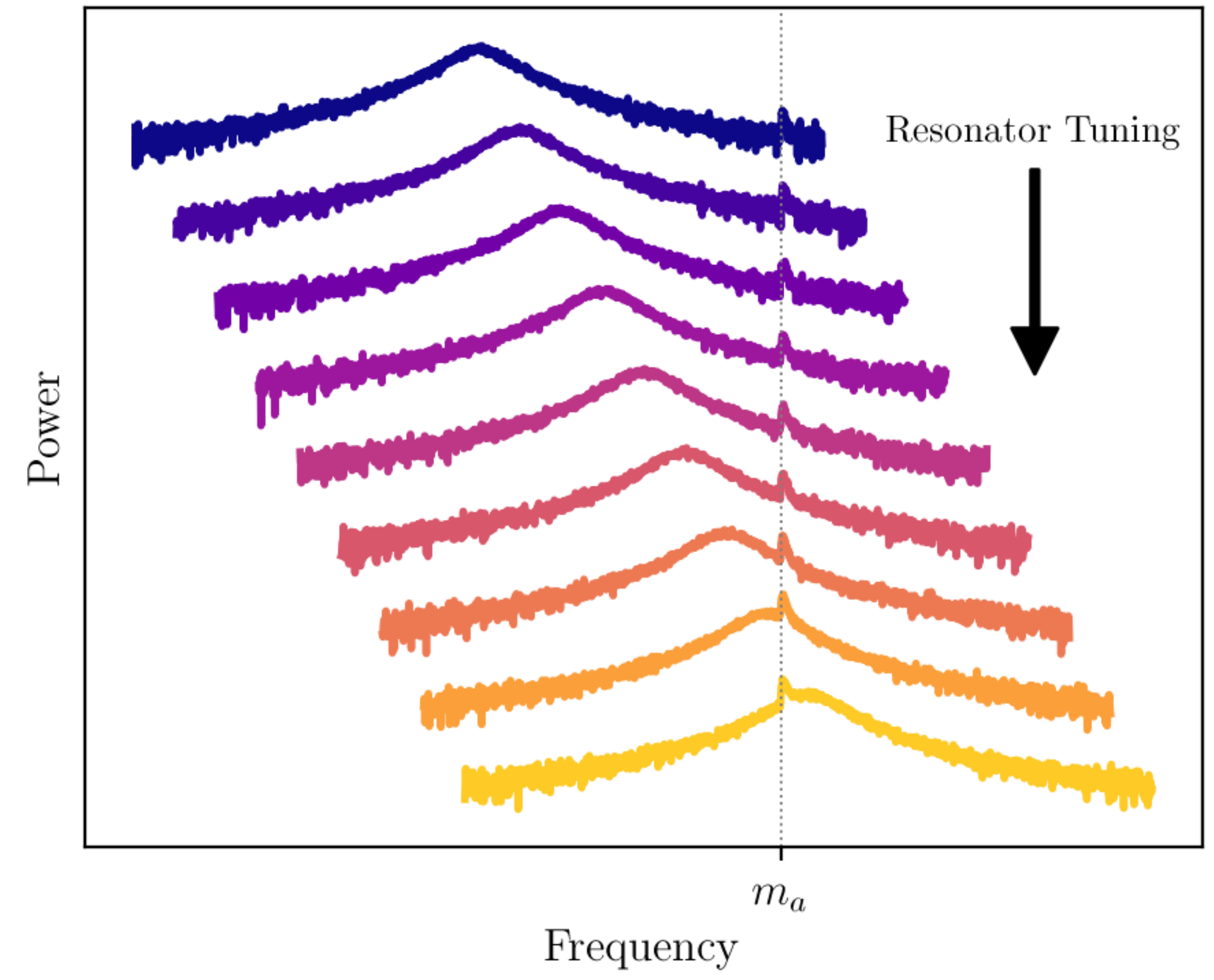
- E.g. ADMX, HAYSTAC, DMRadio

✗ Must scan in frequency

✗ More complicated detector setup

✓ Ultimately better sensitivity (Chaudhuri et. al arXiv:1803.01627)

Optimizing the Scan Rate



- Resonator scan rate

$$\frac{\partial \nu_r}{\partial t} = \frac{g^4_{a\gamma\gamma}}{\mathrm{SNR}^2}\left(\frac{\rho^2_{\mathrm{DM}}}{\nu_0 \nu_{\mathrm{obs}}}\right)\left(\frac{\nu_r c^4_{\mathrm{PU}} V^{10/3} B_0^4 Q}{n_A(\nu_r) k_B T}\right)$$

(Chaudhuri et. al arXiv:1803.01627)

Desired Sensitivity | DM Characteristics | Detector Design

Detector figure of merit:

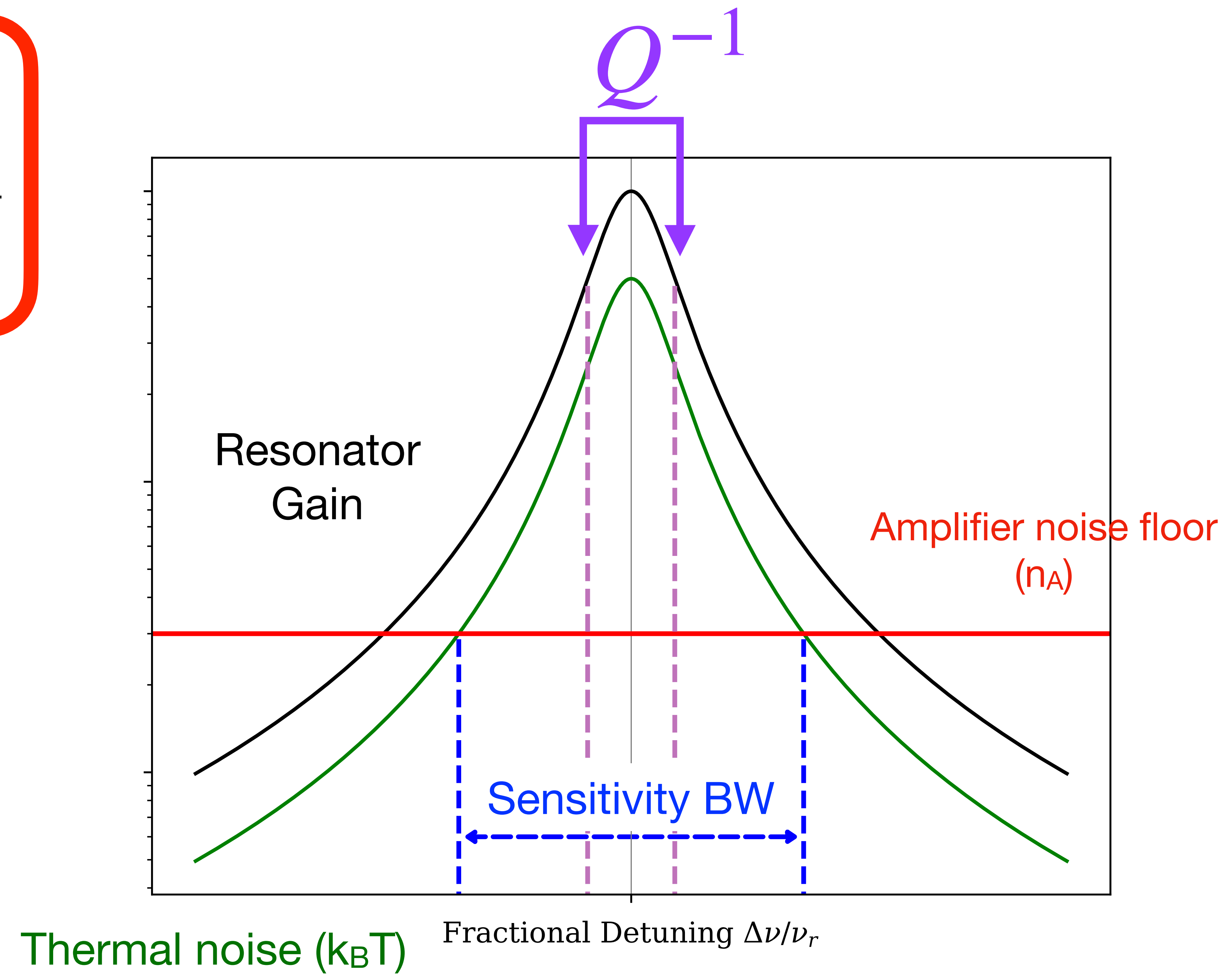
$$\mathcal{F} = \frac{c_{\mathrm{PU}} V^{\frac{5}{6}} B_0 Q^{\frac{1}{4}}}{n_A^{\frac{1}{4}} T^{\frac{1}{4}}}$$

- We want to build a detector with:
  - Large volume (V)
  - Large B field (B_0 ~ Teslas)
  - Strong geometry coupling (c_{PU})
  - Low temperature (T ≲ mK)
  - Low amplifier noise (n_A ~ SQL or better)
  - Low loss resonator (Large Q-factor)

Large signal

Low Noise

Large Gain



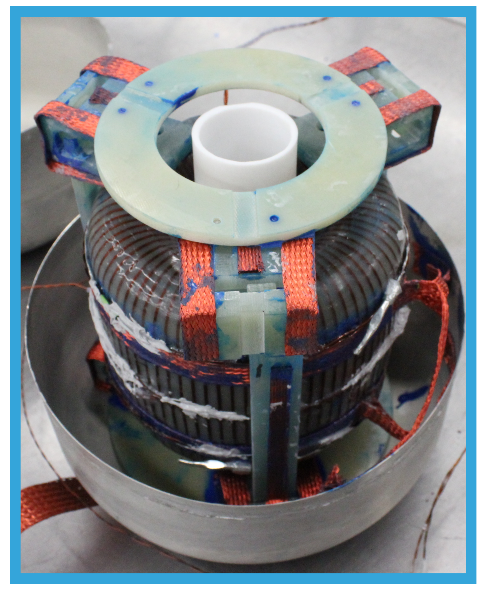
DMRadio

A Multistage Program to Search for Axion Dark Matter Below 1 μeV

ABRACADABRA

Running

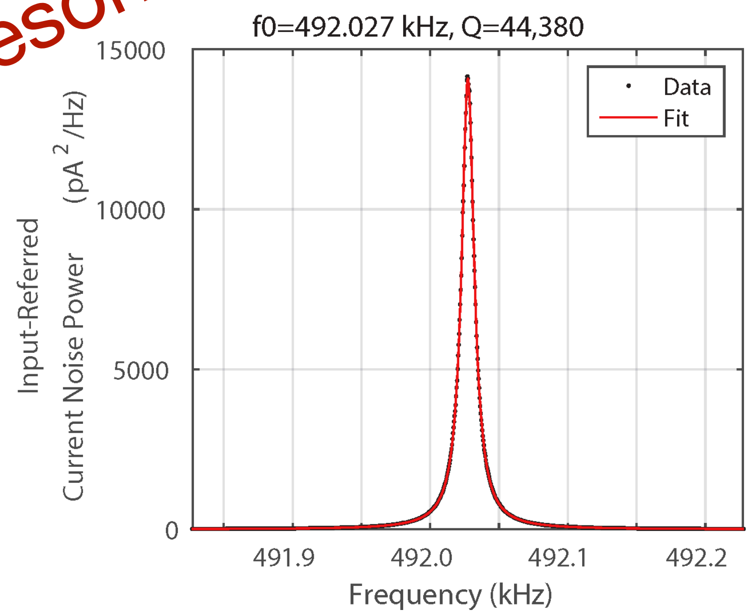
Broadband



- PRL 122, 121802 (2019)
- PRD 99, 052012 (2019)
- PRL 127, 081801 (2021)

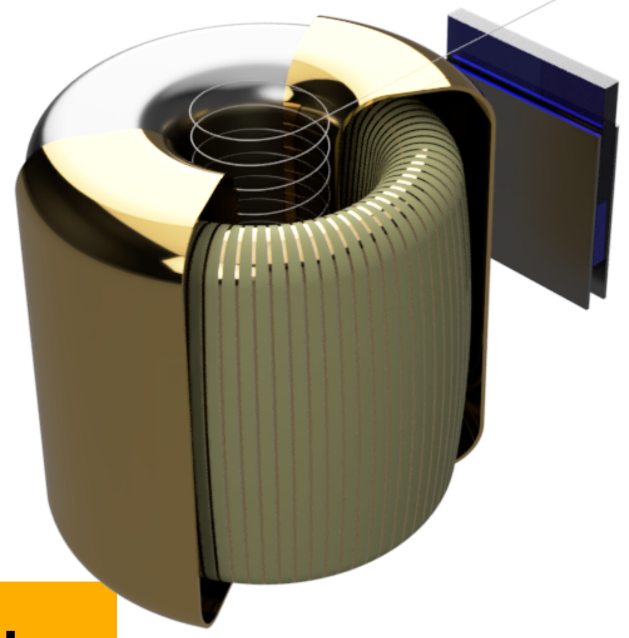
DMRadio-Pathfinder

Resonant



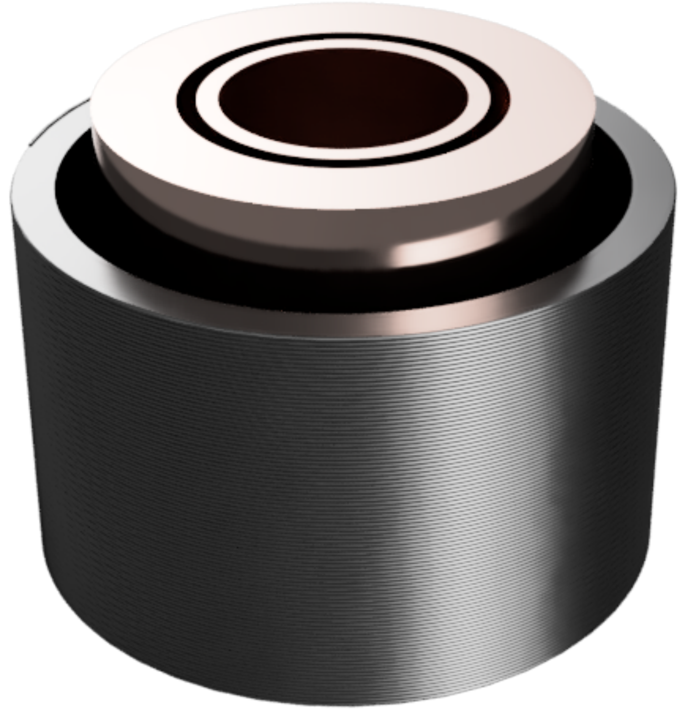
- IEEE Trans. on Appl. Superc., 27, 1(2016)

