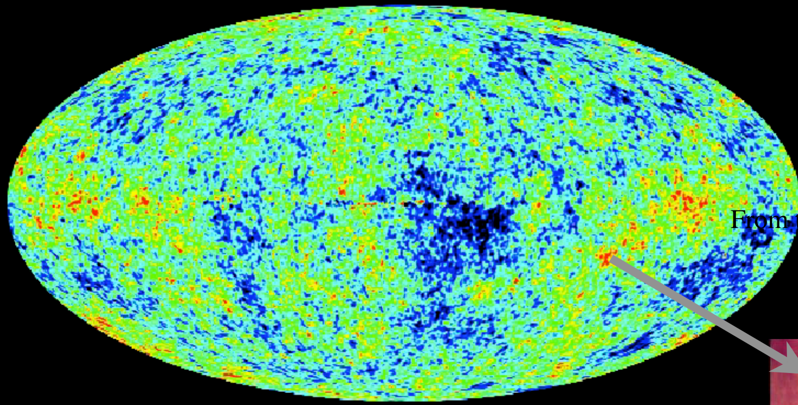
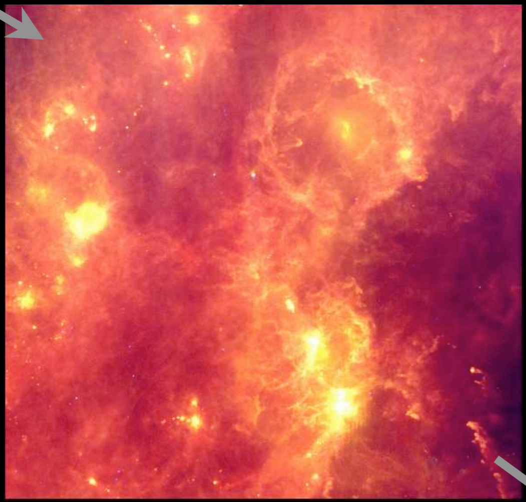


From the Big Bang to the Blue Planet



OCEAN 355
Prof. Julian Sachs
Autumn 2008
M,W,F 11:30-12:20
425 OSB

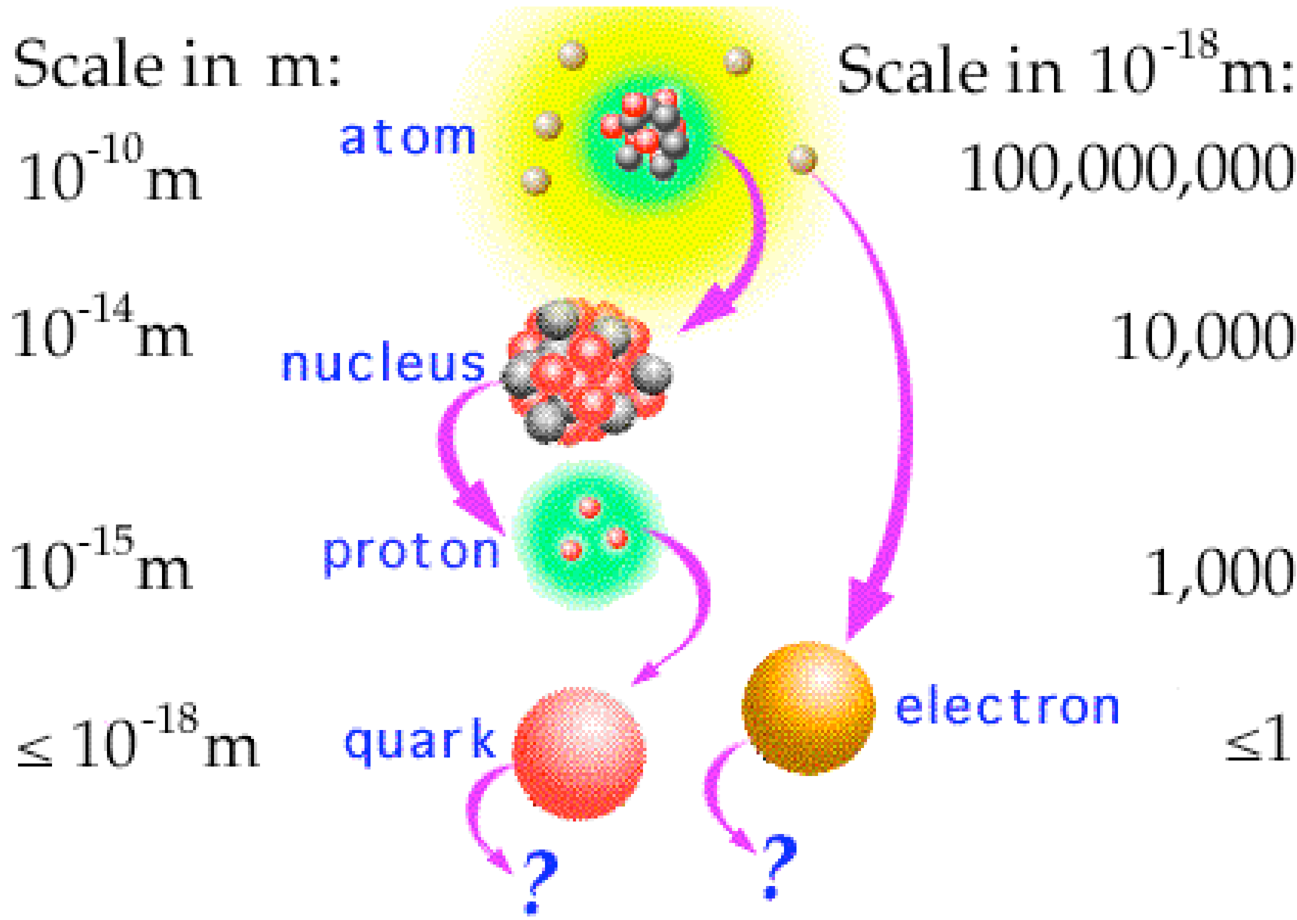
We will explore the origin and evolution of the Earth, ocean, atmosphere & life, with an emphasis on climate as the integrator of changes in the biosphere, cryosphere, hydrosphere, atmosphere, & lithosphere.

Sources and Literature Cited for Astronomy Lectures

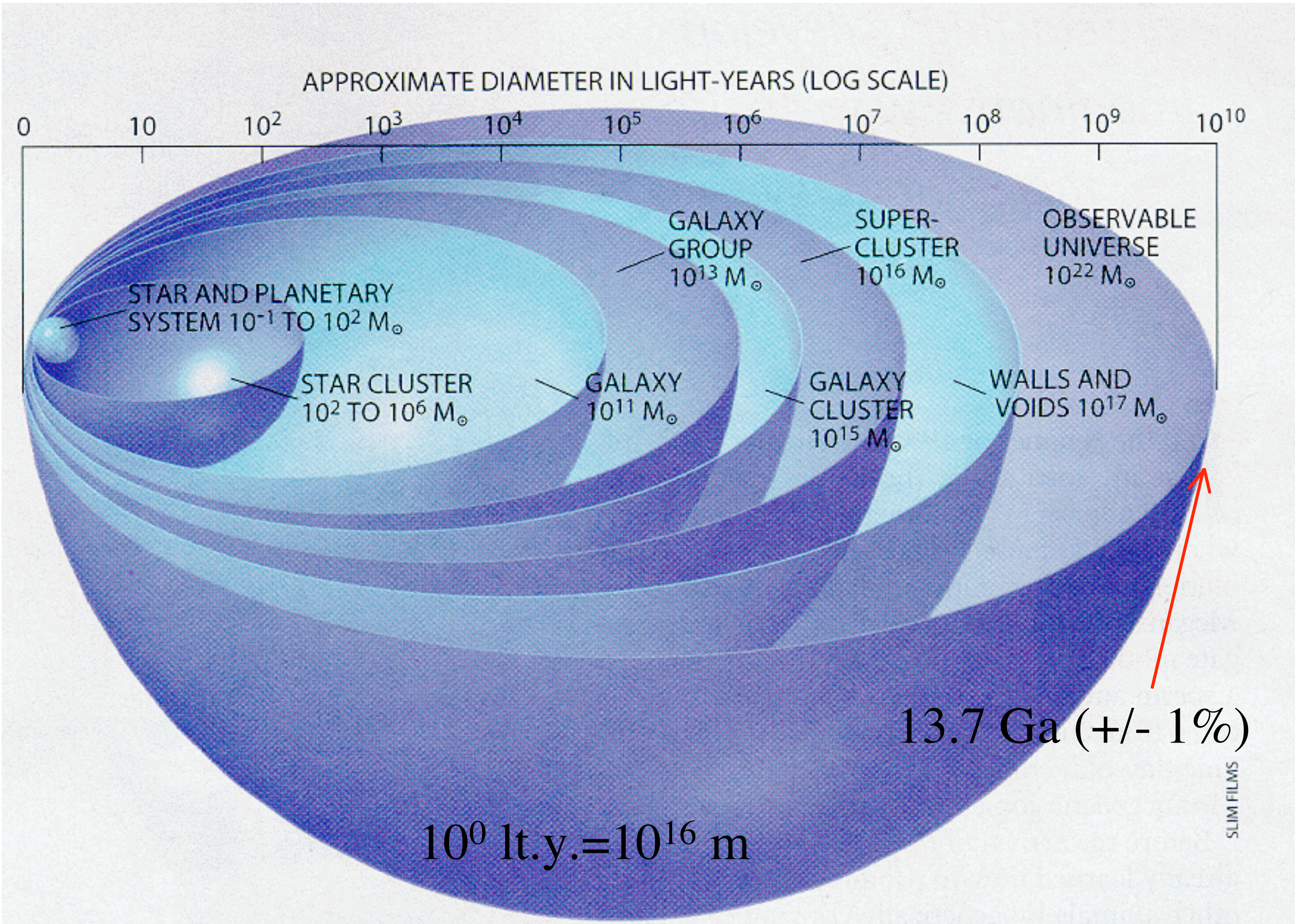
Except where noted, much of the material in these notes comes from:

- Pasachoff & Filippenko (2007) The Cosmos: Astronomy in the New Millennium, 3rd Edition, Brooks/Cole Publishing, 480 p.
- HyperPhysics by Carl R. Nave (Georgia State University), http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html
- Prof. Barbara Ryden's lectures at the Ohio State University, http://www.astronomy.ohio-state.edu/~ryden/
- Prof. Davison Soper's lectures at the University of Oregon, http://zebu.uoregon.edu/~soper/
- The Wilkinson Microwave Anisotropy Probe (WMAP) mission website, http://map.gsfc.nasa.gov/index.html
- The Hubble Space Telescope website, http://hubblesite.org/
- Wikipedia, http://en.wikipedia.org/

Distance Scales-Atomic

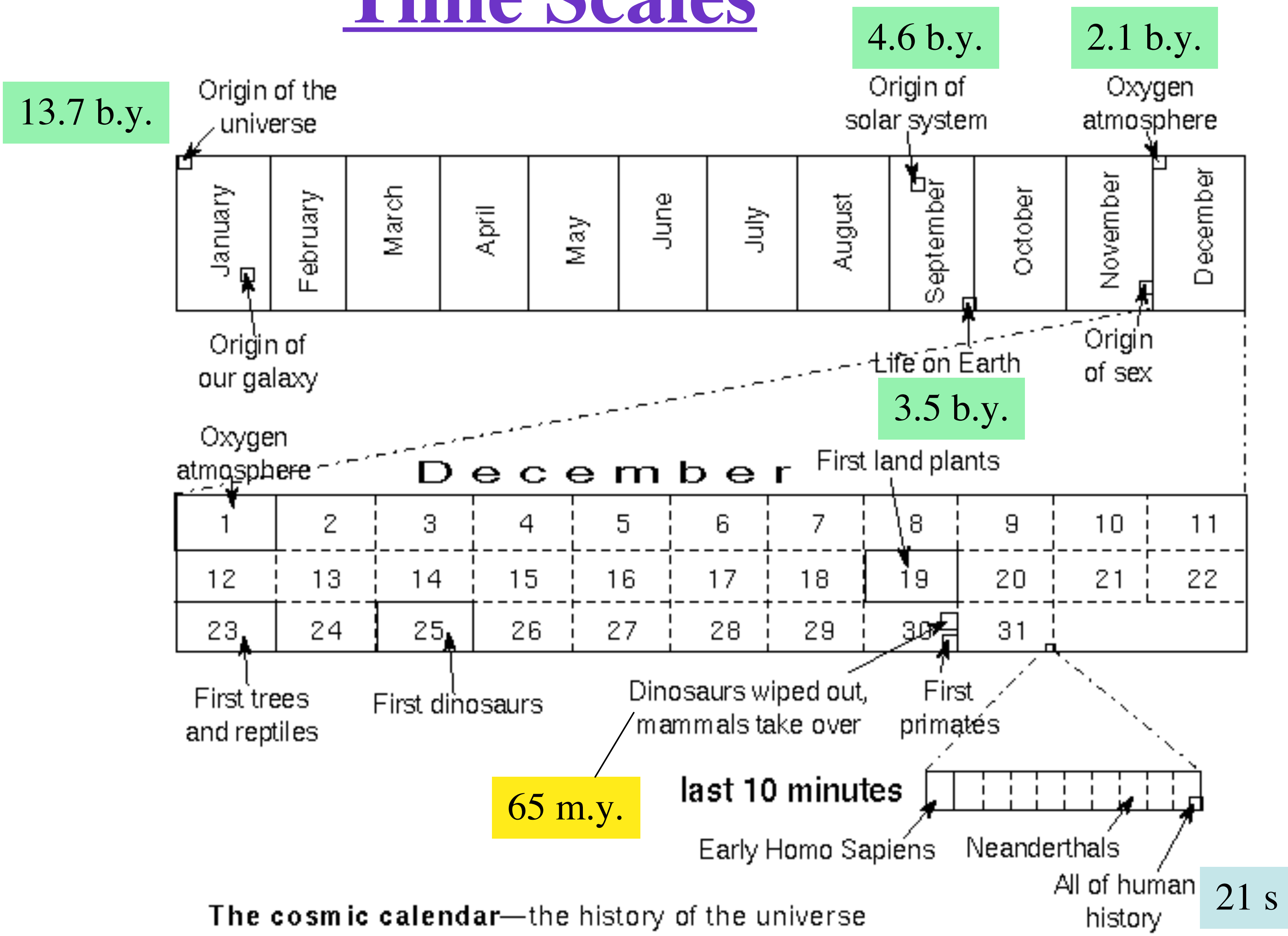


Astronomical Distances



--> Atomic scale to universe scale = 40 orders of magnitude!

Time Scales



The cosmic calendar—the history of the universe compressed to one year. All of recorded history (human civilization) occurs in last 21 seconds!

Avg. human life span=0.15 s

• Inspired by Carl Sagan in television series *Cosmos*

The standard cosmological model of the formation of the universe:

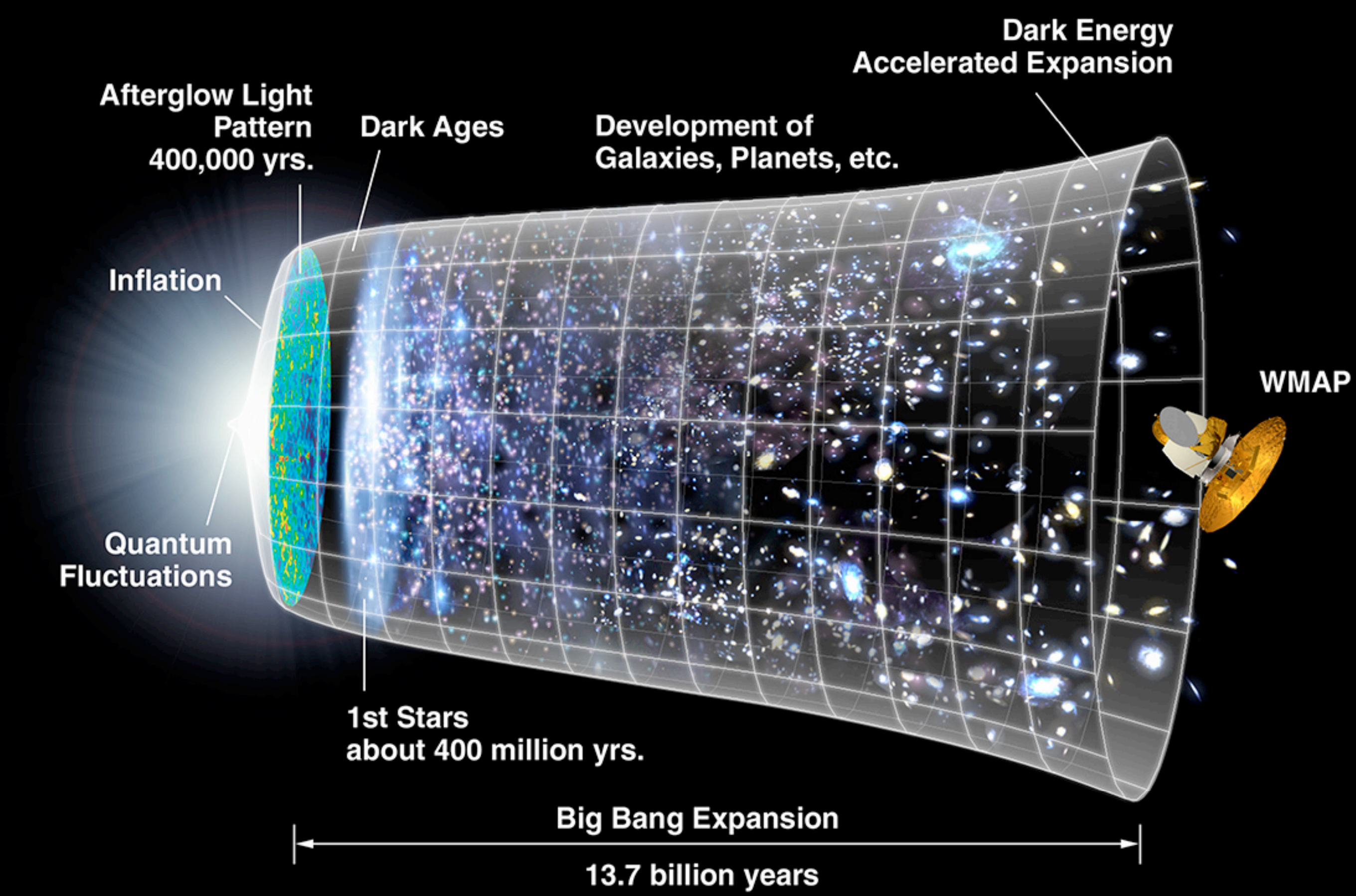
“The Big Bang”

• From Steven Weinberg, ***The First Three Minutes***

•Also see:
http://superstringtheory.com/cosmo/cosmo3.html
for a terrific tour of the Big Bang!

Time	T(K)	E	Density	What’s Happening?
.02 s	10^{11} K	8.6 MeV	4×10^{9}	The universe is mostly light. Electrons and positrons created from light (pair-production) and destroyed at about equal rates. Protons and neutrons being changed back and forth, so about equal numbers. Only about one neutron or proton for each 10^{9} photons.
.11 s	3×10^{10}	2.6 MeV		Free neutrons decaying into protons, so there begins to be an excess of protons over neutrons.
1.09 s	10^{10} K	860 KeV	4×10^{5}	Primeval fireball becomes transparent to neutrinos, so they are released. It is still opaque to light and electromagnetic radiation of all wavelengths, so they are still contained. Electron-positron annihilation now proceeding faster than pair-production.
13.8s	3×10^{9}	260 KeV		Below pair-production threshold
3 m 2 s	10^{9}K	86 KeV		Electrons and positrons nearly all gone. Photons and neutrinos are main constituents of the universe. Neutron decay leaves 86% protons, 14% neutrons but these represent a small fraction of the energy of the universe.
3 m 46s	0.9x 10^{9}K	78 KeV		Deuterium is now stable, so all the neutrons quickly combine to form deuterium and then helium. There is no more neutron decay since they are stable in nuclei. Helium about 26% by weight in universe from this early time. Nothing heavier formed since there is no stable product of mass 5.
34m 40 s	3×10^{8}	26 KeV	10	Nuclear processes are stopped, expansion and cooling continues. About 1 in 10^{9} electrons left because of a slight excess of electrons over positrons in the primeval fireball.
7x 10^{5} yrs	3000 K	0.26 eV		Cool enough for hydrogen and helium nuclei to collect electrons and become stable atoms. Absence of ionized gas makes universe transparent to light for the first time.
10^{10} yrs	3K			Living beings begin to analyze this process.

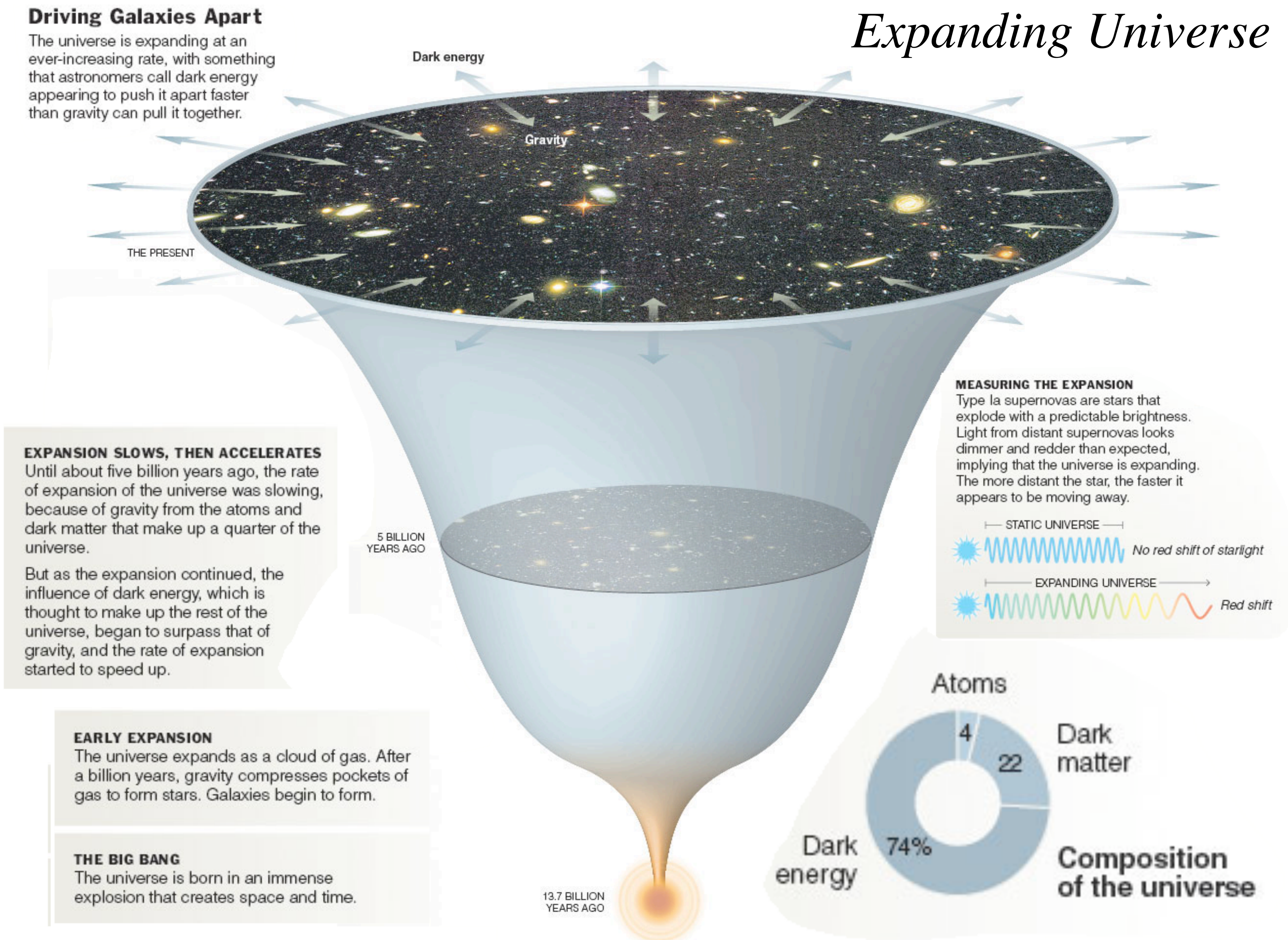
Timeline of the Universe



NASA/WMAP Science Team

Wilkinson Microwave Anisotropy Probe mission, http://map.gsfc.nasa.gov/m_mm.html

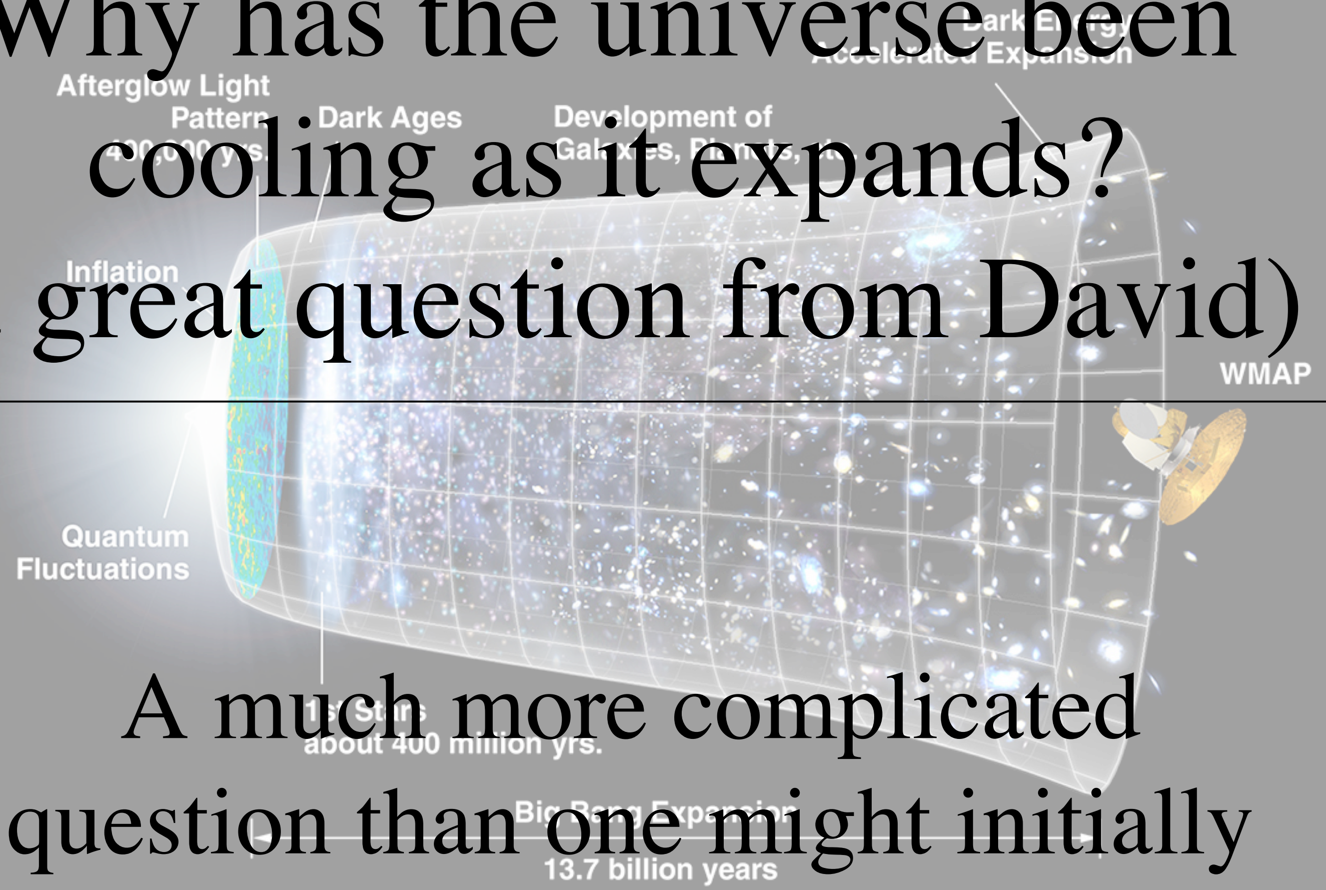
Expanding Universe



NY Times, 6/3/08

*** Stopped Here - 9/24/08 ***

Why has the universe been cooling as it expands? (a great question from David)



A much more complicated question than one might initially expect….

