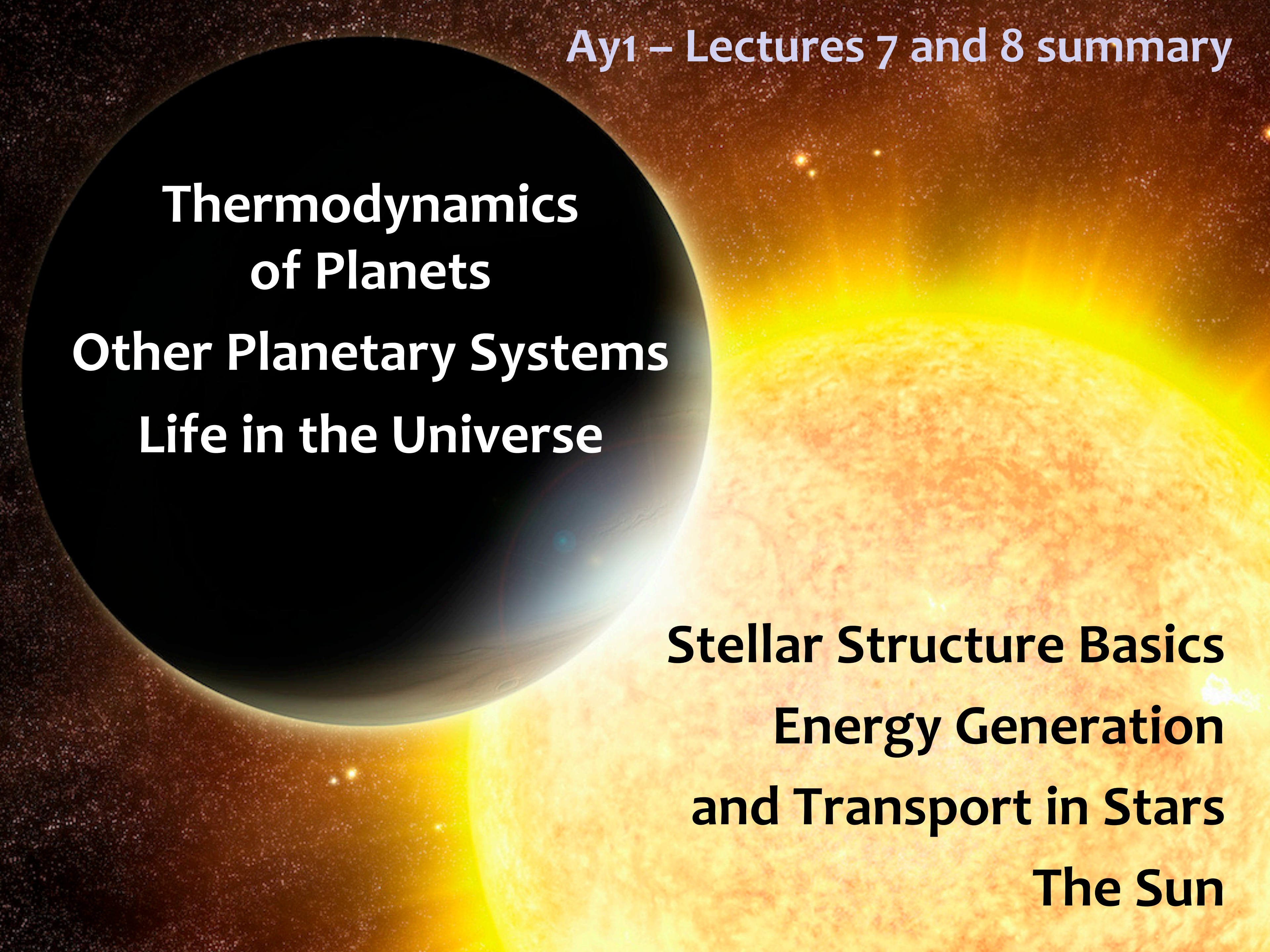


Ay1 – Lectures 7 and 8 summary

Thermodynamics of Planets

Other Planetary Systems

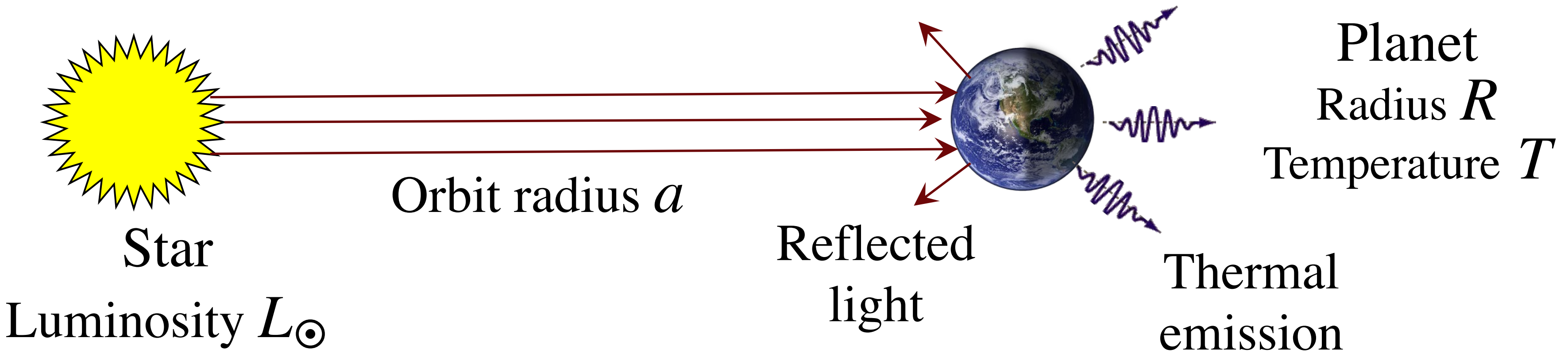
Life in the Universe

Stellar Structure Basics

Energy Generation and Transport in Stars

The Sun

Planets in a Thermal Balance



α = albedo, fraction of the reflected light (for the Earth, $\alpha \sim 0.3 - 0.35$)

Fraction of the intercepted luminosity: $\dfrac{\pi R^2}{4 \pi a^2}$

Absorbed luminosity: $\dfrac{R^2}{4 a^2} (1 - \alpha) L_\odot = 4 \pi R^2 \sigma T^4$ = Emitted luminosity

Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-5}$ erg cm^{-2} s^{-1} K^{-4}

Planet's effective blackbody temperature: $T^4 = L_\odot \dfrac{(1 - \alpha)}{16 \pi \sigma a^2}$

Planet's Temperature

For a given stellar luminosity, it depends *only* on the orbit radius and the albedo

$$T^4 = L_\odot \frac{(1-\alpha)}{16\,\pi\,\sigma\,a^2}$$

For the Earth: $\alpha \sim 0.33,\ a \sim 1.5 \times 10^{13}$ cm

$$\sigma = 5.67 \times 10^{-5}\ \mathrm{erg\ cm^{-2}\ s^{-1}\ K^{-4}}$$

$$L_\odot = 3.85 \times 10^{33}\ \mathrm{erg/s}$$

Estimate $T \sim 253$ K

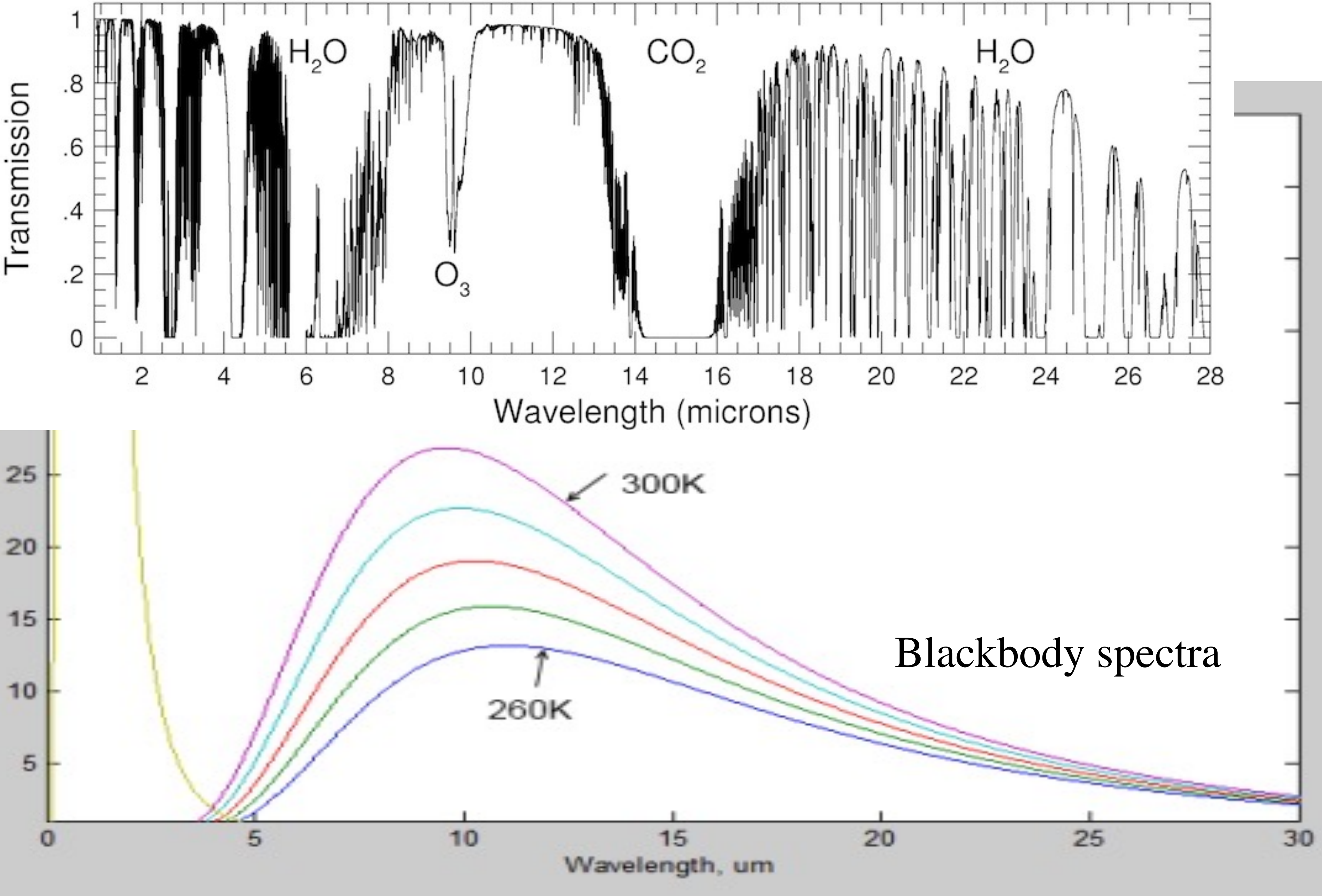
Yet, the actual value is more like $T \sim 287$ K. Why?

The answer: **the Greenhouse Effect**

Various gases in the Earth's atmosphere (mainly CO_2) trap some of the thermal infrared emission.

That effectively acts as an additional incoming luminosity. Temperature increases until a new equilibrium is reached.

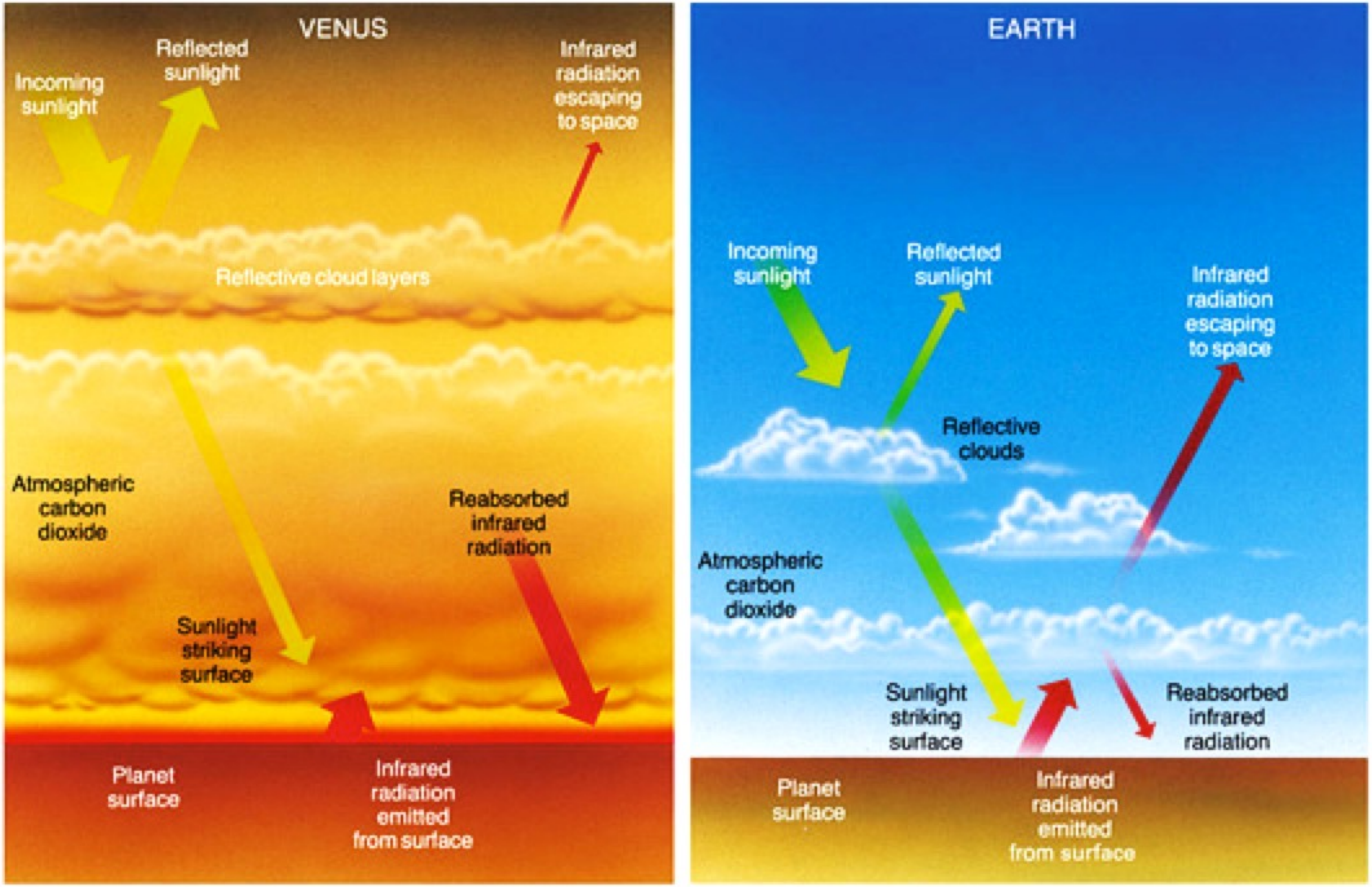
Earth's Atmosphere Absorption Spectrum



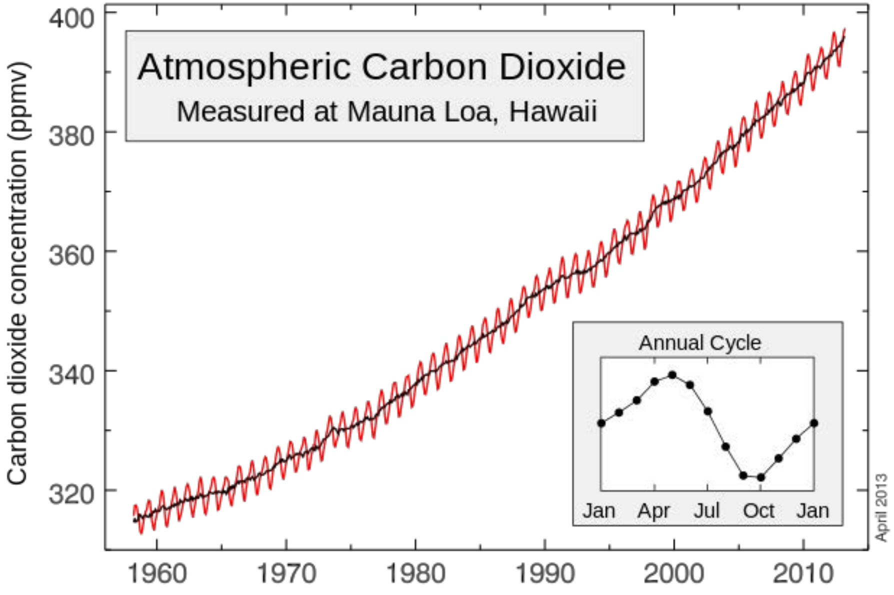
Blackbody spectra

Runaway Greenhouse Effect

If a planet absorbs more heat than it radiates away, the temperature will keep rising until the cooling becomes effective again

