Axion Detection: Techniques Experiments & Instrumentation

Dr. Ben McAllister

Swinburne University of Technology,
University of Western Australia

Axion Detection: Techniques Experiments & Instrumentation

Dr. Ben McAllister

Swinburne University of Technology,
University of Western Australia

ADMX
AXION DARK MATTER EXPERIMENT

ORGAN
Oscillating Resonant Group AxioN Experiment

Overview

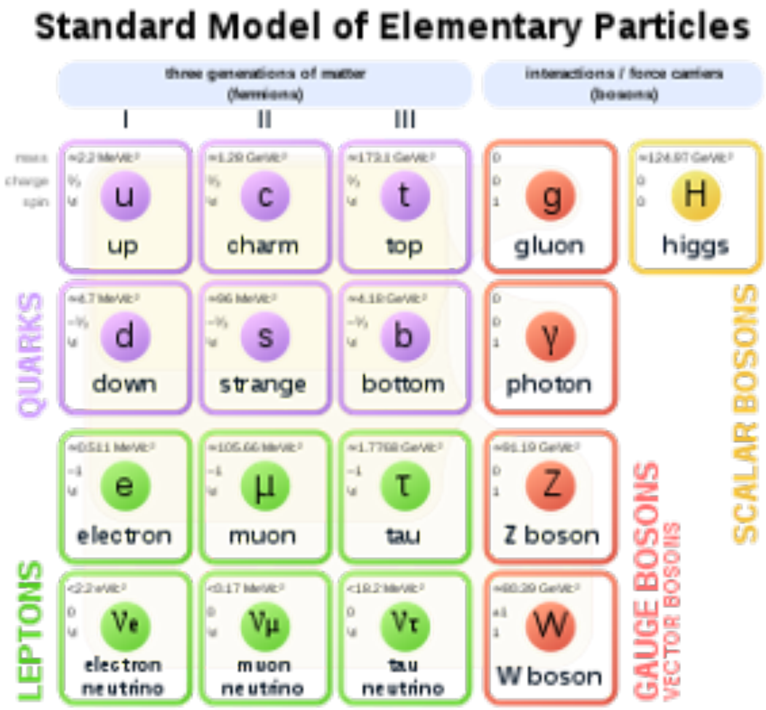
- Dark Matter Problem
- Axions
- Axion Detectors
- Haloscopes
- Current Generation: ADMX, ORGAN
- Future

Introduction

- Quick look back to Standard Model

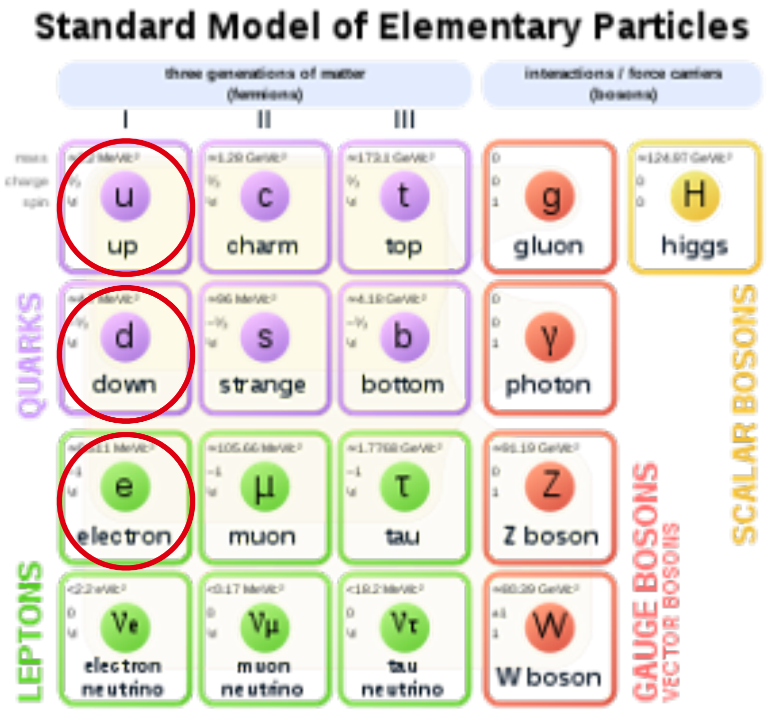
Introduction

- Quick look back to Standard Model



Introduction

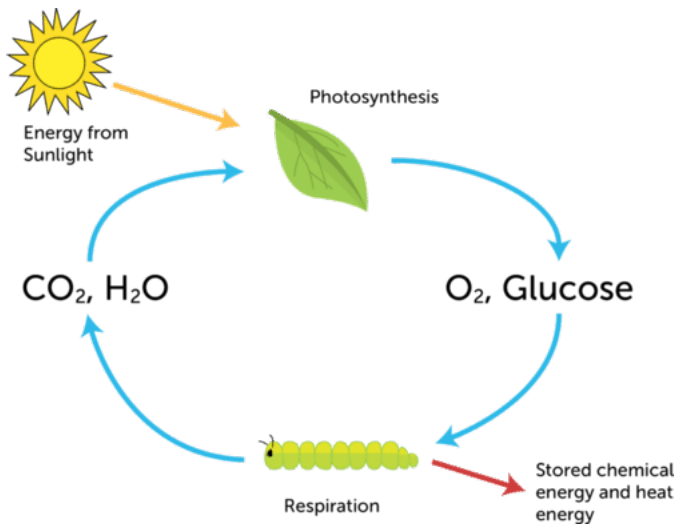
- Quick look back to Standard Model



- Just a handful of particles
- Most of the regular matter made of just three of these things

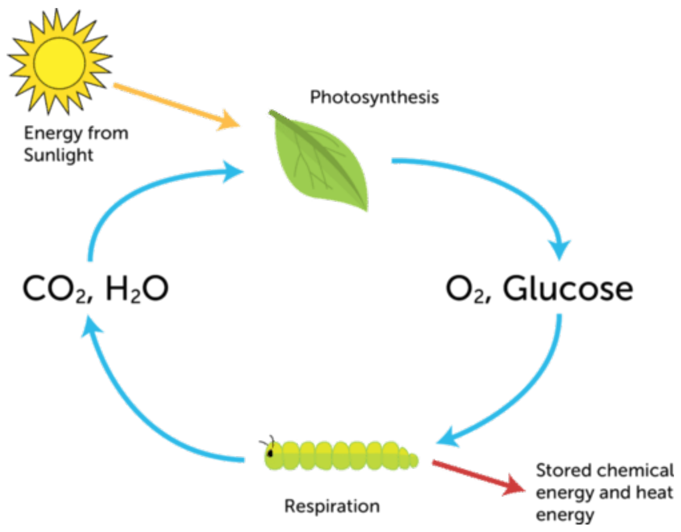
Introduction

- All of biology, chemistry



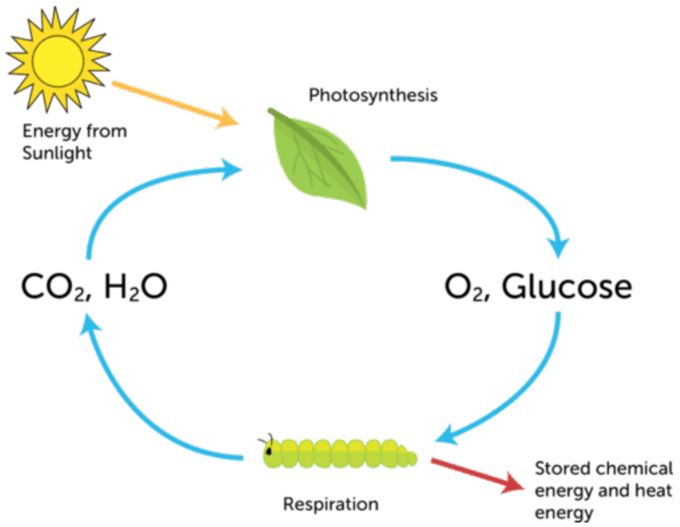
Introduction

- All of biology, chemistry
- People, planets, stars



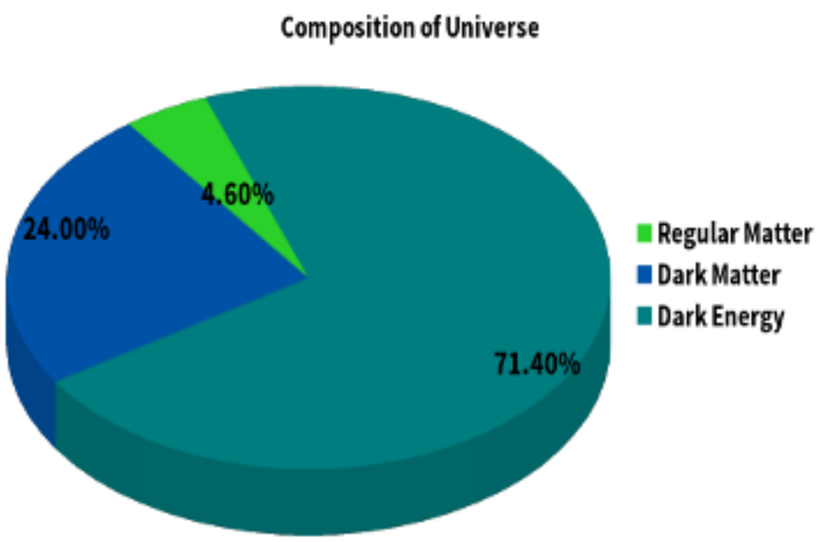
Introduction

- All of biology, chemistry
- People, planets, stars
- But we've known for a while that there's a lot more stuff…



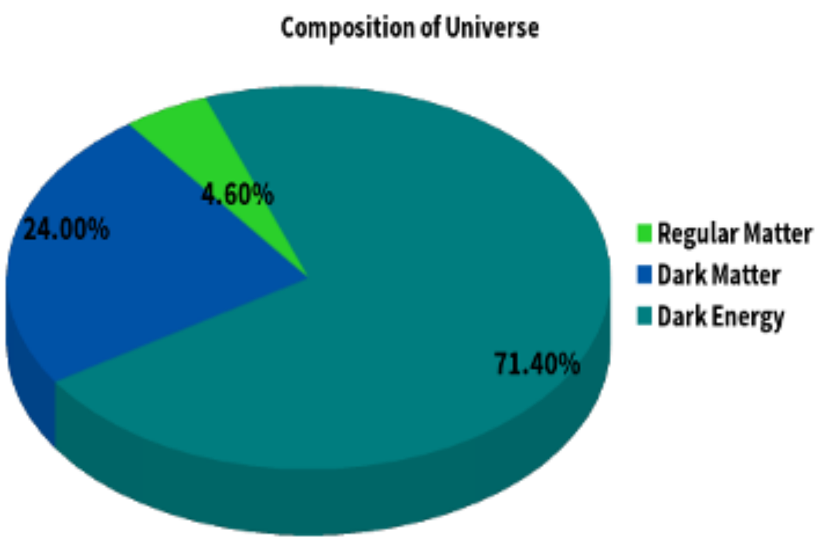
Dark Universe

- Most of Universe made of DE, DM
- What is DM?



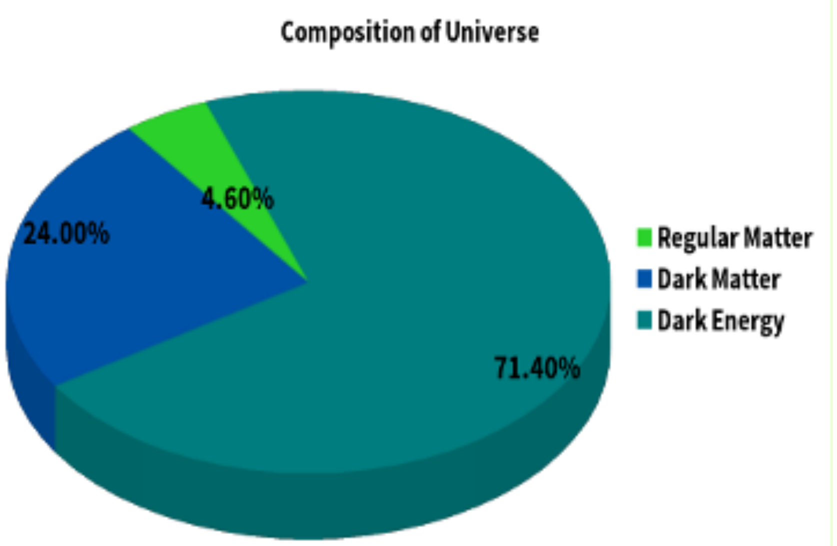
Dark Universe

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



Dark Universe

- 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?



Evidence

- Evidence for Dark Matter is largely cosmological/astrophysical in nature

Evidence

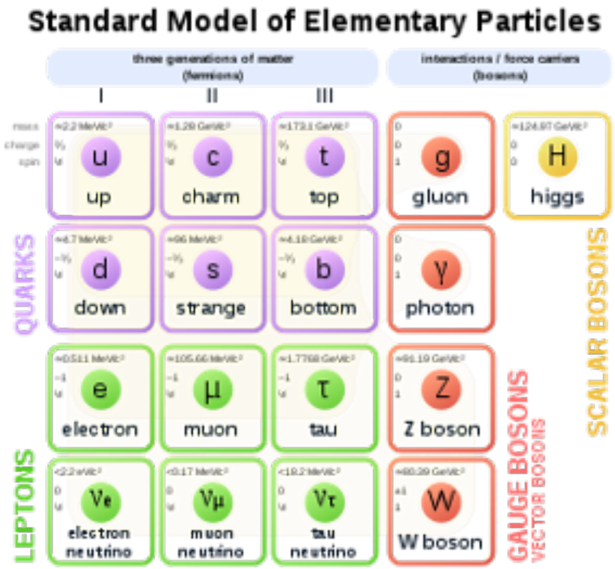
- Evidence for Dark Matter is largely cosmological/astrophysical in nature
- Main pieces of evidence:
  - Galactic Rotation Curves
  - Gravitational Lensing
  - CMB Anisotropies

Evidence

- Evidence for Dark Matter is largely cosmological/astrophysical in nature
- Main pieces of evidence:
    - Galactic Rotation Curves
    - Gravitational Lensing
    - CMB Anisotropies
- What we know:
    - Has mass
    - Weakly coupled to SM (no EM, no strong interaction, maybe weak?)

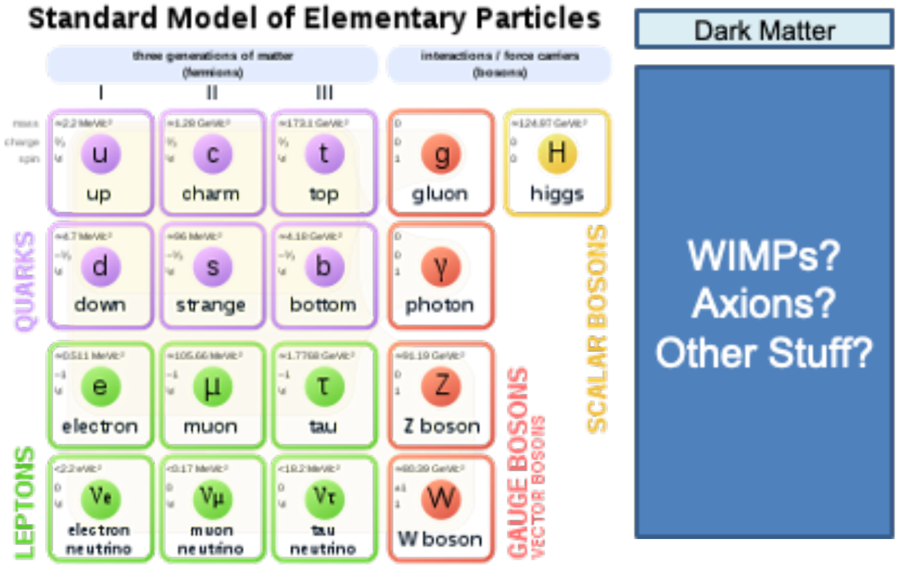
Dark Matter Candidates

- Looking back at our standard model of particle physics:



Dark Matter Candidates

- Looking back at our standard model of particle physics:



Dark Matter Candidates

- Broadly candidates come in a few classes:
    - Weakly Interacting Massive Particles
    - Weakly Interacting Sub-eV Particles
    - Sterile Neutrinos
    - Massive Compact Halo Objects
    - Others…

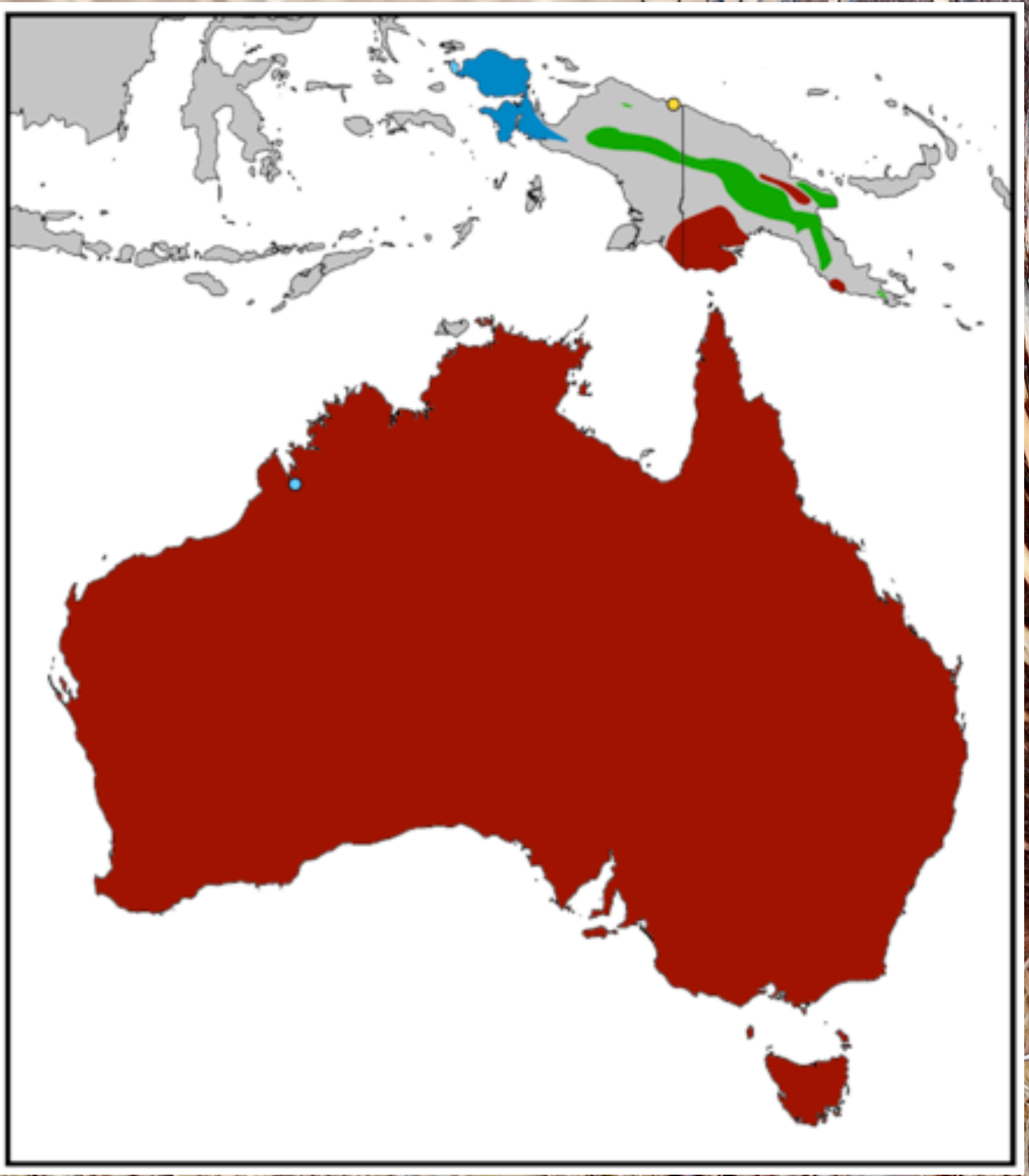
Dark Matter Candidates

- Broadly candidates come in a few classes:
    - Weakly Interacting Massive Particles
    - **Weakly Interacting Sub-eV Particles (especially the axion)**
    - Sterile Neutrinos
    - Massive Compact Halo Objects
    - Others…

Dark Matter Candidates

- Broadly candidates come in a few classes:
    - Weakly Interacting Massive Particles
    - **Weakly Interacting Sub-eV Particles (especially the axion)**
    - Sterile Neutrinos
    - Massive Compact Halo Objects
    - Others…

~THE OTHER DARK MATTER~




Axions

- Light boson first proposed in ‘70s as consequence of solution to the strong CP problem

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

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

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

Axions

- Experiments constrain neutron EDM to be very small if non-zero
- So, a fine tuning problem emerges in this otherwise very precise theory
- Why should this free parameter be zero?

