CF2: Wave-like Dark Matter

Snowmass Meeting July 2022

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Wave-like Dark Matter Candidates

Wave-like Definition: Mass < 1 eV

Broad Candidate Categories:

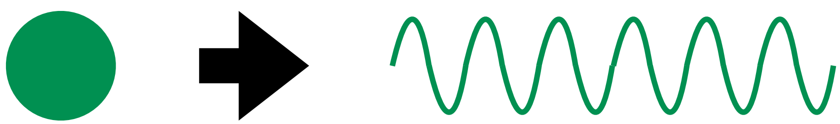
- Pseudo-scalar
- Scalar
- Vector

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)?



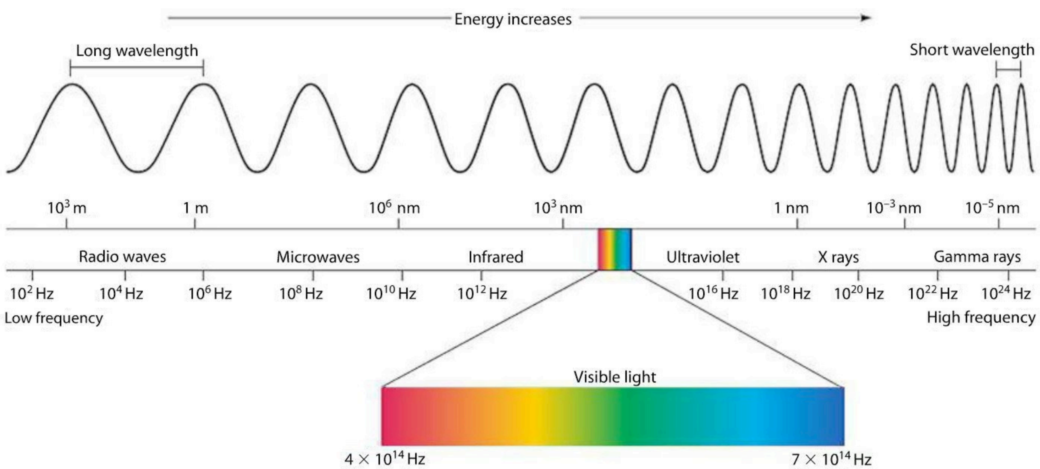
At Masses less than 1 eV, particles cross the wave-particle divide and start behaving as waves.

Detection techniques are inherently quantum!

Detection techniques change as a function of frequency!

Looking for a suite of experiments.

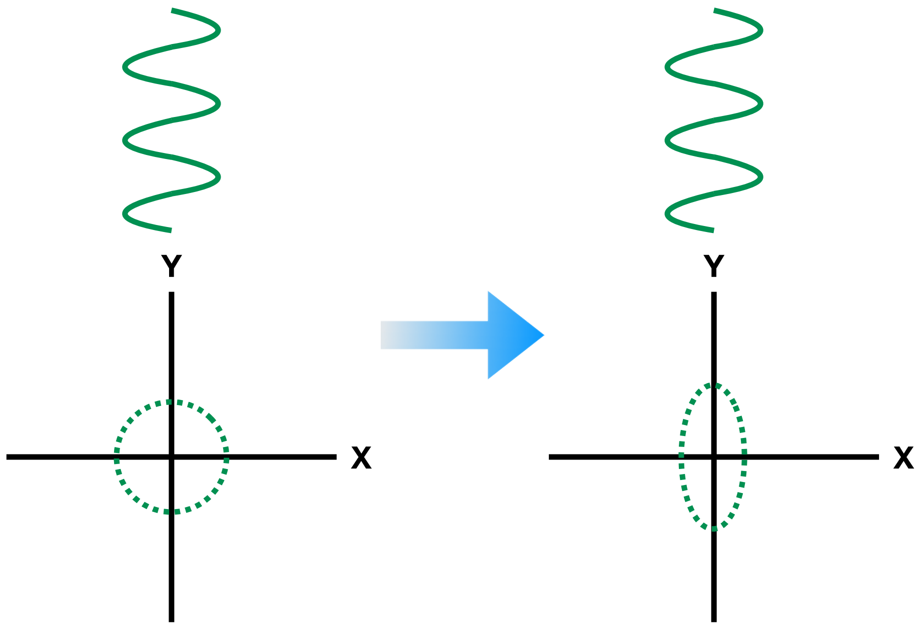
A Suite of Experiments:
Intuition from Electromagnetic Spectrum



The techniques will change as you increase frequency.

