Snowmass 2021

CF2: Wave-like Dark Matter

All Cosmic-Frontier Meeting

Lindley Winslow, Gray Rybka, Joerg Jaeckel

Wave-like Dark Matter Candidates

Wave-like Definition: Mass < 1 eV

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

Production: Athermal production (misalignment).

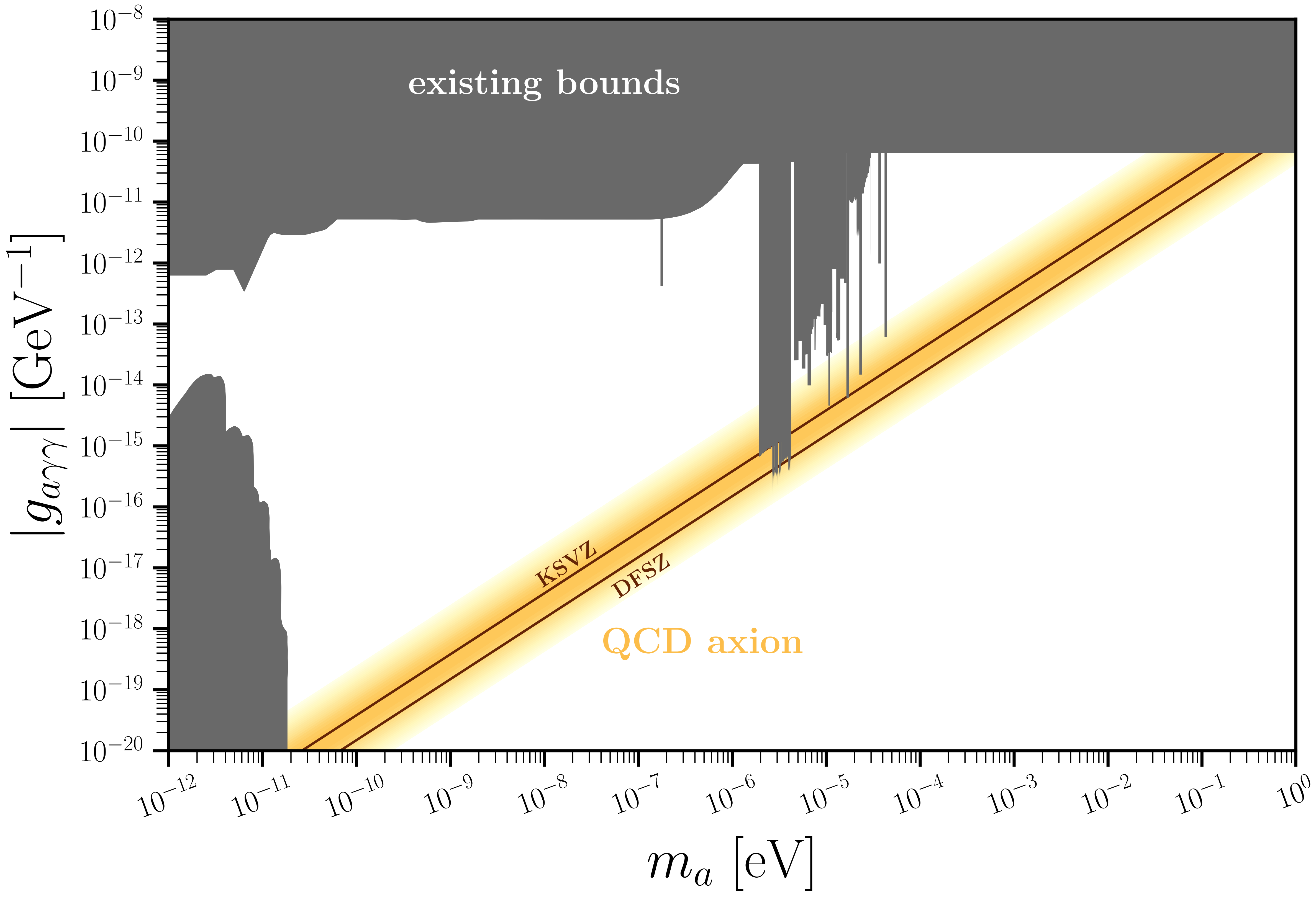
Detection: Coherent interaction of the wave with the detector. Resonant amplification often key.

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

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.

A. Berlin and others



** DFSZ is the benchmark for the field.*

Axion-Photon Searches

$$\underbrace{\nabla \times \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t}} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\text{Comp}} \sim R_{\text{exp}}$

$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\text{eff}}}$$

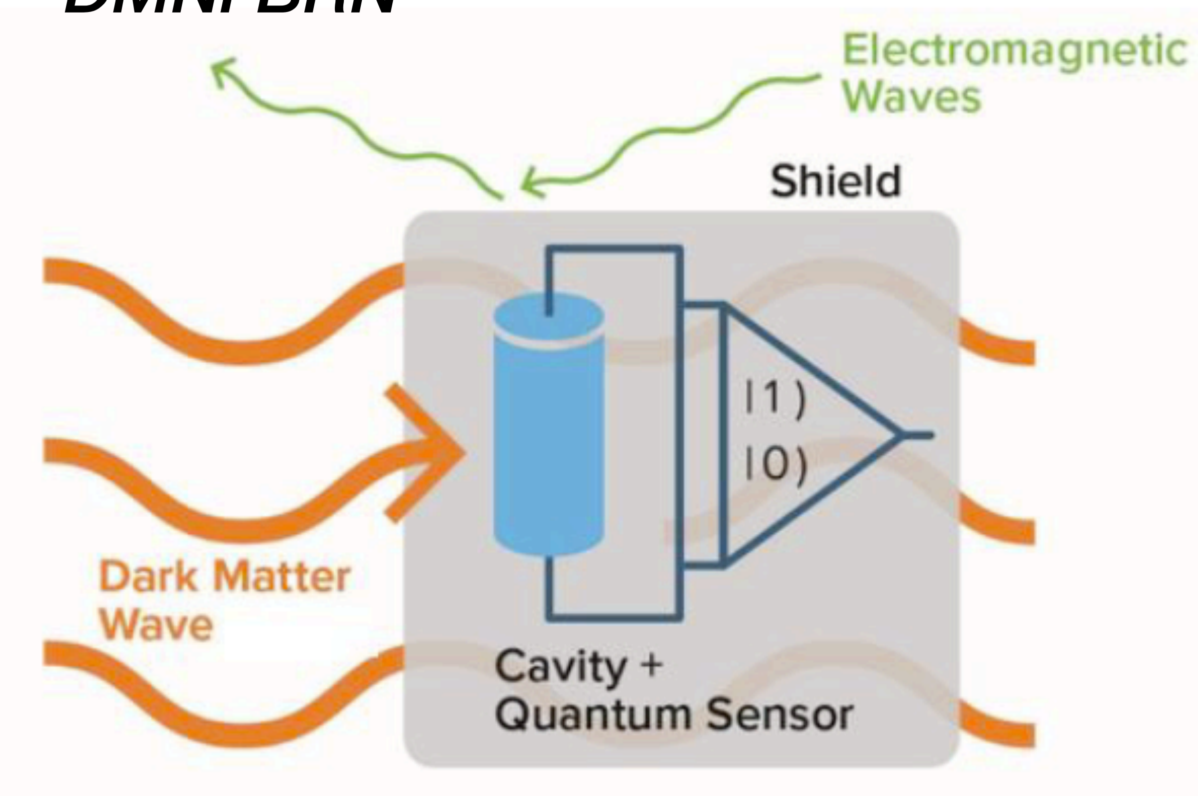
Quasistatic regime: $\lambda_{\text{Comp}} \gg R_{\text{exp}}$

