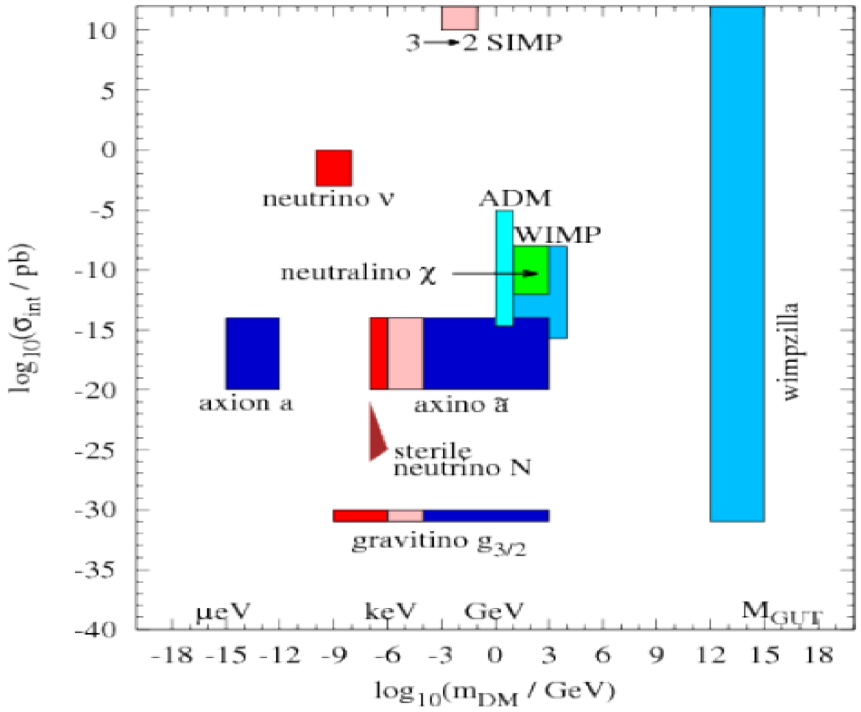

Axion Dark Matter

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2021-02-18

Outline

- ☐ CP Problem || PQ Symmetry || Axion Field
- ☐ Thermal and Non-thermal axion generation
- ☐ Axion Dark Matter experiments: ADMX (a bit on ABRACADABRA and TOORAD)
- ☐ Observational signatures of Axion Dark Matter
  - ☐ Radio conversion in galactic magnetic fields
  - ☐ Radio conversion in magnetospheres of a neutron star
  - ☐ Radio signatures from neutron star encounters with QCD axion miniclusters

PQ Problem

- 1975, U(1) Problem, Steven Weinberg: U(2)$_A$ symmetry observed, but U(1)$_A$ is not a symmetry of the QCD lagrangian (problems with decay rate of η mesons)
- 1976, ‘t Hooft: QCD vacuum is non-trivial, and hence U(1)$_A$ is not a symmetry of the QCD lagrangian
- Lack of U(1)$_A$ symmetry introduces CP violating terms in QCD
- CP violation not observed in QCD
- CP violating term, $\bar{\theta} \in [-\pi, \pi]$ (parameter), any value of $\bar{\theta}$ is equally likely

$$L_{Strong\ CP} = -\bar{\theta}\,\frac{\alpha_s}{8\pi}\,G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$

- electric dipole moment of neutron $\Rightarrow \bar{\theta} \cong 10^{-10}$ [fine tuning problem]

This is called the Strong CP problem!

PQ symmetry

- 1977, Roberto Peccei and Helen Quinn: dynamical solution to the Strong CP problem
- Introduce global U(1)$_{PQ}$ symmetry, called the Peccei-Quinn (PQ) symmetry
- Promote $\bar{\theta}$ to a dynamical field, this field is the axion field
- U(1)$_{PQ}$ is spontaneously broken, and $\bar{\theta}$ is driven to values close to 0
- SSB introduces pseudo Nambu-Goldstone boson, which is our axion (or QCD axion)
- QCD axion is massless above QCD phase transition temperature (~200 MeV)
- As of now, QCD axion has a tiny mass

$$L_{Strong\ CP} = \left(\frac{\phi_a}{f_a} - \bar{\theta}\right)\frac{\alpha_s}{8\pi} G^{\mu\nu a}\tilde{G}^{a}_{\mu\nu}$$

field ϕ_a goes under SSB, takes the value $\bar{\theta} f_a$ – solves the Strong CP problem! (relate this to Higgs mechanism)

Axion field

- pseudoscalar field, ϕ_a
- interaction lagrangian, $L = f_a^{-1} J^\mu \partial_\mu \phi_a$

where, f_a is the decay constant of the axion

sets interaction strength of the axion pseudoscalar with SM fields

f_{PQ} which is PQ symmetry breaking scale is $\mathcal{O}(f_a)$ [depends on the axion model used]

$$m_a = 5.691 \left(\frac{10^{12}\ GeV}{f_a} \right) \mu eV$$

2 prominent axion models

KSVZ axions

- hadronic axions
- new heavy quarks carry $U(1)_{PQ}$ charge, but no electric charge
- no tree-level coupling of axions to usual baryonic and leptonic matter

DFSZ axions

- requires two Higgs doublet in SM
- normal quarks and leptons carry $U(1)_{PQ}$ charge
- QCD axion couples to SM fermions at tree-level
- postulates axion production from pion and lepton scatterings

Axion interactions

- spin 0, electric charge 0, tiny mass
- Can interact with gravitational force
- Can interact with electromagnetism with a 2 photon interaction

$$L_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu}\phi_a = g_{a\gamma\gamma}\left(\vec{E}\cdot\vec{B}\right)\phi_a$$

$L_{a\gamma\gamma}$ should be invariant under CP transformation (that's why we introduced an axion!)

$$\left(\vec{E}\cdot\vec{B}\right)\phi_a \overset{C}{\rightarrow} \left(-\vec{E}\cdot\vec{B}\right)\phi_a \overset{P}{\rightarrow} \left(-\left(-\vec{E}\right)\cdot\vec{B}\right)P(\phi_a) = \left(\vec{E}\cdot\vec{B}\right)P(\phi_a)$$

