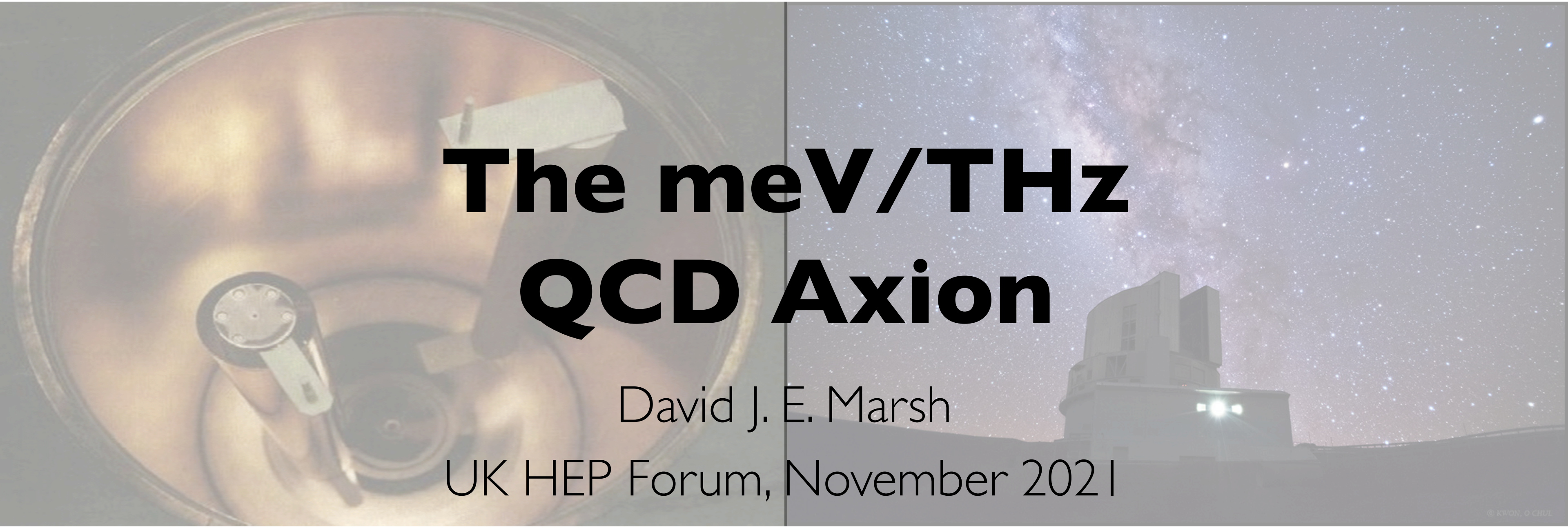


The meV/THz QCD Axion

David J. E. Marsh

UK HEP Forum, November 2021

Science and Technology Facilities Council

King's College London

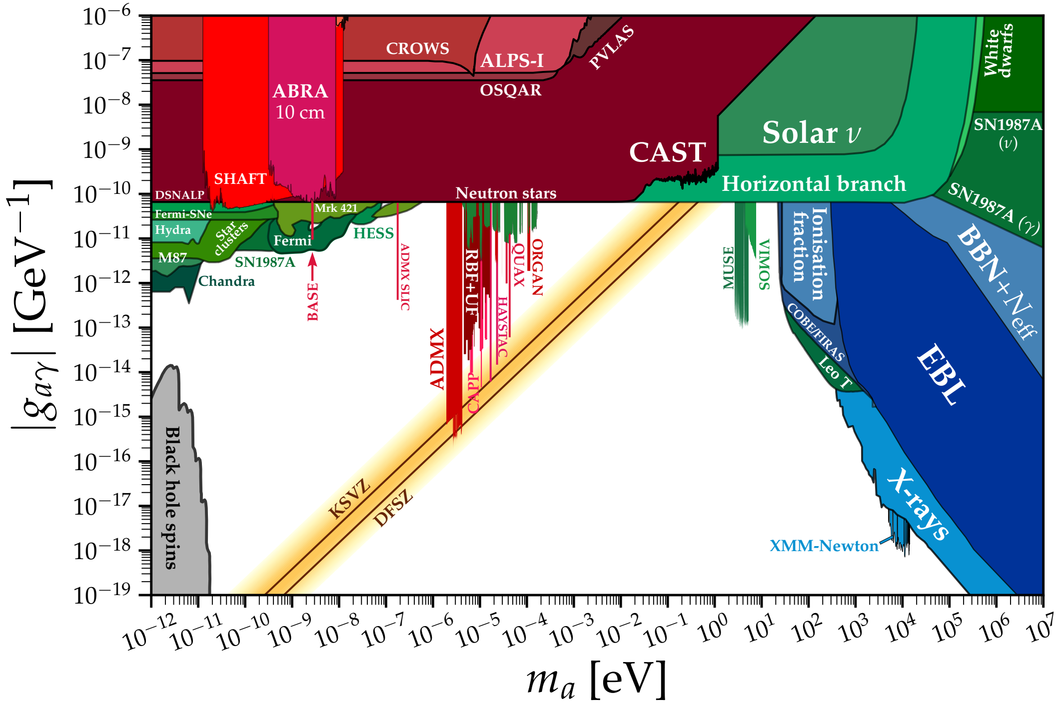
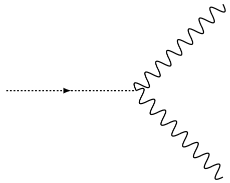


Fig: O'Hare

Low energy interaction:

$$g_{a\gamma\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Axion-photon decays/conversions

$$\phi\vec{E}\cdot\vec{B}$$

"Axion electrodynamics"

Wir müssen wissen – wir werden wissen ("We must know — we will know.") -- Hilbert

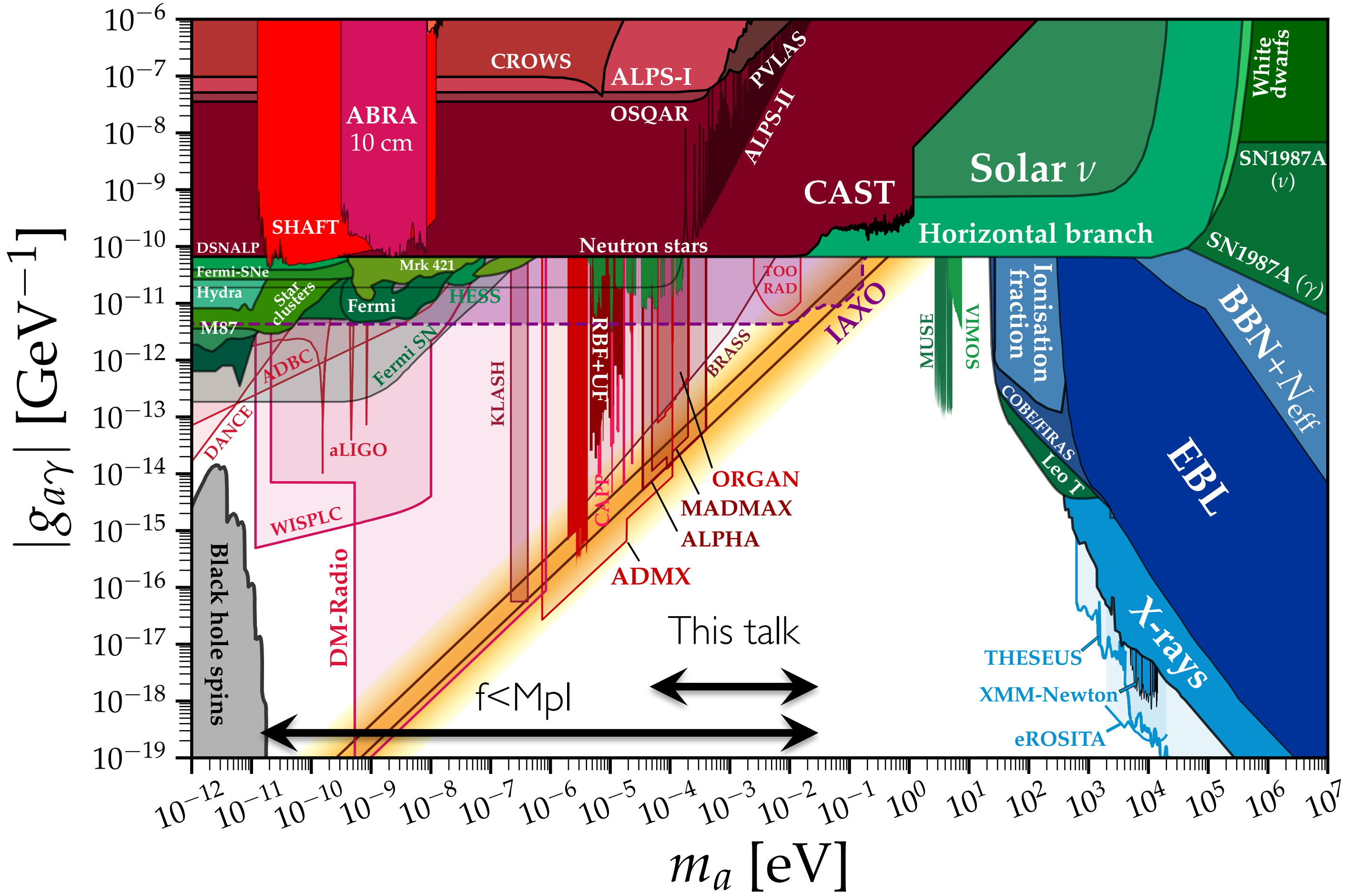
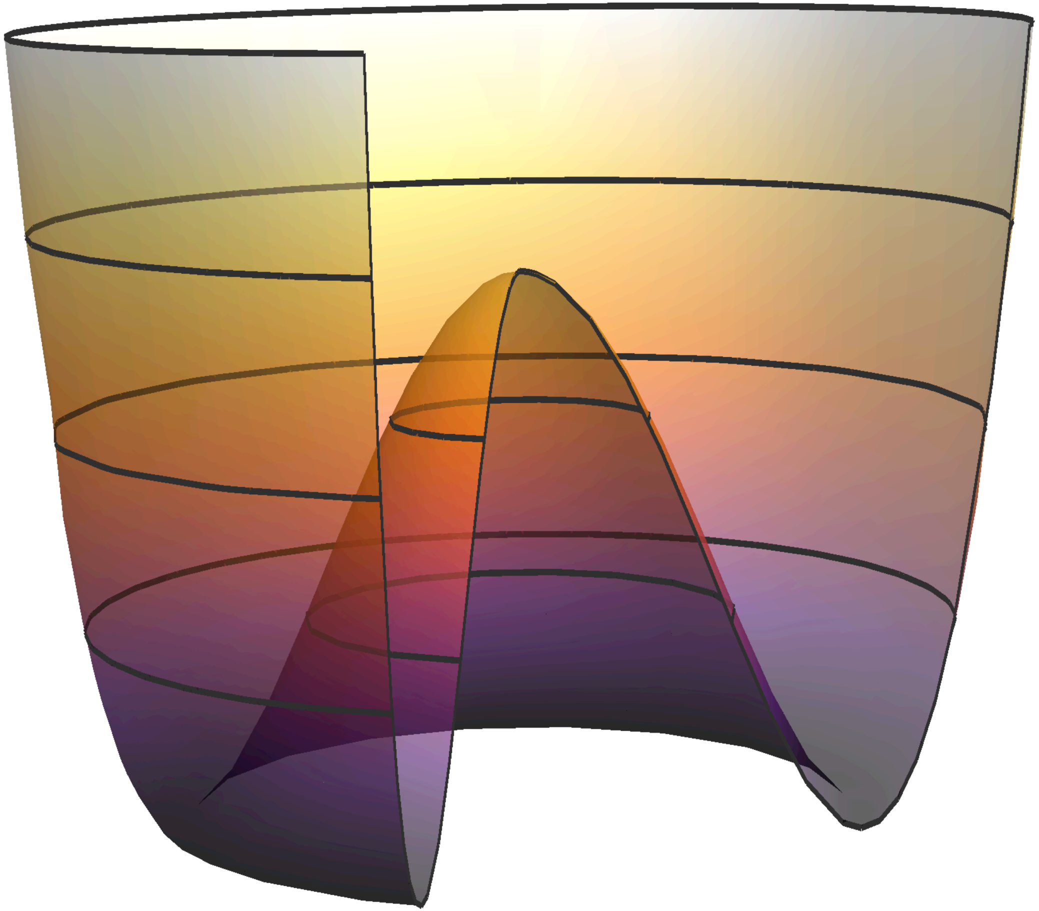


Fig: O'Hare

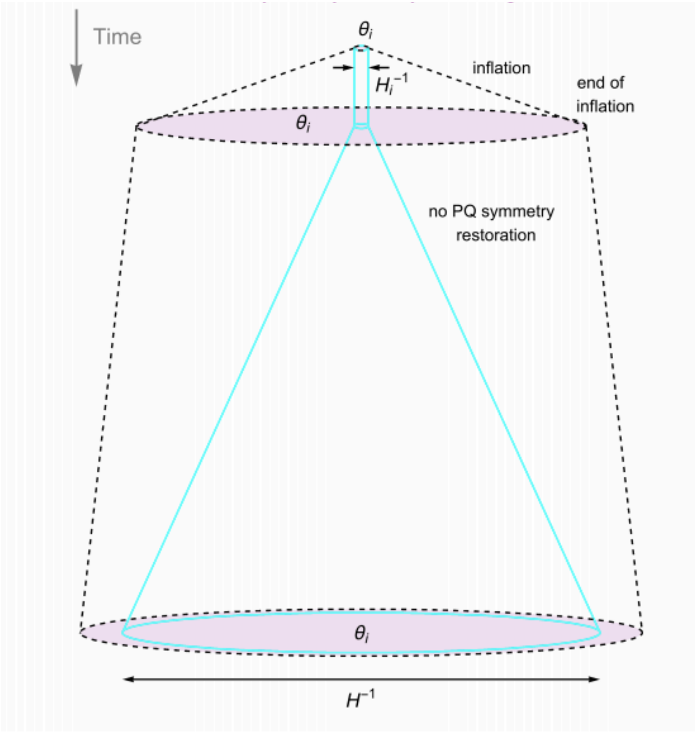
AXION COSMOLOGY



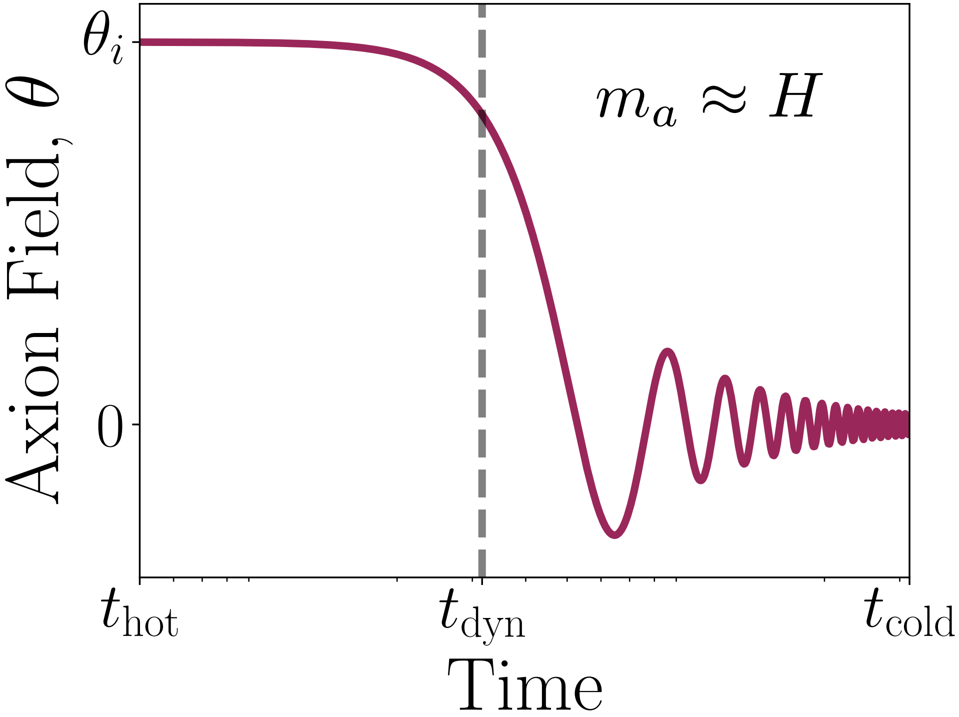
SSB before/during inflation "blows up" one patch of θ to the whole Universe.

Initial θ is random. Cannot predict axion mass from DM density.

Fig: Armengaud et al (2019)



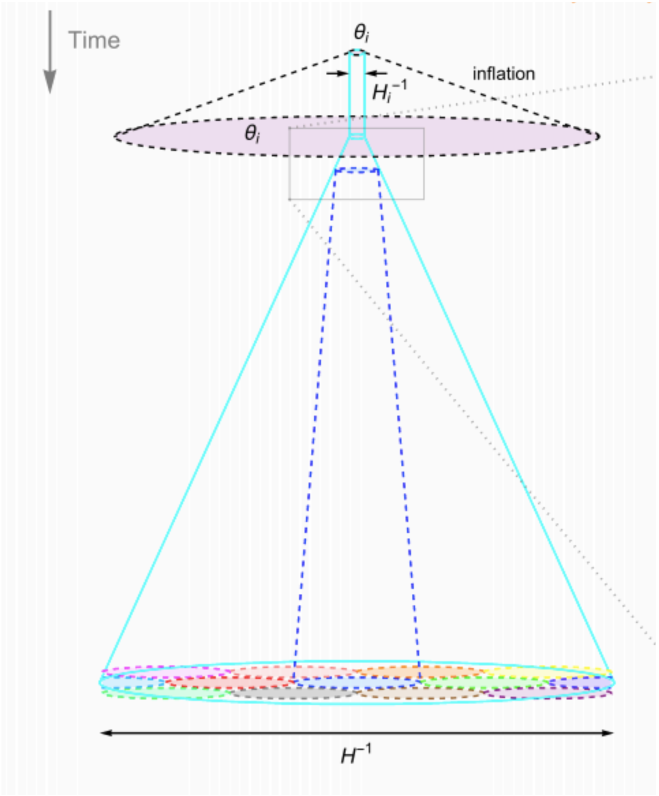
$$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$$



Isocurvature → inconsistent with observably large rT.

SSB after inflation leads to many different θ patches across our Universe.

