Axion Quasiparticles for Axion Dark Matter Detection

David J. E. Marsh

Axion-WIMP (Patras), 2021

DJEM et al PRL (2018) and Schütte-Engel, DJEM et al 2102.05366

UKRI
Science and
Technology
Facilities Council

KING'S
College
LONDON

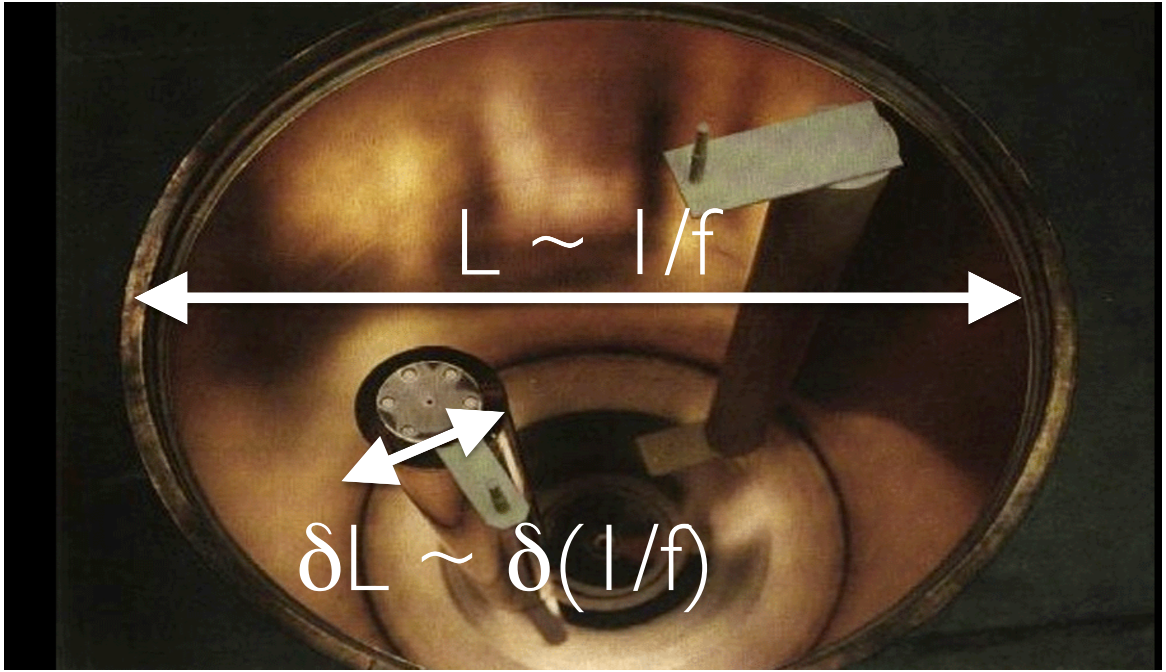
COLLABORATORS

M. Ali (MPI Halle), C. Braggio (INFN), F. Chadha-Day (Durham), K.C. Fong (BBN-Tech), E. Hardy (Liverpool), S. Hoof (Göttingen), E. Lentz (Göttingen), C. Liu (SUS-Tech), A. Millar (Stockholm), J. Schuette-Engel (UIUC), A. Sekine (RIKEN), L. Smejkal (Mainz)

How to Detect Axions

Sikivie Haloscope

Sikivie (1983)
Image: ADMX



Microwave cavity.

Resonance when axion frequency ~ cavity natural frequency.

Volume → works for frequencies ~ GHz

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

meV/THz Challenge

(see Knirck talk about BREAD)

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

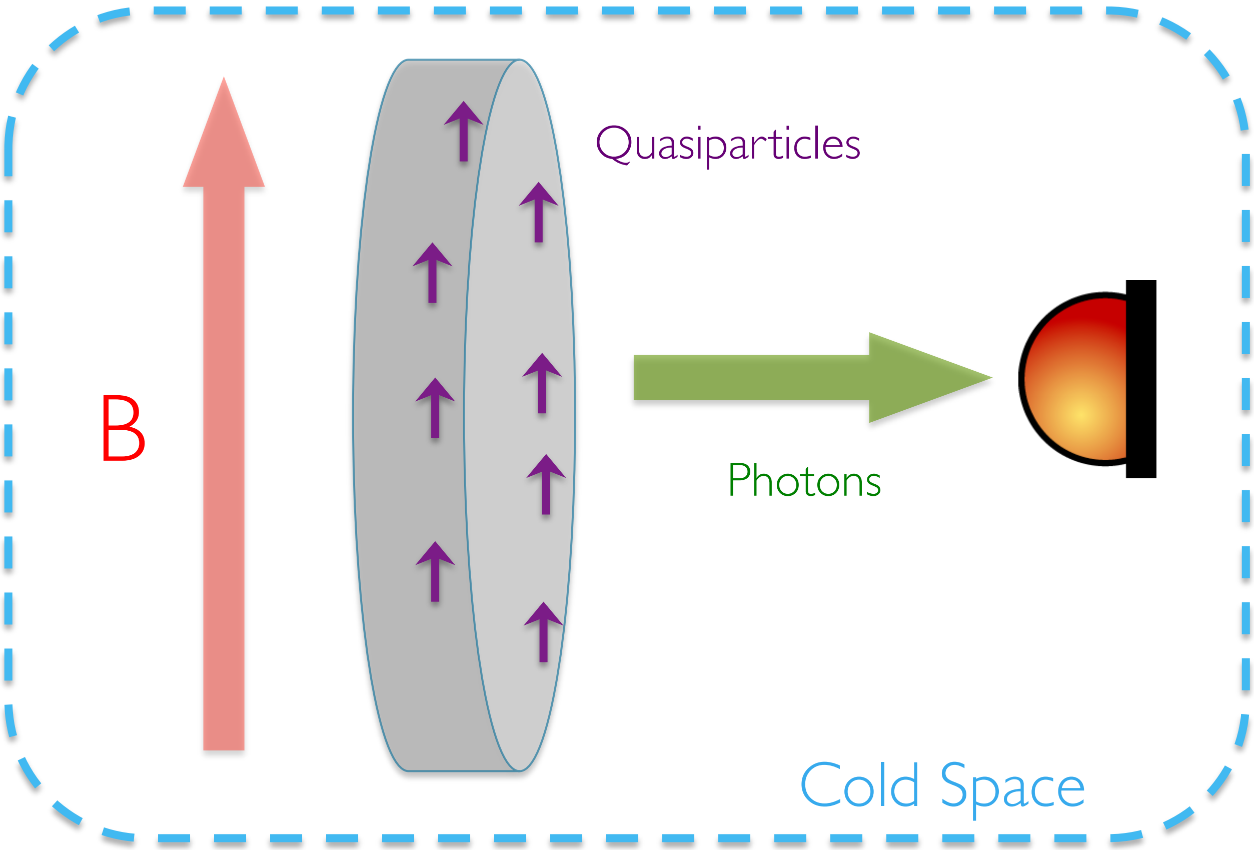
$$P = \boxed{\rho_{\rm DM}}\boxed{\frac{g^2}{m_a}}\boxed{B^2\ Q\ V_{\rm eff}}$$

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

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

Materials Science:

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



“Resonant dish antenna”
meV axion DM search for A~$(20\ \text{cm})^2$

TOORAD = TOpOlogical Resonant Axion Detection

AXION QUASIPARTICLES

Review: Sekine & Nomura 2011.13601

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 magnon has the right properties to couple to E.B → axion quasiparticle.

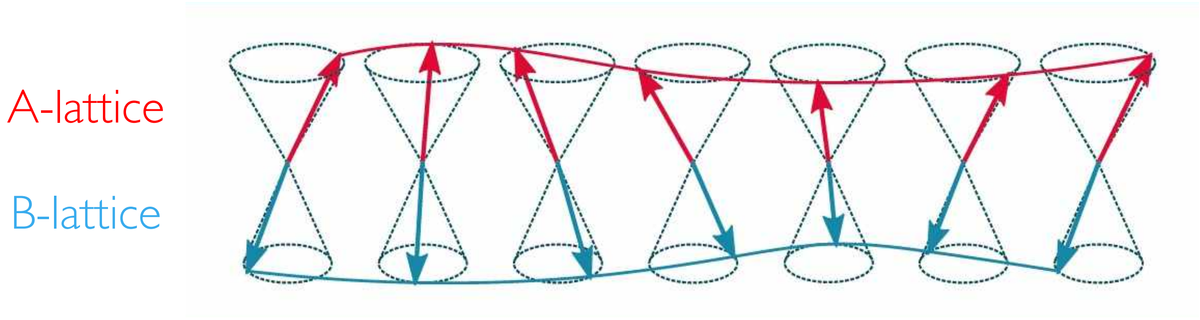
$$\delta\Theta \approx \frac{U}{M_0}\delta n_z$$

U = "Hubbard term" , M_0 = bulk band gap, nz = magnon

Key idea: use the axion quasiparticle to detect axion dark matter.

Antiferromagnetic "Magnons"

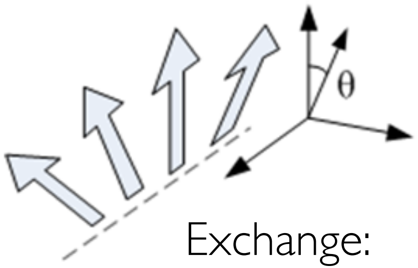
Figs: Joel Cramer and
Wikiwand.com



External field →
spin precession →
"spin wave"

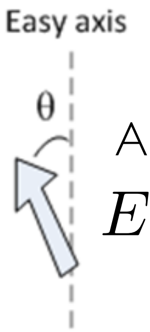
Antiferromagnetic "magnetization": $n = \langle M_A \rangle - \langle M_B \rangle$