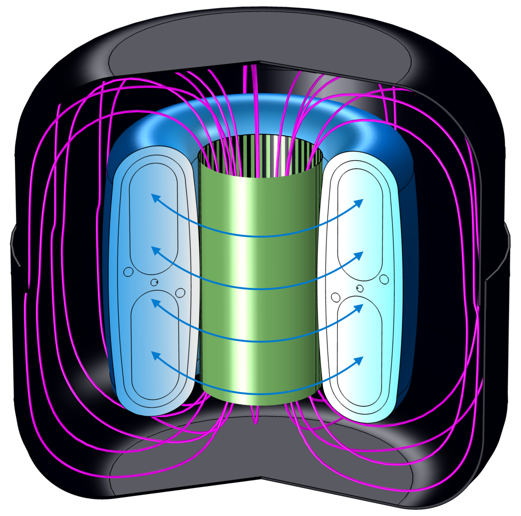
$$\cancel{\nabla \times \mathbf{B}_r} = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

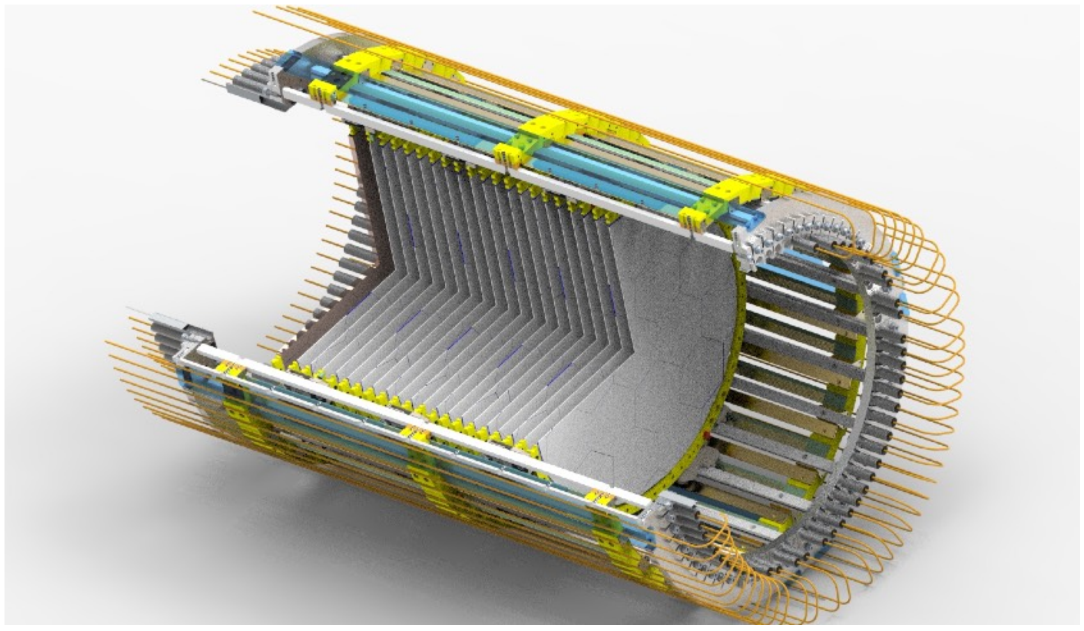
Radiation regime: $\lambda_{\text{Comp}} \ll R_{\text{exp}}$

Y. Kahn

DMNI BRN







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The QCD Axion

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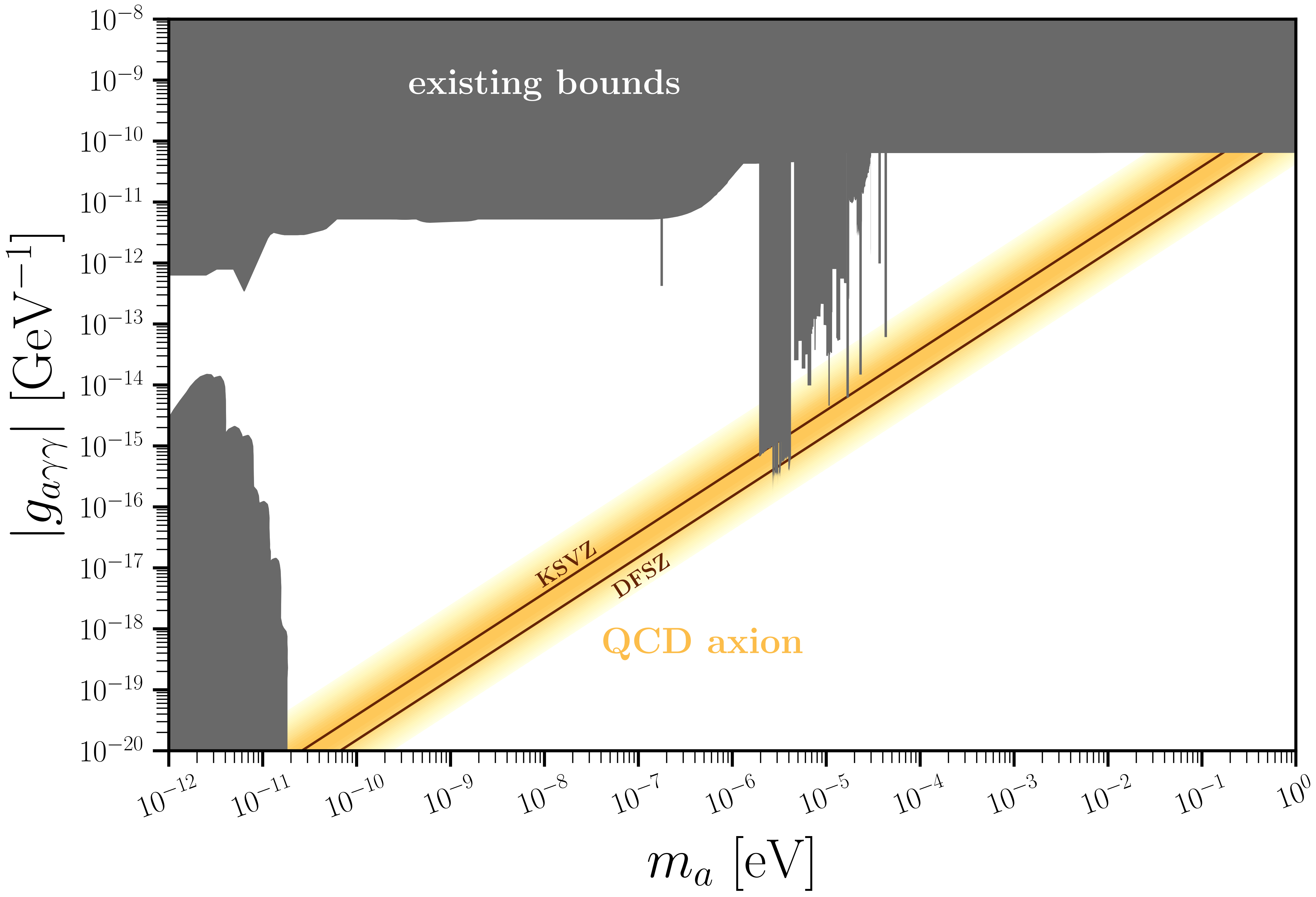
- The QCD axion is a psuedo-Nambu-Goldstone boson produced by the breaking of $U(1)_{PQ}$.
- Couples to **photons**, nucleons, electrons.
- Broad Categories of models:
    - **KSVZ** introduces heavy quarks.
    - **DFSZ** introduces additional Higgs fields.*

