The ORGAN Experiment: Results, Status and Future Plans

Ben McAllister, Aaron Quiskamp, Paul Altin, Maxim Goryachev,
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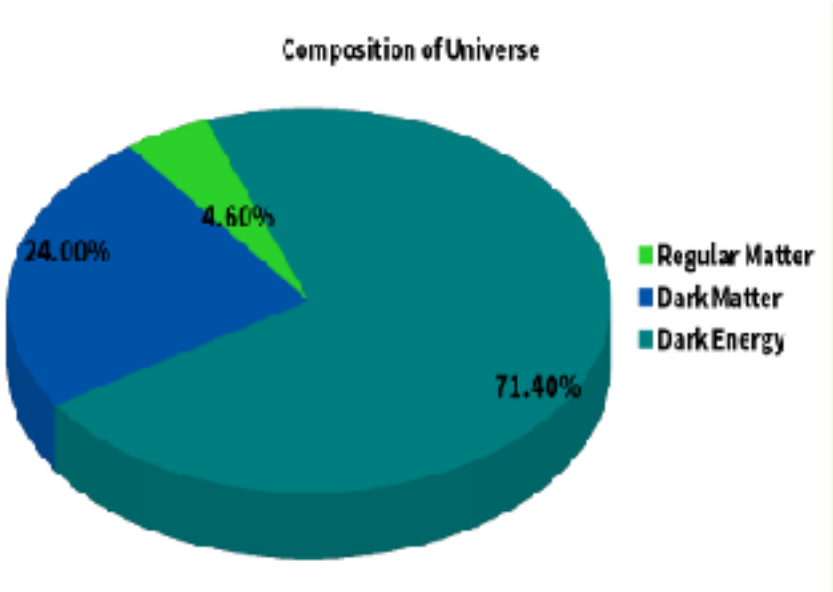
Overview

- General Introduction
- ORGAN
  - Run Plan
  - Phase 1
  - R&D/Future Phases
- ORGAN-Q
- ORGAN Low Frequency

Dark Matter

- Most of Universe made of DE, DM
- What is DM?
  - Doesn't interact with light
  - Has mass
  - ~5x as much as the regular matter
  - New particles?



ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Axions

- Light boson first proposed in ‘70s as consequence of solution to the strong CP problem
- Strong CP problem in quantum chromodynamics
- There exist natural CP violating terms within the QCD Lagrangian

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

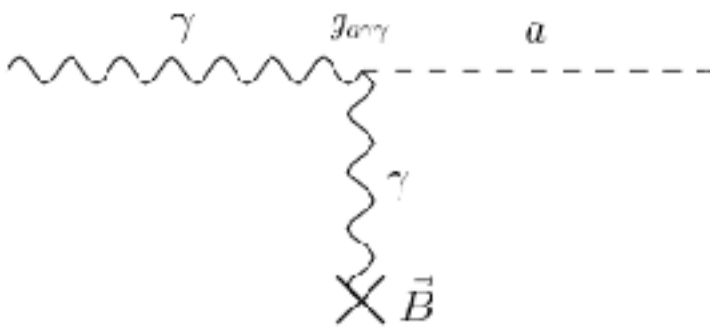
- Key point: if θ is non-zero, CP symmetry is violated, and measurable effects would occur
- Specifically, neutron would develop electric dipole moment

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Axions

- It was later realized that for a certain range of masses axions could comprise dark matter
- They are a neat candidate since they solve the strong CP problem
- Have various interesting couplings to standard model particles

  e.g. photons



- Experiments attempt to exploit this coupling

ORGAN Introduction

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

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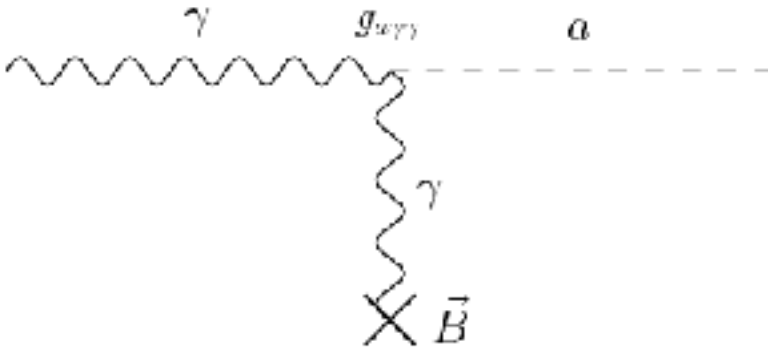

$$\hbar\omega_a \approx m_a c^2 + \frac{1}{2} m_a v_a^2$$

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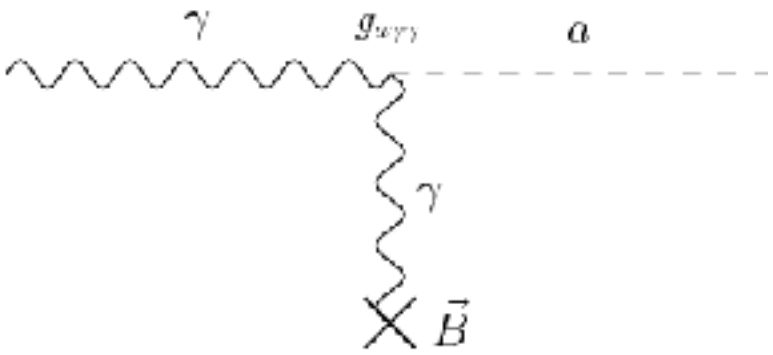

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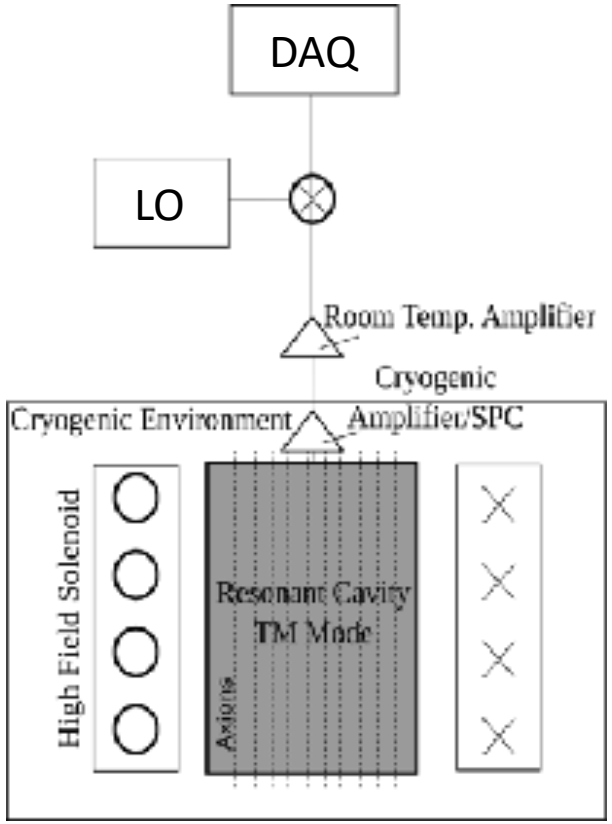

ORGAN Introduction

- Many cavities together
- The Oscillating Resonant Group AxioN Experiment

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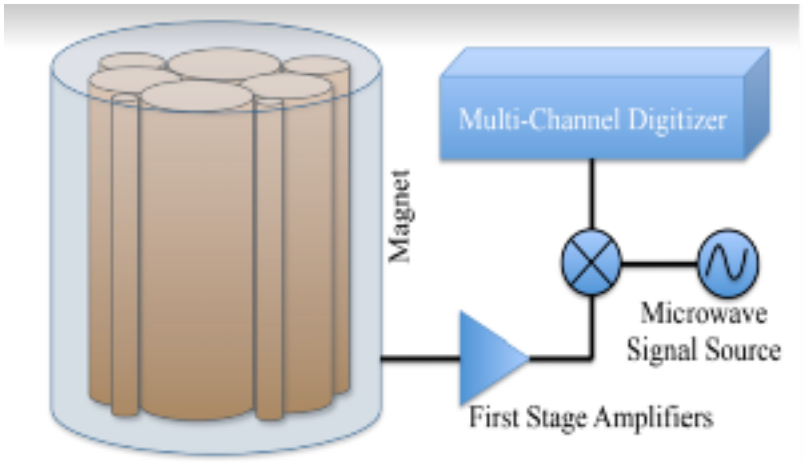

ORGAN Introduction

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- Motivations:

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- Motivations:
  - SMASH model
  - Josephson Junction results
  - High mass range relatively unexplored

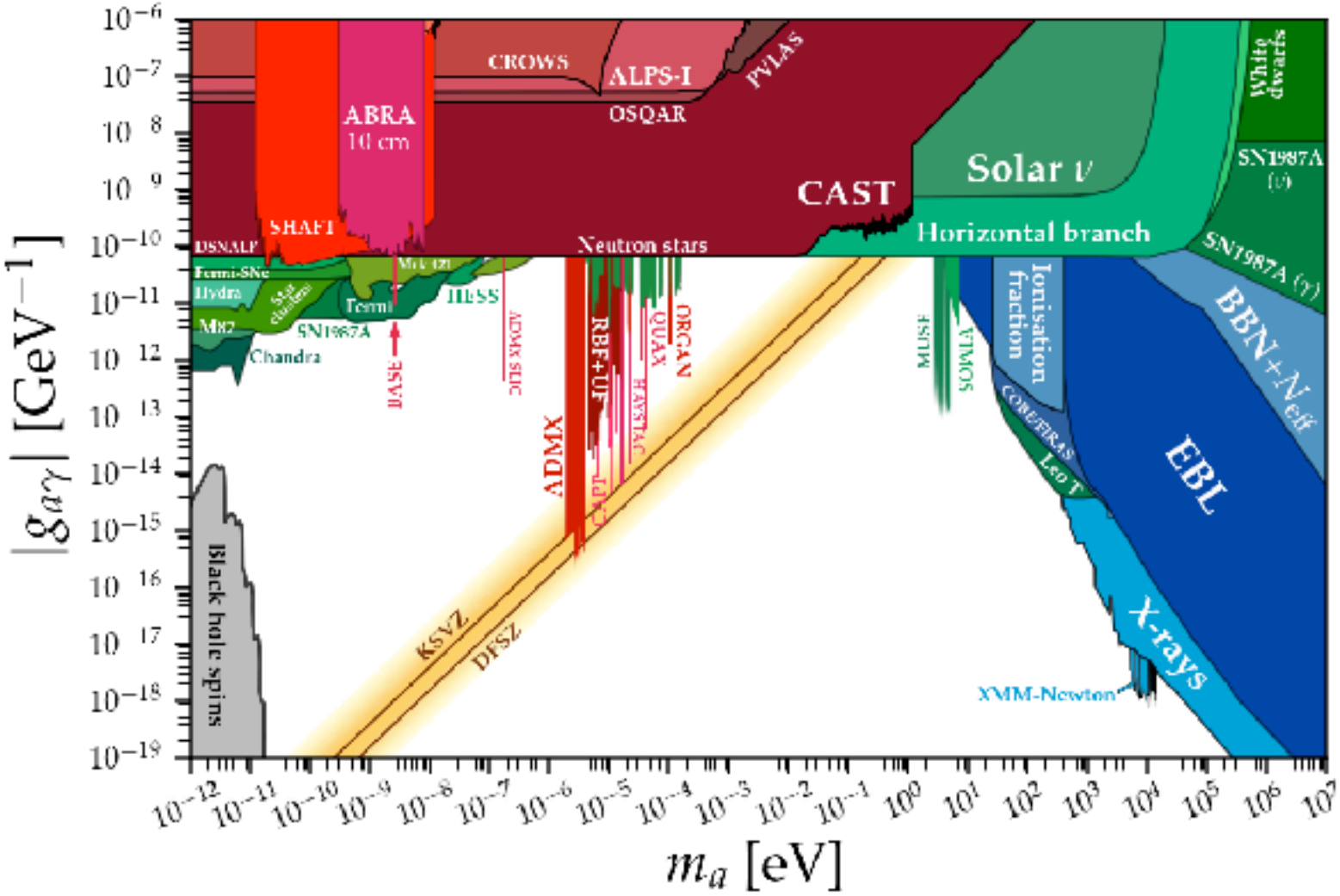
Unifying Inflation with the Axion, Dark Matter, Baryogenesis, and the Seesaw Mechanism

Guillermo Ballesteros, Javier Redondo, Andreas Ringwald, and Carlos Tamarit
Phys. Rev. Lett. **118**, 071802 – Published 15 February 2017

Possible Resonance Effect of Axionic Dark Matter in Josephson Junctions

Christian Beck
Phys. Rev. Lett. **111**, 231801 – Published 2 December 2013

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS



From CA O'Hare's Axion Limit Plotting Tool

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- Motivations:
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- Broken down into Phases:
    - Phase 1 - targeted 1 GHz scans ~month(s) scale
    - Phase 2 - wider scans with enhanced sensitivity, broken into 5 GHz chunks, ~year scale

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- Some auxiliary experiments

ORGAN Introduction

- Critical research areas:

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  - Novel tunable resonators
  - Superconductors

