How to detect axion dark matter … for real

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Quantum Technologies for Fundamental Physics workshop
Erice
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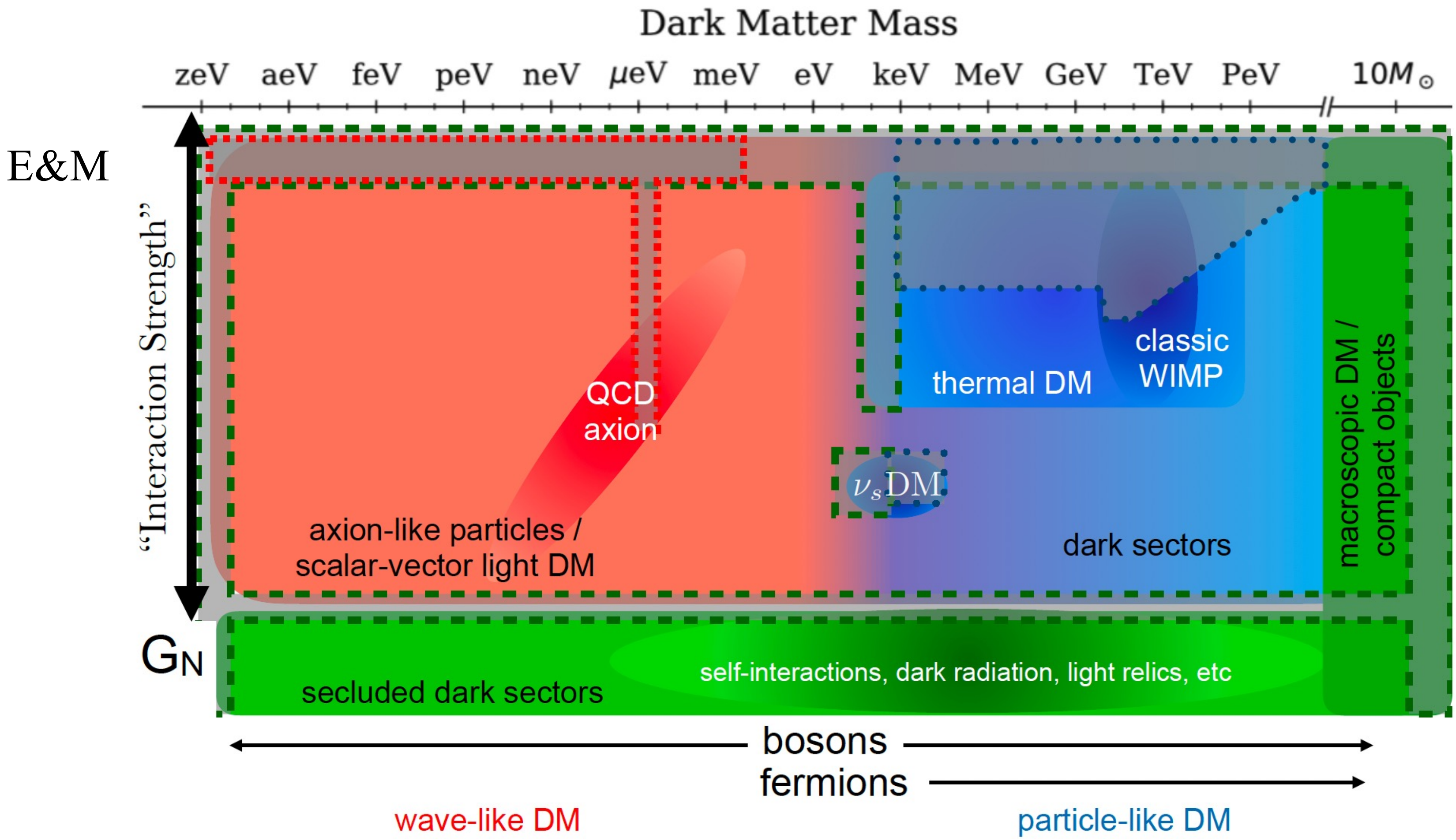
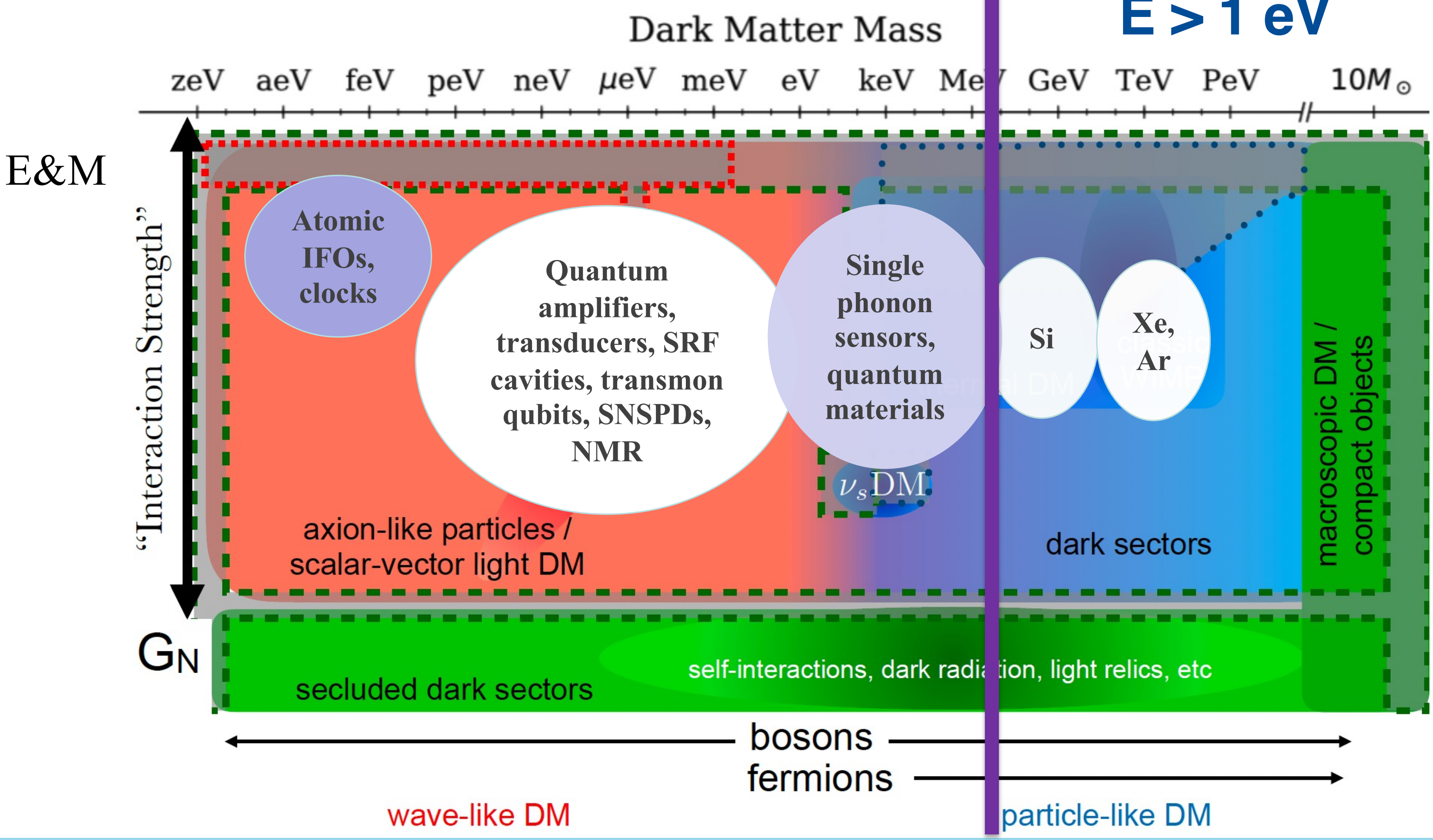
Dark Matter Strategy: Delve Deep, Search Wide … but how?



