Large bore, high field magnets needed for Cosmic Science

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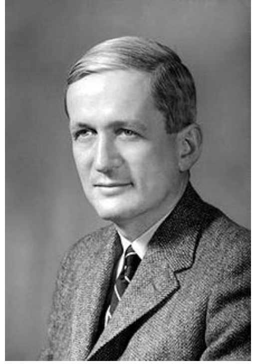
REBCO Roundtable
November 2, 2023

1. Axion dark matter – one of the highest priorities of the Cosmic Frontier
2. Gravitational waves – recent focus of theory community

QCD axion motivated by the Strong-CP Problem:

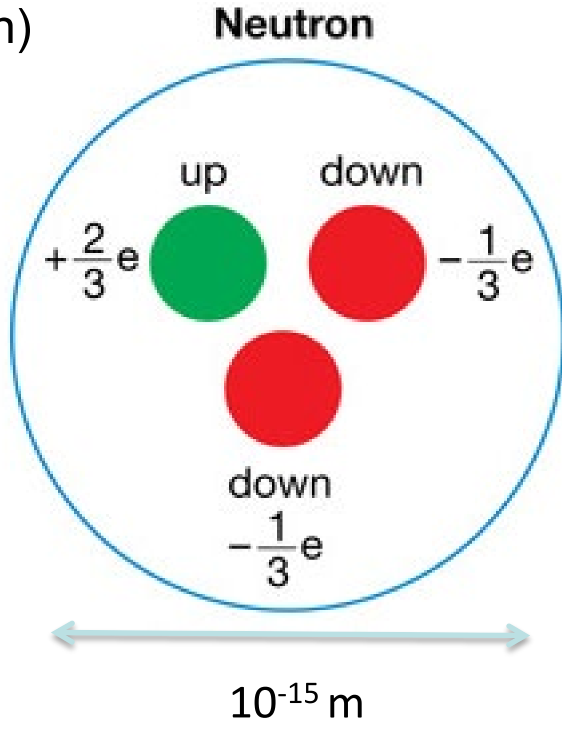
Why is the neutron electric dipole moment so small?

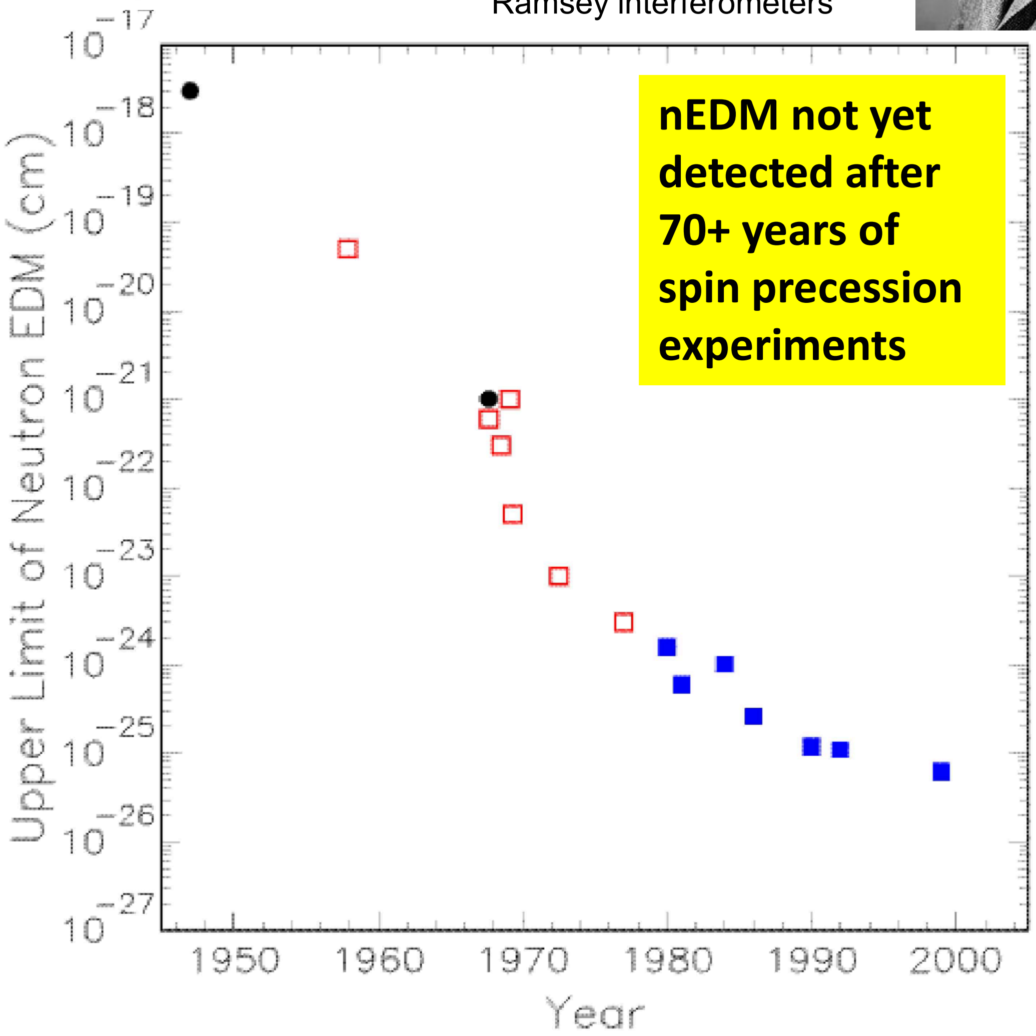
Norman Ramsey
Nobel Prize 1989.
Neutrino oscillation expts are
“Ramsey interferometers”



Naive estimate gives
nEDM ≈ 10^{-16} e-cm

Violates both:
P (spatial inversion)
CP (time reversal)