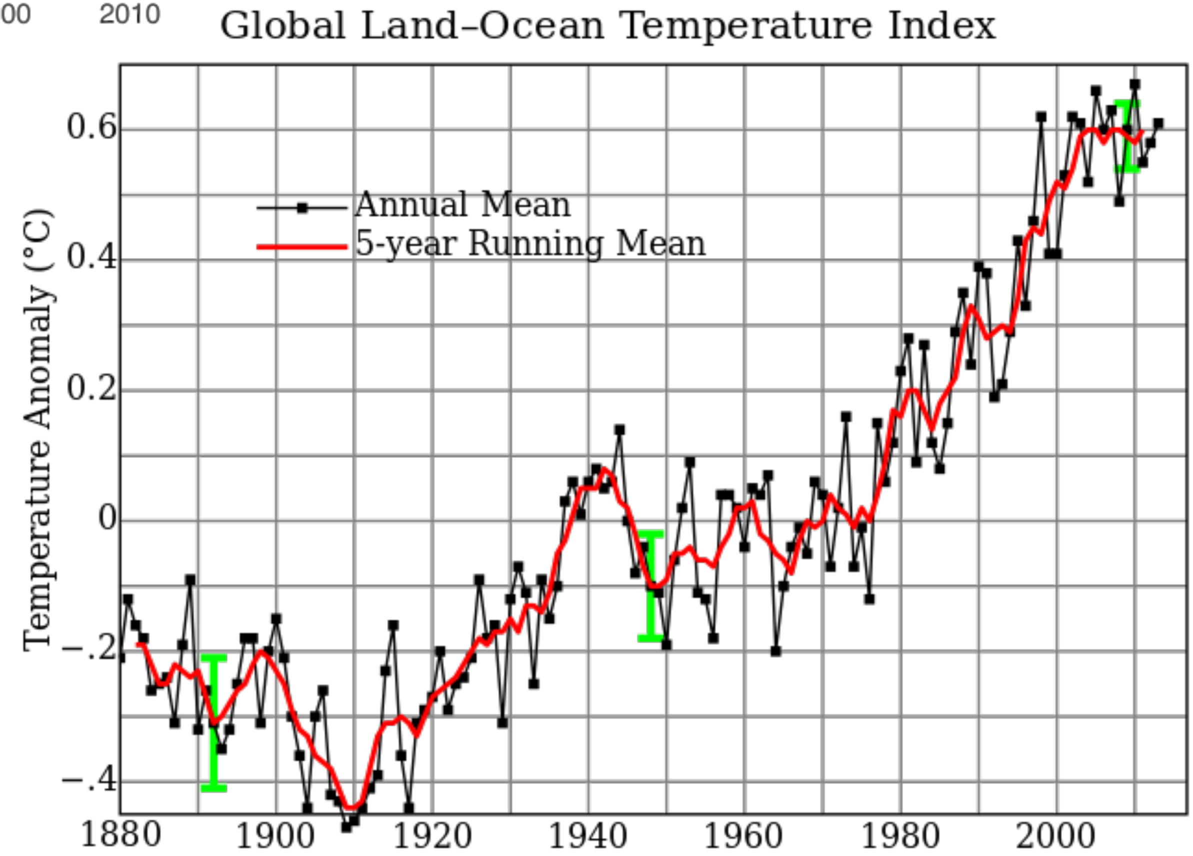


Global Warming



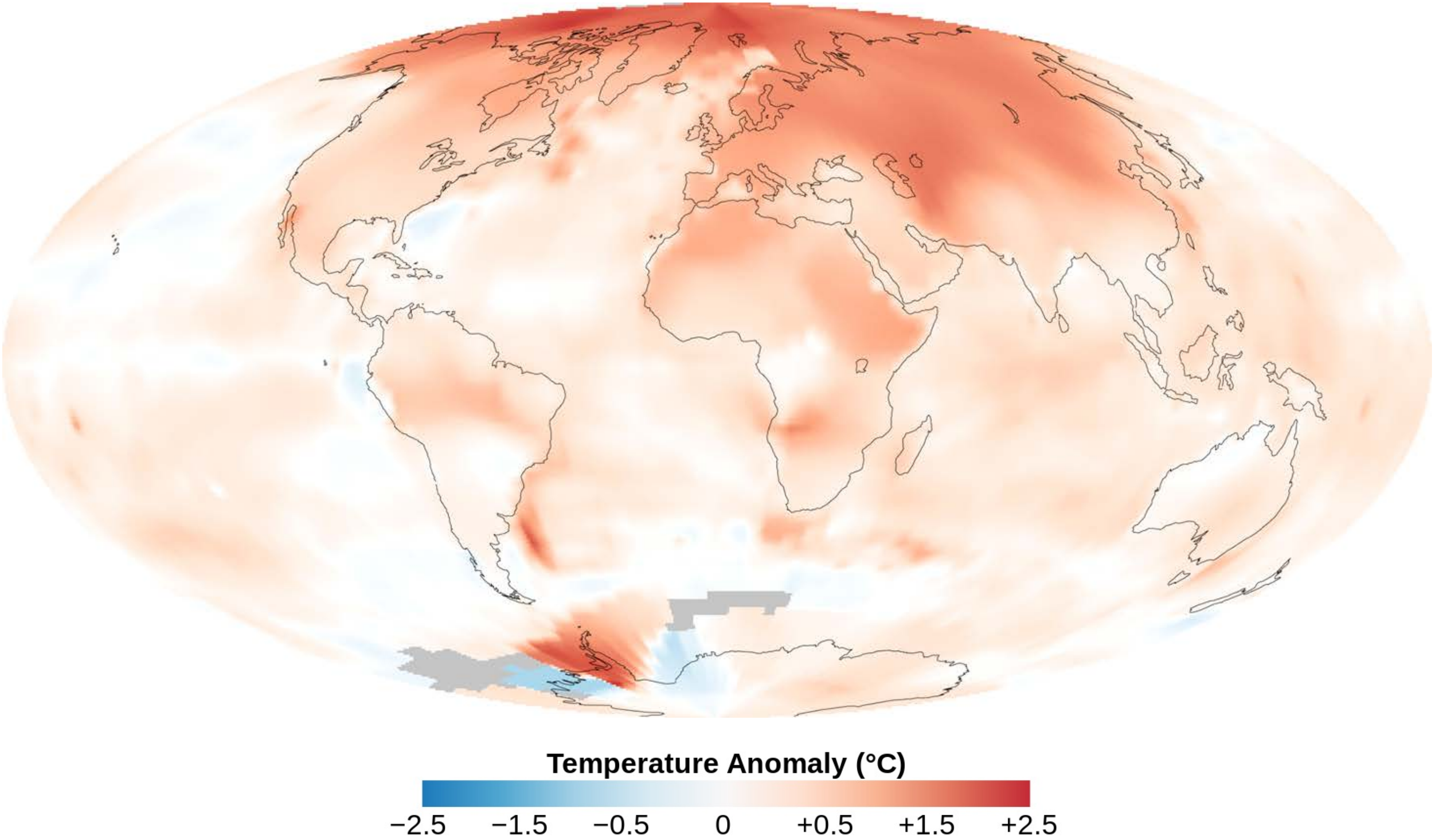
< The cause: increasing concentration of the greenhouse gases

The effect >
Increasing global temperatures



Global Warming

The10-year average (2000–2009) global mean temperature anomaly relative to the 1951–1980 mean

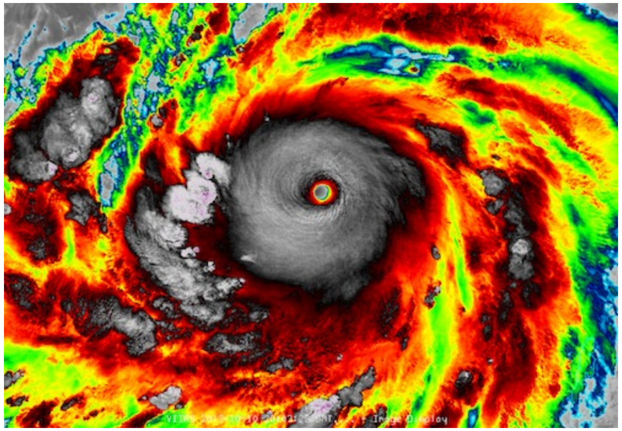


Consequences of the Global Warming

- Average temperature increases
  - ➢ Antarctic and Greenland ice melts and increases the global ocean level; many coastal areas get submerged

- Climate zones expand from the Equator towards the poles
  - ➢ Disruption of agriculture, water supply

- Amplitude and frequency of extreme weather events increase
  - ➢ Major damage, loss of life

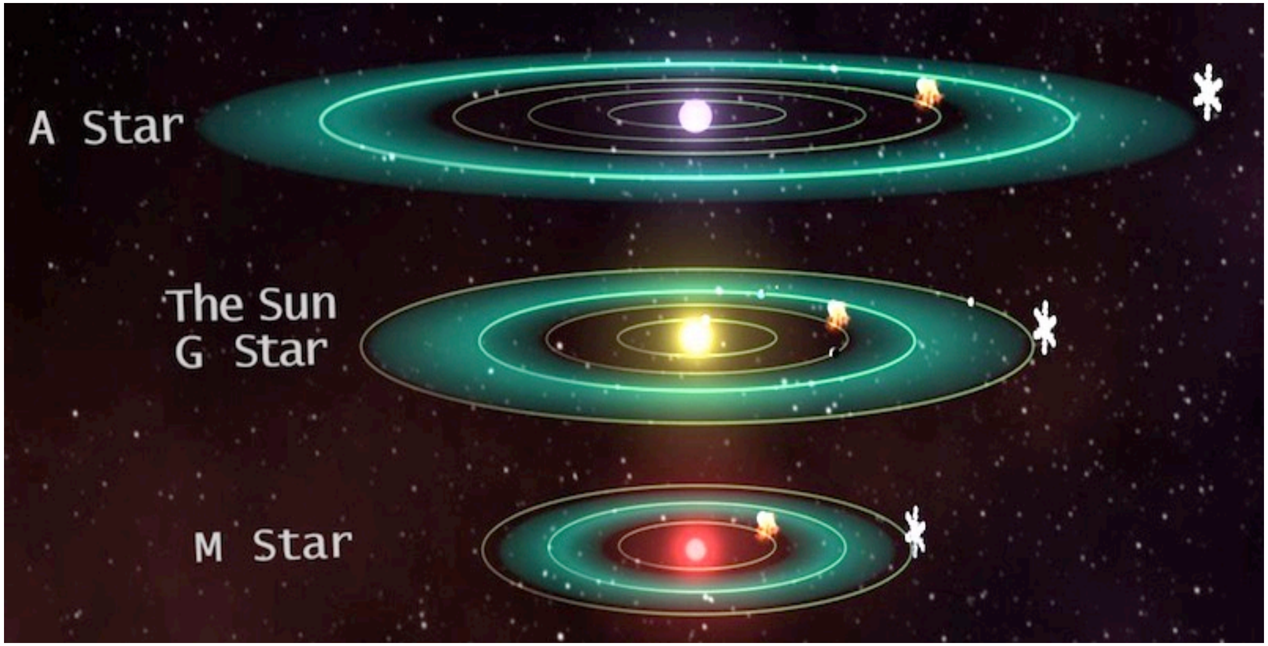


Habitable Zones and Goldilock Planets

For a given stellar luminosity, it depends *only* on the orbit radius and the albedo

$$T^4 = L_\odot \frac{(1-\alpha)}{16\,\pi\,\sigma\,a^2}$$

Liquid water can exist if $273\text{ K} < T < 373\text{ K}$

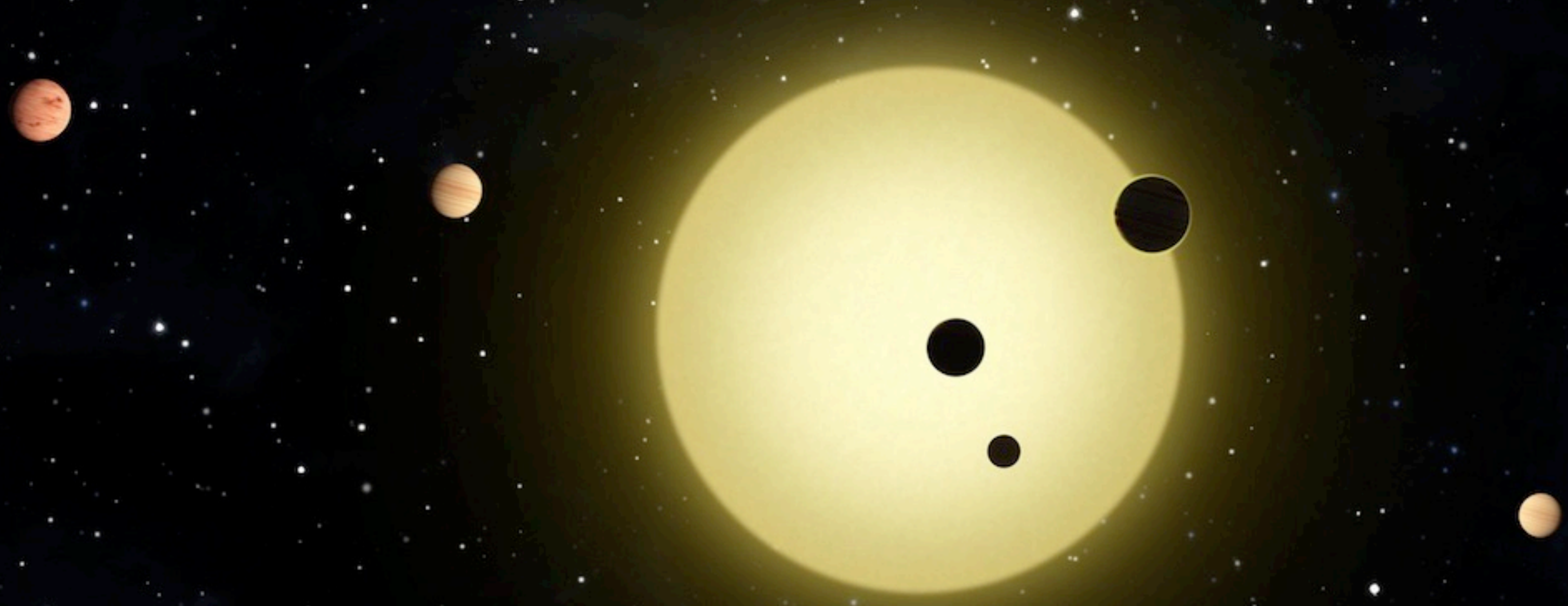


Frost line

Steam line

Since the albedo dependence is relatively weak, this defines a range of planetary orbit radii where liquid water (and thus life?) can exist on the surface

Exoplanets: As of April 2021, there are ~ 4700 confirmed exoplanets known, in ~ 3500 planetary systems, plus many more candidates. There are > 10 billion estimated habitable planets in the Milky Way alone.

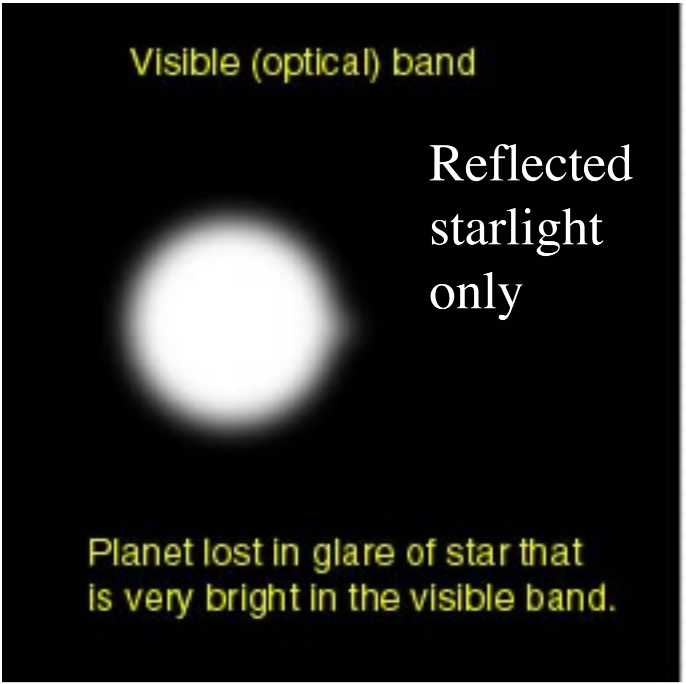


Planetary systems are a natural byproduct of star formation. However, the architecture of our Solar System is not typical.

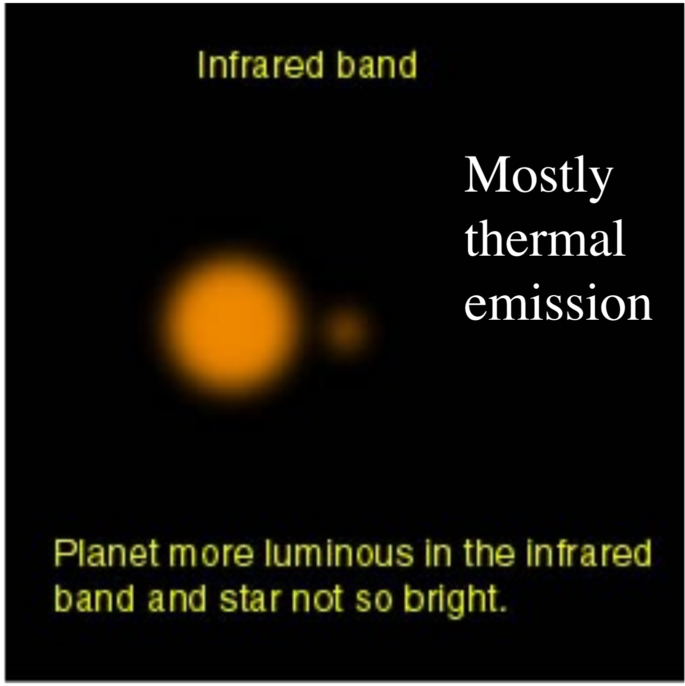
Search Methods for Exosolar Planets

- **Direct imaging**: extremely difficult, since planets may be a billion times fainter than their parent stars
  - Use coronographs and AO to suppress the scattered light
  - Image in thermal IR: the brightness ratio is more favorable
- **Doppler shift:** periodic variation in a star's radial velocity, as the star and the planet orbit a common center of the mass
  - Requires extremely precise spectroscopy
  - More sensitive to more massive and closer planets
- **Eclipses (Transits)** as a planet crosses the stellar disk
  - Requires an extremely precise photometry
- **Gravitational microlensing:** a planet changes the light curve of a microlensing event
  - Rare, requires monitoring of vast numbers of stars