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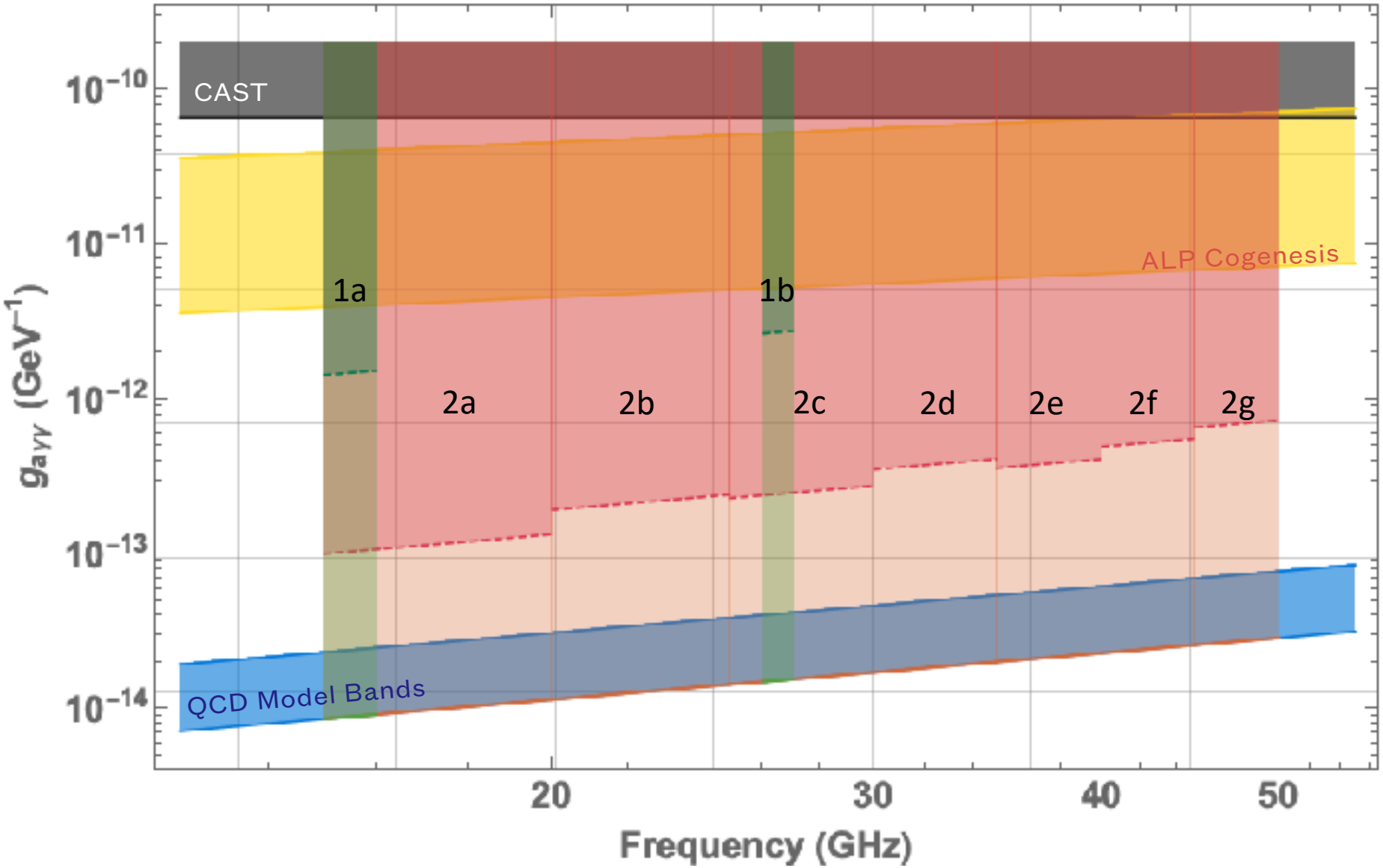
  - Superconductors
  - Low noise amplification/photon counting readout
  - Data acquisition and analysis

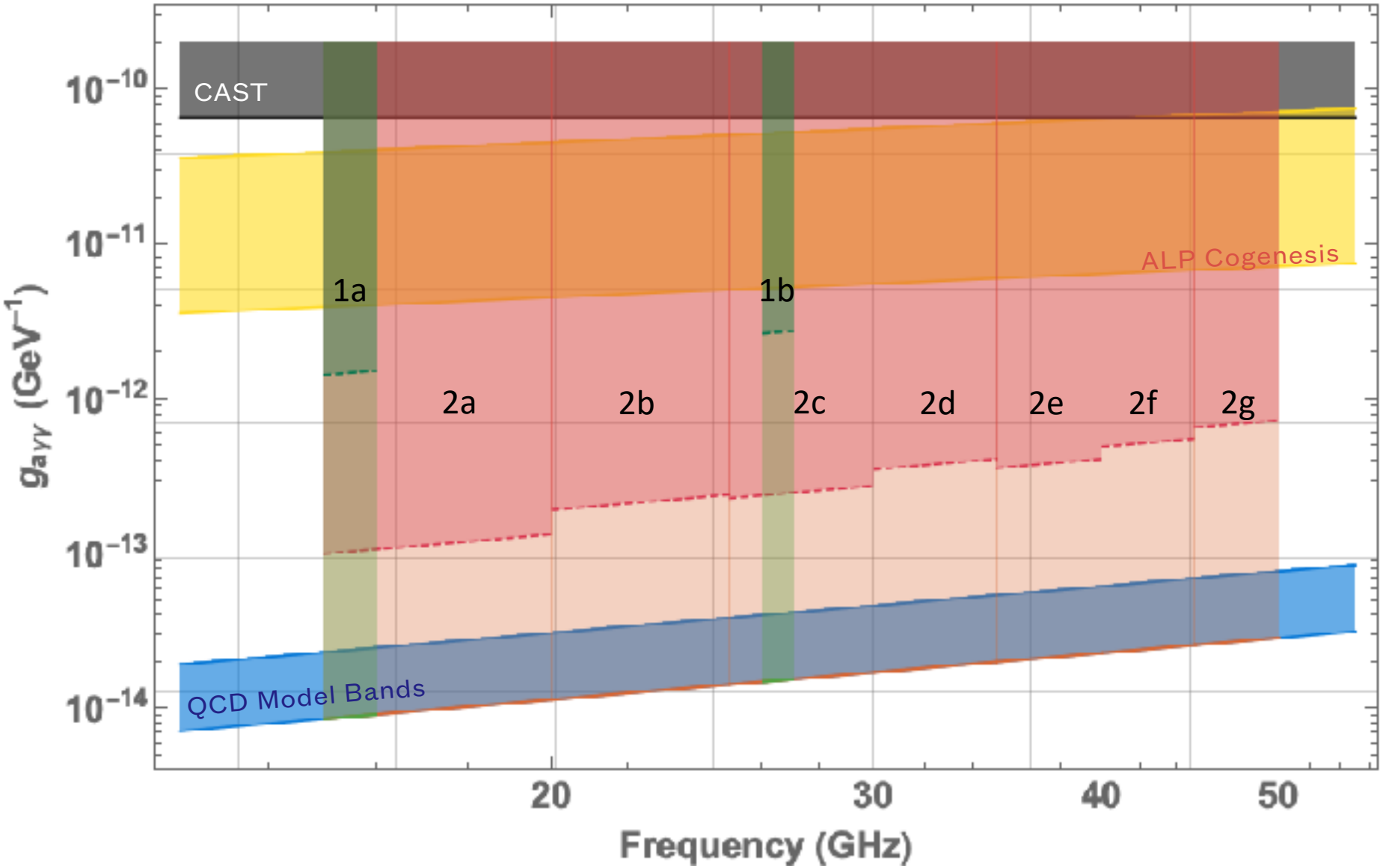
Run Plan


CAST
ALP Cogenesis
QCD Model Bands
1a
1b
2a
2b
2c
2d
2e
2f
2g
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$g_{a\gamma\gamma}$ (GeV^{-1})
20
30
40
50
Frequency (GHz)

Run Plan

Phase 1:

- Standard TM010 Tuning Rod Resonators (mostly)
- HEMT Amplifiers



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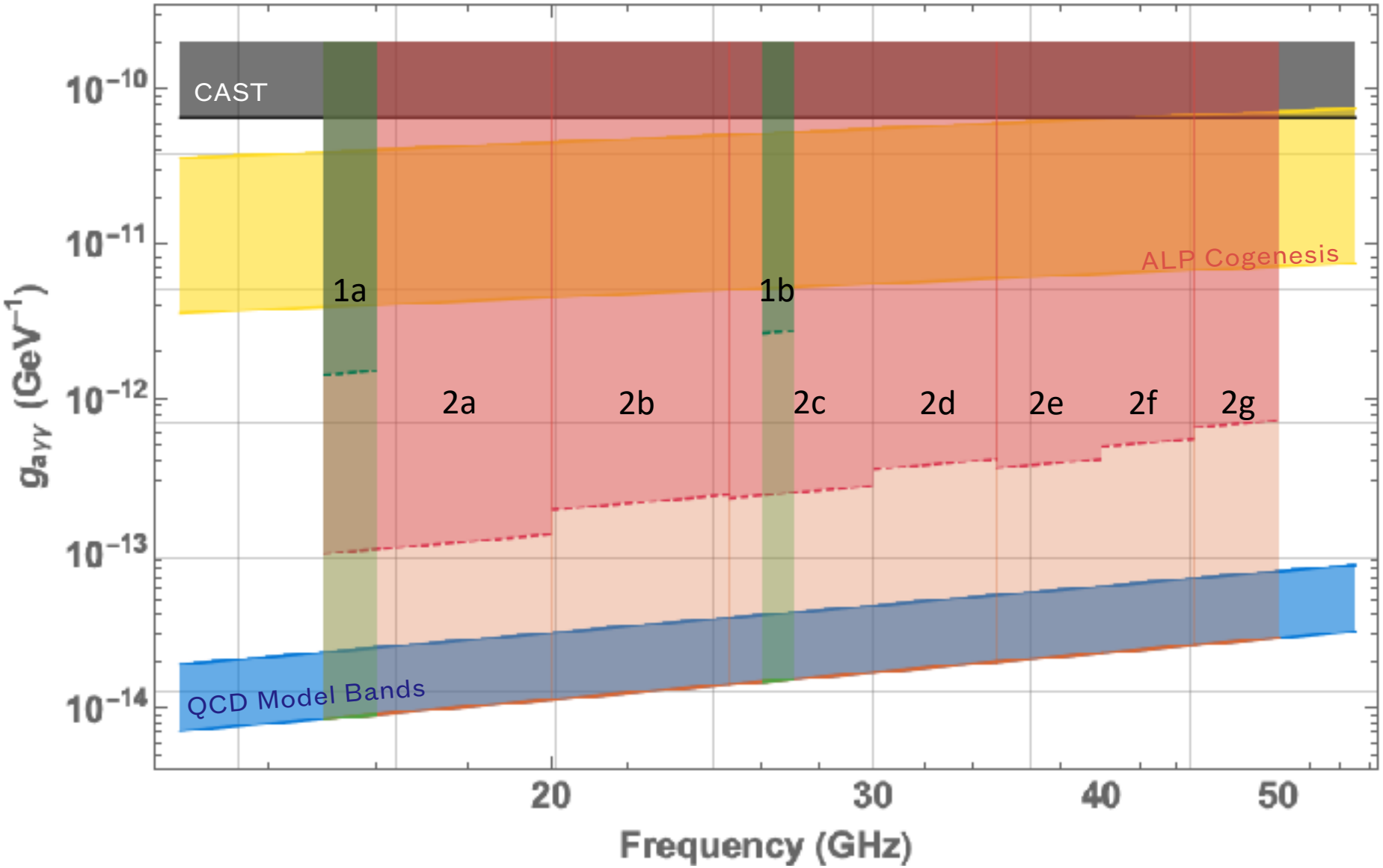
Phase 2:
- Novel Resonators
- Better Qs
- Better Amplifiers/Readout



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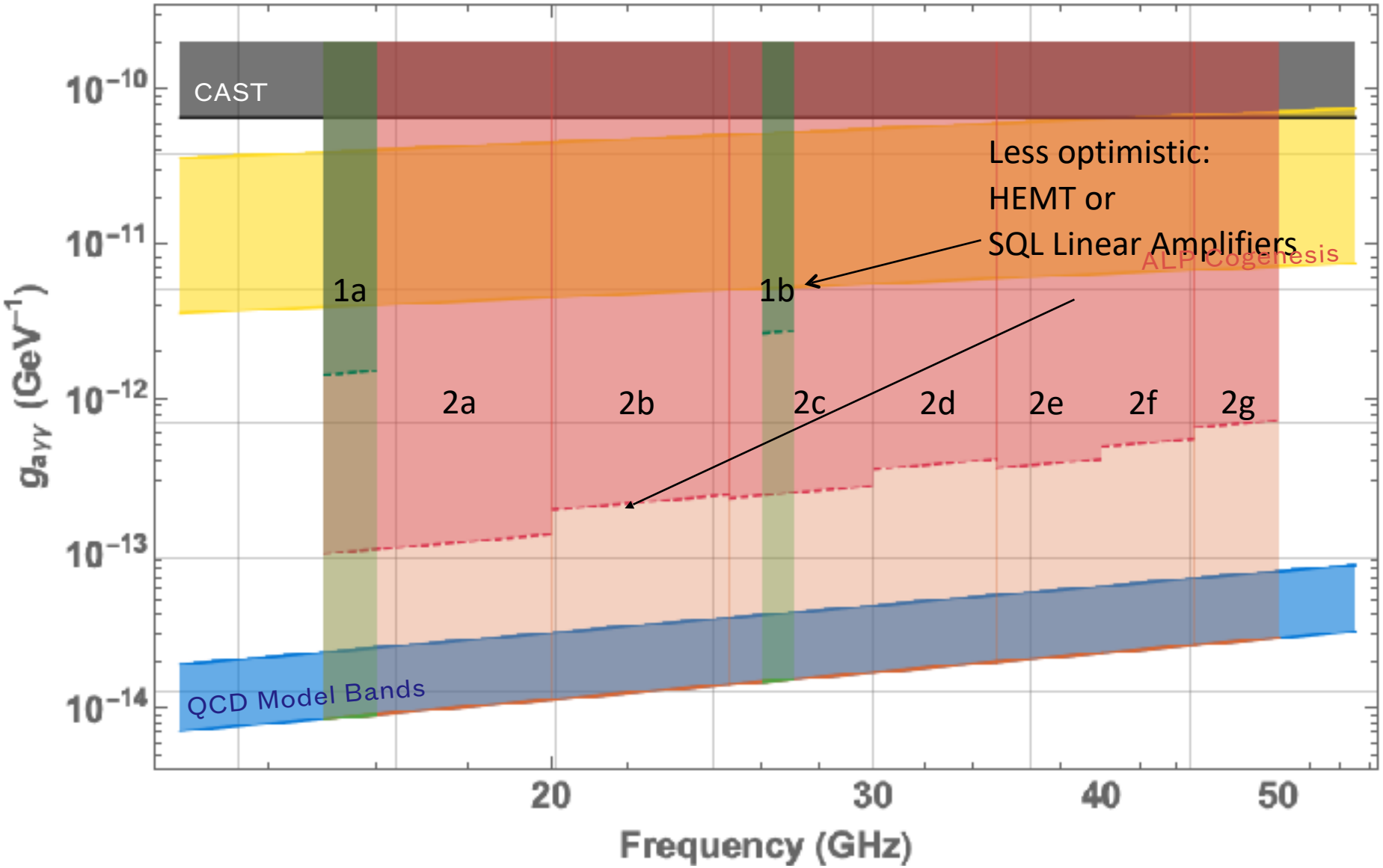

