Contents / Overview

- What do we already know about the universe?
- How do we know something is missing?
- If there is something missing, what are its properties?
- What could it be??
- How do we look for it?
- Have we found anything promising yet?
The Standard Model

- Empirical Theory
- Decades of experimental testing
- Best model we have for explaining our known universe
- Not perfect…
- Not complete…
The Standard Model

<table>
<thead>
<tr>
<th>Quarks</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Charge</td>
<td>Spin</td>
<td>Mass</td>
<td>Charge</td>
<td>Spin</td>
<td>Mass</td>
<td>Charge</td>
</tr>
<tr>
<td>2.4 MeV/c²</td>
<td>2/3</td>
<td>1/2</td>
<td>1.27 GeV/c²</td>
<td>2/3</td>
<td>1/2</td>
<td>171.2 GeV/c²</td>
<td>2/3</td>
</tr>
<tr>
<td>up</td>
<td>charm</td>
<td>top</td>
<td>photon</td>
<td>Higgs boson</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quarks</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Charge</td>
<td>Spin</td>
<td>Mass</td>
<td>Charge</td>
<td>Spin</td>
<td>Mass</td>
<td>Charge</td>
</tr>
<tr>
<td>4.8 MeV/c²</td>
<td>-1/3</td>
<td>1/2</td>
<td>104 MeV/c²</td>
<td>-1/3</td>
<td>1/2</td>
<td>4.2 GeV/c²</td>
<td>-1/3</td>
</tr>
<tr>
<td>d</td>
<td>s</td>
<td>b</td>
<td>gluon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leptons</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Charge</td>
<td>Spin</td>
<td>Mass</td>
<td>Charge</td>
<td>Spin</td>
<td>Mass</td>
<td>Charge</td>
</tr>
<tr>
<td>0.511 MeV/c²</td>
<td>-1</td>
<td>1/2</td>
<td>105.7 MeV/c²</td>
<td>-1</td>
<td>1/2</td>
<td>1.777 GeV/c²</td>
<td>-1</td>
</tr>
<tr>
<td>e</td>
<td>μ</td>
<td>τ</td>
<td>Z boson</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leptons</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Charge</td>
<td>Spin</td>
<td>Mass</td>
<td>Charge</td>
<td>Spin</td>
<td>Mass</td>
<td>Charge</td>
</tr>
<tr>
<td>&lt;2.2 eV/c²</td>
<td>0</td>
<td>1/2</td>
<td>&lt;0.17 MeV/c²</td>
<td>0</td>
<td>1/2</td>
<td>&lt;15.5 MeV/c²</td>
<td>0</td>
</tr>
<tr>
<td>νₑ</td>
<td>νₑ</td>
<td>νₑ</td>
<td>νₑ</td>
<td>νₑ</td>
<td>νₑ</td>
<td>νₑ</td>
<td>νₑ</td>
</tr>
</tbody>
</table>
Is this really all there is?...

- Hierarchy Problem?
- Sterile Neutrinos?
- Gravity?
- Dark Energy?
- Dark Matter
Let’s start from the beginning…

Virial Theorem

- Kinetic energy should be half the gravitational potential binding energy of the system

\[
2 \langle T \rangle = - \sum_{k=1}^{N} \langle F_k \cdot r_k \rangle = n \langle V_T \rangle
\]

\[
T \approx \frac{1}{2} v^2 \approx \frac{3}{2} \sigma^2 \quad \frac{GM}{R} = \frac{GM_{vir}}{R_{vir}} \approx \sigma^2
\]

\[
\frac{M_{vir}}{R_{vir}} \propto v^2
\]
So first, a bit of history

Jan Oort
- Galactic Halo of Milky Way Galaxy (1924)
- Calculated the distance between Milky Way center and Earth (1927)
- First evidence for Dark Matter – measured mass of galactic disc (1932)
  - Data/Calculations Proven Erroneous!

Fritz Zwicky
- Applied Virial Theorem to Coma Cluster to reveal evidence of unseen mass (1933)
- Came to conclusion that there was ~ 400 times more mass than observed in cluster
- “Missing Mass Problem”
First Concrete Evidence

1969 – Vera Rubin and Kent Ford

Utilized spectral emission lines from 67 points on Andromeda Galaxy to calculate velocities

One goal was to observe velocity field and determine mass

Interesting results…
First Concrete Evidence

- Image of M-31
- Emission regions for which velocities have been measured
- Varying distances from ‘galactic bulge’
Just to clarify...
First Concrete Evidence
Proof At Last!

