CONNECTING THE VERY, VERY SMALL WITH THE REALLY, REALLY BIG

"I'll be working on the largest and smallest objects in the universe—supernovae and neutrinos. I'd like you to handle everything in between.
Standard Model of Particle Physics

- c. 1970s

- Explains data down to length scales of $10^{-16}$ cm
Particle Physics – Experiment

High Energy Colliders

\[ \frac{\Delta g_1}{g_1} \sim 10^{-8} \]
\[ \frac{\Delta g_2}{g_2} \sim 10^{-3} \]
\[ \frac{\Delta g_3}{g_3} \sim 10^{-2} \]
Standard Model of Cosmology

- c. 2003
- Explains data up to length scales of $10^{28}$ cm
Cosmology – Experiment

Satellites, telescopes

21 August 2003
Connections – Theory

Why do particle physicists care about cosmology?

Cosmology poses fundamental questions:
– What is dark matter?
– What is dark energy?
– Why is there more matter than anti-matter?

The standard model of particle physics is amazingly successful, but...

It’s missing 96% of the universe, and we don’t understand why the remaining 4% is still here.
Connections – Experiment

• Cosmology also provides tools to help answer these questions
  – Ultrahigh energy collisions now
  – Ultrahigh energies from the Big Bang
  … for FREE!

• Drawbacks
  – “Experimental rates” are low – need BIG detectors
  – Cosmological “experiments” were done a long time ago
  – Cosmological “experiments” are irreproducible
Cosmic Rays – Past

• 1935 Yukawa postulates the pion with mass \( \sim 100 \) MeV.
• 1937 Anderson discovers the “mesotron” in cosmic rays with mass \( \sim 100 \) MeV.
• 1941-45 WW II.
• 1946 Powell and Occhialini discover pions \( \pi^- (139 \) MeV) in cosmic rays. Mesotrons identified as muons \( \mu^- (106 \) MeV).
• 1946 Rochester and Butler discover kaons \( K^0 (494 \) MeV) in cosmic rays.
• 1948 First man-made pions \( \pi^- \) and \( \pi^0 (134 \) MeV) produced at Berkeley 184-inch cyclotron.
Cosmic Rays – Present

- Neutrino masses and mixings discovered through cosmic rays at SuperKamiokande in 1998
- Man-made neutrino sources provide evidence for mixings at KamLAND in 2002
Cosmic Rays – Future

• Cosmic rays observed with energy $E_{CR} \sim 10^{19}$ eV ($\sim$ major league fastball)

• For fixed target collisions, the center-of-mass energy is $E_{CM} = (2 E_{CR} m_p)^{1/2}$, so $E_{CR} \sim 10^{19}$ eV $\Rightarrow E_{CM} \sim 100$ TeV

• Higher energies than any man-made collider
Cosmic Rays – Future

Black Hole produced here
Dark Matter

\[ \frac{M v^2}{r} = \frac{G M M_{\text{tot}}}{r^2} \quad \Rightarrow \quad v \sim r^{-1/2} \]

Begeman, Broeils, Sanders (1991)
Big Bang Nucleosynthesis

- What is the halo made of? Not atoms!

- As the universe cools, protons form nuclei. The number of protons determines the amount of light elements in the universe.

- All light elements agree: protons make up 4% of the universe’s mass, whereas the required amount of halo matter is 29%. The remaining 25% is dark matter.
What is Dark Matter?

• Must be neutral, very long-lived, heavy.

• All known particles are easily eliminated.

• Dark matter is the best evidence that the standard model of particle physics is incomplete, and motivates many extensions.

• Some candidates:
  – WIMPs (e.g., neutralinos)
  – Axions
WIMPs

- Among the best candidates so far: weakly-interacting massive particles. These particles have weak interactions only.

- They are produced in the Big Bang, and interact via $\text{SM} + \text{SM} \leftrightarrow \text{WIMP} + \text{WIMP}$. As the universe expands, they become diluted, and eventually can’t find each other – they “freeze-out.” Their relic density is determined by their interaction strength.

- WIMPs are automatically left with the right amount to be dark matter.
WIMPs

- Universe cools, leaves a residue of dark matter with $\Omega_{DM} \sim 0.1 \ (\sigma_{\text{Weak}}/\sigma)$
- 13 Gyr later, Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidences? Maybe, but worth investigation!
**Supersymmetric WIMPs**

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Cold Dark Matter WIMP candidates: neutralino, sneutrino
WIMP Detection

CDMS in the Soudan mine
½ mile underground in Minnesota
Axions

- Axions are particles predicted in theories designed to explain why CP violation is so small.

- Axions interact with photons and are very light with masses of \( \mu \text{eV} \) to \( \text{meV} \).

- However, they interact extremely weakly.
Axion Detection

1.9-3.4 μeV (ADMX, LLNL-Florida-Berkeley-NRAO)
Dark Matter – Future

Collider Inputs

Dark Matter Parameters

$\chi\chi$ Annihilation

$\chi N$ Interaction

Relic Density

Indirect Detection

Direct Detection

Astrophysical and Cosmological Inputs
Dark Energy

- Cosmology $\rightarrow$ 70% of the mass of the universe is in dark energy (also known as the cosmological constant).
What is Dark Energy?

• Dark energy is the energy stored in a vacuum. From quantum mechanics, recall that an oscillator has energy \( \omega (n \pm \frac{1}{2}) \), where \( \omega^2 = k^2 + m^2 \); \( \pm \omega/2 \) is the vacuum energy. (Set \( \hbar=1 \).)

• In quantum field theory, we must add up vacuum energies for all wave numbers \( k \). For each particle, we get

\[
\pm \frac{1}{2} \int_{\mathbb{E}} d^3k \, (k^2 + m^2)^{\frac{1}{2}} \sim \pm E^4,
\]

where \( E \) is the energy scale where the theory breaks down.
Expectations for Dark Energy

- We expect $E \sim M_{\text{Planck}} \sim 10^{19}$ GeV, or at least $E \sim M_{\text{weak}} \sim 100$ GeV. But cosmology tells us $E \sim 10^{-3}$ eV! Independent contributions must cancel to incredible accuracy.

- Problems:
  - Why is $\Omega_\Lambda$ so small?
  - Why is $\Omega_\Lambda$ not zero?
  - Why is $\Omega_\Lambda \sim \Omega_M$?

- The cosmological constant problems are the most profound problems facing particle physics today. No reasonable solutions. (Anthropic principle?)
Summary

• Cosmology provides fundamental questions…
  – What is dark matter?
  – What is dark energy?
  – Why is there matter and not anti-matter?

• … and fundamental tools for finding the answers
  – The universe is Nature’s high energy collider

• The big and small are inextricably linked as particle physics and cosmology enter a golden era.
Ouroboros