New Precision Experiments for Axion Dark Matter

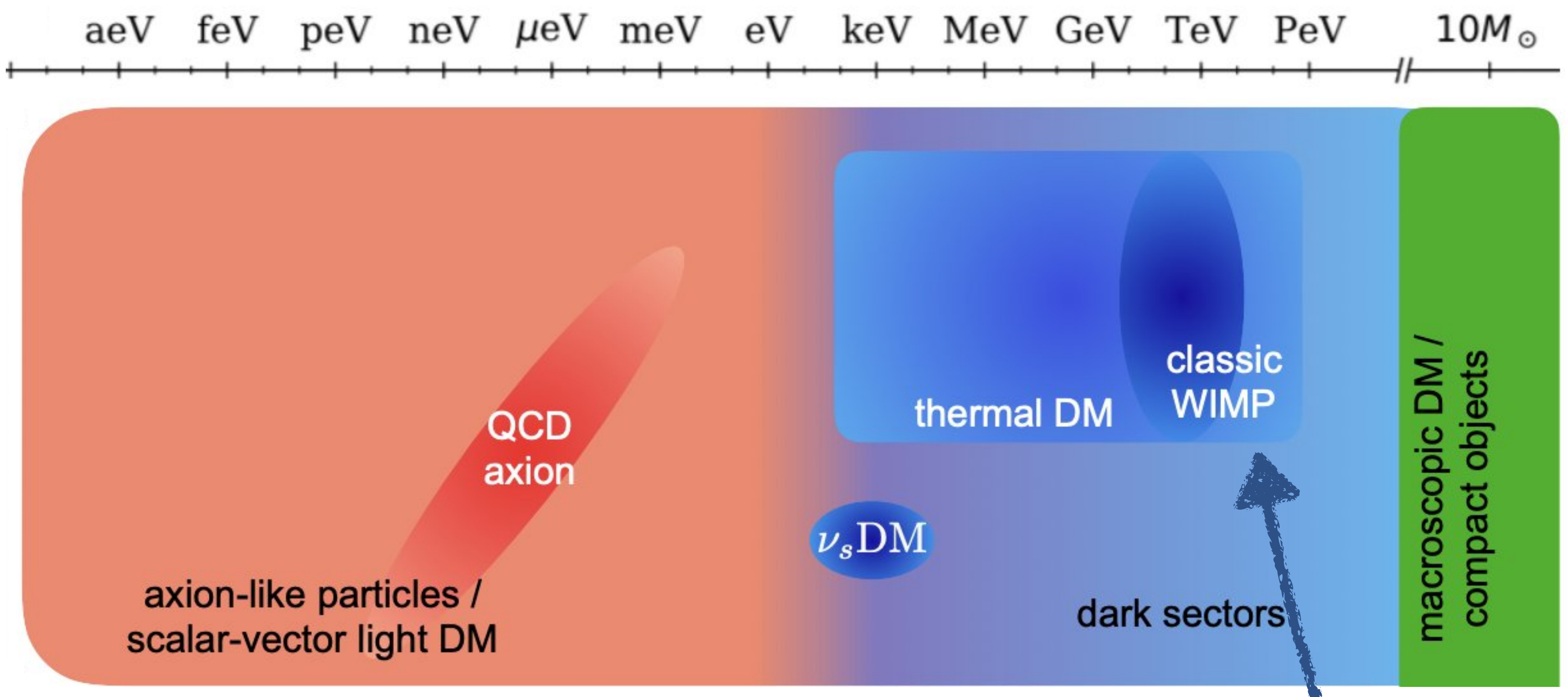
Kevin Zhou

Berkeley UNIVERSITY OF CALIFORNIA

BERKELEY LAB

New Opportunities for Particle Physics — July 20, 2025

Dark Matter Candidates



macroscopic object

well-tested by astrophysical observation

"classic WIMP"

very well-tested by direct detection and astrophysics

~95% of funding, effort

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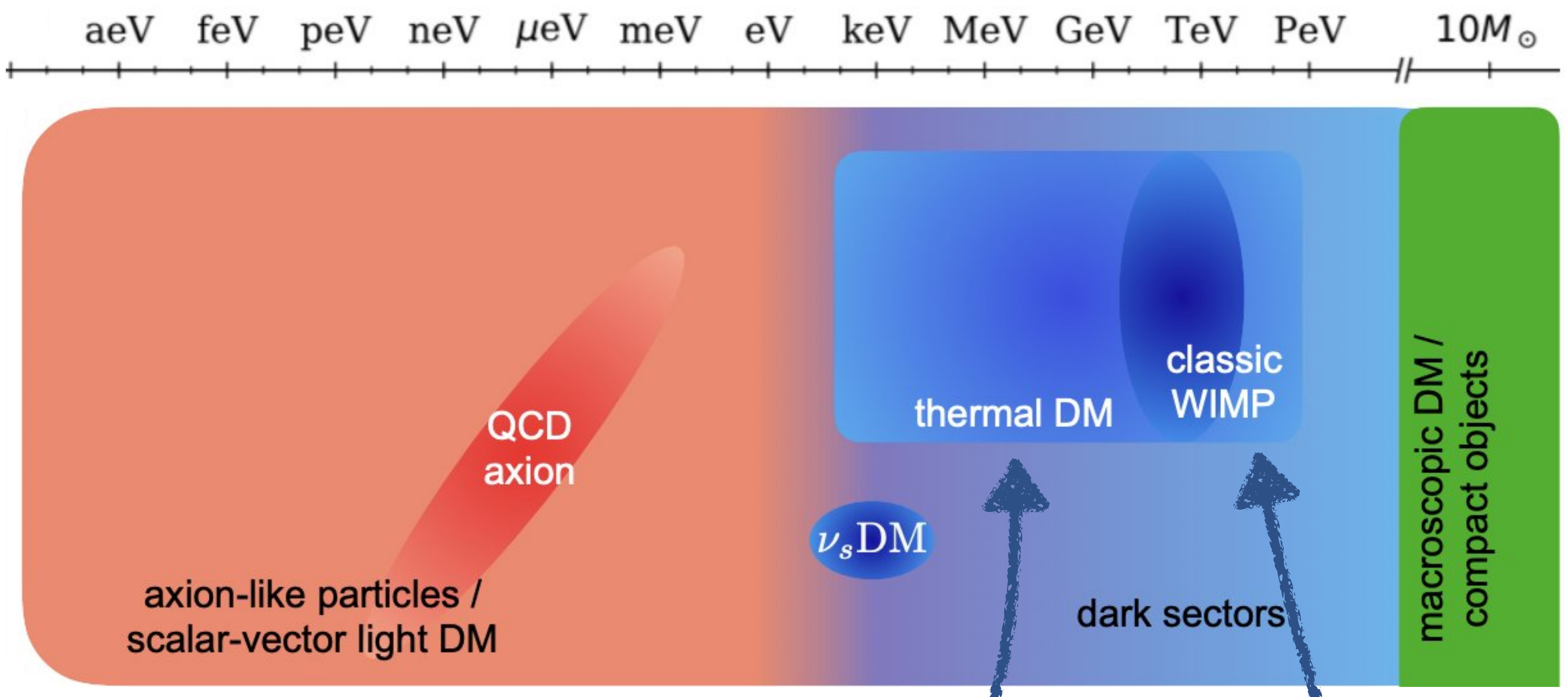

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"lighter particle"

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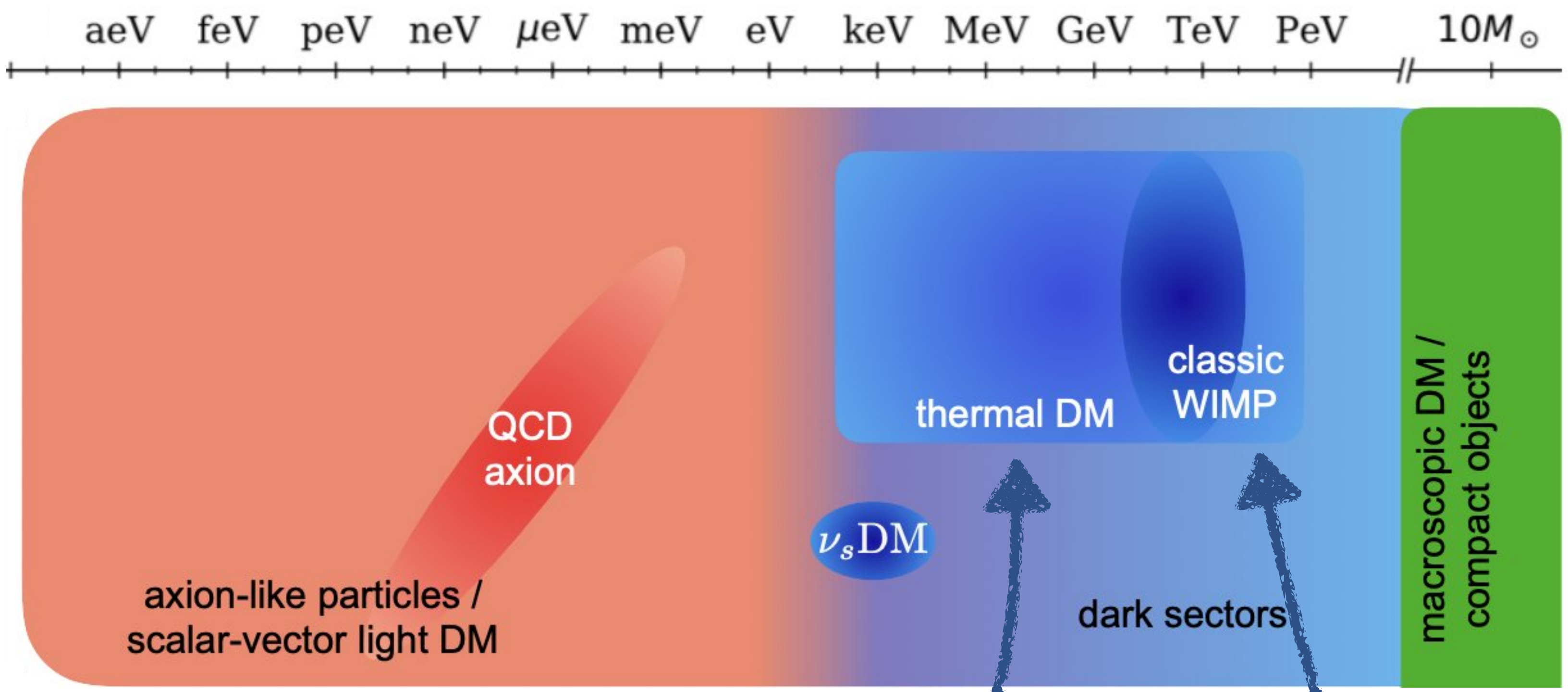

ultralight field

acts like oscillating classical field

$$\frac{f}{\mathrm{GHz}} \sim \frac{m_{\mathrm{DM}}}{\mu\mathrm{eV}}$$

field's weak forces, torques, currents can be probed by new precision experiments

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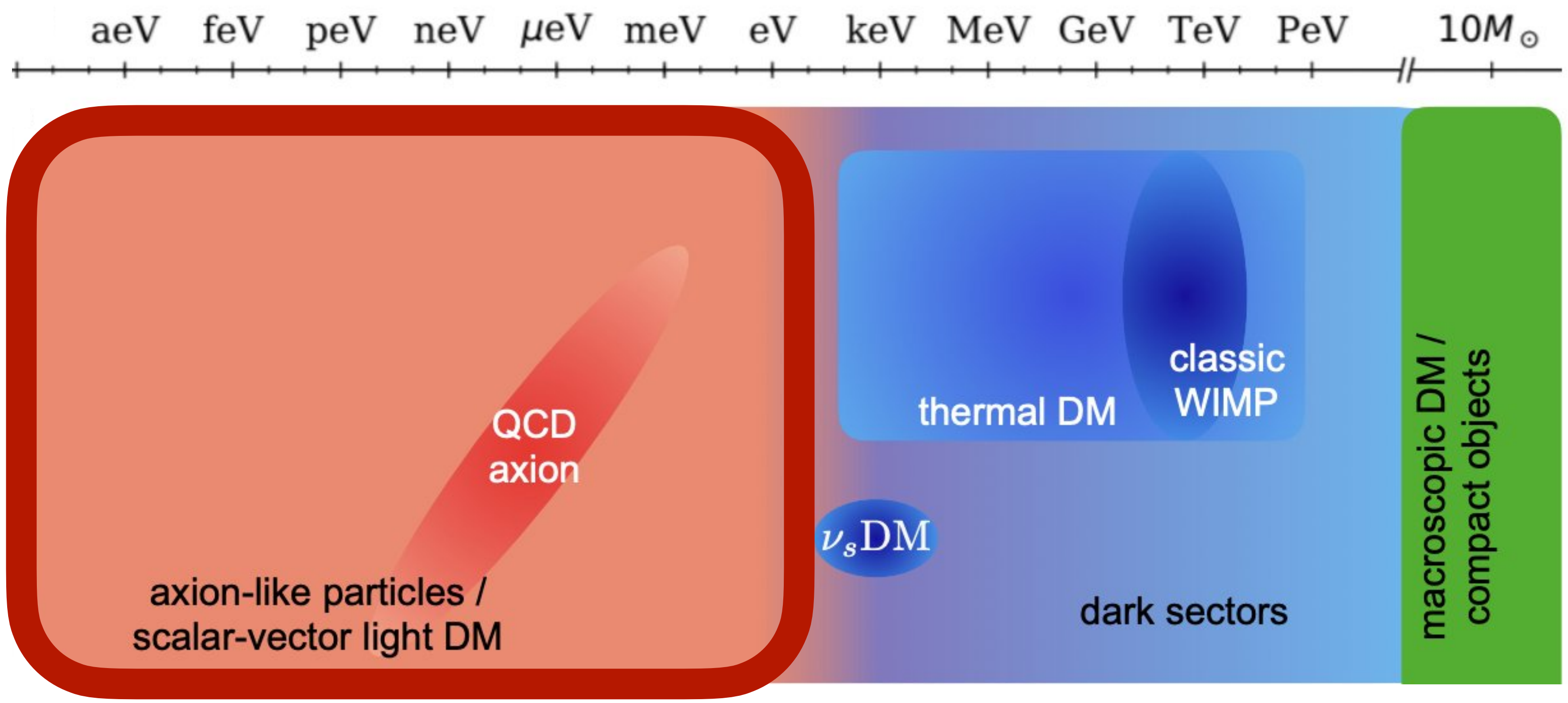
Why Search for Ultralight Dark Matter?



- Simply produced: gives right amount of dark matter with minimal cosmology
- Generic: required ultralight fields automatically appear in many models
- Minimal: requires introduction of only a single new field at low energies
- Low-hanging fruit: new experiments are needed, inexpensive, and very effective
- Bounded: only a few interactions are natural and leading in effective field theory

Ultralight Dark Matter Candidates

In field theory, only a few candidates are possible!

	pseudoscalar a	scalar ϕ	vector A'_μ	tensor $h'_{\mu\nu}$
naturally light with leading coupling	✓		✓	?
arises in high energy theories	✓	✓	✓	
solves tuning problems	✓	?		
simply produced	✓	✓	?	?