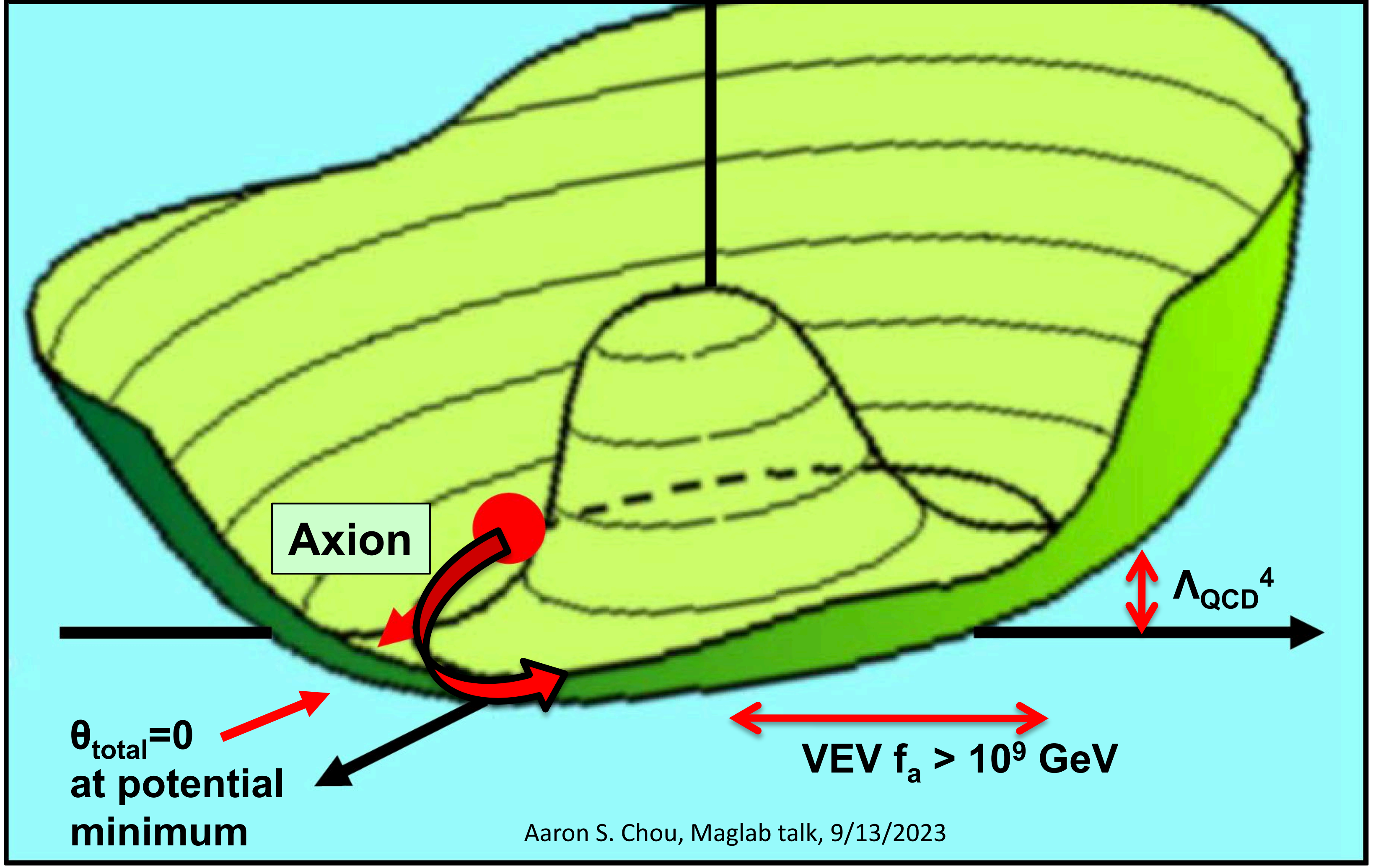


nEDM not yet detected after 70+ years of spin precession experiments

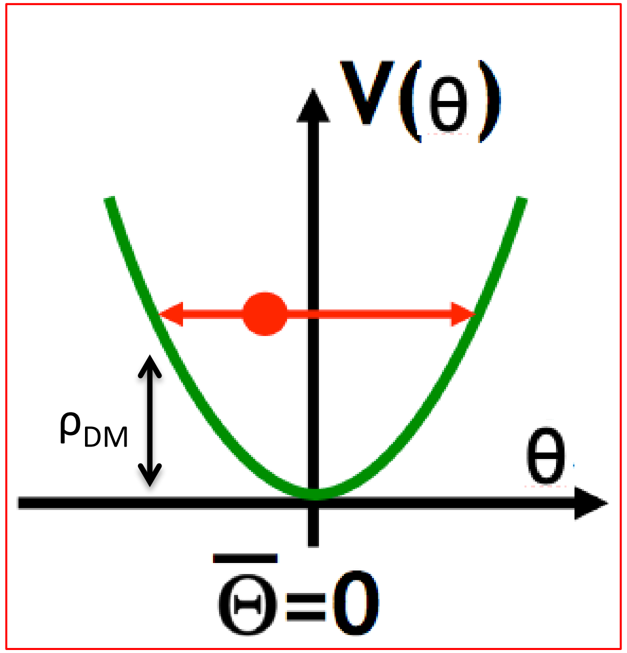
Need CP-violating phase angle θ to create charge asymmetry. But QCD theory has this!

Natural cosmological potential energy function would cause a putative dynamical axion field A to zero out the CP-violating angle θ_{total}

$$V(A) = -f_a^2 A^2 + \frac{\lambda}{4!} A^4 + \left(\frac{g^2}{32\pi^2} \arg(A) - \frac{\alpha_s}{8\pi} \left(\theta_{QCD} + \theta_{quark} \right) \right) \langle G\tilde{G} \rangle$$



Axion dark matter = waves of oscillating θ_{CP}



Any feedback control loop will suffer from residual oscillations about the dc set point!

In this case, the gravitational potential wells of the galaxy focus the oscillation energy to form classical waves with large occupation number.

This is equivalent to a coherent oscillation of the QCD θ angle about its CP-conserving minimum:

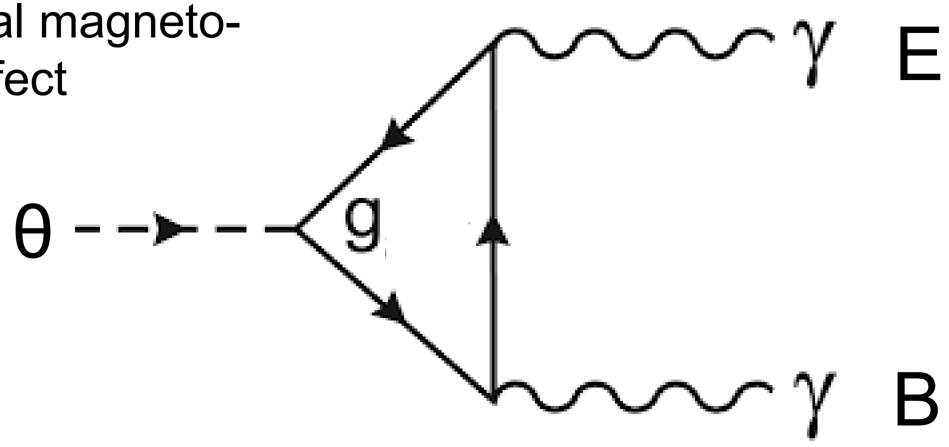
$$\theta(x,t) = \theta_{\text{max}} e^{i(kx - m_a t)}$$

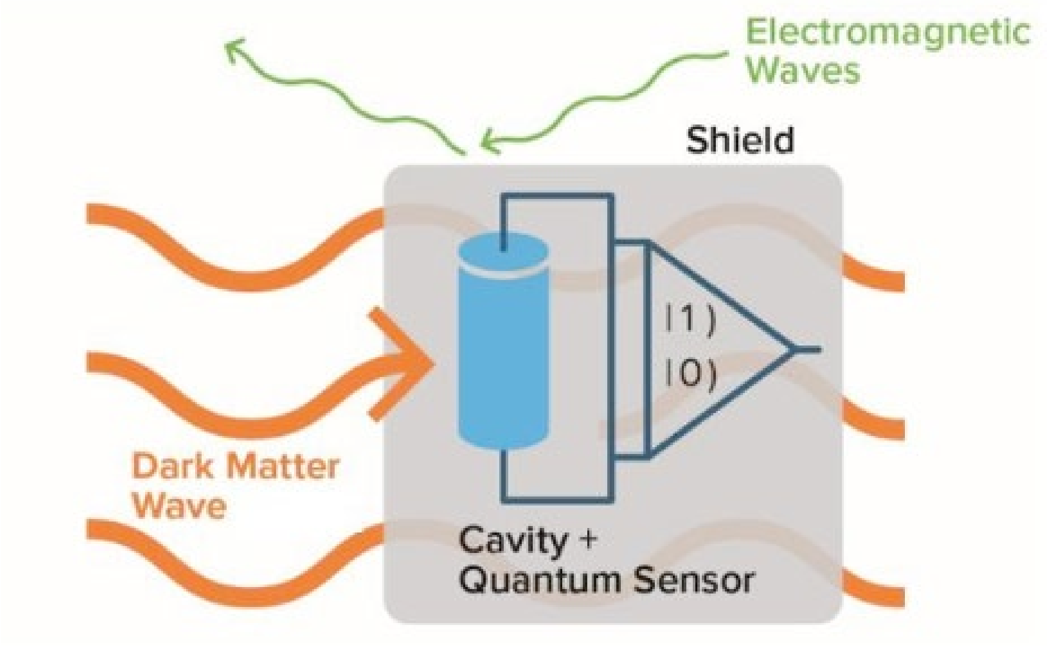
with amplitude

$$\theta_{\text{max}} = \sqrt{\frac{2\rho_a}{\Lambda_{\text{QCD}}^4}} \approx 3.7 \times 10^{-19} \text{radians}$$

Axion signal comes from 3-wave mixing interaction.
Need large B field to induce the mixing between axions and photons

