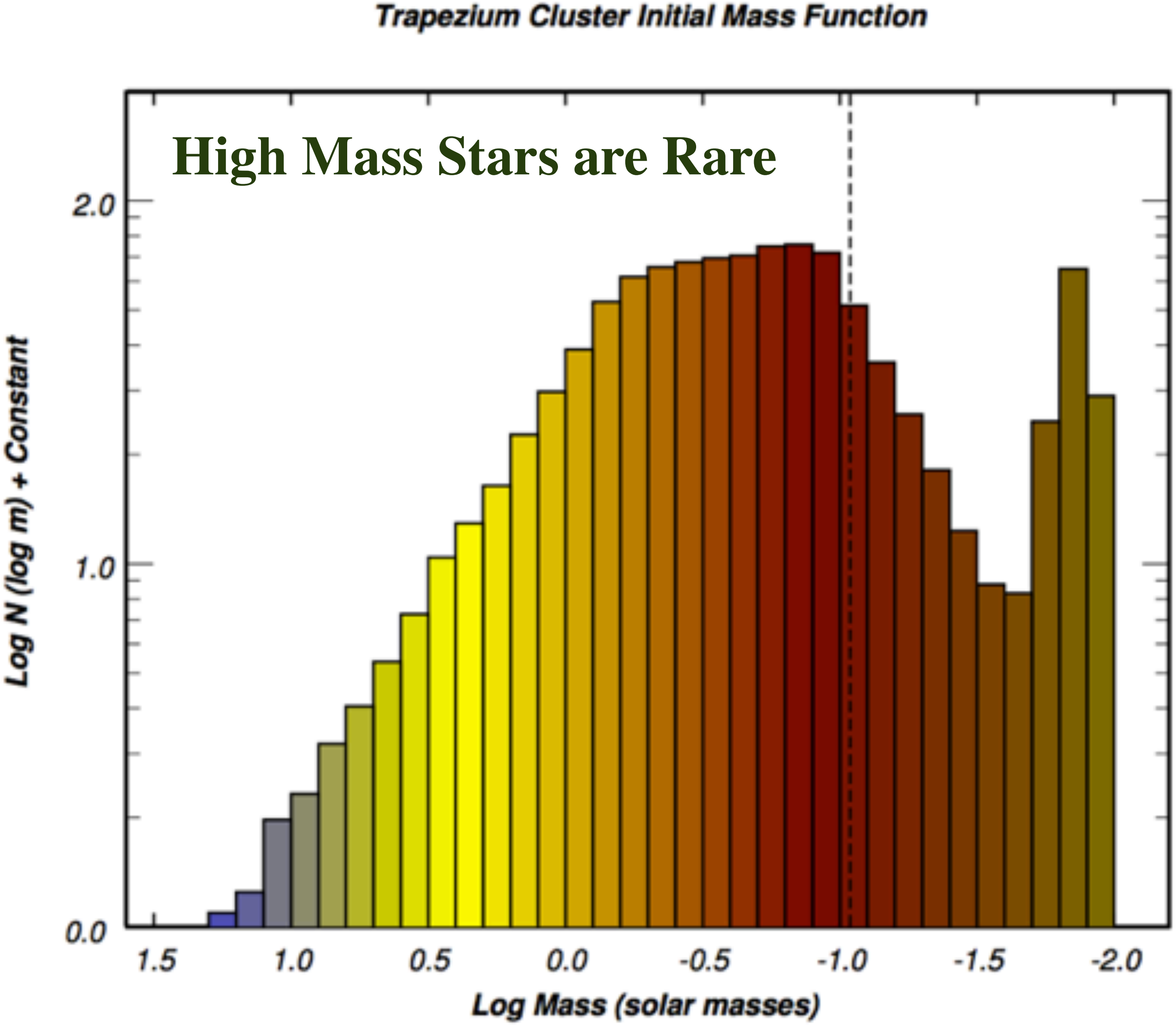
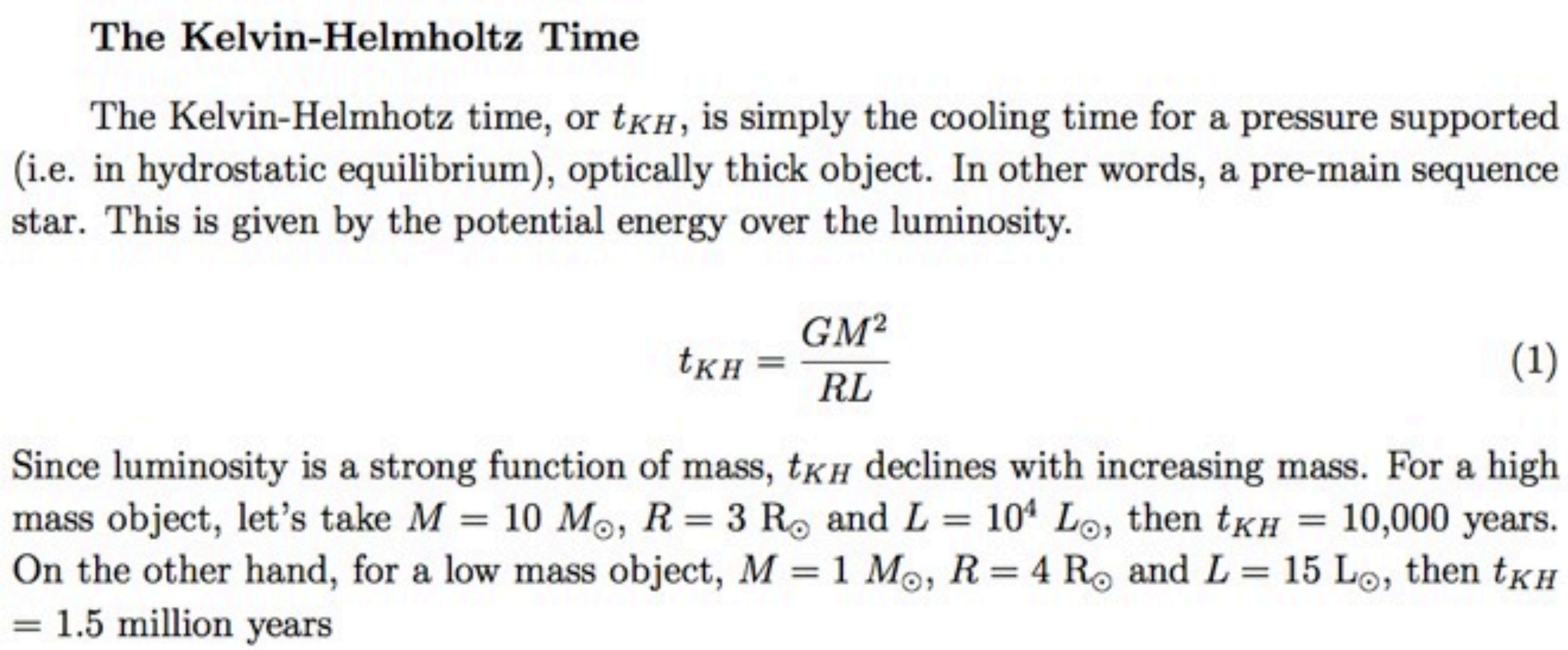
Lecture 17: High Mass Star Formation

Why is high mass star formation different than low mass star formation?



Why is high mass star formation different than low mass star formation?

A Short Kelvin-Helmholtz Time!!



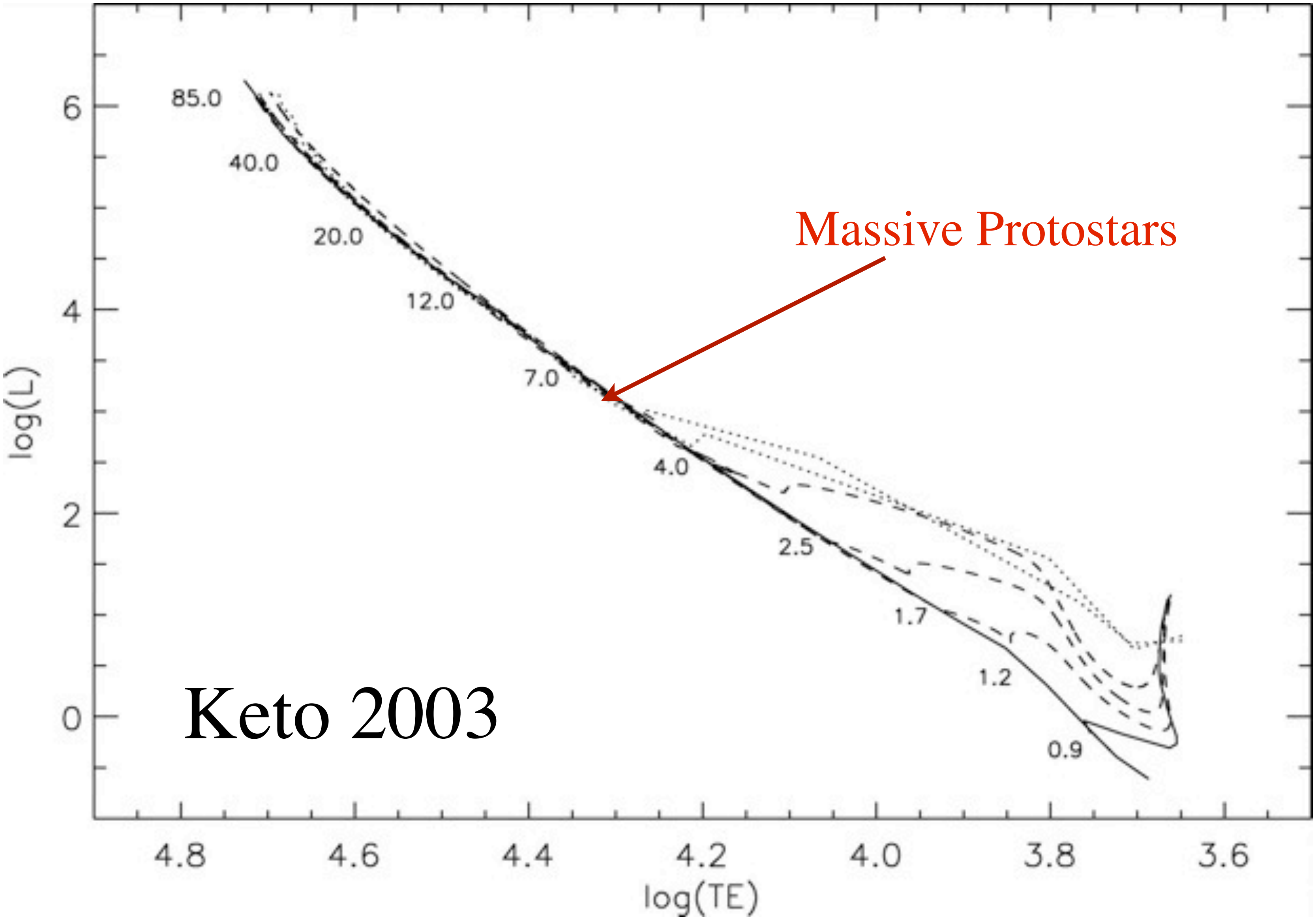
The Kelvin-Helmholtz Time

The Kelvin-Helmhotz time, or t_{KH}, is simply the cooling time for a pressure supported (i.e. in hydrostatic equilibrium), optically thick object. In other words, a pre-main sequence star. This is given by the potential energy over the luminosity.

$$t_{KH} = \frac{GM^2}{RL} \tag{1}$$

Since luminosity is a strong function of mass, t_{KH} declines with increasing mass. For a high mass object, let's take $M = 10\ M_\odot$, $R = 3\ \mathrm{R}_\odot$ and $L = 10^4\ L_\odot$, then t_{KH} = 10,000 years. On the other hand, for a low mass object, $M = 1\ M_\odot$, $R = 4\ \mathrm{R}_\odot$ and $L = 15\ \mathrm{L}_\odot$, then t_{KH} = 1.5 million years

Massive Stars Reach the Main Sequence while Protostars

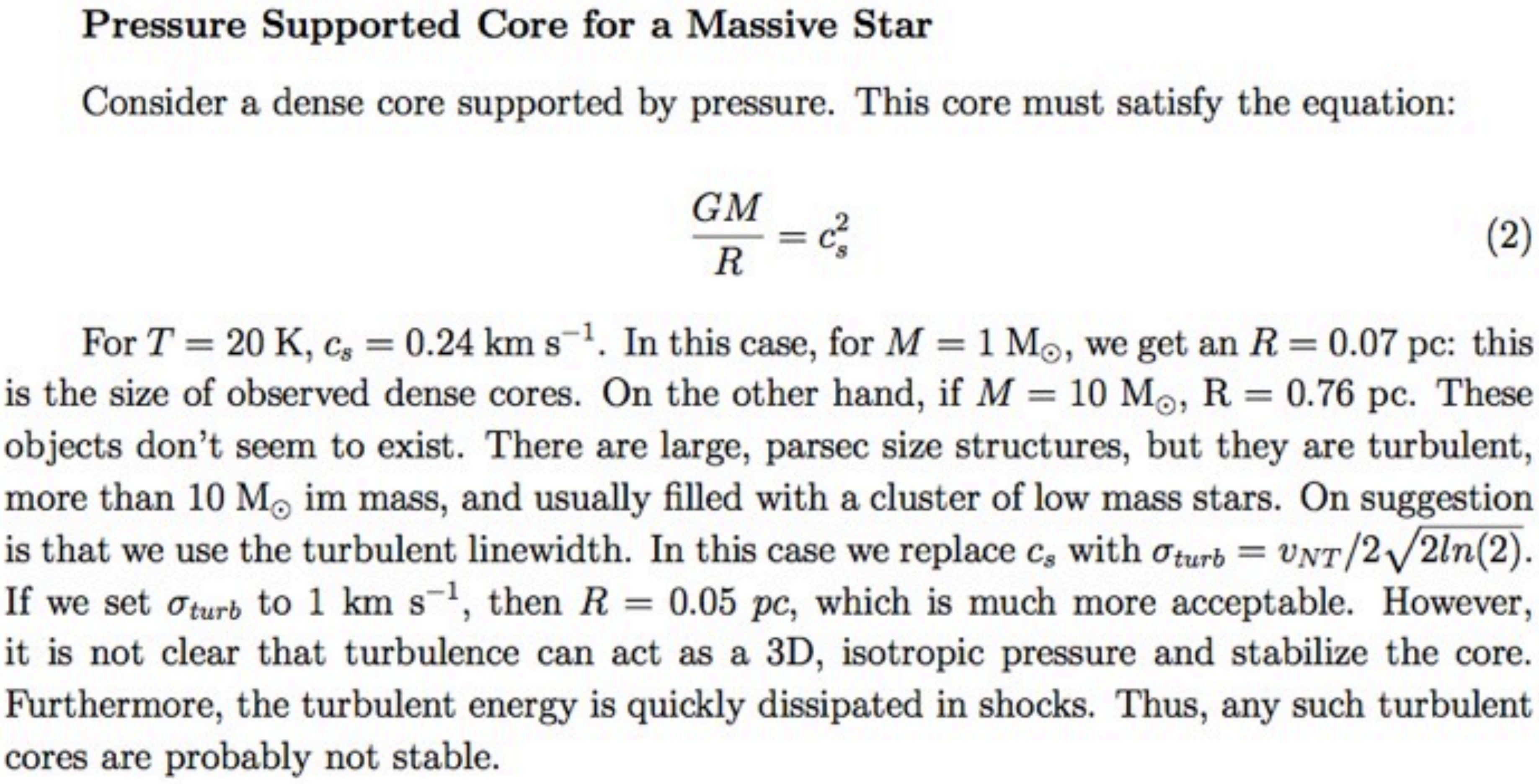


Massive Protostars

Keto 2003

Why is high mass star formation different than low mass star formation?

Massive Cores are not Thermal Pressure Supported
(and probably not in equilibrium)



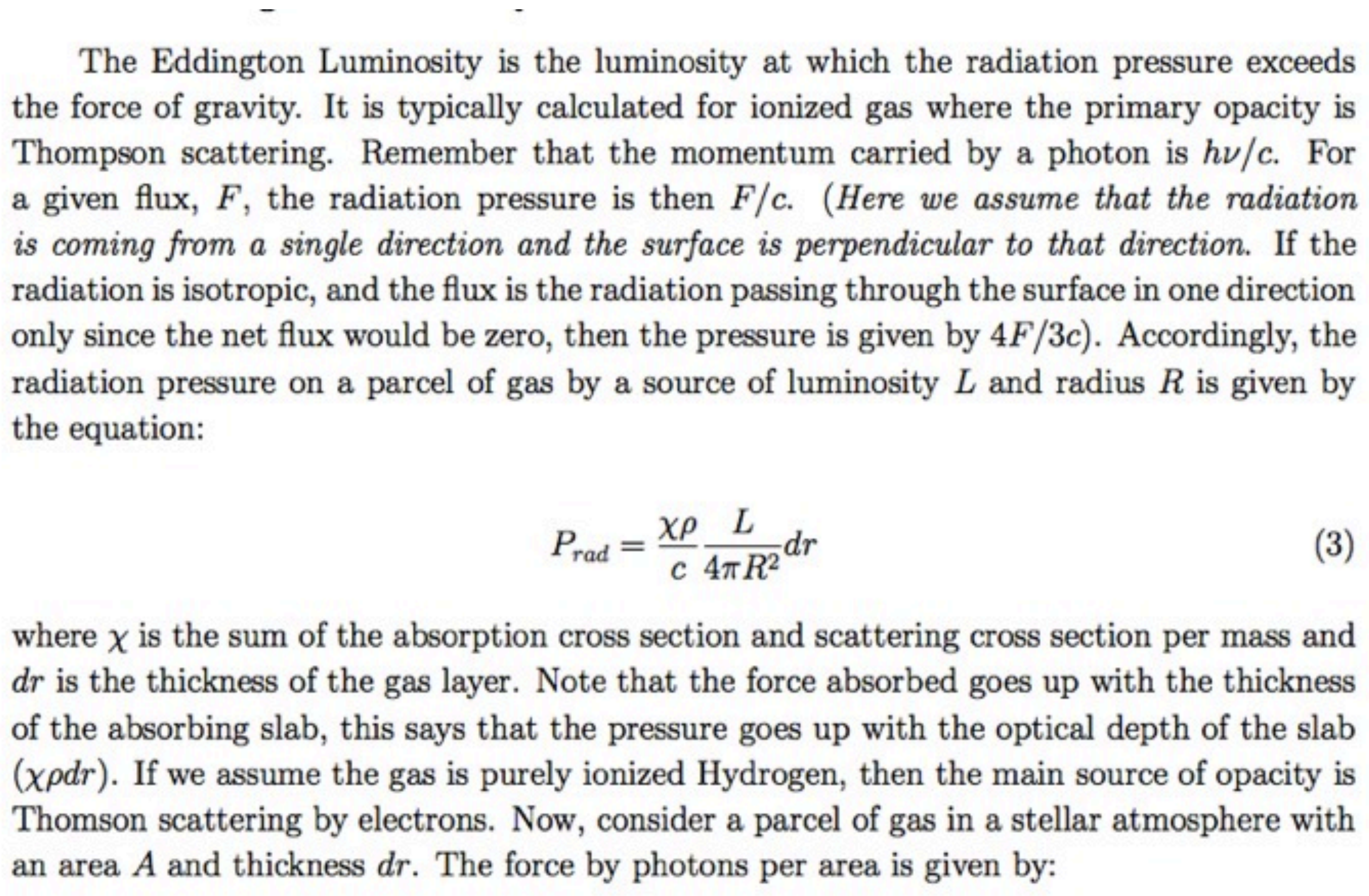
Pressure Supported Core for a Massive Star

Consider a dense core supported by pressure. This core must satisfy the equation:

$$\frac{GM}{R} = c_s^2 \tag{2}$$

For $T = 20$ K, $c_s = 0.24$ km s^{-1}. In this case, for $M = 1$ M$_\odot$, we get an $R = 0.07$ pc: this is the size of observed dense cores. On the other hand, if $M = 10$ M$_\odot$, R $= 0.76$ pc. These objects don't seem to exist. There are large, parsec size structures, but they are turbulent, more than 10 M$_\odot$ im mass, and usually filled with a cluster of low mass stars. On suggestion is that we use the turbulent linewidth. In this case we replace c_s with $\sigma_{turb} = v_{NT}/2\sqrt{2ln(2)}$. If we set σ_{turb} to 1 km s^{-1}, then $R = 0.05$ pc, which is much more acceptable. However, it is not clear that turbulence can act as a 3D, isotropic pressure and stabilize the core. Furthermore, the turbulent energy is quickly dissipated in shocks. Thus, any such turbulent cores are probably not stable.