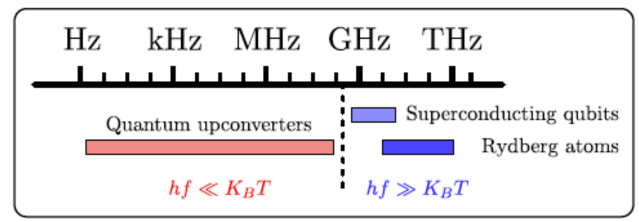
The same is true for WLDM!

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

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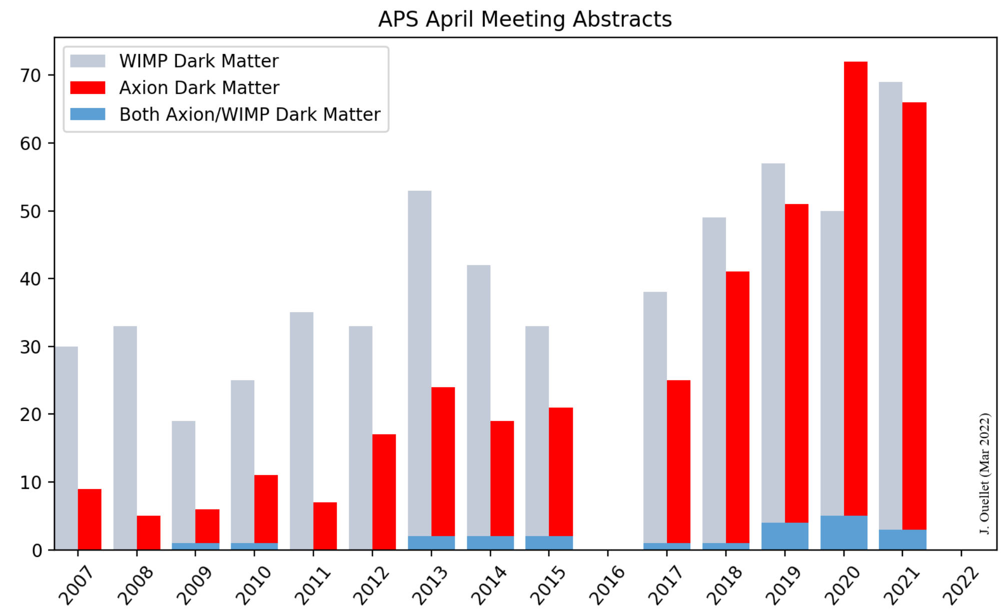
With advancements in cryogenics, magnet and quantum sensing coupled with better theoretical understanding of the cosmology of wave-like dark matter, the community has grown quickly.



J. Ouellet

Community Goals

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 in Scalar/Vector Dark Matter

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

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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.

