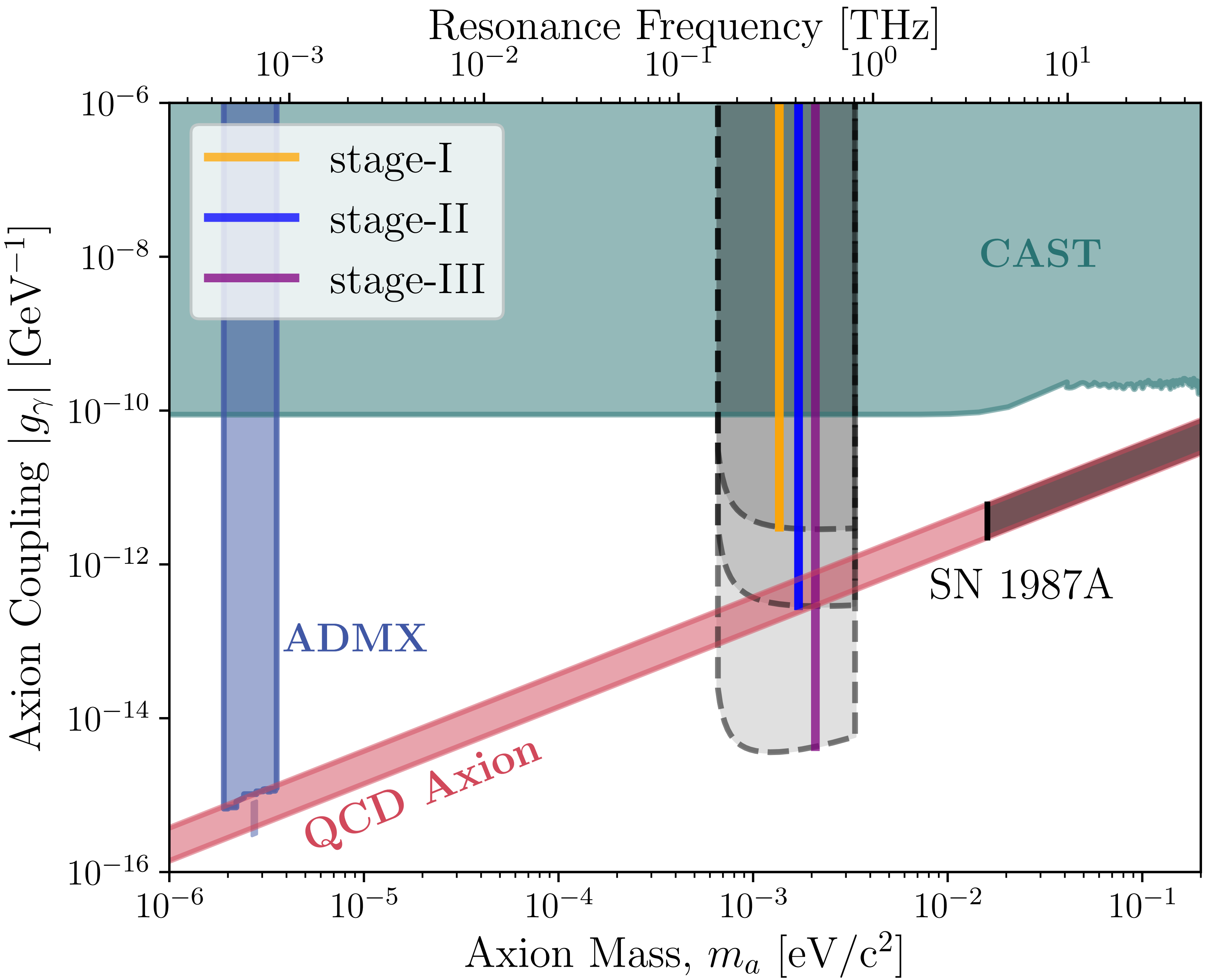
# meV Axion DM Detection with Topological Antiferromagnets

David J. E. Marsh, Quantum Connections 2018

With: Mazhar Ali, Kin-Chun Fong, Erik Lentz,
Libor Smejkal & Chris Weber

arXiv:1807.08810



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$10^{-1}$
Axion Mass, $m_a$ [eV/c$^2$]

# "TOORAD": TOpOlogical Resonant Axion Detection

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

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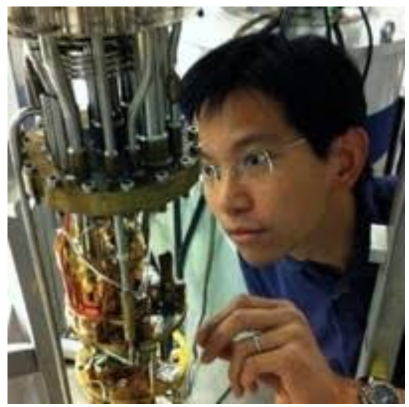
Alexander von Humboldt
Stiftung / Foundation

Mazhar Ali

Erik Lentz



Kin-Chung Fong

Libor Smejkal

Chris Weber

MAX-PLANCK-GESELLSCHAFT

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# Axion-Photon Coupling

Chern-Simons term mediates interactions:

$$\mathcal{L} \supset C\frac{\alpha}{2\pi}\theta_D \vec{E}\cdot\vec{B}$$

$$g_\gamma = C\frac{\alpha}{2\pi f_a} \approx 10^{-13}\left(\frac{C}{0.75}\right)\left(\frac{10^{10}\ \mathrm{GeV}}{f_a}\right)\ \mathrm{GeV}^{-1}$$

Axion couples to Maxwell's equations → "axion electrodynamics"

→ Linearize with DM and B source

→ Driven E-field → poss. resonance

$$\ddot{E} - \nabla^2\vec{E} = 4\pi\vec{B}_0 g_\gamma \theta_D(t)$$

# THz Challenge

$$P_0 = \frac{1}{2} E_0^2 V_{\text{eff}} \omega_a = g_\gamma^2 B_0^2 \frac{\rho_{\text{DM}}}{m_a^2} V_{\text{eff}} \omega_a$$

Taking V as $(c/\text{THz})^3$ and g at the CAST limit, power is $10^{-27}$ W.