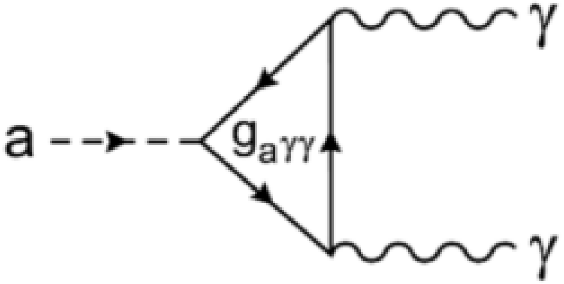
$$\Rightarrow P(\phi_a) = \phi_a$$

Or, ϕ_a is a pseudoscalar field and the associated boson is pseudoscalar

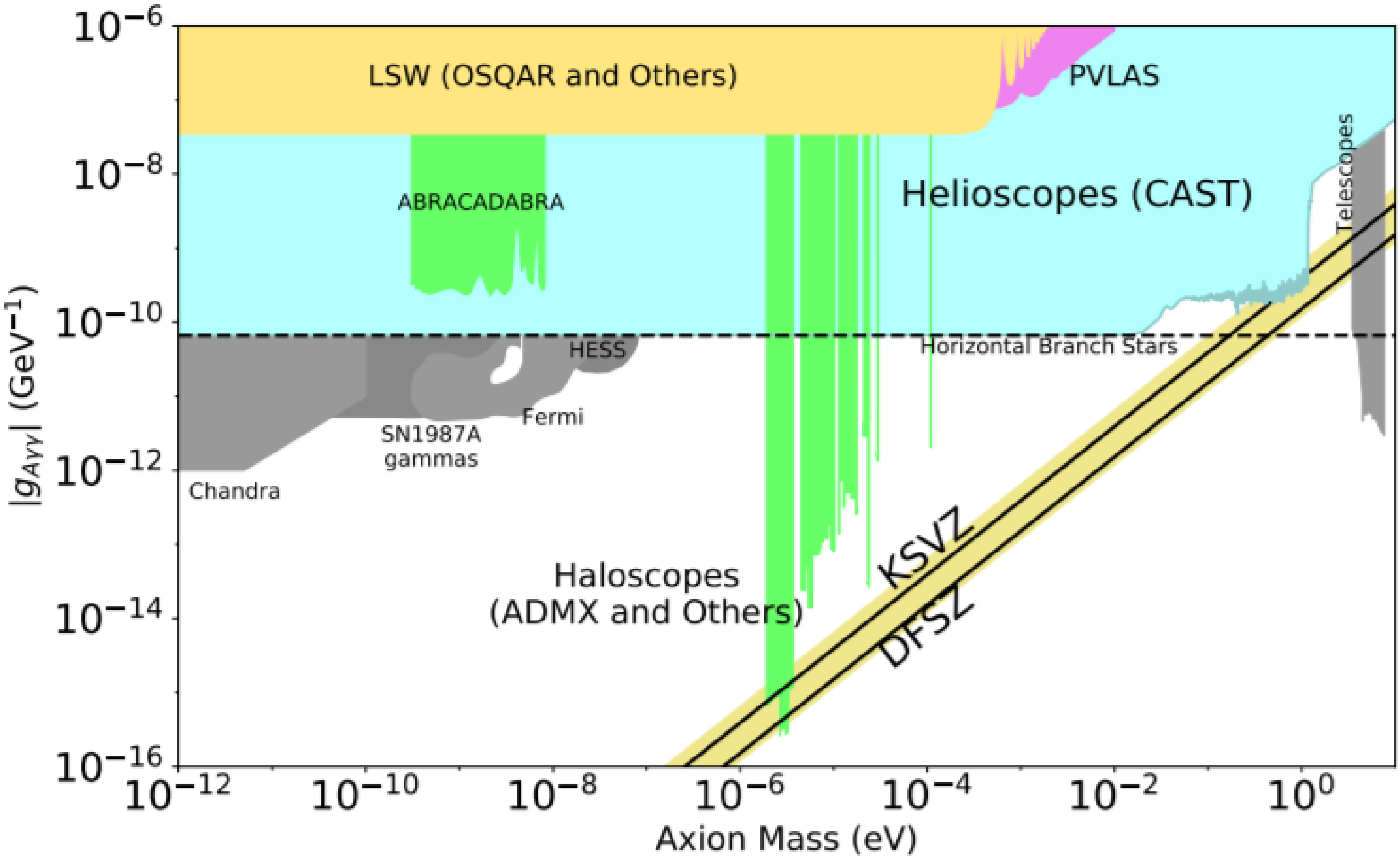
$g_{a\gamma\gamma} = C\, m_a$ (the prefactor, C is some constant depending on the axion model)

Axions thermalized with virial width $\mathcal{O}(10^{-6})$

Decay of DM axions is greatly accelerated with strong magnetic field through inverse Primakoff effect



proves why axion has to be a pseudoscalar particle



Exclusion plot for QCD axion and axion-like-particles as of June 2020

Thermal and non-thermal axion generation

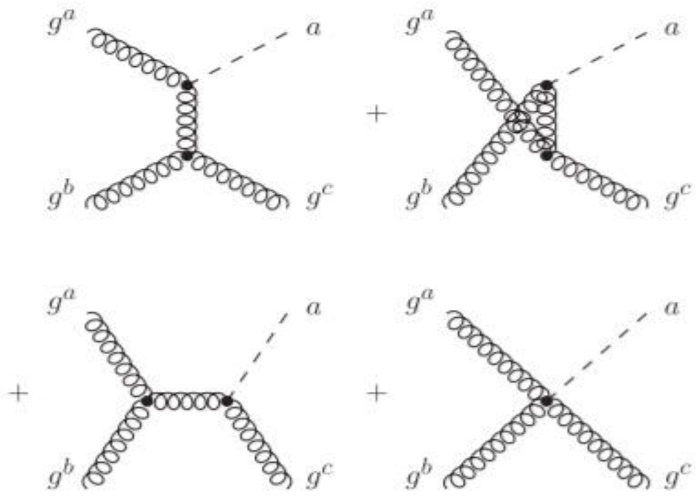
Thermal

- Axion generation in sun by the Primakoff process
- Thermal axion production in the primordial quark-gluon plasma

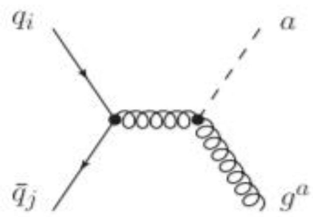
Non-thermal

- With explicit PQ symmetry breaking, string-wall systems become unstable and their late-time collapse produces cold axions
- Puts constraints on axion decay constant $f_a \leq 10^{12}$ GeV

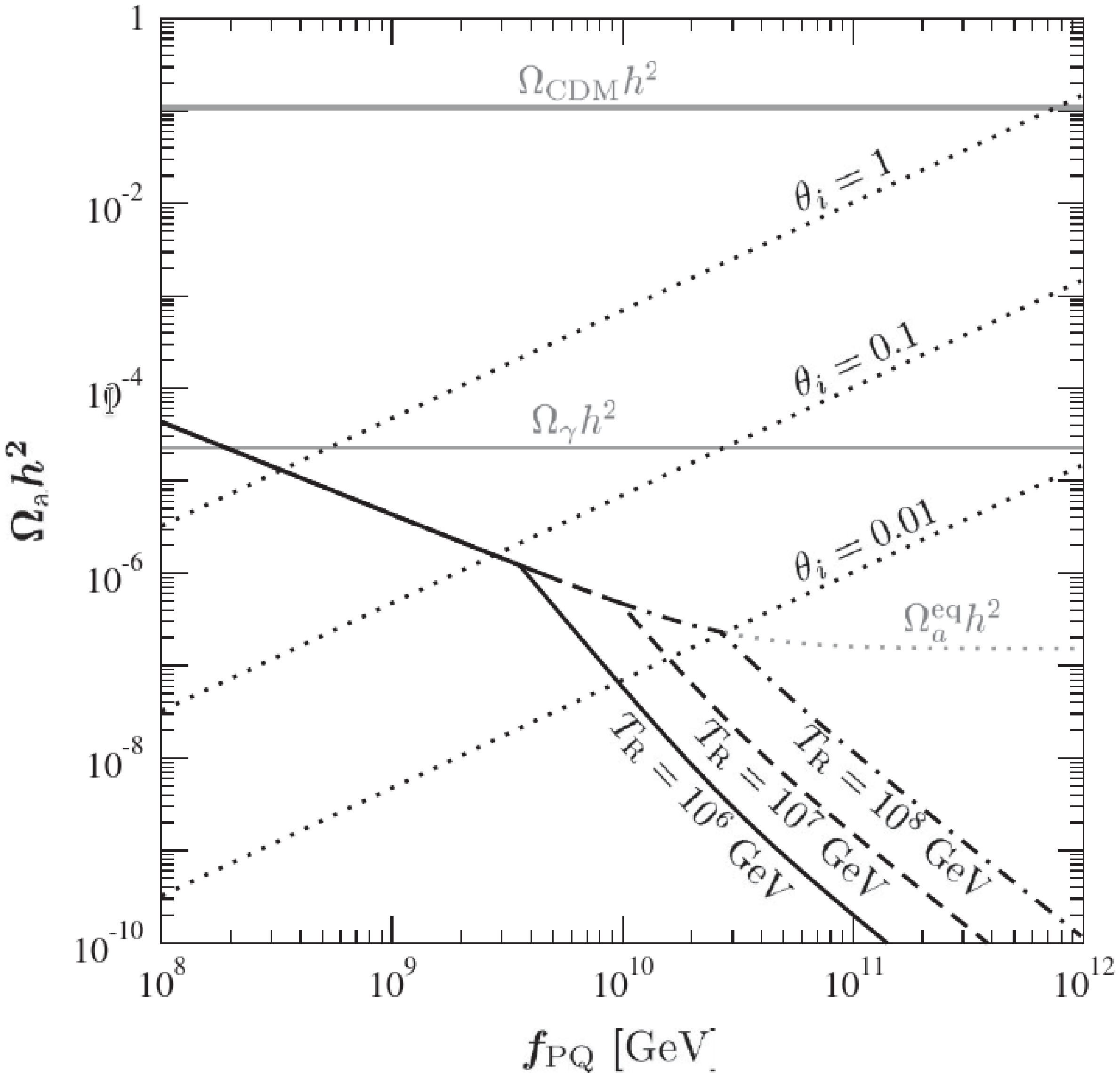
Process A: $g^a + g^b \rightarrow g^c + a$



