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Chapter 11: Cosmology and the Origi of Structure

Our Evolving Universe

Robert Brandenberger McGill University

Fall 2021

Outline

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Chapter 10: Galaxies and

- 1 Ch. 1: Our Place in the Universe
- Ch2: Light and Matter
- 3 Ch. 3: Telescopes
- 4 Ch. 4: General Relativity
- 5 Ch. 5: The Quantum Revolution
- 6 Ch. 6: Our Sun
- 7 Ch. 7: Surveying the Stars
- 8 Ch. 8: Neutron Stars, White Dwarfs and Black Holes
- Our Galaxy
- 10 Chapter 10: Galaxies and Beyond
- 11 Chapter 11: Cosmology and the Origin of Structure

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Chapter 10: Galaxies and

Chapter 11: Cosmology and the Origi

- Overview of Astronomy: from the Solar System to the Cosmos
- Particular emphasis on Black Holes and Cosmology
- Physics Foundations to understand the Cosmos

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Our Galaxy

Chapter 10: Galaxies and Beyond

- Lectures focusing on the important concepts
 - Independent reading: Bennett, Donahue, Schneider and Voit, The Cosmic Perspective: Stars, Galaxies & Cosmology (Pearson)
 - Office hours (via zoom): TBA (see Outline on myCourses)
- Homework sets (roughly bi-weekly)
- Scientific poster project (instead of a midterm) (in groups)
- Final essay
- Final exam

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Grading Scheme

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Chapter 10: Galaxies and Beyond

Chapter 11: Cosmology and the Origi Homework sets: 35%

Poster project: 20%

Final essay: 15%

Final exam (3 hrs): 30%

My Research: Theoretical Cosmology

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Chapter 10: Galaxies and Beyond

- 1. Understand origin and early evolution of the universe.
 - What is the "Big Bang"?
 - Was there a "Big Bang"?
 - What was before the "Big Bang"?

Optical Telescopes: Gemini Telescope

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Galaxies: Building Blocks of the Cosmology

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Large-Scale Structure

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South Pole Microwave Telescope

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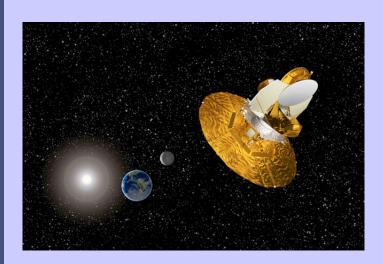
Chapter 11: Cosmology and the Origin



WMAP Microwave Telescope

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Isotropic CMB Background

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WMAP Map of the Cosmic Micrwave Background

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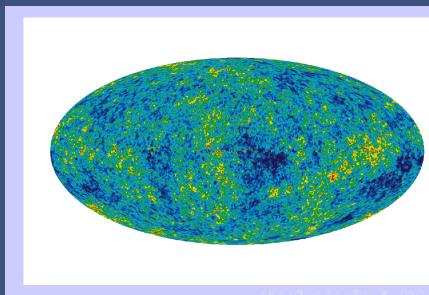
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History of the Universe

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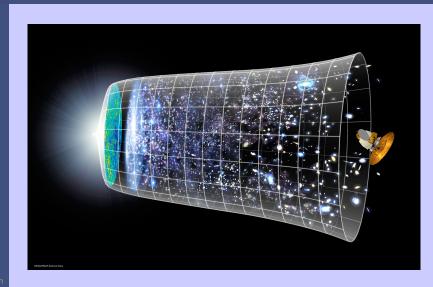
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Goals of Early Universe Cosmology

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Our Galaxy

Chapter 10: Galaxies and Beyond

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 - Was there a "Big Bang"?
 - What was before the "Big Bang"?
- 2. Explain observed large-scale structure.
 - Patterns in the distribution of galaxies on large scales.
 - Anisotropies in CMB maps.
- Make predictions for future observations

Goals of Early Universe Cosmology

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Chapter 10: Galaxies and Beyond

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- 3. Make predictions for future observations.

The Night Sky

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Chapter 10: Galaxies an Beyond



Our Solar System

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Our Galaxy

Chapter 10: Galaxies and

- Planets are part of our solar system.
- Planets orbit the sun.

Solar System: Sizes

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Solar System: Sizes and Distances

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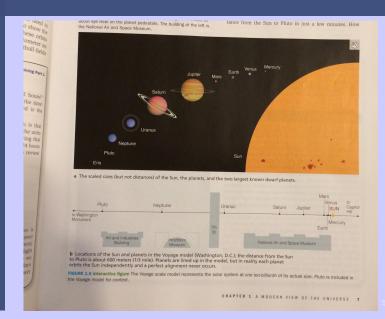
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Solar System: Distances

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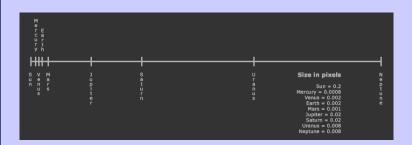
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How to determine distances within the solar system?

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Chapter 10: Galaxies and Beyond

Chapter 11: Cosmology and the Original How to determine distances within the solar system?

- Motion in the sky
- Parallax

How to determine distances within the solar system?

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How to determine distances within the solar system?

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Chapter 11: Cosmology and the Origi How to determine distances within the solar system?

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Parallax Method

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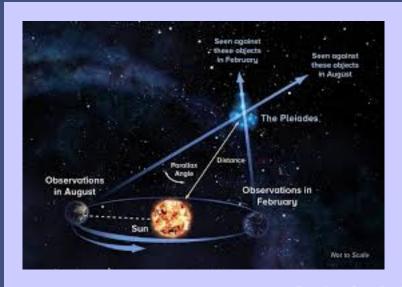
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The Night Sky

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Visible Spectrum

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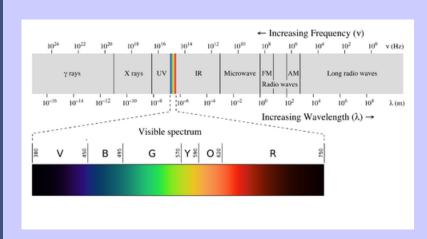
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Atmospheric Windows

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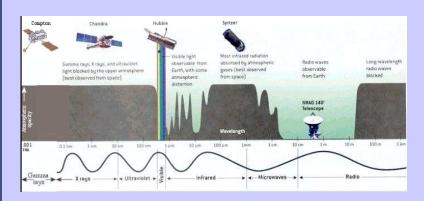
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Galaxy Magnitudes and Colours: HR Diagram

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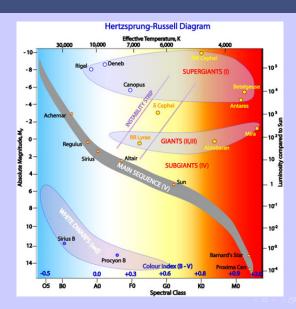
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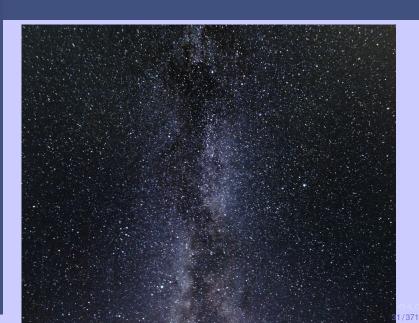
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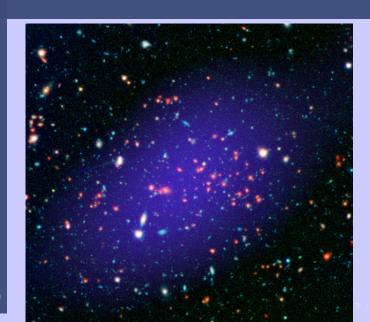
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Hubble Deep Field

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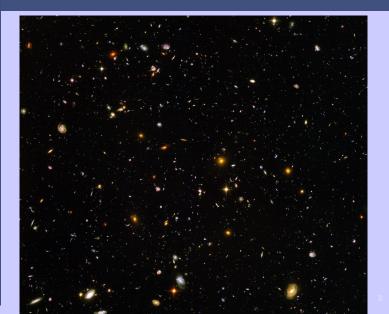
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Milky Way - Our Galaxy

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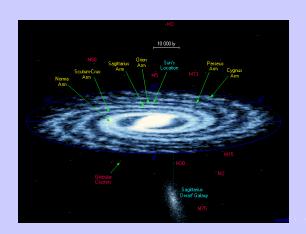
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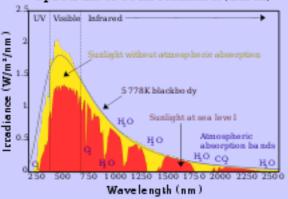
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Spectrum of Solar Radiation (Earth)



Hydrogen Spectrum

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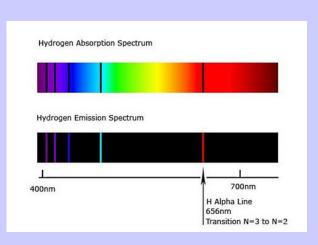
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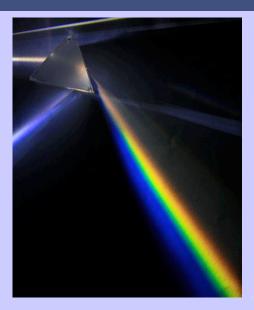
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Galaxy Spectrum

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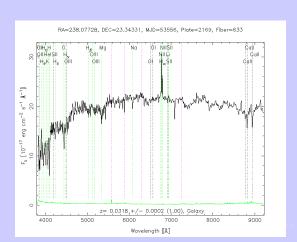
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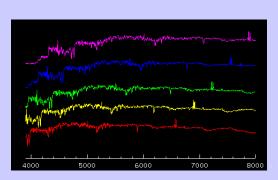
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Doppler Effect

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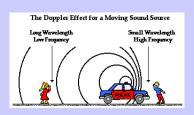
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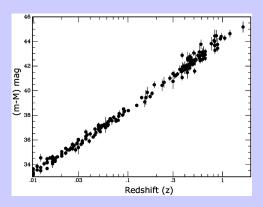
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The Expanding Universe

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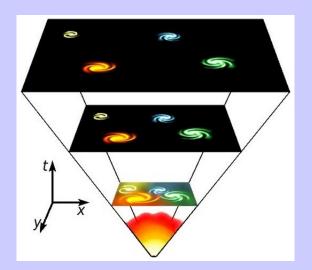
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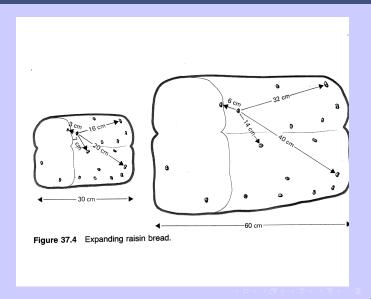
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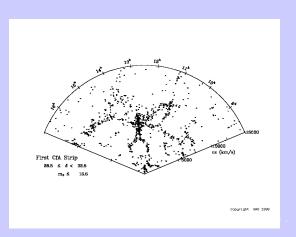
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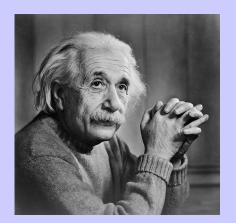
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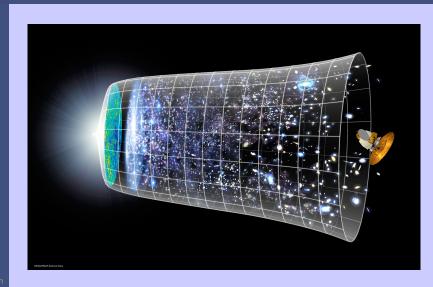
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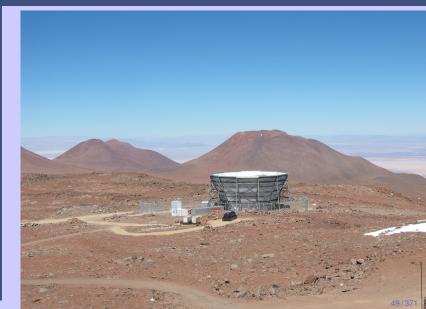
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Microwave Telescopes in Space: WMAP Telescope

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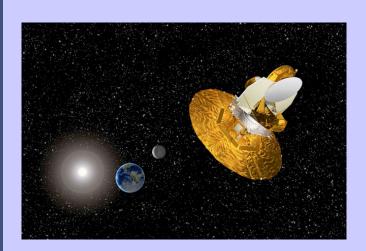
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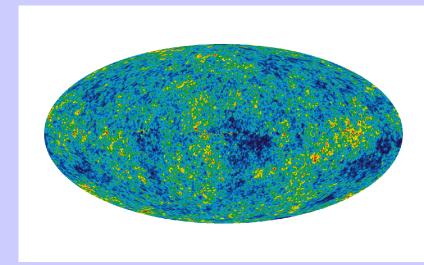
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Credit: NASA/WMAP Science Team