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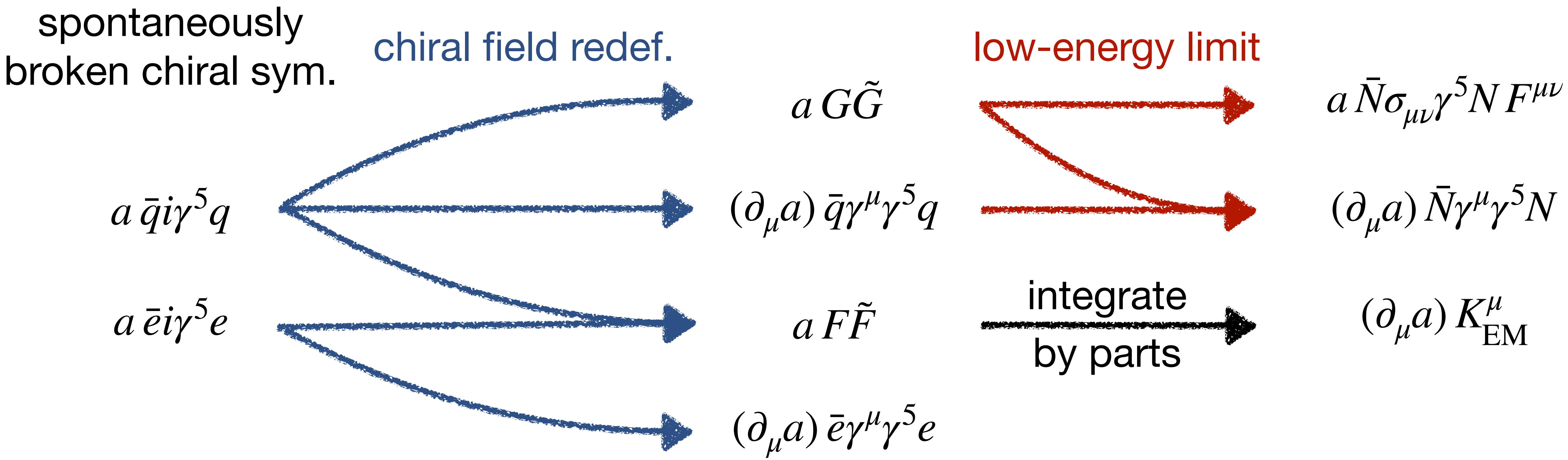
Couplings of a Field Theory Axion



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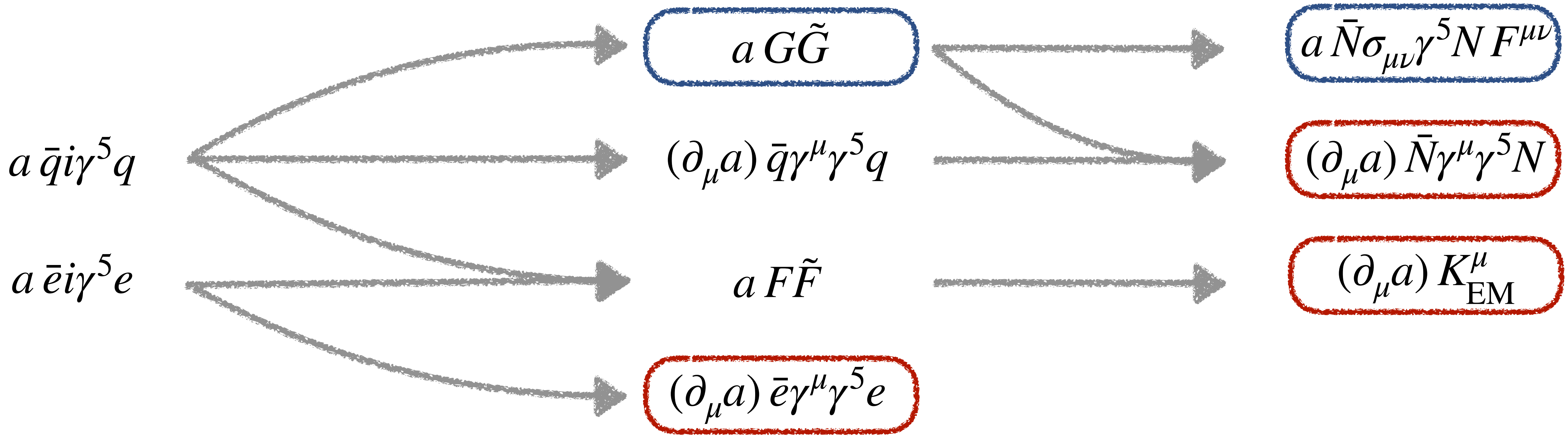
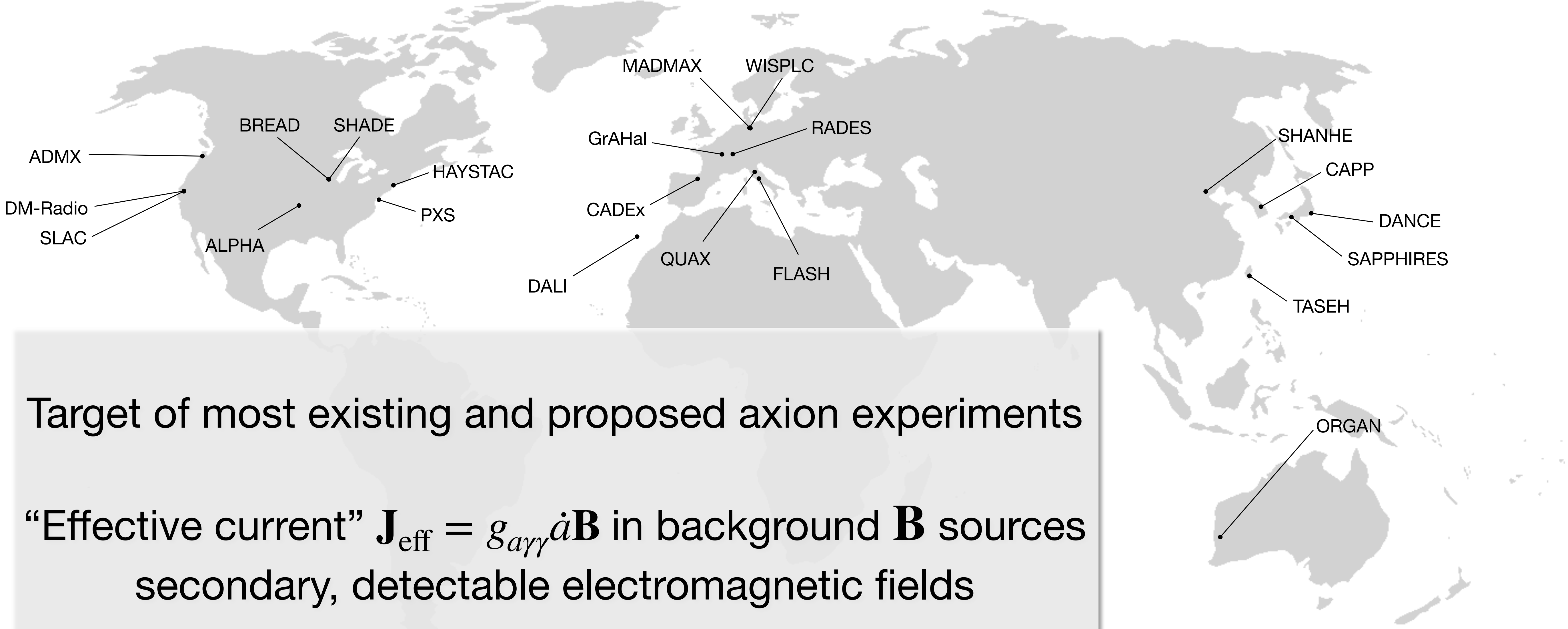


Only a few dimension 5 operators possible, and all appear, independent of UV details

Needs caution: effects depend only on the axion derivative $\partial_\mu a$

However, a QCD axion can have signatures proportional to a

$(\partial_\mu a)\, K^\mu_{\text{EM}}$	$(\partial_\mu a)\, \bar{N}\gamma^\mu\gamma^5 N$	$(\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e$	$a\, \bar{N}\sigma_{\mu\nu}\gamma^5 N\, F^{\mu\nu}$
axion-photon	axion-nucleon	axion-electron	axion-EDM



Target of most existing and proposed axion experiments

"Effective current" $\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma}\dot{a}\mathbf{B}$ in background $\mathbf{B}$ sources secondary, detectable electromagnetic fields

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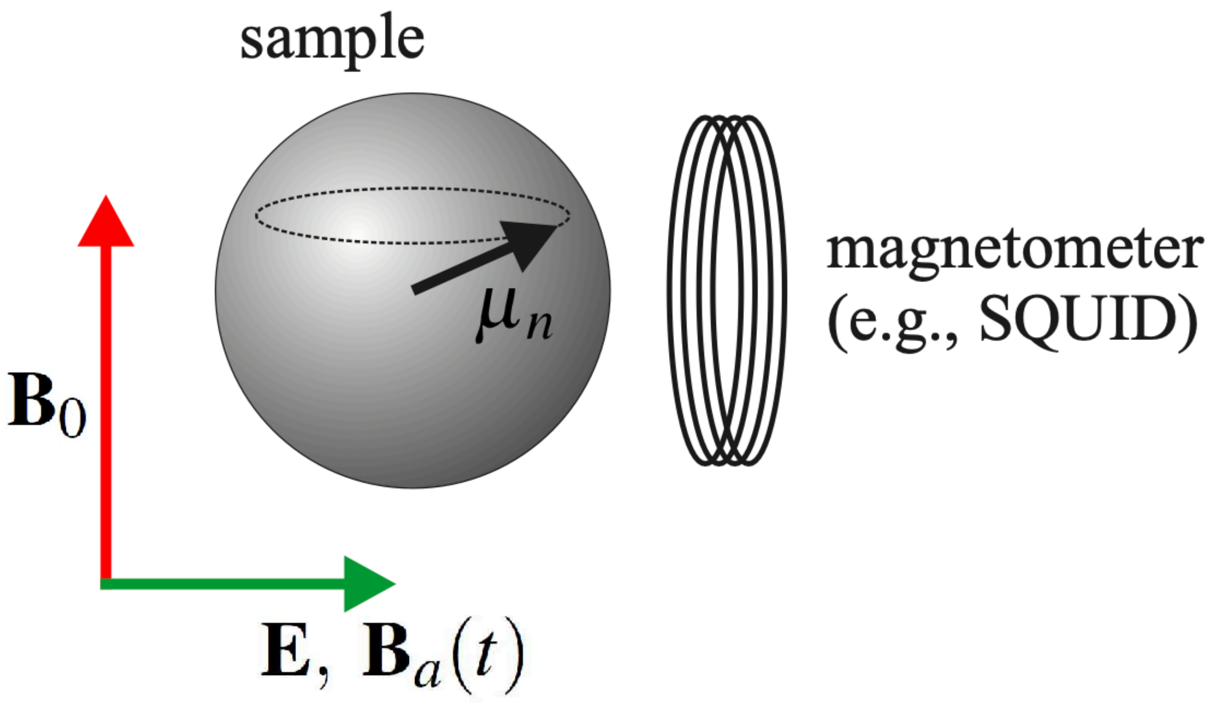

Exerts nuclear spin torque $\tau = \hat{\mathbf{s}} \times \mathbf{B}$ through effective magnetic field $\mathbf{B}_{\text{eff}} = g_{aN}\, \nabla a$

Very weak field must be amplified, e.g. with nuclear magnetic resonance

Detection quite hard, due to weak nuclear spin polarization, small nuclear magneton

$(\partial_\mu a)\, K^\mu_{\rm EM}$

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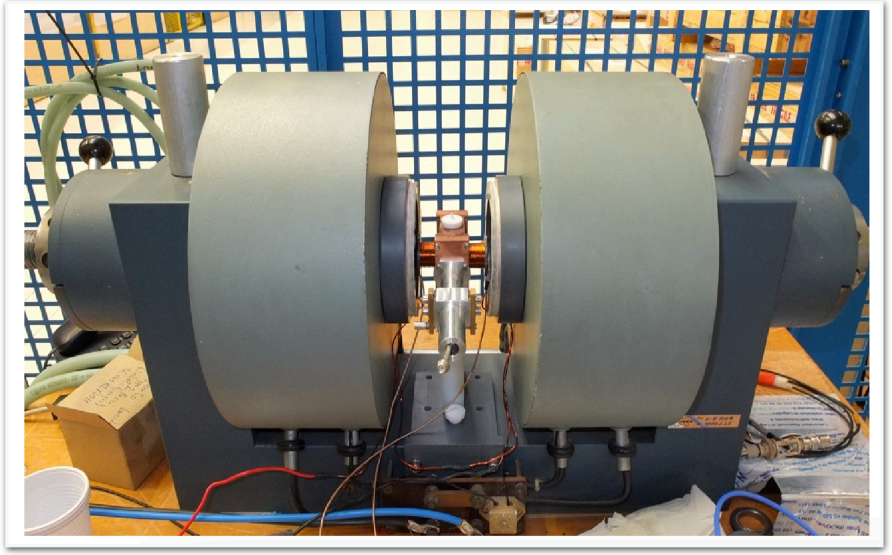

Exerts electron spin torque $\tau = \hat{\mathbf{s}} \times \mathbf{B}$ through effective magnetic field $\mathbf{B}_{\rm eff} = g_{ae}\, \nabla a$

Stronger signals than nuclear case, but electron spins are “messier”

Existing prototypes use ferromagnetic resonance, let sample excite a microwave cavity

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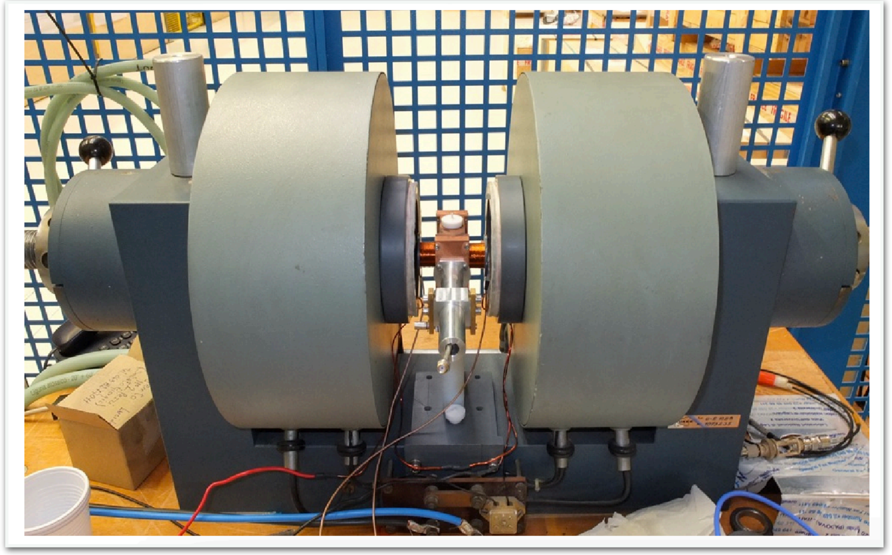

