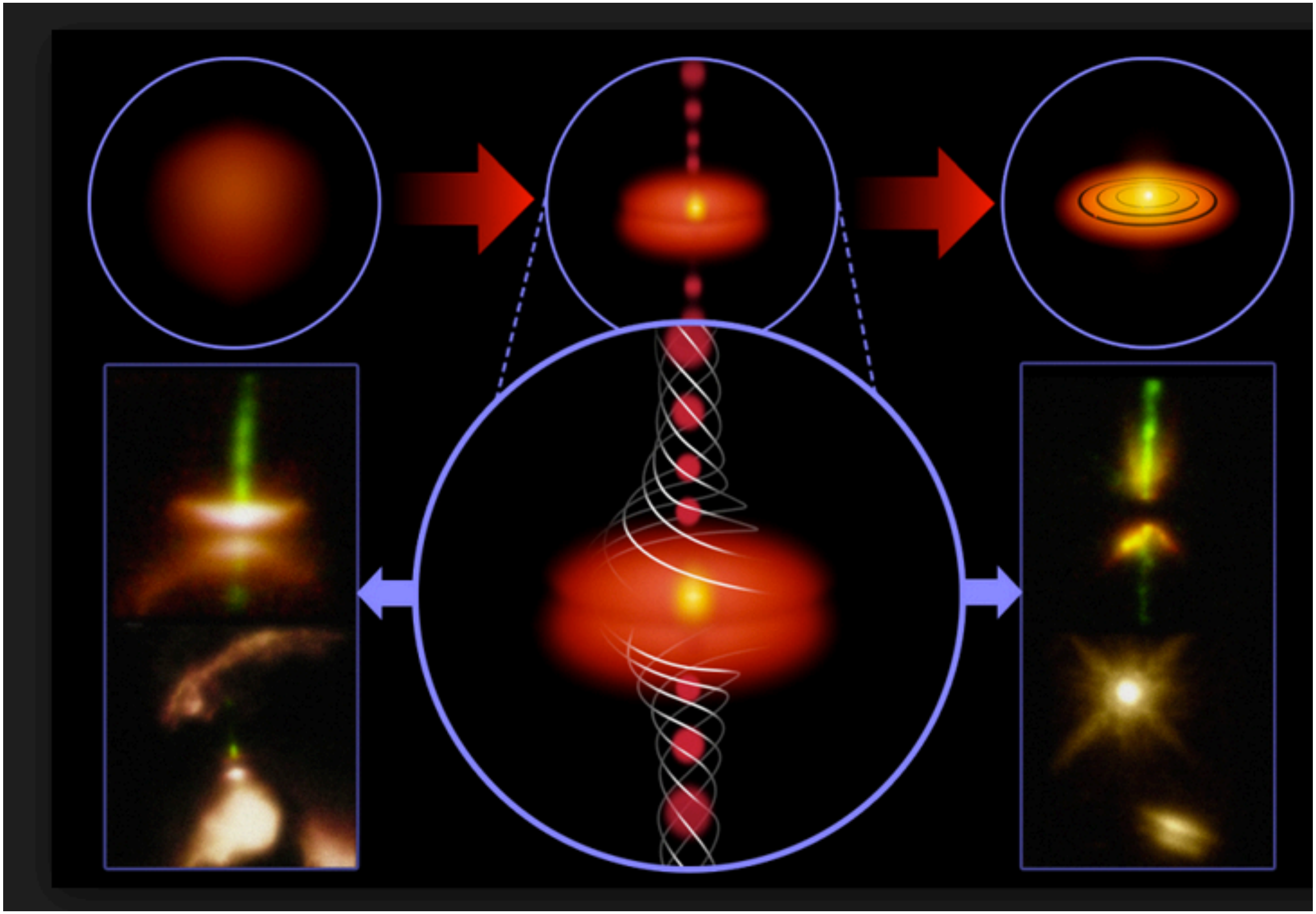
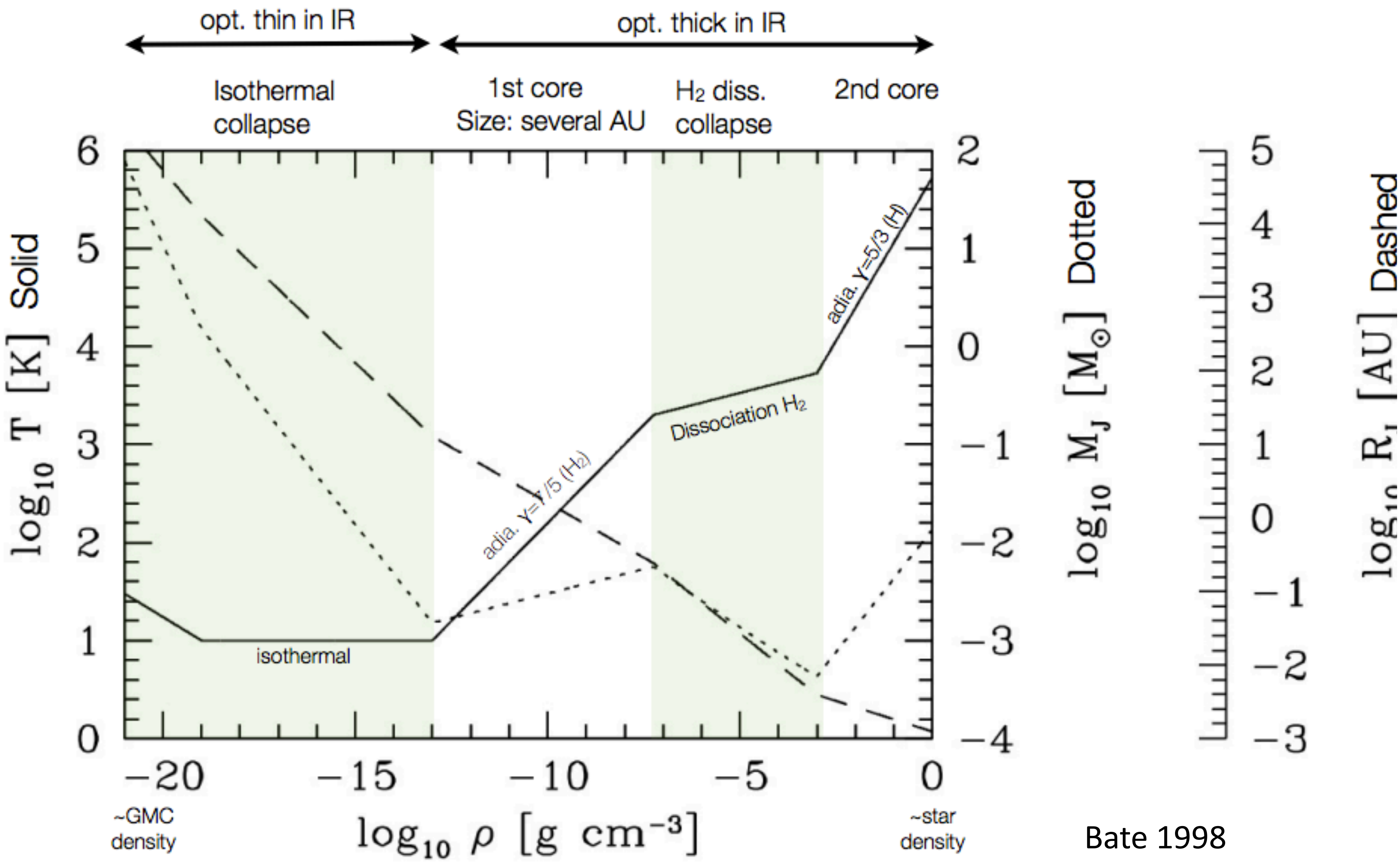
Proto-stellar evolution



