The ORGAN Experiment: Results, Status and Future Plans

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Overview

- ORGAN
  - General Introduction
  - Design Considerations
  - Run Plan
  - Phase 1a
  - R&D/Future Phases
- ORGAN-Q
- ORGAN Low Frequency
- Other experiments

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

ORGAN Introduction

- High mass axion haloscope collaboration
- Axion-photon conversion in resonant cavity

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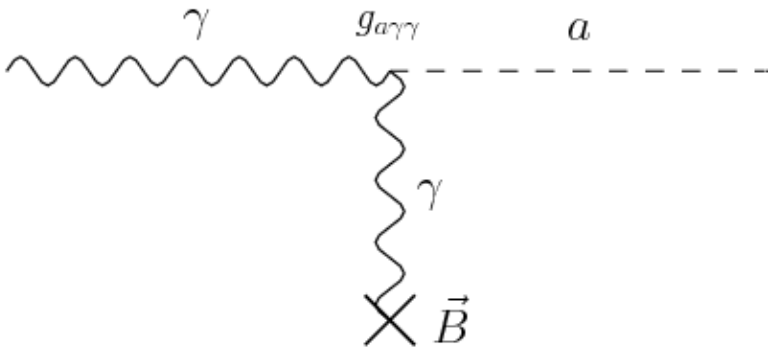

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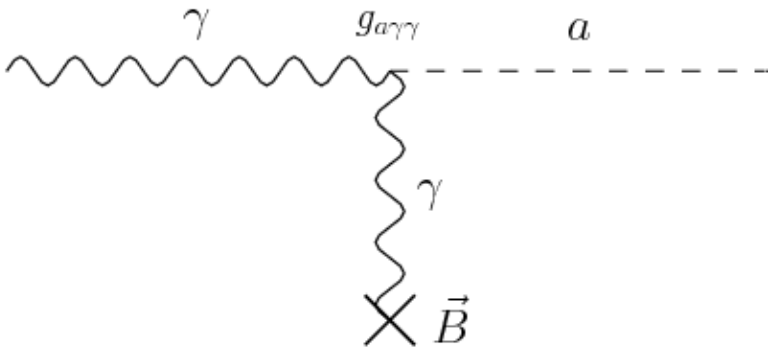

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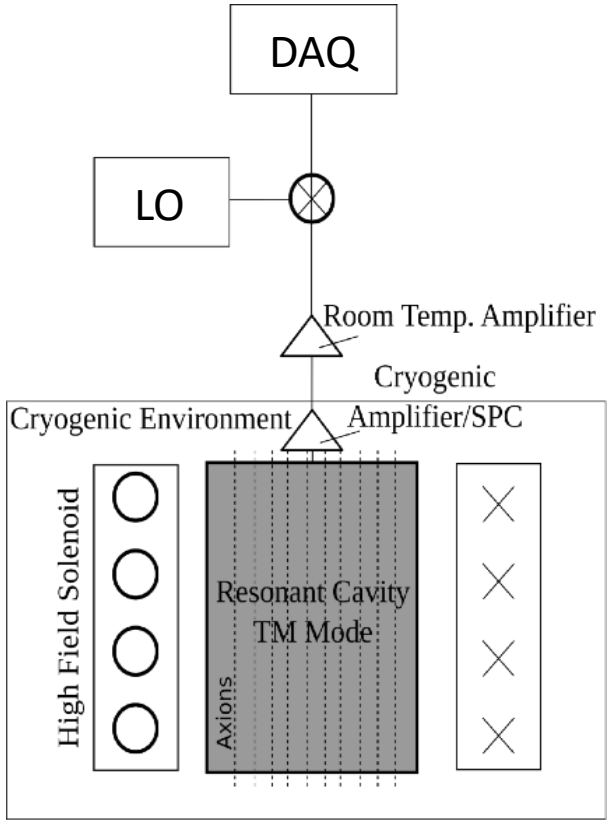

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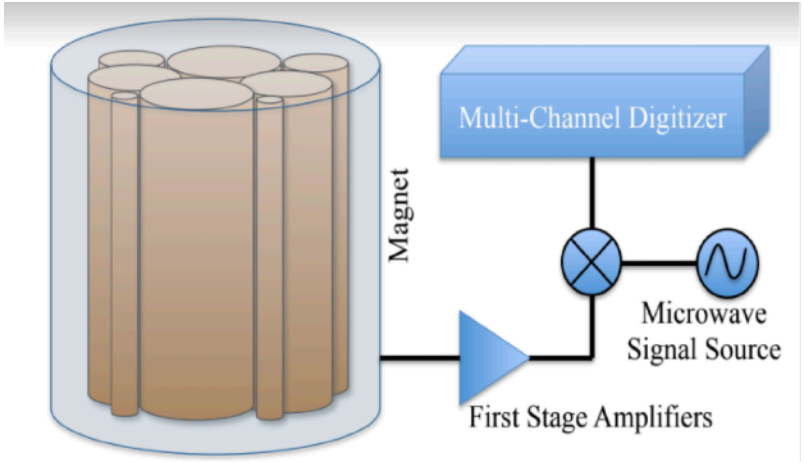

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- Some auxiliary experiments

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  - Novel tunable resonators
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  - Low noise amplification/photon counting readout
  - Data acquisition and analysis

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$$\frac{df}{dt} \propto \frac{1}{SNR^2_{goal}} \frac{g^4_{a\gamma\gamma} B^4 C^2 V^2 \rho^2_a Q_L Q_a}{m^2_a (k_B T_n)^2}$$

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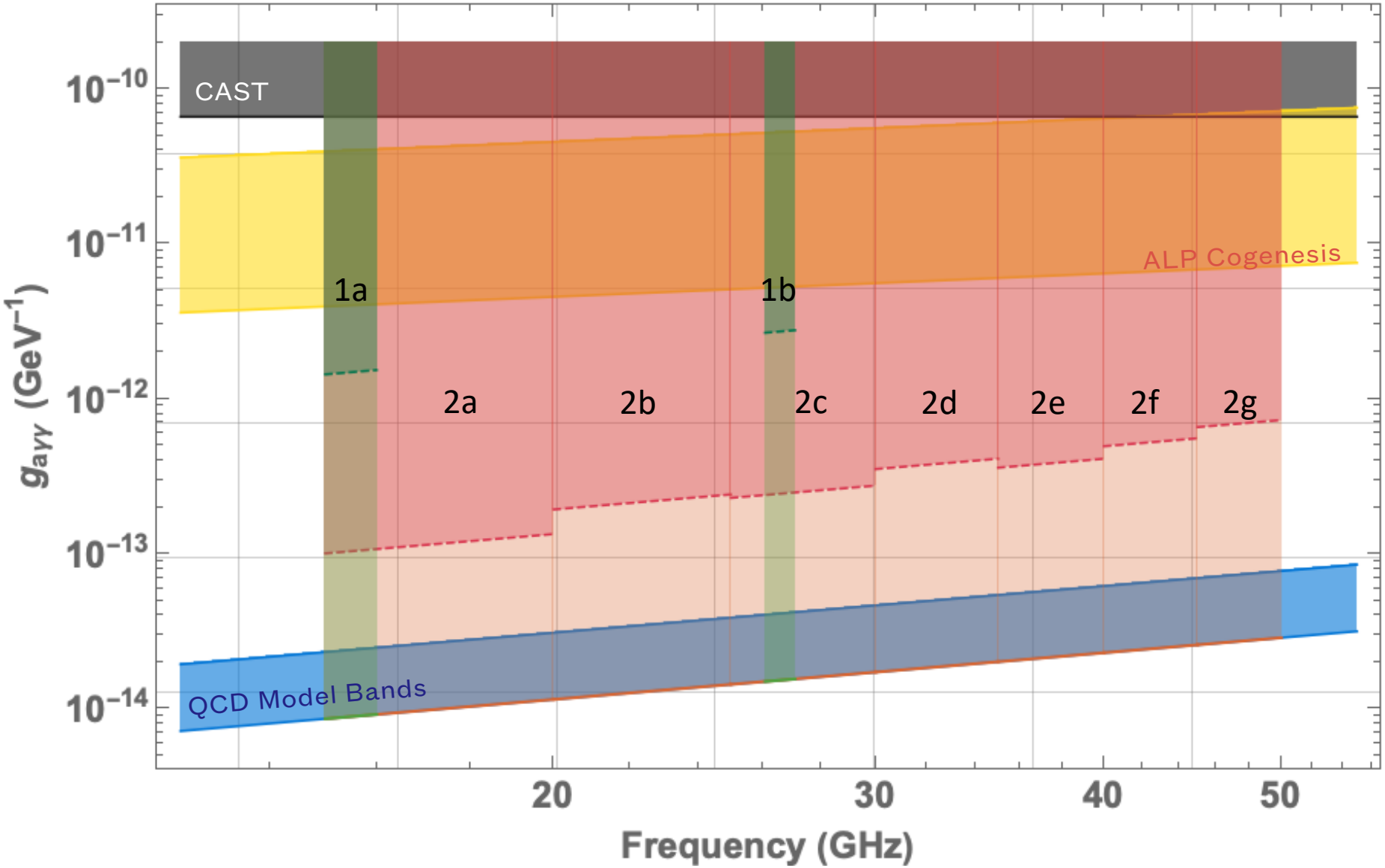

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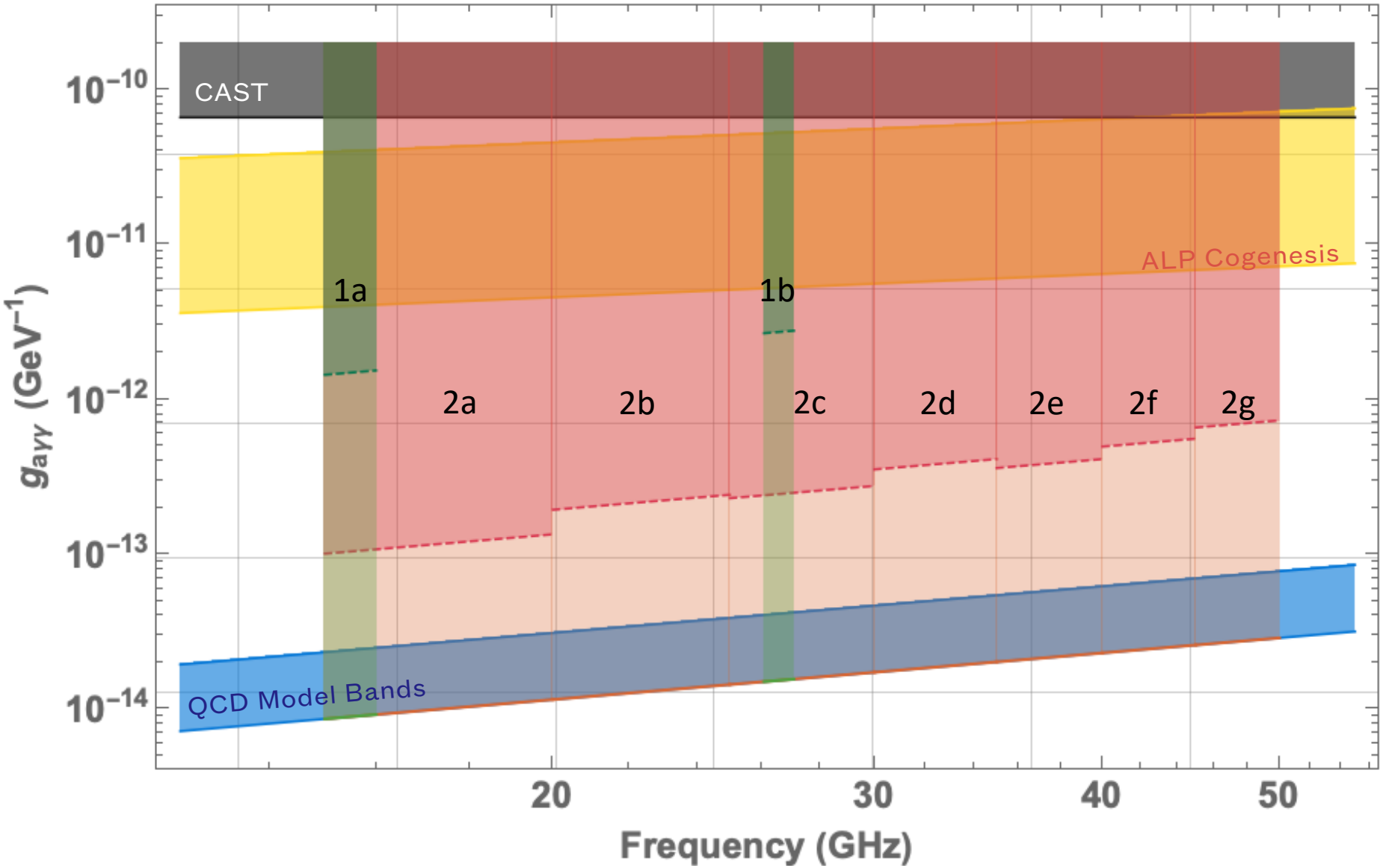

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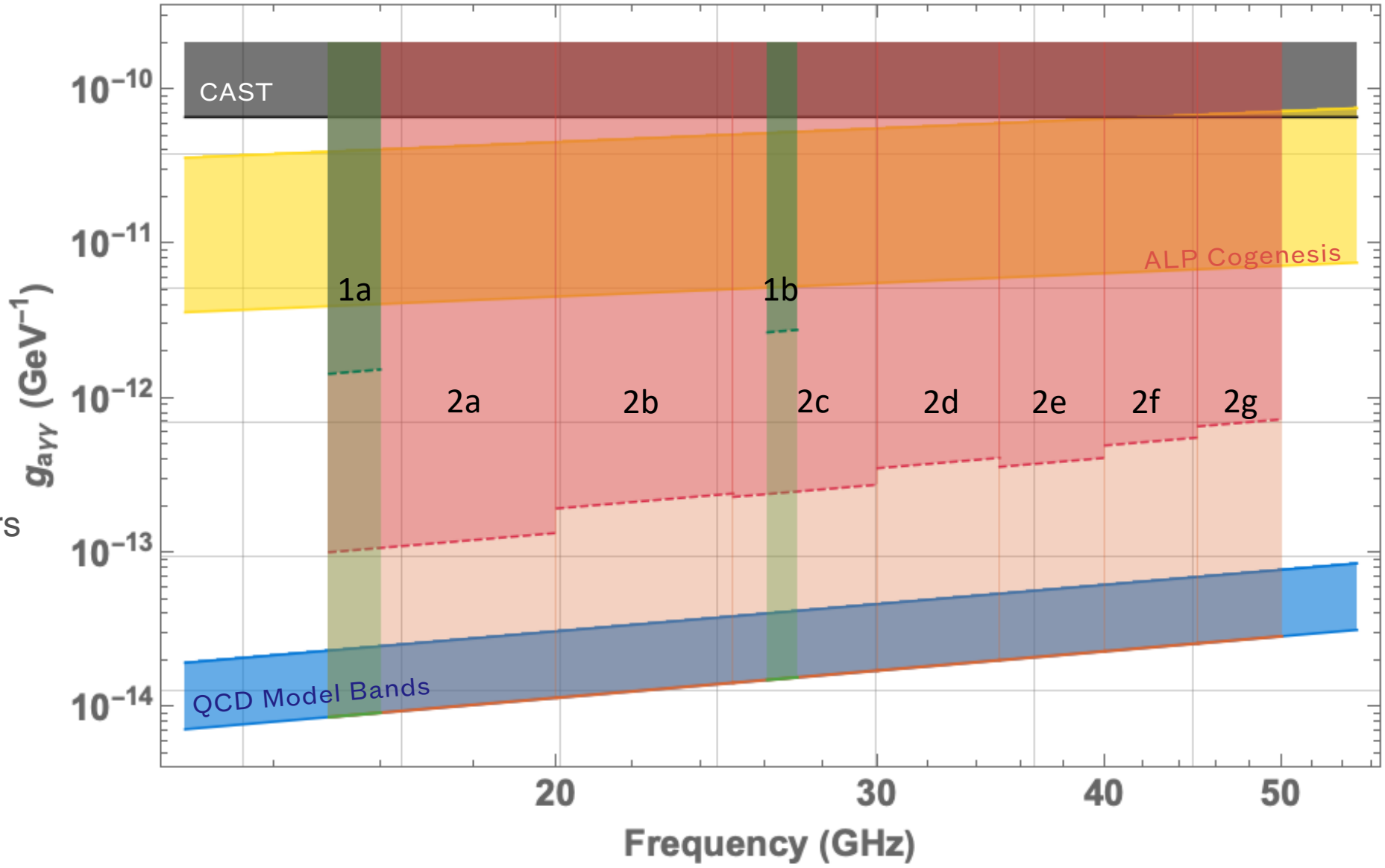