Axions

- Experiments constrain neutron EDM to be very small if non-zero
- So, a fine tuning problem emerges in this otherwise very precise theory
- Why should this free parameter be zero?
- Possible solution: introduce a new broken symmetry to QCD which has the effect of “cancelling out” the θ term
- Peccei and Quinn in 1977
- When this symmetry is broken at some point in the Universe’s history, a particle is created which has been named the axion
- Has some mass
- Weak coupling to SM particles

Axions

- Experiments constrain neutron EDM to be very small if non-zero
- So, a fine tuning problem emerges in this otherwise very precise theory
- Why should this free parameter be zero?
- Possible solution: introduce a new broken symmetry to QCD which has the effect of “cancelling out” the θ term
- Peccei and Quinn in 1977
- When this symmetry is broken at some point in the Universe’s history, a particle is created which has been named the axion
- Has some mass
- Weak coupling to SM particles
- Most properties governed by a single unknown parameter:

$$m_a \propto \frac{1}{f_a}$$

$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

- f_a is a number which defines the energy level at which the symmetry breaks, and is completely unconstrained by this theory

Axions

- It was later realized that for a certain range of masses (neV to a meV) axions could comprise dark matter

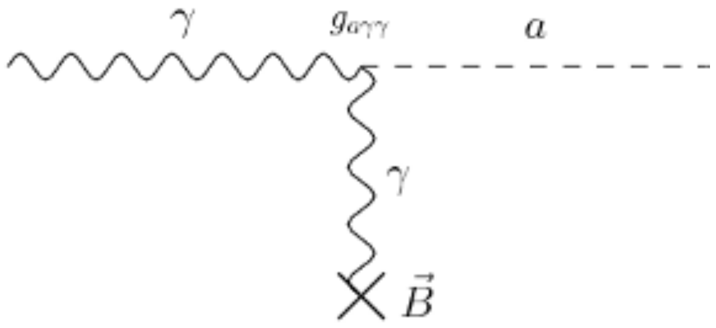
Axions

- It was later realized that for a certain range of masses (neV to a meV) 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

Axions

- It was later realized that for a certain range of masses (neV to a meV) 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

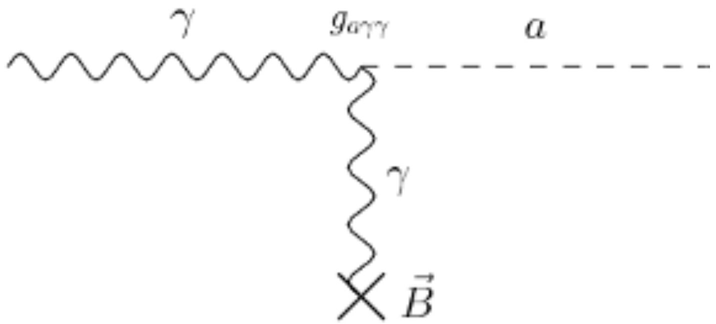
e.g. photons



Axions

- It was later realized that for a certain range of masses (neV to a meV) 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

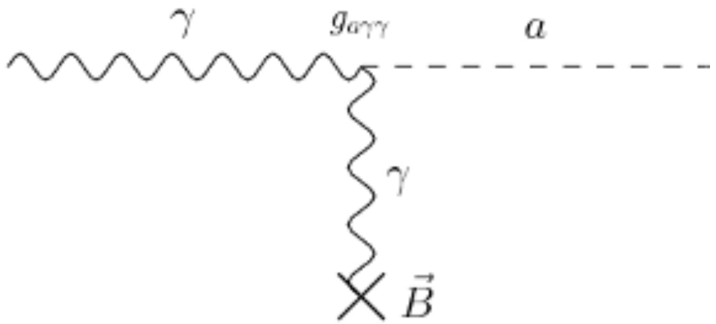


- Experiments attempt to exploit this coupling

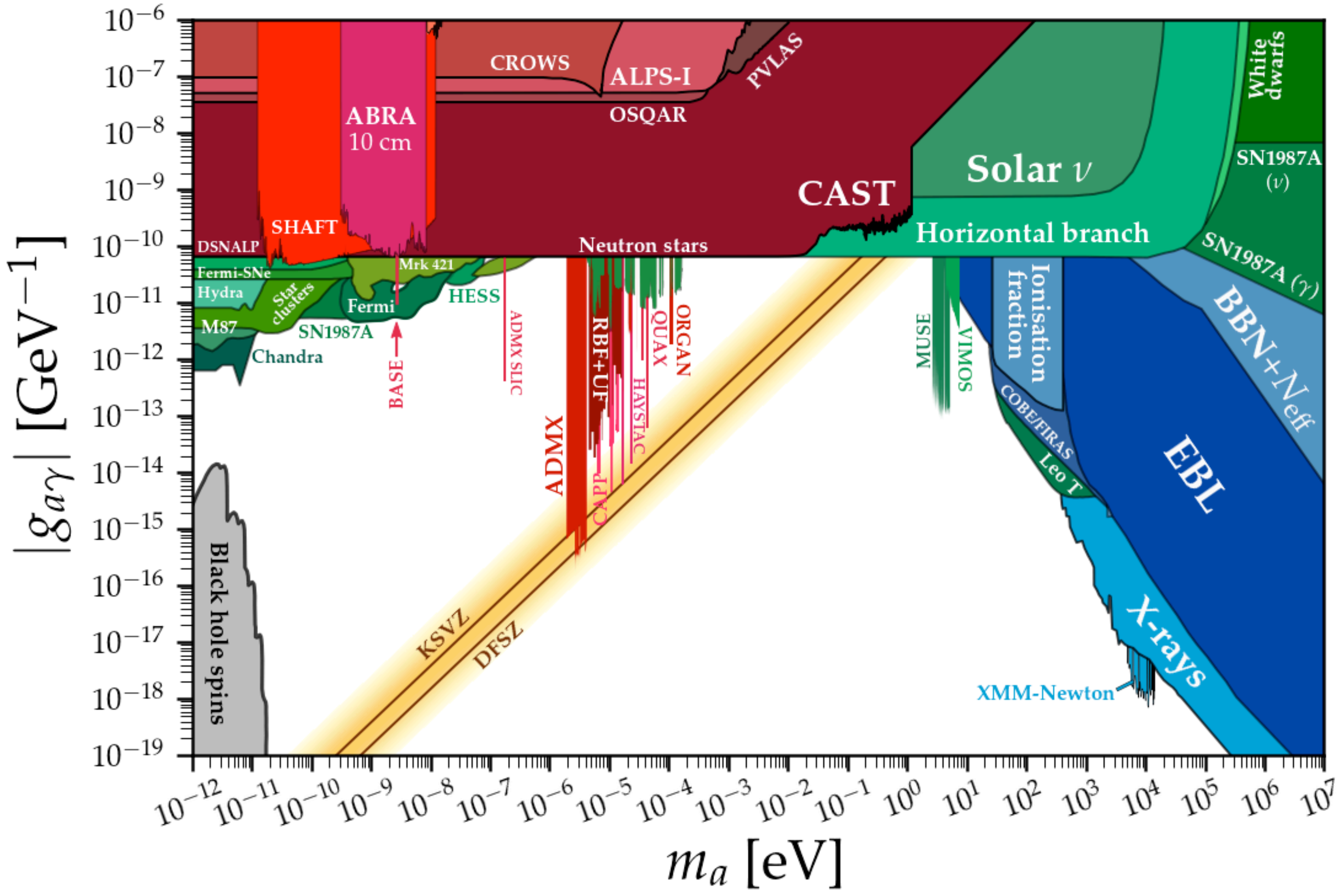
Axions

- It was later realized that for a certain range of masses (neV to a meV) 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

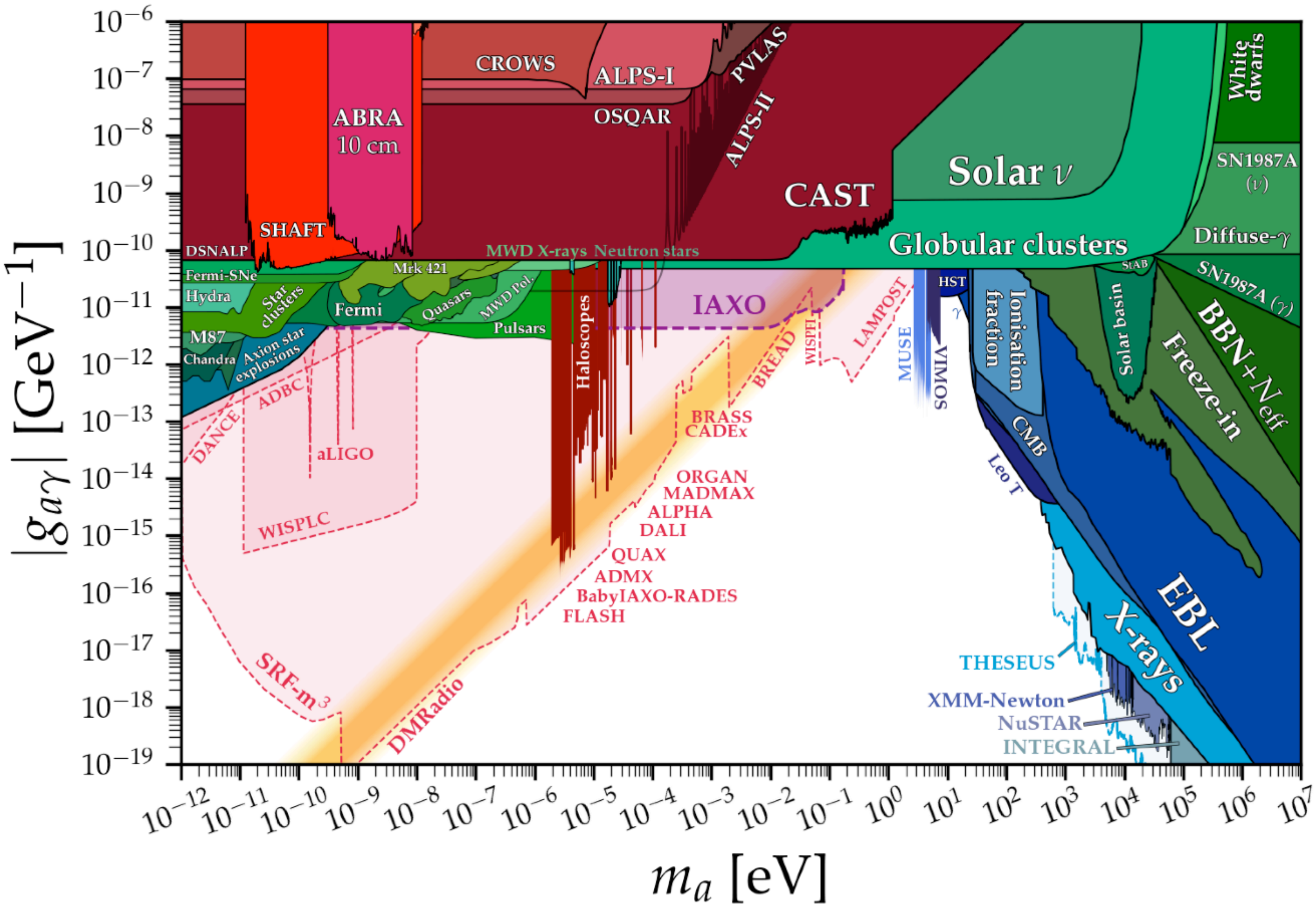
  e.g. photons



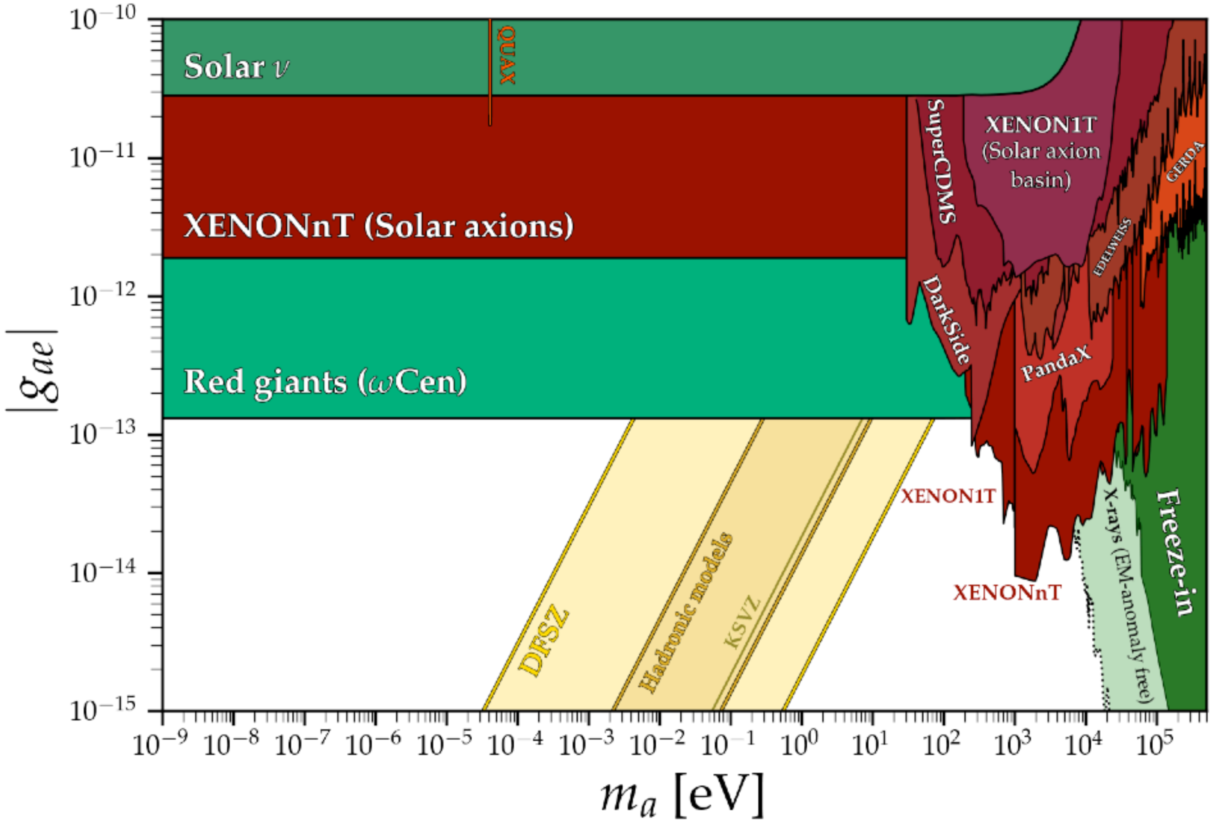
- Experiments attempt to exploit this coupling
- Plenty of other couplings, too - electrons, nucleons, etc

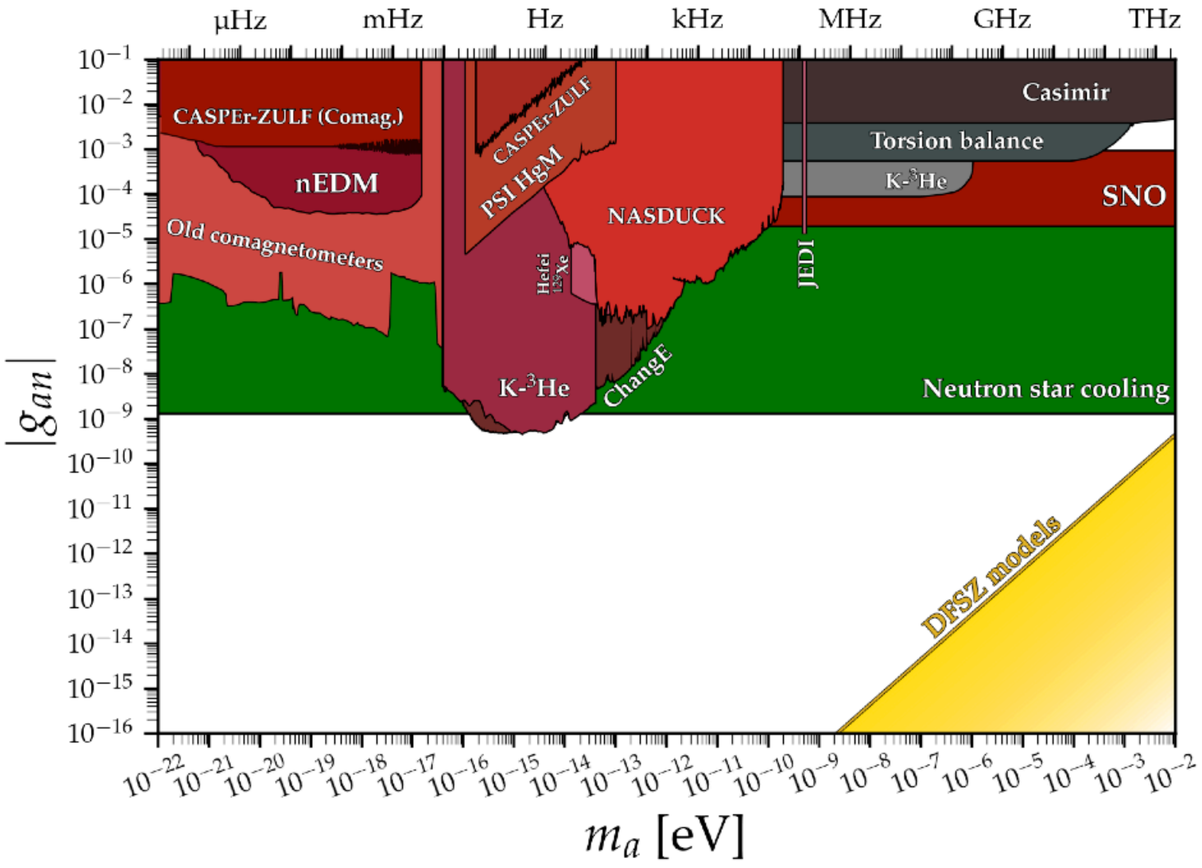


From CA O'Hare's Axion Limit Plotting Tool



From CA O'Hare's Axion Limit Plotting Tool

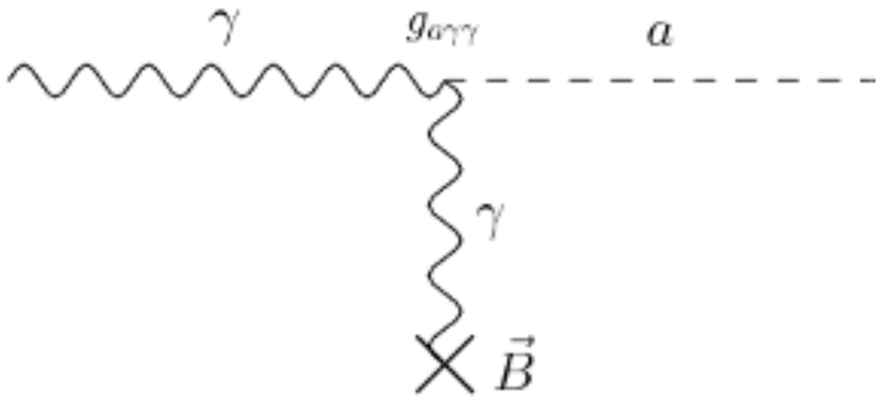




From CA O'Hare's Axion Limit Plotting Tool

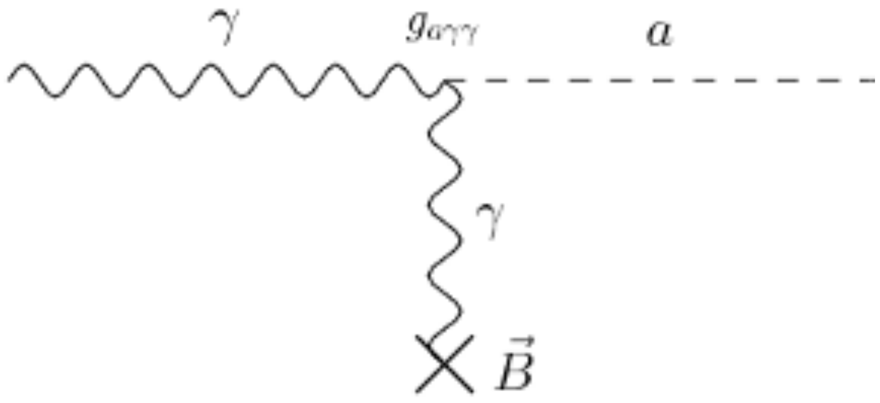
Axion Detectors

- Going to focus on axion-photon coupling



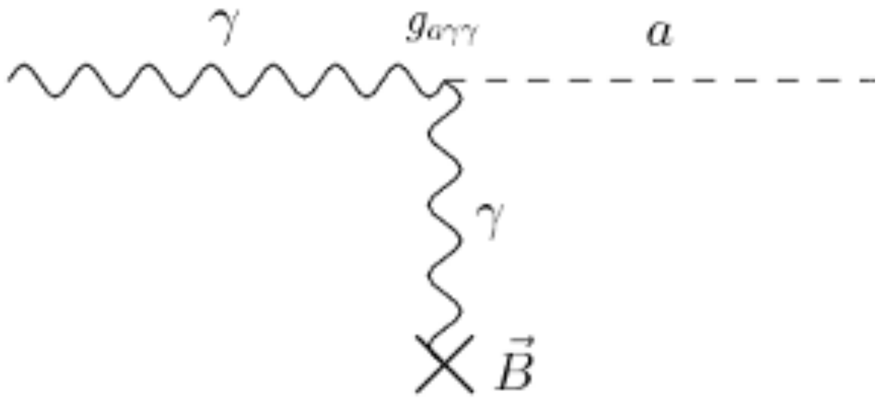
Axion Detectors

- Going to focus on axion-photon coupling
- Broadly speaking, three classes of detector:
  - Light shining through a wall
  - Helioscope
  - Haloscope



Axion Detectors

- Going to focus on axion-photon coupling
- Broadly speaking, three classes of detector:
  - Light shining through a wall
  - Helioscope
  - **Haloscope**



Light Shining Through a Wall

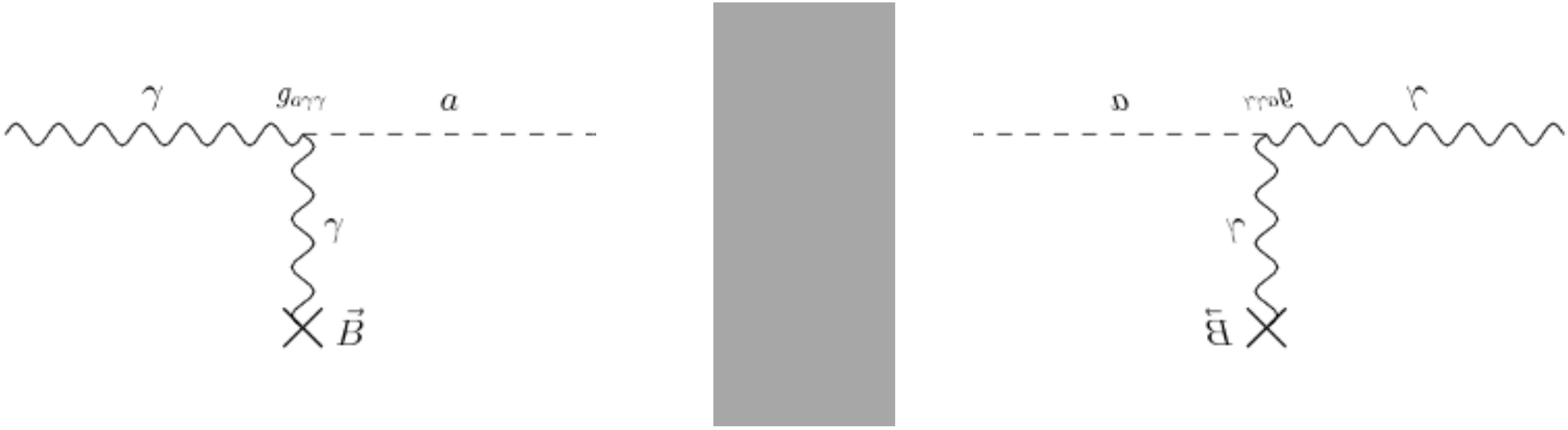
- Experiments that exploit axion-photon coupling twice
- Do not require axions to be DM

Light Shining Through a Wall

- Experiments that exploit axion-photon coupling twice
- Do not require axions to be DM
- Less assumptions, but less sensitive than DM experiments

