Black Holes:
a journey through modern astronomy

I) Introduction:

- **-Ancient vs. Modern Astronomy**
- **-Electromagnetic Radiation**
- **-Astro-Physics: matter, force, energy**

II) Astronomical neighborhood:

- **-Solar system**
- **-our Galaxy**
- **-our Universe**

III) Black holes:

- **-Life of a star**
- **-Stellar vs. Supermassive Black Holes**
- **-X-ray view of black holes**

I) Introductory concepts

* Ancient vs. modern astronomy

* Electromagnetic radiation

* Physics: Matter, Force & Energy

Ancient Astronomy

*Oldest science:

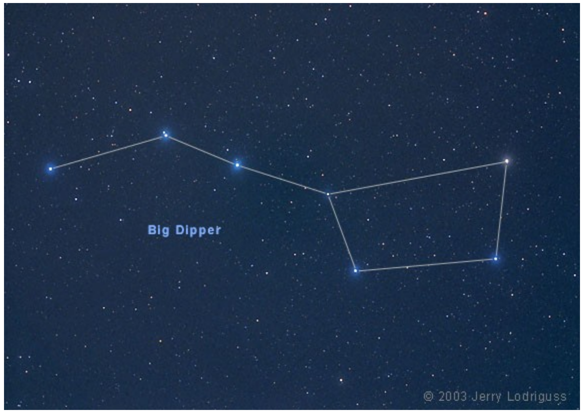
in Mesopotamia, Egypt, China, Greece, India, Central America

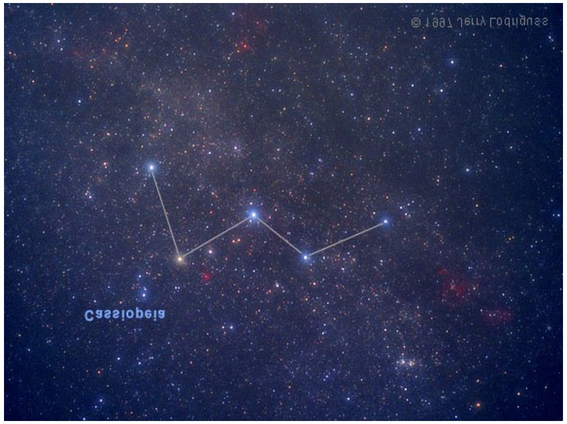
*First astronomical discoveries:

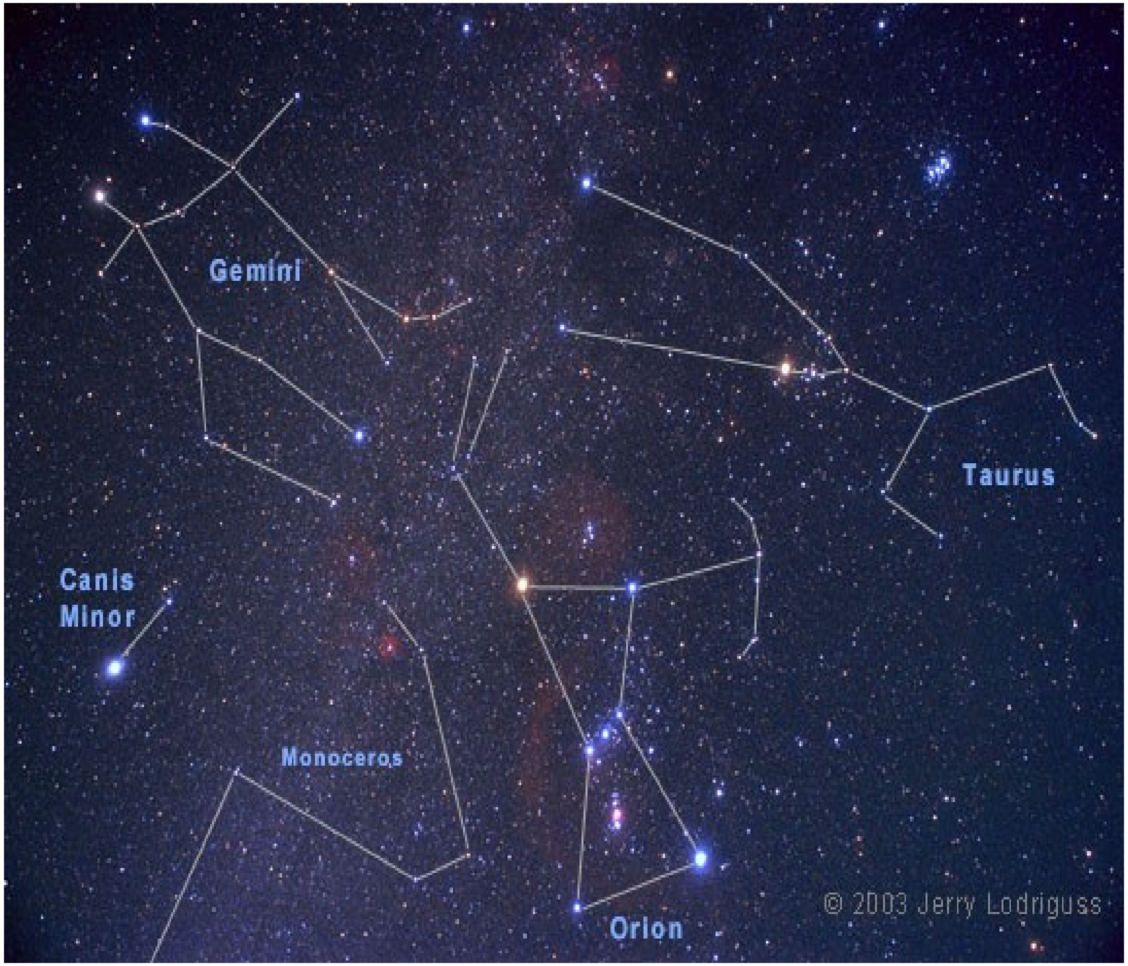
- -cycle of seasons
- -duration of the year
- -lunar cycles & eclipses
- -shape & size of the Earth
- -discovery of planets
- -definition of constellations

Comparison with modern Astronomy

***Same objects:**







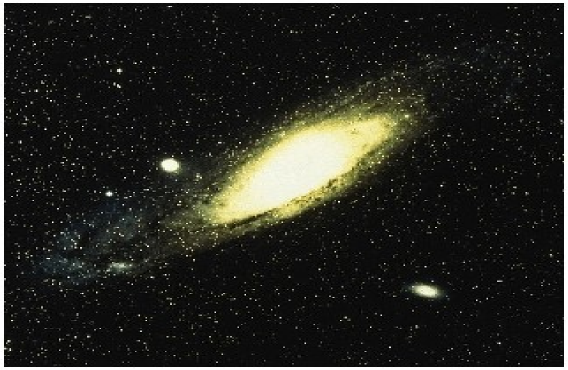
Comparison with modern Astronomy

***Different Tool:**  **vs.** 

***Telescope Advantages:**

-light gathering power (~instrument area)

(a)

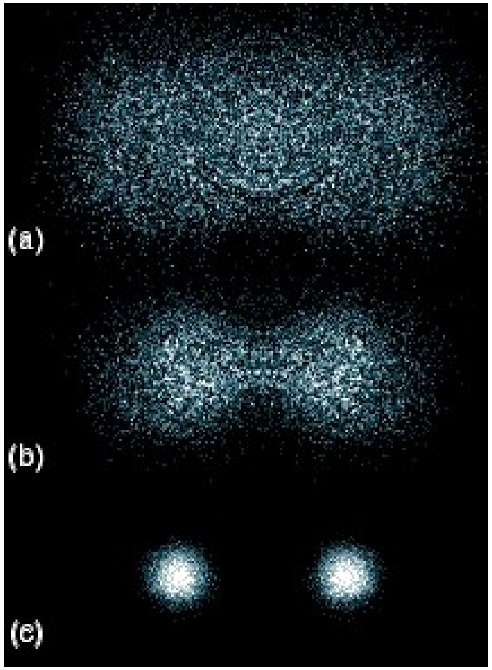


Comparison with modern Astronomy

***Different Tool:**  **vs.** 

***Telescope Advantages:**

-resolving power (~instrument diameter)

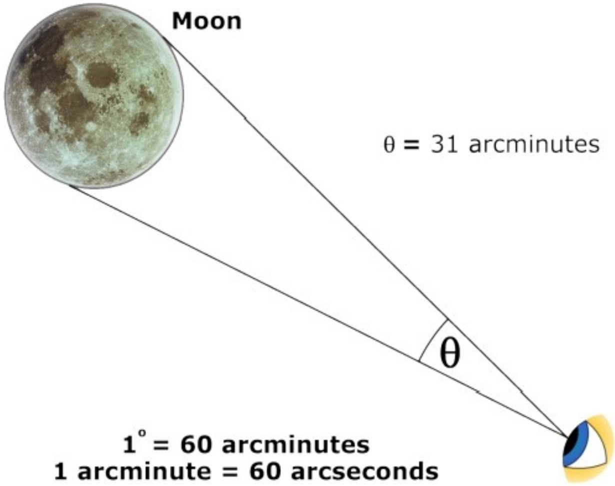


Comparison with modern Astronomy

***Different Tool:**  **vs.** 

***Telescope Advantages:**

-resolving power (~instrument diameter)



Large telescopes angular resolution of fraction of arcsecond (1”=1'/60= 1 degree/3600)

Comparison with modern Astronomy

***Different Tool:**  **vs.** 

***Beyond the ancient sky:**

-very distant sources: galaxies

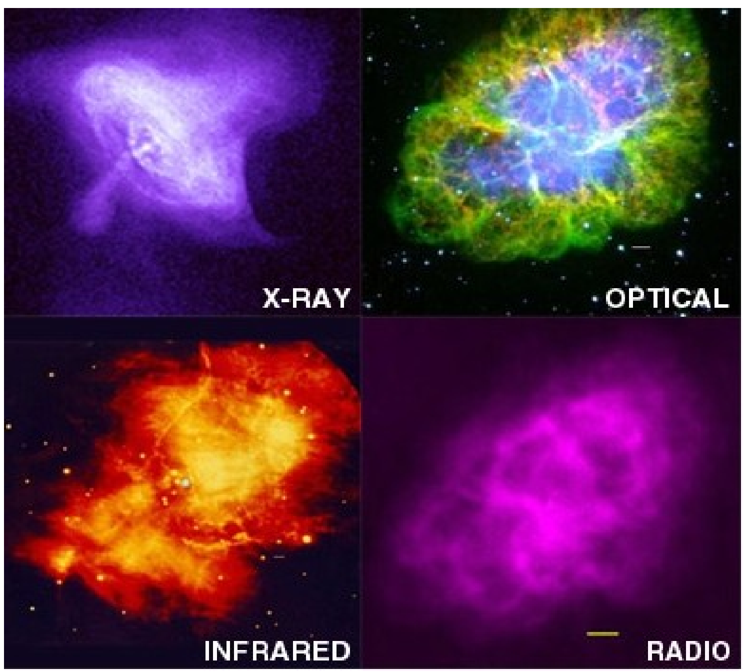
Comparison with modern Astronomy

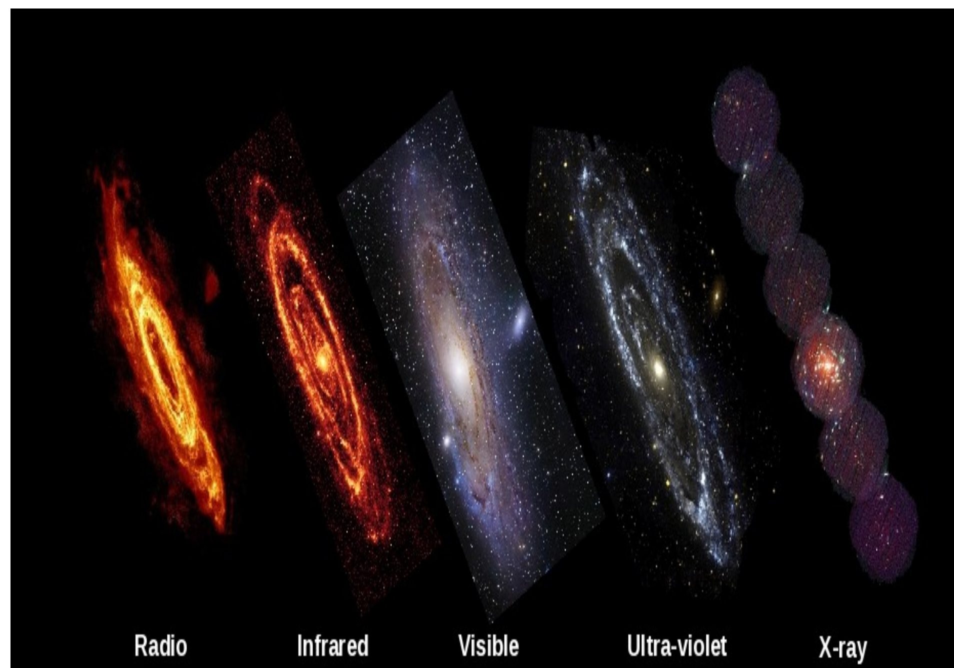
***Different Tool:**

vs.

