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Dark Photons and other non-ALP WISPs

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PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

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

Light particles with **feeble** interactions:

- The QCD axion
- Axion-like particles
- **Hidden photons**
- HNLs + neutrinos
- Light DM

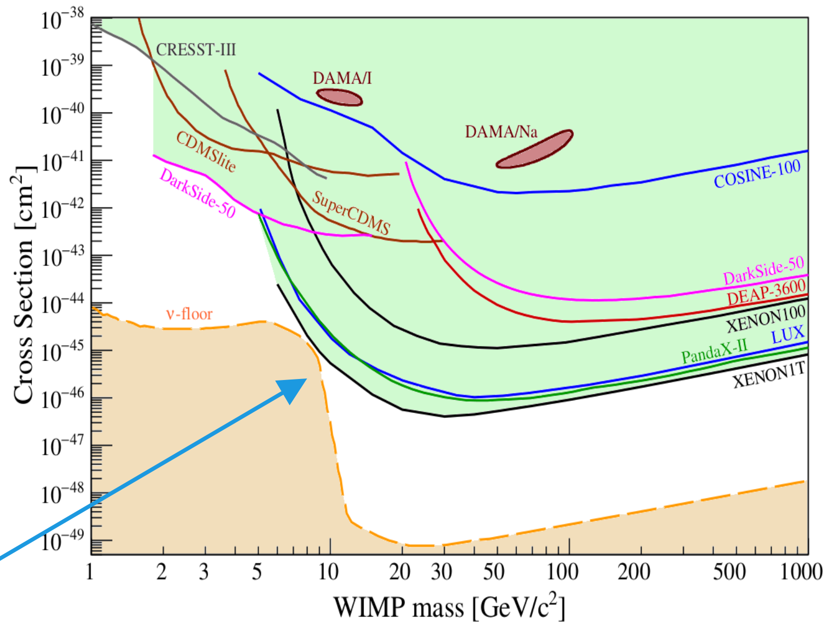
Overview

- Motivations for (non-ALP) WISPs
- Hidden Photons
- Their origin in string theory
- (Some) recent developments in experiments vs model building

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

And some recent hints:

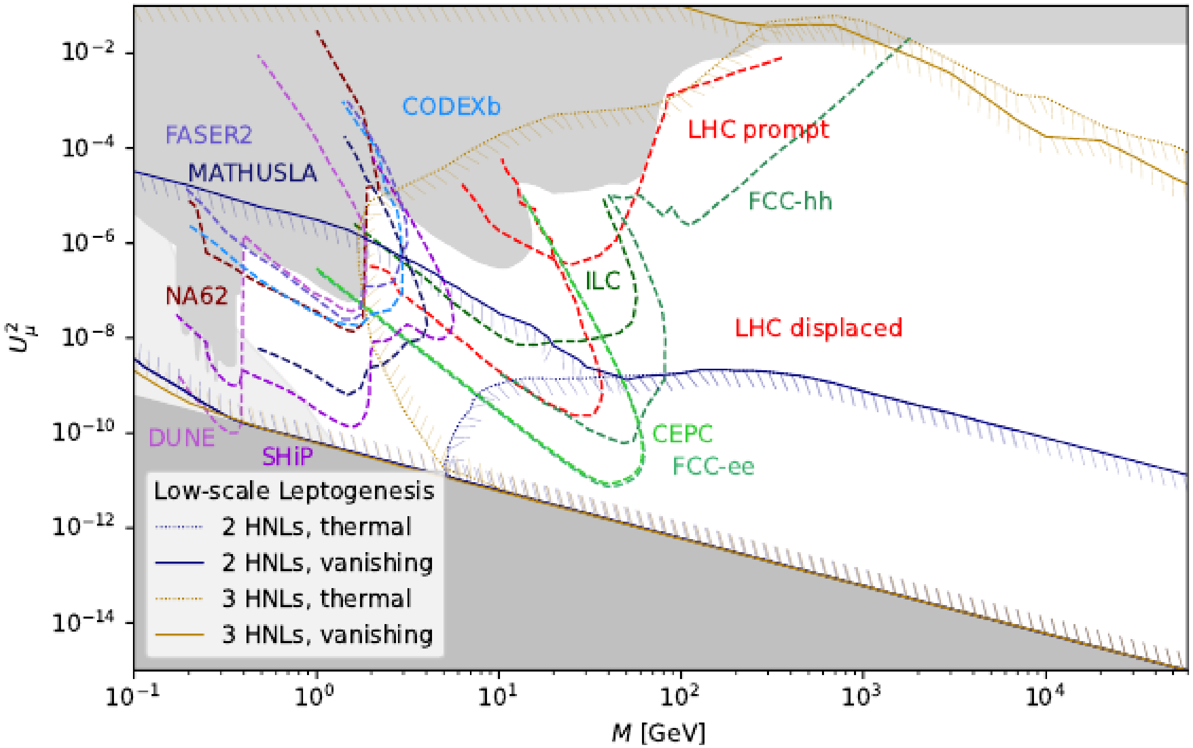
- Extra-galactic background light excess at 4σ: 2202.04273
- Xenon-1T low energy events stimulated a lot of interest… before they went away – some of the models may remain interesting
- Muon g-2 *might* be related to light new physics (once upon a time hidden photons could explain it)
- … now perhaps a hidden photon might explain discrepancy between lattice and R-ratio
- Atomki Anomaly possibly related to 17 MeV boson
- Attempts to explain the W boson mass by CDF …
- Several long-standing astrophysics hints, e.g. 3.5 keV line ...