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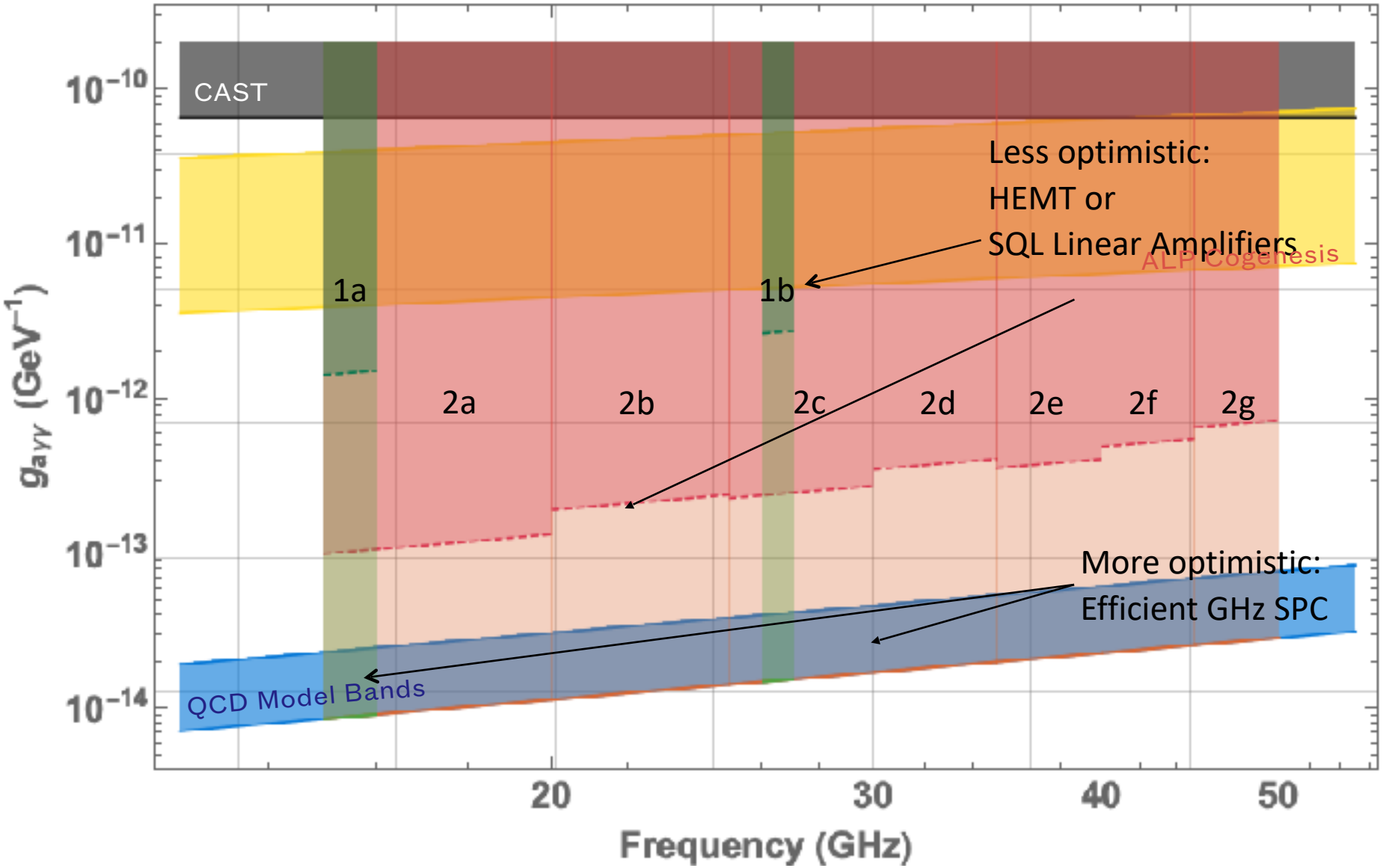

Phase 1a

- Targeted scan around 15 GHz
- Commenced in 2021, now complete

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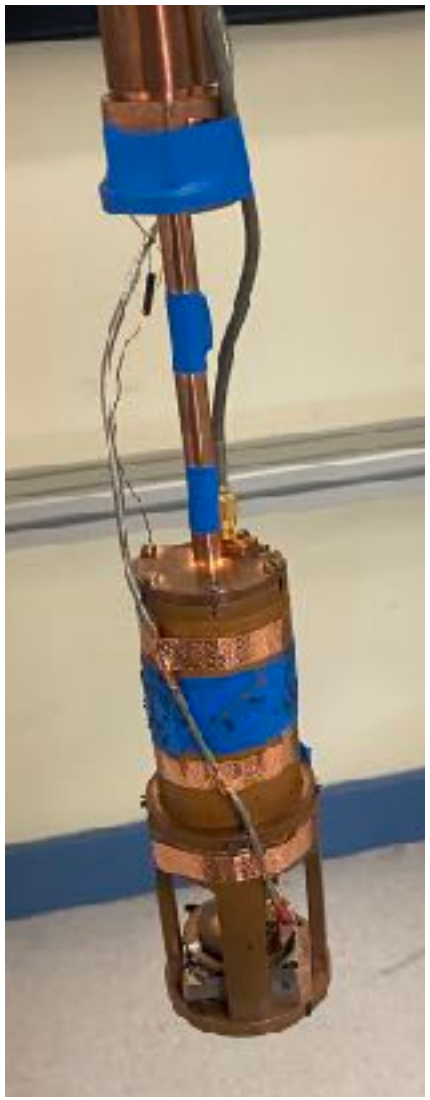
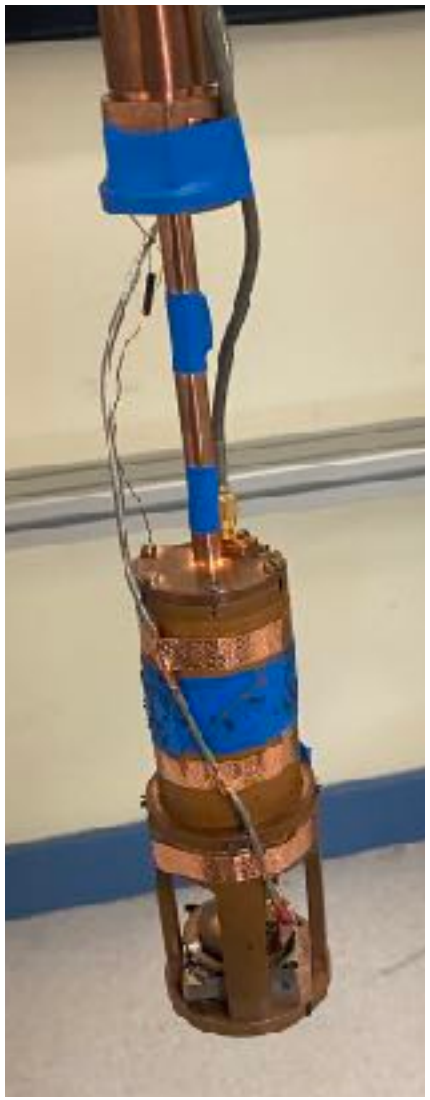


ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Phase 1a

- Targeted scan around 15 GHz
- Commenced in 2021, now complete
- Tuning rod resonator, TM010 mode
- HEMT amplifier
- Zero-dead-time FFT on FPGA (from ANU)



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Phase 1a

- ~3.5 weeks of data
- ~600 cavity positions
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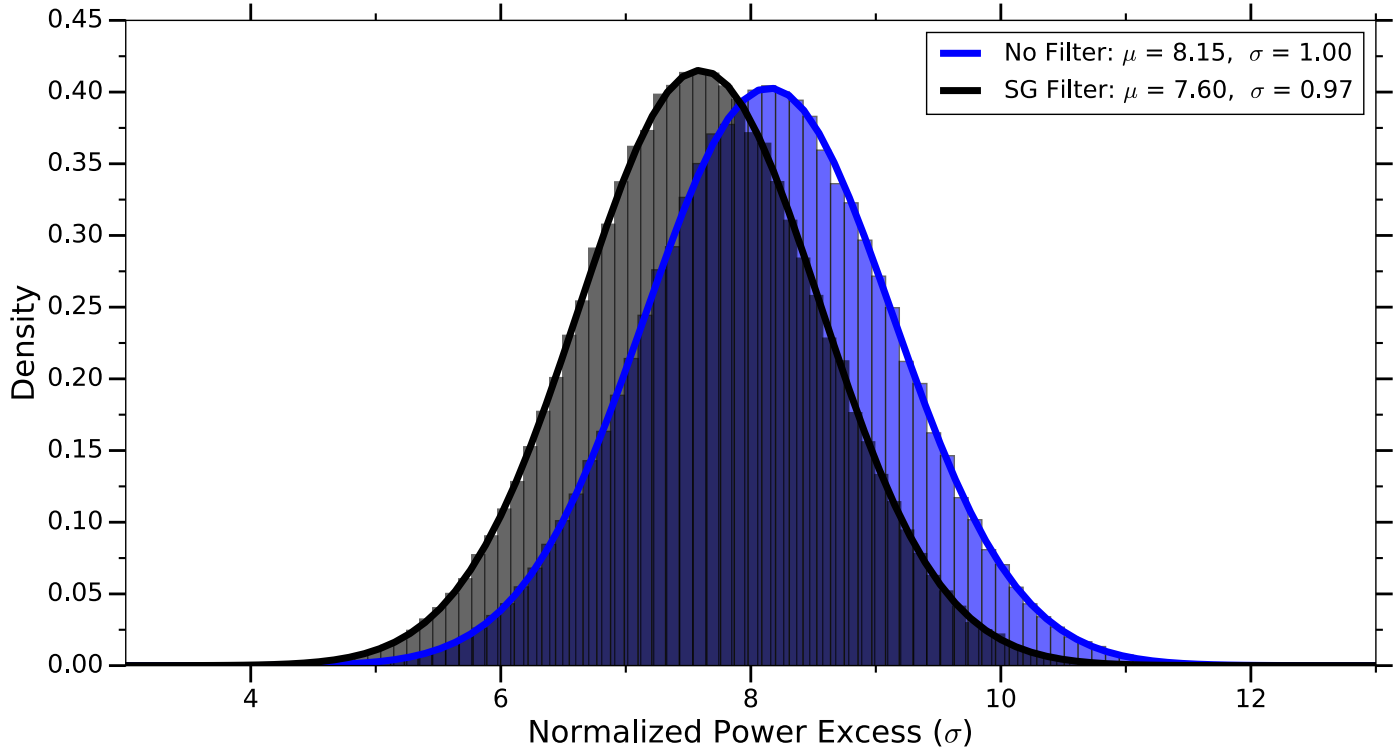