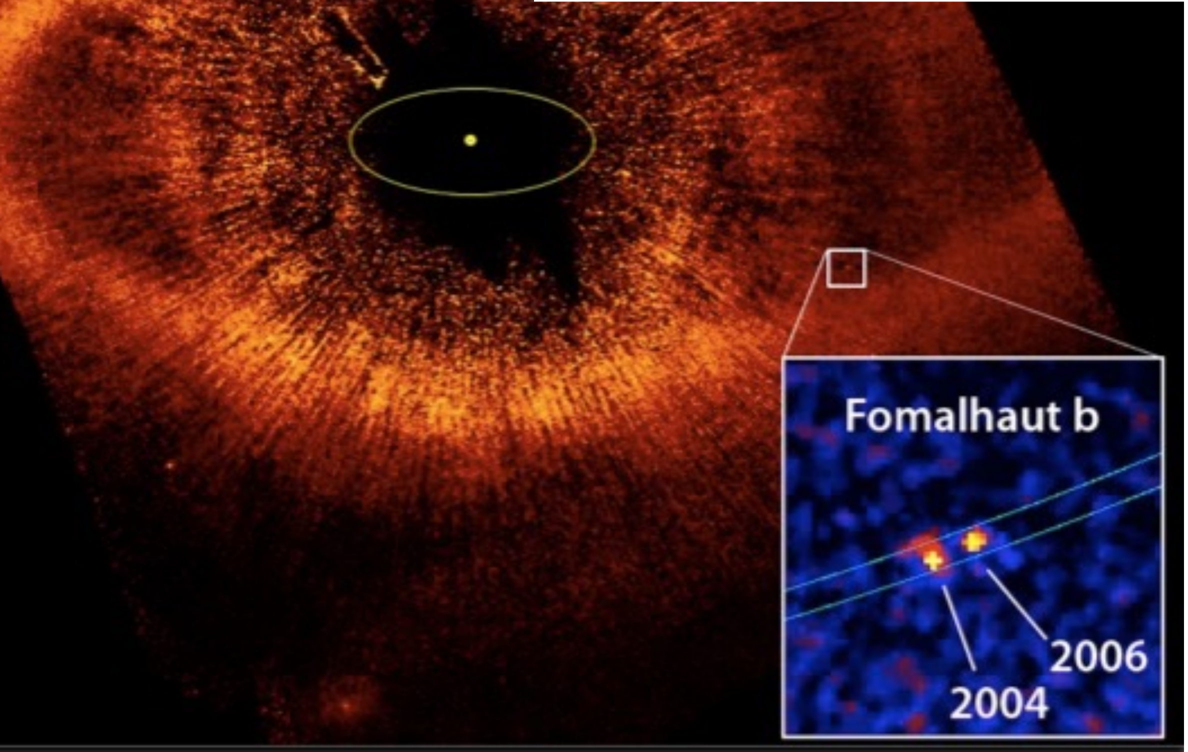
Direct Imaging



Reflected starlight only



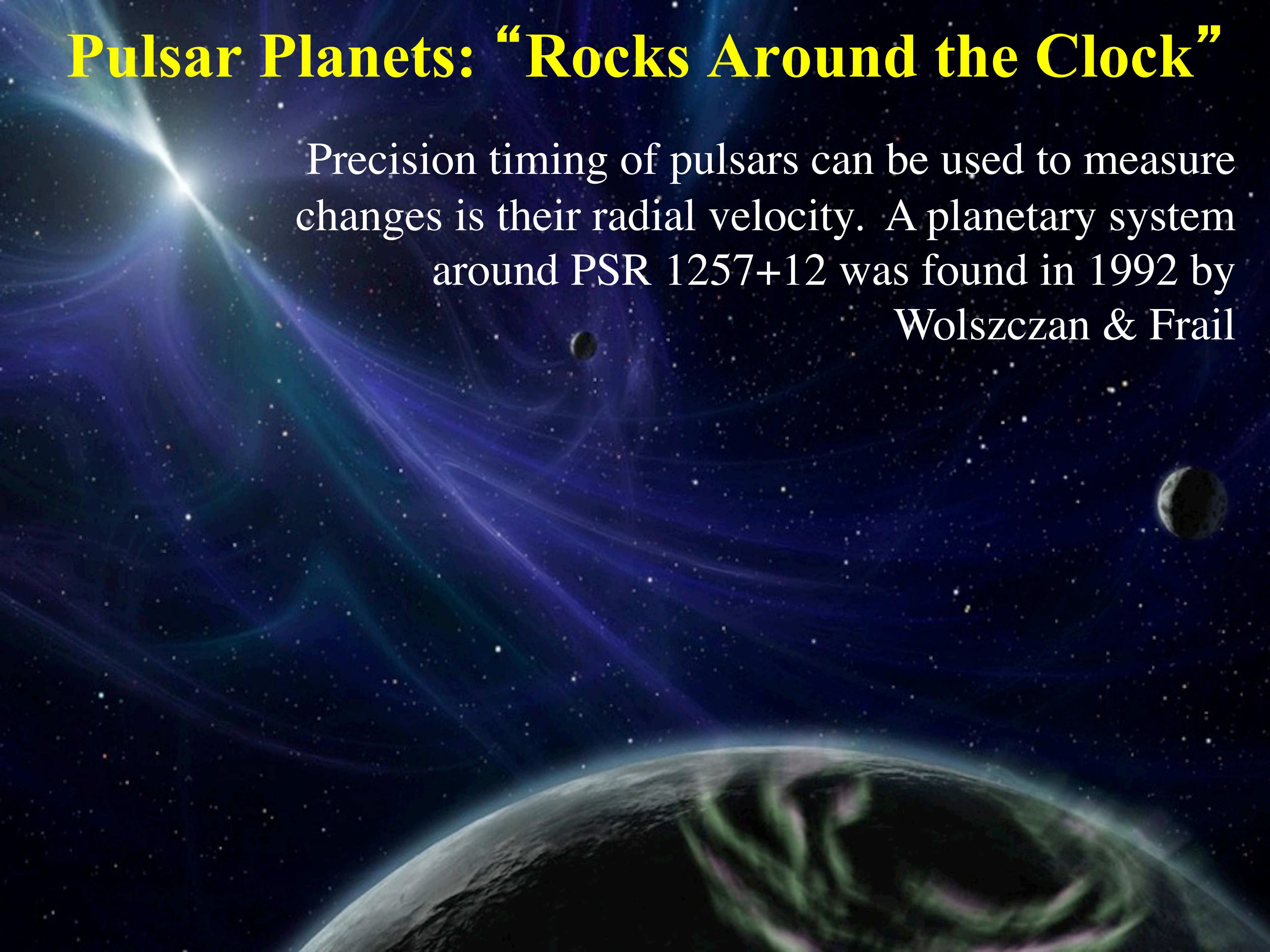
Mostly thermal emission



< Coronographic image of Fomalhaut

< Comparing images 2 years apart shows the planet moving

Pulsar Planets: "Rocks Around the Clock"



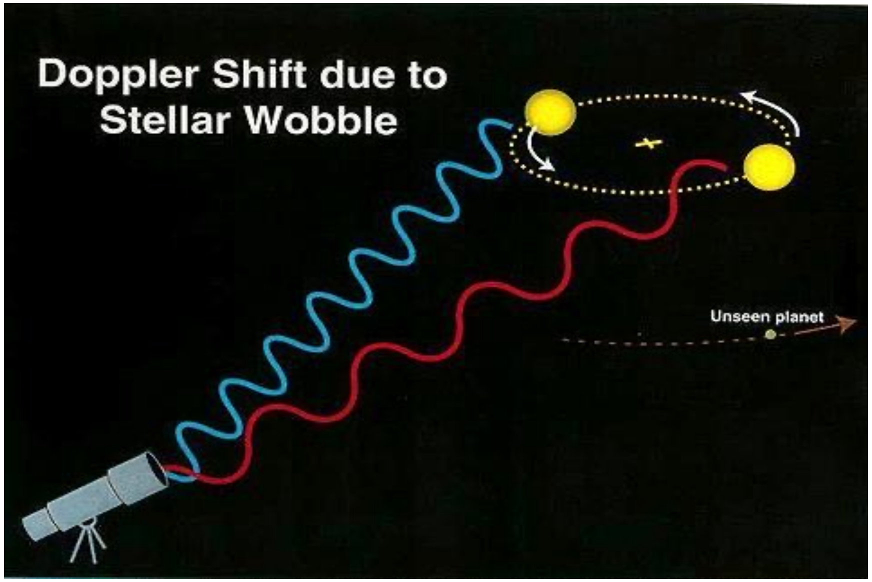
Precision timing of pulsars can be used to measure changes is their radial velocity. A planetary system around PSR 1257+12 was found in 1992 by Wolszczan & Frail

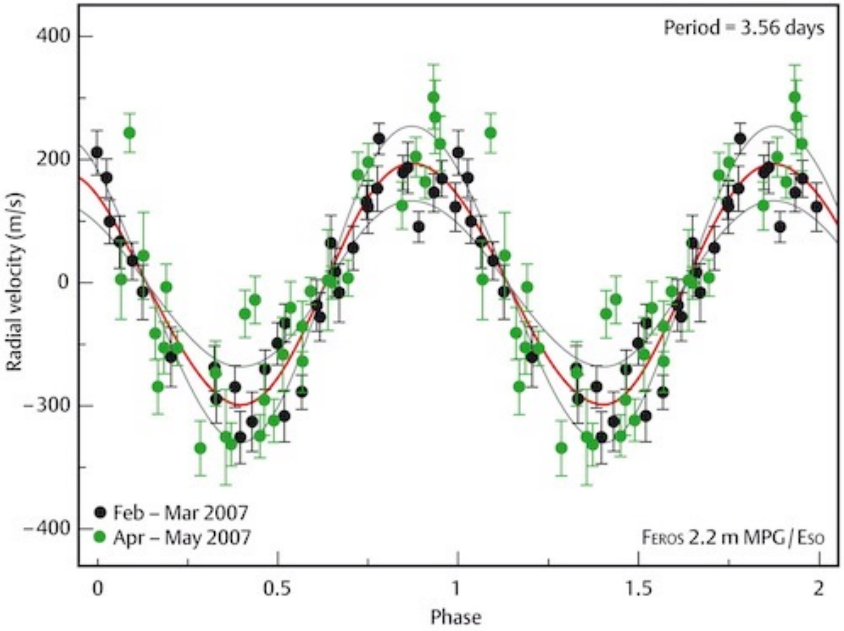
Radial Velocity Method

Both the star and the planet orbit the common center of mass:

$$M_{planet}\, V_{planet} = M_{star}\, V_{star}$$

Observe variations in the star's radial velocity as the whole system moves in space:





For example:

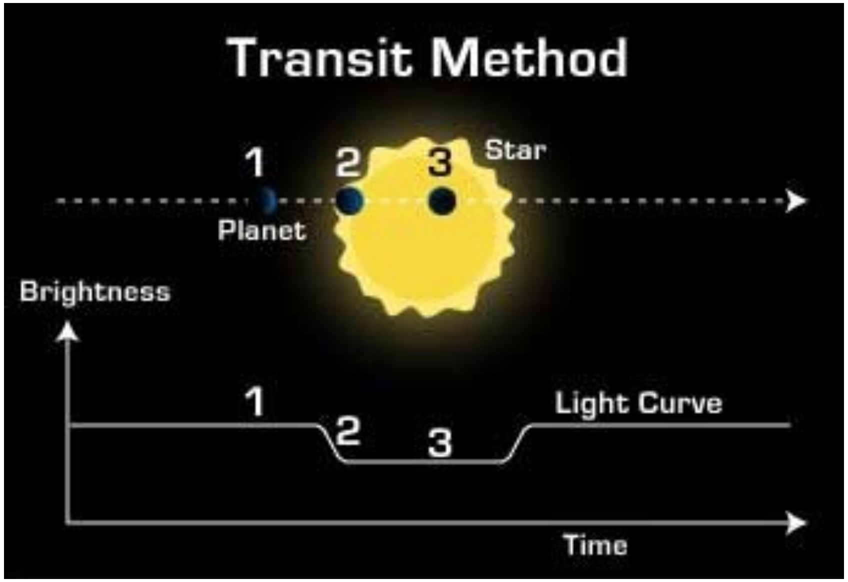
$M_{Earth} / M_{\odot} \approx 3 \times 10^{-6}$

$V_{Earth} = 30$ km/s $\quad V_{\odot} \approx 9$ cm/s

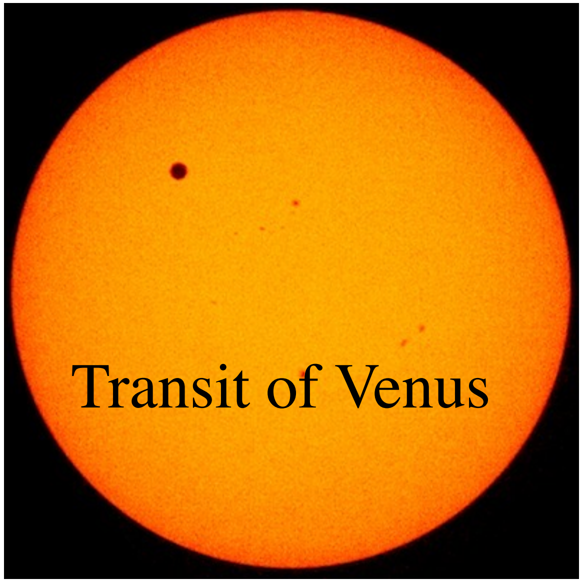
But consider a planet with $M_{planet} = 10\, M_{jupiter}$ in a Mercury's orbit. Then $V_{star} \approx 460$ m/s

State of the art precision ~ 1 m/s

Planetary Transits (Eclipses)

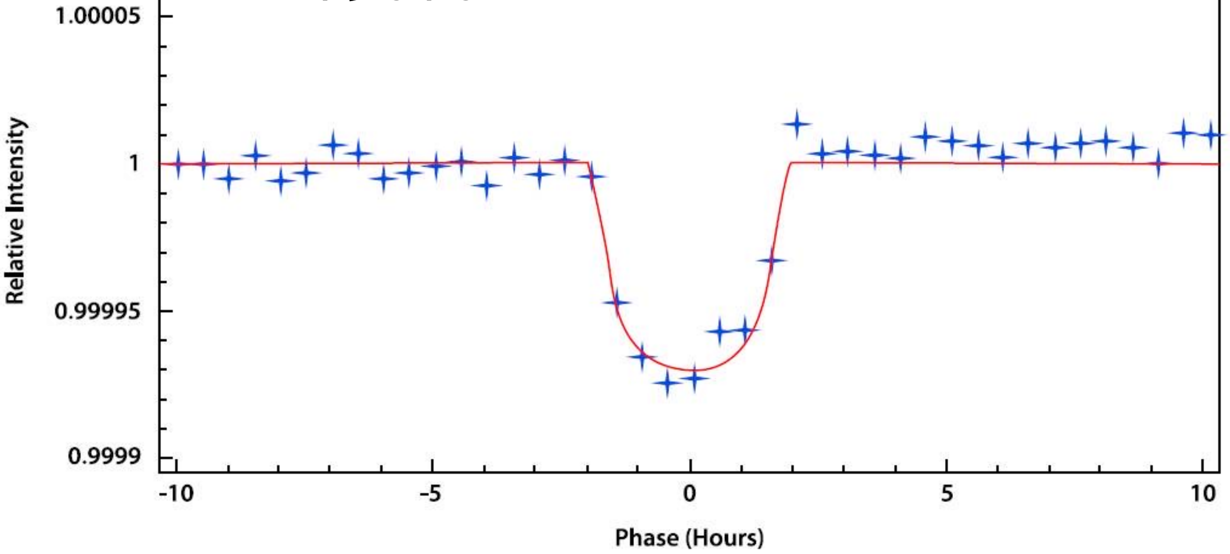


An Earth-sized planet crossing a Sun-like stellar disk would cause a 10^{-4} eclipse → need a very high precision photometry



Transit of Venus

Kepler light curve of HD 179070

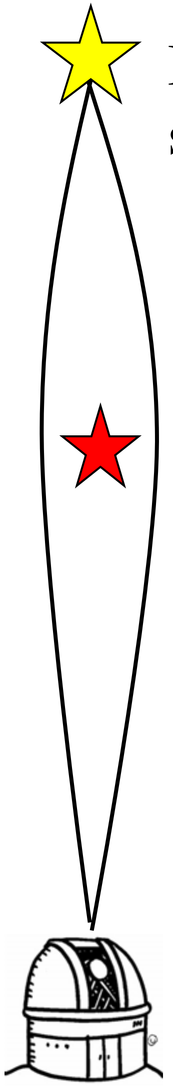


The dominant exoplanet producers are the satellites that use transit photometry

Kepler

TESS

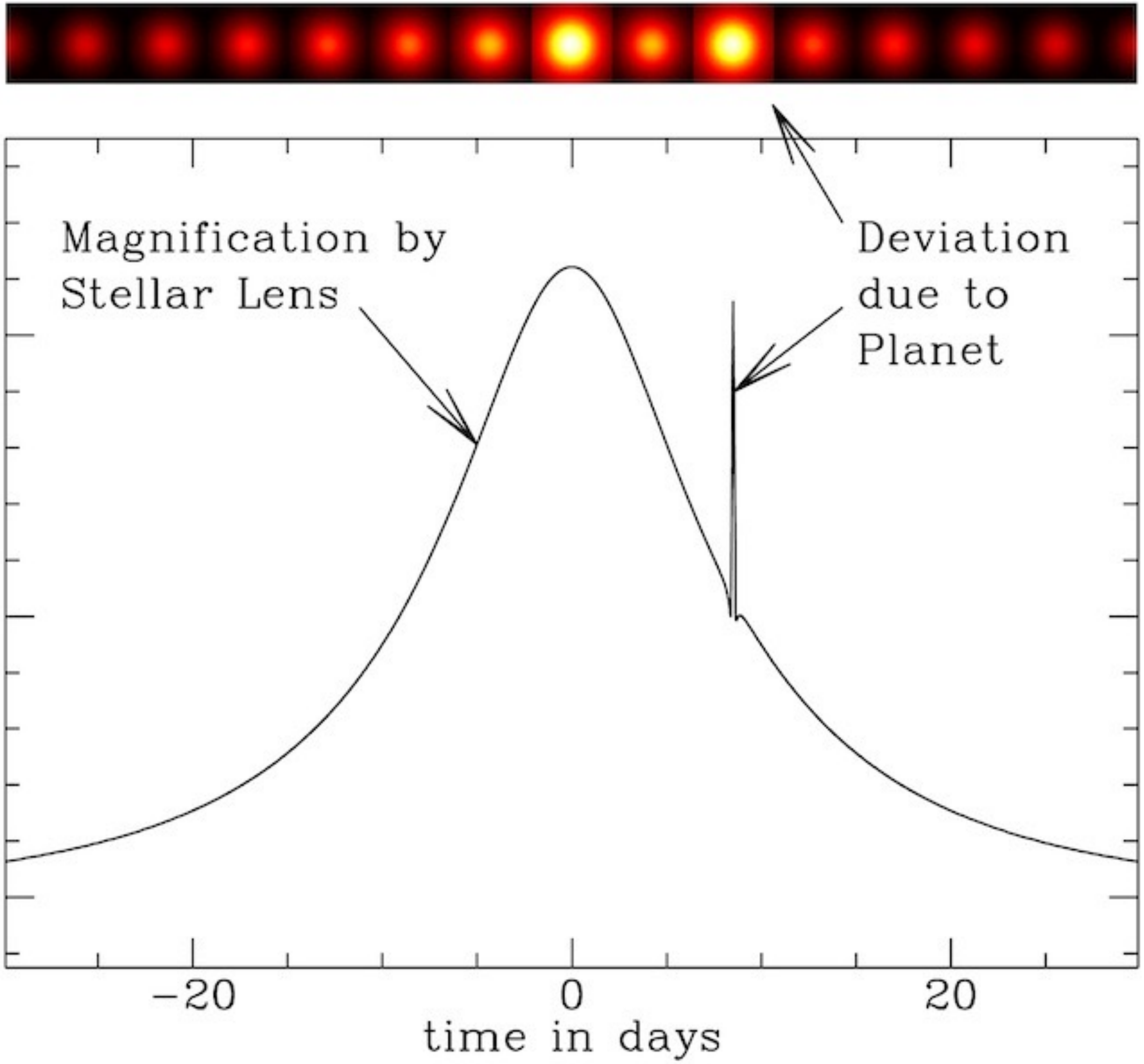
Gravitational Microlensing



Background star

Foreground star bends light rays, magnifies the bgd star

Observer sees a light curve like this



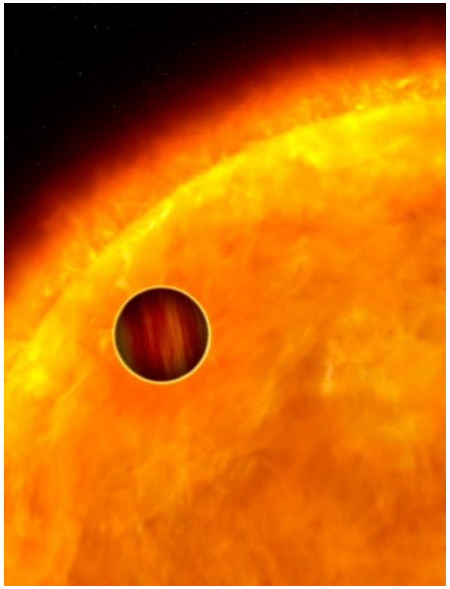
Characterizing Exoplanets

From radial velocities:

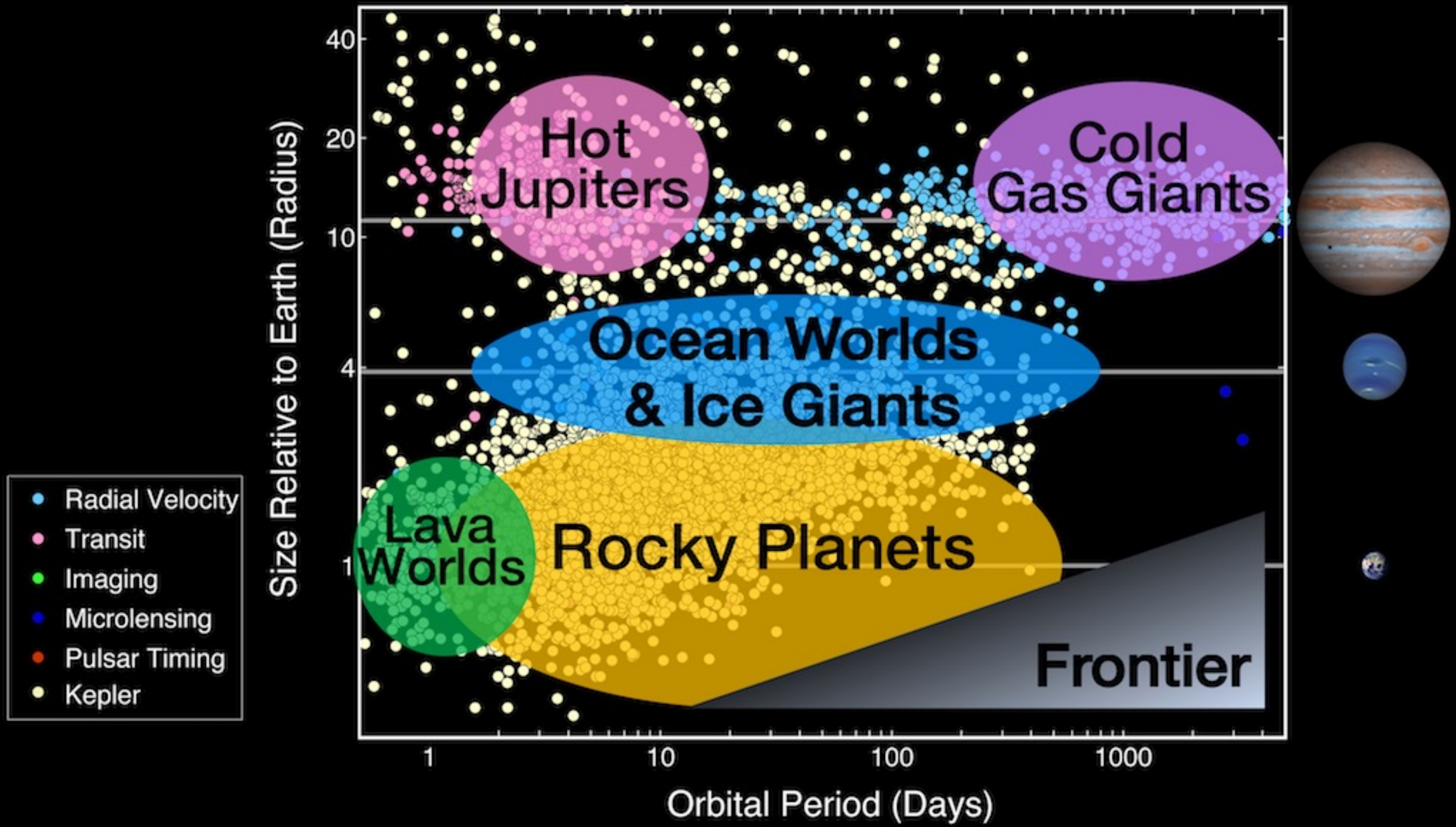
- Measure velocity, period, thus the size of the orbit, infer the mass using Kepler's laws
- Also infer orbital shape (eccentricity)

From transits:

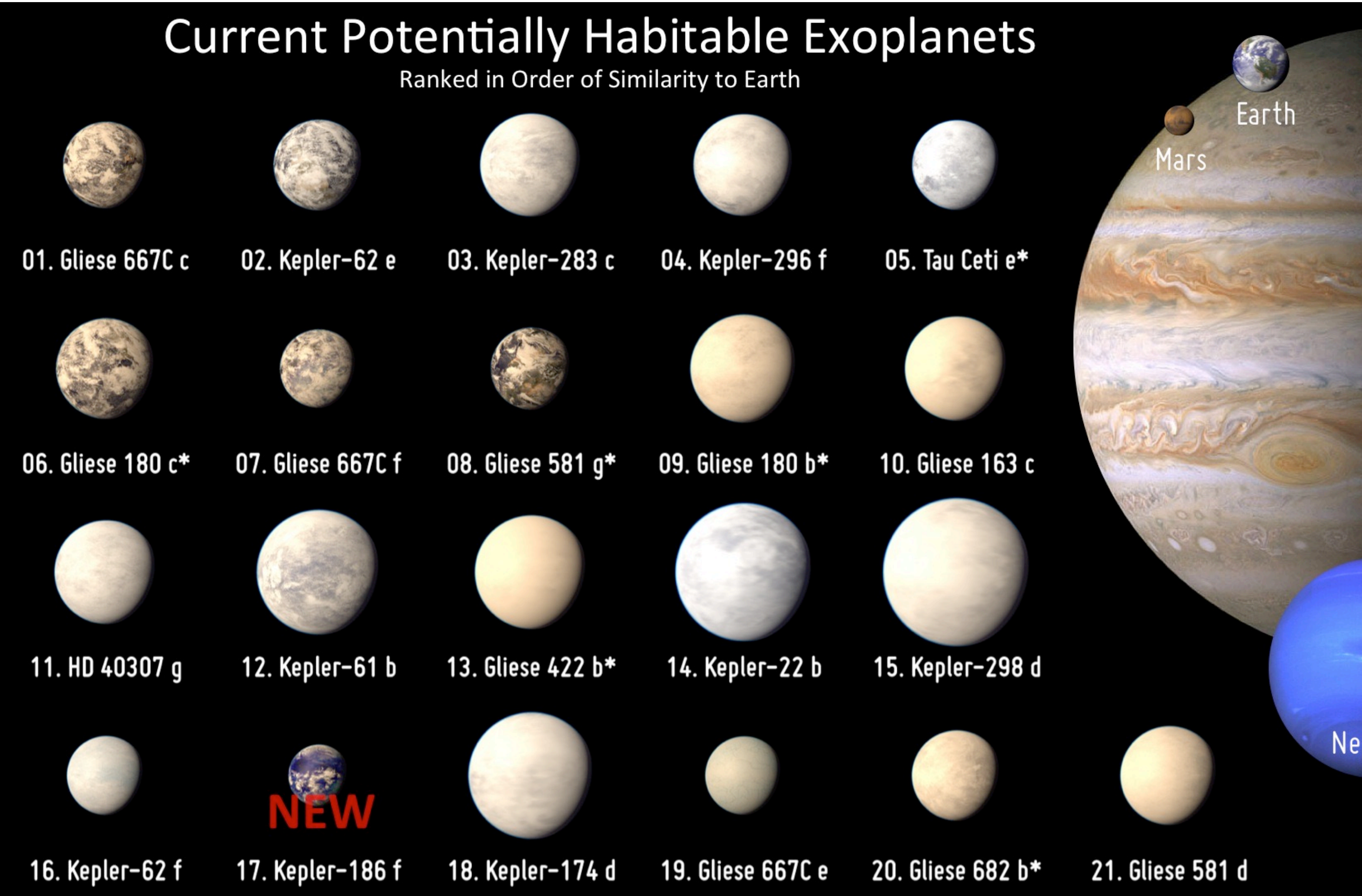
- Infer planetary radii, thus densities, possible composition
- From the proximity to the star, infer the temperature
- Measure the composition of the atmosphere



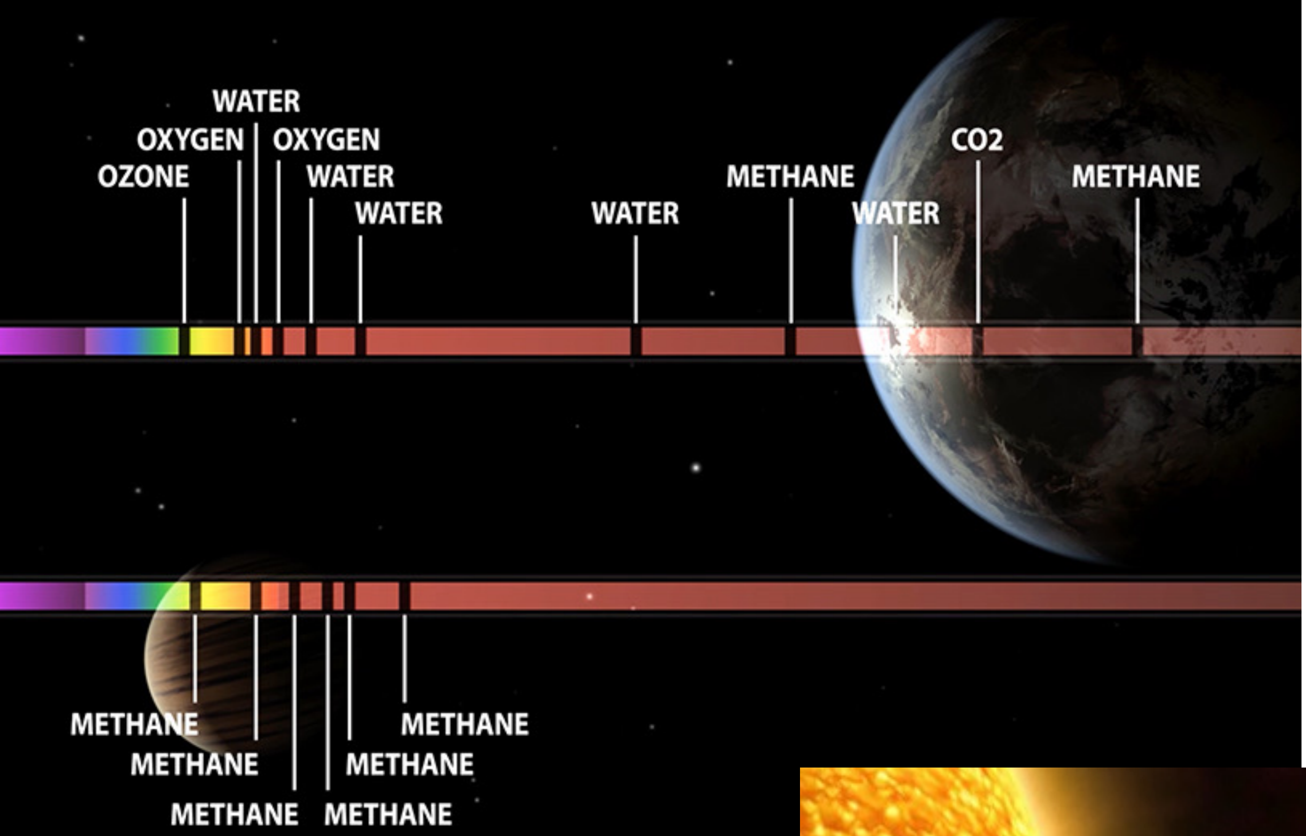
Exoplanet Populations



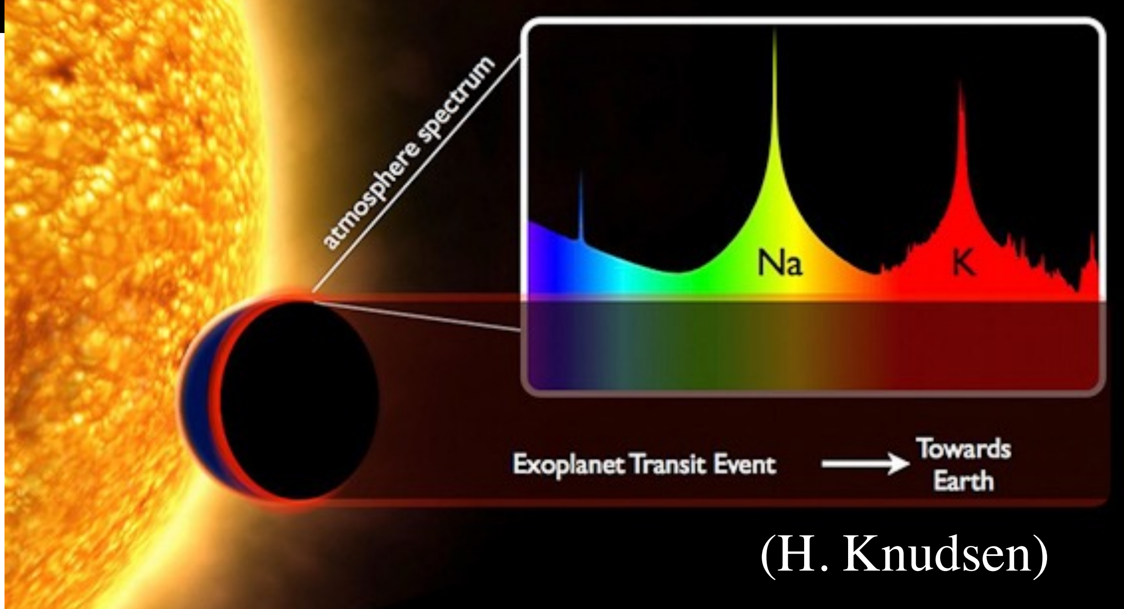
Planets in the Habitable Zones



Spectroscopic signatures of a habitable exoplanet



Subtract the spectra of the star during and out of the eclipse: extra absorption by the planet’ s atmosphere

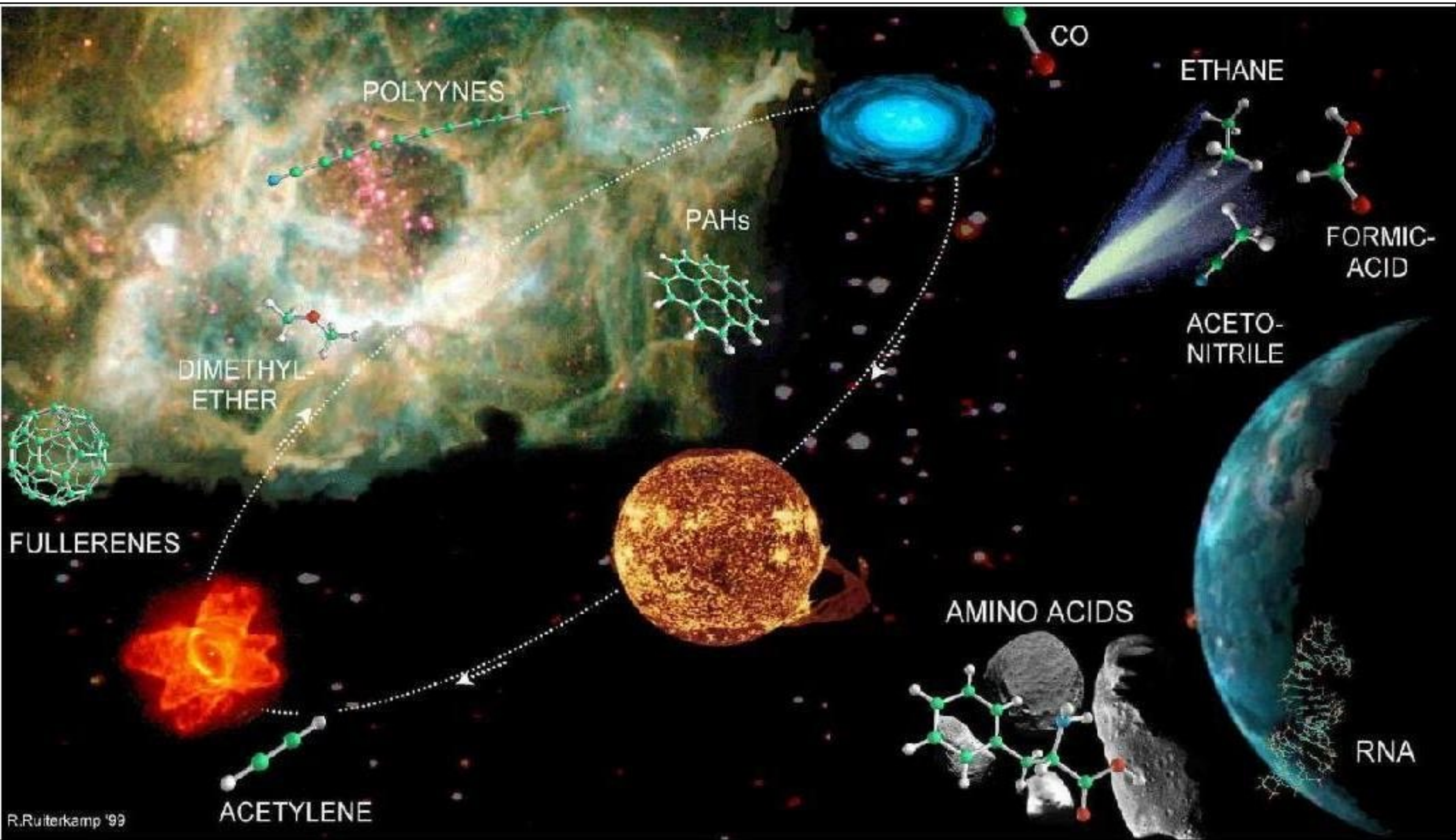


(H. Knudsen)

Rogue or Interstellar Planets

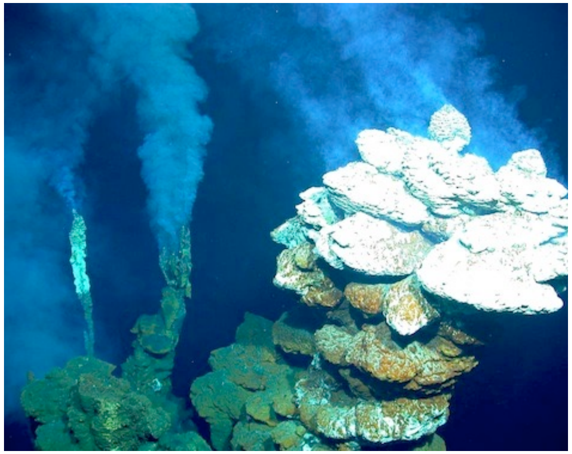
Life in the Universe: the Building Blocks

Water and organic compounds (sometimes very complex) are common in the ISM, the material from which planets form



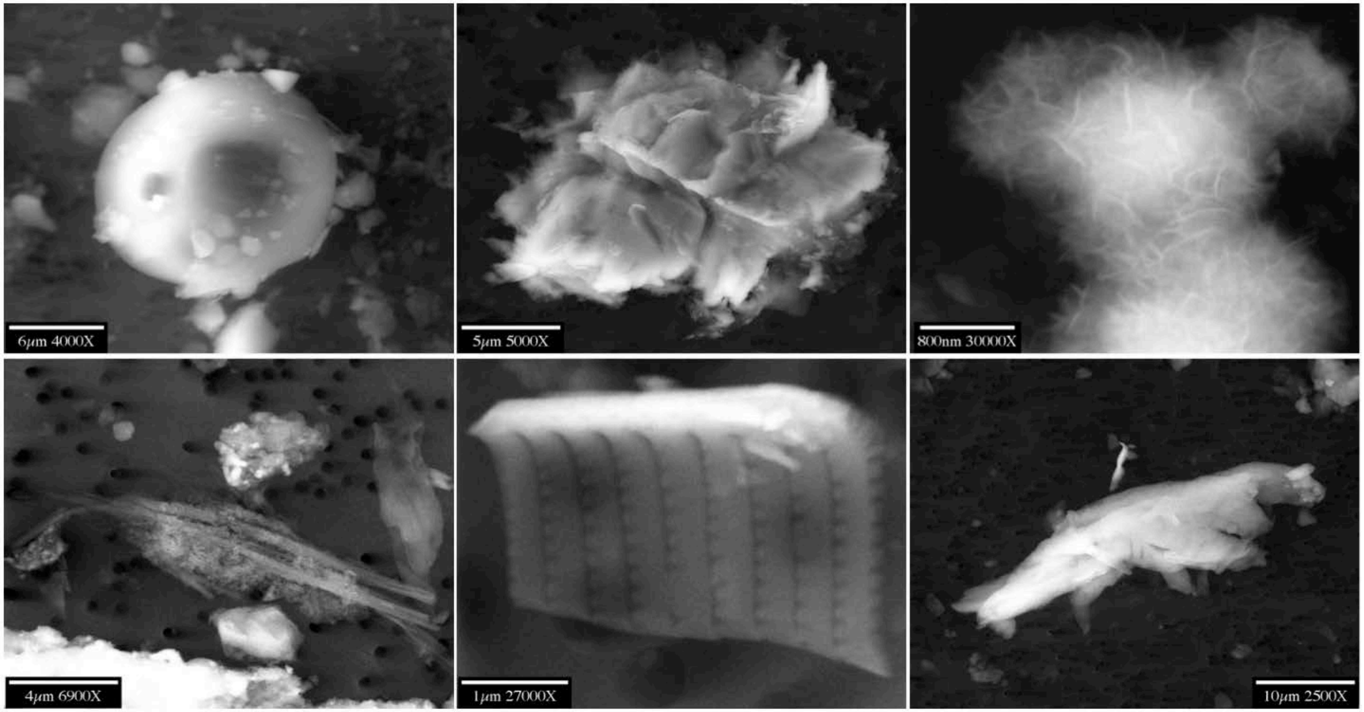
Astrobiology

- Life in extreme environments on the Earth
  - E.g., sulphur-based metabolism in the bacteria found near deep undersea vents; inside rocks; deep under ice (lake Vostok), in volcanic lakes, etc.
- Possibilities for life on other planets