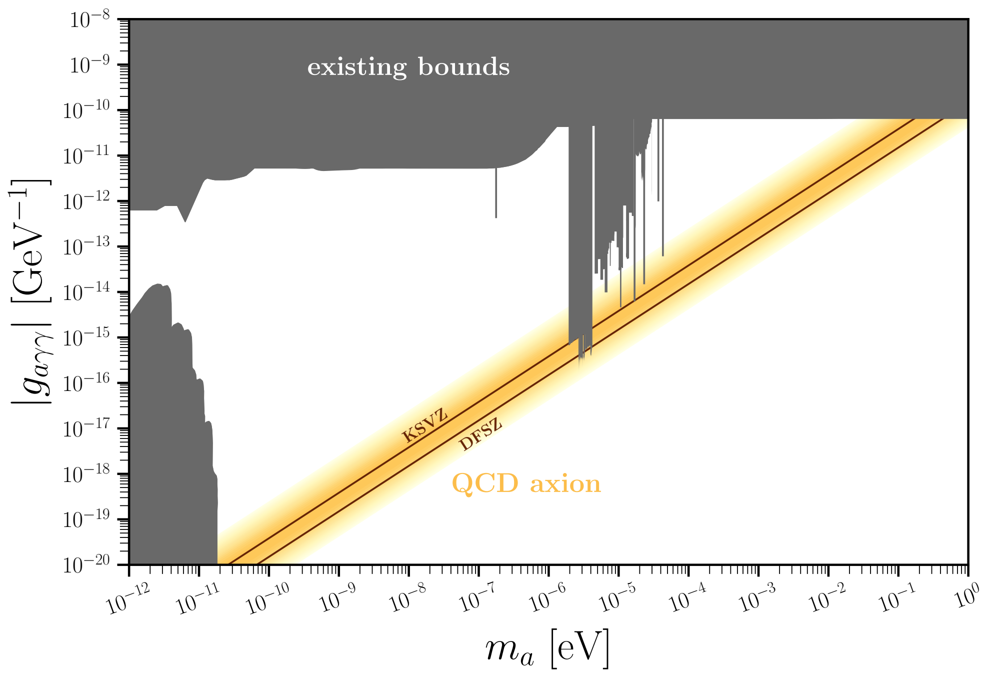
Support Theory Beyond the QCD Axion

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

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.*

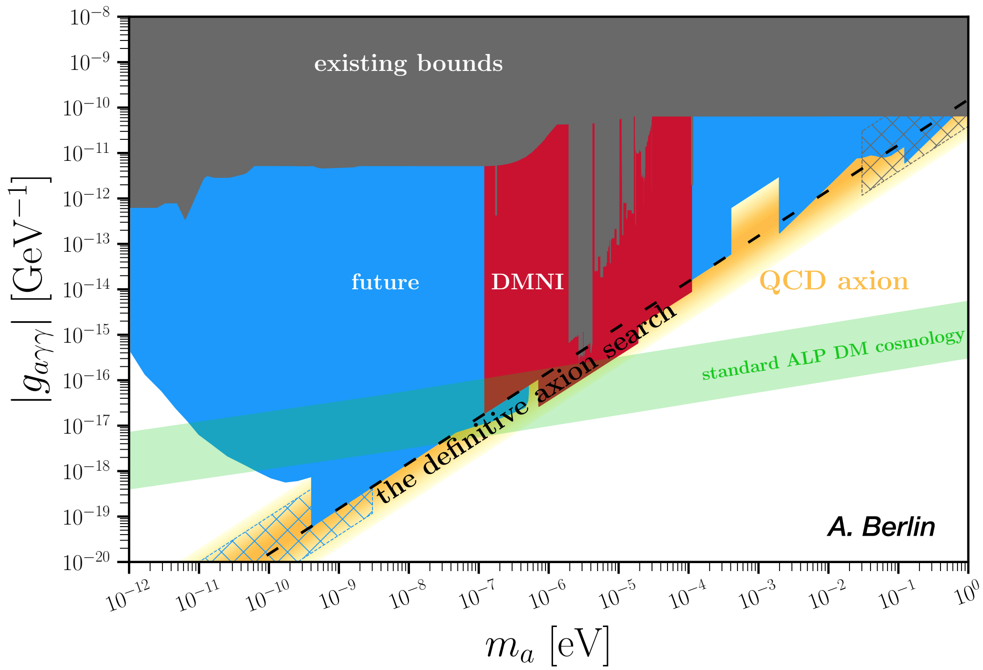
A. Berlin and others



** DFSZ is the benchmark for the field.*

Goal: Definitive QCD Axion Search

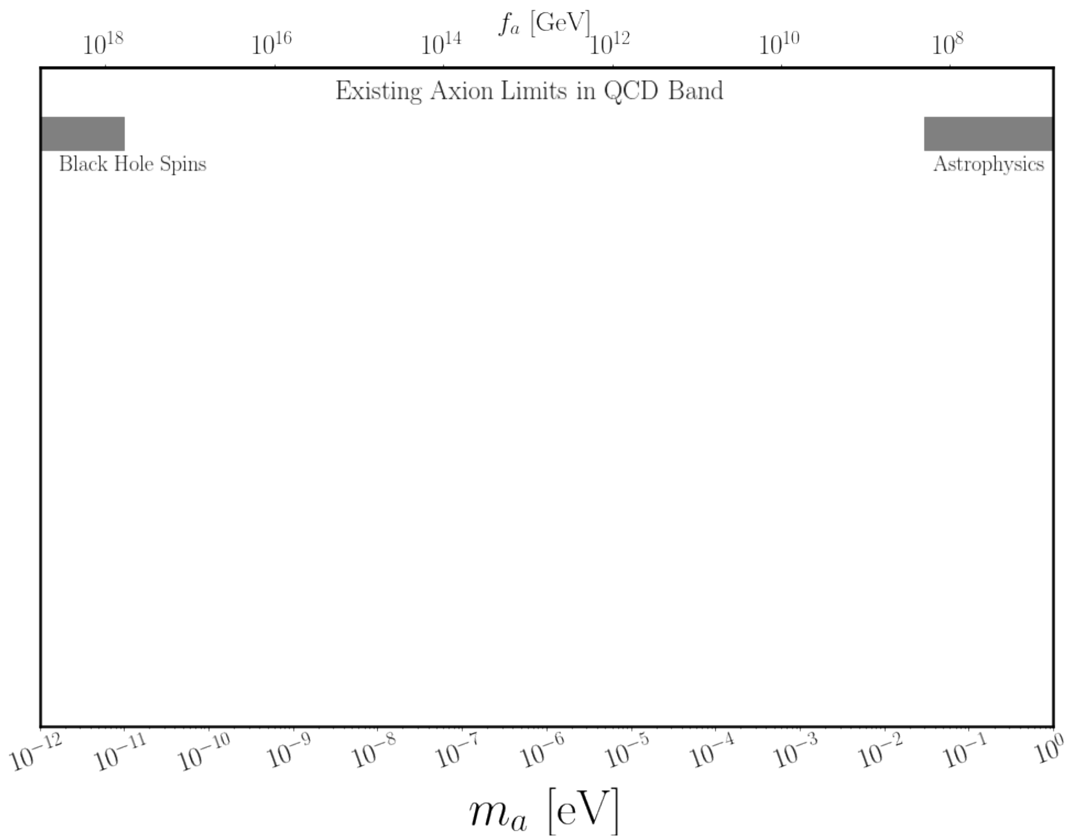
- ADMX-G2, HAYSTAC, CAPP are into the QCD axion band.
- The DMNI projects: ADMX-EFR and DMRadio-m³ are ready to start construction.
- Several Demonstrator scale experiments would be ready for a new DMNI process.