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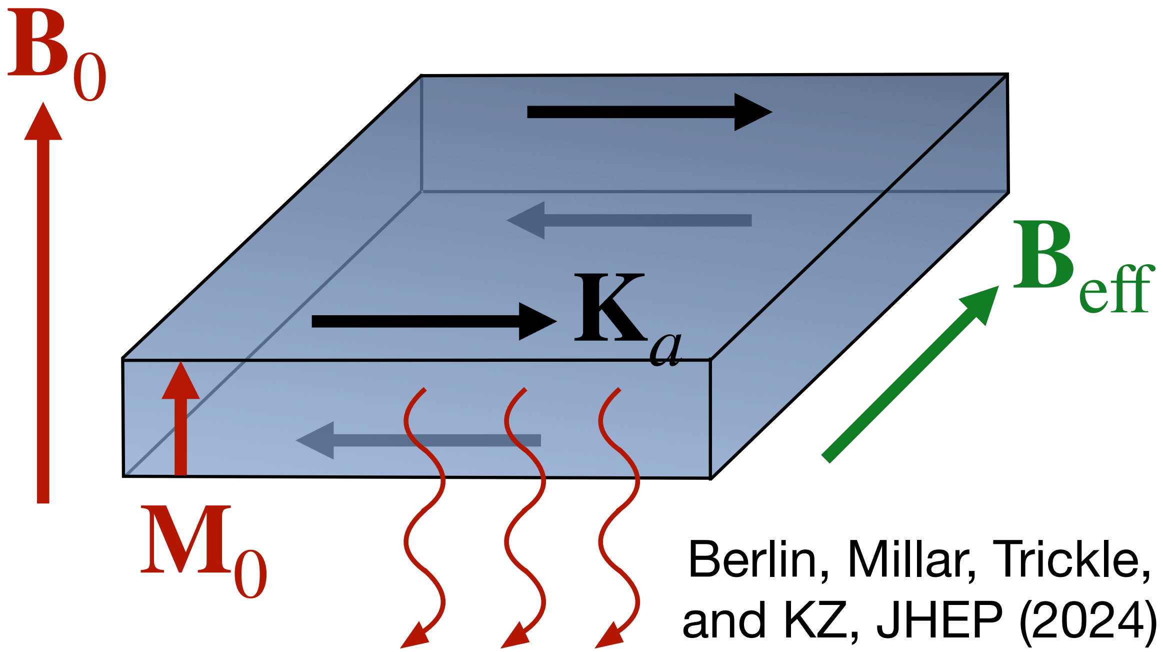

Berlin, Millar, Trickle, and KZ, JHEP (2024)

Existing prototypes use ferromagnetic resonance, let sample excite a microwave cavity

New concept: emit radiation from "magnetic multilayer", substituting scale for resonance

$(\partial_\mu a)\, K^\mu_{\rm EM}$

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axion-EDM

Leads to time-dependent nuclear and atomic electric dipole moments

Traditional EDM experiments don't work, as the EDM oscillates rapidly in time

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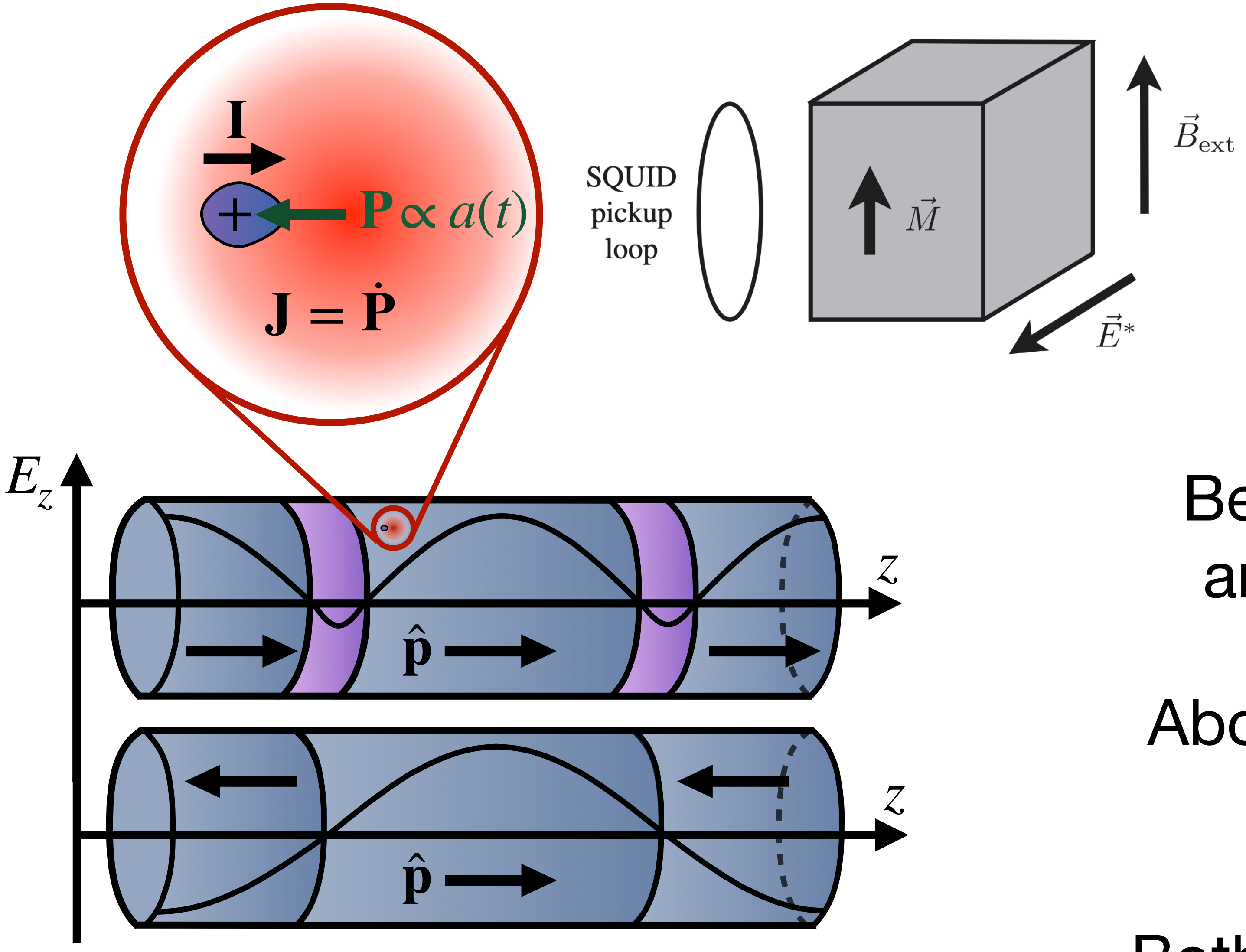

Berlin and KZ, PRD (2023)

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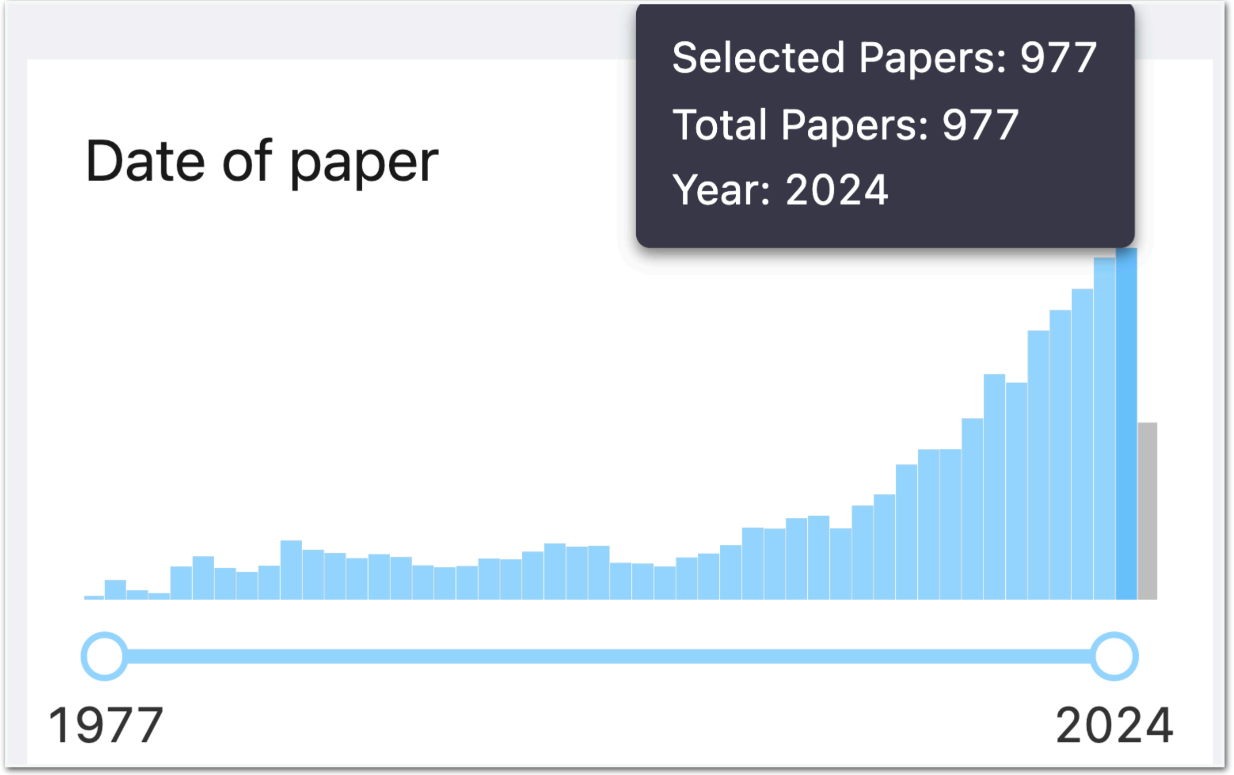
Below GHz: in sample with background $\mathbf{E}$, amplify with nuclear magnetic resonance

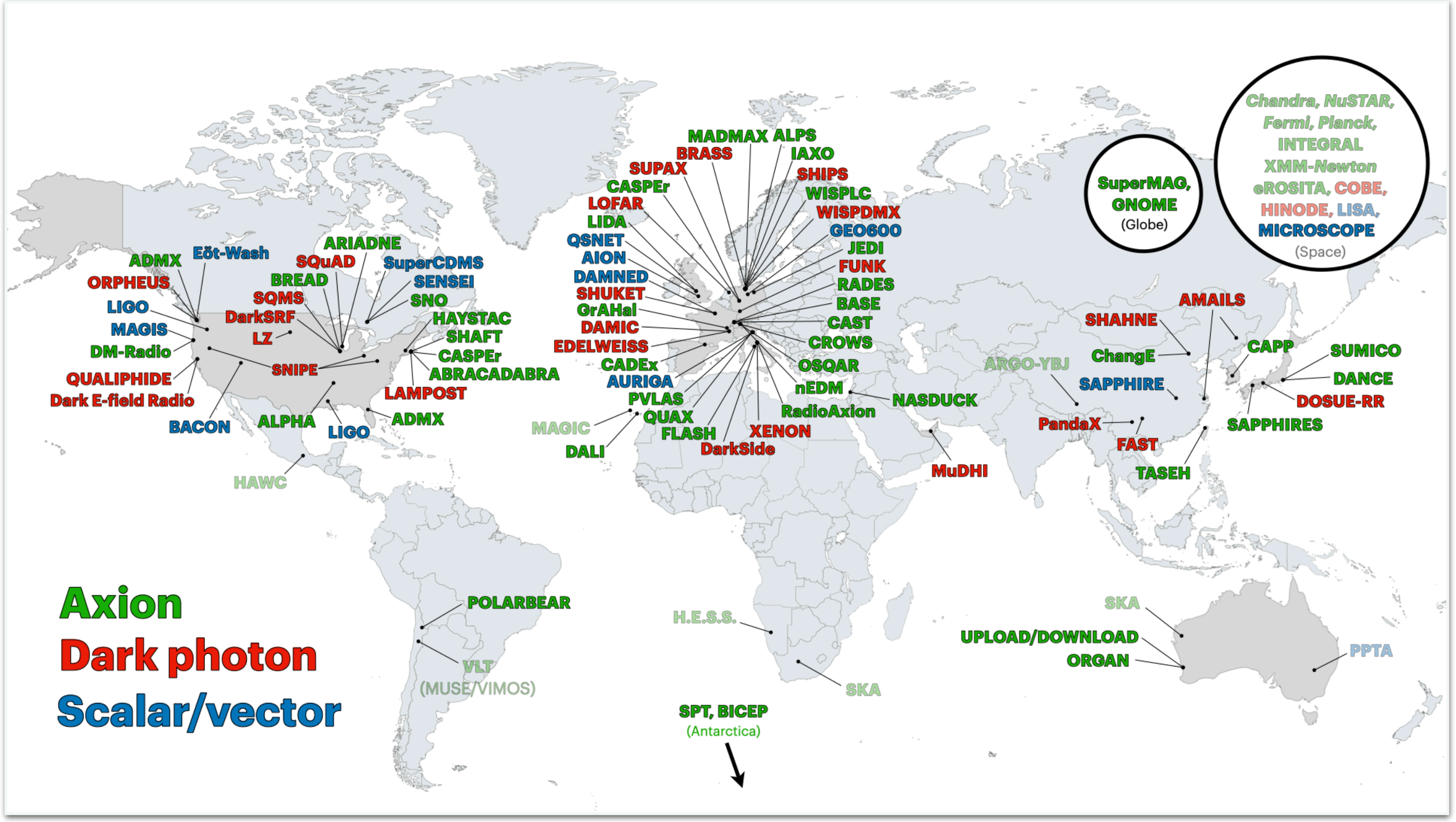
Above GHz: use oscillating current $\mathbf{J} = d\mathbf{P}/dt$ to excite a resonant microwave cavity

Both quite difficult, better for "post discovery"

Axion Searches: Theory and Practice

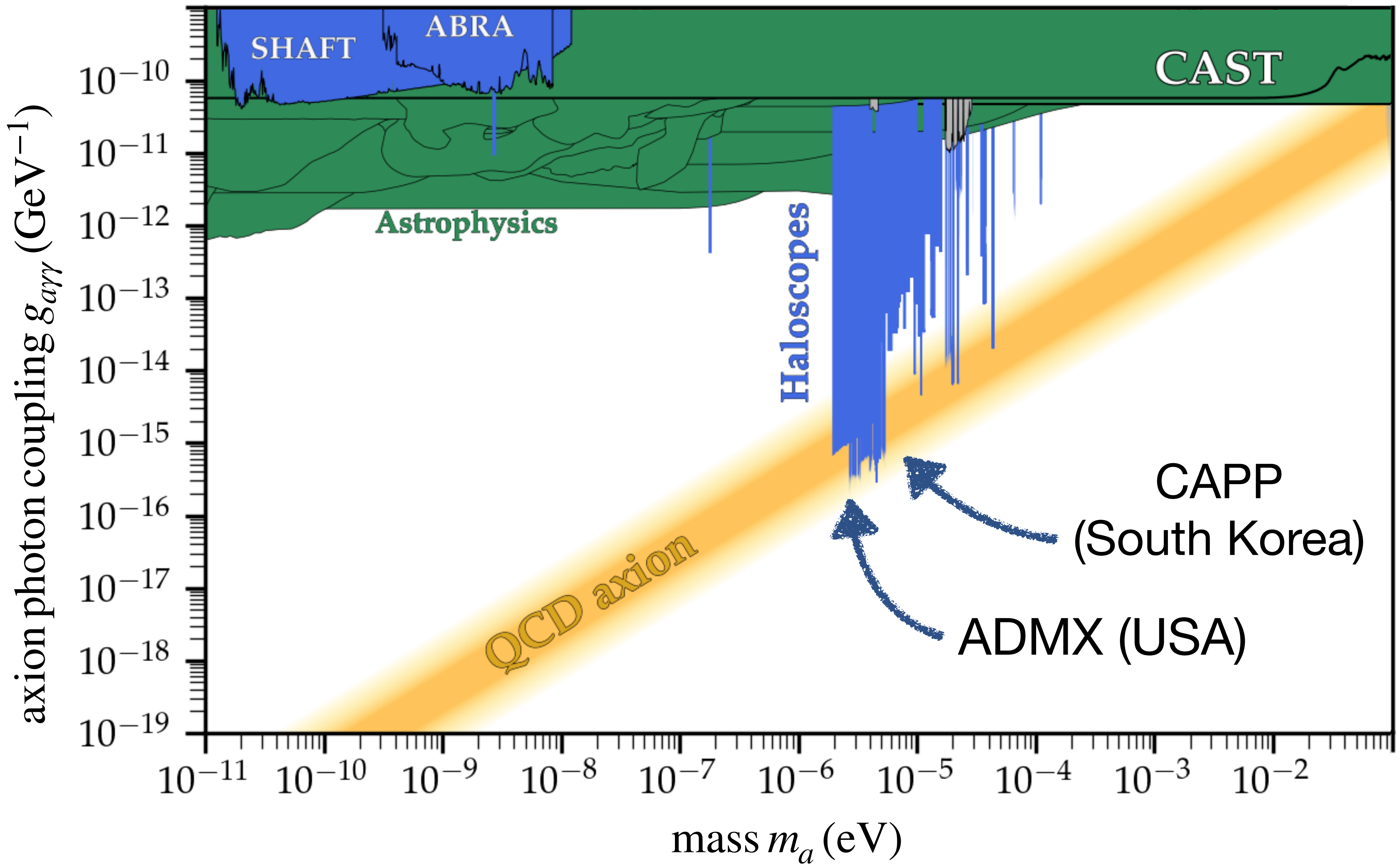
Many papers have been written, and many experimental collaborations formed