Collapse



Bate 1998

Accretion onto the Proto-star

At the moment, when the gas hits the accretion shock, it gets stopped. The velocity is the free fall velocity

$$v_{ff} \approx \sqrt{\frac{2GM}{r}}$$

Super-sonic shock

$$= 280 \text{ km/s} \left(\frac{M_*}{1M_\odot}\right)^{1/2} \left(\frac{R_*}{5R_\odot}\right)^{-1/2}$$

The kinetic energy liberated per second which is the accretional luminosity, is

$$L_{acc} = \frac{1}{2}\dot{M}v_{ff}^2 = \frac{GM_*\dot{M}}{R_*}$$

$$= 61L_\odot \left(\frac{\dot{M}}{10^{-5}M_\odot/\text{yr}}\right)\left(\frac{M_*}{1M_\odot}\right)\left(\frac{R_*}{5R_\odot}\right)^{-1}$$

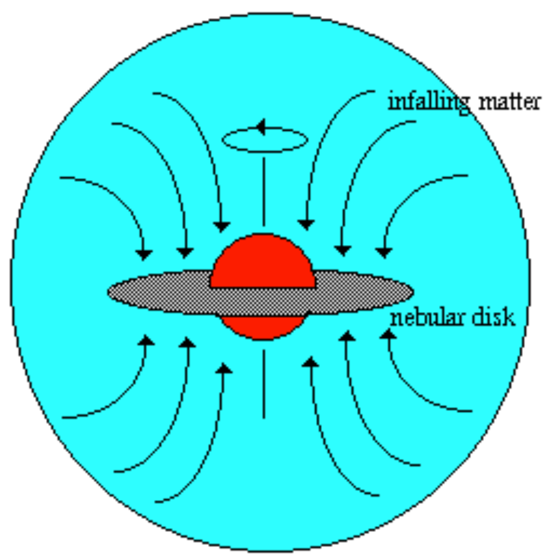
This accretional luminosity is the main energy source of a protostar, at least for low and intermediate mass protostars. The accretion shock produces hard radiation, which gets absorbed both in the settling region and in the radiative precursor. The effective temperature is

$$L_{acc} \approx 4\pi R_*^2 \sigma T_{eff}^4$$

For typical values, we find T_{eff}~7300 K.

Accretion Disk

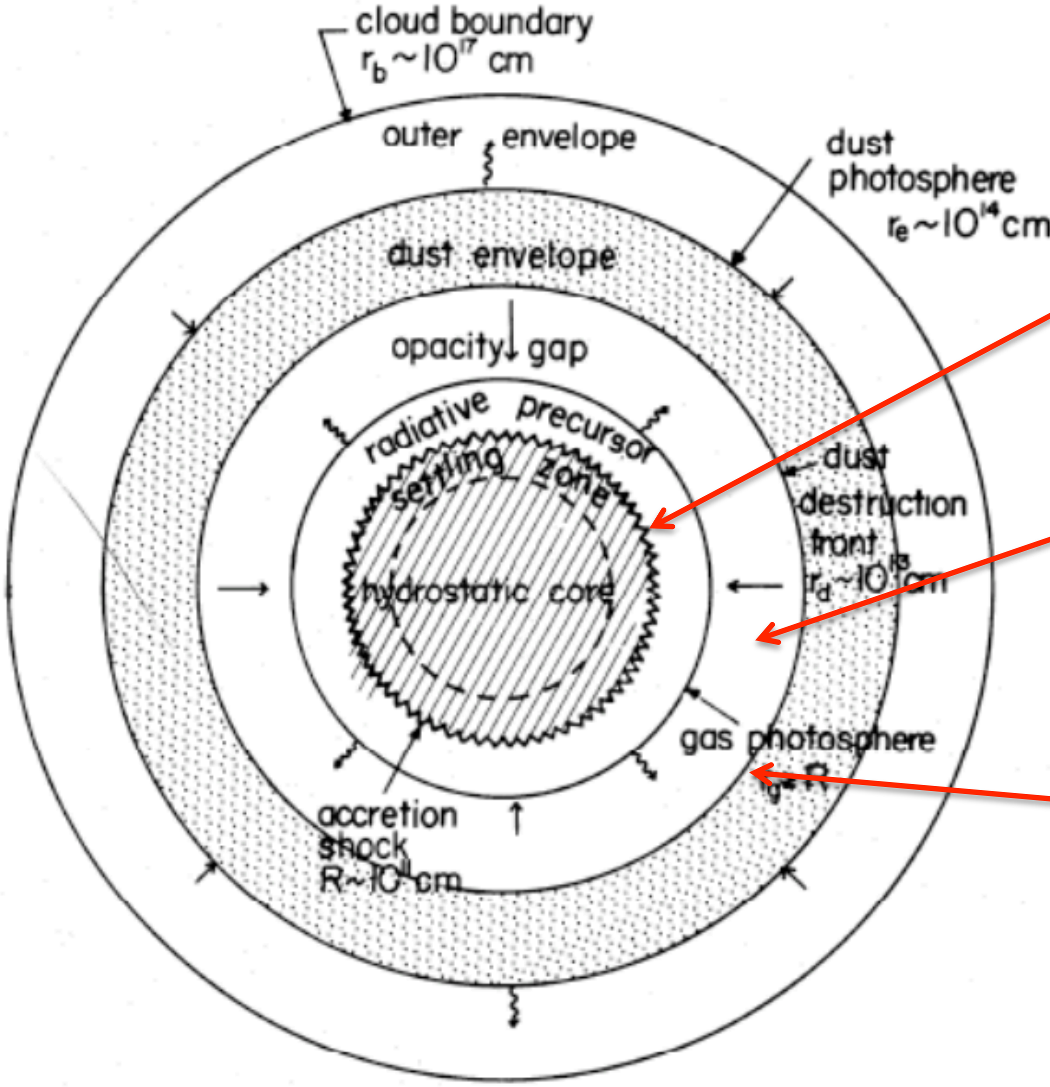
- Any collapsing, rotating, gas cloud will give rise to the formation of an accretion disk
  - Typical rotational velocity of $\Omega c=10^{-14}$- 10^{-13} s^{-1}
- Disk size ~400 a.u.
- Role of disk:
  - Supply material: star increase size by a factor ~100
  - dissipate angular momentum



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

Schematic Structure of a proto-star

Figure 12.5. Structure of a protostar: schematic dimensions are given to illustrate the large dynamic range that is involved in this problem.