Status: Previous Snowmass

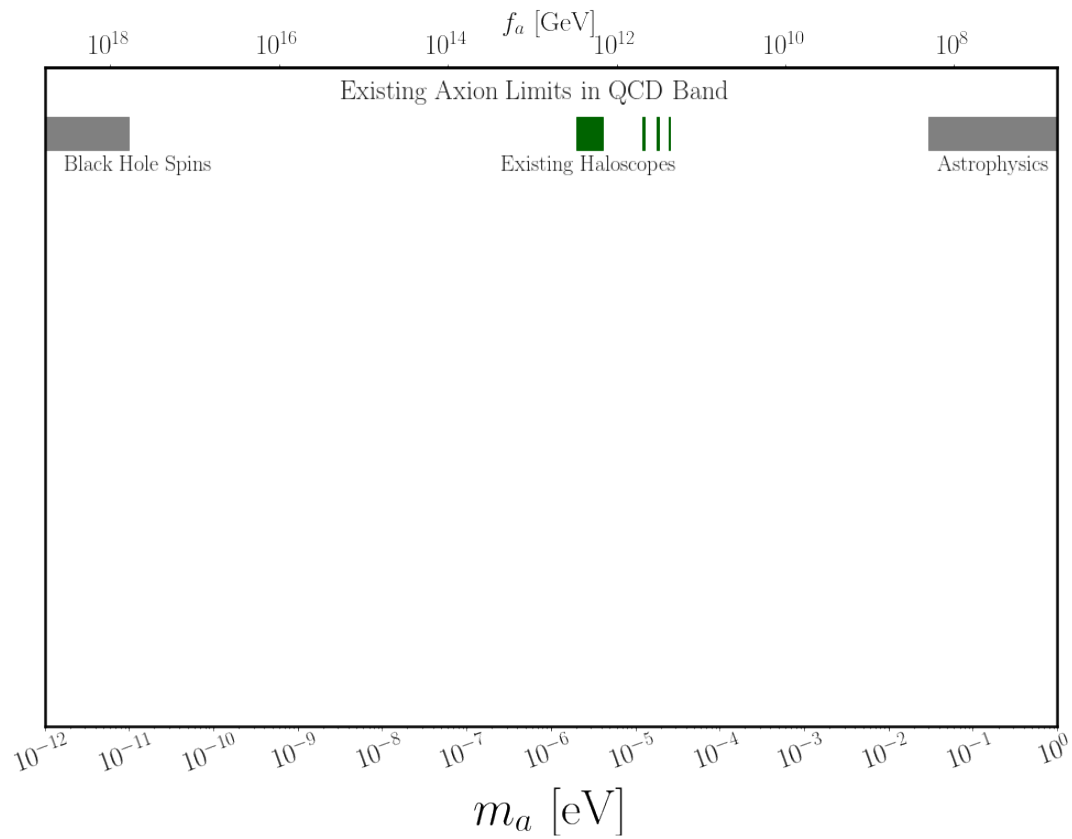
- No Experiments had probed the QCD band.

