

# **CF2: Wave-like Dark Matter**

**Snowmass Meeting July 2022 - Frontier Report**

**Lindley Winslow, Gray Rybka, Joerg Jaeckel**

# Wave-like Dark Matter Candidates

**Wave-like Definition:** Mass  $< 1$  eV

**Broad Candidate Categories:**

- Pseudo-scalar
- Scalar
- Vector

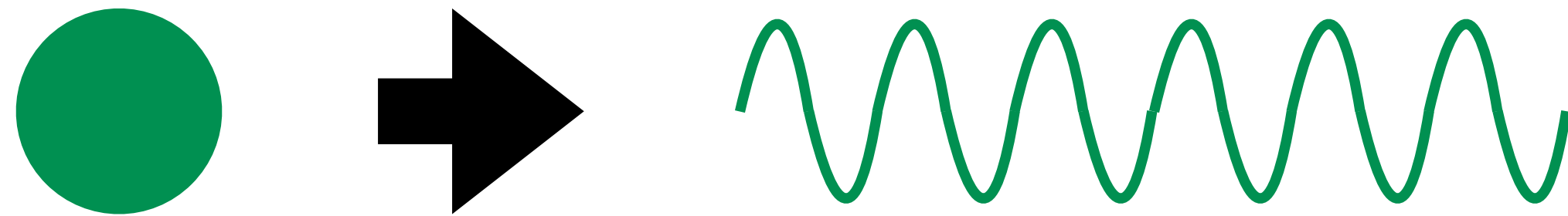
**Production:** Athermal production (misalignment).

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



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

# Why Wave-like Dark Matter (WLDM)?



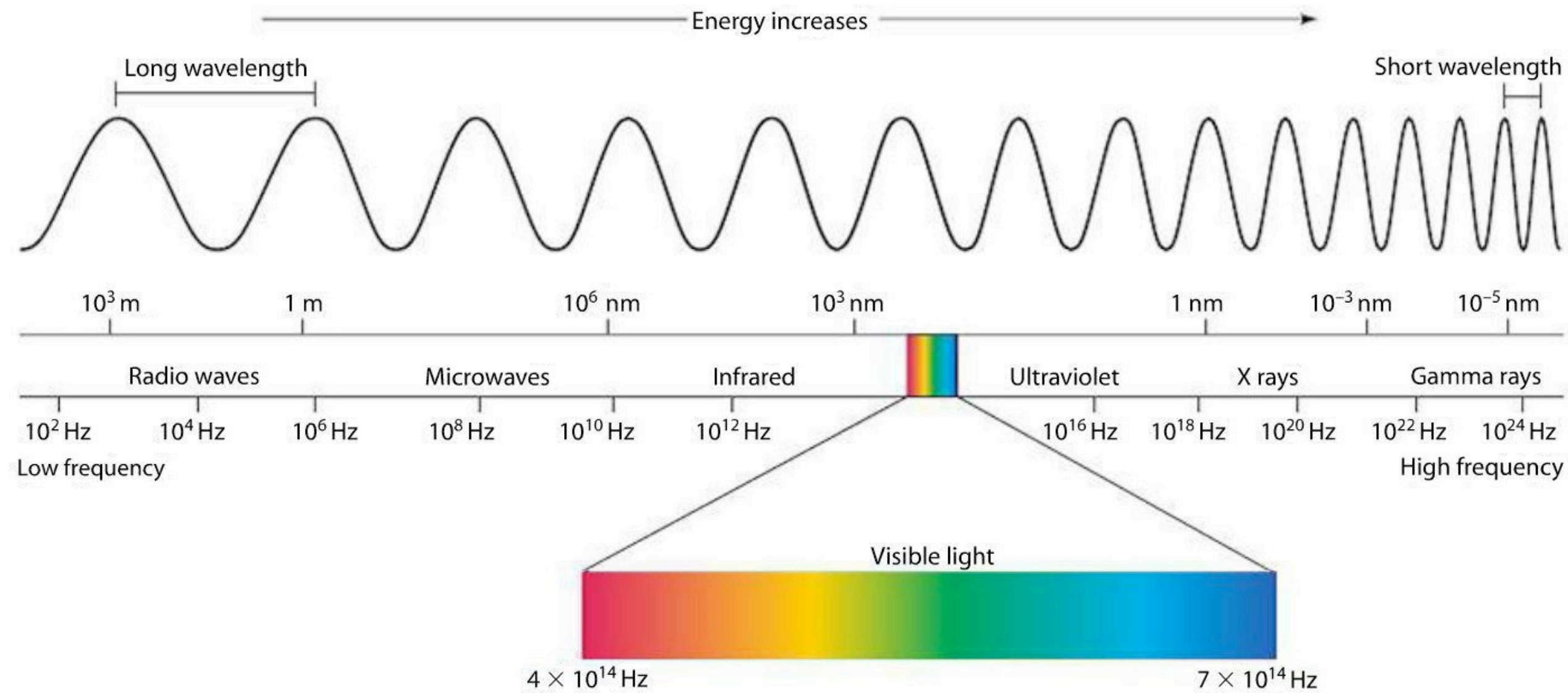
*At Masses less than 1 eV, particles cross the wave-particle divide and start behaving as waves.*

*Detection techniques are inherently quantum!*

*Detection techniques change as a function of frequency!*

*Looking for a suite of experiments.*

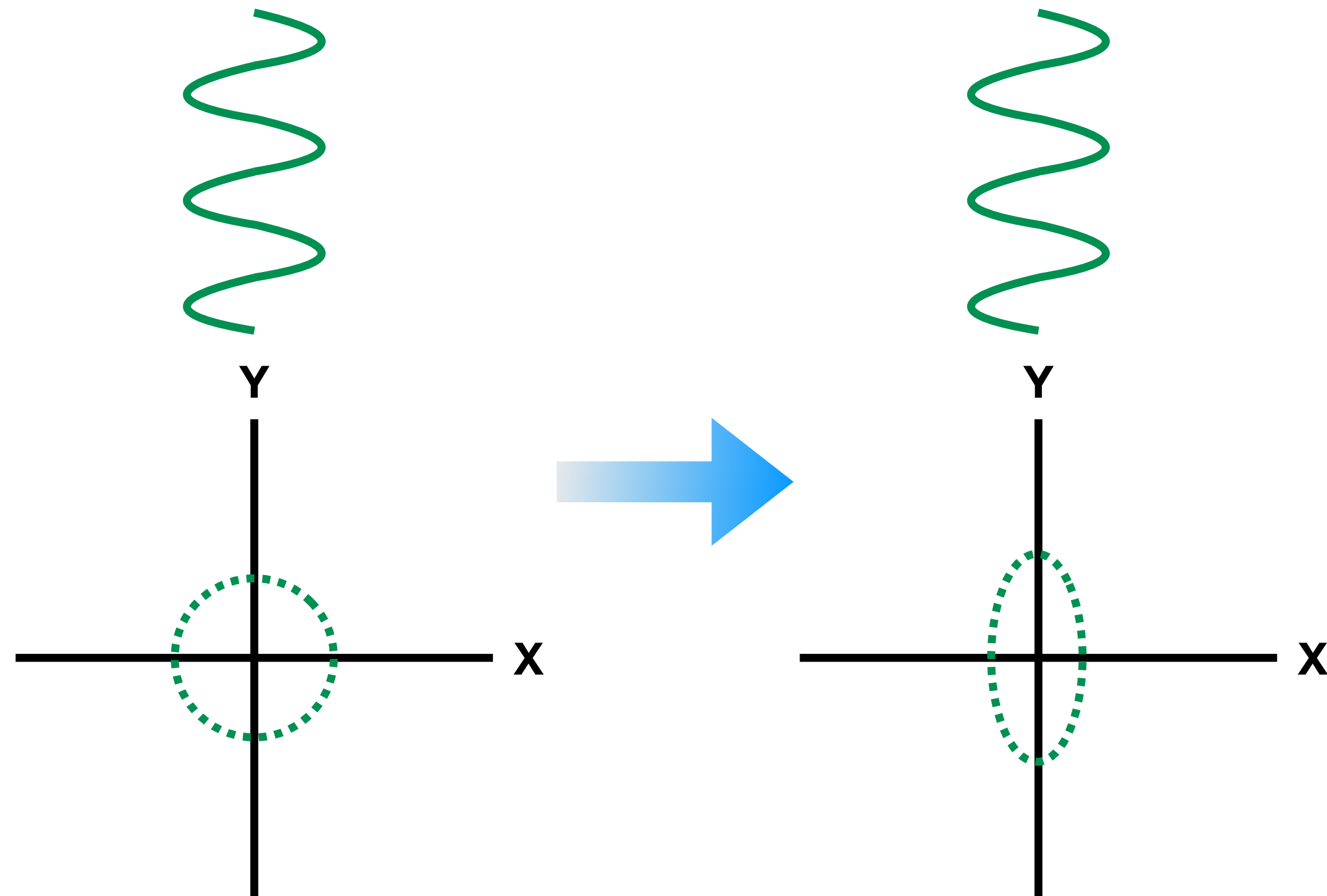
# A Suite of Experiments: Intuition from Electromagnetic Spectrum