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



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, 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:

$$\mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu$$

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

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

Hidden photons as new forces

For a massive hidden photon, we diagonalise by a non-unitary transformation:

$$A_\mu \to A_\mu - \frac{\epsilon}{\sqrt{1-\epsilon^2}} X_\mu, \quad X_\mu \to \frac{1}{\sqrt{1-\epsilon^2}} X_\mu$$

This means that *visible* particles pick up a small coupling under the *new force*:

$$A_\mu J^\mu_{\rm em} \to A_\mu J^\mu_{\rm em} - \frac{\epsilon}{\sqrt{1-\epsilon^2}} X_\mu J^\mu_{\rm em}$$

This is the basis of constraints using tests of coulomb's law etc

Oscillations

Suppose instead we make the opposite transformation (the physics should be equivalent)

$$X_\mu \to X_\mu - \frac{\epsilon}{\sqrt{1-\epsilon^2}} A_\mu, \quad A_\mu \to \frac{1}{\sqrt{1-\epsilon^2}} A_\mu, \quad e \to e\sqrt{1-\epsilon^2}$$

Now we redefine the electromagnetic charge, and we also have a mass mixing term:

$$\mathcal{L} \supset \frac{1}{2} m_X^2 (X_\mu - \frac{\epsilon}{\sqrt{1-\epsilon^2}} A_\mu)^2$$

This can be diagonalised by a *unitary* transformation with angle $\tan\theta = -\frac{\epsilon}{\sqrt{1-\epsilon^2}}$

The difference is that we now have *flavour* eigenstates where one is genuinely hidden … also, like neutrinos they oscillate into each other with probability after distance L of

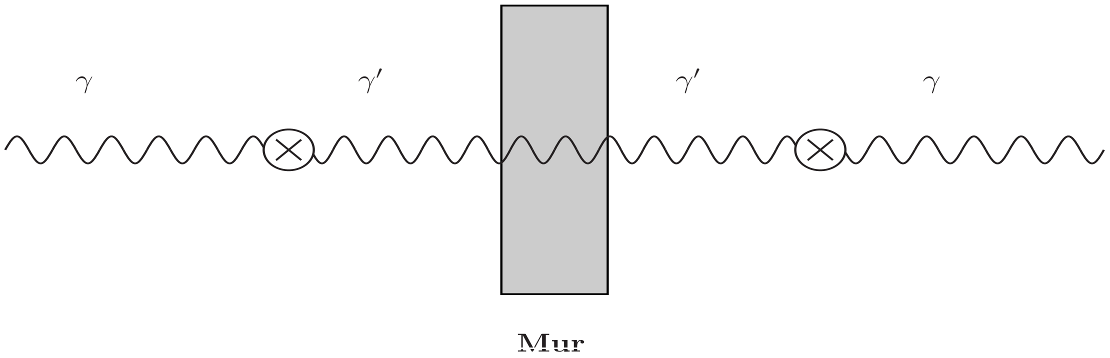
$$P(\gamma \to \gamma') \simeq 4\epsilon^2 \sin^2\left(\frac{m_X^2 L}{4E}\right)$$

Now if it passes through some matter target, the ‘hidden’ flavour eigenstate is the only one that survives.

We can compute the probability that a particle oscillates to a hidden photon, passes through a target, and then oscillates back again in a given distance:

$$P(\gamma \to \gamma' \to \gamma) = P(\gamma \to \gamma')P(\gamma' \to \gamma) = 16\epsilon^4 \sin^4\left(\frac{m_X^2 L}{4E}\right)$$

So we can have light shining through walls!



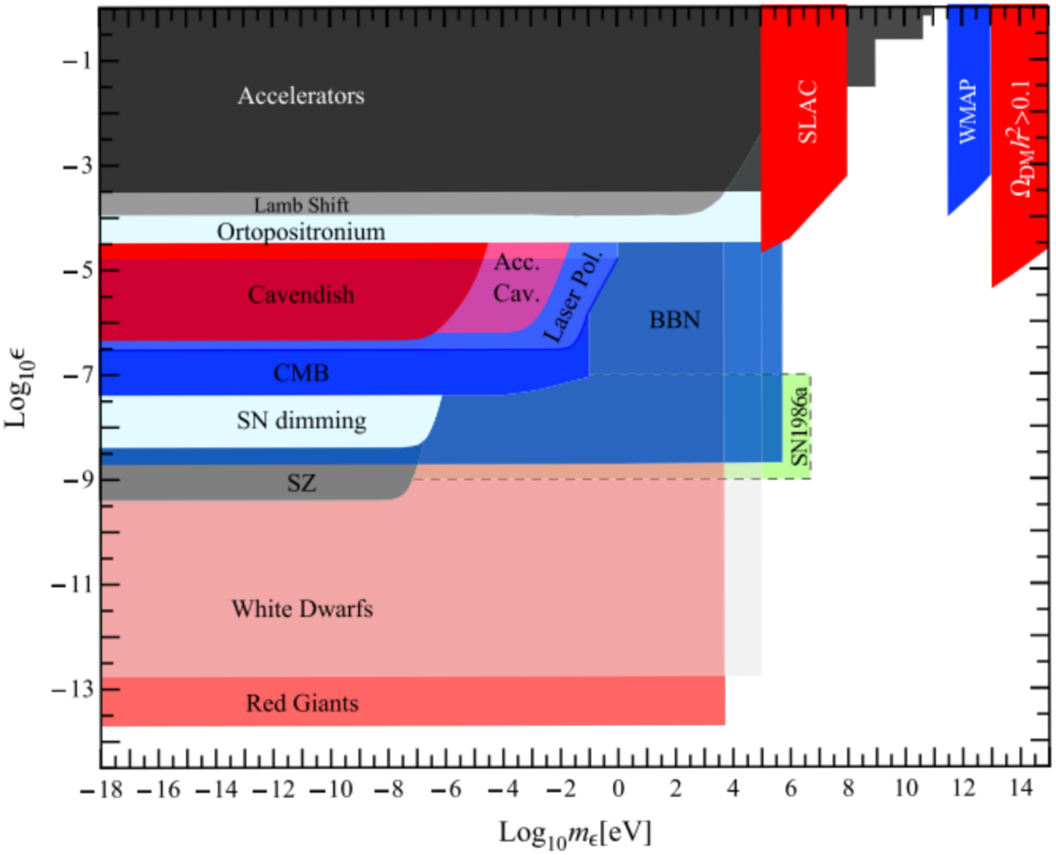
This is the basis of LSW experiments and many astrophysical searches for hidden photons … if we put a cavity on either side then the definition of L is fixed and the quality of the cavity enhances the signal greatly; this is also at the basis of haloscopes

Millicharges

In the same basis, if there are any particles in the hidden sector, they acquire a small electric charge:

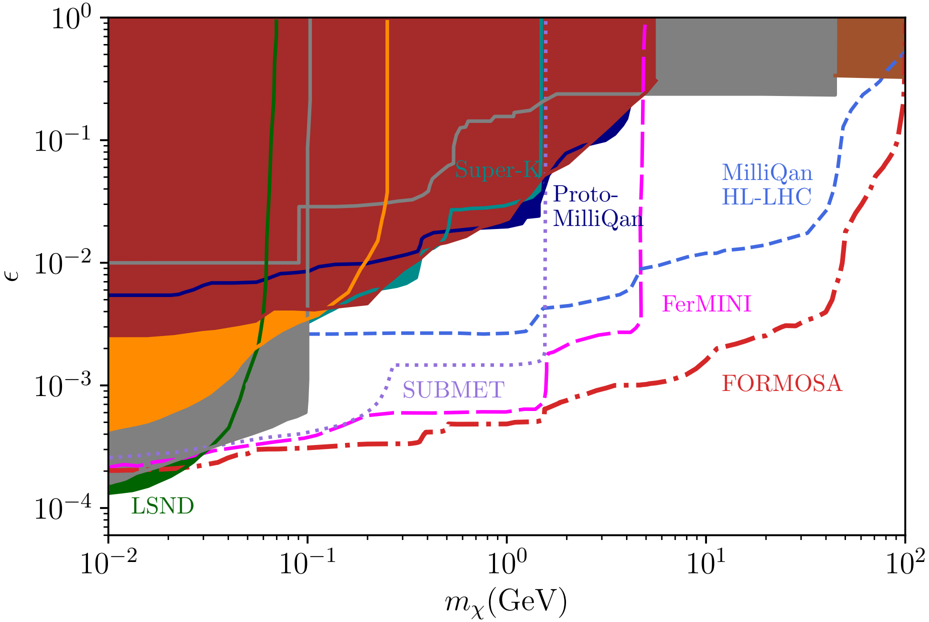
$$g_h J_\mu^{\text{hidden}} X^\mu \to g_h J_\mu^{\text{hidden}} X^\mu - g_h \frac{\epsilon}{\sqrt{1-\epsilon^2}} J_\mu^{\text{hidden}} A^\mu$$

These can be produced in pairs in stars and carry energy away if they are light enough, O(keV) and are very strongly constrained



Lots of recent work, see e.g.

2102.12143



Hidden Higgs Mechanism

The hidden photon could have a hidden Higgs mechanism to give it mass.
We'd then require a whole hidden sector, second hierarchy problem etc.

But in principle it could be almost arbitrarily light this way.

We just have an upper limit on the hidden Higgs mass

$$\mathcal{L} \supset \mu^2|\Phi|^2 - \frac{\lambda_X}{4}|\Phi|^4 \qquad m^2_{\text{hidden higgs}} = \frac{1}{2}\lambda_X v^2_{\text{hidden}} = \frac{\lambda_X}{2g_X^2} m_X^2 \lesssim \frac{4\pi}{g_X^2} m_X^2$$

unitarity

But the hidden Higgs is charged under the hidden gauge group, so if it is light enough it can behave like a millicharged particle!

Stueckelberg mechanism

The alternative mechanism to give mass to a U(1) is the Stueckelberg mechanism, where we add an ALP as the longitudinal mode:

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a - m_X X_\mu)^2$$

It looks a bit like the Higgs mechanism but there is no quartic coupling:

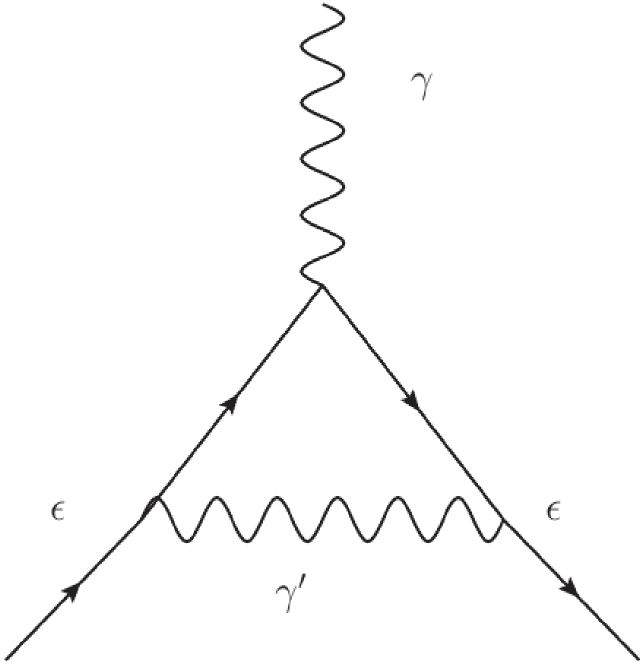
$$\mathcal{L} \supset -\frac{\lambda_X}{16} a^4$$

It is well-known from String Theory and related to the Green-Schwarz anomaly-cancellation mechanism … but the U(1) does not need to be anomalous to get a mass!

Hidden photons and g-2

A loop of a hidden photon gives:

$$\Delta a_\ell = \frac{\alpha}{2\pi}\epsilon^2 \times \begin{cases} 1 & m_\ell \gg m_X \\ \frac{2m_\ell^2}{3m_X^2} & m_X \ll m_\ell \end{cases}$$



Comparing to the discrepancy:

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

yields a kinetic mixing of $\epsilon \sim \mathcal{O}(10^{-3})$

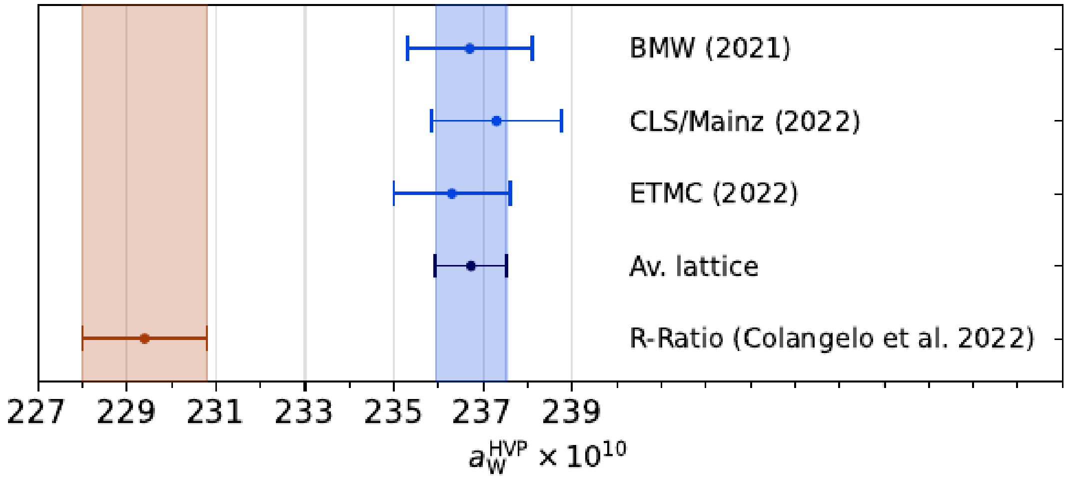
If there are no hidden particles for the hidden photon to decay to then such a hidden photon is already ruled out anyway