***Beyond the ancient sky:**

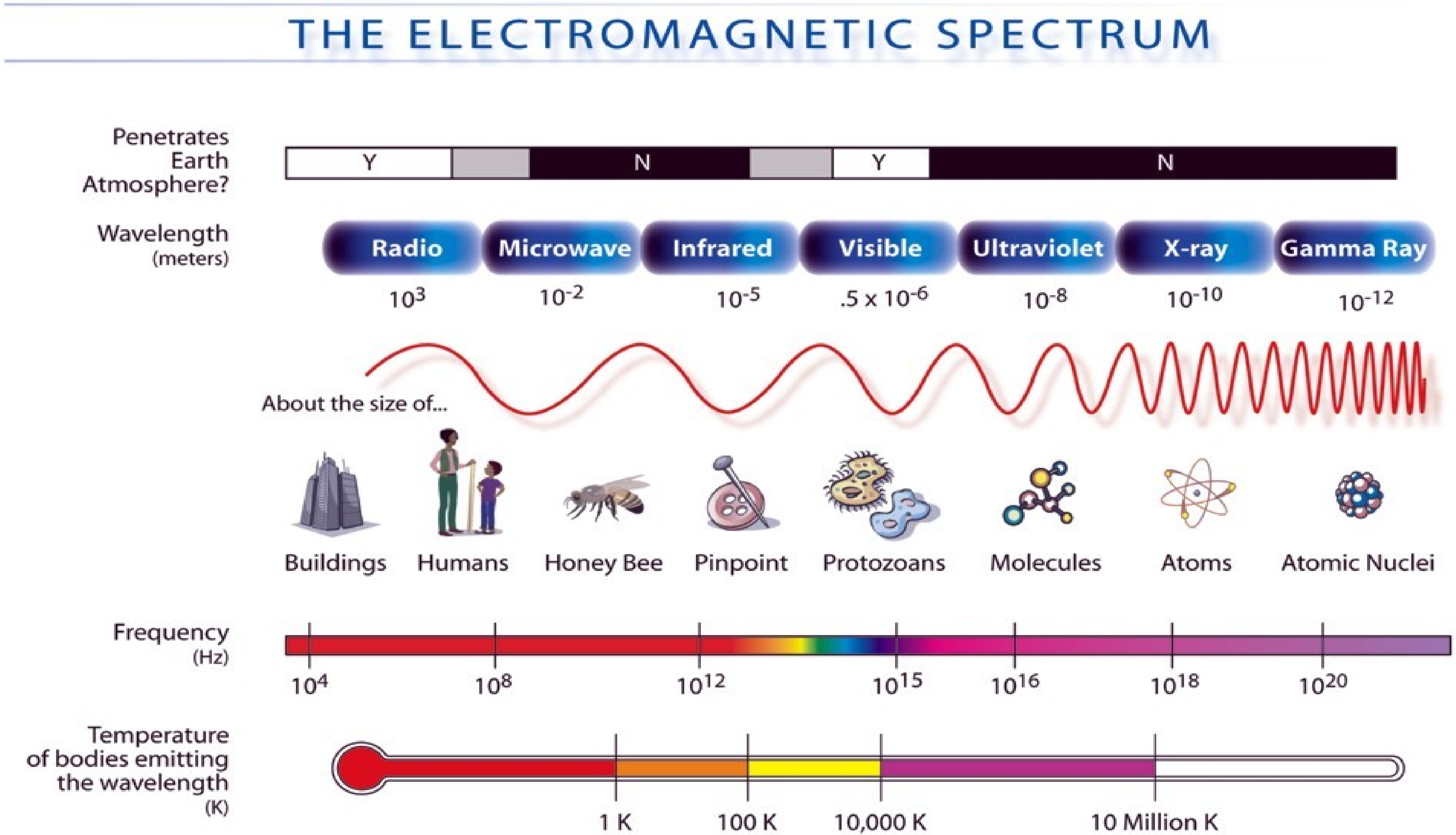
-multiwavelength astronomy





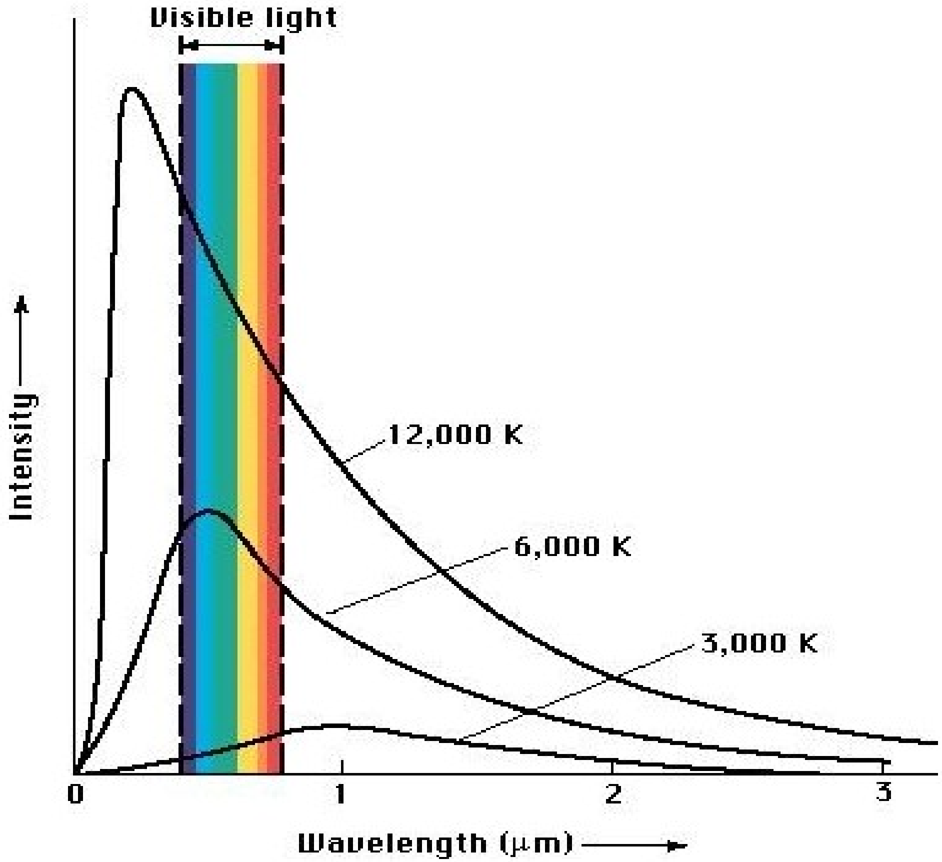
Electromagnetic Radiation

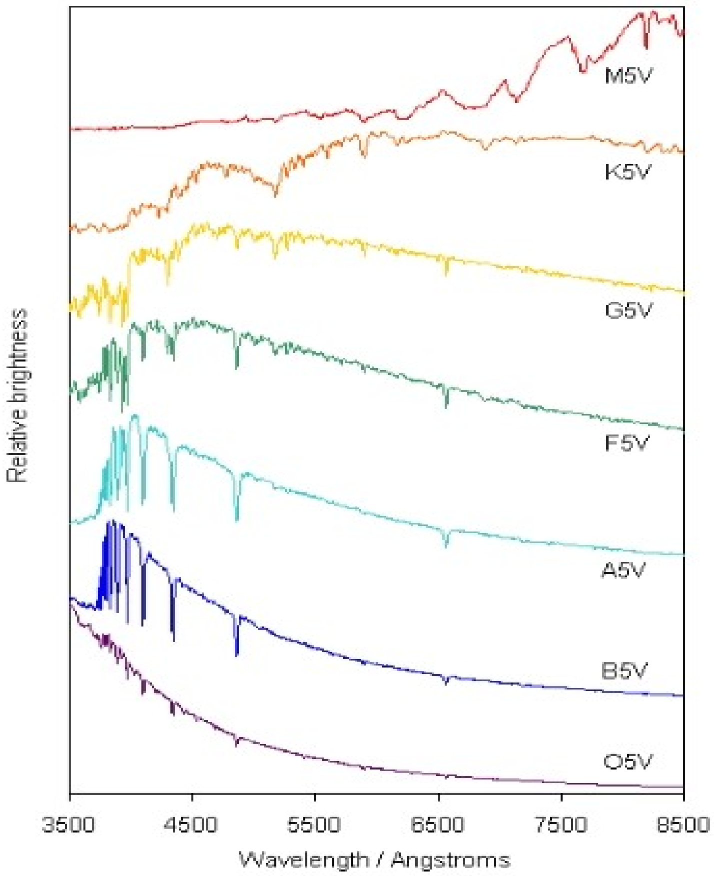
Crucial importance in astronomy: 99% of the information



Continuous Spectrum

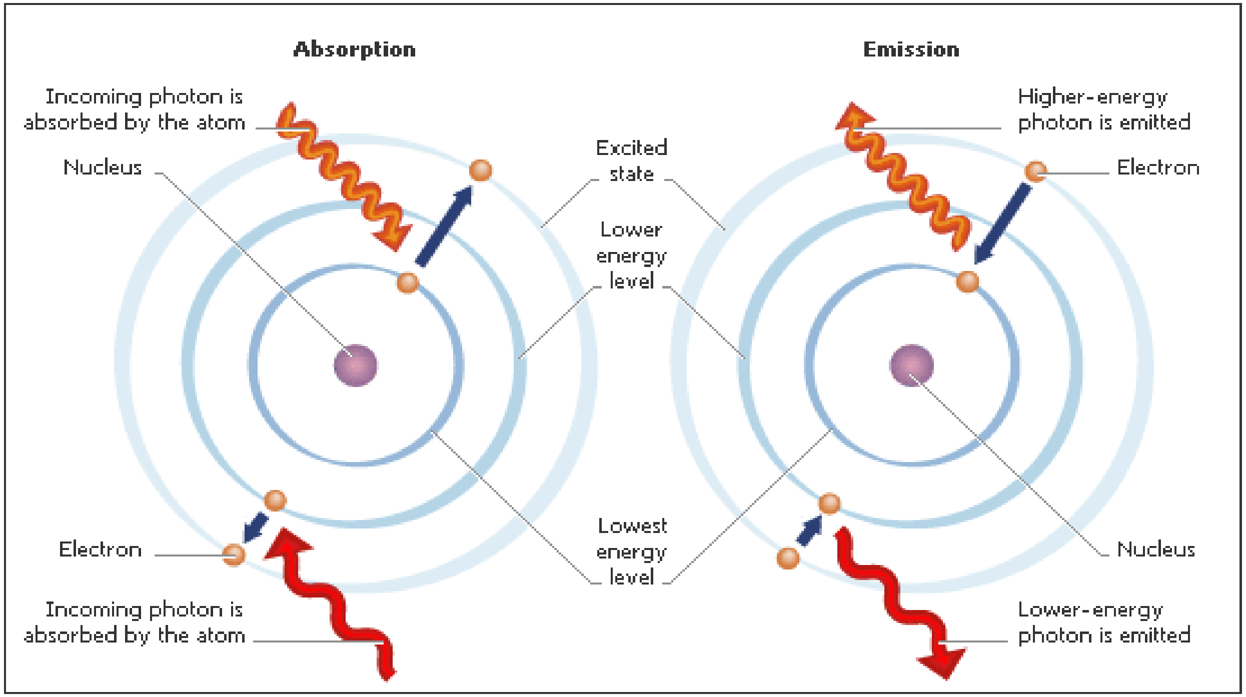
Thermal continuous spectra are produced by accelerated charged particles in dense objects (stars, planets)



