

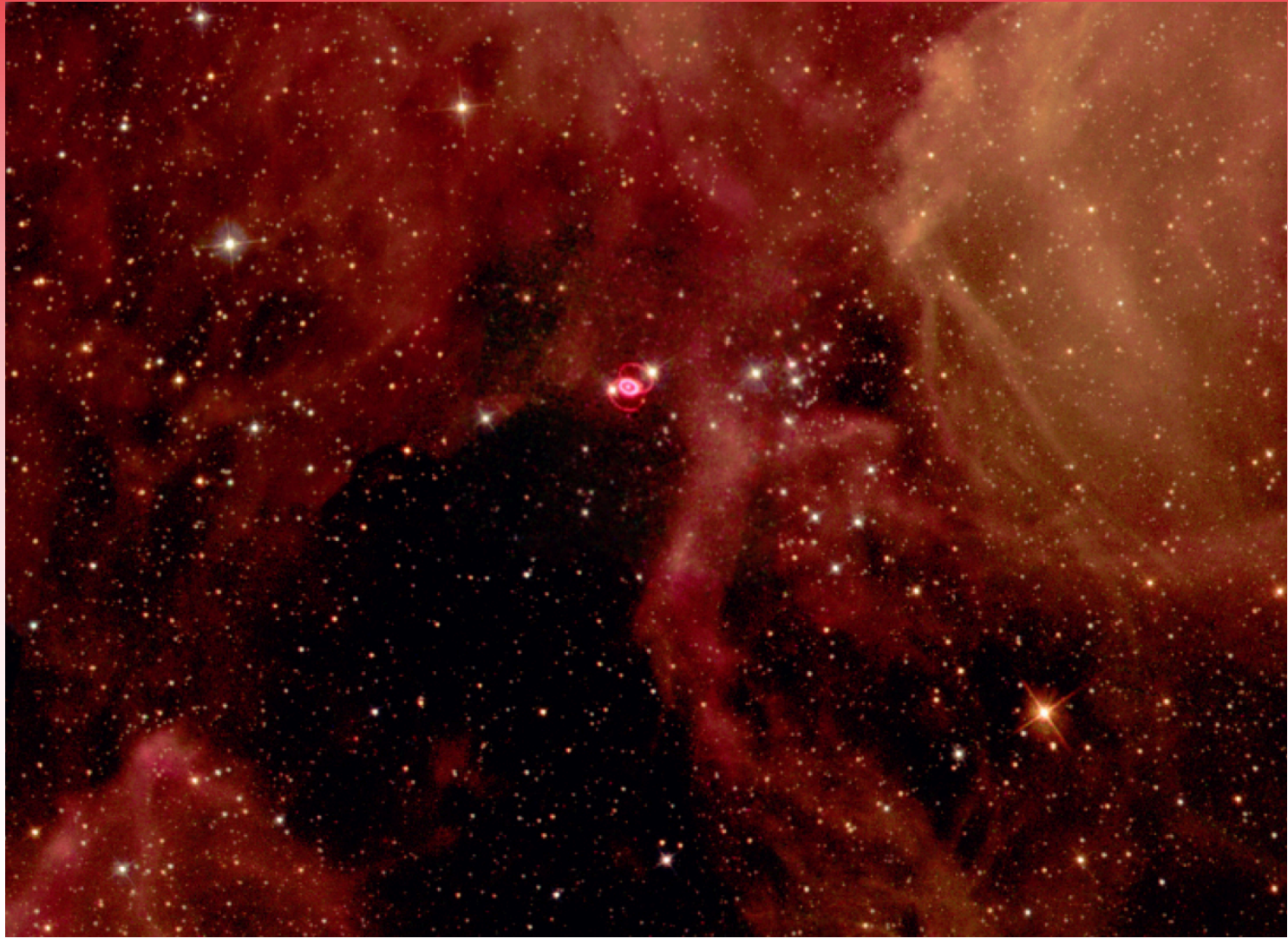
# Type Ia Supernovae, and the High-Z Supernovae Search