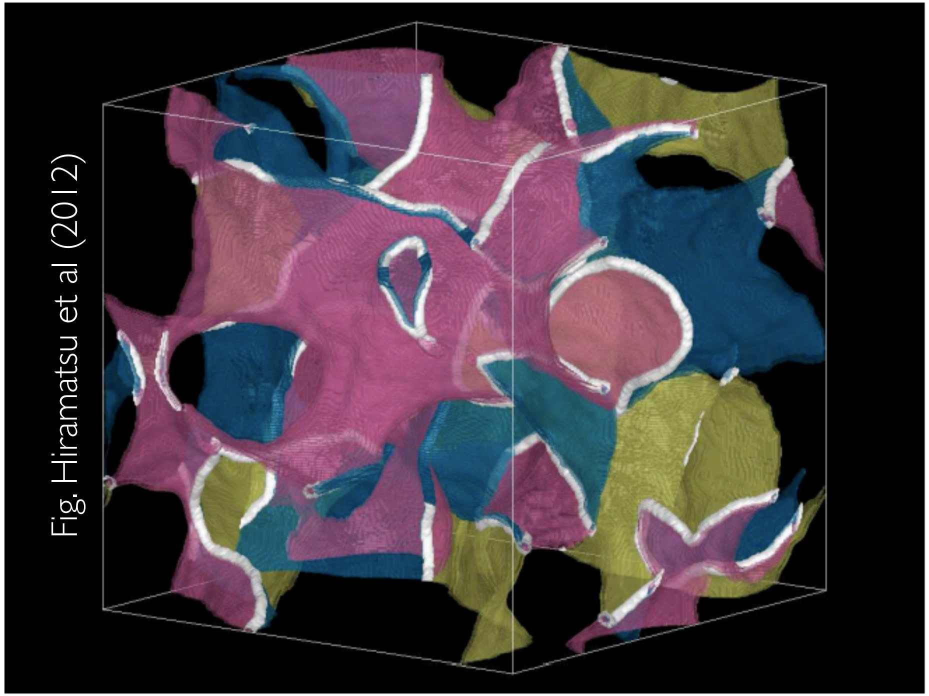
Fig: Armengaud et al (2019)



Averages out the random value of θ → predictive.

Kibble mechanism → topological defects. Decay produces oscillations in the axion field.

Fig. Hiramatsu et al (2012)



No isocurvature → consistent with large rT.

Strings decay when the axion potential drives $\theta \rightarrow 0$ vacuum (broken shift symmetry). This occurs when $H \sim m_a$. String size$\sim/m_r \sim 1/f_a$. Simulate the classical, non-linear field evolution on the lattice.

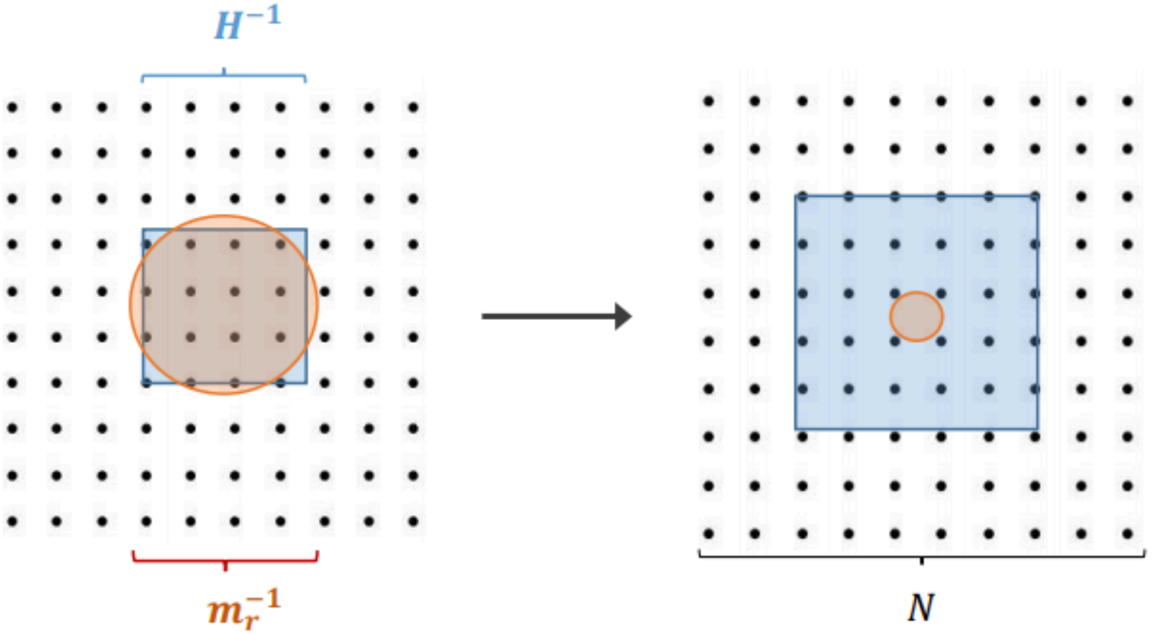
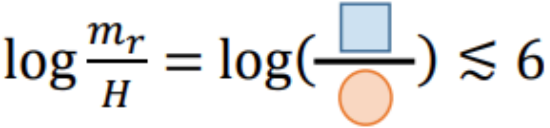


Fig: Gorghetto et al (2018)



Numerical problems limit the separation of scales.

Strings form at SSB. Hubble scales around fa$\sim 10^{10}$ GeV.

The Universe expands. Strings decay when axion field oscillates, Hubble ~ ma.

Physical scale log~70 → need extrapolations → large theoretical error.

Gorghetto et al (2018)
https://www.youtube.com/watch?v=DbvM7emtodo

RELIC DENSITY → mEV AXONS

Riess, Hoof, DJEM, arXiv:2108.09563

A statistical treatment of available simulations → predict the axion mass from $\Omega_d h^2$=0.12.

Axions From String Decay

Davis (1986) [and many others]

$$\rho_s(t) := \frac{\mu\xi}{t^2}$$

String density with cosmic time.

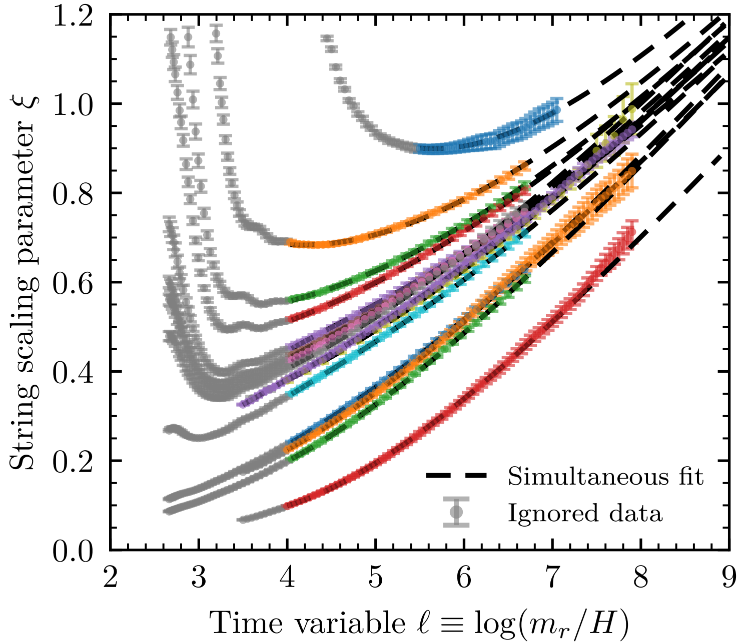
$$\mu \sim \pi f_a^2 \log\left(\frac{m_r}{H\sqrt{\xi}}\right)$$

tension

ξ String length parameter

Approximate axion density from string density when H~ma.

Scaling solution: length parameter goes to a constant after initial transients die out.



Scaling violation → large number of strings per horizon at physical log.

(Gorghetto et al, 2018)

Scaling is maintained by continuous axion emission:

Sims: Gorghetto+

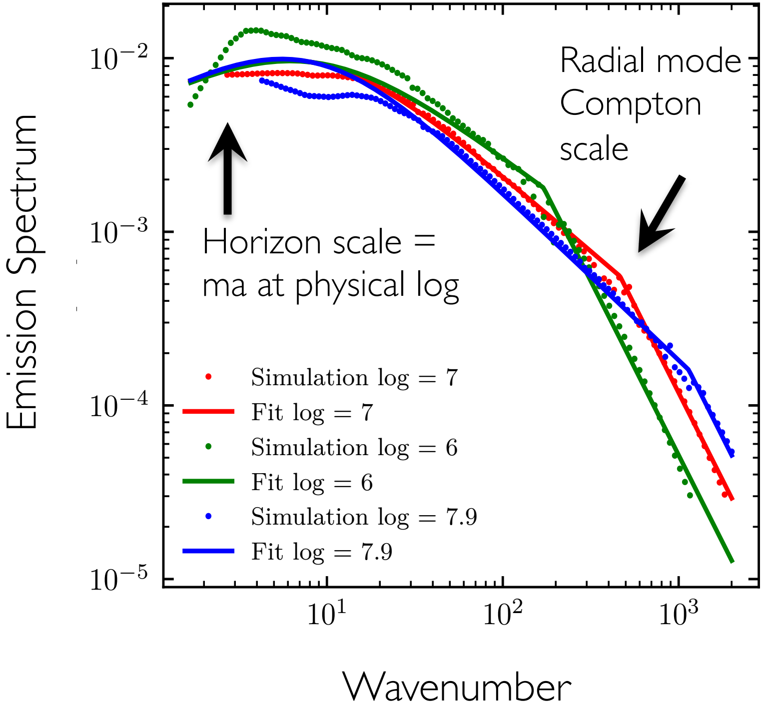
$$\dot{\rho}_s + 2H\rho_s \approx -\Gamma_a$$

$$\frac{\partial \Gamma_a}{\partial k} := \frac{\Gamma_a(t)}{H} F(k/H, m_r/H)$$

F = "instantaneous emission spectrum".
Integrate → total emitted axion density.

$$F(x,y) = \frac{1}{x_0} \frac{q-1}{1-(z_0/y)^{q-1}} \left(\frac{x_0}{x}\right)^q$$

q<1: UV dominated, axions from strings sub-dominant.
q>1: IR dominated, axions from strings dominant.



Gorghetto+: q also has log scaling violation →
Extrapolated spectrum is IR dominated (q>1).

What do current simulations say? Treat available works on same footing. Hoof, DJEM, Riess (2021)

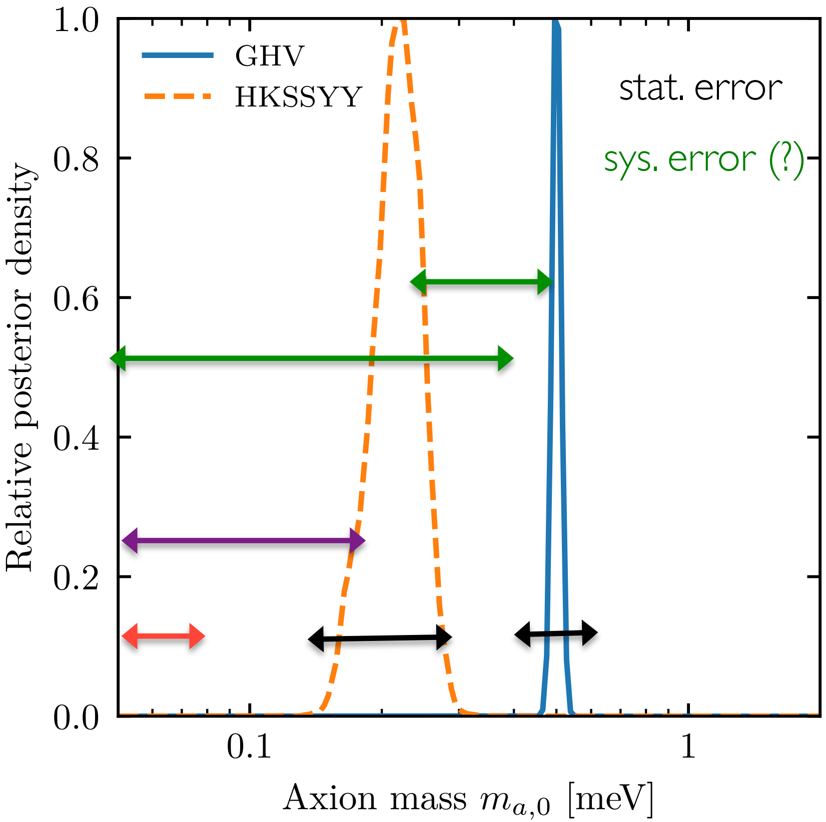
Model and add all DM contributions:

- Realignment. Solve homogeneous e.o.m. and numerically average over initial conditions.
- Strings. Fit the spectrum and extract q and ξ.
- Domain walls (fit Hiramatsu+).
- "Non-linear transient" (fit Gorghetto+).

Model uncertainties and DM likelihood:

- String spectrum fitting parameters.
- QCD topological susceptibility (fit from lattice QCD, Borsanyi et al).
- Planck DM density: fix axions as all DM.

MCMC using emcee, 12/13 dimensional parameter space. Marginalise to find axion mass.



Buschmann+ AMR simulations (log~9).

Scale invariance (q=1). Theory prediction?

If the QCD axion is produced by string decay, the mass is relatively large.

$$50\ \mu\mathrm{eV} \lesssim m_a \lesssim 20\ \mathrm{meV}$$

Too heavy for ADMX!

SN1987A upper limit
(Neff <0.2 →80 meV)

How can we test this scenario with astrophysics and in the lab?

MINICLUSTERS

Ellis, DJEM+ (2020, and forthcoming), History: Kolb & Tkachev (1990's)

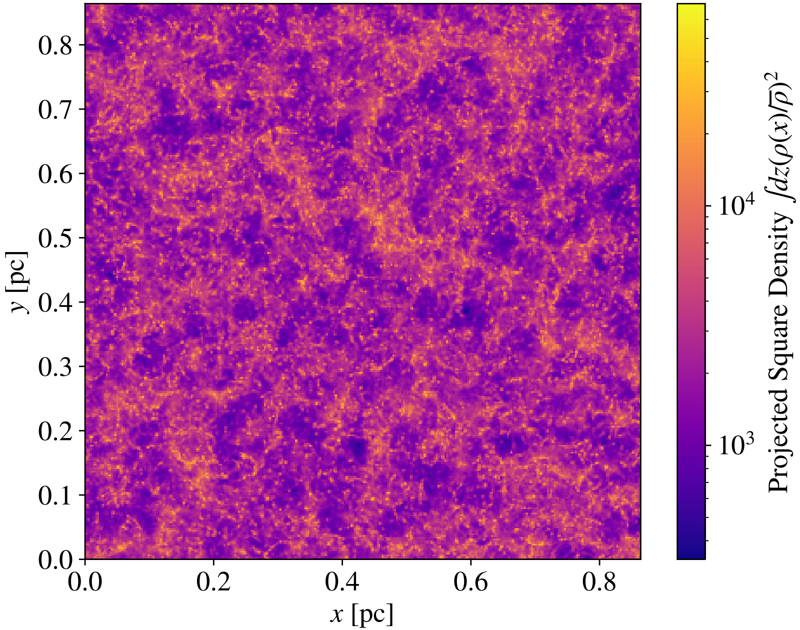
Miniclusters Seeds

Vaquero, Redondo, Stadler (2018), lattice field theory.

- PQ field evolution through SSB and string decay using "fat string" method.
- Final axion field configuration @ z~10^5, T~ MeV.
- Identify "minicluster seeds":

$$M_{\rm MC} \approx \rho_a(T_1)[a(T_1)H(T_1)]^{-3}$$

$$\approx 5 \times 10^{-13} M_\odot (m_a/50\mu{\rm eV})^{-0.5}$$

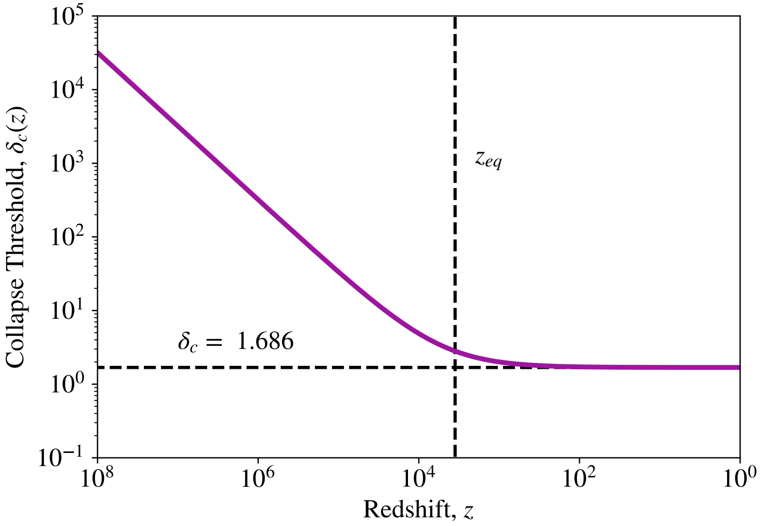


These sims do not include gravity → don't give the final MC masses and radii.
How much DM is in miniclusters? Astrophysical probes? → depends on mass and density.