Cartoon from Snowmass

Quantum sensors: E < 1 eV

Current expts: E > 1 eV

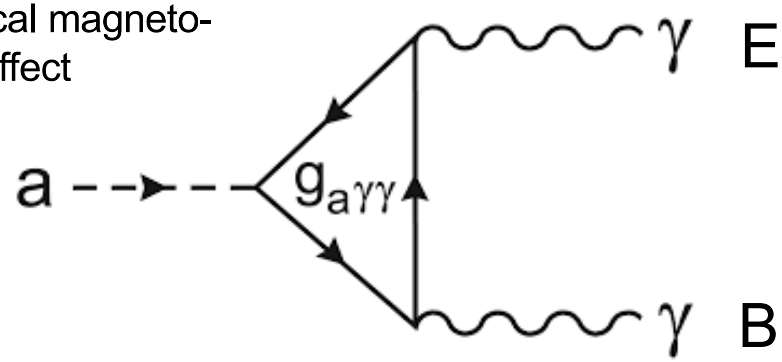


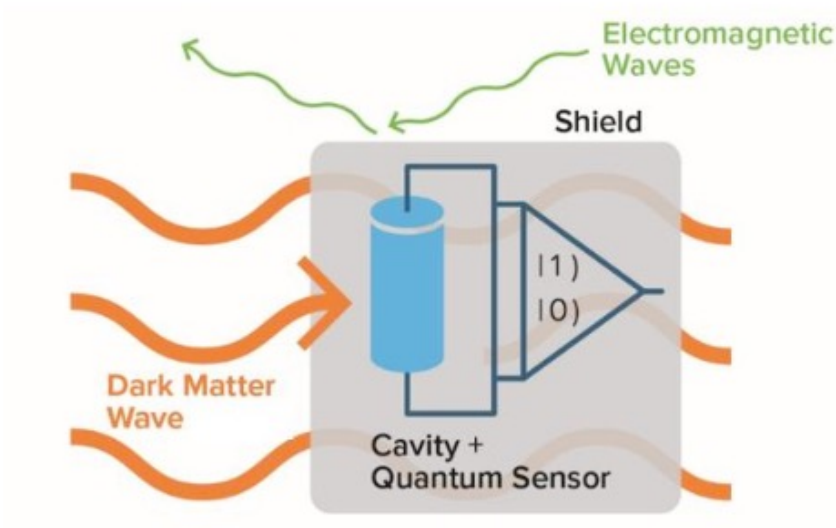
Cartoon from Snowmass

Quantum sensors are a necessary ingredient, but by themselves, they are not enough…

Signal rate enhancement. Need large B field to induce the mixing between axions and photons

Topological magneto-electric effect

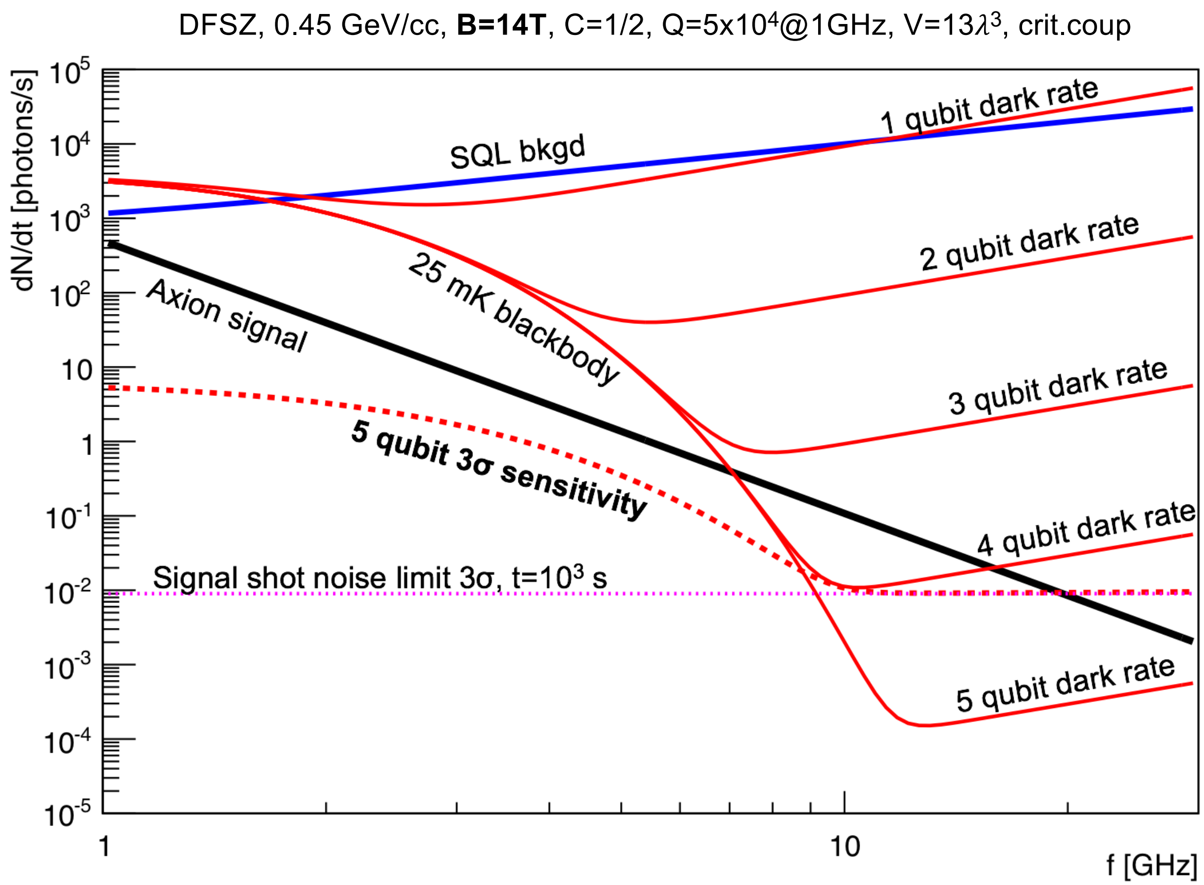




Resulting force from classical dark matter waves can deliver energy/momentum in the form of single photons that mysteriously appear in your well-shielded apparatus.

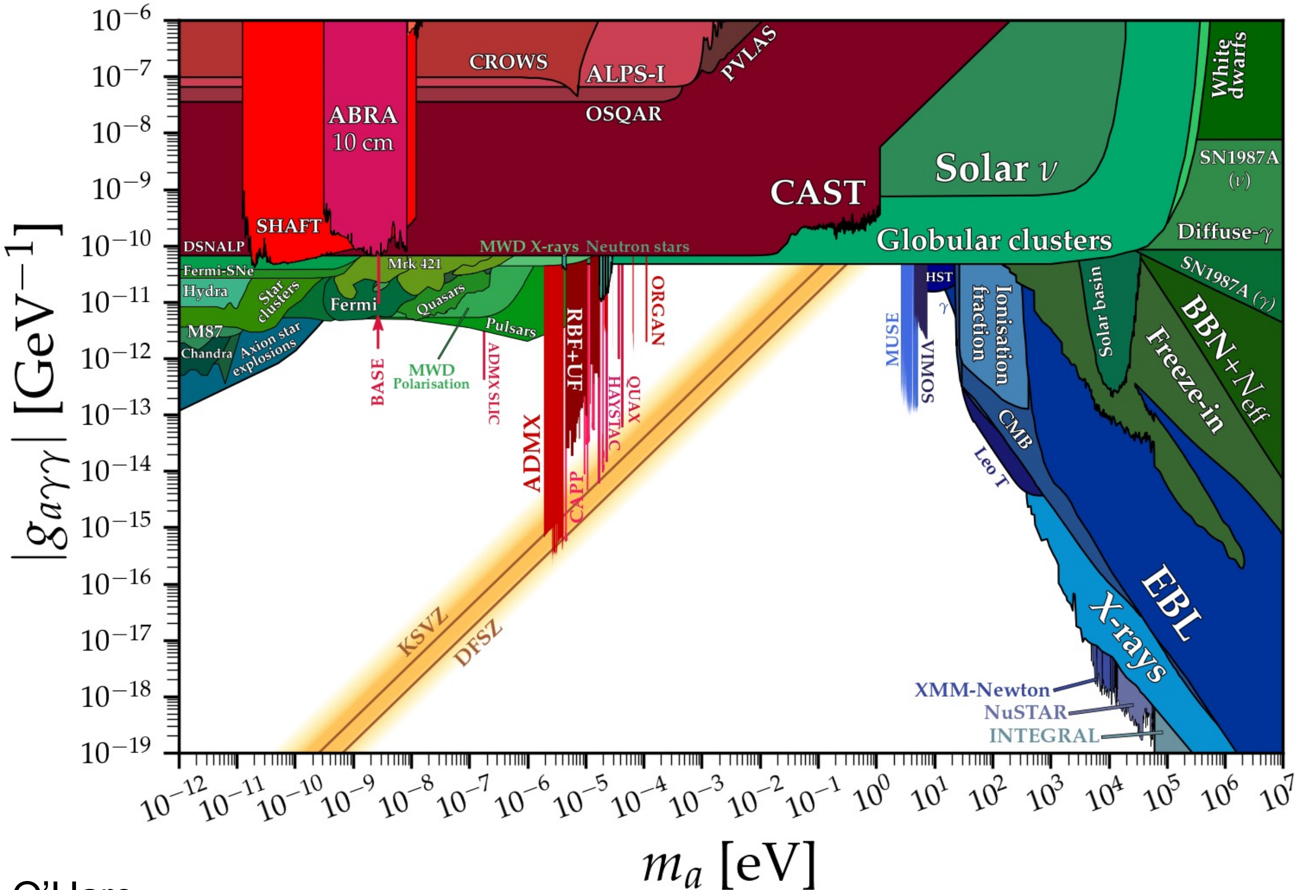
Need better magnets! Even when noise is reduced to zero by quantum sensors, dark matter sensitivity will be limited by the signal photon rate.