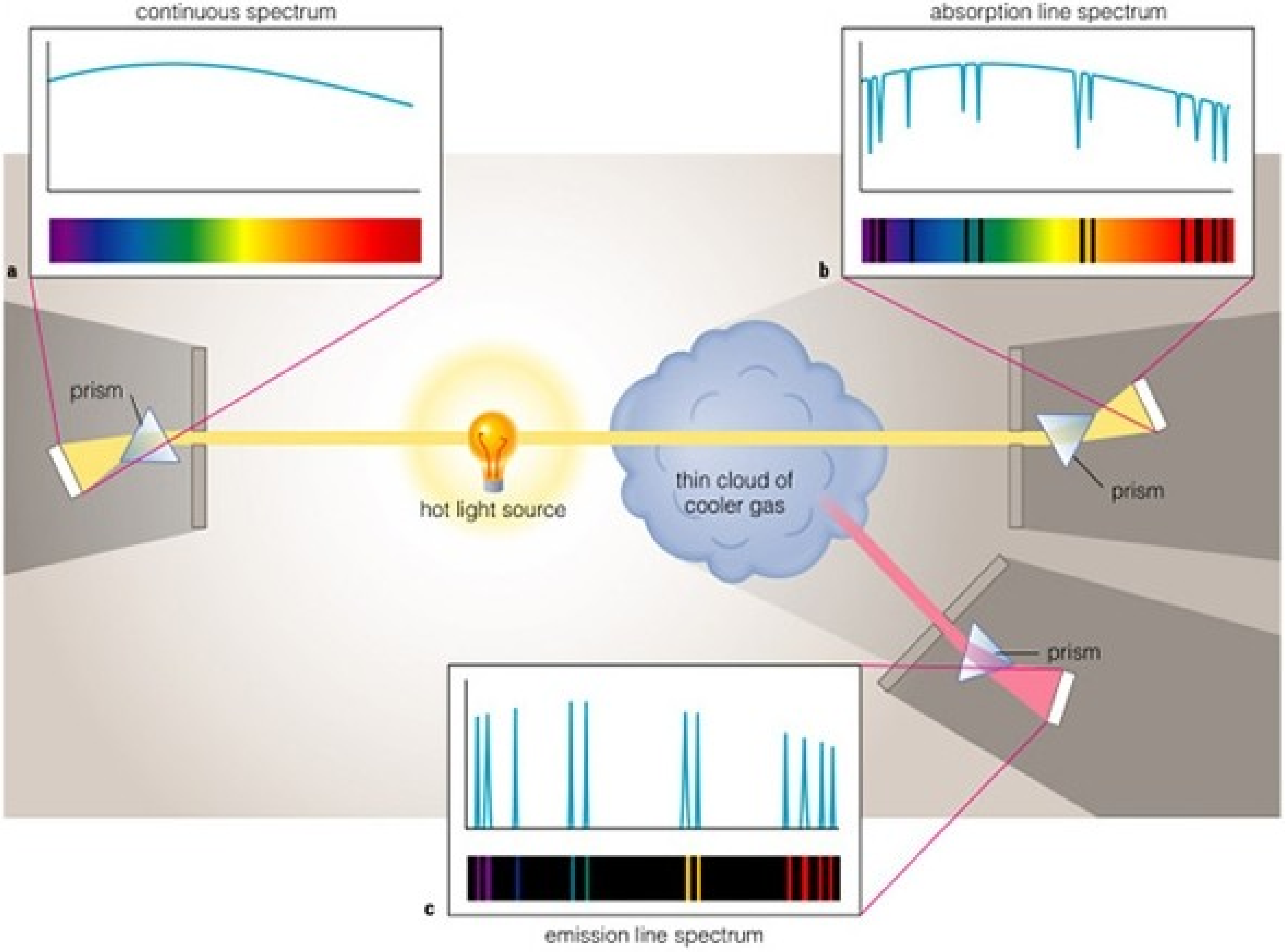


Line Spectrum

Produced by electron transitions in atoms in low-density gas:



Continuous & line Spectra combined



Observational Tools in Astronomy

1) Spatial Analysis: IMAGE

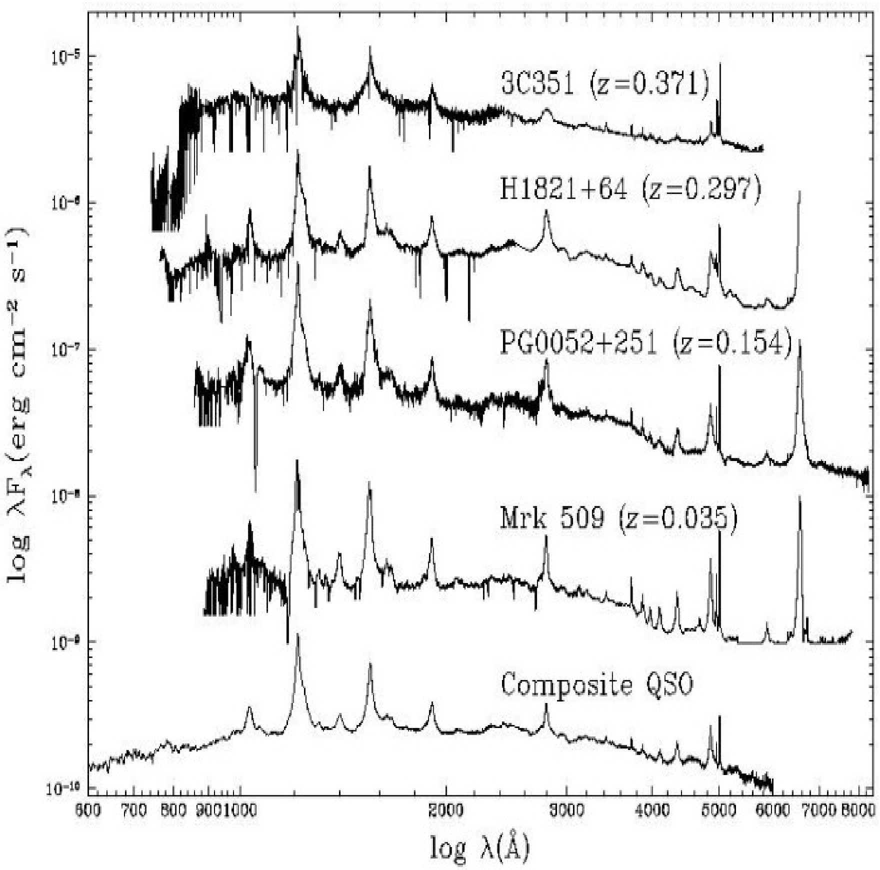
Study of how photons are spatially distributed

Observational Tools in Astronomy

1) Spatial Analysis: IMAGE

2) Spectral Analysis: SPECTRUM

Study of the distribution of photons over wavelength



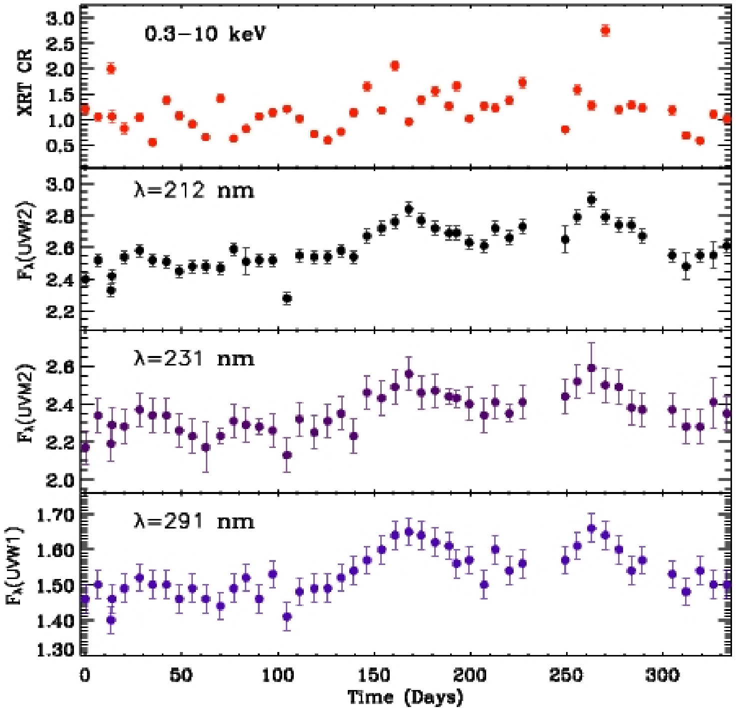
Observational Tools in Astronomy

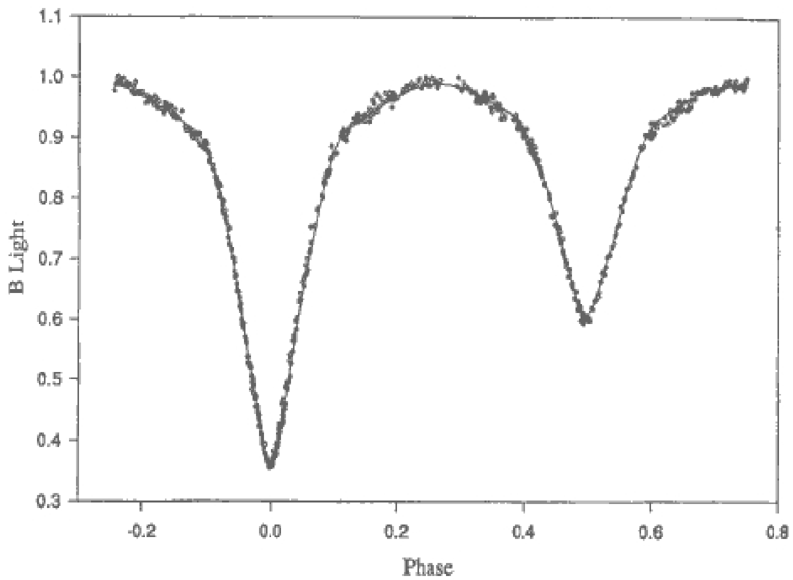
1) Spatial Analysis: IMAGE

2) Spectral Analysis: SPECTRUM

3) Temporal Analysis: LIGHT CURVE

Study of the distribution of photons over time



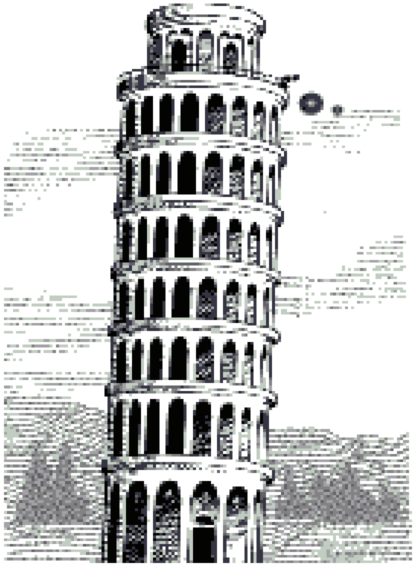


New Approach: Scientific Method

Observation / Experiment

Hypothesis / Prediction

Theory / Physical law

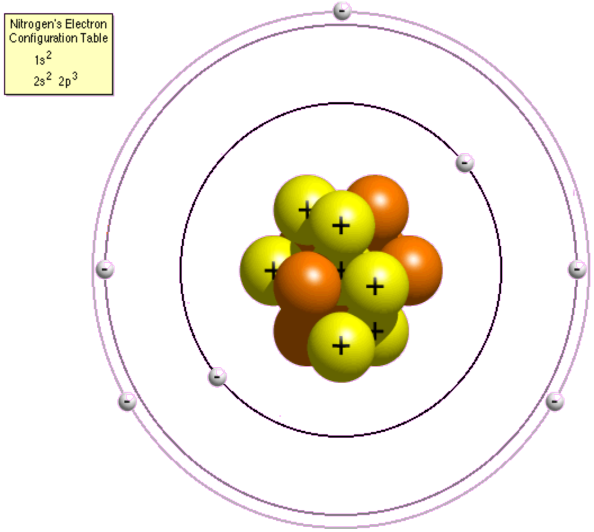


Example: Galielo's experiment on falling objects

Astronomy = Astrophysics

Stars are made of *MATTER*, they are subject to FORCES and produce ENERGY.

The basic blocks of matter are atoms made of
electrons (negative charge)
protons (positive charge)
neutron (no electrical charge)



Simple & most abundant atoms:
-Hydrogen (H): 1p, 1e
-Helium (He): 2p, 2n, 2e

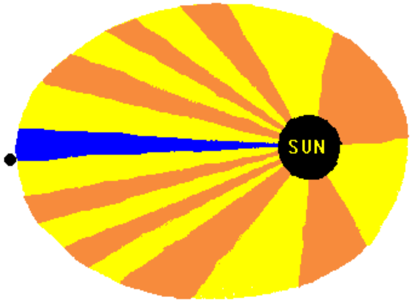
Astronomy = Astrophysics

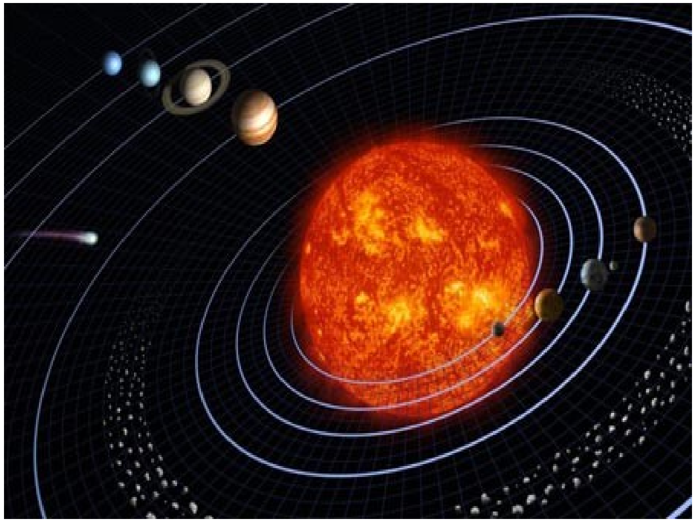
Stars are made of MATTER, they are subject to *FORCES* and produce ENERGY.

