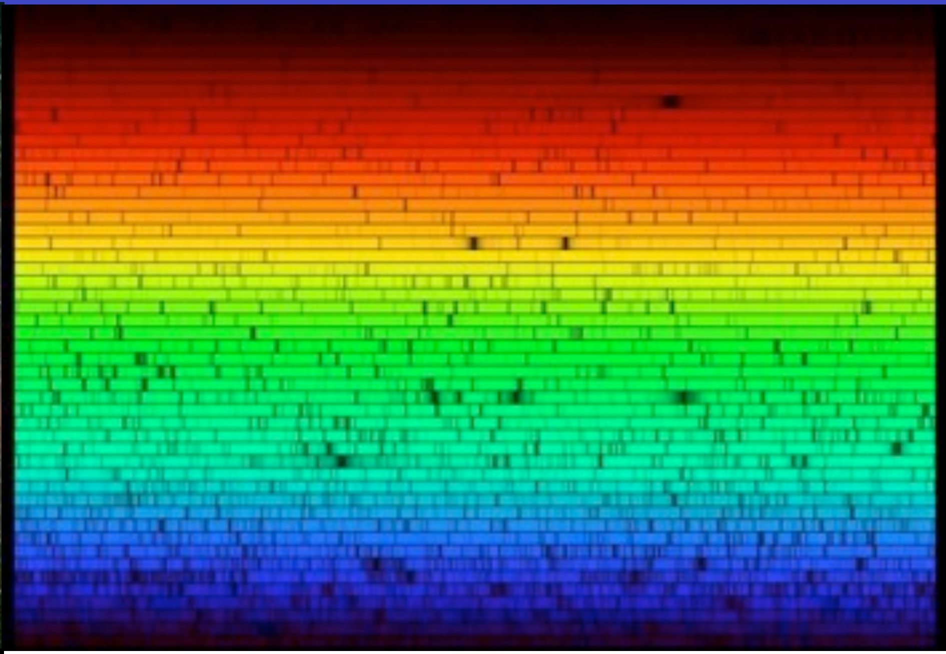
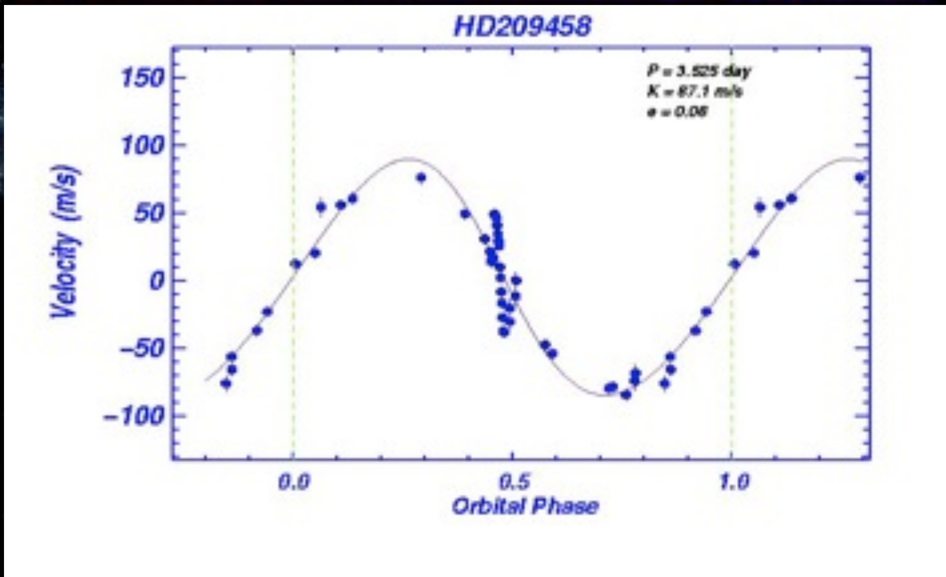
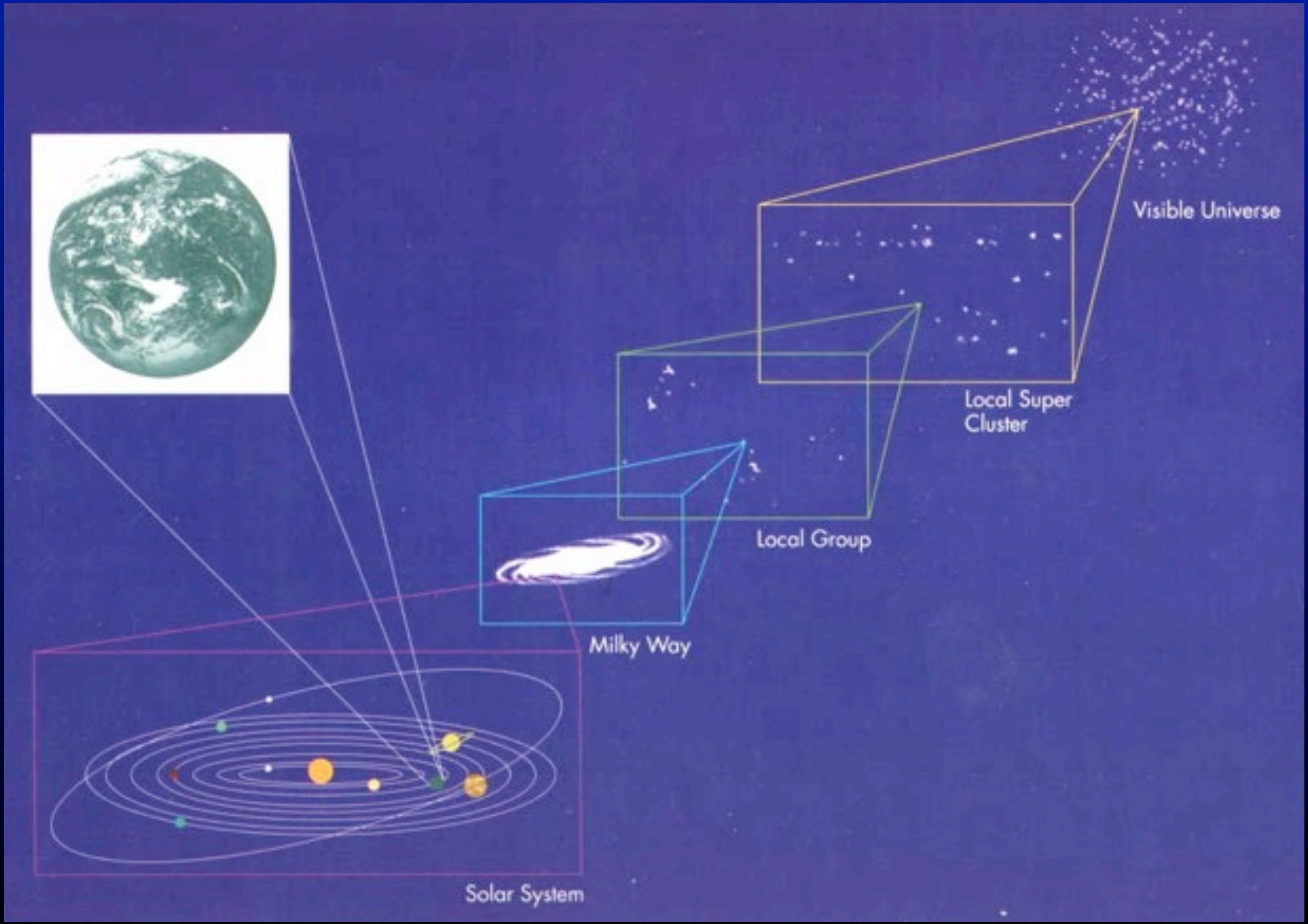
Astro 7A: Introduction to Astrophysics



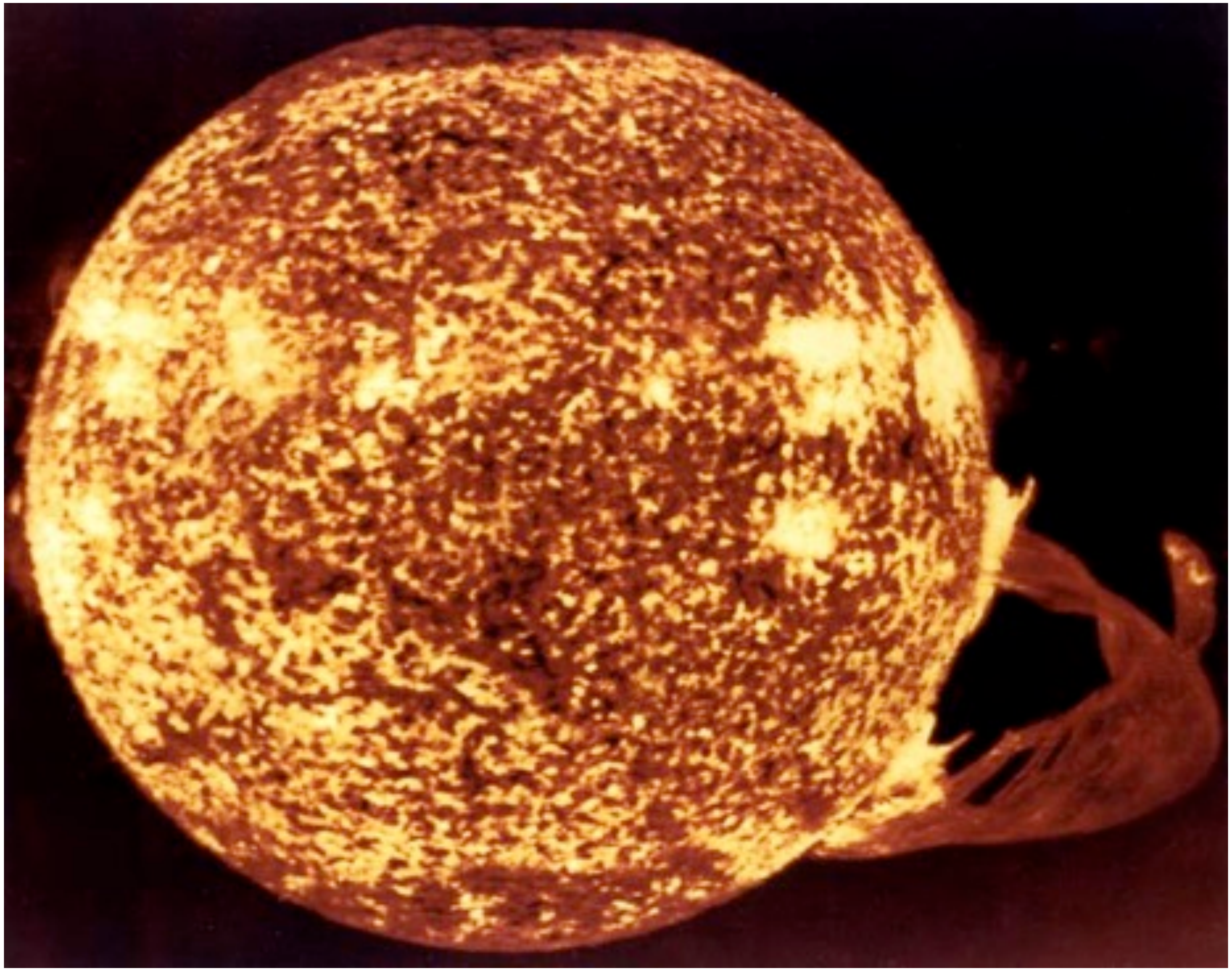


Tour of the Cosmos

see the "Logarithmic Map" (astro.princeton.edu/universe)



The Sun, Our Star



The sun is a big hot ball of hydrogen & helium.
Its surface temperature is ≈ 6000 K.
At the center, the temperature is ≈ 1.5×10^7 K.

Radius of Sun

$R_\odot = 7 \times 10^8$ m
$= 7 \times 10^{10}$ cm
$= 100\ R_\oplus$

Mass of Sun

$M_\odot = 2 \times 10^{30}$ kg
$= 2 \times 10^{33}$ g
$= 3 \times 10^5\ M_\oplus$

Luminosity of Sun
= Radiant power (energy per time)

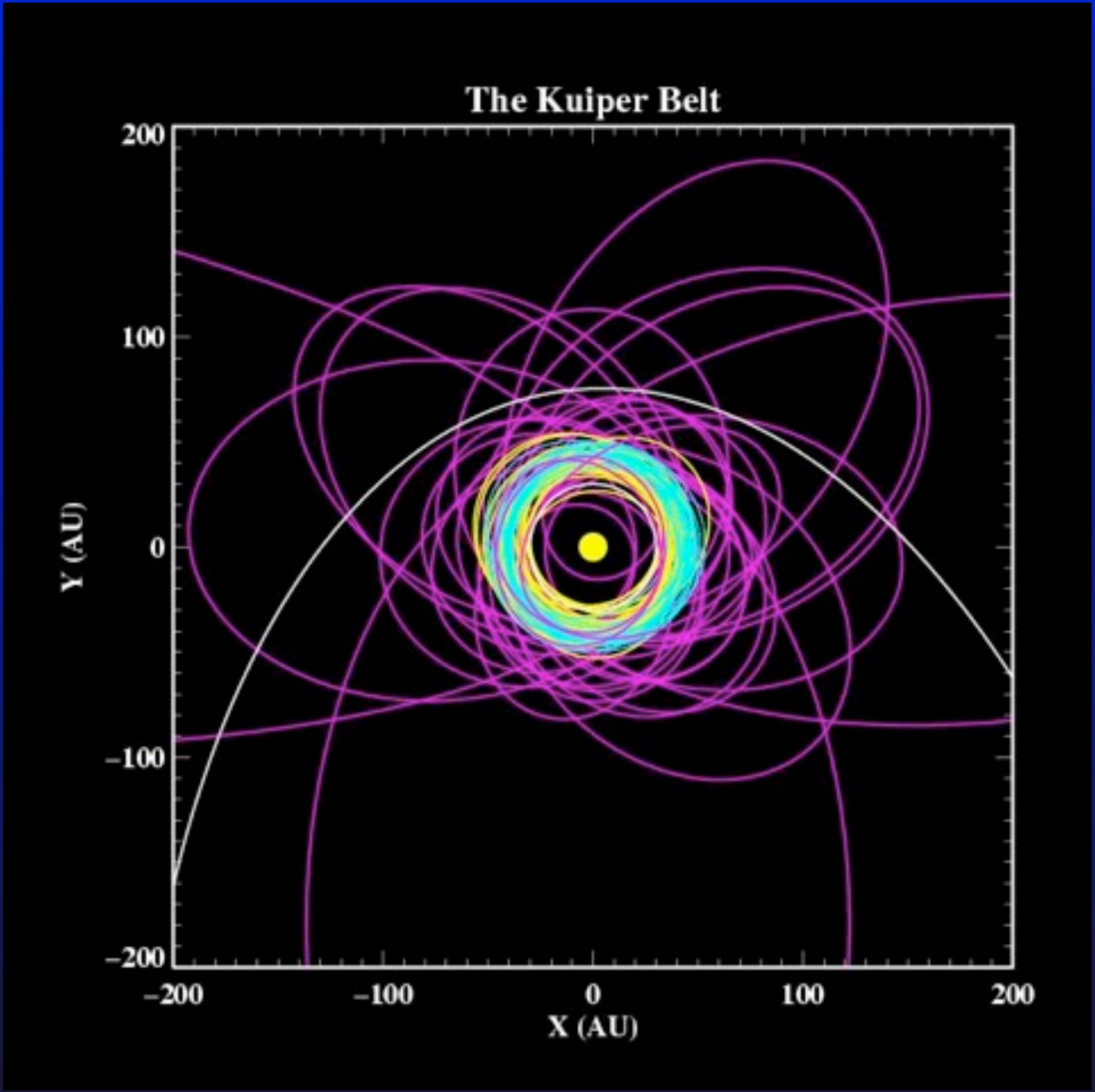
$L_\odot = 4 \times 10^{33}$ erg/s
$= 4 \times 10^{26}$ W (J/s)
≈ 10^{14} x power used by humanity

⊙ = symbol for Sun
⊕ = symbol for Earth

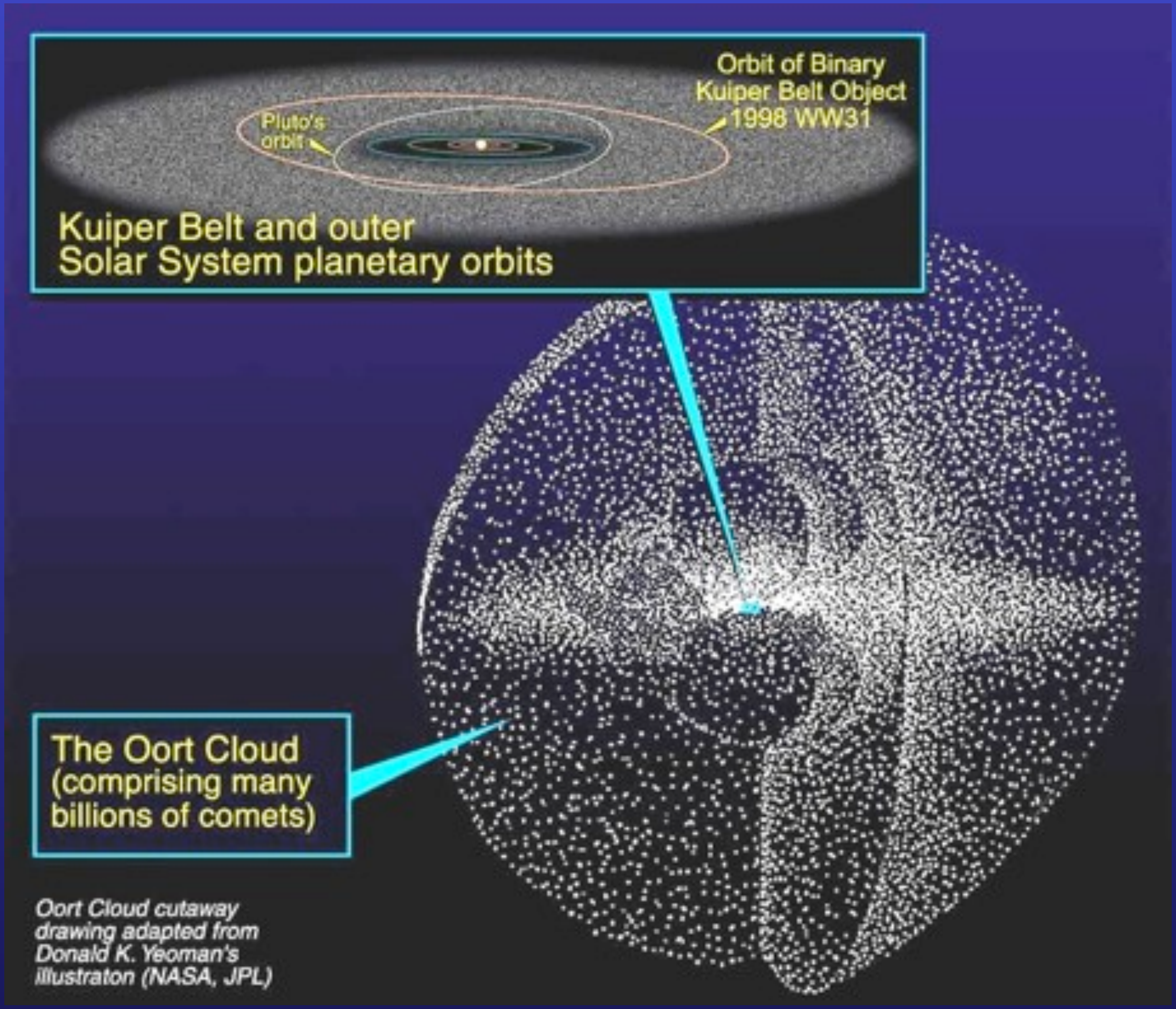
The Solar System

Rocky, icy debris left over from formation of solar system

$\Rightarrow$ craters on moon, extinction of dinosaurs, planet formation theory



The Kuiper Belt
200
100
0
−100
−200
Y (AU)
−200
−100
0
100
200
X (AU)



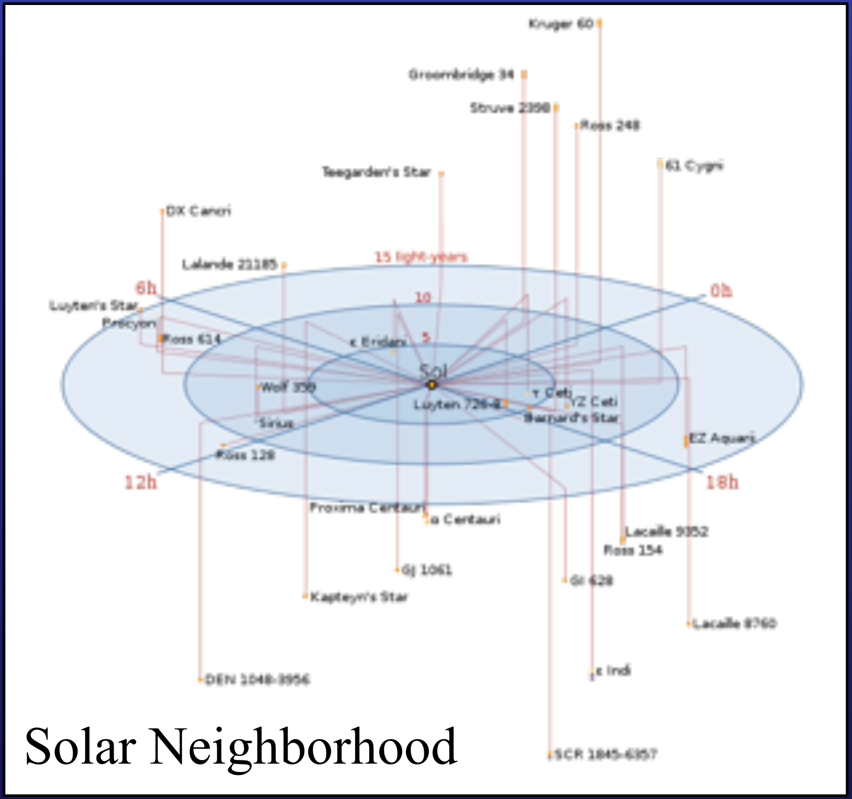
Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
The Oort Cloud
(comprising many
billions of comets)
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)

Other Stars

$R \sim 0.1\text{-}100\ R_\odot$

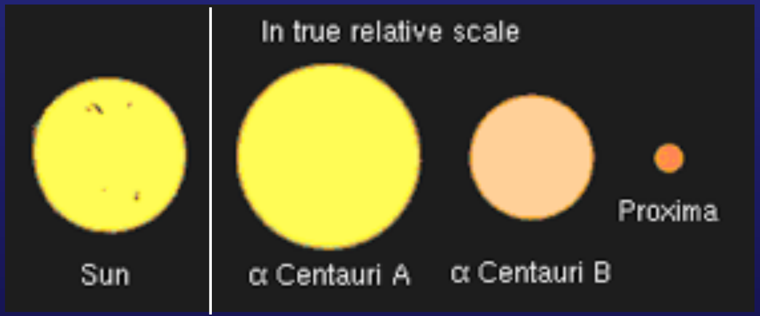
$M \sim 0.1\text{-}100\ M_\odot$

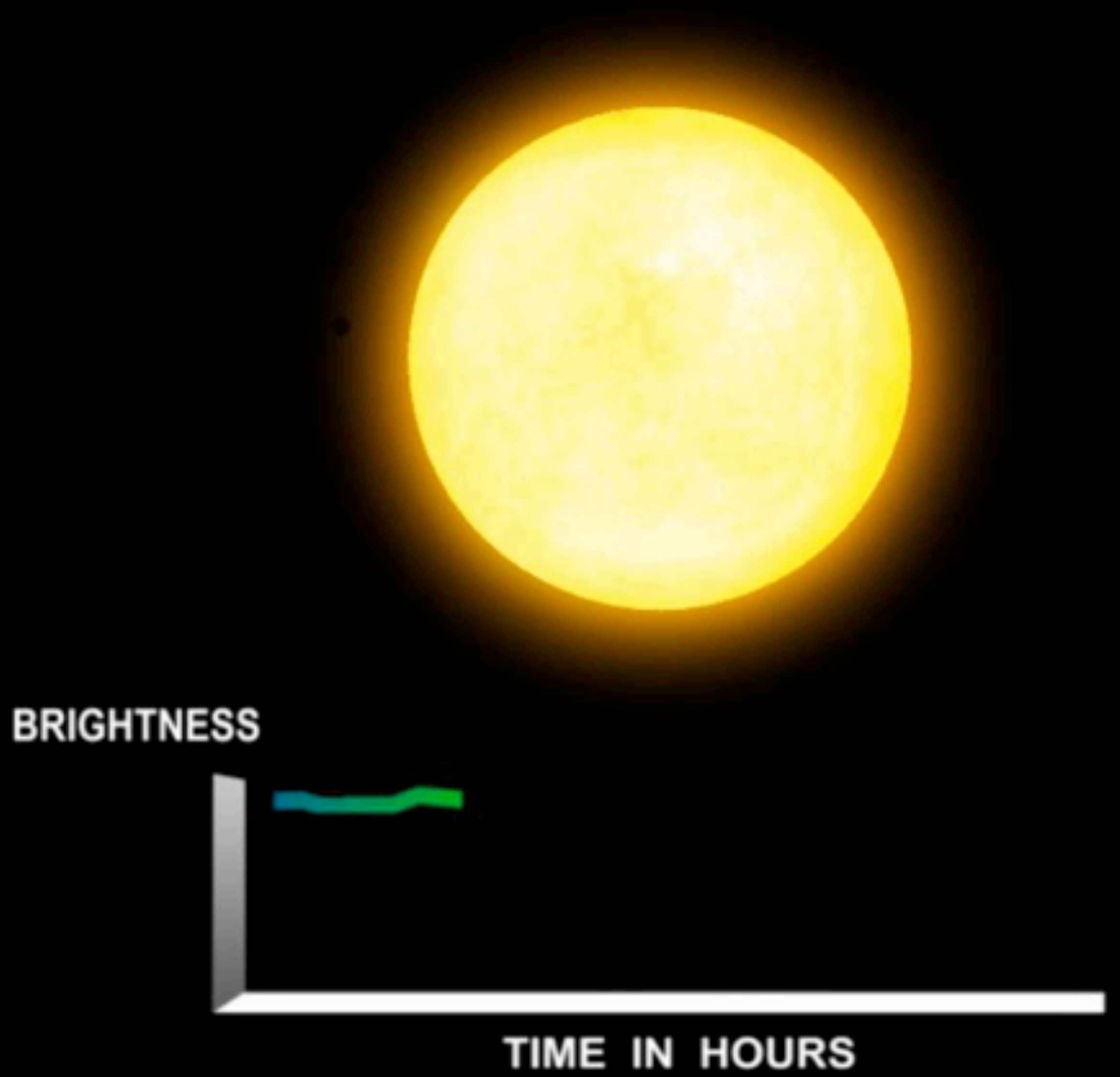
$L \sim 10^{-4}\text{-}10^{6}\ L_\odot$

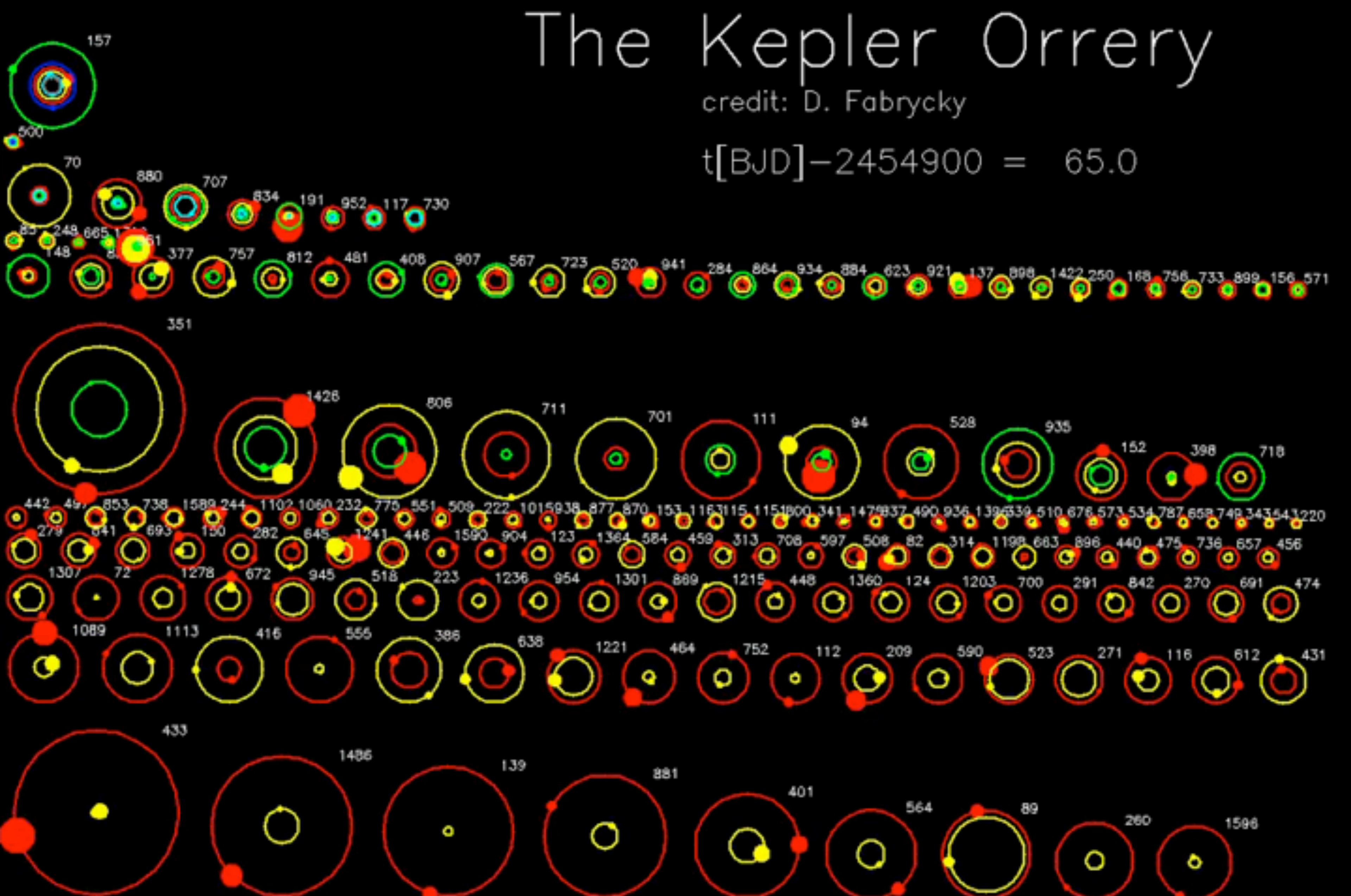


Solar Neighborhood

Distance between stars
≈ 3 light-years
~ 10^3 x size of solar system



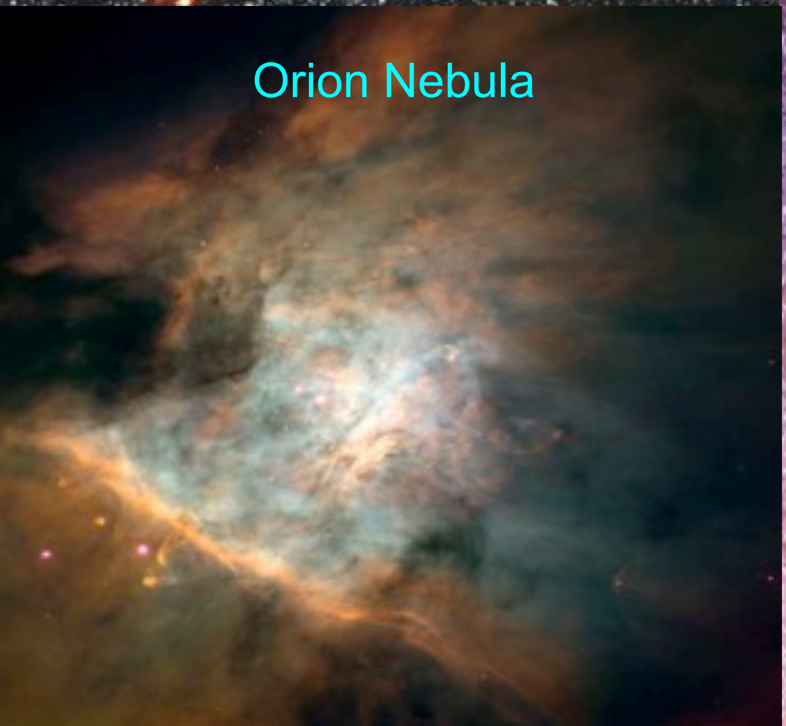

BRIGHTNESS
TIME IN HOURS


The Kepler Orrery
credit: D. Fabrycky
t[BJD]−2454900 = 65.0

The Interstellar Medium

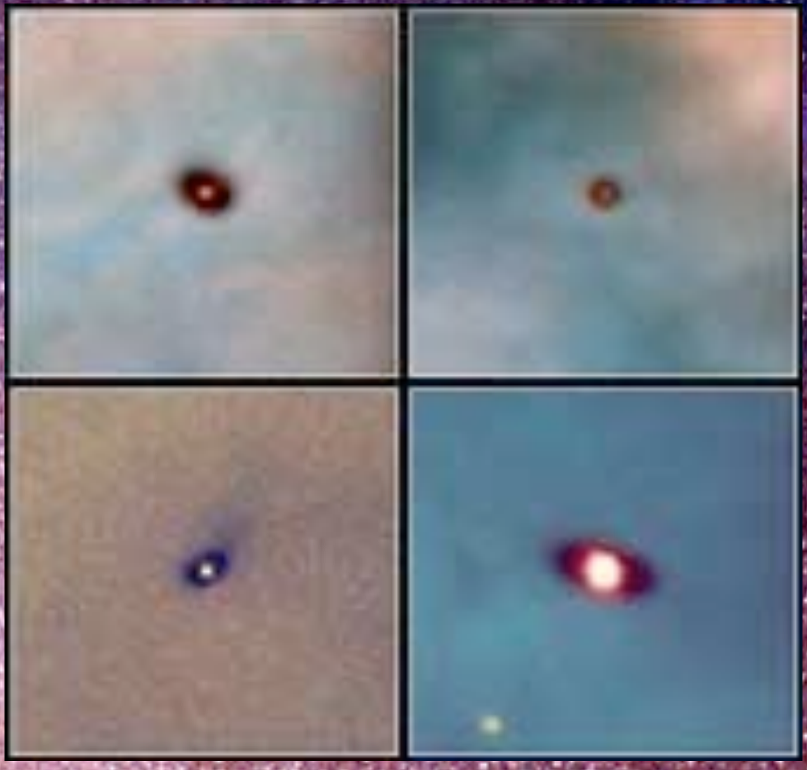
- Gas, dust, cosmic rays, magnetic fields
- Recycles stars
- Galaxy-scale calorimeter

Barnard 64: A “dark cloud”



Orion Nebula

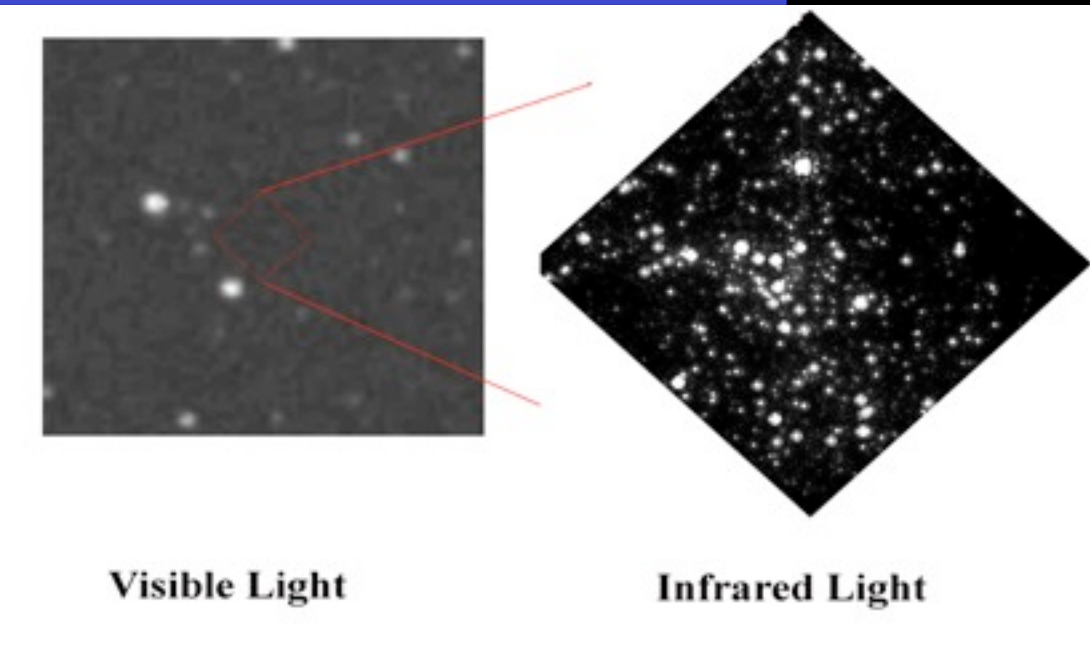
Planetary nurseries: Circumstellar disks

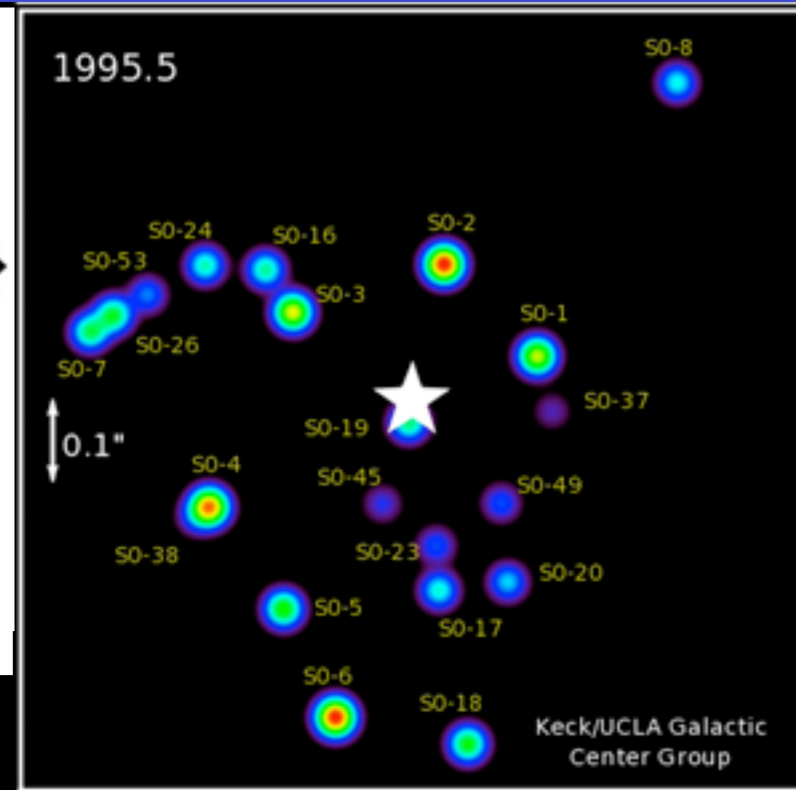


Galaxies

Diameter ~ 20 kpc
Number of stars ~ 2 x 10^{11}
$M \sim 10^{11} M_\odot$
Rotation period at Sun's location ≈ 250 Myr


The Milky Way Galaxy
Actually, we're here.



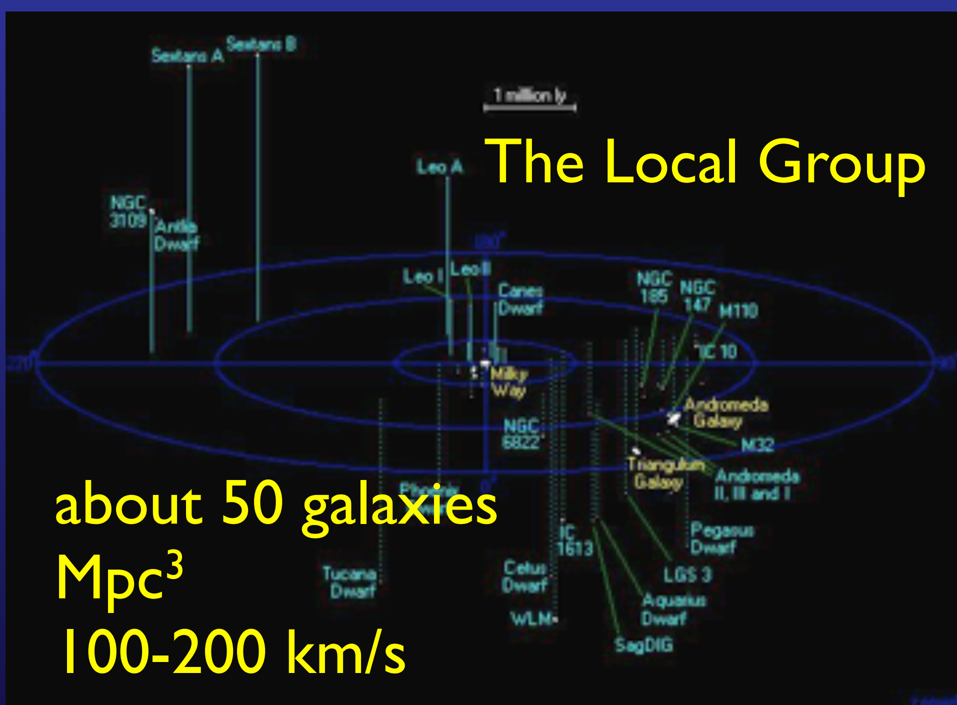


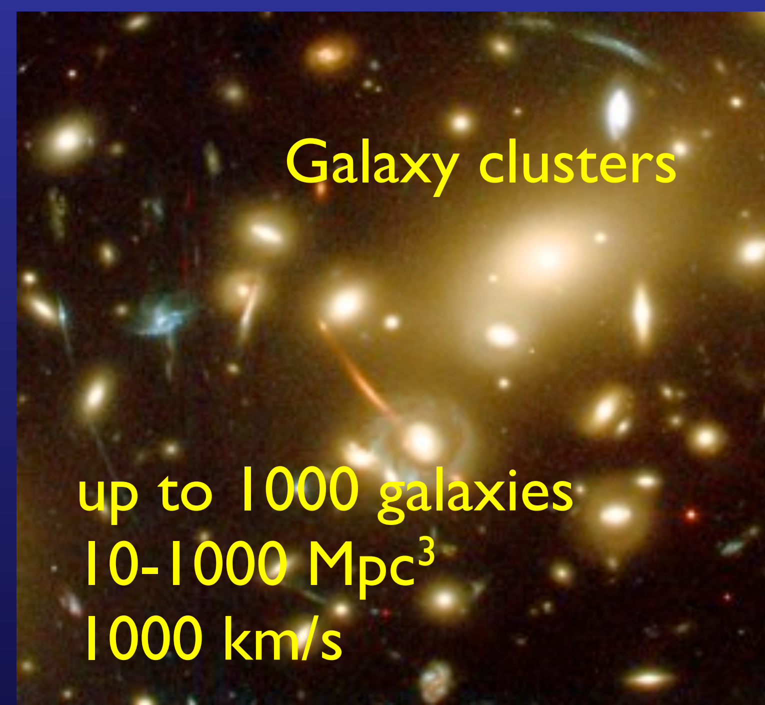
The Supermassive Black Hole at the Galactic Center

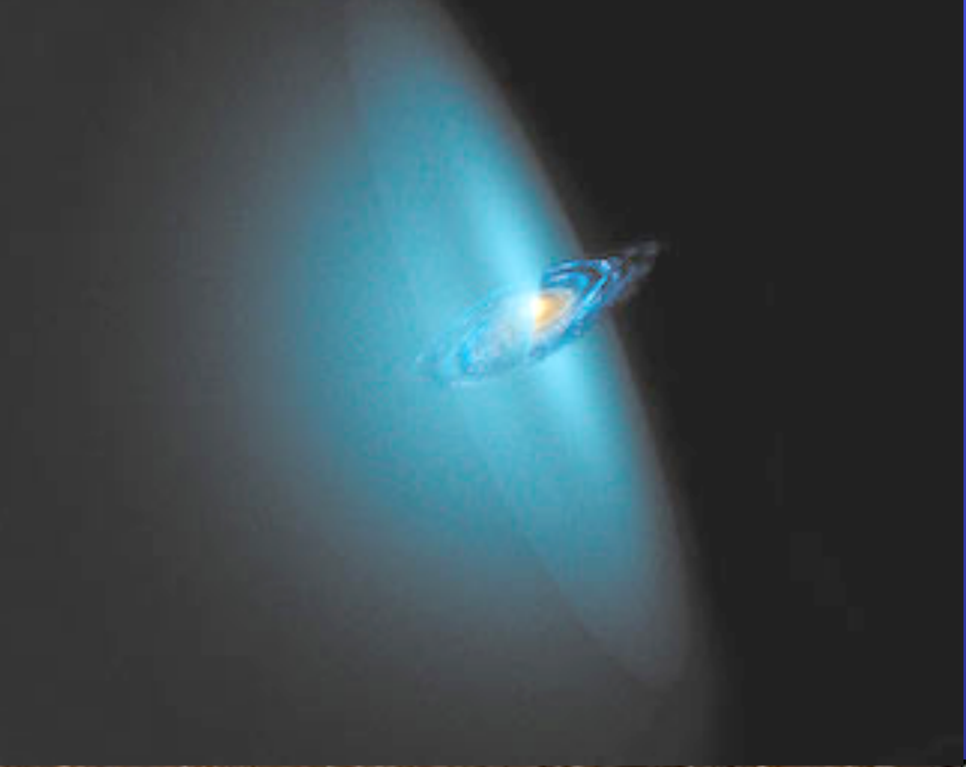
$M \approx 3.5 \times 10^{?} M_{\odot}$

$R \approx 0.07$ AU


Galaxy zoo


The Local Group
about 50 galaxies
Mpc^3
100-200 km/s
Sextans A
Sextans B
1 million ly
Leo A
NGC 3109
Antlia Dwarf
Leo I
Leo II
Canes Dwarf
NGC 185
NGC 147
M110
IC 10
Milky Way
Andromeda Galaxy
NGC 6822
M32
Triangulum Galaxy
Andromeda II, III and I
Pegasus Dwarf
IC 1613
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
SagDIG


Galaxy clusters
up to 1000 galaxies
10-1000 Mpc^3
1000 km/s



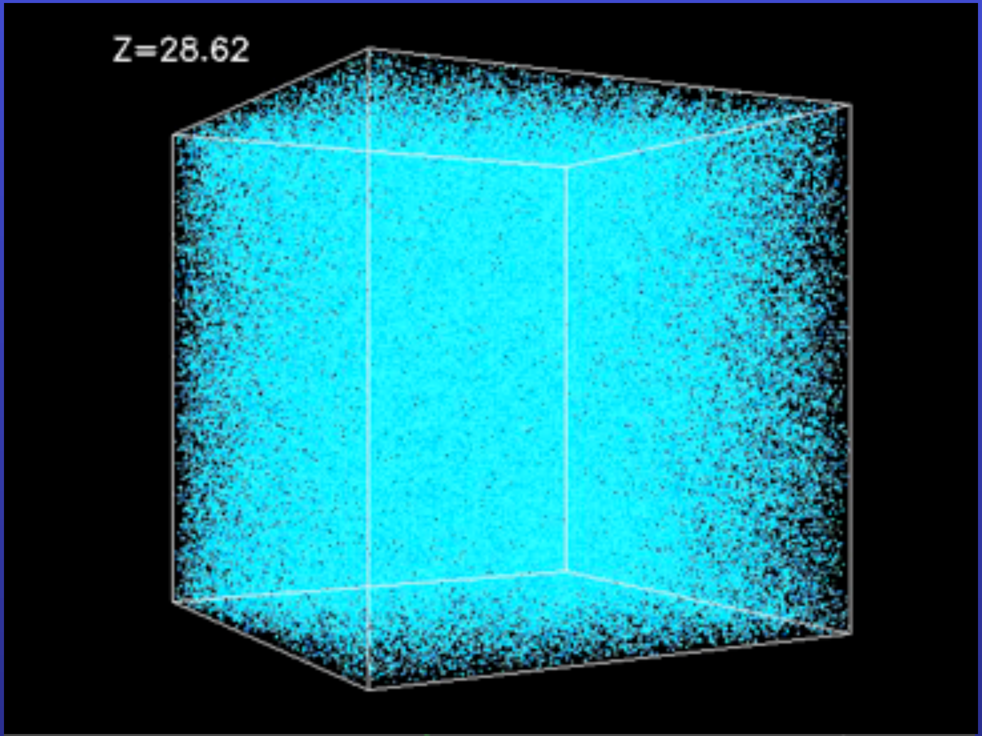
Dark Matter Halos

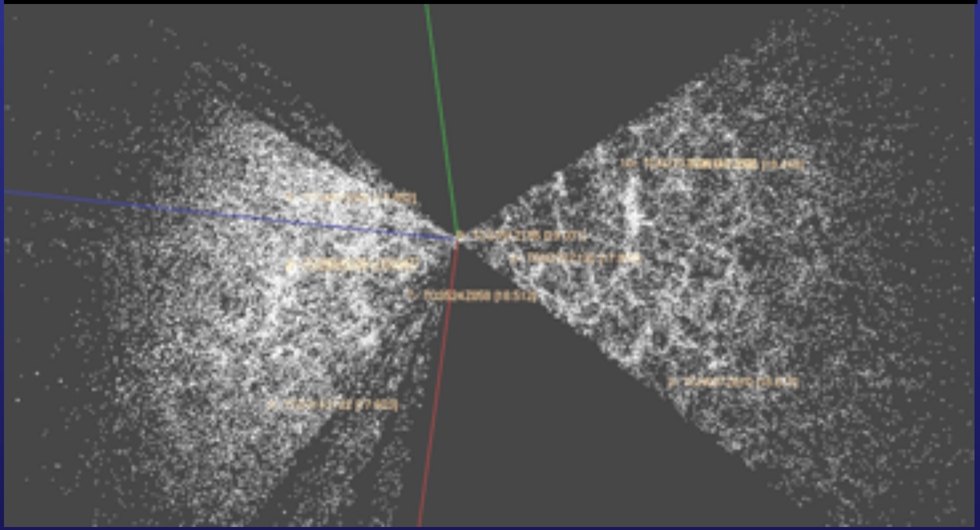
$M \sim 20 \times M_{stars}$

$R \sim Mpc$

~80% of matter consists neither of protons nor neutrons, but some "cold" (non-relativistic) particle, to be identified

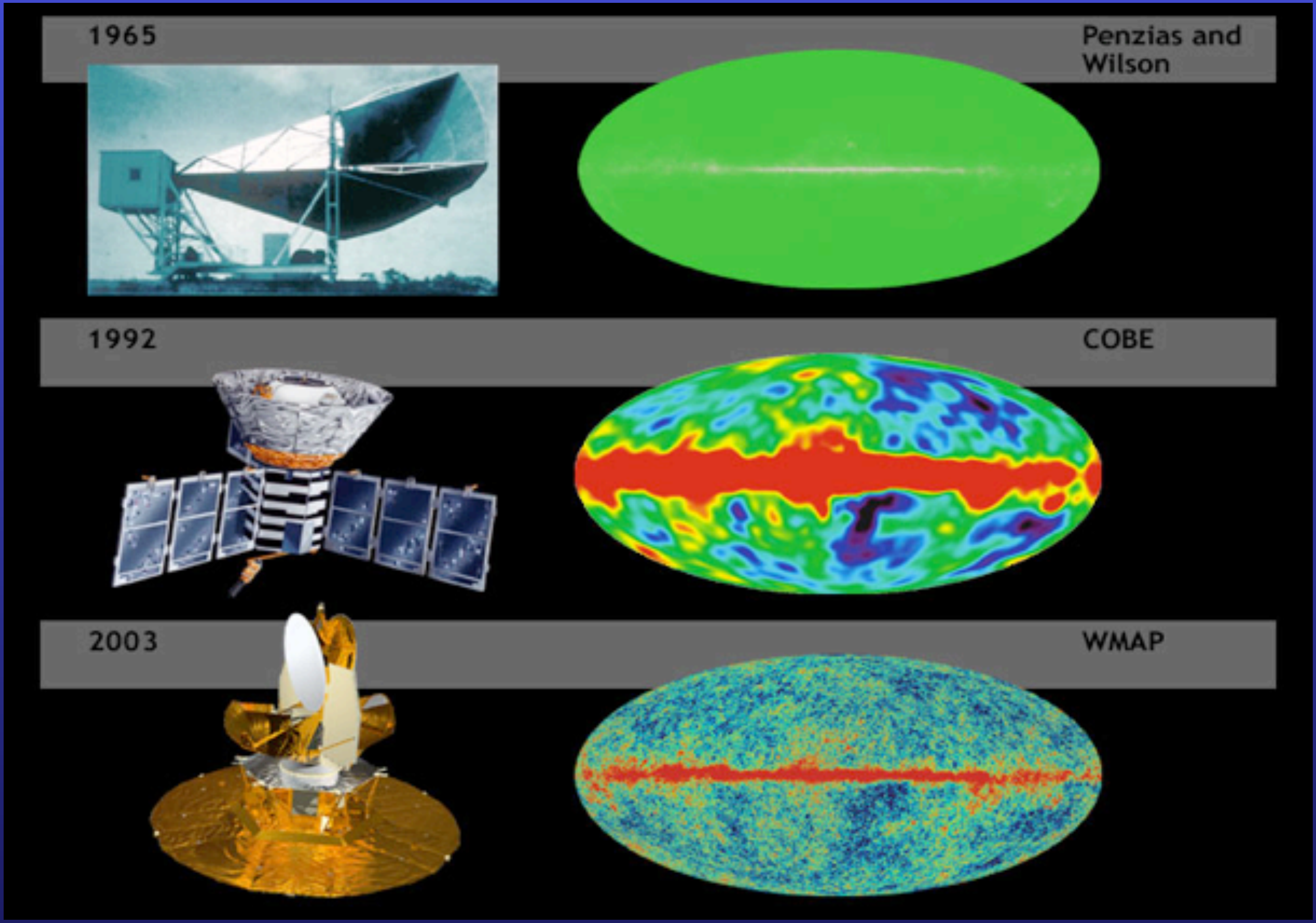
100 GeV neutralino? (1 GeV = 1 proton) or 1 eV axion?