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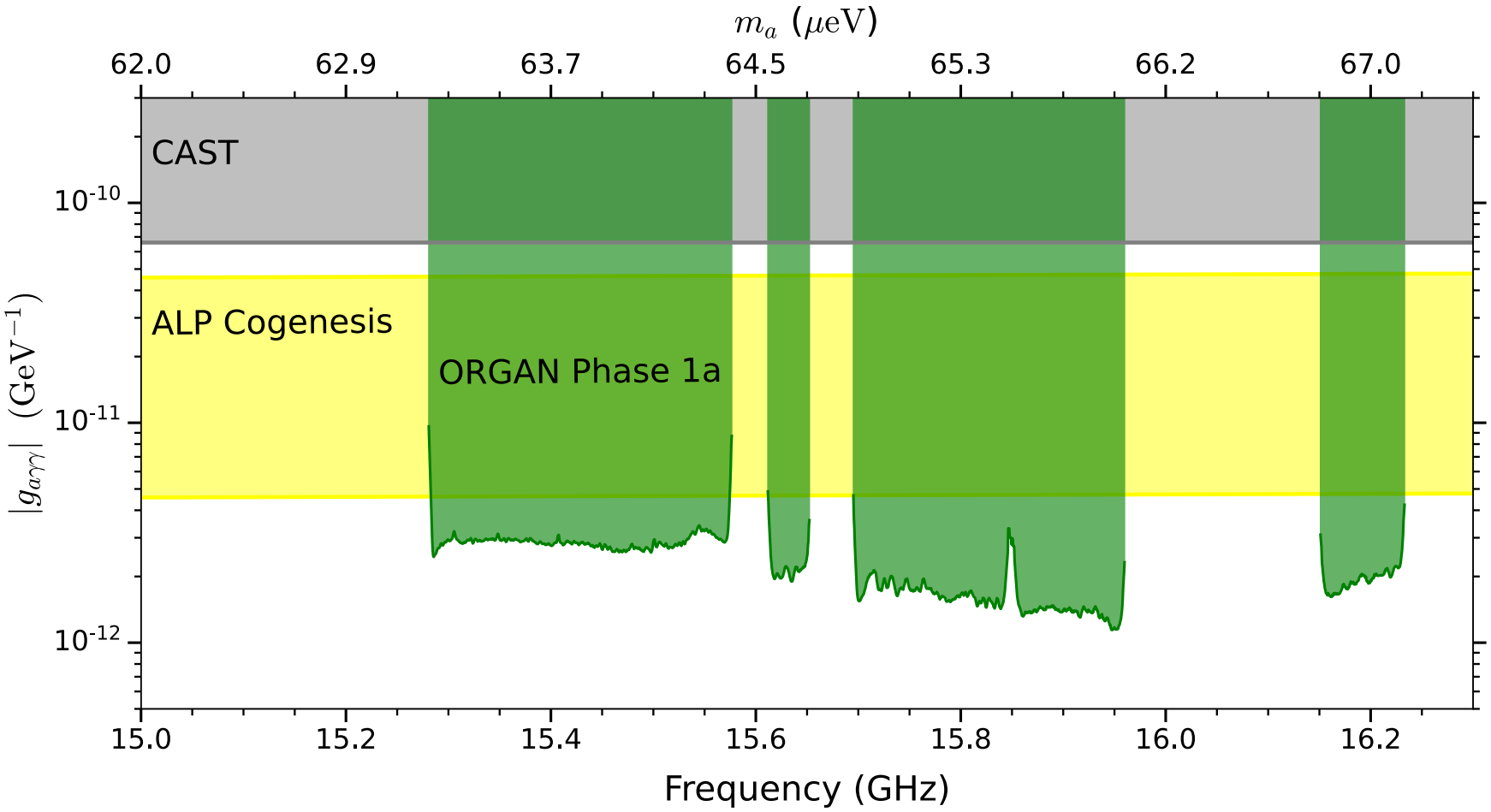
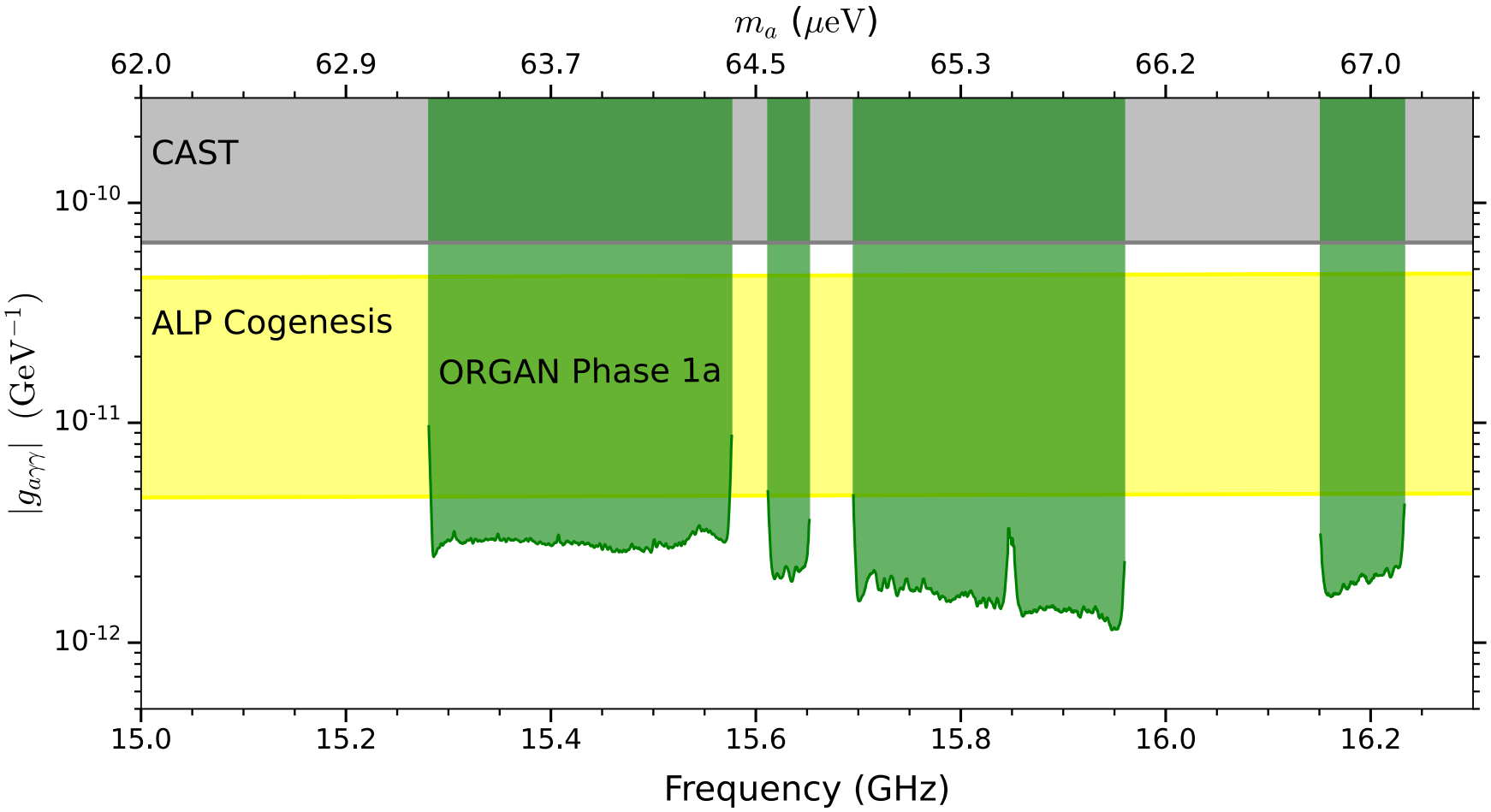

m_a (μeV)
62.0
62.9
63.7
64.5
65.3
66.2
67.0
CAST
ALP Cogenesis
ORGAN Phase 1a
10^{-10}
10^{-11}
10^{-12}
$|g_{a\gamma\gamma}|$ (GeV^{-1})
15.0
15.2
15.4
15.6
15.8
16.0
16.2
Frequency (GHz)

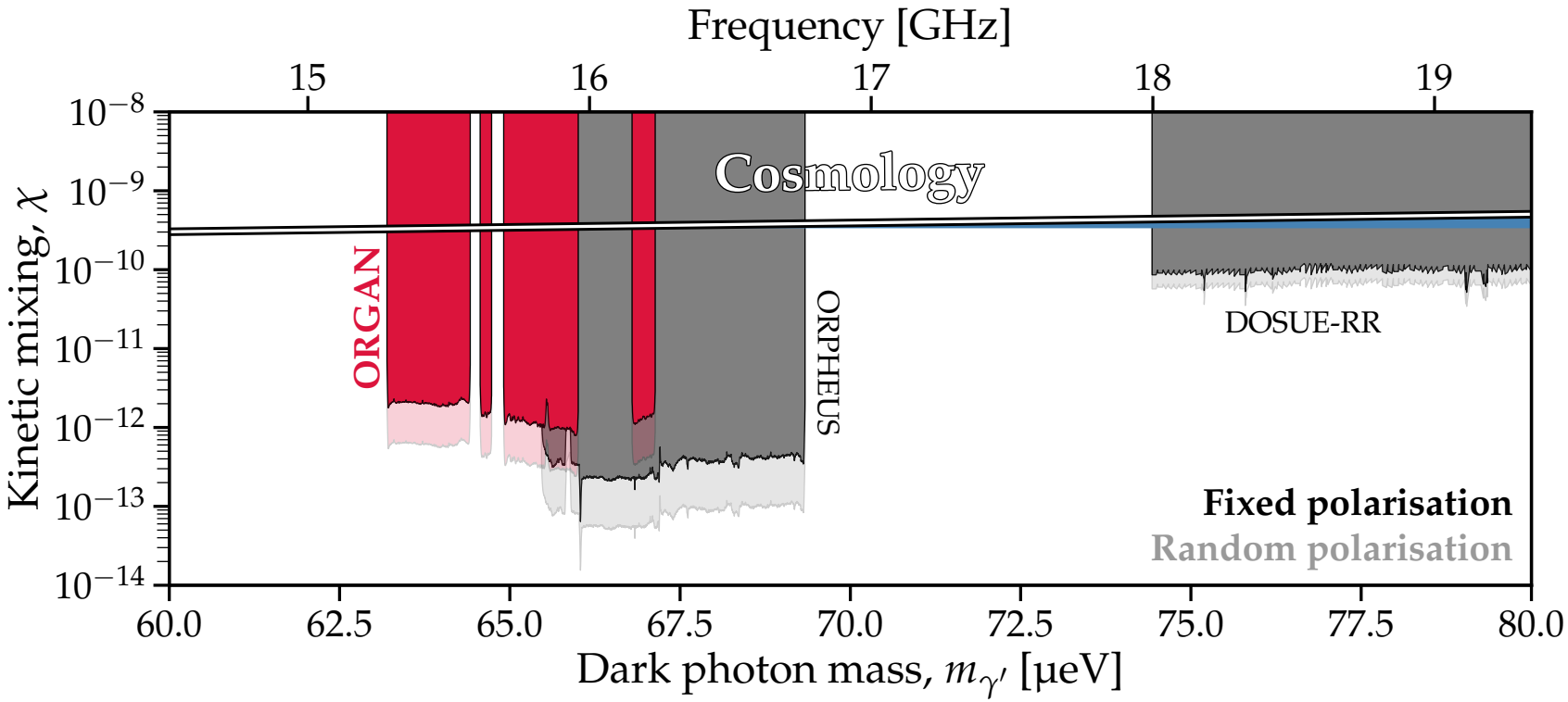
Phase 1a

- Gaps to be filled in future phases with better sensitivity



Phase 1a

- Also limits on dark photons and scalar dark matter



https://arxiv.org/abs/2212.01971

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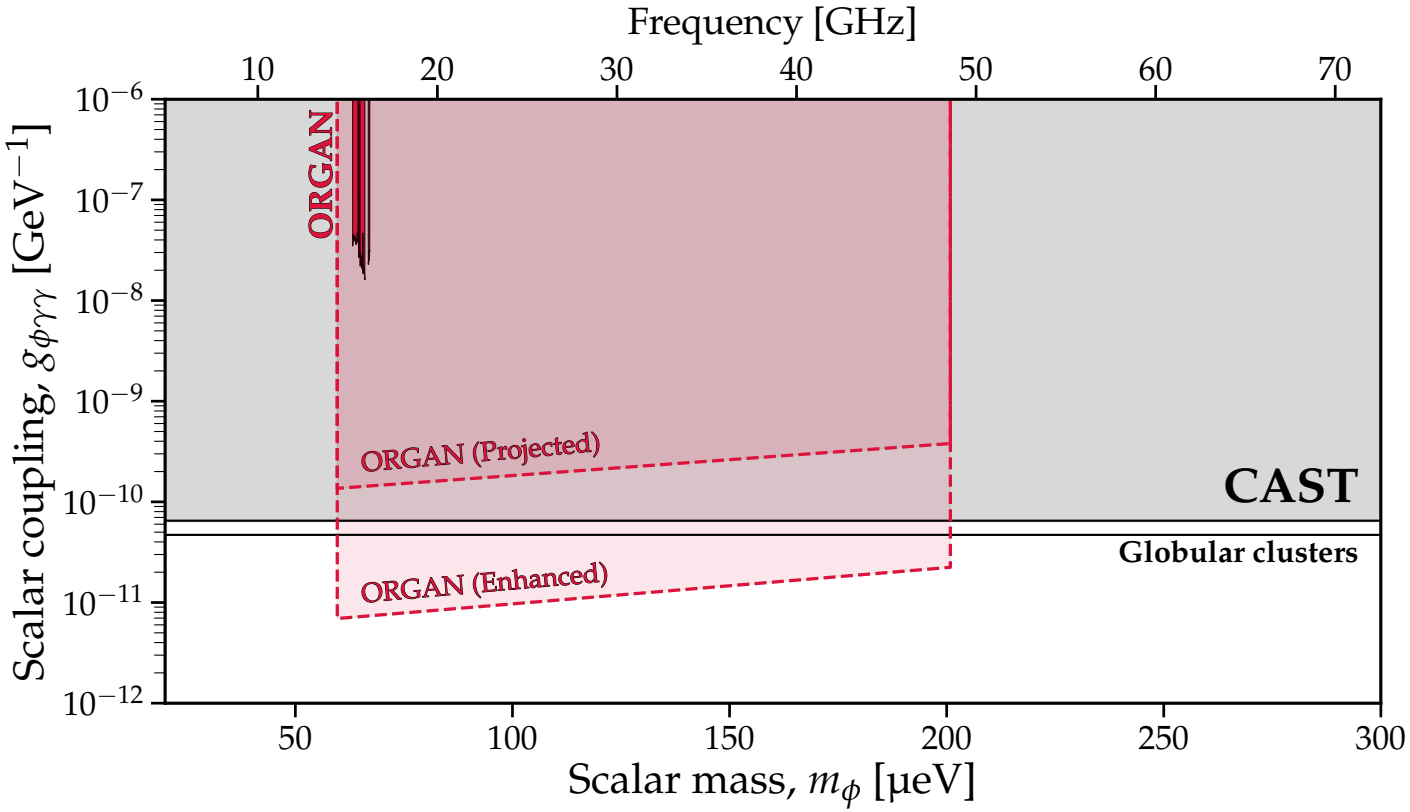

