Dark Matter and Dark Sector: Theory

Tim M.P. Tait

University of California, Irvine

SSI 2020
August 18, 2020
Outline

- 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 1

• Despite the fact that we know very little about its fundamental nature, constructing a realistic theory of dark matter is actually a highly constrained enterprise because of the need for it to be long-lived, electrically and SU(3)-charge neutral, and the symmetries of the Standard Model.

• Once we have a theory of dark matter, we can ask ourselves how it may have been produced in the early universe.

• For thermal processes, a Boltzmann equation tracks how the number density evolves and can lead to the correct abundance in different regimes. Both freeze out and freeze in can reproduce the observed abundance in different regimes of parameter space.
Some Caveats about Cosmological Dark Matter Production
Early Times are Uncertain

- EW Phase Transition?
- QCD Confinement
- DM Freeze Out?
- Baryogenesis?
- Big Bang Nucleosynthesis
- CMB

Today

100 GeV
GeV
MeV
eV

High Energy Physics

Nuclear Physics

Atomic Physics
Before BBN, most of what we know about the physics in the early Universe is an extrapolation based on the Standard Model + ingredients such as dark matter.

Features such as inflation, dark matter, and the existence of a baryon asymmetry are all indications that ingredients are missing at earlier times... the extrapolation is uncertain!
Freeze Out Relic?

As an example to illustrate this point, let’s imagine what could go wrong with the freeze out calculation.

But what do we know about the history of the Universe?
Freeze Out Relic?

But what do we know about the history of the Universe?

We understand the Universe back to the time of Nucleosynthesis from the abundance of H, He, and Li.
Freeze Out Relic?

What does that mean for DM?

A typical WIMP had already frozen out through annihilation

We understand the Universe back to the time of Nucleosynthesis
Lots Could Happen

We understand the Universe back to the time of Nucleosynthesis.

A typical WIMP had already frozen out through annihilation.

Some other particle could decay into DM.

MeV

T
Lots Could Happen

Physics could look different from our expectations (because of a VEV, etc)

A typical WIMP had already frozen out through annihilation

Some other particle could decay into DM

We understand the Universe back to the time of Nucleosynthesis
 Lots Could Happen

We understand the Universe back to the time of Nucleosynthesis.

A typical WIMP had already frozen out through annihilation.

Some other particle could decay into SM stuff, diluting the dark matter we had.

Some other particle could decay into DM.

Physics could look different from our expectations (because of a VEV, etc).

We understand the Universe back to the time of Nucleosynthesis.
Lots Could Happen

Physics could look different from our expectations (because of a VEV, etc)

A typical WIMP had already frozen out through annihilation

Some other particle could decay into SM stuff, diluting the dark matter we had.

Some other particle could decay into DM

There could be an unexpected early period of matter domination or inflation

We understand the Universe back to the time of Nucleosynthesis
Lots Could Happen

- Physics could look different from our expectations (because of a VEV, etc).
- A typical WIMP had already frozen out through annihilation.
- Some other particle could decay into SM stuff, diluting the dark matter we had.
- Some other particle could decay into DM.
- There could be an unexpected early period of matter domination or inflation.

This is a feature!

Understanding the annihilation cross section could verify the WIMP miracle and push back our understanding of the Universe to earlier times.

We understand the Universe back to the time of Nucleosynthesis.

MeV

T
Isn't it weird how scientists can imagine all the matter of the universe exploding out of a dot smaller than the head of a pin, but they can't come up with a more evocative name for it than "The Big Bang"?

I've been reading about the beginning of the universe. They call it "The Big Bang."

What would you call the creation of the universe? "The Horrendous Space Kablooie!"

Hmm... that is better. Almost anything would be.

We should lobby to change that.

And I think "Tyrannosaur" should be changed to "Monstrous Killer Death Lizard."
Recap: Part I

- Despite the fact that we know very little about its fundamental nature, constructing a realistic theory of dark matter is actually a highly constrained enterprise because of the need for it to be long-lived, electrically and SU(3)-charge neutral, and the symmetries of the Standard Model.

- Once we have a theory of dark matter, we can ask ourselves how it may have been produced in the early universe.

- For thermal processes, a Boltzmann equation tracks how the number density evolves and can lead to the correct abundance in different regimes. Both freeze out and freeze in can reproduce the observed abundance in different regimes of parameter space.