DMRadio-50L



Beginning Construction

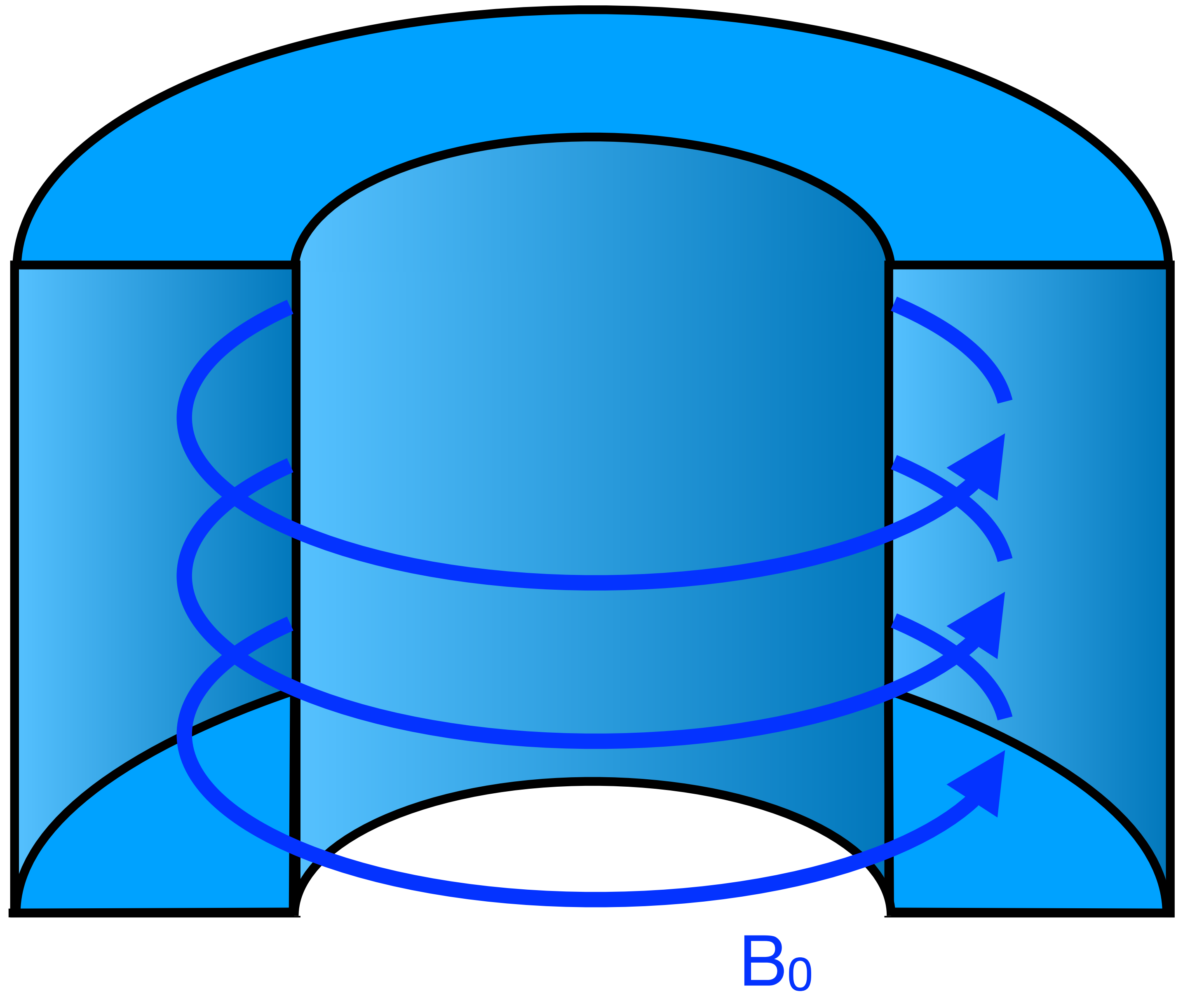
DMRadio-m^3



Future

Two Magnetic Field Geometries

Toroidal Geometry



Solenoidal Geometry

Phys. Rev. Lett. 117, 141801 (2016)

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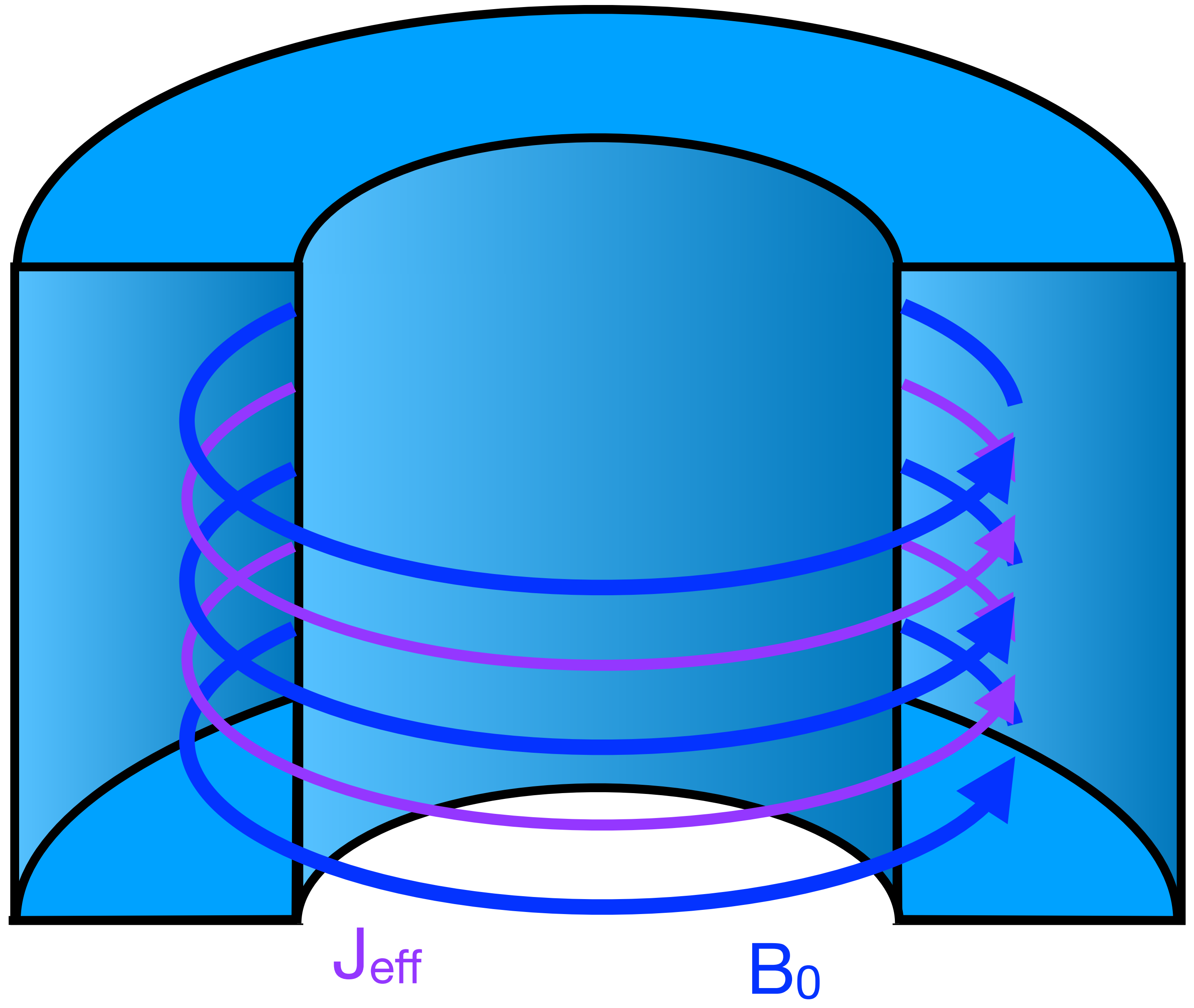

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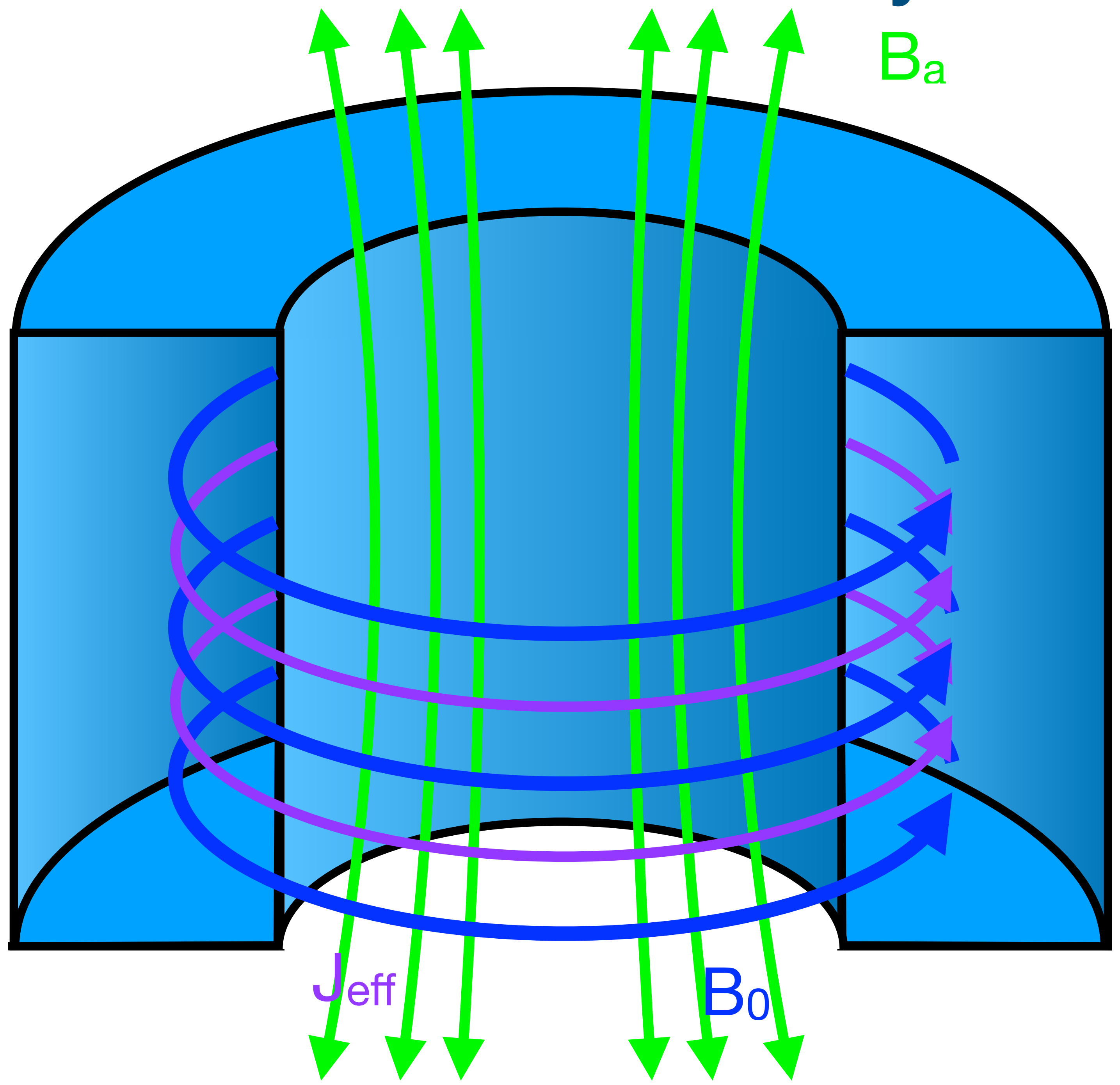

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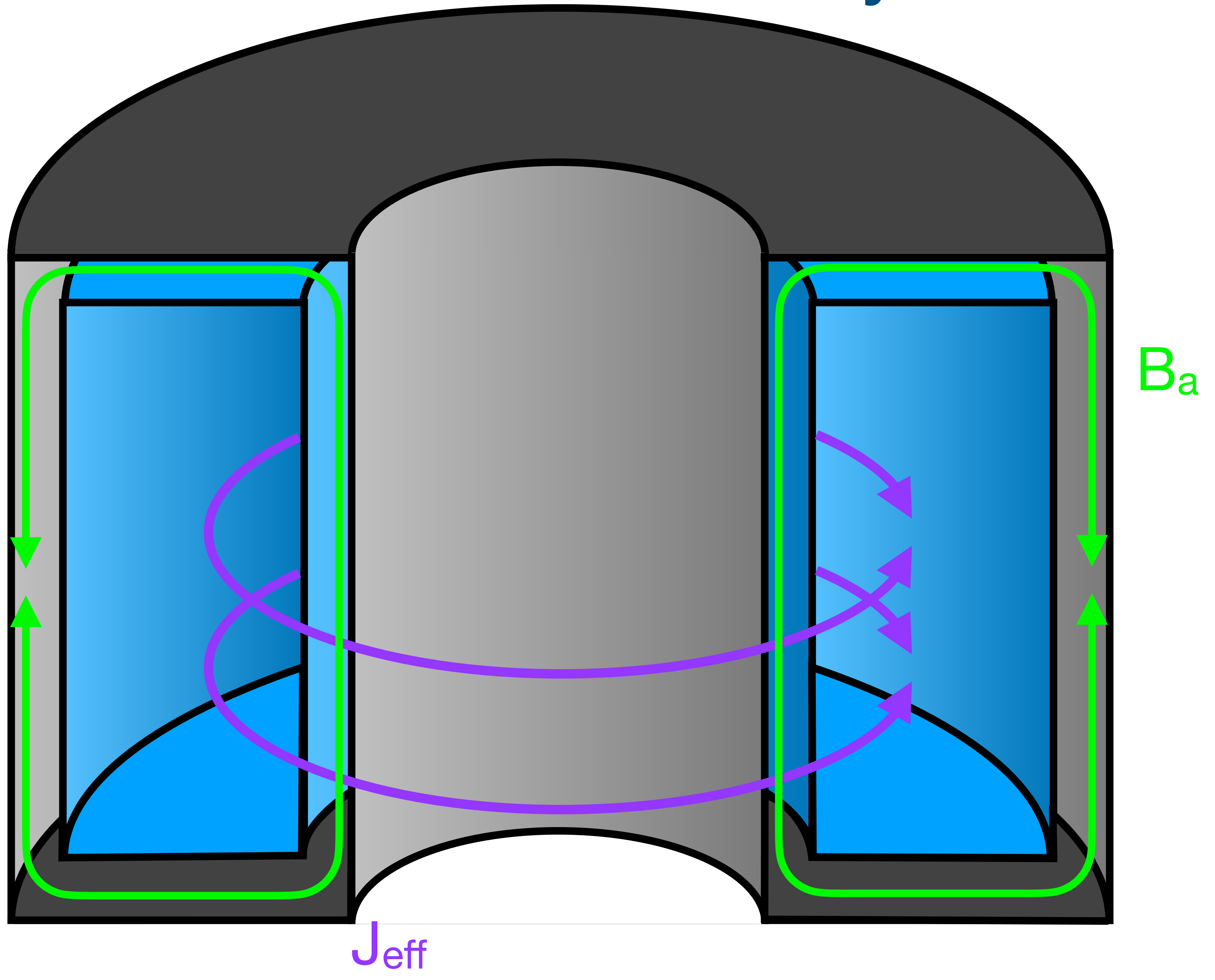

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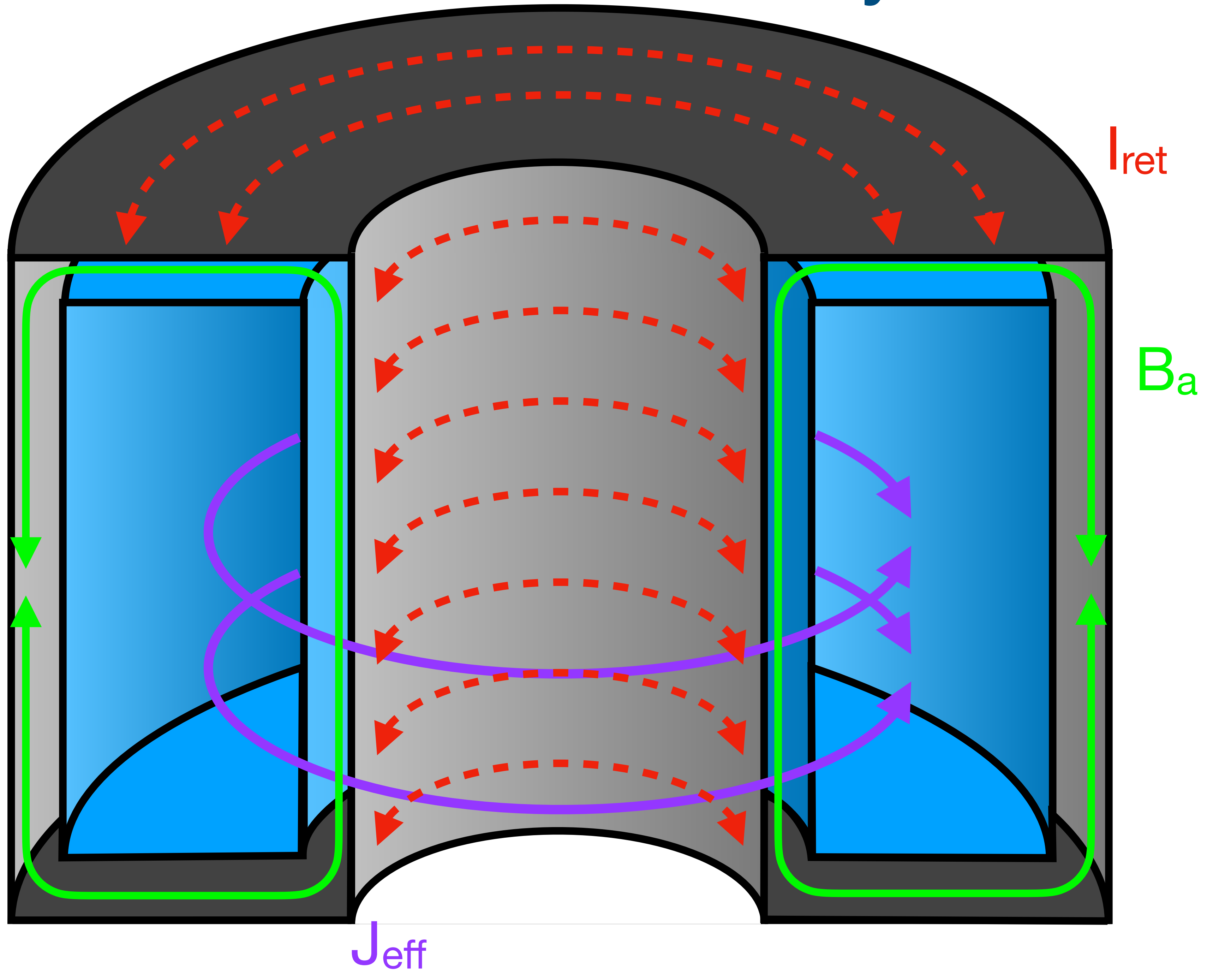

