COSMOLOGY NOW

We are living through a revolution in our understanding of the Universe on the largest scales

For the first time in history, we have a complete picture of the Universe
• Remarkable agreement

Dark Matter: 23% ± 4%
Dark Energy: 73% ± 4%
[Baryons: 4% ± 0.4%
Neutrinos: ~0.5%]

• Remarkable precision (~10%)

• Remarkable results
OUTSTANDING QUESTIONS

• Dark Matter: What is it? How is it distributed?

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

• Baryons: Why not $\Omega_B \approx 0$?

• UHE Cosmic Rays: What are they? Where do they come from?

... 

What tools do we need to address these?
LHC Schedule

2007

April: Hardware commissioning
May: Machine checkout
June: Usen commissioning
July: Pilot proton run
August: Shutdown
September: Machine checkout
October: 75ns commissioning
November: First 10ns run
December: 75ns run

2008

January: Shutdown
February: Machine checkout
March: Startup and scrabbling
April: Half intensity 20ns run
May: Full intensity 20ns run
June: Startup
July: Half intensity 20ns run
August: Full intensity 20ns run
September: Expansion to full intensity
October: Startup
November: Half intensity 20ns run
December: Full intensity 20ns run

2009

January: Shutdown
February: Machine checkout
March: Startup and scrabbling
April: Half intensity 20ns run
May: Full intensity 20ns run
June: Startup
July: Half intensity 20ns run
August: Full intensity 20ns run
September: Expansion to full intensity
October: Startup
November: Half intensity 20ns run
December: Full intensity 20ns run

2010

January: Shutdown
February: Machine checkout
March: Startup and scrabbling
April: Half intensity 20ns run
May: Full intensity 20ns run
June: Startup
July: Half intensity 20ns run
August: Full intensity 20ns run
September: Expansion to full intensity
October: Startup
November: Half intensity 20ns run
December: Full intensity 20ns run

2011

January: Shutdown
February: Machine checkout
March: Startup and scrabbling
April: Half intensity 20ns run
May: Full intensity 20ns run
June: Startup
July: Half intensity 20ns run
August: Full intensity 20ns run
September: Expansion to full intensity
October: Startup
November: Half intensity 20ns run
December: Full intensity 20ns run

~ 3 \times 10^{33} \quad \sim 2 \times 10^{33} \quad \sim 7 \times 10^{32} \quad \sim 5 \times 10^{33} \quad 10^{34} \quad \sim 4 \times 10^{32}
23 September 05

LHC

ATLAS

Drawings

Reality!

Dipole installation in the tunnel
DARK MATTER

• Requirements: cold, non-baryonic, gravitationally interacting

• Candidates: primodial black holes, axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,…

• Masses and interaction strengths span many, many orders of magnitude
THERMAL RELICS

(1) Initially, DM is in thermal equilibrium:
\[ \chi \chi \leftrightarrow \bar{f} f \]

(2) Universe cools:
\[ N = N_{EQ} \sim e^{-m/T} \]

(3) \(\chi\)s “freeze out”:
\[ N \sim \text{const} \]
• Impose a natural relation: $\sigma_A \sim \alpha^2/m^2$

• Final $N \sim 1/\sigma_A$.

What’s the constant of proportionality?

Remarkable “coincidence”: even without the hierarchy problem, cosmology tells us we should explore the weak scale.
STABILITY

• This assumes the new weak-scale particle is stable

• Problems (p decay, extra particles, large EW corrections)

  Discrete symmetry

  Stability

• In many theories, dark matter is easier to explain than no dark matter
QUANTITATIVE ANALYSIS OF DM

Battaglia, Feng, Graf, Peskin, Trodden et al. (2005)

The Approach:

- Choose a concrete example: neutralinos
- Choose a simple model framework that encompasses many qualitatively different behaviors: mSUGRA
- Relax model-dependent assumptions and determine parameters
- Identify cosmological, astroparticle implications
Neutralino DM in mSUGRA

Cosmology excludes much of parameter space ($\Omega_\chi$ too big)

Cosmology focuses attention on particular regions ($\Omega_\chi$ just right)

Choose representative points for detailed study

Baer et al., ISAJET  Gondolo et al., DARKSUSY  Belanger et al., MICROMEGA
BULK REGION LCC1 (SPS1a)

$m_0, M_{1/2}, A_0, \tan\beta = 100, 250, -100, 10 \ [\mu > 0, m_{3/2} > m_{\text{LSP}}]$

- Correct relic density obtained if $\chi$ annihilate efficiently through light sfermions:

- Motivates SUSY with light $\chi, \tilde{f}$

Allanach et al. (2002)
PRECISION MASSES

- Kinematic endpoints, threshold scans:
  - variable beam energy
  - e⁻ beam polarization
  - e⁺e⁻ option

- Must also verify insensitivity to all other parameters

Feng, Peskin (2001)
Freitas, Manteuffel, Zerwas (2003)

Weiglein, Martyn et al. (2004)
BULK RESULTS

• Scan over ~20 most relevant parameters
• Weight each point by Gaussian distribution for each observable
• ~50K scan points

Battaglia (2005)

• (Preliminary) result: $\Delta \Omega_\chi/\Omega_\chi = 2.2\%$ ($\Delta \Omega_\chi h^2 = 0.0026$)
RELIC DENSITY DETERMINATIONS

Parts per mille agreement for $\Omega_\chi \rightarrow$ discovery of dark matter
FOCUS POINT REGION LCC2

\[ m_0, M_{1/2}, A_0, \tan\beta = 3280, 300, 0, 10 \ [ \mu > 0, m_{3/2} > m_{\text{LSP}} ] \]

- Correct relic density obtained if \( \chi \) is mixed, has significant Higgsino component to enhance

Feng, Matchev, Wilczek (2000)

- Motivates SUSY with light neutralinos, charginos

\[ \mathcal{M}_N = \begin{pmatrix}
    \frac{M_1 \sin^2 \theta_W + M_2 \sin^2 \theta_W}{\sin \alpha} & (M_2 - M_1) \sin \alpha \cos \alpha \\
    (M_2 - M_1) \sin \alpha \cos \alpha & \frac{M_1 \sin^2 \theta_W + M_2 \cos^2 \theta_W}{\sin \alpha}
\end{pmatrix} \]

\[ \mu \sin 2\beta \]

\[ -\mu \cos 2\beta \]

\[ -\mu \sin 2\beta \]

\[ m_\chi \]

\[ M_2 \]

\[ \sqrt{2m_W \sin \beta} \]

\[ \mu \]
FOCUS POINT RESULTS

- $\Omega_\chi$ sensitive to Higgsino mixing, chargino-neutralino degeneracy

Alexander, Birkedal, Ecklund, Matchev et al. (2005)

(Preliminary) result: $\Delta \Omega_\chi / \Omega_\chi = 2.4\% \ (\Delta \Omega_\chi h^2 = 0.0029)$
RELIC DENSITY DETERMINATIONS

Parts per mille agreement for $\Omega_\chi \rightarrow$ discovery of dark matter
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 $\Omega_{\text{hep}}$ and $\Omega_{\text{cosmo}}$ identical?

Yes

Did you make a mistake?

No

Which is bigger?

$\Omega_{\text{cosmo}}$

Yes

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

No

Can you discover another particle that contributes to DM?

No

Yes

Can you identify a source of entropy production?

No

Yes

Can this be resolved with some wacky cosmology?

No

Yes

Think about the cosmological constant problem

Yes

Does it account for the rest of DM?

No

Yes

Does it decay?
IMPLICATIONS FOR ASTROPARTICLE PHYSICS

Correct relic density $\rightarrow$ Efficient annihilation then $\rightarrow$ Efficient scattering now $\rightarrow$ Efficient annihilation now
Direct Detection

Gaitskell (2001)

DAMA Signal and Others’ Exclusion Contours

WIMP Mass [GeV/c^2]

WIMP–Nucleon Cross–Section [cm^2]
ILC IMPLICATIONS

LCC2 $\rightarrow m < 1$ GeV, $\Delta \sigma/\sigma < 10\%$

Comparison tells us about local dark matter density and velocity profiles

Baer, Balazs, Belyaev, O'Farrell (2003)
INDIRECT DETECTION

Dark Matter may annihilate in the center of the Sun to neutrinos, which are detected by AMANDA, IceCube.

- Comparison with colliders constrains dark matter density in the Sun, capture rates
Dark Matter annihilates in the galactic center to a place photons, which are detected by GLAST, HESS, … an experiment

Comparison with colliders constrains DM density at the center of the galaxy
Dark Matter annihilates in ____ the halo _______ to a place ____ positrons ____, which are detected by ____ AMS on the ISS _____.

some particles an experiment

- Comparison with colliders constrains dark matter density profiles in the halo

ASTROPHYSICS VIEWPOINT:
ILC ELIMINATES PARTICLE PHYSICS UNCERTAINTIES, ALLOWS ONE TO UNDERSTAND STRUCTURE FORMATION
ALTERNATIVE DARK MATTER

• All of these signals rely on DM having electroweak interactions. Is this required?