Simplest, (Least Controversial?) Explanation

- The result of a conversion of thermal energy produced by the Big Bang into non-thermal forms of energy, such as kinetic energy, resulting in a decrease of heat in the universe (I.e., cooling)

Generally Accepted Principles-1

- Conservation of energy
  - though on a Universe-wide, or cosmological scale, even this is not unanimously agreed upon:

    "While cosmologists usually have no problem with applying laws of physics, as they are known under the earthly conditions, locally, they face uncertainty when these laws are applied to the universe as a whole (which is connected to the curvature of space-time). The law of conservation of energy is no exception. However, this peculiarity of the cosmological interpretation of the energy conservation law is not negating the explanation of the cooling effect which attributes it to the conversion of thermal energy into non-thermal form. Indeed, this explanation does not require extending the conservation law to the universe as a whole. Acts of conversion occur locally and that is where the law of conservation of energy works in cosmology as it does anywhere else."

    "Cooling of the universe: Hugh Ross's pseudo-thermodynamics revisited," By Mark Perakh on *Panda's Thumb,* 5/14/04, http://www.pandasthumb.org/archives/2004/05/cooling-of-the-1.html

Where the Controversy Seems to Begin

- Do the Laws of Thermodynamics apply to the universe as a whole?
  - The Fundamental Thermodynamic Relation: a mathematical summation of the 1st and 2nd Laws of Thermodynamics

    $$dE = TdS - PdV$$

    Where E is internal energy, T is temperature, S is entropy, P is pressure, and V is volume
  - If $dE=0$, then $TdS = PdV$
  - Entropy of the universe is believed to be increasing (2nd Law of Thermodynamics--entropy increases in an isolated system)
- "Extending classical thermodynamics to the universe requires caution. The concept of a thermodynamic system makes no sense without the concepts of a boundary and of the surrounding.… The universe expands not into vacuum, as gas into an empty compartment, but into nowhere."

Adapted from Wikipedia & Mark Perakh on *Panda's Thumb,* 5/14/04,
http://www.pandasthumb.org/archives/2004/05/cooling-of-the-1.htm

Cosmological Explanation for Cooling of the Universe: Expansion of space-time-1

- "If we don't want to easily discard the law of energy conservation - which would be a rather non-parsimonious approach - we have to attribute the universe's cooling to the conversion of thermal energy into non-thermal forms of energy. As to specific forms of non-thermal energies which are beneficiaries of the conversion, their relative contributions to cooling, and specific mechanisms of conversion - [there is room] for various hypotheses and models.
- In cosmology the cooling of the universe is often attributed to the cosmological red shift of photons, or the expansion of space-time.
  - (There seem to be various ca[u]ses of red shift. One is the red shift of light coming from remote galaxies which is usually attributed to Doppler's effect and obeys Hubble's law. Another is the gravitational red shift caused by the space-time's curvature which is due to the presence of large masses. One more is the cosmological red shift caused by the expansion of the space-time per se. General relativity, however, reveals that all three cases, if explained by the properties of the metric tensor, differ only in interpretations based on various approximations and can all in fact be attributed to space-time's expansion.)

Adapted from Wikipedia & Mark Perakh on *Panda's Thumb,* 5/14/04, http://www.pandasthumb.org/archives/2004/05/cooling-of-the-1.htm

Cosmological Explanation for Cooling of the Universe: Expansion of space-time-2

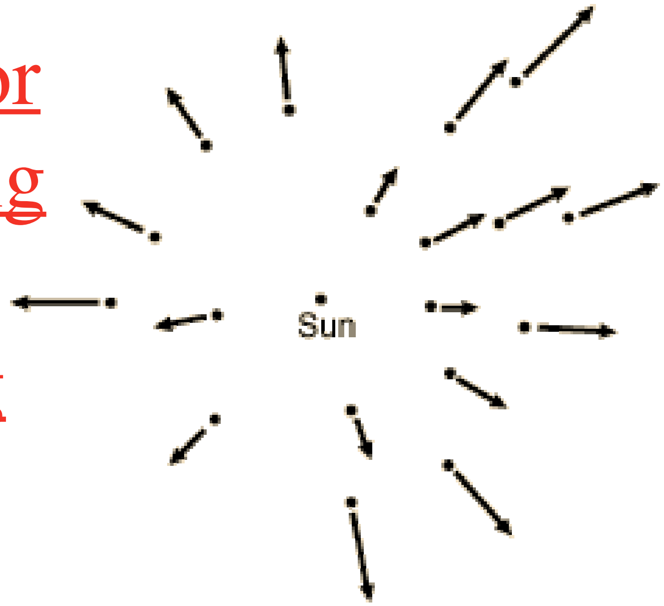
- As an illustration, this cooling effect can be juxtaposed with what is called Wien's displacement law. It relates to the spectra of black body radiation. The dependence is as follows:

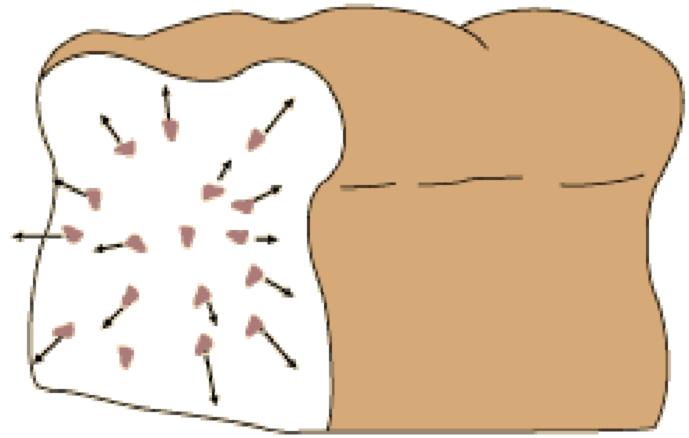
  $$T= K/\lambda_{max}$$

  where T is temperature and λ_{max} is the wavelength corresponding to the maximum of the spectrum (i.e. the most common wavelength in the radiation). $K=2.898\times10^{-3}$ Kelvin-meter is Wien's constant.
- In the course of the universe's expansion, the wavelength of radiation increases together with the expansion of space-time (that is the red shift mentioned above). This, according to Wien's law, means a temperature drop. It is in this sense that cosmologists say that expansion causes cooling."

Adapted from Wikipedia & Mark Perakh on *Panda's Thumb,* 5/14/04, http://www.pandasthumb.org/archives/2004/05/cooling-of-the-1.htm

Evidence for the Big Bang #1: An Expanding Universe

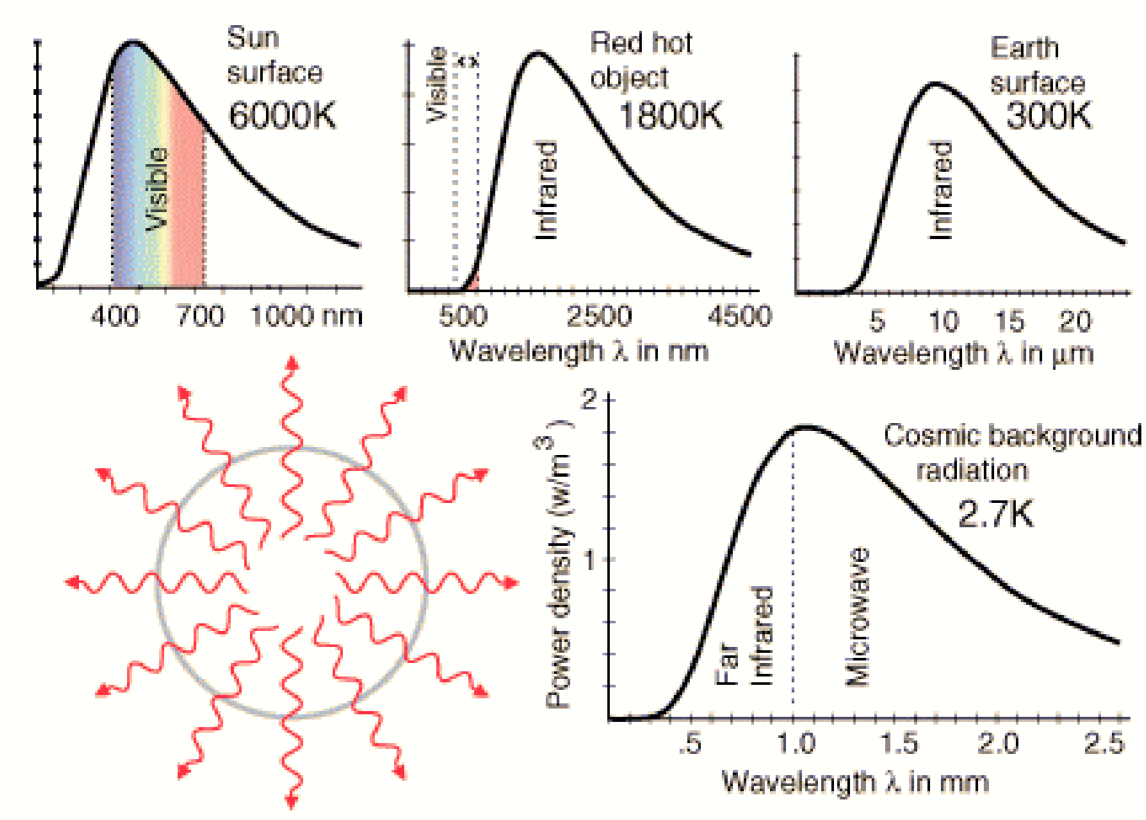




- The galaxies we see in all directions are moving away from the Earth, as evidenced by their red shifts.
- The fact that we see all stars moving away from us does not imply that we are the center of the universe!
- All stars will see all other stars moving away from them in an expanding universe.
- A rising loaf of raisin bread is a good visual model: each raisin will see all other raisins moving away from it as the loaf expands.

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html & http://map.gsfc.nasa.gov/m_uni/uni_101bbtest1.html & http://en.wikipedia.org/wiki/Metric_expansion_of_space

Evidence for the Big Bang #2: The 3K Cosmic Microwave Background

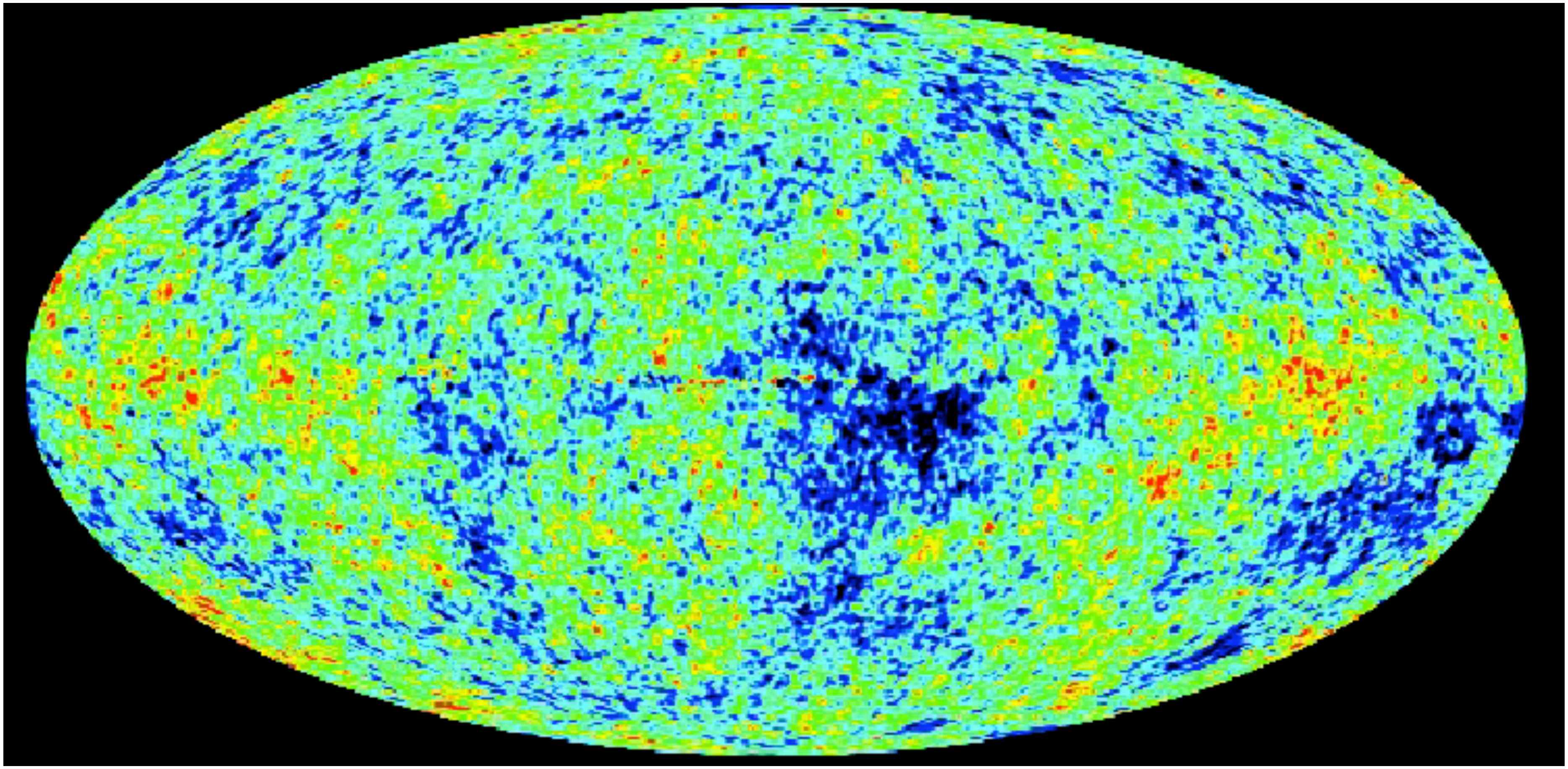


- Uniform background radiation in the microwave region of the spectrum is observed in all directions in the sky.
- Has the wavelength dependence of a Blackbody radiator at ~3K.
- Considered to be the remnant of the radiation emitted at the time the expanding universe cooled sufficiently to be transparent to radiation: ~3000 K (above that T matter exists as a plasma (ionized atoms) & is opaque to most radiation.) This happened ~0.5 Myr after the initial burst.

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html & http://map.gsfc.nasa.gov/m_mm.html

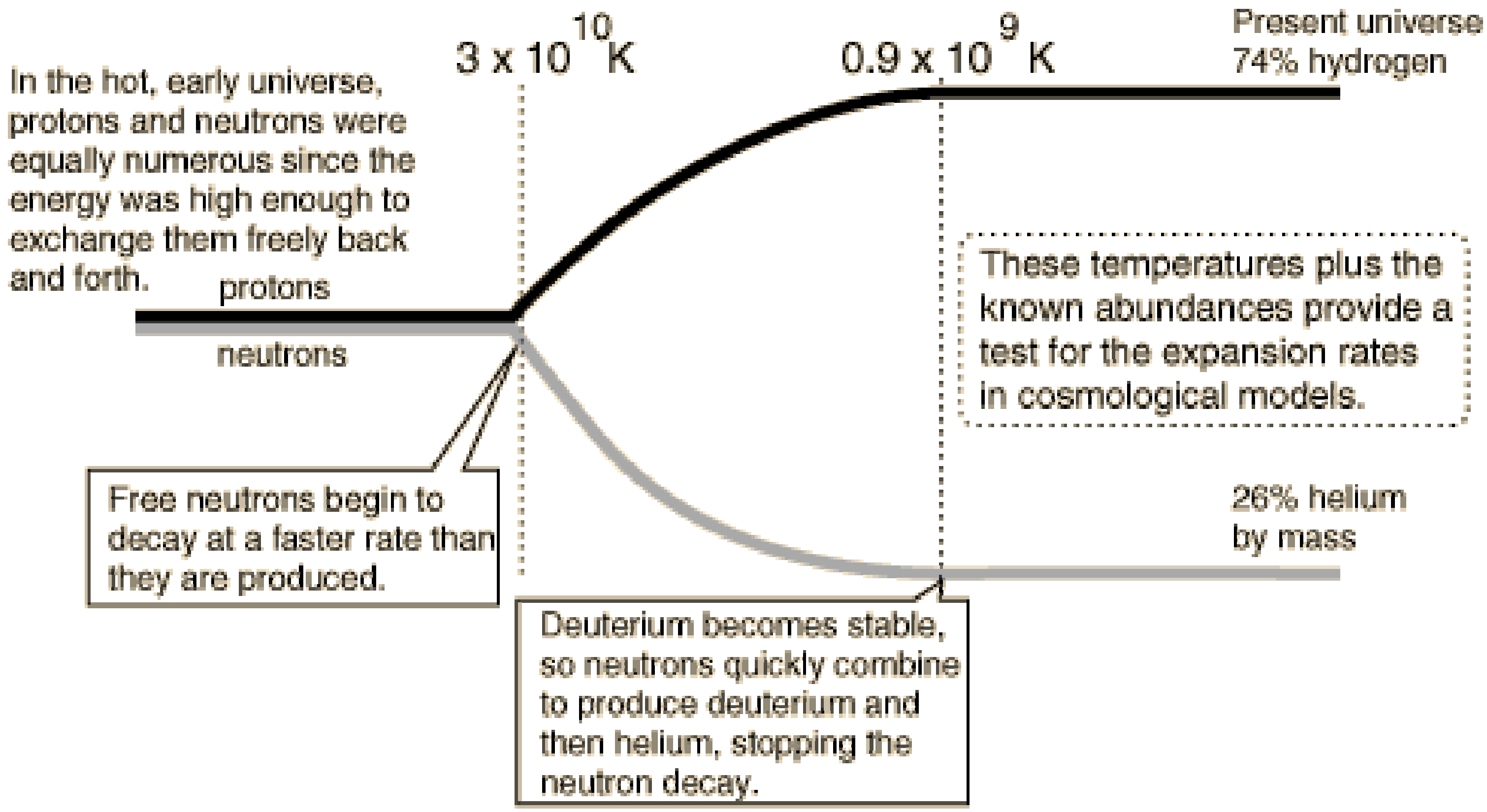
The Cosmic Microwave Background

Age of universe: 13.7 +/- 0.14 Ga



Results from the Cosmic Microwave Anisotropy Probe (CMAP), Seife (2003) *Science*, Vol. 299:992-993.

Evidence for the Big Bang #3: H-He Abundance



•Hydrogen (73%) and He (25%) account for nearly all the nuclear matter in the universe, with all other elements constituting < 2%.

•High % of He argues strongly for the big bang model, since other models gave very low %.

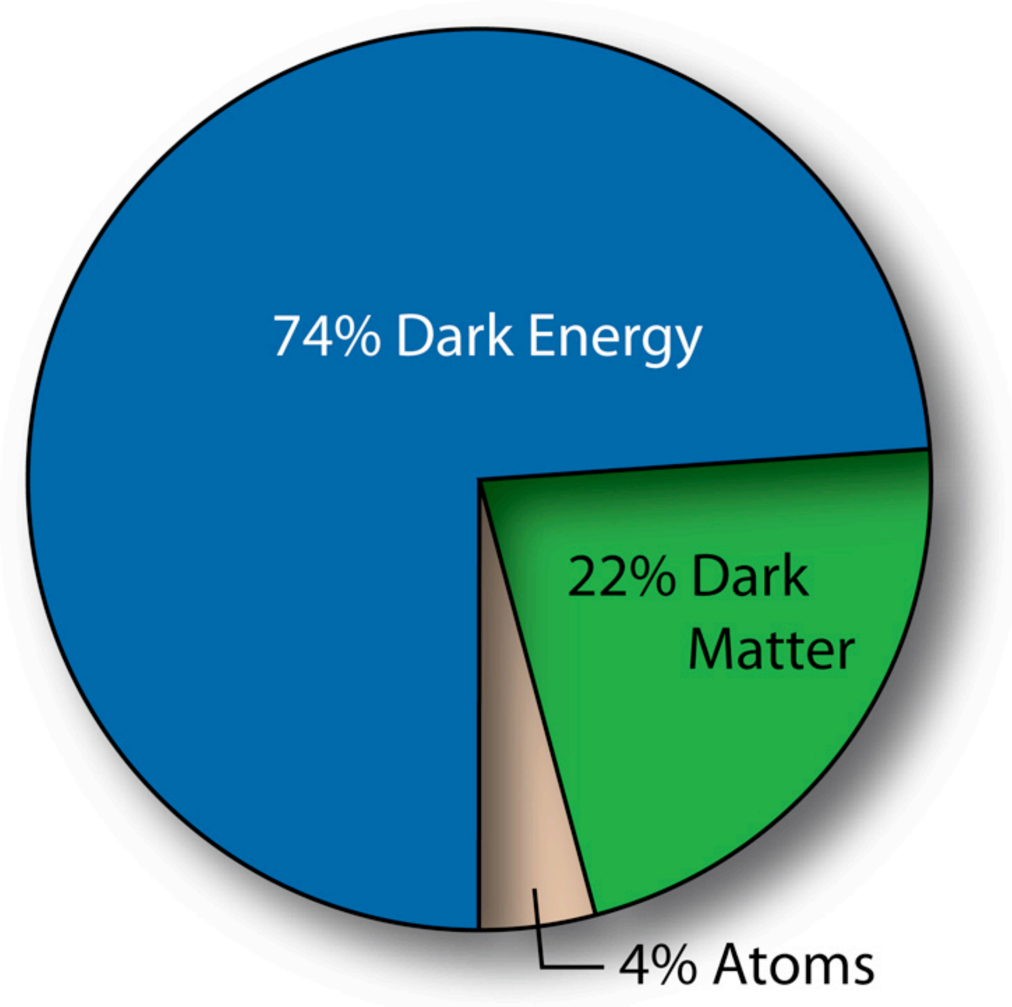
•Since no known process significantly changes this H/He ratio, it is taken to be the ratio which existed at the time when the deuteron became stable in the expansion of the universe.

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Galaxy Formation (Problem)

- Random non-uniformities in the expanding universe are not sufficient to allow the formation of galaxies.
- In the presence of the rapid expansion, the gravitational attraction is too low for galaxies to form with any reasonable model of turbulence created by the expansion itself.
- "..the question of how the large-scale structure of the universe could have come into being has been a major unsolved problem in cosmology….<u>we are forced to look to the period before 1 millisecond to explain the existence of galaxies</u>.” (Trefil p. 43)

What is the Universe Made of?



- **4% Atoms** The building blocks of stars & planets.
- **22% Dark Matter** This matter, distinct from atoms, does not emit or absorb light. It has only been detected indirectly by its gravity.*
- **74% Dark Energy** A sort of anti-gravity. This energy, distinct from dark matter, is responsible for the present-day acceleration of the universal expansion.*

* The nature of 96% of the contents of the universe remain unknown!

http://map.gsfc.nasa.gov/m_mm.html

Galaxies!

- A remarkable deep space photograph made by the Hubble Space Telescope
- Every visible object (except the one foreground star) is thought to be a galaxy.