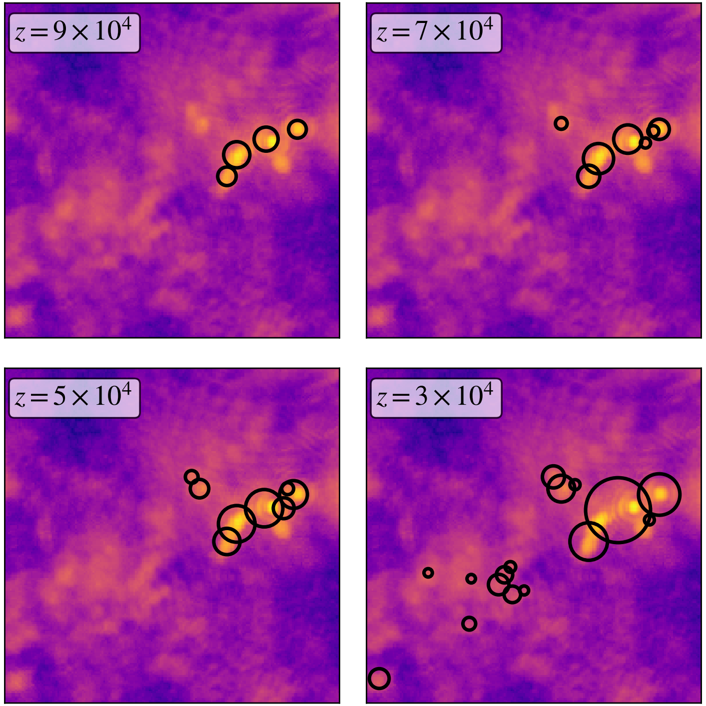
Semi-Analytical Model

Ellis, DJEM, Behrens (2020)

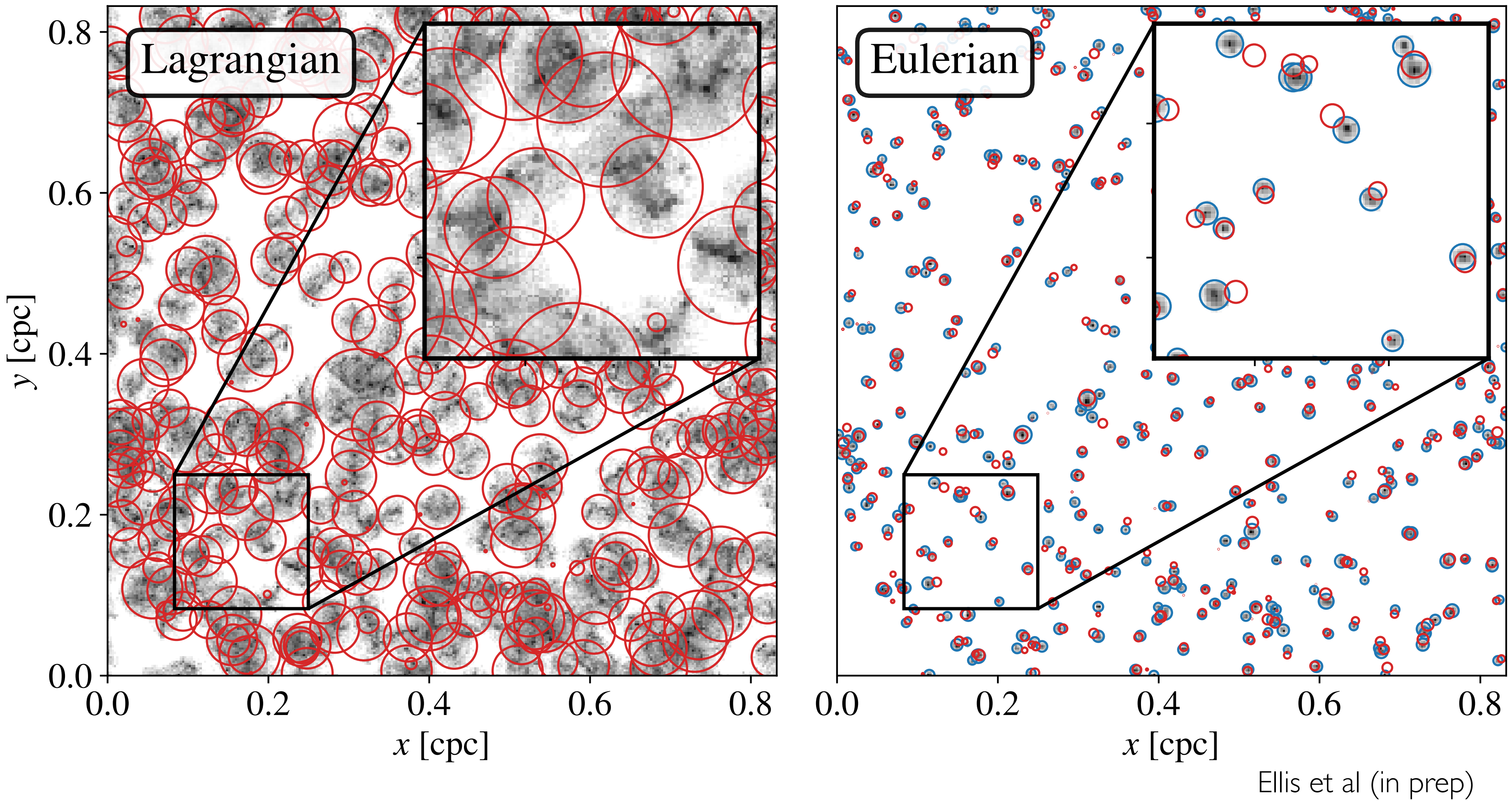
Our approach: solve the "excursion set" spherical collapse barrier crossing problem in real space. Use "peak-patch" method (Stein et al, Bond+)



Threshold <-> redshift of collapse

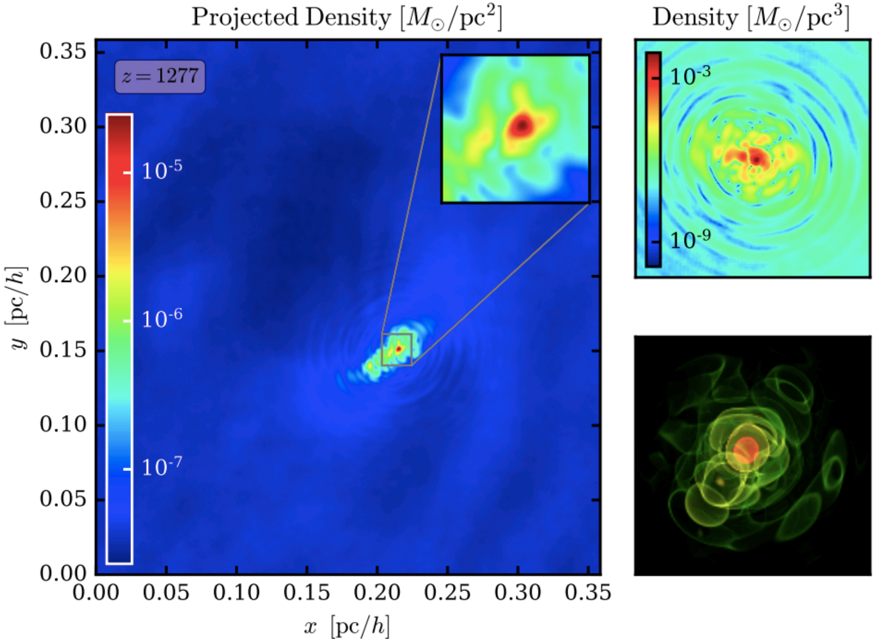


Identify seeds and predict collapse and merger history.


Lagrangian
Eulerian
y [cpc]
x [cpc]
x [cpc]
0.0
0.2
0.4
0.6
0.8
Ellis et al (in prep)

Numerical Simulation

Eggemeier+ (2019,2020)



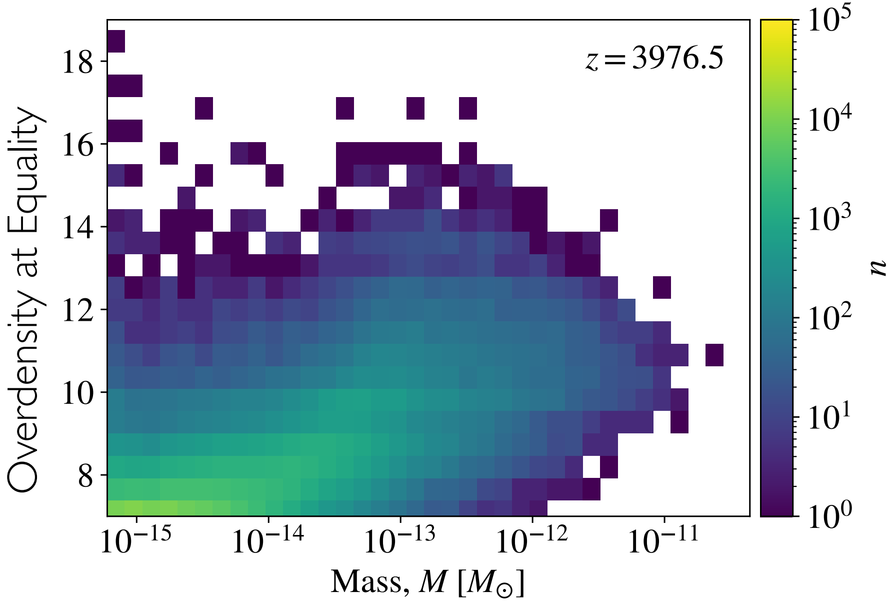
Hierarchical structure formation after equality → NFW-like minicluster halos.
While very dense compared to adiabatic "ordinary" halos, pheno is still relatively boring.

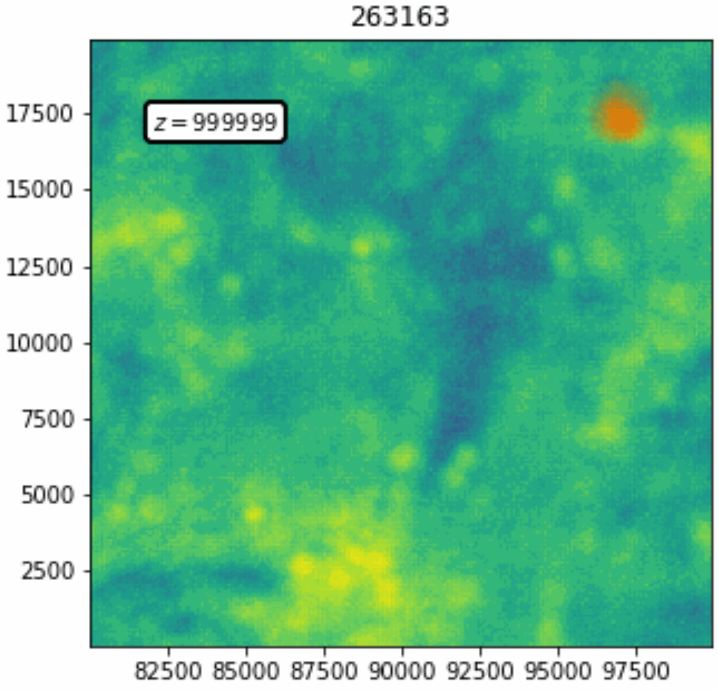
MCs contain axion stars: "core-halo relation".
Miniclusters are just ordinary DM halos and are NOT single axion stars!

What happened to the "seeds"?

Ellis et al (in prep)

Self-similar collapse before equality. Denser minicluster seeds, Δ>>200? Power law profiles?
Are simulations/halo finders missing the seeds? Swallowed as substructure? Missed dense cores?



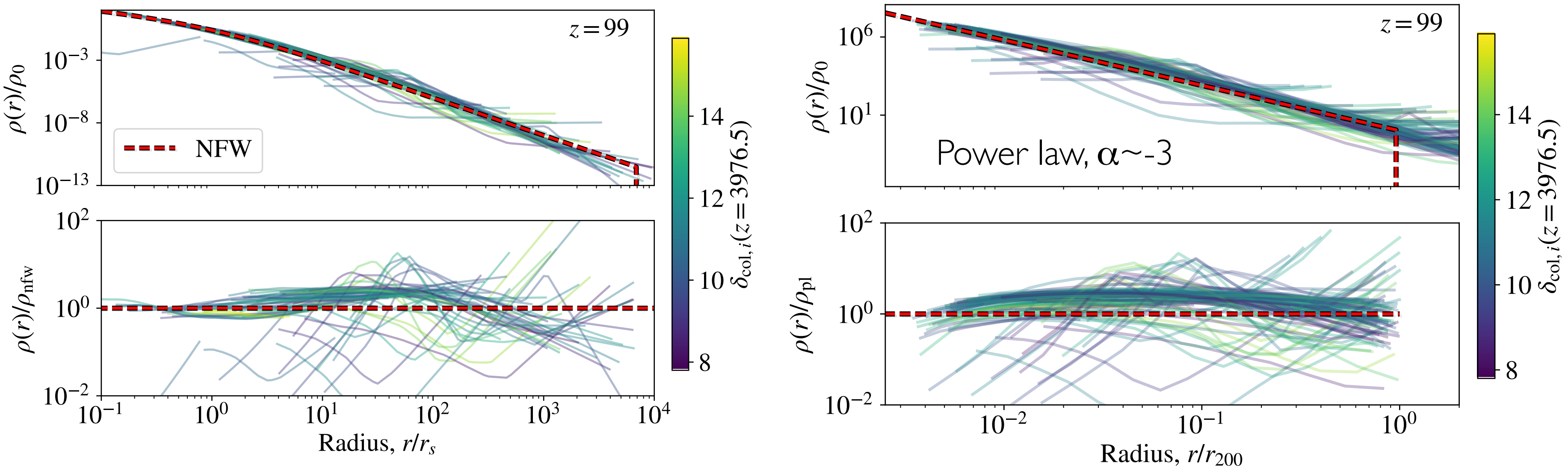


Tag seeds at equality. Overdensity, δ, defined via collapse redshift of Peak-Patch merger tree.

Morphology of Miniclusters

Ellis et al (in prep)

Most identified rare seeds end up as NFW minicluster halos predicted from hierarchical mergers.



NFW and power law predictions for halos matching seeds >75%. No evident correlation with δ.

Microlensing?

Fairbairn, DJEM, Quevillon (2017)
Ellis et al (in prep)

Older studies with power law profiles and extrapolated δ → possible lensing in HSC.
NFW profiles with predicted c(M) cannot lens due to shallow inner slope → no caustics.
Most optimistic case: assign profiles with rs unresolved as r^{-3} profile and central axion star.

WATCH THIS SPACE

Radio Lines & Transients

Edwards et al (2020)

MC-neutron star collision → convert axions to photons in magnetosphere → radio transient.
Tidal stripping model → events. Highly dependent on profile. Hope?

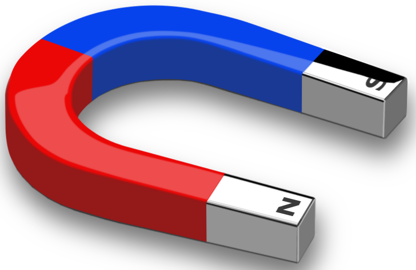
WATCH
THIS
SPACE

DIRECT DETECTION:TOORAD!

DJEM et al (PRL, 2019); Schuette-Engel, DJEM et al (JCAP, 2021)

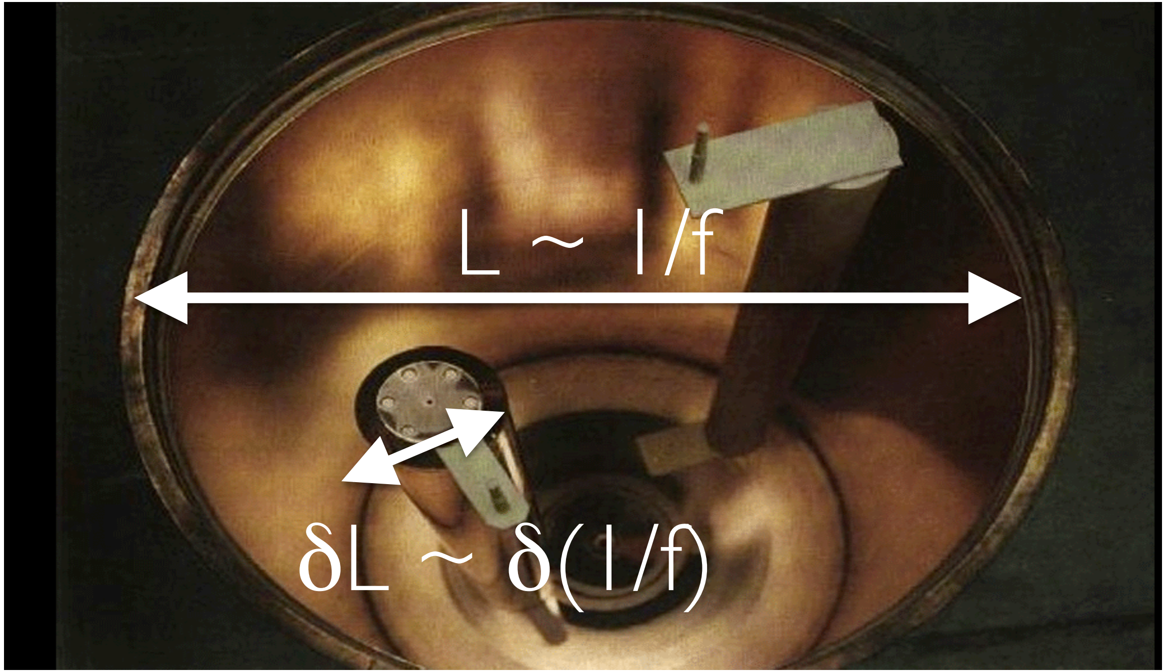
How to Detect Axions

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



Sikivie Haloscope

Sikivie (1983)
Image: ADMX



Microwave cavity.

Resonance when axion frequency ~ cavity frequency (tune the radio)

Volume → works for frequencies ~ GHz

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

meV/THz Challenge

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

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

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).

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

See also Wilczek (1987)

Dynamical axion field in topological magnetic insulators

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

Hypothetical phase in candidate materials: $Bi(Fe)_2Se_3$ $Mn_2Bi_2Te_5$

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.

Compute axion-induced electric field, E.