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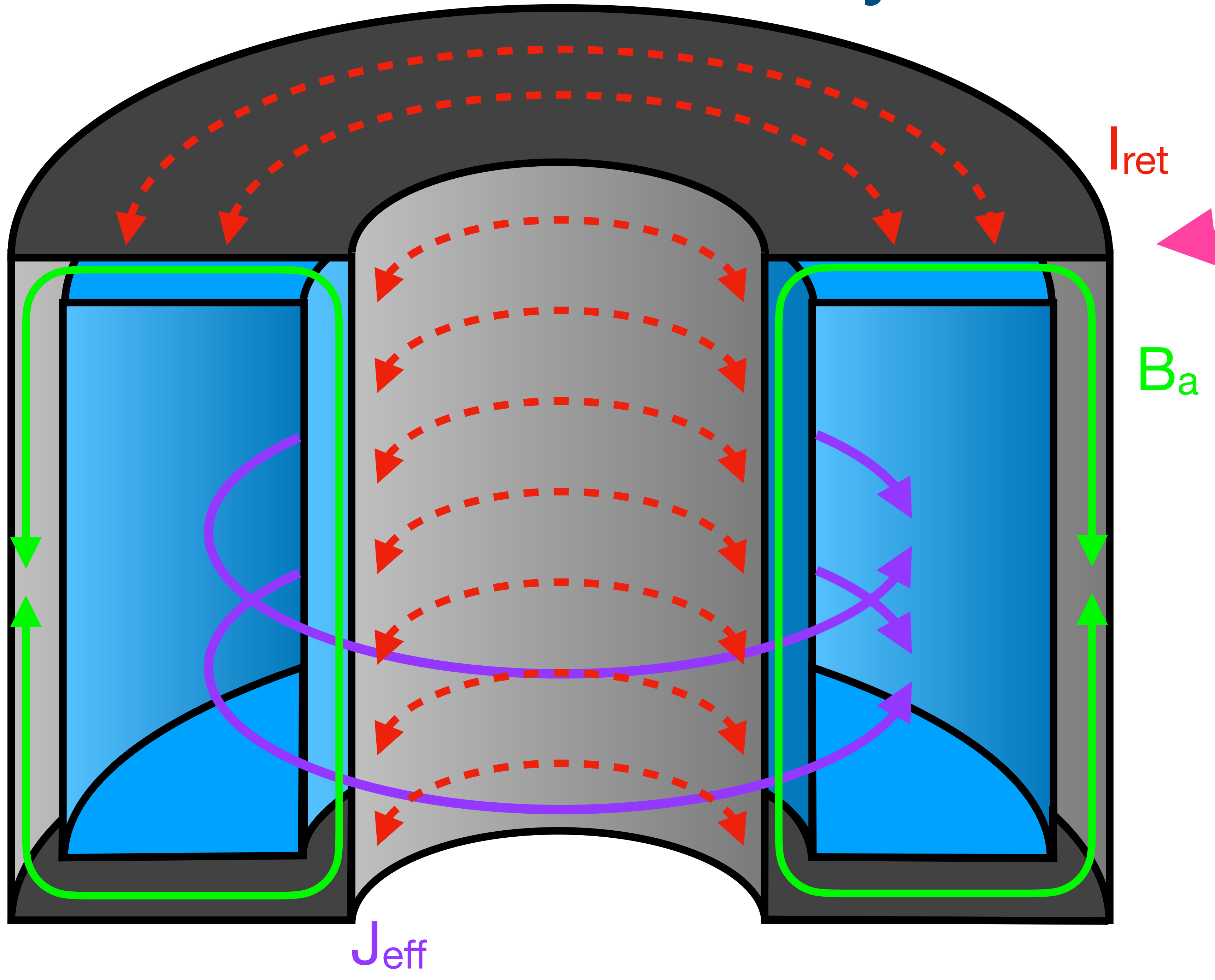

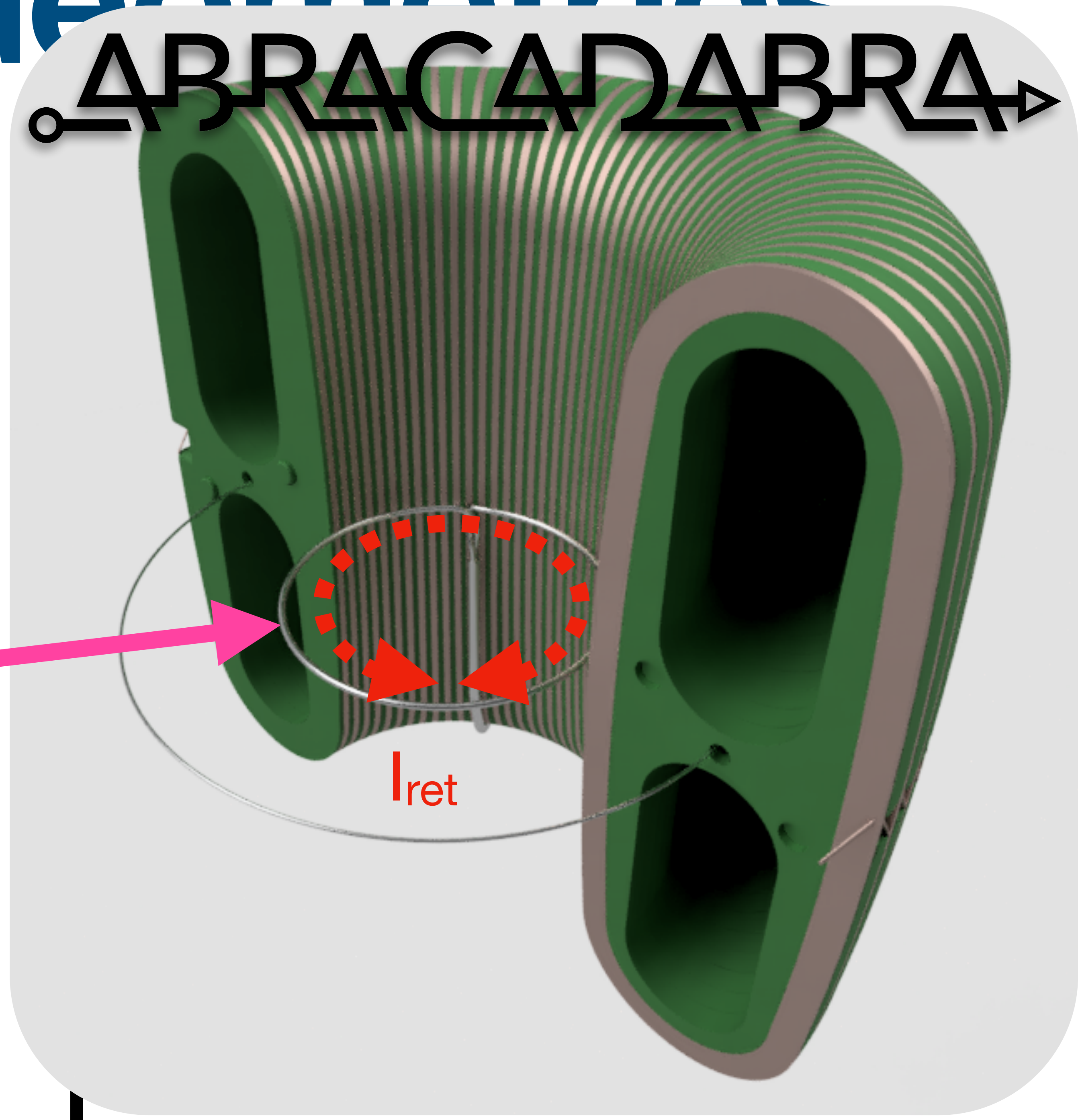

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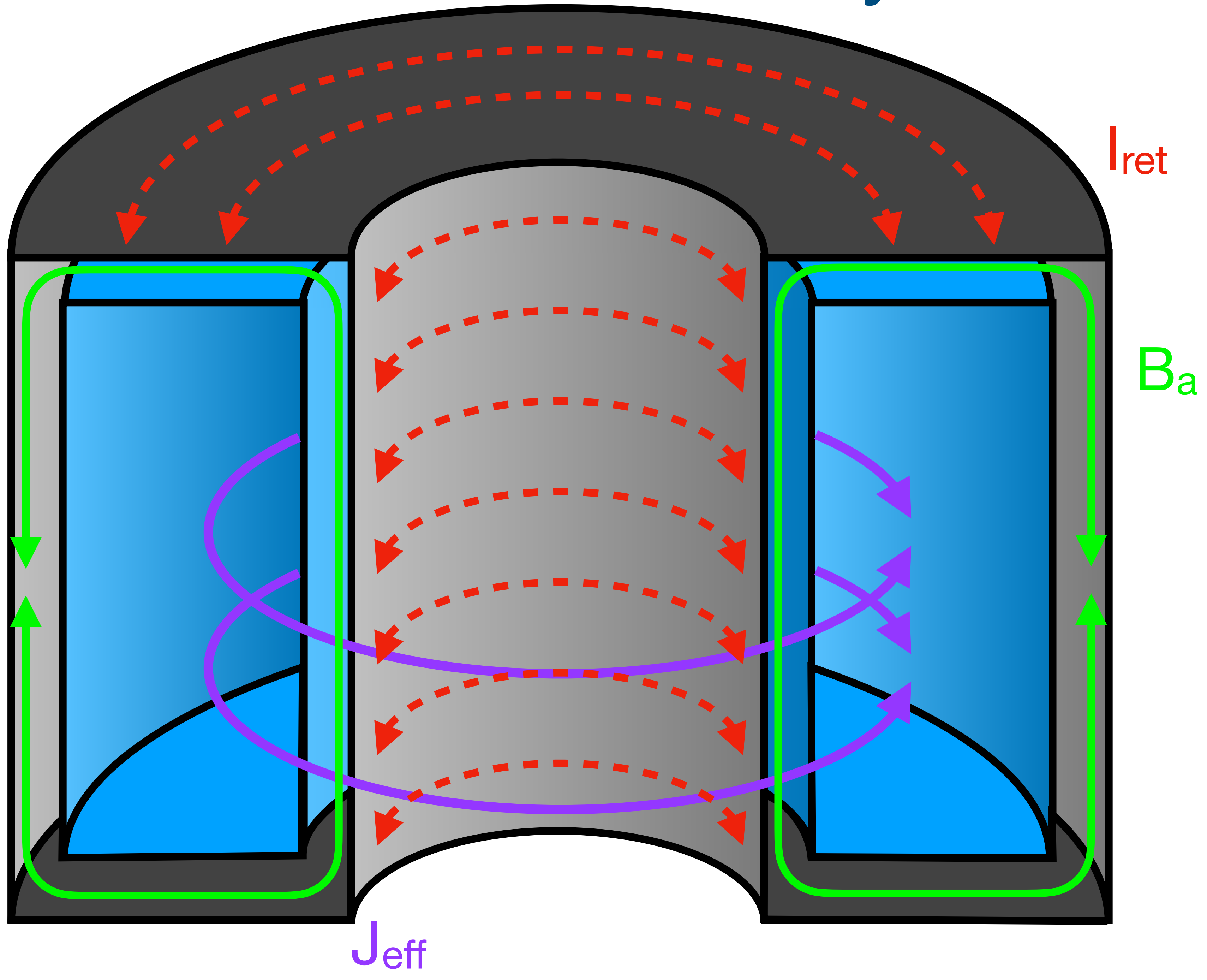

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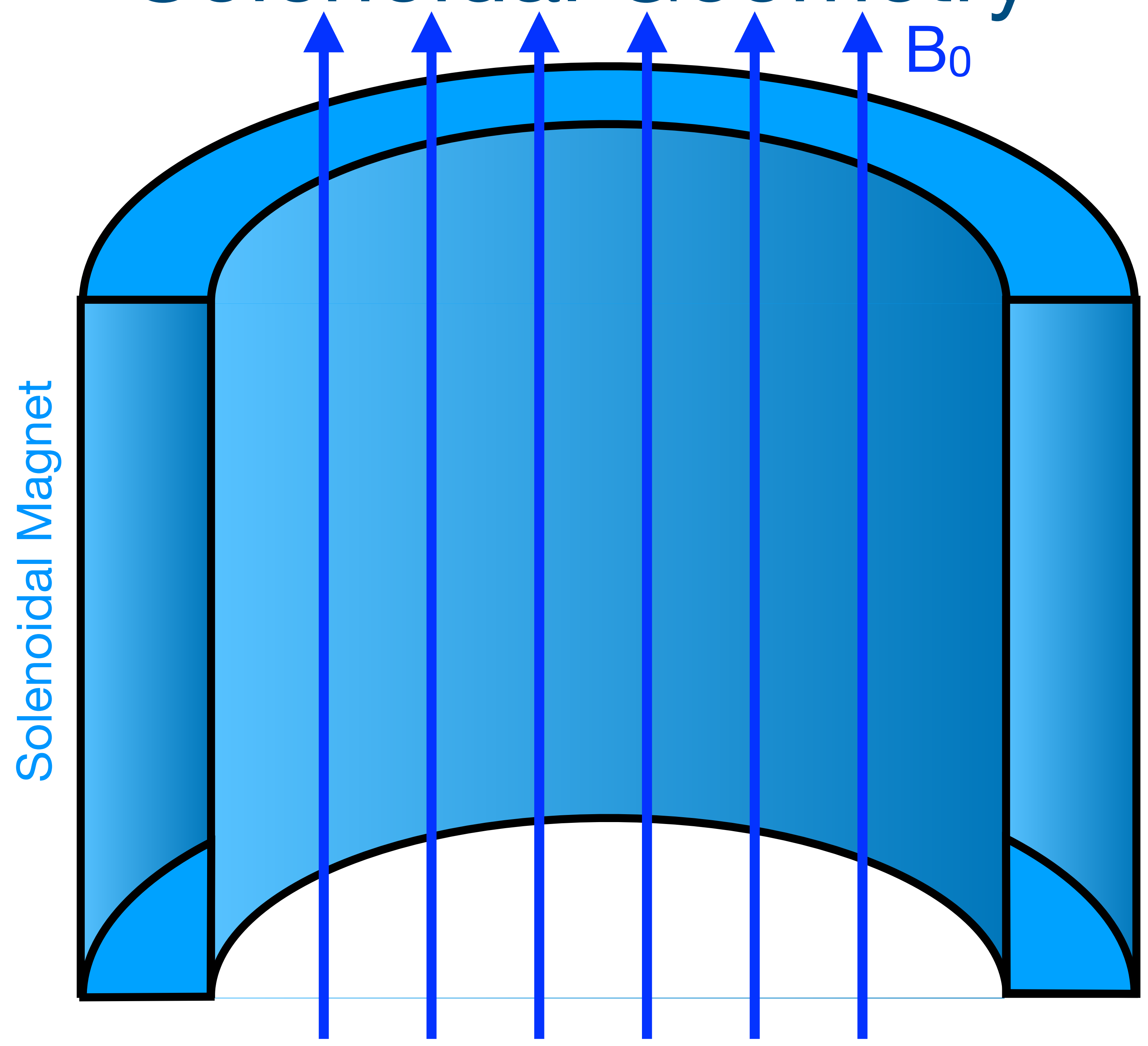