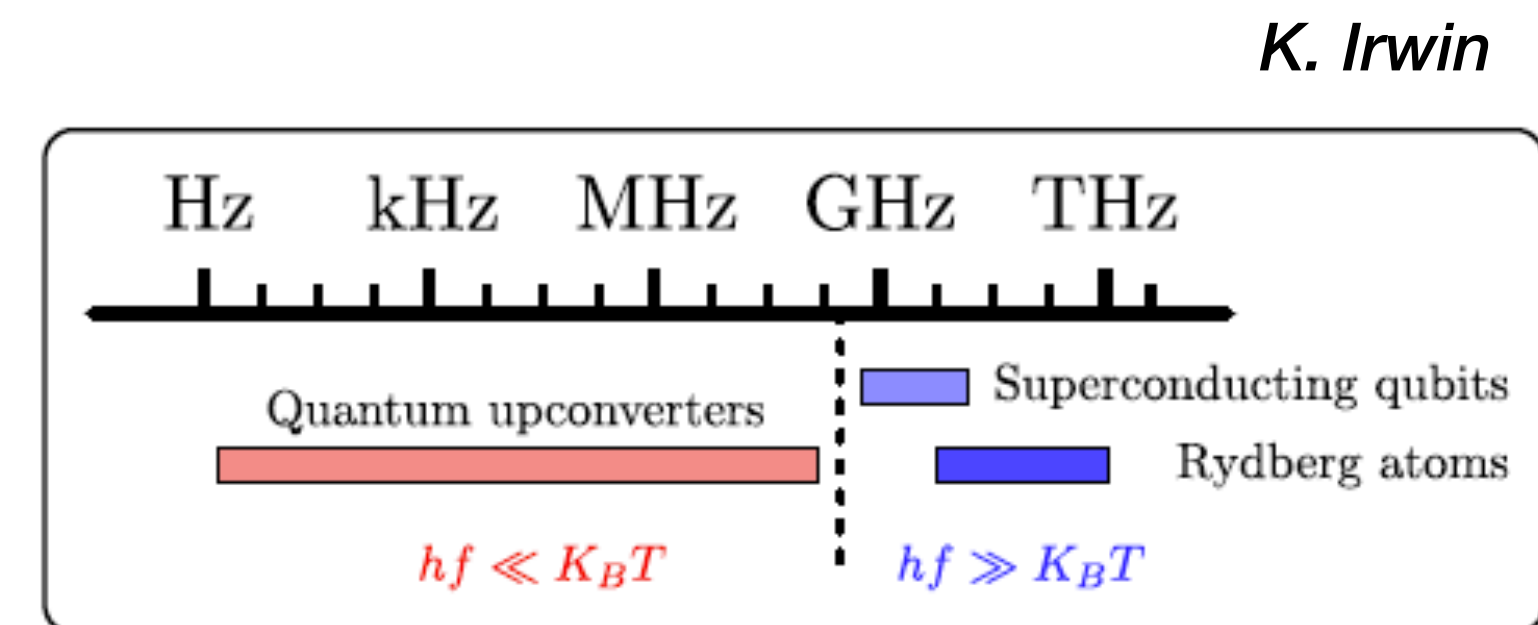
The techniques will change as you increase frequency.

The same is true for WLDM!

# Key Technology: Beyond the Standard Quantum Limit



Beat the Quantum Limit by Pushing Noise into Different Observable

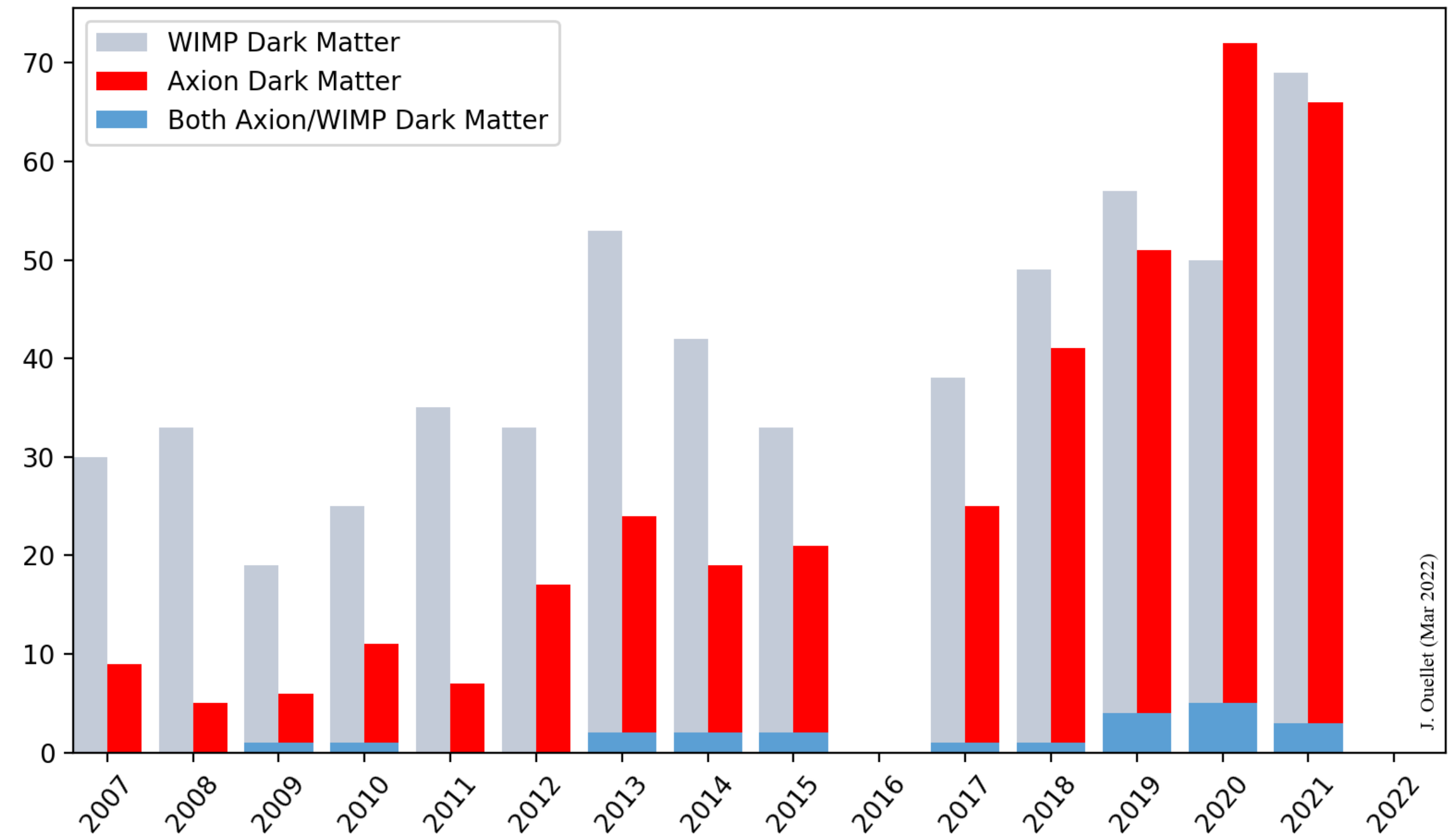


**Different noise sources**  
**Different frequency ranges**  
**Different Techniques**

# 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.*

APS April Meeting Abstracts



J. Ouellet

J. Ouellet (Mar 2022)

# Community Goals

## **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

## **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.

## **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.

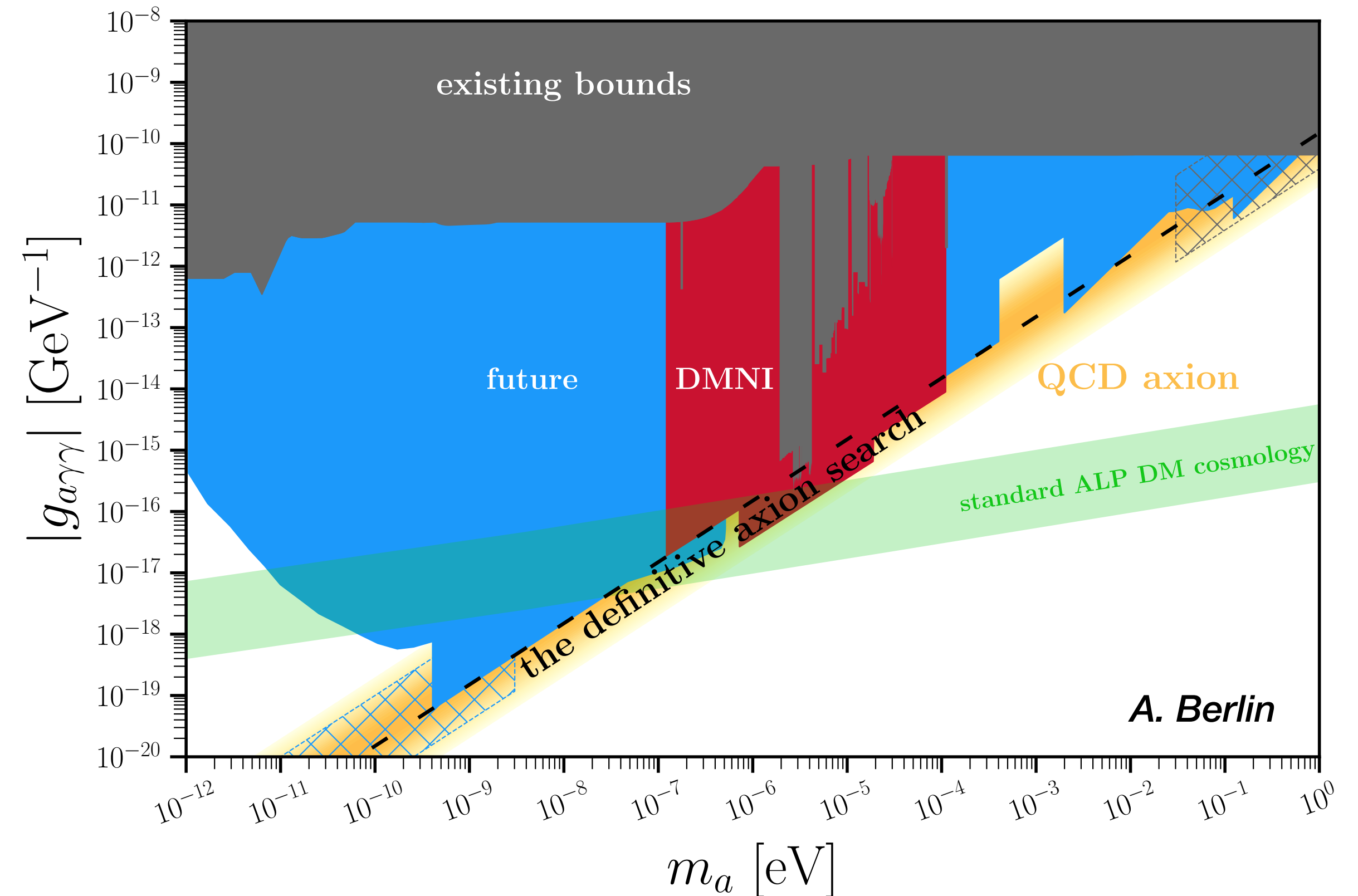
## **Support Theory Beyond the QCD Axion**

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. ADD  
Detection Modalities



