COSMOLOGY NOW

• Remarkable agreement
  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Baryons: 4% ± 0.4%
  Neutrinos: 0.2% (Σmν/0.1eV)

• Remarkable precision

• Remarkable results
OPEN QUESTIONS

DARK MATTER

– Is it a fundamental particle?
– What are its mass and spin?
– How does it interact?
– Is it absolutely stable?
– What is the symmetry origin of the dark matter particle?
– Is dark matter composed of one particle species or many?
– How and when was it produced?
– Why does $\Omega_{\text{DM}}$ have the observed value?
– What was its role in structure formation?
– How is dark matter distributed now?

DARK ENERGY

– What is it?
– Why not $\Omega_\Lambda \sim 10^{120}$?
– Why not $\Omega_\Lambda = 0$?
– Does it evolve?

BARYONS

– Why not $\Omega_B \approx 0$?
– Related to neutrinos, leptonic CP violation?
– Where are all the baryons?
THE DARK UNIVERSE

The problems appear to be completely different

DARK MATTER
- No known particles contribute
- Probably tied to $M_{\text{weak}} \sim 100 \text{ GeV}$
- Several compelling solutions

DARK ENERGY
- All known particles contribute
- Probably tied to $M_{\text{Planck}} \sim 10^{19} \text{ GeV}$
- No compelling solutions
DARK MATTER

Known DM properties

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

Unambiguous evidence for new physics
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 equally motivated.

HEPAP/AAAC DMSAG Subpanel (2007)
NEW PARTICLES AND NATURALNESS

\[ m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \]

\[ m_h \sim 100 \text{ GeV}, \ \Lambda \sim 10^{19} \text{ GeV} \rightarrow \text{cancellation of 1 part in } 10^{34} \]

At \sim 100 \text{ GeV} we expect new particles: supersymmetry, extra dimensions, something!
THE “WIMP MIRACLE”

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

$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \leftrightarrow \bar{f} f$$

(3) $\chi$'s “freeze out”:

$$\chi\chi \nleftrightarrow \bar{f} f$$

Zeldovich et al. (1960s)
• The amount of dark matter left over is inversely proportional to the annihilation cross section:

\[ \Omega_{DM} \sim <\sigma A v>^{-1} \]

• What is the constant of proportionality?

• Impose a natural relation:

\[ \sigma_A = k\alpha^2/m^2 \], so \[ \Omega_{DM} \sim m^2 \]

Remarkable “coincidence”: \( \Omega_{DM} \sim 0.1 \) for \( m \sim 100 \text{ GeV} - 1 \text{ TeV} \)
STABILITY

• This all assumes the new particle is stable. Why should it be?

• Problems
  \[\uparrow\]
  Discrete symmetry
  \[\downarrow\]
  Stability

• In many theories, dark matter is easier to explain than no dark matter
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, mass $\sim 100$ GeV. All the right properties for WIMP dark matter!
$\Omega_{DM} = 23\% \pm 4\%$ stringently constrains models

Cosmology excludes many possibilities, favors certain regions
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 ______ the halo______ to a place ______ positrons____, which are detected by ___________ PAMELA_____.

some particles an experiment

Cirelli, Strumia (2008)
DIRECT DETECTION

- **WIMP properties:**
  - $v \sim 10^{-3} \text{ c}$
  - Kinetic energy $\sim 100 \text{ keV}$
  - Local density $\sim 1 \text{ / liter}$

- Detected by recoils off ultra-sensitive underground detectors

- DAMA has reported a signal in annual modulation

- Theory predictions vary, but many models $\rightarrow 10^{-44} \text{ cm}$
DIRECT DETECTION: DAMA

$8\sigma$ signal for annual modulation with $T \sim 1$ year, max $\sim$ June 2
PARTICLE COLLIDERS

LHC: $E_{\text{COM}} = 14$ TeV, $10^6 - 10^8$ top quarks/yr

Tevatron: $E_{\text{COM}} = 2$ TeV, $10^2 - 10^4$ top quarks/yr
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?
Contributions to Neutralino WIMP Annihilation

