Lecture 13:
Stellar evolution –
The formation of stars

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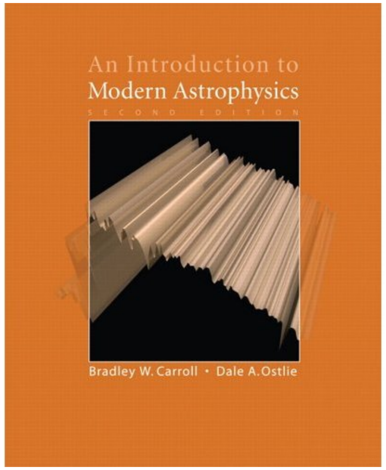
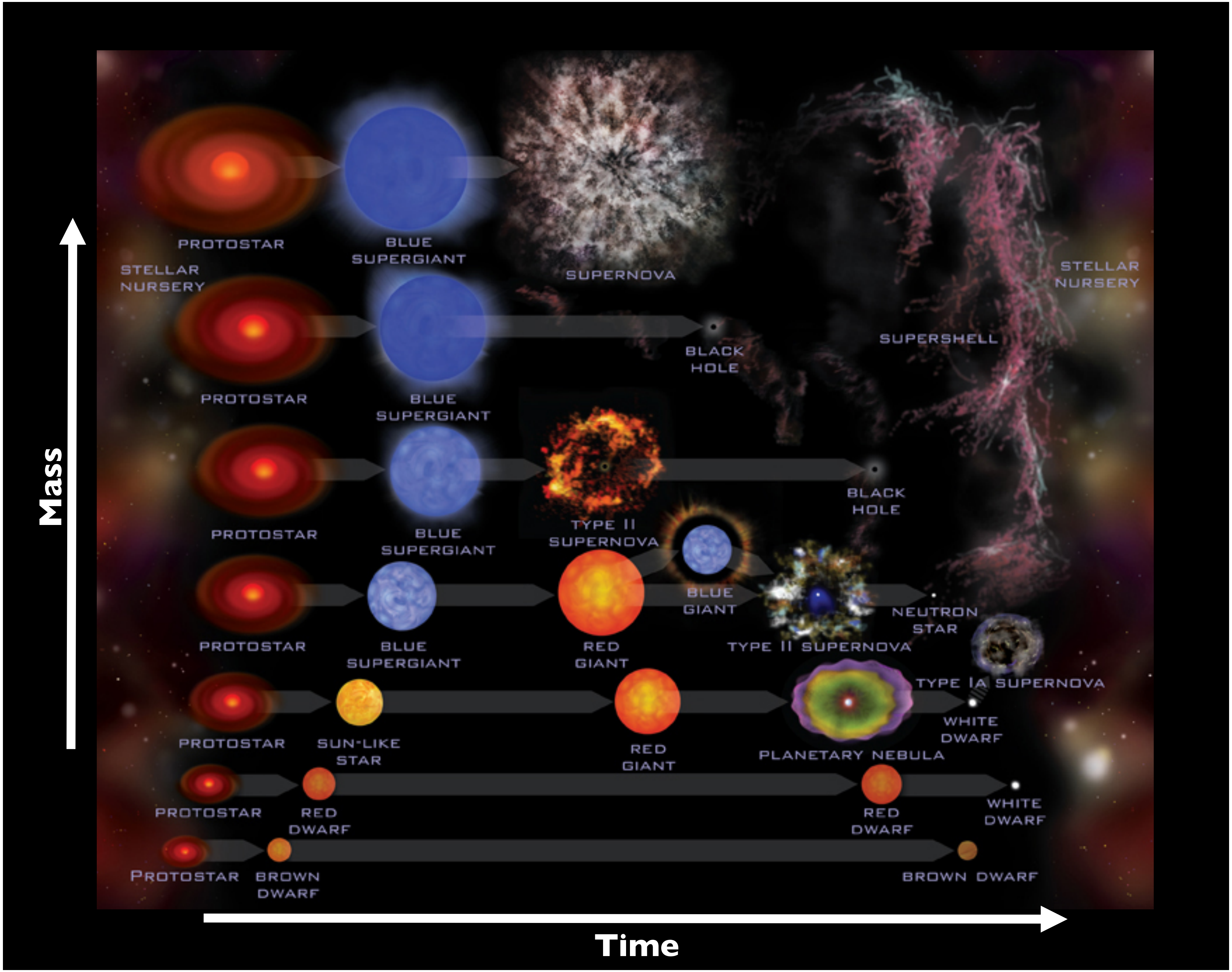
Ogden Centre West 119

