CF2: Wave-like Dark Matter

Snowmass Meeting July 2022 - Frontier Report

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Wave-like Dark Matter Candidates

Wave-like Definition: Mass < 1 eV

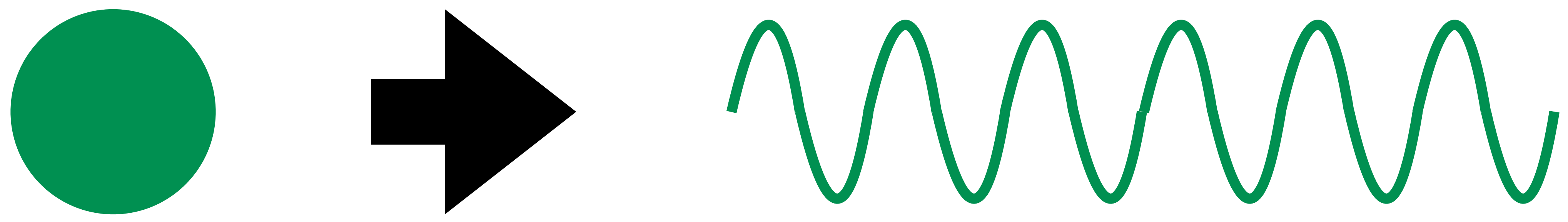
Broad Candidate Categories:
- Pseudo-scalar
- Scalar
- Vector

Production: Athermal production (misalignment).

Detection: Coherent interaction of the wave with the detector. Resonant amplification often key.

The most famous candidate in this group is the QCD axion.

Why Wave-like Dark Matter (WLDM)?



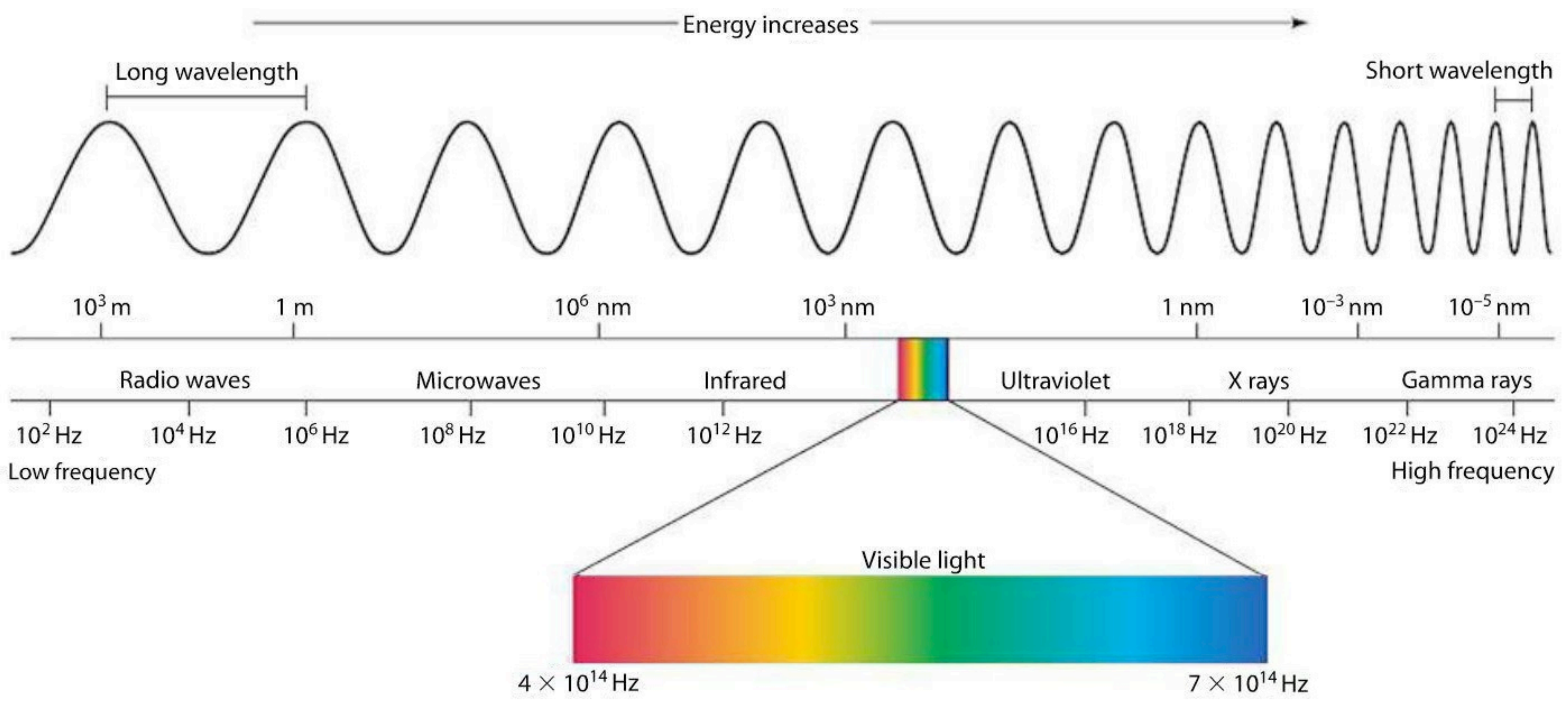
At Masses less than 1 eV, particles cross the wave-particle divide and start behaving as waves.

Detection techniques are inherently quantum!

Detection techniques change as a function of frequency!

Looking for a suite of experiments.

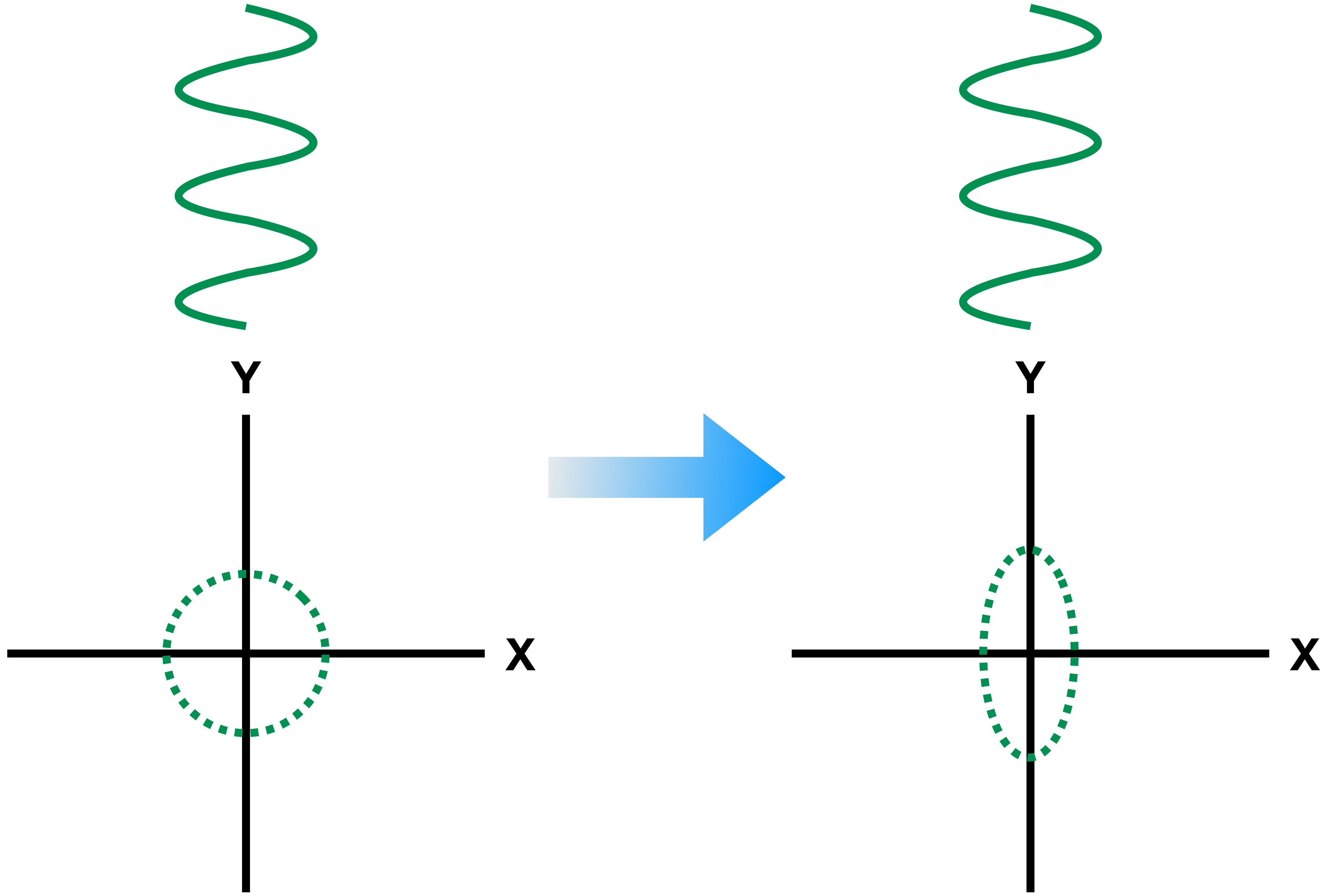
A Suite of Experiments:
Intuition from Electromagnetic Spectrum



The techniques will change as you increase frequency.

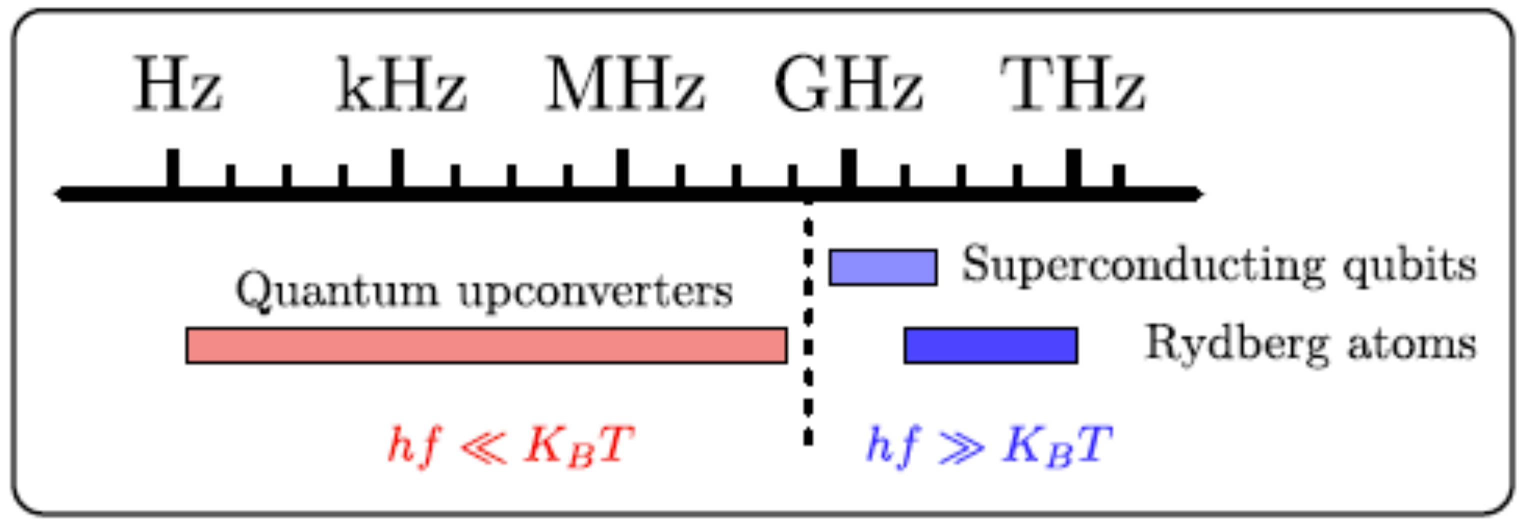
The same is true for WLDM!