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)

QCD axion model parameter space (yellow band)



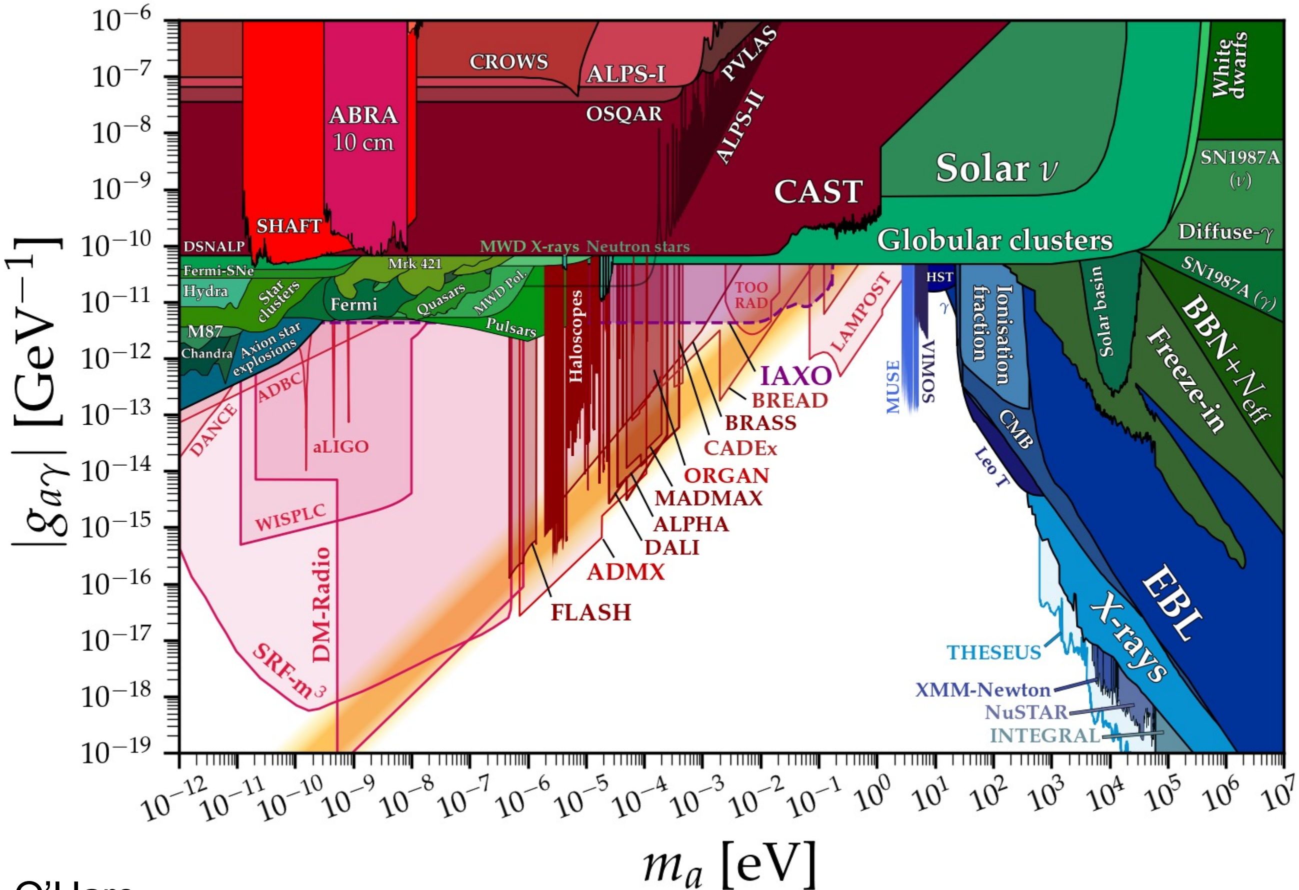
Ciaran O'Hare

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

Scan speed is at least linearly proportional to investment in magnets as the scattering target.

Brute force: Go 10x faster by 10 magnets instead of 1. Or buy a couple of big magnets? Or both?

Axion detector technologies are nearly shovel-ready (other than gap in coverage around 100 GHz) … but still need magnets



With a large investment in magnet infrastructure, we can achieve full coverage of axion masses **within our lifetimes.**

Scan speed for resonant cavity search

$$\frac{df}{dt} = \frac{(g\theta BR)^4}{(kT)^2} Q_c Q_a$$

R = linear size of expt.

Ciaran O'Hare

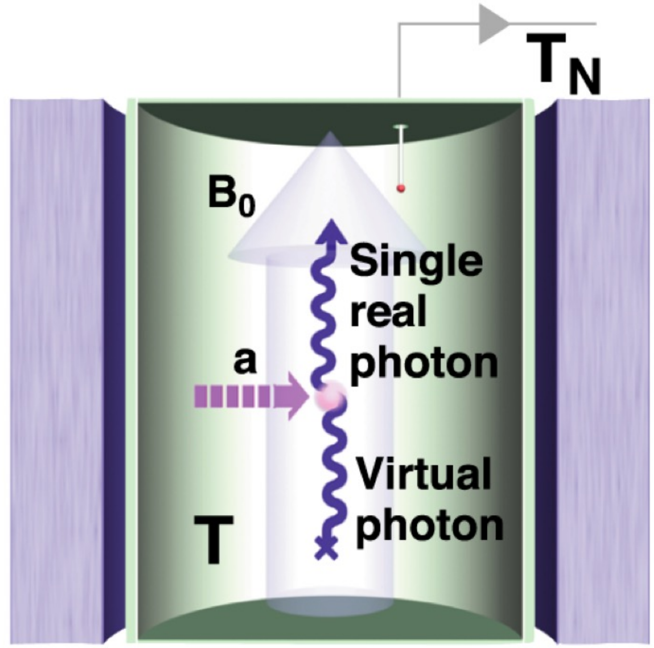
The Dark Matter Haloscope: Classical axion wave drives RF cavity mode

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 ???**



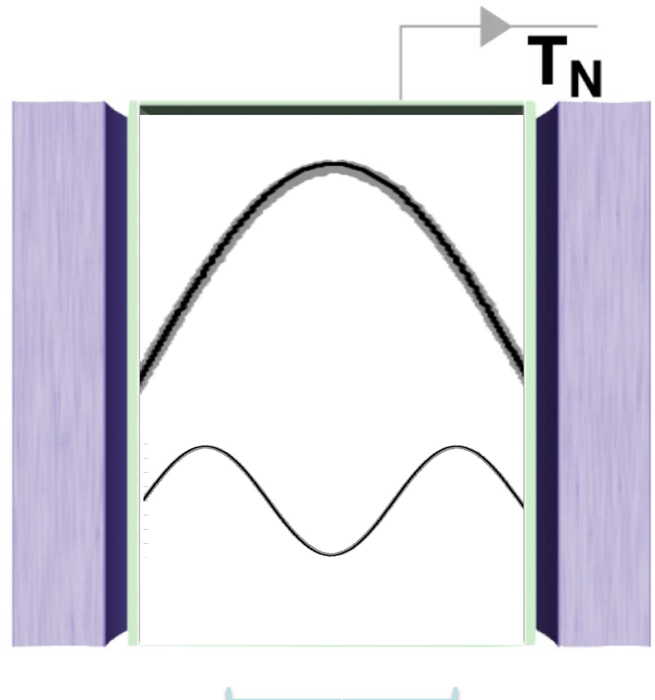
Actually, only the cavity volume within one Compton wavelength from the wall matters