## *The Evidence for Dark Energy*

*Physics 090*

*2020-05-15*

# Review Supernovae

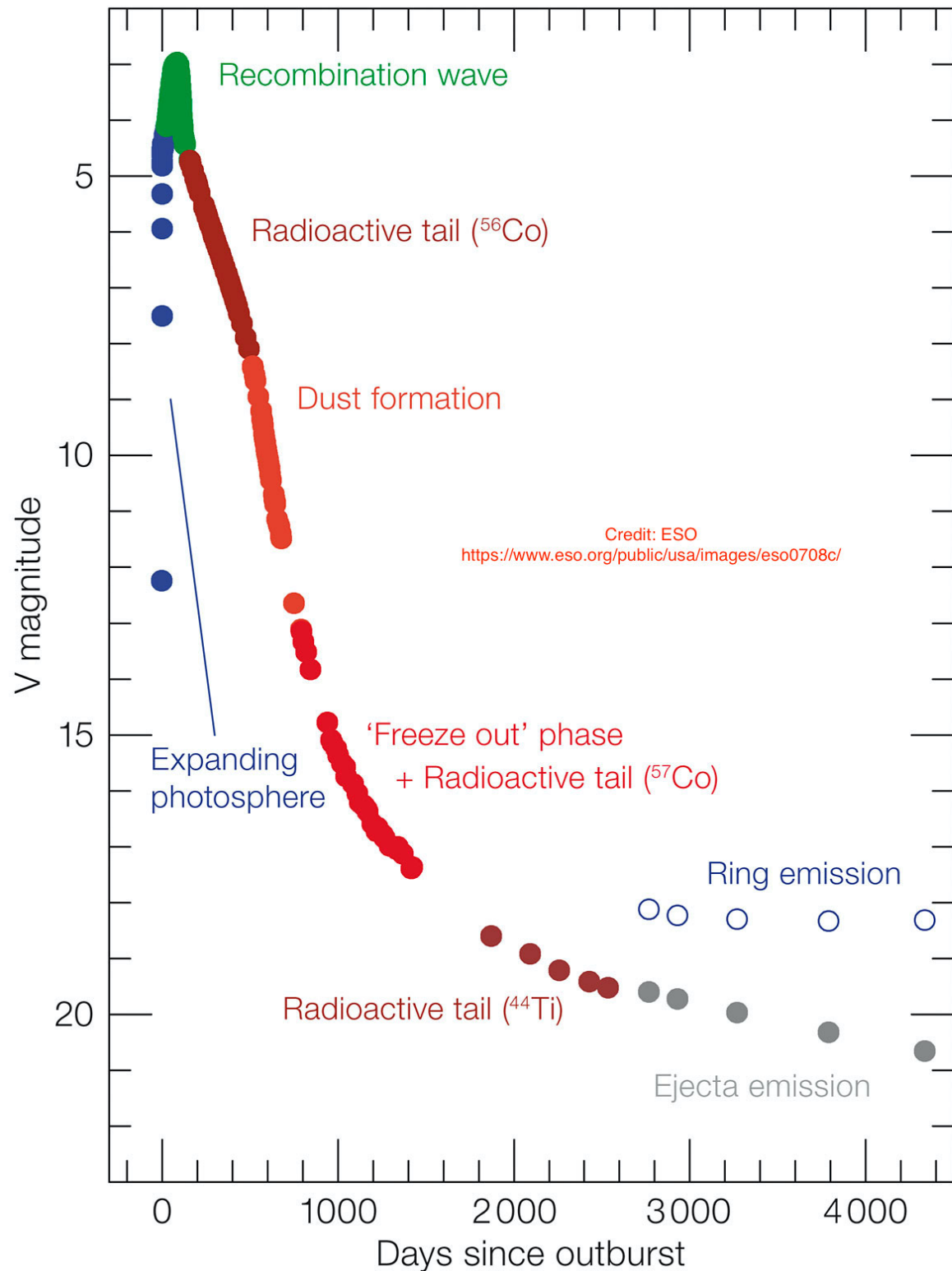


Hubble Space Telescope Image  
Supernova 1987A in Large Magellanic Cloud

# Light Curve

## Supernova 1987A

European Southern Observatory



# Another Kind of Supernova

Secondary star



Primary star



Main-sequence star



Red giant



Main-sequence star



White dwarf



Red giant



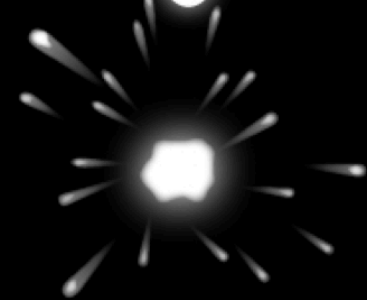
White dwarf



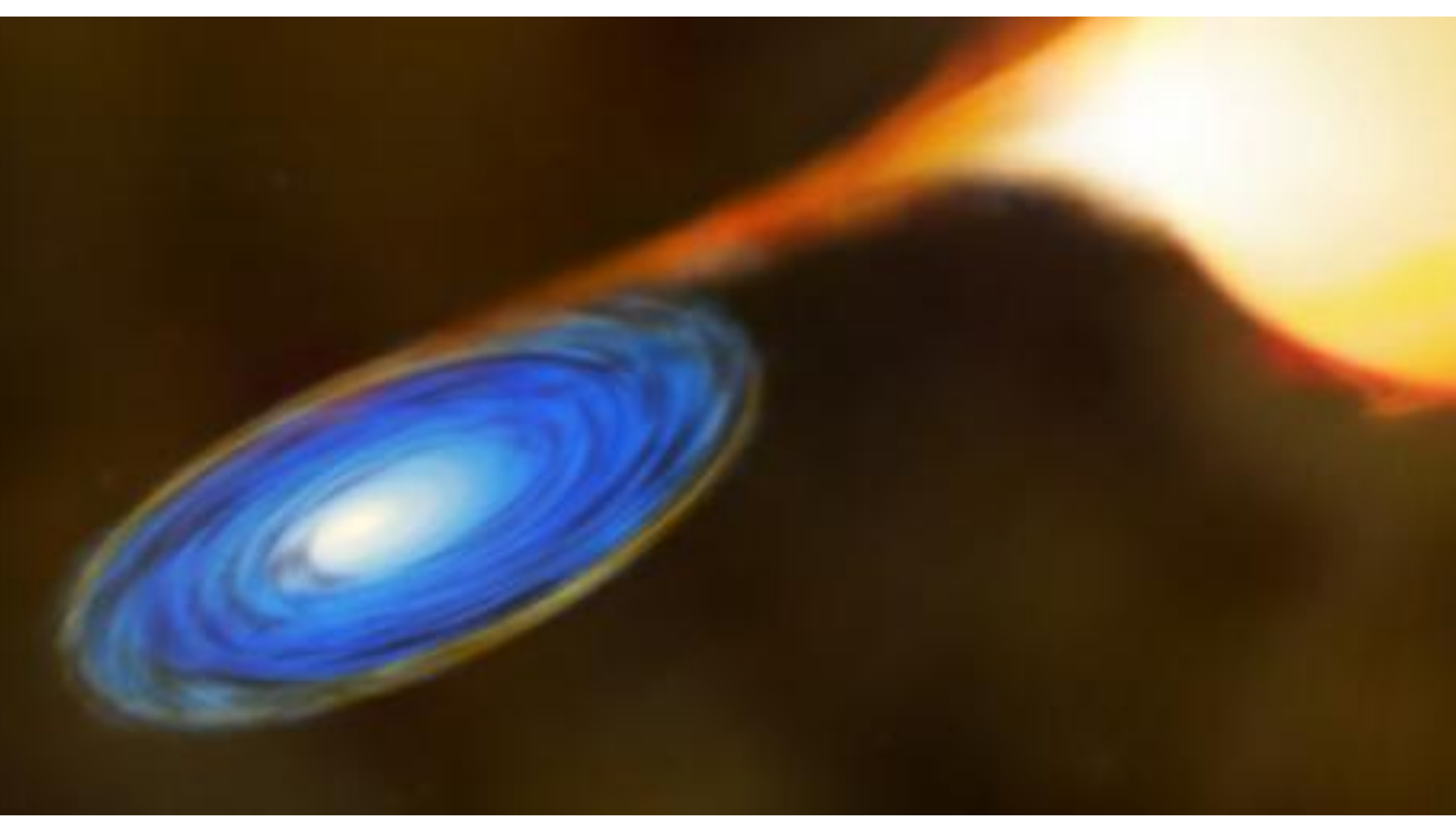
Red-giant remnant



Type Ia supernova



*Not to scale*



## Red Giant "Feeding" a White Dwarf

Harvard Center for Astrophysics, <https://www.cfa.harvard.edu/news/2011-04>

# Review Hubble Plot



## Doppler Shift

$\lambda$ =wavelength

$f$ =frequency

$o$ =observed

$s$ =source

$$\beta = v/c$$

$v$ =velocity of source

$c$ =speed of light

$z$ =fractional shift in  
wavelength

$$\frac{\lambda_o}{\lambda_s} = \frac{f_s}{f_o} = \sqrt{\frac{1 + \beta}{1 - \beta}},$$