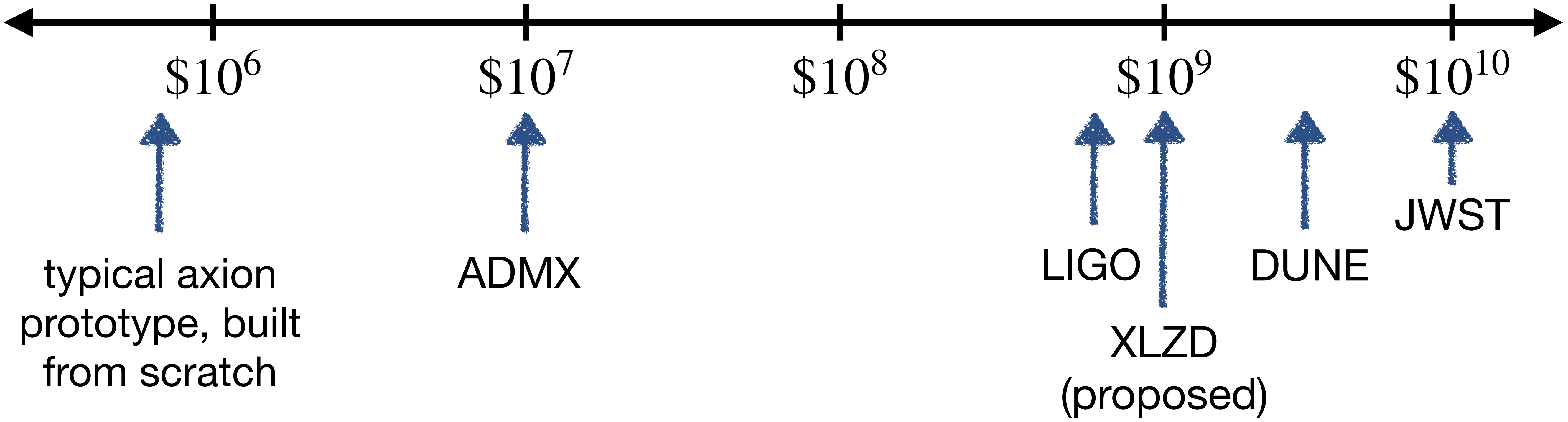
But field is just starting: only a few theoretical ideas become experiments, and most experiments are still prototypes

Axion Searches: Theory and Practice



Currently, only the axion-photon coupling has been probed significantly, and largely by just two experiments using the same method

Axion Searches: Theory and Practice

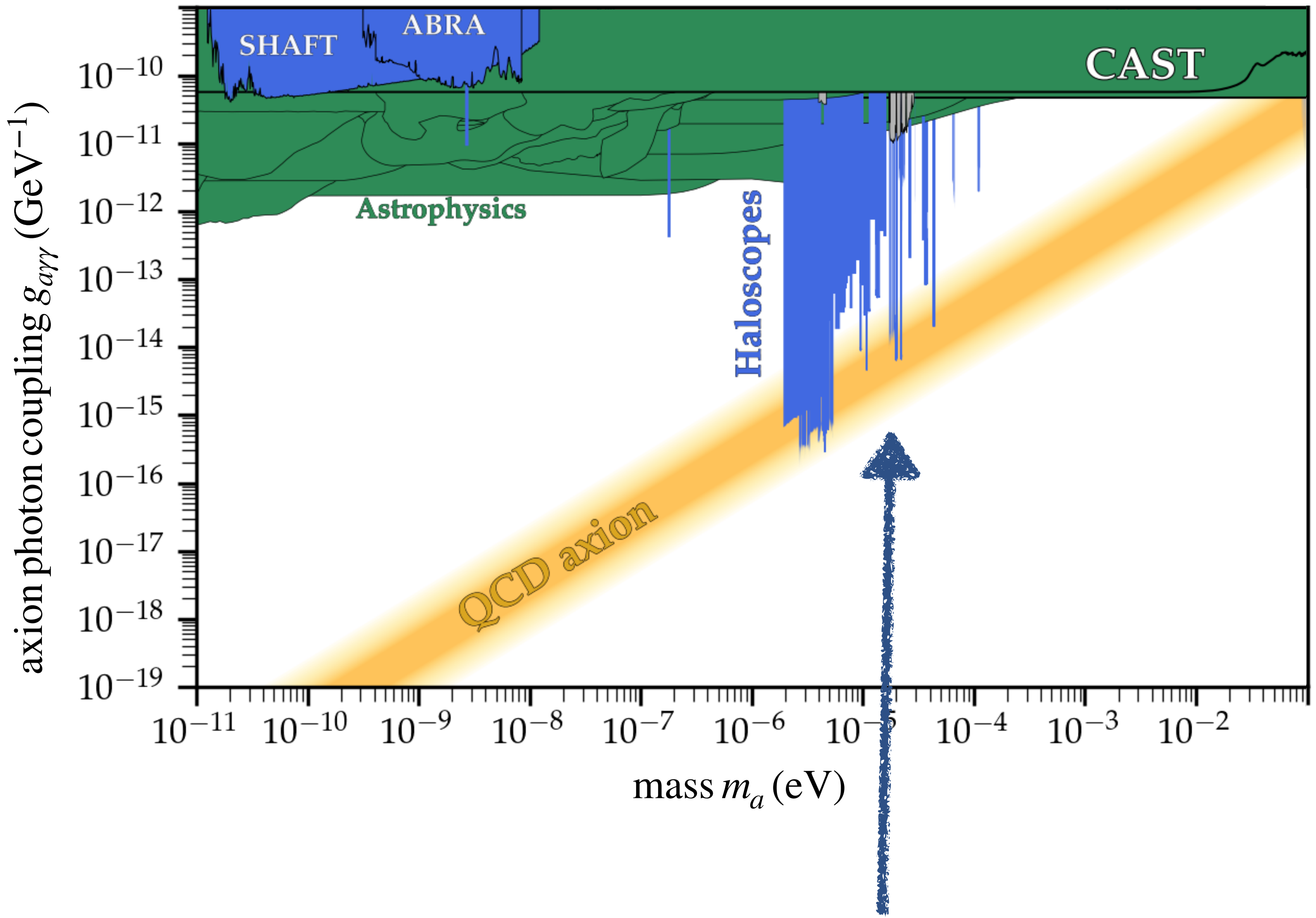


Axion experiments are “small scale” science

Achieving leading sensitivity costs more than an average graduate student, but fits within the scale of a university lab

Decisive next-generation axion experiments would still be a very small fraction of particle physics budget, and would complement other efforts

Axion Mass Benchmarks



"central" mass, $f \sim \mathrm{GHz}$

motivation: standard misalignment production of QCD axion

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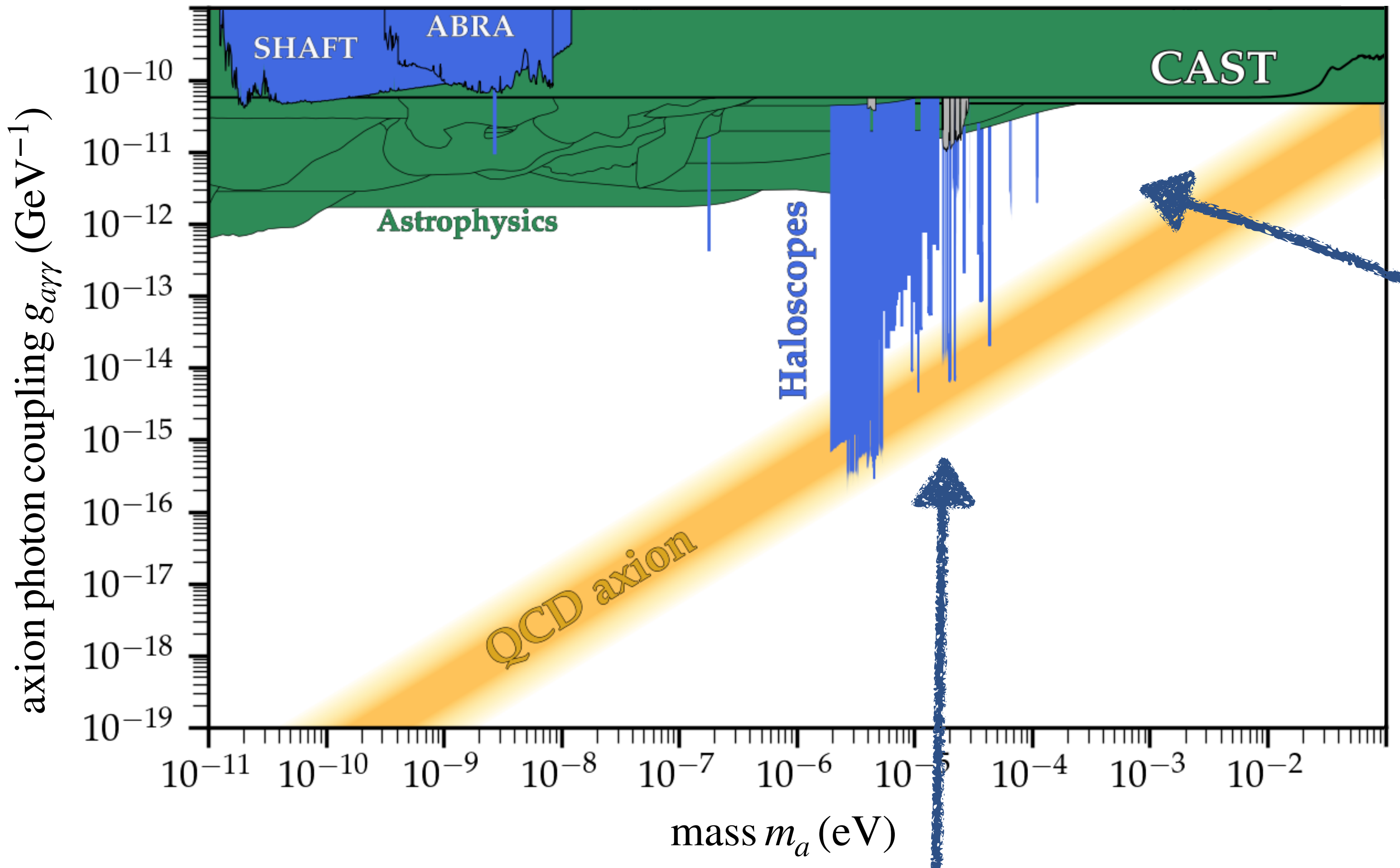

“high” mass

motivation: post-inflation production of QCD axion

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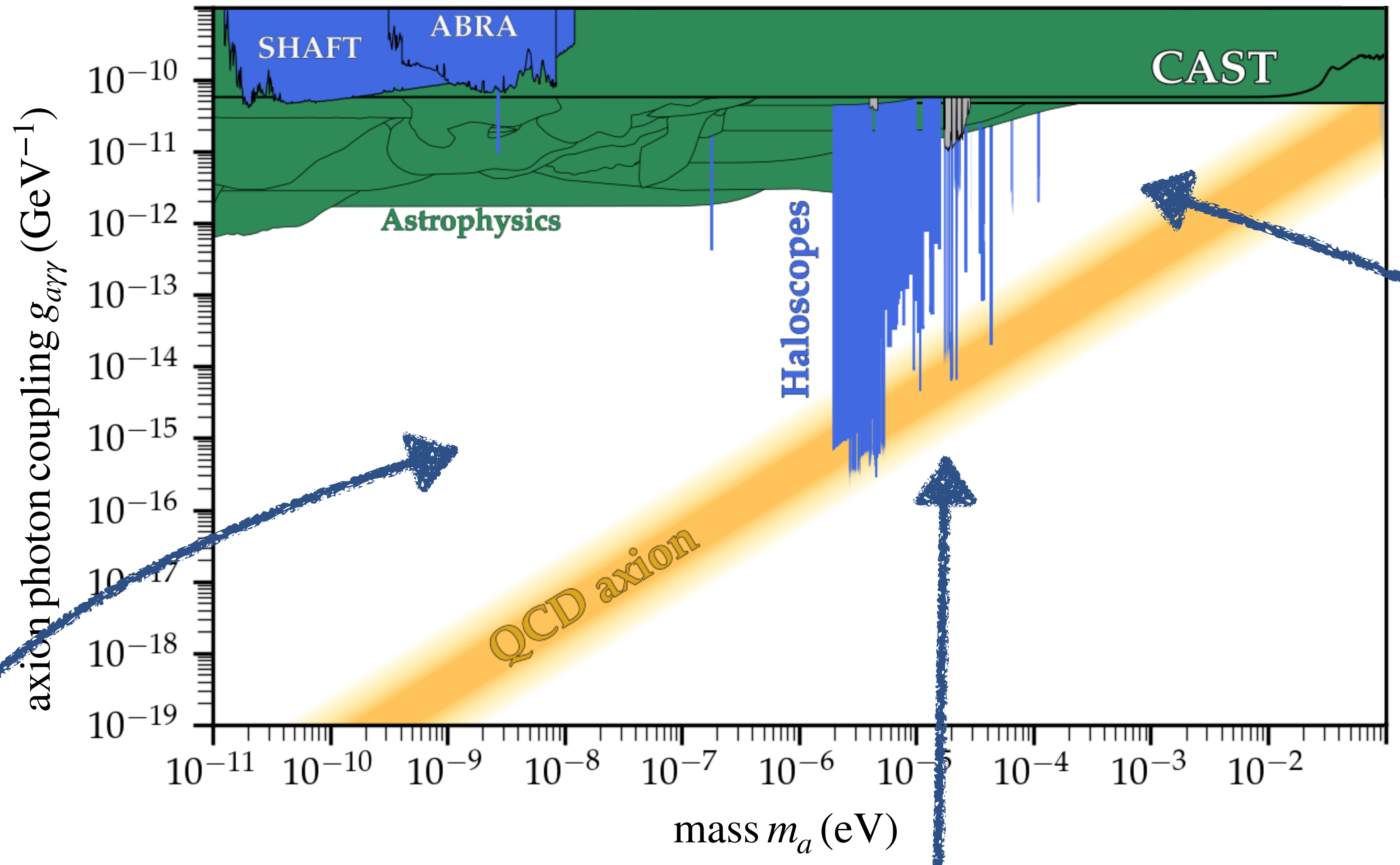


