Dark Matter and Dark Sector: Theory

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• Preliminaries

• How to build a theory of dark matter

• Dark Matter production in the Early Universe

• Theories of Dark Matter

• Theories of Dark Sectors
Recap : Part 2

• There are many specific detailed models of dark matter. They range from theories designed to solve some other mystery, to theories for which dark matter is the principle raison d’etre.

• Supersymmetry, while often maligned these days, is an interesting theory which easily accommodates a WIMP (freeze-out relic) which is typically a neutralino. Its specific properties are highly dependent on the complicated parameter space.

• A rich program of particle physics experiments can access a wide swath of supersymmetric parameter space.
Axion Dark Matter

- The axion is motivated by the strong CP-problem, where the QCD $\theta$ term is cancelled by introducing a scalar field -- the QCD axion.  

  \[ m_a \sim \frac{f_\pi}{f_a} \times m_\pi \]

- The axion’s mass and coupling are determined by virtue of its being a pseudo-Goldstone boson and are characterized by the energy scale $f_a > 10^9$ GeV.

- The axion is unstable, but its tiny mass and weak couplings conspire to predict that for much of the viable parameter space its lifetime is much greater than the age of the Universe itself.

- More generally, string theories often contain axion-like particles which are long-lived and can play the role of dark matter but have less tight correlations between their masses and couplings.
Axion Conversion

(Gianpaolo’s Lectures)

- The axion has a model-dependent coupling to electromagnetic fields that is somewhat smaller than $1 / f_a$.

- There is a rich and varied program of axion searches based on this coupling.

- One particular search looks for ambient axions converting into EM signals in the presence of a strong background magnetic field.

- Other very interesting new ideas are to look for time variation in the neutron EDM or the induced current in an LC circuit.
Sterile Neutrino DM

- Dark matter may be connected to one of the other incontrovertible signals of physics beyond the SM: neutrino masses.
- The simplest way to generate neutrino masses in the SM is to add some number of gauge singlet fermions to play the role of the right-handed neutrinos.
- If the additional states are light and not strongly mixed with the active neutrinos (as required by precision electroweak data), they can be stable on the scale of the age of the Universe and play the role of dark matter.
- Arriving at the right amount of dark matter via oscillations typically requires delicately choosing the mass and mixing angle, or invoking some other new physics.

Figure 9. Bounds on the mass

Phase-space density constraints

10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15}

Y-axis: sin^2 \theta, mixing angle with active neutrinos.

Ω_{N1} > Ω_{DM}

X-ray constraints

Ω_{N1} < Ω_{DM}

BBN limit: L_{\alpha} = 2500

L_{\alpha} = 25

L_{\alpha} = 70

L_{\alpha} = 700

NRP

1 keV

50 [keV]

M_{1} [keV]
Sterile Neutrino Decay

- Though rare, sterile neutrinos can decay into ordinary neutrinos and a photon, resulting in (mono-energetic) keV energy photons.
- Constraints from the lack of observation of such a signal put limits in the plane of the mass versus the mixing angle.

### Figure 4
Sterile neutrino parameters to the right of the solid red curve are excluded by the X-ray observations, if the sterile neutrinos make up all of dark matter. If the sterile neutrino abundance is determined by neutrino oscillations and no other mechanism contributes, then the excluded region is smaller (shaded area). Lower bounds from structure formation depend on the production mechanism, because they constrain the primordial velocity distribution whose connection to mass and mixing is model dependent.

Also shown is the range in which the pulsar velocities can be explained by anisotropic emission of sterile neutrinos from a supernova.

#### Possible X-ray Signal
[Bulbul et al 2014]

(Extracted from Abazajian 2014)
Simplified Models

- Rather than studying complete theories we can also consider a simplified model containing the dark matter as well as the most important particle mediating its interaction with the Standard Model.

- For example, if we are interesting in dark matter interacting with quarks, we can sketch a theory containing a SU(3)-charged scalar particle which mediates the interaction.

- Minimal flavor violation suggests we consider mediators with a flavor index corresponding to \{uR, cR, tR\}, \{dR, sR, bR\}, or \{Q1, Q2, Q3\} and/or combinations.

- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, masses, etc.

- There are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength with quarks.