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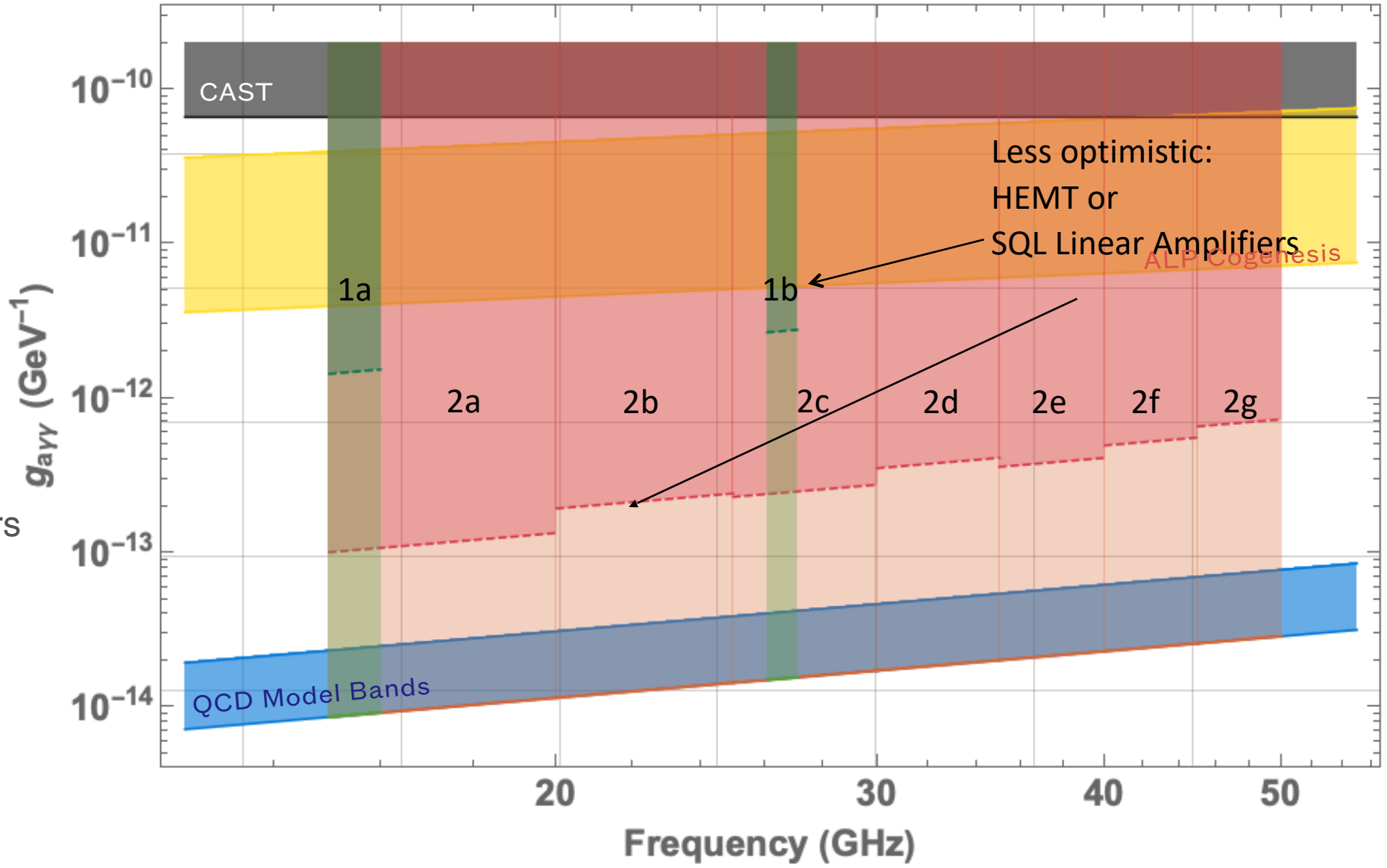

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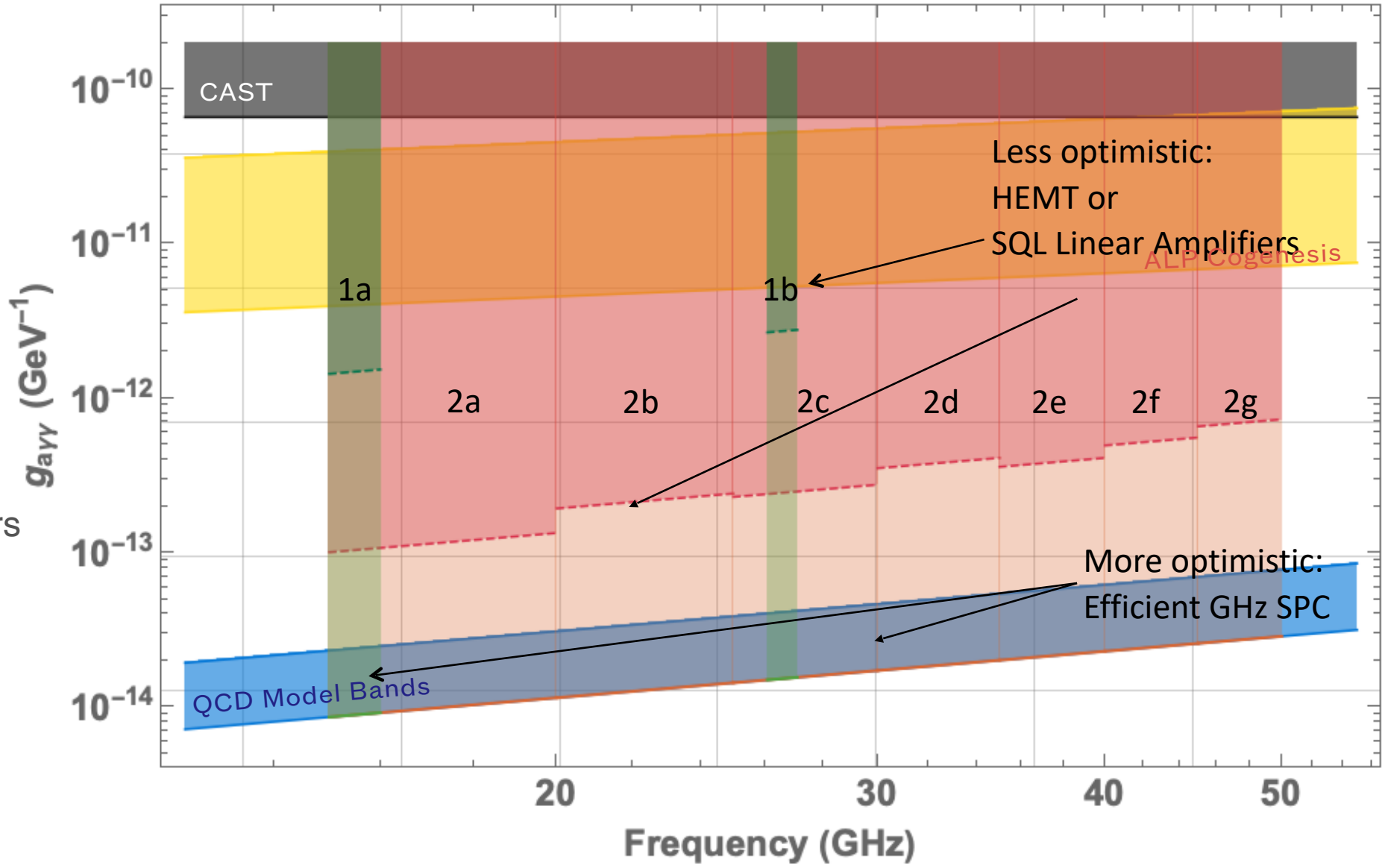

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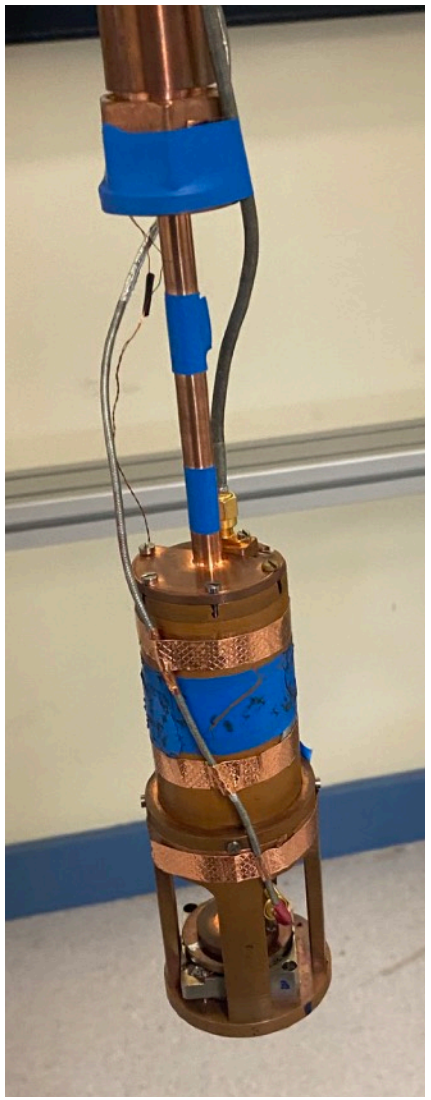

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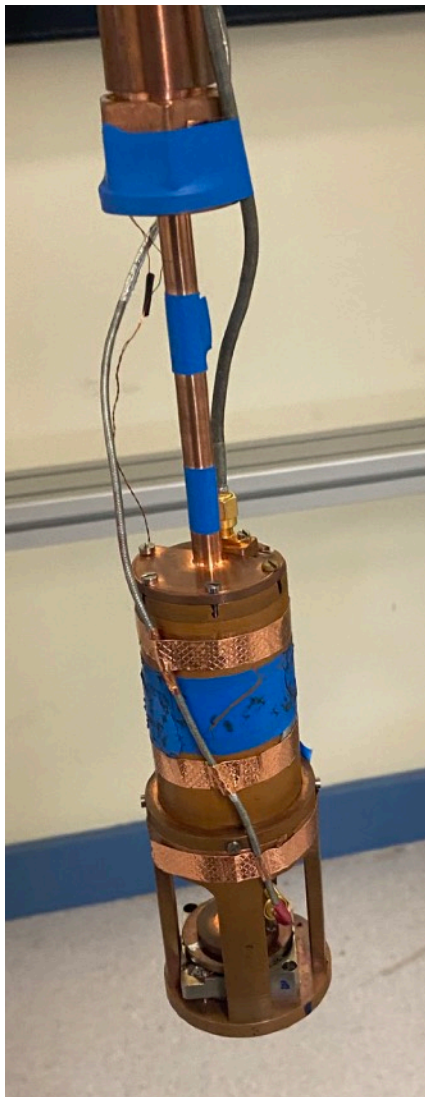

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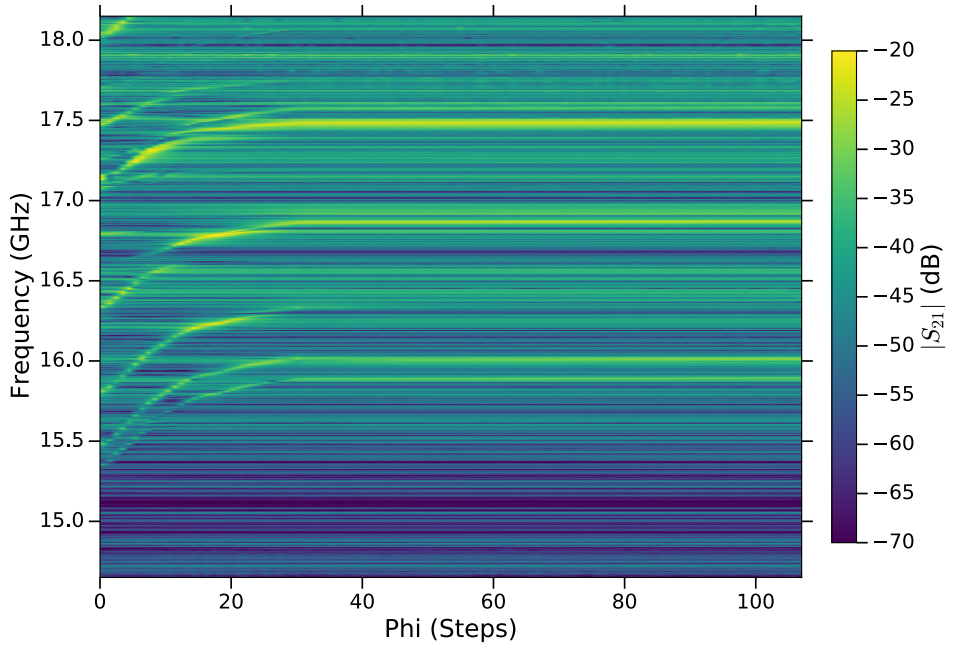

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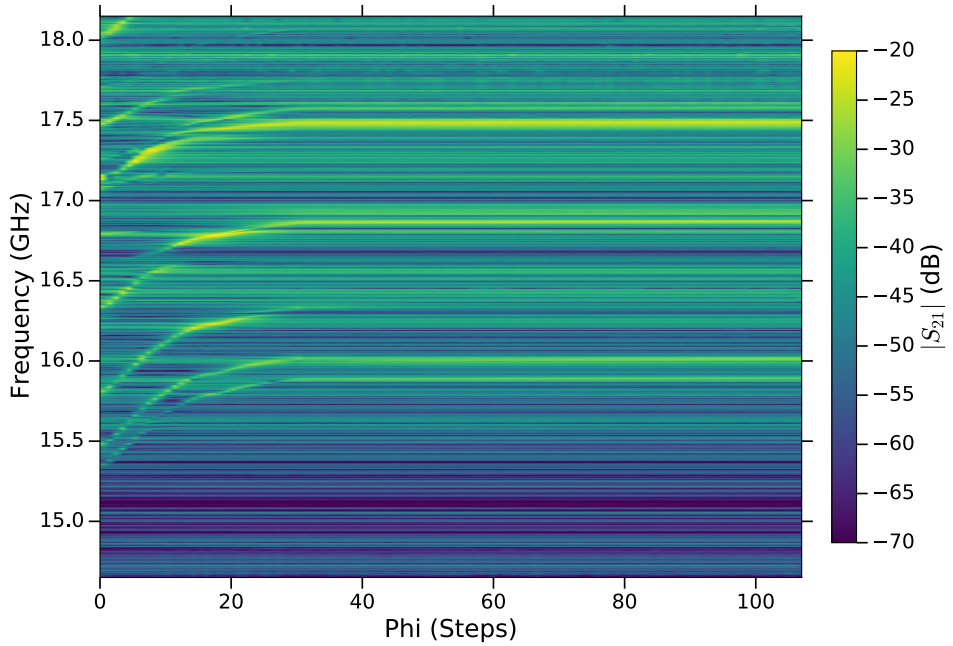

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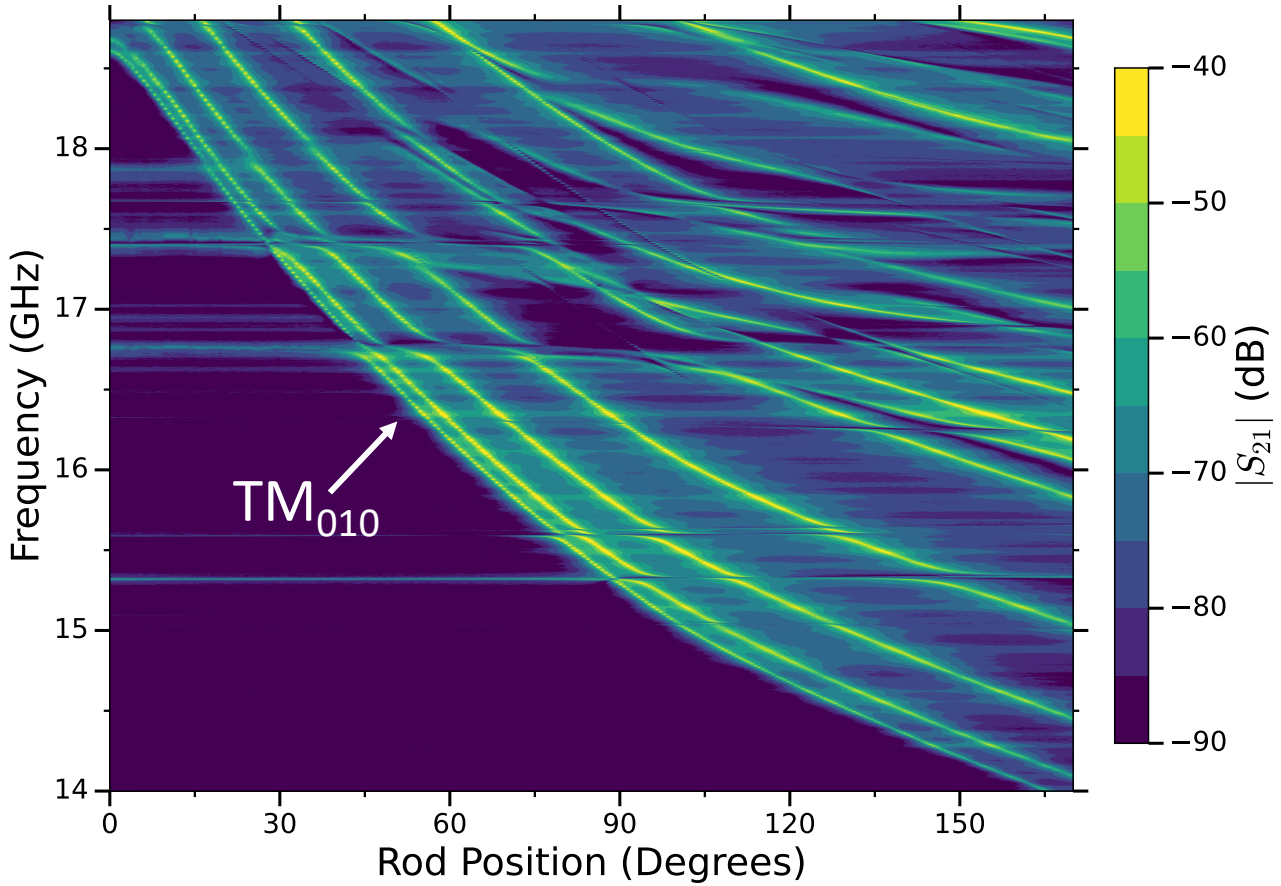
- Iterations of design - increase alignment, tolerances etc