# Goal: Definitive QCD Axion Search

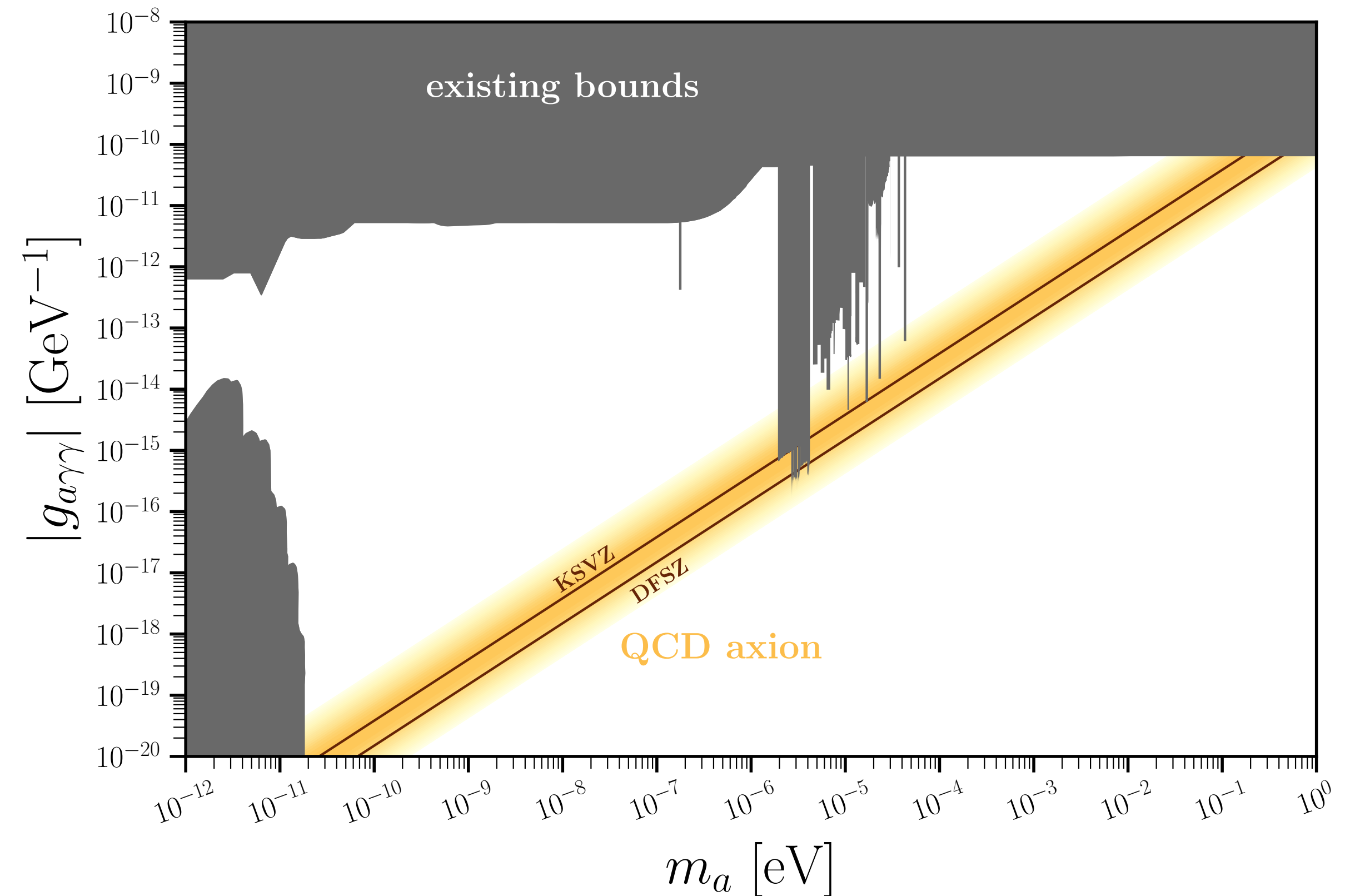
With a suite of experiments discover the QCD axion in the mass range of  $10^{-12}$  eV to 1 eV.



# The QCD Axion

- $U(1)_{PQ}$  introduced to preserve CP symmetry in the Strong Interaction.
- The QCD axion is a pseudo-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.\*

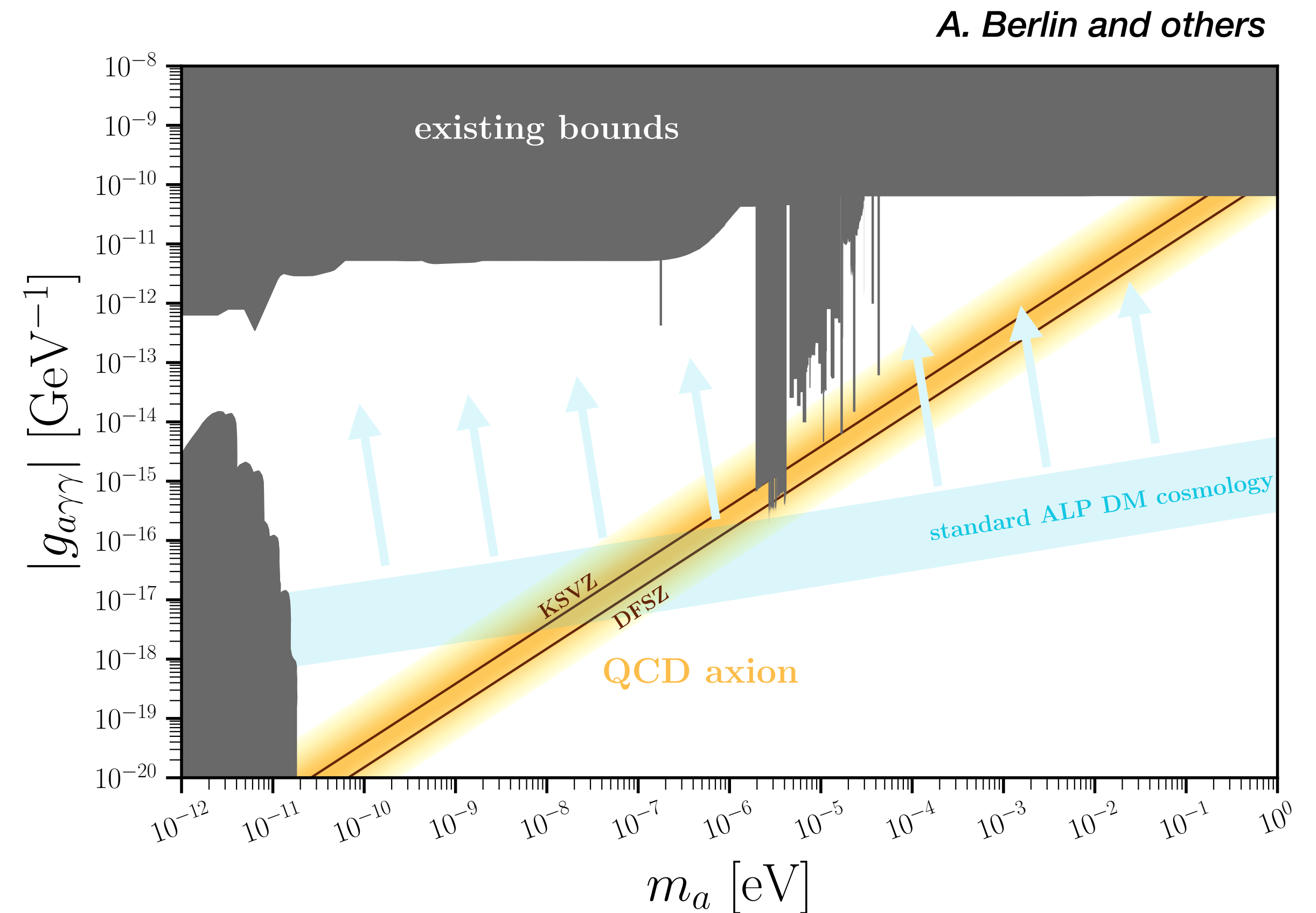
A. Berlin and others



\* *DFSZ is the benchmark for the field.*

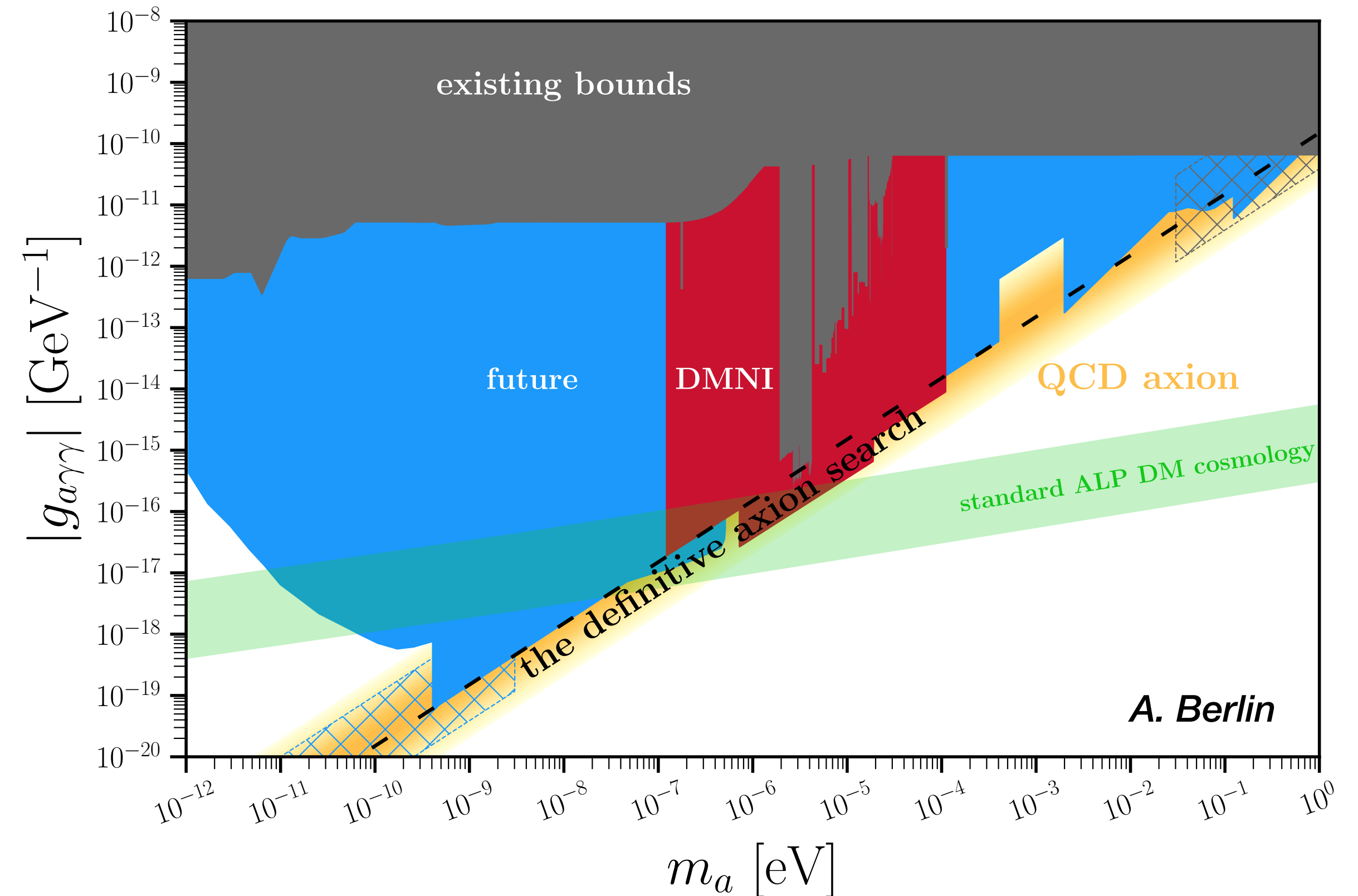
# Axion-Like Particles (ALPs)

- 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.