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



Exchange:

$$E = \mu H_E$$

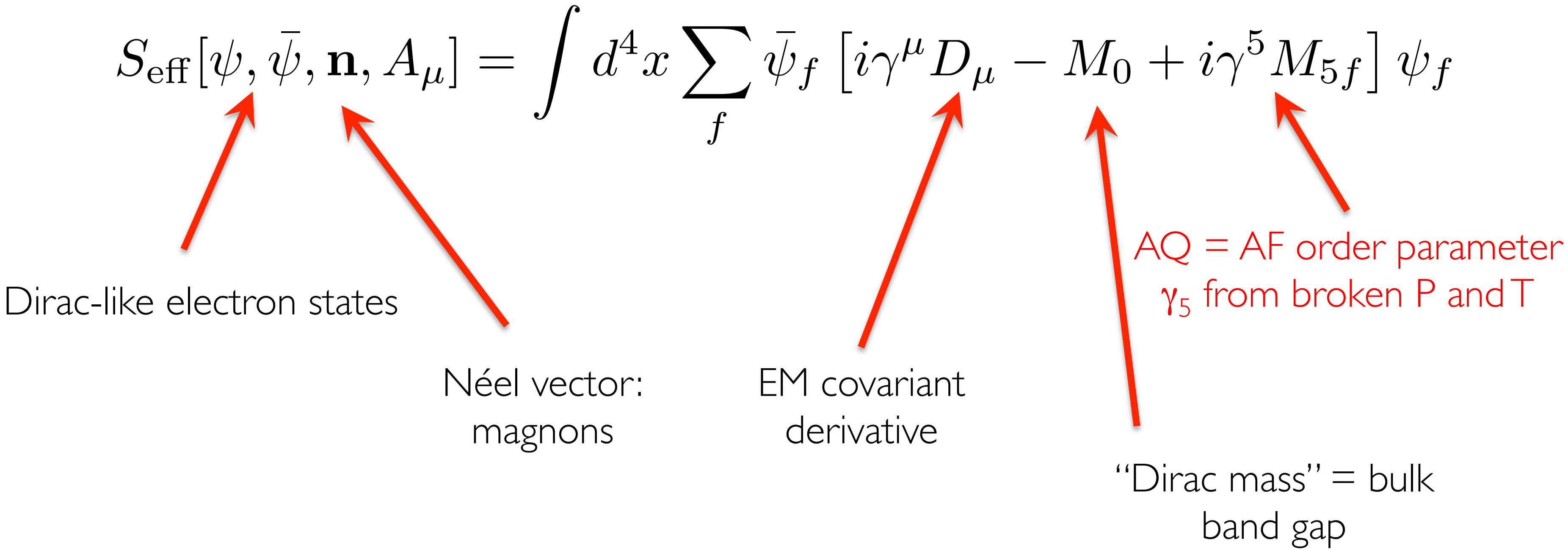


Anisotropy:

$$E = \mu H_A$$

Axion Quasiparticles

In our material candidates (*), the AQ is the longitudinal (amplitude) magnon mode.



$$S_{\text{eff}}[\psi,\bar{\psi},\mathbf{n},A_\mu]=\int d^4x\sum_f\bar{\psi}_f\left[i\gamma^\mu D_\mu-M_0+i\gamma^5 M_{5f}\right]\psi_f$$

Dirac-like electron states

Néel vector: magnons

EM covariant derivative

"Dirac mass" = bulk band gap

AQ = AF order parameter

γ_5 from broken P and T

Axion Quasiparticles

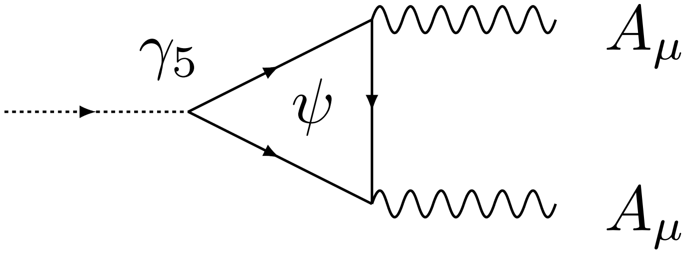
In our material candidates (*), the AQ is the longitudinal (amplitude) magnon mode.

$$S_{\text{eff}}[\psi, \bar{\psi}, \mathbf{n}, A_\mu] = \int d^4x \sum_f \bar{\psi}_f \left[i\gamma^\mu D_\mu - M_0 + i\gamma^5 M_{5f} \right] \psi_f$$

"Integrate in" dynamics for the order parameter M_5=Un. Triangle diagram → E.B coupling.

$$S_{\text{eff}}[\Theta] = \frac{f_\Theta^2}{2} \int d^4x \left[(\partial_t \delta\Theta)^2 - (v_i \partial_i \delta\Theta)^2 - m_\Theta^2 \delta\Theta^2 \right] + \frac{\alpha}{\pi} (\delta\Theta + \Theta_0)\, E \cdot B$$

$$\delta\Theta \approx \frac{\delta M_5}{M_0}$$



$\Theta_0 = \pi$ in topological insulators: surface Hall currents

Axion Quasiparticles

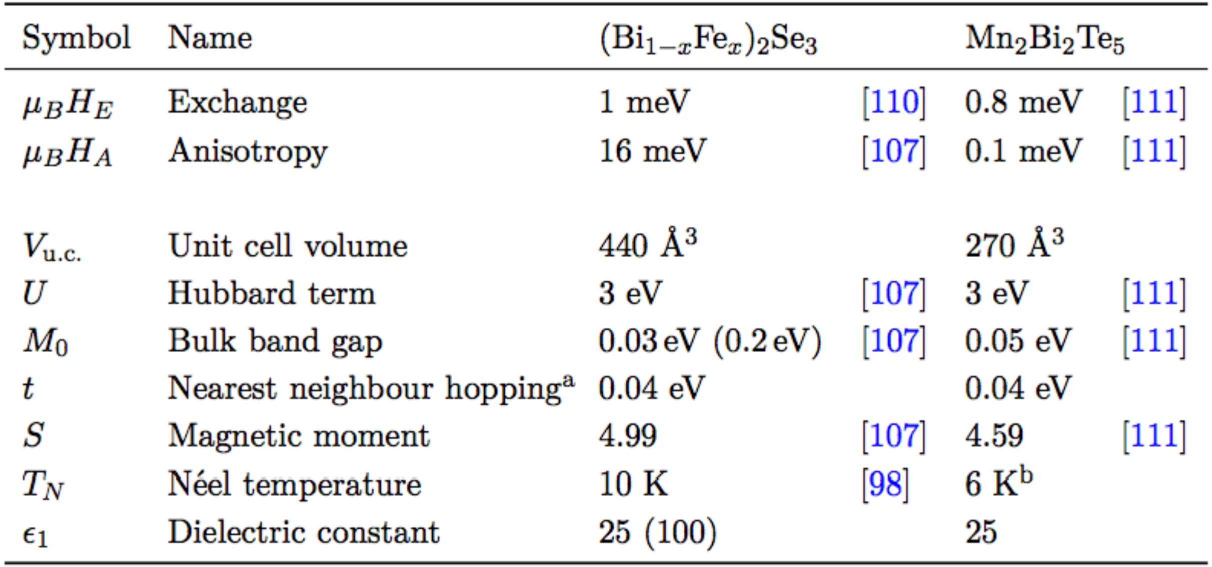
Li et al (2010) *ab initio* cubic lattice calculation → electron bands → AQ parameters:

$$f_\Theta = 30\ \mathrm{eV}\left(\frac{M_0}{0.03\ \mathrm{eV}}\right)^{0.5}\left(\frac{V_{\mathrm{u.c.}}}{440\mathrm{\AA}^3}\right)^{-0.5}\left(\frac{t}{0.04\ \mathrm{eV}}\right)^{-1.5}\left(\frac{\mathcal{I}_1}{4\times 10^{-7}}\right)^{0.5}$$

$$m_\Theta = 2\ \mathrm{meV}\left(\frac{S}{4.99}\right)\left(\frac{U}{3\ \mathrm{eV}}\right)\left(\frac{\mathcal{I}_2/\mathcal{I}_1}{4\times 10^{-8}}\right)^{0.5}$$

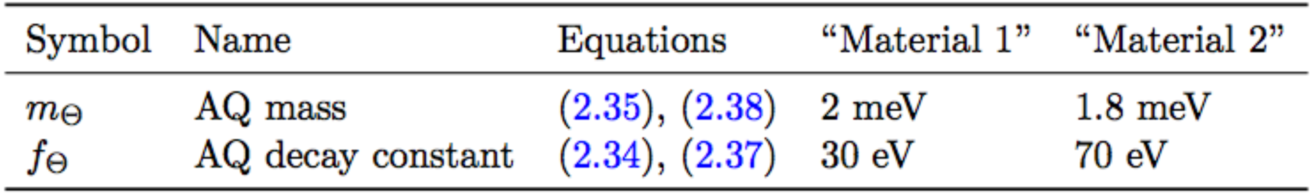
Band integrals from DFT

Measured Simulated



Symbol	Name	$(Bi_{1-x}Fe_x)_2Se_3$		$Mn_2Bi_2Te_5$	
$\mu_B H_E$	Exchange	1 meV	[110]	0.8 meV	[111]
$\mu_B H_A$	Anisotropy	16 meV	[107]	0.1 meV	[111]
$V_{\text{u.c.}}$	Unit cell volume	440 Å^3		270 Å^3	
U	Hubbard term	3 eV	[107]	3 eV	[111]
M_0	Bulk band gap	0.03 eV (0.2 eV)	[107]	0.05 eV	[111]
t	Nearest neighbour hopping[a]	0.04 eV		0.04 eV	
S	Magnetic moment	4.99	[107]	4.59	[111]
T_N	Néel temperature	10 K	[98]	6 K[b]	
ϵ_1	Dielectric constant	25 (100)		25	

Rescaled estimates from cubic lattice model



Symbol	Name	Equations	"Material 1"	"Material 2"
m_Θ	AQ mass	(2.35), (2.38)	2 meV	1.8 meV
f_Θ	AQ decay constant	(2.34), (2.37)	30 eV	70 eV

At fixed frequency and B field, larger f_Θ is slightly favourable.

BOOST AMPLITUDE & LOSSES

Coupled Perturbations (lossless)

$$\epsilon \ddot{E} + k^2 E + \boxed{\frac{\alpha}{\pi} B_0 \delta\ddot{\Theta}} = \boxed{\frac{2 g_{a\gamma} B_0 \sqrt{\rho_{\mathrm{DM}}}}{m_a} \cos m_a t}$$

$$\delta\ddot{\Theta} + m_\Theta^2 \delta\Theta + \boxed{\frac{\alpha}{4\pi^2 f_\Theta^2} B_0 E} = 0$$

(assumed vs<<c)

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

Axion quasiparticle E-B coupling mixes E and **Θ** → effective photon mass ~ m_Θ ~meV

$$\ddot{\phi}_\pm + \omega_\pm^2 \phi_\pm = J_\pm \cos m_a t \qquad \{m_\Theta, f_\Theta\} \to \omega_+^2 = m_\Theta^2 + b^2$$

$$b = \frac{\alpha}{\pi\sqrt{2}} \frac{B_0}{\sqrt{\epsilon} f_\Theta} = 1.8 \text{ meV} \left(\frac{25}{\epsilon}\right)^{1/2} \boxed{\left(\frac{B_0}{2 \text{ T}}\right)} \left(\frac{64 \text{ eV}}{f_\Theta}\right),$$

Scan the resonance!