- That said, we should be cautious in terms of how we use the relic abundance to motivate the parameter space of a model. If our assumptions about the history of the universe are incorrect, it may point us into the wrong direction.

- A better way to look at the relic abundance is that once we discover the particle nature of dark matter, we can use it to constrain the properties of early cosmology.
Specific Theories of Dark Matter
The dark matter model predicts the rates of these processes, and relates them to each other.
Indirect Detection

(Tracy’s Lectures)

- Indirect detection tries to see dark matter annihilating.

- Dark Matter particles in the galaxy can occasionally encounter one another, and annihilate into SM particles which can make their way to the Earth where we can detect them.

- In particular, photons and neutrinos interact sufficiently weakly with the interstellar medium, and might be detected on the Earth with directional information.

- Charged particles will generally be deflected on their way to us, but high energy anti-matter particles are rare enough that an excess of them could be noticeable.
• The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when dark matter brushes against it.

• Direct detection looks for the dark matter in our galaxy’s halo, and a positive signal would be a direct observation.

• Heavy shielding and secondary characteristics of the interaction, such as scintillation light or timing help filter out backgrounds.

• In the non-relativistic ($v \rightarrow 0$) limit, the DM-nucleon interaction can either be a constant (Spin-Independent scattering) or the dot product of their spins (Spin-Dependent scattering).
Collider Production

- If dark matter couples to quarks or gluons, we should also be able to produce them at high energy colliders.
- Collider detectors are not typically sensitive to dark matter.
- It’s typically too weakly interacting to leave any trace in a detector as “small” as ATLAS or CMS.
- Thus, it manifests as something missing in the energy and momentum of the collision.
- Since we don’t know the initial Parton energies along the beam direction, we can only reliably infer missing momentum in the transverse directions.
- This is a lot like neutrinos in the SM.
LHC can't produce WIMPs.

LHC can produce WIMP siblings or mediators, which decay into WIMPs and other SM particles.

LHC can directly produce WIMP pairs.

LHC can't produce WIMPs.
**Supersymmetry (SUSY)**

- The most famous candidate for dark matter is a supersymmetric particle.
- Supersymmetry famously doubles the number of fields by postulating a symmetry that rotates bosons into fermions (and vice versa).
- I’ll focus on how to pick out the features of a supersymmetric theory such as the MSSM that are important to understand how it describes dark matter.
SUSY Interactions

• If we break supersymmetry “softly”, the masses of the super-partners will separate, but the interactions remain fixed by supersymmetry.

• Despite having many, many new parameters, SUSY theories inherit a huge structure from the SM.

• This implies that many things can be calculated in supersymmetric theories in terms of the masses of the superpartners.

• See: Martin, hep-ph/9709356 for a more complete introduction to SUSY.
Exercise:

Given the interactions of the Higgs boson in the SM, using the same logic as on the previous slide, try to guess what kinds of vertices exist for the super-partner of the neutral Higgs boson in the supersymmetric version of the Standard Model.

R-Parity

• By itself, supersymmetry does not imply a stable massive particle.

• It has interactions which would naively violate baryon and lepton number, and do scary things like make protons decay.

• The usual take on this is to simply forbid all of these interactions by invoking a symmetry: R-parity.

• R-parity insures that the superpartners only couple in pairs to the SM.

• It produces a stable particle!

\[ R_P \equiv (-1)^{3(B-L)+2S} \]

SM particles: +1
Superpartners: -1
Identity of the LSP

• If the Lightest Supersymmetric Particle is stable, any superpartners present in the early universe will eventually decay into them.

• The LSP had better turn out to be neutral if we would like it to play the role of dark matter.

• For a given model of SUSY breaking, we can calculate the spectrum and determine which particle is the lightest.

• In fact, there are some generic trends that come about from the renormalization group.

![Graph showing running mass vs. Log10(Q/GeV)](mSUGRA)

Model-specific Parameters

Resulting Masses

At TeV energies.

K. Olive, astro-ph/0301505
Neutralino Dark Matter

- In the MSSM, the 4 neutralinos are Majorana fermions which are mixtures of the superpartners of $W_3$, B, and the two neutral Higgses.

- As a result, their interactions are a little complicated: it depends on what admixture of each state is present in the lightest neutralino.