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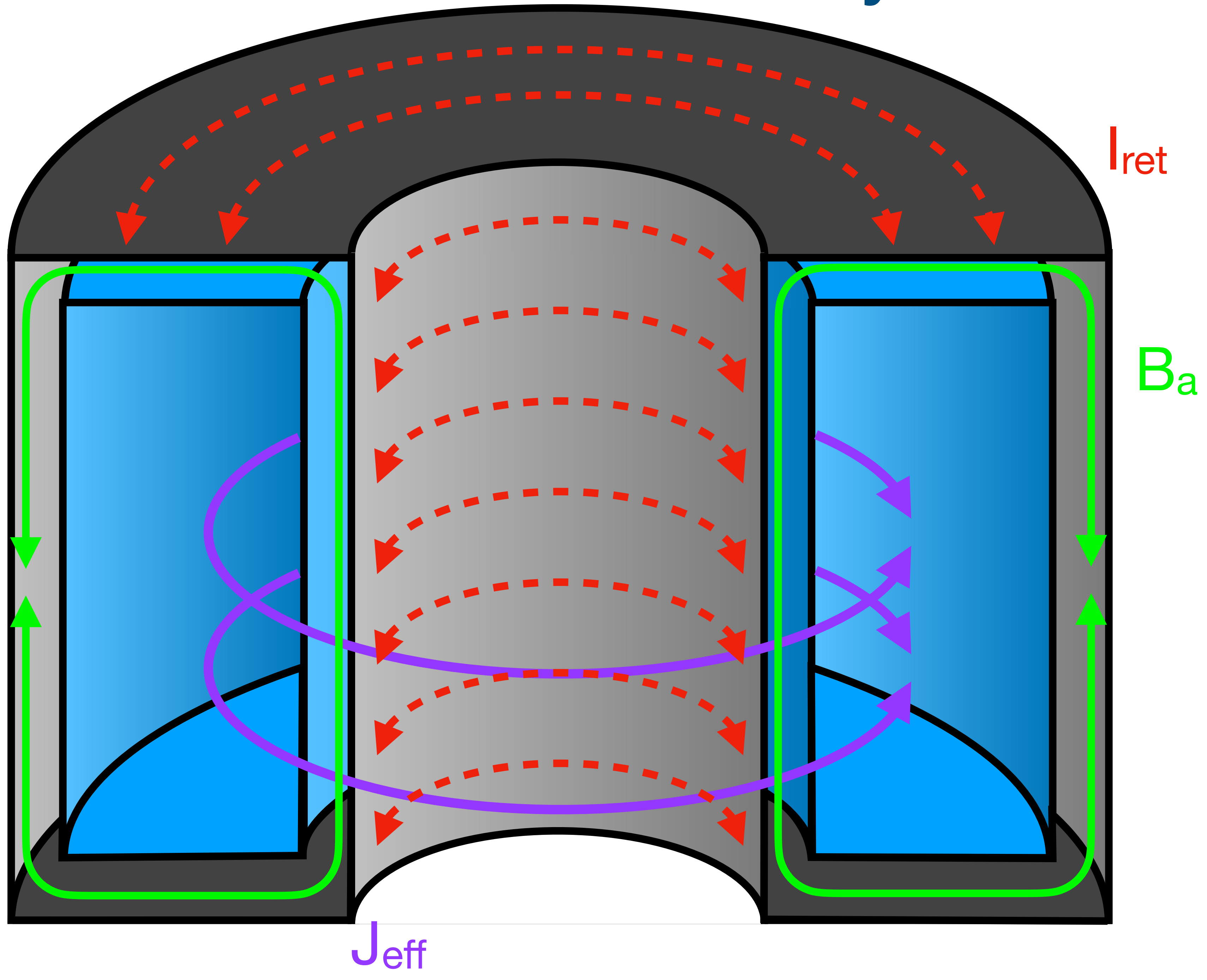

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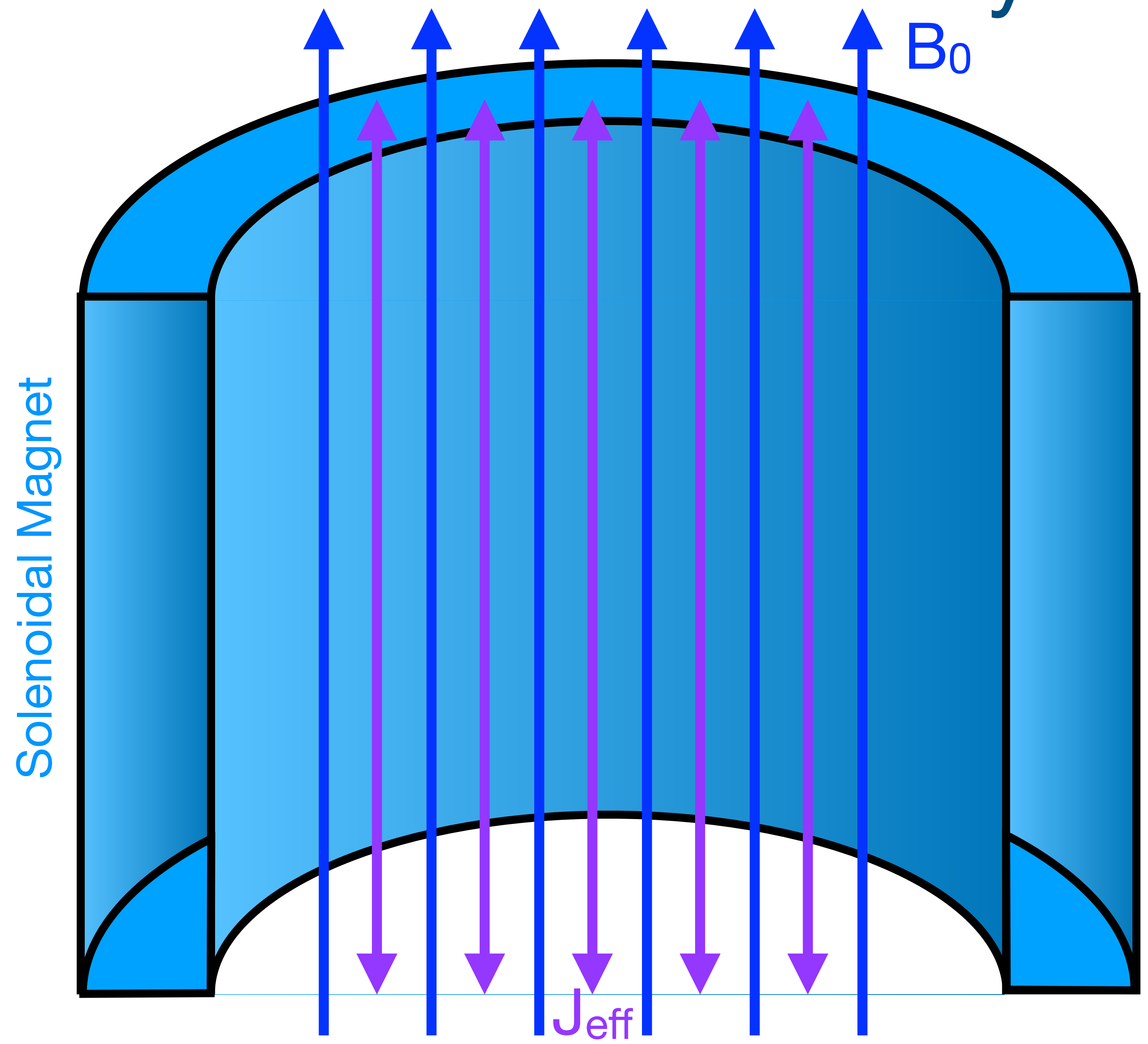

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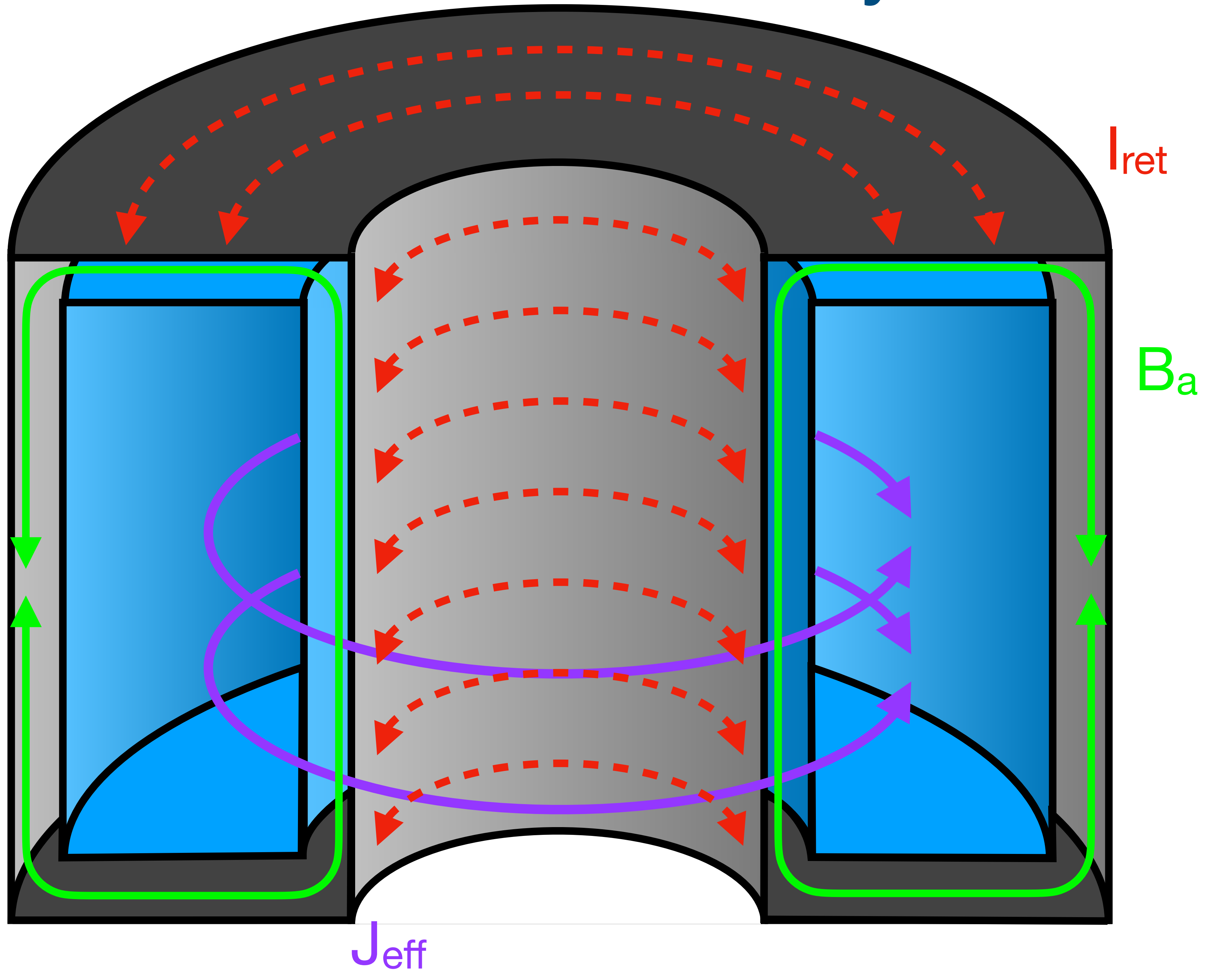

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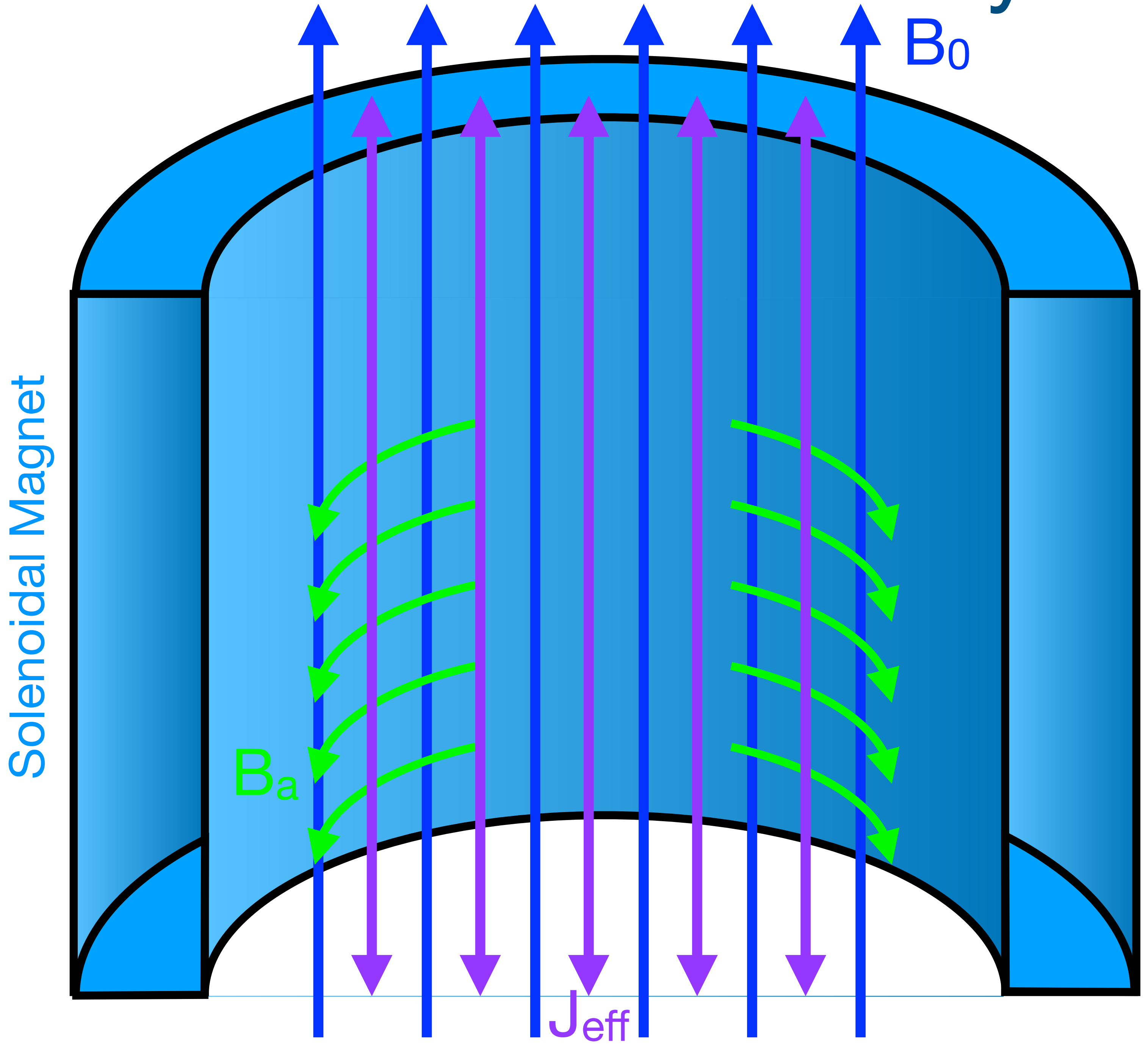

