

PHYS 182

R. Branden-
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Our Place

Light and
Matter

Telescopes

Relativity

Quantum

Sun

Stars

Star Death

Our Galaxy

Chapter 10:
Galaxies and
Beyond

Chapter 11:
Cosmology
and the Origin
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Our Evolving Universe

Robert Brandenberger
McGill University

Fall 2021

Outline

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- 5 Ch. 5: The Quantum Revolution
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- Particular emphasis on **Black Holes** and **Cosmology**
- Physics Foundations to understand the Cosmos

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Grading Scheme

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- Homework sets: 35%
- Poster project: 20%
- Final essay: 15%
- Final exam (3 hrs): 30%

My Research: Theoretical Cosmology

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1. Understand **origin** and **early evolution** of the universe.

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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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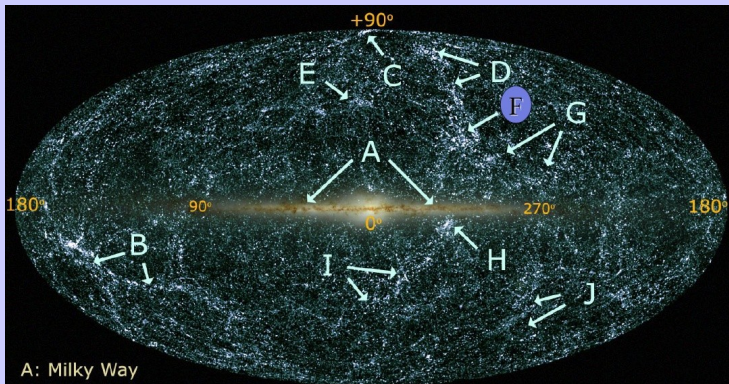
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A: Milky Way

B: Perseus-Pisces Supercluster

C: Coma Cluster

D: Virgo Cluster/Local Supercluster

E: Hercules Supercluster

F: Shapley Concentration/Abell 3558

-90°

G: Hydra-Centaurus Supercluster

H: "Great Attractor"/Abell 3627

I: Pavo-Indus Supercluster

J: Horologium-Reticulum Supercluster

From: talk by O. Lahav

South Pole Microwave Telescope

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WMAP Microwave Telescope

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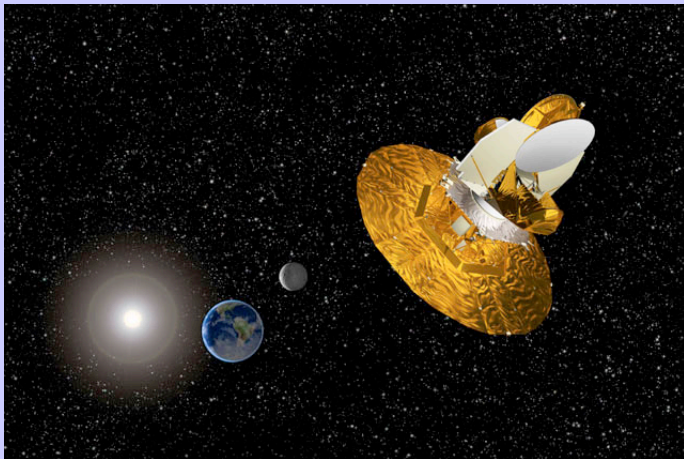
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Isotropic CMB Background

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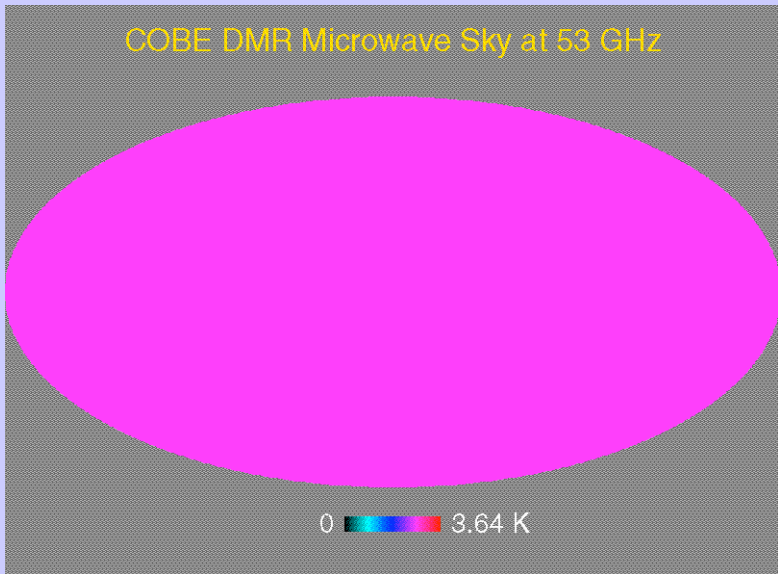
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COBE DMR Microwave Sky at 53 GHz



WMAP Map of the Cosmic Microwave Background

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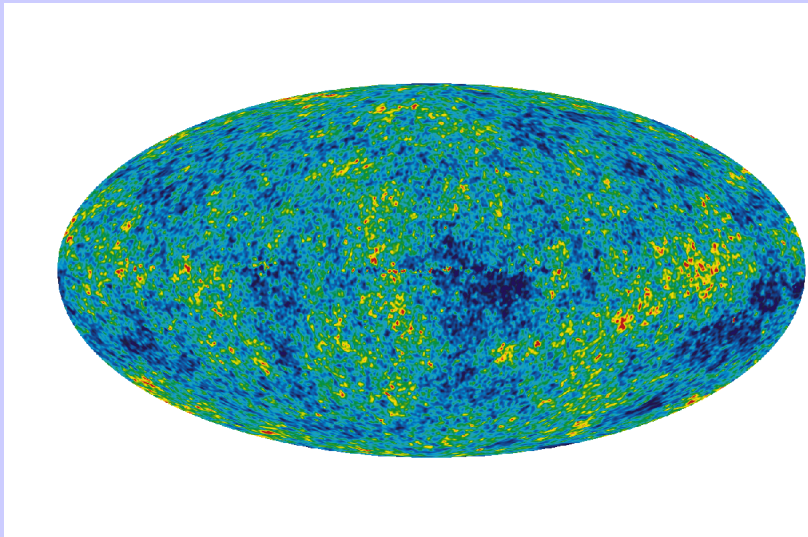
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History of the Universe

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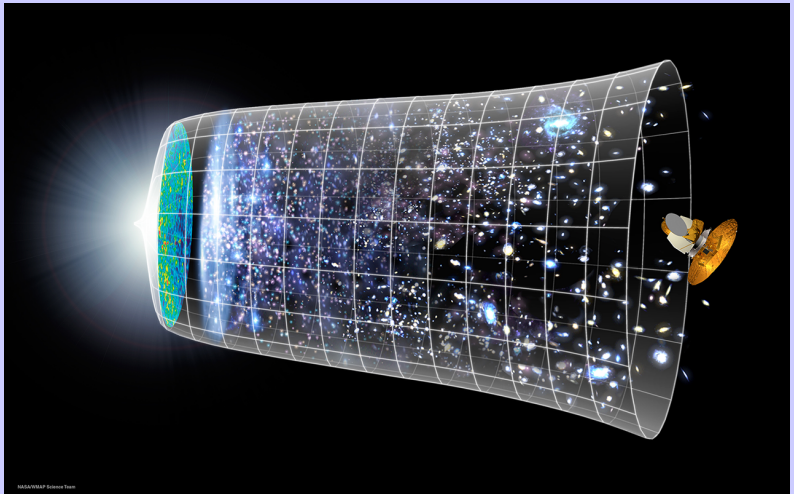
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NASA/WMAP Science Team

Goals of Early Universe Cosmology

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 - Anisotropies in **CMB maps**.
3. Make **predictions** for future observations.

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The Night Sky

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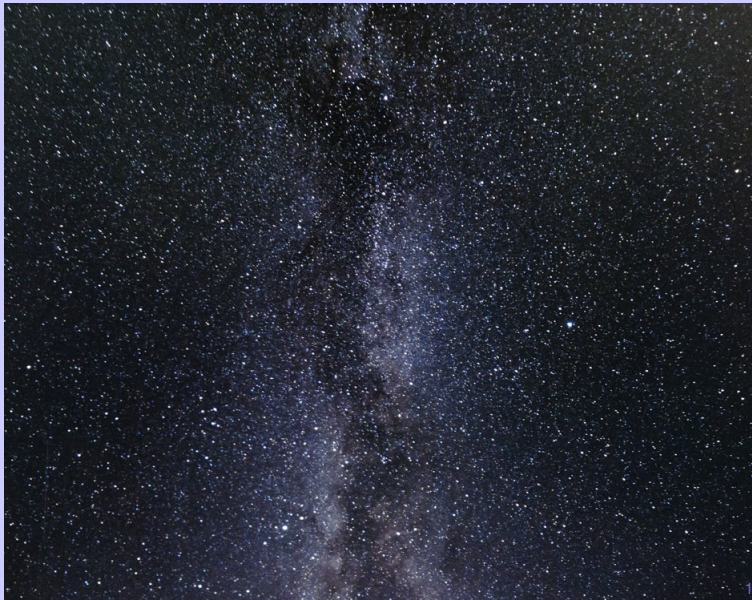
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Our Solar System

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

Solar System: Sizes

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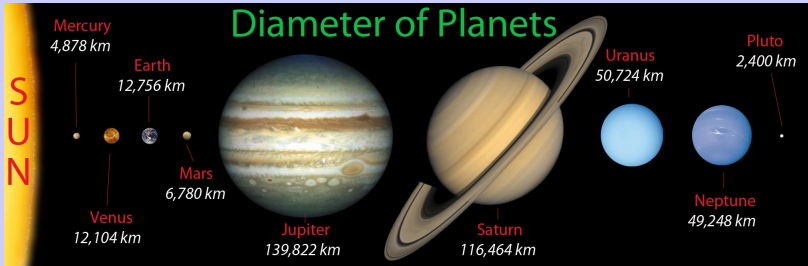
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Solar System: Sizes and Distances

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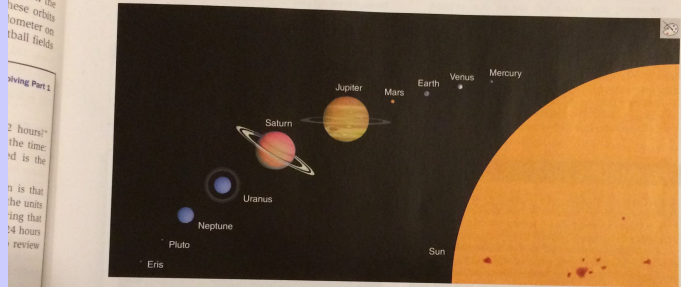
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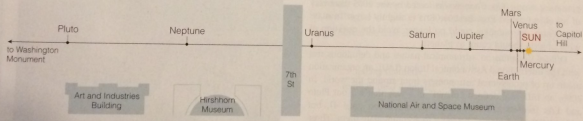
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... need to show these orbits on a scale of football fields
... about eye level on the planet pedestals. The building at the left is the National Air and Space Museum. ... tance from the Sun to Pluto in just a few minutes. How



a The scaled sizes (but not distances) of the Sun, the planets, and the two largest known dwarf planets.



b Locations of the Sun and planets in the Voyage model (Washington, D.C.): the distance from the Sun to Pluto is about 600 meters (1/3 mile). Planets are lined up in the model, but in reality each planet orbits the Sun independently and a perfect alignment never occurs.

FIGURE 1.6 Interactive figure The Voyage scale model represents the solar system at one ten-billionth of its actual size. Pluto is included in the Voyage model for context.

Solar System: Distances

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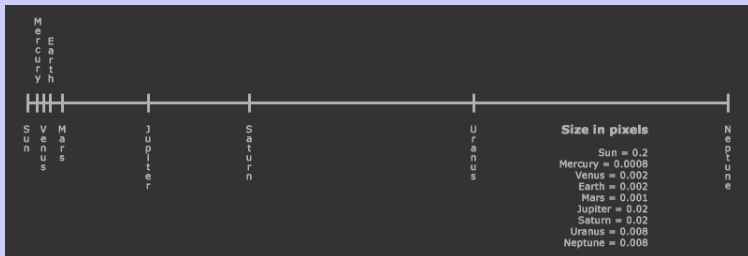
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How to determine distances within the solar system?

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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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Parallax Method

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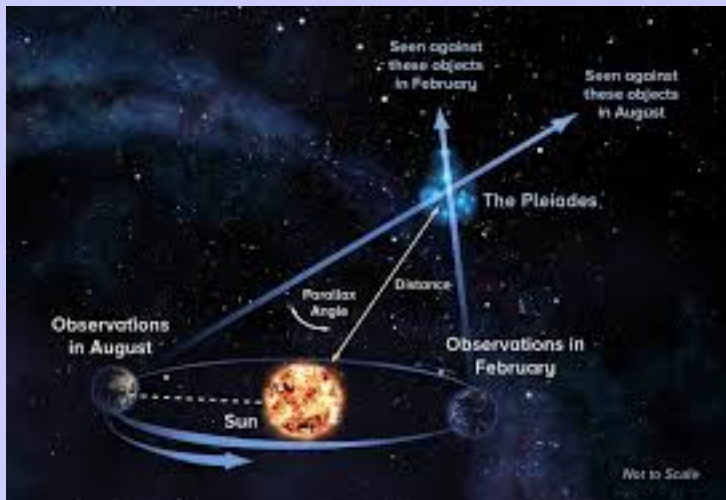
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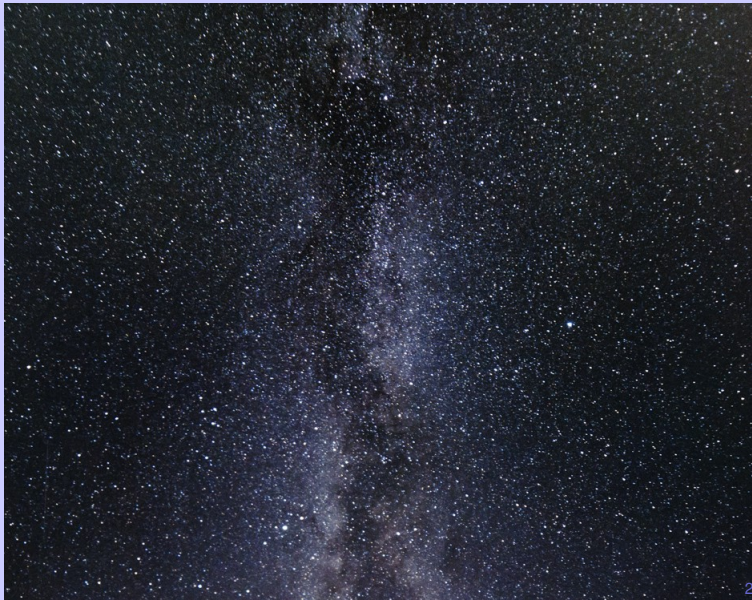
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Spectrometer

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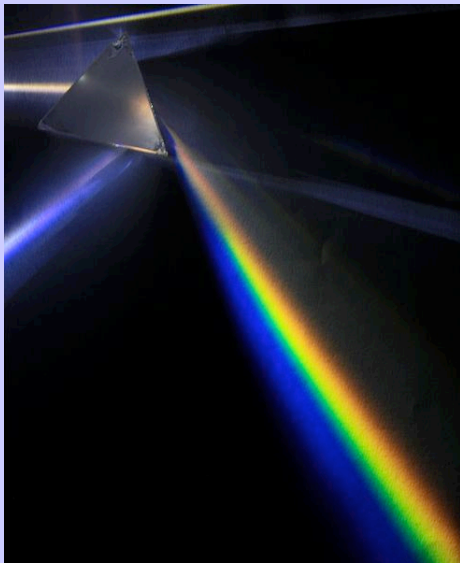
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Visible Spectrum

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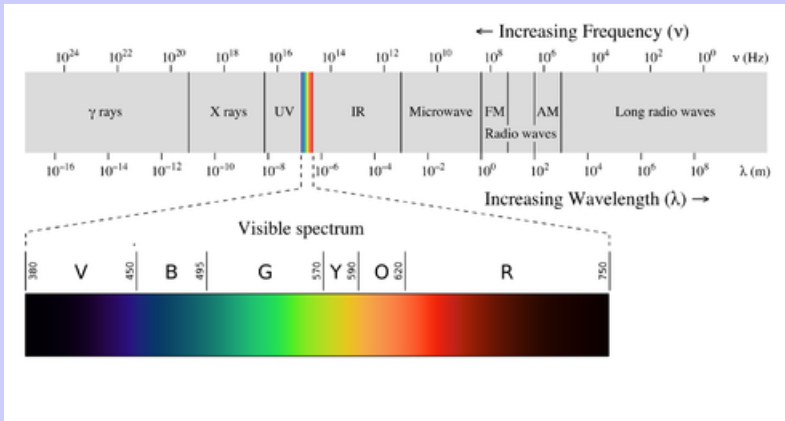
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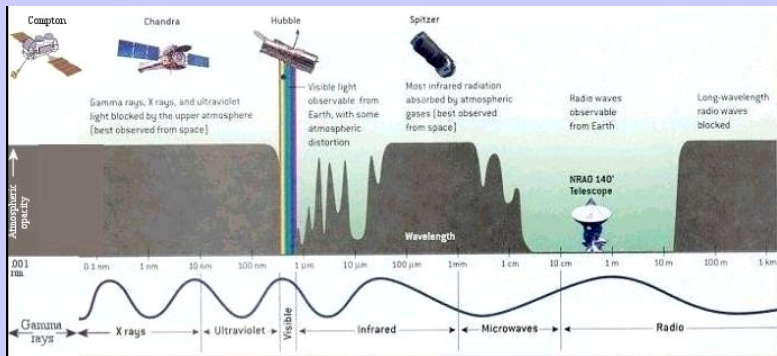
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Galaxy Magnitudes and Colours: HR Diagram

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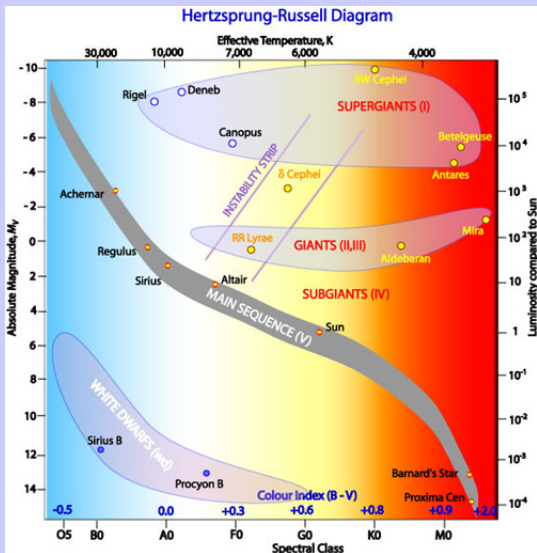
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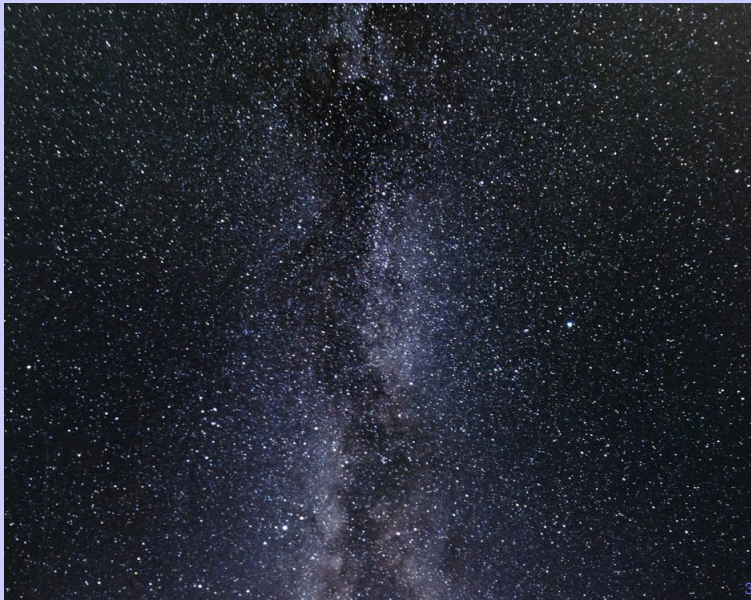
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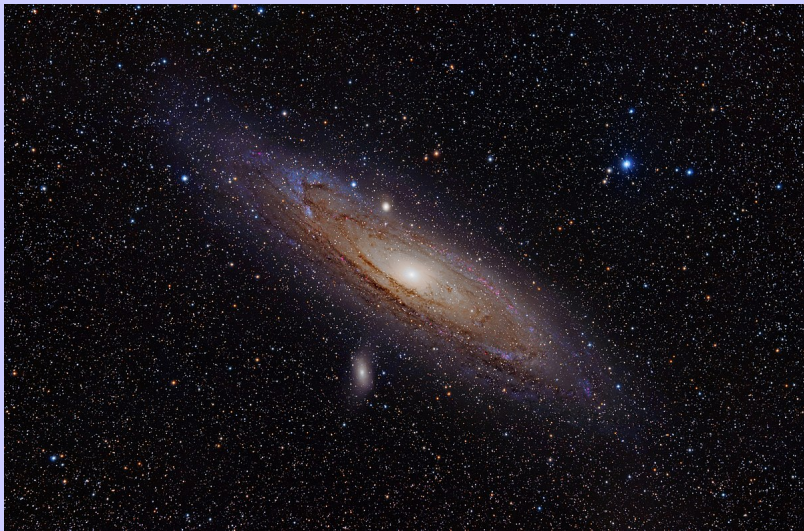
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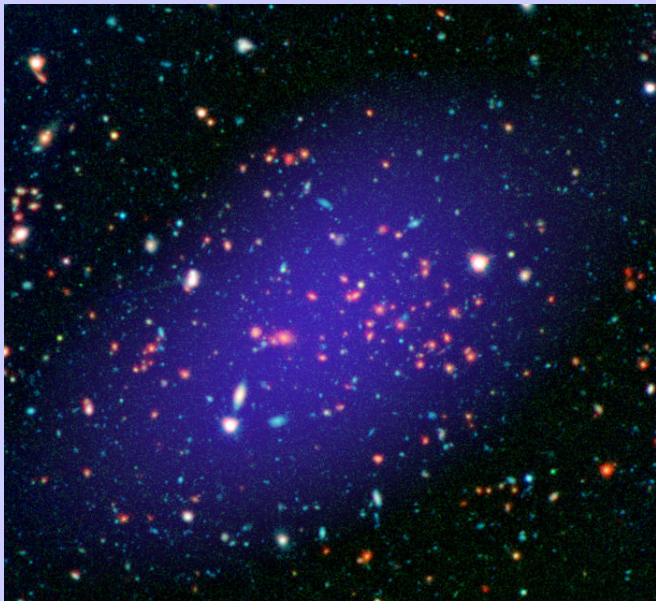
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Hubble Deep Field

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Milky Way - Our Galaxy

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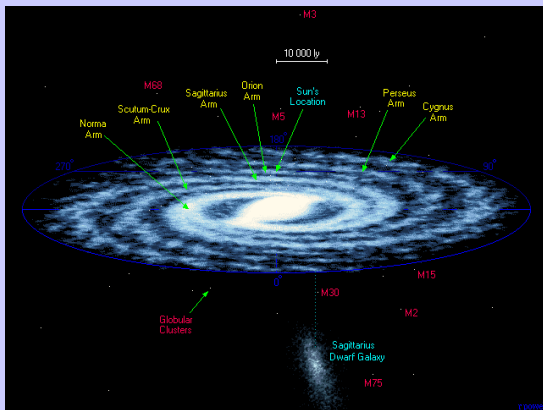
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Solar Spectrum

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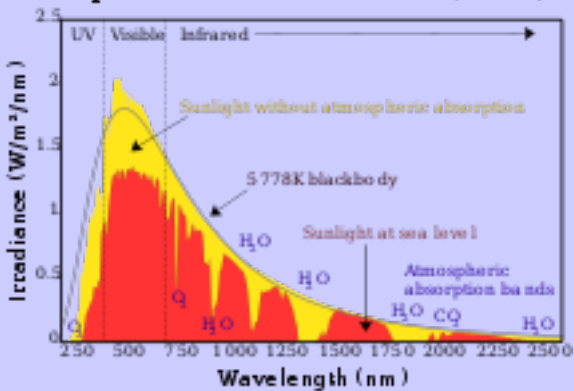
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Spectrum of Solar Radiation (Earth)



Hydrogen Spectrum

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Hydrogen Absorption Spectrum



Hydrogen Emission Spectrum



Spectrometer

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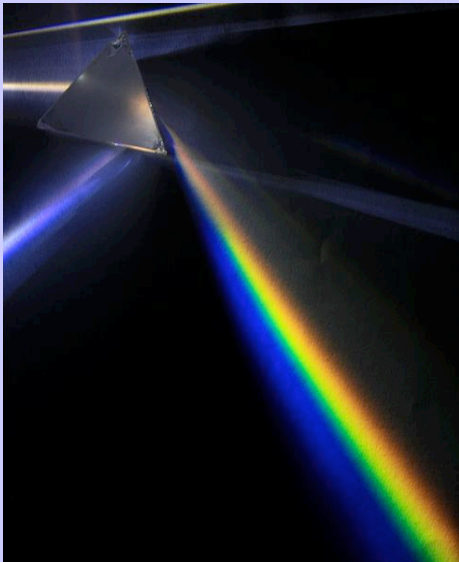
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Galaxy Spectrum

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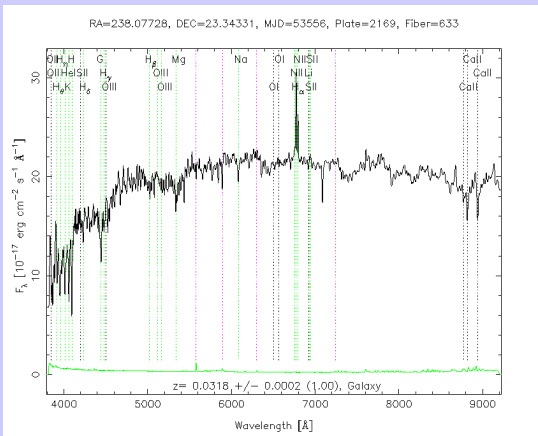
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Galaxy Redshift

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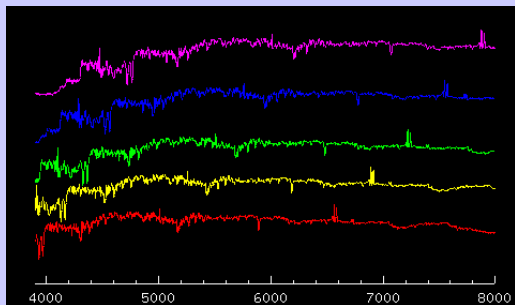
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Doppler Effect

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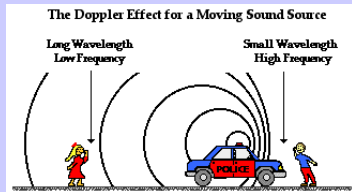
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Hubble Diagram

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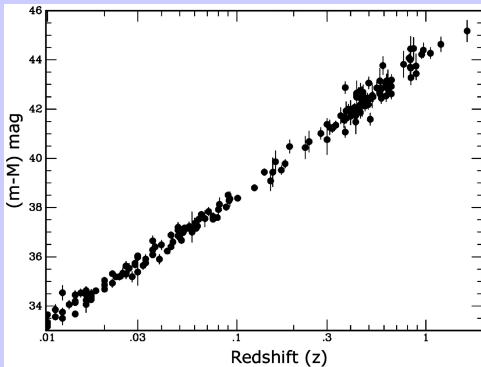
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The Expanding Universe

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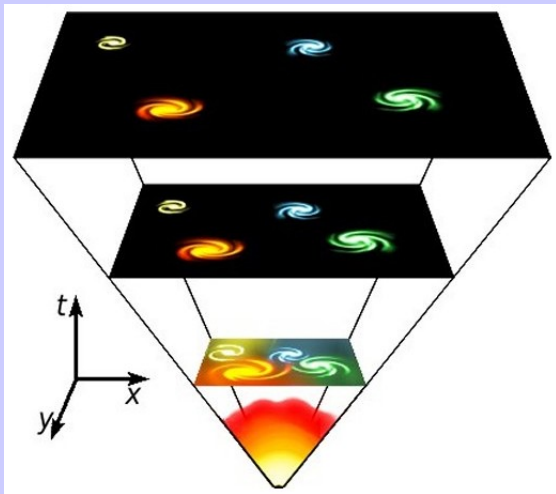
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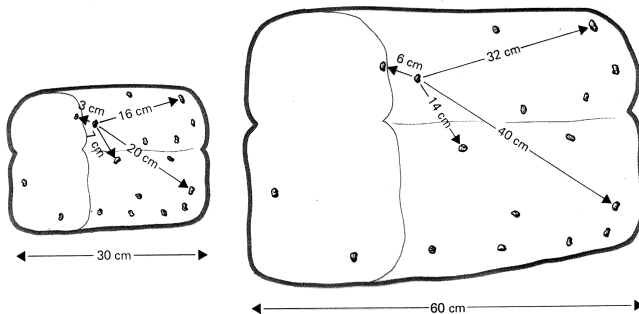


Figure 37.4 Expanding raisin bread.

The Expanding Universe

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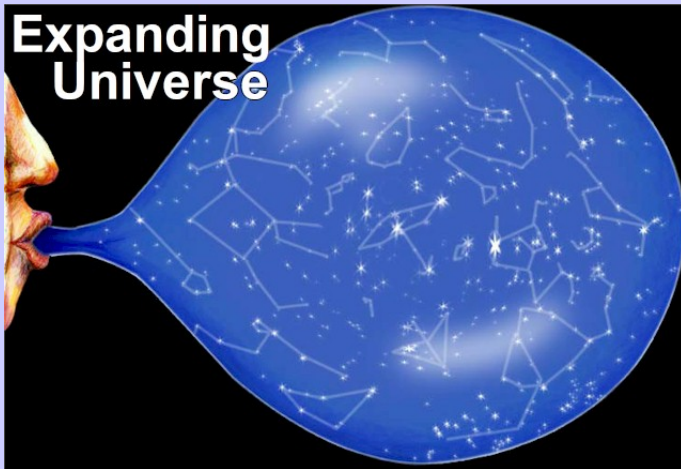
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Redshift Survey Results in 1989

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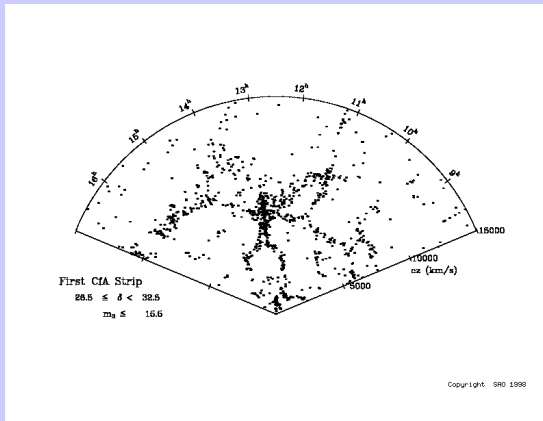
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Einstein

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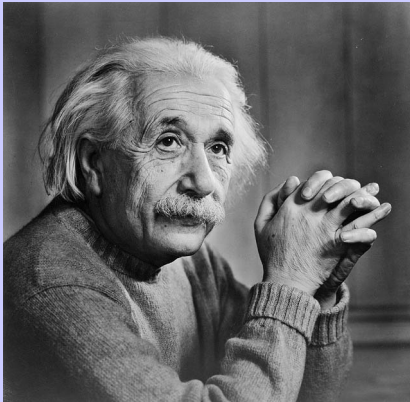
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History of the Universe

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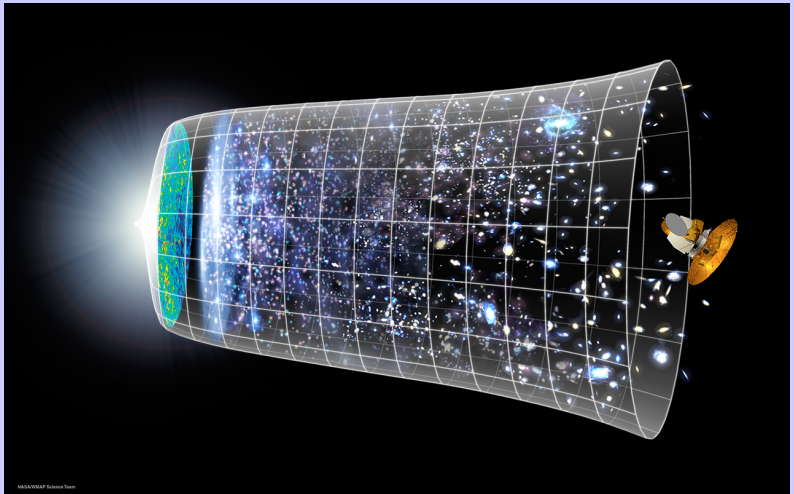
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NASA/WMAP Science Team

Microwave Telescopes on the Earth: ACT Telescope

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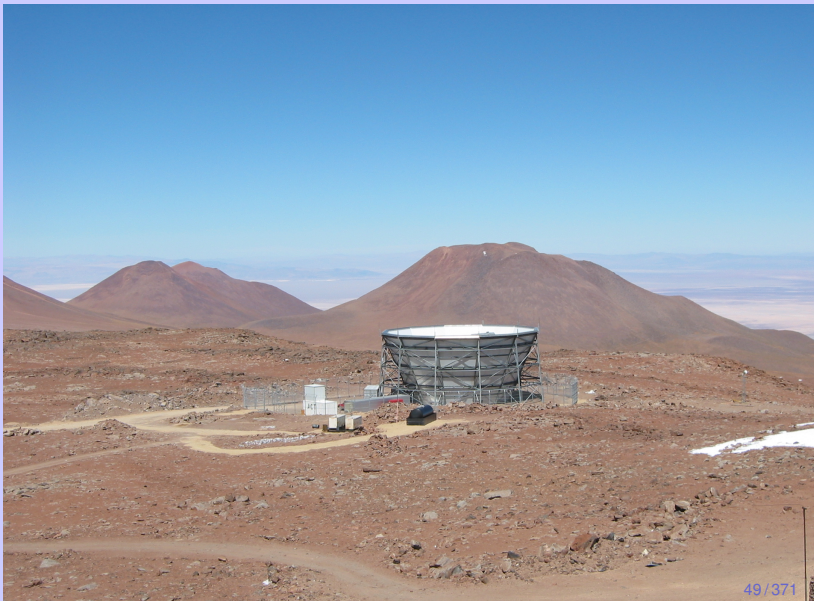
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Microwave Telescopes on the Earth: SPT Telescope

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Microwave Telescopes in Space: WMAP Telescope

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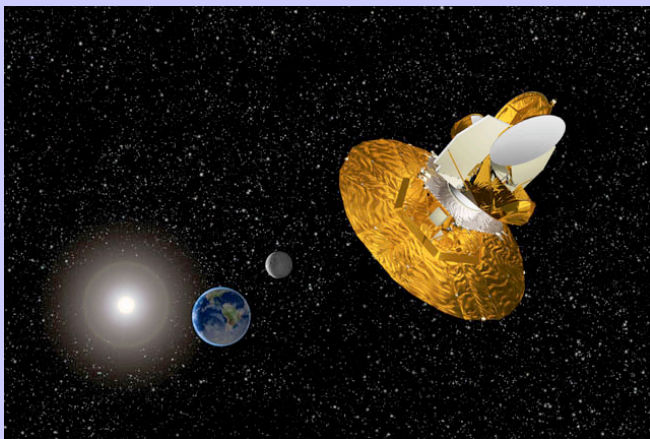
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Isotropic CMB Background