Universe is expanding---even accelerating by some mysterious "dark energy"

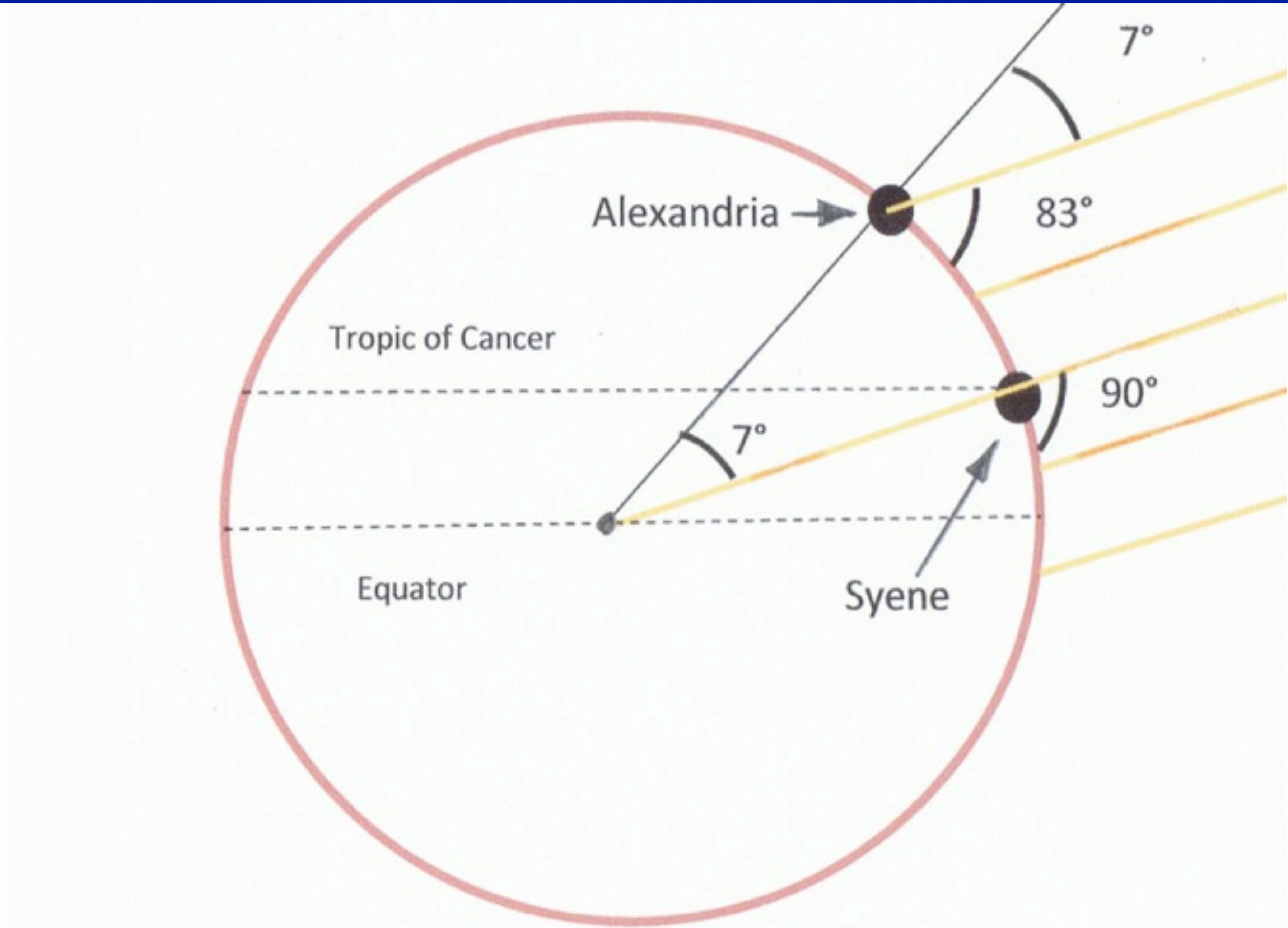
Gravity pulls dark matter together to form galaxies and clusters of galaxies



Universe is flat in space and has a finite age (14 Gyr)

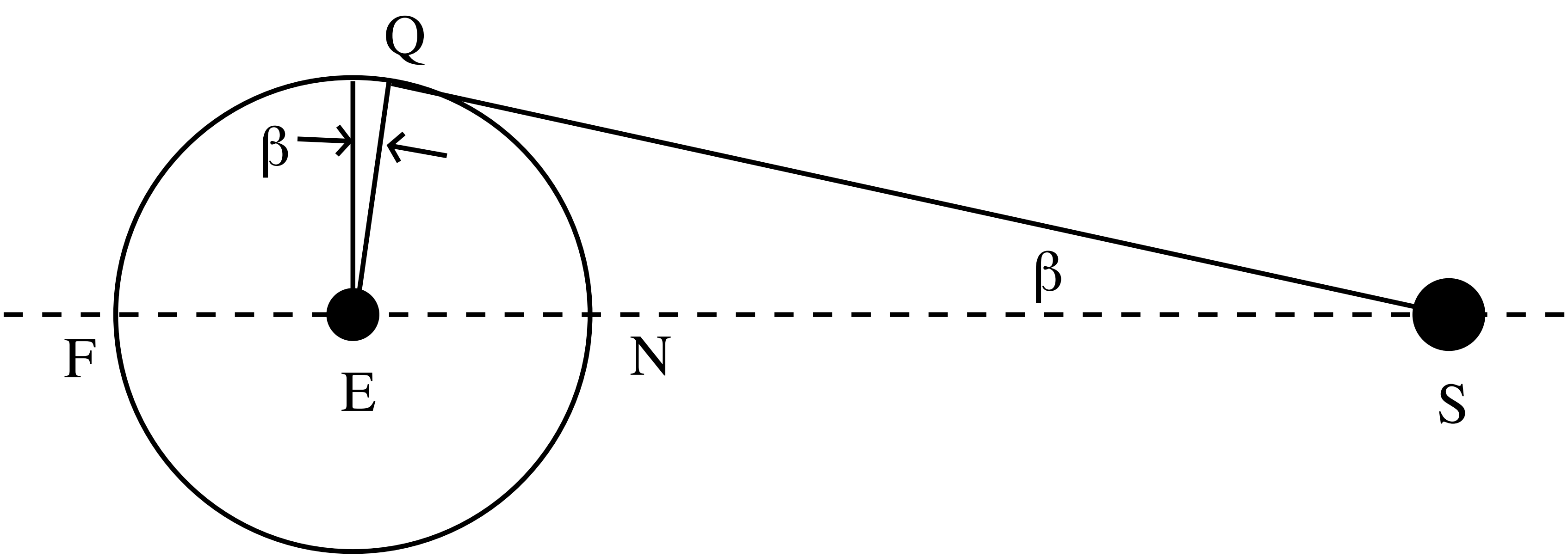
but we don't know whether it is finite or infinite in space

Measuring the Radius of the Earth Using Shadows



Earth-Moon distance in units of Earth radii

Earth-Sun distance (AU) in units of Earth-moon separation



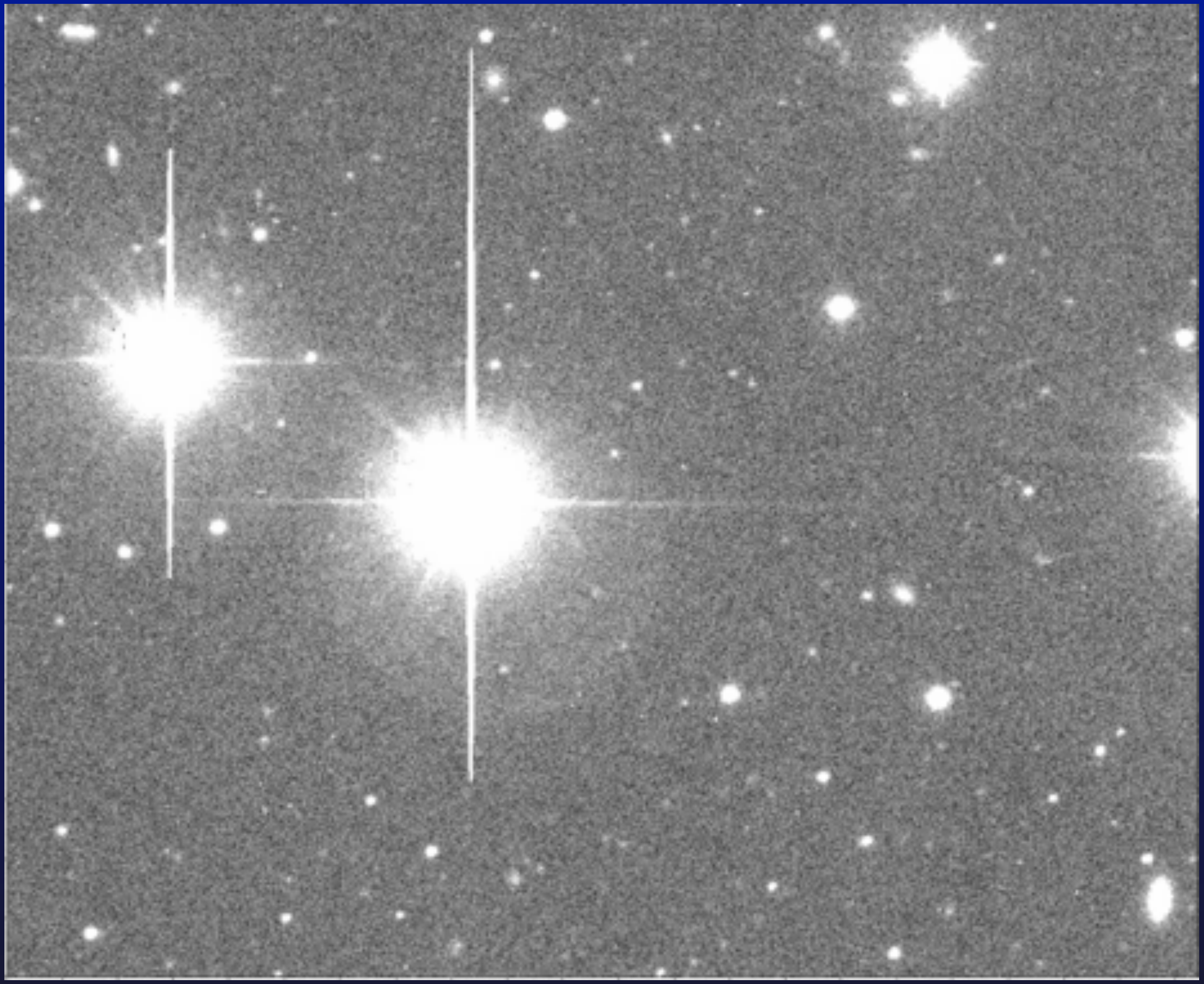
From the Sun to the Stars:
Parallax

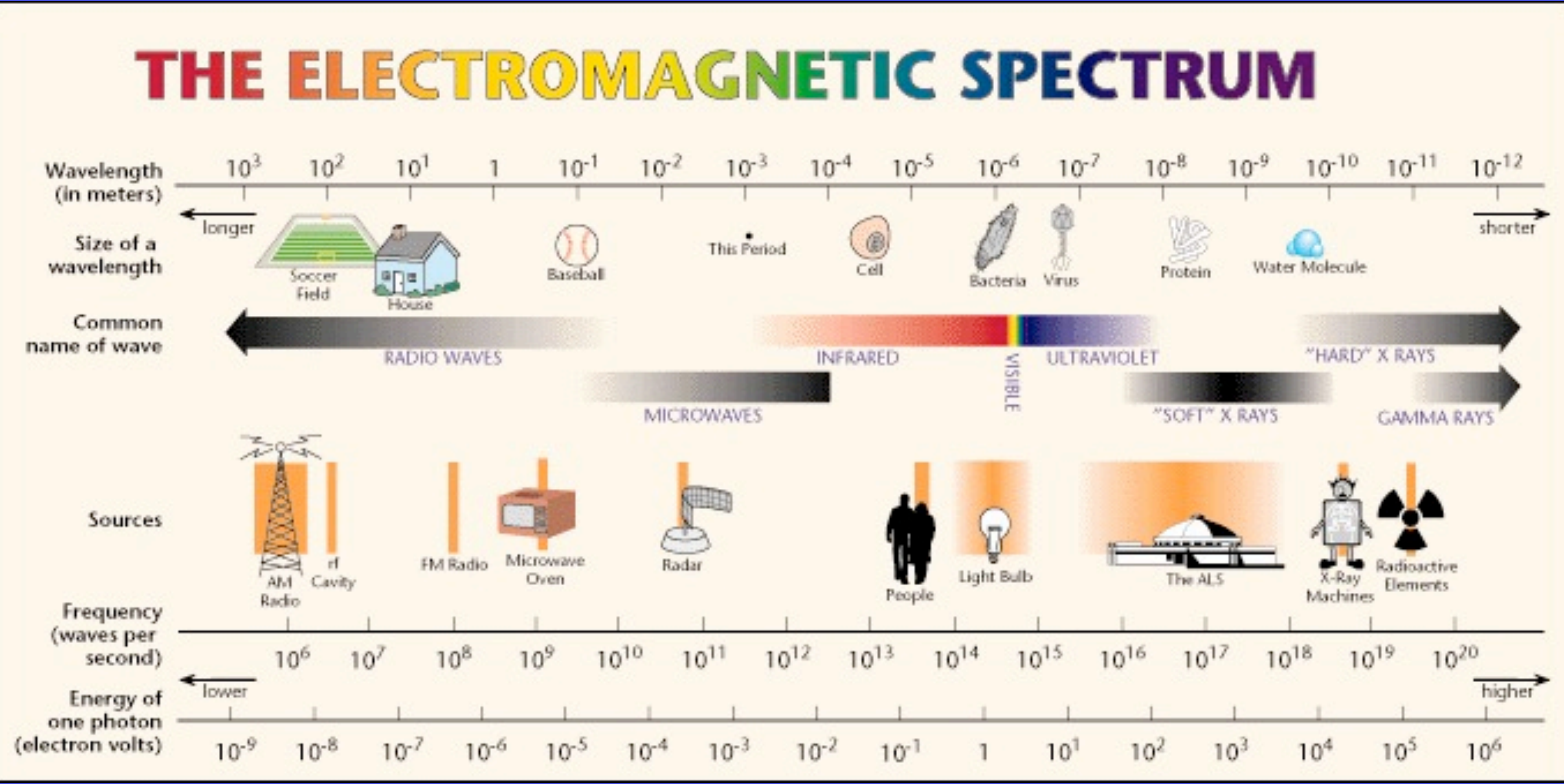
Transverse Sky Velocity:
Proper Motion

Radial Velocity:
Doppler Shift

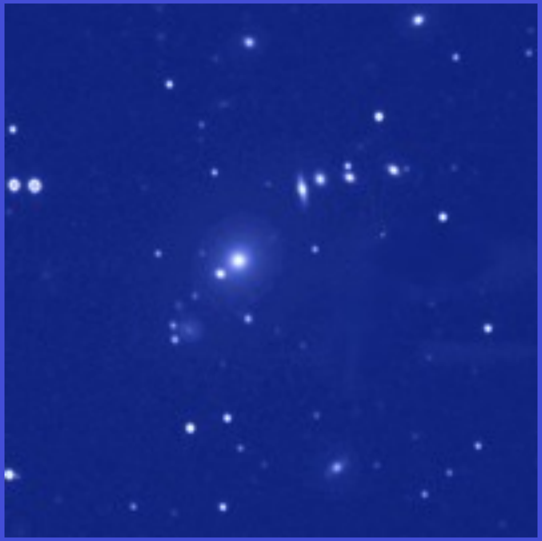
Simulations at www.astro.ubc.ca/~scharein/a311/Sim.html

Sample Blinking

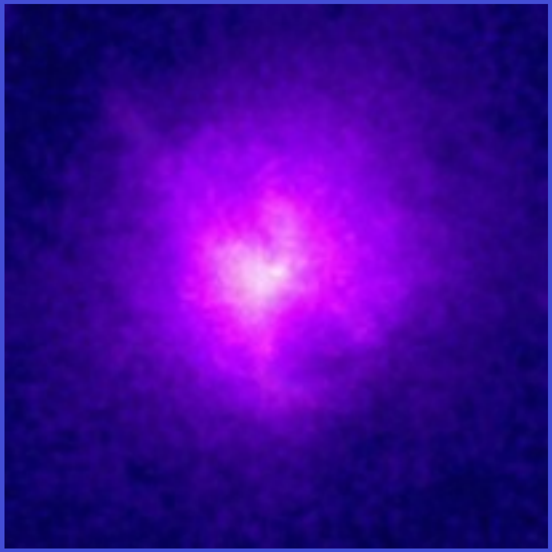



THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10³ 10² 10¹ 1 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹²
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
Energy of one photon (electron volts)
lower
higher
10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶

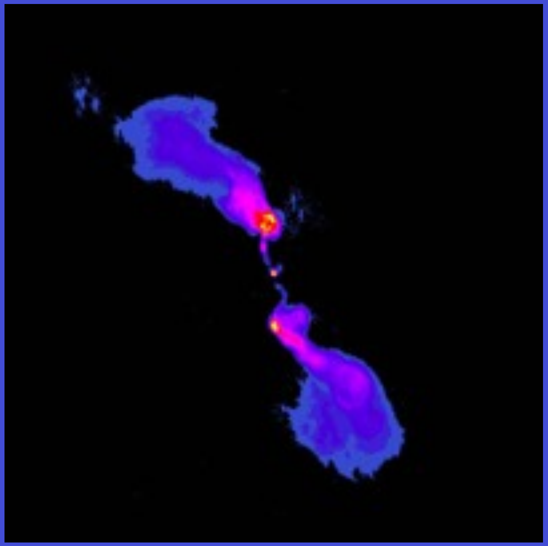
Hydra Cluster of Galaxies
(Mpc scales)



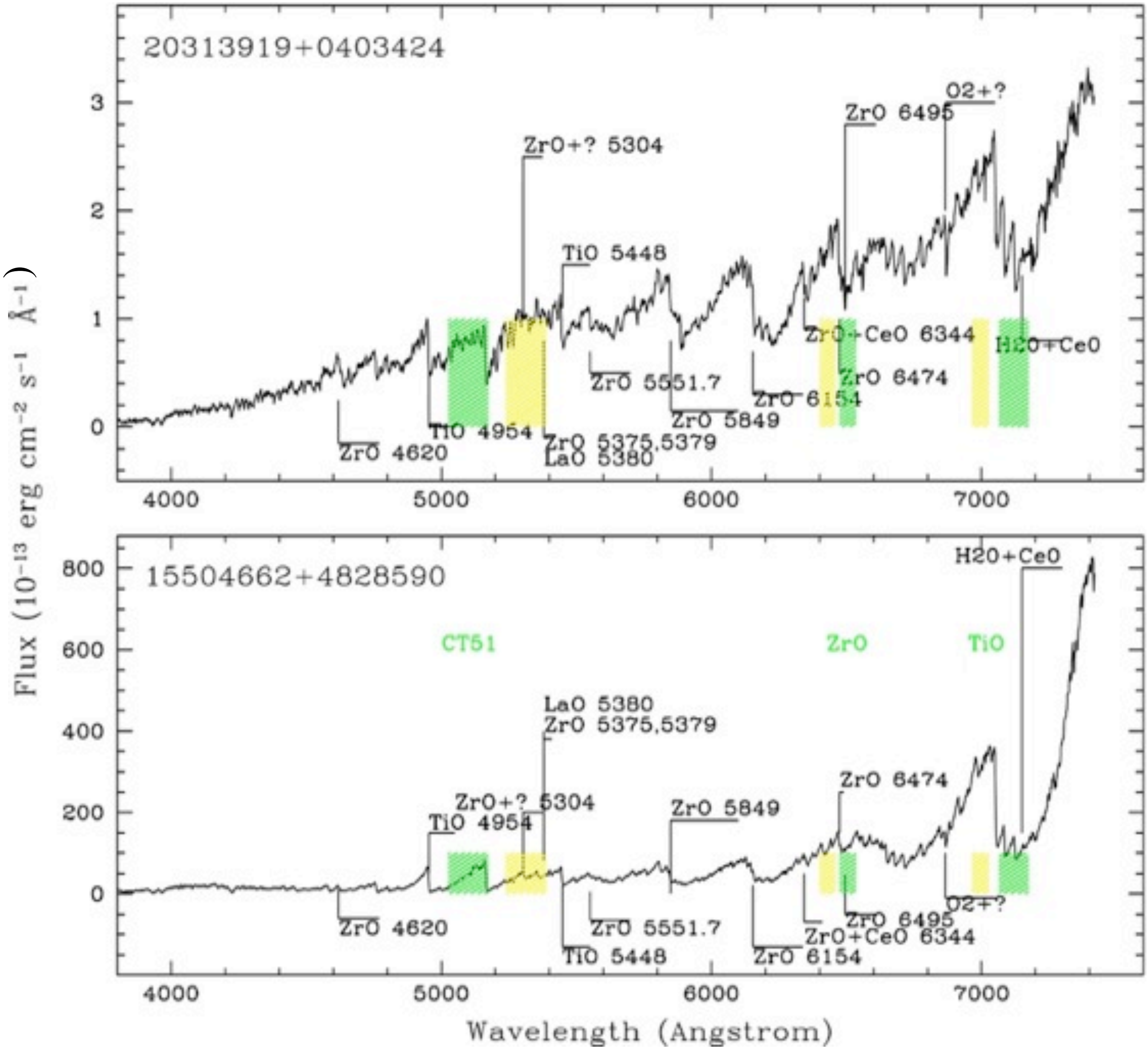
Optical
(~100 galaxies)

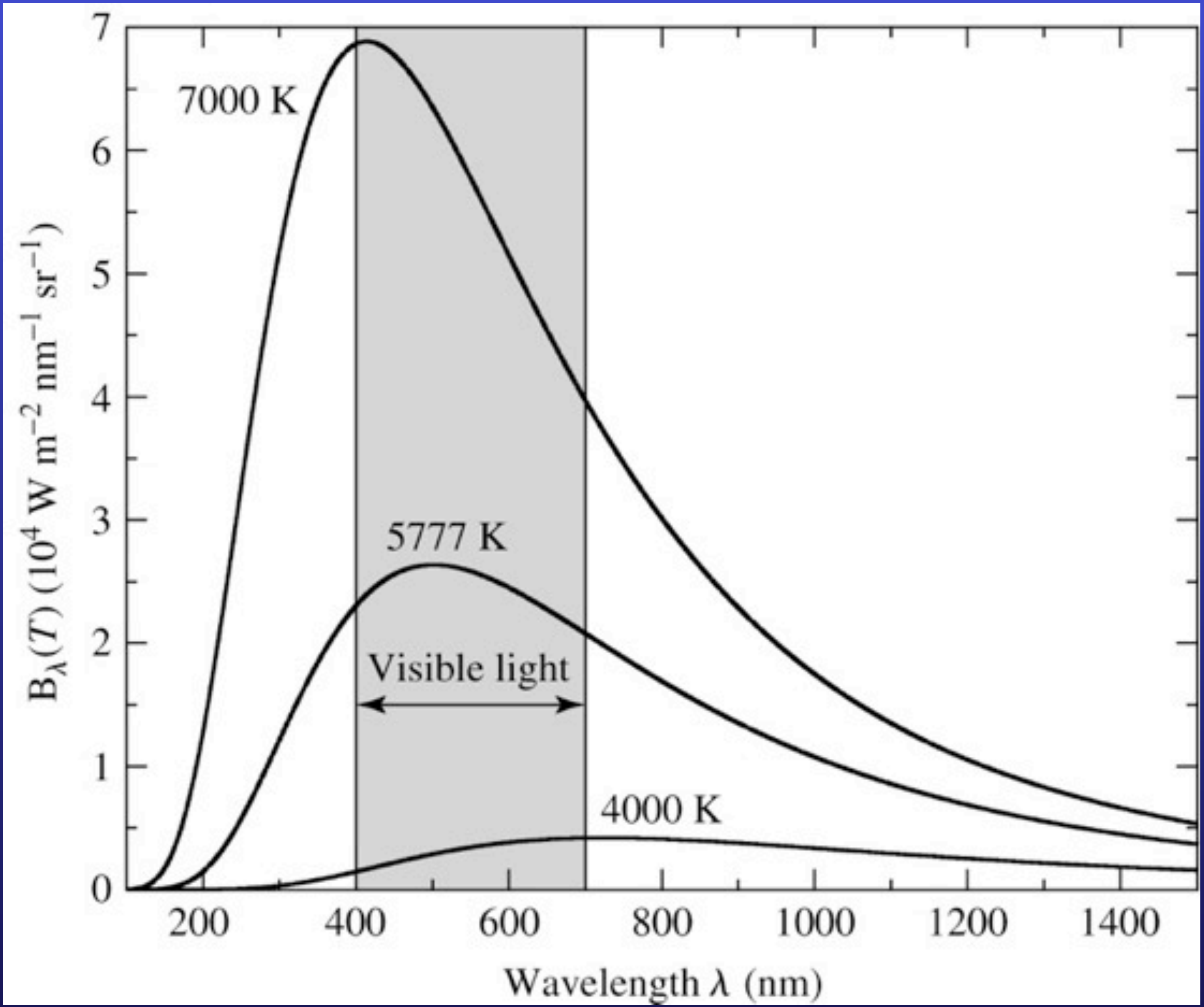


X-ray (1 keV)
Bremsstrahlung

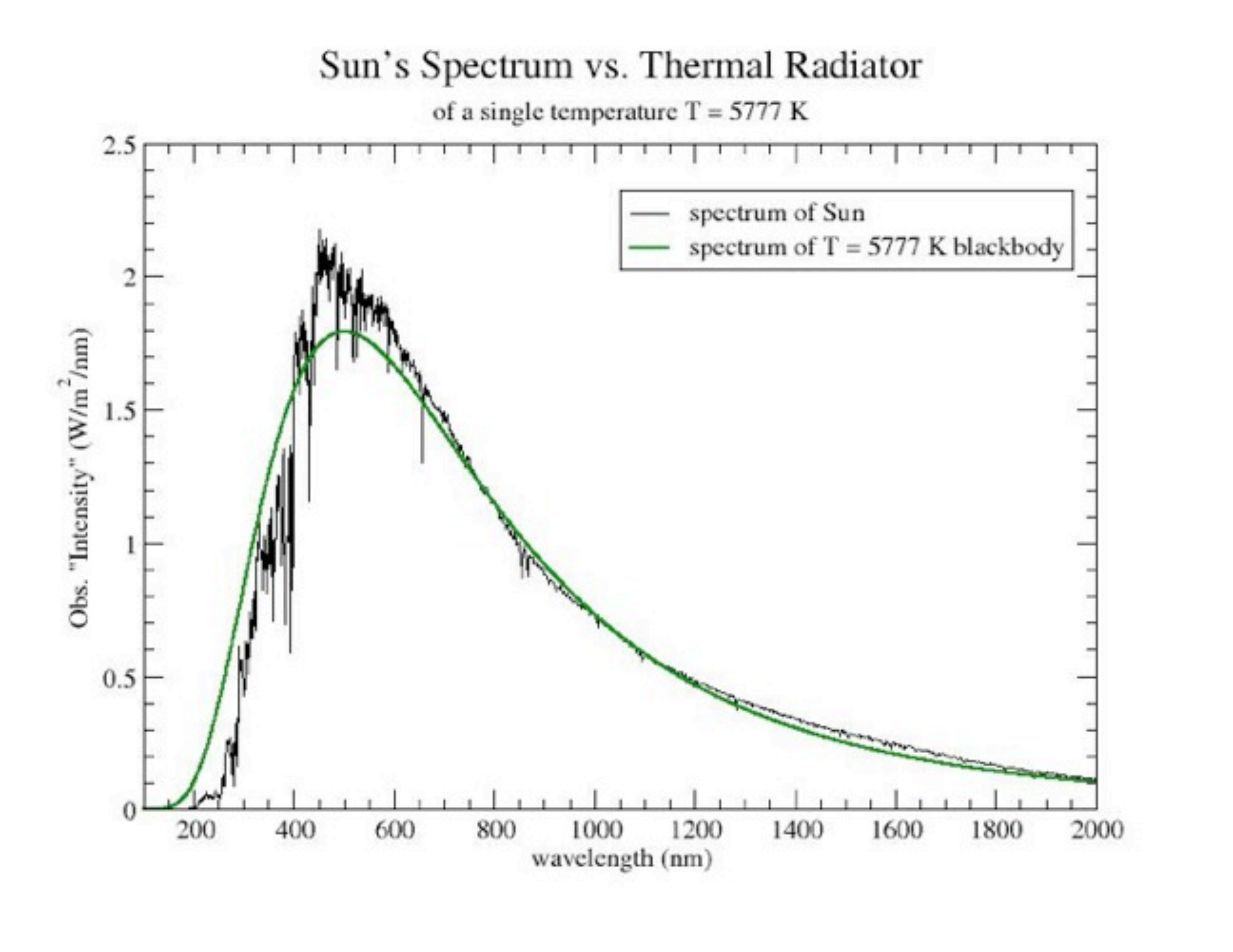


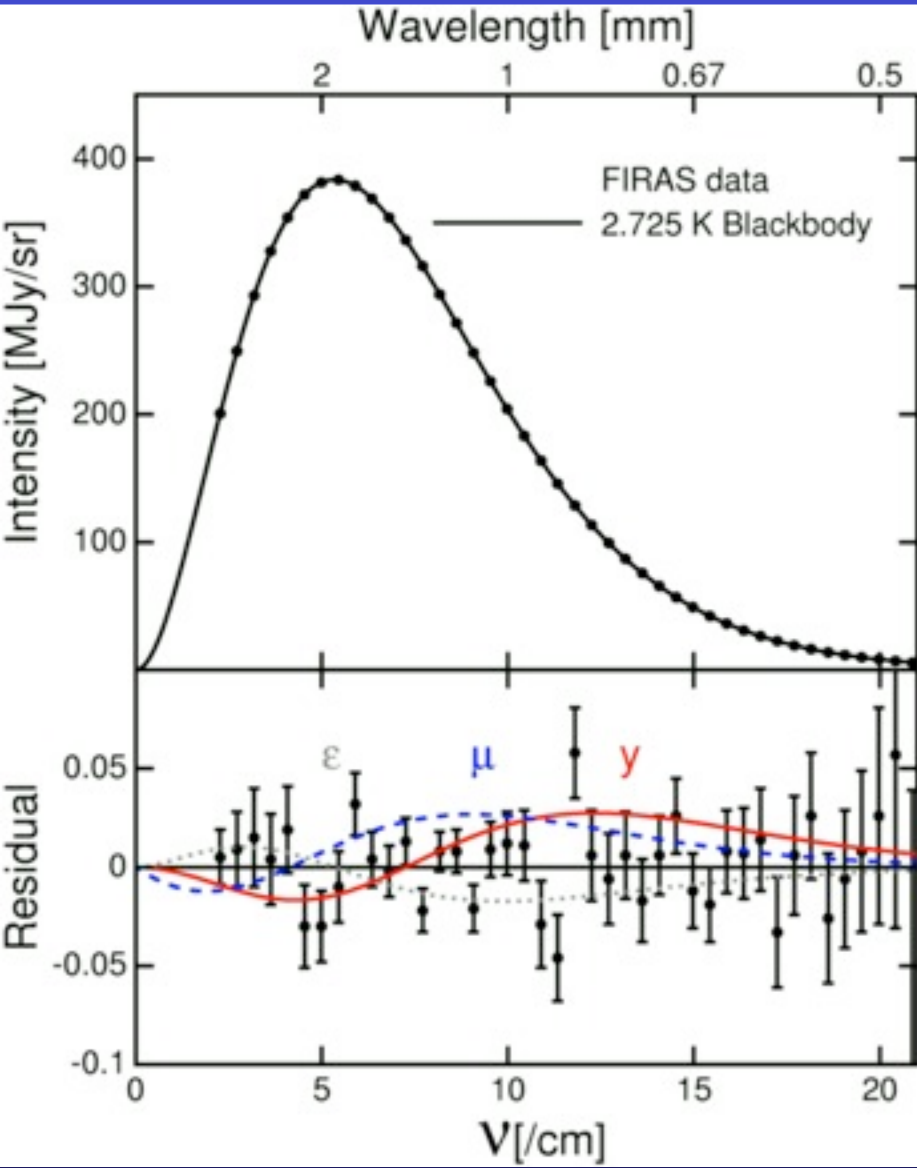
Radio
Synchrotron


20313919+0403424
ZrO+? 5304
ZrO 6495
O2+?
TiO 5448
ZrO+CeO 6344
H2O+CeO
ZrO 5551.7
ZrO 6474
ZrO 6154
ZrO 5849
TiO 4954
ZrO 5375,5379
LaO 5380
ZrO 4620
15504662+4828590
H2O+CeO
CT51
ZrO
TiO
LaO 5380
ZrO 5375,5379
ZrO 6474
ZrO+? 5304
ZrO 5849
TiO 4954
ZrO 4620
ZrO 5551.7
O2+?
ZrO 6495
ZrO+CeO 6344
TiO 5448
ZrO 6154
Flux (10^{-13} erg cm^{-2} s^{-1} Å^{-1})
Wavelength (Angstrom)

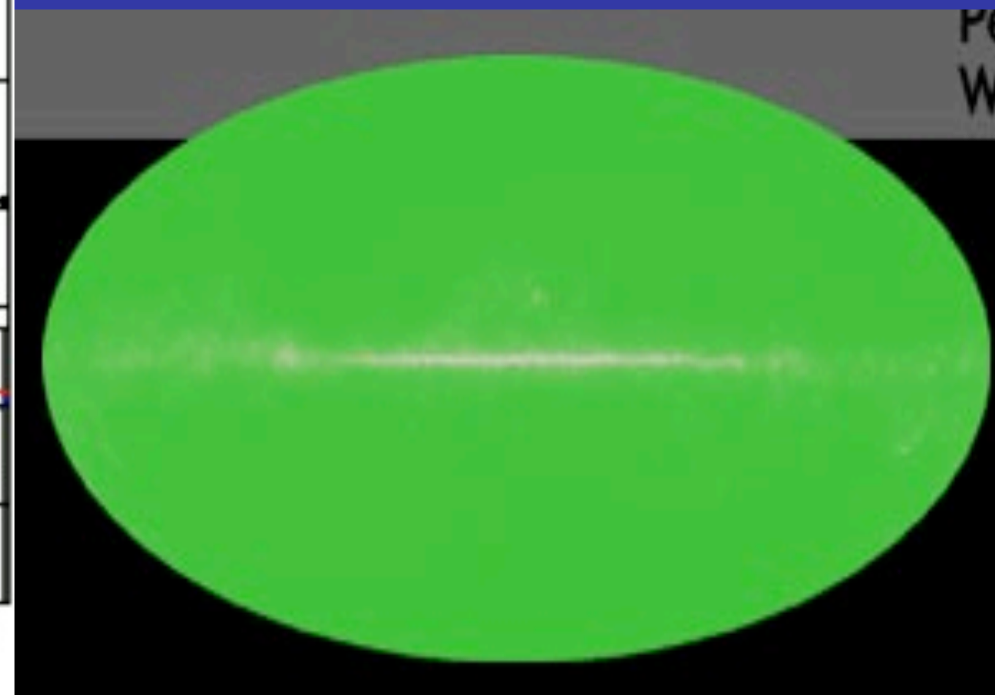


7000 K
5777 K
4000 K
Visible light
$B_\lambda(T)$ (10^4 W m^{-2} nm^{-1} sr^{-1})
Wavelength λ (nm)
0
1
2
3
4
5
6
7
200
400
600
800
1000
1200
1400

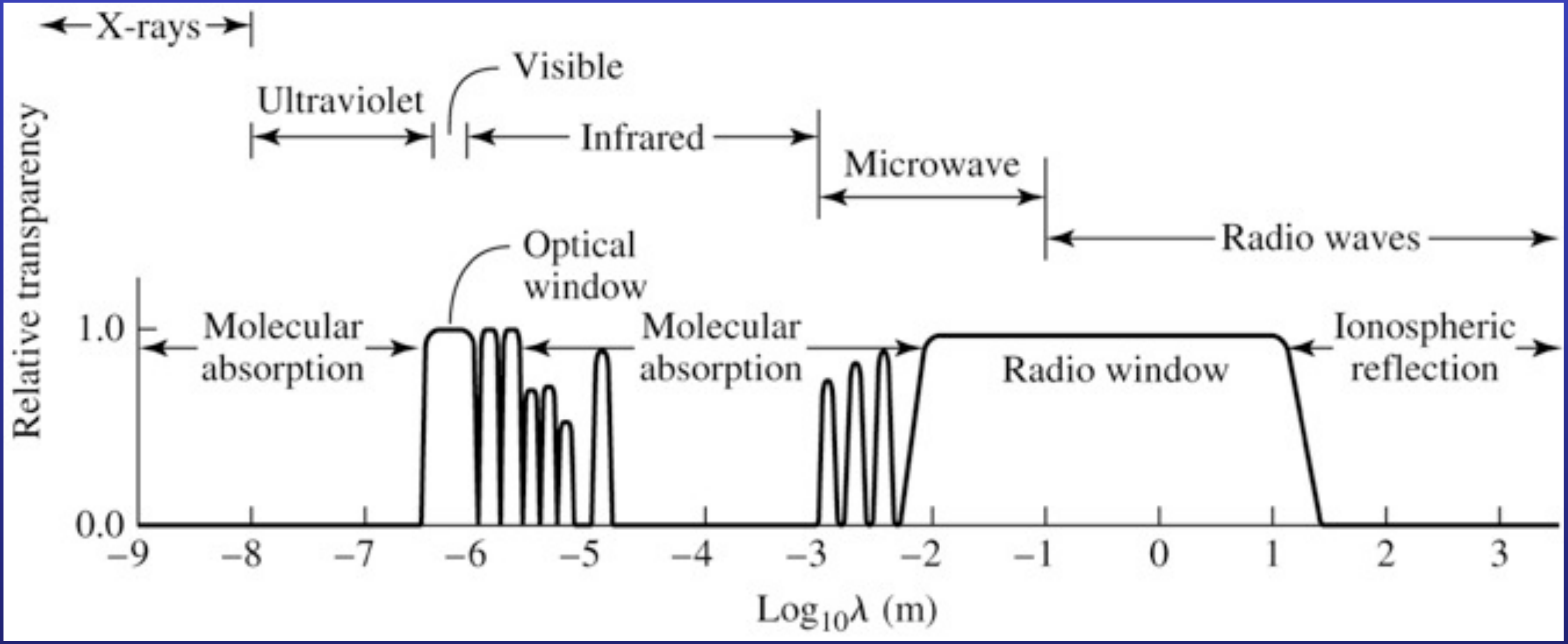

Sun's Spectrum vs. Thermal Radiator
of a single temperature T = 5777 K
spectrum of Sun
spectrum of T = 5777 K blackbody
Obs. "Intensity" (W/m^2/nm)
wavelength (nm)
0
0.5
1
1.5
2
2.5
200
400
600
800
1000
1200
1400
1600
1800
2000



Cosmic Microwave Background Radiation is nearly perfect Blackbody Radiation

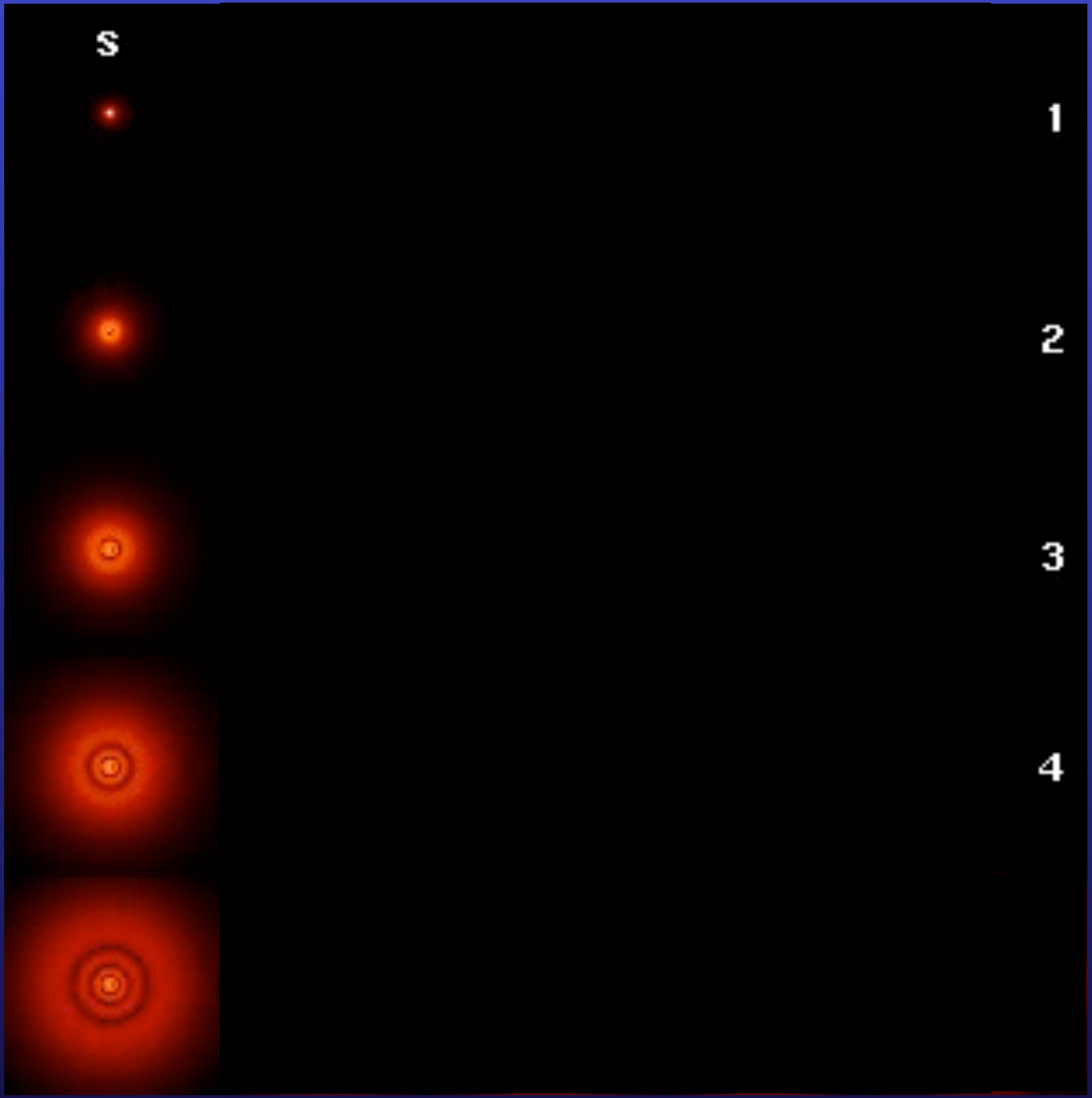


Electromagnetic Windows

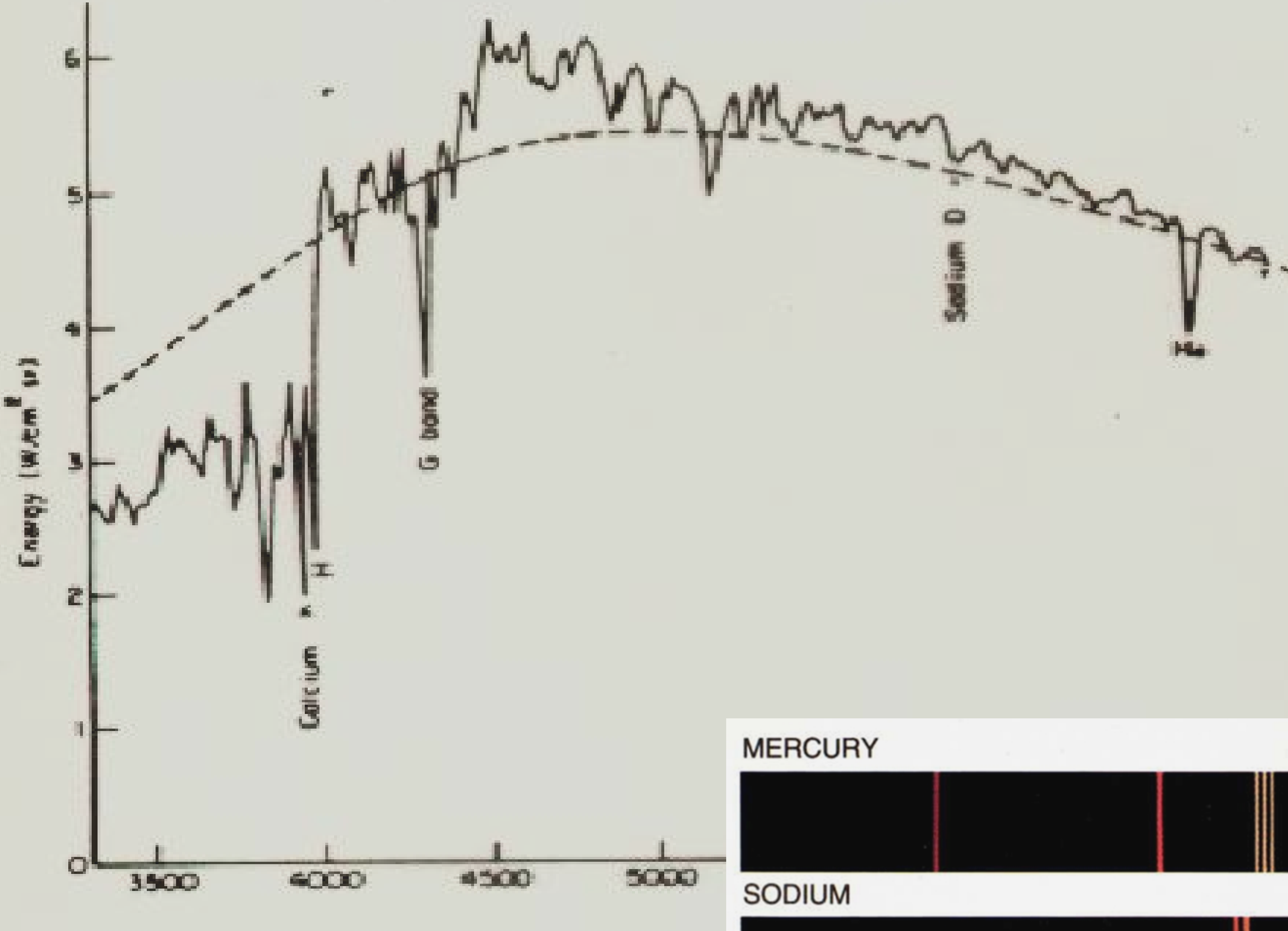


Actual Electron Wavefunctions

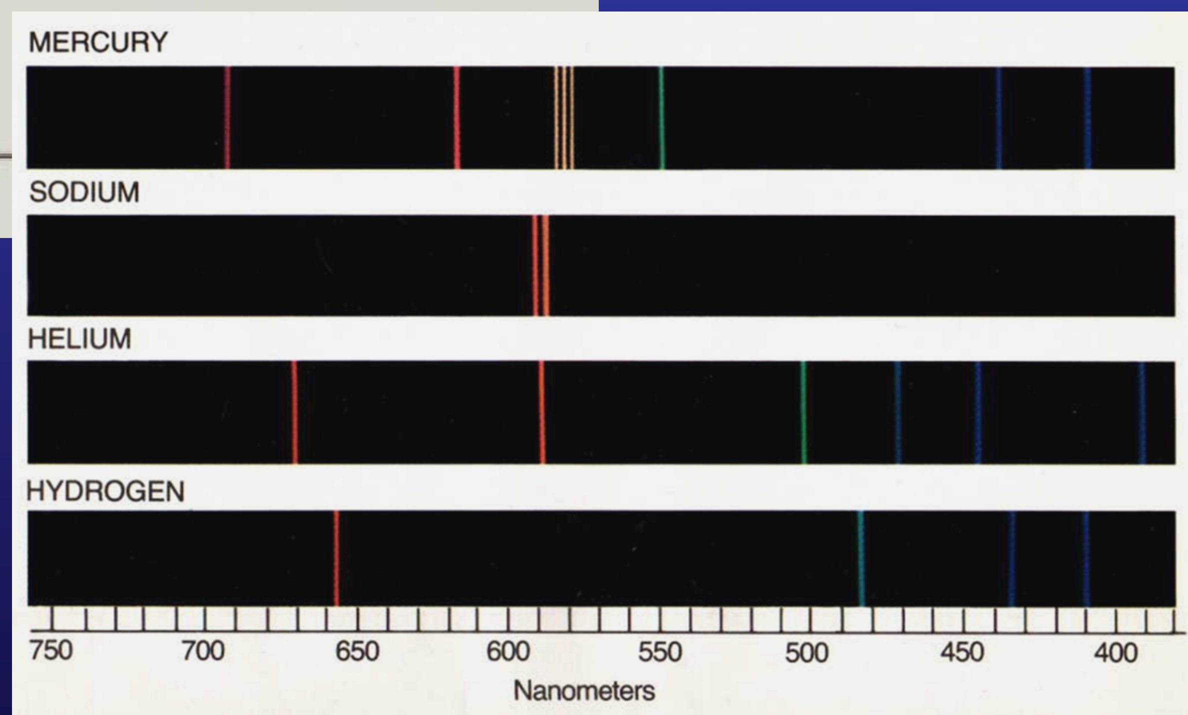
Angular momentum ℓ

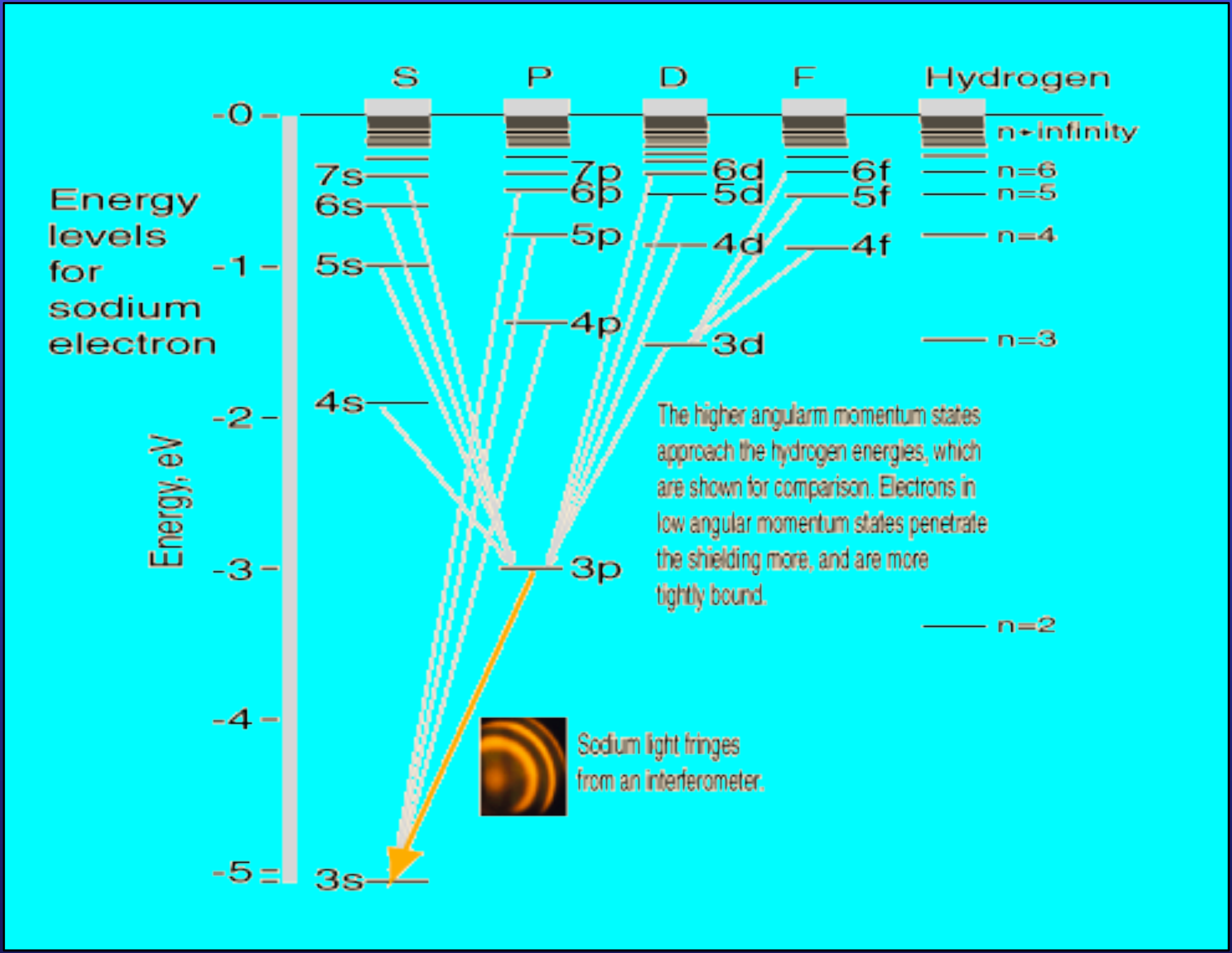


Principal quantum number n

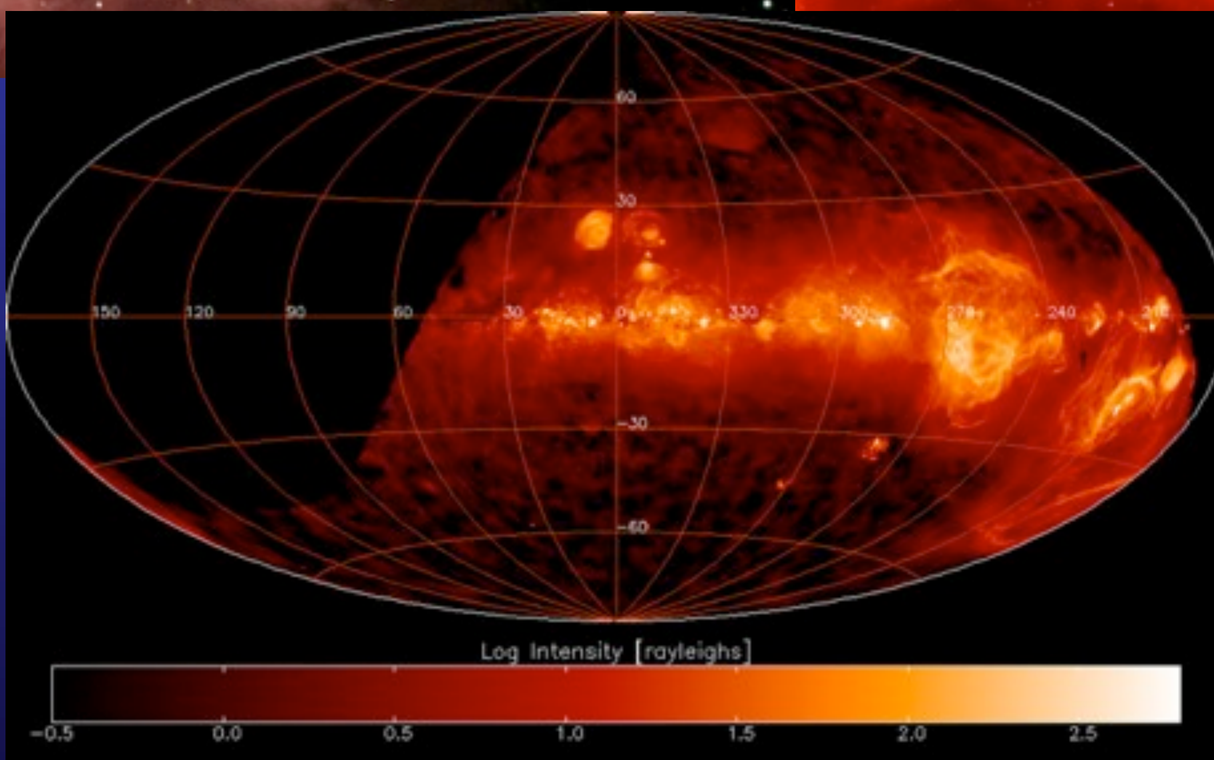


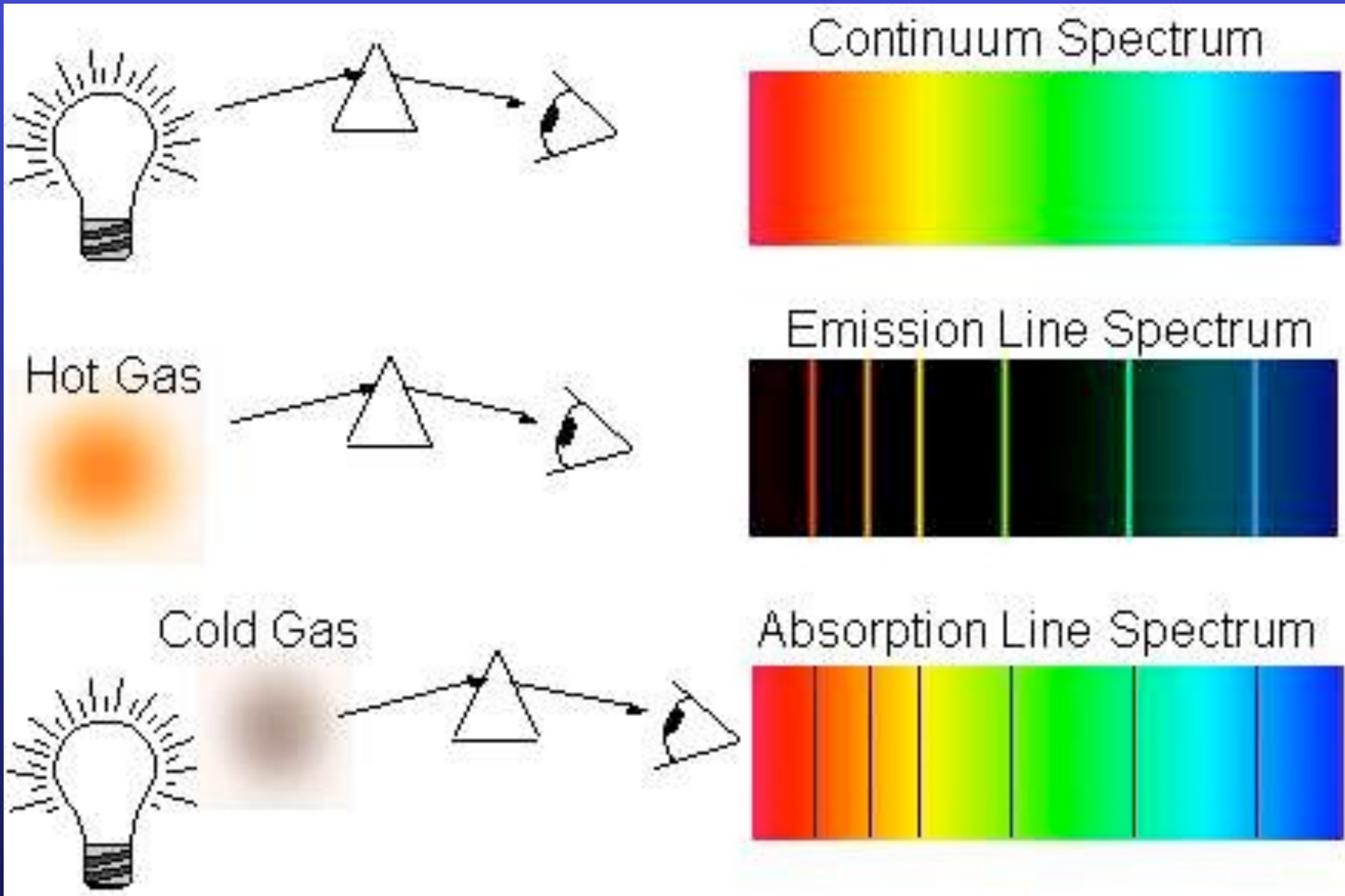
Spectral Fingerprints



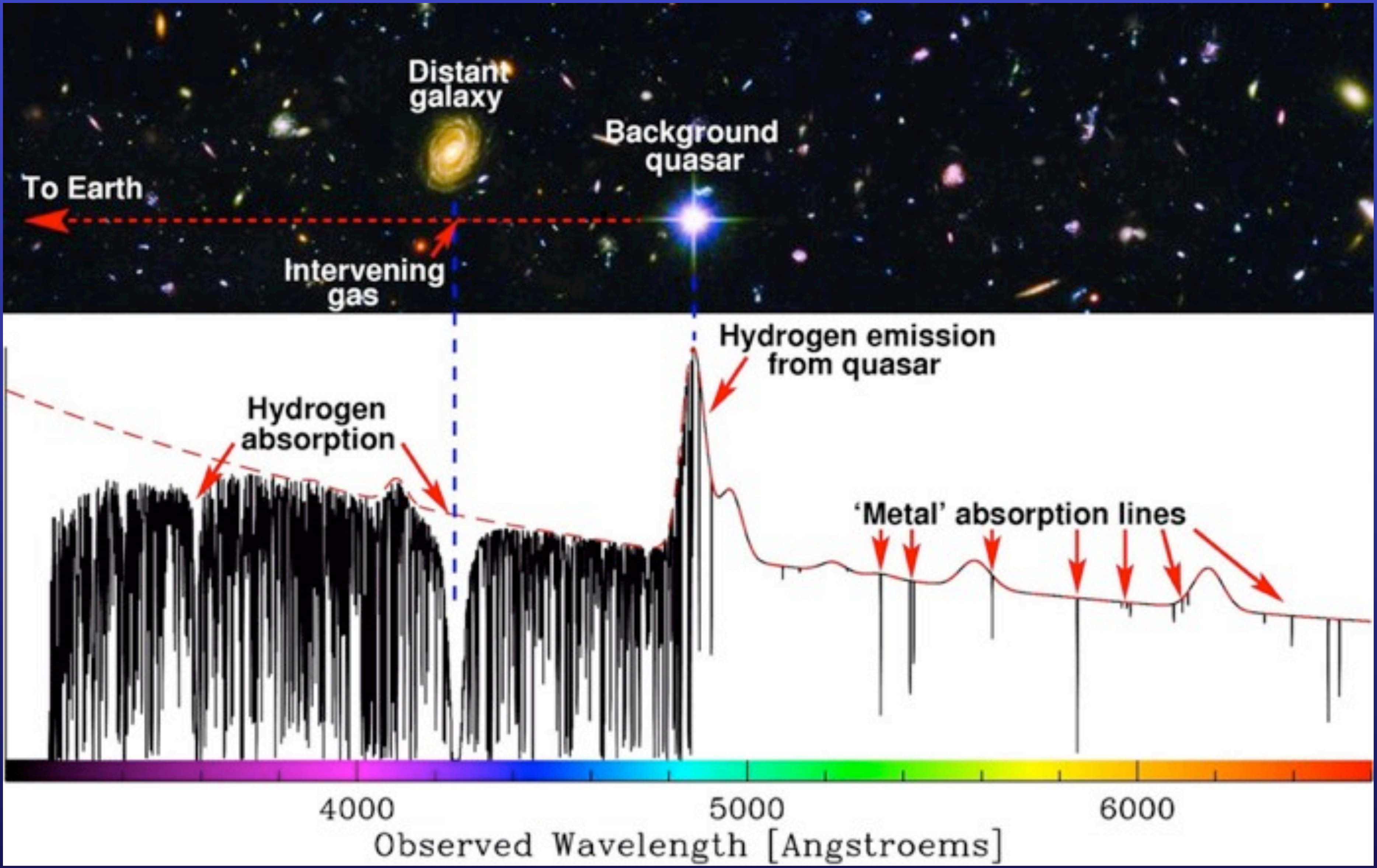


S
P
D
F
Hydrogen
Energy levels for sodium electron
Energy, eV
-0
-1
-2
-3
-4
-5
n→infinity
n=6
n=5
n=4
n=3
n=2
7s
6s
5s
4s
3s
7p
6p
5p
4p
3p
6d
5d
4d
3d
6f
5f
4f
The higher angularm momentum states approach the hydrogen energies, which are shown for comparison. Electrons in low angular momentum states penetrate the shielding more, and are more tightly bound.
Sodium light fringes from an interferometer.