Process B: $q_i + \bar{q}_j \rightarrow g^a + a$



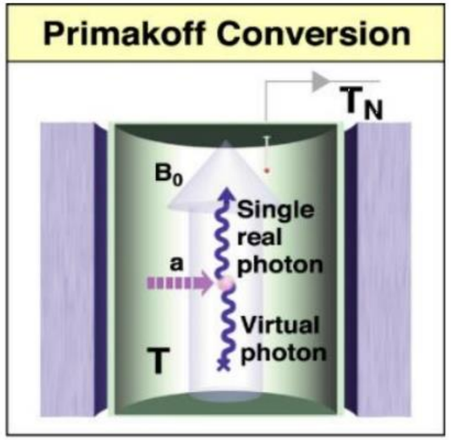
Process C: $q_i + g^a \rightarrow q_j + a$ (crossing of B)

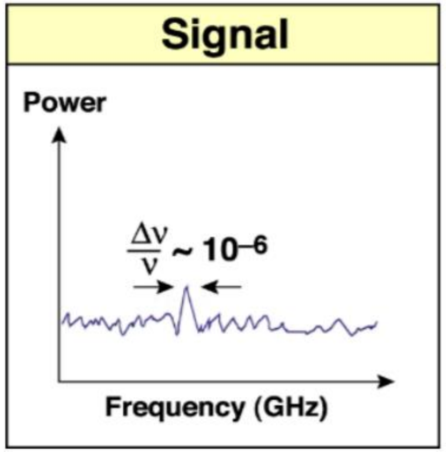


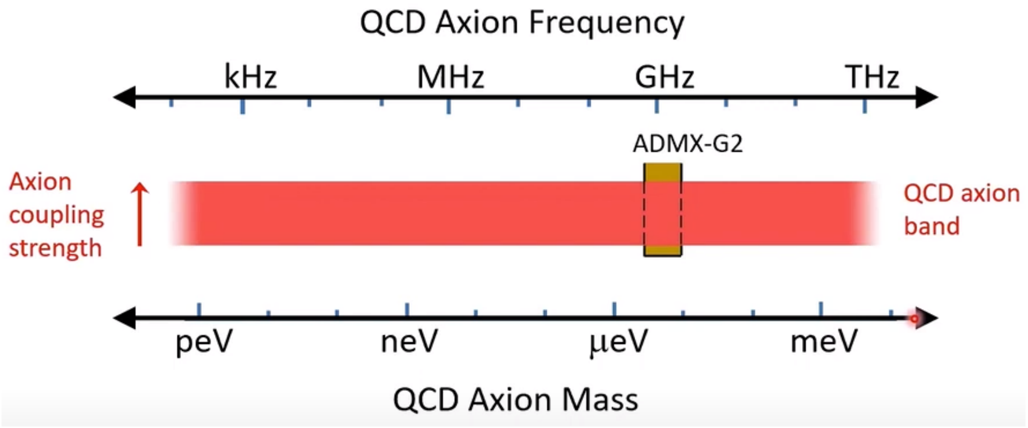
$\Omega_{\mathrm{CDM}} h^2$
$\theta_i = 1$
$\theta_i = 0.1$
$\Omega_\gamma h^2$
$\theta_i = 0.01$
$\Omega_a^{\mathrm{eq}} h^2$
$T_R = 10^6$ GeV
$T_R = 10^7$ GeV
$T_R = 10^8$ GeV
$\Omega_a h^2$
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^8
10^9
10^{10}
10^{11}
10^{12}
f_{PQ} [GeV]

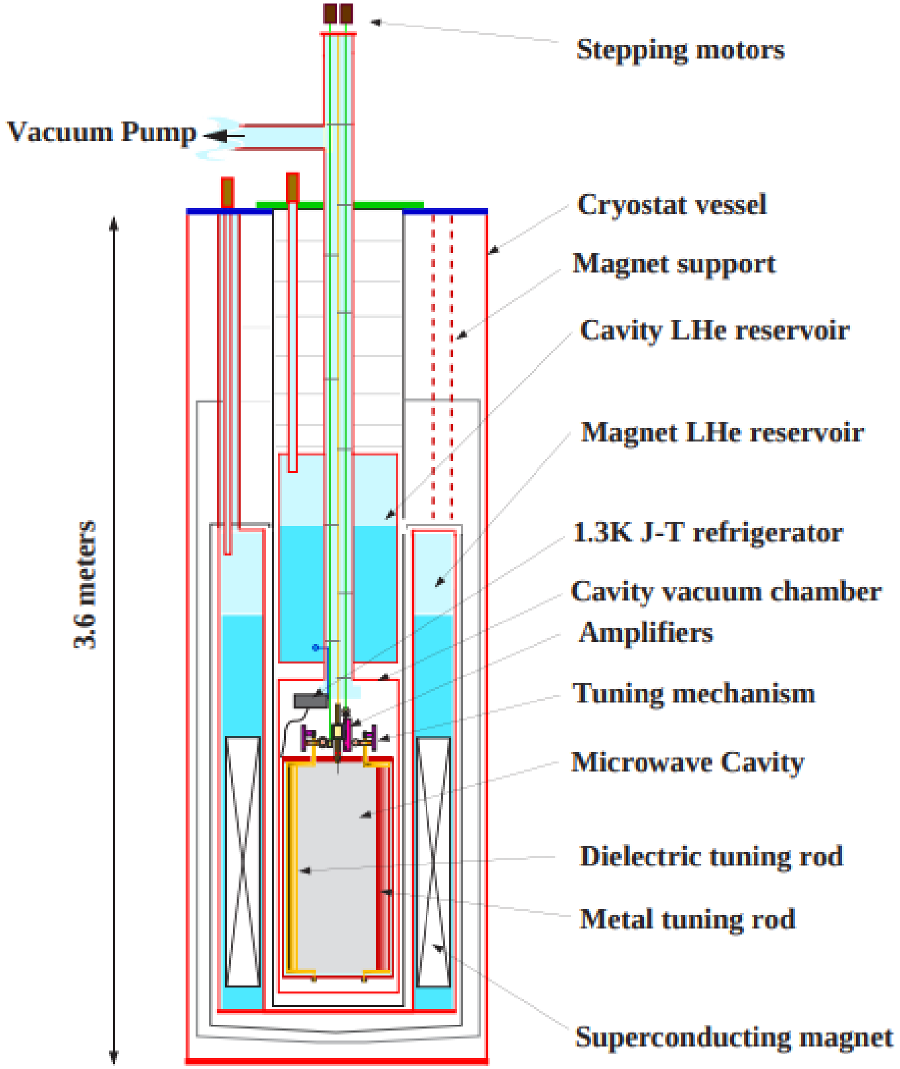
ADMX (Axion Dark Matter eXperiment)

- Largest and most sensitive microwave cavity axion initiative so far
- Axion haloscope [axion search data and noise characterization]
- Located at the University of Washington
- TM_{010} frequency of the cavity is tuned using two copper rods incrementally rotated
- Signal measurement is extracted through an antenna
- Successfully excluding axions with KSVZ coupling in the range 1.9 – 3.7 μeV
- 2 runs, 1A and 1B
- Excluded DFSZ axions at 100% DM density in the range 2.81 – 3.31 μeV



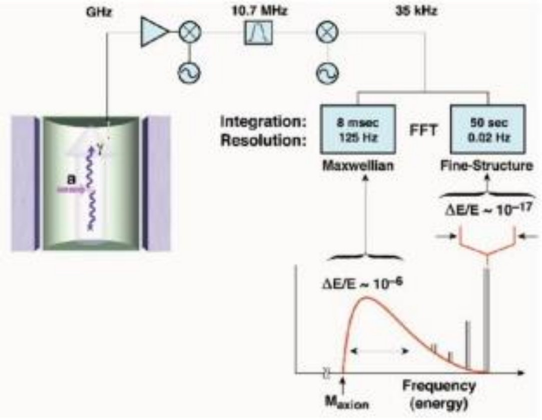



QCD Axion Frequency
kHz
MHz
GHz
THz
ADMX-G2
Axion coupling strength
QCD axion band
peV
neV
μeV
meV
QCD Axion Mass