A. Berlin and others

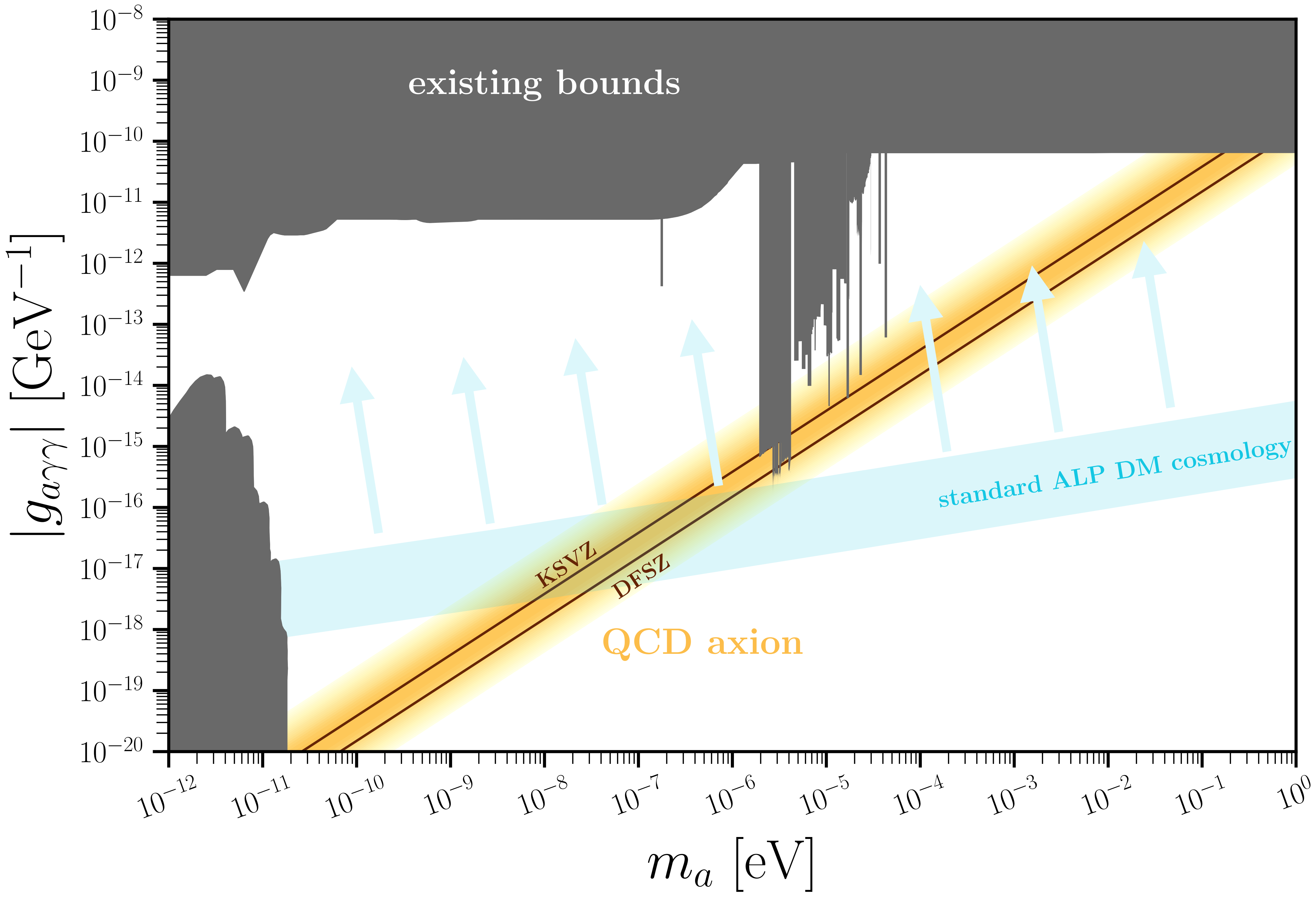


** DFSZ is the benchmark for the field.*

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.