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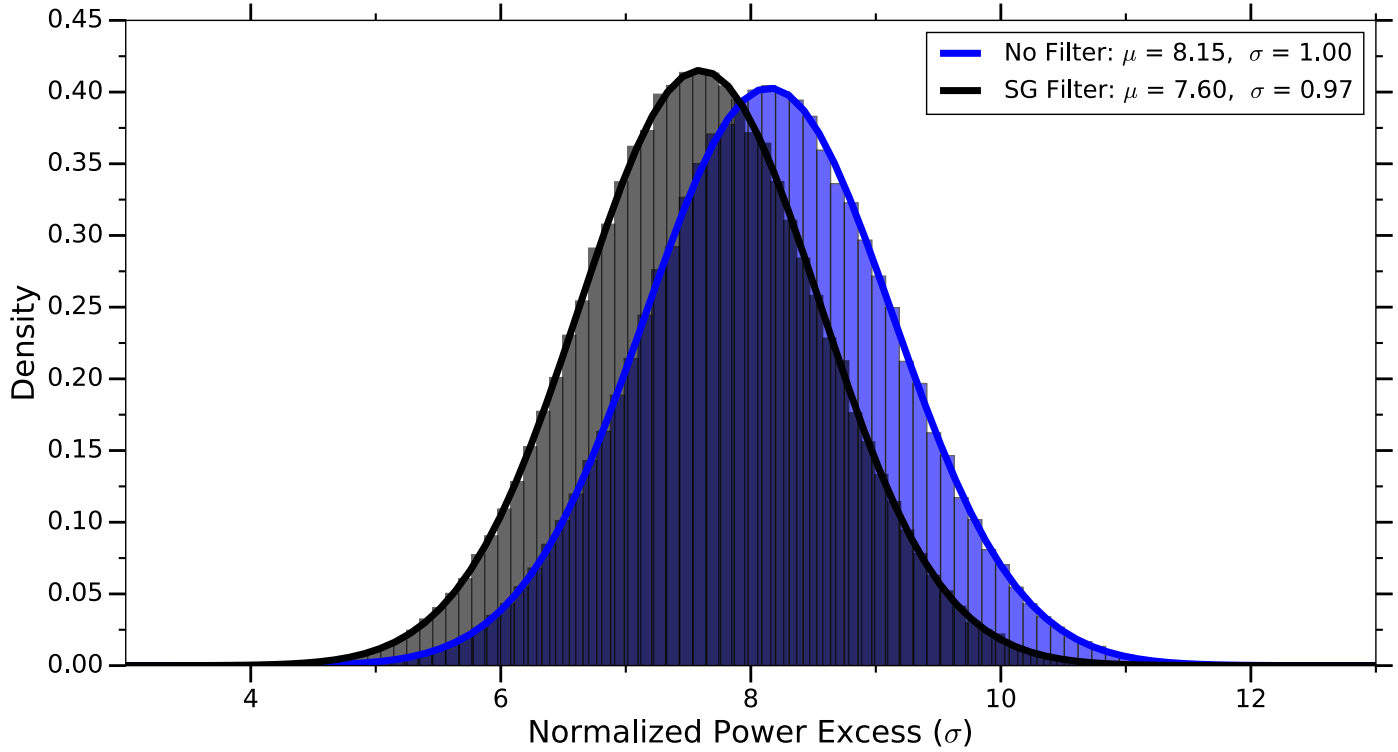

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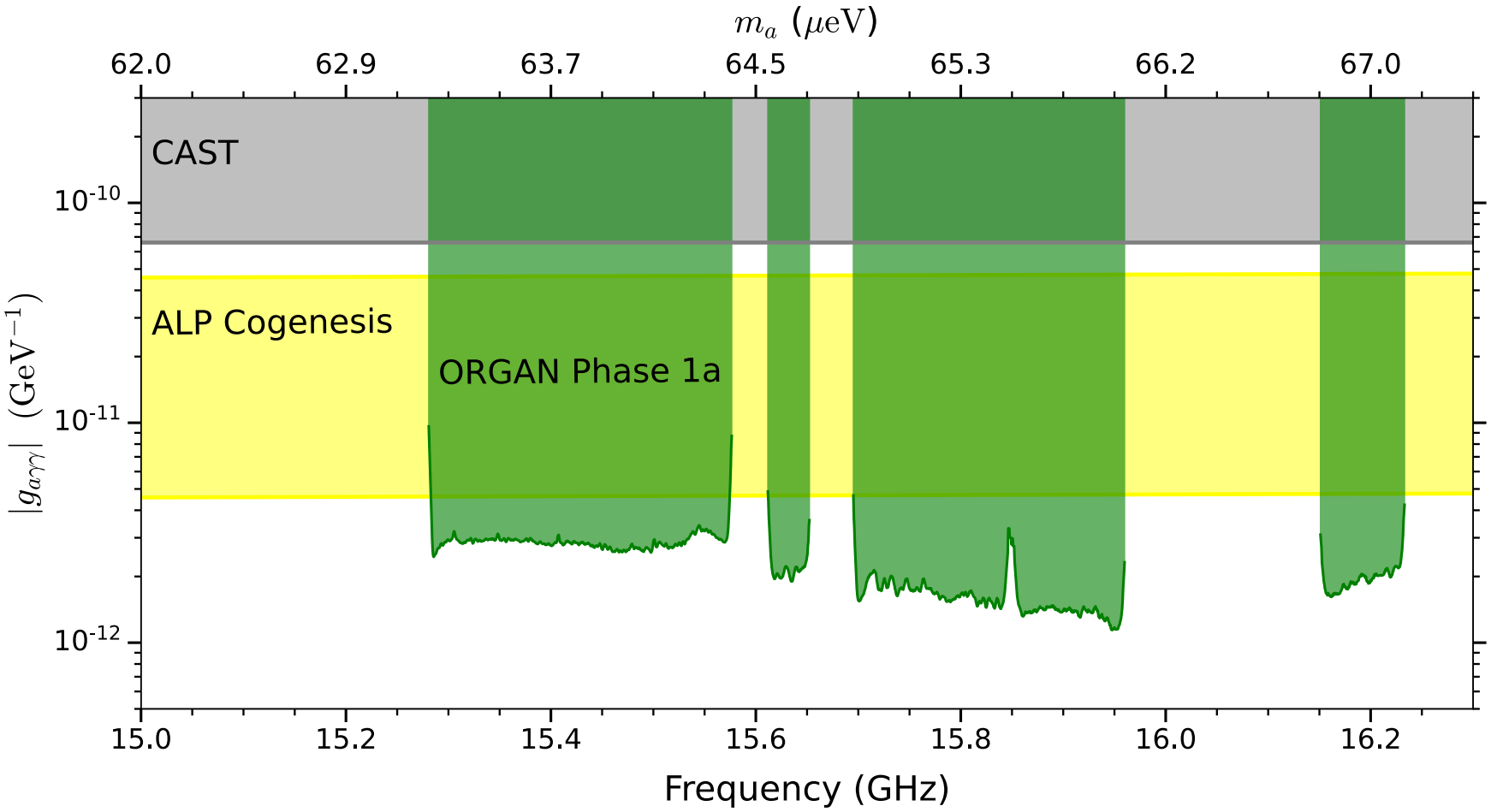

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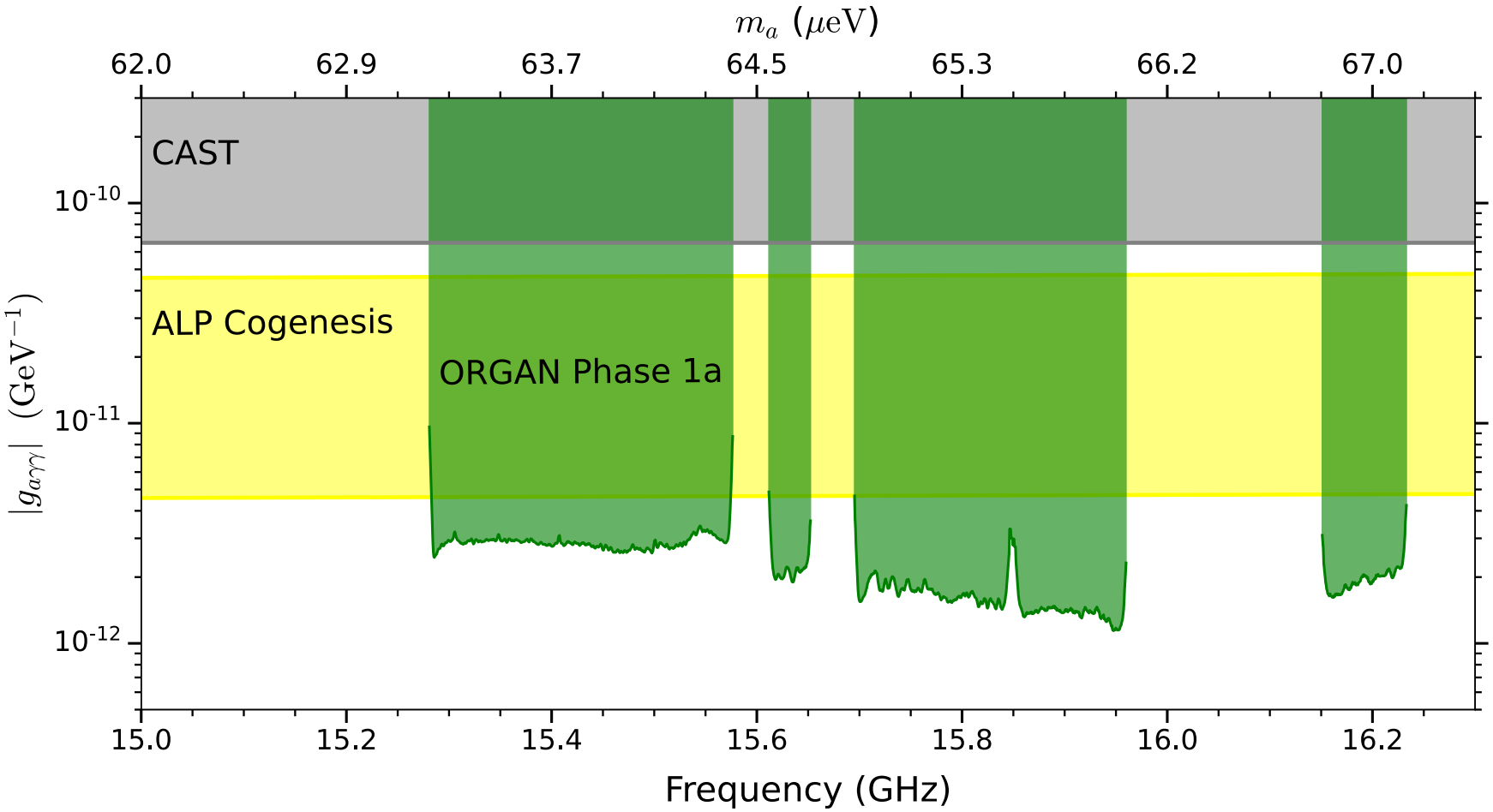
- Better sensitivity



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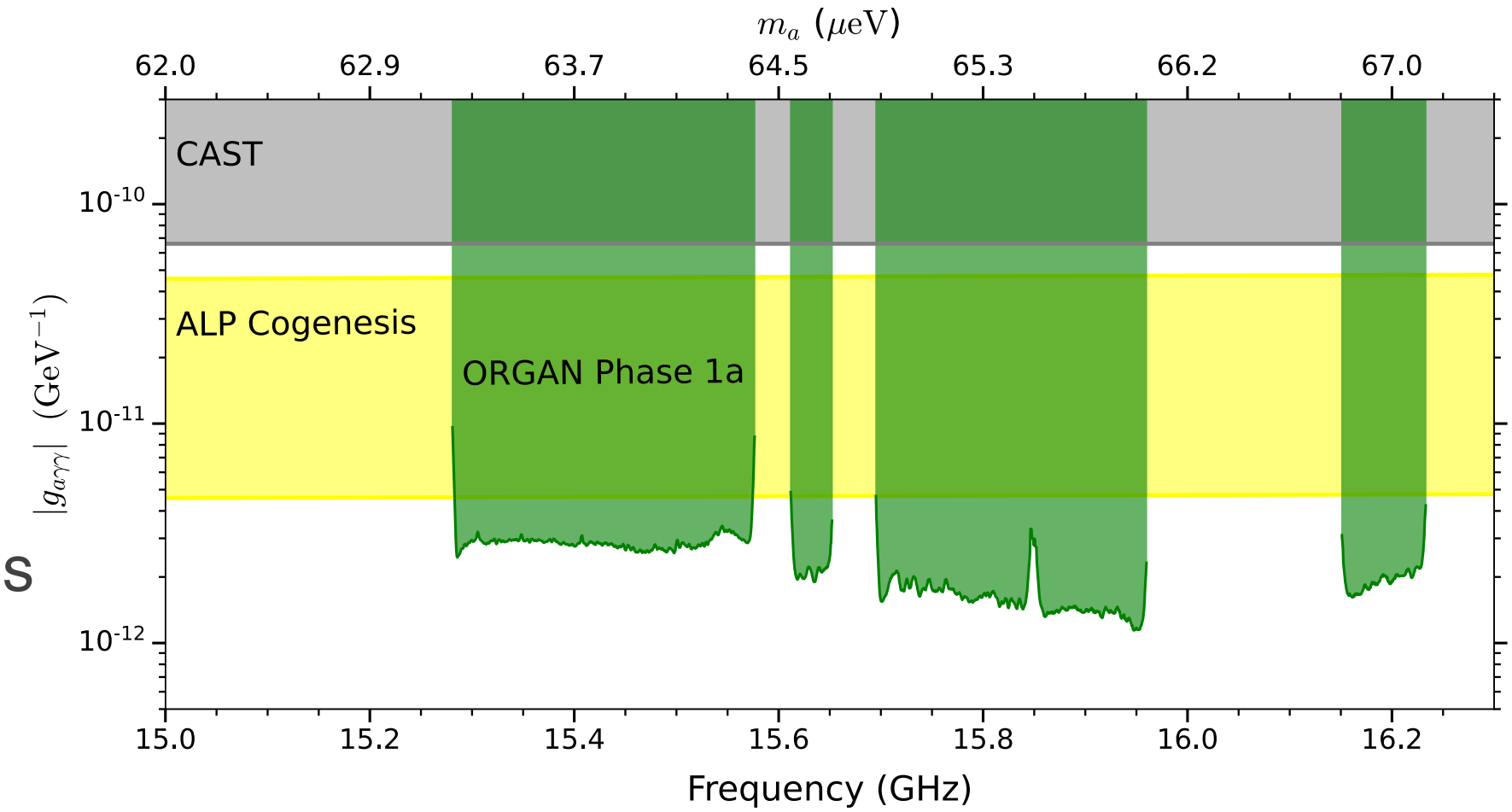

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- 26 - 27 GHz

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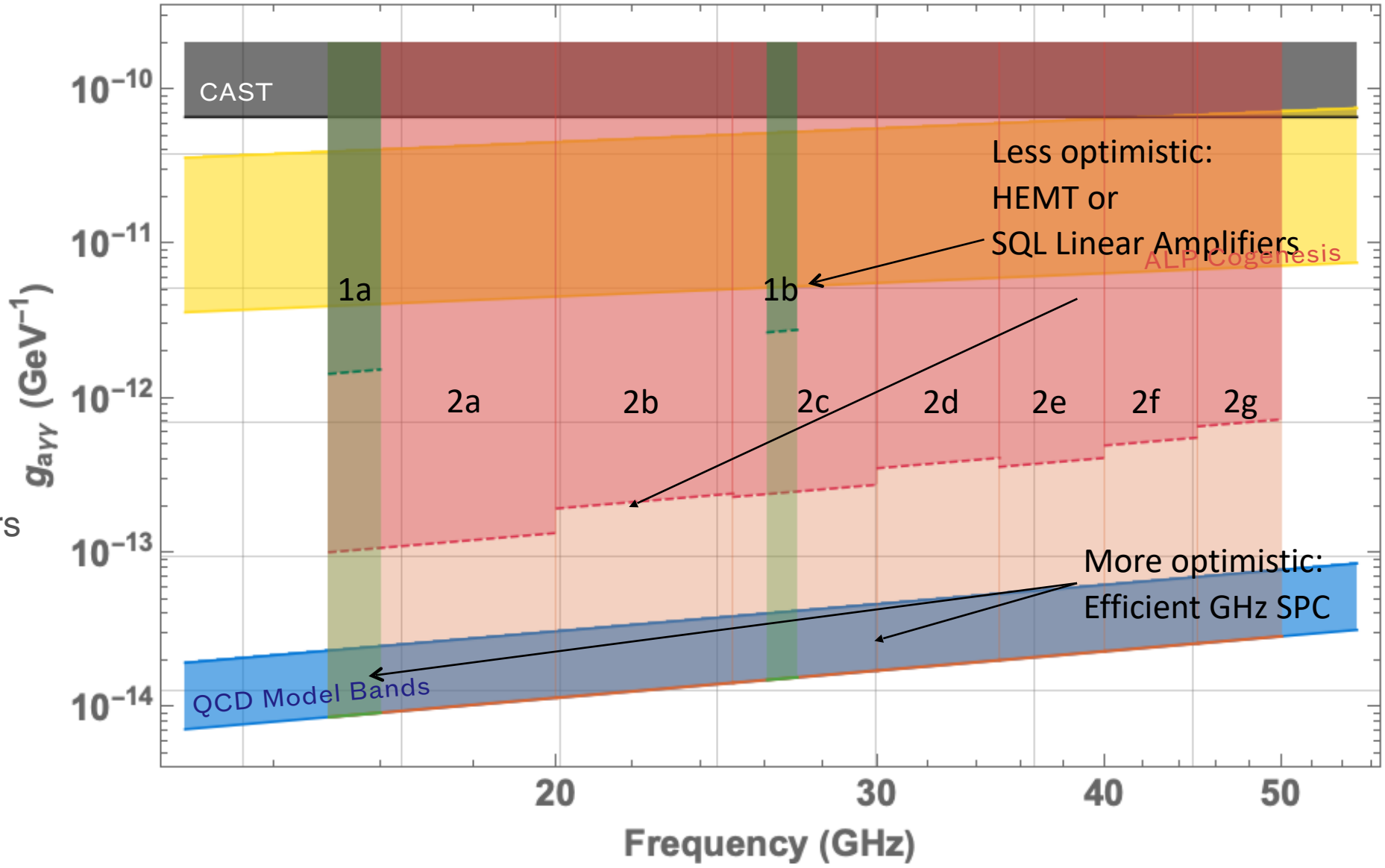