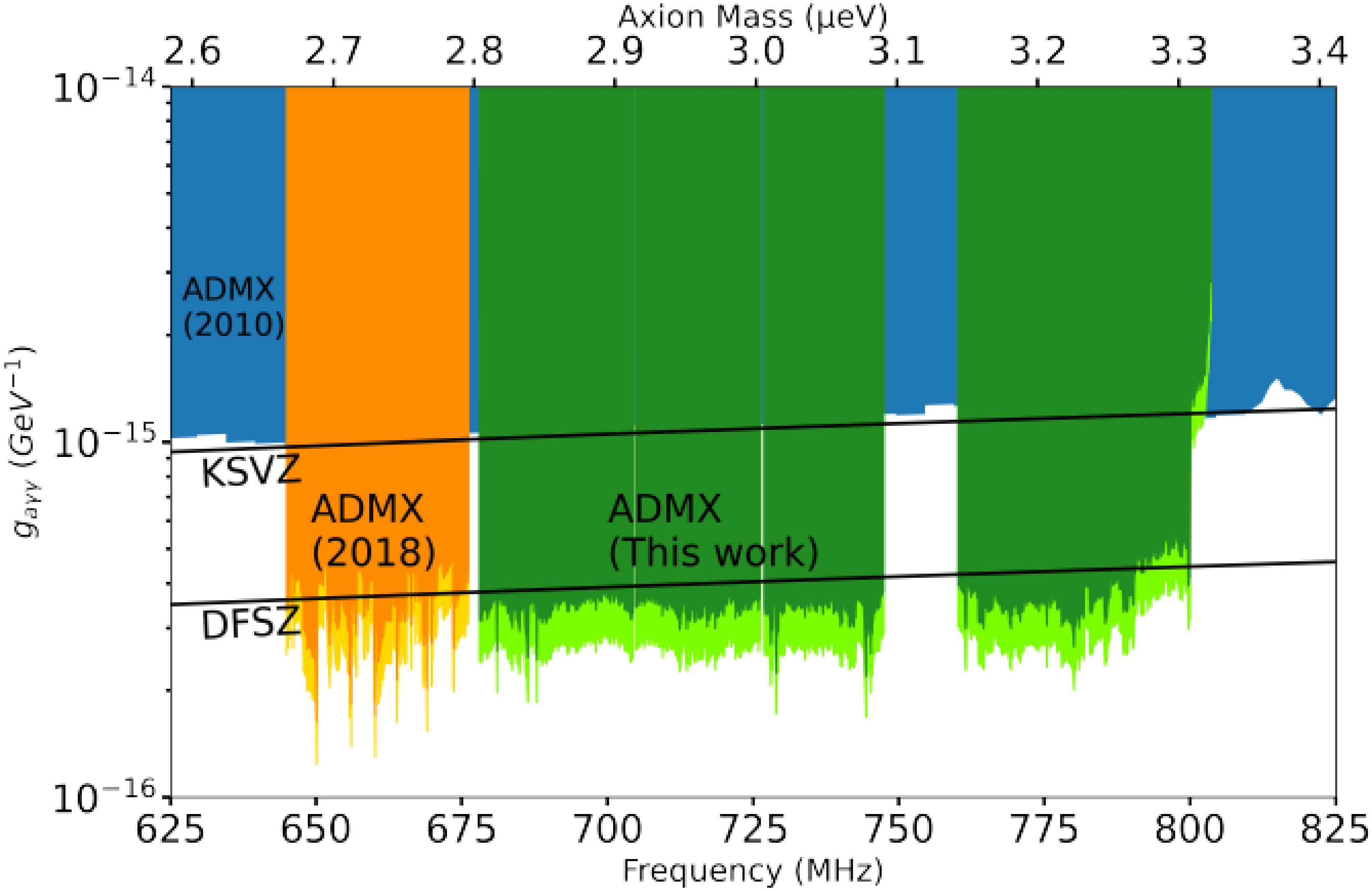

Stepping motors
Vacuum Pump
Cryostat vessel
Magnet support
Cavity LHe reservoir
Magnet LHe reservoir
1.3K J-T refrigerator
Cavity vacuum chamber
Amplifiers
Tuning mechanism
Microwave Cavity
Dielectric tuning rod
Metal tuning rod
Superconducting magnet
3.6 meters

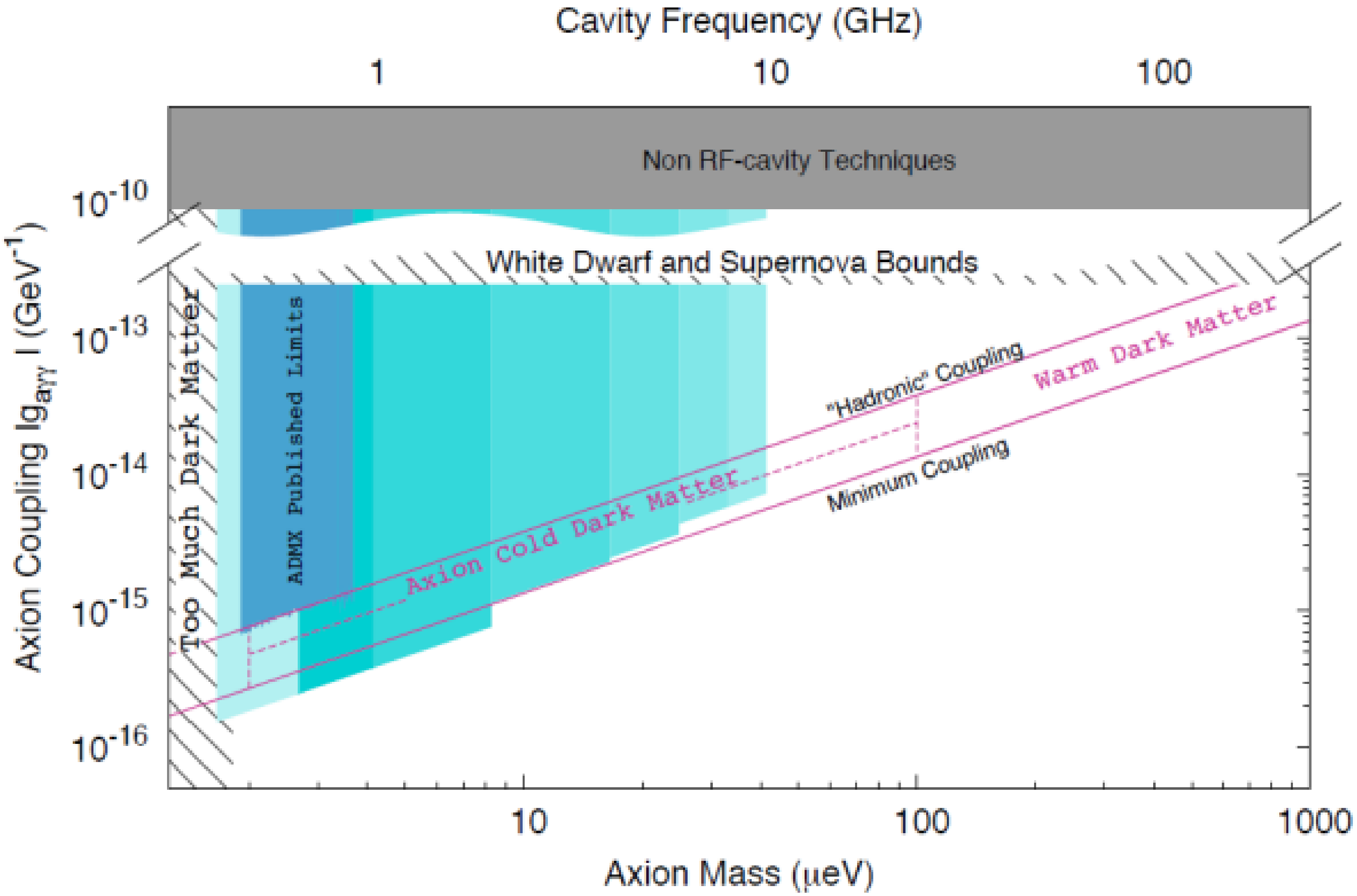
ADMX – Experimental Setup

- High-Q cavity, cryogenic, microwave cavity immersed in a high field solenoid
- Designed for up to 8.5 T, but operating at 7.6 T
- To detect the axion signal, the microwave cavity must be tuned to match the signal frequency
- Achieved DFSZ sensitivity: using quantum amplifier (Josephson Parametric Amplifier) and dilution refrigerator
- Proposal to use superconducting radio frequency cavity



$$P_{axion} = 2.2 \times 10^{-23} W \left(\frac{\beta}{1+\beta}\right)\left(\frac{V}{136\ l}\right)\left(\frac{B}{7.6\ T}\right)^2\left(\frac{C_{010}}{0.4}\right)^2\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho}{0.45\ GeV\ cm^{-3}}\right)\left(\frac{Q_{axion}}{10^6}\right)\left(\frac{f}{740\ Mhz}\right)\left(\frac{Q_L}{30000}\right)\left(\frac{1}{1+\left(\frac{2\delta f_a}{\Delta f}\right)^2}\right)$$