Our method: magnetic resonance and increased volume.
Increased SNR using single photon detection.

Magnetic resonance decouples the resonant frequency from the volume. Antiferromagnetism → THz.

CASPEr: nuclear couplings (MHz). QUAX: electron coupling (GHz).

Topological insulator → AF resonance driven by photon coupling.

# AXION QUASI-PARTICLES

Li et al, Nat. Phys. (2010); Wang et al, PRL (2011)

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## Quantum Spin Hall Effect and Topological Phase Transition in HgTe Quantum Wells

B. Andrei Bernevig[1,2], Taylor L. Hughes[1], Shou-Cheng Zhang[1,*]
+ See all authors and affiliations

*Science* 15 Dec 2006:
Vol. 314, Issue 5806, pp. 1757-1761
DOI: 10.1126/science.1133734

HgTe first topological insulator

nature physics

Letter | Published: 10 May 2009

## Observation of a large-gap topological-insulator class with a single Dirac cone on the surface

Y. Xia, D. Qian, D. Hsieh, L. Wray, A. Pal, H. Lin, A. Bansil, D. Grauer, Y. S. Hor, R. J. Cava & M. Z. Hasan

*Nature Physics* **5**, 398–402 (2009) | Download Citation

$Bi_2 Se_3$ "second generation"

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Editors' Suggestion

## Realization of the Axion Insulator State in Quantum Anomalous Hall Sandwich Heterostructures

Di Xiao, Jue Jiang, Jae-Ho Shin, Wenbo Wang, Fei Wang, Yi-Fan Zhao, Chaoxing Liu, Weida Wu, Moses H. W. Chan, Nitin Samarth, and Cui-Zu Chang

Phys. Rev. Lett. **120**, 056801 – Published 31 January 2018

$(Bi,Sb)_2Te_3$ layers. Possible "axion insulator"

Condensed matter: Chern-Simons term is in magneto-electric materials. This effect is predicted to occur in topological insulators, with $\theta=\pi$.

$$\theta = \frac{1}{4\pi}\int d^3k\,\epsilon^{ijk}\mathrm{Tr}\left[A_i\partial_j A_k + i\frac{2}{3}A_iA_jA_k\right] \qquad A_i^{\alpha\beta}(\vec{k}) = -i\langle\alpha\vec{k}|\partial/\partial k_i|\beta\vec{k}\rangle$$

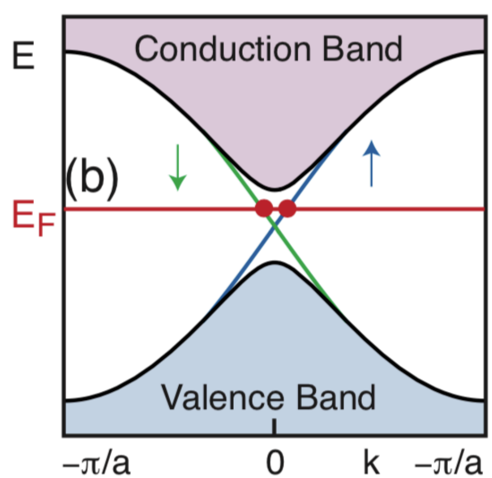
Chern-Simons form

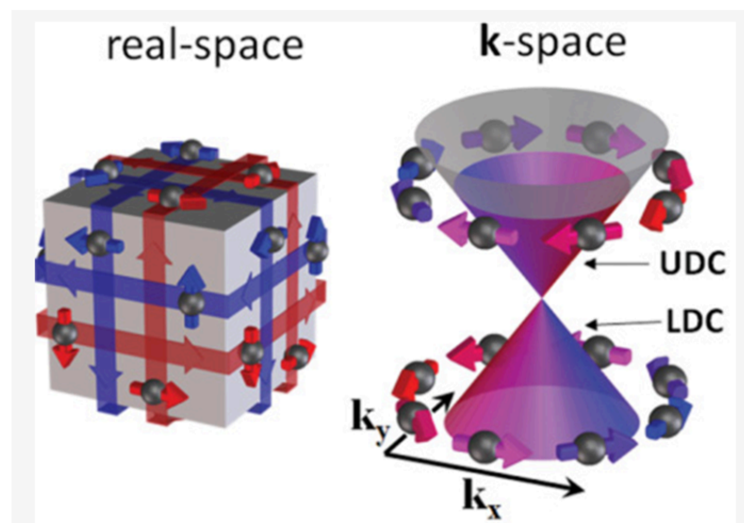
Berry phase gauge field for Bloch wavefunctions in band $\alpha$.

In "ordinary" TI's, the axion term is locked to 0 or $\pi$ by T-invariance.