Lots of Recent Activity:
- Chang, Edezhath, Hutchinson, Luty 1307.8120
- An, Wang, Zhang 1308.0592
- Berger, Bai 1308.0612
- Di Franzo, Nagao, Rajaraman, TMPT 1308.2679
- Papucci, Vichi, Zurek 1402.2285
- Garny, Ibarra, Rydbeck, Vogl 1403.4634


"Squarks"

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**Pair Production**

**Monojet**

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Mohan, Sengupta, TMPT, Yan, Yuan in progress
• At tree level, the fact that Majorana particles have vanishing vector current implies that the scattering with nuclei is spin-dependent.

• But at one loop, the scattering is spin-independent, and these are the dominant constraint- the smaller rate is compensated by the stronger experimental bounds.
Vector Simplified Model

- One simple picture introduces a vector particle as a dark force carrier which couples to both (parts of) the SM and the dark matter.
- Chiral structure (left- versus right-handed) charges for each SM fermion can be very important.
- There could be kinetic mixing with $U(1)_Y$.
- There are theoretical considerations (such as a dark Higgs sector, more particles to cancel gauge anomalies, etc), which are important but may or may not be very important for some searches.

Many Parameters: $\{M_{DM}, g, M_{Z'}, z_q, z_u, z_d, z_\ell, z_e, z_H + \eta\}$

NB: Simplified by assuming some couplings are equal, or zero.
Vector vs Axial Vector

**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Vector Mediator

Dirac Fermion DM

$g_{q} = 0.25$, $g_{x} = 1.0$

95% CL limits

$\bar{q} \rightarrow m_{\text{Med}} \rightarrow \chi$

$m_{\chi}$ [GeV]  

$m_{Z^{\prime}}$ [GeV]  

- Expected limit $\pm 2 \sigma_{\text{exp}}$
- Expected limit $(\pm 1 \sigma_{\text{exp}})$
- Observed limit $(\pm 1 \sigma_{\text{theory}})$
- Relic Density (MadDM)

$m_{\text{DM}}$ [GeV]

$\Omega_{\chi} h^{2} \geq 0.12$

$\text{CMS}$

Axial med, Dirac DM, $g_{q} = 0.25$, $g_{\text{DM}} = 1$

- Median expected 95% CL
- $\pm 1 \sigma_{\text{experiment}}$
- Observed 95% CL
- Observed $\pm$ theory unc.

Mono-jet Searches
Axial Vector

Mapped into the plane of Direct Detection
Mediator Searches

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**ATLAS**

<table>
<thead>
<tr>
<th>$\sqrt{s} = 13$ TeV, 3.6-37.0 fb$^{-1}$</th>
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<tbody>
<tr>
<td>95% CL upper limits</td>
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<tr>
<td><strong>Observed</strong></td>
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<td><strong>Expected</strong></td>
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<tr>
<td>Dijet 8 TeV</td>
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<tr>
<td>Boosted dijet + ISR</td>
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<tr>
<td>26.8 fb$^{-1}$</td>
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<tr>
<td>arXiv:1601.00769</td>
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<tr>
<td>Resolved dijet + ISR ($\gamma$)</td>
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<tr>
<td>Abstract, 34.6 fb$^{-1}$</td>
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**CMS**

27 fb$^{-1}$ & 36 fb$^{-1}$ (13 TeV)

95% CL limits

Vector mediator & Dirac DM

$g_{\text{DM}} = 1.0$
Dark Matter Coupled to Gluons

- An interesting variation is possible when both the dark matter and the colored mediator are scalars.
- In that case, a quartic interaction can connect the two.

\[ \lambda_d \left| \chi \right|^2 \left| \phi \right|^2 \]

- This interaction does not require the scalar to be \( \mathbb{Z}_2 \)-stabilized, and (given an appropriate choice of EW charges) it can decay into a number of quarks, looking (in some cases) more like an R-parity violating squark.
- The color and flavor representations \((r, N_f)\) of the mediator are free to choose.
- For perturbative \(\lambda\), a thermal relic actually favors \(m_{\phi} < m_{\chi}\) so annihilation into \(\phi \phi^*\) is open.