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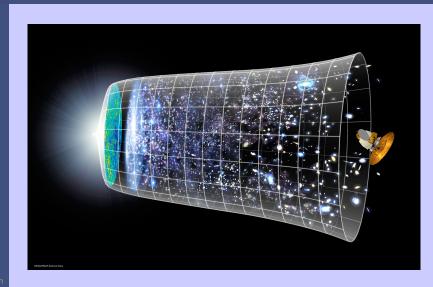
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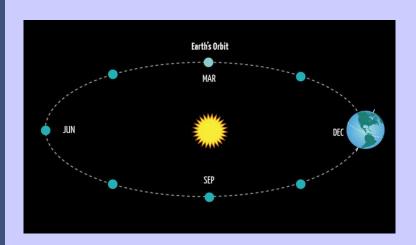
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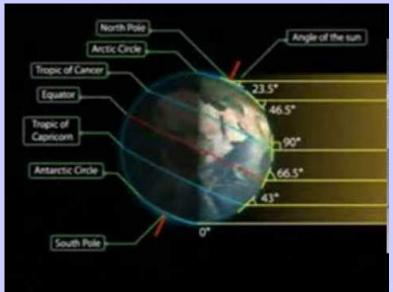
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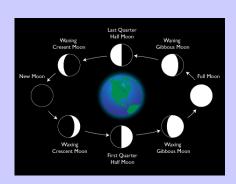
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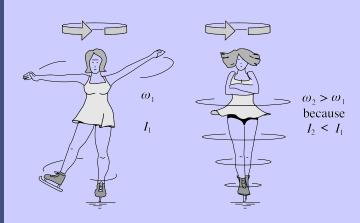
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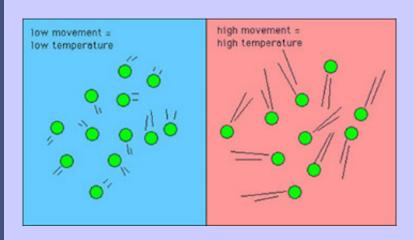
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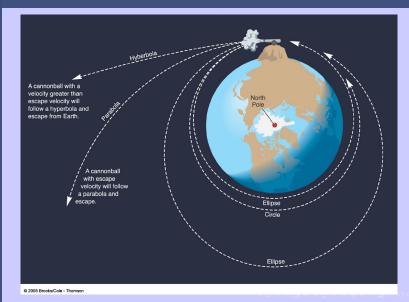
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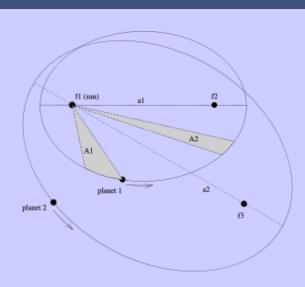
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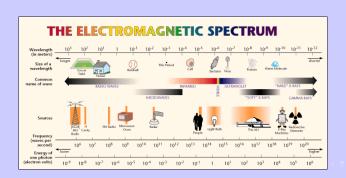
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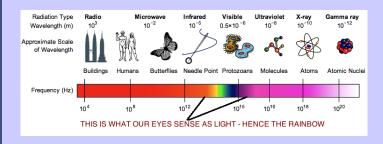
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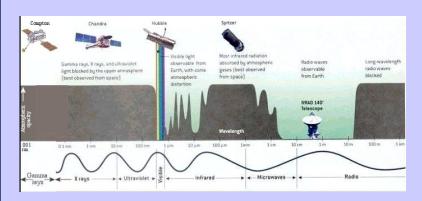
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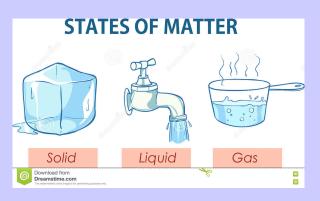
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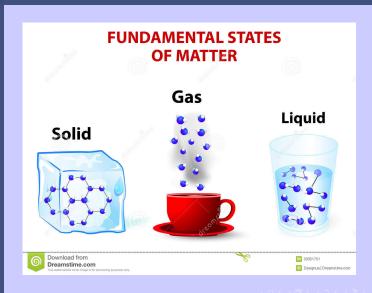
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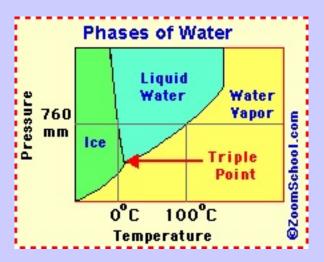
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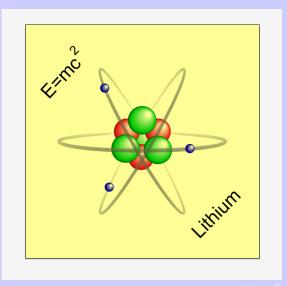
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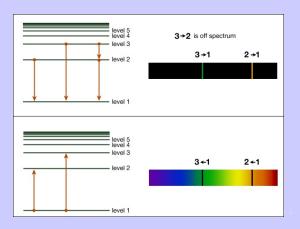
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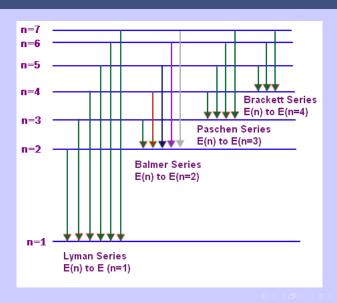
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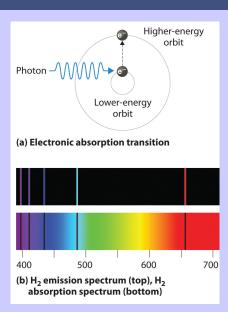
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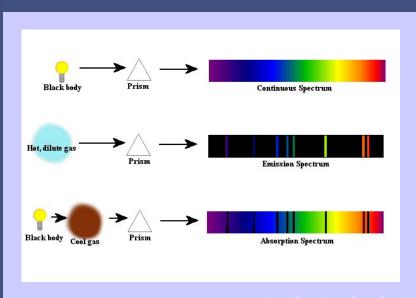
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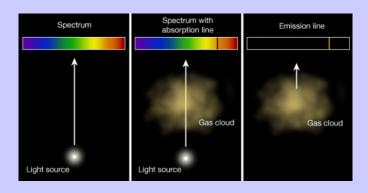
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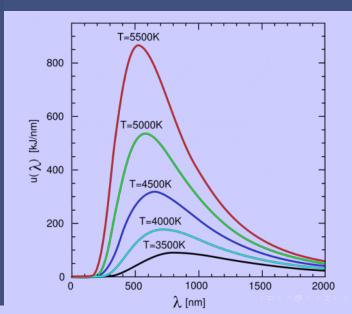
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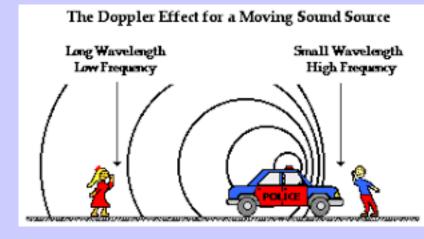
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Refraction of Sunlight

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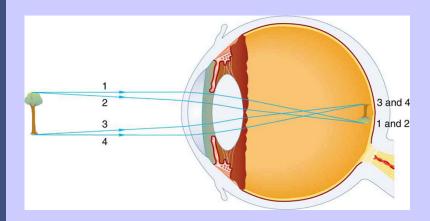
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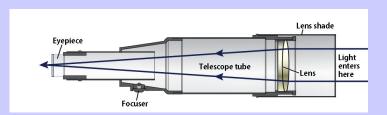
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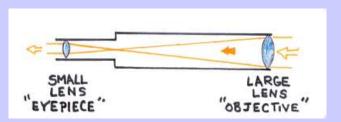
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### Reflecting Telescope

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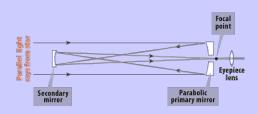
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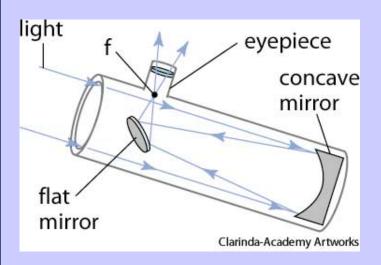
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#### Electromagnetic Spectrum

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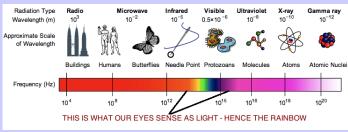
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## **Atmospheric Windows**

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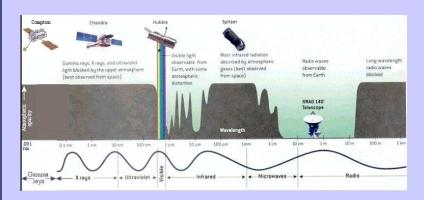
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#### Canada-France-Hawai Optical Telescope

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### Arecibo Radio Telescope

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### FAST Radio Telescope

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# CHIME 21cm Telescope

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### South Pole Telescope CMB Experiment

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#### WMAP CMB Satellite

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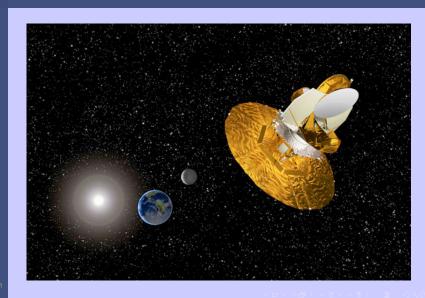
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### ALMA: Infrared Telescope Array

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# Hubble Space Telescope: UV and Visible

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### CHANDRA X-Ray Telescope

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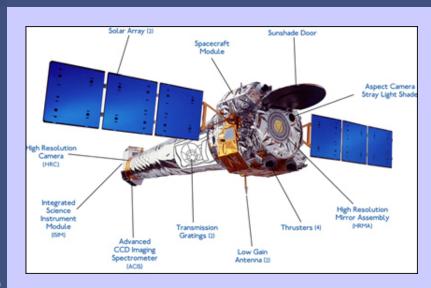
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### FERMI: Gamma-ray Telescope

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### **Curved Space**

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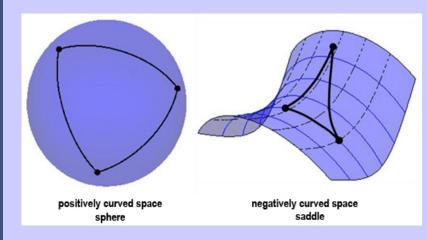
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# Mass curves Space-Time

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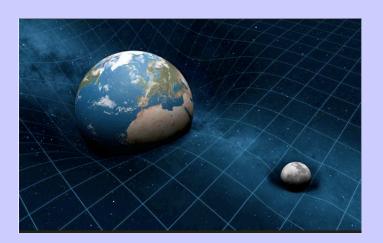
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#### Sun as a Black Hole

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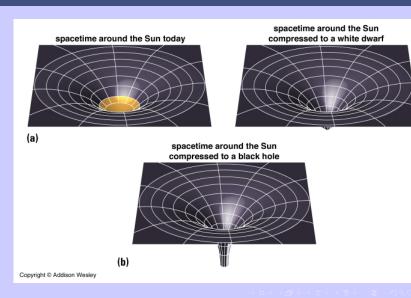
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### **Curved Space-Time**

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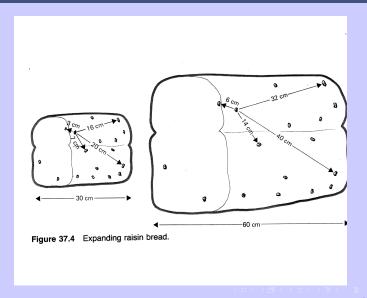
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### Geodesics on the Earth

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### Postdiction: Perhelion Precession of Mercury

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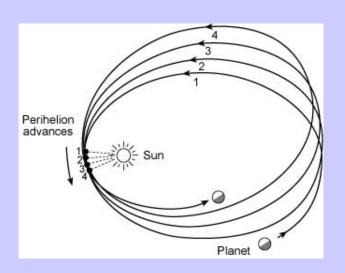
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### Prediction: Bending of Light

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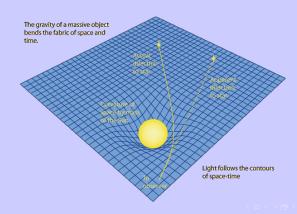
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### Prediction: Black Holes

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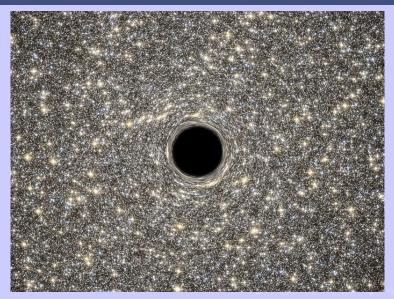
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### Prediction: Expansion of the Universe