Of course, now several lattice groups report on the HVP contribution that differ in total from the R-ratio method by over 4σ in the 'Window' region:

	a_{SD}^{HVP}	a_{W}^{HVP}	a_{LD}^{HVP}	a_{μ}^{HVP}
Data-driven [30]	68.4(5)	229.4(1.4)	395.1(2.4)	693.0(3.9)
BMWc [24]	–	236.7(1.4)	–	707.5(5.5)
Mainz/CLS [26]	–	237.30(1.46)	–	–
ETMC [27]	69.27(34)	236.3(1.3)	–	–
lattice average [27]	–	236.73(80)	–	–

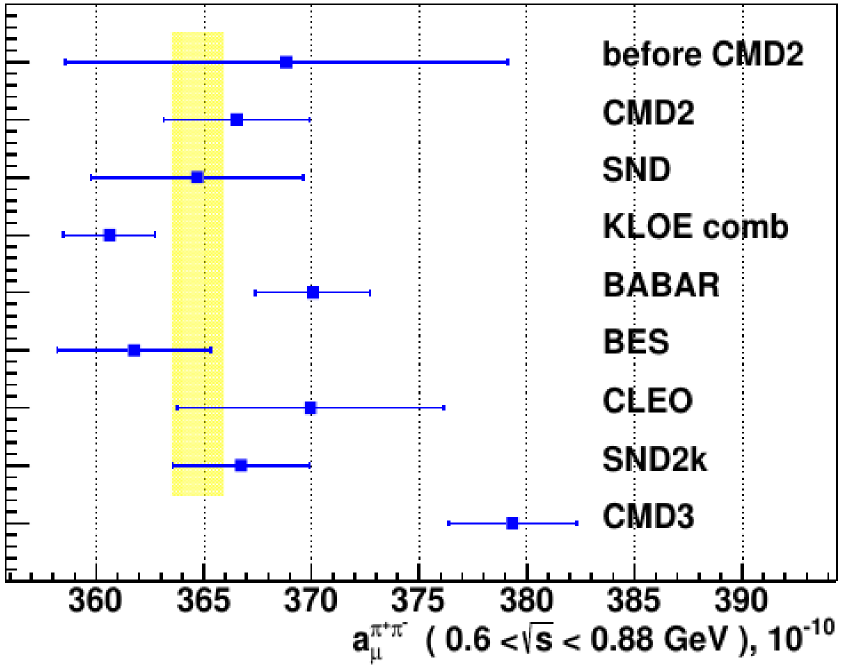
$$a_\mu^{HVP} = (720 \pm 7) \times 10^{-10}$$

Required for no new physics



And recently the CMD3 experiment threw a new spanner in the works with a new measurement of the pion production cross-section

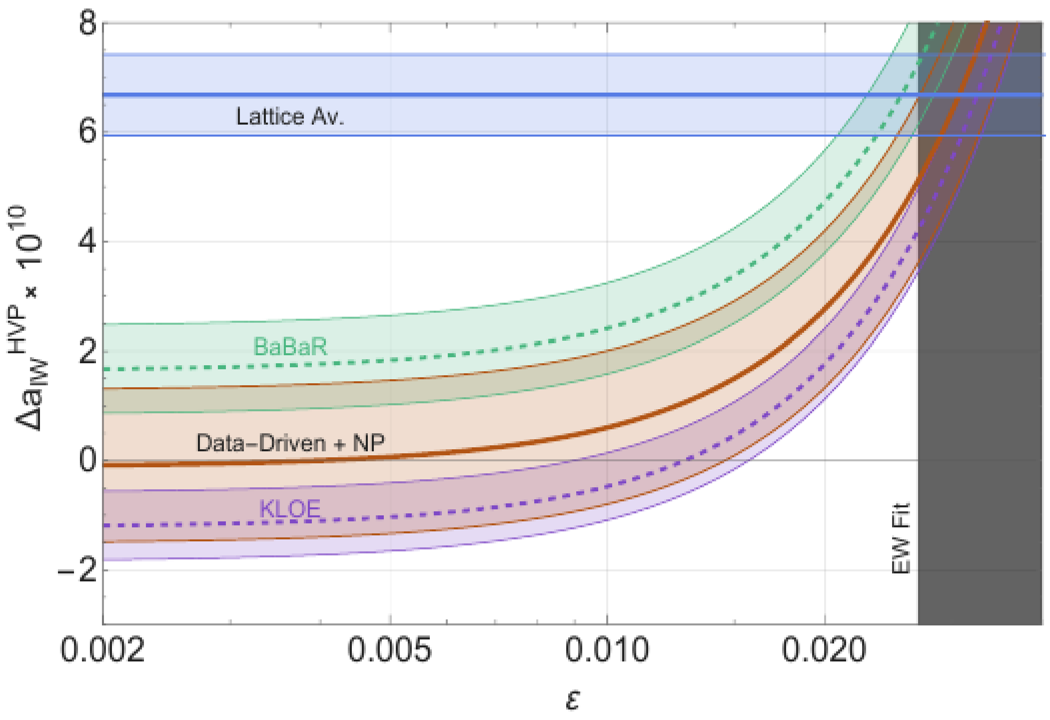
arXiv:2302.08834



Darmé, Grilli di Cortona, Nardi
arXiv:2212.03877

considered instead that a hidden photon could explain the difference between R-ratio and lattice data if it has a mass close to the KLOE CoM energy ~ 1.02 GeV!

The key idea is that it changes the measurement of the *luminosity* by changing the number of μμγ final states produced!



Hidden photons and dark matter

Hidden photons can be very relevant for dark matter:

- As possibly the most generic mediator to a dark sector
- As dark matter themselves!

Freeze-out if there is a Z_2

Other mechanisms if the kinetic mixing/mass is small enough to hamper decays

$$\gamma' \to 3\gamma, \quad \gamma' \to 2e, \ldots$$

Generating Hidden photon DM

Longitudinal modes of hidden photons are like axions – so can be generated by misalignment!

