Materials Science Meets Dark Matter Detection: TOORAD!

David J. E. Marsh

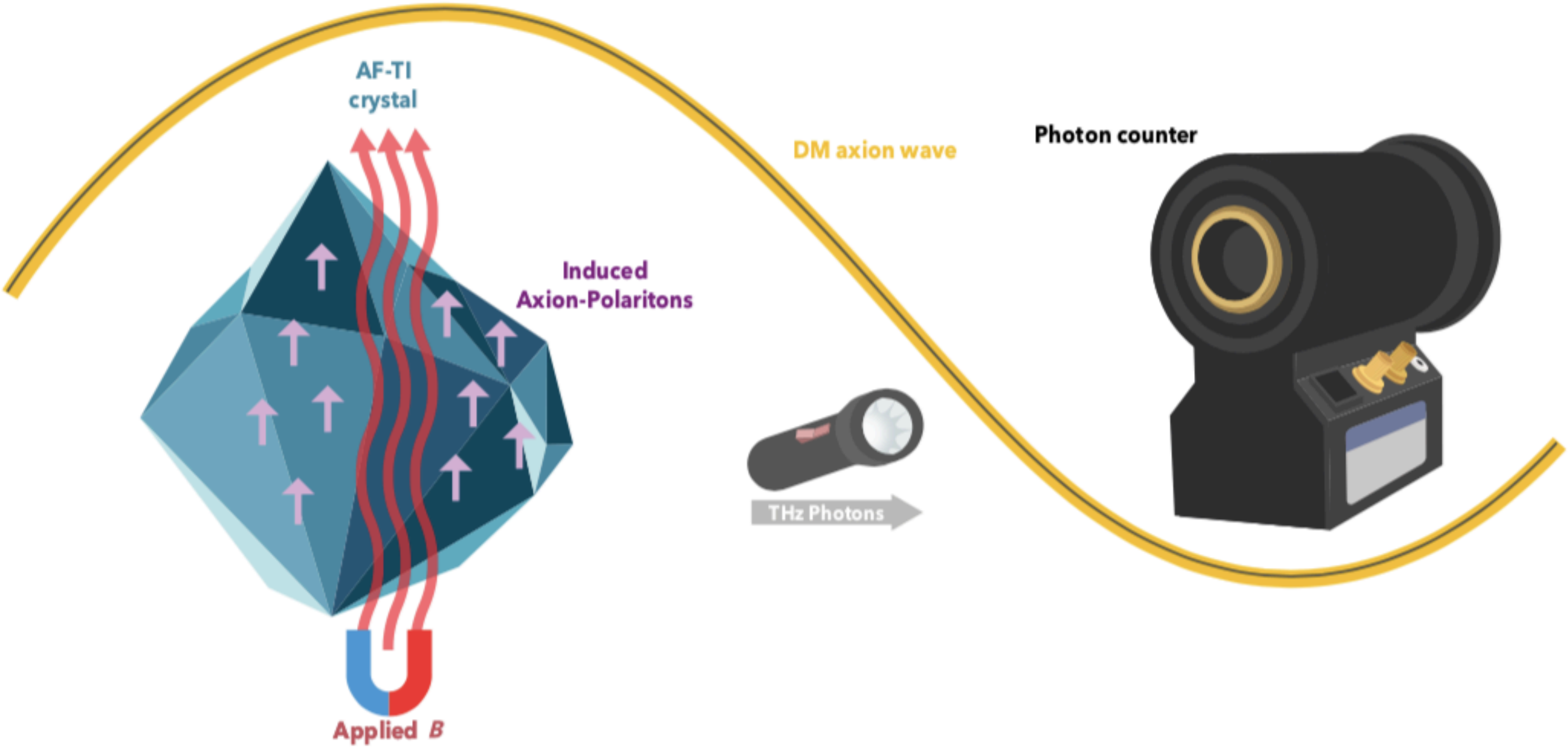
KCL, Oct (2020)

Based on DJEM et al PRL (2018) and forthcoming

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

Schematics of experimental concept



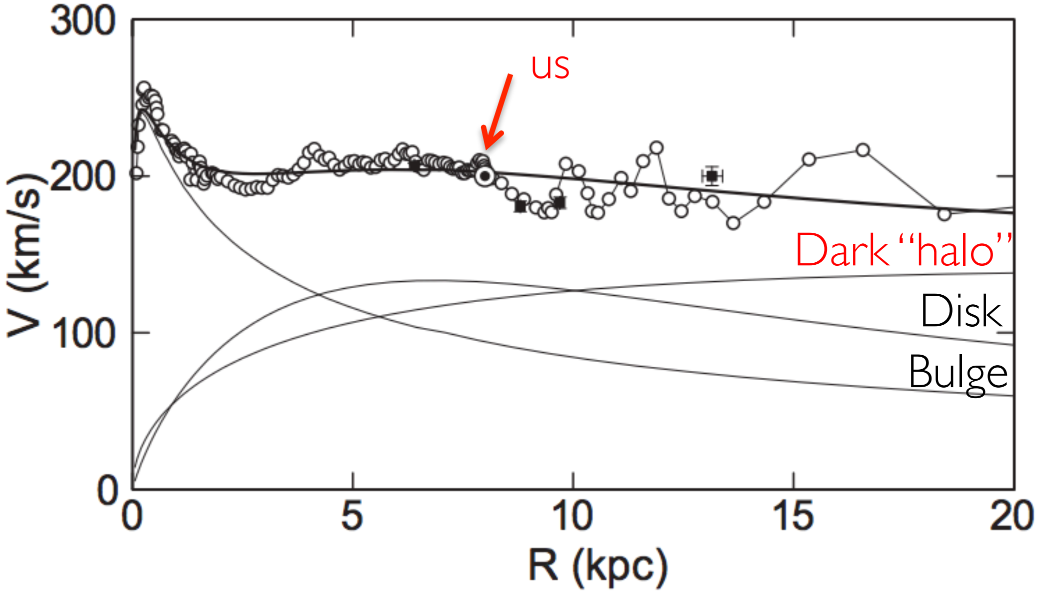
TOORAD = TOpOlogical Resonant Axion Detection

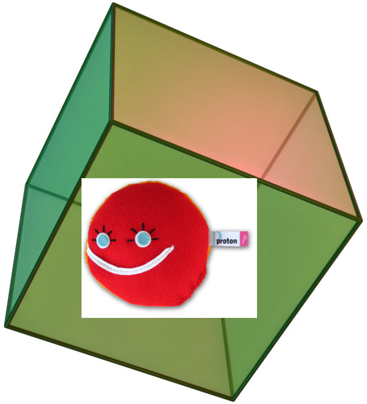
AXION DARK MATTER

A neat theory for the "glue" of the Universe…

Dark Matter on Earth

Milky Way Rotation Curve, Sofue (2012)



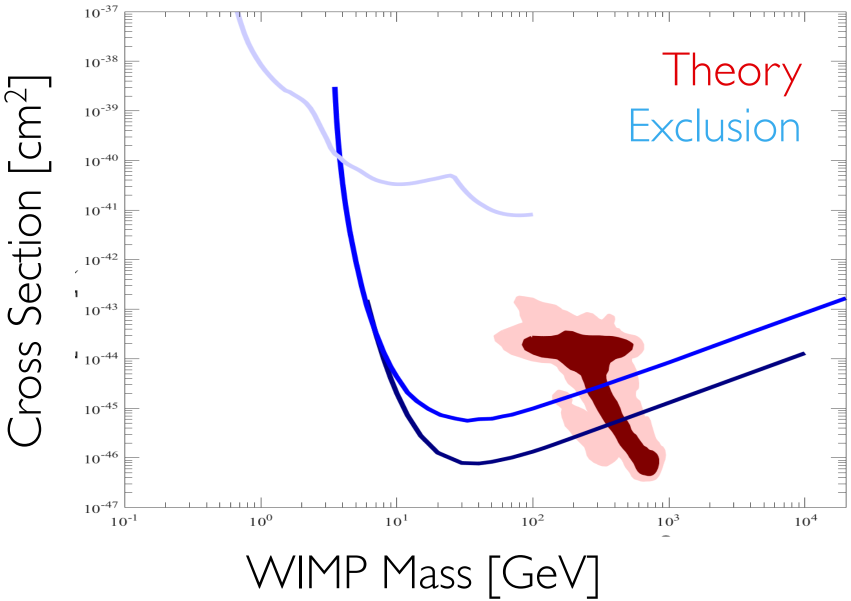


$$\rho_{\mathrm{DM}} \approx 0.3\,\mathrm{GeV\,cm^{-3}}$$

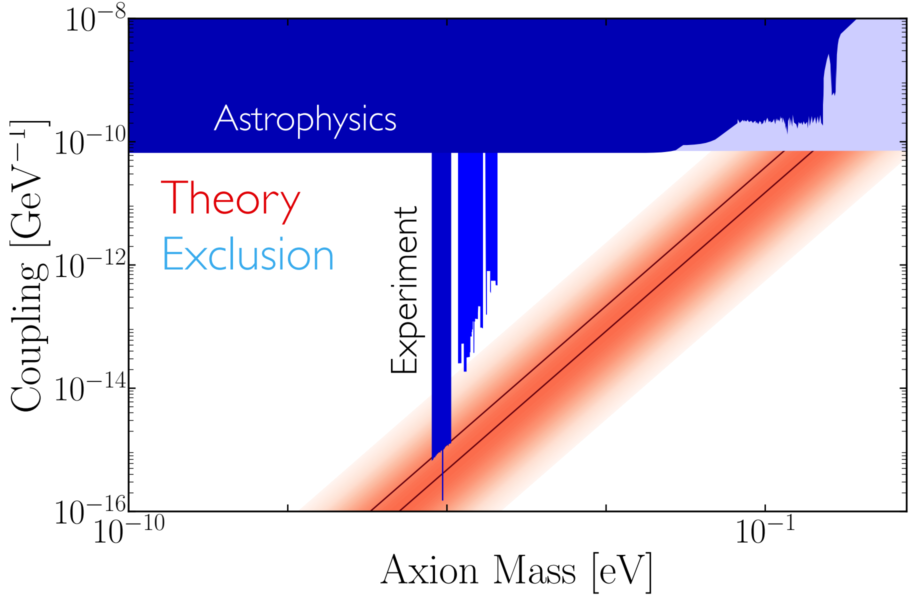
(measured to ~ 25% precision)

Axions vs WIMPs

Two historical dark matter theories proposed in 70's/80's.



DMTools



O'Hare github

Axion Dark Matter

For the purposes of this talk, all you need to know is that axions can be modeled as an oscillating classical field:

$$\phi = \phi_0 \cos \omega_a t$$

$$\omega_a = m_a + \frac{1}{2} m_a v^2 = m_a [1 + \mathcal{O}(10^{-6}]$$

$$\boxed{\nu_a \approx 1\,\mathrm{GHz} \times \left(\frac{m_a}{6\,\mu\mathrm{eV}} \right)}$$

Local DM density given as a harmonic oscillator:

$$\rho_{\mathrm{DM}} = \frac{1}{2} m_a^2 \phi_0^2$$

→ if we know m_a we know field amplitude & frequency

What is the Axion Mass?

Units: eV = electronvolts

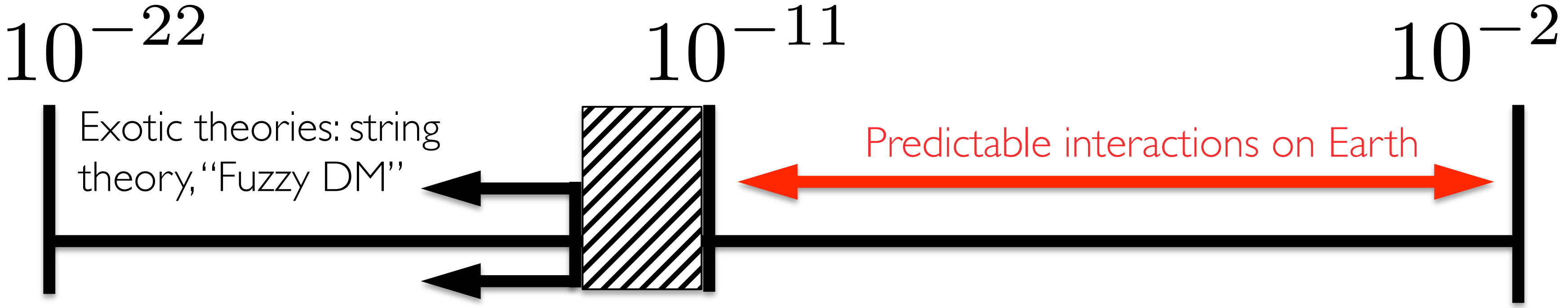
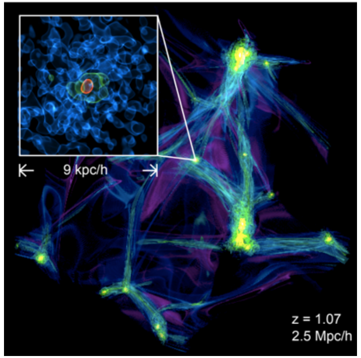
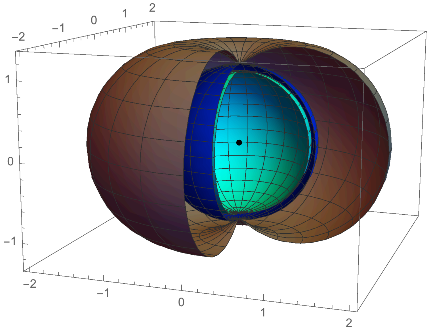


Fig: Veltmaat et al (2018)

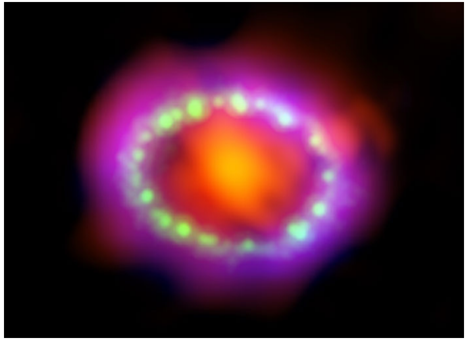


Galaxy formation
e.g. DJEM (2016)



“Black Hole Superradiance”
e.g. DJEM & Stott (2018)

Fig: Physics World



SN1987A Neutrino Burst
e.g. Chang et al (2018)

What is the Axion Mass?