"high" mass

motivation: post-inflation production of QCD axion

"low" mass

motivation: axions from grand unification/string theory

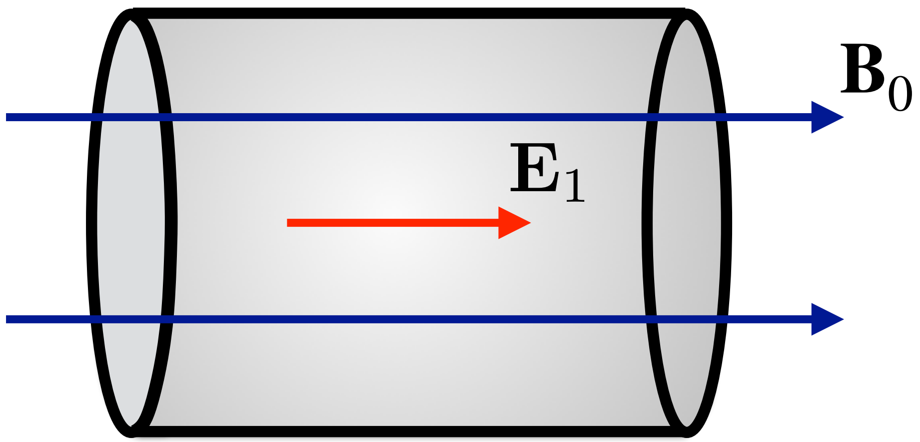
or standard misalignment production of non-QCD axion

"central" mass, $f \sim$ GHz

motivation: standard misalignment production of QCD axion

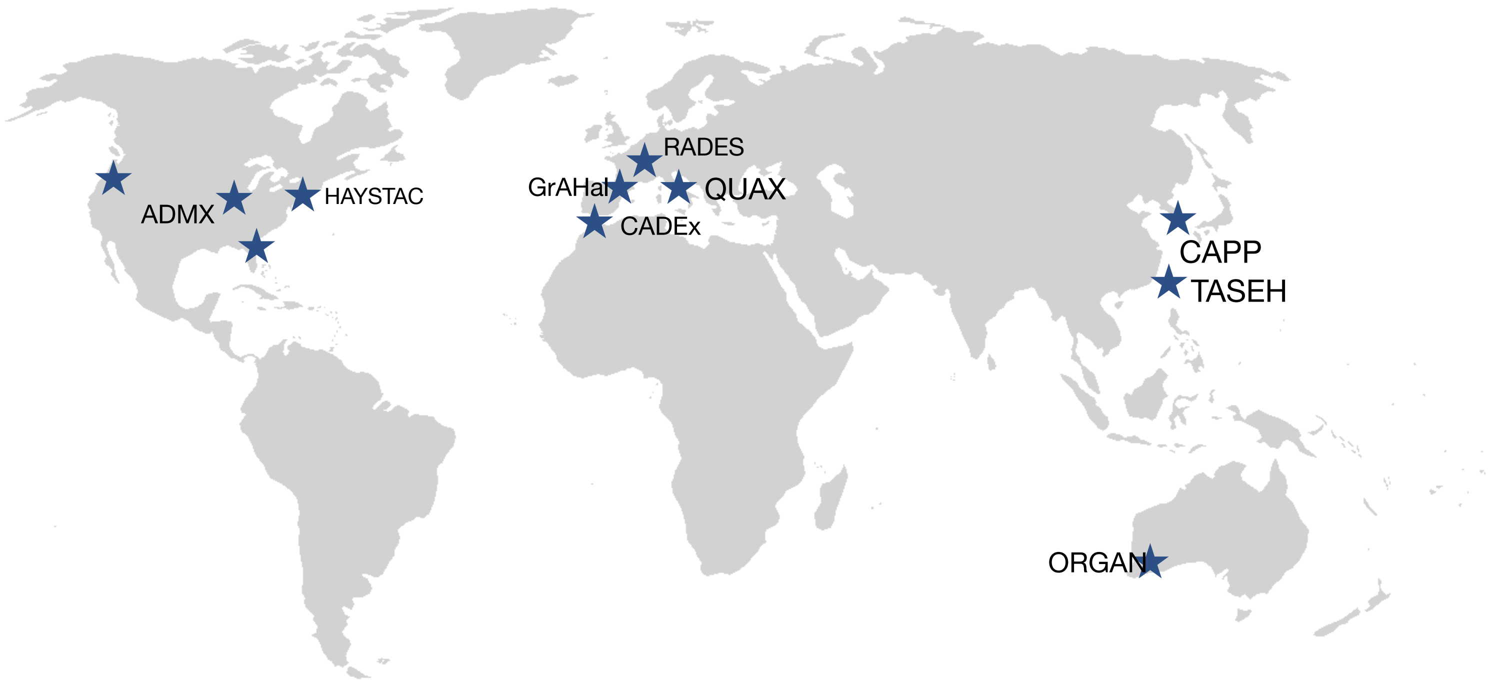
"Central" Mass: The Cavity Haloscope

In background $\mathbf{B}_0$, axion drives cavity mode with profile $\mathbf{E}_1$ by $g_{a\gamma\gamma}\,\dot{a}\int_V \mathbf{B}_0\cdot\mathbf{E}_1$



use large static $\mathbf{B}_0$, resonantly excite mode

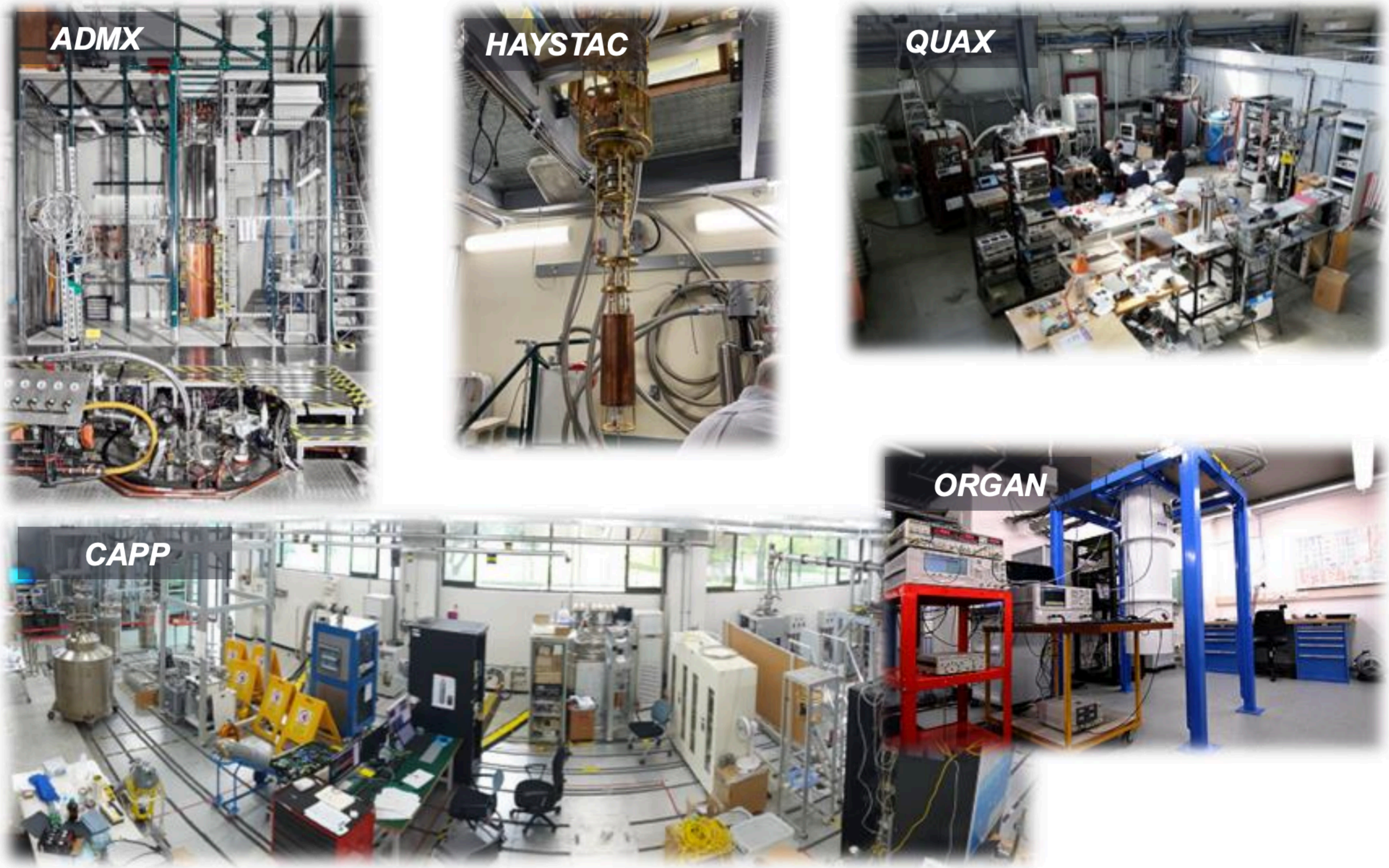
$$P_{\rm sig} \sim (g_{a\gamma\gamma}^2 \rho_{\rm DM})\,(B_0^2 V)\,(Q/m_a)$$

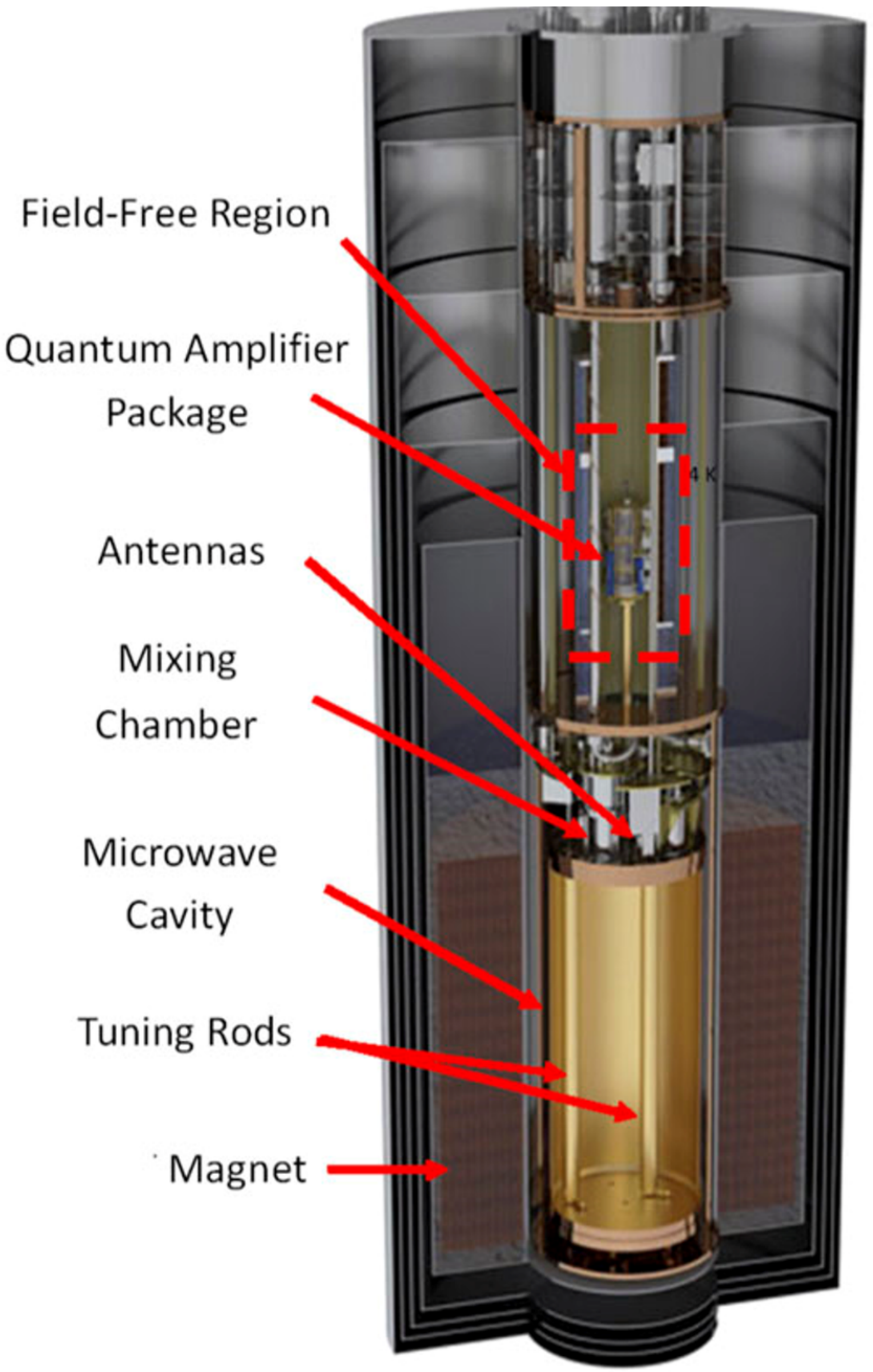


currently, ~10 active collaborations, with ADMX and CAPP leading

proven concept, ~1/3 of relevant parameter space currently probed

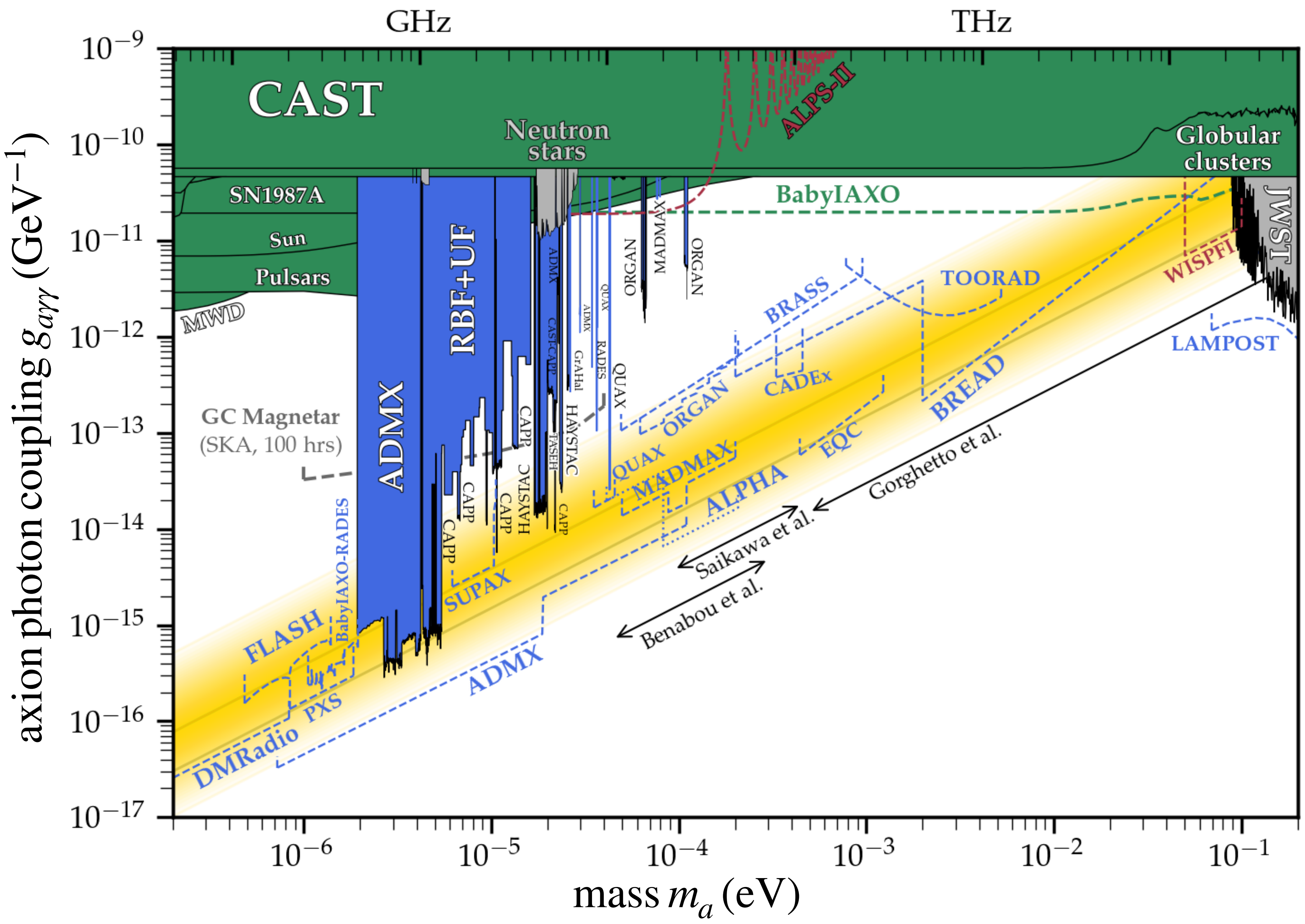
Cavity Haloscopes in the Lab





(slide by Sungwoo Youn, present director of CAPP)