In the shock region T~1e6 K

The Opacity Gap is the region where dust extinction is greatly reduced

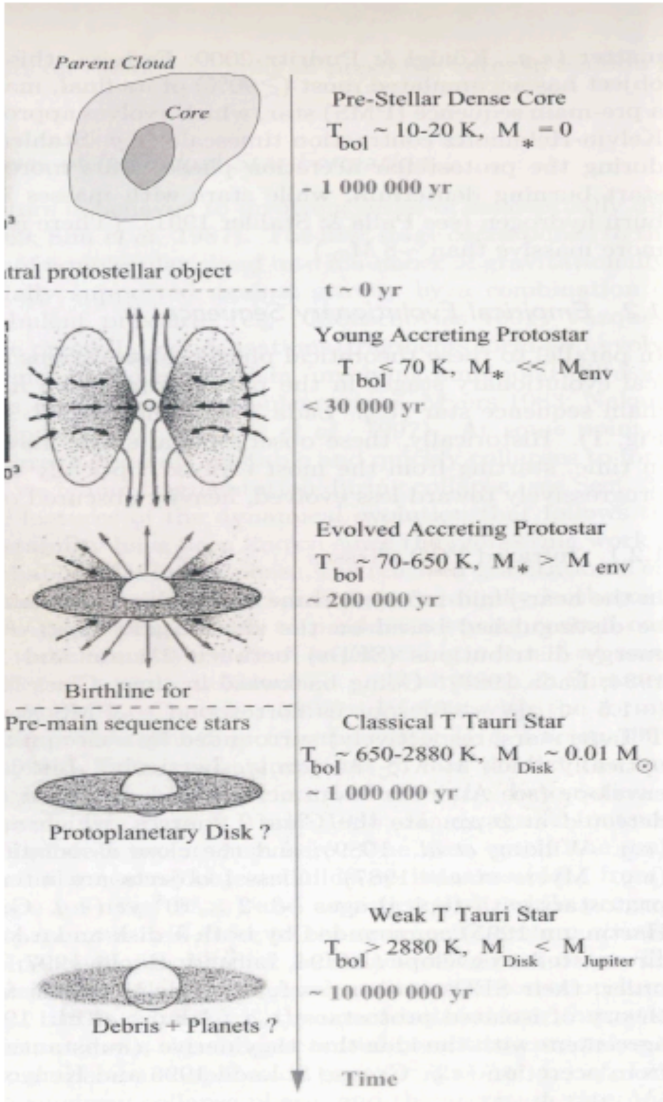
For T>1500K dust grains will vaporize

Stellar Evolution

1. The initial proto-stellar mass is only ~1% of the final:
   1. E.g. the accretion phase is very important and adds 99% of the stellar mass
2. When star has reached ~0.2 $M_{\odot}$ deuterium burning will start burning and this keeps the protostar from contracting as its mass continues to increase. $^{1}\mathrm{H} + ^{2}\mathrm{H} \rightarrow ^{3}\mathrm{He} + \gamma$
3. As the envelope becomes depleted of matter, the optically thick region shrinks in size and the spectrum of emitted radiation shifts towards shorter wavelengths, until eventually the central star begins to shine through and a composite spectrum with both visible and infrared components is seen.

Class	peak emission	duration (Years)	description
0	submillimeter	10^4	early accretion
I	far-infrared	10^5	main accretion phase
II	near-infrared	10^6	classic T Tauri star
III	visible	10^7[3]	'weak line' T Tauri star

Proto-star evolution



Ph. André et. al. 2002, EAS publication series, vol. 2

1) Isothermal phase

2) Adiabatic phase (Class 0)

3) Protostar (Class I)

3 stages of collapse

4) "Classic" T Tauri phase (Class II)

Disk still present

5) "Weak" T Tauri phase (Class III)

Disk is very weak

Dasi

Observational Signatures

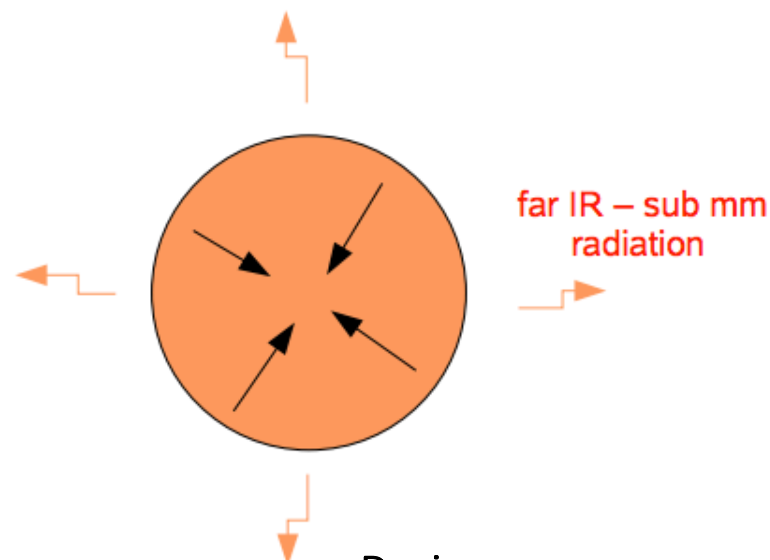
Isothermal phase

What is going on?

- T ~ 10K
- ρ is tenuous enough for gravitational energy to dissipate through the radiation coming from the thermal excitation of the atoms.
- As a consequence of this, the temperature remains low and it keeps contracting.

Where can we observe it?

Object observable through its infrared thermal emission.



Dasi

Observational Signatures

Adiabatic phase

What is going on?

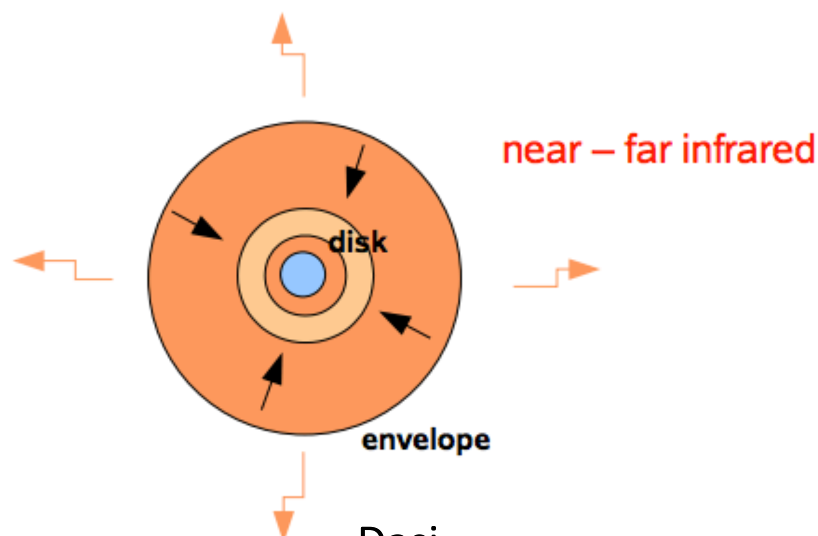
- ρ increases --> κ increases
- κ reaches the point where the energy released by the contraction cannot escape by radiation: opaque
- As a consequence of this, the temperature rises until contraction stops because of pressure built up:

Hydrostatic equilibrium

PROTOSTAR!!
(class 0)

Where can we observe it?

