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Light New Particles at the Intensity Frontier

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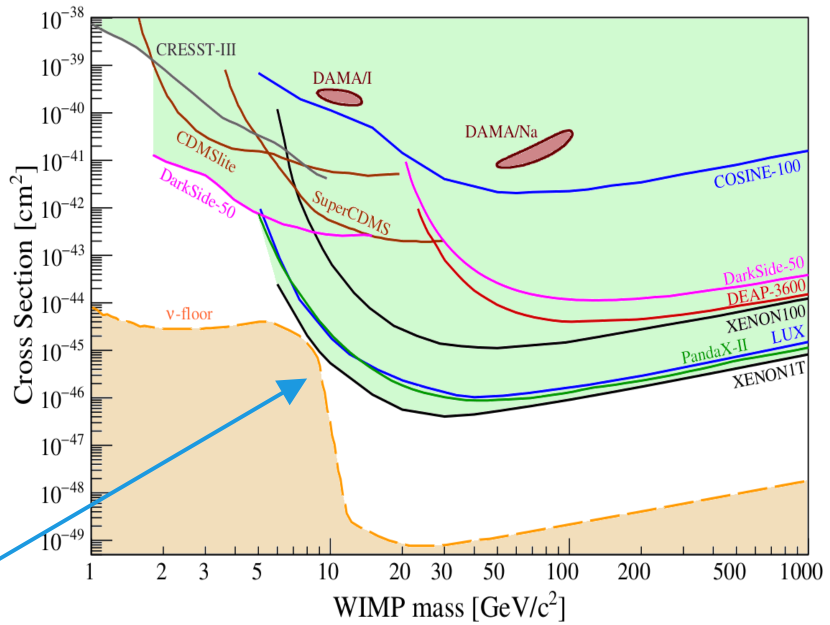
Overview

- Light new particles: HNLS/WISPs/axions/ALPs/FIMPs??
- (Some) latest developments in theory
- Recent and planned activities of GdR InF

Increasing interest in light new particles in the theory and experimental communities



Absence of signs for WIMPS:

- Other production methods for DM?
  - ✗ Misalignment (axions/ALPs/Hidden Photons?)
  - ✗ Freeze-in
  - ✗ Inflaton decay
  - ✗ Gravitational production
  - ✗ <insert your favourite model here>
- Above 10 GeV race to approach neutrino floor
- Gap in the sensitivity below 10 GeV: motivates experiments and models
  - ➢ Interest in new technologies
  - ➢ New models required to explain relic abundance while allowing signals
- No signs for heavy WIMPs at LHC either:
  - ✘ Look for different signatures at ATLAS/CMS (ALPs …)
  - ✘ Light DM at Belle II/LHCb?
  - ✘ Huge interest in LLPs

Increasing interest in light new particles in the theory and experimental communities

(Still) many theoretical motivations:

- No compelling alternative to the QCD axion:
  ✗ Spontaneous CP violation models seem fine-tuned/contrived
  ✗ Nothing else has really appeared after more than 40 years
  ✗ Perhaps some recent controversy (see 2001.07152 contradicted by 2209.14219)
- Axions and extra gauge groups are natural/ubiquitous ‘predictions’ of string theory models
- Right-handed neutrinos, e.g. in νMSM have keV and O(GeV).

Increasing interest in light new particles in the theory and experimental communities

And some recent hints:

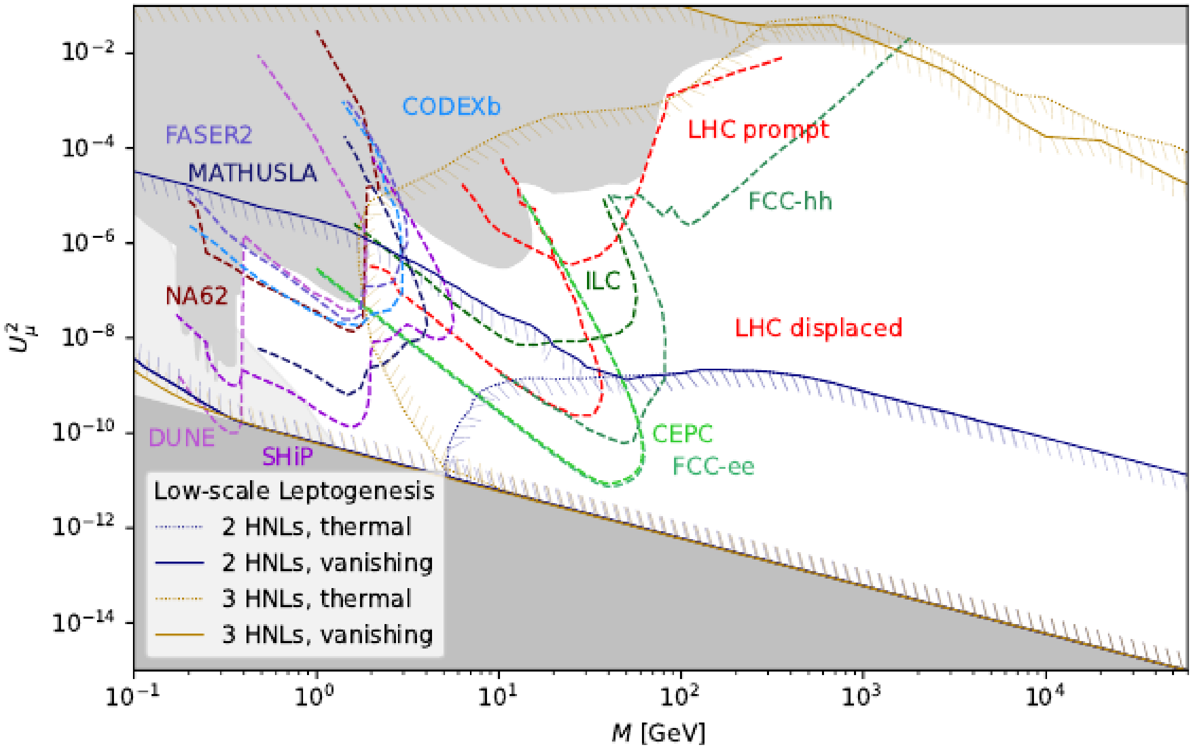
- Extra-galactic background light excess at 4σ: 2202.04273
- Xenon-1T low energy events stimulated a lot of interest… before they went away – some of the models may remain interesting
- Muon g-2 *might* be related to light new physics (once upon a time hidden photons could explain it; now perhaps something explains discrepancy of R-ratio and lattice)
- B meson anomalies remain interesting and *might* be explained by light particles
- Attempts to explain the W boson mass by CDF …
- Several long-standing astrophysics hints for ALPs