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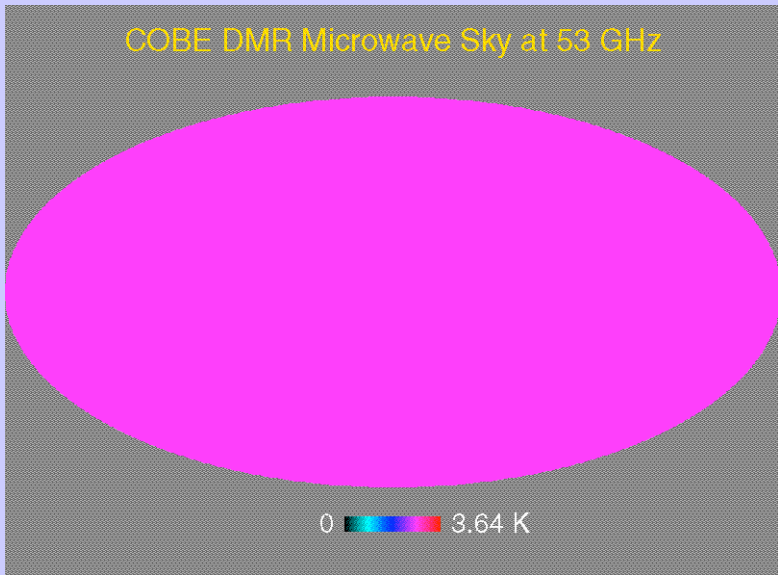
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COBE DMR Microwave Sky at 53 GHz



Anisotropies in the Cosmic Microwave Background (CMB)

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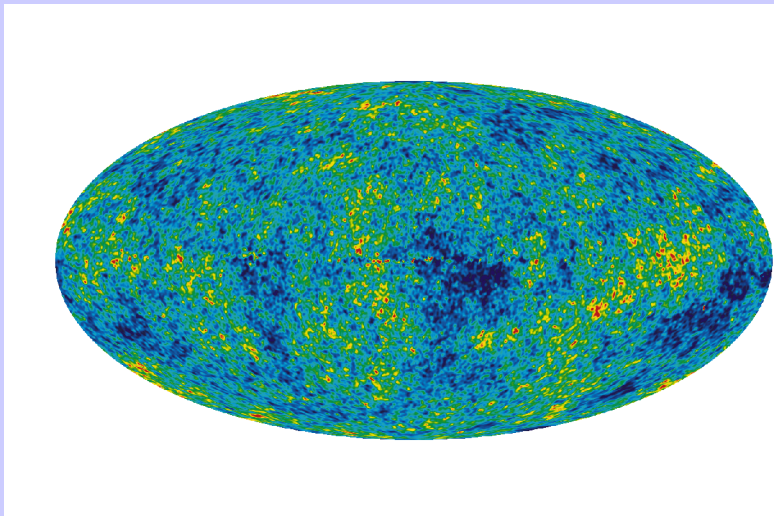
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Credit: NASA/WMAP Science Team

History of the Universe

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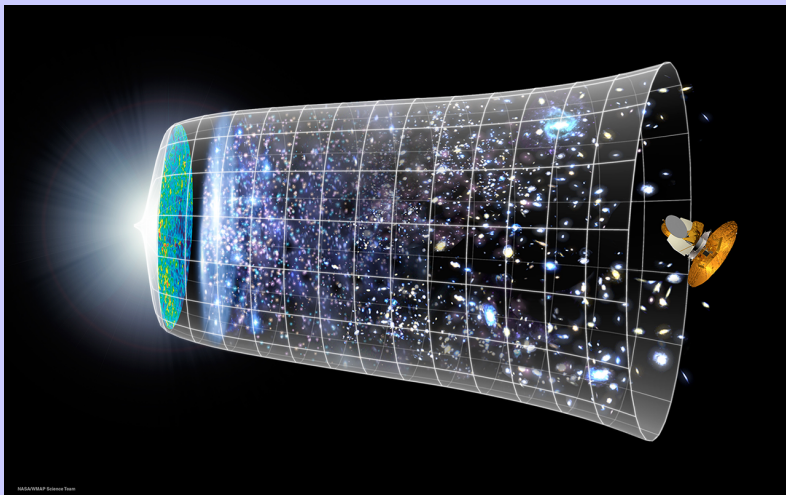
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Seasons

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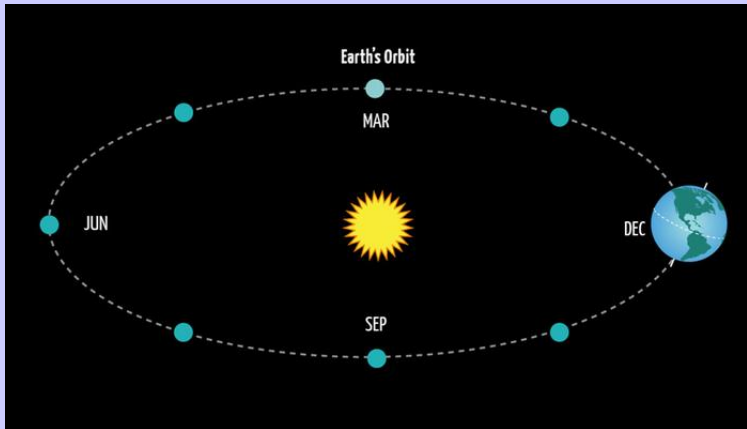
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Seasons

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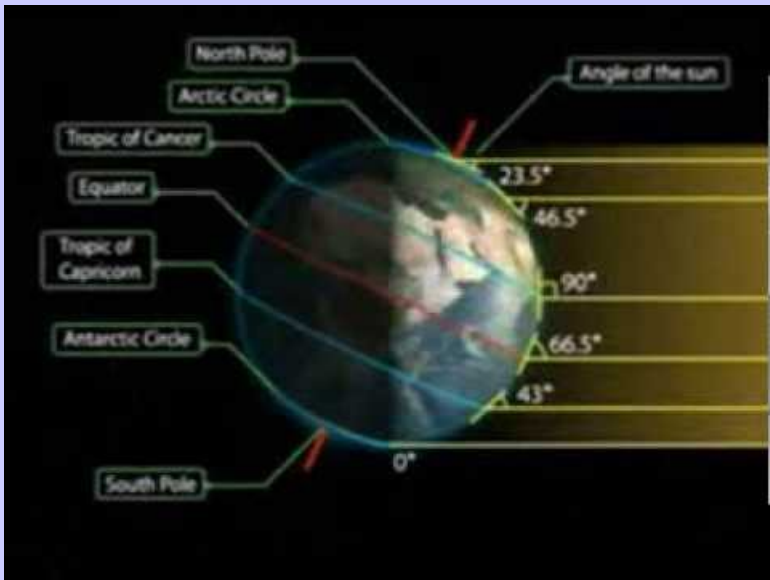
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Phases of the Moon

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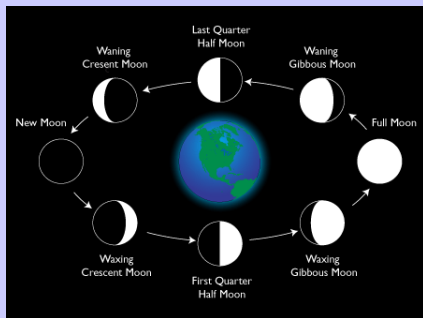
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Free Fall in Outer Space

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Angular Momentum

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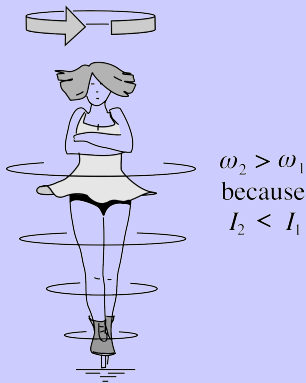
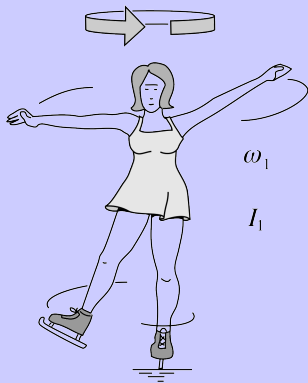
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Thermal Energy

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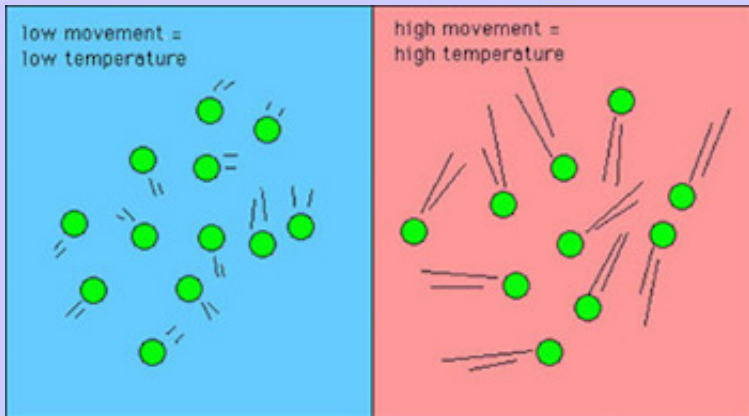
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Energy from Mass

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Kepler's First Law

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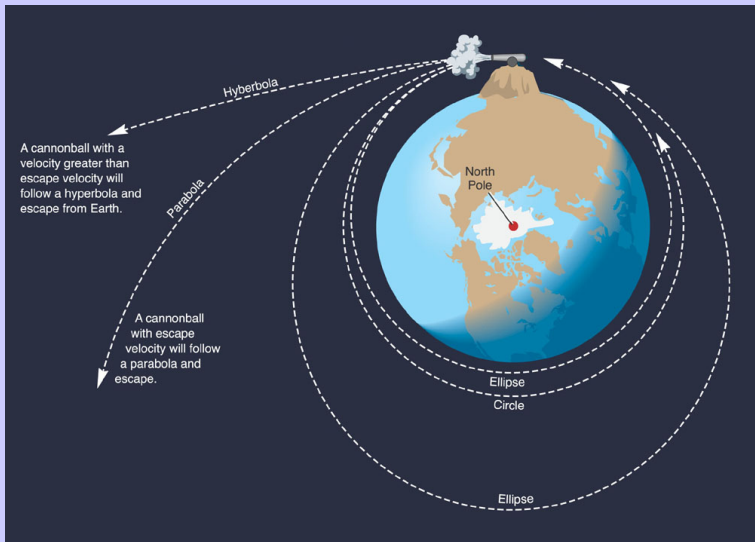
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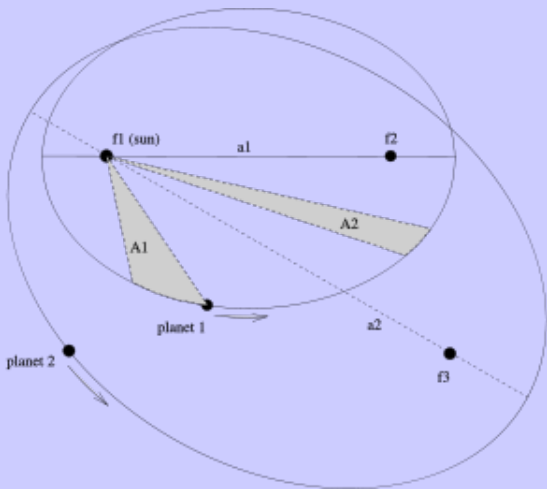
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Electromagnetic Spectrum

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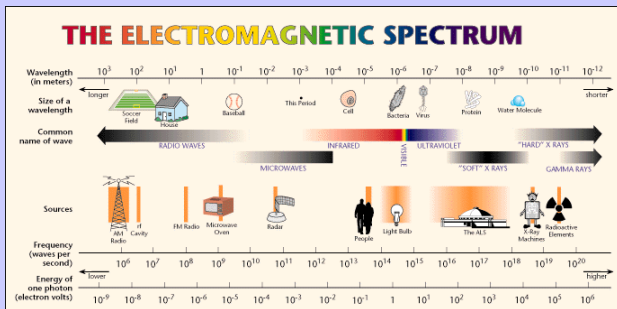
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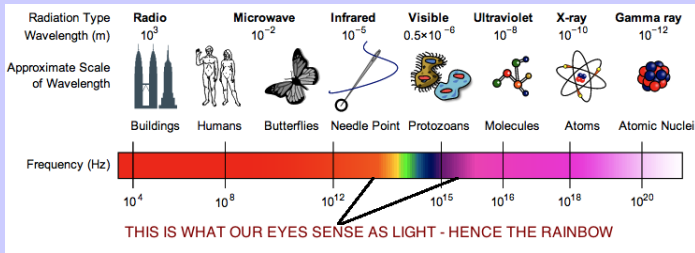
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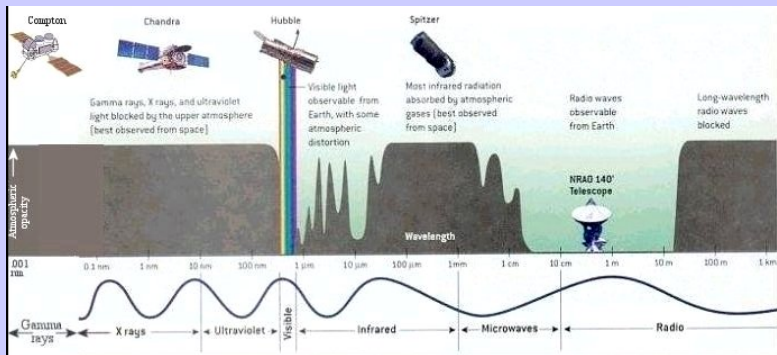
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Phases of Water

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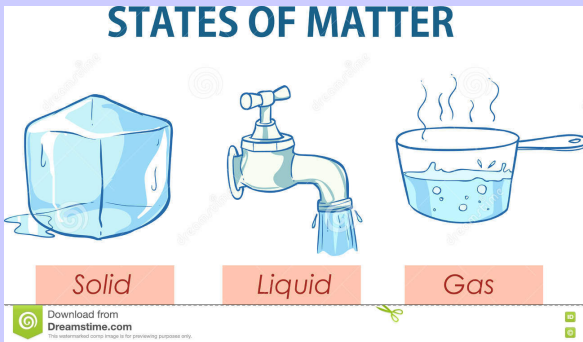
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Phases of Matter

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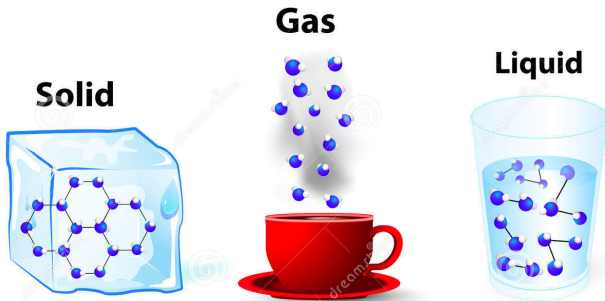
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FUNDAMENTAL STATES OF MATTER



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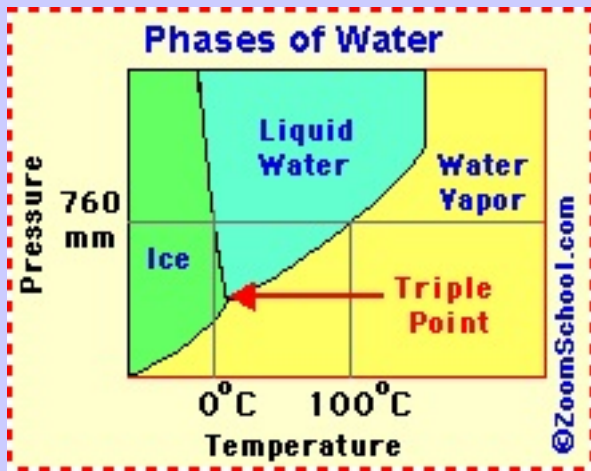
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The Picture of an Atom

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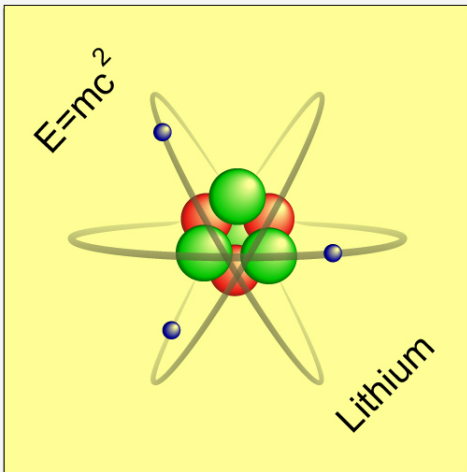
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Energy Levels of Hydrogen

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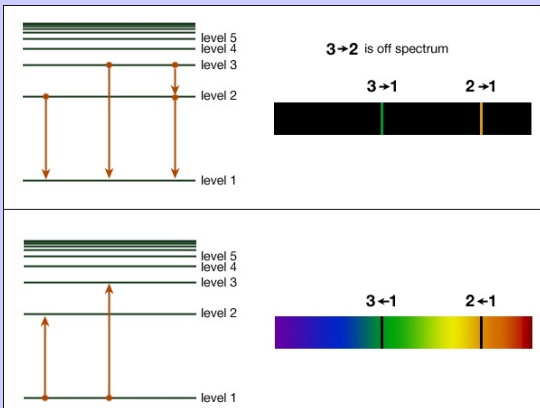
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Spectrum of Hydrogen

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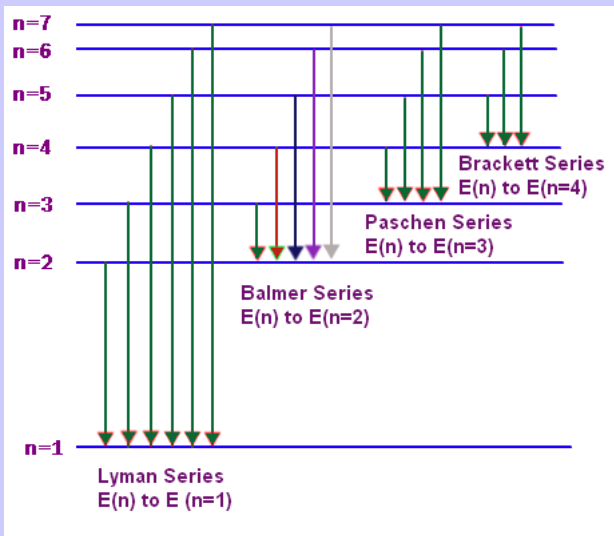
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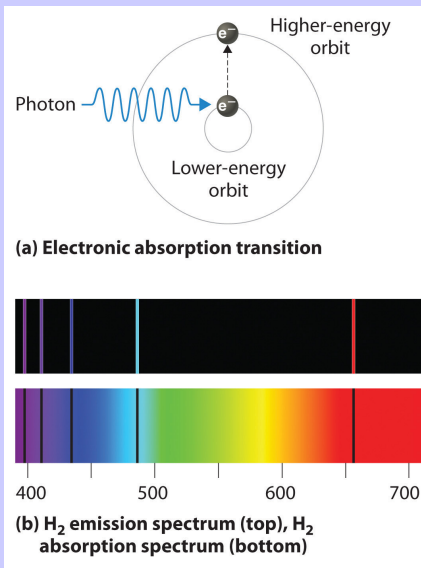
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Three Types of Spectra

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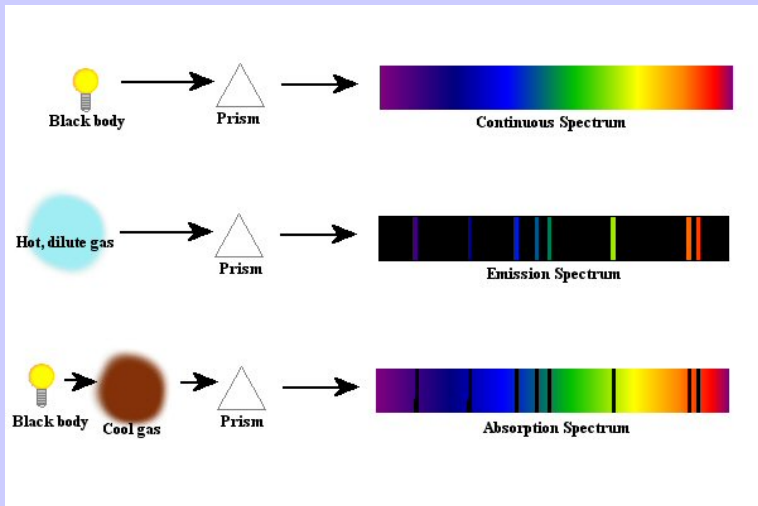
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Three Types of Spectra

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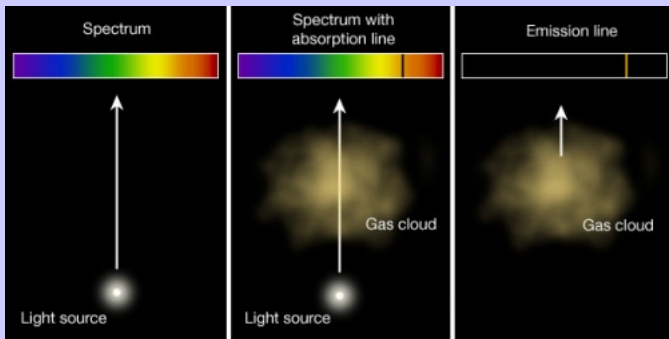
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Spectrum of Star and its Temperature

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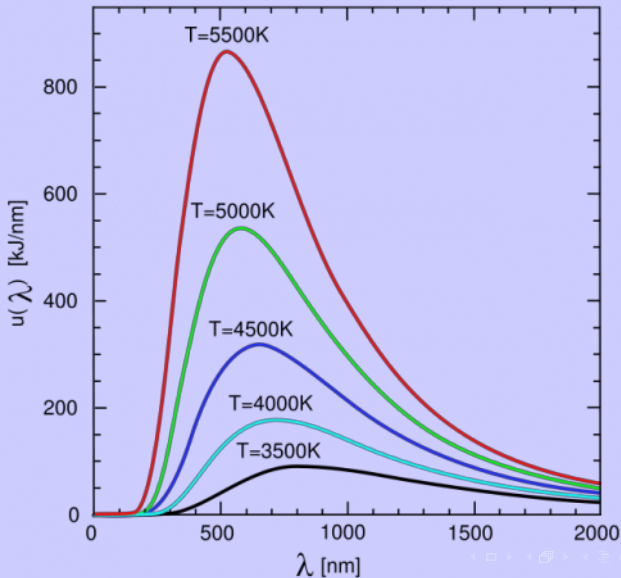
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Doppler Effect

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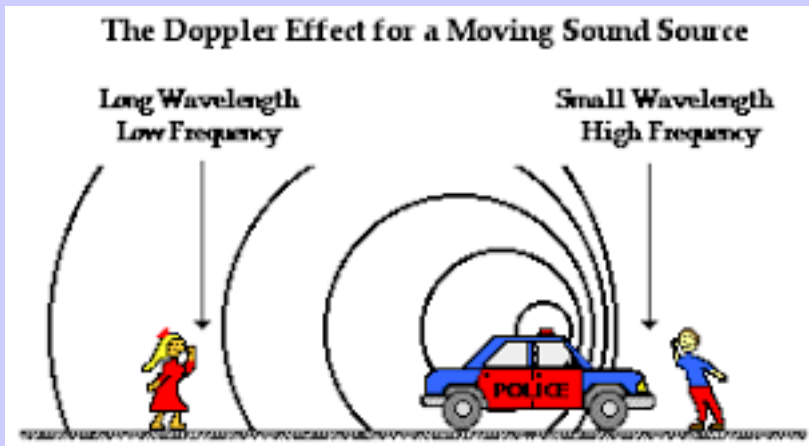
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Spectrometer

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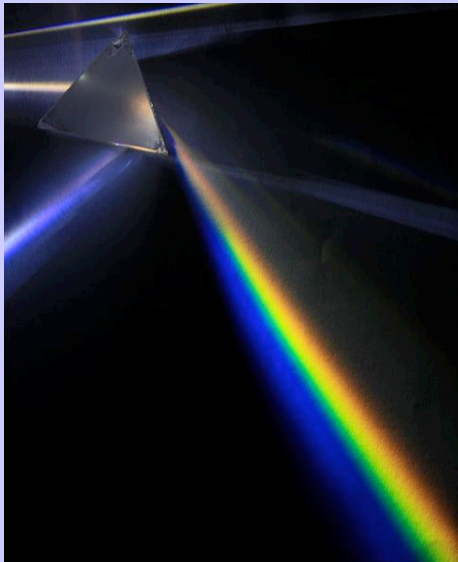
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Refraction of Sunlight

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Refraction of Sunlight

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The Eye

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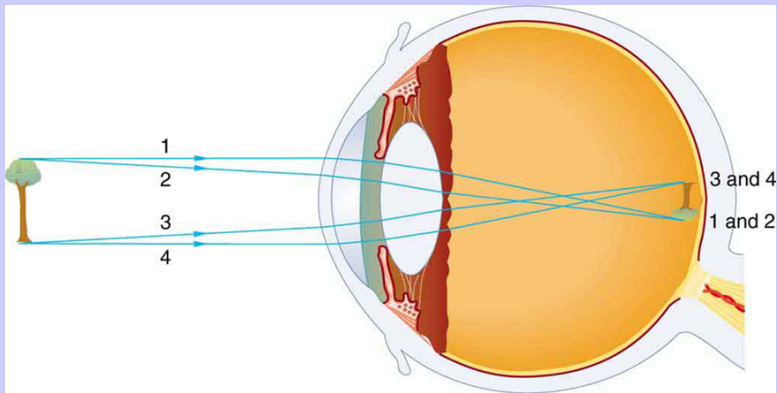
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Refracting Telescope

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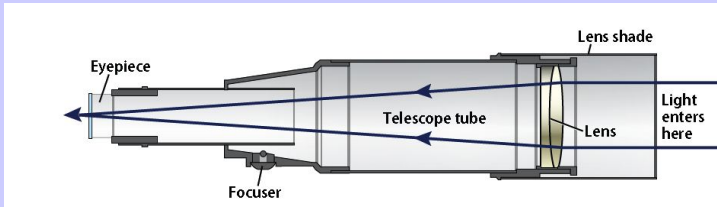
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Refracting Telescope

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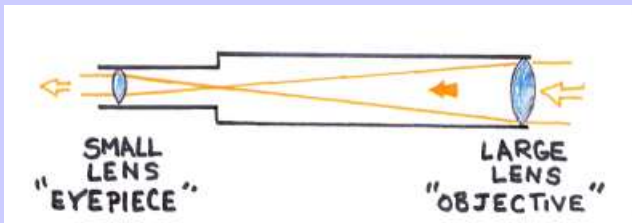
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Reflecting Telescope

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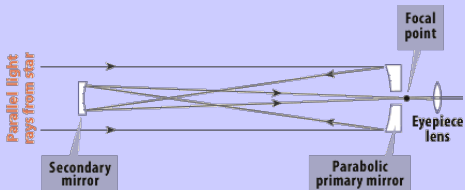
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Reflecting Telescope

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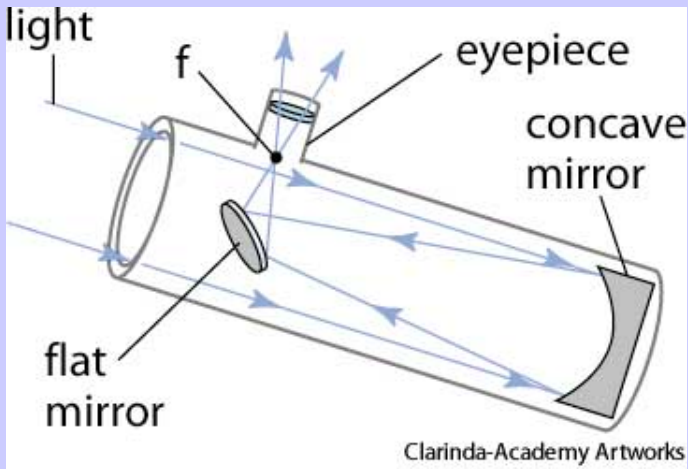
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Electromagnetic Spectrum

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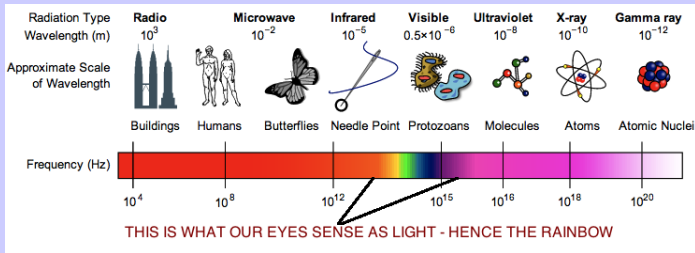
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Atmospheric Windows

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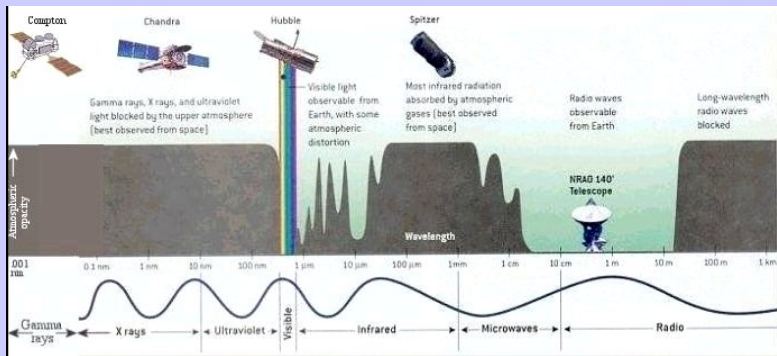
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Canada-France-Hawaii Optical Telescope

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Arecibo Radio Telescope

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CHIME 21cm Telescope

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South Pole Telescope CMB Experiment

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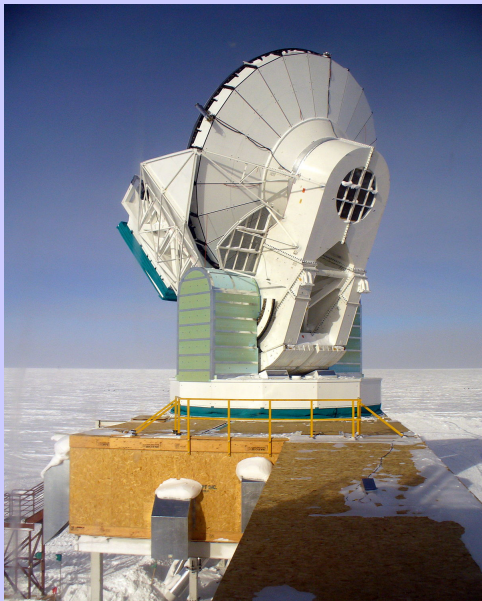
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WMAP CMB Satellite

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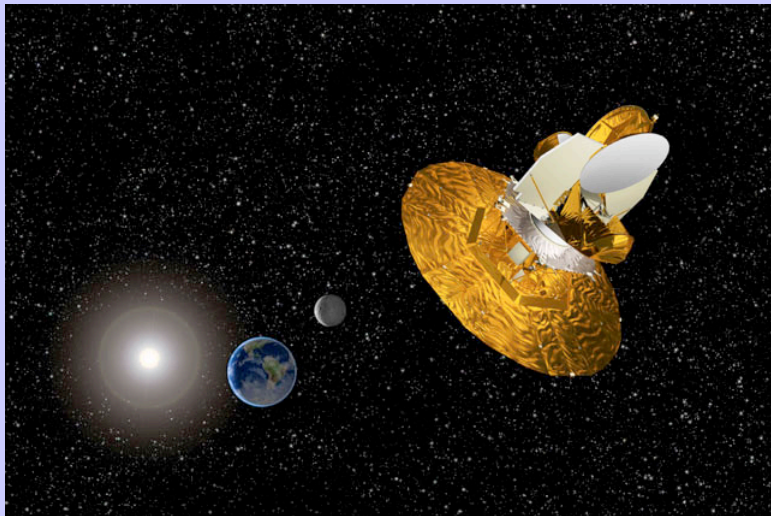
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ALMA: Infrared Telescope Array

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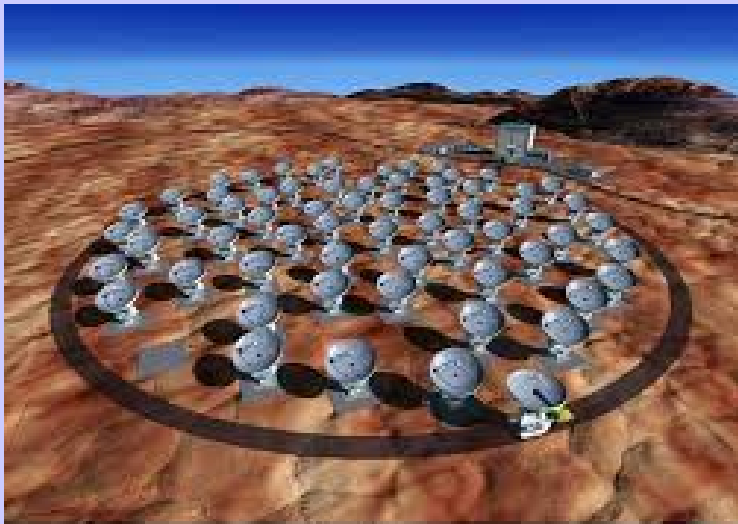
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ALMA at Chajnantor

Hubble Space Telescope: UV and Visible

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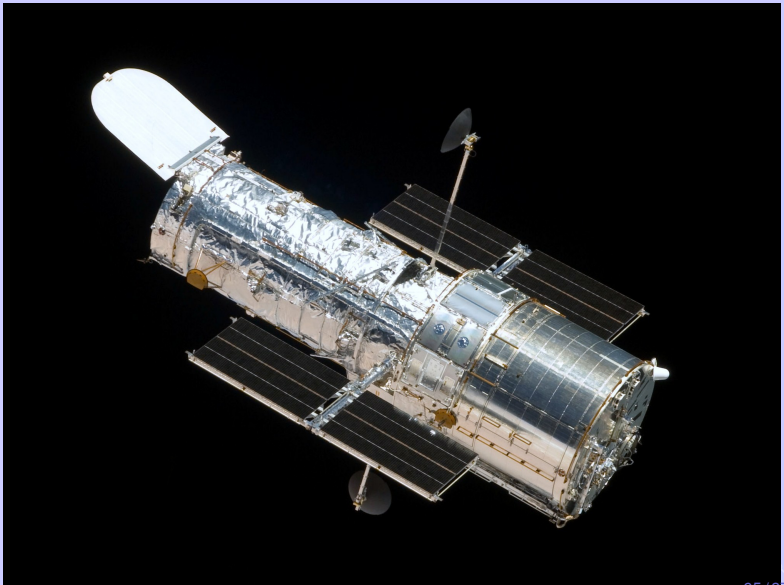
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CHANDRA X-Ray Telescope

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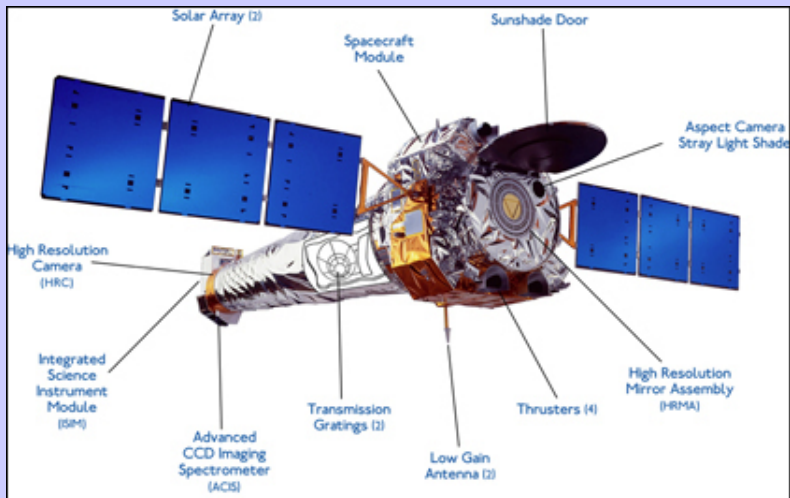
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FERMI: Gamma-ray Telescope

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Curved Space

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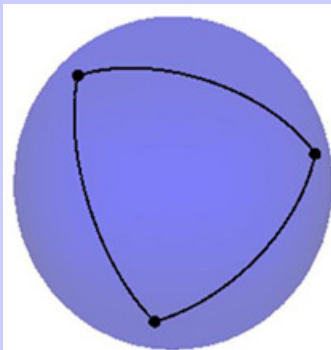
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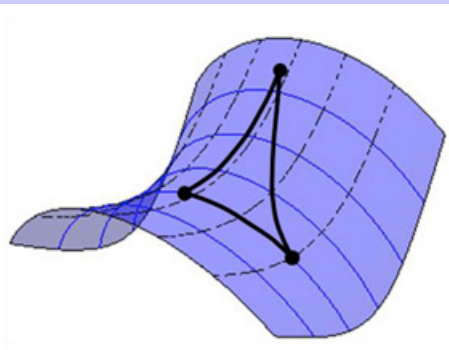
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positively curved space
sphere



negatively curved space
saddle

Mass curves Space-Time

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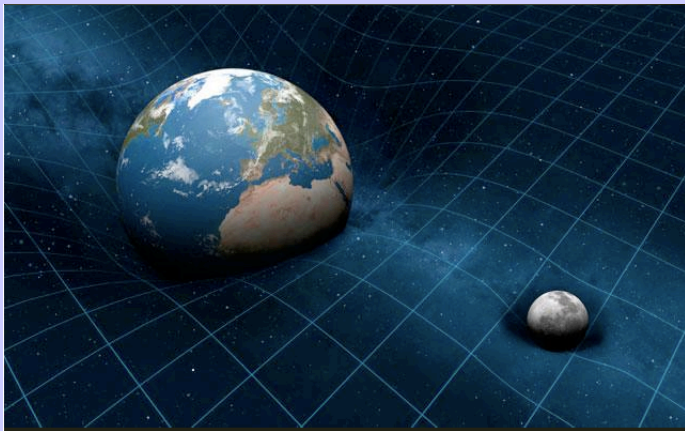
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Sun as a Black Hole

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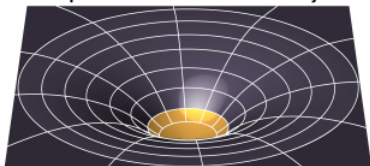
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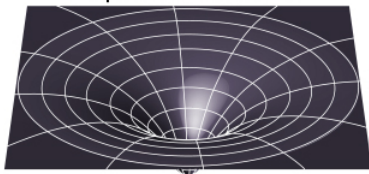
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spacetime around the Sun today

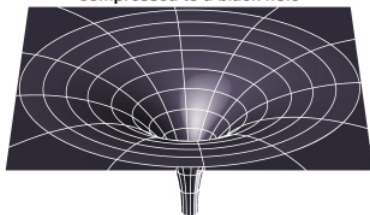


spacetime around the Sun
compressed to a white dwarf



(a)

spacetime around the Sun
compressed to a black hole



(b)

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Curved Space-Time

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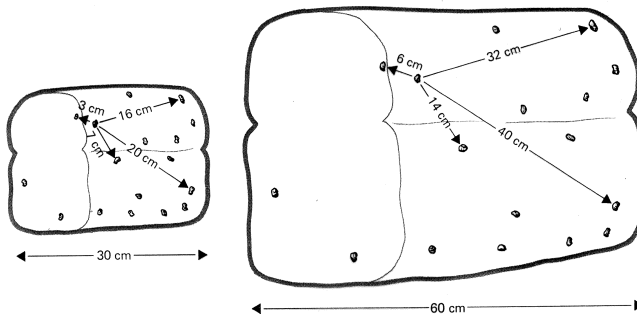


Figure 37.4 Expanding raisin bread.