Deep undersea vents

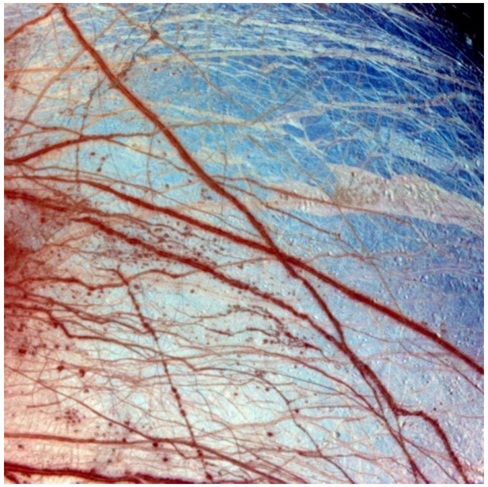
Grand Prismatic Spring, Yellowstone

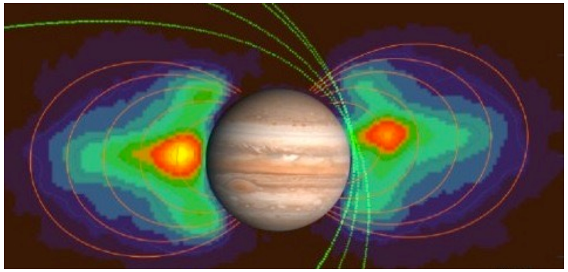


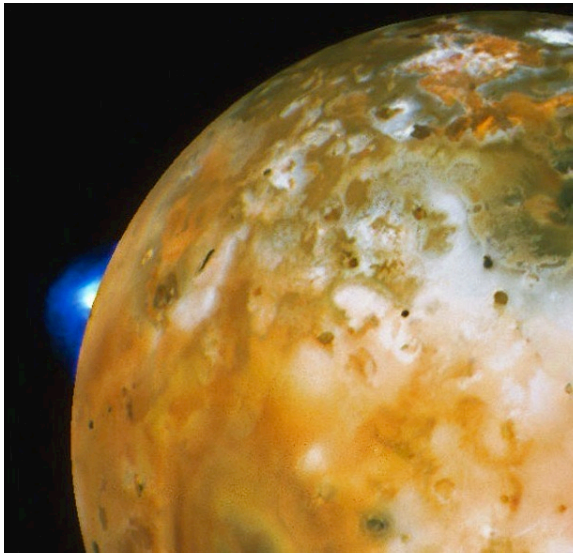
< Microorganisms found under the ice in lake Vostok, Antarctica

Life Elsewhere in the Solar System?

- Mars once had an ocean and the atmosphere
- Oceans on Europa, Enceladus, and maybe other moons of Jupiter and Saturn
- Volcanoes on Io, Jupiter’s radiation belts

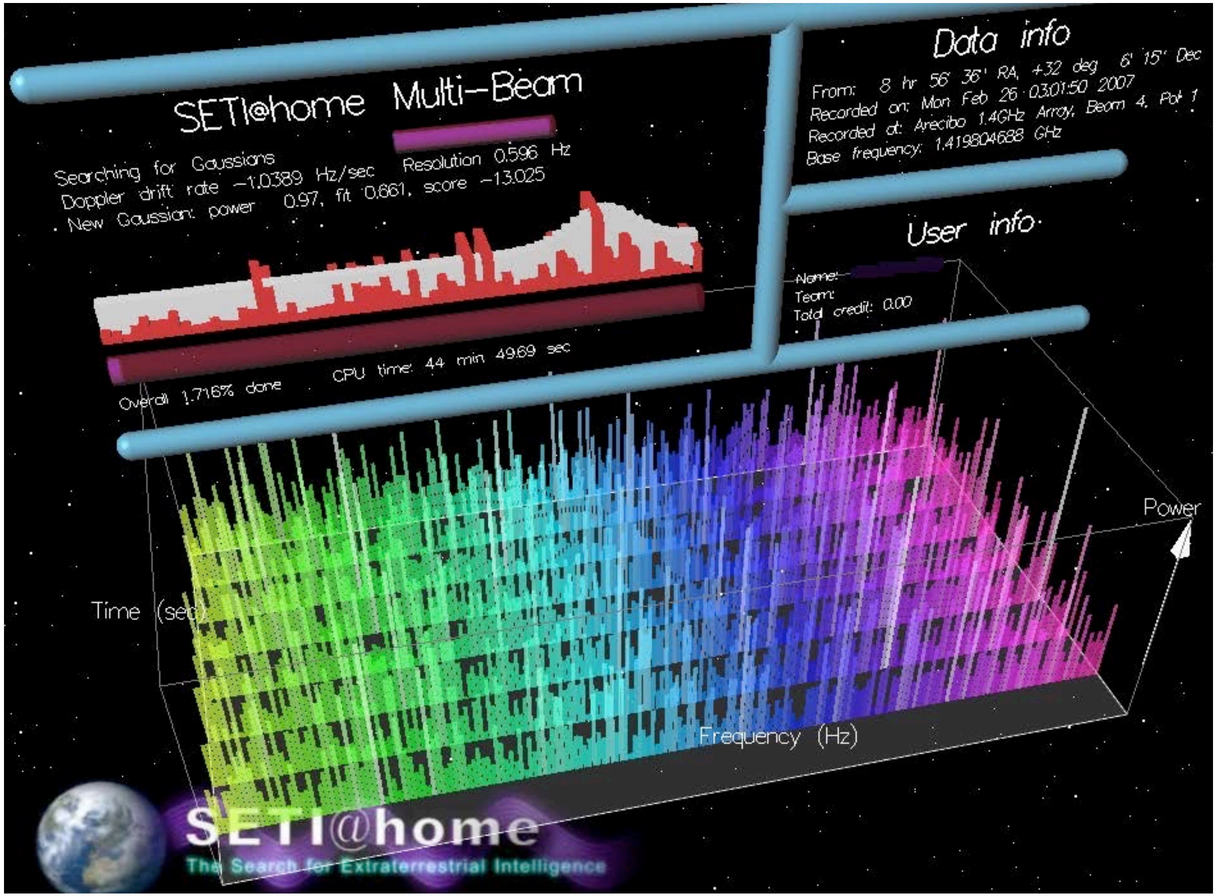






Search for ExtraTerrestrial Intelligence

- Assumes that advanced civilizations would communicate by radio…
- SETI@home: a piggyback search using observations from Arecibo, VLA, ATA, etc.
- Or we can send them



SETI@home Multi-Beam

Searching for Gaussians
Doppler drift rate −1.0389 Hz/sec Resolution 0.596 Hz
New Gaussian: power 0.97, fit 0.661, score −13.025

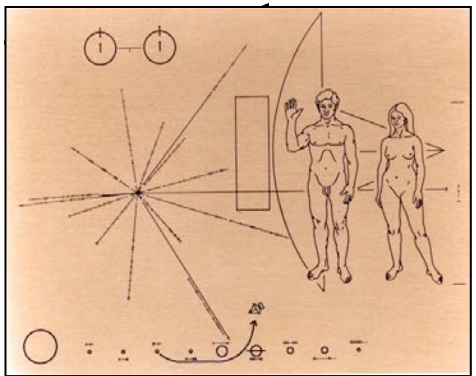
Overall 1.716% done CPU time: 44 min 49.69 sec

Data info

From: 8 hr 56' 36' RA, +32 deg 6' 15' Dec
Recorded on: Mon Feb 26 03:01:50 2007
Recorded at: Arecibo 1.4GHz Array, Beam 4, Pol 1
Base frequency: 1.419804688 GHz

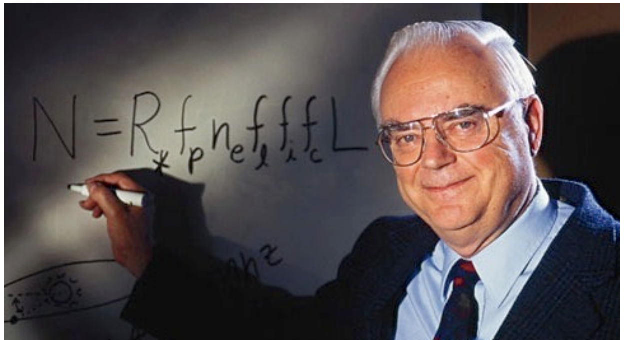
User info

Name:
Team:
Total credit: 0.00



The Drake Equation

$$N = R^{*} \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$



N = The number of civilizations in The Milky Way Galaxy whose electromagnetic emissions are detectable

R^{*} = The rate of formation of stars suitable for the development of intelligent life

f_p = The fraction of those stars with planetary systems

n_e = The number of planets, per solar system, with an environment suitable for life

f_l = The fraction of suitable planets on which life actually appears

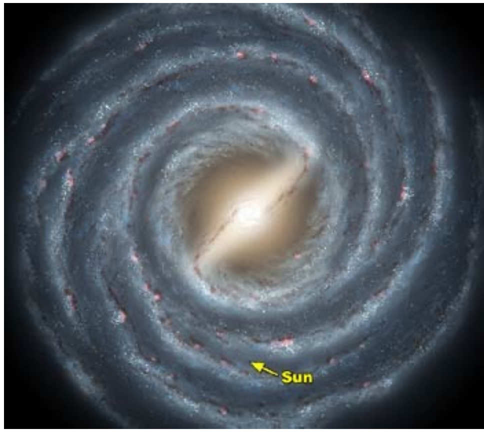
f_i = The fraction of life bearing planets on which intelligent life emerges

f_c = The fraction of civilizations that develop a technology that releases detectable signs of their existence into space

L = The length of time such civilizations release detectable signals

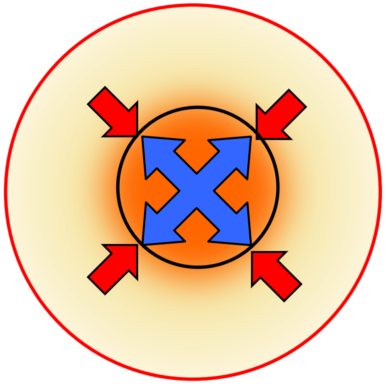
The Fermi Paradox

- Or: *Where are they?*
- A civilization that can do interstellar travel at velocities ~ 1% of the speed of light would still conquer the Galaxy in ~ 10 million years
- Galaxy is ~ 12 billion years old
- So why don’t we see them?
- Or do we?
- Or is something wrong with our implicit beliefs as to what advanced civilizations might do?
- **What do you think?**



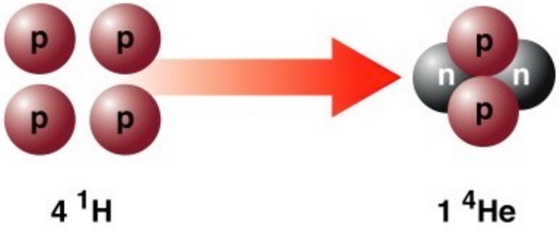
How Stars Work

- **Hydrostatic Equilibrium**: gas and radiation pressure balance the gravity

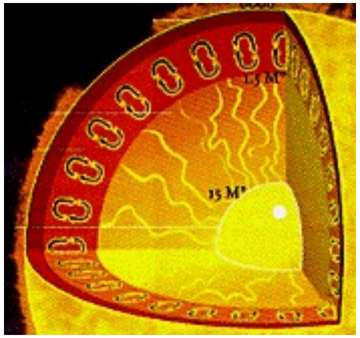


- **Thermal Equilibrium:** Energy generated = Energy radiated

- **Thermonuclear Reactions:** The source of the energy



- **Energy Transport:** How does it get from the core to the surface

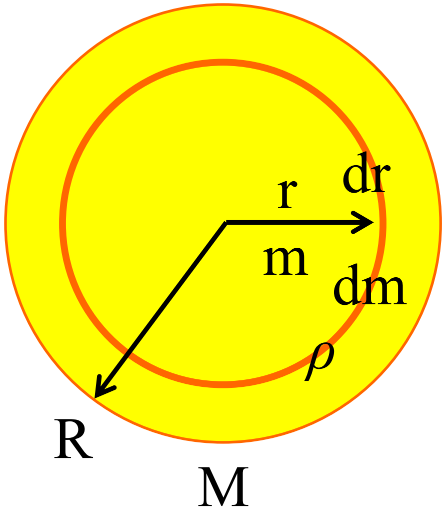


Equations of the Stellar Structure

Mass vs. radius:

$$dm = 4\pi r^2 \rho dr$$

$$\frac{dm}{dr} = 4\pi r^2 \rho$$



Luminosity vs. radius:

$$dL = 4\pi r^2 \rho dr \times q$$

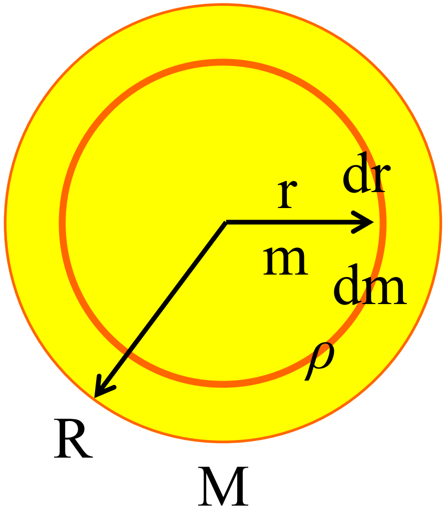
$$\frac{dL}{dr} = 4\pi r^2 \rho q$$

q = rate of energy generation per unit mass

Hydrostatic Equilibrium

At a given radius, the gravitational force on a shell is:

$$F_g = -\frac{Gm\Delta m}{r^2}$$



The weight of that mass shell over the area has to be the difference between the pressures on an inner and an outer surface of the shell.

$$dm = 4\pi r^2 \rho dr$$

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho$$

Pressure of What?

Total pressure: $P = P_{gas} + P_{radiation}$

The equation of state for an ideal gas is: $P_{gas} = nkT$

n = the number of particles per unit volume (ions and electrons)

Or: $$P_{gas} = \frac{\rho}{\mu m_H} \times kT$$

ρ = mass density

m_H = the mass of hydrogen atom

μ = average particle mass in units of m_H

↑

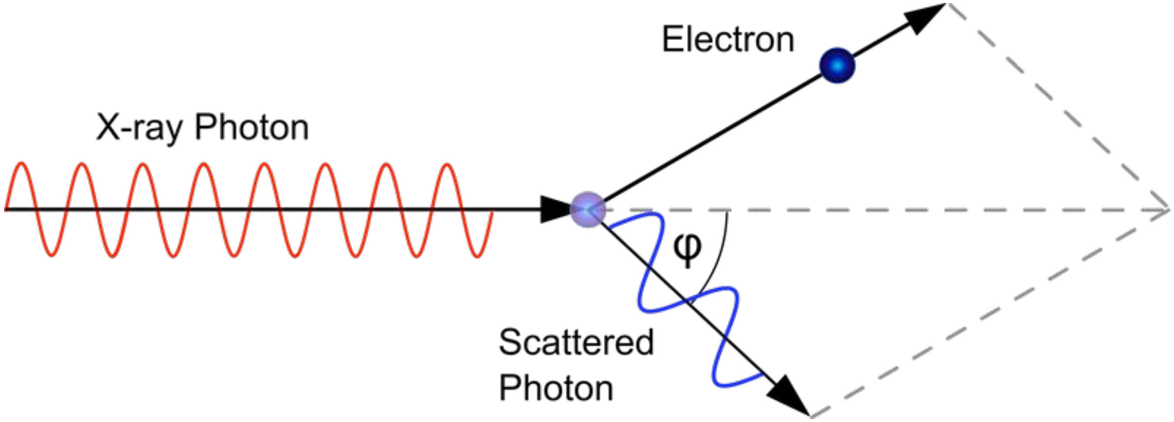
Depends on the chemical composition. Typically $\mu \sim 0.8$

The ideal gas constant: $$R \equiv \frac{k}{m_H}$$

Thus: $$P_{gas} = \frac{R}{\mu} \rho T$$

Radiation Pressure

Momentum exchange between photons and electrons/ions results in a radiation pressure



For blackbody radiation: $$P_r = \frac{1}{3}aT^4$$

…where a is the *radiation constant*:

$$a = \frac{8\pi^5 k^4}{15c^3h^3} = \frac{4\sigma}{c} = 7.565\times10^{-15} \text{ erg cm}^{-3} \text{ K}^{-4}$$

Radiation pressure dominates over the gas pressure inside very massive stars, which are hotter

Equations of Stellar Structure

At radius *r* in a static, spherically symmetric star and the density ϱ:

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

Mass conservation

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho$$

Hydrostatic equilibrium

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L}{4\pi r^2}$$

Energy transport due to radiation (only)

$$\frac{dL}{dr} = 4\pi r^2 \rho q$$

Energy generation

4 equations with 4 unknowns - enough for a solution once we know P(ϱ ,T), opacity κ, and *q*

Some Order-of-Magnitude Estimates

Let's see if we can estimate roughly the conditions in the Solar core. **Pressure** $P = F / A$:

$$F \approx G M_{\odot}^2 / R_{\odot}^2$$

$$A \approx 4 \pi R_{\odot}^2$$

$$P \approx G M_{\odot}^2 / 4 \pi R_{\odot}^4$$

($M_{\odot} \approx 2 \times 10^{33}$ g, $R_{\odot} \approx 7 \times 10^{10}$ cm, $G \approx 6.7 \times 10^{-8}$ cgs)

Thus: $P_{est} \sim 10^{15}$ dyn / cm^2 -- and surely an underestimate

True value: $P_c \approx 2 \times 10^{17}$ dyn / cm^2

Now the **temperature:** $3/2\, k\, T \approx G\, m_p\, M_{\odot} / R$

($k \approx 1.4 \times 10^{-16}$ erg/K, $m_p \approx 1.7 \times 10^{-24}$ g)

Thus: $T_{est} \approx 1.6 \times 10^{7}$ K

True value: $T_c \approx 1.57 \times 10^{7}$ K -- not bad!