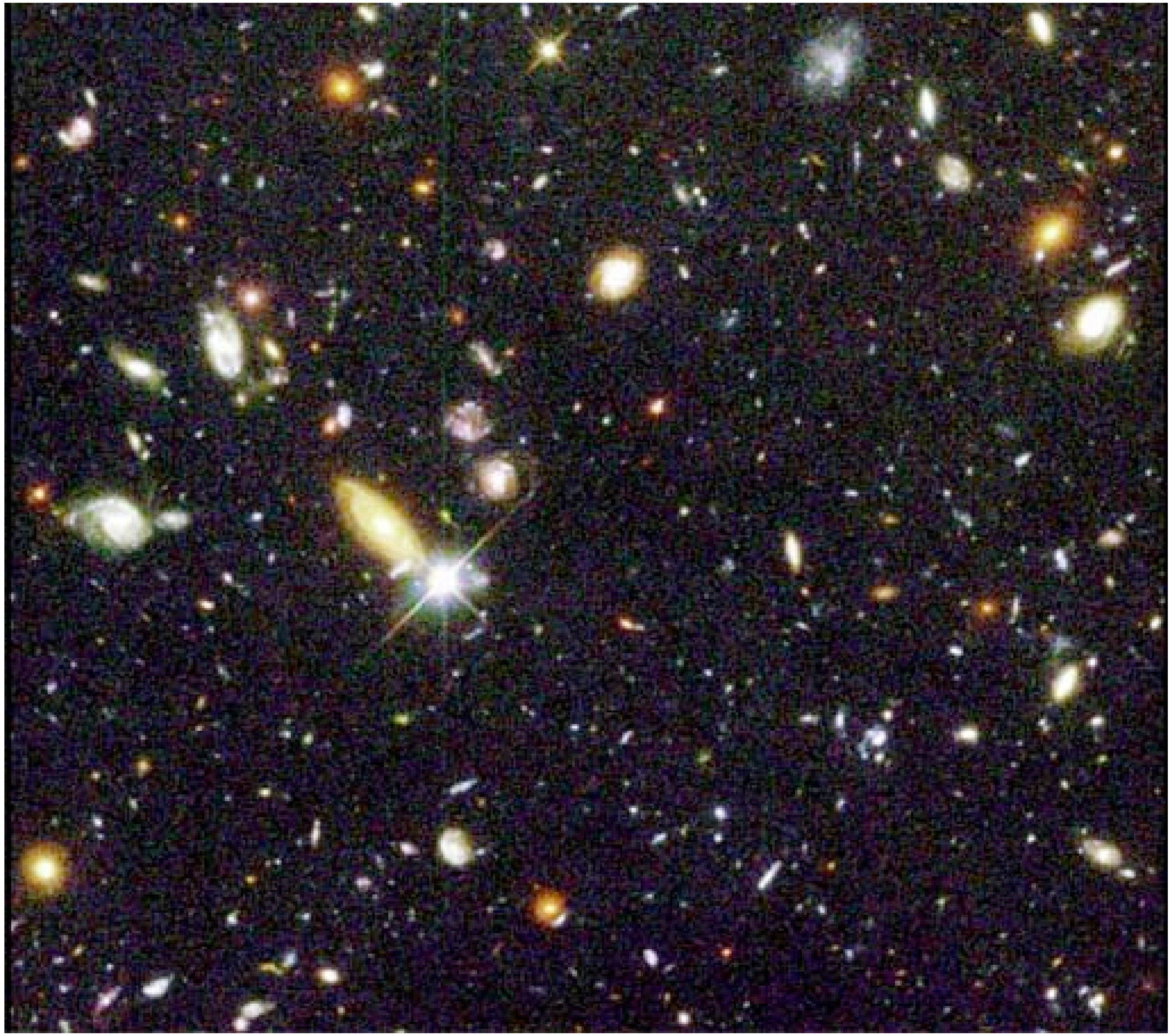
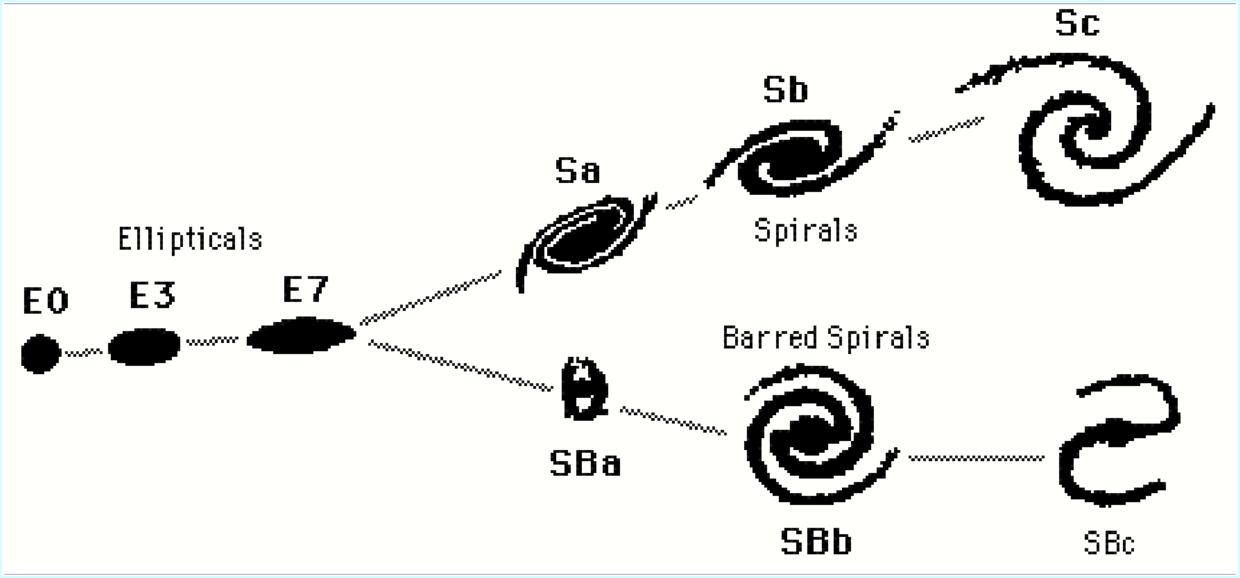
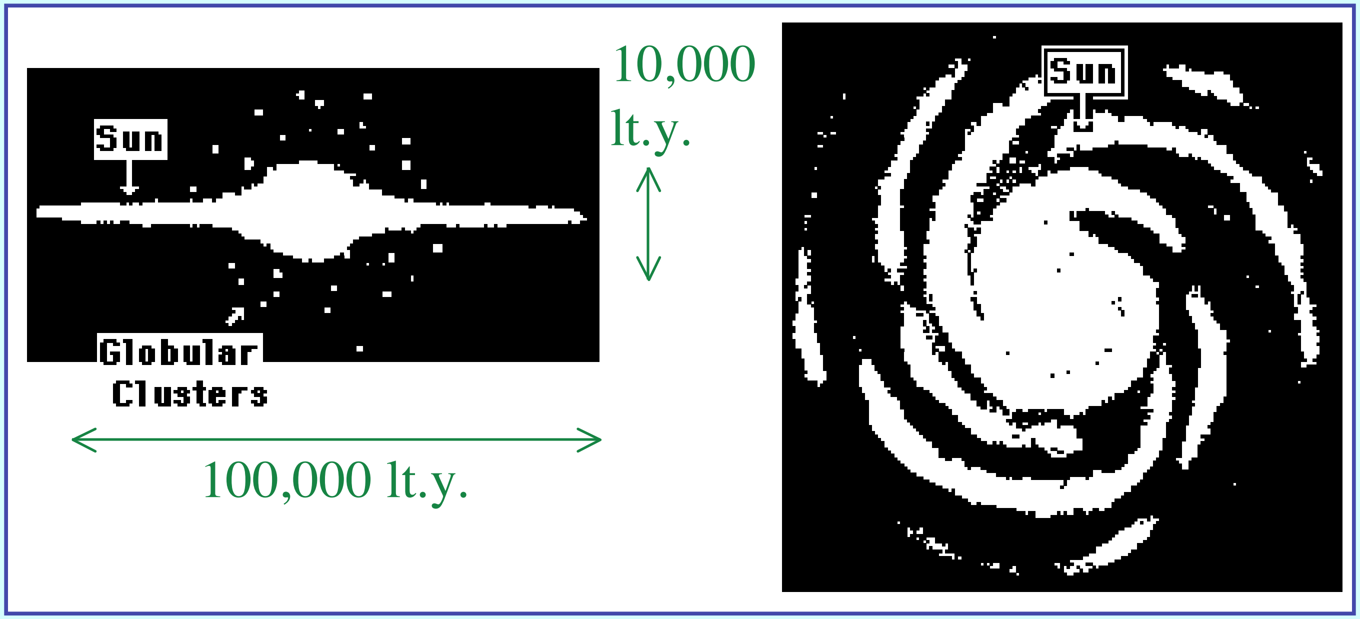


Image by the Hubble Space Telescope's Wide Field and Planetary Camera 2, NASA

Galaxy Geometries & The Milky Way

• There are many geometries of galaxies including the spiral galaxy characteristic of our own Milky Way.



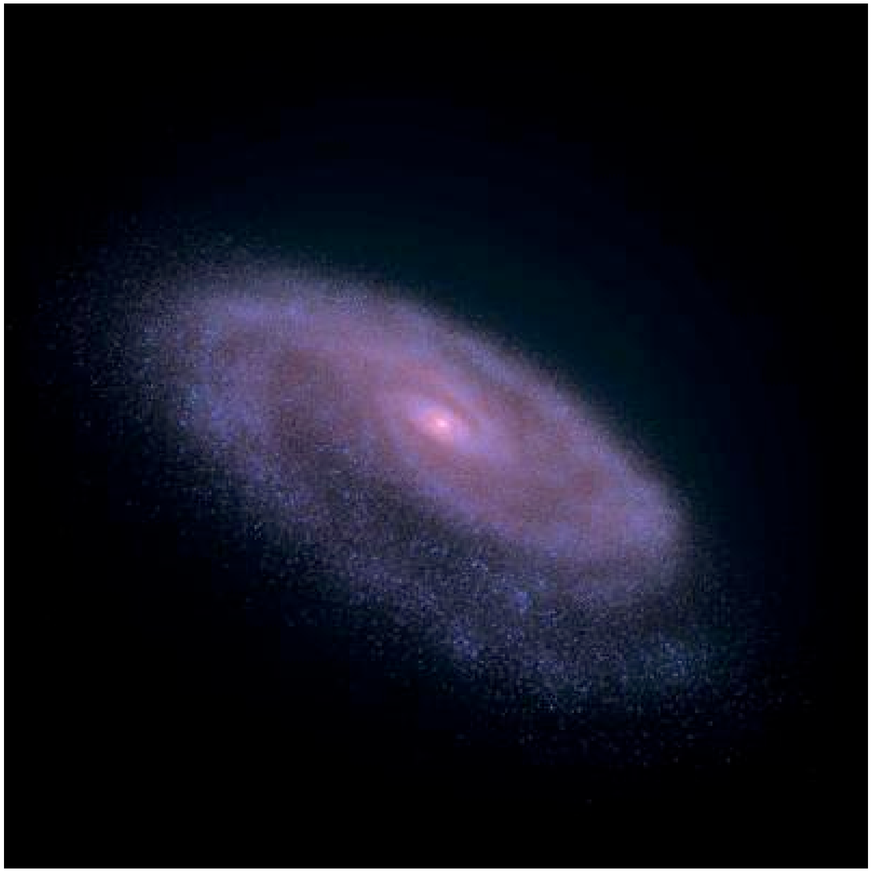


• Several hundred billion stars make up our galaxy
• The sun is ~26,000 lt.y. from the center

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Stars Appear to Migrate Long Distances In Spiral Galaxies like the Milky Way

- The sun might have traveled far from where it formed, contradicting a belief that stars generally remain static
- According to UW astronomers, 9/16/08, using “*N*-body + smooth particle hydrodynamics simulations of disk formation” (100,000 hrs of computer time!)
- May challenge idea of “habitable zones” in galaxies -- where metal abundances, radiation, water, etc. are amenable to life



Roskar et al. (2008) Riding the Spiral Waves: Implications of Stellar Migration for the Properties of Galactic Disks. *The Astrophysical Journal Letters*, 684(2), L79-L82.

Immigrant Sun: Our Star Could Be Far From Where It Started In Milky Way, *Science Daily*, 9/16/08

Sun might be a long-distance traveler, *UPI.com*, 9/16/08

Simulation of Spiral Galaxy formation: http://www.astro.washington.edu/roskar/astronomy/12M_hr_rerun_angle.mpg

Spiral Galaxies

• NASA Hubble Space Telescope images

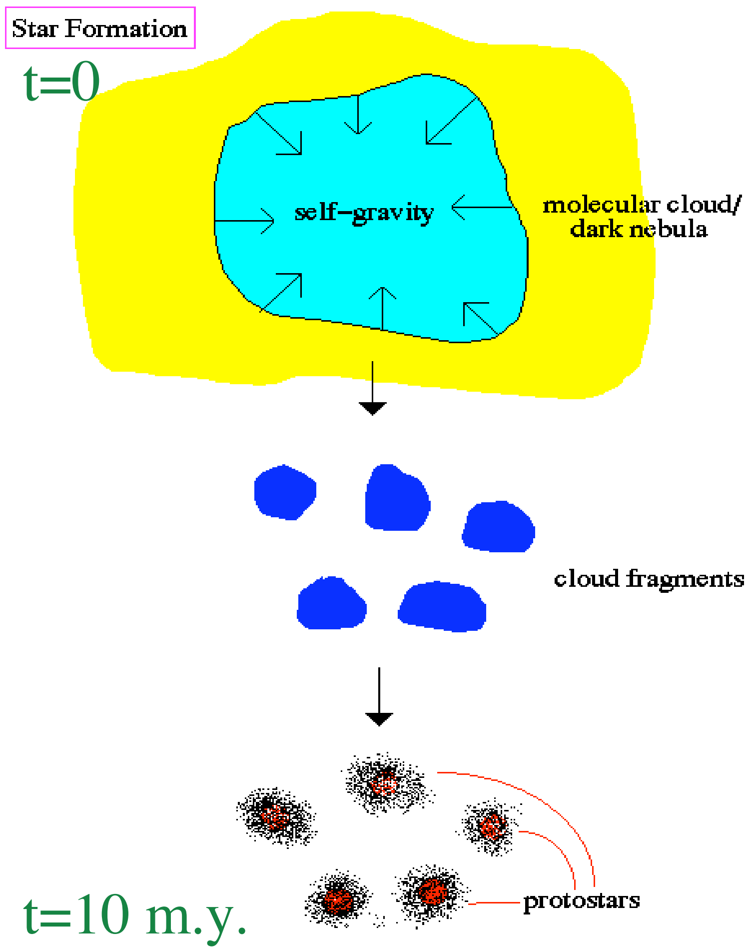
NGC 4414

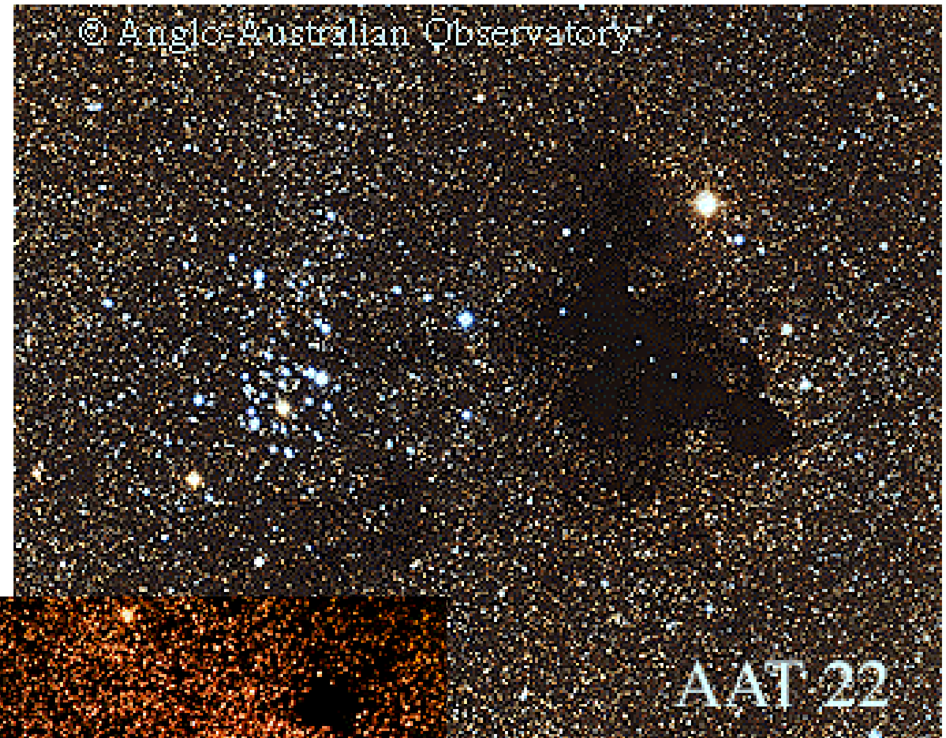
NGC 4414

NGC 6744

*** Ended here - 9/26/08 ***

Protostar Formation from Dark Nebulae





- High density of dust & gas make these molecular clouds opaque to visible light
- Observed by IR & radio telescopes
- T = 10-20 K

<u>Dark Nebulae</u>: Opaque clumps or clouds of gas and dust. Poorly defined outer boundaries (e.g., serpentine shapes). Large DN visible to naked eye as dark patches against the brighter background of the Milky Way.

Star Formation in the Trifid Nebula

•*Left, National Optical Astronomy Observatory; right, NASA Jet Propulsion Laboratory/Caltech/Dr. Jeonghee Rho*

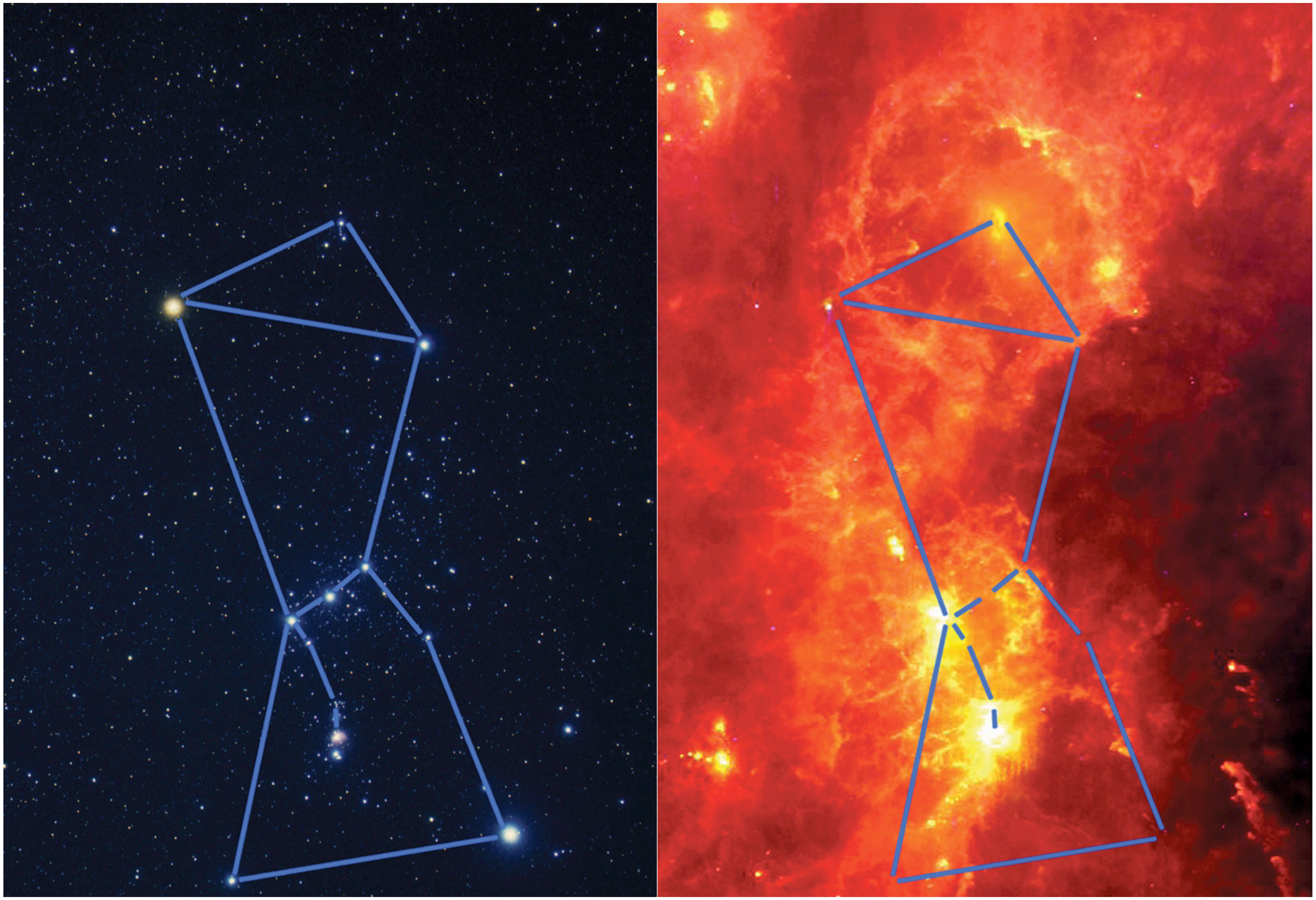
In the visible spectrum, left, the 20-lightyear- wide Trifid Nebula glows pink and blue, with dark arms of dust and gas stretching out from its center. Astronomers have now seen the nebula in a different light — longer wavelength infrared — and discovered that it is about to give birth to a family of new stars. In the infrared image, right, taken by NASA's Spitzer Space Telescope, 30 embryonic stars, including 10 that had been obscured by the dust, appear as points of light. Dr. Jeonghee Rho, the principal investigator, said the future stars were still warming up and would not ignite for tens of thousands of years. --*NY Times, 1/31/05*

Protostar Formation from a Dark Nebula in Constellation Serpens

- Stars form at terminations of huge columns of gas dust
- Primary gases are H_2 & CO

Hubble Space Telescope image

Orion Nebula in Visible (L) & Infrared (Rt)



- The constellation Orion (left) captured by the Infrared Astronomical Satellite (right)
- Hot interstellar gas & dust is brighter (right)
- Lines show bright stars, two supernova remnants, and other features.

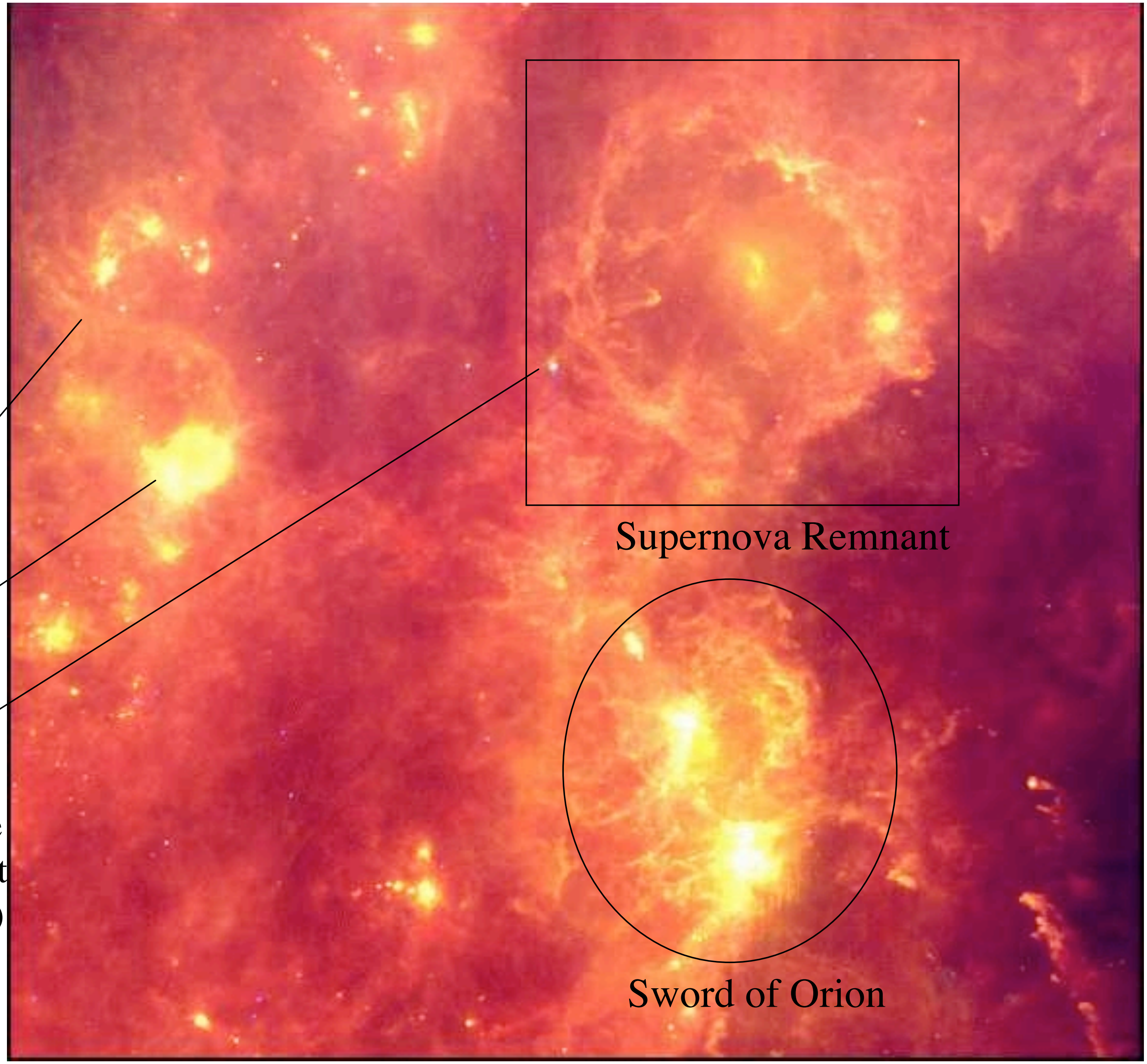
http://www.nasa.gov/centers/dryden/images/content/178941main_Orion_vis-ir_lg.jpg

A Tour of the Orion Nebula in IR

Horsehead Nebula

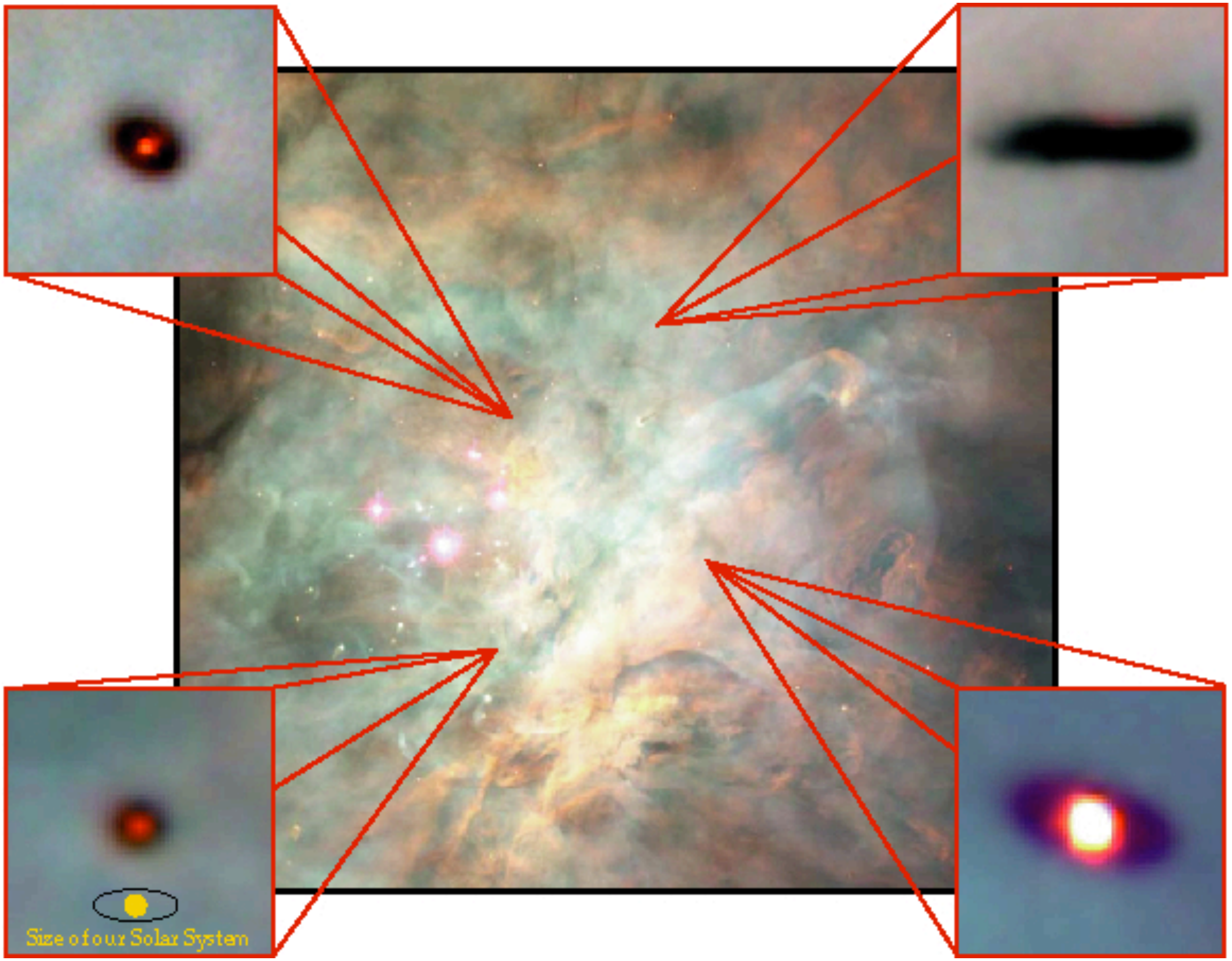
Rosette Nebula

Betelgeuse (though most stars that are bright in the visible image are not prominent in the IR)



http://www.ipac.caltech.edu/Outreach/Gallery/IRAS/orion.html

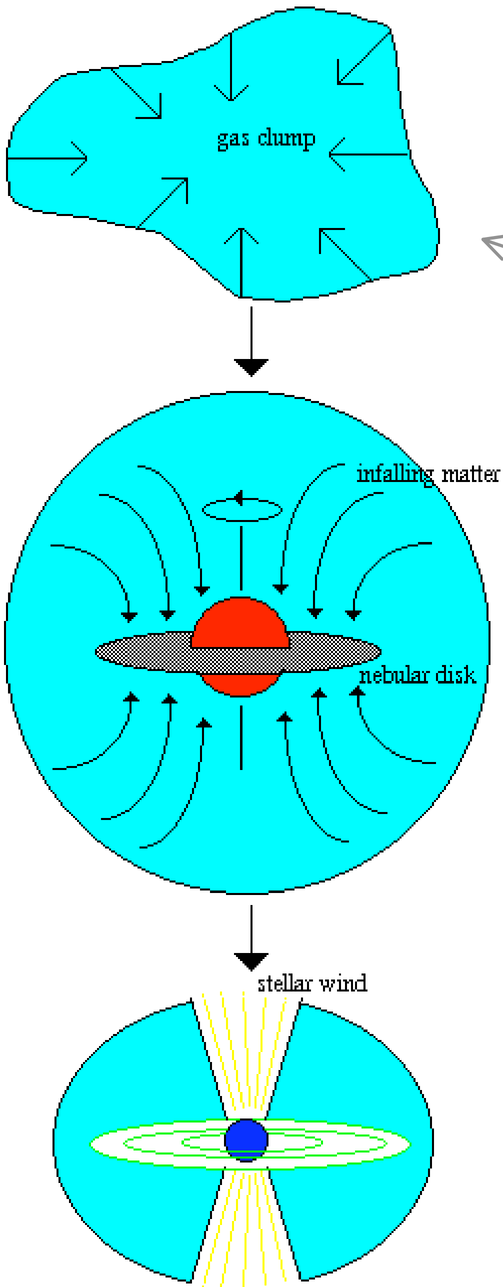
Candidate Protostars in the Orion Nebula