But there is no axion mass term – only a kinetic term – so the energy dissipates away too quickly

So we can add a non-minimal coupling to gravity: $\mathcal{L} \supset \frac{R}{12} X_\mu X^\mu$

Gives e.o.m.: $$\ddot{A}_i + \frac{\dot{a}}{a} A_i + (m^2 + \frac{R}{6}) A_i = 0, \quad R = -6(\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a})$$

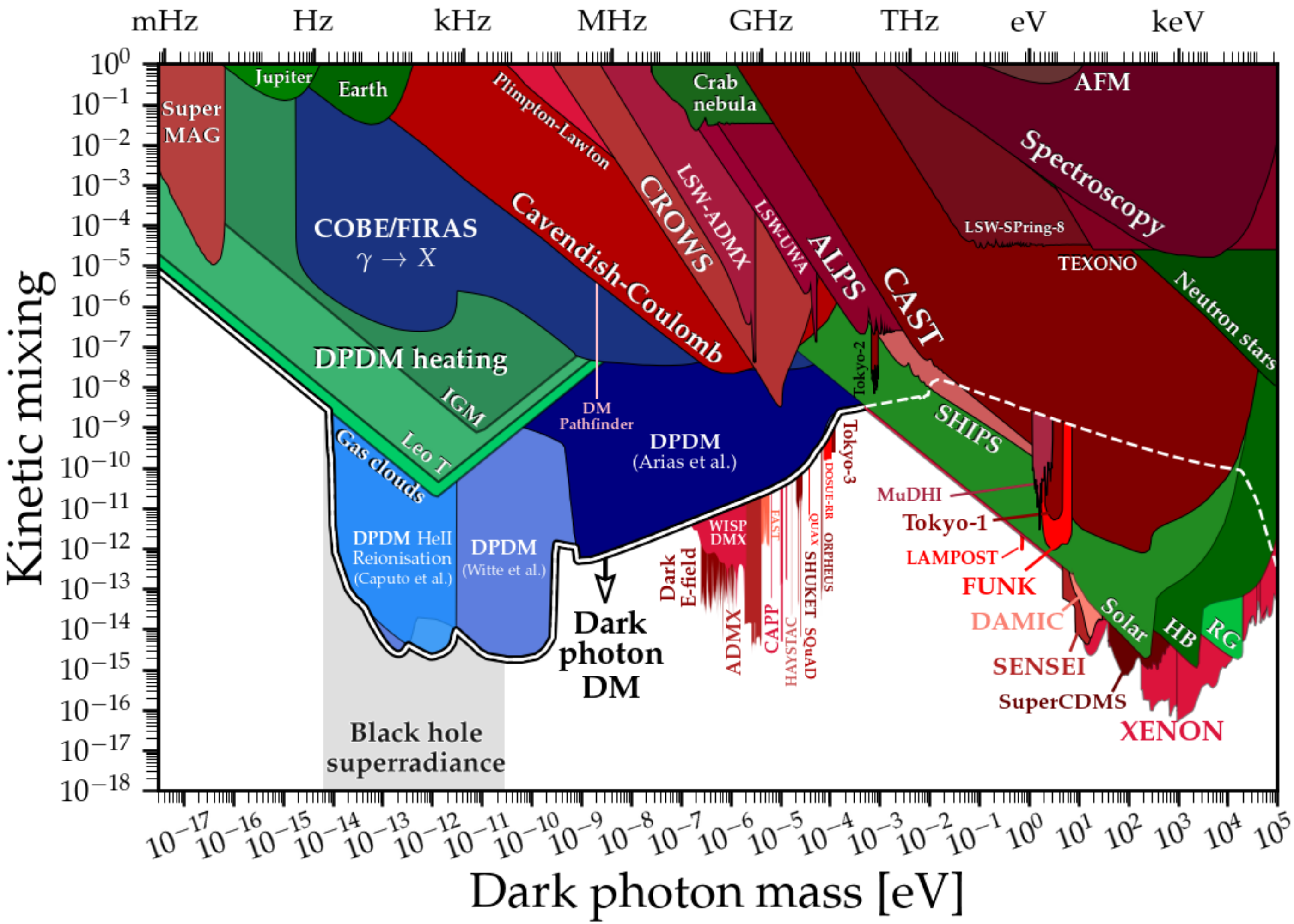
So we can instead write in terms of B=A/a which scales as a scalar:

$$\ddot{B}_i + 3H\dot{B}_i + m_X^2 B_i = 0$$

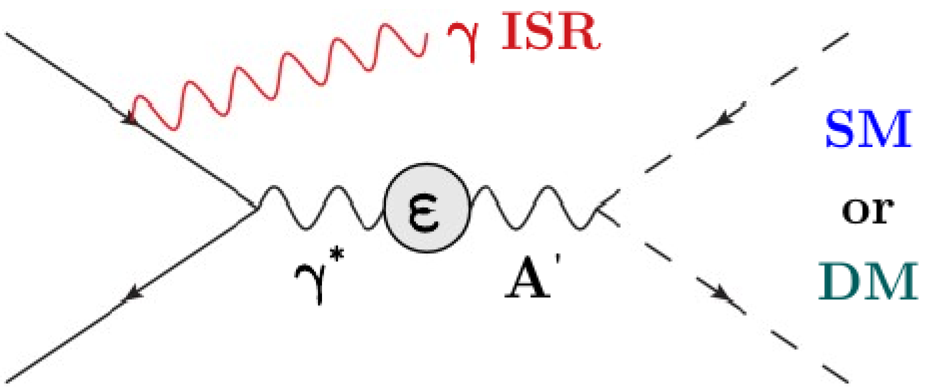
Of course, they could also be produced by coupling to the inflaton, or decays of other fields, freeze-in, etc … without the need for an exotic gravity coupling

