INTRODUCTION

• The Higgs discovery at the LHC was a landmark achievement

• It capped a 50-year saga and completed the particle content of the Standard Model

• But we expect there are more particles to discover, and the Higgs may be just the opening act for the LHC. Why?

Source: AAAS
EVIDENCE FOR DARK MATTER

• We have also learned a lot about the Universe in recent years.

• There is now overwhelming evidence that normal (atomic) matter is not all the matter in the Universe:

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Normal Matter: 4% ± 0.4%
  Neutrinos: 0.2% ($\Sigma m_\nu/0.1\text{eV}$)

• To date, all evidence is from dark matter’s gravitational effects; to identify it, we need to see it in other ways.
A PRECEDENT

• In 1821 Alexis Bouvard found anomalies in the observed path of Uranus and suggested they could be caused by dark matter.

• In 1845-46 Urbain Le Verrier determined the expected properties of the dark matter and how to find it. With this guidance, Johann Gottfried Galle discovered dark matter in 1846.

• Le Verrier wanted to call it “Le Verrier,” but it is now known as Neptune, the farthest known planet (1846-1930, 1979-99, 2006-present).
DARK MATTER

Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Unambiguous evidence for new particles

Source: AAAS
WHAT COULD DARK MATTER BE?

These are not mutually exclusive – multi-component DM is certainly possible.
DARK MATTER CANDIDATES

- Clearly the observational constraints are no match for the creativity of theorists

- Masses and interaction strengths span many, many orders of magnitude

- But not all candidates are similarly motivated
THE WEAK MASS SCALE

• Fermi’s constant $G_F$ introduced in 1930s to describe beta decay

\[ n \rightarrow p \; e^- \; \bar{\nu} \]

• $G_F \approx 1.1 \cdot 10^{-5} \text{ GeV}^{-2}$ → a new mass scale in nature

\[ m_{\text{weak}} \sim 100 \text{ GeV} \]

• We still don’t understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale
FREEZE OUT

(1) Assume a new heavy particle $X$ is initially in thermal equilibrium:

$$XX \leftrightarrow \bar{qq}$$

(2) Universe cools:

$$XX \leftrightarrow \bar{qq}$$

(3) Universe expands:

$$XX \leftrightarrow \bar{qq}$$

Zeldovich et al. (1960s)
The relation between $\Omega_X$ and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$$m_X \sim 100 \text{ GeV}, \ g_X \sim 0.6 \Rightarrow \Omega_X \sim 0.1$$

Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter.
STABILITY

• This all assumes the WIMP is stable

• How natural is this?
LEP’S COSMOLOGICAL LEGACY

• Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable:

  LEP constraints ↔ Discrete Symmetry ↔ Stability

  Cheng, Low (2003); Wudka (2003)

• The result: new, stable particles at the weak scale are predicted in many models and are ideal DM candidates

Gauge Hierarchy requires

Higgs new particle Higgs

Precision EW excludes

SM

new particle

SM

SM

SM
WIMPS FROM SUPERSYMMETRY

The classic WIMP: neutralinos predicted by supersymmetry

Goldberg (1983); Ellis et al. (1983)

Supersymmetry: extends rotations/boosts/translations, string theory, unification of forces,… For every known particle $X$, predicts a partner particle $\tilde{X}$

Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$

Particle physics alone $\rightarrow \chi$ is lightest supersymmetric particle, stable, weakly-interacting, mass $\sim 100$ GeV. All the right properties for WIMP dark matter!
ASYMMETRIC DARK MATTER

• The SM matter relic density was not generated by freeze-out, but by an asymmetry

• If the dark matter relic density was generated in a similar way,

\[ n_{\text{DM}} \sim n_{\text{B}} \]

\[ \frac{m_{\text{DM}}}{m_{\text{B}}} \sim \frac{\Omega_{\text{DM}}}{\Omega_{\text{B}}} \sim 5 \]

Asymmetric DM \( \rightarrow \) \( m_{\text{DM}} \sim 5 \text{ GeV} \)

“Light WIMPs”
Correct relic density $\rightarrow$ Efficient annihilation then

Efficient production now (Particle colliders)

Efficient scattering now (Direct detection)

Efficient annihilation now (Indirect detection)
DIRECT DETECTION

- **WIMP properties**
  - If mass is 100 GeV, local density is ~1 per liter
  - Velocity ~ $10^{-3} \, c$

Look for normal matter recoiling from WIMP collisions in detectors deep underground.

Dark matter elastically scatters off nuclei.