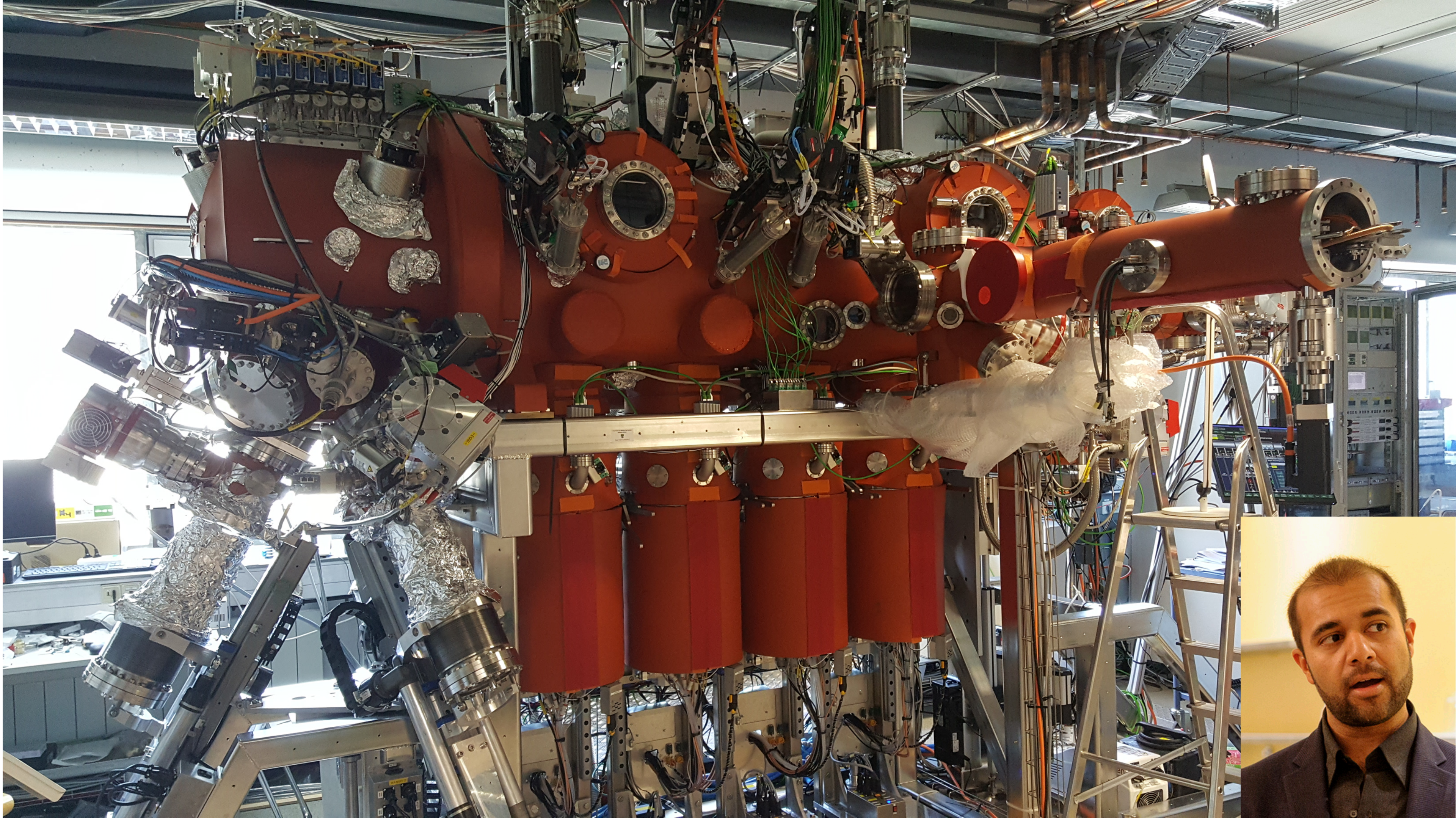
Qi et al (2008)

Band structure → Dirac equation. T-symmetry → protected states.




Hasan & Kane (2010)



Making thin film heterostructures.

"Mango": hybrid deposition tool. MPI Microstructure Physics, Halle.


Making thin film heterostructures.

"UFOs": sputtering, same way computer chips are made.

MPI Microstructure Physics, Halle.

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]*

**Axions are weakly interacting particles of low mass, and were postulated more than 30 years ago in the framework of the Standard Model of particle physics. Their existence could explain the missing dark matter of the Universe. However, despite intensive searches, axions have yet to be observed. Here we show that magnetic fluctuations of topological insulators couple to the electromagnetic fields exactly like the axions, and propose several experiments to detect this dynamical axion field. In particular, we show that the axion coupling enables a nonlinear modulation of the electromagnetic field, leading to attenuated total reflection. We propose a new optical-modulator device based on this principle.**

# “Wilczek Criteria”

Wilczek (1987)

Material properties necessary for an axion quasiparticle (AQ):

1. Effective Chern-Simons EM term.
2. Dirac equation for electrons.
3. Variable Dirac masses.

1. Requires the existence of non-zero diagonal elements of magneto-electric polarisability.

$$\alpha_{ij} = \left(\frac{\partial M_j}{\partial E_i}\right)_{\mathbf{B}=0} = \left(\frac{\partial P_i}{\partial B_j}\right)_{\mathbf{E}=0}$$

2. Requires Dirac quasi-particle materials.
3. Dynamical $\theta$ varies the band structure. Possible with magnetic fluctuations.