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

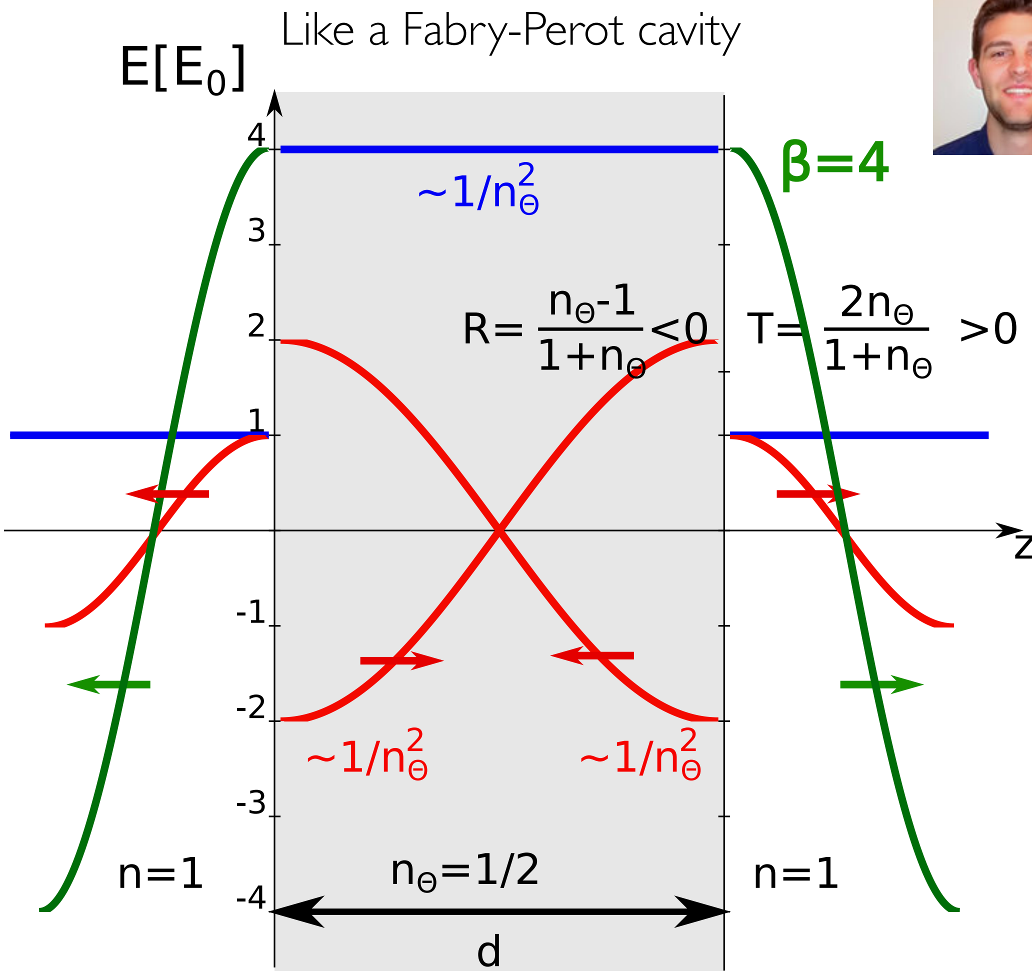
$$n_\Theta = n\left[1 - \frac{b^2}{\omega^2 - m_\Theta^2}\right]$$

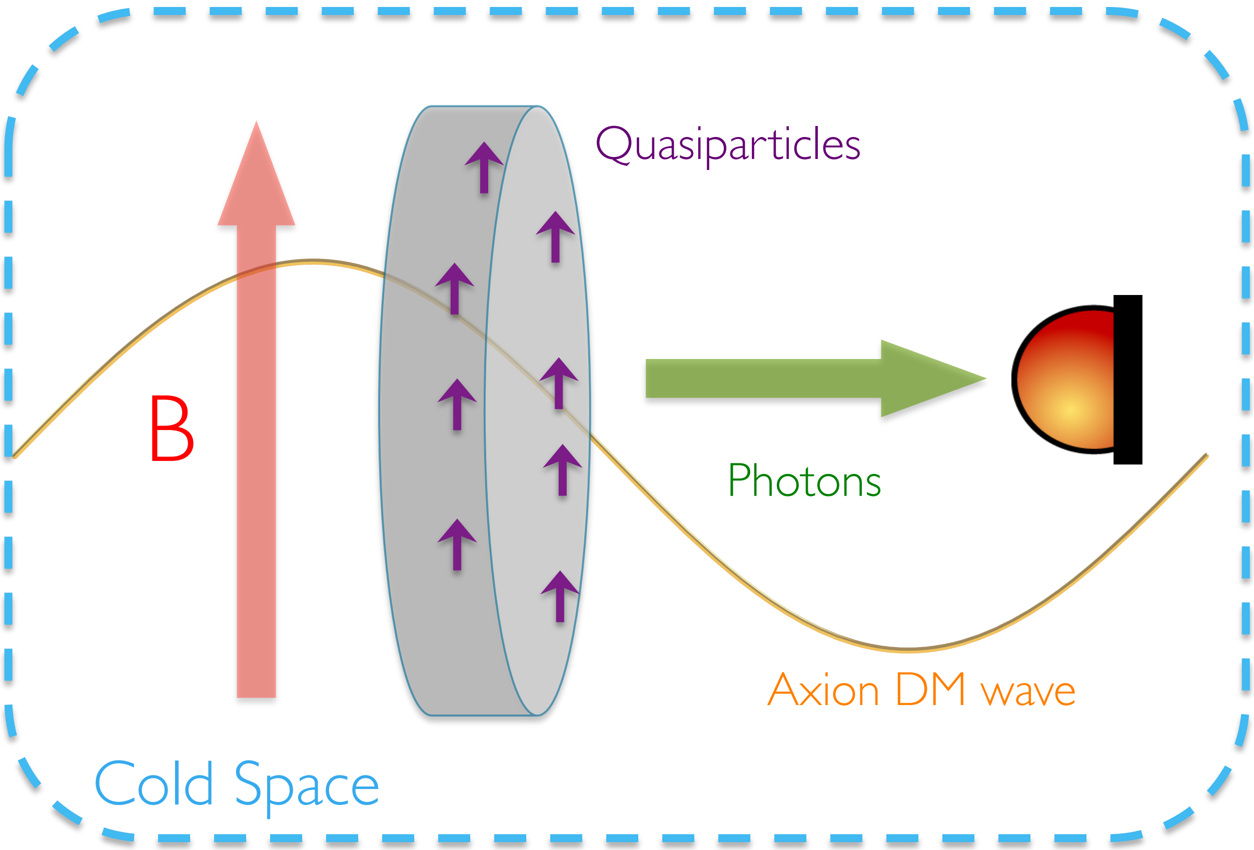
Constructive interference of reflected waves → boost amplitude $1/n_\Theta^2$.

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

(E_0 = induced field in vacuum)

Boundary condition calculation follows MADMAX





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

TOORAD = TOpOlogical Resonant Axion Detection

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:

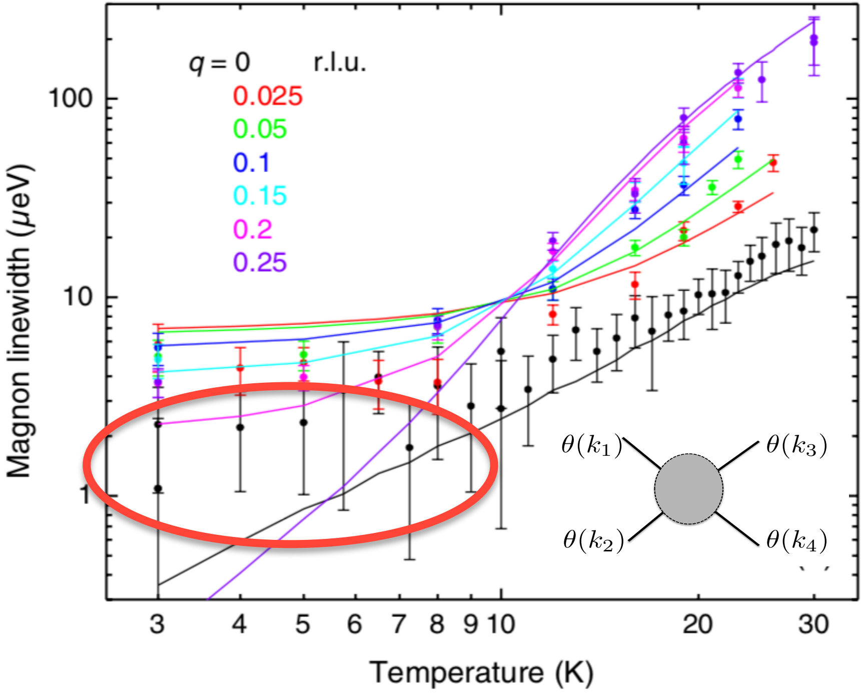
$$\Gamma = \frac{\delta L}{L}\omega$$

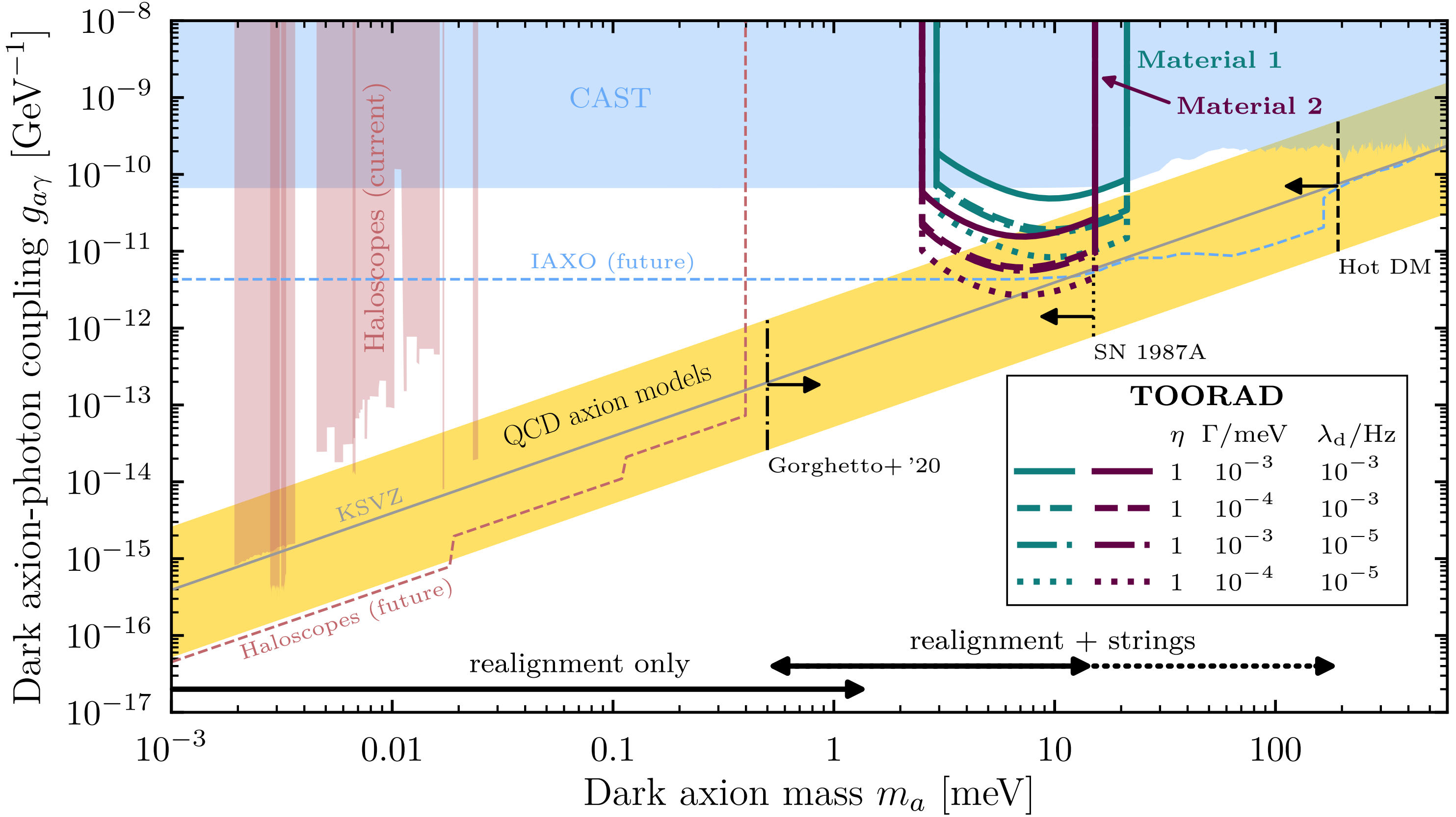
Typical impurities on the scale of microns, while lattice scale ~ 10 Angstroms →

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

→ Skin depth of material ~ mm, and maximal power enhancement $\beta^2 \sim 10^{3\text{-}4}$

Neutron scattering on MnF_2





meV/THz lacks technology. TOORAD is the highest frequency resonant haloscope proposed in QCD band.

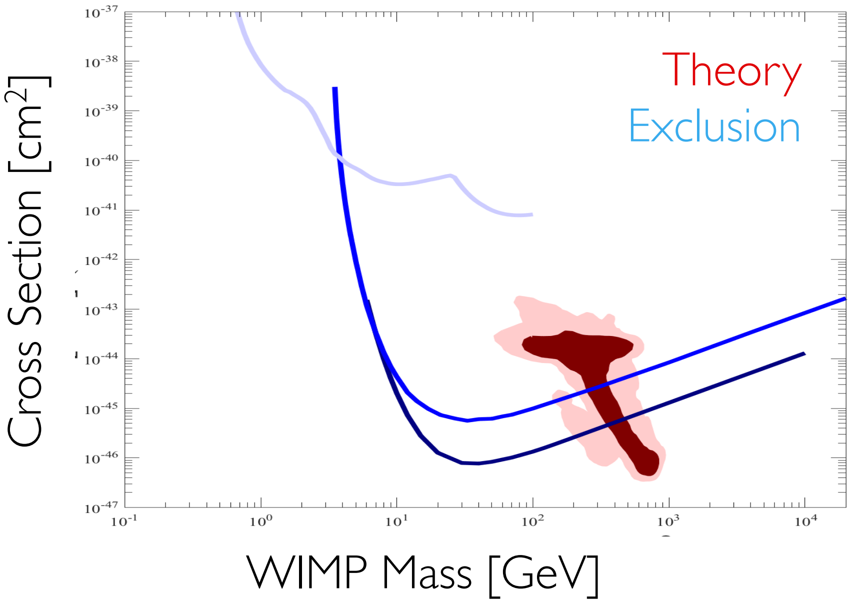
- Post inflation SSB predicts axion mass ~meV if the string spectrum is IR dominated.
- Dense, low mass "miniclusters". What are their density profiles? Lensing? Radio?
- meV/THz is a gap in haloscope technology. Use axion quasiparticle materials?

Thank You!

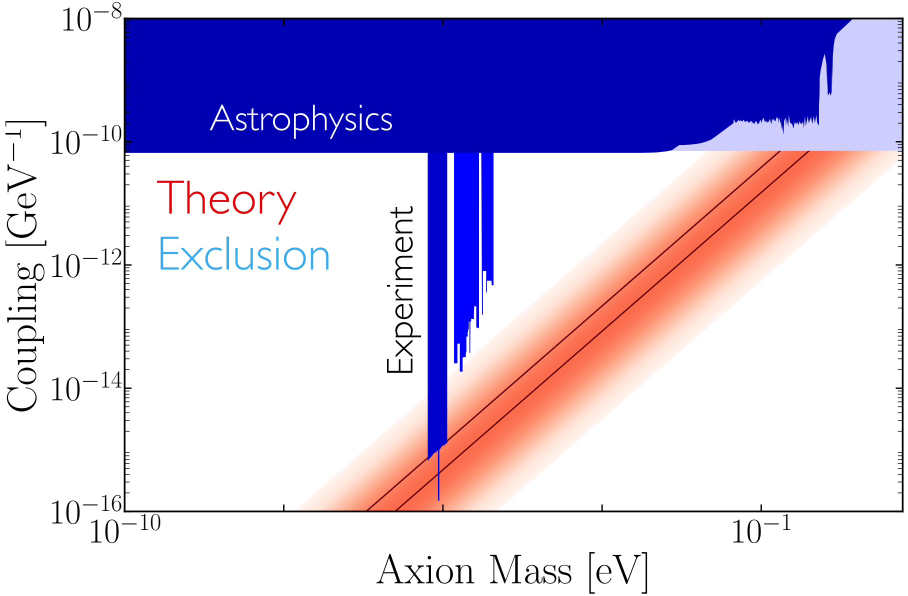
BACKUP SLIDES

Axions vs WIMPs

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

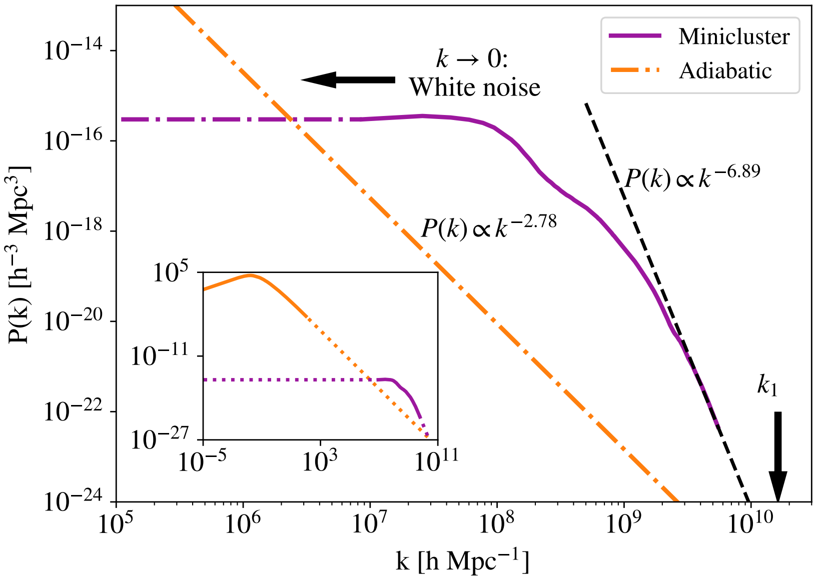


DMTools



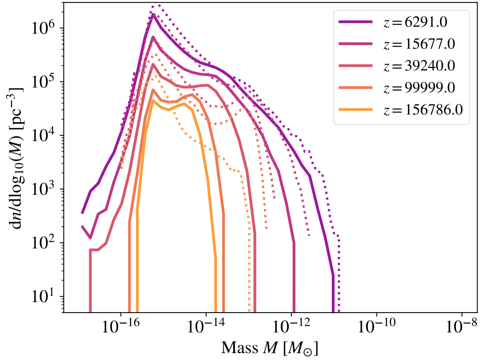
O'Hare github

Gravitational Collapse

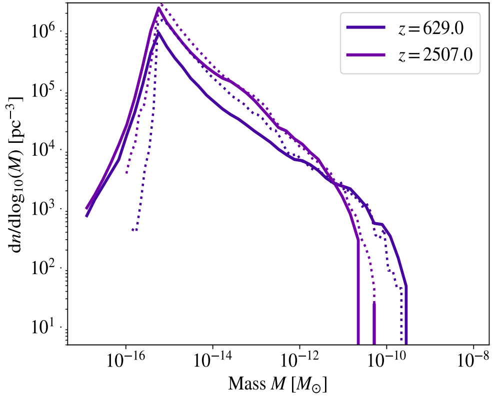


String decay → enhanced power spectrum (and large non-Gaussianity) on small scales → enhanced early structure formation.