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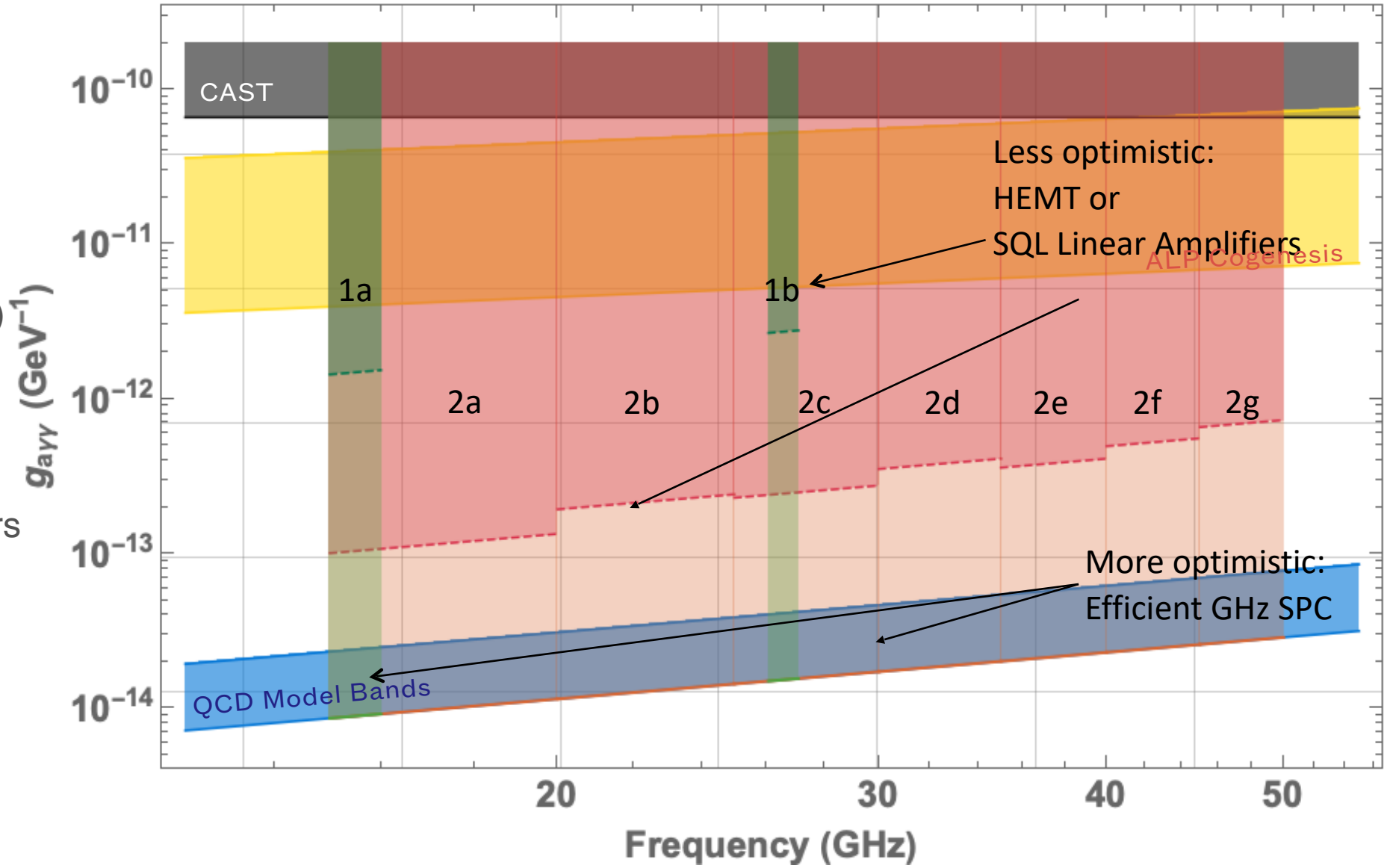

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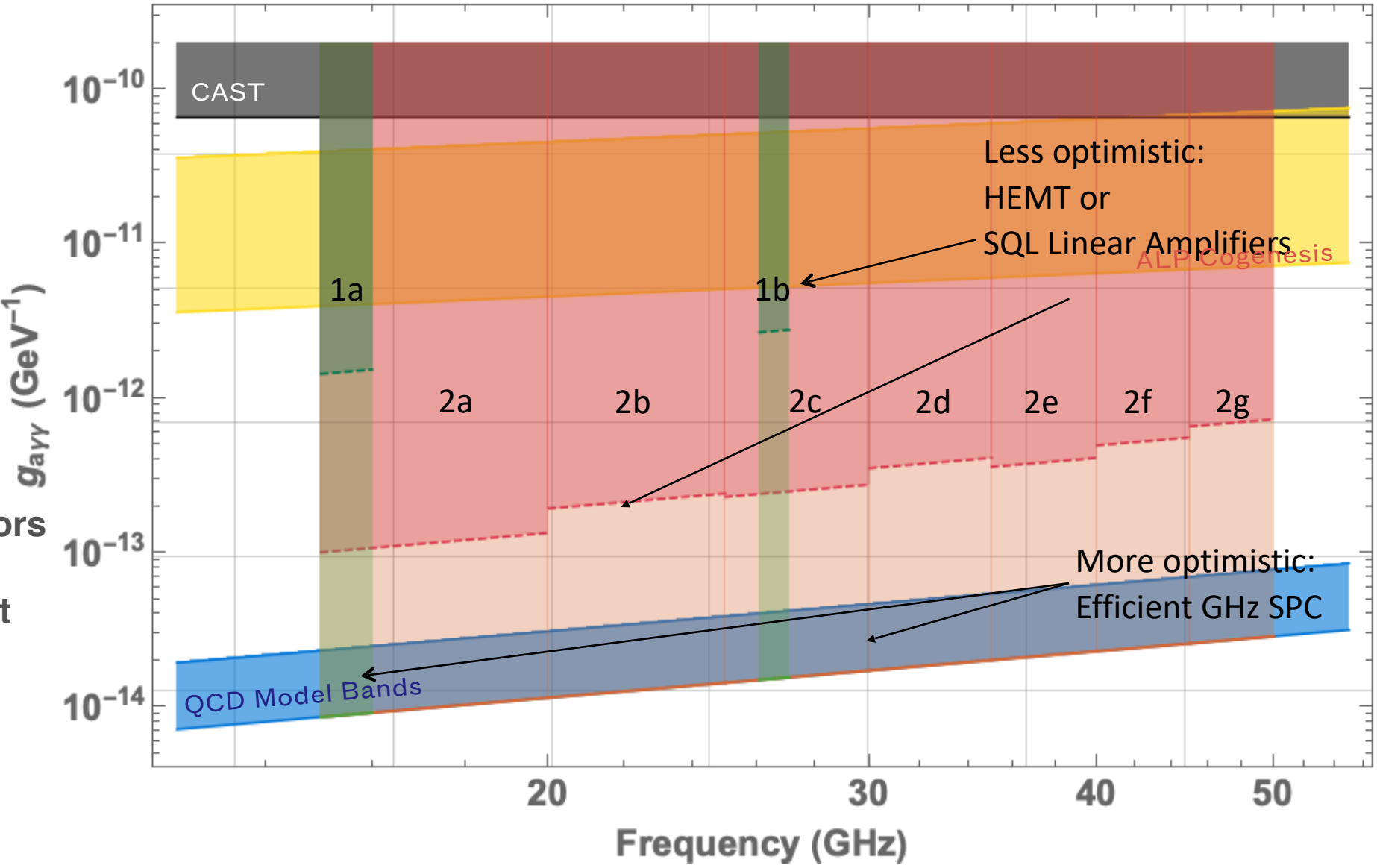

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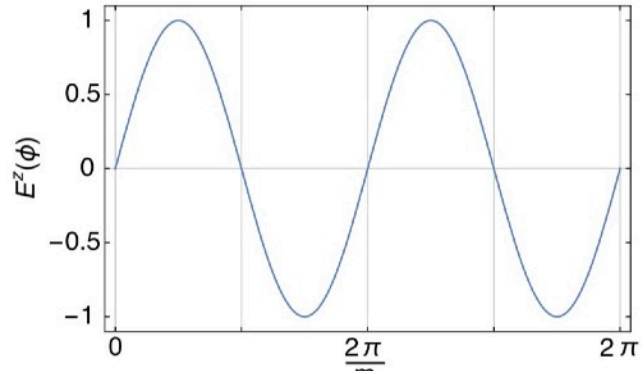
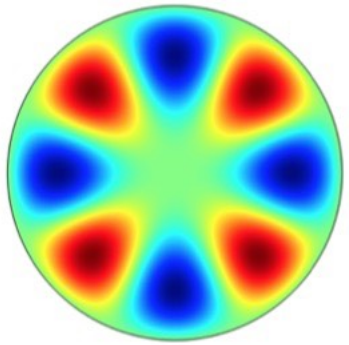


TM_{410}



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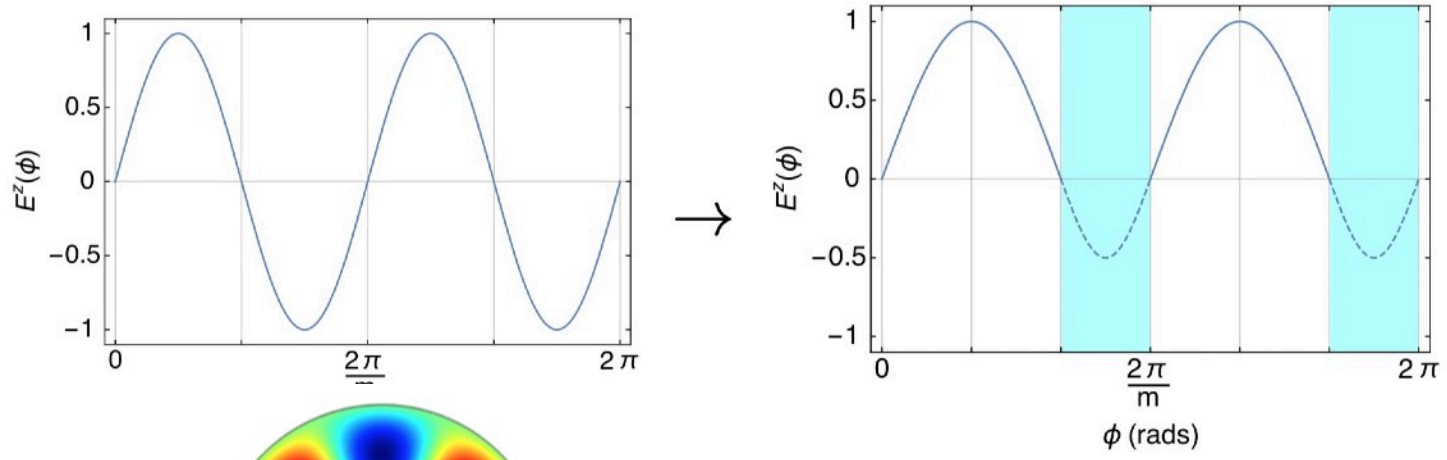

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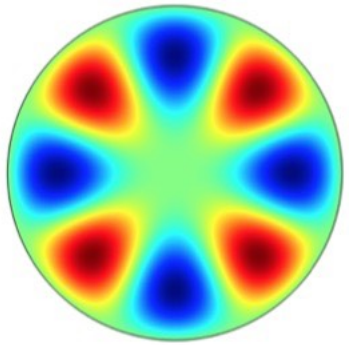

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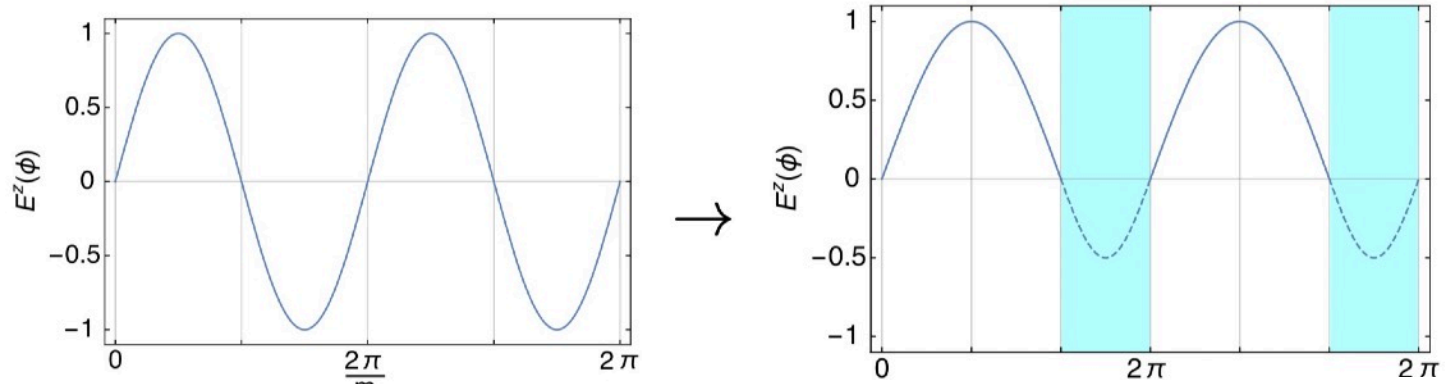

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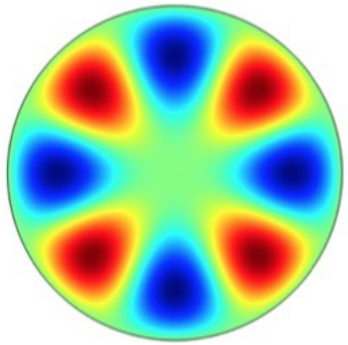

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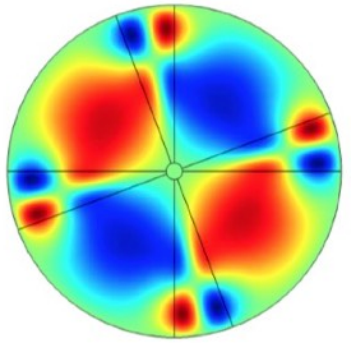

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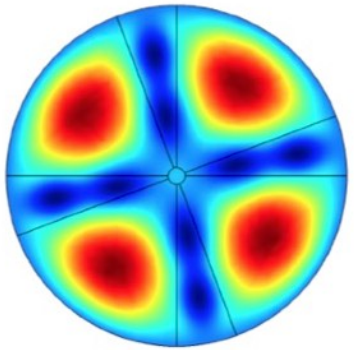

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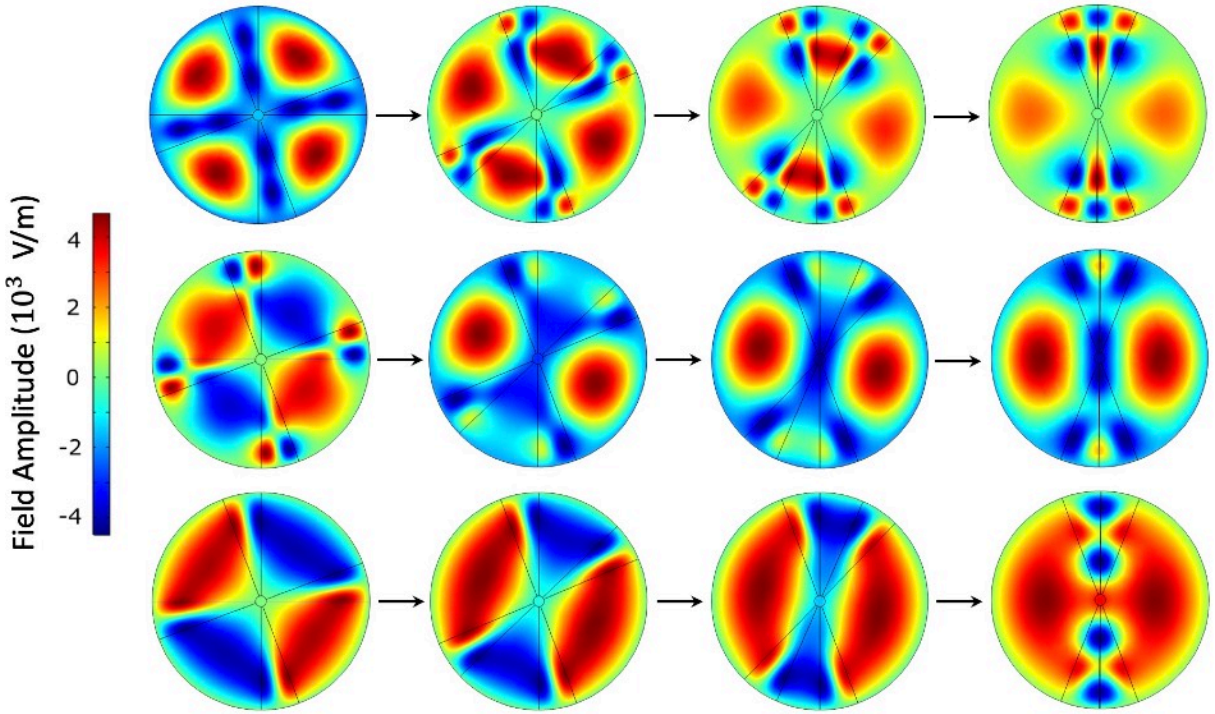

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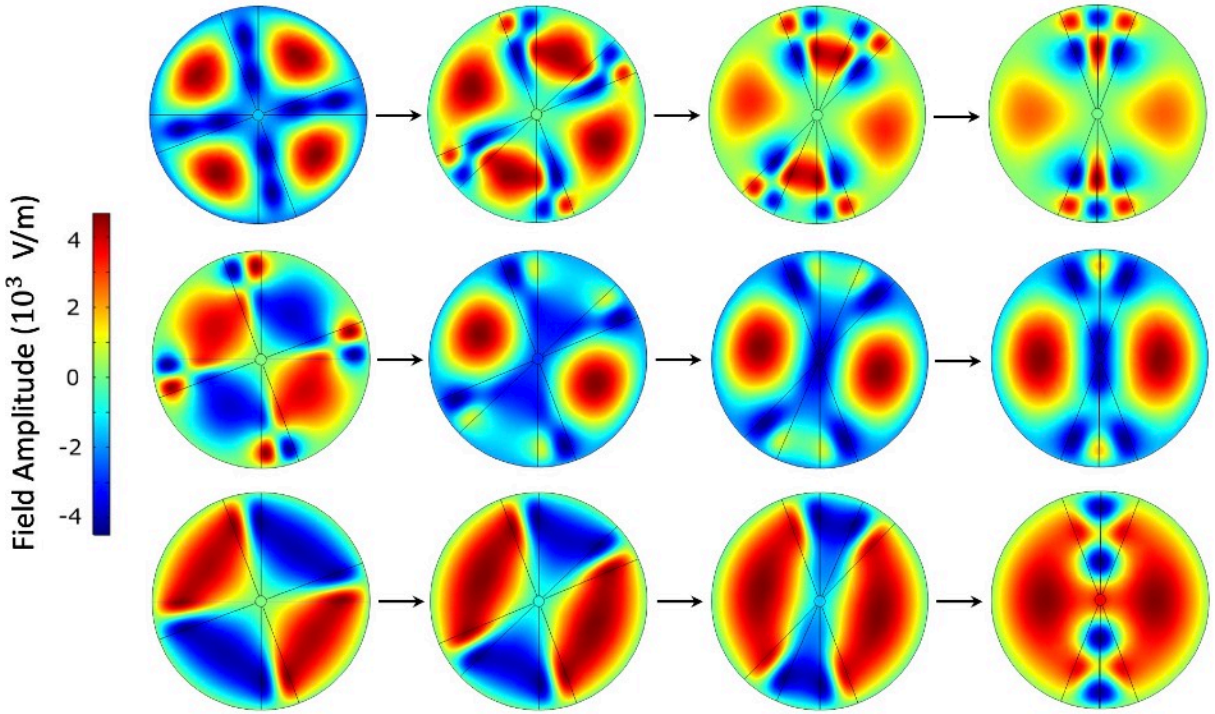