Nuclear Strong Force: keeps nucleus together.

Electromagnetic Force: keeps atom together.

Gravitational Force responsible for:
- **feet on the ground**
- **sea tides**
- **planets orbiting the Sun**



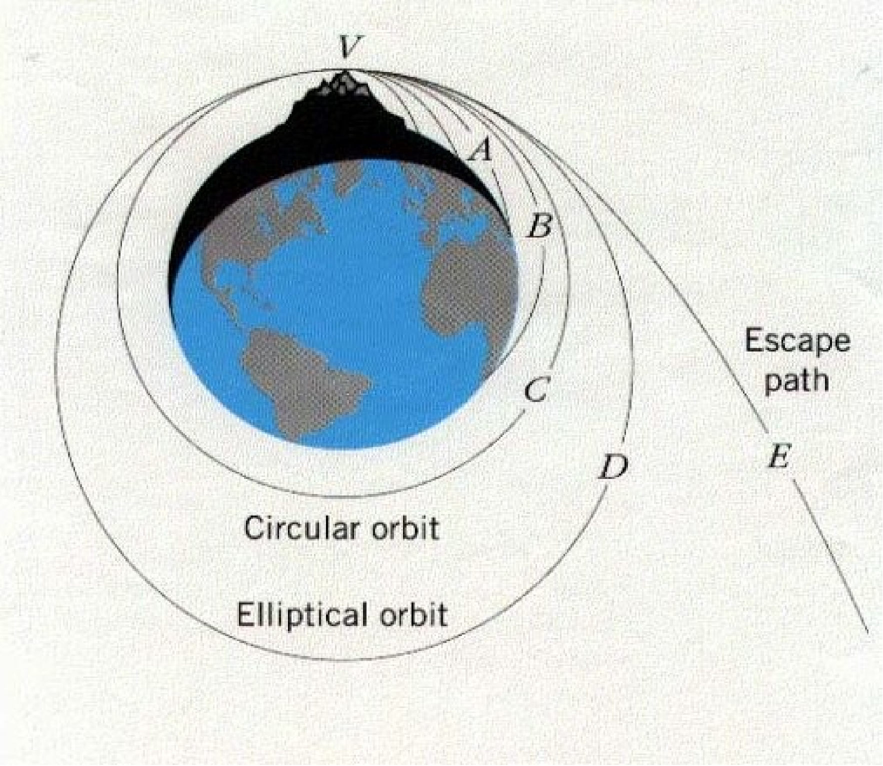


Astronomy = Astrophysics

Newton's Second Law ***Force = mass * acceleration***

Escape velocity: Initial speed needed to escape from an object's gravitational pull.

(on Earth v_esc= 11 km/s = 7 mi/s)



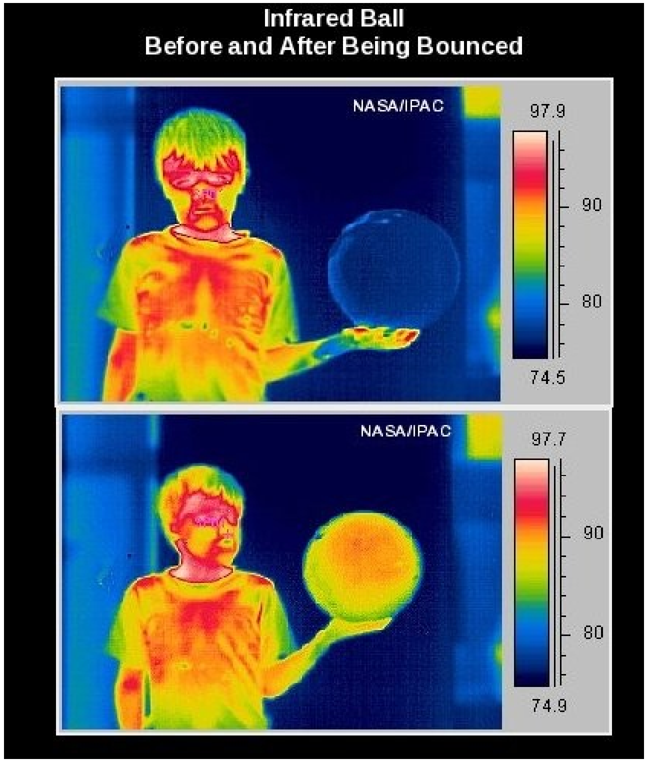
Astronomy = Astrophysics

Stars are made of MATTER, they are subject to FORCES and produce *ENERGY*.

Many forms of Energy:

Example: bouncing ball

Gravitational potential energy into kinetic energy + Thermal Energy (Heat)



Astronomy = Astrophysics

Stars are made of MATTER, they are subject to FORCES and produce *ENERGY*.

Many forms of Energy:

Example: bouncing ball

Gravitational potential energy into kinetic energy

+ Thermal Energy (Heat)

DIFFERENCE HEAT TEMPERATURE

Heat is a form of energy: it depends on the number of particles and their speed.

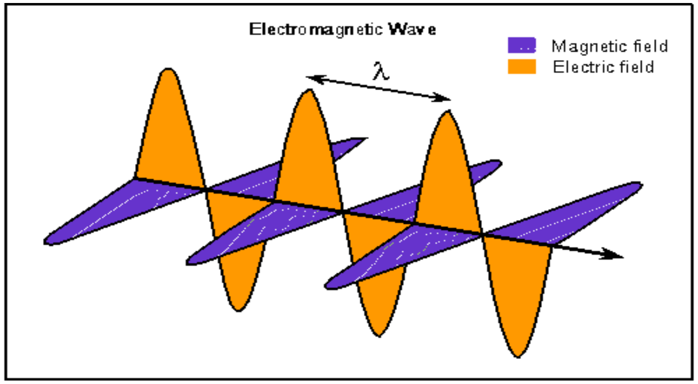
***Temperature* is NOT energy: it is related to heat but depends only on the average speed of particles (atoms and molecules).**

Astronomy = Astrophysics

Stars are made of MATTER, they are subject to FORCES and produce *ENERGY*.

Energy can be transformed in different forms but is always conserved.

Electromagnetic Radiation is a form of energy.
It has a dual nature: wave and particle (photon)



II) Our Astronomical Neighborhood

* The Solar System

* Our Galaxy

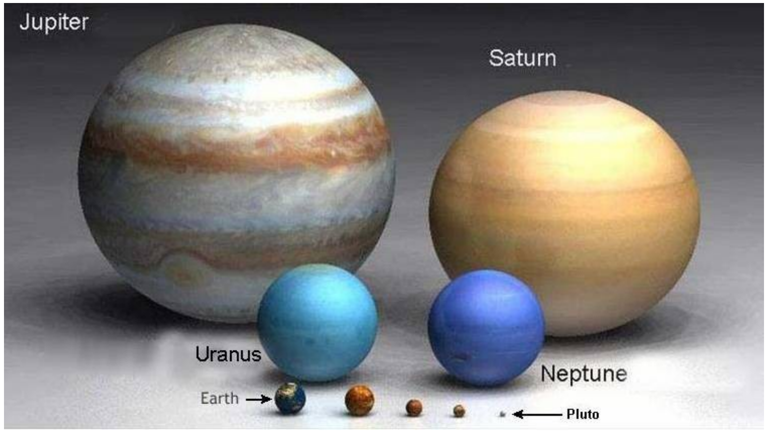
* Distant galaxies

Solar System sizes scaled-down

Units for sizes: kilometers (1 km~ 0.6 mi)

Earth diameter d_{Earth} = 12,756 km

SCALE: d_{Earth} = 1 tennis ball



$d_{Mercury}$ ~ 1 big marble

d_{Venus} ~ 1 tennis ball

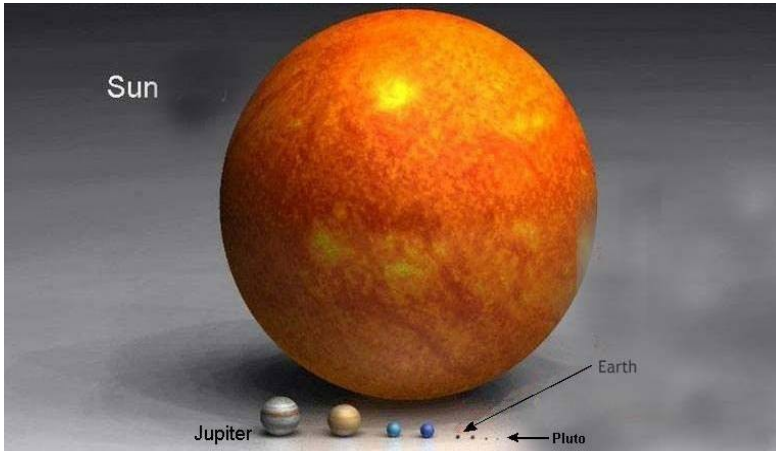
d_{Mars} ~ 0.5 tennis ball

$d_{Jupiter}$ ~ 2.5 soccer balls

d_{Saturn} ~ 2 soccer balls

d_{Uranus} ~ 1 soccer ball

$d_{Neptune}$ ~ 1 soccer ball



$d_{Pluto} < d_{Moon}$ ~ 1 small marble

d_{Sun} > 1 car

Solar System distances scaled-down

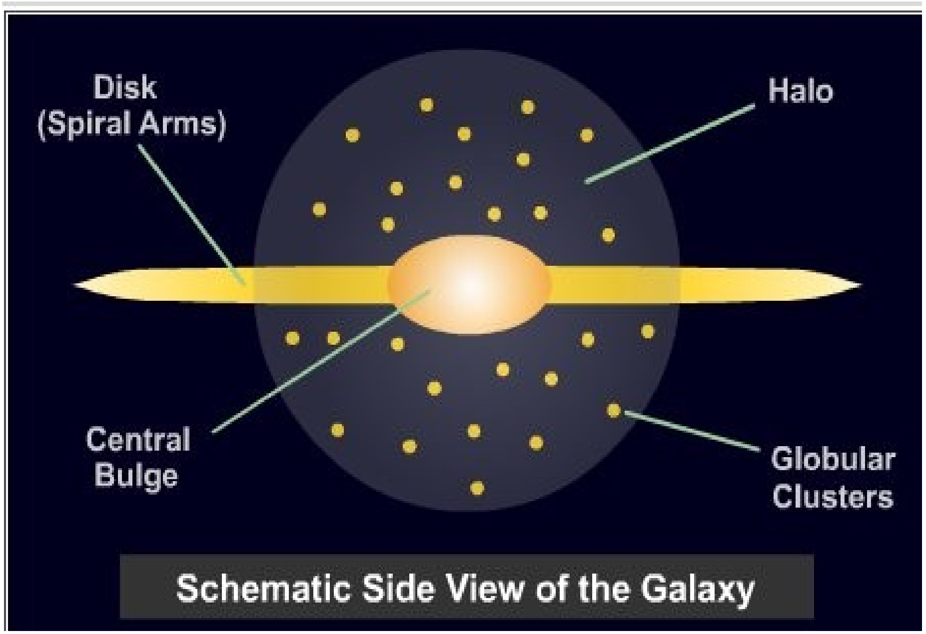
Units: Astronomical Unit (AU)= $d_{Earth\text{-}Sun}$ = 150 million km

light year (ly) ~ 10 trillion km

SCALE: d_{Sun} = 1 tennis ball (1 big step = 1 m)

$D_{Mercury\text{-}Sun}$	~ 2 steps	~ 3 light minutes
$D_{Venus\text{-}Sun}$	~ 4 steps	~ 6 light minutes
$D_{Earth\text{-}Sun}$	~ 5.5 steps	~ 8 light minutes
$D_{Mars\text{-}Sun}$	~ 8 steps	~ 40 light minutes
$D_{Jupiter\text{-}Sun}$	~ 30 steps	~ 0.7 light hours
$D_{Saturn\text{-}Sun}$	~ 0.5 soccer field	~ 1.3 light hours
$D_{Uranus\text{-}Sun}$	~ 1 soccer field	~ 2.7 light hours
$D_{Neptune\text{-}Sun}$	~ 1.5 soccer fields	~ 4 light hours
$D_{Pluto\text{-}Sun}$	~ 2 soccer fields	~ 5.5 light hours

