Unveiling the Secrets of the Universe: iDMEu Initiative - Exploring Axion-like Particles in Dark Matter Research

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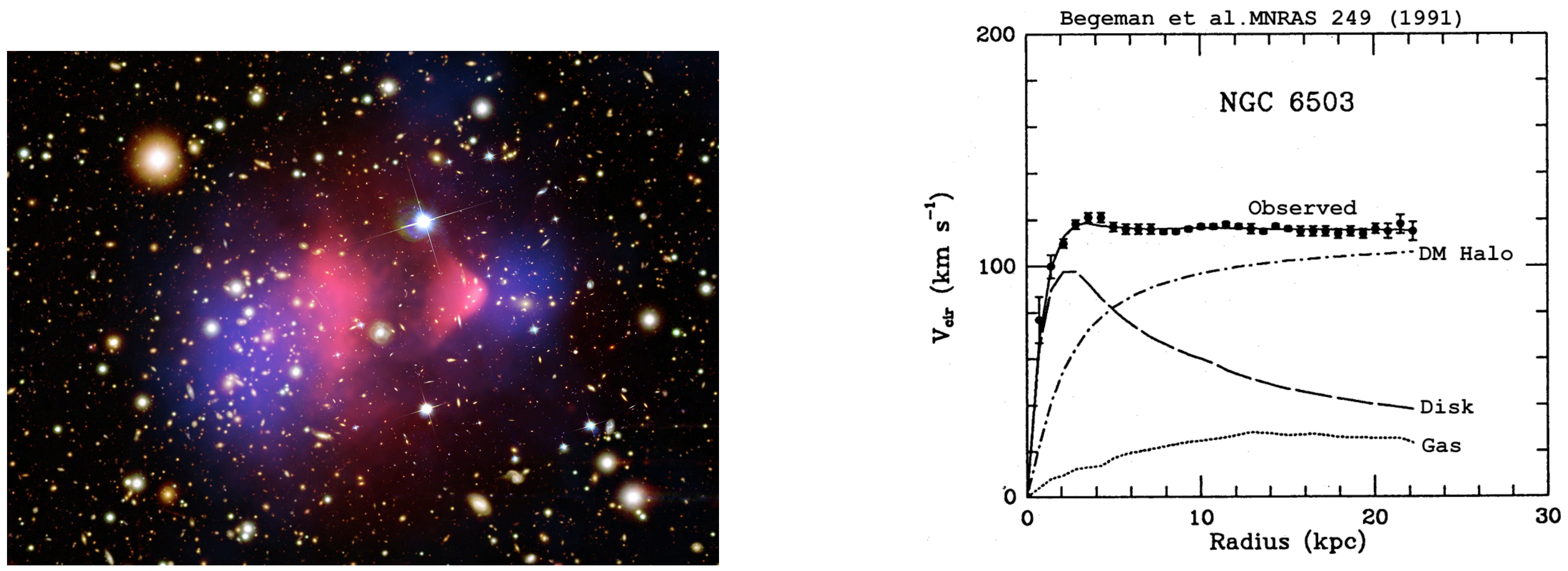
What is Dark Matter?

A large amount of evidence suggests that *ordinary or baryonic* matter only contributes 5% of the Mass-Energy of the Universe. The remaining 95% consists of *Dark Matter* and *Dark Energy*, of which Dark Matter contributed 26.8%. Dark Matter is a hypothetical form of matter that does not interact electromagnetically or produce light. We hypothesise its existence based on several gravitational phenomena which cannot be explained otherwise. Some examples include the galaxy rotation curves, dynamics of galaxy clusters and microlensing-based evidence.



(a) The Bullet Cluster, credits: NASA

(b) Rotation Curves of NGC 6503

Figure 1. Examples of Astrophysical Proofs for Existence of Dark Matter

Candidates for Dark Matter

Any potential Dark Matter candidate must satisfy the below properties:

- DM must be *Non-baryonic*
- DM must be *Electromagnetically Neutral*
- DM must be *stable*
- DM is expected to *cold* at freeze-out

Currently, there are two popular models which can satisfy the above properties while having a strong theoretical motivation along with feasible production mechanisms:

WIMPs: Weakly Interacting Massive Particles

- Popular because of *WIMP Miracle*: they give correct relic abundance at the weak scale
- Has potential particle candidates in MSSM: Neutralino and Gravitino
- Cold DM at the GeV - TeV scale

Axions: pseudo-Nambu-Goldstone Boson

- They arise from the Peccei-Quinn solution of the Strong CP problem in QCD
- They constitute ultra-light Dark Matter models in the sub-eV range at the μeV-meV scale
- Theorised production mechanisms allow for "cold" production despite low mass

The iDMEu Project

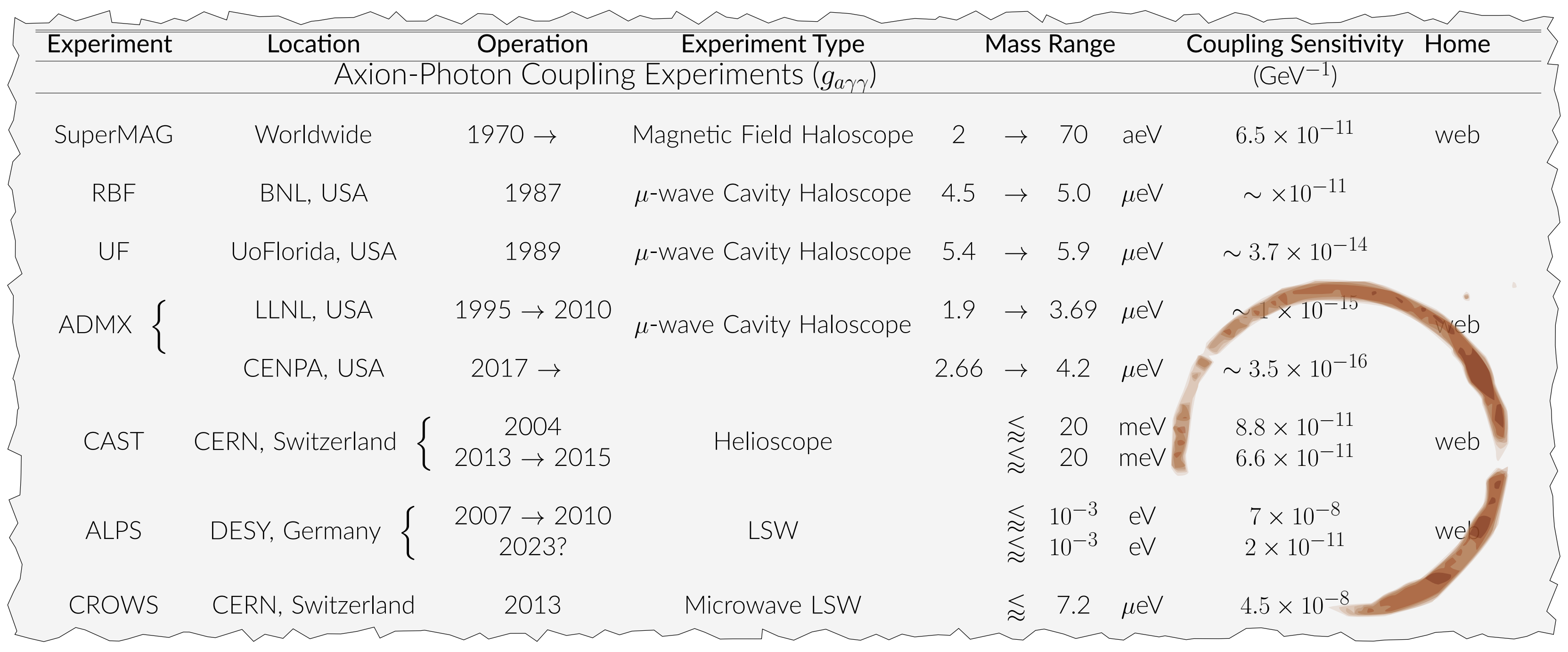
The Initiative for Dark Matter in Europe and Beyond (iDMEu) project is an initiative that emphasizes the importance of collaboration and result-sharing to advance research in this field. The project will facilitate a common portal for important Dark Matter resources and constraints in an easy-to-use and accessible format.