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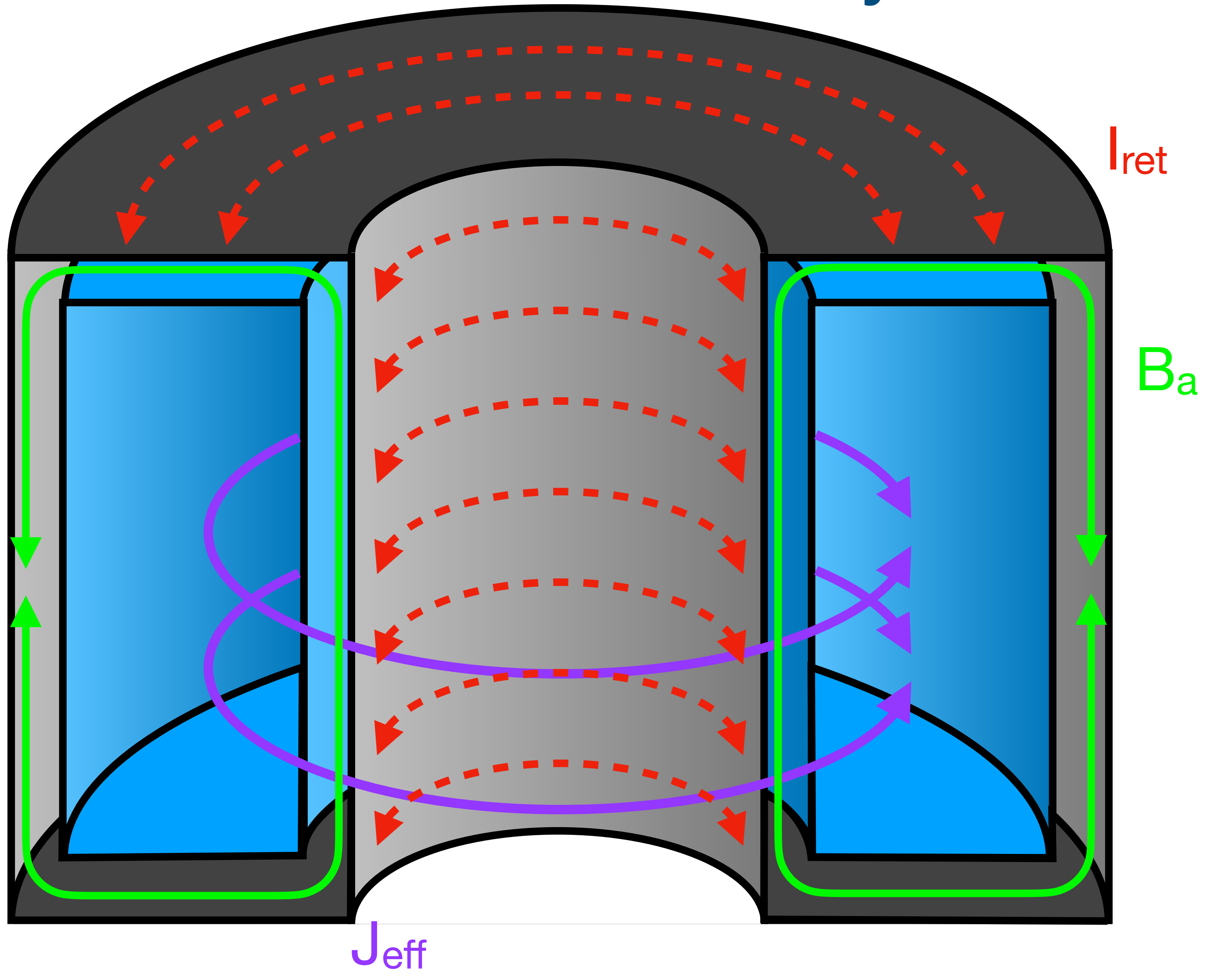

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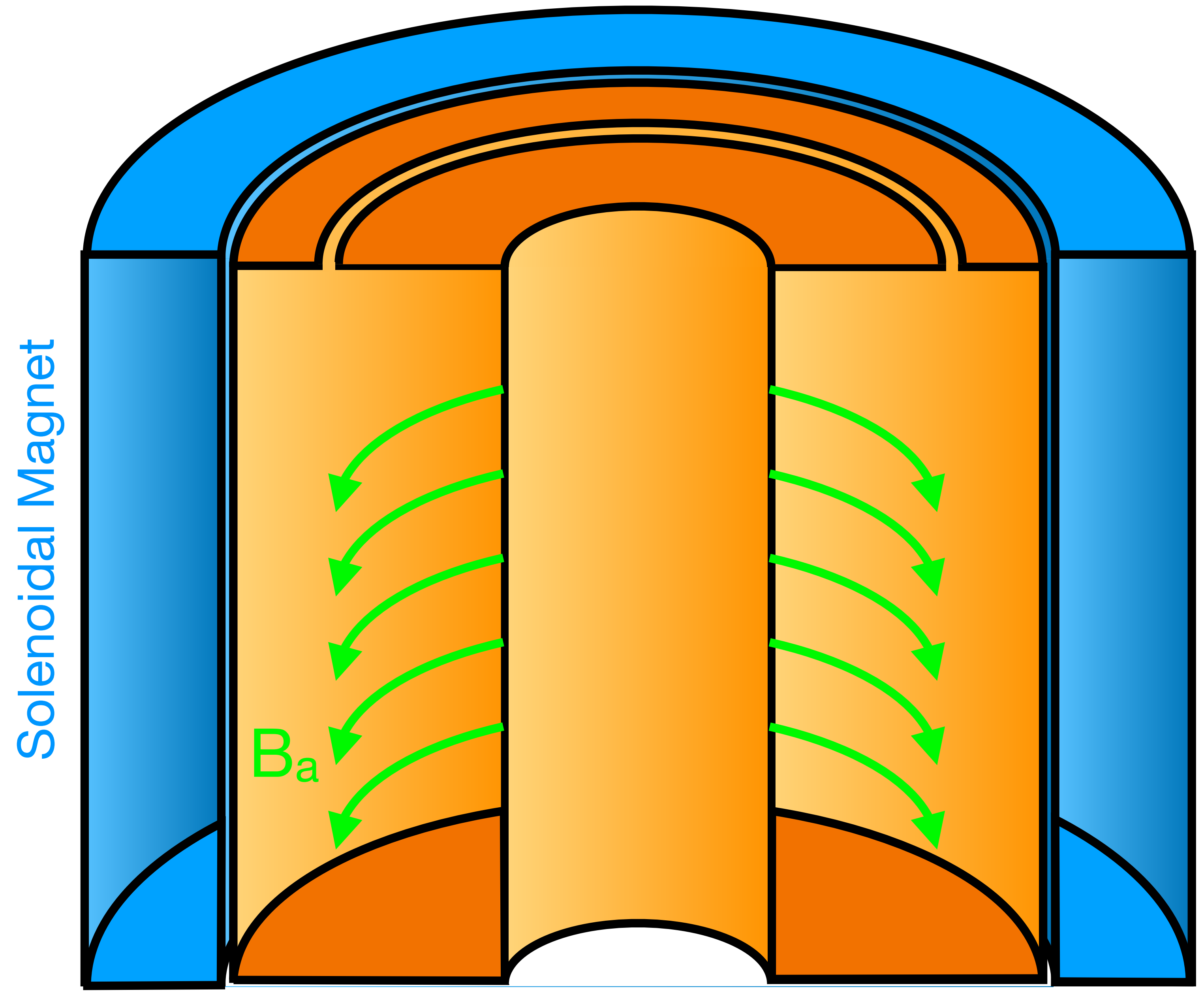

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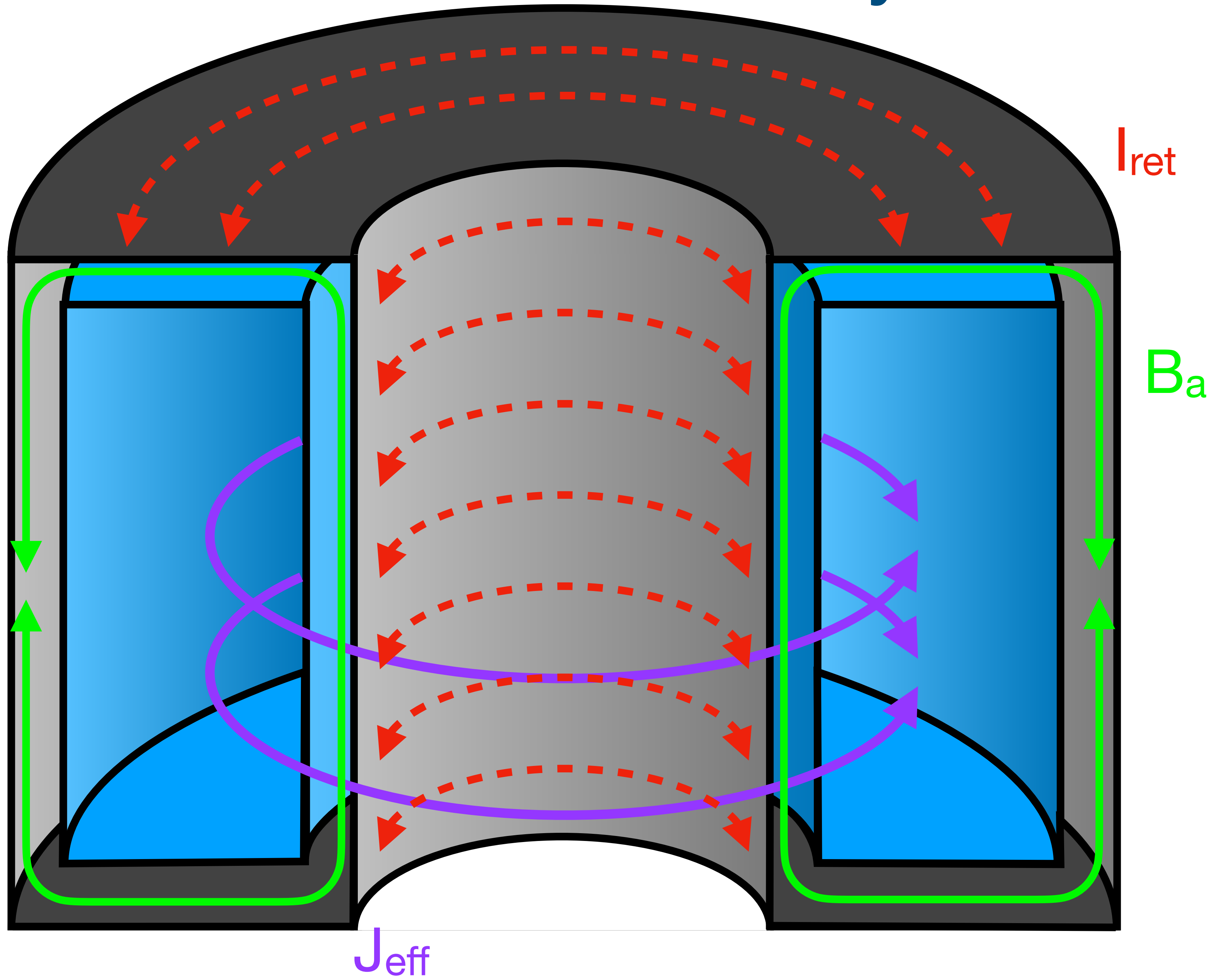

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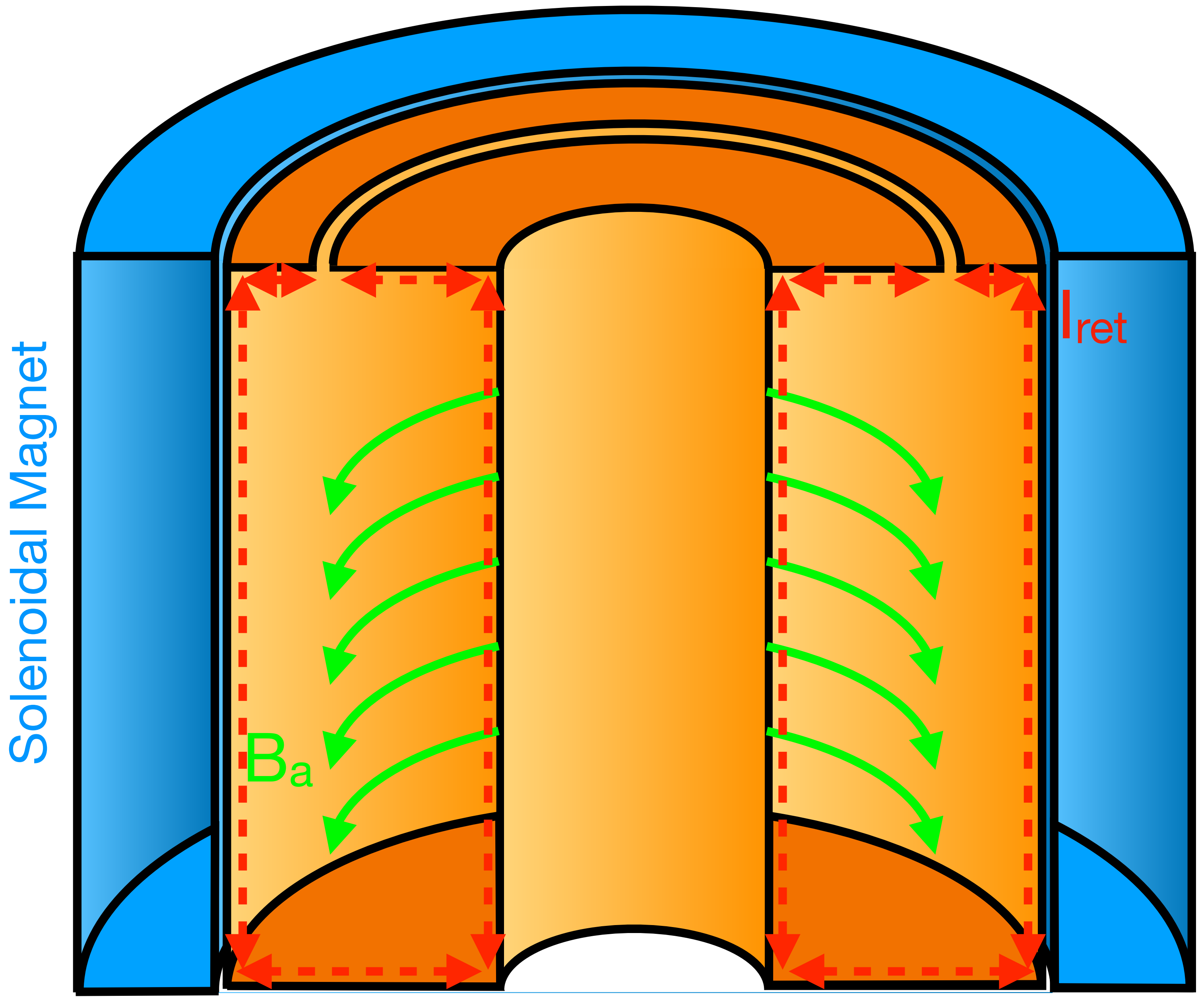