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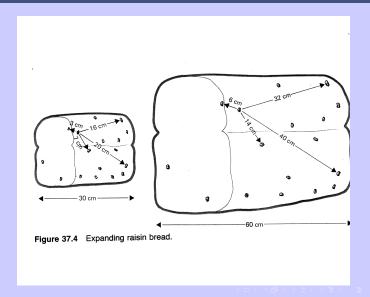
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### Prediction: Gravitational Waves Exist

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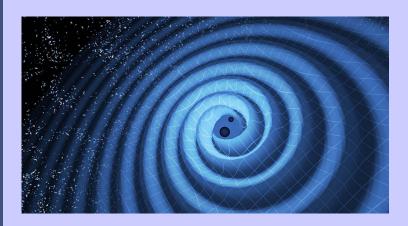
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#### LIGO Schematic

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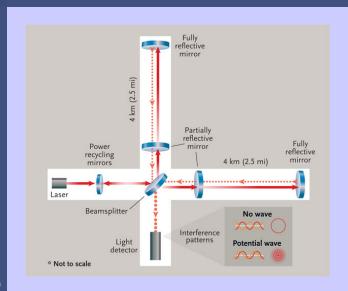
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#### LIGO Hanford Site

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### Binary Black Hole

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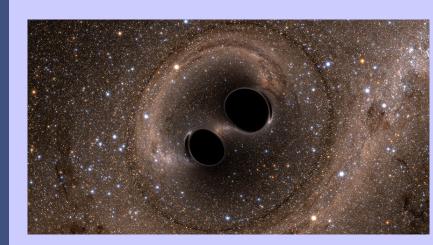
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### LIGO Event

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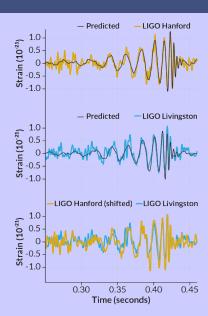
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### Principle of Gravitational Lensing

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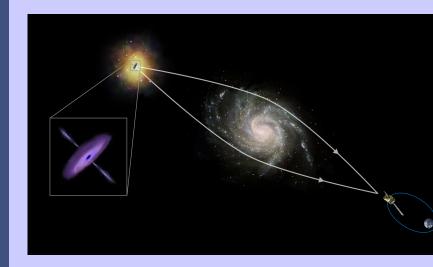
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### Gravitational Lensing Ring (Einstein Ring)

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### Gravitational Lensing (HST Picture)

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### Roemer: Determination of the speed of light

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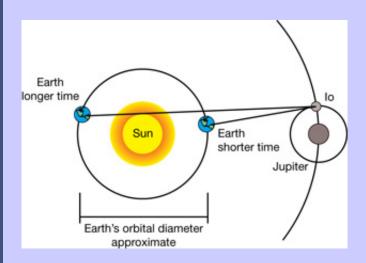
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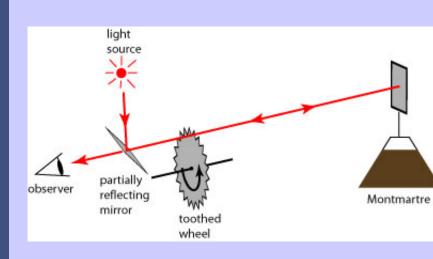


### Fizeau Experiment

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### Michelson-Morley Experiment

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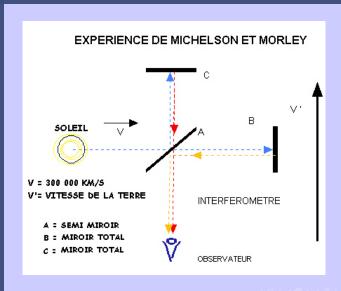
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### Length Contraction

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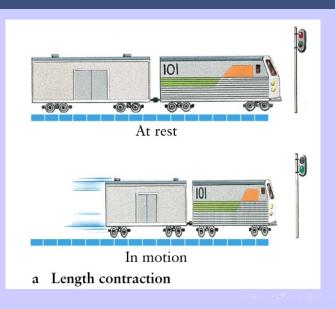
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#### **Ernest Rutherford**

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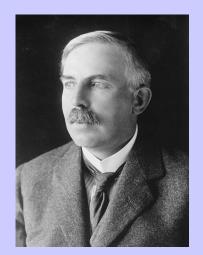
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#### Niels Bohr

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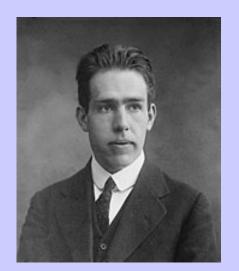
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#### Max Planck

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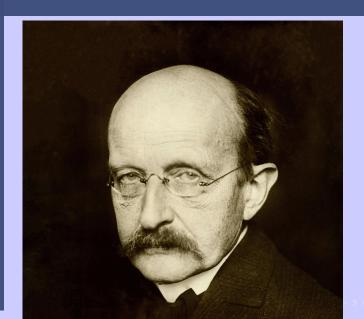
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# Erwin Schroedinger

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### Werner Heisenberg

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#### Marie Curie

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#### Bohr Model of the Atom

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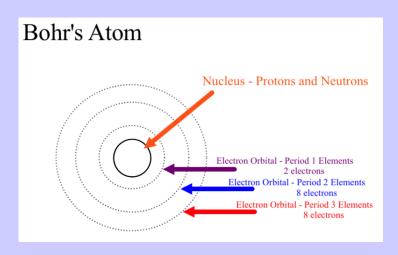
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## Spectrum of Hydrogen

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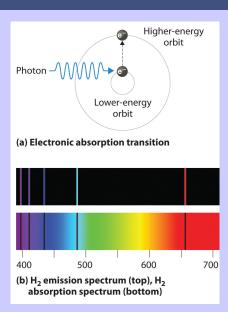
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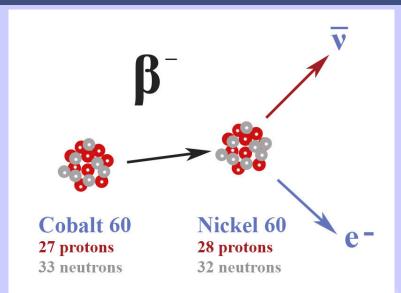
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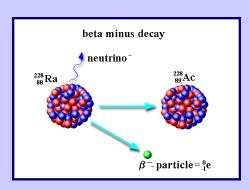
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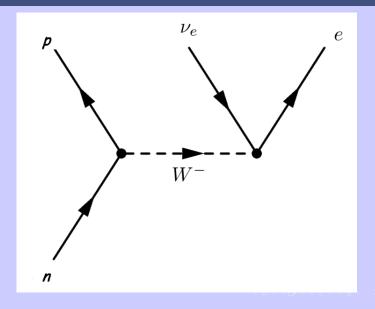
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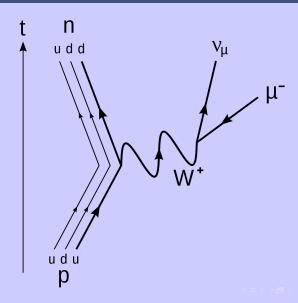
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## Standard Model of Particle Physics

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mūon

tau

# Hydrogen Wave Functions

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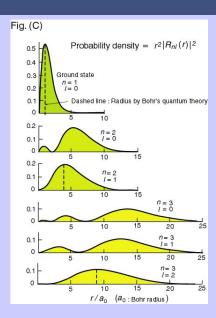
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## Hydrogen Wave Functions

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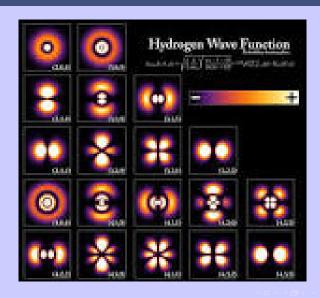
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### Fission vs. Fusion

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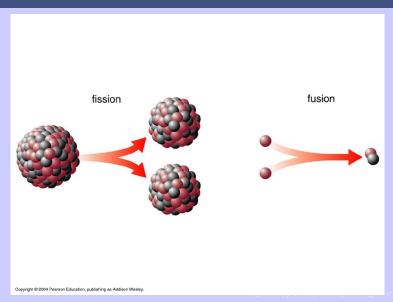
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## Solar Spectrum

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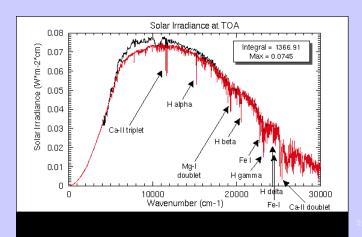
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### The Proton-Proton Fusion Chain

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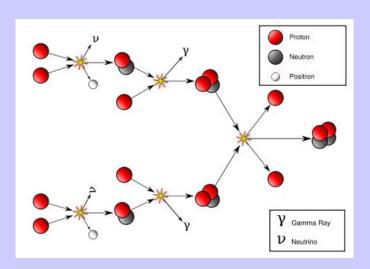
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#### Structure of the Sun

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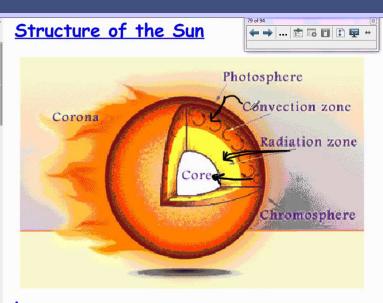
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## Temperature Profile of the Sun

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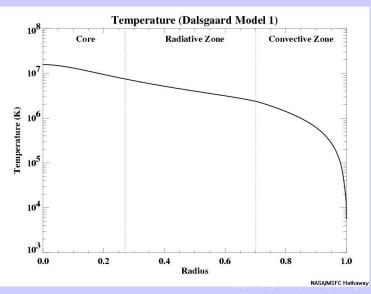
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## Radiative Zone

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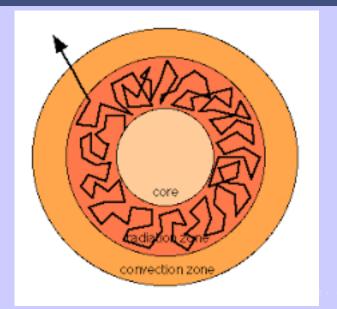
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## Convection

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#### Convection

The process of hot gas rising and cool gas sinking.

Since hot material radiates more light, the rising hot parts appear bright; since cool material radiates relatively less light, the sinking cool parts appear "dark".

# Hot gas rises.

Cool gas descends

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### Solar Thermostat

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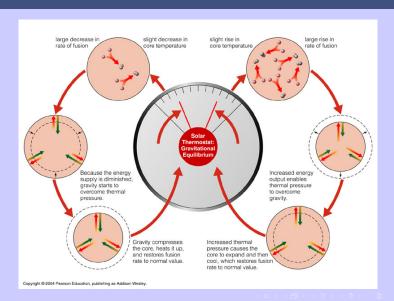
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#### Radiative Zone

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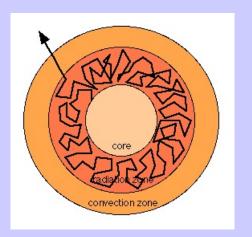
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#### Convective Zone

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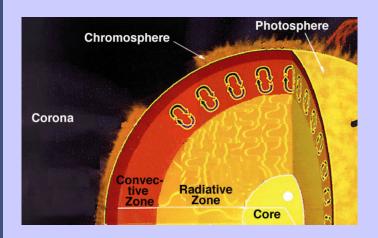
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## Convection

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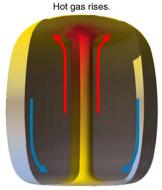
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#### Convection

The process of hot gas rising and cool gas sinking.

Since hot material radiates more light, the rising hot parts appear bright; since cool material radiates relatively less light, the sinking cool parts appear "dark".