Key Technology: Beyond the Standard Quantum Limit



Beat the Quantum Limit by Pushing Noise into Different Observable

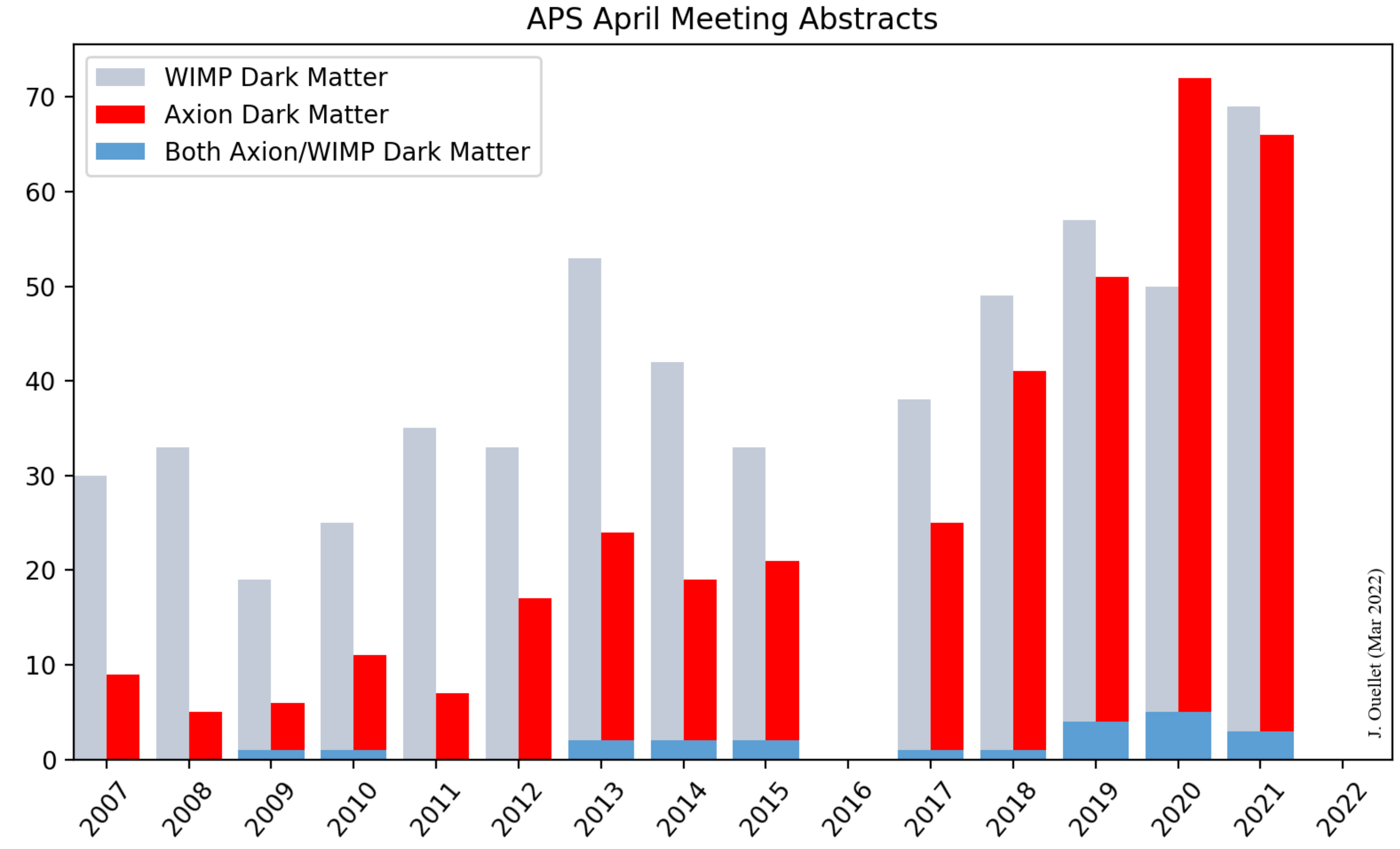
K. Irwin



Different noise sources
Different frequency ranges
Different Techniques

Why Now? - Growing Community

With advancements in cryogenics, magnet and quantum sensing coupled with better theoretical understanding of the cosmology of wave-like dark matter, the community has grown quickly.



J. Ouellet

Community Goals

Snowmass 2021

Definitive Search for the QCD Axion

The QCD axion is the theoretically most-studied and strongest motivated WLDM candidate. Decades of experimental work along with advances in quantum measurement technologies has put us in the unique position: this decade we can build experiments that are sensitive to the most plausible theoretical predictions of QCD axion couplings at nominal dark matter densities. The community intends moving from building technology demonstrators to building machines designed for a discovery.

Pursue a Theory and R&D program to elucidate the opportunities beyond the QCD axion

We are in the process of understanding how WLDM dark matter candidates beyond the QCD axion can work. There are already experimental techniques that promise to reach previously-unexplored parameters for scalars and vectors. This snowmass period we would like to see these experimental techniques refined, and theoretical studies of new WLDM candidates to inform the direction of developing experiments and help them target the most interesting physics.

Community Roadmap

Snowmass 2021

Pursue the QCD Axion by Executing the Current Projects

The ADMX G2 effort continues to scan exciting axion dark matter parameter space and the experiments DMRadio-m3 and ADMX-EFR are prepared to start executing their project plans.

Pursue WLDM with a Collection of Small-Scale Experiments

The search for WLDM requires a variety of techniques. The community would benefit from a concerted effort to foster small scale projects. The DOE DMNI process has worked very well for this. In addition, we should pursue opportunities to harness key US expertise for International projects.

Support Enabling Technologies and Cross Disciplinary Collaborations

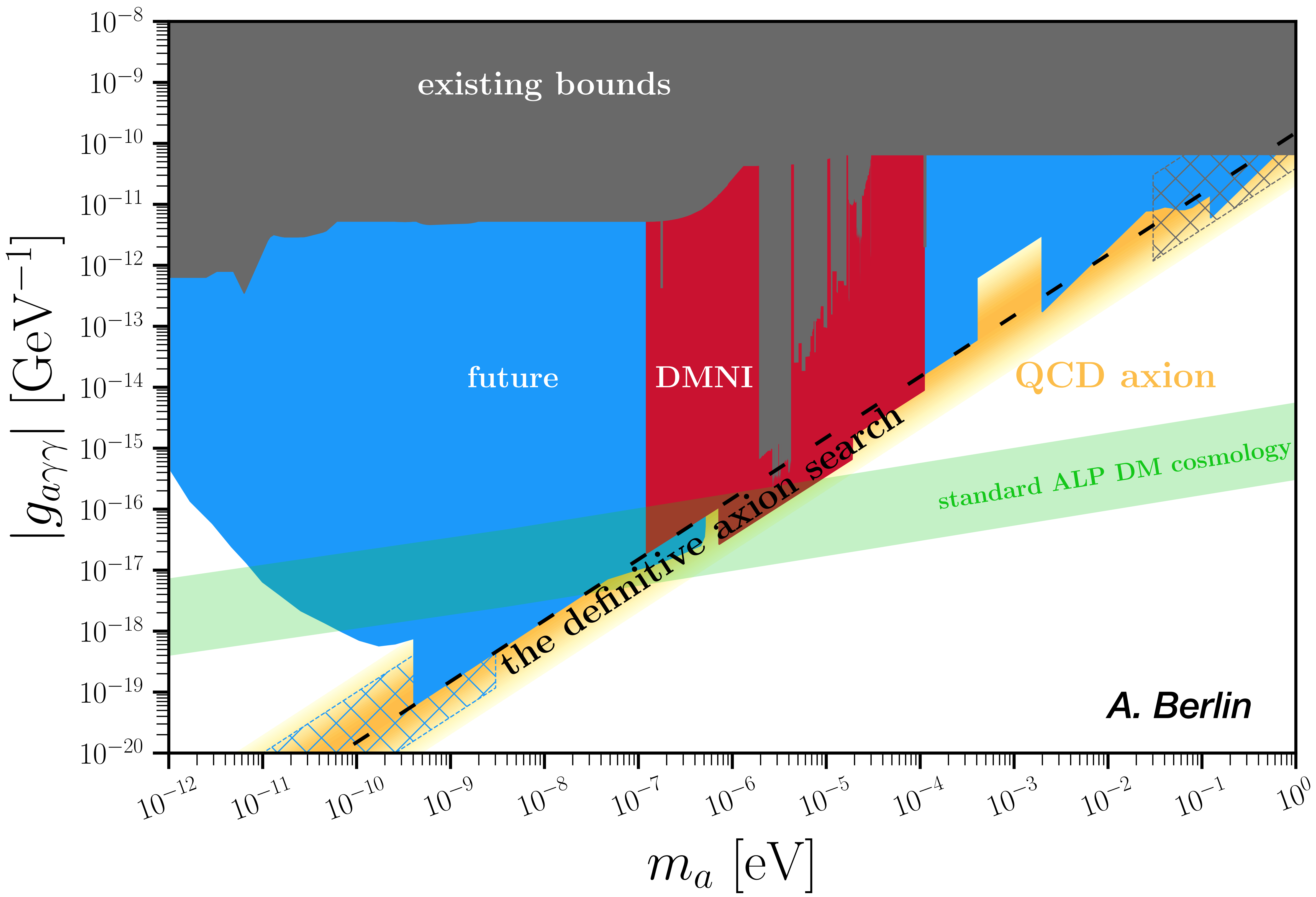
Common needs include ultra-sensitive quantum measurement and quantum control, large high-field magnets, spin ensembles, and sophisticated resonant systems. Strong synergies with other HEP needs.

Support Theory Beyond the QCD Axion

The QCD axion is an important benchmark model, but not the only motivated one. Theoretical effort should be supported to understand the role of scalars, vectors and ALPs in dark matter cosmology and astrophysics and to explore new detection modalities.

Goal: Definitive QCD Axion Search

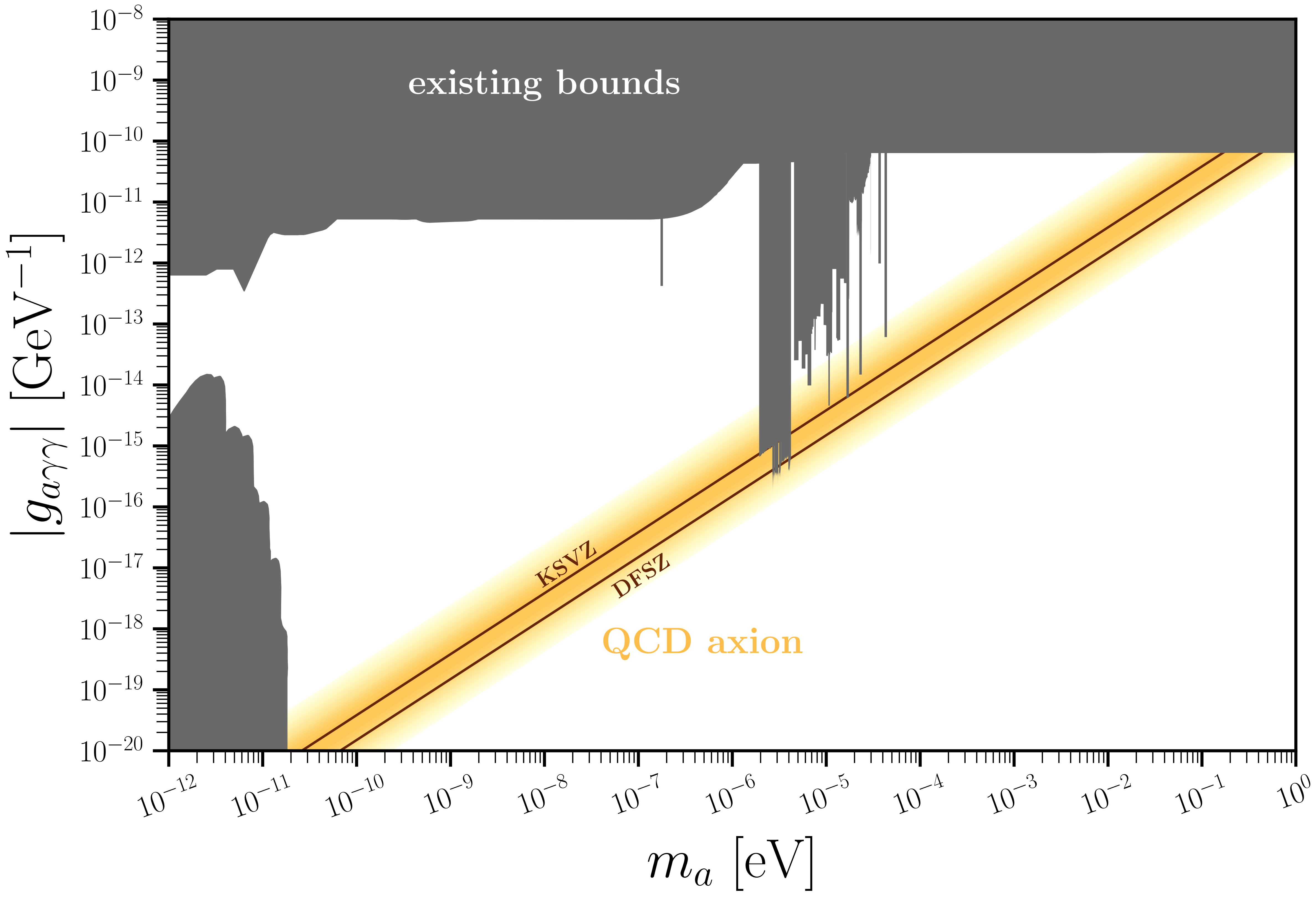
With a suite of experiments discover the QCD axion in the mass range of 10^{-12} eV to 1 eV.