Our Galaxy: the Milky Way

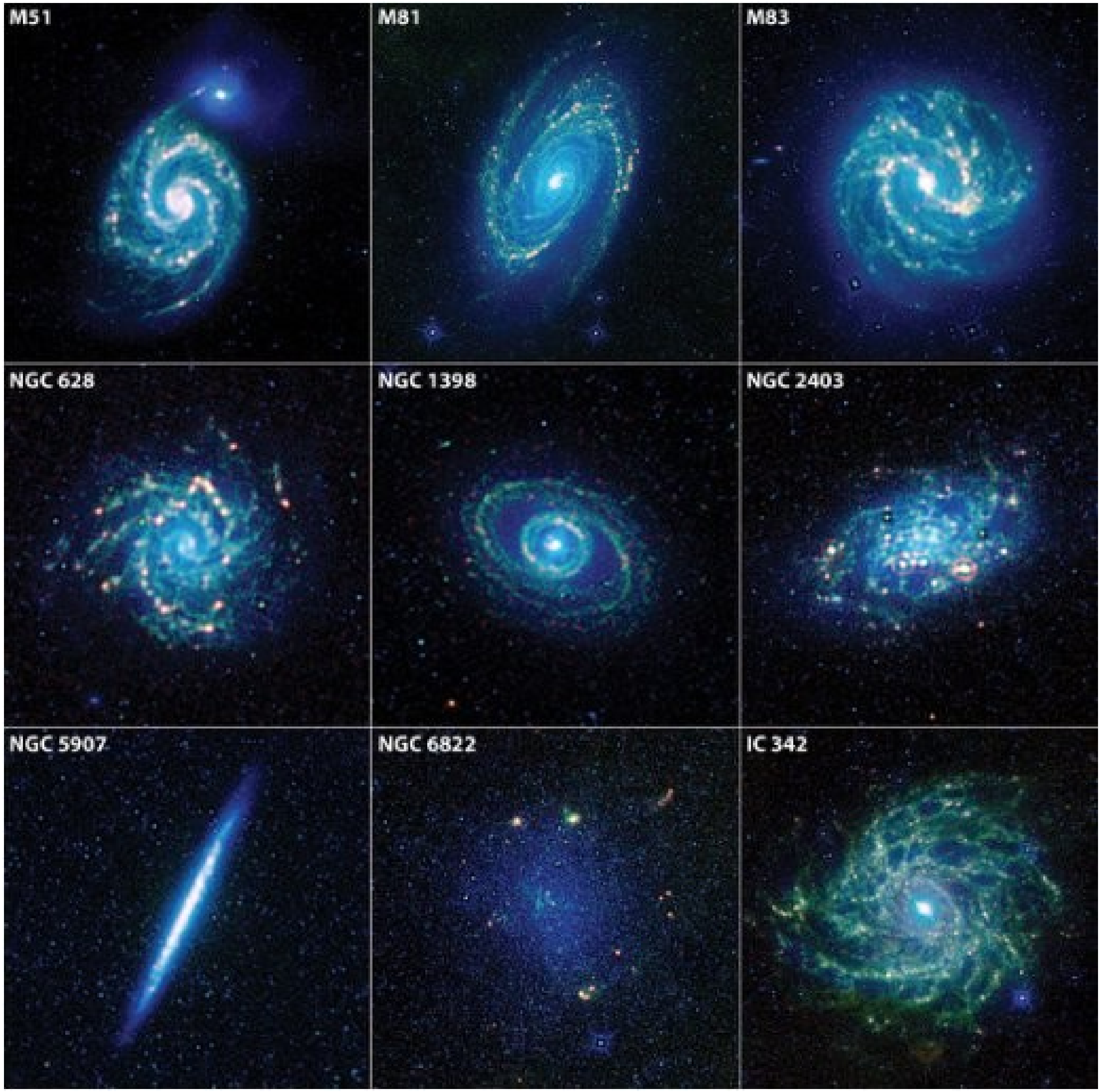


Diameter ~ 100,000 ly
Thickness ~ 1000 ly
$d_{Sun\text{-}center}$ ~ 25,000 ly
closest star ~ 4 ly
 # stars ~ 100 billion

Basic components:
Disk: a lot of gas, dust, many young stars.
Bulge: central spheroid with highest density of stars.
Halo: little gas, old stars in globular clusters.
Dark matter: no ordinary matter but with gravity.

Beyond our Galaxy

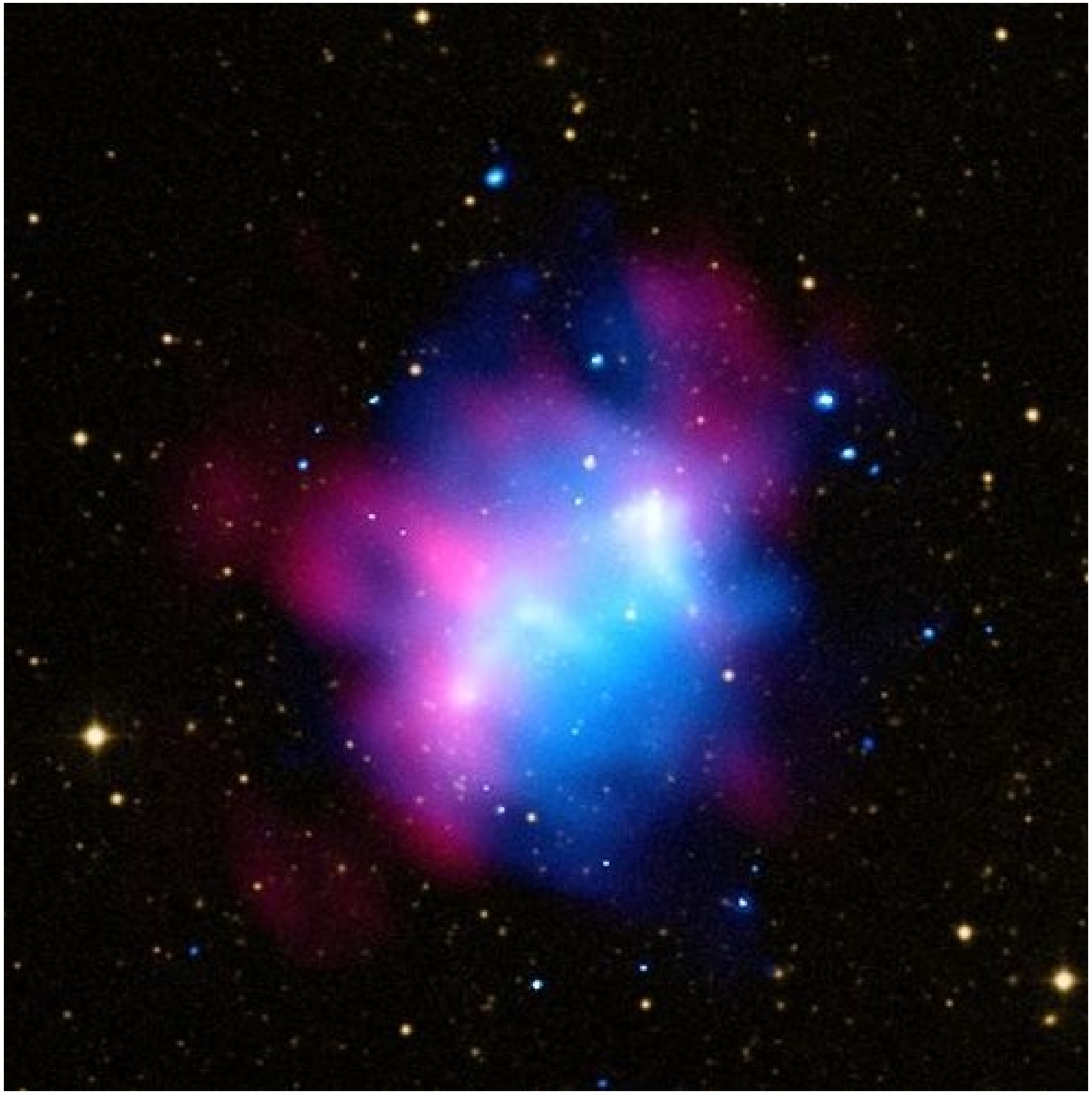
Many types of galaxies: spirals, elliptical, Irregular.



Beyond our Galaxy

Many types of galaxies: spirals, elliptical, Irregular.

Galaxies grouped in clusters, superclusters.

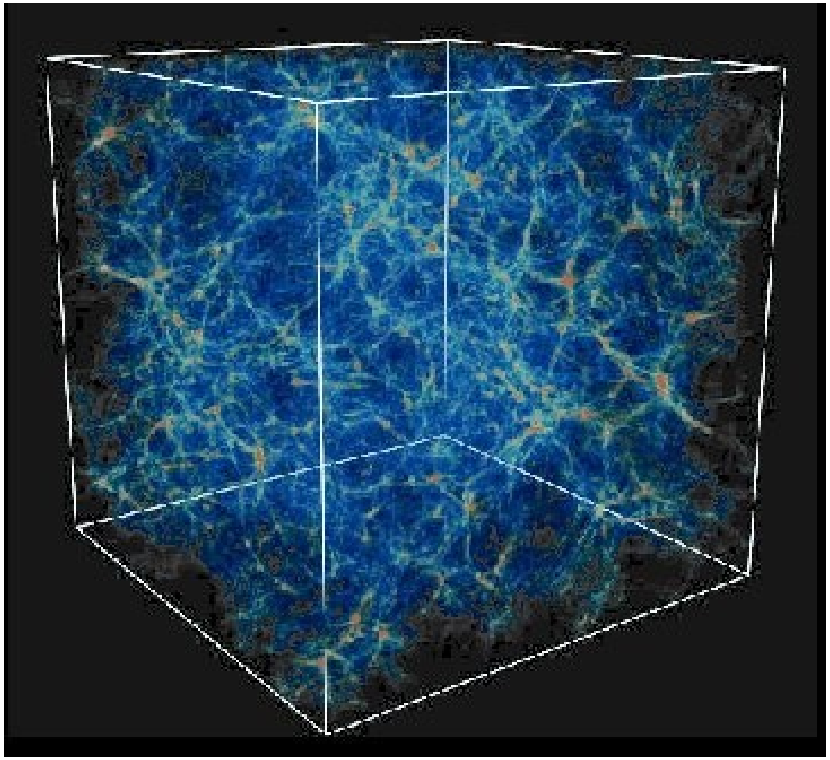


Beyond our Galaxy

Many types of galaxies:
spirals, elliptical,
Irregular.

Galaxies grouped in
clusters, superclusters.

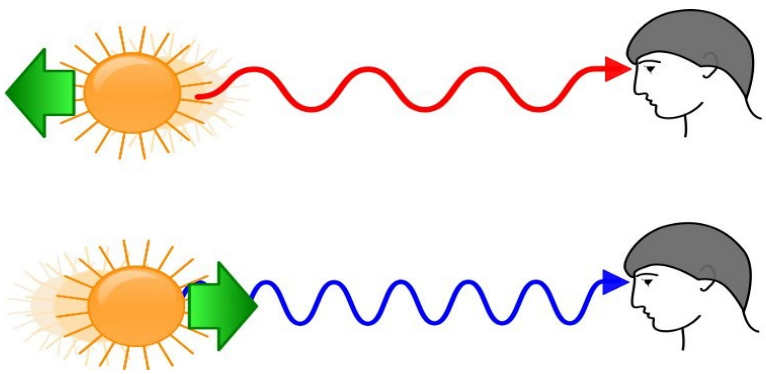
Clusters clumped in
“walls” with “voids”
in between:
the Cosmic Web



Large scale galaxy motion

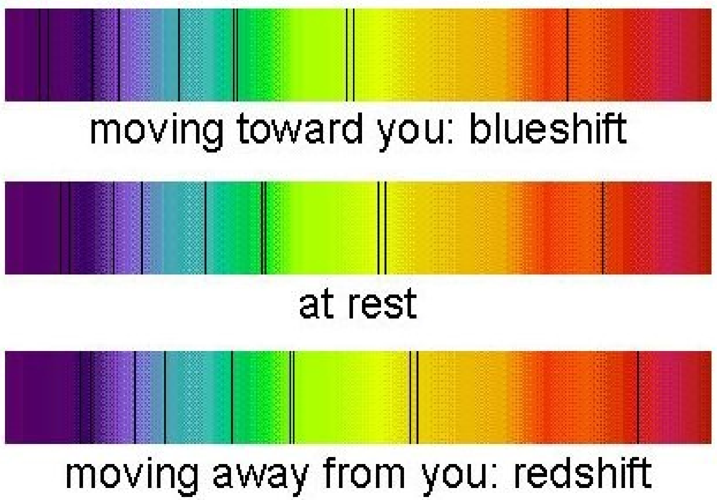
Doppler effect:

Change of frequency of a wave due to the relative motion between source and observer.