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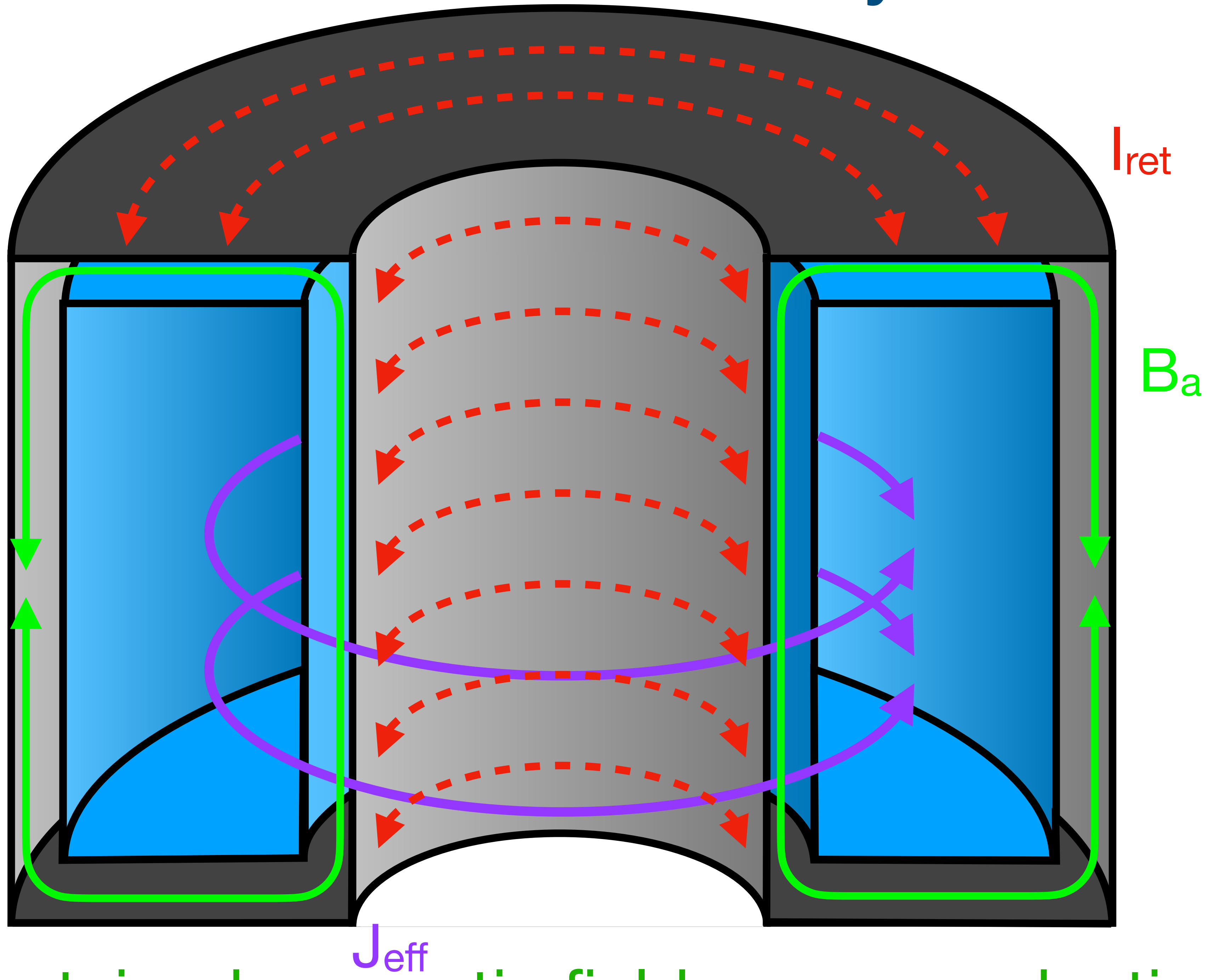
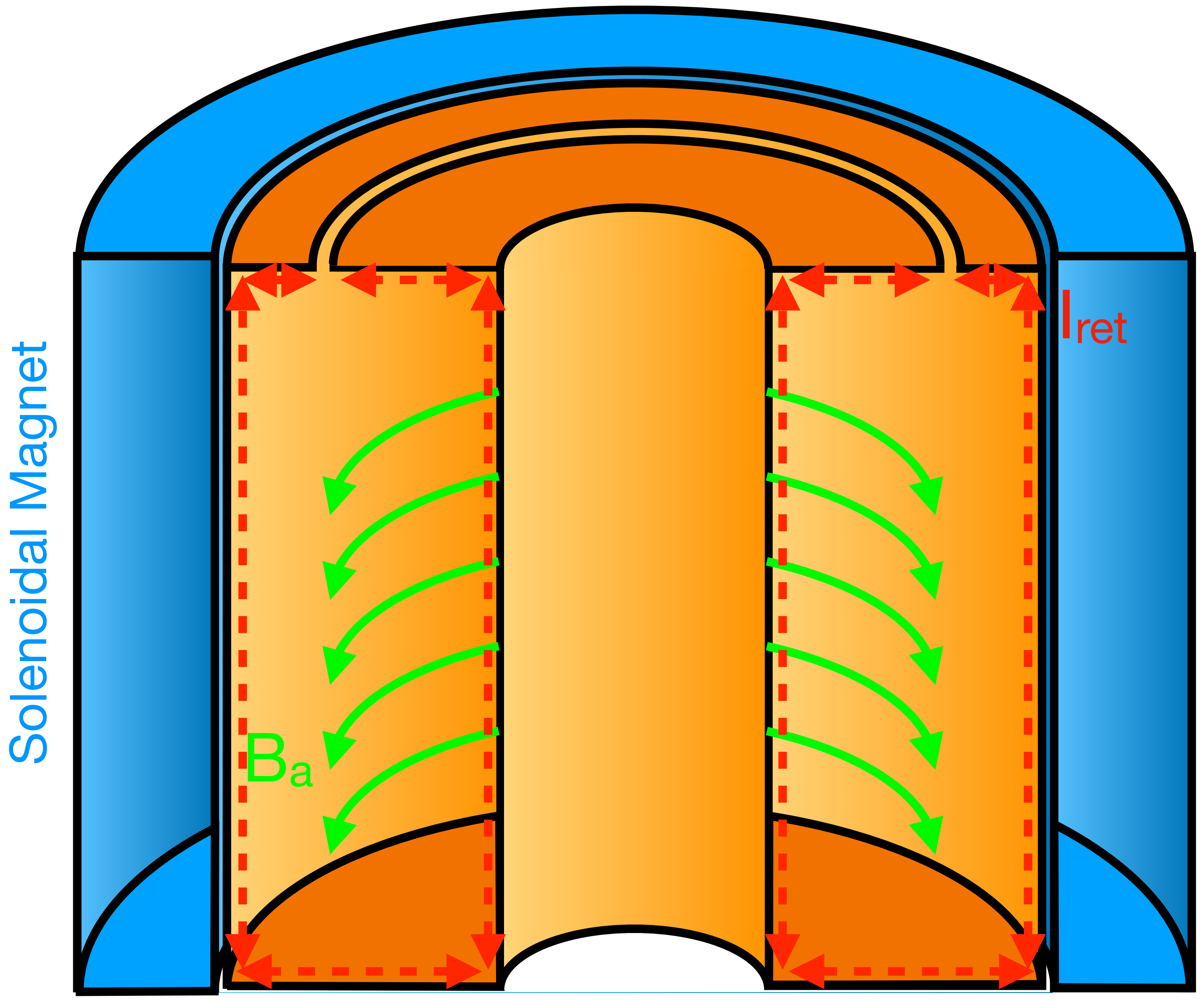


✓ Contained magnetic field, superconducting components, lower stray fields

✗ Less common magnet geometry, difficult to scale

Solenoidal Geometry



✓ Common magnet geometry, fewer parasitics (easier to scale to large volume)

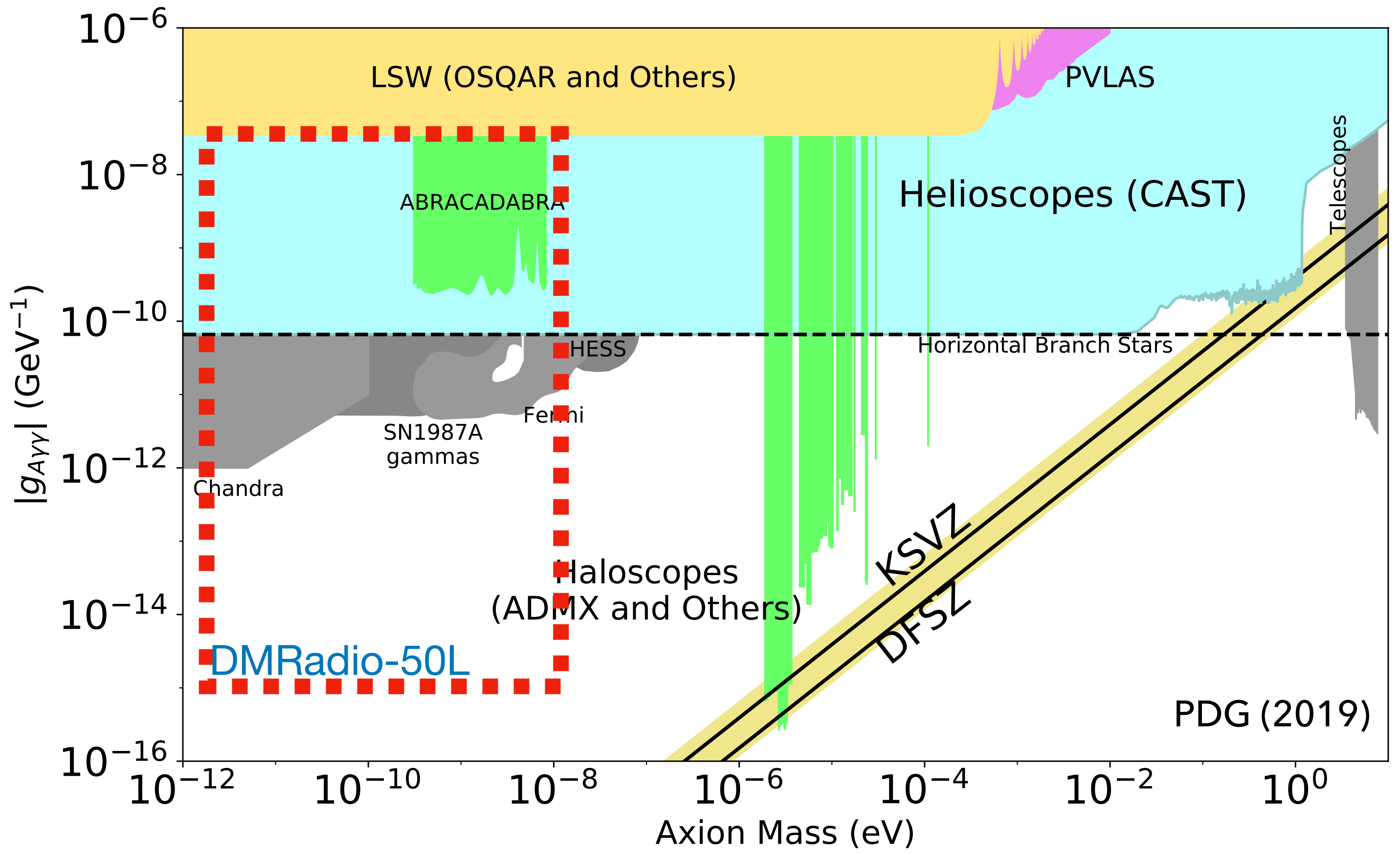
✗ Stray magnetic fields

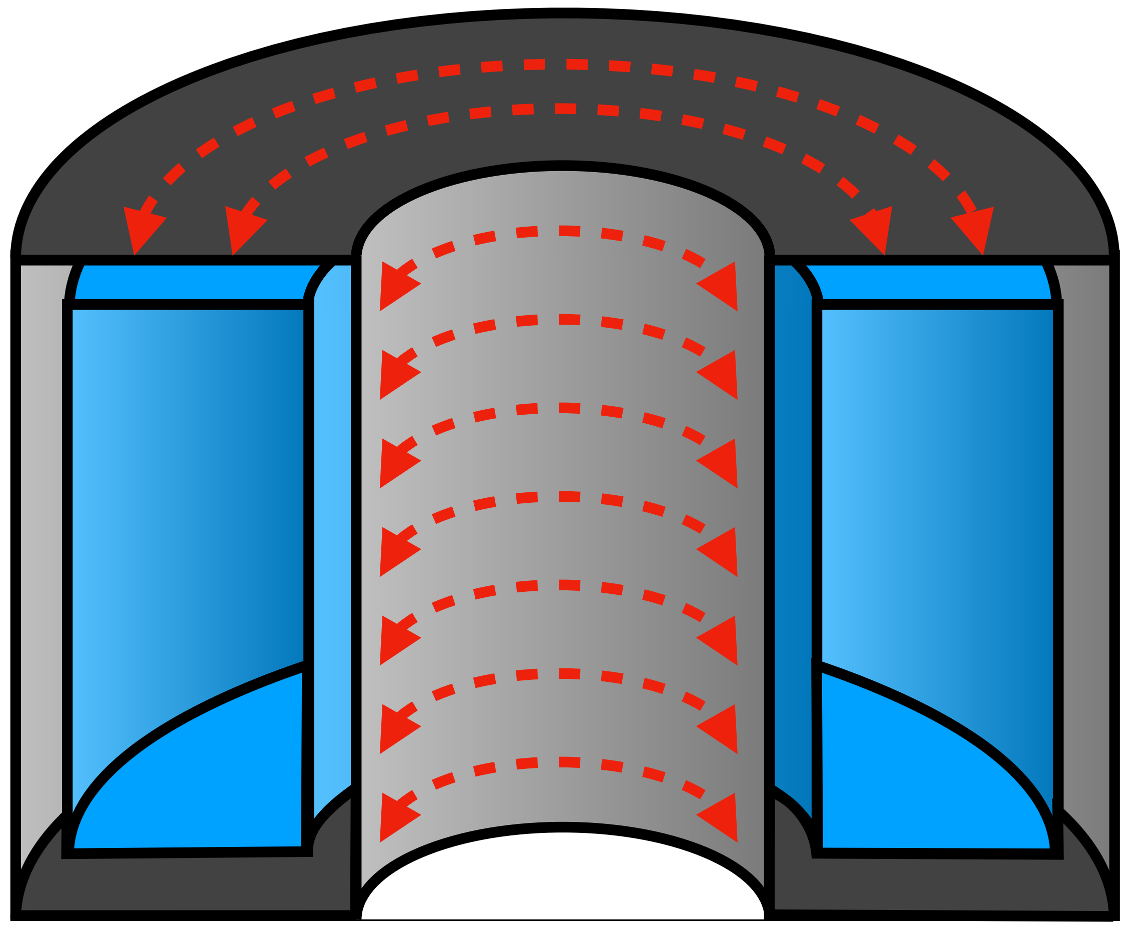
Phys. Rev. Lett. 117, 141801 (2016)

DMRadio-50L

DMRadio-50L

Toroidal Geometry

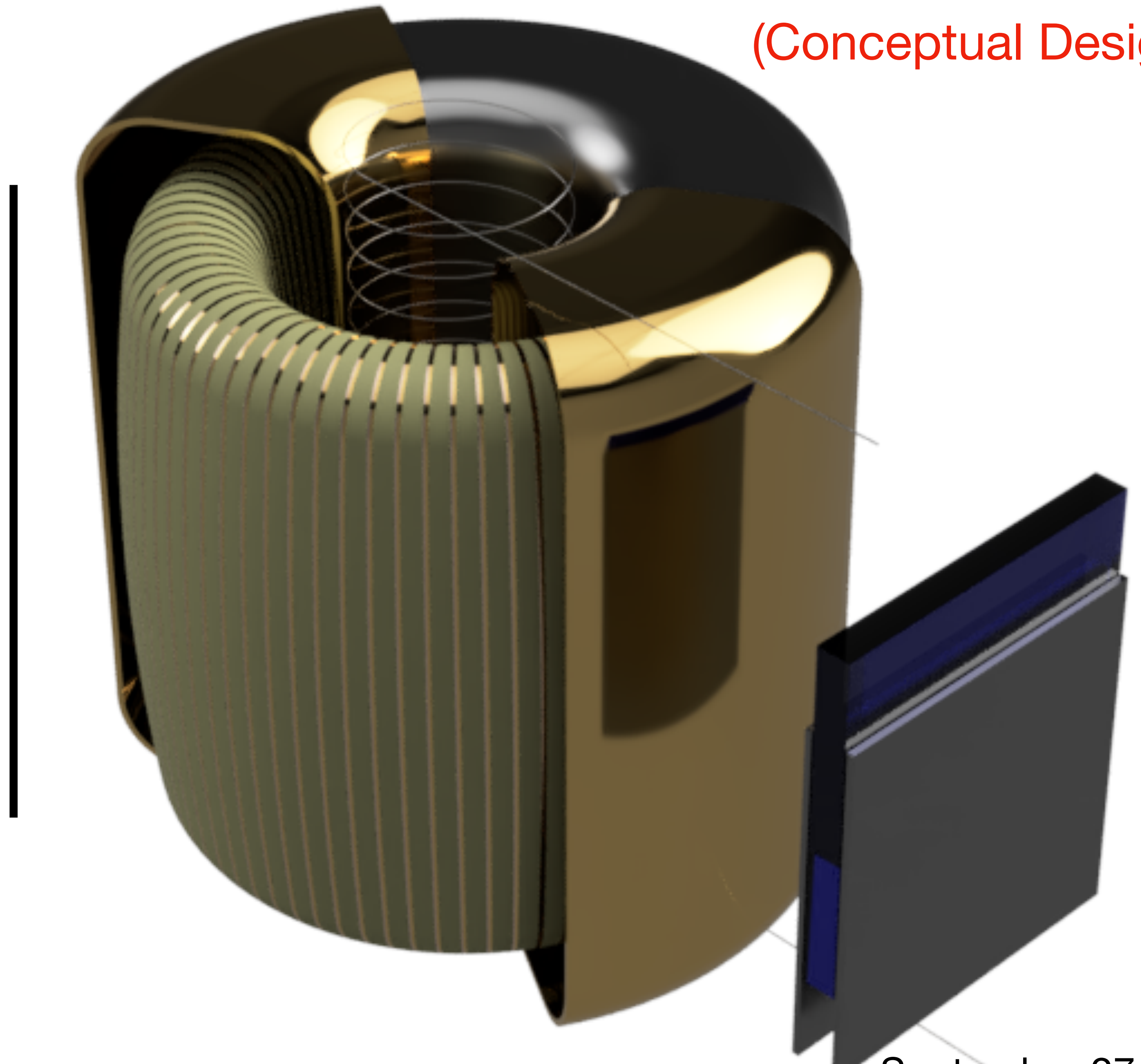




- 50L toroidal magnet, 1T maximum field
- Optimized for lower mass/lower frequency range
  20 peV < m_a < 20 neV (5 kHz < ν_a < 5 MHz)
- Superconducting sheath carries the return current
- Aiming for a resonator quality factor of Q~10^6
  - Entirely superconducting components minimize loss
  - Pickup geometry prevents coupling loss from magnet materials into resonator
- Targeting operational temperature of T~100 mK
- Currently in the late design stages, beginning construction soon