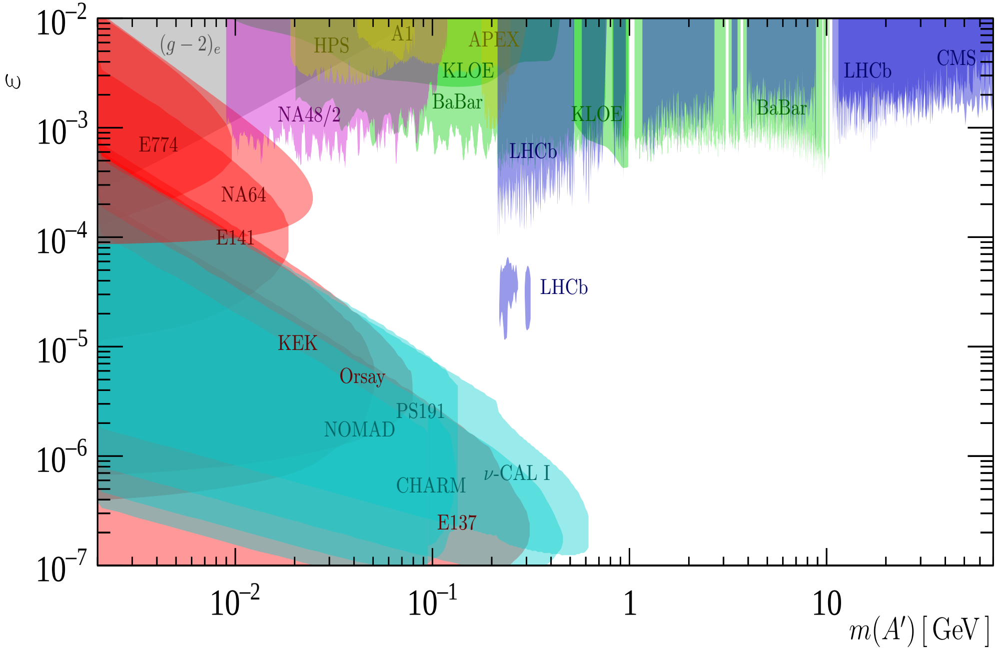
Latest constraints summarised on Ciaran O'Hare's github (see also the "Hidden Photon Cookbook")

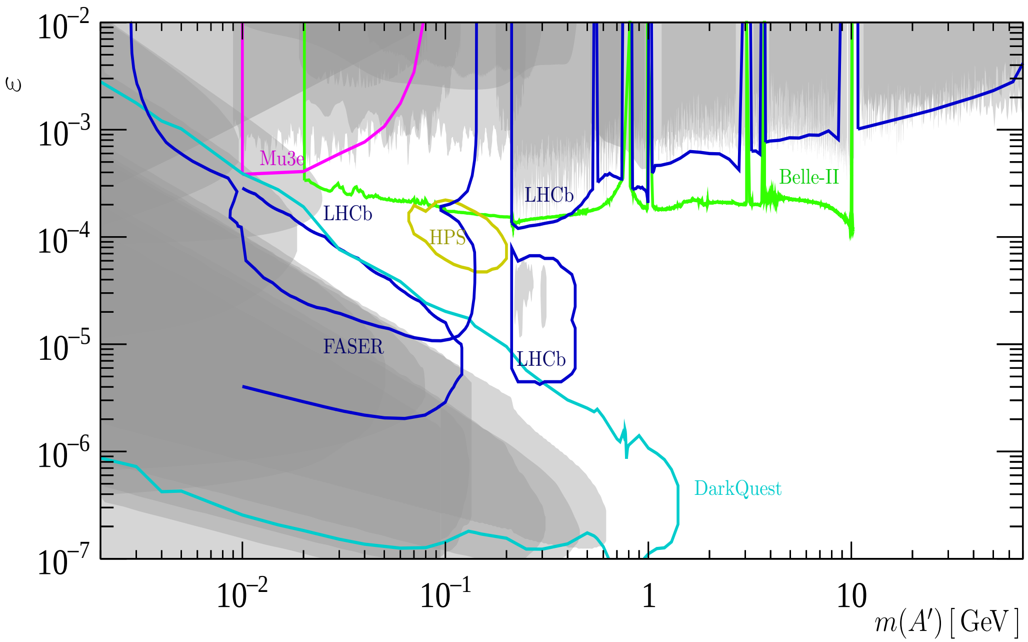
Lots of activity in other working groups on new constraints/searches



Also interest in direct searches at heavier masses:







Hidden photons from string theory

Extra U(1)s are *ubiquitous* in string theory:

- In IIB, R-R U(1)s exist in the bulk (but have gravitational-strength couplings). There are equivalent objects in F-theory.
- D-Branes carry U(N) = SU(N) x U(1) gauge group. Not all of the U(1)s will be anomalous
- Hidden sectors are a generic requirement from tadpole cancellation
- Heterotic models can also contain hidden sectors: breaking from E8 x E8 or SO(32) to the SM leaves a lot of room ...

Kinetic mixing in string theory

In SUSY theories, kinetic mixing, like the gauge kinetic term, is a *holomorphic quantity:*

$$\mathcal{L} \supset \int d^2\theta \frac{1}{4} f_{ab} W_a W_b + h.c.$$

This means it is generated/runs only at one loop

BUT the physical interaction is then determined by a Kaplunovsky-Louis formula:

$$\frac{\epsilon_{ab}}{g_a g_b} = \mathrm{Re}(f_{ab}) + \frac{1}{8\pi^2}\mathrm{tr}(Q_a Q_b \log Z) - \frac{1}{16\pi^2}\kappa K \,\mathrm{tr}(Q_a Q_b)$$

Wavefunction renormalisation terms summed over light fields – vanishes for a hidden U(1)

Vanishes for anomaly free

In general, this leads to the generic expectation $\epsilon \sim g_Y g_X \times \mathcal{O}(1 - \text{loop})$

This is especially interesting in type II string theory where the gauge coupling depends on the size of the D-brane supporting it

$$\frac{1}{g_a^2} = \frac{2\pi}{g_s}\mathcal{V}_a$$

So we can predict the kinetic mixing from just the hidden gauge coupling!

In string theory, the volume of the total compact space (in string units) relates the Planck and string scales:

$$M_P^2 = \frac{4\pi}{g_s^2}\mathcal{V}M_s^2$$

If the hidden U(1) is supported on a 'large' brane and/or the volume is large, then the gauge coupling can be weak