Cool gas descends

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# Solar Surface: Sunspots

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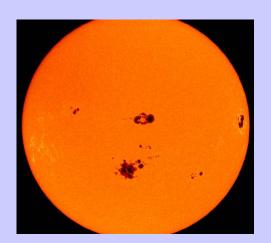
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Sunspot Mechanism

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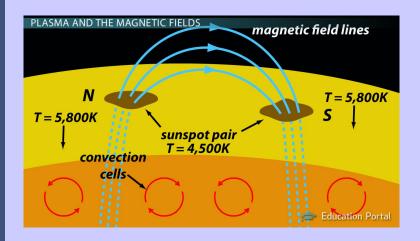
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Solar Photosphere

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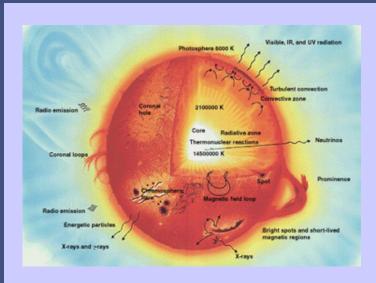
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Solar Prominence

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Solar Chromosphere

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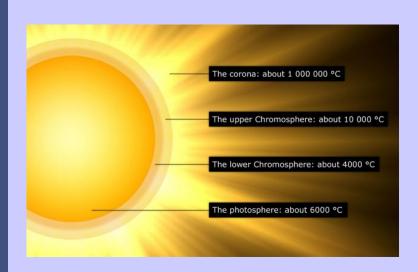
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Structure of the Sun

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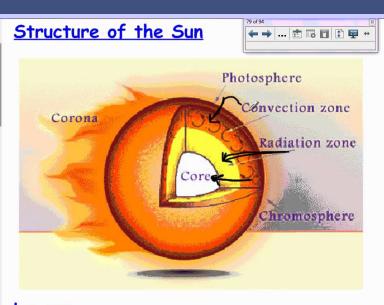
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The Night Sky

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Constellations: Orion

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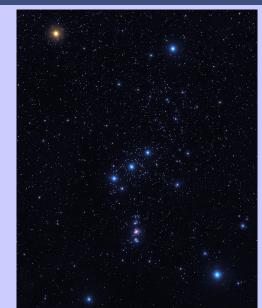
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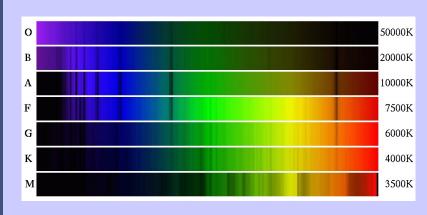
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Visual Binary Star System

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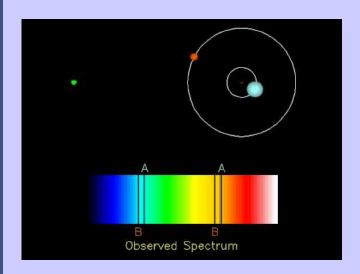
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Eclipsing Binary Star System

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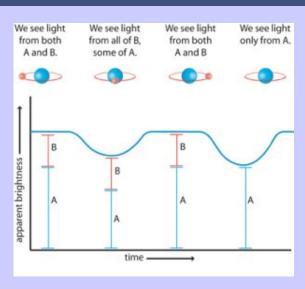
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Eclipsing Binary Star System - Model

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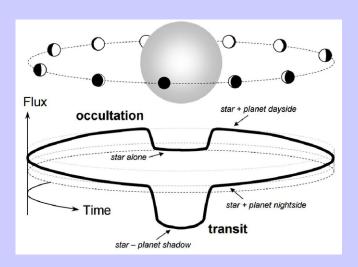
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Eclipsing Binary Star System - Data

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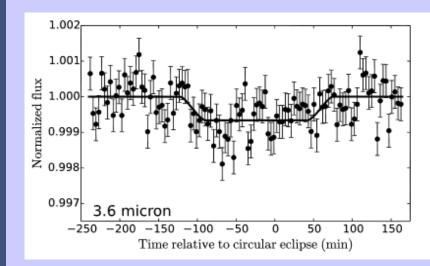
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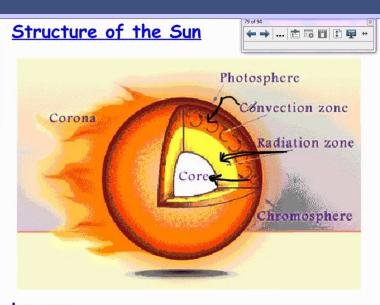
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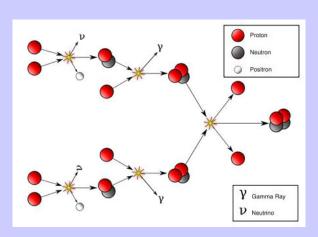
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Hertzsprung-Russell Diagram

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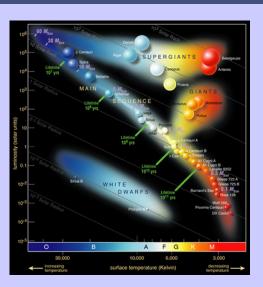
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Sub-Giant Star

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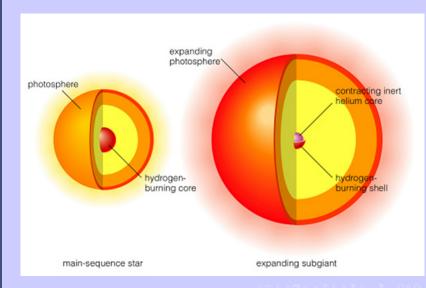
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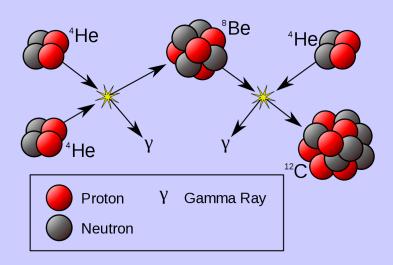
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Red Giant

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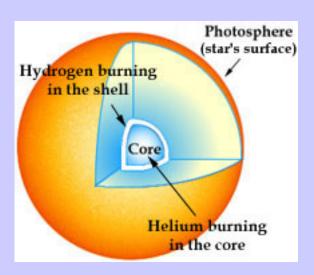
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Evolution off the Main Sequence

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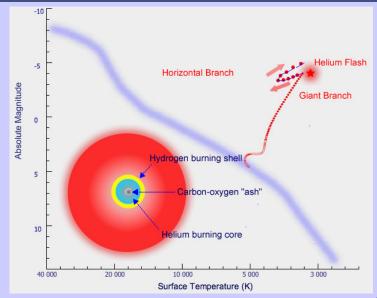
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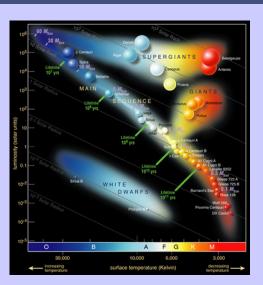
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Variable Star

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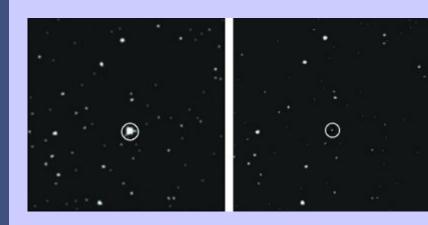
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Variable Star Intensity

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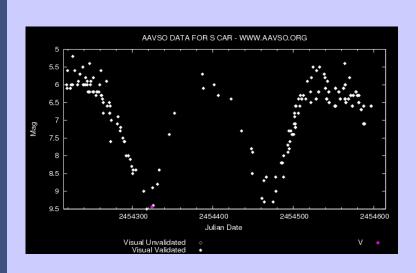
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Open Star Cluster

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Globular Cluster

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Globular Cluster Age

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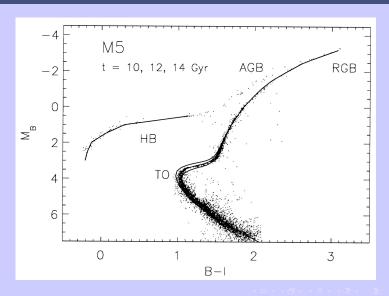
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History of the Universe

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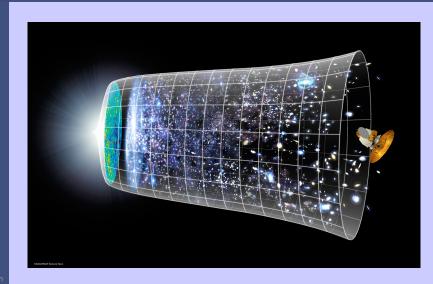
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Molecular Cloud (Eagle)

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Molecular Cloud in IR

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Approaching the Main Sequence

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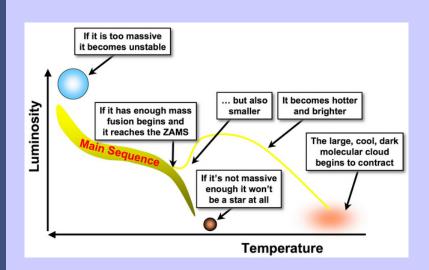
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Chapter 10: Galaxies and Beyond



Approaching the Main Sequence

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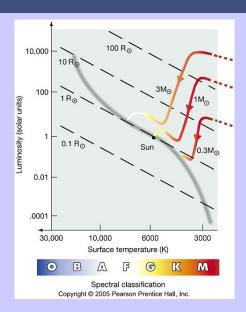
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Protostellar Disk

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Protostellar Jet

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Structure of the Sun

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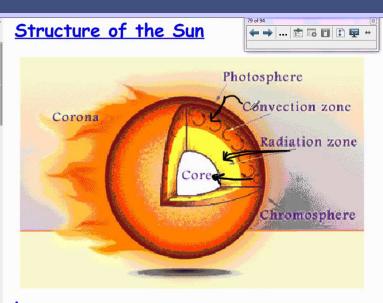
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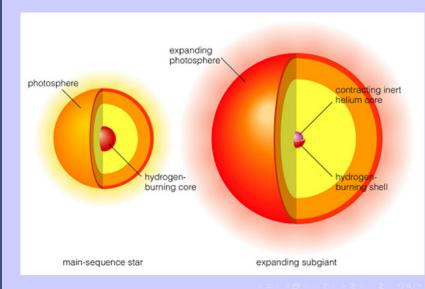
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Chapter 10: Galaxies and



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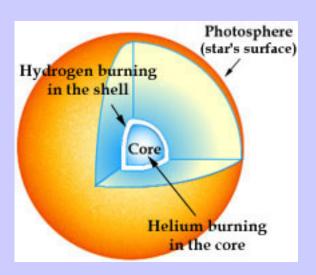
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Helium Fusion

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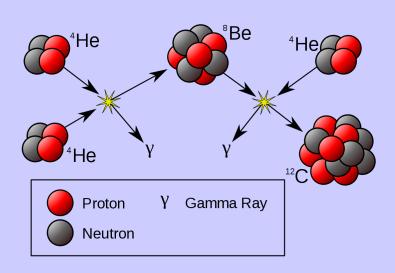
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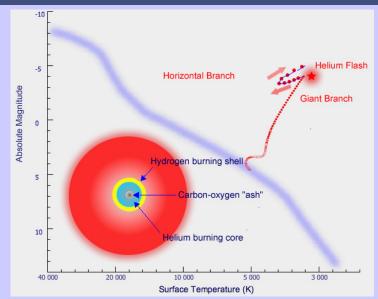


Evolution off the Main Sequence

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Planetary Nebula

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Evolution after the Red Giant Stage

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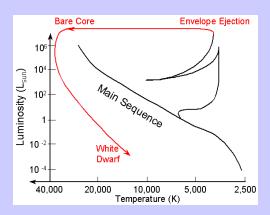
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Evolution of a Low Mass Star

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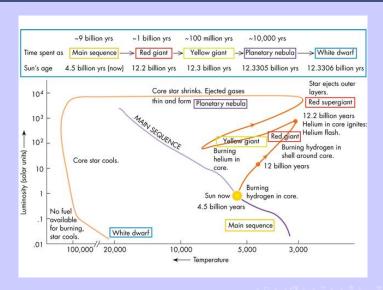
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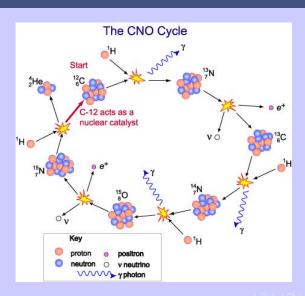
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Red Supergiant Evolution

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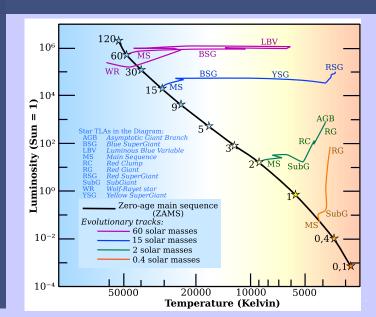
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Heavier Element Formation

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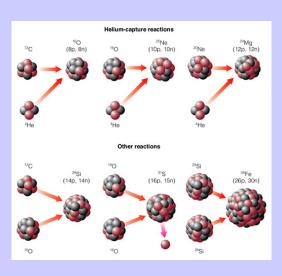
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Structure of a Massive Star

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The End of the Line for Massive Stars



- Massive stars burn a succession of elements.
- Iron is the most stable element and cannot be fused further.
 - Instead of releasing energy, it uses energy.