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



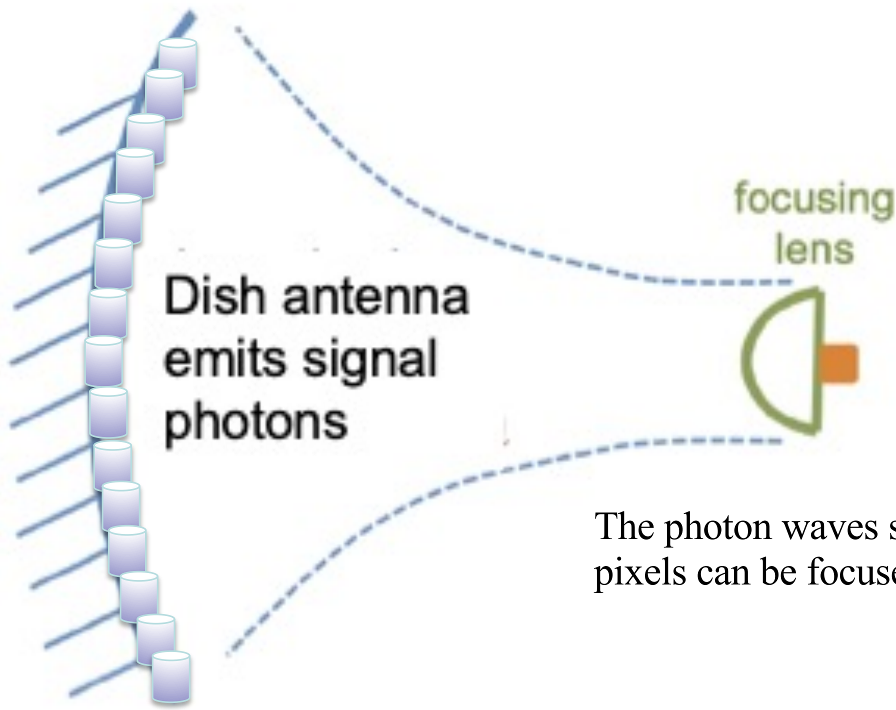
The interior region integrates to zero

Broadband dish reflectors at higher axion frequencies.
Signal power scales as B^2 x (Area), not B^2 x (volume) of the scattering target.

Volume * (form factor) = Area * (Compton wavelength)

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

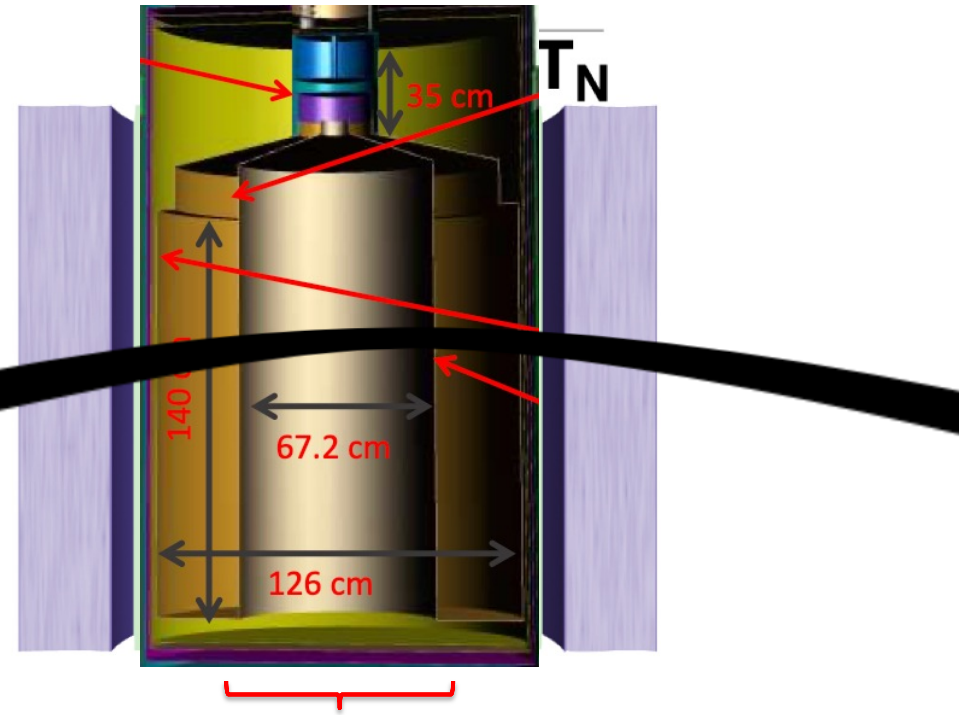
D. Horns, et.al, JCAP 1304, 016 (2013)



The photon waves sourced from the individual pixels can be focused using geometric optics.

For longer Compton wavelengths 1/m, an apparatus of size R acts as a high pass filter with a transfer function "zero" at frequency 1/R.

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

R = (volume)$^{1/3}$

For lumped-element circuit resonators at lower frequencies, the antenna transfer function scales as (m R)^2.
→ **Signal power scales as B^2 x (Volume)$^{5/3}$**

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
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 DFSZ with a lot of hand-waving

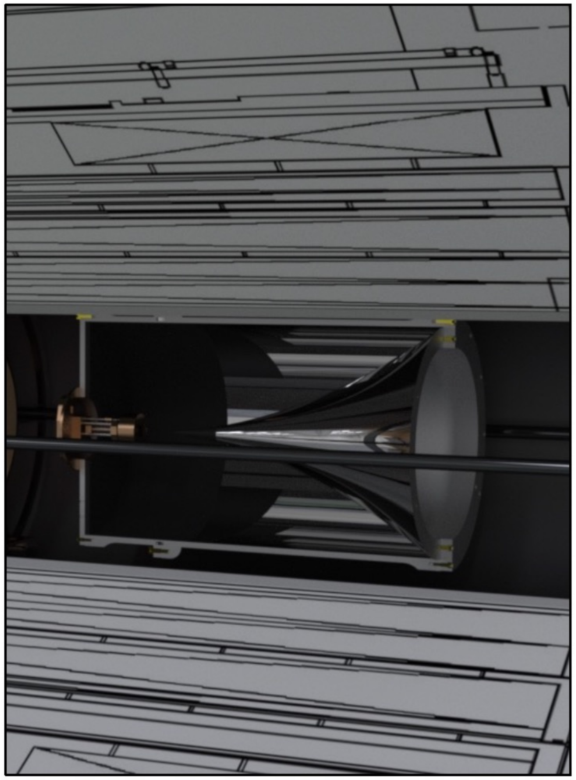
Decisively reach DFSZ (g=0.3)

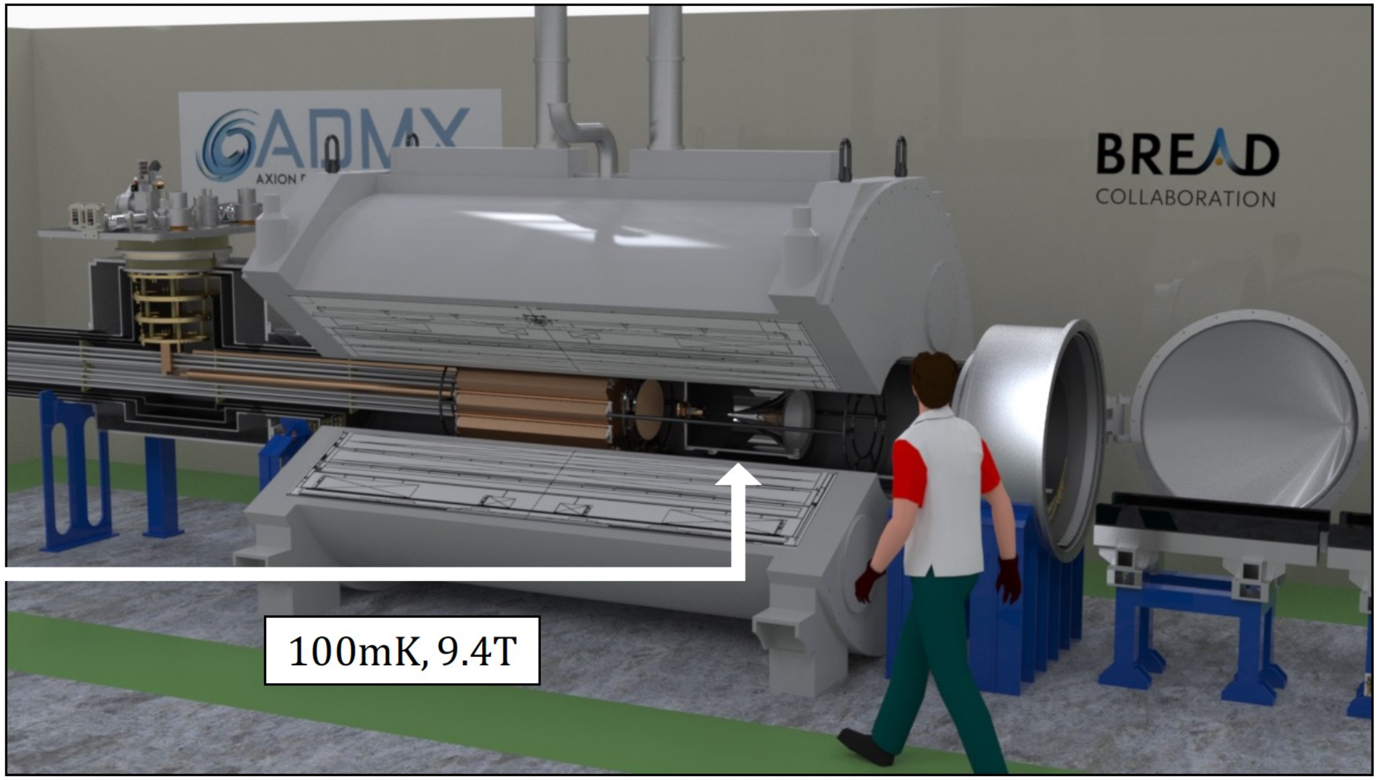
Push to g=0.1 !