- The RGEs typically result in an LSP which is mostly Bino, with a small amount of Higgsino and $W_3$ino.

- Specific models of SUSY breaking may upset these expectations.

  - AMSB: $W_3$ino WIMP
Neutralino Dark Matter

- In the MSSM, the 4 neutralinos are Majorana fermions which are mixtures of the superpartners of $W_3$, $B$, and the two neutral Higgses.

- As a result, their interactions are a little complicated: it depends on what admixture of each state is present in the lightest neutralino.

- The RGEs typically result in an LSP which is mostly Bino, with a small amount of Higgsino and W3ino.

- Specific models of SUSY breaking may upset these expectations.
  - AMSB: $W_3$ino WIMP
Neutralino Dark Matter

- In the MSSM, the 4 neutralinos are Majorana fermions which are mixtures of the superpartners of $W_3$, $B$, and the two neutral Higgses.

- As a result, their interactions are a little complicated: it depends on what admixture of each state is present in the lightest neutralino.

- The RGEs typically result in an LSP which is mostly Bino, with a small amount of Higgsino and $W_3$ino.

- Specific models of SUSY breaking may upset these expectations.
  - AMSB: $W_3$ino WIMP

\[
\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0
\]
Neutralino Dark Matter

- In the MSSM, the 4 neutralinos are Majorana fermions which are mixtures of the superpartners of $W_3$, $B$, and the two neutral Higgses.

- As a result, their interactions are a little complicated: it depends on what admixture of each state is present in the lightest neutralino.

- The RGEs typically result in an LSP which is mostly Bino, with a small amount of Higgsino and $W_3$ino.

- Specific models of SUSY breaking may upset these expectations.

  - AMSB: $W_3$ino WIMP
Neutralino Dark Matter

- In the MSSM, the 4 neutralinos are Majorana fermions which are mixtures of the superpartners of \( W_3, \ B, \) and the two neutral Higgses.

- As a result, their interactions are a little complicated: it depends on what admixture of each state is present in the lightest neutralino.

- The RGEs typically result in an LSP which is mostly Bino, with a small amount of Higgsino and \( W_3 \)ino.

- Specific models of SUSY breaking may upset these expectations.
  - AMSB: \( W_3 \)ino WIMP
Annihilation

- Now we have everything we need to look at neutralino annihilations. This is a complicated process... but we can understand some general features.

- Neutralinos are Majorana fermions.
  - In the non-relativistic limit, they are Pauli-blocked from an initial $S=1$ state.
  - No annihilation through an s-channel vector particle.
  - Sfermion exchange likes to produce SM fermions of like-chirality, ($S=1$) and is suppressed by $m_f$ for an $S=0$ initial state.

Bottom Line: Suppressed $<\sigma \nu>$ leads generically to too many Binos.
A Plethora of Processes
Degenerate stau active during 
“Coannihilation Region”:
Degenerate stau active during freeze-out

“Bulk Region”: Light sfermions 
(~excluded by LHC)

“Focus Point”: Mixed χ LSP

Relic Density: Small Tan β

mSUGRA

Ωh^2 > 0.3
Ωh^2 < 0.1
Ωh^2 < 0.3
excluded by theory

tan β = 10
µ < 0

Baer, Balazs, Belyaev, hep-ph/0211213
Degenerate stau active during "Coannihilation Region": Degenerate stau active during freeze-out.

"Funnel Region": Higgs close to on-shell in decay.

Large Tan $\beta$

mSUGRA

"Focus Point": Mixed $\chi$ LSP

\[ \int \sigma v \, dx (F_b) \]

$\tan \beta = 45$

$\mu < 0$

$0 \leq \Omega h^2 < 1.0$

$0.1 \leq \Omega h^2 < 0.3$

Excluded by theory

Baer, Balazs, Belyaev, hep-ph/0211213
Cosmic Neutralino Signals

- We’ve already learned a fair amount about how neutralinos annihilate by studying the relic density.

- The same physics controls the search for them annihilating in the halo.

- As Majorana particles, they tend to annihilate into heavier fermions and/or W bosons.

  - Indirect searches for bb spectra are motivated by this observation...

- Loops of charged particles allow them to annihilate into γγ or γZ.

  - A “smoking gun” signal!