The dominant coupling to the SM is often at one loop to gluons!
Mediator Searches

- The physics of the mediators is model-dependent, depending on the color and EW representation.

- As a starting point, we considered mediators of charge 4/3 coupling to 2 uR quarks.

- In this case, a MFV theory can be obtained by coupling anti-symmetrically in flavor indices:
  \[ y \epsilon^{ijk} \phi_i \bar{u}_j u^c_k + h.c. \]

- There are interesting searches for pairs of dijet resonances and also potential impacts on top quark physics.

- All of these constraints are rather weak.

Decays into unflavored jets are bounded by \( m_\phi > 350 \text{ GeV} \).
DM Searches

- Direct detection generally provides a strong bound unless the dark matter mass is particularly small.
- At a hadron collider, the mono-jet signature occurs at one loop.
- As a result, prospects at the LHC are not particularly hopeful, though for large enough $r$ and $\lambda$, it is possible to see something with a very large data set.
- A 100 TeV pp collider would do better…
From Sketch to Life
Recap : Part 2

• There are many specific detailed models of dark matter. They range from theories designed to solve some other mystery, to theories for which dark matter is the principle raison d’etre.

• Supersymmetry, while often maligned these days, is an interesting theory which easily accommodates a WIMP (freeze-out relic) which is typically a neutralino. Its specific properties are highly dependent on the complicated parameter space.

• A rich program of particle physics experiments can access a wide swath of supersymmetric parameter space.

• Axions and sterile neutrinos are well-motivated in extensions of the Standard Model to explain the strong CP problem or neutrino masses.

• More specialized observations aim to detect them as well.

• Simplified Models have been adopted as a bridge between searches for dark matter and theoretical constructions. They don’t contain the full distracting details of a complete theory, but hopefully summarize the broad impacts of searches on many of them.
Examples of Dark Sectors
Composite Dark Matter
Composite Dark Matter

• Dark matter must be weakly interacting with the Standard Model.

• But it could be part of a dark strongly interacting system which plays an important role in terms of dark matter in the Galaxy.

• The dark matter could have a light force carrier, leading to “dark atoms” or even “dark molecules”.

• It could confine into “dark hadrons”.

• There could be a whole range of possible stable states, “dark nuclei”.

• These are areas of active research, still not entirely mapped out. The references give you some place to start to learn about these ideas, but they are far from complete (sorry about that!).
A Dark SU(N)

- The simplest module we can consider is a pure gauge theory consisting of a hidden sector SU(N).
- To begin with, we imagine that any matter charged under the hidden gauge group and the SM is extremely heavy, and thus irrelevant for the low energy physics.
- This is a variation on models where the dark matter is e.g. a dark pion-like object.
- The theory is defined by the number of colors $N$ and confinement scale $\Lambda$, which characterizes the mass of the lowest glueball state, and the splitting between the various glueballs.
- From here on, dark/hidden should be understood whenever I use terms like “gluons” or “glueballs”.

Boddy, Feng, Kaplinghat, TMPT arXiv:1402.3629
Glueball Interactions

• One interesting feature of this type of theory is the fact that the glueballs interact strongly with one another.

• Because of the strong dynamics, nothing can be computed very reliably in perturbation theory.

• Lattice may help: pure glue is much easier...

• We can cartoon the self-interactions of the glueballs by a geometric cross section of strongly coupled objects of size $\sim 1 / \Lambda$.

\[
\sigma (\text{gb gb} \rightarrow \text{gb gb}) \sim \frac{4\pi}{\Lambda^2 N^2}
\]

• Since the single parameter $\Lambda$ controls both the mass and the cross section (for small $N$), arranging for an interesting value of $\sigma/m$ essentially fixes $\Lambda \sim 500$ MeV. Amusingly close to $\Lambda_{\text{QCD}}$...
Glueball Relic Density

- We can estimate the relic density of the glueballs by tracking the relic density of the gluons to the temperature at which the theory confines.

- At this temperature, something around $\Lambda$, the energy in the dark gluons will get converted into glueballs.

- We can estimate the relic density of glueballs by matching across the phase transition.

- If there are no relevant connectors between the visible and hidden sectors, the temperature in the hidden sector $T^h$ and the visible temperature $T$ could generically be different.