- Rubin, Ford, Thonnard 1979
- Performed precise galactic velocity mapping for numerous galaxies ranging in luminosity and radius
- Results were conclusive: velocity did not diminish with distance from rotation point
- There must be a spherically-symmetric “hidden” mass distribution about every galaxy!
Clearly a trend…
Virial Theorem states that for the velocity curves given, there must be a spherically-symmetric “hidden mass” distribution about each galaxy (most galaxies contain about 6 times as much DM as LM).
But how *else* do we know?

- Galaxy *Clusters* are important!
  - Radial velocity distributions of galaxies inside them provide clues (we know that now)
  - X-Ray emission from galaxies – provide insight on temperature and pressure of gasses allowing us to build a mass profile comparing temperature and gravity
- Gravitational Lensing
Gravitational Lensing
In conclusion...

So, we know from the dynamics of galactic rotations, and from looking at the space-time distortion of galactic clusters that there is extra ‘hidden’ mass in galaxies everywhere – and A LOT of it!

So…what could it be??
So what is Dark Matter??

- We can’t see it
- It does not interact via Electromagnetic Force
- It *may* interact weakly…
- It DOES interact gravitationally!
Viable Theories Proposed

- Massive Compact Halo Objects (MACHOs)
- Neutrinos (Sterile Neutrinos)
- Weakly Interacting Massive Particles (WIMPs)
  - Supersymmetry (SUSY Neutralinos)
- Axions
- MOND
- Etc…etc…etc…
MACHOs

- Black holes, Neutron Stars, Brown Dwarfs, rouge planets, etc…
- Attractive because no BSM model necessary!
- Any massive, rouge body amidst the galactic halo
  - Composed of baryonic matter
  - Produces little to no radiation
  - Unassociated with any planetary system
- Very hard to detect…
MACHO Searches…

- Search for PBHs/MACHOs using Kepler Mission Data (Griest et. al. 2013)
- Utilized gravitational microlensing
  - PBH’s ~ size of large asteroid
  - $2 \times 10^{-10} \, M_\odot$ - $2 \times 10^{-6} \, M_\odot$
- Obtain light curves for different stars and look for microlensing events
  - Compare to background data
    - Variable stars, flares, comets, asteroids, etc…
MACHOs

- Found no microlensing candidates after removing background
- Constrained masses of MACHO candidates to $2 \times 10^{-9} M_\odot - 2 \times 10^{-7} M_\odot$
- Turns out, this isn’t a huge problem...
- After looking for evidence of MACHOs, we see there are simply not enough of them to explain the “Missing Mass Problem”
WIMPs

“Weakly Interacting Massive Particles”

Many theories involving WIMPs!
   Literally. Hundreds.

What we DO know:
   Electrically neutral
   Massive
   Weakly Interacting
   Gravitationally Interacting
But, what *are* they?

- “Relic Dark Matter Particles”
  - Relationship to thermal equilibrium of early universe
- Very low interactions cross sections
  - For the current DM mass abundance, self-annihilation cross section can be no larger than the weak scale
- Very low self-annihilation rates
  - Low probability for detection!
‘Direct’ vs ‘Indirect’ DM Searches

Direct Searches
- The goal is to cause a particle reaction in which SUSY particles (DM candidates) are produced and recorded/inferred
- Particle colliders

Indirect Searches
- DM particles interact with SM particles and cause a reaction which we subsequently record/infer.
- Self-annihilation
We are pretty familiar with SUSY by now…

SUSY Partners have same parameters as SM particles with exception of spin

Well…okay, mass

Lightest SUSY Particle (LSP) could be stable, and weakly interacting

Good WIMP Candidate…

Can we produce it?!?

Particle Colliders

LHC
MSSM Recap

- Simplified parameter space of SUSY and the SM
  - Conceived in 1981 to stabilize weak scale
  - 120 parameters

- All super-partners fall into one of five categories
  - Sleptons
  - Charginos
  - Neutralinos
  - Squarks
  - Gluinos

- Expect SUSY particles to be 100-1000 times the proton mass ($\approx 100 - 1000 \text{ GeV}/c^2$)
R-Parity is a symmetry associated with the MSSM
- R = +1 for SM particles, R = -1 for SUSY particles

SUSY does not require B and L be conserved
- Experimentally, this is a problem for Proton decay

R-Parity is a quantum number which may or may not be conserved

If R-Parity is conserved:
- The lightest supersymmetric particle (LSP) must be stable
- Non-LSP SUSY particles must decay to an odd number of LSPs (and SM particles)
- In collider experiments, SUSY particles can only be produced in even numbers (pairs)
SUSY Particles as WIMPs

- If R-Parity conserved, sparticle production eventually results in LSP (lightest supersymmetric particle)
- Neutral LSP (Neutralino) is ideal Dark Matter candidate!
- Neutral
- Massive
- Electroweak-strength interactions
- Neutralino does not have to be LSP…
SUSY Neutralinos

The neutralino is a mix of SUSY partners of SM fields

- 2 Higgs Doublet Model

It is the lightest mass eigenstate of the mixture of the following superfields:

- Bino
- Wino
- Up-type Higgsino
- Down-type Higgsino

\[ \tilde{\chi}_1^0 = Z_1 \tilde{B} + Z_2 \tilde{W} + Z_3 \tilde{H}_u + Z_4 \tilde{H}_d \]
Parameter space is big...