Objectives of the iDMEu Project

- Objective 1: `Online Meta Repository`
  Easy access to experimental information via searchable tables containing name, location, experimental parameters, home page and TDR that make it accessible to a wide scientific community.
- Objective 2: `Town Hall Meetings`
  Provide a common platform to organise conferences and workshops to improve interactions among the different communities to enable a broader approach towards Dark Matter research.
- Objective 3: `A Story of DM Research`
  Providing a common narrative on Dark Matter research for the general population and non-experts that captures the breadth of DM research and informs the stakeholders about the advancements in the field.

The iDMEu Meta-Repository

The table below highlights the key features of the Meta-Repository that will be hosted on the iDMEu website for Wave-Like Dark Matter, including Axions and ALPs.



Experiment	Location	Operation	Experiment Type	Mass Range				Coupling Sensitivity (GeV^{-1})	Home
Axion-Photon Coupling Experiments ($g_{a\gamma\gamma}$)									
SuperMAG	Worldwide	1970 →	Magnetic Field Haloscope	2	→	70	aeV	6.5×10^{-11}	web
RBF	BNL, USA	1987	μ-wave Cavity Haloscope	4.5	→	5.0	μeV	$\sim \times 10^{-11}$	
UF	UoFlorida, USA	1989	μ-wave Cavity Haloscope	5.4	→	5.9	μeV	$\sim 3.7 \times 10^{-14}$	
ADMX	LLNL, USA	1995 → 2010	μ-wave Cavity Haloscope	1.9	→	3.69	μeV	$\sim 1 \times 10^{-15}$	web
	CENPA, USA	2017 →		2.66	→	4.2	μeV	$\sim 3.5 \times 10^{-16}$	
CAST	CERN, Switzerland	2004 2013 → 2015	Helioscope		$\lessapprox$ $\lessapprox$	20 20	meV meV	8.8×10^{-11} 6.6×10^{-11}	web
ALPS	DESY, Germany	2007 → 2010 2023?	LSW		$\lessapprox$ $\lessapprox$	10^{-3} 10^{-3}	eV eV	7×10^{-8} 2×10^{-11}	web
CROWS	CERN, Switzerland	2013	Microwave LSW		$\lessapprox$	7.2	μeV	4.5×10^{-8}	

Theoretical Motivation for Axions

Strong CP Problem

- In QCD, the $\mathcal{CP}$ symmetry is not necessarily respected. This is what is called the "Strong-CP" problem in QCD.
- This an be seen in the QCD Lagrangian: $\mathcal{L}_{QCD} \supset \theta \frac{g_s^2}{32\pi} G_{\mu\nu,a} \tilde{G}^{\mu\nu,a}$
- We expect θ to be $\mathcal{O}(1)$; however, that would yield a value of nEDM much higher than that measured experimentally.

Peccei-Quinn Theory and the Axions

- PQ theory postulates a $U(1)$ symmetry that is spontaneously broken at high energy scales.
- Weinberg and Wilczek realised this leads to an ultra-light particle: the pseudo-Nambu-Goldstone boson or the *axion*
- This leads to $\theta \to 0$, solving the CP problem and giving a stable particle.

Axion Production Mechanism

- PQ-Theory allows "cold" production via a *phase transition*. This can happen *pre* or *post* inflation
- Vacuum Realignment can produce axions in both cases.
- Decay of Topological Defects in the Axion field can lead to abundant production in post-inflation scenario.

Axion Detection

Axion Detection Scheme

Axion-Electron Coupling Experiments
Ge Detector
LXe Detectors
Ferromagnetic Haloscope
LAr Detectors

Axion-Nucleon Coupling Experiments
Comagnetometers
Atomic Spin Measurement
NMR
nEDM
Storage Rings
Neutrino Observatory

Axion-Photon Coupling Experiments
Resonant Cavity Haloscopes
Helioscopes
Light-Shining-Through-a-Wall
Dielectric Haloscope
Radio and Dish Antenna
Lumped Element Haloscope