60
30
150
120
90
60
30
330
300
240
-30
-60
Log Intensity [rayleighs]
-0.5
0.0
0.5
1.0
1.5
2.0
2.5

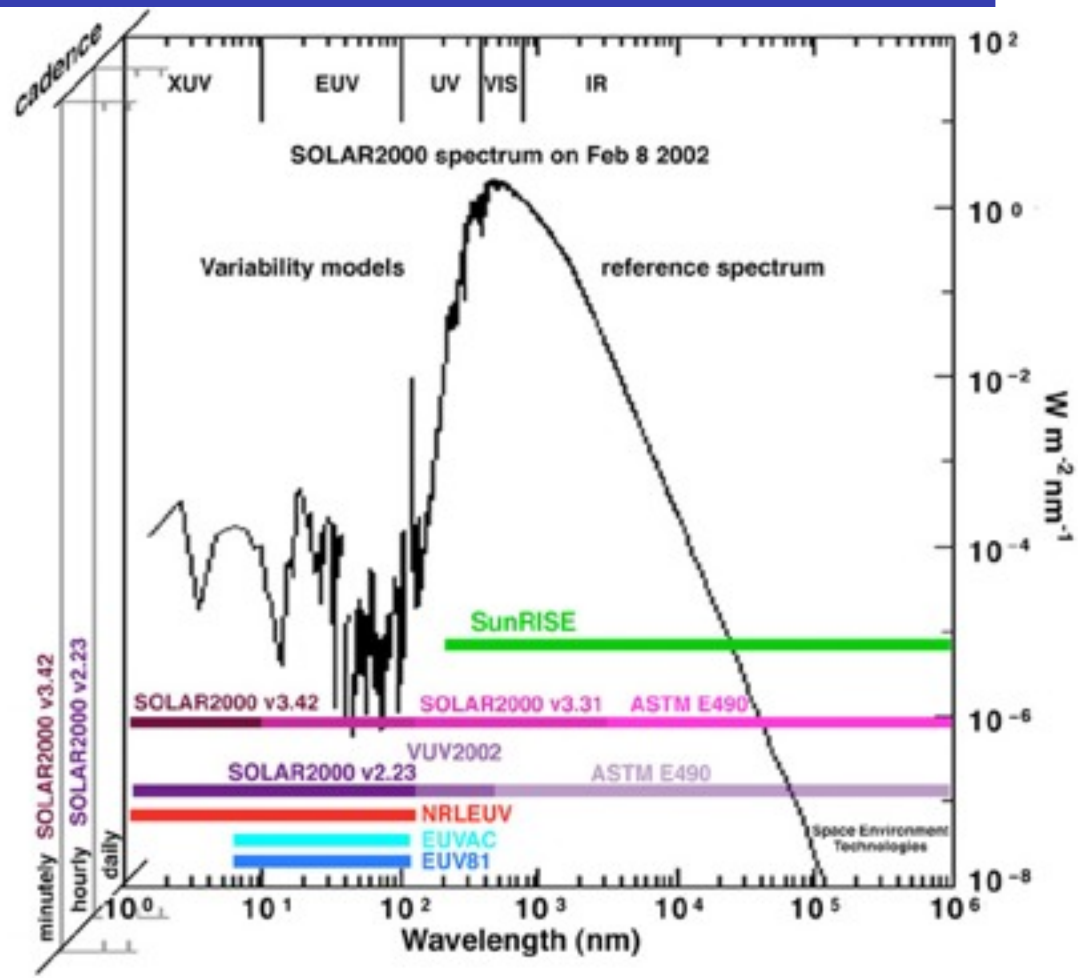

Continuum Spectrum
Hot Gas
Emission Line Spectrum
Cold Gas
Absorption Line Spectrum

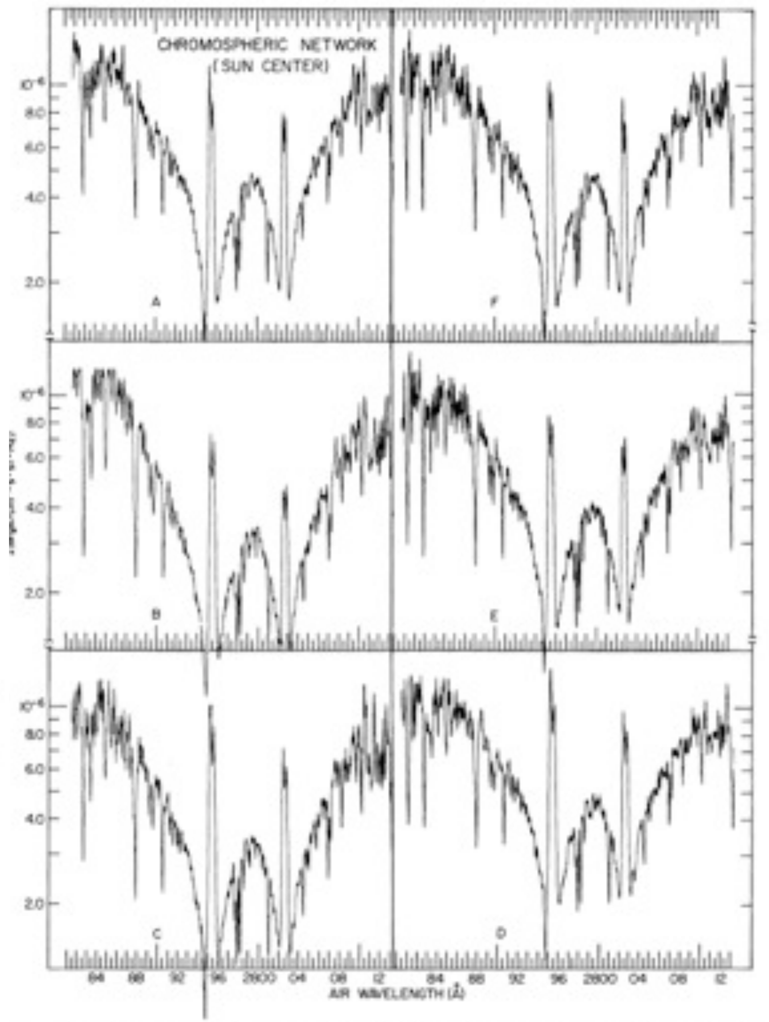
Lyman Alpha "Forest"



Not every line is an absorption line

Left: Lyman alpha emission line
Right: Mg II “H and K” self-reversed lines





2.—A sequence of Mg II spectra obtained over different positions relative to a supergranulation cell boundary and cell . See Table 2 for location of each spectrum. For these spectra and the spectra shown in Figs. 3, 4, 5, 7, 8, and 9, the in- nt efficiency has not been removed. Between 2780 Å and 2820 Å, the efficiency of the instrument decreases by 22.0%. The of the curve is linear.

Temperature Profile of Solar Atmosphere (CO Figure 11.18)

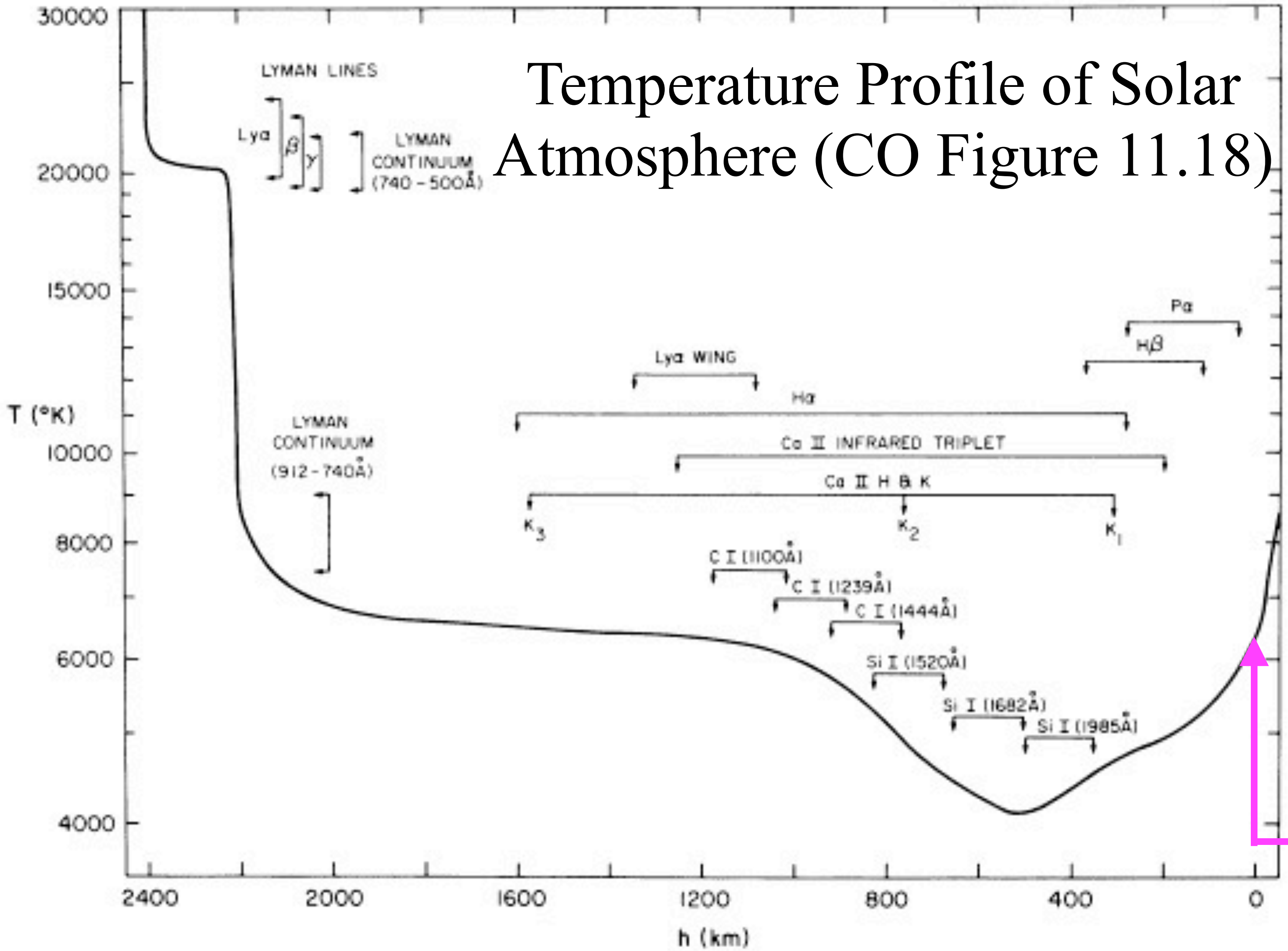
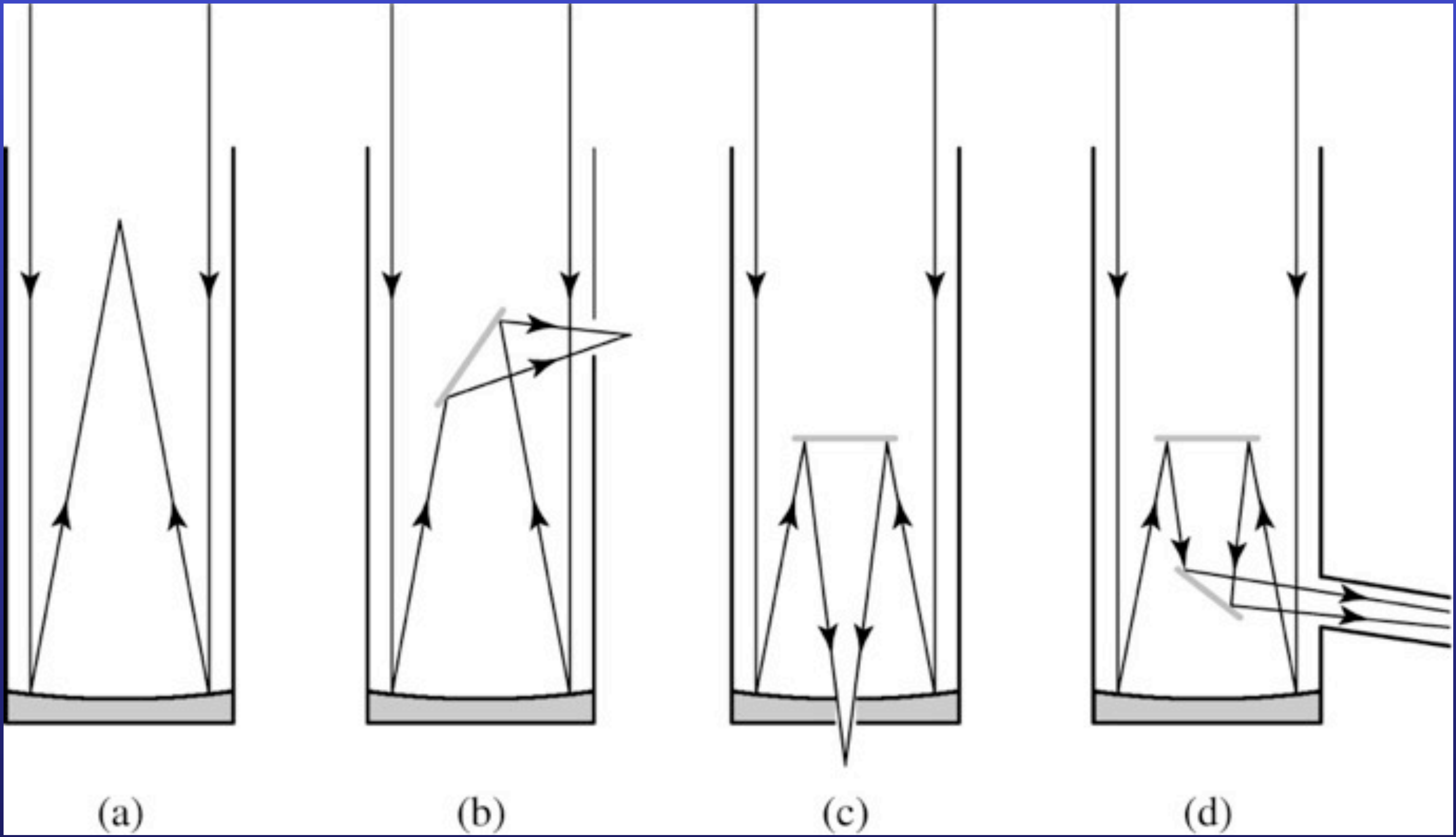
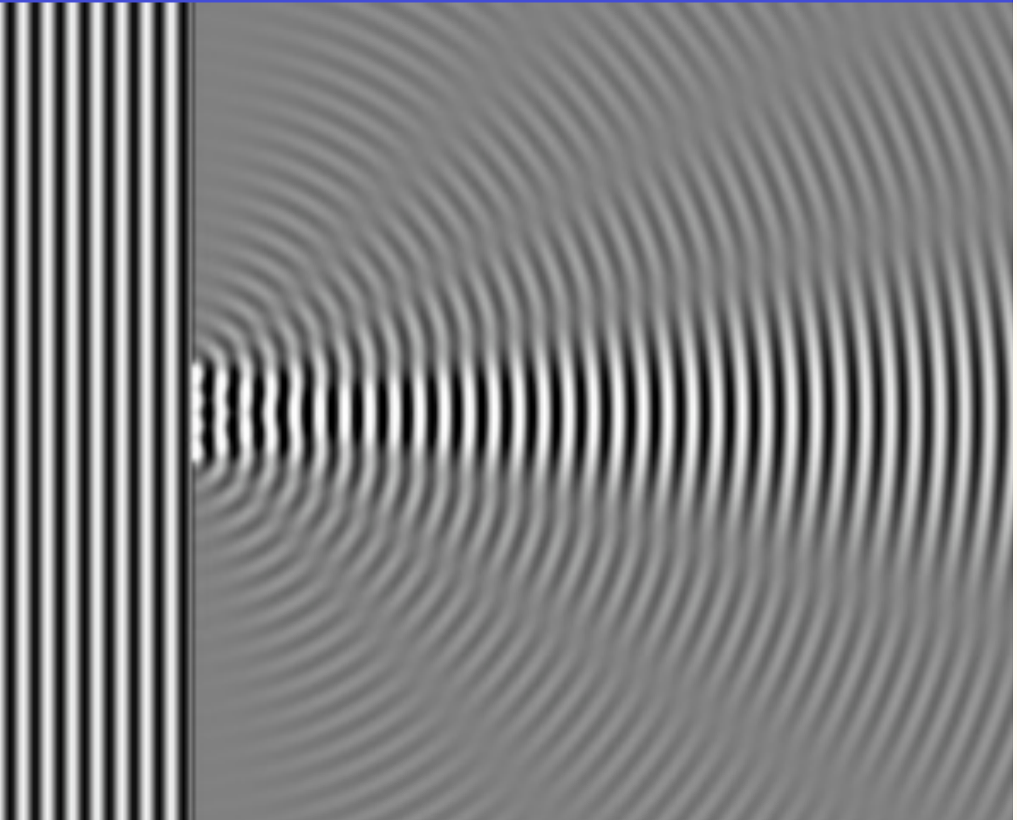


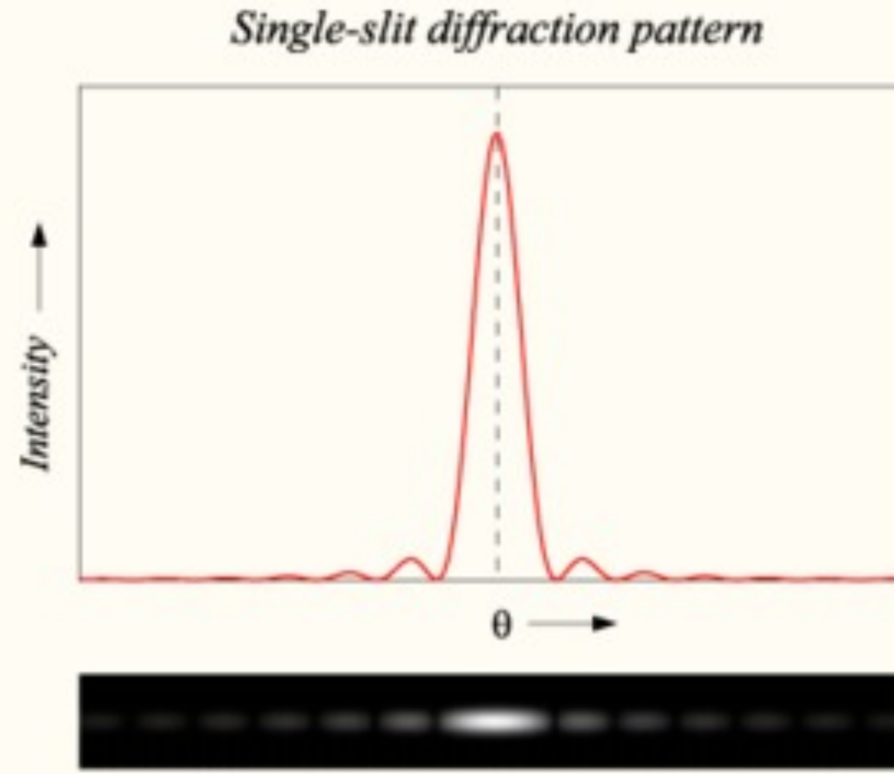
FIG. 1.—Our adopted temperature-height distribution for the photosphere (on the right), temperature-minimum, chromosphere, and chromosphere-corona transition zone. Also indicated are the regions of formation of the various lines and continua we have studied.

Photospheric "surface" $\equiv \tau(5000\ \text{Å}) = 1$

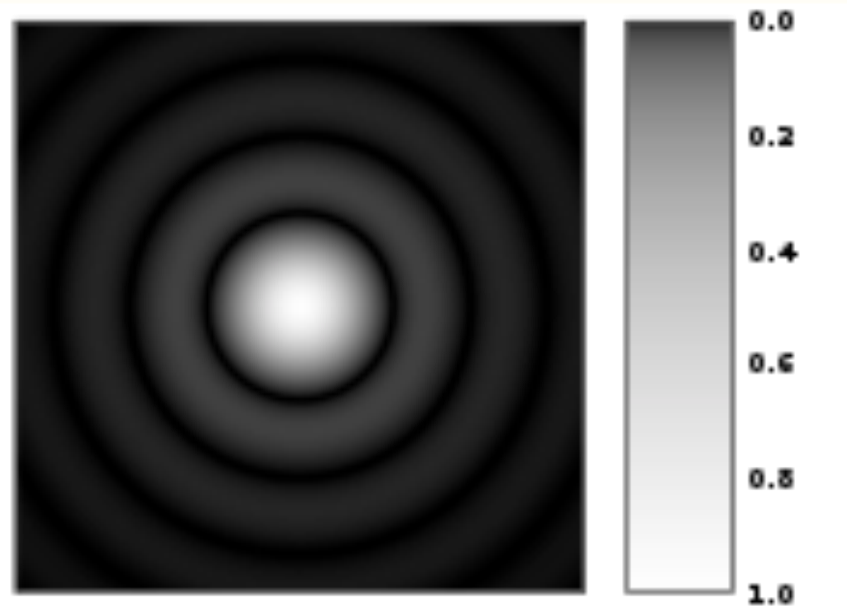
Optical Telescope Design





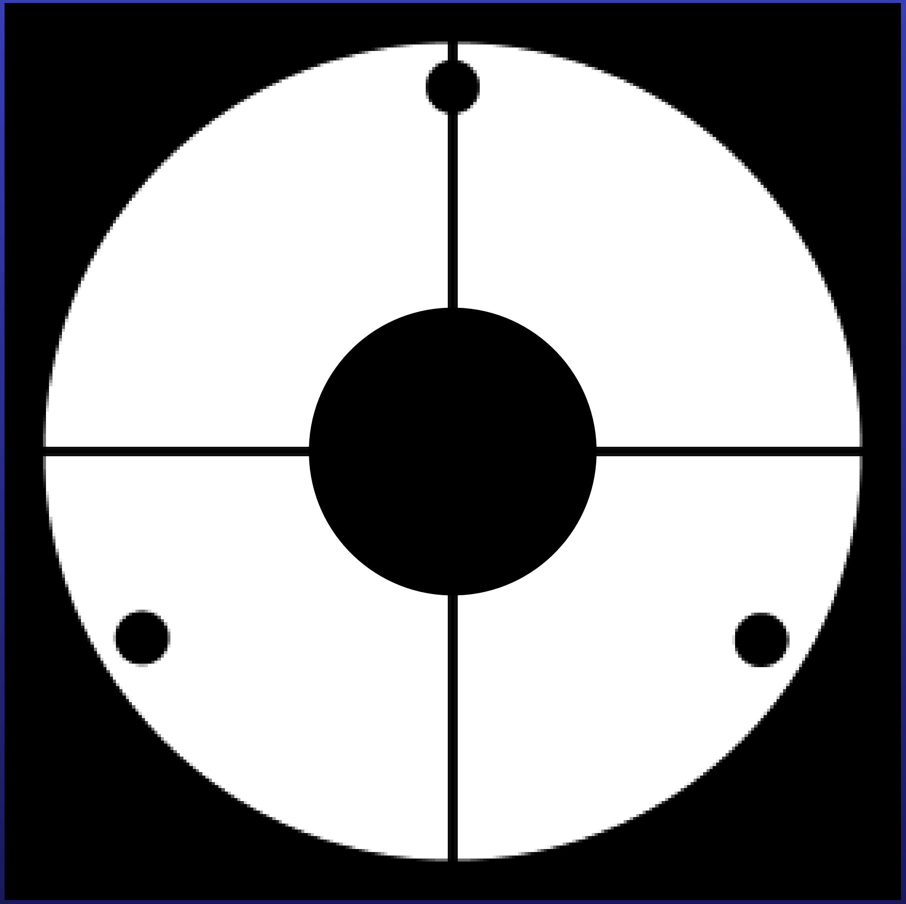


Diffraction

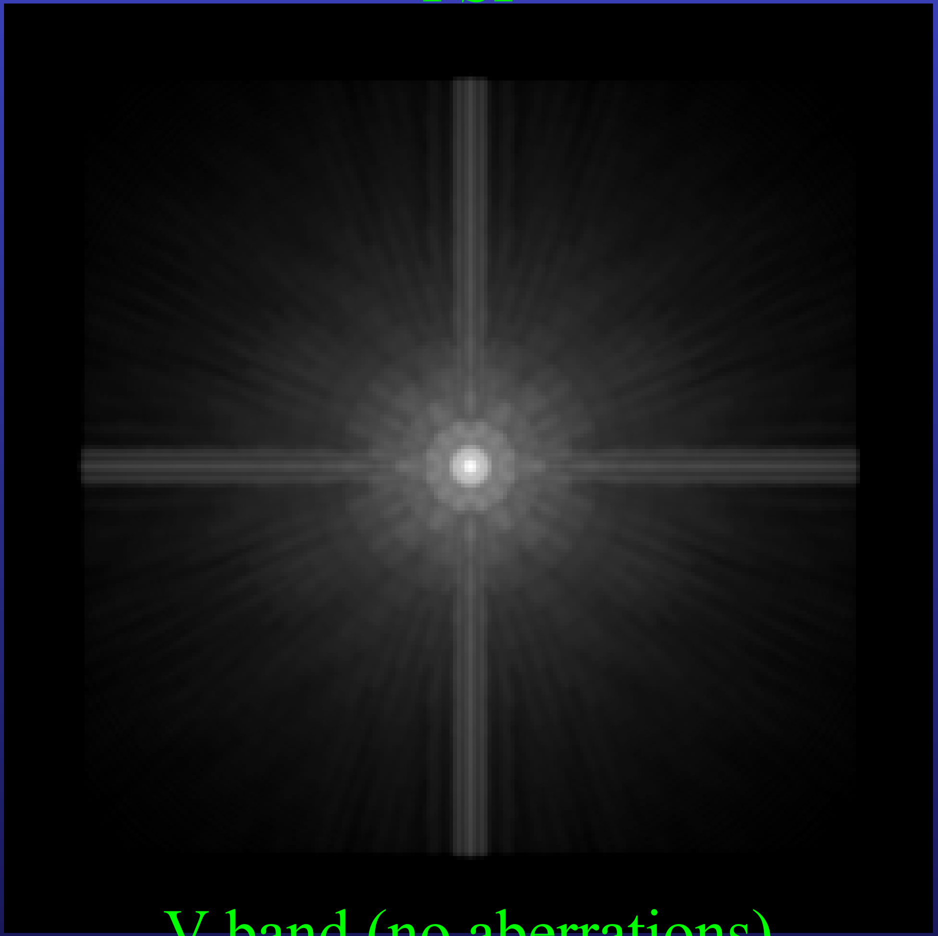


Diffraction from Obscurations

HST Entrance Pupil



PSF



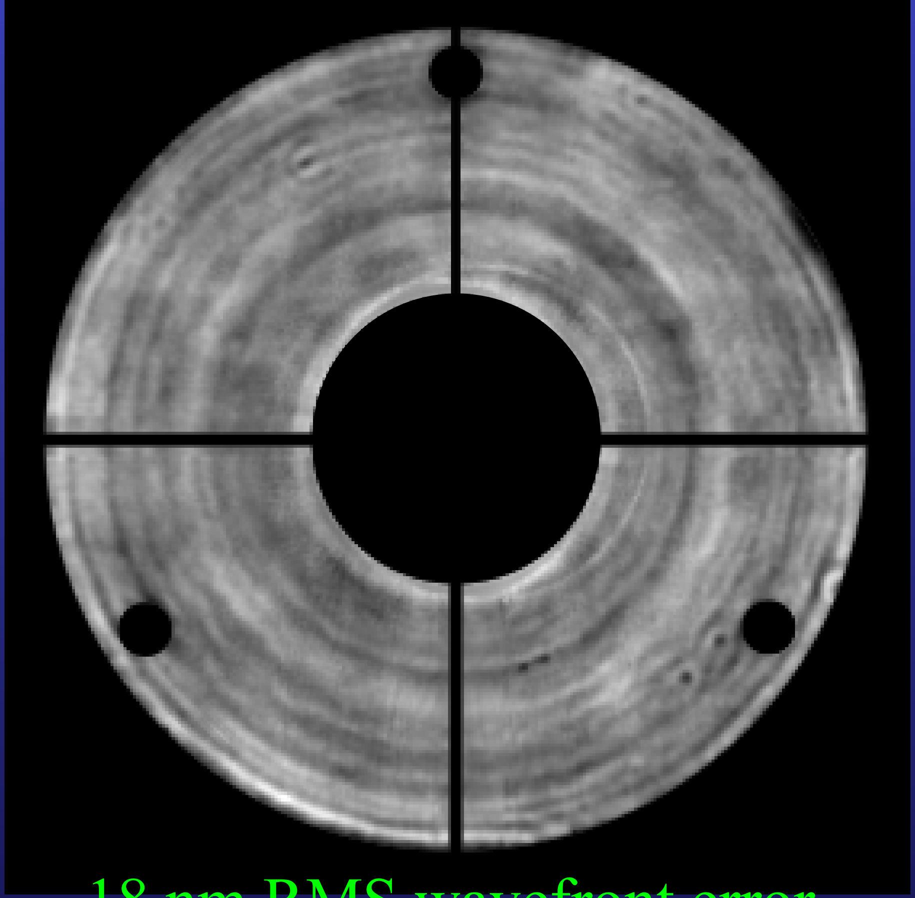
V band (no aberrations)

Model

Scatter from Optical Surface Errors

Midfrequency Error Map

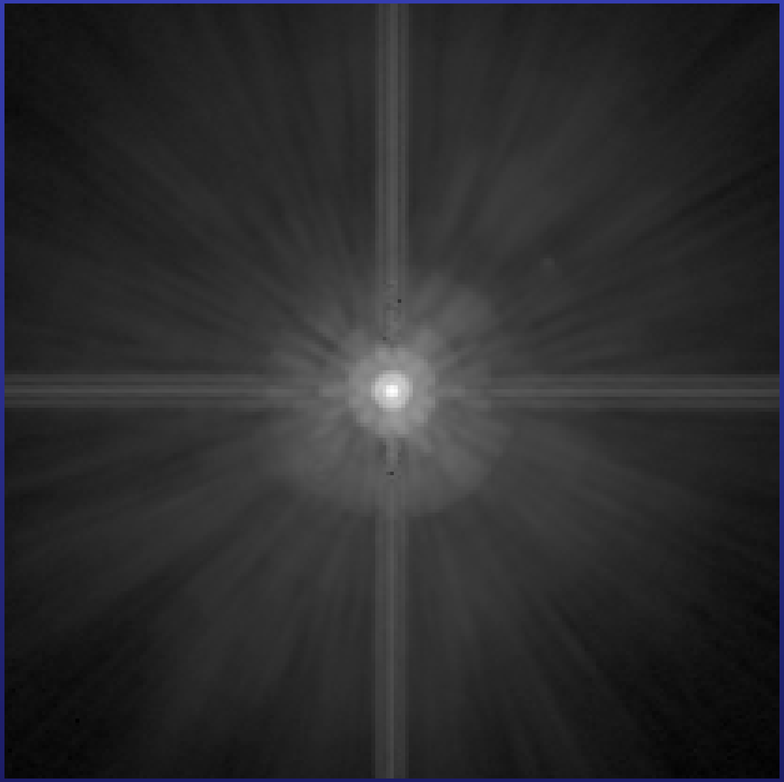
Phase retrieval derived



18 nm RMS wavefront error

Krist & Burrows (1995)

PSF



V band (ACS/HRC)

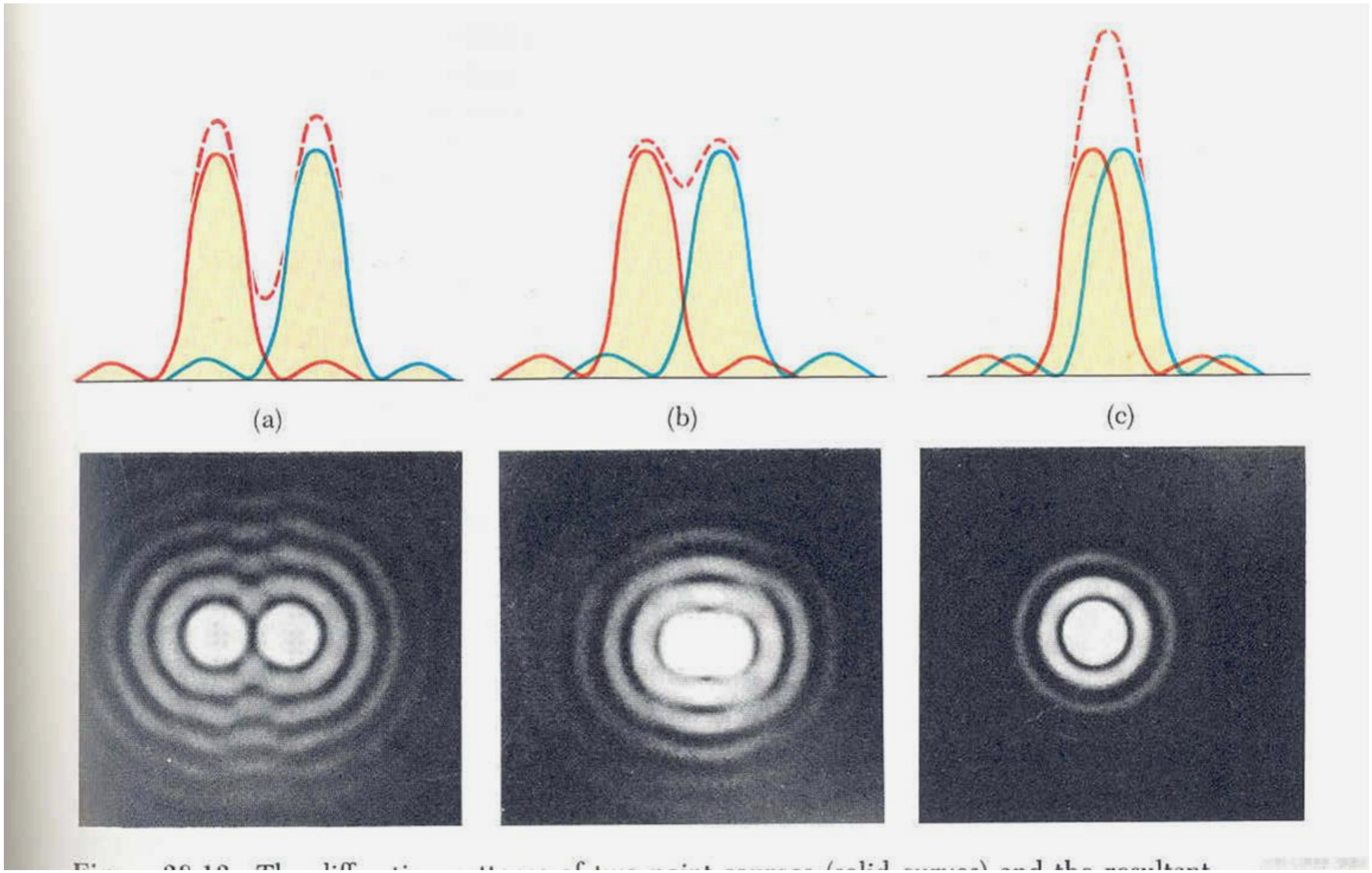
Observed

Hubble Space Telescope – 2.4 m Telescope in Space: Observes at Visible, IR, & UV λ's

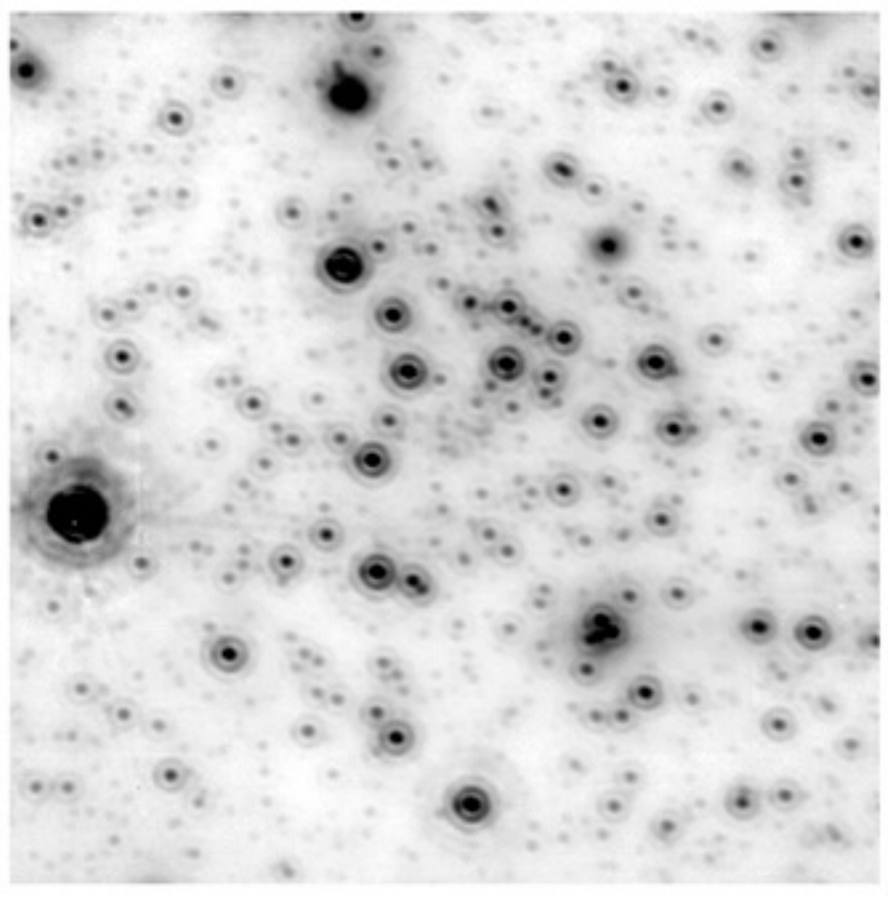
NICMOS – one of the detectors onboard Hubble

Cannot "resolve" (distinguish, tell apart, …) sources of light that are too close together

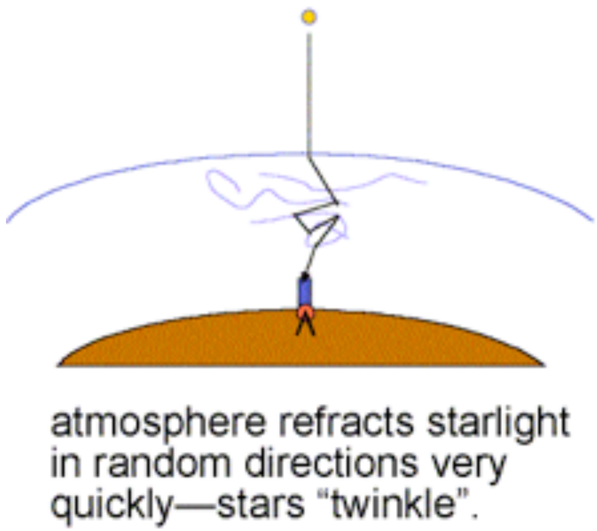
"Diffraction limit"

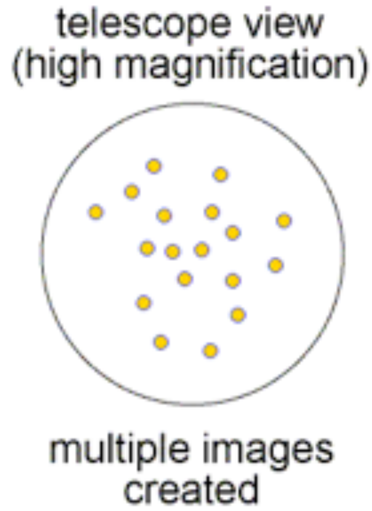


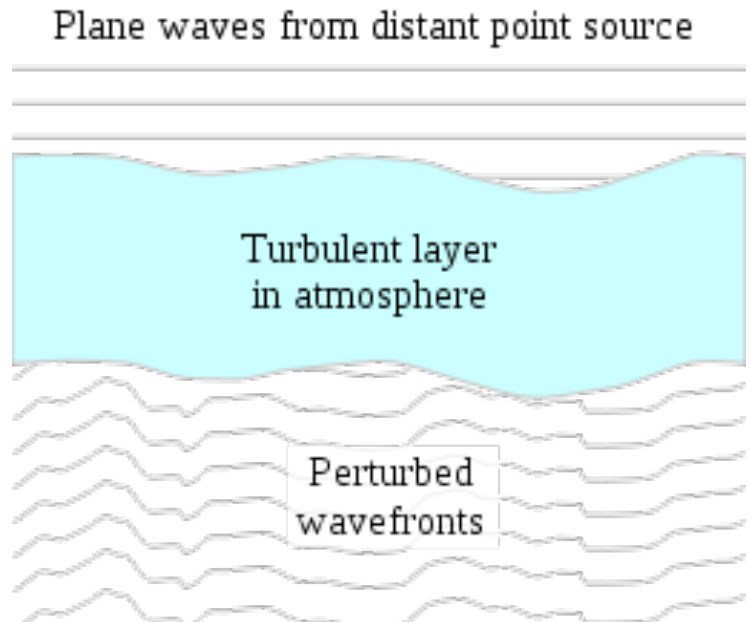
Diffraction-limited performance of 3.6 m CFHT at K band (2.2 microns)



not to be confused with “donuts” (bad focus)

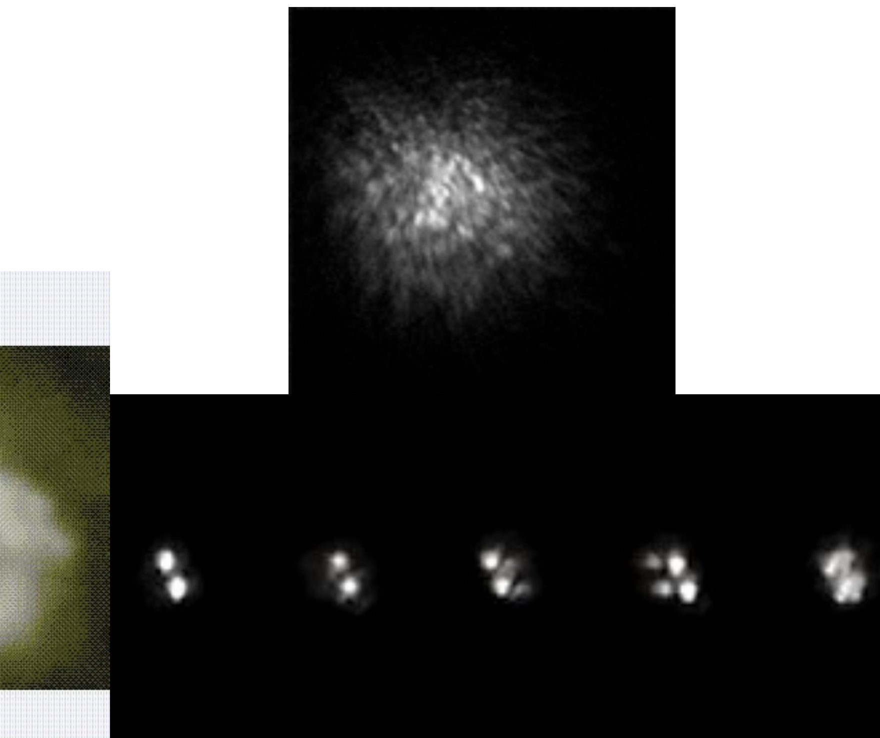


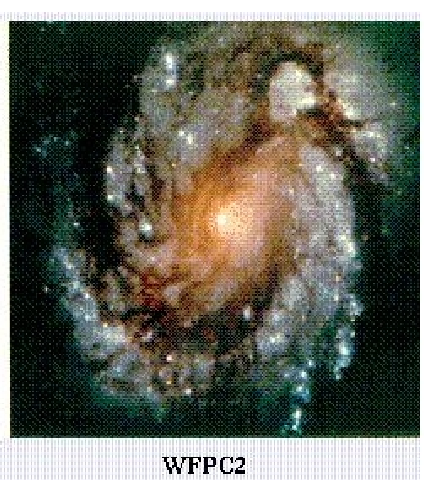


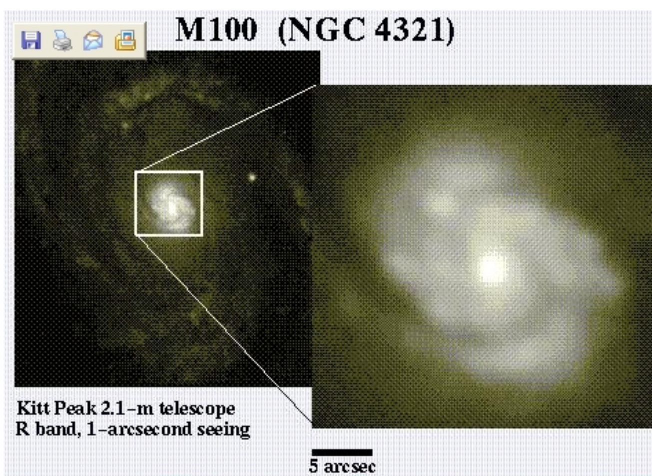


Atmospheric "Seeing"

http://www.astronomynotes/com/telescop/s11.htm

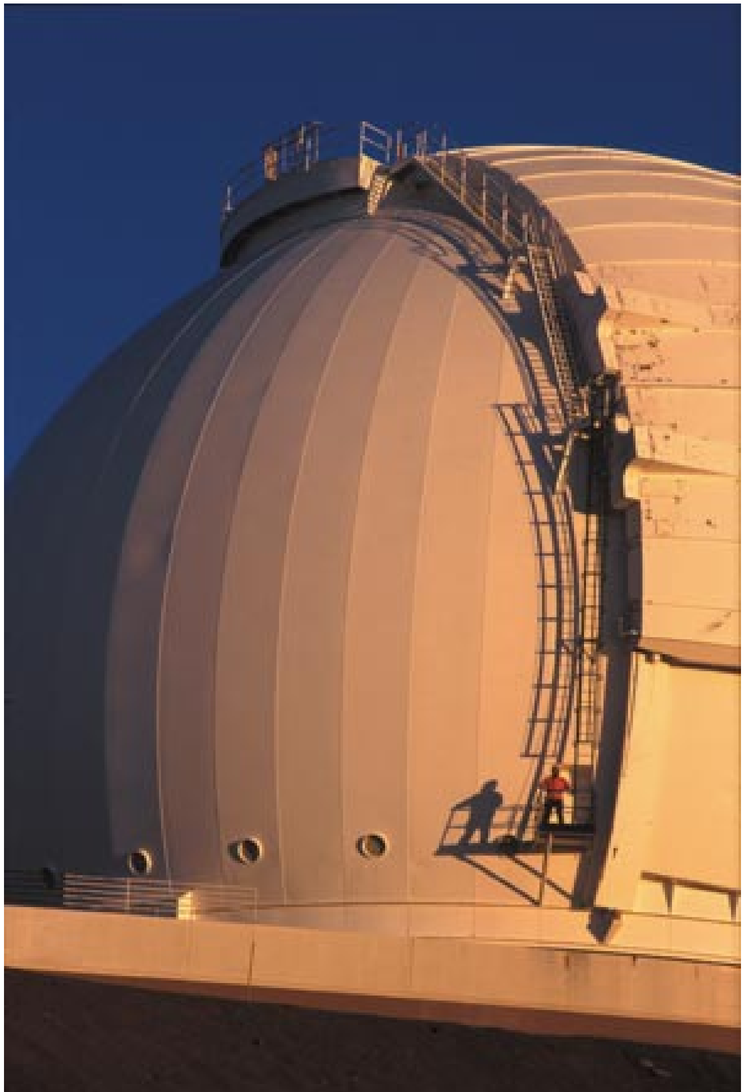




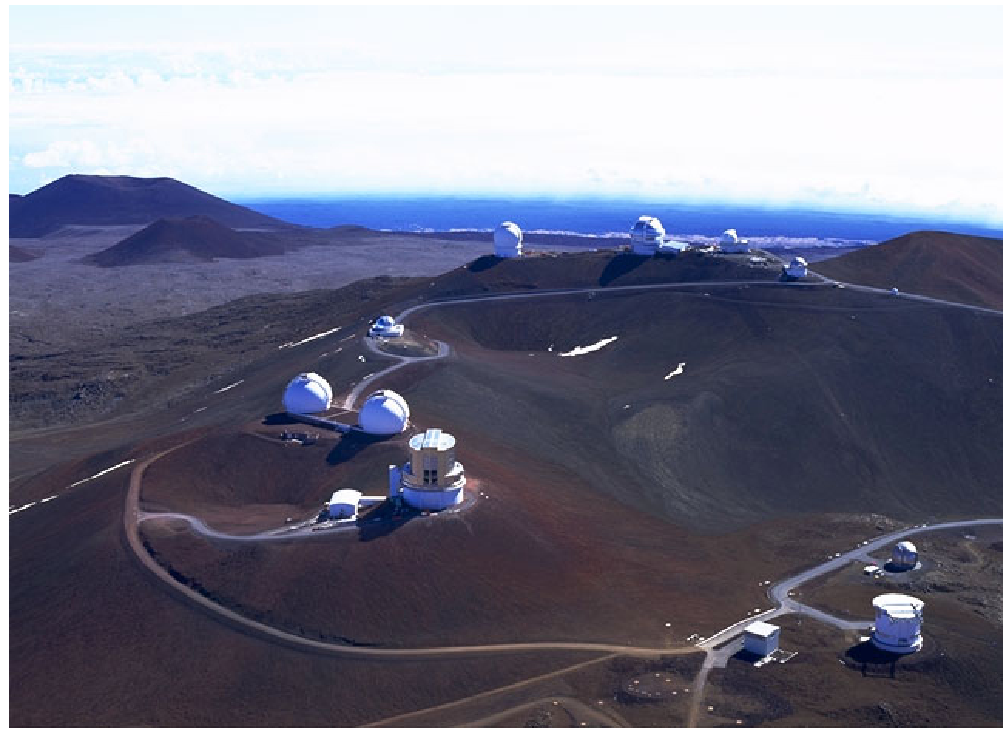


Segmented Mirrors

Keck Telescopes – 2 10 m Telescopes Observing at Visible, IR, & UV λ's



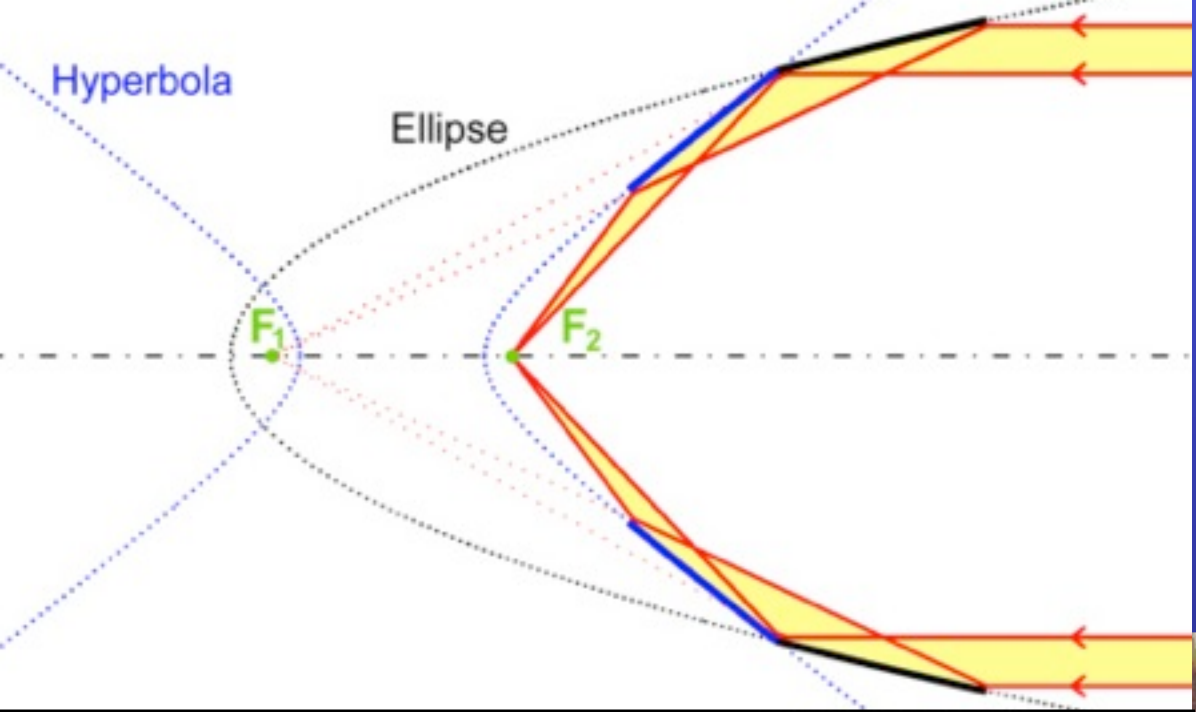
Operated by Caltech & UC

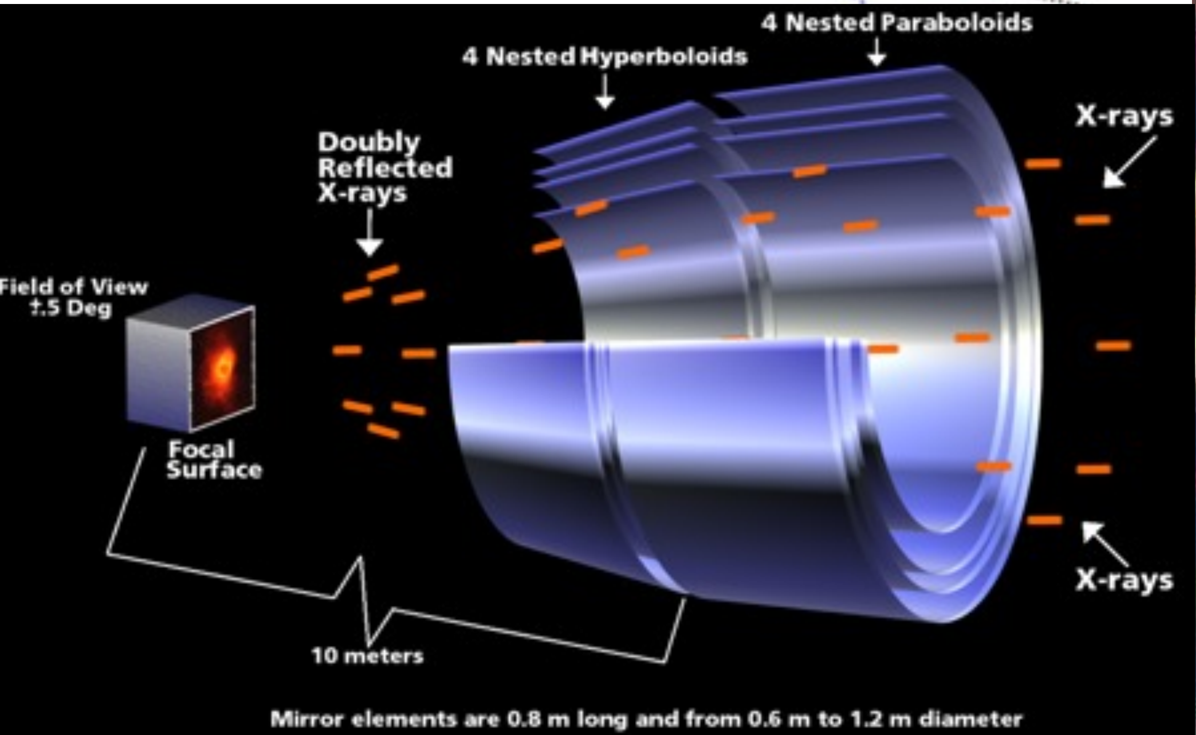


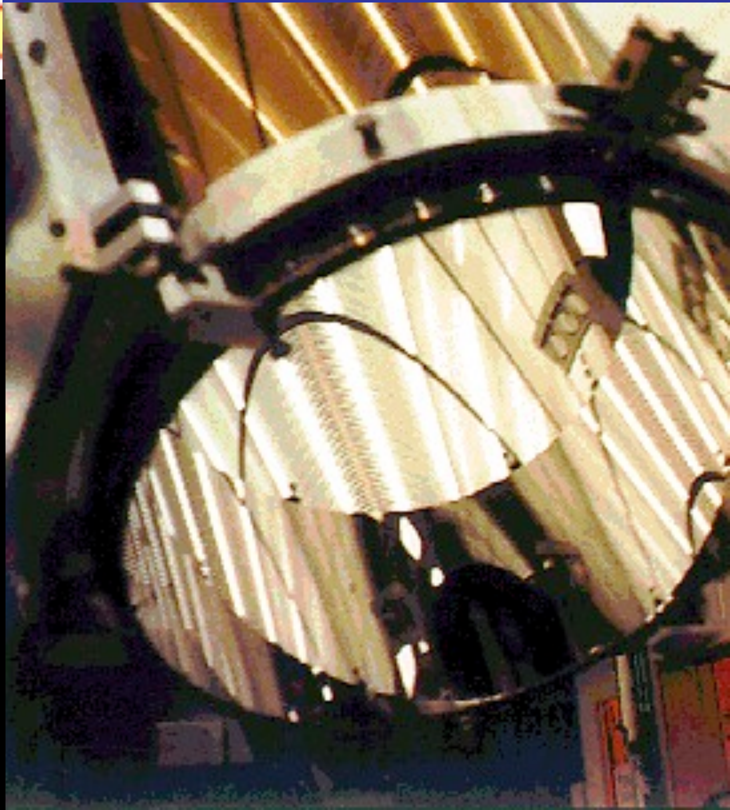
On top of Mauna Kea in Hawaii at 14,000 ft. (dormant volcano)