Hubble telescope images

Star Formation from Protostar

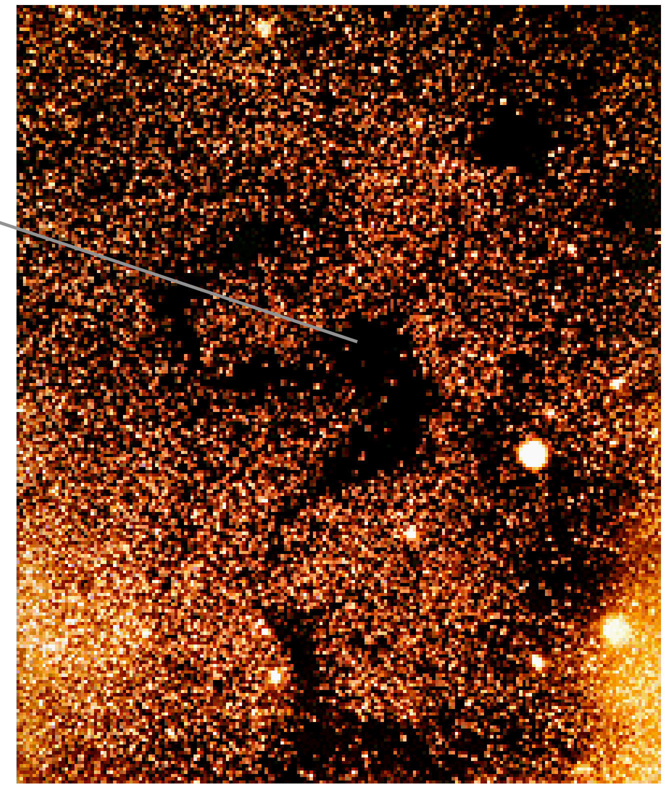
Protostar Formation



A dense gas clump breaks off from molecular cloud and collapses Angular momentum turns the irregular clump into a rotating disk

The central region is denser and forms into a protostar, the nebular disk forms slower to become a planetary system. Infalling matter increases the size of the protostar by a factor of 100

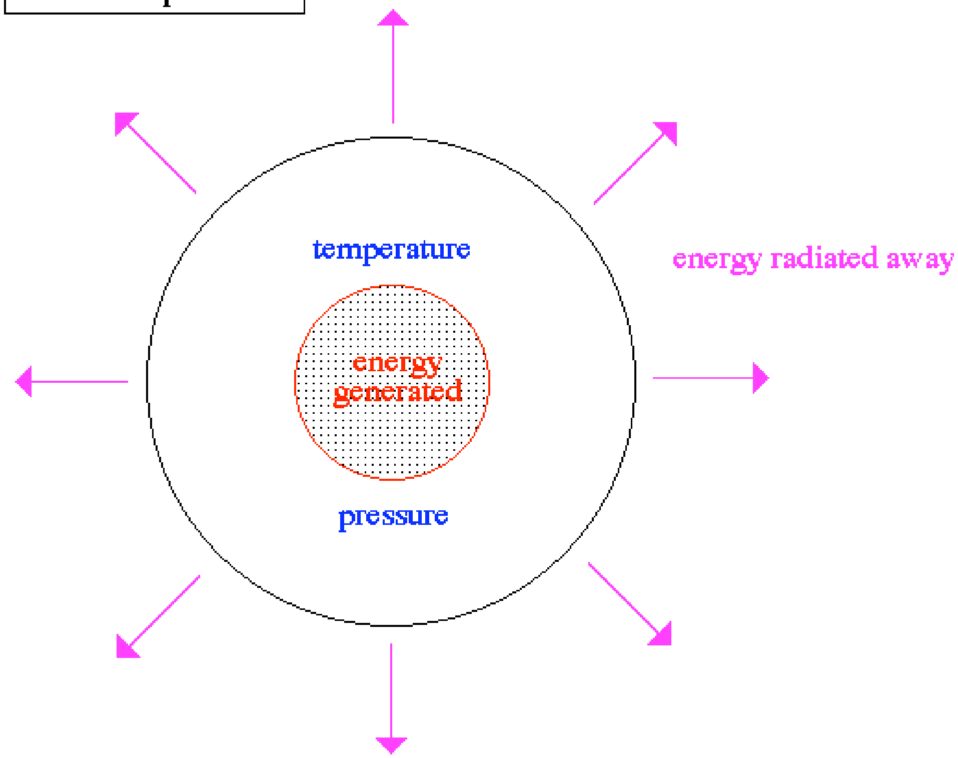
Infall is stopped when the protostar begins thermonuclear fusion and produces a strong stellar wind



Star Maintenance

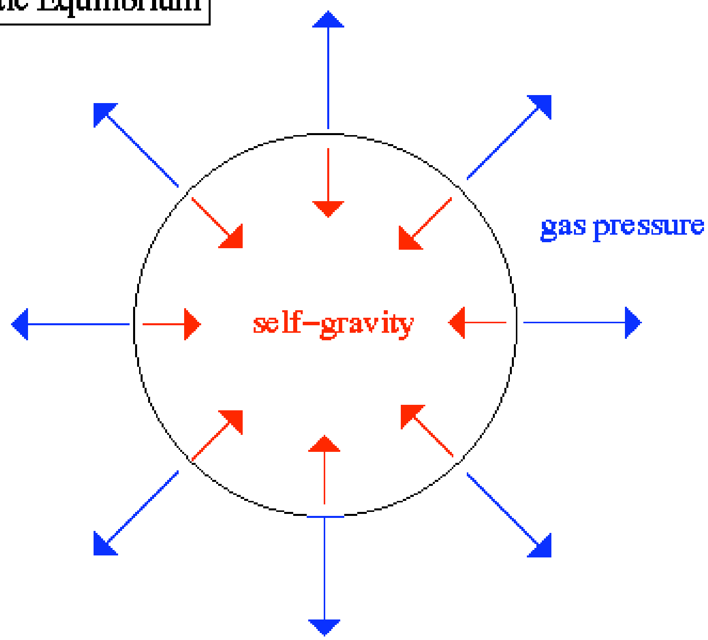
- Gravity balances pressure (Hydrostatic Equilibrium)
- Energy generated is radiated away (Thermal Equilibrium)

Thermal Equilibrium



the energy generated must be radiated away, if the energy production is increased, the temperature goes up, therefore the pressure goes up and the star expands – the surface area increases and more energy is radiated to space to balance the increased production

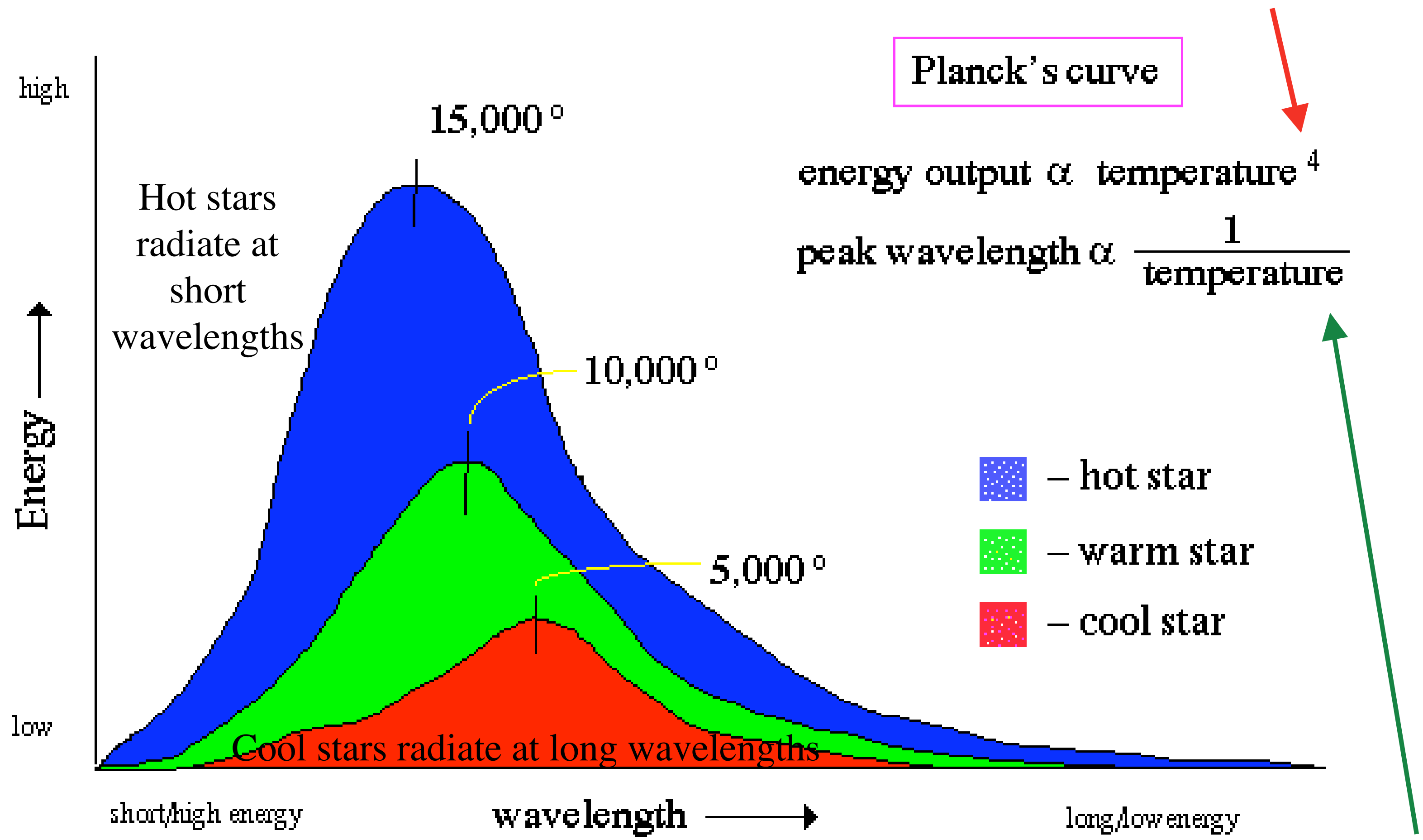
Hydrostatic Equilibrium



the Sun is not expanding or contracting, therefore it is in equilibrium, the downward force of gravity is balanced by the higher force of pressure

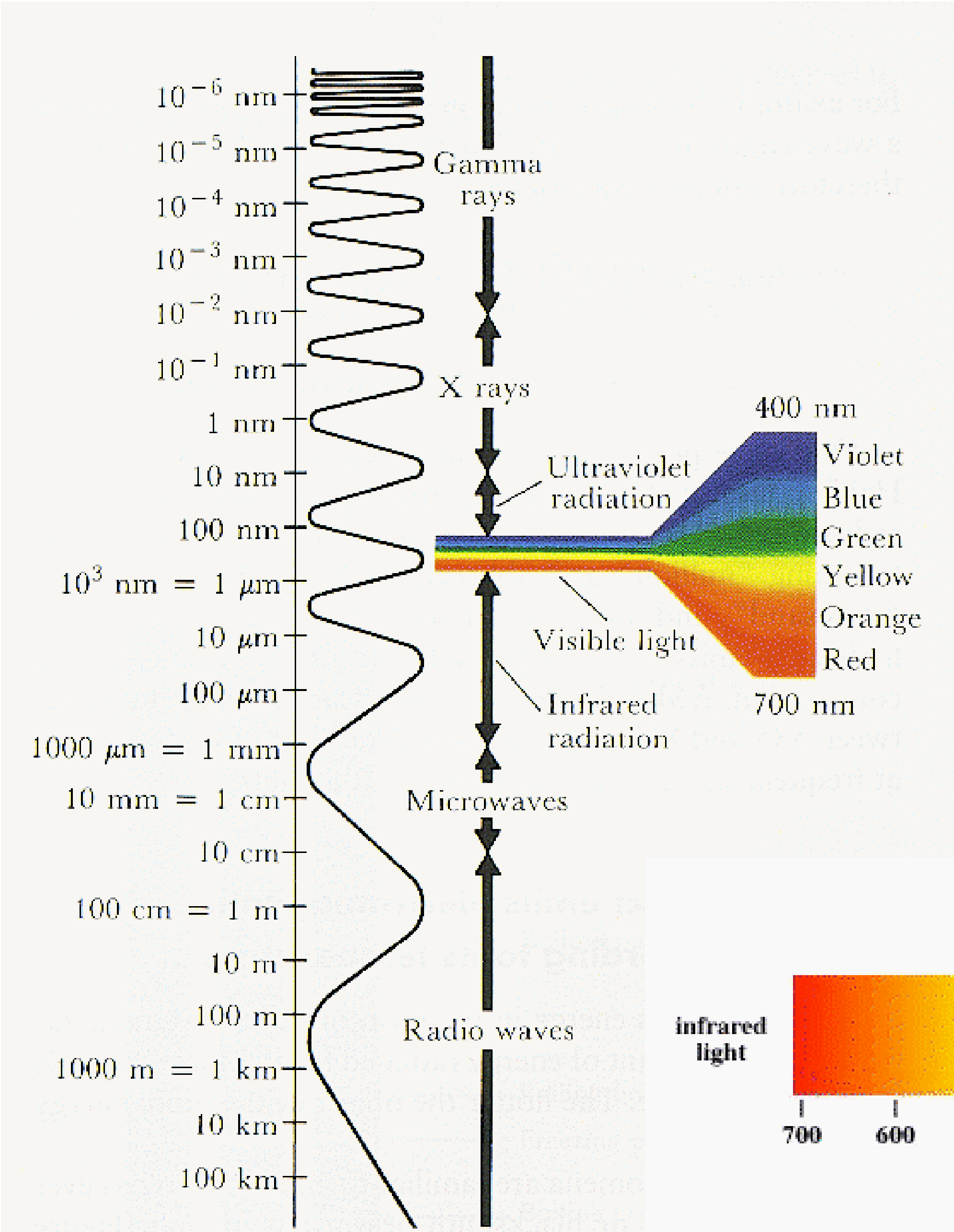
All objects emit energy according to Planck's Law, graphically depicted here by Planck's curve, which states that the amount & the frequency (or wavelength) of energy vary only as the temperature of the body.

- *The E output is proportional to the 4th power of T!*

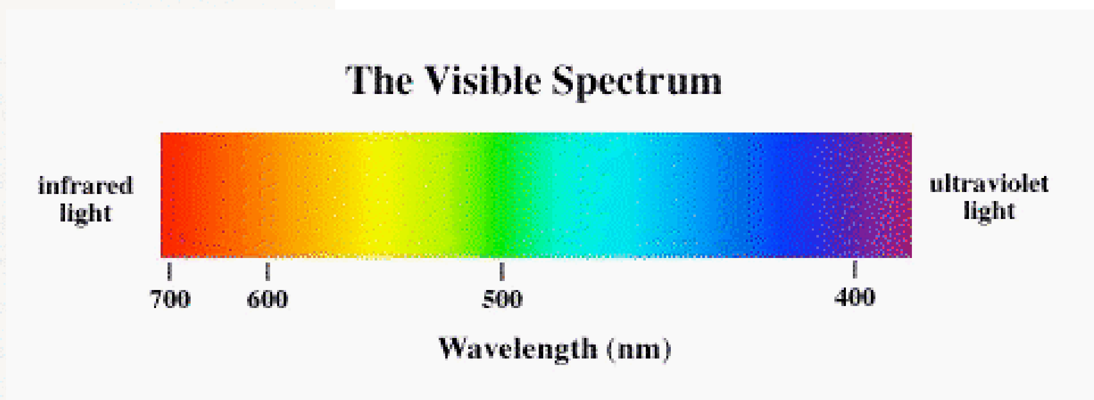


- *The wavelength of the radiation is inversely proportional to T*

Electromagnetic Spectrum

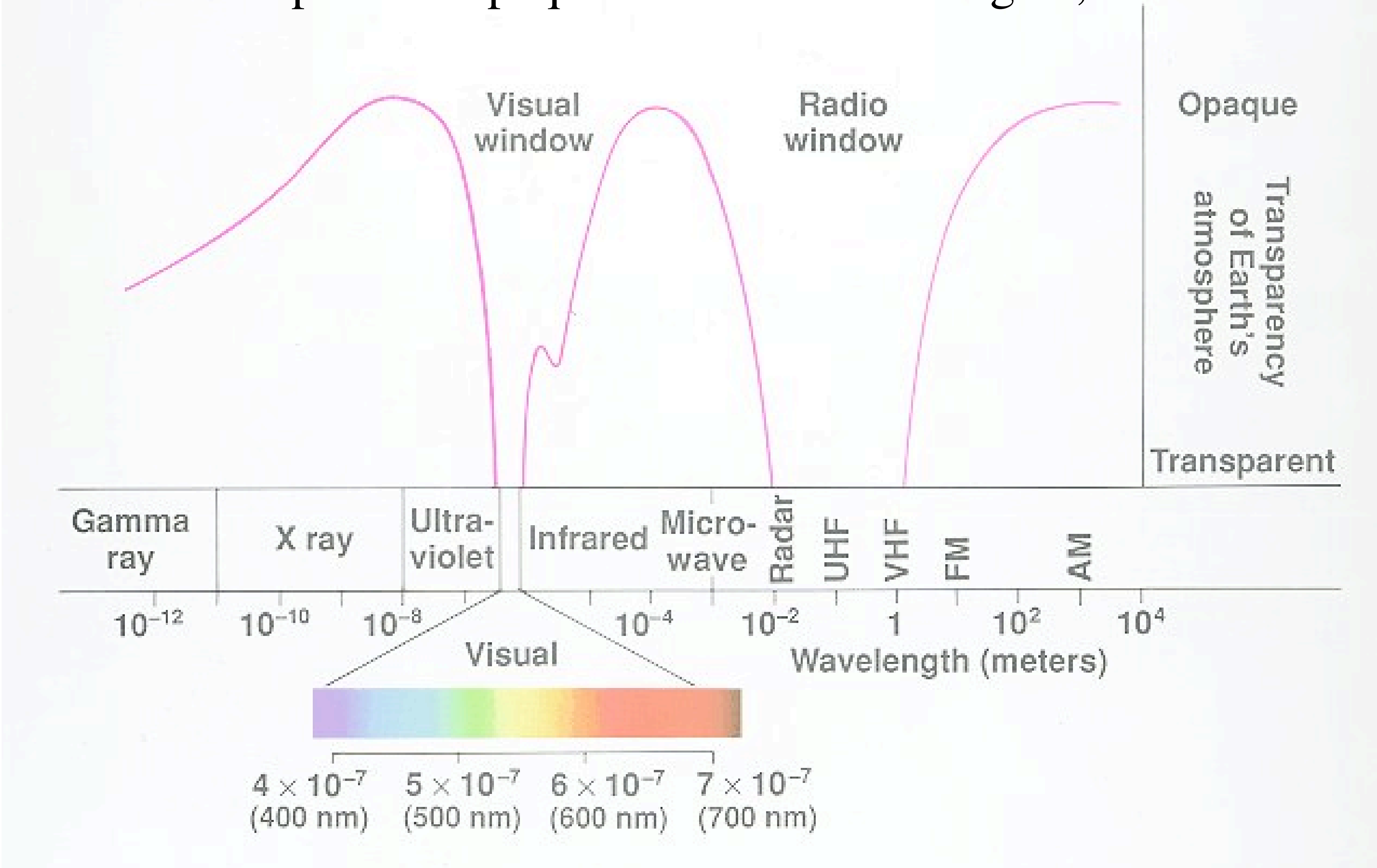


- The Sun, a relatively small & cool star, emits primarily in the visible region of the electromagnetic spectrum.
- Fainter & hotter objects emit energy at longer & shorter λ's, respectively.



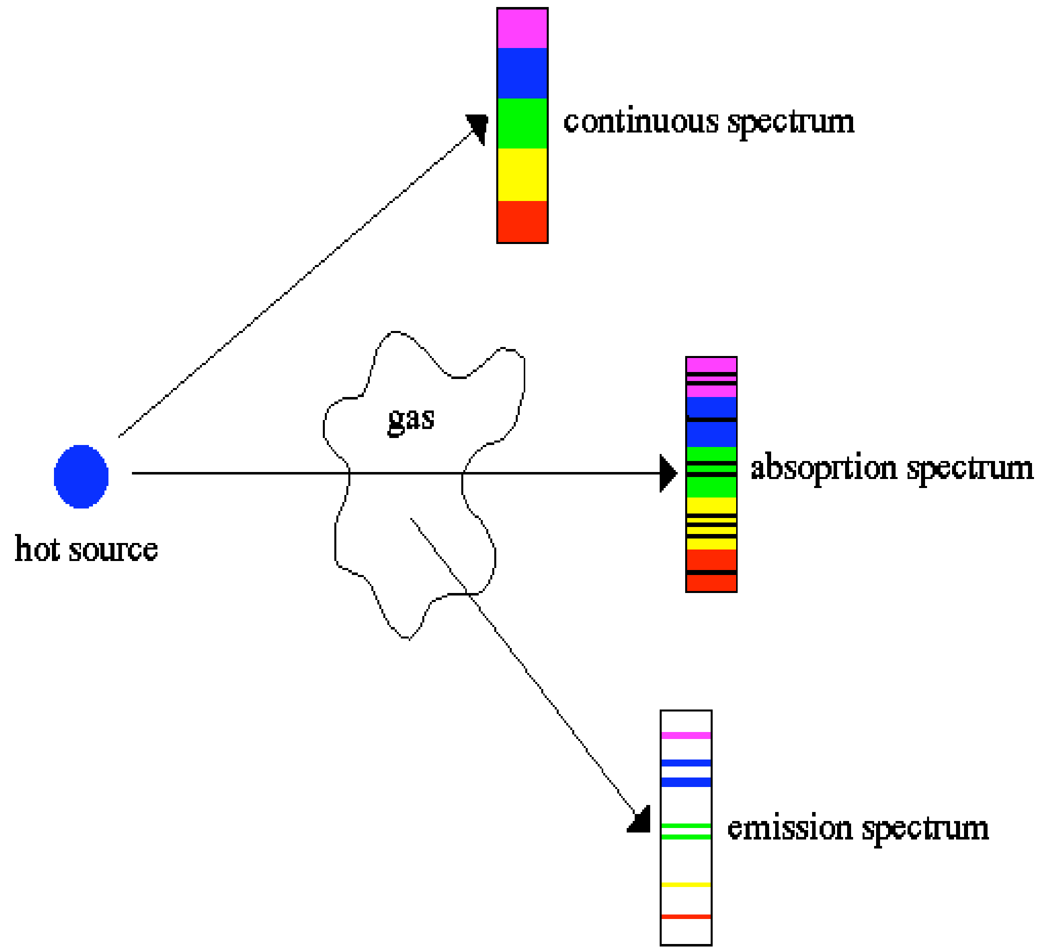
Transparency of Earth's Atmosphere

- Earth's atmosphere is opaque to certain wavelengths, such as UV



Spectra of Elements -1

- All elements produce a unique chemical fingerprint of "spectral lines" in the rainbow spectrum of light.
- Spectra are obtained by spectroscope, which splits white light into its component colors.