1.5 TeV (Mostly) Higgsino LSP

\[
\frac{d(\sigma v)}{dE_T} \times 10^{-29} \text{cm}^3 \text{s}^{-1} \text{TeV}^{-1}
\]
Cosmic Neutralino Signals

- We’ve already learned a fair amount about how neutralinos annihilate by studying the relic density.
- The same physics controls the search for them annihilating in the halo.
- As Majorana particles, they tend to annihilate into heavier fermions and/or W bosons.
- Indirect searches for bb spectra are motivated...
- Loops of charged particles allow them to annihilate into a γγ or Z lines already are pronounced for better detector resolutions.
- A “smoking gun” signal!

![Diagram](Image)
A Window to Winos!

H.E.S.S. limits on the line signal already restrict wino dark matter.
Direct Detection of Neutralinos

• The Majorana character also has important consequences for direct detection.

• No vector currents imply the Z exchange can only mediate spin-dependent interactions.

• The Higgs exchange requires both gaugino and higgsino admixture: the rate is very sensitive to the neutralino mixing angles.

• Direct detection is sensitive to MSSM parameter space!
Collider Signals

- At hadron colliders like the LHC, the largest signals tend to come from producing the colored superpartners.
- There can be “Cascade” decays down to the LSP.
- The LSP passes through the detector, leading to missing momentum.
- Hard jets are also present.
- Depending on the decay chain, there may be hard leptons as well.
- Often pairs of leptons will have the same charge, a signal with small expected SM backgrounds.

![Graph](image)

**Squark-gluino-neutralino model, m(0^+) = 0 GeV**

**ATLAS**

\[ \bar{t} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

- 0-leptons, 2-6 jets
- All limits at 95% CL

- 0L obs. limit (±1 \sigma_{\text{theory}})
- Exp. limits (±1 \sigma_{\text{exp}})
- Observed limit (8 TeV, 20.3 fb\(^{-1}\))

**pMSSM Scan**
Collider Signals

- At hadron colliders like the LHC, the largest signals tend to come from producing the colored superpartners.

- There can be “Cascade” decays down to the LSP.

- The LSP passes through the detector, leading to missing momentum.

- Hard jets are also present.

- Depending on the decay chain, there may be hard leptons as well.

- Often pairs of leptons will have the same charge, a signal with small expected SM backgrounds.
The best limits are on the SU(3)-charged super-particles, but those may not be the most important ones in terms of the physics of neutralino dark matter.
Reconstructing the MSSM

• While we can hope to eventually have many, many signals to measure, the parameter space is also very large.

• Even simplified versions like the “pMSSM” have ~20 parameters!

• Mapping from signal to parameter space is very complicated and not generally one to one: there is a complicated inverse problem.

• The connection to dark matter specifically is often not very clear, leading to statistical approaches based on simulating many (many) model points in the parameter space.
Coverage Distribution

We remind the reader that this is an ongoing analysis and that several future updates will be made to what we present here before completion. In particular, the LHC analyses will require updating to include more results at 8 TeV along with our extrapolations to 14 TeV. While these are important pieces to the DM puzzle it is our expectation that the addition of these new LHC results will only strengthen the important conclusions based on the existing analyses to be discussed below.

Figure 9: Comparisons of the models surviving or being excluded by the various searches in the LSP mass-scaled SI cross section plane as discussed in the text. The SI XENON1T line is shown as a guide to the eye.

Fig. 9 shows the survival and exclusion rates resulting from the various searches and their combinations in the LSP mass-scaled SI cross section plane. In the upper left panel we compare these for the combined direct detection (DD = XENON1T + COUPP500) and indirect detection (ID = Fermi + CTA) DM searches. Here we see that 11% (15%) of the models are excluded by ID but not DD (excluded by DD but not ID) while 8% are excluded...
Beyond the MSSM

• As we have seen, the minimal model already contains a lot of interesting physics.
  • But nothing tells us Nature has chosen something minimal!
• Simple extensions such as adding a gauge singlet (i.e. the NMSSM) can have a big impact on the picture of dark matter.
  • New neutralinos
  • New Higgs bosons
  • New couplings
  • New relations between parameters.

Gunion, Hooper, McElrath, hep-ph/0509024
Relic Gravitinos

- Though they are never in equilibrium, we can still produce relic gravitinos through freeze-in.