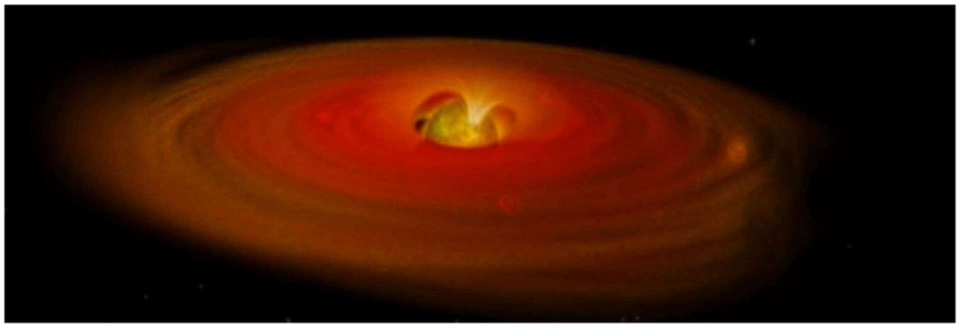
Only the cloud is detectable from radiation from the dust as a black body that peaks in the far infrared --> SED's

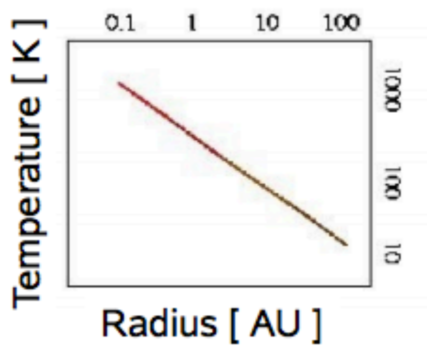


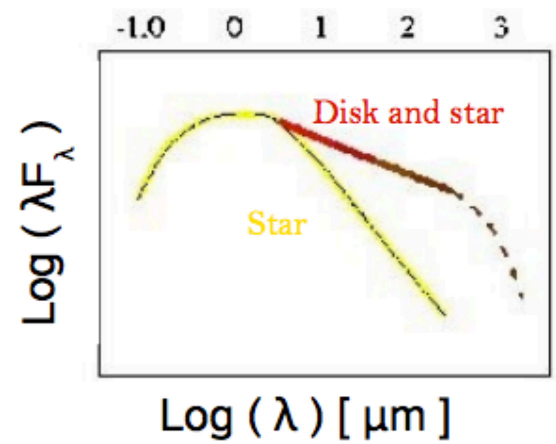
Dasi

⋆ What can we say is going on in a given physical system from its spectral energy distribution (SED)?

Central star surrounded by a disk of gas and dust







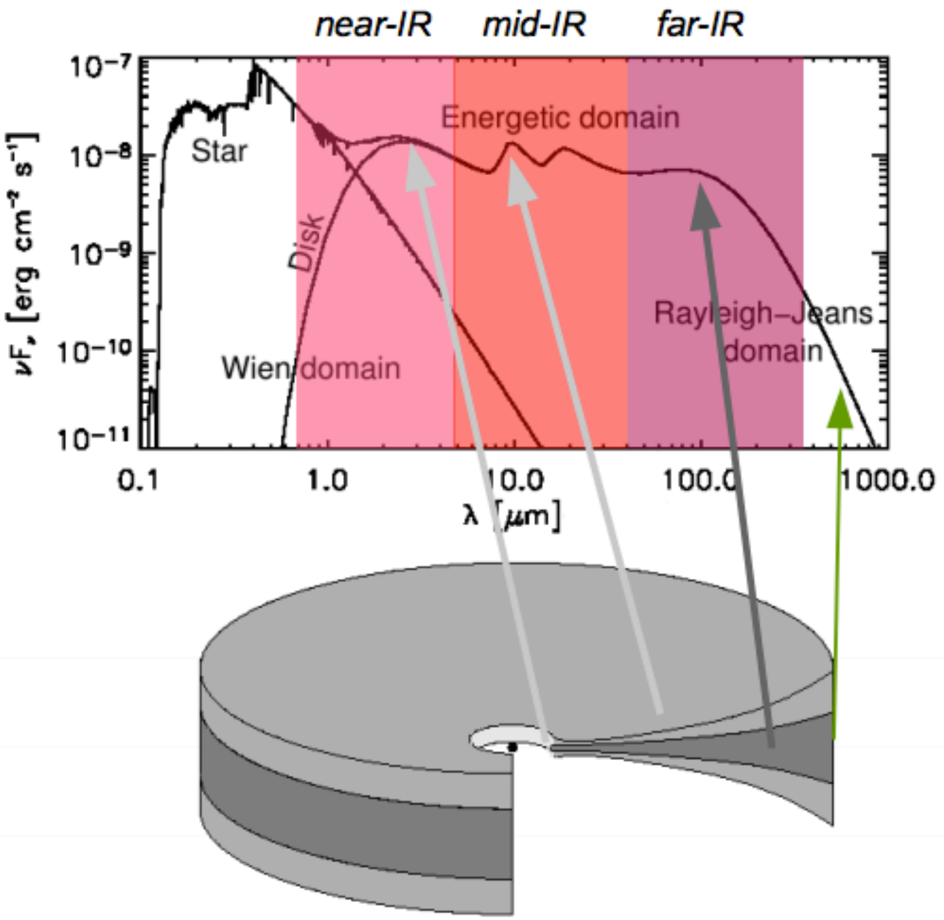
For every distance from the star the dust will be at a different and unique temperature: each radius emits at a characteristic peak wavelength.

The infrared excess seen is due to the gas and dust in the disk and envelope.

Modeling the SED allows to compare observations with what might be going on.

Dasi

Observational Signatures



- ***Near-infrared bump:*** *the inner rim, the infrared dust features from the warm surface layer, and the underlying continuum from the deeper (cooler) disk regions.*
- ***Near-*** *and* ***mid-infrared****:* from small radii.
- ***Far-infrared:*** from the outer disk regions.

(sub-)mm. emission *mostly comes from the mid-plane of the outer disk. This flux probes also the disk mass.*

(Dullemond et al. 2007)

At short λ's SED is in the "Wien domain":

$$B_\lambda(T) \approx \frac{2hc^2}{\lambda^5} e^{\frac{-hc}{\lambda k T}}$$

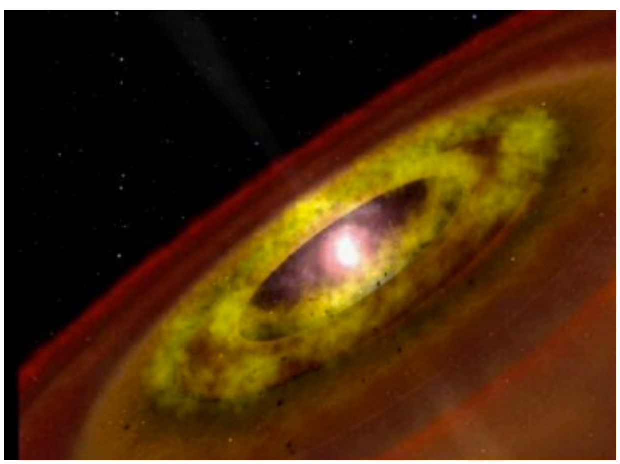
At long λ's the SED is in the "Rayleigh-Jeans domain":