If time-reversal symmetry can be broken → dynamical "anaolgue axion".
Local fluctuations in θ caused by spin-induced shifts in band energies:

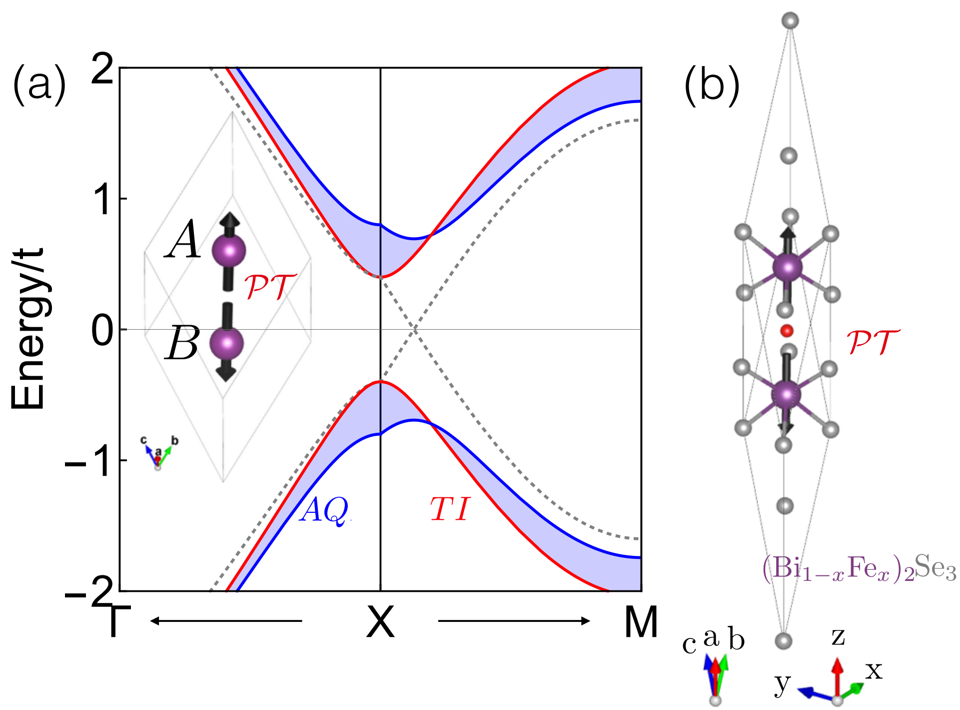
$$\mathcal{L}_{\rm AQ} = \frac{f_Q^2}{2}\left[\dot{\theta}_Q^2 - (v_{s,i}\partial_i\theta_Q)^2 - m_Q^2\theta_Q^2\right] + \frac{\alpha}{2\pi}\theta_Q E\cdot B$$

Spin desnity waves e.g. in Fe doped $Bi_2Se_3$. Li et al (2010)

$$\delta\theta_Q \sim \frac{2}{3}\sum U m_i$$

Spin-wave Néel vector fluctuation.
Z = bulk magnetization direction

AF fluctuations between sub-lattice A,B → pseudoscalar spin waves




$$\epsilon\ddot{\mathbf{E}} - \nabla^2\mathbf{E} + \boxed{\frac{\alpha}{\pi}[\mathbf{B}_0\ddot{\theta}_Q} - \nabla(\nabla\theta_Q \cdot \mathbf{B}_0)] = \boxed{\mathbf{A}\cos\omega_a t\,,}$$

$$\ddot{\theta}_Q - v_Q^2\nabla^2\theta_Q \boxed{+ m_Q^2\theta_Q} \boxed{- \frac{\alpha}{4\pi^2 f_Q^2}\mathbf{B}_0 \cdot \mathbf{E}} = 0$$

Our observation: dark matter axions source an E-field inside the material.

The presence of the Chern-Simons term couples E-field to spin waves via mass mixing (linear).

The spin wave has a mass set by anti-ferromagnetic exchange. Larmour frequency ~ 1 meV.

# Parameters and B-Scaling

In our model we can directly compute $m_Q(B)$ and $f_Q(B)$ for $Bi_2Se_3$.
The AQ dispersion on the diamond lattice is:

$$\hbar\omega_{Q_A} \approx g\mu_B H_0 \pm \sqrt{(8SJf(0) + g\mu_B H_A)^2 - (8SJf(\mathbf{q}))^2},$$

anisotropy exchange

Dilution 3.5%, anisotropy 16 meV, exchange 1 meV.

Kim et al (2013); Zhang et al (2012,2013)

$$\Rightarrow m_Q = [0.12(B_0/2\mathrm{T}) + 0.6]\ \mathrm{meV}$$

The spin wave kinetic term gives: $f_Q = 190\ \mathrm{eV}\dfrac{m_Q(2\mathrm{T})}{m_Q(B_0)}$

Li et al (2010); Wang et al (2016)