Polariton resonance → material acts like effective $n_\Theta < 1$: longer wavelength.

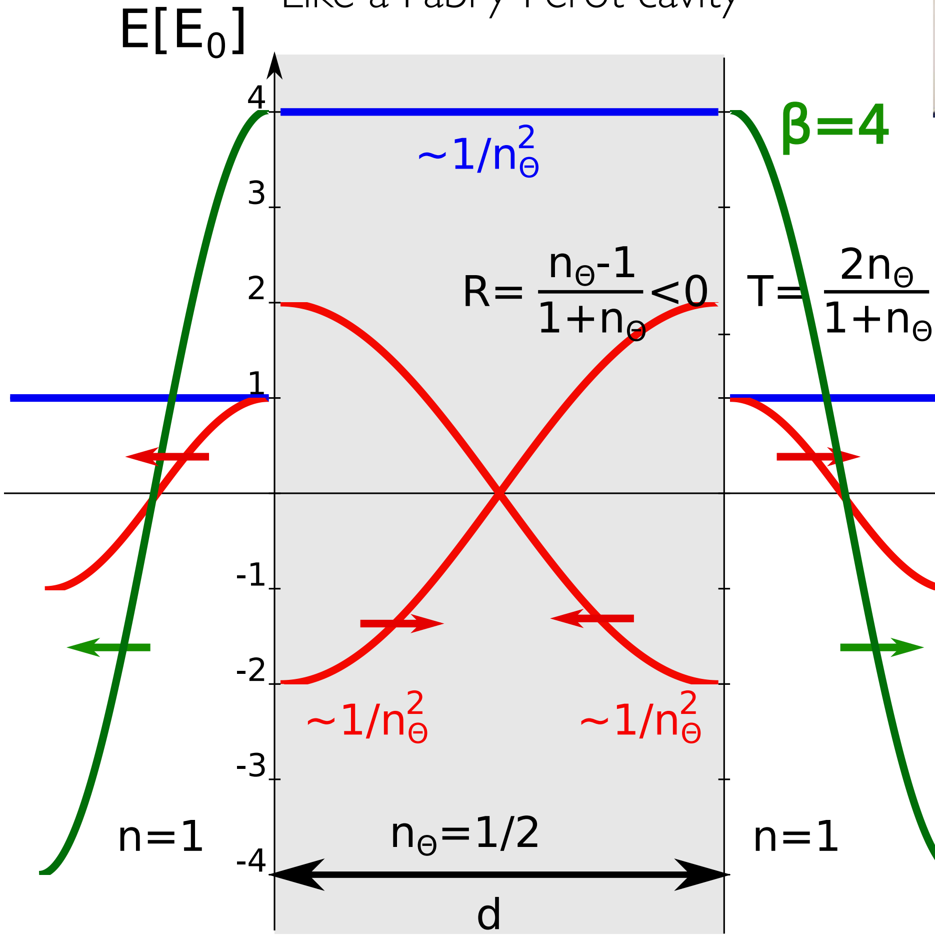
$$n_\Theta = n\left[1 - \frac{b^2}{\omega^2 - m_\Theta^2}\right]$$

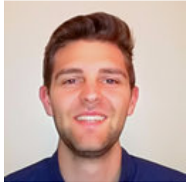
Constructive interference of reflected waves → boost amplitude $1/n_\Theta^2$.

$$P = \frac{E_0^2}{2}\beta^2 A$$

Boundary condition calculation follows MADMAX (Millar et al 2016; see Krieger talk)

Like a Fabry-Perot cavity





Dielectric Function

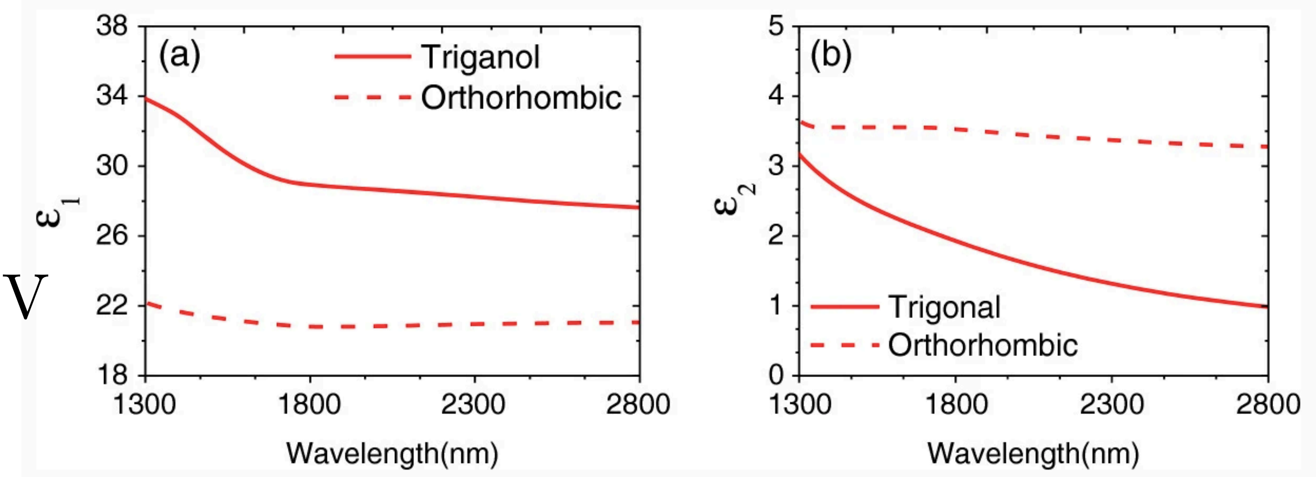
Recall that dielectrics have damping of the electric field:

$$\ddot{E} + \Gamma_\rho \dot{E} + \frac{k^2}{\epsilon_1} E + \frac{\alpha}{\epsilon_1 \pi} \delta \ddot{\Theta} = J \cos \omega_a t$$

Bi_2Se_3 dielectric function.
Power law extrapolation
from optical → THz

$$\epsilon_1 \Rightarrow n \approx 5$$

$$\epsilon_2 \Rightarrow \Gamma_\rho \sim 0.1 - 1\,\mu\text{eV}$$



c.f. THz transparent materials like silicon $\tan\delta \sim 10^{-4}$

Cao & Wang (2013)

Impurities and Domains

Bayrackci et al (2013)
Tveten et al (2015)

At low temperatures, constant effect of impurities dominates the magnon linewidth:

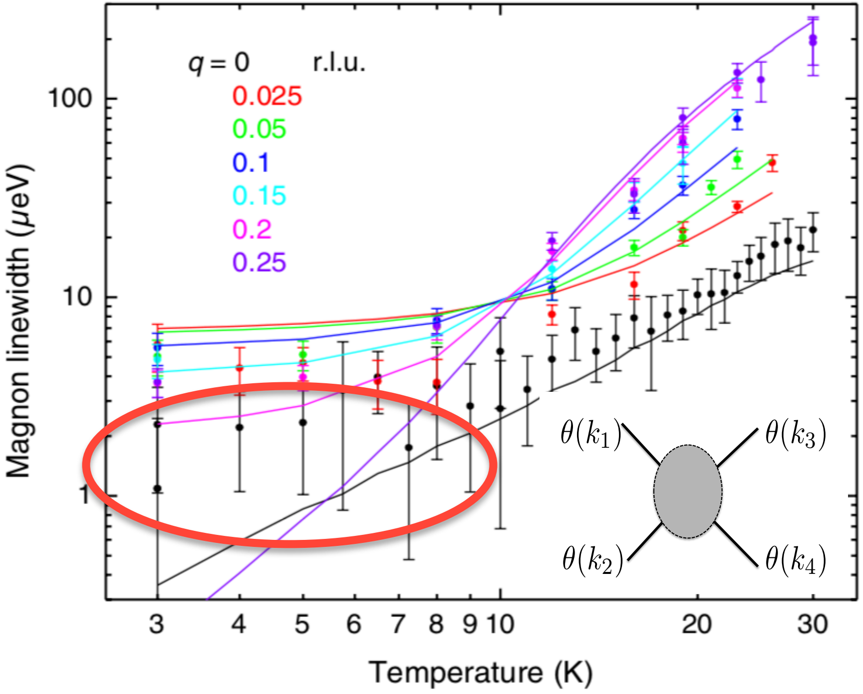
Poorly understood. Estimate for width:

$$\Gamma = \frac{\delta L}{L}\omega$$

Typical impurities on the scale of microns, while lattice scale ~ 10 Angstroms →

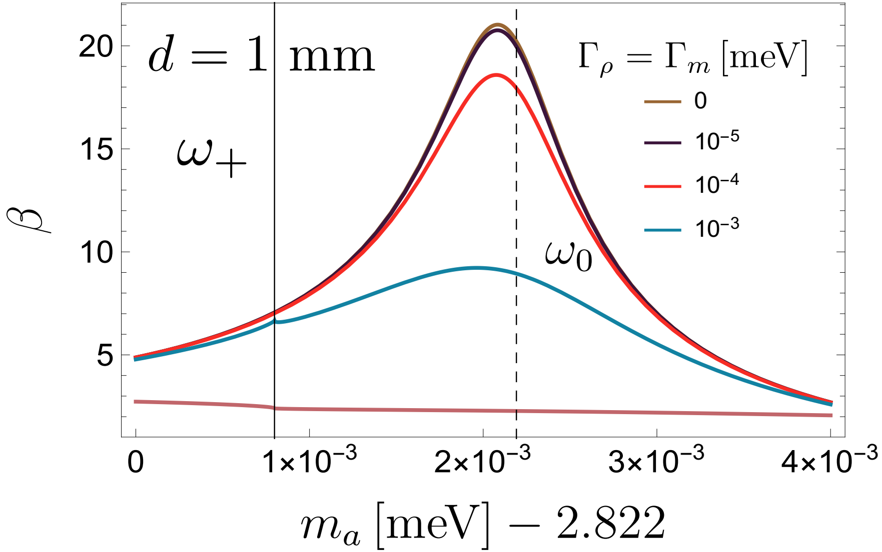
$$\Gamma \sim 1\,\mu\text{eV} \Rightarrow Q \sim 10^3$$

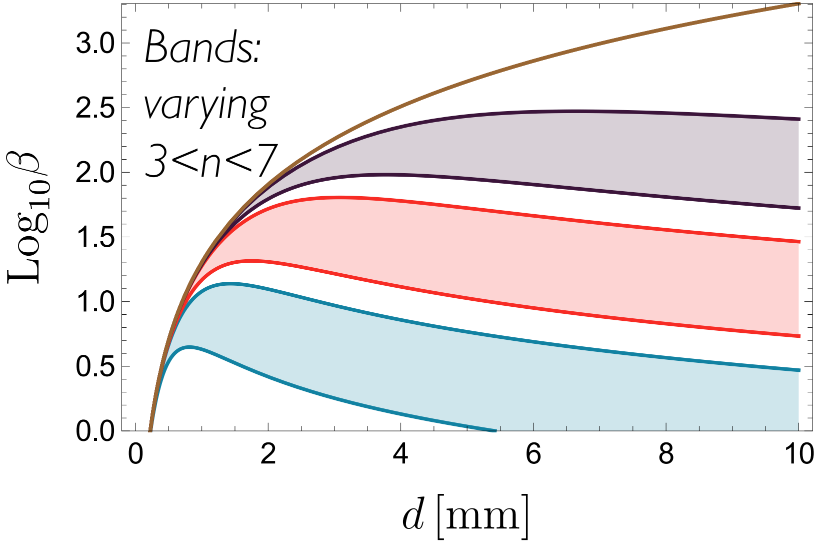
Neutron scattering on MnF$_2$



Boost Amplitude & Losses

“Material 2”: $Mn_2Bi_2Te_5$ at B=2 T





Resonant enhancement near polariton resonance. Increases with thickness. Limited by losses.

