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Stringy Kinetic Mixing from Andreas' brains

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Some personal history

I first heard from Andreas in December 2006: he'd been working with my supervisor Steve Abel on string model-building for PVLAS and thought I might be useful ...

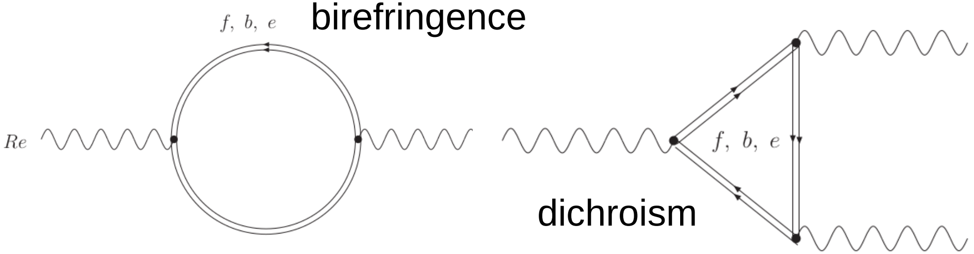
… we started writing a research proposal for me to go to DESY, based on the 'PVLAS anomaly'

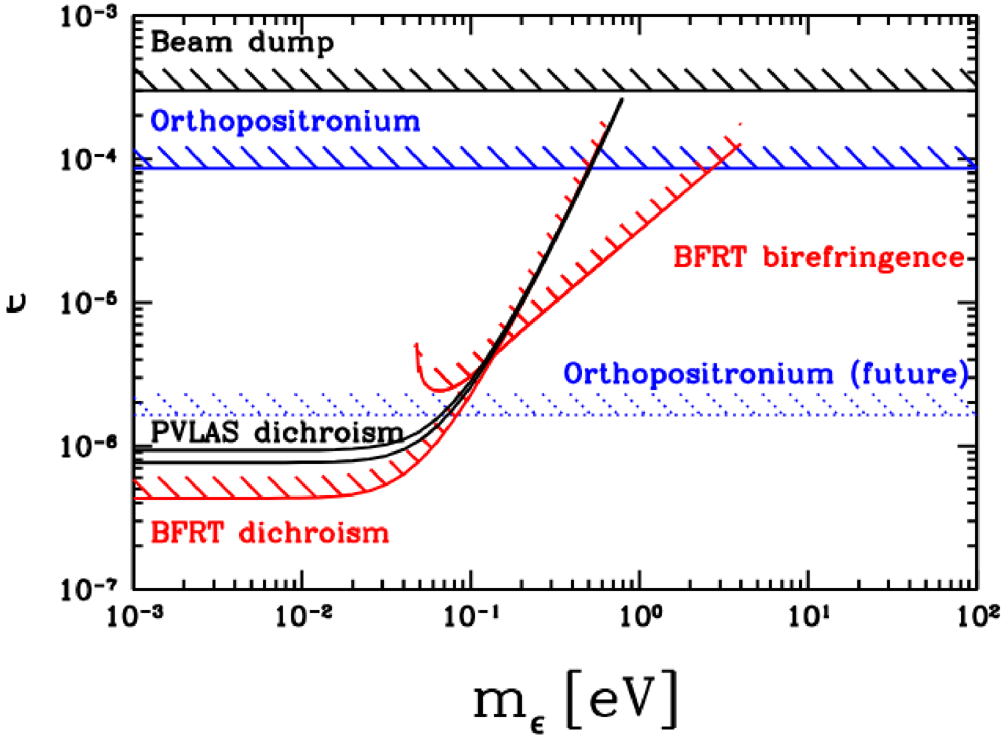
Testing String Theory with a Magnetic Field

The PVLAS experiment [1, 2, 3] is sensitive to physics beyond the standard model, and has reported a deviation from expectations with potentially far-reaching implications. I propose to thoroughly investigate the consequences of their results for string theory.

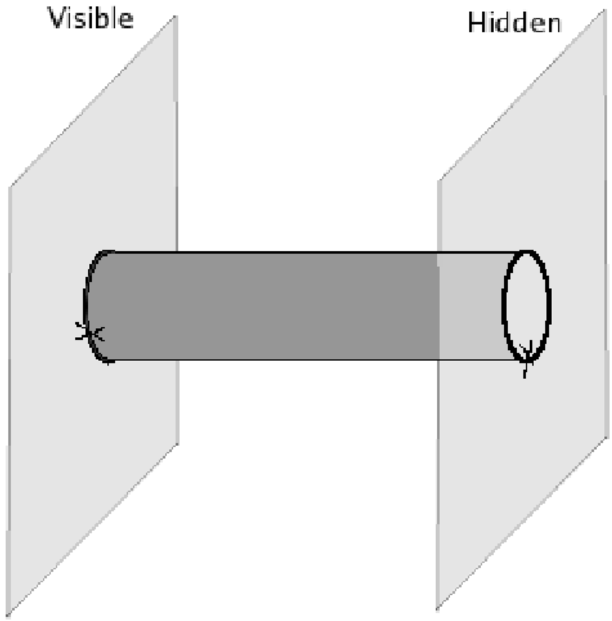
The experiment consisted of trapping polarised laser light in a Fabry-Perot resonator with a powerful magnetic field in the cavity. As the photons resonated in the cavity, the quantum effect whereby a photon temporarily becomes a virtual electron-positron pair allowed an interaction with the mag-

PVLAS reported rotation of the polarisation of a laser which could be interpreted as millicharges of mass less than 0.1 eV (due to the laser energy) and $\epsilon = Q/e \simeq 10^{-6}$





Something like that might quite naturally occur from string theory:



Hidden photons from string theory

After all, 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 ...