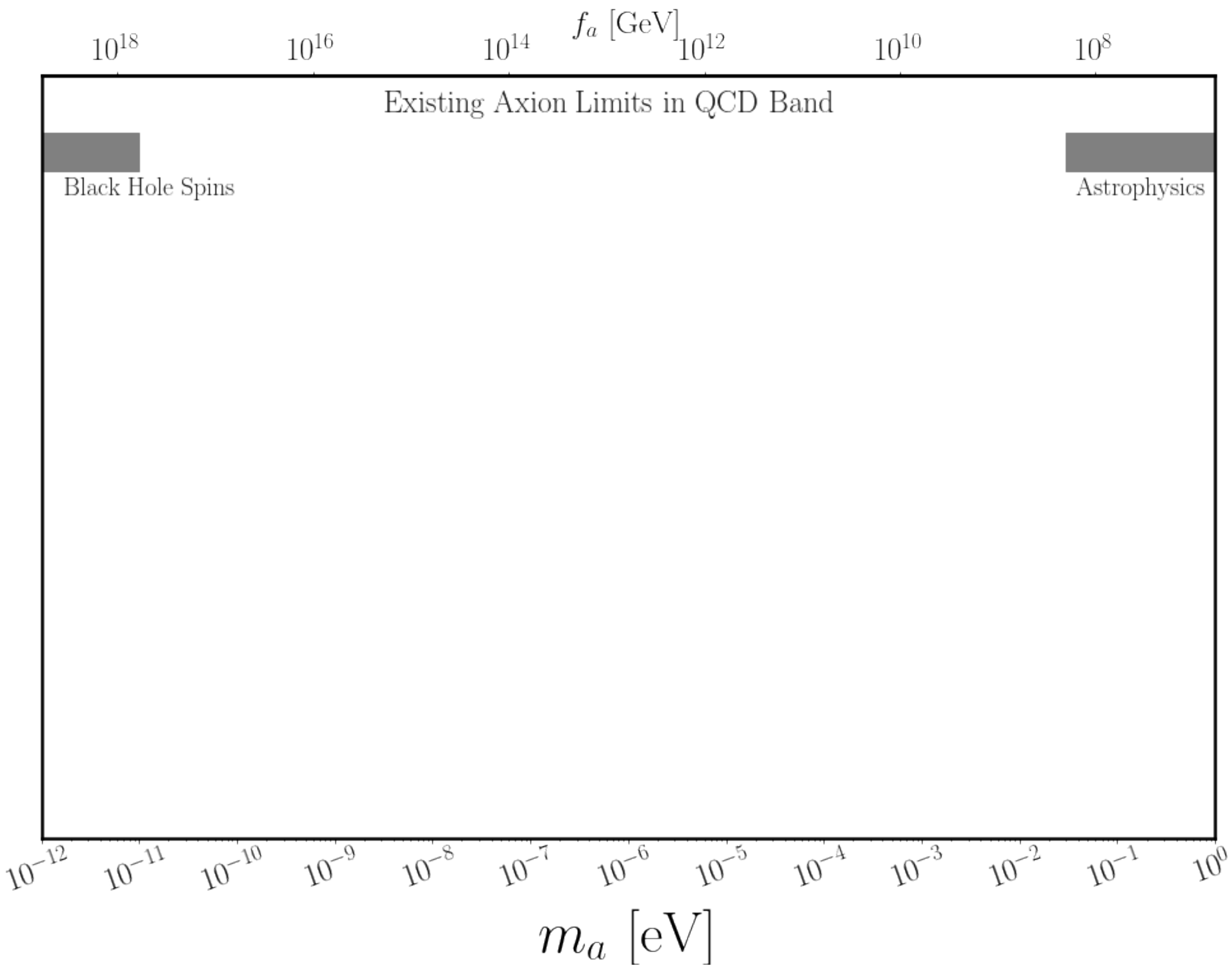
A. Berlin and others



Status: Previous Snowmass

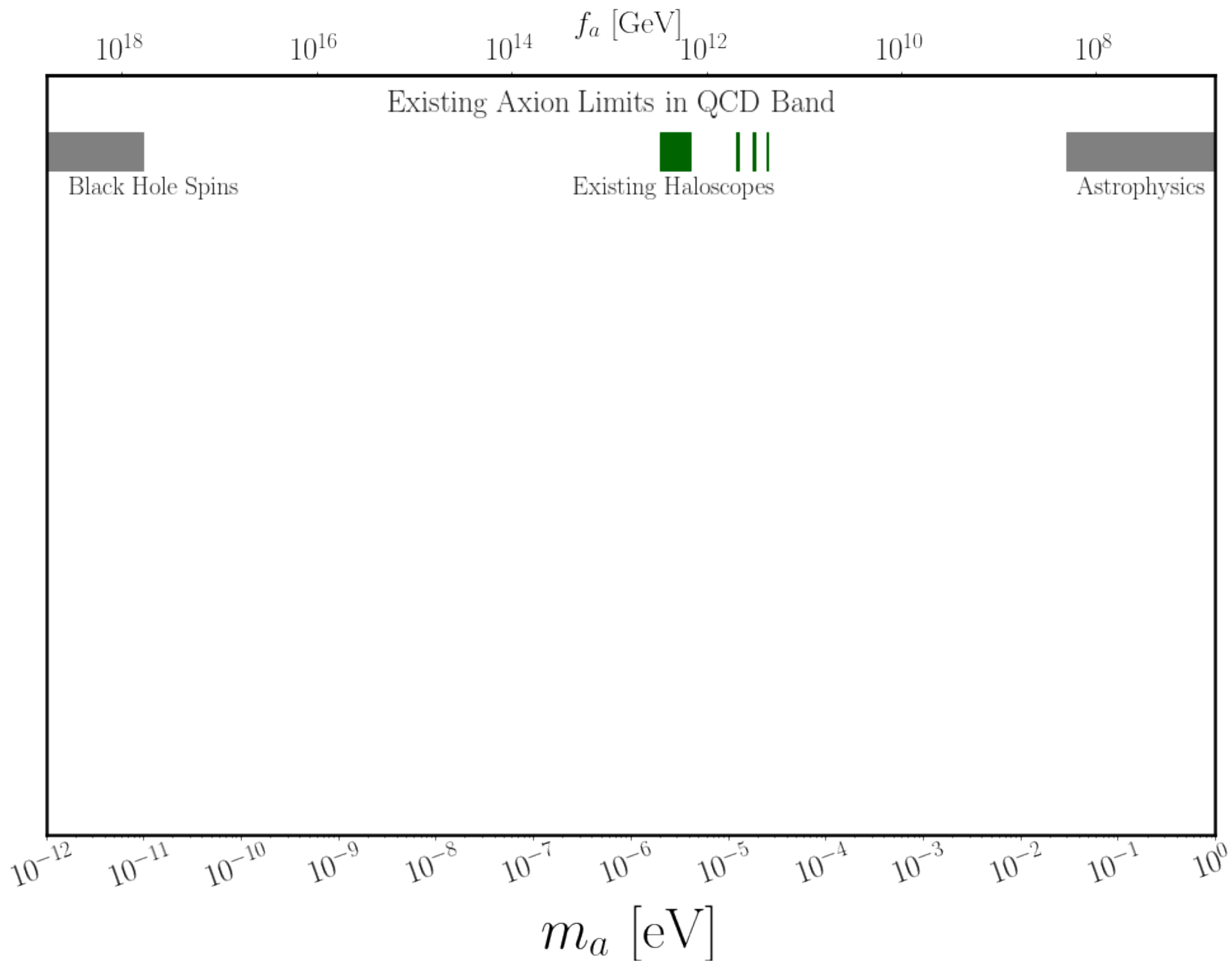
- No Experiments had probed the QCD band.