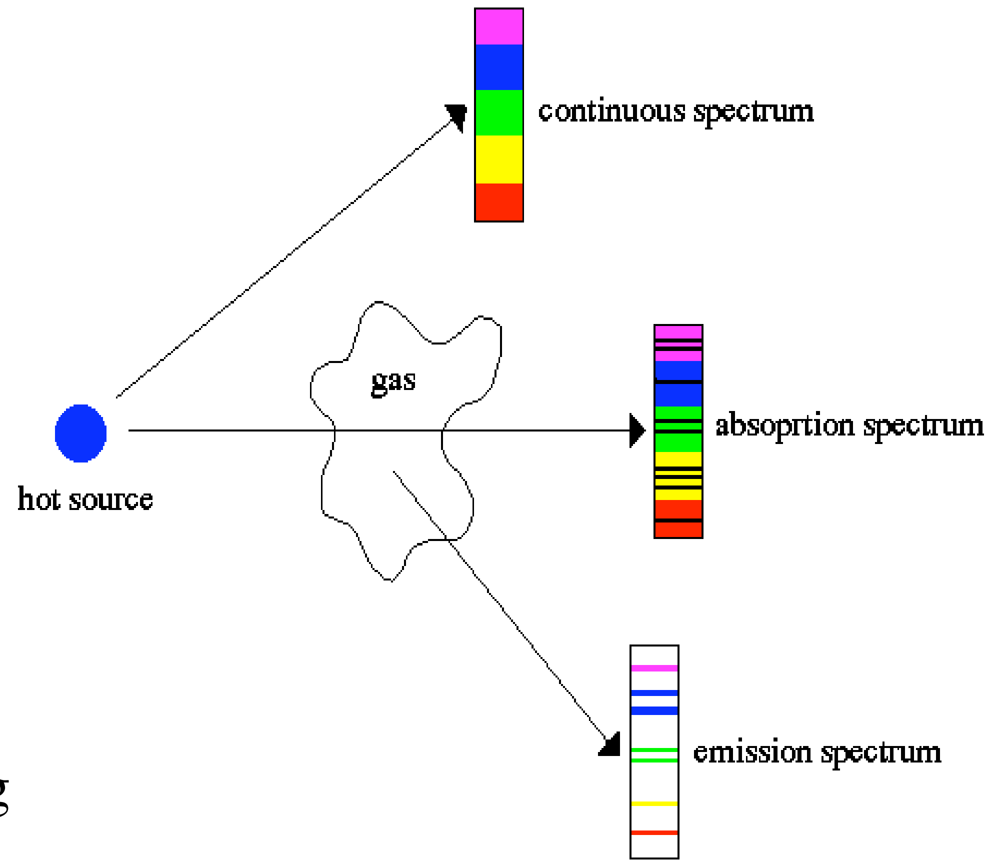
Spectra of Elements - 2

Three types of spectra emitted by objects:

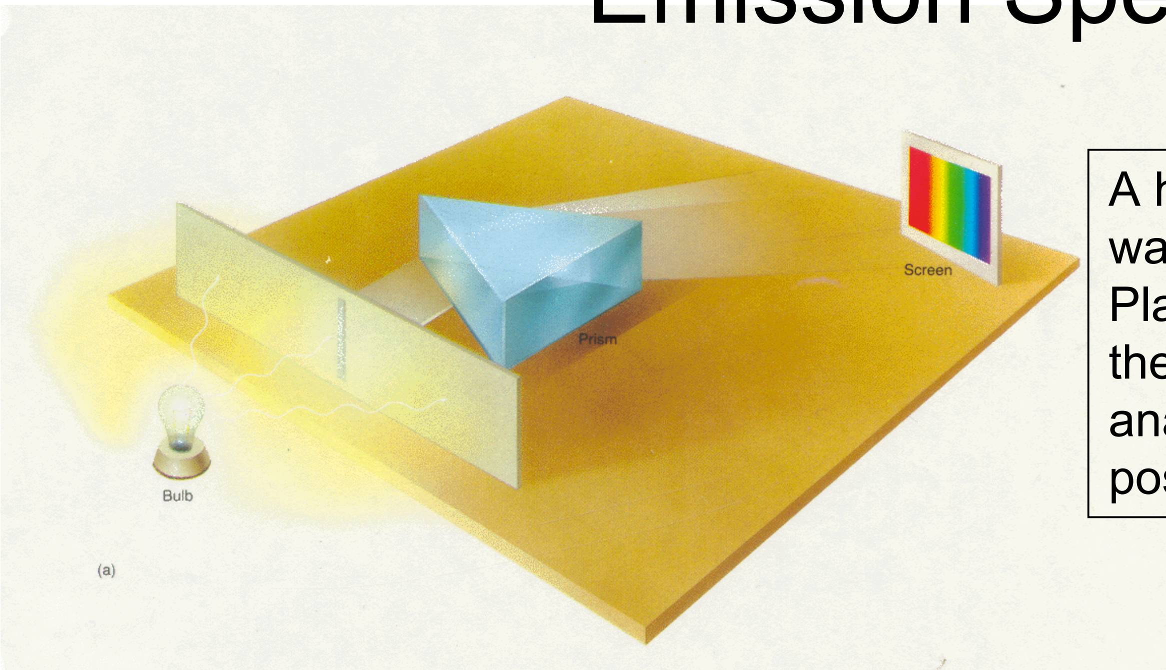
1) Continuous spectrum - a solid or liquid body radiates an uninterrupted, smooth spectrum (called a Planck curve)

2) Absorption spectrum - a continuous spectrum that passes through a cool gas has specific spectral lines removed (inverse of an emission spectrum)

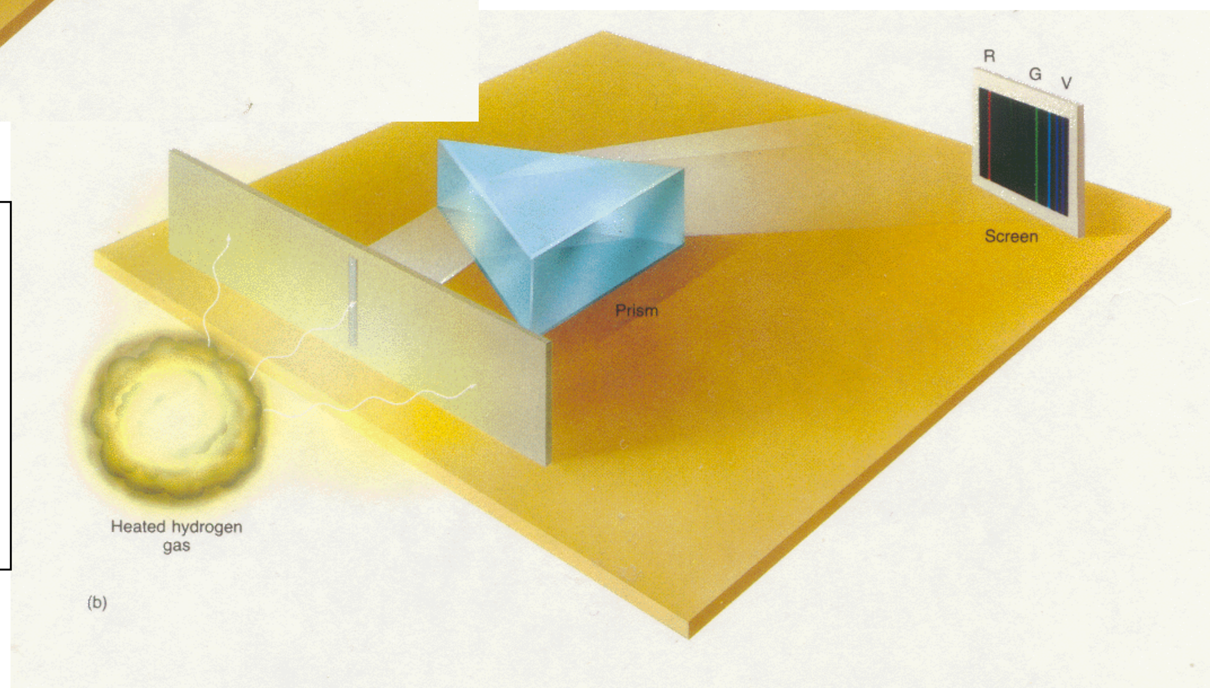
3) Emission spectrum - a radiating gas produces a spectrum of discrete spectral lines



Emission Spectra



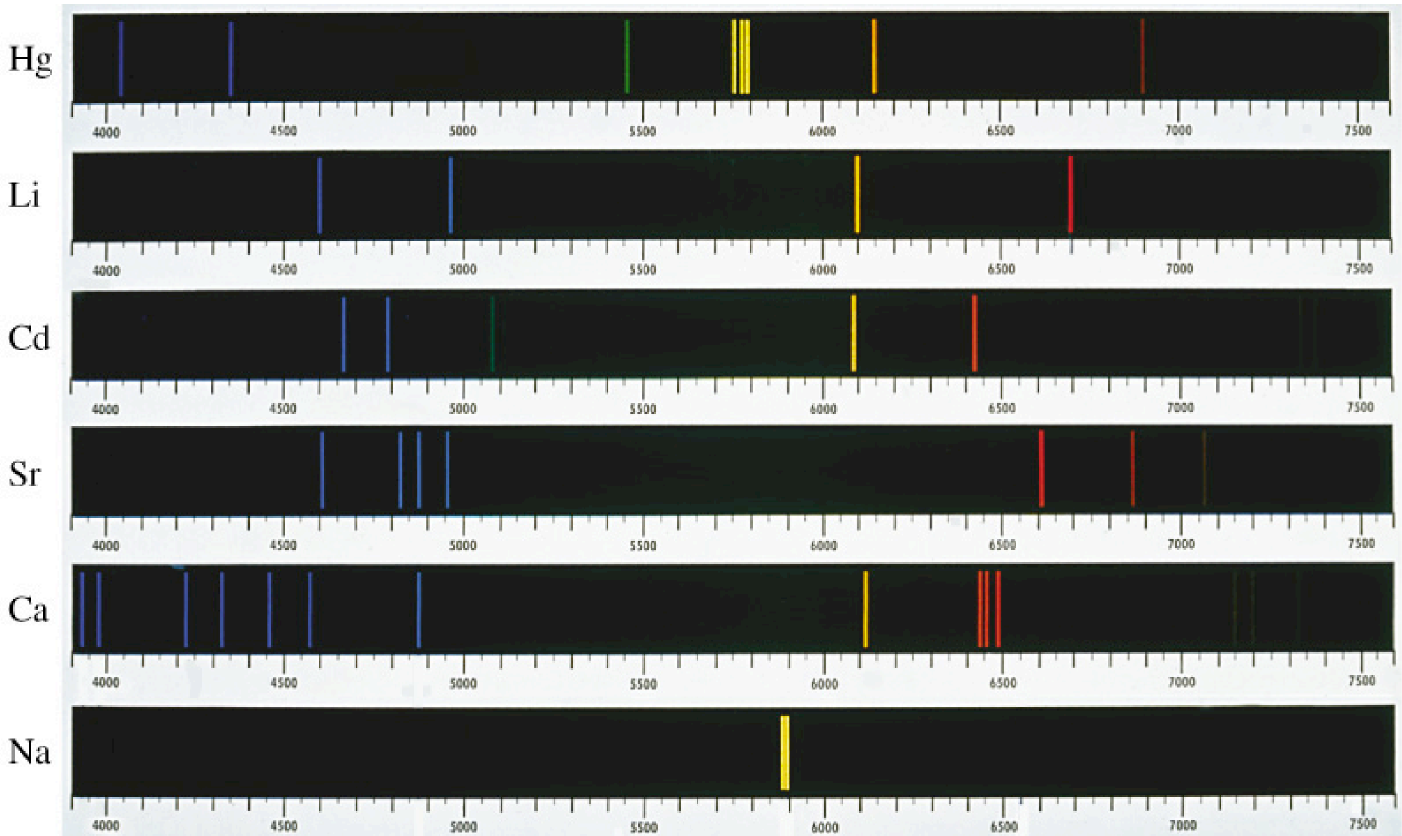
A hot, dense body emits light of all wavelengths (with the familiar Planck spectrum, depending on the temperature). This is analogous to playing every possible note on a piano.



A hot, diffuse low-density gas emits light at only a number of discrete wavelengths. This is analogous to playing a piano only on 'A' keys.

http://www.astro.queensu.ca/~hanes/PHYS015-2007/Notes/Theme_05/6._Meet_Kirchhoff's_Laws.html

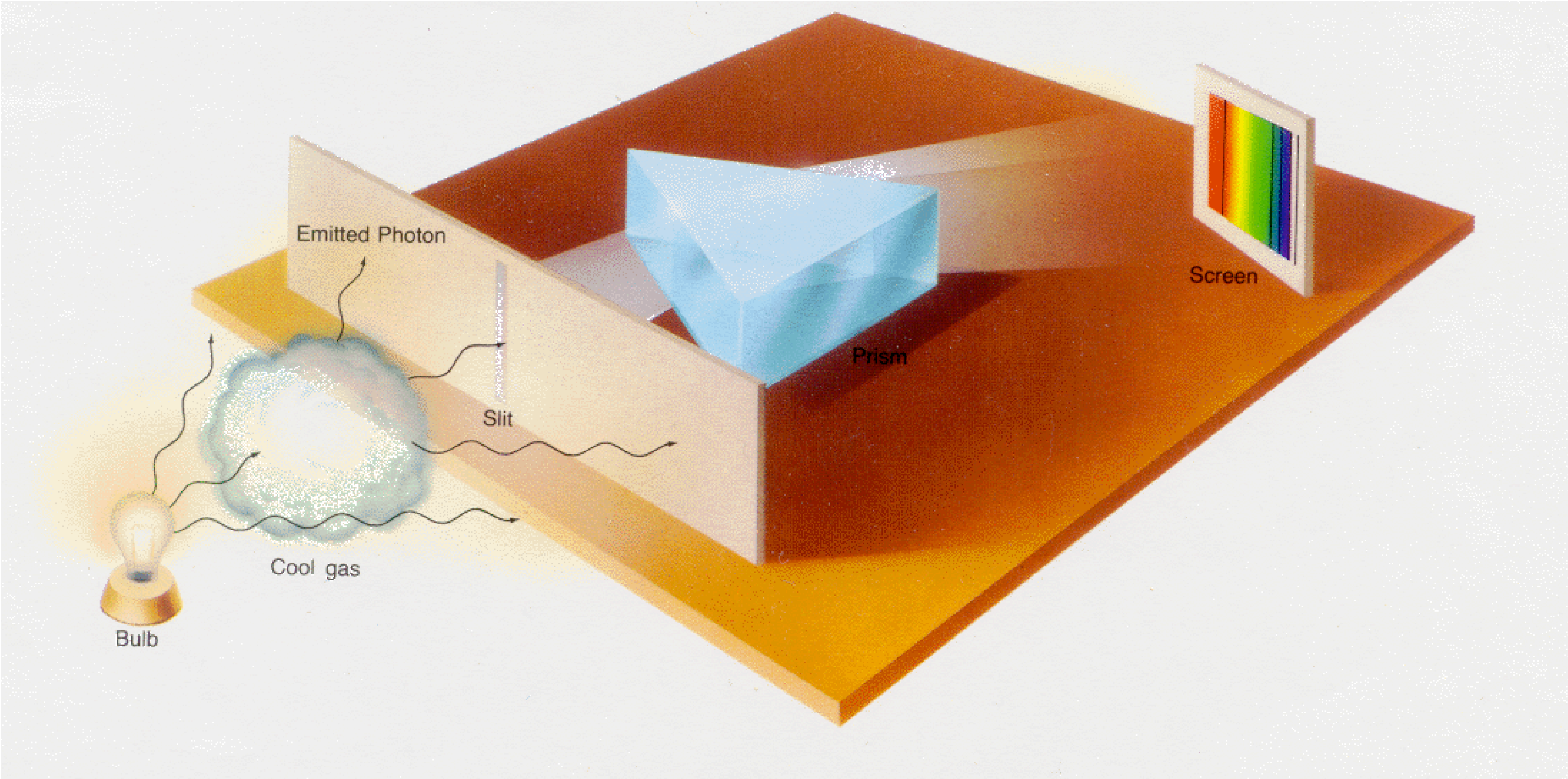
Examples of Emission Spectra



- Each element & molecule produces a distinctive set of <u>emission lines</u>.
- These are emission spectra for the elements: Hg (mercury), Li (lithium), Cd (cadmium), Sr (strontium), Ca (calcium), Na (sodium)
- Produced by heating <u>low-density vapors of each element</u>

http://www.astro.queensu.ca/~hanes/PHYS015-2007/Notes/Theme_05/6._Meet_Kirchhoff's_Laws.html

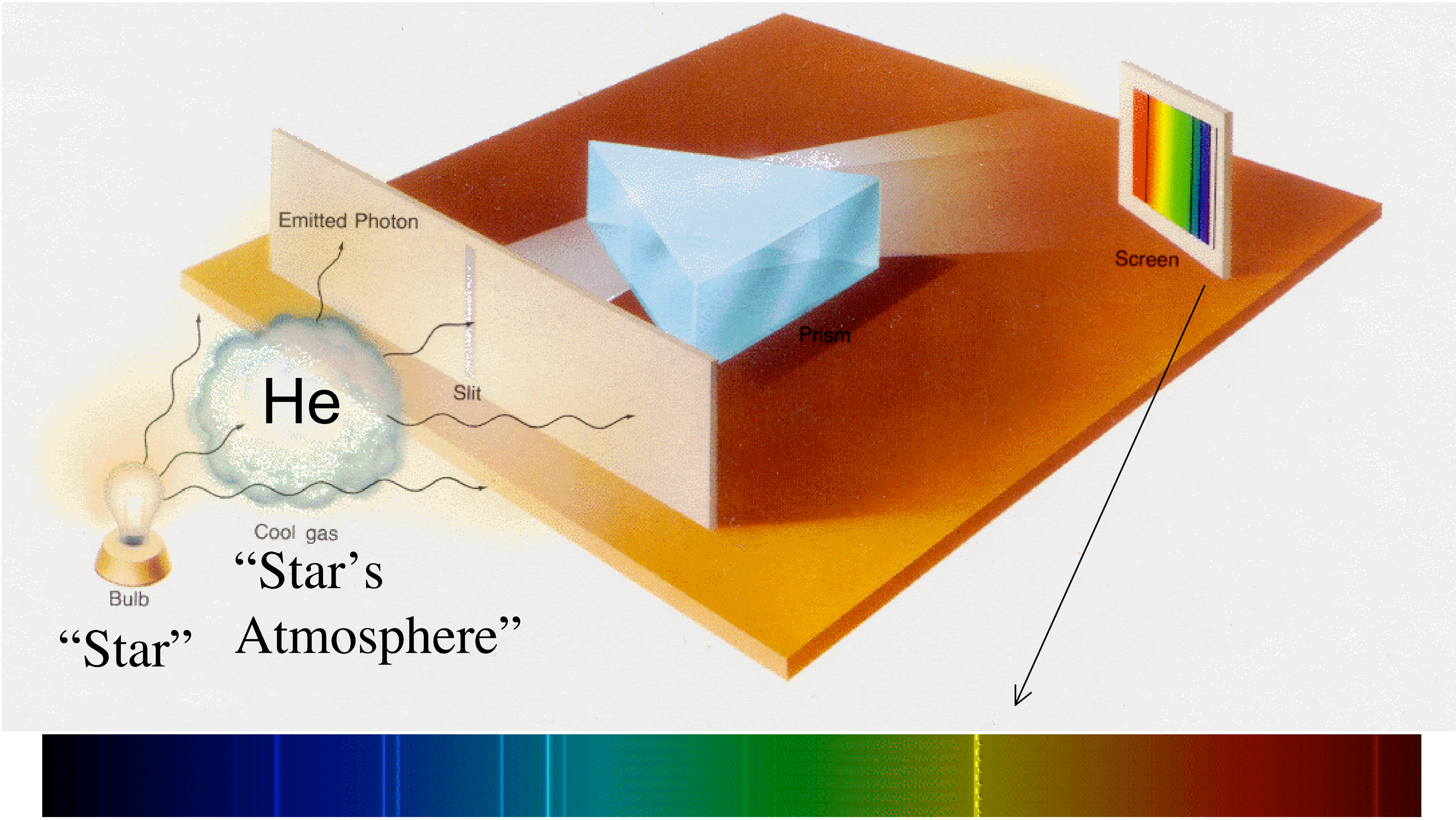
Absorption Spectra - 1



• If the light from a hot, dense body passes through a low-density gas which is cooler than the hot body, its spectrum is seen to be continuous except that it is <u>missing light at certain wavelengths</u> (I.e., **absorption lines**).
• The absorption lines are at exactly the wavelengths which would have been produced by the diffuse gas on its own.

http://www.astro.queensu.ca/~hanes/PHYS015-2007/Notes/Theme_05/6._Meet_Kirchhoff's_Laws.html

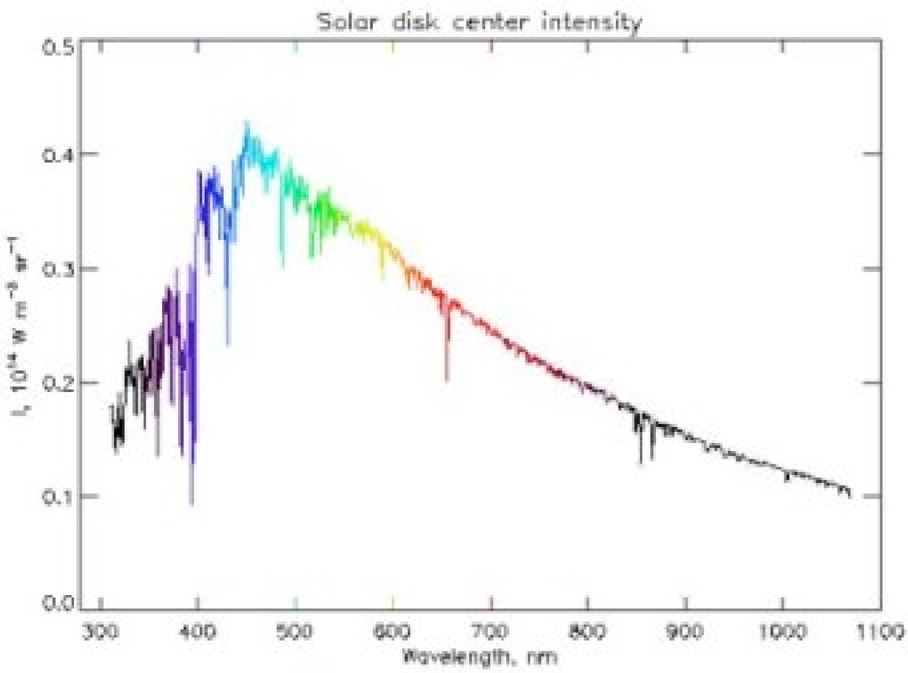
Absorption Spectra -2

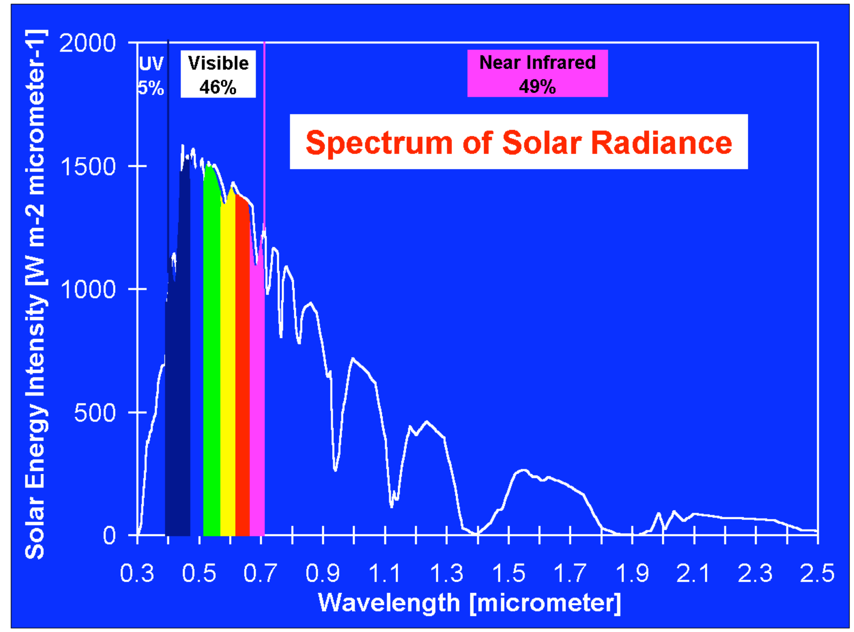


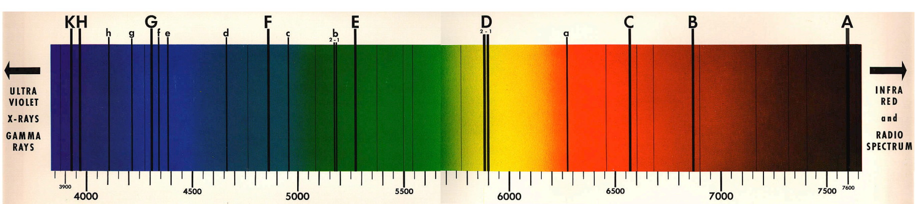
Helium

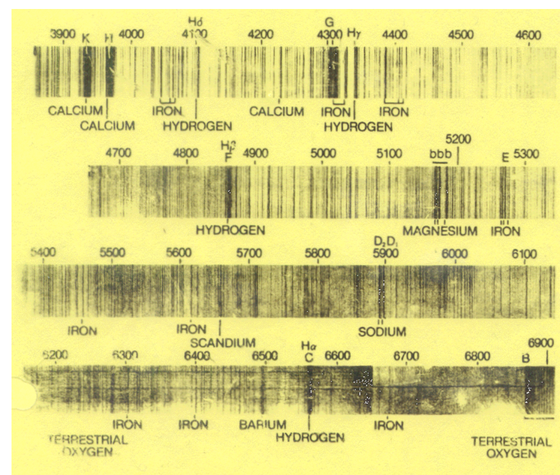
- If the cool gas was Helium this is what the absorption spectrum would look like

The Spectrum of the Sun: The Solar Atmosphere









http://www.astro.queensu.ca/~hanes/PHYS015-2007/Notes/Theme_05/6._Meet_Kirchhoff's_Laws.html

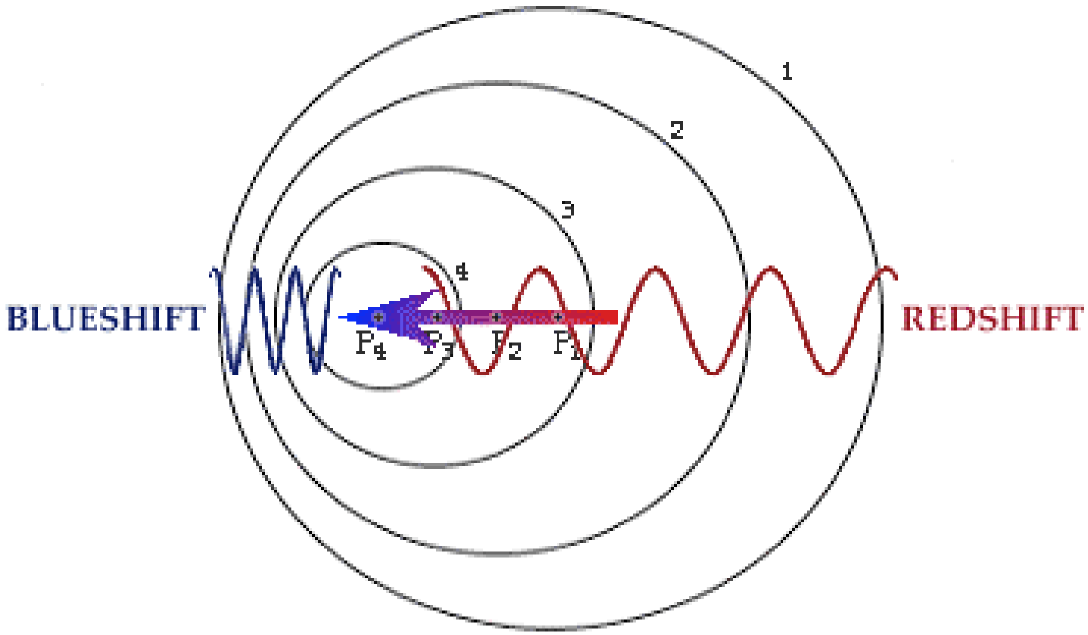
http://eetd.lbl.gov/coolroof/SPECTRUM.gif

http://astroneu.com/plasma-redshift-1/solar-spectrum-from-www-mao-kiev-ua--sol_ukr--terskol--bmv_m.jpg

http://www.astro.queensu.ca/~hanes/PHYS015-2007/Notes/DAH_Figs/Solar_Spectrum.gif

Doppler Effect

Occurs when a light-emitting object is in motion with respect to the observer.



- Motion toward observer: light is "compressed" (wavelength gets smaller). Smaller λ = bluer light, or "<u>blue shifted</u>".

- Object receding from observer: λ increases, or gets "<u>red shifted</u>".