Classic light new particles: heavy neutral leptons

With one RH neutrino ~ keV and two ~ GeV, can have resonant leptogenesis and dark matter at the price of a tuning of the masses of the two heavier sterile neutrinos: this is the νMSM

These HNLs were the original motivation for the SHiP proposal as they can be long lived due to small couplings

More general models are attracting interest these days, especially for non-standard searches



Weakly **I**nteracting **S**lim **P**articles

WISP is an umbrella term for light particles with feeble interactions:

- The QCD axion
- Axion-like particles
- Hidden photons

QCD axion

A CP-violating term in the QCD lagrangian must exist because of CP violation in the quark sector:

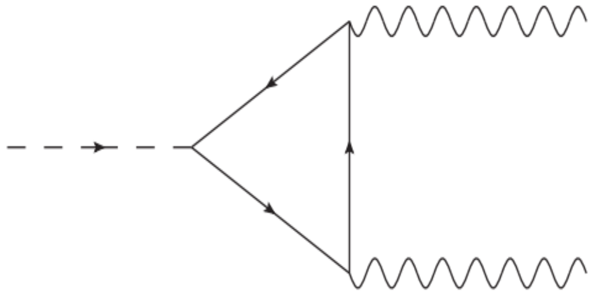
$$\mathcal{L}_{\not{C}\not{P}} \supset \frac{\alpha_s}{8\pi}\theta\, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

We can make this dynamical by a field that couples to the topological density:

$$\mathcal{L} \supset (\theta + \frac{a}{f})\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

Such a coupling typically arises when an anomalous global symmetry is spontaneously broken

$$\mathcal{L} \supset -y\phi\psi\chi \longrightarrow \phi = f e^{ia/f} \quad \text{or } \phi = f(1 + \frac{\phi_r + ia}{f})$$



See Quevillon and Smith, 2019 for a recent discussion of the generation of the term in the effective Lagrangian and relation (or not) to anomalies

Models may have couplings to fermions and other gauge bosons:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \sum_f g_{aff} \partial_\mu a \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

See the GdR axion workshop from 2018

These are (usually) the ones crucial for phenomenology!

Couplings to the photon and to quarks are also generated automatically at low energy: when we remove the QCD anomaly via

$$u \to e^{-i\alpha_u \gamma_5} u, \quad d \to e^{-i\alpha_d \gamma_5} d, \quad \alpha_u + \alpha_d = -\frac{1}{2}(\theta + \frac{a}{f})$$

Get a coupling to photons:

$$\delta g_{a\gamma\gamma} = \frac{2\alpha}{f} \mathrm{tr}(Q^2(\alpha_u + \alpha_d)) = -\frac{1}{6} \frac{4m_d + m_u}{m_d + m_u}$$

The mixing with pions also gives mass to the axion:

$$m_a^2 \propto \frac{m_\pi^2 f_\pi^2}{f^2} \longrightarrow m_a = 5.70(7)\mathrm{meV} \times \left(\frac{10^9 \mathrm{GeV}}{f}\right)$$

Misalignment Dark Matter

Any scalar field during inflation can have an initial expectation value.

Fluctuations give: $\langle \delta\phi \rangle = \frac{H}{2\pi}$

The axion is a periodic field with no potential at high energies, so $\frac{\langle a_0 \rangle}{f} \in [0, 2\pi]$

At later times the scalar field behaves classically with e.o.m.: $\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$

Initially the field is stuck by friction, but eventually, when $3H < m_\phi$
it starts to oscillate and behave like a bath of particles.