Axion Mass (μeV)
2.6
2.7
2.8
2.9
3.0
3.1
3.2
3.3
3.4
10^{-14}
10^{-15}
10^{-16}
$g_{a\gamma\gamma}$ (GeV^{-1})
ADMX (2010)
KSVZ
ADMX (2018)
ADMX (This work)
DFSZ
625
650
675
700
725
750
775
800
825
Frequency (MHz)


Cavity Frequency (GHz)
1
10
100
Non RF-cavity Techniques
White Dwarf and Supernova Bounds
Too Much Dark Matter
ADMX Published Limits
Axion Cold Dark Matter
"Hadronic" Coupling
Warm Dark Matter
Minimum Coupling
10^{-10}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Axion Coupling $|g_{a\gamma\gamma}|$ (GeV^{-1})
10
100
1000
Axion Mass (μeV)

ABRACADABRA

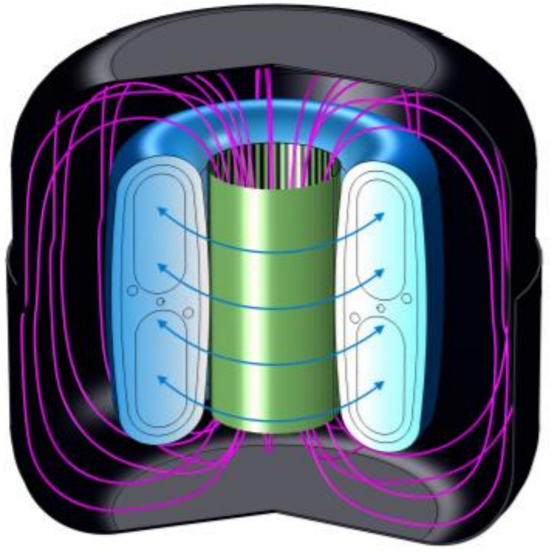
- As ABRACADABRA-10cm now, in future to build a larger 75cm detector
- To search for low mass axions (neV range)
- Axion DM modifies Ampere's law as:

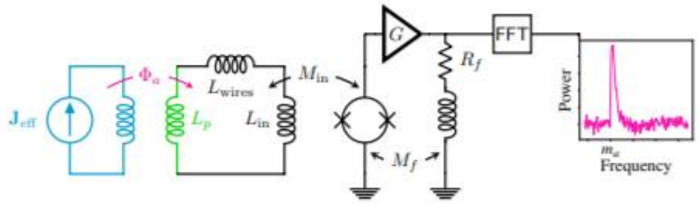
$$\nabla \times \vec{B} = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}\left(\vec{E} \times \nabla \phi_a - \frac{\partial \phi_a}{\partial t}\vec{B}\right)$$

- Axion DM behaves as an effective current density $\vec{J}_{eff} = g_{a\gamma\gamma}(\partial_t \phi_a)\vec{B}$
- To leading order in DM velocity, $\partial_t \phi_a = \sqrt{2\rho_{DM}}\cos(m_a t)$

ABRACADABRA-10cm

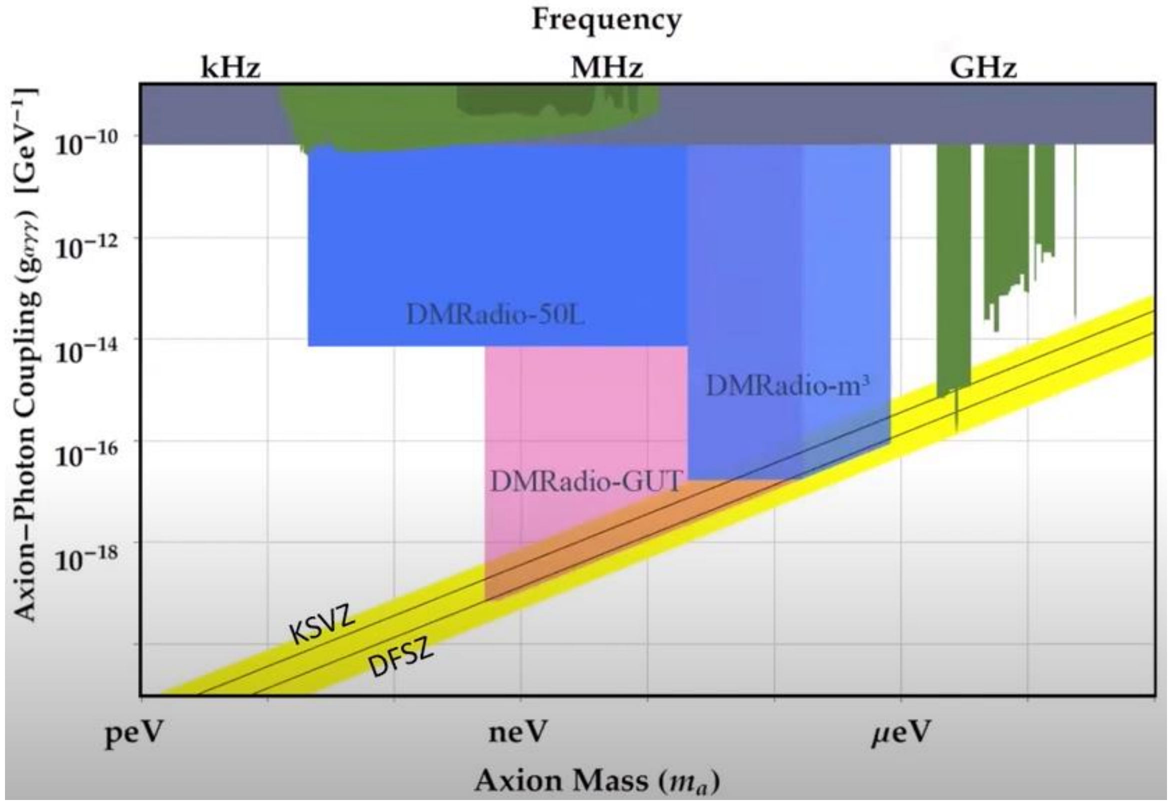
- Built around 12 cm diameter, 12 cm tall, 1T toroidal magnet
- located on MIT’s campus
- Axion interacts with toroidal magnetic field and induces an effective current, $\vec{J}_{eff}$
- Oscillating magnetic field flux is read by DC-SQUID
- Calibrated against fake axion signals
- Found no evidence for axion DM in 0.41-8.27 neV range