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)

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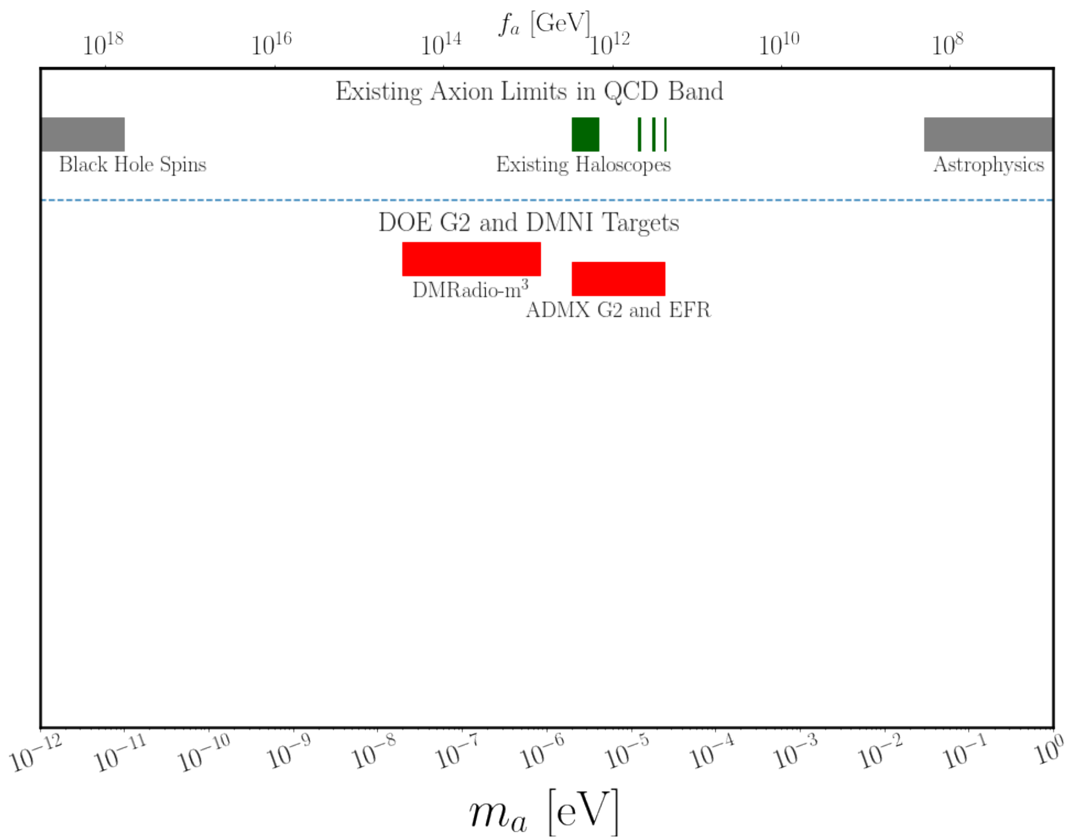
- The BRN for Dark Matter New Initiatives and subsequent call for proposals was very successful.
- DMRadio-m3 and ADMX-EFR are poised to make significant inroads into the QCD axion parameter space.



Technological Advancements

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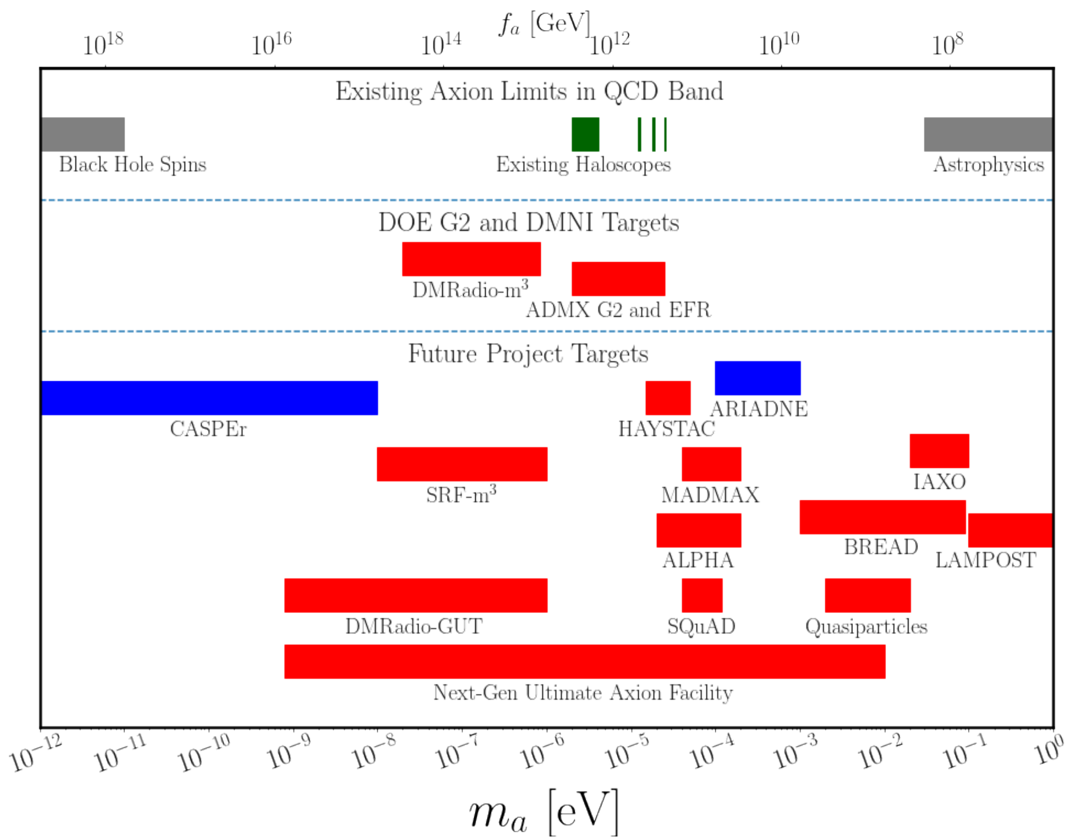
- We have developed techniques to address the full axion parameter space.
- This includes techniques to probe the non-photon couplings (indicated in **blue**).
- These techniques vary in readiness from proof-of-principle to operating experiments.