Unfortunately in march 2007 (hep-ph/0703144) PVLAS seemed to be excluded by cosmology:

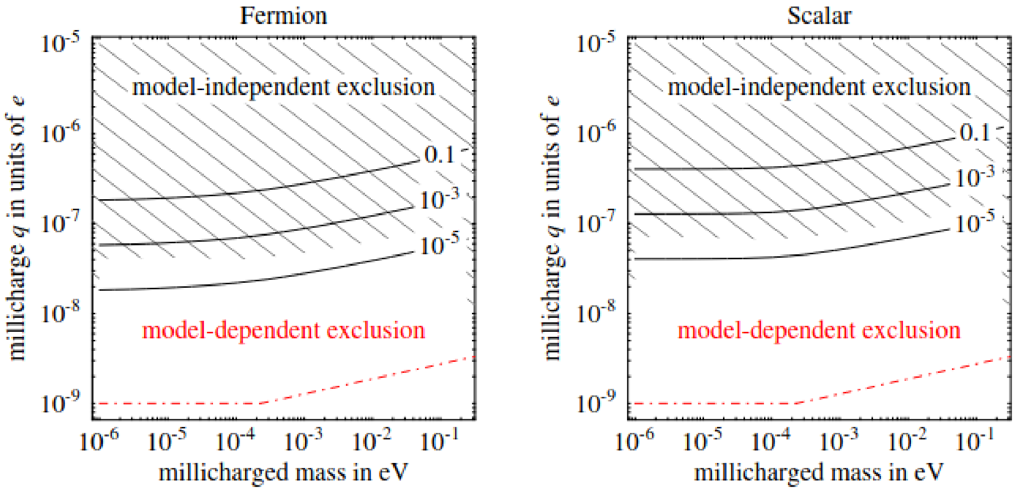


Figure 1: *Isocurves of the cosmological abundance n_q/n_γ of fermionic (left plot) or scalar (right plot) millicharged particles as function of their mass m_q and charge q. The shaded region is excluded by the CMB energy spectrum. The dot-dashed curve is the (robust, but not fully model-independent) constraint estimated in eq. (5), for $q' \sim e$. For comparison, the PVLAS anomaly can be interpreted as production of millicharges with $q \sim \text{few} \times 10^{-6} e$ and maybe $m_q \sim 0.1\,\text{eV}$ [3].*

And in June (0706.3419) PVLAS excluded their previous results

… luckily for me I had already accepted a postdoc in Paris, but our collaboration was born

We had started to ask the questions:

- What values of kinetic mixing does string theory predict?
- What values of the hidden photon/millicharge masses?

But there was also some controversy about whether the kinetic mixing would just be zero!

So we also wanted to answer:

- When does kinetic mixing occur (is non-zero)?
- How generic are hidden sectors that mix?
- Can we compute it for more complicated backgrounds, or just toy models?
- Can we build *realistic* models that include hidden U(1)s?
- How does moduli stabilisation and SUSY breaking affect the picture?

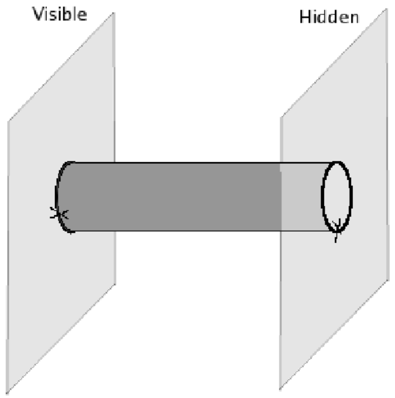
In a series of papers starting from 2008 to 2012 that involve also Javier, Jörg, Michele and Valya (and others) we went a some way to answering these questions

Not a bad outcome from a sunk cost fallacy!

- [Abel, Schofield, 2003] and [Abel, Jaeckel, Khoze, Ringwald, 2006] considered interaction between branes and antibranes on tori.
- Concluded

$$\chi \propto \left(\frac{M_s}{M_p}\right)^{\frac{2(5-p)}{6-p}} \left(\frac{R}{r}\right)^{\frac{d-p+3}{6-p}}$$

- Claim intermediate $M_s \sim 10^{11} GeV$ predicts $\epsilon \geq 0.4 \times 10^{-9}$
- $\rightarrow$ Kinetic mixing places bound on string scale



But such models are unstable and break SUSY at the string scale!