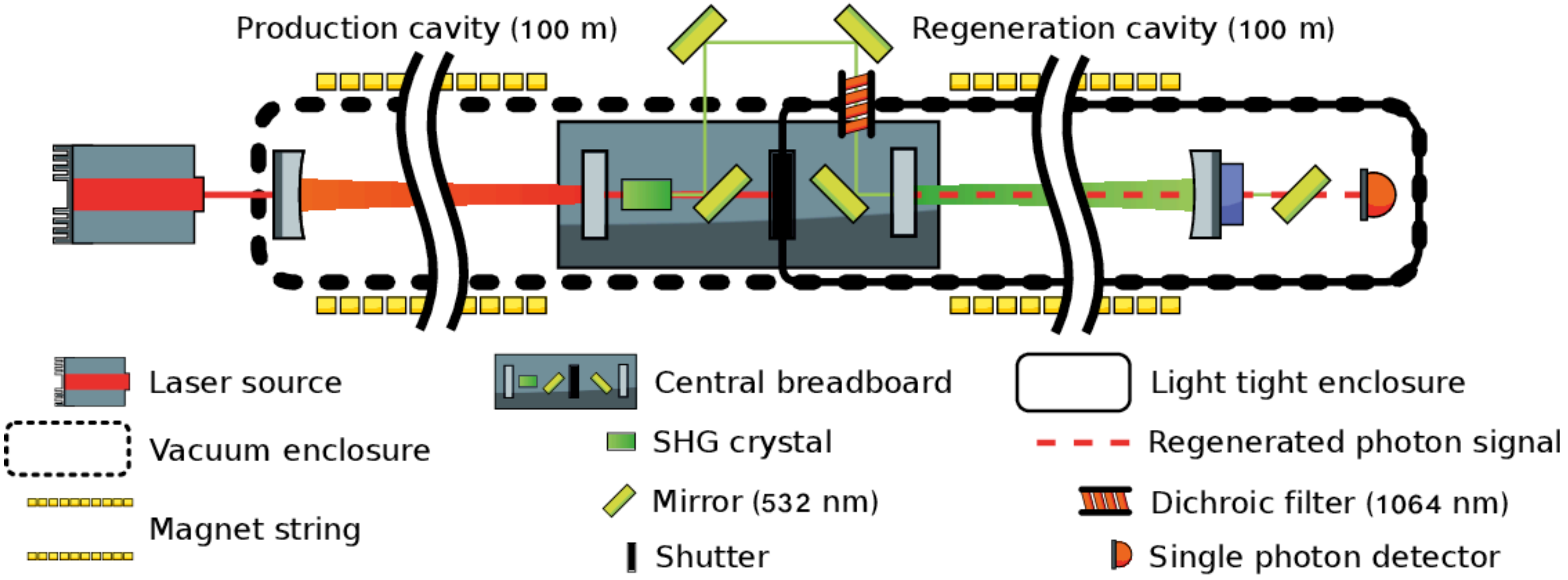
Light Shining Through a Wall

- Experiments that exploit axion-photon coupling twice
- Do not require axions to be DM
- Less assumptions, but less sensitive than DM experiments

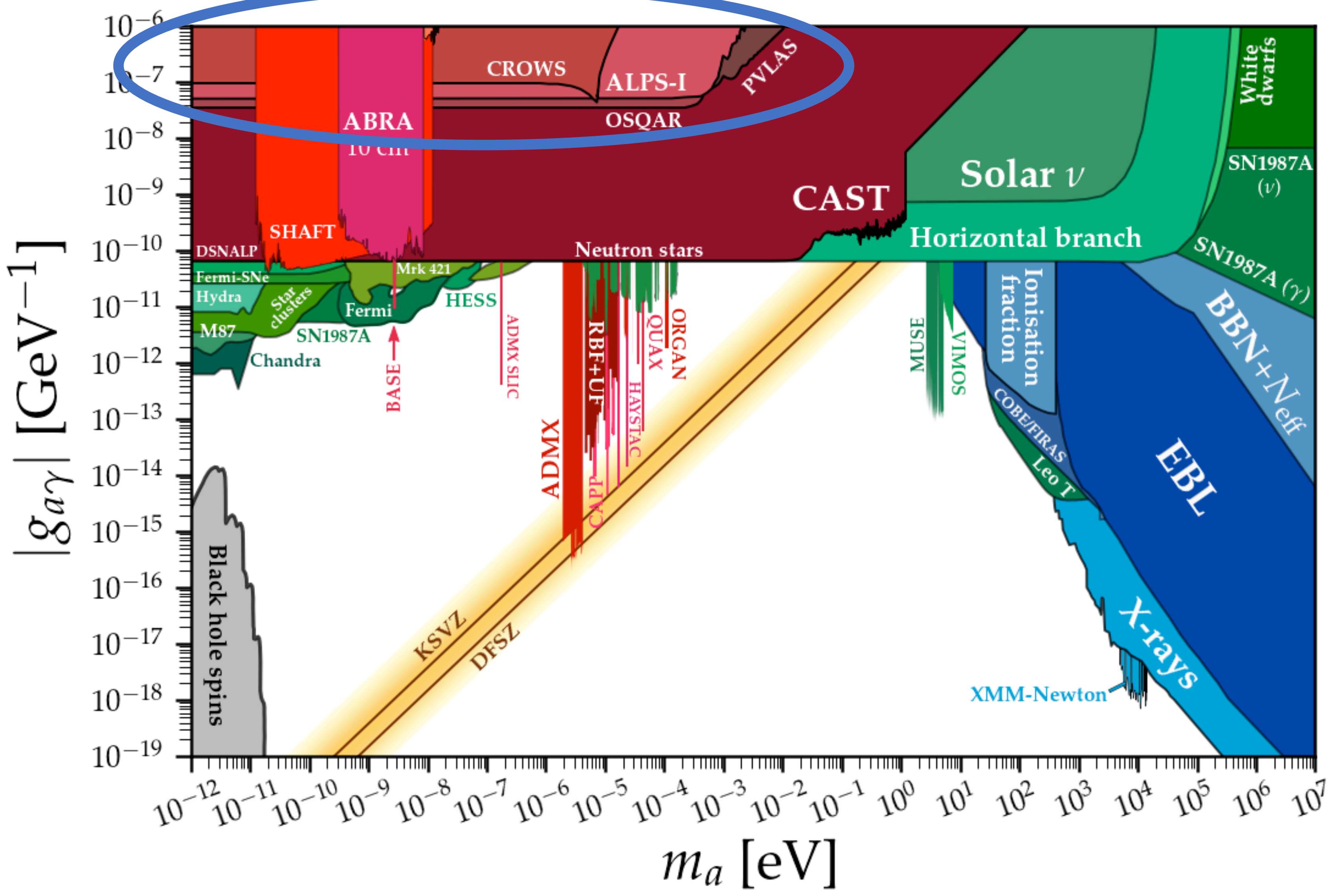


Light Shining Through a Wall

- ALPS, OSQAR



ALPS II Technical Report



From CA O'Hare's Axion Limit Plotting Tool

Helioscopes

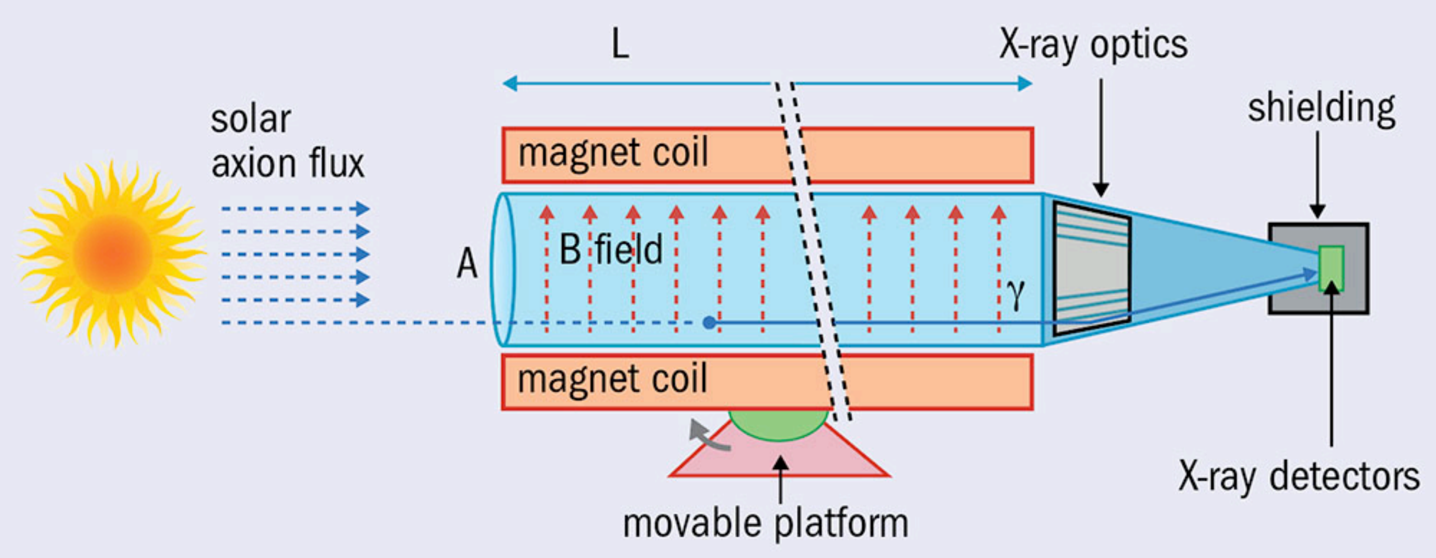
- Assume axions generated in the sun, stream to earth

Helioscopes

- Assume axions generated in the sun, stream to earth
- Track sun with telescope-like structures, convert axions back to photons

Helioscopes

- Assume axions generated in the sun, stream to earth
- Track sun with telescope-like structures, convert axions back to photons



IAXO

Helioscopes

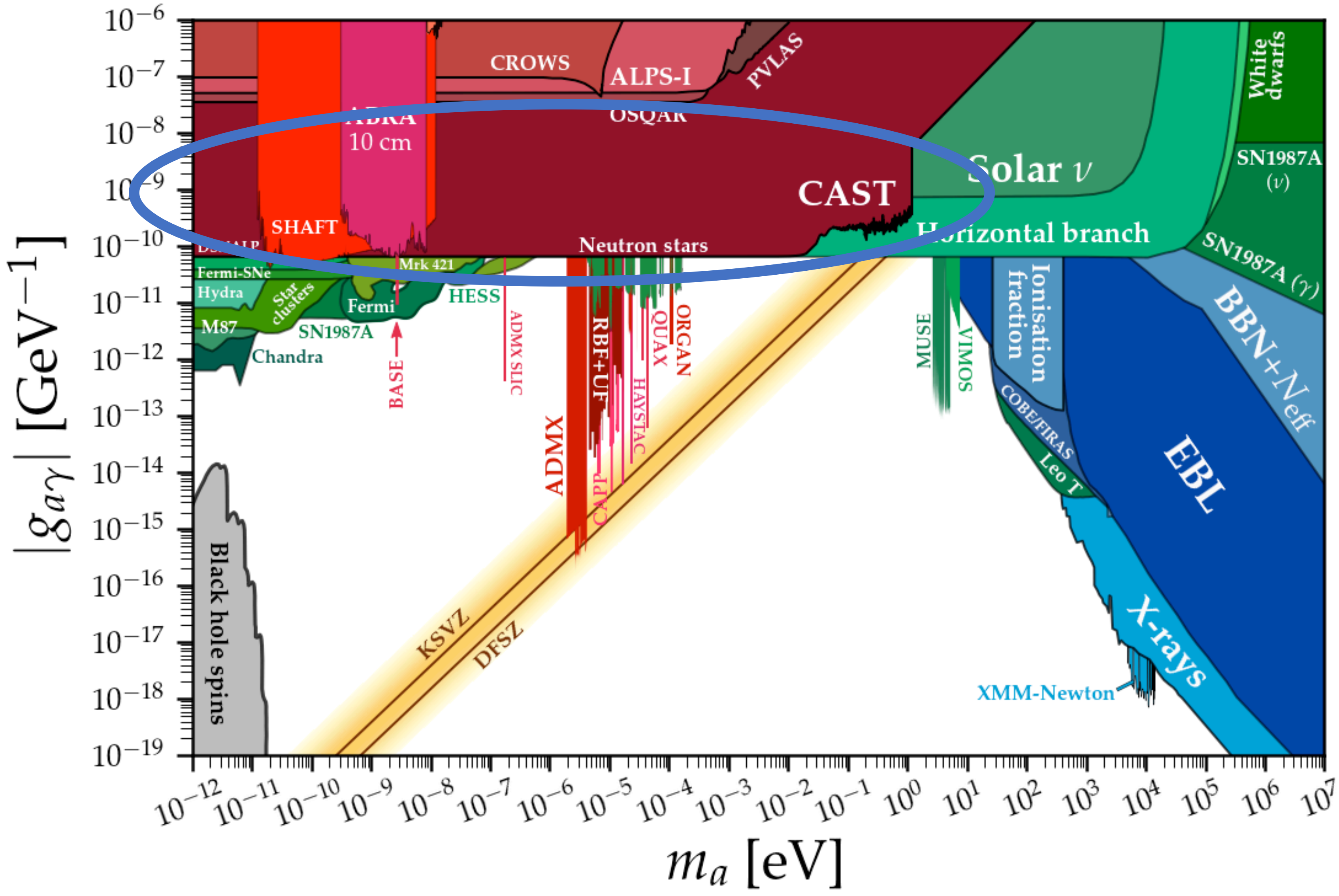
- CAST, IAXO

Helioscopes

- CAST, IAXO
- CAST in particular is a long running, broadband experiment

Helioscopes

- CAST, IAXO
- CAST in particular is a long running, broadband experiment
- Also doesn't assume local DM density of axions



From CA O'Hare's Axion Limit Plotting Tool

Haloscopes

- Axions convert into photons in presence of strong magnetic field

Haloscopes

- Axions convert into photons in presence of strong magnetic field
- Conservation of energy dictates that

$$hf = m_a c^2 + \frac{1}{2} m_a v_a^2$$

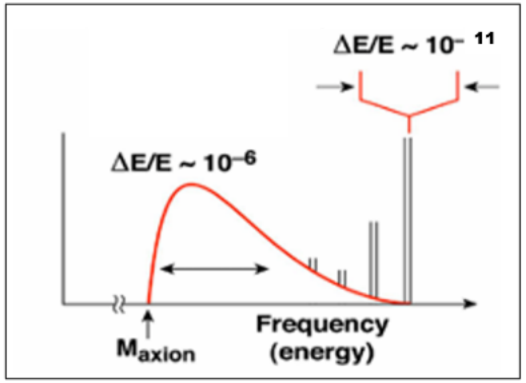
- Velocity comes from velocity of DM halo with respect to detector ($v_a \approx 10^{-3}c$ for isothermal halo model, but possibly much narrower for other models)

Haloscopes

- Axions convert into photons in presence of strong magnetic field
- Conservation of energy dictates that

$$hf = m_a c^2 + \frac{1}{2} m_a v_a^2$$

- Velocity comes from velocity of DM halo with respect to detector ($v_a \approx 10^{-3} c$ for isothermal halo model, but possibly much narrower for other models)



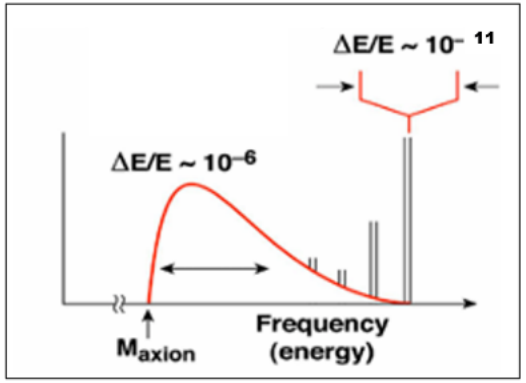
Duffy et al.
Snowmass 2021 Letter of Interest

Haloscopes

- Axions convert into photons in presence of strong magnetic field
- Conservation of energy dictates that

$$hf = m_a c^2 + \frac{1}{2} m_a v_a^2$$

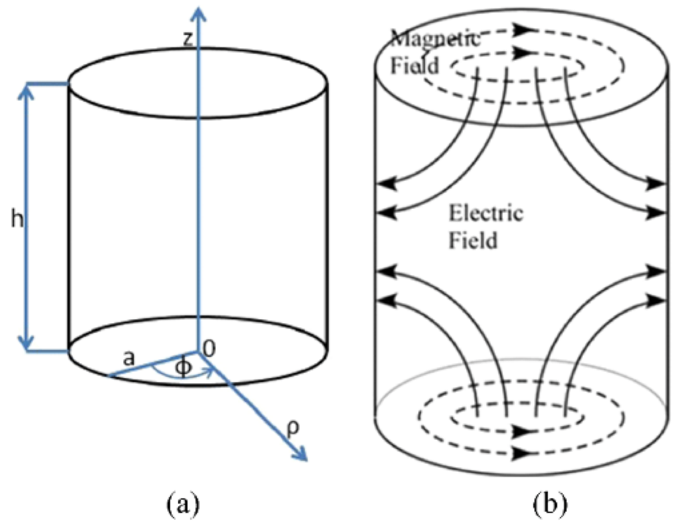
- Velocity comes from velocity of DM halo with respect to detector ($v_a \approx 10^{-3}c$ for isothermal halo model, but possibly much narrower for other models)
- Mass is unknown
- So: narrowband photon signal of an unknown frequency is generated
- If resonant cavity has correct frequency, photons resonate inside cavity, and can be read out



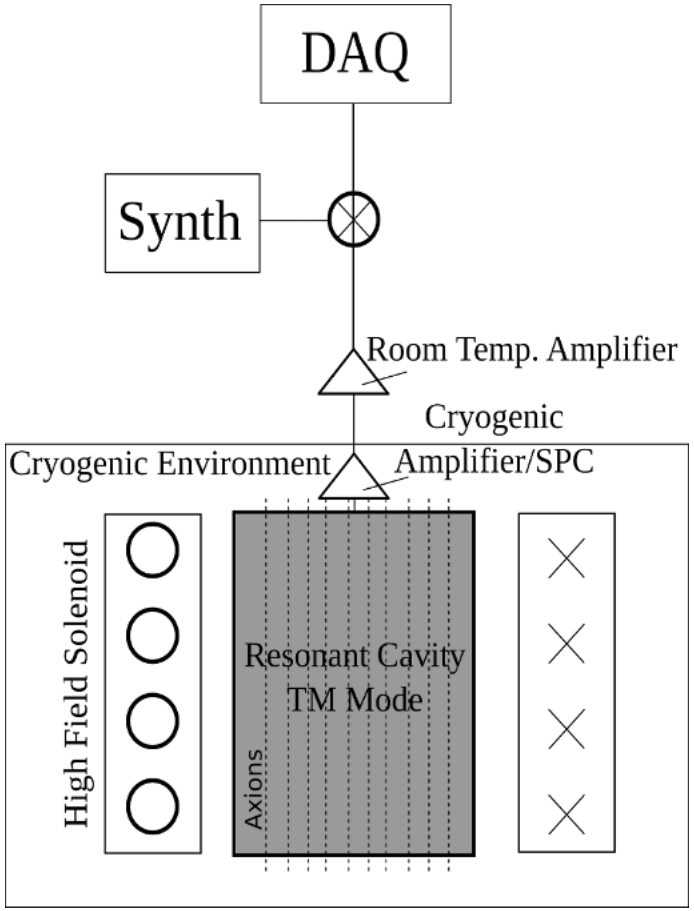
Duffy et al.
Snowmass 2021 Letter of Interest

Haloscopes

- If resonant cavity has correct frequency, photons resonate inside cavity, and can be read out
- Embed tuneable resonant cavity inside magnet, and wait for axion conversion to occur inside

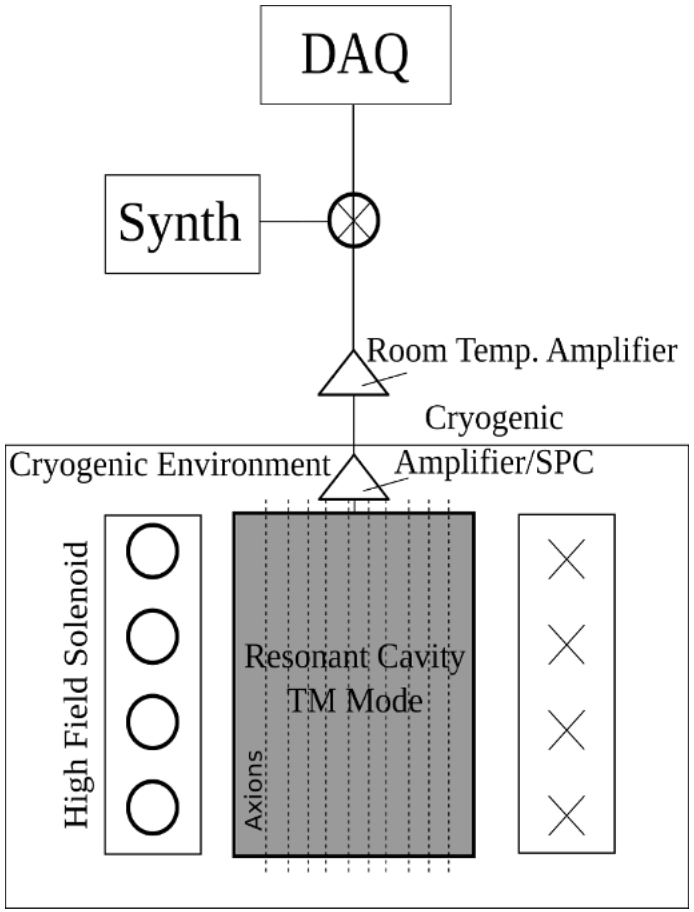


Haloscopes


DAQ
Synth
Room Temp. Amplifier
Cryogenic
Amplifier/SPC
Cryogenic Environment
High Field Solenoid
Resonant Cavity
TM Mode
Axions

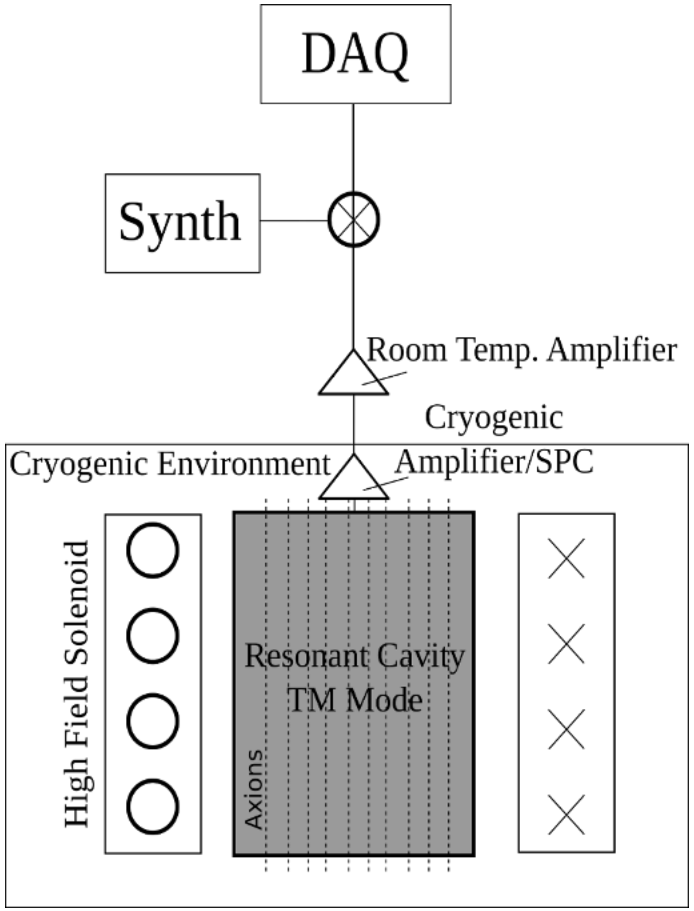
Haloscopes

- Detector must be very well shielded from environment, to reduce ambient photon noise
- Thermal photons are also dominant noise source -> cryogenic temperatures
- Also, cryogenics allows for strong superconducting magnets, and quantum technology in readout
- Cavity must be tuneable