Extending to "High" Mass



Many proposals and prototypes under development, and two common themes…

Maintaining Sensitivity at "High" Mass

$$P_{\text{sig}} \sim (g_{a\gamma\gamma}^2 \rho_{\text{DM}})\,(B_0^2 V)\,(Q/m_a) \qquad V \propto 1/m_a^3 \qquad S_{\text{SQL}} \sim \hbar m_a$$

As axion frequency increases, signal power decreases but SQL noise increases

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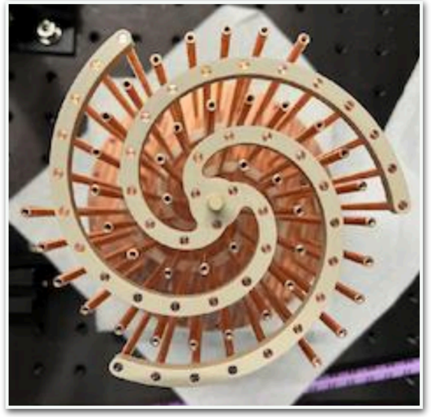
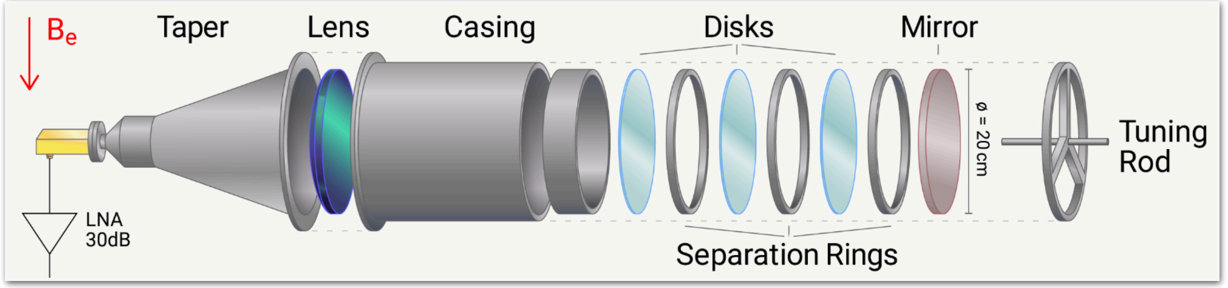
exotic design to maintain large volume







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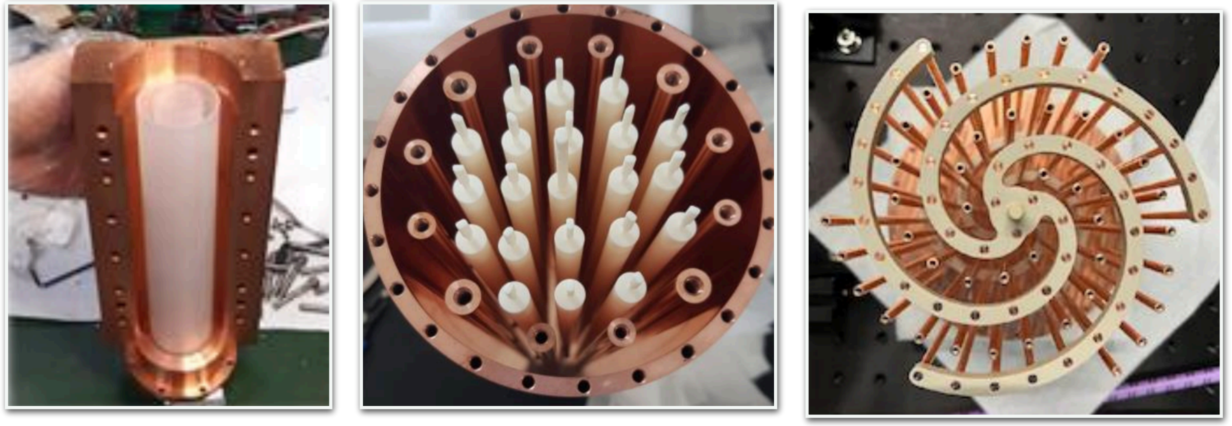
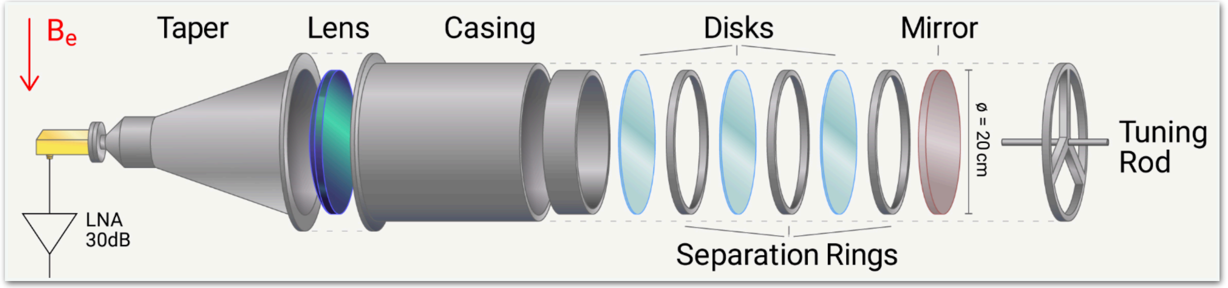
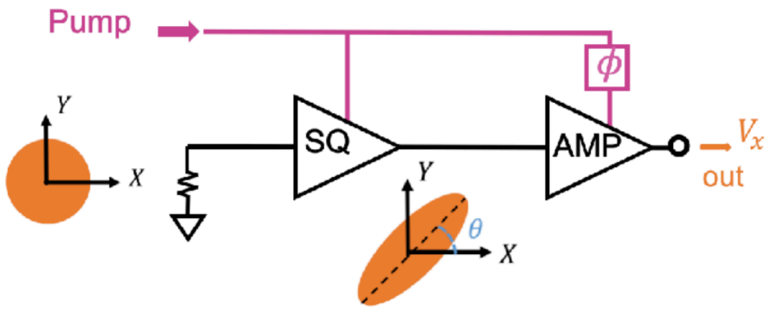
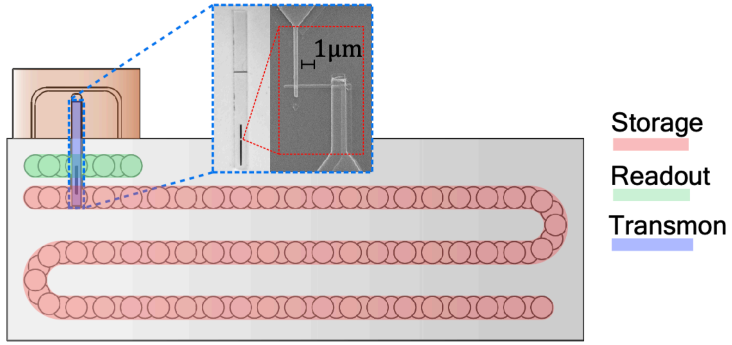




quantum measurement to evade SQL



squeezed vacuum



meV single photon detection

Naturally suited for many small-scale efforts, and “quantum” science initiatives

The Challenge of “Low” Mass

Difficult for a cavity haloscope to have resonant frequency $m_a \ll \mathrm{GHz}$

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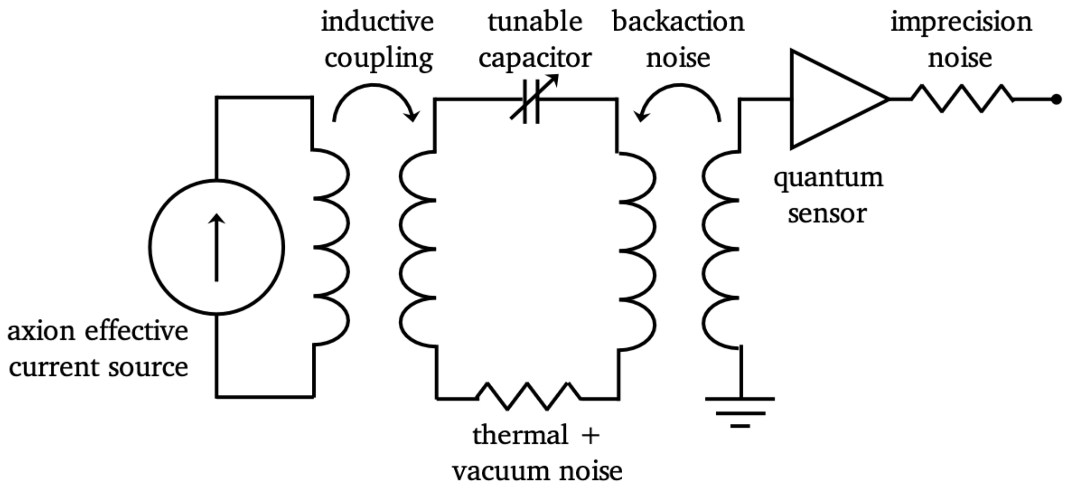

LC circuit approach

use an LC circuit, with low resonant frequency

electric field suppressed, $\mathbf{E}_1 \sim m_a L \, \mathbf{B}_1$

leads to suppressed signal power, $P \propto (m_a L)^2$

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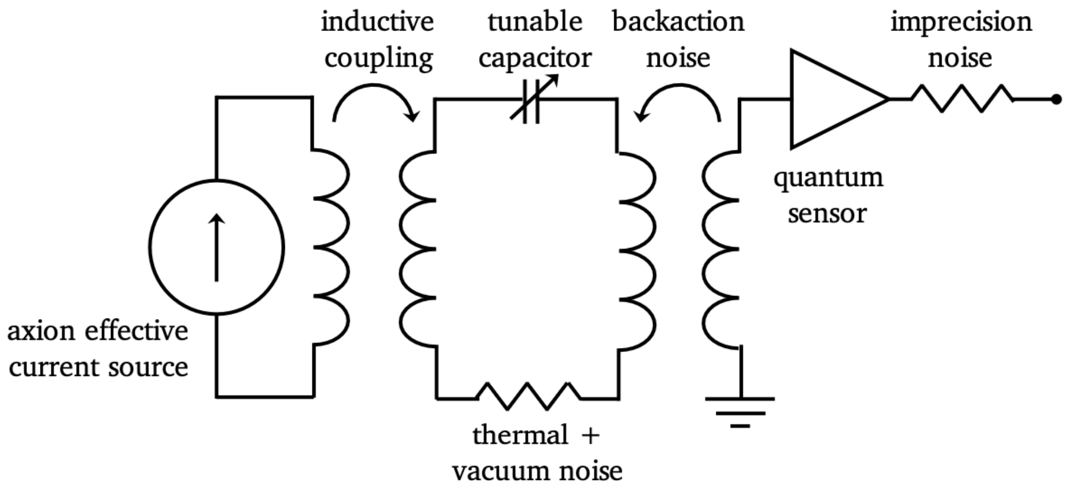

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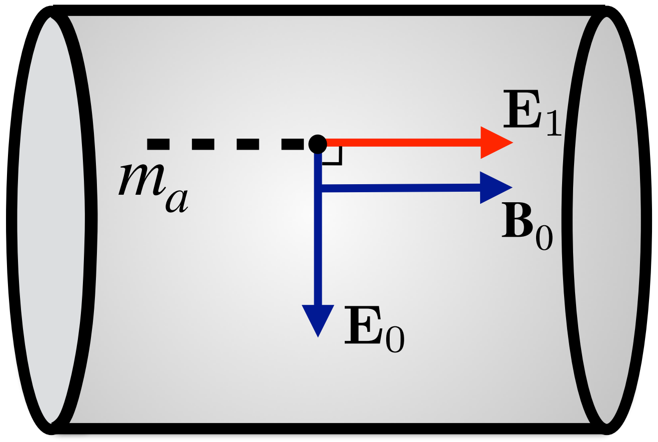


heterodyne approach

drive cavity mode, $\mathbf{B}_0 \sim 0.2\,\mathrm{T}$ oscillates at $\omega_0 \sim \mathrm{GHz}$

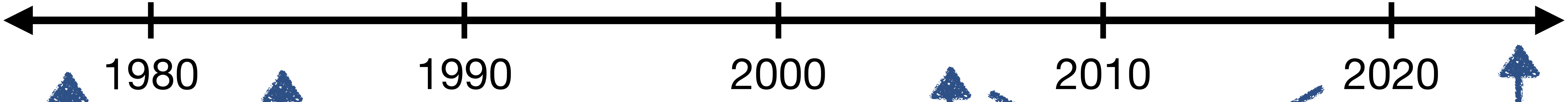
use superconducting cavity to maintain large field

excites signal mode at $\omega_1 = \omega_0 \pm m_a$

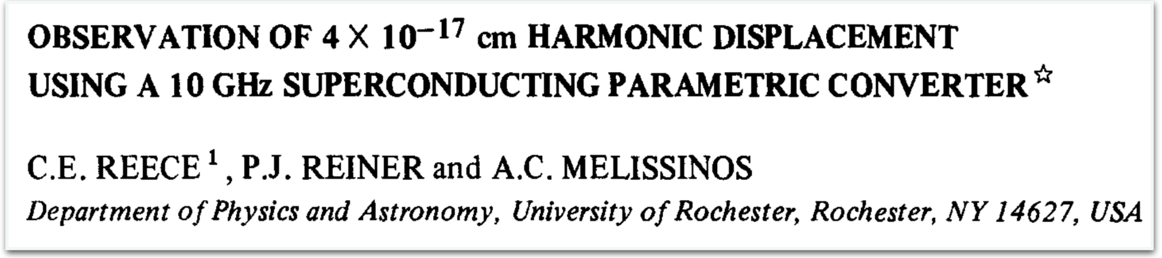
scanning small difference probes $m_a \ll \mathrm{GHz}$