In SUSY D-brane string models, a single open-string diagram gives both mass terms and kinetic mixing terms:

$$\langle V^a V^b \rangle = m_{ab}^2 A_\mu^a A_b^\mu + \frac{\chi_{ab}}{g_a g_b} k^2 A_\mu^a A_b^\mu$$

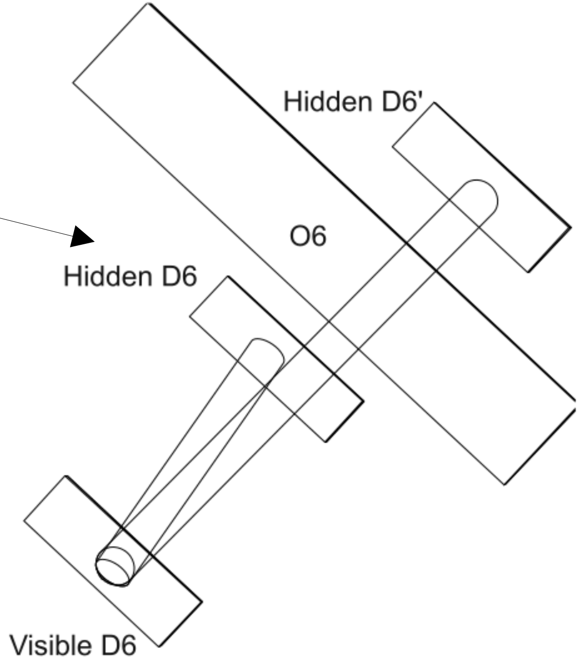
So both are proportional to the same chan-paton factors:

$$\langle V^a V^b \rangle \propto \mathrm{tr}(\gamma\lambda^a)\mathrm{tr}(\gamma\lambda^b)$$

Cancellation of anomalies/masses often forces these traces to vanish → no kinetic mixing!

… except when the U(1) is supported on several branes:

Now we could have stable, anomaly-free light U(1)s mixing



- I collaborated with Andreas while I was in Paris 2007 – 2009 (with a certain amount of bother to my employers there) and visited Hamburg for the ‘calculationshop’
- I was only too happy to get the offer to be a postdoc at DESY from 2009 – 2011.
- … I was sharing an office opposite Andreas and he’d drop in and chat every day, always full of enthusiasm and ideas … it was also a great way to improve my german!
- That time was amazing: so many great people, staff, so many postdocs and students
- The Werkstattseminar was fantastic and I learnt a lot on many different topics.
- I had been bitten by the phenomenology bug and was steadily heading downwards in energy from string theory (Andreas likes to take the credit)
- … I started working on SUSY kinetic mixing too (with Andreas and his student Sarah Andreas)

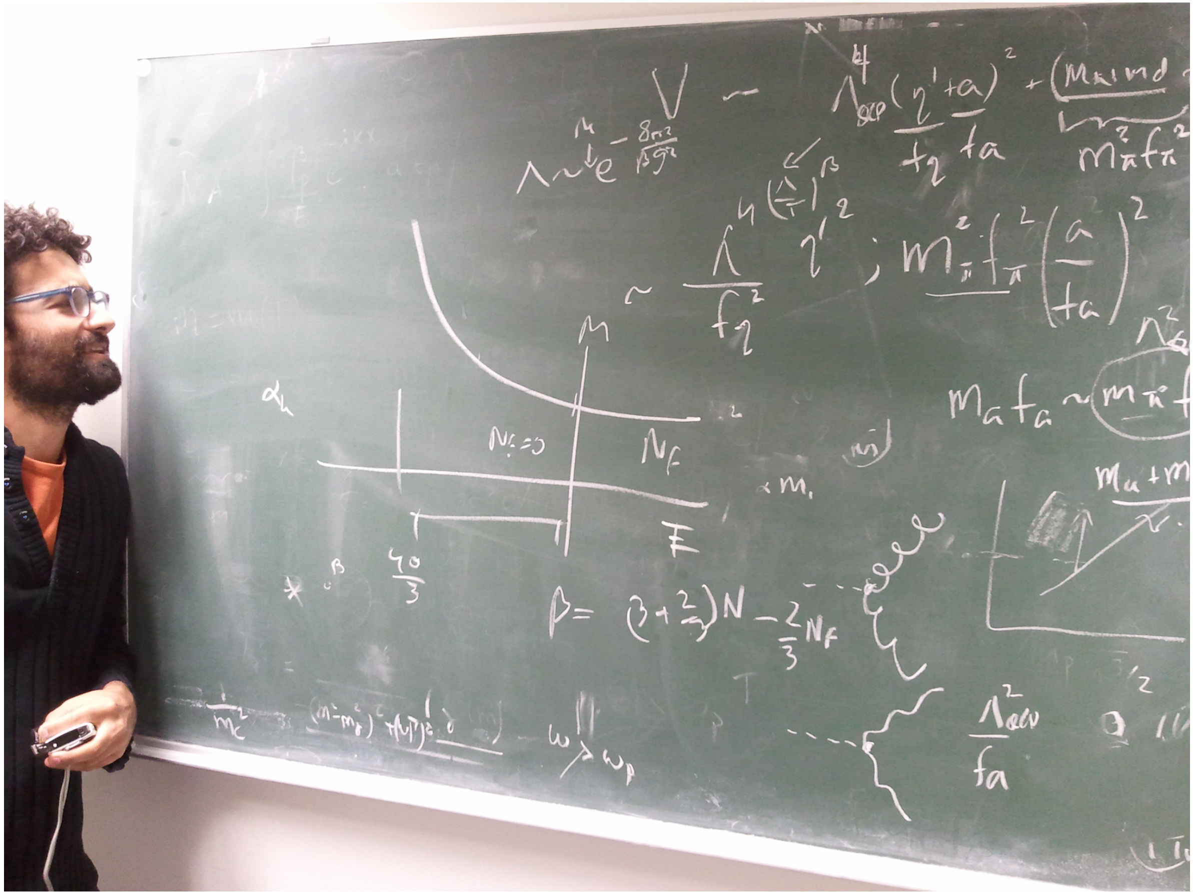
Around the summer 2010 I was moved into my own office in exile in building 6, on a floor with the administrators, as part of some kind of DESY theory power play …