The Eddington Luminosity

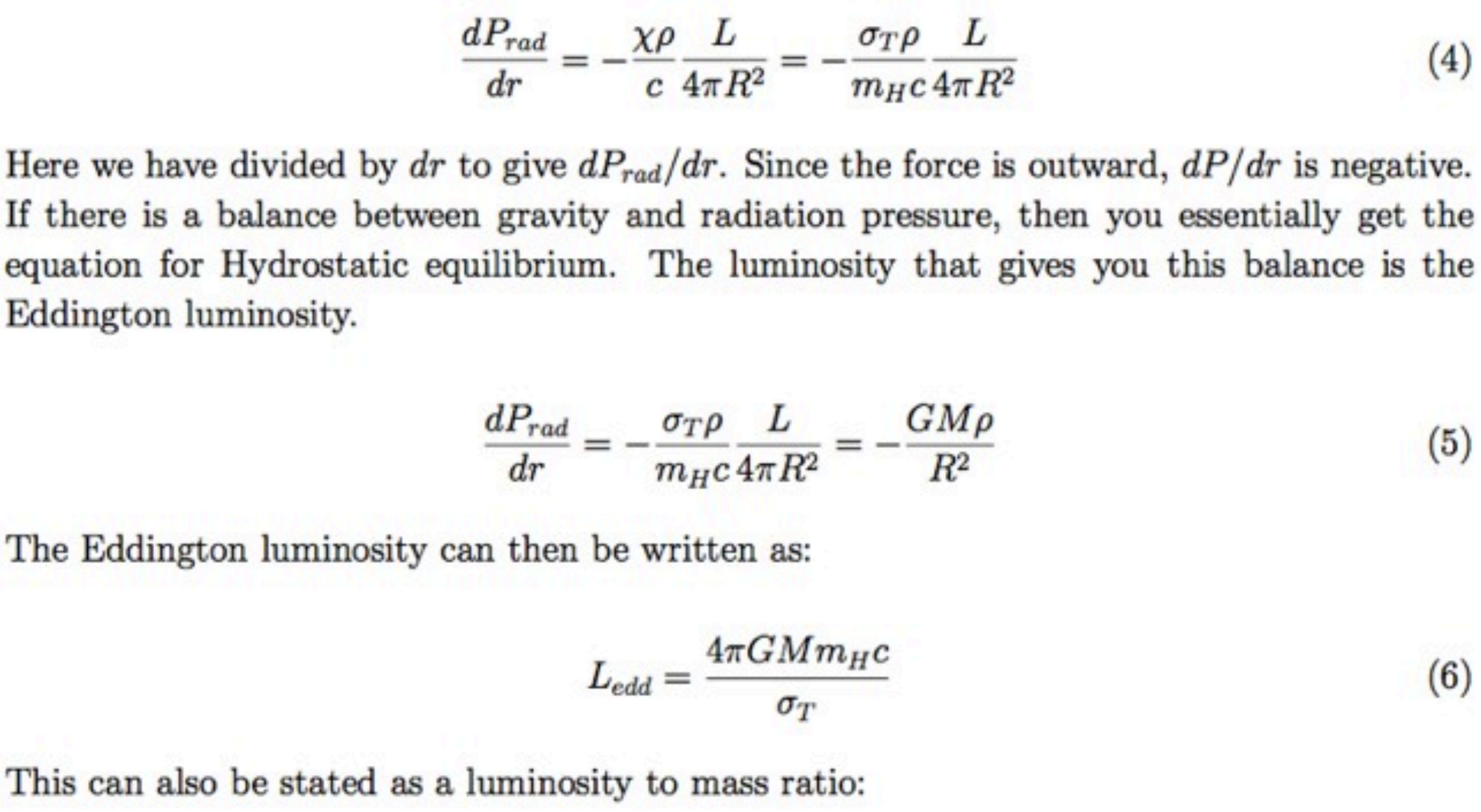


The Eddington Luminosity is the luminosity at which the radiation pressure exceeds the force of gravity. It is typically calculated for ionized gas where the primary opacity is Thompson scattering. Remember that the momentum carried by a photon is $h\nu/c$. For a given flux, F, the radiation pressure is then F/c. (*Here we assume that the radiation is coming from a single direction and the surface is perpendicular to that direction.* If the radiation is isotropic, and the flux is the radiation passing through the surface in one direction only since the net flux would be zero, then the pressure is given by $4F/3c$). Accordingly, the radiation pressure on a parcel of gas by a source of luminosity L and radius R is given by the equation:

$$P_{rad} = \frac{\chi\rho}{c}\frac{L}{4\pi R^2}dr \tag{3}$$

where χ is the sum of the absorption cross section and scattering cross section per mass and dr is the thickness of the gas layer. Note that the force absorbed goes up with the thickness of the absorbing slab, this says that the pressure goes up with the optical depth of the slab ($\chi\rho dr$). If we assume the gas is purely ionized Hydrogen, then the main source of opacity is Thomson scattering by electrons. Now, consider a parcel of gas in a stellar atmosphere with an area A and thickness dr. The force by photons per area is given by:

The Eddington Luminosity (Cont)



$$\frac{dP_{rad}}{dr} = -\frac{\chi\rho}{c}\frac{L}{4\pi R^2} = -\frac{\sigma_T\rho}{m_H c}\frac{L}{4\pi R^2} \tag{4}$$

Here we have divided by dr to give dP_{rad}/dr. Since the force is outward, dP/dr is negative. If there is a balance between gravity and radiation pressure, then you essentially get the equation for Hydrostatic equilibrium. The luminosity that gives you this balance is the Eddington luminosity.

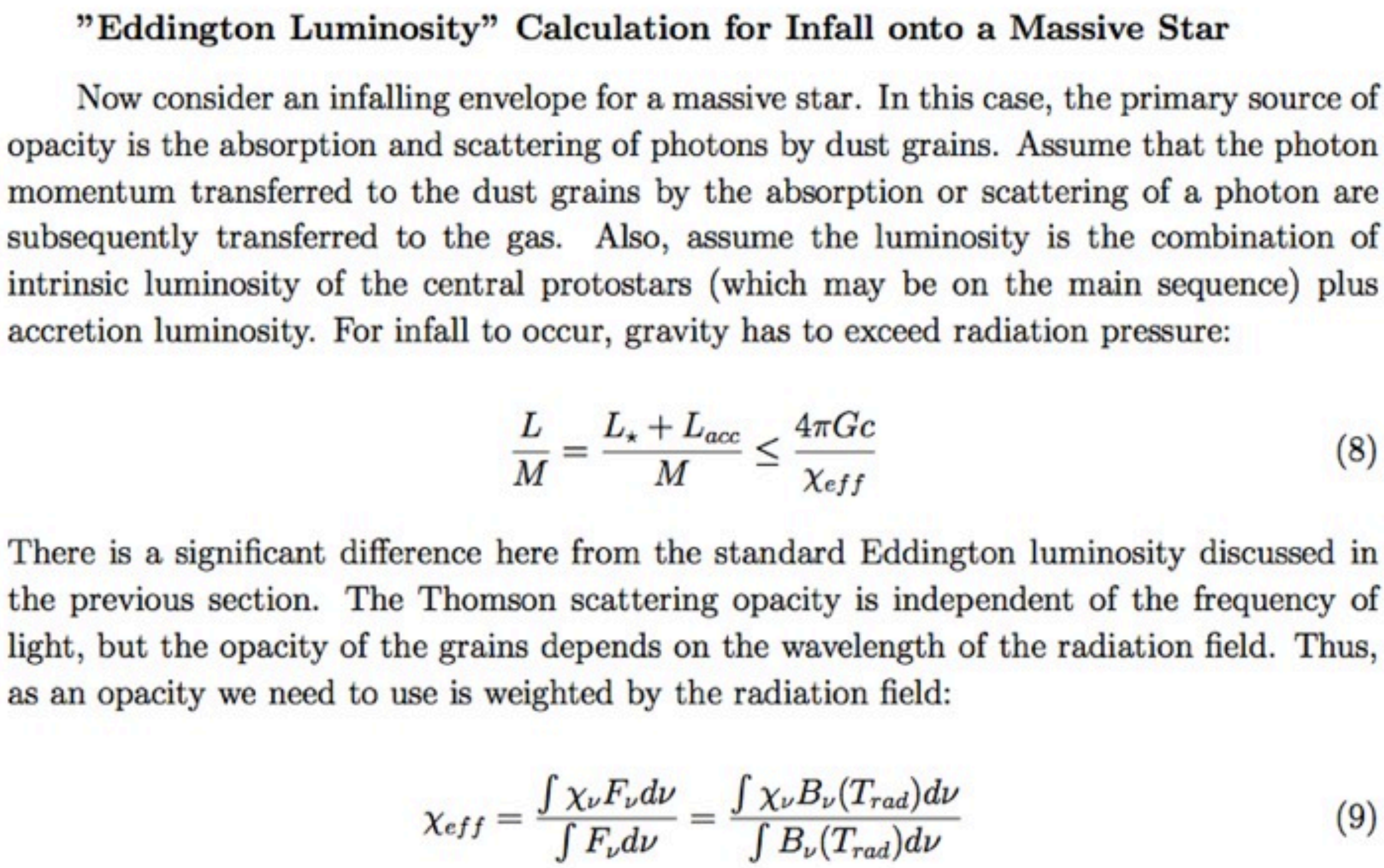
$$\frac{dP_{rad}}{dr} = -\frac{\sigma_T\rho}{m_H c}\frac{L}{4\pi R^2} = -\frac{GM\rho}{R^2} \tag{5}$$

The Eddington luminosity can then be written as:

$$L_{edd} = \frac{4\pi GMm_H c}{\sigma_T} \tag{6}$$

This can also be stated as a luminosity to mass ratio:

Why is high mass star formation different than low mass star formation?



"Eddington Luminosity" Calculation for Infall onto a Massive Star

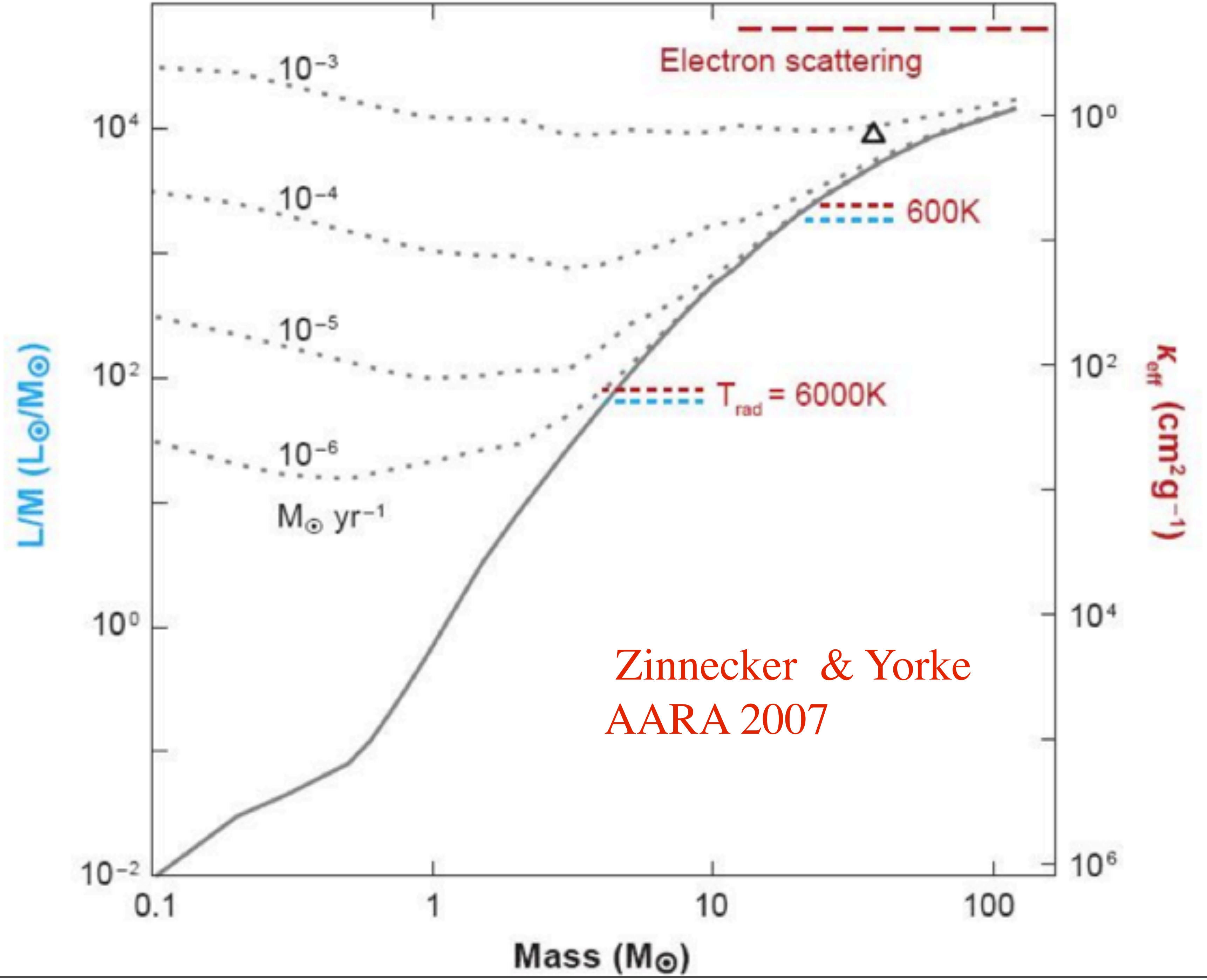
Now consider an infalling envelope for a massive star. In this case, the primary source of opacity is the absorption and scattering of photons by dust grains. Assume that the photon momentum transferred to the dust grains by the absorption or scattering of a photon are subsequently transferred to the gas. Also, assume the luminosity is the combination of intrinsic luminosity of the central protostars (which may be on the main sequence) plus accretion luminosity. For infall to occur, gravity has to exceed radiation pressure:

$$\frac{L}{M} = \frac{L_\star + L_{acc}}{M} \leq \frac{4\pi G c}{\chi_{eff}} \tag{8}$$

There is a significant difference here from the standard Eddington luminosity discussed in the previous section. The Thomson scattering opacity is independent of the frequency of light, but the opacity of the grains depends on the wavelength of the radiation field. Thus, as an opacity we need to use is weighted by the radiation field:

$$\chi_{eff} = \frac{\int \chi_\nu F_\nu d\nu}{\int F_\nu d\nu} = \frac{\int \chi_\nu B_\nu(T_{rad}) d\nu}{\int B_\nu(T_{rad}) d\nu} \tag{9}$$

We can assume the radiation field is described by the Planck equation. What is the temperature of the radiation field? Consider an infalling envelope. As the gas and dust falls inward, the temperature increases until, at a temperature between 1000 and 2000 K, the grains sublimate. This is called the dust destruction radius. At this point, the opacity of the gas drops. Thus, the light of star travels freely until it reaches the dust destruction radius and is radiated. We assume all the light is absorbed and re-emitted at the dust destruction radius. That temperature is approximately the dust sublimation temperature. Thus $T_{rad} \sim 2000$ K, much lower than that of the stellar photosphere. This reduces the effect of the radiation pressure significantly. As shown in the lecture, this may allow infall to occur, depending on the assumed dust opacities.



Zinnecker & Yorke
AARA 2007

Wolfire & Cassinelli 1987

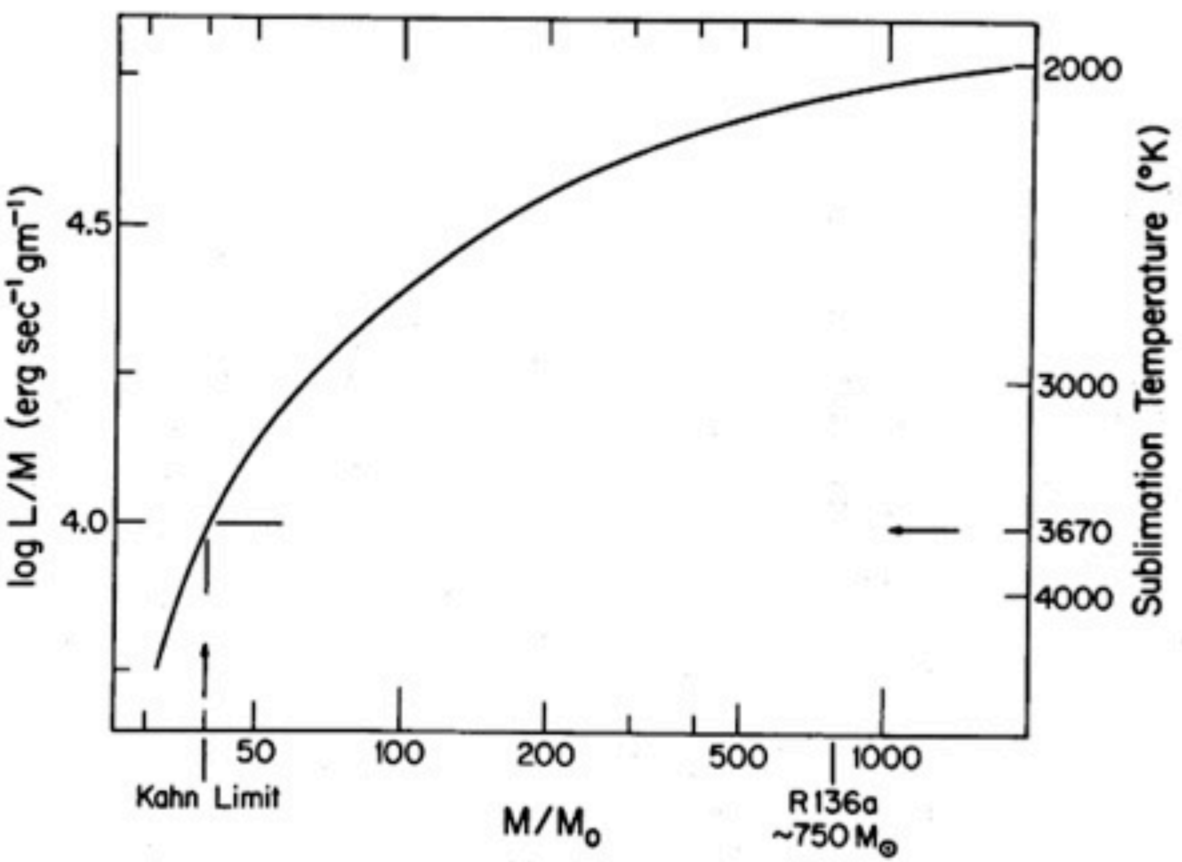
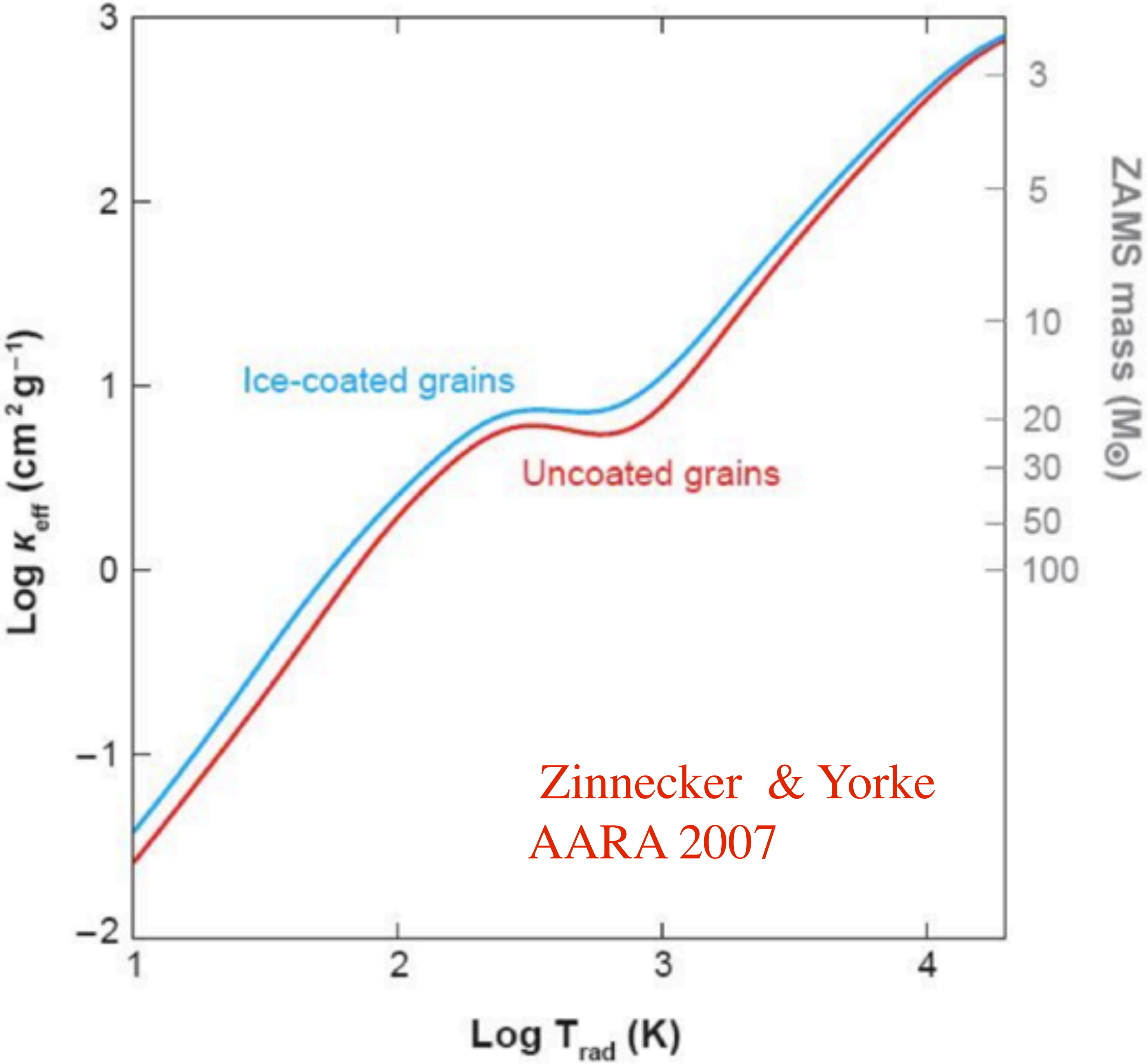


FIG. 1.—Relation between the Kahn upper mass limit and the dust sublimation temperature. Decreasing the sublimation temperature allows the core to have a larger L/M and a correspondingly larger mass. The sublimation temperature of ~ 3600 K, assumed by Kahn, allows a maximum L/M of $\sim 10^4$ ergs s^{-1} g^{-1} or a core mass of $\sim 40\ M_{\odot}$.