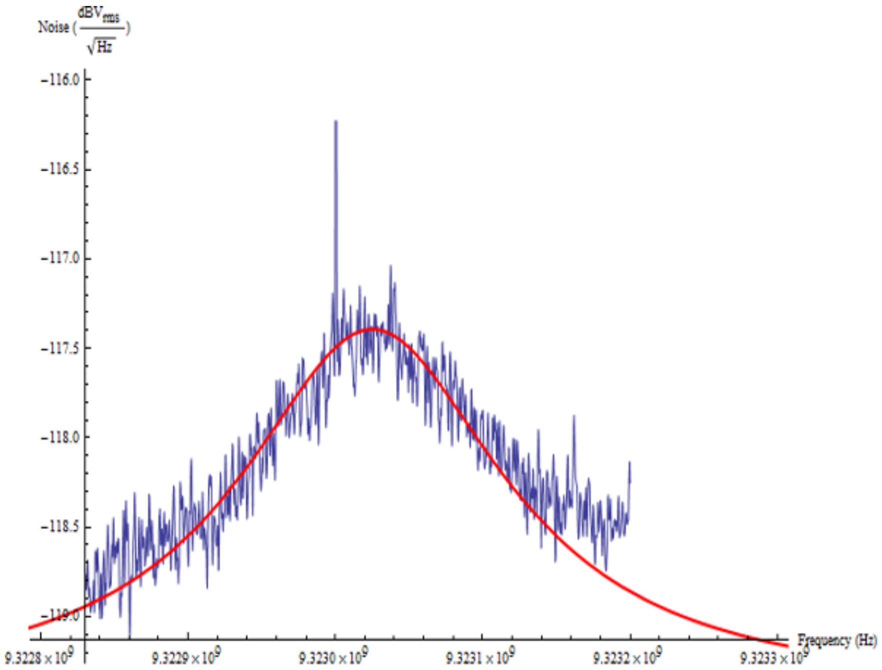
Haloscopes

- Detector must be very well shielded from environment, to reduce ambient photon noise
- Thermal photons are also dominant noise source -> cryogenic temperatures
- Also, cryogenics allows for strong superconducting magnets, and quantum technology in readout
- Cavity must be tuneable
- A bunch of haloscopes these days: ADMX, ORGAN, CAPP, QUAX, MADMAX, etc



Haloscopes

- Expected Signal
- Note: Shape of signal, its motion in time will shed light on nature of DM distribution



Haloscopes

- Because photon frequency (axion mass) is unknown, must scan large range of cavity frequencies
- Difficult engineering problem

Haloscopes

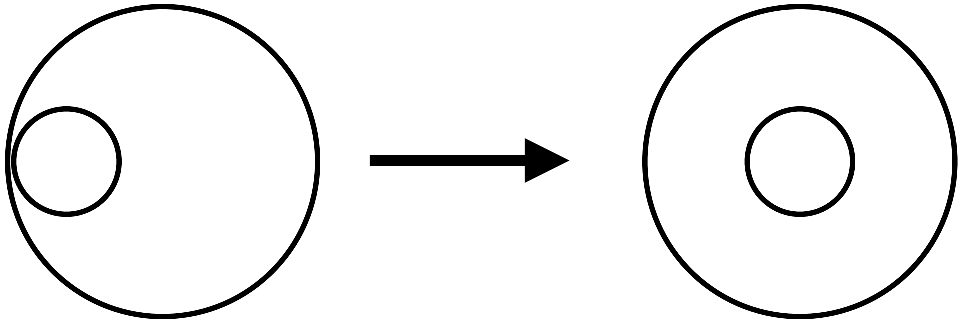
- Because photon frequency (axion mass) is unknown, must scan large range of cavity frequencies
- Difficult engineering problem
- Figure of merit for experiment is allowable rate of frequency scanning:

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

Haloscopes

- Because photon frequency (axion mass) is unknown, must scan large range of cavity frequencies
- Difficult engineering problem
- Figure of merit for experiment is allowable rate of frequency scanning:

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



Top-down view of cavity cross-section as rod tunes

Haloscopes Detector Design

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

Haloscopes Detector Design

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

- Things set by nature

Haloscopes Detector Design

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

- Things set by nature
- Things to do with readout, refrigeration system, magnet

Haloscopes Detector Design

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

- Things set by nature
- Things to do with readout, refrigeration system, magnet
- Things to do with resonant cavity

Haloscopes Detector Design

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

- Things to do with resonant cavity

Haloscopes Detector Design

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

- Things to do with resonant cavity
    - C - ‘form factor’, to do with EM field pattern of resonant mode

Haloscopes Detector Design

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

- Things to do with resonant cavity
    - C - ‘form factor’, to do with EM field pattern of resonant mode
    - V - volume, inversely proportional to frequency

Haloscopes Detector Design

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

- Things to do with resonant cavity
    - C - ‘form factor’, to do with EM field pattern of resonant mode
    - V - volume, inversely proportional to frequency
    - Q - quality factor, how long photons live inside resonator

Haloscopes Detector Design

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

- Form factor

$$C = \frac{\left(\int \vec{E} \cdot \vec{B}_0 \, dV\right)^2}{\left(\int \vec{B}_0 \cdot \vec{B}_0 \, dV\right)\left(\int \vec{E} \cdot \vec{E} \, dV\right)}$$

Haloscopes Detector Design

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

- Form factor

$$C = \frac{\left(\int \vec{E} \cdot \vec{B}_0 \, dV \right)^2}{\left(\int \vec{B}_0 \cdot \vec{B}_0 \, dV \right) \left(\int \vec{E} \cdot \vec{E} \, dV \right)}$$

- For typical haloscopes, only TM0n0 modes have non zero C

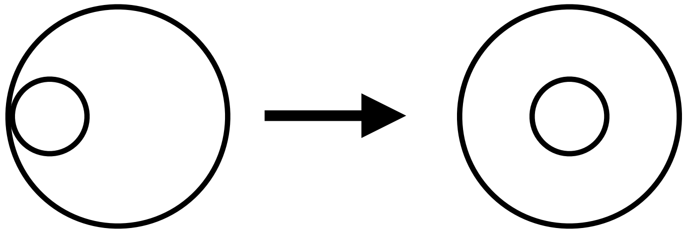
Haloscopes Detector Design

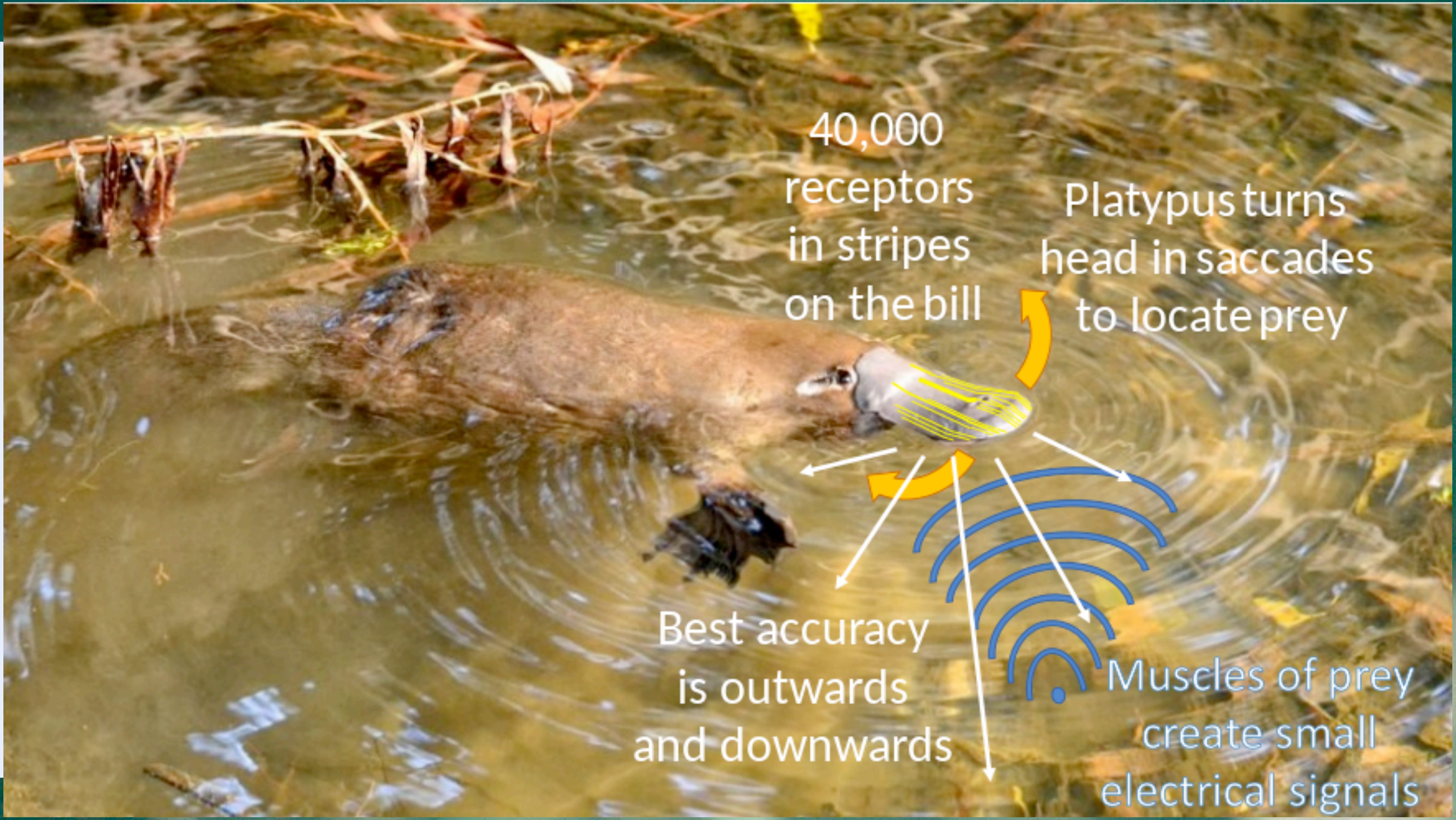
$$\frac{df}{dt} \propto \frac{1}{SNR_{goal}^2} \frac{g_{a\gamma\gamma}^4 B^4 C^2 V^2 \rho_a^2 Q_L Q_a}{m_a^2 (k_B T_n)^2}$$

- Form factor

$$C = \frac{\left(\int \vec{E} \cdot \vec{B}_0 \, dV \right)^2}{\left(\int \vec{B}_0 \cdot \vec{B}_0 \, dV \right) \left(\int \vec{E} \cdot \vec{E} \, dV \right)}$$

- For typical haloscopes, only TM0n0 modes have non zero C
- Very uniform modes, hard to tune -> need for tuning rods




40,000
receptors
in stripes
on the bill
Platypus turns
head in saccades
to locate prey
Best accuracy
is outwards
and downwards
Muscles of prey
create small
electrical signals

ADMX Searches

A Search for Halo Axions

by

Edward John Daw

Bachelor of Arts, New College, Oxford University, England.

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 1998

ADMX Searches

A Search for Halo Axions

by

Edward John Daw

Bachelor of Arts, New College, Oxford University, England.

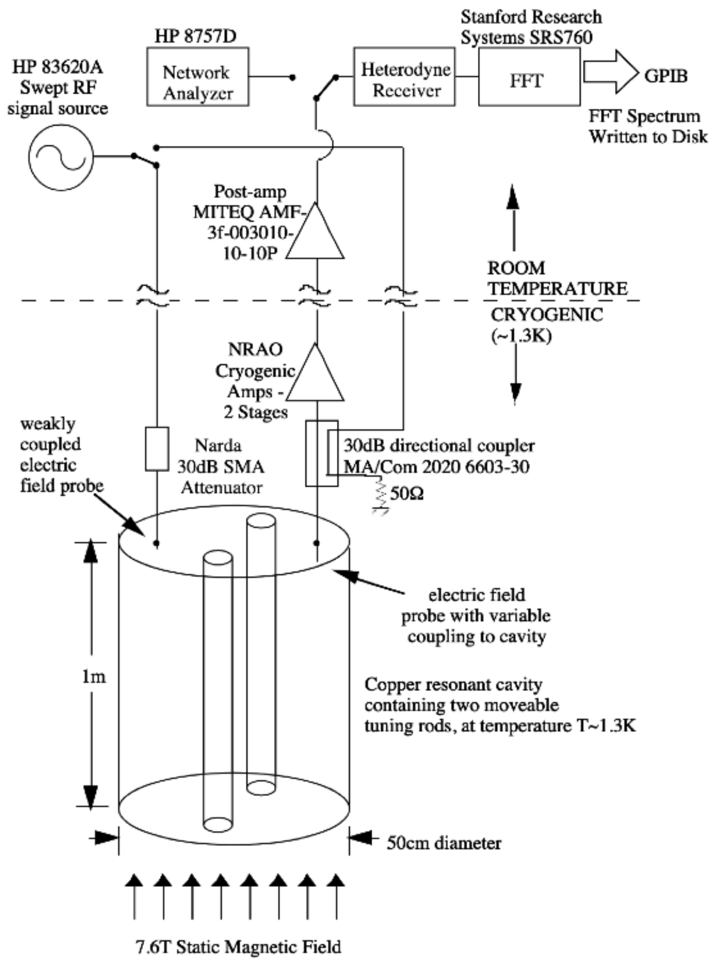
Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 1998

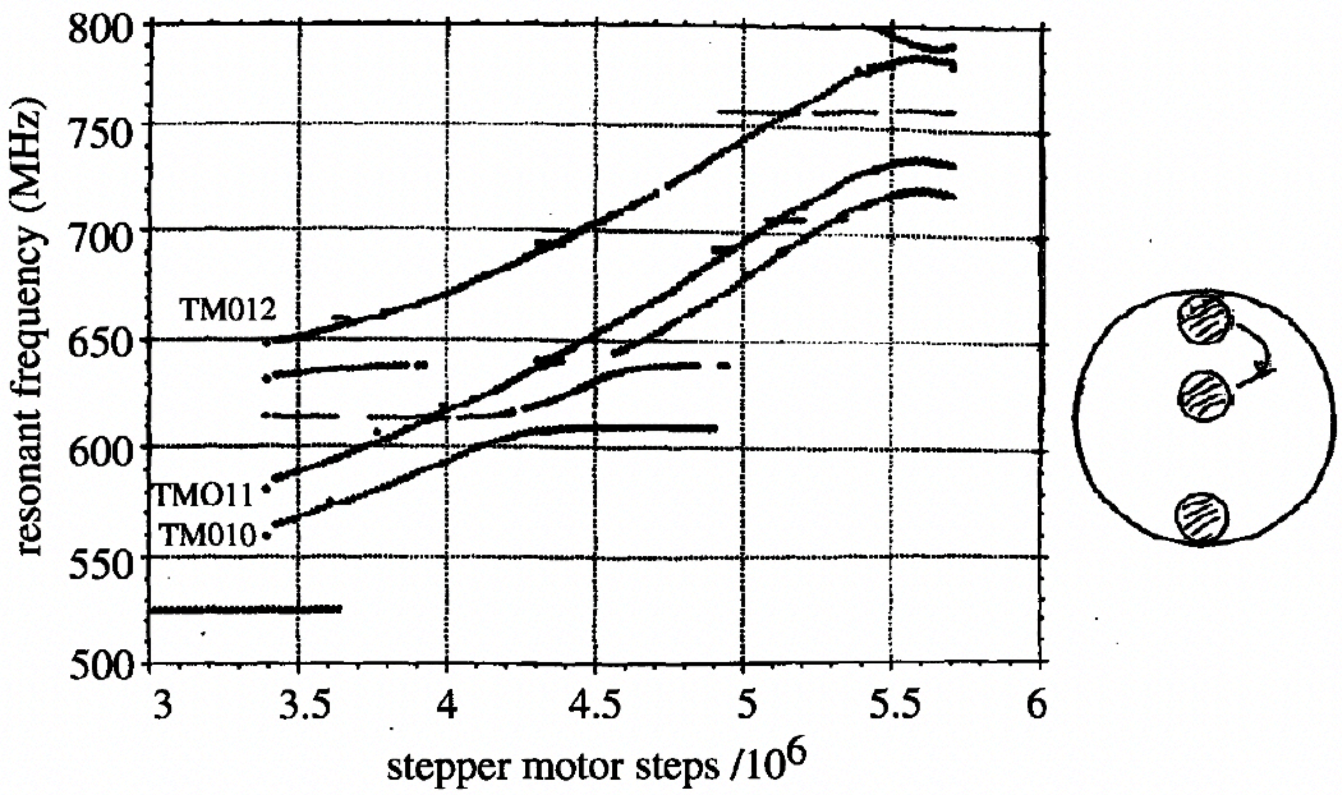


ADMX Searches

- Only certain modes (TM0n0 modes) are axion sensitive

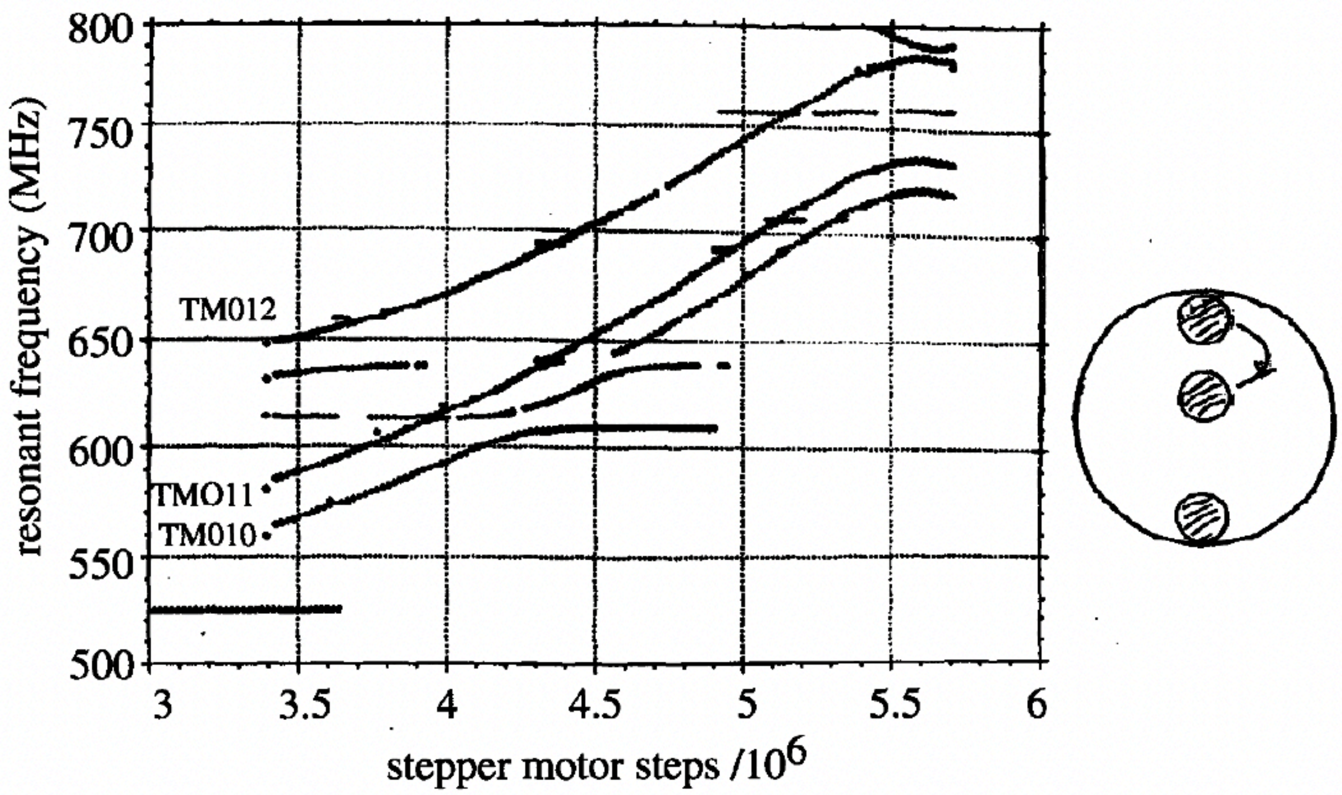
ADMX Searches

- Only certain modes (TM0n0 modes) are axion sensitive
- As they tune they run into intruder modes