Red Shift vs. Distance Relationship

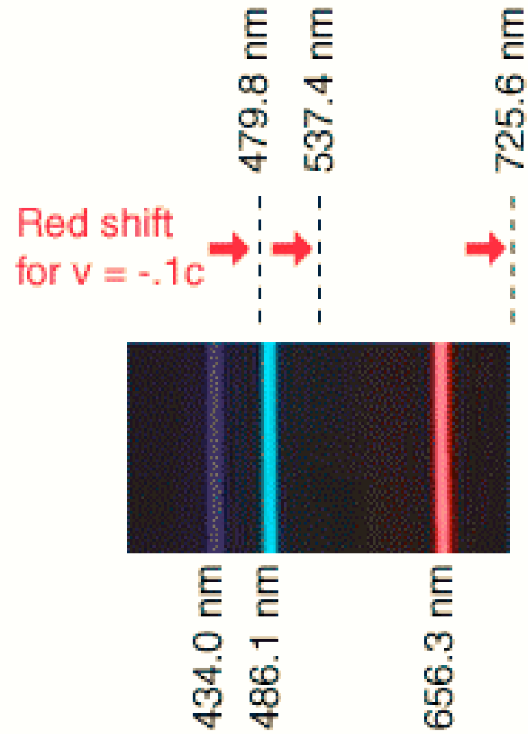
• Spectral lines become shifted against the rainbow background when a distant object is in motion (see Example).

• All observed galaxies have red shifted spectra, hence all are receding from us.

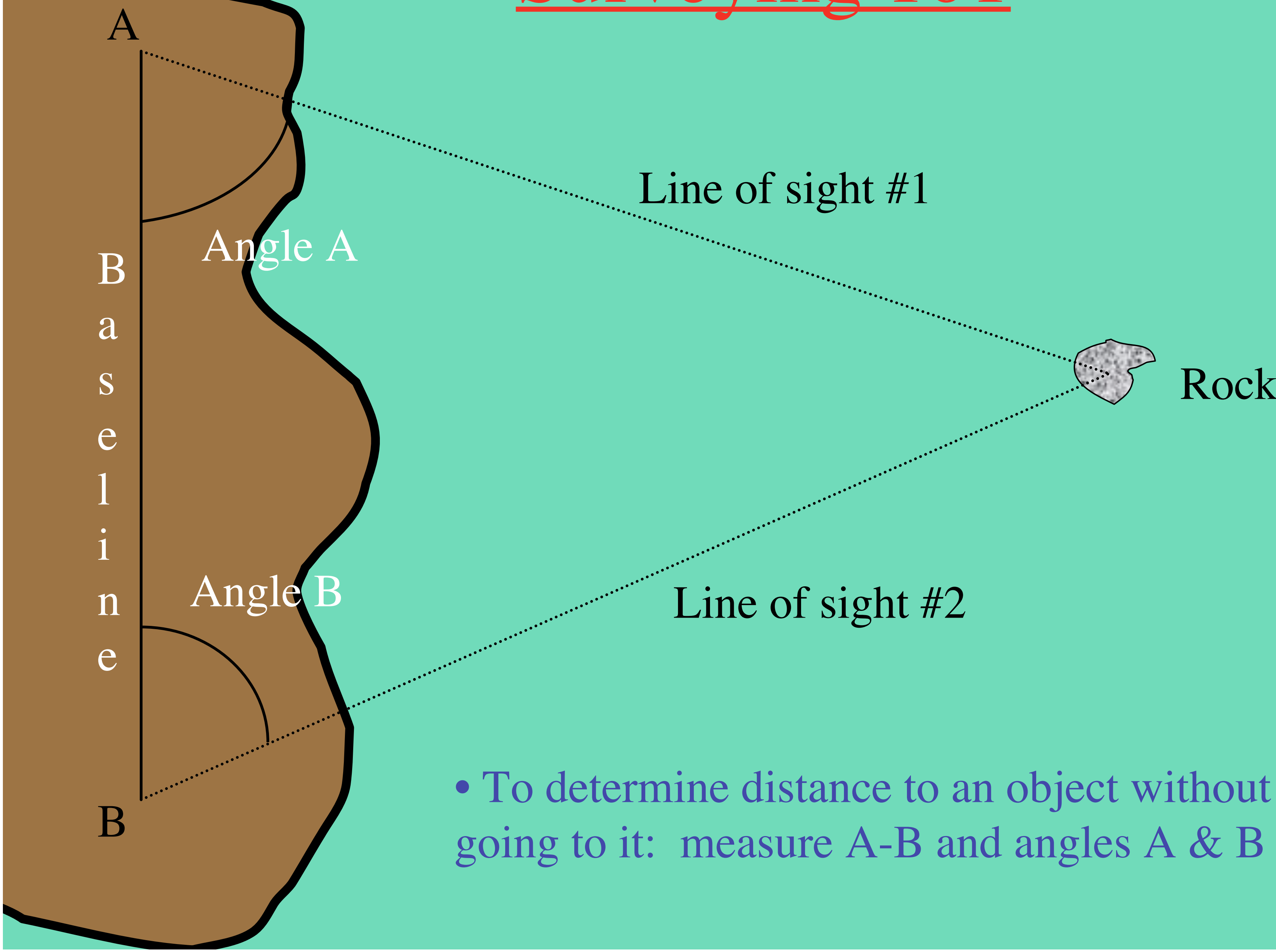
• More distant galaxies appear more red shifted than nearer ones, consistent with expanding universe.

• <u>Hubble's Law</u>: red shift (recession speed) is proportional to distance.

<u>Example</u>: If a shift toward red of hydrogen spectral lines from a distant galaxy of 10% is observed the galaxy is speeding away from Earth at 67 million miles per hour (0.1*c*).

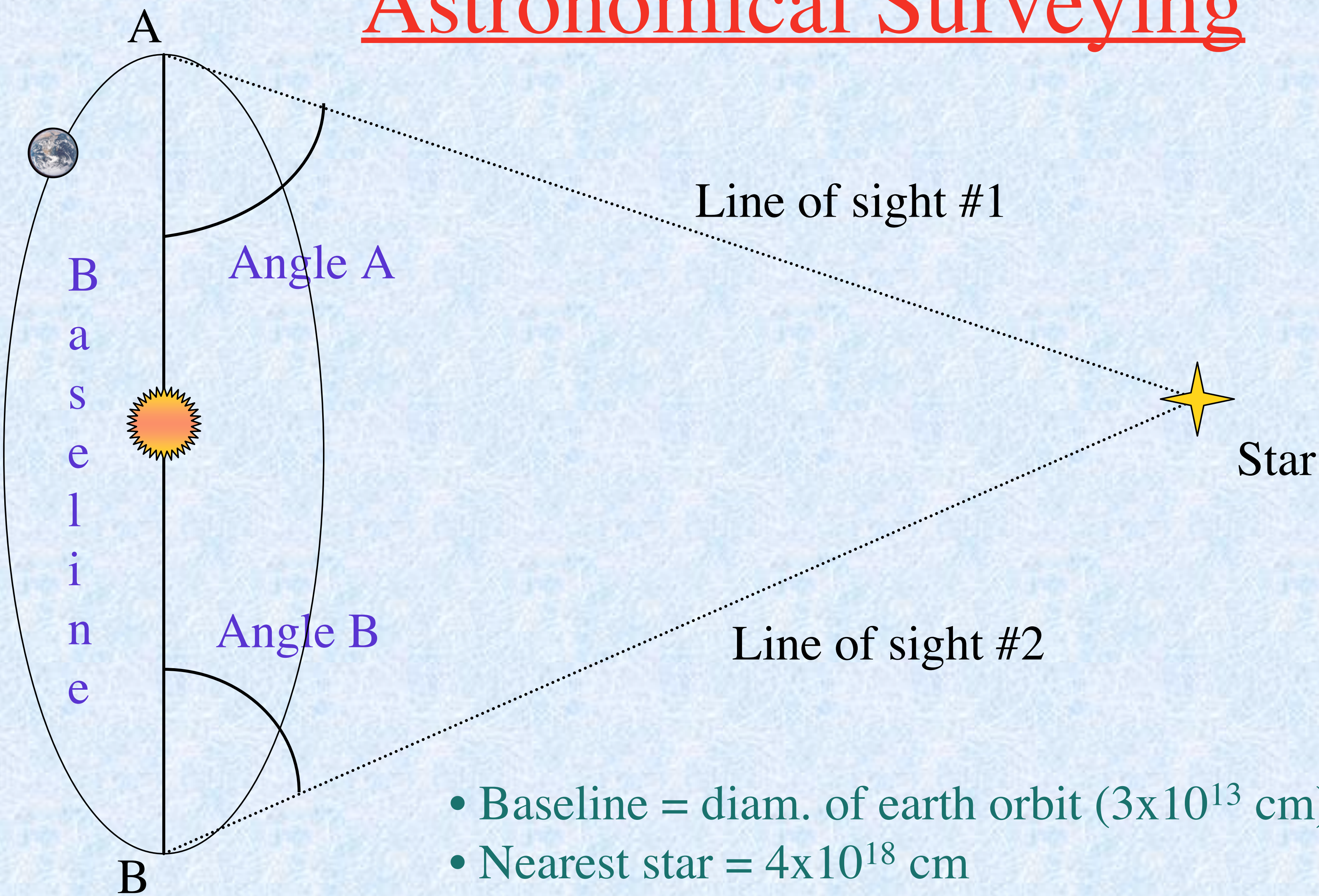


Surveying 101



• To determine distance to an object without going to it: measure A-B and angles A & B

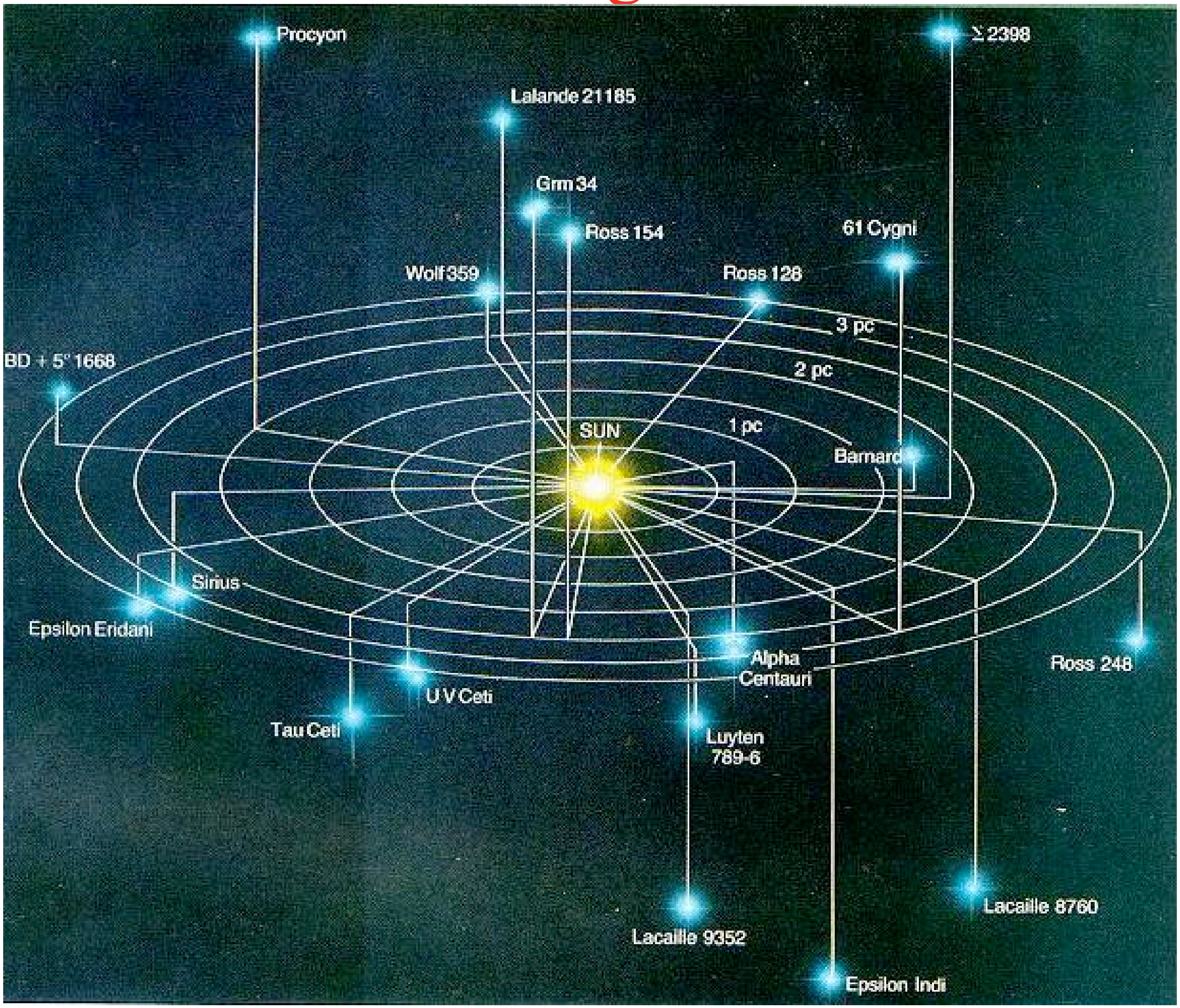
Astronomical Surveying



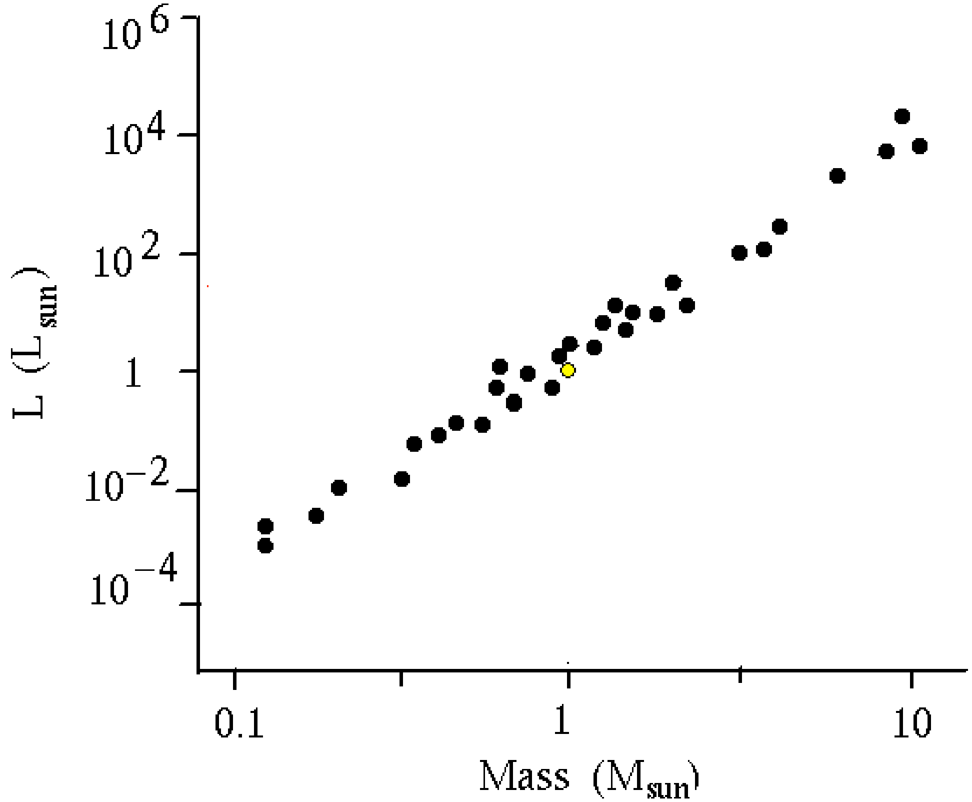
- Baseline = diam. of earth orbit ($3x10^{13}$ cm)
- Nearest star = $4x10^{18}$ cm

Our Stellar Neighborhood

1 pc=3.26 lt-yr



Mass-Luminosity Relationship for Stars within an order of magnitude of the Sun's mass



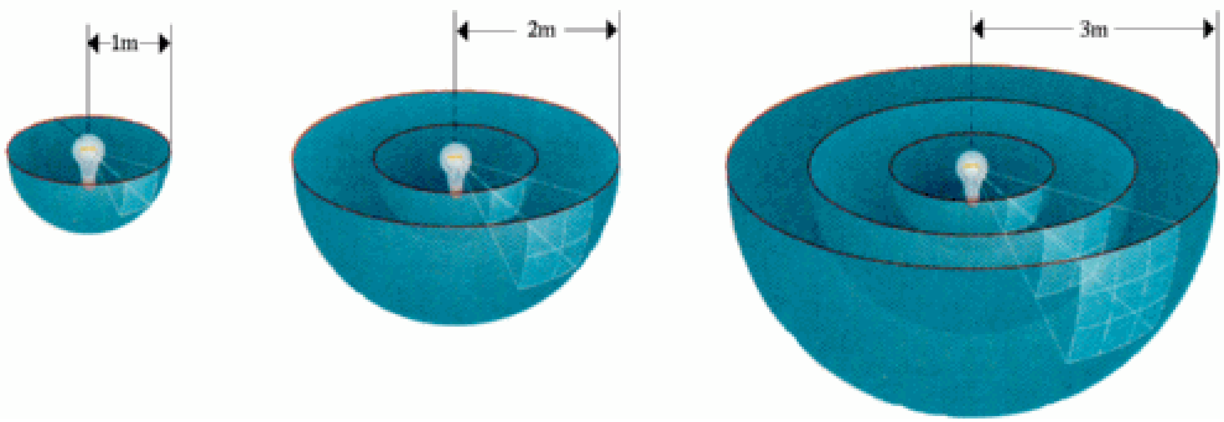
- A small sampling of stars near the sun. Actual range of masses in our galaxy is 0.08-100 M_{sun}.

- Luminosity is energy output per second (I.e., Watts)
- The mass of a star controls the rate of energy production, which is thermonuclear fusion in the core.
- The rate of energy generation determines the star's luminosity.
- This relation applies to stars before they evolve into giant stars (those stars which burn hydrogen in their core).

Much of the material on stellar evolution is adapted from lectures by Prof. Barbara Ryden at Ohio State University, http://www.astronomy.ohio-state.edu/~ryden/ and Prof. Davison Soper at the University of Oregon, http://zebu.uoregon.edu/~soper/

Inverse Square Law

The brightness of an object varies inversely with the square of the distance from that object.

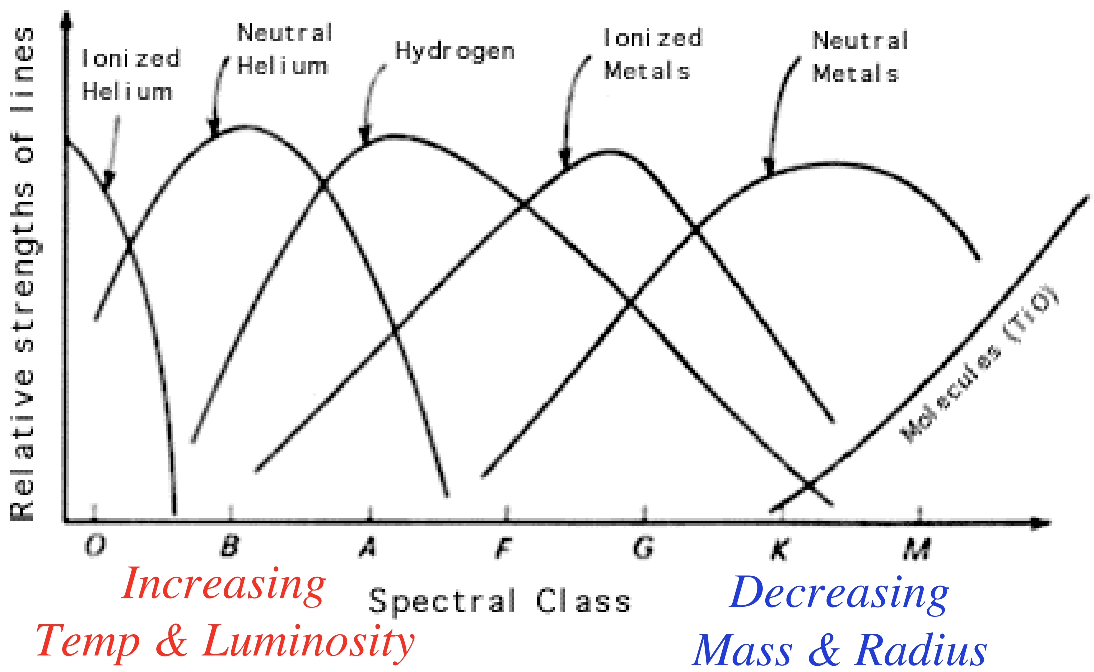


$$\text{brightness} \;\alpha\; \frac{1}{\text{distance}^{2}}$$

Example: What is the apparent brightness of the Sun as seen from Jupiter?

$$\frac{b_{\text{Jupiter}}}{b_{\text{Earth}}} = \frac{D^2_{\text{Earth}}}{D^2_{\text{Jupiter}}} = \frac{1^2}{5^2} = \frac{1}{25}$$

Classification of Stellar Spectra

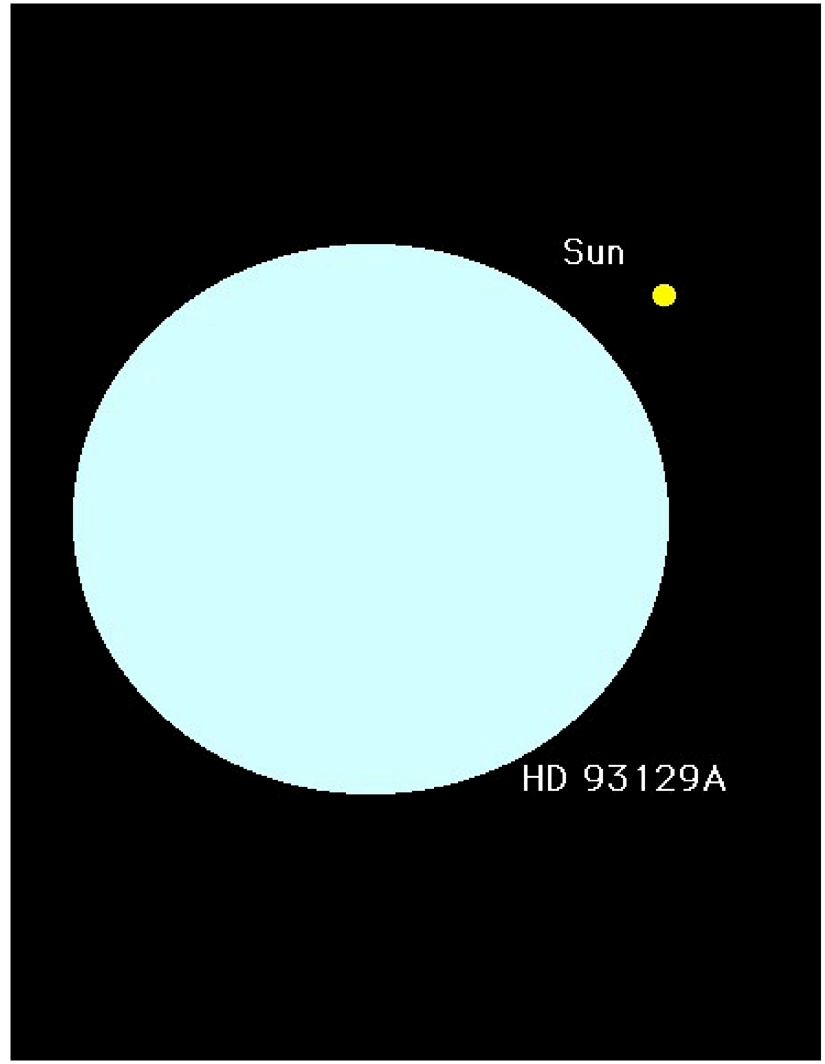


type	Mass	Temp	Radius	Lum (Sun=1)
O	60.0	50,000	15.0	1,400,000
B	18.0	28,000	7.0	20,000
A	3.2	10,000	2.5	80
F	1.7	7,400	1.3	6
G	1.1	6,000	1.1	1.2
K	0.8	4,900	0.9	0.4
M	0.3	3,000	0.4	0.04

- Luminosity α Mass
- T α λ^{-1}
- Spectral classification & color dictated almost solely by surface T, not chemical composition
- Chemical composition, like T, is a *consequence* of fusion reactions in the core

Adapted from Prof. Barbara Ryden's Astronomy lectures, Ohio State Univ., http://www.astronomy.ohio-state.edu/~ryden/

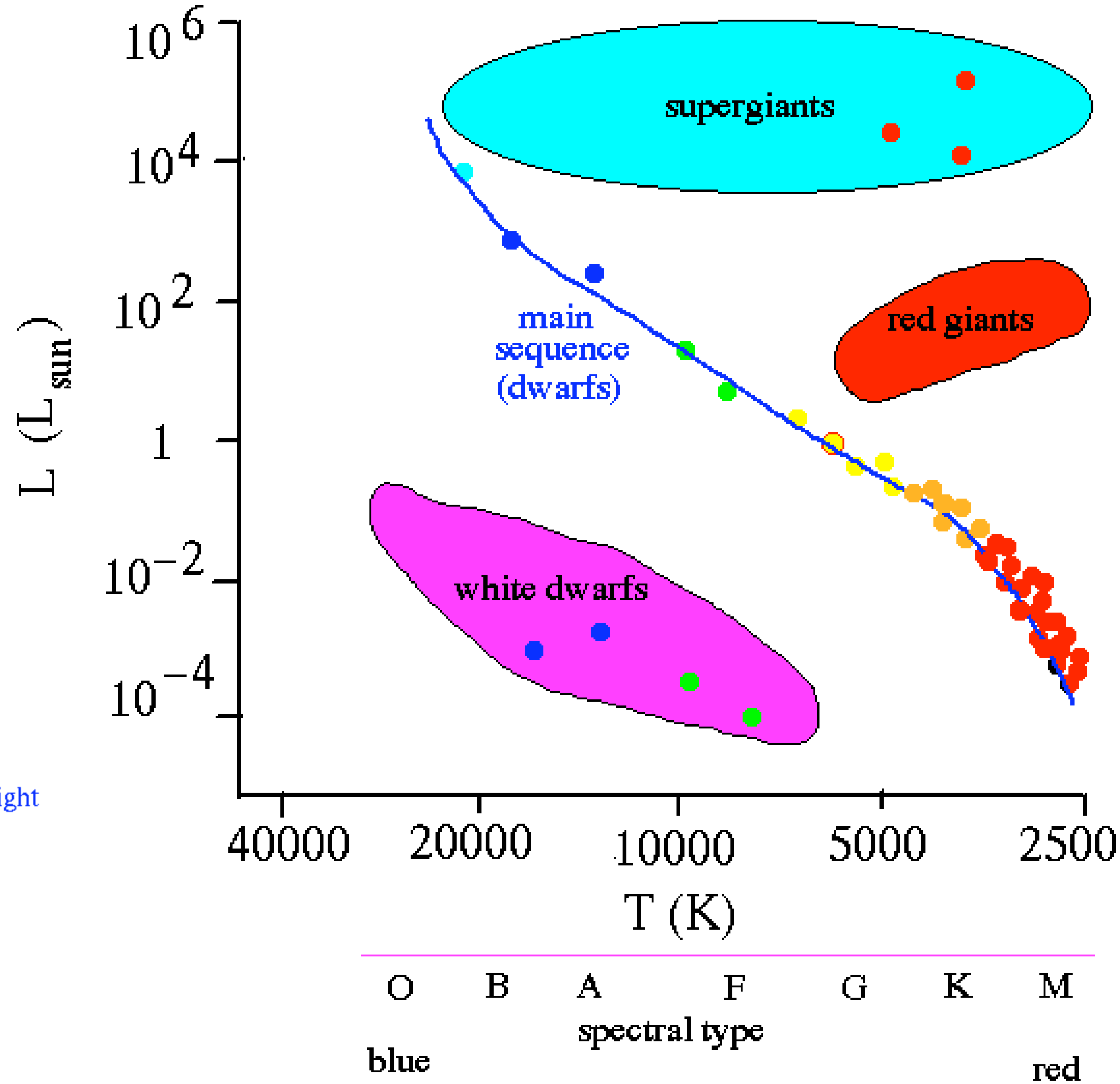
Examples of Stars

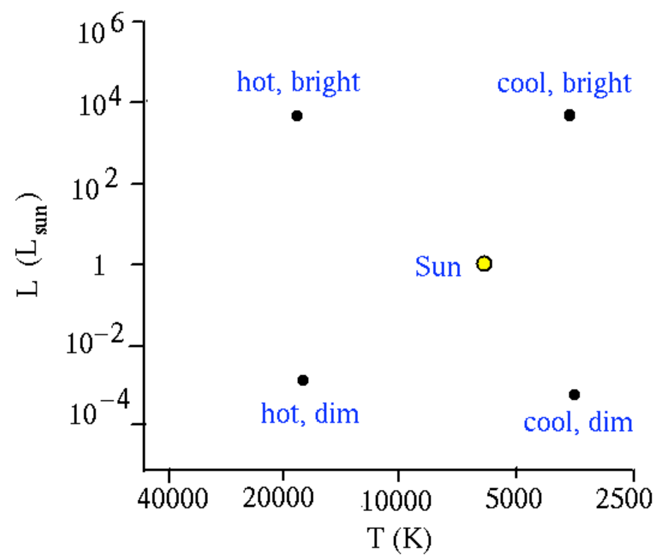


- Sun: middle-of-the-road G star.