Zinnecker & Yorke
AARA 2007

Wolfire & Cassinelli 1987

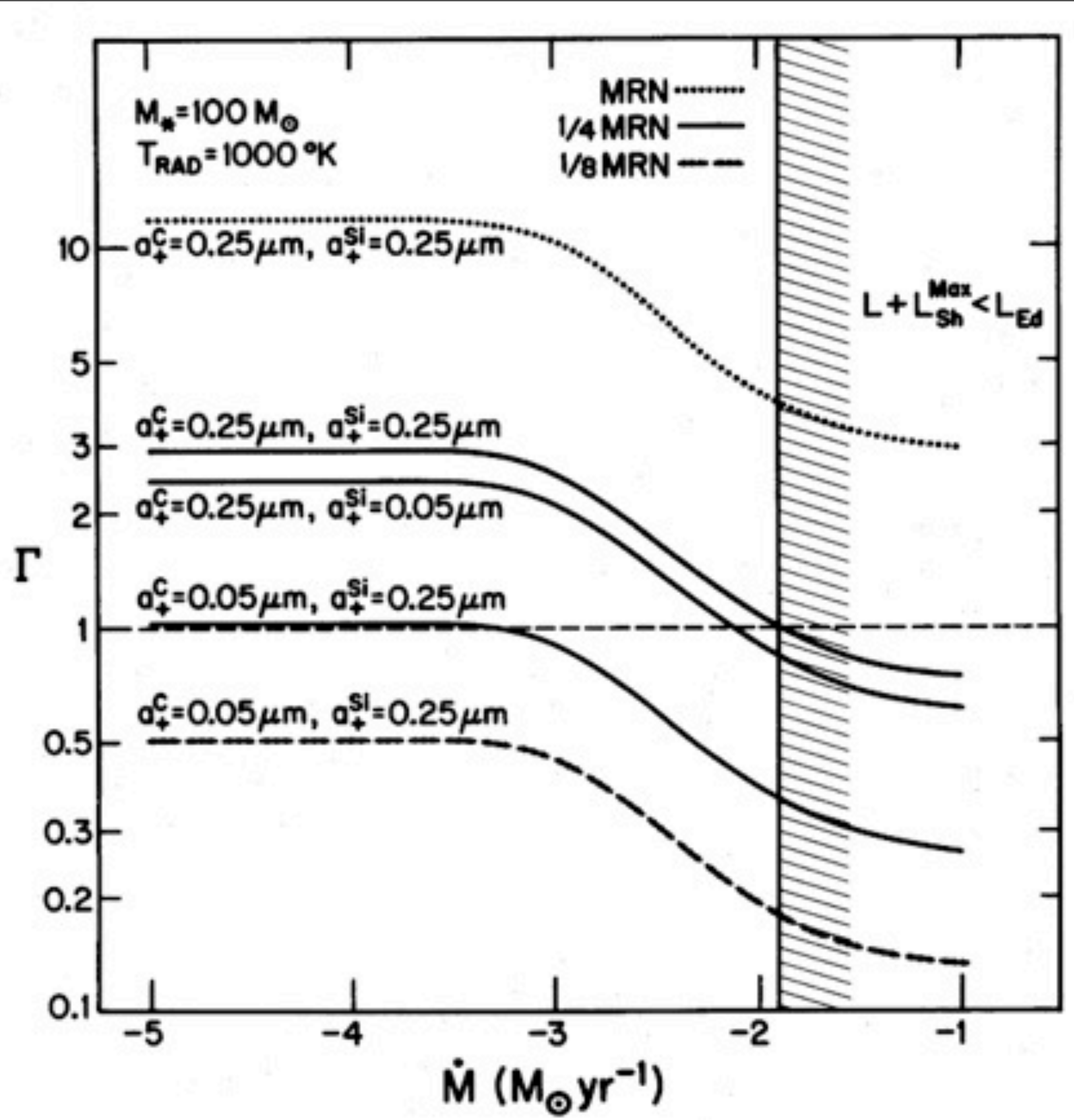
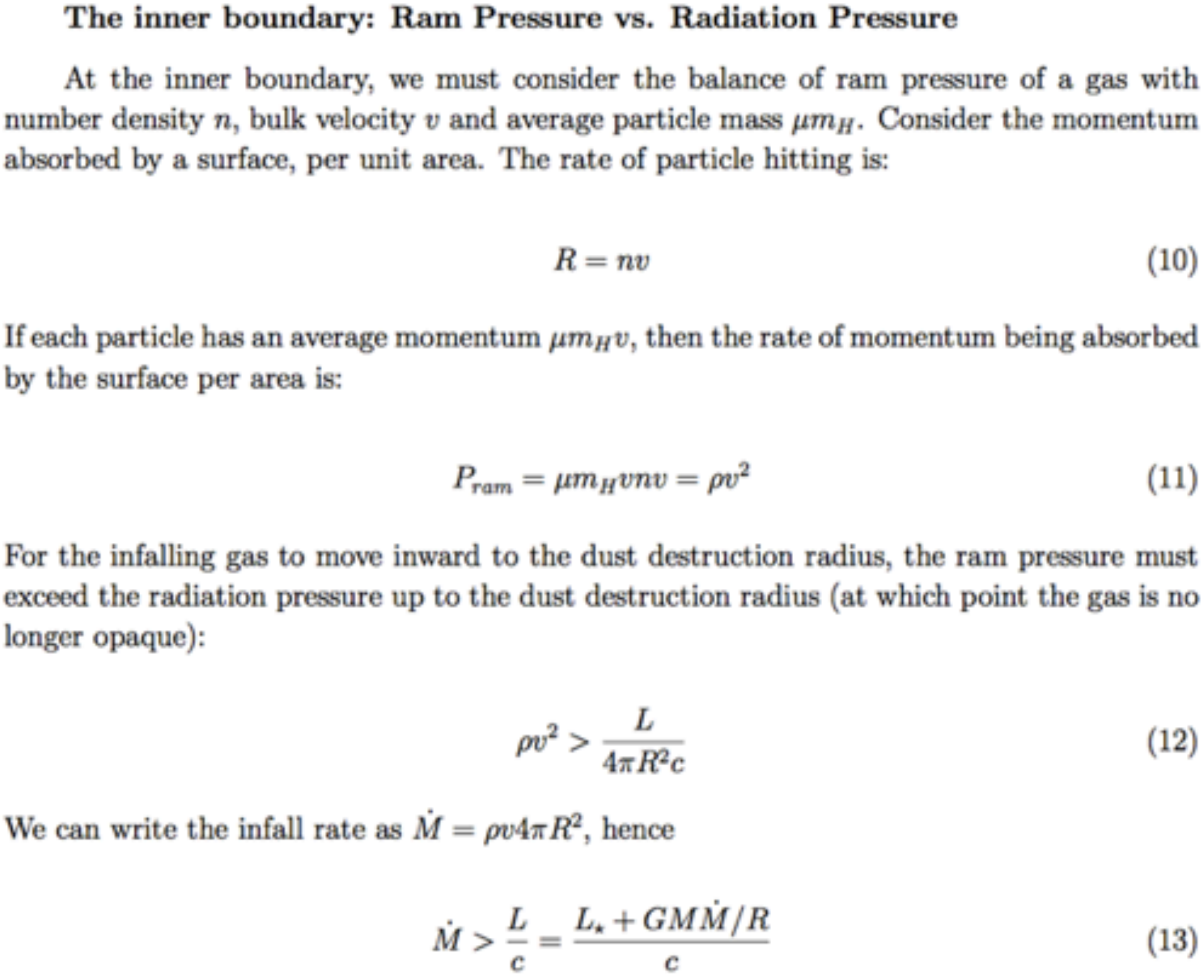


FIG. 3.—Ratio of outward radiative acceleration to inward gravitational acceleration, Γ, evaluated for $T_{\rm rad} = 1000$ K at the outer boundary of the dust shell vs. mass accretion rate. Shown are curves for the MRN diffuse cloud grain model (*dotted*), grain models where the overall scale factors for both compositions are reduced by a factor of 4 (*solid*), and overall scale factors reduced by a factor of 8 (*dashed*). Accretion rates greater than $\dot{M} = 1.2 \times 10^{-2}$ produce a total luminosity greater than the core's Eddington luminosity.

The Inner Boundary



The inner boundary: Ram Pressure vs. Radiation Pressure

At the inner boundary, we must consider the balance of ram pressure of a gas with number density n, bulk velocity v and average particle mass μm_H. Consider the momentum absorbed by a surface, per unit area. The rate of particle hitting is:

$$R = nv \tag{10}$$

If each particle has an average momentum $\mu m_H v$, then the rate of momentum being absorbed by the surface per area is:

$$P_{ram} = \mu m_H v n v = \rho v^2 \tag{11}$$

For the infalling gas to move inward to the dust destruction radius, the ram pressure must exceed the radiation pressure up to the dust destruction radius (at which point the gas is no longer opaque):

$$\rho v^2 > \frac{L}{4\pi R^2 c} \tag{12}$$

We can write the infall rate as $\dot{M} = \rho v 4\pi R^2$, hence

$$\dot{M} > \frac{L}{c} = \frac{L_\star + GM\dot{M}/R}{c} \tag{13}$$

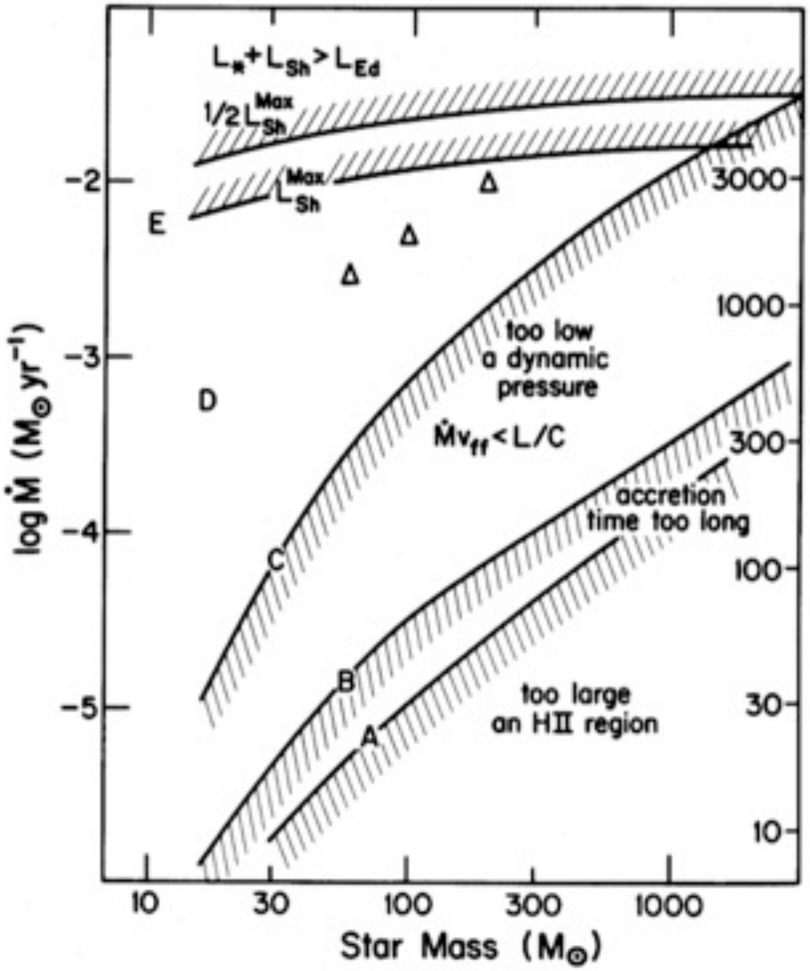
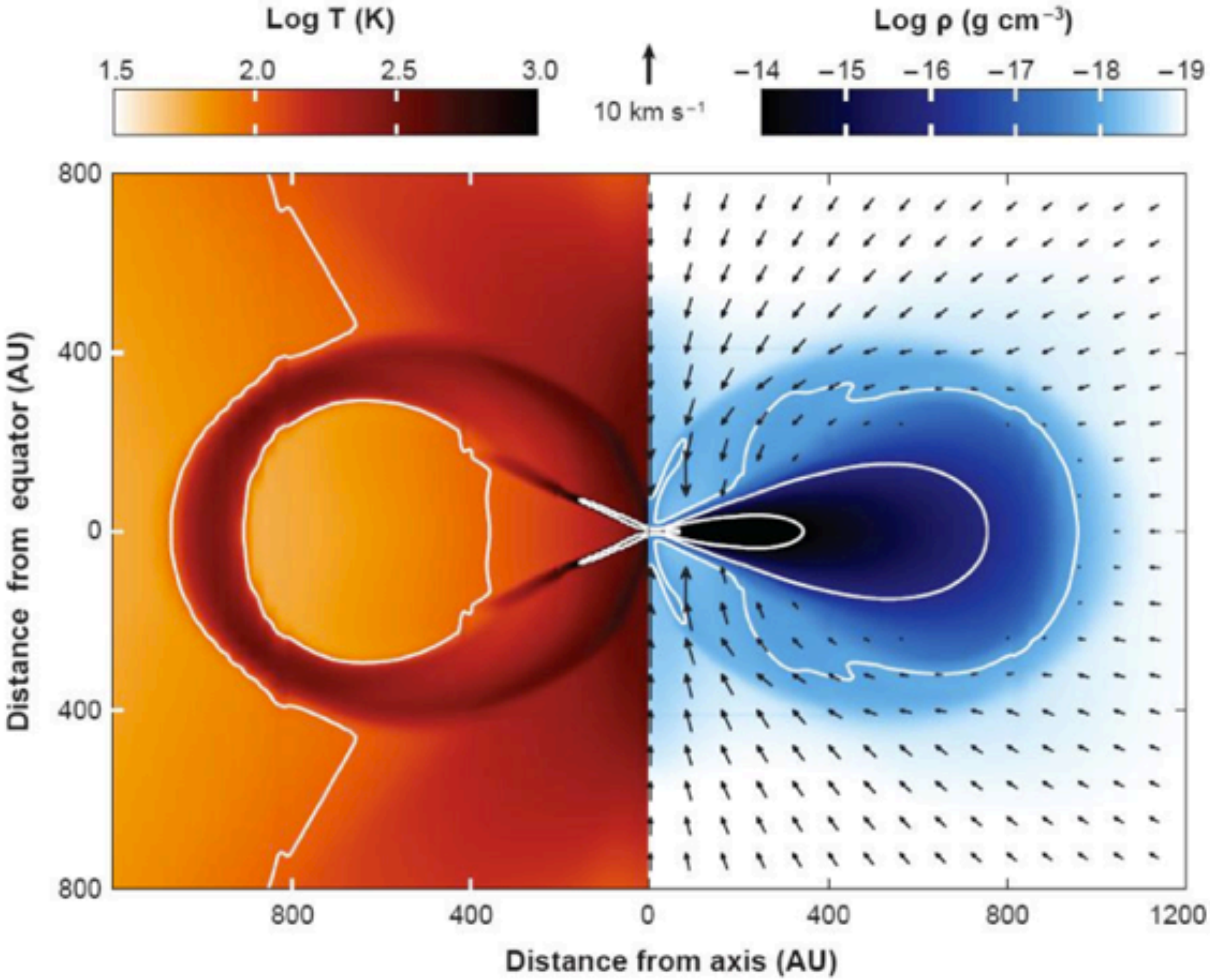
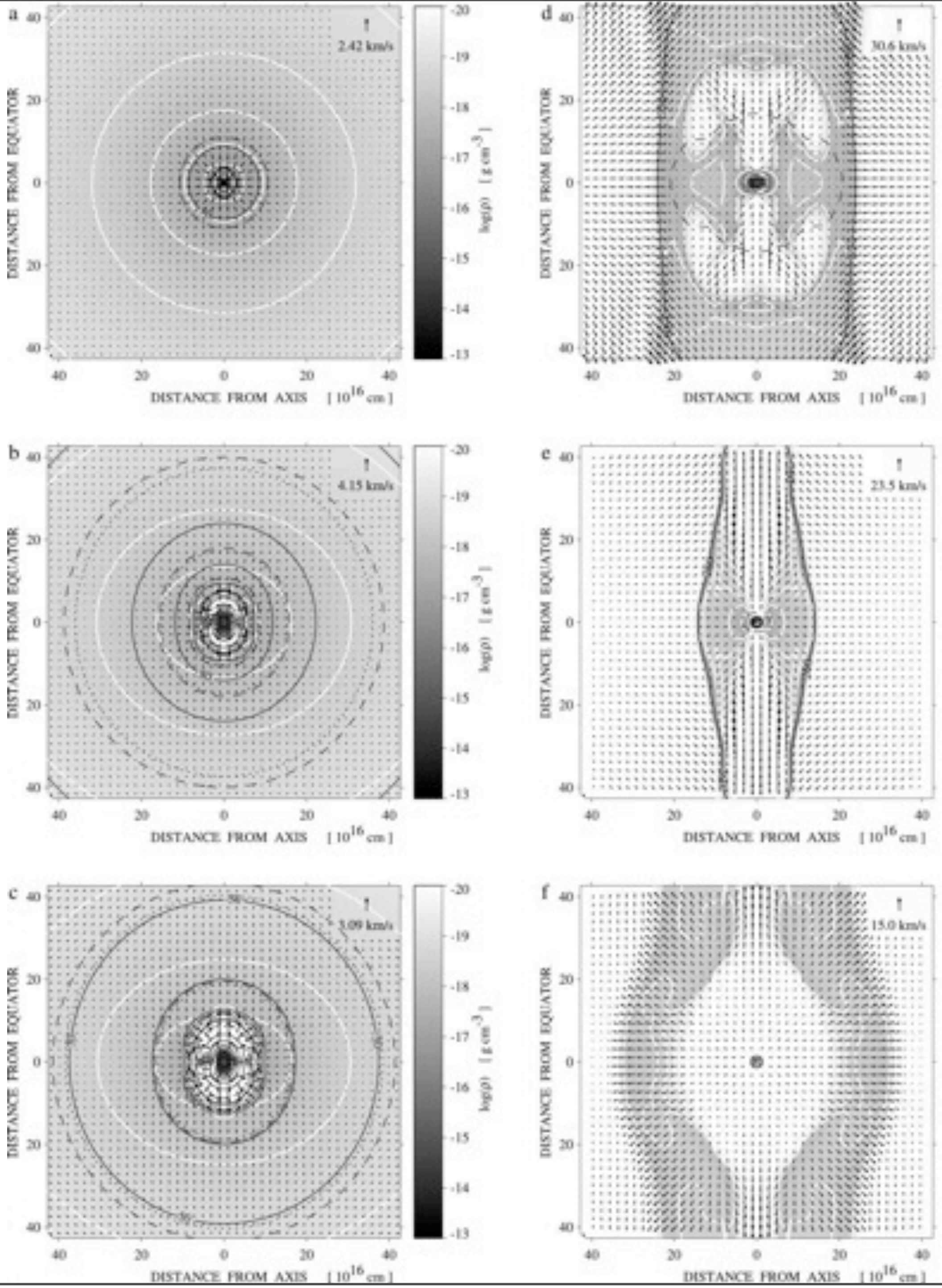


FIG. 5.—Region of accretion rate vs. core mass that allows inflow to occur (region D). Cores with accretion rates in region A have H II regions that expand beyond the dust destruction radius. Below the limit B the mass accretion time ($M_*/\dot{M}$) exceeds the core evolutionary lifetime. Inflows with accretion rates below C are halted by the stellar radiation field. Above the limit E the core plus shock luminosity exceeds the core's Eddington luminosity. Shown are curves for the maximum and one-half the maximum shock luminosity. The equivalent support temperature (eq. [21]) is shown on the right-hand side. The accretion rates of our numerical inflow models (§ V) are plotted (Δ).