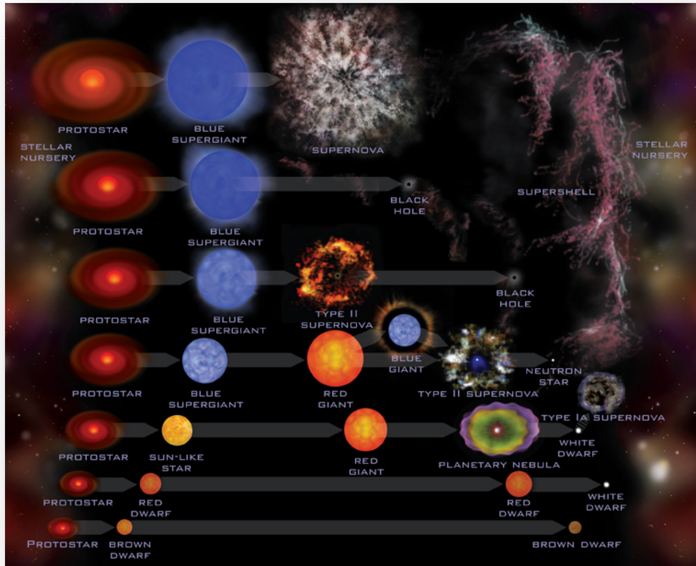
Chapter 12 of Carroll and Ostlie





Mass
Time
PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

Stellar Evolution



(1) Formation of stars (lecture 13)
- **Jeans mass and cloud collapse**
- **properties of protostars**

(2) Evolution of stars (lecture 14)
- **drivers of stellar evolution**

(3) Evolution of massive stars (lecture 15)
- **core collapse and supernovae**

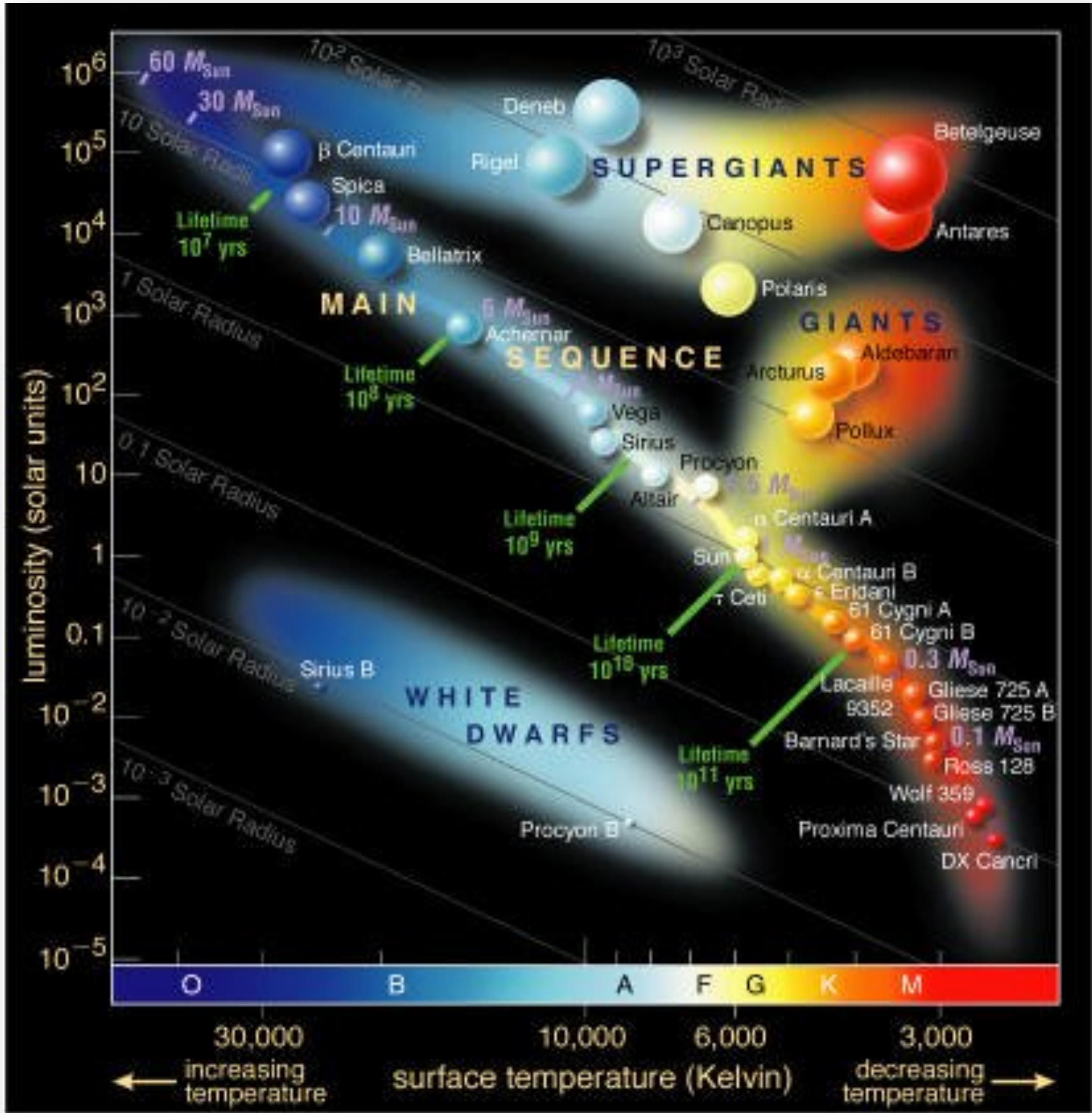
(4) Degenerate stars: white dwarfs (lecture 16)
- **properties of white dwarfs**
- **electron degeneracy pressure**

(5) Degenerate stars: neutron stars and black holes (lecture 17)
- **properties of neutron stars, pulsars, and black holes**

These lectures use a lot of the concepts learnt earlier in the course

Hertzsprung-Russell: global perspective

Stellar evolution - moving off the main sequence. Here we will find forming stars, rapidly evolving stars, and the degenerate remnants of stars.