Stability of Nuclei

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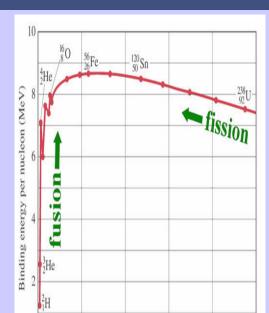
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Type II Supernova

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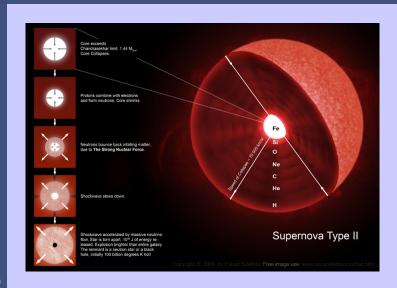
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Supernova Discovery

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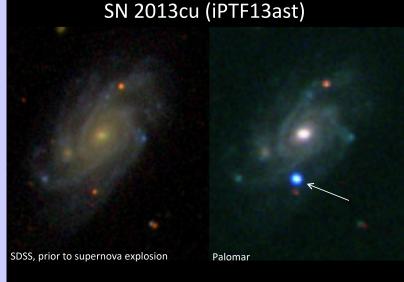
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Crab Nebula

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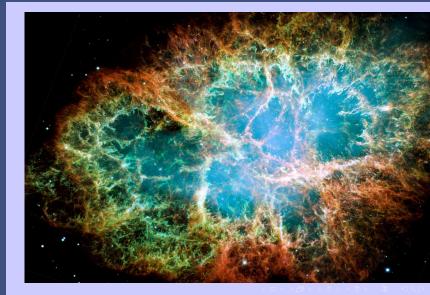
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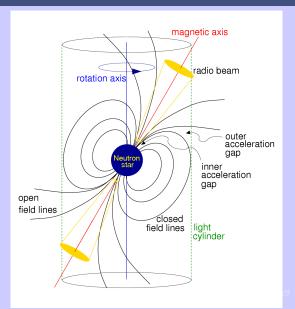
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Pulsar Picture

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Pulsar Discovery

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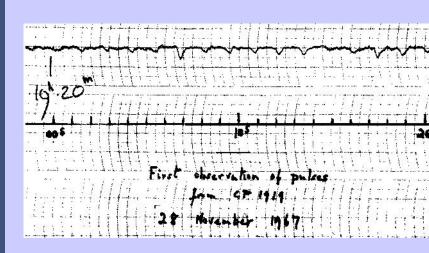
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Pulsar Periods

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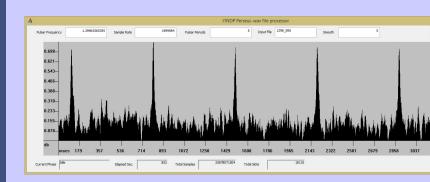
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Pulsar Binary

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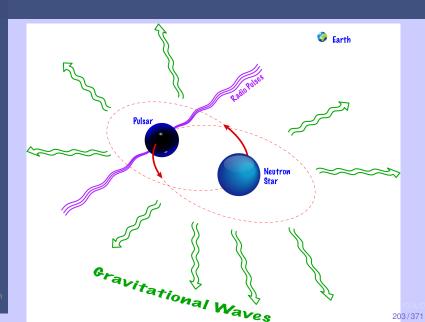
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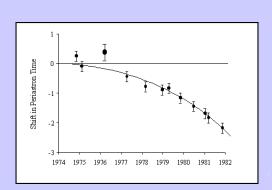
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Hulse and Taylor, Nobel Prize

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White Dwarf Binary

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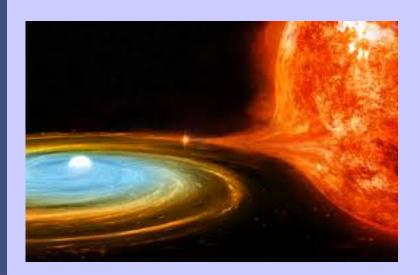
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Neutron Stars

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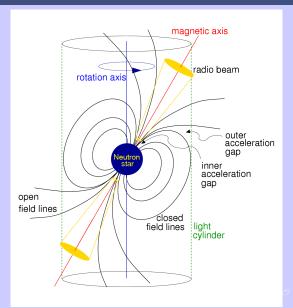
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X-Ray Binary

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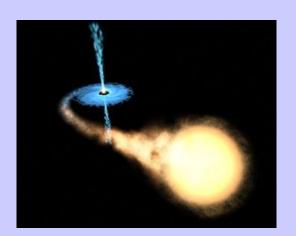
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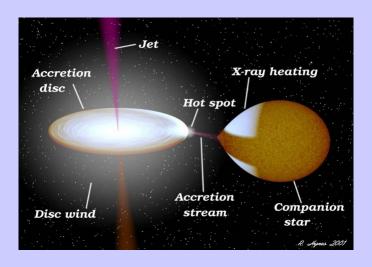
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X-Ray Burst

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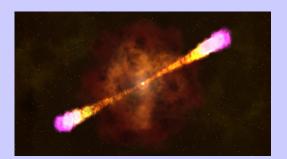
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Intensity Spectrum of a X-Ray Burst

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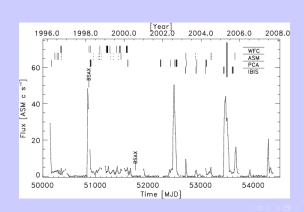
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Sun as a Black Hole

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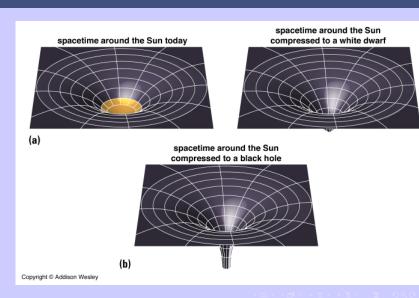
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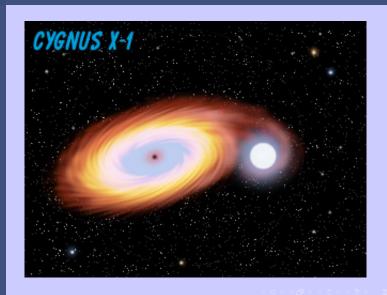
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The Expanding Universe

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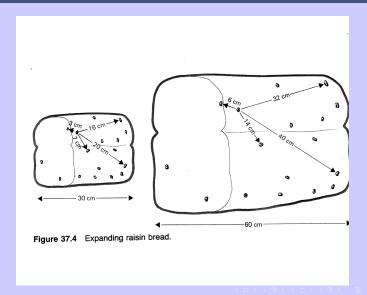
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Prediction: Gravitational Waves Exist

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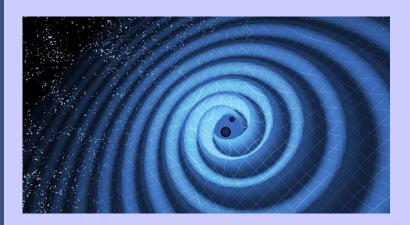
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Chapter 10: Galaxies and

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- Fluctuations of vacuum space-time.
- Obey the wave equation.
- Travel with c.
- Two polarization states.
- Are created by localized accelerating matter with a non-vanishing quadrupole moment.

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Chapter 10: Galaxies and Beyond

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- Fluctuations of vacuum space-time.
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LIGO Schematic

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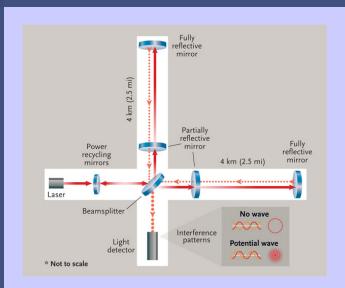
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Michelson-Morley Interferometer

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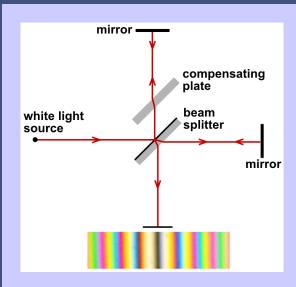
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LIGO Schematic

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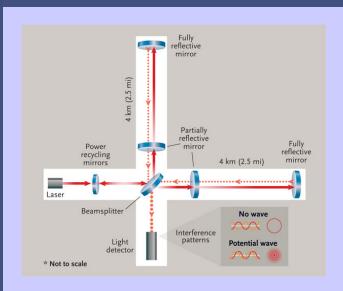
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LIGO Laser (Prototype)

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LIGO Mirrors

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LIGO Seismic Isolation

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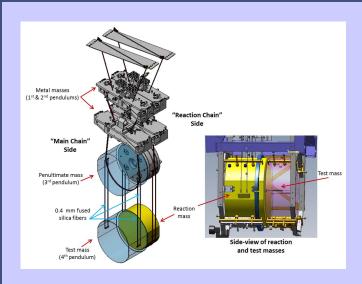
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LIGO Hanford Site

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LIGO Livingstone Site

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LIGO Sensitivity

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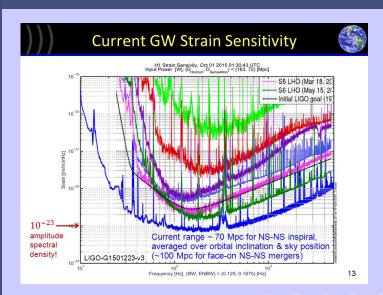
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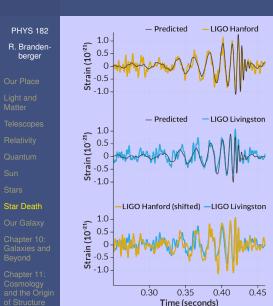
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LIGO Event (Sept. 2015): Nobel Prize 2017



Prediction (Numerical GR)

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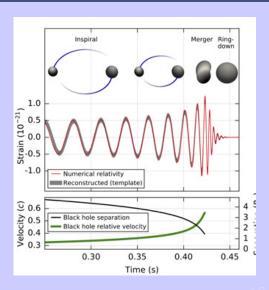
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Binary Black Hole

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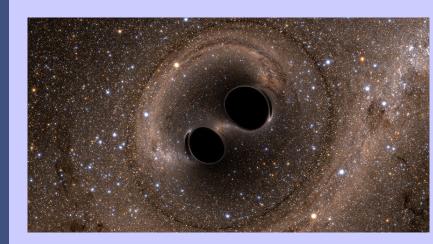
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Chapter 10: Galaxies and

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- First direct detection of gravitational waves.
- Best evidence for the existence of a black hole horizon
- Best test of General Relativity close to a black hole horizon.
- First detection of a black hole binary system.
- Rate of black hole binaries

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Chapter 10: Galaxies and

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Chapter 10: Galaxies and Beyond

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Chapter 10: Galaxies and Beyond

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Neutron Star Merger Discovery: August 17 2017

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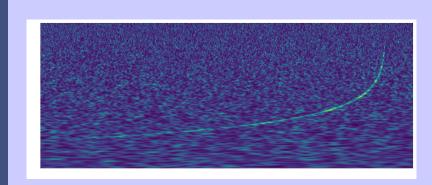
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Birth of Multimessenger Astronomy: August 17 2017

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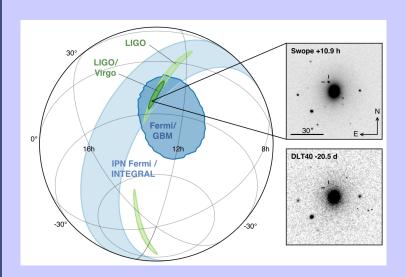
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Chapter 10: Galaxies and

- First detection of an optical counterpart to a direct gravitational wave signal.
- Birth of the field of Multi-Messenger Astronomy.
- First multi-wavelength observation of a kilonova.
- Verification that kilonovae can produce heavy elements (like supernovae).
- Stringent test of the Einstein equivalence principle.
- Many alternative gravity models ruled out.
- New standard candle → new way to directly measure the Hubble expansion rate.

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Chapter 10: Galaxies and Beyond

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Chapter 10: Galaxies and Beyond

- First detection of an optical counterpart to a direct gravitational wave signal.
- Birth of the field of Multi-Messenger Astronomy.
- First multi-wavelength observation of a kilonova.
- Verification that kilonovae can produce heavy elements (like supernovae).
- Stringent test of the Einstein equivalence principle.
- Many alternative gravity models ruled out.
- New standard candle → new way to directly measure the Hubble expansion rate.