Gorghetto et al (2018); Hiramatsu et al (2012), and many, many more!

Spontaneous symmetry breaking → primoridal oscillations of axion field.

Cosmic DM density is a function of axion mass.

Challenging, but *solvable* computational problem.

This scenario seems to favour meV → THz

"Defects" form and decay, emitting axions (not shown)

Axions and Maxwell's Equations

Our last ingredient: how do axions interact with us? Answer: via classical electromagnetism!

$$\nabla \cdot \mathbf{E} = \rho_f$$

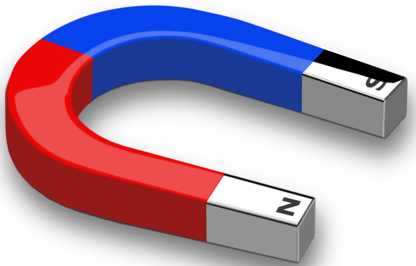
$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J}_f$$

Axion field ϕ acts as an oscillating source for E parallel to B → amplify with resonance.
Amplitude of source fixed by ρ_{DM} and coupling constant, g.

$$\mathcal{L} = \frac{\alpha}{2\pi f_a} c_\gamma \ \phi \tilde{F}^{\mu\nu} F_{\mu\nu} \qquad m_a = 5 \text{ meV} \left(\frac{10^9 \text{ GeV}}{f_a} \right)$$

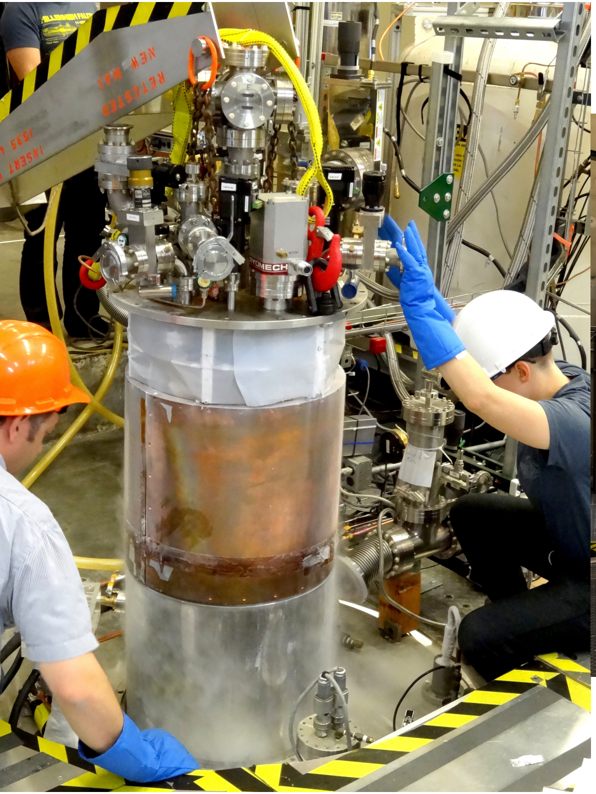
→ If we know the axion mass, we know what resonator to make & strength of induced fields

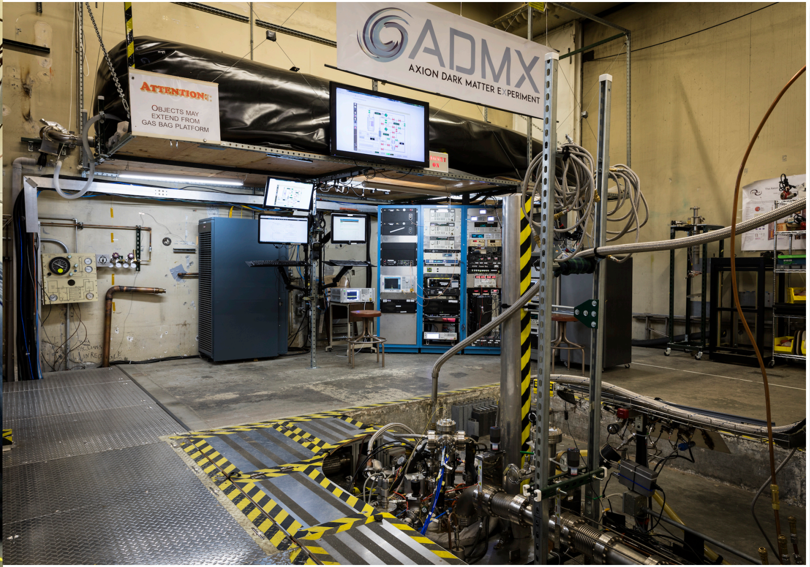
How to Detect Axions

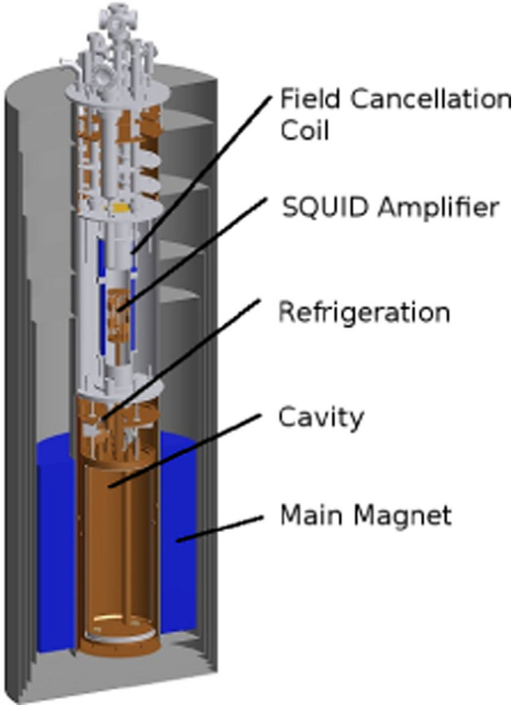


ADMX Axion "Haloscope"

Sikivie (1983)
Braine et al (2020)

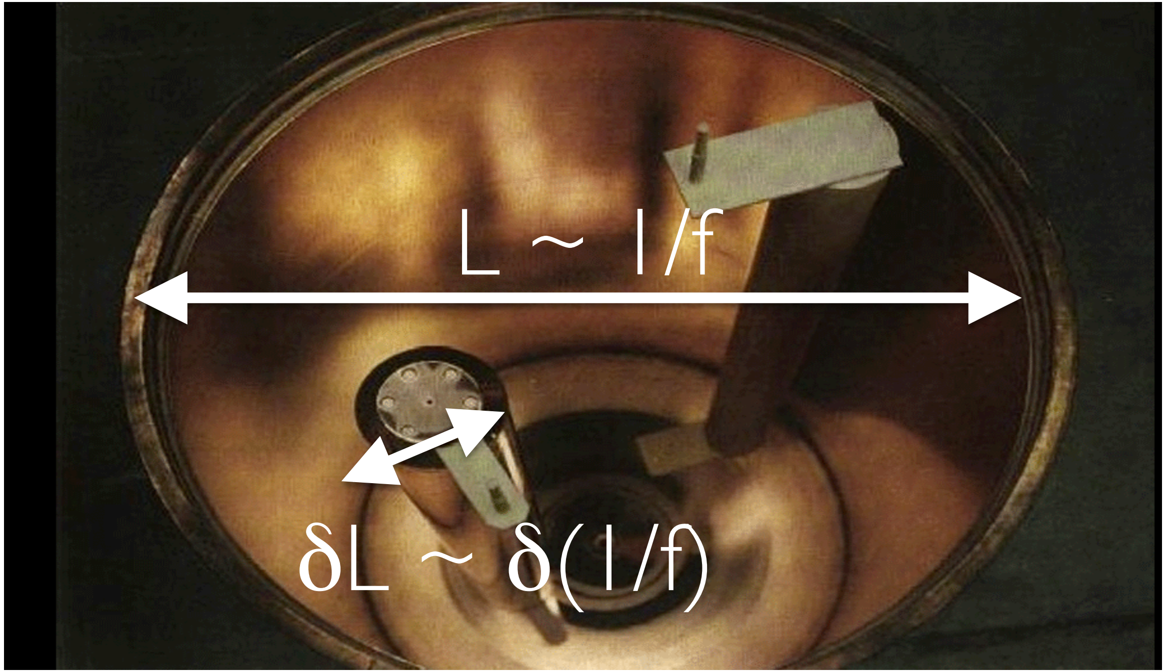






ADMX Axion "Haloscope"

Sikivie (1983)
Braine et al (2020)



Microwave cavity.

Resonance when axion frequency ~ cavity natural frequency.

Large volume → works for frequencies ~ GHz

Production of radio waves inside the cavity. Power ~10^{-22} W (!), detect with e.g. JPA.

THz Detection Challenge

Fixed by MW rotation curve.
Predicted from theory.
Experimental parameters.

$$P = \boxed{\rho_{\rm DM}} \boxed{\frac{g^2}{m_a}} \boxed{B^2\ Q\ V_{\rm eff}}$$

Reference THz cavity has very low power → 10^{-29} W for the axion. Tune $\delta L \sim$ nanometre.

Magnetic resonance overcomes these problems!
V is independent of ω, and tuning can happen on $B \sim \mu$T.

<u>Materials Science:</u>

Antiferromagnetic resonance (AFMR) → THz from "anisotropy field" ~ 10 meV.
Topological insulator → AFMR driven by axion-photon coupling (DJEM et al, 2018).

SOME CONDENSED MATTER THEORY

Nobody said this was going to be easy… enjoy the unity of physics!

Topological Insulators

e.g. Kane & Mele (2005)

Materials based on Bismuth (e.g. Bi_2Se_3, Bi_2Te_3), and Antimony (e.g. Sb_2Te_3)


A crystal of Bismuth

Topological Insulators

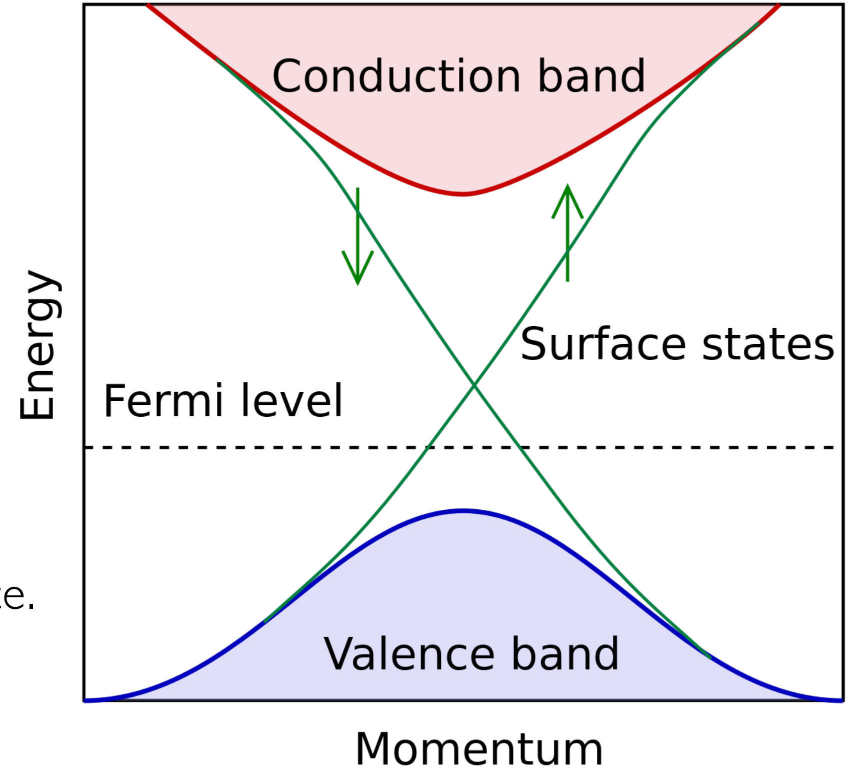
e.g. Kane & Mele (2005)
Fig: Wikipedia

Class of new materials with insulating bulk and conducting surface.