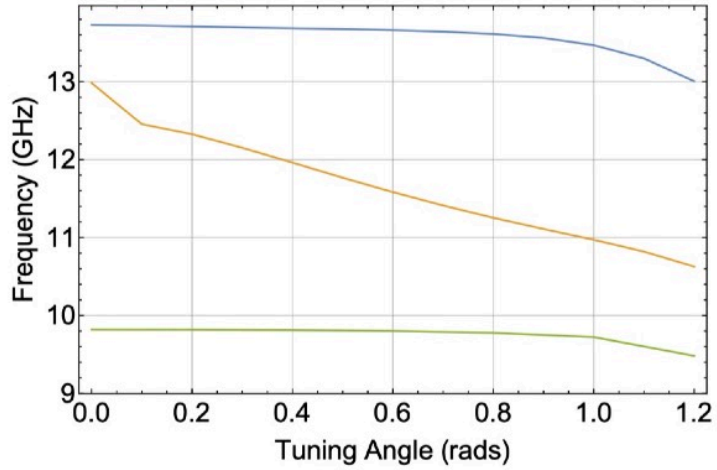

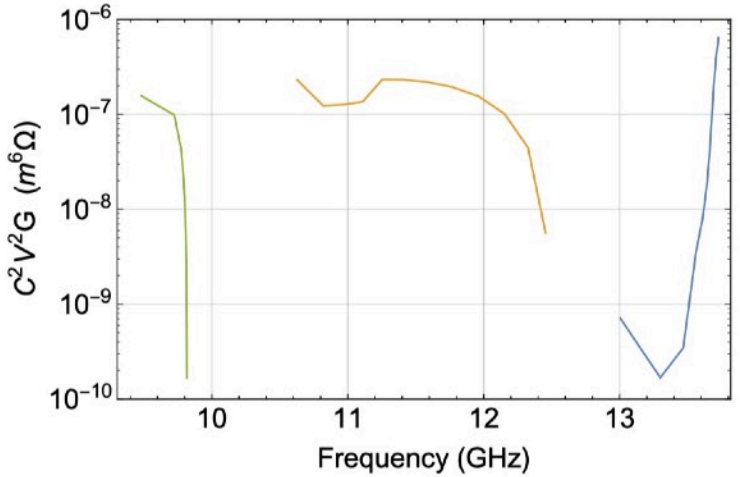

https://doi.org/10.1103/PhysRevApplied.14.044051

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

R&D: Novel Resonators

- Prototype resonator built
- 4 sapphire wedges

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ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

R&D: Novel Resonators

- Prototype resonator built
- 4 sapphire wedges
- Investigating utilisation in Phase 1b
- Failing that, continue to analyse for Phase 2 (among other ideas)

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

R&D: Superconductors

- New collaborator within ORGAN
- Swinburne University of Technology - nanofabrication capacity

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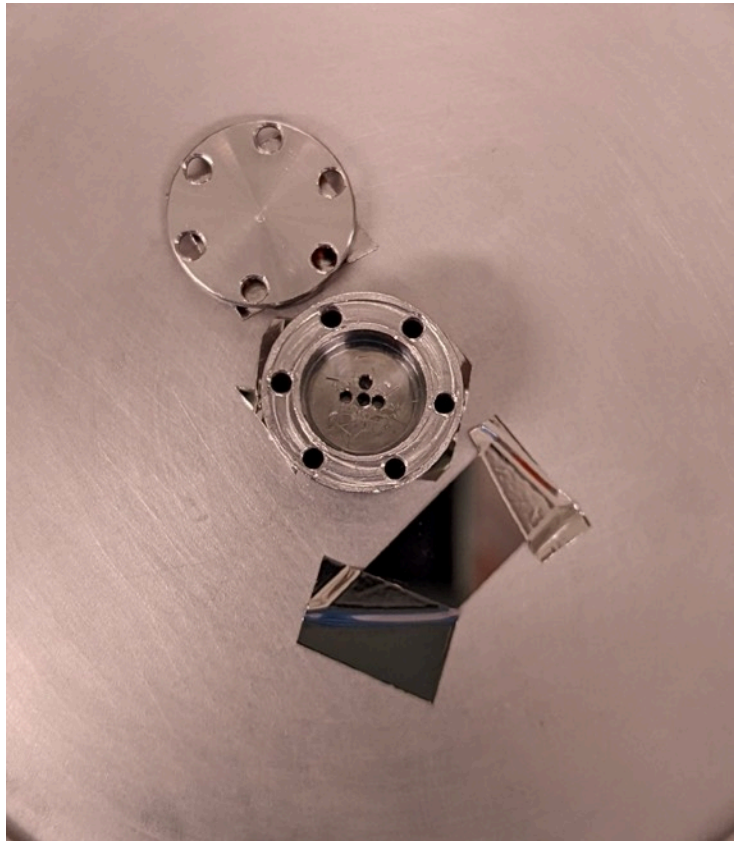

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

R&D: Superconductors

- Can characterise the internal field with magnonic sensor

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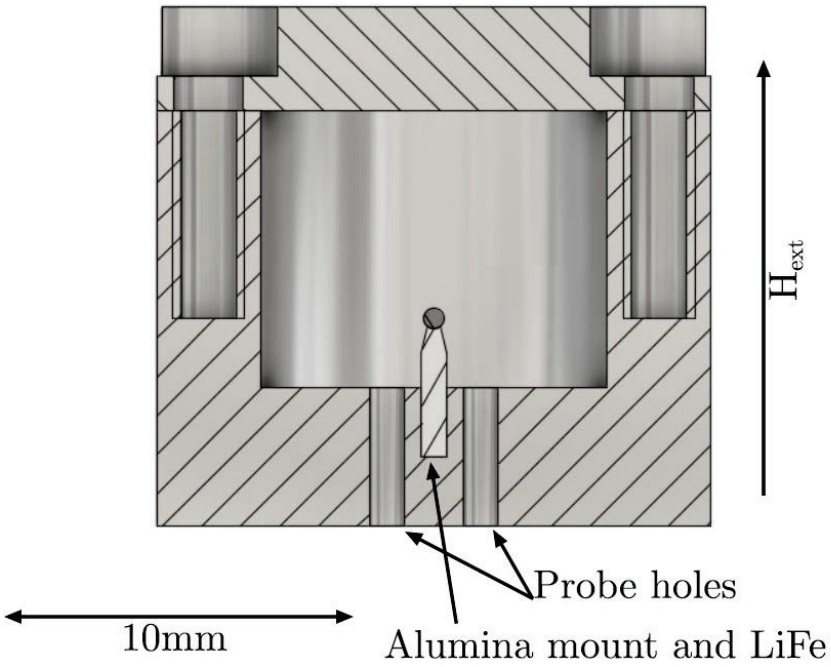

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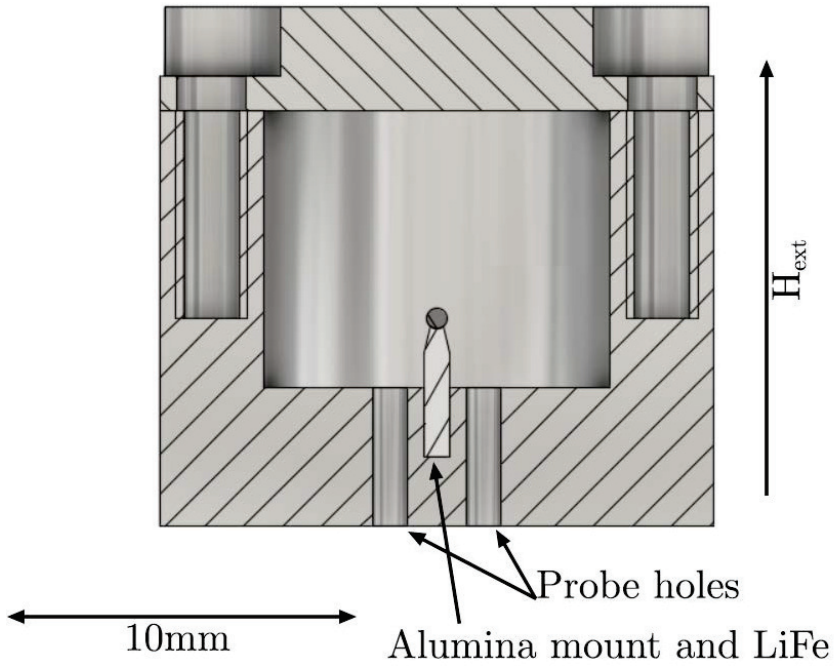

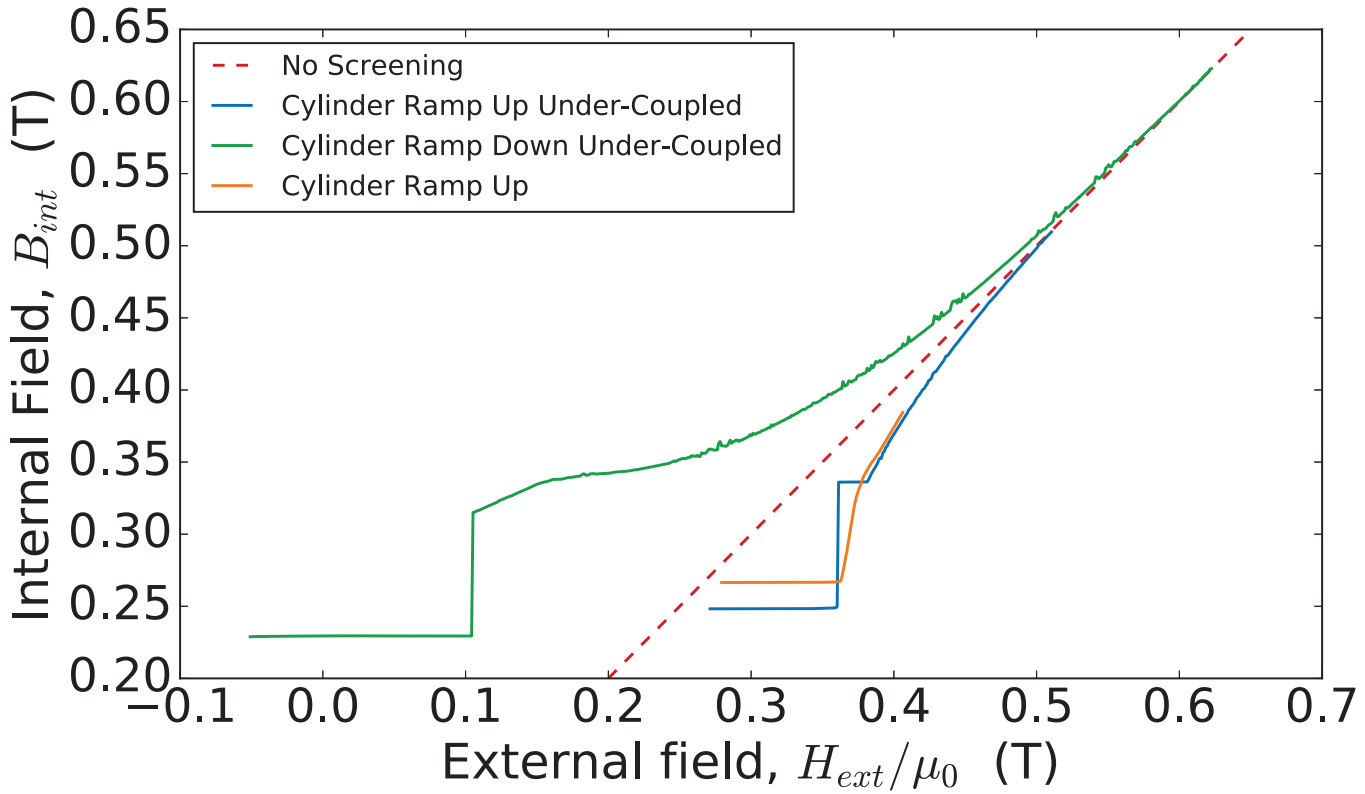

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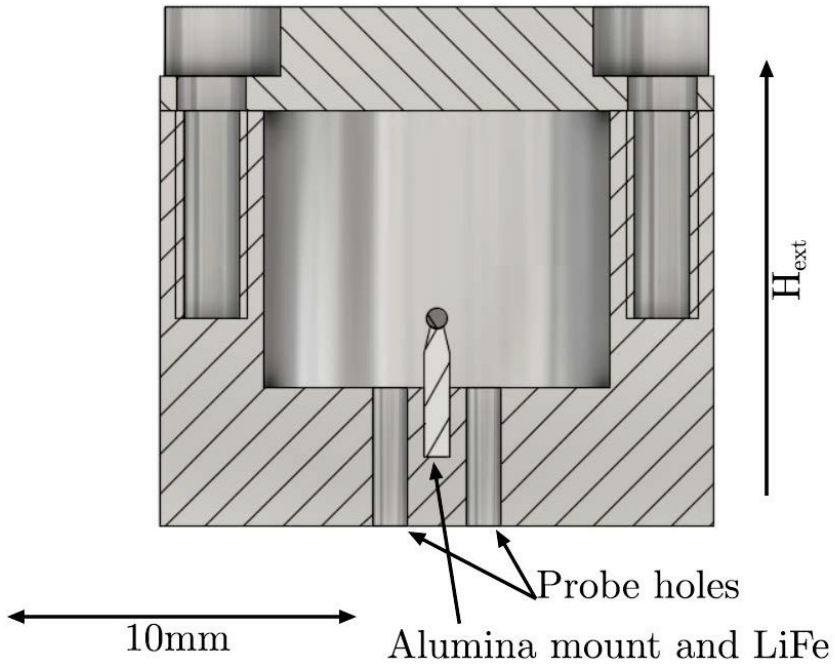

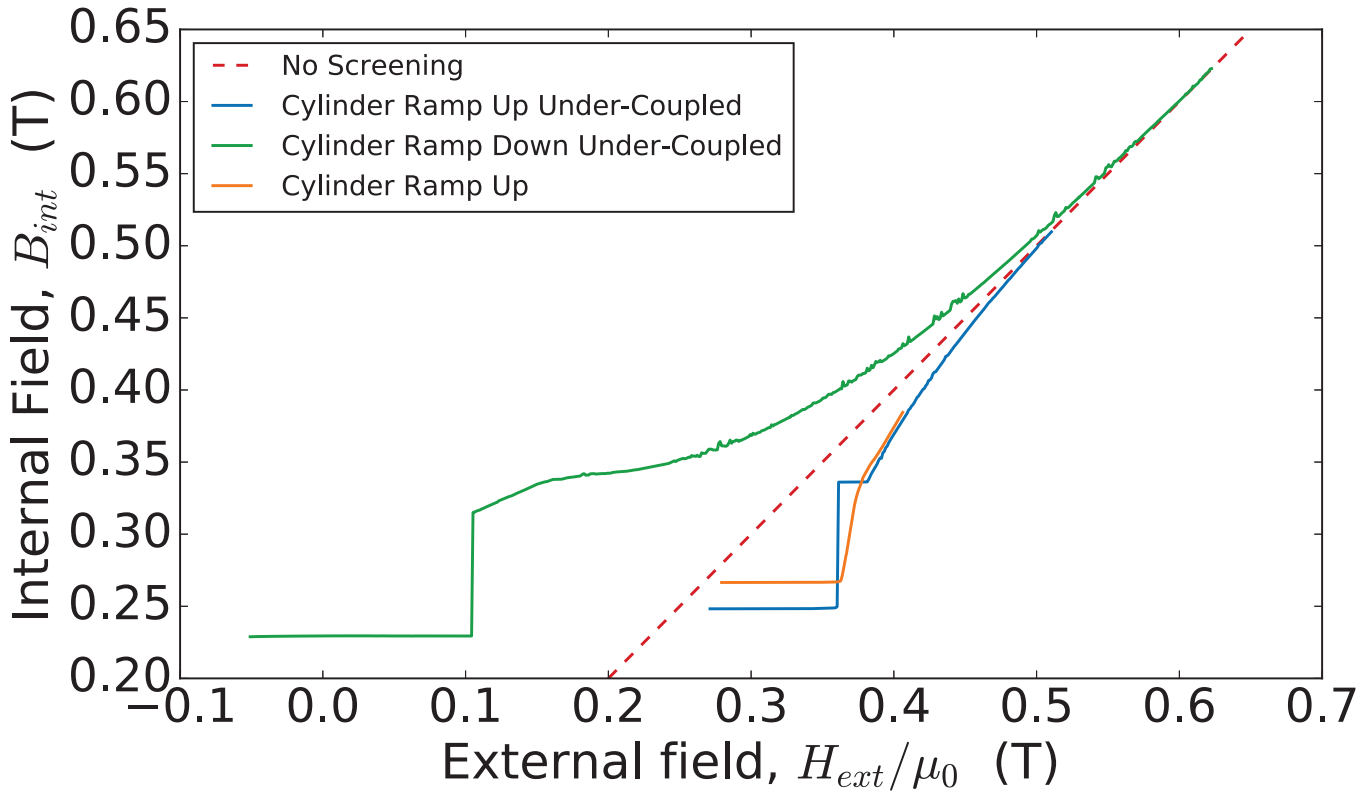

https://doi.org/10.1063/5.0023547

Design Considerations

$$\frac{df}{dt} \propto \frac{1}{SNR_{goal}^2} \frac{g_{a\gamma\gamma}^4 B^4 C^2 V^2 \rho_a^2 Q_L Q_a}{m_a^2 (k_B T_n)^2}$$

- ~~Cavity stuff~~
- ~~Fridge/magnet stuff~~
- Amplifier/readout stuff
- Stuff we can't really control
- Best version of each of these things is highly mass range dependent…
- Begin to see some of the issues with going to, e.g. high or low frequencies
- Particularly - VOLUME

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

R&D: Readout

- Single Photon Detection is superior to SQL linear amplification under the right conditions
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$$\frac{P_\ell}{P_{sp}} = \frac{\bar{n}+1}{\sqrt{\bar{n}}}\sqrt{\frac{\Delta\nu_a}{\eta\Gamma}}$$