… but I was almost opposite Michele so we started working together too! At least we had no distractions, it was one of the most fun and productive times of my career.

Andreas had to trek over to see us, but was always full of ideas and enthusiasm.
I still miss it!

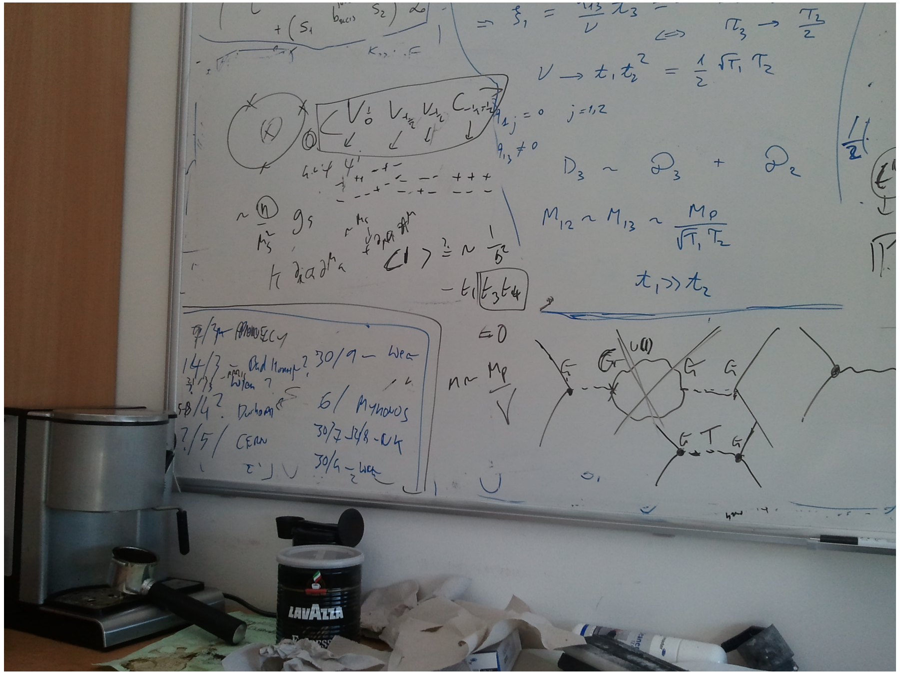
Andreas and Javier were pioneers/evangelists for the original iphone … so I decided to get the first Samsung smartphone.

In the end, to my shame, I only have one(!) photo of Andreas from this time:



But here’s Javier in 2011

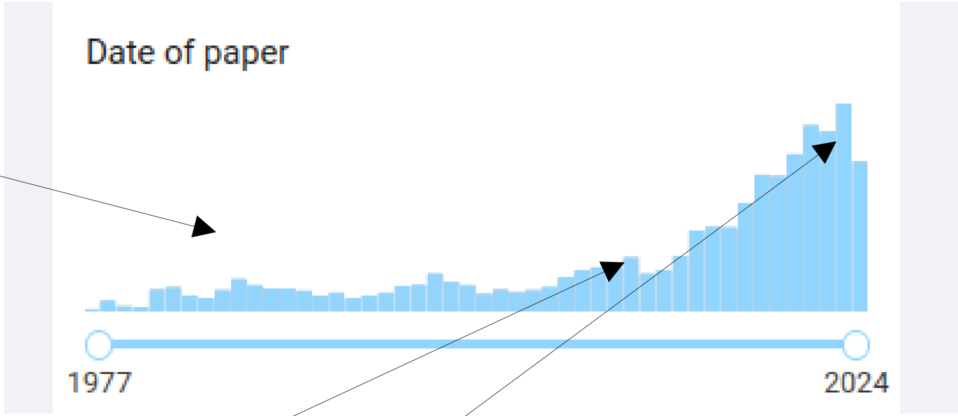
And my DESY office:



In 2010, axions and hidden photons from string theory were viewed with suspicion/contempt by string theorists (and many others).