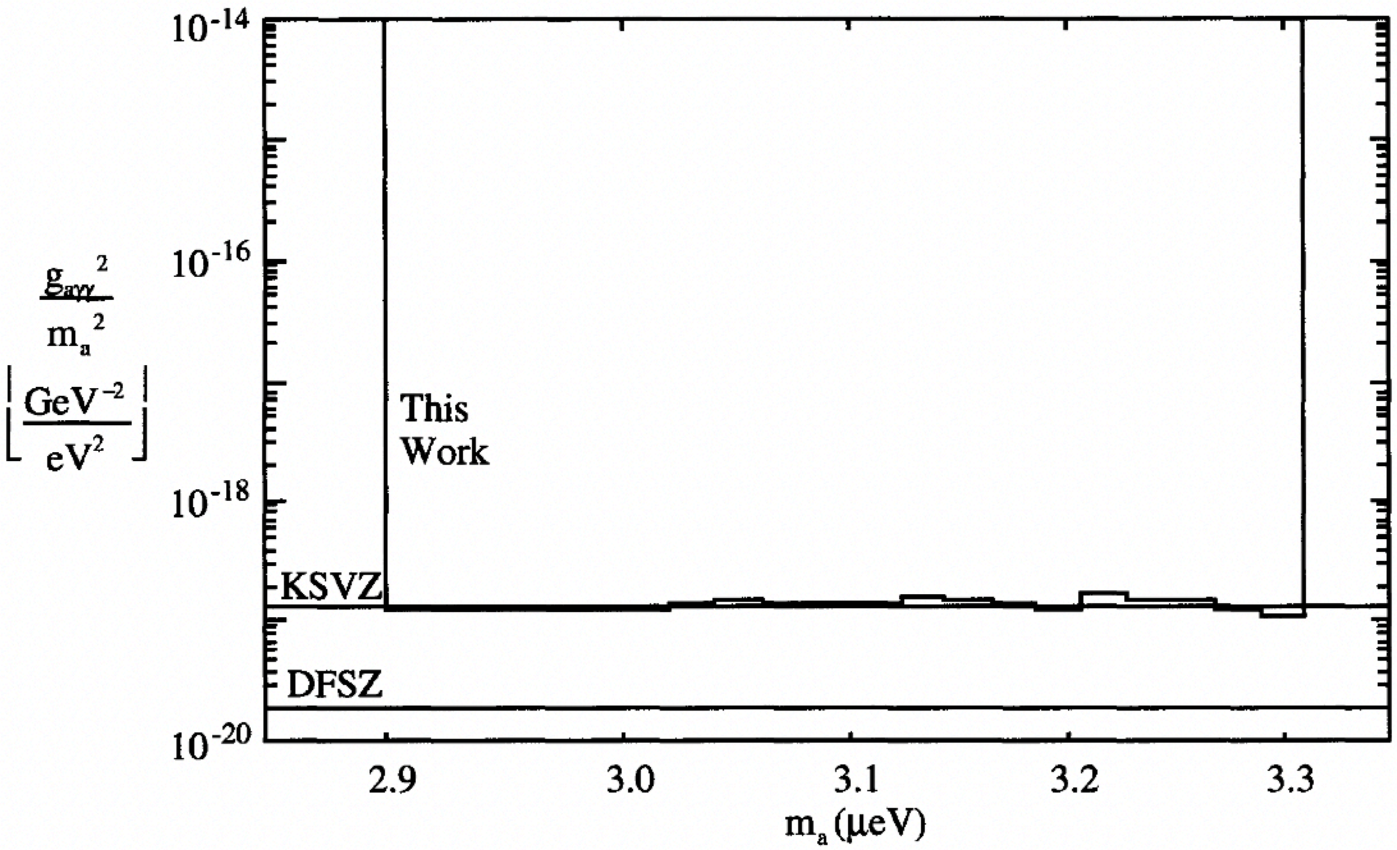


ADMX Searches

- Only certain modes (TM0n0 modes) are axion sensitive
- As they tune they run into intruder modes
- This is a significant design issue in all resonant haloscope experiments



ADMX Searches

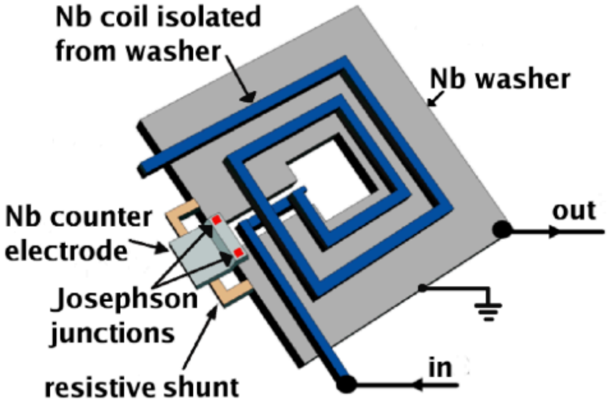


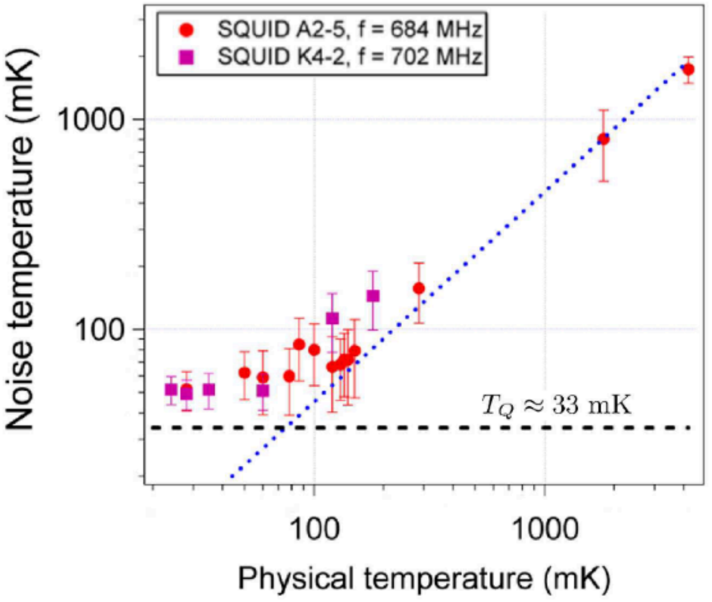
ADMX Searches - Quantum Readout

- Experiment upgraded in the 2000s
- Implemented a SQUID-based amplifier

ADMX Searches - Quantum Readout

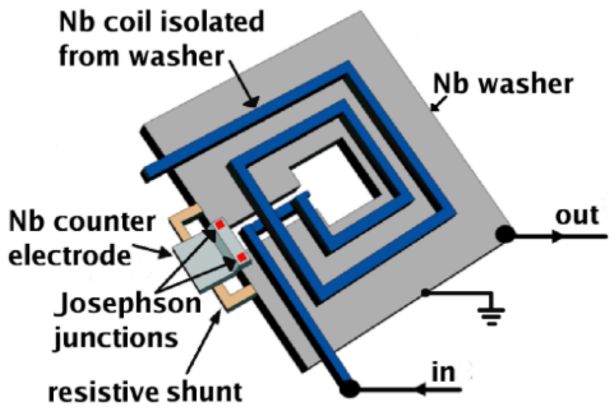
- Experiment upgraded in the 2000s
- Implemented a SQUID-based amplifier

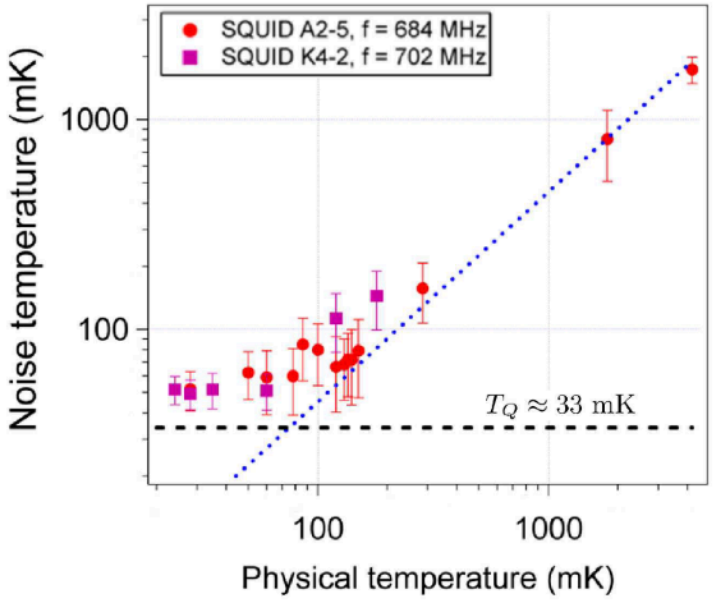




ADMX Searches - Quantum Readout

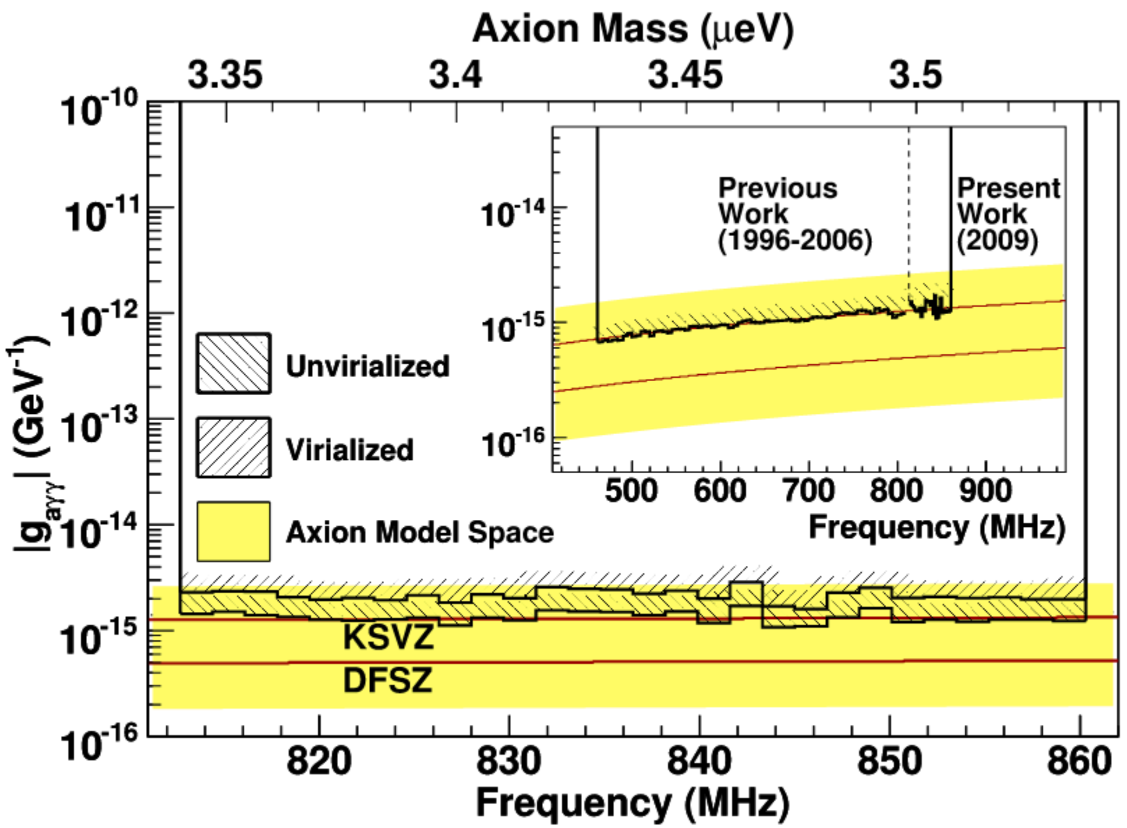
- Experiment upgraded in the 2000s
- Implemented a SQUID-based amplifier
- Phys. Rev. Lett 104, 041301 (2010)





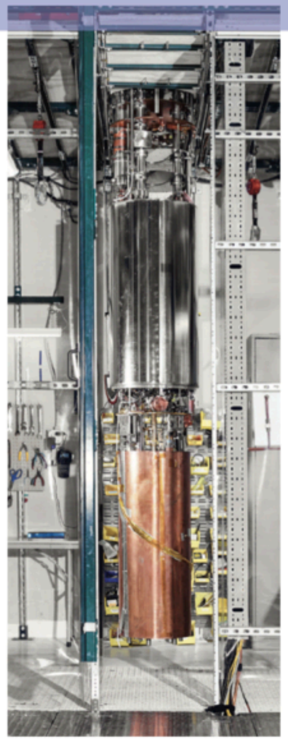
ADMX Searches - Quantum Readout

- Experiment upgraded in the 2000s
- Implemented a SQUID-based amplifier
- Phys. Rev. Lett 104, 041301 (2010)

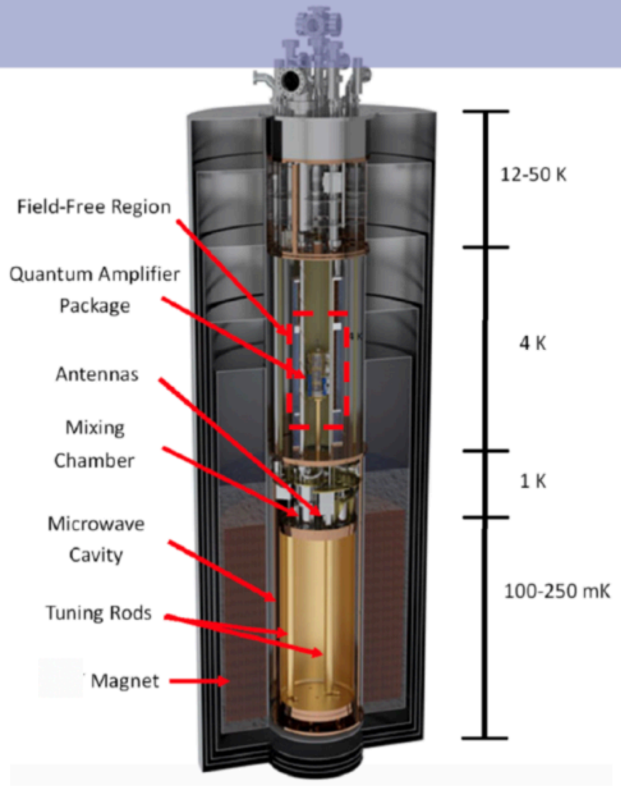


ADMX Searches - Current Generation

- Run 1a - Run 1d with current setup
- Hosted at University of Washington
- Custom Dil Fridge ~100 mK
- Custom magnet - 8T
- Uses Josephson Parametric Amplifier
- Targets ~650 - ~1200 MHz



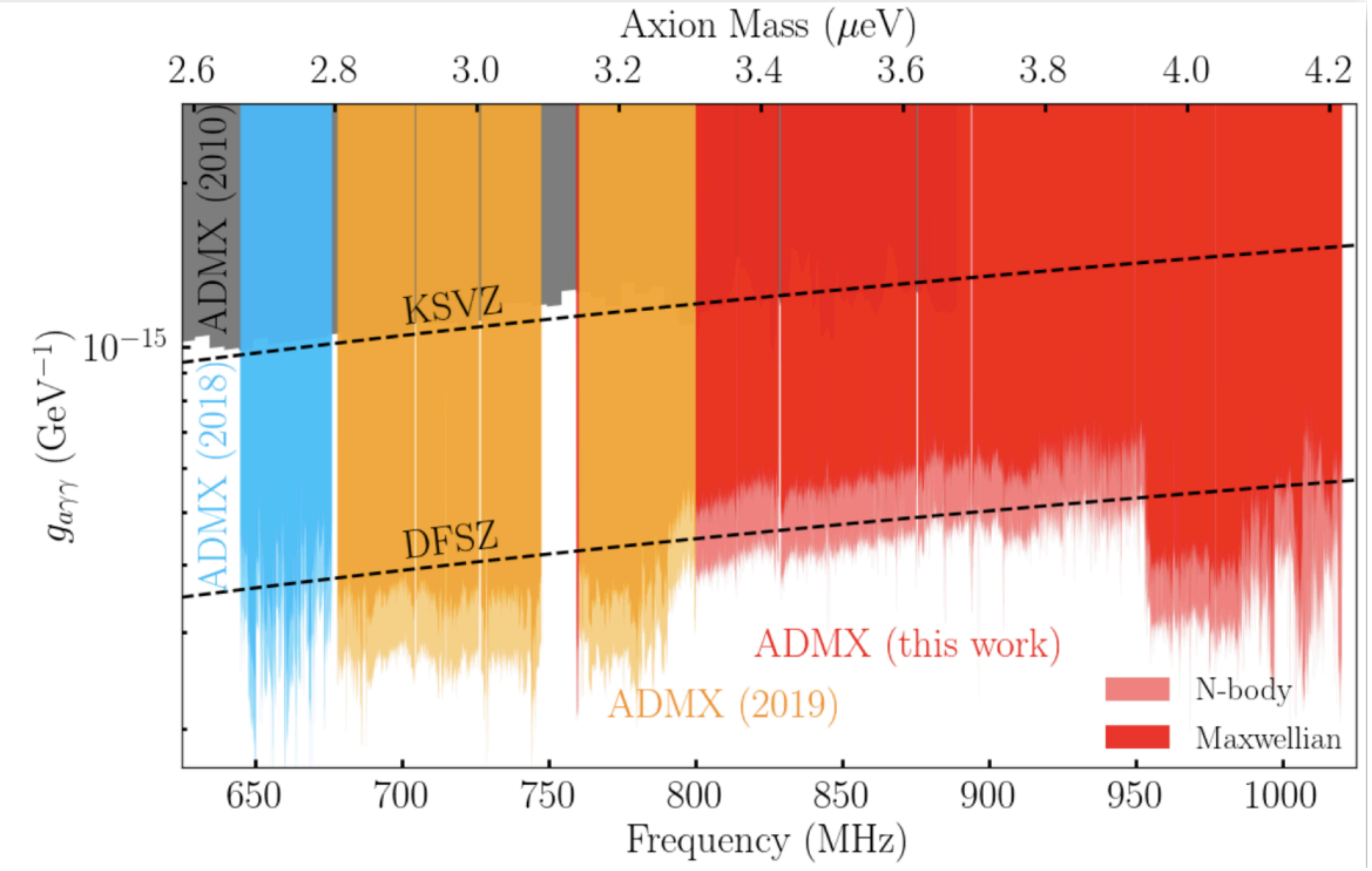
In cleanroom



In magnet bore

Images borrowed from Chelsea Bartram

ADMX Searches - Current Generation



ADMX Searches - Future

- Significant design challenges going higher in frequency

ADMX Searches - Future

- Significant design challenges going higher in frequency

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

ADMX Searches - Future

- Significant design challenges going higher in frequency

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

- Cavity volume inversely proportional to TM010 mode frequency
- Noise temperature goes up

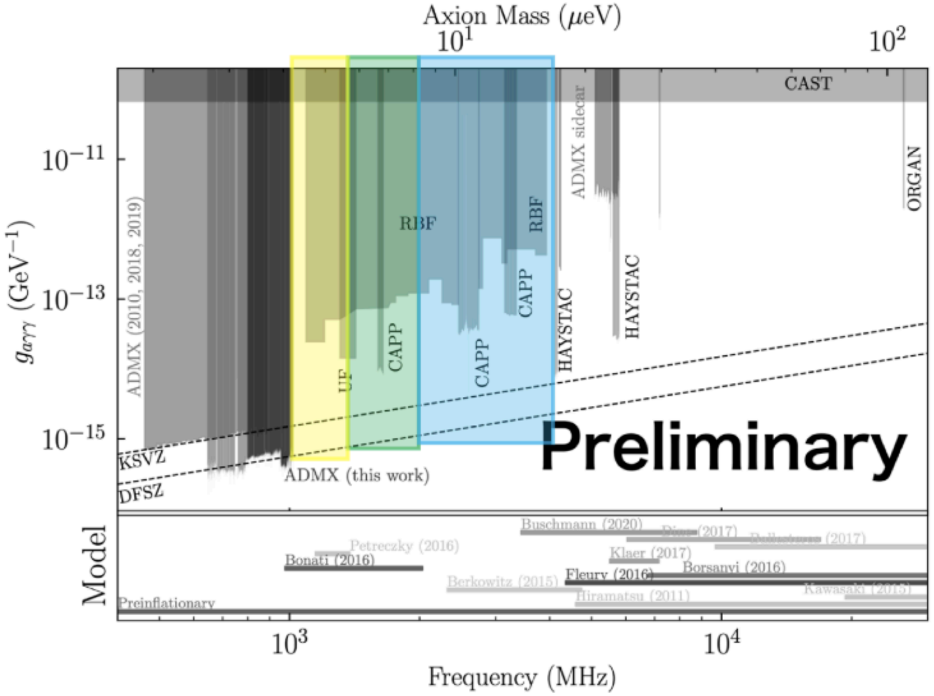
ADMX Searches - Future

- Significant design challenges going higher in frequency

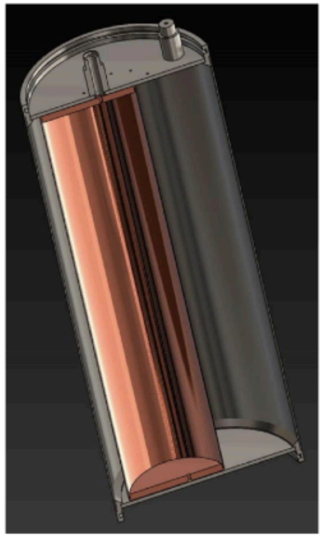
$$\frac{df}{dt} \propto \frac{1}{SNR^2_{goal}} \frac{g^4_{a\gamma\gamma} B^4 C^2 V^2 \rho_a^2 Q_L Q_a}{m_a^2 (k_B T_n)^2}$$

- Cavity volume inversely proportional to TM010 mode frequency
- Noise temperature goes up
- Solution -> more cavities in sync