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Chapter 10: Galaxies and Beyond

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Super-Massive Black Hole in the Center of the Milky Way

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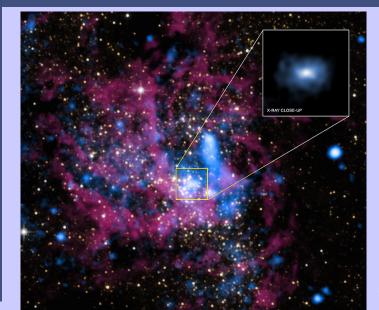
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Galaxies and Beyond



Sagittarius A* in X-Ray

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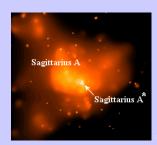
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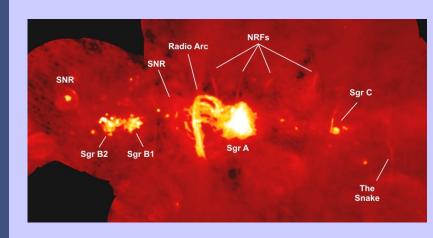
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Orbits of Stars about our Super-Massive Black Hole

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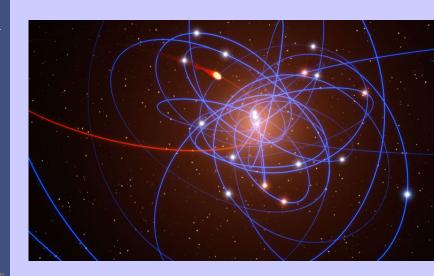
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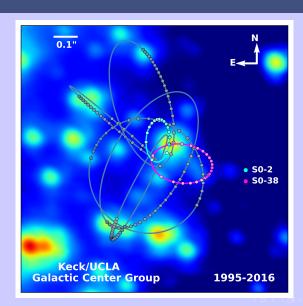
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Orbits of Stars about our Super-Massive Black Hole

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Leader of the UCLA Group: Prof. A. Ghez (Nobel Prize 2020)

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Illustration of our Super-Massive Black Hole

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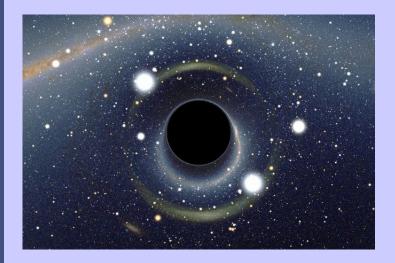
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Event Horizon Telescope Program

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Event Horizon Telescope Image (2019)

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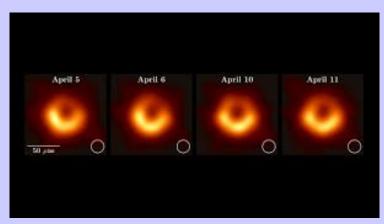
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Note: Breakthrough Prize, 2019

Event Horizon Telescope Image (2019)

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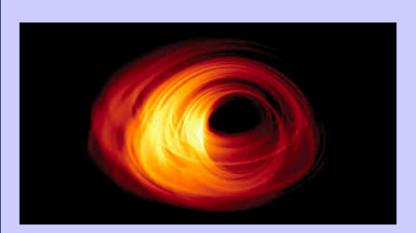
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Milky Way Galaxy from Earth

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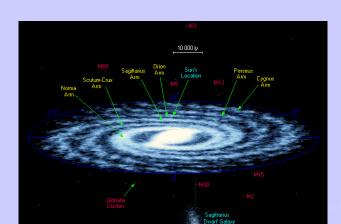
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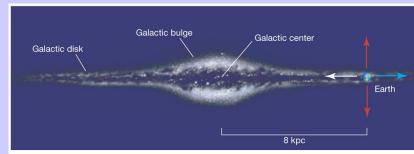


Side View of the Milky Way Galaxy

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Structure of the Milky Way Galaxy

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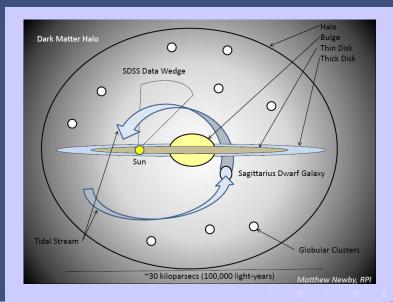
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Galaxy Rotation Velocity

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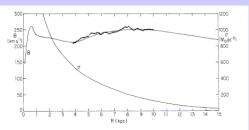


Figure 2 Variation with distance from the galactic center of the linear velocity of differential rotation, $\Theta(R)$, according to Simonson & Mader (1973) at R < 5 kpc and according to Schmidt (1965) at R > 5 kpc, and of the corresponding total galactic mass surface density, $\sigma(R)$, according to Innanen (1973). The dots show the rotational velocities found from H I observations of the subcentral-point region by Shane & Bieger-Smith (1966).

Galaxy Rotation Velocity

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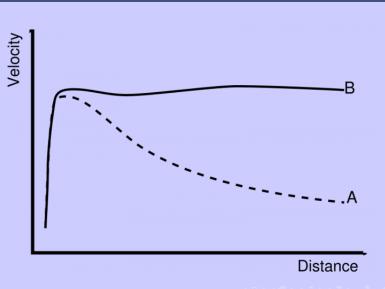
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Galaxy Rotation Velocity

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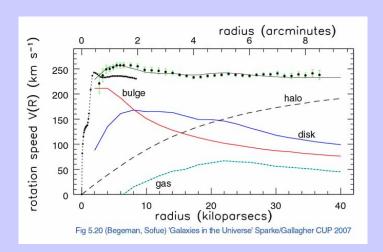
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History of the Universe

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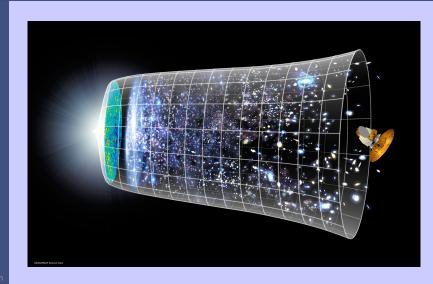
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Spectrum of the Microwave Background

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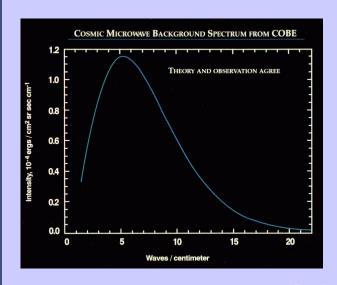
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Star Forming Cloud

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Planetary Nebula

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Crab Nebula - a Supernova Remnant

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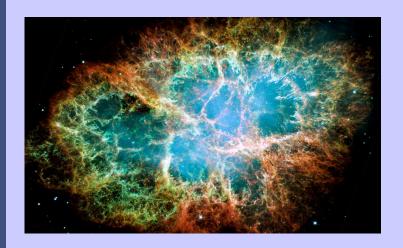
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Supernova Remnant

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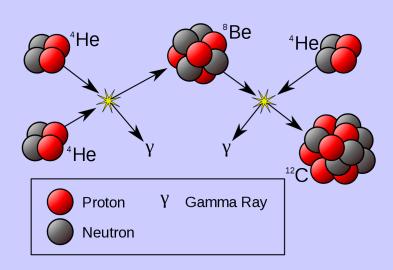
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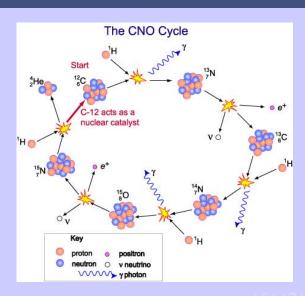
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Heavier Element Formation

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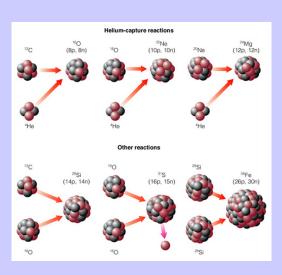
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Planetary Nebula Spectrum

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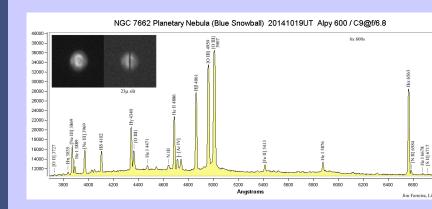
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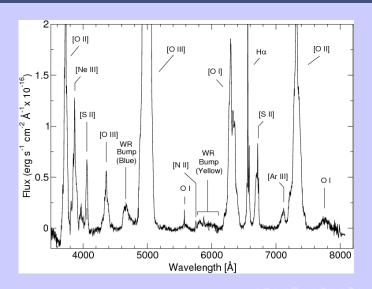
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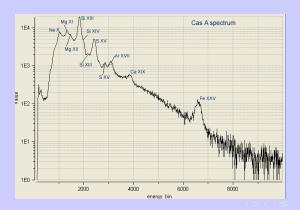
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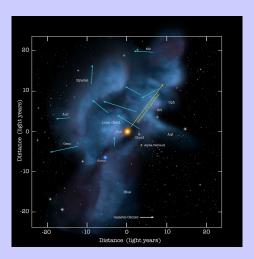
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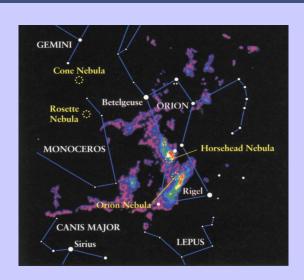
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Star-Gas-Star Cycle

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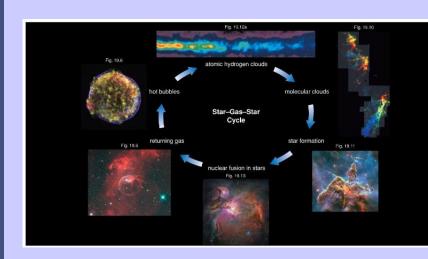
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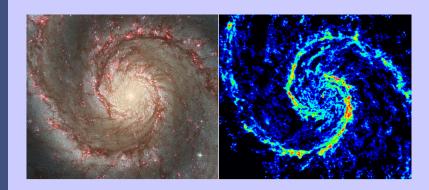
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Optical View of the Milky Way

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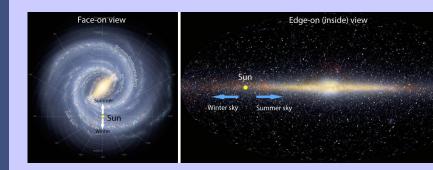
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Infrared View of the Milky Way

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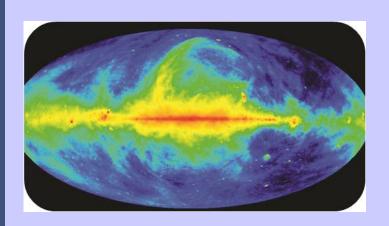


Radio View of the Milky Way

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X-ray View of the Milky Way

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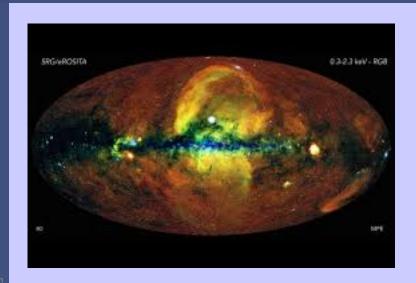
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Sea of Galaxies

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Hubble Deep Field

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Spiral Galaxy

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Barred Spiral Galaxy

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Elliptical Galaxy - M87

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Elliptical Galaxy - M110

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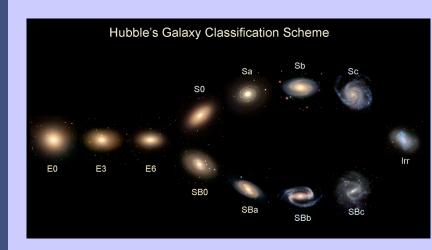
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Redshifted Galaxy Spectra

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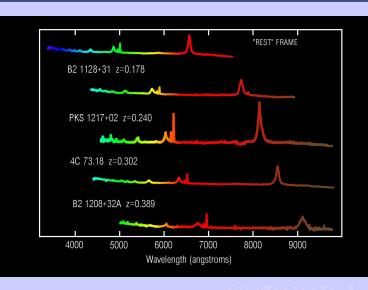
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Hubble's Data

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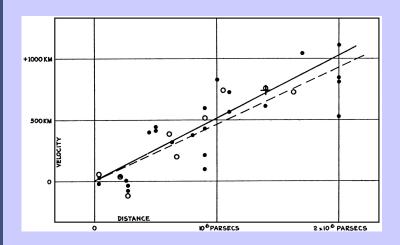
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Sea of Galaxies

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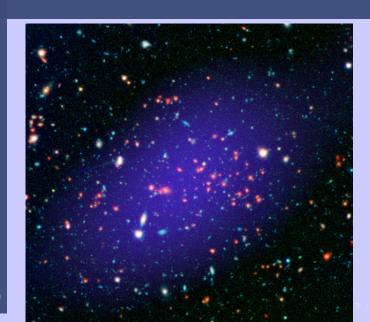
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Distance Ladder Steps

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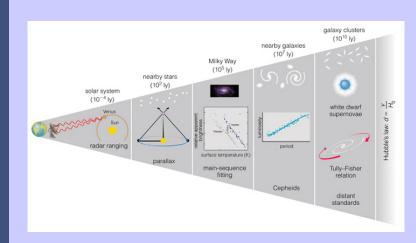
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Parallax Method

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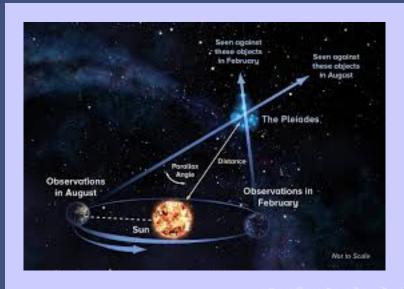
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Hertzsprung-Russell Diagram