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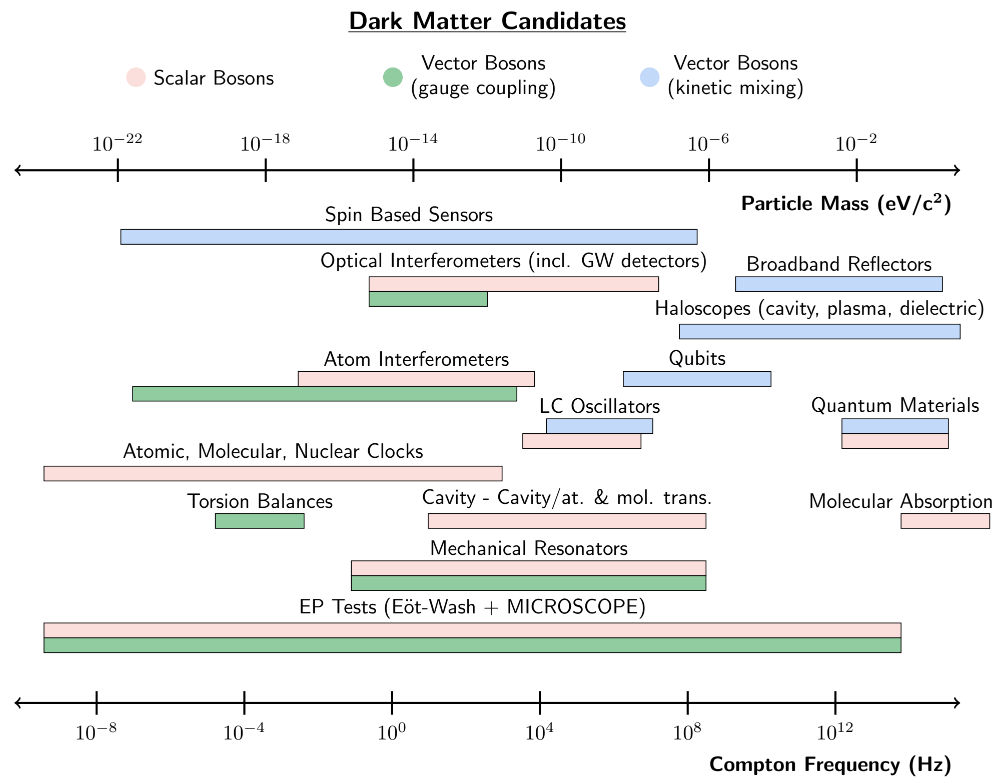
New Horizons:

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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Add something on low mass ALPs