Large TI dielectric constant: $\epsilon \sim 100$

# Quality Factor

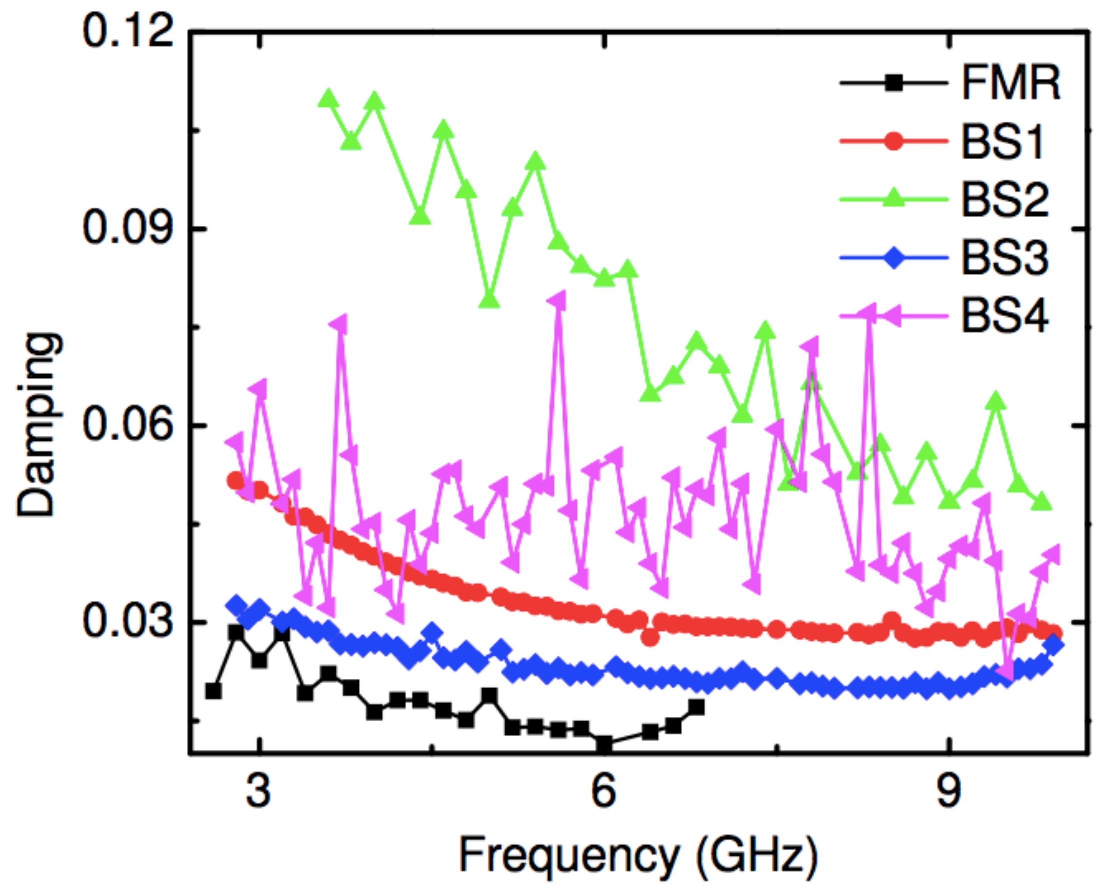
References found yesterday after our discussion over lunch!

Gilbert damping of spin waves sets the width

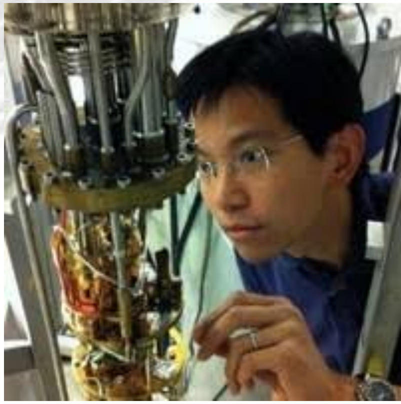
AFMR in NiCO with $\alpha \sim 3 \times 10^{-3}$ has $Q \sim 3 \times 10^{6}$. Khymyn et al (2017)

Spin-pumping of FMR in Bi2Se3 measured by Jamali et al (2014): $\alpha \sim 3 \times 10^{-2}$