Energy Production in Stars: Thermonuclear Reactions

Mass of nuclei with several protons and / or neutrons does not exactly equal mass of the constituents - slightly smaller because of the **binding energy** of the nucleus

The main process is hydrogen fusion into helium:

$$4 \times {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \text{photons and neutrinos}$$

4 protons, total mass =
4 × 1.0081 = 4.0324 amu

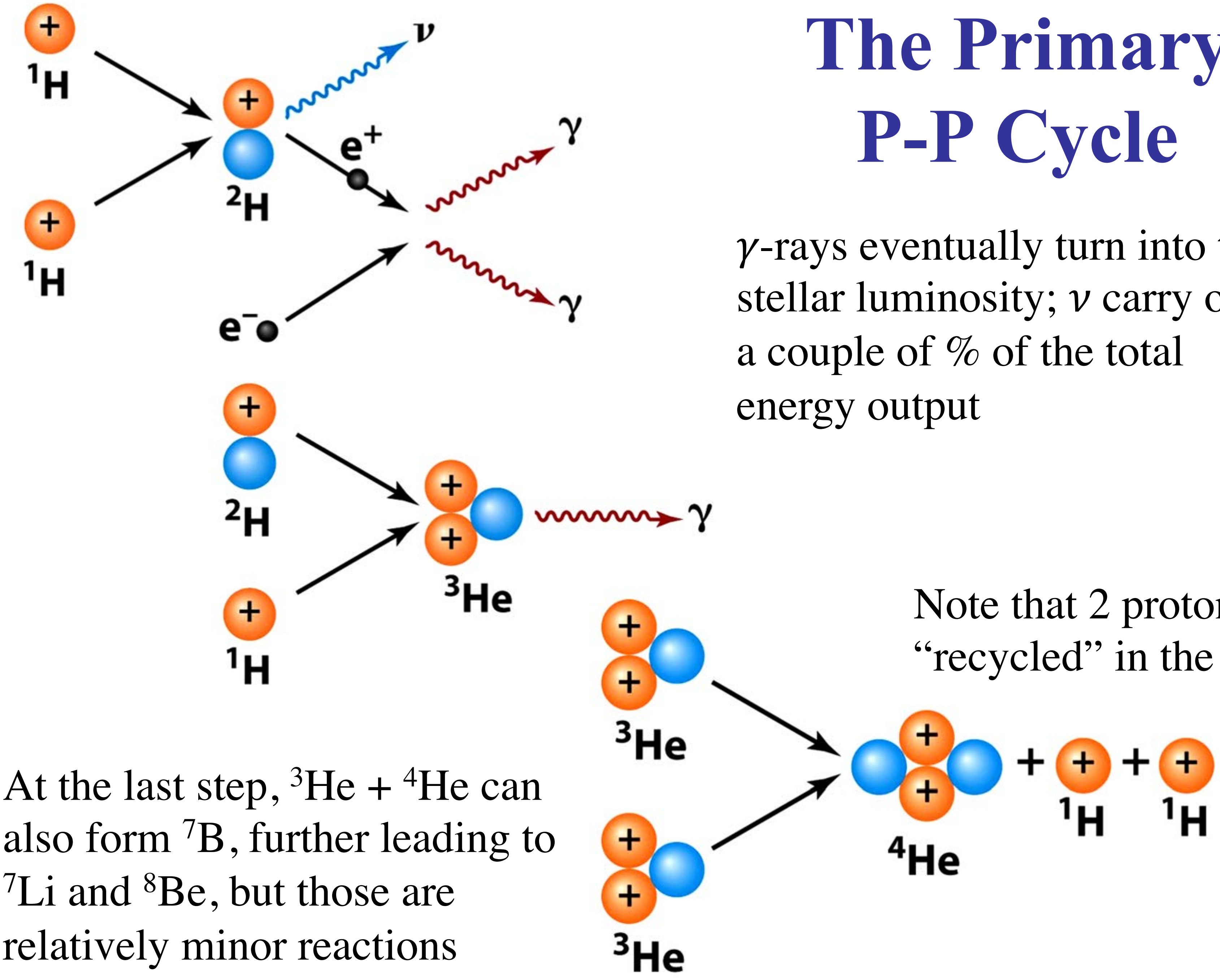
helium nucleus, mass =
4.0039 amu

Mass difference: 0.0285 amu = 4.7 x 10^{-26} g

$$\Delta E = \Delta M c^2 = 4.3 \times 10^{-5}\ \mathrm{erg} = 27\ \mathrm{MeV}$$

Or about 0.7% of the total rest mass

The Primary P-P Cycle

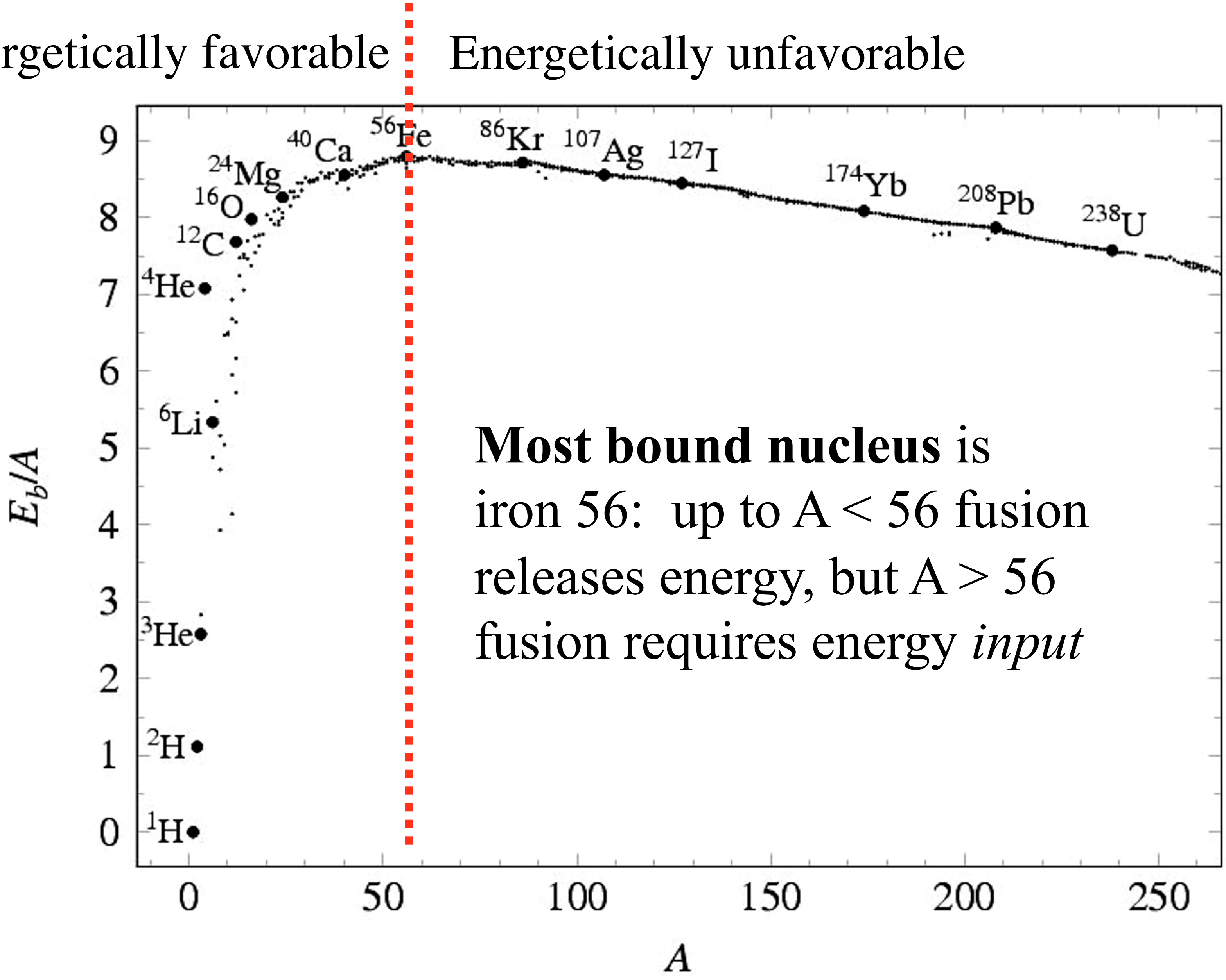


γ-rays eventually turn into the stellar luminosity; ν carry only a couple of % of the total energy output

Note that 2 protons are "recycled" in the end

At the last step, ^{3}He + ^{4}He can also form ^{7}B, further leading to ^{7}Li and ^{8}Be, but those are relatively minor reactions

Binding Energy Per Nucleon vs. Atomic Number

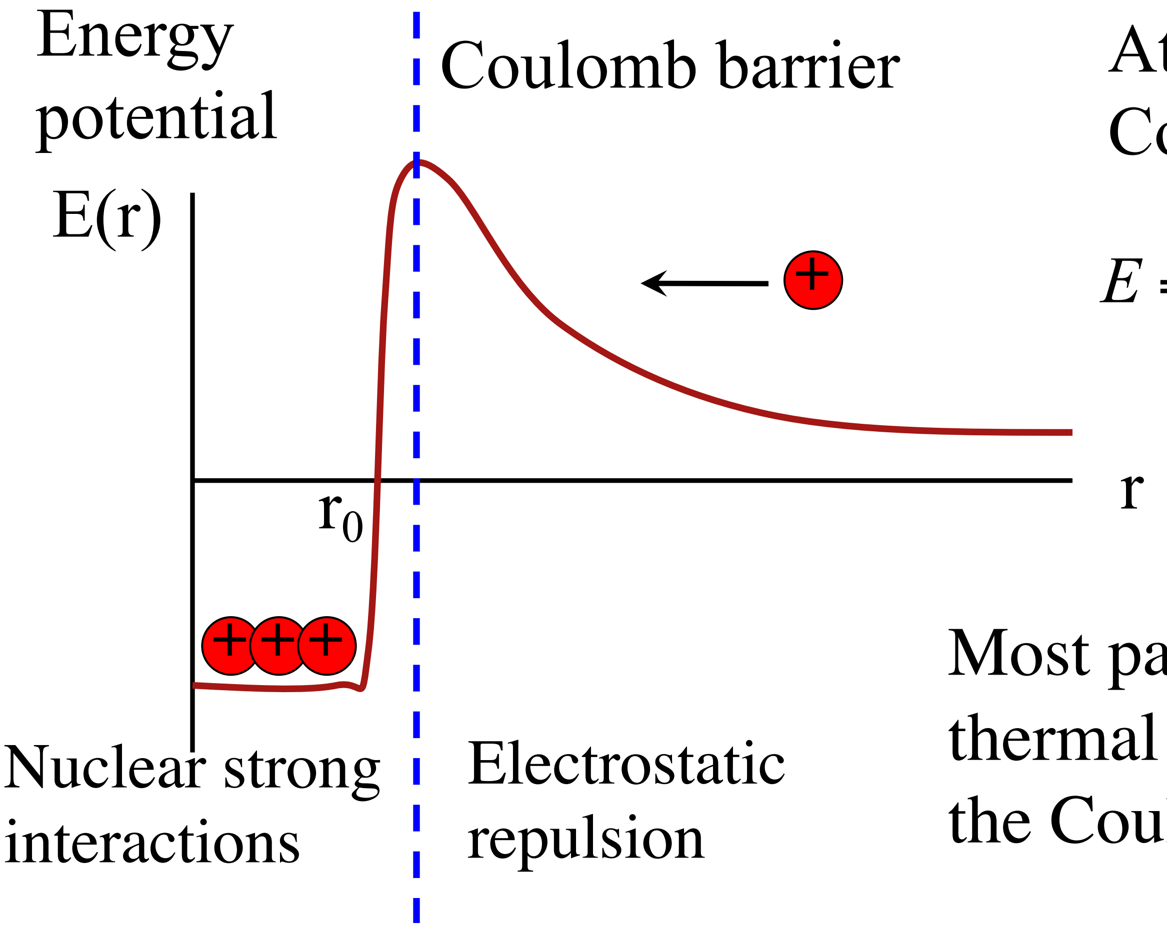


Energetically favorable

Energetically unfavorable

Most bound nucleus is iron 56: up to A < 56 fusion releases energy, but A > 56 fusion requires energy *input*

Overcoming the Electrostatic Barrier



Energy potential

Coulomb barrier

Nuclear strong interactions

Electrostatic repulsion

At r = r_0, height of the Coulomb barrier is:

$$E = \frac{Z_1 Z_2 e^2}{r_0} \sim Z_1 Z_2 \text{ MeV}$$

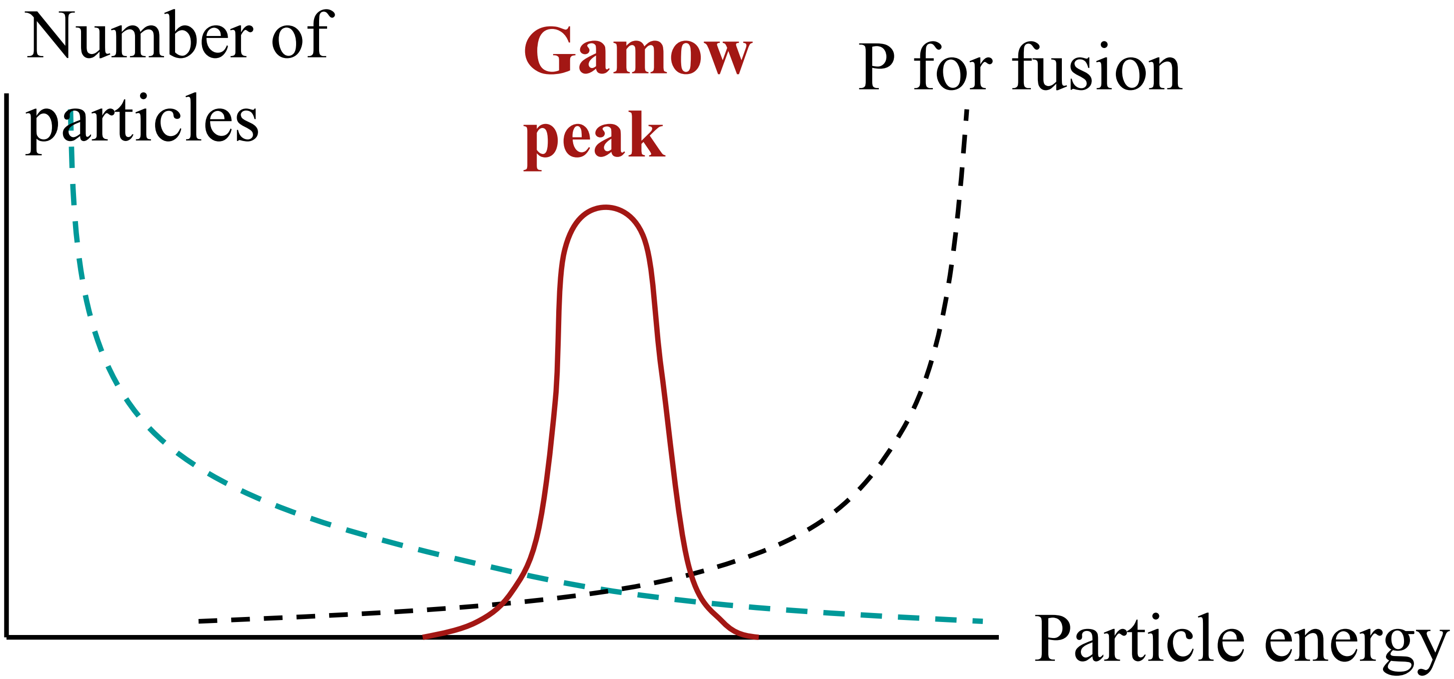
Most particles have too low thermal energies to overcome the Coulomb barrier!

What makes the fusion possible is the ***quantum tunneling*** effect

Probability of tunneling increases steeply with particle energy

The Gamow Peak

The most energetic nuclei are the most likely to fuse, but very few of them in a thermal distribution of particle speeds:



Narrow range of energies around the Gamow peak where significant numbers of particles in the plasma are able to fuse. Energy is >> typical thermal energy, so fusion is slow

Thermonuclear Reactions (TNR)

- Burning of H into He is the only energy generation process on the Main Sequence, where stars spend most of their lives; all others happen in post-MS evolutionary stages
  - Solar luminosity ~ 4.3 million tons of H into He per second
- In addition to the **p-p cycle**, there is the **CNO Cycle**, in which the C, N, O, nuclei catalyze the burning of H into He
- The rates of TNR are usually very steep functions of temperature, due to high potential barriers
- Generally, more massive stars achieve higher T_c , and can synthesize elements up to Fe; beyond Fe, it happens in SN explosions

Self-Regulation in Stars

Suppose the fusion rate increases slightly. Then,

(1) Temperature increases
(2) Pressure increases
(3) Core expands
(4) Density and temperature decrease
(5) Fusion rate decreases

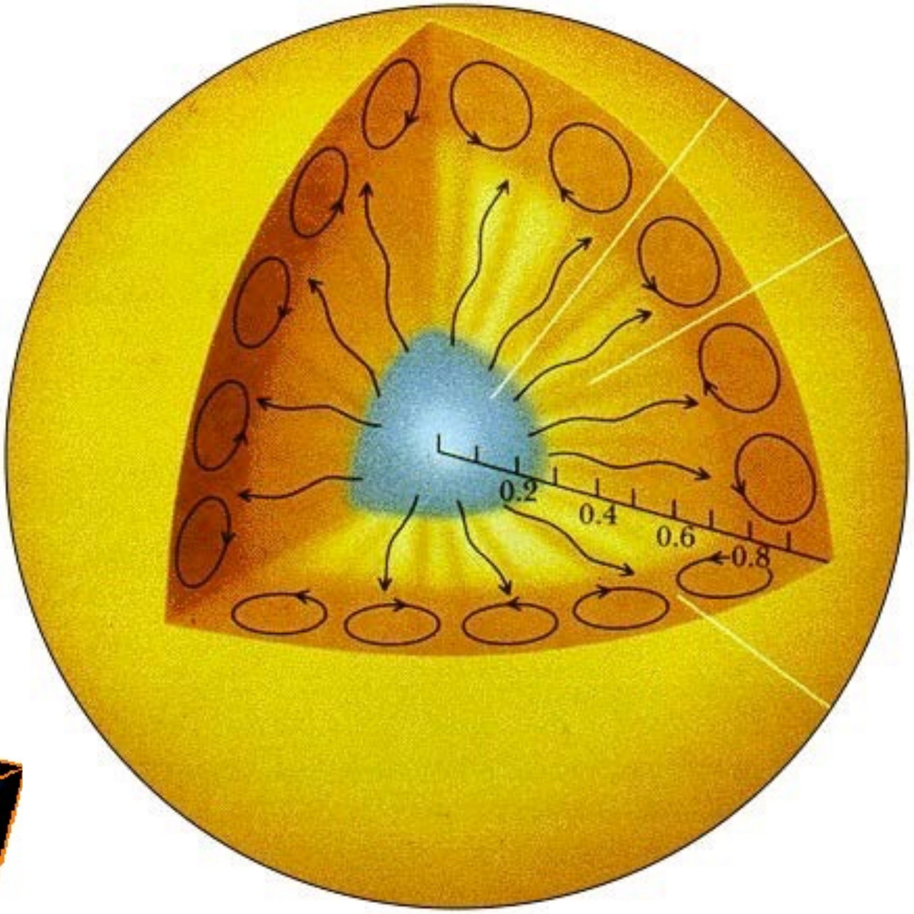
So there's a feedback mechanism which prevents the fusion rate from skyrocketing upward

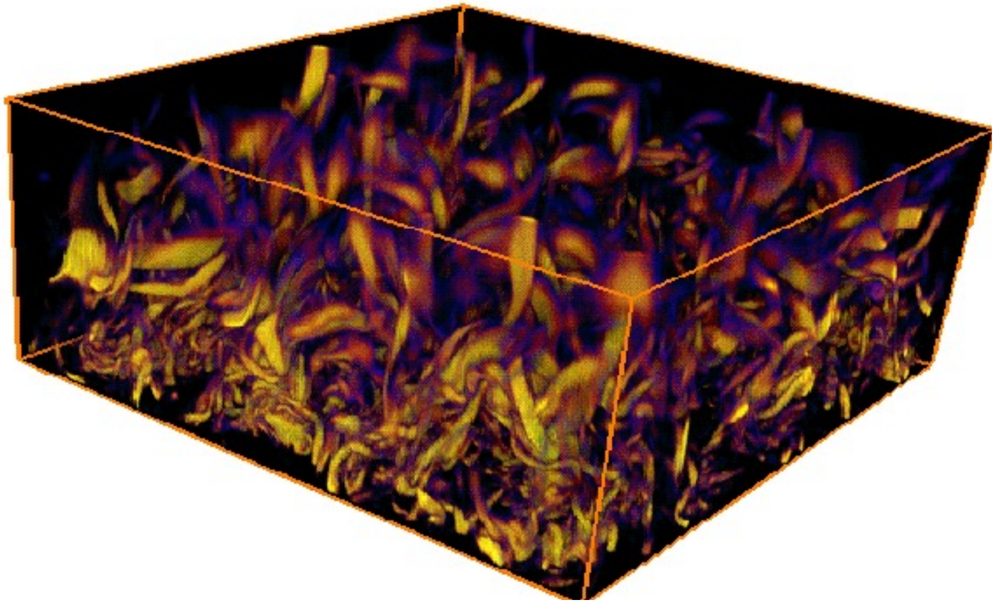
This is the inverse of the core collapse mechanism discussed for the protostars

Energy Transport Mechanisms in Stars

How does the energy get out?