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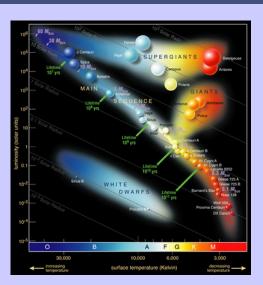
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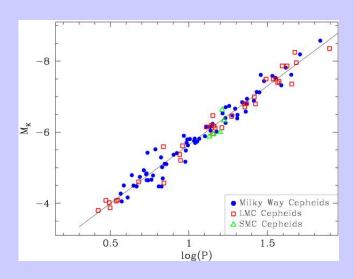
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White Dwarf Supernovae (SN Type IA)

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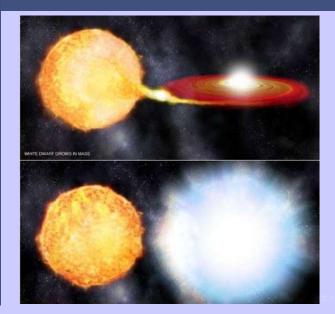
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Supernova Phillips Relation

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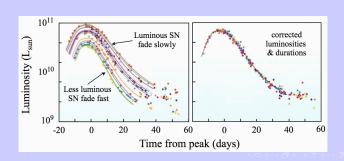
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The Expanding Universe

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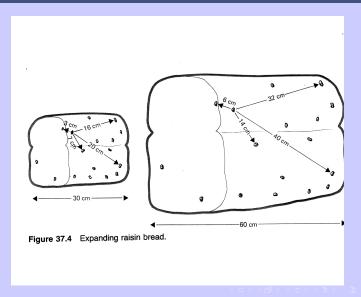
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Supernova Hubble Law

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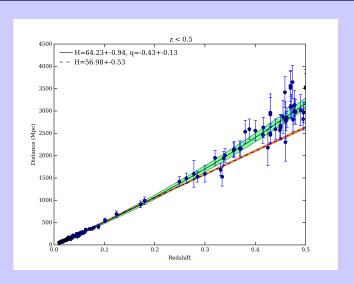
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Large-Scale Structure

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Galaxy Clusters

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Prediction: Bending of Light

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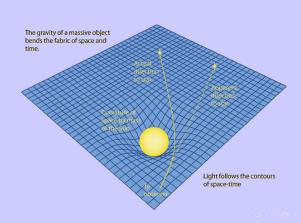
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Gravitational Lensing by a Galaxy Cluster

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Redshift Survey Results in 1989

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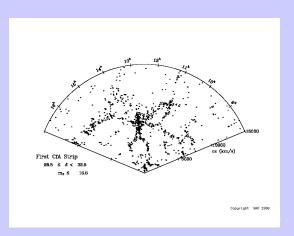
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Redshift Survey Results in 2003

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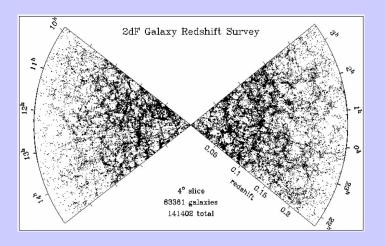
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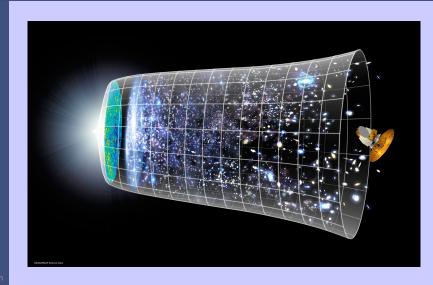
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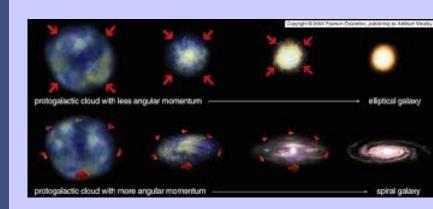
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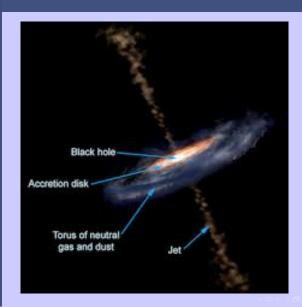
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Super-Massive Black Hole in the Center of the Milky Way

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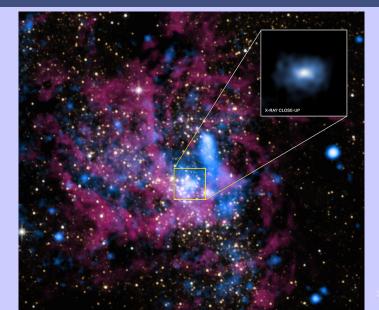
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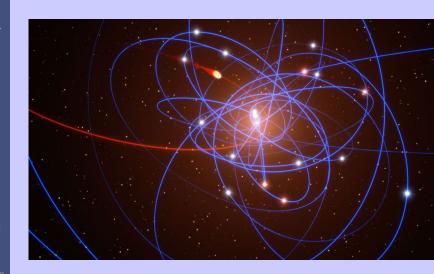
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Leader of the UCLA Group: Prof. A. Ghez (Nobel Prize 2020)

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Illustration of our Super-Massive Black Hole

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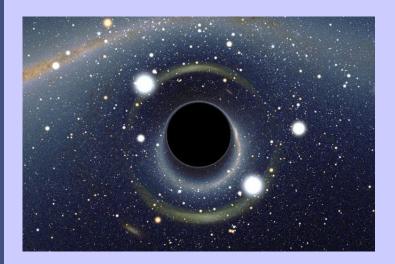
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Event Horizon Telescope Program

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Event Horizon Telescope Image (2019)

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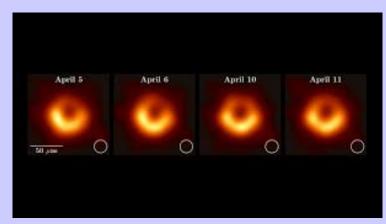
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Note: Breakthrough Prize, 2019

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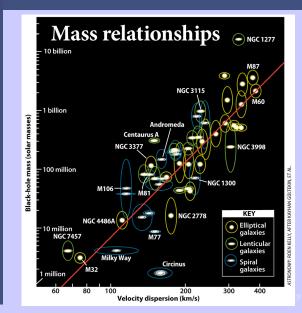
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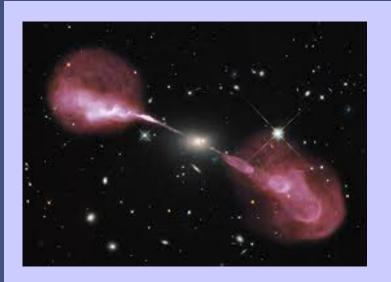
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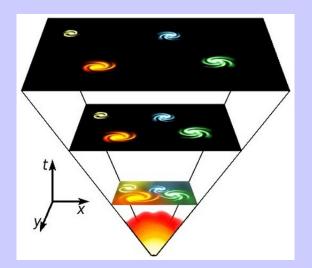
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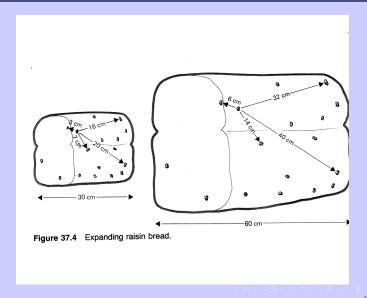
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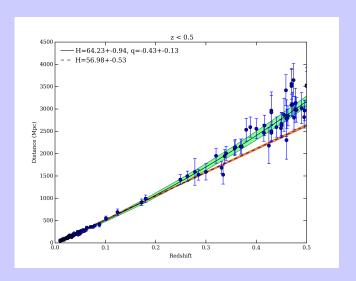
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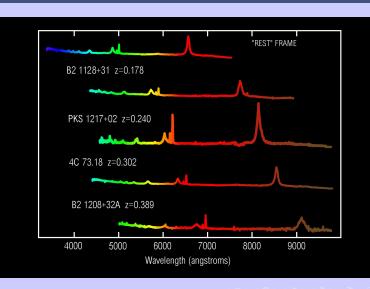
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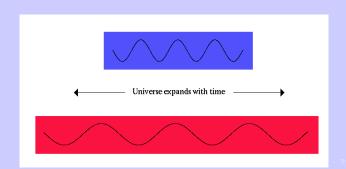
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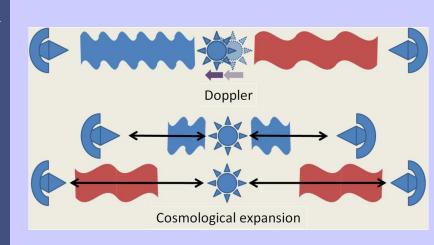
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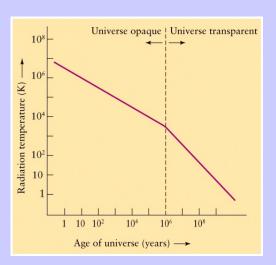
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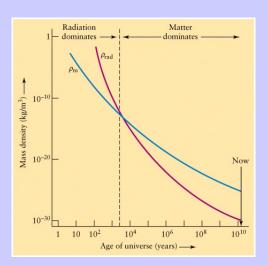
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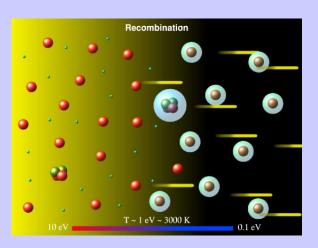
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Jim Peebles: Nobel Prize 2019

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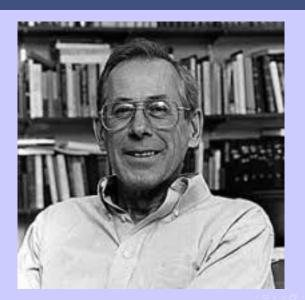
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Prediction of the Cosmic Microwave Background

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of the first four interlopers, provided the initial clue to the existence of radio-quiet, blue, quasi-stellar galaxies (QSG) whose optical properties are similar to those of QSS's (Sandage 1965).

Spectrograms were subsequently obtained for BSO 1, BSO 8, and BSO 16 by Schmidt

Spectrograms were subsequently obtained for BSD 1, 8903, 8, and BSD 16 by Schmidt and by Sandage in an attempt to verify the existence of QSG. The spectrum of BSD 16 above that this object is a flot star having the Balmer lines in absorption near their rest shows that this object is a flot star having the Balmer lines in absorption near their rest. The spectrum of BSD 6 (called "BSD 108" by Sandage 1965 on an older numbering system) is continuous with no prominent absorption or emission lines. BSD 1 has a large redshift of 4.0½ bs — 1.244 (b), a described elsewhere (Sandage 1965).

positions, accurate to perhaps ± N', for the thirty-one survey objects. Where a valishly, the colors and magnitudes determined photoelectrically at the 200-inch are also shown. These blue objects are undoubtedly of the same class as the faint objects in the catherine and Chavin (1957), Chavin (1958), and Baro and Layten (1952). With the identification of most of these objects as intrinsically bright soldier-apposing continued to the color of t

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Chavira, E. 1988, Ball. Obs. Ten., No. 17, p. 15. Hare, G., and Luyten, W. J. 1962, Ball Obs. Ten., No. 22, p. 1. Friarte, B., and Chavira, E. 1987, Ball. Obs. Ten., No. 16, p. 3. Ryle, M., and Santage, A. 1964, 49, J., 139, 419. Sandage, A. 1965, 49, J., 144 (in press).

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COSMIC BLACK-BODY RADIATION*

One of the basic problems of comodogy is the singularity characteristic of the familiar cosmological obstitions of Einstein's field equations. Also paralling is the presence of matter in cross over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

 The assumption of continuous creation (Bondi and Gold 1948; Hoyle 1948), which avoids the singularity by postulating a universe expanding for all time and a continuous but slow creation of new matter in the universe.

but slow creation of new matter in the universe.

2. The assumption (Wheeler 1964) that the creation of new matter is intimately related to the existence of the singularity, and that the resolution of both paradoxes may be found in a proper quantum mechanical treatment of Einstein's field equations.

