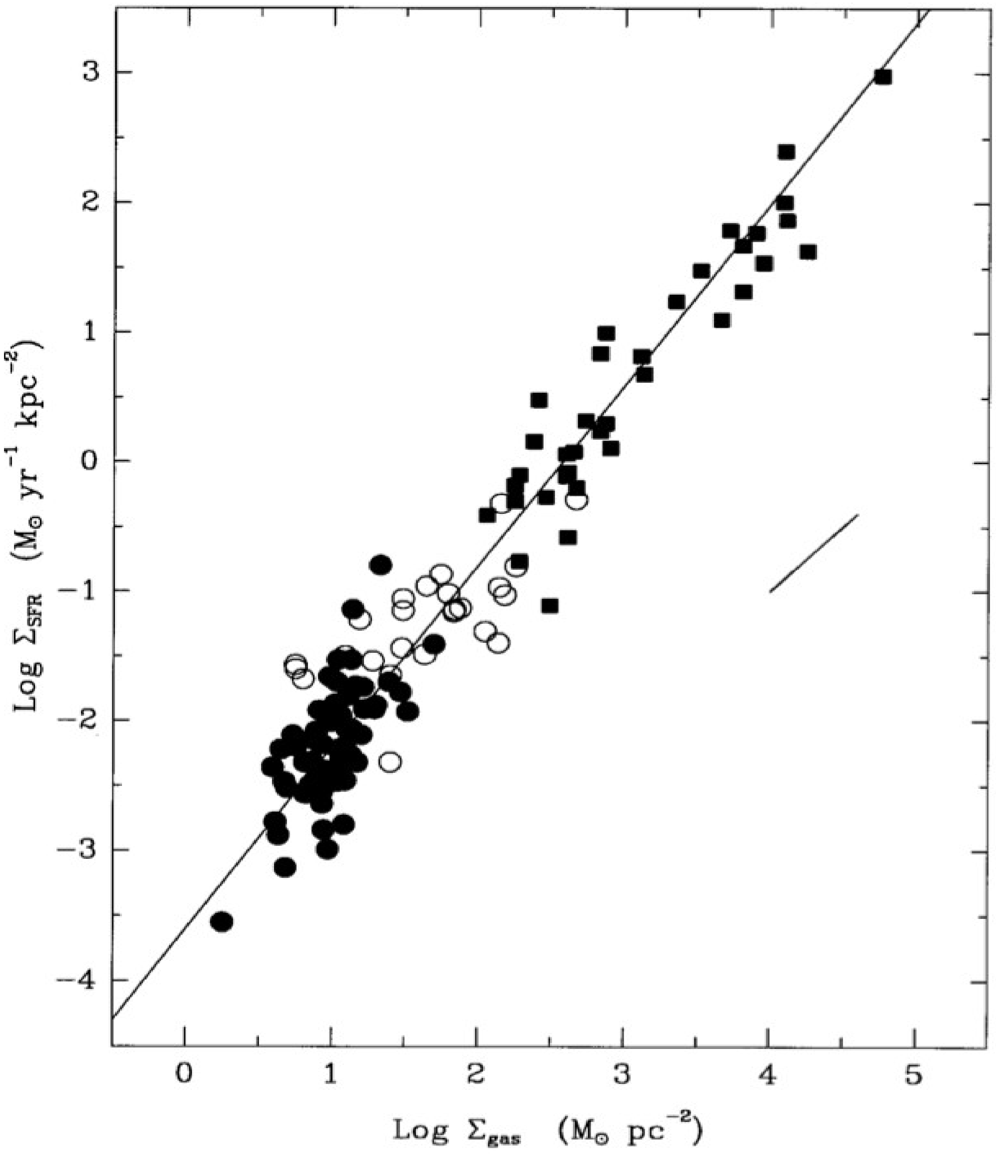
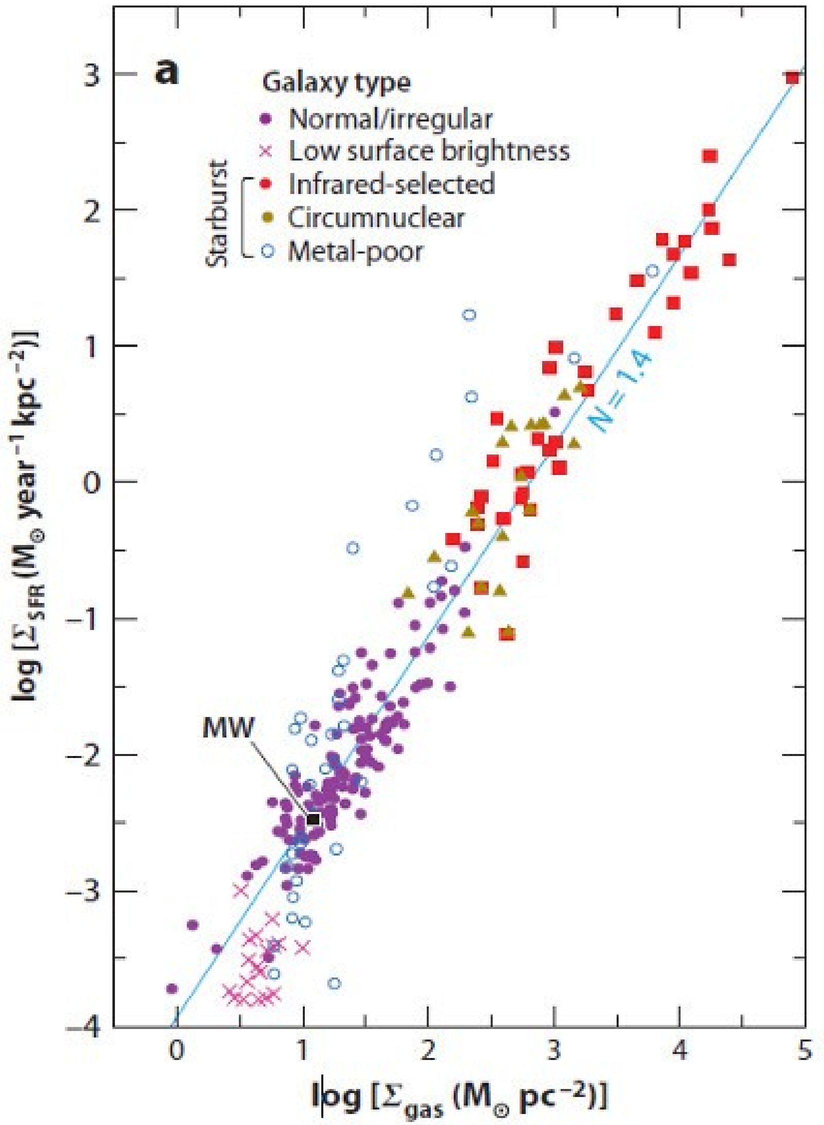
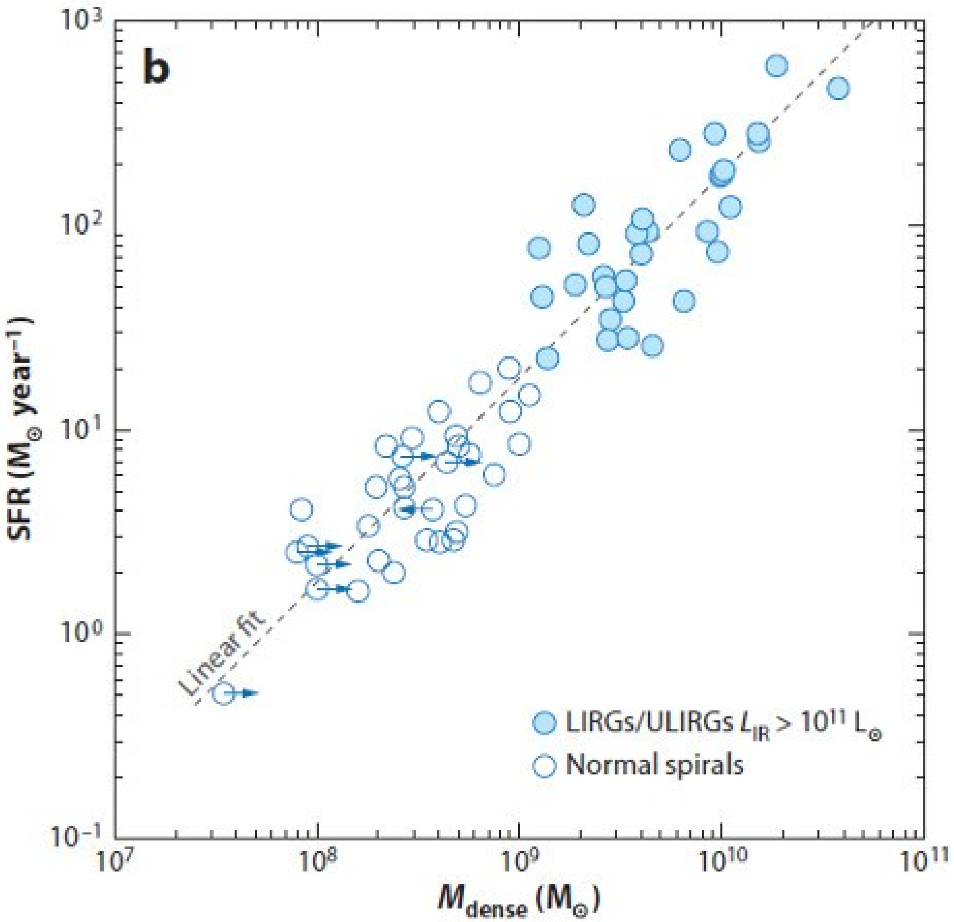
Star formation