Surface Hall currents described by electromagnetic "**Θ**-term", with **Θ=π**.

$$\mathcal{L} = \Theta \mathbf{E} \cdot \mathbf{B}$$

Static **Θ** (symmetry)→ only affect EM on surface.
Note: E is parallel to B just like axion source!

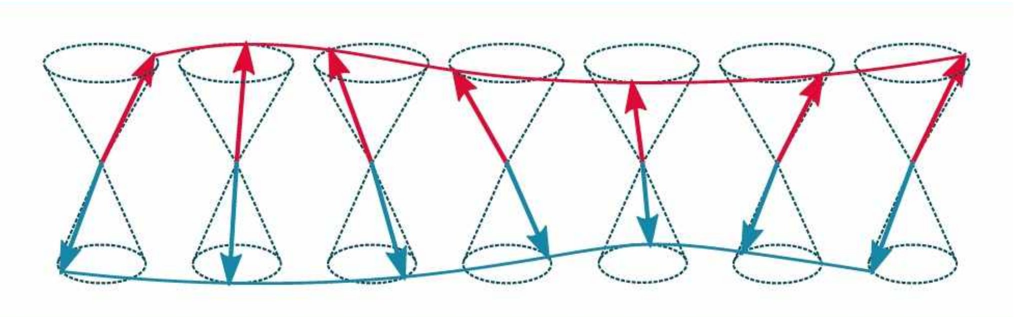


Antiferromagnetic "Magnons"

Figs: Joel Cramer and Wikiwand.com

A-lattice

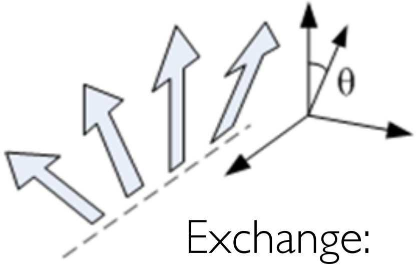
B-lattice



External field → spin precession → "spin wave"

Antiferromagnetic "magnetization": $\Sigma_s = \langle M_A \rangle - \langle M_B \rangle$

Spins have magnetic fields→ interact via "exchange" with each other, and "anisotropy" to "easy axis" direction in crystal.



Exchange:

$$E = \mu H_E$$

Anisotropy:

$$E = \mu H_A$$

Antiferromagnetic "Magnons"

e.g. Haldane (1983), Hofmann (1998)

Mean field theory for Heisenberg model in crystal. Use Noether's theorem.
Magnetic order breaks SO(3) and T → goldstone bosons called magnons (spin waves).
c.f .crystal structure breaks rotation symmetry → goldstone bosons called phonons.

Terms in Lagrangian (and scattering amplitudes!) just like pions and axions:

$$\mathcal{L} = \frac{F_1^2}{2}(D_t n^i)^2 - \frac{F_2^2}{2}(D_x n^i)^2 + O_i n^i$$

n live on coset space: G/H = SO(3)/U(1) = S^2

Oscillation frequency given by exchange (F1), anisotropy (O), applied (D) fields:

"Kittel shift" $$\omega_{\mathrm{AFMR}} = \mu H_0 + \boxed{\sqrt{H_A(2H_E + H_A)}}\; m_s$$ Spin wave "mass"

"Gell-Mann-Oakes-Renner relation" $$F^2 m_s^2 = L H_A$$ (spontaneous) * (explicit) symmetry breaking

Spin wave "stiffness"

ARTICLES
PUBLISHED ONLINE: 7 MARCH 2010 | DOI: 10.1038/NPHYS1534
nature physics

Dynamical axion field in topological magnetic insulators

Rundong Li[1], Jing Wang[1,2], Xiao-Liang Qi[1] and Shou-Cheng Zhang[1]*

The longitudinal mode has the right properties to couple to E.B → axion quasiparticle.

Key idea: use the axion quasiparticle to detect axion dark matter (DJEM et al, 2018)

Coupled Perturbations

Applied field:
$\mathbf{B} = (0, 0, B_0)$

$$\epsilon \ddot{E}_z + k^2 E_z + \boxed{\frac{\alpha}{\pi} B_0 \ddot{\theta}} = \boxed{\frac{2B_0\sqrt{\rho_{\rm DM}}}{m_a} \cos m_a t}$$

$$\ddot{\theta} + v_s^2 k^2 \theta + m_s^2 \theta + \boxed{\frac{\alpha}{4\pi^2 F^2} B_0 \cdot E_z} = 0$$

Axion dark matter drives the system at frequency given by axion mass.

Topological insulator E-B coupling mixes E and θ → effective photon mass ~ m_s ~H_A ~meV

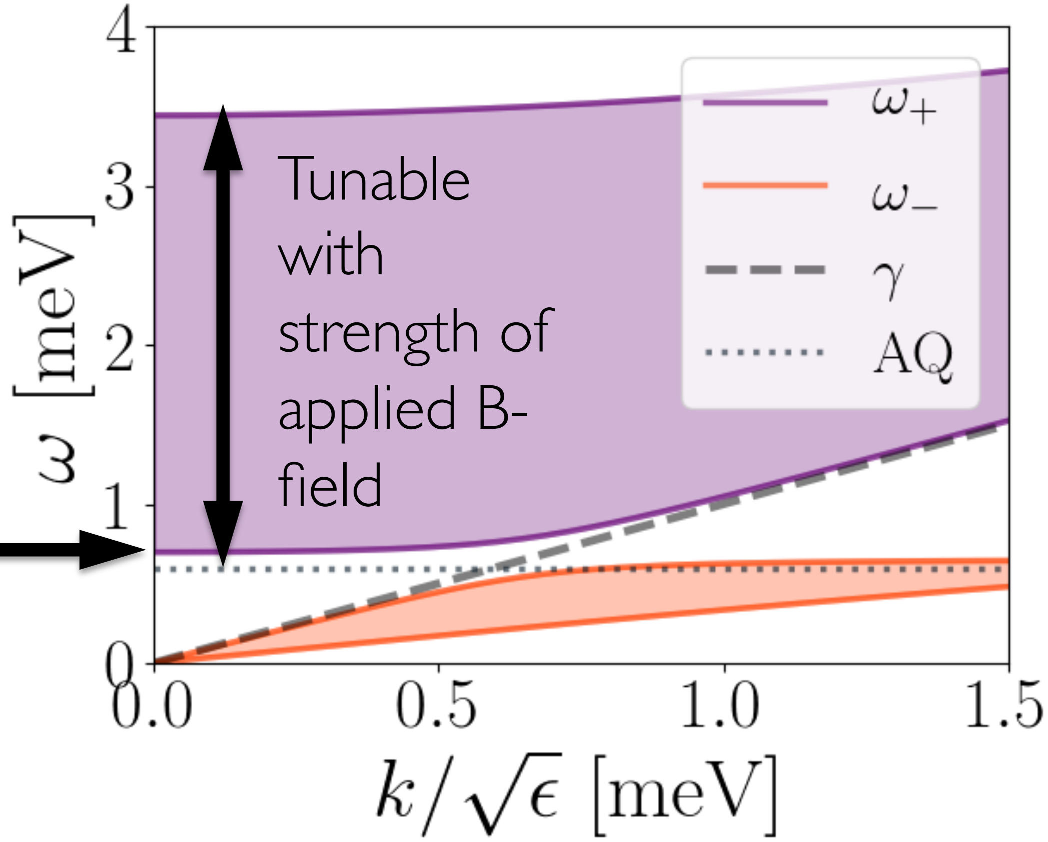
Matrix equation→ diagonalise left hand side → "polaritons" mix of E and θ.

$$\ddot{\phi}_\pm + \omega_\pm^2 \phi_\pm = J_\pm \cos m_a t$$

AXION DARK MATTER DETECTION

Axion quasiparticle materials are large volume, tunable, THz resonantors!

Polariton Dispersion Relation



Resonance when:

$$\omega_+ = \omega_a$$

- Polaritons at material boundary convert into photons via dielectric boundary conditions.
- Resonance is independent of sample size → increase V.
- V~10 cm^3 → P~10^{-23} W = 0.1 THz photon per second.