I recall Andreas writing to Dieter Lüst to complain that he was ignoring our work when they were holding a workshop in Munich …

Clearly Andreas was well ahead of the curve: papers with ‘axion’ or ‘axions’ in the title:



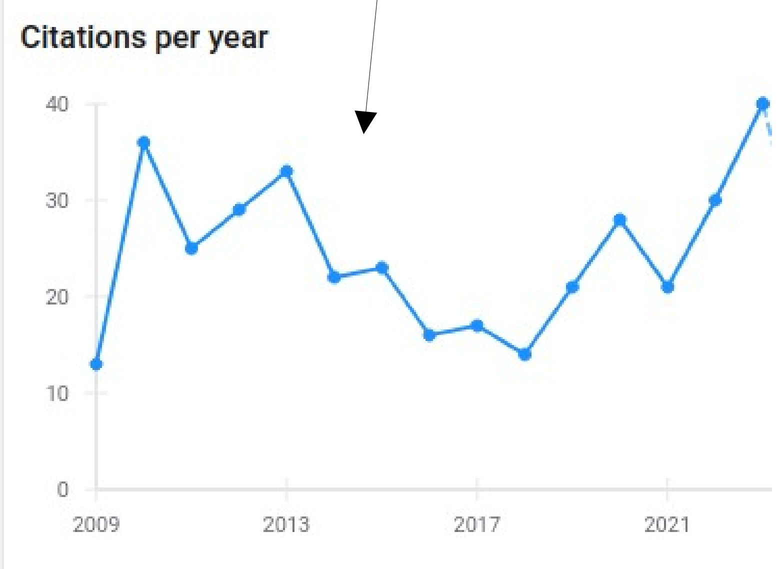
92 in 2009

457 papers last year! And not all of them by Andreas or Javier!

Naturally Light Hidden Photons in LARGE Volume String Compactifications

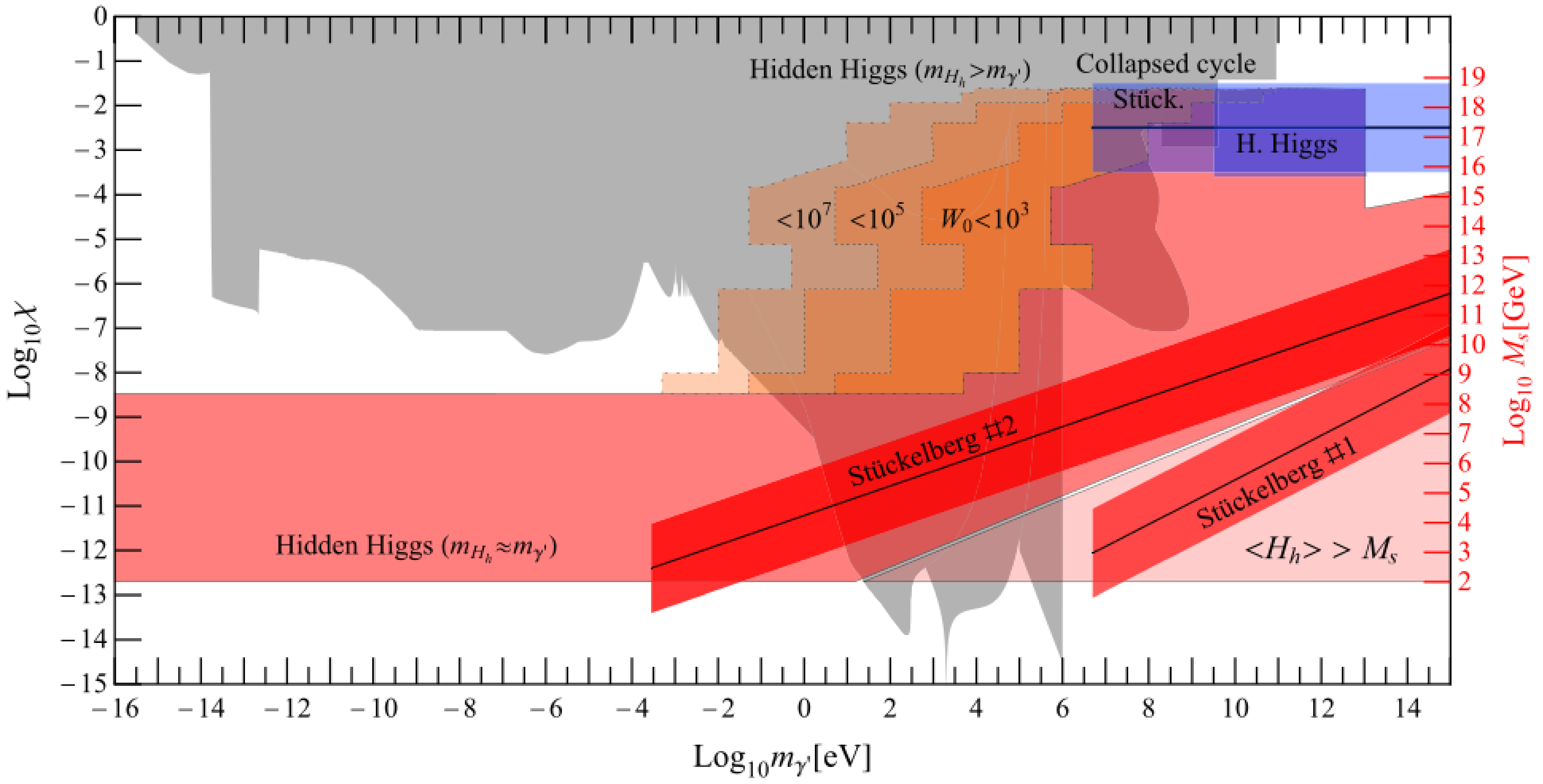
Mark Goodsell (Paris, LPTHE), Joerg Jaeckel (Durham U., IPPP), Javier Redondo (DESY), Andreas Ringwald (DESY)