- HD93129A a B star, is much larger, brighter and hotter.

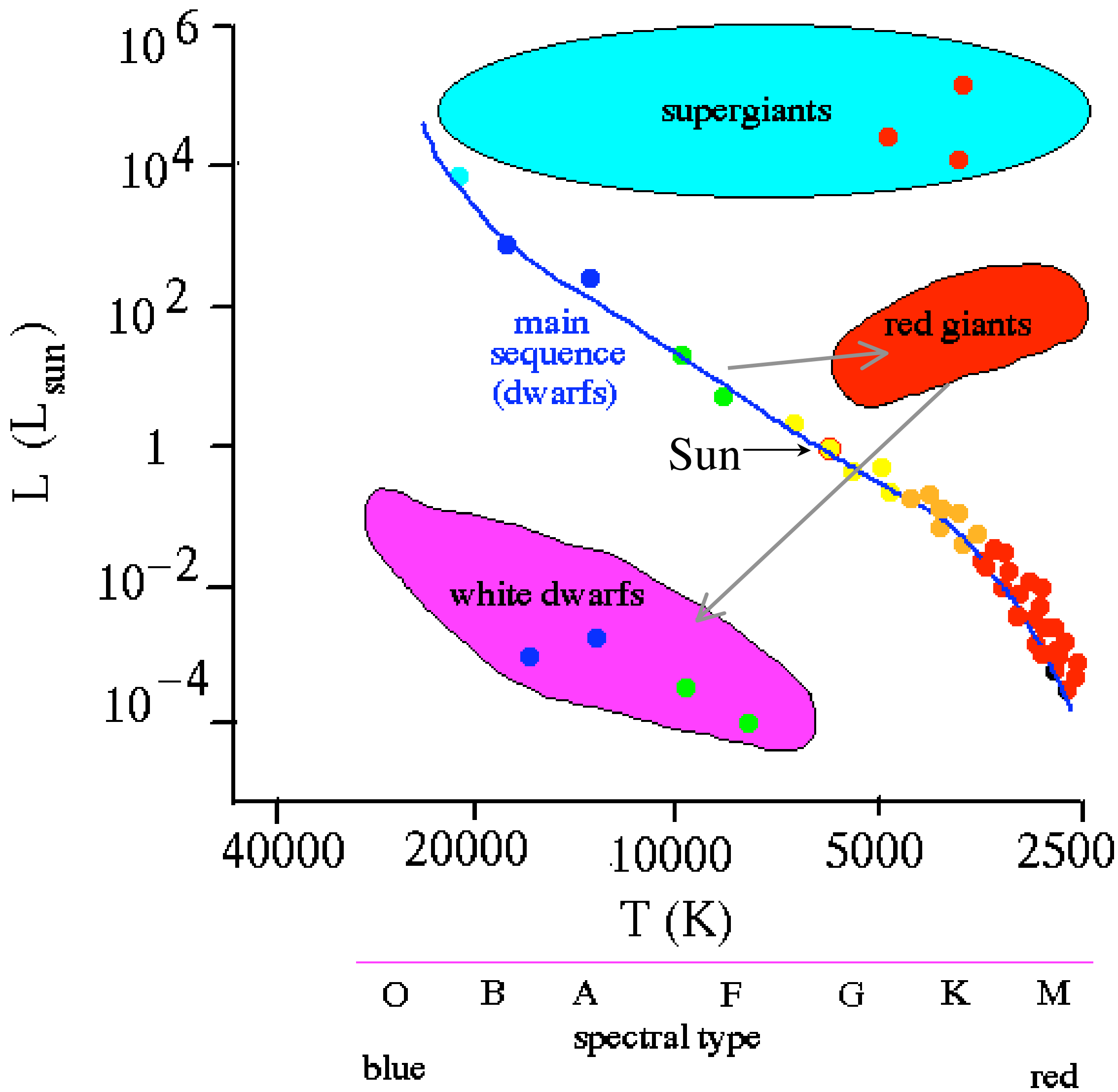
Hertzsprung -Russell Diagram





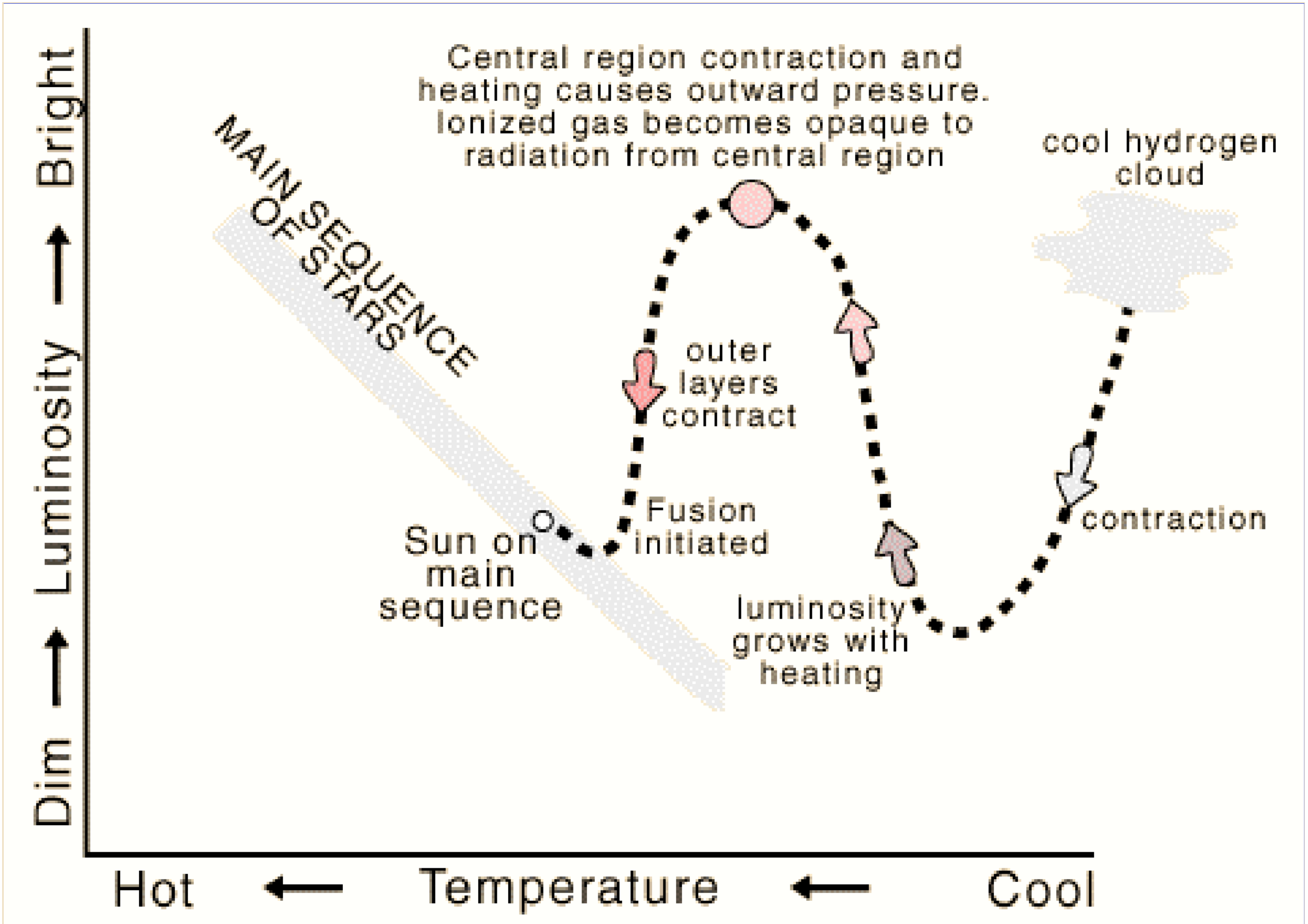
- 90% of all stars lie on main sequence
- Above Stars are from solar Neighborhood

Stellar Evolution



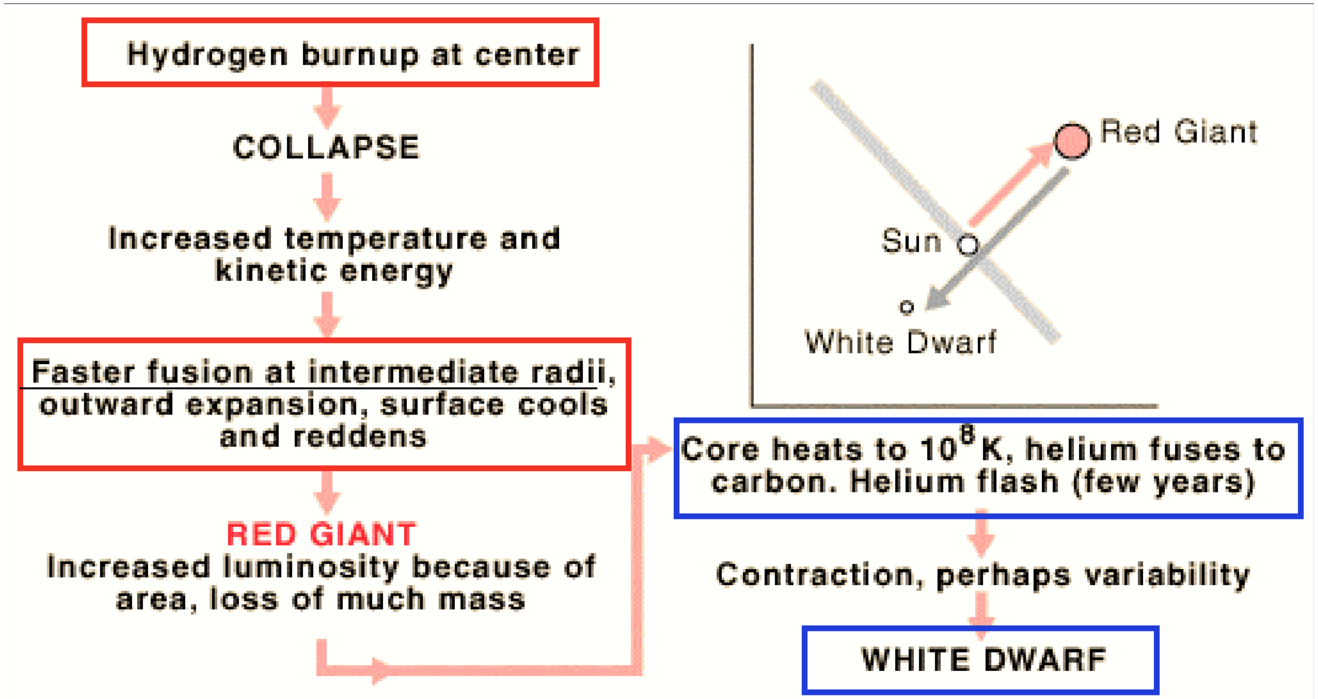
- Main Sequence stars are burning hydrogen
- When H is all converted to He by fusion the star leaves the Main Sequence and becomes a Red Giant, then a White Dwarf

Sun’s Evolution Onto the Main Sequence



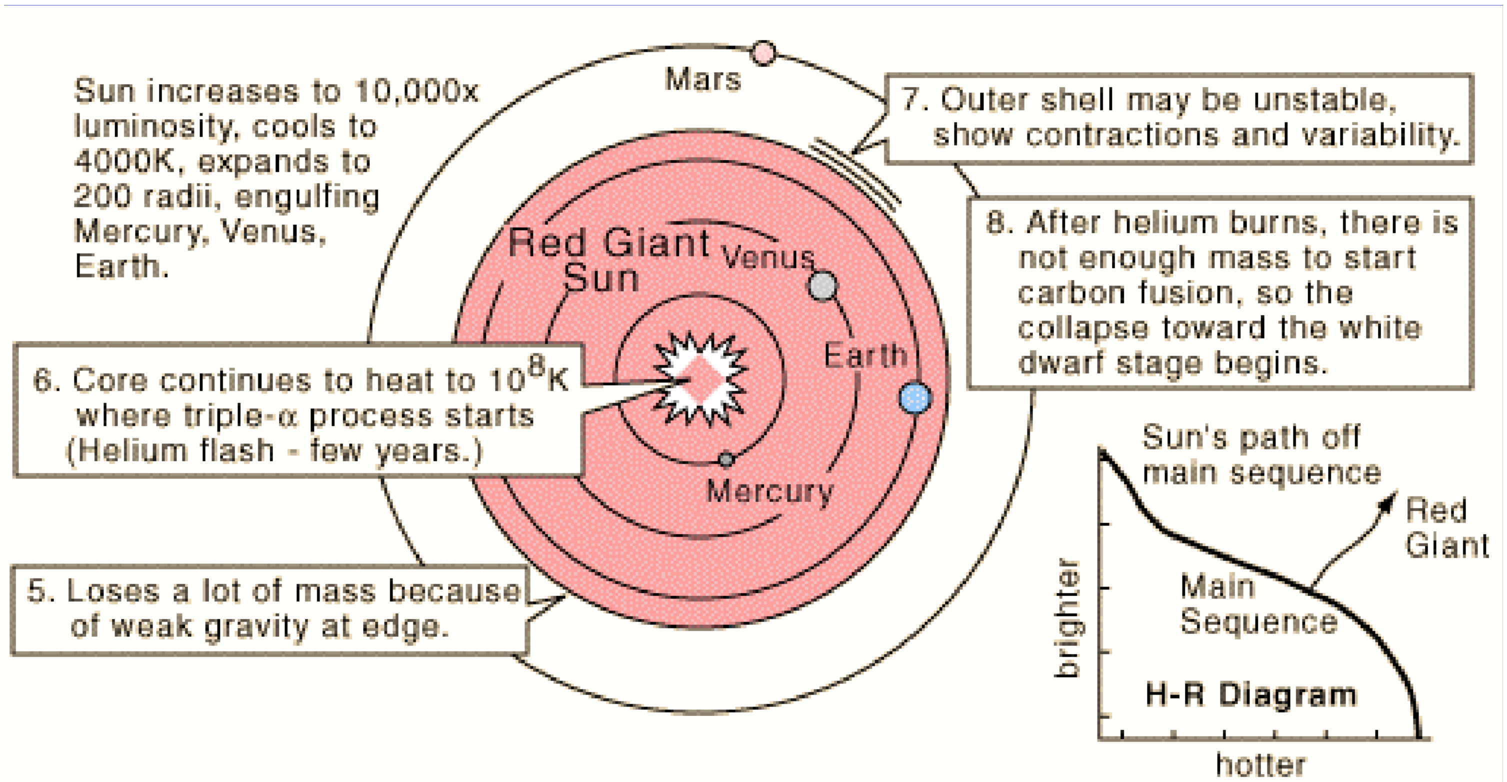
- Where it will stay for ~10 b.y. (4.6 of which are past) until all hydrogen is exhausted…

Sun's Future Evolution Off the Main Sequence



- In another ~5 b.y. the Sun will run out of hydrogen to burn
- The subsequent collapse will generate sufficiently high T to allow fusion of heavier nuclei
- Outward expansion of a cooler surface, sun becomes a Red Giant
- After He exhausted & core fused to carbon, Helium Flash occurs
- Followed by rapid contraction to White Dwarf

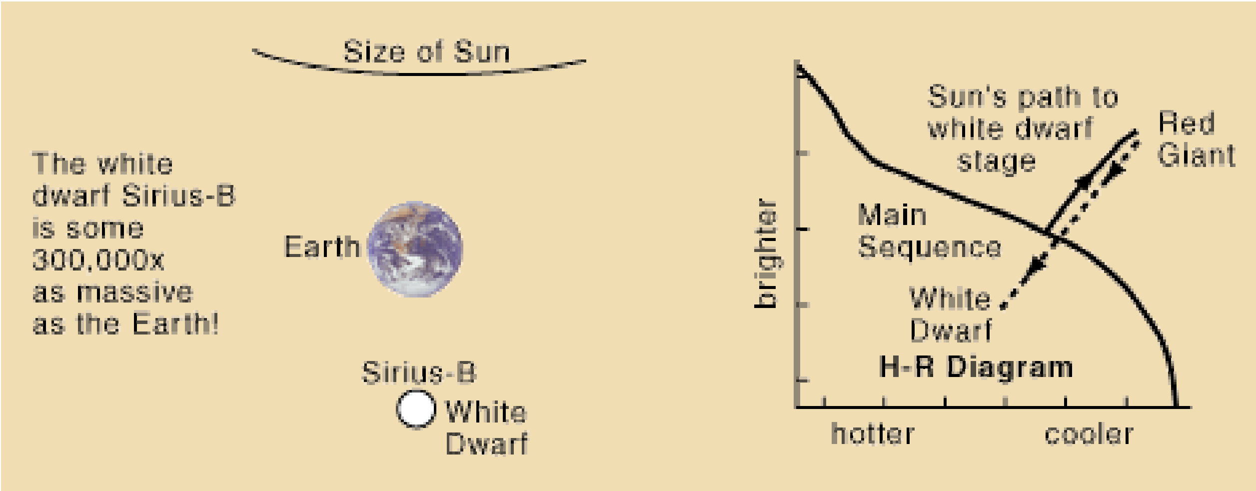
Red Giant Phase of Sun: t minus 5 b.y.



- For stars of less than 4 solar masses, hydrogen burn-up at the center triggers expansion to the red giant phase.

White Dwarf Phase of Sun

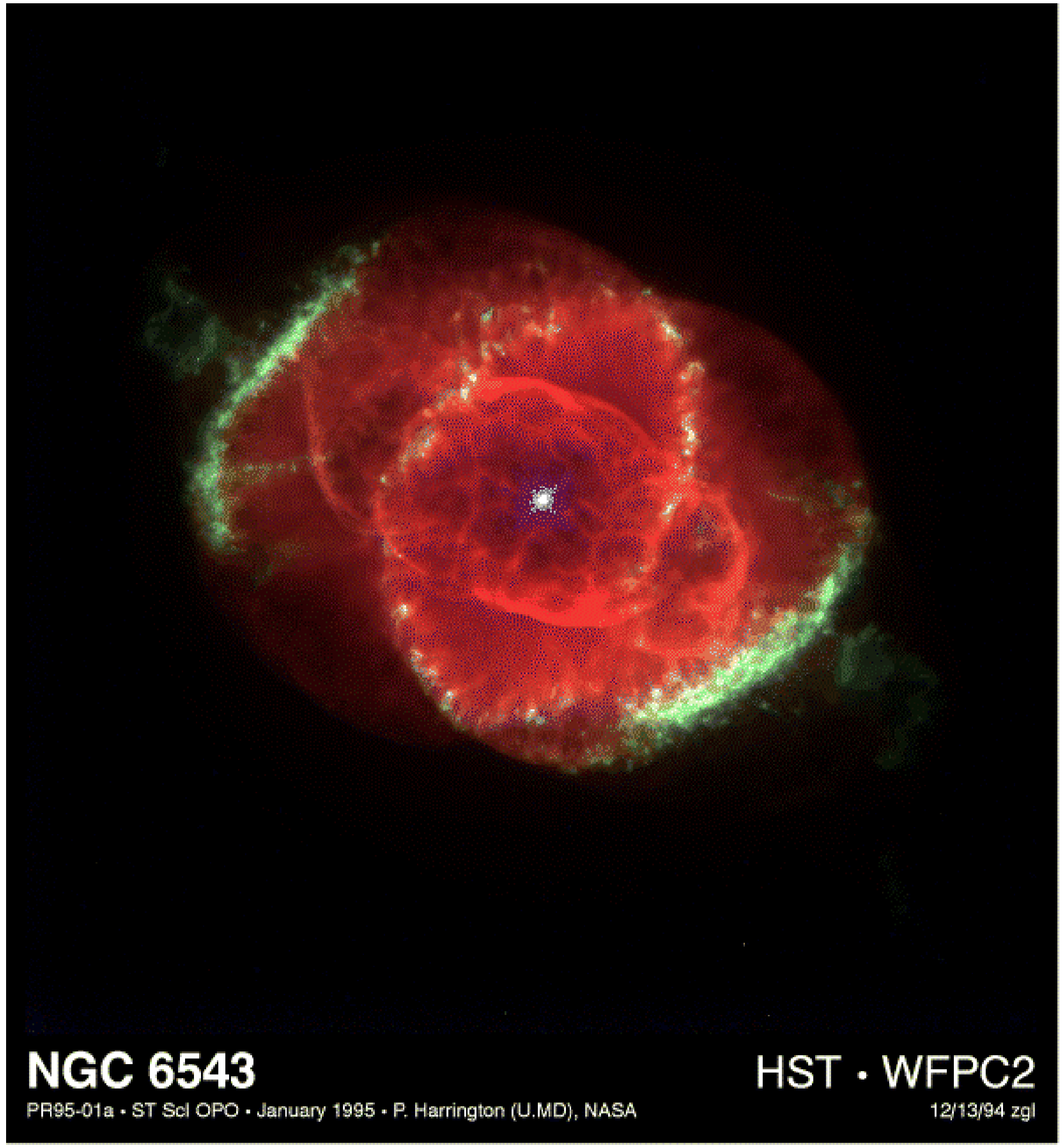
•When the triple-alpha process (fusion of He to Be, then C) in a red giant star is complete, those evolving from stars < 4 M_{sun} do not have enough energy to ignite the carbon fusion process.
•They collapse, moving down & left of the main sequence, to become white dwarfs.
•Collapse is halted by the pressure arising from electron degeneracy (electrons forced into increasingly higher E levels as star contracts).



• 1 teaspoon of a white dwarf would weigh 5 tons
• A white dwarf with solar mass would be about the size of the Earth

End of a Star's Life: White Dwarfs

- Stars **< 25 M_{sun}** evolve to **white dwarfs** after substantial mass loss.
- Due to atomic structure limits, all white dwarfs must have mass less than the Chandrasekhar limit (1.4 M_s).
- If initial mass is > 1.4 M_s it is reduced to that value catastrophically during the planetary nebula phase when the envelope is blown off.
- This can be seen occurring in the Cat's Eye Nebula:



Supernovae: Death of Massive Stars

carbon fusion
(600 years)

↓

neon fusion
(1 year)

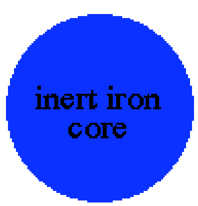
↓

oxygen fusion
(6 months)

↓

silicon fusion
(1 day)

→



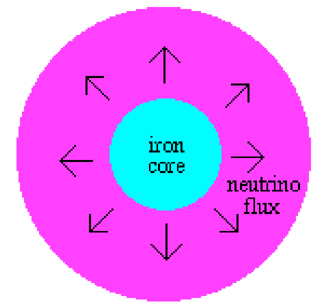
Stars > 25 solar masses

Supernova Explosion

Inert iron core stops producing energy, but continues to produce neutrinos which release energy from core

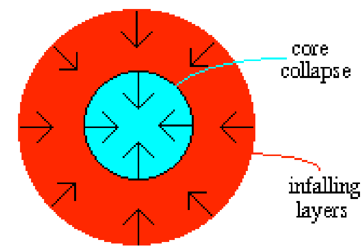
Densities climb, protons and electrons combine to produce neutrons and more neutrinos

Sudden lost of energy causes core to collapse from lack of pressure support



Regions around core are unsupported and plunge onto core at speeds up to 15% the speed of light

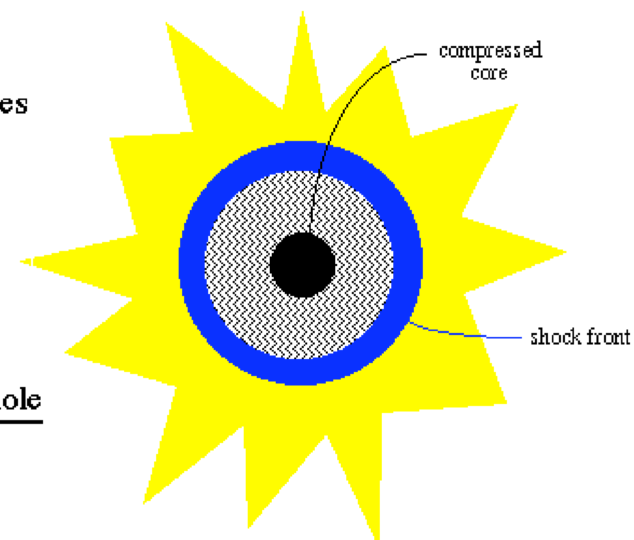
Neutron densities are so high in core that it is incompressible and rigid. Infalling layers strike core and rebound.



In a fraction of a second, a wave of matter forms a shock front and moves outward towards stellar surface.