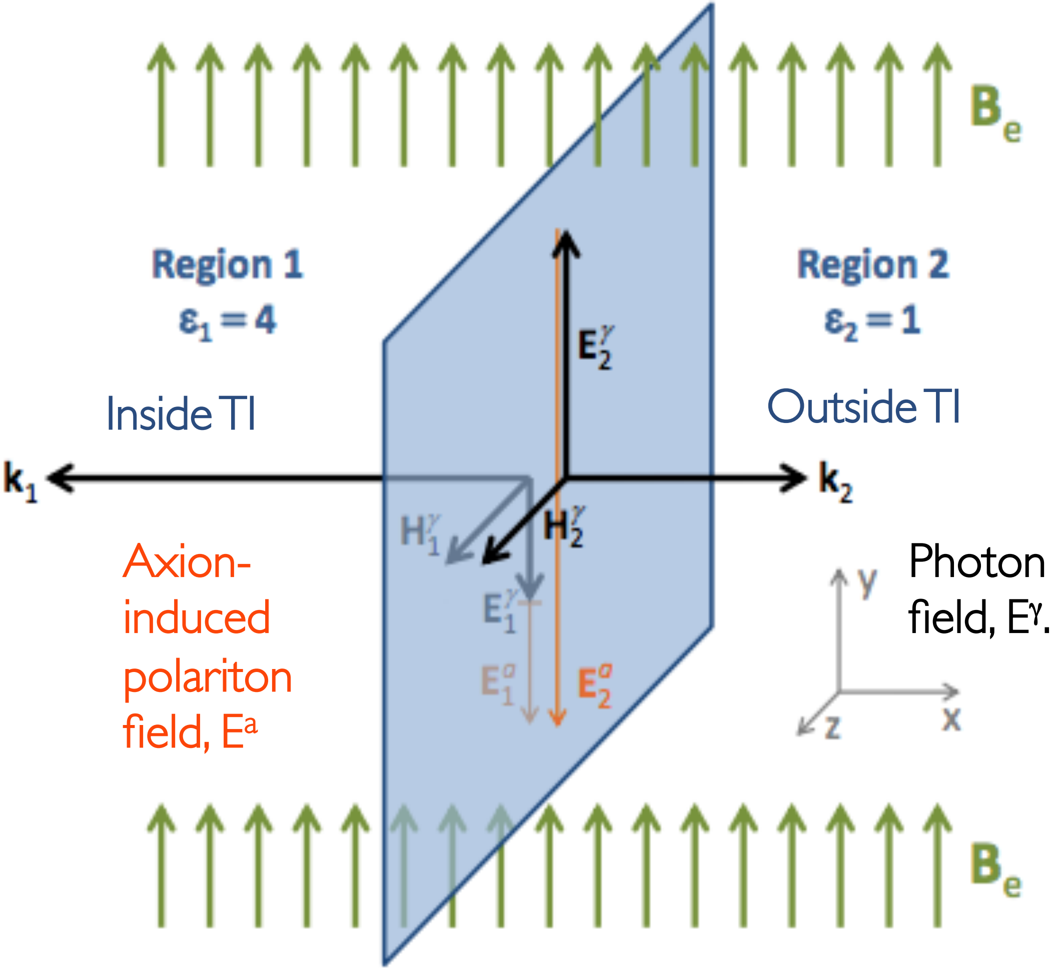
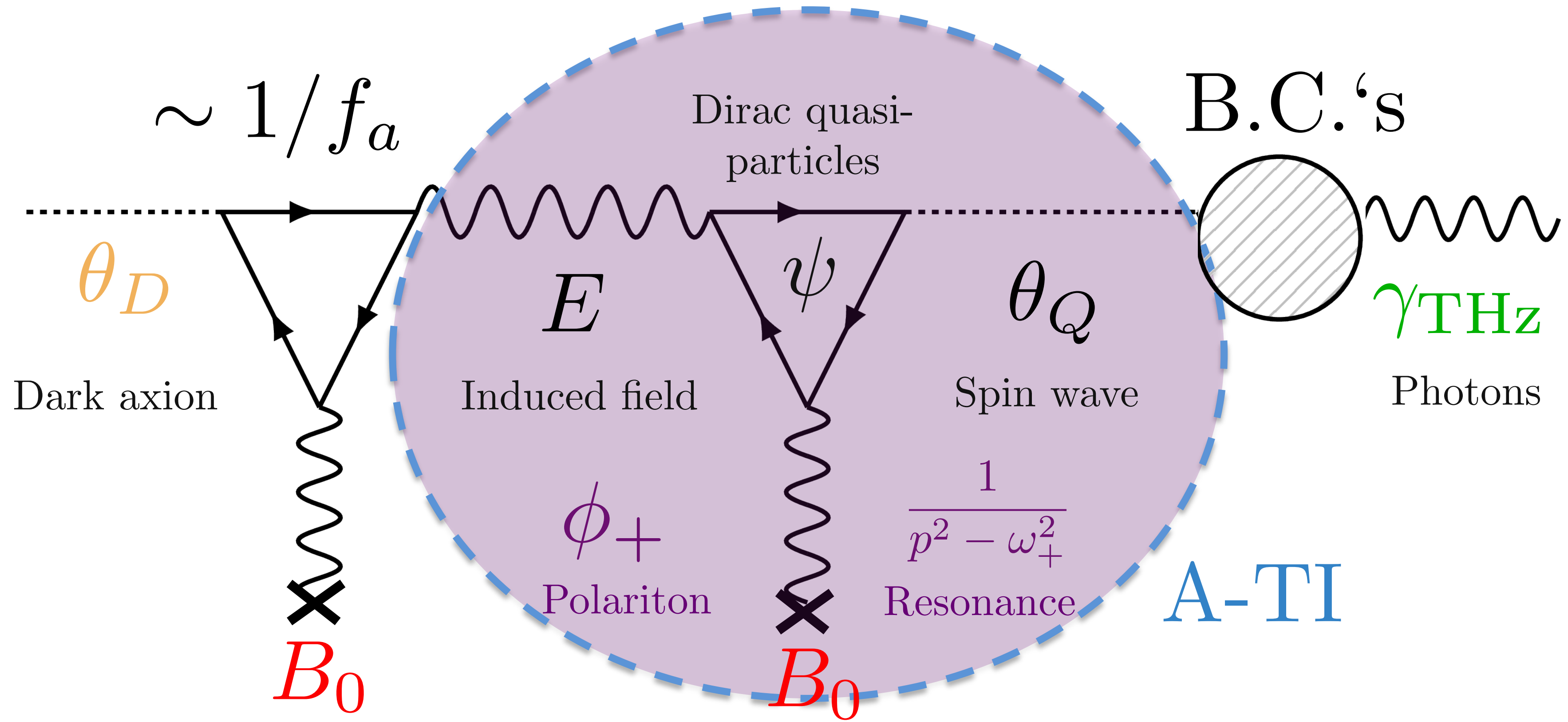
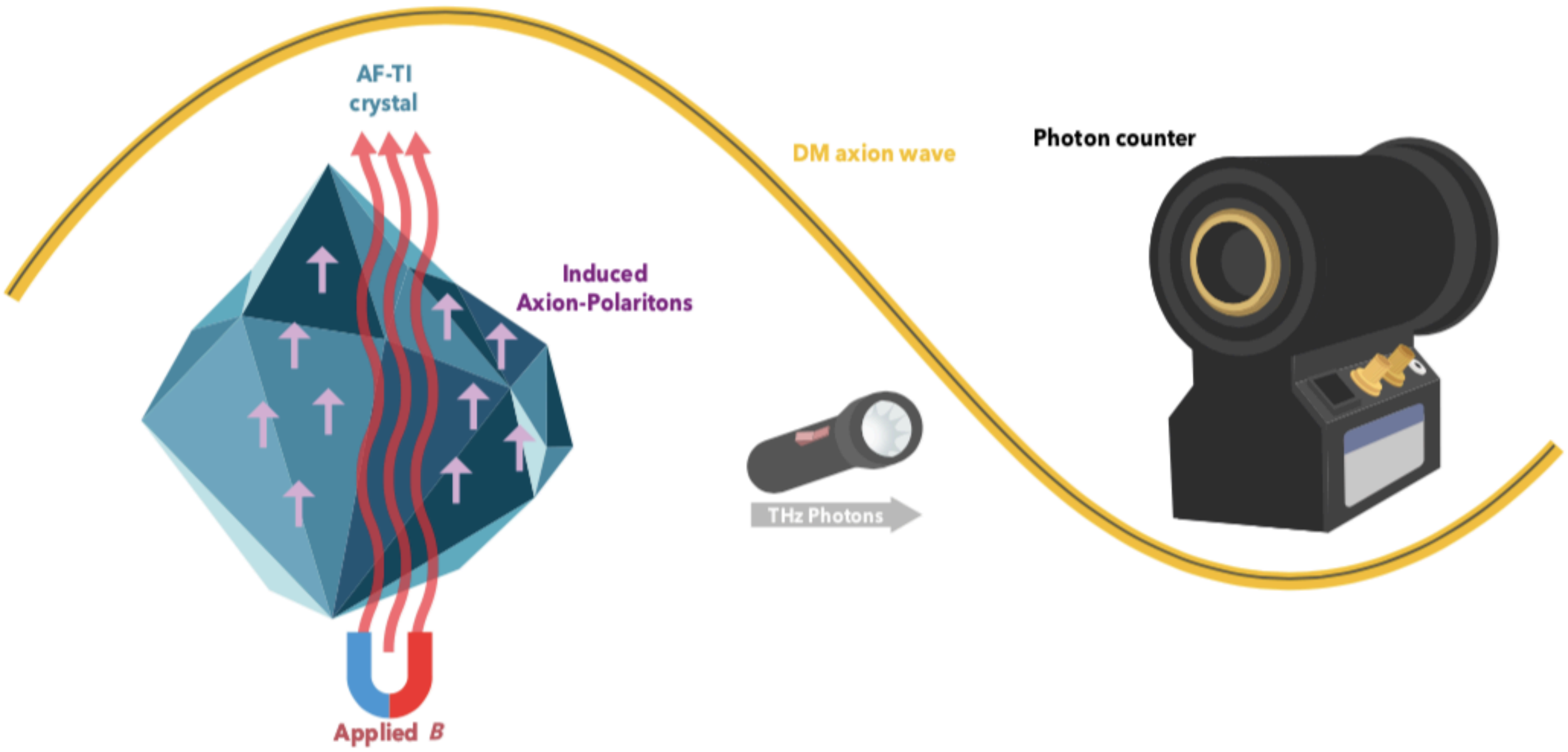


Fig: Millar et al (2016)



$\sim 1/f_a$
Dirac quasi-
particles
B.C.'s
θ_D
E
ψ
θ_Q
γ_{THz}
Dark axion
Induced field
Spin wave
Photons
$\frac{1}{p^2 - \omega_+^2}$
ϕ_+
Polariton
Resonance
A-TI
B_0
B_0

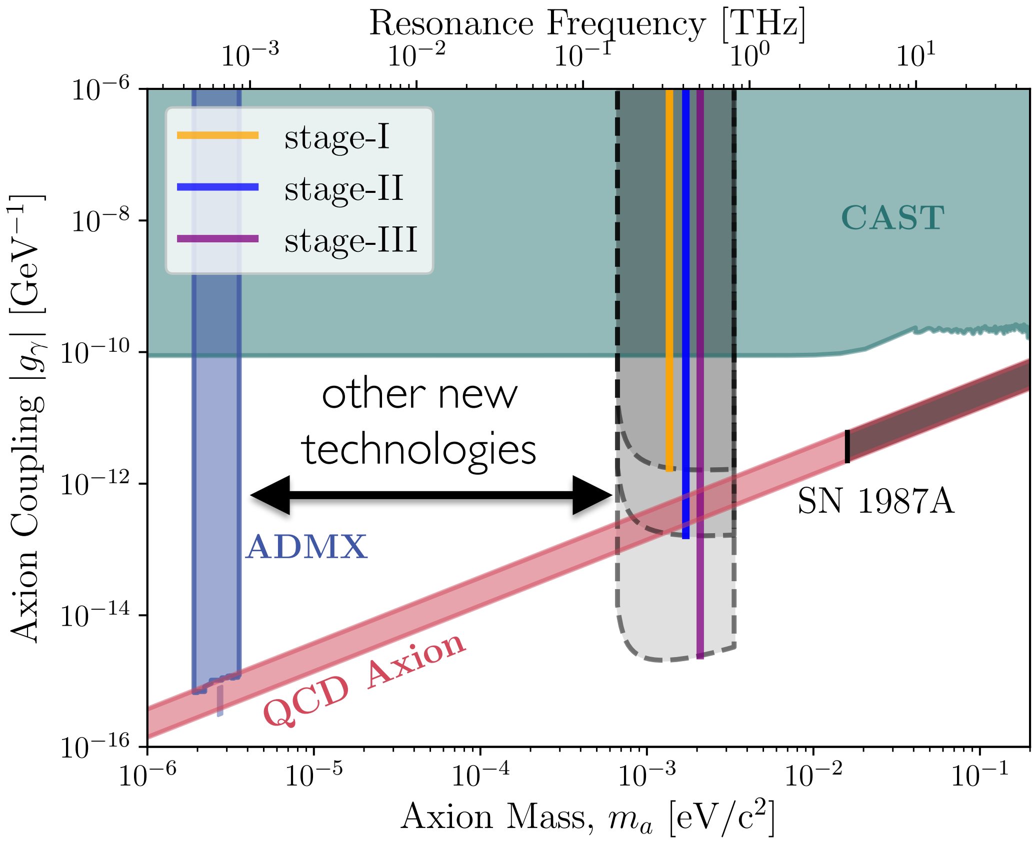
Schematics of experimental concept



TOORAD = TOpOlogical Resonant Axion Detection

Predicted Sensitivity to Axion DM

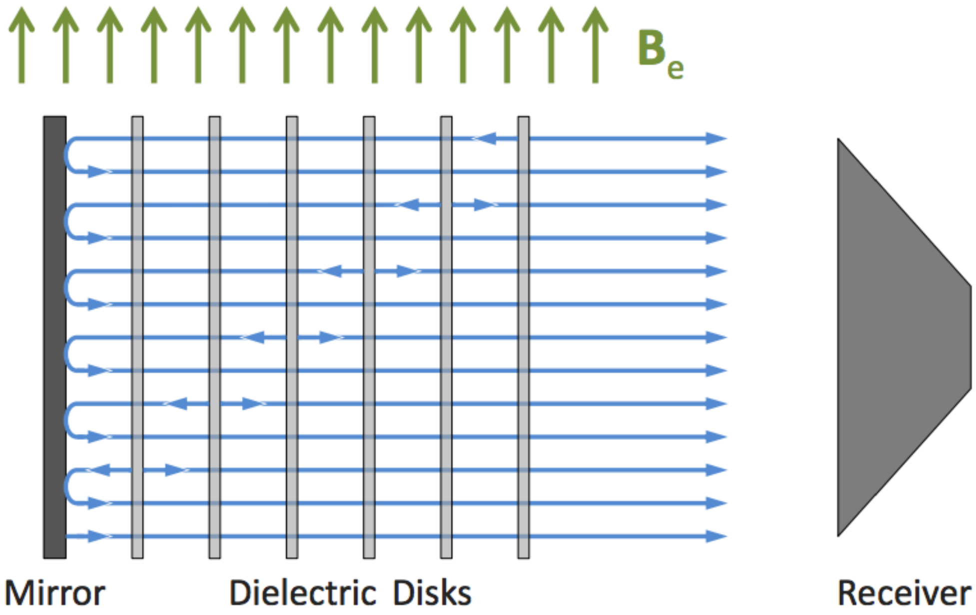
- Wide bandwidth THz SPD.
- Simplified loss model with $Q=10^2$ to 10^5.
- Material $Bi(Fe)_2Se_3$.

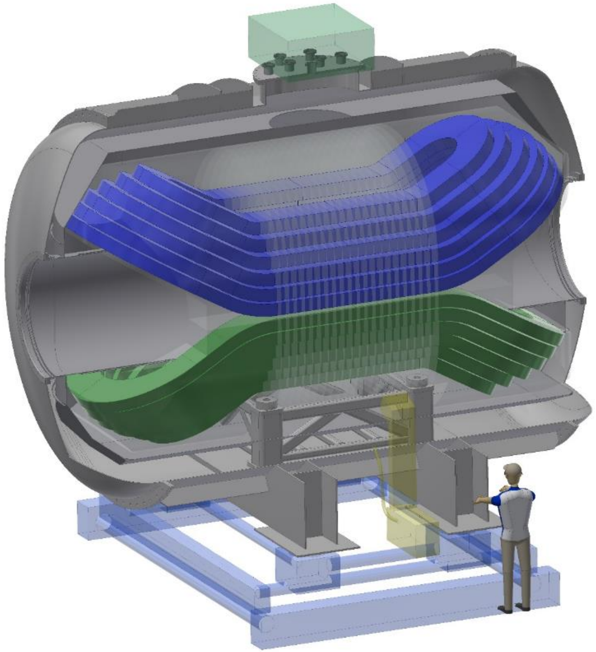


Figs: MADMAX collaboration

"MADMAX" Dielectric Haloscope

Experiment to be built at DESY (Hamburg) in 5-10 years. Frequency 10-100 GHz.





Different technologies target different frequencies. Nature will decide who chose correctly.