and the resulting redshift

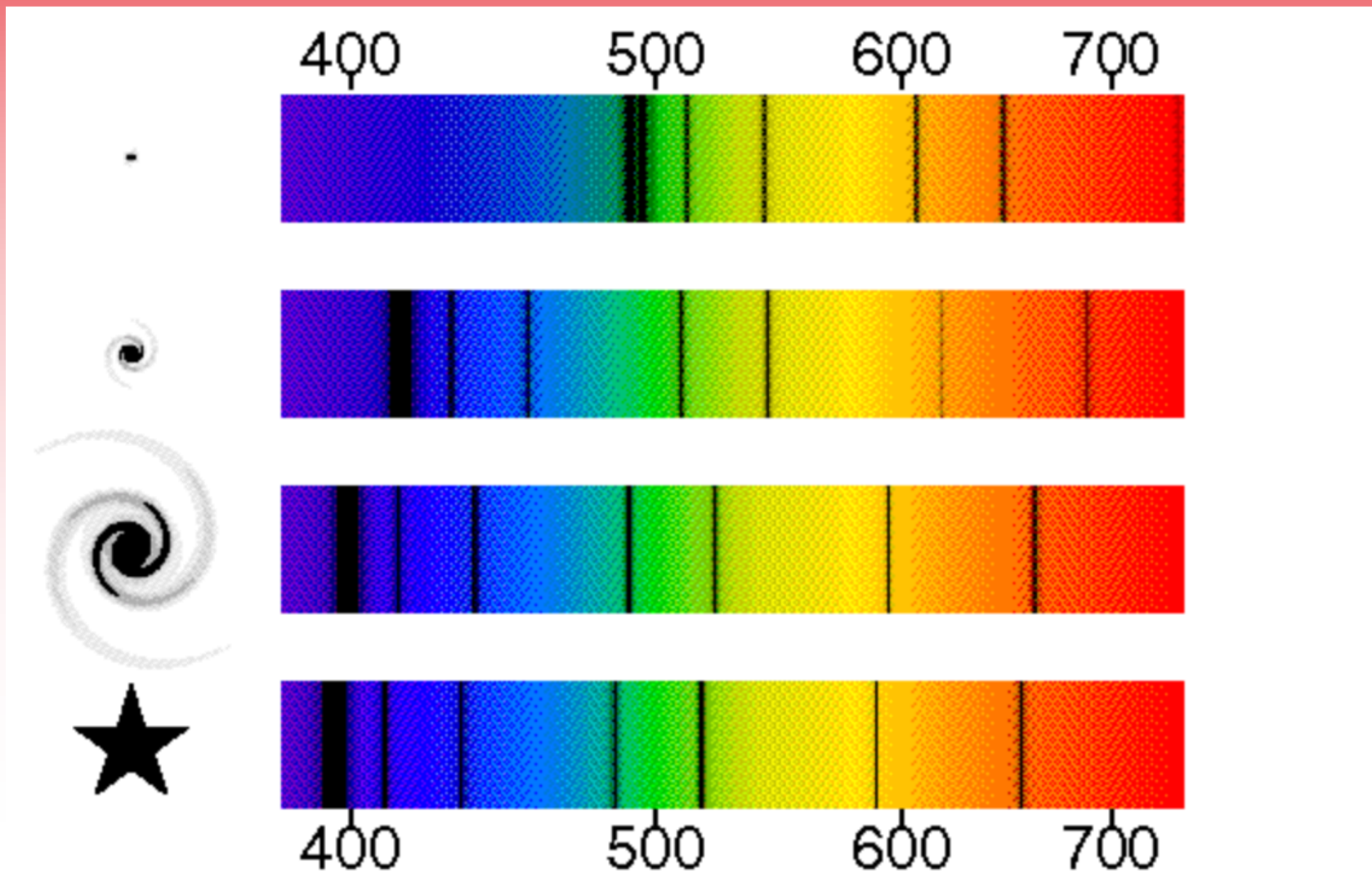
$$z = \frac{\lambda_o - \lambda_s}{\lambda_s} = \frac{f_s - f_o}{f_o}$$