Aims of lecture

Key concept: gravitational collapse of a gas cloud

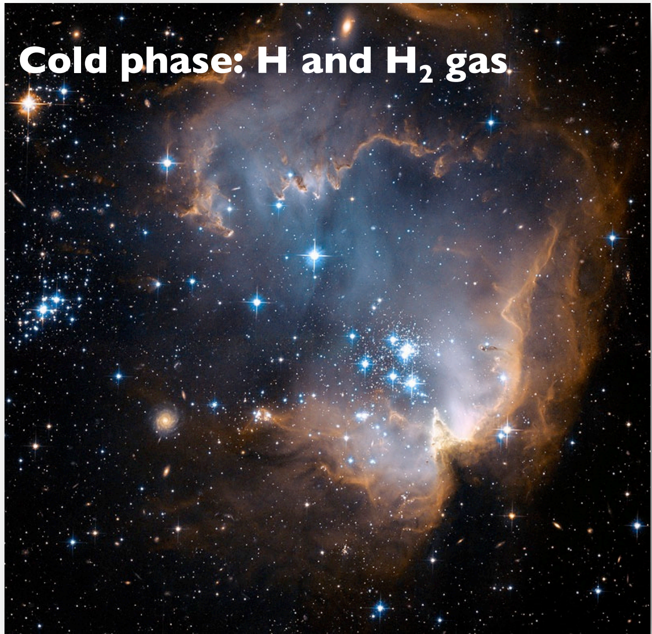
Aims:

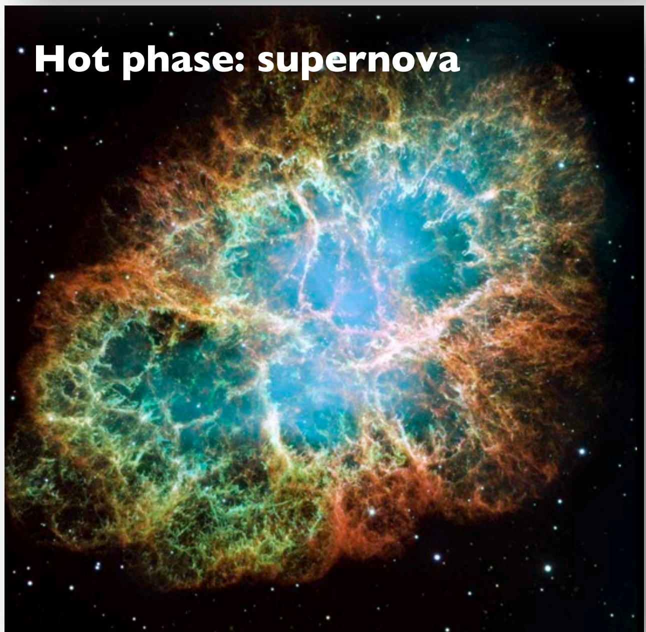
- Understand the basic physics behind cloud collapse and fragmentation: optically thin and optically thick collapse
- Understand the paths that protostars take on the HR diagram ("Hayashi tracks") and be able to describe the basic properties of protostars
- Be able to define the term "Jeans mass" and show that it is given by:

$$M_J \cong \left(\frac{5kT}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

Condition required for gravitational collapse

Interstellar medium: star-formation ingredients





The interstellar medium (ISM) is the material in galaxies not within stars/ planets: it is a mixture of gas (~99% by mass) of different phases and dust

The ISM plays an important role in star formation. There are three phases in the ISM:

Cold dense phase ($T<300$ K), comprised of neutral and molecular hydrogen.

Warm phase ($T\sim1{,}000$-$10{,}000$ K), neutral and ionised gas.

Dynamic hot phase ($T>1{,}000{,}000$ K) gas shock-heated by supernovae.

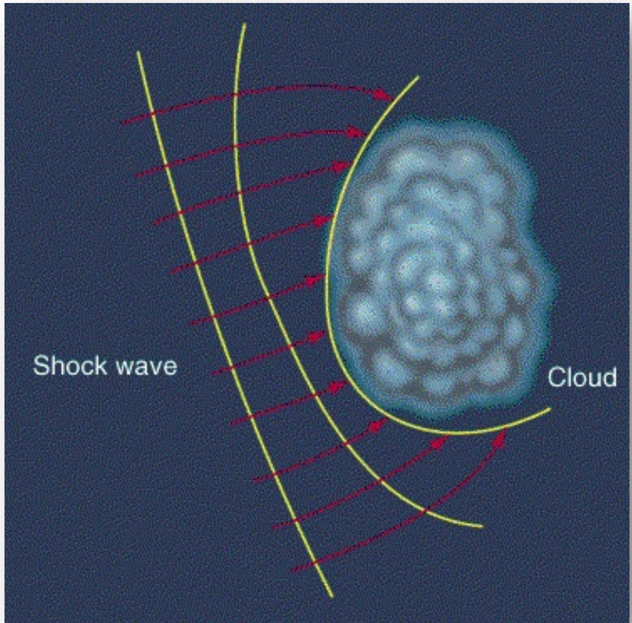
In addition to dust: silicate & carbon particles