The QCD Axion

- $U(1)_{PQ}$ introduced to preserve CP symmetry in the Strong Interaction.
- The QCD axion is a psuedo-Nambu-Goldstone boson produced by the breaking of $U(1)_{PQ}$.
- Couples to **photons**, nucleons, electrons.
- Broad Categories of models:
    - **KSVZ** introduces heavy quarks.
    - **DFSZ** introduces additional Higgs fields.*

A. Berlin and others

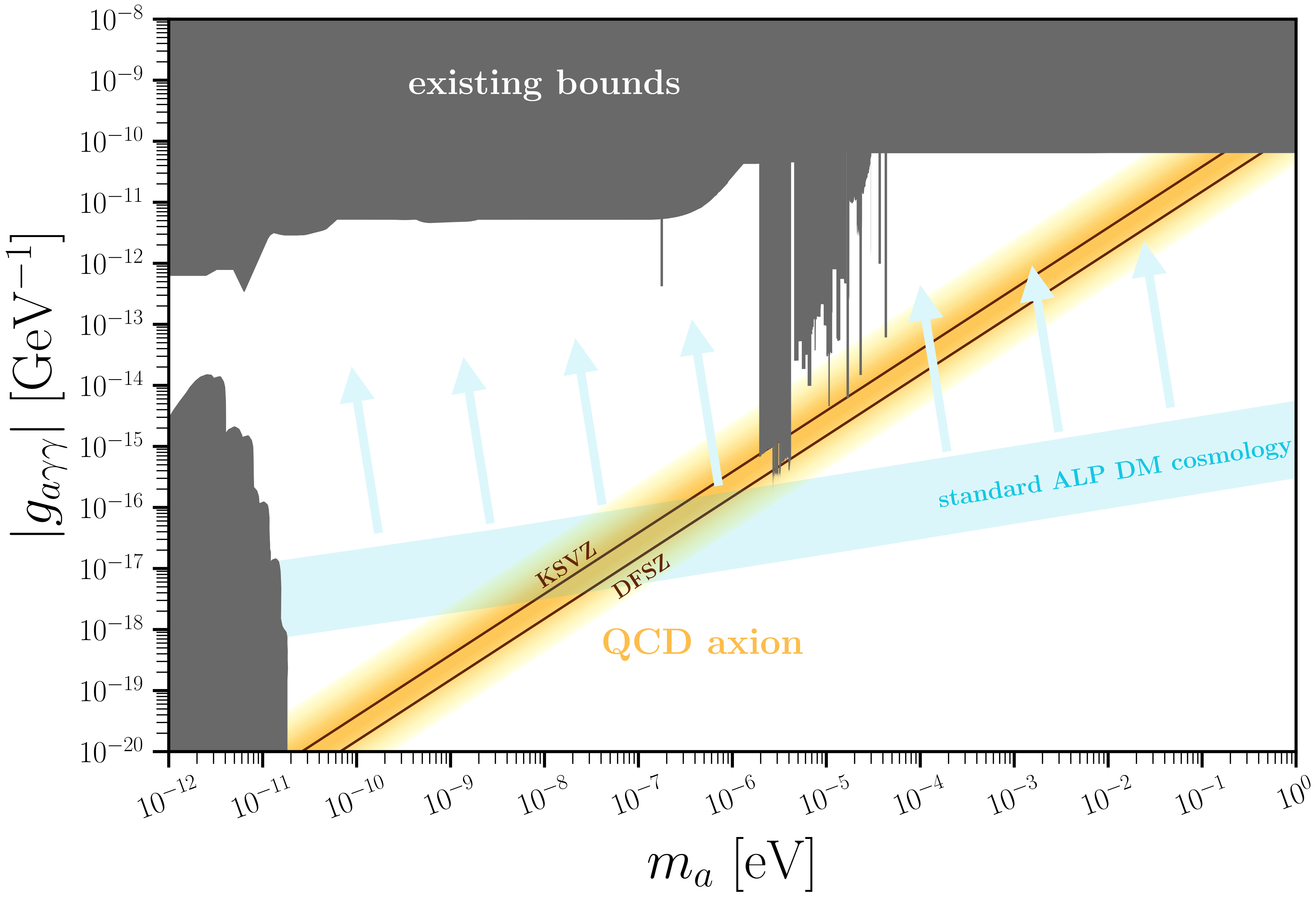


** DFSZ is the benchmark for the field.*

Axion-Like Particles (ALPs)

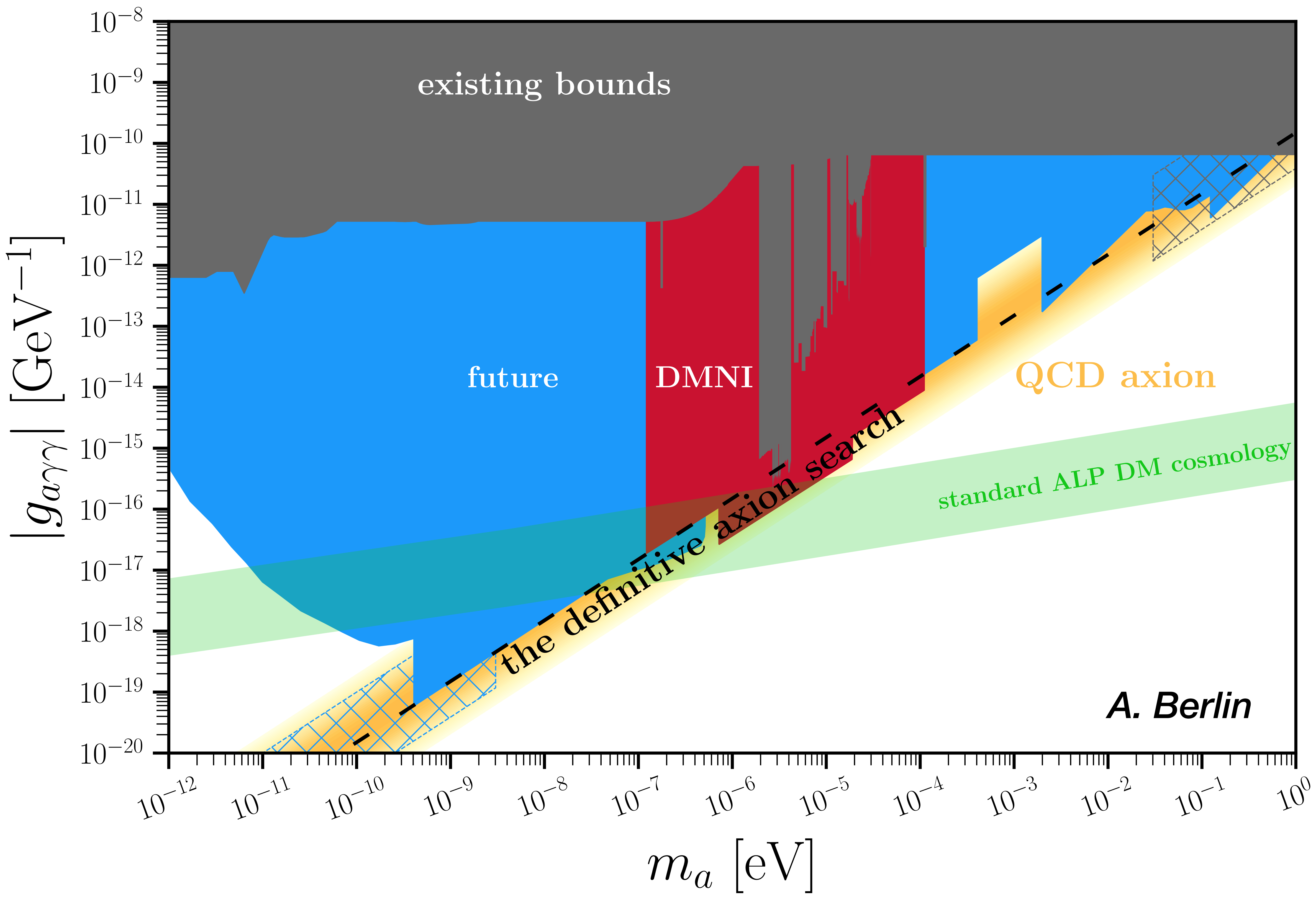
- Similar particles produced in many higher order theories.
- Depending on the details of the theory and the cosmology, discovery possible in many intermediate scale experiments.
- Effectively get this search for free as part of QCD axion search.

A. Berlin and others



Goal: Definitive QCD Axion Search

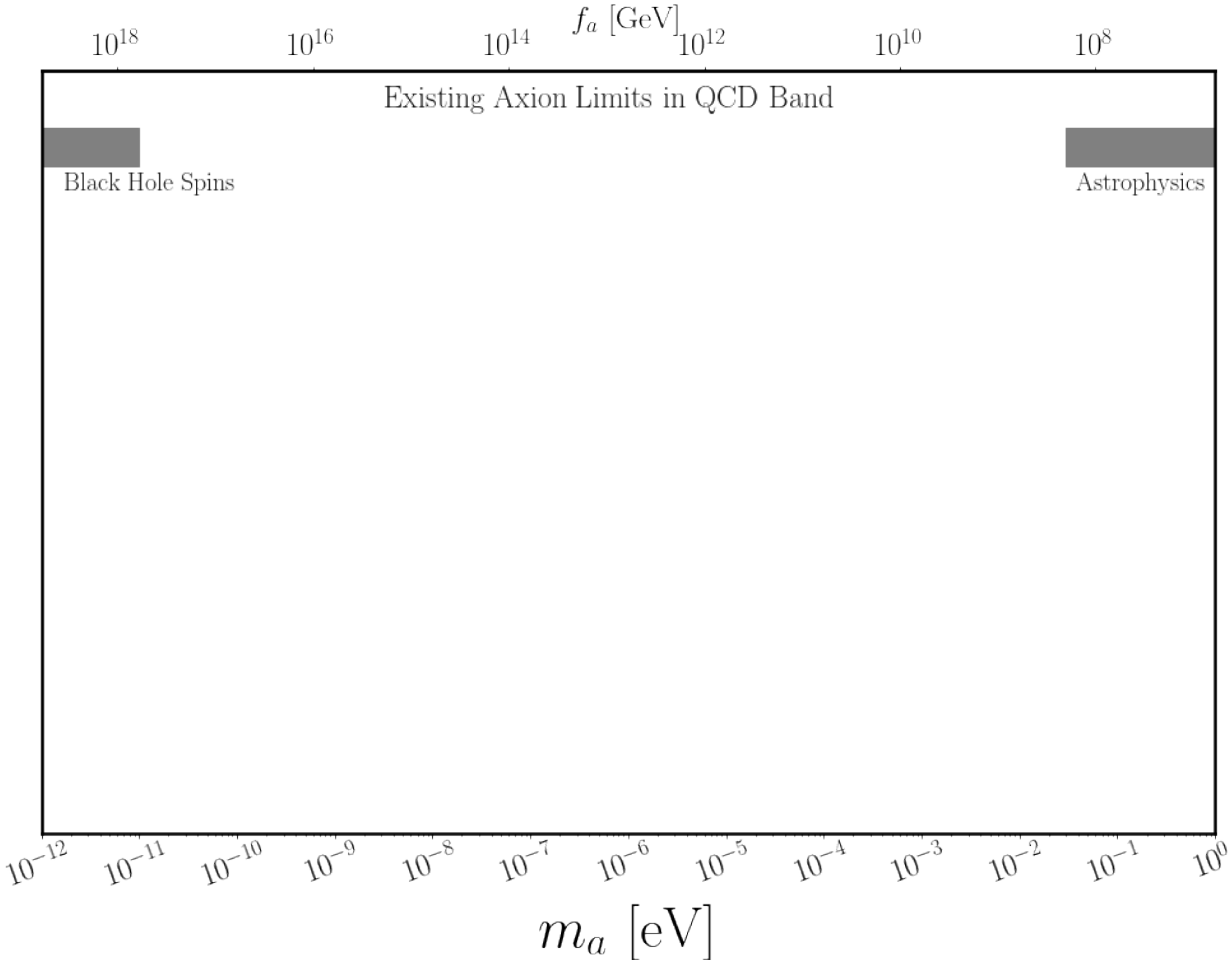
- ADMX-G2, HAYSTAC, CAPP are into the QCD axion band.
- The DMNI projects: ADMX-EFR and DMRadio-m³ are ready to start construction.
- Several Demonstrator scale experiments would be ready for a new DMNI process.