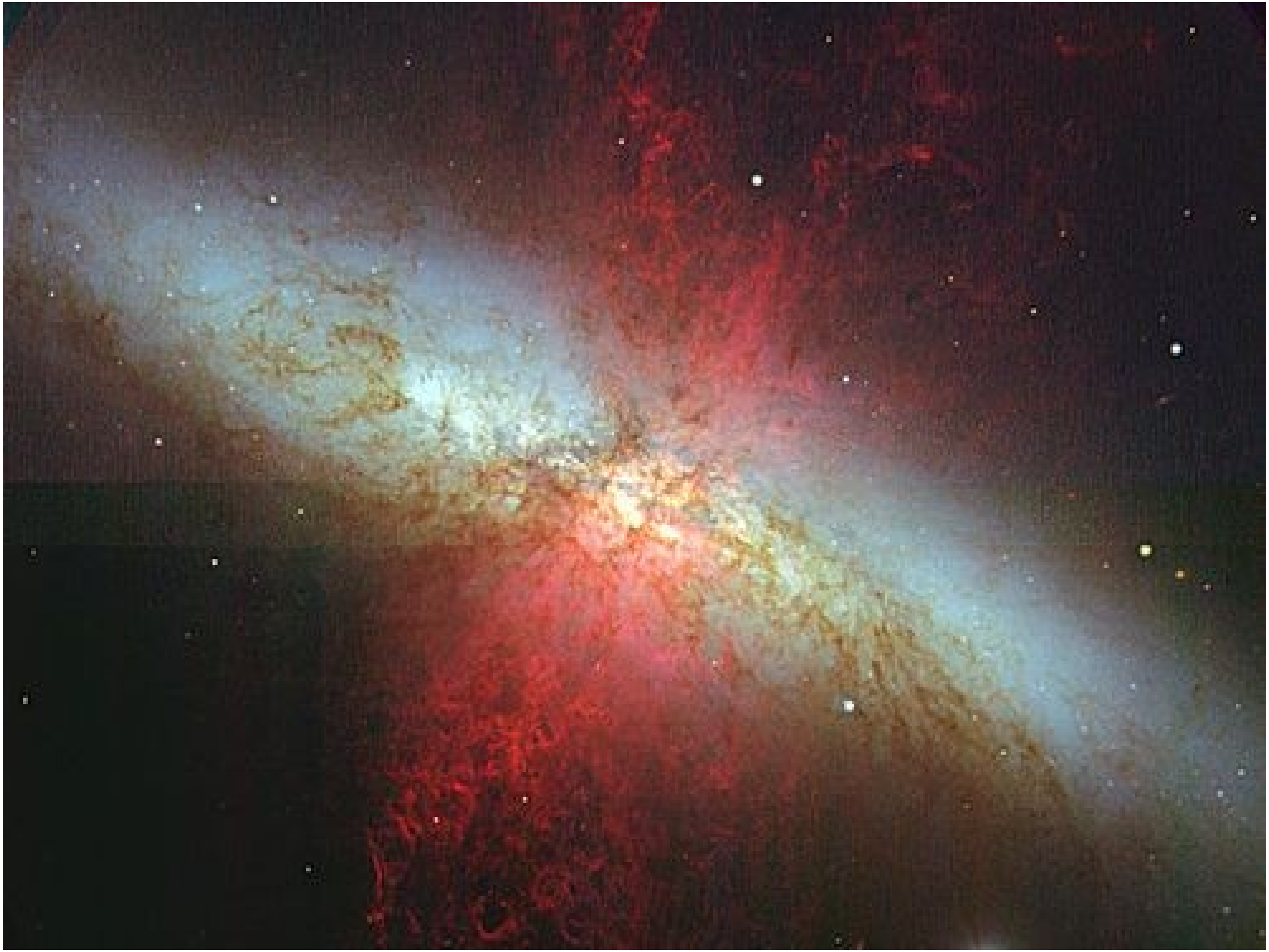
Schmidt-Kennicut law



Schmidt-Kennicut law







Cloud contraction

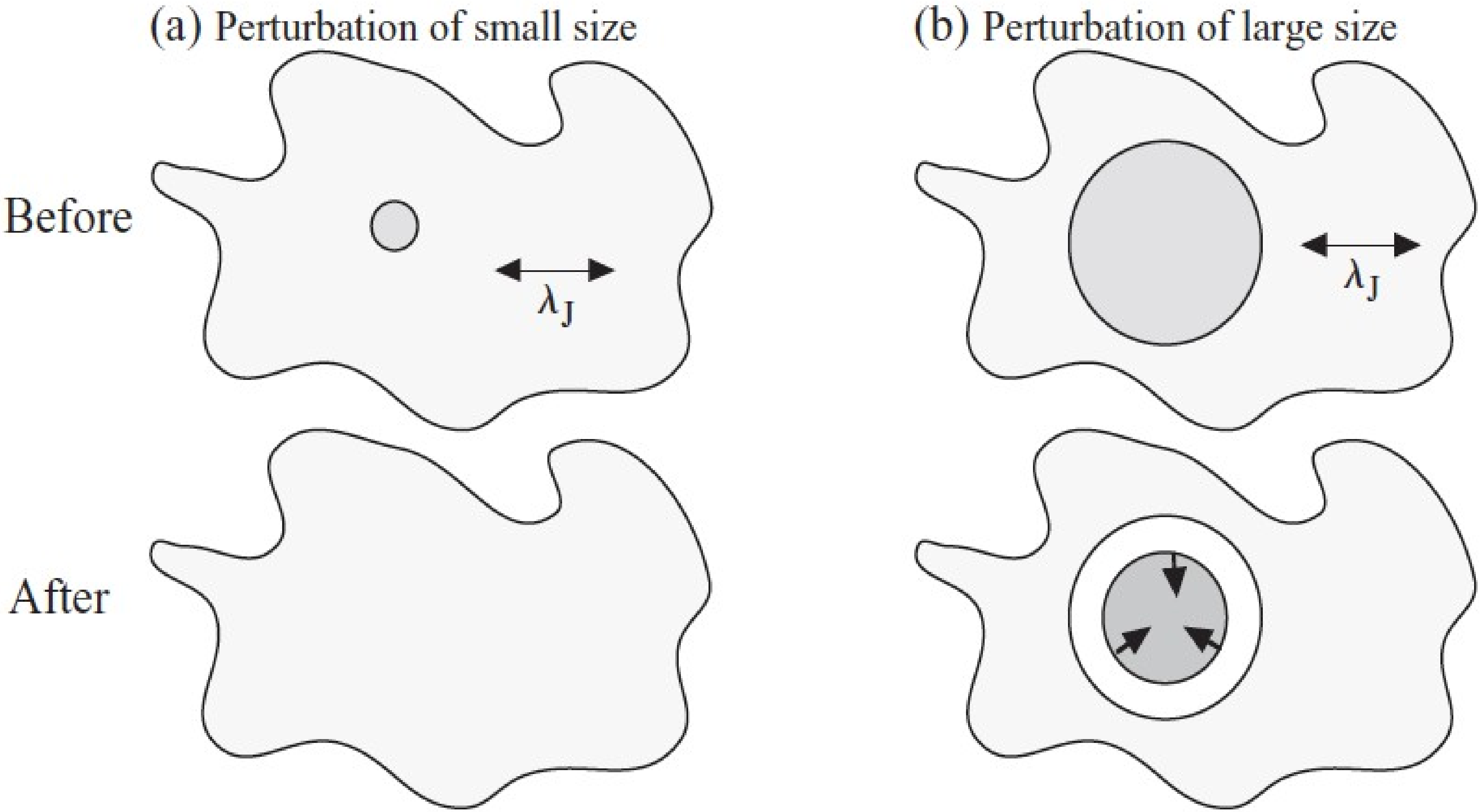
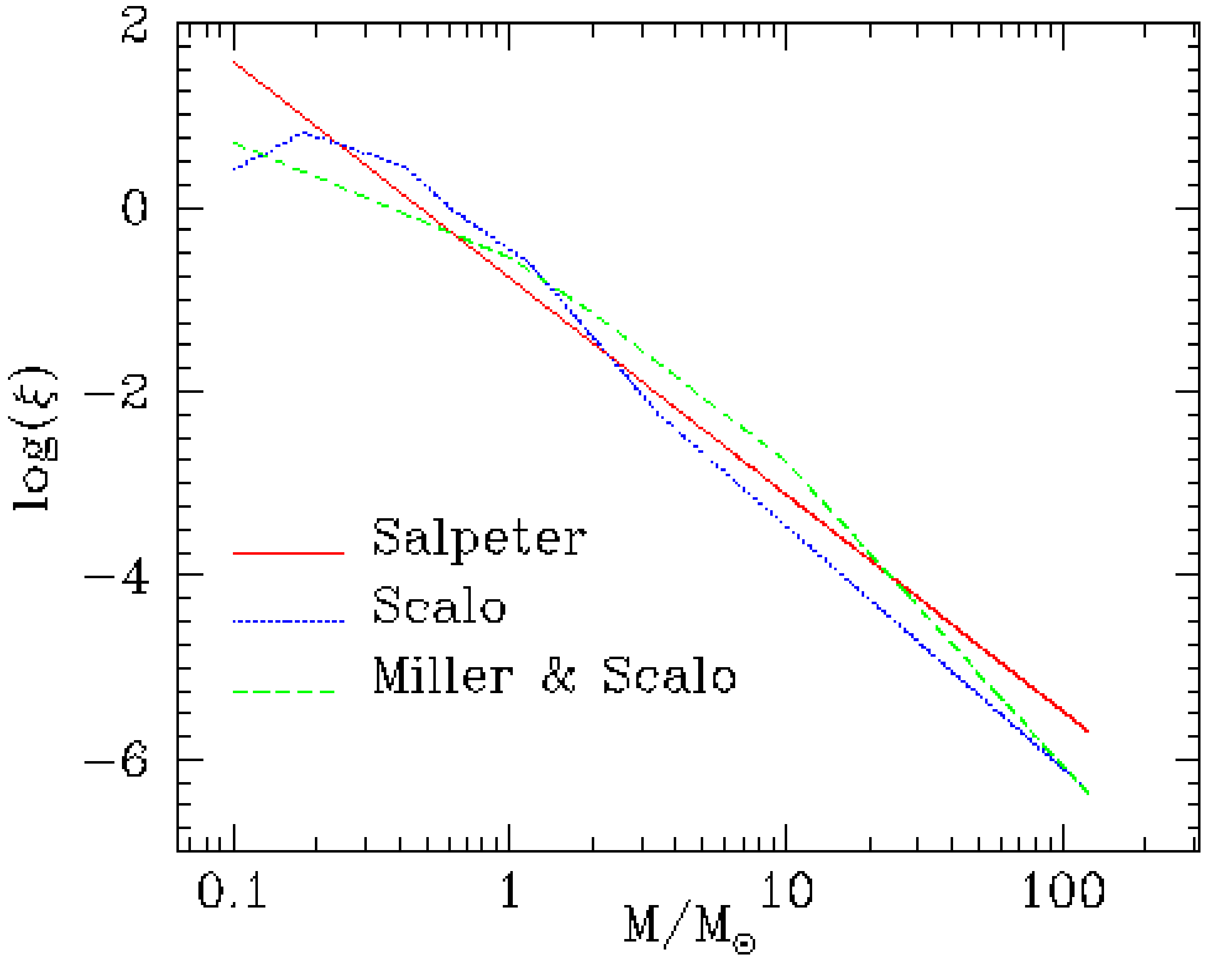
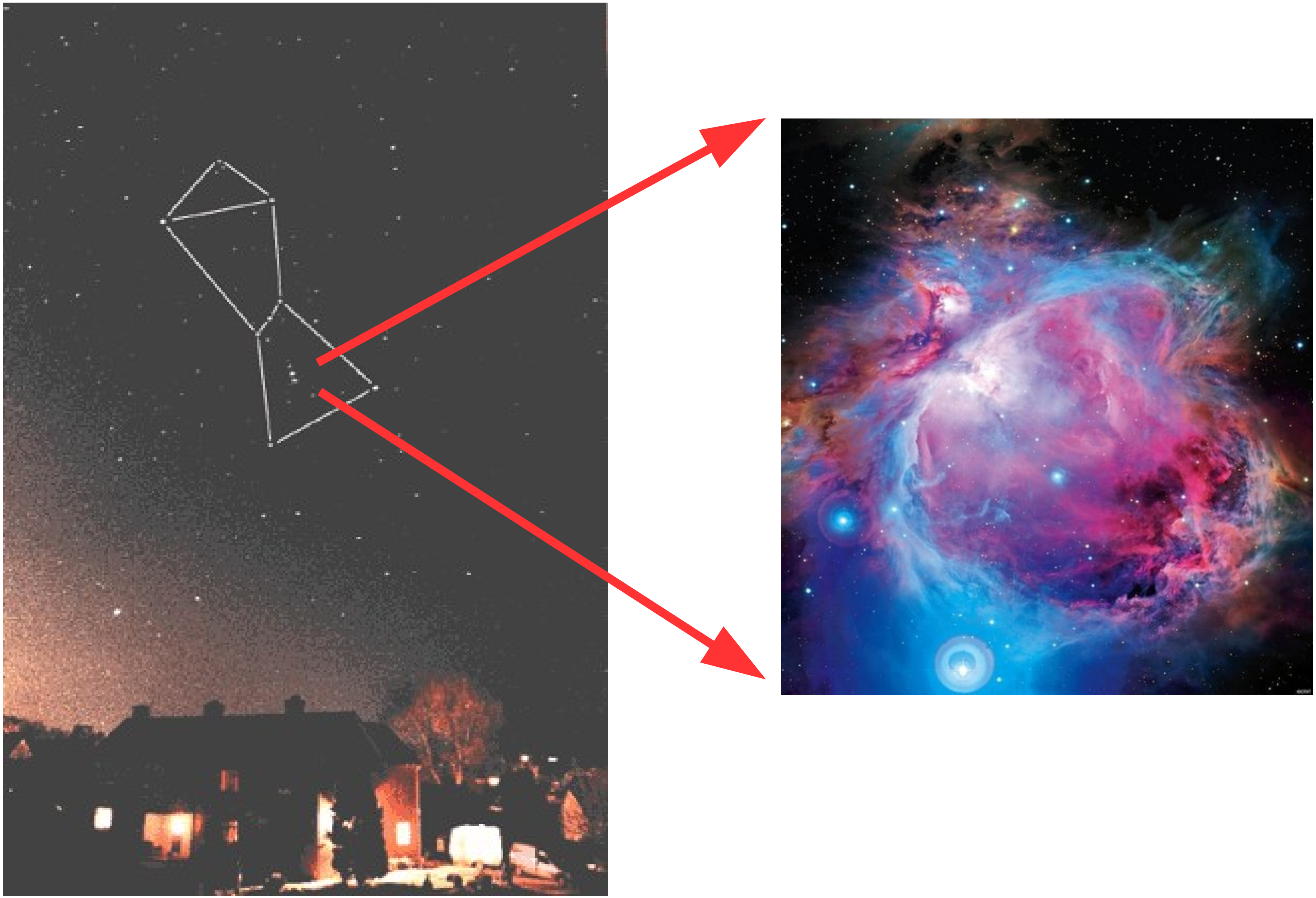


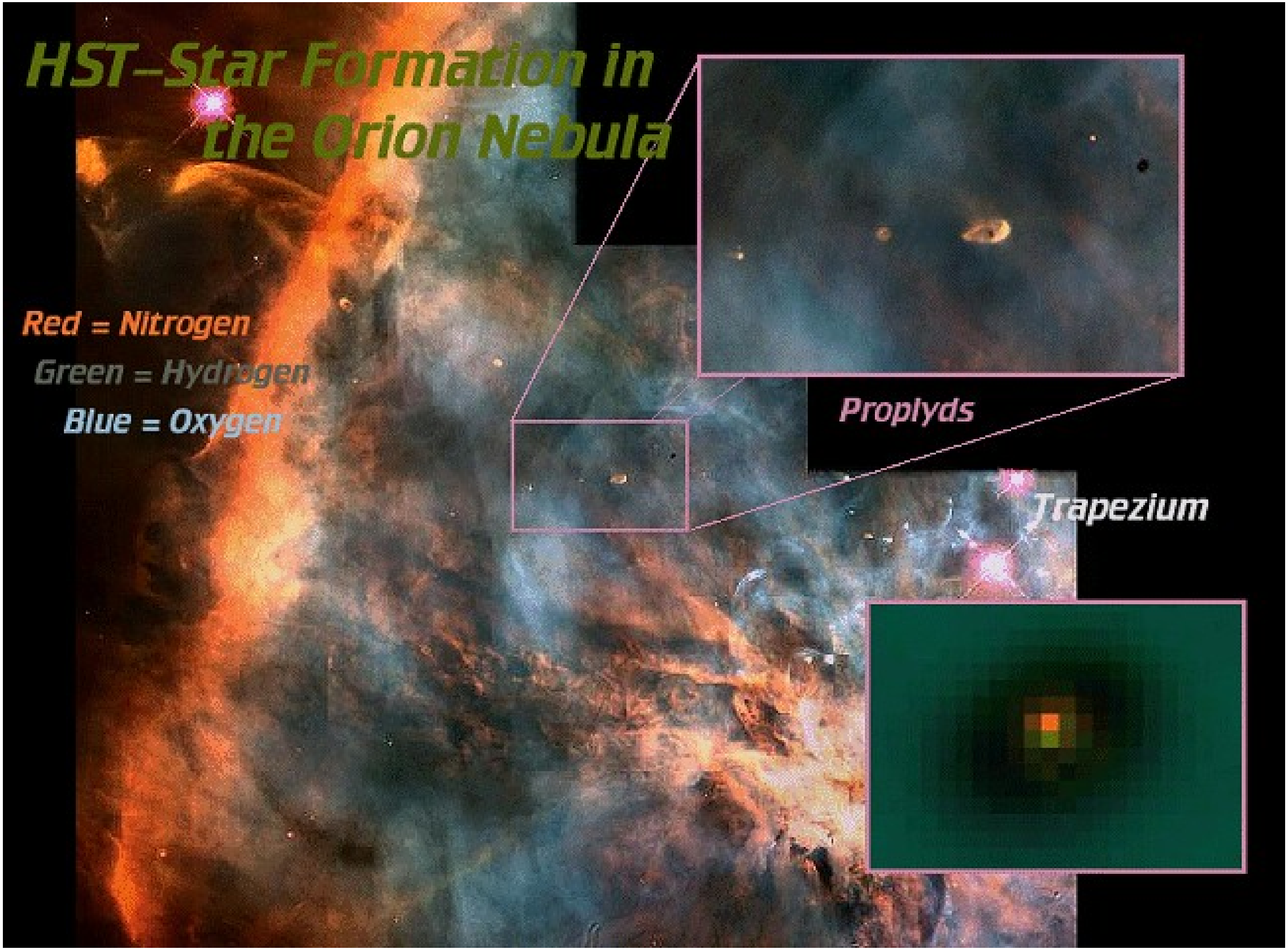
Table 12.4 The Jeans criterion and the contents of giant molecular clouds.