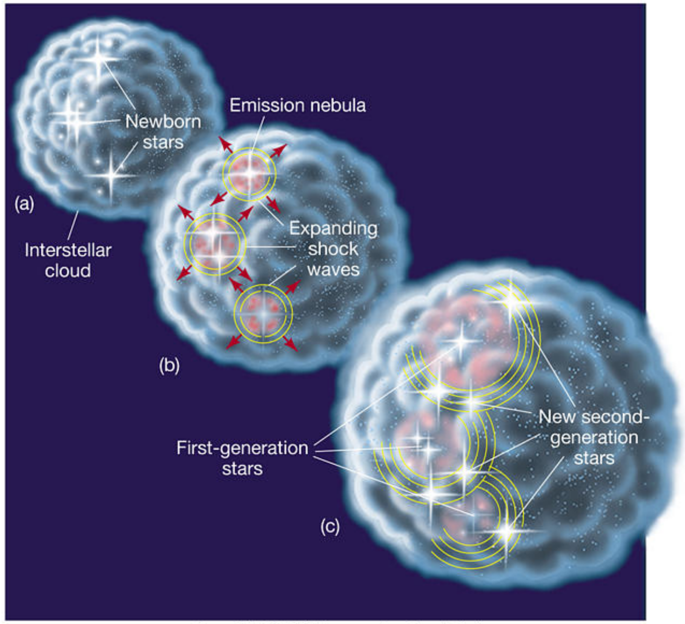
We will explore how stars form from the gas in the ISM

The battle for star formation

Star formation: this occurs when a mass of gas exceeds a critical density and begins to collapse. Typical ISM densities are ~1 atom cm^{-3} while the critical density is typically >10 times higher. While collapsing the cloud will fragment (when it exceeds a local critical density) into smaller clouds. Fragmentation will continue until protostars are formed.

Battle for star formation: between gravitational pressure and thermal pressure, which requires low temperatures and high densities for gravity to win. Often a strong external pressure is required to initiate the collapse: shocks from supernovae, the spiral arms of the galaxy, or from hot young stars





Gravitational collapse of a molecular cloud

Assuming a spherical cloud of constant density, the gravitational potential energy (from lecture 5) is approximately:

$$U \sim -\frac{3}{5}\frac{GM_c^2}{R_c}$$

While the clouds kinetic energy is:

$$K = \frac{3}{2}NkT \qquad \text{where} \qquad N = \frac{M_c}{\mu m_H}$$

On the basis of the virial theorem the condition for collapse ($2K < |U|$) is:

$$\frac{3M_c kT}{\mu m_H} < \frac{3}{5}\frac{GM_c^2}{R_c}$$

Since we have assumed constant density, we can replace R_c with the initial density of the cloud ρ_0:

$$R_c = \left(\frac{3M_c}{4\pi\rho_0}\right)^{1/3}$$

Gravitational collapse of a molecular cloud

Substituting back into the original equation we can solve for the minimum mass required for spontaneous collapse. This condition is known as the Jeans criterion and is given as:

$M_c > M_J$ where

$$M_J \cong \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

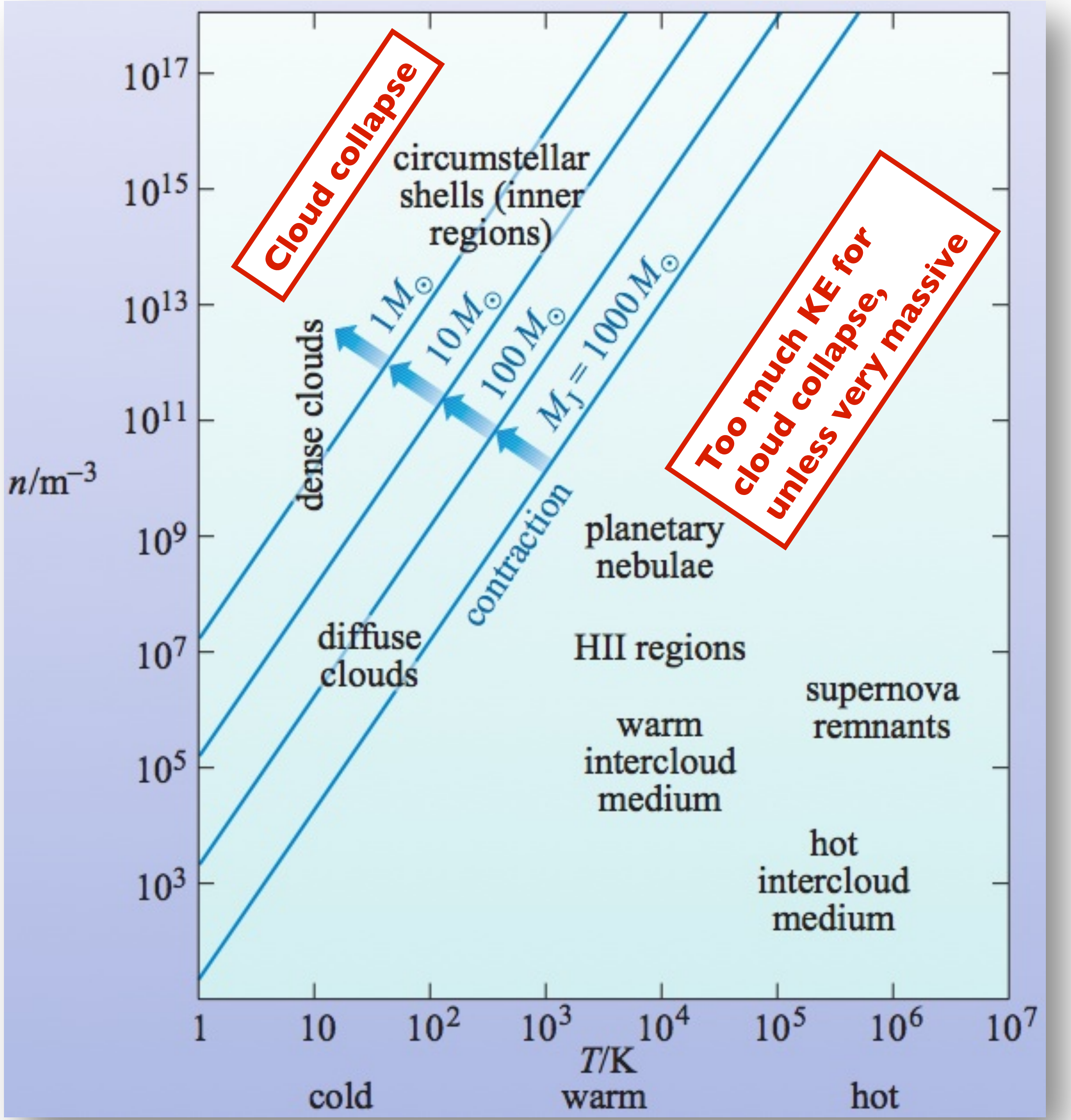
which is called the **Jeans mass** **Equation 25**

The Jeans mass is the <u>minimum mass for instability.</u>

What are the main factors that dictate the Jeans mass?
In which ISM gas phase is a gas cloud likely to collapse?

Note, the Jeans mass derivation does not take account of external gas pressure from the surrounding ISM (see section 12.2 of CO book) or the presence of magnetic fields.

Allowed range of parameter space for collapse



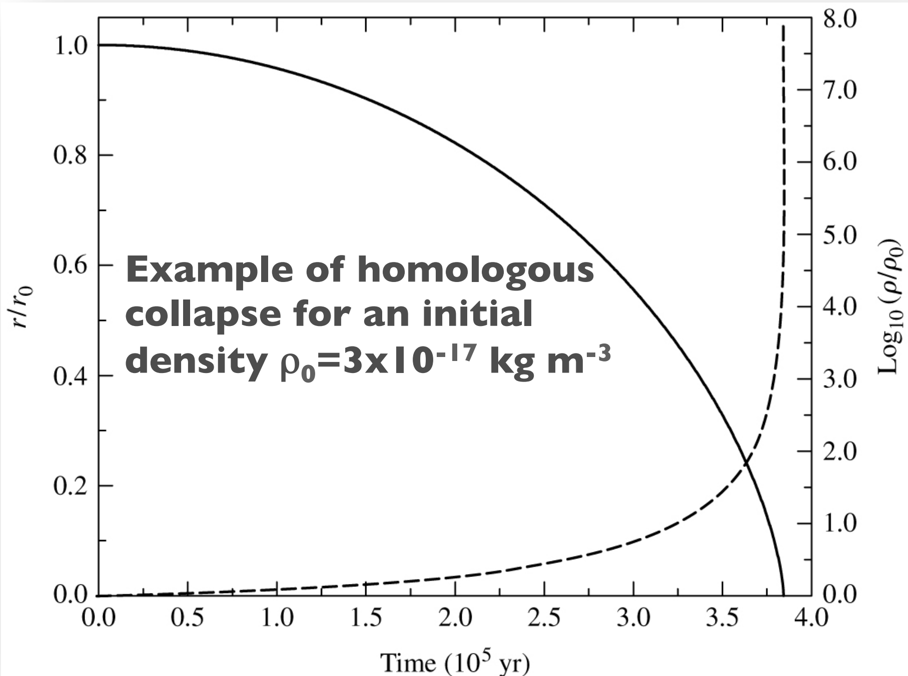
Initial free-fall gravitational collapse

The initial phase of the gravitational collapse is likely to be in free fall (i.e., internal pressure unimportant and temperature remains broadly constant). The free-fall time is:

$$t_{ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2}$$

The cloud will be optically thin (lecture 9) therefore radiation from the collapse can escape so temperature does not increase

The free-fall timescale does not depend on the radius, it is scale independent (homologous). Free-fall collapse is reasonable for the initial stages but not for later stages when the cloud becomes optically thick to radiation, causing the temperature to increase and the collapse to slow (due to an increase in the internal pressure).