Wolfire & Cassinelli 1987

Massive Star Formation in a Rotating Core





Yorke & Sonnhalter 2002

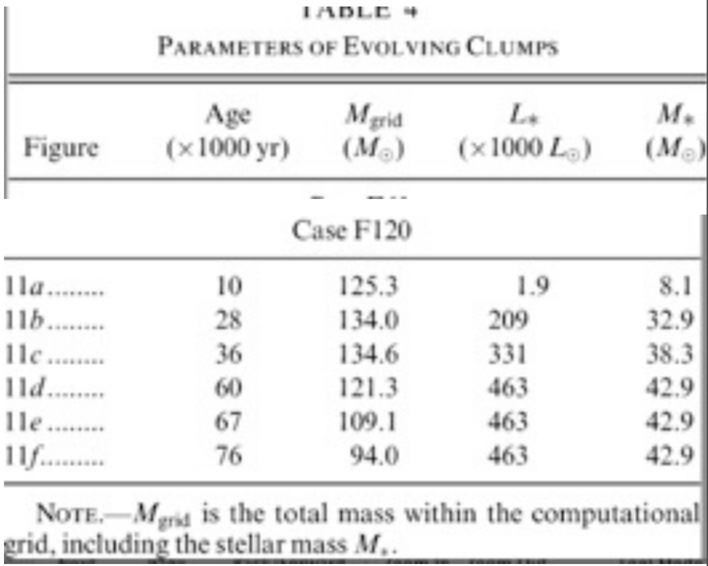
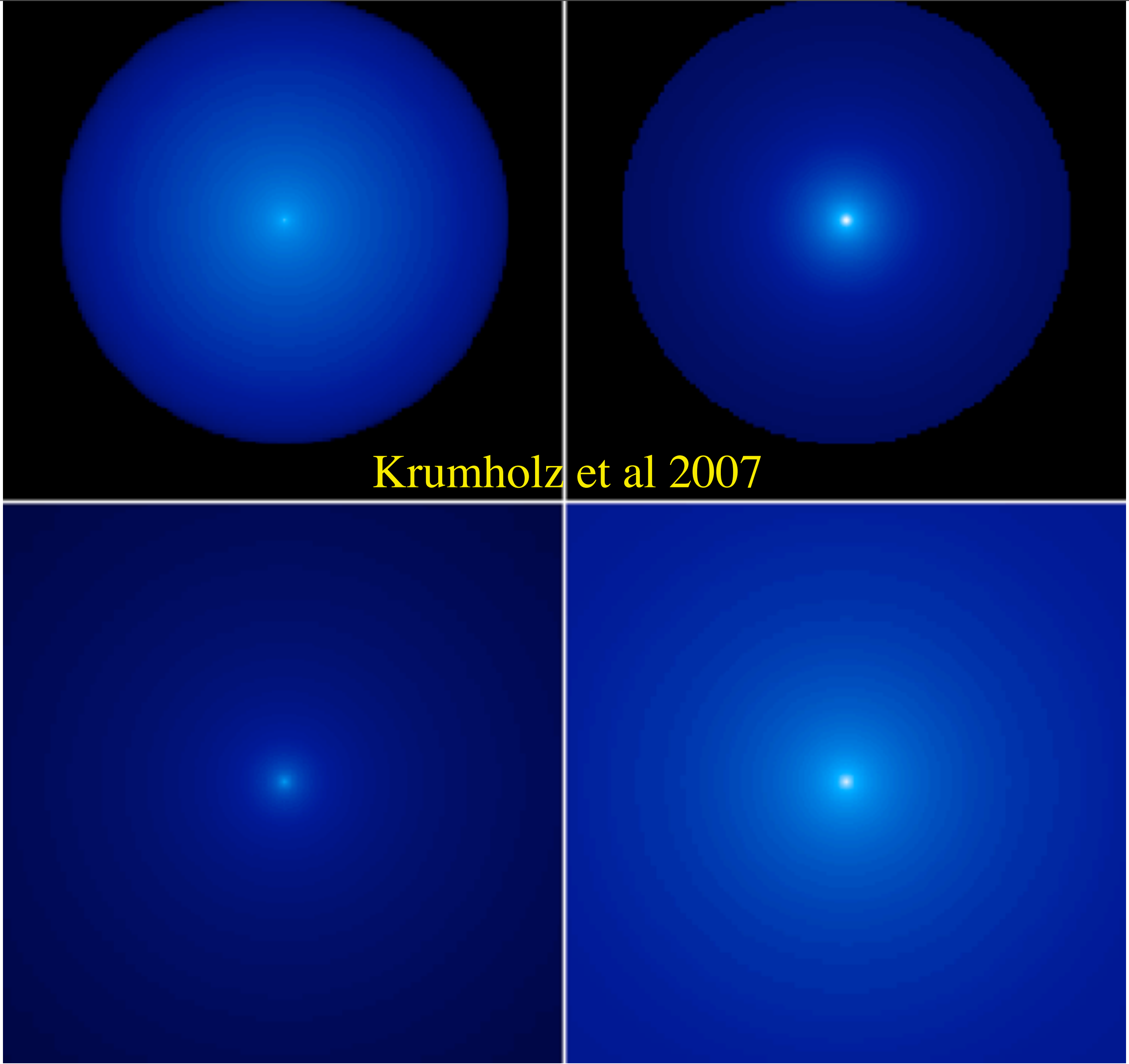


TABLE 4

PARAMETERS OF EVOLVING CLUMPS

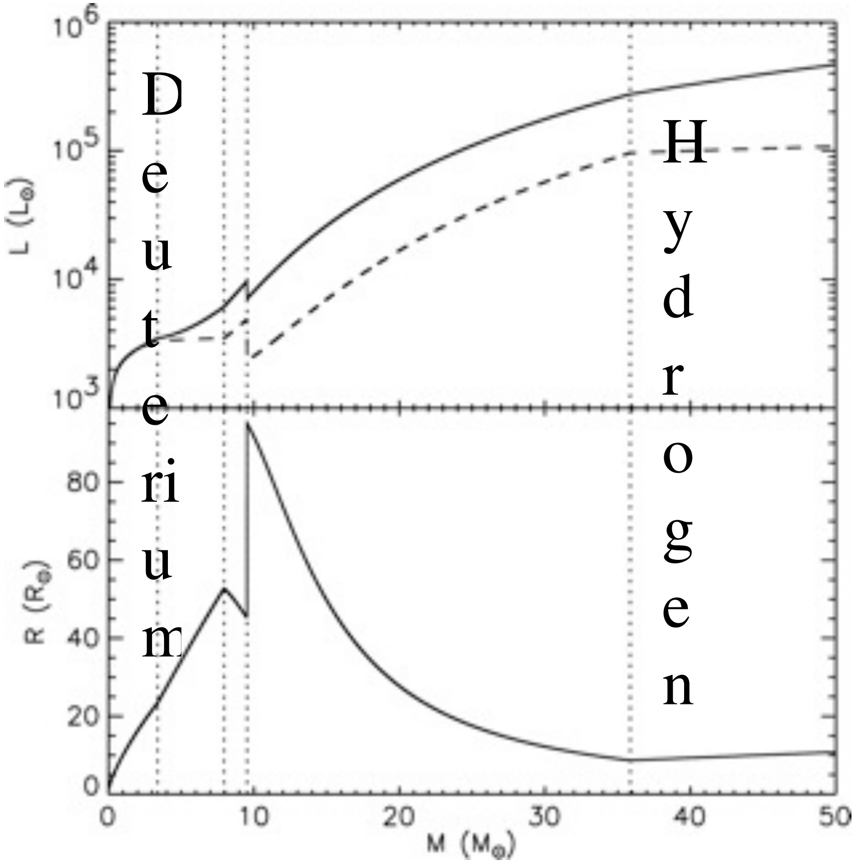
Figure	Age ($\times$1000 yr)	$M_{\rm grid}$ ($M_\odot$)	L_* ($\times$1000 $L_\odot$)	M_* ($M_\odot$)
Case F120				
11*a*........	10	125.3	1.9	8.1
11*b*........	28	134.0	209	32.9
11*c*........	36	134.6	331	38.3
11*d*........	60	121.3	463	42.9
11*e*........	67	109.1	463	42.9
11*f*........	76	94.0	463	42.9

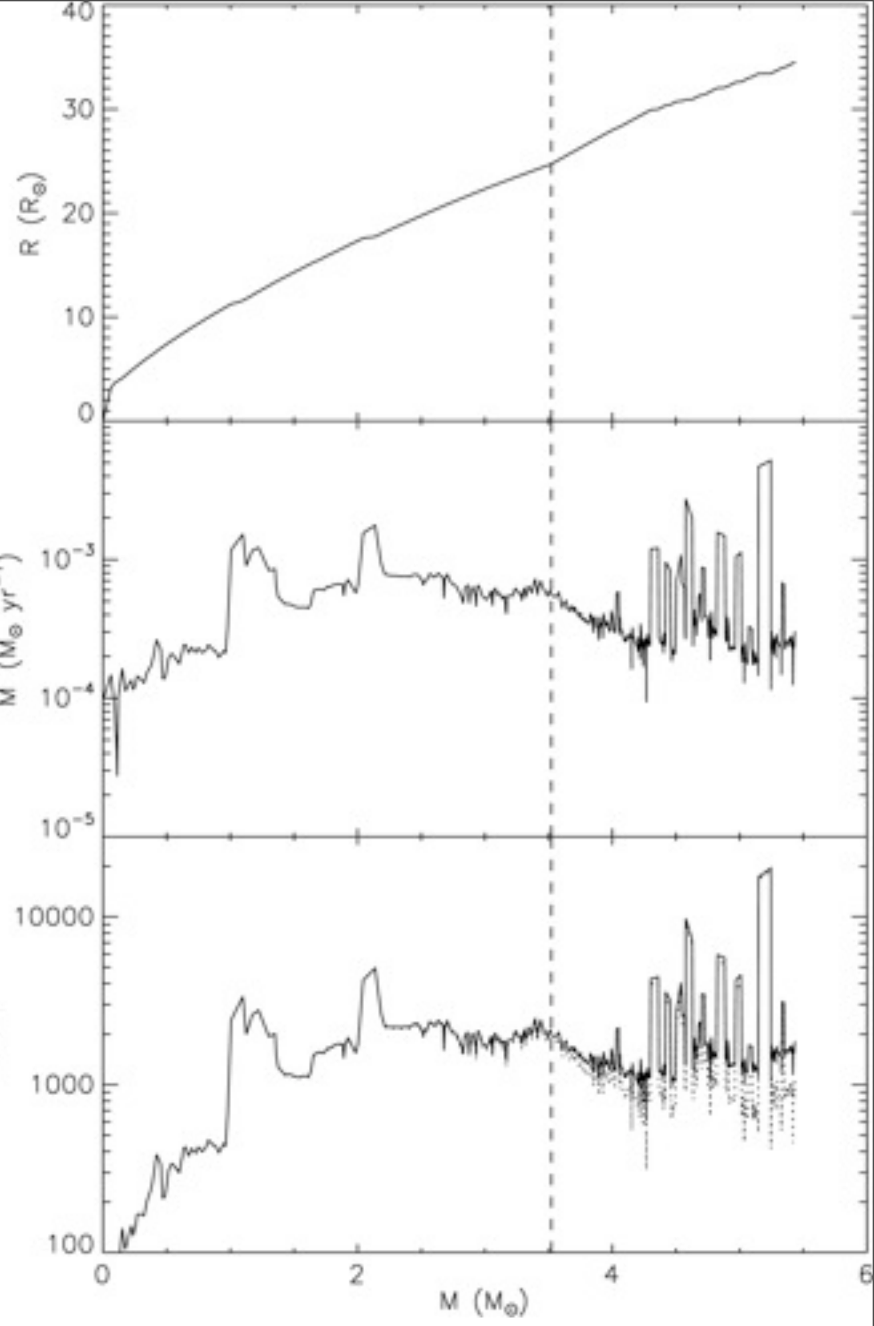
NOTE.—$M_{\rm grid}$ is the total mass within the computational grid, including the stellar mass M_*.



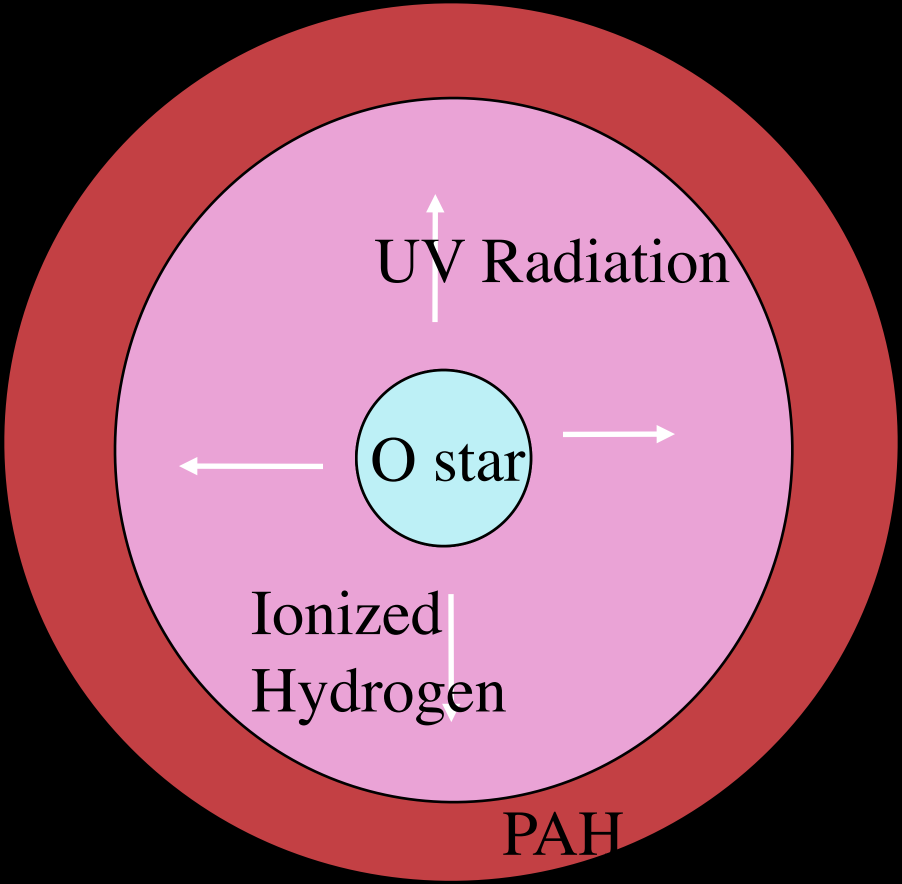
Krumholz et al 2007

Growth of high mass protostar: Krumholz et al. 2007, McKee & Tan 2003





HII Regions



UV radiation from hot stars can ionize hydrogen atoms in the surrounding cloud.

The ionized Hydrogen is referred to as HII

Neutral hydrogen: HI
Ionized hydrogen: HII

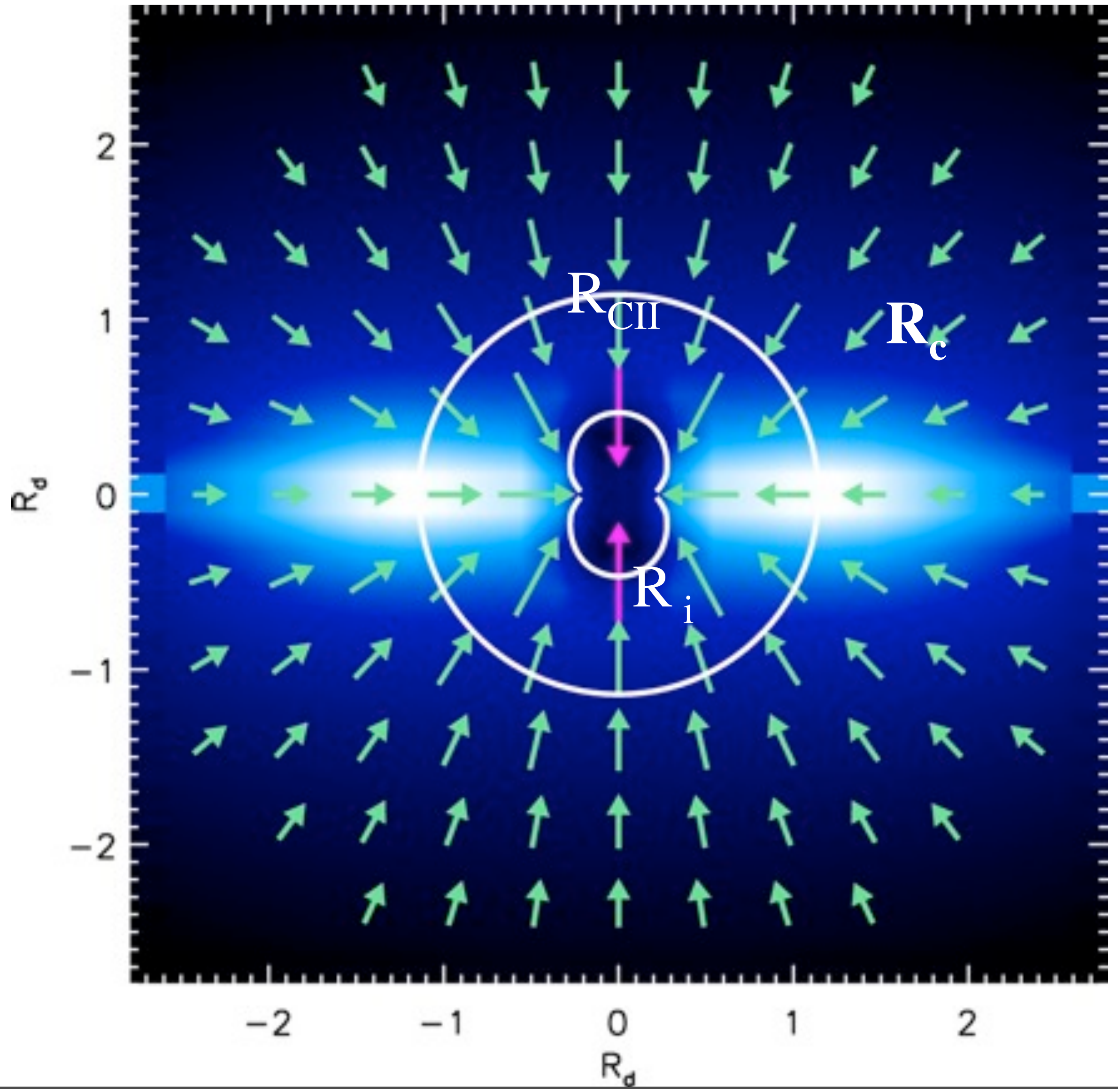
$H + UV \rightarrow p^{+} + e^{-}$ Ionization

$p^{+} + e^{-} \rightarrow H$ Recombination

An equilibrium is reach where the number of ionizations equal the number of recombinations.

All UV radiation with wavelengths of $\lambda < 912$ Angstroms or $\lambda < 0.0912$ Microns is absorbed.