Status: Previous Snowmass

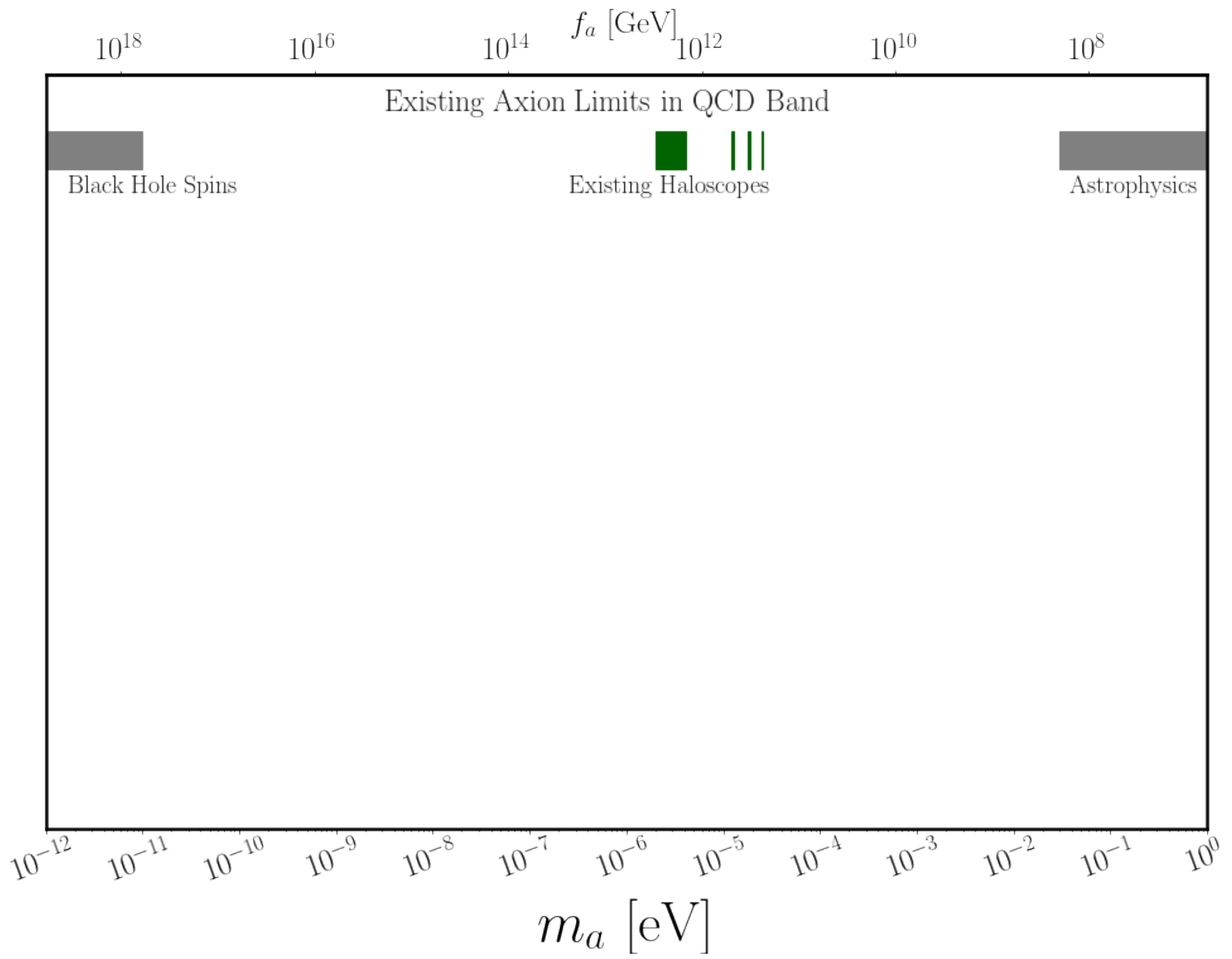
- No Experiments had probed the QCD band.

Note: Astrophysical probes provide key constraints at high and low masses.



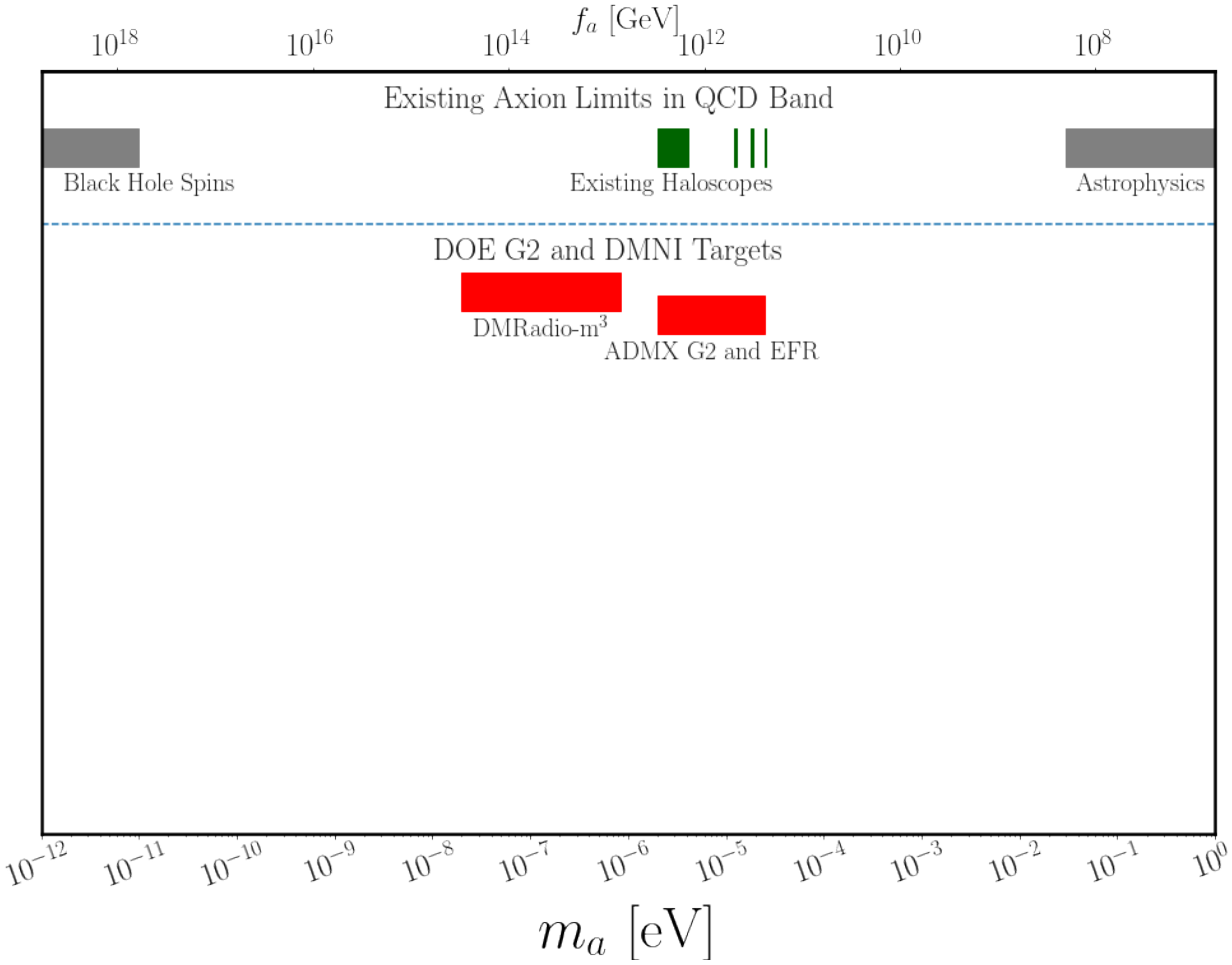
Status: Current

- ADMX G2 has reached DFSZ in some parameter space.
- HAYSTAC and CAPP are exploring the QCD band.



Dark Matter New Initiatives (DMNI)

- The BRN for Dark Matter New Initiatives and subsequent call for proposals was very successful.
- DMRadio-m3 and ADMX-EFR are poised to make significant inroads into the QCD axion parameter space.



Technological Advancements

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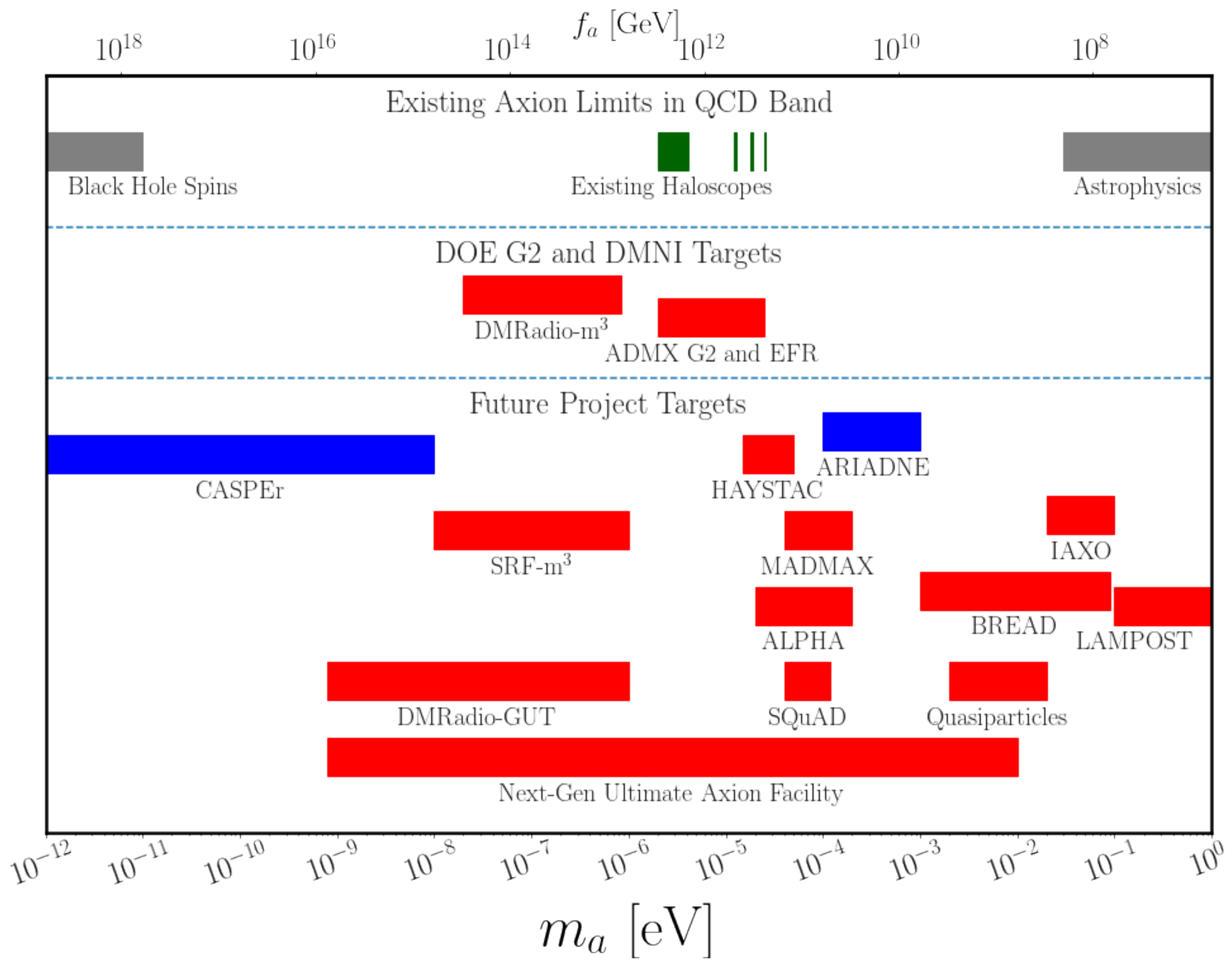
- We have developed techniques to address the full axion parameter space.
- This includes techniques to probe the non-photon couplings (indicated in **blue**).
- These techniques vary in readiness from proof-of-principle to operating experiments.
- Pursue common facilities for these efforts.



