We have 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% ($\Sigma m_\nu/0.1eV$)

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
DARK MATTER CANDIDATES

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

- $G_F \approx 1.1 \cdot 10^{-5}$ 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:
$$XX \rightarrow \bar{qq}$$

(3) Universe expands:
$$XX \not\leftrightarrow \bar{qq}$$

Zeldovich et al. (1960s)
THE WIMP MIRACLE

The relation between $\Omega_X$ and annihilation strength is wonderfully simple:

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

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

- $m_X \sim 100 \text{ GeV}, g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$
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!
WIMP DETECTION

Correct relic density $\rightarrow$ Efficient annihilation then

Efficient annihilation now
(Indirect detection)

Efficient scattering now
(Direct detection)

Efficient production now
(Particle colliders)
INDIRECT DETECTION

Dark Matter annihilates in ______________ to ______________, which are detected by ______________, an experiment.

positrons ______________, which are detected by ______________.
CURRENT STATUS

Solid lines are the astrophysical bkgd from GALPROP (Moskalenko, Strong)
ARE THESE DARK MATTER?

- Energy spectrum shape consistent with WIMP dark matter candidates
- Flux is a factor of 100-1000 too big for a thermal relic; requires
  - Enhancement from astrophysics (very unlikely)
  - Enhancement from particle physics
  - Alternative production mechanism

  Cirelli, Kadastik, Raidal, Strumia (2008)
  Feldman, Liu, Nath (2008); Ibe, Murayama, Yanagida (2008)
  Guo, Wu (2009); Arvanitaki et al. (2008)

- Pulsars can explain PAMELA

  Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
  Yuksel, Kistler, Stanev (2008); Profumo (2008)
  Fermi-LAT Collaboration (2009)
DIRECT DETECTION

• WIMP properties
  – \( m \sim 100 \text{ GeV} \)
  – local density \( \sim 1 \text{ per liter} \)
  – velocity \( \sim 10^{-3} \text{ c} \)
  – \( \sim 1 \text{ interaction per kg per year} \)

• Can look for normal matter recoiling from WIMP collisions in ultra-sensitive detectors placed deep underground

• An area of rapid progress on two fronts
CURRENT STATUS

- Results typically normalized to X-proton cross sections

- Weak interaction frontier: For masses \( \sim 100 \) GeV, many models \( \rightarrow 10^{-44} \) cm\(^2\) (see LHC below)
CURRENT STATUS

Low mass frontier: Collision rate should change as Earth’s velocity adds constructively/destructively with the Sun’s → annual modulation

Druker, Freese, Spergel (1986)

DAMA: $8\sigma$ signal with $T \sim 1$ year, max ~ June 2

DAMA low mass signal now supplemented by CoGeNT
CURRENT STATUS

• Puzzles
  – Low mass and high $\sigma$
  – DAMA $\neq$ CoGeNT
  – Excluded by XENON, CDMS

• Many proposed resolutions
  – An example: typical plot assumes couplings: $f_n = f_p$
  – Can reconcile data with $f_n = -0.7 f_p$

Giuliani (2005); Chang, Liu, Pierce, Weiner, Yavin (2010)
Feng, Kumar, Marfatia, Sanford (2011)
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]
LHC MAY PRODUCE DARK MATTER

Yellow: pre-WMAP
Green: post-WMAP

$\Omega_\gamma > \Omega_{DM}$

$\sigma_p \sim 10^{-44} \text{ cm}^2$
$
\Omega \chi < \Omega_{DM}$

$\tan \beta = 10$

Feng, Matchev, Wilczek (2003)
WHAT THEN?

• What LHC actually sees:
  – E.g., $\tilde{q}\tilde{q}$ pair production
  – Each $\tilde{q} \rightarrow$ neutralino $\chi$
  – 2 $\chi$’s escape detector
  – missing momentum

• This is not the discovery of dark matter
  – Lifetime > $10^{-7}$ s $\rightarrow$ $10^{17}$ s?
THE EXAMPLE OF BBN

- Nuclear physics $\rightarrow$ light element abundance predictions
- Compare to light element abundance observations
- Agreement $\rightarrow$ we understand the universe back to $T \sim 1\,\text{MeV}$, $t \sim 1\,\text{sec}$
DARK MATTER ANALOGUE

- Particle physics $\rightarrow$ dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?
WIMP ANNIHILATION PROCESSES

Jungman, Kamionkowski, Griest (1995)
% level comparison of predicted $\Omega_{\text{collider}}$ with observed $\Omega_{\text{cosmo}}$.
IDENTIFYING DARK MATTER

Are $\Omega_{\text{collider}}$ and $\Omega_{\text{cosmo}}$ identical?