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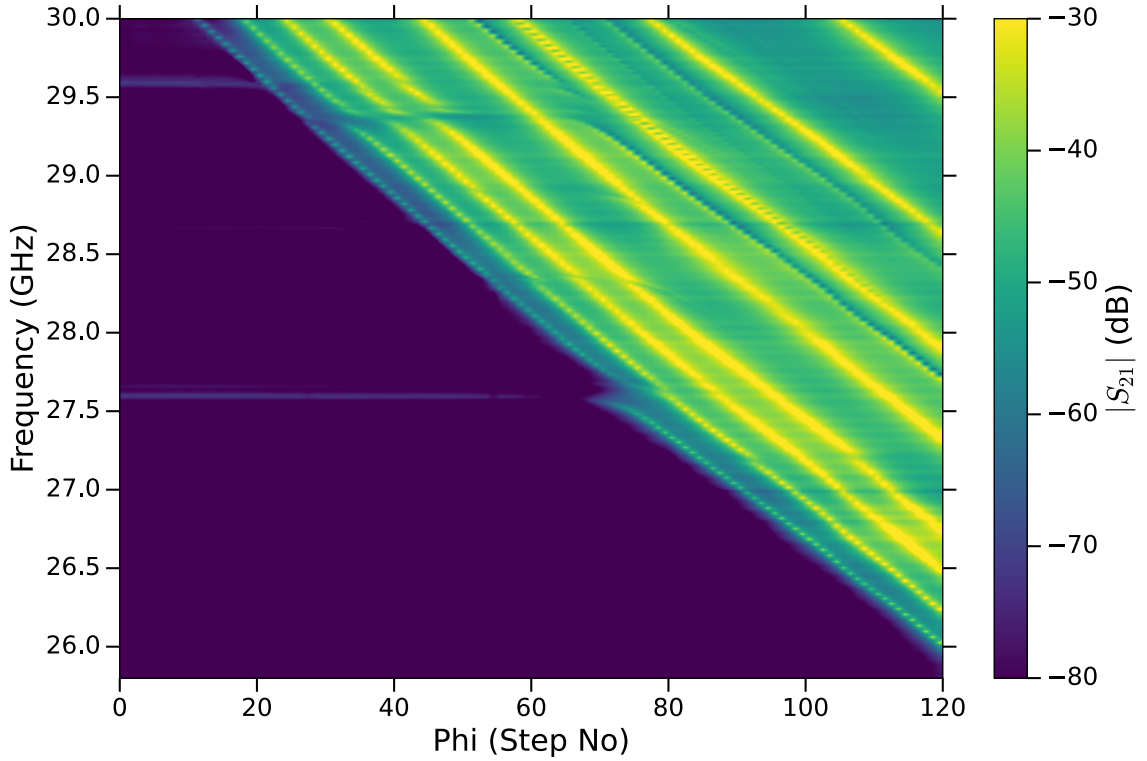
Phase 1b

- Commencing now!
- 26-27 GHz

Phase 1b

- Commencing now!
- 26-27 GHz
- Novel resonator I am not going to talk about…yet
- Also investigating upgrades with second cavity in parallel



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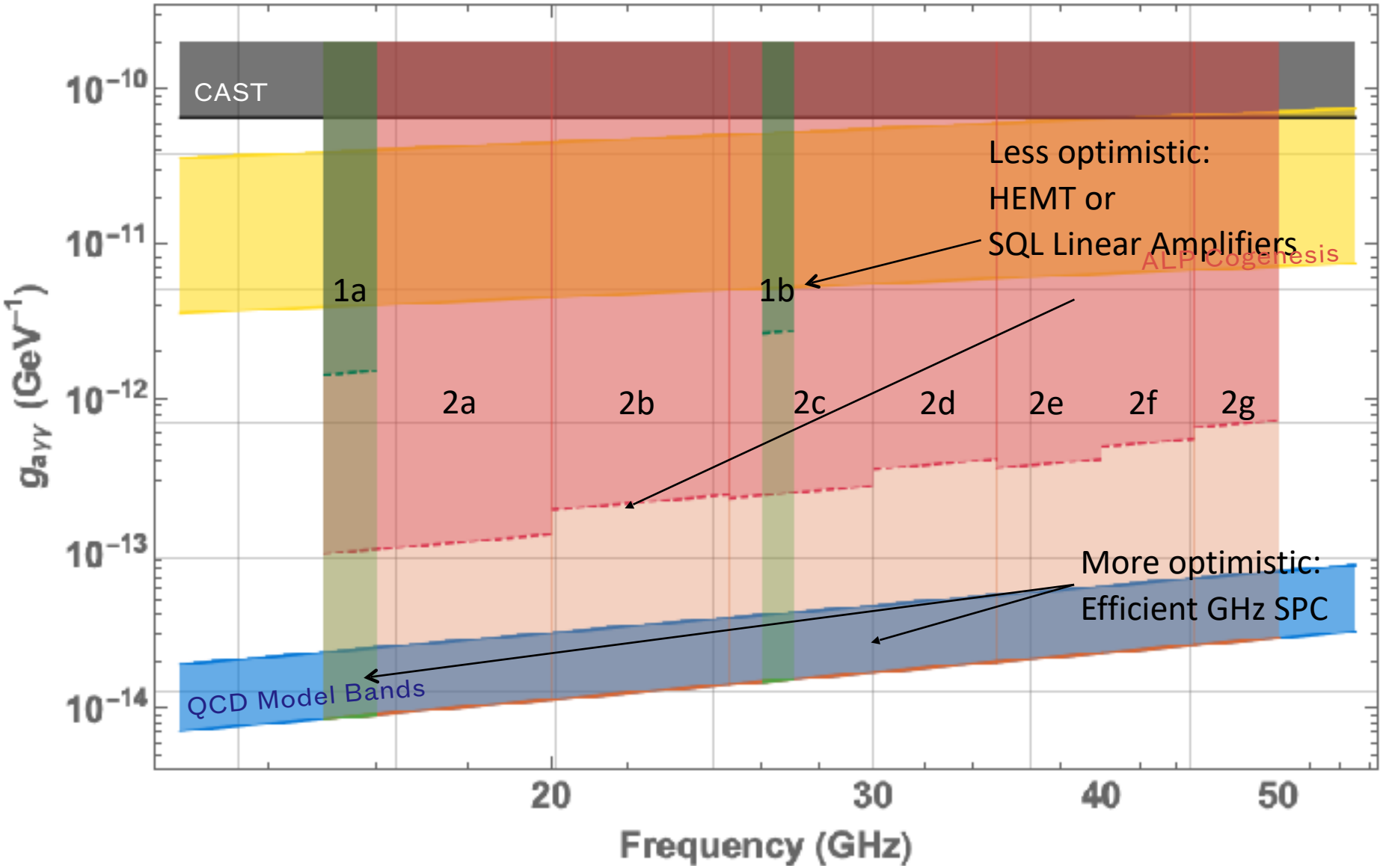

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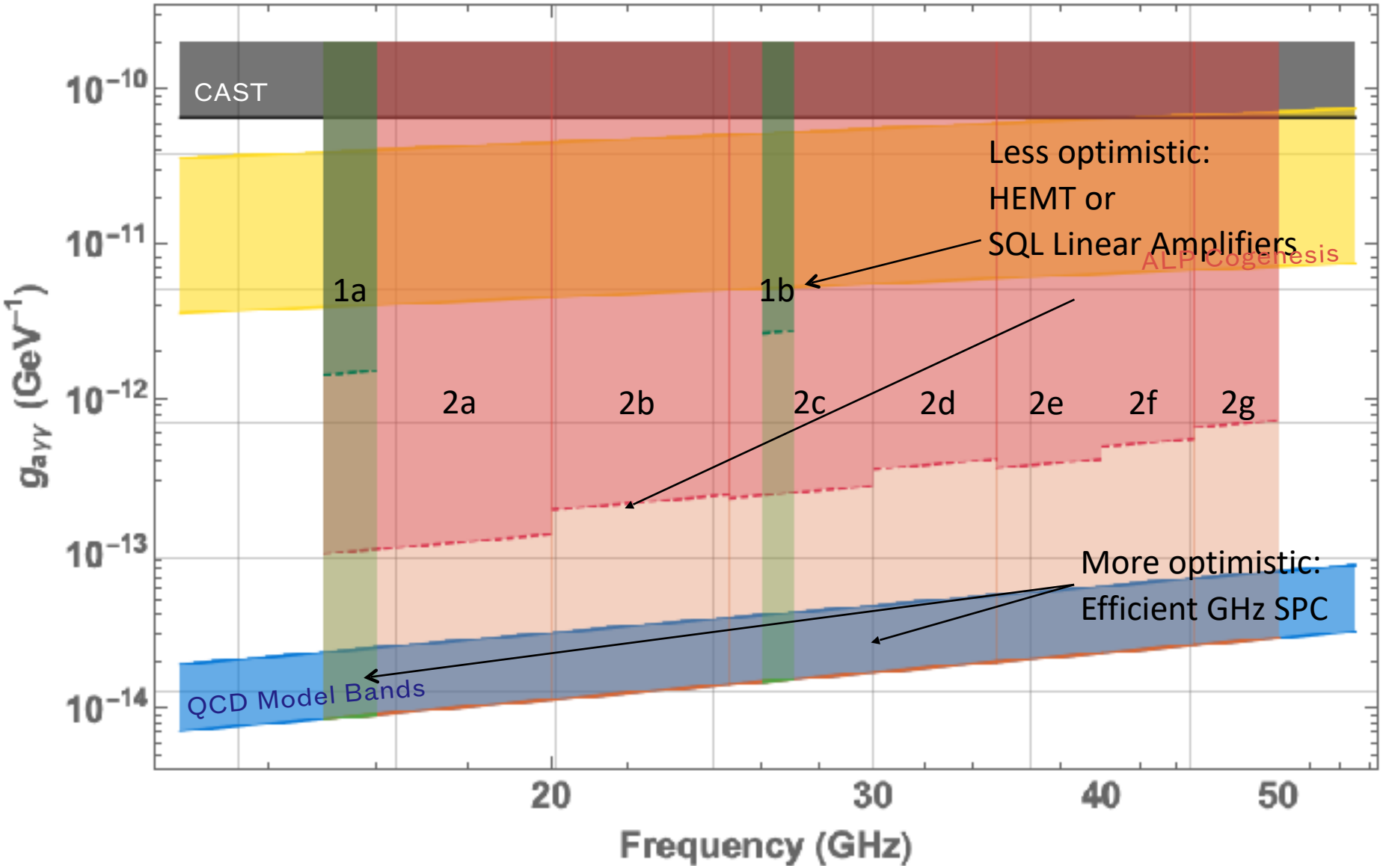

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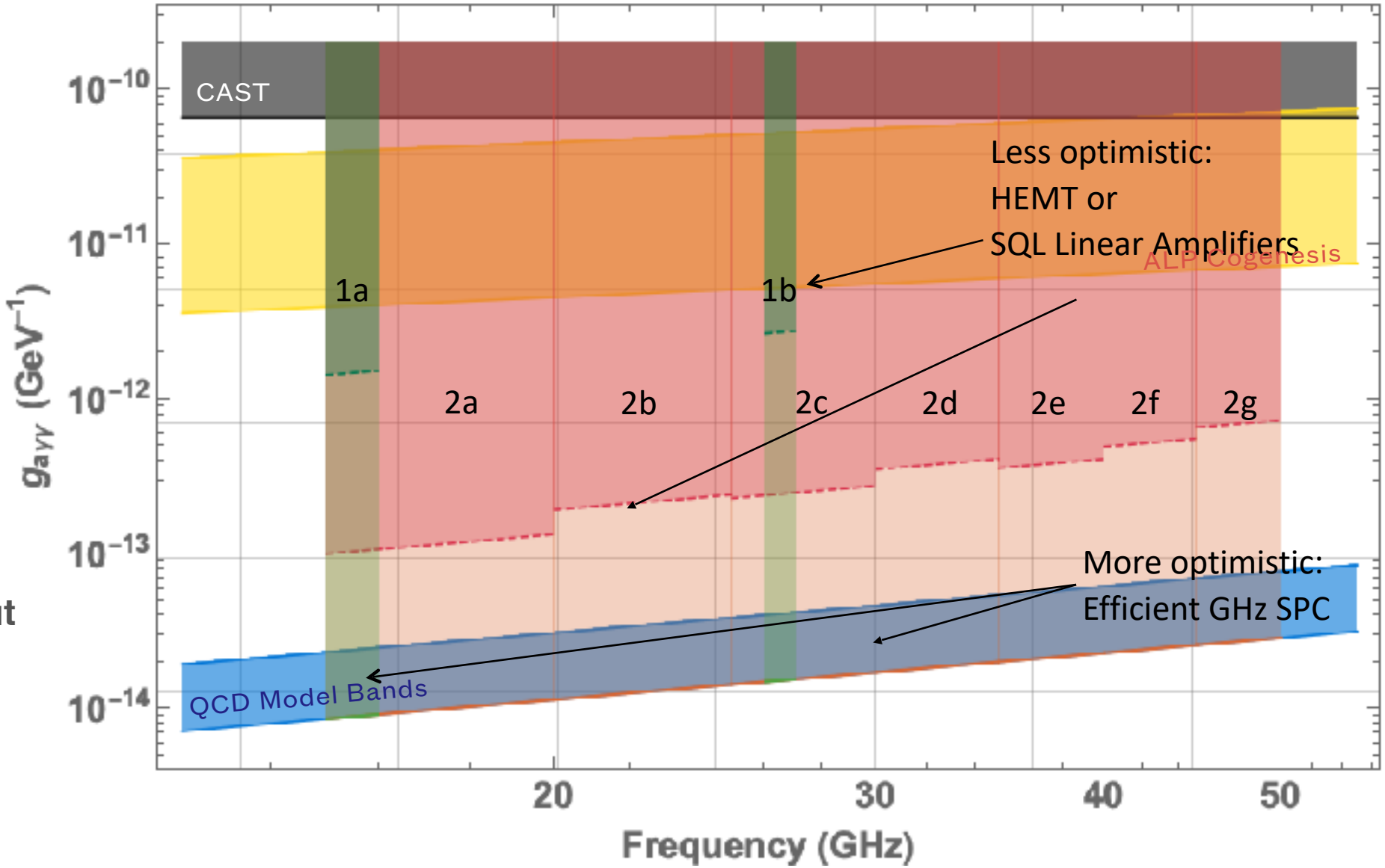