Berlin, D'Agnolo, …, KZ, JHEP (2020)
Berlin, D'Agnolo, Ellis, KZ, PRD (2021)

History of the Heterodyne Approach



prototyped

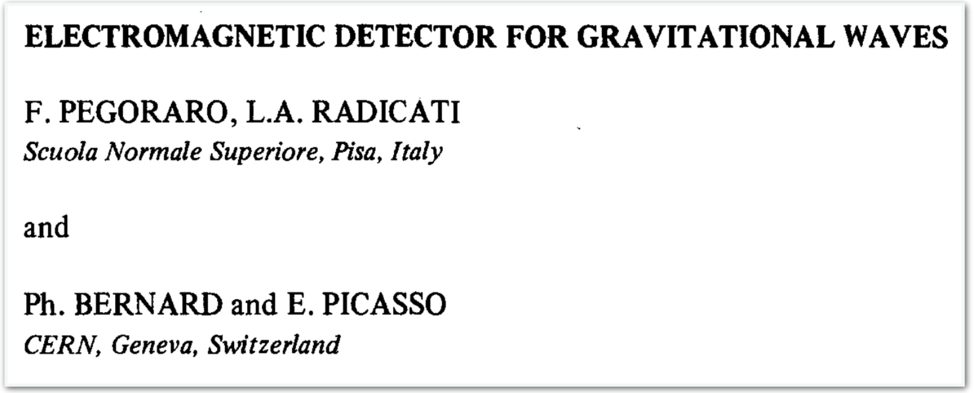

OBSERVATION OF 4×10^{-17} cm HARMONIC DISPLACEMENT USING A 10 GHz SUPERCONDUCTING PARAMETRIC CONVERTER ☆

C.E. REECE [1], P.J. REINER and A.C. MELISSINOS
Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA

SRF cavities keep improving, $Q \gtrsim 10^{11}$

our work

suggested for gravitational waves


ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy

and

Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

MAGO experiment

~5 groups developing prototypes

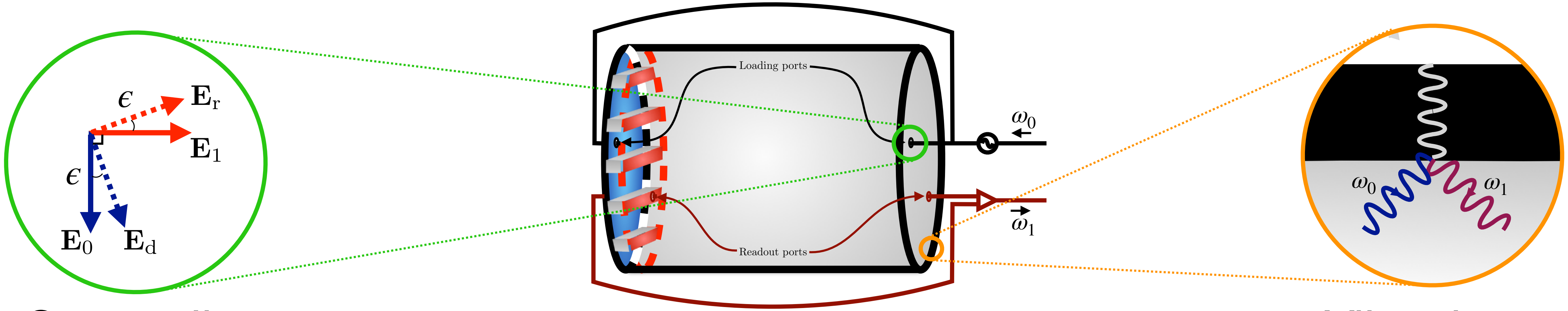
Leakage Noise

Key technical issue: input power can "leak" to signal

Suppressed by geometric factors, and frequency separation of modes

$$S_{\text{leak}}(m_a) \propto P_{\text{in}} \times \begin{cases} \epsilon^2 S_\varphi(m_a) & \text{oscillator phase noise} \\ \epsilon^2 S_\delta(m_a) & \text{mode frequency jitter} \\ \eta^2 S_\delta(m_a) & \text{mechanical mode mixing} \end{cases}$$

Dominates at kHz, but subdominant at MHz if $\epsilon, \eta \ll 1$, requiring good cavity design



Crosstalk

Vibrations

1912.11048, 1912.11056, 2007.15656

Global Status of the Heterodyne Approach

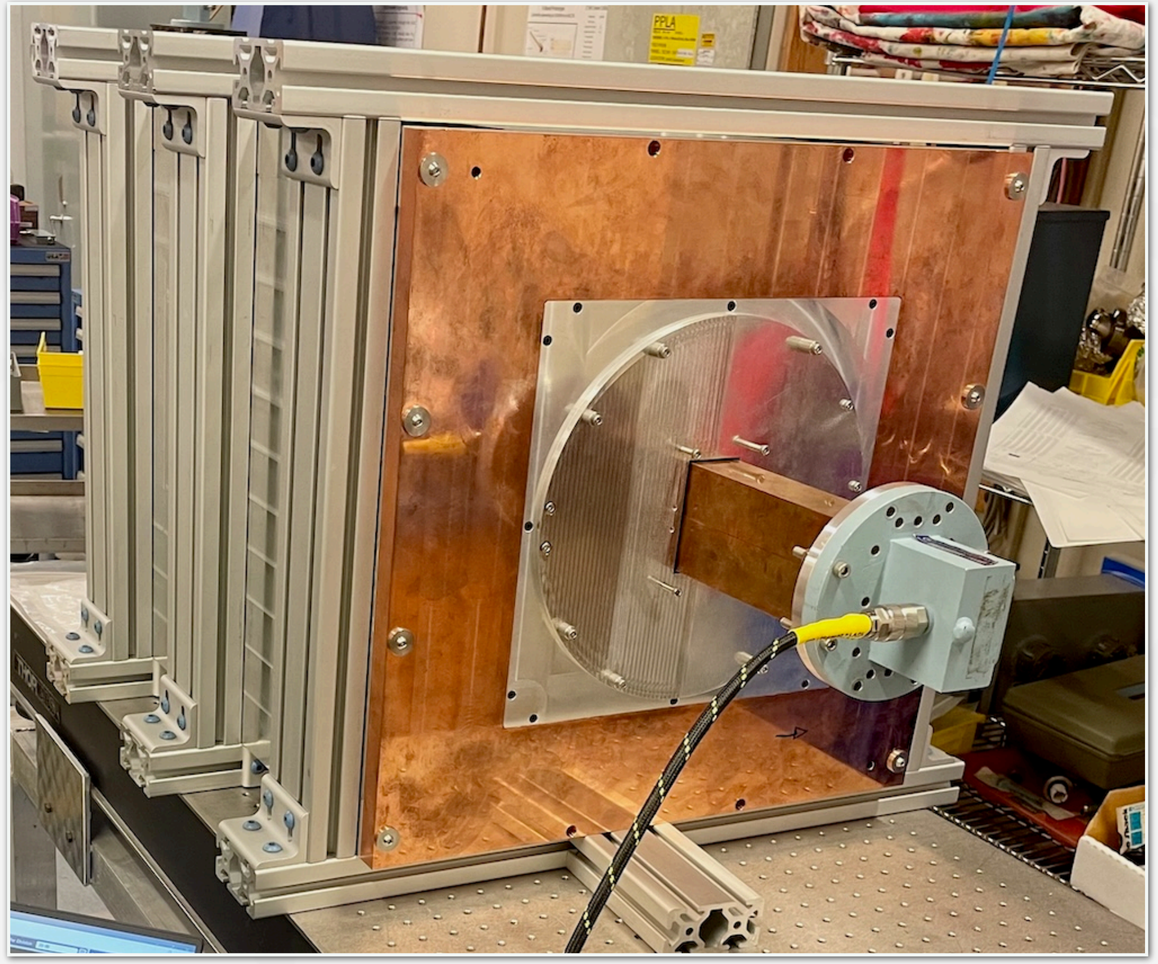
Several groups, at labs with expertise in superconducting cavities, are currently designing prototypes and taking measurements

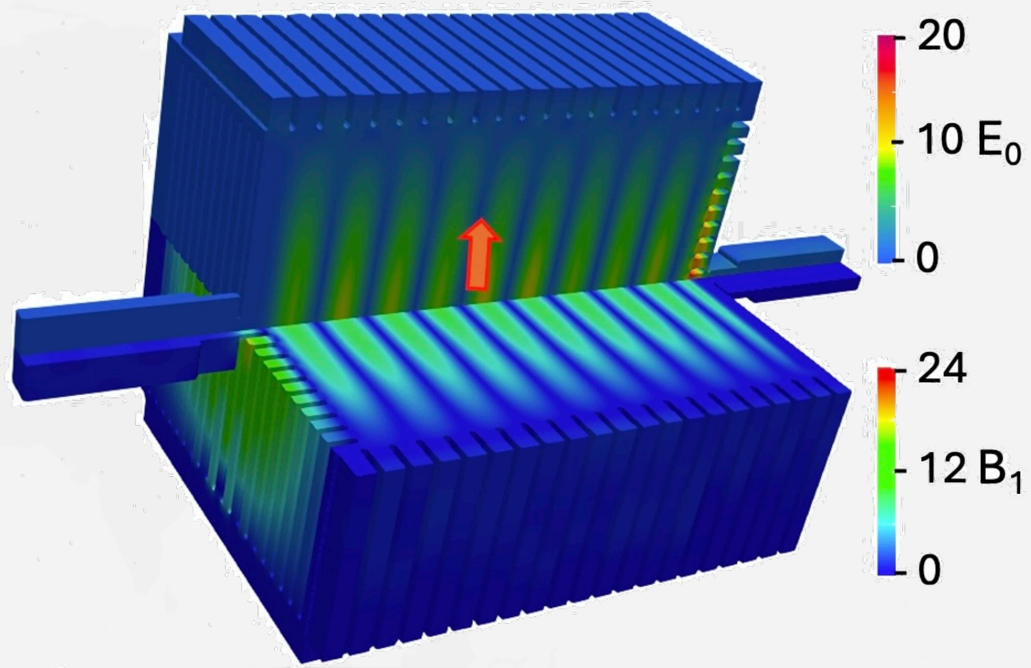
Current level of funding is sufficient to demonstrate proof of principle and probe far beyond astrophysical bounds

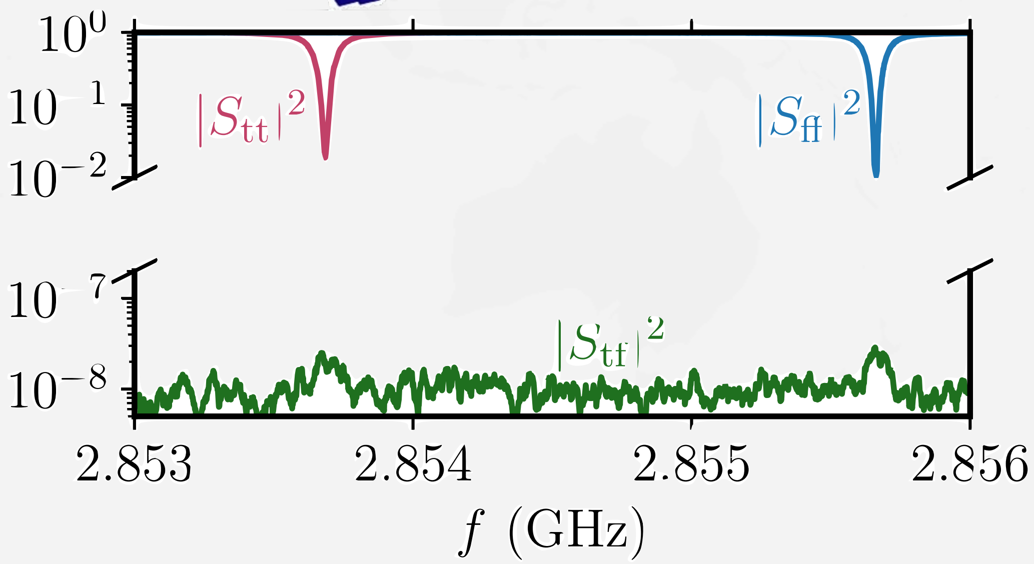
Scaling to QCD axion sensitivity requires qualitative increase in funding

SLAC

LDRD effort at SLAC (since 2022)



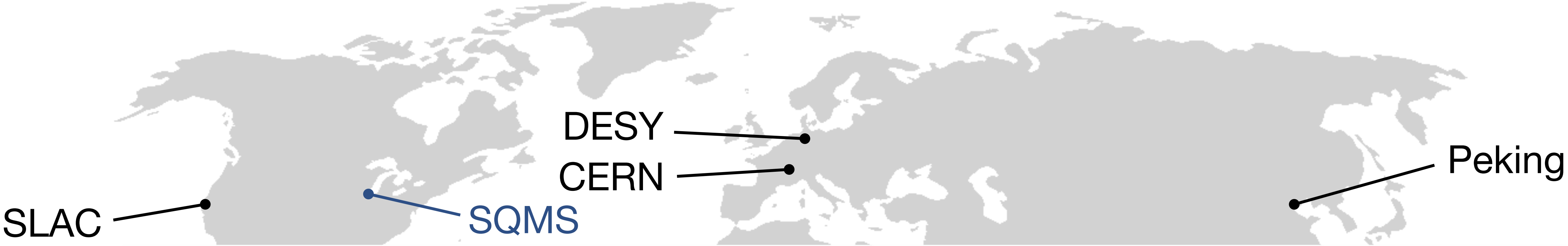




corrugated cavity has hybrid modes with $\mathbf{B}_0$ aligned to $\mathbf{E}_1$

tunable by $\Delta f = 4\,\mathrm{MHz}$, mode profiles enable $\eta \ll 1$ and $\epsilon \lesssim 10^{-4}$

2507.07173 (Li, KZ, Oriunno, et al.)