Jungman, Kamionkowski, Griest (1995)
PRECISION SUSY @ LHC

- Masses can be measured by reconstructing the decay chains

\[
\begin{align*}
(m_{\tilde{g}_L}^2)_{\text{edge}} &= \frac{(m_{\tilde{\chi}_2^0}^2 - m_{i_R}^2)(m_{i_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{i_R}^2} \\
(m_{q_l}^2)_{\text{edge}} &= \frac{(m_{q_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\chi}_2^0}^2} \\
(m_{q_l}^2)_{\text{min}} &= \frac{(m_{q_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{i_R}^2)}{m_{\tilde{\chi}_2^0}^2} \\
(m_{q_l}^2)_{\text{max}} &= \frac{(m_{q_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{i_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{i_R}^2} \\
(m_{q_H}^2)_{\text{thres}} &= \left[(m_{q_L}^2 + m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{i_R}^2)(m_{i_R}^2 - m_{\tilde{\chi}_1^0}^2)\right. \\
&\quad - (m_{q_L}^2 - m_{\tilde{\chi}_2^0}^2)\sqrt{(m_{\tilde{\chi}_2^0}^2 + m_{i_R}^2)^2(m_{i_R}^2 + m_{\tilde{\chi}_1^0}^2)^2 - 16m_{\tilde{\chi}_2^0}^2m_{i_R}^4m_{\tilde{\chi}_1^0}^2} \\
&\quad + 2m_{i_R}^2(m_{q_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)/(4m_{i_R}^2m_{\tilde{\chi}_2^0}^2) \\
&\left.\right]
\end{align*}
\]

Weiglein et al. (2004)
RELIC DENSITY DETERMINATIONS

% level comparison of predicted $\Omega_{\chi}^{\text{collider}}$ with observed $\Omega_{\chi}^{\text{cosmo}}$
IDENTIFYING DARK MATTER

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)

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

Yes

No

Which is bigger?

Yes

No

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

Did you make a mistake?

Yes

No

Can you discover another particle that contributes to DM?

Yes

No

Can you identify a source of entropy production?

Yes

No

Does it decay?

Yes

No

Can this be resolved with some non-standard cosmology?

Yes

No

Does it account for the rest of DM?

Yes

No

Think about dark energy
TAKING STOCK

• WIMPs are astrophysically identical
  – Weakly-interacting
  – Cold
  – Stable

• Is this true of all DM candidates?

• No. But is this true of all DM candidates independently motivated by particle physics and the “WIMP miracle”?

• No! SuperWIMPs: identical motivations, but qualitatively different implications
SUPERWIMPS: BASIC IDEA

Supersymmetry: Graviton $\rightarrow$ Gravitino $\tilde{G}$
Mass $\sim 100$ GeV; Interactions: only gravitational (superweak)

- $\tilde{G}$ not LSP
- $\tilde{G}$ LSP

• Assumption of most of literature
• Completely different cosmology and particle physics
SUPERWIMP RELICS

• Suppose gravitinos $\tilde{G}$ are the LSP
• WIMPs freeze out as usual
• But then all WIMPs decay to gravitinos after $M_{Pl}^2/M_W^3 \sim$ seconds to months

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs (also KK gravitons, quintessinos, axinos, etc.)

Feng, Rajaraman, Takayama (2003); Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Feng, Su, Takayama (2004); Buchmuller, Hamaguchi, Ratz, Yanagida (2004); Roszkowski, Ruiz de Austri, Choi (2004); Brandenburg, Covi, Hamaguchi, Roszkowski, Steffen (2005); …
Charged Particle Trapping

• SuperWIMPs are produced by decays of metastable particles. These 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)
IMPLICATIONS FROM CHARGED PARTICLE DECAYS

\[ \tau(\tilde{l} \rightarrow l \tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{l}^5} \left[ 1 - \frac{m_{\tilde{G}}^2}{m_{l}^2} \right]^{-4} \]

- Measurement of \( \tau \), \( m_{\tilde{l}} \) and \( E_l \rightarrow m_{\tilde{G}} \) and \( G_N \)
  - Probes gravity in a particle physics experiment!
  - Measurement of \( G_N \) on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines \( \Omega_{\tilde{G}} \): SuperWIMP contribution to dark matter
  - Determines \( F \): supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

Hamaguchi et al. (2004); Takayama et al. (2004)
SUPERWIMP COSMOLOGY

Late decays can modify BBN (Resolve $^6,^7\text{Li}$ problems?)

Late decays can modify CMB black body spectrum ($\mu$ distortions)

Fields, Sarkar, PDG (2002)

Fixsen et al. (1996)
SMALL SCALE STRUCTURE

- SuperWIMPs are produced in late decays 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)
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: Qualitatively new possibilities (warm, only gravitationally interacting)
  – Many others

• LHC collisions begin in 2009, direct and indirect detection are improving rapidly – this field will be transformed soon