The gas cloud may initially be >1000 solar masses

However, it probably won't collapse to just a single object: why not?

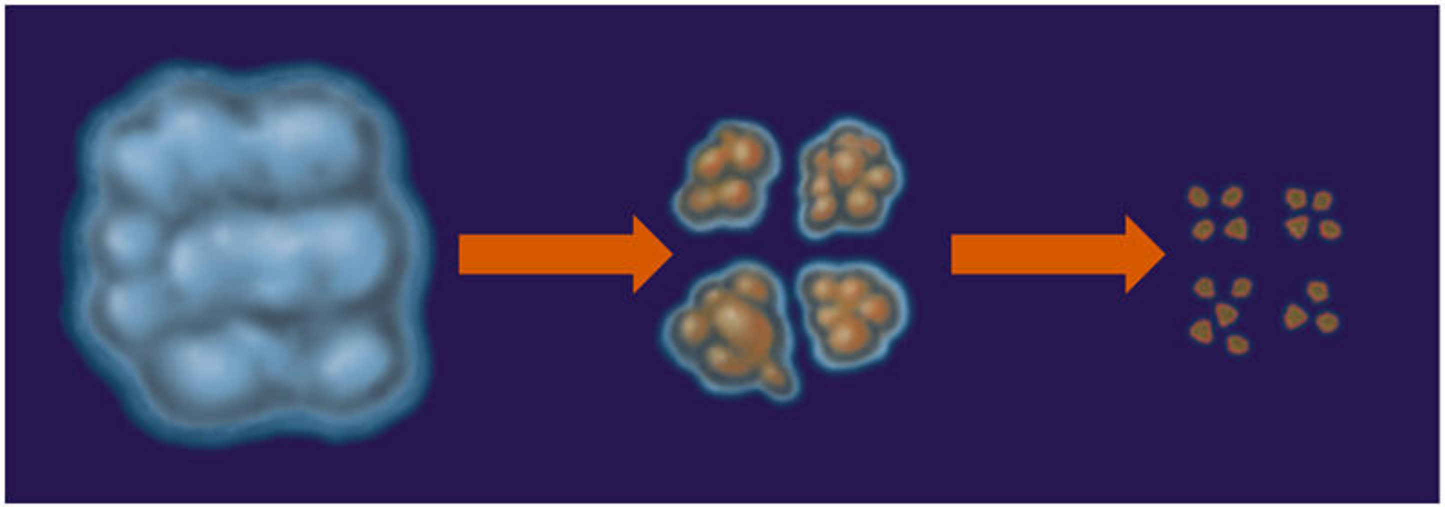
Cloud fragmentation: early stage of protostars

As the cloud collapses in free fall it will **fragment** as individual regions exceed the local Jeans mass; i.e., the density of the cloud will increase during collapse. Note also that the cloud will be inhomogeneous and so not a constant density throughout and hence why we talk about a "local Jeans mass". For example, the density may increase by several orders of magnitude without any significant temperature increase.

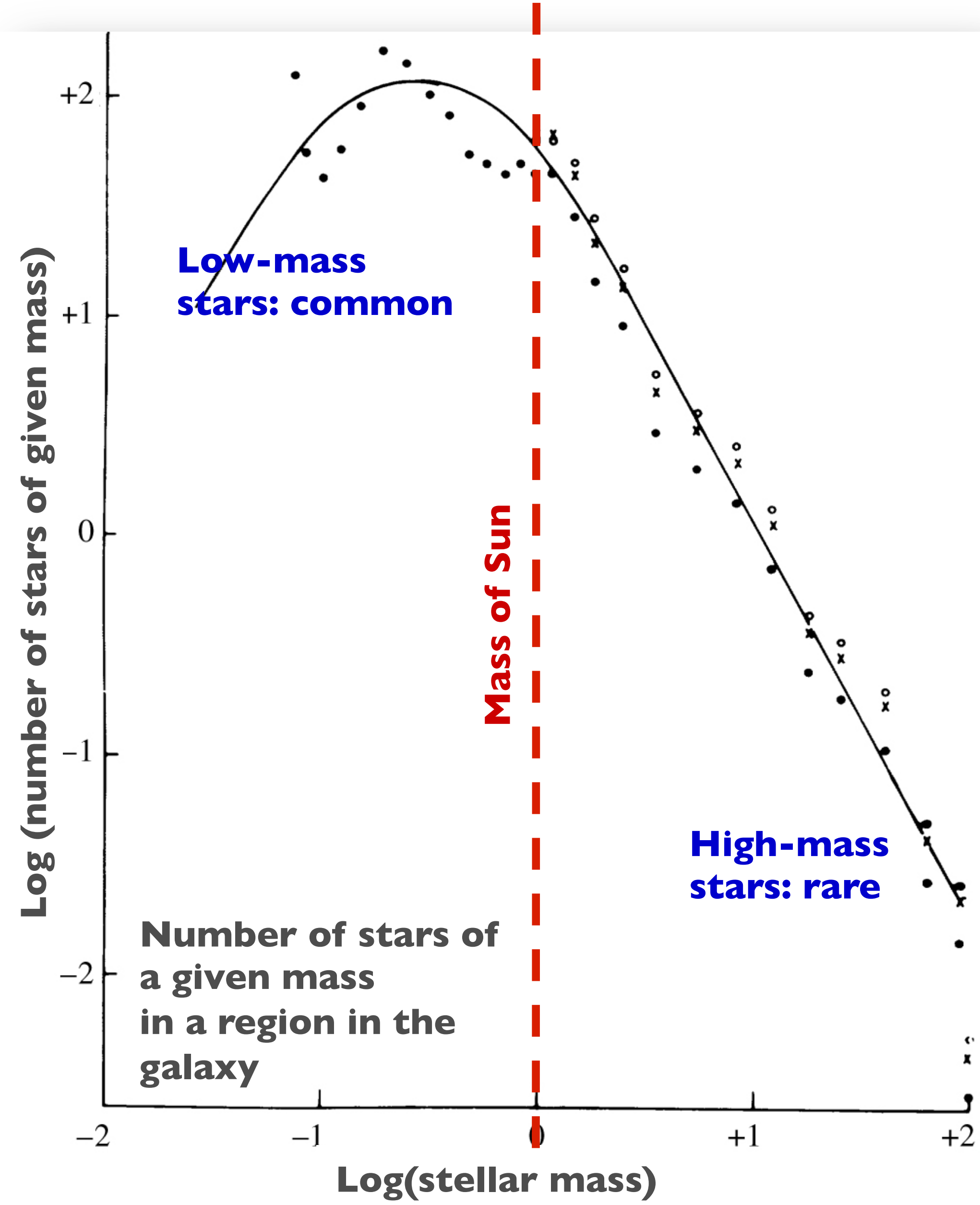
How much will the Jeans mass change for a change in density of 4 orders of magnitude (for no change in temperature)?