Geodesics on the Earth

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Postdiction: Perihelion Precession of Mercury

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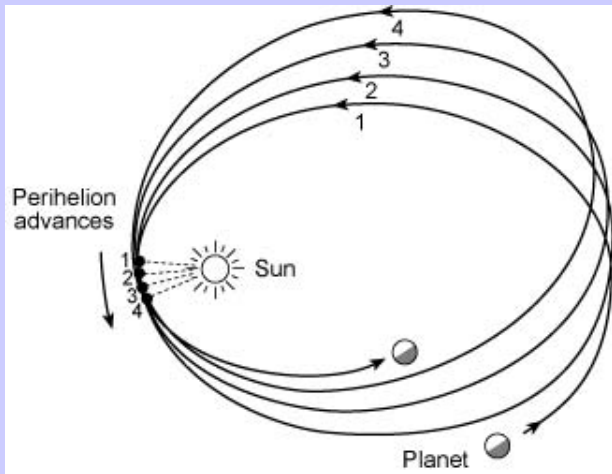
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Prediction: Bending of Light

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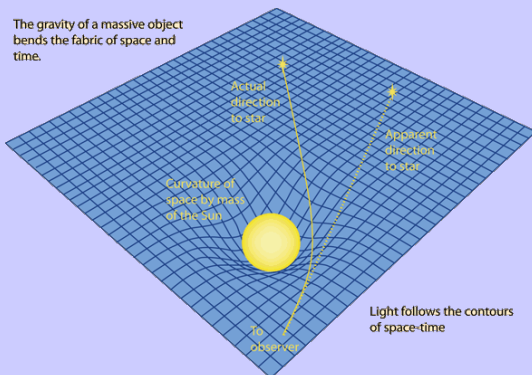
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Prediction: Black Holes

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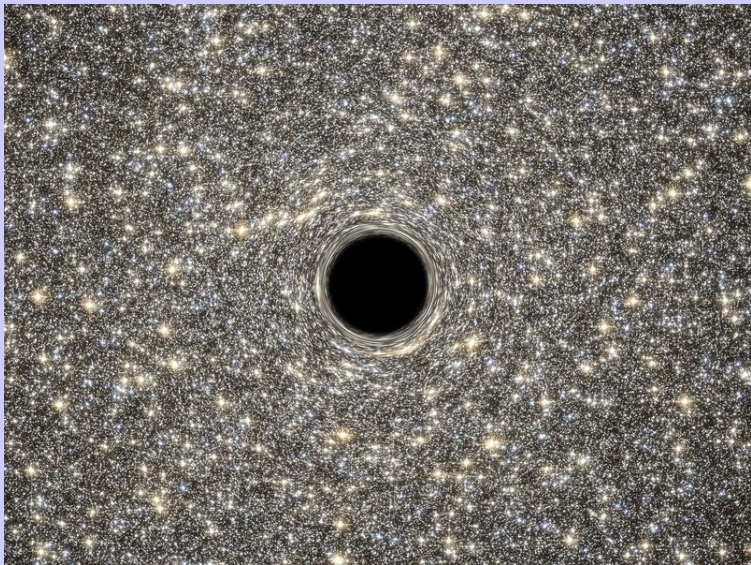
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Prediction: Expansion of the Universe

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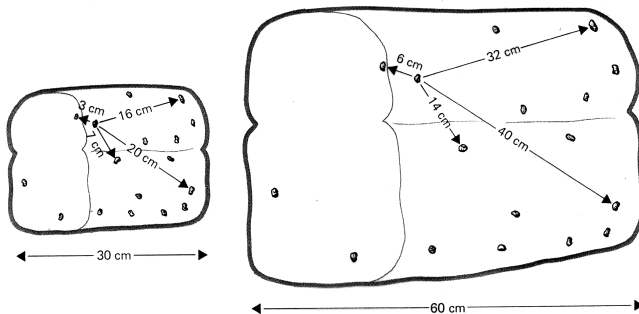


Figure 37.4 Expanding raisin bread.

Prediction: Gravitational Waves Exist

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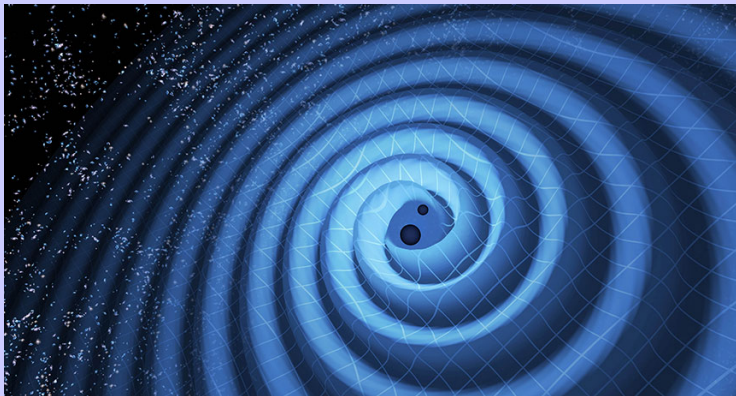
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LIGO Schematic

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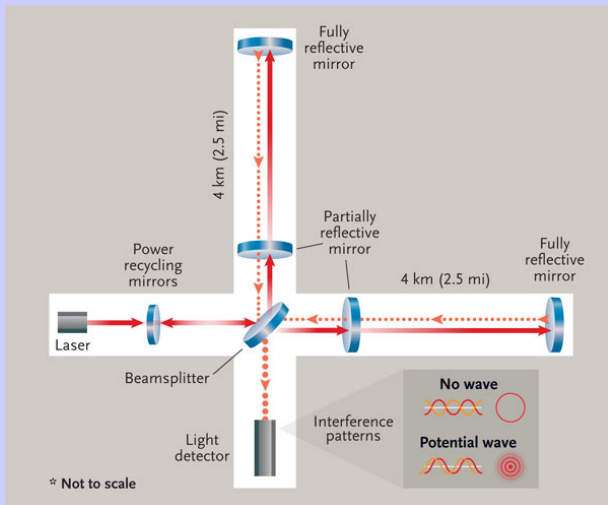
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LIGO Hanford Site

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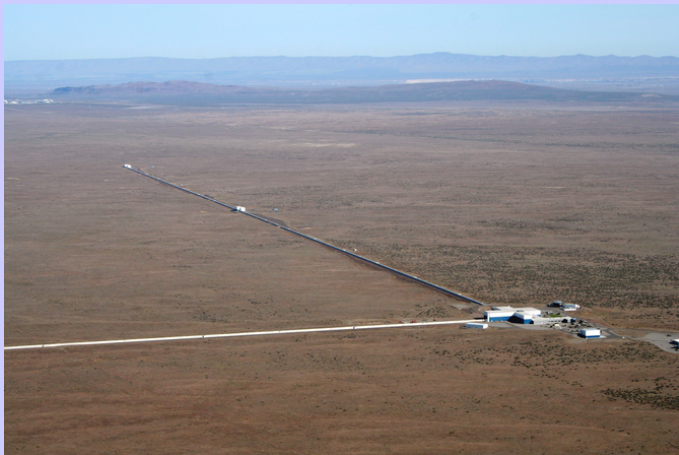
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Binary Black Hole

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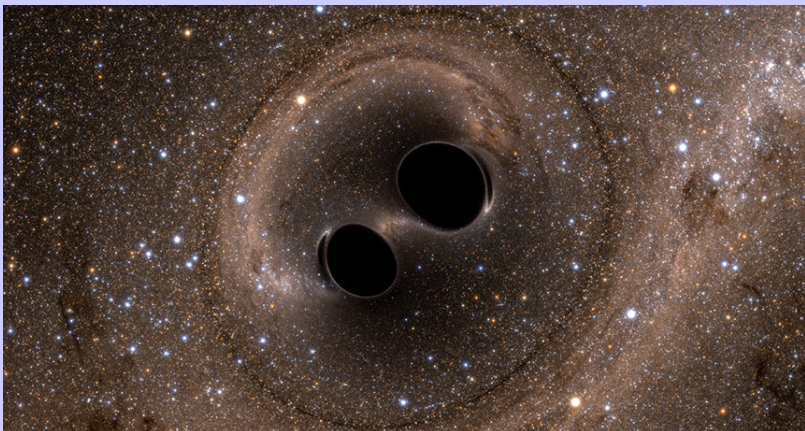
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LIGO Event

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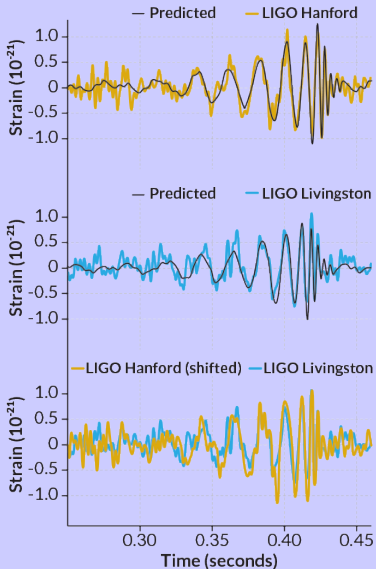
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Principle of Gravitational Lensing

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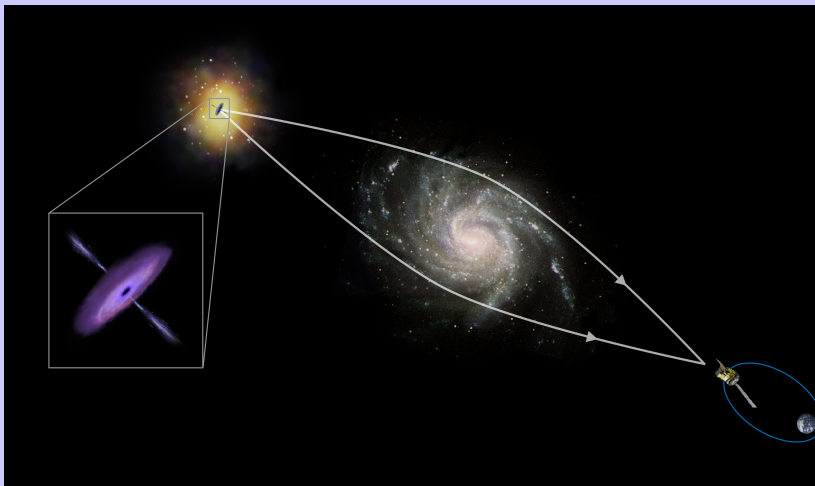
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Gravitational Lensing Ring (Einstein Ring)

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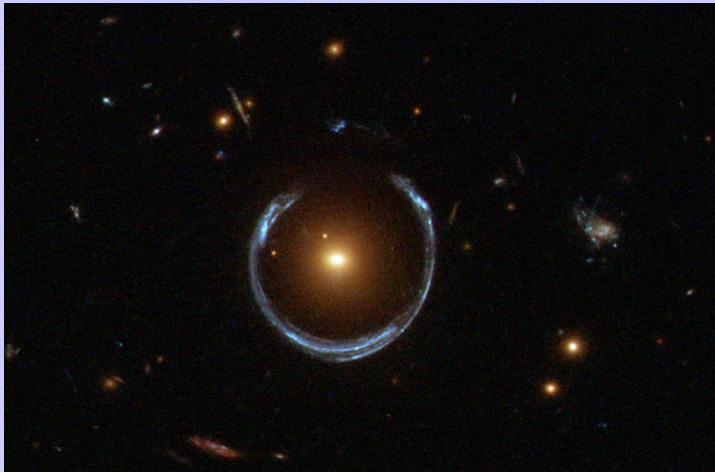
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Gravitational Lensing (HST Picture)

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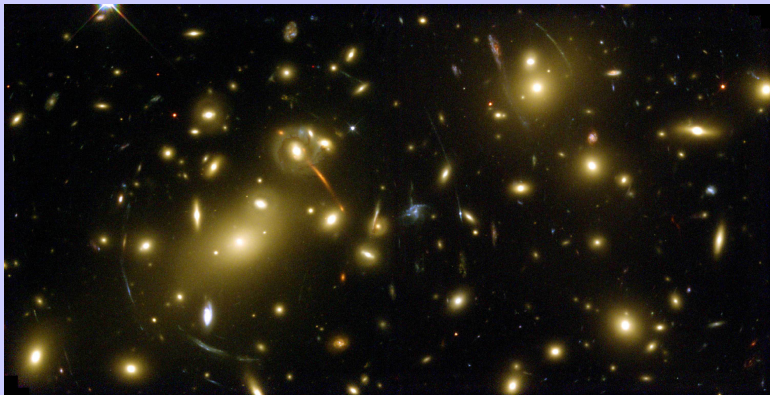
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Roemer: Determination of the speed of light

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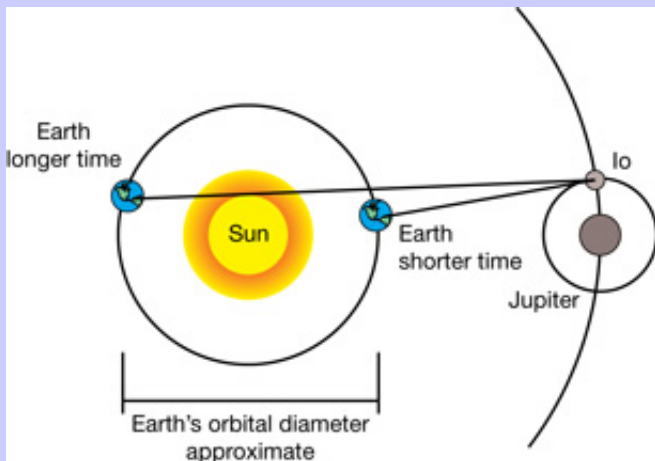
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Fizeau Experiment

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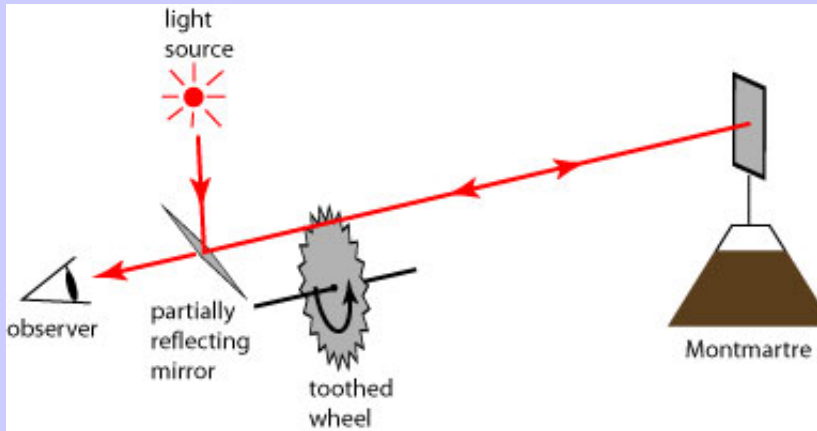
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Michelson-Morley Experiment

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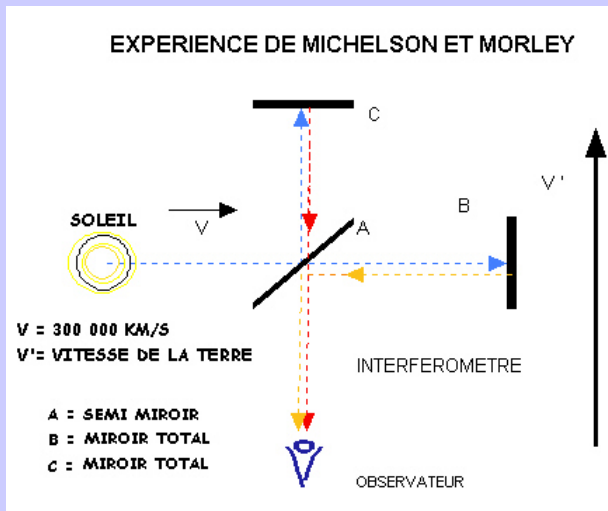
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Length Contraction

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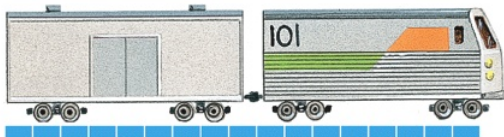
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At rest



In motion

a Length contraction

Ernest Rutherford

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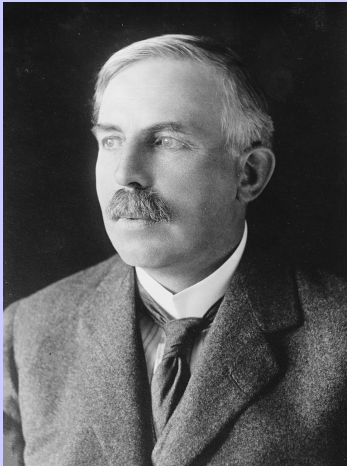
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Niels Bohr

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Max Planck

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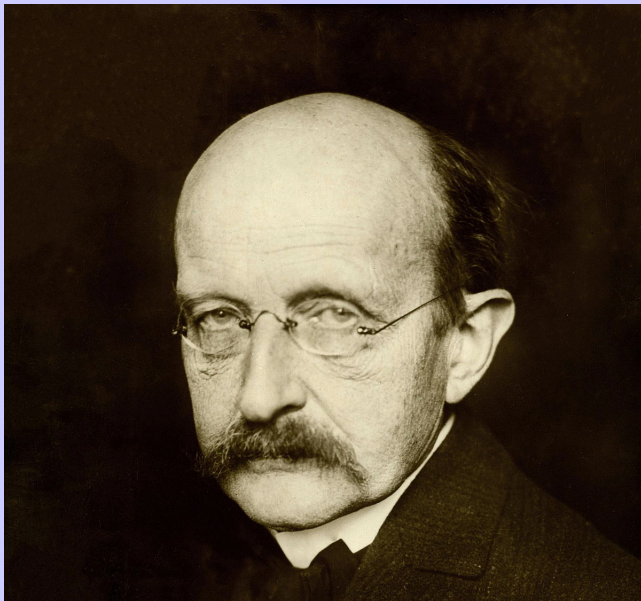
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Erwin Schroedinger

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Werner Heisenberg

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Marie Curie

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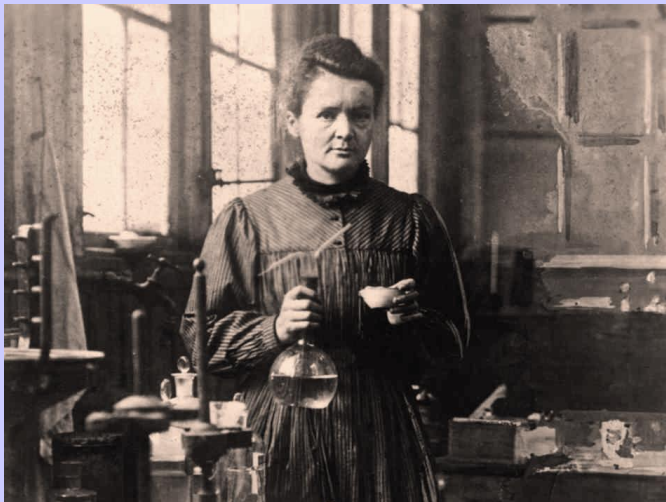
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Bohr Model of the Atom

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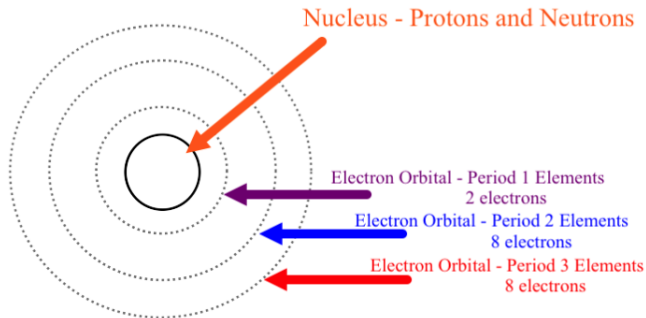
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Bohr's Atom



Spectrum of Hydrogen

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Our Place

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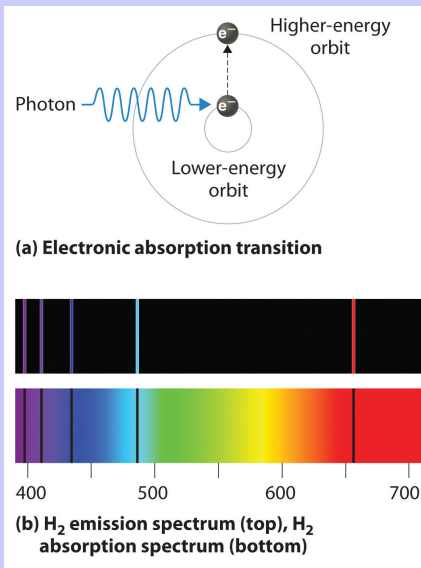
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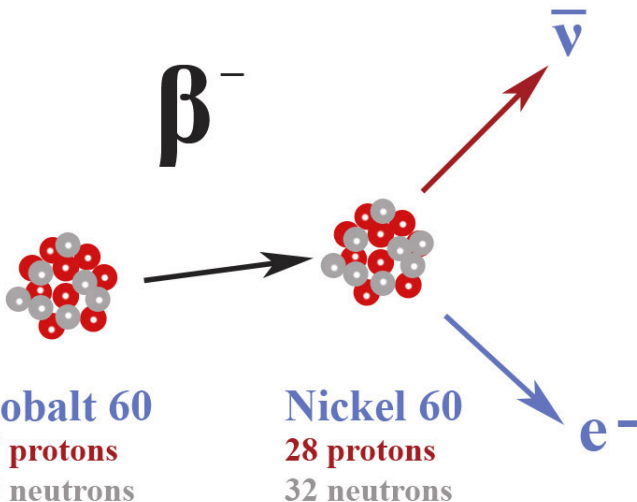
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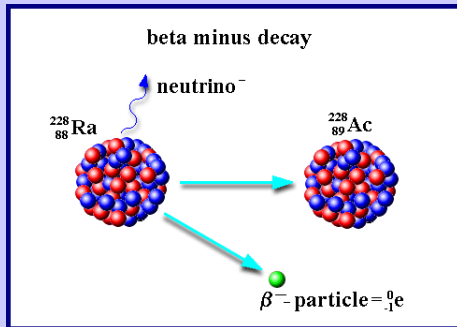
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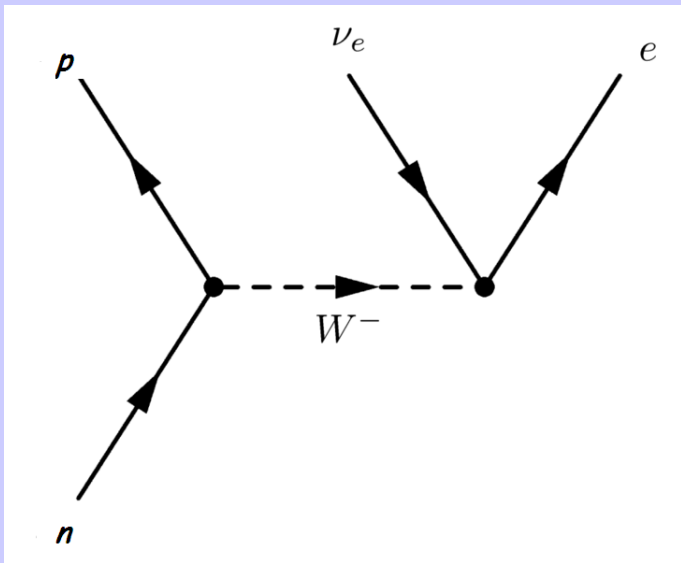
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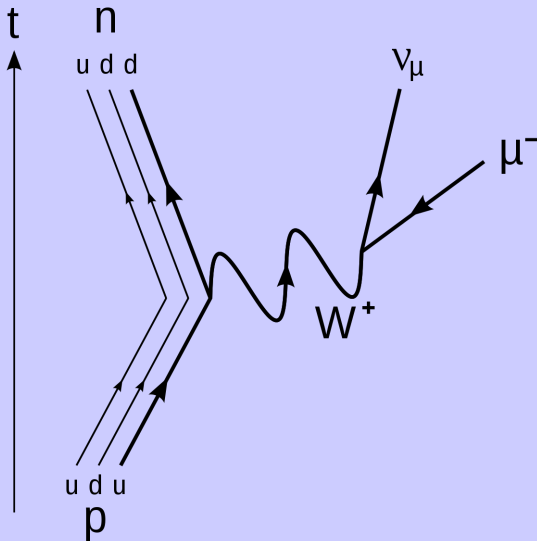
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Standard Model of Particle Physics

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Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
Quarks	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
	$\ll 2.2$ eV 0 $\frac{1}{2}$ ν_e electron neutrino	$\ll 0.17$ MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	$\ll 15.5$ MeV 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV 0 1 Z weak force
	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	80.4 GeV ± 1 1 W weak force
Leptons				Bosons (Forces)

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Hydrogen Wave Functions

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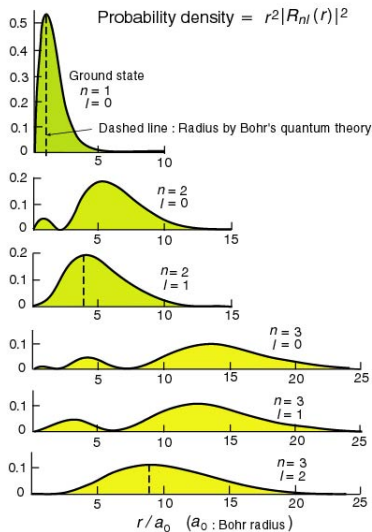
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Fig. (C)



Hydrogen Wave Functions

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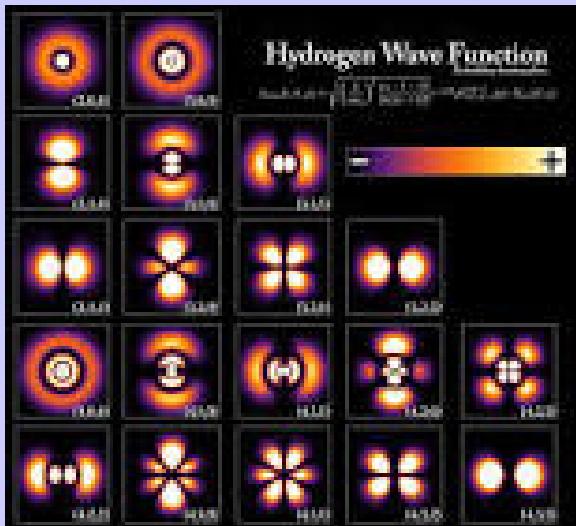
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Fission vs. Fusion

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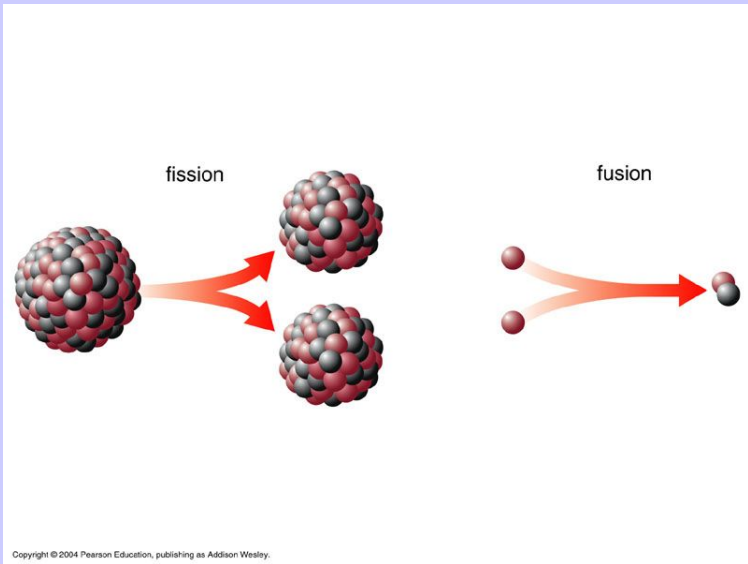
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Solar Spectrum

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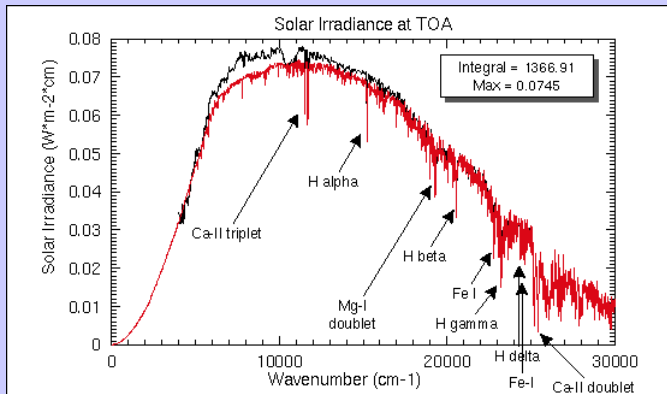
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The Proton-Proton Fusion Chain

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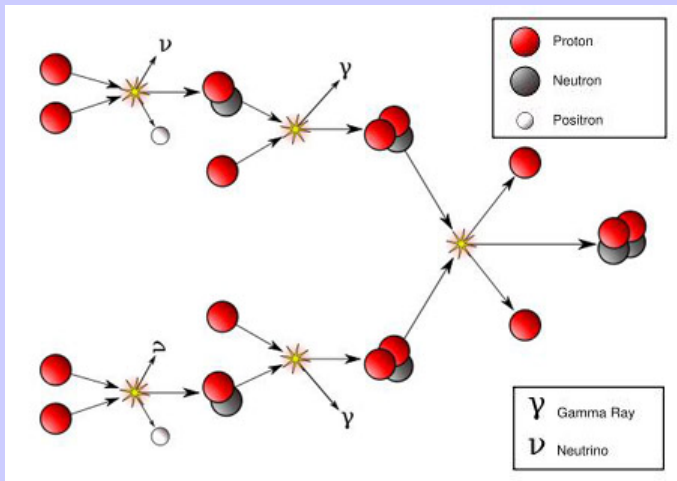
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Structure of the Sun

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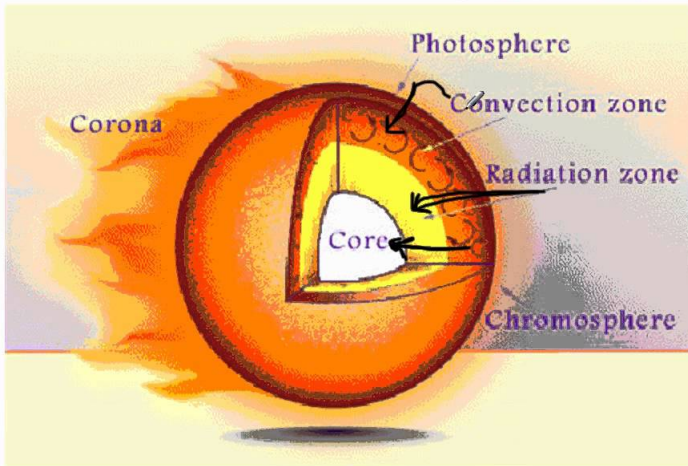
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Layers

Temperature Profile of the Sun

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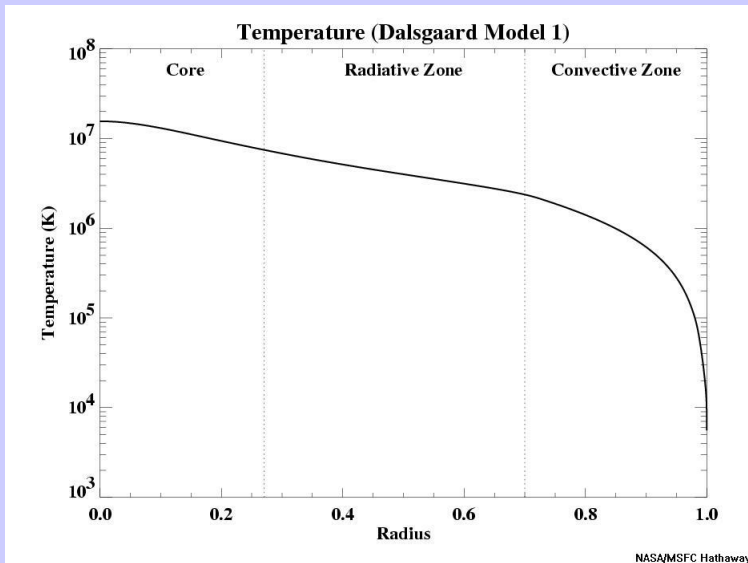
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Radiative Zone

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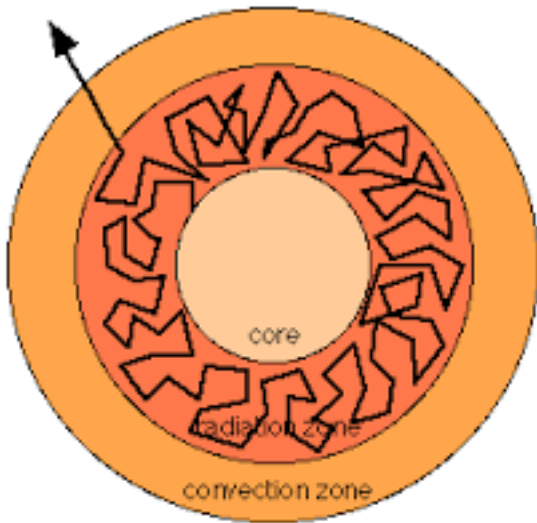
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Convection

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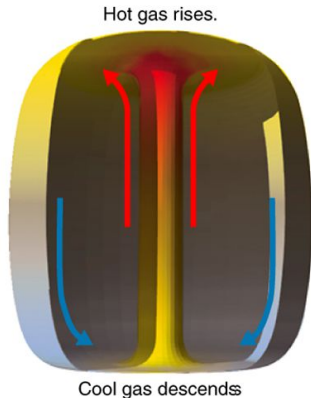
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Convection

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”.