• No – the only required DM interactions are gravitational (much weaker than electroweak).

• But the relic density argument strongly prefers weak interactions.

Is there an exception to this rule?
SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

• Consider SUSY again:
  \[ \text{Gravitons} \rightarrow \text{gravitinos} \ G \bar{G} \]

• What if the \( \bar{G} \) is the lightest superpartner?

\[ WIMP \quad M_{\text{Pl}}^2/M_W^3 \sim \text{month} \]

• A month passes…then all WIMPs decay to gravitinos – a completely natural scenario with long decay times

Gravitinos naturally inherit the right density, but they interact only gravitationally – they are “superWIMPs”
Big Bang Nucleosynthesis

Late decays may modify light element abundances

After WMAP

- \( \eta_D = \eta_{CMB} \)
- Independent \(^7\text{Li}\) measurements are all low by factor of 3:

\[
\begin{align*}
{^7\text{Li}}/H & = 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\% \text{ CL}) \ [27] \\
{^7\text{Li}}/H & = 1.72^{+0.28}_{-0.22} \times 10^{-10} \quad (1\sigma + \text{sys}) \ [28] \\
{^7\text{Li}}/H & = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (\text{stat + sys, 95}\% \text{ CL}) \ [29]
\end{align*}
\]

- \(^7\text{Li}\) is now a serious problem

Fields, Sarkar, PDG (2002) 

Jedamzik (2004)
BBN EM Constraints

- NLSP = WIMP $\Rightarrow$ Energy release is dominantly EM (even mesons decay first)

- EM energy quickly thermalized, so BBN constrains ($\tau$, $\zeta_{EM}$)

- BBN constraints weak for early decays: hard $\gamma$, $e^-$ thermalized in hot universe

- Best fit reduces $^7$Li:

Cyburt, Ellis, Fields, Olive (2002)
BBN EM Predictions

• Consider $\tilde{\tau} \rightarrow \tilde{G} \, \tau$

• Grid: Predictions for
  $m_{\tilde{G}} = 100 \, \text{GeV} - 3 \, \text{TeV}$ (top to bottom)
  $\Delta m = 600 \, \text{GeV} - 100 \, \text{GeV}$ (left to right)

• Some parameter space excluded, but much survives

• SuperWIMP DM naturally explains $^7\text{Li}$!
SuperWIMP Warm Dark Matter

• Problems for cold dark matter: cuspy halos, dense cores predicted but not observed.

• Some proposed solutions:

  – Self-interacting cold dark matter

  – 3 extra nm-sized dimensions

• SuperWIMPs are created at late times with significant velocity – they are warm!
SuperWIMP Warm Dark Matter

Late decays around $10^6$ s naturally solve small scale structure problems -- in standard SUSY!

Cembranos, Feng, Rajaraman, Takayama (2005)
WORST CASE SCENARIO?

Looks bad – dark matter couplings suppressed by $10^{-16}$

But, cosmology $\rightarrow$ decaying WIMPs are sleptons: heavy, charged, live ~ a month – can be trapped, then moved to a quiet environment to observe decays.

How many can be trapped?

Feng, Smith (2004)
Large Hadron Collider

If squarks, gluinos light, many sleptons, but most are fast:

$O(1)\%$ are caught in 10 kton trap
International Linear Collider

\[ m_{\tilde{\tau}_R} = 219.3 \text{ GeV} \]  \quad \text{NLSP only}

Can tune beam energy to produce slow sleptons: 75% are caught in 10 kton trap
IMPLICATIONS FROM SLEPTON DECAYS

\[ \Gamma(\tilde{\ell} \rightarrow \ell \tilde{G}) = \frac{1}{48\pi M_*^2 m_\tilde{G}^2} \left[ 1 - \frac{m_\tilde{G}^2}{m_\tilde{G}^2} \right]^4 \]

• Measurement of \( \Gamma \) and \( E_I \rightarrow m_\tilde{G} \) and \( M_* \)
  – Probes gravity in a particle physics experiment!
  – Measurement of \( G_{\text{Newton}} \) on fundamental particle scale
  – Precise test of supergravity: gravitino is graviton partner
  – BBN, CMB in the lab
  – Determines \( \Omega_\tilde{G} \): SuperWIMP contribution to dark matter
  – Determines \( F \): supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant
CONCLUSIONS

• Cosmology now provides sharp problems that require particle physics answers.

• Dark matter at colliders is highly motivated; two classes: WIMPs and superWIMPs

• If DM is either of these, we will identify DM with the LHC and ILC.