Topological magneto-electric effect



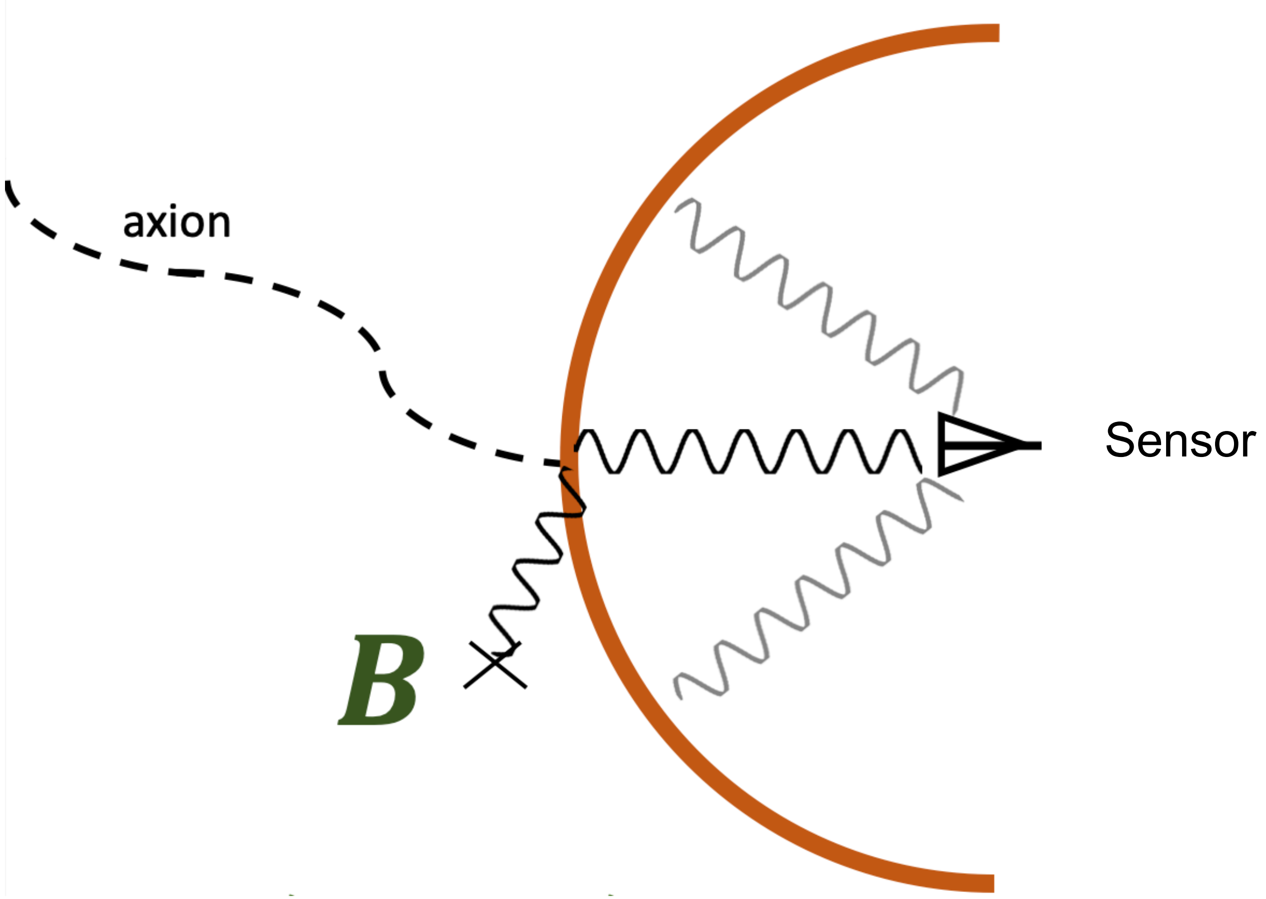


Resulting force from classical dark matter waves can deliver energy/momentum in the form of single photons that mysteriously appear in your well-shielded apparatus.

Put broadband dish reflectors inside magnets to absorb the recoil momentum. Signal power scales as B^2 x (Area) of the scattering target.

Dark matter emits transition radiation upon seeing the impedance mismatch between metal and vacuum.

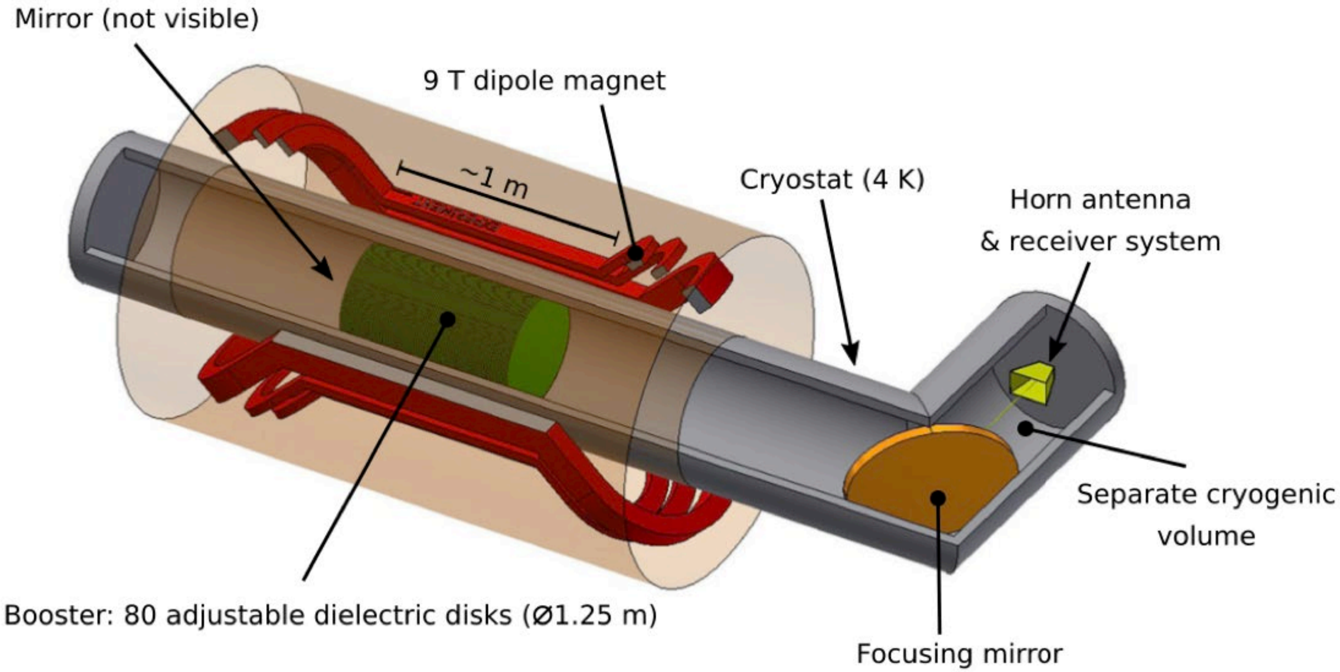
D. Horns, et.al, JCAP 1304, 016 (2013)