$$B_\nu(T) \approx \frac{2k\nu^2}{c^2} T$$

Dasi

T-Tauri Stars

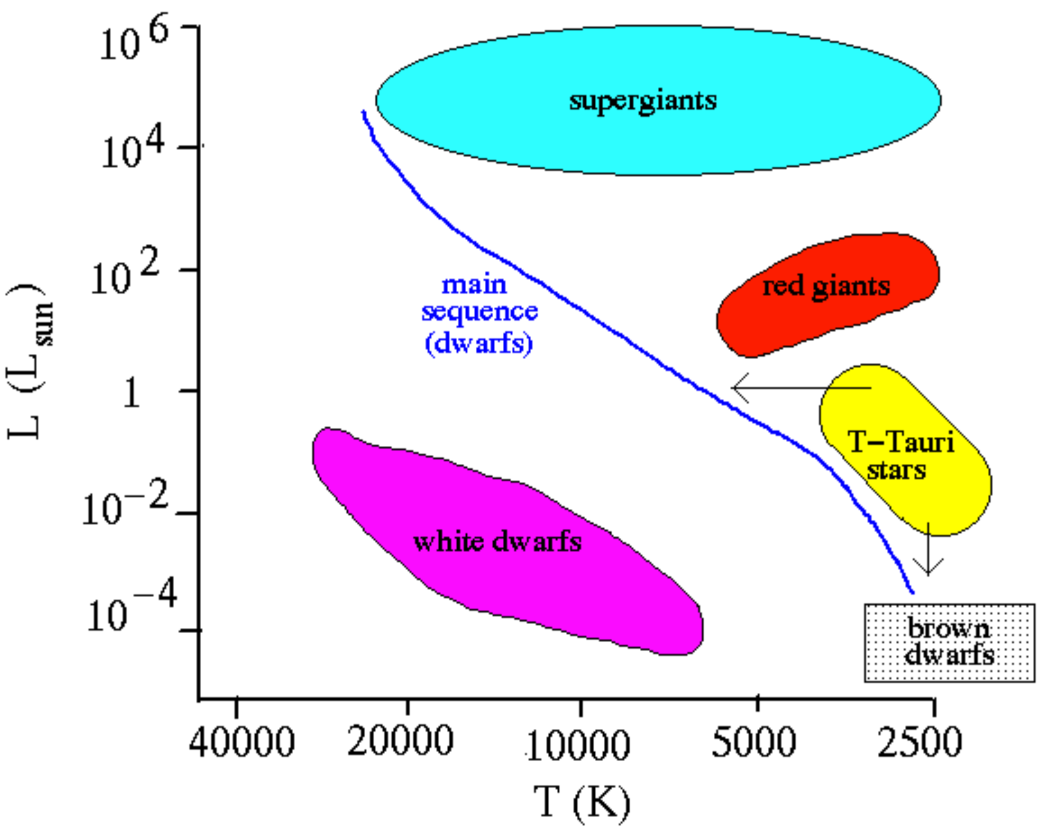
- Pre-main seq. stars in the process of contracting to the main sequence along the Hayashi tracks
- T Tauri stars are the youngest visible F, G, K, M spectral type stars with similar temperature but larger radii -> more luminous
  - Low core temperatures -> no H-burning (yet)
  - Powered by gravitational energy as they contract
  - Reach the main sequence in ~100 Myr
  - 50% has proto-planetary disks
  - Have strong winds



Note: if a proto-star has a mass of <0.08 $M_\odot$ it will never reach Hydrogen fusion temperature: these are Brown Dwarfs . They have an electron degenerate core. They live of ~15Myr (Kelvin-Helmotz timescale)

Birth-line

- Newly formed stars of low/moderate mass are born with the same radius-> should appear in the same locus of HR diagram
- Birth-line: *the locus along which stars are predicted to make their first visible appearance after emerging from their birth clouds.*



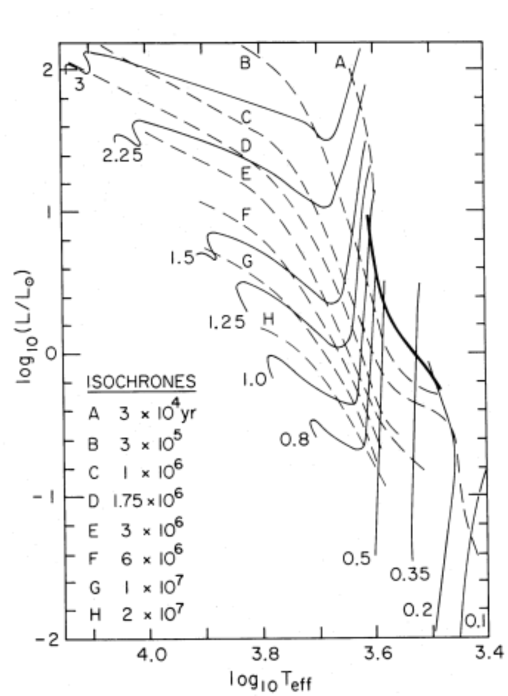
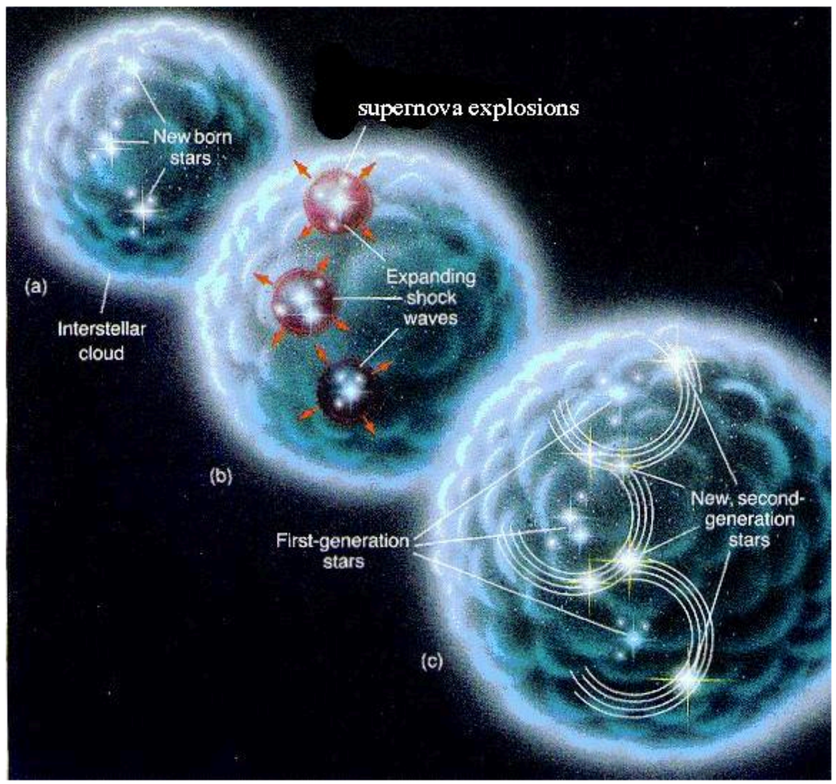