# Goal: Definitive QCD Axion Search

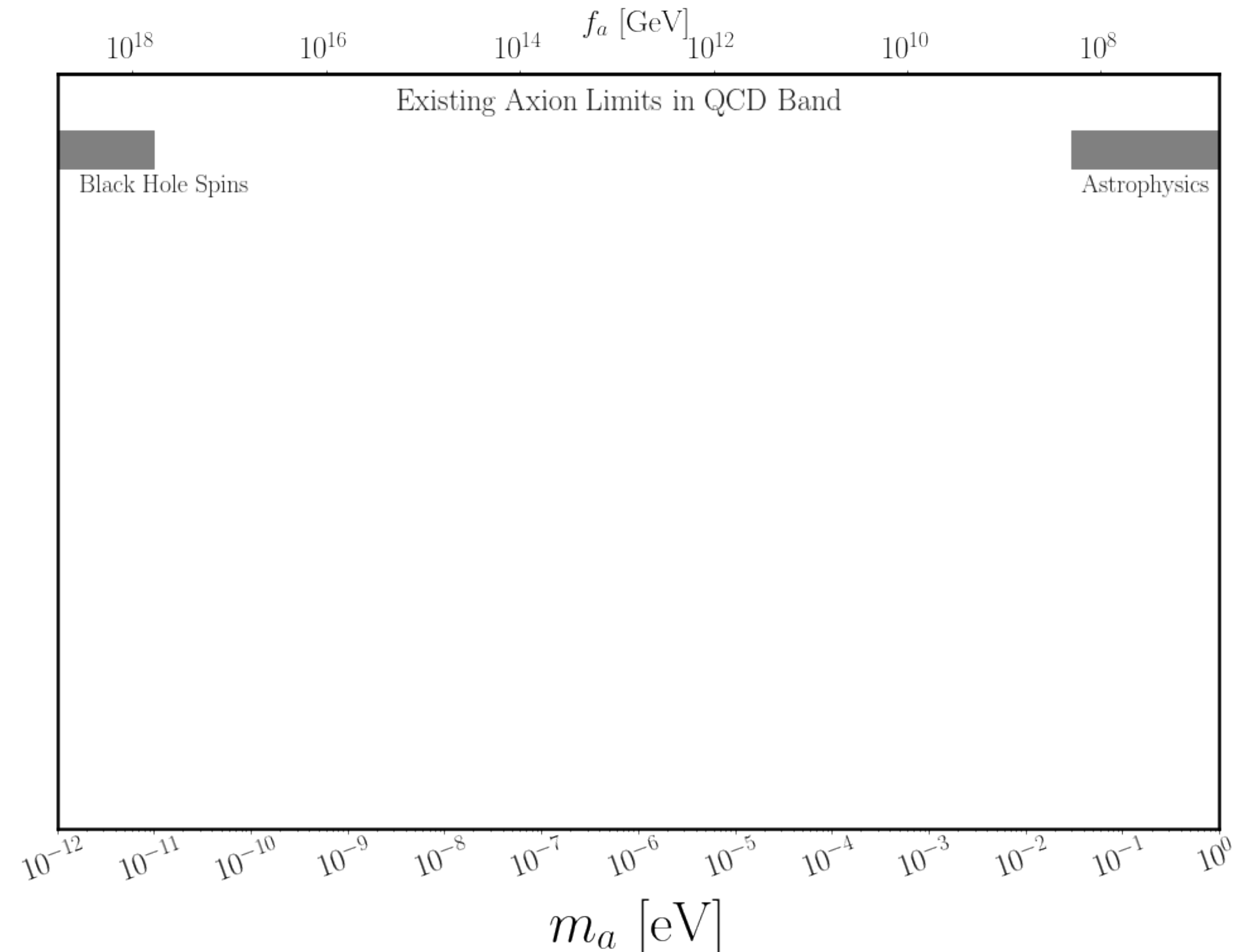
- ADMX-G2, HAYSTAC, CAPP are into the QCD axion band.
- The DMNI projects: ADMX-EFR and DMRadio- $m^3$  are ready to start construction.
- Several Demonstrator scale experiments would be ready for a new DMNI process.



# Status: Previous Snowmass

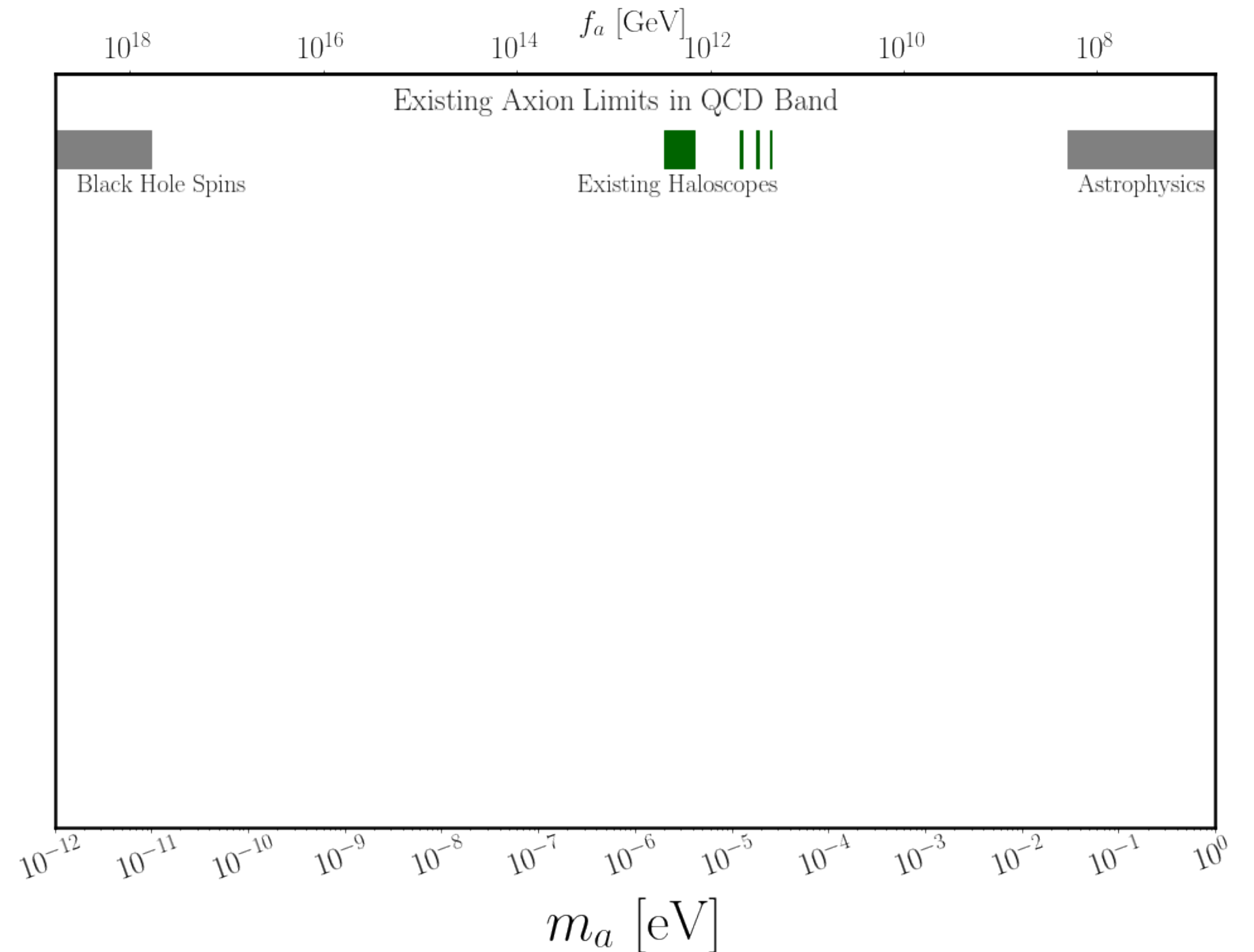
- No Experiments had probed the QCD band.