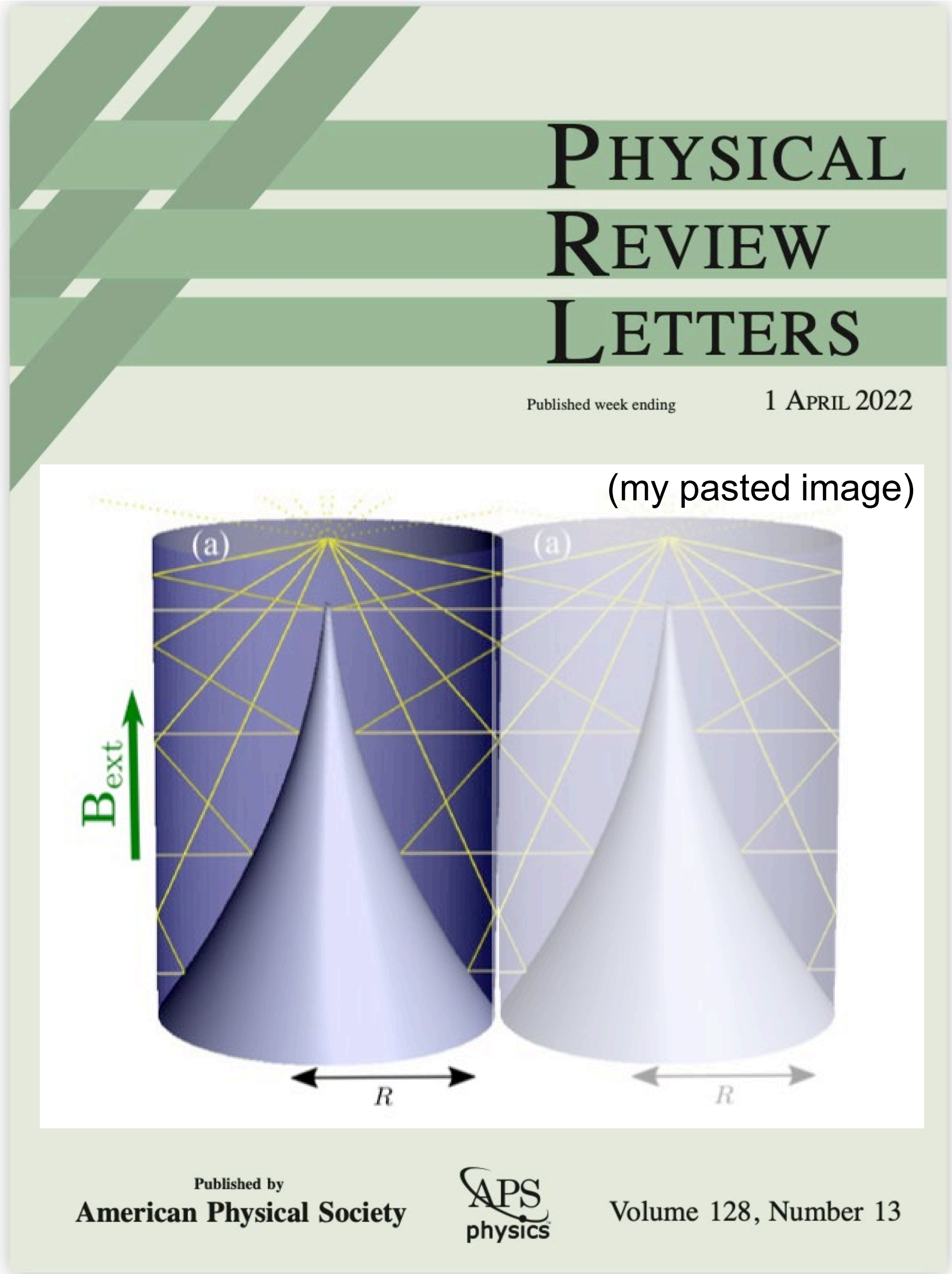
Aaron S. Chou, Maglab talk, 9/13/2023

Examples of dish antenna experiments

MADMAX concept: 9T-1.35m bore dipole



BREAD concept: 10T-2m bore solenoid



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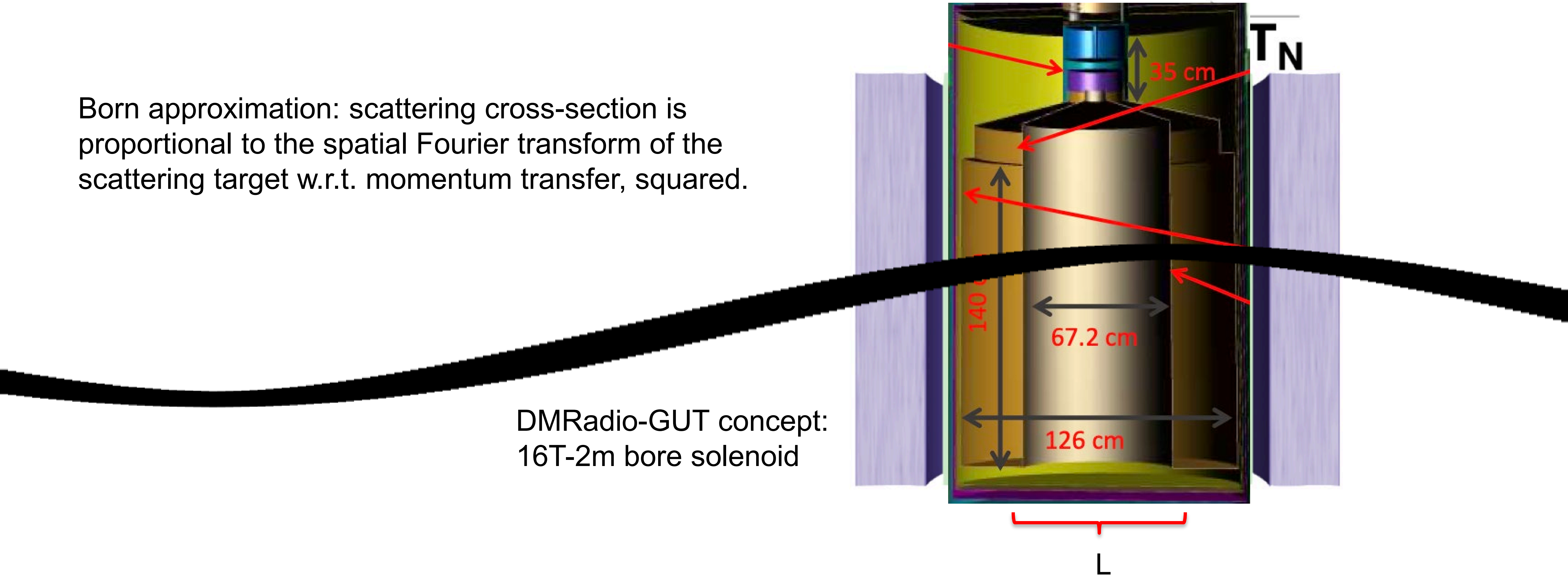
For lower frequencies and long Compton wavelengths, an apparatus of size L acts as a high pass filter with a transfer function "zero" at frequency $f_0=1/L$.

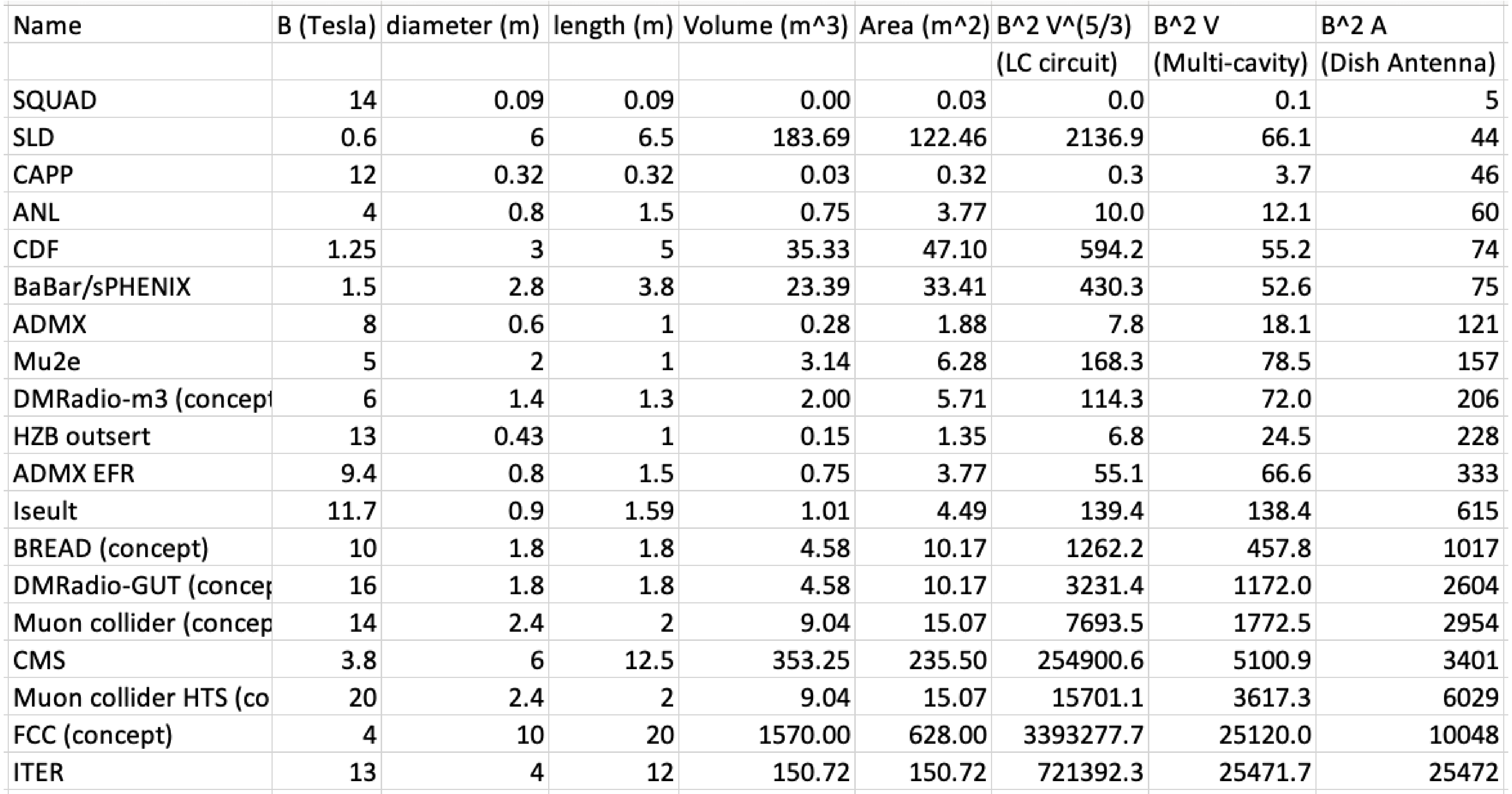
Born approximation: scattering cross-section is proportional to the spatial Fourier transform of the scattering target w.r.t. momentum transfer, squared.