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Solar Thermostat

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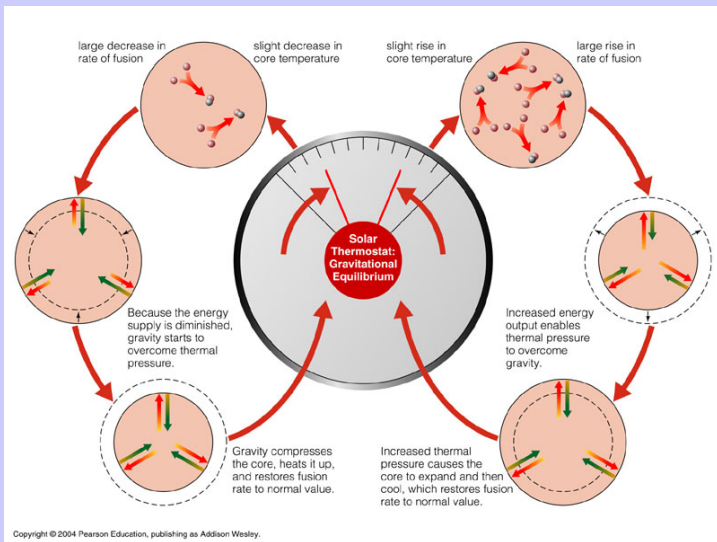
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Radiative Zone

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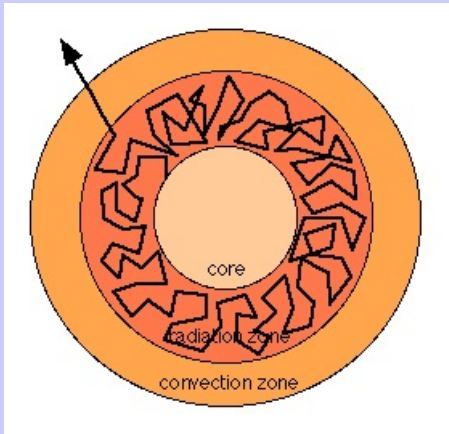
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Convective Zone

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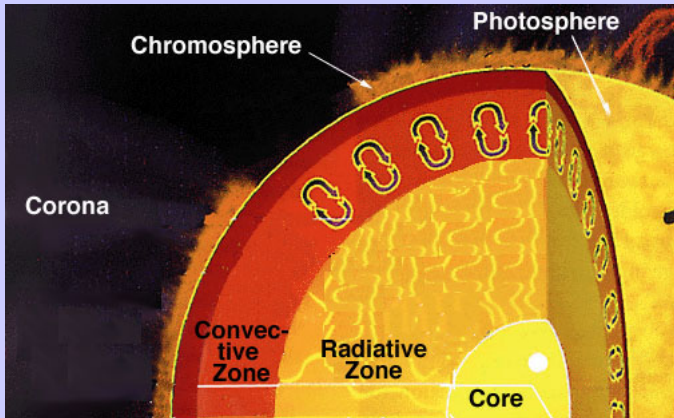
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Convection

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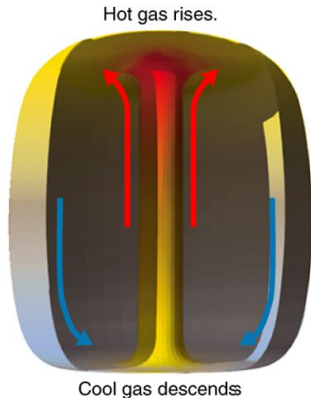
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Convection

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”.



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Solar Surface: Sunspots

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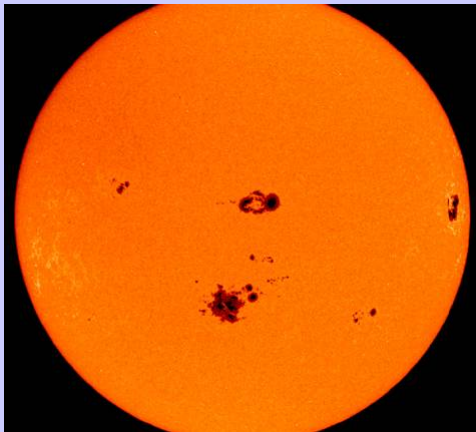
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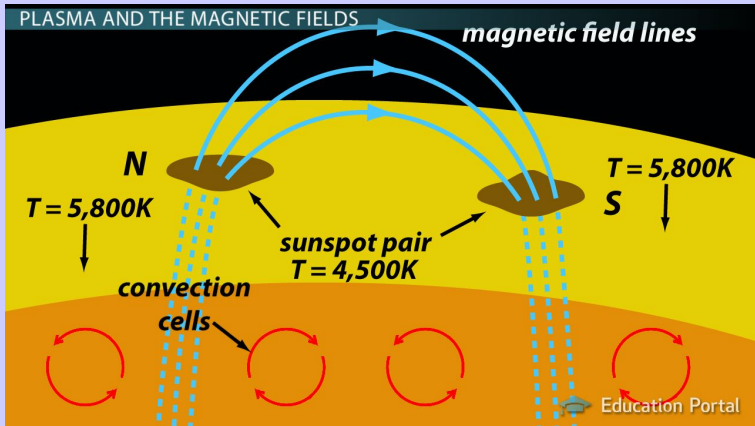
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Sunspot Mechanism



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Solar Photosphere

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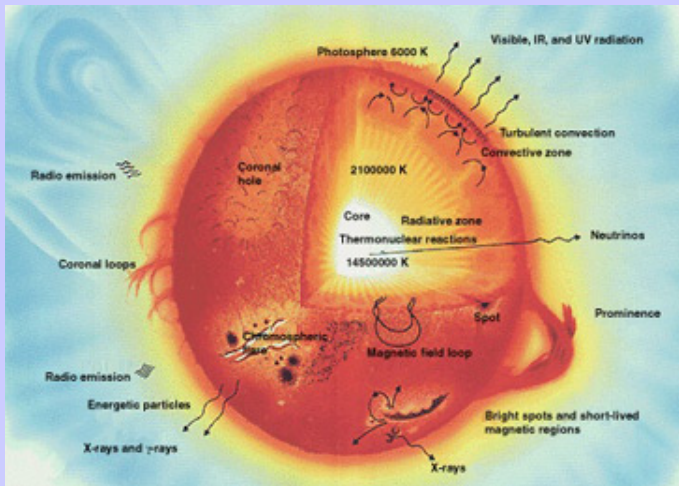
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Solar Prominence

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Solar Eruption

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Solar Chromosphere

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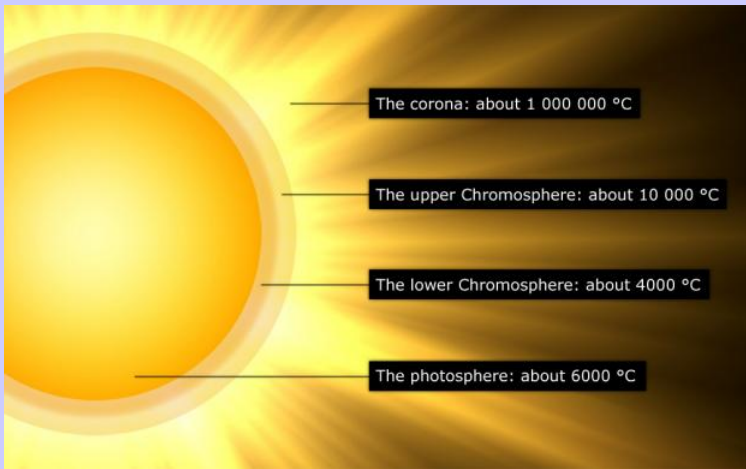
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Structure of the Sun

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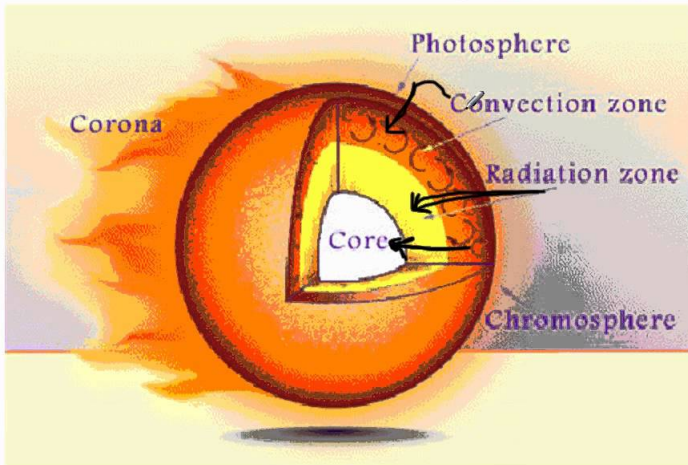
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Layers

The Night Sky

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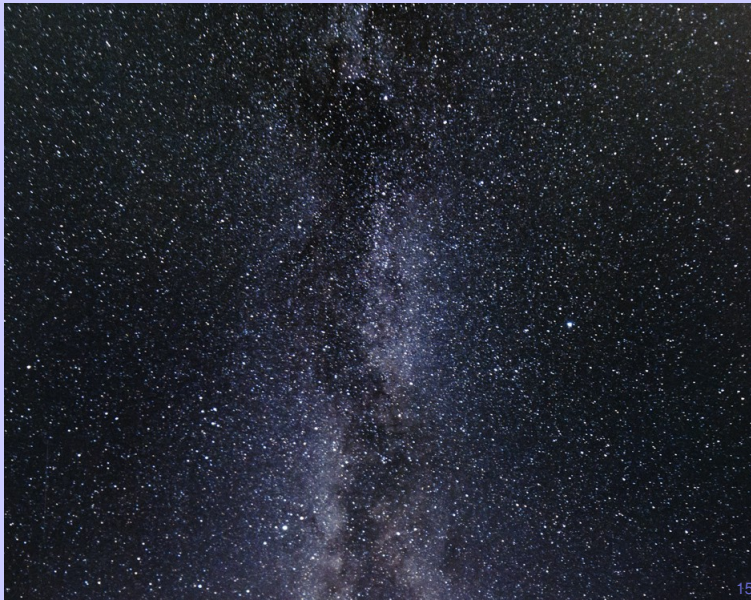
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Constellations: Orion

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Spectral Sequence

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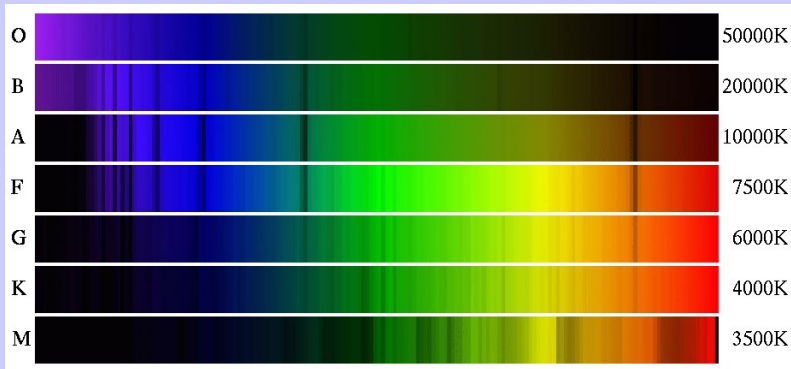
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Visual Binary Star System

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Spectroscopic Binary Star System

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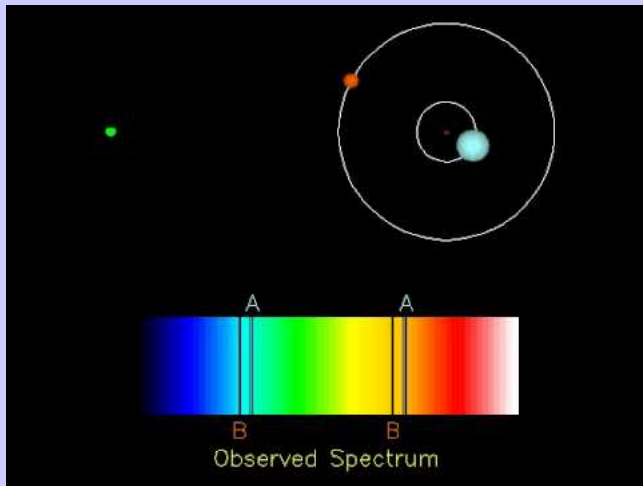
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Eclipsing Binary Star System

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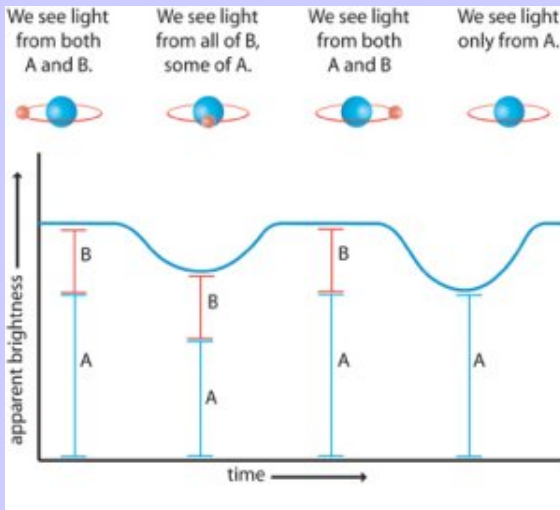
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Eclipsing Binary Star System - Model

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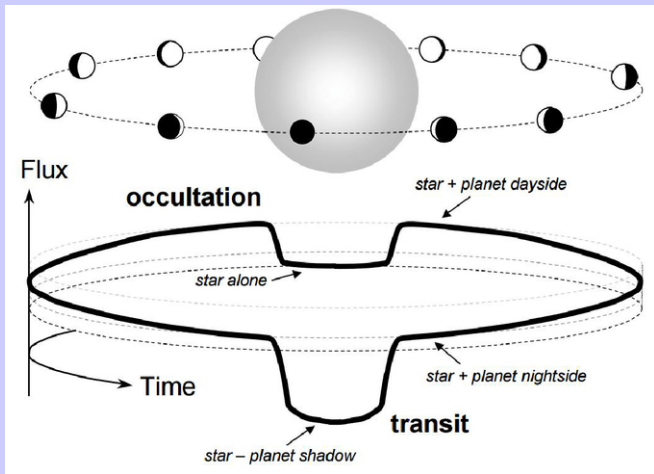
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Eclipsing Binary Star System - Data

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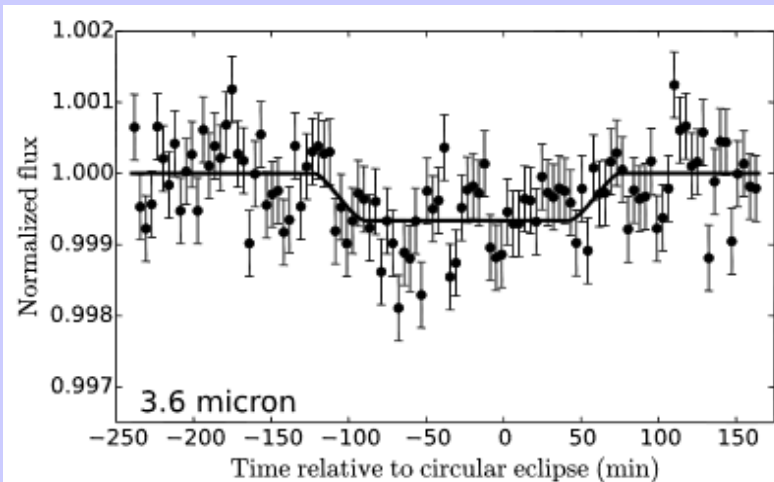
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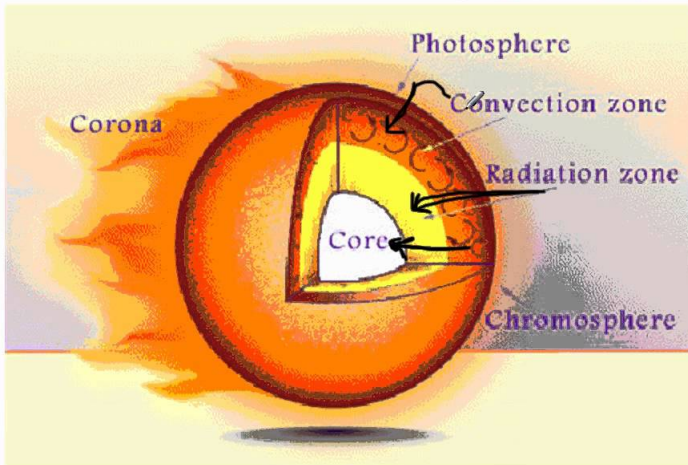
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The Proton-Proton Fusion Chain

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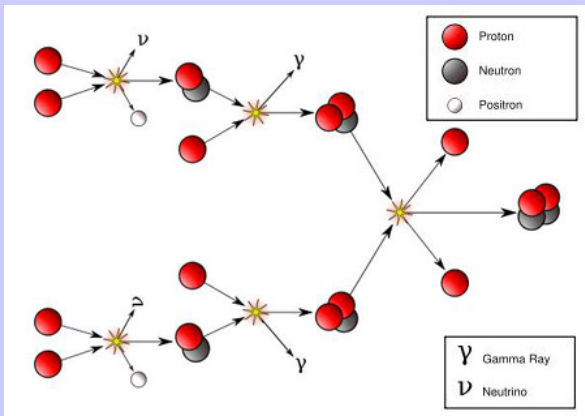
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Hertzprung-Russell Diagram

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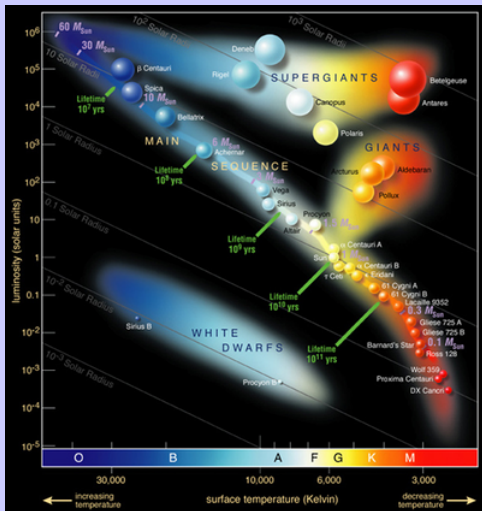
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Sub-Giant Star

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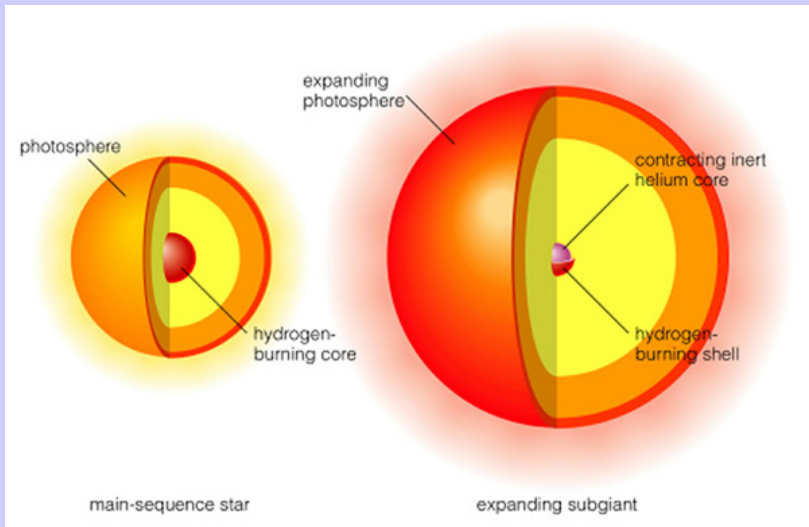
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Helium Fusion

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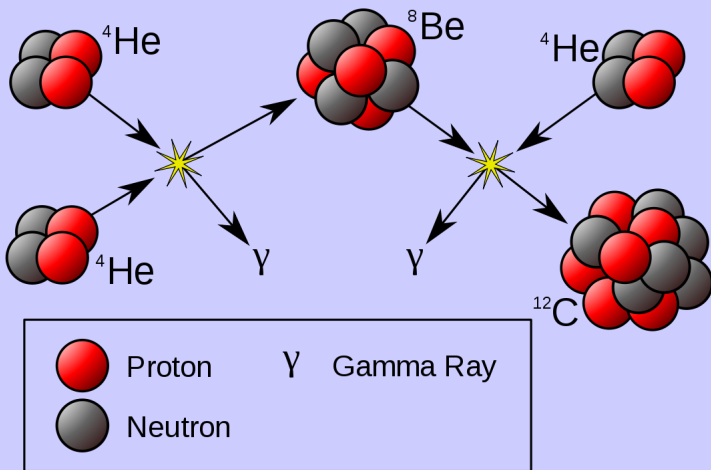
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Red Giant

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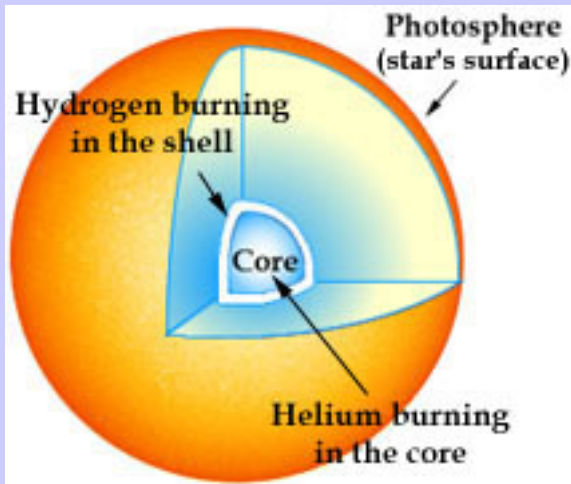
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Evolution off the Main Sequence

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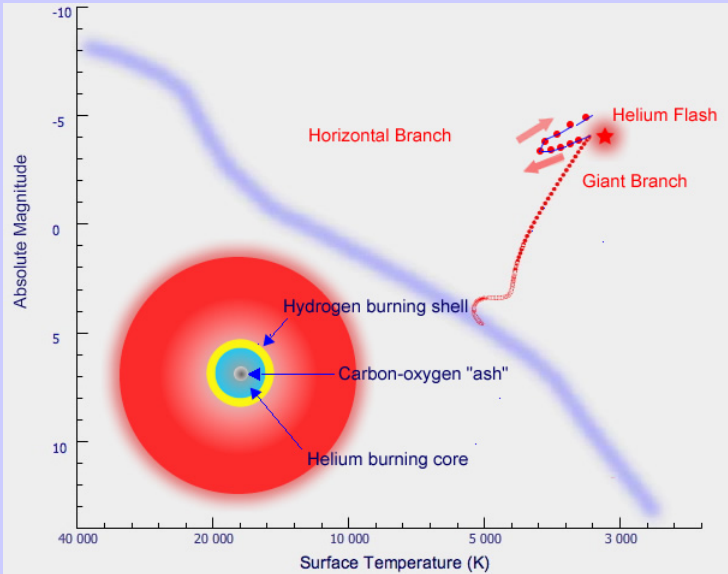
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Hertzprung-Russell Diagram

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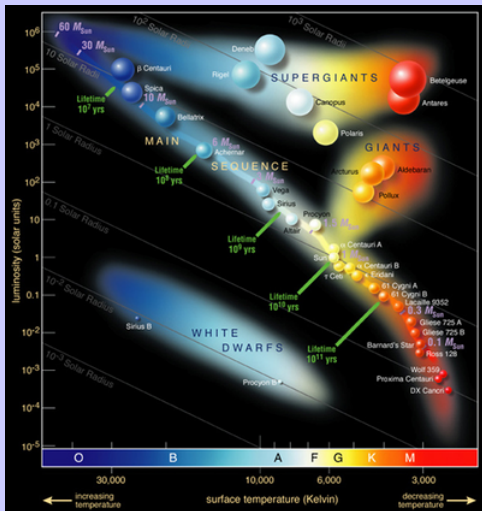
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Variable Star

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Variable Star Intensity

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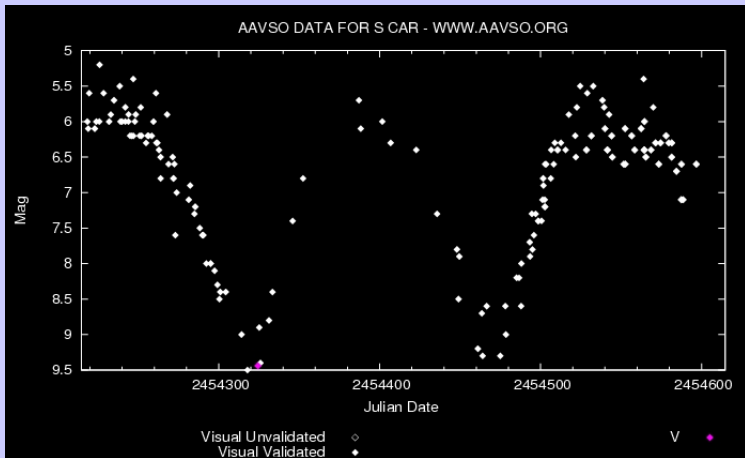
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Open Star Cluster

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Globular Cluster

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Globular Cluster Age

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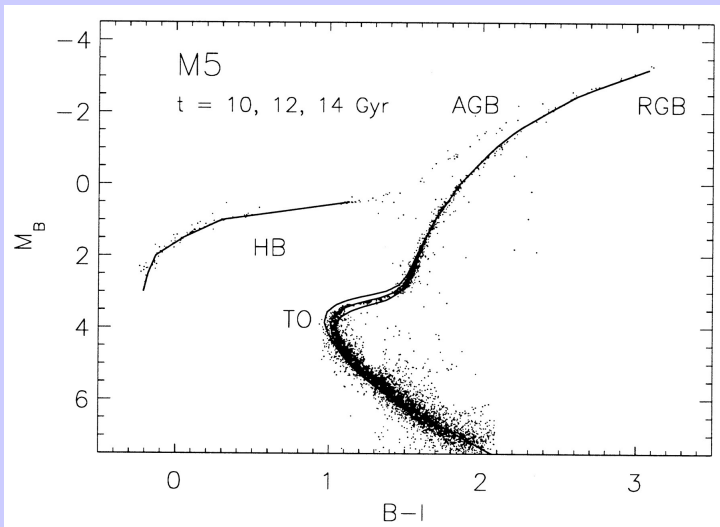
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History of the Universe

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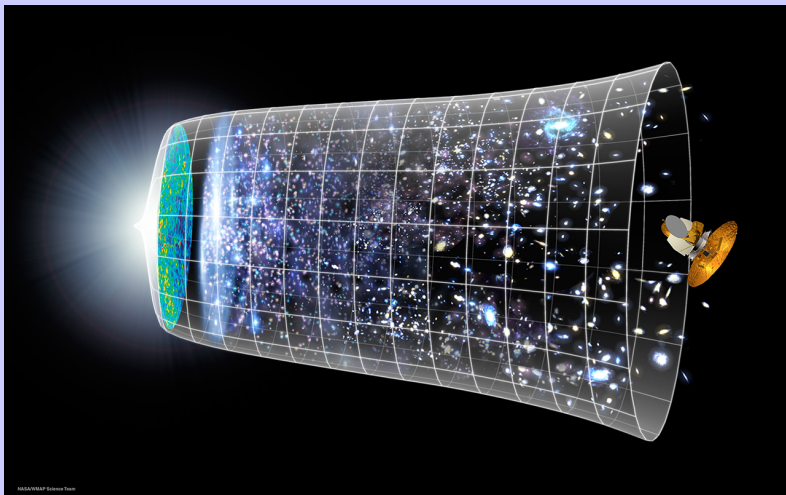
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NASA/WMAP Science Team

Molecular Cloud (Eagle)

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Molecular Cloud in IR

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Approaching the Main Sequence

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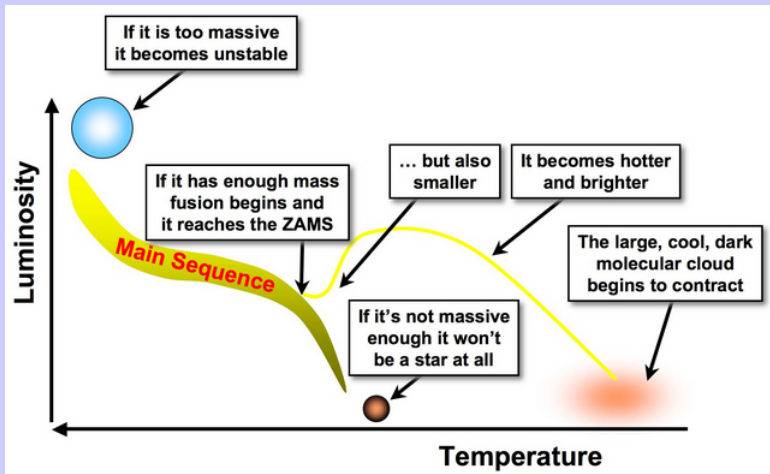
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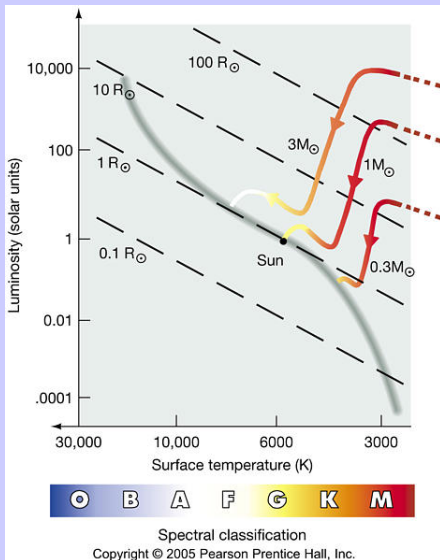
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Protostellar Disk

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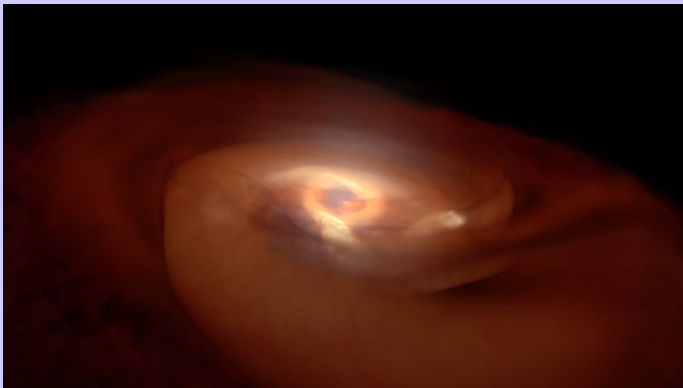
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Protostellar Jet

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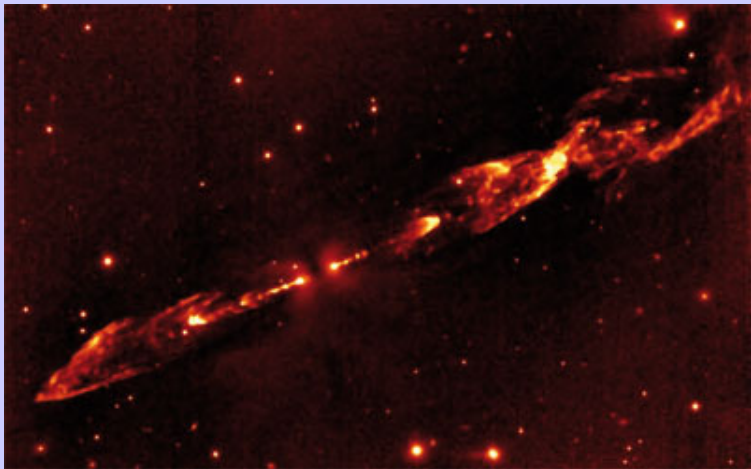
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Structure of the Sun

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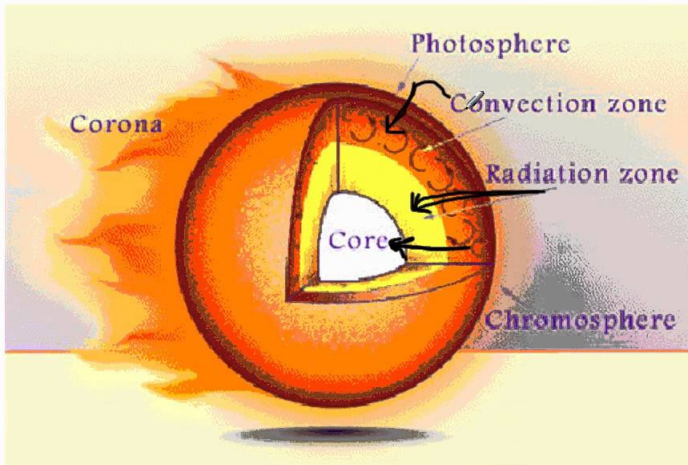
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Structure of the Sun

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Layers

Sub-Giant Star

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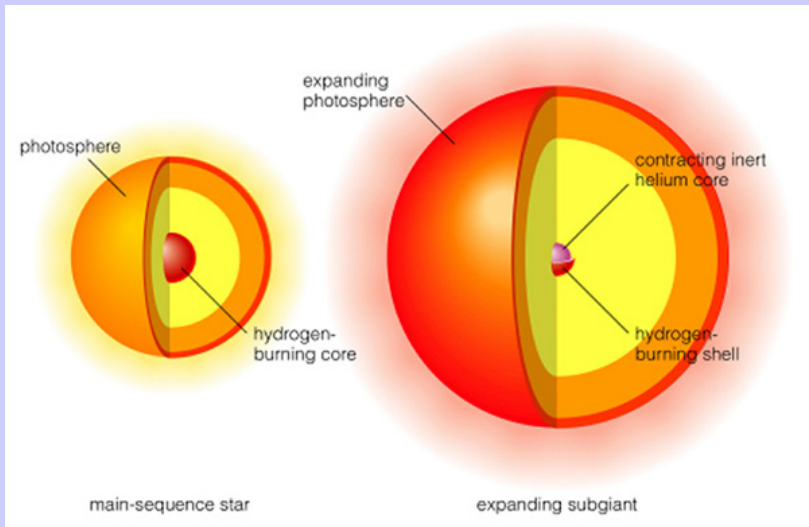
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Red Giant

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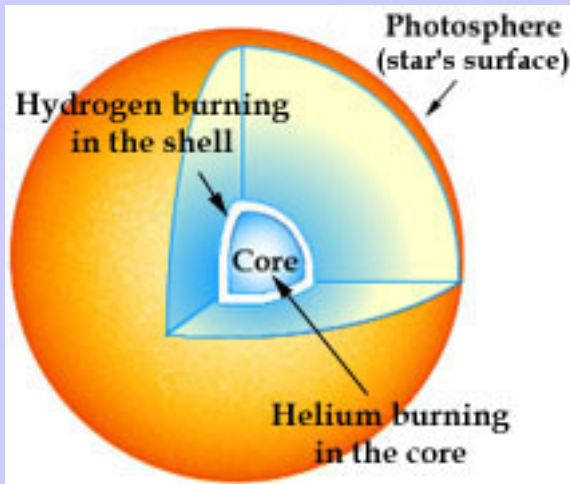
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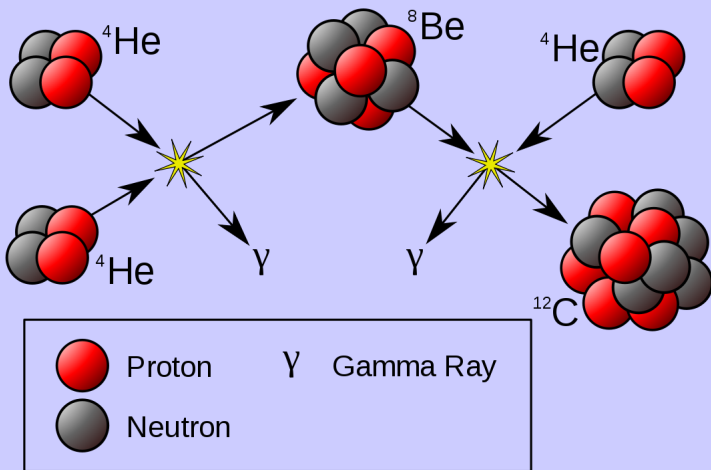


Helium Fusion

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Evolution off the Main Sequence