ADMX Searches - Future



2022--23

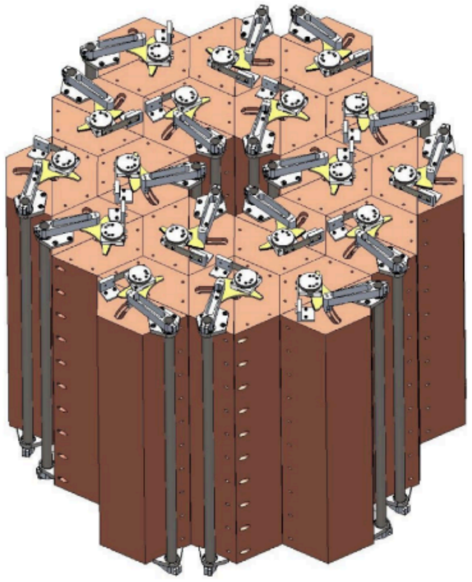


Single cavity
Big tuning rod

2023--25

4-Cavity array

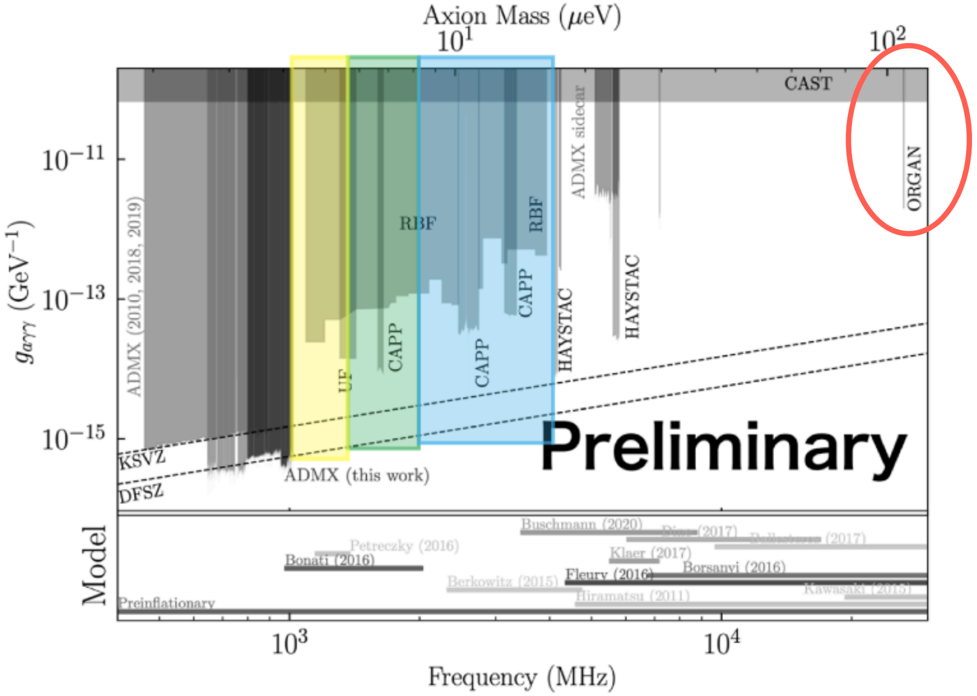
2025--

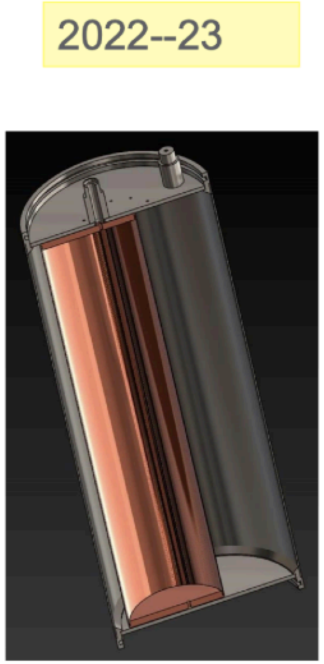


18-Cavity array

Images borrowed from Chelsea Bartram

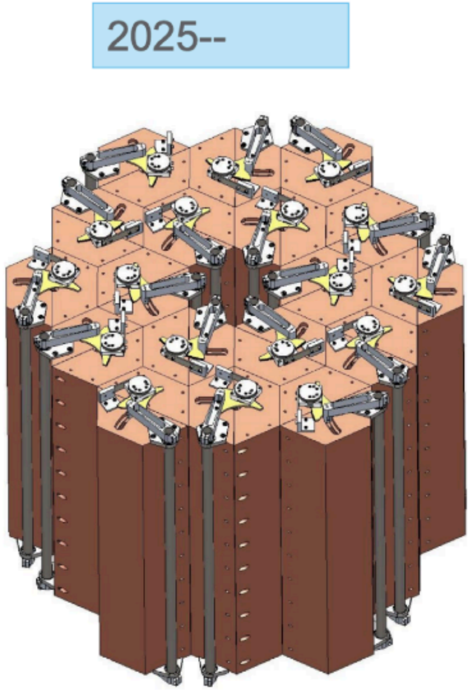
ADMX Searches - Future





Single cavity
Big tuning rod

4-Cavity array



18-Cavity array

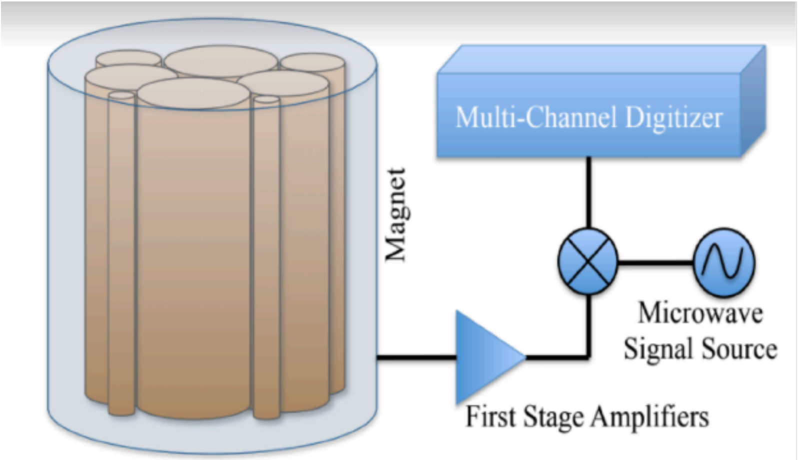
Images borrowed from Chelsea Bartram

ORGAN Introduction

- Haloscope in Australia
- Many cavities together
- The Oscillating Resonant Group AxioN Experiment

ORGAN Introduction

- Haloscope in Australia
- Many cavities together
- The Oscillating Resonant Group AxioN Experiment



ORGAN Introduction

- Mass range of interest – 60-200 micro-eV
- Motivations:

ORGAN Introduction

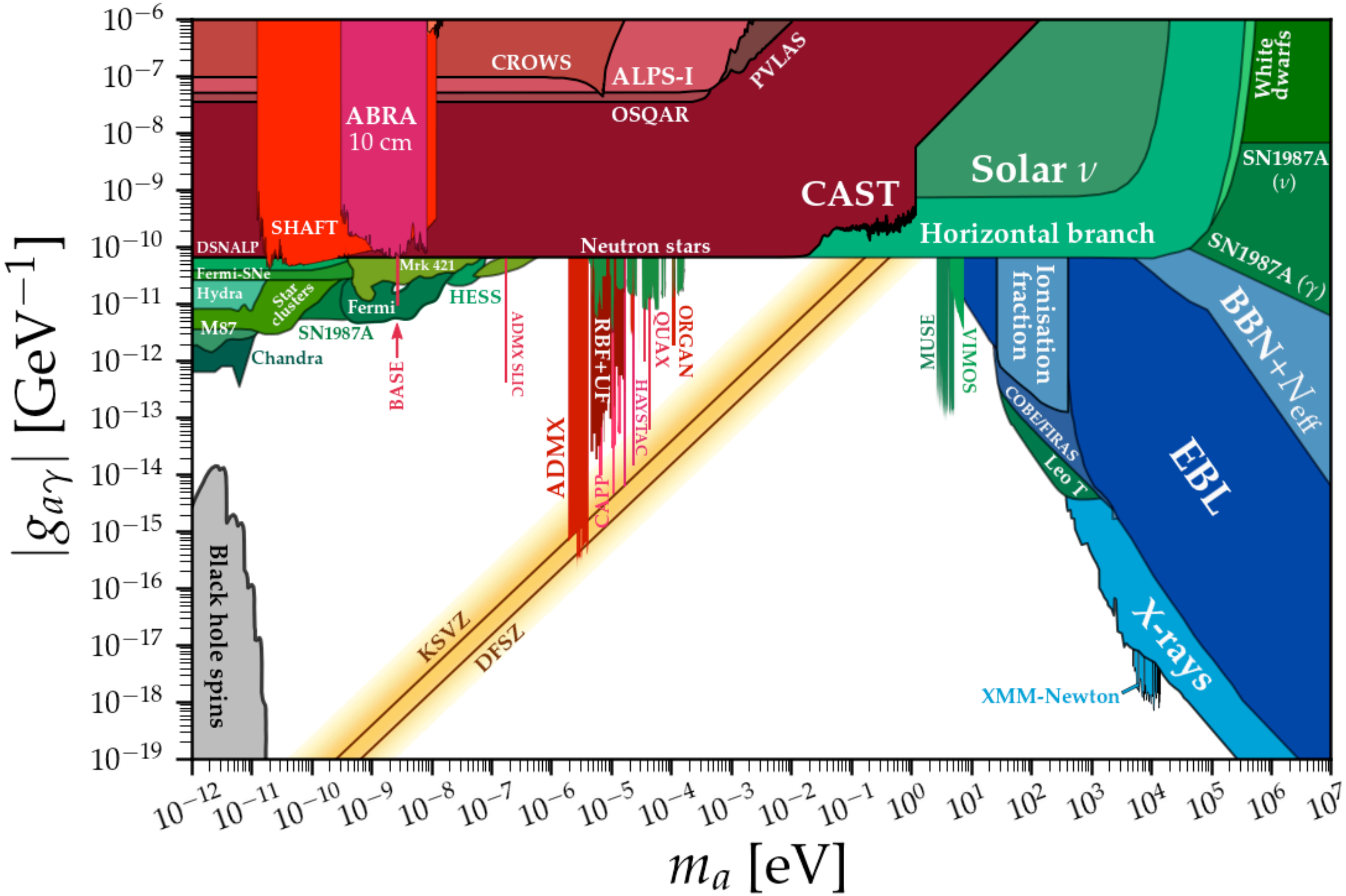
- Mass range of interest – 60-200 micro-eV
- Motivations:
    - SMASH model
    - Josephson Junction results

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



CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
CAST
Solar ν
White dwarfs
SN1987A (ν)
Horizontal branch
SHAFT
DSNALP
Neutron stars
SN1987A (γ)
Mrk 421
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
BBN+N_eff
COBE/FIRAS
Leo T
EBL
X-rays
XMM-Newton
Black hole spins
KSVZ
DFSZ
|g_aγ| [GeV^-1]
m_a [eV]

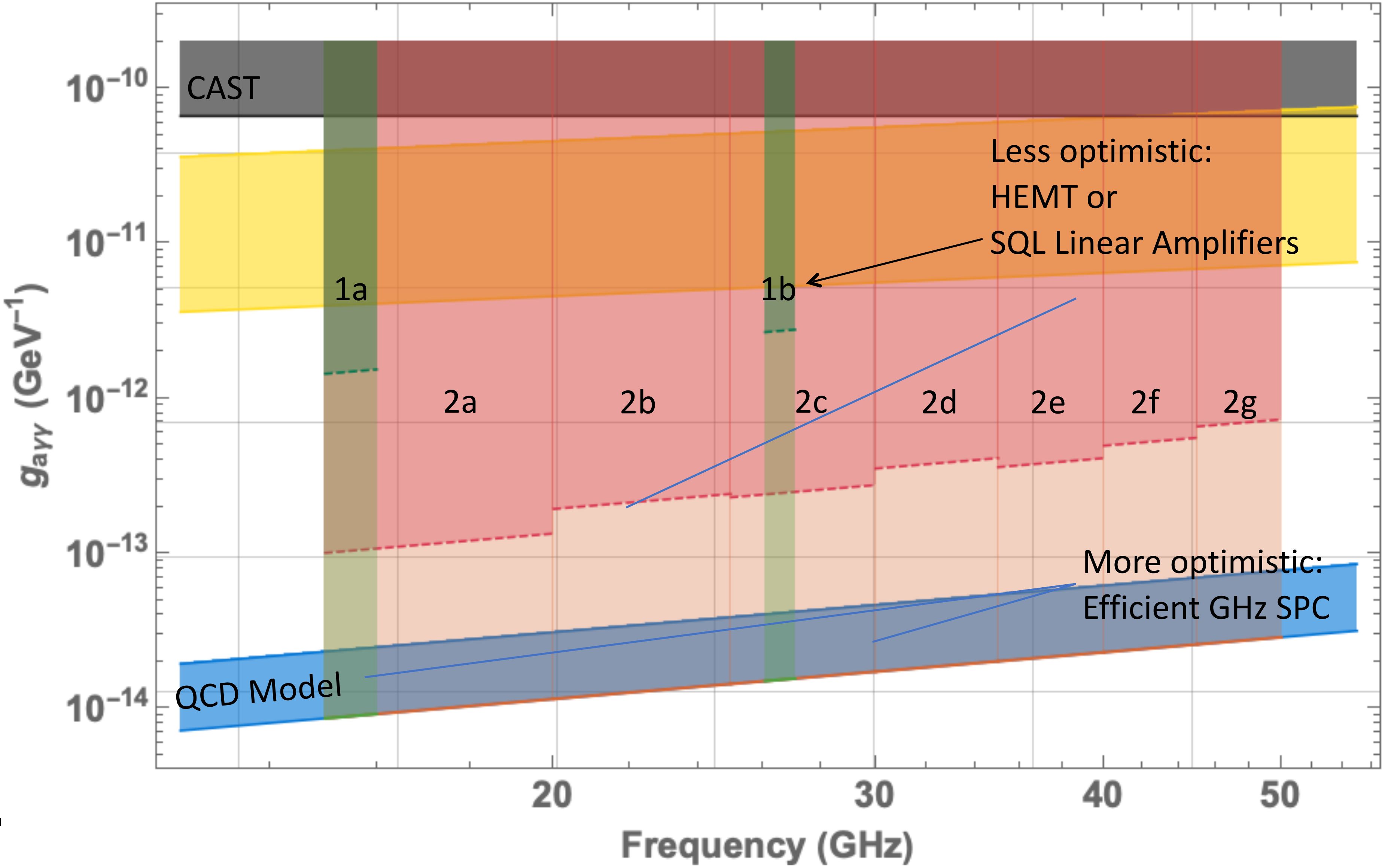
ORGAN Introduction

- Mass range of interest – 60-200 micro-eV
- Motivations:
  - SMASH model
  - Josephson Junction results
  - High mass range relatively unexplored
- 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

Run Plan

Phase 1:
Existing Haloscope Technology
Current Standard Designs

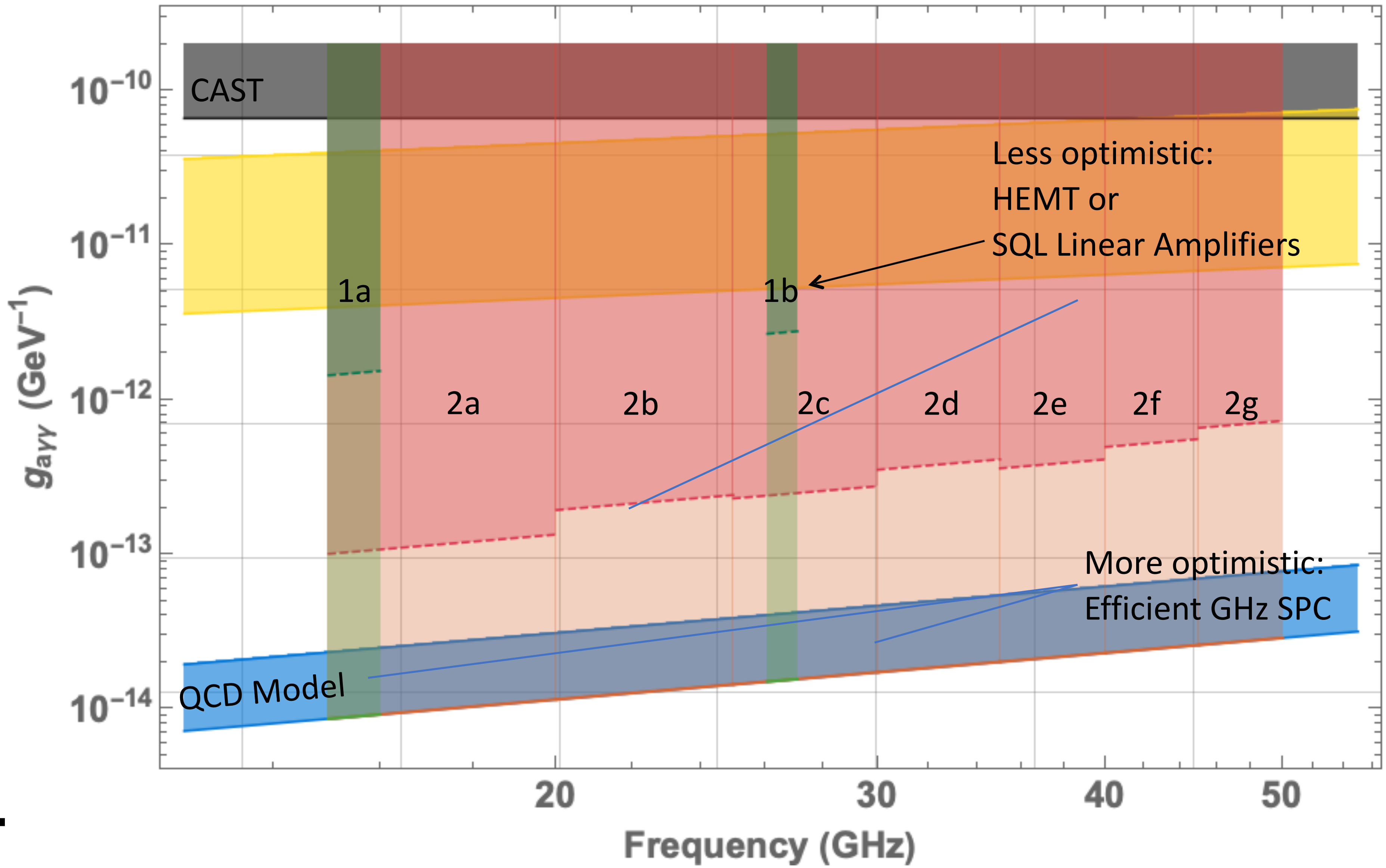
Phase 2:
Novel Resonators
Better Qs
Better Amplifiers/Readout



Run Plan

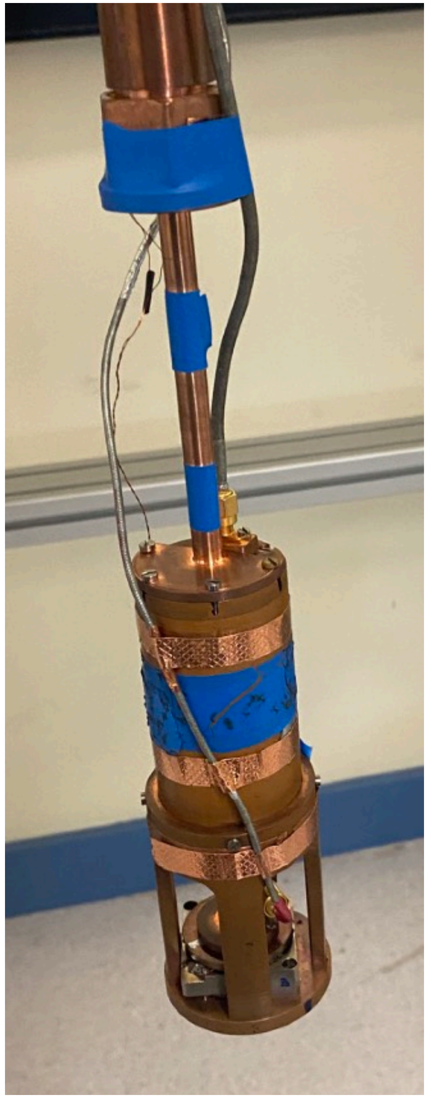
Phase 1:
Existing Haloscope Technology
Current Standard Designs

Phase 2:
Novel Resonators
Better Qs
Better Amplifiers/Readout

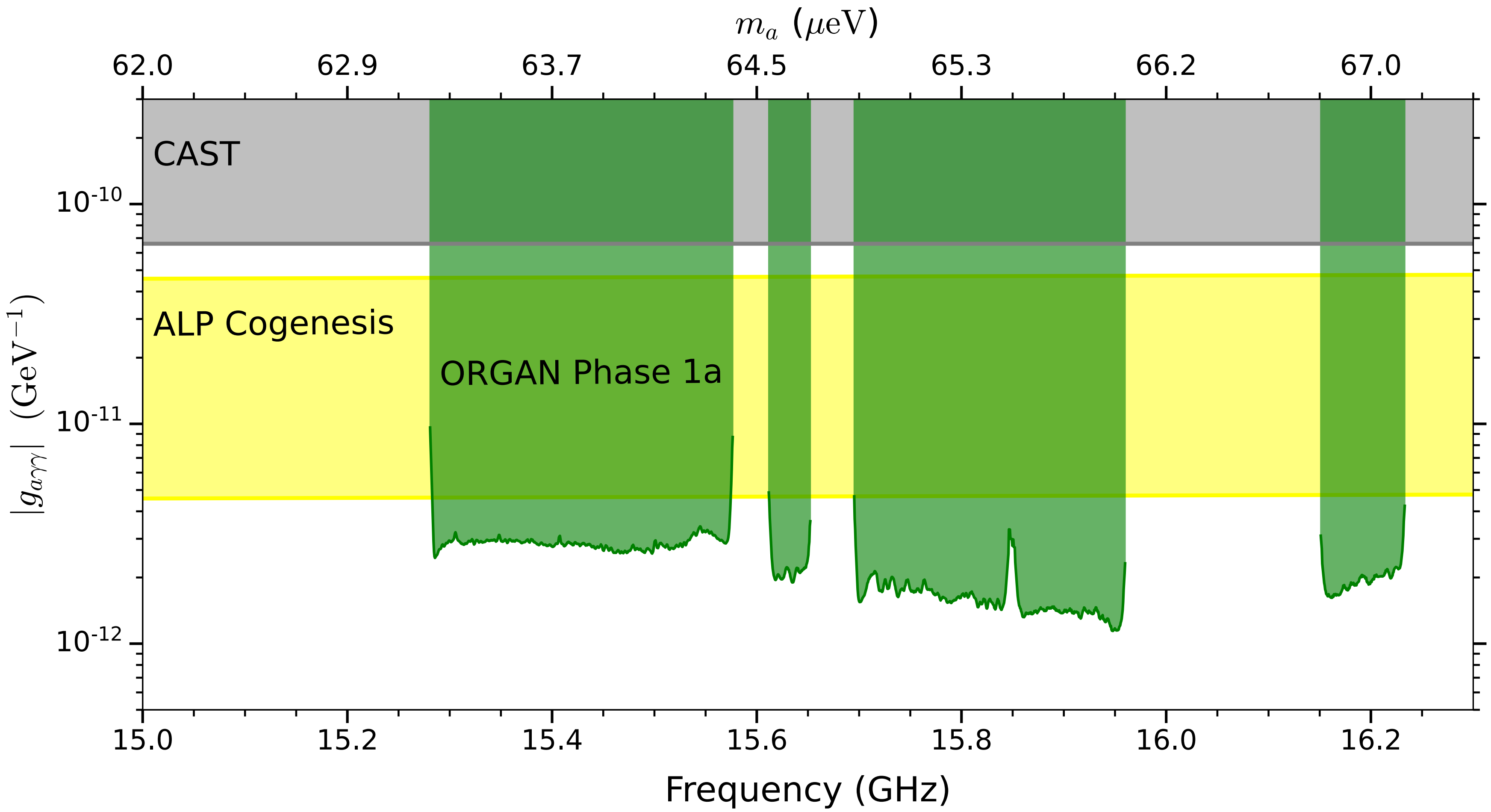


Phase 1

- Targeted scans around 15 GHz and 26 GHz
- Commenced in 2021, completed 2023
- Traditional, ADMX-like haloscope technology
- HEMT amplifiers