DMRadio-GUT concept:
16T-2m bore solenoid

Need even larger magnet bore L due to the power filtering factor $(f/f_0)^2= (f\ L)^2$ at low frequencies f.

What we really need for all experiments are bigger magnets



Name	B (Tesla)	diameter (m)	length (m)	Volume (m^3)	Area (m^2)	B^2 V^(5/3) (LC circuit)	B^2 V (Multi-cavity)	B^2 A (Dish Antenna)
SQUAD	14	0.09	0.09	0.00	0.03	0.0	0.1	5
SLD	0.6	6	6.5	183.69	122.46	2136.9	66.1	44
CAPP	12	0.32	0.32	0.03	0.32	0.3	3.7	46
ANL	4	0.8	1.5	0.75	3.77	10.0	12.1	60
CDF	1.25	3	5	35.33	47.10	594.2	55.2	74
BaBar/sPHENIX	1.5	2.8	3.8	23.39	33.41	430.3	52.6	75
ADMX	8	0.6	1	0.28	1.88	7.8	18.1	121
Mu2e	5	2	1	3.14	6.28	168.3	78.5	157
DMRadio-m3 (concept	6	1.4	1.3	2.00	5.71	114.3	72.0	206
HZB outsert	13	0.43	1	0.15	1.35	6.8	24.5	228
ADMX EFR	9.4	0.8	1.5	0.75	3.77	55.1	66.6	333
Iseult	11.7	0.9	1.59	1.01	4.49	139.4	138.4	615
BREAD (concept)	10	1.8	1.8	4.58	10.17	1262.2	457.8	1017
DMRadio-GUT (concep	16	1.8	1.8	4.58	10.17	3231.4	1172.0	2604
Muon collider (concep	14	2.4	2	9.04	15.07	7693.5	1772.5	2954
CMS	3.8	6	12.5	353.25	235.50	254900.6	5100.9	3401
Muon collider HTS (co	20	2.4	2	9.04	15.07	15701.1	3617.3	6029
FCC (concept)	4	10	20	1570.00	628.00	3393277.7	25120.0	10048
ITER	13	4	12	150.72	150.72	721392.3	25471.7	25472

Barely reach axion coupling g with a lot of hand-waving, even with the best quantum sensors

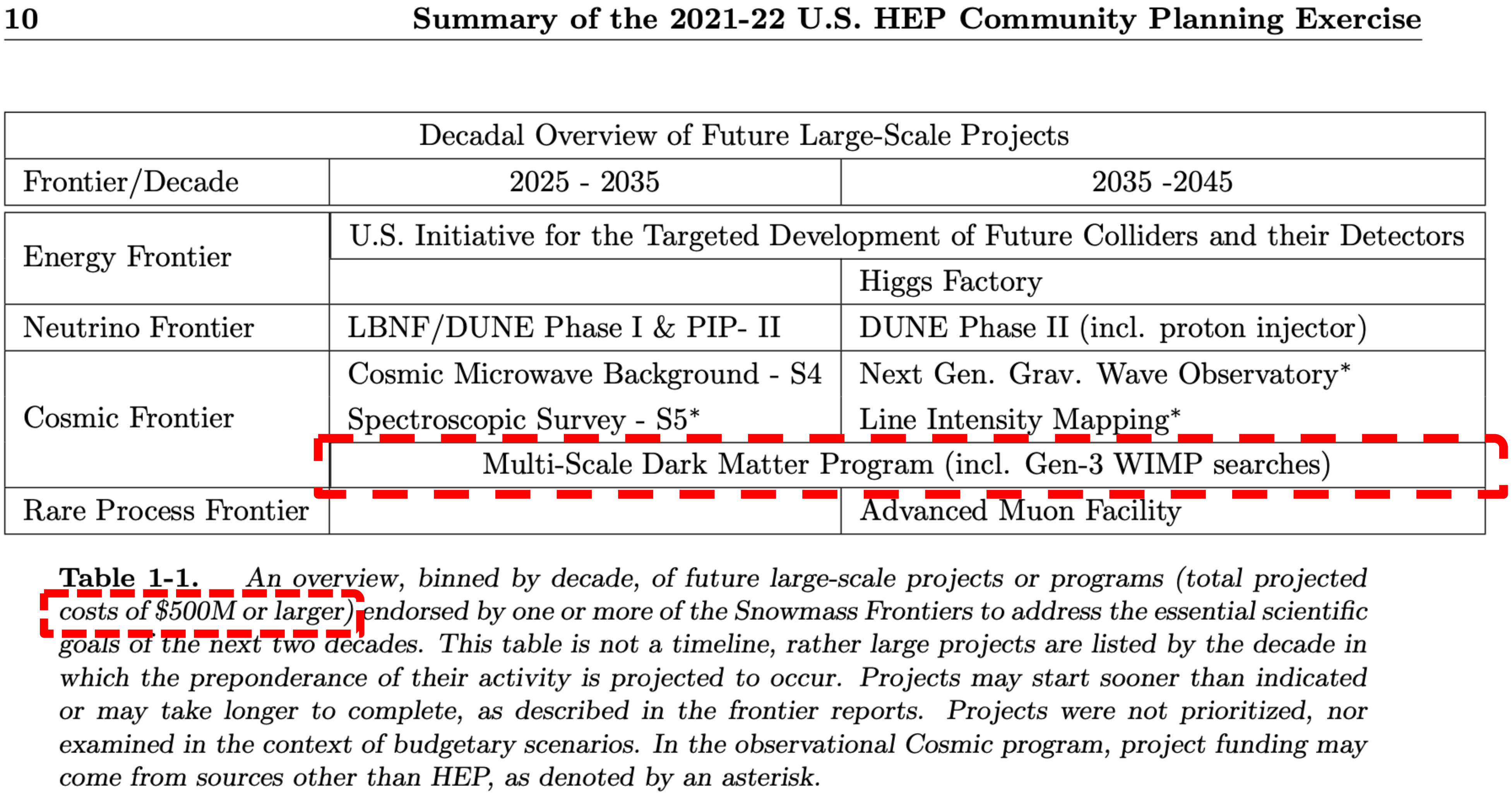
Decisively detect axions! (g=0.3)

Push to g=0.1 !

Dish antenna: $g \sim 5\,(R_b/t)^{1/4}\,B^{-1}\,L^{-1}$

Even better scaling with magnet size L for multi-cavity or LC experiments.