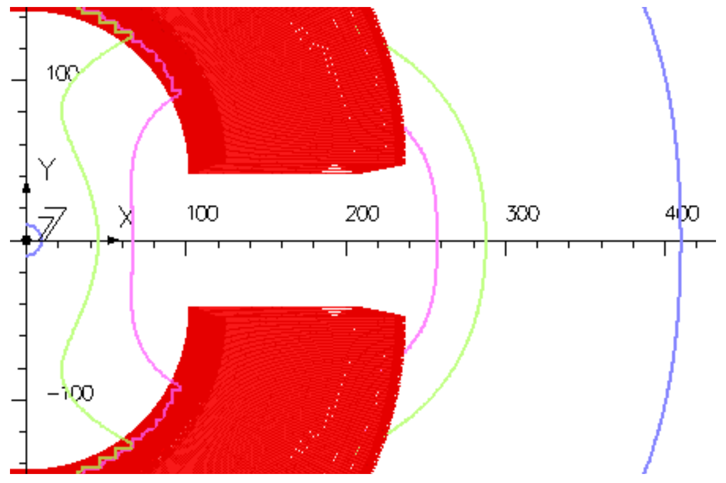
(Conceptual Design)

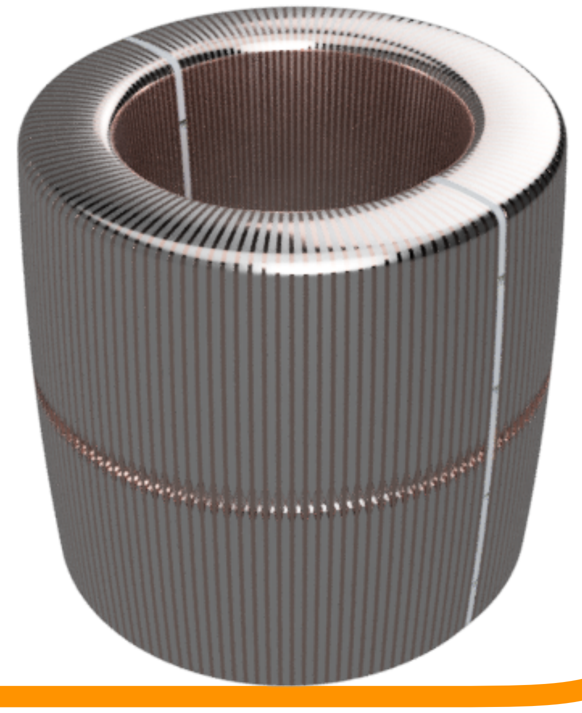
~50 cm



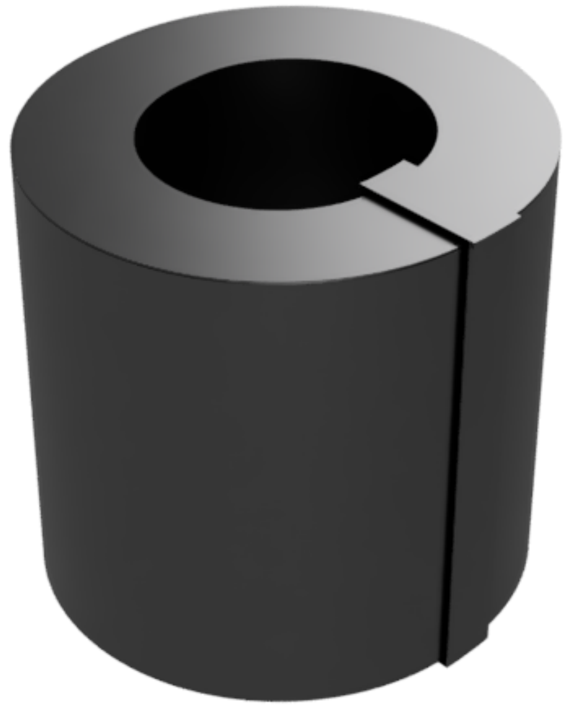
Ongoing DMRadio-50L Design Campaigns

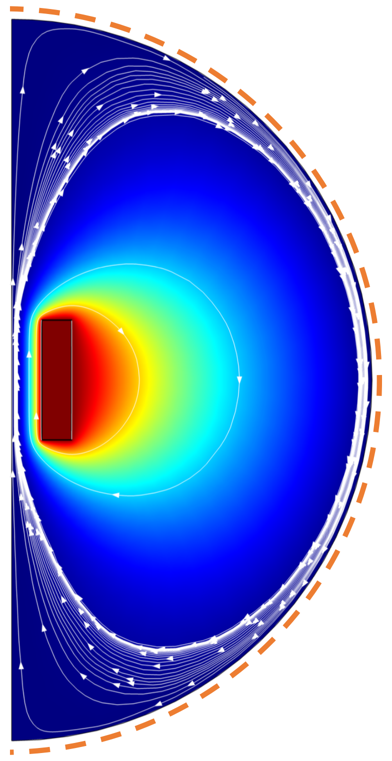
Magnet Design



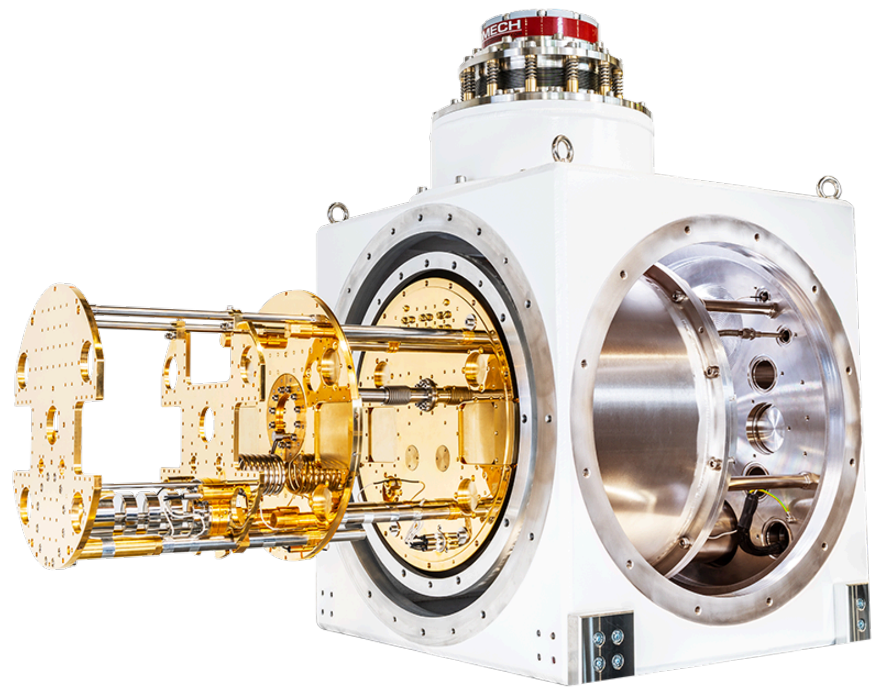


Sheath Design



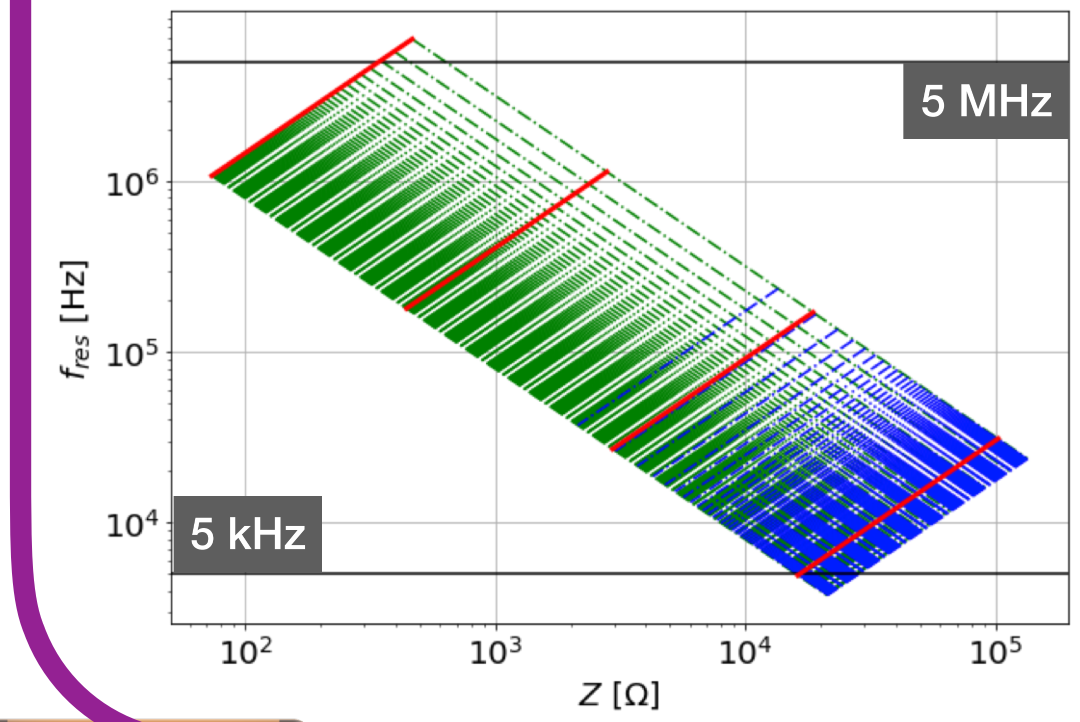


Cryostat Design



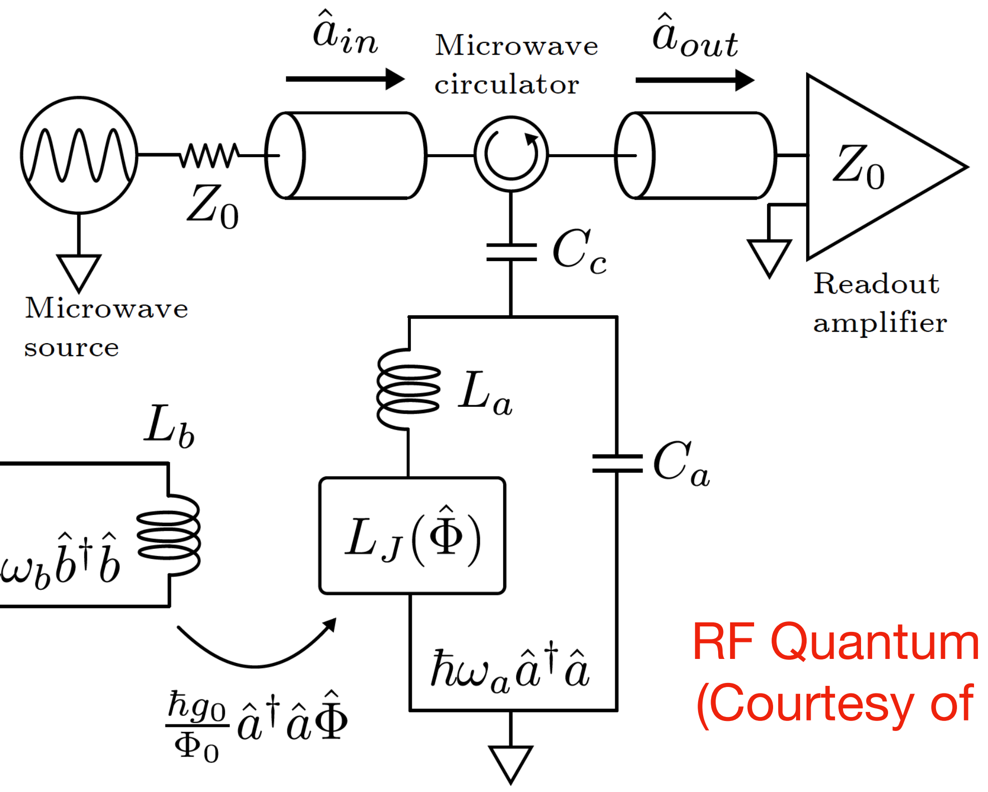
High-Q Resonator Development

Potential 50L Resonator Tuning Strategy



Test Resonator Dip Probe
(Courtesy J. Singh)