- We parameterize this possibility with the ratio of temperatures $\xi = T^h / T$.

- There are interesting corrections to the usual thermal distribution: cannibalization!

$$Y \equiv \frac{n_{gb}}{s} = \frac{g_{\text{eff}} [\zeta (3)/\pi^2] T_h^3}{g_s S [2\pi^2/45] T^3} = \frac{g_{\text{eff}} 45 \zeta (3)}{g_s S 2\pi^4} \times \xi^3_f$$

For SU(N), $g_{\text{eff}} = 2 \times (N^2-1)$

$$\Omega_{gb} \sim \frac{Y s_0 \Lambda}{\rho_{c0}}$$

Carlson, Machacek, Hall 1991
Hochberg, Kuflik, Volansky, Wacker 2014
E.g. Erickcek, Ralegankar, Shelton 2008.04311
For a given $N$, there are two parameters, the confinement scale and the ratio of hidden to visible temperatures at the time of confinement, $\xi_{\Lambda}$. Provided one allows for a somewhat colder hidden sector, one can achieve interesting self-interaction rates at the observed relic density!

- For a given $N$, there are two parameters, the confinement scale and the ratio of hidden to visible temperatures at the time of confinement, $\xi_{\Lambda}$. Provided one allows for a somewhat colder hidden sector, one can achieve interesting self-interaction rates at the observed relic density!
A very simple extension is to add an adjoint (Majorana) fermion to the dark sector.

If one likes, this could be considered a supersymmetrized version of the pure gauge model, with the adjoint playing the role of the gluino.

The spectrum consists of glueballs as before, and (for $m \gg \Lambda$) a family of fermionic glueballinos at mass $\sim m$.

These glueballinos are strongly interacting with the glueballs and are sort of analogues of heavy-light mesons in this theory.
Self Interactions

• The glueballinos are strongly interacting with the glueballs, which mediate scattering.

• When $m \gg \Lambda$, one generally expects large cross sections with the possibility of Sommerfeld-like enhancements.

• One can model the glueball exchange as a Yukawa potential characterized by mass $\sim \Lambda$ and strong coupling.

• The transfer cross section is a function of the masses of the glueballs and glueballinos, which must be averaged over the velocity distribution of the dark matter for each system of interest.

\[
\sigma_T \equiv \int d\Omega (1 - \cos \theta) \frac{d\sigma}{d\Omega}
\]
Glueballino Scattering

- One obtains scattering cross sections in the ballpark of the interesting region for gluino masses on the order of TeV and $\Lambda \sim \text{MeV}$.

- Since each type of astrophysical object is characterized by a different DM velocity, the cross sections are different for each one.

- If the typical kinetic energy is large enough, inelastic channels will open up, and our transfer cross section may not characterize the scattering very well.

- Clusters are very likely to have inelastic processes playing some role.

\begin{center}
\begin{tabular}{|c|c|}
\hline
Object & Typical $v$ \\
\hline
Clusters & 700-1000 km/s \\
LSB & 50-130 km/s \\
Dwarf & 20-50 km/s \\
\hline
\end{tabular}
\end{center}

\[ E_{\text{kin}} = \frac{1}{2} m v^2 \geq \Lambda \]