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



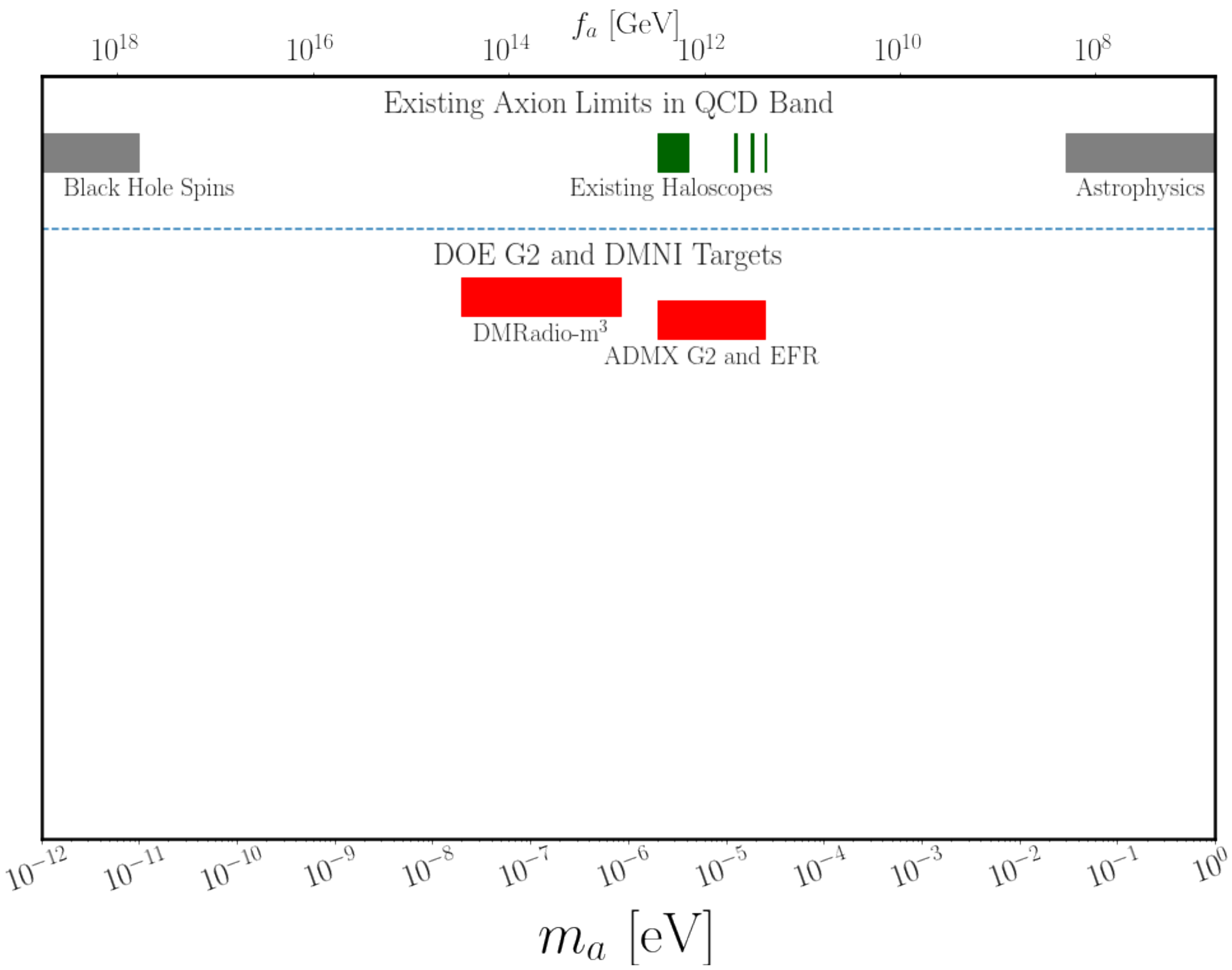
Status: Current

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



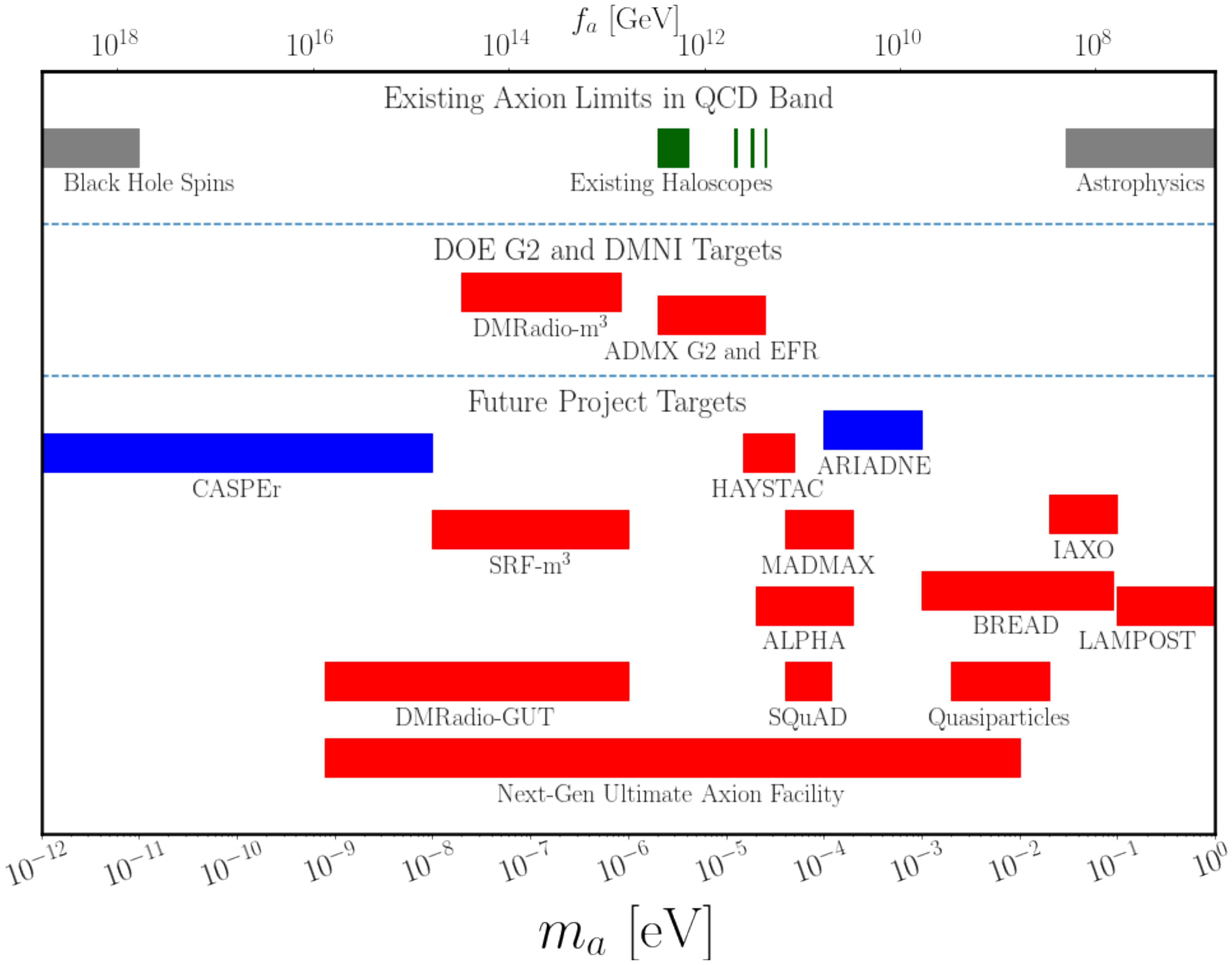
Dark Matter New Initiatives (DMNI)

- 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

- 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.



Community Roadmap

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 the QCD Axion with a Collection of Small-Scale Experiments

The entire axion mass range 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.

Support Enabling Technologies

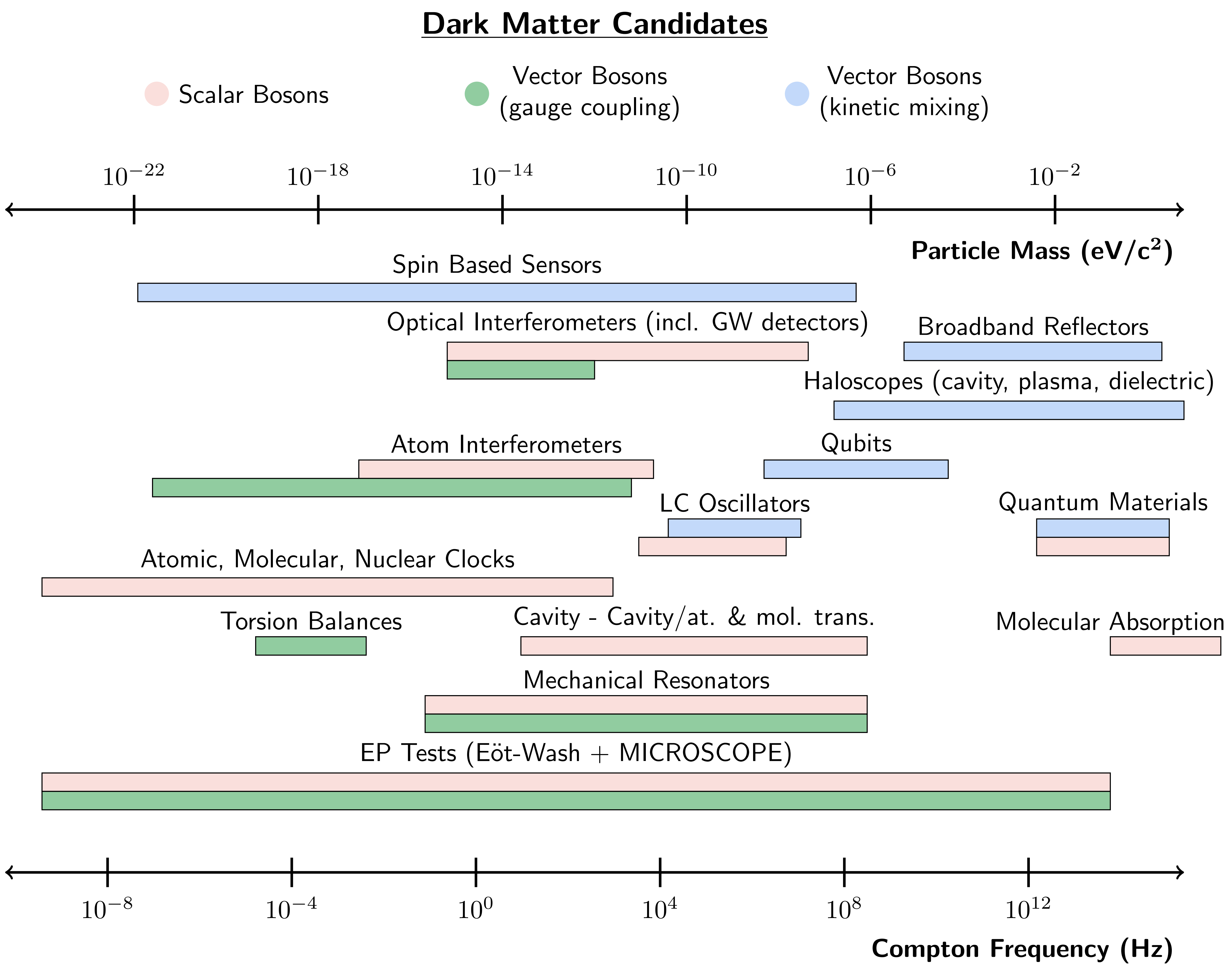
Common needs include ultra-sensitive quantum measurement and quantum control, large high-field magnets, spin ensembles, and sophisticated resonant systems. Strong synergies with other HEP needs.

Support Theory and Astrophysics Beyond the Standard QCD Axion

Theoretical effort should be supported to understand models and cosmology beyond the QCD axion and to better understand the roles axions play in astrophysical phenomena.

New Horizons:
Scalar and Vector Dark Matter

- Wave-like < 1eV dark matter must be bosonic because its fermi velocity is greater than escape velocity of the galaxy.
- Beyond the pseudoscalar (Axion/ALPs), we can have scalar and vector candidates.
- A variety of mechanisms including misalignment.