As the density increases the cloud will start to become optically thick to radiation – free-fall collapse is no longer valid since the temperature will rise with density. A point is reached where the internal pressure prevents further rapid collapse and this provides a lower limit to the masses of the cloud fragments (**~0.01-0.1 solar masses**).

Recall optically thin and optically thick (opacity) from lecture 9



Initial mass function in the Milky Way

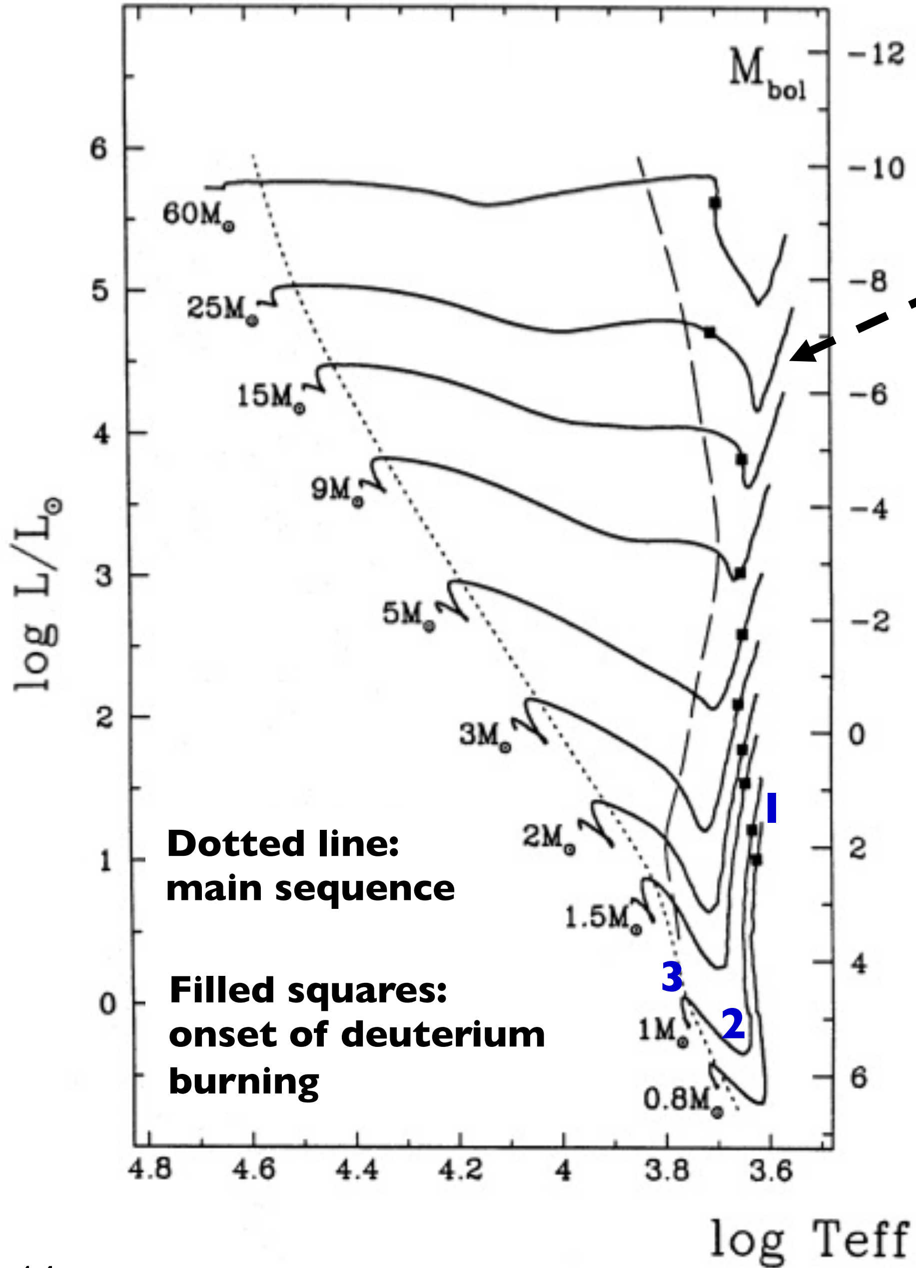


Evidence of this fragmentation process is found from the space density of stars of a given mass in the Milky Way, often called the initial mass function or the "birth function"

This is the number of stars that form as a function of the mass of the star

We will now explore what physically goes on when protostars form from the gas cloud

Hayashi tracks: protostar evolution



The curves are called **Hayashi tracks** – they are the tracks protostars follow on the HR diagram until the core temperature becomes high enough for nuclear fusion to occur and they join the main sequence.

Initial mass	Contraction time
$60M_\odot$	0.0282
25	0.0708
15	0.117
9	0.288
5	1.15
3	7.24
2	23.4
1.5	35.4
1	38.9
0.8	68.4

Contraction times onto the main sequence (in Myrs above) are similar to the Kelvin-Helmholtz time (recall lecture 5)

- What does this tell us about the physical processes of protostar evolution?

- What can we tell about the radii of protostars from these tracks?

Hayashi tracks: protostar evolution

