# An Expanding Universe

Survey of the 2011 Nobel Prize in Physics

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# Overview

The Nobel laureates sought to measure a theoretical "deceleration parameter" for the universe.

1. Historical development of the deceleration parameter
2. Method of measurement
3. Results and implications
4. Future work

# Development of General Relativity

- Einstein's published the General Theory of Relativity published in 1915

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- In 1917, Einstein introduced the cosmological constant to his field equations to make his universe static

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- Alexander Friedmann's work in 1924 showed that Einstein's static universe still unstable
- Georges Lemaître obtained similar results independently in 1927

# Multiple Galaxies

- In 1912, the Vesto Slipher observed the redshift of several nebulae and determined that the bodies moved faster than the Milky Way's escape velocity.
- Edwin Hubble published his discovery that far away "nebulae" were galaxies along with "Hubble's Law"

$$v = H_0 D$$

# Cosmological Principle

- The universe is homogeneous and isotropic
- Implies that the energy-momentum tensor is similar to a fluid fluid
- Verified in 1964 with discovery of Cosmic Microwave Background
- Motivated Howard Robertson and Arthur Walker to find a general metric that meets the cosmological principle

$$d\tau^2 = -c^2 dt^2 + a(t)^2 [\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin(\theta)^2 d\phi^2]$$

# Friedmann Equations

- The "Friedmann" equations may be found from the Einstein field equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} \Rightarrow \begin{cases} H^2 = \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G \rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} \\ \frac{\ddot{a}}{a} = \frac{-4\pi G}{3} (\rho + 3P) + \frac{\Lambda}{3} \end{cases}$$

# Deceleration Parameter

- From the Friedmann equations, the "critical" density is derived. It is also beneficial to define density ratios and the equations of state.

$$\rho_c = \frac{3H^2}{8\pi G} \qquad \Omega_i = \frac{\rho_i}{\rho_c} \qquad w_i = \frac{P_i}{\rho_i}$$

- We can now write the deceleration parameter, especially in a matter dominated universe

$$q_0 = \frac{-\ddot{a}\,a}{\dot{a}^2} = \frac{-\ddot{a}}{aH^2} \qquad q_0 = \frac{1}{2}\sum_i \Omega_i (1+3w_i) = \frac{\Omega_m}{2}$$

# Measuring Cosmological Distances

- If we know the intrinsic luminosity of an astronomical object, the luminosity distance can be determined through the formulae

$$d_l = \sqrt{\frac{L}{4\pi l}}$$

$$z = \frac{\Delta\lambda}{\lambda} = \frac{a(t_0)}{a(t)} - 1$$

$$d_l(z; H_0, \Omega_m, \Omega_\Lambda) = \frac{1+z}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

# Standard Candle

- Type Ia supernovae suspected as good candidates in 1938
- Extremely bright and can be observed over a period of weeks
- Physical features are nearly uniform


Figure 1: Type Ia supernova

# Saul Perlmutter

- Supernova Cosmology Project (SCP) started in 1988
- Digital Image Subtraction
- Supernova on Demand
- Observed 42 Type Ia supernovae

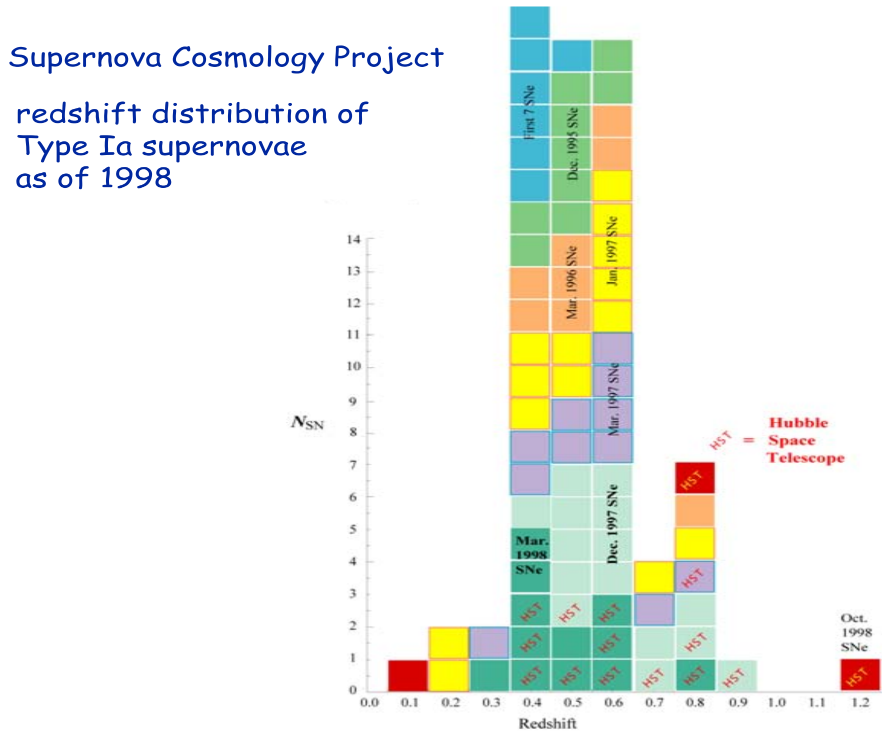
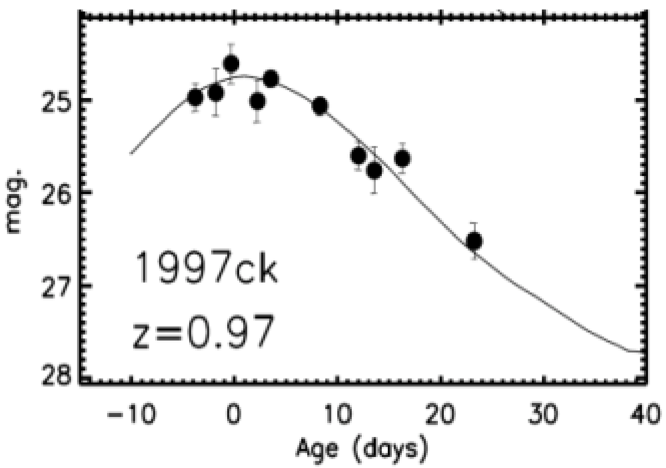