can be written as

$$z = \sqrt{\frac{1 + \beta}{1 - \beta}} - 1.$$

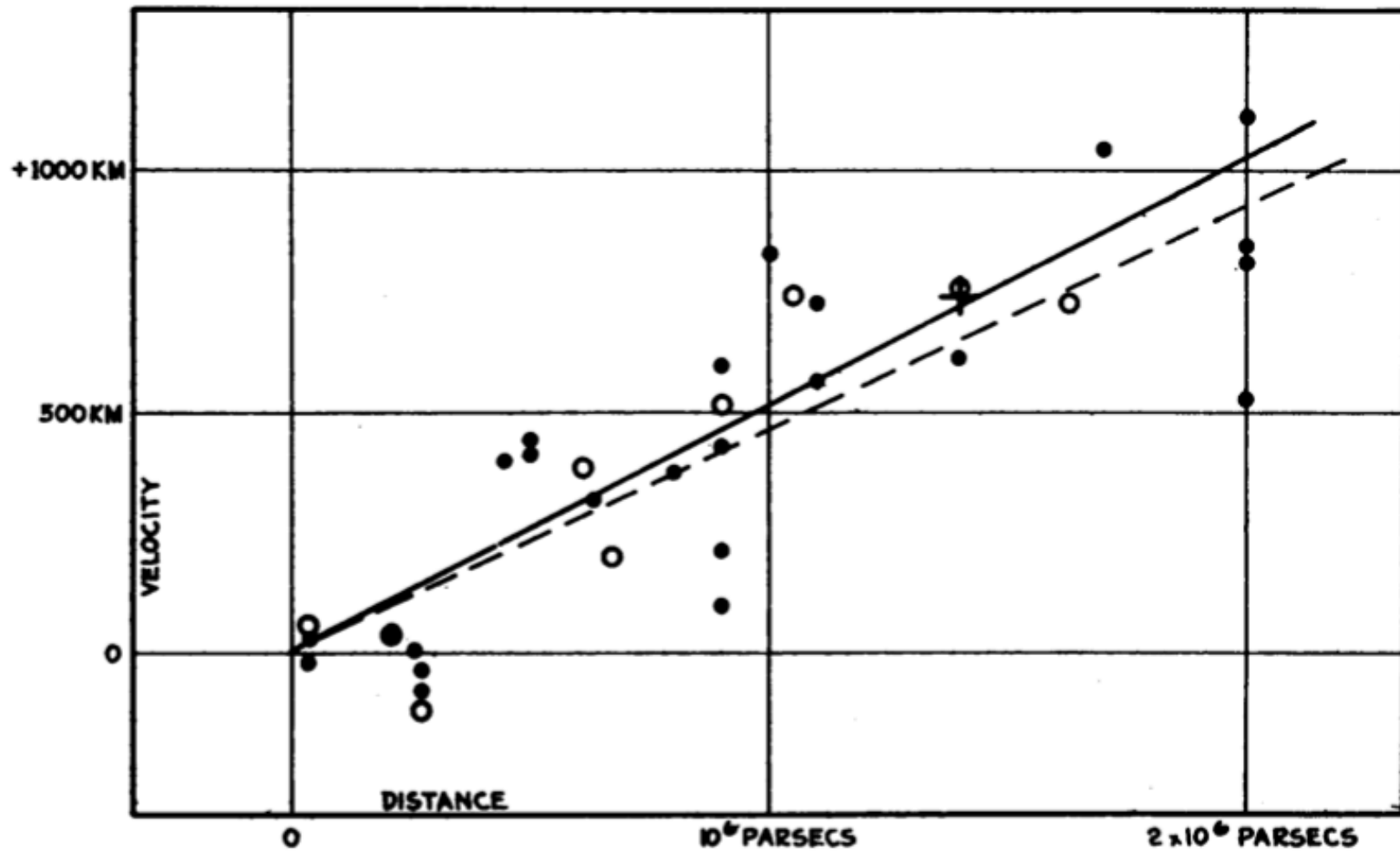
In the non-relativistic limit (when  $v \ll c$ )