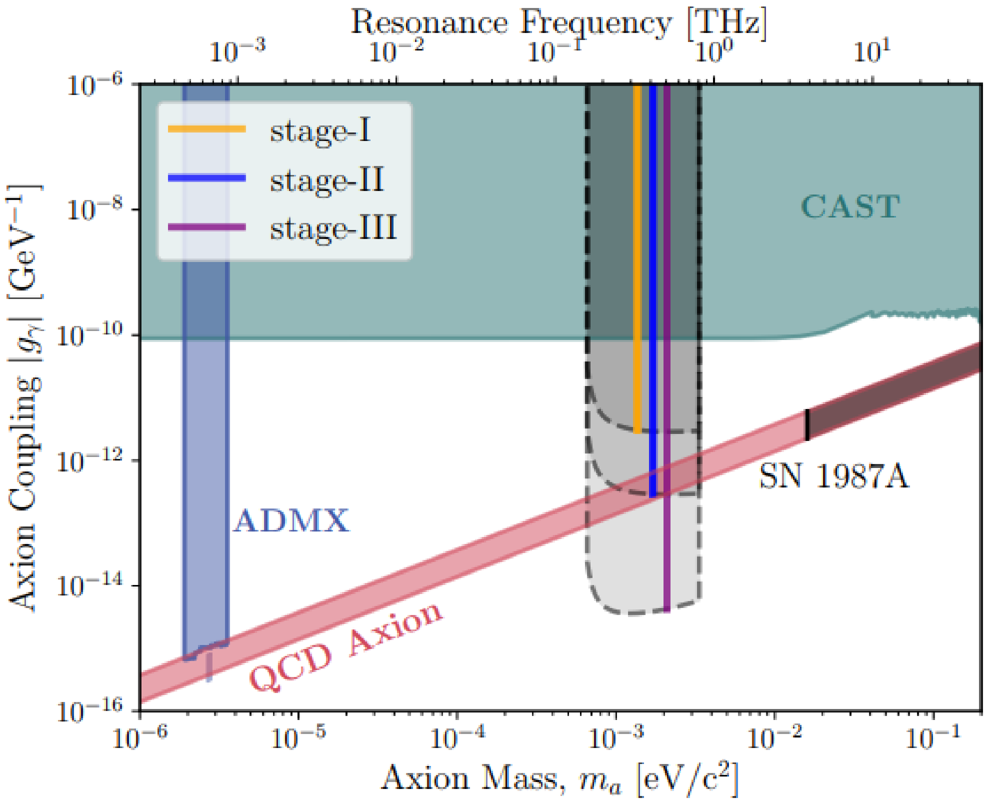
DM Radio

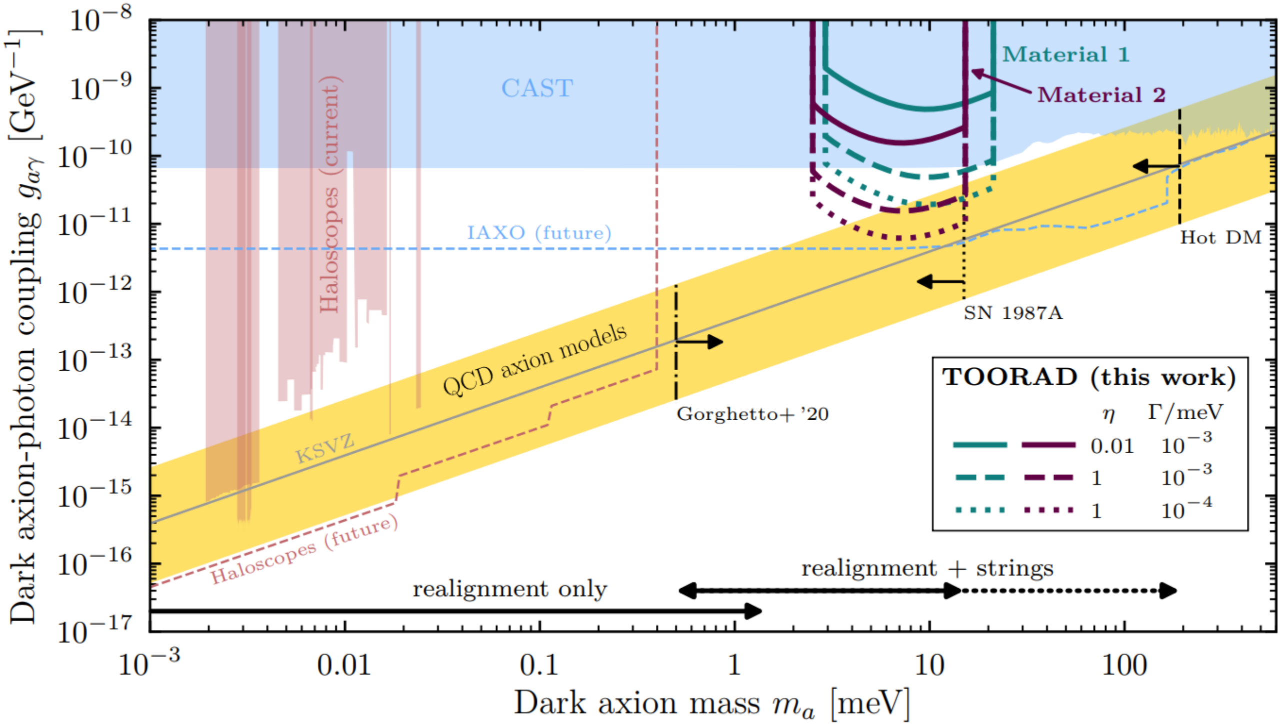
Look for axions across wide range of masses



TOORAD (TOpolOgical Resonant Axion Detection)

- In proposal stage as of now
- Use Antiferromagnetically doped topological insulators (A-TI)
- A-TI’s can host axion fields and axion-polaritons
- Search for axions in meV range
- Axion-electron interaction excites AFMR (antiferromagnet resonance) in TMI (topological magnetic insulator)
- AFMR has been successfully constrained with NMR and ferromagnetic resonance – can help the detector have better sensitivity


Resonance Frequency [THz]
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
stage-I
stage-II
stage-III
CAST
ADMX
SN 1987A
QCD Axion
Axion Coupling $|g_\gamma|$ [GeV^{-1}]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Axion Mass, m_a [eV/c^2]


Material 1
Material 2
CAST
Haloscopes (current)
IAXO (future)
Hot DM
SN 1987A
QCD axion models
KSVZ
Gorghetto+ '20
Haloscopes (future)
TOORAD (this work)
η
Γ/meV
0.01
10^{-3}
1
10^{-3}
1
10^{-4}
realignment only
realignment + strings
Dark axion-photon coupling $g_{a\gamma}$ [GeV^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-3}
0.01
0.1
1
10
100
Dark axion mass m_a [meV]

Radio conversion in galactic magnetic fields

- Photon-Axion conversion induced by galactic magnetic fields
- Photons while travelling oscillate to an axion or axion-like-particle state
- This conversion can cause apparent attenuation in the photon flux
- Attenuation depends on distance, energy of photon, and transversal magnetic field along the line-of-sight
- Photon energy range from MeV to GeV range can be relevant [from galaxy parameters]
- Better description of large scale magnetic fields will be helpful

Analysis part

Data from Fermi-LAT for 12 bright pulsars, systematic uncertainties from the pulsar Vela

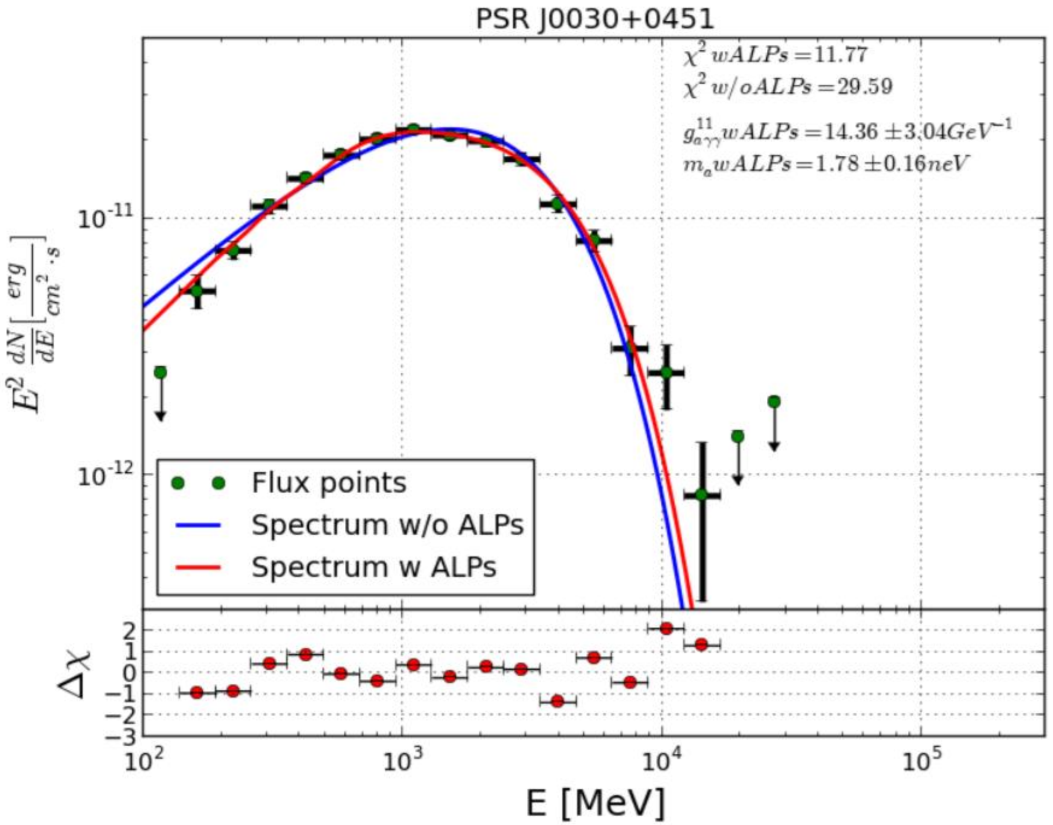
- Pulsar spectrum modelled by a power law with exponential cutoff