First step: new Fermilab “Dark Wave Lab” can house 2 MRI magnets

First donated 9 T, warm bore MRI magnet ~$7M
to be moved to Fermilab this year for ADMX-EFR.

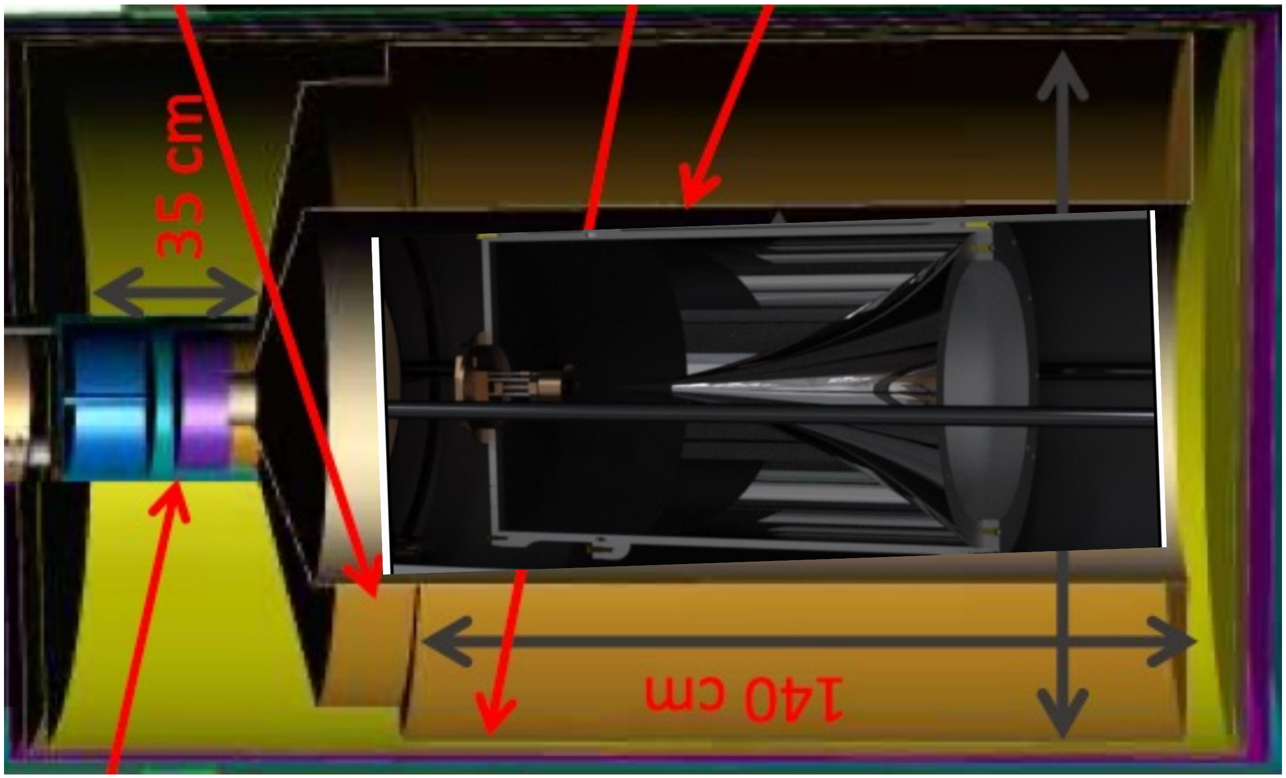
Medium-scale BREAD can potentially share ADMX-EFR magnet



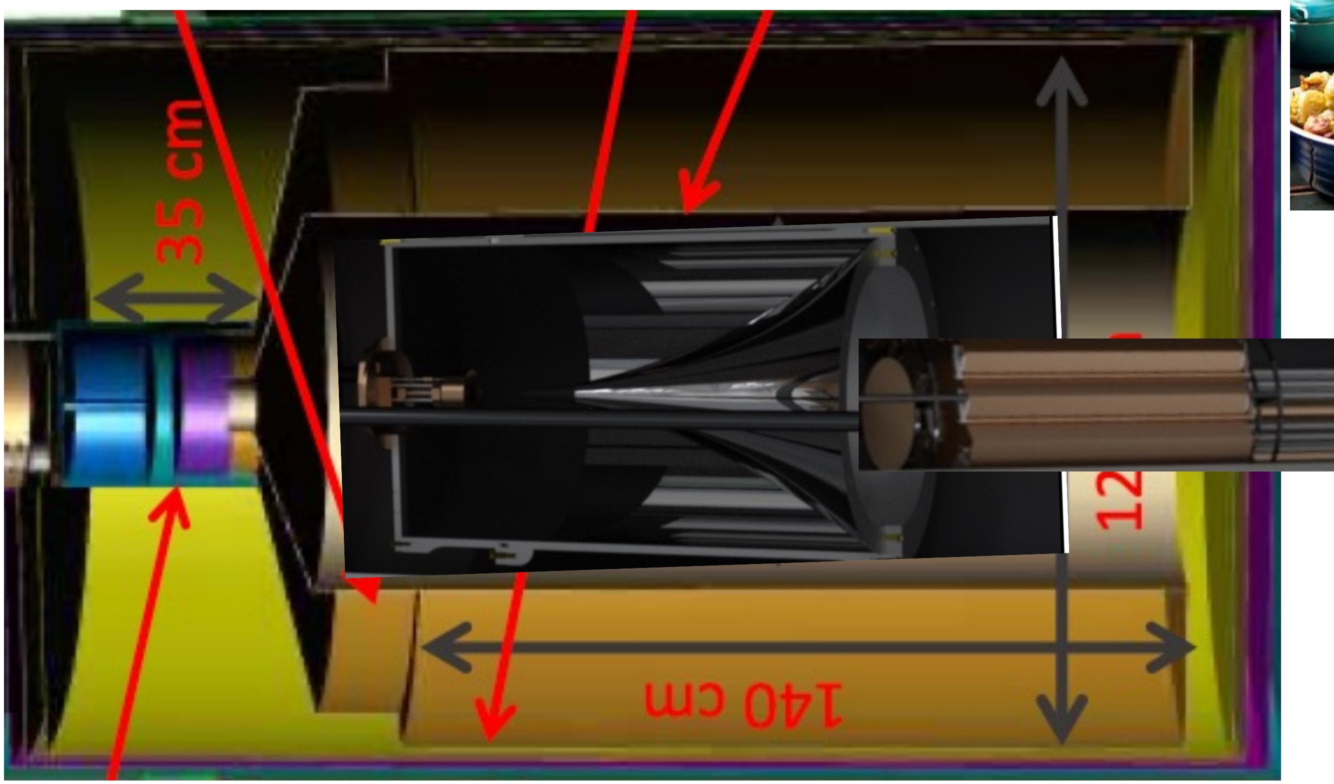


possible larger-scale version ($A \sim 4\ m^2$) as side-experiment to ADMX-EFR at Fermilab

Can we also make BREAD stuffing for DMRadio?