- Since they fail to reach equilibrium and their interactions are non-renormalizable, the quantity generated depends very sensitively on the reheating temperature at the end of inflation.

- This is different from the cases we looked at before, where the interactions responsible for freeze-in were less energy-dependent, and thus more insensitive to initial conditions.

- This can be a problem -- if they are overproduced, we can end up with too much dark matter, leading to a bound on $T_R$.

- For just the right $T_R$, we get $\Omega h^2 \sim 0.1$. 

\[\text{Figure 4: For a sufficiently short lifetime, the density parameter }\]
\[\Omega_{\tilde{G}} h^2 \text{ (as function of } X_{\text{NSP}} \text{ decays) is bounded by different gravitino masses.}\]

\[m_{\tilde{G}} = 1 \text{ GeV, } 10 \text{ GeV, } 50 \text{ GeV, } 250 \text{ GeV.}\]

\[\text{Bolz, Brandenburg, Buchmuller hep-ph/0012052}\]
Late Decay

- A gravitino LSP can also be produced by the late decay of a more conventional WIMP, inheriting its relic density.

- The NLSP need not even be neutral!

- Some care is needed to have the decay not destroy light elements.

- WIMPs freeze out as usual...

  ...but then decay to superWIMPs

- \( M_{\text{Pl}}^2/M_W^3 \approx 10^3 - 10^6 \text{ s} \)

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. Peccei, Quinn ’77

• 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.

$$m_a \sim f_\pi / f_a \times m_\pi$$

• 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.

Preskill, Wise, Wilczek ’83
Abbott, Sikivie ’83
Dine, Fischler ’83
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

(Andre/Scott’s Lectures?)

- 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.

![Diagram](image)

Y-axis: \(\sin^2 \theta\), mixing angle with active neutrinos.
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.
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.
“Squarks”

Pair Production

“Monojet”

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**

\[ m_{\chi} \text{ [GeV]} \]

13 TeV, 36.1 fb\(^{-1}\)

Vector Mediator

Dirac Fermion DM

\( g_q = 0.25, \ g_x = 1.0 \)

95\% CL limits

\[ m_{Z_V} \] vs \[ m_{\chi} \]

**CMS**

25 fb\(^{-1}\) (13 TeV)

Axial med, Dirac DM, \( g_q = 0.25, \ g_x = 1 \)

- Median expected 95\% CL
- \( \pm 1\sigma_{\text{theory}} \)
-\( \pm 1\sigma_{\text{experimental}} \)

Panel on the left:

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

Panel on the right:

35.9 fb\(^{-1}\) (13 TeV)

- Observed 95\% CL
- Observed ± theory unc.

Mono-jet Searches
Axial Vector

Mapped into the plane of Direct Detection
Mediator Searches

**ATLAS**

\[ \sqrt{s} = 13 \text{ TeV}, \; 3.6-37.0 \text{ fb}^{-1} \]

95% CL upper limits
- Observed
- Expected

- Dijet 8 TeV
  - arXiv: 1801.02119
- Boosted dijet + ISR
  - Preliminary, 15.3 fb
- Resolved dijet + ISR (\gamma)
  - Journal, 35.5 fb
- Resolved dijet + ISR (j)
  - Preliminary, 15.3 fb
- ATLAS-COM-2016-070
- Dijet
- Dijet TLA
  - JHEP 121 (2018) 011901
- Resonances
  - Dijet angular
  - JHEP 95 (2016) 036

**CMS**

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

95% CL limits

**Mediator width:**

Result sensitive to the interplay of \( g_{\text{SM}} \), \( g_{\text{DM}} \).

- \( g_{\text{SM}} \) too small: mono-jet preferred to resonance search
- \( g_{\text{SM}} \) too large: peak too wide for resonance search

\[ \text{if } M_{\text{DM}} > M_{\text{med}}/2: \] no branching ratio to DM \( \rightarrow \text{just } \text{Z}^\prime \) search.
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.

\[ \lambda_d \, |\chi|^2 |\phi|^2 \]

- 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 \(m_\varphi < m_\chi\) so annihilation into \(\varphi \varphi^*\) is open.
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:
  \[ y_1^i j k \phi_i \bar{u}_j u_k^c + h.c. \]
- There are interesting searches for pairs of dijet resonances and also potential impacts on top quark physics.
- All of these constraints are rather weak.
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.