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



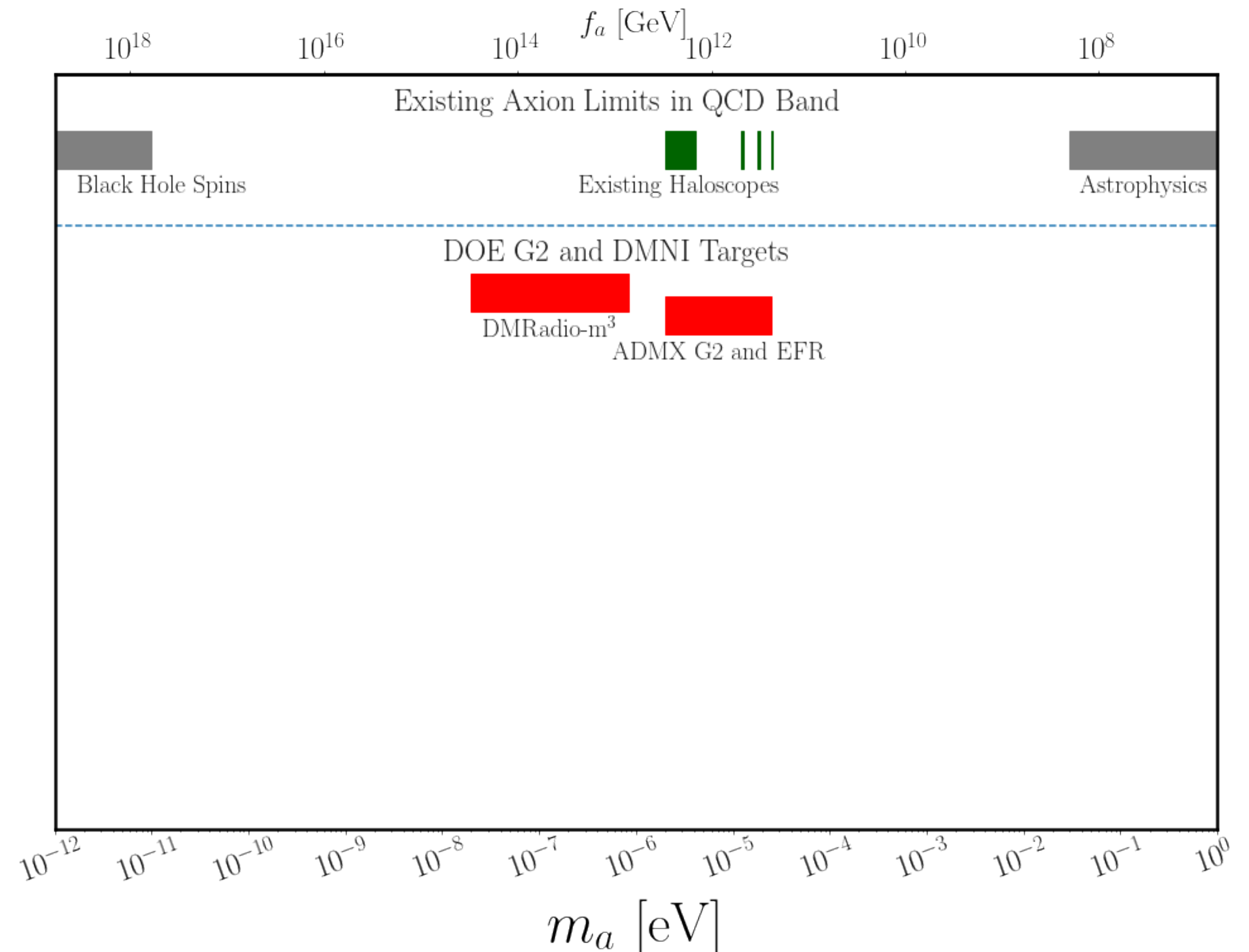
# Status: Current

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



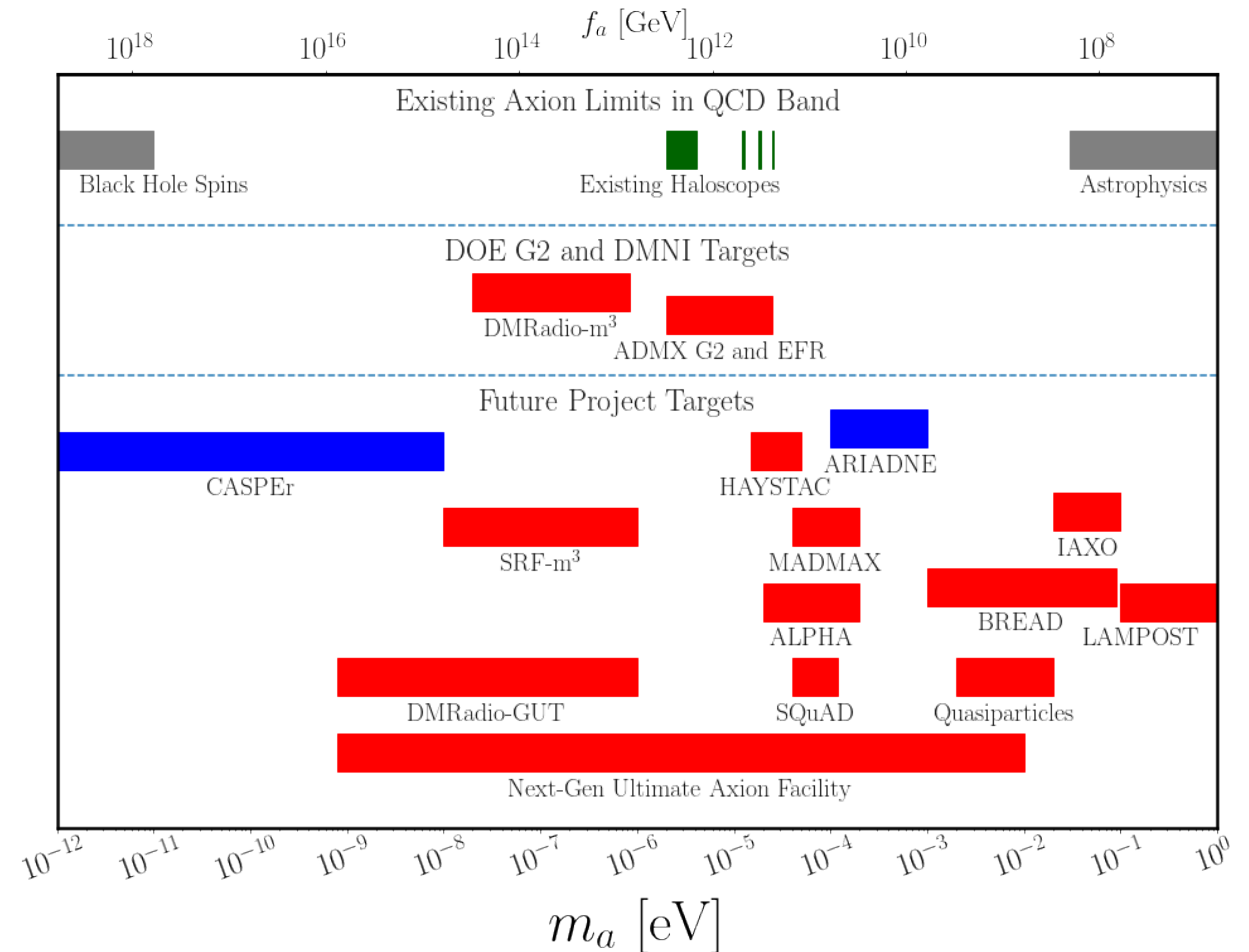
# Dark Matter New Initiatives (DMNI)

- 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

- 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.





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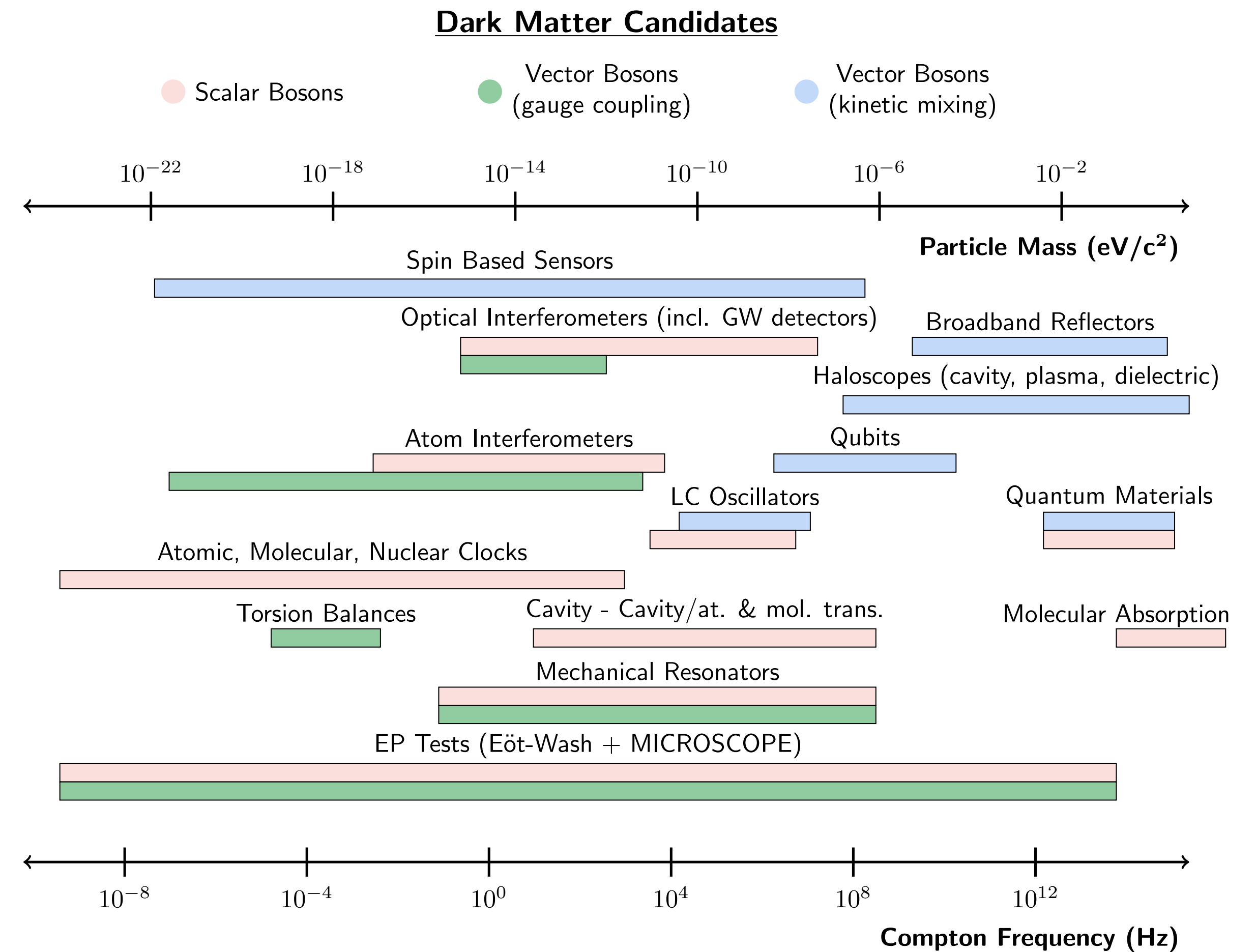
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# New Horizons: Scalar and Vector Dark Matter