Wolter Type I X-ray optics

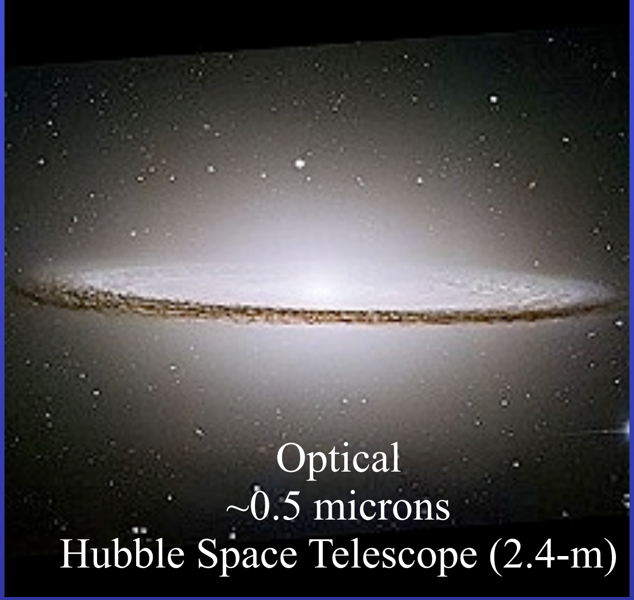
Chandra Observatory

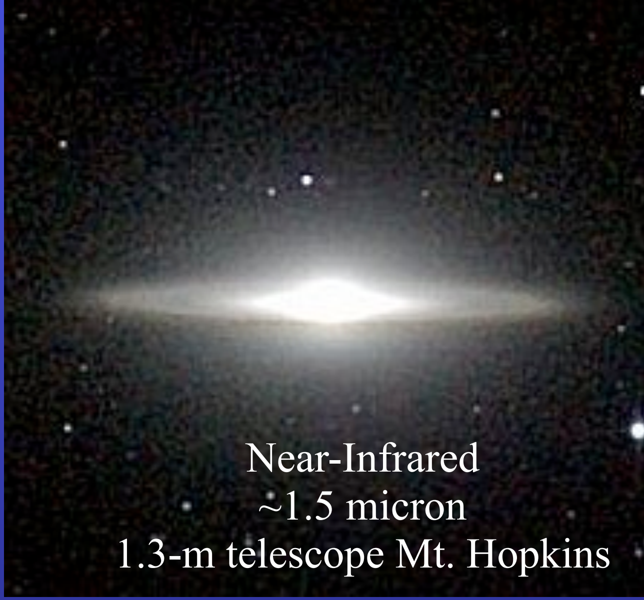


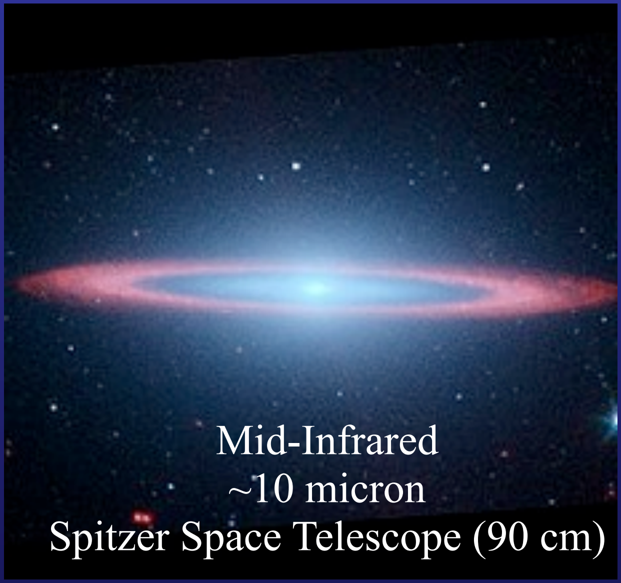


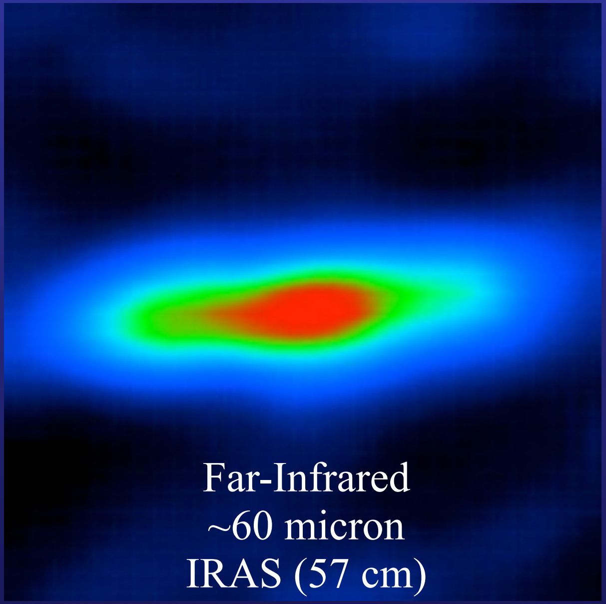


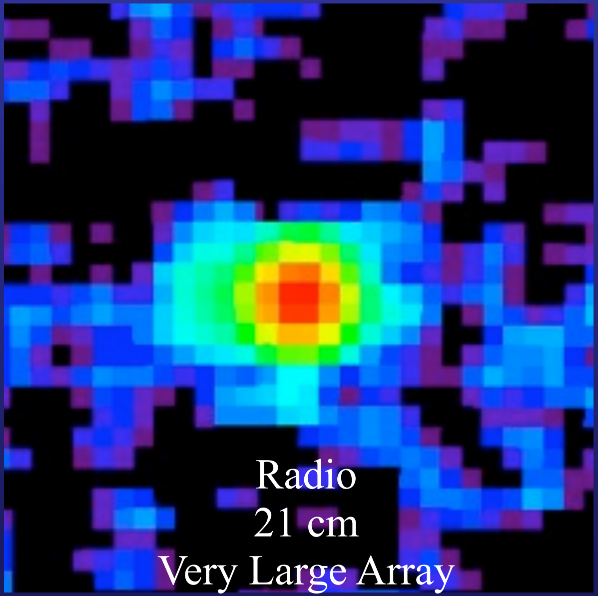

X-ray
~1 keV
Chandra Observatory (0.04 sq. m)


Optical
~0.5 microns
Hubble Space Telescope (2.4-m)

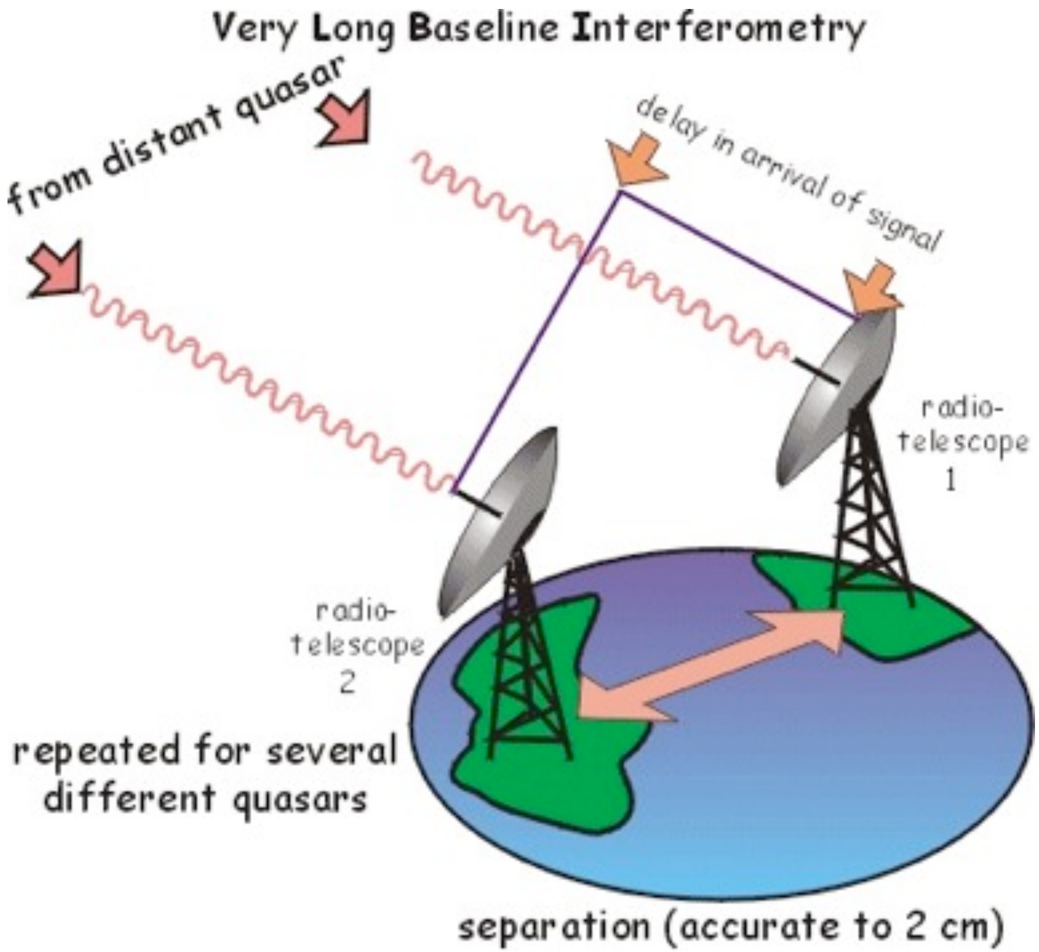

Near-Infrared
~1.5 micron
1.3-m telescope Mt. Hopkins


Mid-Infrared
~10 micron
Spitzer Space Telescope (90 cm)

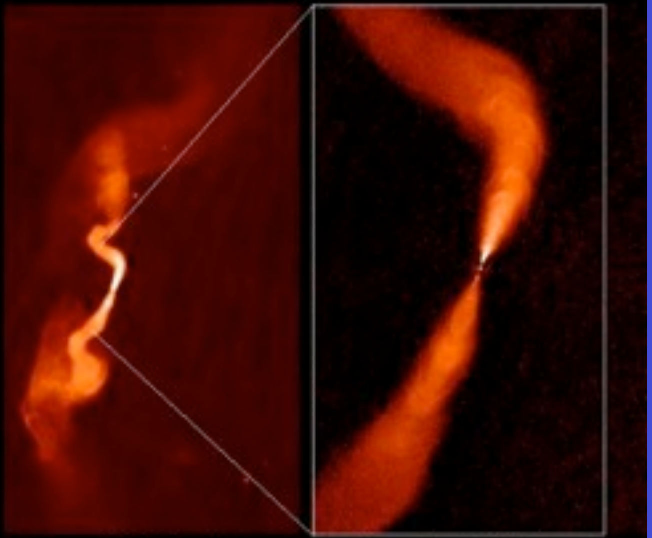

Far-Infrared
~60 micron
IRAS (57 cm)

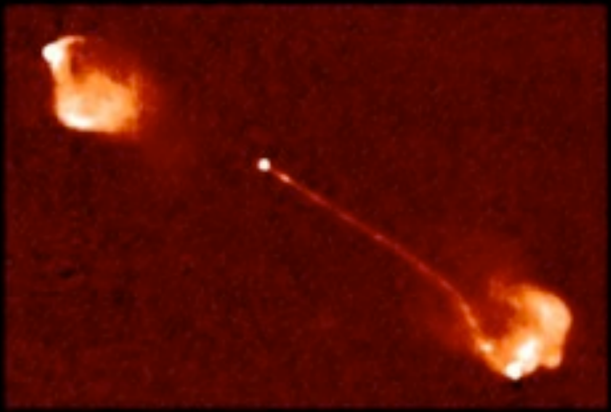

Radio
21 cm
Very Large Array

Very Large Array


Very Long Baseline Interferometry
from distant quasar
delay in arrival of signal
radio-
telescope
1
radio-
telescope
2
repeated for several
different quasars
separation (accurate to 2 cm)

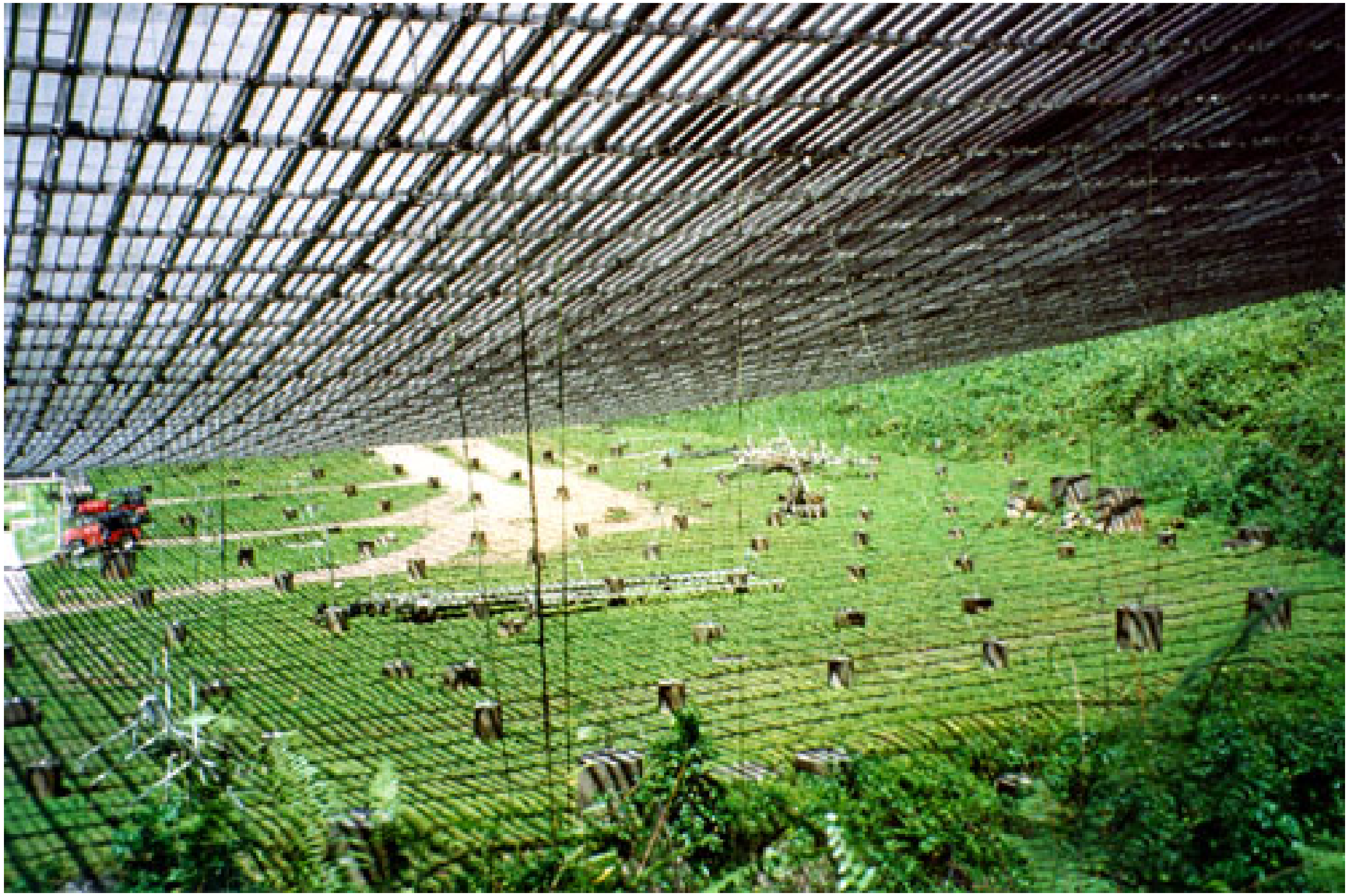
Radio jets from quasars
on kpc (VLA)
to pc (VLBI) scales


FR Class I source: radio galaxy 3C31

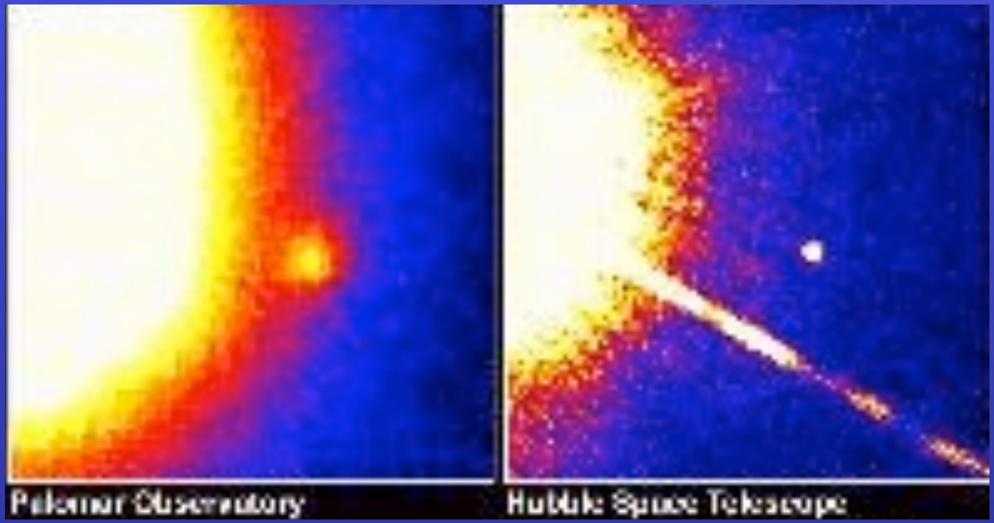

FR Class II source: quasar 3C175

Arecibo – 305 m diameter Radio Telescope in Puerto Rico

View from beneath Arecibo



Lots of visible light gets through but radio waves (λ > 3 cm) are efficiently reflected } **smooth enough for radio λ's, but not for visible λ's**



Brown dwarfs

Too big to be a planet

Too small to be a star

Binary separation ~ 40 AU

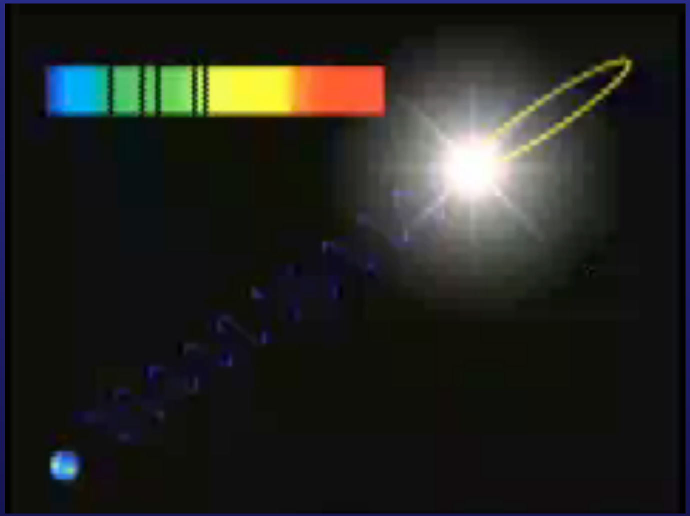
$M \sim 30\ M_J$

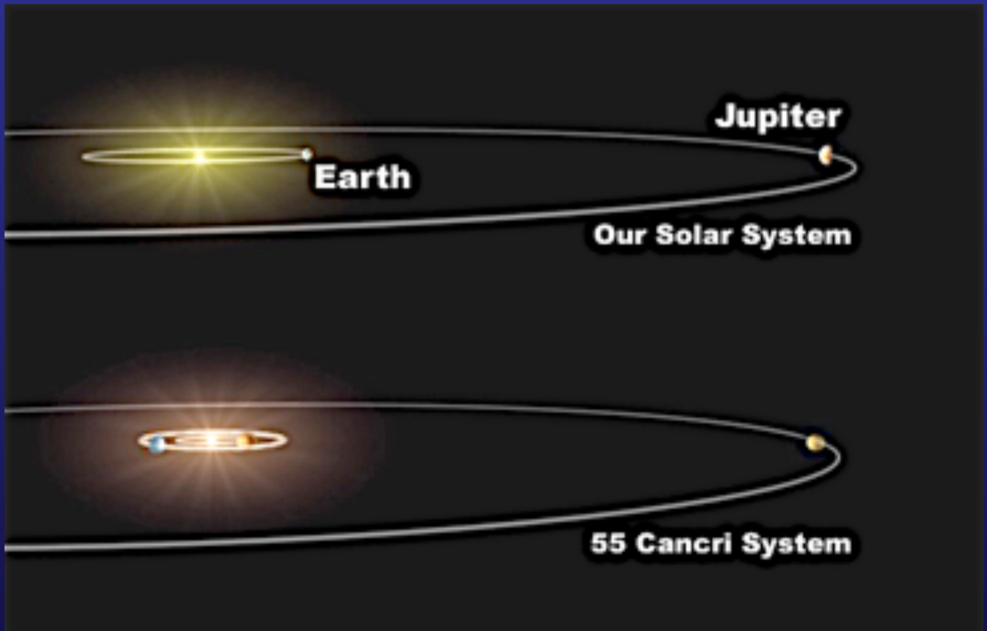
$L \sim 10^{-5}\ L_\odot$

Extrasolar planets

Super-Earths (10 $M_\oplus$)
to Super-Jupiters (10 M_J)

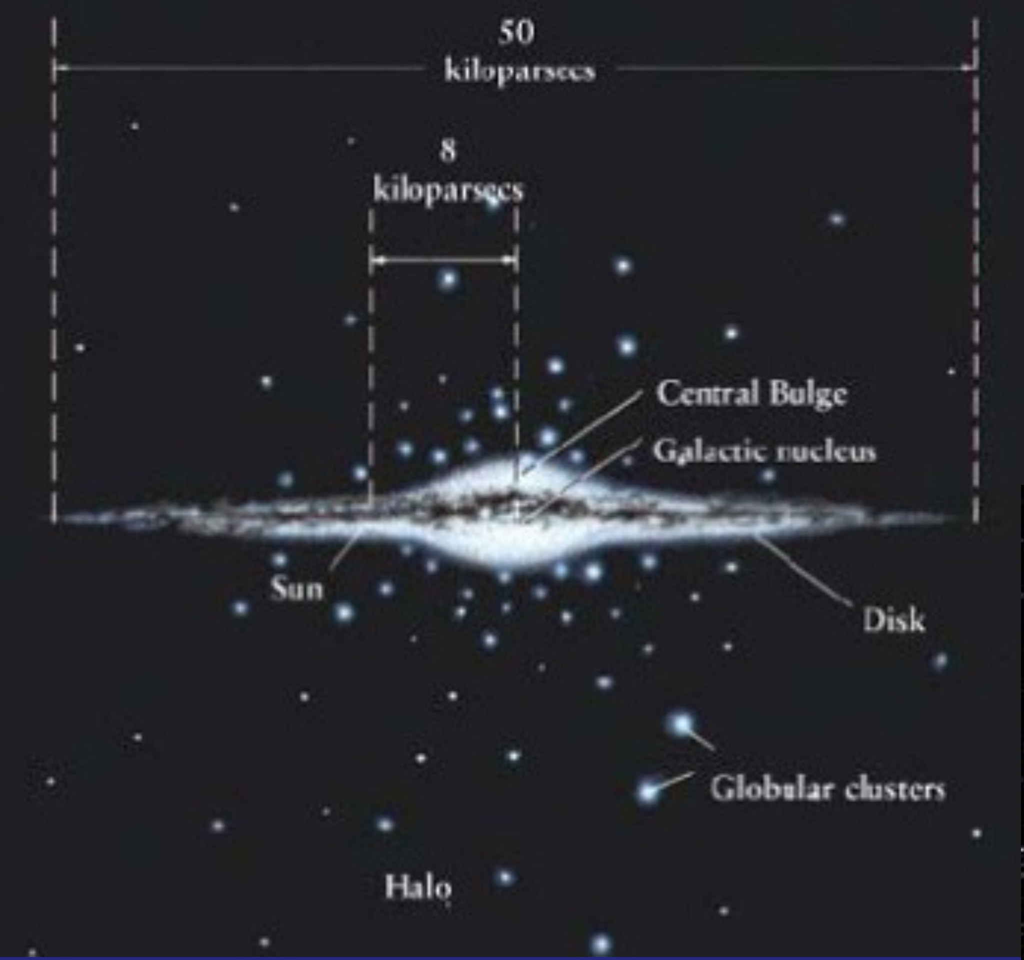
Mostly detected by stellar Doppler effect





Globular Clusters

10^4-10^6 $M_\odot$ in R ~ 1 pc



Globular clusters obey the virial theorem

THE MASSES OF NEBULAE 227

III. THE VIRIAL THEOREM APPLIED TO CLUSTERS OF NEBULAE

If the total masses of clusters of nebulae were known, the average masses of cluster nebulae could immediately be determined from counts of nebulae in these clusters, provided internebular material is of the same density inside and outside of clusters.

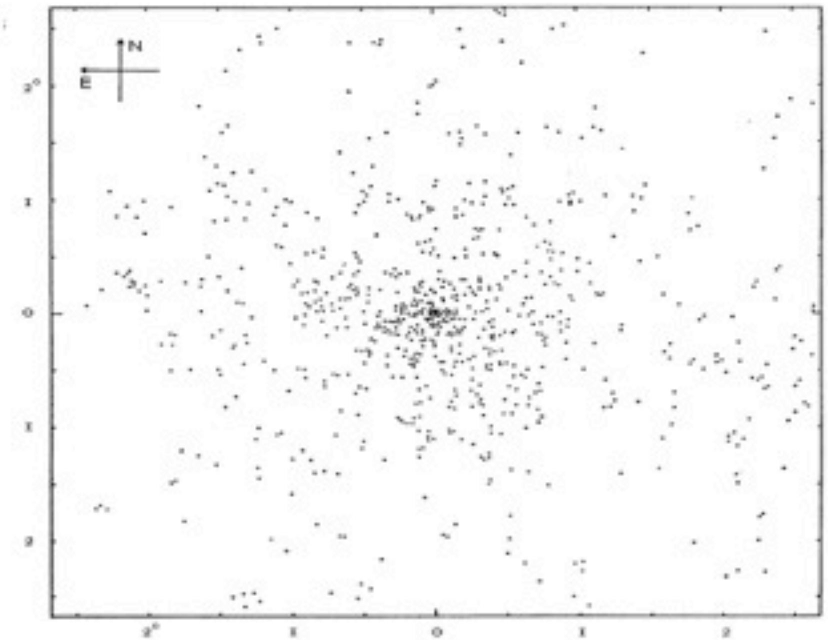


FIG. 3.—The Coma cluster of nebulae

$$-\overline{E_p} = 2\overline{K_T} = \overline{\sum_{\sigma} M_{\sigma} v_{\sigma}^2} = \sum_{\sigma} M_{\sigma} \overline{v_{\sigma}^2} ,$$

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_{\odot} . \qquad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

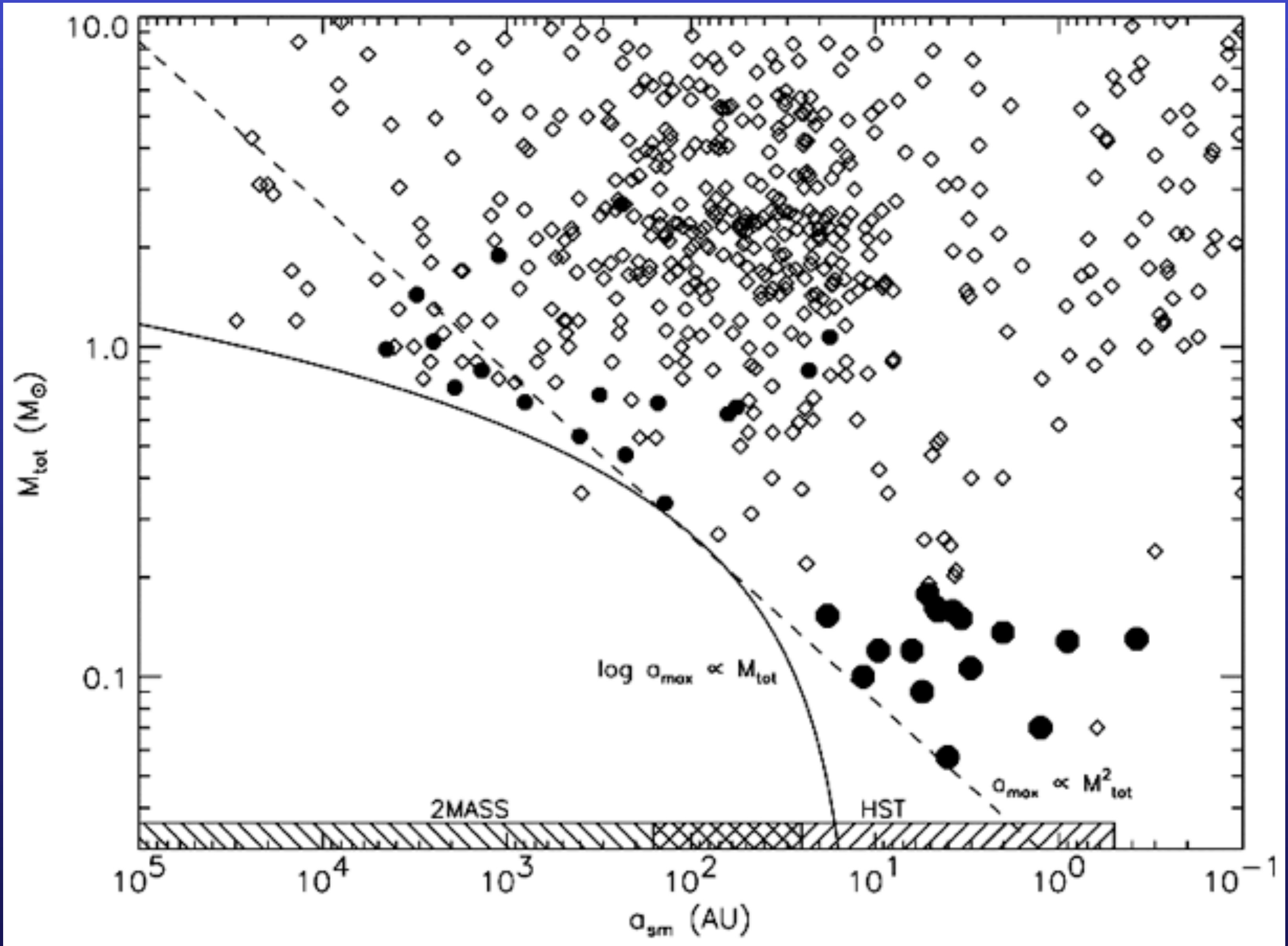
$$\gamma = 500 , \qquad (37)$$

In his preface to "The Catalogue of Galaxies and Subcompact Galaxies" (also known simply as "The Red Book"), Zwicky described his colleagues “scatterbrains,” “sycophants and plain thieves” who “have no love for any of the lone wolves who are not fawners and apple polishers,” who “doctor their observational data to hide their shortcomings and to make the majority of the astronomers accept and believe in some of their most prejudicial and erroneous presentations and interpretations of facts,” and who therefore publish “useless trash in the bulging astronomical journals.”[1]

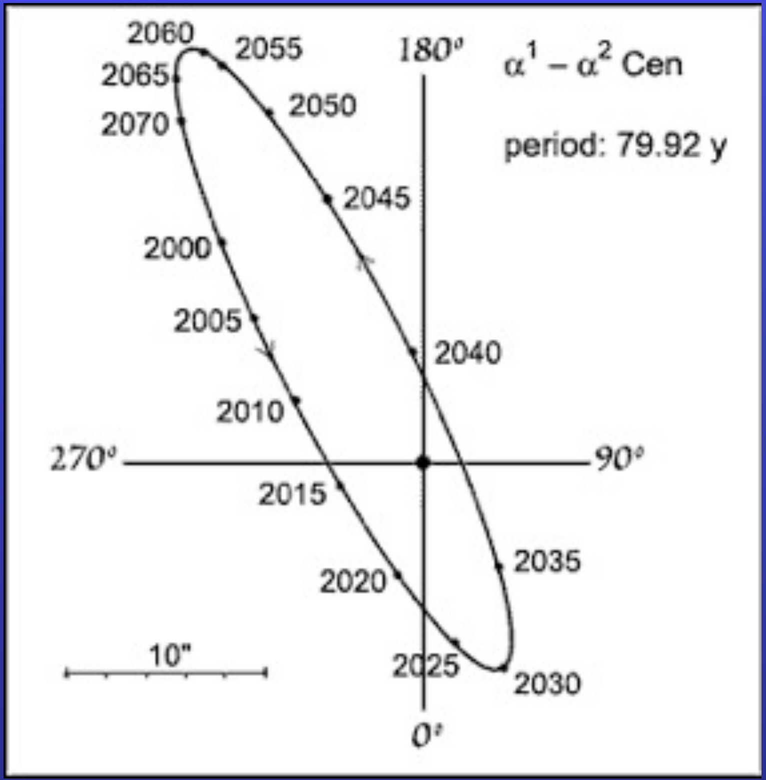
Fritz Zwicky

“Lone Wolf”

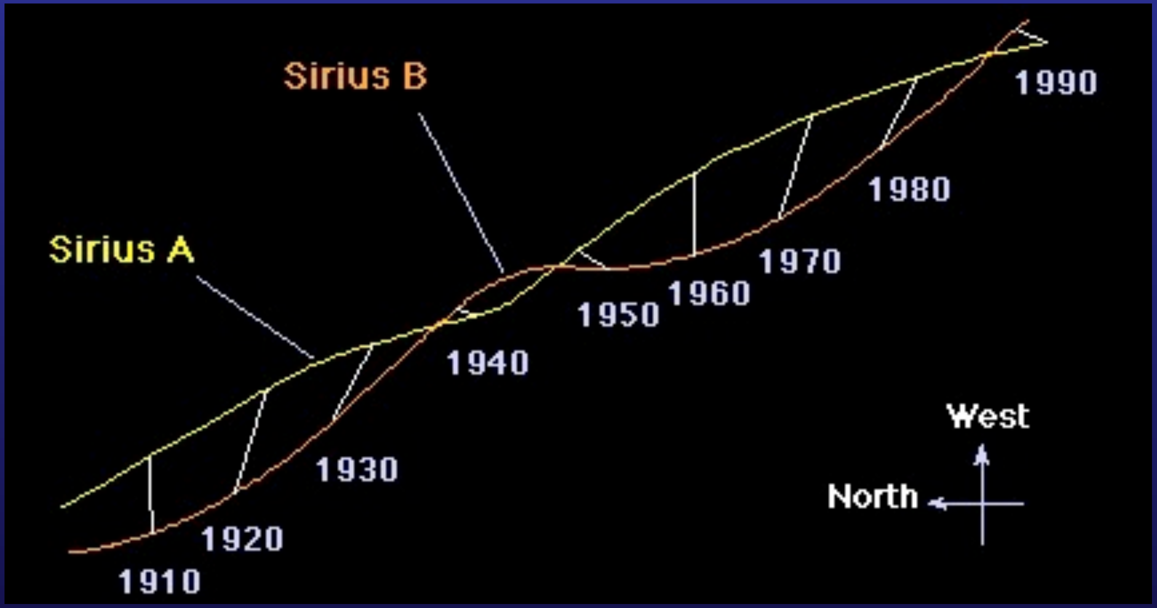
Sampling of Binaries

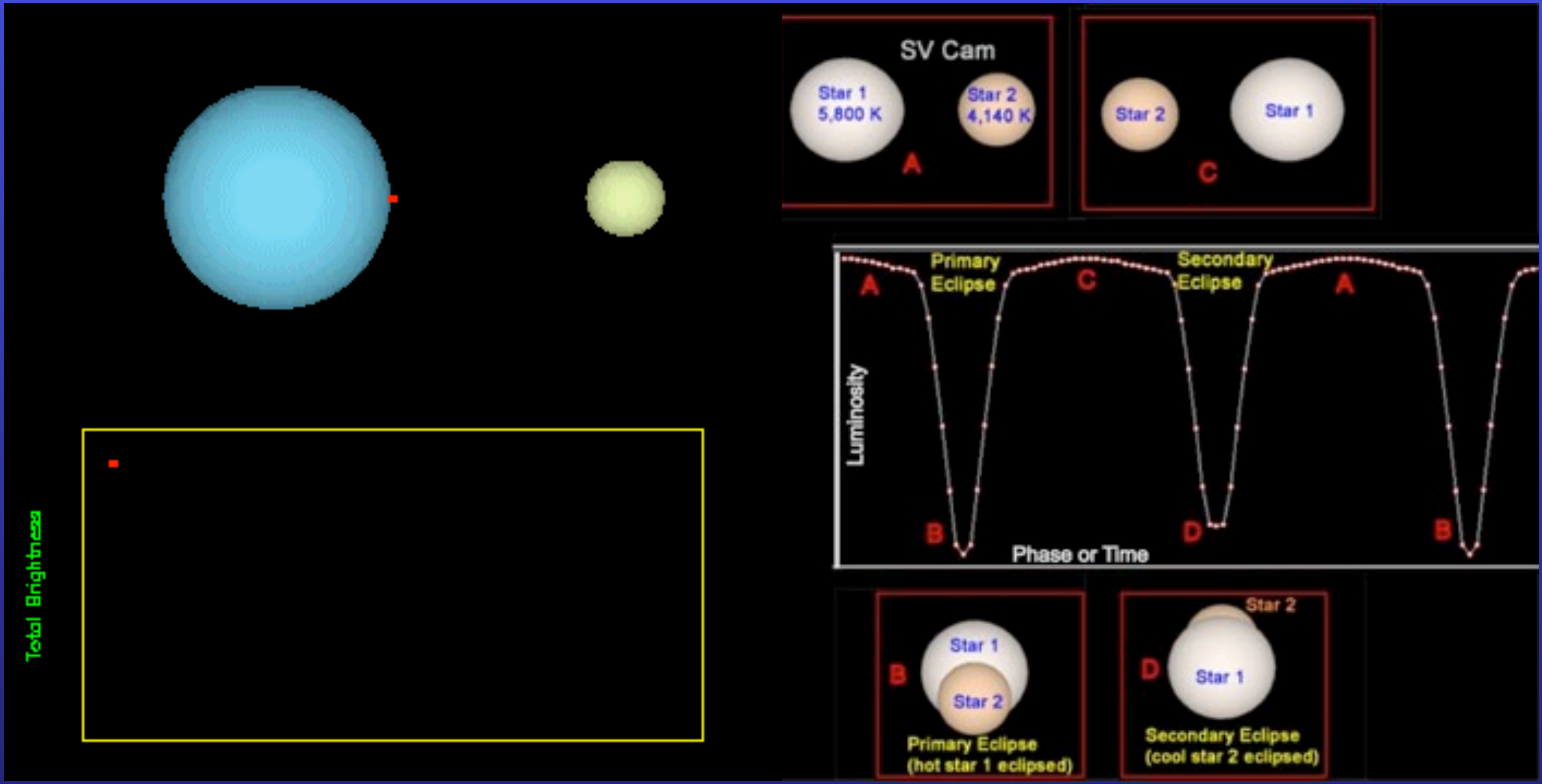


Visual Binary



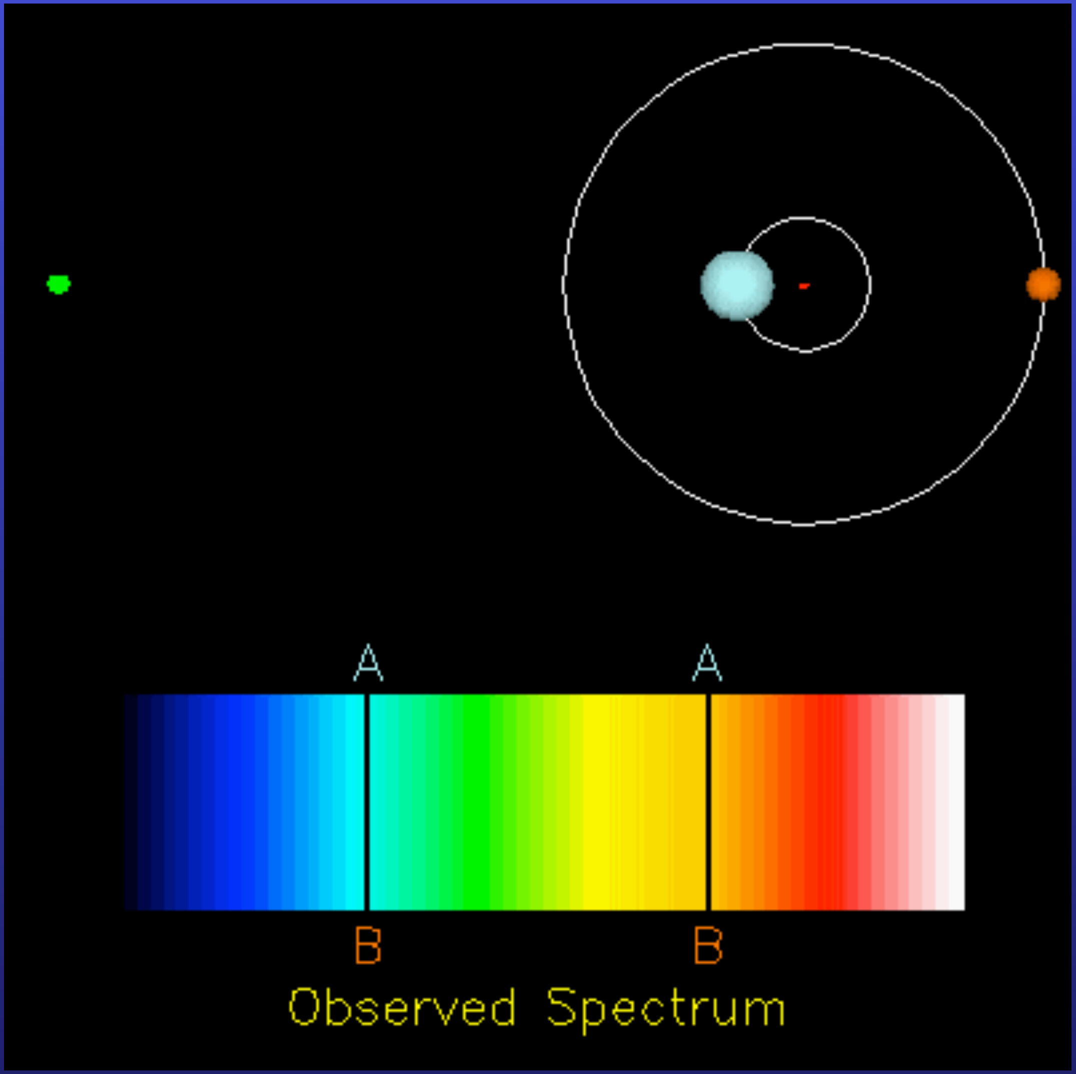
Astrometric Binary





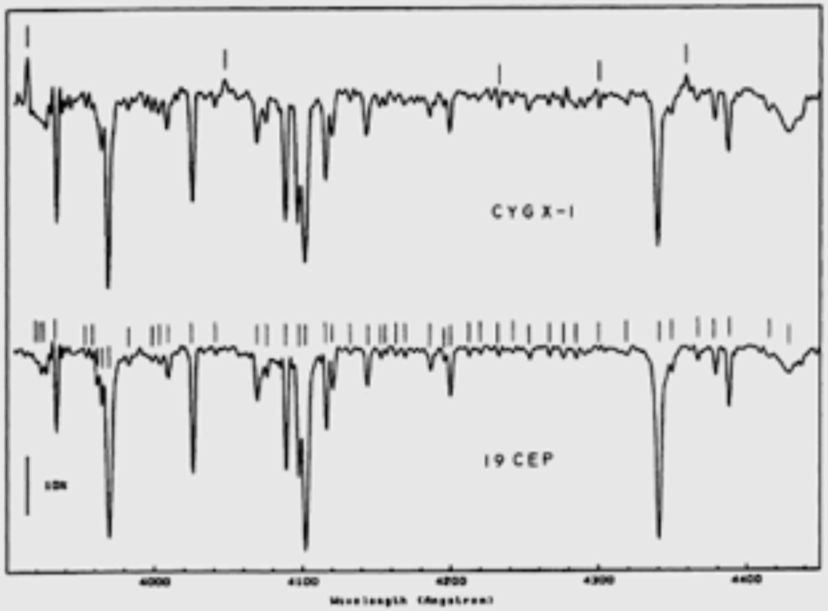
Eclipsing Binaries

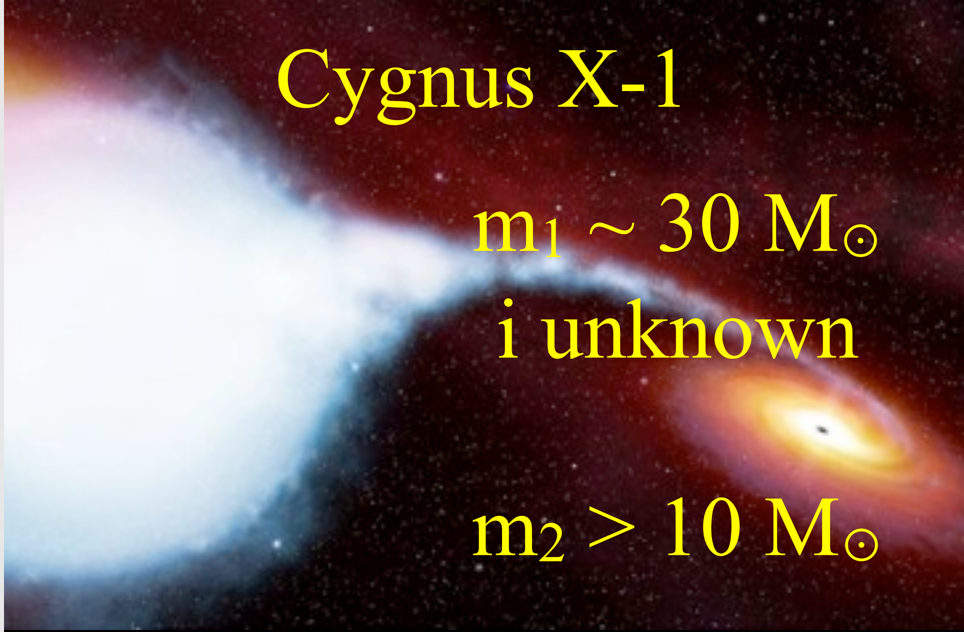
Animation by R. Pogge, Ohio State



Spectroscopic Binary Simulator

Animation by R. Pogge, Ohio State





PRIMARY ORBIT AND ABSORPTION LINES OF CYG X-1 431

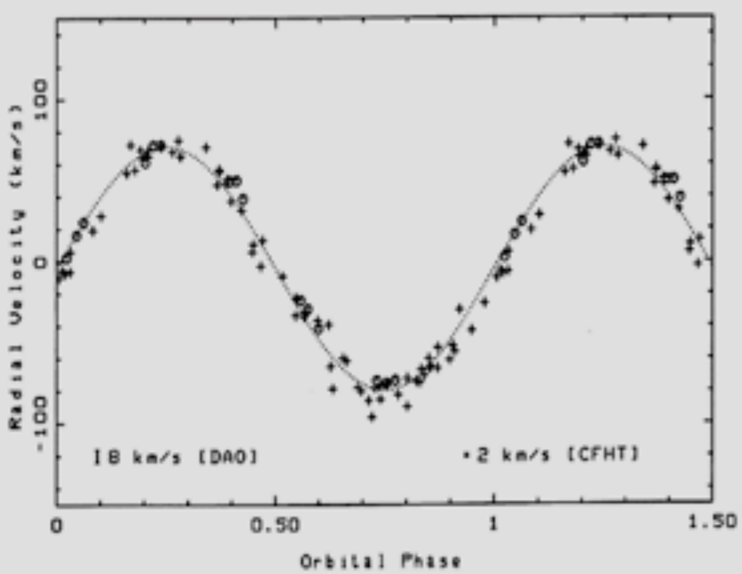
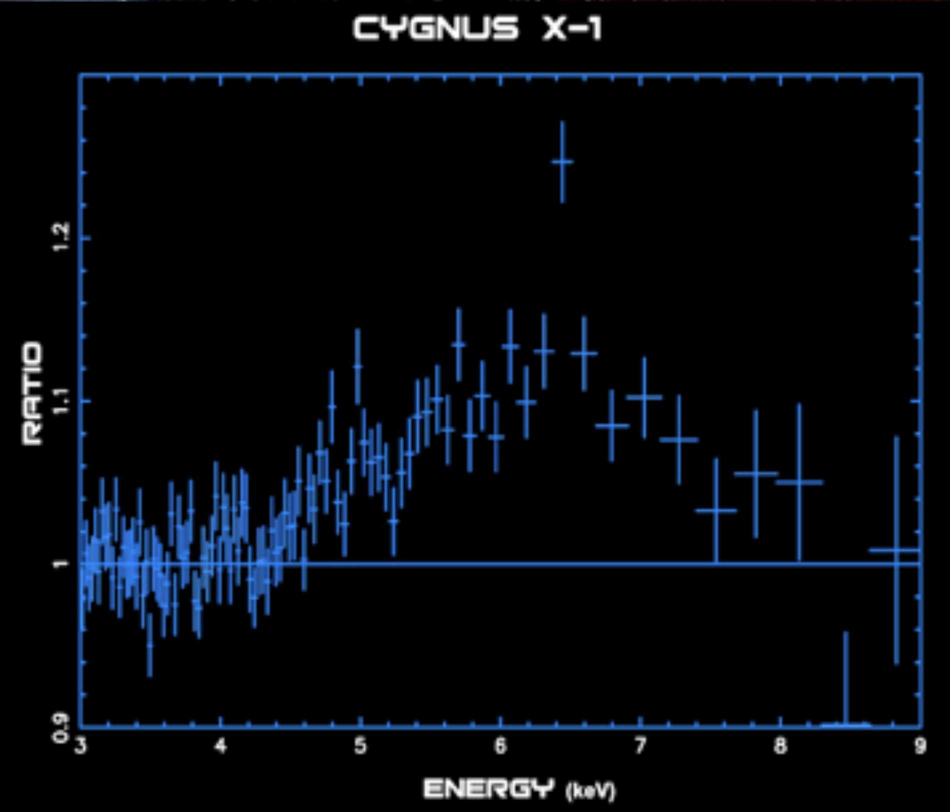
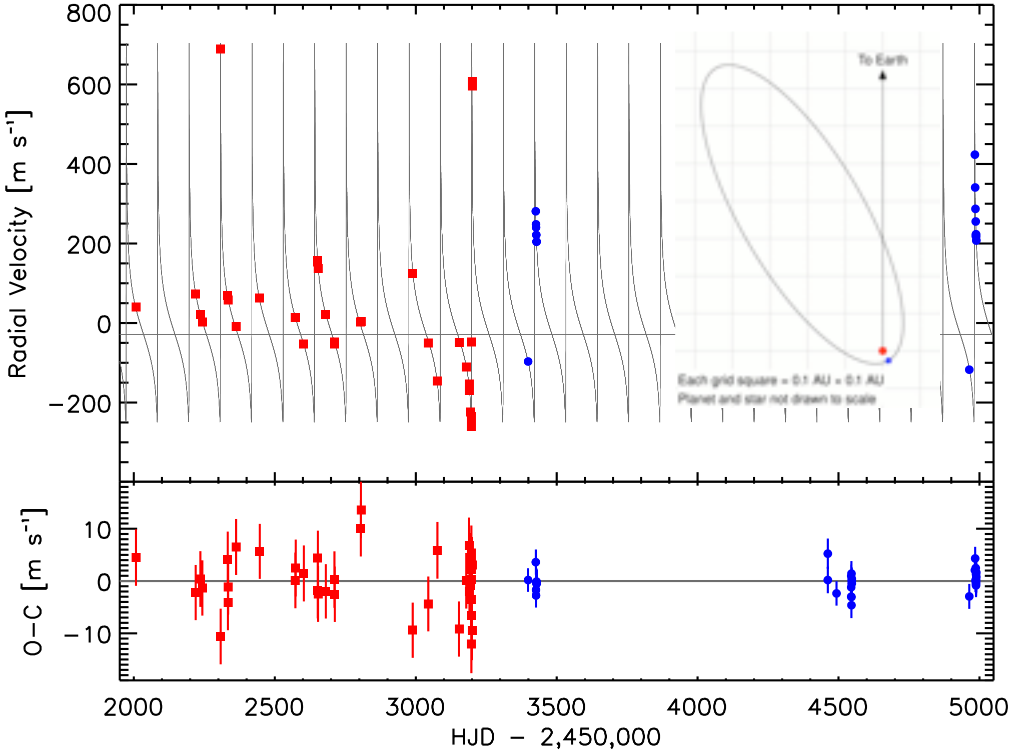
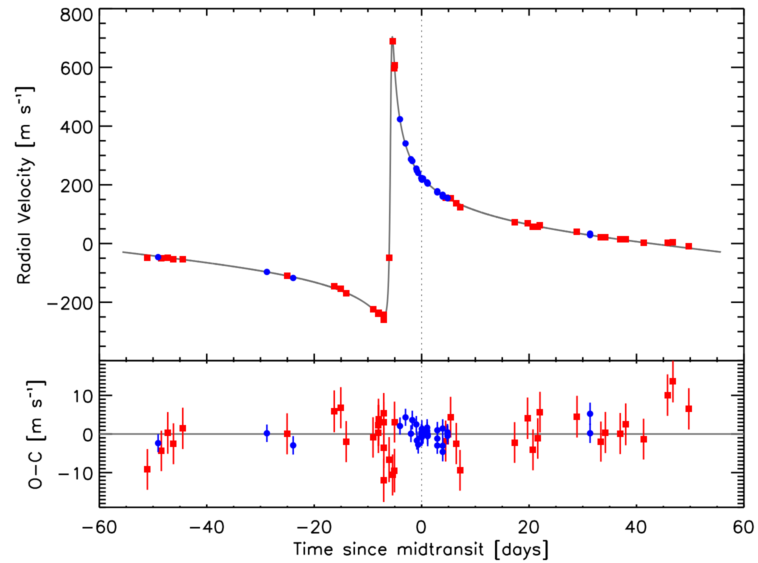


FIG. 2.—Mean He I line radial velocity curve for HDE 226868. Crosses denote data from DAO, circles indicate CFHT data, dotted curve is best orbital solution to the data as given in Table 3. The 2 σ error bars are indicated.