The 3 r's (Keto 2007)

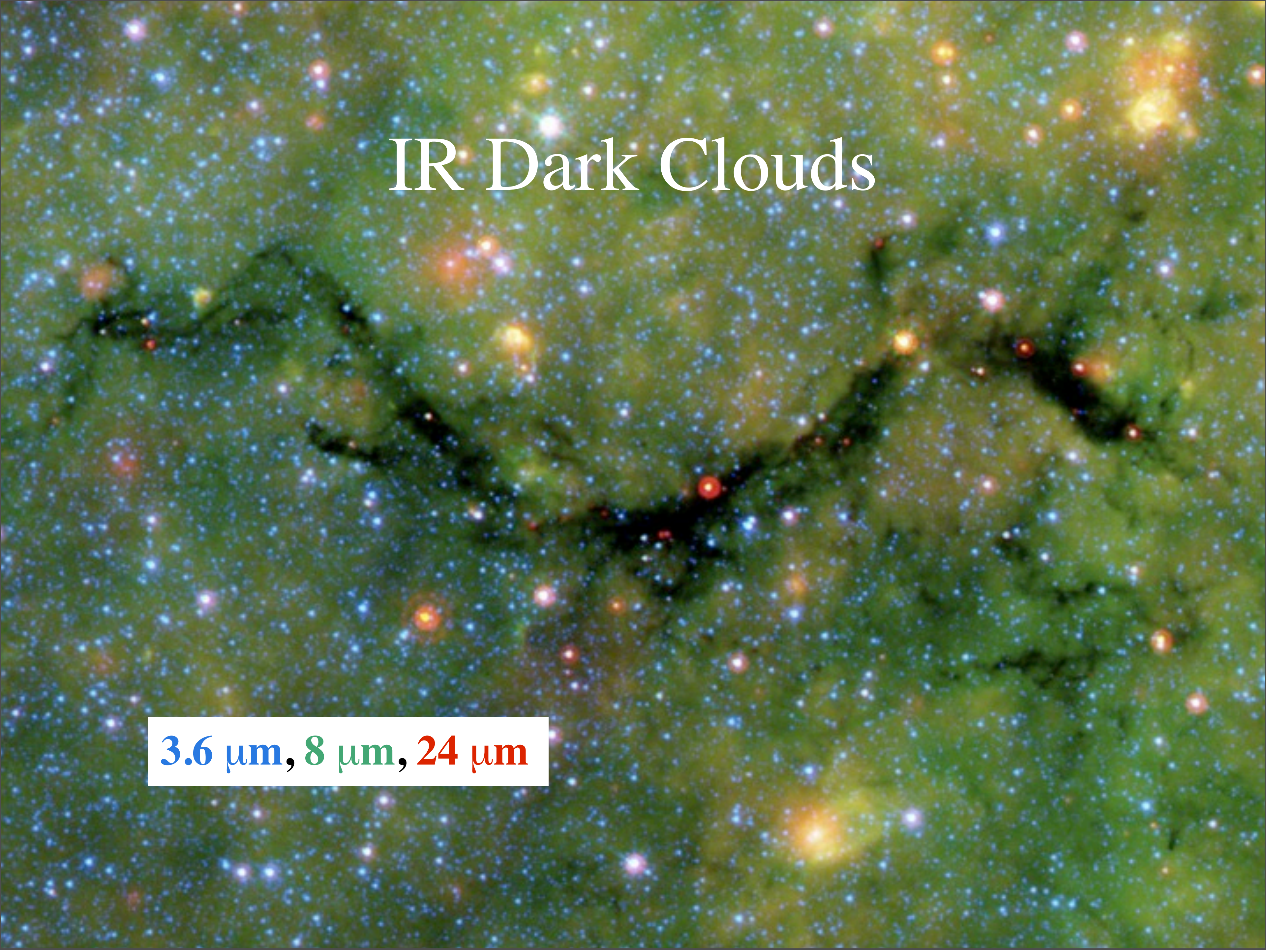


Massive Star Evolution

Formation sites: IR Dark Cloud

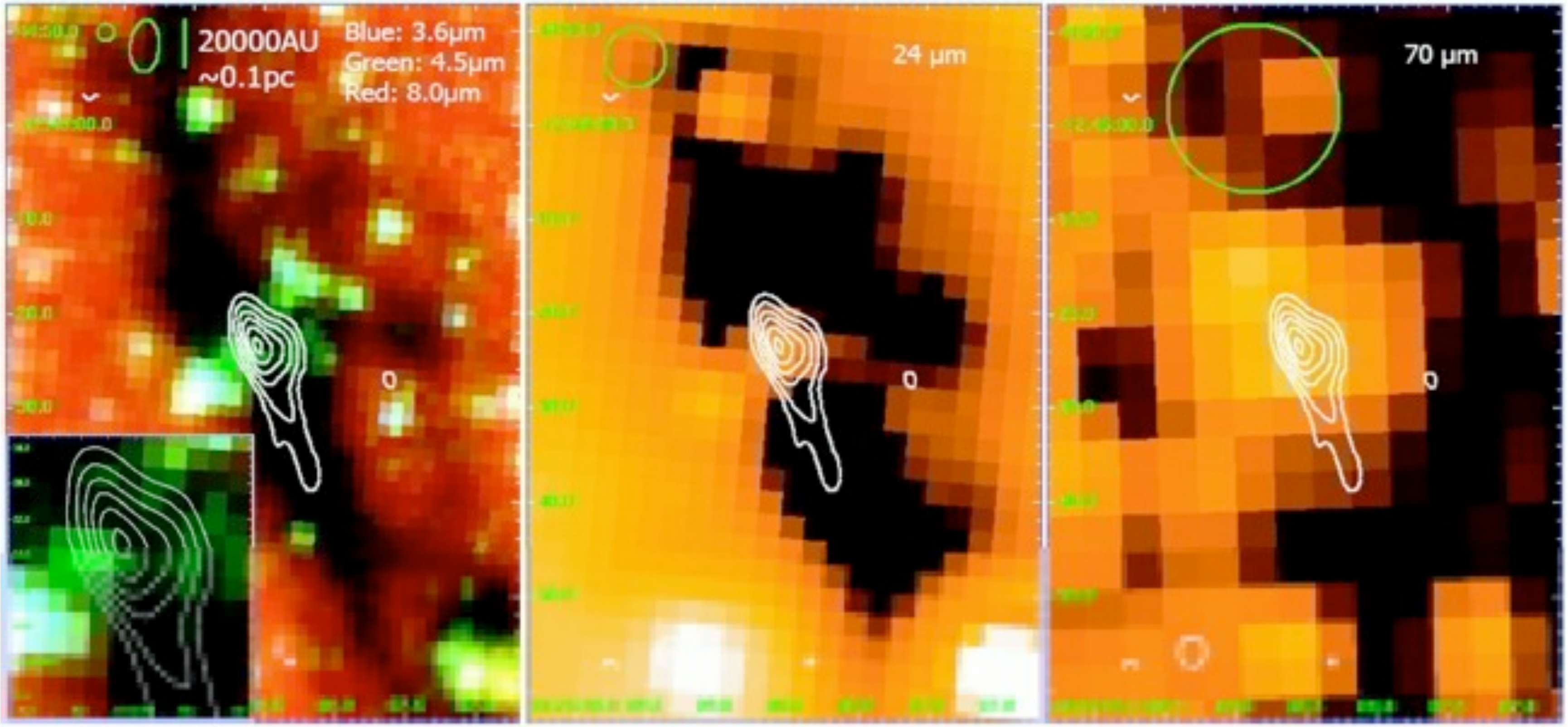
1. Detection of earliest phases (10^4 years):
   - i Dust continuum source such as Orion IRC2 or W3 IRS 5
   - ii Hot Cores such as G29.96
   - iii. Outflows
2. Hypercompact HII regions (10^4 years)
3. Final phase: Ultracompact, Compact HII Regions (10^5 years)

IR Dark Clouds



3.6 μm, 8 μm, 24 μm

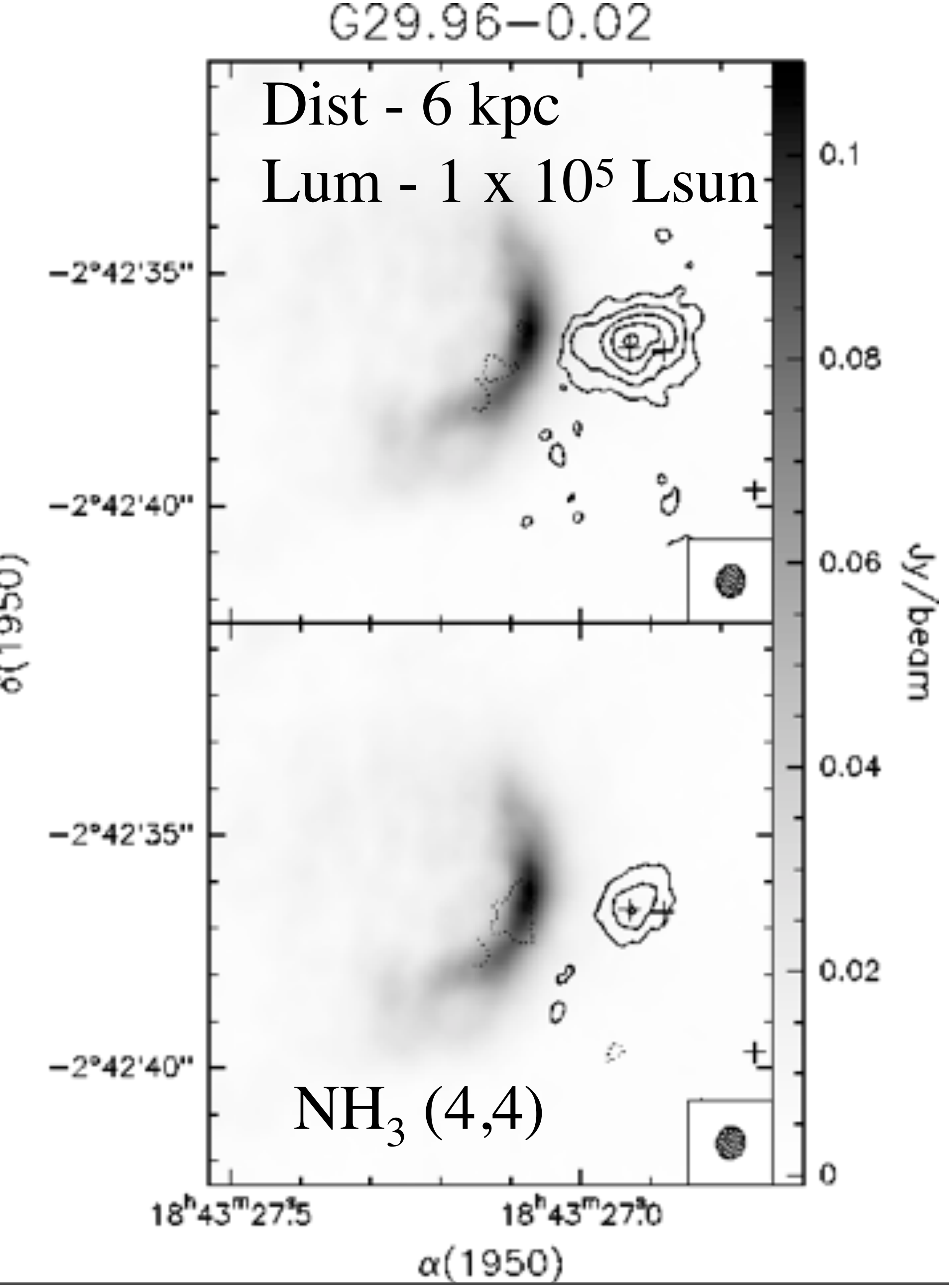
Infrared Dark Clouds with Dust Continuum Source



Contours: SMA 850 μm

Beuther et al. 2007

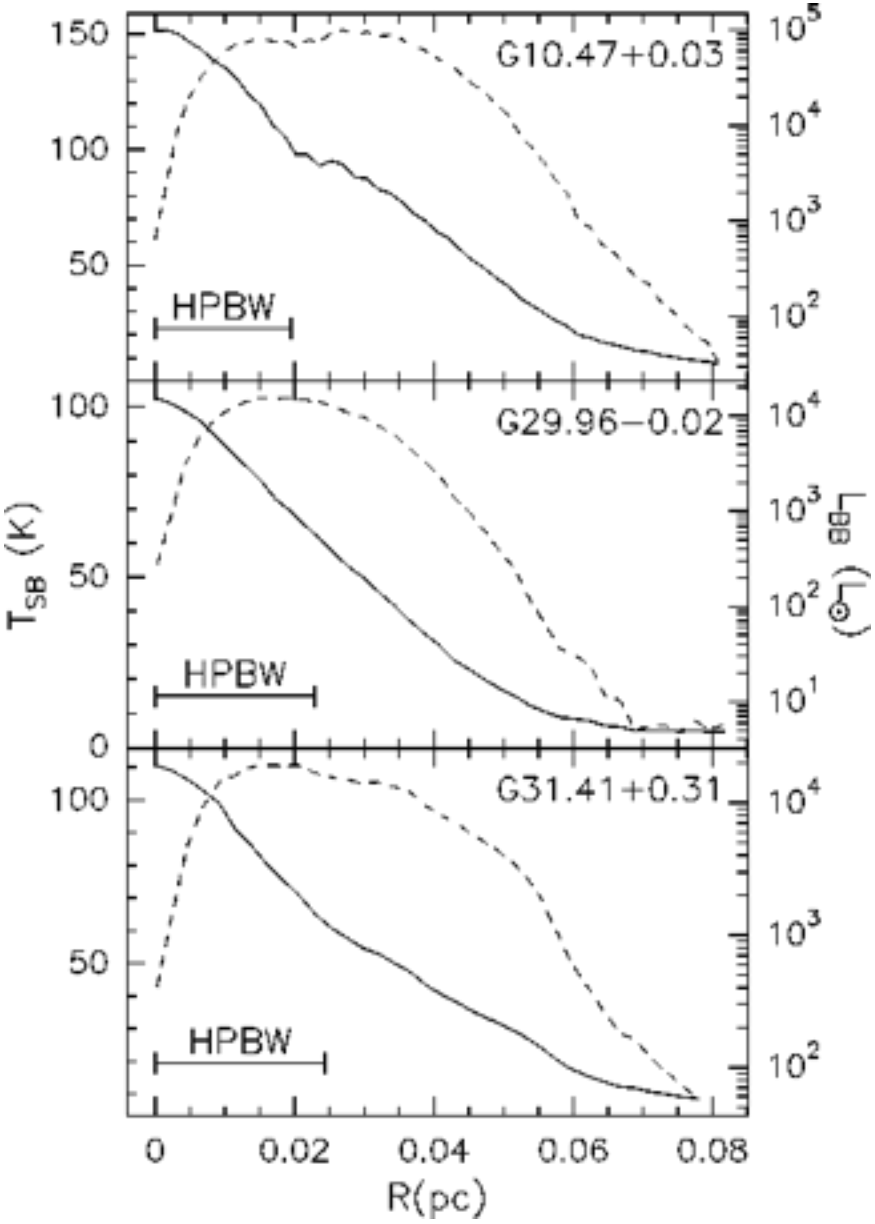
Hot Cores: Cesaroni



Dist - 6 kpc

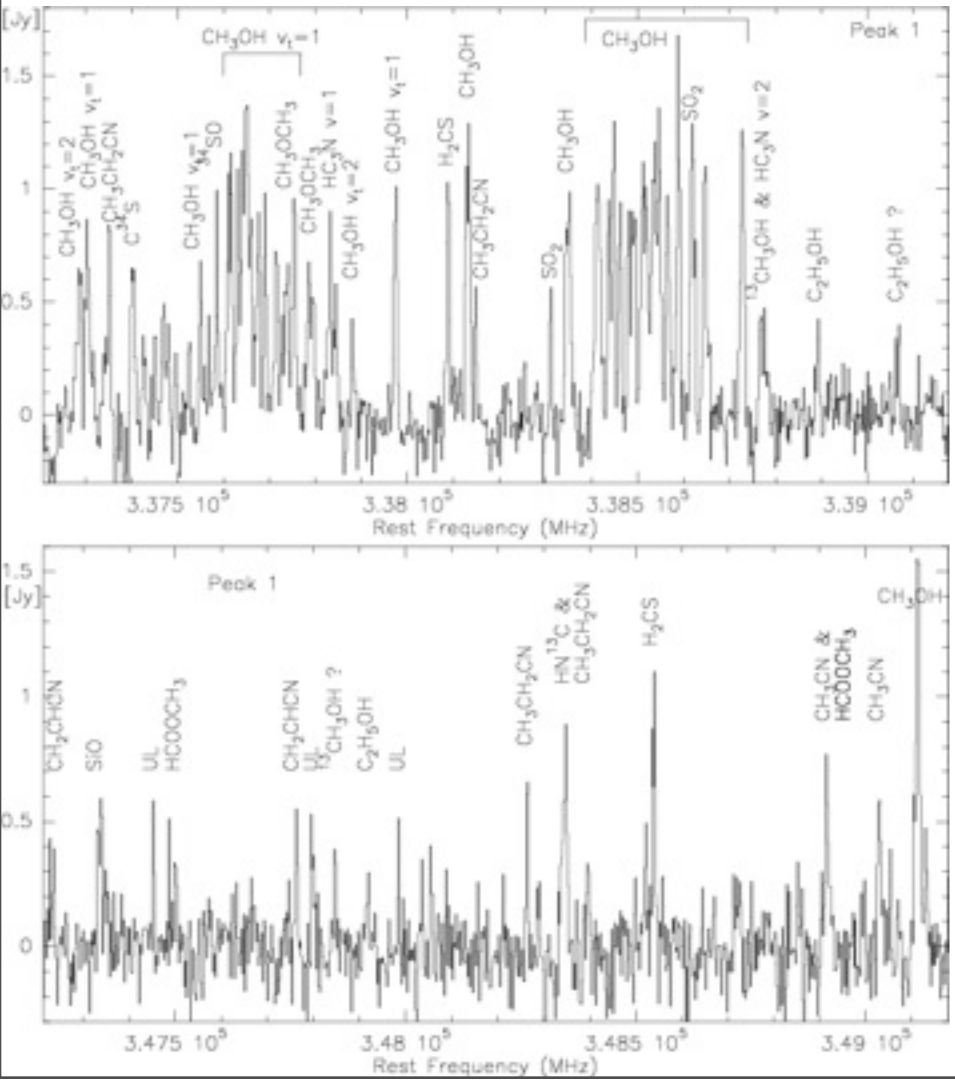
Lum - 1 x 10^5 Lsun

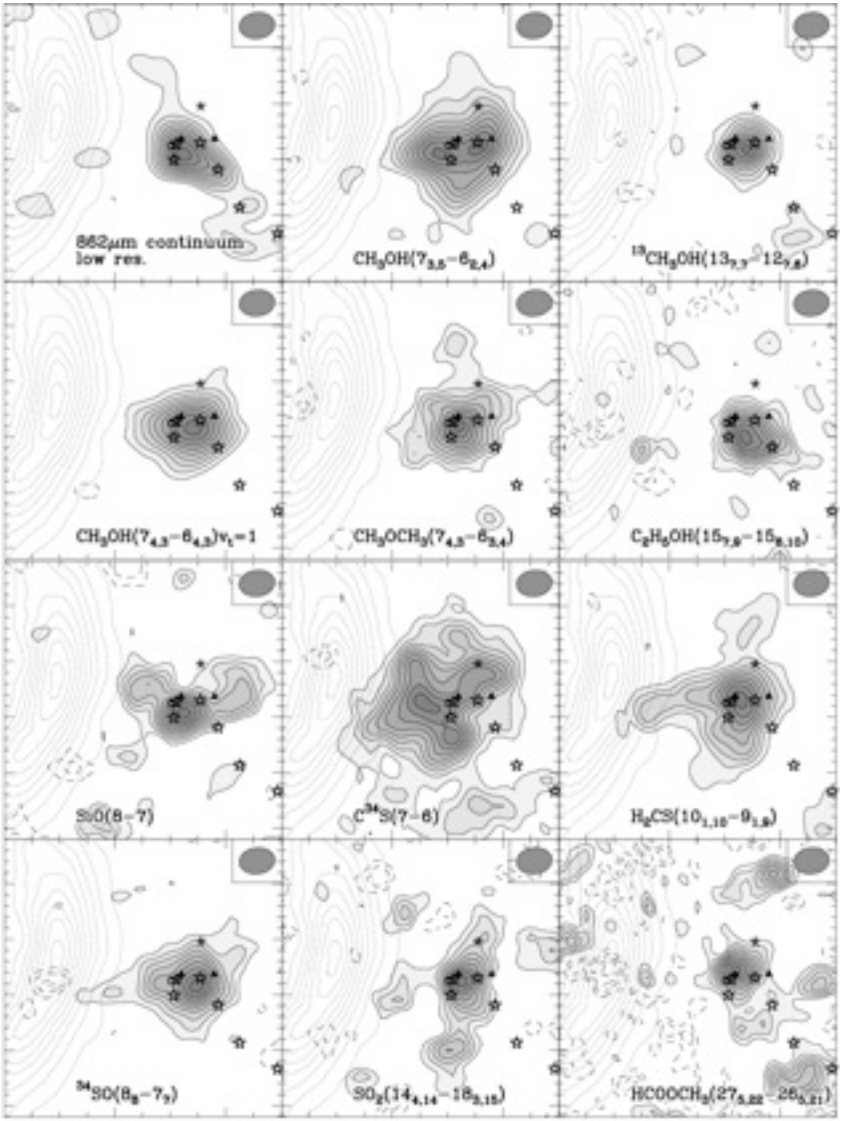
NH_3 (4,4)