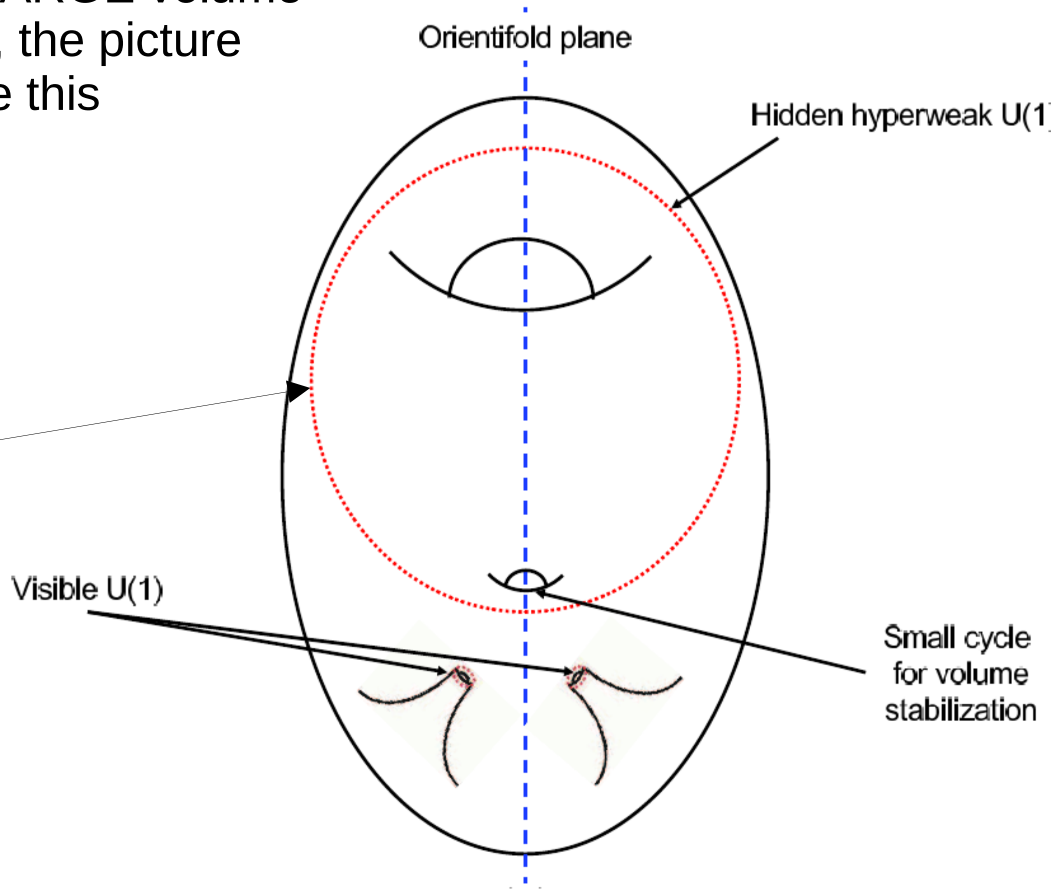
e.g. in the new 'dark dimension' scenario of Montero, Vafa, Valenzuela 2205.12293 there is a dark dimension of a scale 1/meV.

$$M_s = \left(\frac{M_P^2 g_s^2}{4\pi l_{\text{dark}}}\right)^{1/3} \sim 10^7 \text{ GeV}$$

If there were a dark gauge group, it would be very weak:

$$g_{\text{dark}} \sim \sqrt{\frac{g_s}{2\pi l_{\text{dark}}/l_{\text{string}}}} \sim 10^{-11}$$

In top-down LARGE volume constructions, the picture might look like this



Hyperweak gauge group might wrap a 'large' cycle with

$$\mathcal{V}_{\mathrm{hidden}} \sim \mathcal{V}^{2/3} - \mathcal{V}$$

In the extreme case we would have

$$\epsilon \sim 10^{-3} \left(\frac{M_s}{M_P} \right) \gtrsim 10^{-19}$$

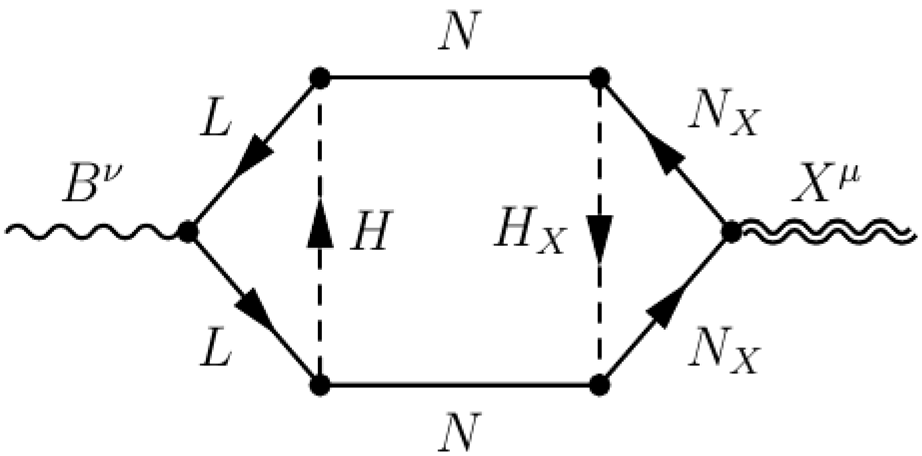
Kinetic Mixing beyond SUSY

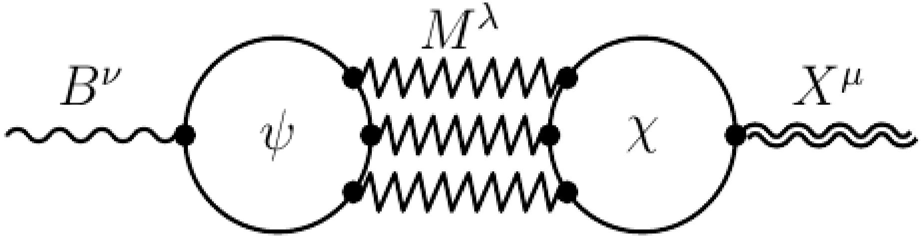
If we have zero mixing at the SUSY level, can have a large suppression.

E.g. in softly-broken SUSY can have $\int d^4\theta W^\alpha (D_\alpha \Xi) \overline{W}'_{\dot\alpha} \overline{D}^{\dot\alpha} (\overline{\Xi})$ $\langle \Xi \rangle = F_\Xi (\theta\theta)$

Suppression by $\dfrac{|F|^2}{M^4}$

Recently Gherghetta, Kersten, Olive, Pospelov 1909.00696 examined many examples,





Or even gravity mediation!