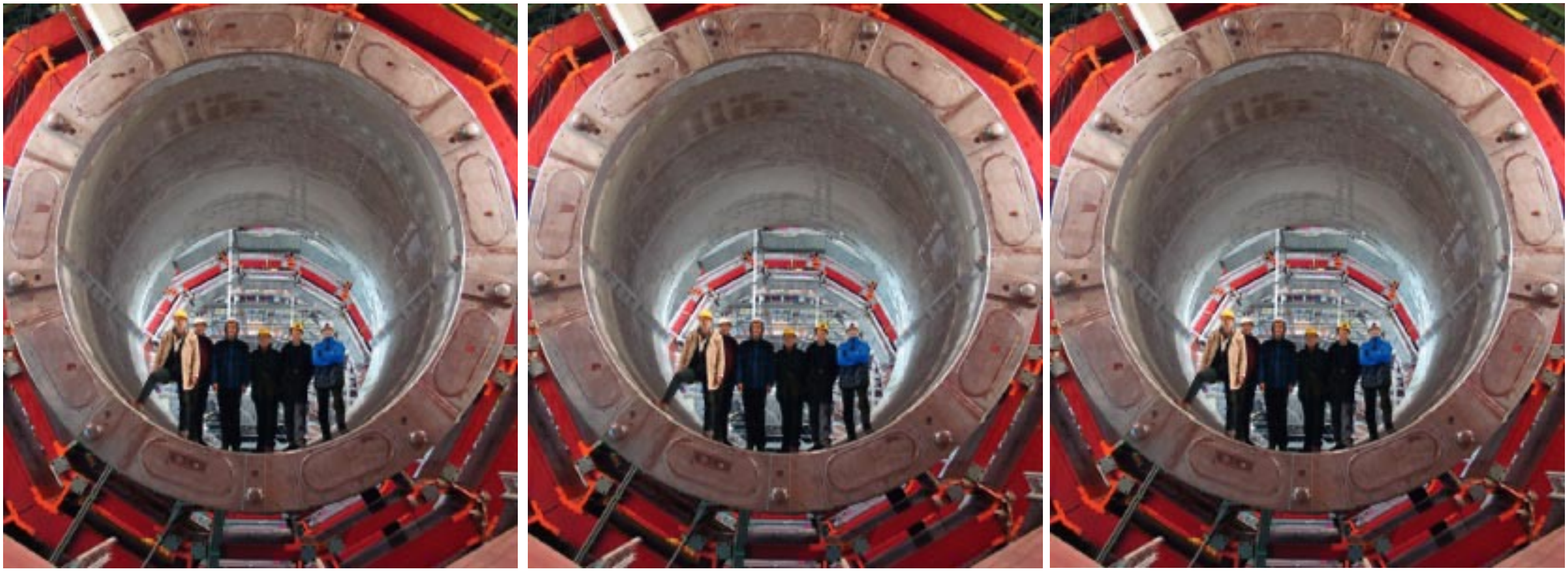
TurDucken!



Cavity expt.

Are we prepared to come together as an international community and ask for $500M-scale, multi-use magnet facilities, utilized by many experiments?

CMS magnet → need similar for muon collider / neutrino factory, need 10x scale-up for FCC detector



Or should we continue cutting off slivers of parameter space for the next 1,000 years?

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

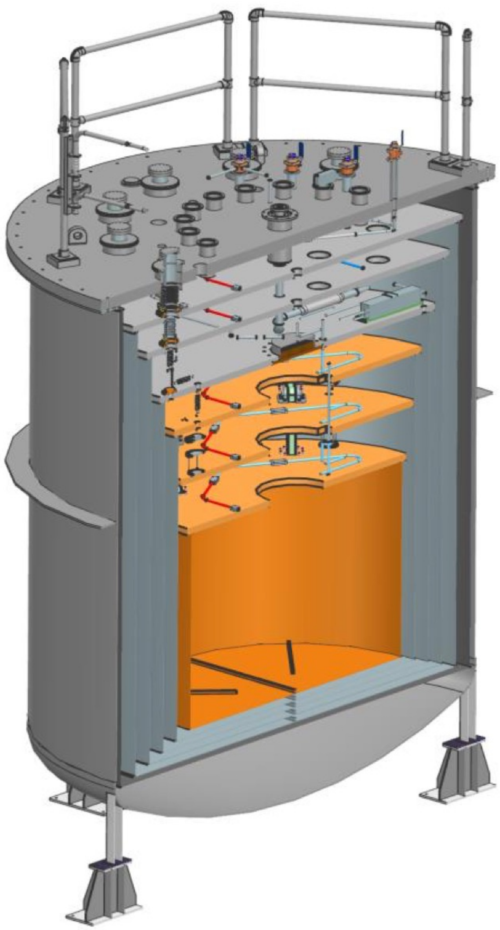
Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	Spectroscopic Survey - S5*	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.*

Let's make this an international HEP facility!

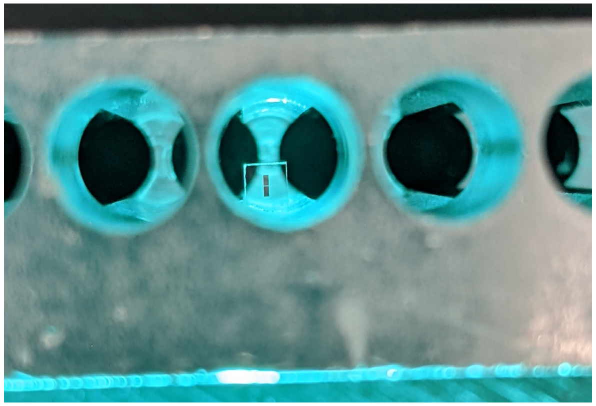
4 miscellaneous points

Point #1: **Problem of large dark matter cryostats for large bore magnets seems to have been solved**



Colossus!

Well done, SQMS! (haha)



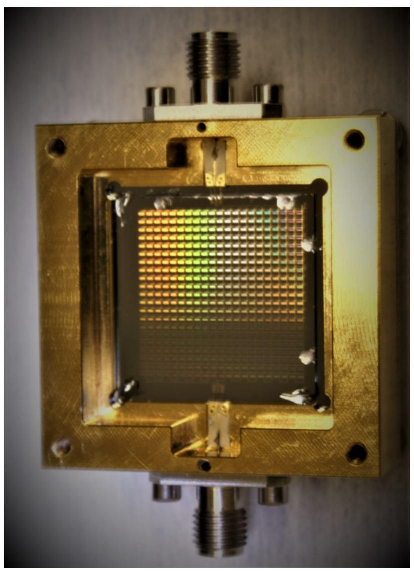
A. Chou (FNAL)

Point #2: Coherent detection makes no sense at higher frequencies.

Signal/noise improvement vs the standard quantum limit for single, sub-eV photon detectors

Transmon qubits (quantum non-demolition @ 10 GHz)
Effective occupation number $n<10^{-3}$
Effective noise squeezing factor = 1/sqrt(n) = 40x

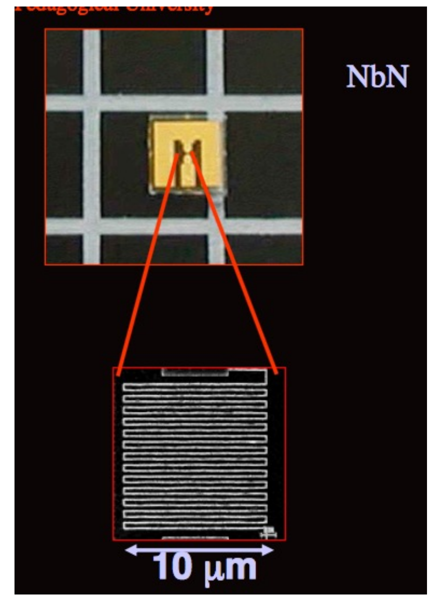
n=1 for zero-point noise



P. Echternach (JPL)

Quantum capacitance detector (charge qubits @ 1 THz)
Dark Rate R = 1 Hz
Bandwidth B = 1 THz
Effective occupation number $n = R / B = 10^{-12}$
Effective noise squeezing factor = 1/sqrt(n) = 10^{6}