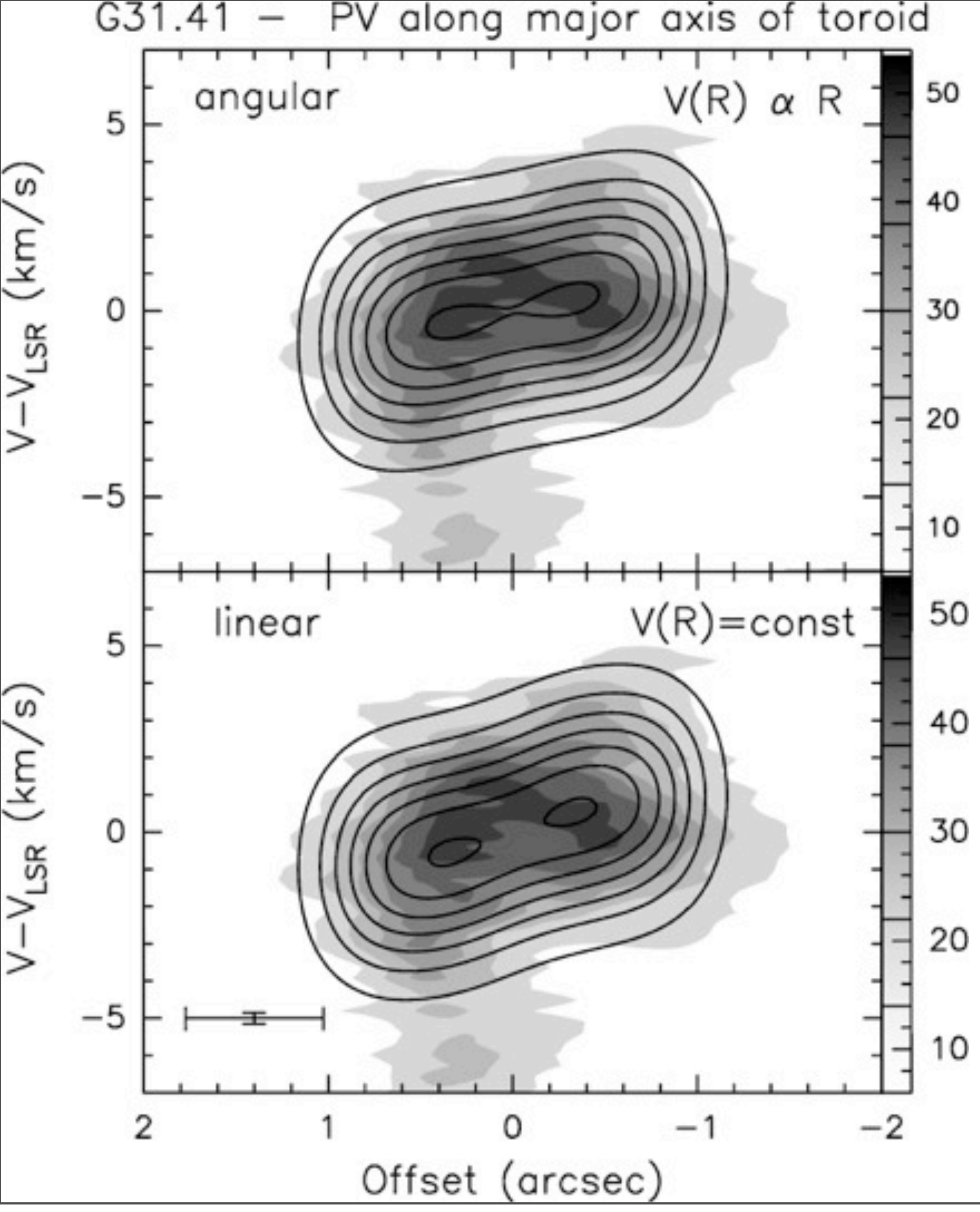


Hot Core Chemistry

Beuther et al. 2007

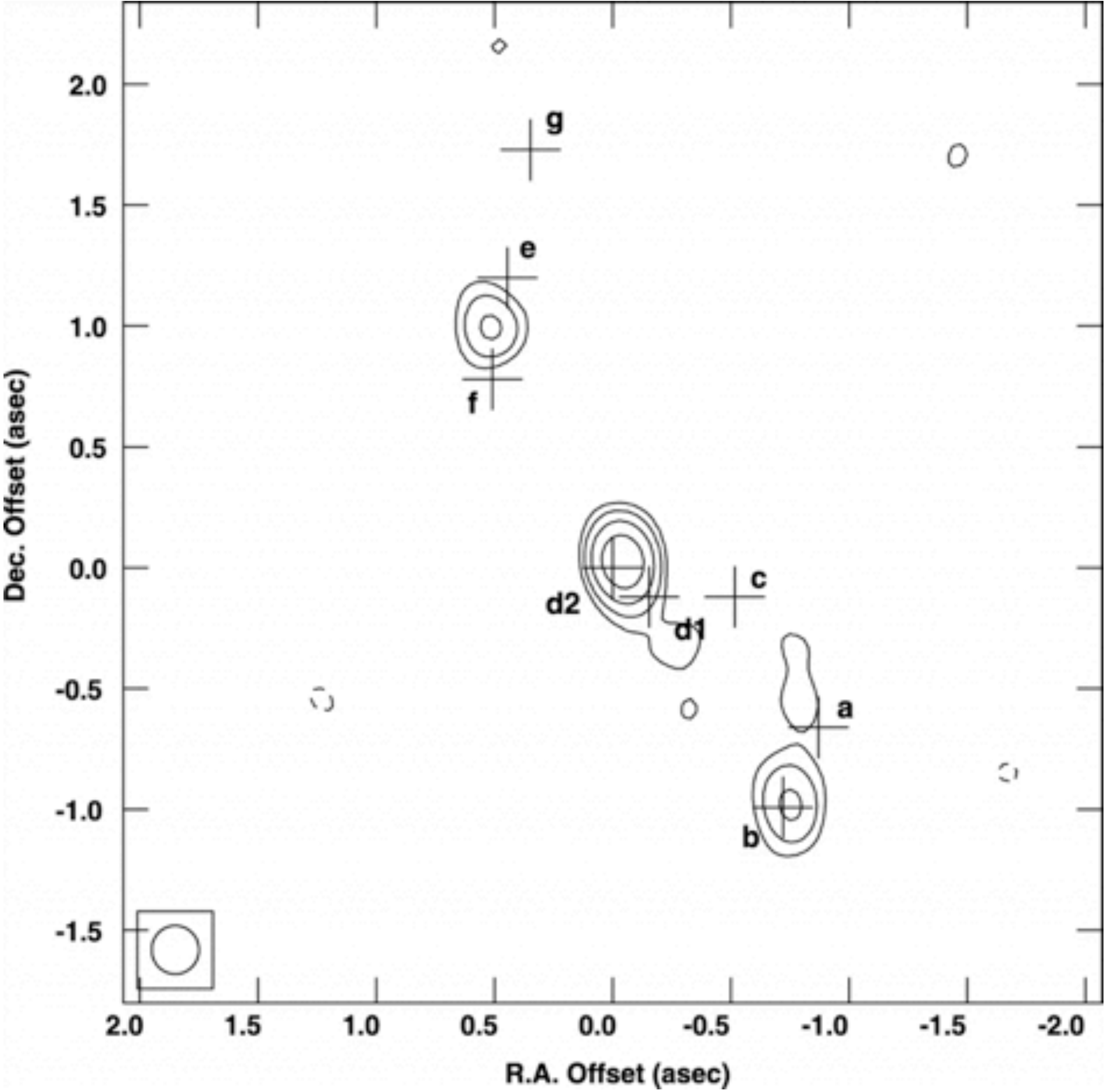


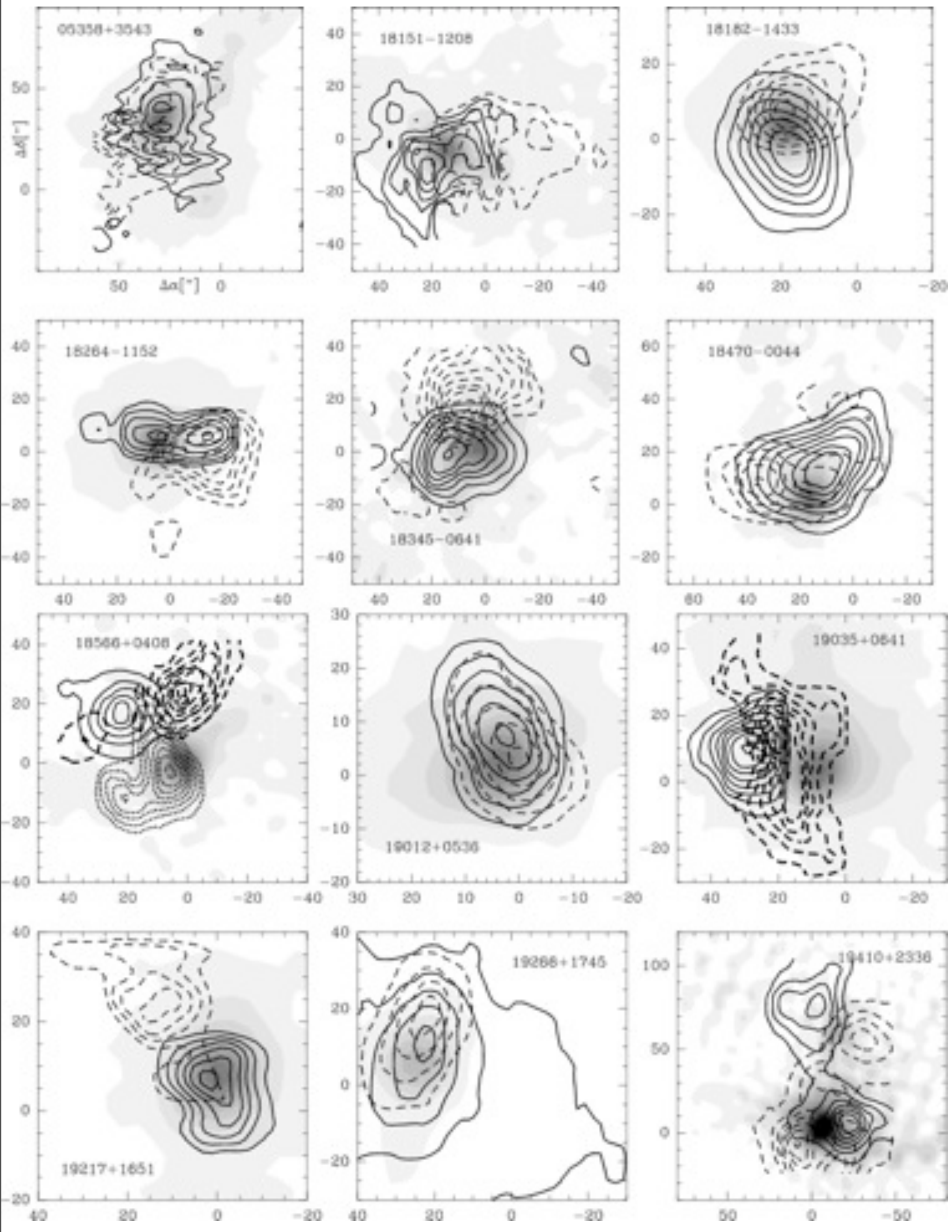




Rotating Toroids: Beltran et al. 2005

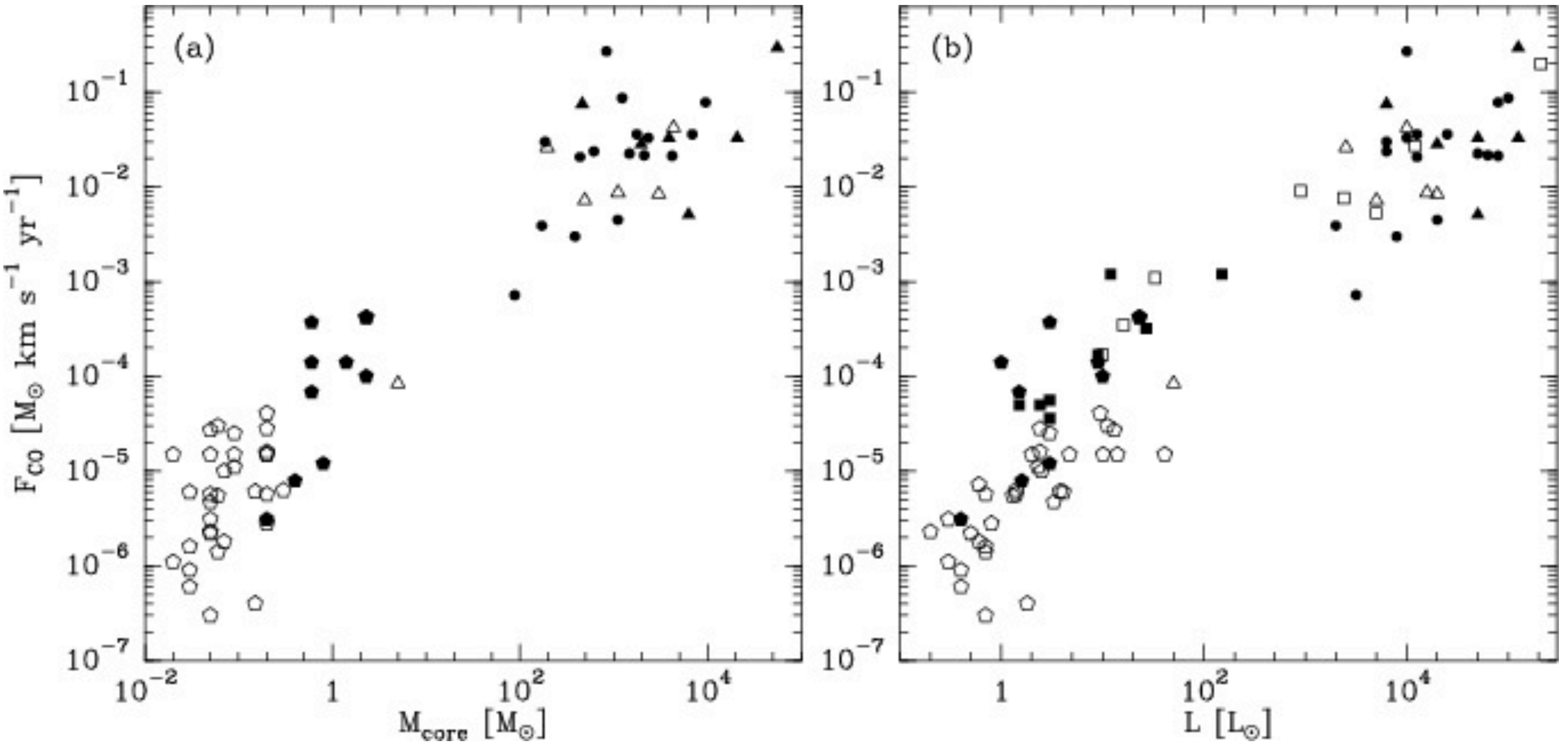
Hypercompact HII Regions



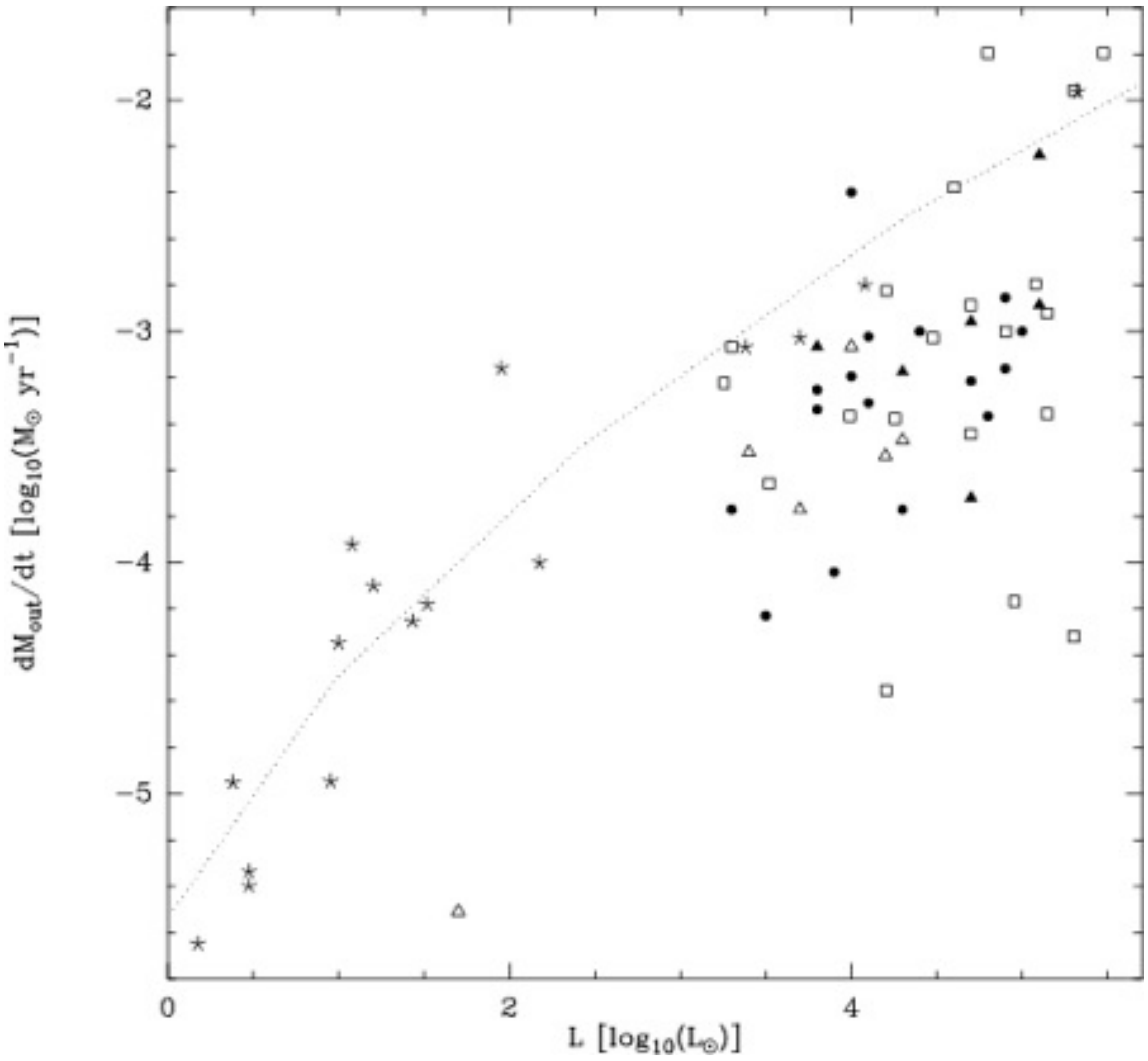


Survey of Outflows Toward HMPO: Beuther et al. 2002

Outflows: Beuther et al. 2002



Outflows: Beuther et al. 2002

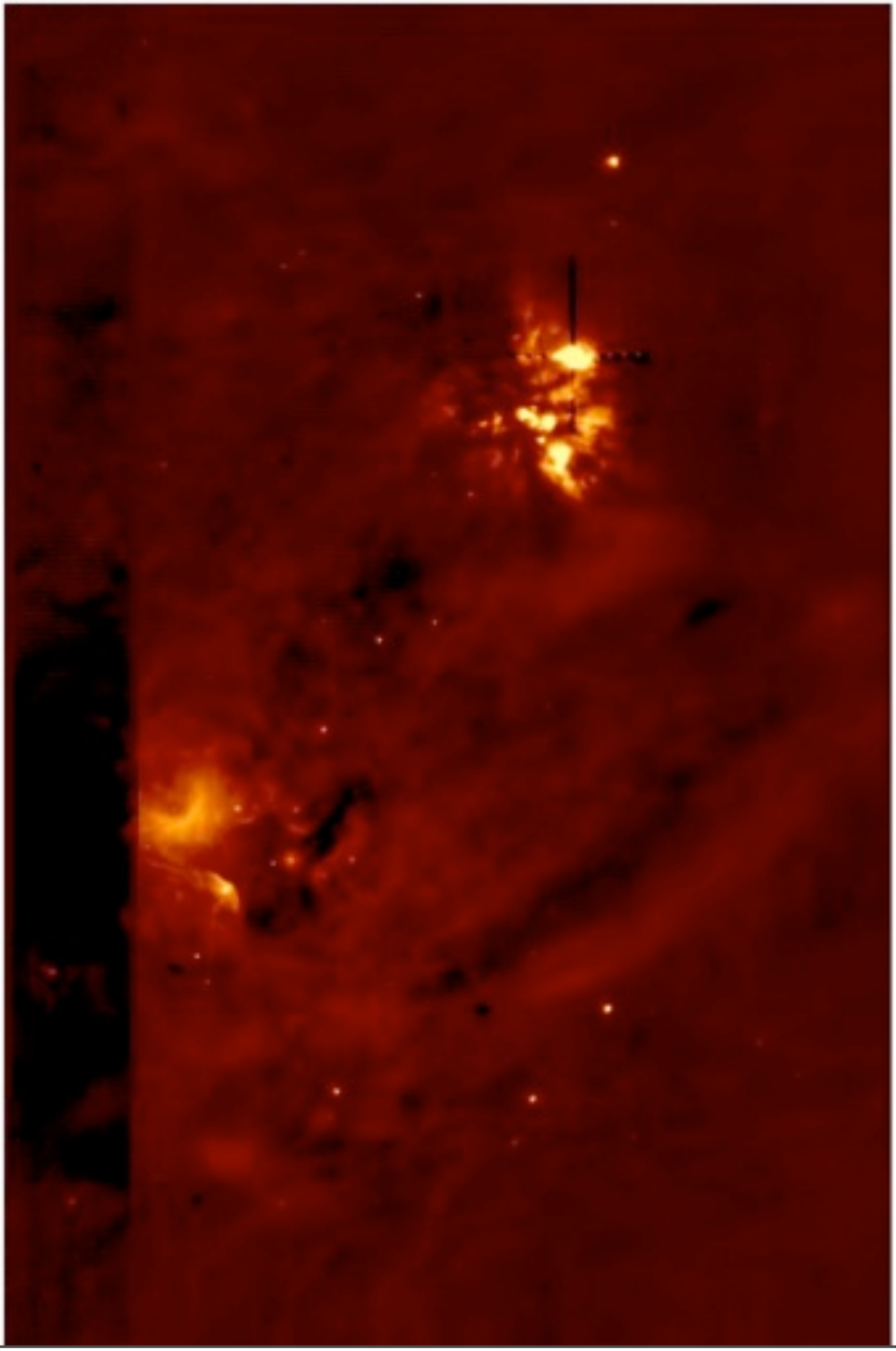


Where do we stand?

It is pretty clear that stars up 10^5 Lsun accrete like low mass stars - although disks not yet detected.

Some question about more massive objects.

