WHAT IS THE UNIVERSE MADE OF?

An age old question, but…

Recently there have been remarkable advances in our understanding of the Universe on the largest scales

We live in interesting times: for the first time in history, we have a complete picture of the Universe
The Evidence

Rotation curves of galaxies and galactic clusters

- Expect $v_c \sim r^{-1/2}$ beyond luminous region
- Instead find $v_c \sim$ constant
- Discrepancy resolved by postulating dark matter
Supernovae

Then

Constrains $\Omega_\Lambda - \Omega_M$

Cosmic Microwave Background

Constrains $\Omega_\Lambda + \Omega_M$

Now
Synthesis

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

• Remarkable precision (~10%)

• Remarkable results
Historical Precedent

Eratosthenes measured the size of the Earth in 200 B.C.

- Remarkable precision (~10%)
- Remarkable result
- But just the first step in centuries of exploration
Cosmology marches on

earth, air, fire, water

baryons, vs, dark matter, dark energy
What are Dark Matter and Dark Energy?

We have no idea. But so far, these 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

- Stable
- Non-baryonic
- Cold

DM: precise, unambiguous evidence for new particles
Dark Matter Candidates

• The Wild, Wild West of particle physics: 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

• But independent of cosmology, new particles are required to understand the weak force
Weak Force and Higgs Boson

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

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

At \( M_{\text{weak}} \sim 100 \text{ GeV} \) we expect new weakly interacting particles: supersymmetry, extra dimensions, something!
Cosmological Implications

(1) Initially, new particle is in thermal equilibrium:
\[ \chi \chi \leftrightarrow \overline{f} f \]

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

(3) $\chi$s “freeze out”:
\[ N \sim \text{const} \]
• Final $N$ fixed by annihilation cross section:
  \[ \Omega_{DM} \sim 0.1 \left( \sigma_{\text{weak}}/\sigma_A \right) \]
  Remarkable!

• Domestic diva Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidences? Maybe, but worth serious investigation!
NOTE

• I’ve assumed the new particle is stable

• Problems (proton decay, extra particles, …)

  ▲

  Discrete symmetry

  ▼

  Stability

• In many theories, dark matter is easier to explain than no dark matter
DARK MATTER CANDIDATES

Candidates that pass the Martha Stewart test

Ones you could bring home to mother. – V. Trimble
WIMP Dark Matter

WIMPs: weakly-interacting massive particles

Supersymmetry: extends rotations/boosts/translations, string theory, unification of forces, … Predicts a partner particle for each known particle

The prototypical WIMP: neutralino \( \chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d) \)

Particle physics alone \( \rightarrow \) all the right properties: lightest superpartner, stable, mass \( \sim 100 \text{ GeV} \)

Goldberg (1983)
\[ \Omega_{DM} = 23\% \pm 4\% \] stringently constrains models

Cosmology highlights certain regions, detection strategies
Extra Dimensional Dark Matter

• Extra spatial dimensions could be curled up into small circles.

• Particles moving in extra dimensions appear as a set of copies of normal particles.

WIMP Detection: No-Lose Theorem

\[ \chi \rightarrow f \rightarrow \bar{f} \]
Annihilation

\[ \chi \rightarrow \chi \]
Scattering

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

DAMA Signal and Others’ Exclusion Contours

CDMS (2004)
Direct Detection: Future

Theoretical Predictions

Current Sensitivity

Near Future

Future

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 the galactic center to a place photons, which are detected by Cerenkov telescopes. For some particles an experiment

Typically \( \chi\chi \rightarrow \gamma\gamma \), so \( \chi\chi \rightarrow f\bar{f} \rightarrow \gamma \)

HESS: \( \sim 1 \) TeV signal

If DM, \( m_\chi \sim 12 \) TeV

Horns (2004)
Dark Matter annihilates in the center of the Sun to a place neutrinos, which are detected by AMANDA, IceCube. Some particles \[ \nu \rightarrow \mu (\text{km}^{-2} \text{ yr}^{-1}) \]

(a) \[ \tan \beta = 10 \]
Dark Matter annihilates in the halo to a place, which are detected by AMS on the ISS. Some particles an experiment.
SuperWIMP Dark Matter

Feng, Rajaraman, Takayama (2003)

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

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

• But the relic density argument strongly prefers weak interactions.

Is there an exception to this rule?
No-Lose Theorem: Loophole

- Consider SUSY again: Gravitons $\rightarrow$ gravitinos $\tilde{G}$
  Pagels, Primack (1982)

- What if the $\tilde{G}$ is the lightest superpartner?

- A month passes... then all WIMPs decay to gravitinos

Gravitinos naturally inherit the right density, but they interact only gravitationally – they are “superWIMPs”
SuperWIMP Detection

- SuperWIMPs evade all conventional dark matter searches. But superweak interactions → very late decays $\tilde{l} \rightarrow G \tilde{l} \rightarrow$ cosmological signals. For example: BBN, CMB.
PROSPECTS

If the relic density “coincidence” is no coincidence and DM is either WIMPs or superWIMPs, the new physics behind DM will very likely be discovered in this decade:

Direct dark matter searches
Indirect dark matter searches

The Tevatron at Fermilab
The Large Hadron Collider at CERN (2008)
What then?

- Cosmology can’t discover SUSY
- Particle colliders can’t discover DM

Lifetime > $10^{-7}$ s $\rightarrow$ $10^{17}$ s?
Colliders as WIMP Labs

- The LHC and International Linear Collider will discover WIMPs and determine their properties at the % level.

- Consistency of
  
  WIMP properties (particle physics)
  WIMP abundance (cosmology)

  will extend our understanding of the Universe back to

  \[ T = 10 \text{ GeV}, \ t = 1 \text{ ns} \]

  (Cf. BBN at \( T = 1 \text{ MeV}, \ t = 1 \text{ s} \))
RELIC DENSITY DETERMINATIONS

Parts per mille agreement for $\Omega_\chi \rightarrow$ discovery of dark matter
Colliders as SuperWIMP Labs

Sleptons are heavy, charged, live ~ a month – can be trapped, then moved to a quiet environment to observe decays.

LHC, ILC can trap as many as ~10,000/yr in 10 kton trap.

Feng, Smith (2004)

Lifetime \(\rightarrow\) test gravity at colliders, measure \(G_N\) for fundamental particles.
Mapping the Dark Universe

Once dark matter is identified, detection experiments tell us about dark matter distributions.

ASTROPHYSICS VIEWPOINT:
LHC/ILC ELIMINATE PARTICLE PHYSICS UNCERTAINTIES, ALLOW ONE TO DO REAL ASTROPHYSICS
CONCLUSIONS

Extraordinary progress, but a long way from complete understanding

Cosmology + Particle Physics →
New particles at 1 TeV: just around the corner

Bright prospects!