- For above parameters, with efficiency of 0.9: SQL about 50 times noisier

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- If we lower the temperature this ratio can become order of thousands

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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- We want single photon counters in the ~10s of GHz range
- Not a lot…but a few options

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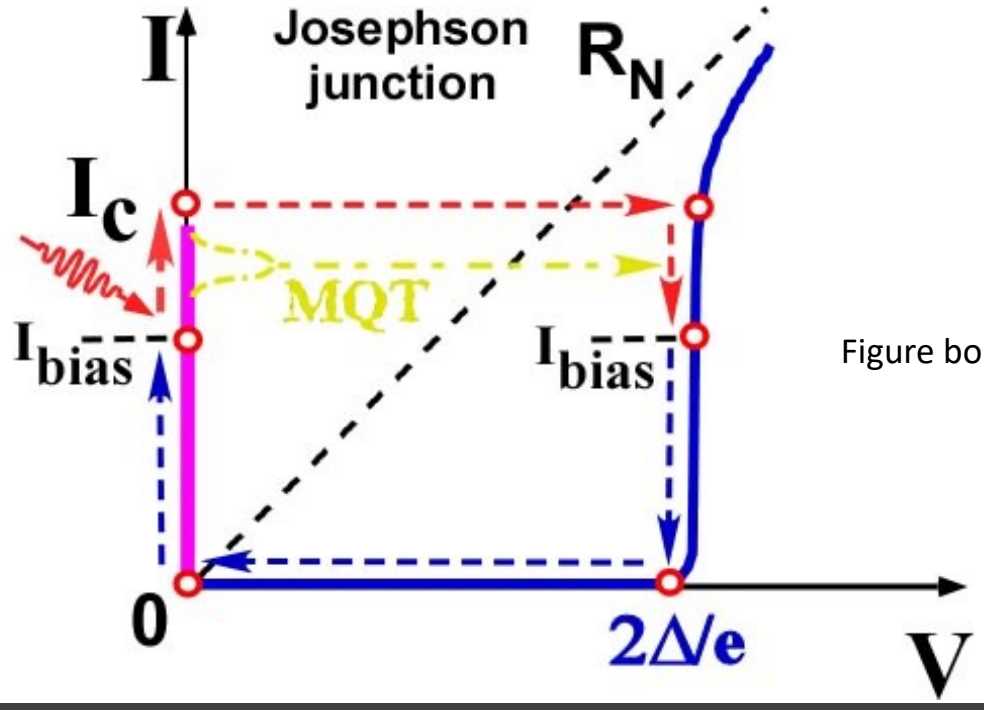

Figure borrowed from Leonid Kuzmin

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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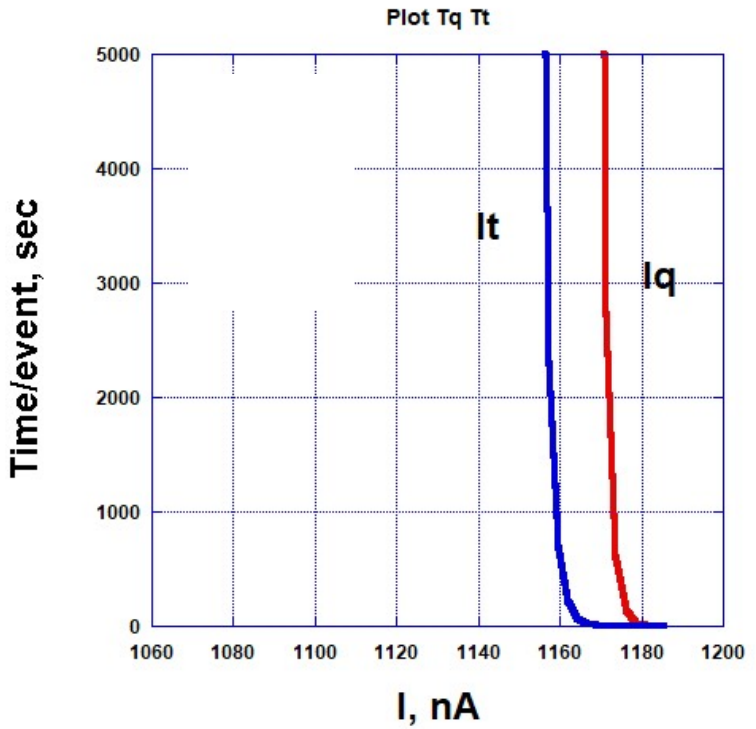
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

R&D: Readout

- Design is non-trivial
- Have some samples (from Chalmers) currently integrated on PCB
- Undergoing testing



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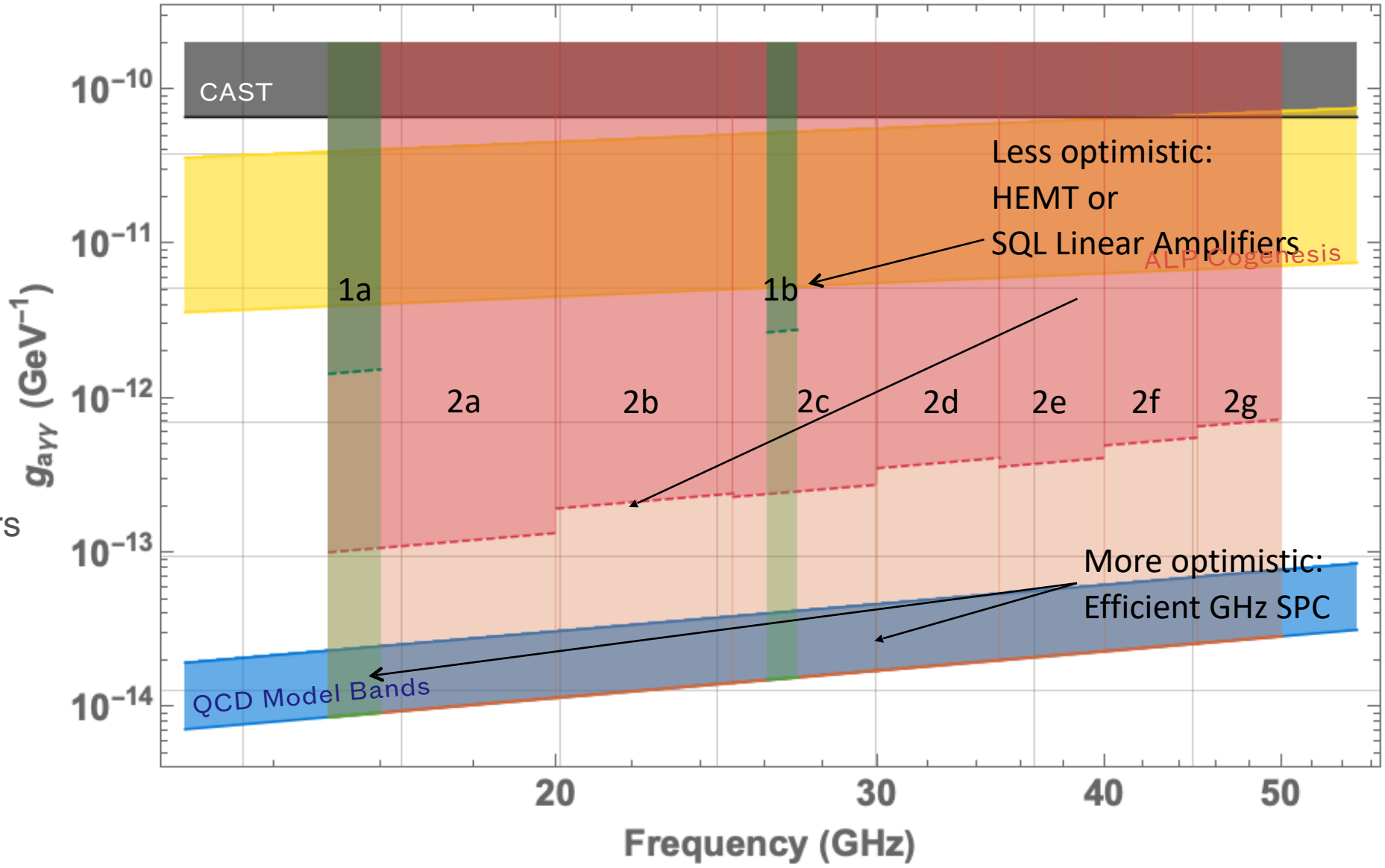
Run Plan

Phase 1:
- Standard TM010 Tuning Rod Resonators (mostly)
- HEMT Amplifiers

Phase 2:
- Novel Dielectric Resonators
- Better Qs
- Better Amplifiers/Readout



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Auxiliary ORGAN Experiments

ORGAN Q

- New experiment around 6-10 GHz (TBD)

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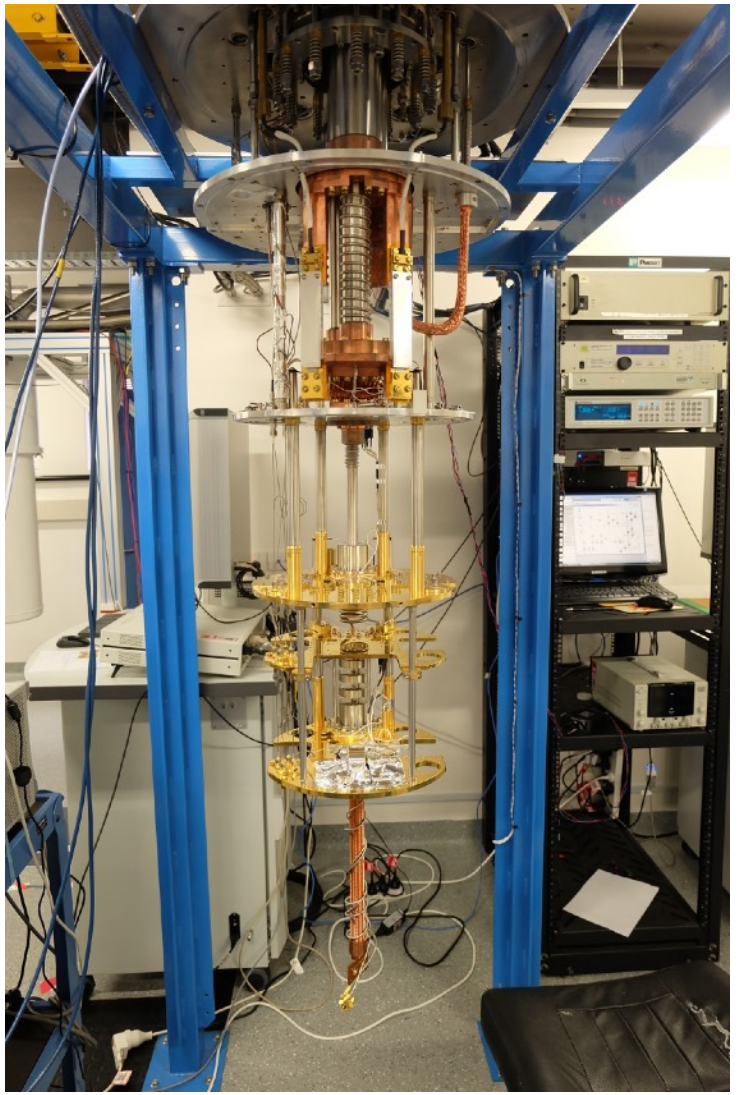
- Commence in 2022/2023 in larger bore 7 T Magnet



ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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- Plan 5-10 x KSVZ sensitivity

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- Potential solution…

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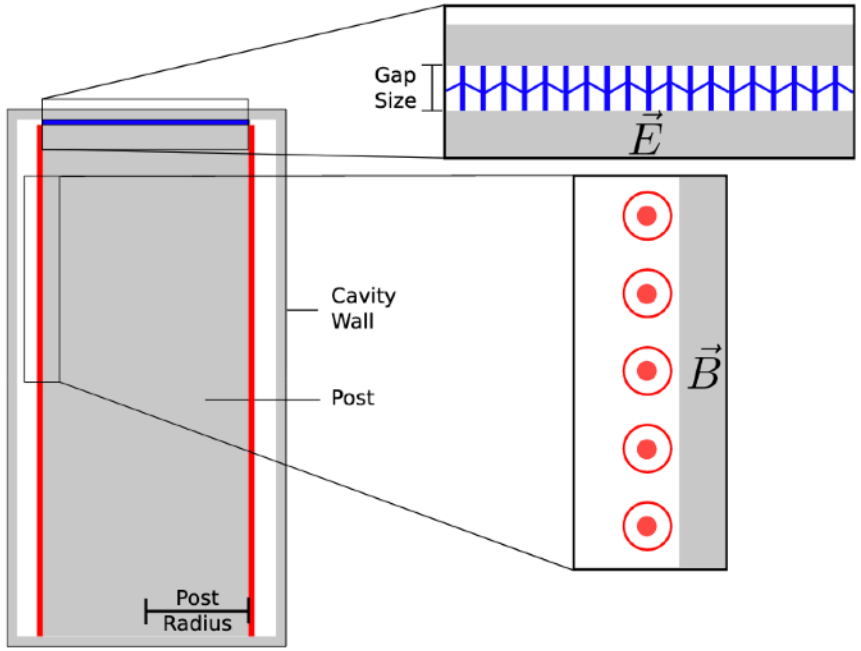

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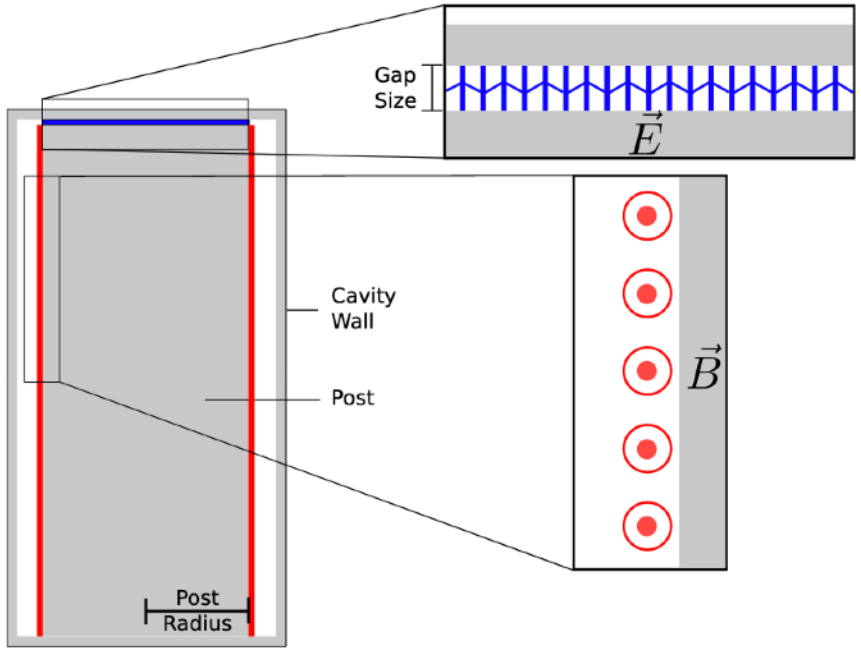
- Re-entrant cavities (lumped LC resonators)
- Lower frequency, take hit to form factor
- Actually plan to use a novel re-entrant cavity…watch this space



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ORGAN Low Frequency

- Where do you put a big re-entrant cavity?

ORGAN Low Frequency

- Where do you put a big re-entrant cavity?
- 3 T MRI Machine at Swinburne University
- Have approval to run experiment there

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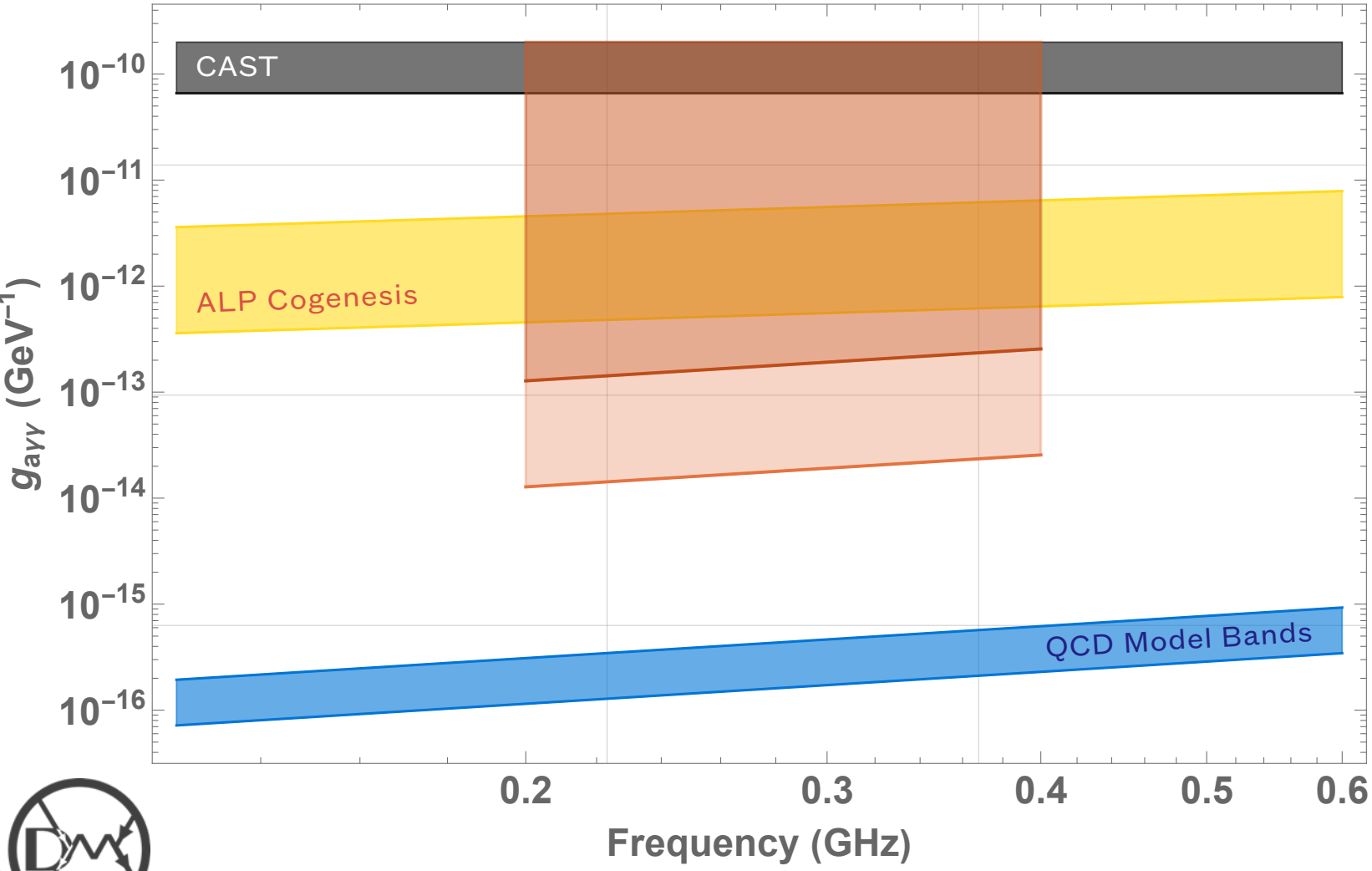