11.7 μm

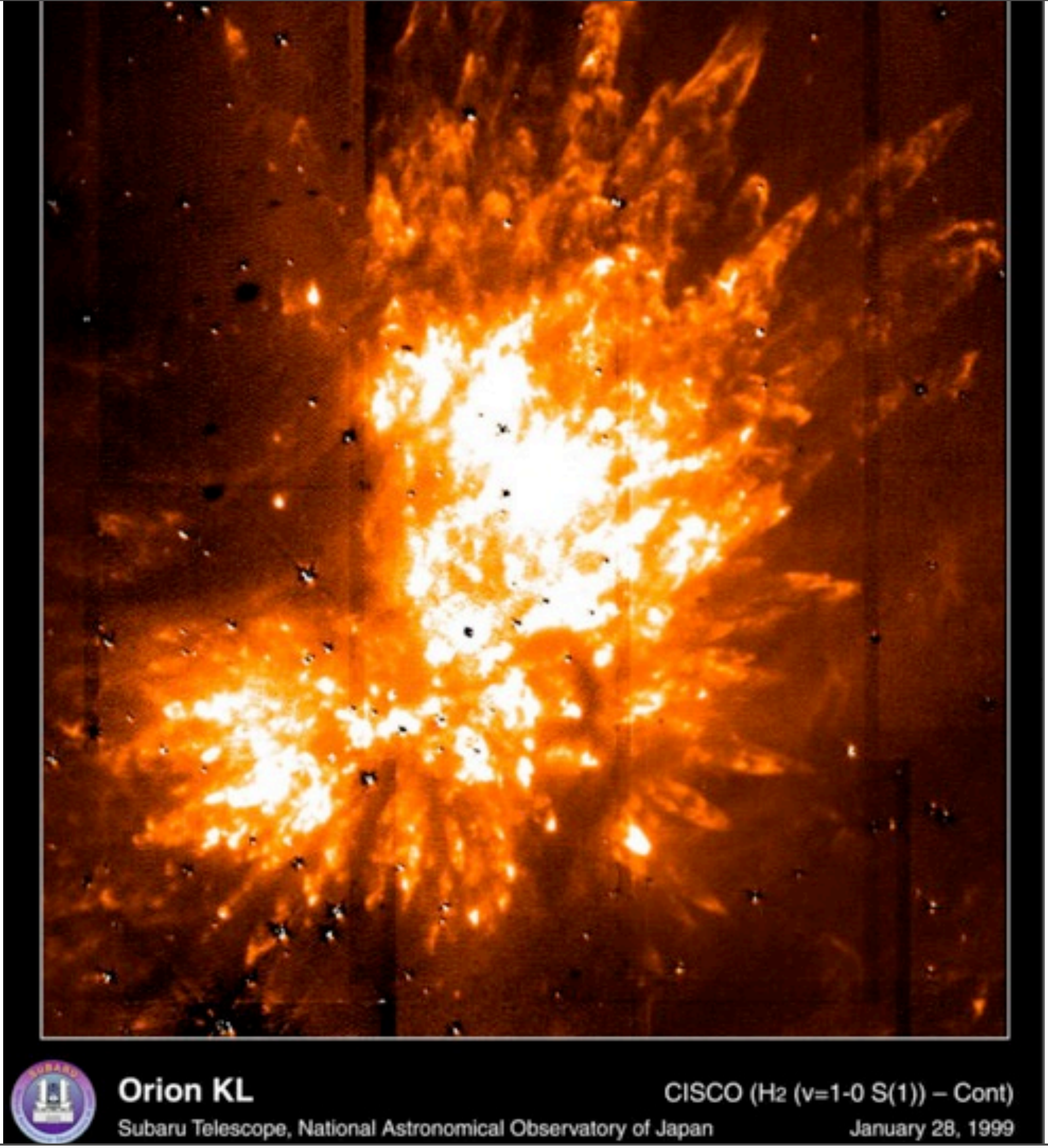


Orion Nebula

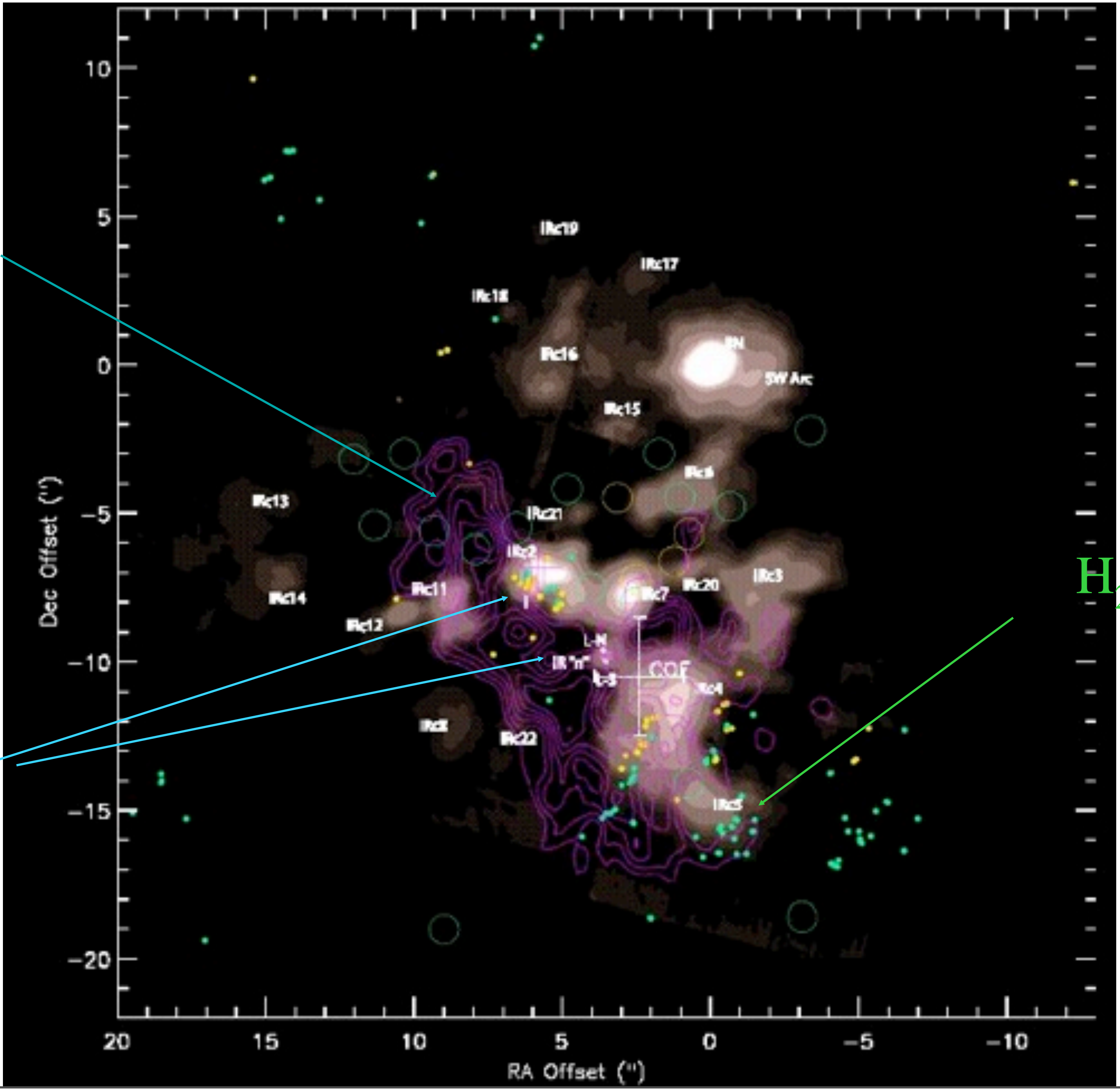
Hidden Massive Protostar:

Produced explosion 1,000 ago

Near Infrared



OMC1 - (Shuping et al. 2004)



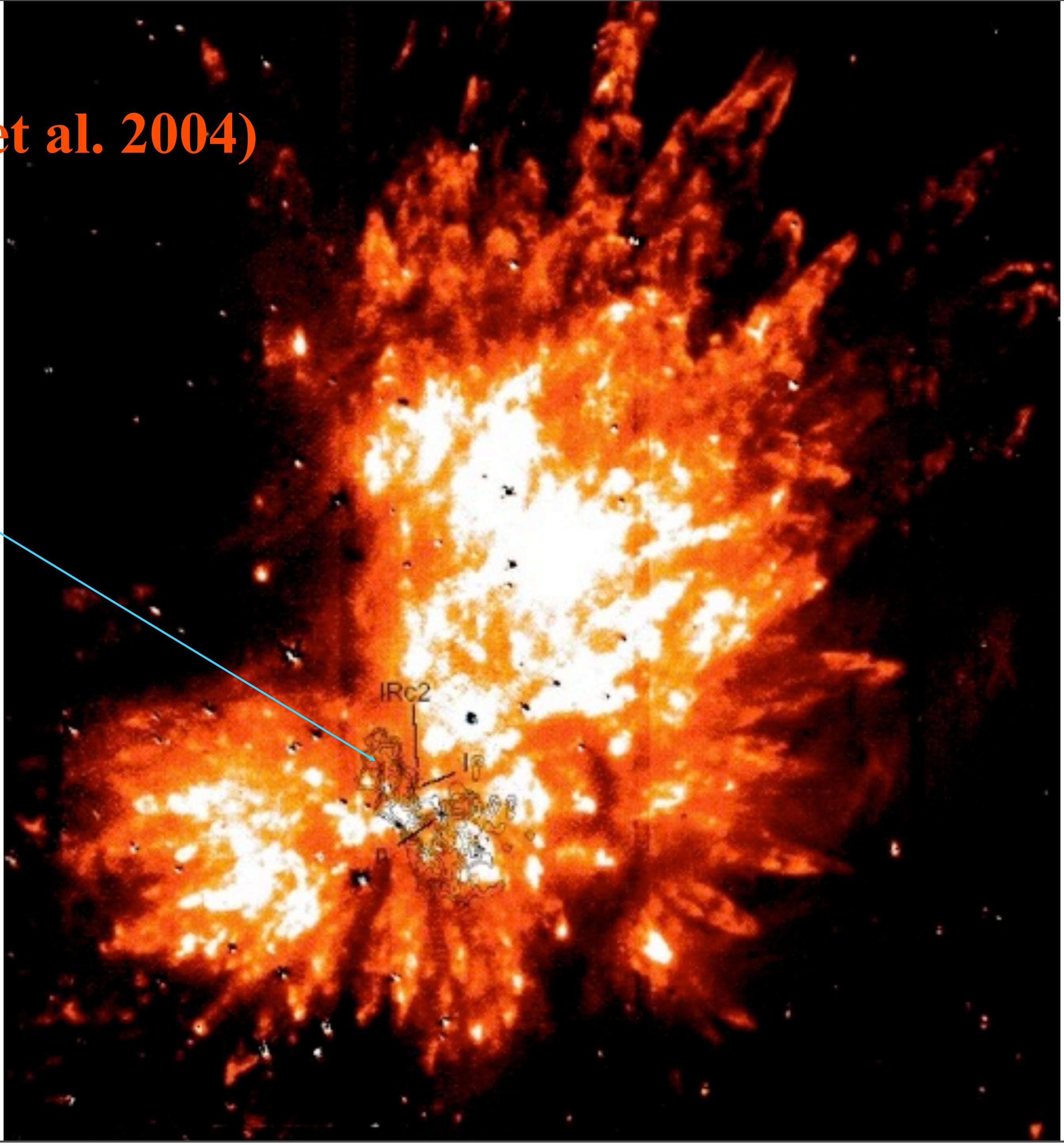
NH_3

Radio sources

H_2O masers

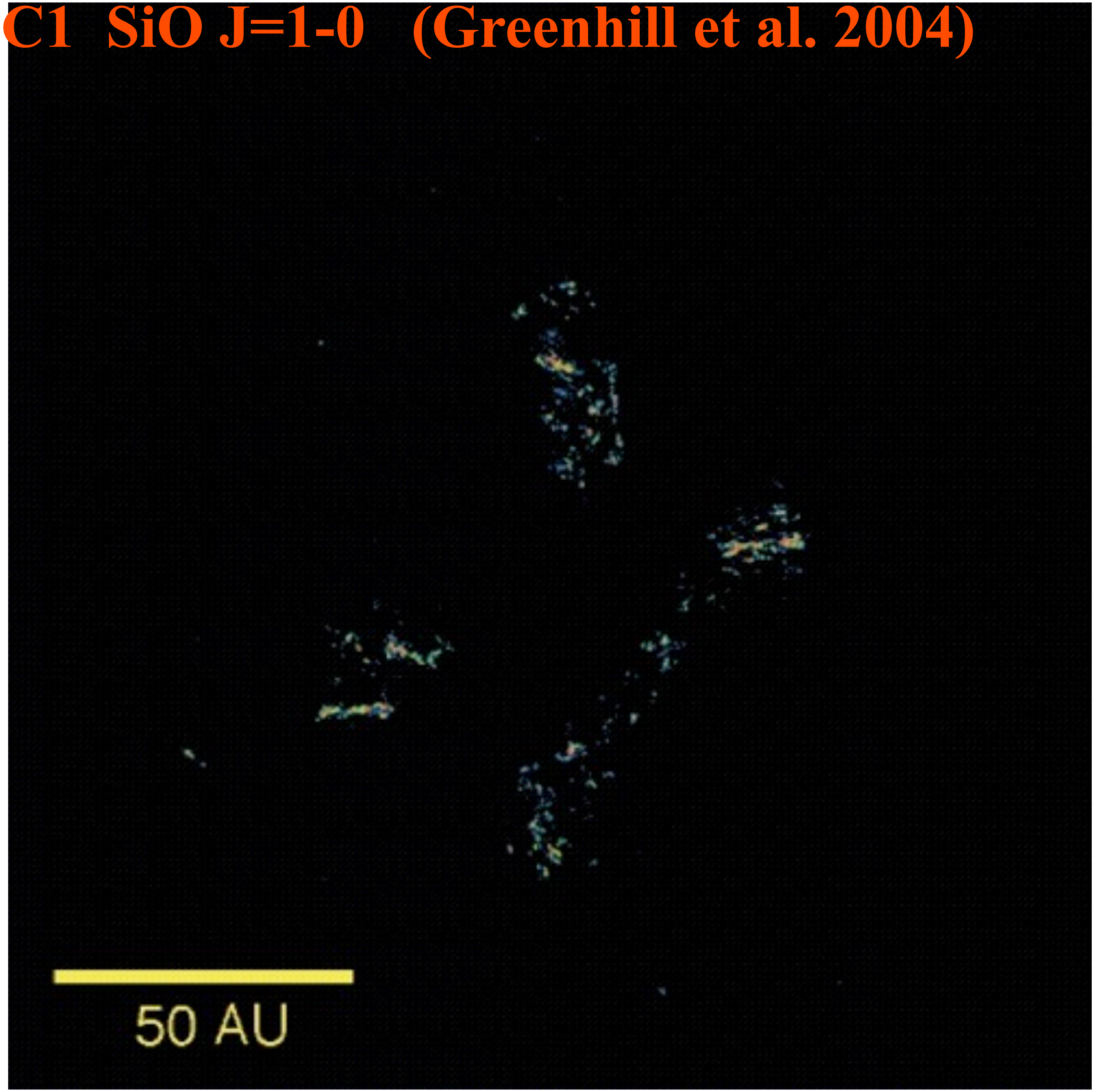
OMC1

(Shuping et al. 2004)

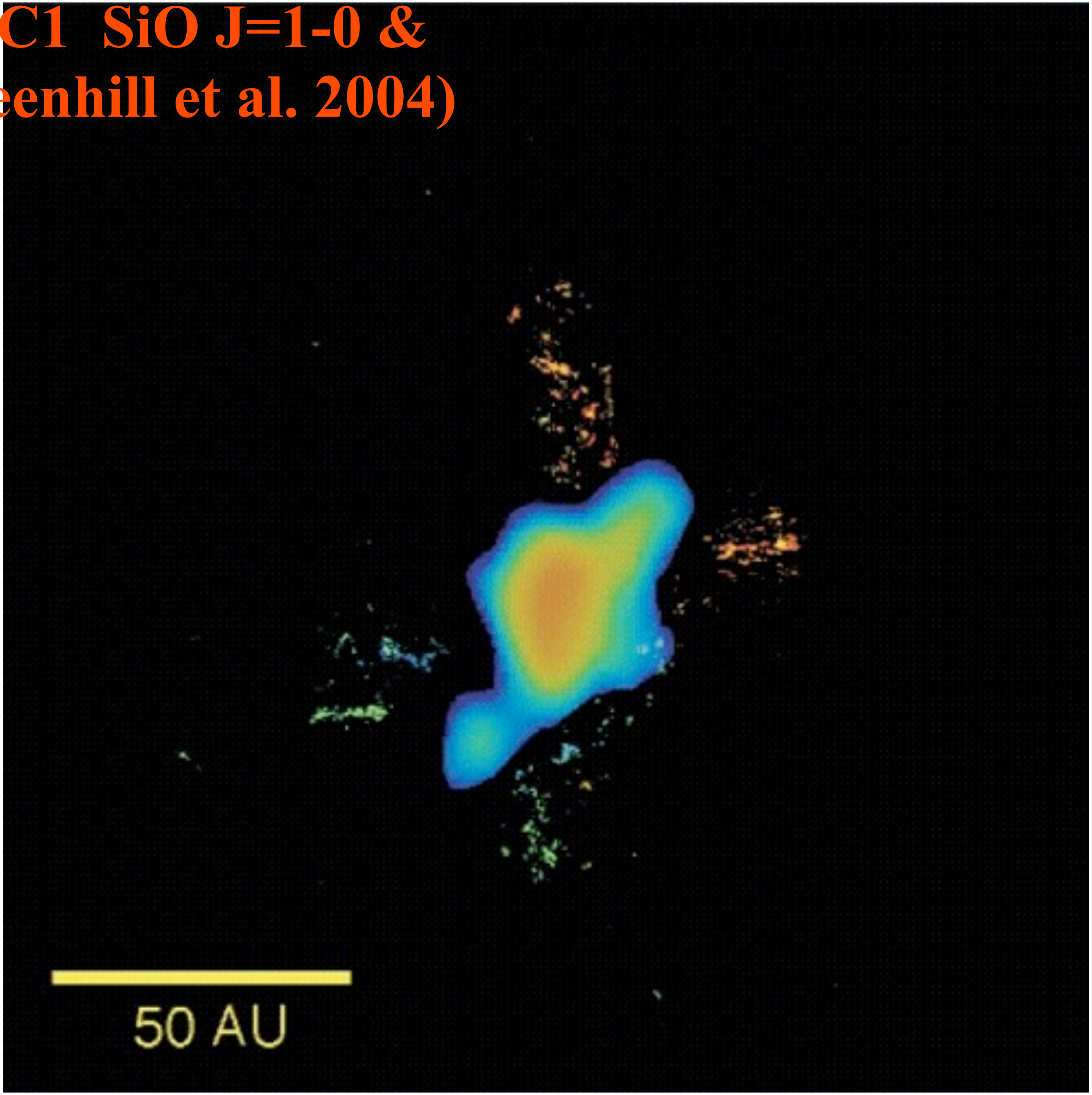


NH_3

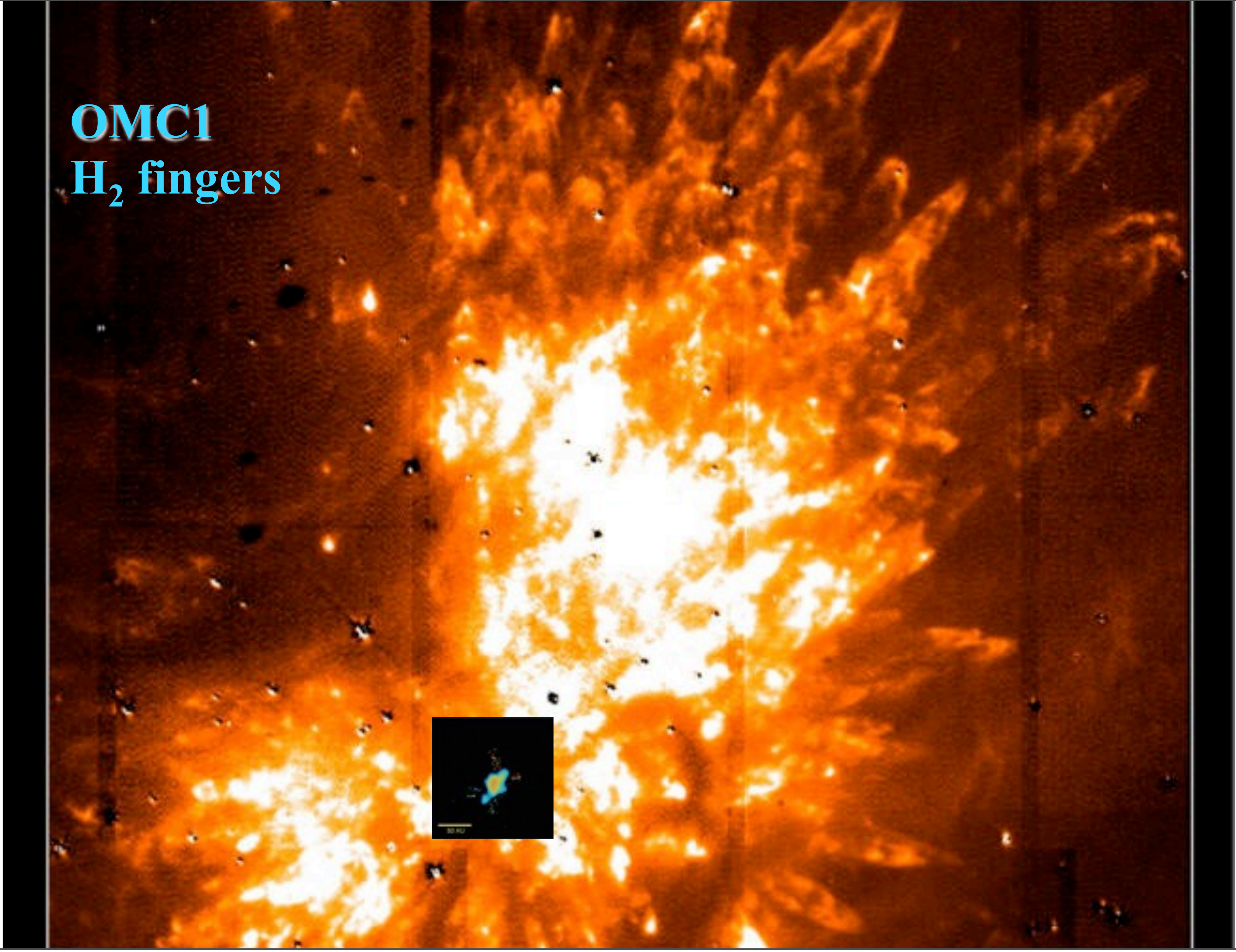
OMC1 SiO J=1-0 (Greenhill et al. 2004)