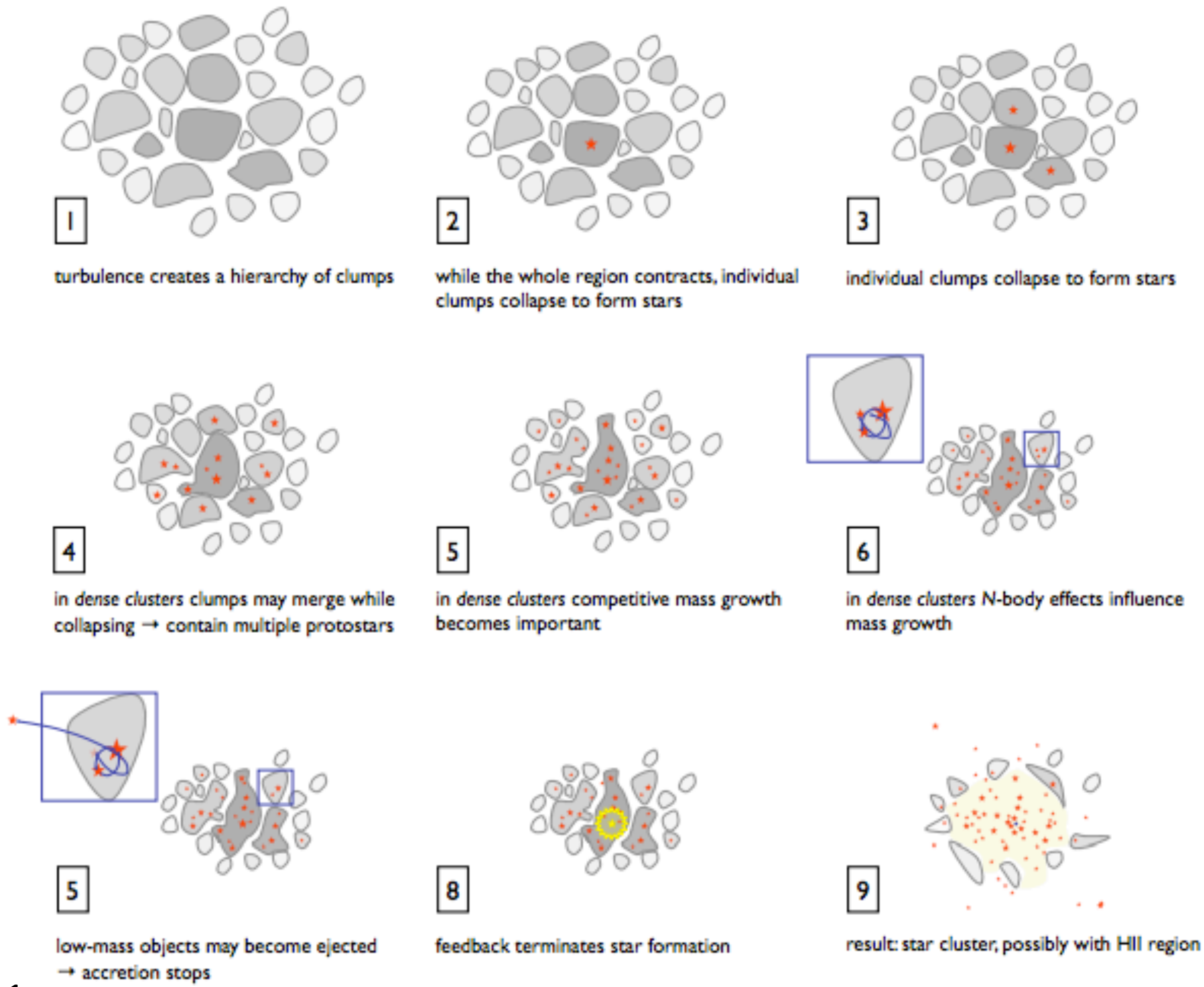
FIG. 1.—The theoretical birthline in the Hertzsprung-Russell diagram. The birthline for stars with masses between 0.2 $M_\odot$ and 1.0 $M_\odot$ is shown as the heavy solid curve. The lighter solid curves are the Hayashi tracks for the indicated values of mass (in units of $M_\odot$). The dashed curves are isochrones of Kelvin-Helmholtz age, as explained in § IV of the text. Figures 1–5 are adapted from the corresponding figures in Cohen and Kuhi (1979).

SN Induced Star-formation

- Often in galaxies we find clusters of young stars near other young stars. The very massive stars form first and explode into supernova. This makes shock waves into the molecular cloud, causing nearby gas to compress and form more stars. This allows a type of stellar coherence (young stars are found near other young stars) to build up



Star Clusters



Klessen 2011

Fig. 8. Star cluster formation in a turbulent molecular cloud core.

Initial Mass Function

- All stars are created from pressure supported fragment, their initial masses are a few \`Jupiter' as given by the opacity/fragmentation limit. They then accrete to become Brown Dwarfs (<75 Jupiters) or stars (>75 Jupiters)
  - All start as pressure supported fragment
  - The \`final' mass distribution depends on the competition of between accretion and ejection
    - *Stars and Brown Dwarf form the same way and accrete mass in the same way. Stars accrete for longer than B.D. which, due to interactions stop accreting*

- It is possible to calculate the \`initial mass function'
  - E.g. the mass distribution of stars at birth

Initial Mass Function (IMF)

Starting from the observed luminosity function, possible to derive an estimate for the Initial Mass Function (IMF). To define the IMF, imagine that we form a large number of stars. Then:

$$\xi(M)\Delta M \quad = \quad \text{the \textbf{number} of stars that have been born with initial masses between } M \text{ and } M+\Delta M$$

(careful not to confuse mass and absolute magnitude here)

this is the Initial Mass Function or IMF

The IMF is a more fundamental theoretical quantity which is obviously related to the star formation process. Note that the IMF only gives the distribution of stellar masses immediately after stars have formed - it is **not** the mass distribution in, say, the Galactic disk today.

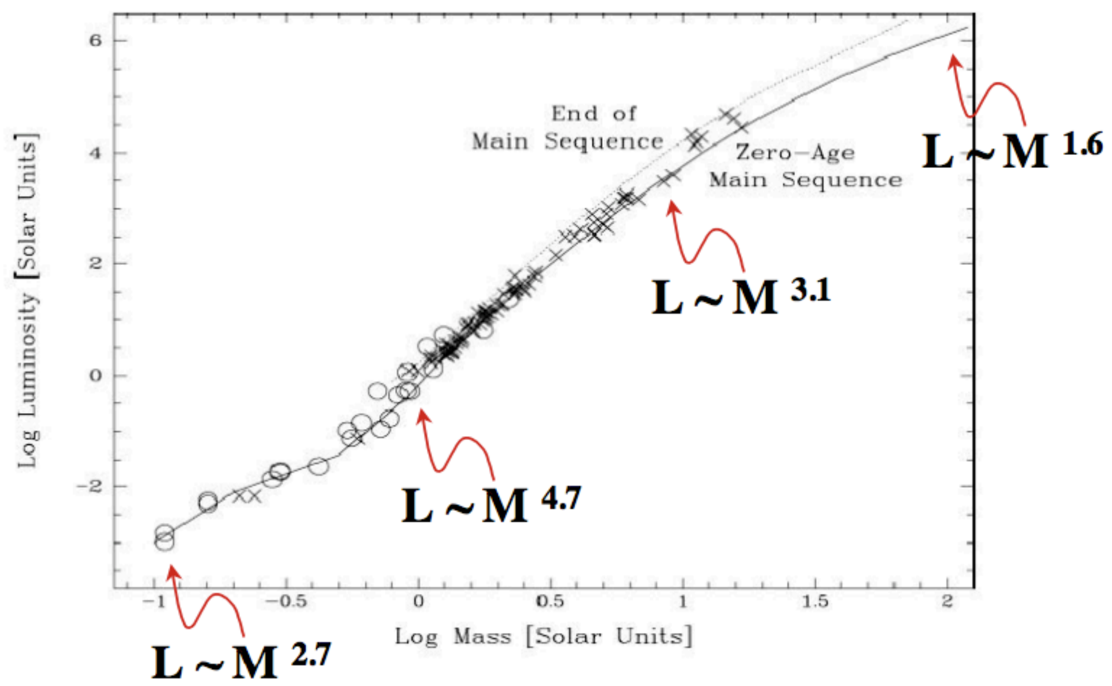
(From P. Armitage)