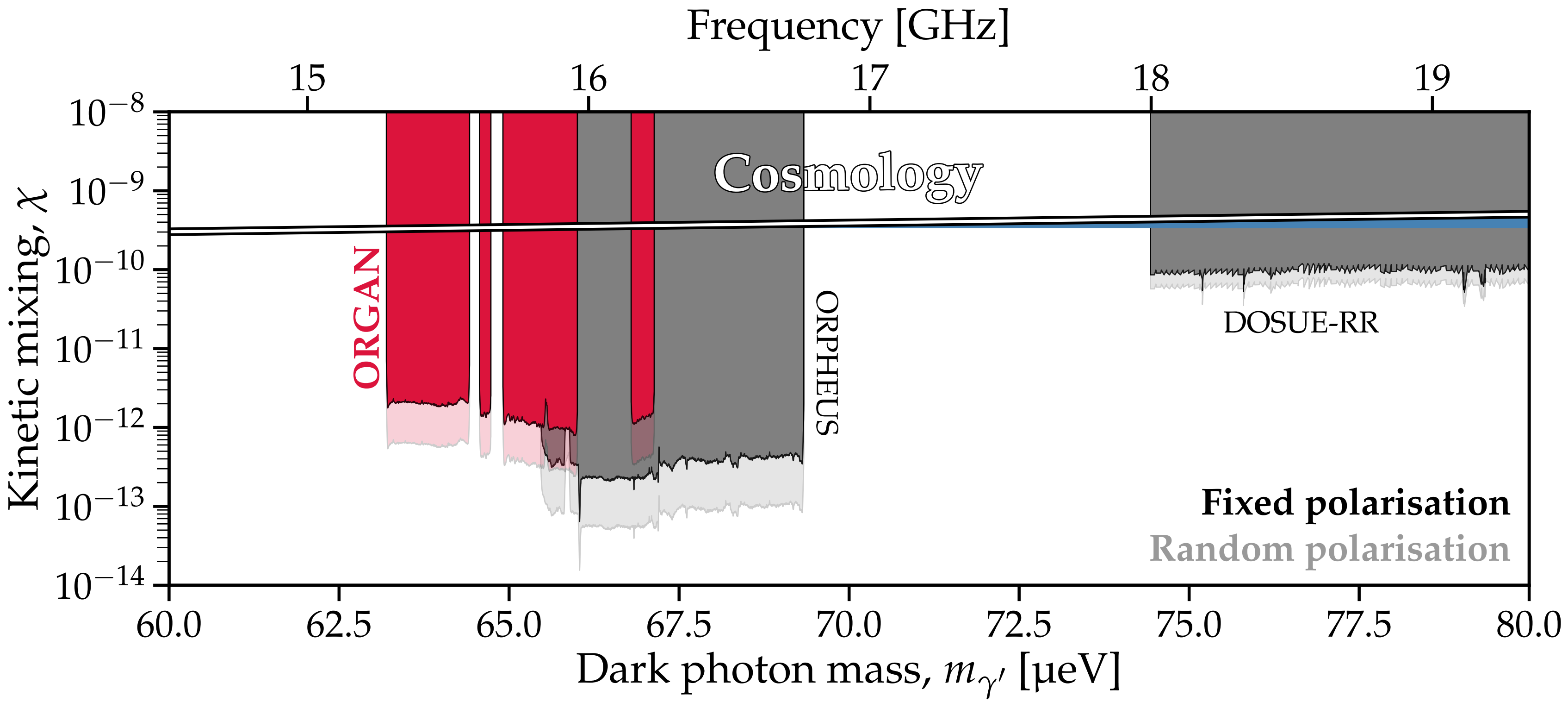
Phase 1a



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

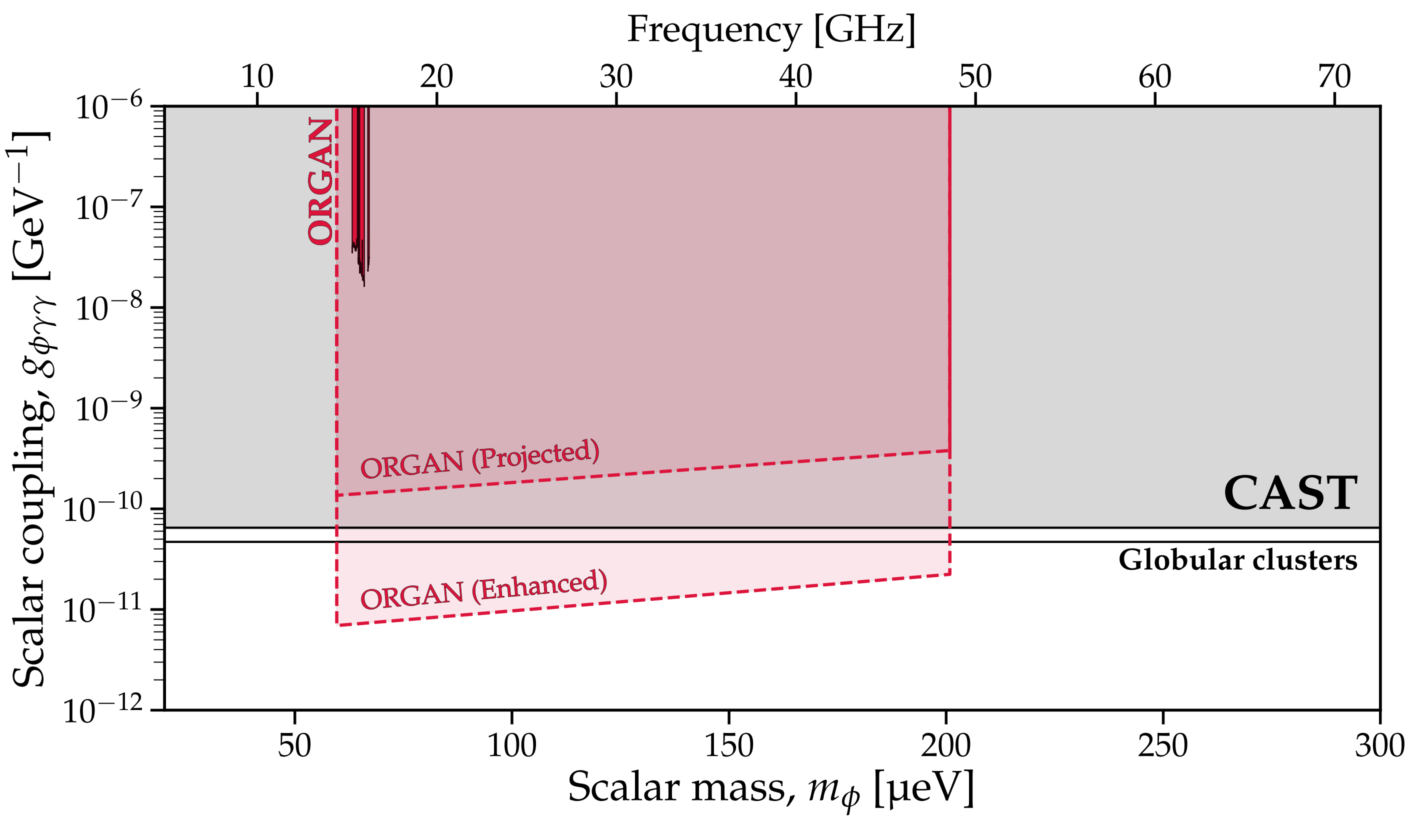
- Also limits on dark photons and scalar dark matter



https://arxiv.org/abs/2212.01971

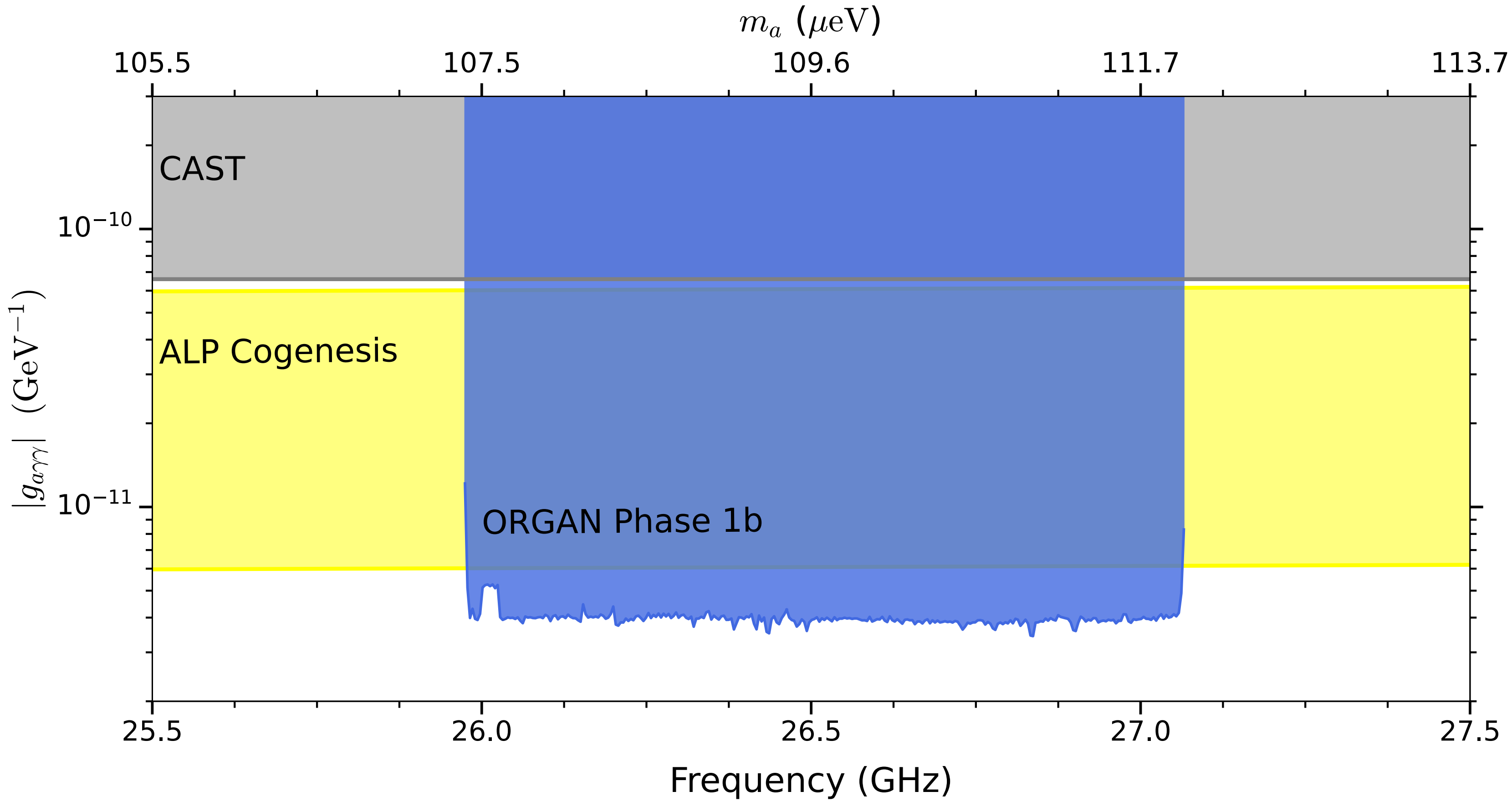
Phase 1a

- Also limits on dark photons and scalar dark matter



https://arxiv.org/abs/2212.01971

Phase 1b

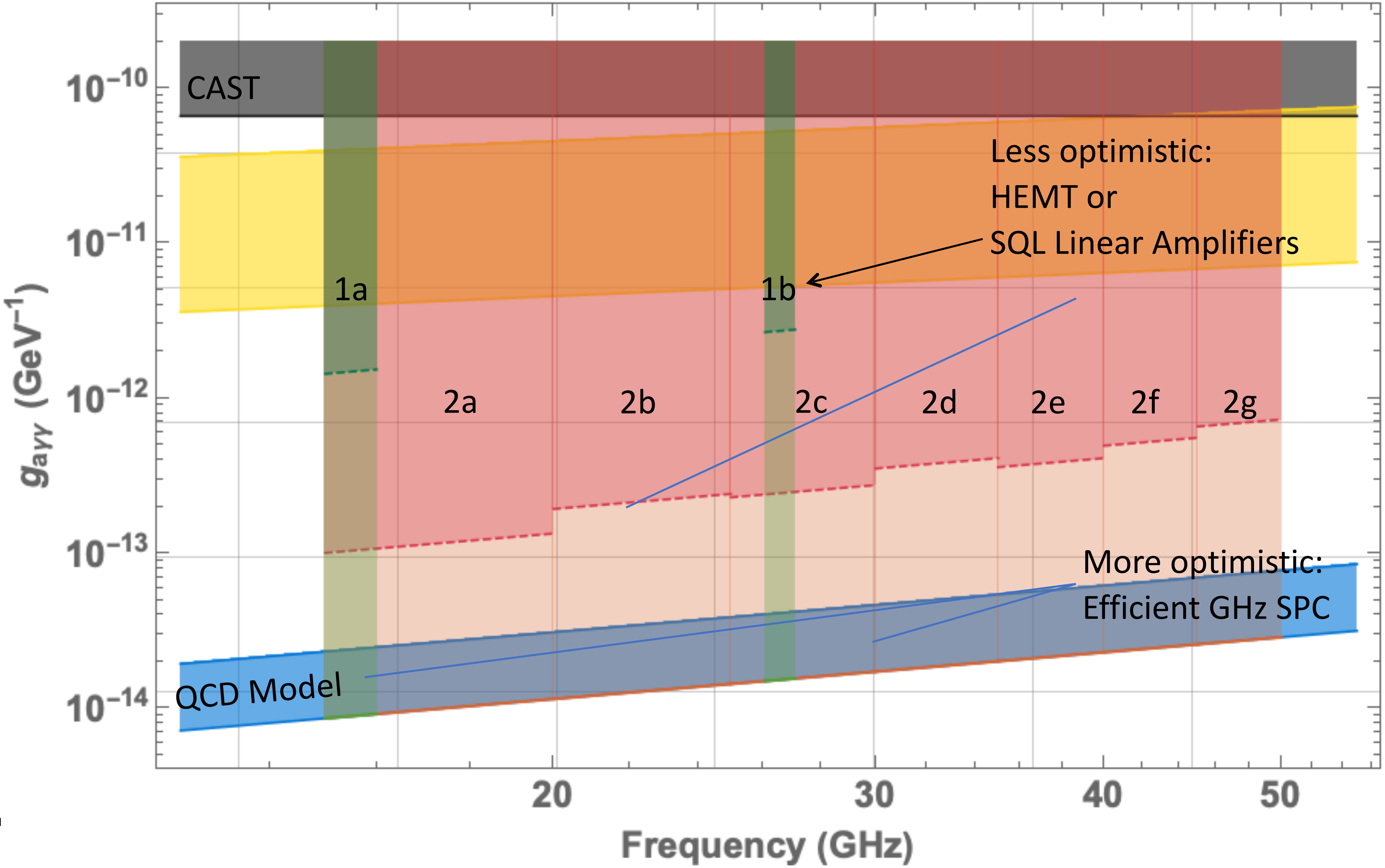


m_a (μeV)
105.5
107.5
109.6
111.7
113.7
CAST
ALP Cogenesis
ORGAN Phase 1b
10^{-10}
10^{-11}
$|g_{a\gamma\gamma}|$ (GeV^{-1})
25.5
26.0
26.5
27.0
27.5
Frequency (GHz)

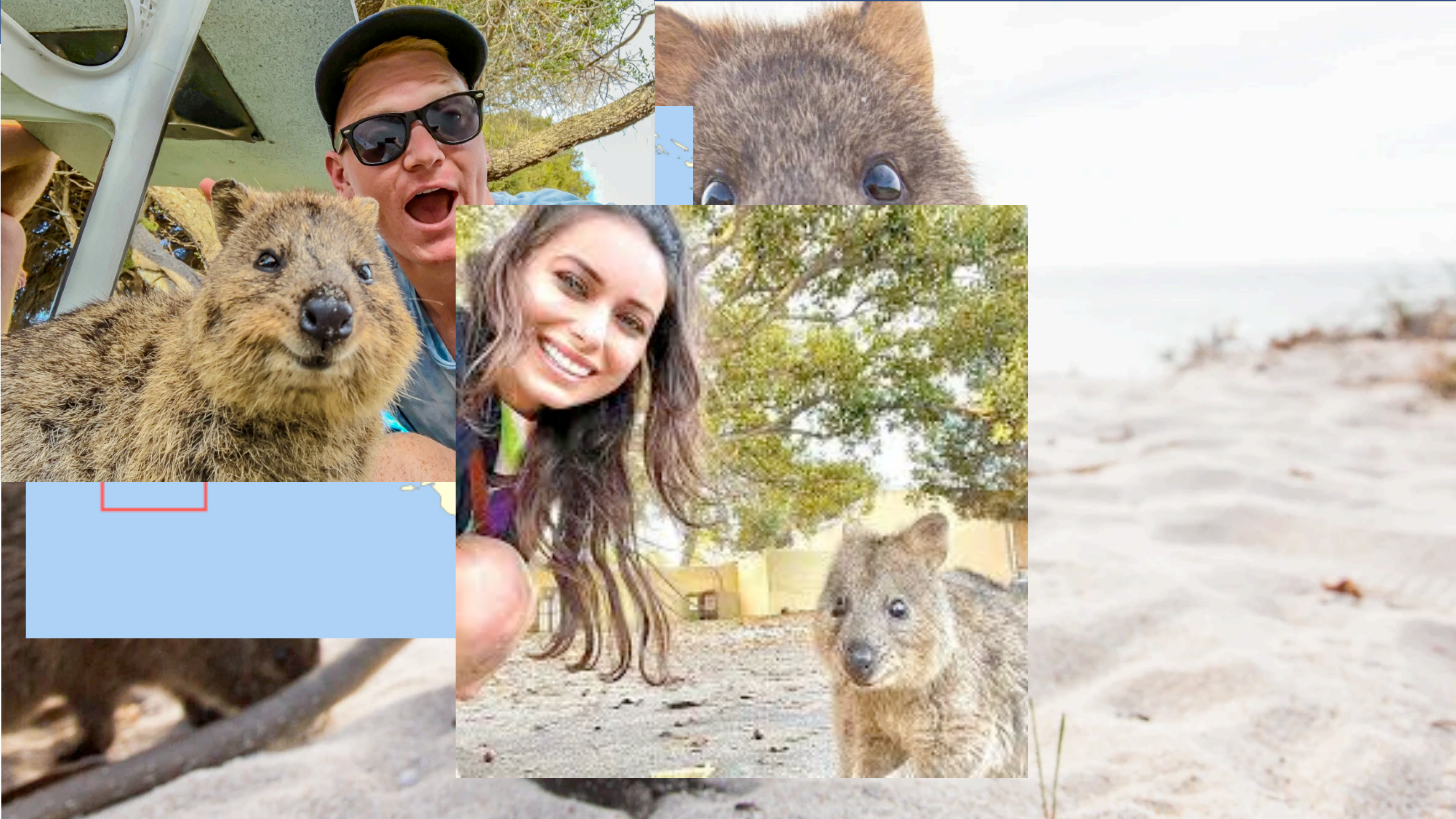
Run Plan

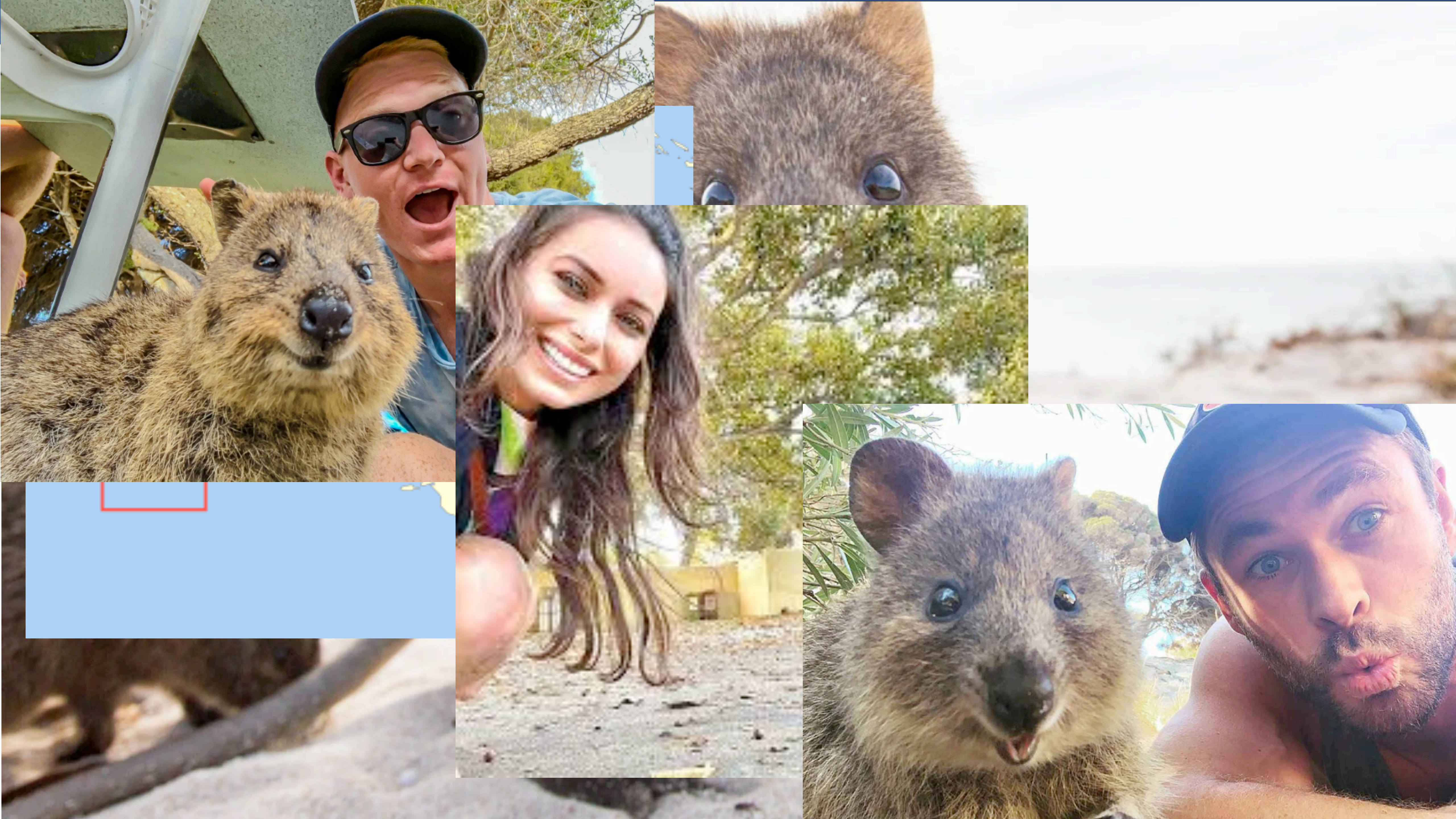
Phase 1:
Existing Haloscope Technology
Current Standard Designs

Phase 2:
Novel Resonators
Better Qs
Better Amplifiers/Readout




ADAMS





Future Haloscopes

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

- Things to do with readout, refrigeration system, magnet
- Things to do with resonant cavity

Future Haloscopes

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

- Things to do with readout, refrigeration system, magnet
- Things to do with resonant cavity
- Attack these things wherever possible

Future Haloscopes

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

- Things to do with readout, refrigeration system, magnet
- Things to do with resonant cavity
- Attack these things wherever possible
- Even harder at higher frequencies for a few reasons…

Future Haloscopes - Resonators

- Lots of idea for new types of resonator beyond standard TM010 tuning rod resonators