1. **Radiatively** (photon diffusion)
2. **Convectively**
3. Conduction (generally not important in stars)

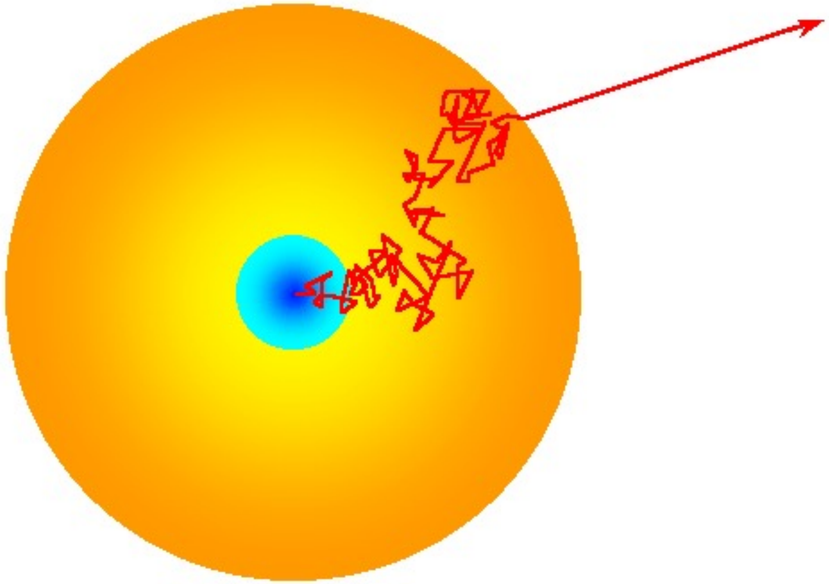




… and the reality is fairly complex

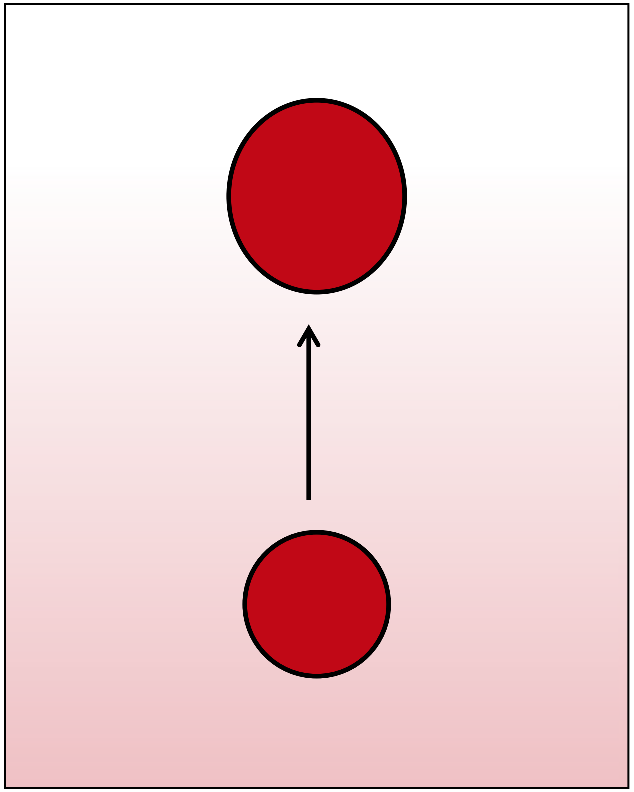
Radiative Energy Transfer

- As the heat diffuses from the core outwards, the photons are scattered by the dense plasma inside the star
- For the Sun, it takes ~ 250,000 years for the energy to reach the surface



- The opacity of the plasma depends on the temperature, density, and chemical composition
- If the plasma is too opaque, convection becomes a more efficient mechanism for the energy transfer

When Does the Convection Happen?



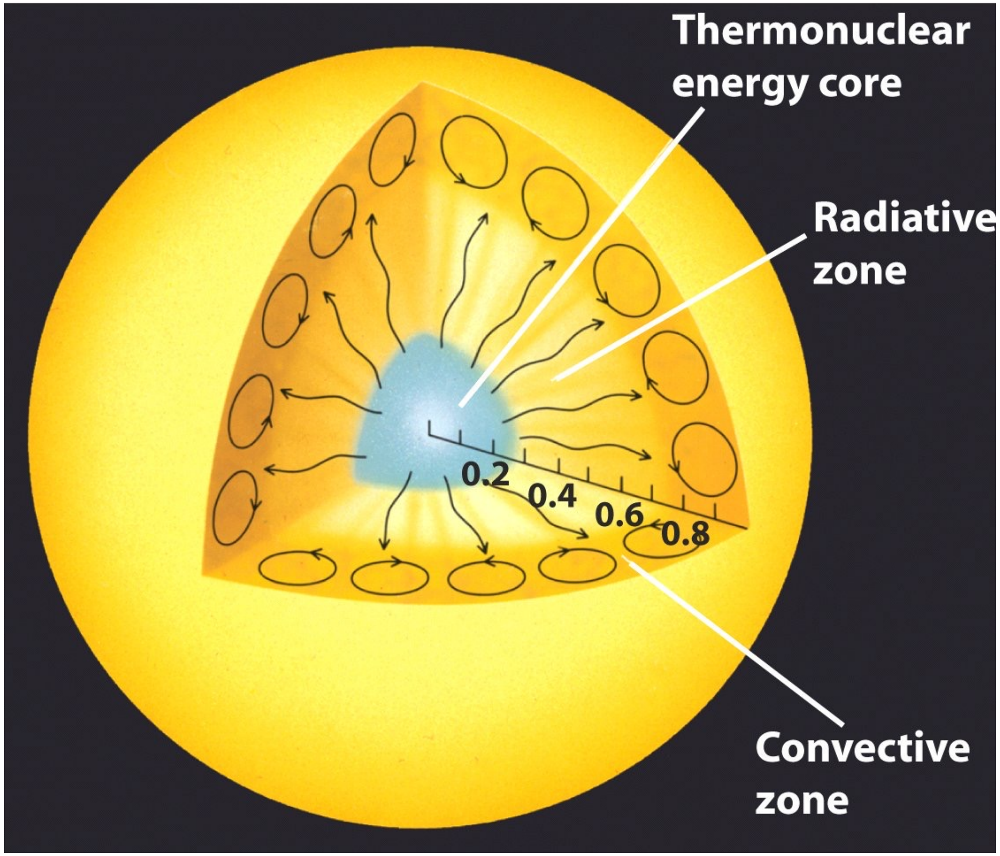
The Schwarzschild criterion: Imagine displacing a small mass element vertically upward by a distance dr. Assume that **no heat** is exchanged with the surrounding, i.e. the process is **adiabatic**:

- Element expands to stay in pressure balance
- New density will *not* generally equal the new ambient density

If this mechanical energy transport is more efficient than the radiative case, the medium will be **convectively unstable**

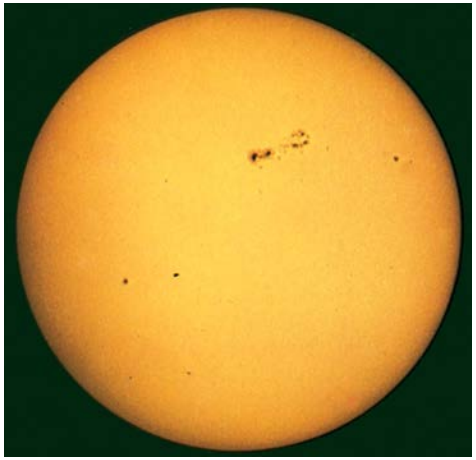
A Theoretical Model of the Energy Transfer in the Sun

- Hydrogen fusion takes place in a core extending out to about 0.25 solar radius
- The **core** is surrounded by a radiative zone extending to about 0.71 solar radius. Energy transfer through *radiative diffusion*
- The **radiative zone** is surrounded by a rather opaque **convective zone** of gas at relatively low temperature and pressure. Energy transfer through *convection*

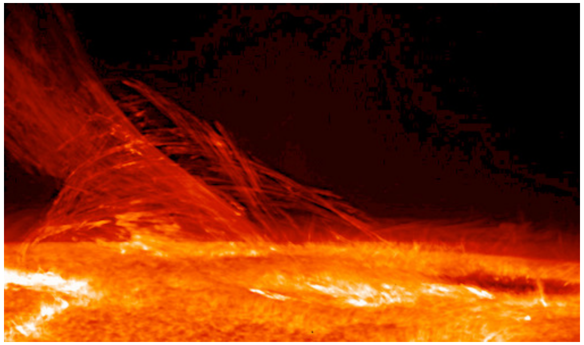


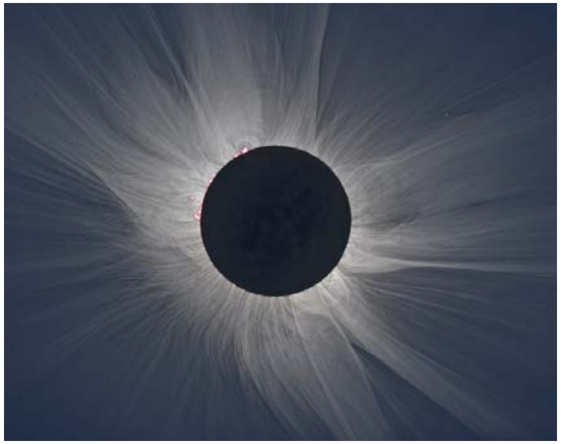
Solar Atmosphere / Surface Layers

The Sun's atmosphere has three main layers:

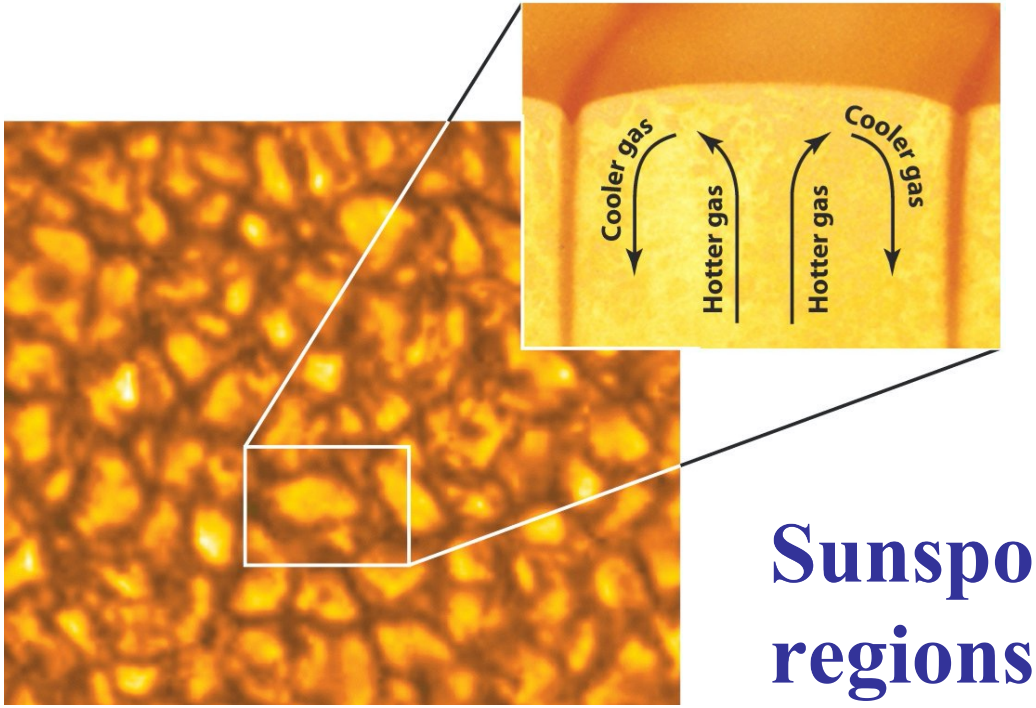


1. **The photosphere**
   - The visible surface of the Sun, the emergent spectrum is a ~ 5800 K blackbody
2. **The chromosphere**
   - Where most of the Solar activity happens, temperature ~ 10000 K
3. **The corona**
   - Extends millions of km into space, temperature > million K, heated by the chromospheric activity, source of the Solar wind and Coronal Mass Ejections

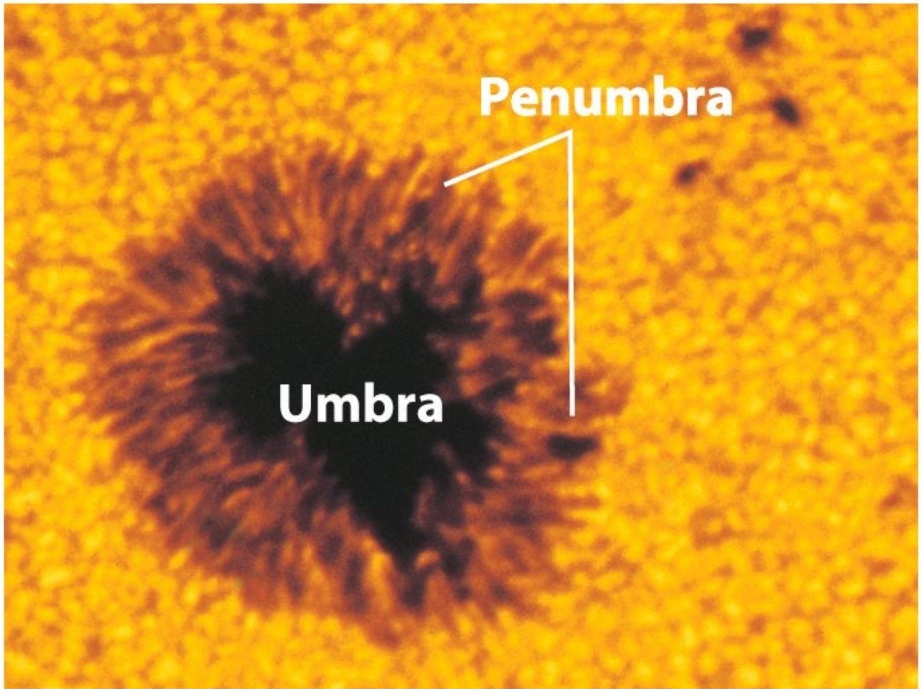


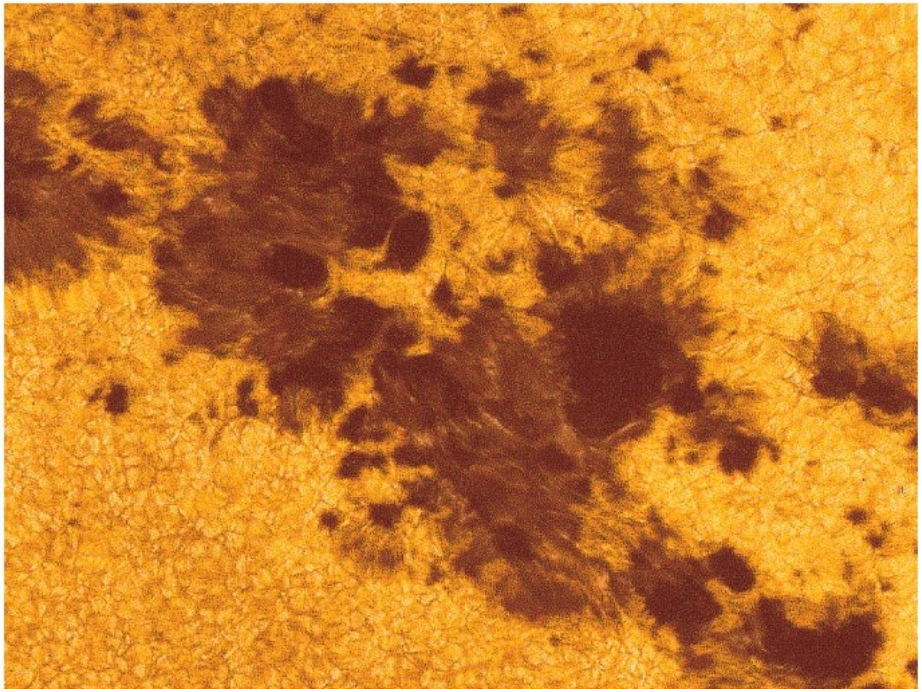


Convection in the photosphere produces granules



Sunspots are low-temperature regions in the photosphere





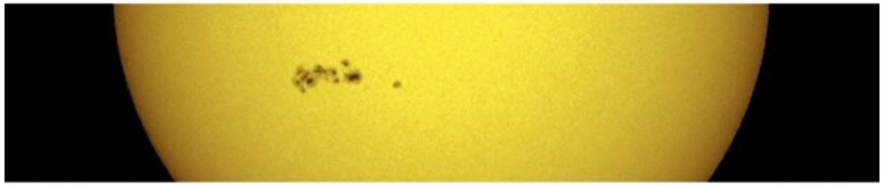
Sunspots come in groups, and follow the Sun’s differential rotation. They start from the higher latitudes and migrate towards the Solar equator.

They correlate well with other manifestations of the Solar activity.