Losses → finite skin depth → optimal thickness ~ 1-2 mm for realistic values.

$$\beta^2 \sim 10^2 - 10^4$$

AXION DARK MATTER DETECTION

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

Photon rate on resonance for QCD axion: (see Knirck, Spagnolo, Kuzmin, McAllister…)

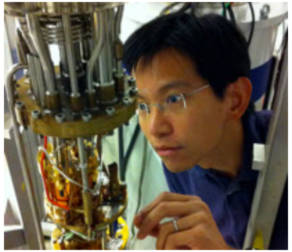
$$\Gamma_{a\to\gamma} = 3\times 10^{-4}\ \mathrm{Hz}\ C_{a\gamma}^2 \left(\frac{B}{10\mathrm{T}}\right)^2 \left(\frac{10\ \mathrm{meV}}{m_a}\right) \left(\frac{\beta^2}{10^3}\right) \left(\frac{A}{(20\ \mathrm{cm})^2}\right)$$

Article | Published: 30 September 2020

Graphene-based Josephson junction microwave bolometer

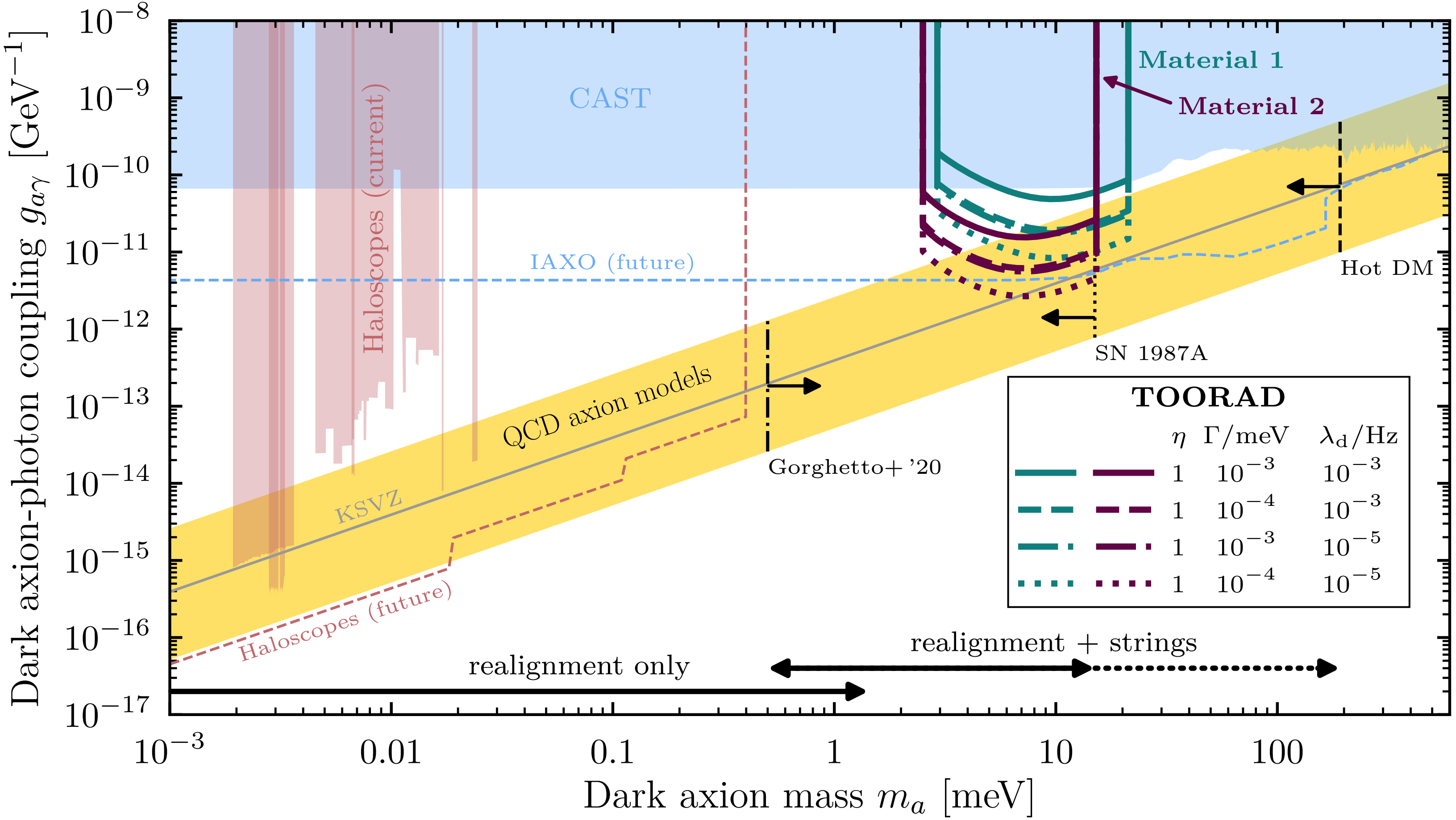
Gil-Ho Lee, Dmitri K. Efetov, Woochan Jung, Leonardo Ranzani, Evan D. Walsh, Thomas A. Ohki, Takashi Taniguchi, Kenji Watanabe, Philip Kim, Dirk Englund & Kin Chung Fong ✉

Nature **586**, 42–46(2020) | Cite this article



Need low dark count, high efficiency detector.
Possible collaboration with BRASS. Aim for f ~ 800 GHz.

Surface area ~ $(\lambda_{dB})^2$ ~$(20\ \mathrm{cm})^2$. d~2mm. Scan 3 years.



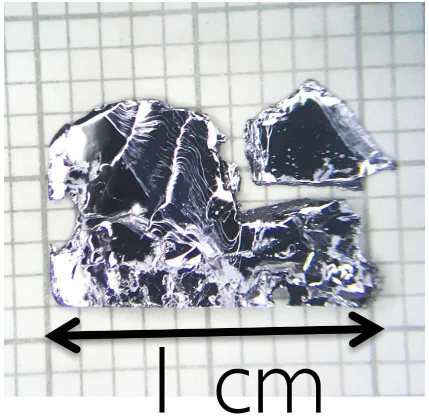
FINDING THE AXION QUASIPARTICLE

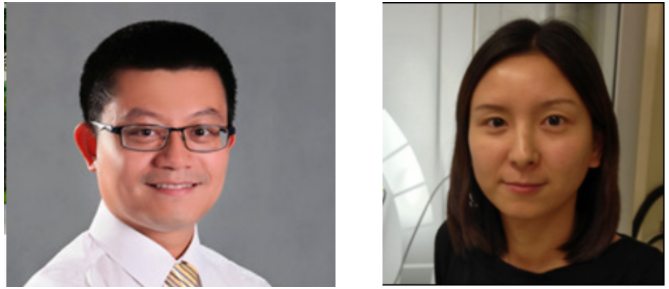
The right material hasn't been found, yet…

Manganese Bismuth Telluride: $Mn_xBi_yTe_z$

New class of intrinsically magnetic topological insulators: hot topic in materials science.
Hunt for dynamical axion is on!

(124) phase crystals supplied. Wrong symmetry → AFMR but no axion quasiparticle, metallic. ☹
Test case for characterisation ☺
(225) axion quasiparticle candidate: no recipe yet ☹

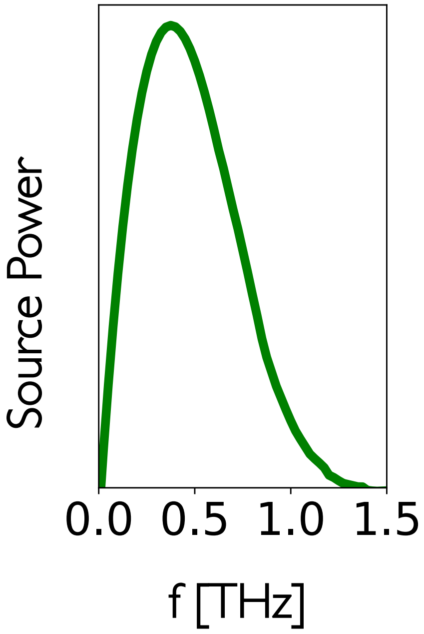


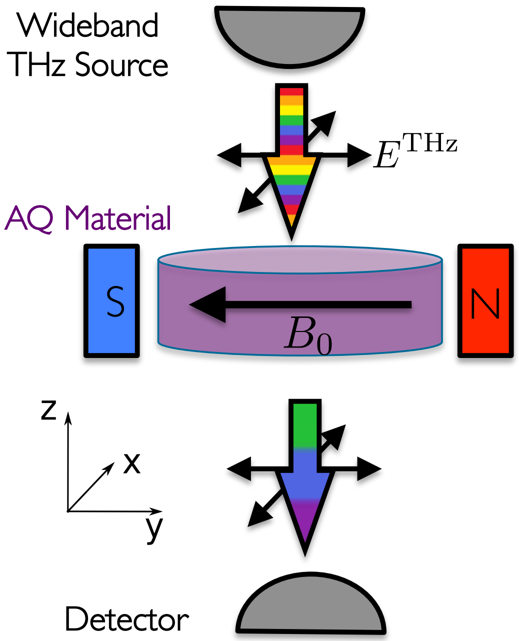


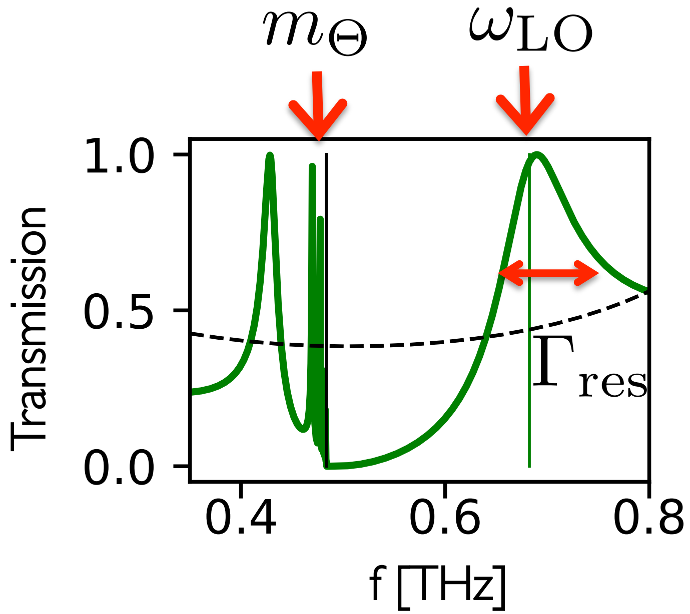
Chang Liu (SUS-Tech), Ni Ni (UCLA)