Details of the pre-main sequence evolution of a 1 solar mass star

From point 1-2: during the initial stage the protostar is undergoing gravitational collapse. During this stage the protostar is completely convective due to its high opacity. Some nuclear reactions can occur, specifically:

$${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + \gamma \qquad \text{(deuterium burning; early stage of PP chain)}$$

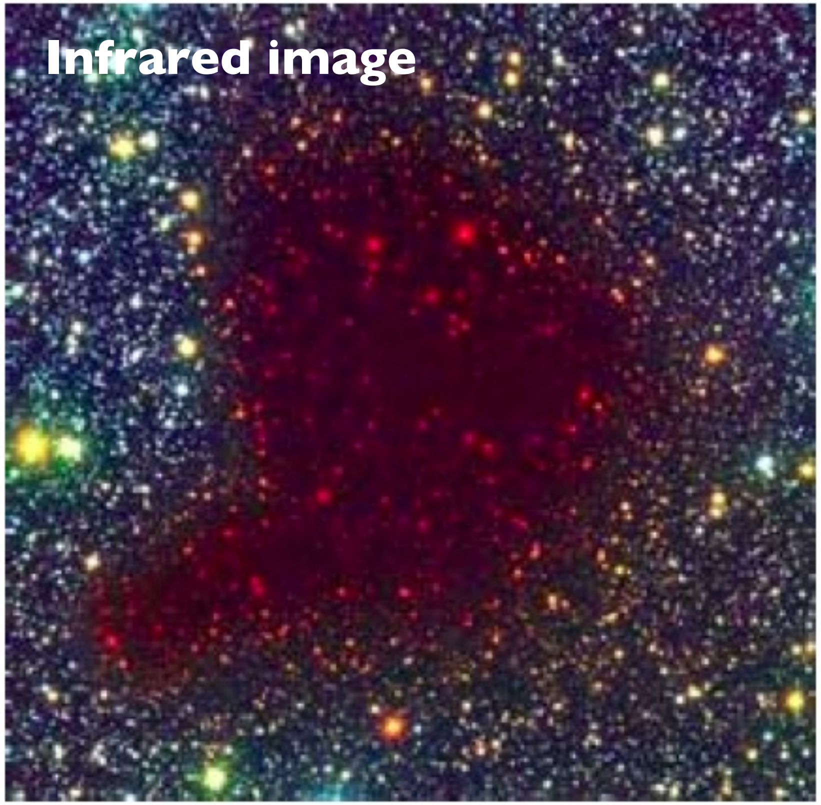
This reaction is favoured because it has a high probability of occurring at low temperatures. However, ${}^{2}_{1}H$ isn't very abundant, so the reactions only slightly slow the rate of collapse.

From point 2-3: as the central temperature rises (due to the gravitational collapse), increasing ionization decreases the opacity, and a radiative core develops. The radiative core allows energy to escape into the convective envelope and as the star is still shrinking, T_{eff} rises. Some nuclear fusion occurs and the luminosity increases.

By point 3: the temperature in the core is high enough for nuclear reactions to start properly (PP chain) – it has a few expansions and contractions to undergo as the core settles, and then the star joins the main sequence and reaches stardom!

For massive stars, the temperature quickly becomes hot enough for the CNO cycle to establish itself.

Challenges in identifying protostars



Two images of a protostar (dark patch) but taken at different wavelengths: why do we not see the background stars in the centre of the optical image?