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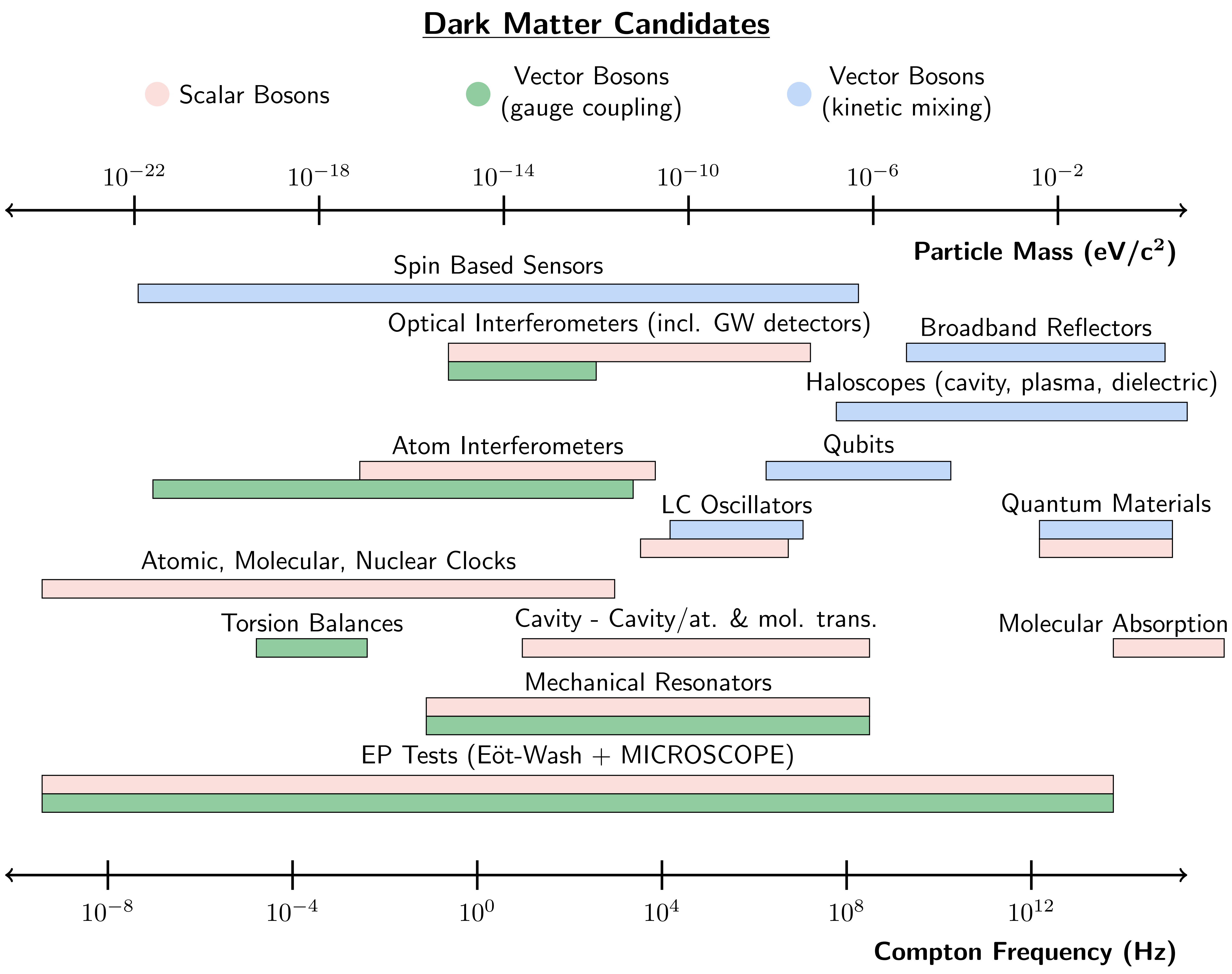
New Horizons:

Scalar and Vector Dark Matter

Detection Signals:

- Precession of nuclear or electron spins.
- Drive currents in electromagnetic systems, produce photons.
- Induce equivalence principle-violating accelerations of matter.
- Modulate the fundamental constants.
    - ➡ Induce changes in atomic transition frequencies.
    - ➡ Induce changes in local gravitational field.
    - ➡ Affect the length of macroscopic bodies.



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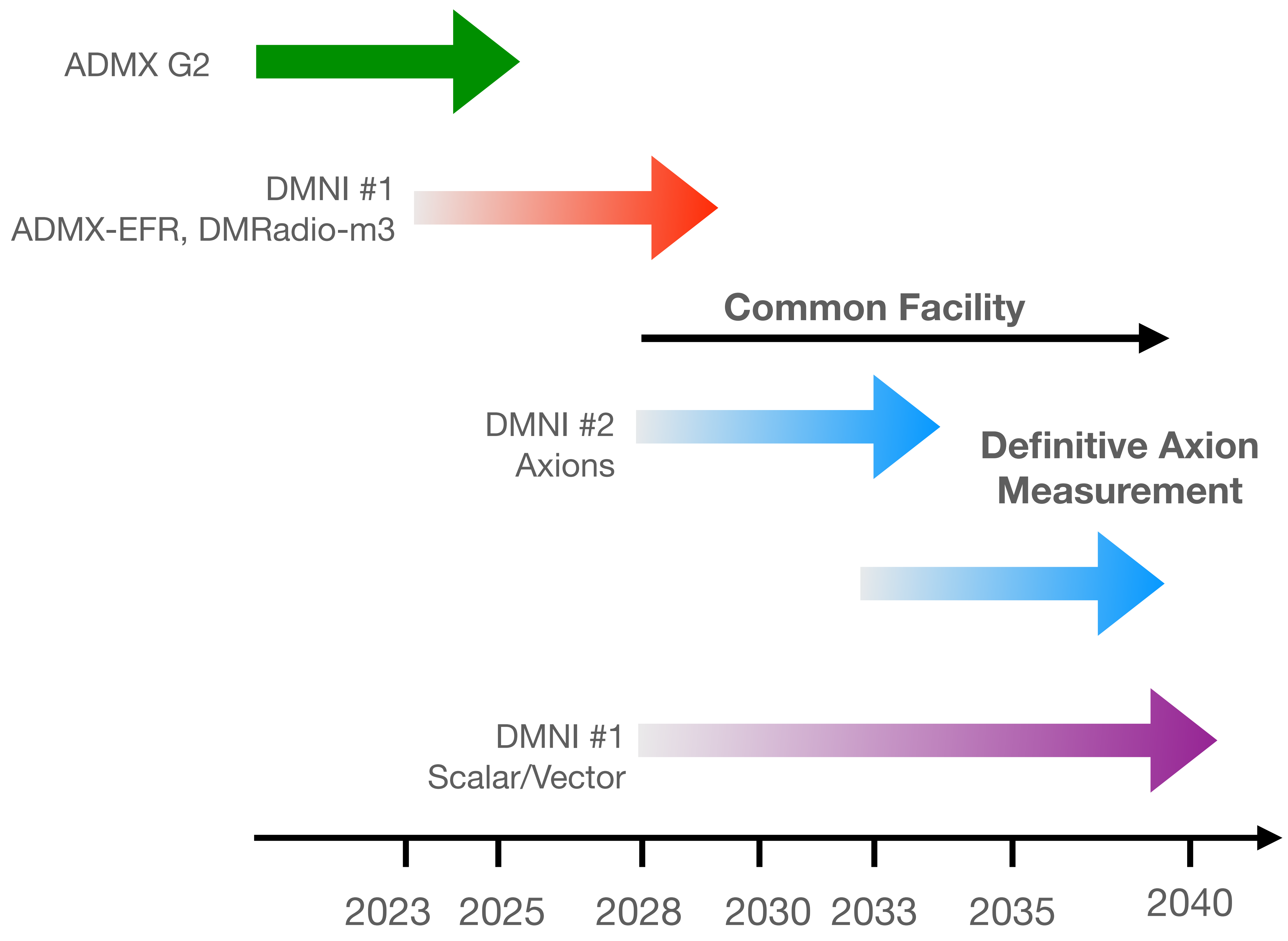
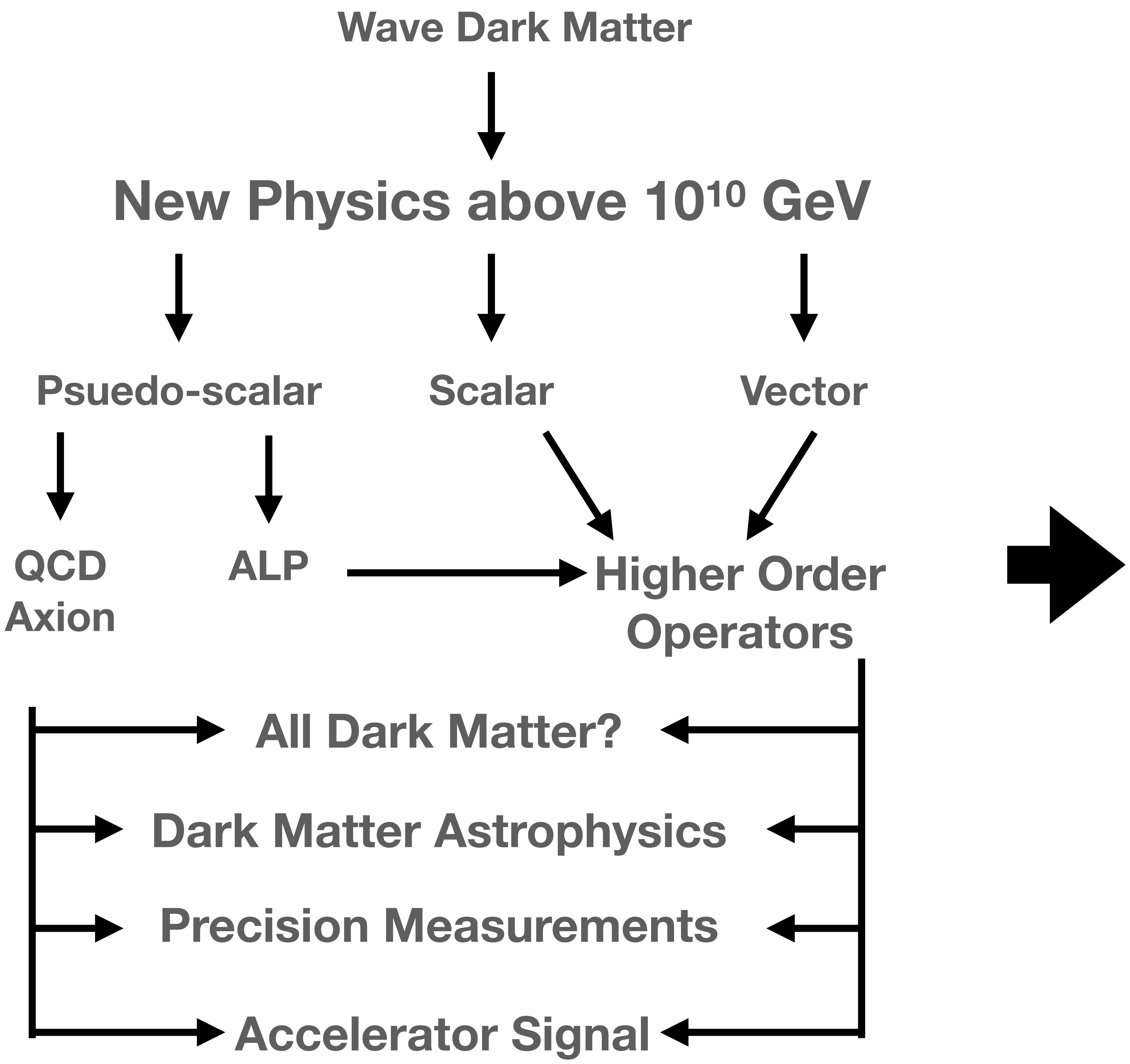
Community Roadmap: Time Line