"Sound and fury drowns my heart / Every nerve is torn apart."

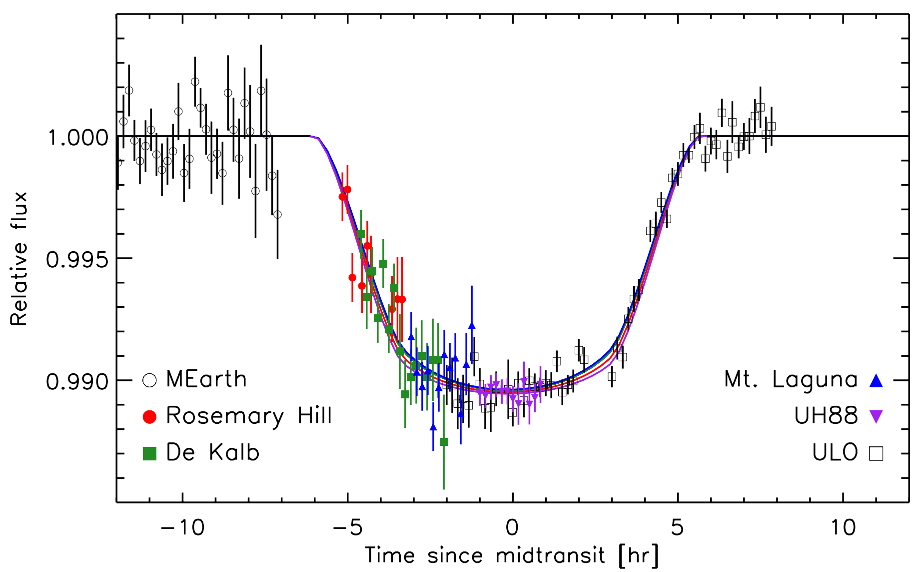


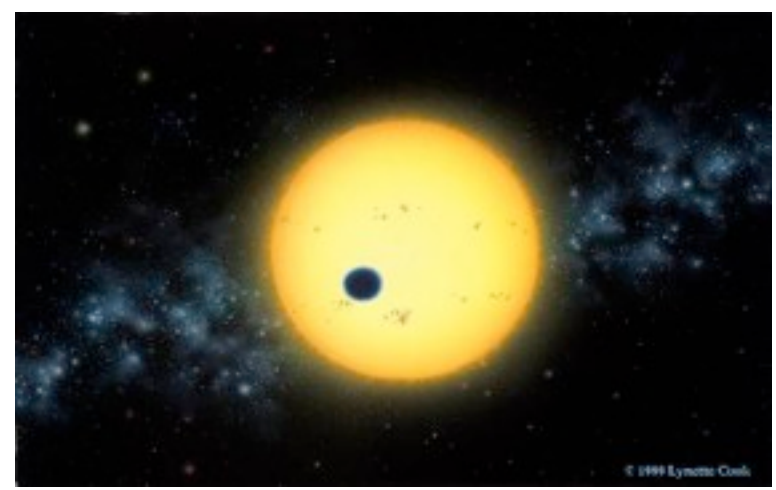


HD 80606, $m_1 = 0.9\ M_\odot$

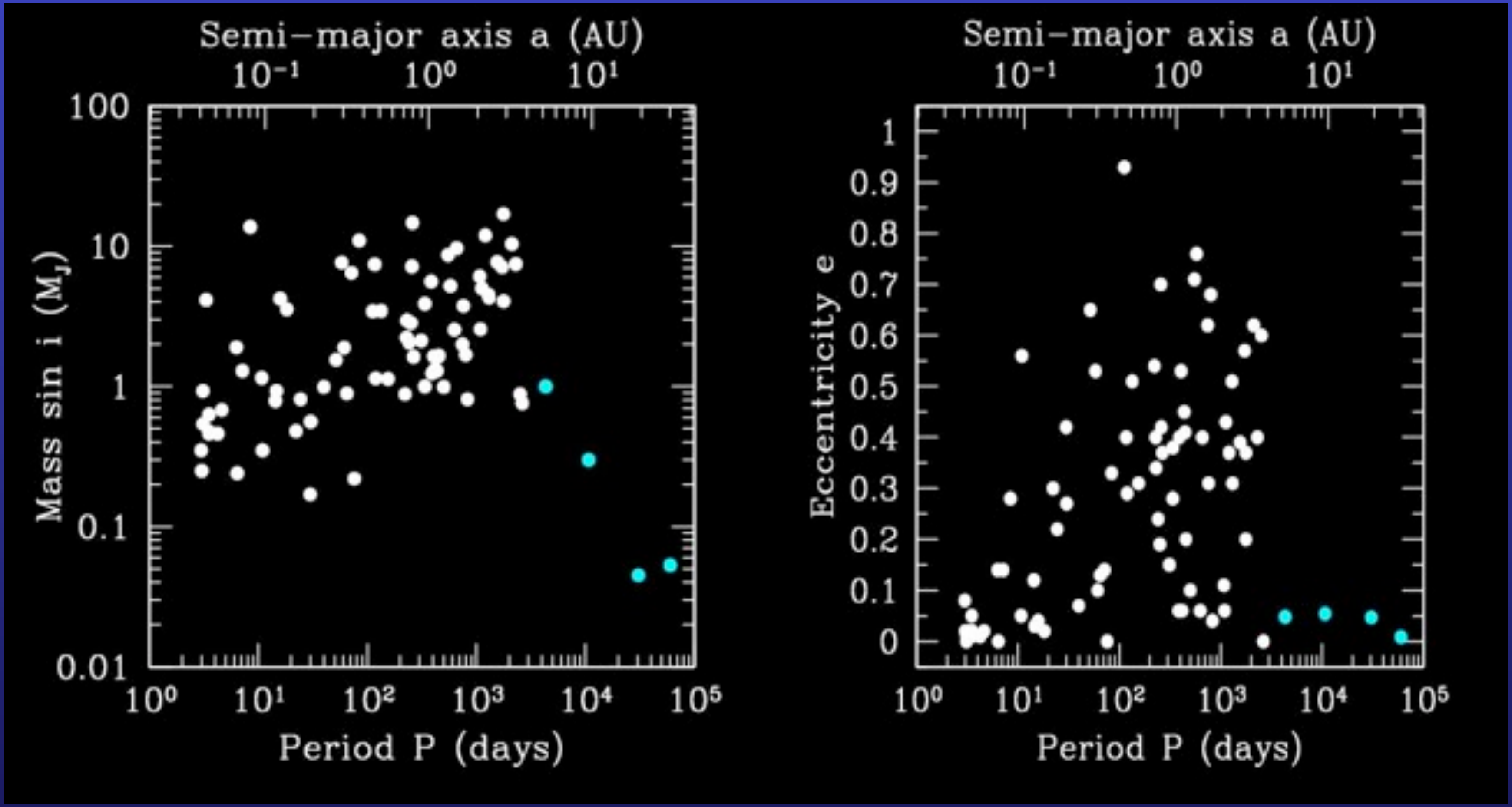
$e = 0.934$

$m_2 \sin i = 4\ M_J = m_2$!

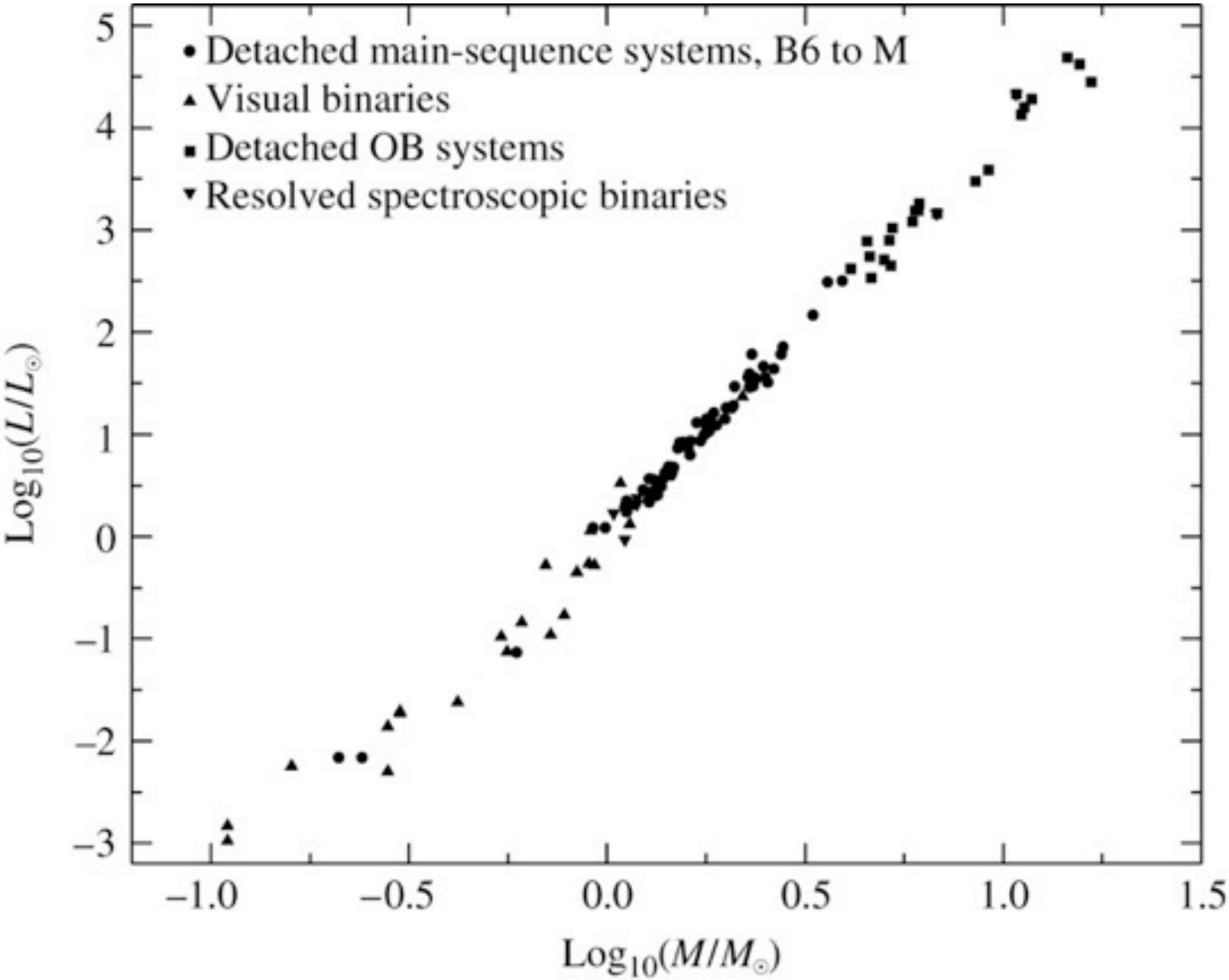




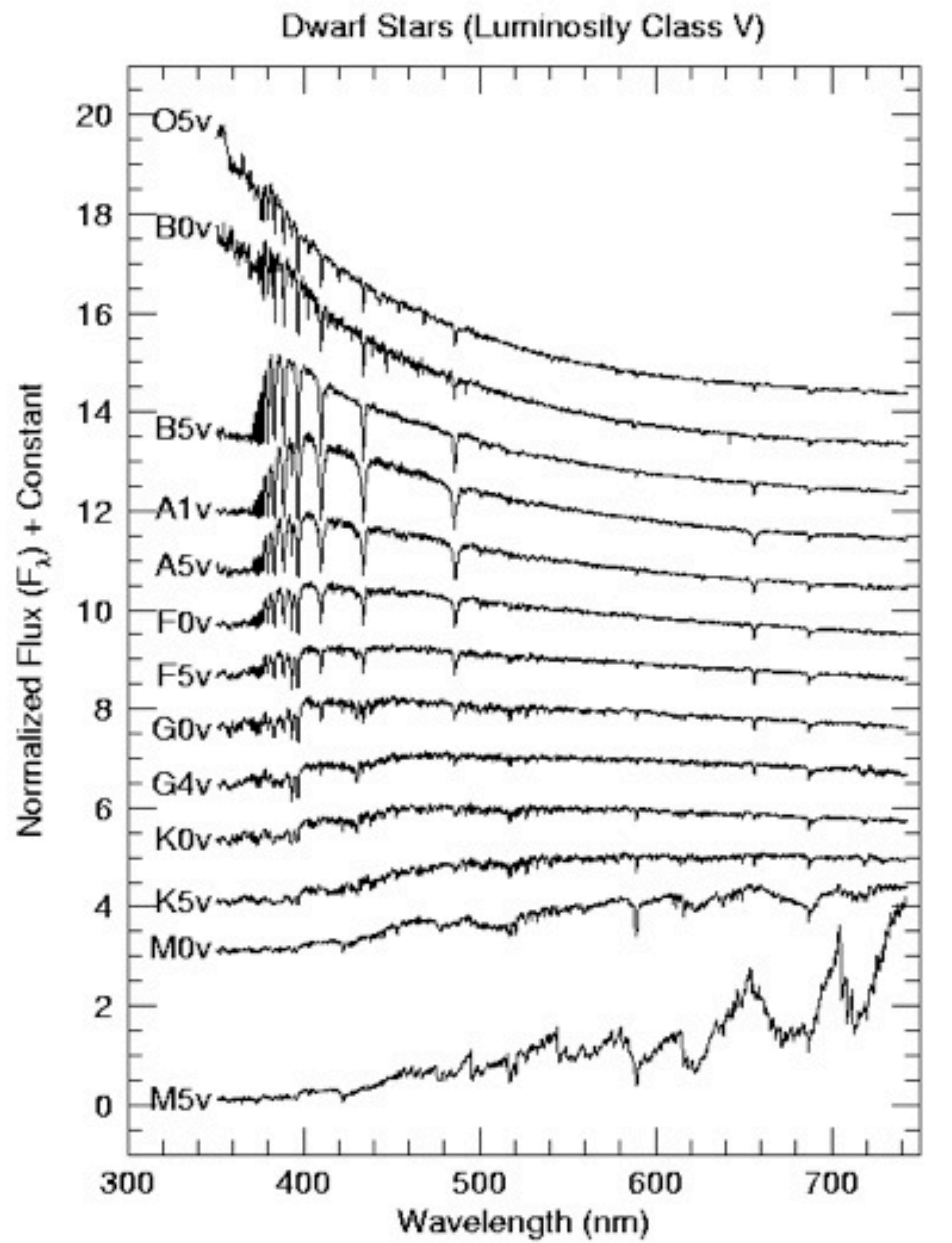
Planetary Systems in Solar Neighborhood



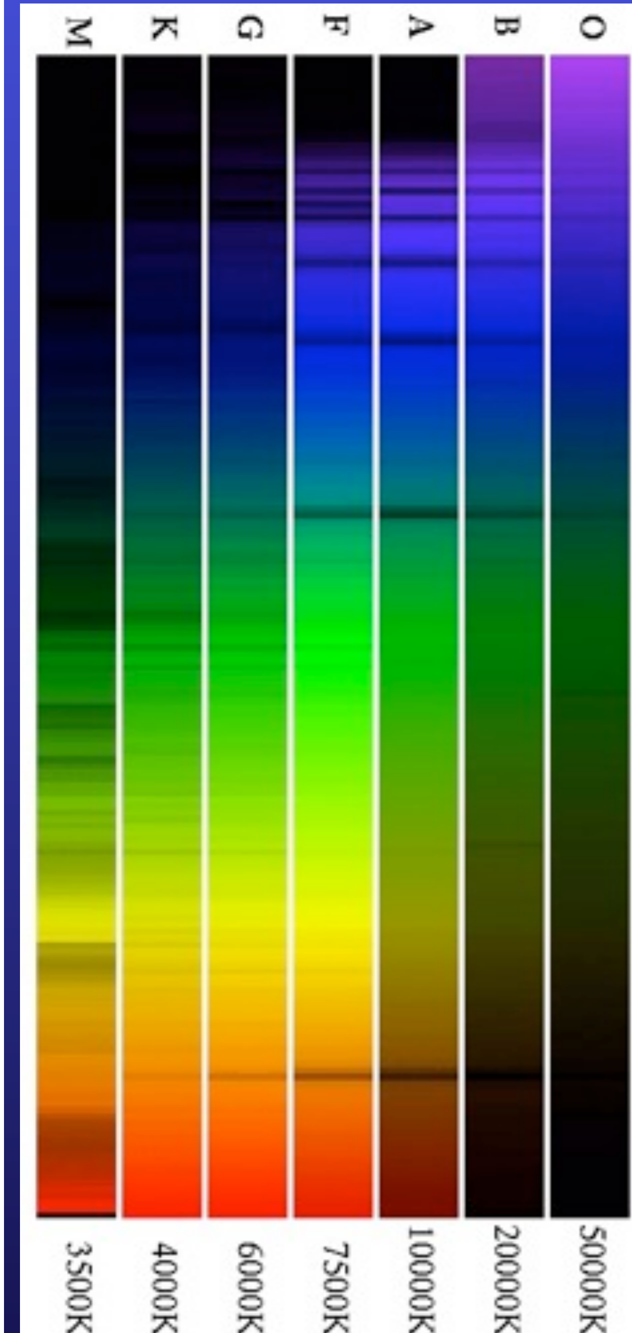
http://exoplanets.org



• Detached main-sequence systems, B6 to M
▲ Visual binaries
■ Detached OB systems
▼ Resolved spectroscopic binaries
$\text{Log}_{10}(L/L_\odot)$
$\text{Log}_{10}(M/M_\odot)$
5
4
3
2
1
0
−1
−2
−3
−1.0
−0.5
0.0
0.5
1.0
1.5



Dwarf Stars (Luminosity Class V)
Normalized Flux (F_λ) + Constant
Wavelength (nm)
O5v
B0v
B5v
A1v
A5v
F0v
F5v
G0v
G4v
K0v
K5v
M0v
M5v
0
2
4
6
8
10
12
14
16
18
20
300
400
500
600
700



M
K
G
F
A
B
O
3500K
4000K
6000K
7500K
10000K
20000K
50000K

Spectral Classes

Spectral Class	Approximate Temperature (K)	Hydrogen Balmer Lines	Other Spectral Features
O	40,000	Weak	Ionized helium
B	20,000	Medium	Neutral helium
A	10,000	Strong	Ionized calcium weak
F	7,500	Medium	Ionized calcium weak
G	5,500	Weak	Ionized calcium medium
K	4,500	Very weak	Ionized calcium strong
M	3,000	Very weak	Titanium oxide strong

Strength Of Line

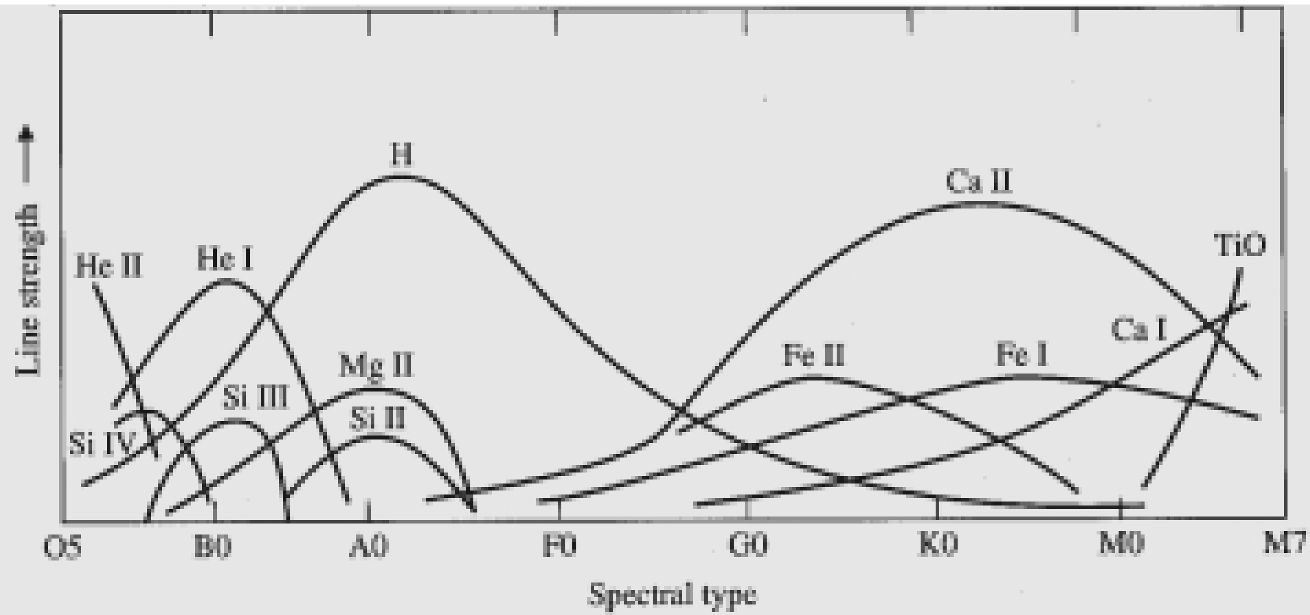
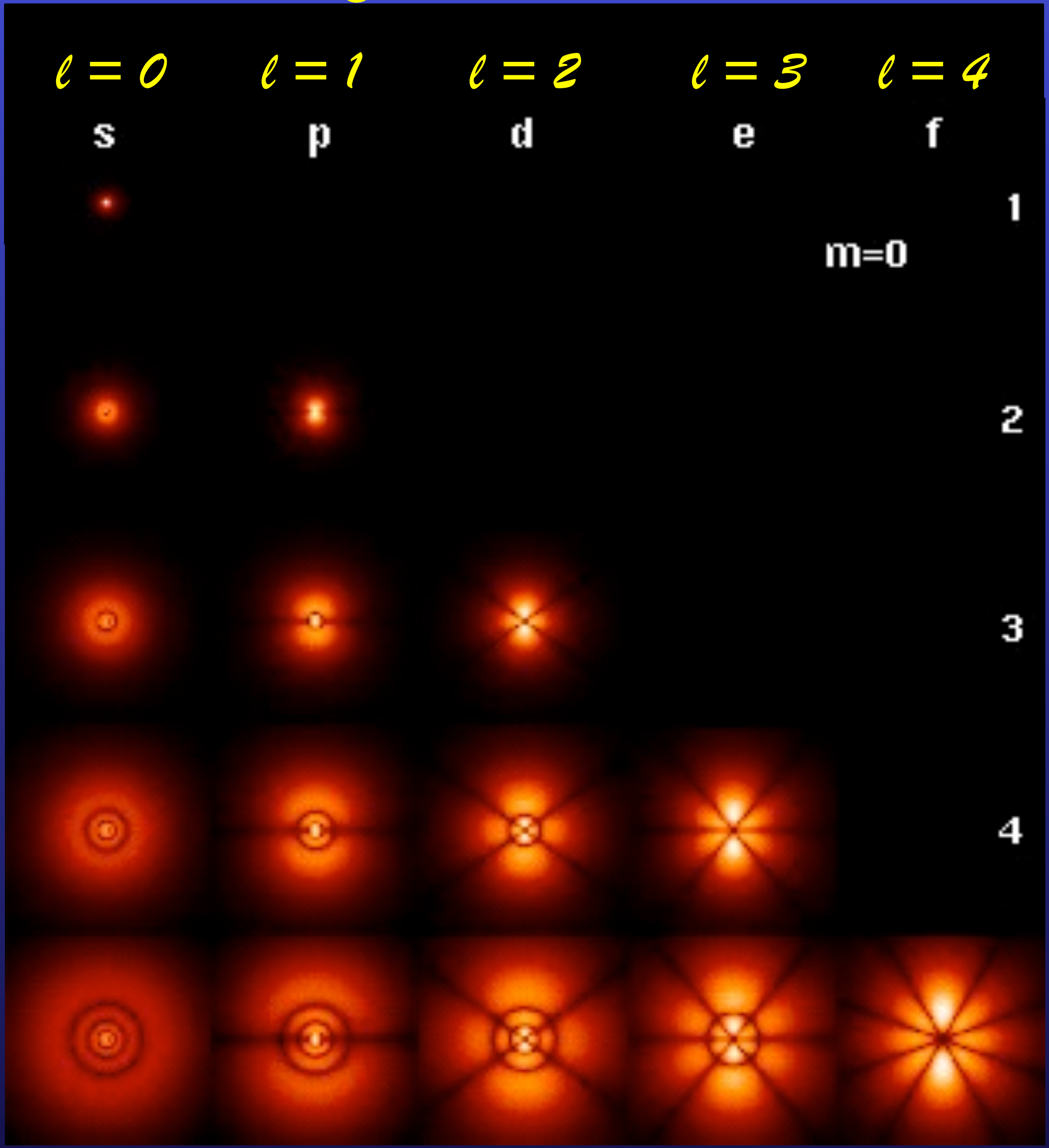


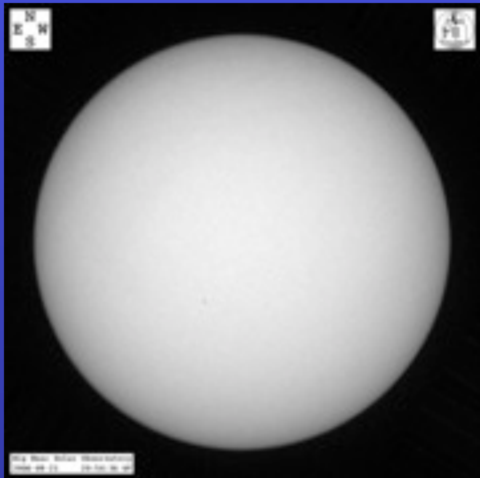
Figure 8.9 The dependence of spectral line strengths on temperature.

Angular momentum ℓ

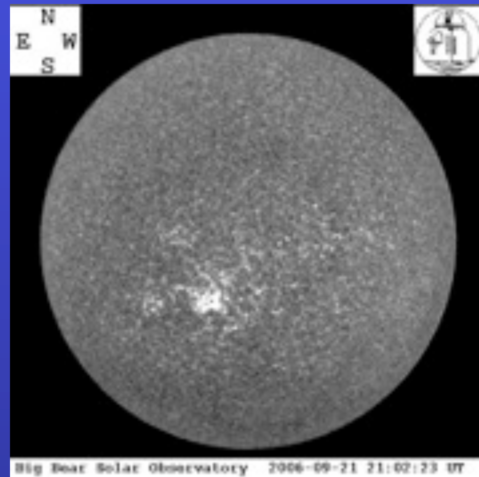


Electron Wavefunctions

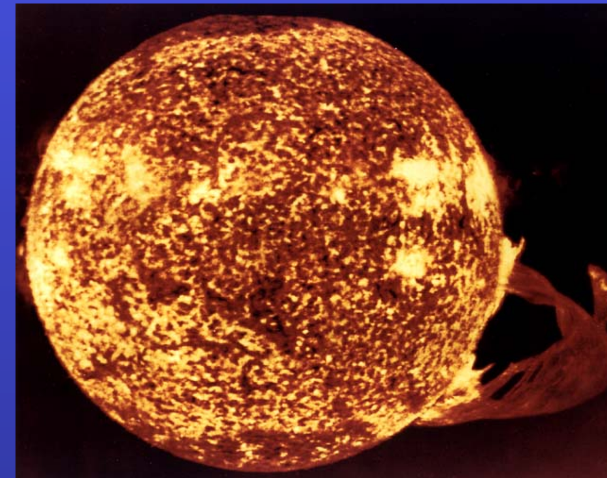
Principal quantum number n



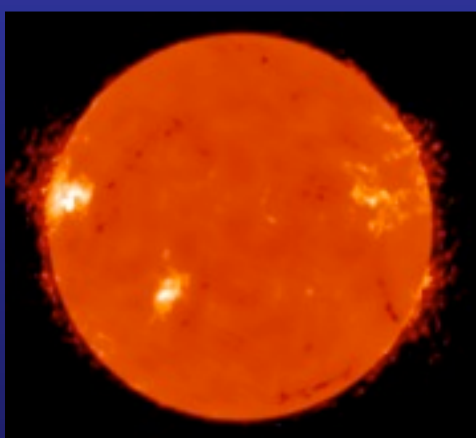
White light
(continuum)



Ca II K-line

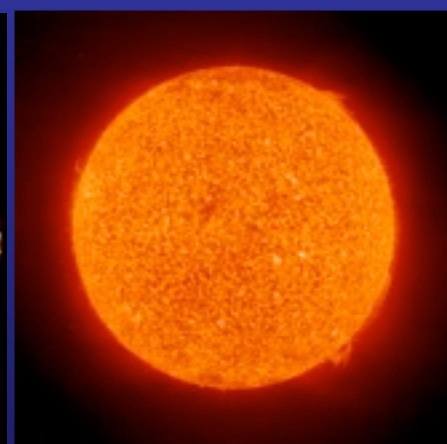


H-alpha line

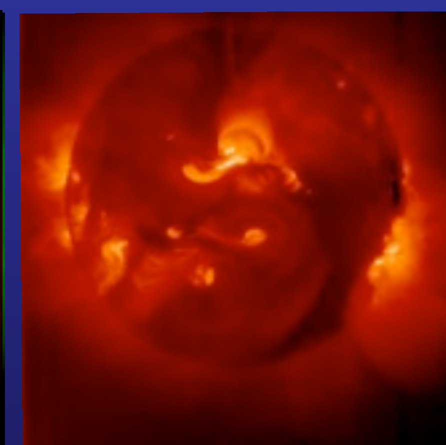


1.7 cm
(continuum)

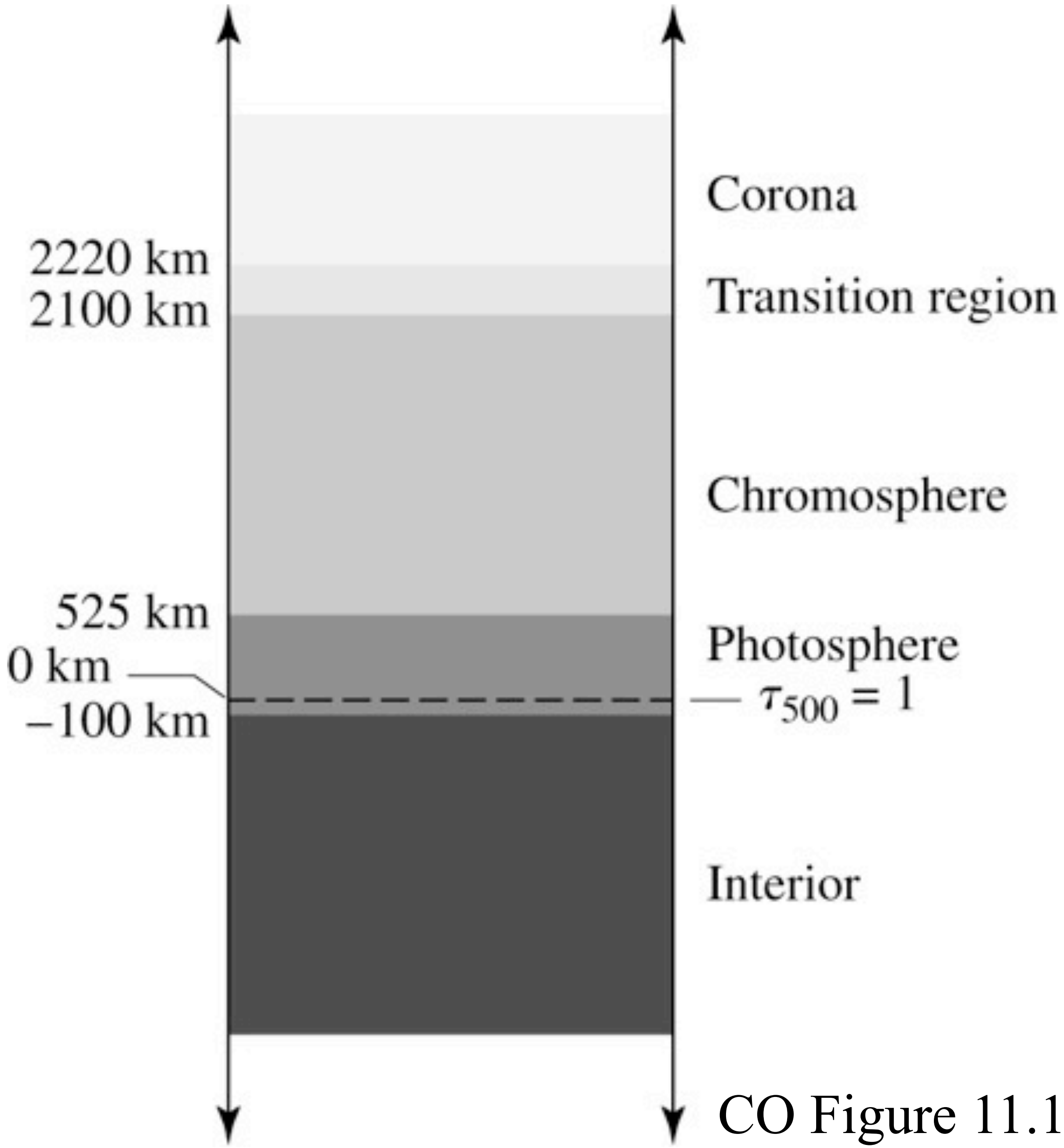
10830 Å
infrared filter



300 Å
UV

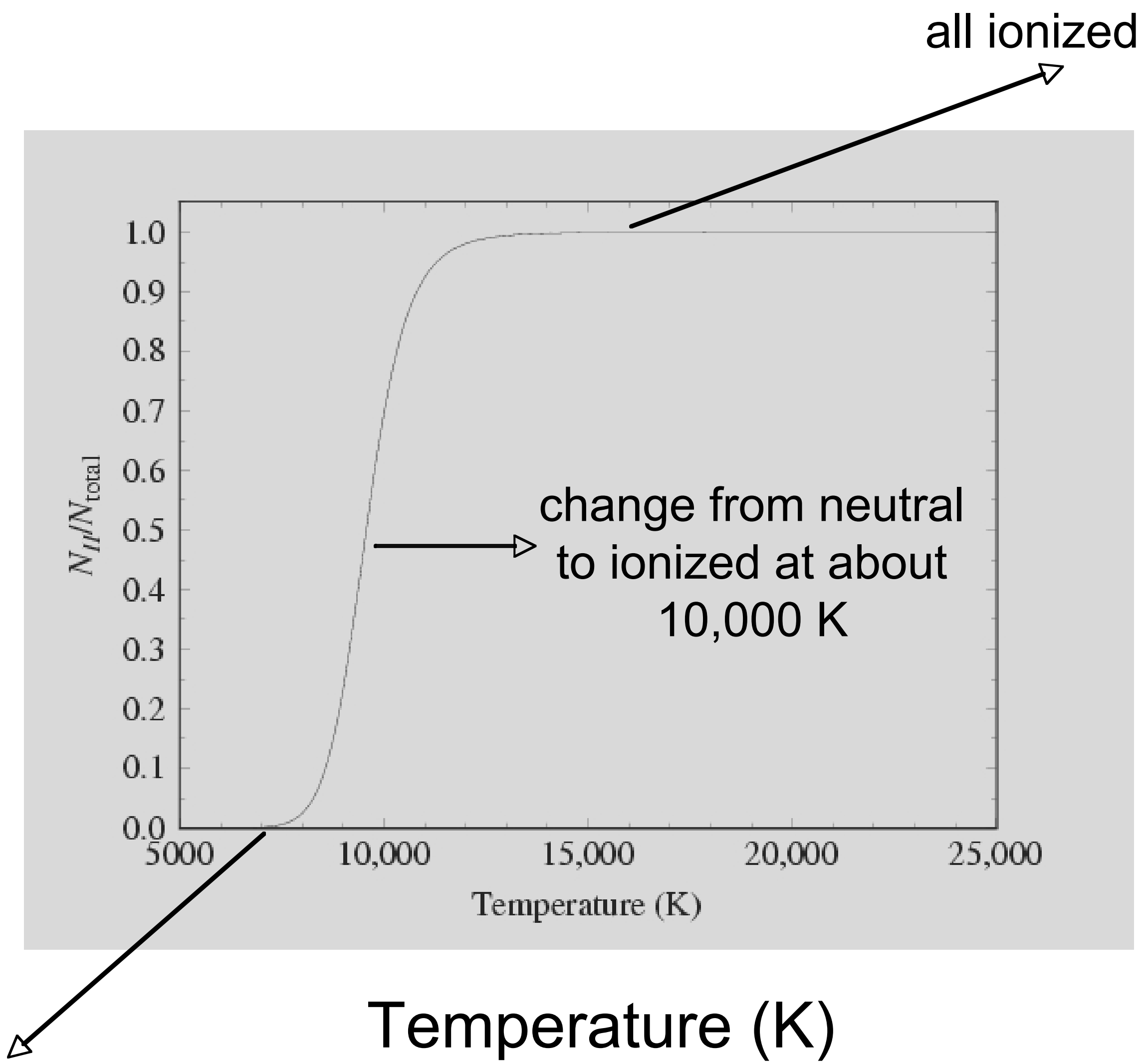


100 Å
X-ray



CO Figure 11.12

Saha Eqn: Ionization of Hydrogen



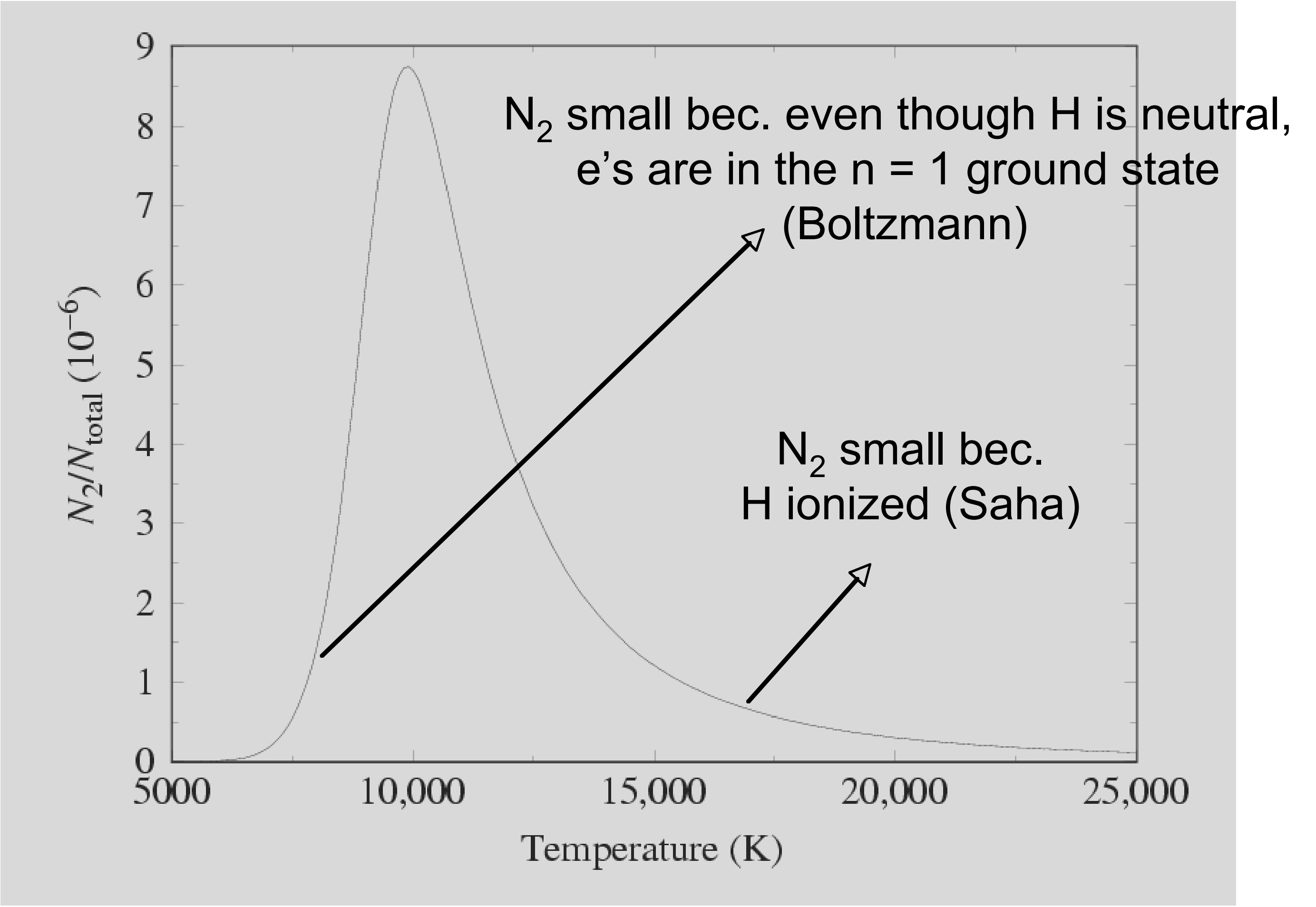
Fraction of H atoms that are ionized

Temperature (K)

Boltzmann + Saha

Fraction of Hydrogen Atoms in the n = 2 “excited state”

(electrons in this energy level produce the “Balmer” absorption lines)



Temperature (K)

Photoionization Cross Sections

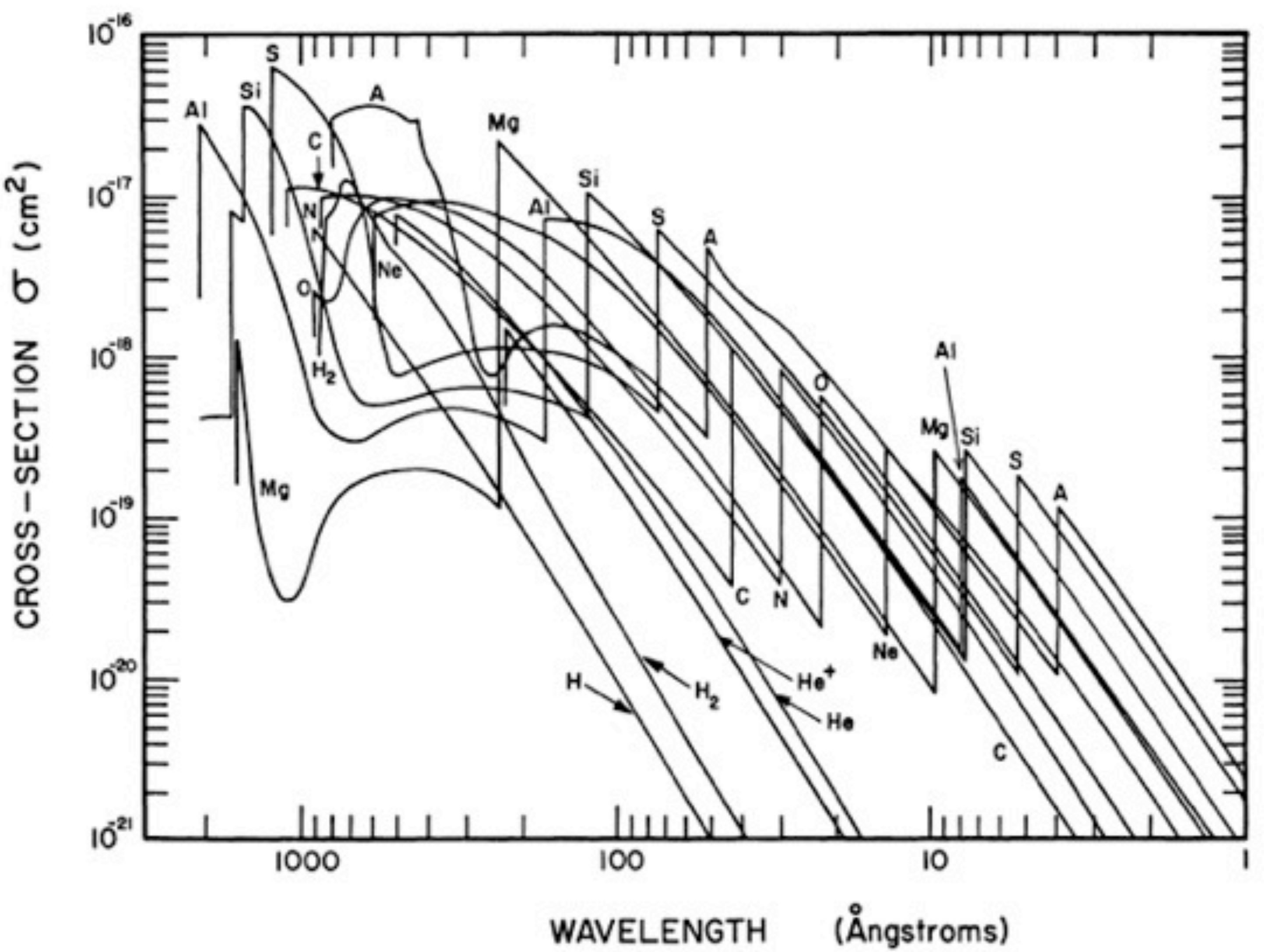


FIG. 1.—Photoabsorption cross-sections of the abundant elements in the interstellar medium as a function of wavelength

Photoionization Cross Section for gas of "cosmic" composition

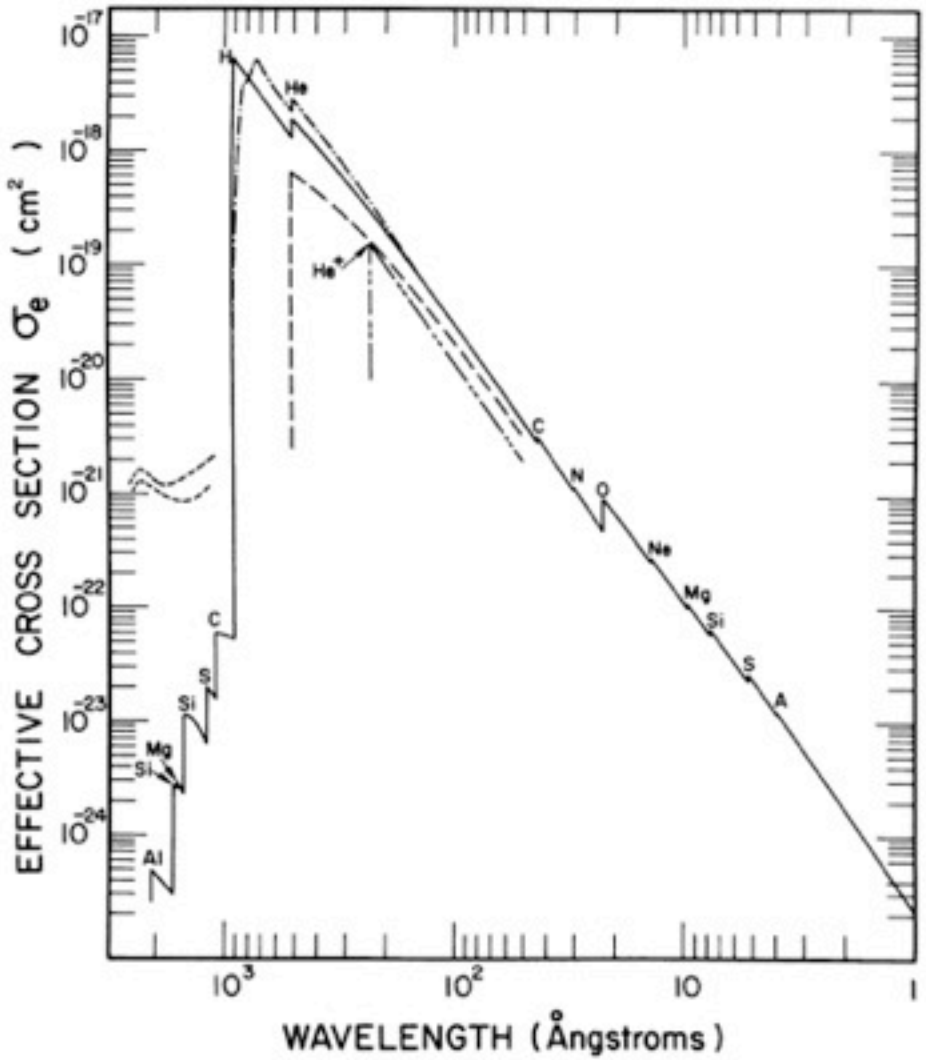
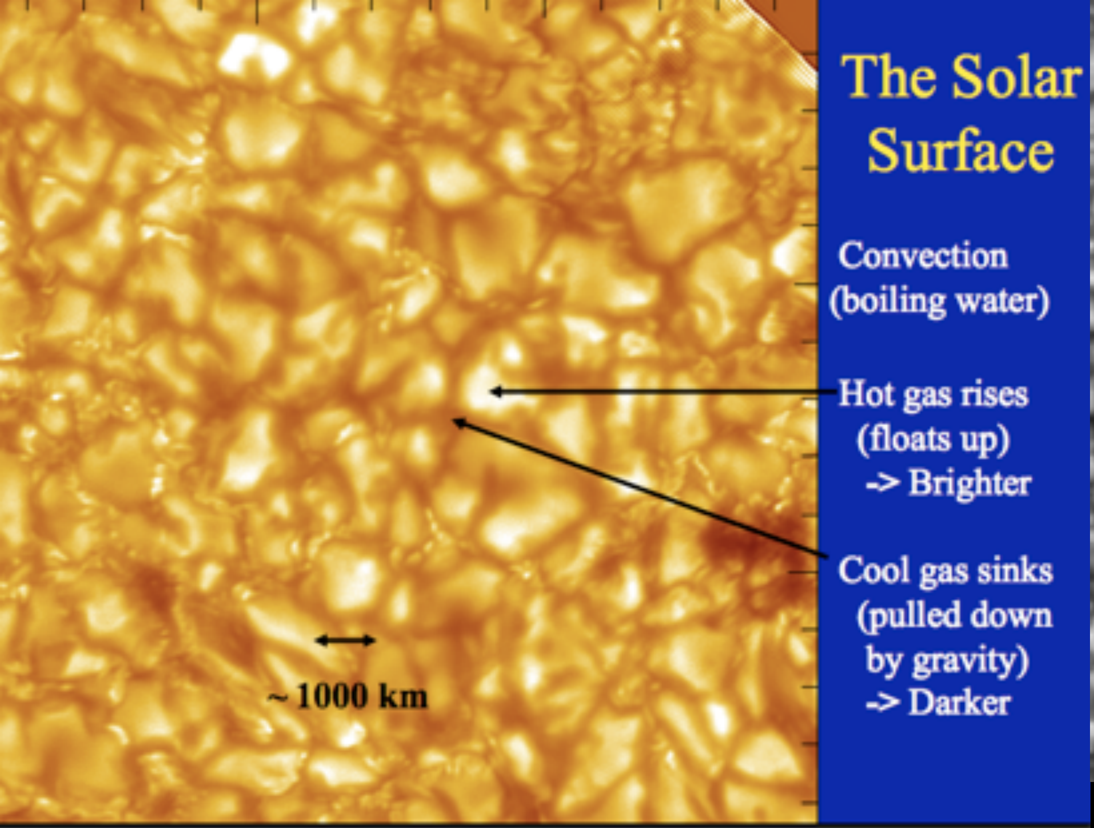
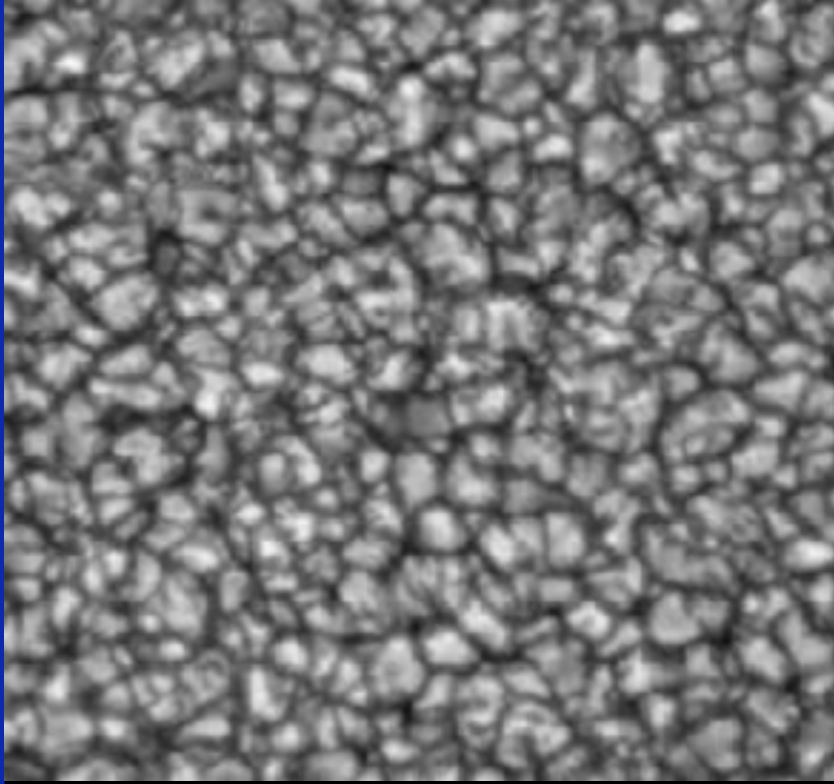
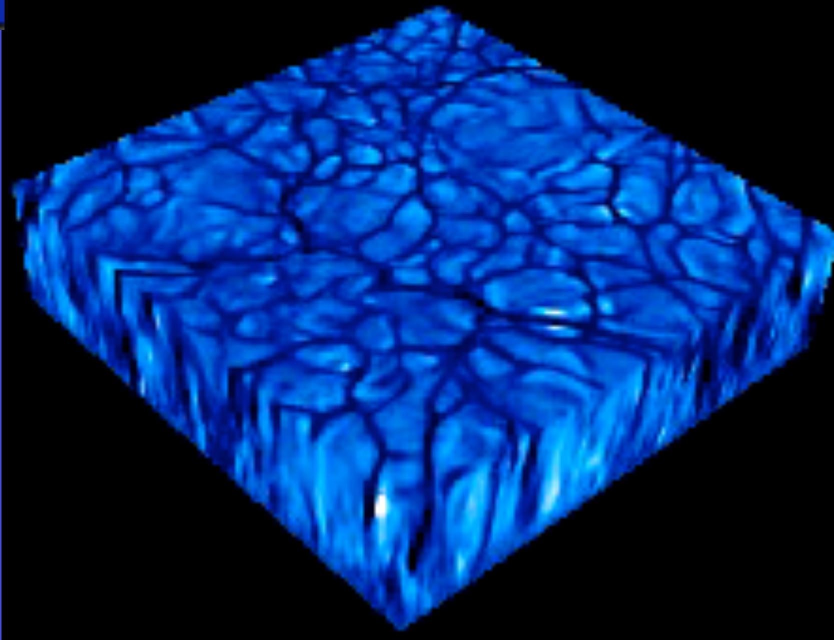


FIG. 2.—Effective cross-section (cross-section per hydrogen atom or proton) of the interstellar medium. ——— gaseous component with normal composition and temperature; —·—hydrogen, molecular form; —— —— H II region about a B star; —— -- H II region about an O star; ---- dust.