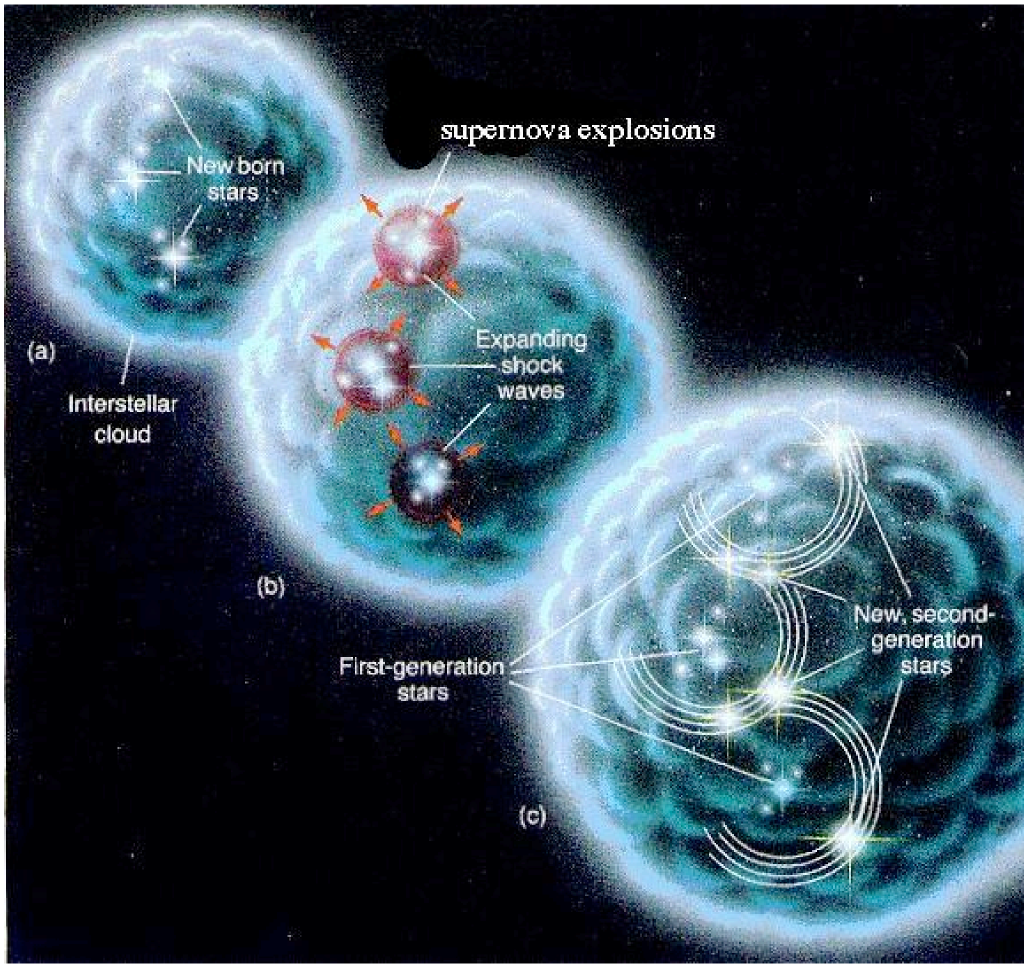
Shock wave hits surface of star and explodes

Inward shock compresses remaining stellar core into neutron star or black hole



Supernovae

•E release so immense that star outshines an entire galaxy for a few days.

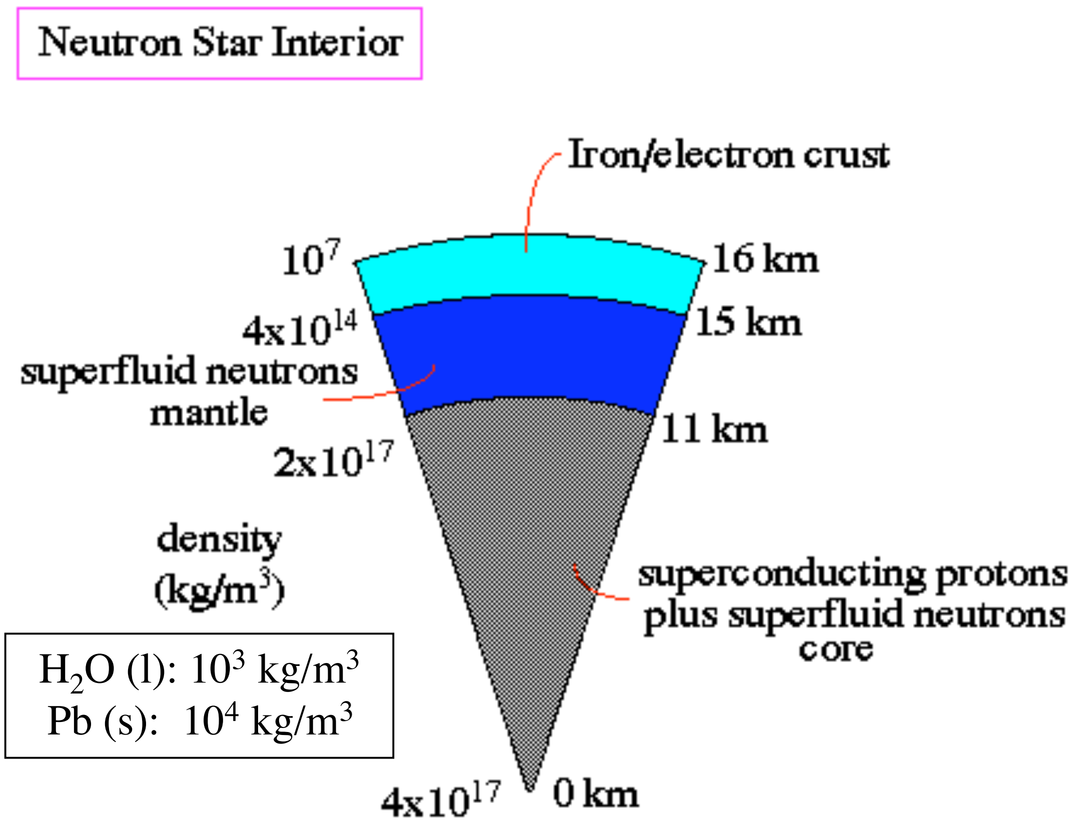


Supernova 1991T in galaxy M51

•Supernova can be seen in nearby galaxies, ~ one every 100 years (at least one supernova should be observed if 100 galaxies are surveyed/yr).

Neutron Stars

- Remnant of supernova.
- Composed solely of degenerate neutrons (combined protons & electrons).
- As a neutron star increases in mass:
  - its radius gets smaller (as with white dwarf)
  - it rotates more quickly (conservation of angular momentum).
- A neutron star with a surface T of 50,000 K could have such a small radius that its total luminosity would be a million times fainter than the Sun (with a surface T=6,000 K).



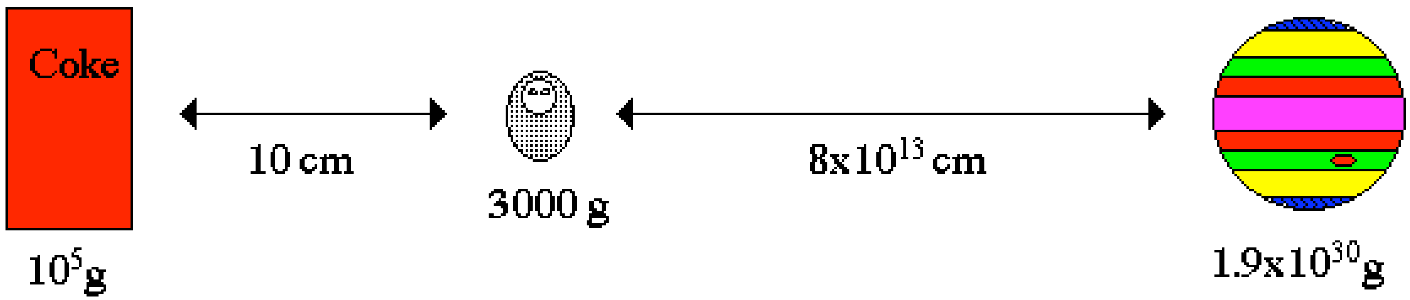
H_2O (l): 10^3 kg/m^3
Pb (s): 10^4 kg/m^3

1 teaspoon ~ 1 billion tons

(compared to 5 tons/tsp of white dwarf)

Force of Gravity Decreases with the Square of Distance

Example: what is the force of gravity from Jupiter on you at birth compared to the force of gravity from a nearby Coke machine?



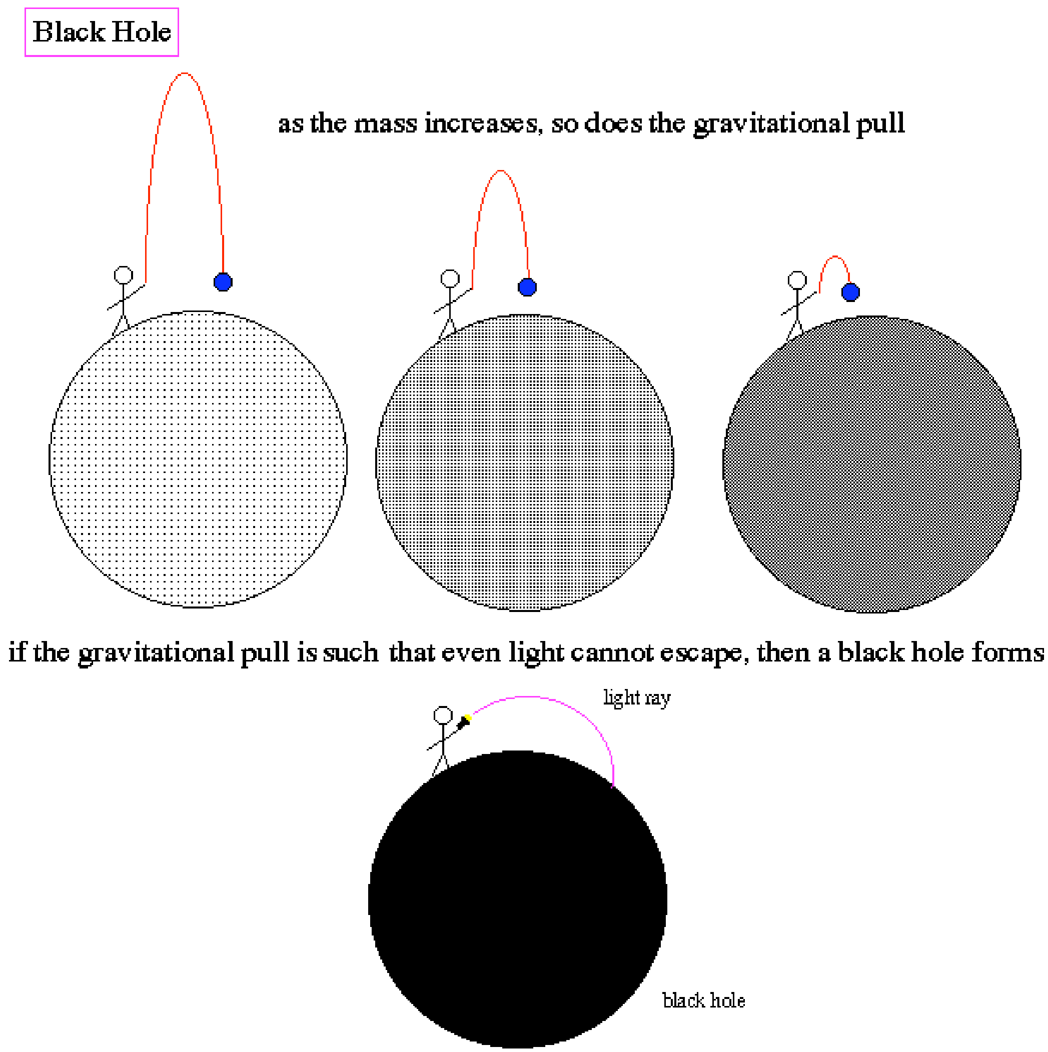
$$F_{Coke} = \frac{G(10^5 g)(3000 g)}{(10\ cm)^2} = 2x10^{-1}\ dynes$$

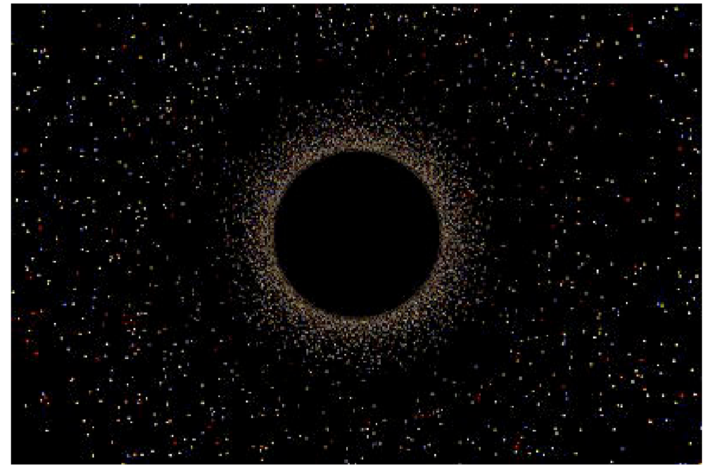
$$F_{Jupiter} = \frac{G(1.9x10^{30} g)(3000 g)}{(8x10^{13}\ cm)^2} = 5.9x10^{-2}\ dynes$$

therefore, the force of gravity from the Coke machine is about 3 times more than the force of gravity from Jupiter.

Black Holes

• Following a supernova, the most massive stars evolve into





•The visual image of a black hole is one of a dark spot in space with no radiation emitted.

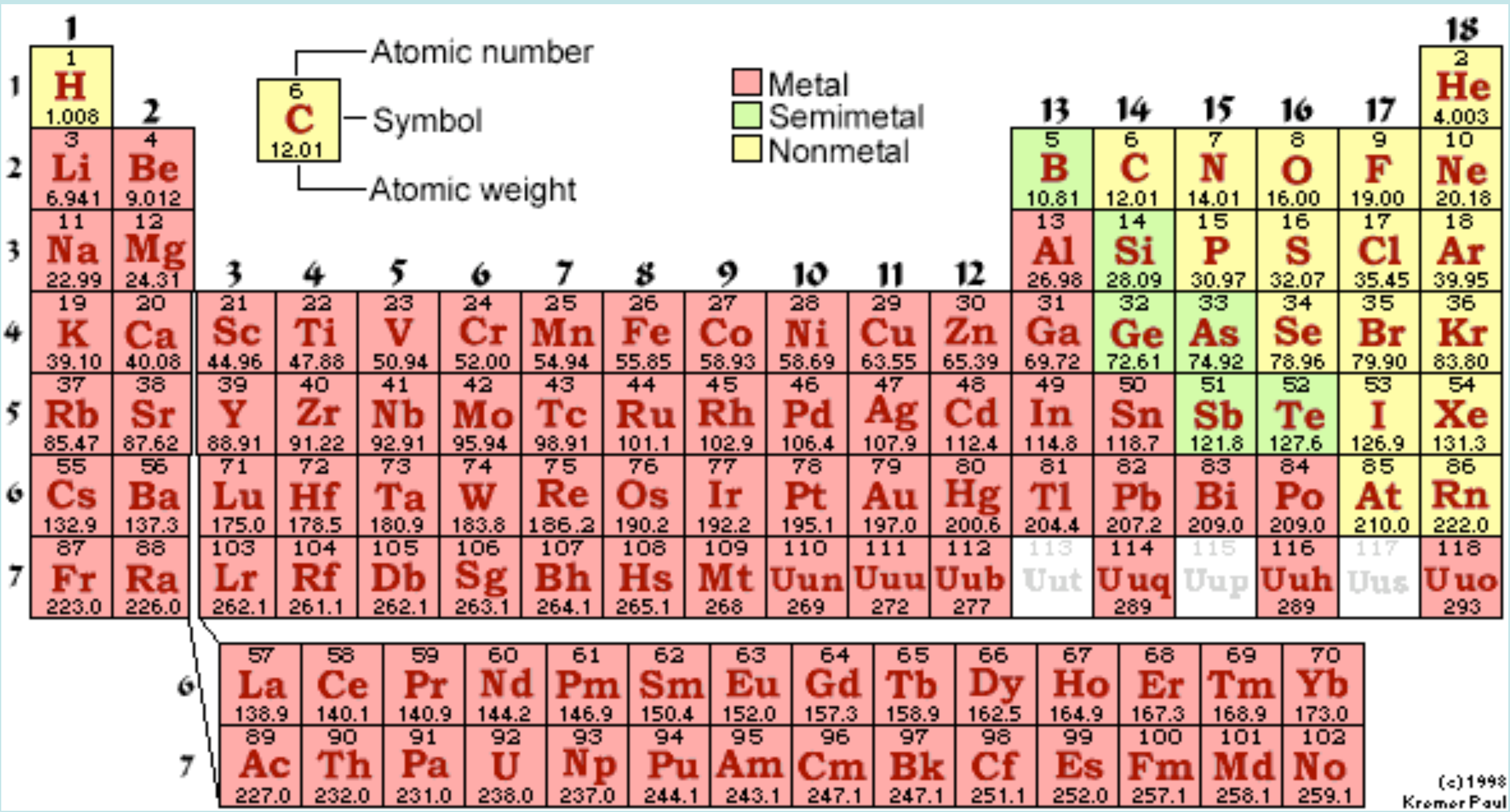
•Its mass can be detected by the deflection of starlight.

•Since the forces of matter can not overcome the force of gravity, all the mass of a black hole compresses to zero volume at its center, making its density and gravitational pull infinite, producing a “singularity”.

•Infinite values & zero volumes cause most physical equations and theories to break down….

•Supermassive Black holes thought to exist at the center of most galaxies, including the milky Way

Nucleosynthesis



Nucleosynthesis: Fusion Reactions in Stars

Fusion Process	**Reaction**	**Ignition T (10^6 K)**
Hydrogen Burning	H-->He,Li,Be,B	50-100
Helium Burning	He-->C,O	200-300
Carbon Burning	C->O,Ne,Na,Mg	800-1000
Neon, Oxygen Burning	Ne,O-->Mg-S	2000
Silicon Burning	Si-->Fe	3000

Produced in early universe & Main Sequence stars

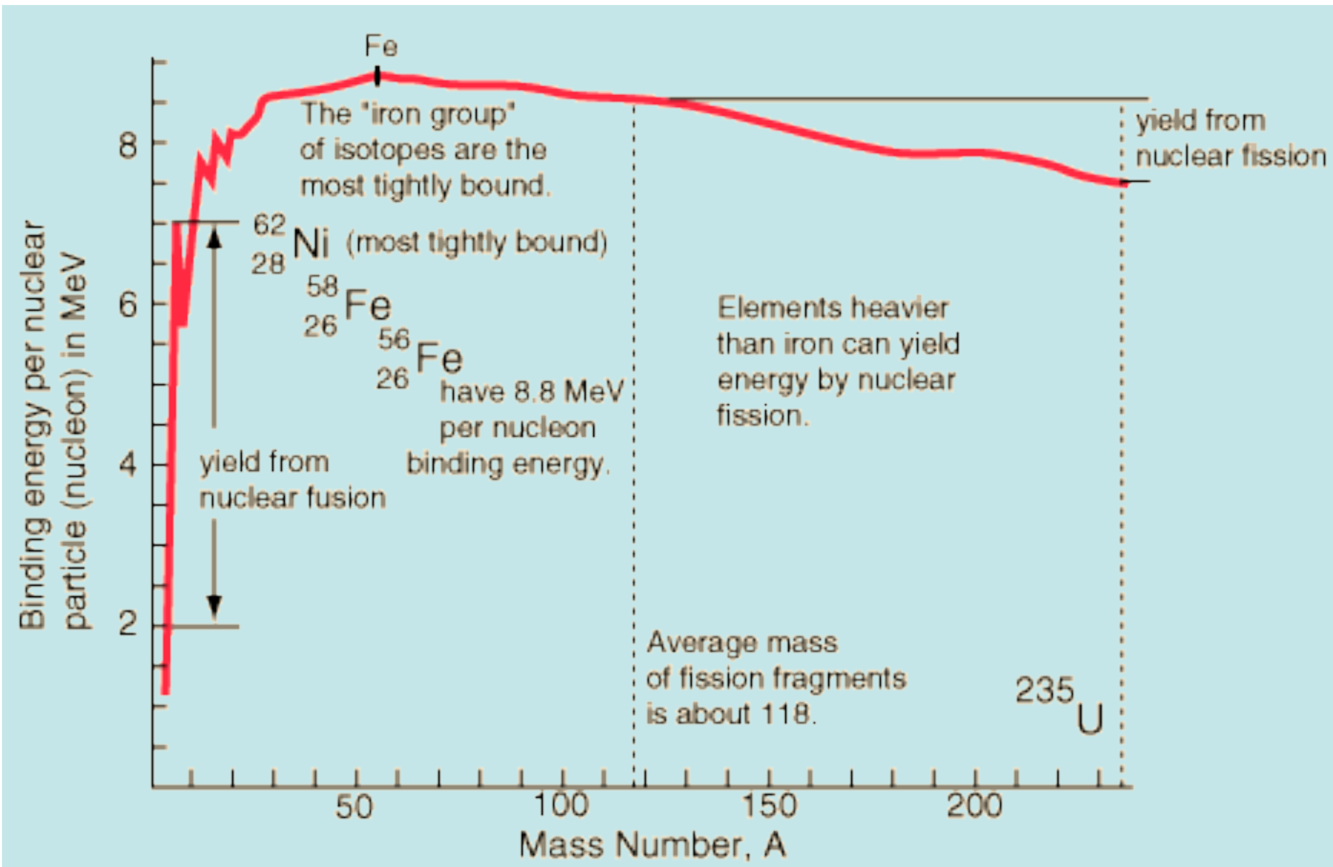
Red Giants: 3He=C, 4He=O

Supernovae, > 25 M_s

Fe is the end of the line for E-producing fusion reactions...

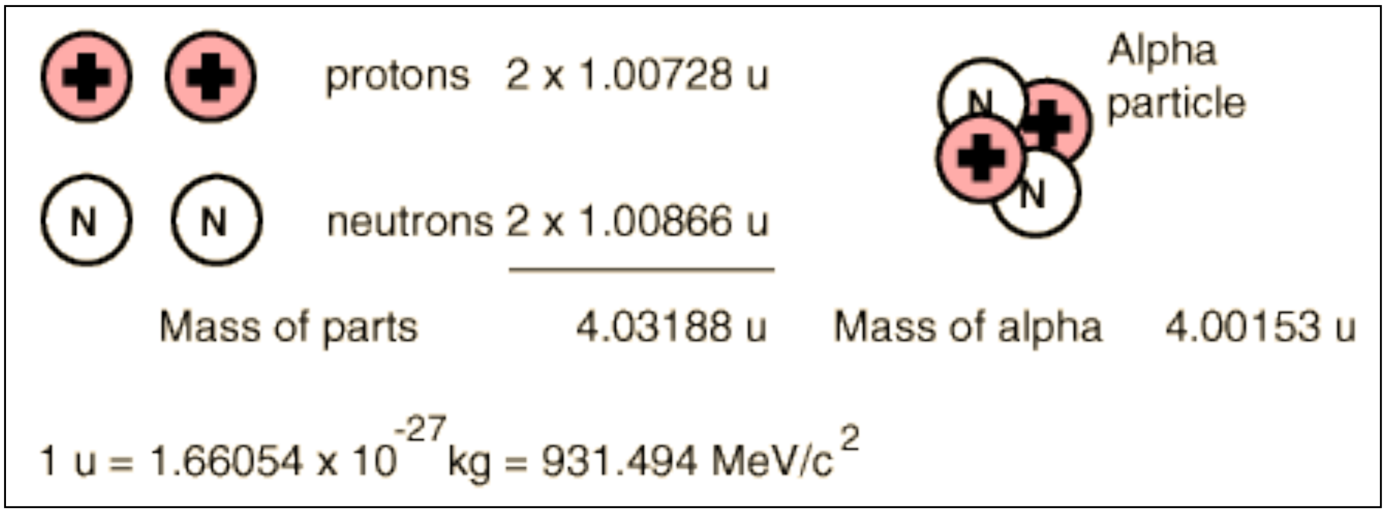
Hydrogen to Iron

•Elements above iron in the periodic table cannot be formed in the normal nuclear fusion processes in stars.
•Up to iron, fusion yields energy and thus can proceed.
•But since the "iron group" is at the peak of the binding energy curve, fusion of elements above iron dramatically absorbs energy.



Nuclear Binding Energy

- Nuclei are made up of protons and neutrons, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.
- The difference is a measure of the nuclear binding energy which holds the nucleus together.
- This energy is released during fusion.



- BE can be calculated from the relationship: BE = Δmc^2
- For α particle, Δm= 0.0304 u, yielding BE = 0.03034 x 931.4940 = 28.3 MeV
- Kinetic energy of a flying mosquito [CERN LHC website] ~ 10^6 MeV

*Mass of nuclei heavier than Fe is *greater* than mass of nuclei merged to form it.

http://en.wikipedia.org/wiki/Orders_of_magnitude_%28energy%29

Elements Heavier than Iron

- To produce elements heavier than Fe, enormous amounts of energy are needed which is thought to derive solely from the cataclysmic explosions of supernovae.

- In the supernova explosion, a large flux of energetic neutrons is produced and nuclei bombarded by these neutrons build up mass one unit at a time (neutron capture) producing heavy nuclei.

- The layers containing the heavy elements can then be blown off by the explosion to provide the raw material of heavy elements in distant hydrogen clouds where new stars form.

Neutron Capture & Radioactive Decay

- Neutron capture in supernova explosions produces some unstable nuclei.

- These nuclei radioactively decay until a stable isotope is reached.

Nucleosynthesis by Neutron Capture

construction of elements beyond iron involves the capture of a neutron to produce isophotes. Unstable isotopes decay into new elements

atomic mass = number of protons + neutrons

$$^{110}\mathrm{Cd}_{48}$$

atomic number = number of protons

element name

$^{110}\mathrm{Cd}_{48} + {}^{1}\mathrm{n}_{0} \longrightarrow {}^{111}\mathrm{Cd}_{48}$ <u>neutron capture</u>

$^{111}\mathrm{Cd}_{48} + {}^{1}\mathrm{n}_{0} \longrightarrow {}^{112}\mathrm{Cd}_{48}$ stable isotope

$^{112}\mathrm{Cd}_{48} + {}^{1}\mathrm{n}_{0} \longrightarrow {}^{113}\mathrm{Cd}_{48}$ stable isotope

$^{113}\mathrm{Cd}_{48} + {}^{1}\mathrm{n}_{0} \longrightarrow {}^{114}\mathrm{Cd}_{48}$ stable isotope

$^{114}\mathrm{Cd}_{48} + {}^{1}\mathrm{n}_{0} \longrightarrow {}^{115}\mathrm{Cd}_{48}$ unstable isotope

$^{115}\mathrm{Cd}_{48} \longrightarrow {}^{115}\mathrm{In}_{49} + e^{-} + \nu$ <u>radioactive decay</u>

Cosmic Abundance of the Elements

- H (73%) & He (25%) account for 98% of all nuclear matter in the universe.
- Low abundances of Li, Be, B due to high combustibility in stars.
- High abundance of nuclei w/ mass divisible by ^4He: C,O,Ne,Mg,Si,S,Ar,Ca
- High Fe & Ni abundance due to max binding energy.
- Even heavy nuclides favored over odd due to lower "neutron-capture cross-section" (smaller target = higher abundance).
- All nuclei with >209 particles (^{209}Bi) are radioactive.