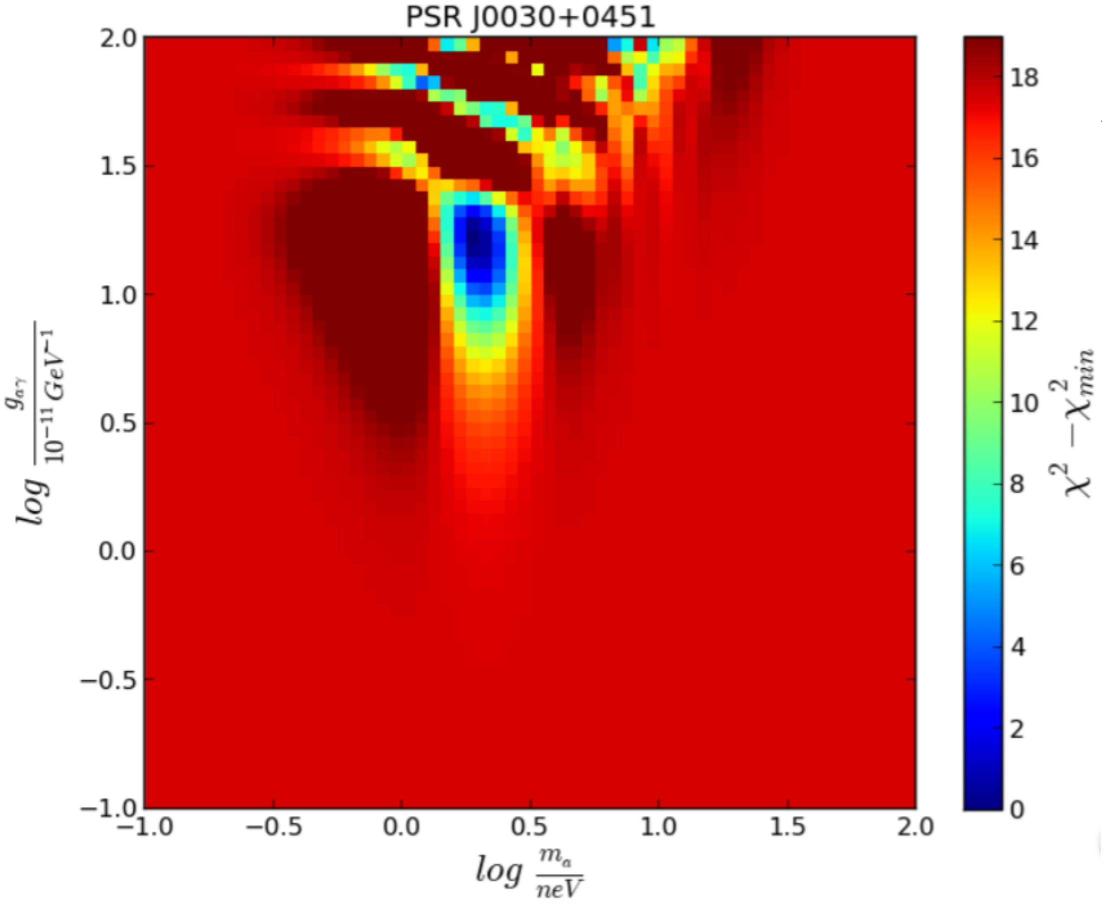
$$\frac{d\mathrm{N}}{\mathrm{dE}} = \mathrm{N}_0 \left(\frac{\mathrm{E}}{\mathrm{E}_0}\right)^{-\Gamma} \exp\left(-\frac{\mathrm{E}}{\mathrm{E}_{\mathrm{cut}}}\right)$$

- Minimize χ^2 of the fit [D_{kk_p} is the energy dispersion matrix]

$$\left(\frac{dN}{dE}\right)_{fit} = D_{kk_p}\left(1 - P_{\gamma\to a}(E, g_{a\gamma\gamma}, m_a, d)\right)\left(\frac{dN}{dE}\right)$$

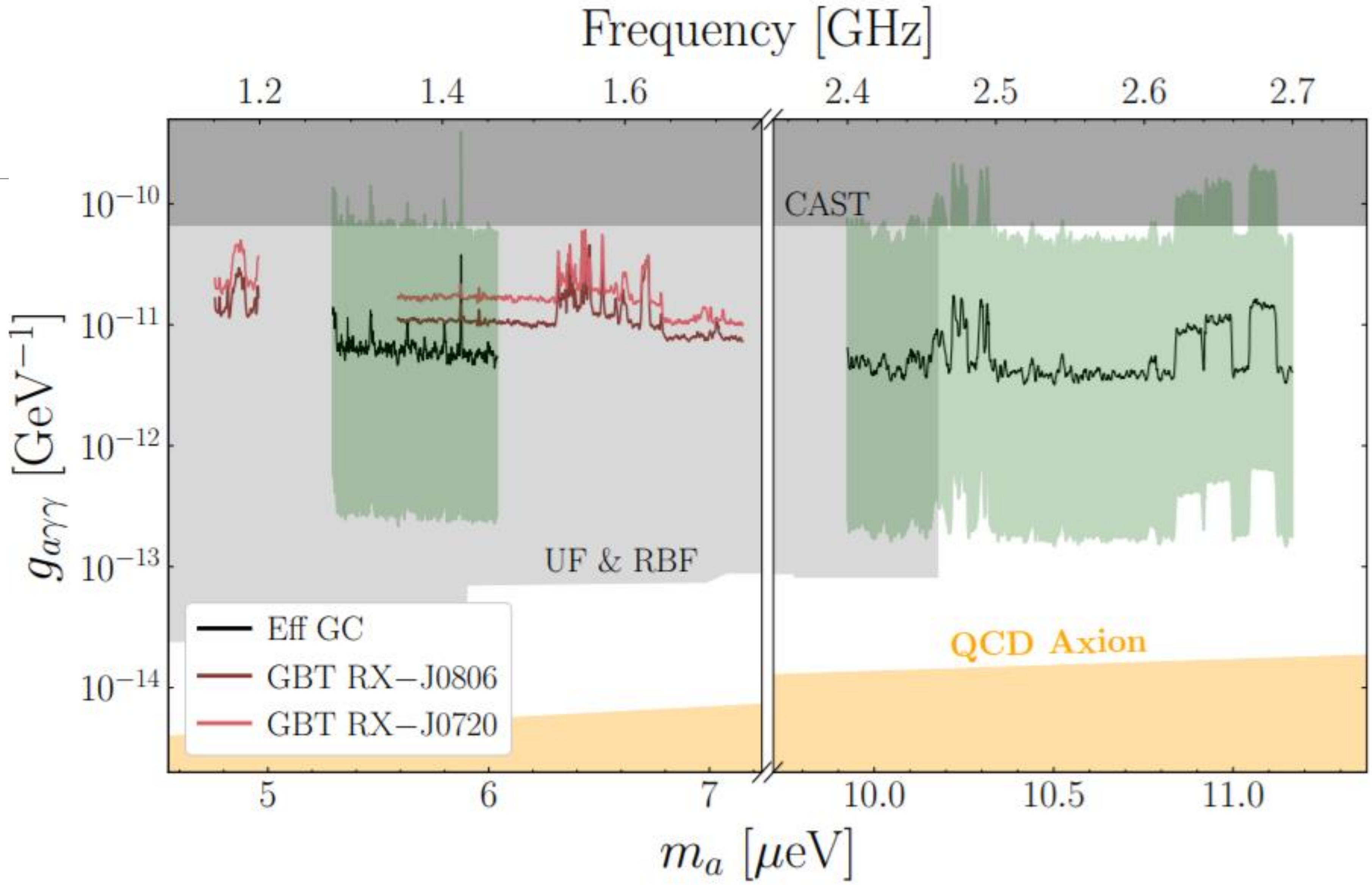
- Estimated axion-like-particle's (ALP) mass to be a few neV
- Estimated $g_{a\gamma\gamma} \sim 10^{-12}$ GeV^{-1}