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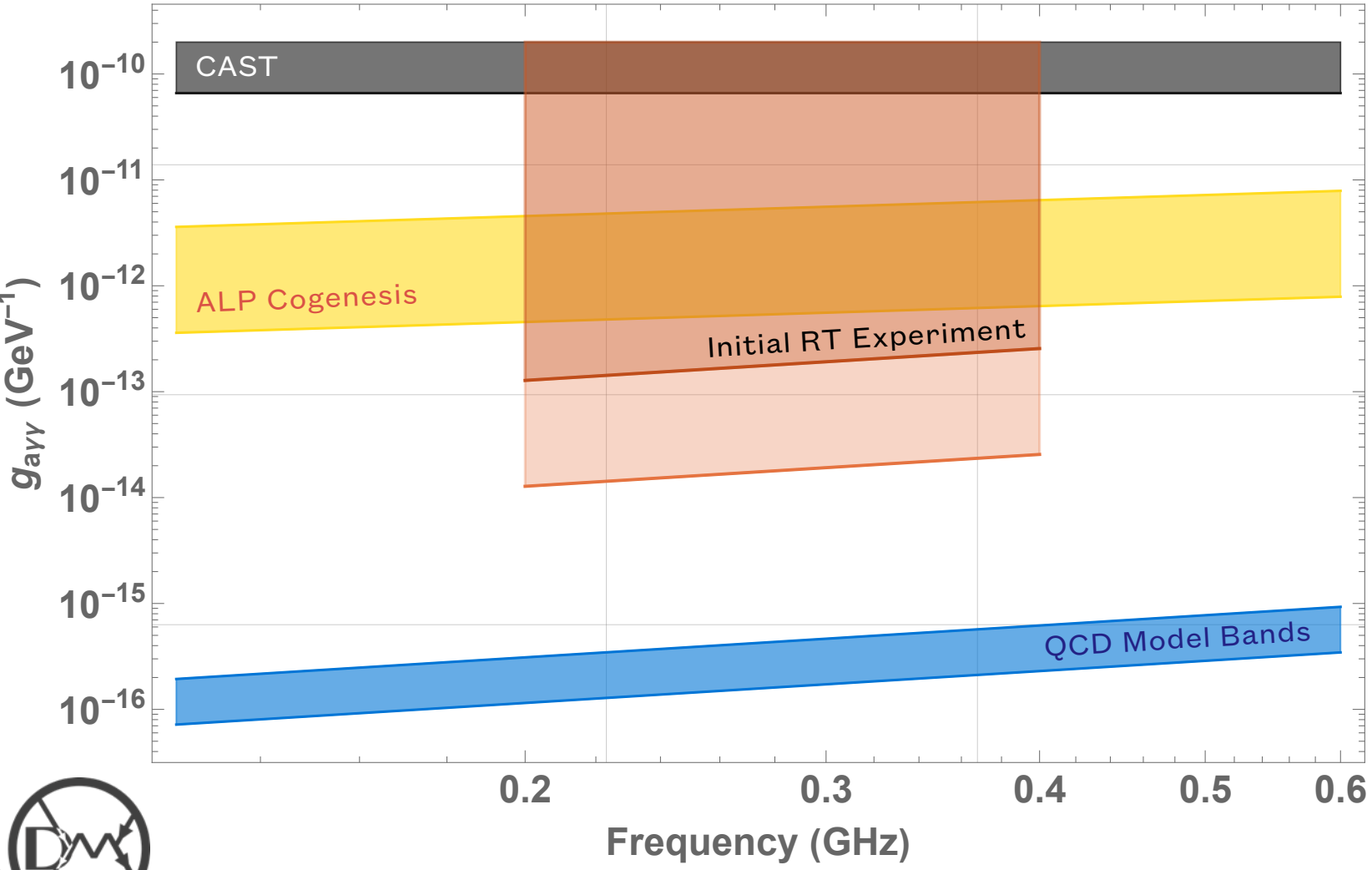

HEMT Amplifier

Room Temperature

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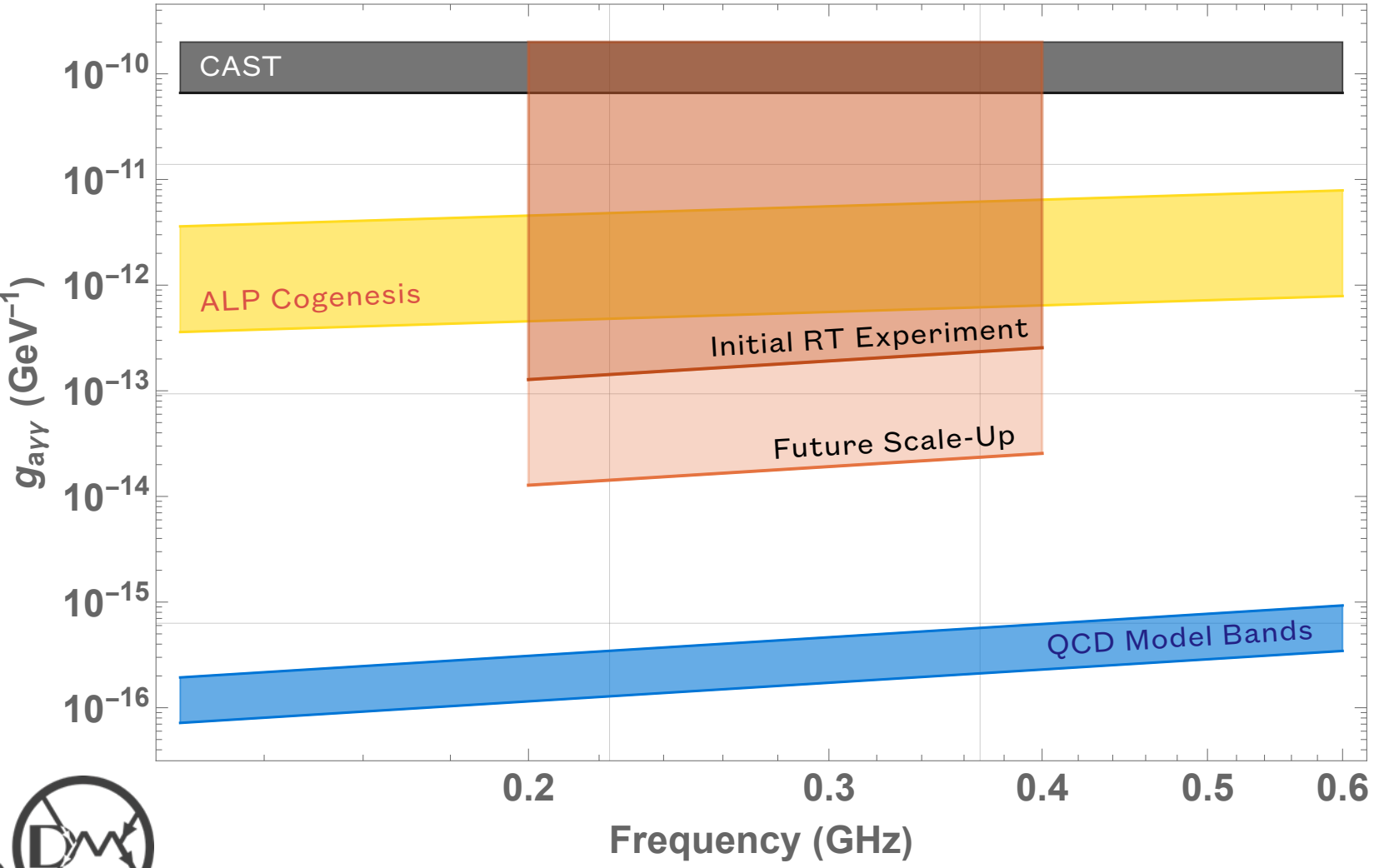

HEMT Amplifier

Room Temperature

SQUID Amplifier

4K System

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SHAMELESS PLUGFEST

UWA Scalar DM Experiment

Scalar Dark Matter

The introduction of an **ultra light scalar** field **with non-trivial coupling** to the **standard model** that we identify as the majority component of the local **dark matter** density.

Coupling of such an ultralight scalar to the standard model causes the **fundamental constants** of nature to **oscillate** at the Compton wavelength corresponding to the scalar field's mass value

Light dilaton field ⟷ Parameterised **standard model** sectors → Fundamental constant **variation**

$$\mathcal{L}_{\rm int} = \varphi\left[\frac{d_e}{4\mu_0}(F_{\mu\nu})^2 - \frac{d_g\beta_g}{2g_3}(F^A_{\mu\nu})^2 - c^2\sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right], \quad (1)$$

$$\alpha_{\rm EM}(\varphi) = \alpha_{\rm EM}\left(1 + d_e^{(i)}\frac{\varphi^i}{i}\right).$$

$$m_j(\varphi) = m_j\left(1 + d_{m_j}^{(i)}\frac{\varphi^i}{i}\right) \quad \text{for } j = e, u, d.$$

$$\Lambda_3(\varphi) = \Lambda_3\left(1 + d_g^{(i)}\frac{\varphi^i}{i}\right).$$

Damour, T., & Donoghue, J. F. (2010). Equivalence principle violations and couplings of a light dilaton. *Physical Review D - Particles, Fields, Gravitation and Cosmology*, *82*(8), 084033. https://doi.org/10.1103/PhysRevD.82.084033

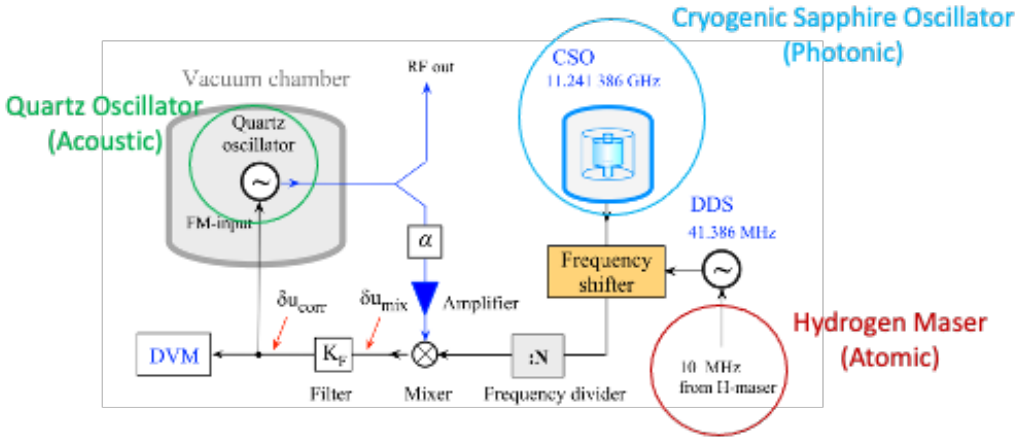
Hees, A., Minazzoli, O., Savalle, E., Stadnik, Y. V, & Wolf, P. (2018). Violation of the equivalence principle from light scalar dark matter. *Physical Review D*, *98*(6). https://doi.org/10.1103/physrevd.98.064051

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

UWA Scalar DM Experiment

Frequency modes of **clocks** depend on fundamental constants

Compare modes of clocks of **differing architecture** to **constrain** fundamental constant variation ⟶ ***Constrain scalar DM coupling***



$$f_Q \propto m_e\alpha^2\sqrt{\frac{m_e}{m_p}} \propto m_e\alpha^2\sqrt{\frac{m_e}{\Lambda_{QCD}}}. \quad (9)$$

The dependencies of both the CSO and Maser frequencies are given in Appendix A of Ref. [41],

$$f_{CSO} \propto m_e\alpha, \quad (10)$$

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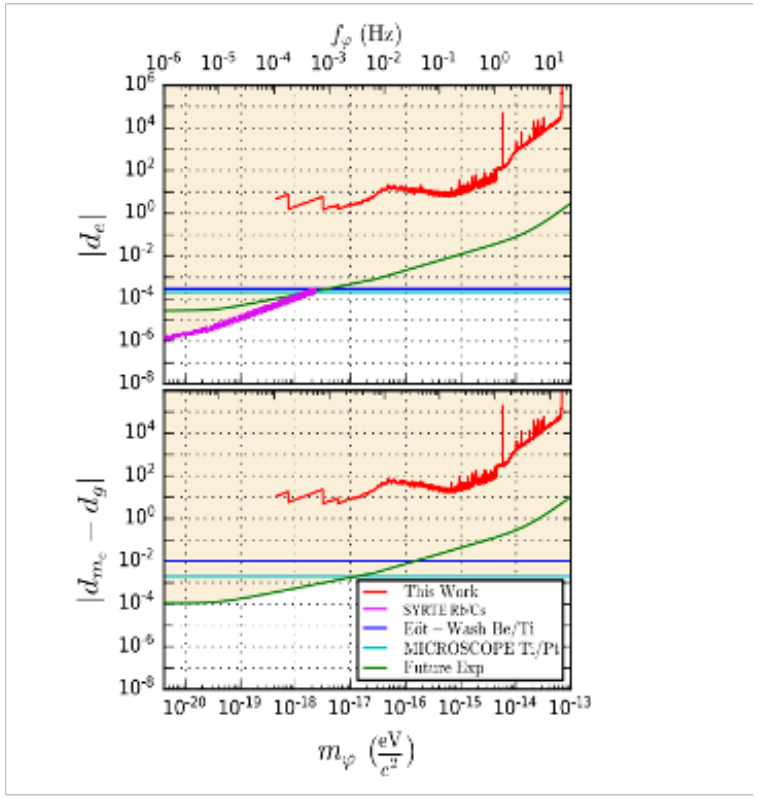

Campbell, W. M., McAllister, B. T., Goryachev, M., Ivanov, E. N., & Tobar, M. E. (2021). Searching for Scalar Dark Matter via Coupling to Fundamental Constants with Photonic, Atomic, and Mechanical Oscillators. *Physical Review Letters*, *126*(7), 71301. https://doi.org/10.1103/PhysRevLett.126.071301

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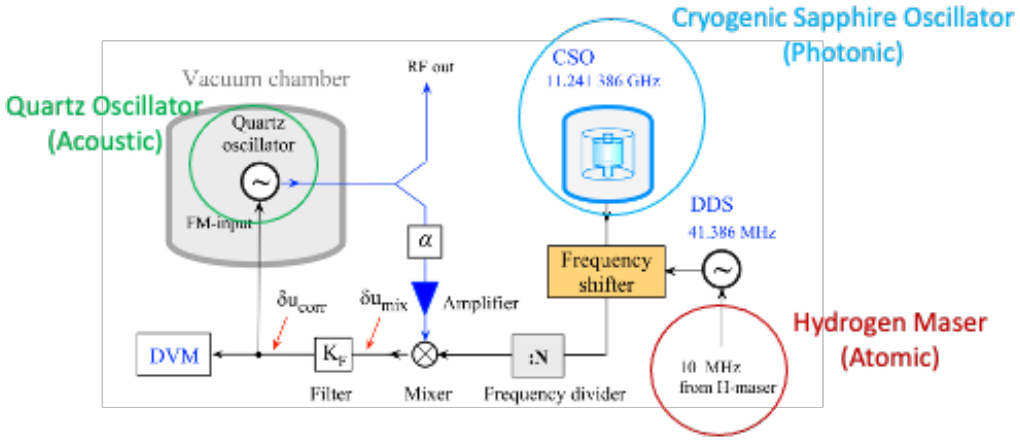

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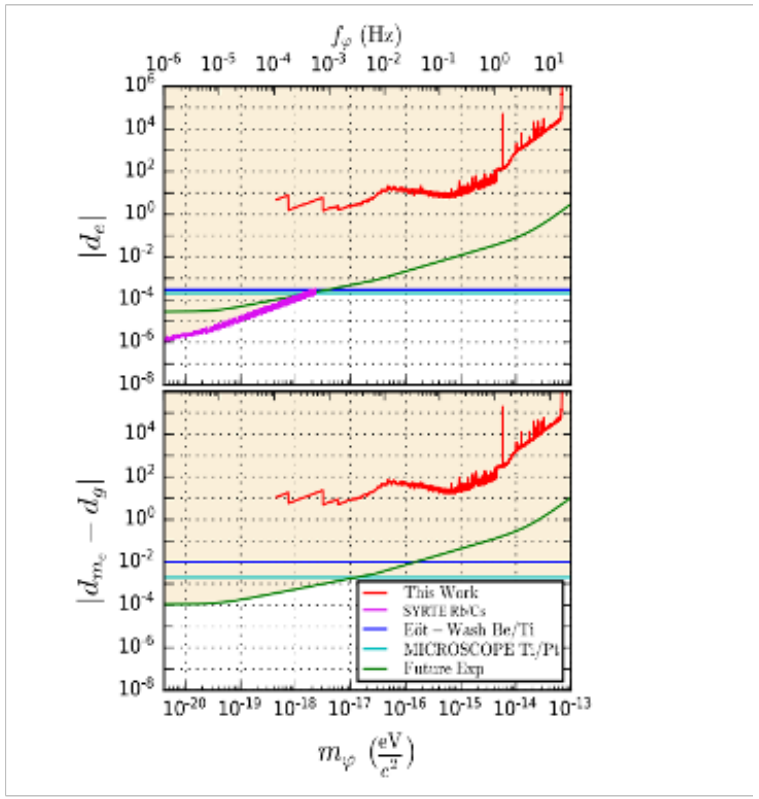

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See William Campbell's Poster!