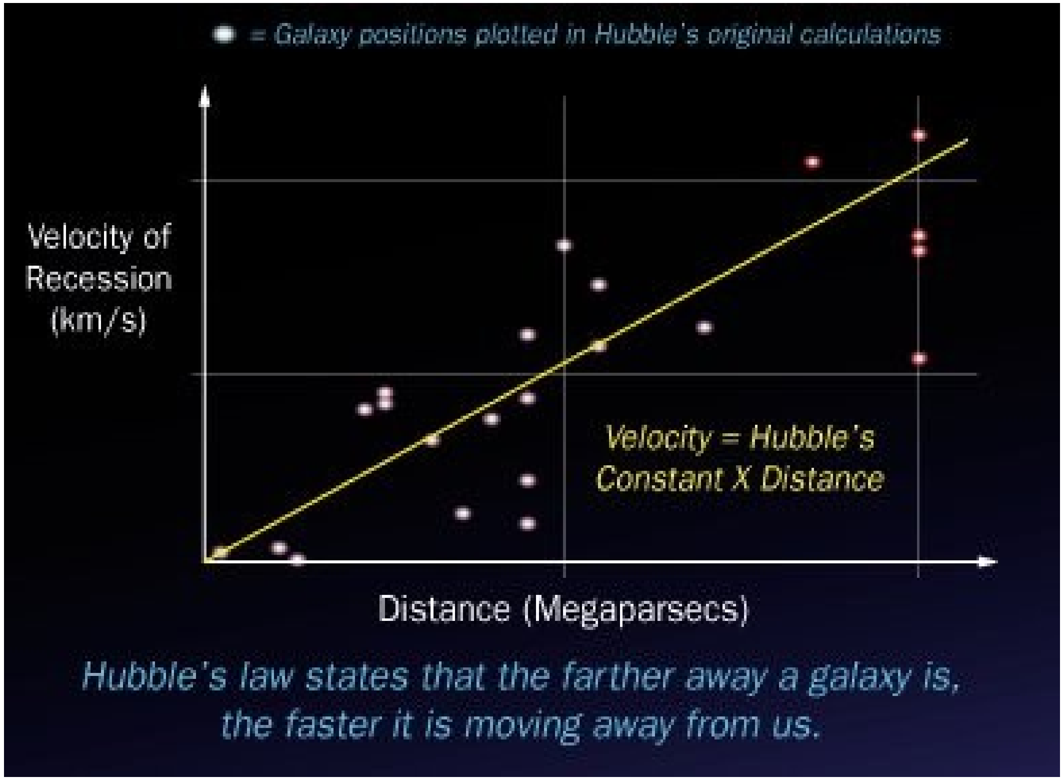


Spectral Analysis:

Shift in spectra = information on source motion.



Large scale galaxy motion: Hubble Law



Evidence that the Universe is expanding

Basis of the Big bang theory of the Universe origin

III) Black Holes

* Life of a star

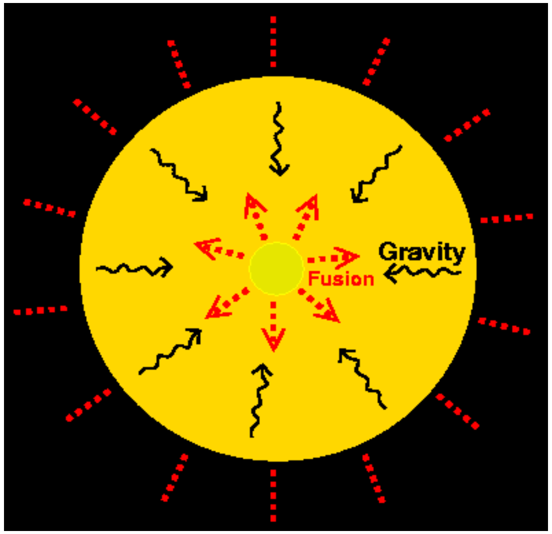
* Stellar vs. supermassive black holes

* X-ray view of black holes

Birth of a star

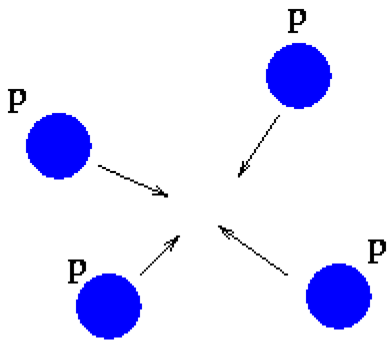
Stars are formed in **nebulae**, clouds of dust and gas (H) in the spiral arms of galaxies.

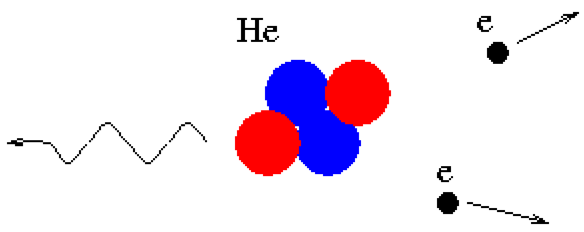
The clouds start contracting (collapse) under the force of gravity and the Temperature increases.



The collapse stops when the internal pressure balances the force of gravity.

Nuclear fusion in a star





Thermonuclear reaction: **T~ few million degrees Kelvin makes H nuclei (protons) so fast that they overcome their electric repulsion.**

Result: **He nuclei + Energy (Radiation)**

Stars spend > 90% of their life in this stage (Main Sequence).

Lifespan of a star

The star lifespan depends on the available fuel (mass) and the speed the fuel is used up (efficiency).

Small (mass) stars are more efficient than large stars, they live longer.

Star Mass	Lifespan
$0.5\ M_{solar}$	~ 700 billion yr
$1\ M_{solar}$	~ 10 billion yr
$2\ M_{solar}$	~ 1 billion yr
$5\ M_{solar}$	~ 100 million yr
$8\ M_{solar}$	~ 8 million yr

Properties of a star

Color and luminosity depend on the star mass.

Large Mass Stars :

large size, high $T_{surface}$

blue color and very bright

Small Mass Stars :

smaller size, lower $T_{surface}$

red color and less bright

The Sun is an average mass star:

average brightness and yellow color

Death of a star

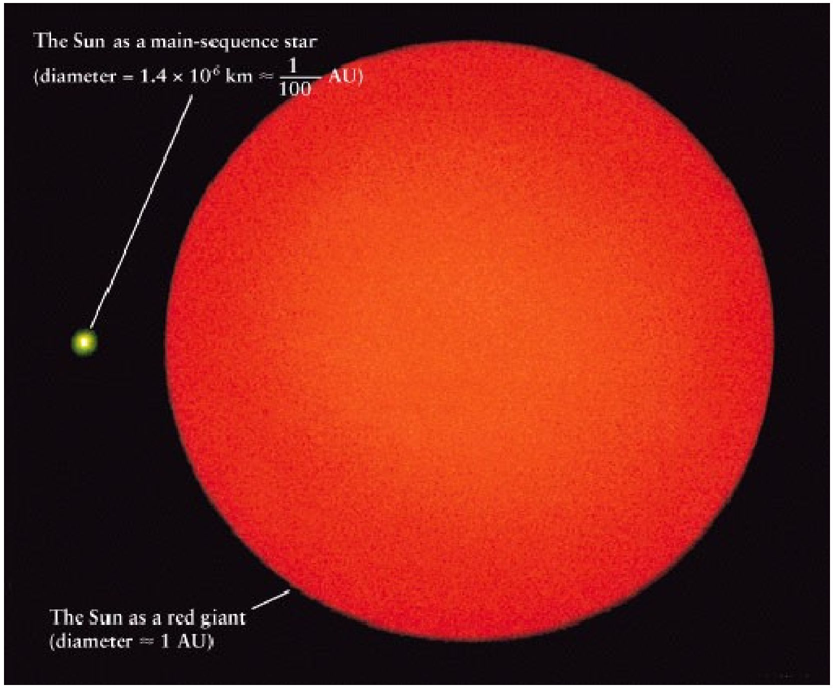
The final stage of a star depends on the star mass.

Average Mass Stars :

after H fusion, He fusion

expansion of outer part:

Red Giant phase



Death of a star

The final stage of a star depends on the star mass.

Average Mass Stars :

after H fusion, He fusion

expansion of outer part:

Red Giant phase

No final explosion, mass
Loss through winds

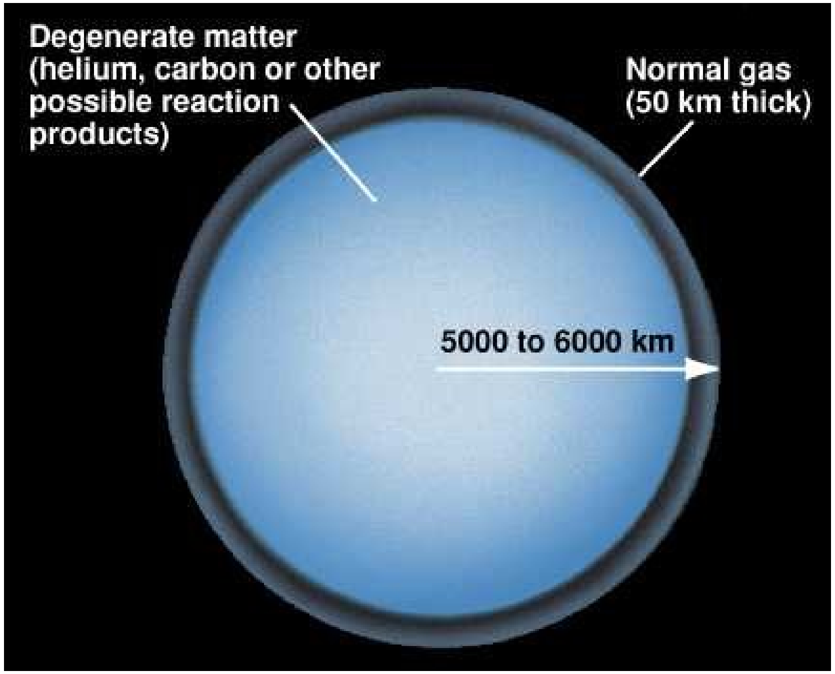
Final stage:

White Dwarf

$M < 1.4\ M_{sun}$, $R \sim R_{Earth}$:

Force balancing F_G:

electron degeneracy pressure



Death of a star

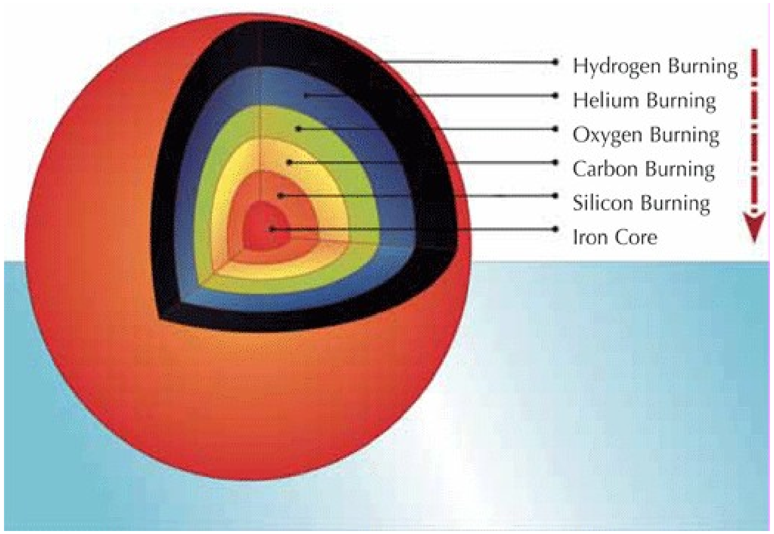
The final stage of a star depends on the star mass.

Large Mass Stars :

several fusion phases

expansion of outer part:

Red Supergiant phase



Death of a star

The final stage of a star depends on the star mass.