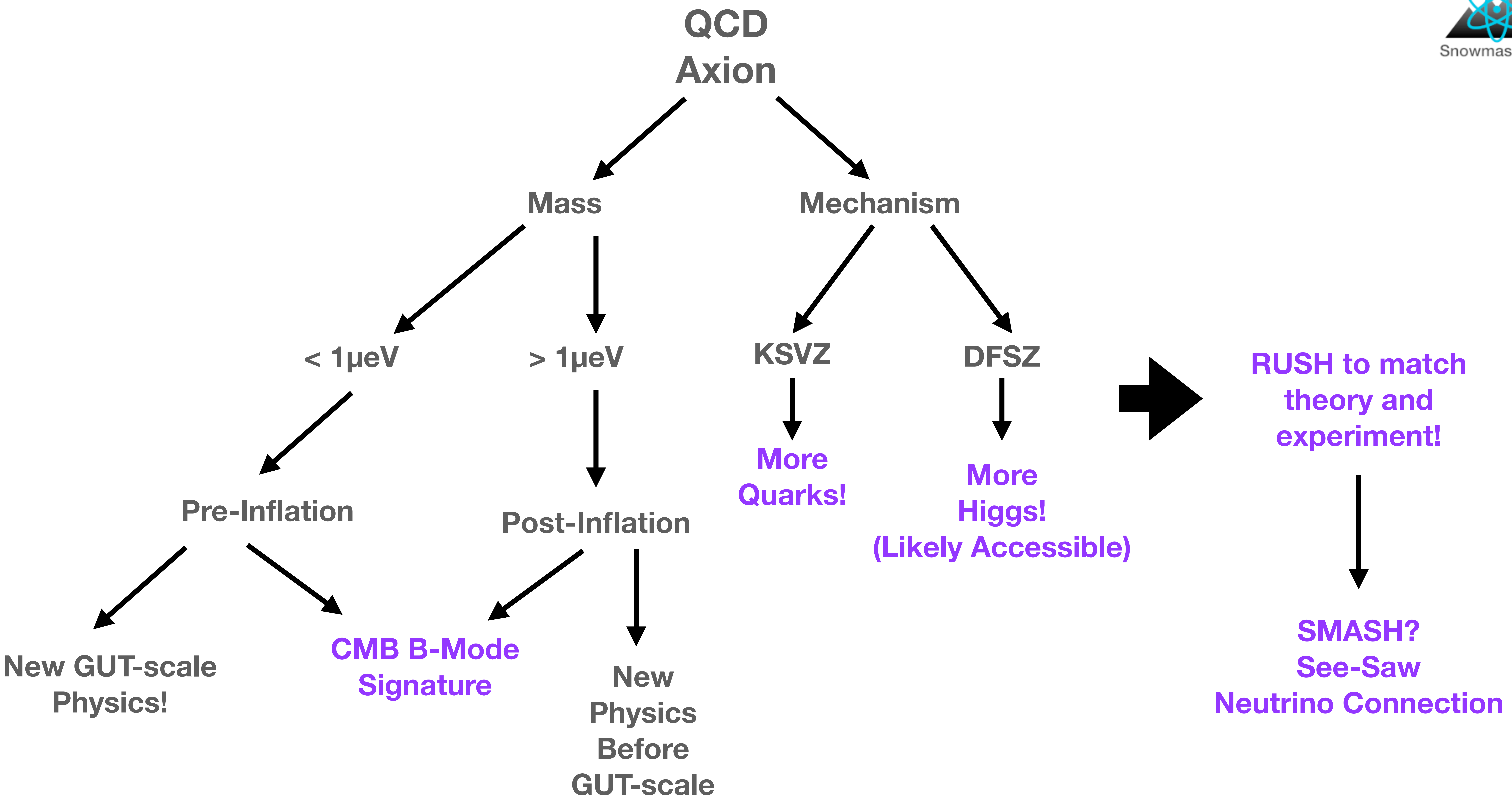
- Currently waiting to start construction on DMNI #1.
- A suite of small projects would provide a definitive axion measurement and search significant scalar/vector parameter.
- Community would like to pursue a common facilities for hosing these experiments.



Preparing for Discovery: Wave DM complementarity



RUSH to match theory and experiment!


QCD
Axion
Mass
Mechanism
< 1μeV
> 1μeV
KSVZ
DFSZ
Pre-Inflation
Post-Inflation
More
Quarks!
More
Higgs!
(Likely Accessible)
RUSH to match
theory and
experiment!
New GUT-scale
Physics!
CMB B-Mode
Signature
New
Physics
Before
GUT-scale
SMASH?
See-Saw
Neutrino Connection

Community Whitepapers

The community road map, theory, cosmology, and experimental details are presented in our two community white papers.

Axion Dark Matter
arXiv:2203.14923
Editors: J. Jaeckel, G. Rybka, L. Winslow

New Horizons:
Scalar and Vector Ultralight Dark Matter
arXiv:2203.14915
Editors: M. Safronova and S. Singh

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass 2021 White Paper
Axion Dark Matter

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass 2021 White Paper
New Horizons: Scalar and Vector Ultralight Dark Matter

D. Antypas,[1,2] A. Banerjee,[3] C. Bartram,[4] M. Baryakhtar,[4] J. Betz,[5] J. J. Bollinger,[6] C. Boutan,[7] D. Bowring,[8] D. Budker,[2,1,9] D. Carney,[10] G. Carosi,[11,4] S. Chaudhuri,[12] S. Cheong,[13,14] A. Chou,[8] M. D. Chowdhury,[15] R. T. Co,[16] J. R. Crespo López-Urrutia,[17] M. Demarteau,[18] N. DePorzio,[19] A. V. Derbin,[20] T. Deshpande,[21] M. D. Chowdhury,[15] L. Di Luzio,[22,23] A. Diaz-Morcillo,[24] J. M. Doyle,[19,25] A. Drlica-Wagner,[8,26,27] A. Droster,[9] N. Du,[11] B. Döbrich,[28] J. Eby,[29] R. Essig,[30] G. S. Farren,[31] N. L. Figueroa,[1,2] J. T. Fry,[32] S. Gardner,[33] A. A. Geraci,[21] A. Ghalsasi,[34] S. Ghosh,[35,36] M. Giannotti,[37] B. Gimeno,[38] S. M. Griffin,[39,40] D. Grin,[41] D. Grin,[41] H. Grote,[42] J. H. Gundlach,[4] M. Guzzetti,[4] D. Hanneke,[43] R. Harnik,[8] R. Henning,[44,45] V. Irsic,[46,47] H. Jackson,[9] D. F. Jackson Kimball,[48] J. Jaeckel,[49] M. Kagan,[13] D. Kedar,[50,51] R. Khatiwada,[8,52] S. Knirck,[8] S. Kolkowitz,[53] T. Kovachy,[21] S. E. Kuenstner,[14] Z. Lasner,[19,25] A. F. Leder,[9,10] R. Lehnert,[54] D. R. Leibrandt,[6,51] E. Lentz,[7] S. M. Lewis,[8] Z. Liu,[55] J. Manley,[56] R. H. Maruyama,[35] A. J. Millar,[57,58] V. N. Muratova,[20] N. Musoke,[59] S. Nagaitsev,[8,27] O. Noroozian,[60] C. A. J. O'Hare,[61] J. L. Ouellet,[32] K. M. W. Pappas,[32] E. Peik,[62] G. Perez,[3] A. Phipps,[48] N. M. Rapidis,[14] J. M. Robinson,[50,51] V. H. Robles,[63] K. K. Rogers,[64] J. Rudolph,[14] G. Rybka,[4] M. Safdari,[13,14] M. Safdari,[14,13] M. S. Safronova,[5] C. P. Salemi,[32] P. O. Schmidt,[62,65] T. Schumm,[66] A. Schwartzman,[13] J. Shu,[67] M. Simanovskaia,[14] J. Singh,[14] S. Singh,[56,5] M. S. Smith,[18] W. M. Snow,[54] Y. V. Stadnik,[61] C. Sun,[68] A. O. Sushkov,[69] T. M. P. Tait,[70]

Thank you Wave-like Dark Matter Community!

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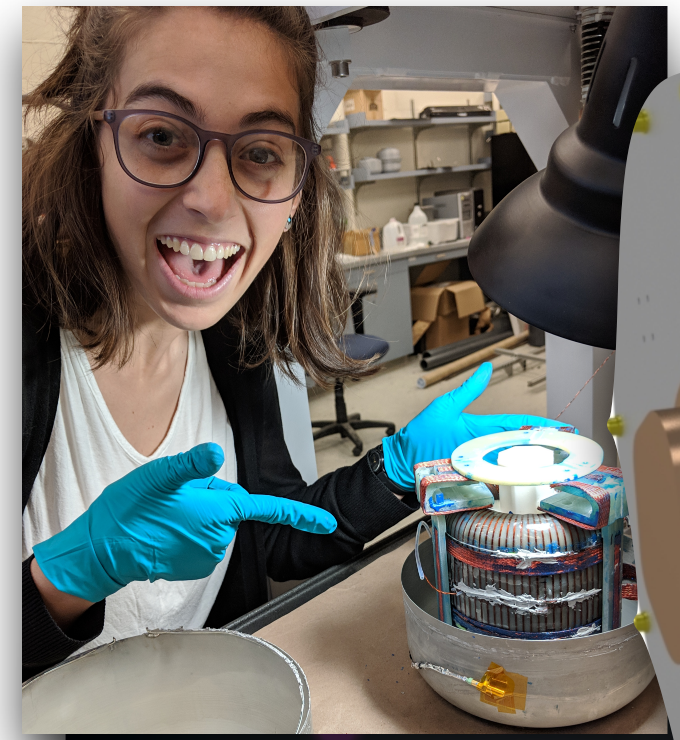

