Outline of Lecture I

• Characteristics of a Dark Matter Candidate Particle
  • Stabilization
  • Relic Density
• WIMPs
  • R-parity: The SUSY WIMP
    • Relic Density
    • Indirect Signals
    • Direct Detection
    • Colliders
Evidence for dark matter is overwhelming…
So what is this stuff?

- As a particle physicist, my job is to explore how dark matter fits into the bigger picture of particles.

- What do we know about dark matter?
  - Dark (neutral)
  - Massive
  - Still around today
  - Stable or with a lifetime of the order of the age of the Universe itself.

- Nothing in the Standard Model of particle physics fits the description.
Physics Beyond the SM

• The Standard Model of particle physics has nothing with the right properties to be dark matter:
  • Photons, leptons, hadrons, and W bosons all shine too brightly.
  • Neutrinos are too light.
  • Z and Higgs bosons are too short-lived.

• Dark matter is a manifestation of physics beyond the Standard Model.

• We have lots of ideas for what it could be…
3. Dark Matter Candidates

Although the evidence for dark matter presented in Sec. 2 is overwhelming, the constraints on its microscopic properties are weak. The particle or particles that make up the bulk of dark matter must be non-baryonic, cold or warm, and stable or metastable on 10 Gyr time scales. Such constraints leave open many possibilities, and there are numerous plausible dark matter candidates that have been discussed in the literature. The masses and interaction cross sections of these candidates span many orders of magnitude, as shown in Figure 20.

Some Dark Matter Candidate Particles

- neutrinos
- neutralino
- KK photon
- branon
- LTP
- axion
- axino
- gravitino
- KK graviton
- SuperWIMPs: wimpzilla
- WIMPs: Black Hole Remnant
- Q-ball
- fuzzy CDM

Figure 20: The locus of various dark matter candidate particles on a mass versus interaction cross-section plot.
The Dark Matter Questionnaire

- Mass
- Spin
- Stable?
  - Yes
  - No

Couplings:
- Gravity
- Weak Interaction?
- Higgs?
- Quarks / Gluons?
- Leptons?
- Thermal Relic?
  - Yes
  - No
• One of the mysteries of dark matter is why it is very massive but (at least to very good approximation) stable.

• This is actually telling us something very important about how it can interact with the Standard Model.

• We need a symmetry (at least approximately) to prevent dark matter particles from decaying.

• The simplest example is a new kind of parity (a $Z_2$ discrete symmetry) which forces them to couple in pairs to SM fields.

• We could explore larger (and continuous) symmetries as well.
WIMPs

- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.

- WIMPs naturally can account for the amount of dark matter we observe in the Universe.

- WIMPs automatically occur in many models of physics beyond the Standard Model, such as i.e. supersymmetric extensions.

- WIMPs are a vision of dark matter for which we can use particle physics experimental techniques to search very effectively.

- Are we looking under the lamp post?

- We will classify different WIMPs based on which symmetry allows them to be stable.

$59.99 for 20 servings

Available in Blue Raspberry, Fruit Punch, and Grape flavors...
The WIMP Miracle

• One of the primary motivations for WIMPs is the “WIMP miracle”, an attractive picture explaining the density of dark matter in the Universe today. Tracy already explained this, but it is important so I will go through it quickly again.

• While not strictly a requirement for a successful theory of dark matter, this picture is very attractive [meaning: we think it is likely that things work this way], and so it is worth understanding the argument.

• The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.

• Equilibrium is maintained by scattering of WIMPs into SM particles, $X X \rightarrow $ SM and vice-versa.
Boltzmann Equation

• The evolution of the dark matter number density \( n \) is controlled by a Boltzmann equation, which tracks the effect of the expansion of the Universe \( (H) \) and the creation and destruction of dark matter.

• A Universe where WIMPs stayed in equilibrium would be pretty boring.

• As the temperature falls, there will be fewer and fewer WIMPs present, since the fraction of the plasma with enough energy to produce them will become smaller and smaller.