RESONANCE WIDTH AND LOSSES

There's always a catch…

Dielectric Function and Conduction

Recall that conductivity, σ, leads to damping of the electric field by charge redistribution:

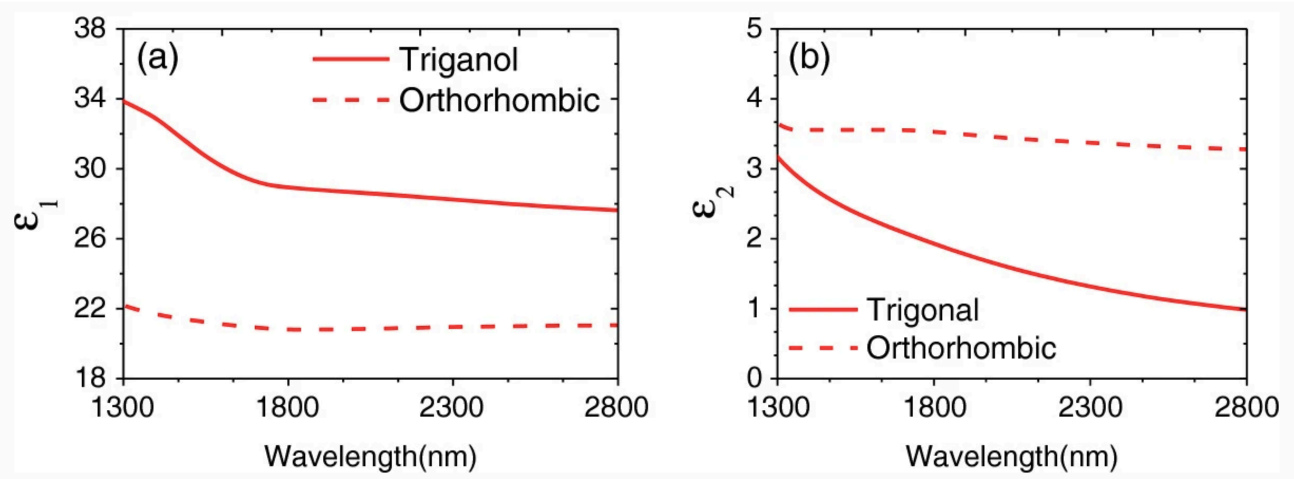
$$\epsilon\ddot{E} + \sigma\dot{E} + k^2 E + \frac{\alpha}{\pi}B_0\ddot{\theta} = J\cos m_a t$$

Changing units: $\sigma = 0.6\,\mathrm{meV}(\Omega\mathrm{cm}/\rho)$ high ρ → high Q, but TIs not good insulators.

Bi_2Se_3 dielectric function.
A good guide?
Power law extrapolation:

$$\Rightarrow \tan\delta \sim 10^{-4}$$

$$\sigma \sim 1\,\mu\mathrm{eV} \;\; Q \sim 10^3$$



Cao & Wang (2013)

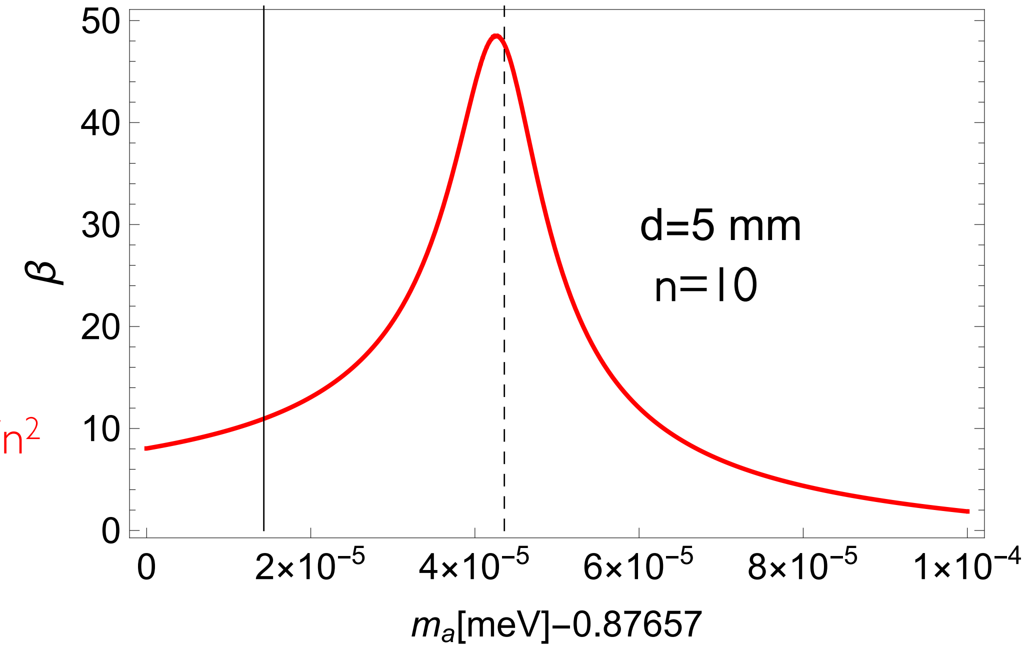
"Boost Factor" Resonance Width

In a finite dielectric, life isn't as simple as Q alone. Compute "Fabry-Perot boost", β.

Lossless limit: $\beta_{\max} = \left(\frac{d\omega}{\pi}\right)^2$

$$Q_{\rm eff} = 10^5 (\nu d/\mathrm{THz\ cm})^3$$

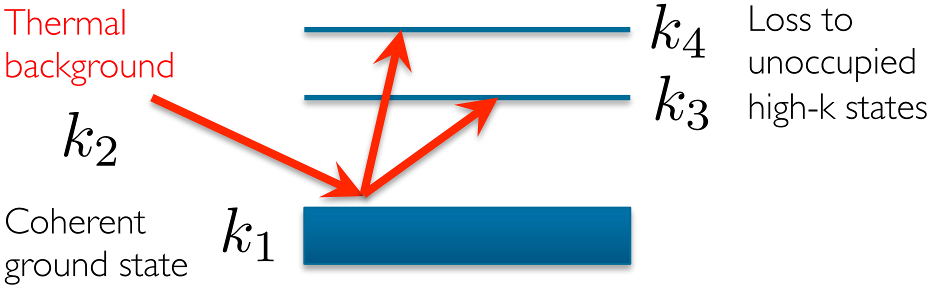
Refraction → narrow band power, by $1/n^2$

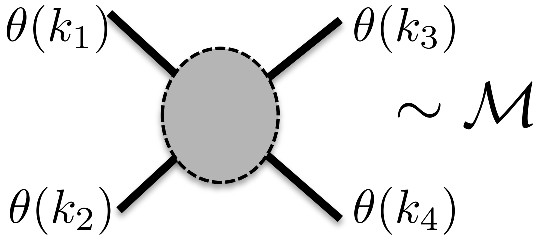


Magnetic Losses

Lvov, *Wave Turbulence* (1994)
Bayrackci et al (2013)

Thermal magnons can scatter off the ground state and destroy its coherence:





Scattering appears in the collision term in the Boltzmann equation → coherence time.

$$\dot{n}_1 = -\int n_1 n_2 |\mathcal{M}|^2 \,\mathrm{d}\Phi = -n_1 \langle \sigma v n_2 \rangle = -\Gamma(T) n_1$$

Neutron scattering measurement of antiferromagnet MnF_2:

$$\Gamma(4\mathrm{K}) \sim \mu\mathrm{eV} \Rightarrow Q \sim 10^3$$

FINDING THE AXION QUASIPARTICLE

The right antiferromagnetic topological insulator hasn't been found, yet…

Manganese Bismuth Telluride: $Mn_xBi_yTe_z$

New class of intrinsically magnetic TIs, hot topic in materials science.
Hunt for dynamical axion is on!

(124) phase crystals supplied by UCLA. Wrong symmetry → AFMR but no axion quasiparticle. ☹
Test case for characterisation ☺
Doping with Sb increases resistivity → reduce losses. Samples shipped from SUS-Tech ☺
(225) axion quasiparticle candidate under production ☺

THz Spectroscopy @ INFN Padova

a

Polariton spectrum has a gap near spin wave mass, m_s.

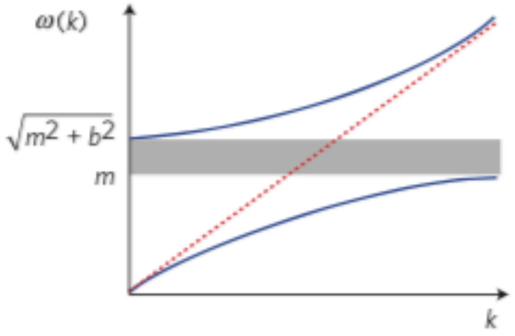
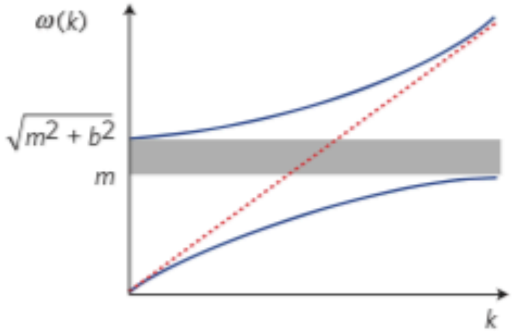


Fig: Li et al (2010)

THz Spectroscopy @ INFN Padova

a Polariton spectrum has a gap near spin wave mass, m_s.



b No E.B → no polariton. Ordinary transmission

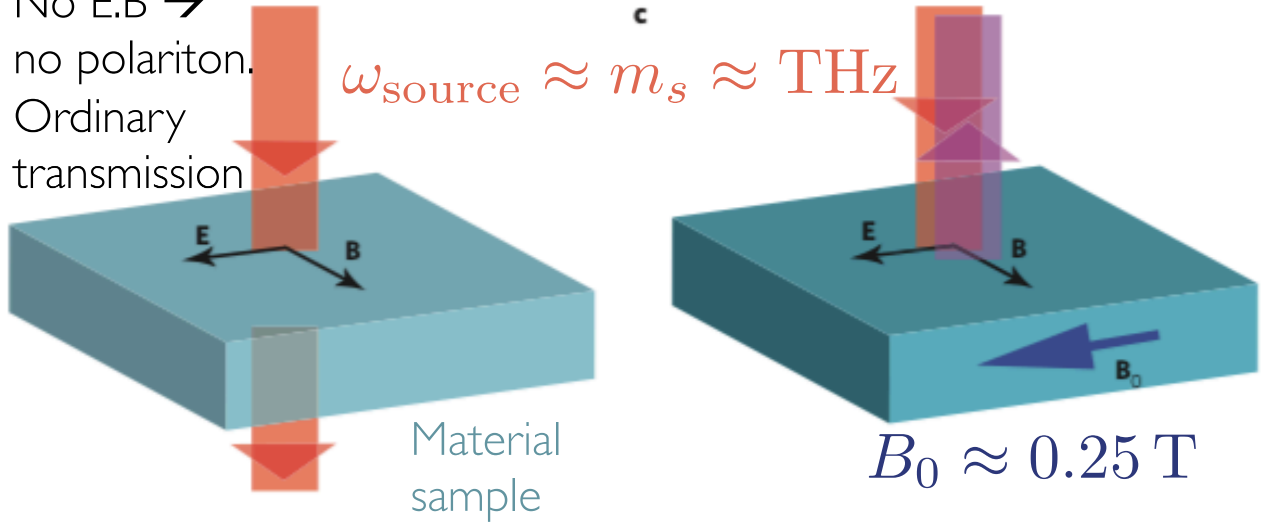


Fig: Li et al (2010)

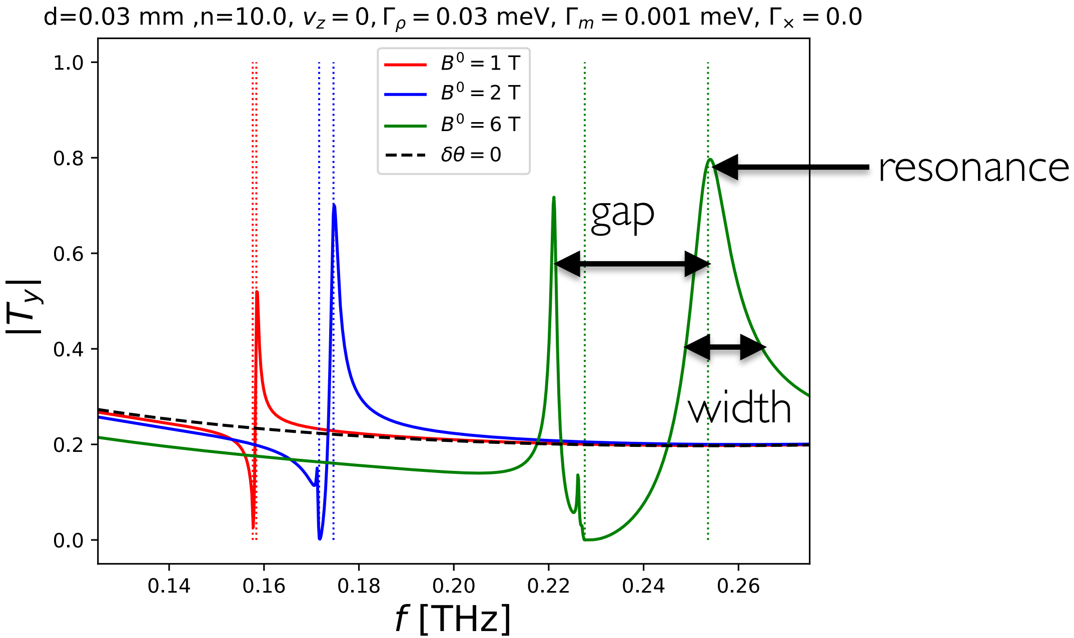
c. Applied B mixes photon to polariton. There are no states allowed with gap frequencies. → there can be no transmission for a source beam in the gap → total reflectance.