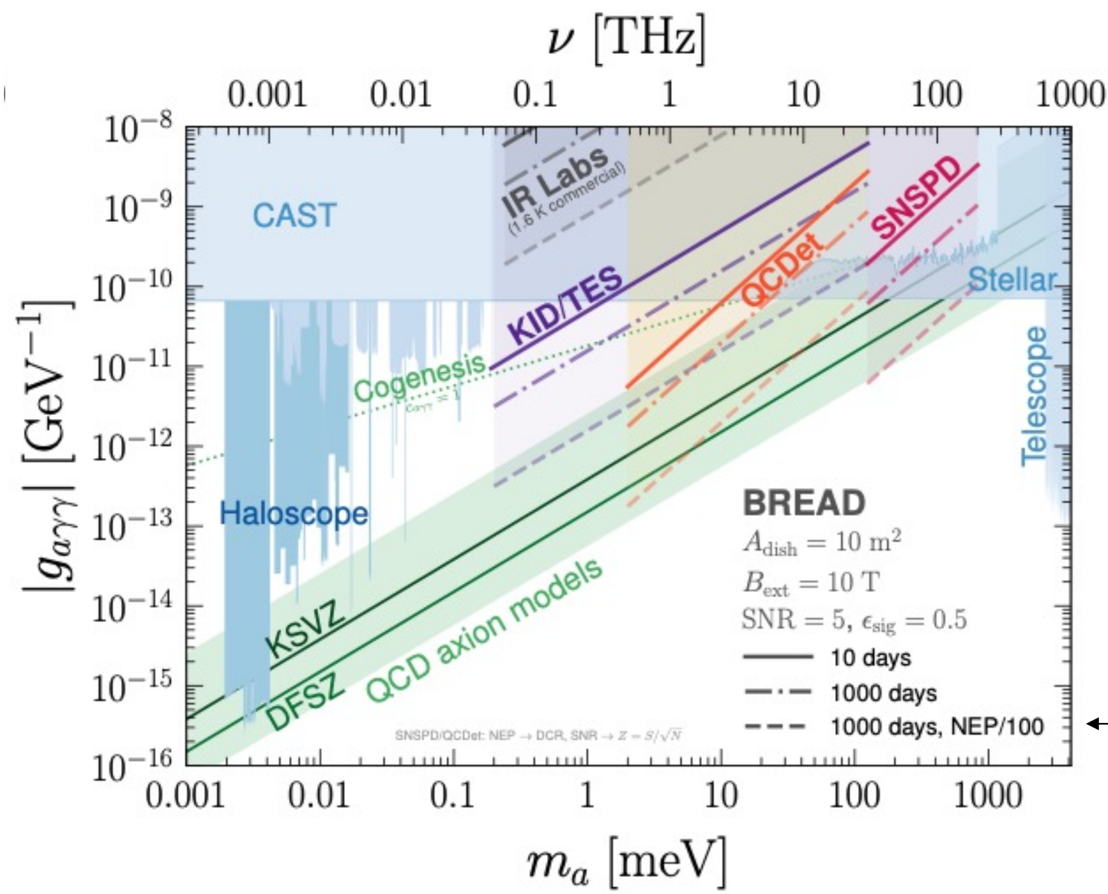
Superconducting nanowire detectors @ >60 THz
Dark Rate $R = 10^{-5}$ Hz (!)
Bandwidth $B = 10^{15}$ Hz (or smaller if narrow band filtered)
Number of modes N_{modes}= Area/(wavelength)^2 = 10^2
Effective occupation number $n = (R / B) / N_{modes} = 10^{-22}$
Effective noise squeezing factor = 1/sqrt(n) = 10^{11}



K. Berggren (MIT), S. Nam (NIST), M. Shaw (JPL)

Far, far better than squeezing… but still not good enough for dark matter.

(Tiny) dark count rates (DCR) are still too high for axion searches!



(Too) optimistic projections for the BREAD dish antenna experiment.

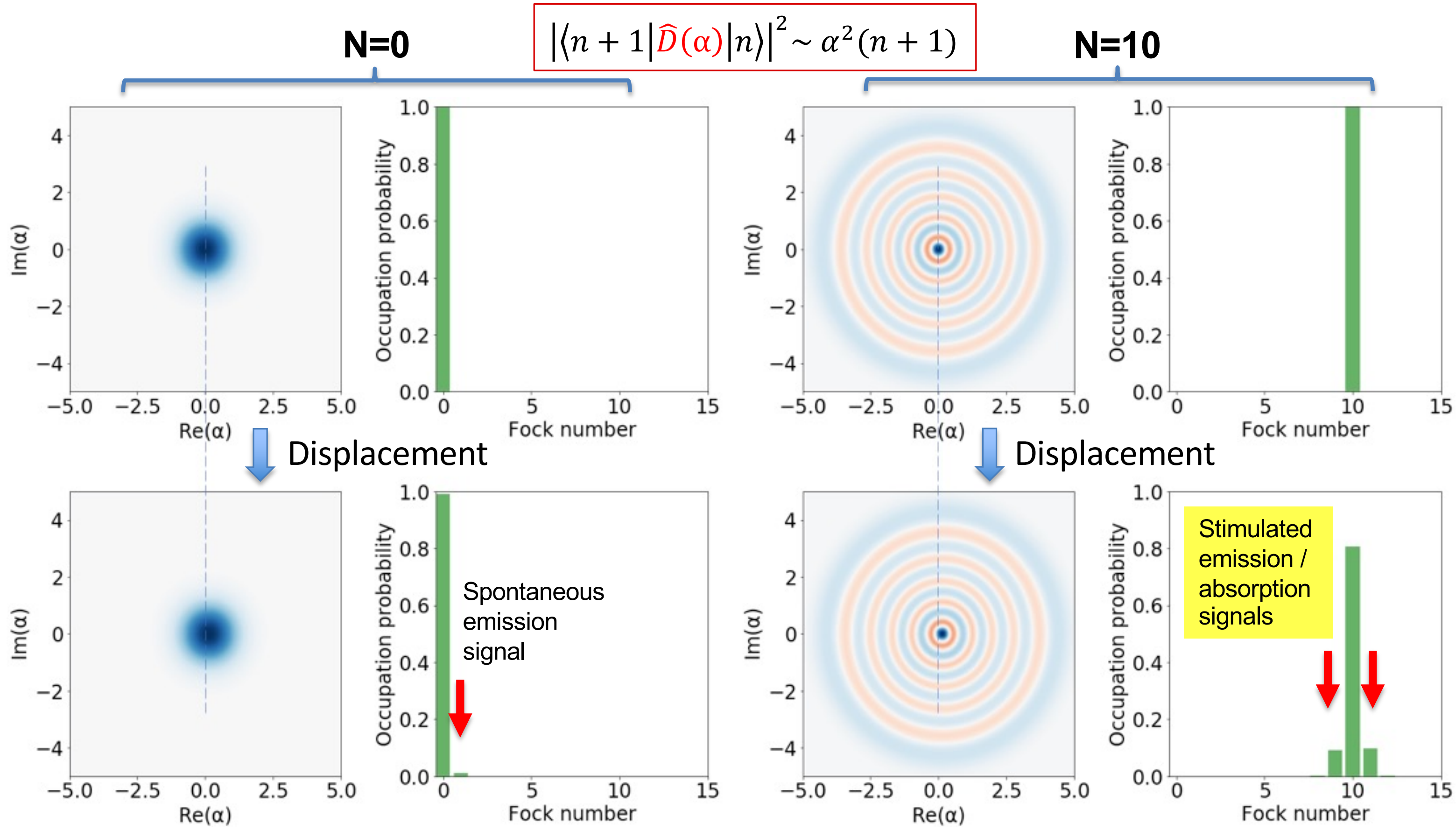
NEP/100 = DCR / 10^4
This is not easy! Also no path to 100 GHz experiment.

We really need larger, stronger magnets to increase signal rates. Cannot rely only on sensor noise reduction.
Sensitivity: B^2 A x10 ←→ DCR/100

Point #3: Quantum tricks can slightly increase signal rates by factor of a few.

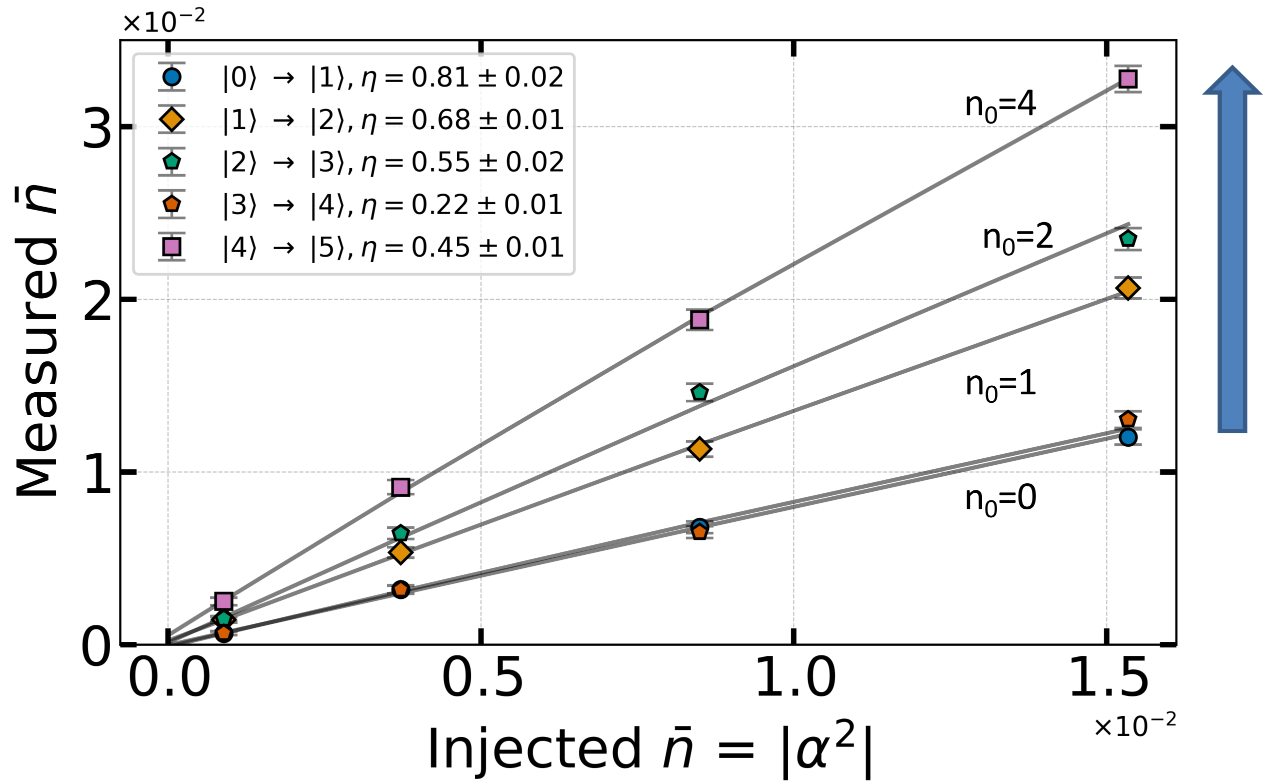
Prepare resonant cavity in a Fock state to enhance the transfer of quanta from DM to photons:

$$\boxed{\left|\langle n+1|\hat{D}(\alpha)|n\rangle\right|^2 \sim \alpha^2(n+1)}$$