z>zeq dense regions undergo infall

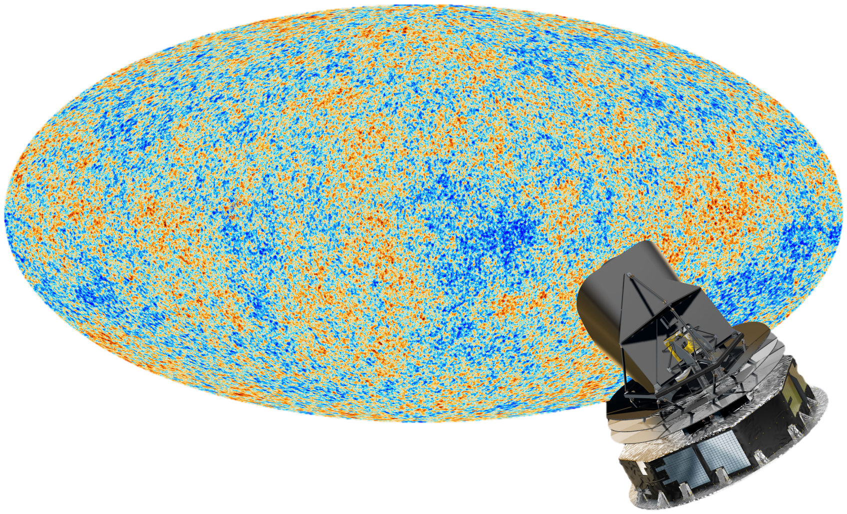


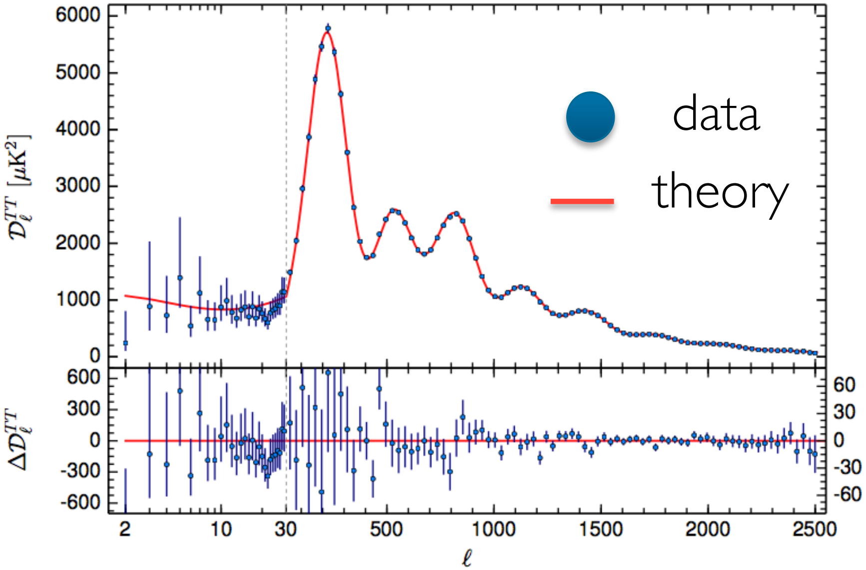
z<zeq hierarchical structure formation



Dark Matter in the Cosmos

Planck Collaboration





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

$$\Omega_d h^2 = 0.12$$

(measured to 1% precision)

The Strong CP Problem

A neutron electric dipole moment (nEDM) would violate CP-symmetry of QCD.

Wigner-Eckhart: EDM and magnetic dipole must be parallel.

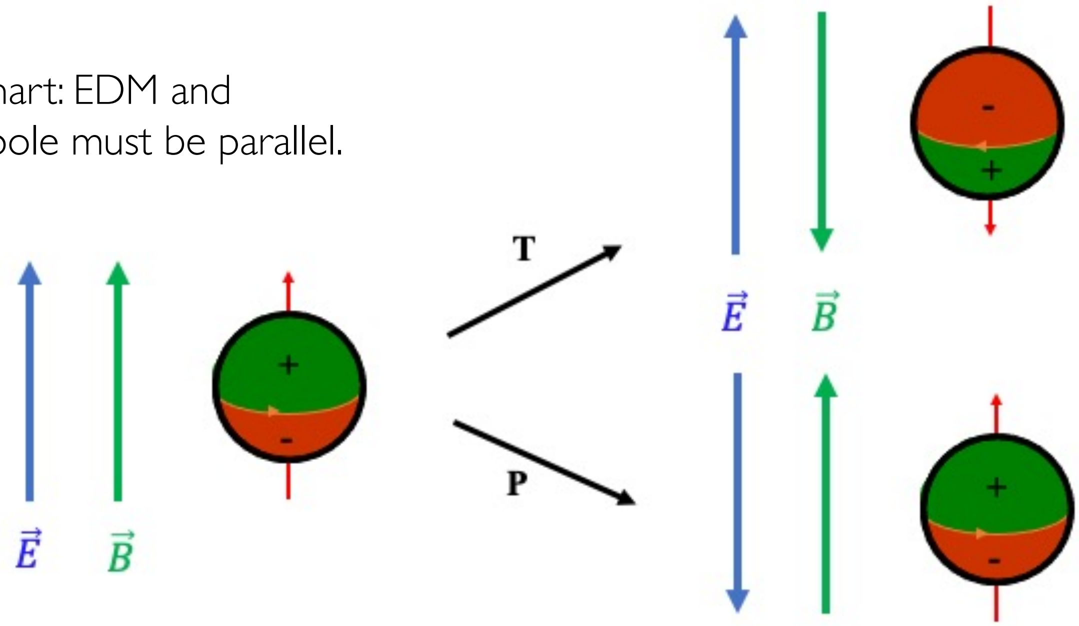


Fig: Day, Ellis DJEM (2021)

The Strong CP Problem

nEDM, Abel et al (2020)

The nEDM is measured using cold neutrons:

$$d_n = 0 \pm 1.3 \times 10^{-26}\, ecm$$

QCD topological term

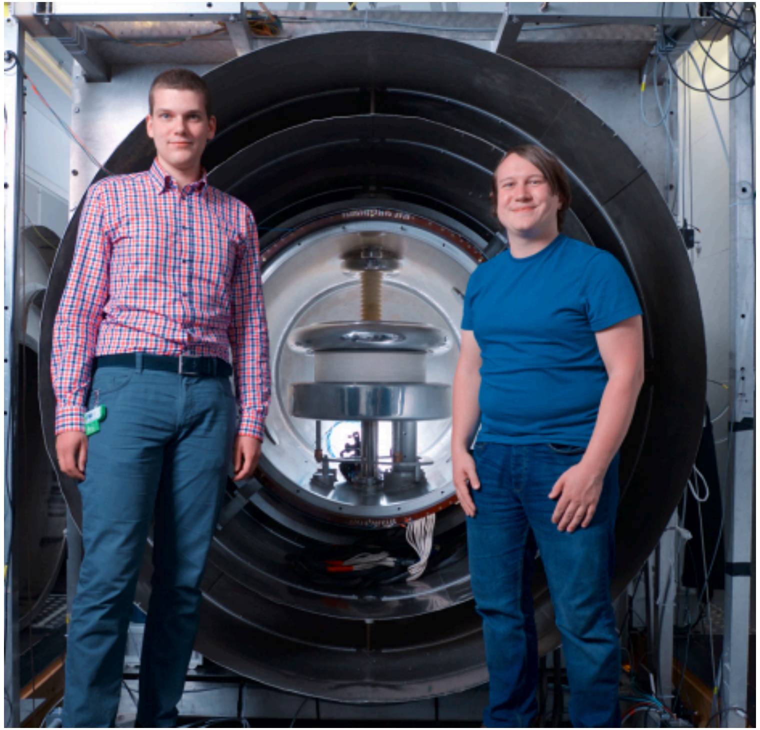
$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2}\, \mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\Rightarrow d_n = 3.6 \times 10^{-16}\theta\, ecm$$

θ has a contribution from electroweak CP-violation

$$\theta = \theta_{\mathrm{QCD}} + \arg\det M_u M_d$$

Why is $\theta < 10^{-10}$? $\theta \sim 1$ allowed by symmetry.



Rawlik & Ayres at nEDM, Switzerland (2017)

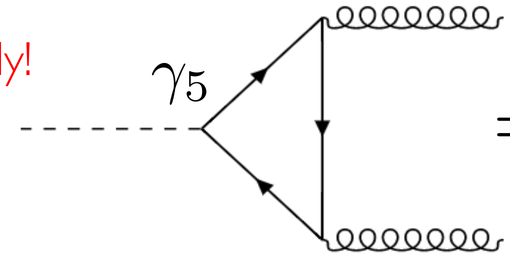
Enter the Axion

Peccei & Quinn (1977);
Weinberg, Wilczek (1978)

Make θ dynamical, with a potential possessing a CP symmetric minimum. Recipe follows…

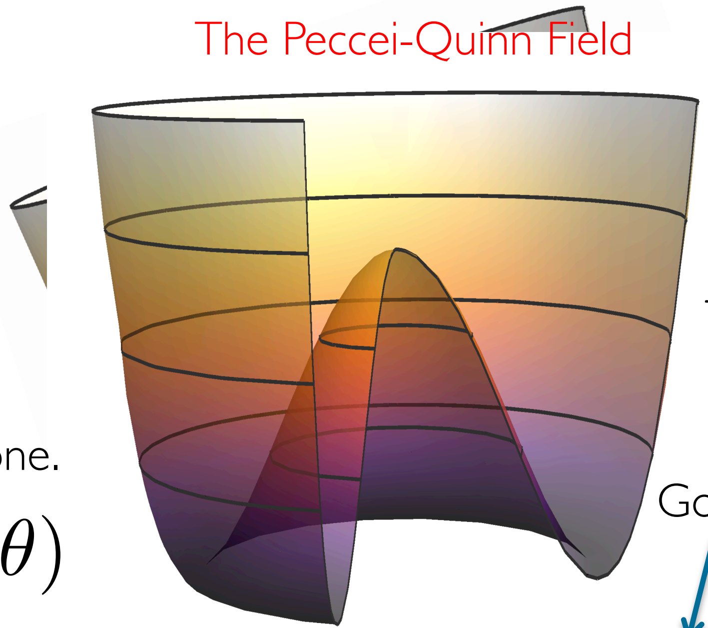
First introduce a U(1) symmetric theory.
Next, chirally charge quarks under U(1).

Anomaly!



$$\Rightarrow \theta G\tilde{G}$$

The Peccei-Quinn Field



$$\theta \neq 0 \quad \Phi = (\rho + v)e^{i\theta}$$

Absosrb the original θ with a shift in the PQ goldstone.

Instantons! $E_{\rm vac} = -\cos\theta = V_{\rm eff}(\theta)$

Minimise V: axion θ "cleans up" the CP problem.


MAGNETIC POWER
100% EFFECTIVE GREASE REMOVAL
AXION®
TOUGH
CP CLEANER
Lime

Enter the Axion - II

Abbott & Sikivie; Dine & Fischler; Preskill, Wise & Wilczek (1983)

The axion is a new pseudo-Goldstone boson. Relic oscillations ("realignment") → dark matter.

$$m_a^2 f_a^2 = m_q \Lambda^3_{\mathrm{QCD}} \qquad m_a = 5 \times 10^{-6}\ \mathrm{eV}\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)$$

Local DM density given as a harmonic oscillator: $\phi = f_a \theta$

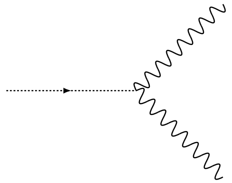
$$\omega_a = m_a + \frac{1}{2} m_a v^2 = m_a[1 + \mathcal{O}(10^{-6})] \qquad \rho_{\mathrm{DM}} = \frac{1}{2} m_a^2 \phi_0^2$$

Axion DM is spatial/temporal variations in the nEDM/θ angle + instanton potential energy.

Low energy interaction:

$$g_{a\gamma\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

→



Axion-photon decays/conversions

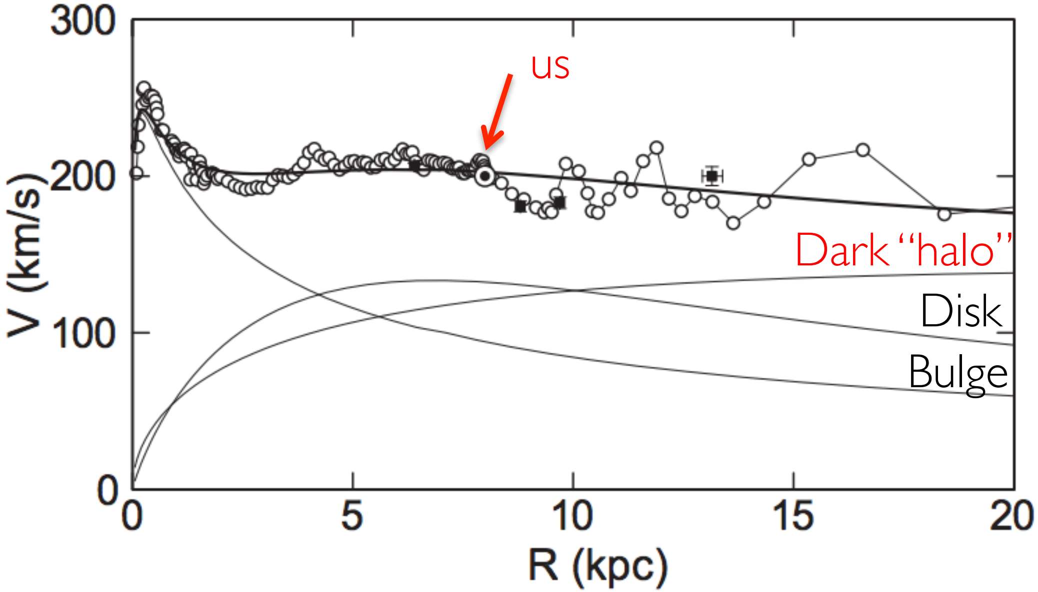
$$\phi \vec{E} \cdot \vec{B}$$

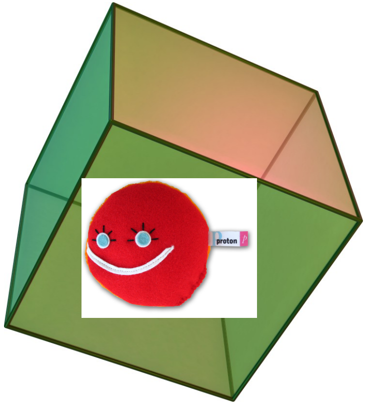
"Axion electrodynamics"


IMPROVED...
BETTER DETERGENT
BOOSTER THAN EVER!
AXION
NOW WITH
DARK MATTER!
Safe whitening brightening power
for all your wash...pre-soaks too!
CAUTION: EYE IRRITANT
READ IMPORTANT INFORMATION ON SIDE PANEL
NET WT. 25 OZS.
(1 LB. 9 OZS.)

Dark Matter on Earth

Milky Way Rotation Curve, Sofue (2012)





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

(measured to ~ 25% precision)

What is the Axion Mass?

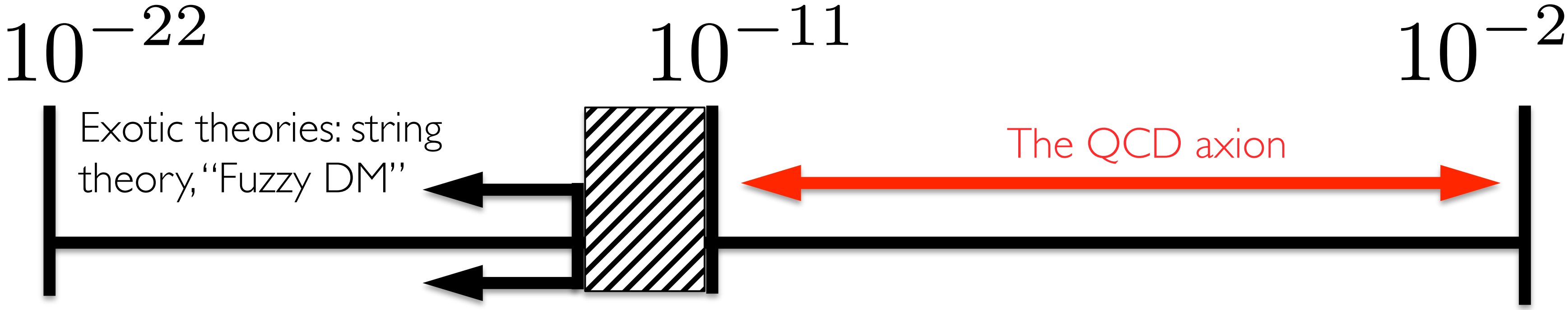
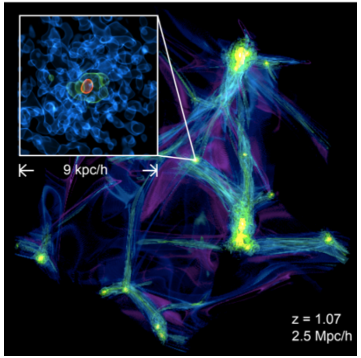
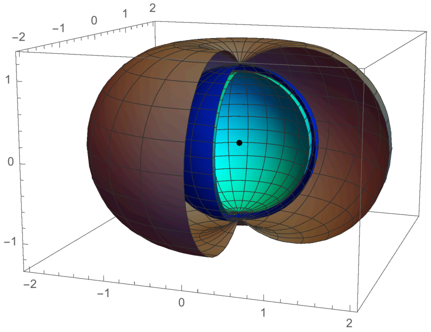


Fig: Veltmaat et al (2018)

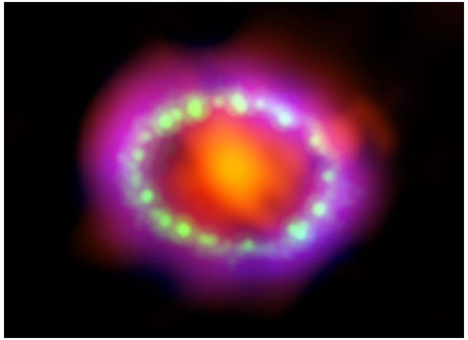


Galaxy formation
e.g. DJEM (2016)