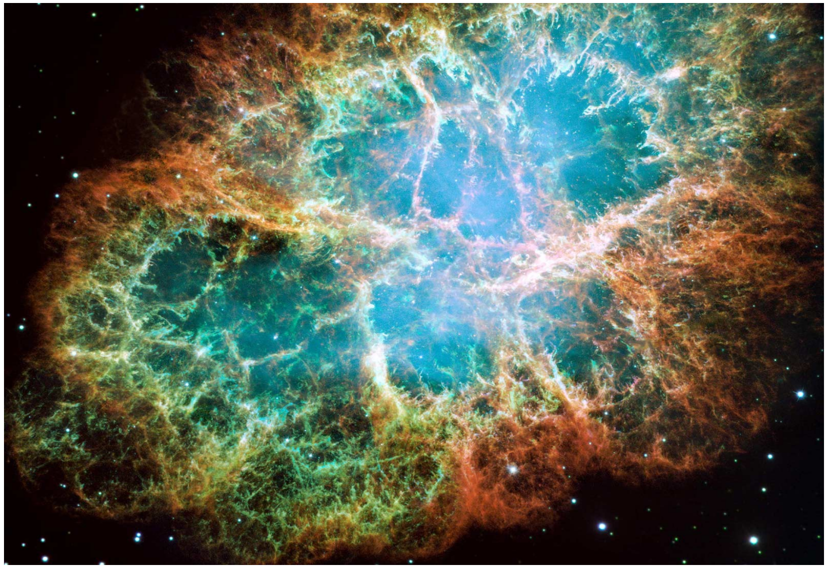
Large Mass Stars :

several fusion phases

expansion of outer part:

Red Supergiant phase

Supernova: Big explosion



Death of a star

The final stage of a star depends on the star mass.

Large Mass Stars :

several fusion phases

expansion of outer part:

Red Supergiant phase

Supernova: Big explosion

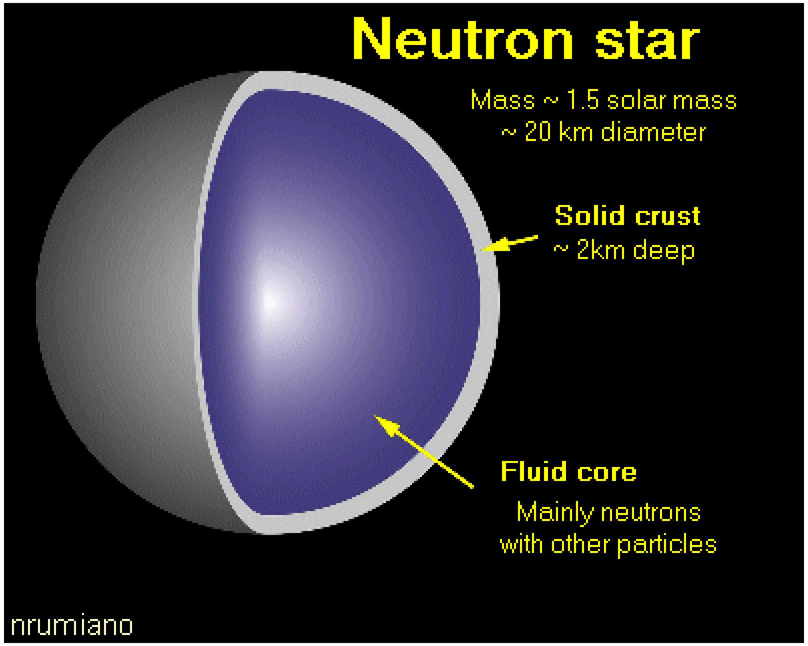
Final stage:

Neutron Star

$M < 3\ M_{sun}$, $R \sim 10$ km:

Force balancing F_G:

neutron degeneracy pressure



Death of a star

The final stage of a star depends on the star mass.

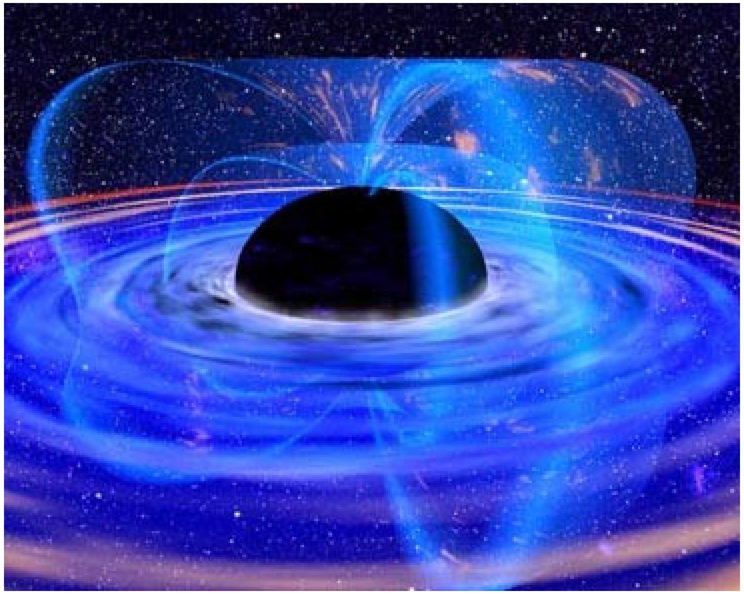
Very Large Mass Stars :

several fusion phases

expansion of outer part:

Red Supergiant phase

Supernova: Big explosion



Final stage:

Black Hole

$M \sim 3\text{-}10\ M_{sun}$, $R \sim 5$ km:

Force balancing F_G:

none

Brief History of Black Holes

1687 Newton introduced Gravity.

1783 Michell speculated on Dark Stars.

1796 Laplace predicted invisible massive stars.

1915 Einstein introduced General Relativity.

1916 Schwarzschild using GR found a singularity.

1931 Chandrasekhar introduced mass limit white dwarf.

1939 Oppenheimer introduced limit neutron star.

1960-70 Hawking & Penrose demonstrated that
BH unavoidable final stage of massive stars.

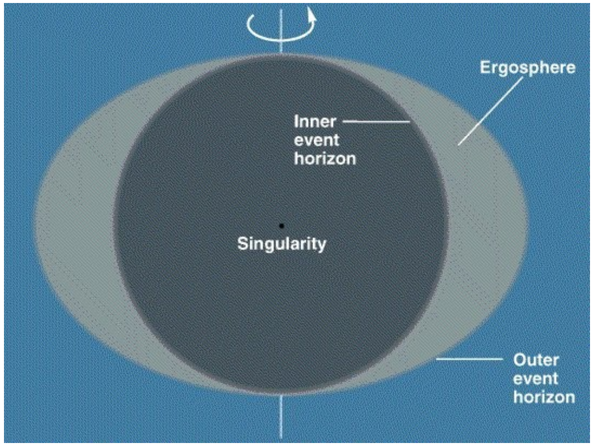
1967 Wheeler coined the term ”black hole”.

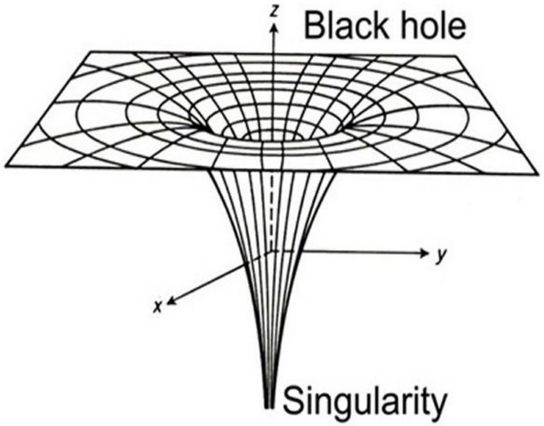
“Theoretical” Black Holes

Definitions:

BH: Region of space where gravity is so strong that nothing (not even light) can escape.

Singularity: region of space time where some quantities (density, curvature) become infinite.





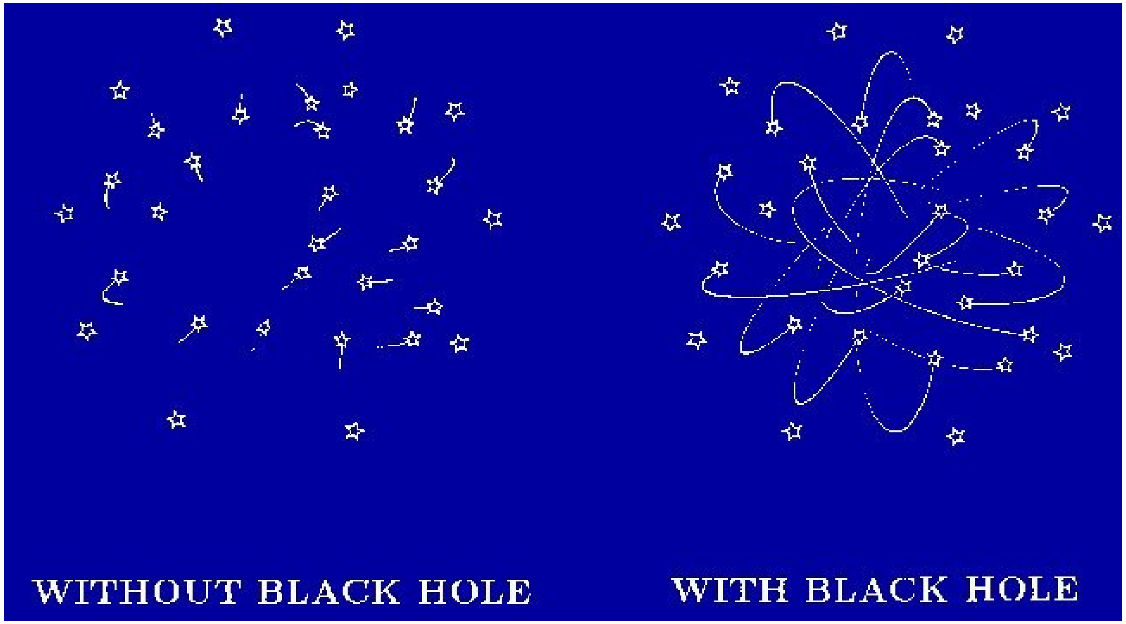
BHs are defined by only 3 quantities: mass, spin, charge.

Mass sets length scale $R_G=GM/c^2$ and time scale $t=R_G/c$

Astrophysical Black Holes:
How can we observe them?

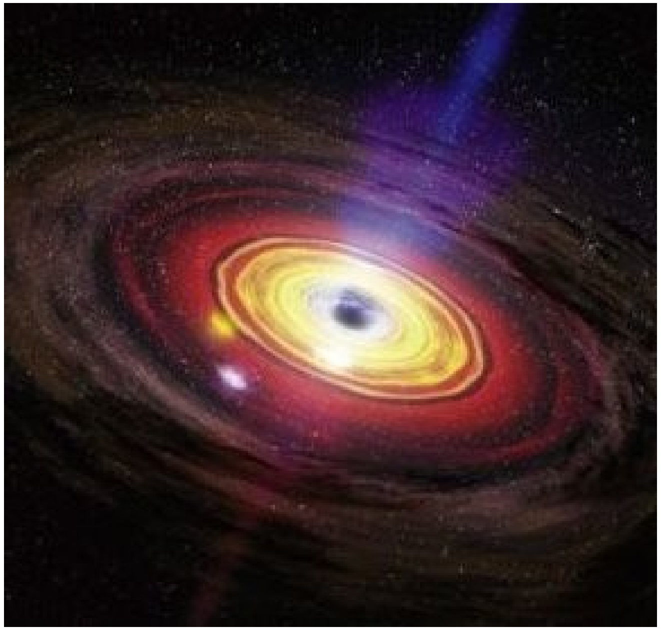
We can observe the effects of BHs on their surrounding:

-Nearby stars orbits rapidly.



Astrophysical Black Holes:
How can we observe them?

We can observe the effects of BHs on their surrounding:



-Nearby stars orbits rapidly.

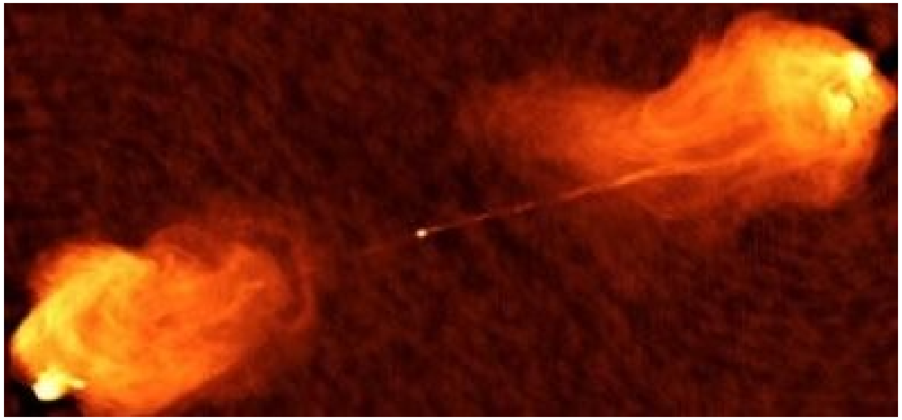
-Surrounding gas forms a hot accretion disk that emits UV and X-ray.