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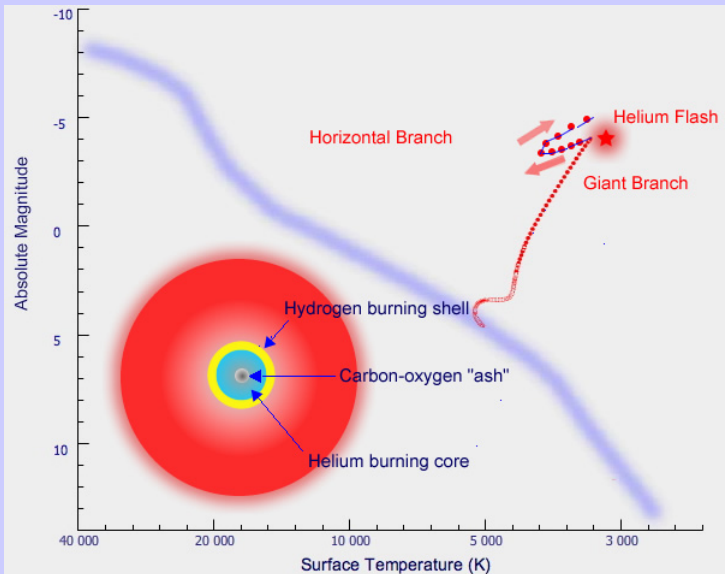
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Planetary Nebula

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Evolution after the Red Giant Stage

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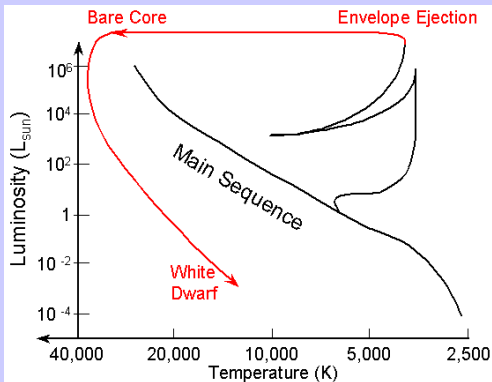
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Evolution of a Low Mass Star

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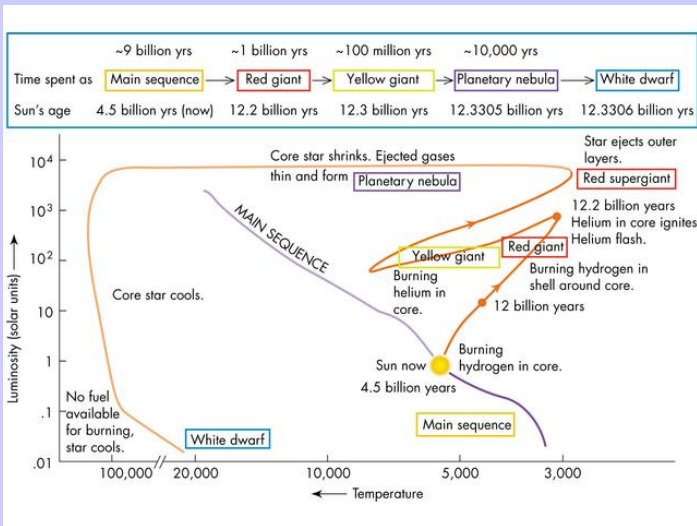
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CNO Cycle

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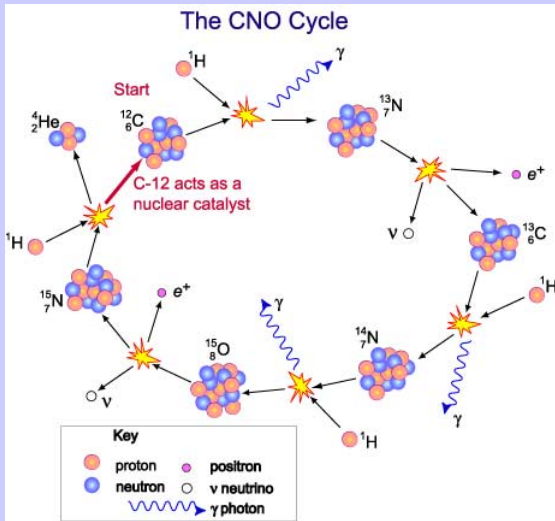
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Red Supergiant Evolution

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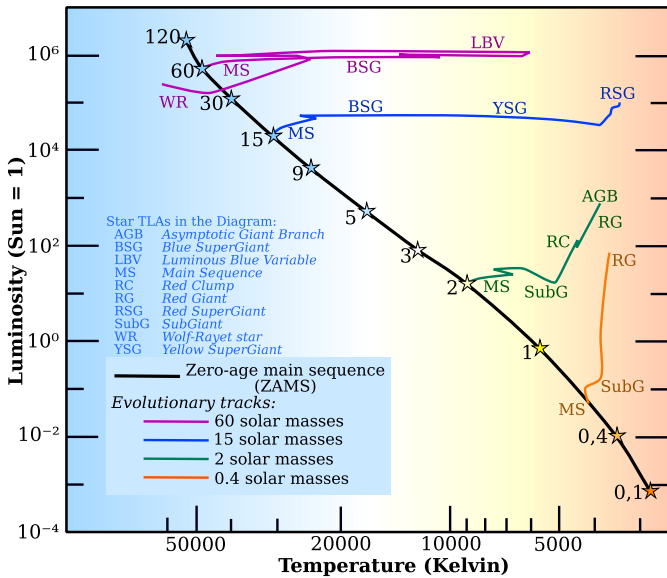
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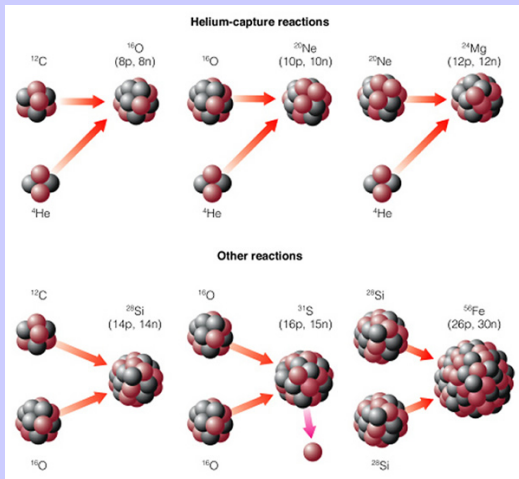


Heavier Element Formation

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Structure of a Massive Star

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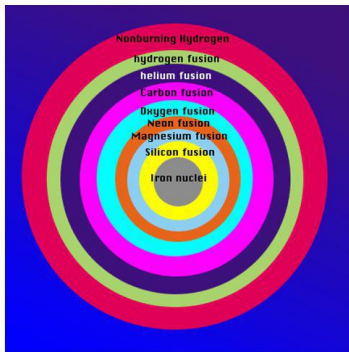
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The End of the Line for Massive Stars



- 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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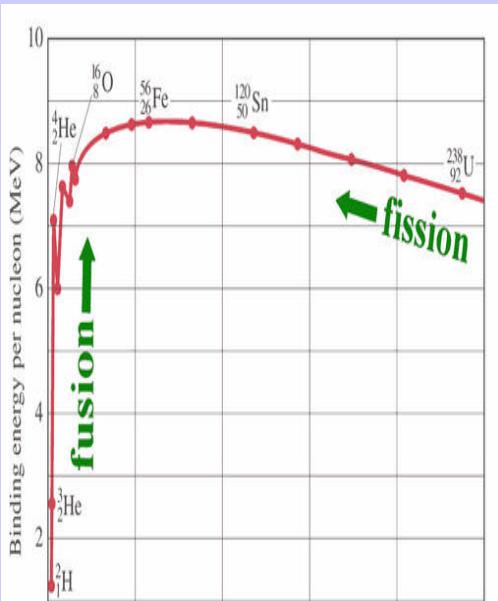
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Type II Supernova

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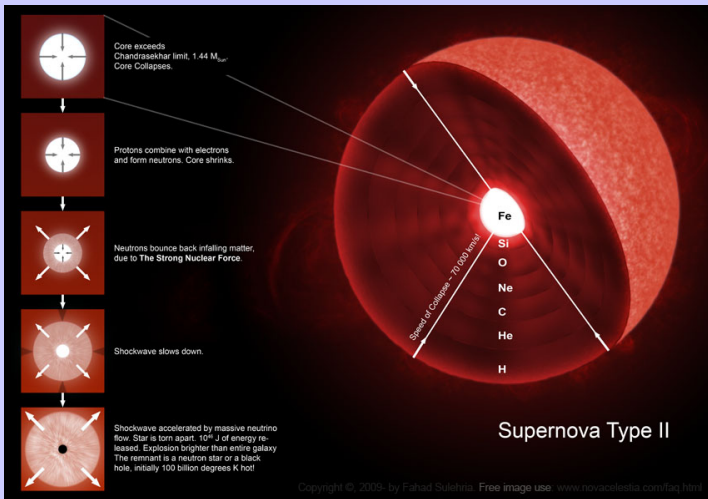
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Supernova Discovery

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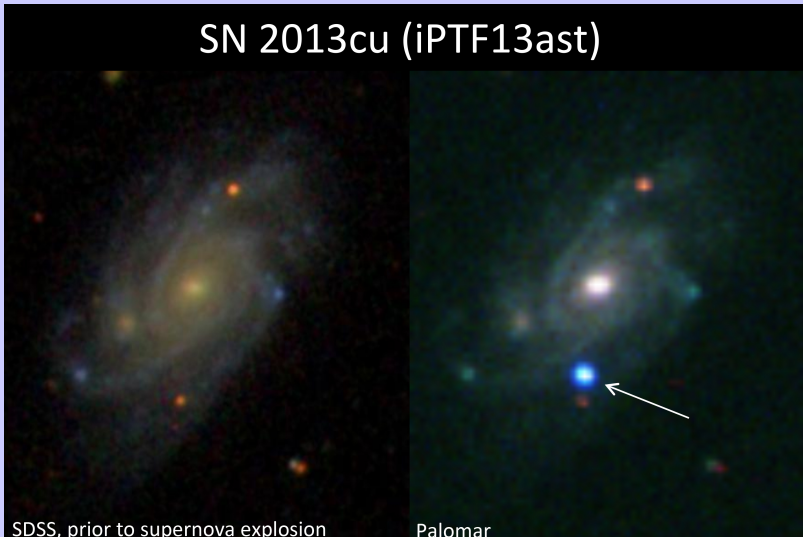
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SDSS, prior to supernova explosion

Palomar

Crab Nebula

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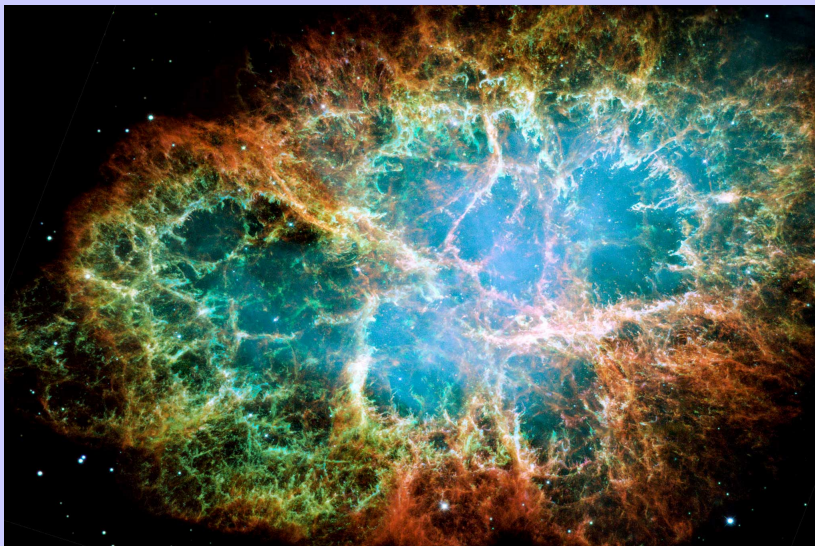
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Pulsars

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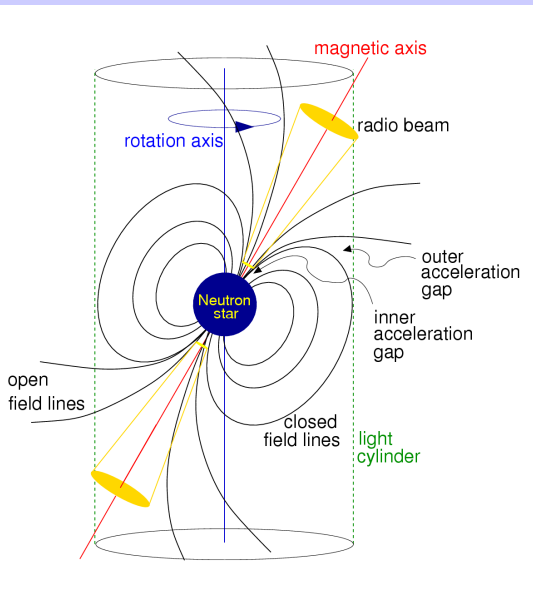
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Pulsar Picture

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Crab Pulsar

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Pulsar Discovery

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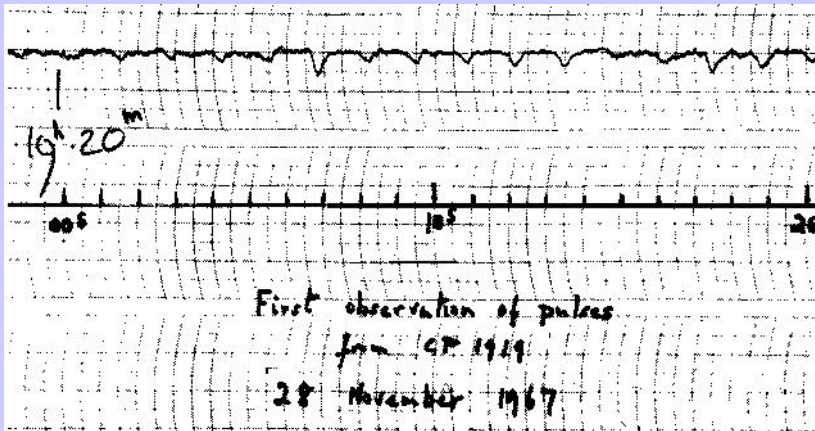
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Jocelyn Bell

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Pulsar Periods

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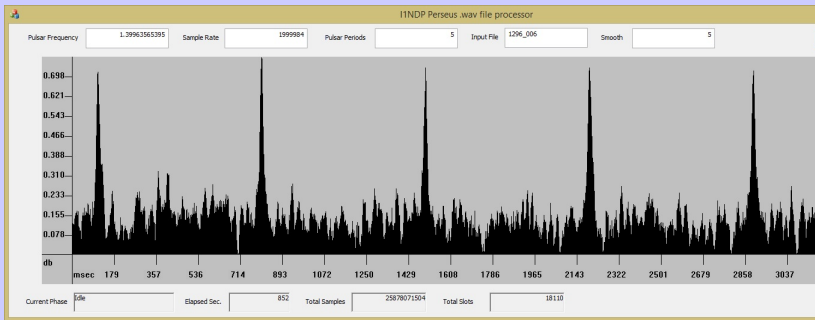
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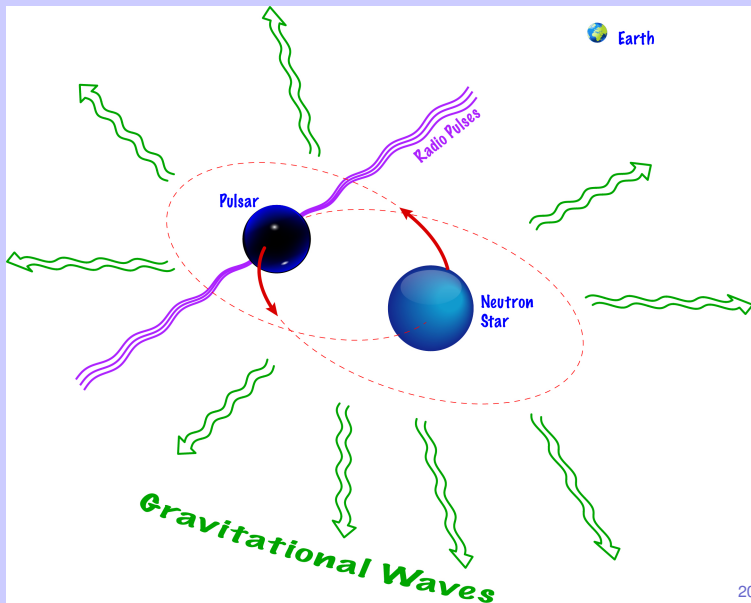
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Pulsar Binary



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Period Decay

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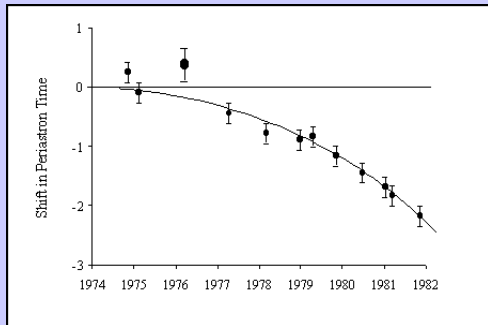
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Hulse and Taylor, Nobel Prize

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White Dwarf Binary

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Neutron Stars

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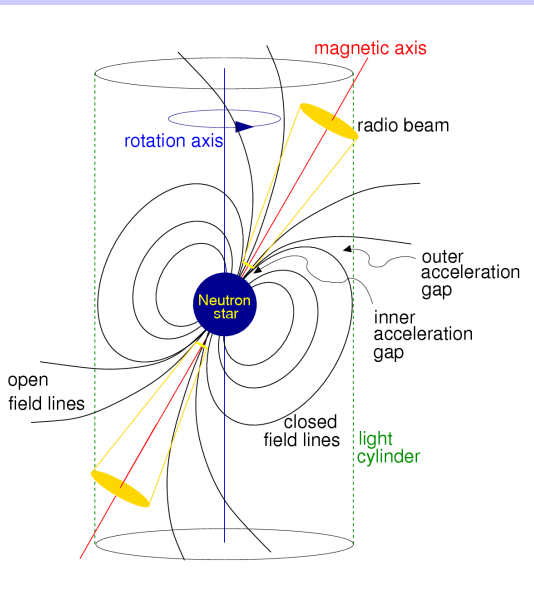
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X-Ray Binary

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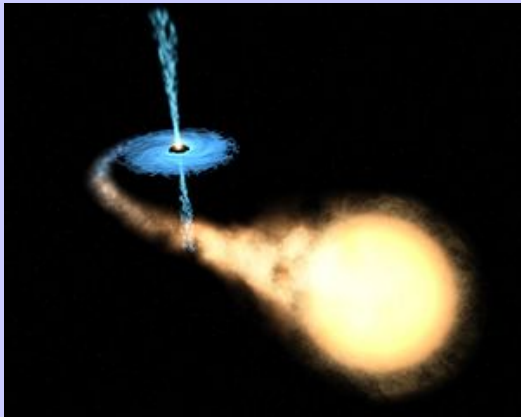
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X-Ray Binary

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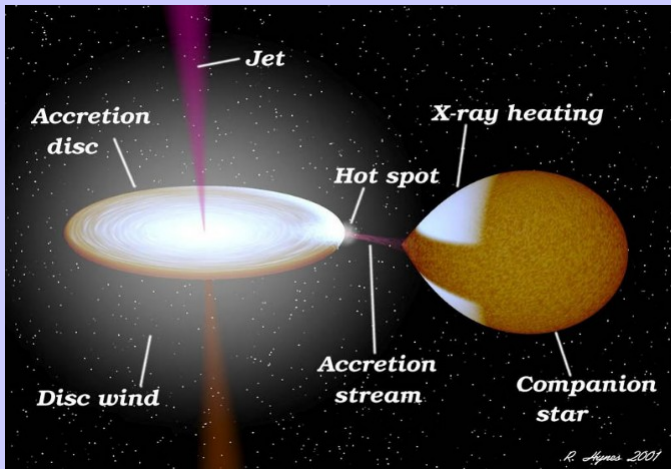
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X-Ray Burst

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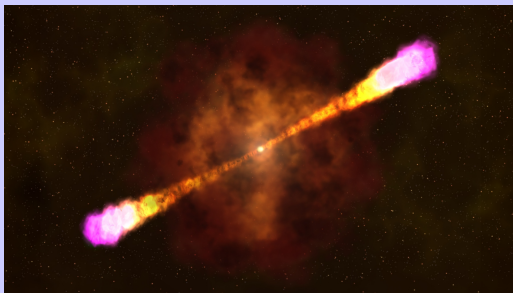
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Intensity Spectrum of a X-Ray Burst

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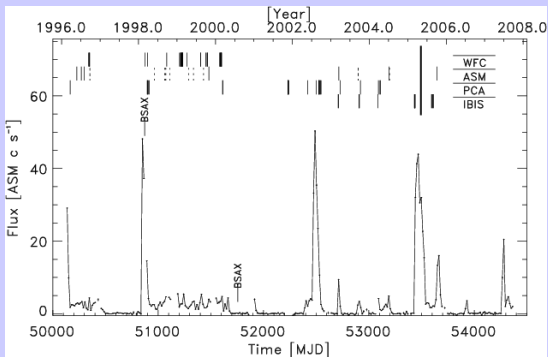
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Sun as a Black Hole

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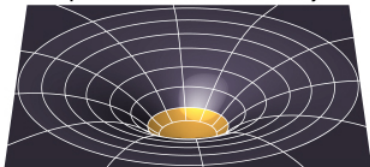
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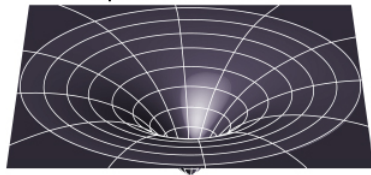
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spacetime around the Sun today

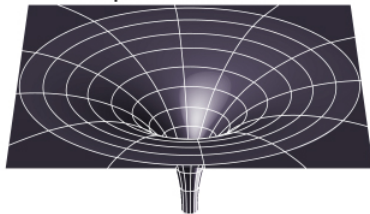


spacetime around the Sun compressed to a white dwarf



(a)

spacetime around the Sun compressed to a black hole



(b)

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Cygnus X1

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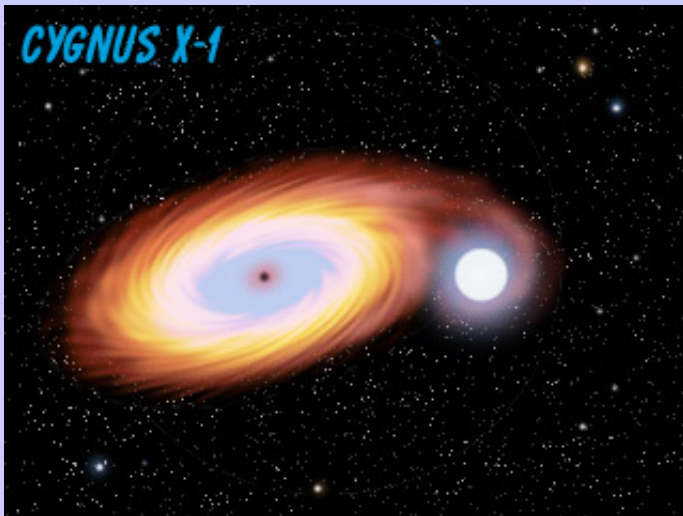
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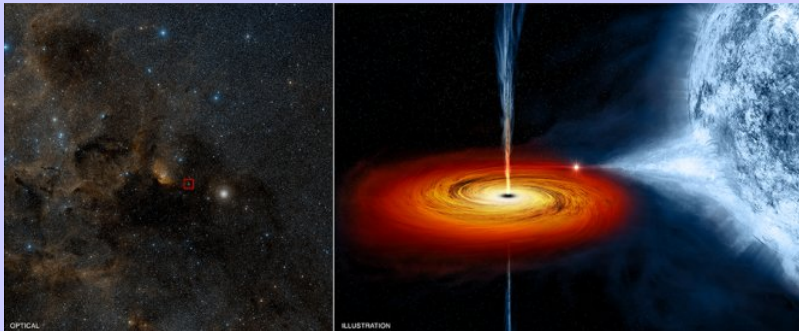
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The Expanding Universe

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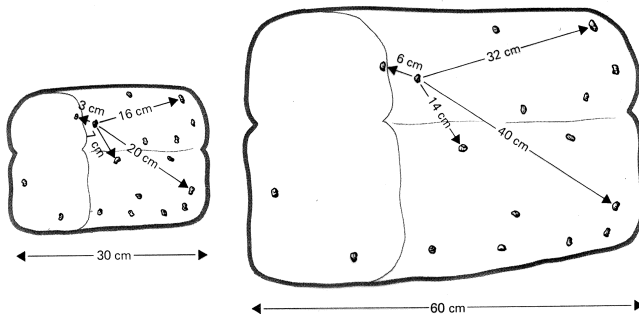


Figure 37.4 Expanding raisin bread.

Prediction: Gravitational Waves Exist

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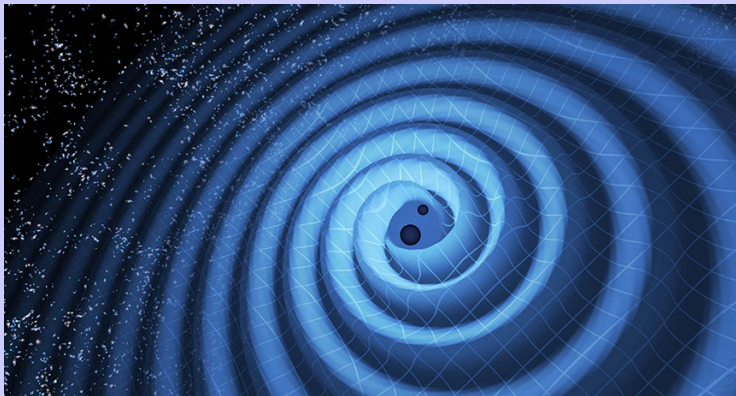
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Gravitational Waves

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Gravitational Waves:

- **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.**

Gravitational Waves

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Gravitational Waves

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Gravitational Waves

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Gravitational Waves:

- **Fluctuations of vacuum space-time.**
- Obey the wave equation.
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LIGO Schematic

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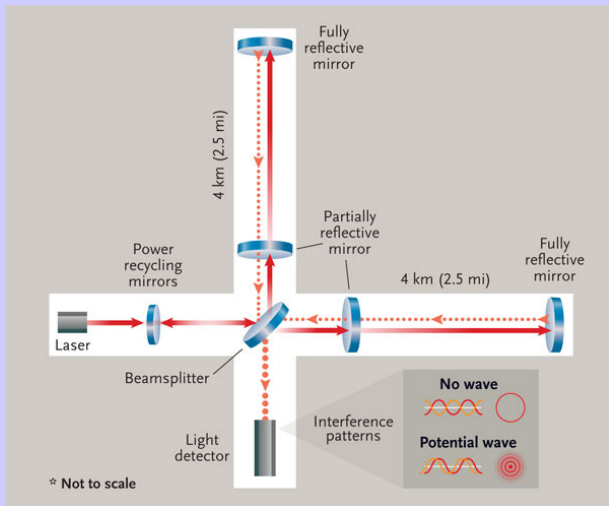
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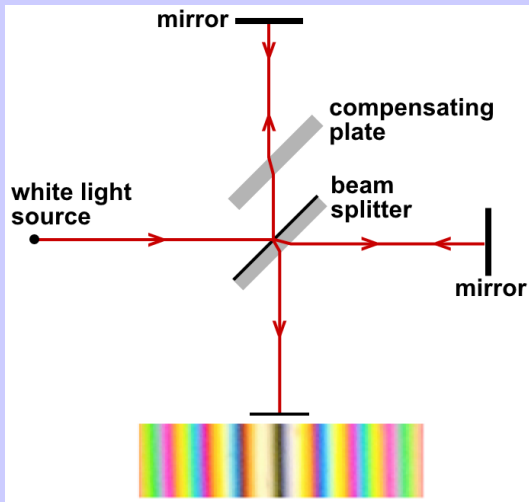
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Michelson-Morley Interferometer



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LIGO Schematic

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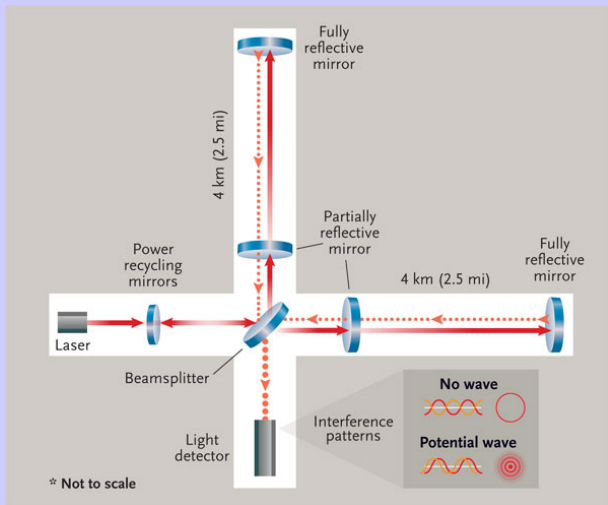
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LIGO Laser (Prototype)

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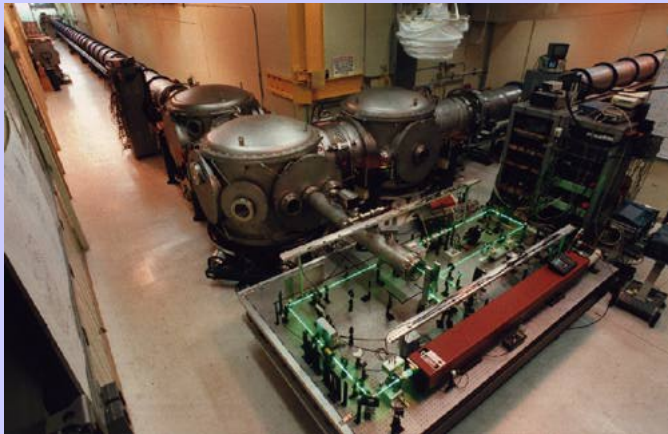
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LIGO Mirrors

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LIGO Seismic Isolation

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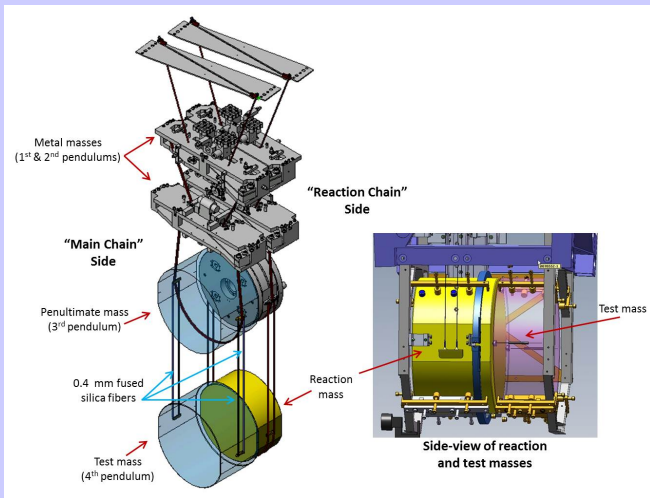
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LIGO Hanford Site

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LIGO Livingstone Site

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VIRGO Laboratory

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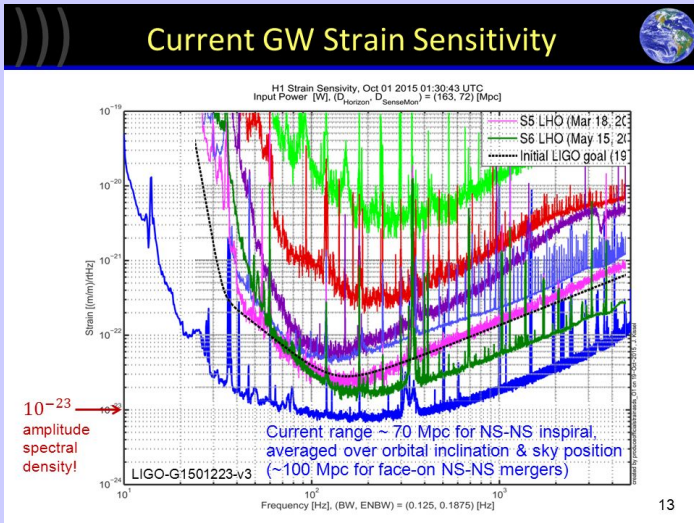
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LIGO Sensitivity

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LIGO Event (Sept. 2015): Nobel Prize 2017

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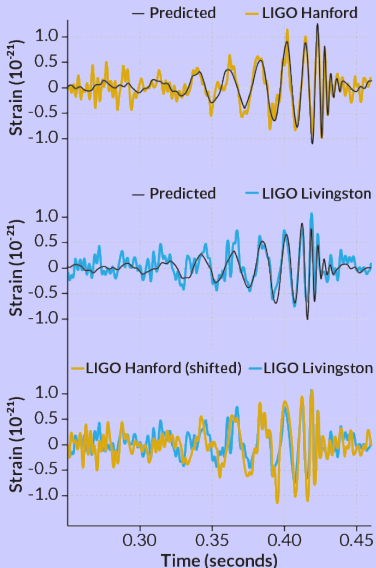
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Prediction (Numerical GR)

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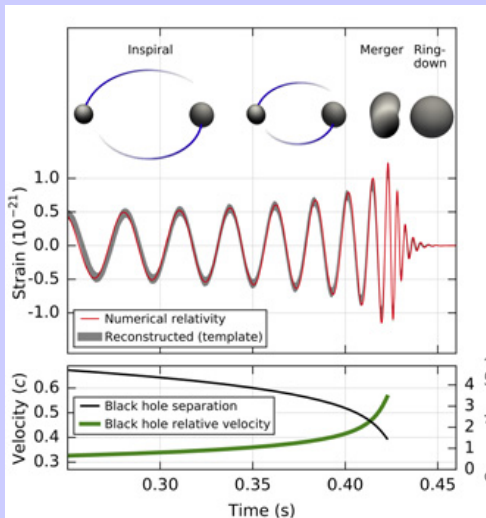
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Binary Black Hole

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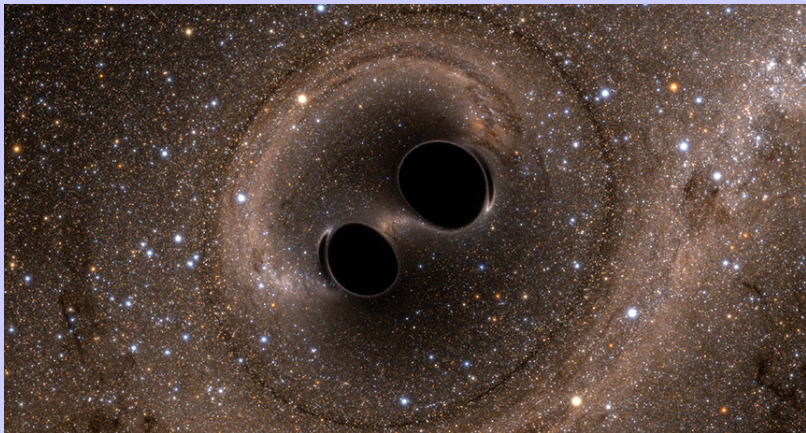
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What have we learned?

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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.

What have we learned?

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Neutron Star Merger Discovery: August 17 2017

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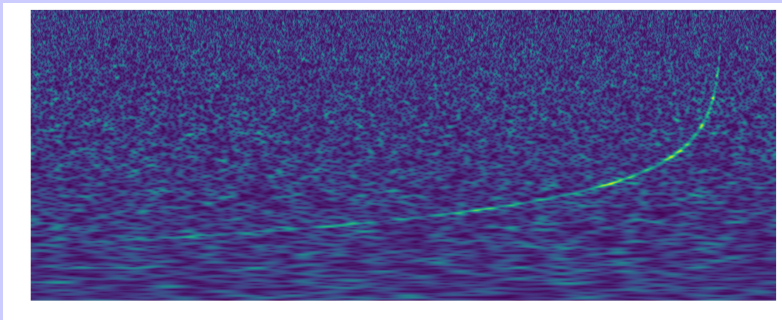
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Birth of Multimessenger Astronomy: August 17 2017

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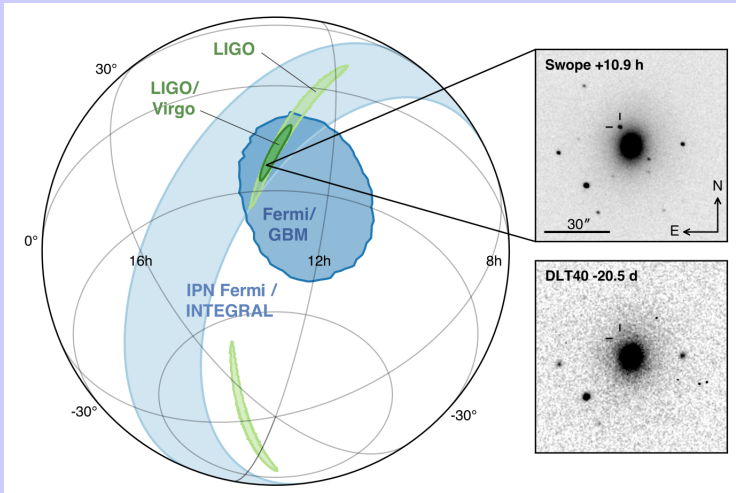
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- **First detection of an optical counterpart to a direct gravitational wave signal.**
- Birth of the field of Multi-Messenger Astronomy.
- First multi-wavelength observation of a kilonova.
- Verification that kilonovae can produce heavy elements (like 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.