## 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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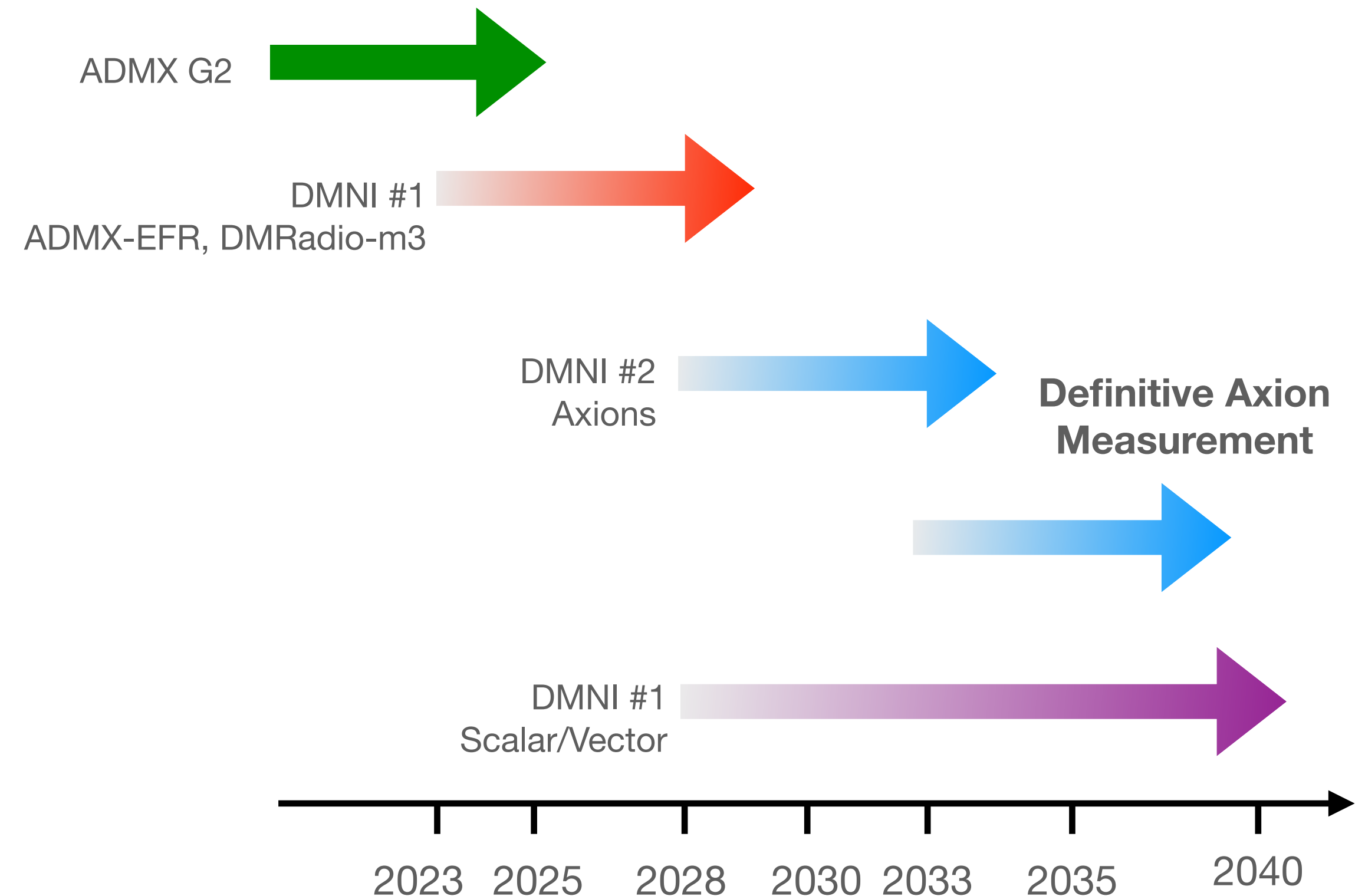
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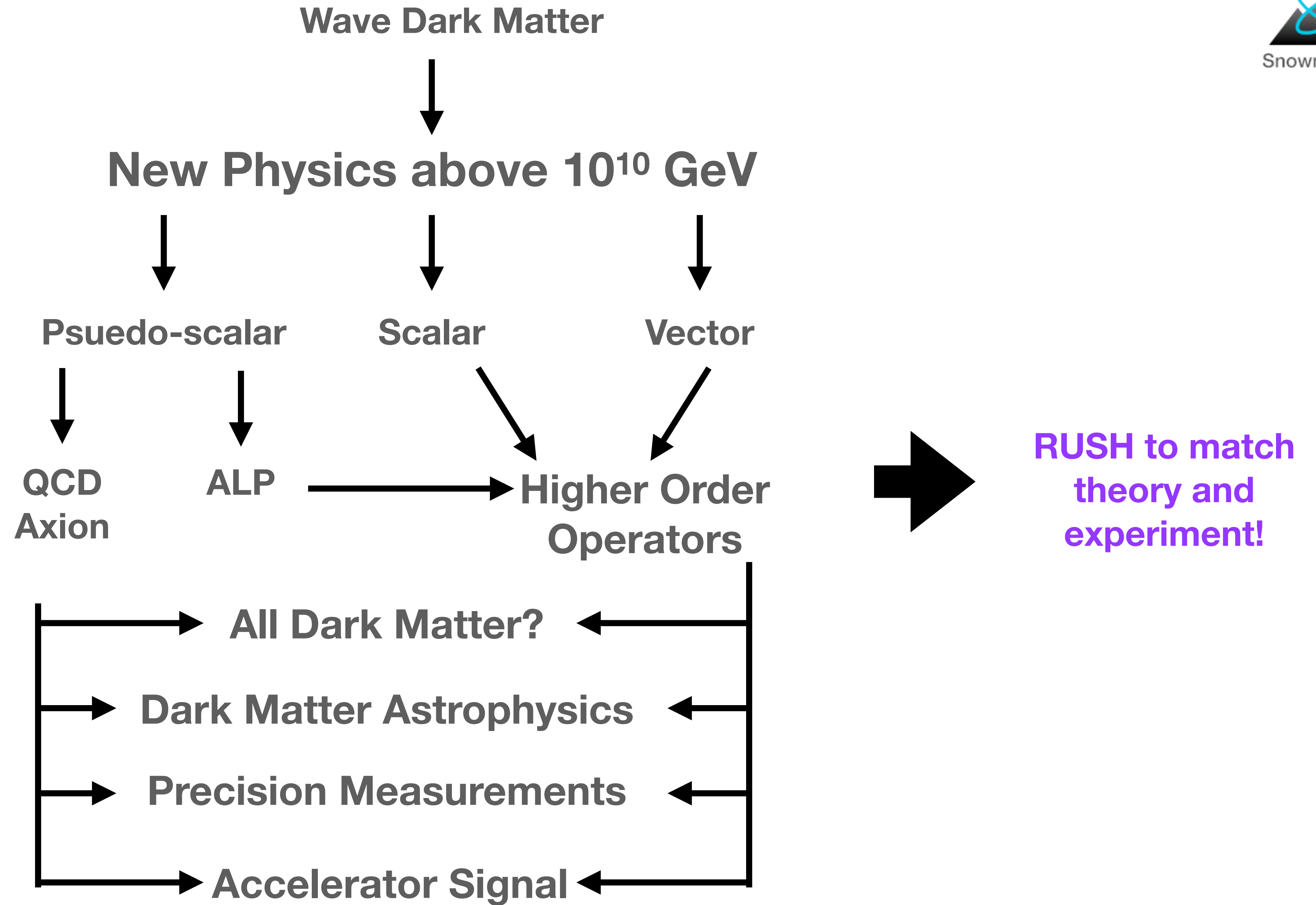
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# Community Roadmap: Time Line

- 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.



# Preparing for Discovery: Wave DM complementarity



# QCD Axion

Mass

Mechanism

$< 1\mu\text{eV}$

$> 1\mu\text{eV}$

KSVZ

DFSZ

More Quarks!

More Higgs!  
(Likely Accessible)

Pre-Inflation

Post-Inflation

RUSH to match theory and experiment!

SMASH?  
See-Saw  
Neutrino Connection

New GUT-scale Physics!

CMB B-Mode Signature

New Physics Before GUT-scale

# Community Whitepapers

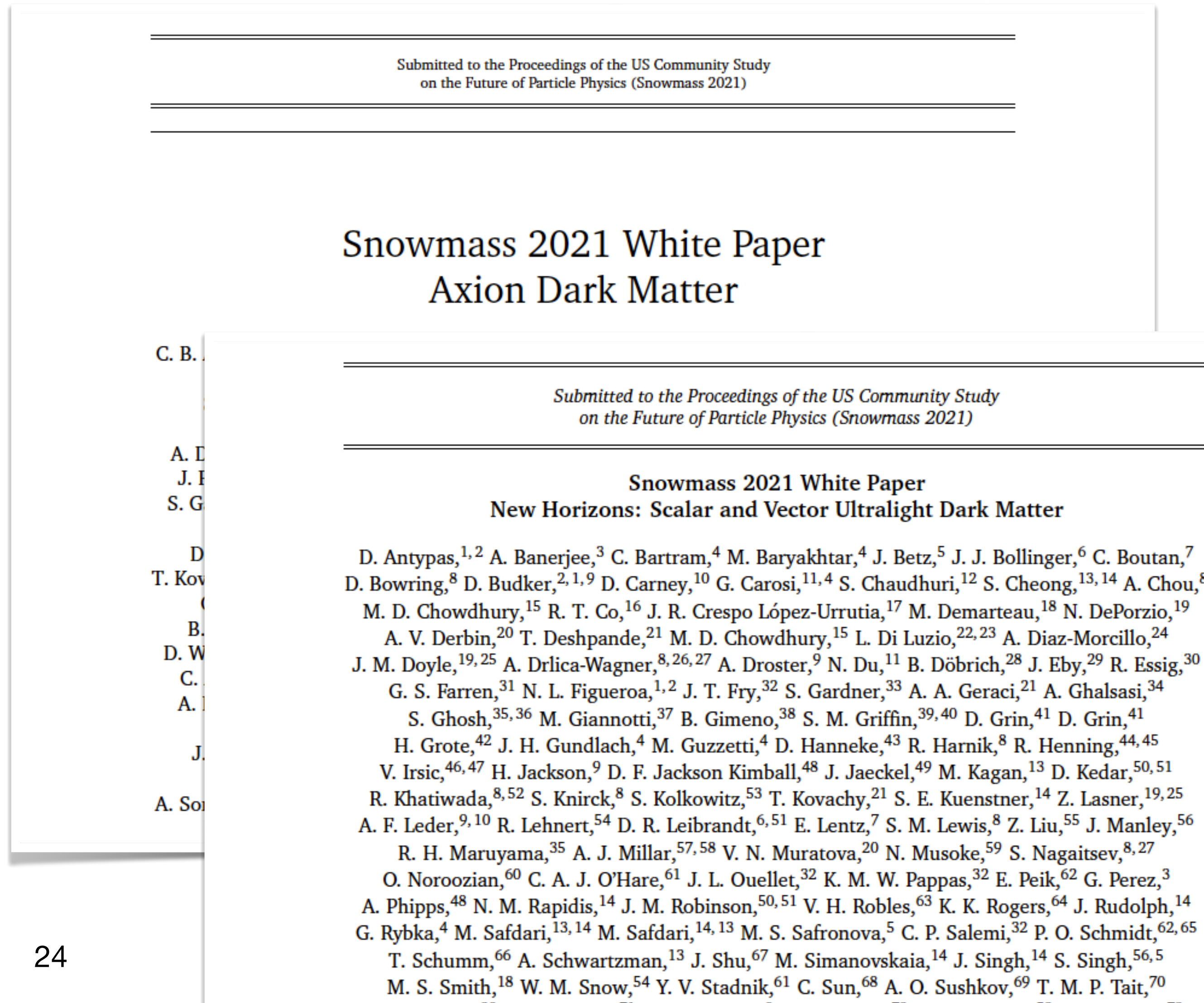
*The community road map, theory, cosmology, and experimental details are presented in our two community white papers.*