R&D: Superconductors

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- Swinburne University of Technology - nanofabrication capacity

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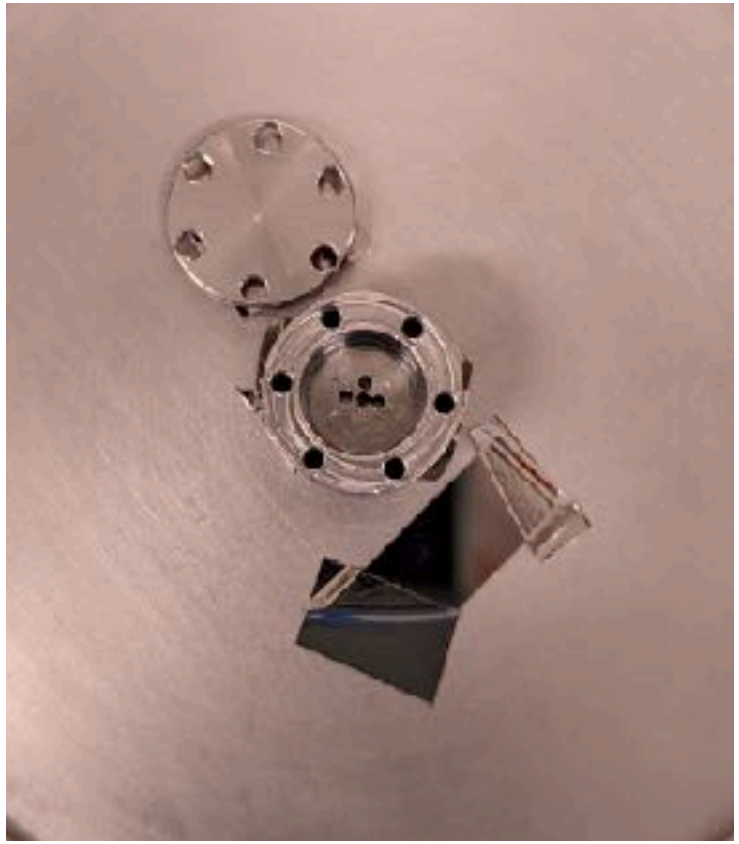

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- Single Photon Detection is superior to SQL linear amplification under the right conditions
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$$\frac{P_\ell}{P_{sp}} = \frac{\bar{n}+1}{\sqrt{\bar{n}}}\sqrt{\frac{\Delta\nu_a}{\eta\Gamma}}$$

- This ratio can be tens or even thousands of times depending on the specifics

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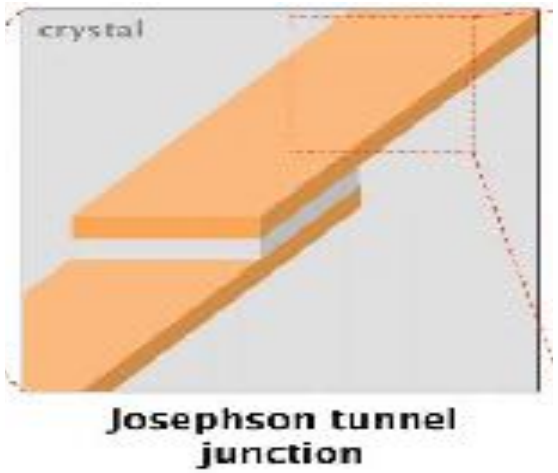
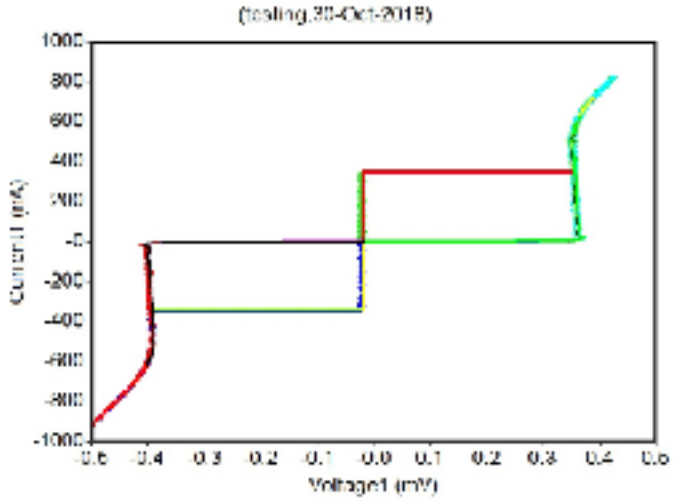
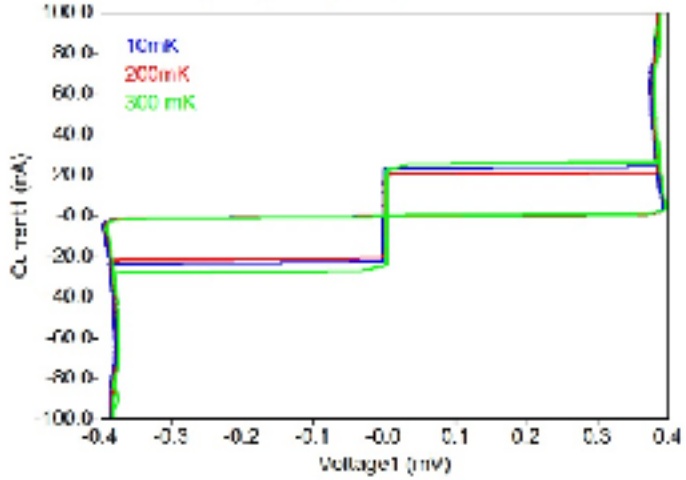
- This ratio can be tens or even thousands of times depending on the specifics
- Not a lot of options for GHz SPCs…but a few!

SIS Josephson Junctions

- Layer of superconductor – insulator – superconductor
- Exhibits Josephson effect: supercurrent across junction until critical current reached -> becomes resistive



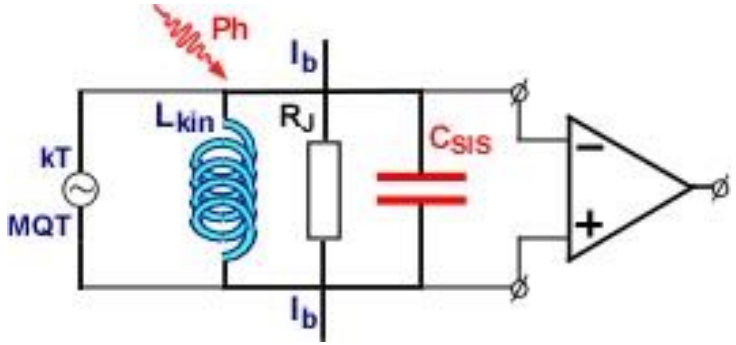


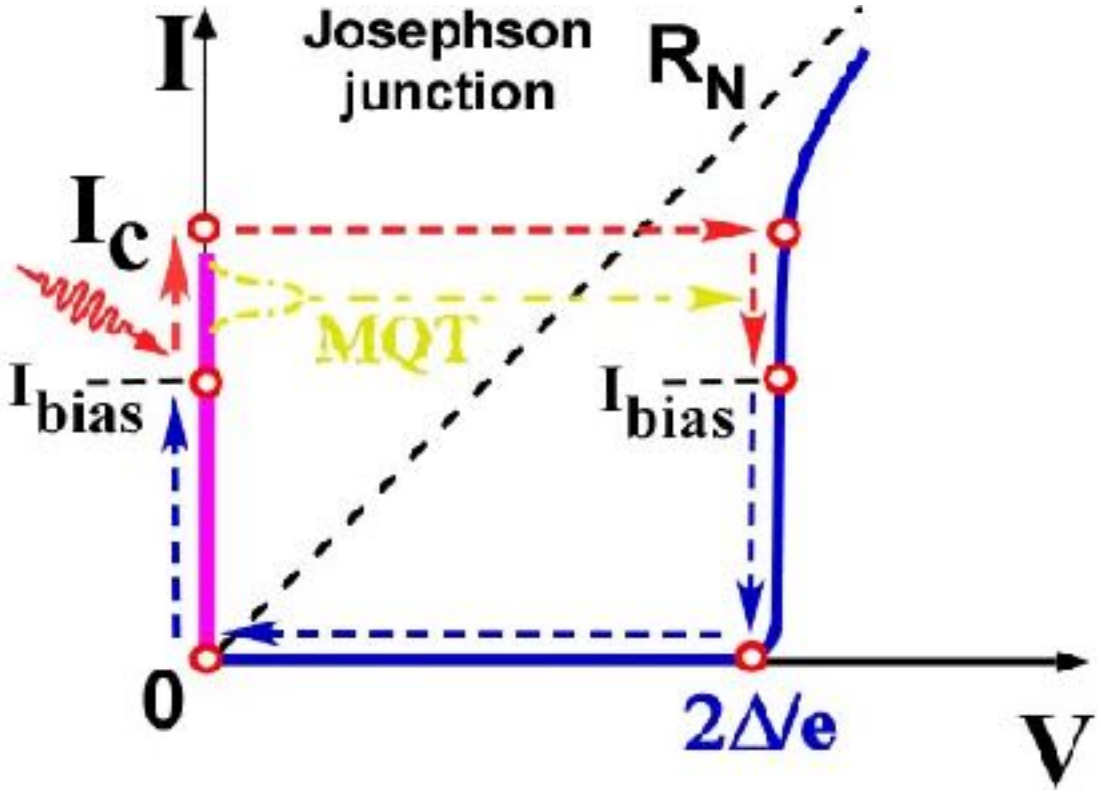


L. S. Kuzmin *et al.*, *IEEE Transactions on Applied Superconductivity*, 2018

SIS Josephson Junctions

- Can be used as weak current sensor in the GHz range...in principle
- 10s of μeV+ energy thresholds
- Gets easier at higher energy…





SIS Josephson Junctions

- Some samples from Chalmers at UWA node under testing for integration in ORGAN

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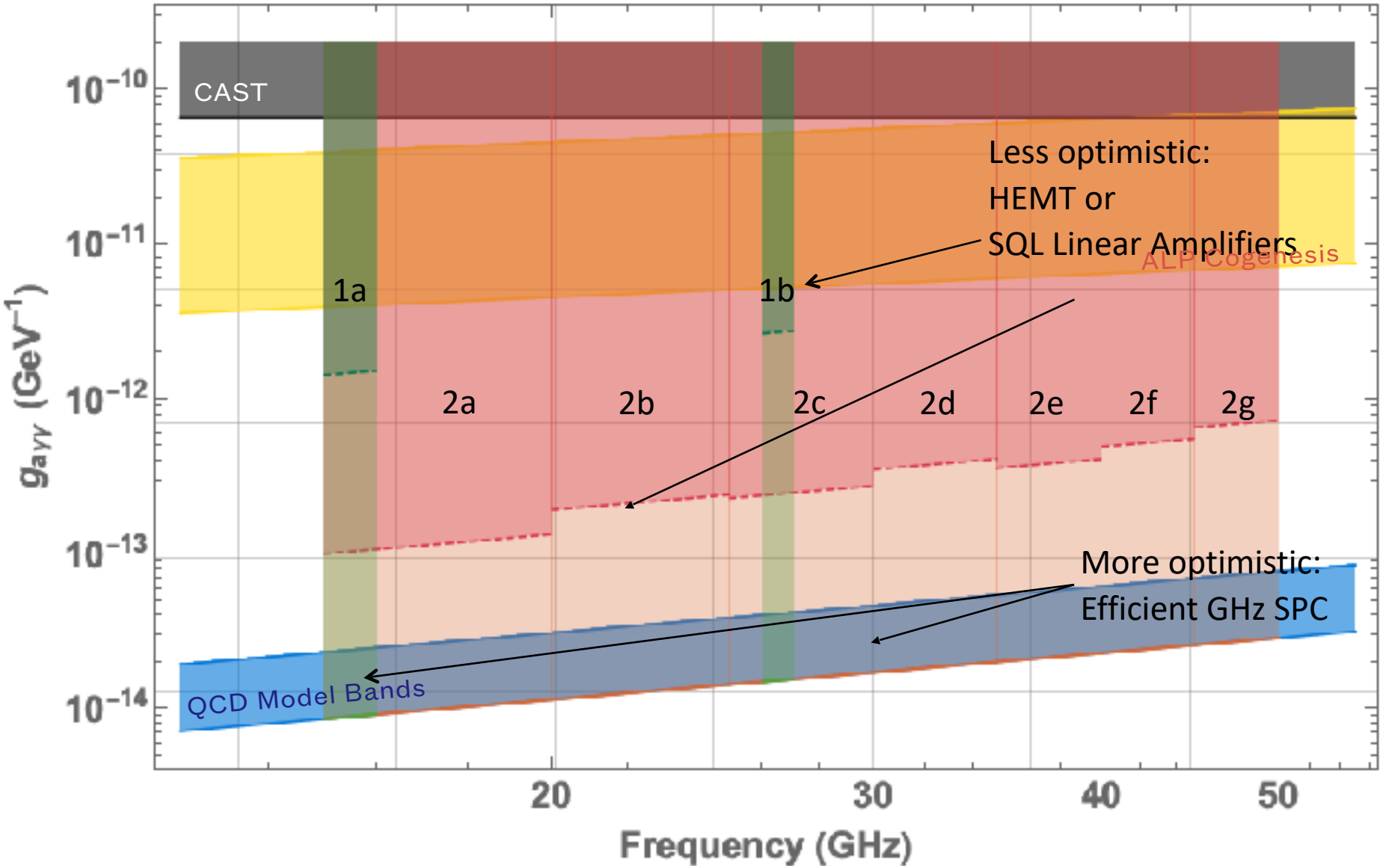