Astrophysical Black Holes: How can we observe them?

We can observe the effects of BHs on their surrounding:

-Nearby stars orbits rapidly.

-Surrounding gas forms a hot accretion disk that emits UV and X-rays.



-Sometimes they produce jets of matter visible in the radio (and other wavelengths).

Astrophysical Black Holes:
Stellar, Supermassive & Intermediate BHs

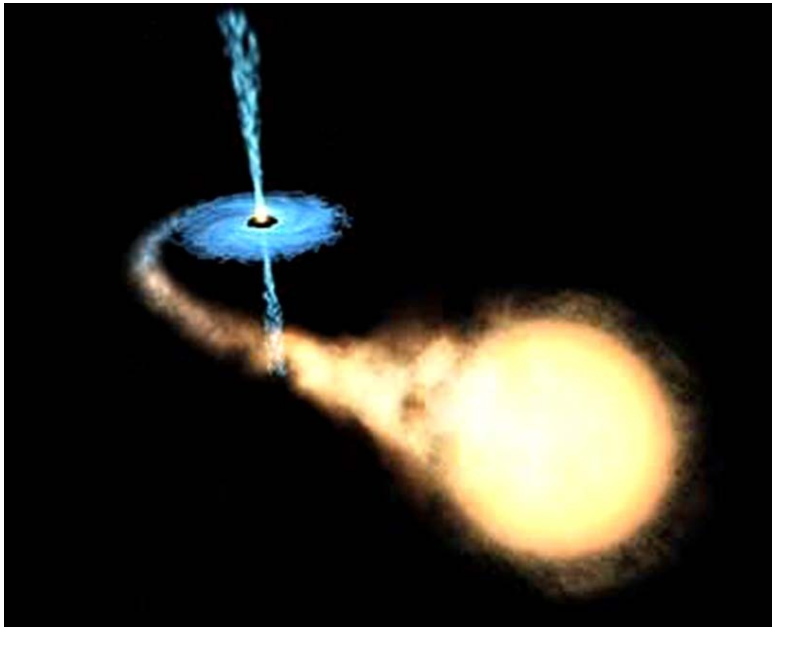
BHs come in different sizes:

1) Stellar BHs:

M_BH~3-20 M_solar in binary systems

Origin: evolution of massive stars

First detection: Cygnus X-1 in 1972 with Uhru satellite



Astrophysical Black Holes:
Stellar, Supermassive & Intermediate BHs

BHs come in different sizes:

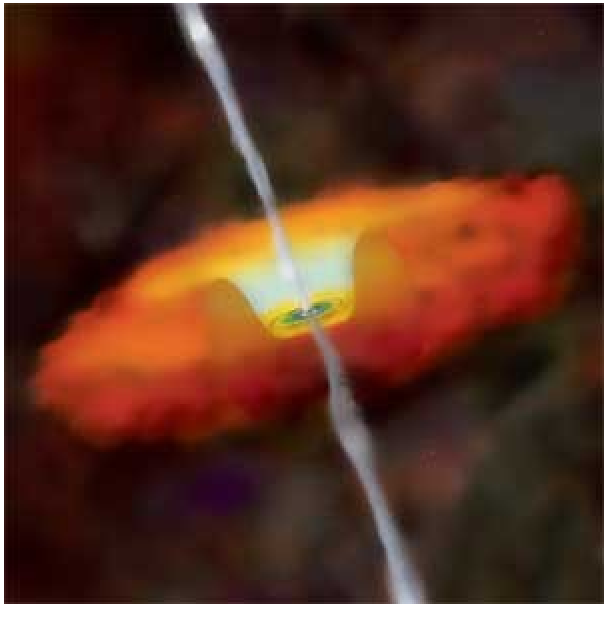
1) Stellar BHs

2) Supermassive BHs:

M_BH~ million-billion M_solar at center of active galaxies

Origin: collapse of very massive stars, merger?

First detection: Quasar 3C 273 in 1963

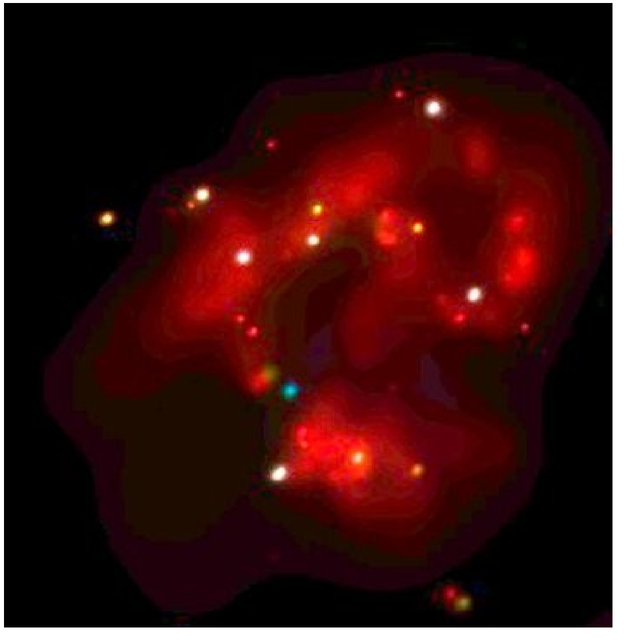


Astrophysical Black Holes: Stellar, Supermassive & Intermediate BHs

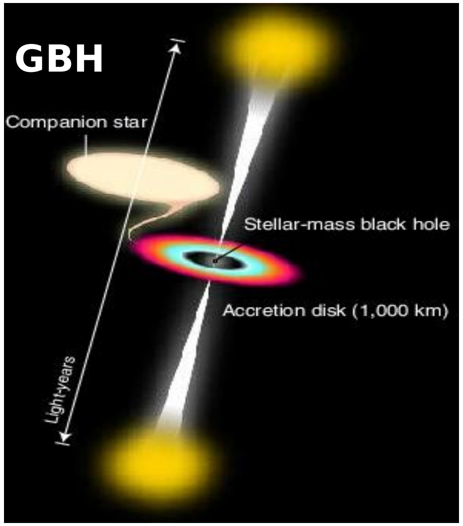
BHs come in different sizes:

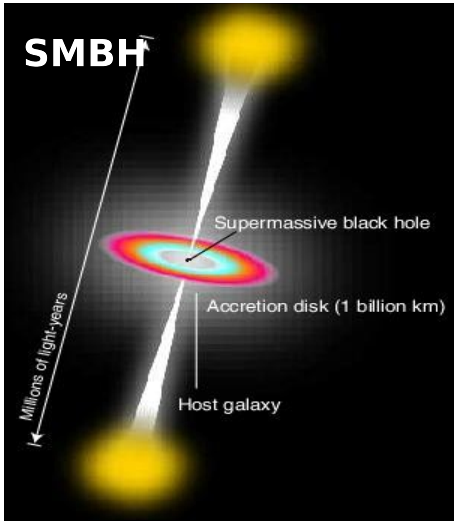
1) Stellar BHs
2) Supermassive BHs
3) Intermediate mass BHs:

M_BH~100-10,000 M_solar in ULXs?



Astrophysical Black Holes: Stellar vs. Supermassive BHs





Same basic ingredients:

***Central engine: BH+ accretion disk + hot corona**

Hot matter swirls at high velocity.

Emission mostly in UV & X-rays

***Relativistic jet:**

Matter is ejected at relativistic speed.

Emission from radio to X-rays.

Different reservoir: binary companion vs. galaxy core gas

Importance of astrophysical Black Holes:

BHs produce the most powerful phenomena in the Universe
Ideal laboratories to study physics in extreme conditions:
high temperature and density, strong gravity.

Supermassive BHs are ubiquitous:
not only in powerful active galaxies but also in normal ones
including our Galaxy.

There is a strong correlation between M_BH and the mass of the galaxy bulge, suggesting a common evolution of BH and galaxy.

BH activity (radiation, jet, winds) affects environment on very large scales (galaxy cluster).

Observing Black Holes: X-ray perspective

Advantages:

*X-ray (variable) emission ubiquitous in BH systems and the X-ray luminosity is a sizeable fraction of the total luminosity.

*X-rays are produced from the innermost regions: closely track BH activity.

*X-rays can penetrate obscuring regions around BH: direct view of central engine

*X-rays are less affected than optical/UV by stellar contribution: easier to disentangle BH activity

Observing Black Holes: (1) Spatial Analysis

What can be resolved by X-ray satellites?

(Chandra spatial resolution 1”)

1) Gas reservoir

2) Relativistic jet:

What CANNOT be resolved by X-ray satellites?

The central engine (accretion disk + corona):

Typical angular size ~10^-5 milliarcsecond or less

Observing Black Holes:
(2) Spectral Analysis

What information is provided by X-ray spectra?

(Chandra, XMM-Newton, Suzaku)

1) Physical conditions of gas reservoir (temperature, chemical composition)

2) Indirect information on accretion flow (density, temperature, accretion rate) and base of the jet.

What is NOT provided by X-ray spectra?

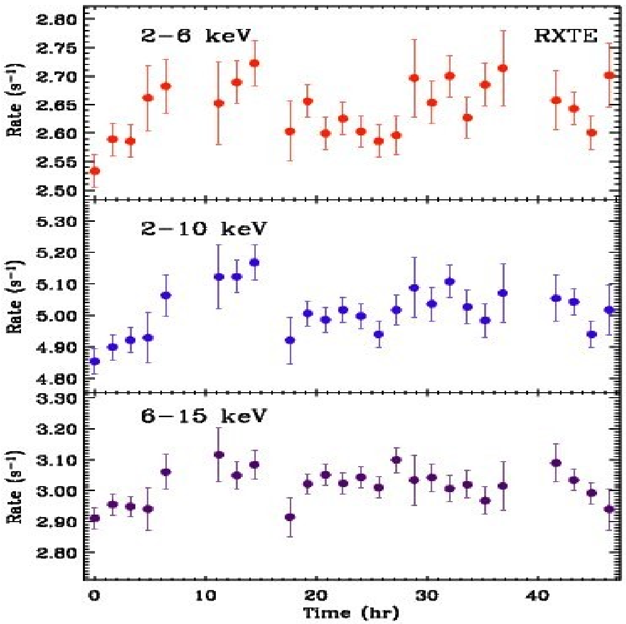
Unequivocal interpretation of spectrum:

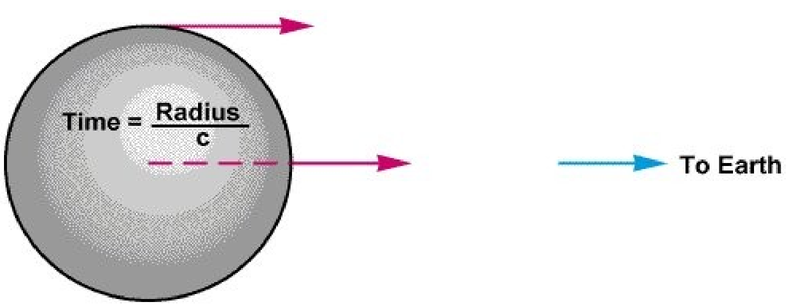
Different physical models can explain the same data (spectral degeneracy)

Observing Black Holes: (3) Temporal Analysis

What information is provided by X-ray light curves?
(XMM-Newton, RXTE, SWIFT)

Upper limit on the dimensions of the emitting region.
Quasars show variability time scales of hours:
emitting region very compact (1 light hour~7 AU)





Observing Black Holes: (3) Temporal Analysis

What information is provided by X-ray light curves?
(XMM-Newton, RXTE, SWIFT)

Upper limit on the dimensions of the emitting region.
Quasars show variability time scales of hours:
emitting region very compact (1 light hour~7 AU)

What is NOT provided by X-ray light curves?

Univocal information on the physical mechanism producing X-rays.

Open questions on Black Holes

1) Primary Energy Source:

Gravitational energy from accreting matter

but nature of accretion process unknown.

2) High-energy radiation Source:

Hot corona (and/or base of the jet)

but geometry and heating mechanism unknown

3) Relativistic jets:

Plasma ejected at relativistic speed

but acceleration, collimation, matter content unknown

How to progress: Synergy

I) Observational:

Combine X-ray spatial, spectral and temporal information

Complement X-ray study with multi-wavelength info.

Combine detailed study of prototypical objects with statistical studies of large samples

II) Observation-Theory:

Observations provide constraints for models

Models incorporate observational constraints and make predictions.

Observations test predictions & refine constraints

III) Stellar BHs (GBHs) – supermassive BHs (SMBHs):

GBH: higher quality data, variable on human timescales

SMBH: larger number allow statistical studies.