## Axion Dark Matter arXiv:2203.14923

*Editors: J. Jaeckel, G. Rybka, L. Winslow*

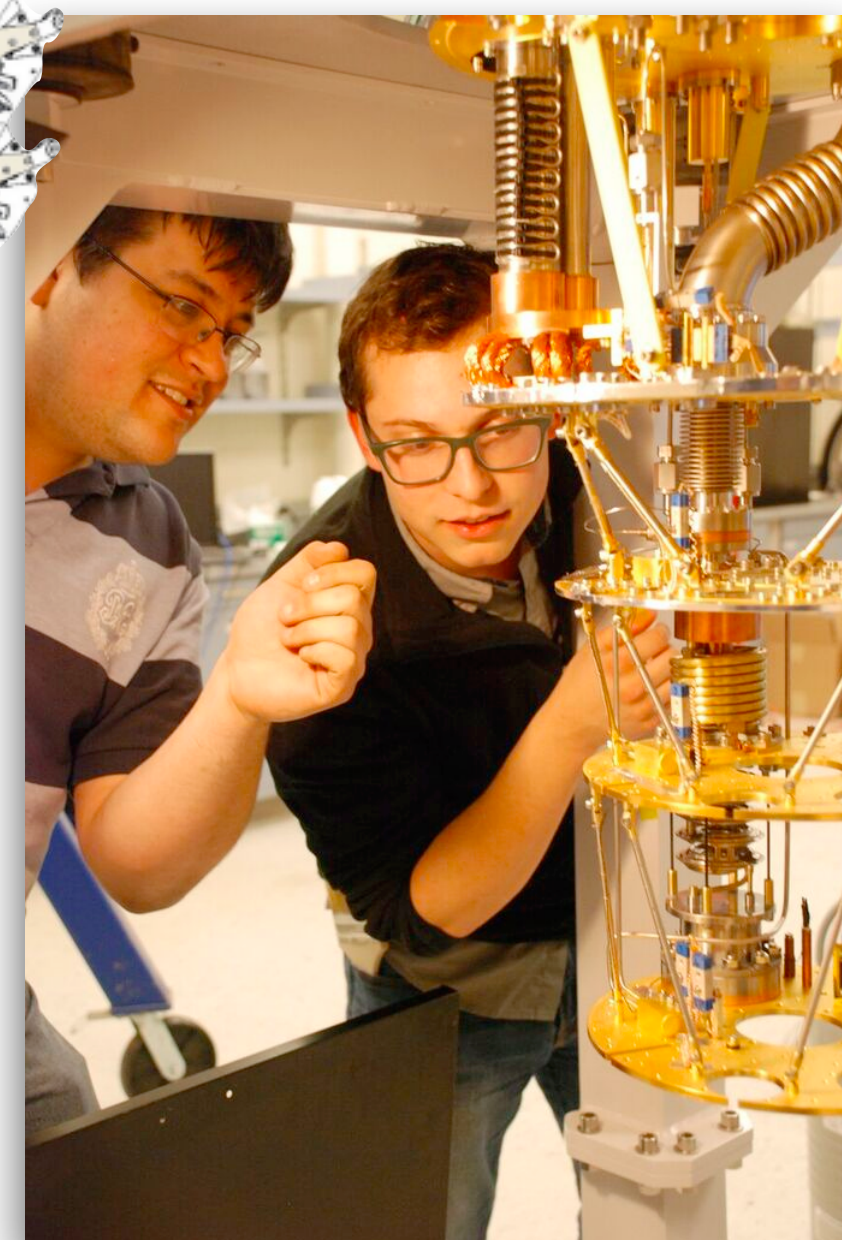
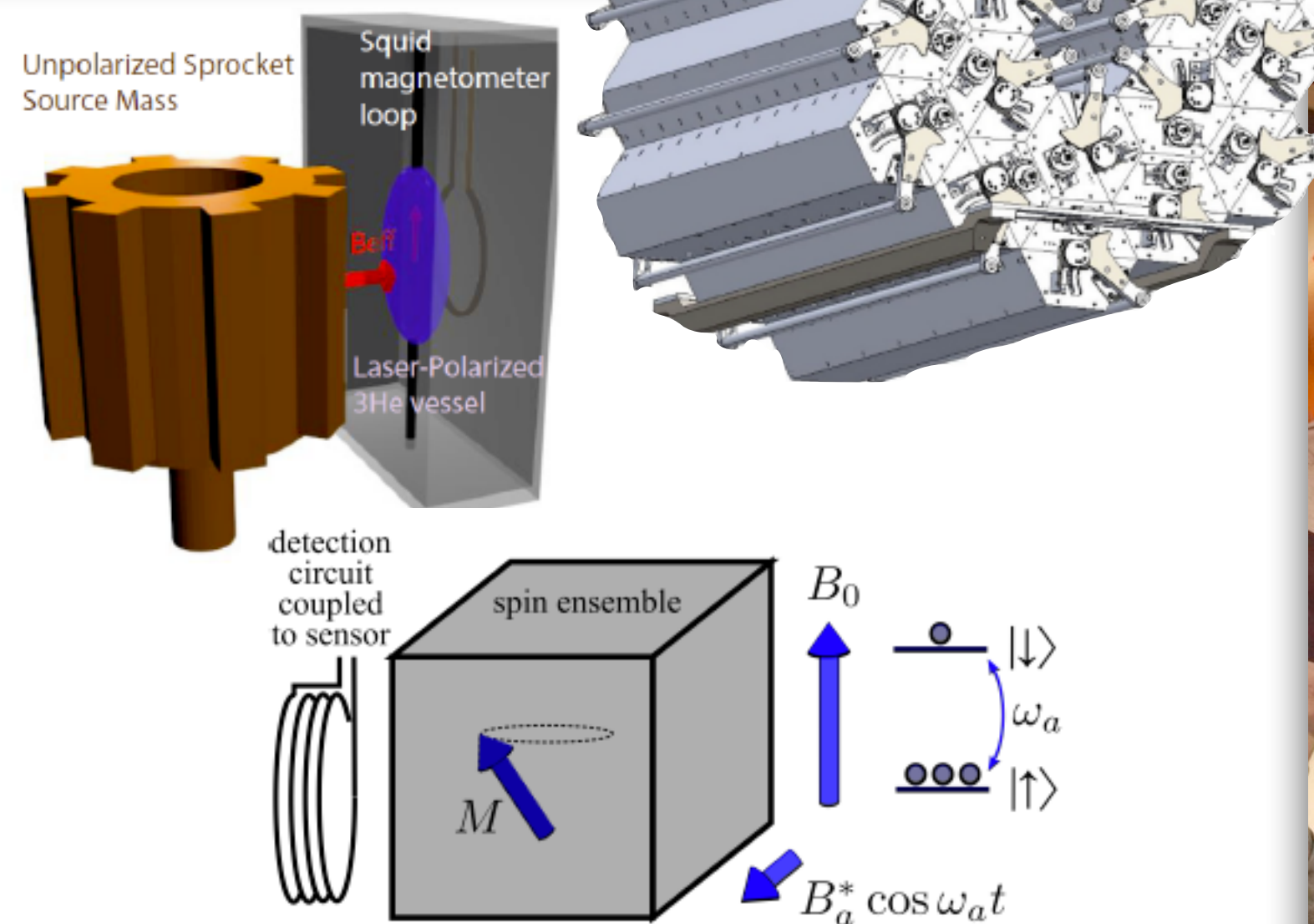
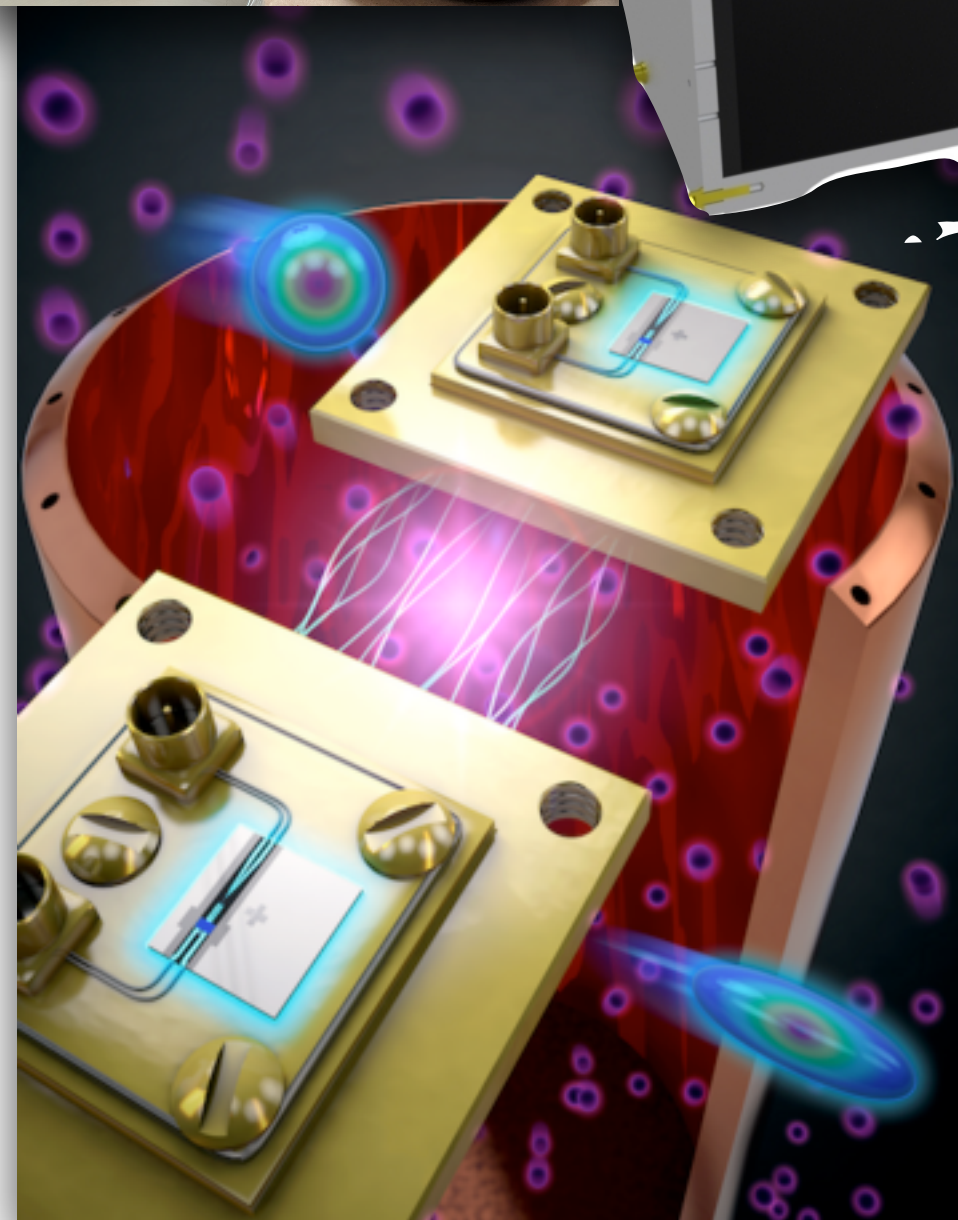
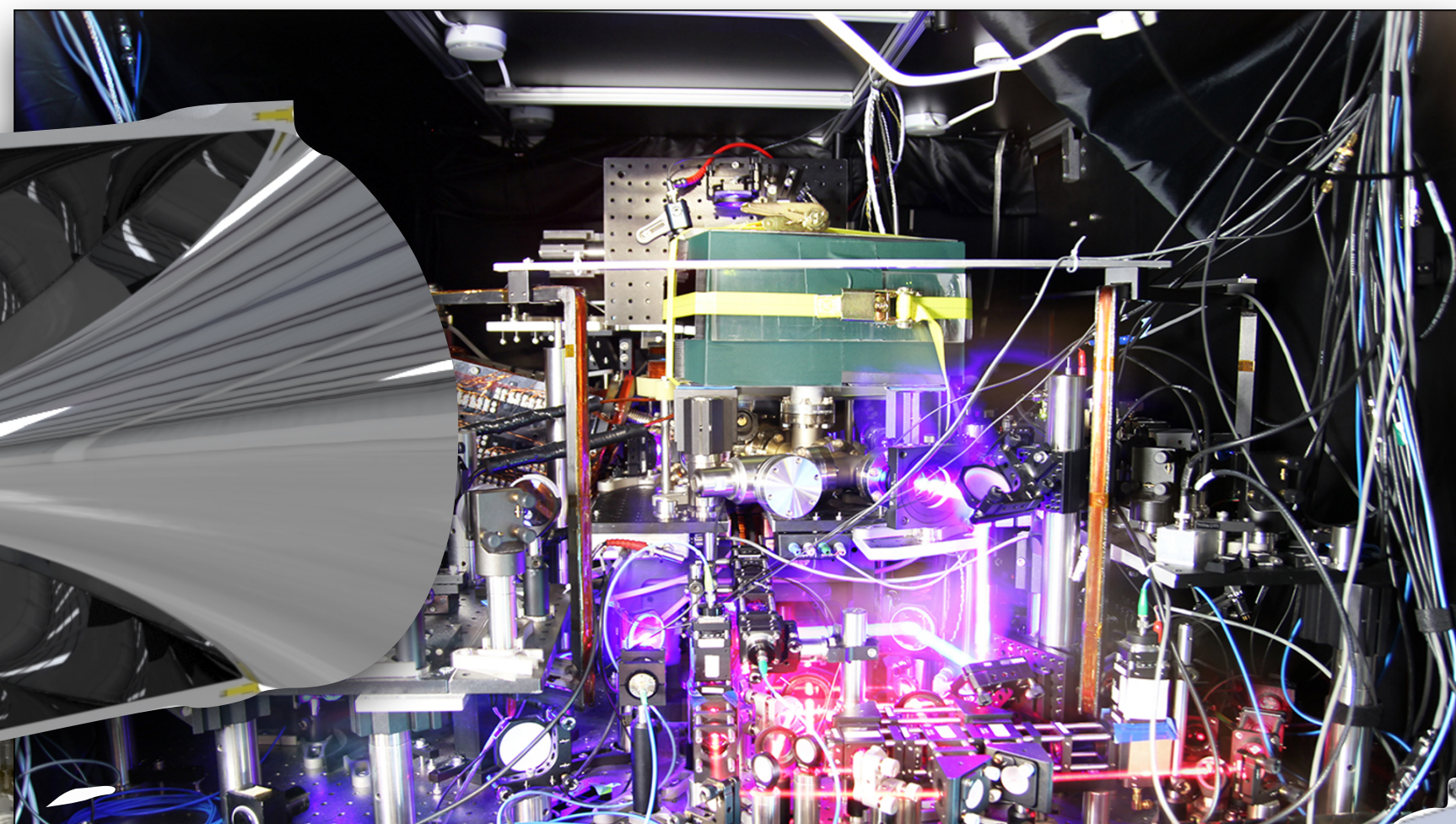
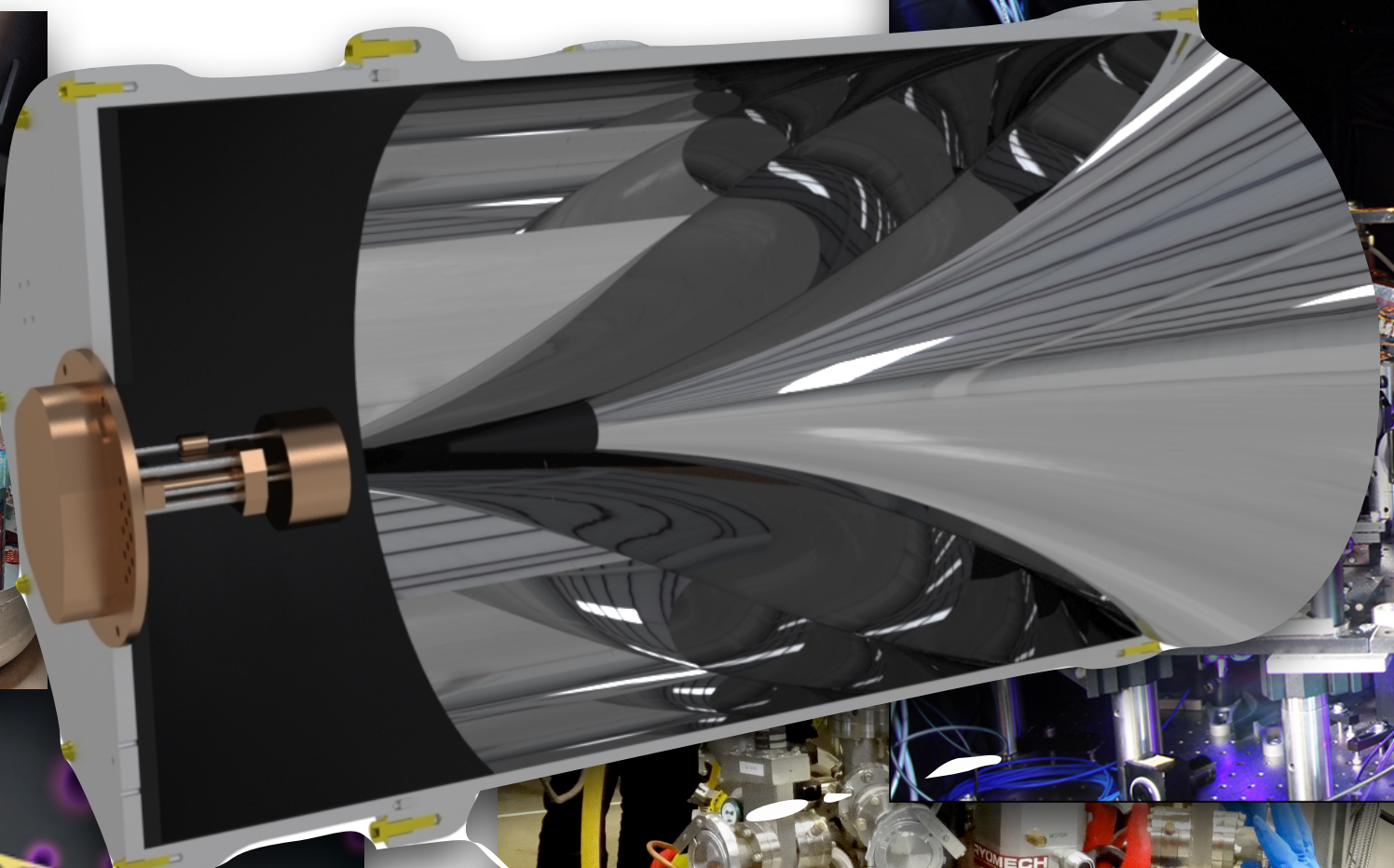