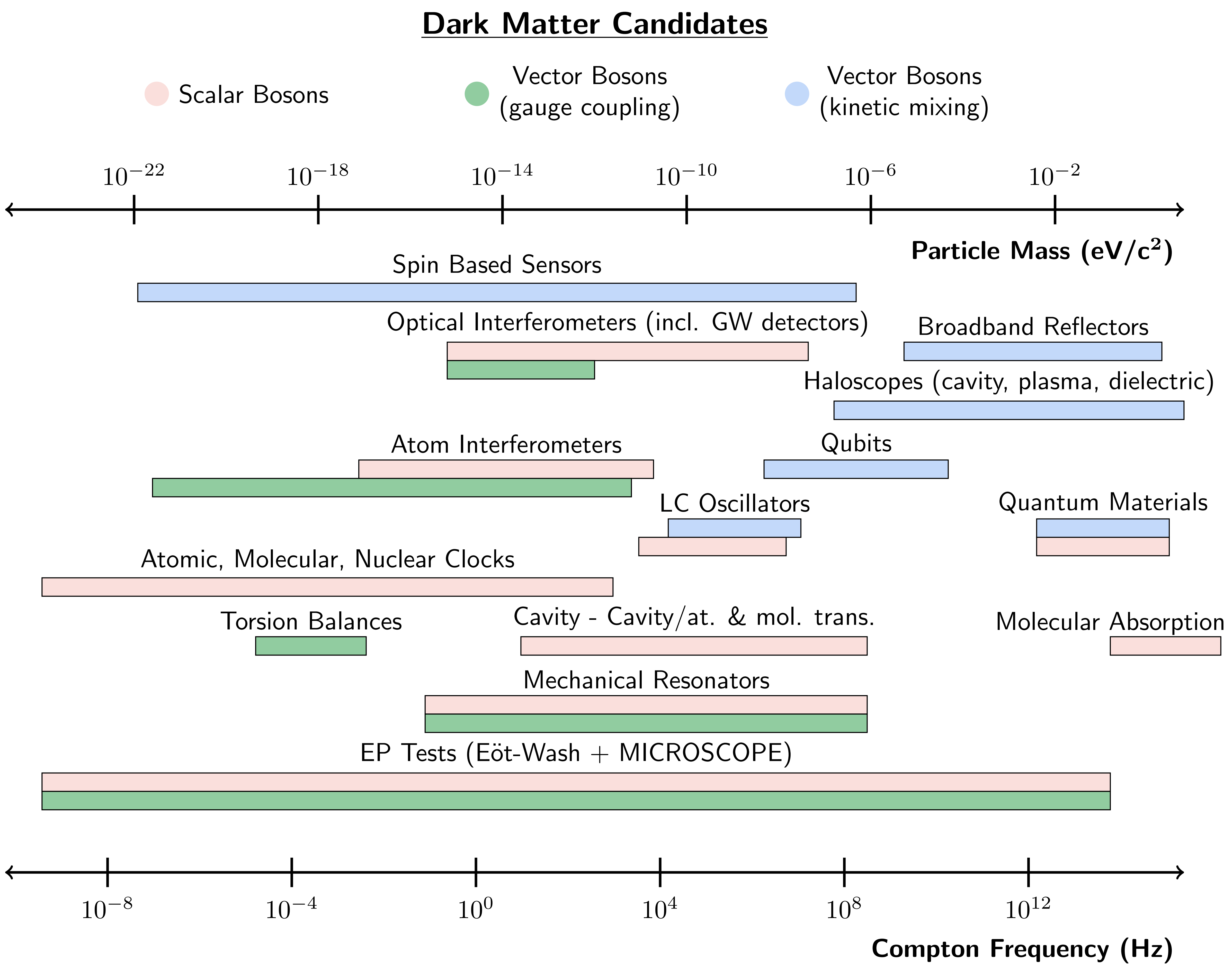


New Horizons:

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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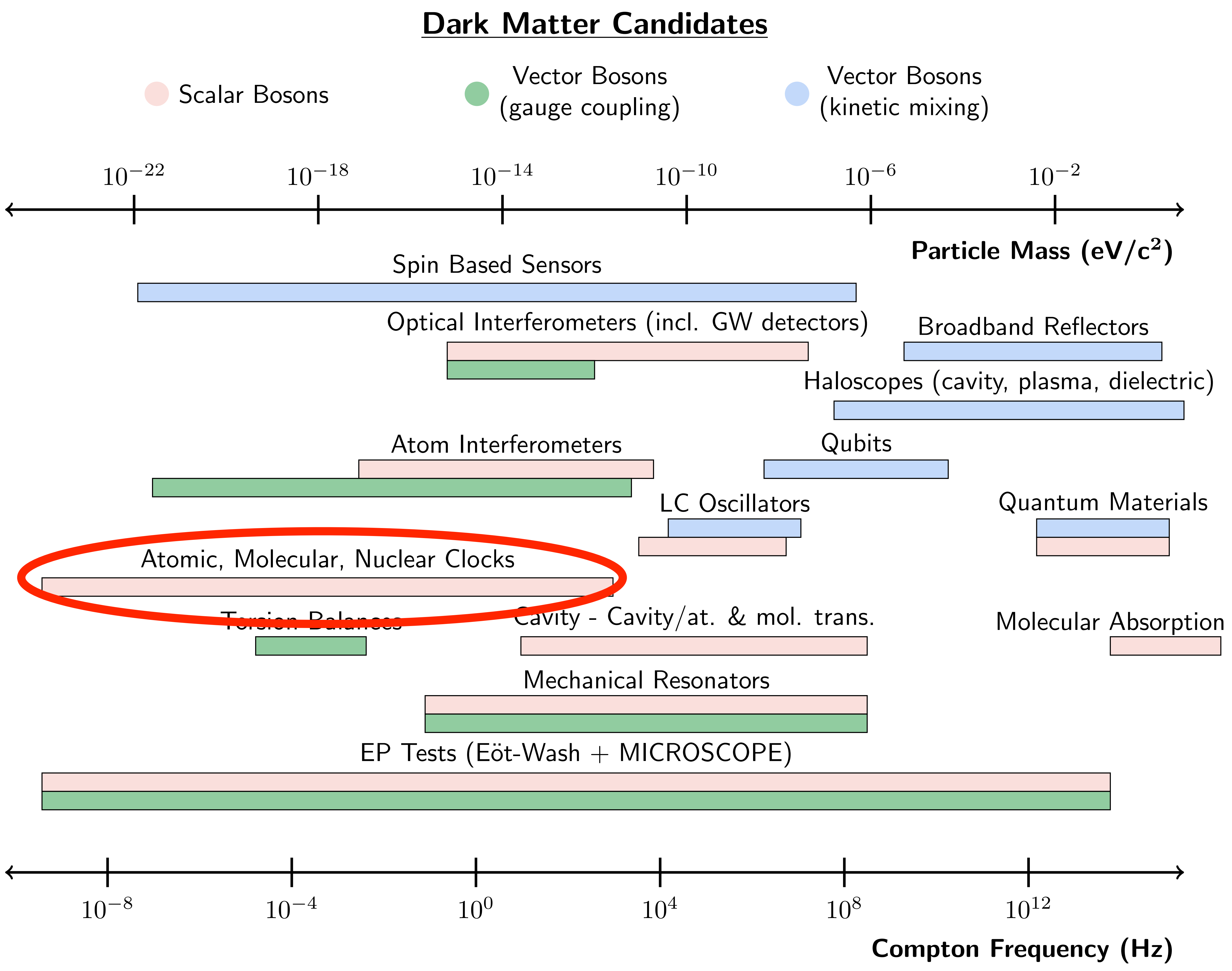
New Horizons:
Scalar and Vector Dark Matter

Example Clocks:

- Scalar candidate causes time varying α, m_e/m_p, m_q/Λ_{QCD}
- Different types of clocks affected differently
- Compare different clocks or networks of clocks.
- Could even send them into space! *



* SpaceQ, see arXiv:2112.07674

Community Roadmap

Iniatiate/Maintain an Extensive Theory Program in Scalar and Vector DM

There are many great scalar and vector DM candidates but there is significant work to do to develop more mature models, production mechanisms and astrophysical signatures.

Enable Strong Collaborations with Quantum Science

Such collaborations are well-positioned to develop new detection signals and strategies including new quantum technologies dedicated to dark matter detection

Initiate Robust R&D Program

The detection of scalar and vector DM requires novel detection strategies and complementary technology, example efforts include the MAGIS program and nuclear clocks. A robust R&D program from proof-of-principle to demonstrator-scale experiments is needed to advance the program.