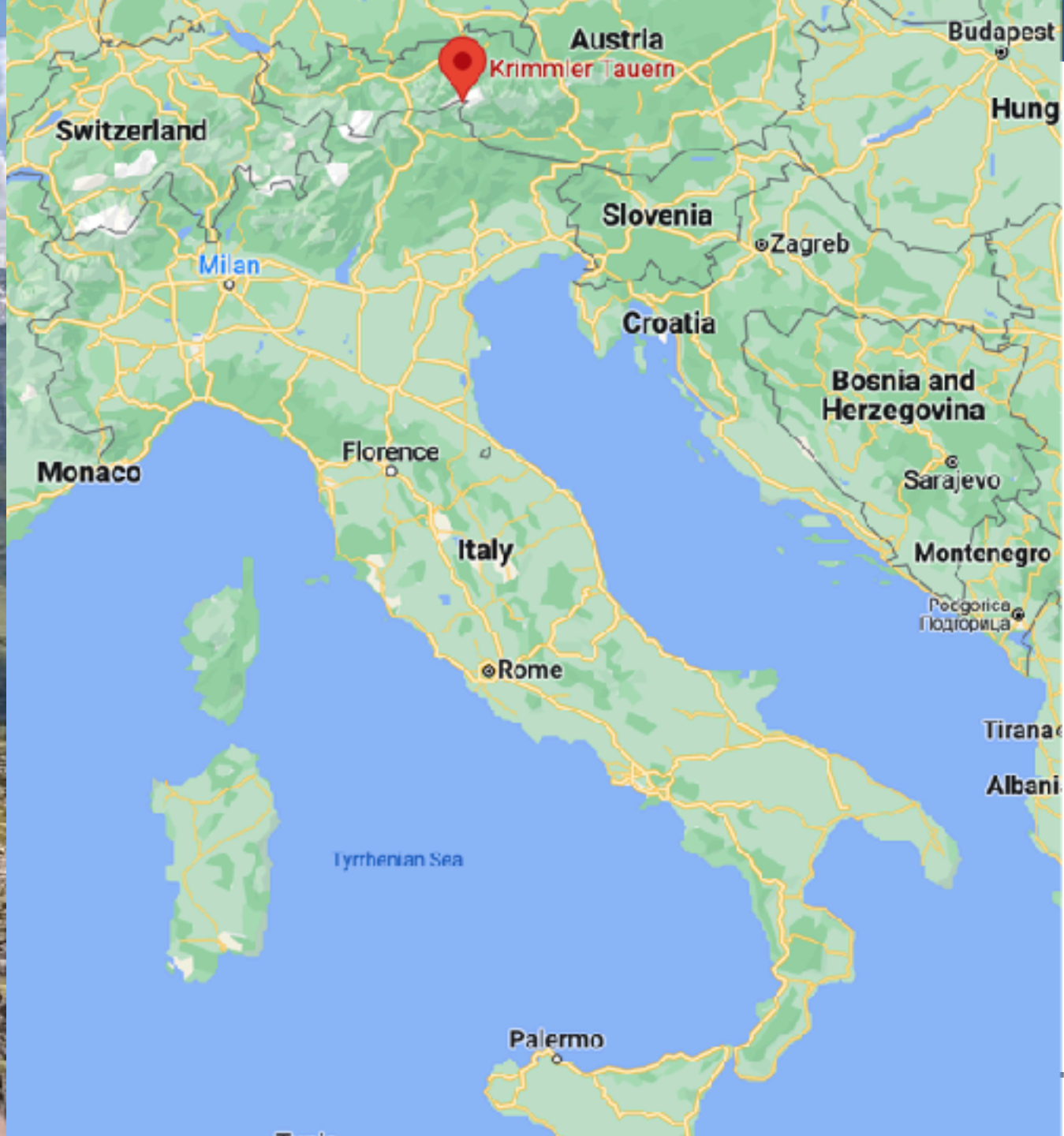
Austria
Krimmler Tauern
Budapest
Switzerland
Slovenia
Zagreb
Milan
Croatia
Bosnia and Herzegovina
Florence
Monaco
Sarajevo
Italy
Montenegro
Rome
Tyrrhenian Sea
Palermo

ORGAN Q

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- Commence in second half of 2023 in larger bore 7 T Magnet

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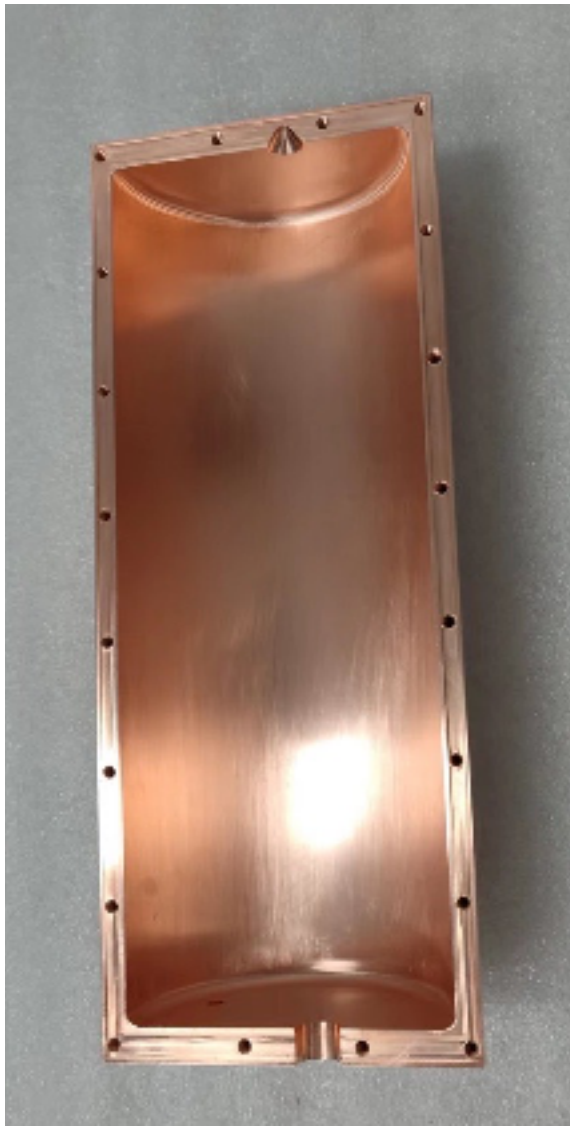

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ORGAN Q

- Cavity prototype produced
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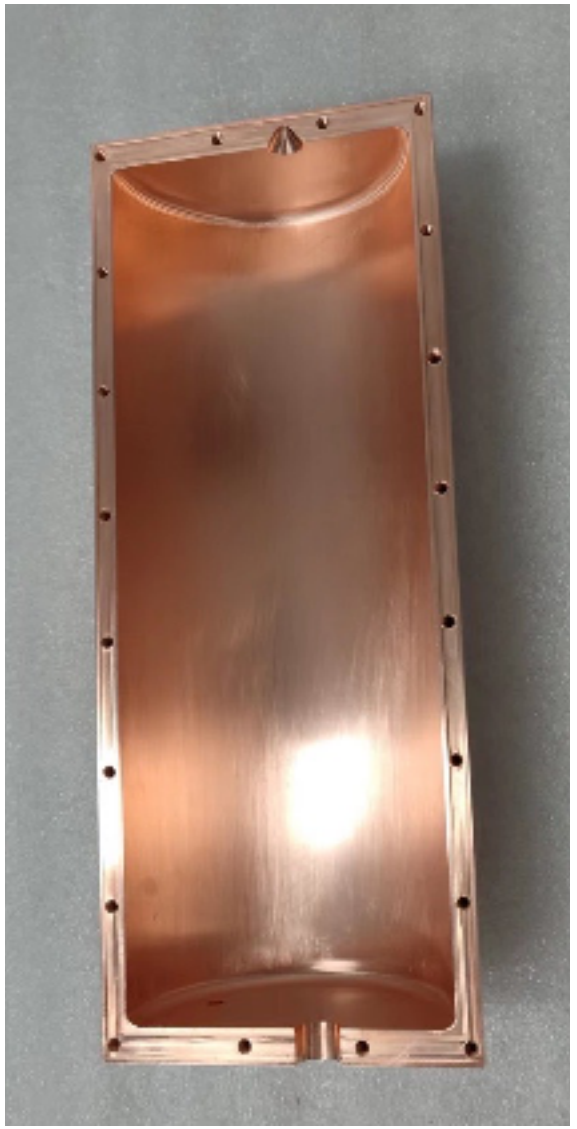
- Test transmission line and shielding options
- 5-10 x KSVZ sensitivity
- Commencing Q3 2023



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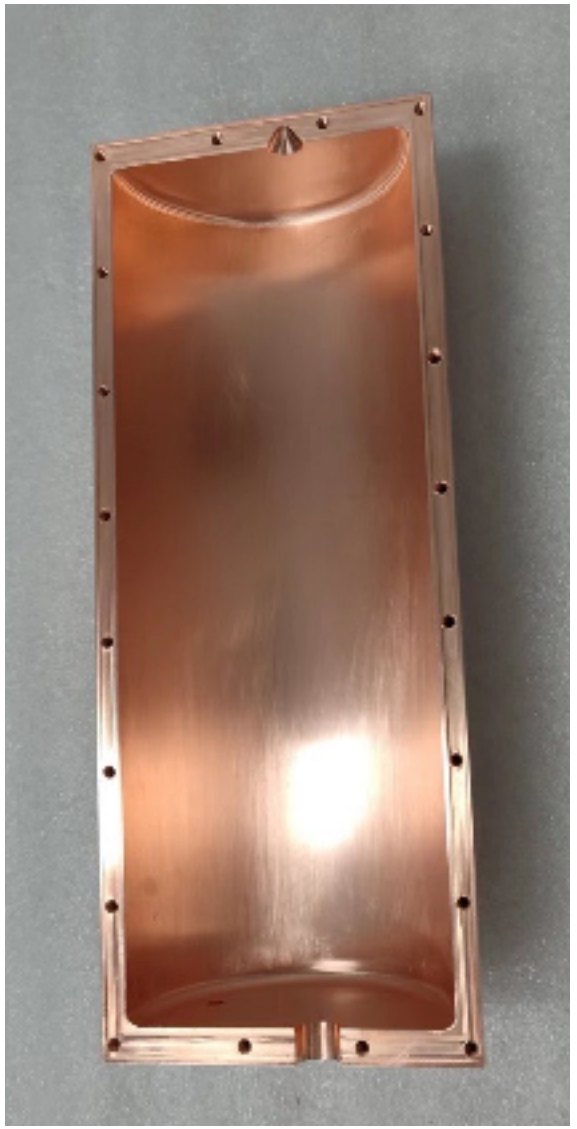
- Cavity prototype produced
- Clamshell-type resonator
- V2 cavity produced and received
- Commercial JPA from Raytheon - **difficulties**
- Test transmission line and shielding options
- 5-10 x KSVZ sensitivity
- Commencing Q3 2023



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- Win in a few ways…

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

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

- Problem: Cavities get HUGE

ORGAN Low Frequency

- Increased interest in low frequency axion searches (<500 MHz) in recent times
- Various cosmological motivations for such axions
- Win in a few ways…

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

- Problem: Cavities get HUGE
- Potential solution…

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ORGAN Low Frequency

- Re-entrant cavities (lumped LC resonators)

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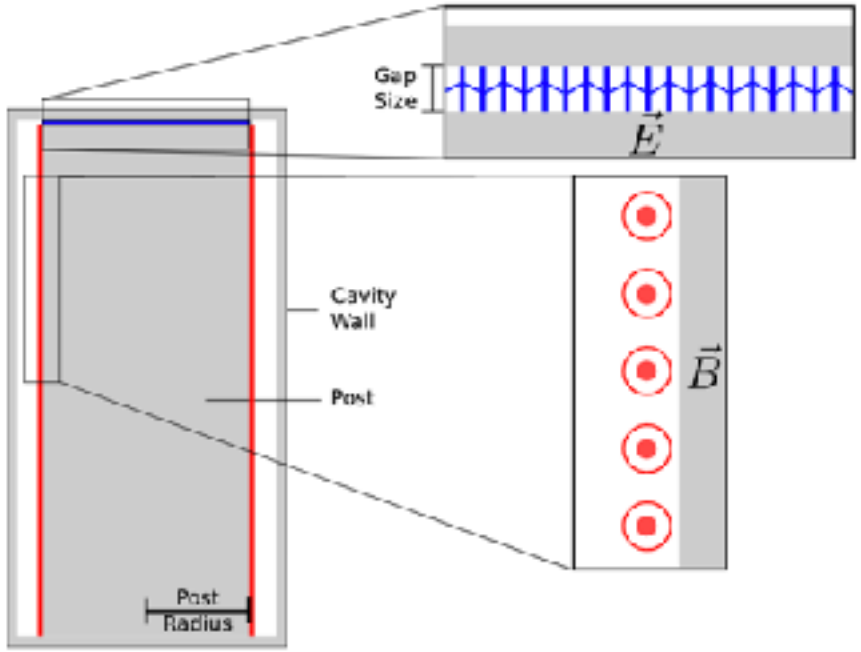
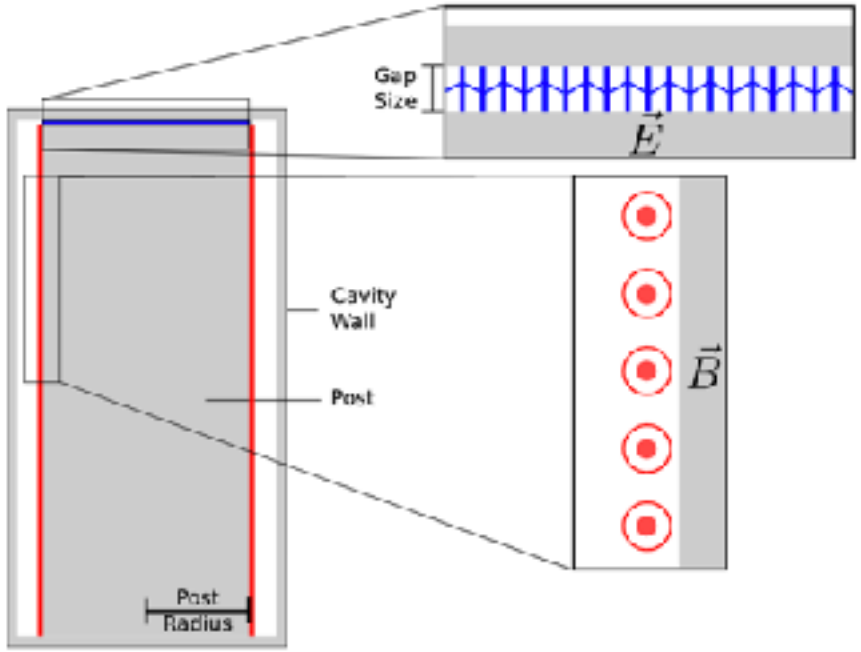