FIG. 4: The ratio of the thermally-averaged transfer cross section to dark matter mass $h T i / m_X$ in the $(m_X, \alpha)$ plane for $\alpha = 1$ and three different astrophysical systems: dwarf galaxies ($V_{\text{max}} = 40 \text{ km/s}$, solid), LSBs ($V_{\text{max}} = 100 \text{ km/s}$, dashed), and clusters ($V_{\text{max}} = 1000 \text{ km/s}$, dotted). For each system, three values of the cross section are shown: $0.1 \text{ cm}^2/\text{g}$ (top), $1 \text{ cm}^2/\text{g}$ (middle), and $10 \text{ cm}^2/\text{g}$ (bottom). The region above the straight magenta lines shows where inelastic processes may modify the picture based on elastic scattering for each type of system. Systems with larger characteristic velocities have smaller cross sections, all else being equal. The LSB line at $0.1 \text{ cm}^2/\text{g}$, for instance, lies below that for dwarfs, because a larger interaction range (smaller $\alpha$) is needed to counter its larger velocity to give the same $T_i$ as the dwarfs. Toward the lower values of $m_X$, the scattering exhibits resonant behavior due to the formation of quasi-bound states \[82\], analogous to Sommerfeld enhancements in annihilations. The region below the straight magenta lines in Fig. 4 is where the dark matter typically has $(1/2) m_X v^2 > \alpha$, and modifications from inelastic scattering processes can be important. We urge the reader to keep in mind that while in this region the classical elastic scattering cross section (for our assumed Yukawa potential) falls below about $3 \pi / \alpha^2$, we expect other energy-exchange mechanisms to become important in dark matter halos. Note that for clusters ($v \approx 3 \times 10^3 \text{ km/s}$), this is a substantial region of the interesting parameter space: $(m_X / \text{TeV}) \& (\alpha / \text{10 MeV})$. This suggests that the elastic glueballino scattering curves plotted for clusters in Fig. 4 and other figures are far from the whole story. We expect new astrophysical phenomenology, especially in clusters of galaxies, and this deserves separate consideration.

V. GLUEBALLINO RELIC DENSITY

One goal of supersymmetrizing the pure gauge hidden sectors considered in Sec. III is to revive the possibility of dark matter with naturally the right relic density, as in the case of WIMPs, but now for self-interacting dark matter. In this section, we first review the machinery required to calculate a glueballino relic density from the freezeout of thermal relic gluinos. We then discuss the possibility of realizing the correct thermal relic density through the WIMPless miracle in AMSB models \[12\].

\[ E_{\text{kin}} = \frac{1}{2} m v^2 \geq \Lambda \]
In the regime $m >> \Lambda$, the dark gluinos will freeze out when their gauge couplings are still perturbative, and this stage looks like a rather standard WIMP.

Without connectors to the SM, they only couple to the dark gluons, and once again there is generally a separate temperature that characterizes the hidden sector.

The context of a SUSY breaking model such as AMSB, this allows us to inherit the nice feature of the ‘WIMPless’ miracle.

We know that weak couplings and masses produce the correct relic density, and AMSB fixes the ratio such that it works out for the hidden sector too.

$\langle \sigma v \rangle \propto \frac{\alpha^2}{m^2}$

$m \sim \frac{\alpha}{4\pi} \beta \times m_{3/2}$

$\frac{\alpha^2}{m^2} \sim \frac{\alpha_W^2}{M_W^2}$

Feng, Kumar 2008
Light (Dark) Force Carriers
Light Mediators

- Recently there has been a lot of attention given to parameter space where the mediating particles have low masses and weak couplings.

- This is a natural parameter space that complements the high mass searches at colliders.

- For dark matter with mass below around 10 GeV, strong constraints favor cases in which annihilation is into mediators.

- If we would like to realize the abundance of dark matter through the freeze-out mechanism, we need light mediators for dark matter masses below the GeV scale.
Light Mediators

- Light Mediators can also help with some of the puzzling measurements that we wonder could be indications of new physics.
- $(g-2)_\mu$
- Long-standing discrepancy between theory and data.
- ATOMKI 17 MeV nuclear transition anomaly.
- Points to a $\sim$17 MeV boson coupled to both quarks (nuclei) and e+e-.
- $\pi^0 \rightarrow e^+e^-$ measured by KTeV
- Longstanding 2-3$\sigma$ discrepancy pointing to axial couplings to quarks and electrons.

A.J. Krasznahorkay, et al. PRL &1504.01527 ; 1910.10459
Feng, Fornal, Galon, Gardner, Smolinsky, TMPT, Tanedo 1604.07411; 1608.03591
Feng, TMPT, Verhaaren, PRD & 2006.01151
Kahn, Schmitt, TMPT arXiv:0712.007 & PRD
Sommerfeld

- Light mediators open up the possibility to invoke a Sommerfeld-like enhancement at small dark matter velocities to enhance annihilation.

- Summing up the effect of the mediator on the scattering can lead to a large enhancement factor compared to the leading order annihilation rate.

- The impact is enhanced for small velocities, and also for mediator masses that are much smaller than the mass of the dark matter.

