Questions and answers - Tracy Slatyer Lecture 1

The following questions were submitted through Zoom Q&A. Some / all may have been answered in the Q&A session already. Nevertheless, we request our lecturers to provide written answers here for the benefit of those who could not attend that session. Thank you!

(1) In the dark photon model, how does the dark photon & the DM get their masses?

That's a good question! There are multiple options. For the dark photon mass, one possibility is to add an Abelian dark Higgs; when the dark U(1) symmetry is broken, the Higgs gets a vacuum expectation value and the dark photon gains a mass. How the dark Higgs couples to the dark matter will depend on the dark matter's charge and spin, but this Higgs coupling can at least contribute to the dark matter mass, whether or not it provides all of it. Here's a very recent paper that explores some of the phenomenology of the dark photon + dark Higgs + DM model: https://arxiv.org/abs/2507.11376 . The main alternative that's discussed for the dark photon mass is adding what's called a "Stueckelberg mass"; there is a modern-ish review at https://arxiv.org/pdf/hep-th/0304245 . There has been considerable debate about whether we can exclude one or both of these mass-generation mechanisms, in particular in the case where the dark photon is actually the dark matter - I'll touch on this briefly in Friday's lecture, but almost certainly won't have time to go into it in detail.

(2) Does the dark photon play a role in the relic density?

In the case where the dark photon is the mediator to the Standard Model, yes, very much so. As I discussed in the talk, the dark matter could potentially annihilate directly to two copies of a lighter mediator – in which case the dark photon would be produced directly in annihilation, and its coupling to the dark matter would control the annihilation cross section. If the dark photon isn't in equilibrium in the Standard Model, we might need to independently track the properties of the bath of dark photons in this case. On the other hand, if the dark photon is heavier than the dark matter, we might expect the dominant annihilation rate to involve an off-shell s-channel dark photon converting into Standard Model particles through the kinetic mixing. In this case the effective coupling would depend on the dark photon's couplings to both the dark matter *and* the Standard Model.

(3) Can all of these portal DM models exist simultaneously in our universe?

In principle, sure. As in question (1), you can certainly have cases where there is one DM candidate but it has multiple portals to the Standard Model; because different portal interactions have different levels of suppression/enhancement in different searches (e.g. one portal may be enhanced for indirect detection but suppressed for direct detection, while the opposite may be true for a different portal), in this case the portal that dominates the experimental signatures might depend on the search. You could also imagine having multi-component dark matter where each component makes up a subdominant fraction of the dark matter. This wouldn't matter for accelerator searches (which don't rely on the dark matter in the halo), but would be very relevant for direct and indirect detection; it might not be the dominant component that is the most visible.

(4) For the dark photon, do we know if the mediator is SM photon on shell, off shell, oscillates into dark photon or dark photon to begin with ?

The Lagrangian contains the interaction that I listed (mixing the Standard Model photon and the dark photon), in addition to a mass term for the dark photon. The exercise I gave about field redefinitions may be informative - you can perform a field redefinition that removes the kinetic mixing term, while keeping the Standard Model photon massless, in exchange for giving all the charged Standard Model particles a small dark U(1) charge as well. Then you can think of the dark photon as coupling directly to the Standard Model matter fields (rather than mixing with the ordinary photon that then couples to the charged matter fields).

Depending on the couplings of the dark photon to the Standard Model, it might or might not get produced as an on-shell particle in large quantities in the early universe. In the freezeout regime it generally does reach equilibrium, so early on there would have been a bath of real dark photons, but unless they're very light and the kinetic mixing is very tiny, they decay before the present day (if they *are* very light with a tiny kinetic mixing, they are a possible dark matter candidate, but getting the right abundance is non-trivial). In the present-day on-shell dark photons could be produced (if they exist) in most circumstances where the available energy exceeds their mass, e.g. in accelerators or potentially in stars or supernovae.

(5) What do you think about using AI to generically scan all possible classes of models avoiding existing constraints?

I think usually it's possible to get a reasonable idea of whether a model is ruled out or not without using AI, but if you could get AI to apply existing constraints reliably, for large classes of models where the parameter space is complicated, that would probably be quite useful - certainly a significant amount of effort has gone into automating the application of constraints to models (see e.g. the GAMBIT and DarkBit packages, e.g. https://arxiv.org/abs/1705.07920). You would need to be able to validate what the AI was doing, however. There are definitely many examples where AI is already being used productively to sweep through large spaces of scenarios - e.g. this paper https://arxiv.org/abs/2501.00091 uses AI to try to predict which organic compounds will be optimized for direct detection.

(6) Since Bosons are indistinguishable henceforth violating the Pauli's exclusion principle. If Dark Photon also follow the same statics of Photon, mathematically, how can we differentiate regular photons from Dark photons?

Bosons of the same type are indistinguishable, but there are multiple types of bosons (e.g. the W boson and the photon are both bosons, but very different from each other - different mass, charge, and interactions). In the usual setup, dark photons have mass whereas photons do not, so they are clearly different (also they carry different types of charge, so their interactions with matter are different). If you take the limit where the dark photon mass goes to zero, however, then at that point you have a lot more freedom to simply absorb the dark photon into the definition of the ordinary photon (matter that's charged under the dark U(1) effectively picks up a tiny electric charge in that case).