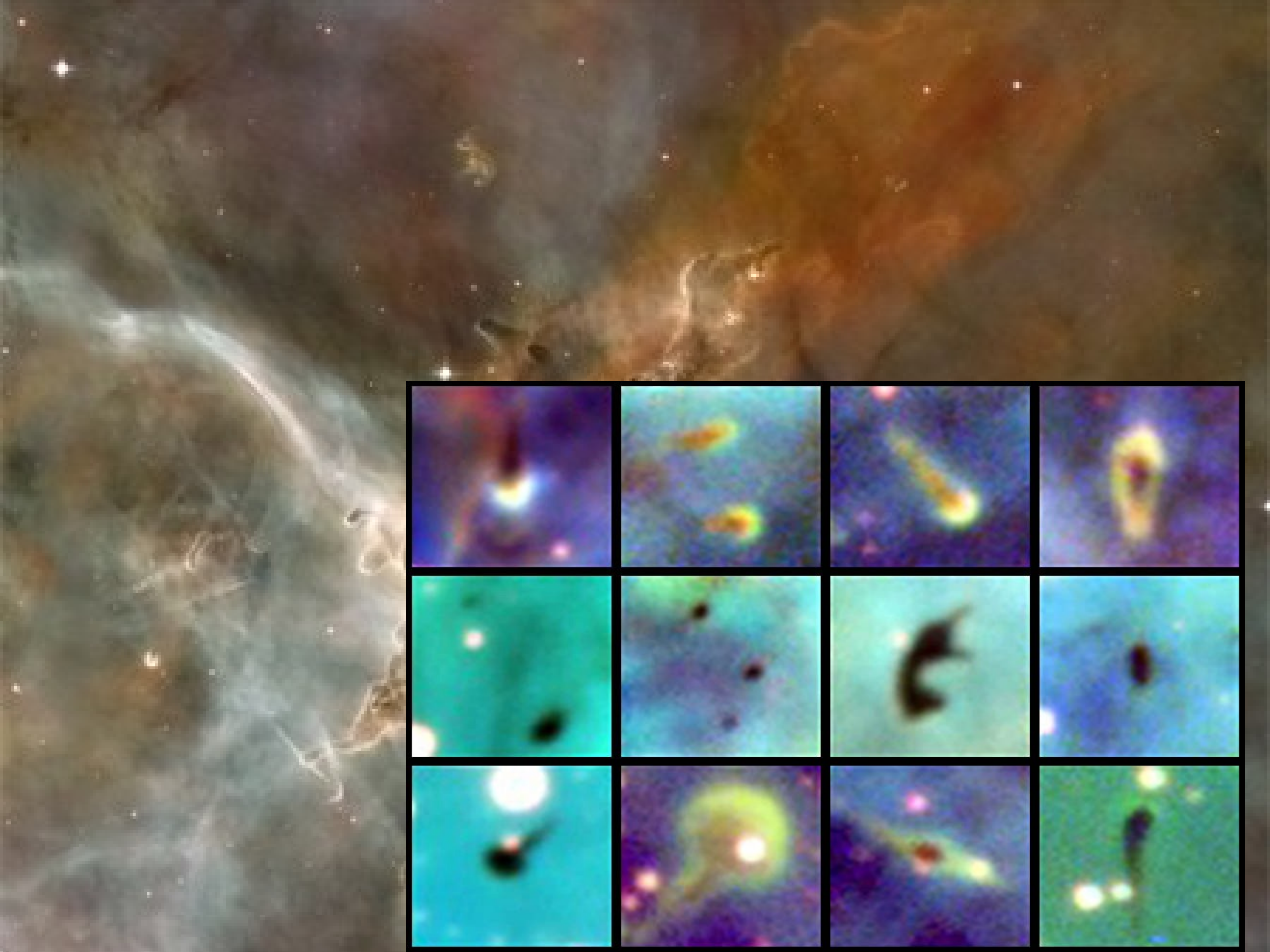
	GMC	Clump	Dense core
Size	50 pc	10 pc	0.1 pc
Mass	$10^5\ M_\odot$	30–$10^3\ M_\odot$	3–$10\ M_\odot$
Number density	$10^8\ \mathrm{m^{-3}}$	$5 \times 10^8\ \mathrm{m^{-3}}$	$5 \times 10^{10}\ \mathrm{m^{-3}}$
Temperature	15 K	10 K	10 K
Jeans length	4 pc	1.5 pc	0.15 pc
Jeans mass	$600\ M_\odot$	$100\ M_\odot$	$30\ M_\odot$

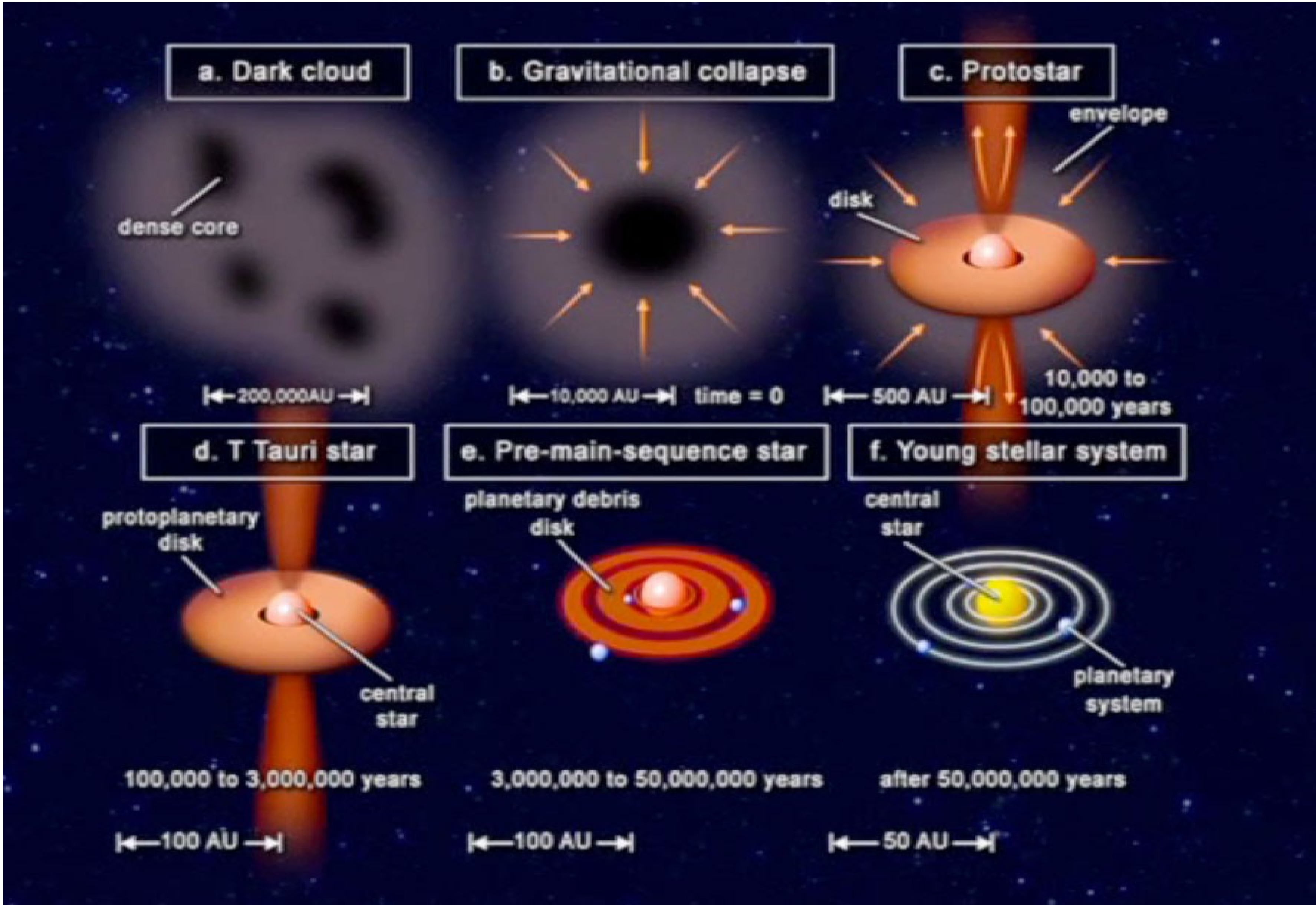
Initial Mass Function





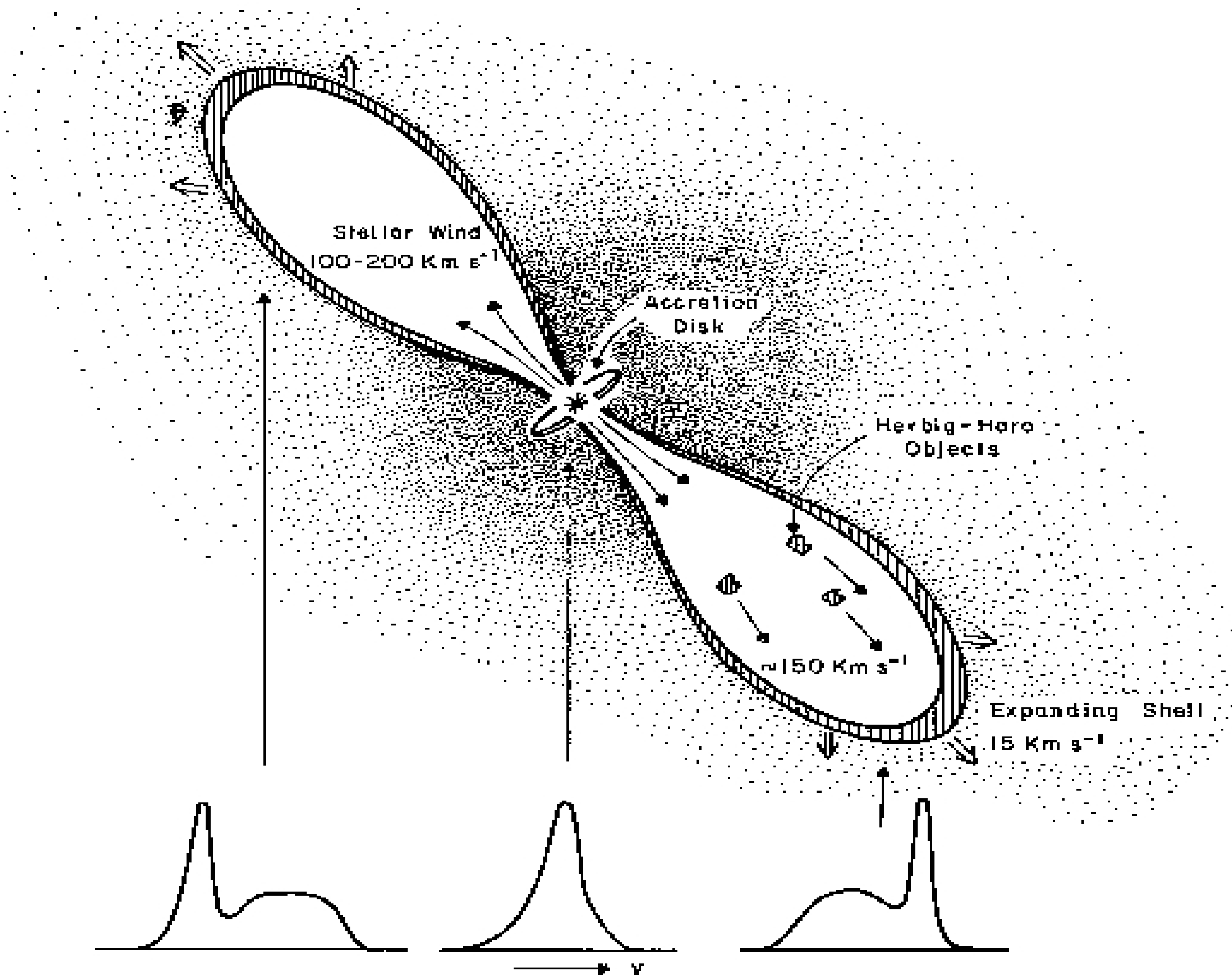

HST–Star Formation in the Orion Nebula
Red = Nitrogen
Green = Hydrogen
Blue = Oxygen
Proplyds
Trapezium