PSR J0030+0451
$\chi^2\, wALPs = 11.77$
$\chi^2\, w/oALPs = 29.59$
$g^{11}_{a\gamma\gamma} wALPs = 14.36 \pm 3.04 GeV^{-1}$
$m_a wALPs = 1.78 \pm 0.16 neV$
$E^2 \frac{dN}{dE}\left[\frac{erg}{cm^2 \cdot s}\right]$
10^{-11}
10^{-12}
Flux points
Spectrum w/o ALPs
Spectrum w ALPs
$\Delta\chi$
2
1
0
−1
−2
−3
10^2
10^3
10^4
10^5
E [MeV]


PSR J0030+0451
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
$\log \frac{g_{a\gamma}}{10^{-11} GeV^{-1}}$
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
$\log \frac{m_a}{neV}$
18
16
14
12
10
8
6
4
2
0
$\chi^2 - \chi^2_{min}$

Radio conversion in magnetospheres of a neutron star (NS)

- Axion DM may convert to radio-frequency EM radiation in strong magnetic field of NS
- Radio signature is an ultra narrow spectral peak at a frequency fixed by axion’s mass
- High-frequency-resolution observations with radio telescopes like: Robert C Byrd Green Bank Telescope (GBT) and Effelsberg 100 m Telescope would be sensitive to vast regions of unexplored axion parameter space
- Point telescopes to isolated NS, or region of high NS and DM density
- Set constraints in the mass range 5-11 μeV
- Additional flux sensitivity needed

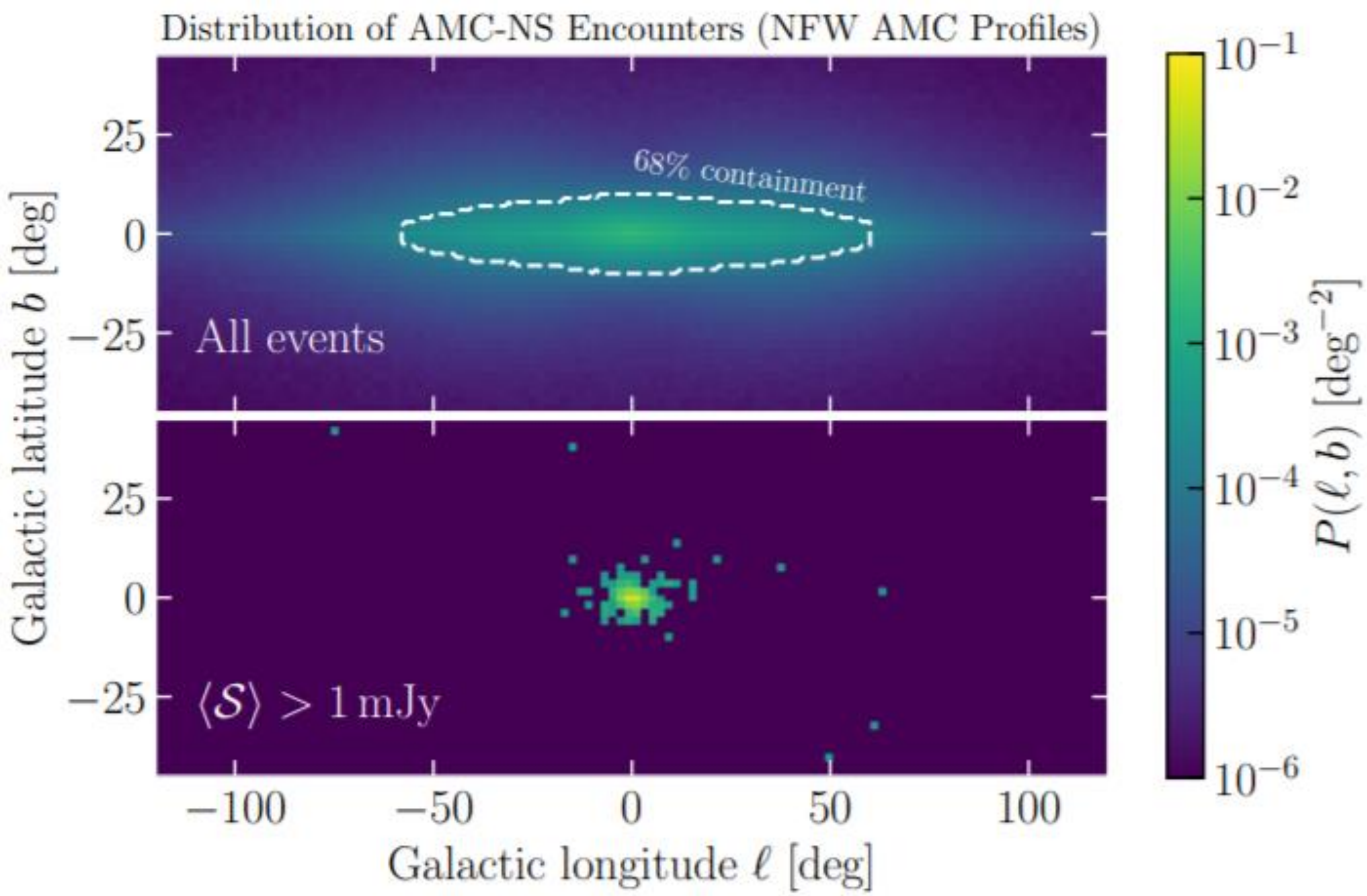

Frequency [GHz]
1.2
1.4
1.6
2.4
2.5
2.6
2.7
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
CAST
UF & RBF
QCD Axion
Eff GC
GBT RX−J0806
GBT RX−J0720
5
6
7
10.0
10.5
11.0
m_a [μeV]

Radio signatures from NS encounters with QCD Axion minicluster

- Resonant conversion at a distance R_c where axion mass equals plasma frequency ω_p
- Goldreich-Julian model for NS magnetosphere
- Power radiated in this resonant conversion per solid angle

$$\frac{dP_a}{d\Omega} \sim \frac{\pi}{3} g_{a\gamma\gamma}^2 (B_0^2) \left(\frac{R_{NS}^6}{R_c^3}\right) \left(\frac{\rho_a}{m_a}\right)$$

- Candidates for strong magnetic fields are: white dwarfs, pulsars, magnetars
- Axion miniclusters (AMC) can have masses between (10^{-19} to 10^{-5}) M_{sun} with radius between (10^{-2} to 10^{-8})parsec


Distribution of AMC-NS Encounters (NFW AMC Profiles)
68% containment
All events
$\langle \mathcal{S} \rangle > 1\,\mathrm{mJy}$
Galactic latitude b [deg]
25
0
−25
25
0
−25
−100
−50
0
50
100
Galactic longitude ℓ [deg]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$P(\ell, b)$ [deg^{-2}]

Takeaways

- Global U(1)$_{PQ}$ (or PQ) symmetry postulated for the SM lagrangian, introduces axion field
- Helps to solve the Strong CP problem by driving the CP violating parameter ($\bar{\theta}$) to 0
- PQ symmetry is spontaneously broken producing pseudoscalar Nambu-Goldstone boson, axion
- A large parameter space to be explored
- Various experiments and cosmological observations used to explore the parameter space
- ADMX searches for μeV axion masses, ABRACADABRA for neV axion masses, TOORAD for meV axion masses
- Axion-photon mixing due to large scale galactic magnetic fields, may modulate gamma ray spectra
- Axions converting to photons in strong magnetic fields such as in NS, leaving a radio signature

You could be involved in discovering a new elementary particle!