Snowmass final report finds that the U.S. community wants a Multi-Scale Dark Matter Program



10 **Summary of the 2021-22 U.S. HEP Community Planning Exercise**

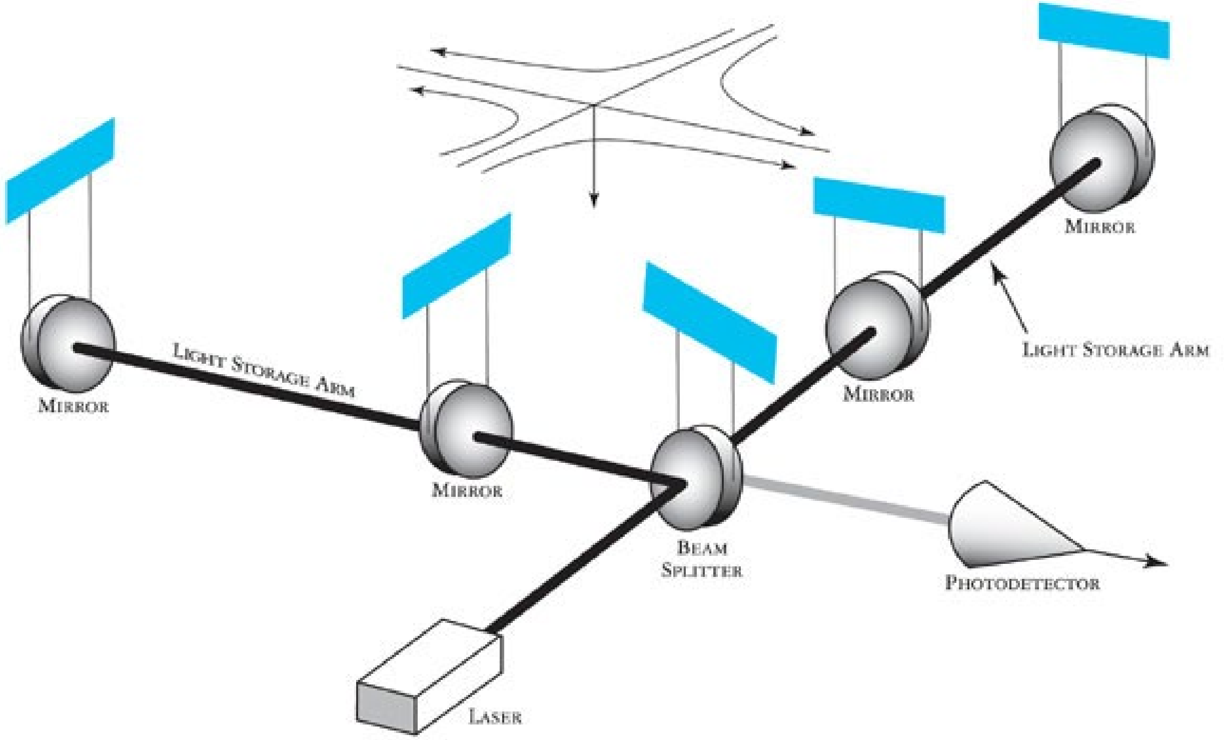
Decadal Overview of Future Large-Scale Projects

Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4 Spectroscopic Survey - S5*	Next Gen. Grav. Wave Observatory* Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Table 1-1. *An overview, binned by decade, of future large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific goals of the next two decades. This table is not a timeline, rather large projects are listed by the decade in which the preponderance of their activity is projected to occur. Projects may start sooner than indicated or may take longer to complete, as described in the frontier reports. Projects were not prioritized, nor examined in the context of budgetary scenarios. In the observational Cosmic program, project funding may come from sources other than HEP, as denoted by an asterisk.*

Scatter GWs on magnets instead of laser interferometers

GWs shakes the walls of a device that contains a large amount of electromagnetic energy.
Changing the boundary conditions releases some of the EM energy in the form of detectable sideband photons.



Coming soon to Fermilab

LIGO uses **10^6 W** of optical laser power.   A 10 T, meter-scale B field provides the equivalent of **10^{16} W** !

Challenge: How to make magnet coils with mechanical Q>1 to filter thermal noise?

Backup slides

Detect cosmic gravitational wave background from early universe phase transitions.

Use large magnets instead of laser interferometers to achieve far greater sensitivity.

Colliding bubbles of new phase (of the space-time vacuum) emit gravitational waves in the early universe

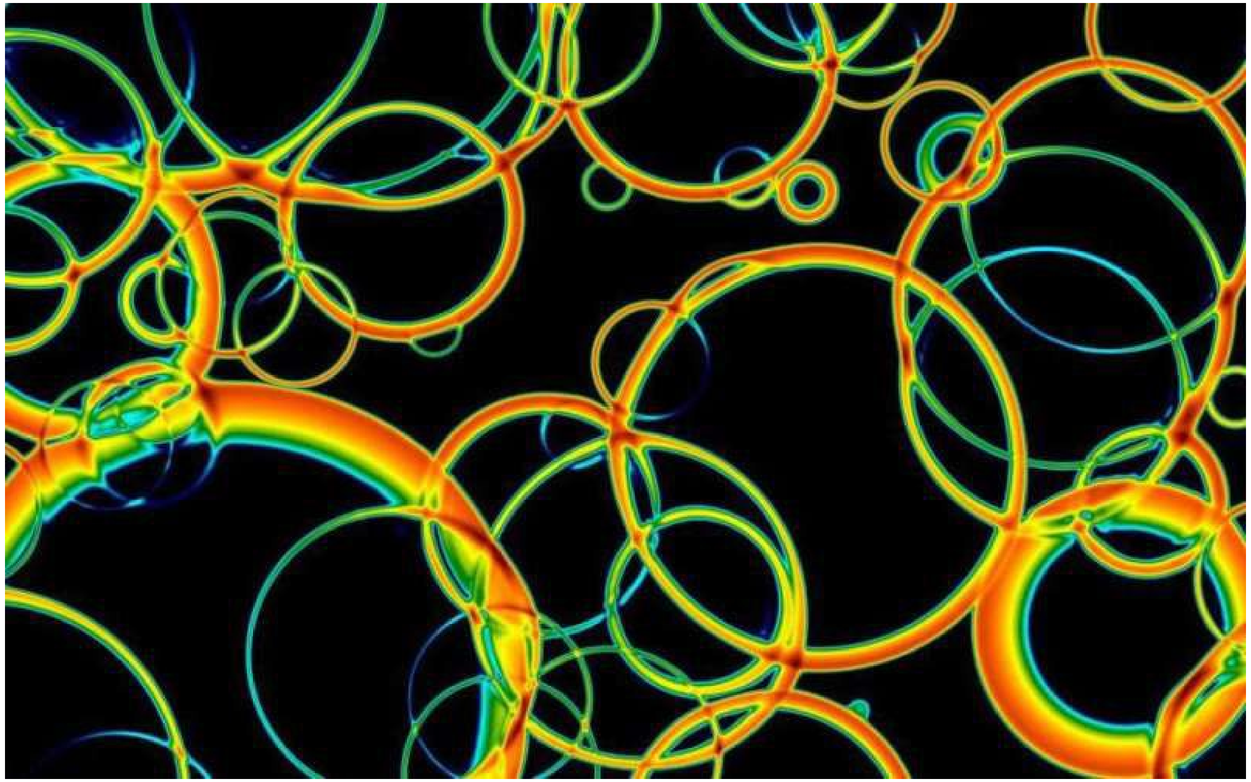
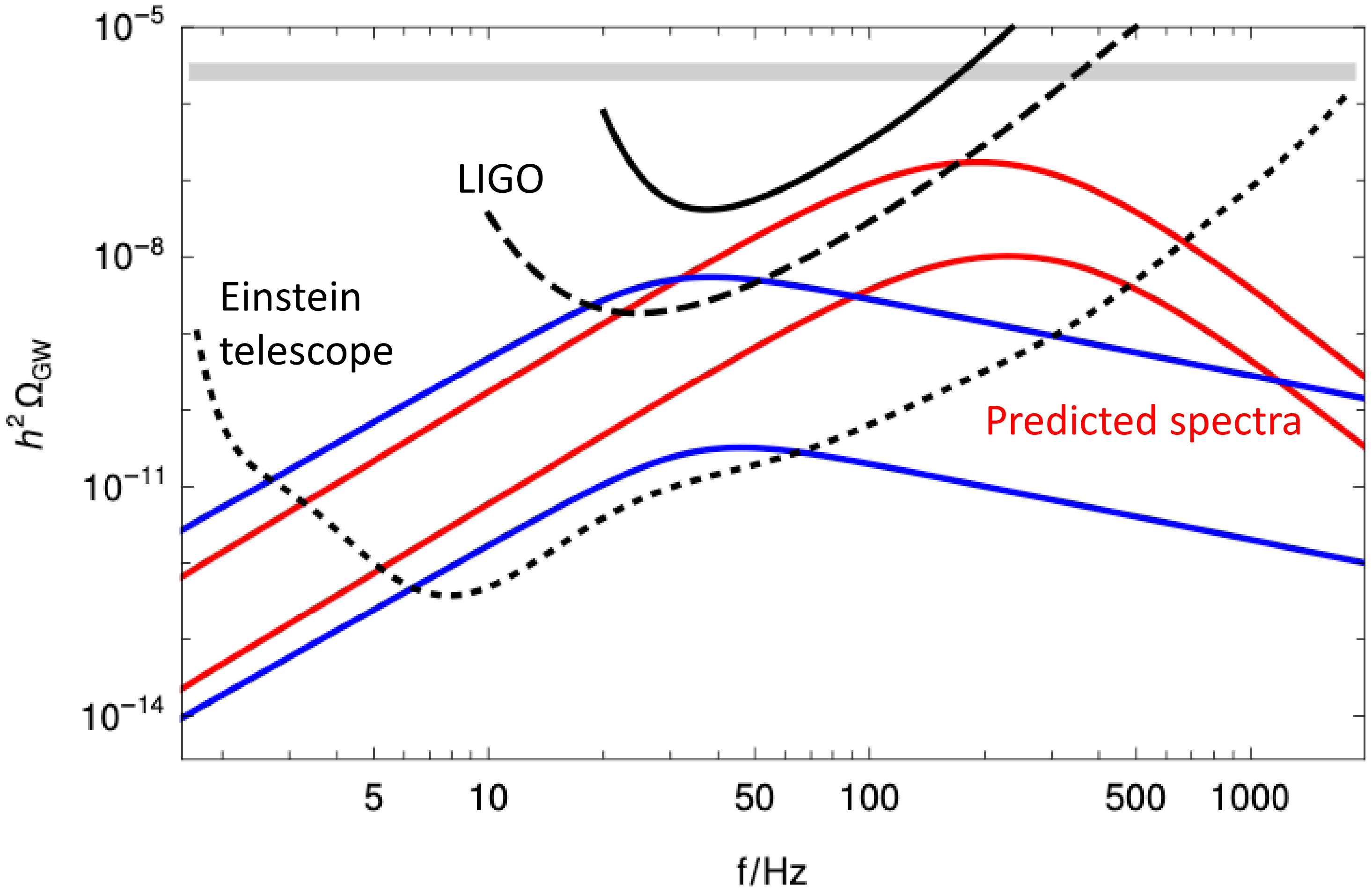