Nuclear recoils detected by phonons, scintillation, ionization, …, …

29 Jan 14
CURRENT STATUS

There are claimed signals: Collision rate should change as Earth’s velocity adds with the Sun’s → annual modulation

Druker, Freese, Spergel (1986)

DAMA: 8σ signal with T ~ 1 year, max ~ June 2

DAMA signal now supplemented by others
CURRENT STATUS AND FUTURE PROSPECTS

ν background: Billard, Strigari, Figueroa-Feliciano (2013)

Asymmetric

$n_{DM} \sim n_B$
MOORE’S LAW FOR DARK MATTER

Evolution of the WIMP–Nucleon $\sigma_{SI}$

$\sigma_{SI}[^{cm^2}]$ for a 50 GeV/c$^2$ WIMP

Year


Higgs-exchange models (hep-ph/1109.2604)

Coherent neutrino scattering signals

Z-exchange models (hep-ph/0209262)
INDIRECT DETECTION

• Dark matter may pair annihilate in our galactic neighborhood to
  • Photons
  • Neutrinos
  • Positrons
  • Antiprotons
  • Antideuterons

• The relic density provides a target annihilation cross section
  \( \langle \sigma_A v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \)
INDIRECT DETECTION: PHOTONS

Current: Veritas, Fermi-LAT, HAWC, and others
INDIRECT DETECTION: PHOTONS

Future: Cerenkov Telescope Array

Core-energy array:
23 x 12 m tel. (MST)
FOV: 7-8 degrees
best sensitivity
in the 100 GeV–10 TeV domain

High-energy section:
30-70 x 4-6 m tel. (SST)
- FOV: ~10 degrees
10 km² area at
multi-TeV energies

Low-energy section:
4 x 23 m tel. (LST)
(FOV: 4-5 degrees)
energy threshold
of some 10s of GeV

First Science: ~2016
Completion: ~2019
INDIRECT DETECTION: PHOTONS

- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV
Dark matter may collect and then annihilate in the Sun, producing the smoking-gun signal of high energy neutrinos from the Sun, providing sensitive probes of spin-dependent interactions.
INDIRECT DETECTION: NEUTRINOS

Current: IceCube/DeepCore

Future: PINGU
INDIRECT DETECTION: ANTI-MATTER

- Positrons (PAMELA, Fermi-LAT, AMS, CALET)
- Anti-Protons (PAMELA, AMS)
- Anti-Deuterons (GAPS)
PARTICLE COLLIDERS

LHC: $E_{\text{COM}} = 7$-14 TeV, $10^5$-$10^8$ top quarks/yr

[Tevatron: $E_{\text{COM}} = 2$ TeV, $10^2$-$10^4$ top quarks/yr]
DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)

Cascades

\( M (\text{GeV}) \)

\[ \begin{array}{cccccc}
0 & 1 & 2 & 3 & 4 & 5 \\
\chi_1^0 & \chi_2^0 & \chi_1^+ & \chi_2^- & \chi_1^- & \chi_2^+ \\
\tilde{g} & \tilde{u}_L & \tilde{d}_R & \tilde{e}_L & \tilde{\nu}_e & \tilde{\tau}_2 \\
\tilde{b}_2 & \tilde{t}_2 & \tilde{e}_R & \tilde{\nu}_{\tau} & \tilde{\tau}_1 & \tilde{\nu}_\mu \\
\tilde{q}_L & \tilde{d}_L & \tilde{b}_1 & \tilde{\nu}_{\mu} & \tilde{\tau}_2 & \tilde{\nu}_e \\
\chi_1^+ & \chi_2^- & \chi_1^- & \chi_2^+ & \chi_1^0 & \chi_2^0 \\
\end{array} \]

\( M_{1/2} (\text{TeV}) \)

\[ \begin{array}{cccccc}
1.5 & 2 & 2.5 & 3 \\
\text{LHC 3000 fb}^{-1} & \text{LHC 100 fb}^{-1} & \text{CMS 4.7 fb}^{-1} & \text{LHC 100 fb}^{-1} & \text{CMS 4.7 fb}^{-1} & \text{LHC 100 fb}^{-1} \\
\end{array} \]

\( \tan \beta = 10 \)

\( A_0 = 0 \)

\( \mu > 0 \)

Feng, Kant, Profumo, Sanford (2013)
DM Effective Theories
(Bare Bones Dark Matter)