• (Almost) Nothing would be left!

\[
\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right]
\]

\[
n_{eq} = g \left( \frac{mT}{2\pi} \right)^{3/2} \text{Exp} \left[ -\frac{m}{T} \right]
\]
Freeze-Out

• However, the expansion of the Universe eventually results in a loss of equilibrium.

\[ \frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[ n^2 - n_{eq}^2 \right] \]

• When \((n_{eq} \langle \sigma v \rangle) \ll H\), the scattering that maintains equilibrium can’t keep up with the expansion.

• The WIMPs become sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.

• Where they “freeze out” obviously depends on how big \(\langle \sigma v \rangle\) is.
Relic Density

- So the basic picture is:
  - We start out with dark matter in equilibrium with the SM plasma.
  - As the temperature falls, the number of WIMPs does too.
  - We track the equilibrium density until freeze-out:
    \[
    n_{eq} \langle \sigma v \rangle \sim H
    \]
    \[
    (mT)^{3/2} e^{-m/T} \sim \frac{g^4}{m^2} \sim \frac{T^2}{M_{Pl}}
    \]
    \[
    \frac{m}{T} \sim \log \left[ \frac{M_{Pl}}{m} \right]
    \]
    \[
    m \sim 100 \text{ GeV} : \frac{m}{T} \sim 40
    \]

...and that’s how much dark matter we get!
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...and that’s how much dark matter we get!
Relic Density

• For a WIMP, once we know its mass and cross section into SM particles, we can predict its relic density.

• I find it remarkable that one simple, reasonable assumption (DM is in equilibrium with the SM at early times) is enough to predict the dark matter density today in terms of the particle physics properties of DM.

Feng, ARAA (2010)
WIMP Interactions

• Ideally, we would like to measure WIMP interactions with the Standard Model, allowing us to compute $\sigma(\chi\chi \rightarrow \text{SM particles})$ and check the relic density.

• If our predictions “check out” we have indirect evidence that our extrapolation backward to higher temperatures is working.

• If not, we will look for signs of new physics to make up the difference.

• The first step is to actually rediscover dark matter by seeing it interact through some force other than gravitational.

• That tells us which SM particles it likes to talk to and in some cases something about its spin, mass, etc.
The common feature of particle searches for WIMPs is that all of them are determined by how it interacts with the Standard Model.
Catalogue of Candidates

• So here is how we’ll catalogue WIMPs:
  • Stability Mechanism
  • How they interact with the SM:
    • Relic density
    • Detection prospects
      • Direct
      • Indirect
    • Collider
  • The picture that emerges will be that there are a lot of interesting ideas for DM -- and we can test them!

G. Bertone
Supersymmetry (SUSY)

- The most famous candidate for dark matter is a supersymmetric particle.
- You are now all experts on SUSY and the MSSM thanks to Yael’s lectures.
- 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: Yael’s lectures or Martin, hep-ph/9709356 for a more complete introduction to SUSY.
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.
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.

- 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

\[
\chi_1^0 = N_{11} \tilde{B} + N_{12} \tilde{W}_3 + N_{13} \tilde{H}_1^0 + N_{14} \tilde{H}_2^0
\]

Bino: Couples to $g1 Y$ (interactions with the SM involve the sfermions)
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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 $<\sigma v>$ leads generically to too many Binos.
Degenerate stau active during “Coannihilation Region”: Light sfermions respectively. Points with intermediate values of low and high relic density, re-velocity, integrated from zero temperature to structure of these plots can be understood by ex-
Higgs searches are not shown on these plots. The to chargino masses below bounds from LEP2; the

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\[ \tan \beta = 10 \]
\[ \mu < 0 \]

“Focus Point”: Mixed \( \chi \) LSP

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

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

mSUGRA

"Coannihilation Region": Degenerate stau active during freeze-out

Large Tan $\beta$

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

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.
    - Fermi searches for bb spectra...
    - Loops of charged particles allow them to annihilate into $\gamma\gamma$ or $\gamma Z$.
    - A “smoking gun” signal!