Polariton Transmission (Theory)

- Identify axion-quasiparticle resonance and measure it's width.

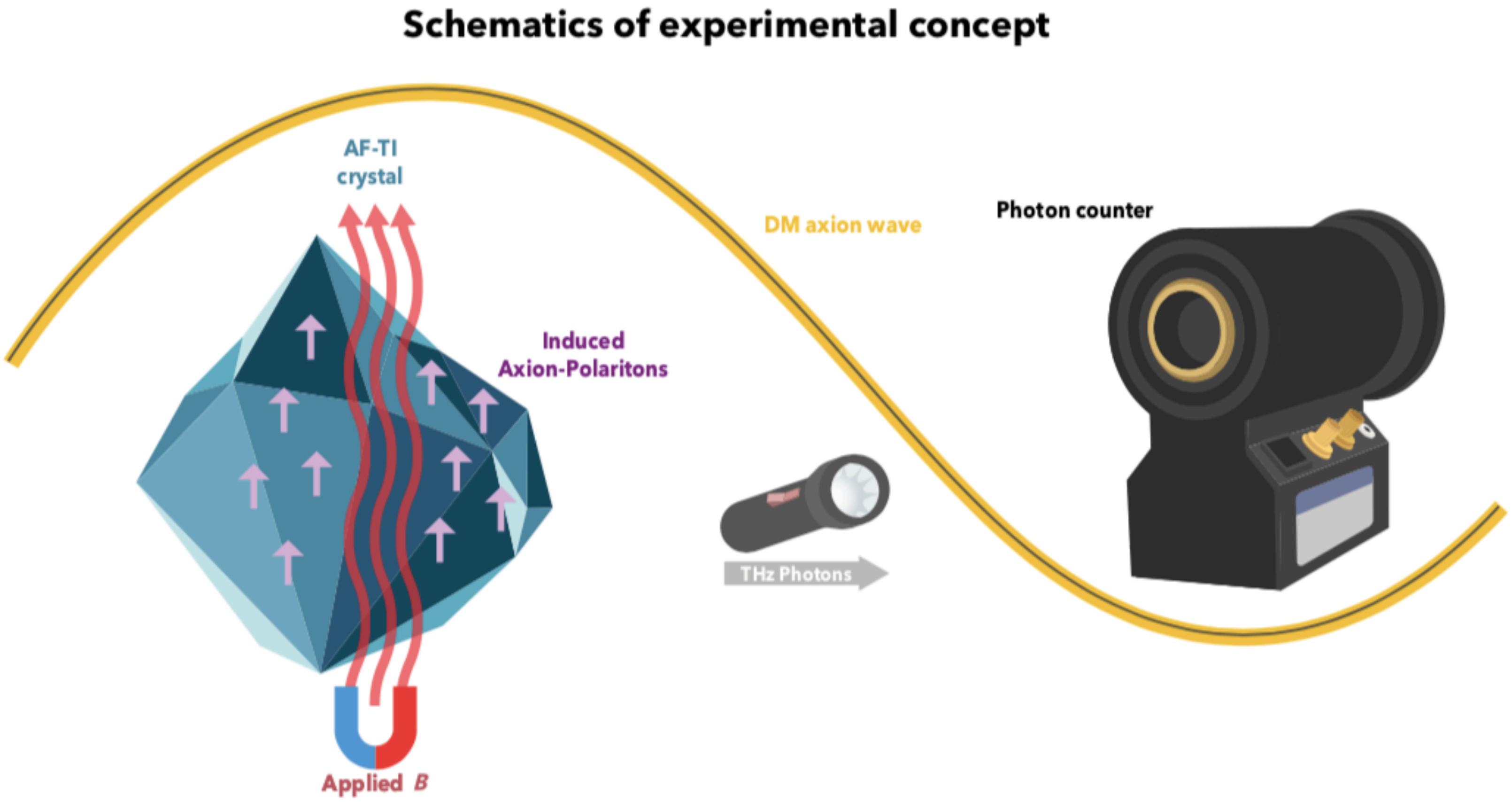
→ Discovery of the axion quasiparticle!

- Work with many materials to find best β and bandwidth.
- Scale up to large volumes
- Detect axion dark matter.



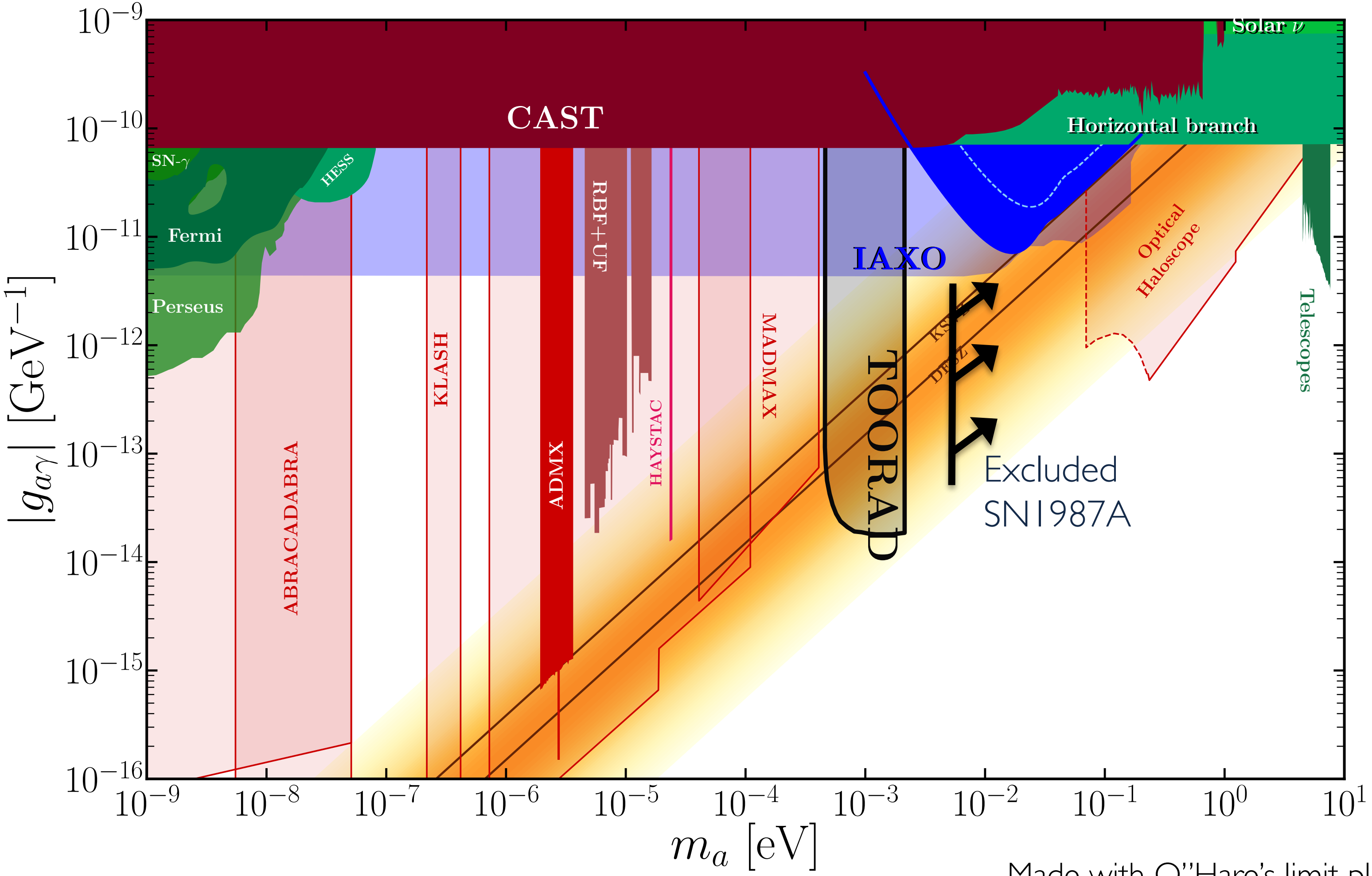
TOORAD COLLABORATION

M. Ali (MPI Halle), C. Braggio (INFN), F. Chadha-Day (Cambridge), N. Crescini (INFN), K.C. Fong (Harvard), E. Hardy (Liverpool), S. Hoof (Göttingen), M. Lawson (Stockholm), E. Lentz (Göttingen), D. J. E. Marsh (Göttingen), A. Millar (Stockholm), J. Schuette-Engel (Hamburg), A. Sekine (RIKEN), L. Smejkal (Mainz)



>80 page paper to appear ~November

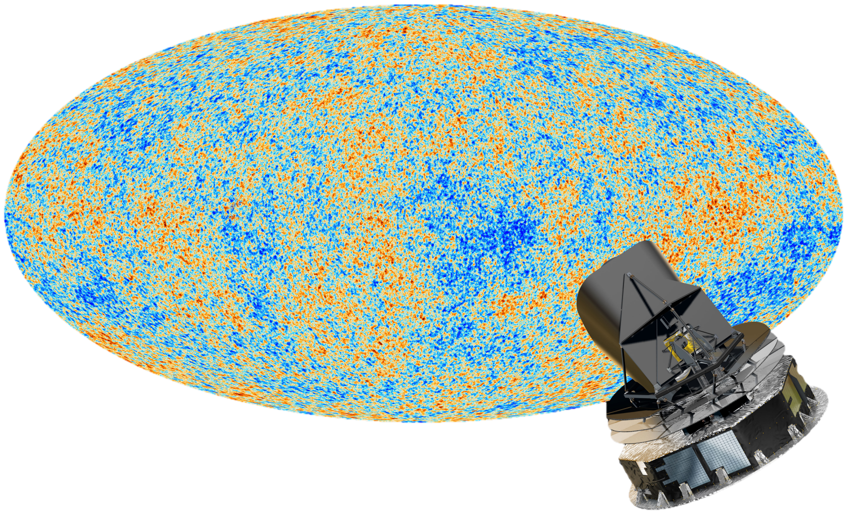
BACKUP SLIDES

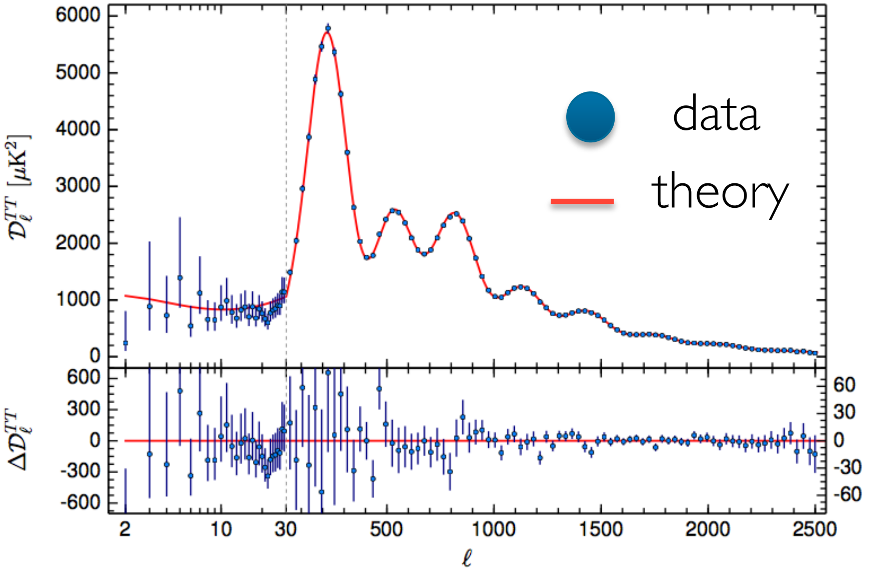


Made with O''Hare's limit plotter.