Then the energy density at this point redshifts as the universe expands $\frac{1}{2} m^2 \phi_0^2 \sim \frac{1}{2} m_a^2 f_a^2 \theta^2$

For the QCD axion, this is complicated because the mass changes with temperature (the mass turns on when QCD becomes strong)

For the QCD axion we have: $$\frac{\Omega_a h^2}{0.112} \simeq 6 \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{7/6} \left(\frac{\theta_a}{\pi}\right)^2$$

We can define an `axion-like particle' (ALP) as one that has couplings to the photon/fermions like the QCD axion, but has a mass from a different source.

This requires some explicit breaking of the global symmetry.

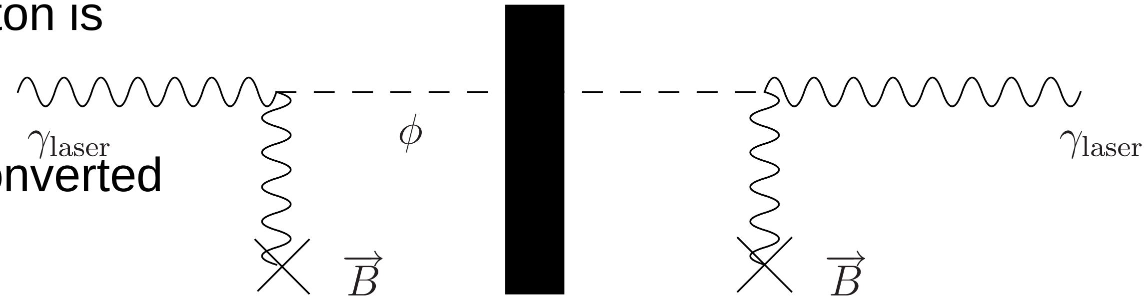
Then the prediction for the dark matter density for an ALP is simpler: $$\frac{\Omega_{a_i} h^2}{0.112} \simeq 1.4 \times \left(\frac{m_{a_i}}{\mathrm{eV}}\right)^{1/2} \times \left(\frac{f_{a_i}}{10^{11}\mathrm{GeV}}\right)^2 \left(\frac{\theta_{a_i}}{\pi}\right)^2$$

Both are may decay to photons which limits the maximum mass for it to be dark matter:

$$\tau_{a_i} = \frac{64\pi}{g_{i\gamma}^2 m_{a_i}^3} \simeq 1.3 \times 10^{25} s \left(\frac{g_{i\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{m_{a_i}}{\mathrm{eV}}\right)^{-3}$$

$$aF_{\mu\nu}F^{\mu\nu} \sim a\mathbf{E}\cdot\mathbf{B}$$

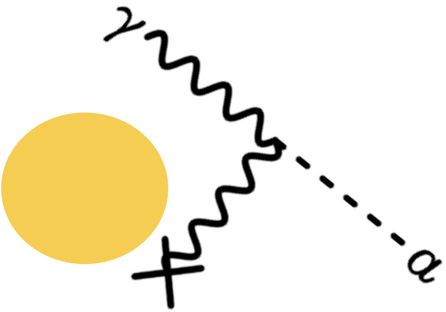
Usually the axion/ALP coupling to the photon is focussed on in searches:



By turning on a B-field, an axion can be converted into a photon and vice versa:

This can be done in the lab through 'light shining through walls' experiments …

Or exploited in helioscopes, where the axion is produced in the sun by a Primakoff process:



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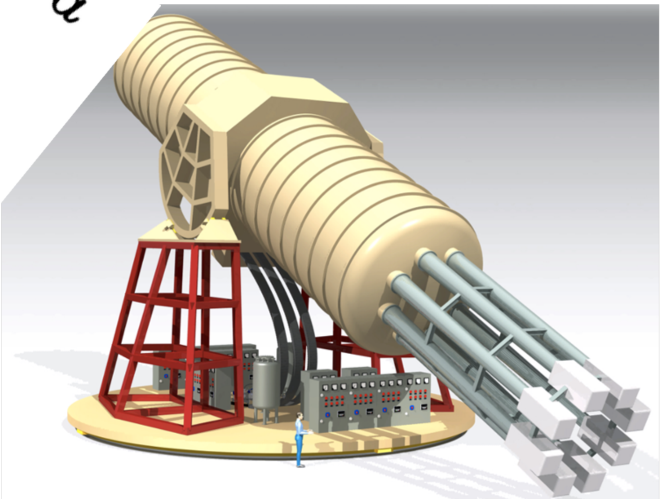
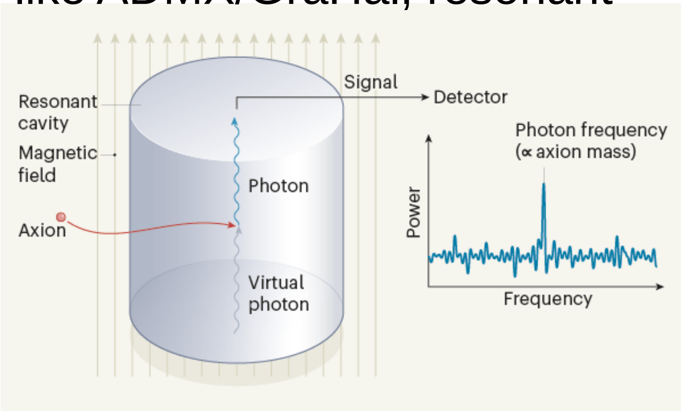
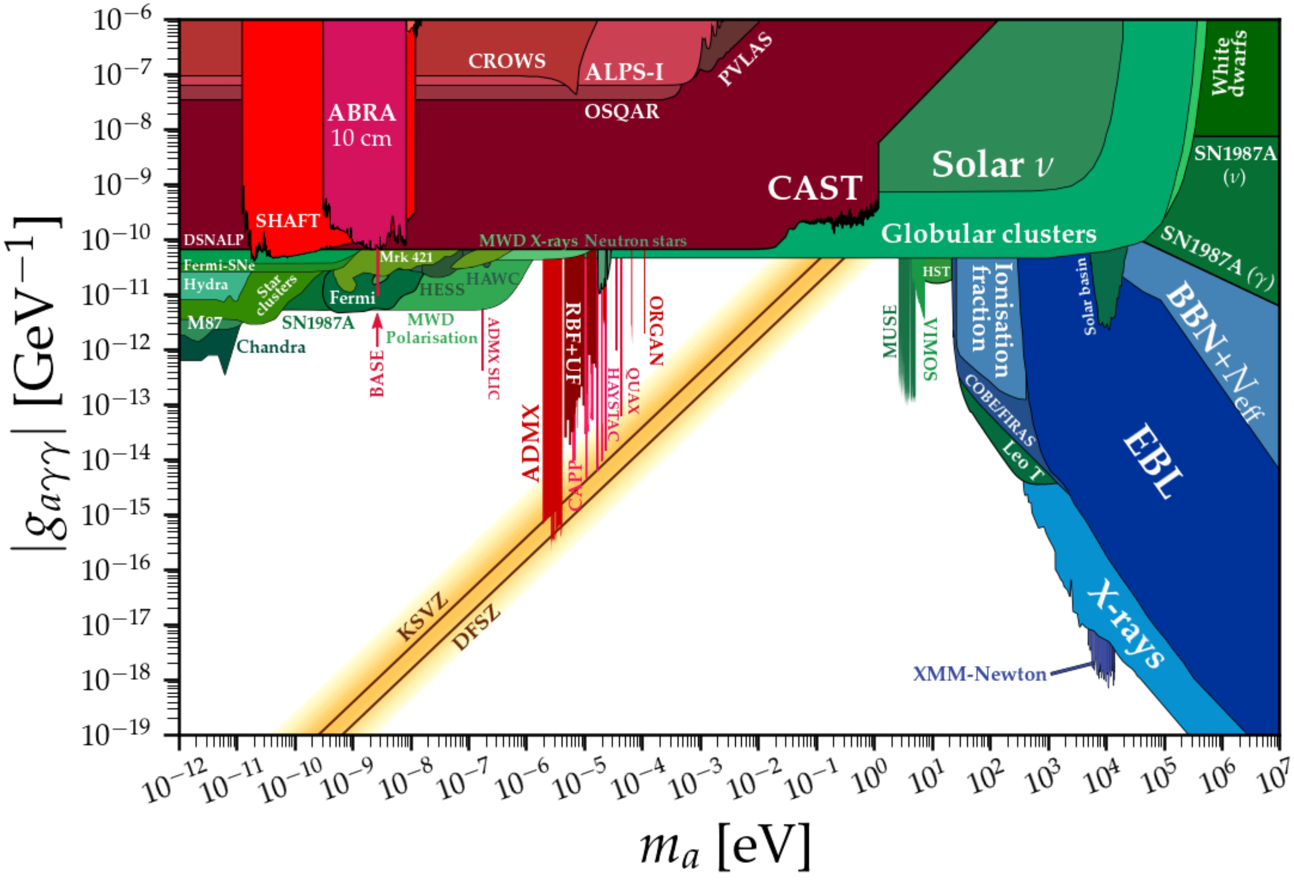


Or in haloscopes like ADMX/GraHal, resonant cavities with a B-field:



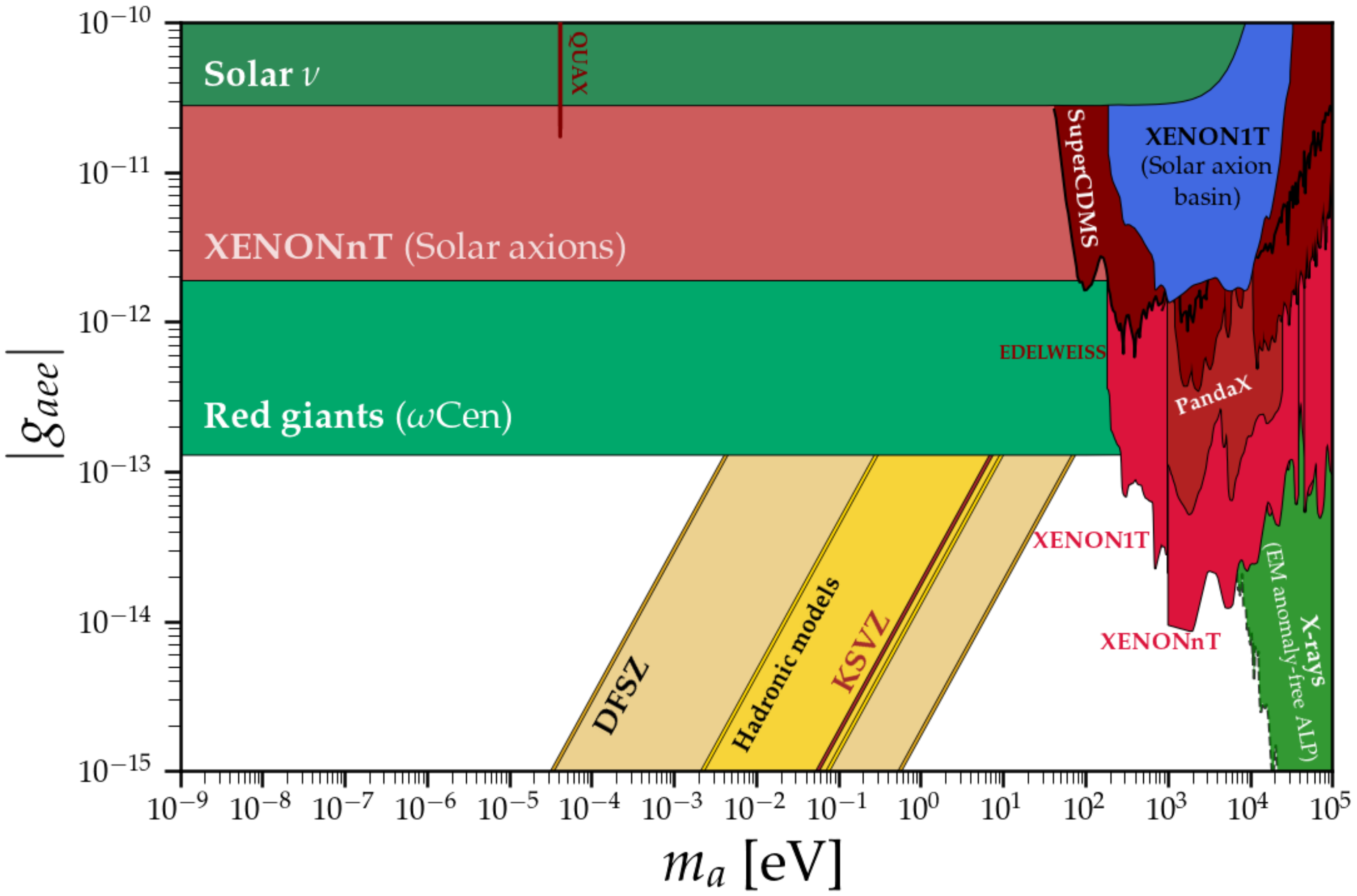
Axion and ALP DM

Over the years more and more constraints have been derived from astrophysics and new tabletop experiments



See Ciaran O'Hare's github page for an up-to-date compilation that you can rebuild yourself to add your own ...

Constraints also on couplings to electrons:



Now a burgeoning activity on WISPs:

- Creating new experimental proposals/strategies is a big industry! E.g.:
  ☺2206.12271 (Haloscope with 18T magnet)
  ☺TASEH (first results)
  ☺CANFRANC / CADEx
  ☺T-RAX
  ☺DANCE
  ☺SUPAX
  ☺QUAX-aγ
  ☺CASPEr (NMR)
  ☺ARIADNE
  ☺Gravitational Waves from axions
  ☺...

Now a burgeoning activity on WISPs:

- New software tools (see talk by Luc Darmé), e.g.
  - ✘ DarkEFT
  - ✘ DARKCAST
  - ✘ ALPINIST, 2201.05170
  - ✘ BDNMC
  - ✘ ALPACA event generator
  - ✘ MadDump
- EFT approach is everywhere, e.g. RGEs for ALP EFT etc
- Interest in searches at every collider (Belle II, NA62, LHCb, etc)
- … ALPs can have non-trivial flavour couplings
- Many (working) group papers now, e.g.:
  - ✘ Snowmass DM at Intensity Frontier
  - ✘ FIPs working group report
  - ✘ Stealth new physics at LHCb
  - ✘ SHiP physics case

Hidden photons

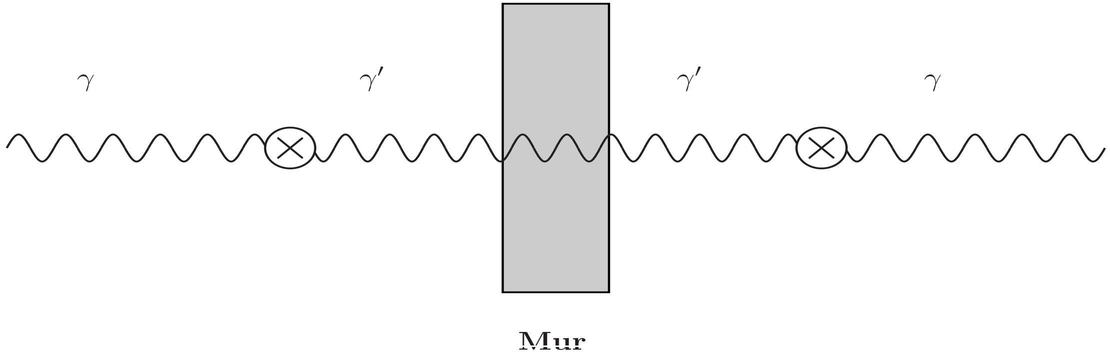
If there is an extra U(1) gauge group in our theory, then it can couple to the photon via a *renormalisable* operator:

$$\mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$$

This is generated by loops integrating out fields charged under both groups, so typically

$$\epsilon \sim \frac{e g_h}{16\pi^2} \log(M_1/M_2) \sim 10^{-3} (g_h/e)$$

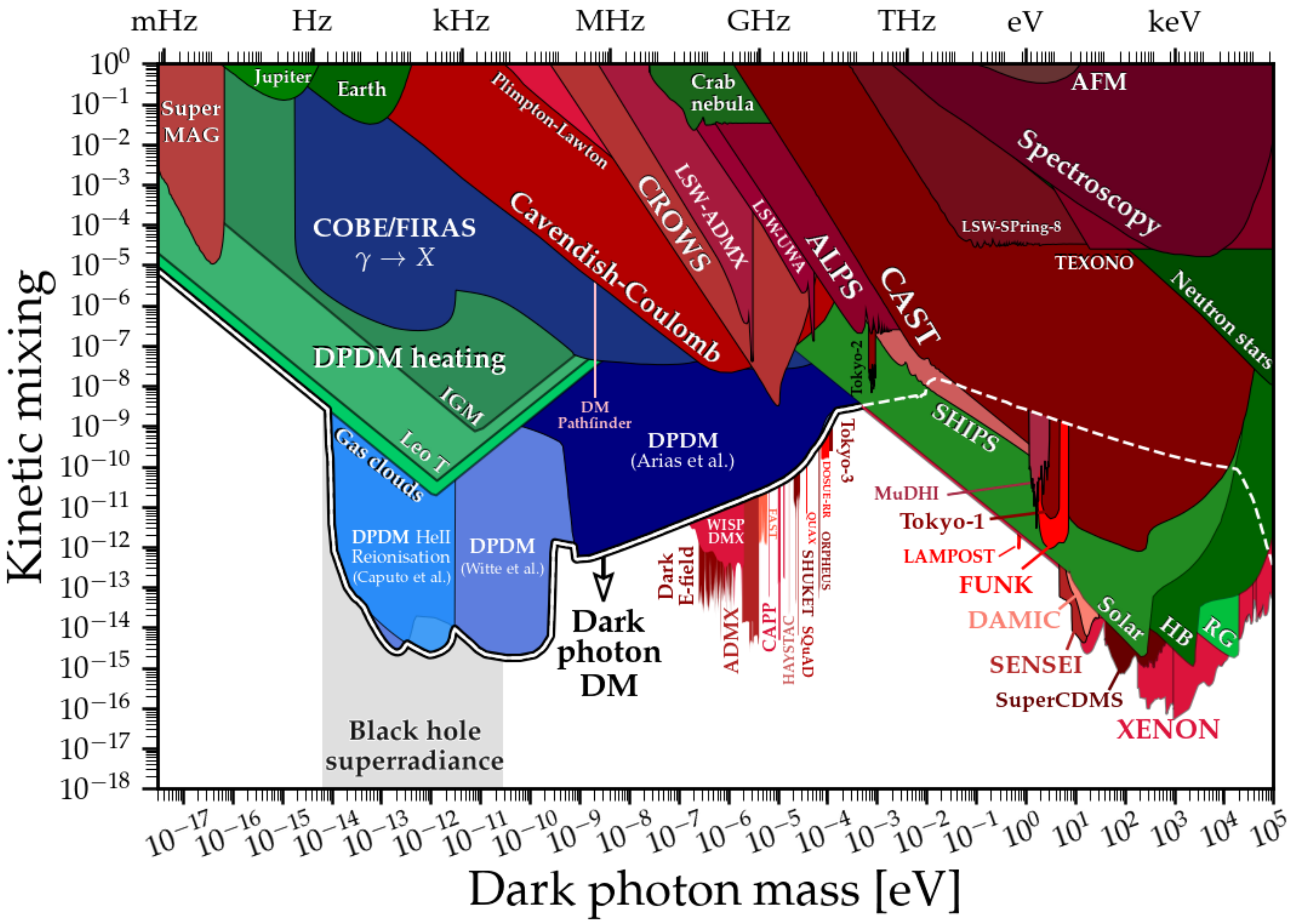
If the hidden photon is massive can have oscillations … without the magnetic field!



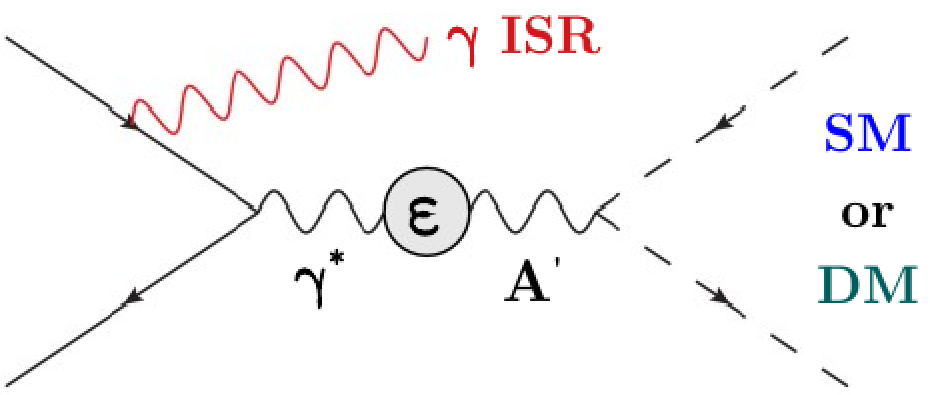
Mass can be from Stückelberg mechanism or a Hidden Higgs