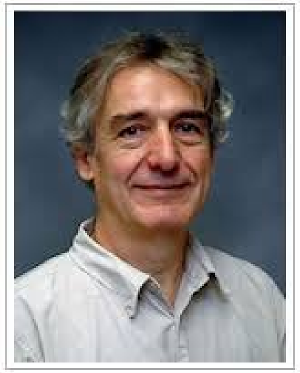
Image: D. Weir,
https://doi.org/10.1098/rsta.2017.0126

Compare to sound waves emitted by violently boiling water

LIGO optical interferometer is marginal for detecting a predicted axion phase transition at temperature 10^9 GeV



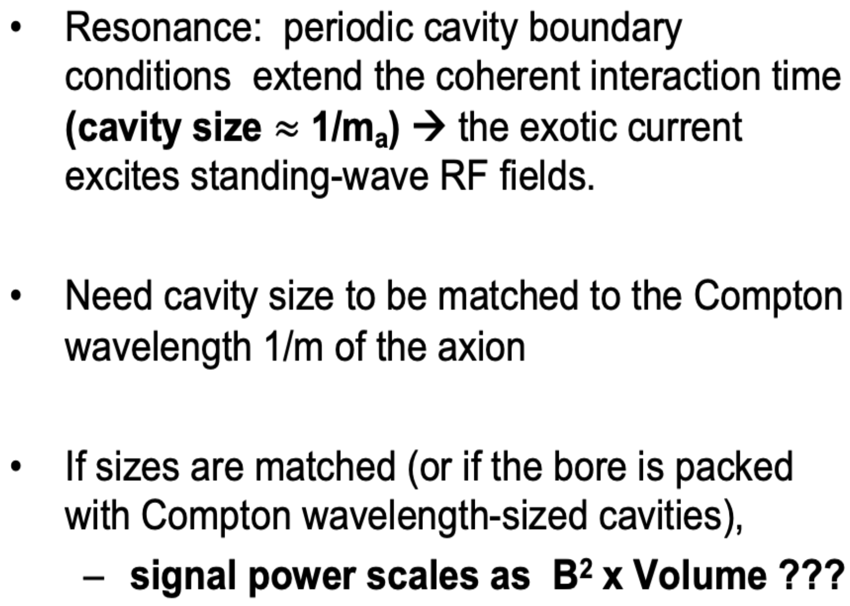
B. von Harling et al., JHEP 195 (2020)



The Dark Matter Haloscope:
Classical axion wave drives RF cavity mode

Pierre Sikivie, Phys.Rev.Lett. 51, 1415 (1983)

- Resonance: periodic cavity boundary conditions extend the coherent interaction time **(cavity size ≈ 1/m$_a$)** → the exotic current excites standing-wave RF fields.
- Need cavity size to be matched to the Compton wavelength 1/m of the axion
- If sizes are matched (or if the bore is packed with Compton wavelength-sized cavities),
  - **signal power scales as B^2 x Volume ???**



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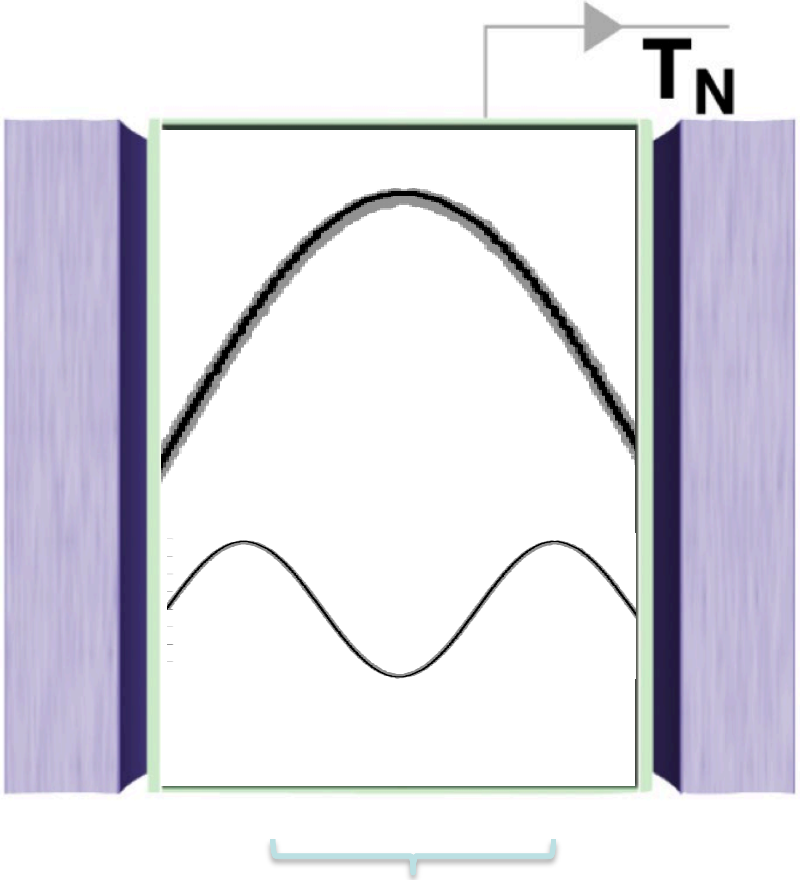
Actually, only the cavity volume within one Compton wavelength from the wall matters

Nothing can possibly happen in the empty space far from a cavity wall since empty space is translation invariant. The extra interior wiggles in the higher frequency mode all cancel each other out in this semi-classical power calculation:

$$P_a(t) = \int \vec{J}_a(t) \cdot \vec{E}_r(t) \, dV$$

J is spatially uniform on laboratory scales and points in the direction of the applied B field