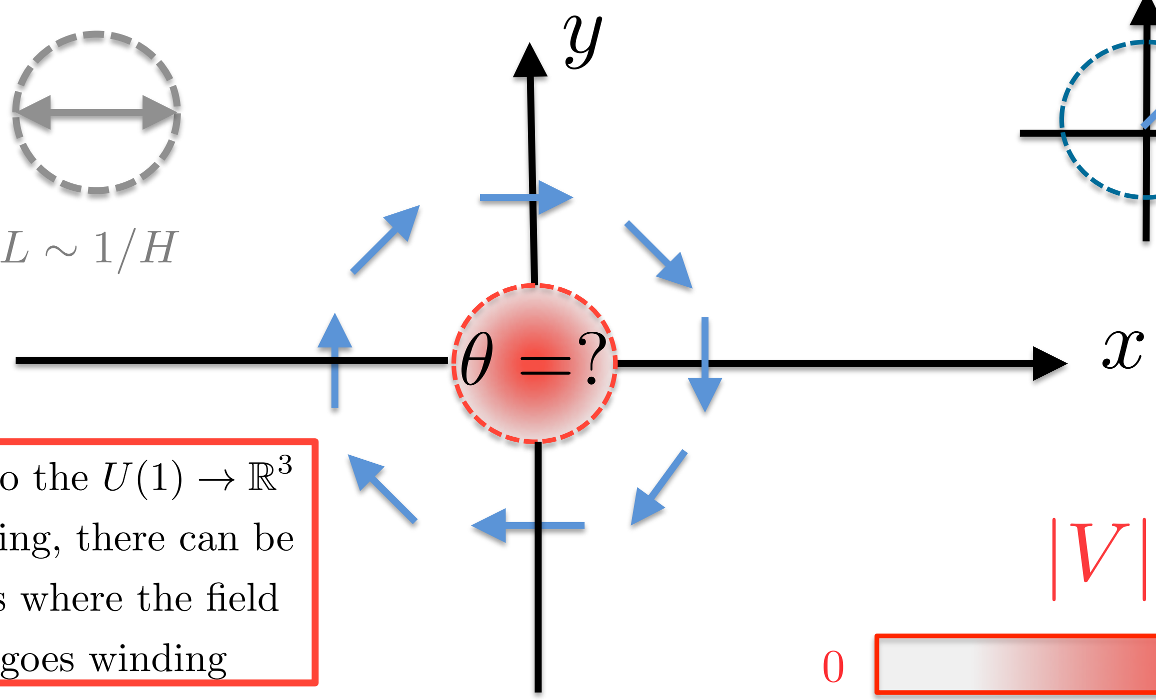
"Black Hole Superradiance"
e.g. DJEM & Stott (2018)

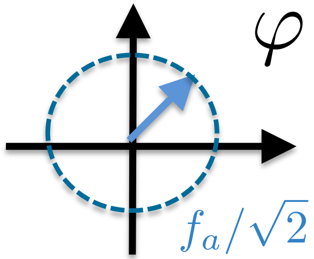
Fig: Physics World



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

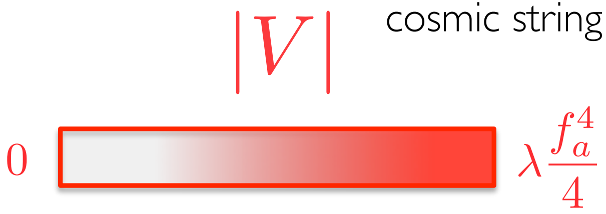
Formation of Defects



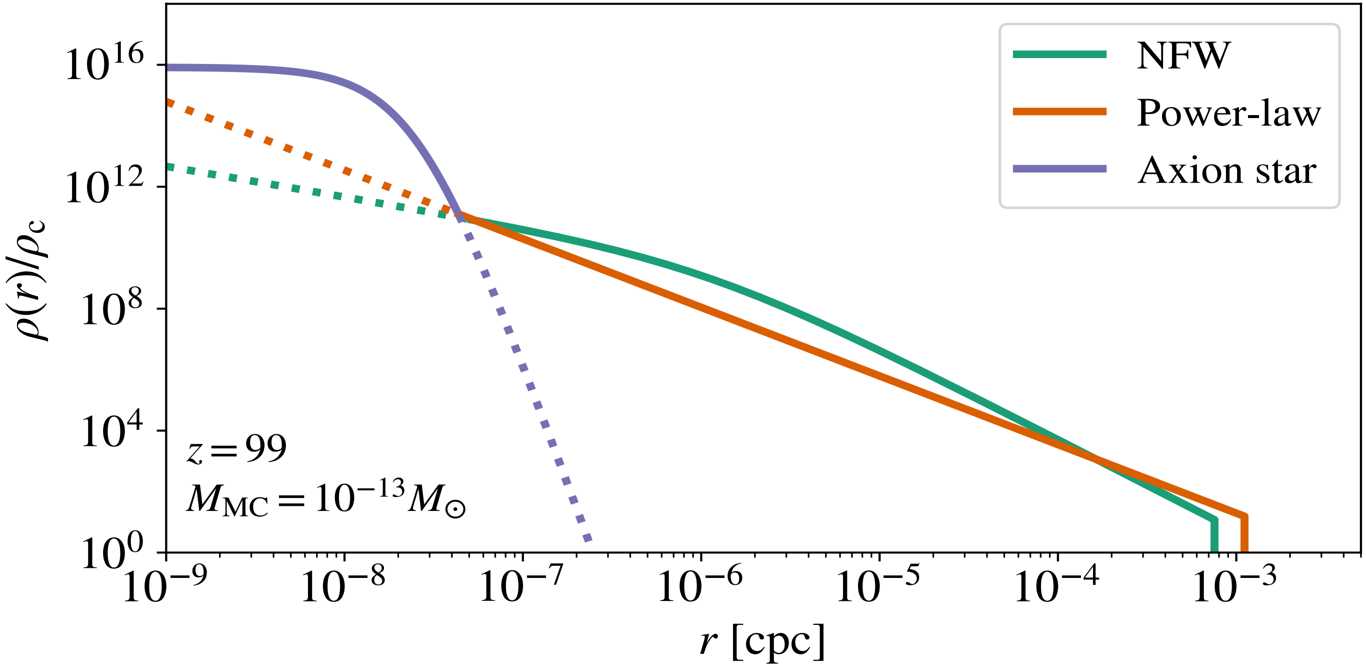


Due to the $U(1) \to \mathbb{R}^3$ mapping, there can be points where the field undergoes winding

ρ=0 → symmetry unbroken along 1D cosmic string



$$\ddot{\phi} + 3H\dot{\phi} + (k^2/a^2 + m^2)\phi = 0$$



$$M_\star = 4.16 \times 10^{-15} \left(\frac{50\mu\text{eV}}{m_a} \right) \left(\frac{v_{\rm vir}}{0.1 \text{m s}^{-1}} \right) M_\odot$$

Coupled Perturbations (lossless)

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

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

(assumed vs<<c)

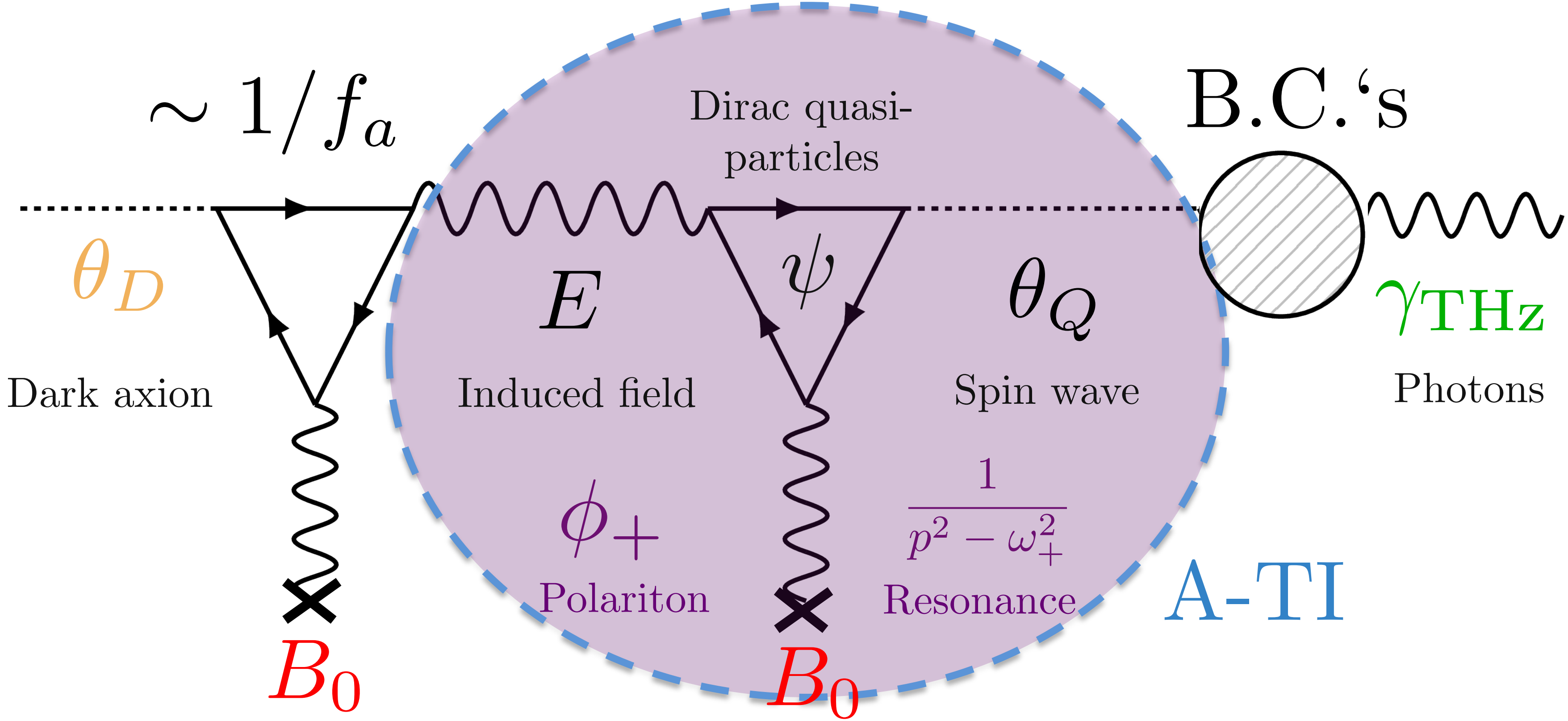
Axion dark matter drives the system at frequency given by axion mass.

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

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

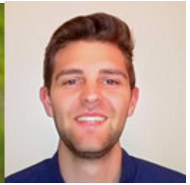
$$b = \frac{\alpha}{\pi\sqrt{2}} \frac{B_0}{\sqrt{\epsilon} f_\Theta} = 1.8 \text{ meV} \left(\frac{25}{\epsilon}\right)^{1/2} \left(\frac{B_0}{2 \text{ T}}\right) \left(\frac{64 \text{ eV}}{f_\Theta}\right),$$

Scan the resonance!

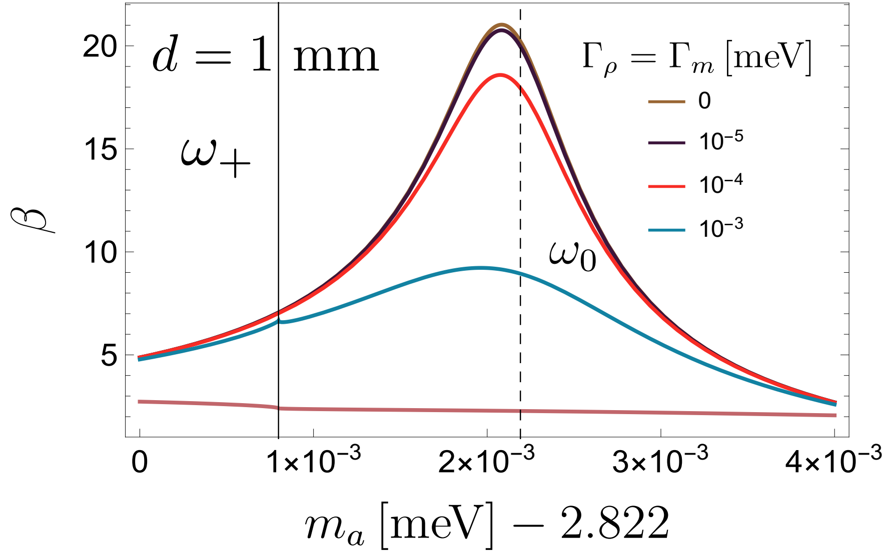


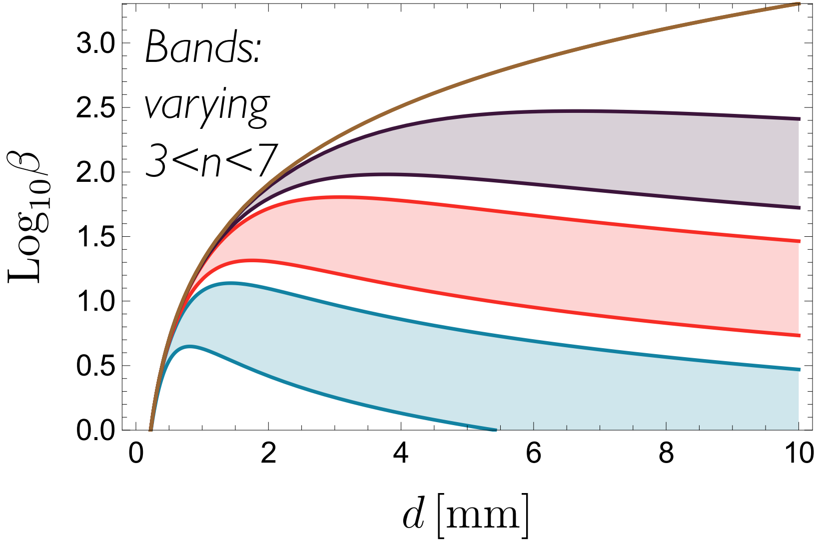
$\sim 1/f_a$
Dirac quasi-particles
B.C.'s
θ_D
Dark axion
E
Induced field
ψ
θ_Q
Spin wave
γ_{THz}
Photons
ϕ_+
Polariton
$\frac{1}{p^2 - \omega_+^2}$
Resonance
A-TI
B_0
B_0

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.

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

Dielectric Function

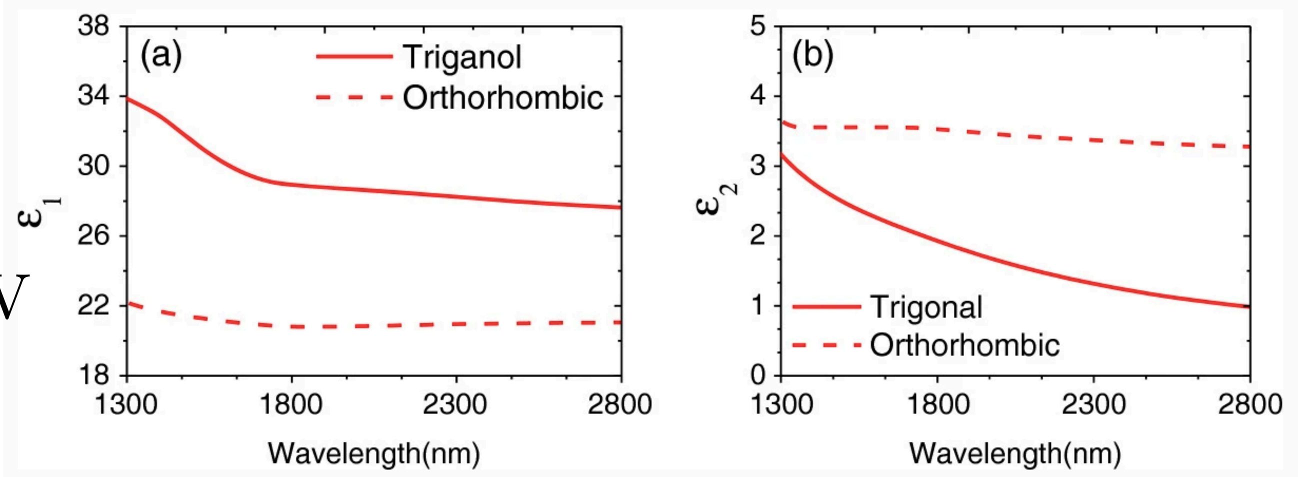
Recall that dielectrics have damping of the electric field:

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

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 tanδ~10^{-4}

Cao & Wang (2013)

Photon rate on resonance for QCD axion:

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

nature

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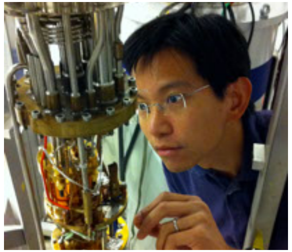
Article | Published: 30 September 2020

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 ✉

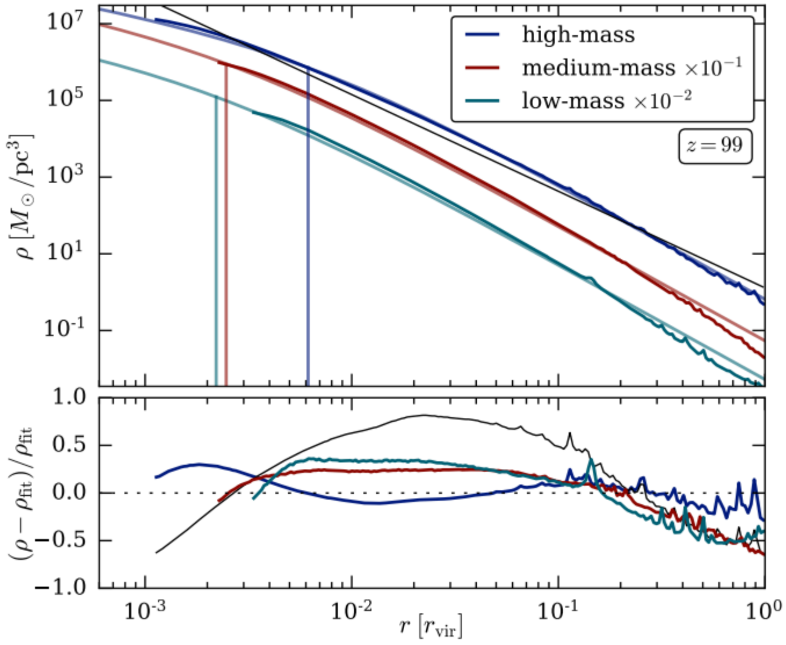
Nature **586**, 42–46(2020) | Cite this article

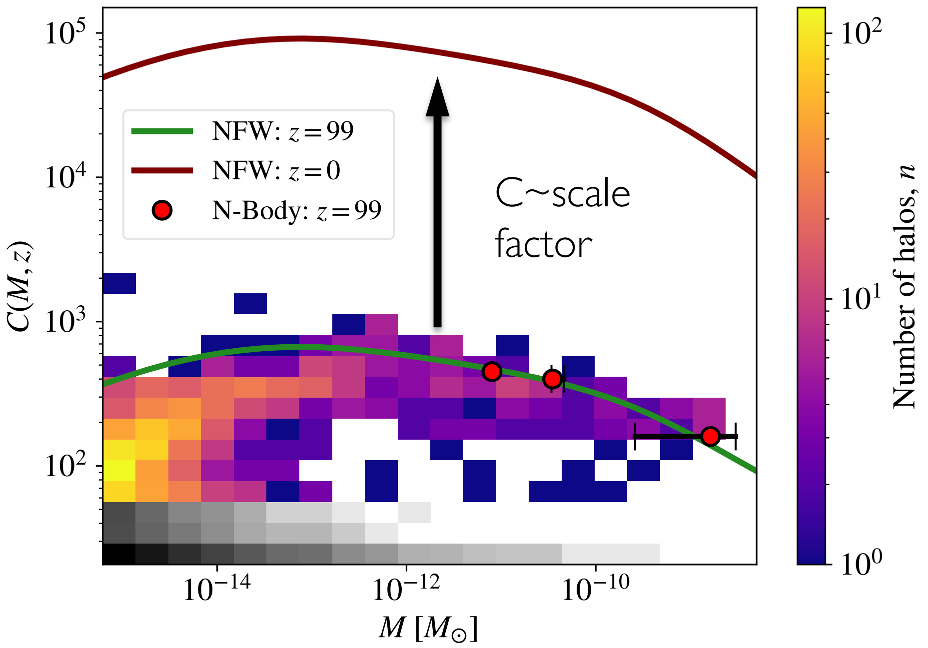


Need low dark count, high efficiency detector.
Possible collaboration with BRASS. Aim for f ~ 800 GHz.