Yes

Yes

No

Which is bigger?

Yes

Yes

No

Calculate the new $\Omega_{\text{hep}}$

Which is bigger?

No

Yes

$\Omega_{\text{cosmo}}$

$\Omega_{\text{collider}}$

Does it decay?

No

Yes

Can you discover another particle that contributes to DM?

No

Yes

Can this be resolved with some non-standard cosmology?

No

Yes

Think about dark energy

Yes

No

Are you sure?

No

Yes

Does it account for the rest of DM?

Can you identify a source of entropy production?

No

Yes

Yes

Congratulations!
You’ve discovered the identity of dark matter and extended our understanding of the Universe to $T=10$ GeV, $t=1$ ns (Cf. BBN at $T=1$ MeV, $t=1$ s)

Did you make a mistake?

No

No

Yes

No

Yes

No

Yes

No

Yes
BEYOND WIMPS

• Dark matter has been detected only through gravity

• But the WIMP miracle is a prime reason for optimism, and it seemingly implies that dark matter is
  – Weakly-interacting
  – Cold
  – Collisionless

Are all WIMP miracle-motivated candidates like this?

• No! Recently, have seem many new classes of candidates. Some preserve the motivations of WIMPs, but have qualitatively different implications
• Suppose the WIMP can decay into a superweakly-interacting particle (superWIMP):

\[ \text{WIMP} \rightarrow \text{superWIMP} \rightarrow \text{SM particles} \]

• This is not completely contrived: it happens about ½ the time in SUSY, where the gravitino plays the role of the superWIMP:

\[ \text{WIMP (mass + charge)} \rightarrow \text{superWIMP (mass)} + \text{SM particles (charge)} \]
FREEZE OUT WITH SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

WIMPs freeze out as usual...

...but then decay to superWIMPs

SuperWIMPs naturally inherit the right density; share all the motivations of WIMPs, but are much more weakly interacting

\[ \frac{M_{Pl}^2}{M_W^3} \sim 10^3 - 10^6 \text{ s} \]
CHARGED PARTICLE TRAPPING

- SuperWIMPs are produced by decays of metastable particles, which can be charged

- Charged metastable particles will be obvious at colliders, can be trapped and moved to a quiet environment to study their decays

- Can catch 1000 per year in a 1m thick water tank

Feng, Smith (2004)
De Roeck et al. (2005)
WARM SUPERWIMPS

- SuperWIMPs are produced at “late” times with large velocity (0.1c – c)
- Suppresses small scale structure, as determined by $\lambda_{FS}$, Q
- Warm DM with cold DM pedigree

Dalcanton, Hogan (2000)
Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)
Strigari, Kaplinghat, Bullock (2006)
Bringmann, Borzumati, Ullio (2006)
HIDDEN DARK MATTER

• Hidden sectors are composed of particles without SM interactions (EM, weak, strong)

• Dark matter may be in such a sector
  – Interesting self-interactions, astrophysics
  – Less obvious connections to particle physics
  – No WIMP miracle

Spergel, Steinhardt (1999); Foot (2001)
THE WIMPINGLESS MIRACLE

• In SUSY, however, there may be additional structure. E.g., in GMSB, AMSB, the masses satisfy $m_X \sim g_X^2$

• This leaves the relic density invariant

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

• “WIMPless Miracle”: hidden sectors of these theories automatically have DM with the right $\Omega$ (but they aren’t WIMPs)
WIMPLESS DM SIGNALS

• Hidden DM may have only gravitational effects, but still interesting: e.g., it may interact through “dark photons”, self-interact through Rutherford scattering

  Ackerman, Buckley, Carroll, Kamionkowski (2008)
  Feng, Kaplinghat, Tu, Yu (2009)

• Alternatively, hidden DM may interact with normal matter through connector particles, can explain DAMA and CoGeNT signals

  Kumar, Learned, Smith (2009)
CONCLUSIONS

• Particle Dark Matter
  – Central topic at the interface of cosmology and particles
  – Both cosmology and particle physics $\rightarrow$ weak scale $\sim 100$ GeV

• Candidates
  – WIMPs: Many well-motivated candidates
  – SuperWIMPs, WIMPless dark matter: Similar motivations, but qualitatively new possibilities (warm, collisional, only gravitationally interacting)
  – Many others

• LHC is running, direct and indirect detection, astrophysical probes are improving rapidly – this field will be transformed soon