Tracy has already told you a lot about how indirect detection works earlier today, so I will focus on a SUSY example of it here.

I.5 TeV (Mostly) Higgsino LSP

```latex
\begin{align*}
\frac{d(\sigma v)}{dE_\gamma} & \approx 10^{-29}\text{cm}^3\text{s}^{-1}\text{TeV}^{-1} \\
E_\gamma & \text{[TeV]}
\end{align*}
```

Bergstrom, Bringmann, Eriksson, Gustafsson hep-ph/0507229
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\[ \frac{d(\sigma v)}{dE} \]

Bergstrom, Bringmann, Eriksson, Gustafsson hep-ph/0507229
A Window to Winos!

In Fig. 2 we compare the NLL cross section to existing limits from H.E.S.S [23] and projected CTA projection (NFW).

H.E.S.S. limits on the line signal already largely exclude wino dark matter.
• Before looking at direct detection of neutralinos, let's review some basic features of the searches.

• 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 ($v \to 0$) limit, the DM-nucleon interaction can either be a constant (Spin-Independent scattering) or the dot product of their spins (Spin-Dependent scattering).
Direct Detection

- The rate of a direct detection experiment depends on one power of the WIMP density (close to the Earth).

\[
\frac{dN}{dE} = \sigma_0 \frac{\rho}{m} \int dv f(v) F(E)
\]

- The energy spectrum of the recoiling nucleus depends on the WIMP mass, its coupling to quarks, and nuclear physics.

- The cross section is dominated by the effective WIMP interactions with quarks and gluons.

- An interesting handle on the signal is an expected annual modulation.
“Blind spot” at low DM mass

Neutrino “Floor”

Spin Independent

WIMP Mass [GeV/c²]

10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴

WIMP–nucleon cross section [pb]
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!
Because of the importance of the coupling to the Higgs, the contours of the SI cross section are highly dependent on the neutralino admixture. A “blind spot” where the neutralino becomes entirely Higgsino occurs for \( M_1 + \mu \sin 2\beta = 0 \).
Collider Production

- If WIMPs couple to quarks or gluons, we should also be able to produce them at high energy colliders.
- By studying the production of WIMPs in collisions of SM particles, we are seeing the inverse of the process which kept the WIMPs in equilibrium in the early Universe.
- Provided they have enough energy to produce them, colliders may allow us to study other elements of the “dark sector”, which are no longer present in the Universe today.

Very sophisticated detectors with many, many (many!) subsystems: But no WIMP detectors.
WIMPs interact so weakly that they are expected to pass through the detector components without any significant interaction, making them effective invisible (much like neutrinos).

There are two ways we can try to “see” them nonetheless:

1. Radiation from the SM side of the reaction.
2. Production of “partners” which decay into WIMPS + SM particles.
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.
3rd Generation Squarks

- Naturalness requires SUSY to have light(ish) stops. This should be balanced by the fact that in the MSSM, the Higgs mass is calculable, suggesting the stops aren’t too light.

- Searches for stops are starting to reach 600-700 GeV, and carving out the natural regions of supersymmetry!
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.

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Cahill-Rowley et al, 1305.6921

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![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.](image)
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.

Curves of constant $\Omega h^2 = 0.1$

Gunion, Hooper, McElrath, hep-ph/0509024
Recap of Lecture I

• There are many ideas for what dark matter could be.

  • Dark, Neutral, and Stable [Symmetry!].

  • WIMPs are a particularly attractive class of dark matter.
    • Their relic density explains the ballpark dark matter abundance.
    • Large interactions give us handles to search for them.

• Supersymmetry is an attractive, representative theory of dark matter.

  • We can explore the features of a Majorana fermion WIMP.
    • Interesting regions with the correct relic density.
    • Distinctive signals of direct, indirect, and collider searches.

  • We’ll see contrasting features tomorrow when we discuss other visions for DM, including Universal Extra Dimensions.