$$z \simeq \beta = \frac{v}{c},$$



Doppler Shift is how Hubble Knew how Fast the Spiral Nebula were Moving Away

Cepheid Brightness is How he Knew How Far Away they Were

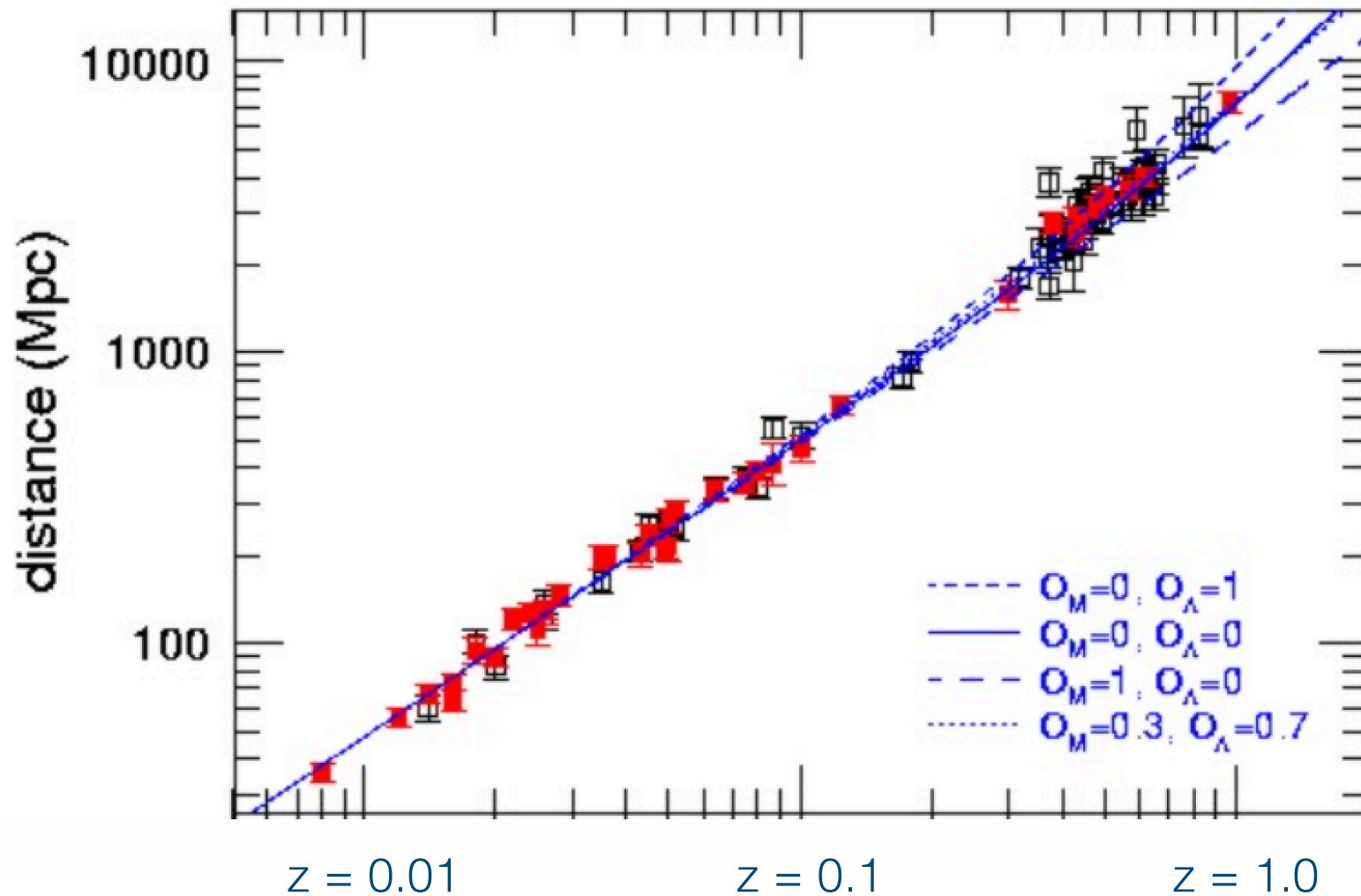


Hubble, 1929

Type Ia Supernovae

The New Standard Candle

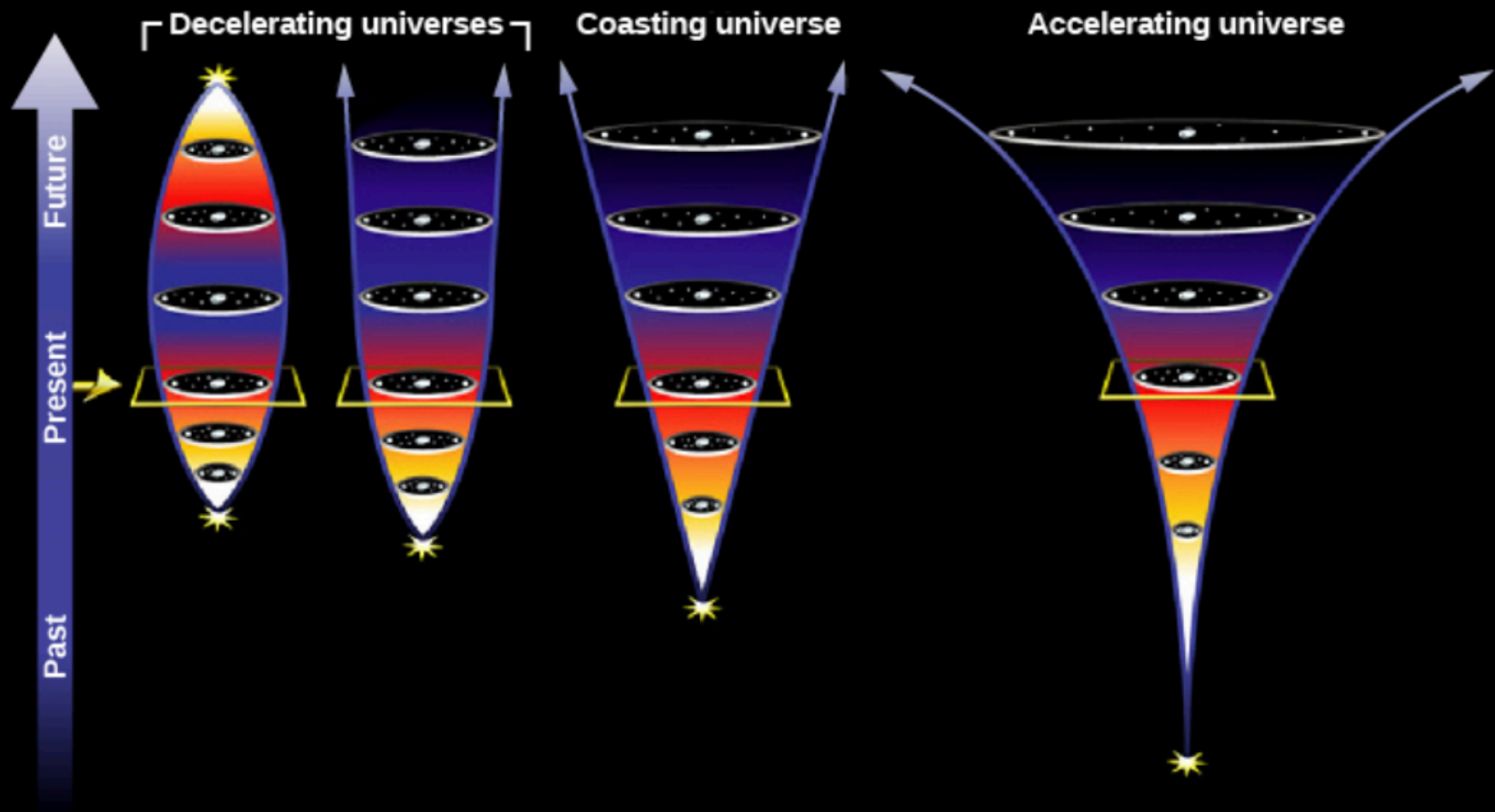
# A New and Better Hubble Plot

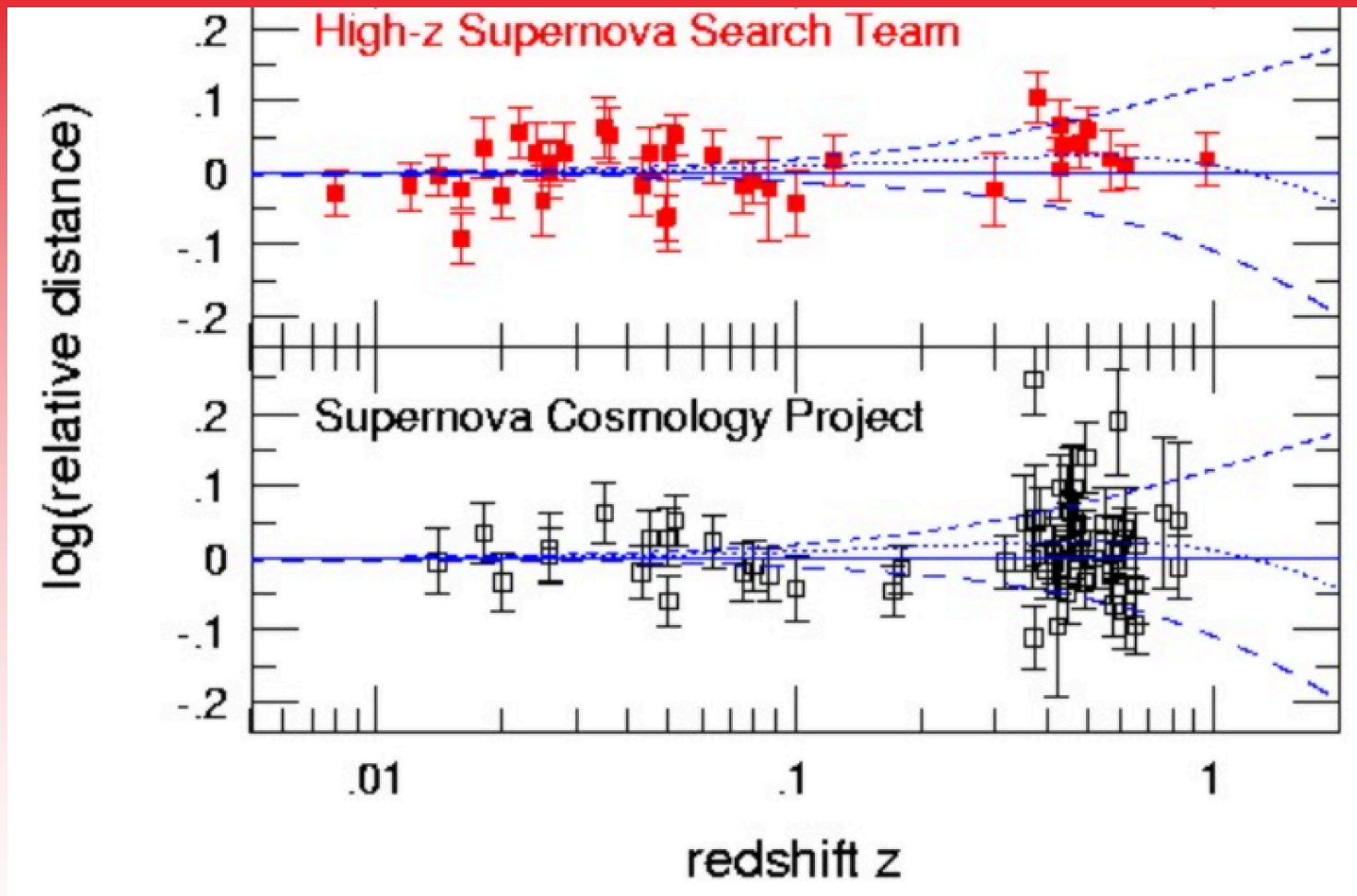


Combined Results:

High-z Supernova Search Team (red)  
Supernova Cosmology Project (black)

# Models of Expansion

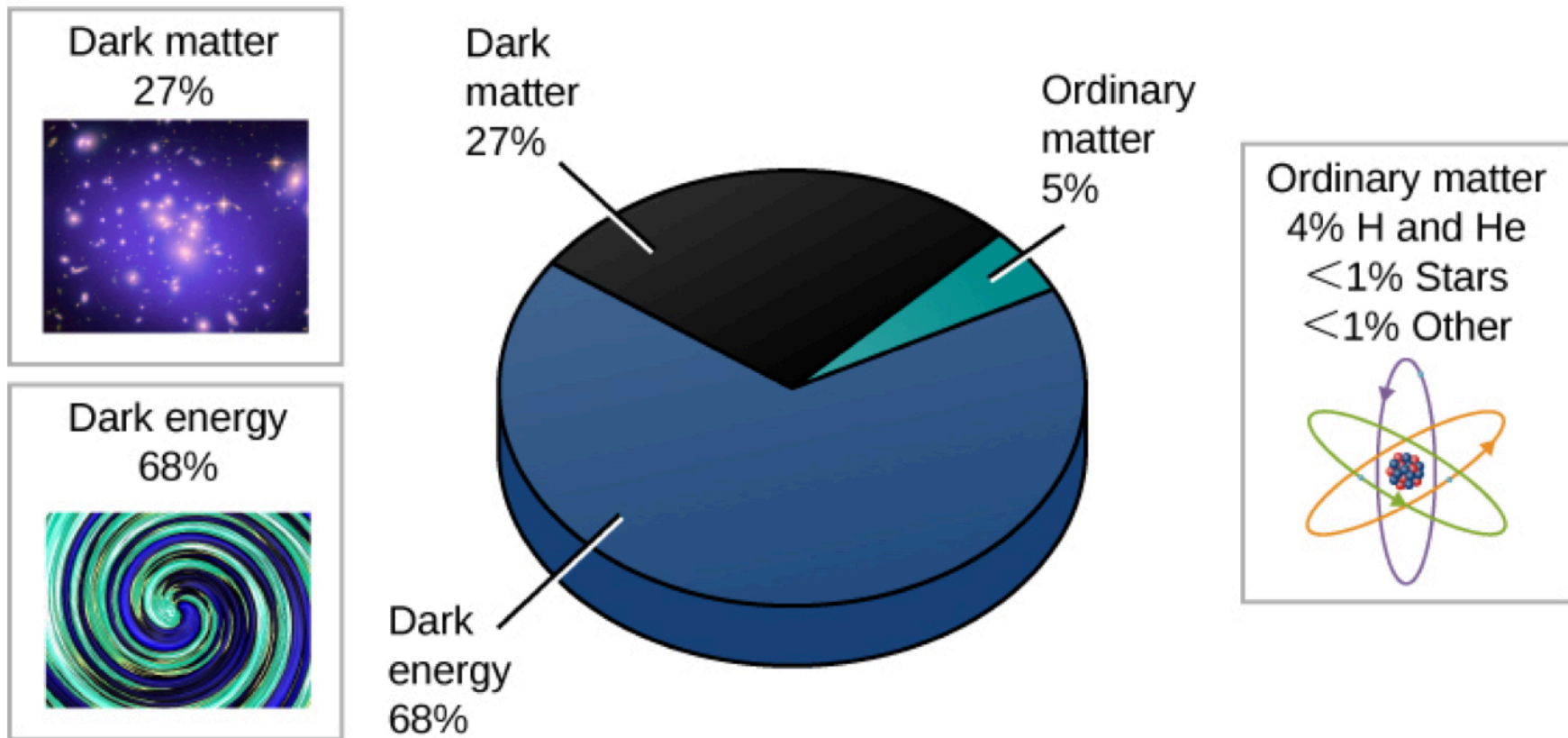




Best Fit to Data is the Dotted Line  
Ordinary Matter + Dark Matter = 30%  
*Dark Energy = 70%*

*2011 Nobel Prize, Perlmutter, Berkeley, Supernova Cosmology Project, Schmidt and Riess, High-z Supernova Search Team*

## Composition of the Universe



Best Estimate today: 5% Matter we understand, 27% dark matter, 68% Dark Energy



## Overall Unit 1 Outline (from [Syllabus](#))

- Unit 1: Coordinates, Magnitudes, The Motion of the Sun (Daily, Annual, Millennial), Frequency, Waves, Light, Color, Temperature, Geometrical Optics, Telescopes.
  - Note: The Geometrical Optics and Telescopes part of this unit will be covered in the Physics 91 labs over the course of the semester. In class we will focus on the other topics above.