The direction of E oscillates up/down

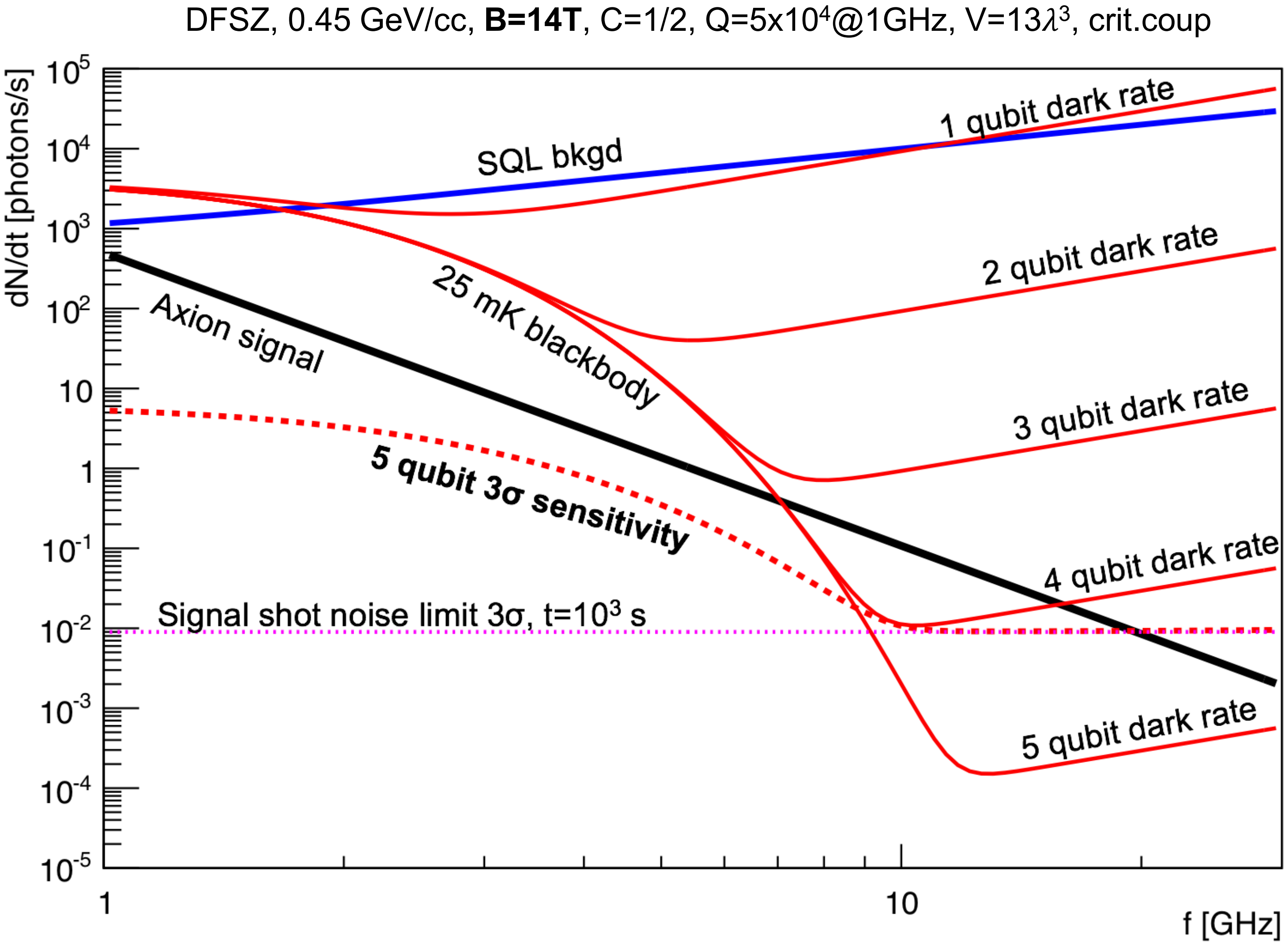


The interior region integrates to zero

Instead pack the magnet full of cavities?
Too complicated as # cavities becomes large.

Need better magnets! Even when noise is reduced to zero by quantum sensors, dark matter sensitivity will be limited by the signal photon rate.

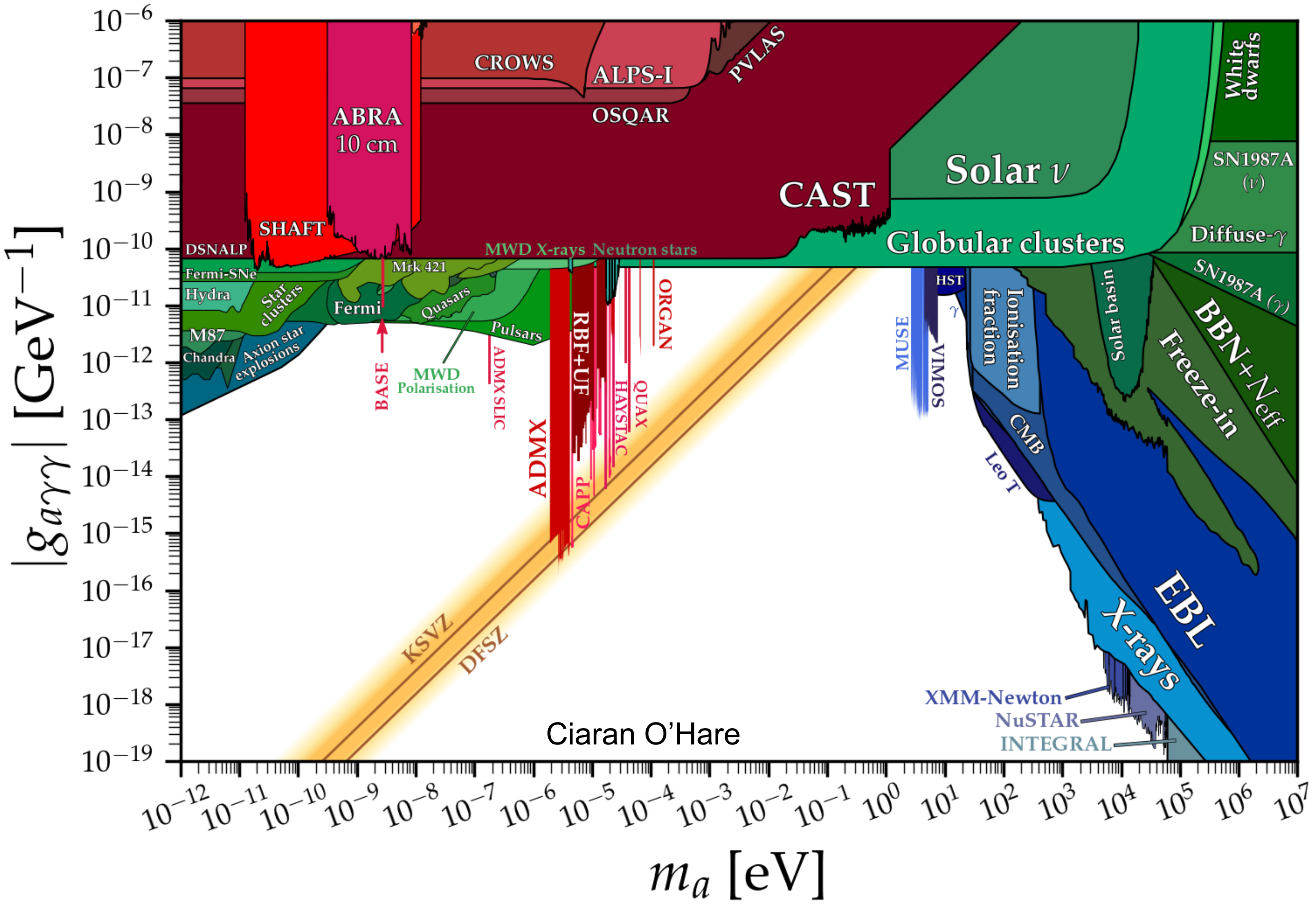
SQuAD experiment



Sensitivity limited only by signal photon shot noise. Cavity experiments cannot go above 20 GHz for 15 minute integration times.

Must transition to dish antennas at higher frequencies. (but then sensitivity dominated by sensor noise)

Must slowly scan through 9 orders of magnitude in mass or signal frequency



Ciaran O'Hare

Ongoing small-scale experiments are only able to cover tiny slivers of mass parameter space.

Small bore, high field magnets can help, but still only covers a sliver where signal wavelength matches the bore size.

Easier to do brute force: Go 10x faster using 10 magnets instead of 1. Or buy a couple of big magnets? Or both?