How to Build the IMF

- Measure a luminosity function (e.g. dN/dL)

- Use the Mass-Luminosity Relation to convert luminosity to mass
  - Quantify the present-day mass function
- Weight the stars by their lifetime
  - Massive stars don't live long
- Account for mass loss

Use virial theorem



Salpeter Mass Function

The Initial Mass Function for stars in the Solar neighborhood was determined by Salpeter in 1955. He obtained:

$$\xi(M) = \xi_0 M^{-2.35}$$ **Salpeter IMF**

↑ constant which sets the local stellar density

Using the definition of the IMF, the number of stars that form with masses between M and M + ΔM is: $\xi(M)\Delta M$

To determine the total number of stars formed with masses between M_1 and M_2, integrate the IMF between these limits:

$$N = \int_{M_1}^{M_2} \xi(M)\, dM = \xi_0 \int_{M_1}^{M_2} M^{-2.35}\, dM$$

$$= \xi_0 \left[\frac{M^{-1.35}}{-1.35} \right]_{M_1}^{M_2} = \frac{\xi_0}{1.35} \left[M_1^{-1.35} - M_2^{-1.35} \right]$$

(From P. Armitage)

Can similarly work out the total **mass** in stars born with mass $M_1 < M < M_2$:

$$M_* = \int_{M_1}^{M_2} M\xi(M)dM$$

Properties of the Salpeter IMF:

- most of the stars (by number) are low mass stars
- most of the **mass** in stars resides in low mass stars
- following a burst of star formation, most of the **luminosity** comes from high mass stars

Salpeter IMF must fail at low masses, since if we extrapolate to arbitrarily low masses the total mass in stars tends to infinity!

Observations suggest that the Salpeter form is valid for roughly $M > 0.5\ M_{sun}$, and that the IMF `flattens' at lower masses. The exact form of the low mass IMF remains uncertain.

(From P. Armitage)

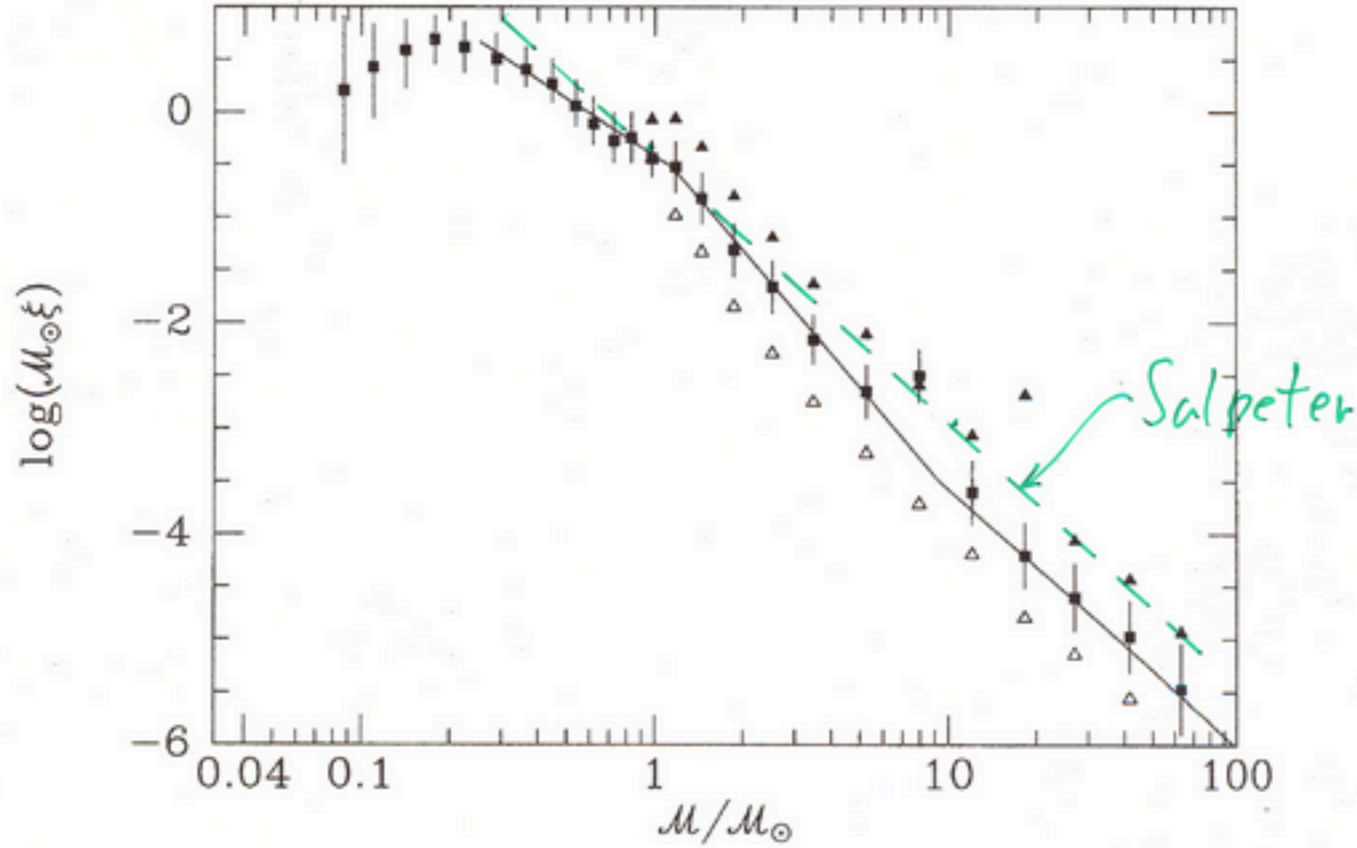
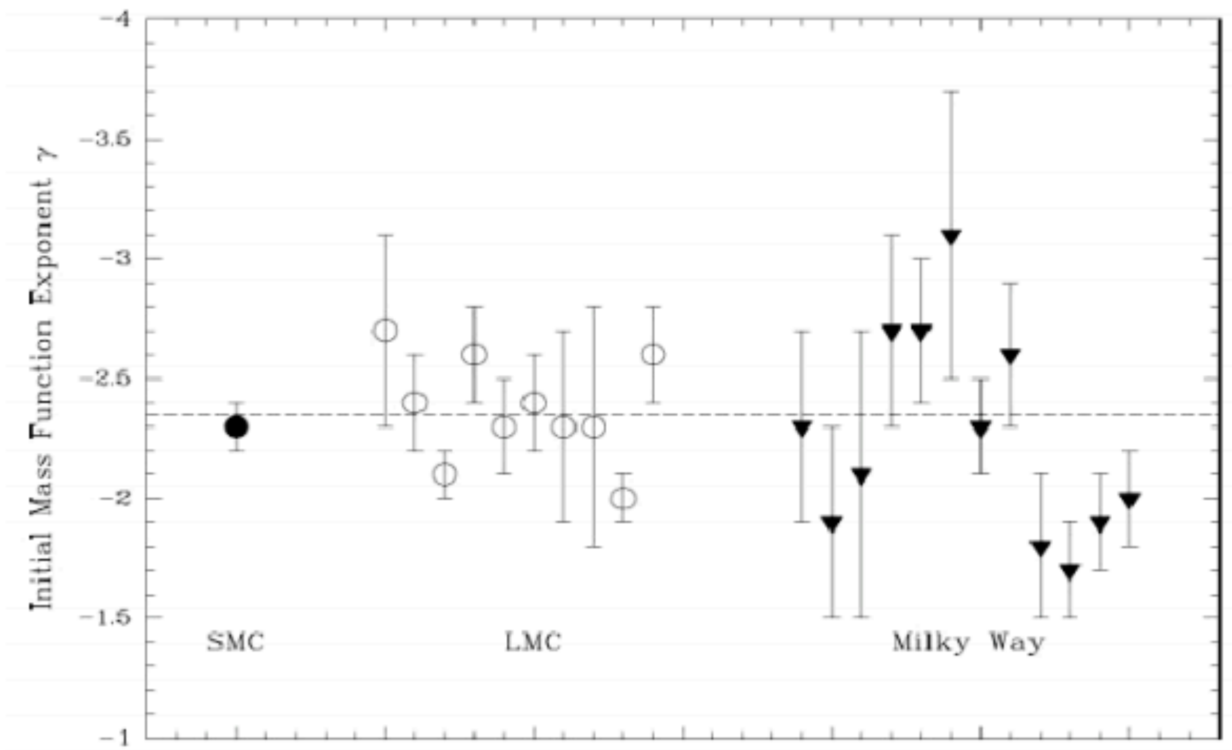