Quantum Sensor Testbed

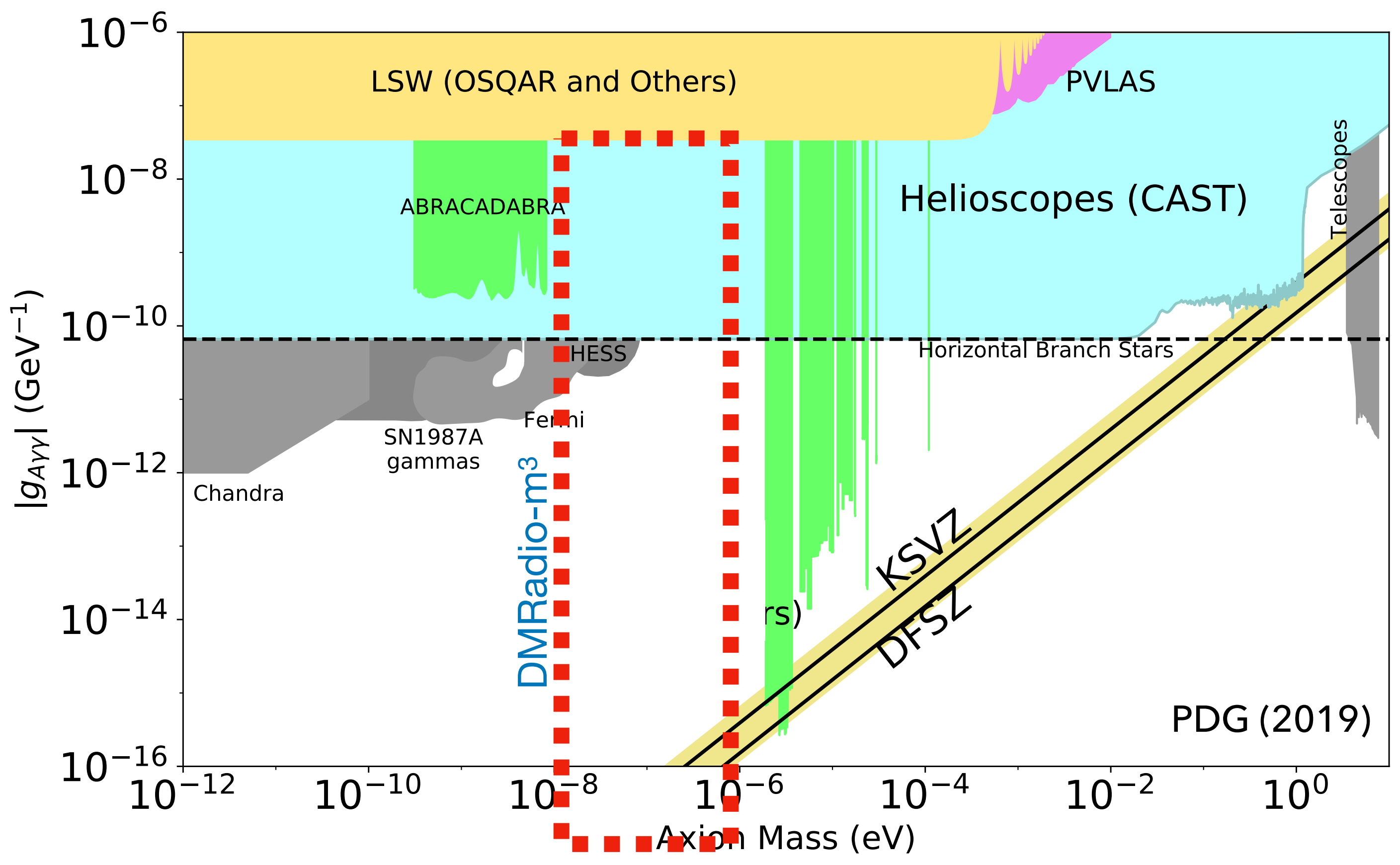


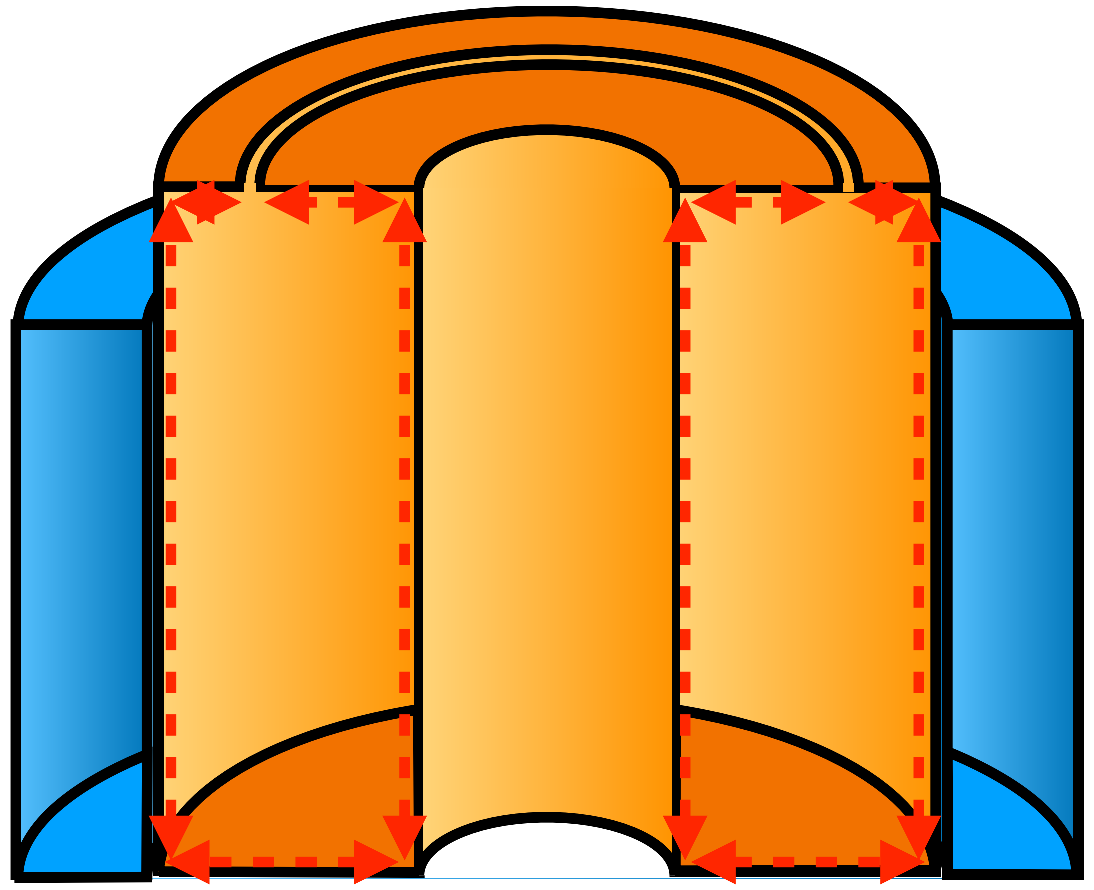
RF Quantum Upconverters
(Courtesy of S. Chaudhuri)

- Dilution refrigerator already obtained
- Magnet and sheath preparing to start construction
- Multiple potential resonator designs and hardware tests on-going
- Aiming for data taking in ~2022

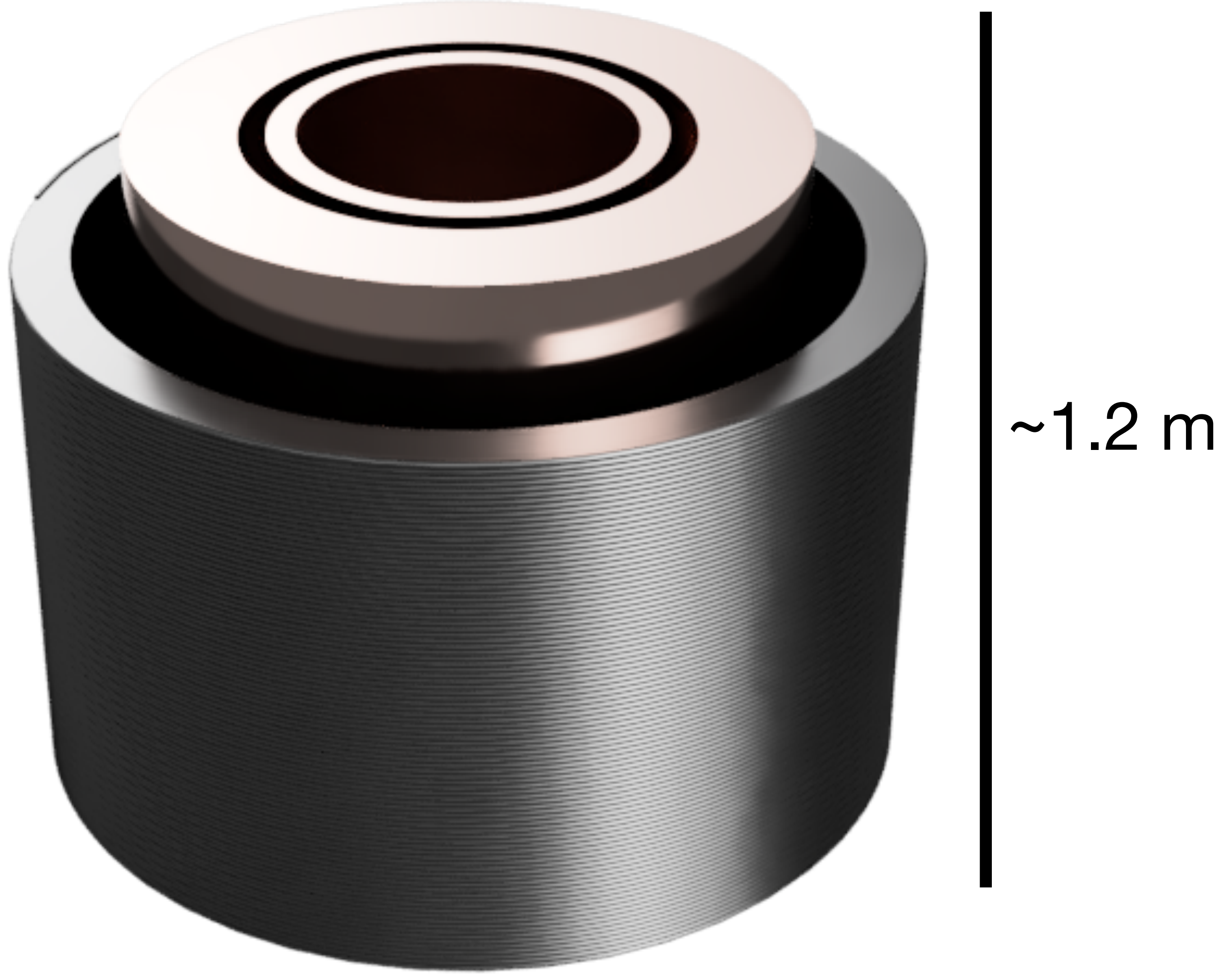
DMRadio-m^3

DMRadio-m³





- m^3 solenoidal magnet, ~4 T field
  - Well understood magnet geometry
- Optimized for higher mass/higher frequency range
  20 neV < m_a < 800 neV (5 MHz < ν_a < 200 MHz)
- Aiming for Q ~ 10^6
  - Lossy (non-superconducting) pickup
  - Larger volume/surface ratio allows for high-Q (low loss) even with normal conductors!
- Noise temperature of ~20 mK, SQUID readouts at 20x SQL (or better!)
- Many challenges to overcome:
  - Placing sensitive superconducting sensors near high B-field region (magnet design)
  - Cryogenics and vibration isolation

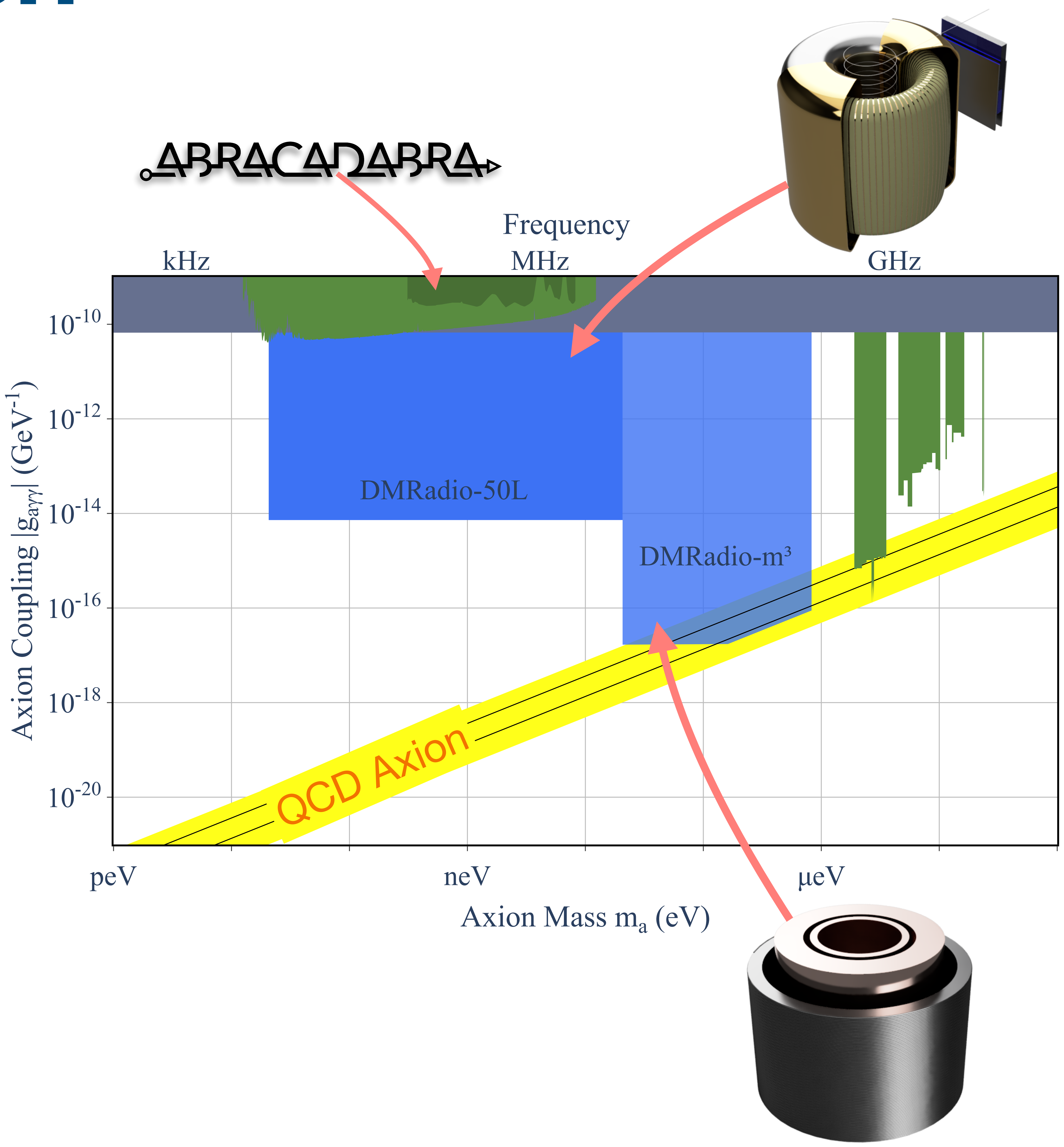


➡ **Design study funded as part of the DOE Dark Matter New Initiatives program**
- **Pre-conceptual design report in preparation**

DMRadio Physics Reach

- **DMRadio-50L**
  - Demonstration of magnet + resonator
  - Search for Axion-like particles
  - 20 peV < m_a < 20 neV (5 kHz < ν_a < 5 MHz)
  - $g_{a\gamma\gamma} < 5\cdot10^{-15}$ GeV^{-1}
  - Beginning Construction
  - 3-year scan starting in ~2022
  - Afterwards: Next generation sensors

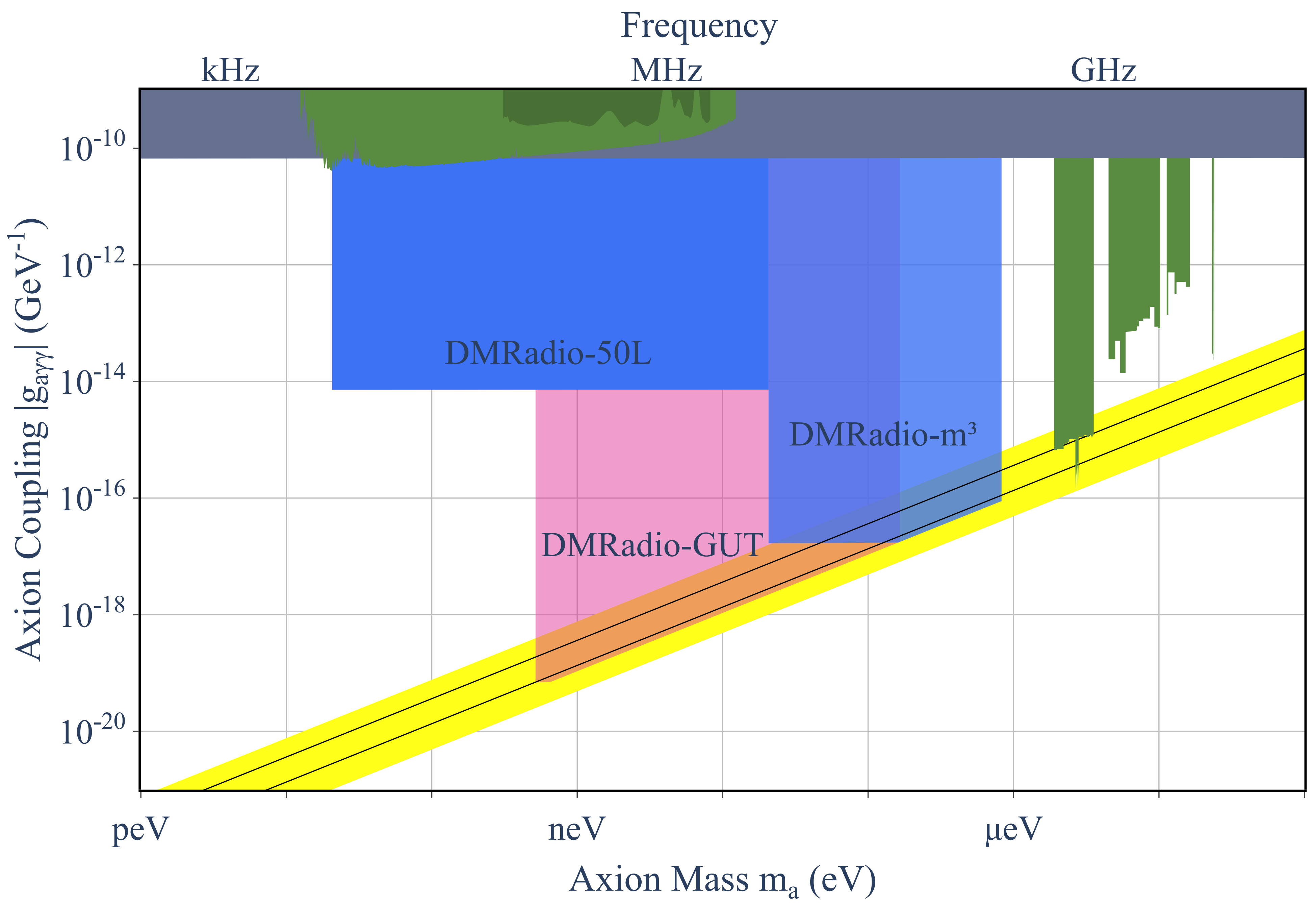
- **DMRadio-m³**
  - Probing QCD axion models
  - 20 neV < m_a < 800 neV (5 MHz < ν_a < 200 MHz)
  - DFSZ axion sensitivity above 100 neV (30 MHz)
  - Design funded by DOI New Initiatives Program
    - PreCDR in preparation
  - 5-year scan time starting in ~2025



DMRadio-GUT

DMRadio-GUT

- DMRadio-GUT
  - Probing QCD scale axion all the way down to the GUT-scale axion
  - 400 peV < m_a < 125 neV (100 kHz < ν_a < 30 MHz)
  - All the detector parameters are turned up to 11!
  - B ~ 12T magnetic field, V~10 m^3 volume
  - Requires sensors capable of pushing beyond the SQL
  - 7-year scan time



Conclusions

- The Axion is one of the most compelling dark matter candidates
- Lumped element detectors are a demonstrated and promising technology to probe ADM below 1 μeV
- DMRadio is a multi-phase program with sensitivity to the QCD axion
  - DMRadio-50L expected to start data taking in 2022
  - DMRadio-m³ expected on the timescale of 2025