Distance to raisin

Apparent speed of raisin
Distance to raisin

Apparent speed of raisin
Visible Light
Visible Light

Increasing Wavelength
Increasing distance to galaxy

More redshift

More expansion of space

??
“Standard Candles”
“Standard Candles”

Dimmer => Further away
Standard Candles in the Universe: “Type Ia” Supernovae
Standard Candles in the Universe: “Type Ia” Supernovae
Standard Candles in the Universe: “Type Ia” Supernovae
Evolution of a Supernova

Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center.
Fainter

More redshift  ↔

Further

More expansion of space
Fainter
Further
More redshift
More expansion of space

Calan/Tololo
(Hamuy et al, A.J. 1996)
Fainter → Further
Calan/Tololo (Hamuy et al, A.J. 1996)

More redshift ↔
More expansion of space

See 2011 Nobel Prize Lectures by S. Perlmutter, B. Schmidt and A. Riess:
• For a given brightness (distance), redshift is less than expected.
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• Universe was expanding at less than the “expected” rate in the past.

See 2011 Nobel Prize Lectures by S. Perlmutter, B. Schmidt and A. Riess:
- For a given brightness (distance), redshift is less than expected.
- Universe was expanding at less than the “expected” rate in the past.
- The Universe is expanding at an ever-increasing rate!
Gravitationally Attracting Matter
32%

Dark Energy
68%
Dark Matter: 27%

Ordinary Matter: 5%

Dark Energy: 68%
simulated dark matter distribution

Simulation: Klypin & Primack
Galaxy model: Busha & Wechsler
Visualization: Kaehler
simulated dark matter distribution

predicted galaxy distribution

Simulation: Klypin & Primack
Galaxy model: Busha & Wechsler
Visualization: Kaehler
Distribution of Galaxies in the Universe

observed

Distribution of Galaxies in the Universe

observed

Distribution of Galaxies in the Universe


Bolshoi Simulation: Klypin, Trujillo-Gomez & Primack 2011
Visualization and galaxy model: Kaehler, Wechsler
Gravitational Lensing by a Galaxy Cluster

Hubble Space Telescope, Wide-Field Planetary Camera 2 and Advanced Camera for Surveys, Abell 2218
The Cosmic Frontier  

Ground
The Cosmic Frontier
Large Synoptic Survey Telescope “All-Hands” Meeting August 2012, Tucson Arizona

The Cosmic Frontier

Ground
The Cosmic Frontier

- Dark Matter: 27%
- Ordinary Matter: 5%
- Dark Energy: 68%

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The Cosmic Frontier

Ground

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Large Synoptic Survey Telescope “All-Hands” Meeting August 2012, Tucson Arizona