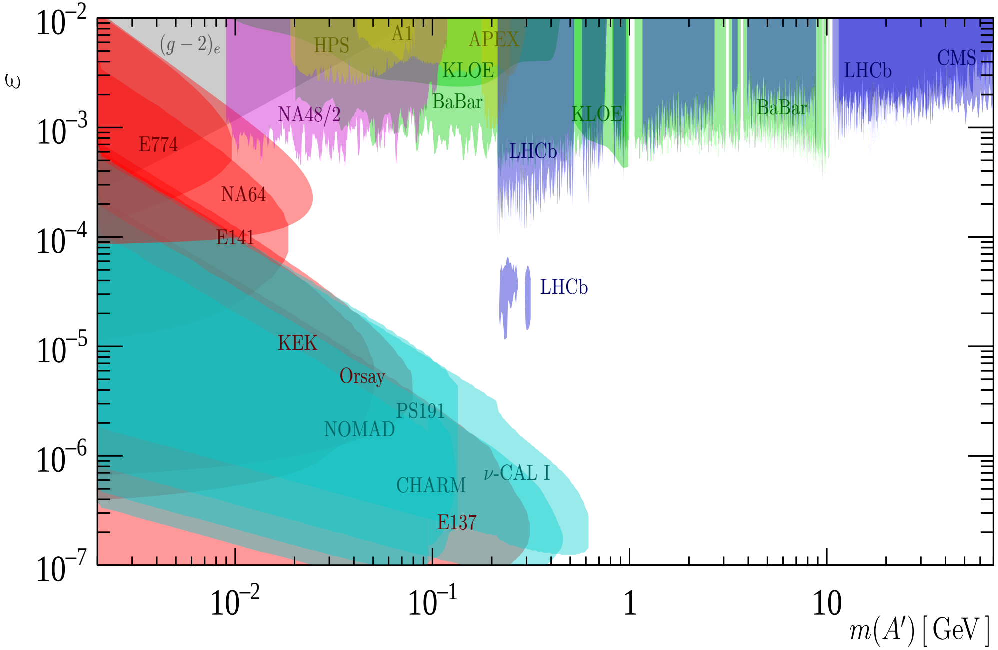
Can have dark photon DM from misalignment, just like for the axion (modulo some special coupling to gravity required)

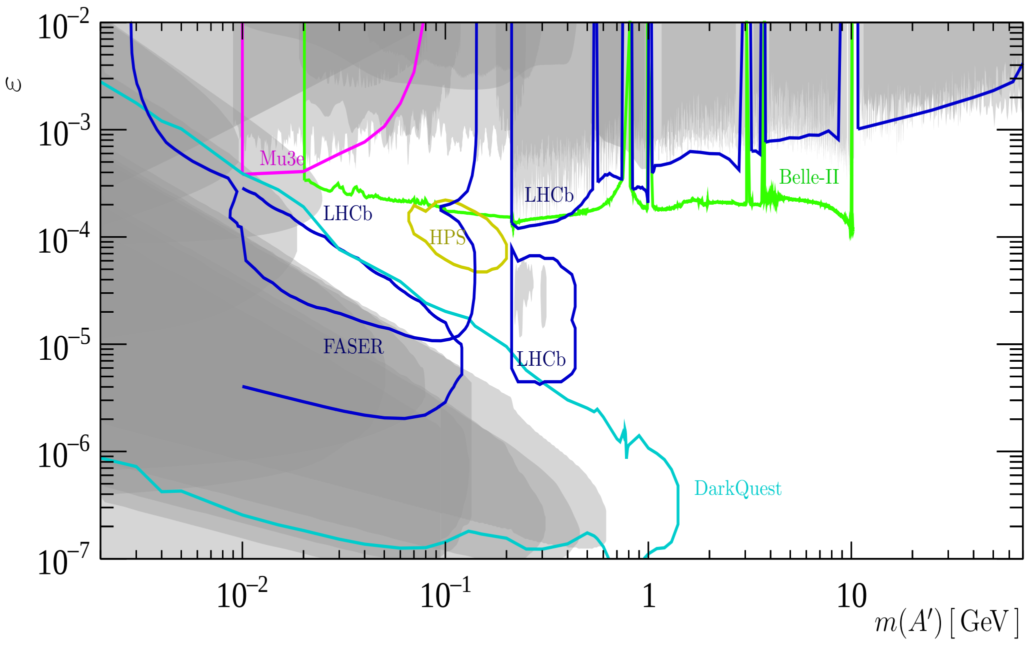
Only makes sense for small masses/kinetic mixing otherwise have decay to three photons



Also interest in direct searches at heavier masses:

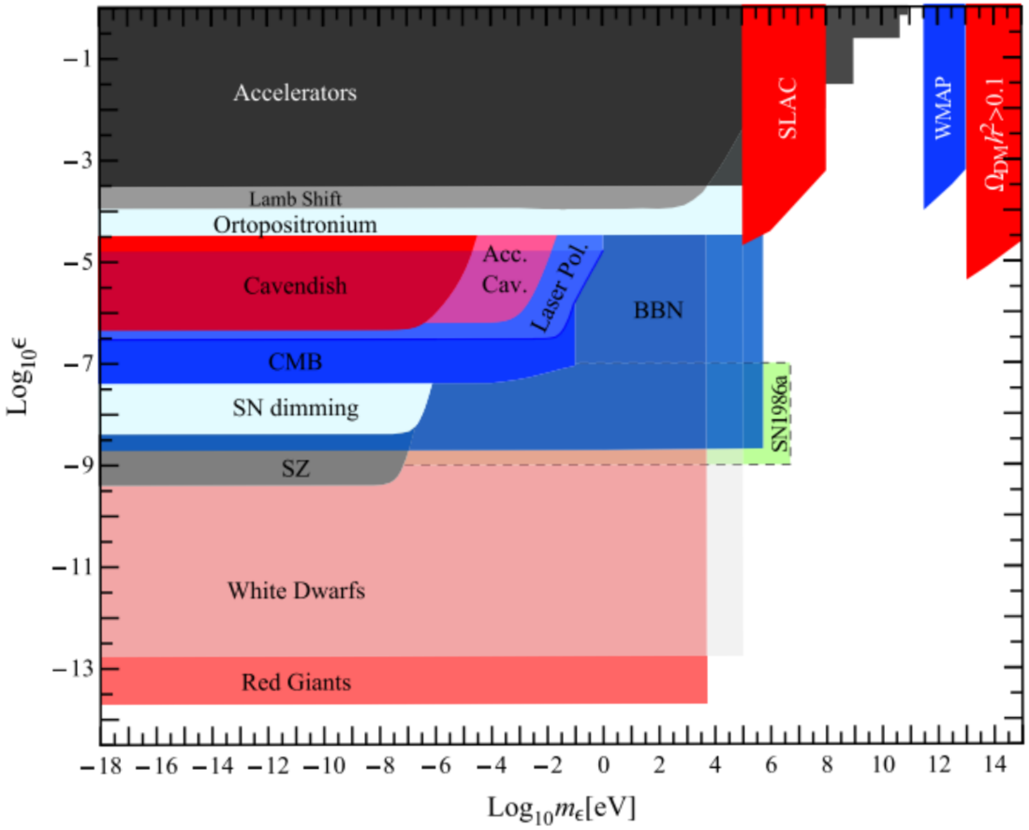


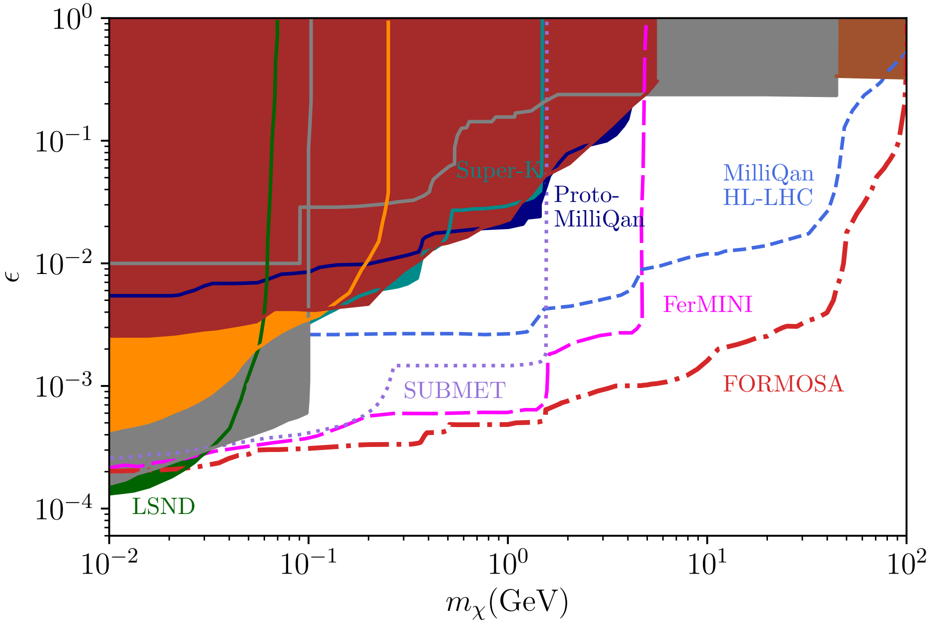




Millicharges

If there is hidden matter coupling to a light hidden photon, then it picks up a ‘millicharge’ and there is a lot of interest in looking for these:





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Activities of GdR InF

Previous workshops dedicated partly or entirely to the topic:

- Workshop on the strong CP problem and axions, June 2018
- Future of the intensity frontier workshop, February 2018
- Journée SHiP/secteur caché, October 2017

There was/is an EDMs discussion group at the annual meeting 2020 (see me!)

In first stages of planning for 2023:

- Axions++ (long overdue!)