What have we learned?

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

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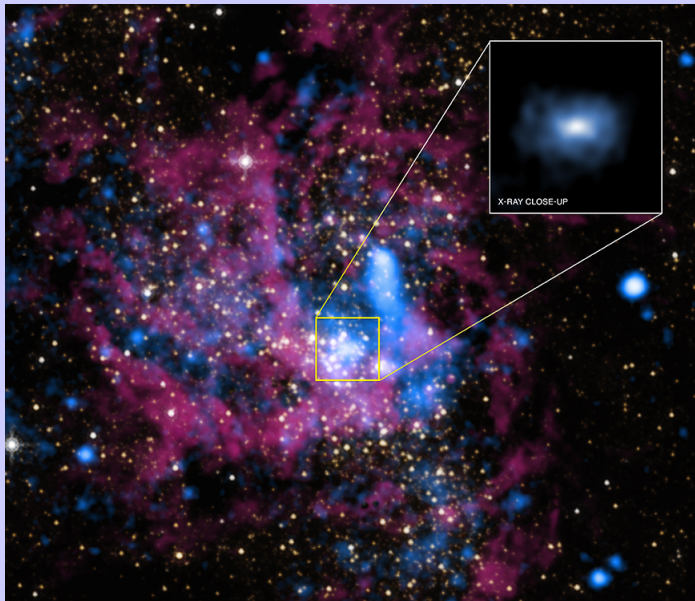
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Sagittarius A* in X-Ray

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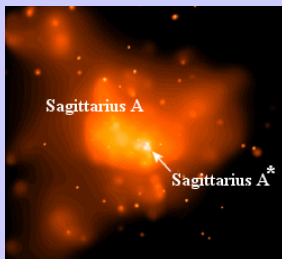
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Sagittarius A* in Radio

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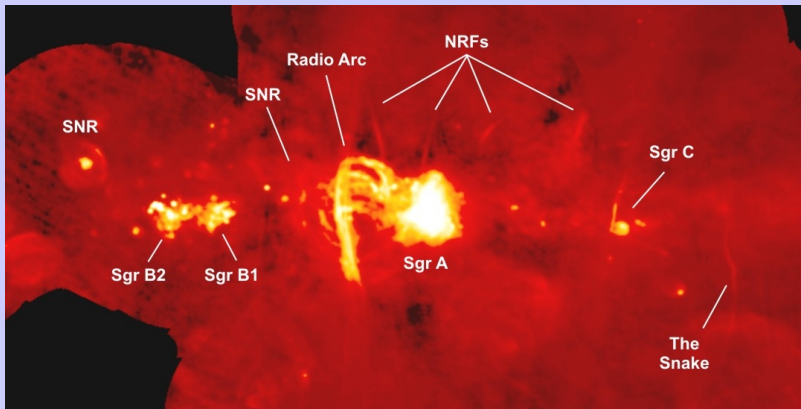
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Orbits of Stars about our Super-Massive Black Hole

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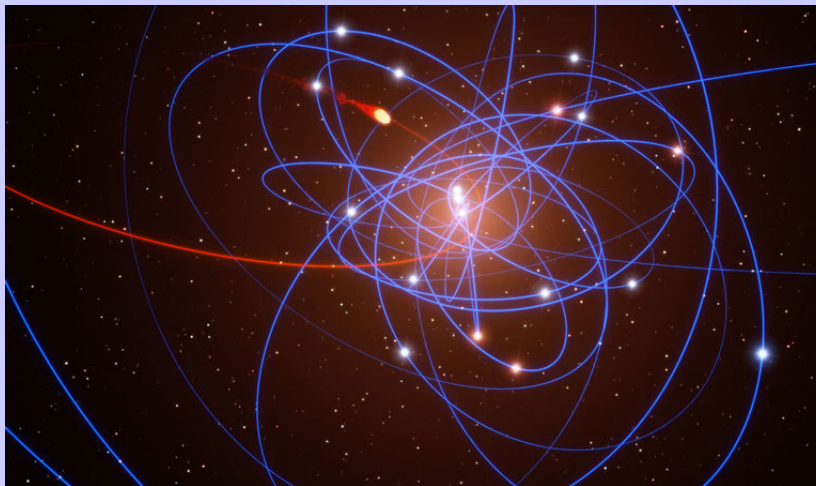
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Orbits of Stars about our Super-Massive Black Hole

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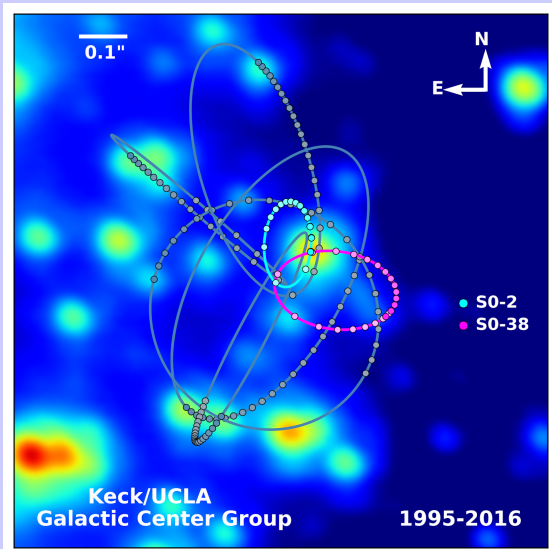
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Leader of the UCLA Group: Prof. A. Ghez (Nobel Prize 2020)

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Illustration of our Super-Massive Black Hole

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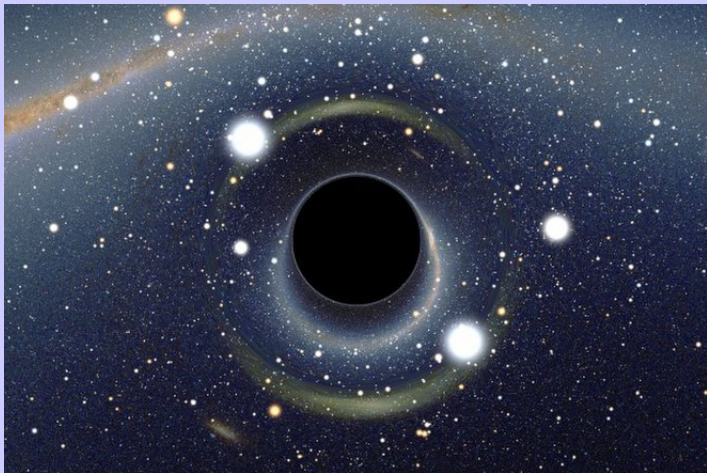
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Event Horizon Telescope Image (2019)

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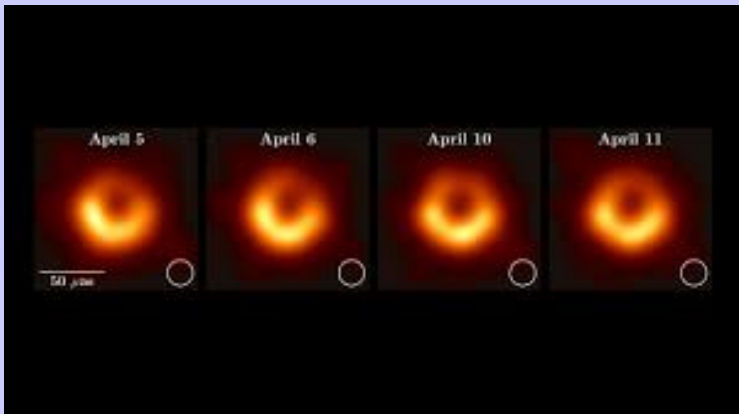
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Note: Breakthrough Prize, 2019

Event Horizon Telescope Image (2019)

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Milky Way Galaxy from Earth

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Time Travel

Milky Way Galaxy

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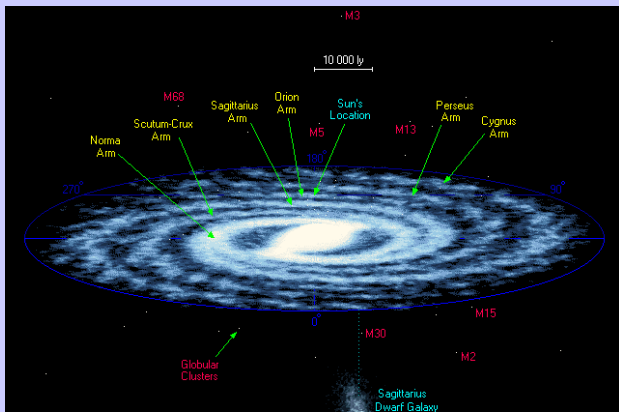
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Side View of the Milky Way Galaxy

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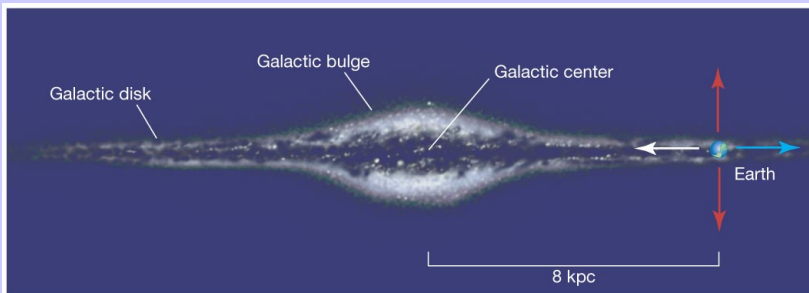
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(a) Artist's view of Milky Way from afar

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Structure of the Milky Way Galaxy

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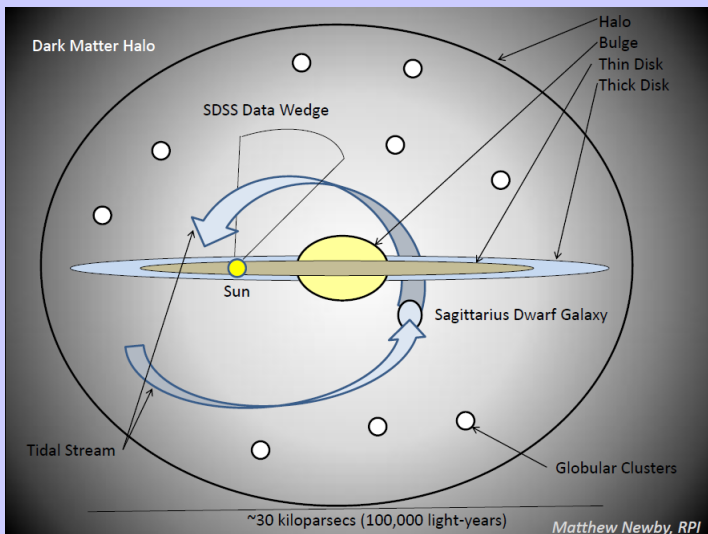
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Galaxy Rotation Velocity

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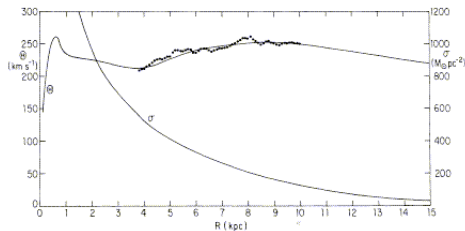


Figure 2 Variation with distance from the galactic center of the linear velocity of differential rotation, $\Theta(R)$, according to Simonson & Mader (1973) at $R < 5$ kpc and according to Schmidt (1965) at $R > 5$ kpc, and of the corresponding total galactic mass surface density, $\sigma(R)$, according 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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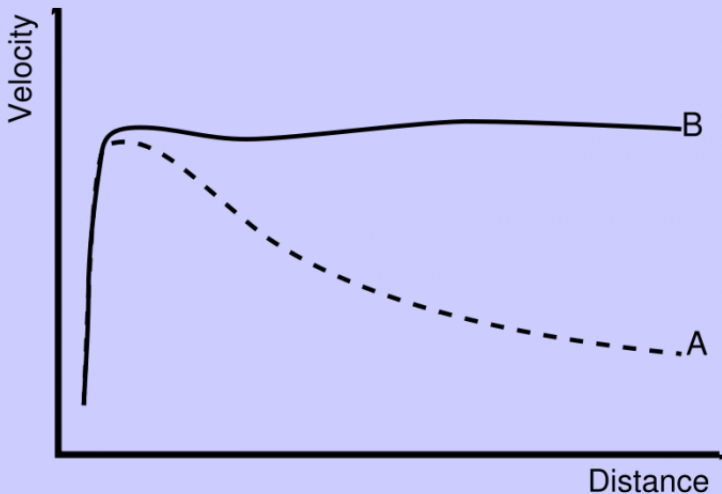
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Galaxy Rotation Velocity

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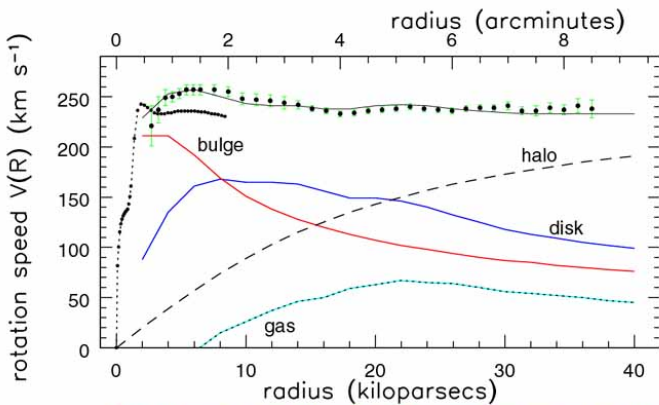


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

History of the Universe

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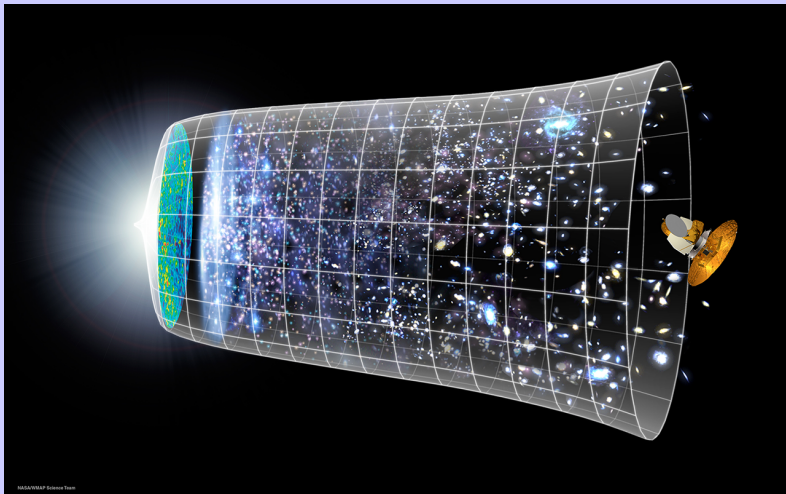
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NASA/WMAP Science Team

CMB Background

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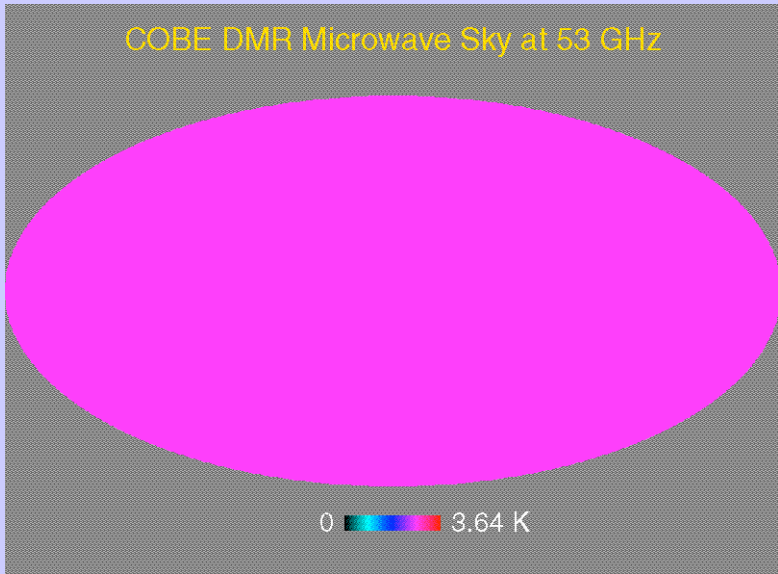
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COBE DMR Microwave Sky at 53 GHz



Spectrum of the Microwave Background

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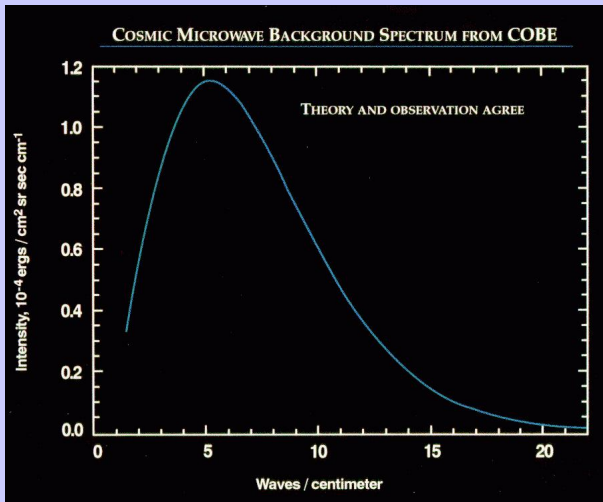
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Star Forming Cloud

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Planetary Nebula

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Crab Nebula - a Supernova Remnant

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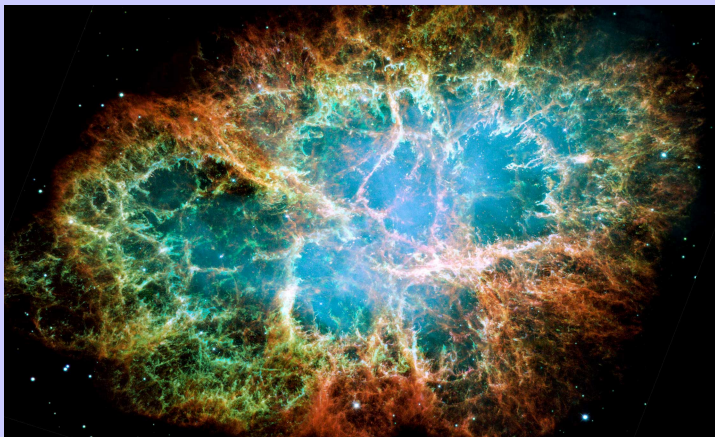
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Supernova Remnant

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Helium Fusion

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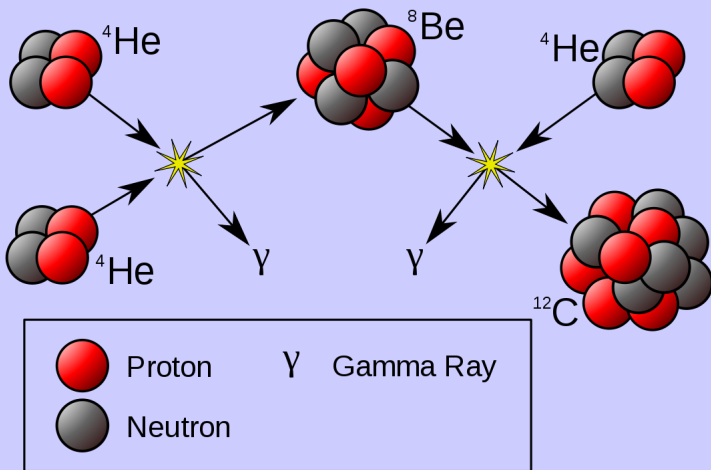
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CNO Cycle

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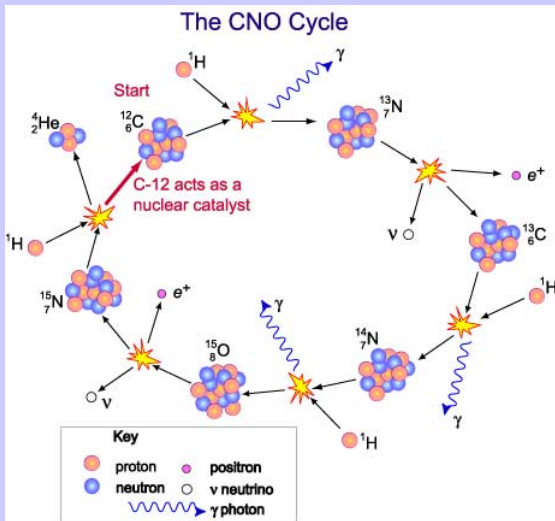
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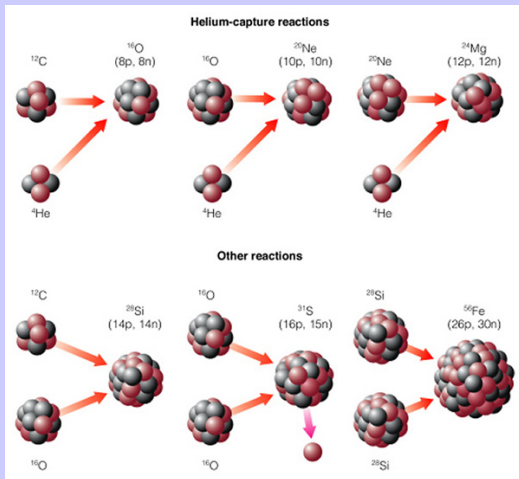


Heavier Element Formation

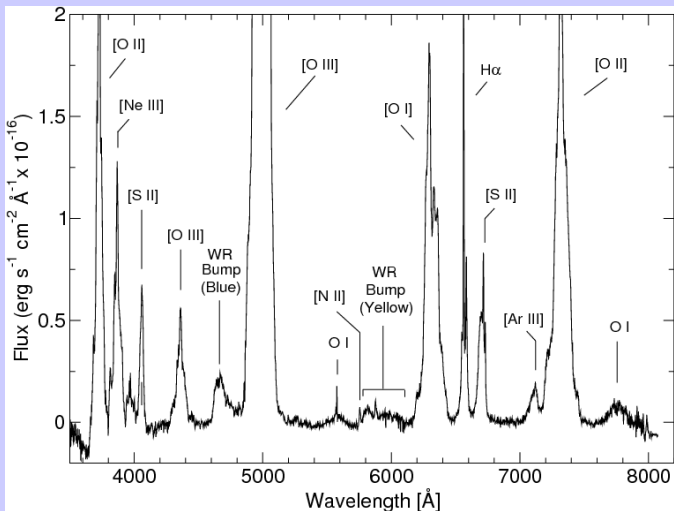
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Supernova Remnant Spectrum



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CAS A Supernova Remnant Spectrum

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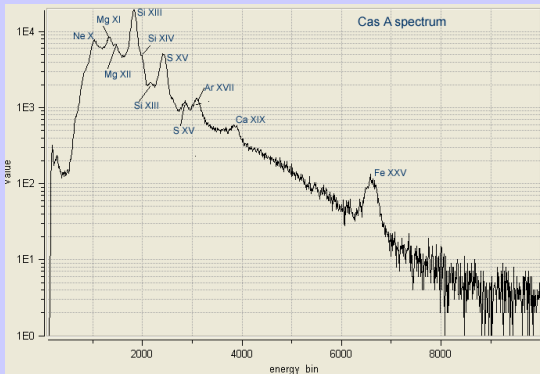
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Atomic Hydrogen Cloud

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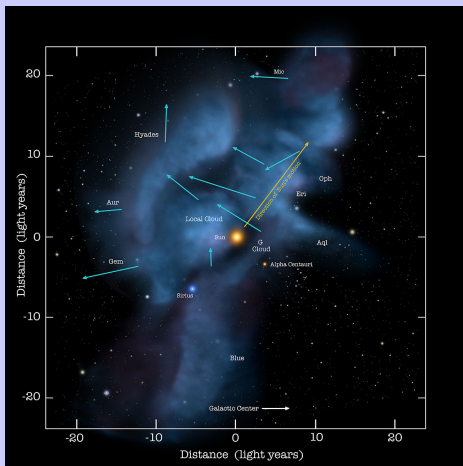
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Cold Molecular Cloud

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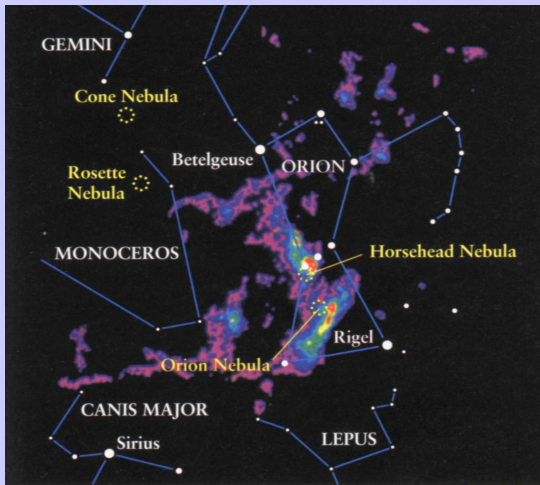
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Star Forming Cloud

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Star-Gas-Star Cycle

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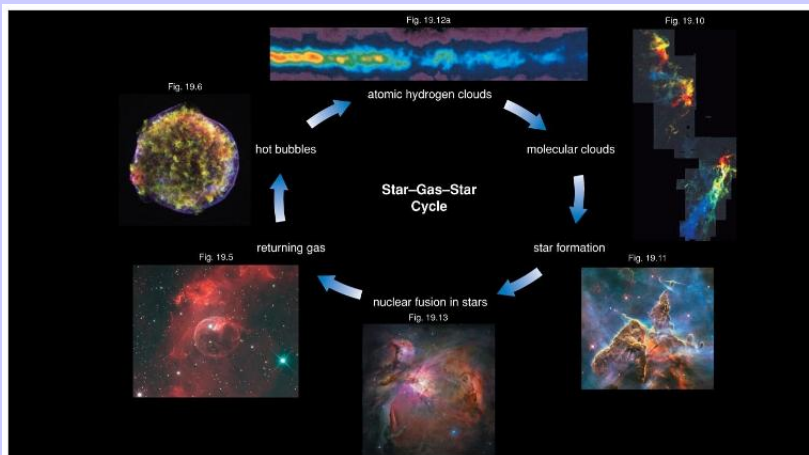
Stars

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Andromeda Galaxy

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M51 Galaxy

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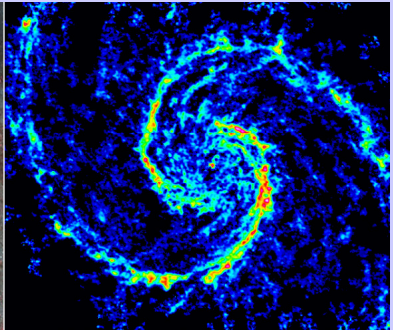
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Optical View of the Milky Way

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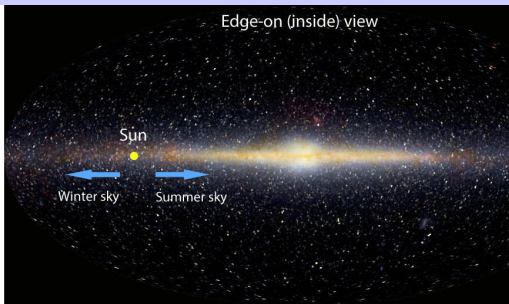
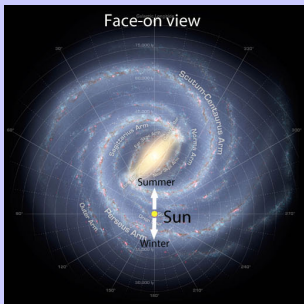
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Infrared View of the Milky Way

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Radio View of the Milky Way

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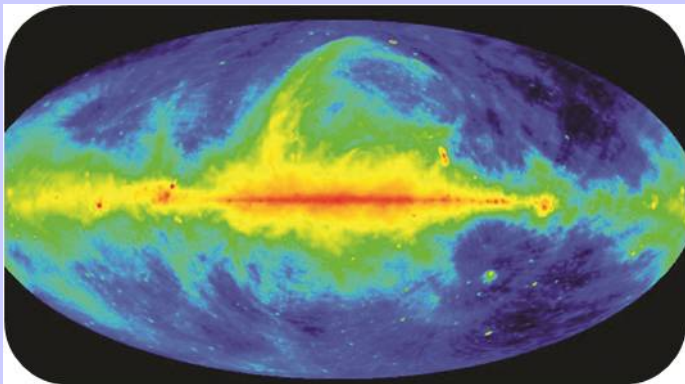
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X-ray View of the Milky Way

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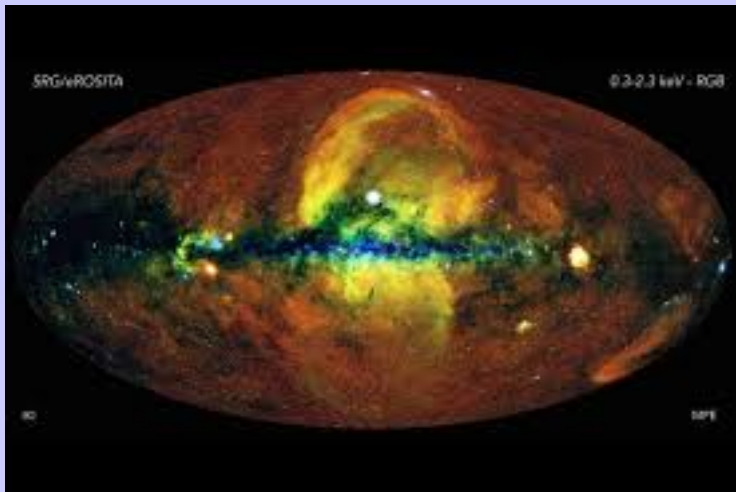
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Sea of Galaxies

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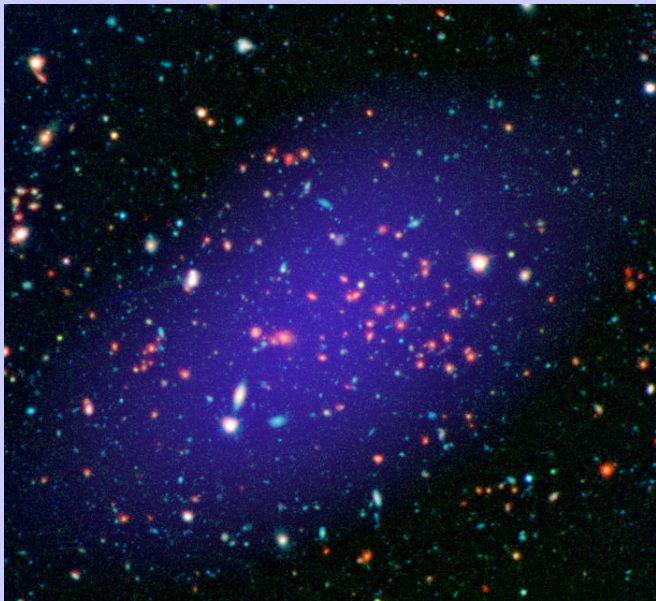
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Hubble Deep Field

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Spiral Galaxy

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Andromeda Galaxy

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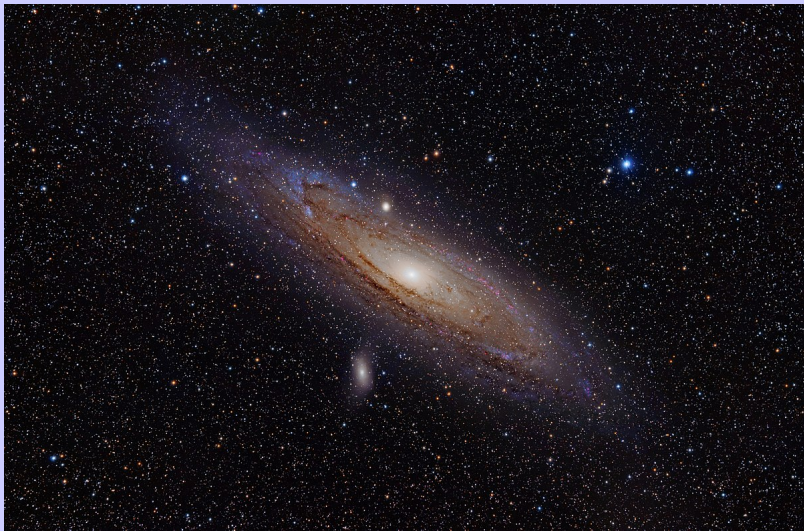
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Barred Spiral Galaxy

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Elliptical Galaxy - M87

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Galaxy Classification

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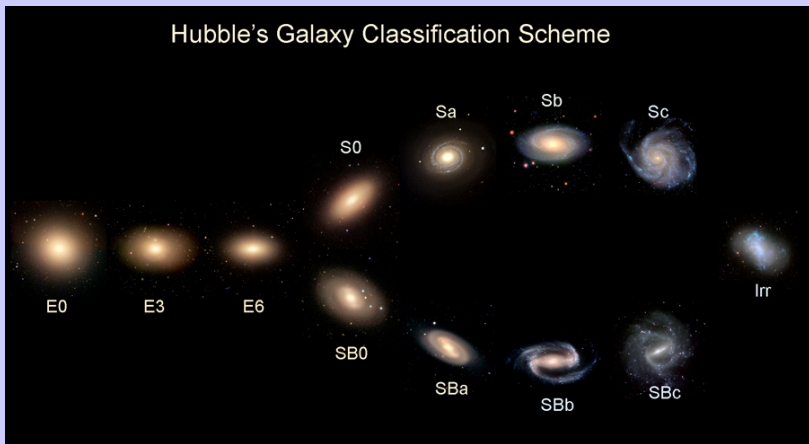
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Redshifted Galaxy Spectra

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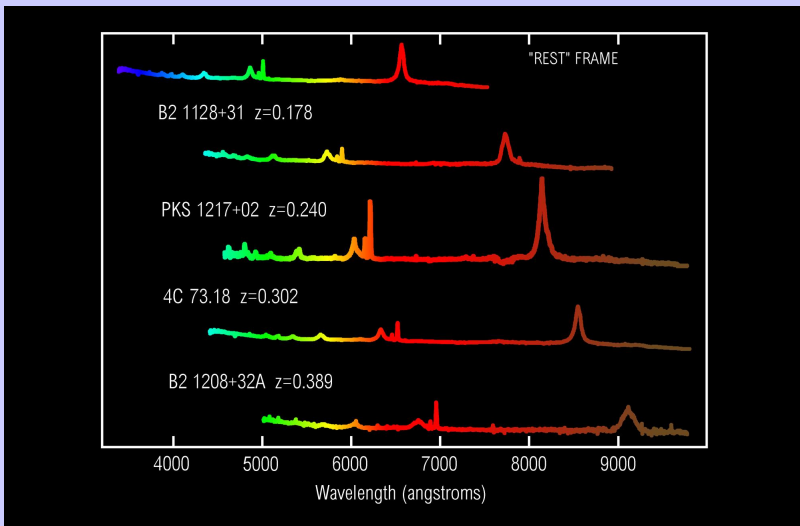
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Hubble's Data

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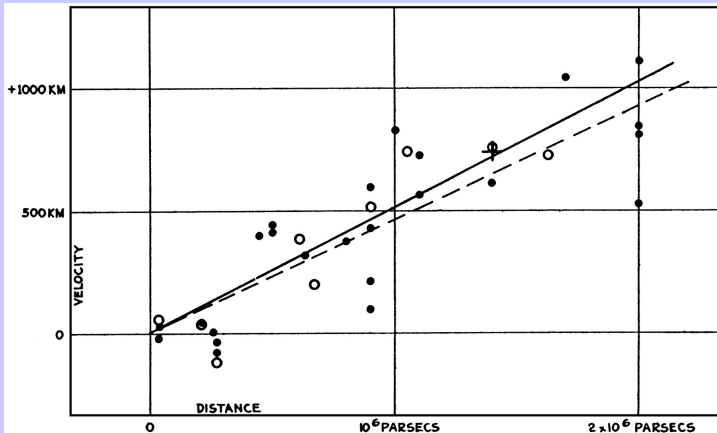
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Sea of Galaxies