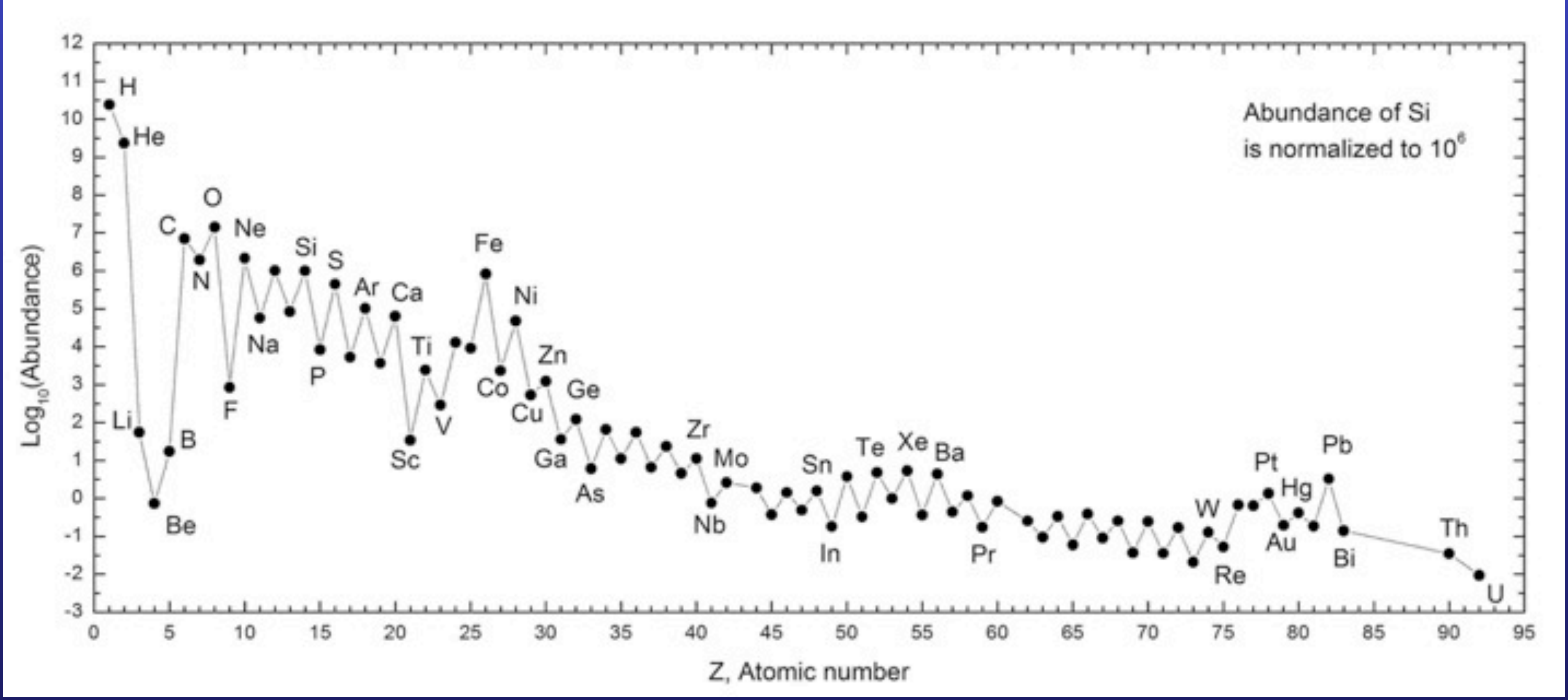


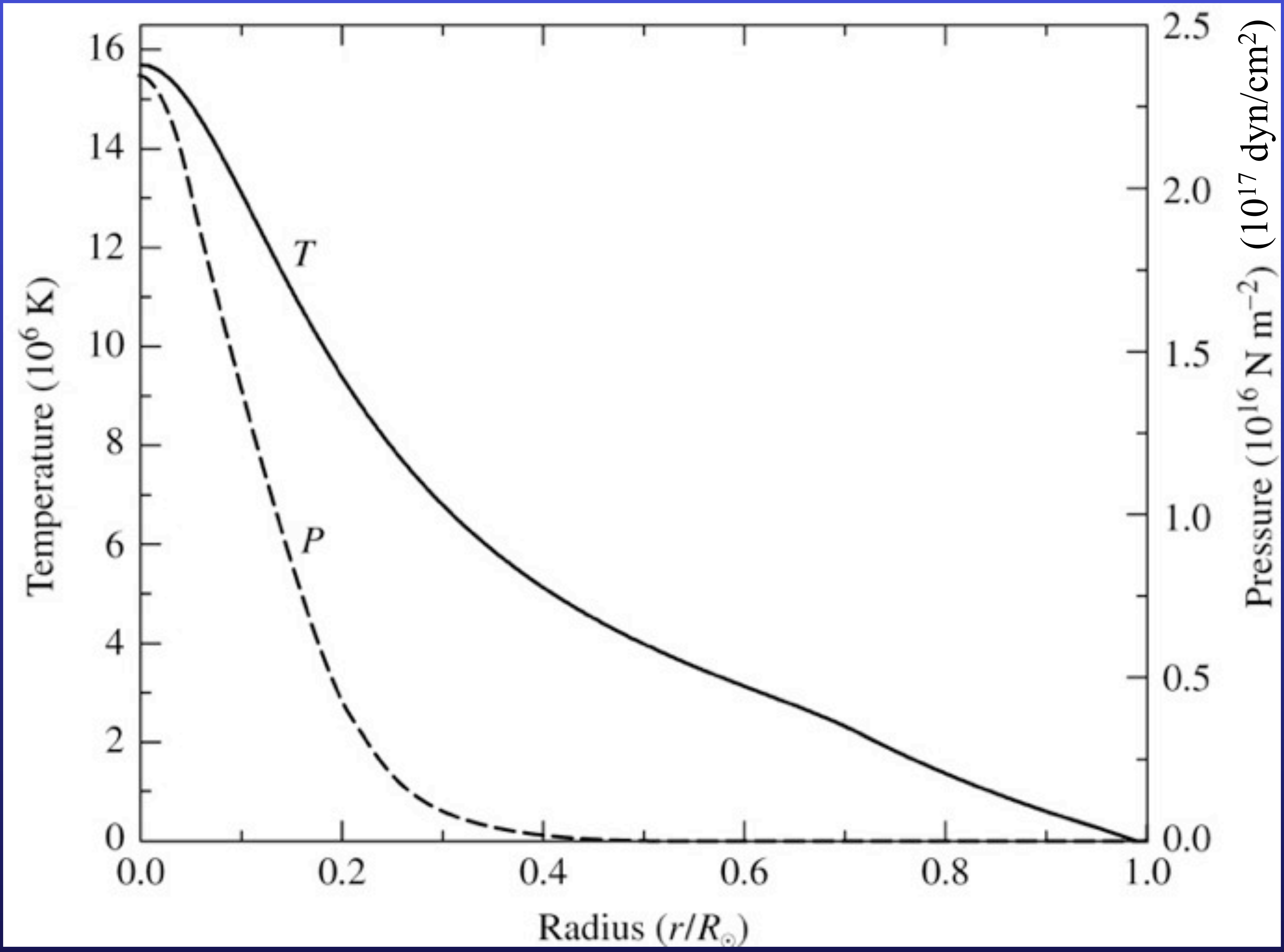


"Granulation"
Seen at, e.g., 468 nm
Granule lifetime ~ 10 minutes
Granule size ~ 1000 km
Consequence of convection



“Cosmic” Composition
(by number)



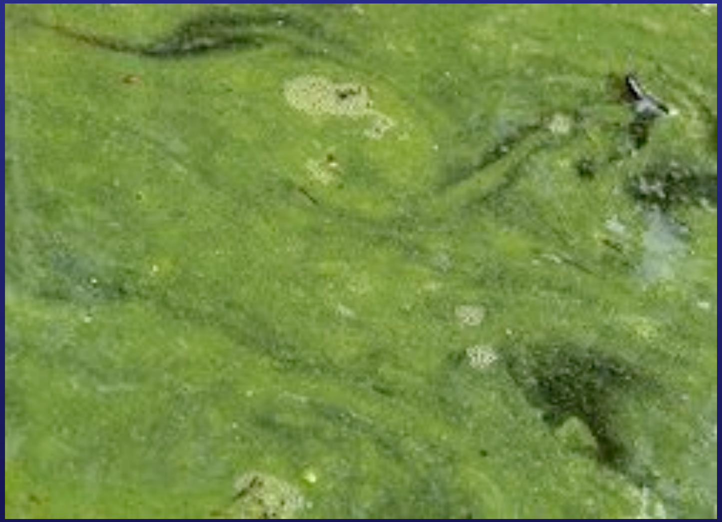


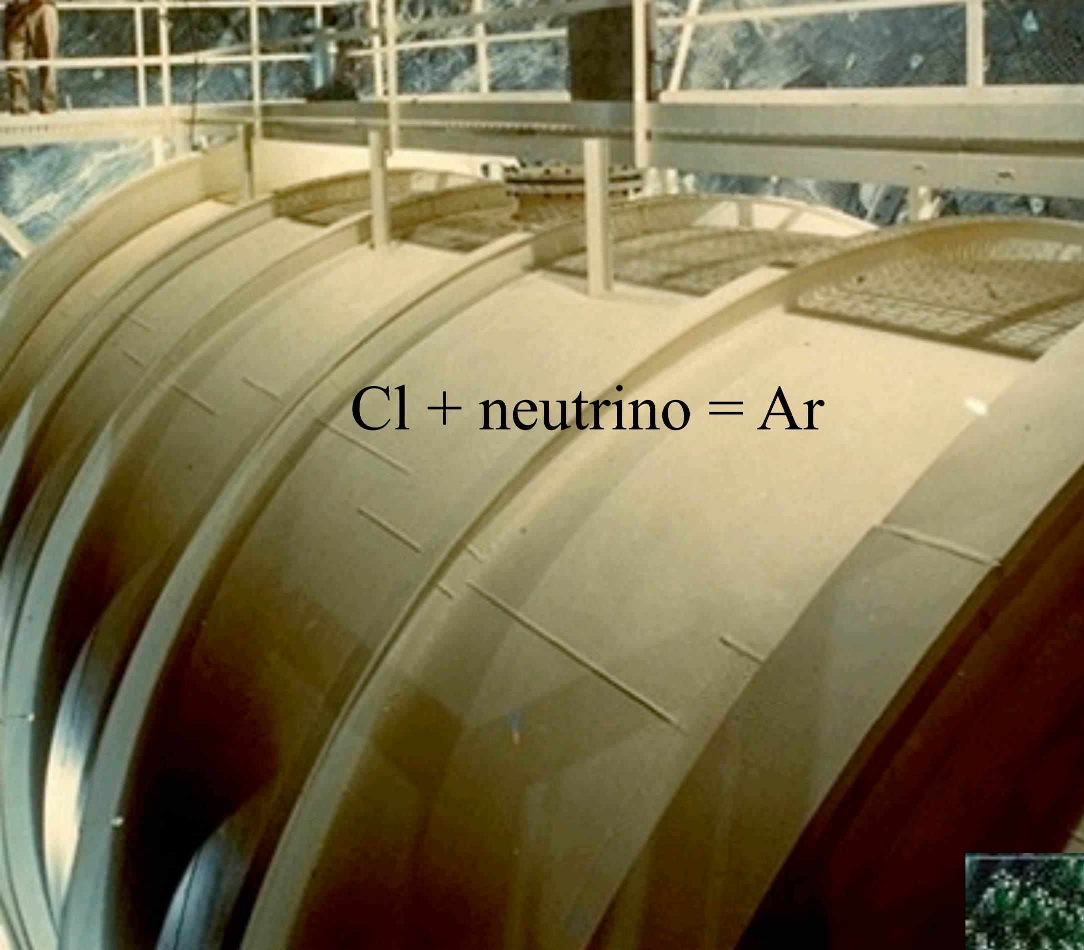
16
14
12
10
8
6
4
2
0
Temperature (10^6 K)
0.0
0.2
0.4
0.6
0.8
1.0
Radius ($r/R_{\odot}$)
2.5
2.0
1.5
1.0
0.5
0.0
Pressure (10^{16} N m^{-2}) (10^{17} dyn/cm^2)
T
P

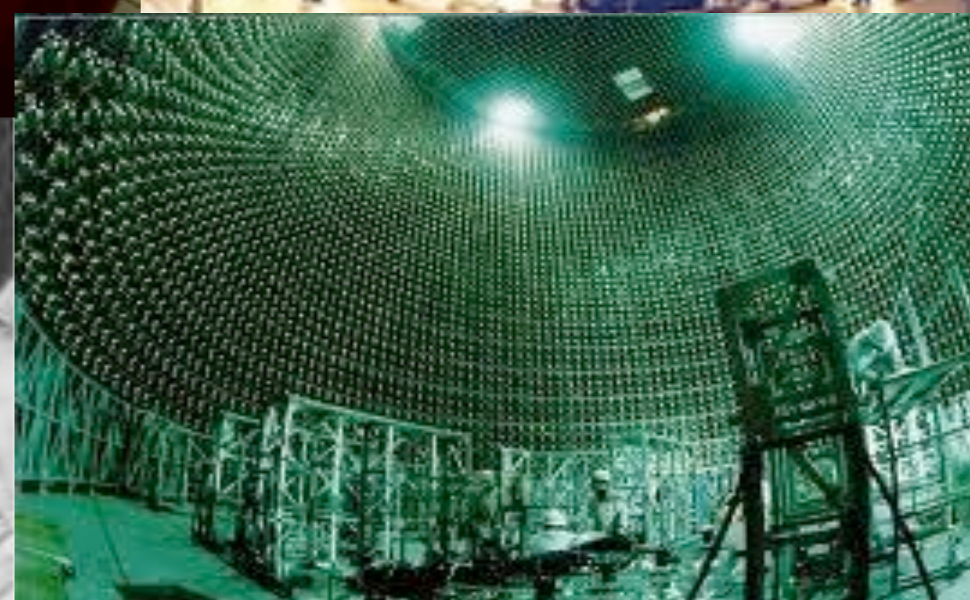
Stromatolites

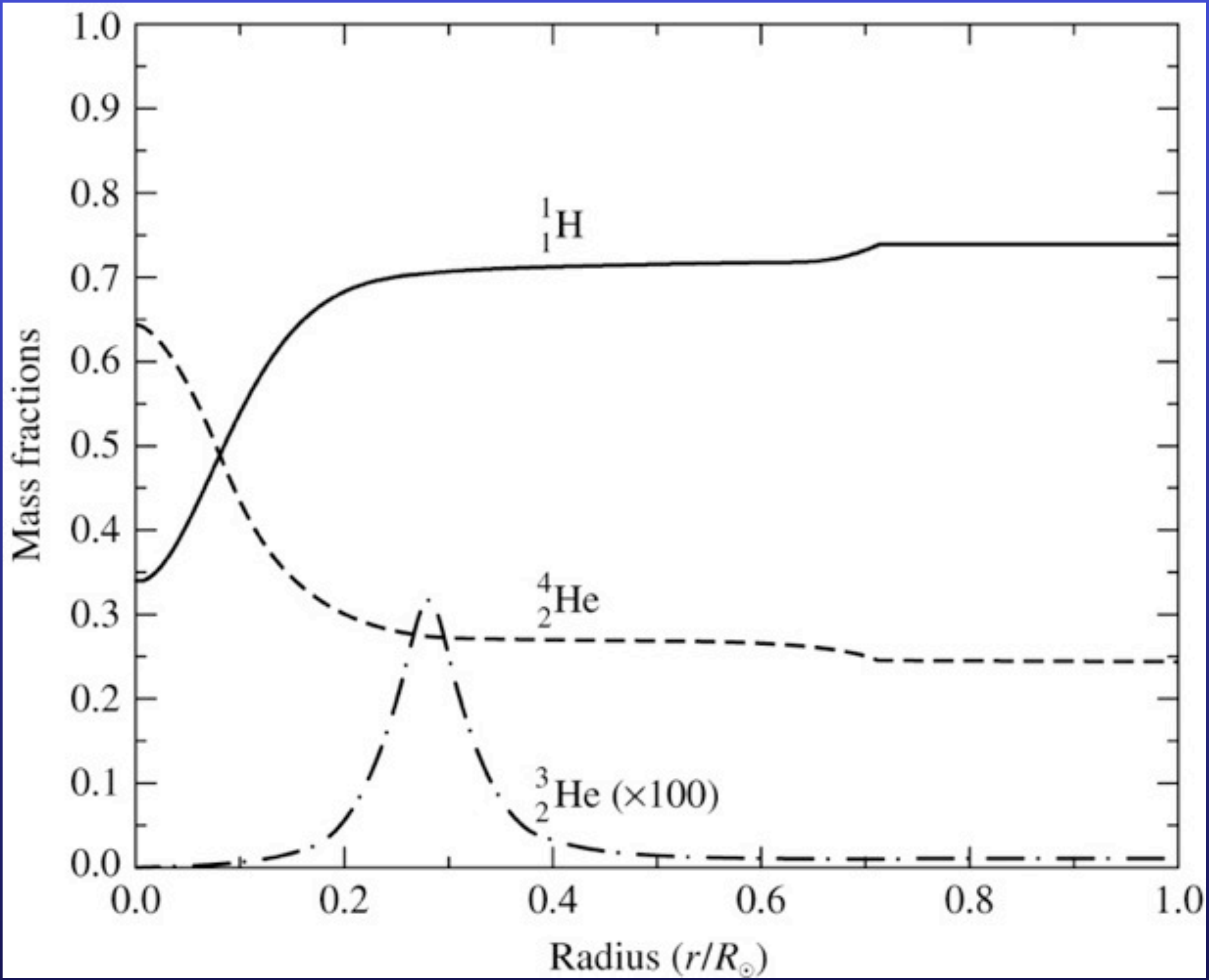
Blue-green algae
that can make
rock formations

Fossil stromatolites
imply Earth had life
(Sun was shining)
> 3 billion years ago



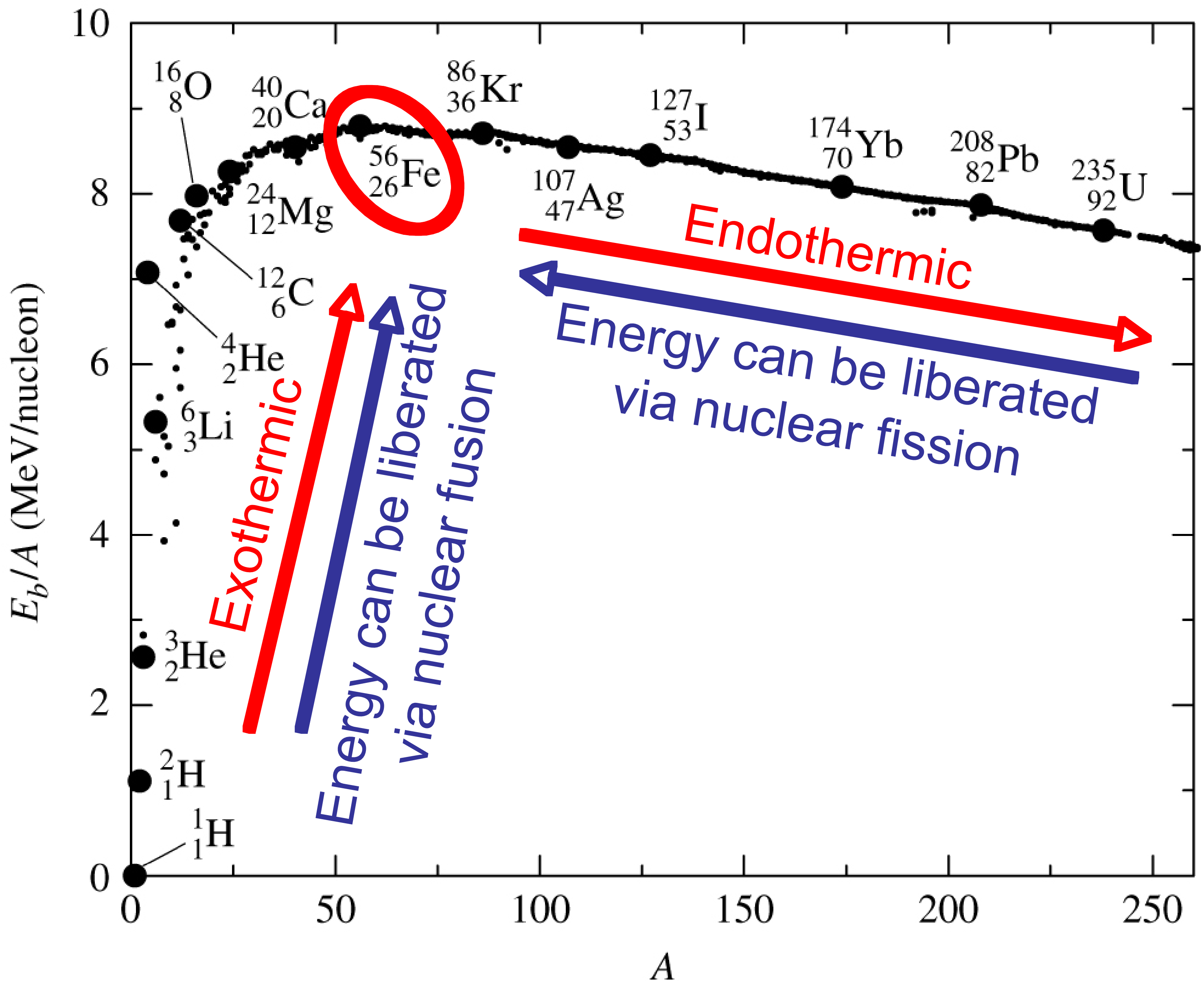

Cl + neutrino = Ar



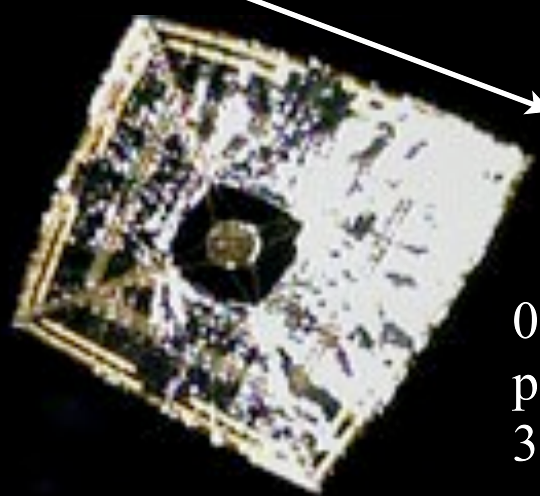


Mass fractions
Radius $(r/R_\odot)$
^1_1H
^4_2He
^3_2He (×100)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0

Binding energy per nucleon



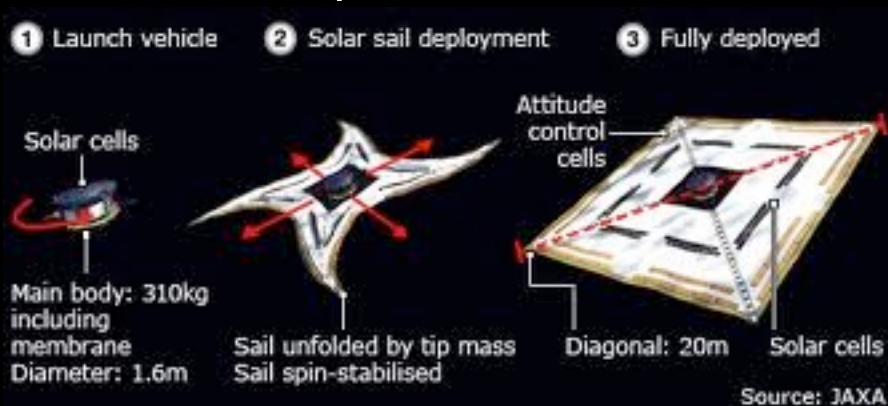
14 m

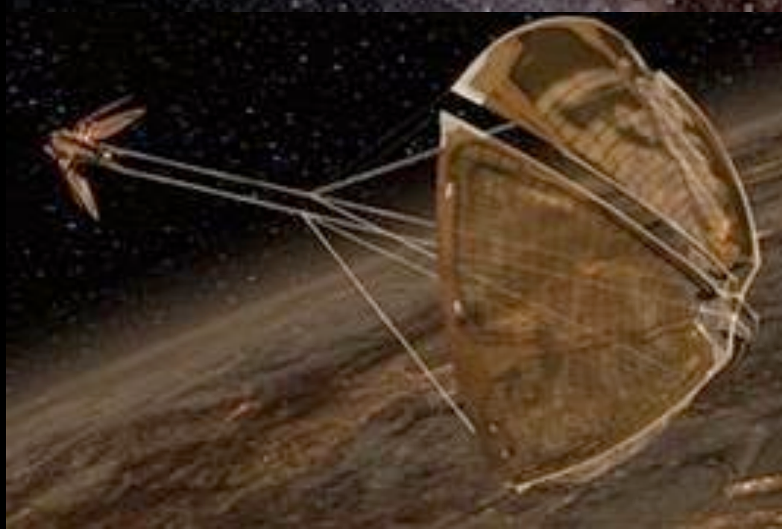


0.0075 mm
polyimide sheet
310 kg

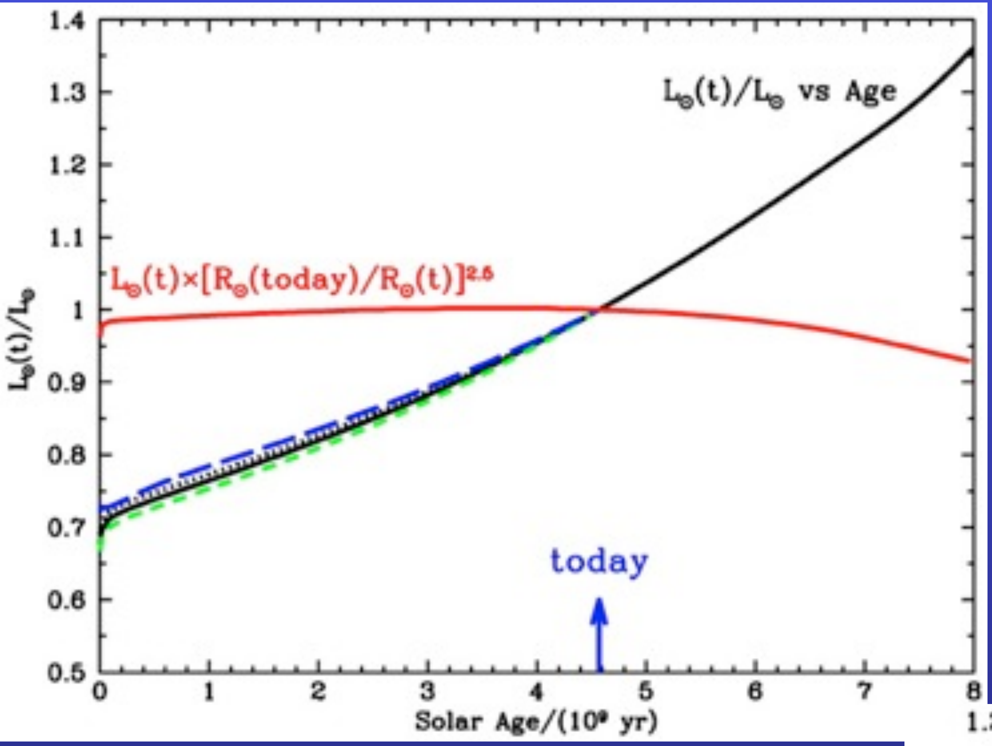
IKAROS

“Interplanetary Kite-craft
Accelerated by Radiation of the Sun”

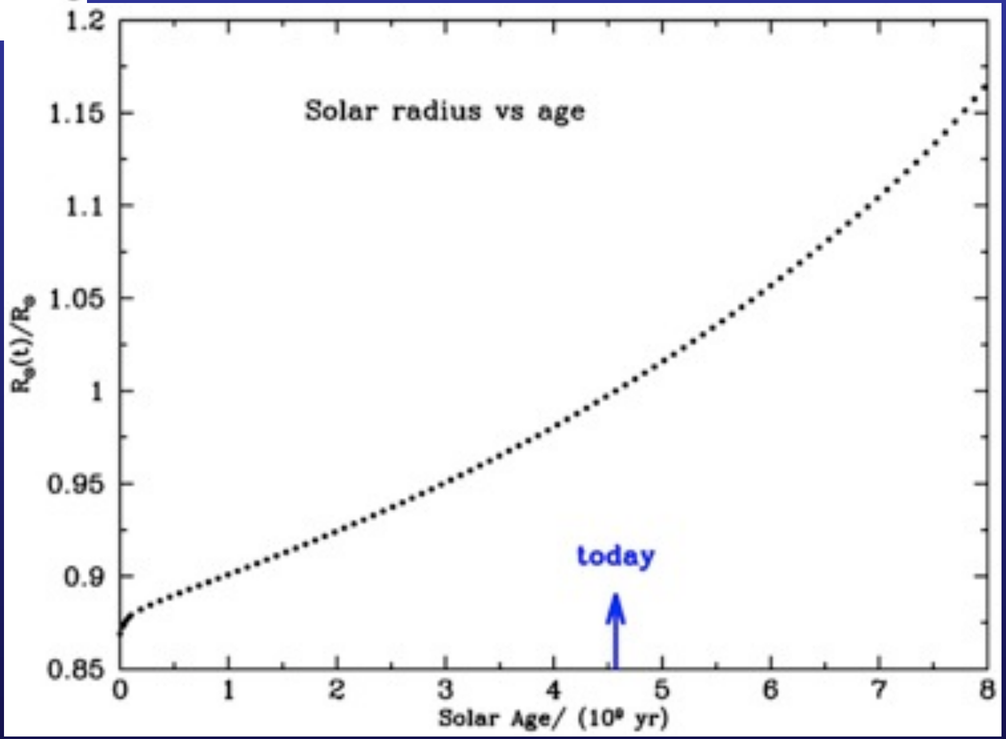




Long-term consequences of increasing mean molecular weight

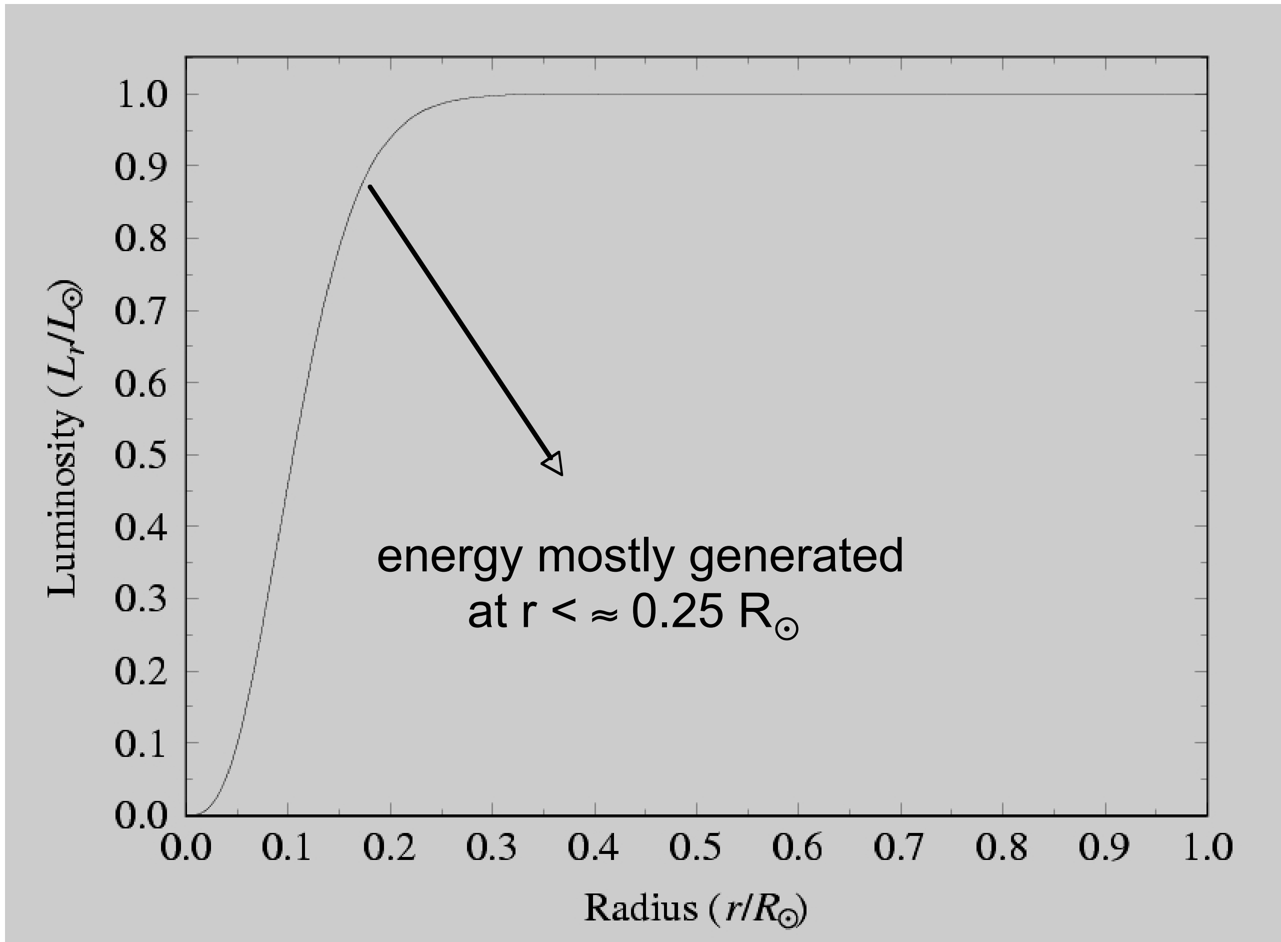


"Faint Young Sun"

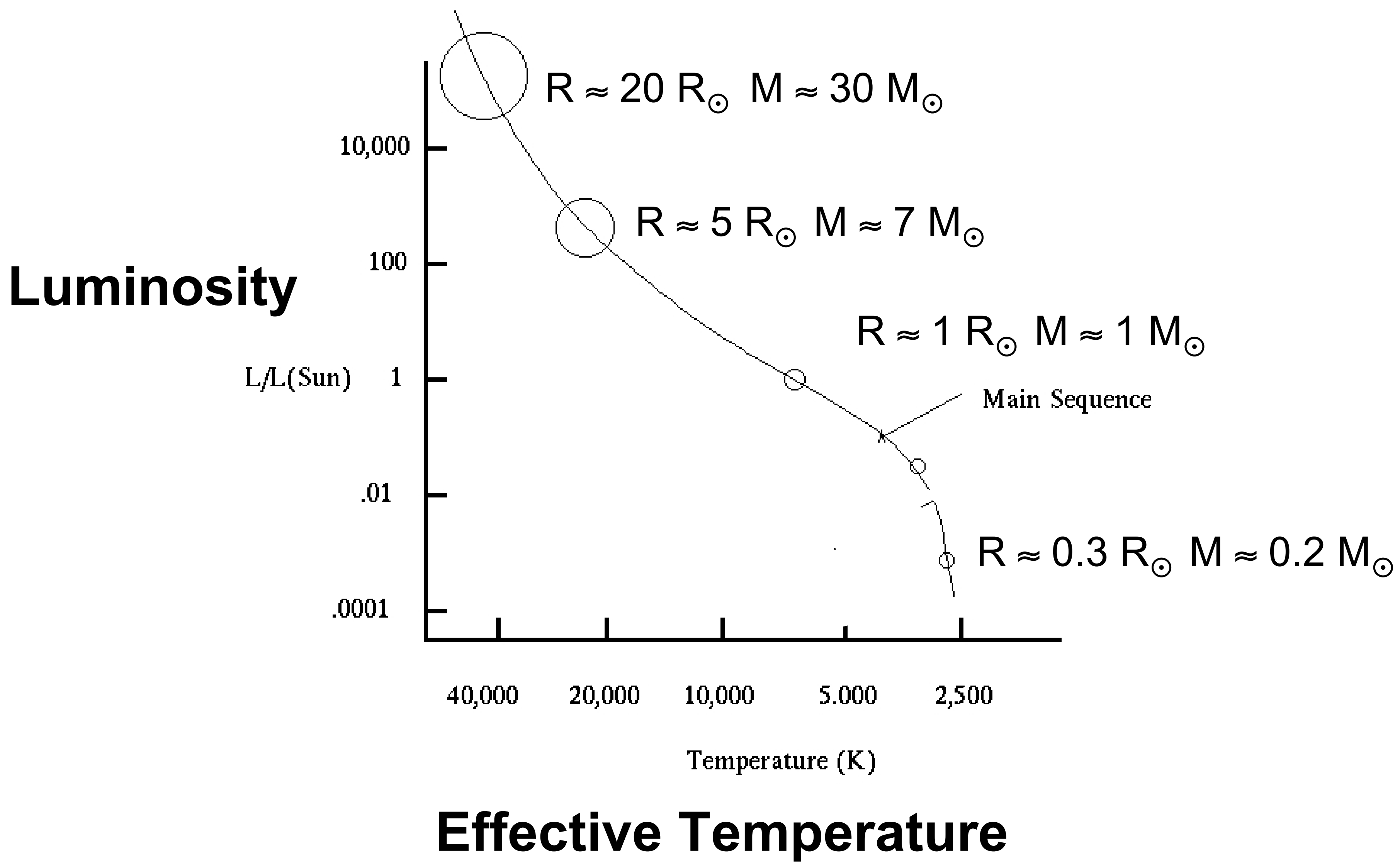


Luminosity generated by the pp chain in the Sun

L_r: luminosity flowing through a spherical shell of radius r

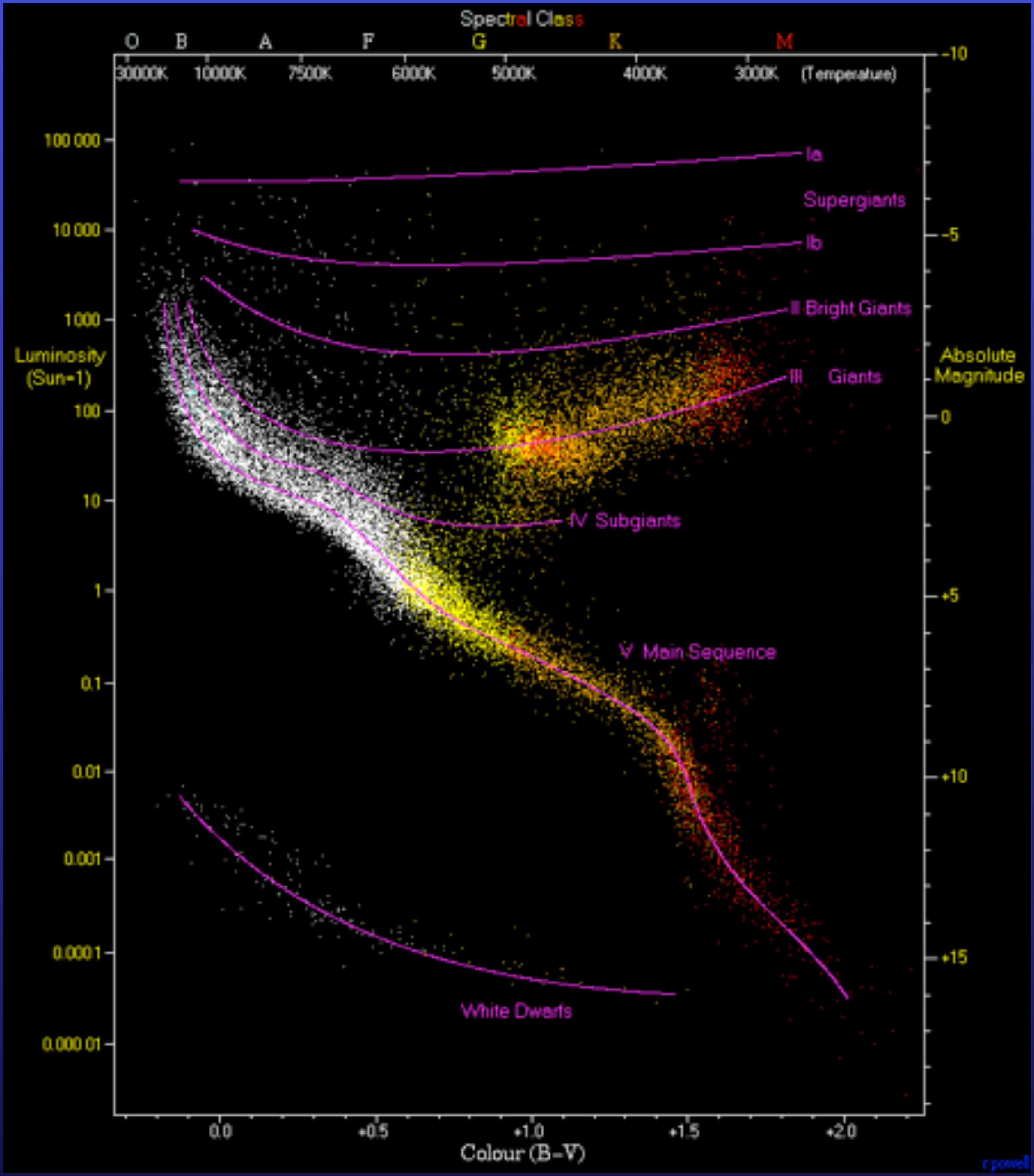


The Stellar "Main Sequence"

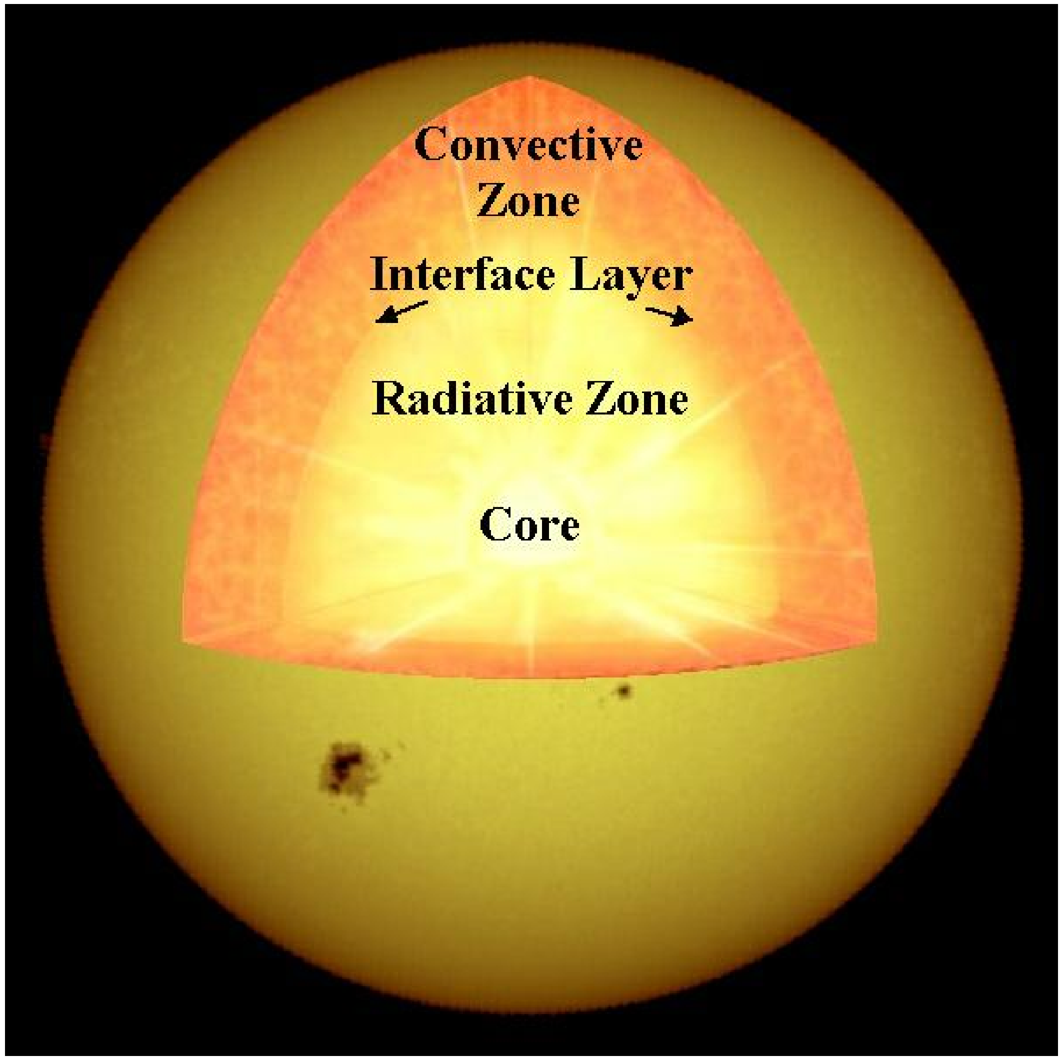


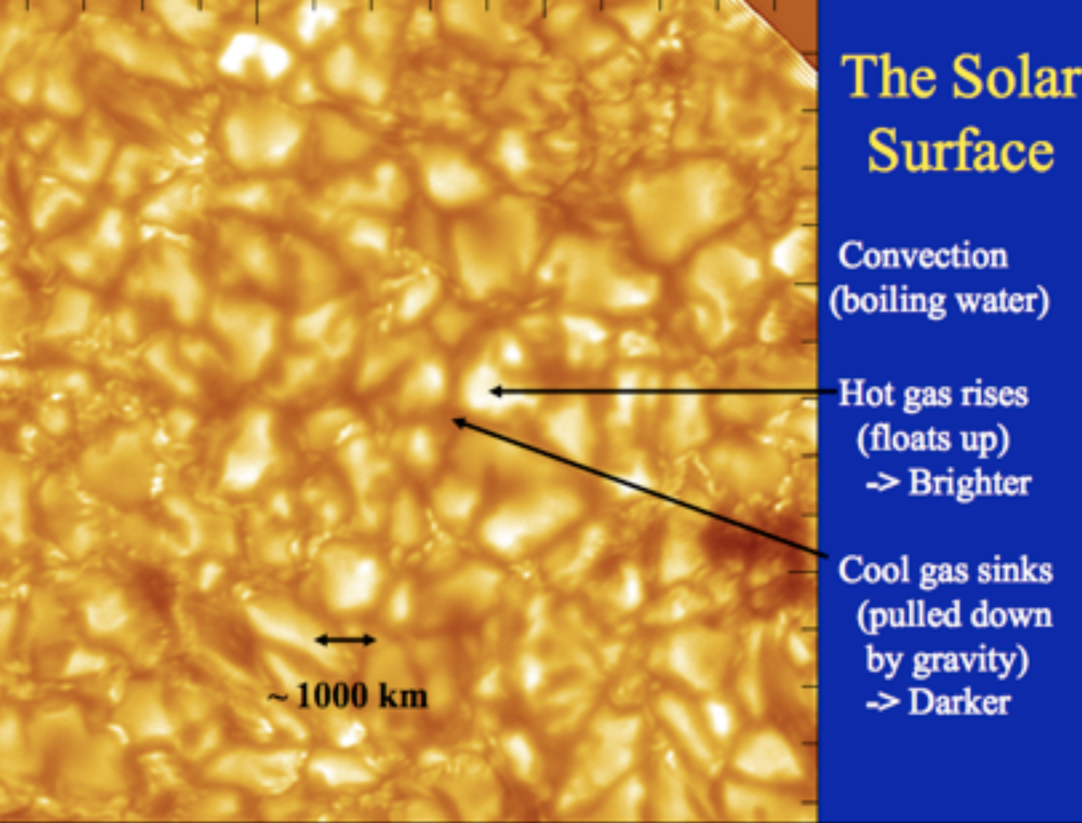
Hertzprung-Russell (H-R) diagram

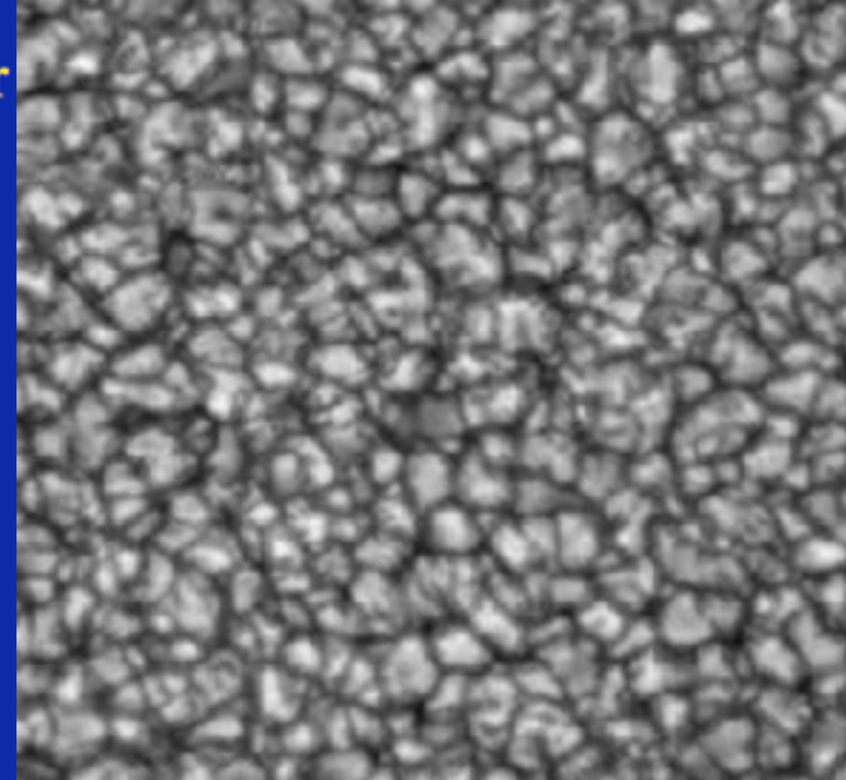
Main Sequence



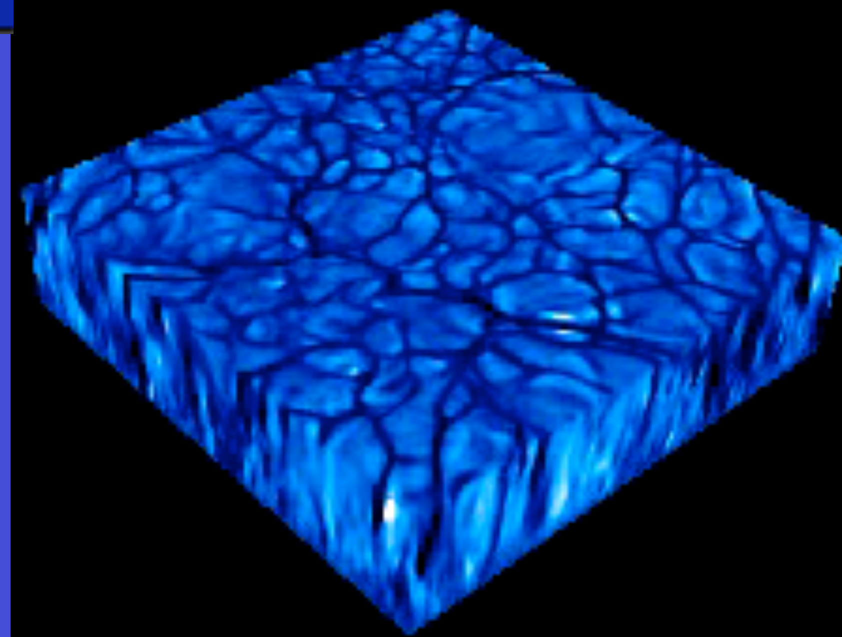
Radiative-convective boundary is at ≈ 0.7 $R_\odot$ in the sun



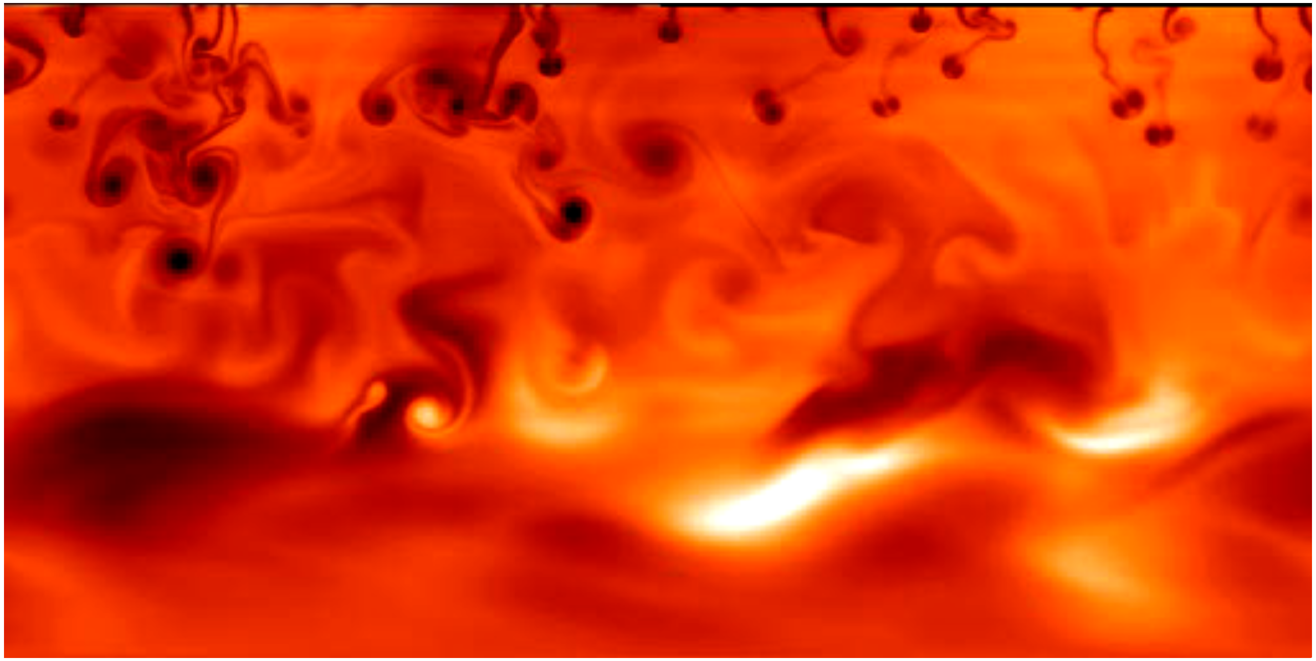




“Granulation”
Seen at, e.g., 468 nm
Granule lifetime ~ 10 minutes
Granule size ~ 1000 km
Consequence of convection



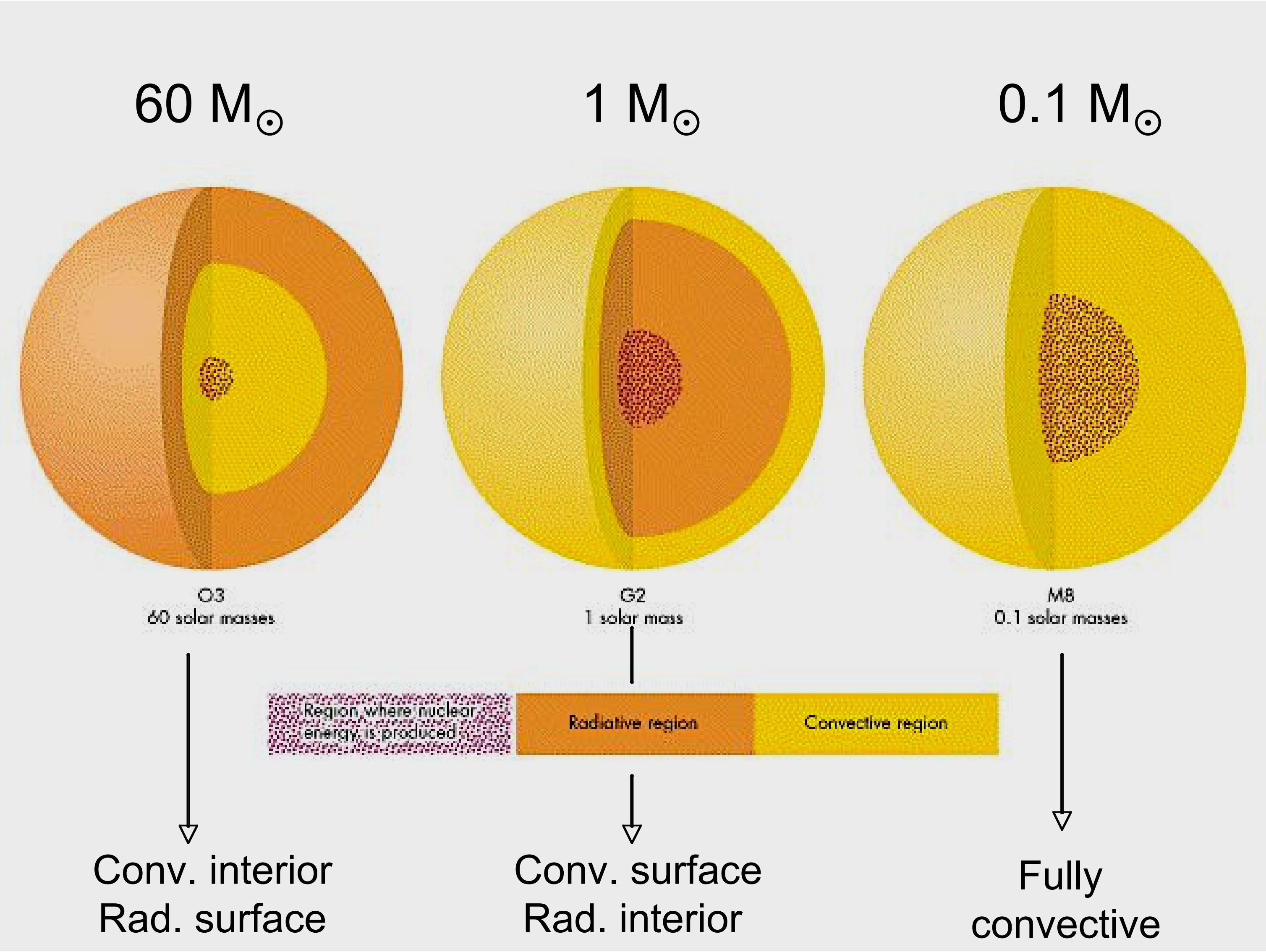
simulation of convection near the radiative-convective boundary in the sun