Community Whitepapers

Snowmass 2021

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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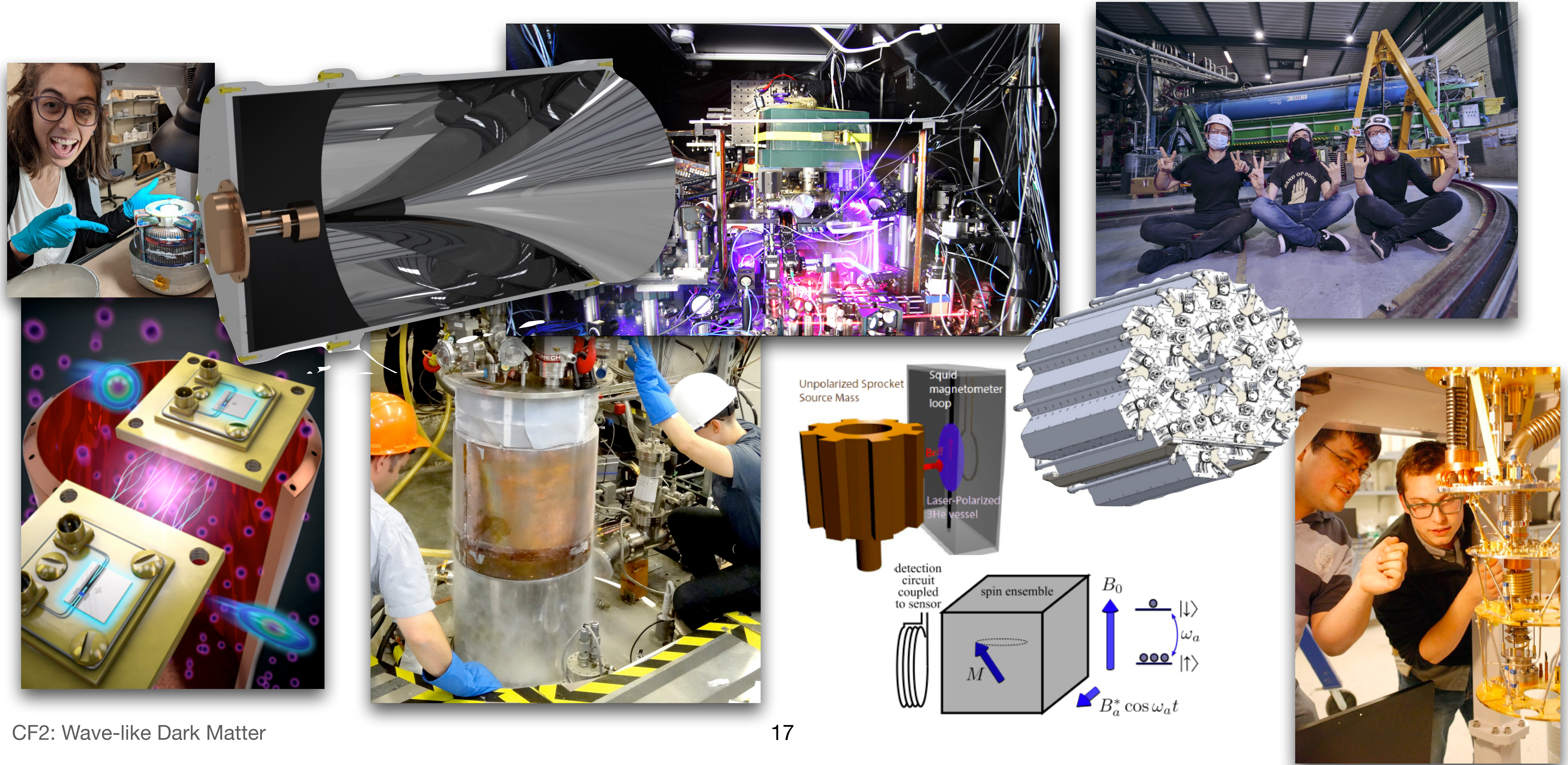
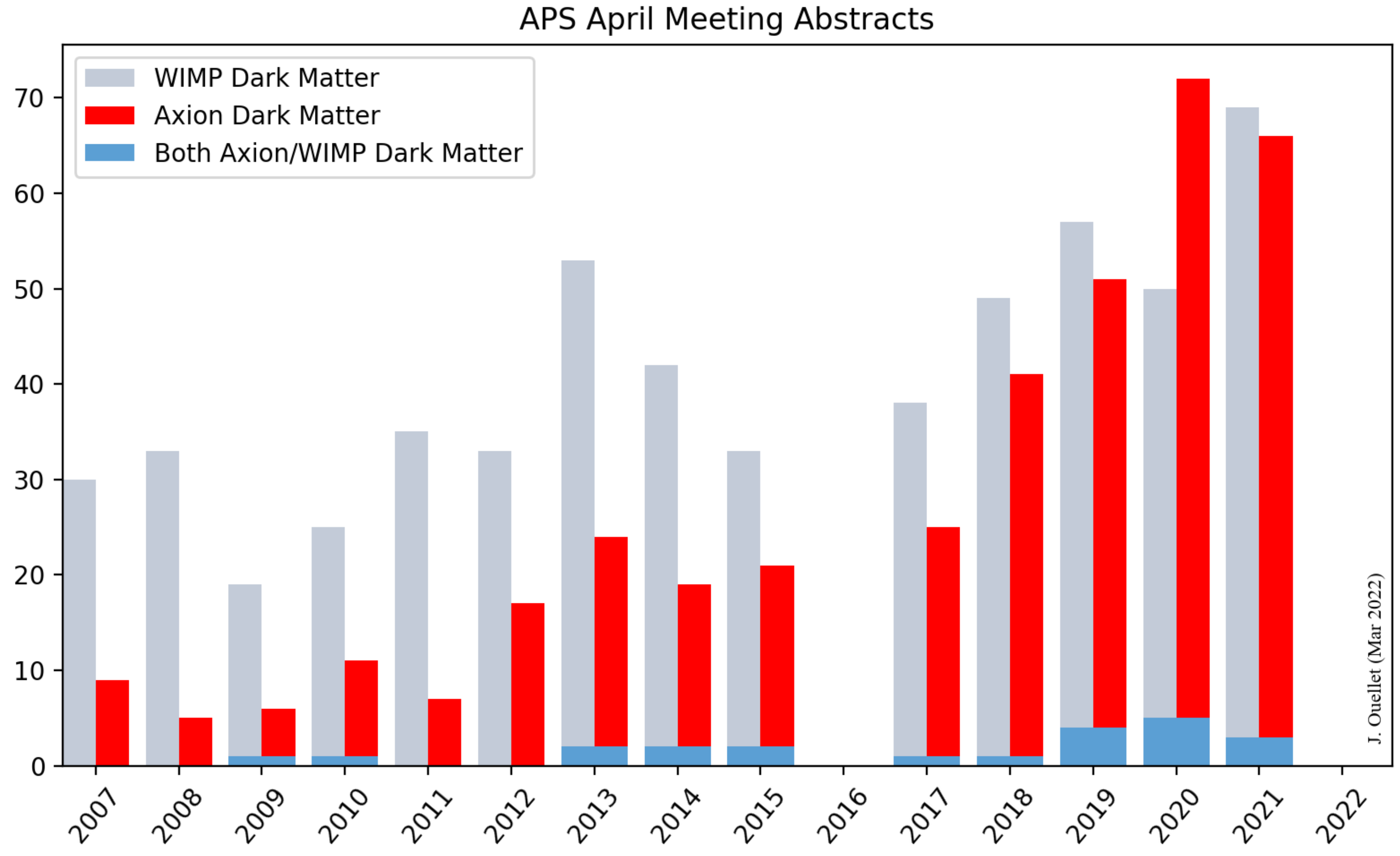


Growing Community

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.