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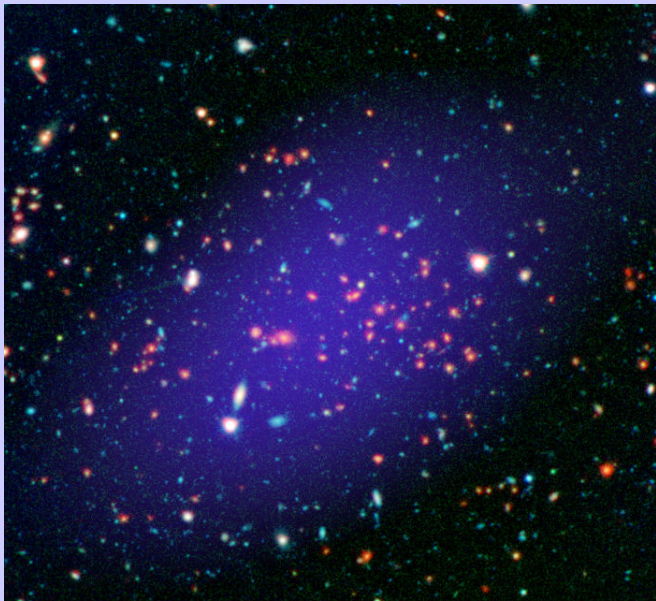
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Distance Ladder Steps

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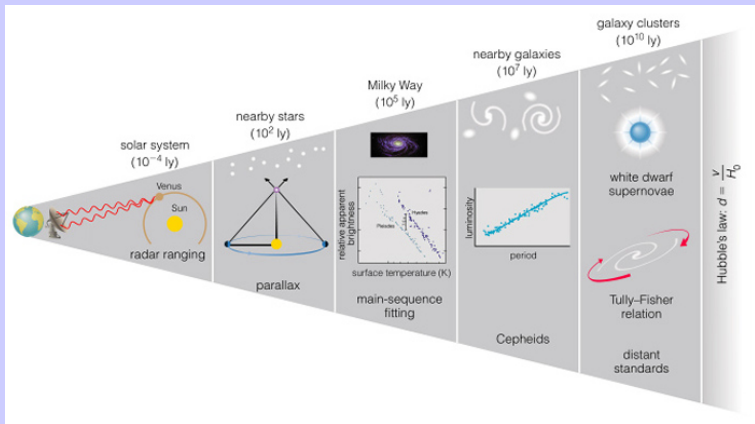
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Parallax Method

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Hertzprung-Russell Diagram

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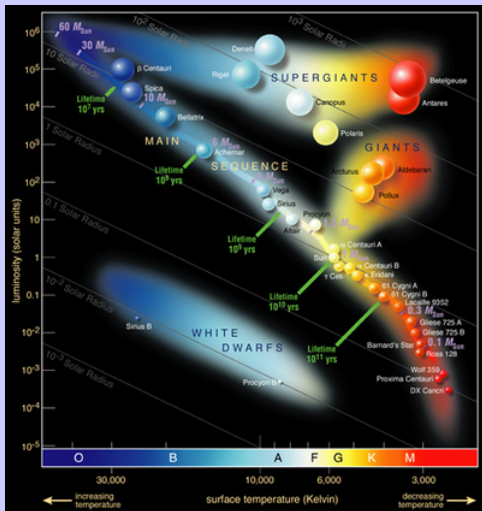
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Cepheid Period Luminosity Relation

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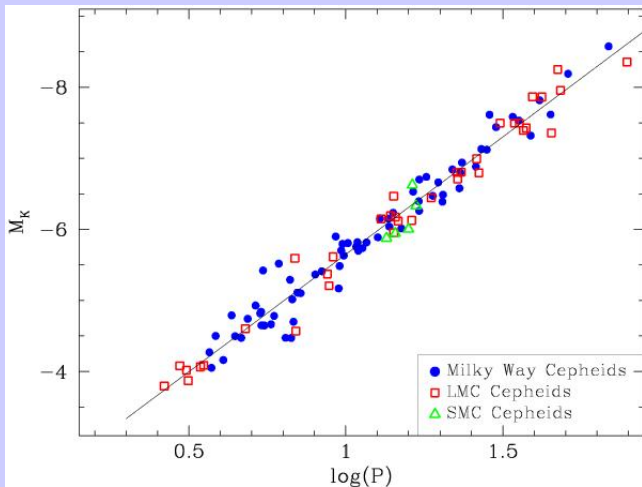
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White Dwarf Supernovae (SN Type IA)

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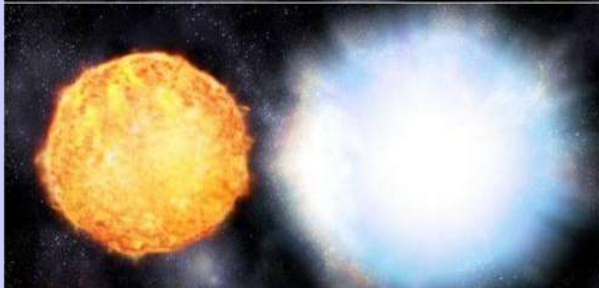
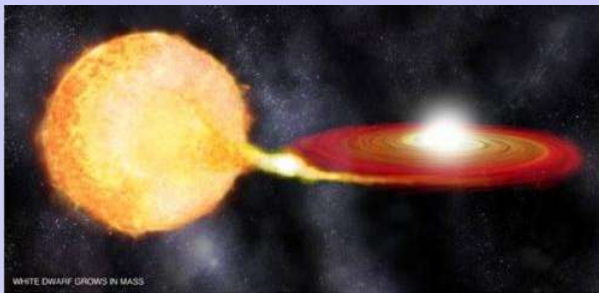
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Supernova Phillips Relation

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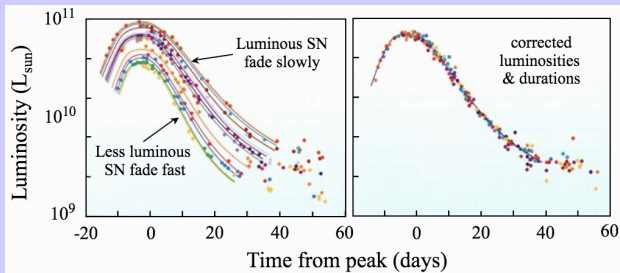
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The Expanding Universe

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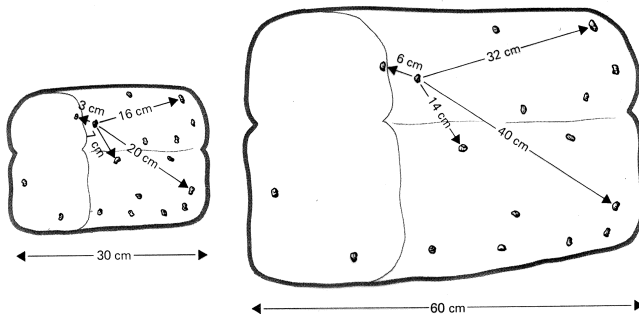


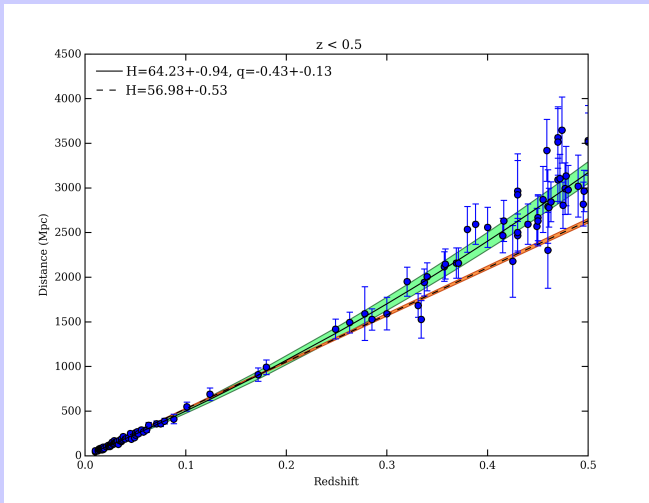
Figure 37.4 Expanding raisin bread.

Supernova Hubble Law

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Large-Scale Structure

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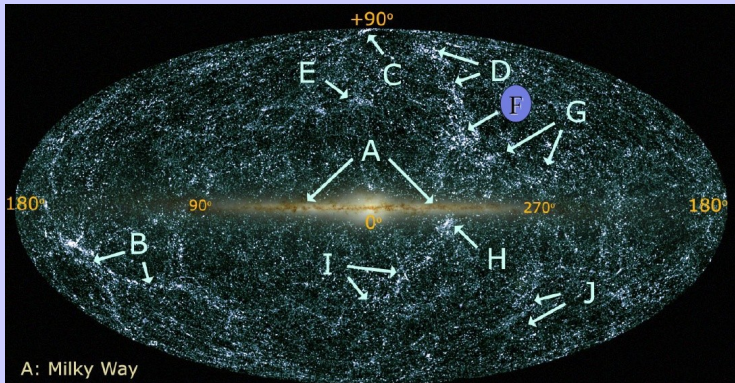
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A: Milky Way

B: Perseus-Pisces Supercluster

C: Coma Cluster

D: Virgo Cluster/Local Supercluster

E: Hercules Supercluster

F: Shapley Concentration/Abell 3558

-90°

G: Hydra-Centaurus Supercluster

H: "Great Attractor"/Abell 3627

I: Pavo-Indus Supercluster

J: Horologium-Reticulum

Supercluster

From: talk by O. Lahav

Galaxy Clusters

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HST Galaxy Cluster

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Prediction: Bending of Light

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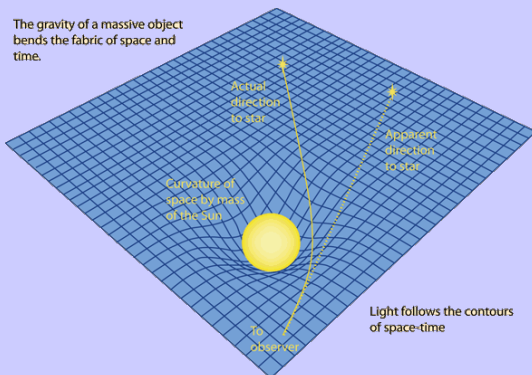
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Gravitational Lensing by a Galaxy Cluster

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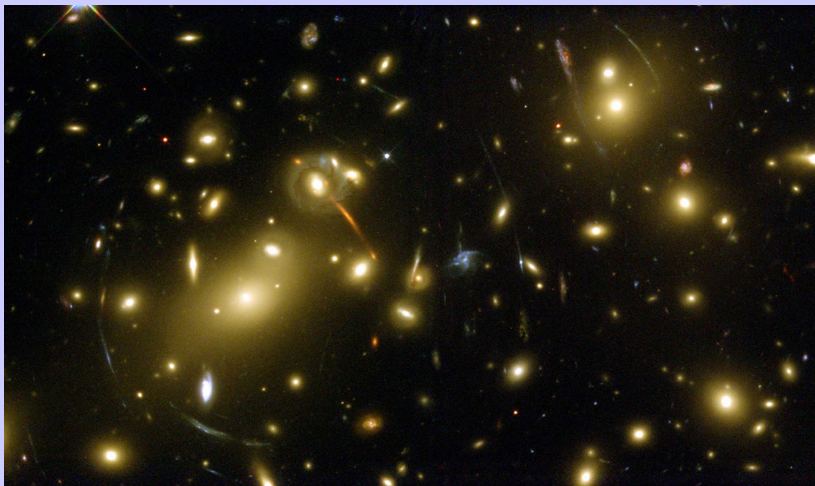
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Bullet Cluster

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Redshift Survey Results in 1989

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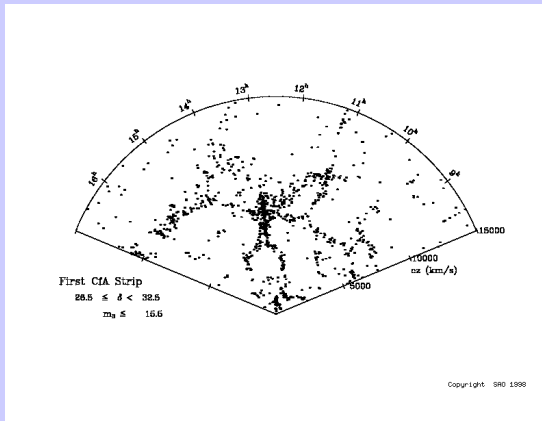
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Redshift Survey Results in 2003

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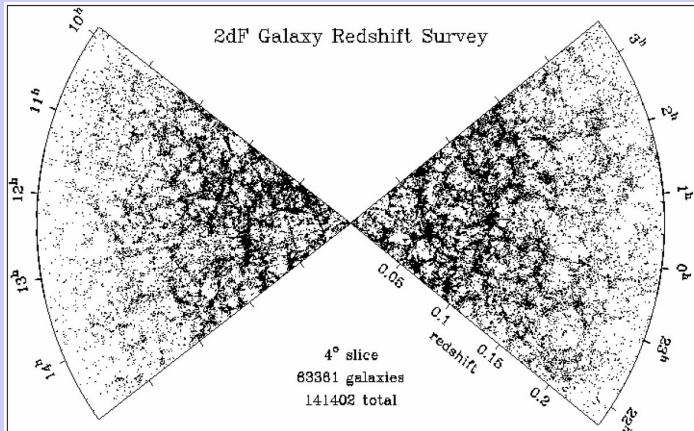
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History of the Universe

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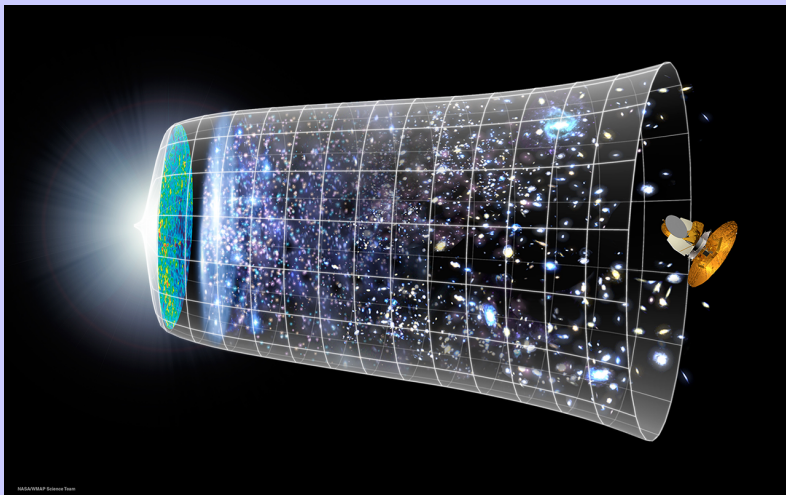
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NASA/WMAP Science Team

CMB Background

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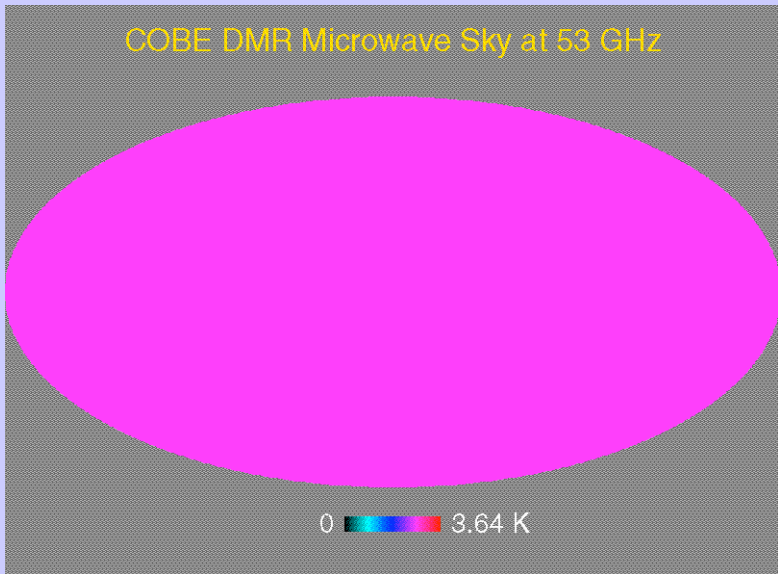
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COBE DMR Microwave Sky at 53 GHz

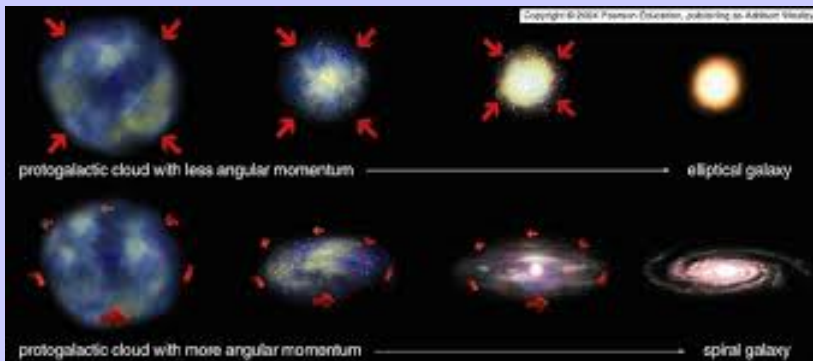


Origin of Galaxy Diversity

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Merging Galaxies

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Active Galactic Nucleus

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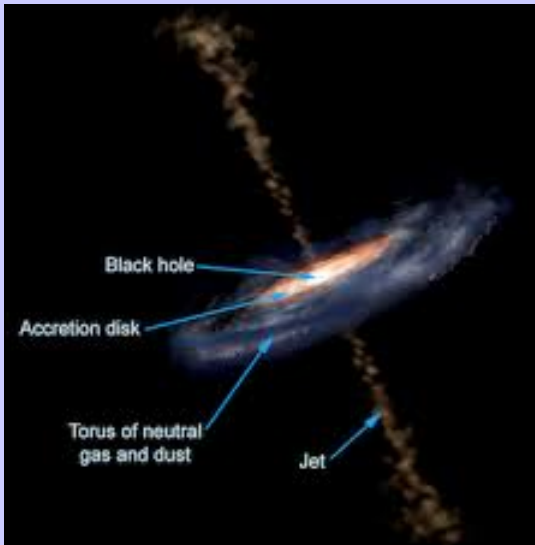
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Active Galactic Nucleus

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

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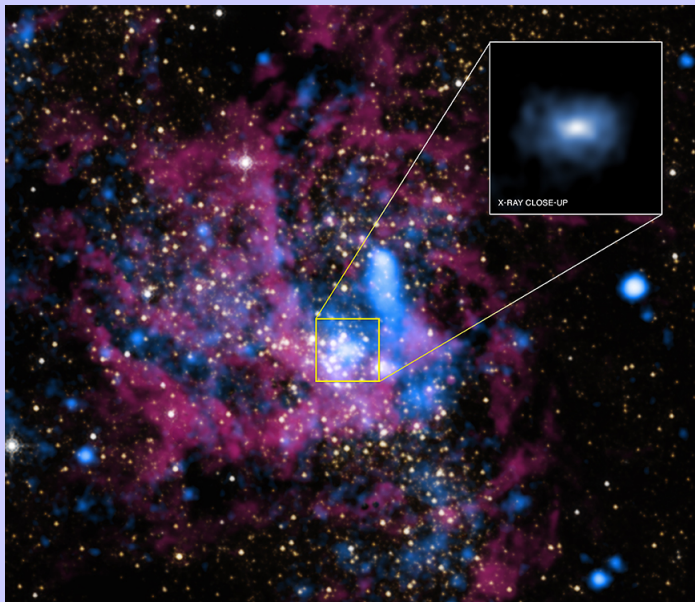
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Orbits of Stars about our Super-Massive Black Hole

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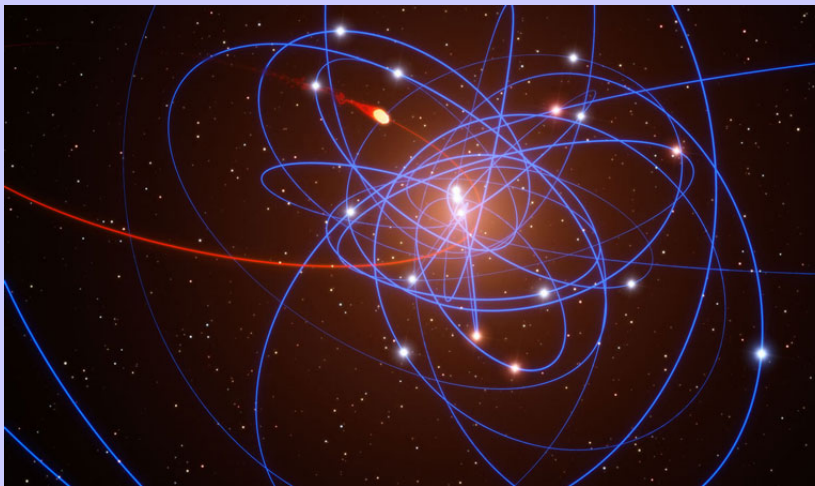
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Leader of the UCLA Group: Prof. A. Ghez (Nobel Prize 2020)

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Illustration of our Super-Massive Black Hole

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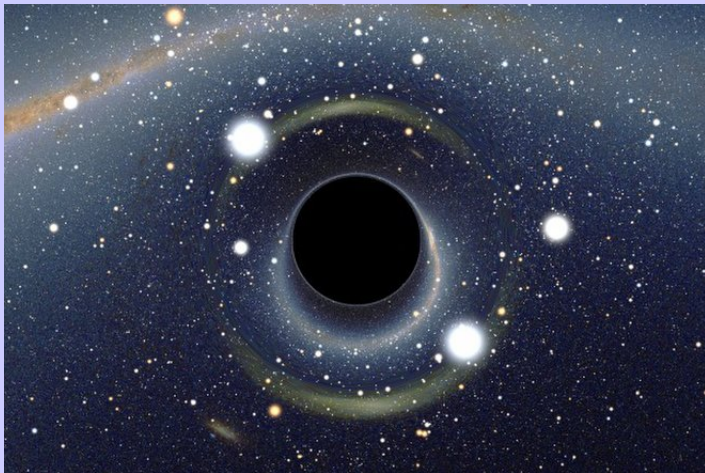
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Event Horizon Telescope Image (2019)

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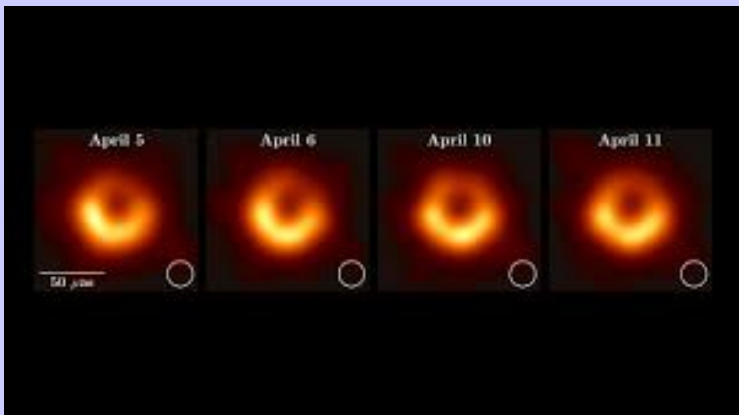
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Note: Breakthrough Prize, 2019

SMBH-Bulge Relationship

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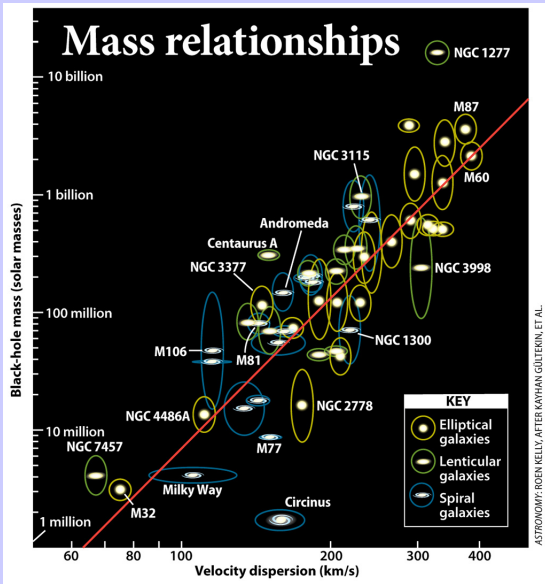
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Radio Galaxy

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Cygnus A Radio Galaxy

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The Expanding Universe

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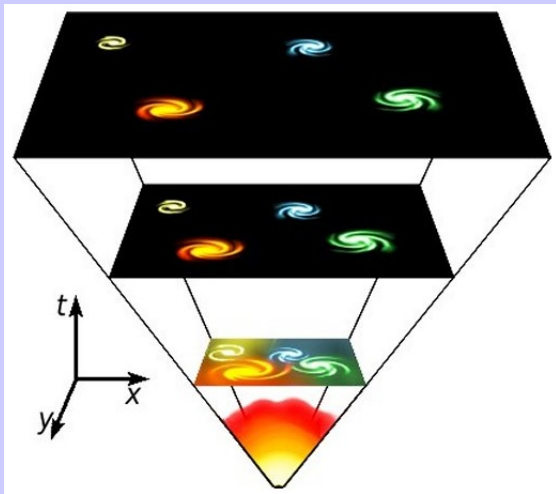
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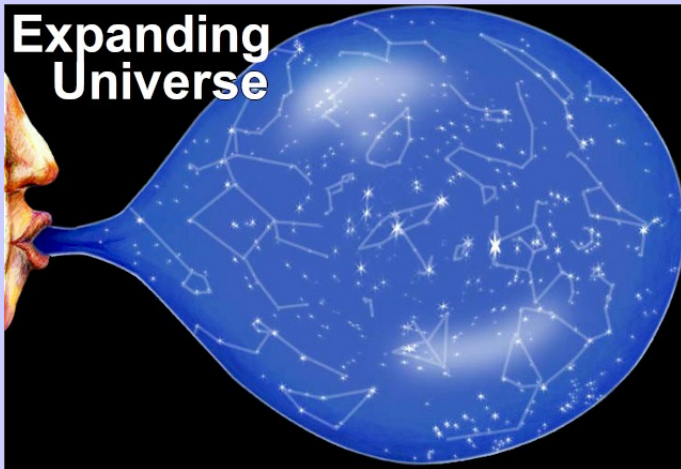
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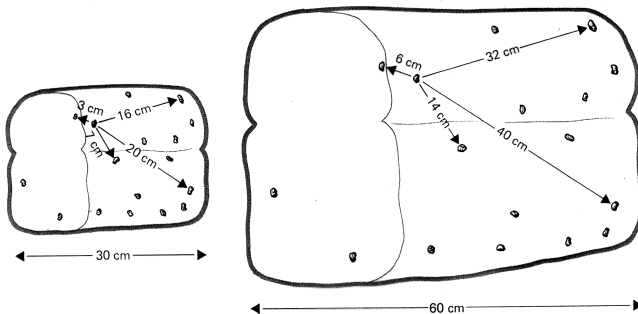


Figure 37.4 Expanding raisin bread.

Supernova Hubble Law

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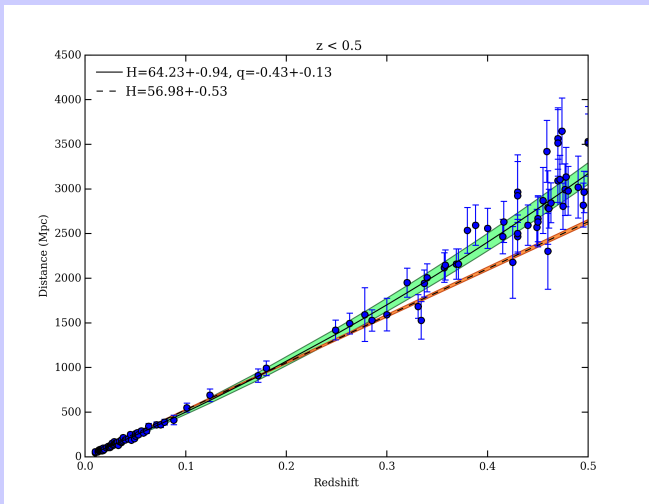
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Redshifted Galaxy Spectra

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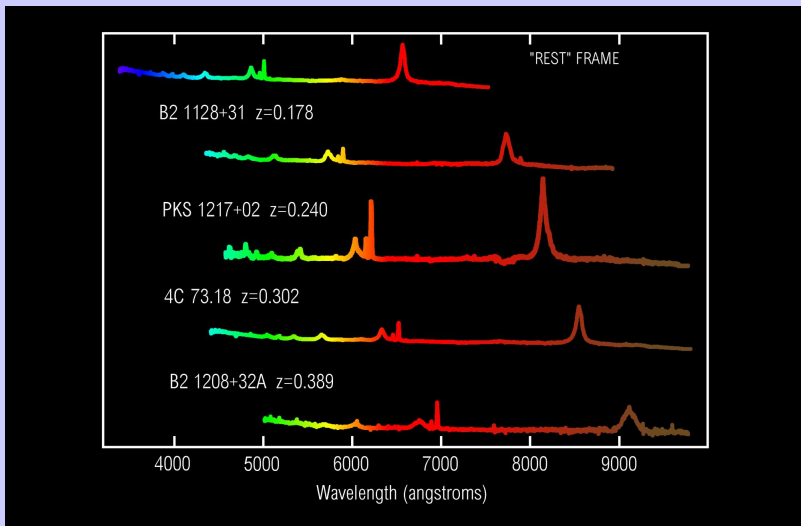
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Expansion Redshift

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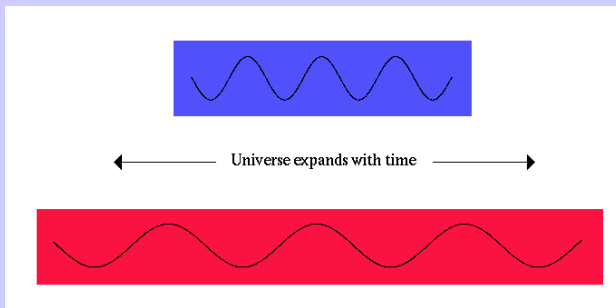
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Expansion redshift vs. Doppler Redshift

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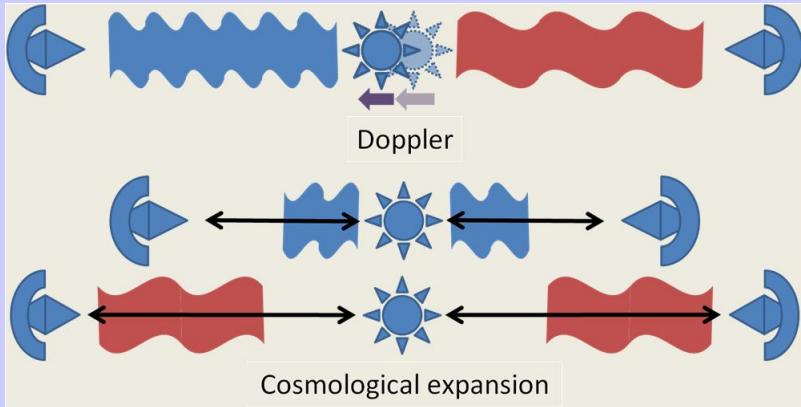
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Temperature History of the Universe

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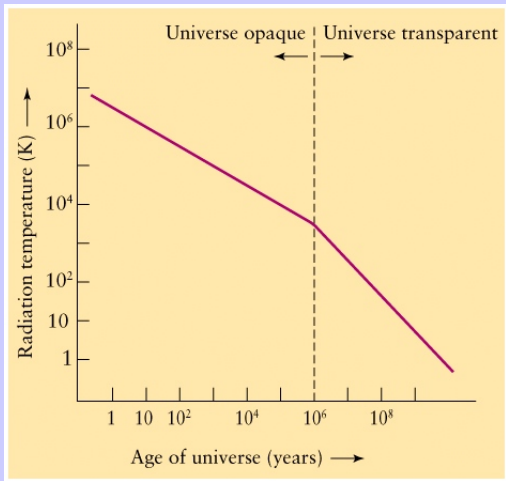
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Matter and Radiation Scaling

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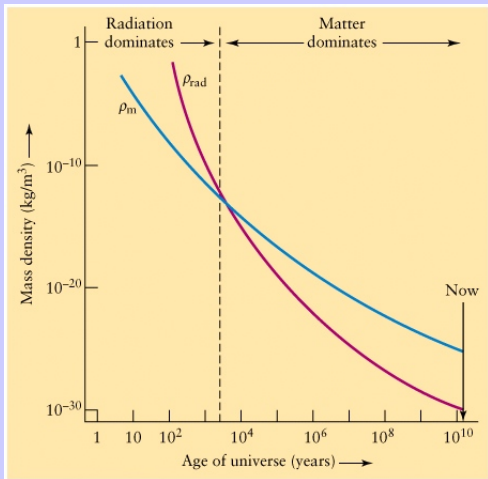
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Recombination

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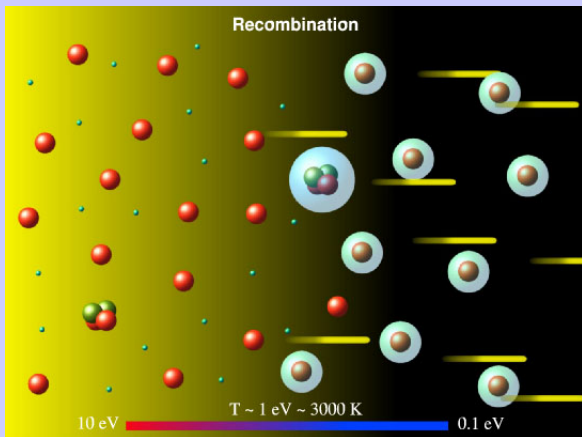
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Jim Peebles: Nobel Prize 2019

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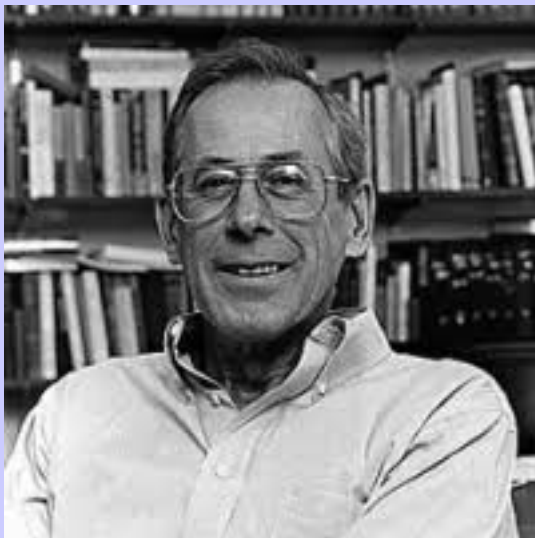
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Prediction of the Cosmic Microwave Background

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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 and by Sandage in an attempt to verify the existence of QSG. The spectrum of BSO 16 shows that this object is a hot star having the Balmer lines in absorption near their rest wavelengths. This was expected on the basis of the non-peculiar $U - B, B - V$ colors. The spectrum of BSO 8 (called "BSO 105" by Sandage 1965 on an older numbering system) is continuous with no prominent absorption or emission lines. BSO 1 has a large reddshift of $\Delta\lambda/\lambda_0 = 1.2410$, as described elsewhere (Sandage 1965).

Table 1 lists the precise optical positions of the first four interlopers, and estimated positions, accurate to perhaps $\pm 20''$, for the thirty-one survey objects. Where available, 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 catalogues of Iriarte and Chavira (1957), Chavira (1958), and Haro and Layten (1962). With the identification of most of these objects as intrinsically bright stellar-appearing galaxies, these catalogues provide a large finding list that can be surveyed by radio techniques to determine if the QSG's are weak radio emitters. It is expected that such study will shed light on the evolutionary process of radio decay after the intense QSS radio phase.

ALLAN SANDAGE
PHILIPPE VERON

May 21, 1965

MOUNT WILSON AND PALOMAR OBSERVATORIES
CARMICHAEL INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

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Haro, G., and Layten, W. J. 1962, *Bull. Obs. Ton.* No. 22, p. 1.
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Sandage, A. 1965, *A. J.*, 141 (in press).