Can systematically classify all possible $qq\chi\chi$ interactions

**Table:**

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$\bar{x}x\bar{q}q$</td>
<td>$m_q/M_*^3$</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{x}\gamma^5\bar{q}g$</td>
<td>$im_q/M_*^3$</td>
</tr>
<tr>
<td>D3</td>
<td>$\bar{x}\bar{q}g\gamma^5q$</td>
<td>$im_q/M_*^3$</td>
</tr>
<tr>
<td>D4</td>
<td>$\bar{x}\gamma^5\bar{q}q$</td>
<td>$m_q/M_*^3$</td>
</tr>
<tr>
<td>D5</td>
<td>$\bar{x}\gamma^\mu\bar{q}g_{\mu}q$</td>
<td>$1/2M_*^2$</td>
</tr>
<tr>
<td>D6</td>
<td>$\bar{x}\gamma^\mu\gamma^5\bar{q}g_{\mu}q$</td>
<td>$1/2M_*^2$</td>
</tr>
<tr>
<td>D7</td>
<td>$\bar{x}\gamma^\mu\bar{q}g_{\mu}\gamma^5q$</td>
<td>$1/2M_*^2$</td>
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<tr>
<td>D8</td>
<td>$\bar{x}\gamma^\mu\gamma^5\bar{q}g_{\mu}\gamma^5q$</td>
<td>$1/2M_*^2$</td>
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<tr>
<td>D9</td>
<td>$\bar{x}\sigma^{\mu\nu}\bar{q}g_{\mu\nu}q$</td>
<td>$1/2M_*^2$</td>
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<tr>
<td>D10</td>
<td>$\bar{x}\sigma^{\mu\nu}\gamma^5\bar{q}g_{\mu\nu}q$</td>
<td>$i/M_*^2$</td>
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<tr>
<td>D11</td>
<td>$\bar{x}xG_{\mu\nu}G^{\mu\nu}$</td>
<td>$\alpha_s/4M_*^3$</td>
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<tr>
<td>D12</td>
<td>$\bar{x}\gamma^5xG_{\mu\nu}G^{\mu\nu}$</td>
<td>$i\alpha_s/4M_*^3$</td>
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<tr>
<td>D13</td>
<td>$\bar{x}xG_{\mu\nu}G^{\mu\nu}$</td>
<td>$i\alpha_s/4M_*^3$</td>
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<tr>
<td>D14</td>
<td>$\bar{x}\gamma^5xG_{\mu\nu}G^{\mu\nu}$</td>
<td>$\alpha_s/4M_*^3$</td>
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</tbody>
</table>

Birkedal, Matchev, Perelstein (2004)
Feng, Su, Takayama (2005)

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)
DM EFFECTIVE THEORY

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
THE FUTURE

If there is a signal, what do we learn?

- Cosmology and dark matter searches can’t prove it’s SUSY
- Particle colliders can’t prove it’s DM

Lifetime > $10^{-7}$ s $\rightarrow 10^{17}$ s ?
DARK MATTER COMPLEMENTARITY

- Before a signal: Different experimental approaches are sensitive to different dark matter candidates with different characteristics, and provide us with different types of information – complementarity!

- After a signal: we are trying to identify a quarter of the Universe: need high standards to claim discovery and follow-up studies to measure properties
COMPLEMENTARITY: FULL MODELS

pMSSM 19-parameter scan of SUSY parameter space

Different expts probe different models, provide cross-checks

Cahill-Rowley et al. (2013)
BEYOND WIMPS

• All evidence for dark matter is gravitational. Perhaps it’s in a hidden sector, composed of particles without EM, weak, strong interactions

• \textit{A priori} there are both pros and cons
  – Interesting self-interactions, astrophysics
  – Less obvious connections to particle physics
  – No WIMP miracle

Spergel, Steinhardt (1999); Foot (2001)
NEW MOTIVATIONS FOR HIDDEN DARK MATTER

- WIMPless Miracle: Consider hidden sectors in SUSY models. In many models, $m_X \sim g_X^2$, which leaves the relic density invariant

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

Restores
- Particle physics motivations
- Structure, predictivity
- The miracle: SUSY hidden sectors automatically have DM with the right $\Omega$

Feng, Kumar (2008)

- Self-interactions: Observations vs. simulations motivate self-interacting DM with $\sigma_T/m \sim 0.1\text{–}1 \text{ cm}^2/\text{g}$ (or barn/GeV)

Rocha et al. (2012), Peter et al. (2012); Vogelsberger et al. (2012); Zavala et al. (2012)
SELF-INTERACTING DM FROM SU(N) HIDDEN SECTOR

- WIMPIless miracle requires weak interactions, self-interactions require strong interactions

- A natural possibility to consider is a non-Abelian hidden sector with weak coupling at high scales and early times, and strong coupling at low scales now (cf. QCD)

\begin{equation}
V(r) = -\frac{\alpha}{r} \exp(-\Lambda r)
\end{equation}

\begin{equation}
\sigma_T = \int d\Omega (1 - \cos \theta) \frac{d\sigma}{d\Omega}
\end{equation}

Feng, Kaplinghat, Yu (2010); Tulin, Yu, Zurek (2013)
SELF-INTERACTING DM FROM SU(N) HIDDEN SECTOR

- WIMPless miracle requires weak interactions, self-interactions require strong interactions
- A simple possibility: a non-Abelian hidden sector with weak coupling at early times, and strong coupling now (cf. QCD)
- For example, SUSY with hidden gluons $g$ and gluinos $\tilde{g}$
  - $\sim 10$ TeV gluinos freezeout with the correct relic density
  - At $\Lambda \sim 1$ MeV, glueball $(gg)$ and glueballino $(g\tilde{g})$ bound states form strongly self-interacting dark matter

CONCLUSIONS

• Particle Dark Matter
  – Central topic at the interface of cosmology and particles
  – Both cosmology and particle physics → new particles at the weak scale ~ 100 GeV

• Candidates
  – WIMPs: Many well-motivated candidates
  – Hidden dark matter: Similar motivations, but qualitatively new properties
  – Many others

• LHC is coming back on line in 2015, direct and indirect detection, astrophysical probes are improving rapidly – this field will be transformed in the next few years