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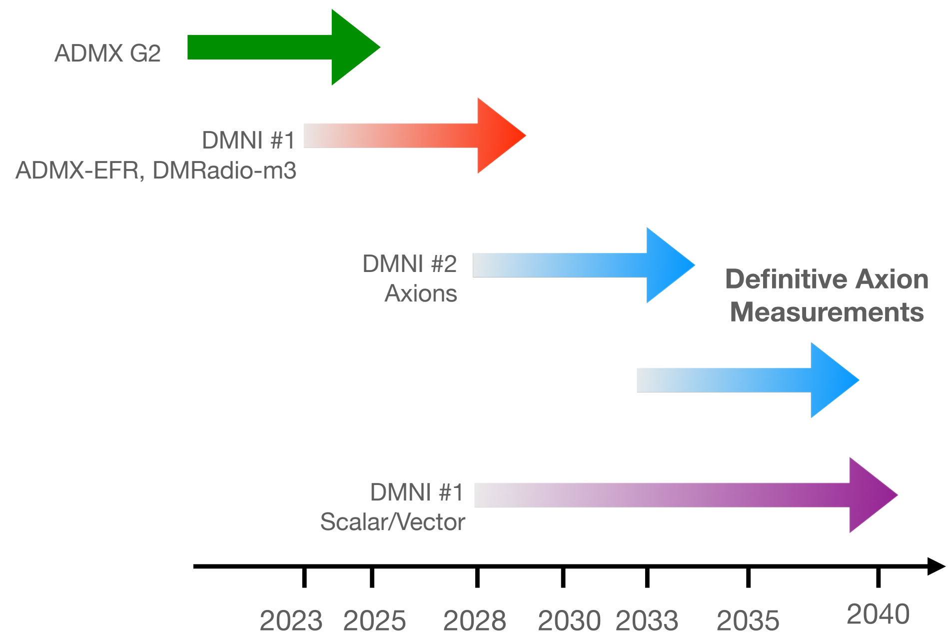
Community Roadmap: Time Line

- 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.



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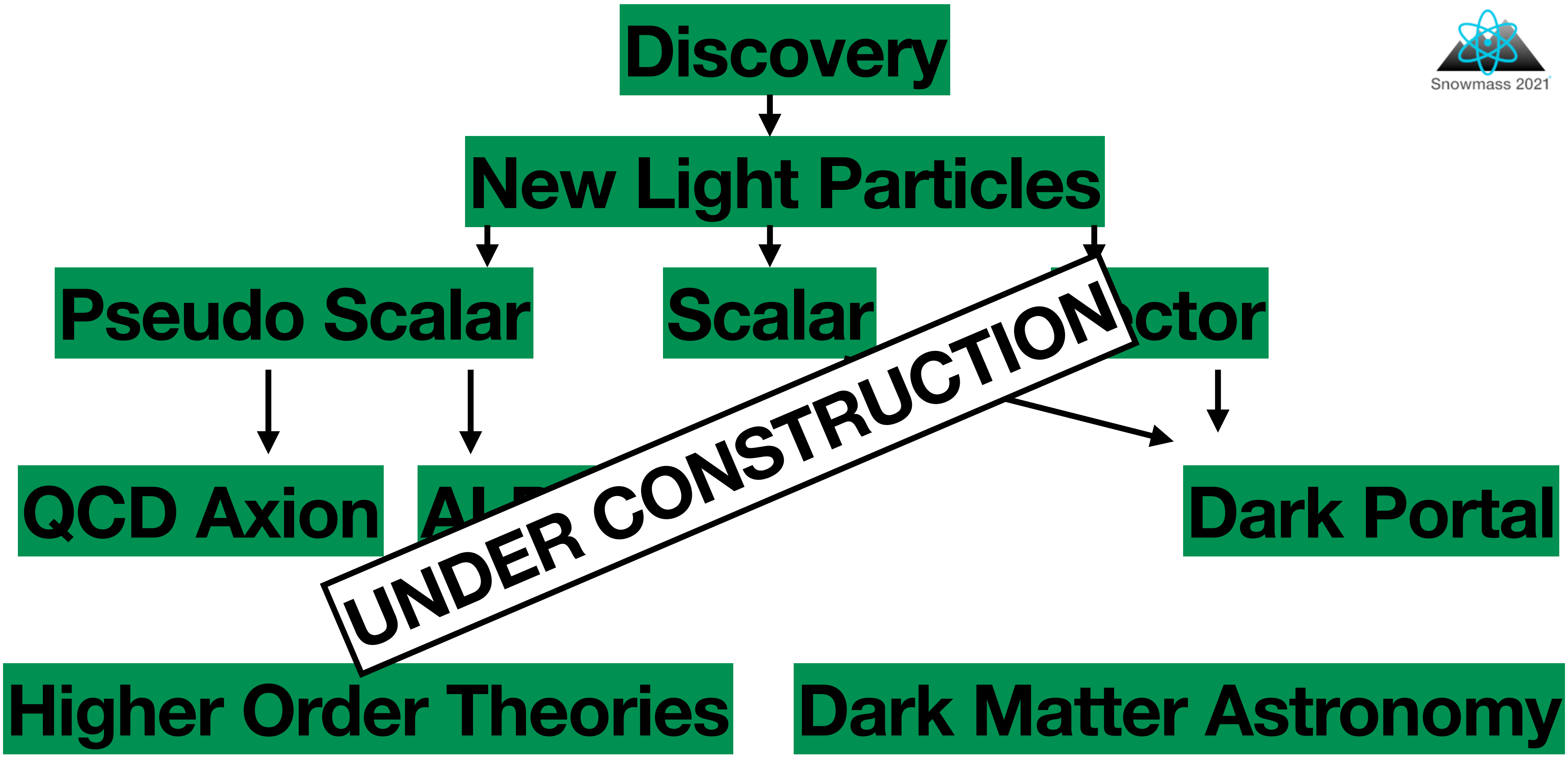