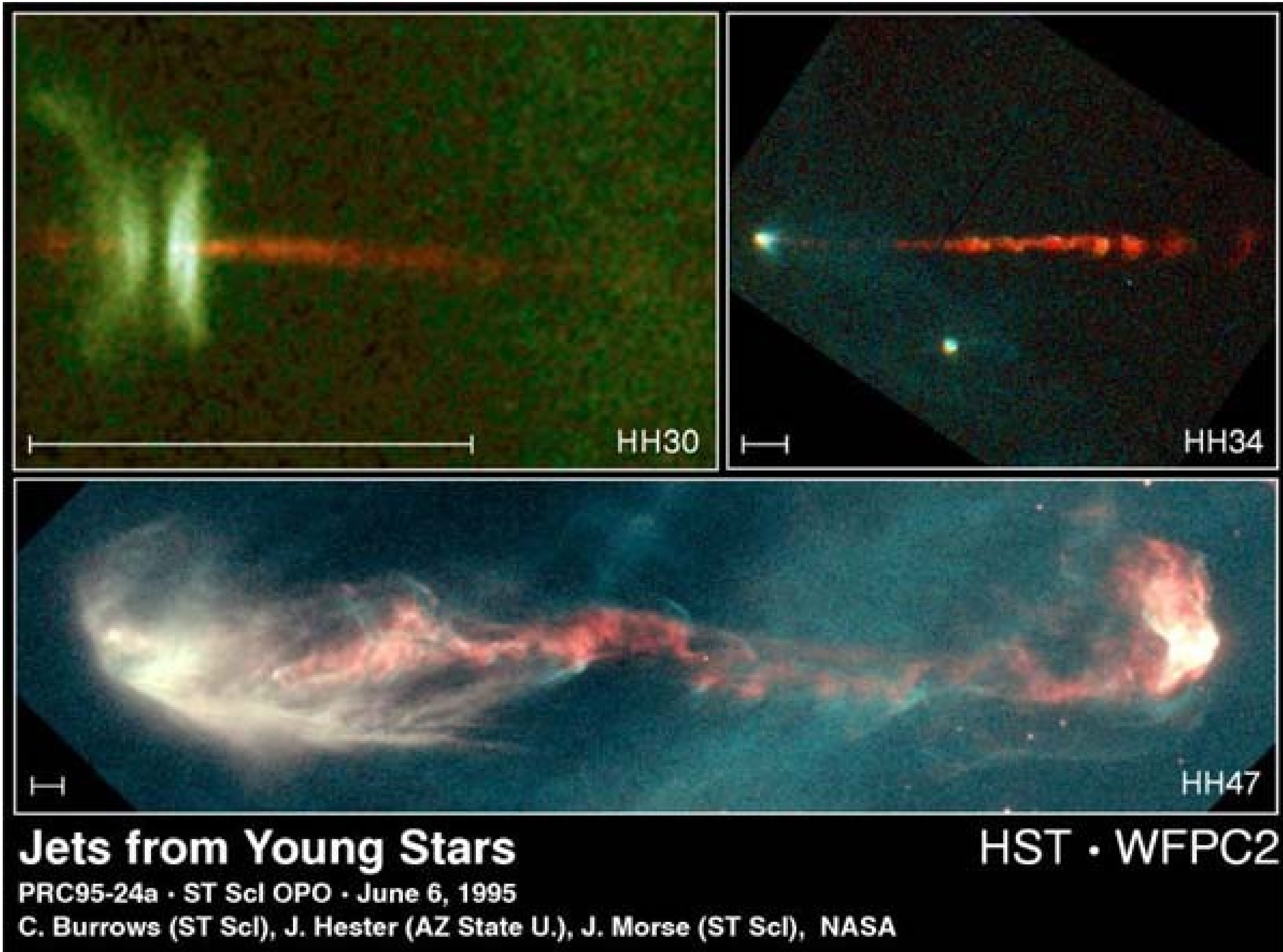




a. Dark cloud
dense core
200,000AU
b. Gravitational collapse
10,000 AU
time = 0
c. Protostar
envelope
disk
500 AU
10,000 to
100,000 years
d. T Tauri star
protoplanetary
disk
central
star
100,000 to 3,000,000 years
100 AU
e. Pre-main-sequence star
planetary debris
disk
3,000,000 to 50,000,000 years
100 AU
f. Young stellar system
central
star
planetary
system
after 50,000,000 years
50 AU

Bipolar outflows



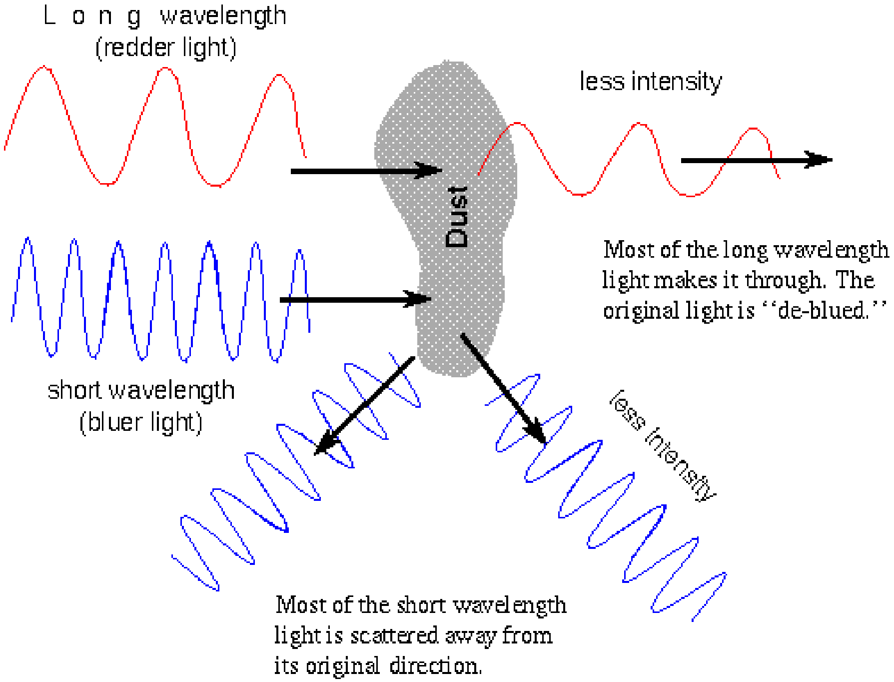

HH30
HH34
HH47
Jets from Young Stars
HST • WFPC2
PRC95-24a • ST ScI OPO • June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

Open/globular clusters

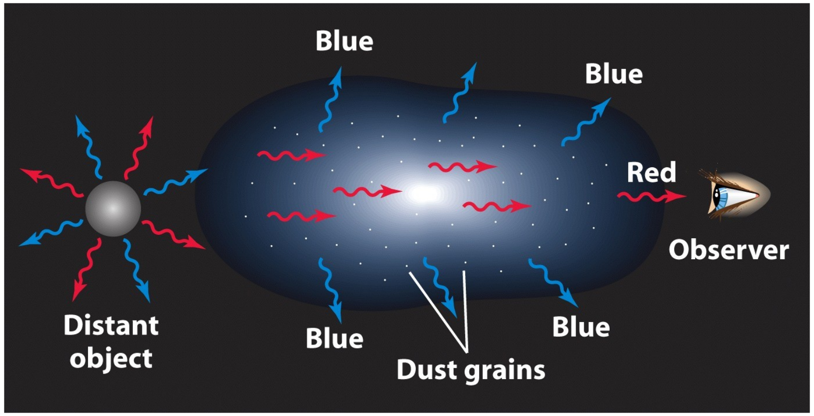
Pleiades

M13

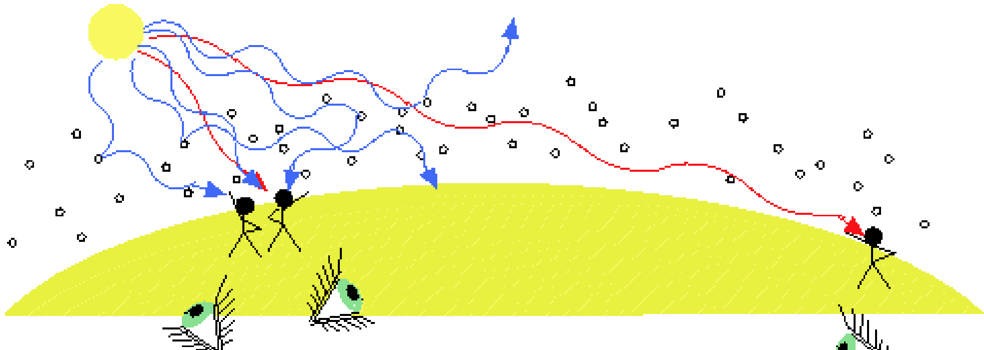
Dust and light



Dust **extinction** and **reddening** in astronomical optical/UV observations

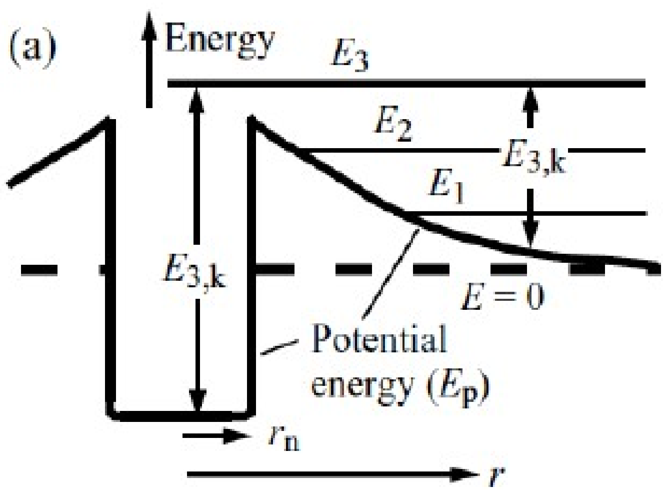


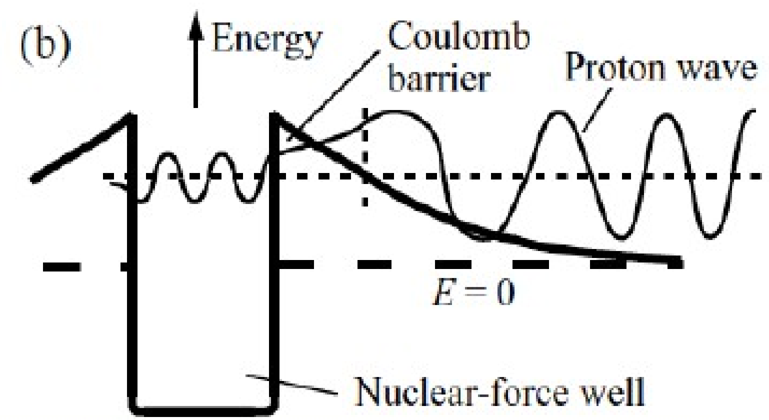
Why is the sky **blue**
(and **red** at sunset)?



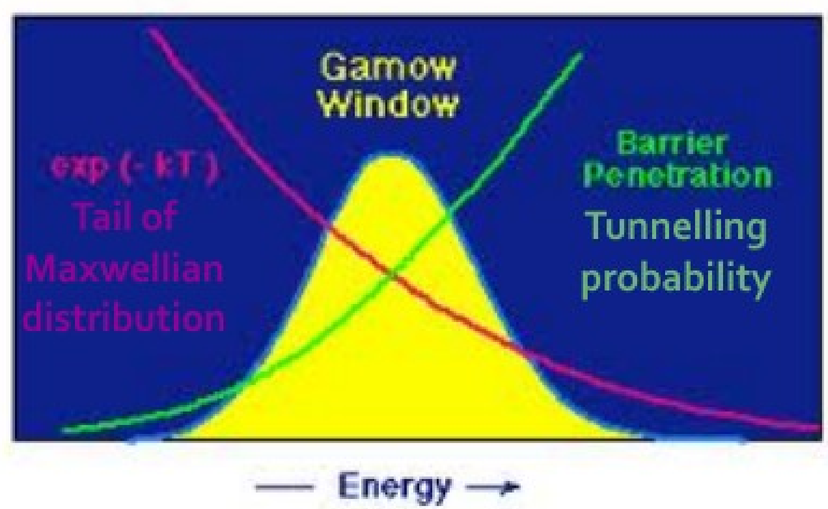
Nuclear reactions

Gamow Window



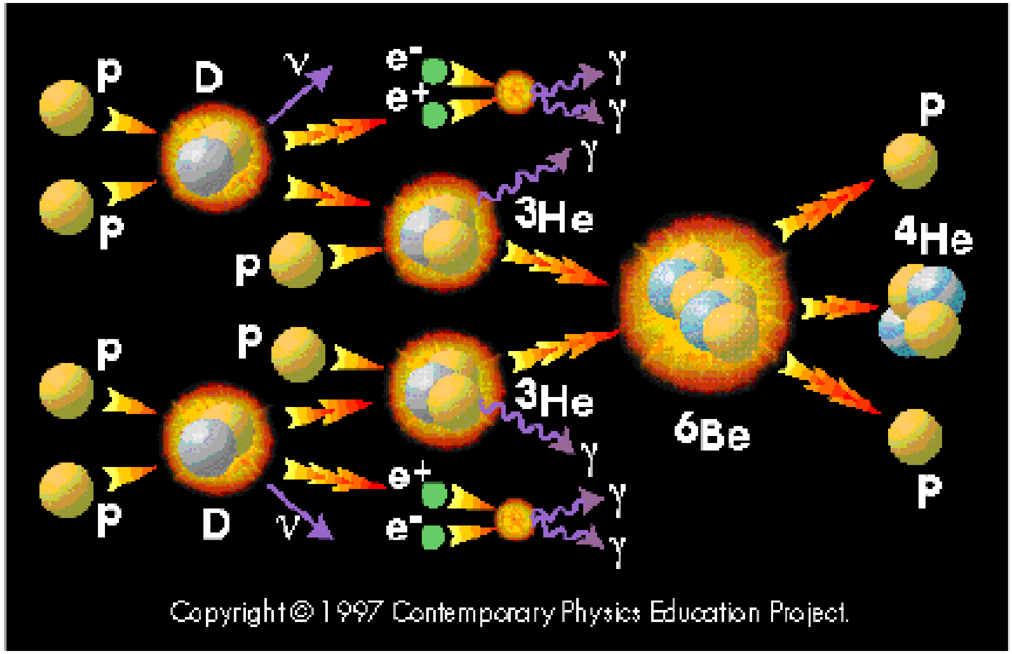


- T > 10[10] K would be required to surmount **Coulomb barrier**
- Quantum effects (**tunnelling**) allow nuclear reactions at much lower temperatures (low, and strongly T-dependent, efficiency)



pp Chain

Most of the nuclear energy from stars is produced by the fusion of four hydrogen atoms into a helium nucleus: the pp chain



$${}_1^1H + {}_1^1H \rightarrow {}_1^2D + e^+ + \nu_e$$

$${}_1^2D + {}_1^1H \rightarrow {}_2^3He + \gamma$$

$${}_2^3He + {}_2^3He \rightarrow {}_2^4He + {}_1^1H + {}_1^1H$$

$$6\,{}^1H^+ \longrightarrow {}^4He^{++} + 2\,{}^1H^+ + 2e^+ + 2\nu + 2\gamma$$

pp Chain

The energy released by the pp chain is simply the mass decrement between the initial and final nuclei

$$6\,{}^{1}H^{+} \longrightarrow {}^{4}He^{++} + 2\,{}^{1}H^{+} + 2e^{+} + 2\nu + 2\gamma$$