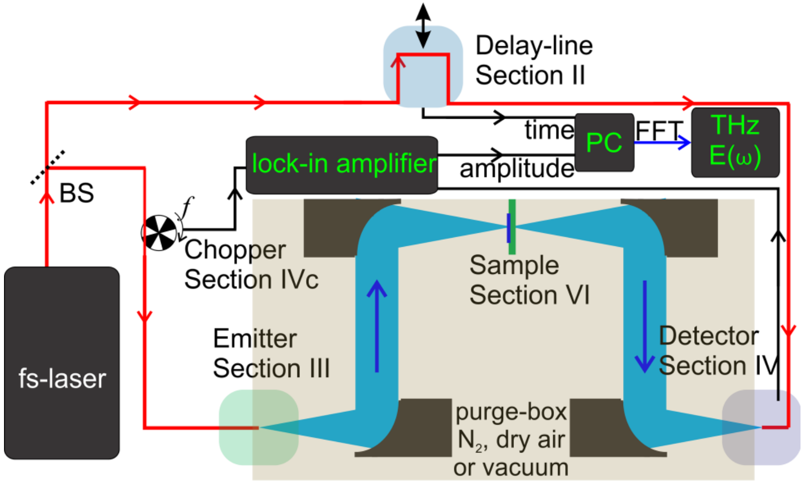
THz Spectroscopy

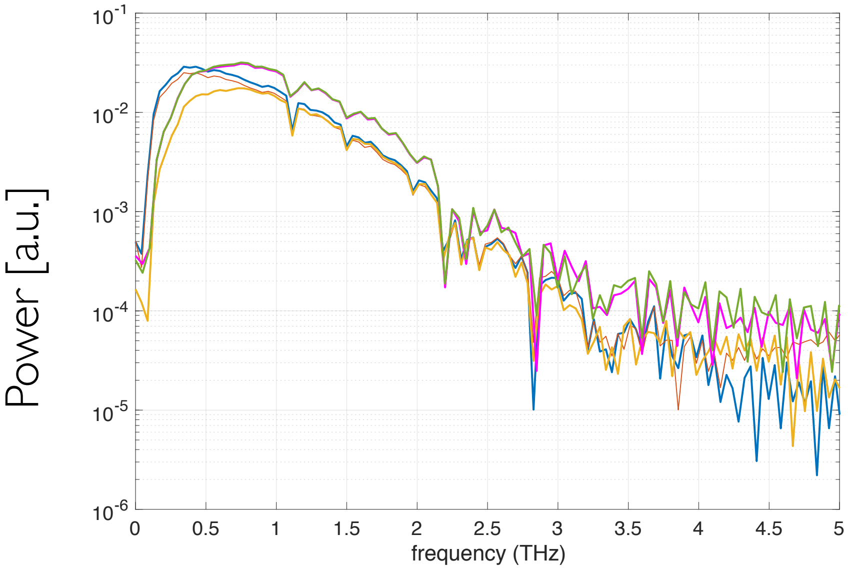
GOAL: identify axion-polariton resonance, measure it's width → discover axion quasiparticle!

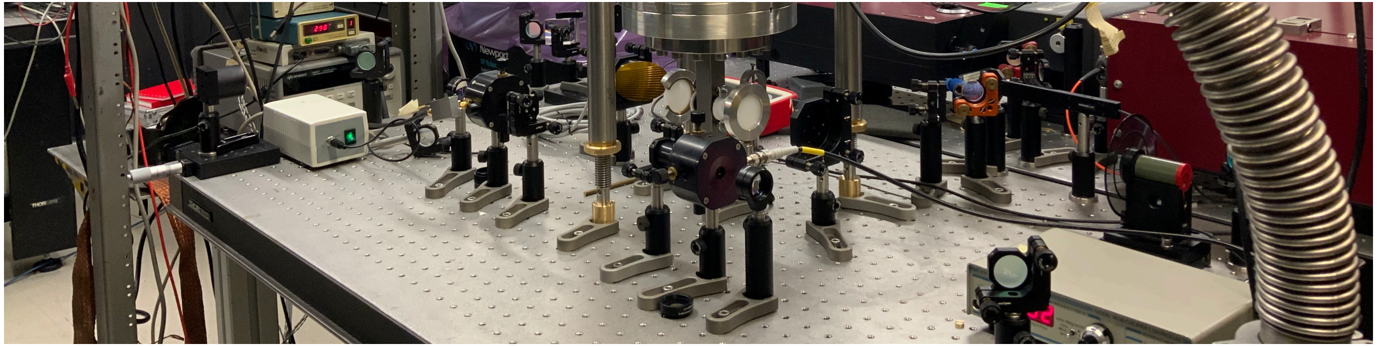






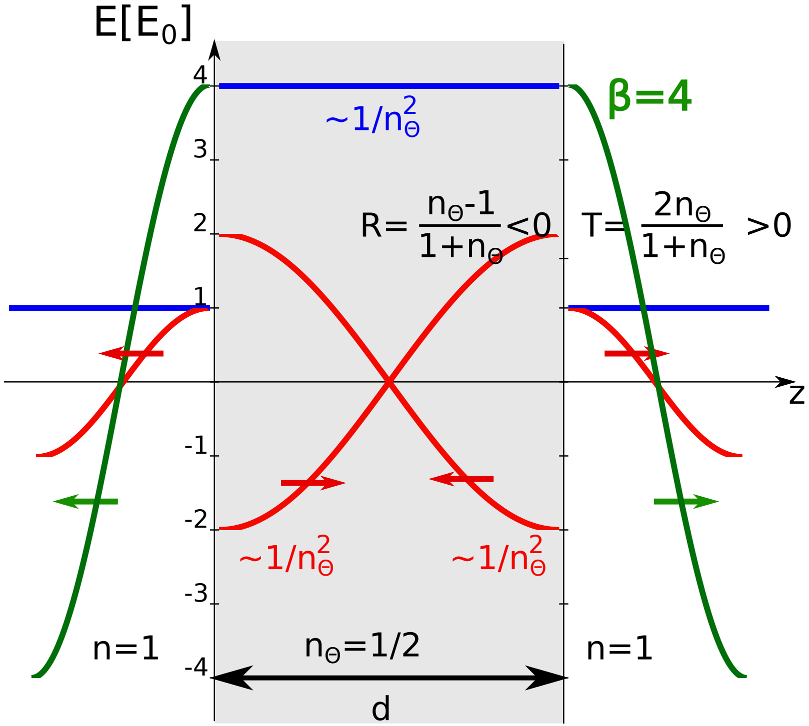




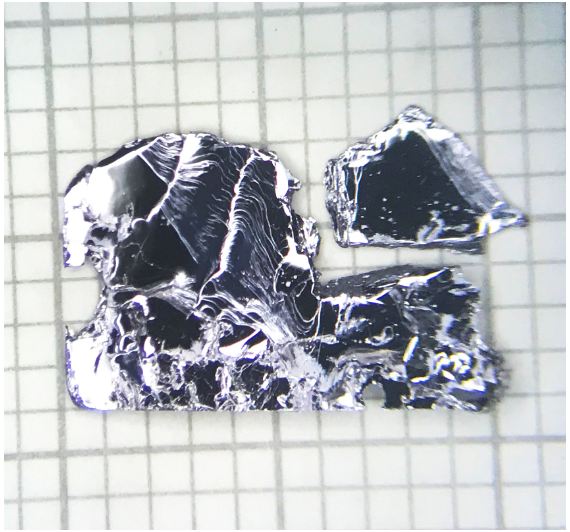


Caterina Braggio, INFN Legnaro.

We now understand how the resonance operates for a range of parameters and losses.