String Stueckelberg masses

The ‘axions’ are the zero modes of two- or four-form RR fluxes in IIB

$$\mathcal{L} \supset -2\pi \frac{e^{-\phi}}{l_s^2} \int_{\mathbb{R}^{3,1}\times D_i} \frac{F_2}{2\pi} \wedge C_4 \wedge \frac{F_2}{2\pi}$$

Stueckelberg masses are determined *exactly* by the volumes they propagate in, encoded by the Kaehler metric

$$m_{ab}^2 = g_a g_b \frac{M_P^2}{4\pi^2} q_{a\alpha} (\mathcal{K}_0)_{\alpha\beta} q_{b\beta}$$

$$q_{ij} = \int_{D_i} \hat{D}_j \wedge \frac{F}{2\pi} = f_i^k k_{ijk}$$

Intersection numbers of CY

4-cycle

Two-form

Flux on D-brane

The metric is just the derivative of the potential w.r.t. four-cycle volumes

$$(\mathcal{K}_0)_{ij} = \frac{\partial^2}{\partial\tau_i \partial\tau_j} \left(-2\log\mathcal{V}\right)$$

It is known for many examples, e.g.

$$\mathcal{V} = 6(t_b^3 - t_s^3) = \frac{1}{9\sqrt{2}} \left(\tau_b^{3/2} - \tau_s^{3/2}\right)$$ Swiss cheese

$$\mathcal{V} = \frac{1}{2}\sqrt{\tau_1}\left(\tau_2 - \frac{2}{3}\tau_1\right)$$ Anisotropic

Hidden Higgses in String Theory

- The simplest hidden Higgs sector is a vector-like pair of chiral multiplets
- The quartic coupling is then determined from the D-terms – given by the hidden gauge coupling!
- This is also true for a chiral hidden Higgs (with hidden matter)

$$W \supset \mu \Phi \tilde{\Phi}$$

$$\mathcal{L} \supset -\frac{g_X^2}{2} |\phi \tilde{\phi}|^2$$

$$m_{\text{hidden higgs}} \sim m_X \gtrsim \text{keV}$$

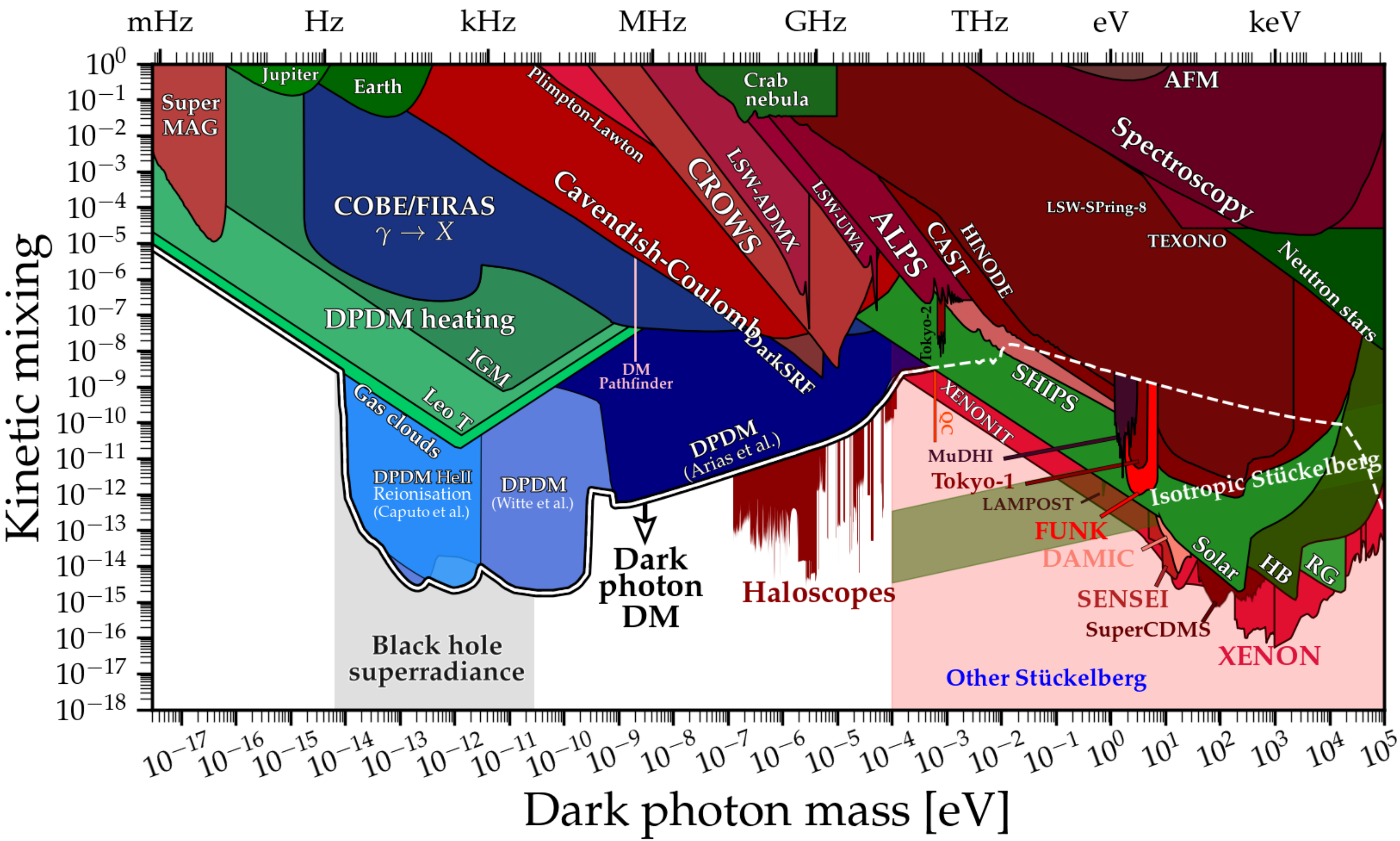
From millicharge searches

This could be relaxed by more involved model building (e.g. NMSSM-like singlet, ...)

Also true for a hidden chiral condensate

$$m_X \sim g_X \Lambda, \quad \Lambda^3 \sim \langle \overline{\psi} \psi \rangle$$

Predictions



Perspectives

Can make quite generic predictions from string theory, but many open questions remain:

- Actual calculation of KM in realistic compactifications has not so far been possible (topological strings, propagators of harmonic forms …)
- While computation of Stueckelberg masses is in principle exact, depends on four-cycle volumes … so moduli stabilisation!
- Not always easy to extract the Kaehler metric in the four-cycle basis.
- Hidden Higgs mechanism also intimately tied to how SUSY is broken (what scale is it?) and detailed model building.
- Once upon a time it was thought hidden photons were always present (see recent papers of Acharya et al in M theory). Is there a ‘string hidden-photon-verse’ or how ubiquitous/hidden are hidden sectors?

Advertising

Planned for 25th - 28th September 2023, at LAPTh Annecy:

- Axions++