Take these values as indicative:
Estimate $Q \sim 10^{5}$



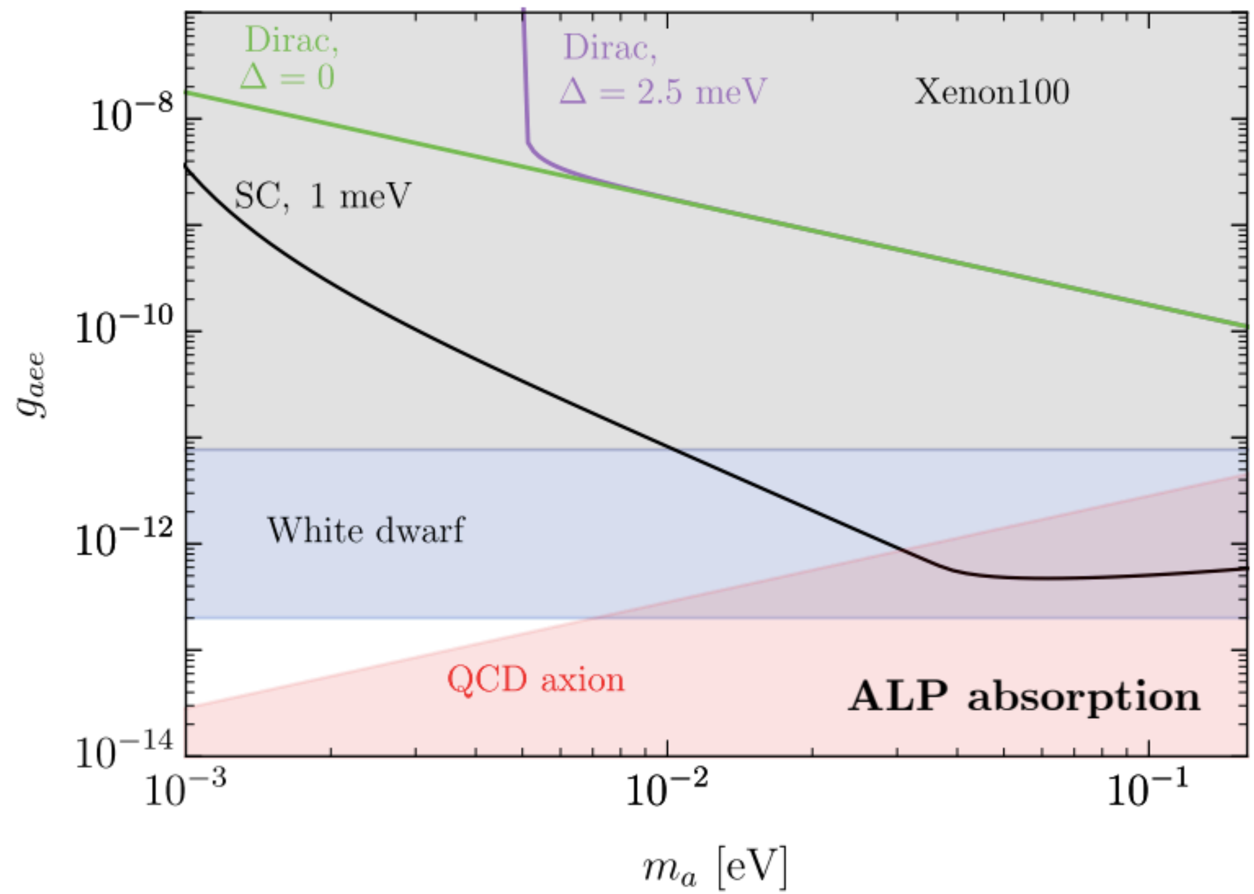
# AFTI'S AS DM DETECTORS



# Other Couplings

Hochberg, Kahn et al (2017)
Liang et al (2018)

Axion-electron coupling could lead to scattering in the TI.




These materials can be good WIMP-like particle detectors too.

# Axion-Polaritons

Li et al (2010)

Diagonalise the equations of motion to find ϕ propgating d.o.f.

$$\omega_\pm^2(k) = (k^2/\epsilon^2 + m_Q^2 + b^2) \pm \sqrt{(k^2/\epsilon^2 + m_Q^2 + b^2)^2 - 4k^2 m_Q^2/\epsilon^2}$$

Mixing parameters:

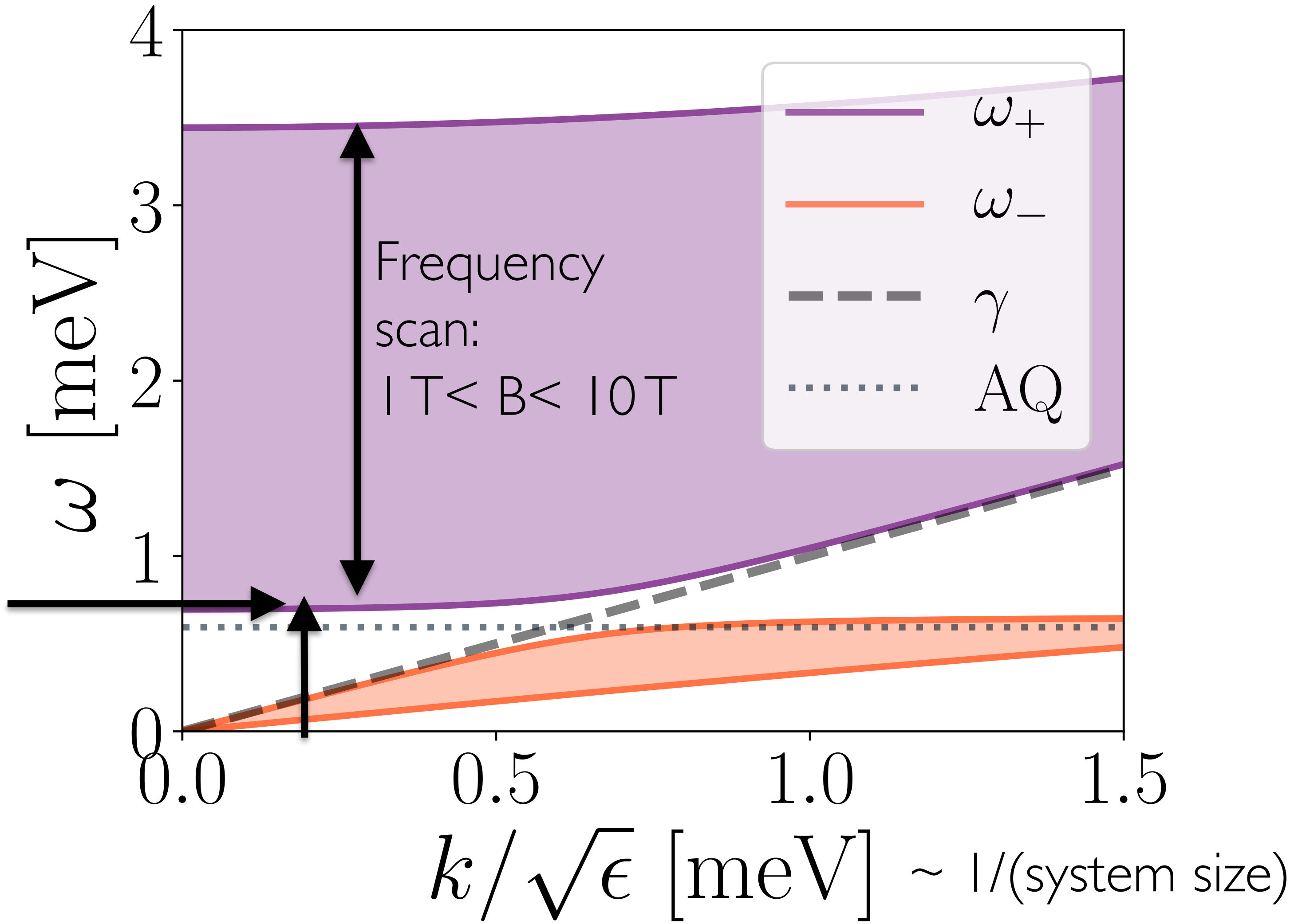
$$b^2 = \alpha^2 B_0^2 / 4\pi^3 \epsilon f_Q^2$$

photon mass term
~ 0.5 meV at 2 T

$$f_+ = b^2/(\omega^2 + b^2)$$

Fractional E-power in + mode
~ 4-40% for our material.