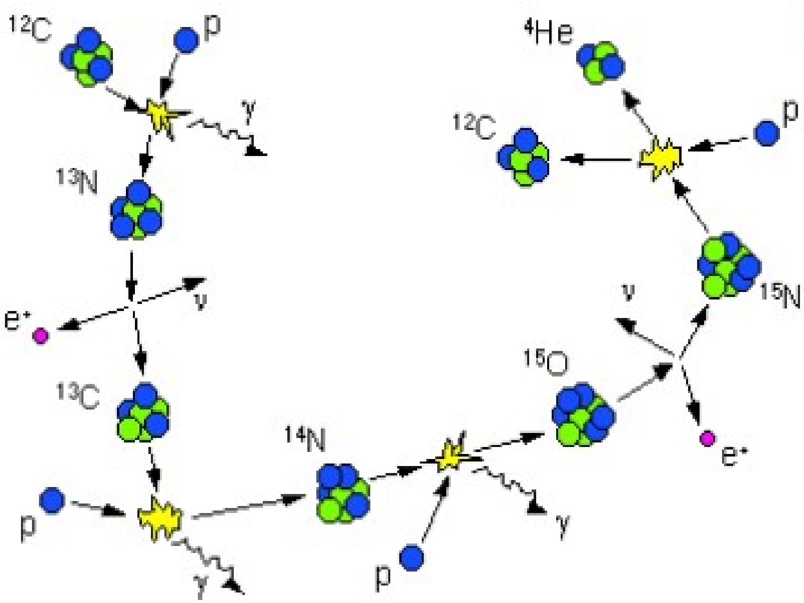
Energy released

Mass difference between initial and final nuclei

$$\begin{aligned} \Delta E &= \Delta m c^2 \\ &= (M_{6H} - M_{2H} - M_{He})c^2 \\ &\sim 26 \text{ MeV} \end{aligned}$$

CNO Chain

The CNO cycle commences once the stellar core temperature reaches 1.4×10^7 K and is the primary source of energy in stars of mass **M > 1.5 M$_\odot$**



Hydrogen in

$$^{12}C + {}^{1}H \longrightarrow {}^{13}N + \gamma$$

$$^{13}N \longrightarrow {}^{13}C + e^{+} + \nu$$

$$^{13}C + {}^{1}H \longrightarrow {}^{14}N + \gamma$$

$$^{14}N + {}^{1}H \longrightarrow {}^{15}O + \gamma$$

$$^{15}O \longrightarrow {}^{15}N + e^{+} + \nu$$

$$^{15}N + {}^{1}H \longrightarrow {}^{12}C + {}^{4}He$$

Helium out

C is only a **catalyst** for the CNO reaction

How much energy is released?

Nuclear reatcions

Many nuclear reactions can occur in stars, with relative efficiencies depending on temperature, density and abundances of chemical elements

⇒ different reactions are dominant in different stages of **stellar evolution**

Nuclear Fuel	Process	Threshold Temperature	Products
H	p-p chain	$\sim 4 \times 10^6$ K	He
H	CNO cycle	15×10^6 K	He
He	3α	100×10^6 K	C, O
C	C + C	600×10^6 K	O, Ne, Na, Mg
O	O + O	1000×10^6 K	Mg, S, P, Si
Si	Disintegration	3000×10^6 K	Co, Fe, Ni

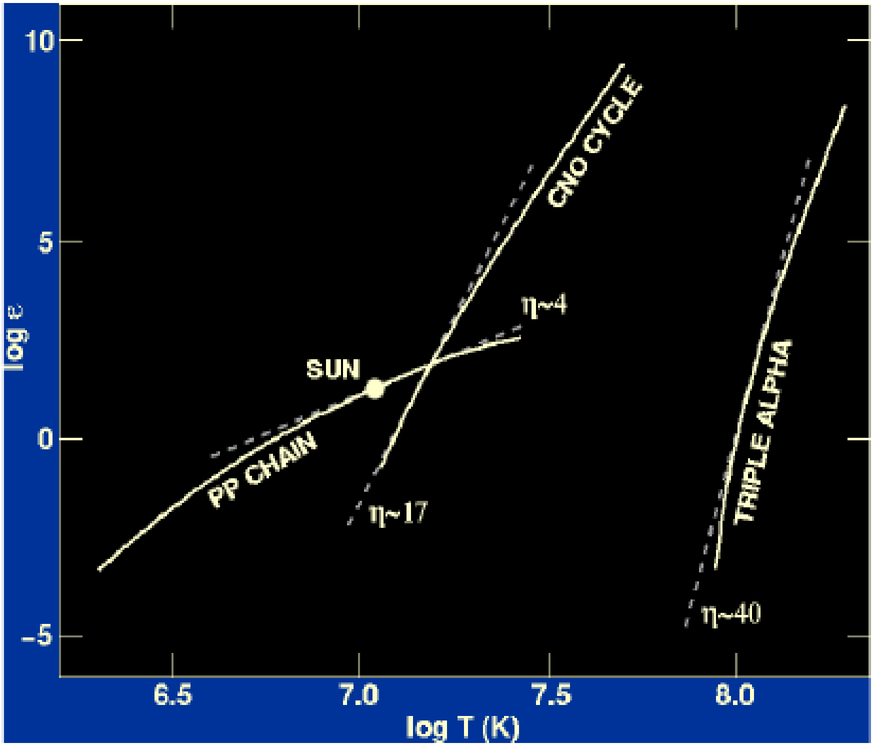
Nuclear reactions

The energy generation rate **ε (energy/mass)** is proportional to the number of interactions per second and strongly depends on temperature:

$$\varepsilon_{PP} \propto \rho X_H^2 T^{4.6}$$

$$\varepsilon_{CNO} \propto \rho X_H X_{CNO} T^{16.7}$$

$$\varepsilon_{3\alpha} \propto \rho^2 T^{40}$$



Neutron capture and beta decay

- Interaction between nuclei and free neutrons (**neutron capture**)
- Neutrons capture by heavy nuclei **is not limited by the Coulomb barrier**, so could proceed at relatively **low temperatures**.
- If enough neutrons available, chain of reactions:

$$\mathbf{I(A,\ Z) + n \rightarrow I_1(A+1, Z)}$$
$$\mathbf{I_1(A+1,\ Z) + n \rightarrow I_2(A+2, Z)}$$
$$\mathbf{I_2(A+2,\ Z) + n \rightarrow I_3(A+3, Z)\quad ...etc}$$

- If a radioactive isotope is formed it will undergo **β-decay**, creating a new element:

$$\mathbf{I_N(A+N,\ Z) \rightarrow J(A+N, Z+1) + e^- + \bar{\nu}_e}$$

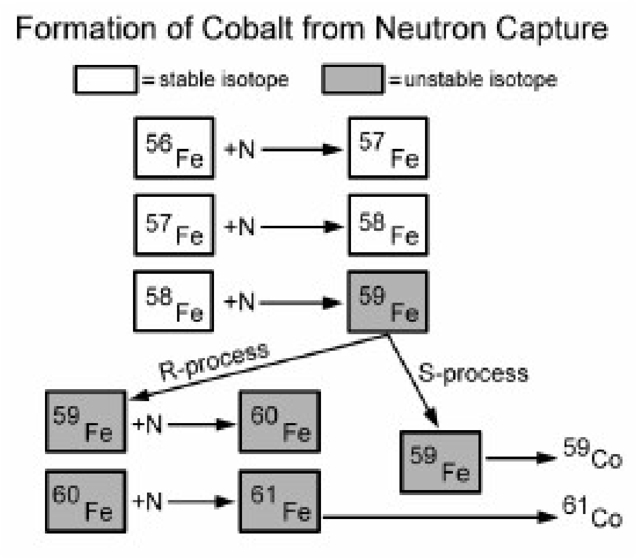
- If new element is stable, it will resume **neutron capture**, otherwise may undergo series of **β-decays**

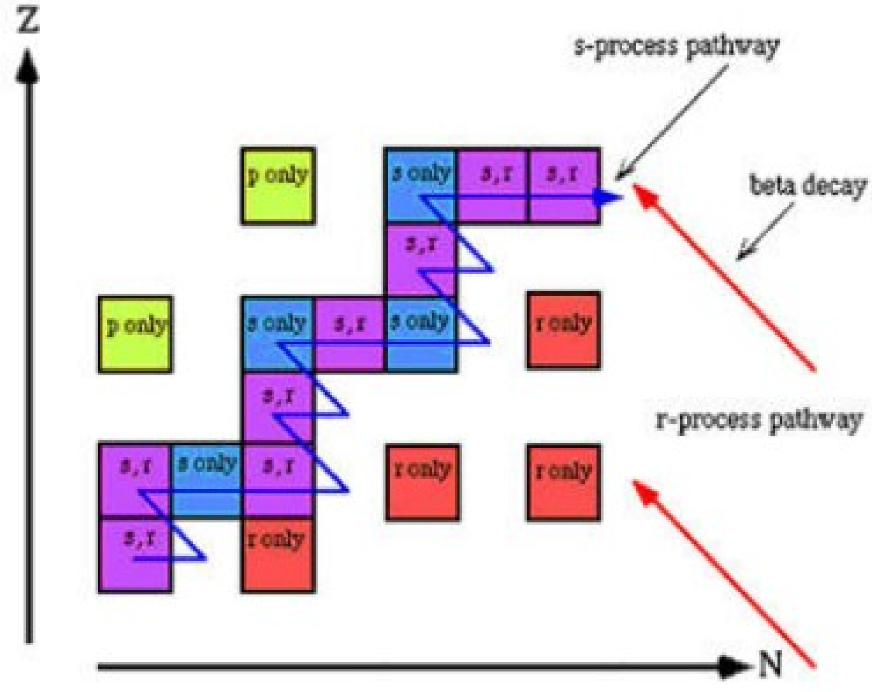
$$\mathbf{J(A+N,\ Z+1) \rightarrow K(A+N, Z+2) + e^- + \bar{\nu}_e}$$
$$\mathbf{K(A+N,\ Z+2) \rightarrow L(A+N, Z+3) + e^- + \bar{\nu}_e}$$

s-process and r-process

Stable nuclei may undergo only neutron captures, unstable ones may undergo both, with the outcome depending on the timescales for the two processes.

Timescales: neutron capture reactions may proceed more ***slowly*** or more ***rapidly*** (if many neutrons are available) than the competing β-decays: ***s-process*** or ***r-process***.





Absorption

Optically thin cloud: $\tau << 1$

- Chances are small that a photon will interact with particle

- Can effectively see right through a cloud

- In the optically thin regime, the amount of extinction (absorption plus scattering) is linearly related to the amount of material: double the amount of gas, double the extinction

→ if we can measure the amount of light absorbed (or emitted) by the gas, we can calculate exactly how much gas there is

Optically thick cloud: $\tau >> 1$

- Certain that a photon will interact many times with particles before it finally escapes from the cloud
- Any photon entering the cloud will have its direction changed many times by collisions, which means that its "output" direction has nothing to do with its "input" direction.

→ ***Cloud is opaque***

- You can't see through an optically thick medium; you can only see light emitted by the very outermost layers.