Sep, 2009



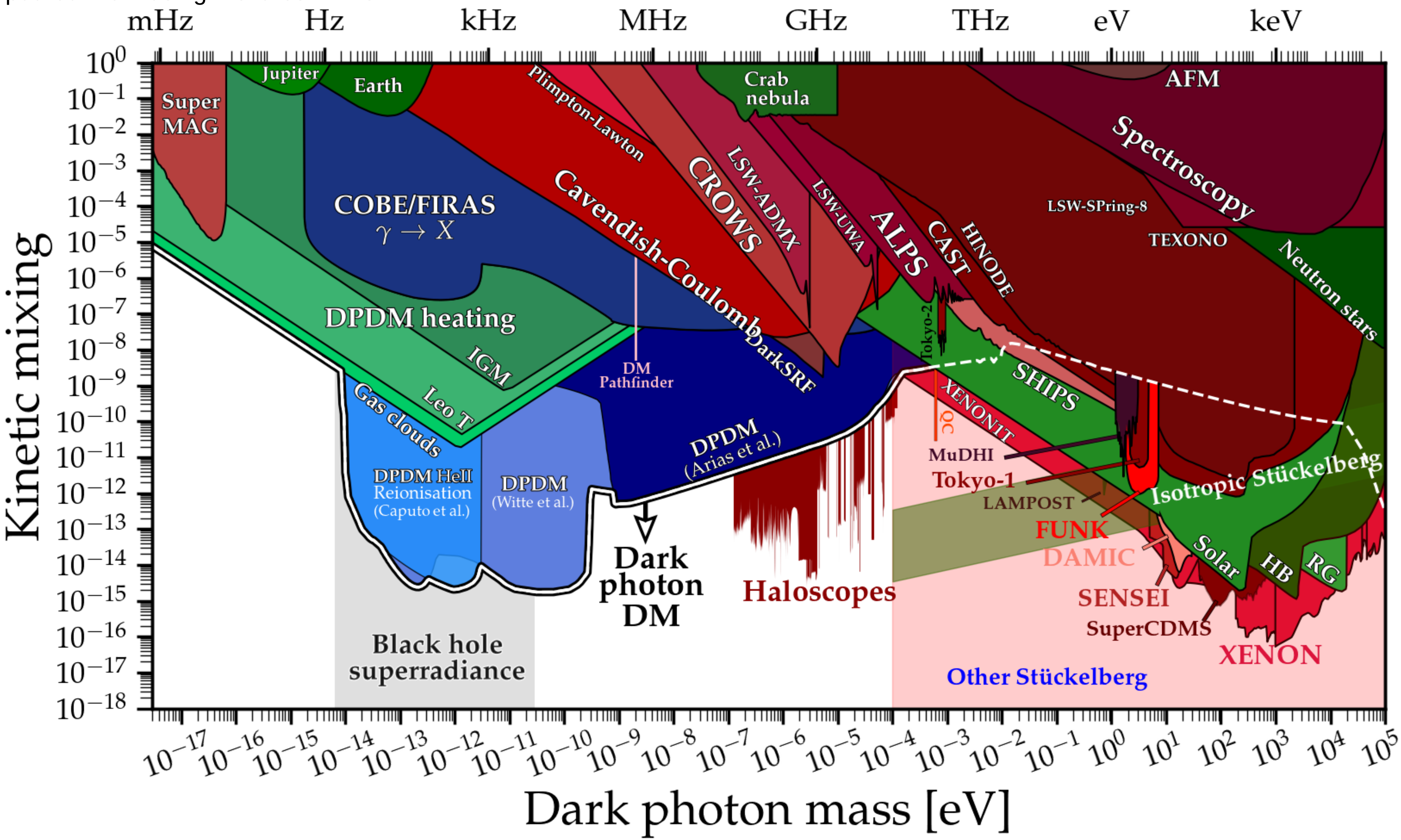
c.f. Hidden photons in string theory are now back in vogue because of the swampland

Here are the predictions from our 2009 paper:



Predictions

Here I updated them using the latest limits



Physics 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?

