The Dark Universe
Dark Matter Matters!

Exploring the Dark Universe
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DARK MATTER

"Extraordinary claims require extraordinary evidence." (Carl Sagan)
"Extraordinary claims require extraordinary proof." (Marcello Truzzi)
"The weight of evidence for an extraordinary claim must be proportioned to its strangeness" (Laplace)
"A wise man, therefore, proportions his belief to the evidence" (David Hume)

Evidence for Dark Matter
- Rotation of galaxies
- Velocities of stars in galaxies
- Gravitational lensing
- Velocities of galaxies in clusters

Why is DARK MATTER important?
The formation of galaxies and the formation of large scale structure in the Universe requires the extra mass provided by dark matter

DARK MATTER Dominates the Structure of the Universe
- Center for Cosmological Physics, University of Chicago
- http://cosmicweb.uchicago.edu/index.html

- The formation of clusters and large-scale filaments proceeds in a universe filled with cold dark matter
- The box is 43 million parsecs (or 140 million light years)
- The simulation begins at z=30 when the age of the Universe was less than 1% of its current age and the distribution of matter is nearly uniform
- Small fluctuations get modeled in a structure box. The resultant bright clumps with sizes and masses similar to those of galaxies to the large filaments
- The structure does not change much between z=0.5 and z=0
- The expansion of the universe is accelerating as the "dark energy" becomes dominant at z<1
- On large scales seen here, gravity cannot compete with the dark energy-driven acceleration and the growth of structure ceases
The Evolution of Dark Matter
- A loose network of dark matter filaments collapses under the relentless pull of gravity, and grows clumpier over time.
- Dark matter filaments formed first and provided the structure for the formation of stars and galaxies from ordinary matter.
- Without dark matter, there would have been insufficient mass in the universe for structures to collapse and galaxies to form.

Galaxy Formation
- A disk galaxy in the process of formation at the epoch where the virtual universe of the simulation was "only" one and a half billion years old.
- The young galaxy forms in a high-density peak in which several large-scale filaments of matter intersect.
- These filaments deliver a fresh supply of gas and dark matter to the galaxy.
- The accreting gas fuels very active star formation, while accreted dark matter and smaller galaxies lead to the rapid growth of the galaxy's mass.

Galaxies Grow through Mergers
- The formation proceeds hierarchically. Small-mass objects form first at z=5, grow in size and merge, creating larger and larger systems.
- Galactic "cannibalism" persists even to the present day epoch.
- The two main objects approaching at z=0 will merge in about a billion years into the future.
- Many of the small systems do not lose their identity and become satellites orbiting in the gravitational pull of larger systems.

Galaxies Grow through Mergers
- The cosmic web of dark matter, gas, and galaxies in a young universe.

Galaxy interactions require more mass than we can see
- The visible portion of a galaxy lies deep in a halo of dark matter.

The real thing
Is Dark Matter Really Necessary?

Modified Newtonian Dynamics (MOND)
- Newton’s theory of gravity must be modified at high acceleration (general relativity)
- Are modifications also needed at very low acceleration?

MOND can explain galaxy rotation curves
- Newton’s laws are modified with a new term at very low acceleration
- Instead of $F=ma$, MOND asserts that...

\[
 F = m\mu\left(\frac{a}{a_0}\right)a 
\]

- where \( \mu(a/a_0) = 1 \) for \( a >> a_0 \)
- \( \mu(a/a_0) = a/a_0 \) for \( a << a_0 \)
- \( a_0 \) is about \( 10^{-10} \text{ m s}^{-1} \)
- The free constant \( a_0 \) is selected to fit the rotation curves of galaxies
- At ‘normal’ accelerations, \( \mu(a/a_0) = 1 \) and Newton’s laws hold

MOND can’t explain it all
- While MOND can reproduce galaxy rotation curves, it is harder to explain
  - Galaxy cluster velocity dispersions
  - Observations of gravitational lenses
  - The Bullet Cluster and the DM ring
- MOND still requires DM to account for all the observations
- Which is a simpler explanation, DM or MOND+DM?

The Dark Universe
- Up until the present epoch, the gravity of dark matter has dominated the universe
- Dark matter filaments concentrated luminous matter to form stars galaxies
- Dark matter dominates the evolution of galaxy clusters and groups
- Dark matter dominates the interactions of galaxies