→ ***you can't observe interior of a star, but only the surface (photosphere)***

- The spectrum of the radiation emitted by optically thick material is a **blackbody**

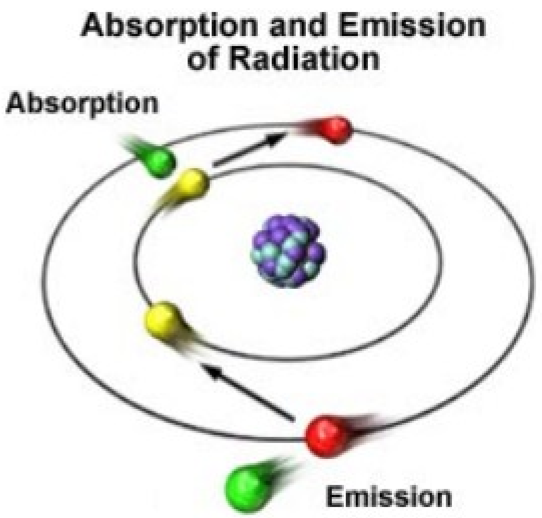
Opacity: $\kappa_\nu=\alpha_\nu/\rho$

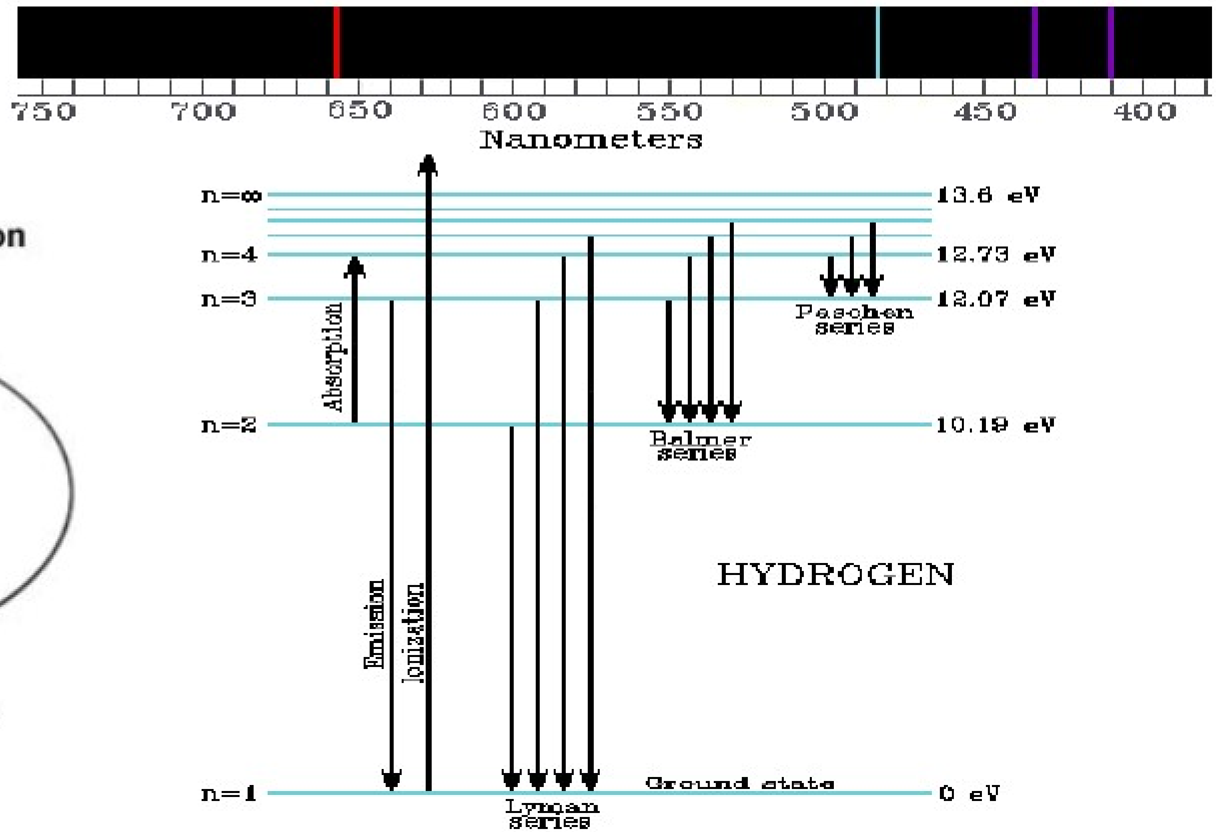
• Opacity in a star is a function of composition and temperature.

• Determined by the details of how photons interact with particles (atoms, ions, free electrons).

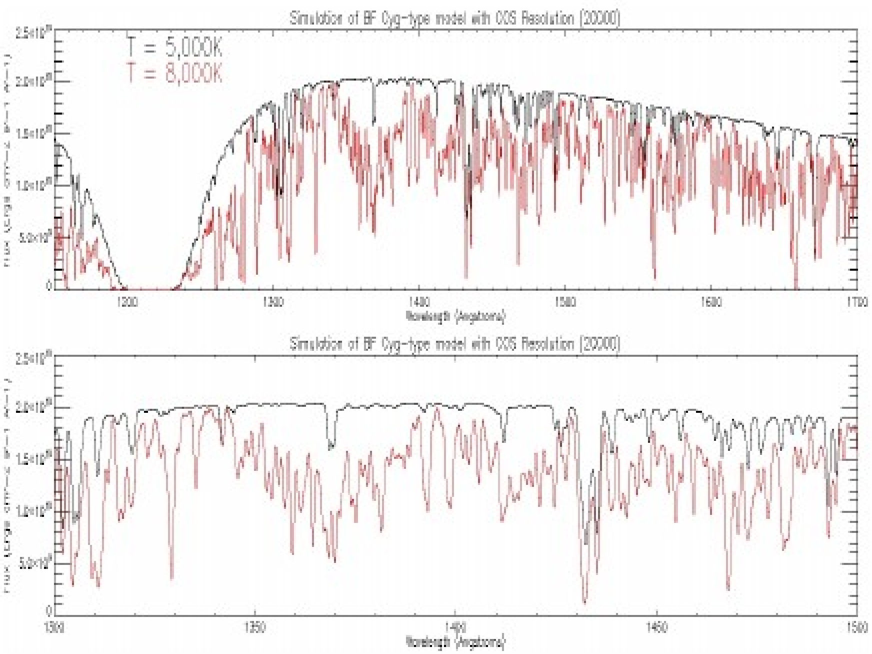
• If the opacity varies slowly with λ it determines the star continuous spectrum (continuum). A rapid variation of opacity with λ produces dark absorption lines in the spectrum.

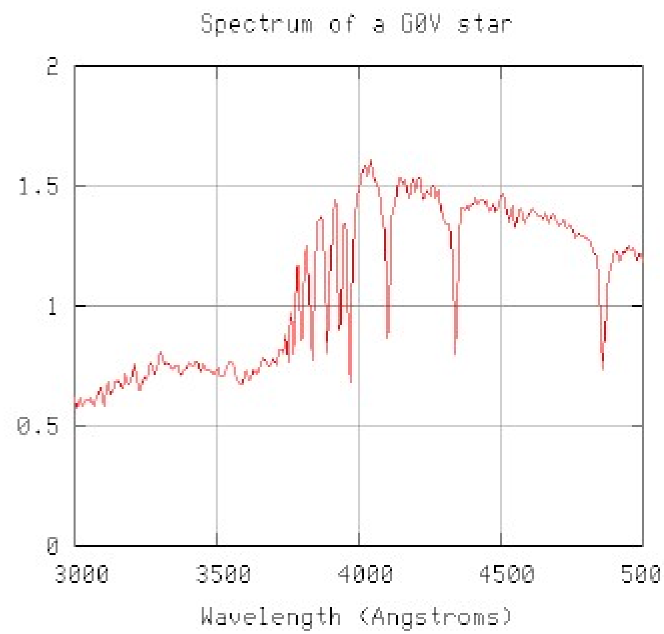
- **Bound-Bound absorption:** Small, except at those discrete wavelengths capable of producing a transition (*absorption lines*)
- **Bound-Free absorption:** *Photoionisation*. Occurs when photon has sufficient energy to ionize atom. The freed e^- can have any energy, thus this is a source of continuum opacity
- **Free-Free absorption:** *Bremsstrahlung*. A free electron absorbs a photon, causing its speed to increase. It is a source of continuum opacity and important at high temperatures (it needs free e^-).
- **Electron scattering:** *Thomson scattering*. A photon is scattered, but not absorbed by a free electron.
- **Dust extinction:** Only important for very cool stellar atmospheres and cold interstellar medium





Structure of the H atom → produces spectral features

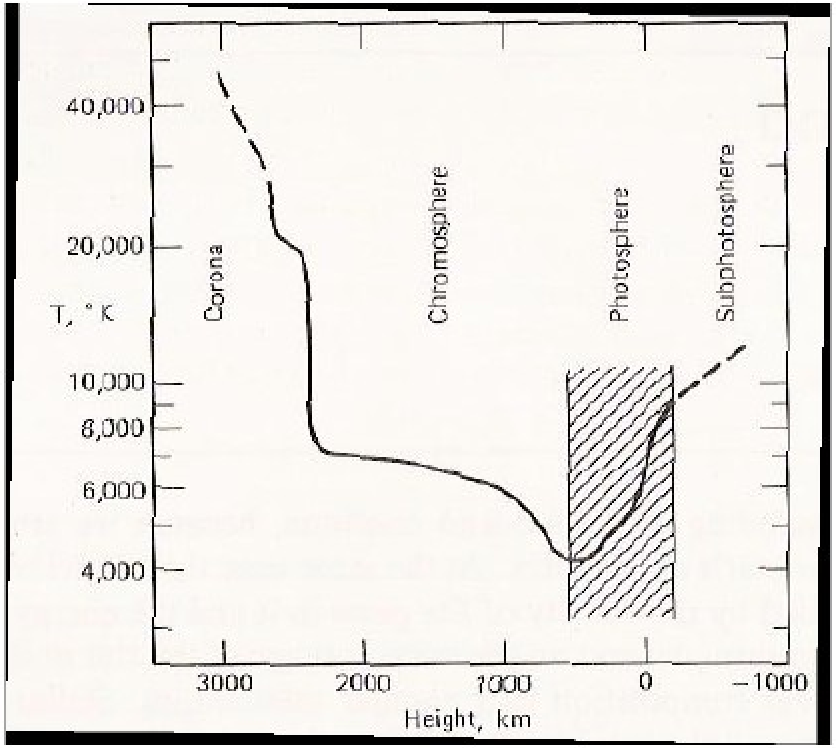




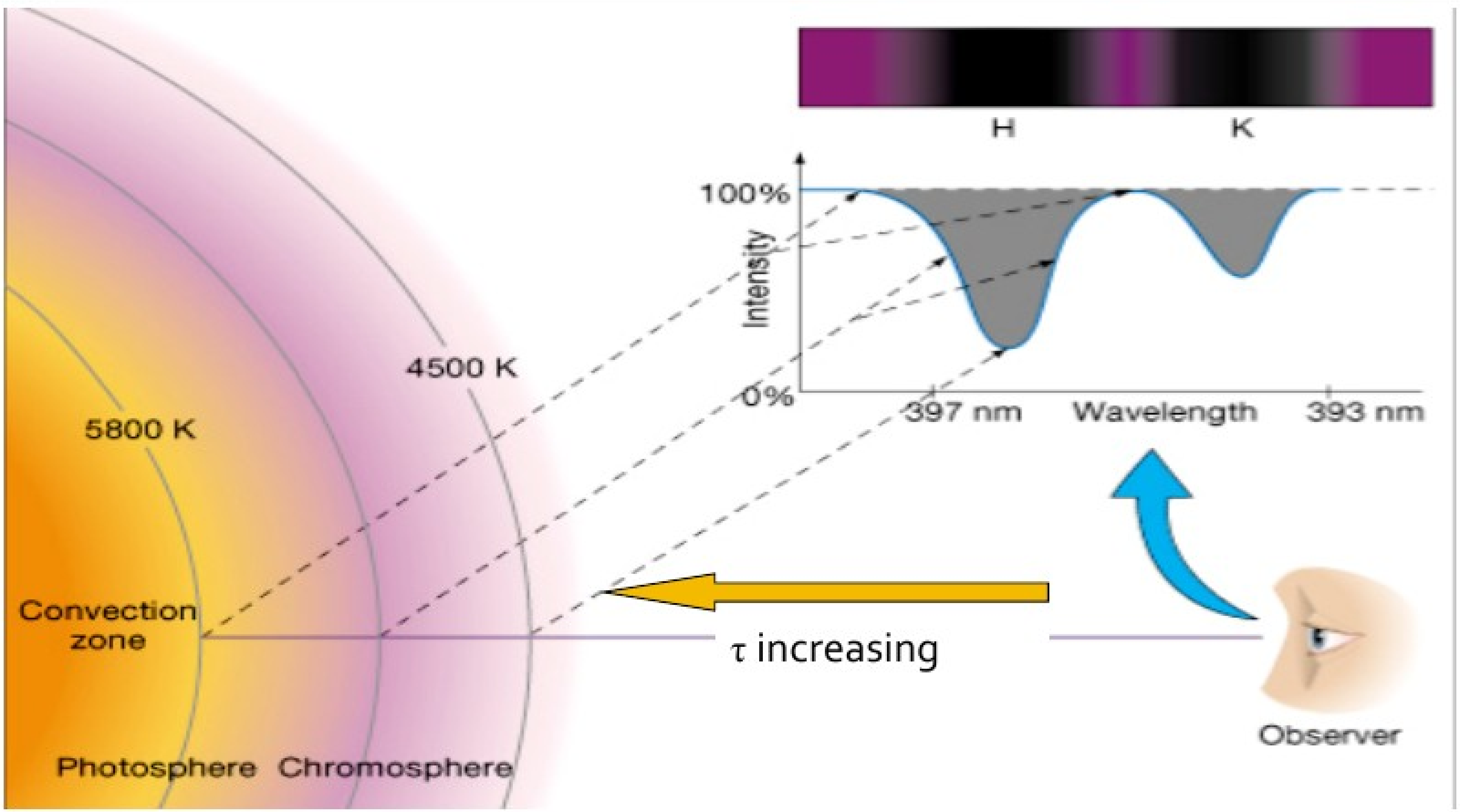
Modelled opacity in the UV due to gas at 5,000K (black) and 8,000K (red). The opacities are due to lines, mostly HI, FeII, SiII, NI, OI, MgII

Balmer series bound-bound transitions (note the Balmer edge → continuous, so bound-free)

- The lower the optical depth, the deeper into the star we see
- For weak lines (lower optical depth) the deeper the line formation region
- For strong lines (higher optical depth), the shallower the line formation region

