Dark Matter

- Atoms: 4.9%
- Dark Matter: 26.8%
- Dark Energy: 68.3%

TODAY
Dark Matter

Galactic Rotation Curves

DISTRIBUTION OF DARK MATTER IN NGC 3198

 TODAY

Atoms 4.9%
Dark Matter 26.8%
Dark Energy 68.3%
Dark Matter

Galactic Rotation Curves

DISTRIBUTION OF DARK MATTER IN NGC 3198

Today

Atoms 4.9%
Dark Matter 26.8%
Dark Energy 68.3%

Weak Lensing
Cosmic Microwave Background

Galactic Rotation Curves

DISTRIBUTION OF DARK MATTER IN NGC 3198

Atoms

Dark Matter

Dark Energy

4.9%

26.8%

68.3%

Large Scale Structure Formation

Weak Lensing

TODAY
WIMPs

WIMP = “Weakly Interacting Massive Particle”
WIMPs

WIMP = “Weakly Interacting Massive Particle”

New Particles
Why WIMPs?

Too much Baryonic Matter

Wrong Primordial Abundances

Element Abundance (Relative to Hydrogen)

Density of Ordinary Matter (Relative to Photons)
Why WIMPs?

Too much Baryonic Matter
Wrong Primordial Abundances

Not:
Black Holes & Non-Luminous Baryonic Matter
Why WIMPs?

“WIMP Miracle”

Weak Scale Mass (~100GeV) + Weak Scale Coupling (~0.1) ~ Correct Abundance
Relic Abundance

Thermal Relics

Dark Matter ↔ Standard Model

\[ DM + DM \leftrightarrow SM + SM \]

Graph showing the comoving number density as a function of time, with increasing \( \langle \sigma v \rangle \).
Dark Matter Searches

1) Collider
   Make Dark Matter

2) Direct Detection
   Detect Local Dark Matter

3) Indirect Detection
   Detect Distant Dark Matter Annihilations
Indirect Detection

Dark Matter Annihilations

Same Basic Process For Relic Abundance

Not Yet Sensitive To Thermal Relics
Indirect Detection

Dark Matter Annihilations

Same Basic Process
For Relic Abundance
Not Yet Sensitive
To Thermal Relics

Not Relevant
Direct Detection

Dark Matter – Nuclei Collisions

Spin Dependent:
Amplitude $\sim$ Spin

Spin Independent:
Amplitude Not $\sim$ Spin
Cross Section $\sim A^2$
Collider Searches

Dark Matter Production

- Dark Matter
- Standard Model

Dark Matter

= Missing Energy (MET)

Monojet
(1 quark/gluon + MET)

&

Jets + MET
(2 quark/gluon + MET)
Dark Matter Searches

1) Collider
   Make Dark Matter

2) Direct Detection
   Detect Local Dark Matter

3) Indirect Detection
   Detect Distant Dark Matter Annihilations
Our Models: Motivations

Preserve “WIMP Miracle”
  Thermal Relic DM
  Renormalizable Interactions

Minimal New Content

Generality
  All Spin Combinations
  Own Antiparticle vs. Not
  Flavor Structures
Our Models: Basics

2 New Particles:
- $\chi$, Dark Matter
- $Q$, Standard Model Partner

1 New Interaction, $\lambda$

3 Parameters $\rightarrow$ 2 Parameters
- Relic Abundance
Basic Processes

collider production

\[ \chi \rightarrow Q \rightarrow q \]

freeze out, indirect detection

direct detection
Collider Production

Jets+MET Production

Monojet Production
Our Model: Variations

<table>
<thead>
<tr>
<th>Spin</th>
<th>0</th>
<th>1/2</th>
<th>1</th>
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<tbody>
<tr>
<td>Own Antiparticle</td>
<td>$\chi$: Real Scalar $Q$: Dirac Fermion</td>
<td>$\chi$: Majorana Fermion $Q$: Complex Scalar</td>
<td>$\chi$: Real Vector $Q$: Dirac Fermion</td>
</tr>
<tr>
<td>Not Own Antiparticle</td>
<td>$\chi$: Complex Scalar $Q$: Dirac Fermion</td>
<td>$\chi$: Dirac Fermion $Q$: Complex Scalar</td>
<td>$\chi$: Complex Vector $Q$: Dirac Fermion</td>
</tr>
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SM Particle = Quarks

3 Flavor Variations:

- u, d, c, s, t, b

- All Generations

- 2 Generations
- 3rd Generation
Our Model: Basic Features

Enhanced Direct Detection Near Degeneracy
Larger $\lambda$ Extends Limits to Larger $m_Q$

Direct Detection Rules Out:

<table>
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</table>
| Own Antiparticle  | $\chi$: Real Scalar  
                   | $Q$: Dirac Fermion    | $\chi$: Majorana Fermion 
                   | $Q$: Complex Scalar  | $\chi$: Real Vector  
                   | $Q$: Dirac Fermion    |
| Not Own Antiparticle | $\chi$: Complex Scalar  
                   | $Q$: Dirac Fermion    | $\chi$: Dirac Fermion  
                   | $Q$: Complex Scalar  | $\chi$: Complex Vector  
                   | $Q$: Dirac Fermion    |
Real Scalar Dark Matter (All Gen.)
Real Scalar Dark Matter (3$^{\text{rd}}$ Gen.)
Majorana Dark Matter (All Gen.)
Majorana Dark Matter (2 Gen.)

Coannihilation Region
- Xenon100
- LUX 1 yr
- Xenon 1T
- CMS Dijet
- No T-channel
- CMS B-tag
- CMS Monojet

Coannihilation Region

Colored Scalar Mass (GeV)

Majorana DM Mass (GeV)
Majorana Dark Matter (3rd Gen.)
Real Vector Dark Matter (All Gen.)
Real Vector Dark Matter (2 Gen.)
Real Vector Dark Matter (3\textsuperscript{rd} Gen.)
Summary

Simplified Models provide straightforward comparisons of collider and direct detection.

Collider & Direct Detection are complementary.

Dark Matter must be its own antiparticle to avoid direct detection.

Jets + MET are more sensitive than Monojet searches to simple models of dark matter.