* This research was supported in part by the National Science Foundation and the Office of Naval

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Prediction of the Cosmic Microwave Background

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No. 1, 1965 LETTERS TO THE EDITOR high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-19} gm/cm3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suprestions of Professor I. A. Wheeler, P. J. E. PEEBLES P. G. ROLL May 7, 1965 Alpher, R. A., Bethe, H. A., and Gamow, G. 1948, Phys. Rev., 78, 803. Alpher, R. A., Follin, J. W., and Herman, R. C. 1953, Phys. Rev., 92, 1347. Brans, C., and Gold, T. 1948, M. N., 108, 252. Brans, C., and Docke, R. H. 1961, Phys. Rev., 124, 925. Dicker, R. H. 1962, Palys. Rev., 128, 2163. Dicker, R. H. 1962, Palys. Rev., 128, 2163. Dicker, R. H. Beringer, R., Kyhl, R. L., and Vane, A. B. 1946, Phys. Rev., 70, 340 Einstein, A., 1950, The Meaning of Relativity (id ed.; Princeton, N.J.: Princeton University Press), p. 107. Hoyke, F. 1948, M. N., 108, 572. Hoyke, F. and Tayler, R. J. 1964, Nature, 203, 1108 Liftshitz, E. M., and Khalitankov, L. M. 1963, Adv. in Phys., 12, 185. Oort, J. H. 1985, L. Savatare at Pérediston de Paristrere (Hith Solvay Cenf. [Brusschi: Éditietu Stoopsa]), p. 163. Prebles, P. J. E. 1965, Phys. Rev. (in press). Prebles, A. A., and Wilson, R. W. 1965, private communication. Wheeler, J. A., 1993, Lo Standare et Prebalation de Paninere (41th Solvay Cool., [Brussels: Editions 1964, in Relativity, Groups and Topology, ed. C. DeWitt and B. DeWitt (New York: Gordon & Brench). Zel'dovich, Yu. B. 1962, Soviel Phys.—J.E.T.P., 14, 1143. AT 4080 Mc/s Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel,

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Discovery of the Cosmic Microwave Background

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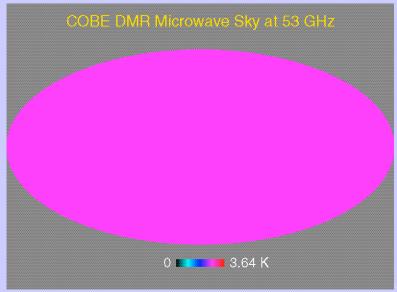
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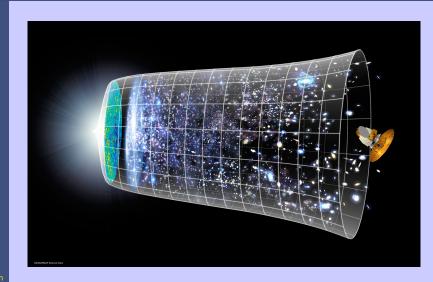
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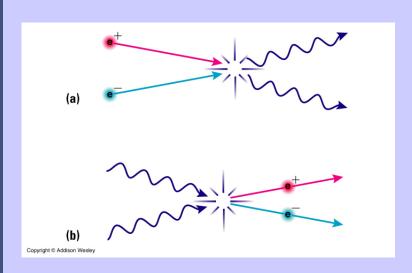
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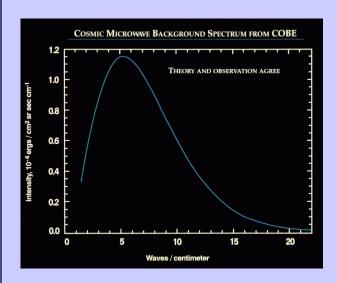
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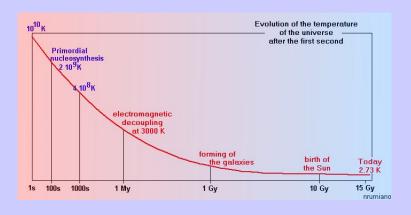
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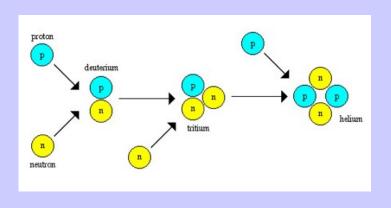
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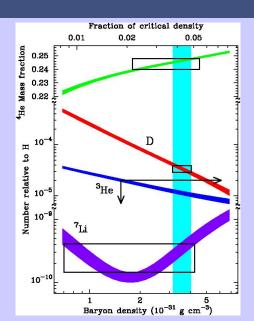
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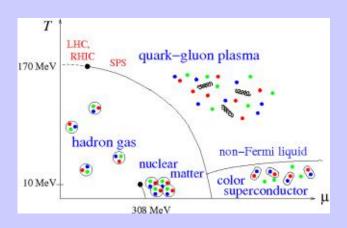
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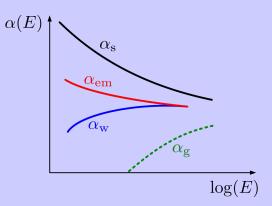
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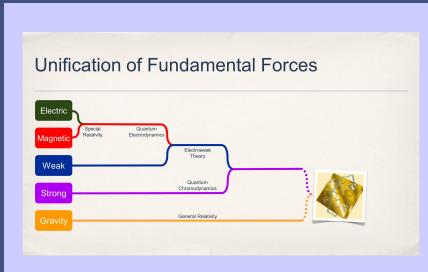
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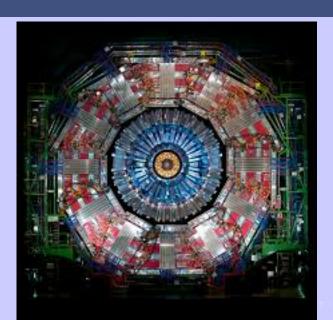
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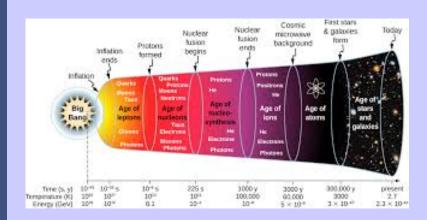
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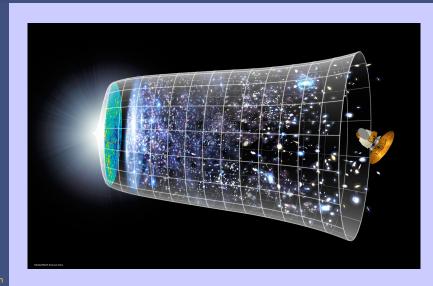


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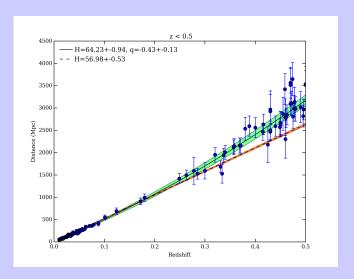
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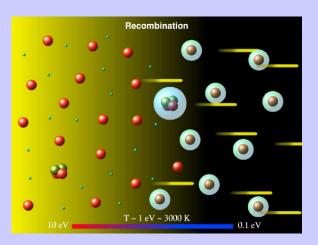
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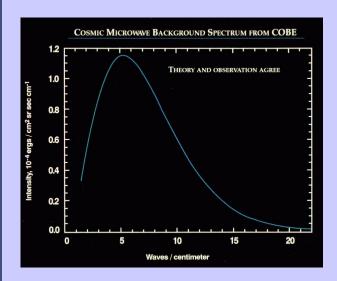
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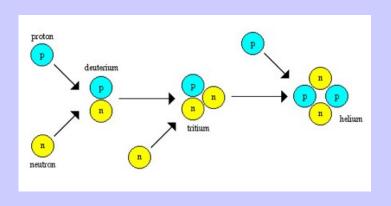
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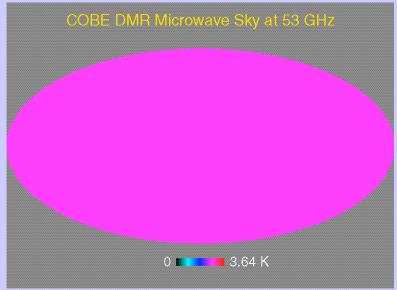
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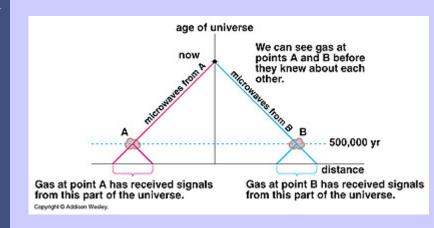
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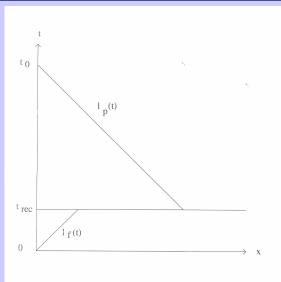
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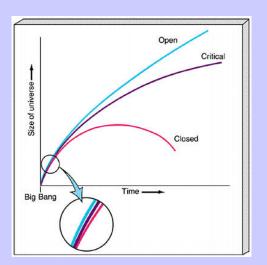
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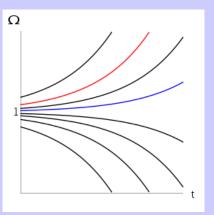
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Structure Formation Problem

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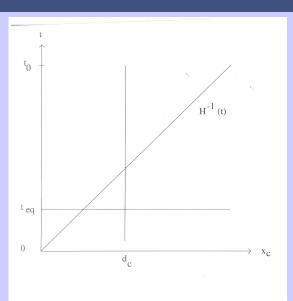
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Cosmological Density Fluctuations

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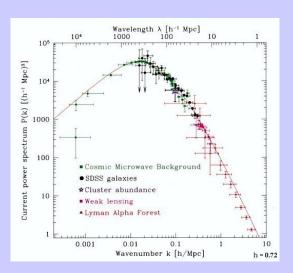
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Anisotropies in the Cosmic Microwave Background (CMB)

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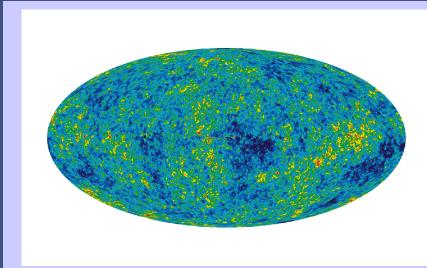
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Credit: NASA/WMAP Science Team

Microwave Anisotropies

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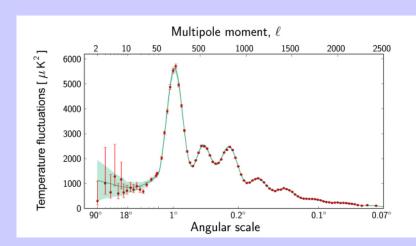
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Early Work

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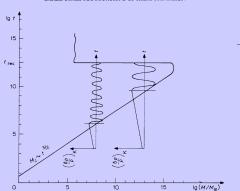


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.

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Composition of the Energy of the Universe

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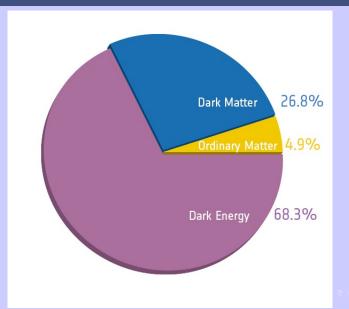
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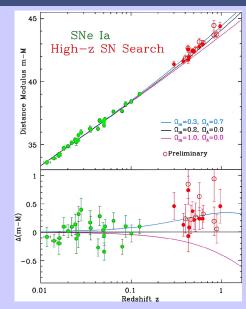


Evidence for Accelerated Expansion from Supernovae





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Angular Power Spectrum of CMB Anisotropies

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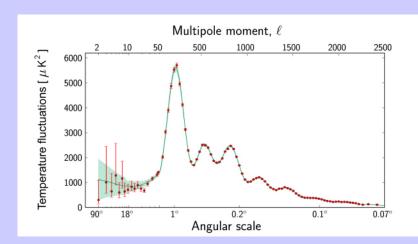
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Spiral Galaxy Rotation Curves

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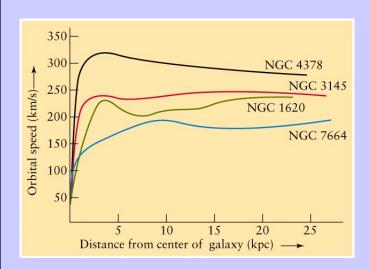
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Elliptical Galaxy Velocity Dispersion

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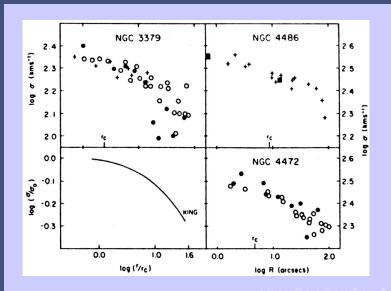
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Hot Gas in Galaxy Cluster

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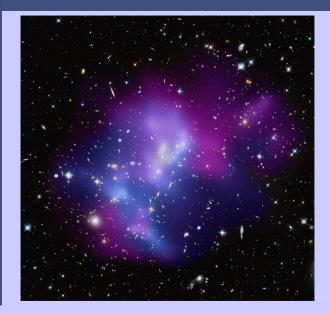
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Gravitational Lensing

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Bullet Cluster

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Nucleosynthesis Limits

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