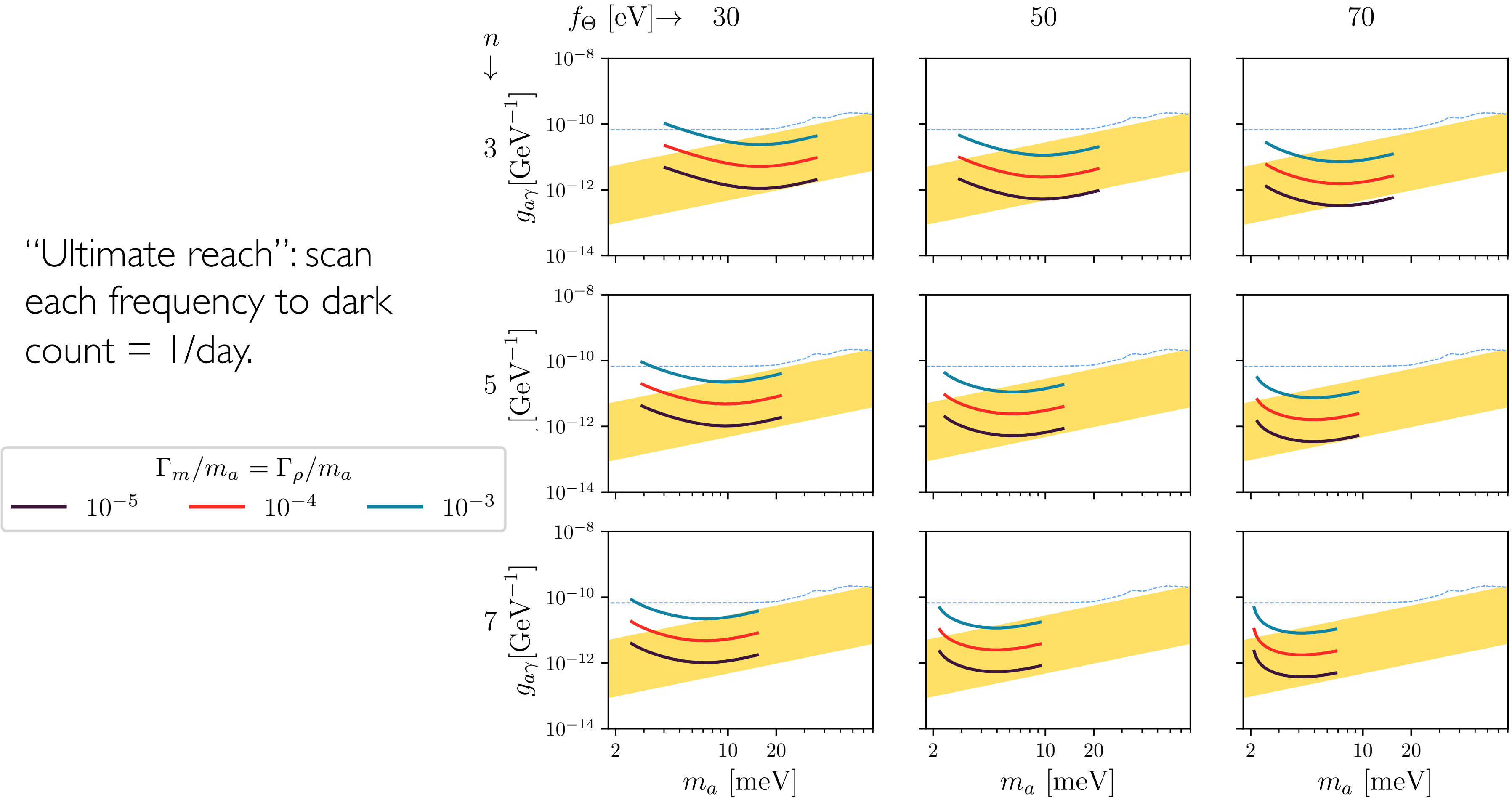
Now: measure real materials and discover axion quasiparticles.



DM detection: scan~1-10 meV range using (20 cm)^2, 2mm thick disk. Require losses equivalent to Q>10^3.

BACKUP SLIDES

"Ultimate reach": scan each frequency to dark count = 1/day.



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

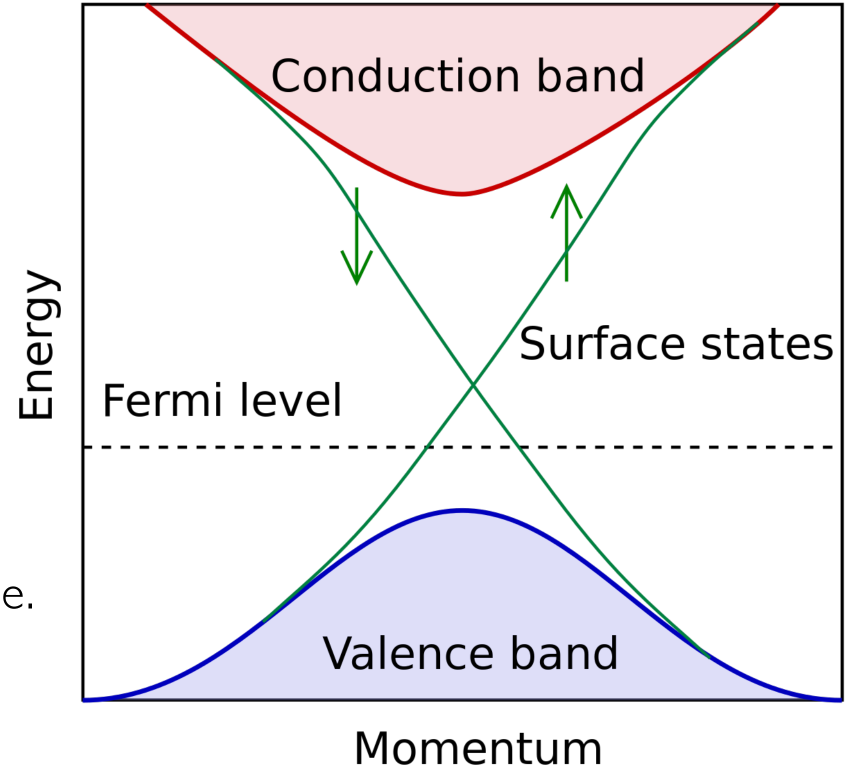
e.g. Kane & Mele (2005)
Fig: Wikipedia

Class of new materials with insulating bulk and conducting surface.

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

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

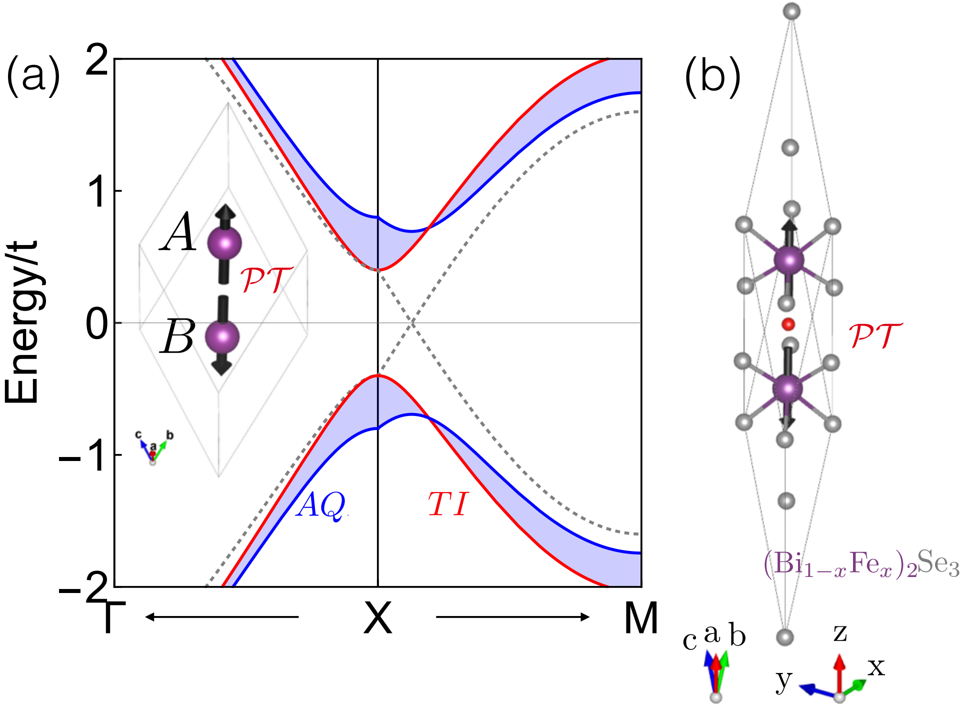
Static **Θ** (symmetry)→ only affect EM on surface.
Note: E is parallel to B just like axion source!



Axion Quasiparticles in AF-TIs

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

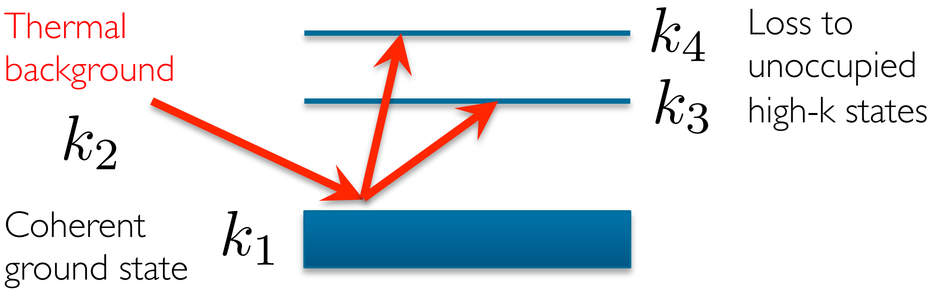
Longitudinal magnons have quantum numbers to couple **Θ**→ dynamical δθ axion-like coupling to E.B



Magnon Losses

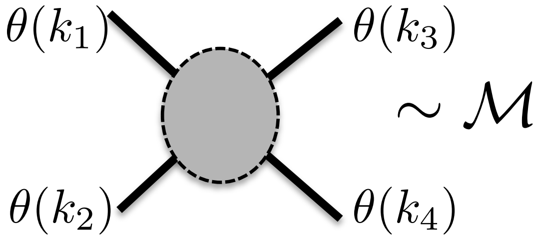
Lvov, *Wave Turbulence* (1994)
Bayrackci et al (2013)

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


Thermal background

Coherent ground state

Loss to unoccupied high-k states



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$_2$:

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

Boltzmann suppressed at T< ω

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 translation symmetry → goldstone bosons called phonons.