Figure 5.12 The IMF from Scalo (1986). For masses $\mathcal{M} > \mathcal{M}_\odot$ three sets of points are shown, each set being for a different assumption about the ratio of the current rate of star formation to its average over the lifetime of the solar neighborhood. The curve defined by the points that are based on the assumption of a constant star-formation rate (squares) can be approximated by the three power-law segments defined in equation (5.16).

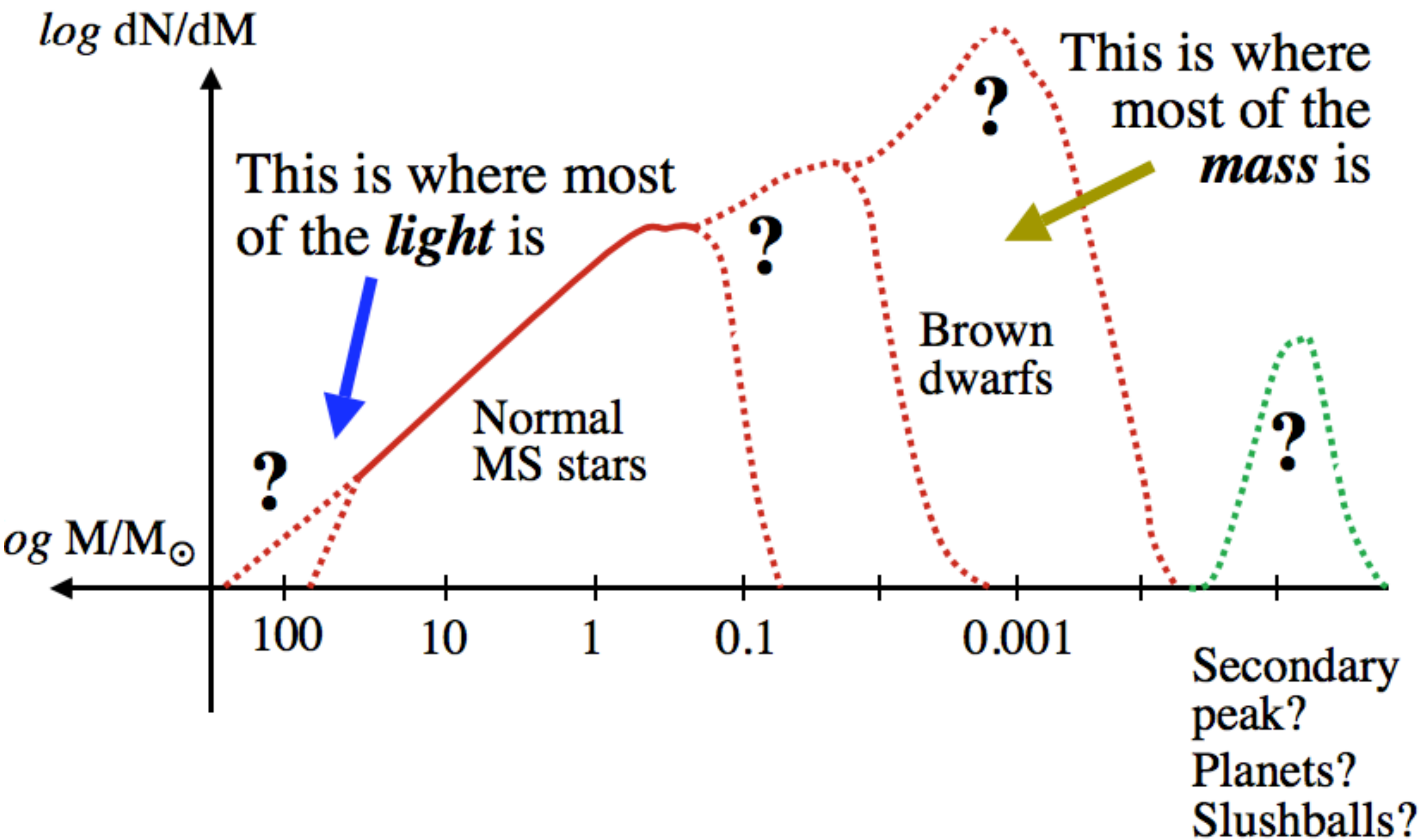
Binney & Merrifield GALACTIC ASTRONOMY

Is the IMF Universal ?

- Fragmentation is easier if gas can cool, so primordial gas without any metals should form more massive stars
- Observationally there is not much difference



Where are the Baryons?



Reading Assignment

- Chapter 5 of Galactic Astronomy (Binney and Merrifield)
- Chapters 3 & 5 of `The Formation of Stars' (Stahler and Palla)
- Star formation in Molecular Clouds:
  - (Klessen et al.) http://arxiv.org/pdf/1109.0467v1.pdf
- The Physics of Star Formation:
  - http://www.ifa.hawaii.edu/~reipurth/reviews/larson.pdf
- IMF: Salpeter et al
  - http://adsabs.harvard.edu/abs/1955ApJ...121..161S