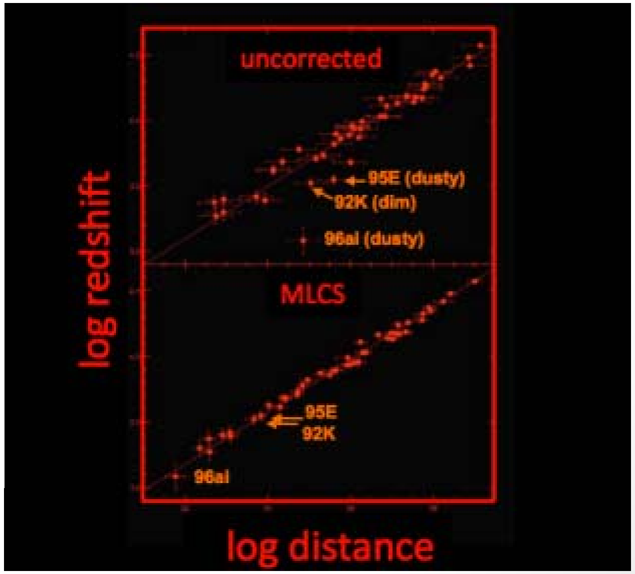

Figure 2: Histogram of supernovae discovered according to redshift

# Brian Schmidt and Adam Riess

- High-z Supernova Search Team (HST) formed in 1994
- 16 Type Ia observations published around same time as SCP with more signal per object than SCP
- Multicolor Light Curve Shape
- "Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant" in 1998

(Left) Figure 3: Example of light curve for a supernova




(Right) Figure 4: Multicolor Light Curve Shape

# Results

- If universe was matter dominated, results should have been ~25% brighter
- The calculated deceleration parameter was negative
- The cosmological constant must drive the acceleration of the universe

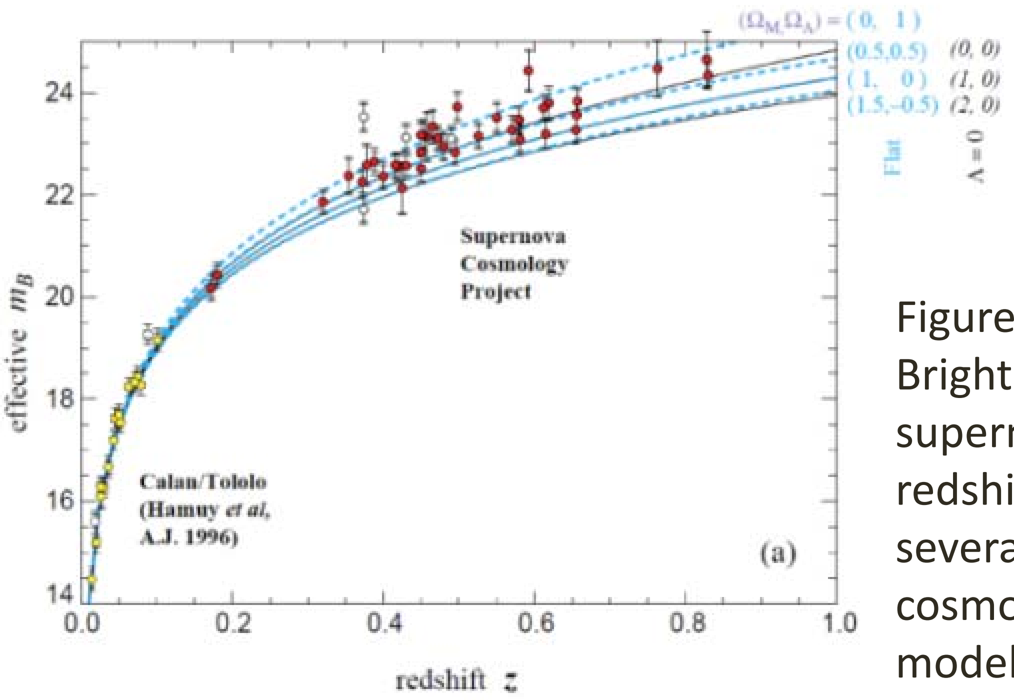



Figure 5: Brightness of supernovae vs. redshift fit to several cosmological models

# Results

- Georges Lemaître suggested a vacuum energy as early as 1934
- Particle physics suggests that vacuum energy is the result of quantum fluctuations and spontaneous symmetry breaking
- Results also suggest a flat (k=0) universe that underwent an early period of inflation
- Early universe (z>1) seems to slow down as originally predicted

# Future work

1. What is the source of dark energy?

2. Why are the mass densities on same order?

1. Is General Relativity a sufficient theory?

# References

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