Our
mode:
high ω,
low k




$\phi_+$ polariton has non-zero frequency at k=0, i.e. massive scalar particle.
→ Long wavelength, large volume THz mode for detection.

# Basic concept: AF-doped TIs → tunable THz resonance coupled to the axion. $V = V_{sample}$

The analogue axion modifies the dispersion relation of the propagating modes, which include an E-component.

Wavenumber k is fixed by the material dimensions, c.f. cavity.

Tune $\omega$ with the applied B-field and look for a resonance with the dark matter axion source.

# Detecting small THz signal

$$P_{\text{signal}} = \frac{\kappa}{\epsilon} f_+ Q_{\text{sys}} P_0$$

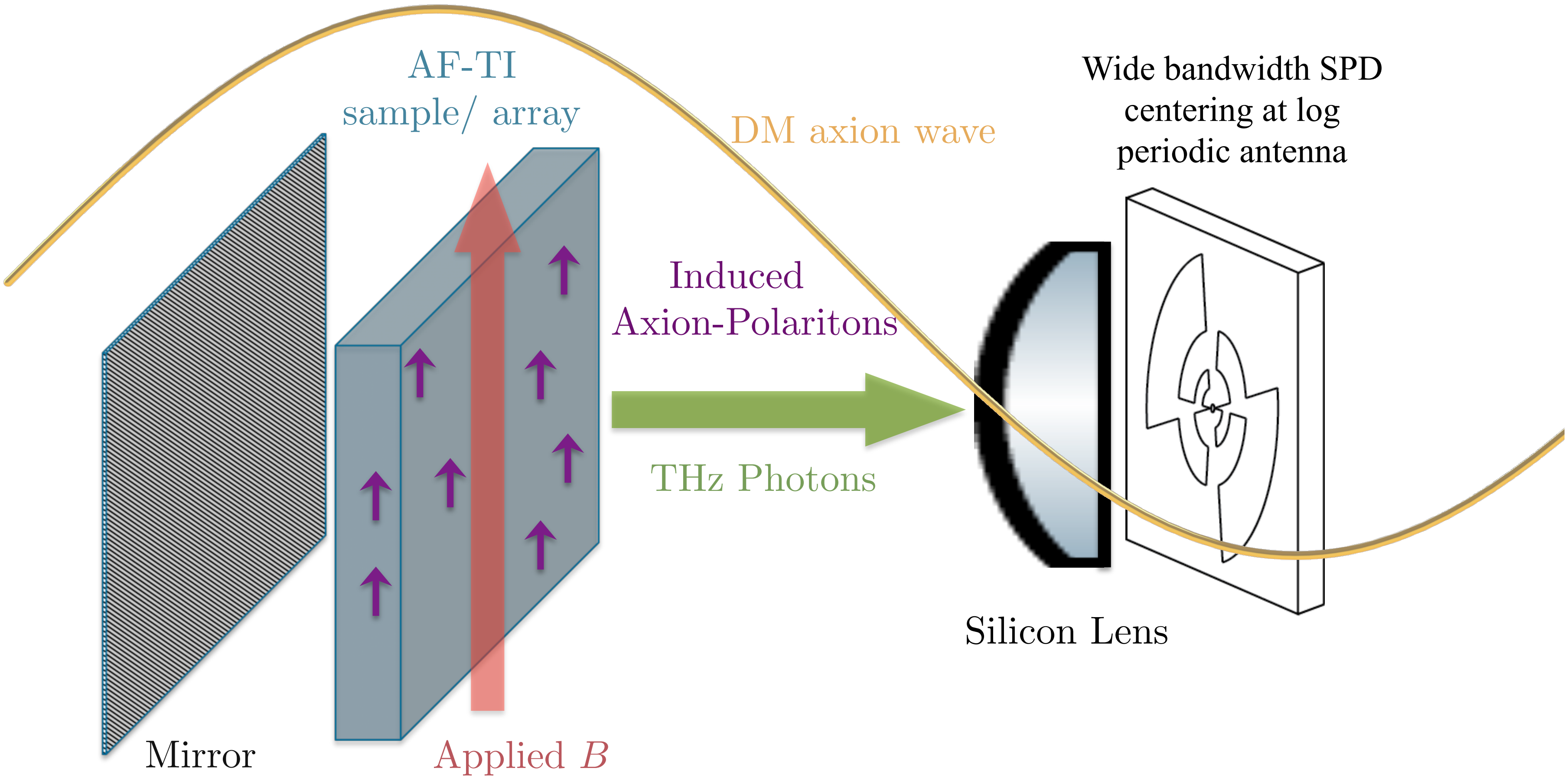
coupling, mixing, resonance

- Following the MADMAX idea, continuity of (D,H) at the dielectric boundary leads to photon emission.

Millar et al (2016)

- Reference params: $Q=10^5$, $V=1\ \text{cm}^3$ → $10^{-22}$ W at CAST limit: approximately 3 photons per second.
- Scan 100 s per frequency → total campaign 6 months.