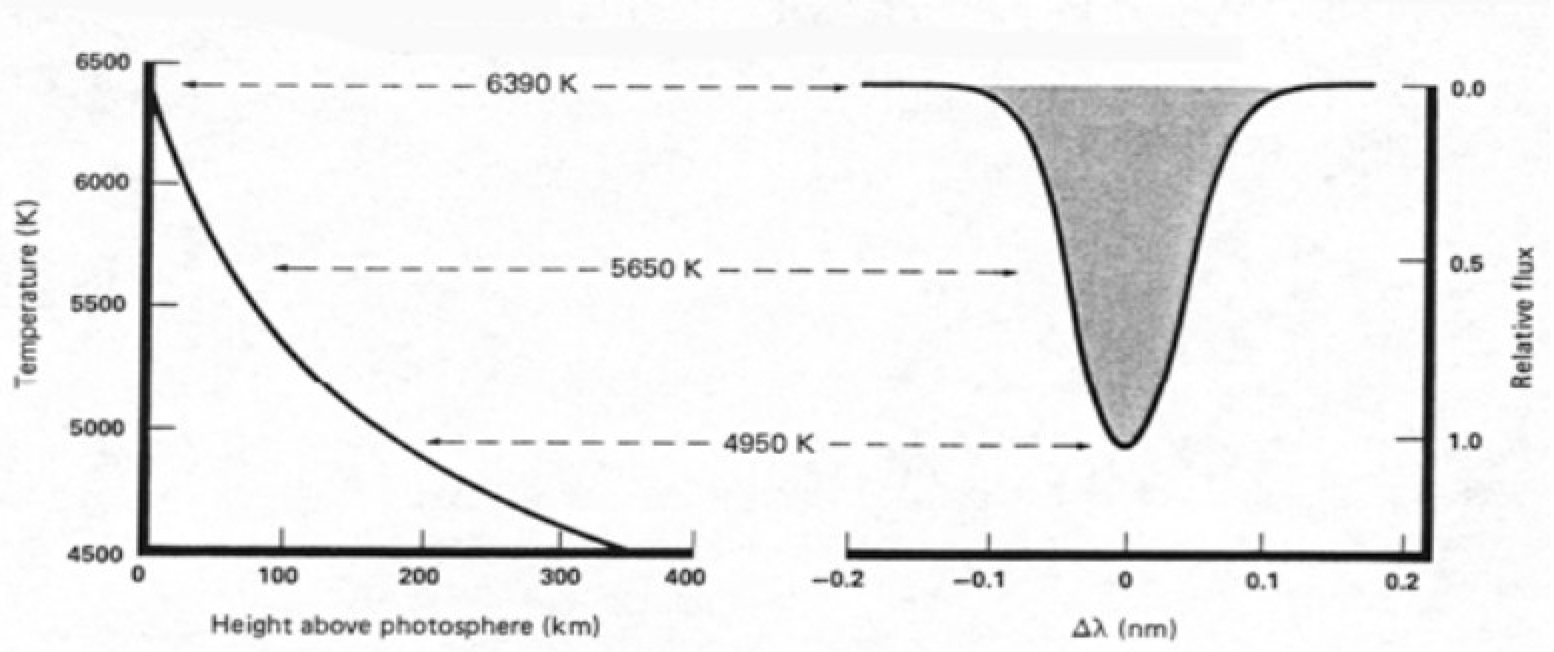


Temperature structure of solar atmosphere

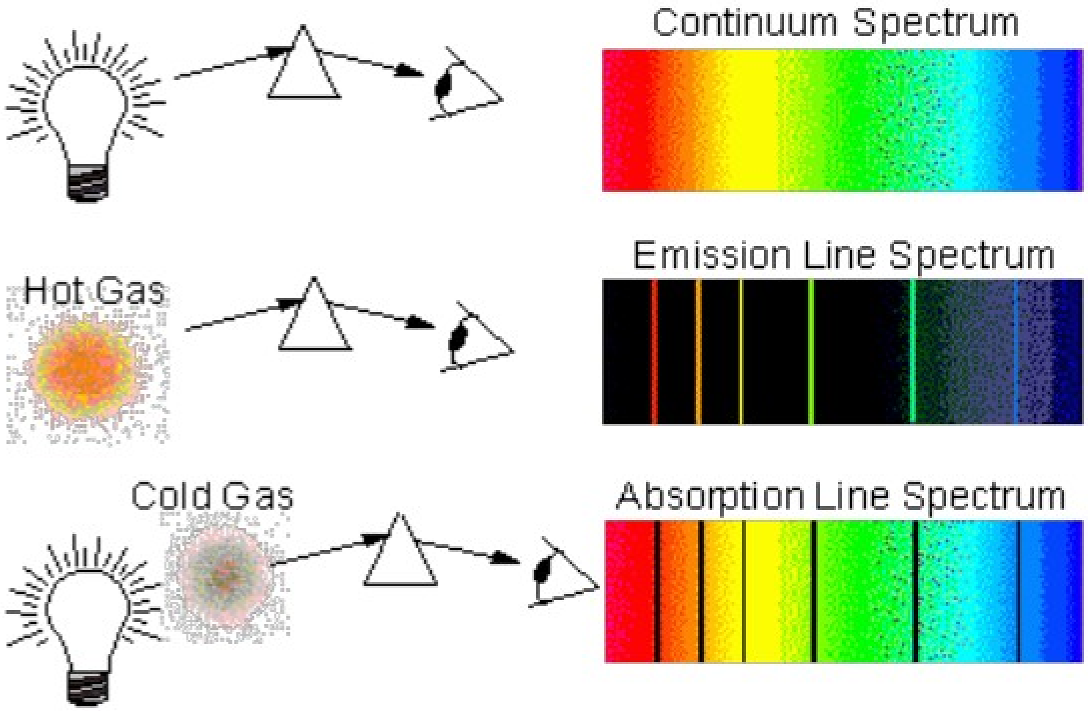


Formation of absorption lines on the Sun

- Formation of absorption features can also be understood in terms of the temperature of the local source function decreasing towards the line centre