Dark Matter in the Cosmos

Planck Collaboration





$$\rho_{\mathrm{DM}} \approx 4 \times \rho_{\mathrm{ordinary}}$$

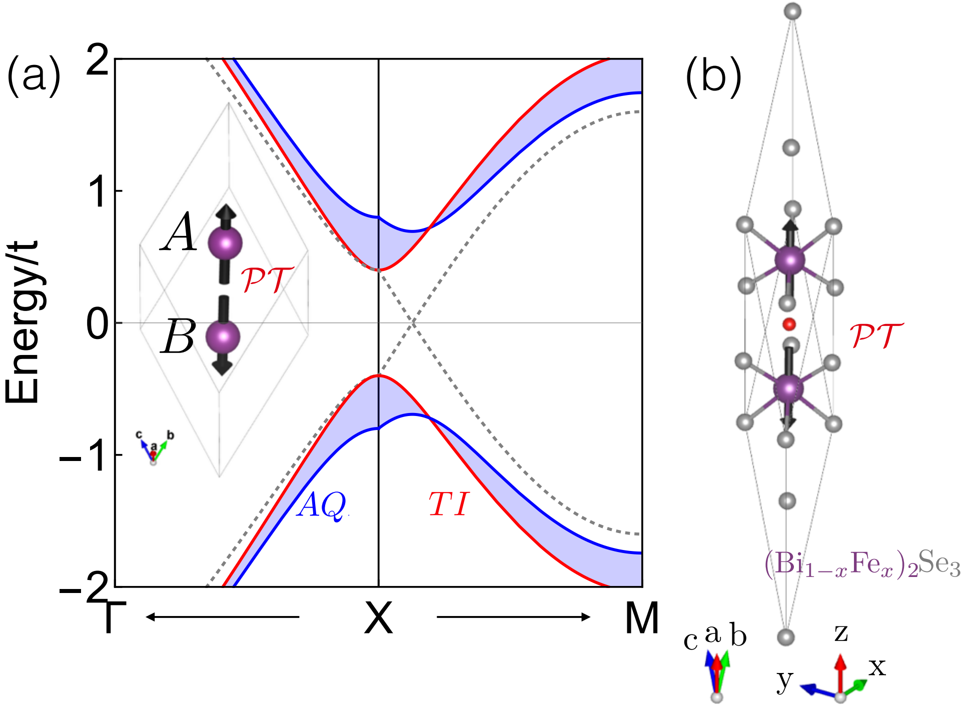
(measured to 1% precision)

NB: "modified gravity" cannot explain the acoustic features in the data.

Axion Quasiparticles in AF-TIs

Magnetic TI with broken symmetries→ Θ-term is dynamical.

Longitudinal magnons have quantum numbers to couple Θ→ dynamical $\delta\theta$ axion-like coupling to E.B



Single Photon Detection

Dicke radiometer eq. in THz. Standard quantum limit (SQL) noise T_Q~10K, is relatively large.
SQL assumes measurement of amplitude & phase of a radio wave, and Hesinberg.

$$\Delta E \Delta t \geq \hbar \Rightarrow k_B T \geq \hbar \omega_a$$

Measurement time τ ends up being many thousands of years for axion signal detection.
Single photon detection (SPD) bypasses this by throwing out the phase information.

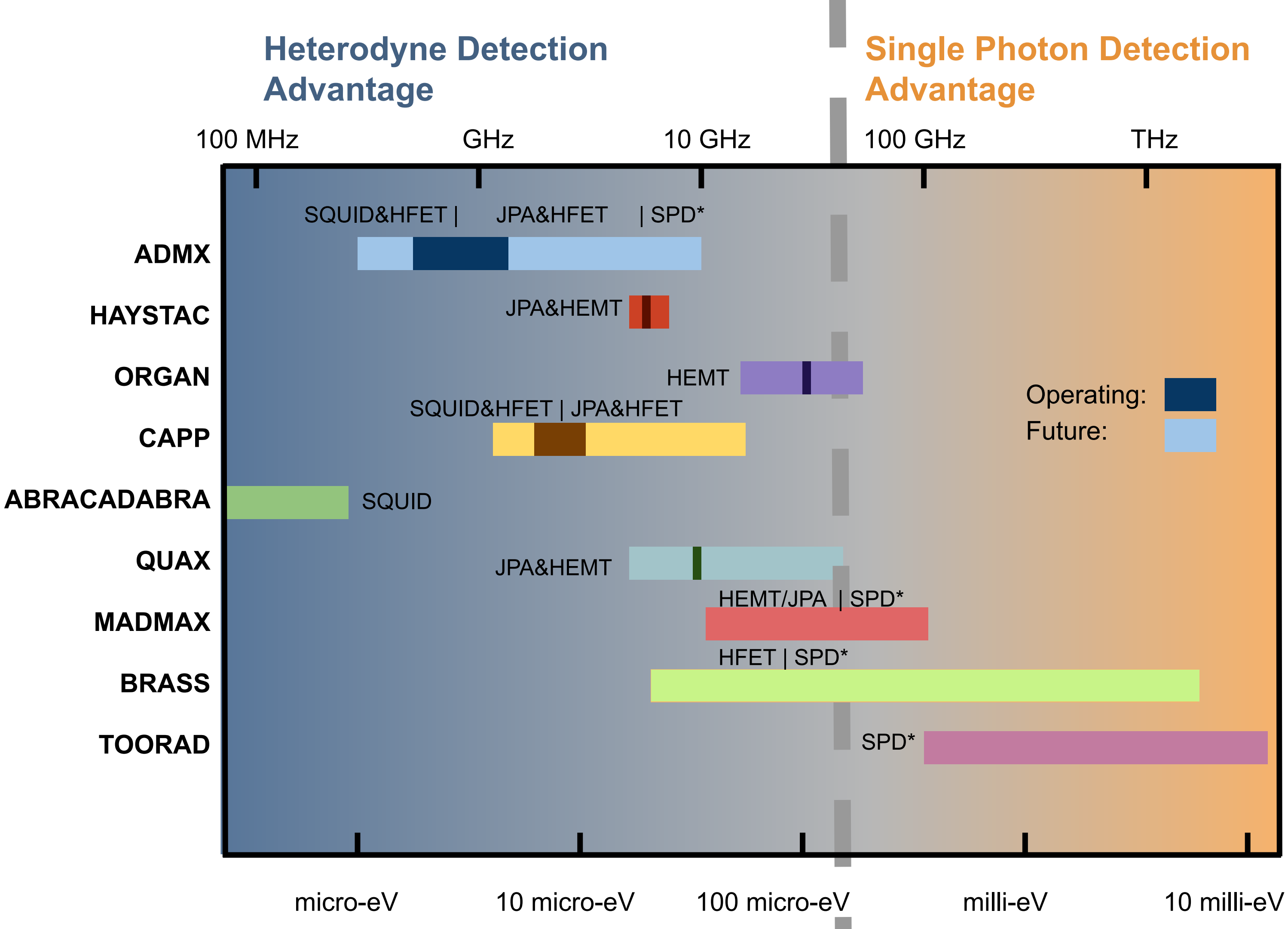
$$P \sim 10^{-23}\,\mathrm{W} \sim 10^{-4} \times 10^{-19}\,\mathrm{J\,s^{-1}} \sim 0.1\,\mathrm{meV\,Hz}$$

1 meV photon
every 10s

SPD is hard at low ~GHz frequencies, but becomes feasible in THz.
Described by dark count, Γ_d, efficiency, ε. Taking $\varepsilon\Gamma_d \sim 10^{-3}$ Hz<R=0.1 Hz → integration time:

$$\mathrm{SNR} = \sqrt{2[(s+b)\ln(1+s/b) - 3]} = 3 \Rightarrow \tau \sim 10\,\mathrm{s}$$

Sometimes there is a free lunch!



Heterodyne Detection Advantage
Single Photon Detection Advantage
100 MHz
GHz
10 GHz
100 GHz
THz
SQUID&HFET | JPA&HFET | SPD*
ADMX
JPA&HEMT
HAYSTAC
HEMT
ORGAN
SQUID&HFET | JPA&HFET
CAPP
ABRACADABRA
SQUID
QUAX
JPA&HEMT
HEMT/JPA | SPD*
MADMAX
HFET | SPD*
BRASS
SPD*
TOORAD
Operating:
Future:
micro-eV
10 micro-eV
100 micro-eV
milli-eV
10 milli-eV

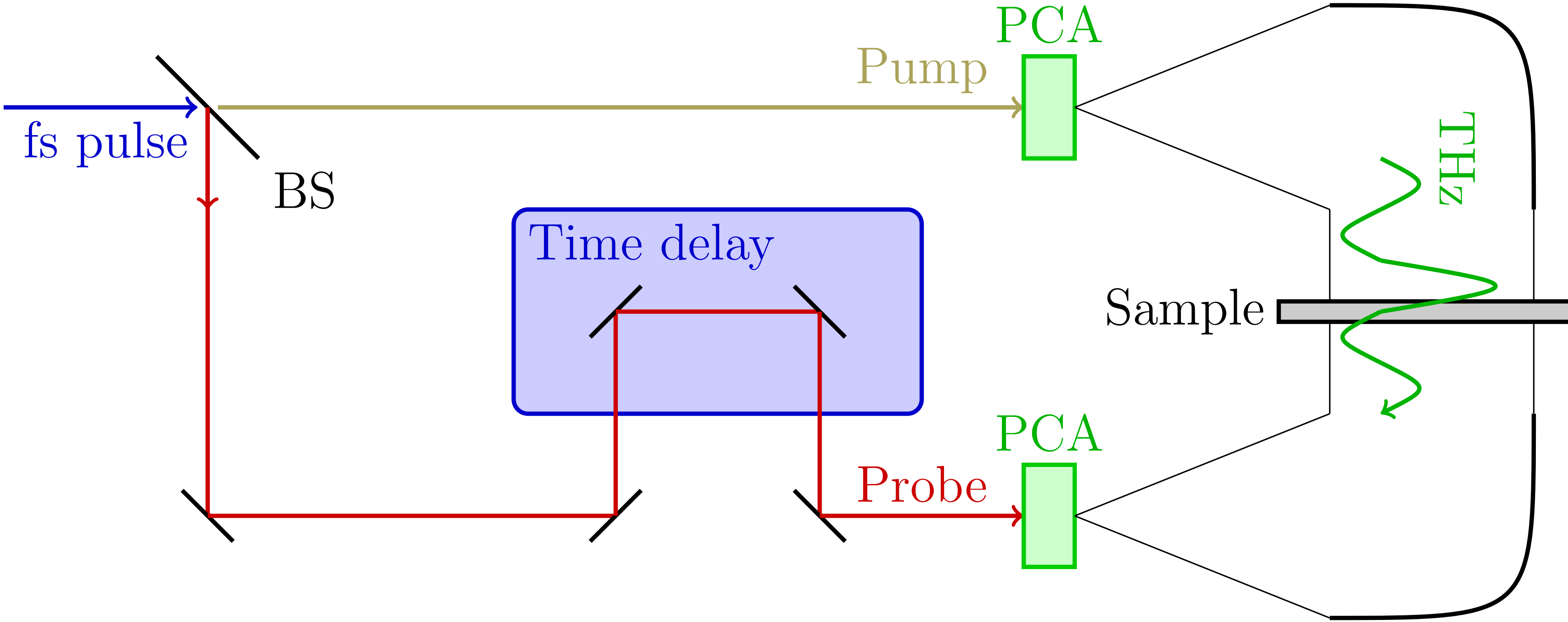
Condensed Matter > Superconductivity

[Submitted on 11 Nov 2019]

Magic-angle bilayer graphene nano-calorimeters -- towards broadband, energy-resolving single photon detection

P. Seifert, X. Lu, P. Stepanov, J. R. Duran, J. N. Moore, K. C. Fong, A. Principi, D. K. Efetov

Because of the ultra-low photon energies in the mid-infrared and terahertz frequencies, in these bands photodetectors are notoriously underdeveloped, and broadband single photon detectors (SPDs) are non-existent. Advanced SPDs exploit thermal effects in nano-structured superconductors, and their performance is currently limited to the more energetic near-infrared photons due to their high electronic heat capacity. Here, we demonstrate a superconducting magic-angle twisted bilayer graphene (MAG) device that is capable of detecting single photons of ultra-low energies by utilizing its record-low heat capacity and sharp superconducting transition. We theoretically quantify its calorimetric photoresponse and estimate its detection limits. This device allows the detection of ultra-broad range single photons from the visible to sub-THz with response time around 4 ns and energy resolution better than 1 THz. These attributes position MAG as an excep-tional material for long-wavelength single photon sensing, which could revolutionize such disparate fields as quantum information processing and radio astronomy.