Inside Minicluster Halos

Ellis, DJEM, Behrens (2020)
N-body: Eggemeier et al (2019)





Minicluster Survival

Kavanagh et al (2020); Tinyakov et al (2016); Dokuchaev(2017)

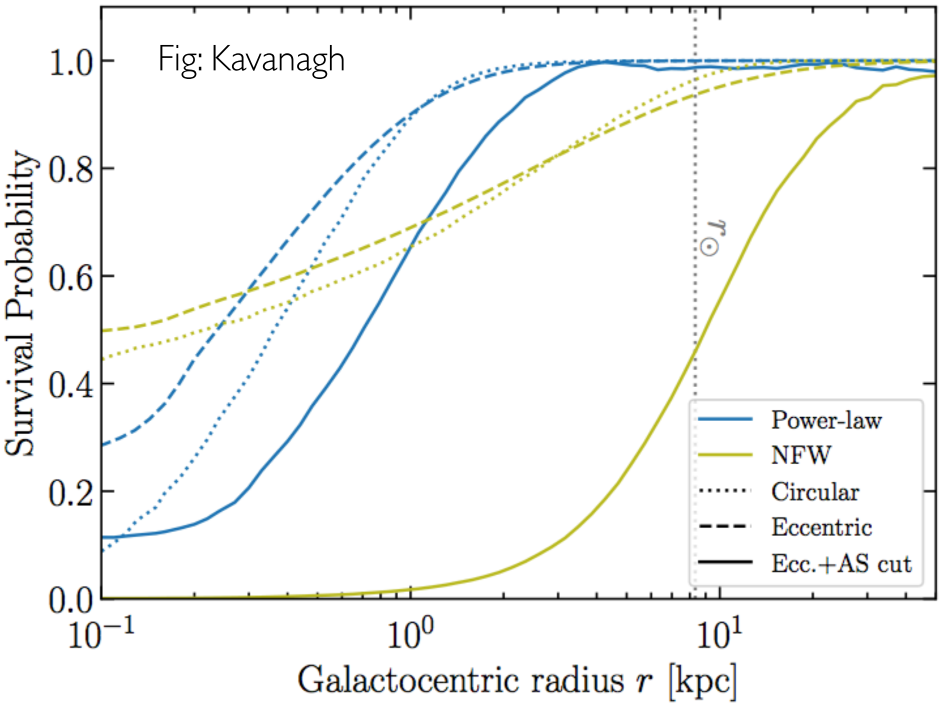
Survival in the Milky Way is critical to whether we can observe axion DM.

Stellar encounters strip miniclusters and minicluster halos.

NFW halos are fluffy → 50% survival probability @ stellar radius.

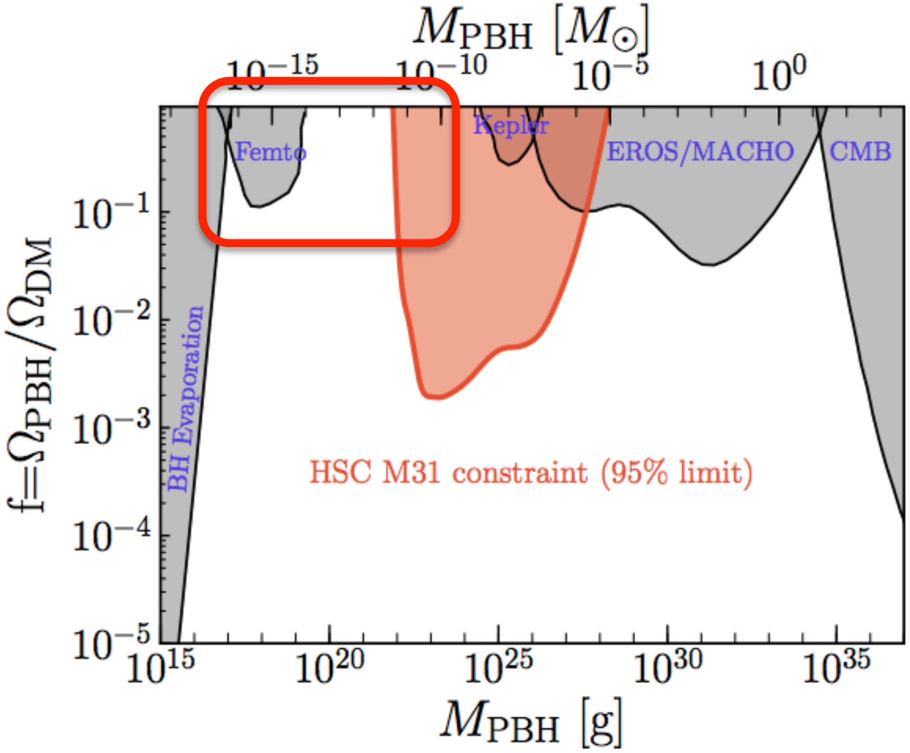
Power law profiles are compact → 100% survival @ stellar radius.

Minicluster-Earth collisions very rare. How much local DM is there?



Microlensing of MCs

Niikura et al (2018)
Fairbairn, DJEM, Quevillon (2017)



- NFW profiles with extrapolated C(M) don't lens.
- Dense, power law MCs lens like PBHs.
- Naïve model → excludes 10^{-2} fraction. Is the post-inflation axion ruled out?

What is the axion mass?

Minicluster Survival

Kavanagh et al (2020); Tinyakov et al (2016); Dokuchaev(2017)

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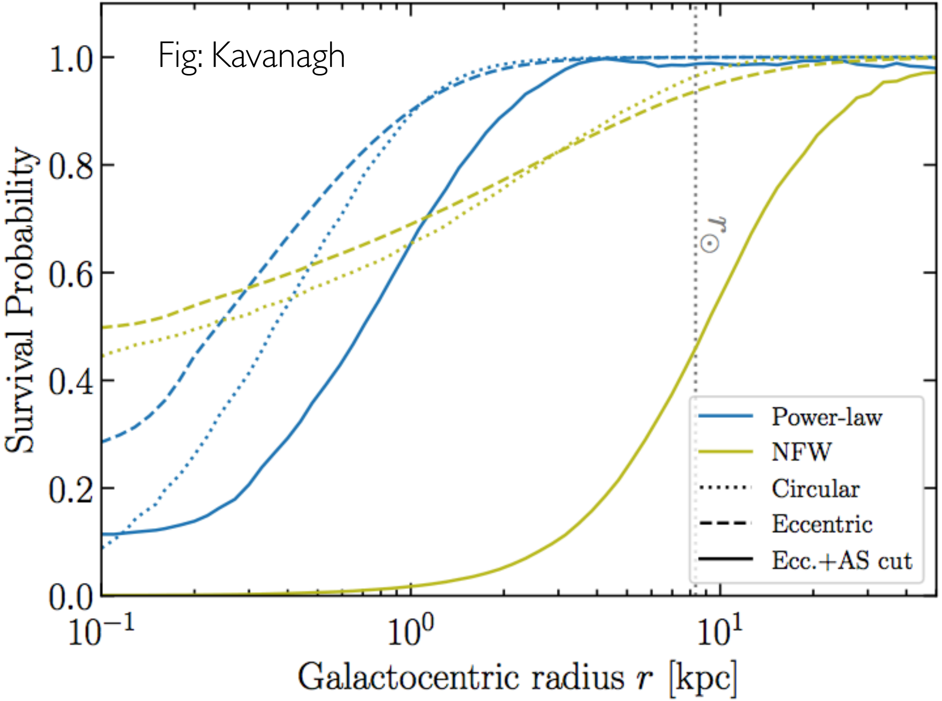
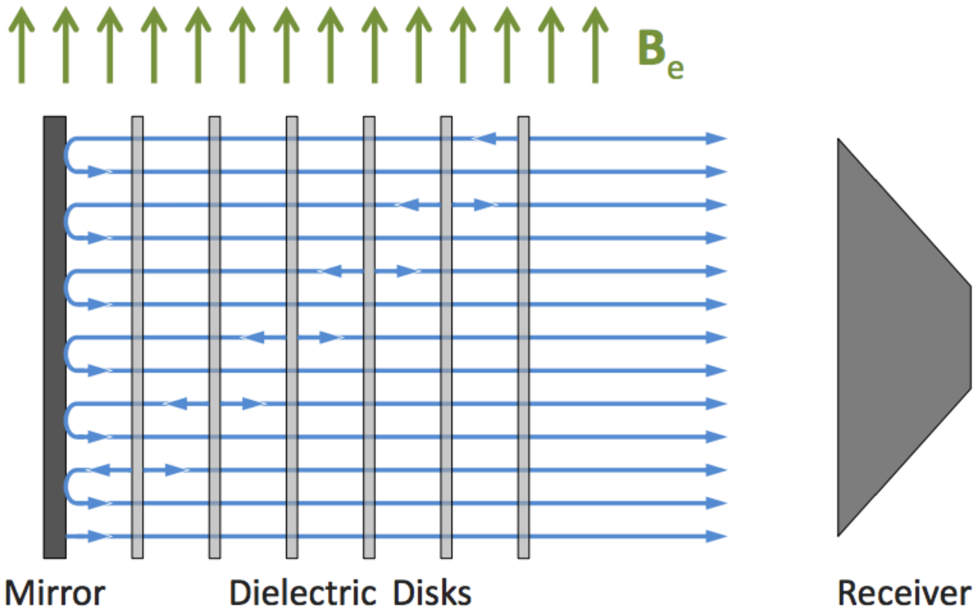
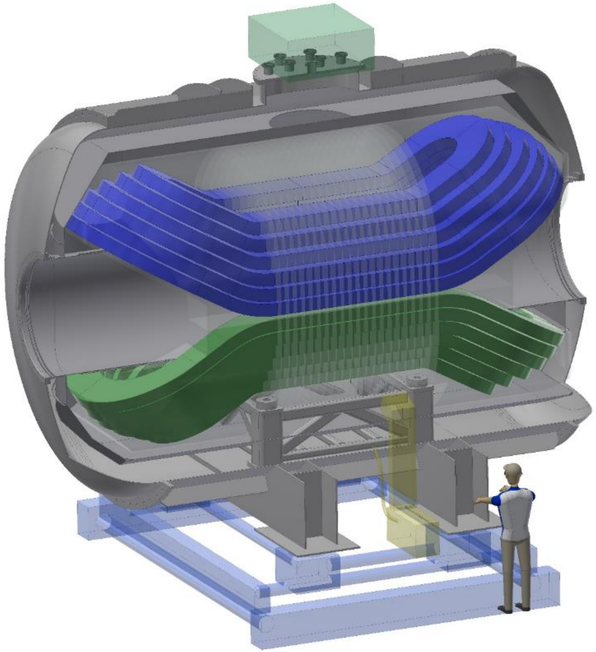


"MADMAX" Dielectric Haloscope

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

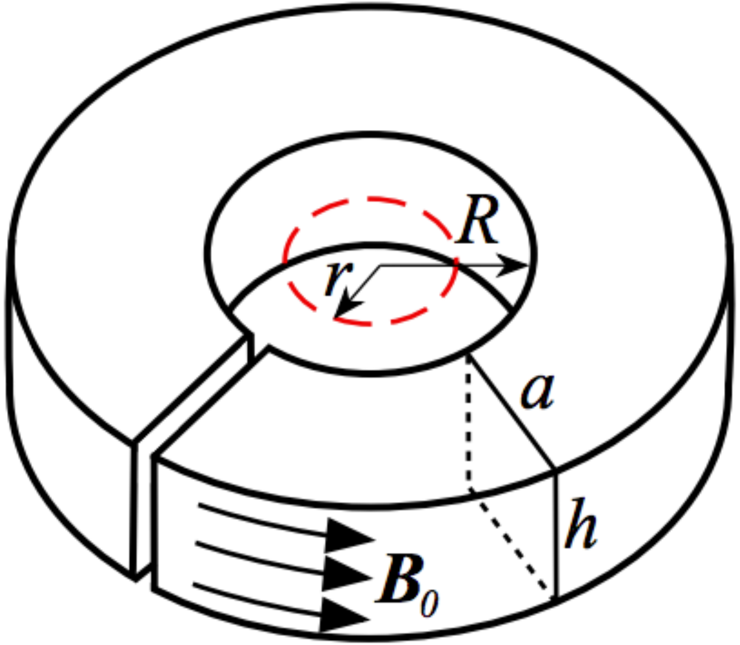




Different technologies target different frequencies. Nature will decide who chose correctly.

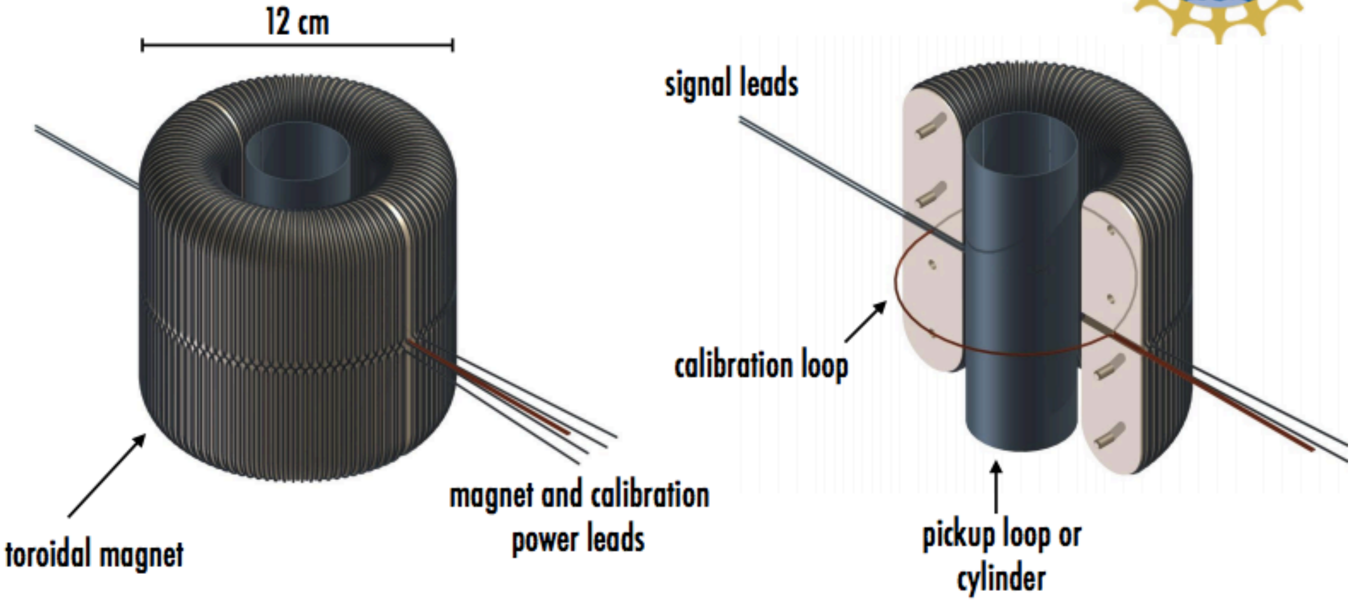
“DMRadio/ABRACADABRA”

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



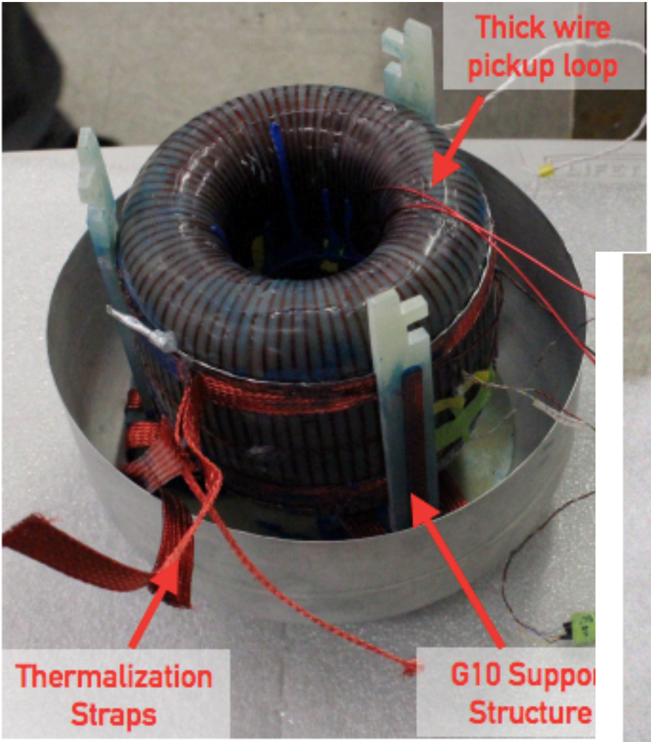
“A Broadband/ Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus”, Kahn et al (2016)