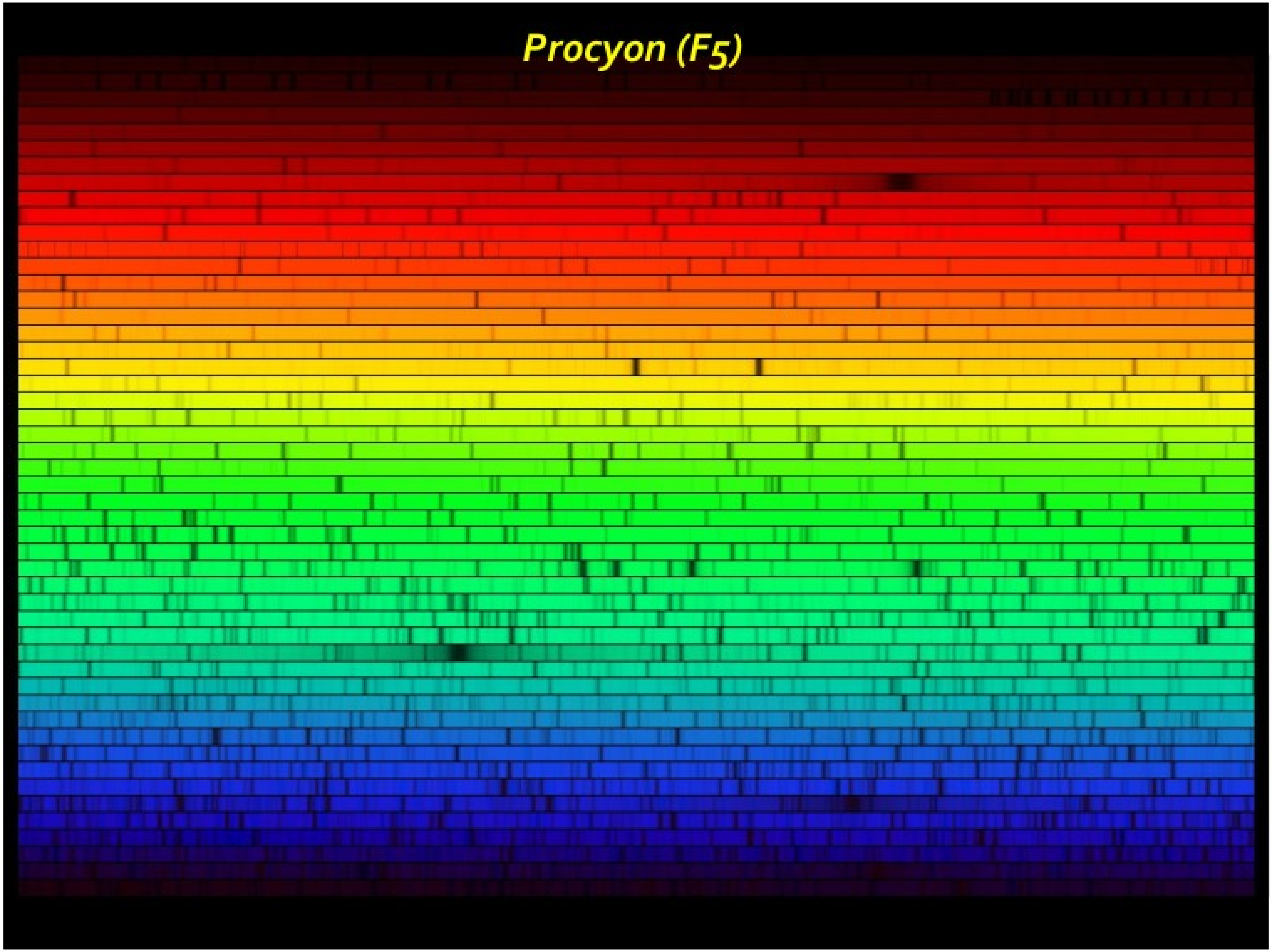
Stellar spectra

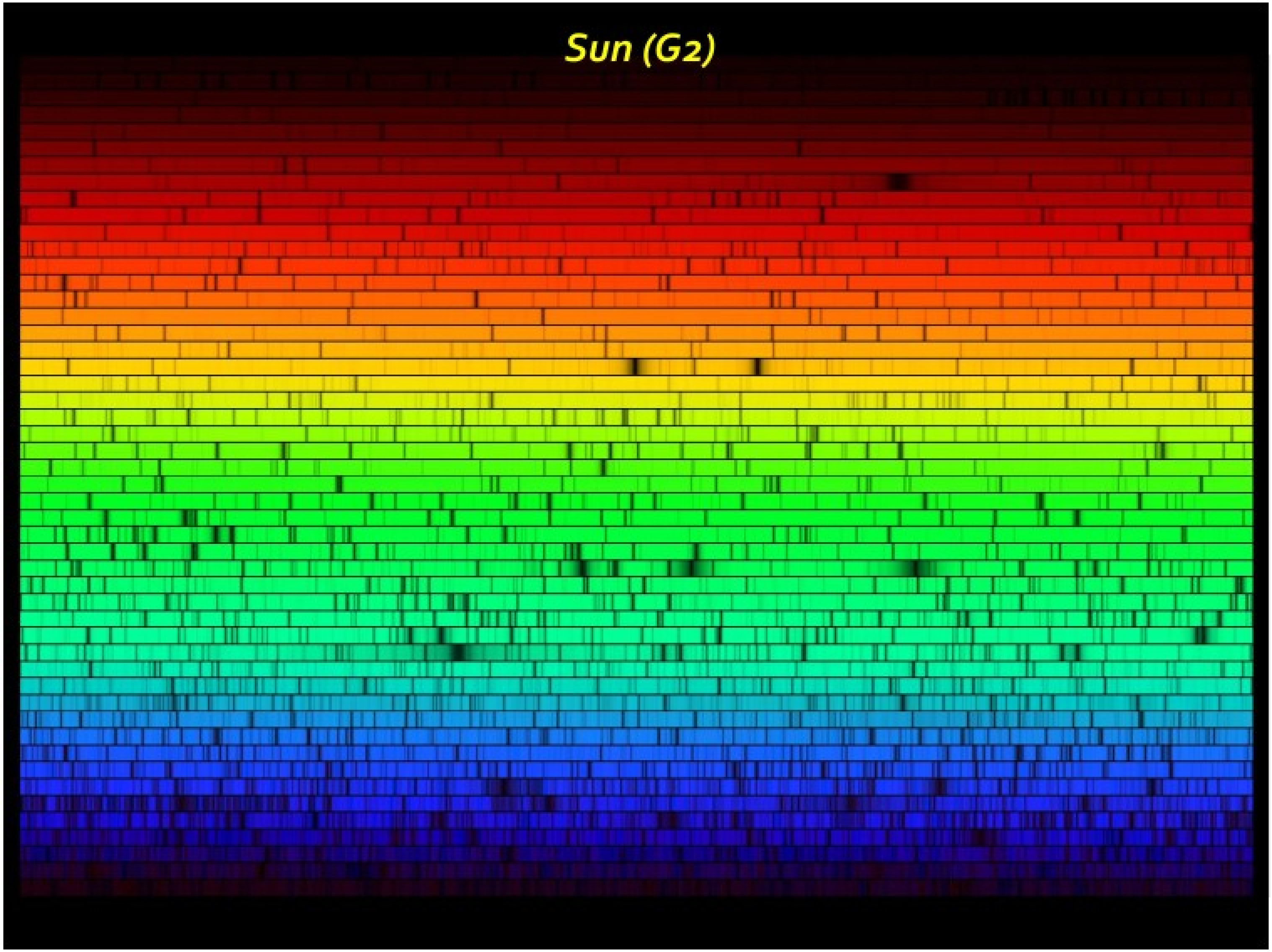


- ***Stellar spectra?***

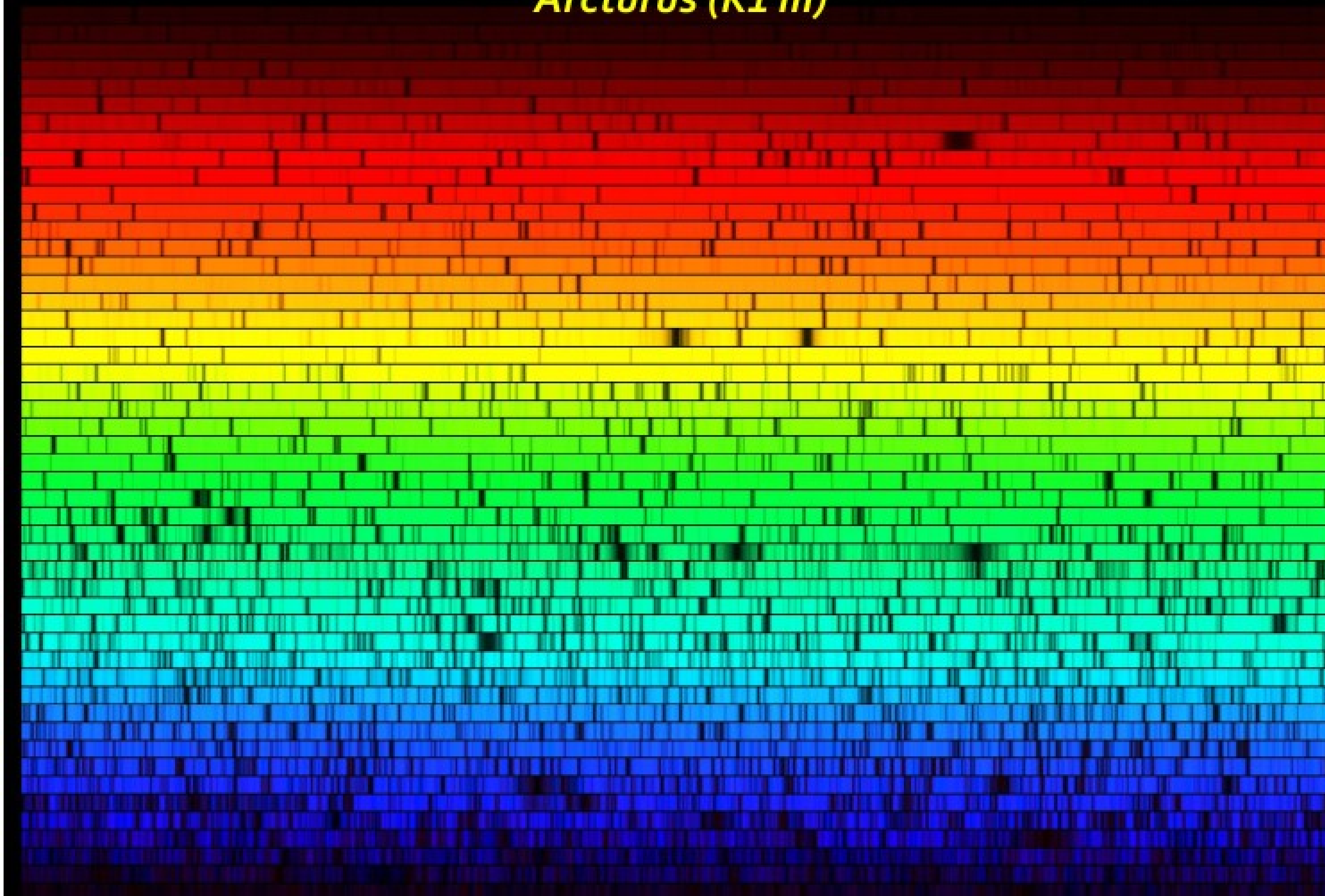
Based on their absorption lines (T indicators) ⇒ spectral types: from warm to cool

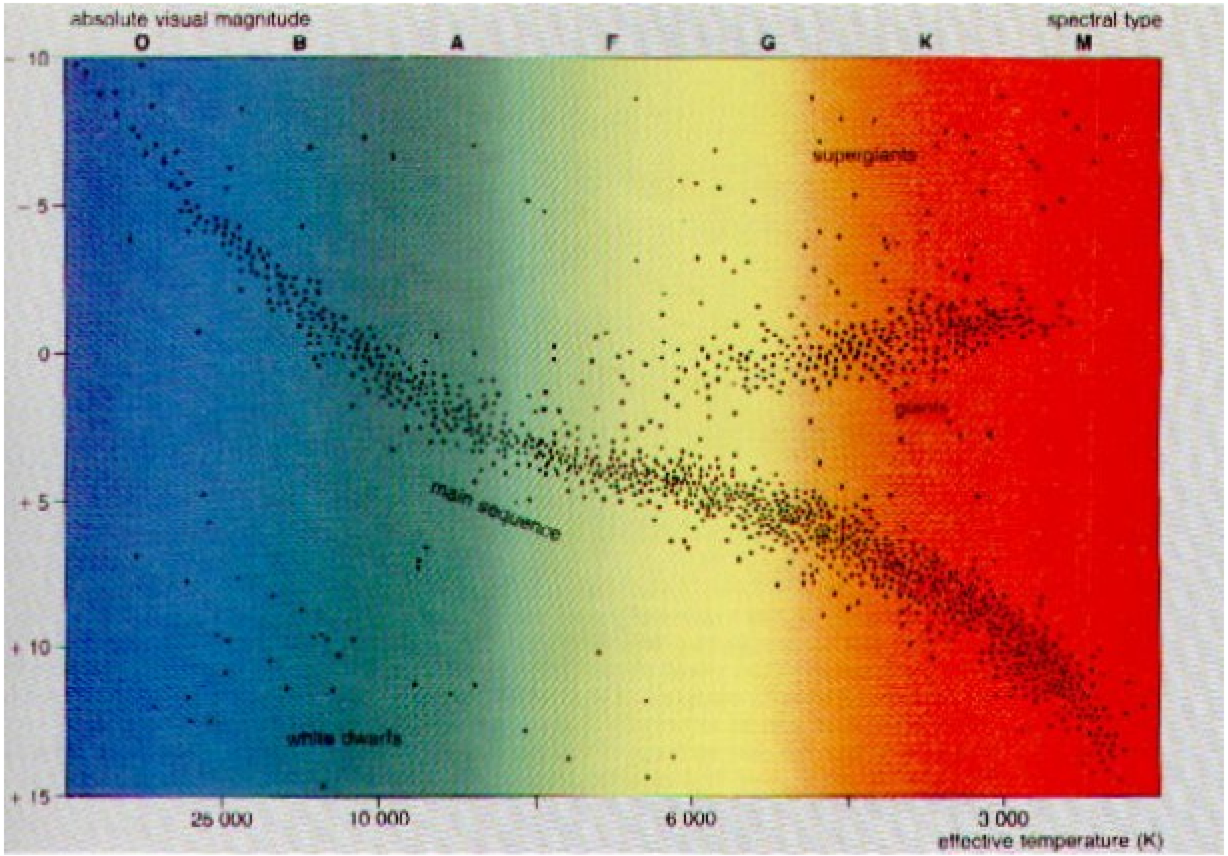
"**O**h **B**e **A** **F**ine **G**irl **K**iss **M**e"


Procyon (F5)


Sun (G2)

Arcturus (K1 III)





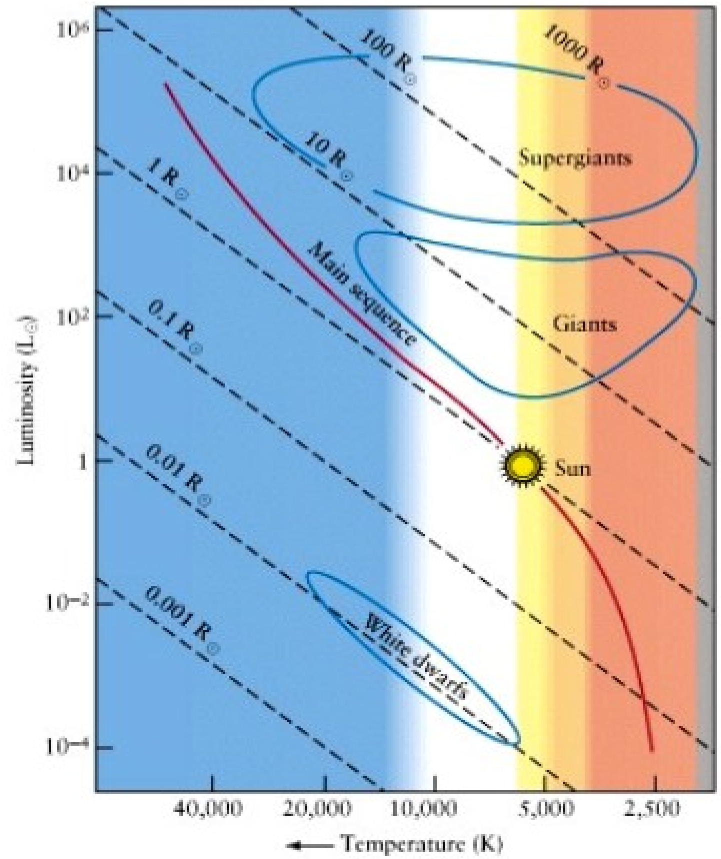
absolute visual magnitude
spectral type
O
B
A
F
G
K
M
− 10
− 5
0
+ 5
+ 10
+ 15
supergiants
giants
main sequence
white dwarfs
25 000
10 000
6 000
3 000
effective temperature (K)

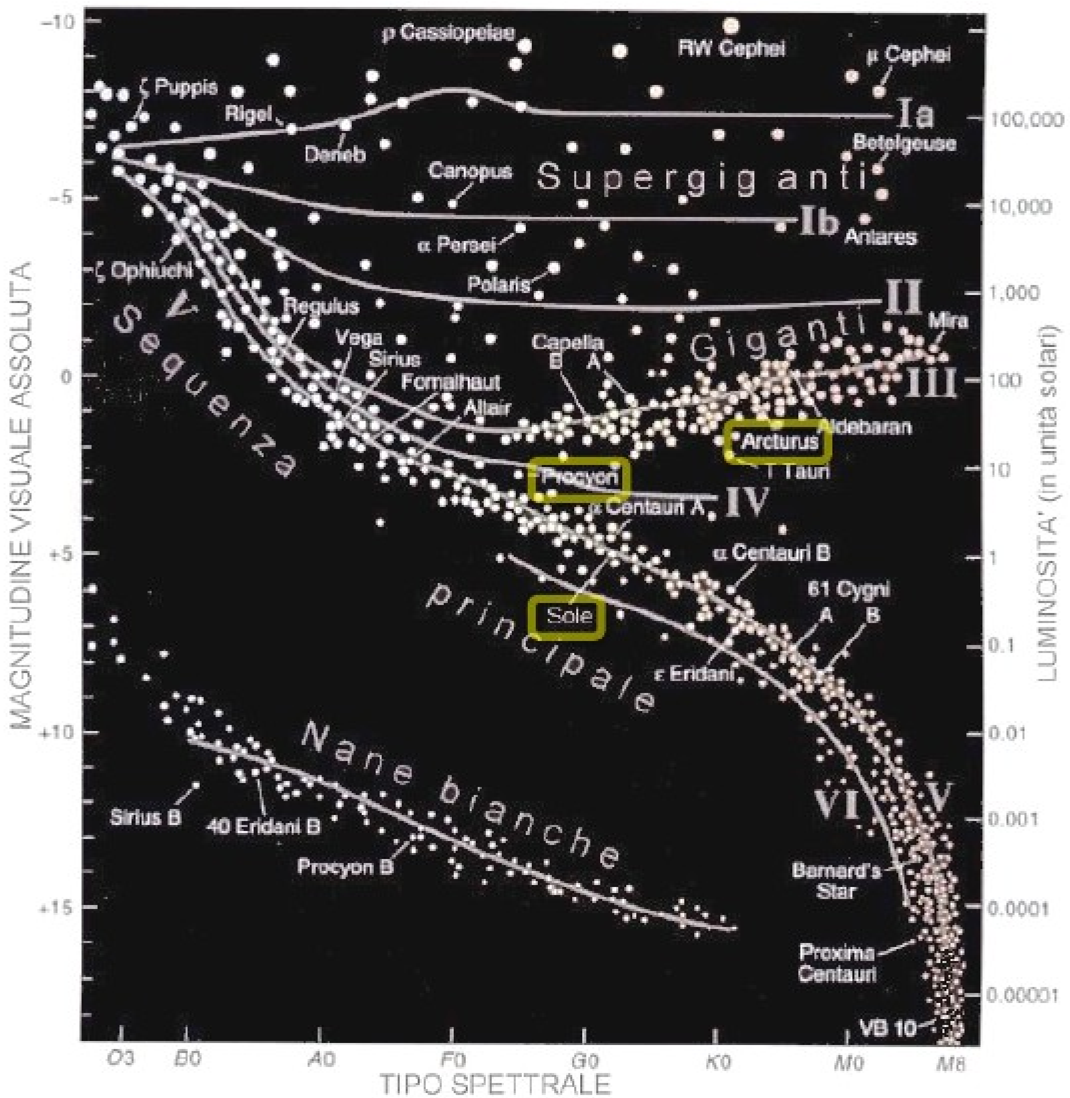
$L \propto T^4$

Why the Main Sequence is not a straight line?

$$L = 4\pi R^2 \sigma T^4$$

defines lines of **constant radius**





MAGNITUDINE VISUALE ASSOLUTA
LUMINOSITA' (in unita solari)
TIPO SPETTRALE
O3
B0
A0
F0
G0
K0
M0
M8
-10
-5
0
+5
+10
+15
100,000
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
ρ Cassiopeiae
RW Cephei
μ Cephei
ζ Puppis
Rigel
Deneb
Canopus
Supergiganti
Betelgeuse
Antares
α Persei
Polaris
ζ Ophiuchi
Regulus
Vega
Sirius
Fomalhaut
Altair
Capella
B A
Giganti
Mira
Aldebaran
Arcturus
Tauri
Procyon
α Centauri A
α Centauri B
61 Cygni
A B
Sole
ε Eridani
Sequenza principale
Nane bianche
Sirius B
40 Eridani B
Procyon B
Barnard's Star
Proxima Centauri
VB 10
Ia
Ib
II
III
IV
V
VI