... probing the ‘stuff’ of the universe

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ROTATION CURVES

Longer arrows represent larger orbital velocities.

Dark Matter in Galaxies

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Figure 24-3
Universe, Eighth Edition
© 2008 W.H. Freeman and Company

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Vera Rubin

Fritz Zwicky and Clusters of Galaxies

The Coma Cluster

Gravity and General Relativity

- Prediction (1916) - gravity "bends" light!
- Eddington eclipse expedition 1919
Dark Matter ~ 23% Universe!

Dark Energy, or The Accelerating Universe

1998: Accelerating Universe named “Breakthrough of the year”

2005: Top of the list of 25 outstanding Science questions: “What is the Universe made of?”

1965: Penzias & Wilson Discover the CMB

Penzias & Wilson: coherent scattering of WIMPs off nuclei (1985)

What is measured (with different target nuclei and detectors): energy of the recoiling nucleus

What are the challenges: very small energy, very large backgrounds and very small rate
The Cosmic Microwave Background Radiation: Snapshot of the Universe When it Was Very Young

$z \approx 1000$
$\frac{a(t)}{t} \approx 1/1000$
$t \approx 400,000$ yrs

The CMB Viewed Through Universes of Different Densities

High Density
Just Right!
Low Density

Hubble Expansion

$z \sim 1000$
$\frac{a(t)}{t} \approx 1/1000$
$t \sim 400,000$ yrs

$\frac{a(t)}{t} = \frac{1}{1+z}$
An object moving away from us is seen with REDshifted emission

\[ \lambda = 42 \text{ cm} \]

\[ z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{rest}}} - 1 \]

\[ \lambda = 21 \text{ cm} \]

Hydrogen atom

Moving away

From us

Hydrogen atom

At rest

1. The more massive member of a pair of Sun-like stars exhausts its fuel and turns into a white dwarf star.

2. A "flame" - a runaway nuclear reaction - ignites in the turbulent core of the dwarf.

3. The flame spreads outward, converting carbon \(^{12}\)C and oxygen \(^{16}\)O to radioactive nickel \(^{56}\)Ni.

4. Within a few seconds, the dwarf has been completely destroyed. Over the following weeks, the radioactive nickel decays, causing the debris to glow.
Nobel Prize in Physics 2011

Saul Perlmutter | Brian Schmidt | Adam Riess

Makeup of the Universe evolves with expansion

Cosmic Timeline

\[ z = 1000 \]
\[ z = 10 \]
\[ z = 1 \]

\[ a(t) = \frac{1}{1+z} \]