# SPD vastly improves SNR over heterodyne power in THz.




Dark count rate 0.001 Hz demonstrated at 0.05 K with Quantum Dot Detector. Need wide bandwidth version.

Komiyama et al (2000)

# Staged Designs

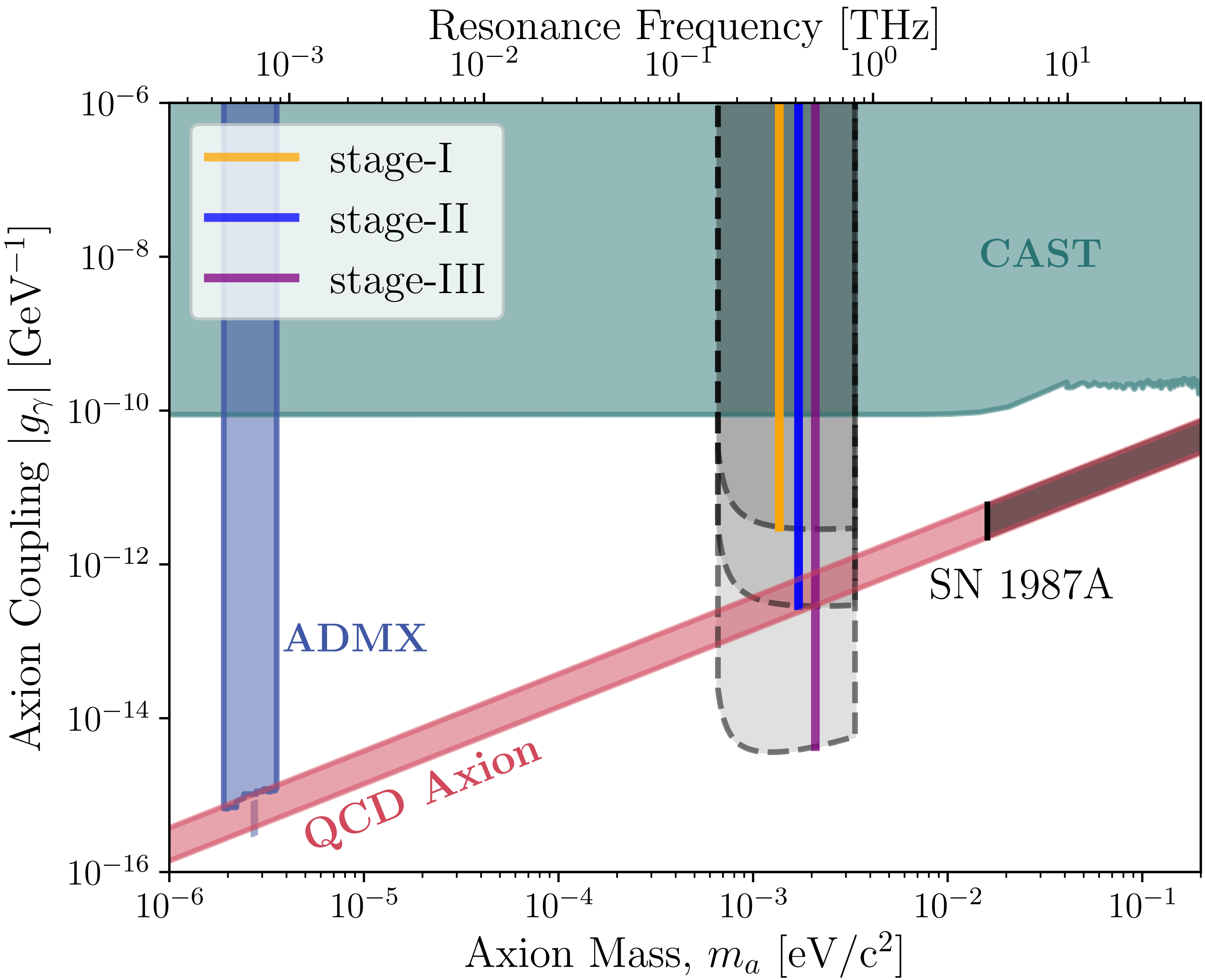
AF-TI samples limited to ~1 $cm^3$ for homogeneous doping.

Challenge: increase the effective volume.

Stage I: Single sample, 1 $cm^3$ in thin film.

Stage II: O(100) samples in "MADMAX style" array to maximize usable volume $V_{eff} \sim 100\ cm^3$.

Stage III: Ultimate limit from coherence length → $V_{eff} \sim (0.1\ \lambda_{dB})^3 \sim 2000 cm^3$.



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$10^{-1}$
Axion Mass, $m_a$ [eV/c$^2$]

Advantages:

Volume does not go down at high frequency (c.f. cavity)

Single photon detection → increase in SNR over quantum limit.

No mechanical tuning: all in external B-field (just like CASPER).

Disadvantages:

Materials do not exist yet. Hard to manufacture in large V.

We do not know the Q factor (and lots else!) very well.

B-field limited by spin-flop. Also an unknown factor.

# Open Questions

This is a haloscope concept, not a full fledged design.
We made a large number of parameterised assumptions.

1. Realise an AQ material in the lab and measure its B-dependent properties.
2. What are the correct AQ boundary conditions? How well can we extract photons?
3. Addition of samples: can this be done?
4. Use of wide bandwidth SPD. How realistic?

Finally: even if we cannot make a *competitive* haloscope, there is lots of interesting AQ science to be done!

# COLLABORATION

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