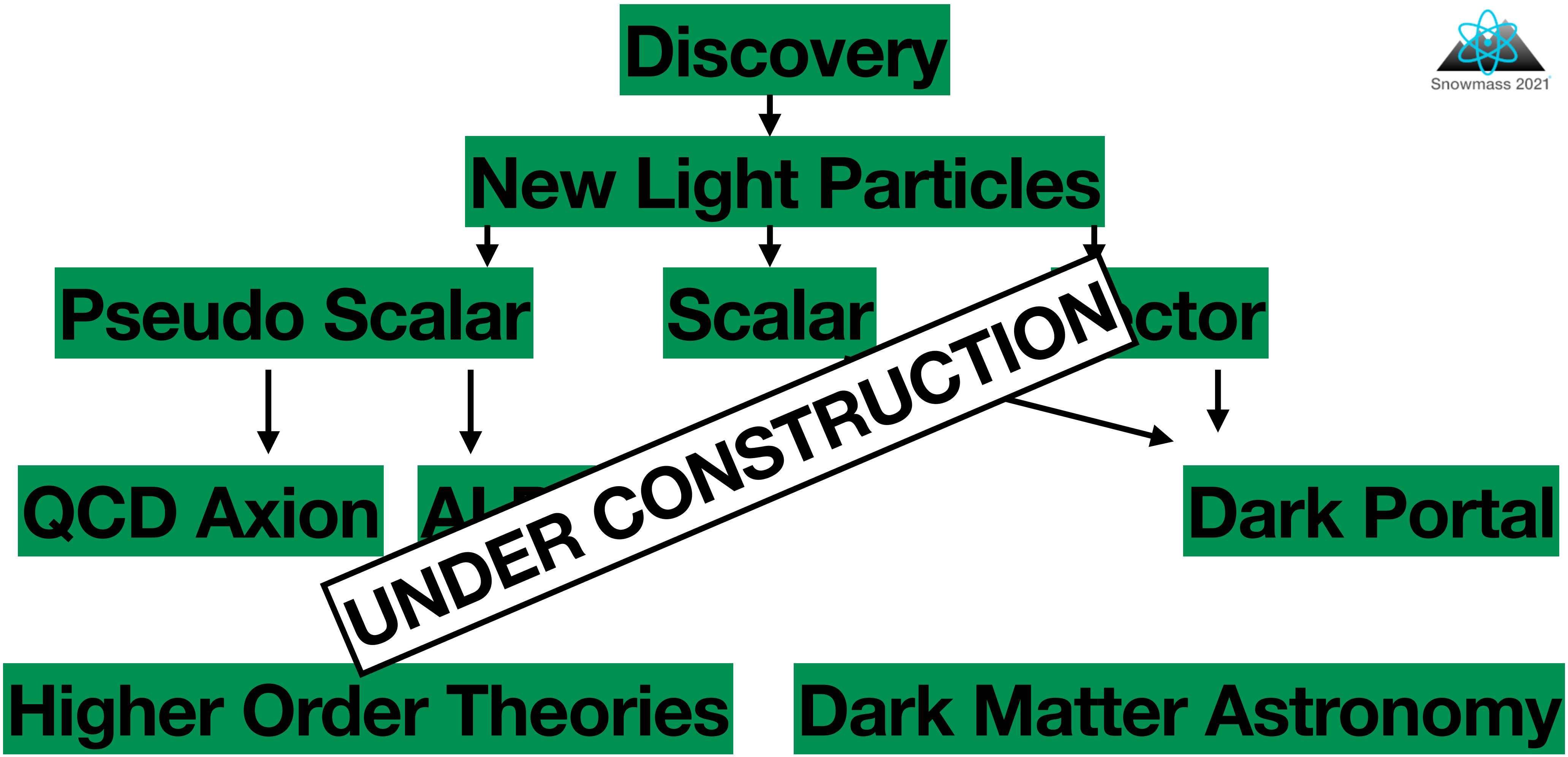
Discovery
New Light Particles
Pseudo Scalar
Scalar
ector
QCD Axion
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Dark Portal
Higher Order Theories
Dark Matter Astronomy

QCD Axion

Light **Heavy** **K** **DFSZ**

↓

No B Modes **New Quarks**

Modes **More Higgs**

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

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Thank you Wave-like Dark Matter Community!

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