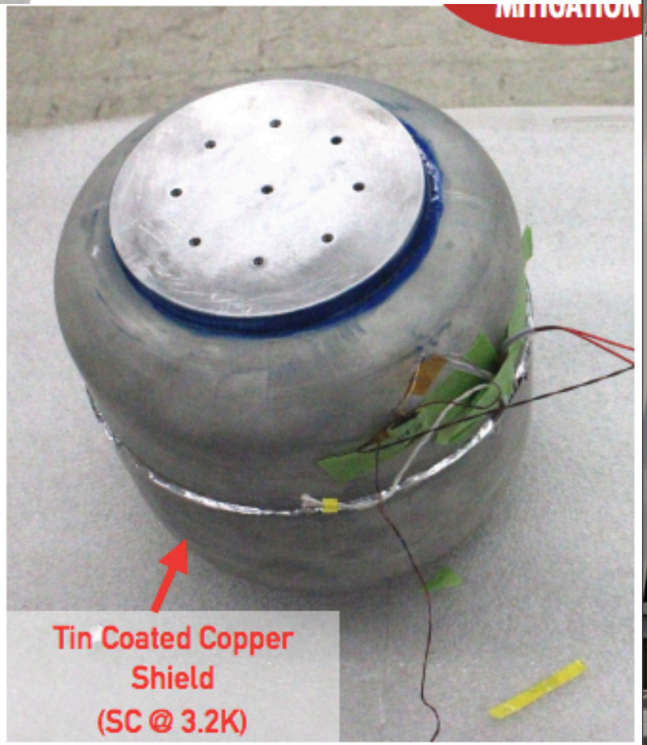
ABRACADABRA



ABRACADABRA-10cm Conceptual Design

Drawings by D. Winklehner


Thick wire pickup loop
Thermalization Straps
G10 Suppo
Structure


Tin Coated Copper Shield
(SC @ 3.2K)


ABRACADABRA
ABRA

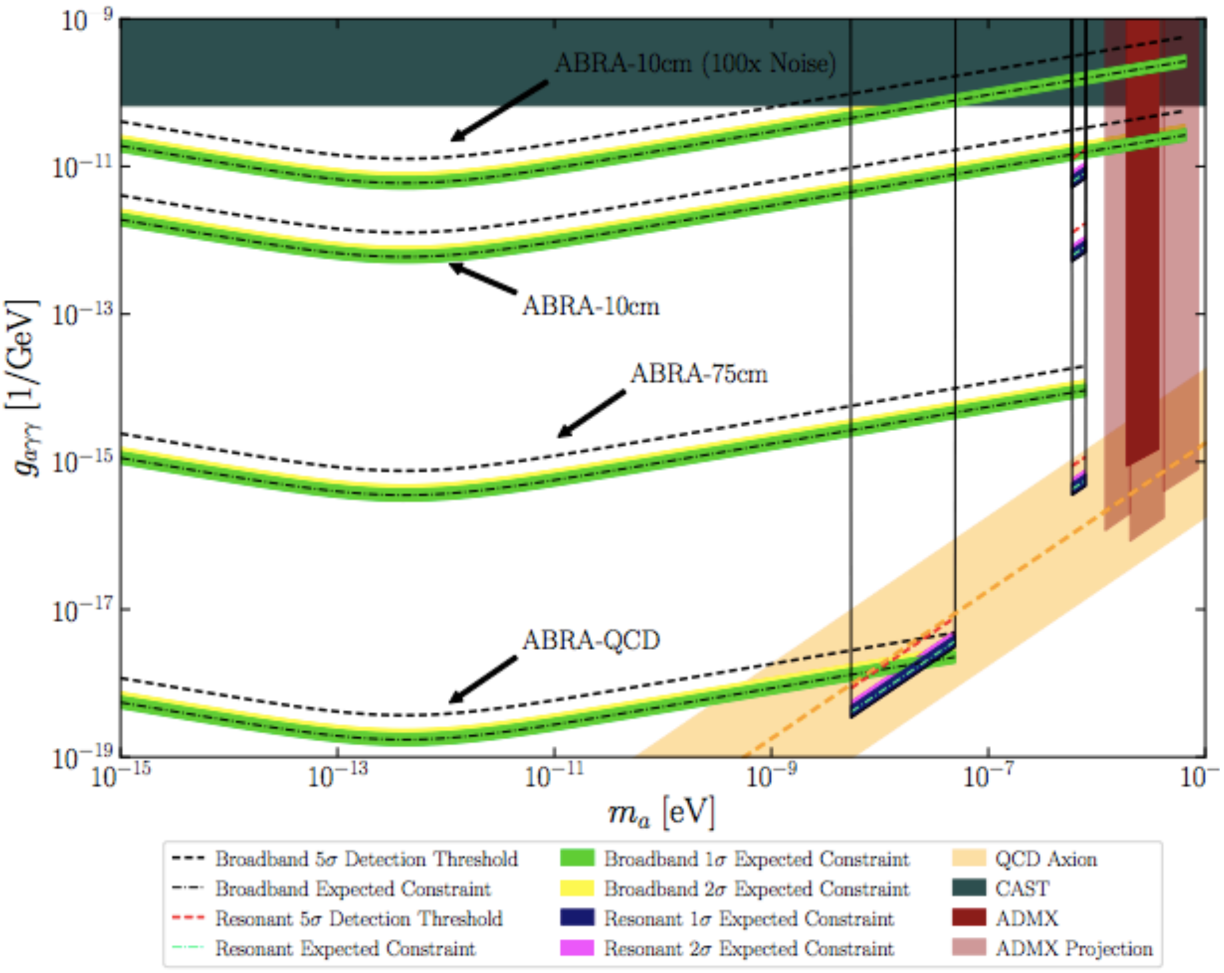


Fig: Winslow, PATRAS-18

AXION QUASIPARTICLES

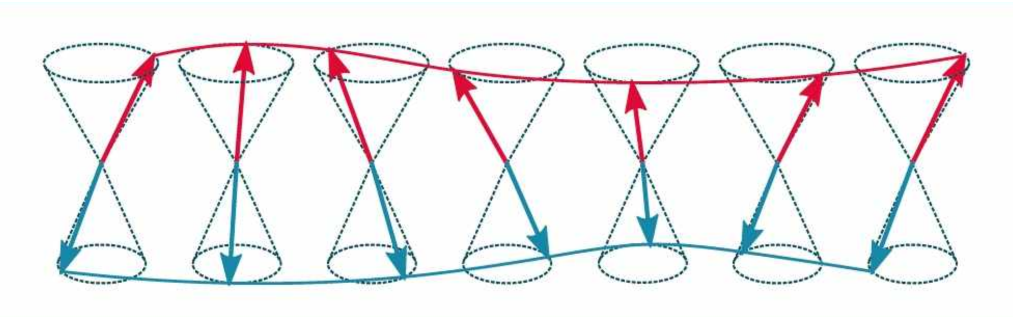
Review: Sekine & Nomura 2011.13601

Antiferromagnetic "Magnons"

Figs: Joel Cramer and Wikiwand.com

A-lattice

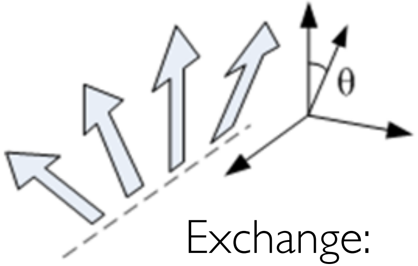
B-lattice



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

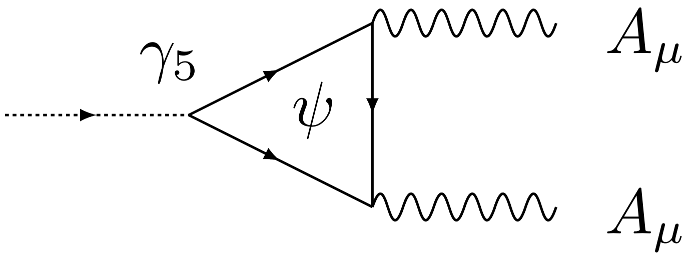
In our material candidates (*), the AQ is the longitudinal (amplitude) magnon mode.

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

"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:

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

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

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]
$V_{u.c.}$	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.

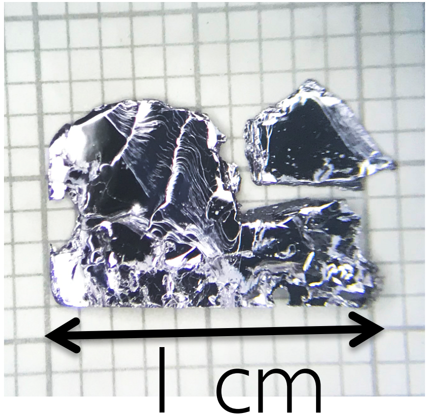
FINDING THE AXION QUASIPARTICLE

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

Manganese Bismuth Telluride: $Mn_xBi_yTe_z$

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

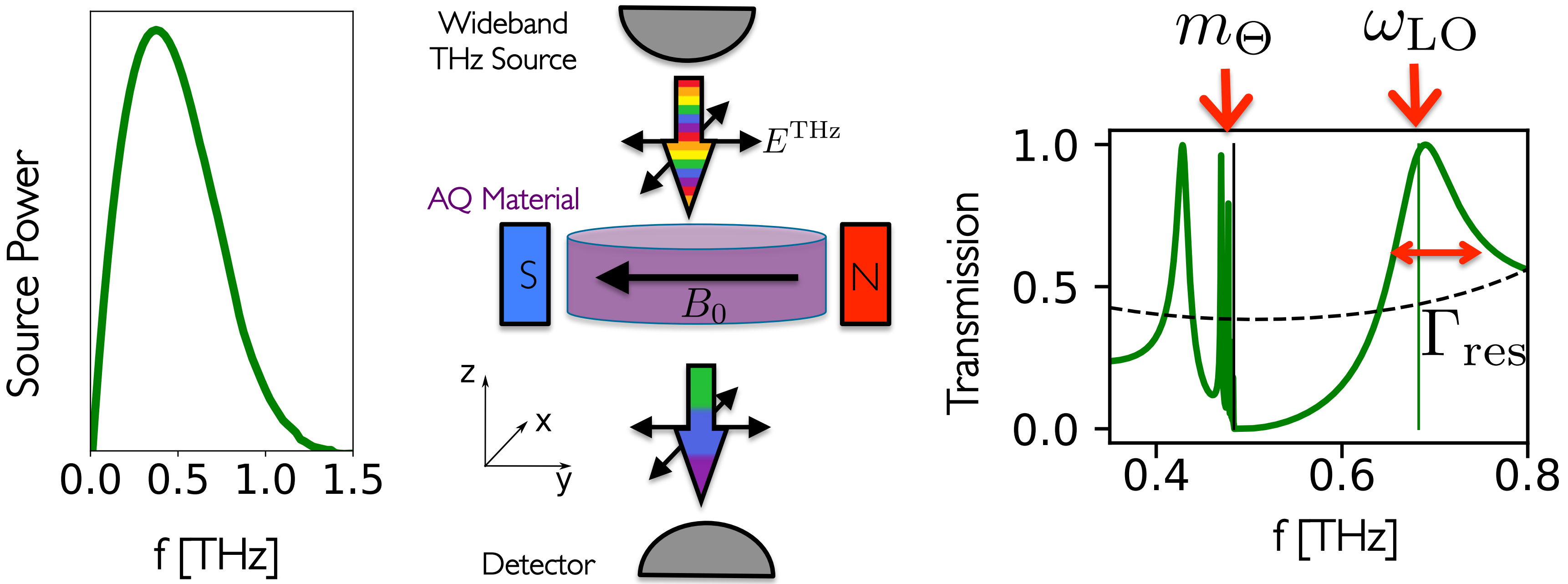
(124) phase crystals supplied. Wrong symmetry → AFMR but no axion quasiparticle, metallic. ☹
Test case for characterisation ☺
(225) axion quasiparticle candidate: no recipe yet ☹



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

THz Spectroscopy

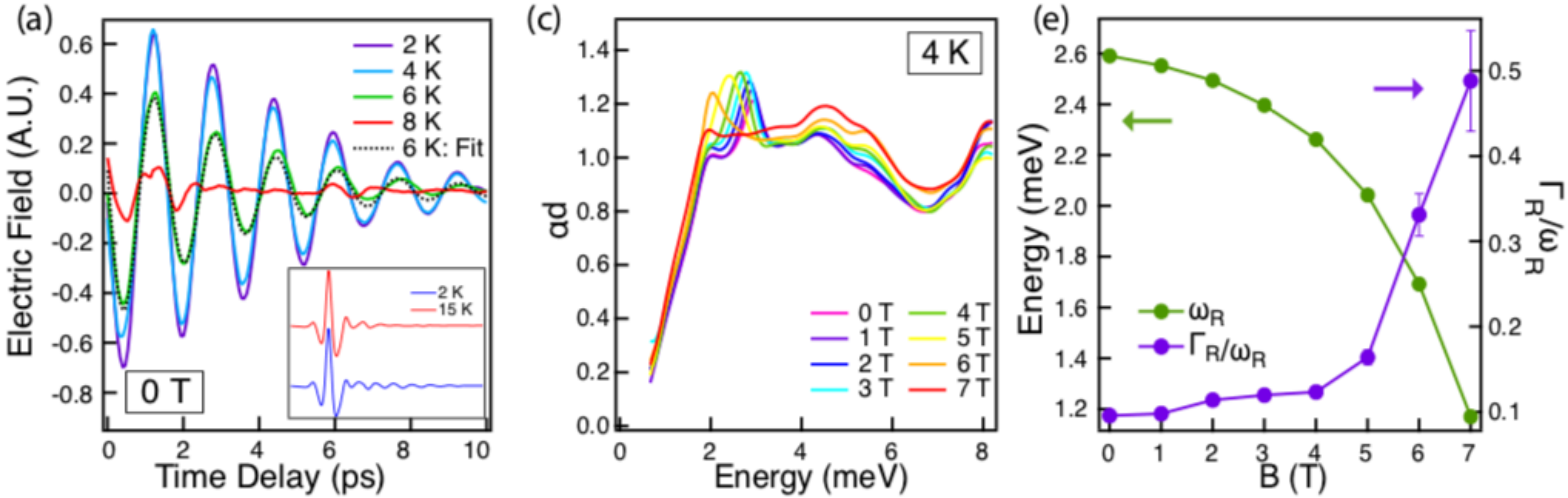
GOAL: identify axion-polariton resonance, measure it's width → discover axion quasiparticle!



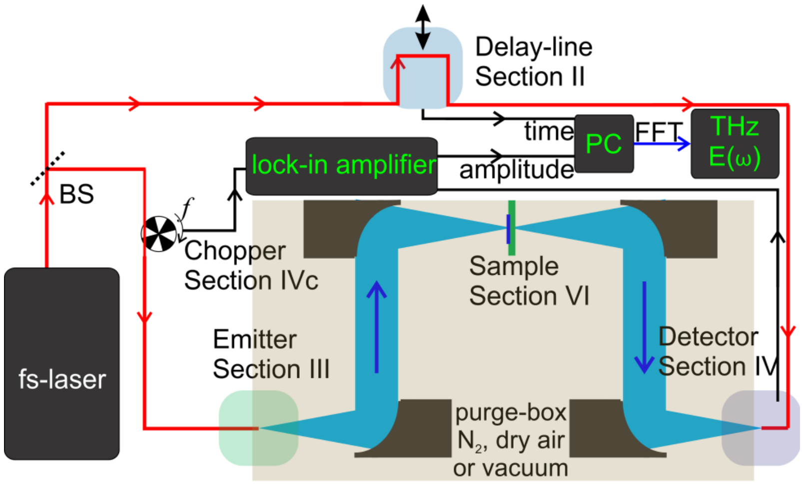
Example: AFMR by Transmission

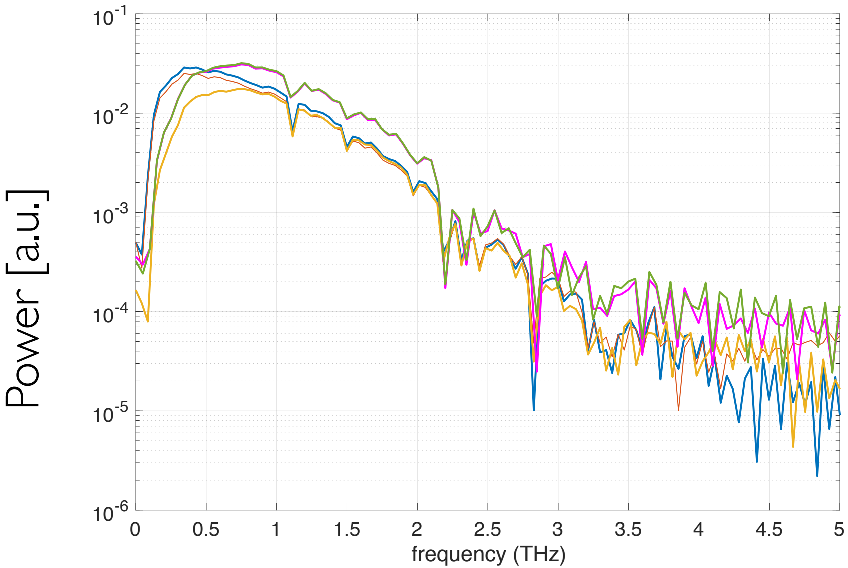
Little et al (2017)

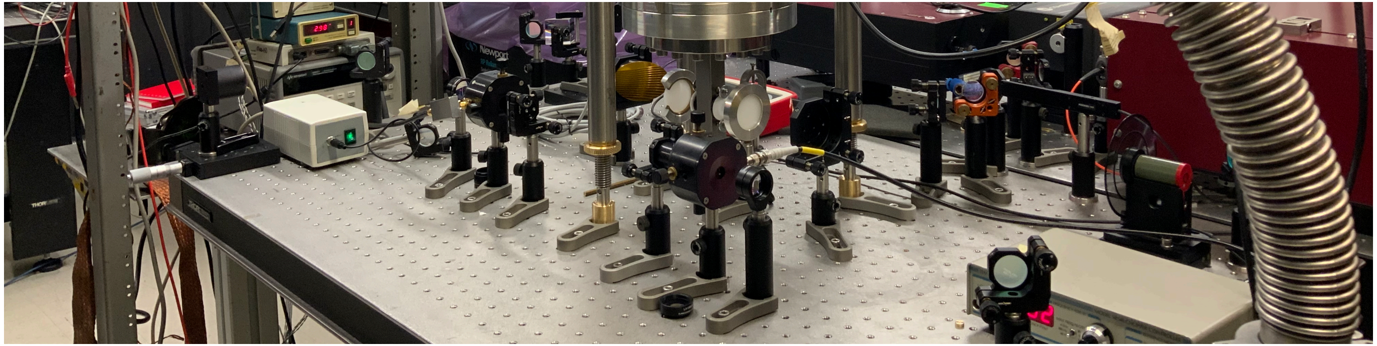
We would like to do measurements of ω and Γ like this (AF material αRuCl):



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







Caterina Braggio, INFN Legnaro.