Future Haloscopes - Resonators

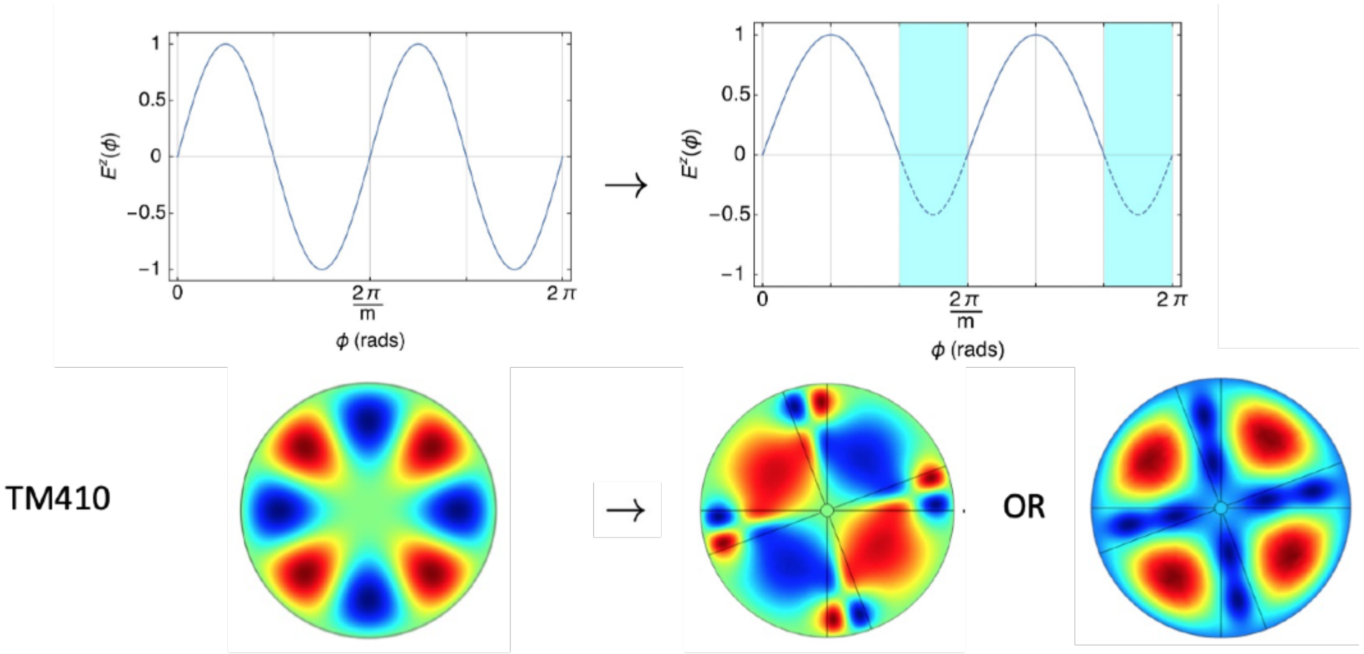
- Lots of idea for new types of resonator beyond standard TM010 tuning rod resonators
- Keep C high, go to higher frequencies, be tunable

Future Haloscopes - Resonators

- Lots of idea for new types of resonator beyond standard TM010 tuning rod resonators
- Keep C high, go to higher frequencies, be tunable
- Use dielectrics, new geometries, combine many resonators
- Ongoing field of research

Future Haloscopes - Resonators

- Lots of idea for new types of resonator beyond standard TM010 tuning rod resonators
- Keep C high, go to higher frequencies, be tunable
- Use dielectrics, new geometries, combine many resonators
- Ongoing field of research

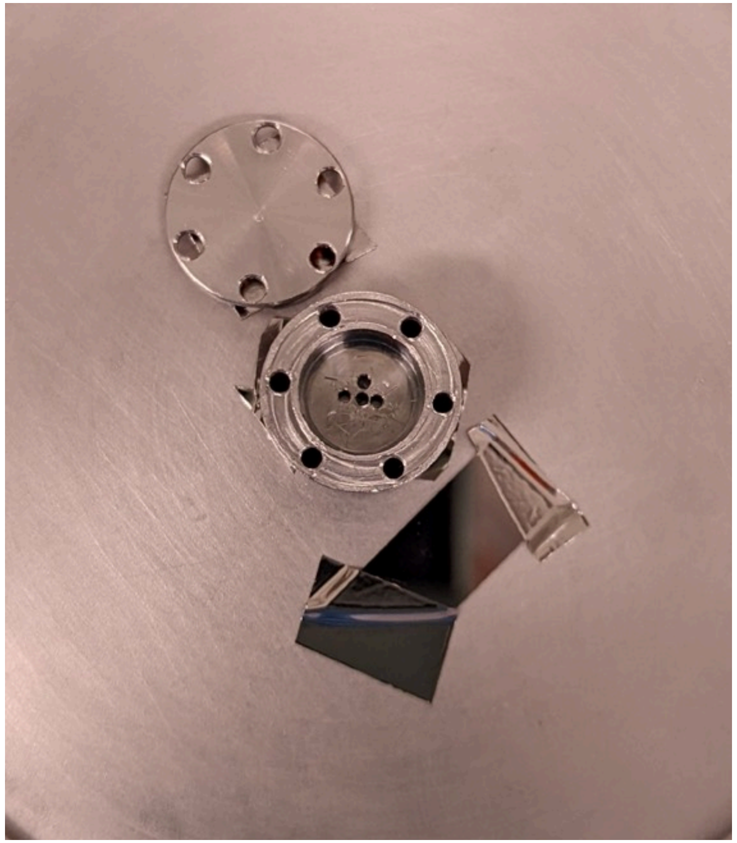


Future Haloscopes - Superconductors

- Can coat cavities with Type-II superconductor

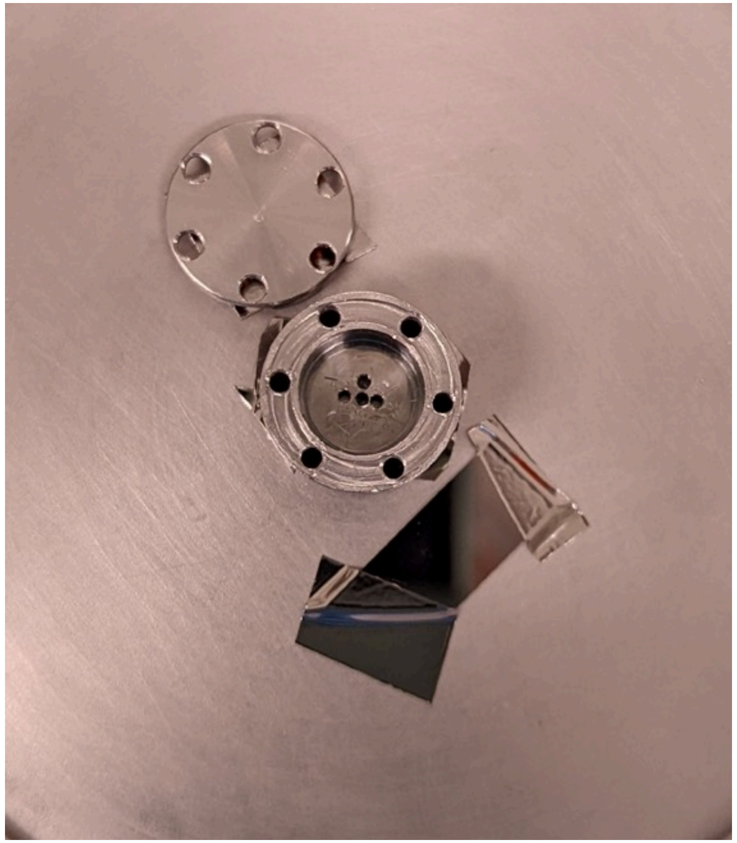
Future Haloscopes - Superconductors

- Can coat cavities with Type-II superconductor
- e.g. Nb3Sn, NbTi
- Allows for higher Q values than bare copper



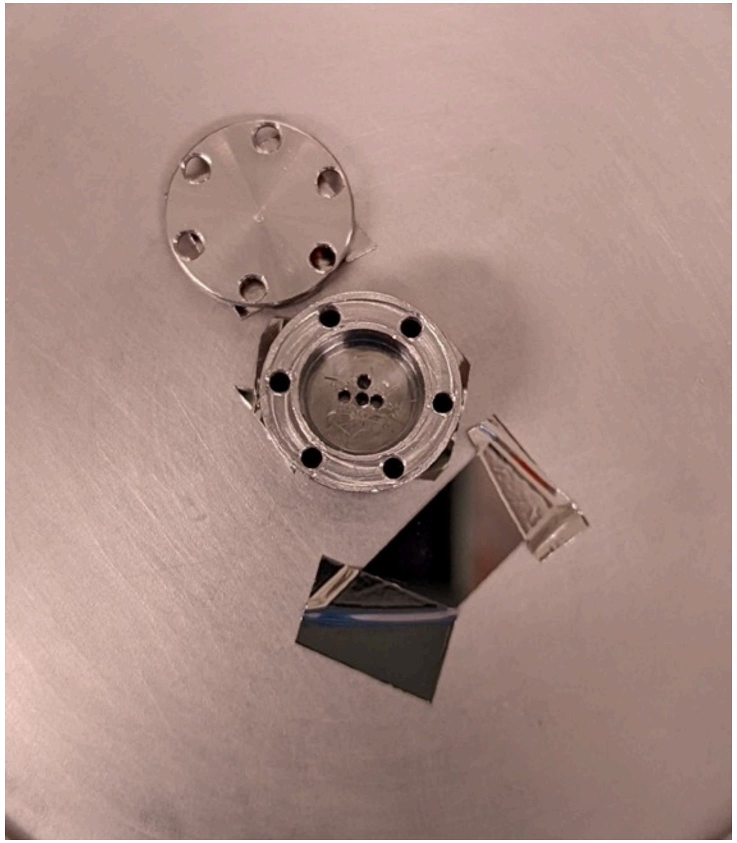
Future Haloscopes - Superconductors

- Can coat cavities with Type-II superconductor
- e.g. Nb_3Sn, NbTi
- Allows for higher Q values than bare copper
- Ongoing R&D to implement



Future Haloscopes - Superconductors

- Can coat cavities with Type-II superconductor
- e.g. Nb3Sn, NbTi
- Allows for higher Q values than bare copper
- Ongoing R&D to implement
- Another option - ReBCO tapes, some success in this area recently



Future Haloscopes - Readout

- Single Photon Detection is superior to SQL linear amplification under the right conditions

Future Haloscopes - Readout

- Single Photon Detection is superior to SQL linear amplification under the right conditions
- Take ORGAN as an example
  - 100 mK
  - 15 GHz
  - SQL Noise ~ 1K
- Ratio of SQL linear amp to SPD noise power:

Future Haloscopes - Readout

- Single Photon Detection is superior to SQL linear amplification under the right conditions
- Take ORGAN as an example
  - 100 mK
  - 15 GHz
  - SQL Noise ~ 1K
- Ratio of SQL linear amp to SPD noise power:

$$\frac{P_\ell}{P_{sp}} = \frac{\bar{n}+1}{\sqrt{\bar{n}}}\sqrt{\frac{\Delta\nu_a}{\eta\Gamma}}$$

Future Haloscopes - Readout

- Single Photon Detection is superior to SQL linear amplification under the right conditions
- Take ORGAN as an example
  - 100 mK
  - 15 GHz
  - SQL Noise ~ 1K
- Ratio of SQL linear amp to SPD noise power:

$$\frac{P_\ell}{P_{sp}} = \frac{\bar{n}+1}{\sqrt{\bar{n}}}\sqrt{\frac{\Delta\nu_a}{\eta\Gamma}}$$

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

Future Haloscopes - Readout

- Single Photon Detection is superior to SQL linear amplification under the right conditions
- Take ORGAN as an example
  - 100 mK
  - 15 GHz
  - SQL Noise ~ 1K
- Ratio of SQL linear amp to SPD noise power:

$$\frac{P_\ell}{P_{sp}} = \frac{\bar{n}+1}{\sqrt{\bar{n}}}\sqrt{\frac{\Delta\nu_a}{\eta\Gamma}}$$

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

Future Haloscopes - Readout

- Single Photon Detection is superior to SQL linear amplification under the right conditions
- Take ORGAN as an example
  - 100 mK
  - 15 GHz
  - SQL Noise ~ 1K
- Ratio of SQL linear amp to SPD noise power:

$$\frac{P_\ell}{P_{sp}} = \frac{\bar{n}+1}{\sqrt{\bar{n}}}\sqrt{\frac{\Delta\nu_a}{\eta\Gamma}}$$

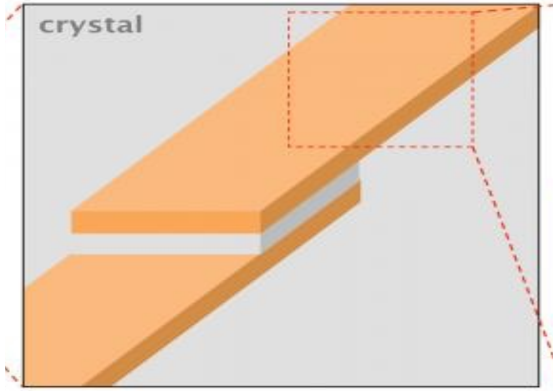
- This ratio can be tens or even thousands of times depending on the specifics
- Not a lot of options for GHz SPCs...but a few!
- SIS Josephson Junctions, SNSPDs, MKIDs...

SIS Josephson Junctions

- Layer of superconductor – insulator – superconductor

SIS Josephson Junctions

- Layer of superconductor – insulator – superconductor

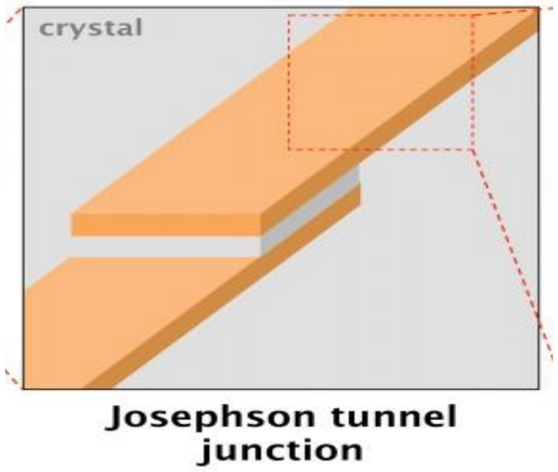


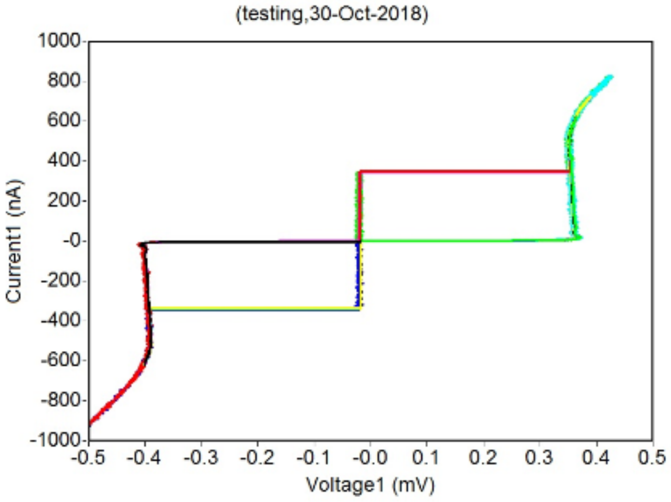
Josephson tunnel junction

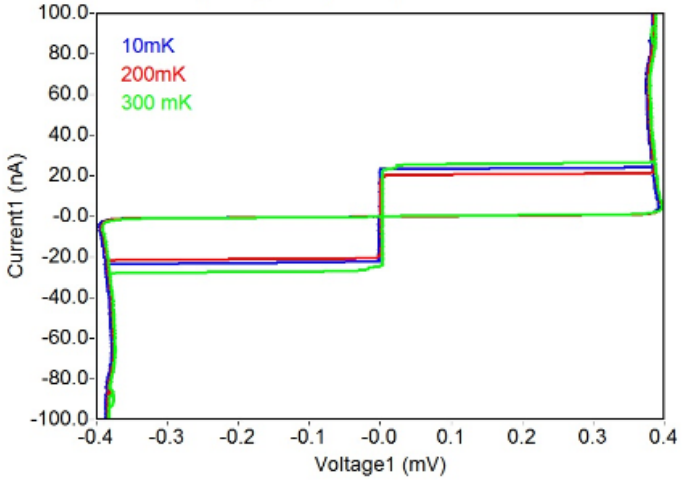
L. S. Kuzmin et al., IEEE Transactions on Applied Superconductivity, 2018

SIS Josephson Junctions

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



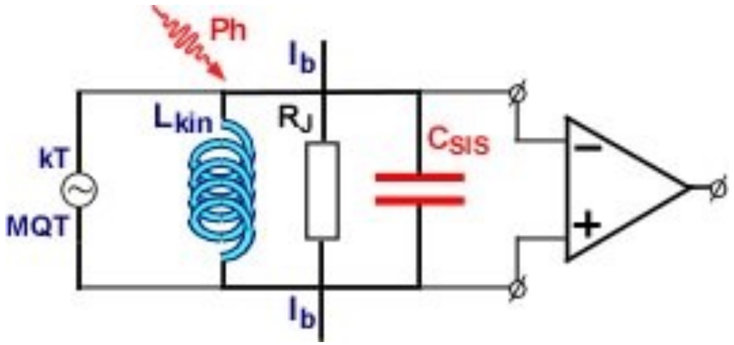




L. S. Kuzmin et al., IEEE Transactions on Applied Superconductivity, 2018

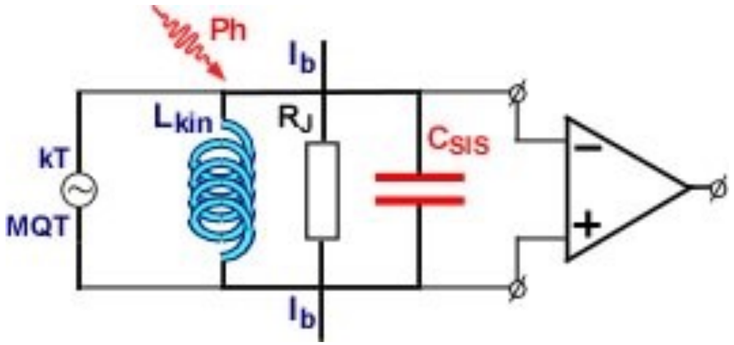
SIS Josephson Junctions

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



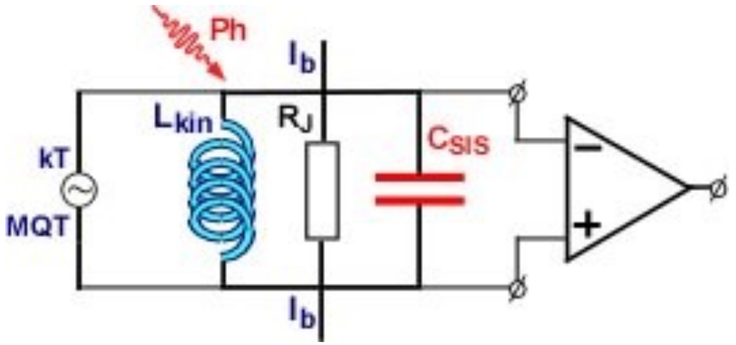
SIS Josephson Junctions

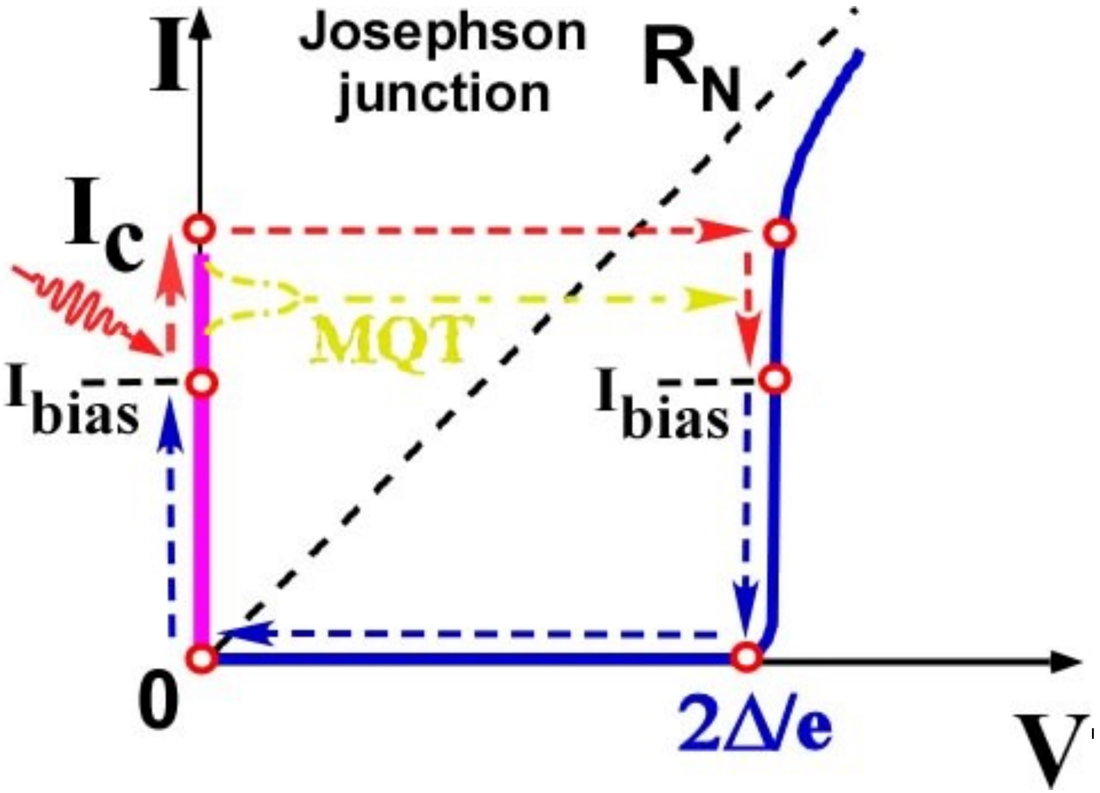
- Can be used as weak current sensor in the GHz range...in principle
- 10s of μeV+ energy thresholds
- Gets easier at higher energy…



SIS Josephson Junctions

- 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

- Samples under testing both for ORGAN and other haloscopes (QUAX, etc)

Conclusions

- Axions are cool particles (and good DM candidates)
- There are a variety of ways to search for them
- Most focus on axion-photon coupling
- Haloscopes are an increasingly common experiment
- Lots of room for innovation!
- ADMX and ORGAN are two such experiments in different mass ranges
- Future haloscopes will require new instrumentation and technology
- Quantum technology is a common area of pursuit for haloscope searches

Conclusions

- Axions are cool particles (and good DM candidates)
- There are a variety of ways to search for them
- Most focus on axion-photon coupling
- Haloscopes are an increasingly common experiment
- Lots of room for innovation!
- ADMX and ORGAN are two such experiments in different mass ranges
- Future haloscopes will require new instrumentation and technology
- Quantum technology is a common area of pursuit for haloscope searches