Depending on mass parameters and interactions of decay products, many different types of sparticle decay are possible...

Many final state signatures
Large Hadron Collider

- Leading the way in direct production searches of DM
- Largest, most powerful collider in the world to date
- Comprised of 4 major experiments

Overall view of the LHC experiments.
Assume that the Neutralino is \textit{not} the LSP!

First paper of its kind

Allow for a hidden sector where the Neutralino decays to SM particles and an LSP

Gravitino – Still a good DM candidate!
Methodology of Search

- Construct variable called “$S_T$”
- First employed by Black Hole searches at LHC
- Scalar Sum of all $P_T$ of final state particles
- Resonances will show a ‘bump’ in the distribution!
- Data-driven analysis!

$$S_T = \sum P_T(Jets) + \sum E_T(Photons) + \sum (MET)$$
Scaling

CMS Simulation
\sqrt{s} = 7 \text{ TeV}

QCD Pythia 6
- N = 2
- N = 3
- N = 4
- N = 5
Summary of CMS SUSY Results* in SMS framework

*SUSY 2013

m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV

future Outlook for DM Searches

40

**Observed limits, theory uncertainties not included**

Only a selection of available mass limits

Probe "up to" the quoted mass limit
Indirect Searches

- DM WIMPs interact gravitationally
  - Could be getting ‘sucked’ into Sun and building up!

- Increased number density = greater self-annihilation rate!!

- Weakly Interacting

- Produce Neutrinos!
  - Among other things…
IceCube Neutrino Observatory
IceCube Neutrino Observatory

- “Neutrino telescope”, located at South Pole
- Comprised of 5,160 (Digital Optical Module) DOM detectors
- Built over the existing, decommissioned AMANDA project
- Relies on neutrino interactions with existing ice/water molecules
Main goal is to look for very high energy neutrinos

We know where and how many neutrinos are produced (pretty well)

Look for sources of extraterrestrial, abnormally high energetic neutrino production

Directional searches show us where they are coming from!
IceCube Detector

IceCube Lab
- 50 m

IceTop
- 80 Stations, each with
  - 2 IceTop Cherenkov detector tanks
  - 2 optical sensors per tank
  - 320 optical sensors

2010: 79 strings in operation
2011: Project completion, 86 strings

IceCube Array
- 86 strings including 6 DeepCore strings
- 60 sensors on each string
- 5160 optical sensors

AMANDA Array
- Precursor to IceCube

DeepCore
- 6 strings—sensor spacing optimized for lower energies

Bedrock

Eiffel Tower
- 324 m
“Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector”

- Looked at Muon neutrinos from the Sun’s core
  - June 2010 – May 2011

- Muons react with ice molecules and produce muons
  - Cherenkov light from muons!
  - DOMs capture blue Cherenkov light and produce a “track” of the muon
    - Measures direction and energy

- Must compare with background events!
IceCube Searches for DM WIMPs

- **Dataset WH (winter, high-energy)**
- **Dataset WL (winter, low-energy)**
- **Dataset SL (summer, low-energy)**

Events vs. \( \cos(\Psi) \)
“Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector”

- Findings were consistent with atmospheric backgrounds (muons and neutrinos)
- Set upper limits on:
  - WIMP-Proton cross sections for WIMP masses 20 – 5000 $\text{GeV}/c^2$
  - Dark Matter annihilation rate
- No evidence of Dark Matter yet…
Summary

So, we pretty much know DM is real, what its general properties are, and where it is.

We have theories that explain DM’s presence and properties, and have implemented searches.

We have set limits on MACHO masses, SUSY Neutralino/LSP masses, and self-annihilation rates of WIMP candidates.

But have not observed anything...yet.
73% Dark Energy
23% Dark Matter
3.6% Intergalactic Gas
0.4% Stars, etc.
Conclusion

- Are there SUSY LSPs in our universe?
- Are there WIMPs in general in our universe?
- Are there more MACHOs that we haven’t observed?
- Do we have this all wrong??
  - MOND
- We need to continue solving the mysteries of our Universe!!
Thank You!!