Effective field theory → simple model of transverse magnons:

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

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

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

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

"Gell-Mann-Oakes-Renner relation" $$F^2 m_s^2 = L H_A$$

(spontaneous) * (explicit)
symmetry breaking

Spin wave "stiffness"

Longitudinal AQ Mass

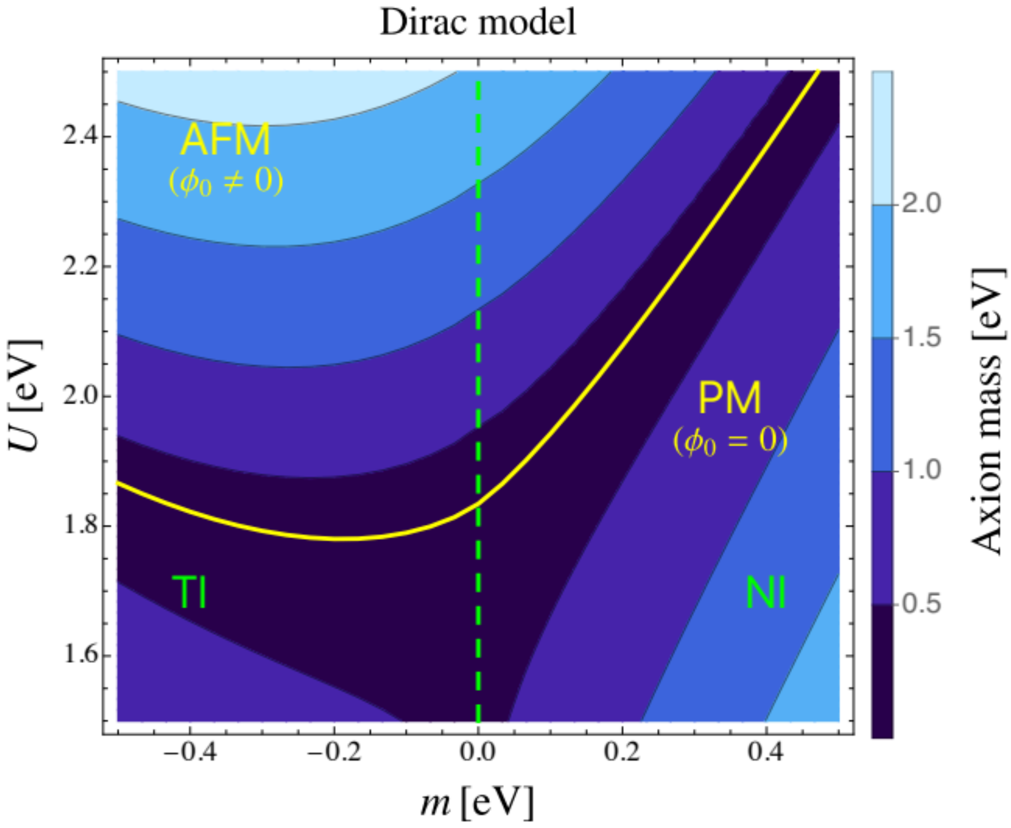
Ishiwata (2021)

Axion potential and kinetic term from "integrating in".

meV axion near AFM-paramagnetic phase boundary.

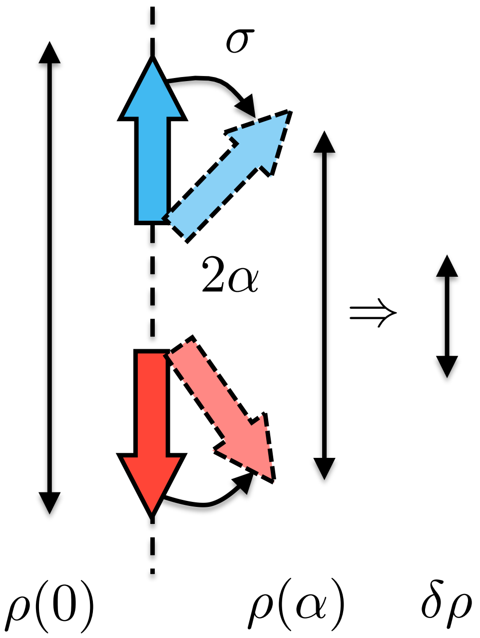
Axions possible in normal insulators → possibly larger resistance than TIs?

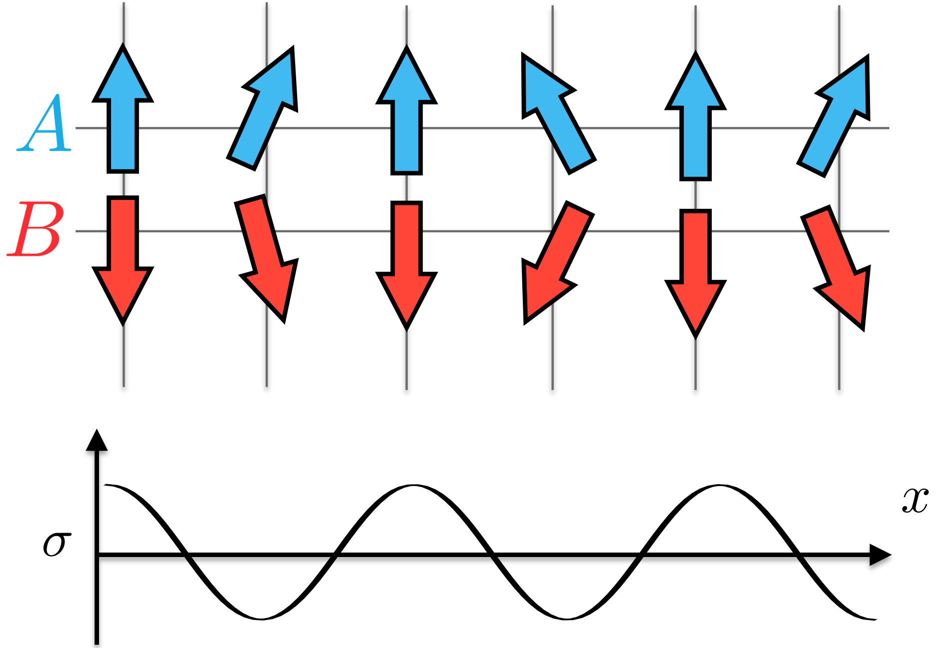
Phase boundary → non-linear effects and larger DM signal?



Longitudinal Magnons

Allow for variation of the length of the Néel vector in the sigma model.
Another option: consider the spin density wave with incommensurate Q.





AQ as Transverse Magnon

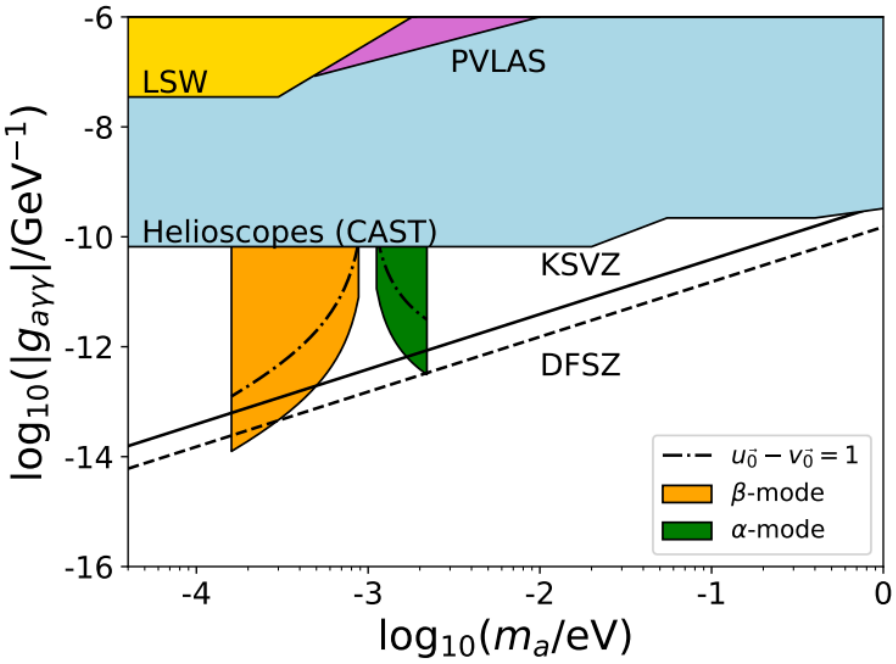
Chigusa, Moroi, Nakayama (2021)

In the "Fu-Kane-Mele-Hubbard" model, the AQ is the transverse magnon → parameters fixed by known AFMR physics. Two modes split by Kittel effect.

Assumes free space resonance and $Q\sim 10^6$ (long magnon lifetime).

Neglect polariton mixing → ignores resistive losses. No model for visible photon production.

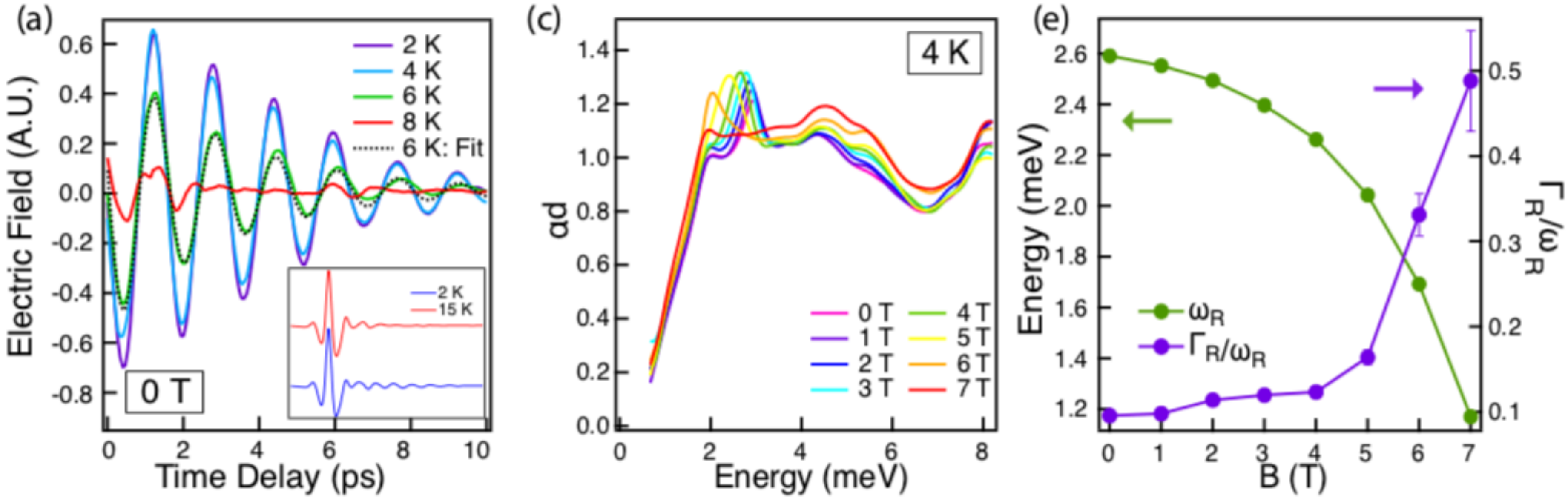
No known materials described by this model.