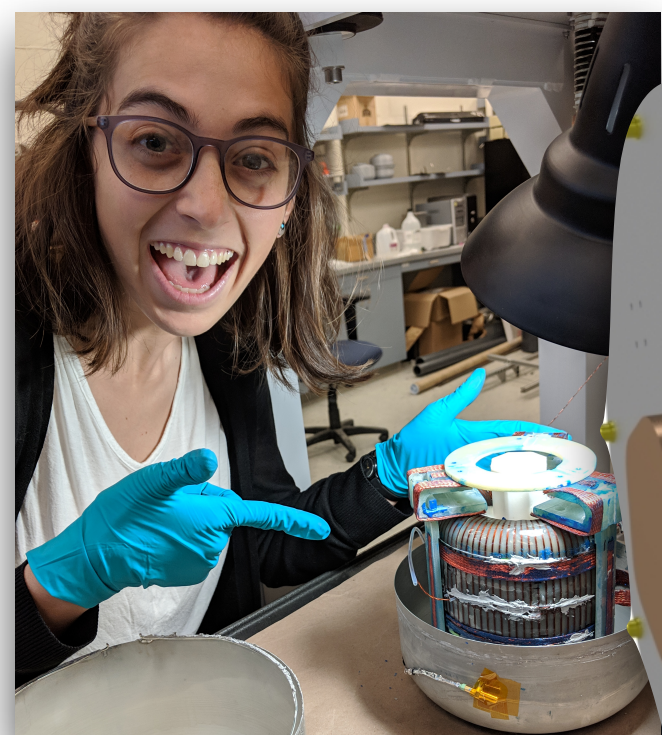
## New Horizons: Scalar and Vector Ultralight Dark Matter arXiv:2203.14915

*Editors: M. Safronova and S. Singh*





# Thank you Wave-like Dark Matter Community!



# 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).
- 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.