Final thoughts

- Enjoy your retirement!
- … at least being free of paperwork!
- Andreas is one of the most enthusiastic and energetic people I know, I’m glad he’s still going to be involved in the experiments to discover WISPs
- I’m immensely grateful for our collaborations and my time here

BACKUP

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

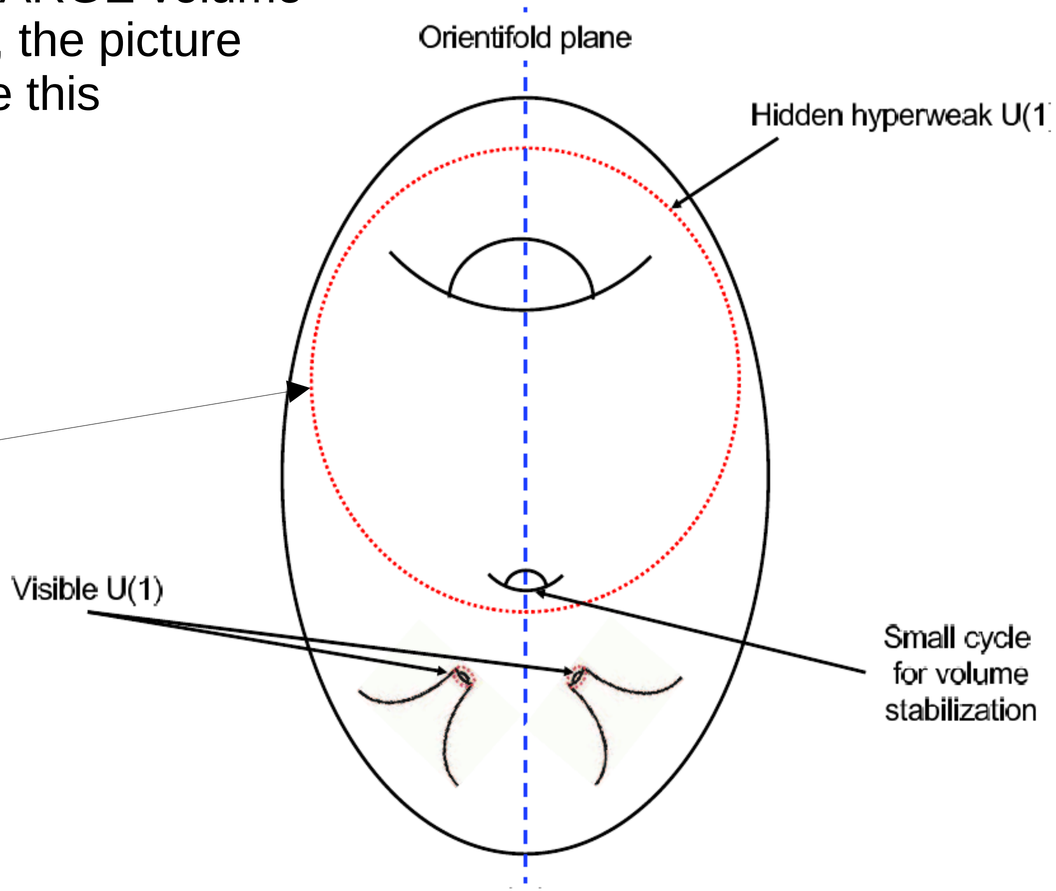
e.g. in the new 'dark dimension' scenario of Montero, Vafa, Valenzuela 2205.12293 there is a dark dimension of a scale 1/meV.

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

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

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

In the extreme case we would have

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

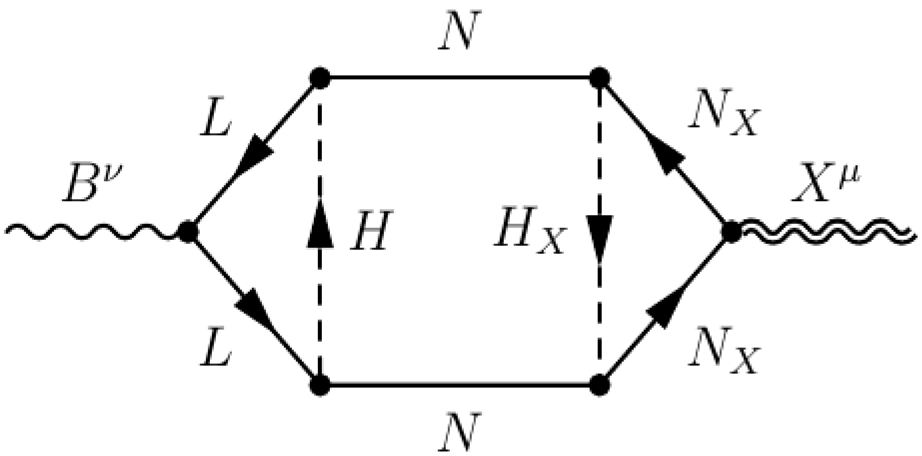
Kinetic Mixing beyond SUSY

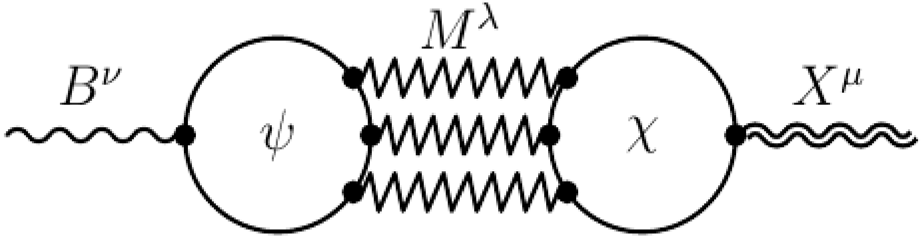
If we have zero mixing at the SUSY level, can have a large suppression.