Astrophysical Searches

Progress in Experimental Detection

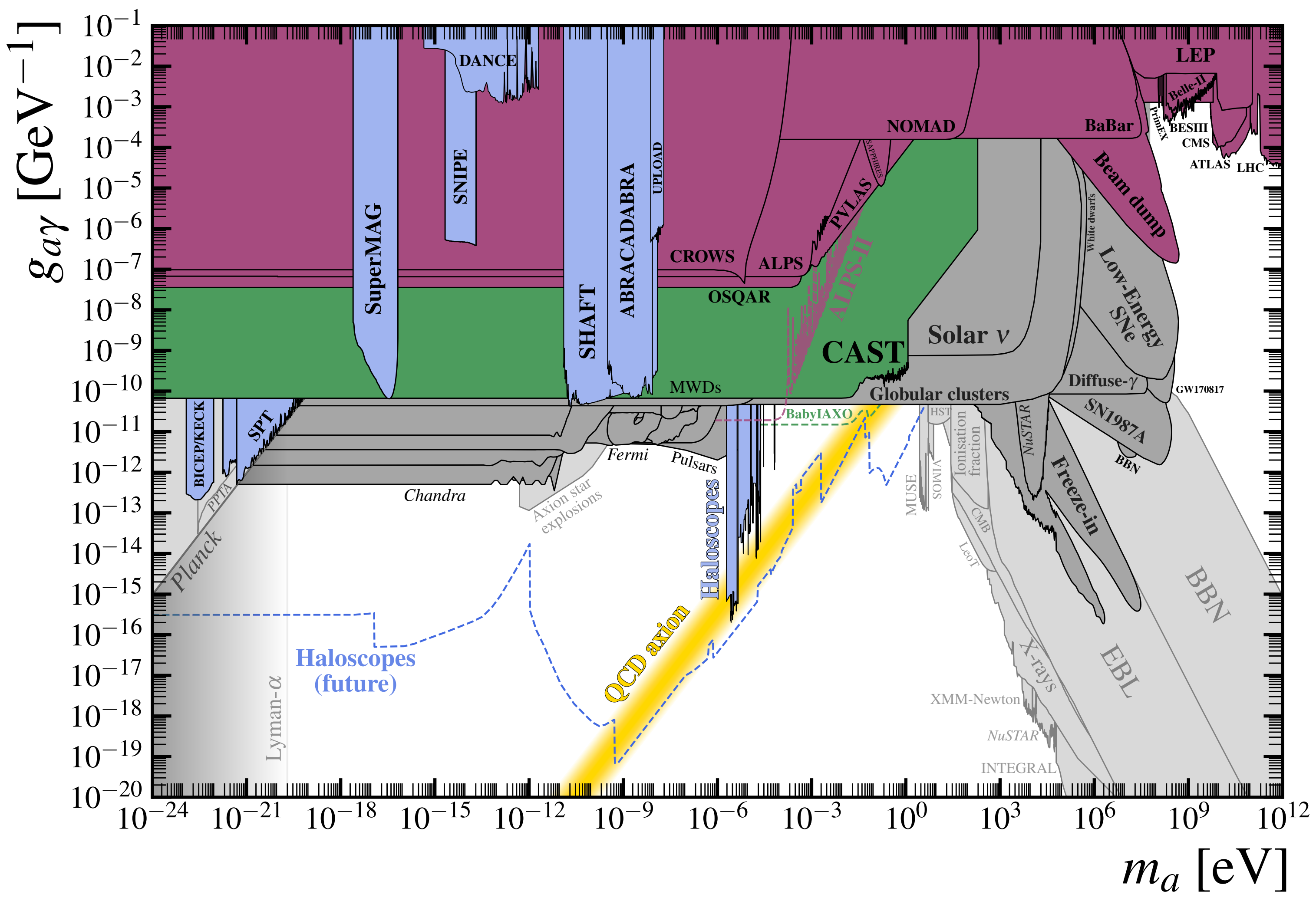


Figure 3. Experiments Exploiting Axion-Photon Couplings. Credits: https://cajohare.github.io/AxionLimits/

What does this project add?

- A new and accessible repository for scientists researching axions to get up-to-date information on the various experiments currently constraining the parameter space of Axions and ALPs
- A common interface for all flavours of Dark Matter research! Easy access to information curated from various publications and reviews.
- An entry point for researchers and students to get acquainted with the theory and state-of-the-art experiments being designed.
- Listing proposed experiments that are currently being built or prototyped to allow researchers to navigate the future of Axion/ALP and Dark Matter research

http://www.idmeu.org (Under Construction) **26ème Congrès Général de la SFP** **aryamanb@iisc.ac.in**