November 9


November 12

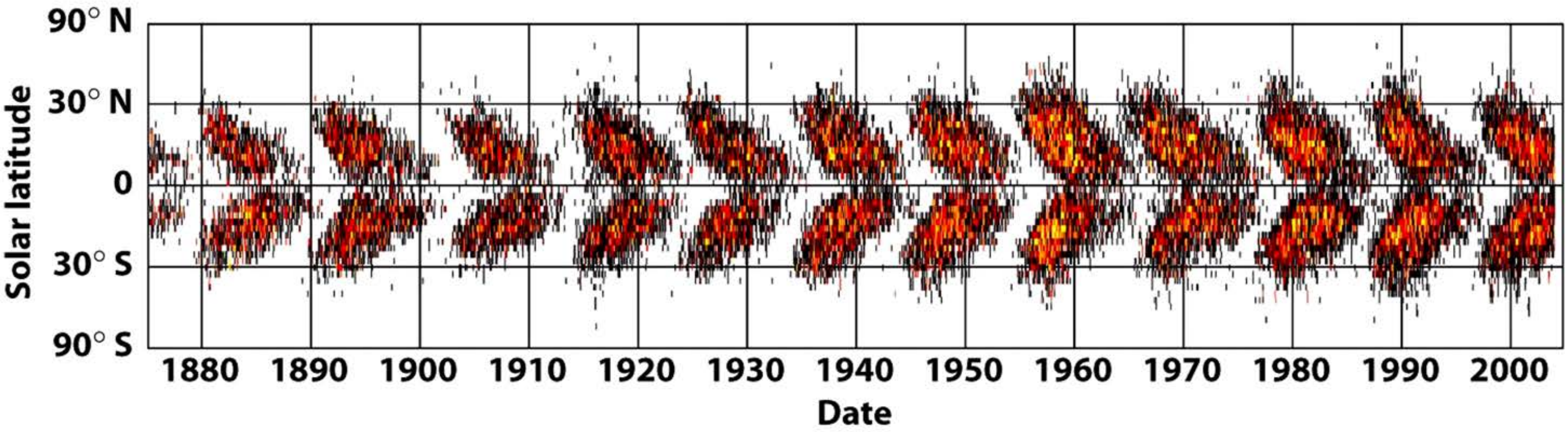

November 14

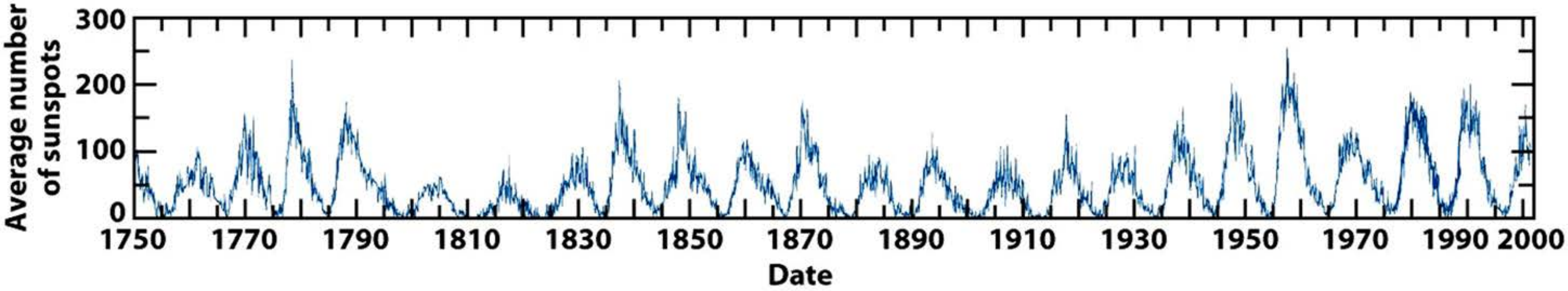

November 15


November 17


November 19

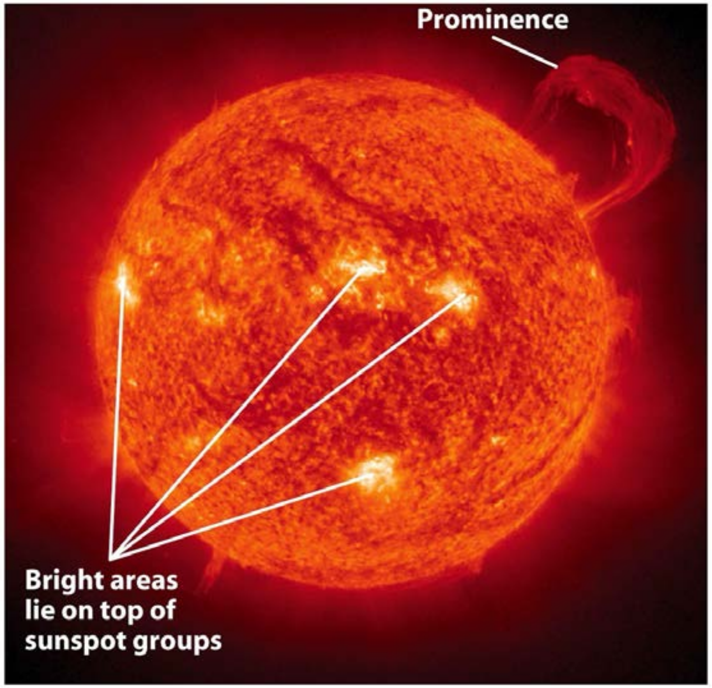
- The Sun’s surface features (including sunspot numbers) vary in an ***11-year cycle***; it is really a ***22-year cycle*** in which the surface magnetic field increases, decreases, and then increases again with the opposite polarity
- There are probably also longer period cycles

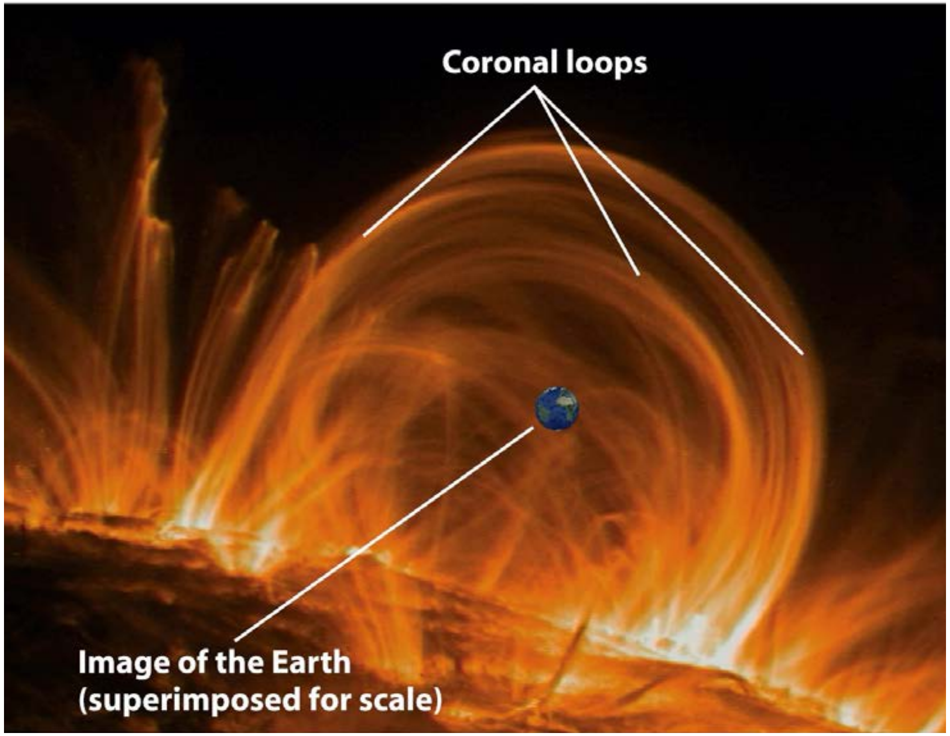


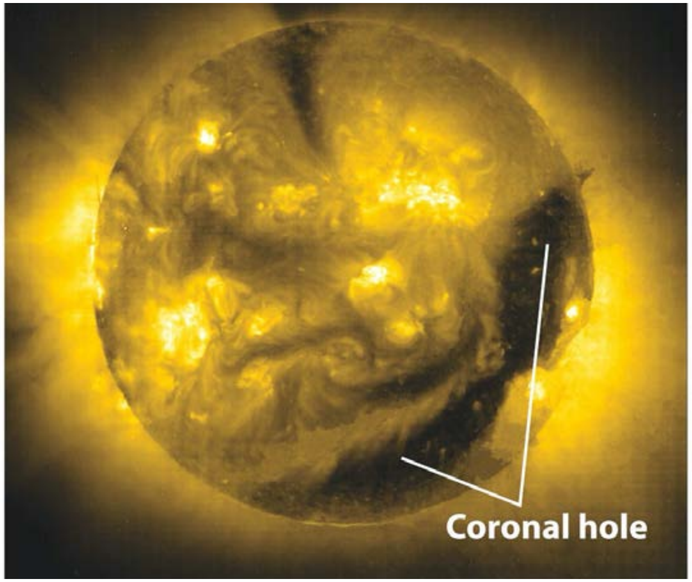


The Sun's magnetic field produces solar activity

- A solar flare is a brief eruption of hot, ionized gases from a sunspot group
- A coronal mass ejection is a much larger eruption that involves immense amounts of gas from the corona

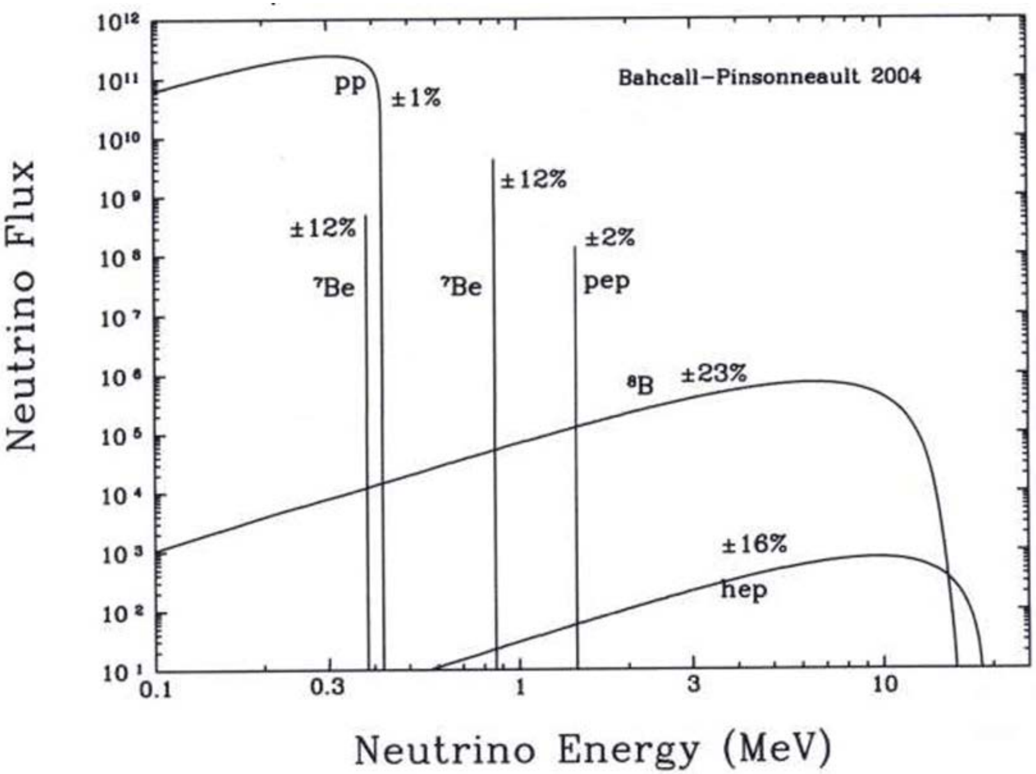






Solar Neutrinos and the Birth of Neutrino Astronomy

- Detection of Solar neutrinos offers a unique probe of deep stellar interiors - a fundamental test of our understanding of stars and their energy production



- For many years, there was a factor of 3 discrepancy between the theoretical predictions and the experiment (the "Solar neutrino problem"). The resolution of it provided a fundamental physical insight (neutrino oscillations)

Solar Neutrino Flux

Neutrinos from the main p-p chain are of very low energy. Less important reactions (energetically) yield a smaller flux of higher energy neutrinos:

$p + e^- + p \rightarrow {}^2H + \nu_e$	‘pep’ - 1.4 MeV neutrino
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	0 - 18.8 MeV
$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$	0.383, 0.861 MeV
${}^8B \rightarrow {}^8Be + e^+ + \nu_e$	0 - 15 MeV

Since we get 2 neutrinos for each 28 MeV of energy, we can use Solar luminosity to calculate neutrino flux at Earth:

$$\text{Neutrino flux} = \frac{2L_{sun}}{28\text{ MeV}} \times \frac{1}{4\pi d^2} \sim 6 \times 10^{10}\ \text{neutrinos/s/cm}^2$$

Homestake Mine Detector

First attempt to detect Solar neutrinos began in the 1960s:

Detector is a large tank containing 600 tons of C_2Cl_4, situated at 1500m depth in a mine in South Dakota.

Neutrinos interact with the chlorine to produce a radioactive isotope of argon:

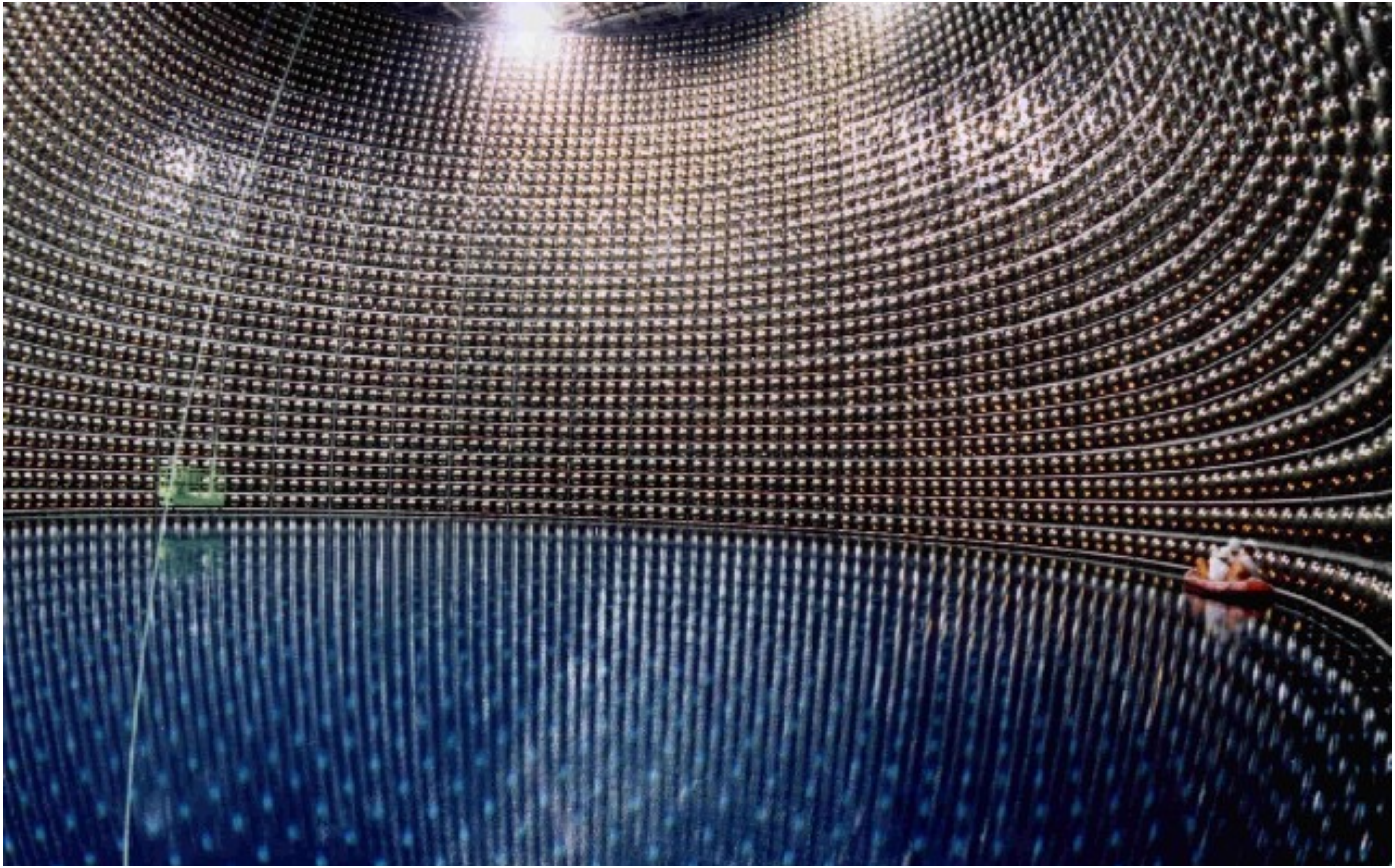
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow \mathrm{e}^- + {}^{37}\mathrm{Ar}$$

+ an electron which is not observed.

Super Kamiokande

look for a Cherenkov radiation from the high energy electrons in ultra-pure water

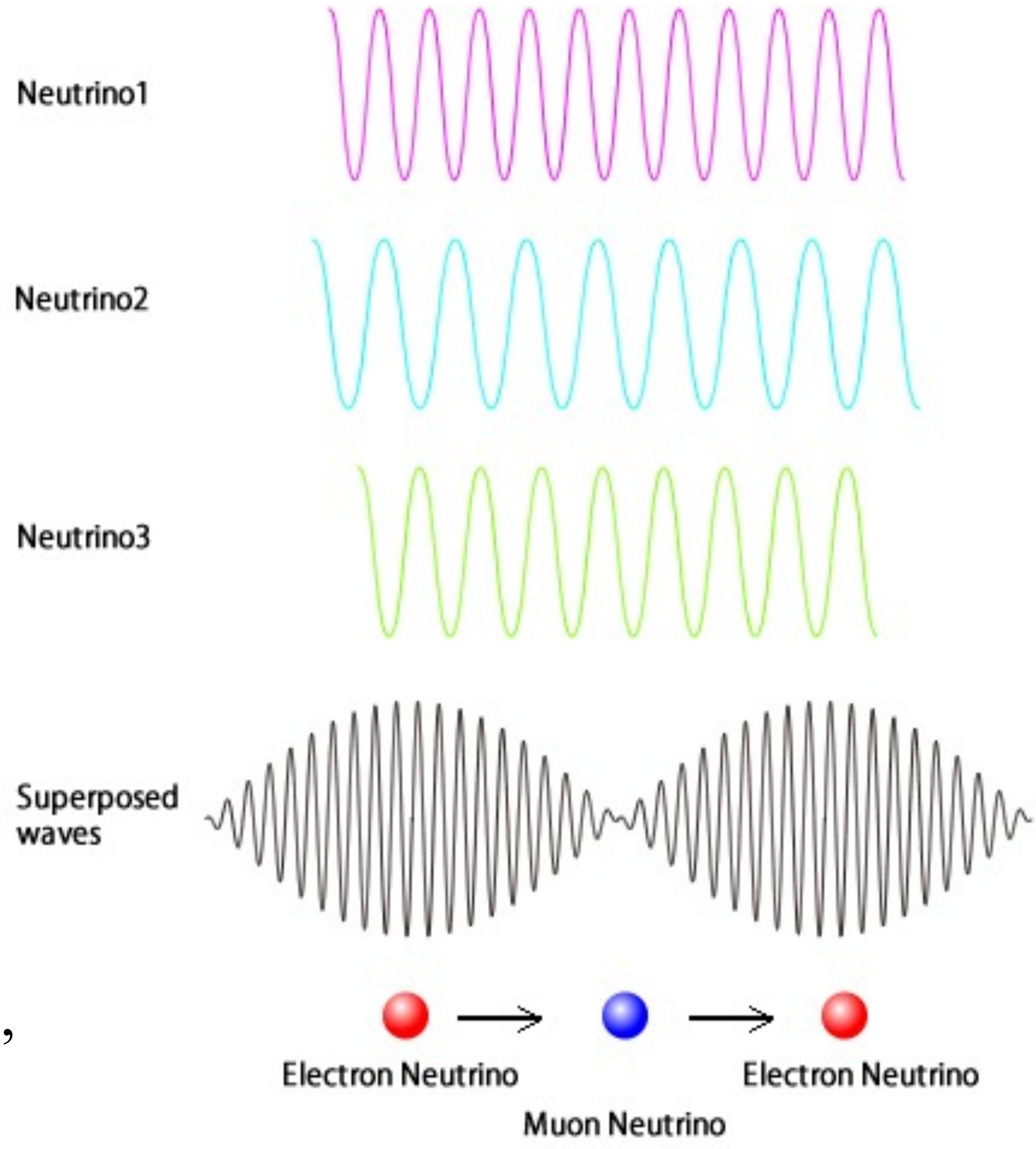
Measure: $\nu_e + e^- \rightarrow \nu_e + e^-$



Neutrino Oscillations

There are 3 flavors of leptons (electron, muon, tau), and the corresponding types of neutrinos:

Flavor	Mass	
● Electron Neutrino	● m_1	Neutrino1
● Muon Neutrino	● m_2	Neutrino2
● Tau Neutrino	● m_3	Neutrino3



Neutrinos are a quantum superposition of the 3 types, and oscillate between them