SHADE collaboration at SQMS (since 2021)

2022: measurement of existing 9-cell cavity at $T = 2\,\mathrm{K}$, no exotic noise observed

2024: new cavities with small η instrumented

2025: cold measurement, tuning test

2207.11346

QUANTUM TECHNOLOGY INITIATIVE

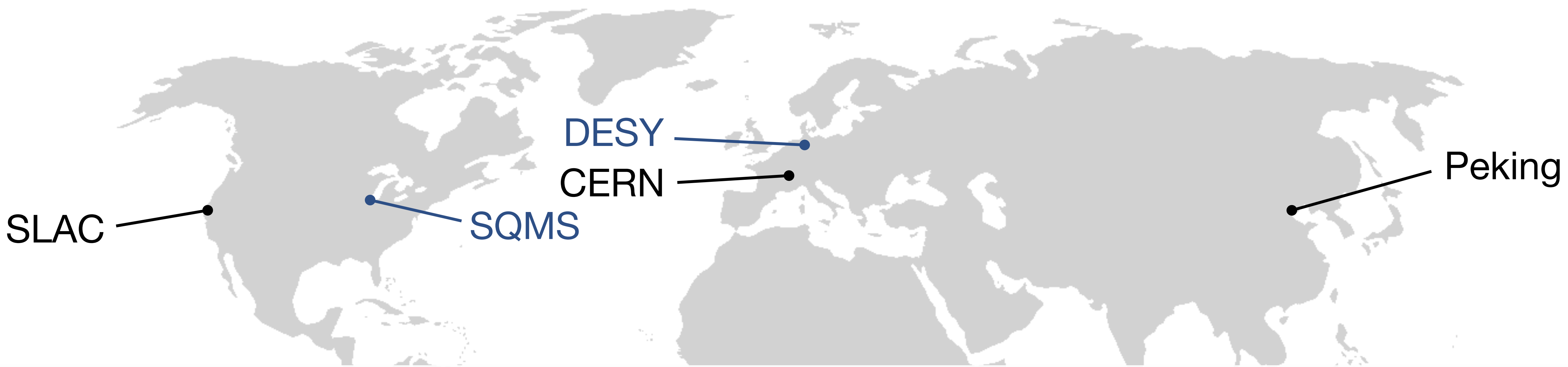
New effort at CERN (since 2025)

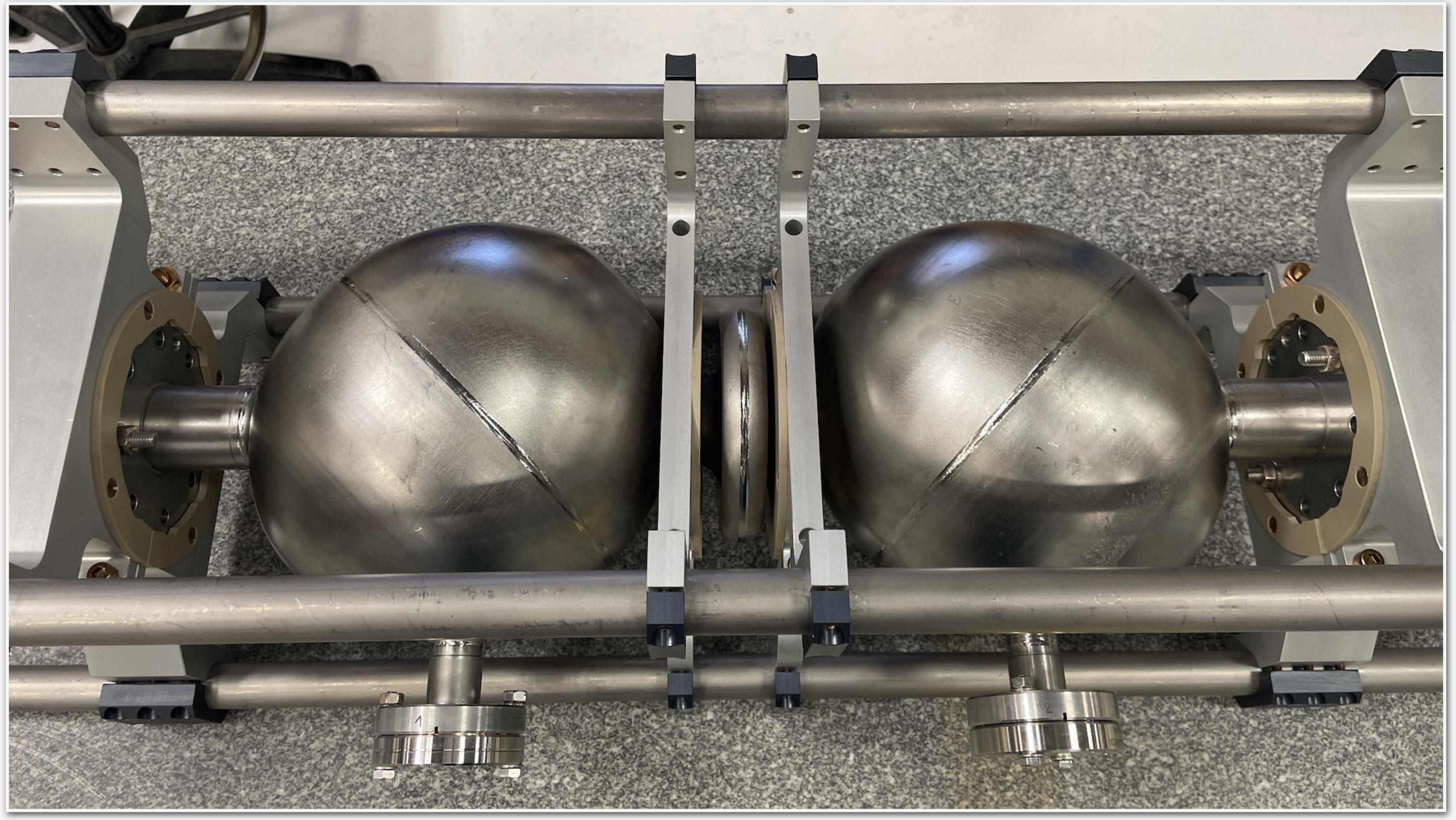
Funded by QTI in affiliation with PBC

Aims to develop and run superconducting prototype in next 2-3 years

cryogenic non-mechanical tuning, cavity designs to reduce ϵ and η

2505.00947





Revival of MAGO (since 2023)

Joint effort of DESY and SQMS

Cavity tuned, electromagnetic and mechanical modes simulated

Optimized for gravitational waves, but shares noise sources

SHANHE collaboration at Peking (since 2022)

2023: dark photon search, no driving

early 2025: calibration run at $T = 4\,\mathrm{K}$, only thermal noise seen

mid 2025: data taking run ongoing

2026: planned run with new cavity designed to reduce ϵ and η

Peking

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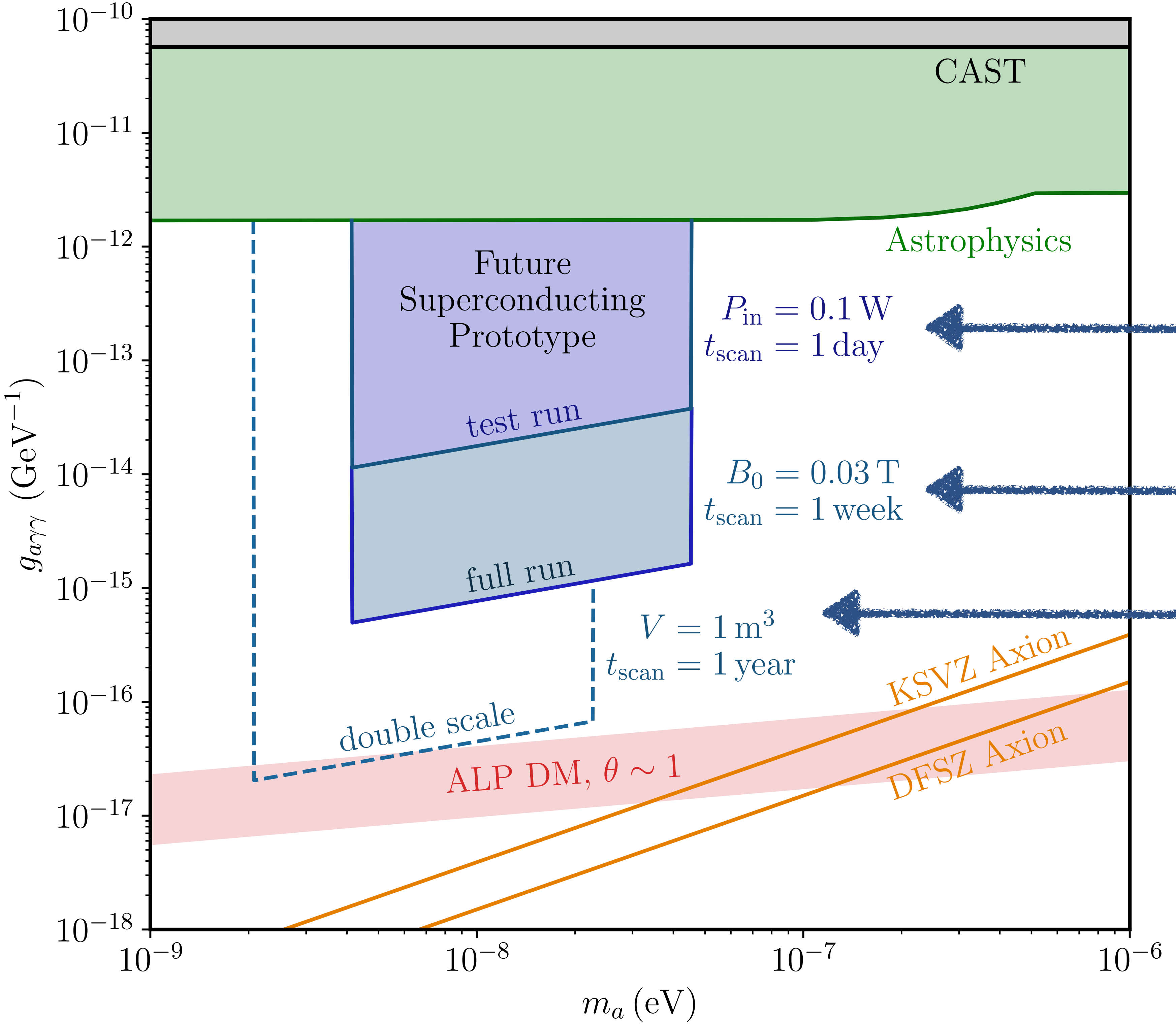
Future Projections for SLAC Design



Superconducting cavity with same geometry as prototype, same surface treatment as LCLS-II

driven by microwave oscillator

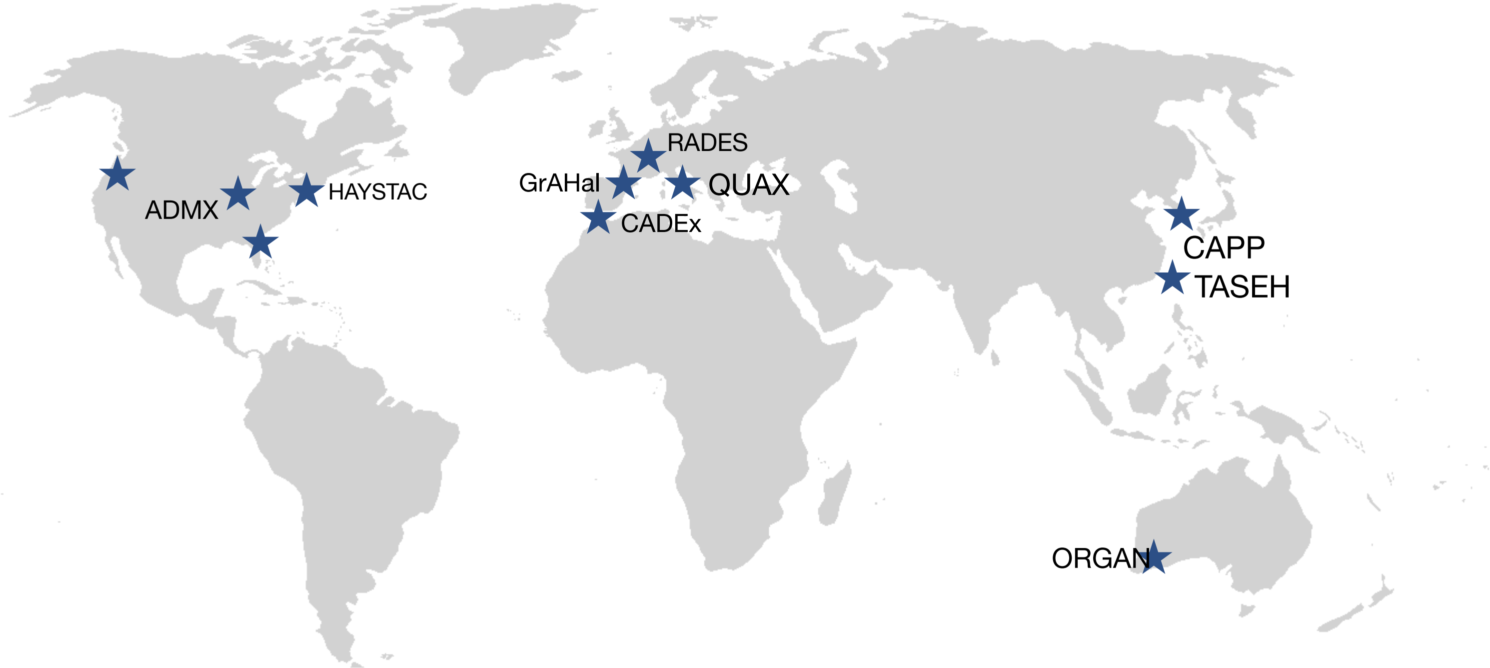
driven like standard SRF cavity

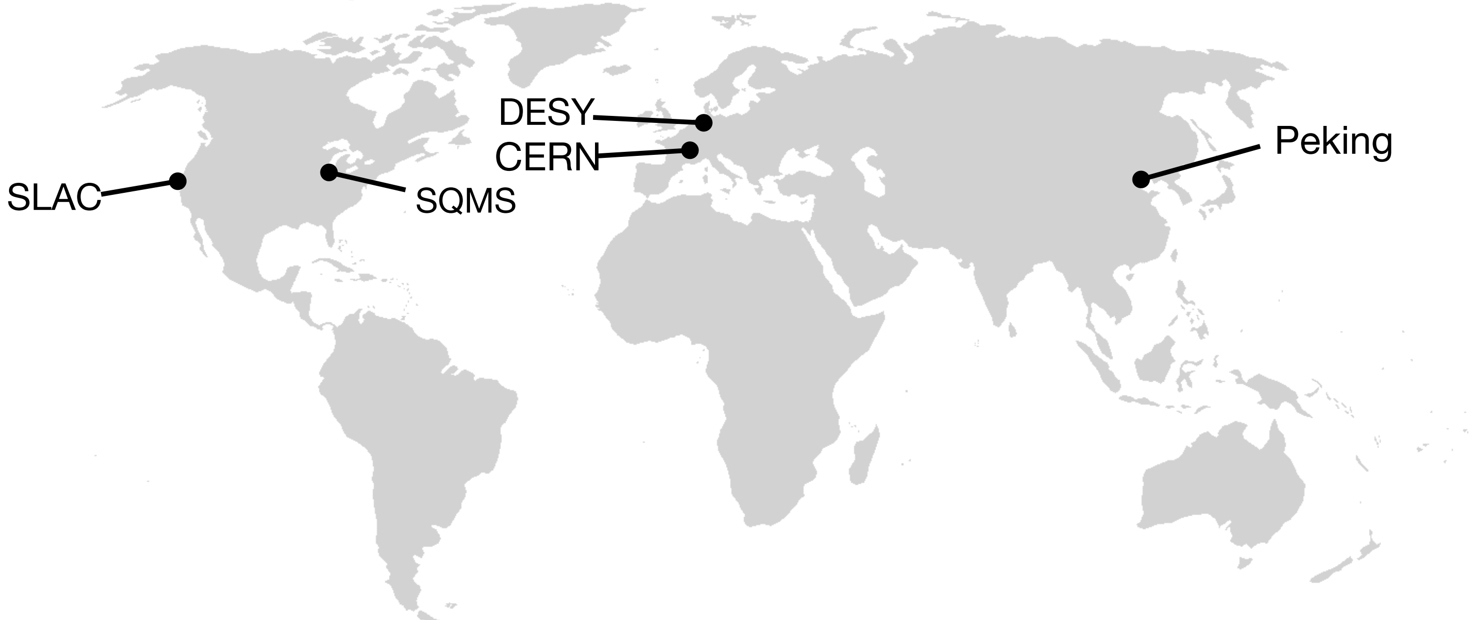
just double all dimensions

Reaching QCD axion requires combination of higher B_0 and volume, better surface treatment

Outlook

The axion is a well-motivated dark matter candidate, can be decisively probed in near-future experiments





Superconducting cavities are well-developed technology, can yield strong sensitivity to lighter axions

Multiple ongoing efforts will demonstrate feasibility in next ~2 years