## Unit 1 Detailed Topic List

- 2020-02-10: Latitude and Longitude. Degrees, Minutes, and Seconds of Arc. First Point of Aries (in Pisces!). Handout: [Latitude-Longitude Handout](#).
- 2020-02-12: Description of Solstices, Equinoxes, Ecliptic. Right Ascension, Declination. Hours, minutes, and seconds of right ascension. Handout: [Right Ascension, Declination, and the Ecliptic](#).
- 2020-02-14: Explanation of The Sun's Daily Motion, Annual Motion, and Millennial Motion, The Ecliptic and the Zodiac. Handout: [The Sun's Motions Explained](#). Animation: [Pixzul's Zodiac Animation](#).
- 2020-02-17: [Tycho Brahe's Observatory](#). Altitude. Converting Altitude to Declination. Measuring Right Ascension with a sidereal clock. Solar vs. Sidereal Day. Sidereal clock runs four minutes fast per day. Textbook Pages 114-117: [Solar vs. Sidereal Day](#). Demonstration with Partners: 4 spins during one orbit yields 3 high noons.
- 2020-02-19: Scheduling of leap years. 366.24 spins of the Earth in one orbit around the Sun yields 365.24 solar days. Powers of 10 Reviewed. Scientific Notation Reviewed. Prefixes k, M, G, T. Magnitude (aka "Apparent Magnitude", in the next unit we will get to "absolute magnitude"). Handout: [Introducing the Magnitude System](#).
- 2020-02-21: Completely optional, hopefully fun and relevant topic: the Richter Scale. Reference I use: [Spence, Sipkin, Choy, USGS, 1989](#).
- 2020-02-21: More Magnitude Formulas, Period and Frequency, Wavelength of Waves, the Speed of Light in terms of Frequency and Wavelength. HW3 handed out 2020-02-21, due 2020-02-24: [Magnitude and Frequency Homework](#) (includes key formulas from lecture).
- 2020-02-24: The Electromagnetic Spectrum. Human Eye and Visible Light. Reddish, White, and Bluish Stars. Color Temperature. Cool Stars, Hot Stars. Handout: [Waves, Light, Color of Stars](#).
- 2020-02-26: Fahrenheit, Celsius, and Kelvin Scales. Absolute Zero. Black-body Spectrum and Wien's Law (the [Wikipedia Entry for Wien's Law](#) is very good). Handouts: [Practice With Frequency and Waves](#), [Practice With Temperature](#). Start [Unit 2](#).
- 2020-02-28: [Unit 1 Exam](#). [Unit 1 Exam Solution](#).
- 2020-03-02: Start [Unit 2](#).

## Overall Unit 2 Outline (from [Syllabus](#))

- Unit 2: The Motions of the Earth, the Moon and the Planets. The scale of the Solar System. Kepler's Laws.
  - Note: A recurring theme in this unit...: In astronomy, objects are usually so big that you cannot get a tape measure very far around them. Or so far away that you have no hope of stretching a tape measure to them. How could you measure such circumferences or distances? Crafty use of trigonometry (straight lines, angles and triangles) is the recurring answer. In later units we will show astronomers' other crafty tricks.

## Unit 2 Detailed Topic List

- 2020-02-28: [Unit 1](#) Exam.
- 2020-03-02: An introduction to Ptolemy's (Earth-centered) view. The motion of the Moon (including the names of the phases). The way the Moon being lit by the Sun results in the various shapes (full, gibbous, crescent). The lunar orbit of 27.3 days ("sidereal lunar cycle" one lunar orbit) vs. the lunar month of 29.5 days ("synodic lunar cycle", time between new moons). Slides: [Ptolemaic Model](#), [Moon Phases](#). YouTube Animation: [Ptolemaic Model](#), [Epicycles](#). Textbook Section 4.5: [Moon Phases](#).
- 2020-03-04: Solar and Lunar Eclipses (Including Umbra, Penumbra, Relation to Phases of Moon). Slides: [Eclipses](#). Retrograde Motion as Explained by the Copernican Model. Construction: [Mars Retrograde](#). Textbook Section 4.7: [Eclipses](#).
  - Note: The coming retrograde of Mars will last from Sep. 10 to Nov. 14 per [AAPS Space](#), an astrology website.
- 2020-03-06: Circumference and Area of a Disk. Circumference, Surface Area, and Volume of a Sphere. The Pie Crust Formula. Construction: [Aristarchus Size of Moon](#).
- 2020-03-09: Construction: [Eratosthenes Size of Earth](#). Table: [Solar System Sizes and Distances](#). Lawn-Sized Scale Model of the Solar System.
- 2020-03-11: Video: [Black Rock Desert Scale Model](#) of the Solar System. Kepler's 1st Law. Properties of Ellipses. Textbook Section 3.1: [Kepler's Laws](#).
- 2020-03-13: Kepler's Second Law. The Astronomical Unit. Example: Earth's Maximum Speed from Minimum Speed and Eccentricity. Kepler's Third Law. Examples: Find P given a, or find a given P. Slides: [Kepler's 2nd and 3rd Laws](#).
- 2020-03-16: Start [Unit 3](#).
- 2020-03-18: [Unit 2 Exam](#). [Unit 2 Exam Solution](#).

## Overall Unit Outline (from [Syllabus](#))

- Unit 3: Newton's Law of Universal Gravitation — The Composition and Properties of The Sun and the Planets.