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

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

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

Intersection numbers of CY

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

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)

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

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

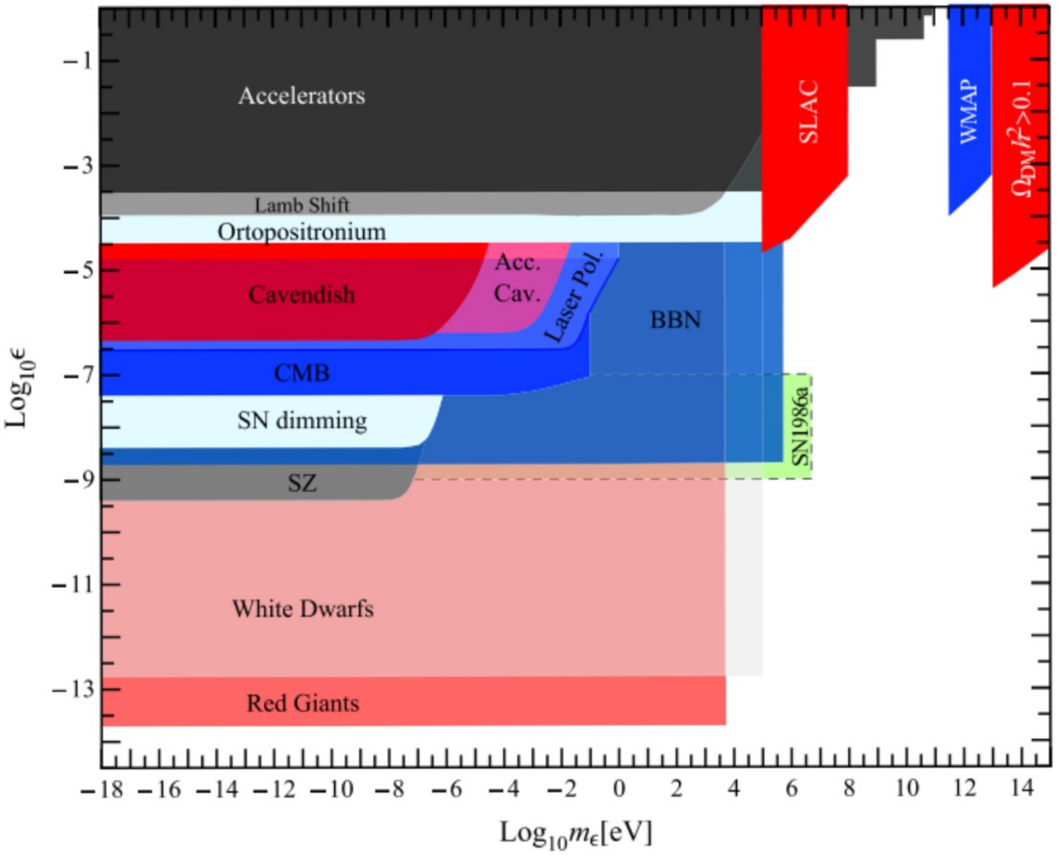
$$m_{\text{hidden higgs}} \sim m_X \gtrsim \text{keV}$$

From millicharge searches

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

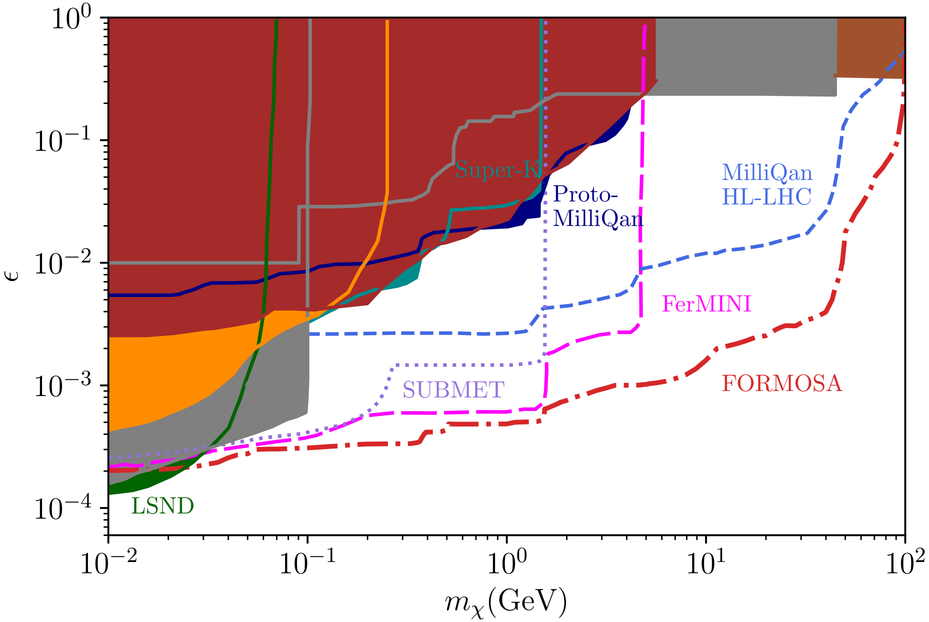
Also true for a hidden chiral condensate

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



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:

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

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 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

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

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