- For ~100 GeV dark matter, this naturally pushes the mediator masses down to somewhere at or below the GeV scale.
Annihilation into Mediators

- An interesting direction to explore is to have the dark matter annihilate into the mediators themselves. The rate for this to happen is fixed by the coupling of dark matter to the mediator, $g$.

- The mediator can have a MUCH smaller coupling to the SM particles, $\varepsilon$. It has kpc distances to travel before it needs to decay into what we observe!

- This is a generic way of getting an indirect signal while suppressing direct detection and collider constraints.

- It has seen some application in terms of the GeV excess of gamma rays from the direction of the Galactic center, in order to reconcile the strong annihilation signal with the lack of evidence for dark matter scattering with heavy nuclei.
**Light Mediators : Building a Theory**

- There are important theoretical constraints on theories with light particles:
  - Experimental constraints on searches for them, or their indirect contributions to other observables.
  - Such constraints are most easily avoided if the mediator carries no SM charge.
  - SM Gauge symmetries
  - Mediator gauge symmetries and breaking (for vector mediators)
  - We need to be able to write down SM Yukawa interactions
  - Anomalies, including with the SM gauge interactions.

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**E.g. Light Axial Vector Particle**

![Diagram](image)

**Family Non-Universal Couplings, \( c_V = 10^{-3} \)**

- **Mollek**
- **\( \eta \rightarrow e^+ e^- \)**
- **BaBar**
- **\( e^+ e^- \rightarrow \gamma A' \)**
- **(g-2)\(e\)** favored
- **(g-2)\(e\)** Allowed

**Beam Dumps**

- **\( \eta \rightarrow e^+ e^- \)**
- **Favored**

**Anomalon**

\[ m_{A'} \text{ [MeV]} \]

**Kahn, Krnjaic, Mishra-Sharma, TMPT**

arXiv:1609.09072
The anomaly cancellation implies a minimum size for the effective $X$ coupling to two SM currents.

The longitudinal modes have the usual E/m enhancement, and so high energy SM processes can be an effective probe.

Processes mediated by these interactions can be used to place relevant bounds on the parameter space.
Dark Photon

- An attractive idea which has received a lot of attention is to postulate that the new light force carrier is a “dark photon”.

- The idea is that there is a new vector boson with a small mass (and thus a whole dark Higgs sector) under which dark matter is charged, but the SM is not:

\[
\mathcal{L} = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} M_{V}^{2} V^{\mu} V_{\mu} + i \overline{\chi} (\not{\partial} - ig \not{V}) \chi + \epsilon V^{\mu\nu} B_{\mu\nu}
\]

- The kinetic mixing with hyper charge changes the mass basis of the states such that the usual massless photon remains unchanged. However, the dark photon picks up a small coupling to the SM particles proportional to their electric charge times the kinetic mixing parameter \( \epsilon \):

\[
geff \sim \begin{cases} 
g & \chi \\
eQ_{\psi} \epsilon & \psi_{\text{SM}} \end{cases}
\]

- There is also some mixing with the Z, but for dark photon masses much less than the Z boson mass, this is extremely tiny and can usually be neglected.
Experimental Searches

(Jonathan’s Lecture)
Recap: Part 3

- A complex dark sector expands the complexity of the physics of dark matter. Given the complexity of the visible sector, it seems natural to imagine that the dark sector could encompass similarly rich physics.

- Dark matter could be a composite, built out of more fundamental ingredients, and held together either by weak (~ atomic) or strong (~ hadronic) self-interactions.

- A light mediator allows for several different phenomena, and has become a standard element of the dark matter model-building tool-kit.

- They could make contact with several interesting low energy anomalies currently observed experimentally.

- They open up new processes for dark matter to participate in.

- They can be searched for at lower energy but higher luminosity facilities.

- While we still exploring the space of possible theories of dark matter, there is a rich experimental program that will explore interesting regions of parameter space. There is still much more to come!
Scientific names?

Sure. Scientists come up with great, wild theories, but then they give them dull, unimaginative names.

For example, scientists think space is full of mysterious, invisible mass, so what do they call it? "Dark matter"? Duuuuh! I tell you, there's a fortune to be made here!

I like to say "quark". Quark, quark, quark, quark.

Instead of making an idiot of yourself, why don't you go find me some scientists?