## Unit 3 Detailed Topic List

- 2020-03-16: Newton's Laws:  $F=ma$ . Mass. Density. Textbook Section 3.2: [Newton's Laws of Motion](#). Galileo's Version of Newton's First Law: [Salvatus and Sagredus Discuss Relativity](#).
- 2020-03-18: [Unit 2](#) Exam.
- 2020-03-20: Newton's Laws:  $F=G \frac{m_1 m_2}{r^2}$ . Textbook Section 3.3: [Newton's Universal Law of Gravitation](#).
- 2020-03-23: Mass, Volume, and Density of the Planets. Textbook Section 7.1: [Solar System Densities](#). Worksheet: [Solar System Densities](#). Javier's Worksheet Solution: [Solar System Densities](#).
- 2020-03-25: Energy and Power. Textbook Section 16.1: [Energy and Power](#). Example: [If the Sun Was Made of Coal](#), how long would it last?.
- 2020-03-27:  $E=mc^2$ . Textbook Section 16.2: [What Powers the Sun](#). Periodic Table. Binding Energy per Nucleon. Slides: [Fission, Fusion, Structure of the Sun](#).
- 2020-03-30: If the Sun Was Made of Hydrogen, how long would it last? Notes and Examples: [Elements, Fusion, and the Sun](#). Textbook Section 15.1: [Structure and Composition of the Sun](#). Luminosity. Intensity.
- 2020-04-01: Chemical Composition of the Planets. Reading Abundances Tables (Log Plot). Solar System Disk. What is Rock? Rocky Planets. Gaseous Planets. Slides: [Elements of the Solar System](#).
- 2020-04-03: Start [Unit 4](#).
- 2020-04-06 to 2020-04-13: Spring Break.
- 2020-04-15: Review of Unit 3. Summaries: [Gravitation Formulas and Examples](#) and [Energy and Power Formulas and Examples](#). Ocean Tides as Explained by Newton. Textbook Section 4.6: [Ocean Tides and the Moon](#). Kepler's  $P^2=a^3$  Explained by Newton. Derivation: Kepler's  $P^2=a^3$  from Newton.
- 2020-04-17: Unit 3 Exam.

## Overall Unit Outline (from [Syllabus](#))

- Unit 4: Other Stars and the Galaxy: Parallax Method. Astronomical Distance Scales (A.U., Light-Year, and Parsec). Hertzsprung-Russell Diagram. The Milky Way. Formation of Stars. Novae and Supernovae, Black Holes. Cepheid Variables.

## Unit 4 Detailed Topic List

- 2020-04-03. Slides: [Distances to Nearby Stars and The Parallax Method](#). The A.U., The Parsec, and The Light-Year. Pages from Textbook Sections 19.1 and 19.2: [The Parallax Method](#).
- 2020-04-06 to 2020-04-17: Spring Break, Review of [Unit 3](#), and Unit 3 Exam.
- 2020-04-20: Slides: [Hertzsprung-Russell Diagram](#) — Discovered.
- 2020-04-22: Hertzsprung-Russell Diagram — Applied. Worksheets: [Hertzsprung-Russell Diagram and The Milky Way Galaxy](#).
- 2020-04-24: Hertzsprung-Russell Diagram — Explained: I. Birth of Stars. Guest Lecture: [Prof. Aaron Lee](#). Slides: [Properties of Stars & Star Formation](#). Stefan-Boltzmann Law. Binary Star Systems. Star Formation from Interstellar Gas. Gravitational Contraction. Fusion Begins. Hydrostatic Equilibrium. Star Enters Main Sequence.
- 2020-04-27: Hertzsprung-Russell Diagram — Explained: II. Death of Stars. Slides: [Death of Stars. The Elements of the Solar System](#). Image: [Planetary Nebulae](#). Image: [Supernova Light Curve](#).
- 2020-04-29: Supernovae, Neutron Stars, Black Holes. Slides: [Supernovae and Neutron Stars](#) and [Observation of a Black Hole](#). Veritasium YouTube Video: [How to Understand the First-Ever Image of a Black Hole](#).
- 2020-05-01: Review of beginning of Unit 4 material. Review Worksheet: [Distance from Absolute Magnitude](#). Start [Unit 5](#). Cepheid Variable Stars.
- 2020-05-04: Unit 4 Exam.

## Overall Unit Outline (from [Syllabus](#))

- Unit 5: Other Galaxies and the Big Bang: The Magellanic Clouds. Leavitt-Pickering Period-Luminosity Relationship. Other Galaxies, The Big Bang. Dark Matter. Dark Energy.

## Unit 5 Detailed Topic List

- 2020-05-01 to 2020-05-04: Review of [Unit 4](#) material and Unit 4 Exam. Start Unit 5. Cepheid Variable Stars. Leavitt-Pickering Period-Luminosity Relationship. Magellanic Clouds. Pages from Textbook: [Variable Stars and Pulsating Variables](#). Leavitt 1908 Paper: [1777 Variables in the Magellanic Clouds](#). Leavitt-Pickering 1912 Paper: [Periods of 25 Variable Stars in the Small Magellanic Cloud](#).
- 2020-05-06: Hubble Discovers Cepheids in the Andromeda Galaxy and the Triangulum Galaxy. Slides: [Cepheid Variable Stars: From Leavitt to Hubble](#). Textbook Pages: [Galaxies](#). Hubble 1925 Paper: [Cepheids in Spiral Nebulae](#).
- 2020-05-08: Slides: [Discovery of the Big Bang: Hubble from 1925 to 1929](#). The Big Bang and Hubble's Law. Worksheet: [Understanding Hubble's Law](#). Textbook Pages: [Hubble's Law](#). Hubble 1929 Paper: [Distance and Radial Velocity Among Extra-Galactic Nebulae](#).
- 2020-05-11: Video: [The Doppler Effect](#). Textbook Pages: [The Doppler Effect](#). Worksheet: [Doppler Shift Examples](#). Slides: [The Early Universe and the Cosmic Microwave Background](#). The Early Universe: Creation of protons and neutrons; Creation of Hydrogen, Helium, and Lithium nuclei; Formation of Atoms. Matter and Radiation Decouple. Red Shift Formulas. Extreme Red Shift,  $z$ . The Cosmic Microwave Background (CMB): Theory, 1948; Observation, 1964; Nobel Prize: 1978. Textbook Pages: [The Cosmic Microwave Background](#).
- 2020-05-13: 21cm Line. Textbook Pages: [Interstellar Gas](#). Mapping the Milky Way. Galactic Rotation Curve. Missing Mass. Dark Matter. Slides: [Mapping the Galaxy, Missing Matter](#). Textbook Pages: [The Mass of the Galaxy](#).
- 2020-05-15: Supernovae in Binary Stars. Textbook Pages: [The Evolution of Binary Star Systems and Type Ia Supernovae](#). Review: Standard Candles and Hubble's Law. Type Ia Supernovae: The New Standard Candle. Dark Energy. 2011 Nobel Prize. Textbook Pages: [What is the Universe Made Of?](#) Slides: [Type Ia Supernovae, and the High-Z Supernovae Search](#).
- 2020-05-18: Final Exam.