Convectively unstable

Convectively stable

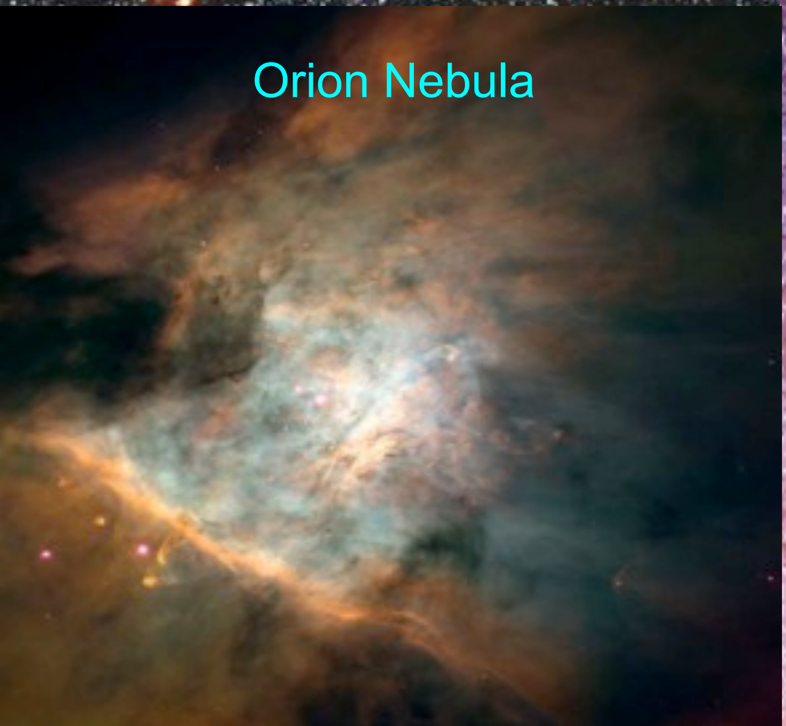
Convection vs. Radiation



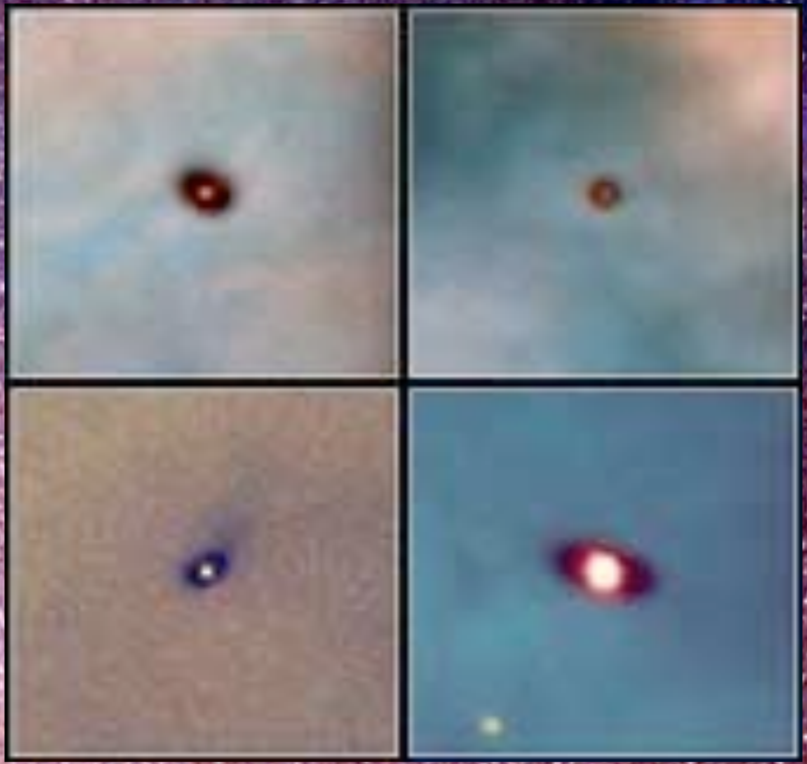
The Interstellar Medium

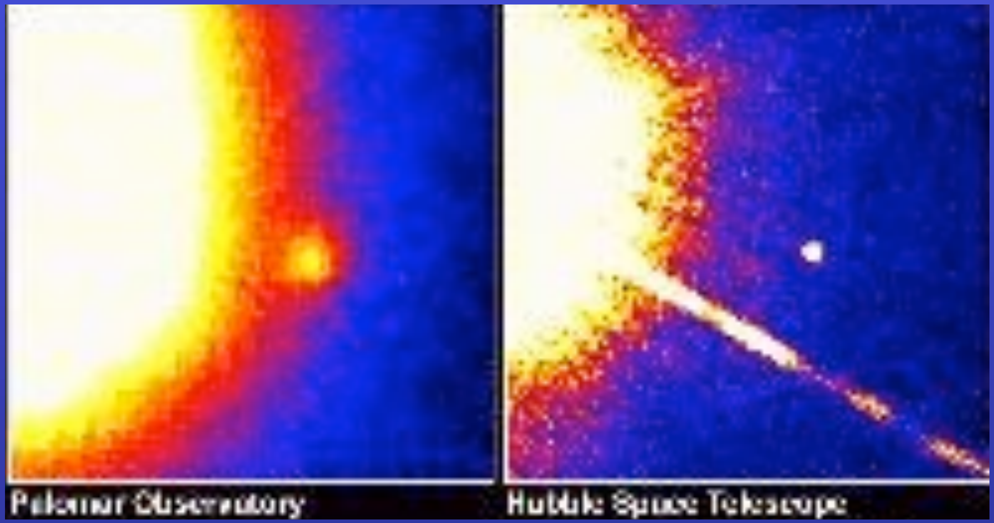
- Gas, dust, cosmic rays, magnetic fields
- Recycles stars
- Galaxy-scale calorimeter


Barnard 64: A “dark cloud”


Orion Nebula

Planetary nurseries: Circumstellar disks





Brown dwarfs

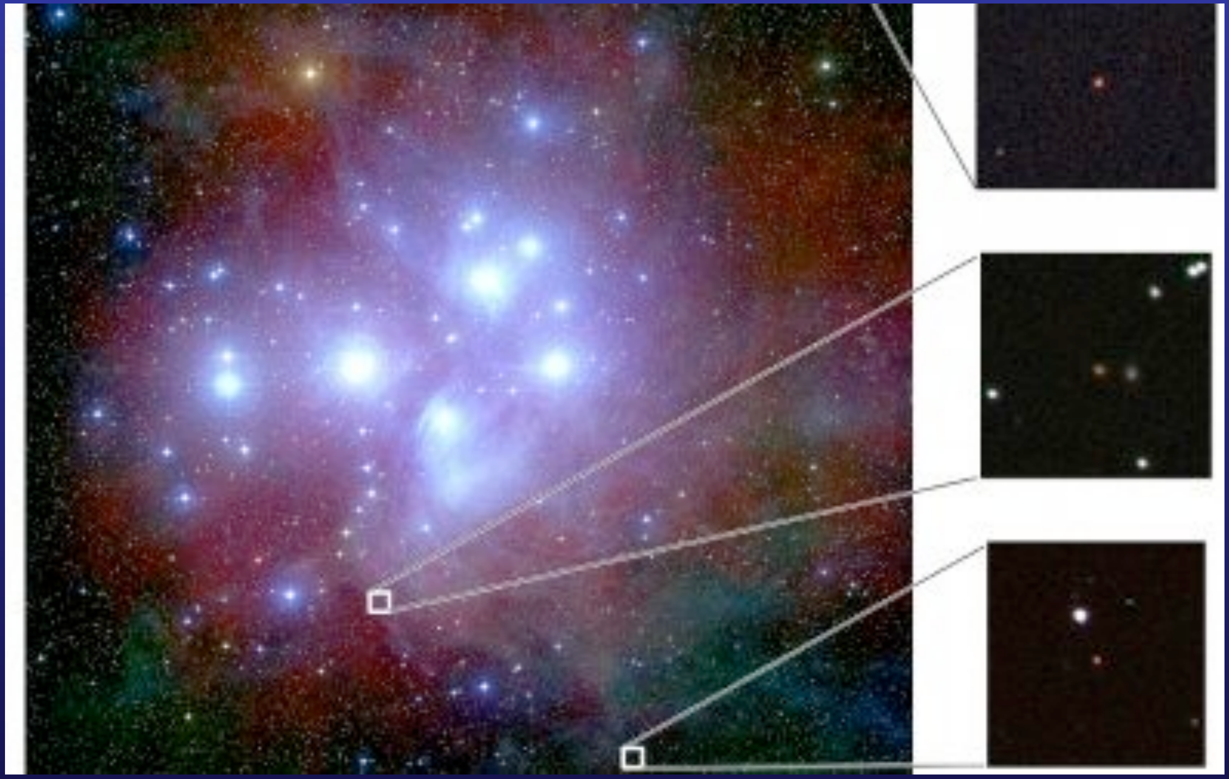
Too big to be a planet

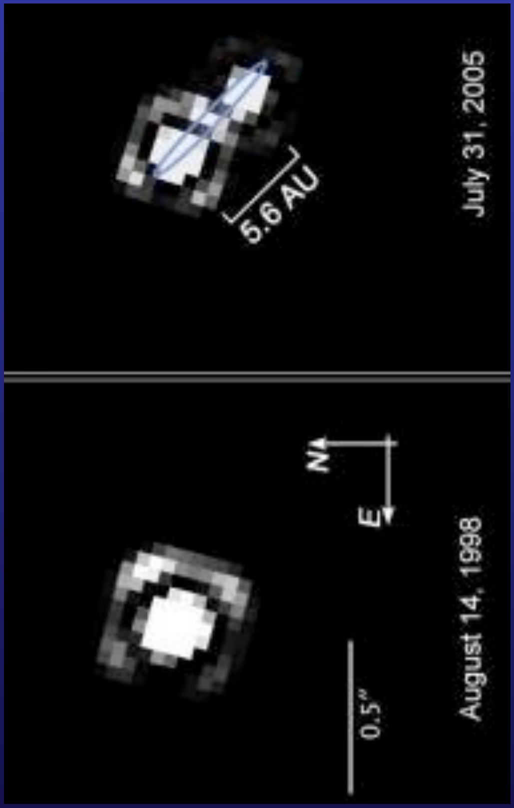
Too small to be a star

Binary separation ~ 40 AU

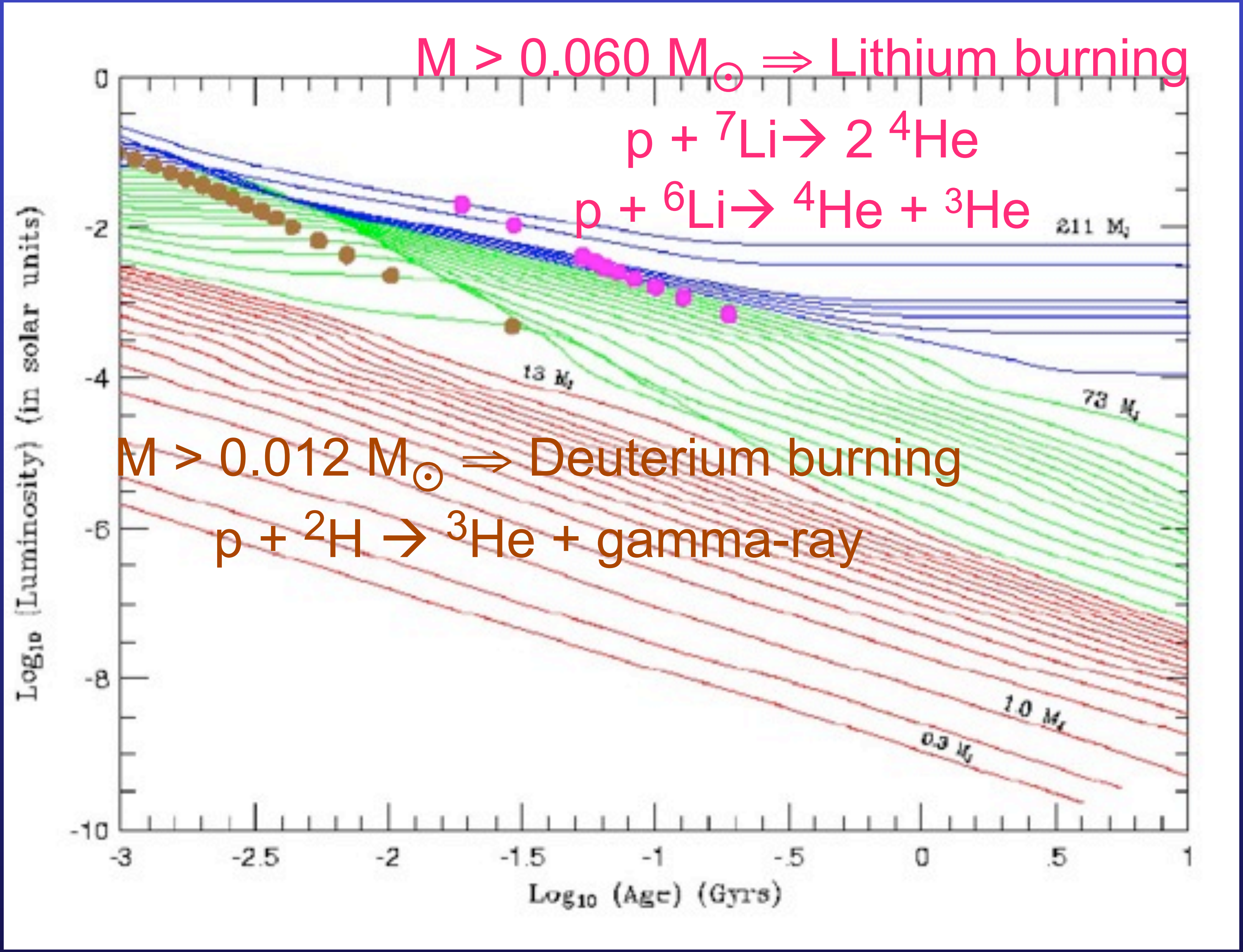
$M \sim 30\ M_J$

$L \sim 10^{-5}\ L_\odot$



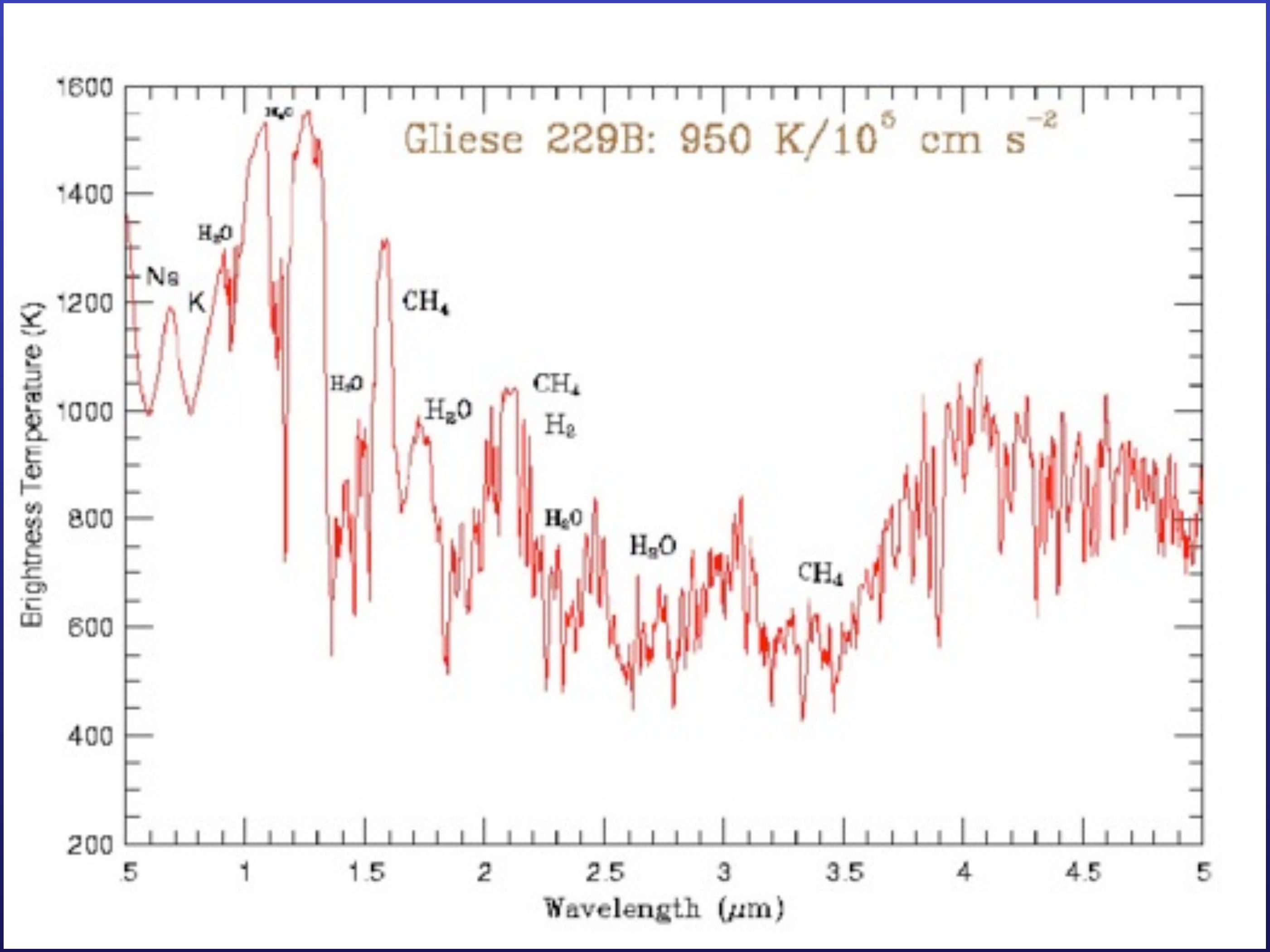


Brown Dwarf Cooling Curves
Dots mark 50% depletion due to thermonuclear burning

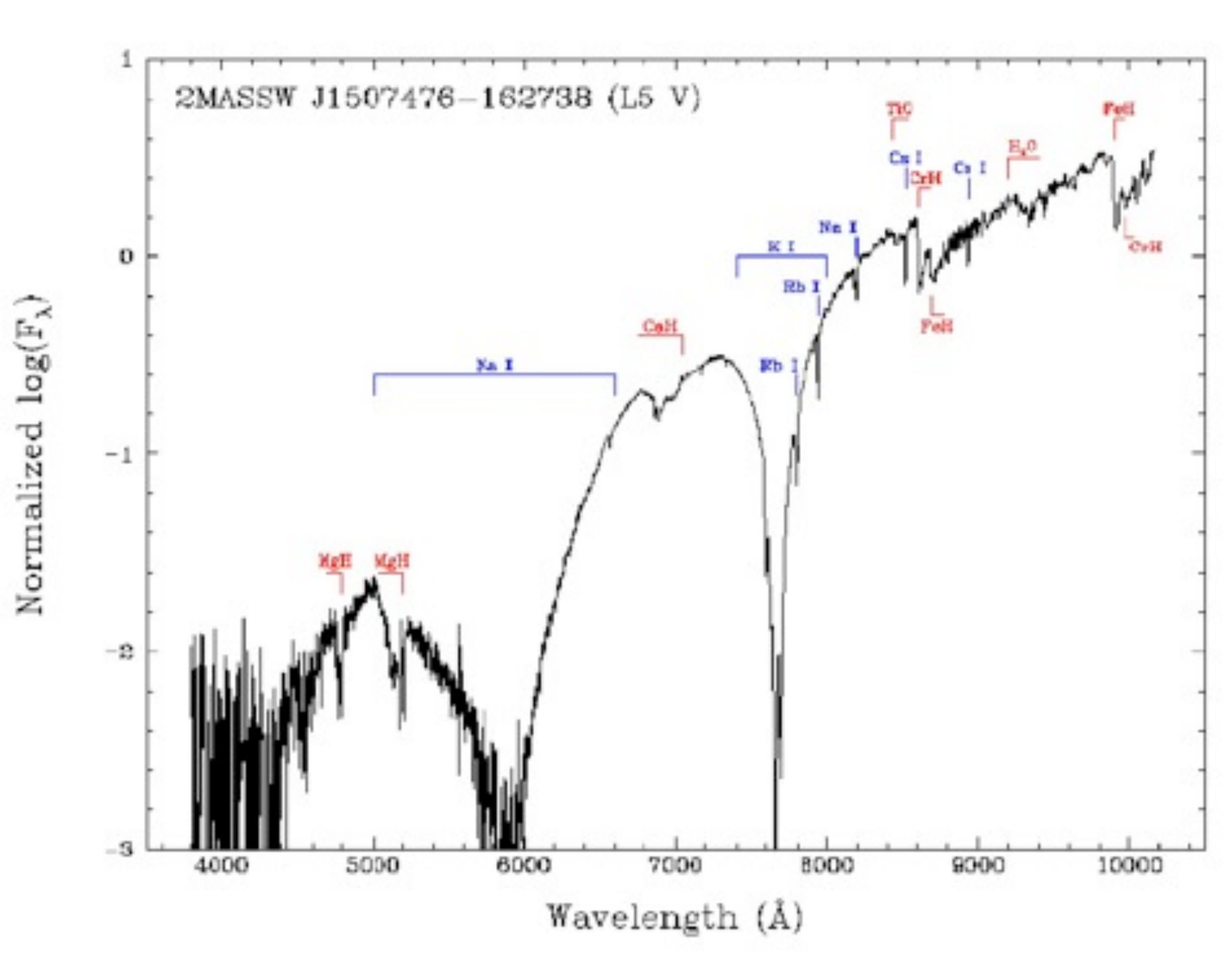


Brown Dwarfs in the Infra-red

Molecular Absorption Bands



Brown Dwarfs Aren't Brown

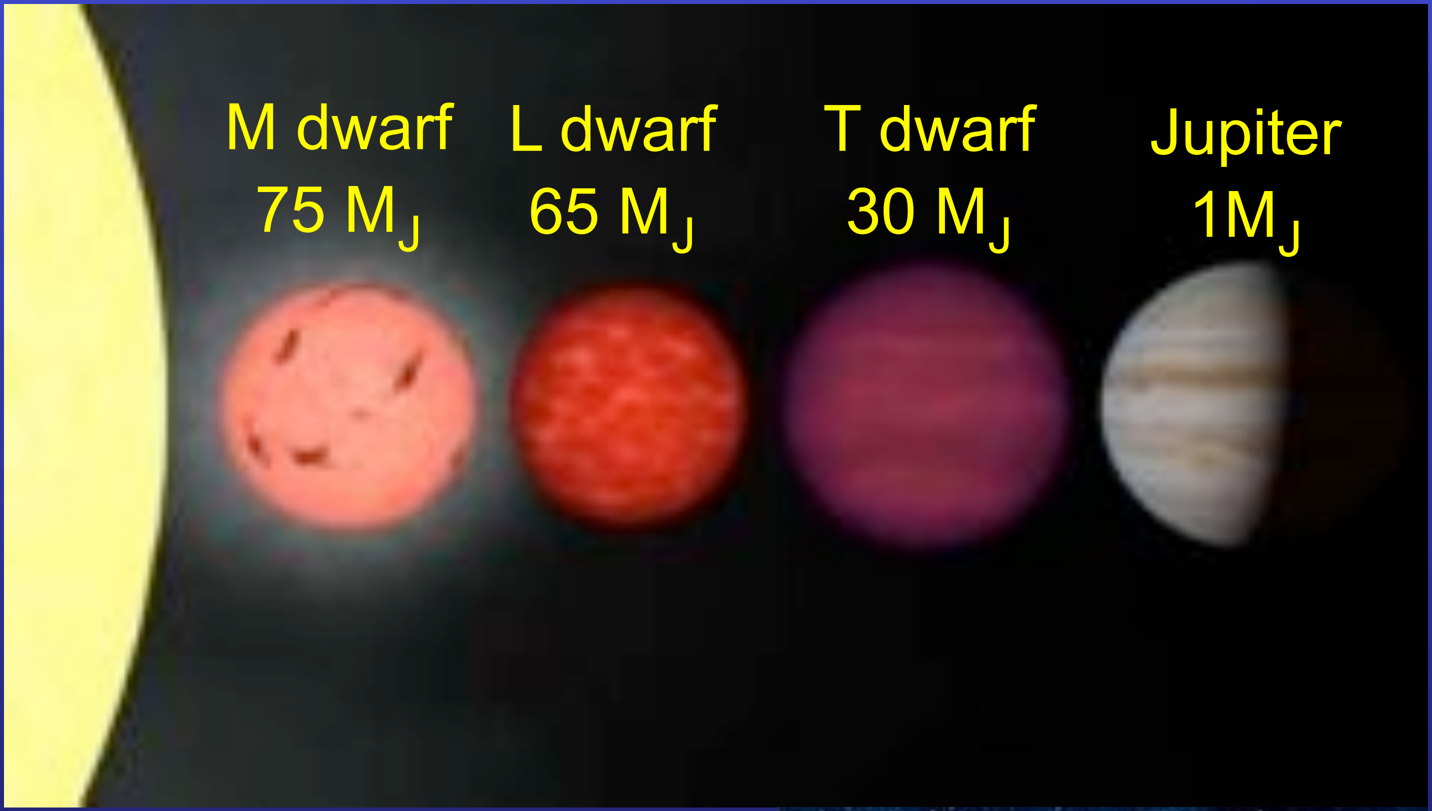


R O Y G B I V

Brown = 2 R + 1 G

Na and K kill Y and G; Above spectrum = 1 R + 0.3 G + 0.42 B

Brown Dwarfs are Magenta

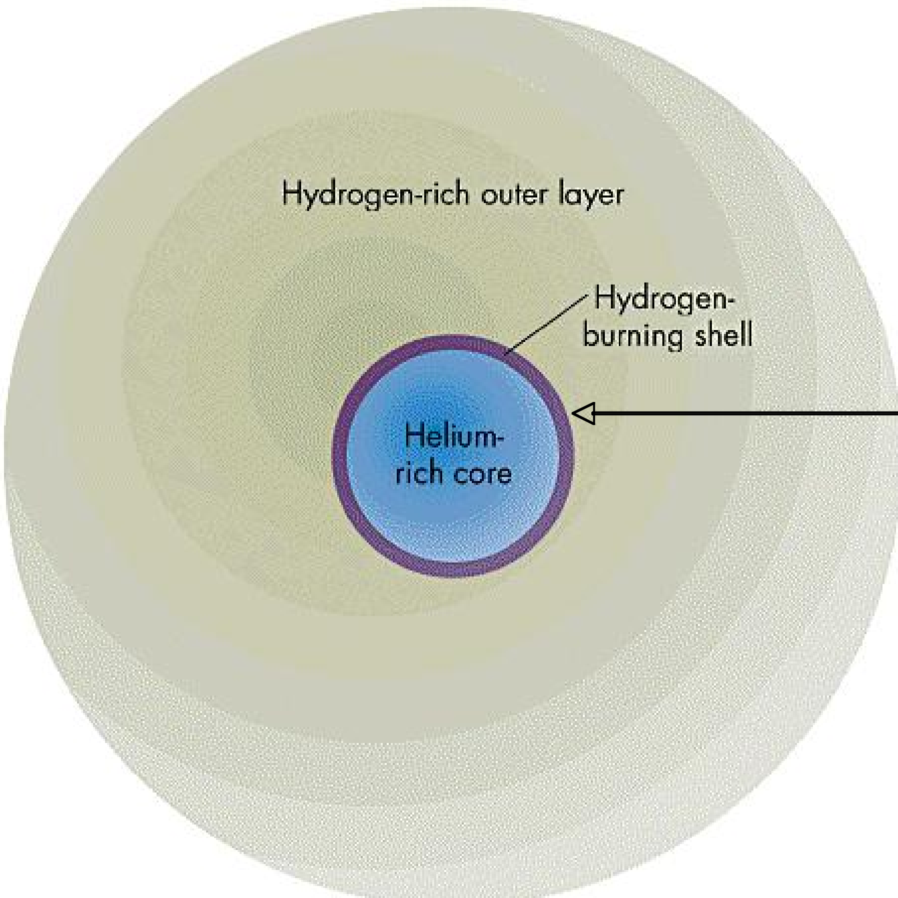


The new spectral classes

O B A F G K M L T Y

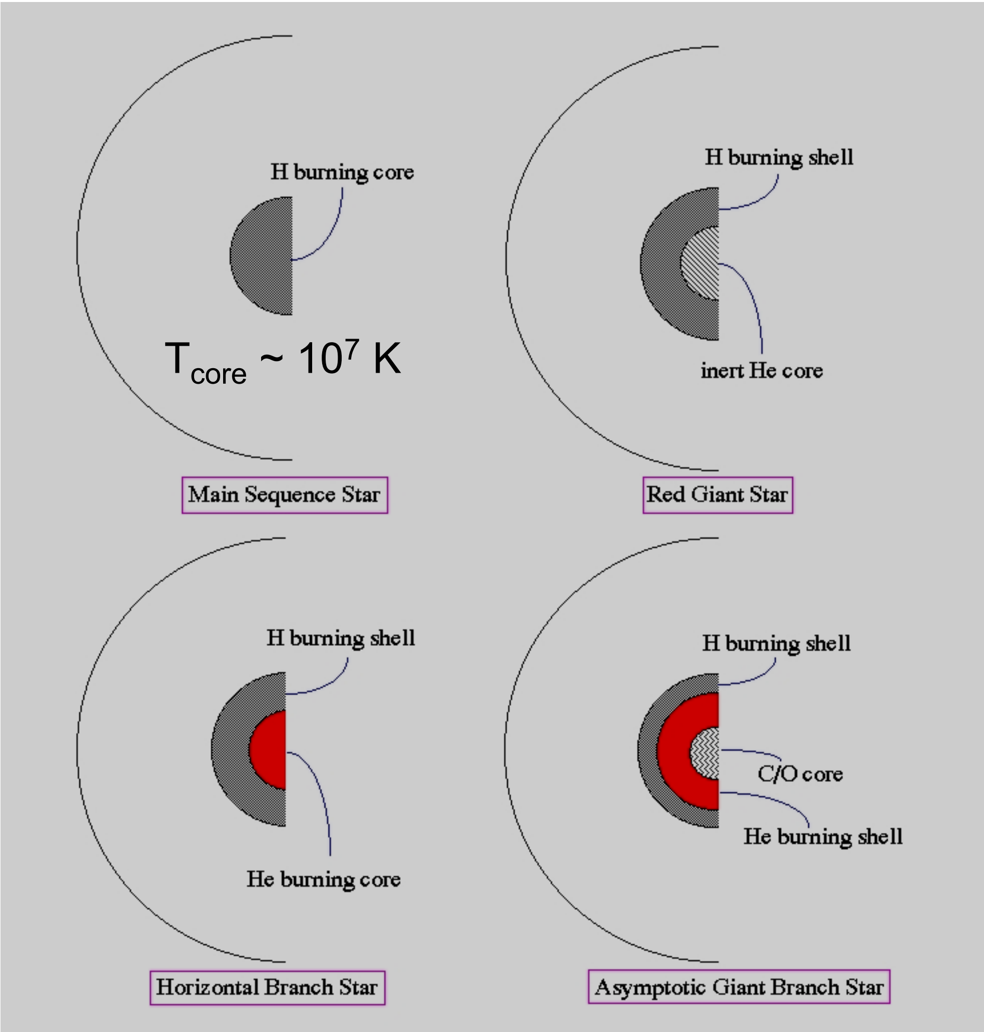
“Superstar” Eta Carina: 100-150 M☉
lost ~30 M☉ in previous eruptions
Eruptions driven by radiation pressure!

“Shell Burning”



after the core has fused all its H to He, core contracts

Fusion kicks in again in Hydrogen-rich shell surrounding He core



$T_{core} > 10^8$ K

not to scale!

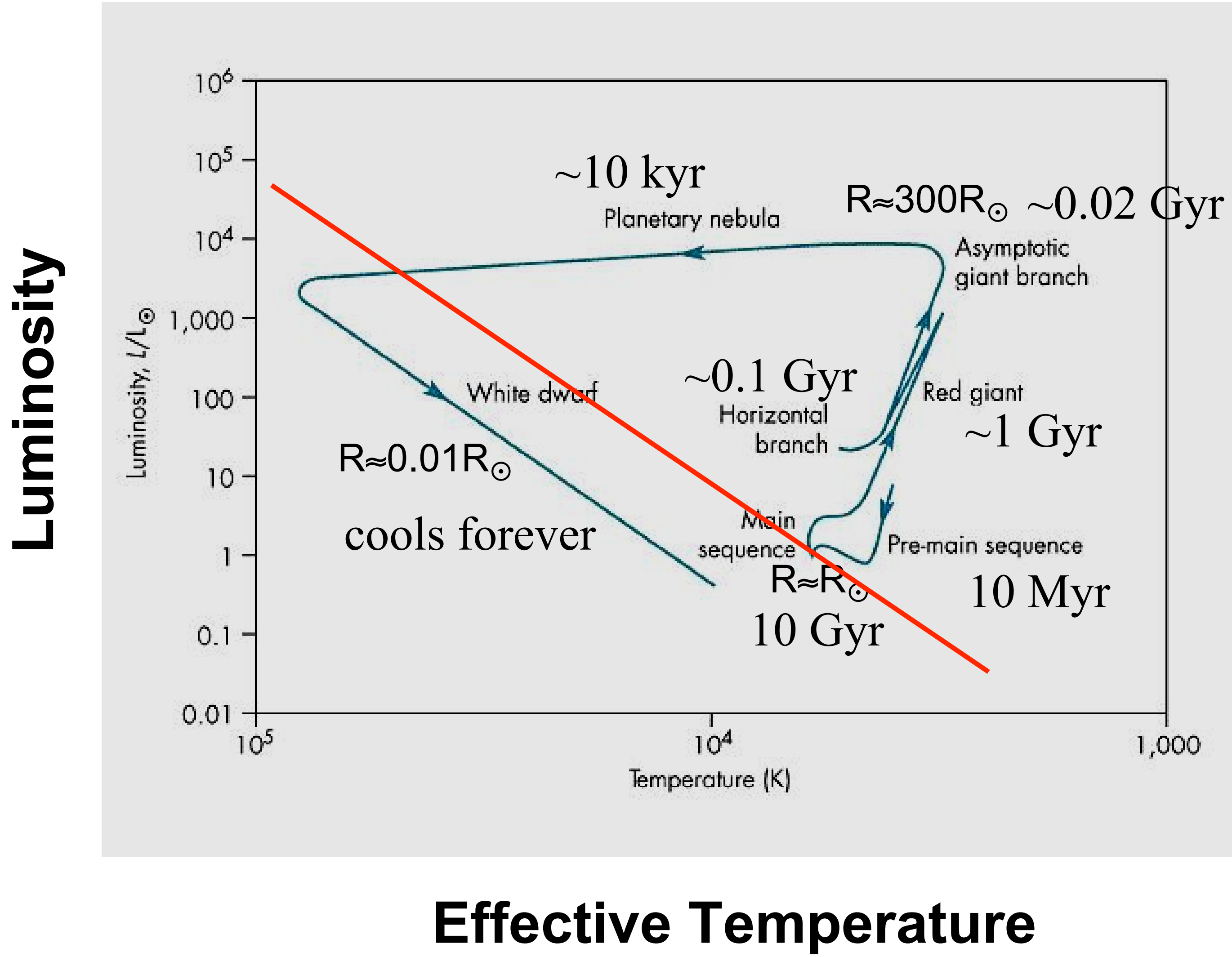
Same Process Repeats

Shell & Core Fusion of Heavier & Heavier Elements as Core Contracts & Heats Up

Luminosity Increases as Core Contracts

Star continues to expand

Evolution of Sun in the HR Diagram

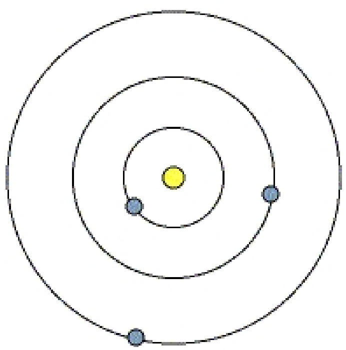


Note: Evolution of a star can be described by **how it moves in the HR diagram with time** (indicated by arrows)

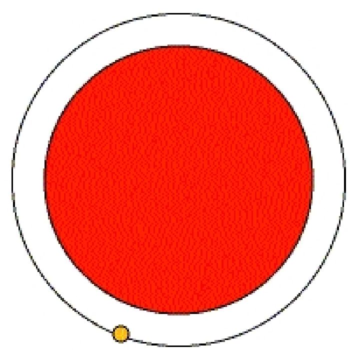
entire evolution to WD phase takes
< 1 billion yrs
< 10% of MS lifetime

Red Giant Phase

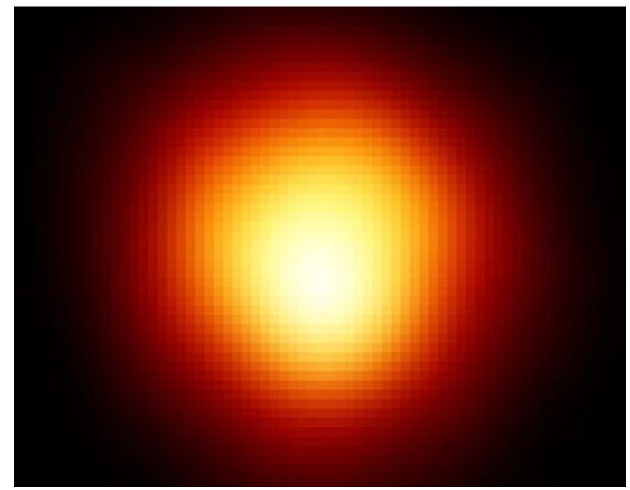
$L \approx 1000\ L_\odot$
$R \approx 1\ \text{AU} \approx 100\ R_\odot$
$T_{eff} \approx 3000$ K (red)



Now: hot core + warm surface; small size.



Future: very hot core + cool surface. Large size but less mass; very bright.

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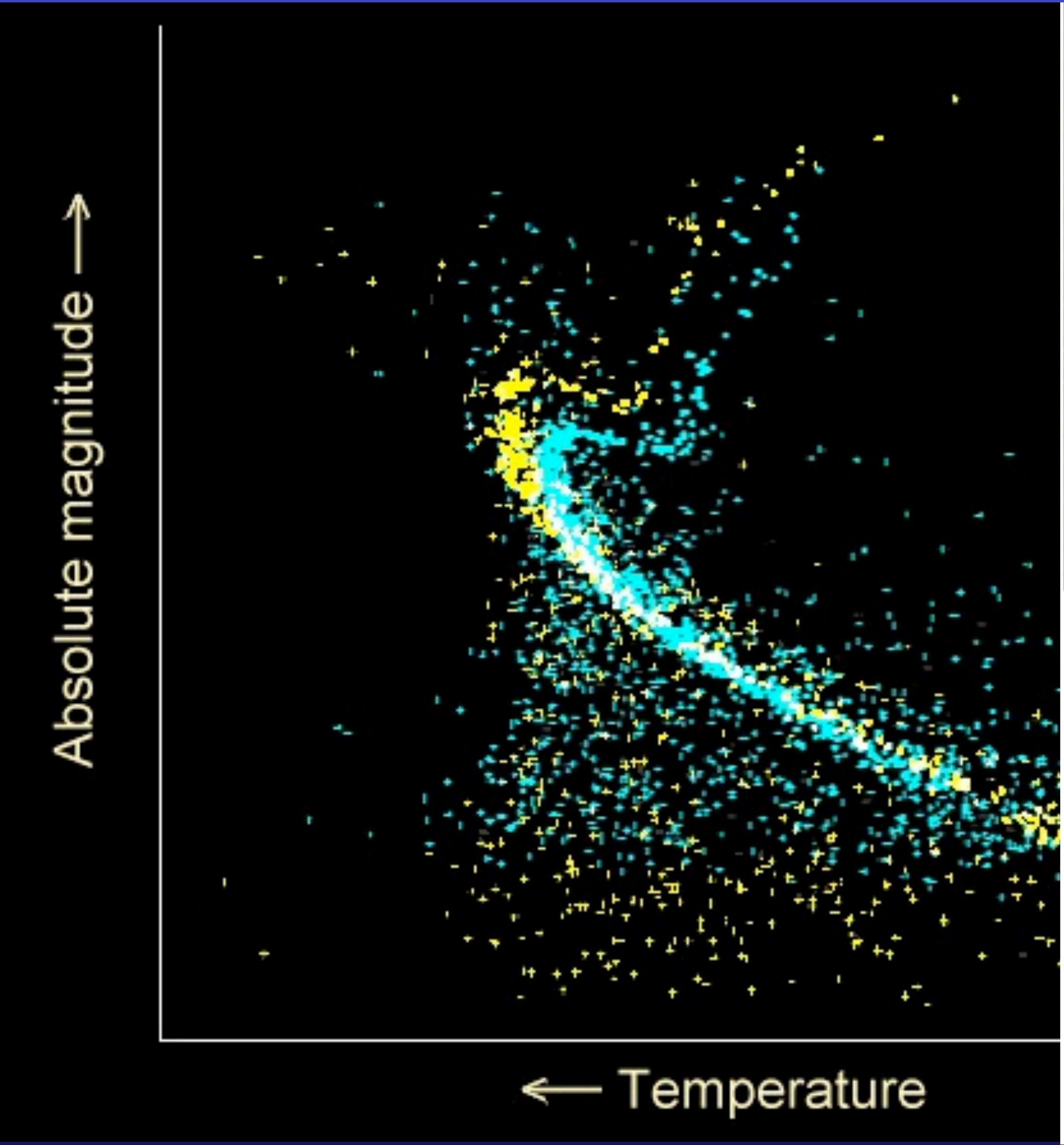
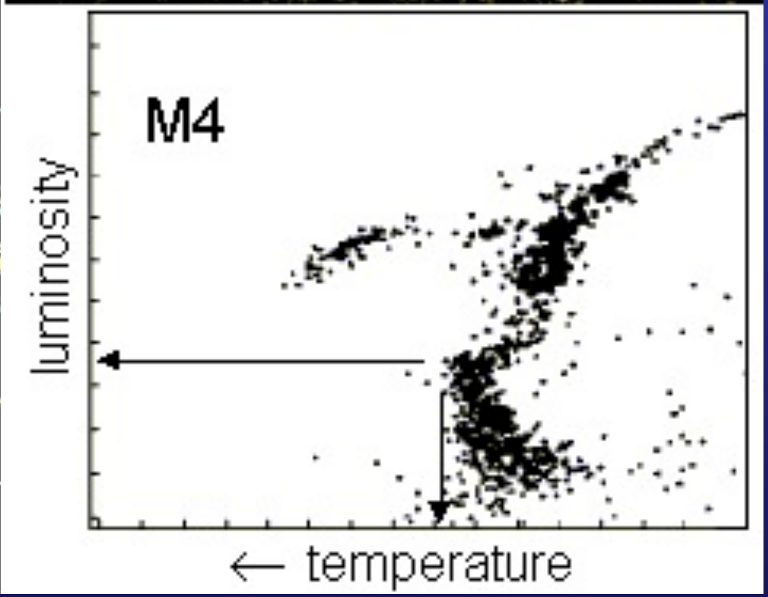
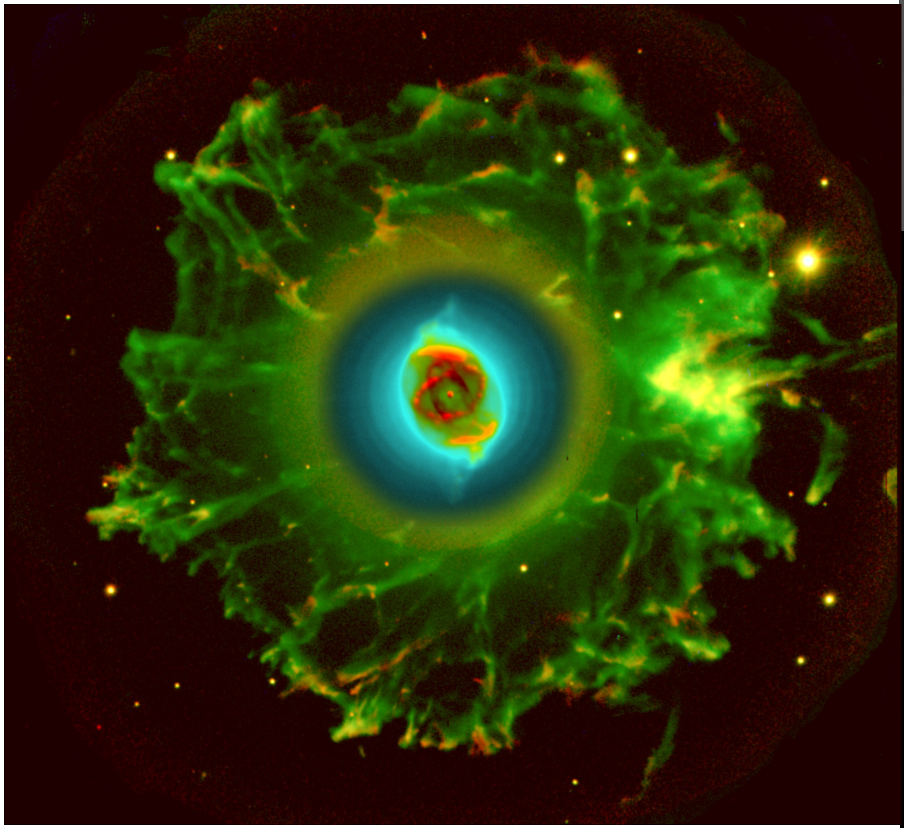
Main-Sequence "Turn-Off" Dating

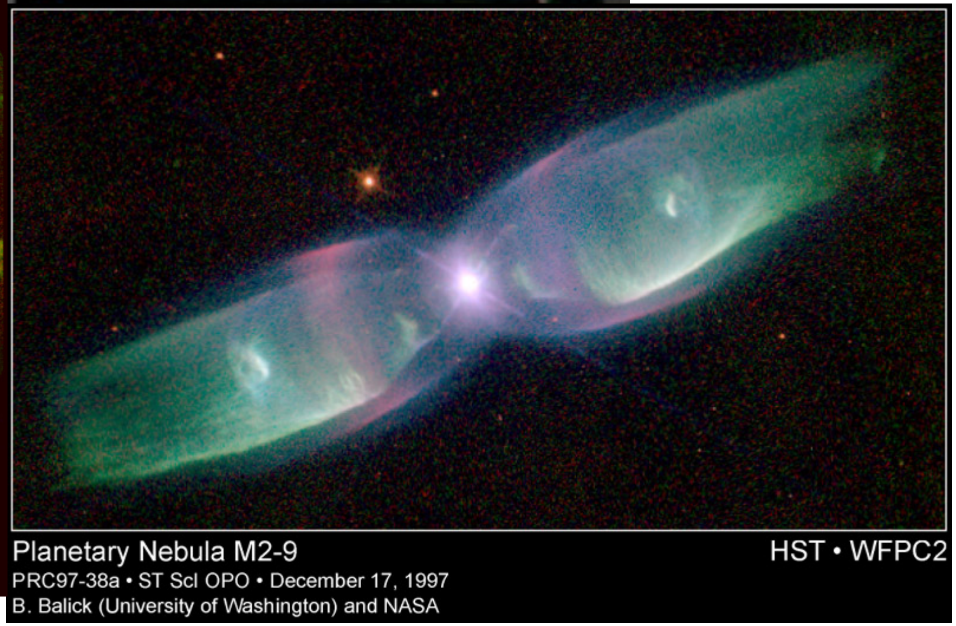


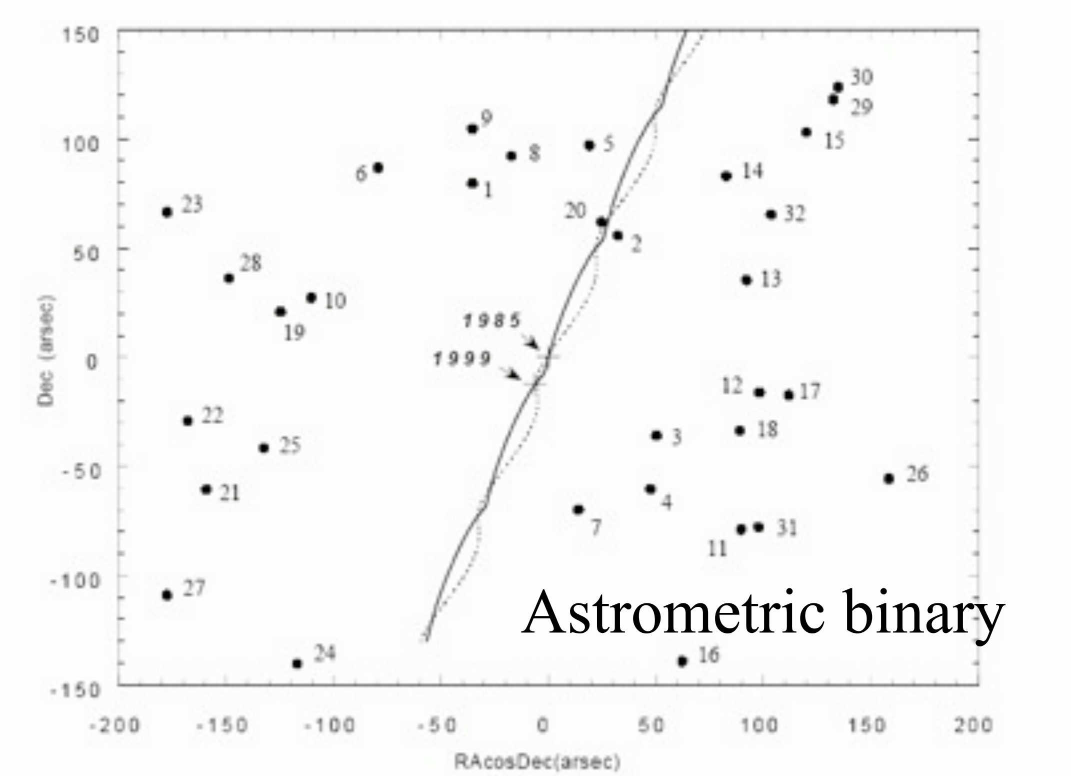


Planetary Nebula

"Cat's Eye Nebula"
(N lines = red
O lines = blue & green)