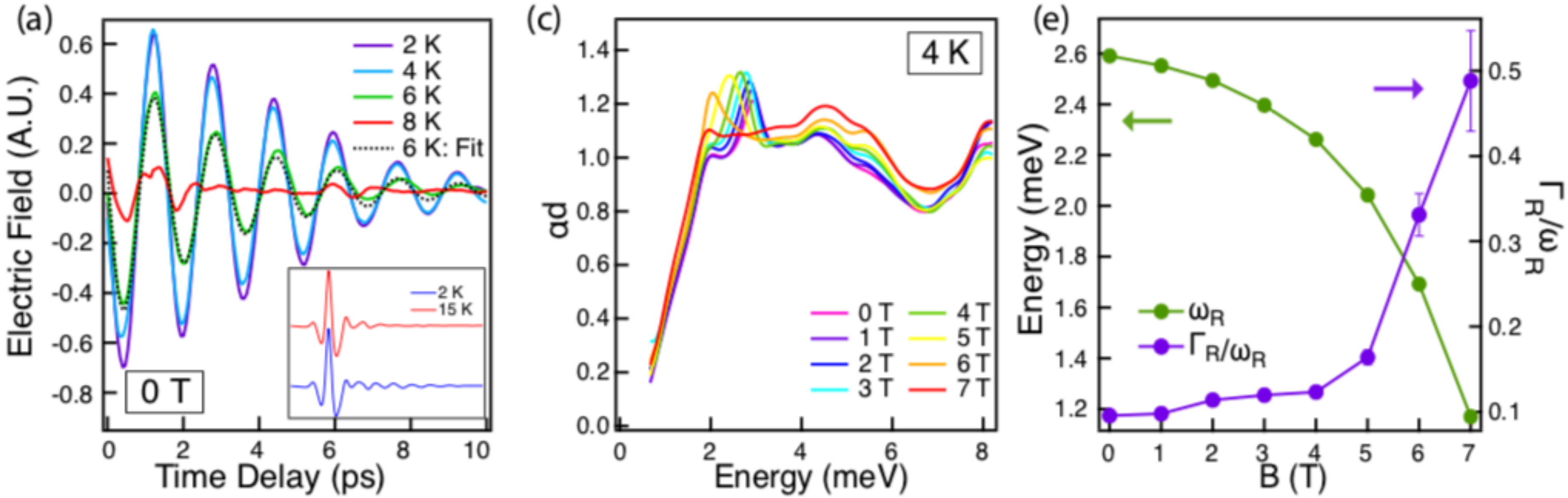


fs pulse
BS
Pump
PCA
Time delay
Probe
PCA
Sample
THz

Example: AFMR by Transmission

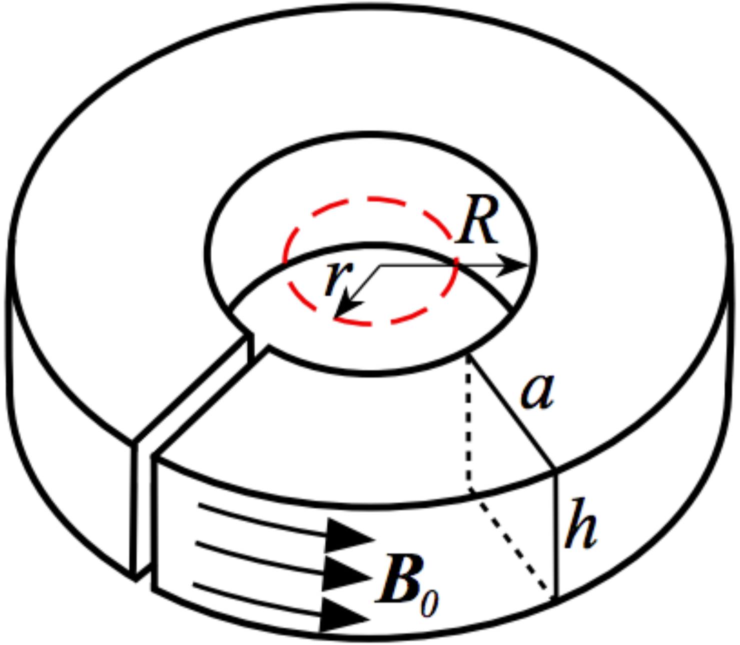
Little et al (2017)

We would like to do measurements of AFMR ω and Γ like this:



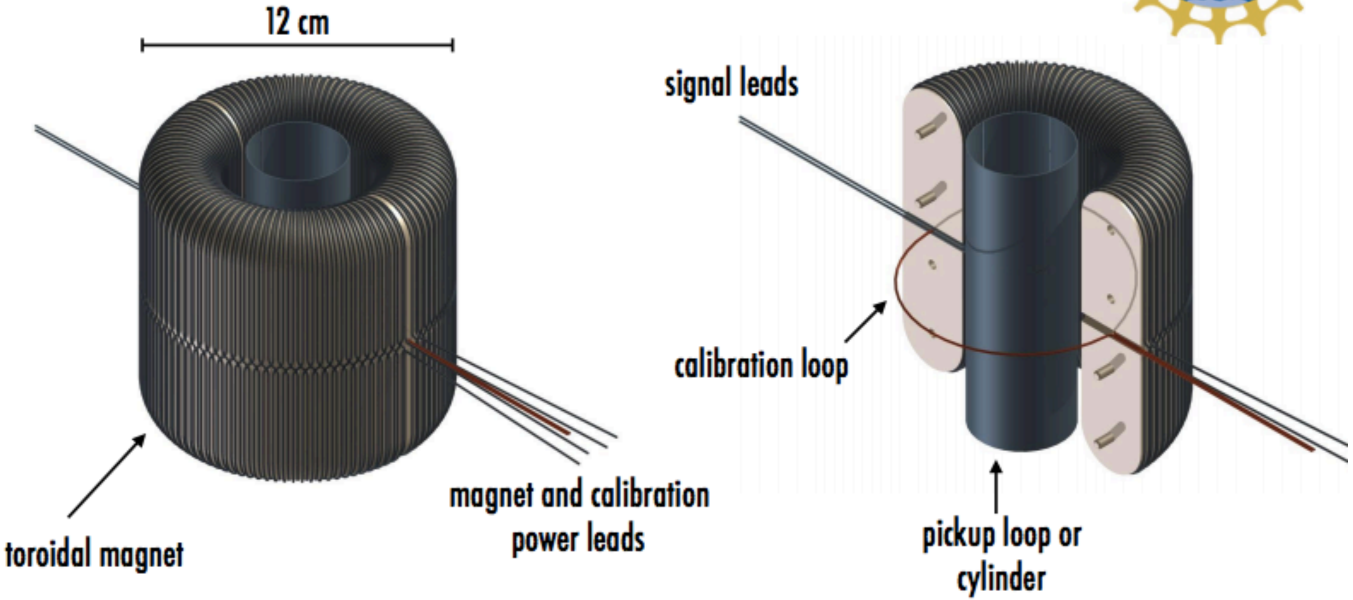
“DMRadio/ABRACADABRA”

Axion induces an effective current in a SQUID pickup loop. Broadband and resonant search. Abra-10cm prototype at MIT.



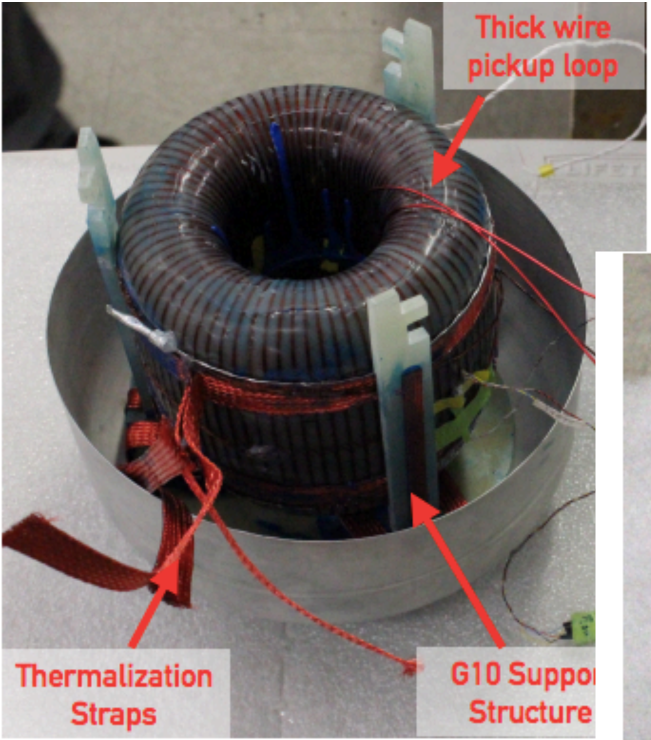
“A Broadband/ Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus”, Kahn et al (2016)

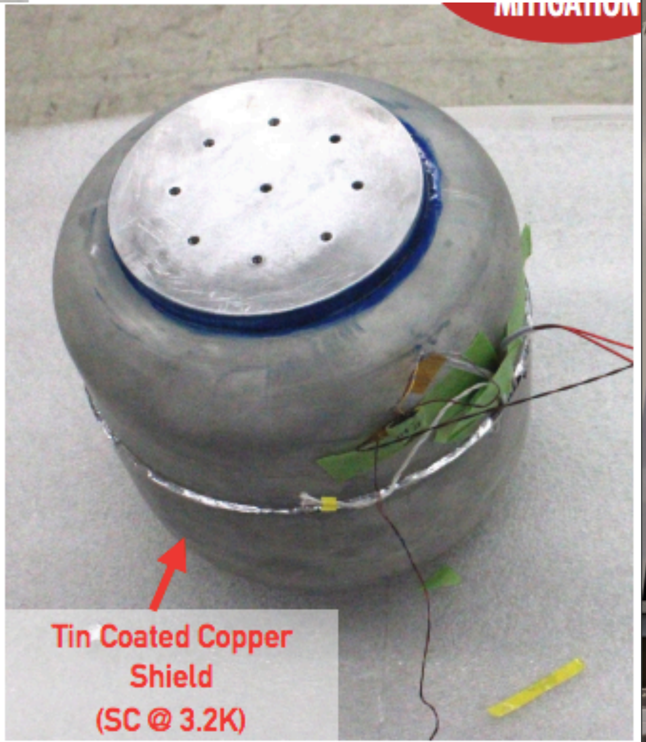
ABRACADABRA



ABRACADABRA-10cm Conceptual Design

Drawings by D. Winklehner


Thick wire pickup loop
Thermalization Straps
G10 Suppor
Structure


Tin Coated Copper Shield
(SC @ 3.2K)


ABRACADABRA
ABRA

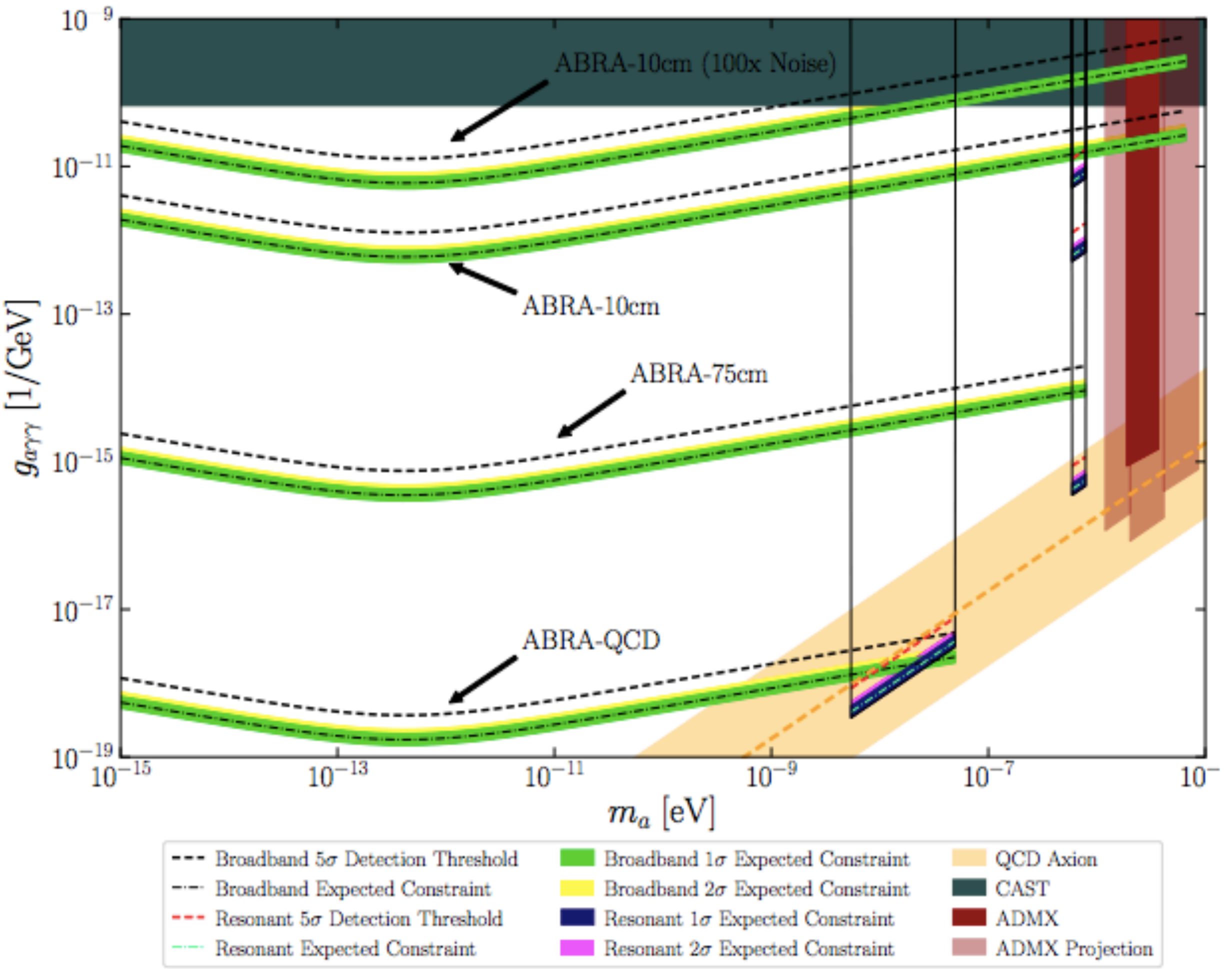


Fig: Winslow, PATRAS-18