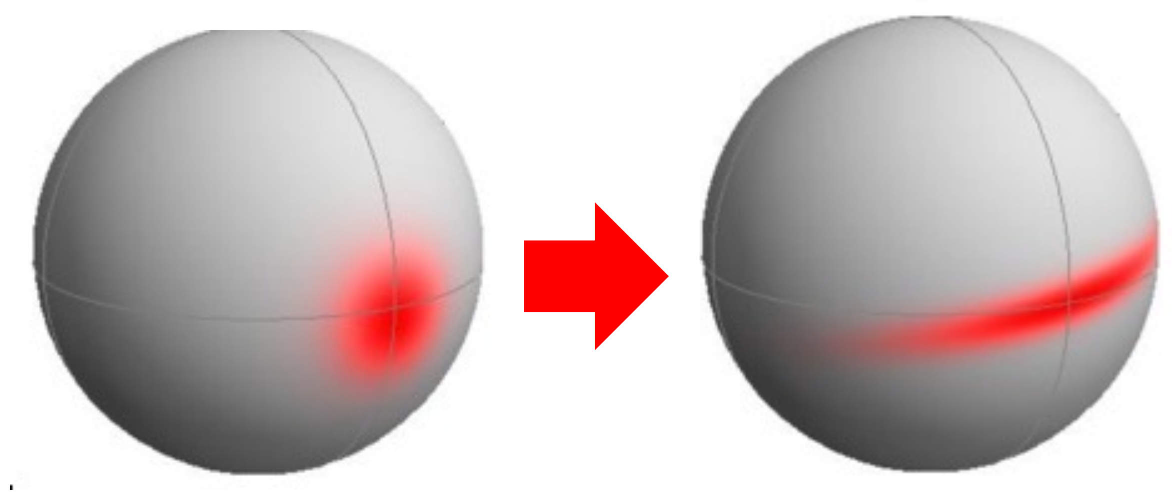
J. Ouellet

Conclusion:

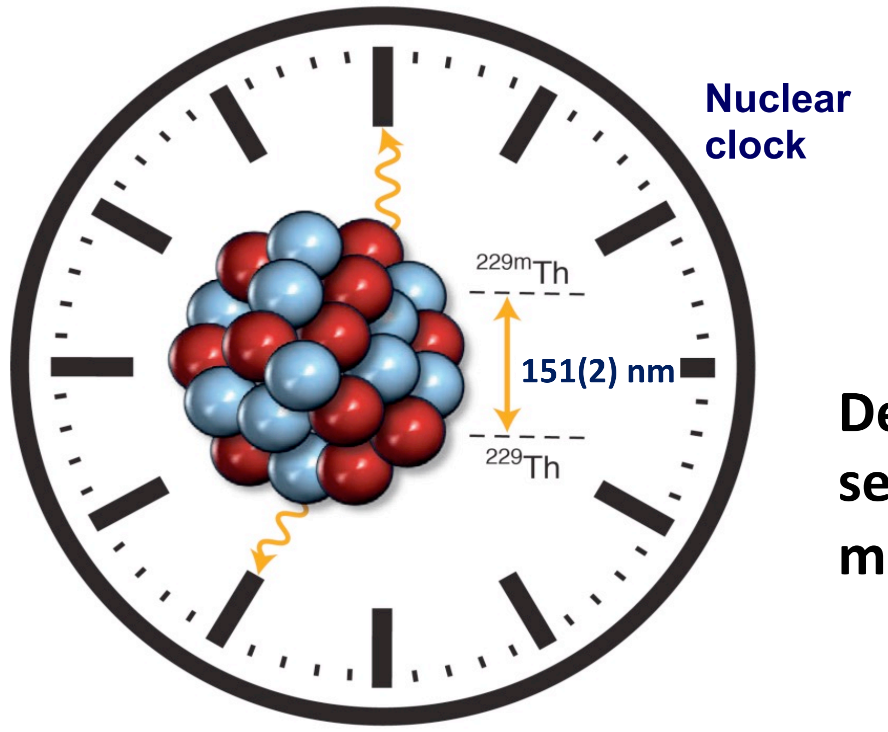
Great Opportunity for Discovery!

- Significant parameter space for the highly motivated QCD axion ready to be explored.
- A good mix of experiments at different scales (Projects, Demonstrators, Proof-of-Concept).
- 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 and strong complementarity to astrophysical probes.

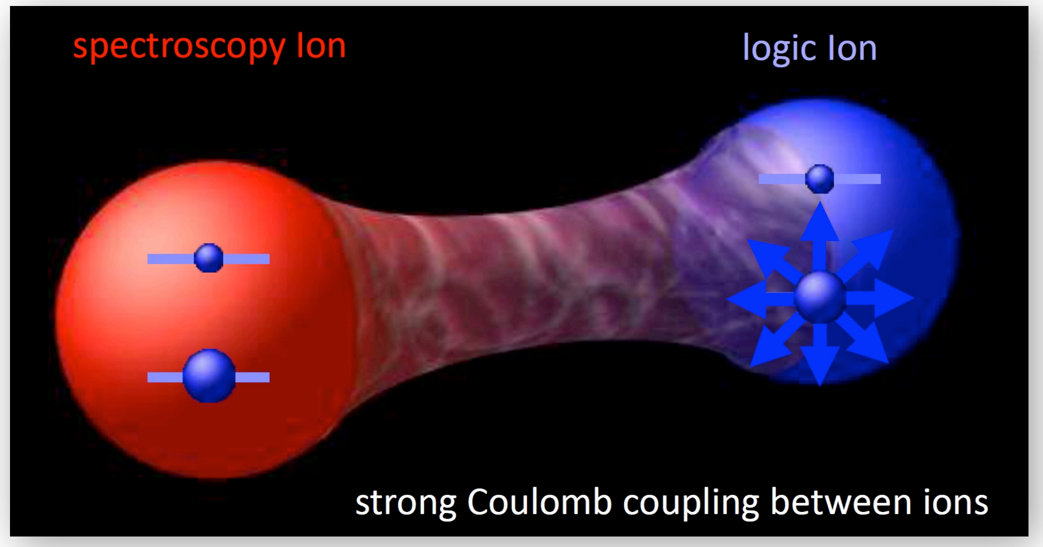
Quantum toolbox & future of quantum sensors for dark matter detection



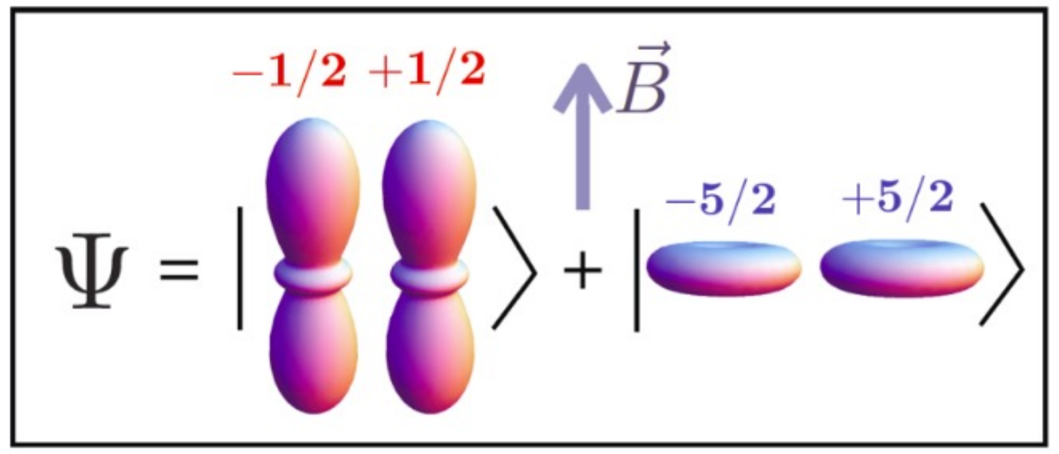
Measurements beyond the standard quantum limit



Dedicated quantum sensors for dark matter detection



Quantum logic spectroscopy



Entanglement: Heisenberg-limited spectroscopy

Image credits: MIT Vuletic group, Piet Schmidt, Nature 517, 592, Nature Physics 14, 198