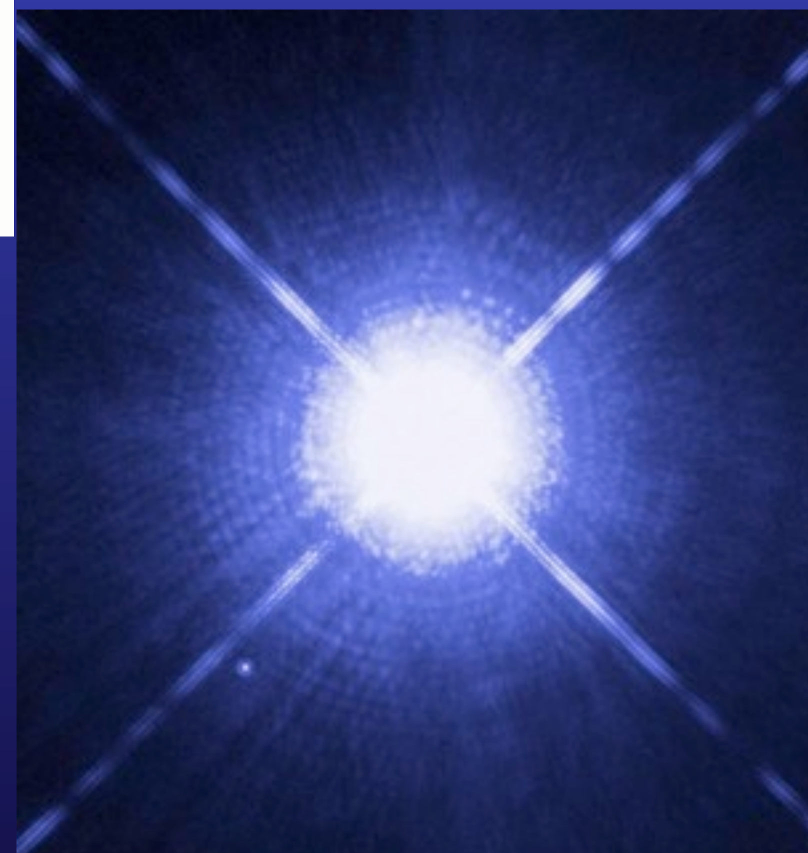




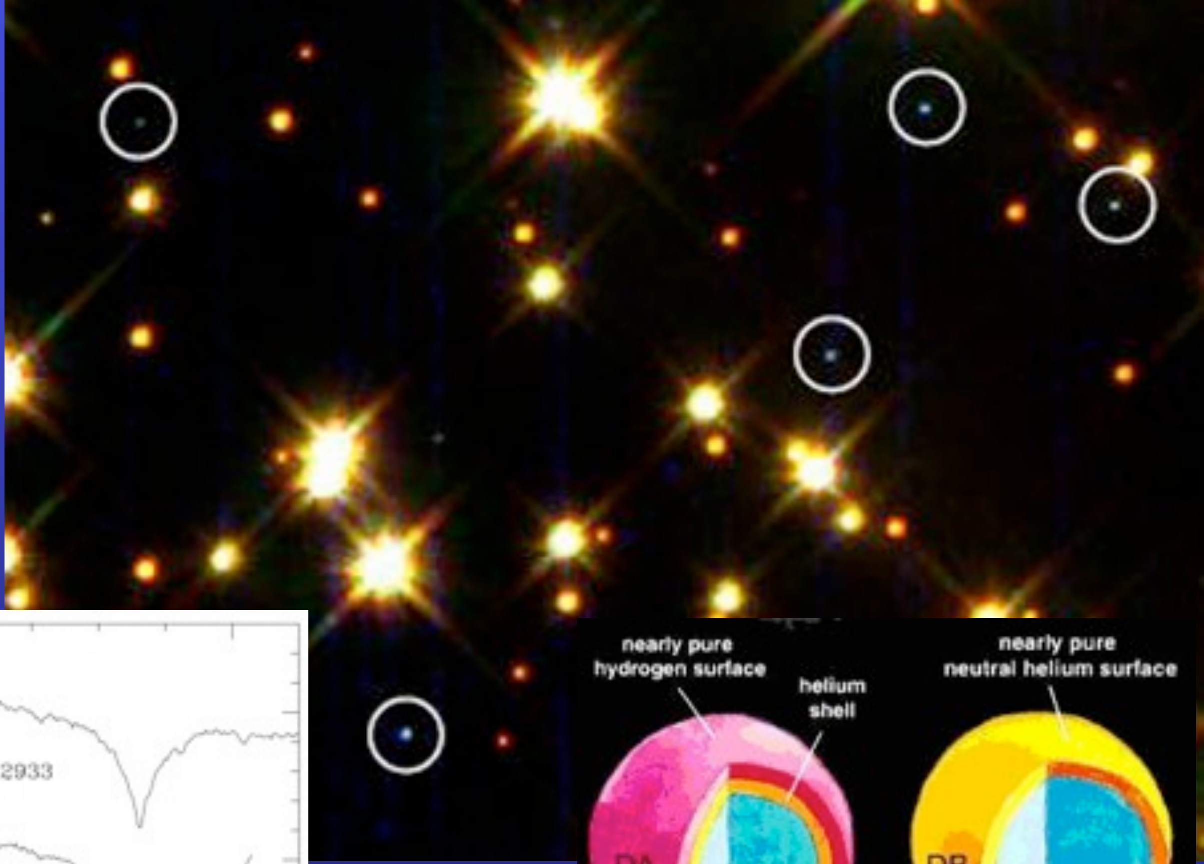


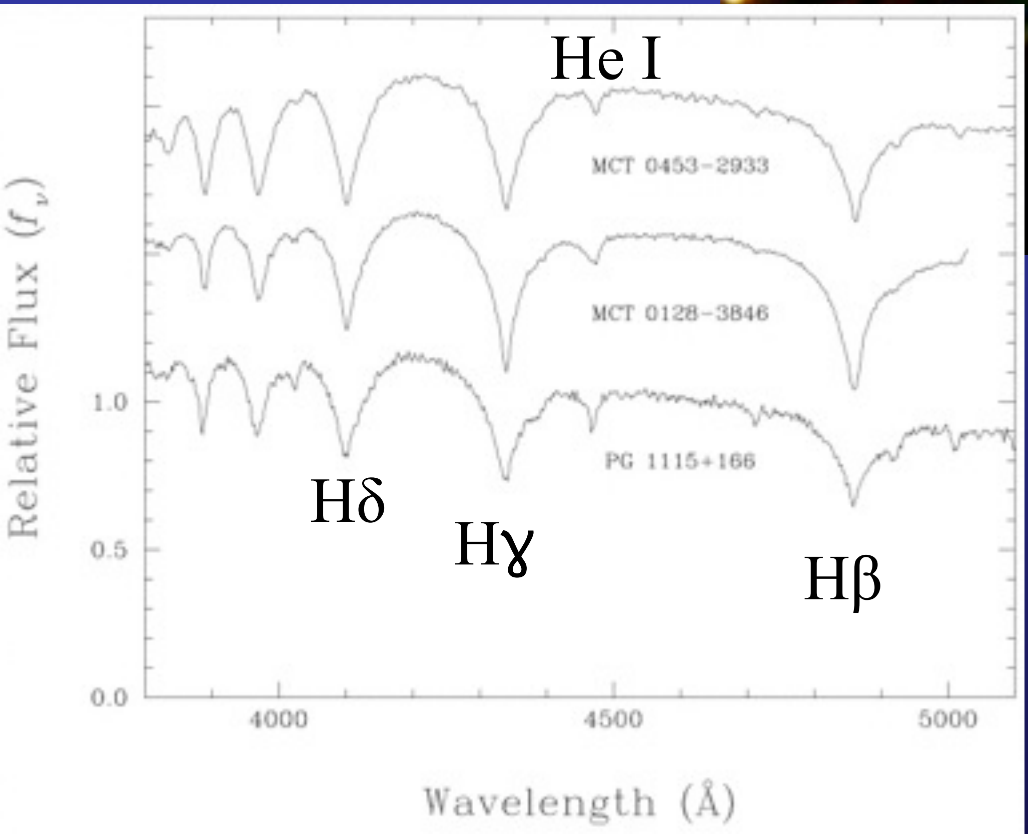
Sirius A and B

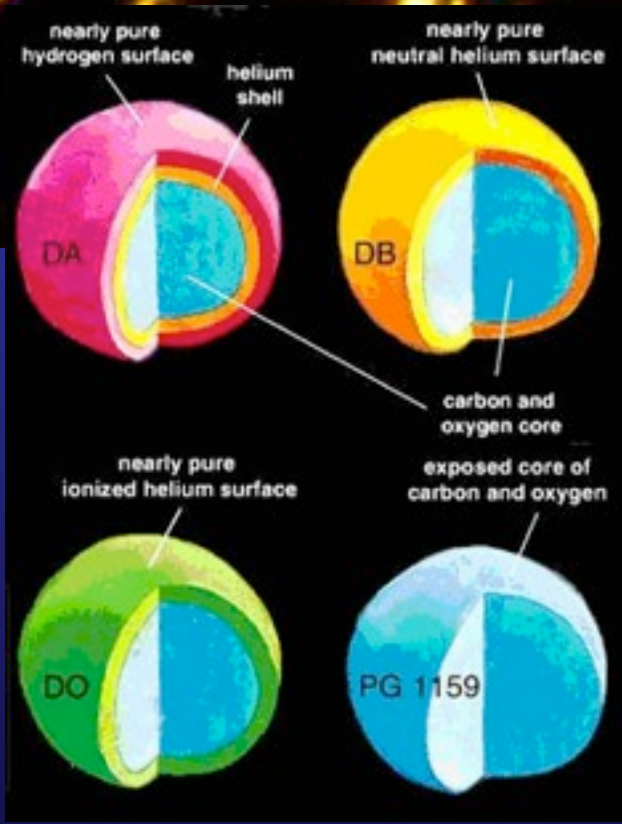
Sirius B is a white dwarf

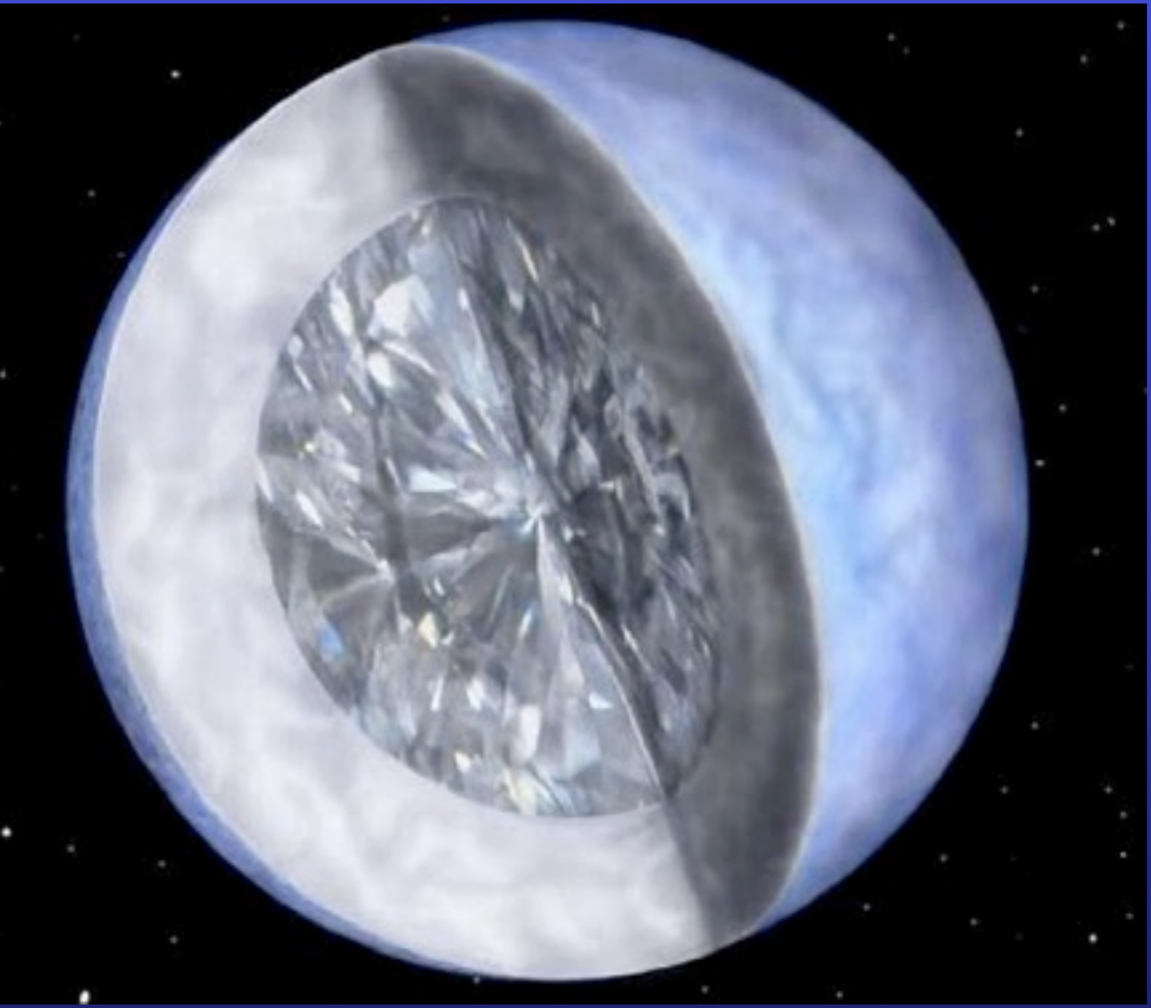


White Dwarf Spectra









White Dwarf
(Earth sized)

Neutron Star
(Berkeley sized)

Whole Earth Telescope

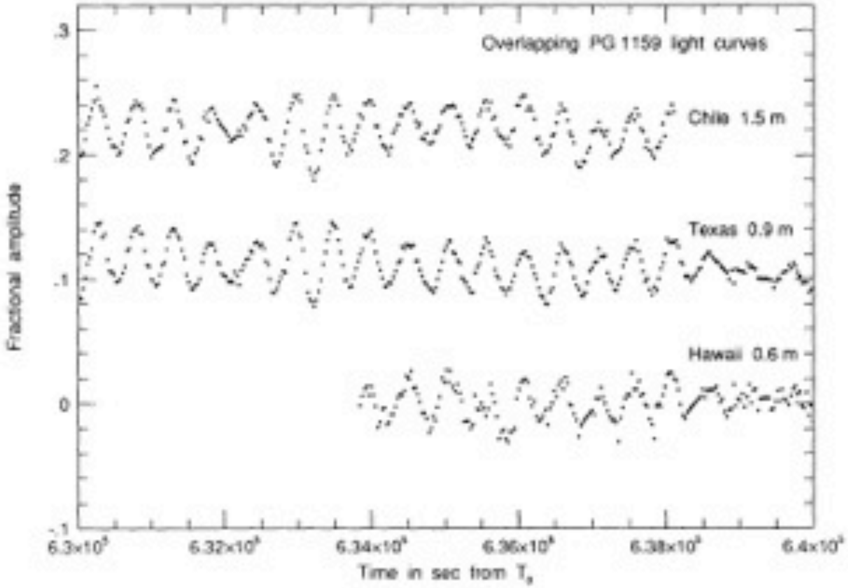
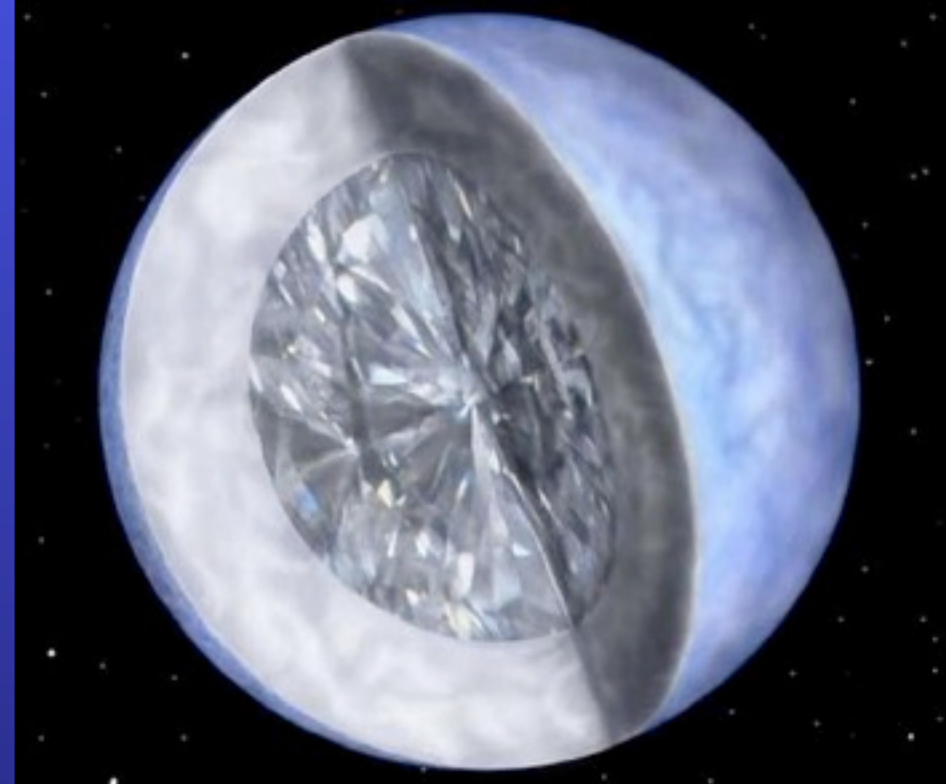


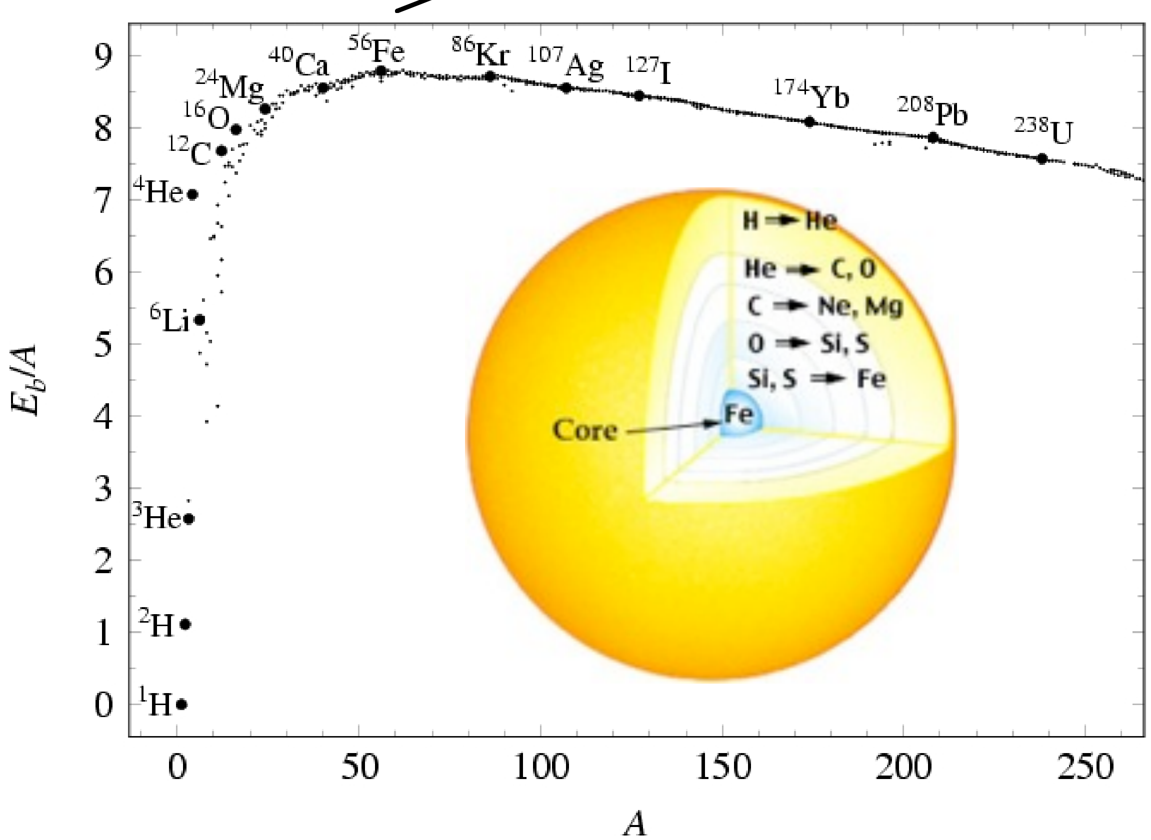
FIG. 6.—Portions of the light curve of PG 1159−035 as seen simultaneously by the 1.5 m telescope in Chile (*top curve*), the 0.9 m telescope in Texas (*middle curve*), and the 0.6 m telescope in Hawaii (*bottom curve*).



Binding Energy Curve

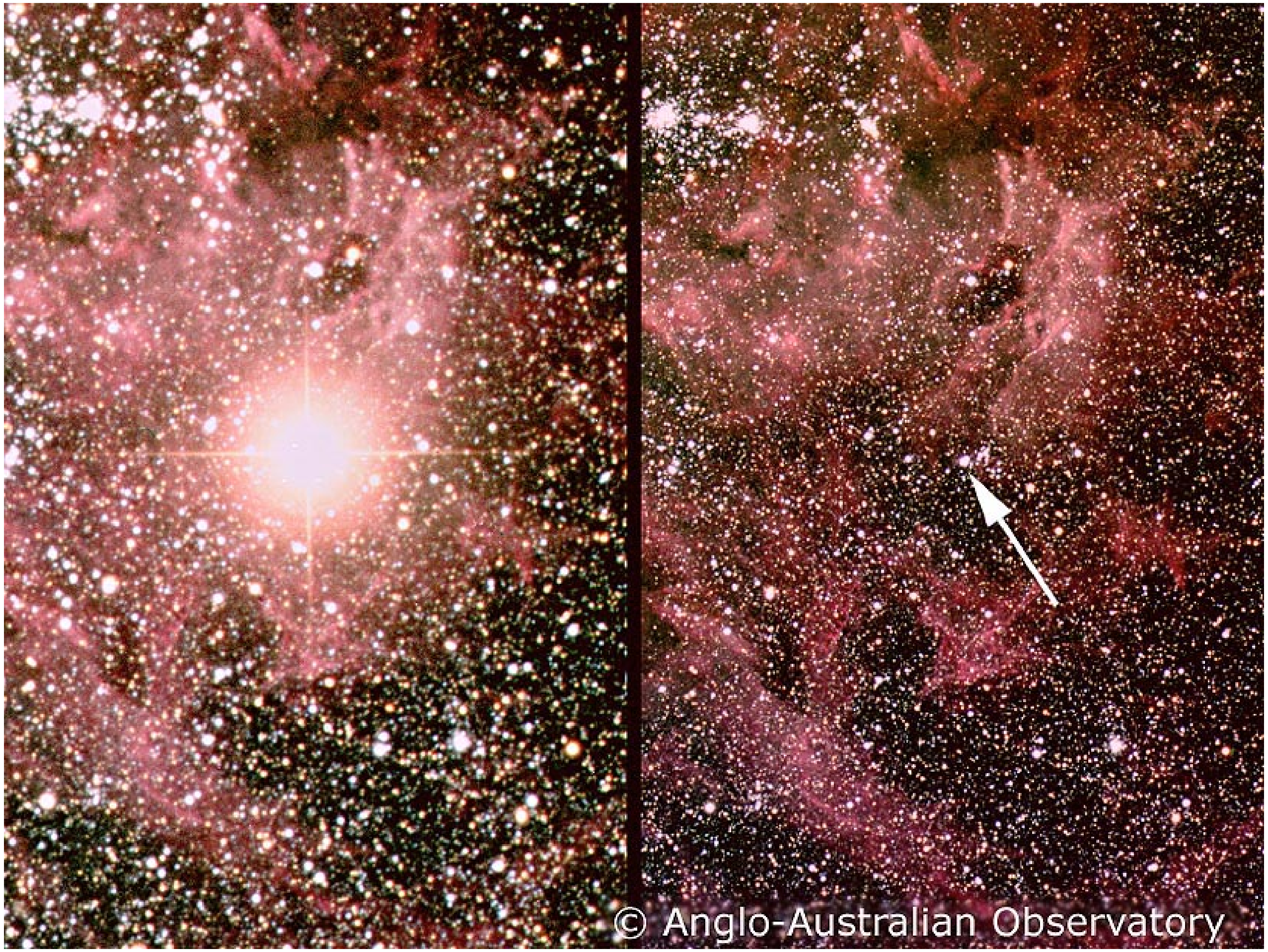
Iron is the most tightly bound nucleus – **cannot fuse above iron without input of energy**

Binding Energy Per Nucleon



Atomic Mass

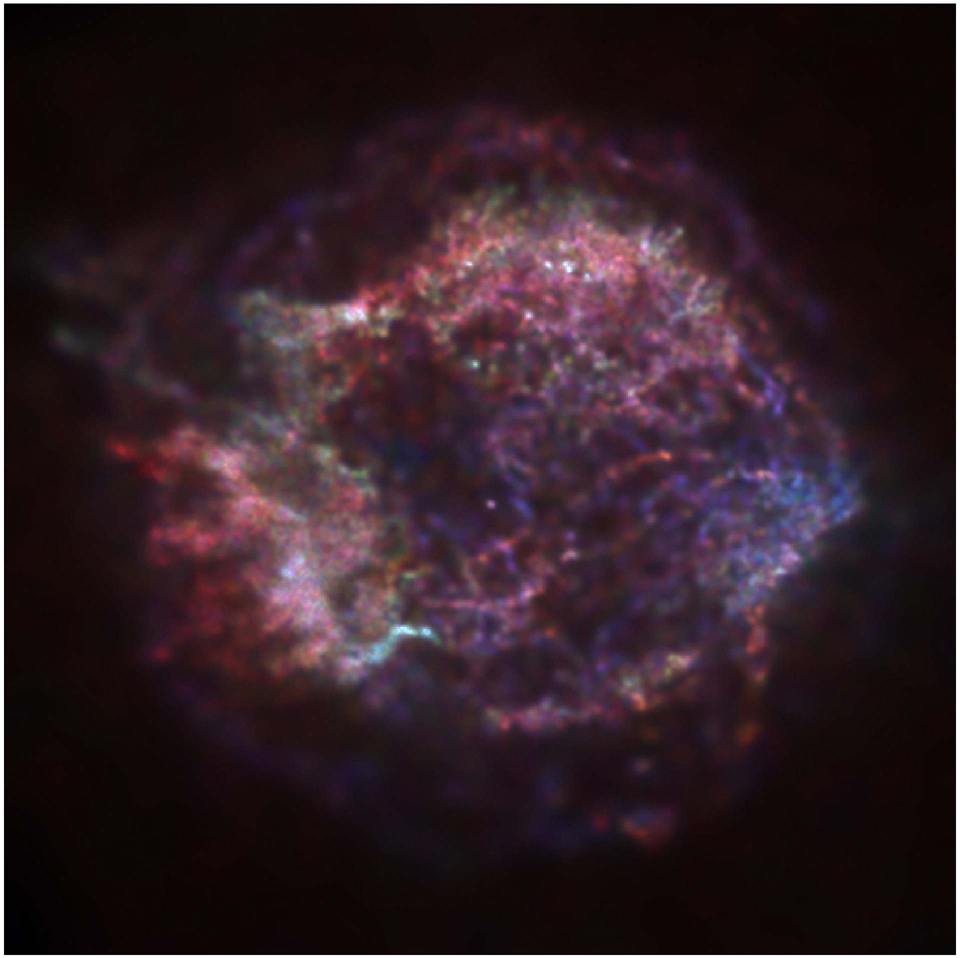
Supernova



After

Before

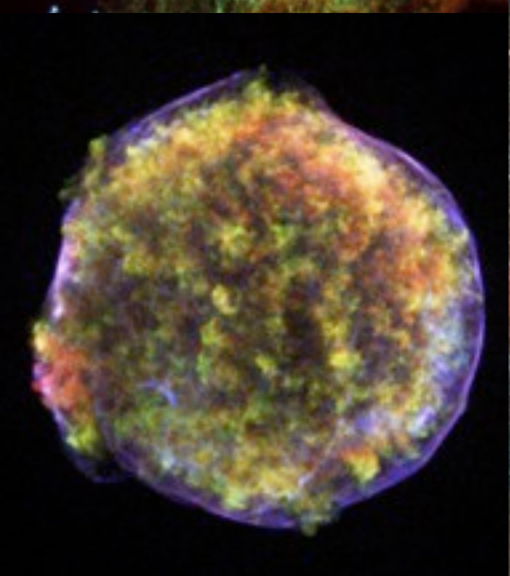
Supernova Remnants



X-ray Picture of SN Remnant Cas A

X-rays are emission lines from different elements (N, O, Fe) created by fusion in the star & its explosion

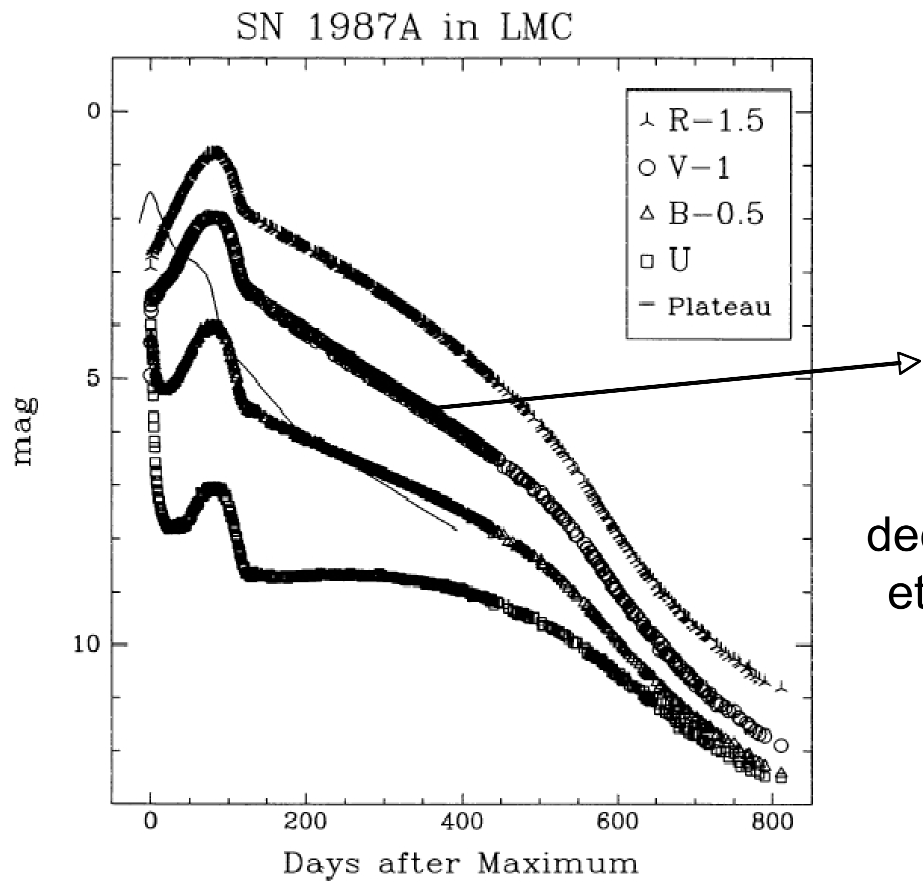





Supernova Remnant LMC N 49
Hubble Heritage
NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2

SN "Light Curves" – Flux vs. Time

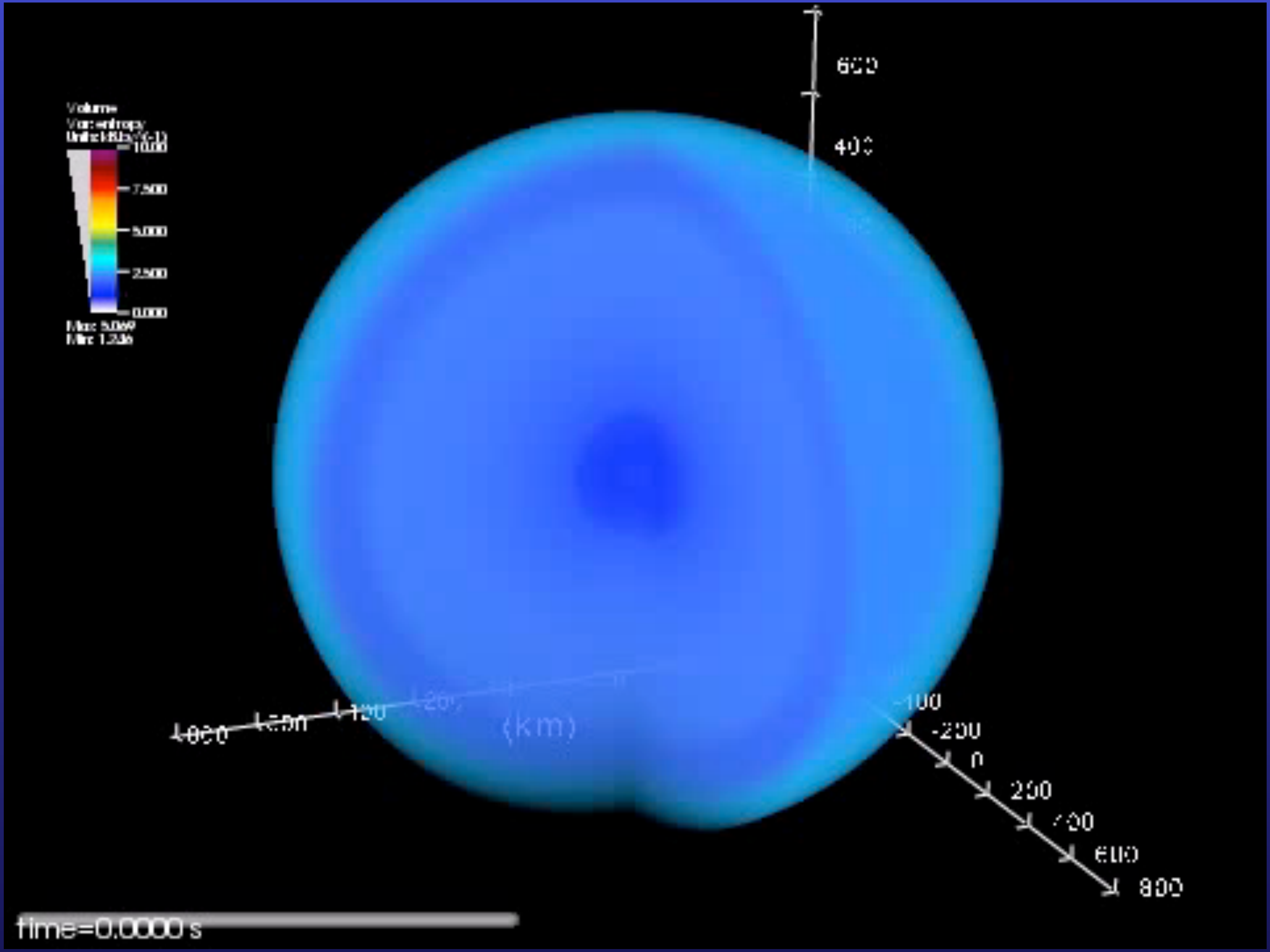
Flux



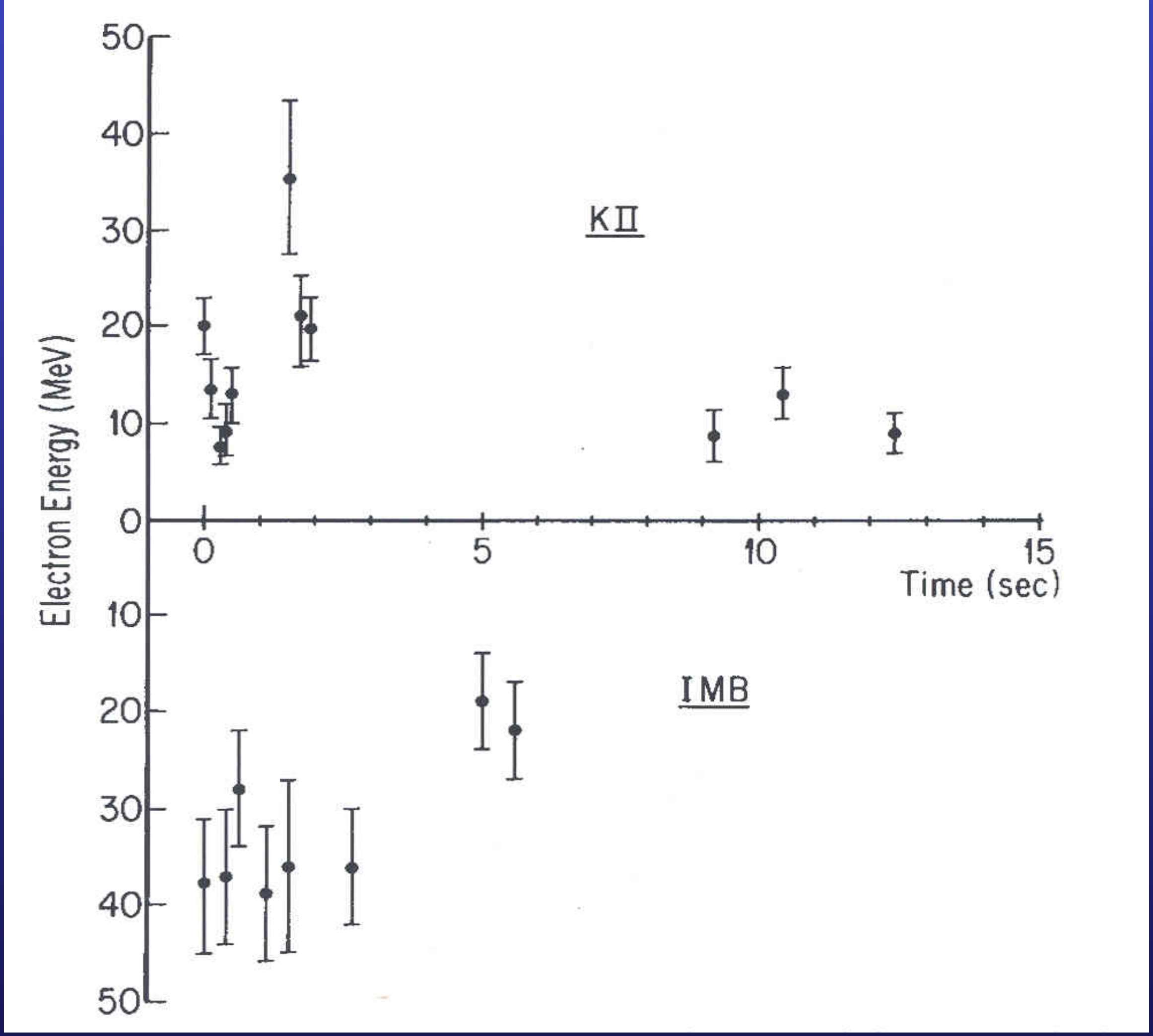
late time emission powered by radioactive decay of ^{56}Ni, ^{57}Co, etc., generated in explosion

time

Type II Supernova



The Neutrino Signature from SN 1987A

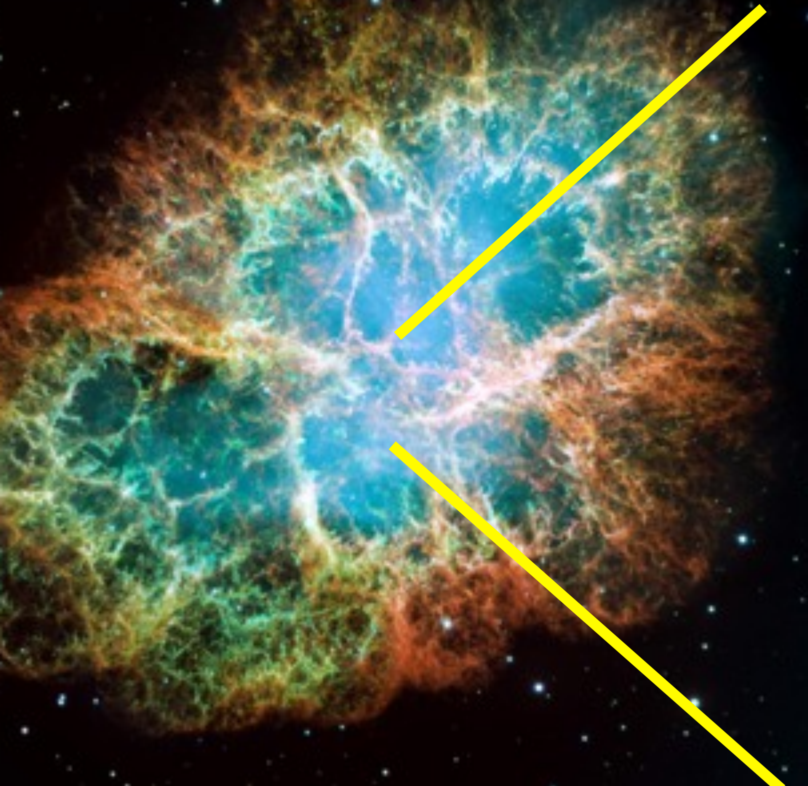


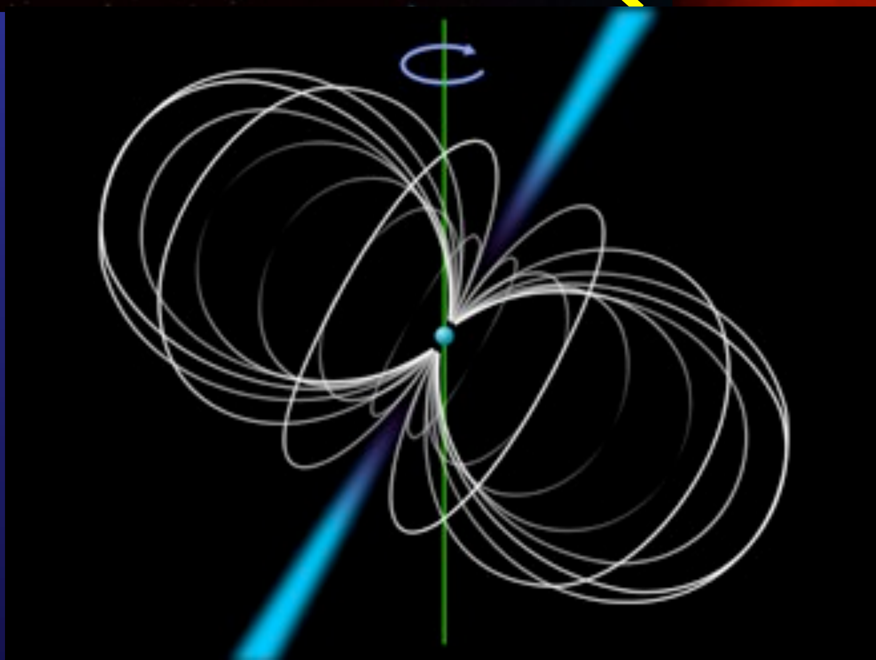
SN 1987A
D~50 kpc
(in a small
neighbor
of the MW)

19 Neutrino
events in
13 seconds.

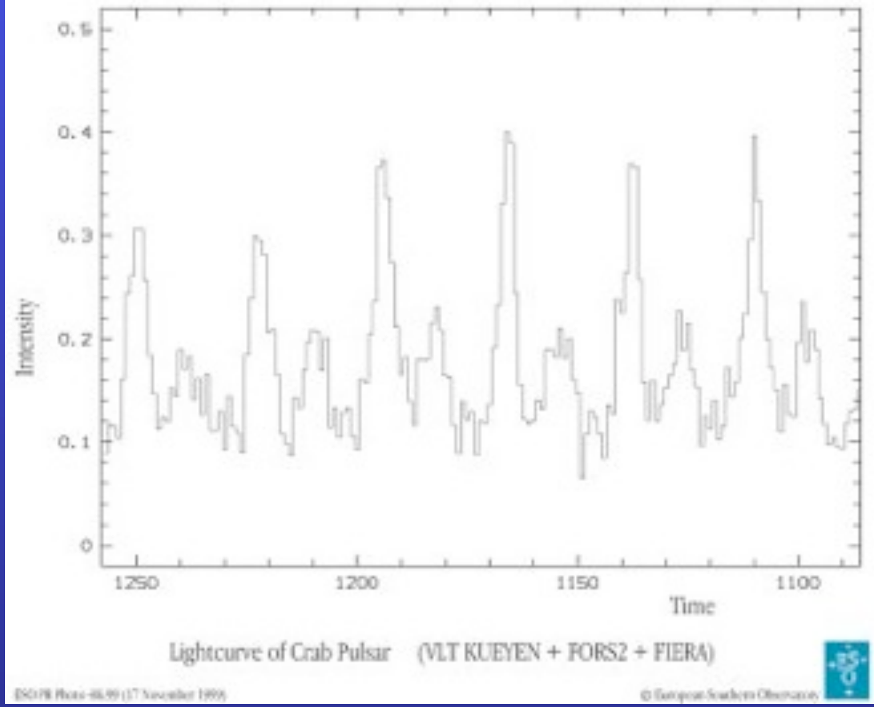
E ~ 2-3 10^{46} J
inferred in nu's

Type Ia Supernova

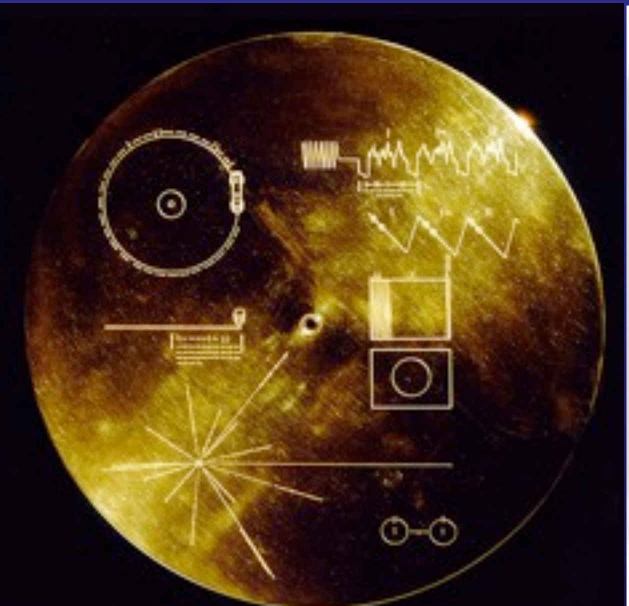




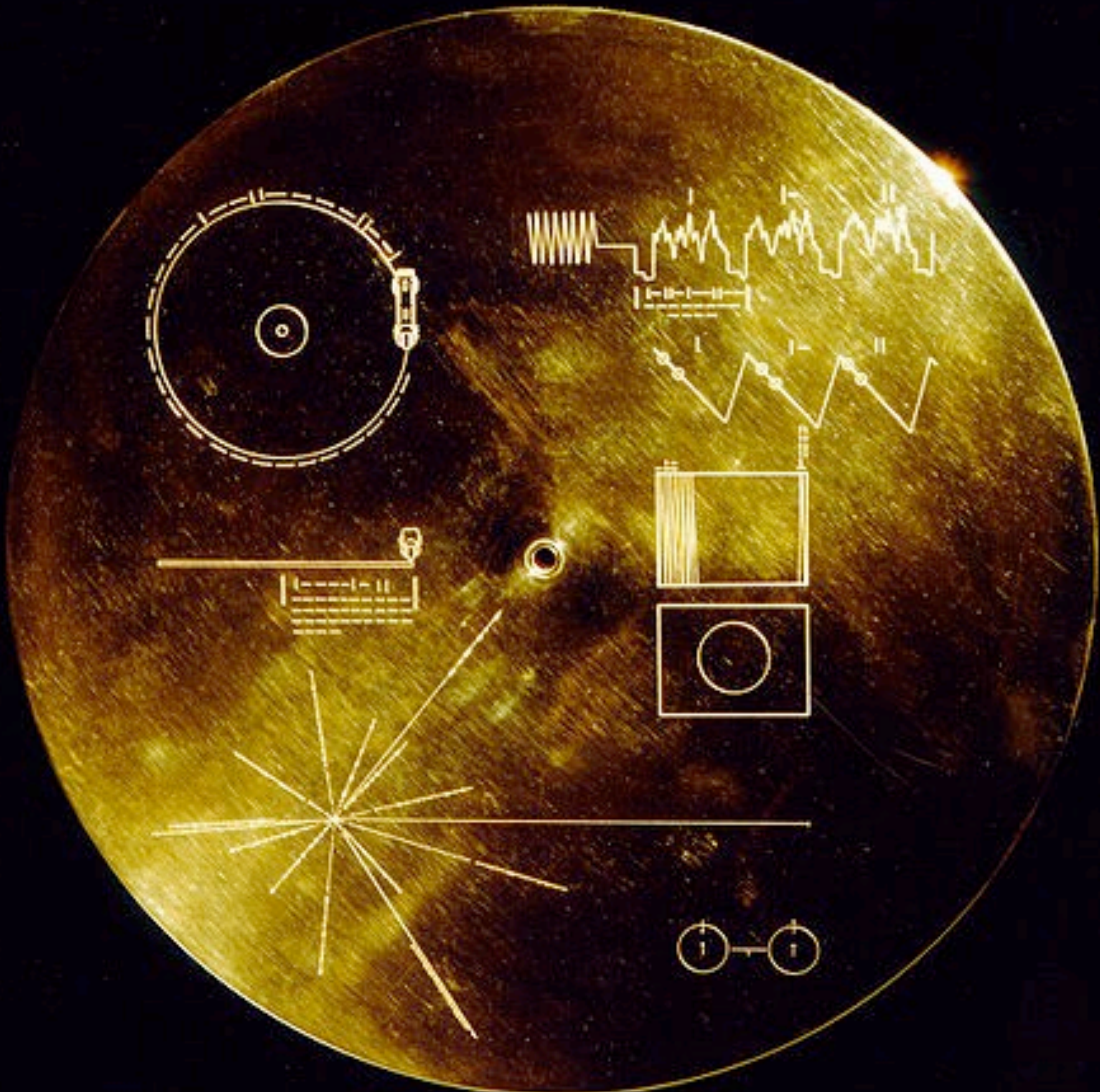
Pulsars = Rotating neutron stars emitting beams of particles and radiation

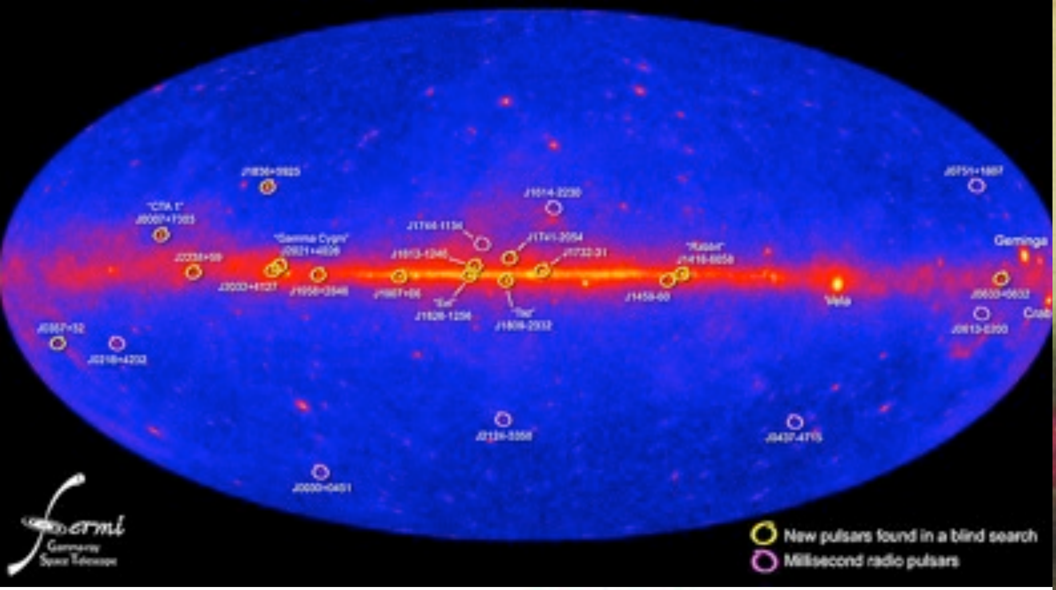


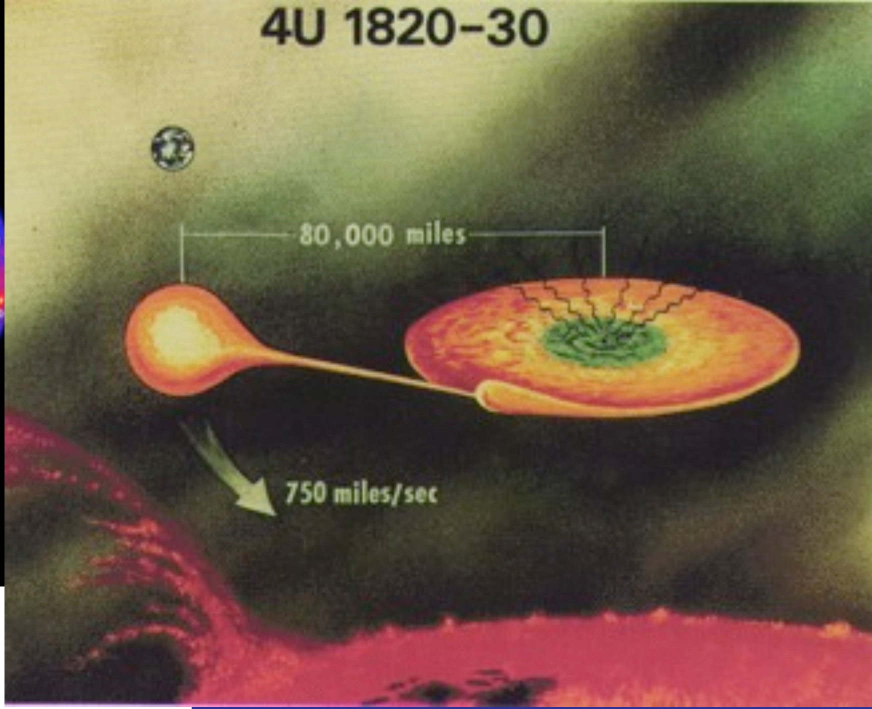
Pulsar periods range from 1 millisecond to 10 seconds

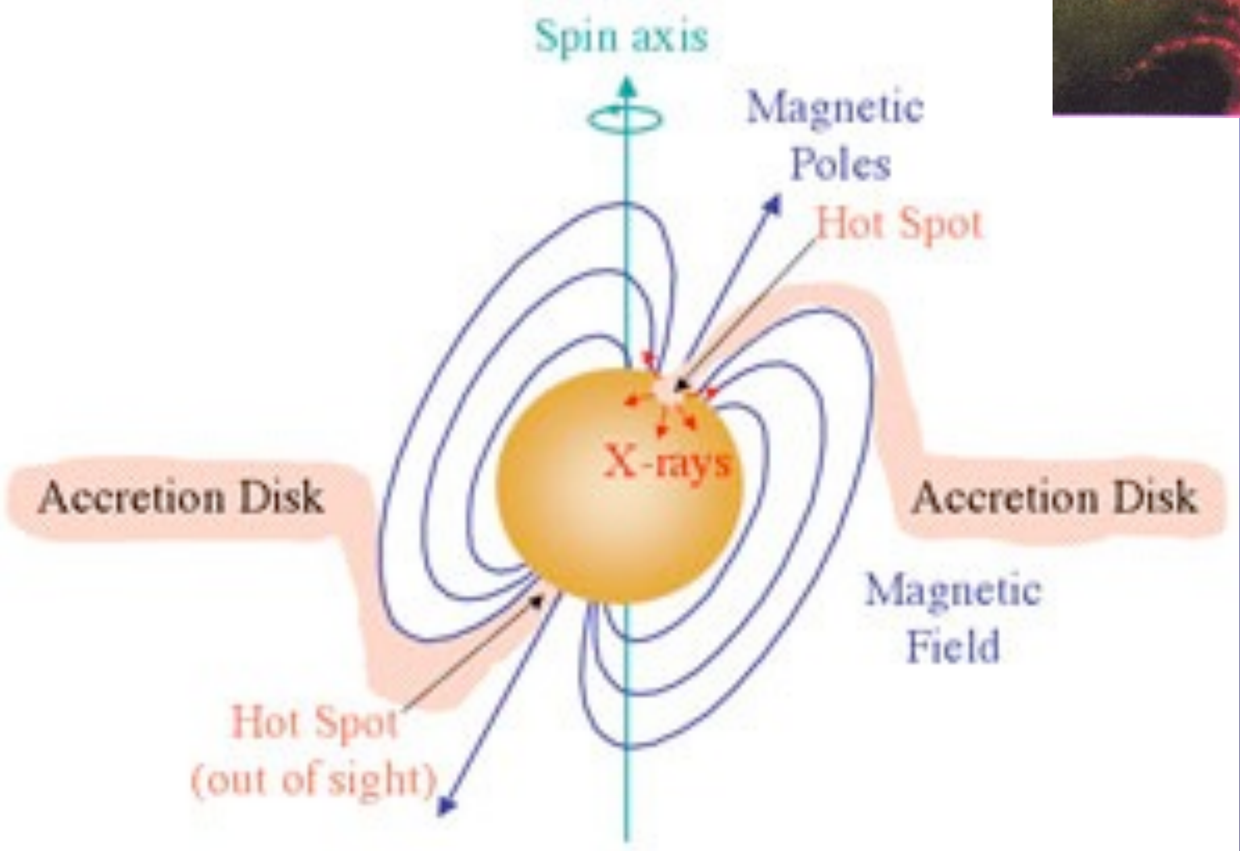


Voyager's "Golden Record" Cover



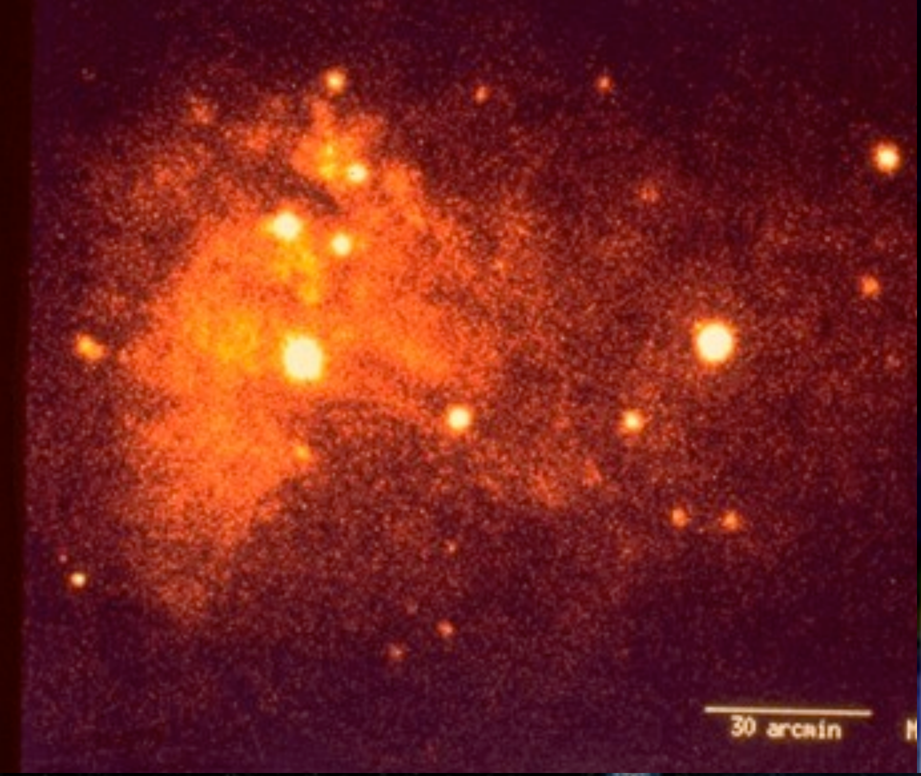


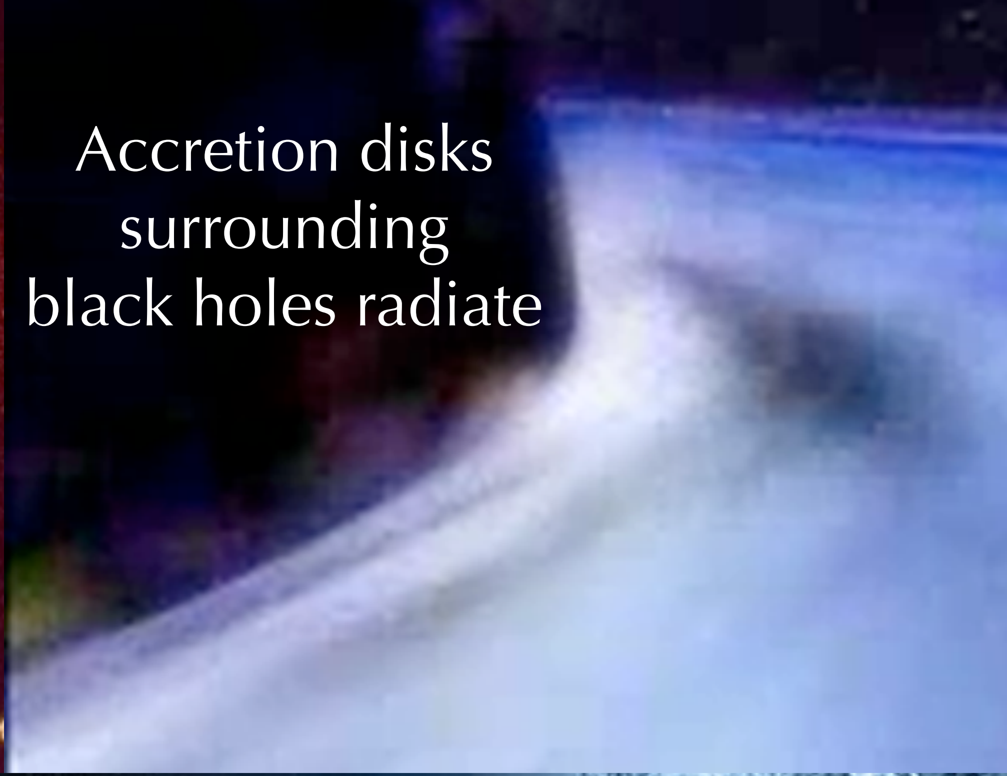




Neutron stars can accrete from companion stars

Accretion disks
surrounding
black holes radiate





Gravity warps space (and time)

Kepler's laws break down

Even photons with no mass can have their trajectories bent ("gravitational lensing")