QuTiP simulation

Counting population in upper Fock sideband gives us slightly better SNR, in the form of extra signal photons



Increased number of signal photons delivered … for the same applied force

This is the first demonstration so far showing signal enhancement with $|n\rangle = |4\rangle$ Fock state

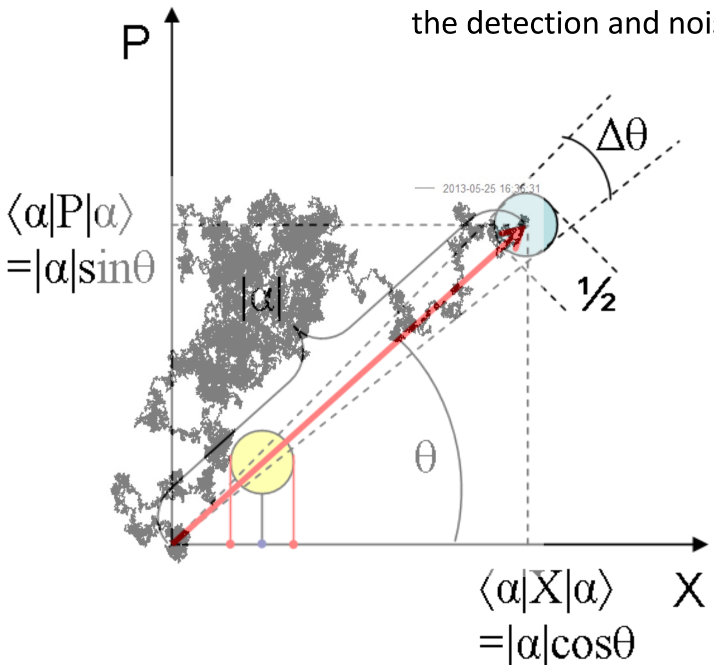
Less than a factor of (n+1) due to measurement inefficiencies, e.g. photon decays during measurement, QND has small demolition probability, etc. HMM optimized for small background rate n_{bkgd}<1%

Slide/data from Ankur Agrawal, arXiv:2305.03700

Point #4: higher Q is ALWAYS better when trying to accumulate power from an undercoupled signal.

Use high-Q_c cavity ($Q_c > Q_a = 10^6$) as signal integrator to match noisy readout rate to the expected signal rate.

Why read out at 10^6 Hz when the signal rate is 10^{-2} Hz? Better to match the detection and noise bandwidth to the signal rate (see Patrice Bertet talk).



Displacement operator product for multiple incoherent pushes (from the dark matter) gives **random walk** accumulation of signal amplitude (1 step per signal coherence time):

$$\hat{D}(\alpha)\hat{D}(\beta) = e^{(\alpha\beta^* - \alpha^*\beta)/2}\hat{D}(\alpha+\beta)$$

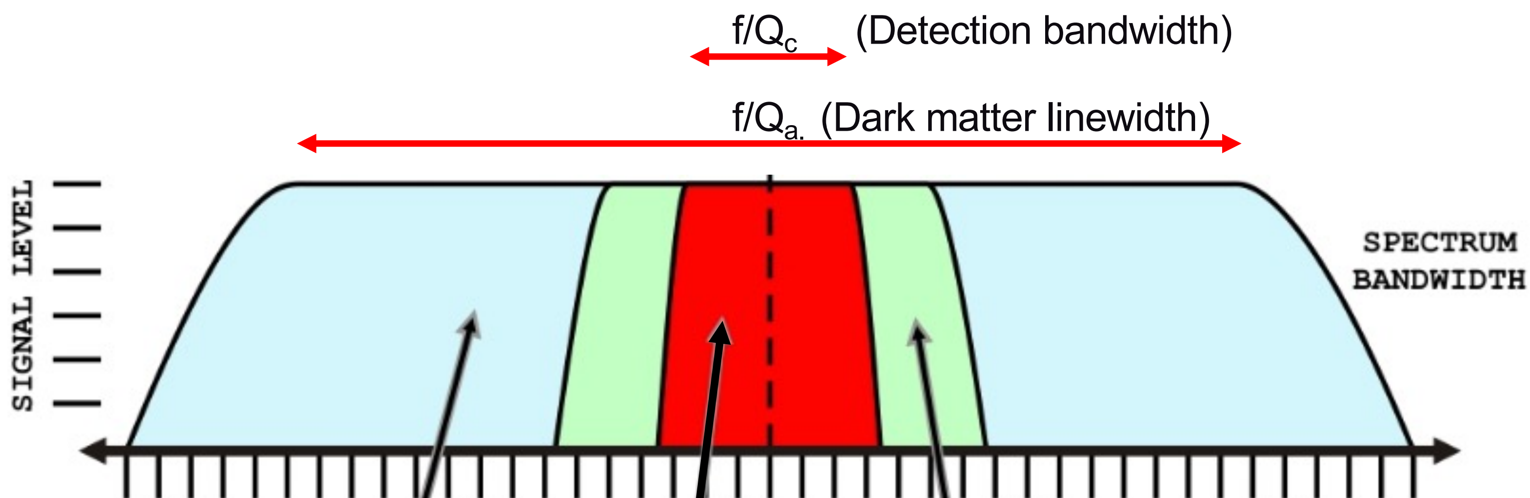
$$\rightarrow \Pi_i\, D(\Delta\alpha_i) = D(\underbrace{\Sigma_i \Delta\alpha_i}_{\sqrt{N_{steps}}\Delta\alpha})e^{i(phase)}$$

$$\boxed{\begin{aligned} E &= \sqrt{N_{steps}}\cdot\Delta\alpha = \sqrt{\frac{Q_c}{Q_a}}\cdot g\theta B Q_a \\ &\rightarrow P_{signal} \sim E^2 V \cdot \frac{m}{Q_c} \propto Q_a \end{aligned}}$$

Better to match the detection bandwidth to the signal rate (Patrice Bertet talk)

but now can accumulate over a much longer time f/Q_c while narrow-banding the readout noise.

Can also view this as collecting the power in a small but highly coherent fraction of the total axion power spectral density



Sideband components decohere with the cavity during the random walk

$$\theta_{frac} = \sqrt{\frac{Q_a}{Q_c} \cdot \frac{2\rho}{m_a}}$$

$$\rightarrow \; P_{signal} \sim E^2 V \cdot \frac{m}{Q_c} = (g\theta_{frac} B Q_c)^2 \; V \cdot \frac{m}{Q_c} \propto Q_a$$

Requires cavity coherence time T2 > axion coherence time T_a.

Cavity frequency can drift as long as it stays within the total axion signal band on the time scale of the accumulation time = cavity T1 lifetime.

Summary

- Full coverage of QCD axion masses from pre-inflationary to post-inflationary models is within reach … within our lifetimes! Detector technology is shovel-ready or as near shovel-ready as it is going to get.

- Large 10 mK cryostats are also under development for quantum computing needs.

- Various quantum tricks (squeezing, stimulated emission) can help a little bit.

- To increase the signal rate from axions, need to plan ahead for a fleet of magnets of various sizes.
  - Overall cost likely to be several $1B with lead times up to 10 years for construction.
  - **Large $100M and mid-scale $10M magnets**: large infrastructure and maintenance costs. These should be provided as large laboratory facilities rather than associated with a single experiment
  - **Smaller $1M magnets** (ADMX, HAYSTAC, CAPP size) can be hosted at universities for sensor development and for smaller experiments. Even in this case, 10 magnets instead of 1 could mean the difference between a 3 year experiment vs a 30 year experiment
  - Leverage stakeholders from other communities (collider, fusion, condensed matter, etc)