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
WHAT IS THE UNIVERSE MADE OF?

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

• Remarkable precision (~10%)

• Remarkable results
In 200 B.C., Eratosthenes measured the size of the Earth.

- Remarkable precision (~10%)  
- Remarkable result  
- But just the first step in centuries of exploration
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?
ALCPG COSMOLOGY SUBGROUP

• Goals (Brau, Oreglia):
  – Identify cosmological questions most likely to be addressed by the ILC
  – Determine the role cosmology plays in highlighting specific scenarios for new physics at the ILC
  – Identify what insights the ILC can provide beyond those gained with other experiments and observatories

• Editors: Marco Battaglia, Jonathan Feng*, Norman Graf, Michael Peskin, Mark Trodden*
  *co-conveners

• 30-50 contributors, international participation
  Preliminary results presented here
G: Cosmological Connections

Conveners:
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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”:
$$N \sim \text{const}$$

$$\Omega_{DM} \sim 0.1 \left(\frac{\sigma_{\text{weak}}}{\sigma_A}\right)$$ – just right for new weak scale particles!
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
EXAMPLES

• Supersymmetry
  – Superpartners
  – R-parity
  – Neutralino $\chi$ with significant $\Omega_{DM}$

• Universal Extra Dimensions
  – Kaluza-Klein partners
  – KK-parity
  – Lightest KK particle with significant $\Omega_{DM}$

• Branes
  – Brane fluctuations
  – Brane-parity
  – Branons with significant $\Omega_{DM}$
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 4 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 $\chi, \tilde{l}$

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

Weiglein, Martyn et al. (2004)

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

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

(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

\[ M_C = \begin{pmatrix} M_2 & \sqrt{2m_W \cos\beta} \\ \sqrt{2m_W \sin\beta} & \mu \end{pmatrix} \]
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
CO-ANNIHILATION REGION LCC3

\[ m_0, M_{1/2}, A_0, \tan\beta = 210, 360, 0, 40 \ [\mu > 0, m_{3/2} > m_{\text{LSP}}] \]

- If other superpartners are nearly degenerate with the \( \chi \) LSP, they can help it annihilate

\[
\begin{align*}
\chi & \rightarrow \tau + \chi \\
\tilde{\tau} & \rightarrow \tau + \gamma
\end{align*}
\]

Griest, Seckel (1986)

- Requires similar \( e^{-m/T} \) for \( \chi \) and \( \tilde{\tau} \), so (roughly)
  \[ \Delta m < T \sim m_\chi/25 \]

- Motivates SUSY with \( \tilde{\tau} \rightarrow \tau + \chi \) with \( \Delta m \sim \text{few GeV} \)
CO-ANNIHILATION RESULTS

Dutta, Kamon; Nauenberg et al.; Battaglia (2005)

(Preliminary) result: $\Delta \Omega_\chi / \Omega_\chi = 7.0\%$ ($\Delta \Omega_\chi h^2 = 0.0084$)
RELIC DENSITY DETERMINATIONS

% level agreement for $\Omega_\chi \rightarrow$ discovery of dark matter
IMPLICATIONS FOR ASTROPARTICLE PHYSICS

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

DAMA Signal and Others’ Exclusion Contours

CDMS (2004)

Gaitskell (2001)
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’Farrill (2003)
INDIRECT DETECTION

Dark Matter Madlibs!

Dark matter annihilates in ________________ to ________, which are detected by ________________ .

particles an experiment
Dark Matter annihilates in **center of the Sun** to a place **neutrinos**, which are detected by **AMANDA, IceCube**.

Some particles an experiment

- Comparison with colliders constrains dark matter density in the Sun, capture rates

AMANDA in the Antarctic Ice
Dark Matter annihilates in **the galactic center** to a place **photons**, which are detected by **GLAST, HESS, ...**. Some particles

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.

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

ASTROPHYSICS VIEWPOINT:
ILC ELIMINATES PARTICLE PHYSICS UNCERTAINTIES,
ALLOWS ONE TO DO REAL ASTROPHYSICS
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: Gravitons $\rightarrow$ gravitinos $\tilde{G}$
- What if the $\tilde{G}$ is the lightest superpartner?
  
  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”
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

Shufang Su, LCWS05
IMPLICATIONS FROM SLEPTON DECAYS

\[ \Gamma(\tilde{\ell} \to \ell \tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_\tilde{\ell}^5}{m_{\tilde{G}}^2} \left[ 1 - \frac{m_{\tilde{G}}^2}{m_\tilde{\ell}^2} \right]^4 \]

- Measurement of \( \Gamma \) and \( E_f \to m_{\tilde{G}} \) 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
DARK ENERGY

- Quantum mechanics:
  \[ \frac{1}{2} \hbar \omega, \quad \omega^2 = k^2 + m^2 \]

- Quantum field theory:
  \[ \int^E d^3 k \left( \frac{1}{2} \hbar \omega \right) \sim E^4, \]
  where \( E \) is the energy scale where the theory breaks down

- All fields contribute to \( \Lambda \). We expect
  \[
  (M_{\text{Planck}})^4 \sim 10^{120} \rho_\Lambda \\
  (M_{\text{GUT}})^4 \sim 10^{108} \rho_\Lambda \\
  (M_{\text{SUSY}})^4 \sim 10^{90} \rho_\Lambda \\
  (M_{\text{weak}})^4 \sim 10^{60} \rho_\Lambda
  \]
ONE APPROACH

• Small numbers ↔ broken symmetry

\[ \rho_\Lambda \sim M_{Pl}^4 \]

A miracle occurs here

\[ \rho_\Lambda = 0 \]

\[ \rho_\Lambda \sim m_\nu^4, \quad (M_W^2/M_{Pl})^4, \ldots \]
ANOTHER APPROACH

\[ \rho_\Lambda \sim M_{Pl}^4 \]

Many, densely spaced vacua (string landscape, many universes, etc.)

\[ -1 < \Omega_\Lambda < 100 \]

Weinberg (1989)
• Two very different approaches. There are others, but none is compelling.

• Ways forward:
  1) Discover a fundamental scalar particle (Higgs would be nice)
  2) $(M_{\text{weak}})^4 \sim 10^{60} \rho_\Lambda$: map out the EW potential
  3) $(M_{\text{SUSY}})^4 \sim 10^{90} \rho_\Lambda$: understand SUSY breaking (see above)
  4) $(M_{\text{GUT}})^4 \sim 10^{108} \rho_\Lambda$: extrapolate to GUT scale
  5) $(M_{\text{Planck}})^4 \sim 10^{120} \rho_\Lambda$: ...

• ILC will be an essential tool for at least 2, 3, and 4.
BARYOGENESIS

• Requires
  – B violation
  – CP violation
  – Departure from thermal equilibrium

• All possible at the electroweak scale with new physics

• For SUSY, requires precise determination of Higgs and top squark parameters, and CP violating phases
• ILC will quickly establish whether EW Baryogenesis is possible

• CP violation: Bartl et al., Zerwas et al., Barger et al., and others

• LCC5: Graf, Strube et al.
CONCLUSIONS

• Cosmology now provides sharp problems that are among the most outstanding in basic science today.

• They require new particle physics, cannot be solved by cosmological tools alone.

• In many cases, the ILC provides an essential tool for discovering the answers.
AN EQUALLY EXCITING AGE OF DISCOVERY AHEAD