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

UWA PERTH · AUSTRALIA

UPLOAD

UPconversion Low-Noise Oscillator Axion Detector

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

Catriona Thomson, the University of Western Australia
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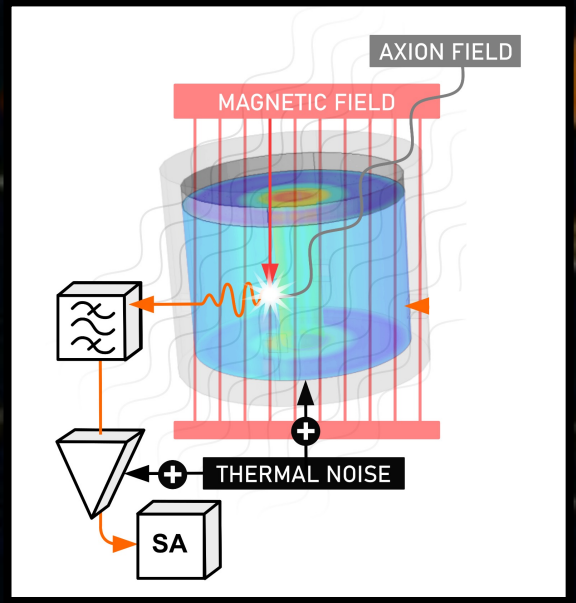
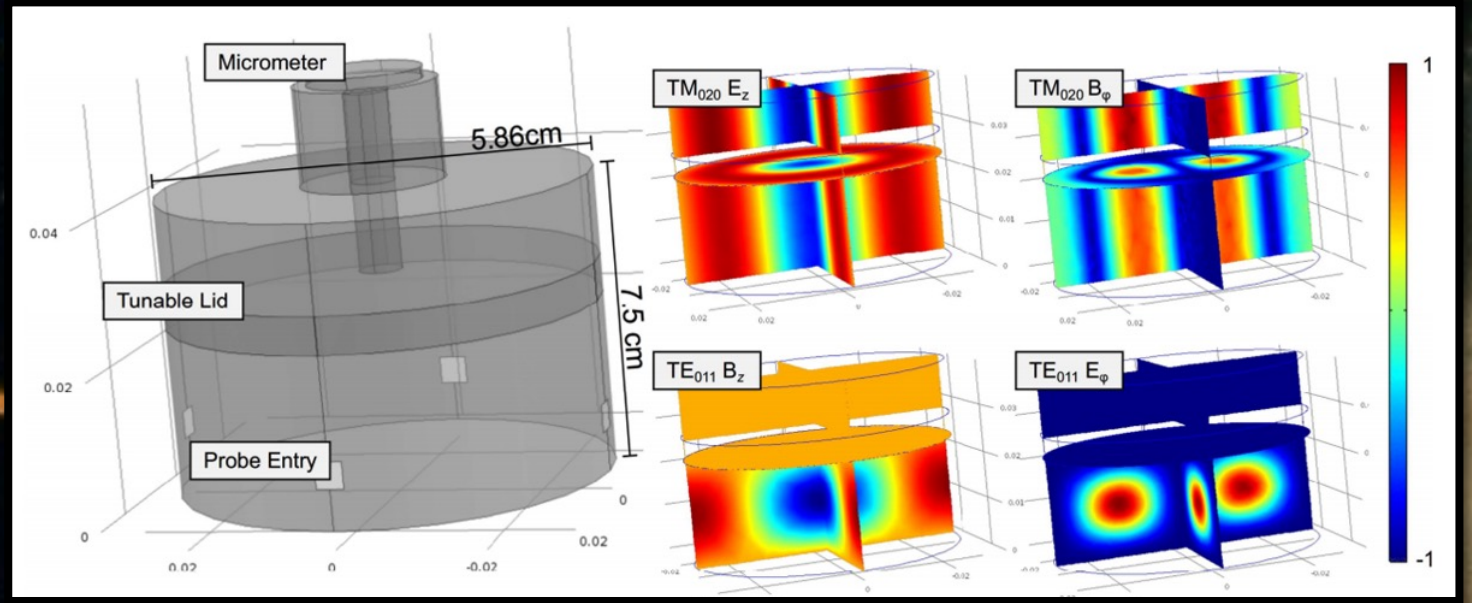
$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



DC HALOSCOPE



"AC HALOSCOPE"

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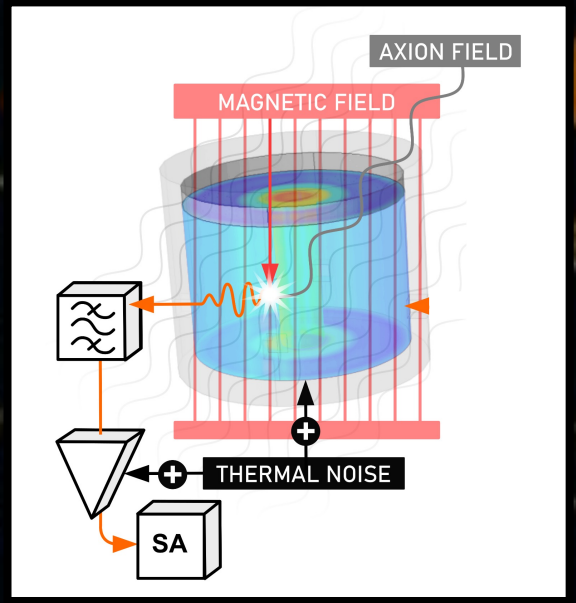

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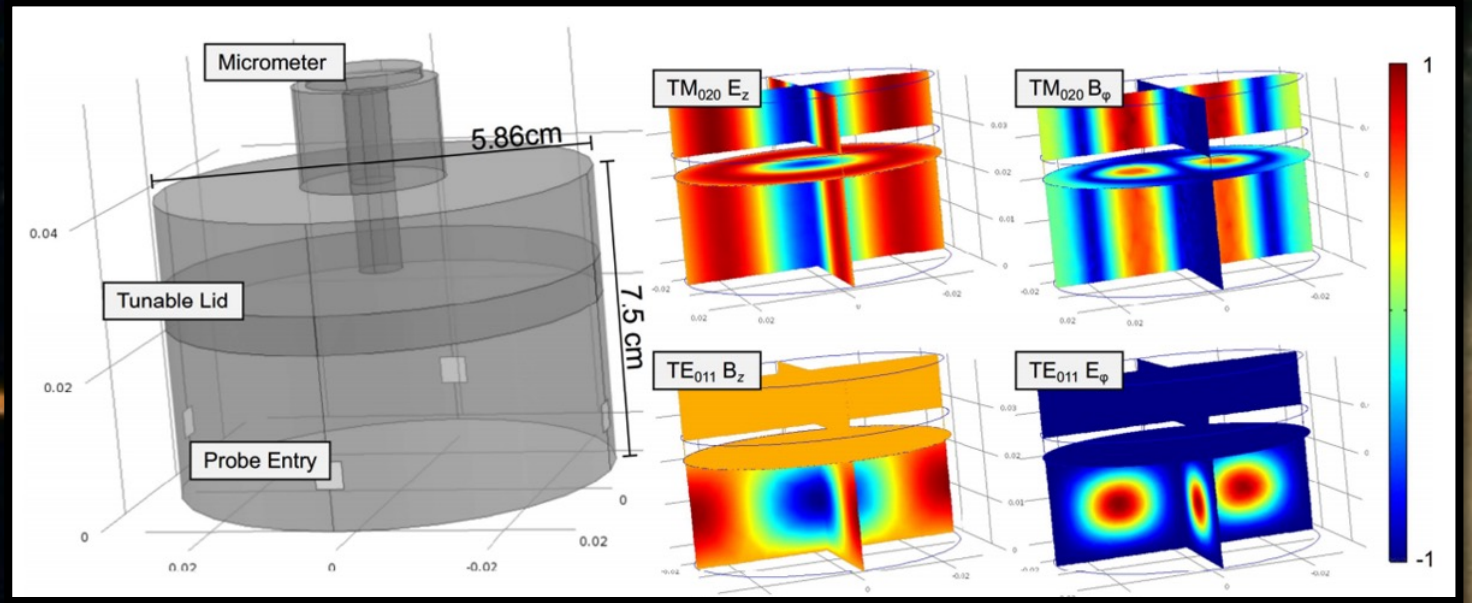

"AC HALOSCOPE"

See Catriona Thomson's Poster!

Scalar DM with ORGAN

arXiv > hep-ph > arXiv:2207.14437

High Energy Physics – Phenomenology

[Submitted on 29 Jul 2022]

Searching for Scalar Field Dark Matter using Cavity Resonators and Capacitors

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See Igor Samsonov's talk yesterday!

Search for HFGW with ORGAN

PHYSICAL REVIEW D **105,** 116011 (2022)

Detecting high-frequency gravitational waves with microwave cavities

Asher Berlin,[1,2,3] Diego Blas,[4,5] Raffaele Tito D'Agnolo,[6] Sebastian A. R. Ellis,[7,6]
Roni Harnik,[2,3] Yonatan Kahn,[8,9,3] and Jan Schütte-Engel[8,9,3]

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Detecting high-frequency gravitational waves with microwave cavities

Asher Berlin,[1,2,3] Diego Blas,[4,5] Raffaele Tito D'Agnolo,[6] Sebastian A. R. Ellis,[7,6]
Roni Harnik,[2,3] Yonatan Kahn,[8,9,3] and Jan Schütte-Engel[8,9,3]

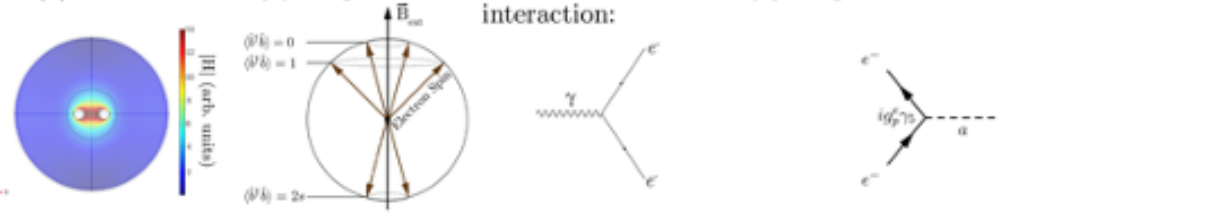
See Mike Tobar's talk Thursday!

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

UWA Axion Magnon Experiment

$$H = \omega_c c^\dagger c + \omega_m b^\dagger b + g_{cm}(c^\dagger + c)(b^\dagger + b) - \gamma B_{aee}\left[\sqrt{\frac{S}{2}}\sin(\phi)(be^{-i\theta} + b^\dagger e^{i\theta}) + b^\dagger b\cos(\phi)\right]$$

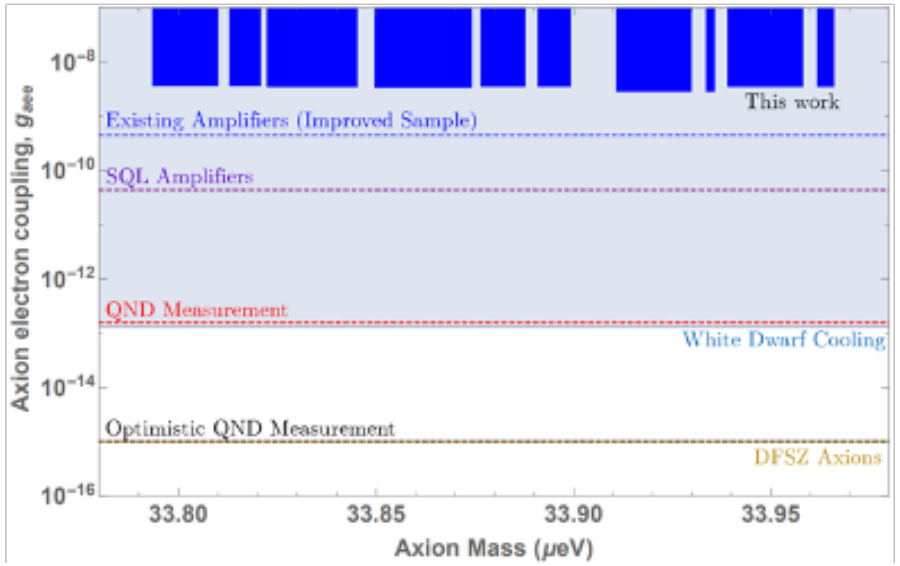
(a) Photons: (b) Magnons: (c) Photon-Magnon interaction: (d) Magnon-Axion interaction:

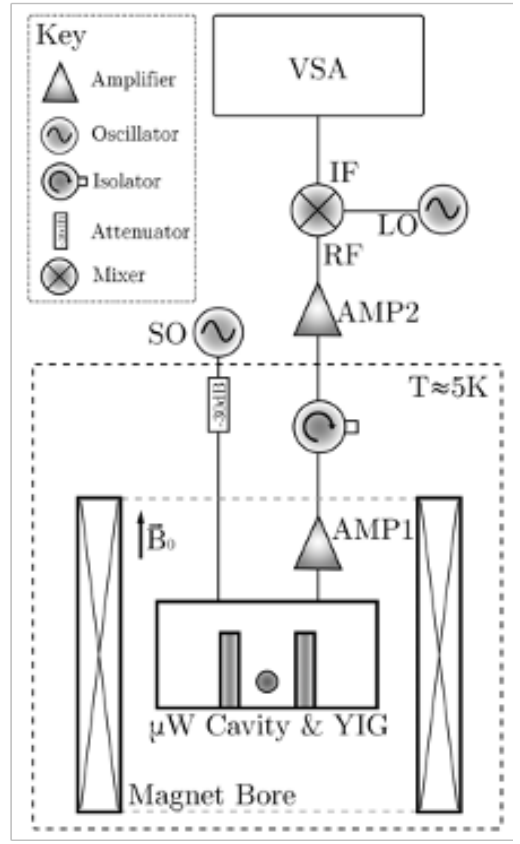


- Detects axions by interaction with electrons
- Can distinguish between axion models
- Is directional/can detect direction of axion wind
- Much lower signal powers.

Conclusion:

Ideal experiment to probe axion properties post-detection





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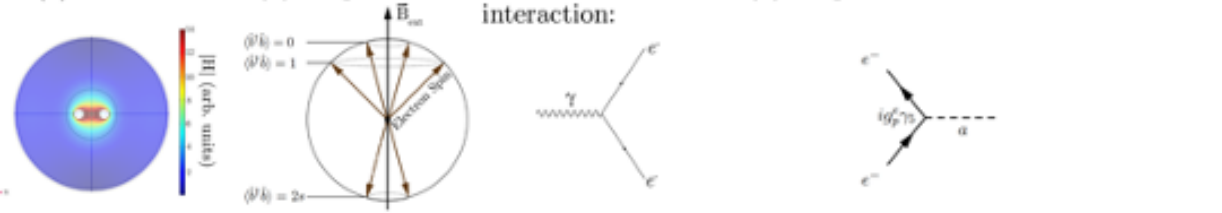

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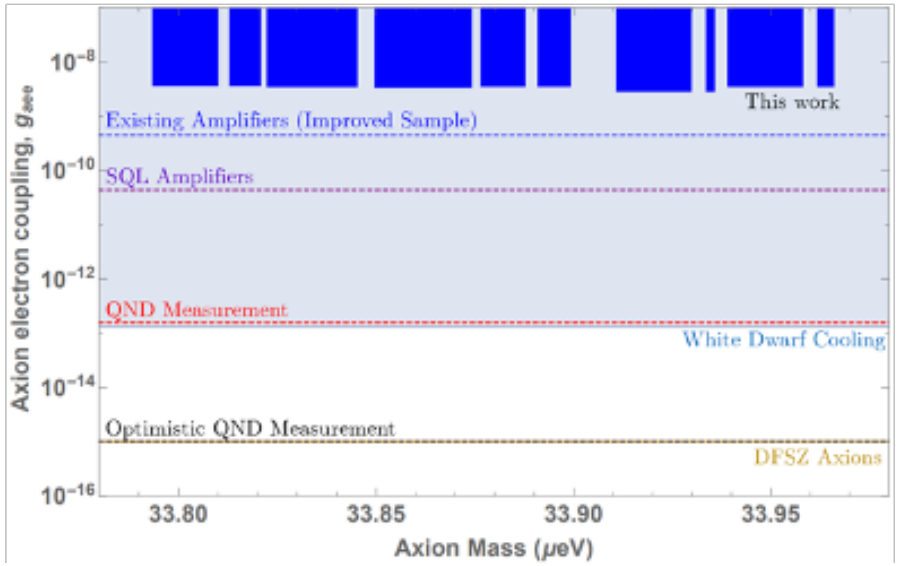

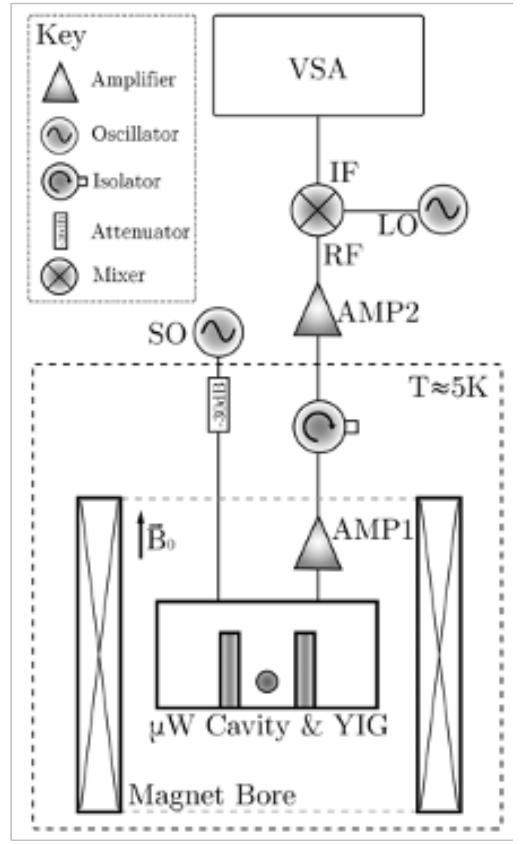

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See https://doi.org/10.1016/j.dark.2019.100306

Conclusion

- ORGAN
  - High mass axion haloscope (15+ GHz)
- Run Plans
  - Phase 1a completed 2021/2022
  - Future phases commencing 2022
  - Various avenues of R&D
- Auxiliary experiments
  - ORGAN-Q
  - ORGAN Low Frequency
- Other DM Experiments
  - Scalar DM Searches
  - Axion-Magnon Coupling
  - UPLOAD
  - Search for HFGW

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