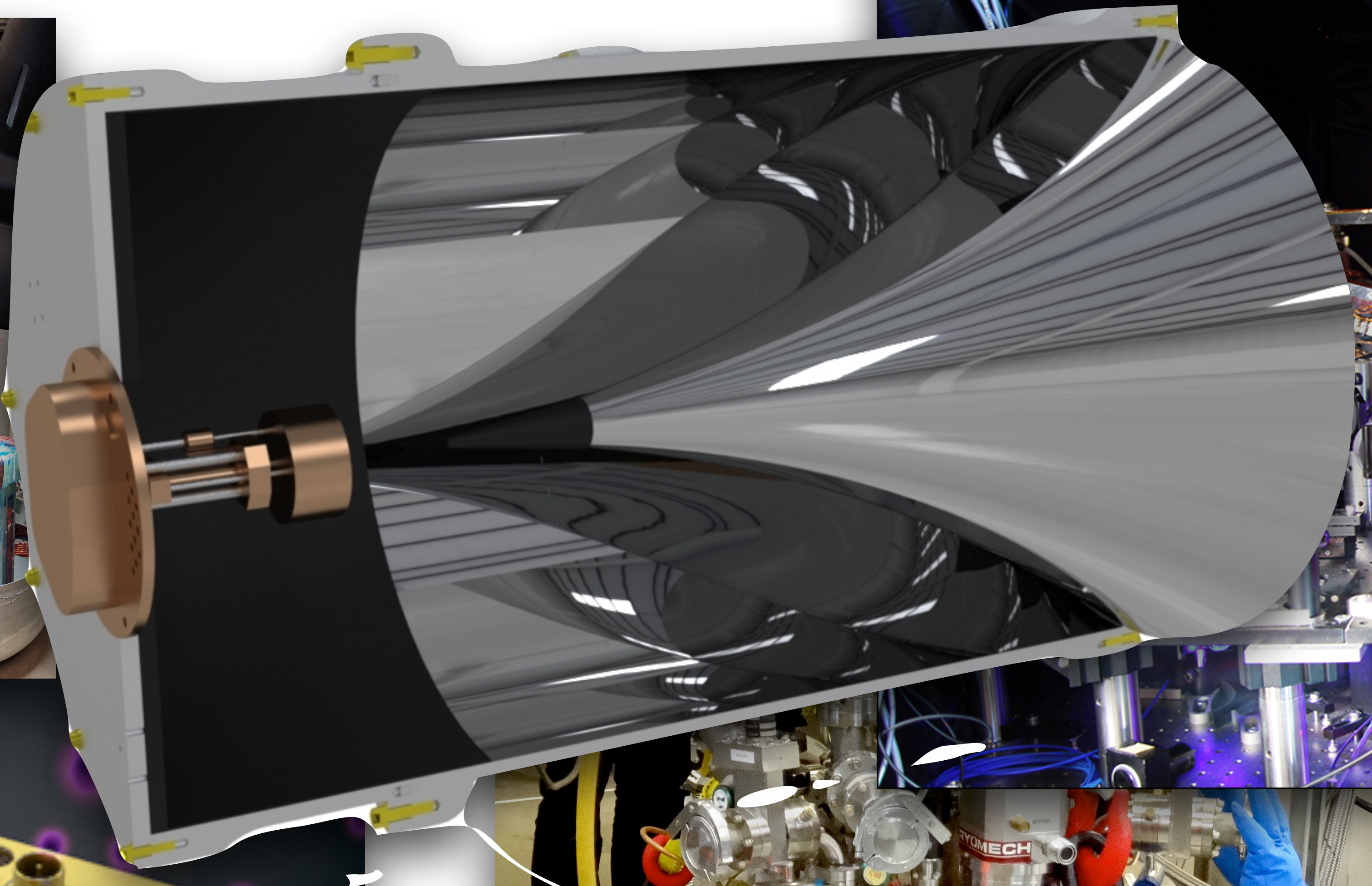

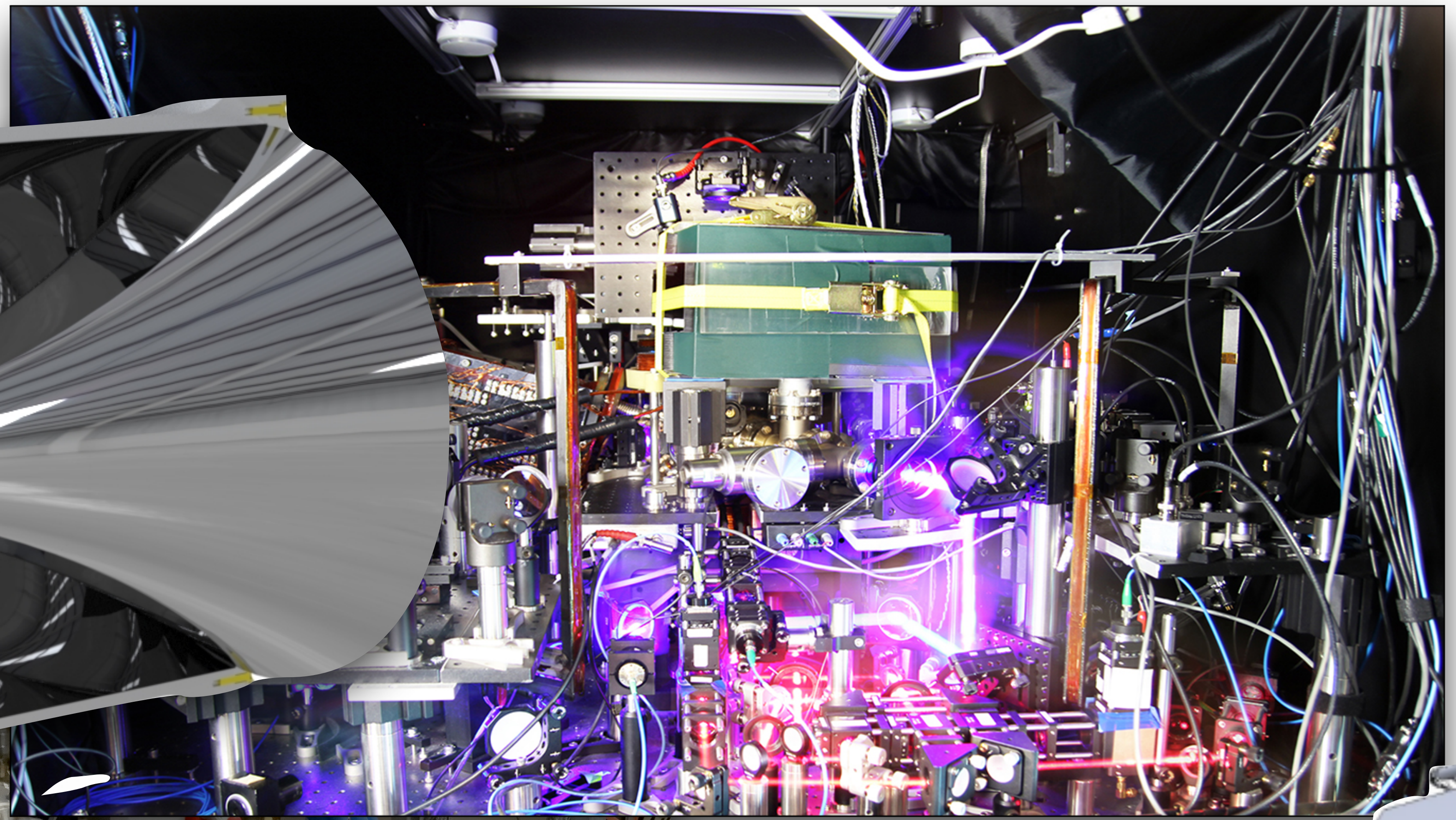

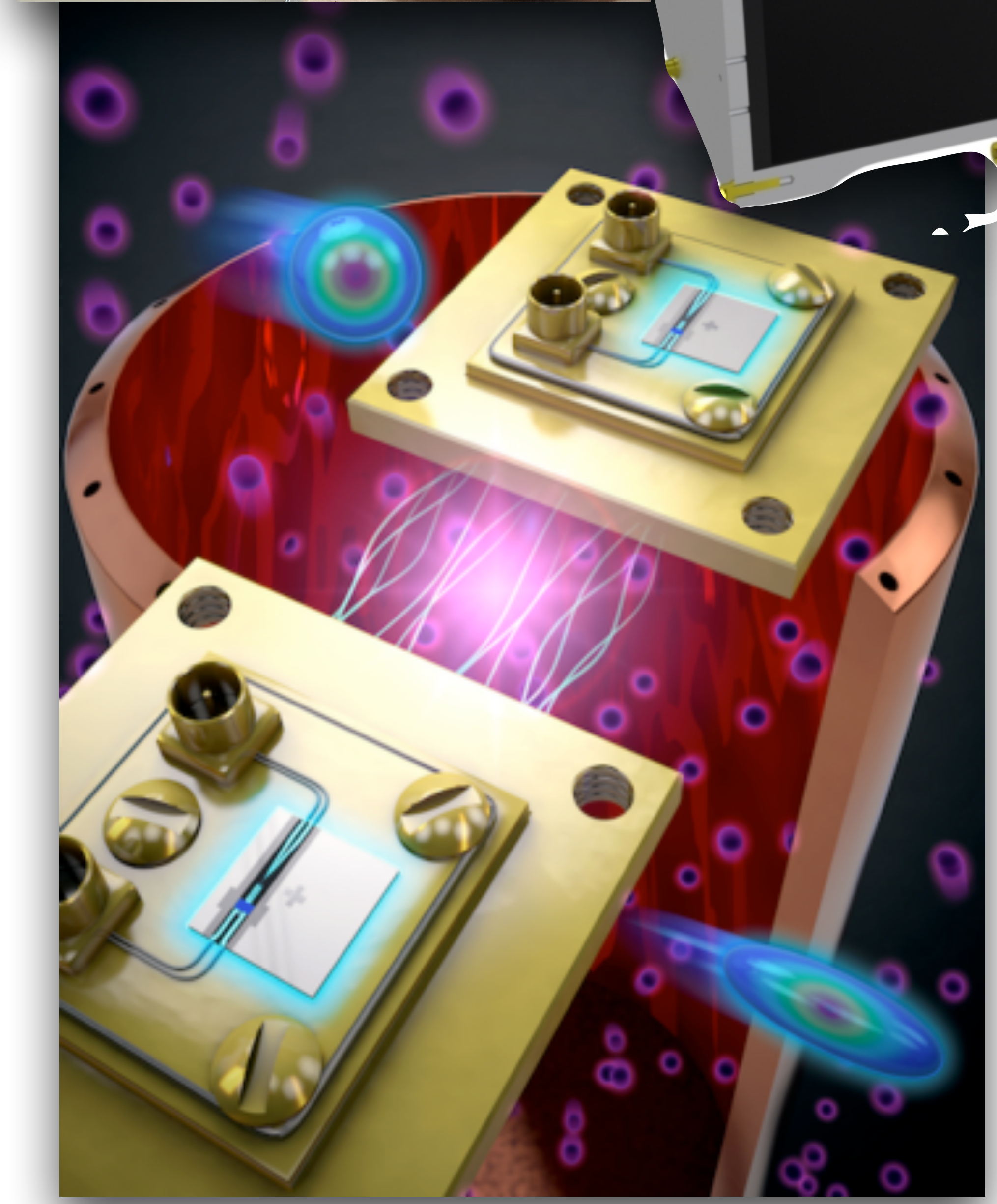

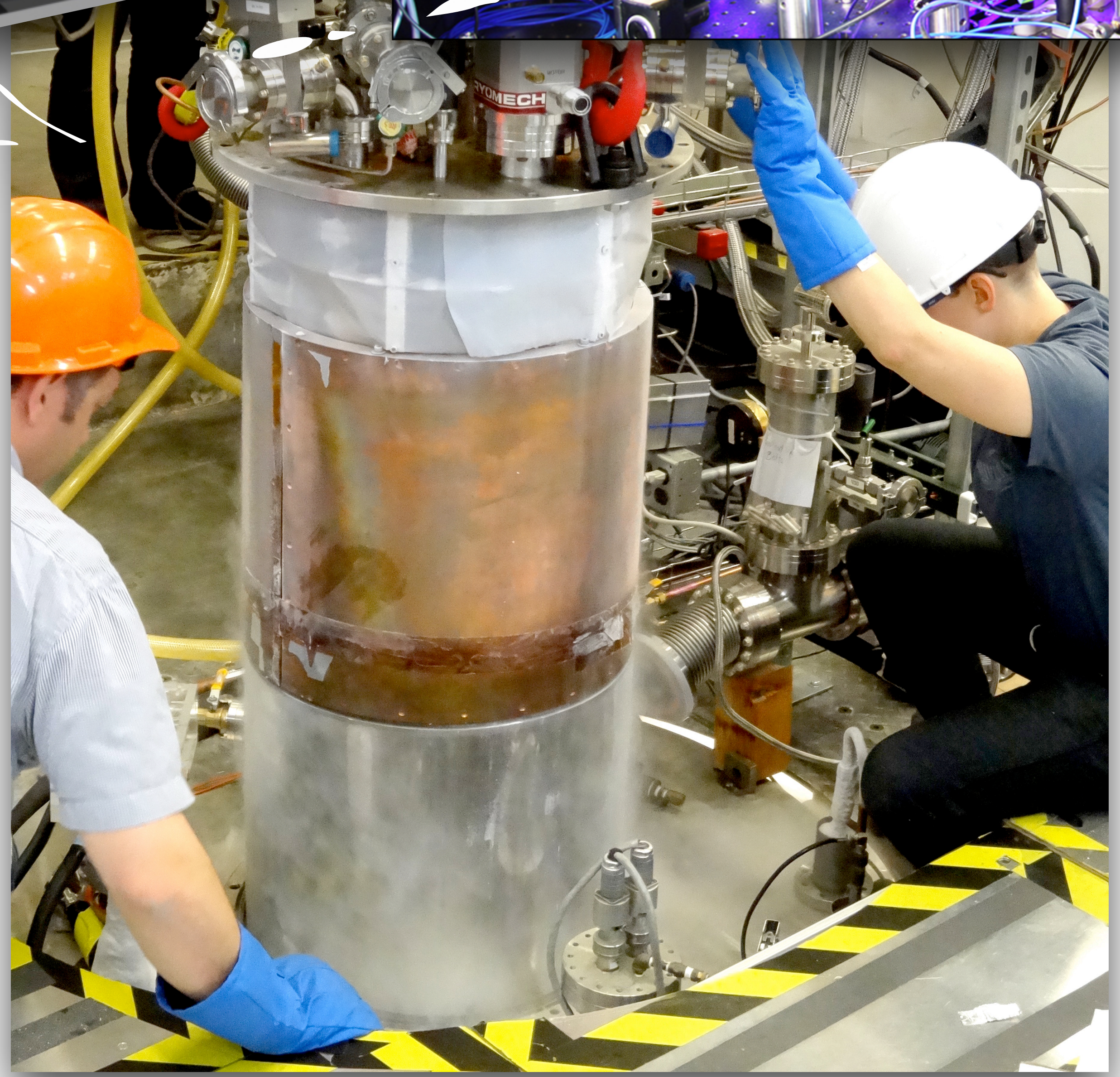

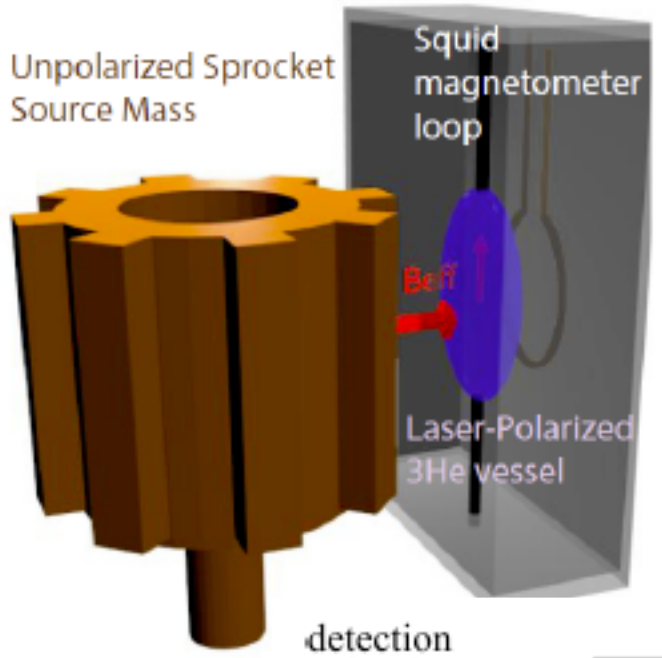

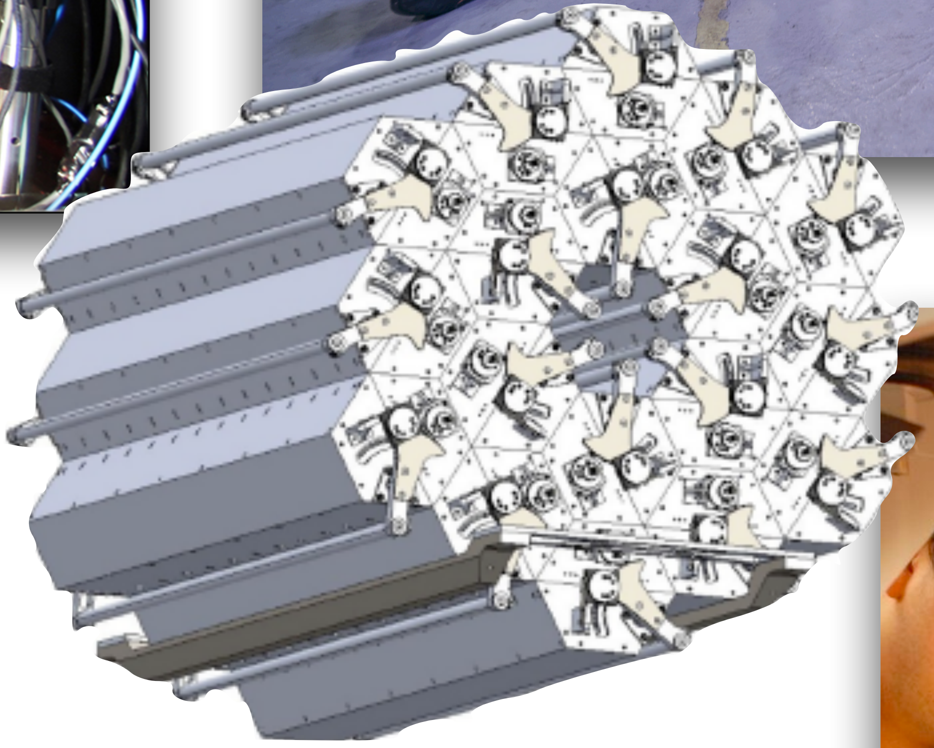

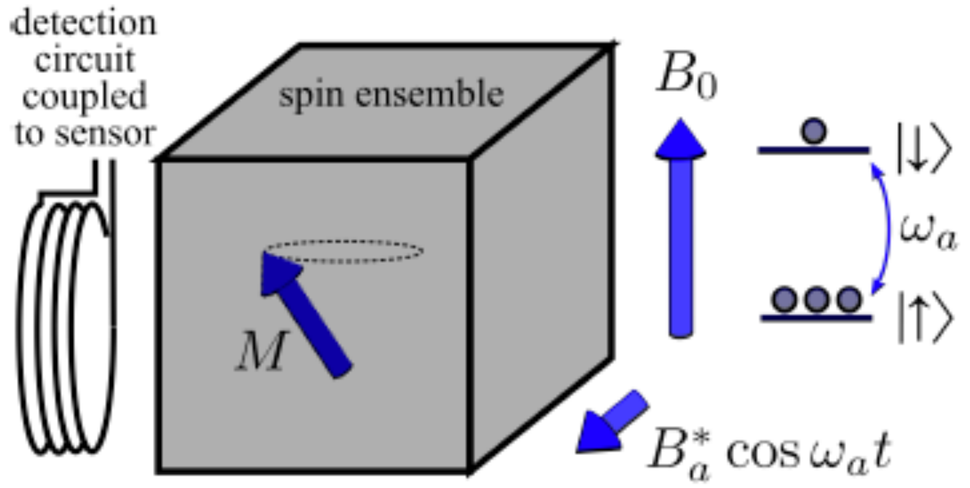

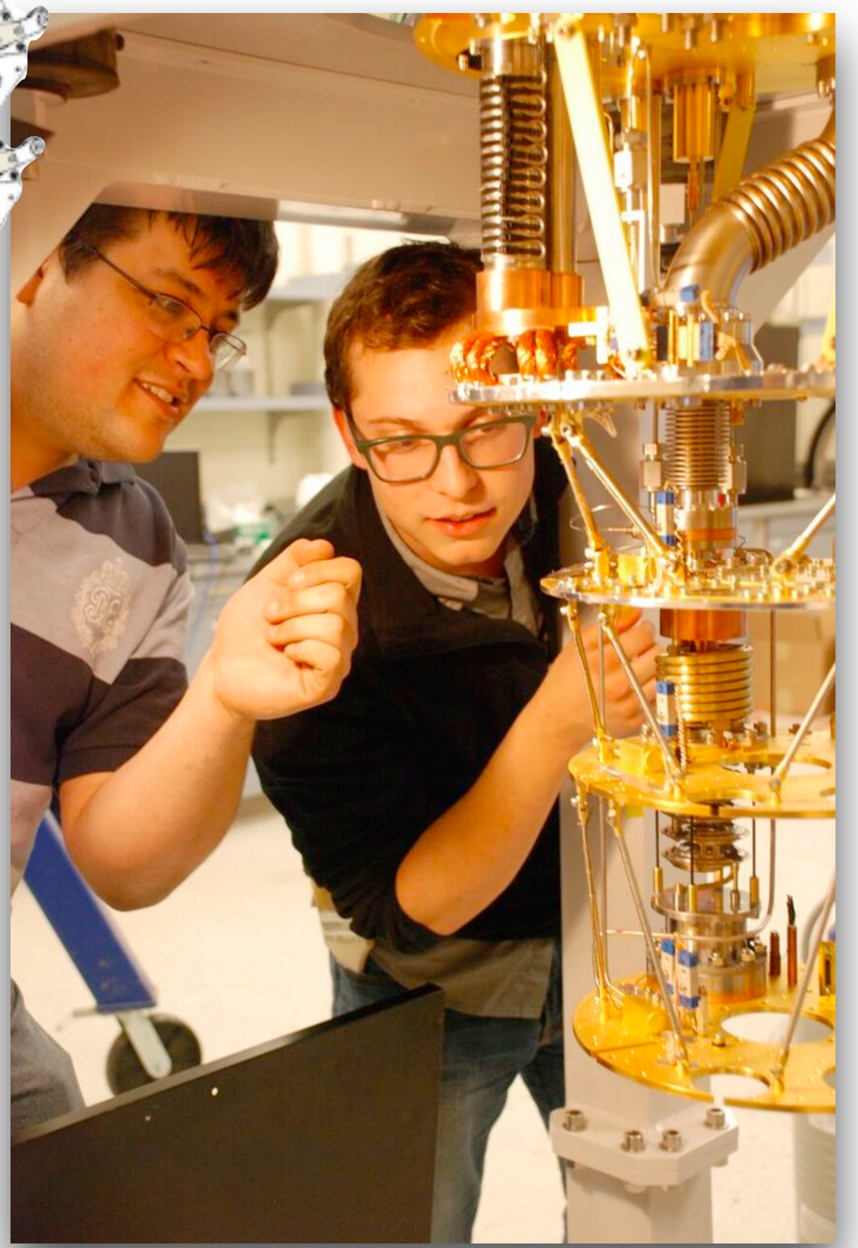

Conclusion:

Great Opportunity for Discovery!

- Significant parameter space for the highly motivated QCD axion ready to be explored with small experiments.
- We need to continue to nurture a healthy mix of experiments at different scales (Small/Medium Projects, Demonstrators, Proof-of-Concept) and pursue opportunities to harness US expertise for International projects.
- R&D opportunities with strong connections across the frontiers with particularly strong ties to quantum measurement and control.
- Interesting theory from model building to cosmology, astrophysical probes and signal characterization and interpretation.

A Larger Dark Matter Message!

Great Opportunity for Discovery!

- Dark Matter is one of the most important and cross-cutting topics.
- Unified message should come from CF, NF, RF, EF (even IF, AF).

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