COSMIC BLACK-BODY RADIATION*

One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess 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.

1. 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.
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.
3. The assumption that the singularity results from a mathematical over-idealization,

* This research was supported in part by the National Science Foundation and the Office of Naval Research of the U.S. Navy.

Prediction of the Cosmic Microwave Background

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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 energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

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 reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

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 suggestions of Professor J. A. Wheeler.

R. H. DICKE
P. J. E. PEBLES
P. G. ROLL
D. T. WILKINSON

May 7, 1965

PALMER PHYSICAL LABORATORY
PRINCETON, NEW JERSEY

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A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE 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, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

Penzias & Wilson give

Discovery of the Cosmic Microwave Background

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CMB Background

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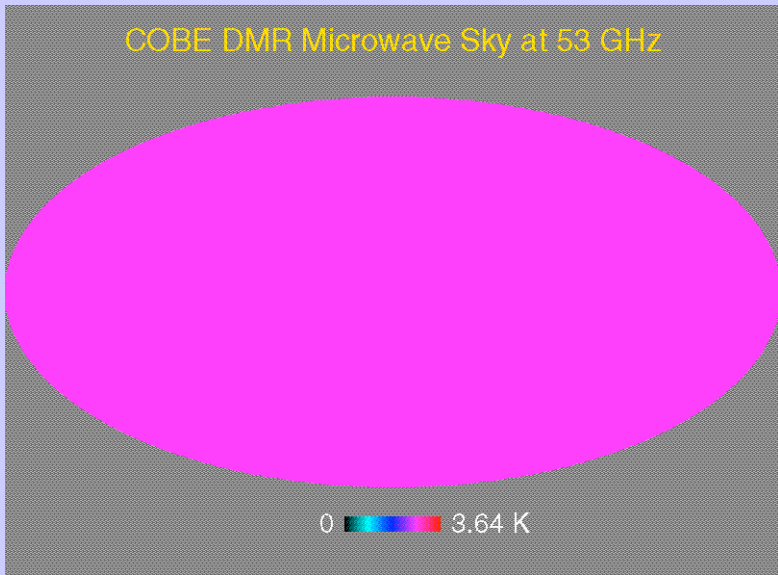
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COBE DMR Microwave Sky at 53 GHz



History of the Universe

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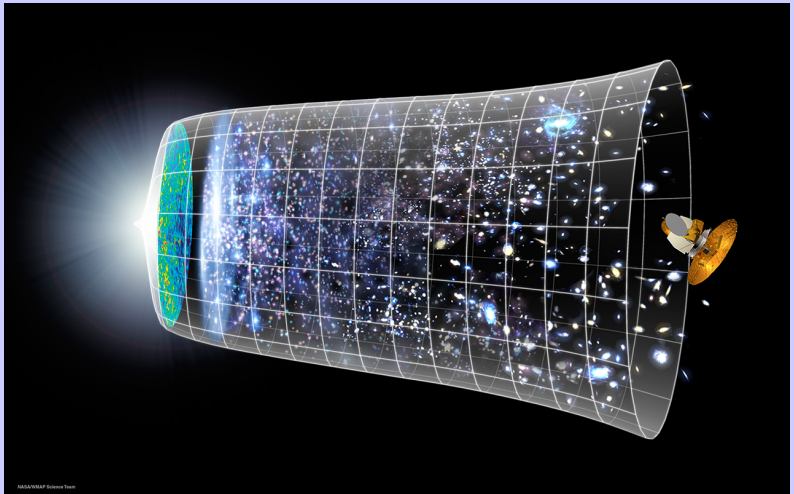
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NASA/WMAP Science Team

Thermal Equilibrium in the Early Universe

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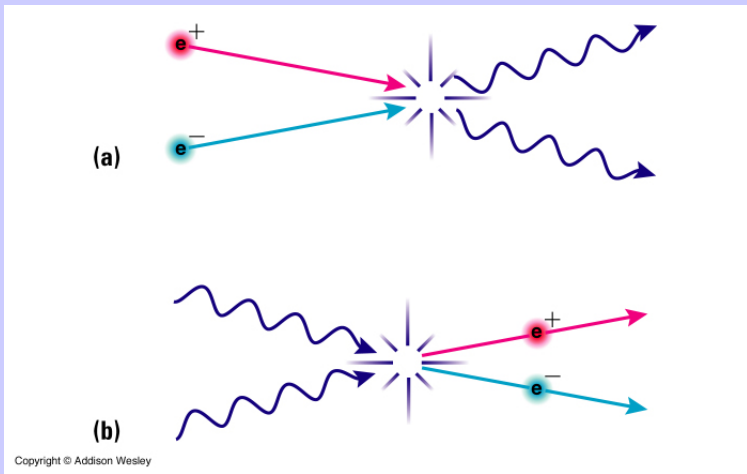
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Spectrum of the Microwave Background

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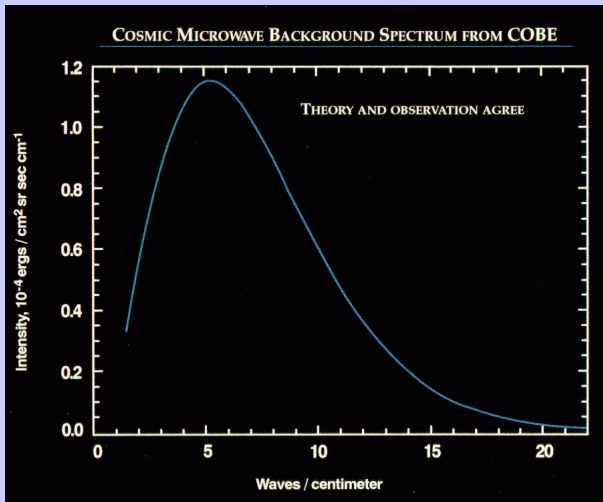
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Cosmological Periods at “Late” Times

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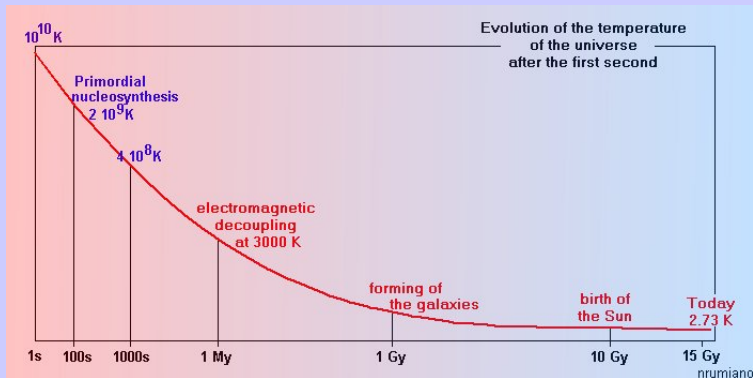
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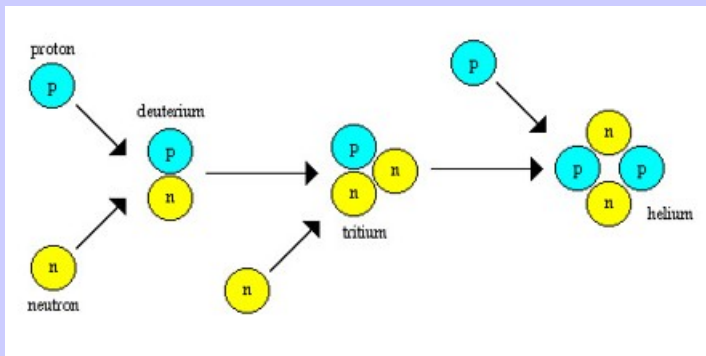


Nucleosynthesis

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Nucleosynthesis: Predictions vs. Observations

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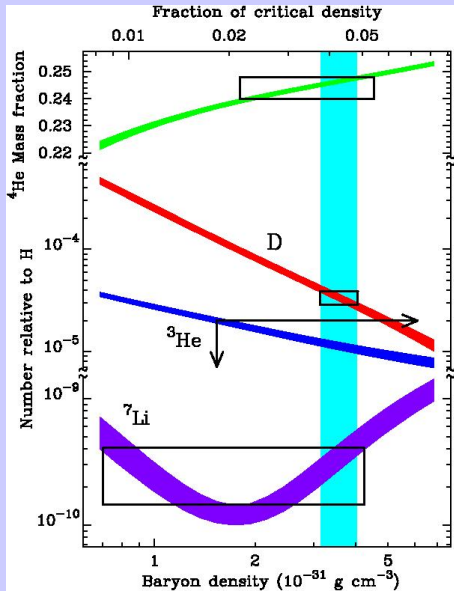
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Quark-Gluon Phase Transition

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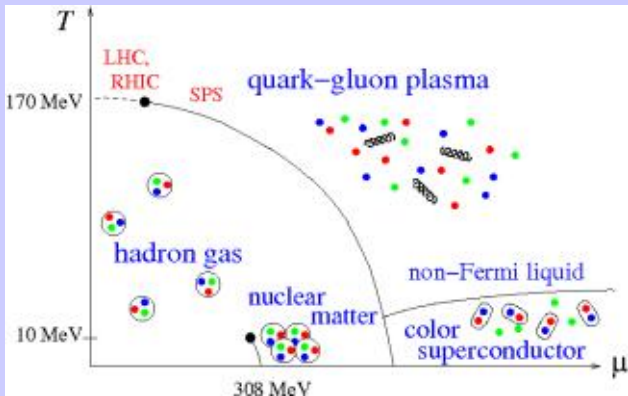
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Running of Coupling Constants

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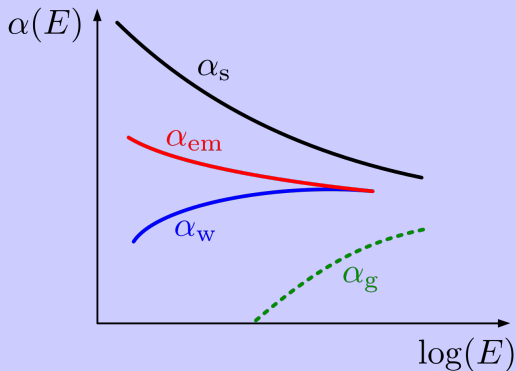
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Particle Physics Unification

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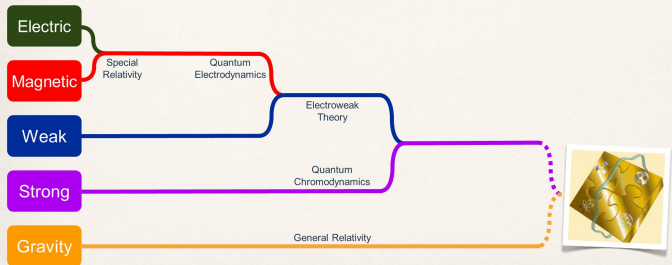
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Unification of Fundamental Forces



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CERN: Beam Pipe

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CERN: Detector

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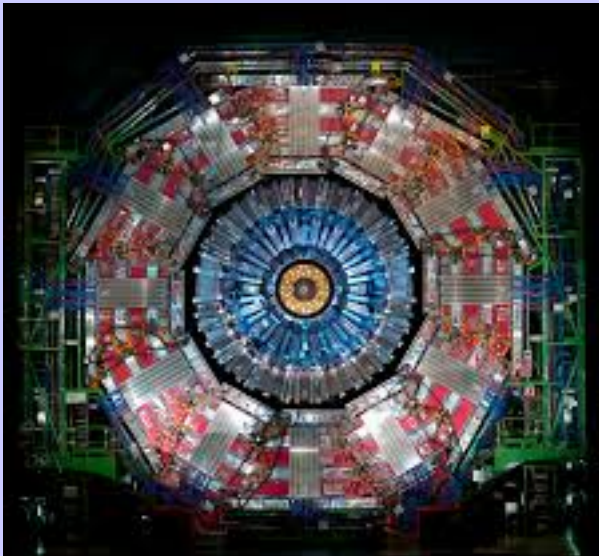
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Physics Phases of the Early Universe

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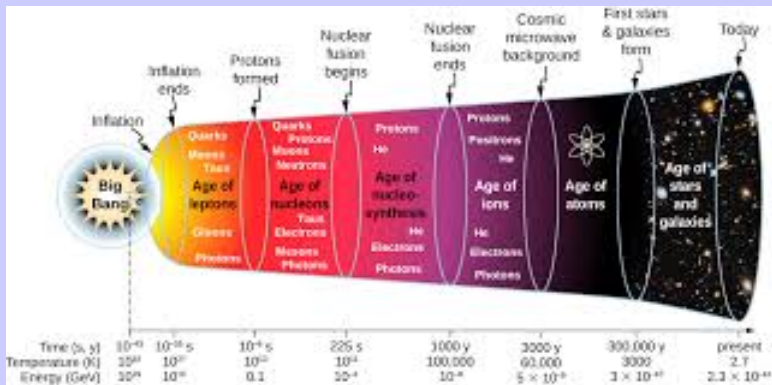
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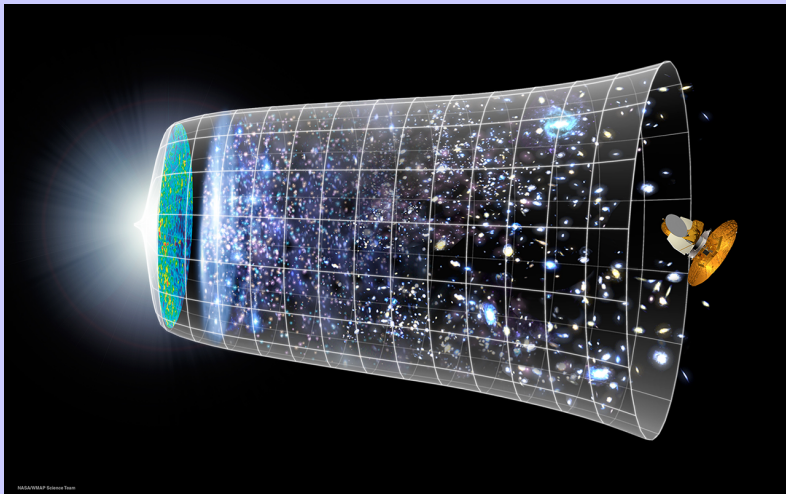
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NASA/WMAP Science Team

Supernova Hubble Law

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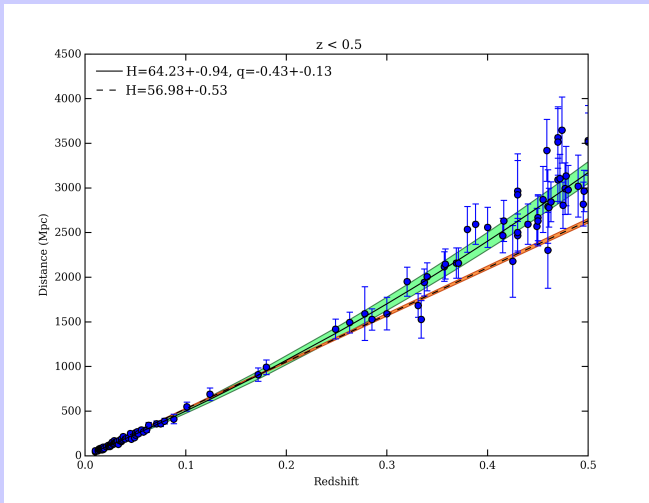
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Recombination

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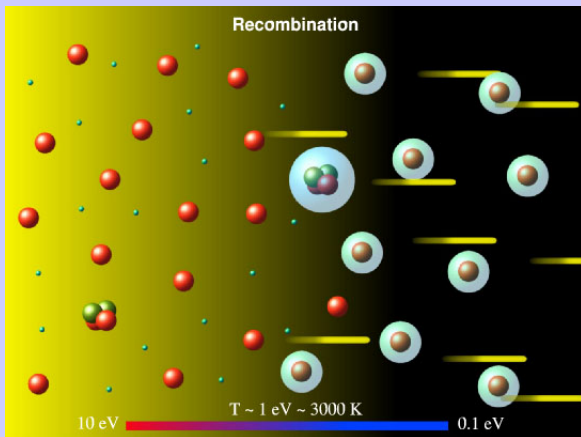
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Spectrum of the Microwave Background

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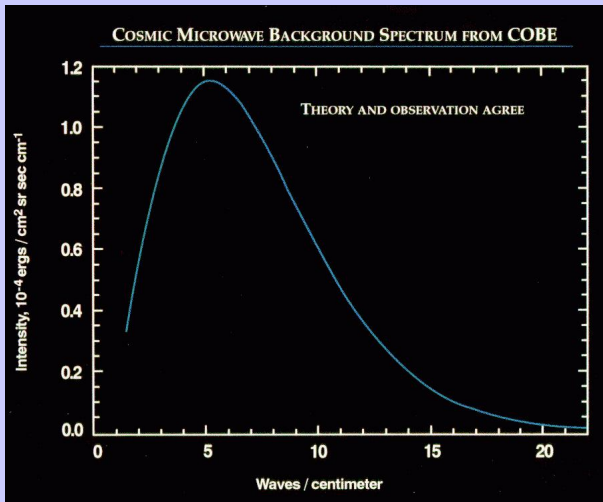
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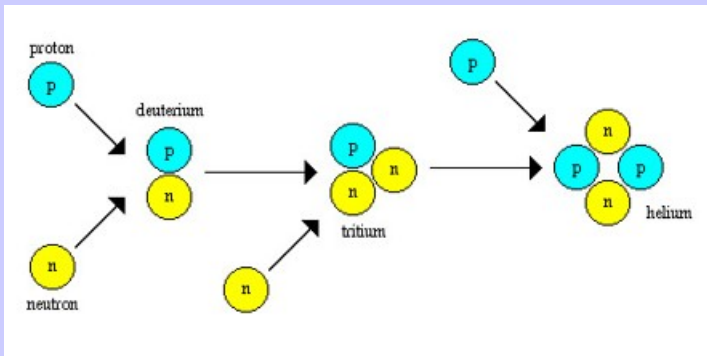


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Isotropy of the CMB Background

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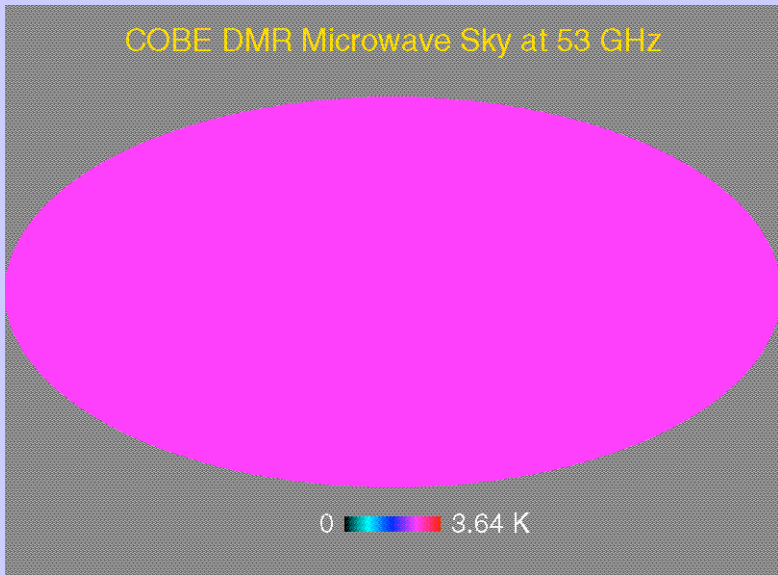
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Horizon Problem

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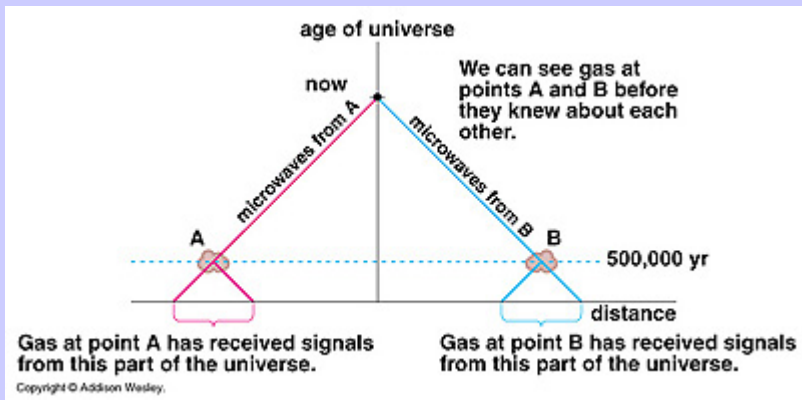
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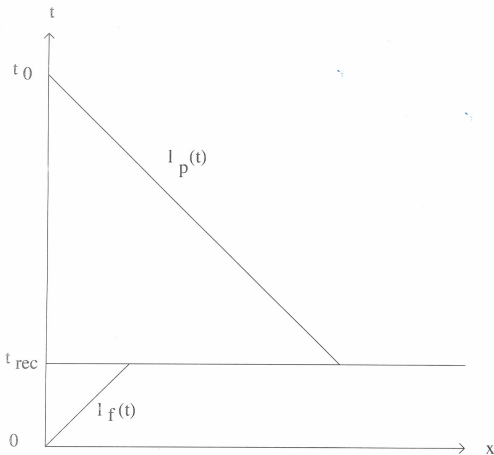
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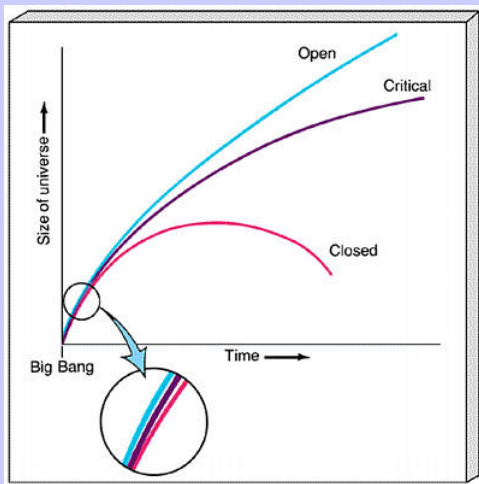
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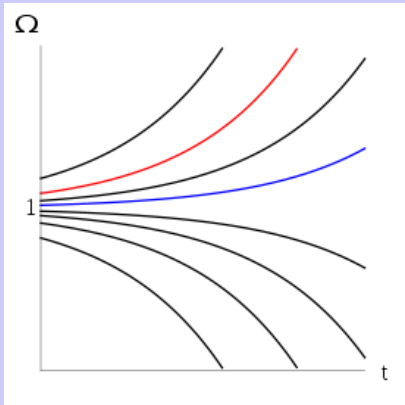
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Large-Scale Structure

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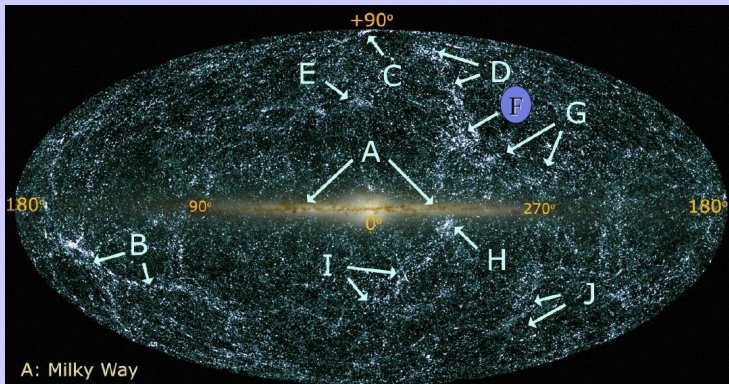
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A: Milky Way

B: Perseus-Pisces Supercluster

C: Coma Cluster

D: Virgo Cluster/Local Supercluster

E: Hercules Supercluster

F: Shapley Concentration/Abell 3558

-90°

G: Hydra-Centaurus Supercluster

H: "Great Attractor"/Abell 3627

I: Pavo-Indus Supercluster

J: Horologium-Reticulum
Supercluster

From: talk by O. Lahav

Structure Formation Problem

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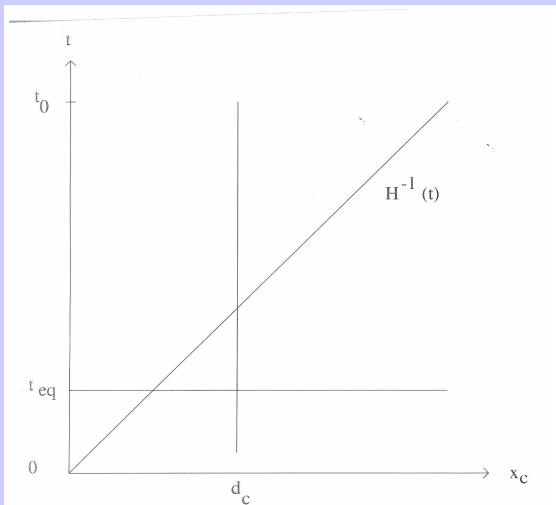
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Cosmological Density Fluctuations

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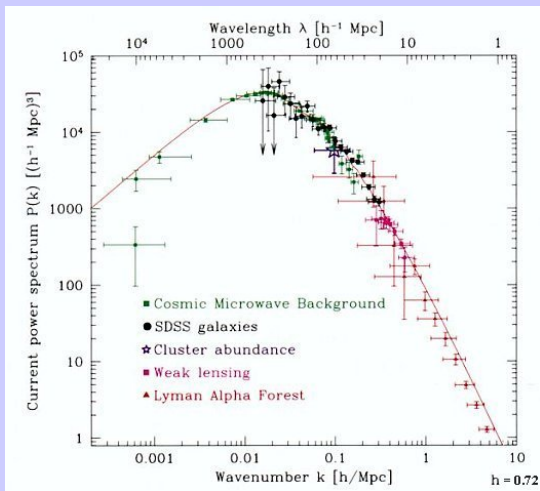
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Anisotropies in the Cosmic Microwave Background (CMB)

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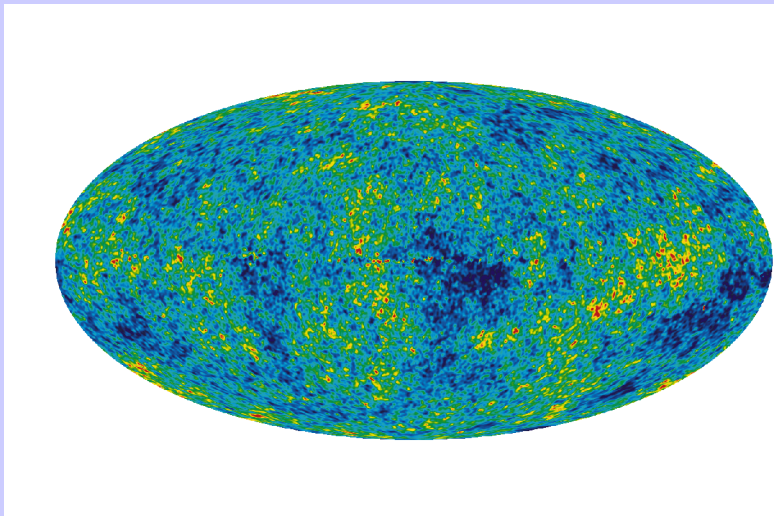
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Credit: NASA/WMAP Science Team

Microwave Anisotropies

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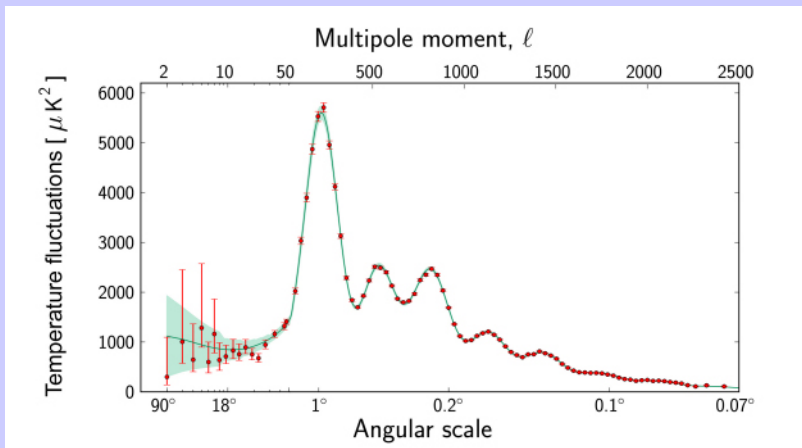
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Early Work

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SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION

9

1970 paper

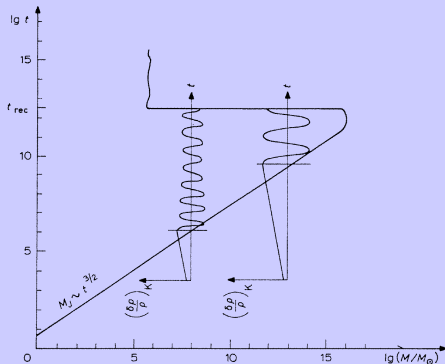


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until 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.

Composition of the Energy of the Universe

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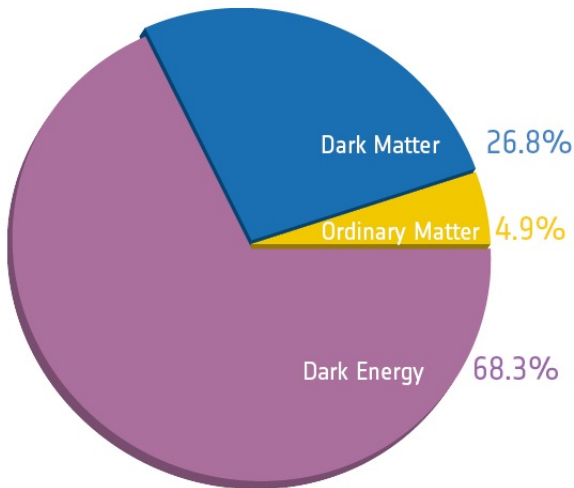
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Evidence for Accelerated Expansion from Supernovae

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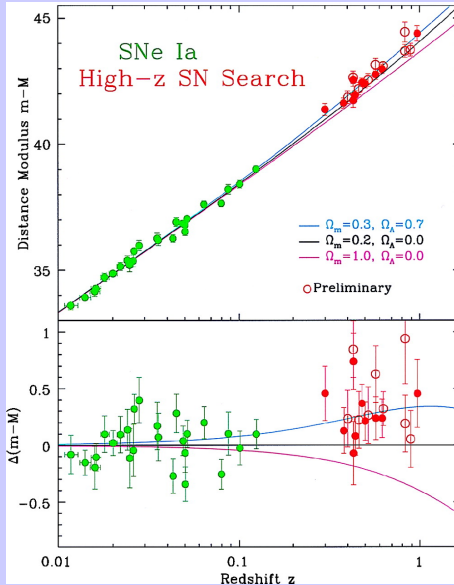
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Angular Power Spectrum of CMB Anisotropies

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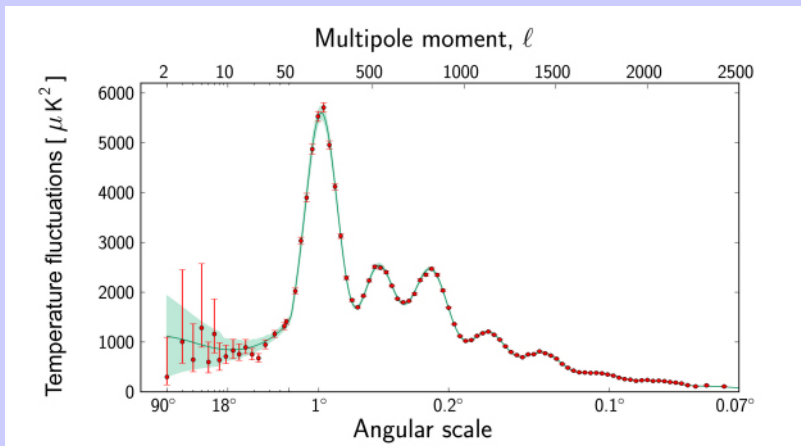
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Spiral Galaxy Rotation Curves

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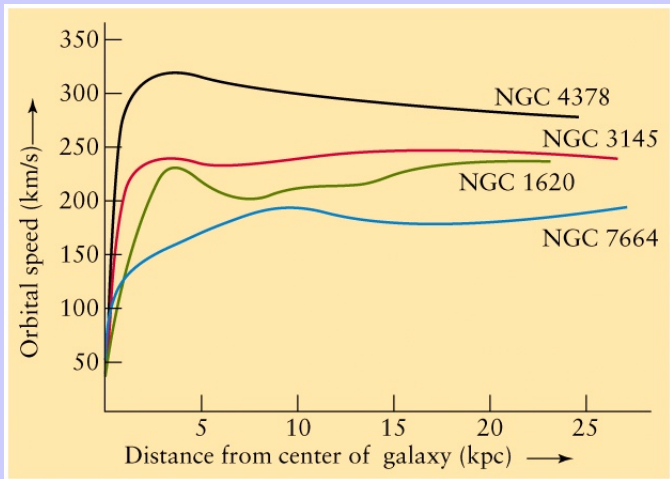
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Elliptical Galaxy Velocity Dispersion

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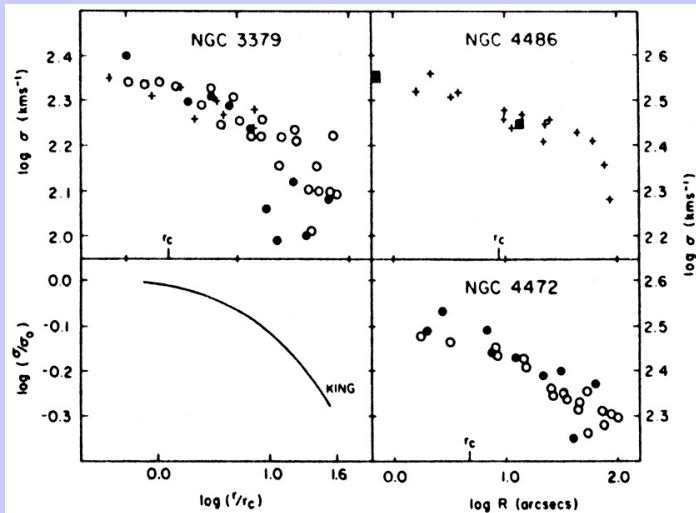
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Hot Gas in Galaxy Cluster

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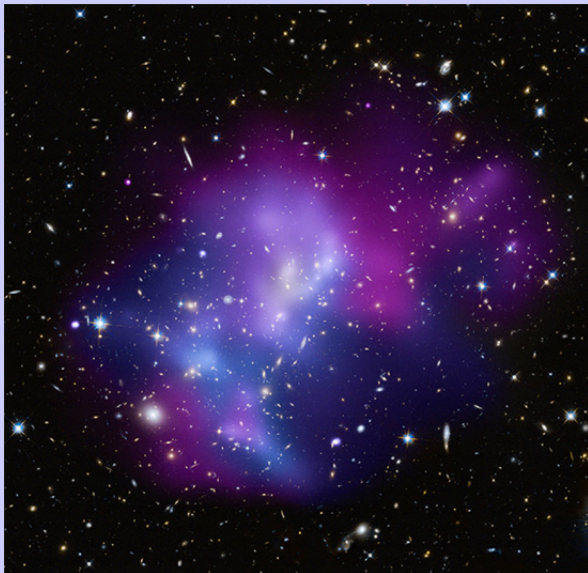
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Gravitational Lensing

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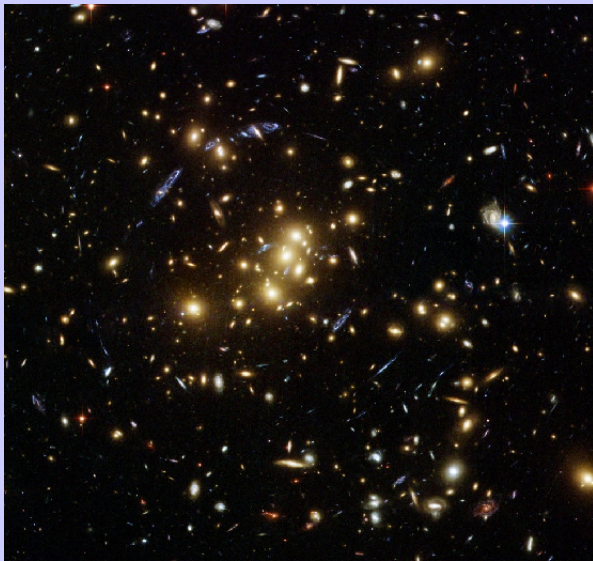
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Bullet Cluster

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Nucleosynthesis Limits

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