Example: AFMR by Transmission

Little et al (2017)

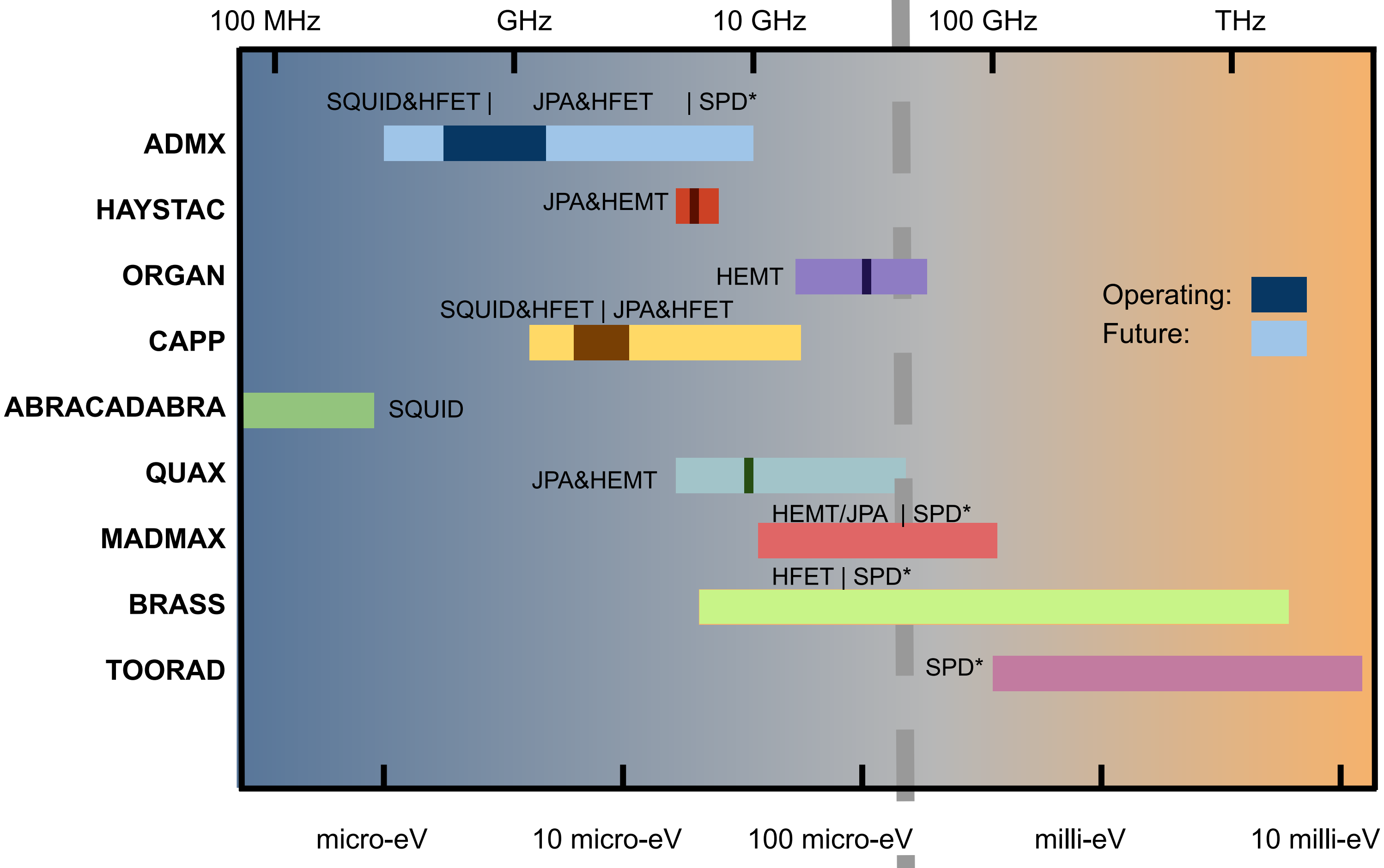
We would like to do measurements of ω and Γ like this (AF material αRuCl):



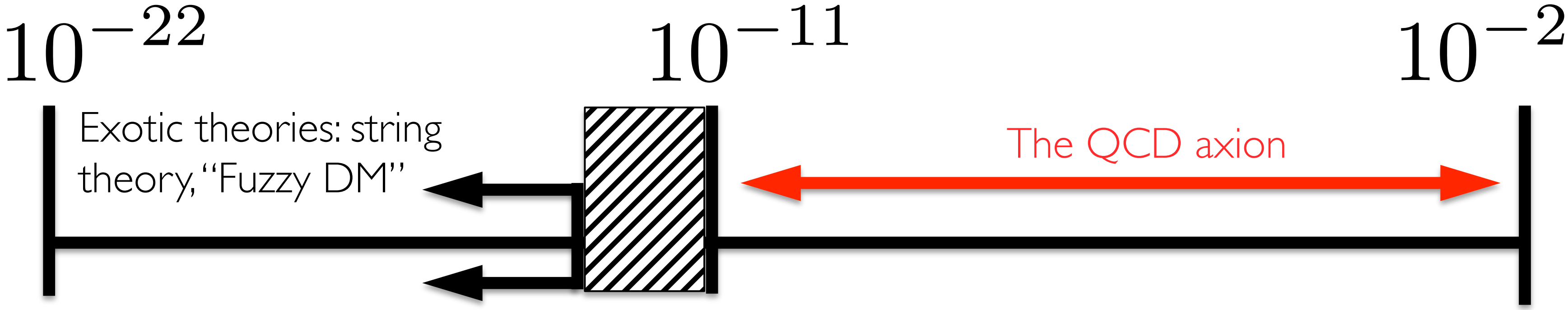
Time domain spectroscopy with femotsecond THz source. Cryogenic temperatures, B~ 1 T.

Heterodyne Detection Advantage

Single Photon Detection Advantage



What is the Axion Mass?

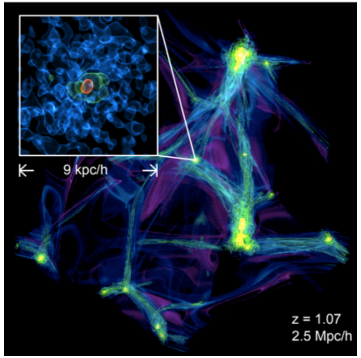


10^{-22} 10^{-11} 10^{-2}

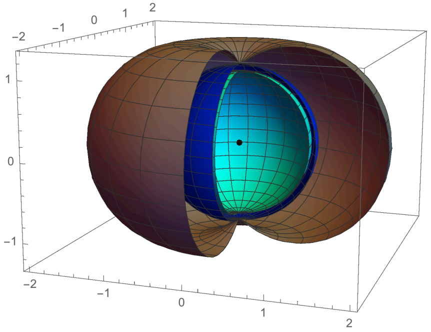
Exotic theories: string theory, "Fuzzy DM"

The QCD axion

Fig: Veltmaat et al (2018)

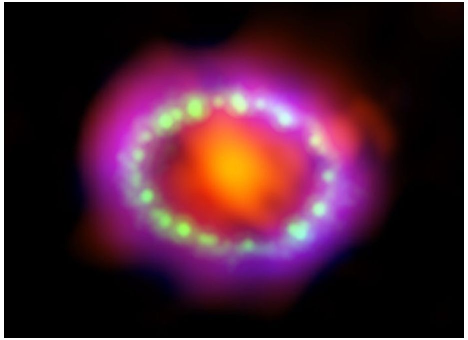


Galaxy formation
e.g. DJEM (2016)



"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?

e.g. Gorghetto et al (2018+);
Riess, Hoof, DJEM (to appear)

Spontaneous symmetry breaking → primoridal oscillations of axion field.

Cosmic DM density is a function of axion mass.

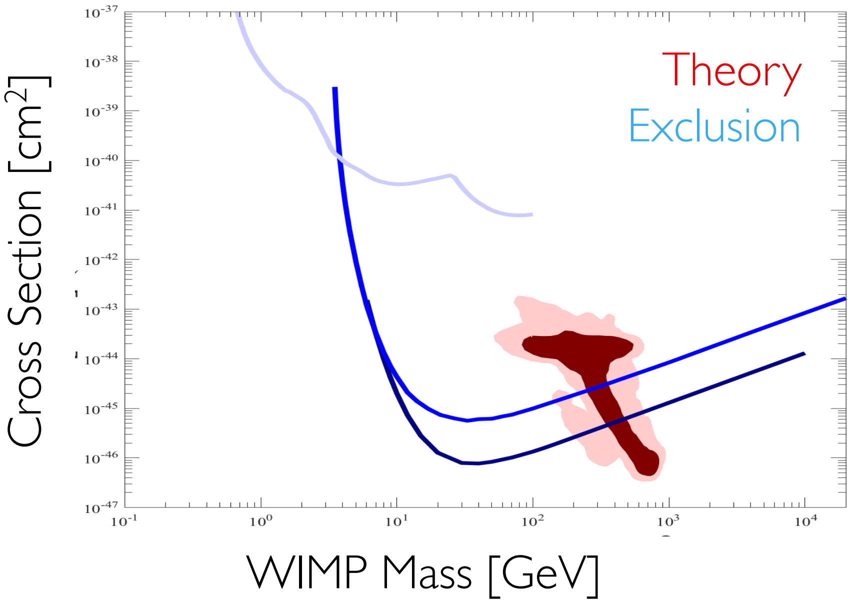
Challenging, but *solvable* computational problem.

This scenario seems to favour meV → THz

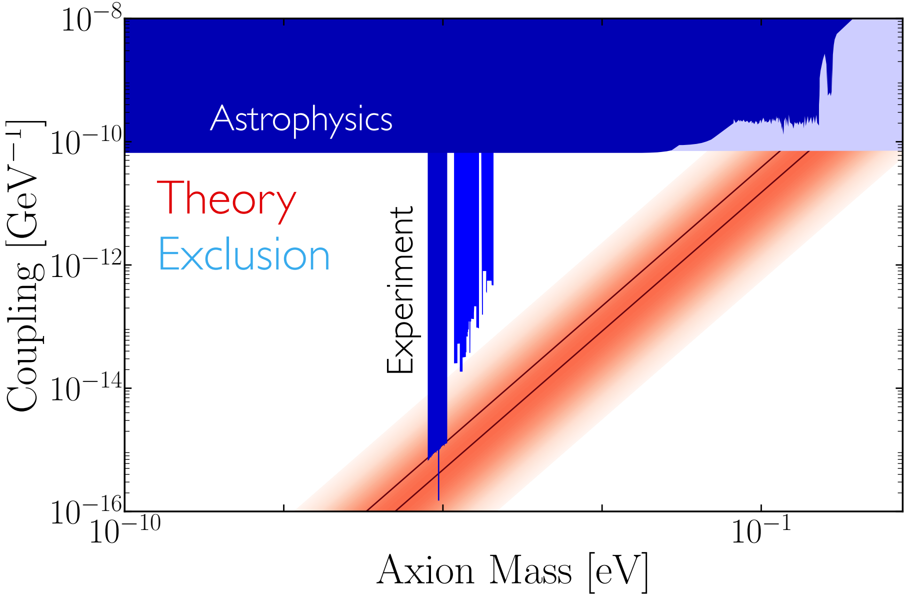
“Defects” form and decay, emitting axions (not shown)

Axions vs WIMPs

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



DMTools



O'Hare github