ORGAN Low Frequency

- 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



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

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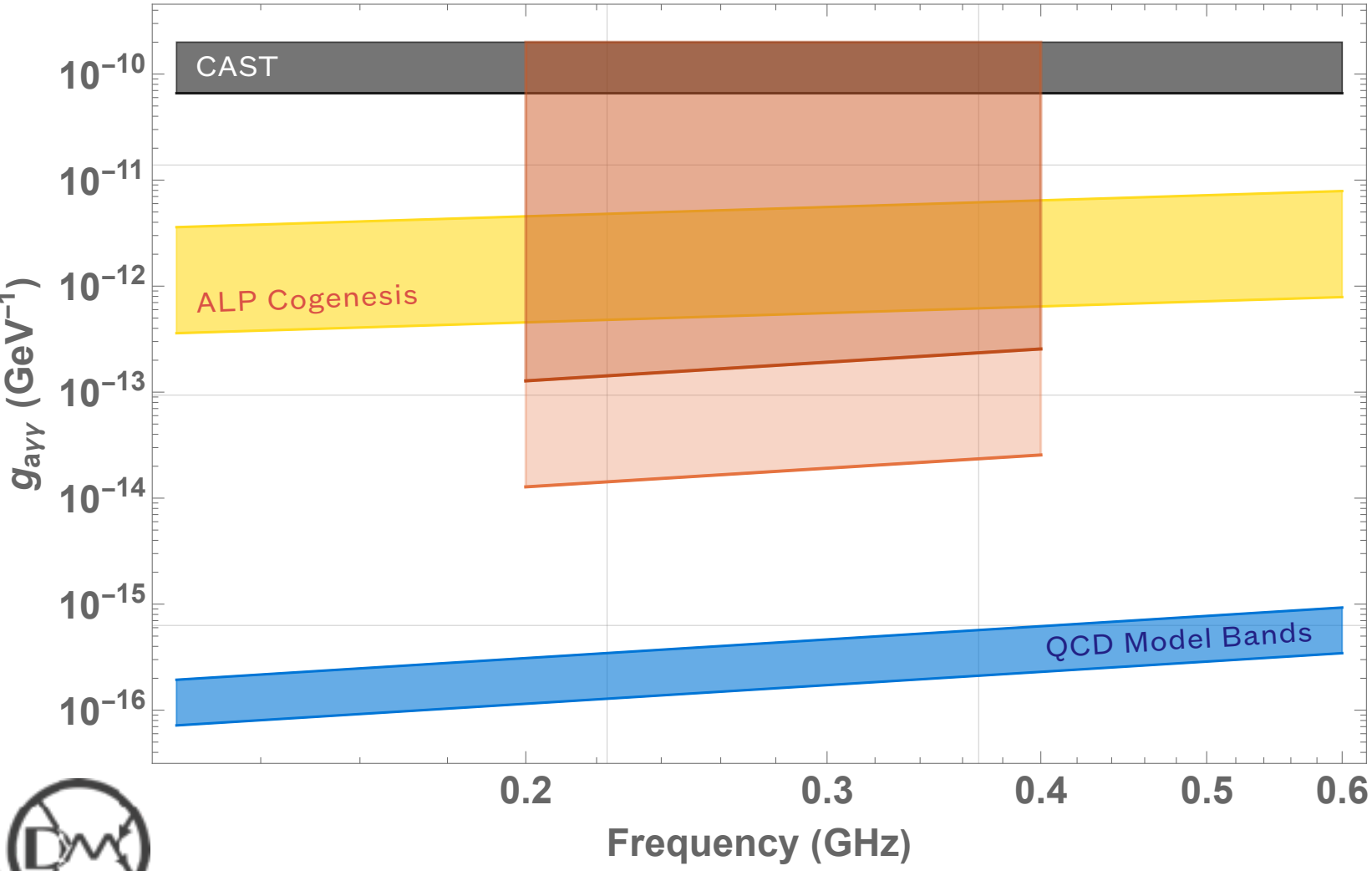
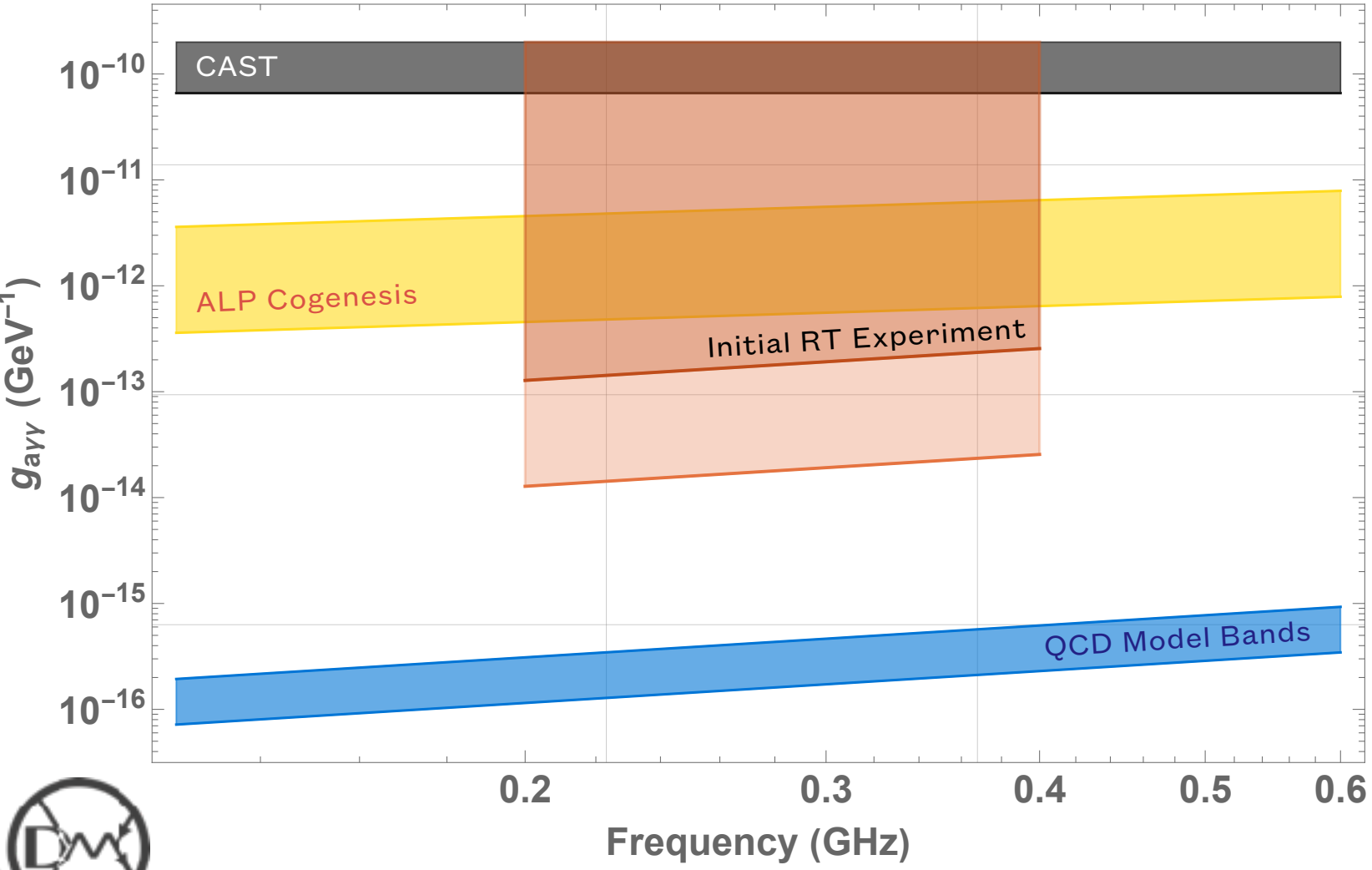
ORGAN Low Frequency



ORGAN Low Frequency



HEMT Amplifier

Room Temperature

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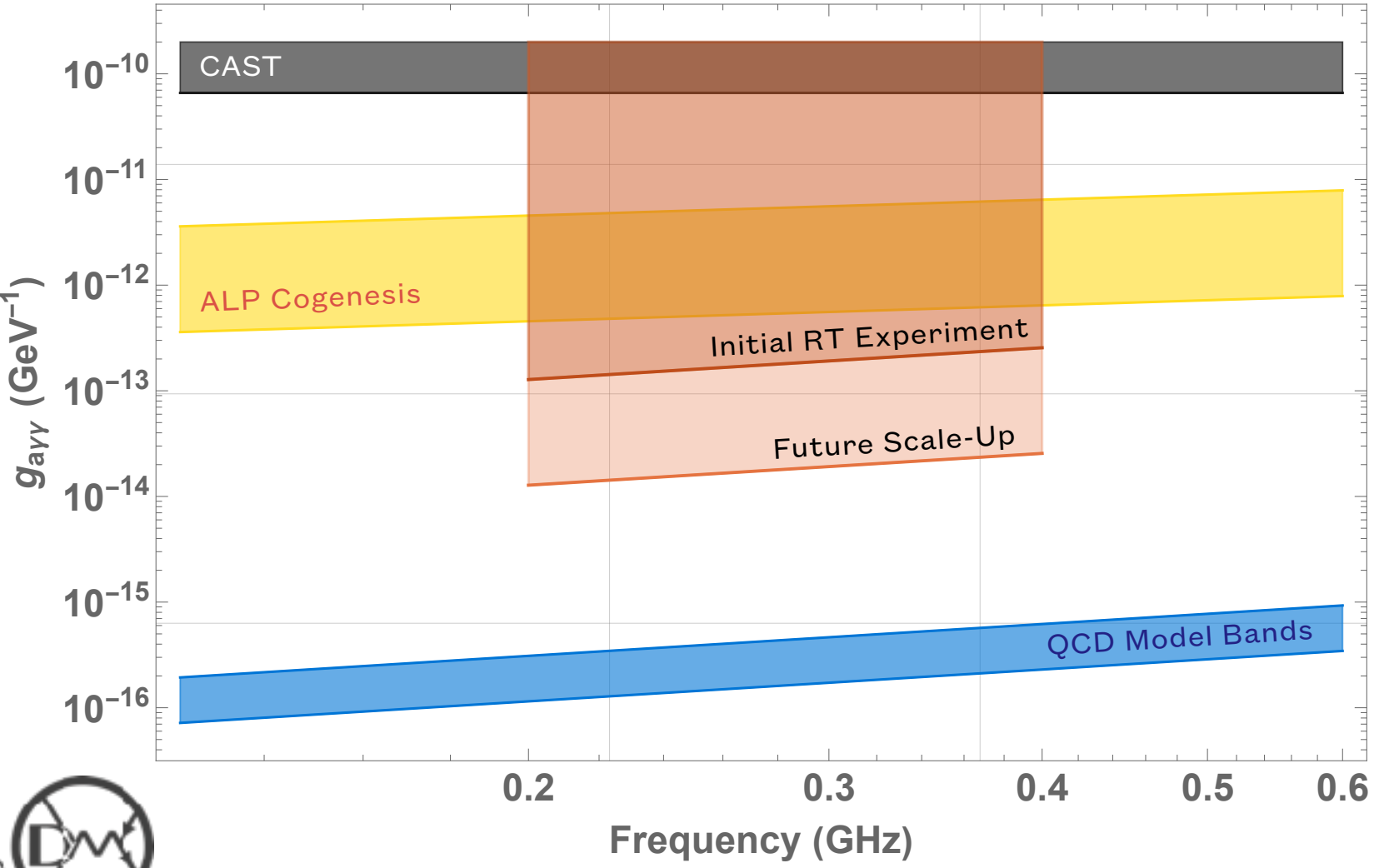
ORGAN Low Frequency



HEMT Amplifier

Room Temperature

SQUID Amplifier

4K System

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Conclusion

- ORGAN
  - High mass axion haloscope (15+ GHz)
- Run Plans
  - Phase 1a completed 2021/2022
  - Phase 1b commencing 2023
  - Future phases commencing 2024
  - Various avenues of R&D
- ORGAN-Q
  - Spin-off/testbed at UWA commencing Q3 2023
- ORGAN Low Frequency
  - Spin-off hosted at Swinburne

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Conclusion

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