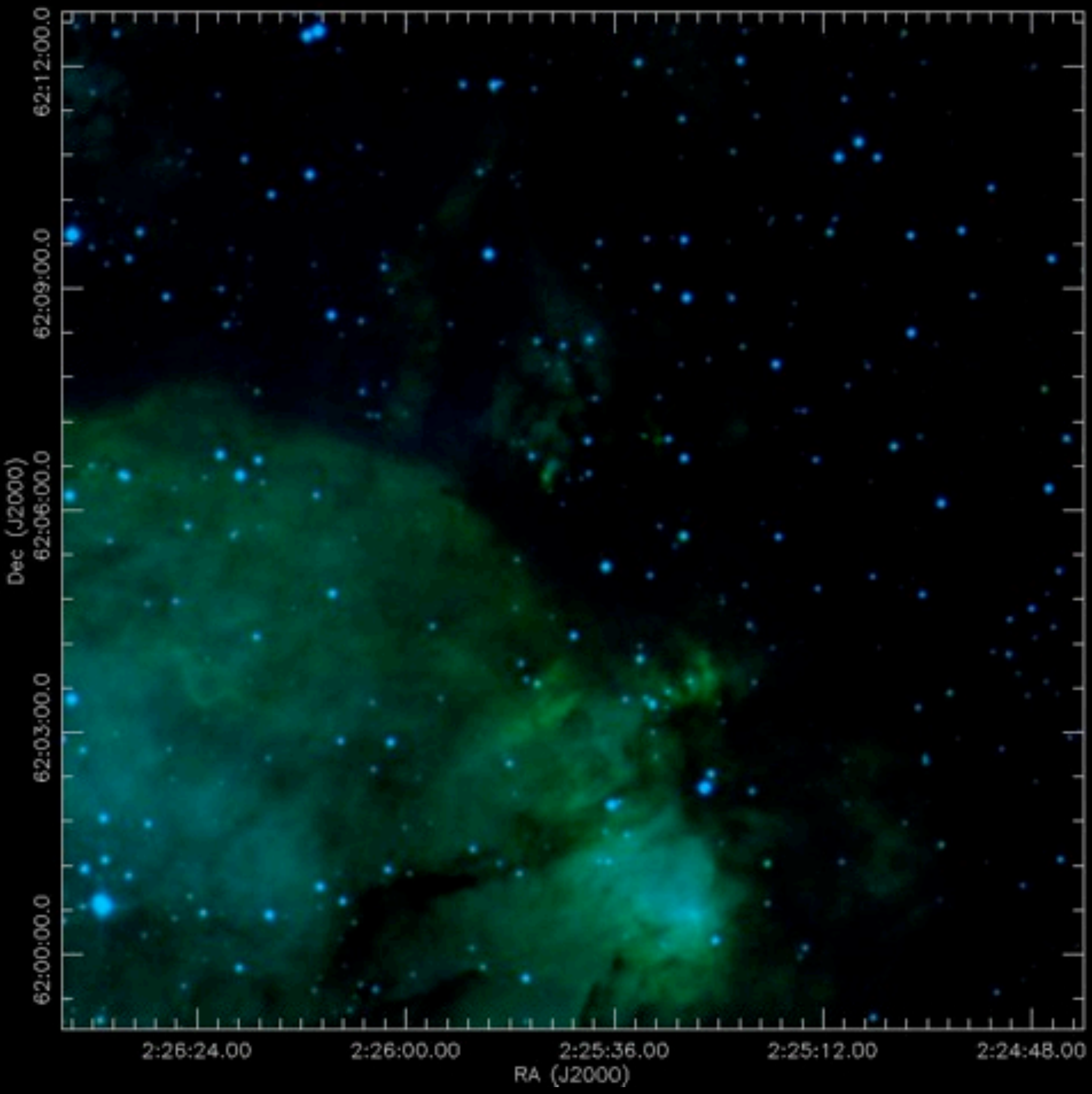
OMC1 SiO J=1-0 & (Greenhill et al. 2004)



OMC1
H_2 fingers

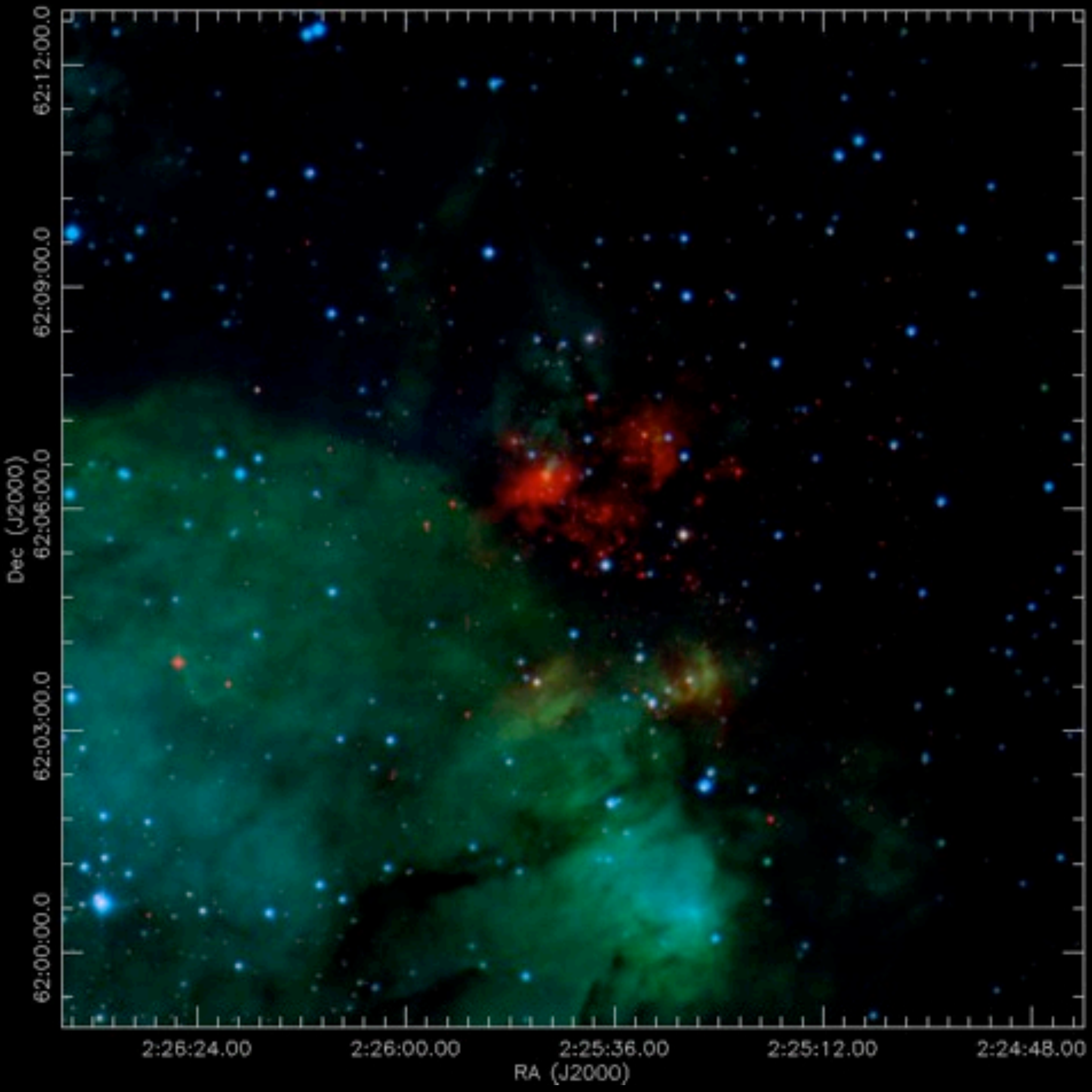


Clusters and Massive Stars



The W3 Main Region
In the Constellation of Cassiopeia

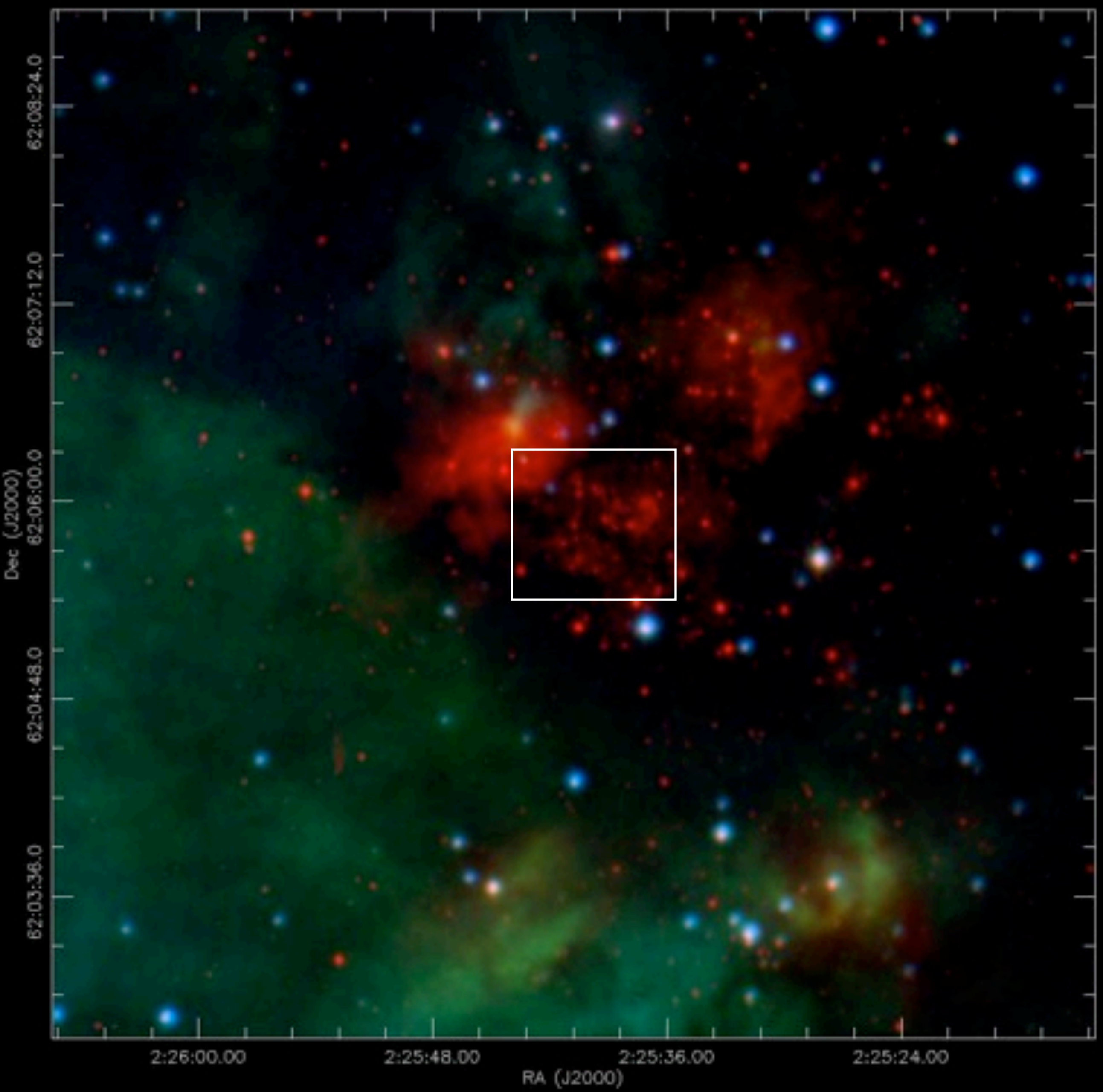
Visible Light Image (Digital Sky Survey)



The W3 Main Region: Visible & Infrared

Red sources are a cluster of young stars and nebulae, their light obscured by a dusty molecular cloud

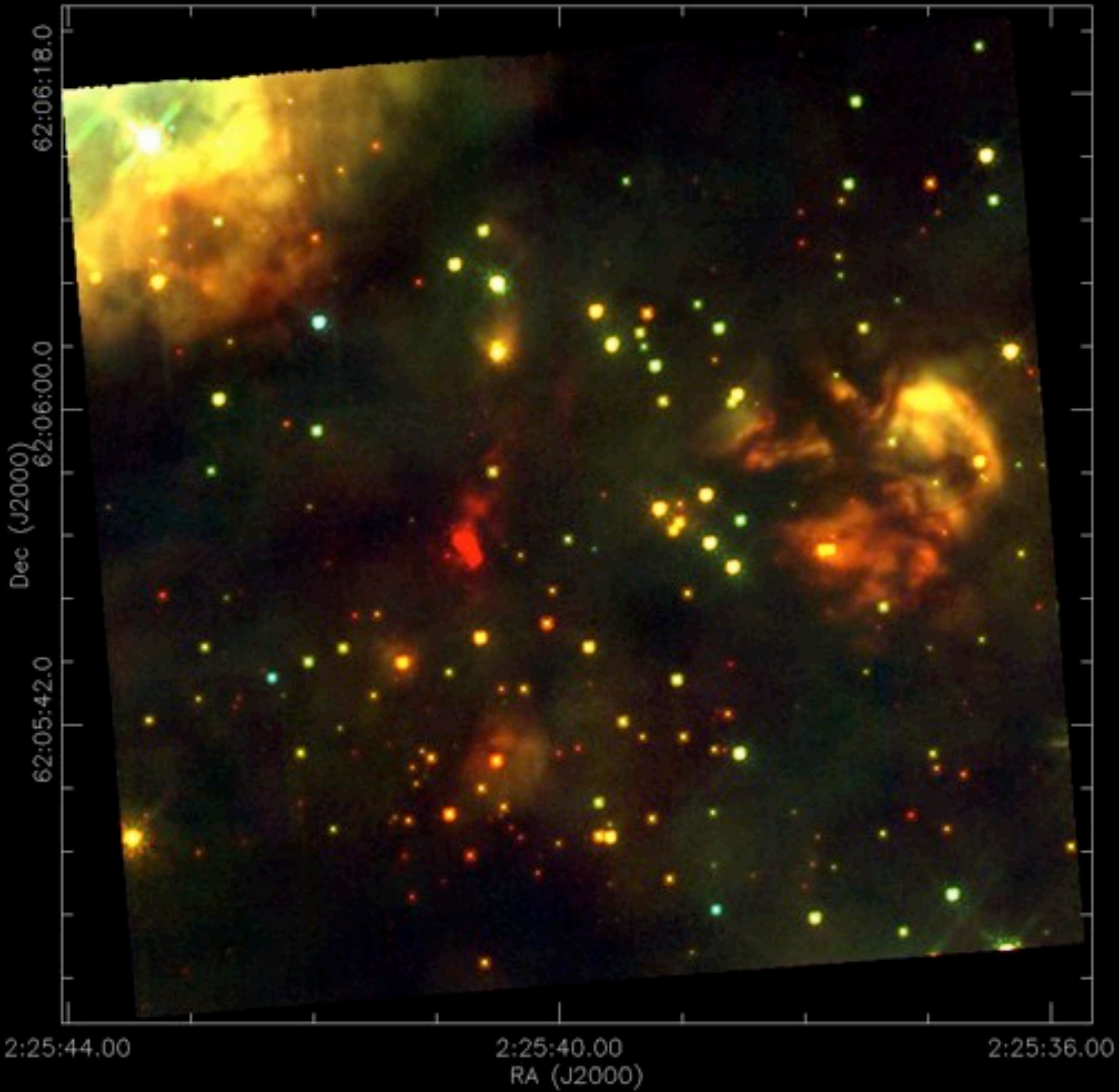
(IR image courtesy of John Rayner, Institute for Astronomy)



The W3 Main region

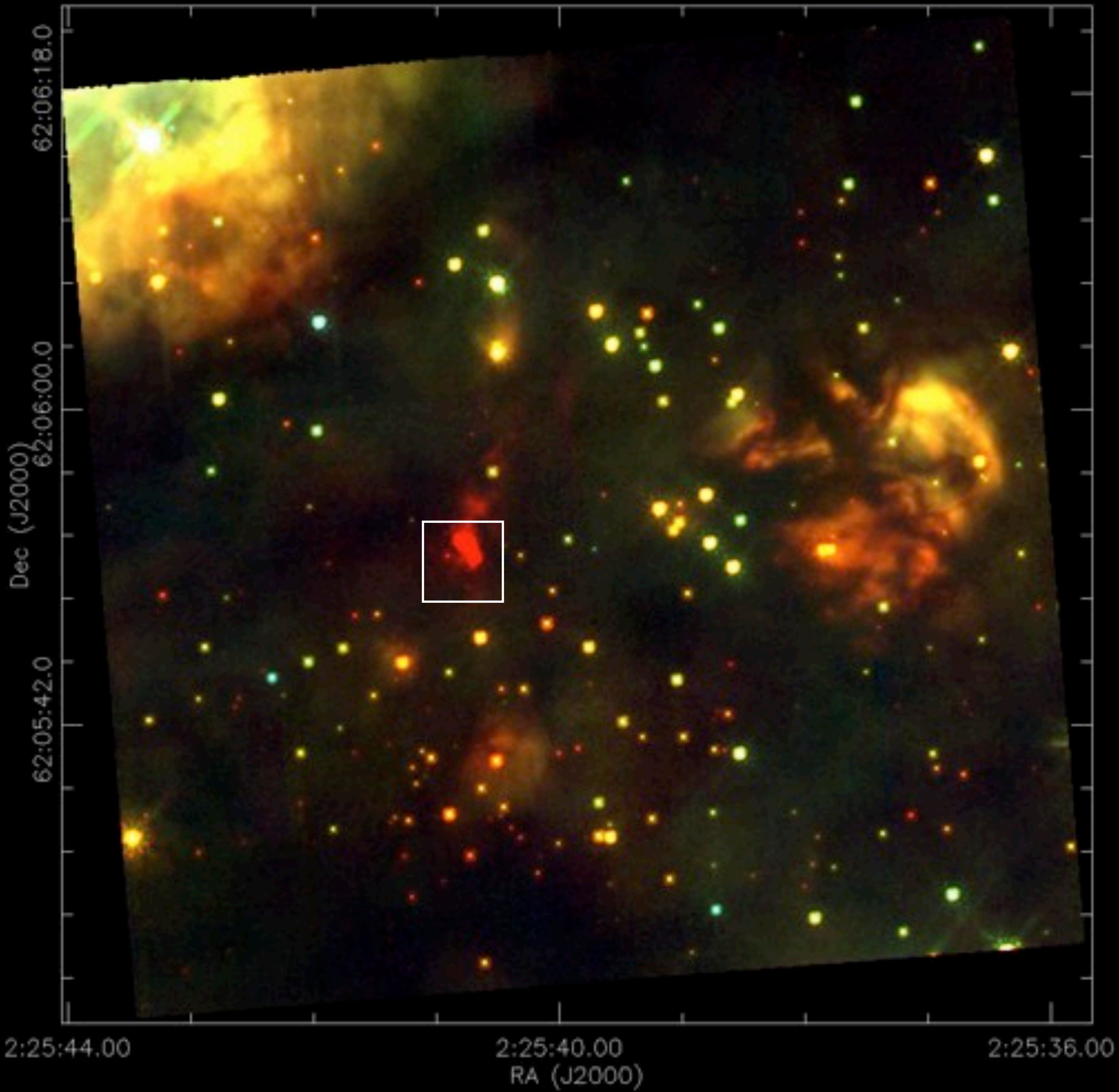
Red sources are a cluster of young stars and nebulae, their light obscured by a dusty molecular cloud

(IR image courtesy of John Rayner, Institute for Astronomy)



Hubble
Space
Telescope/
NICMOS
Infrared
(1-2 micron)
Image

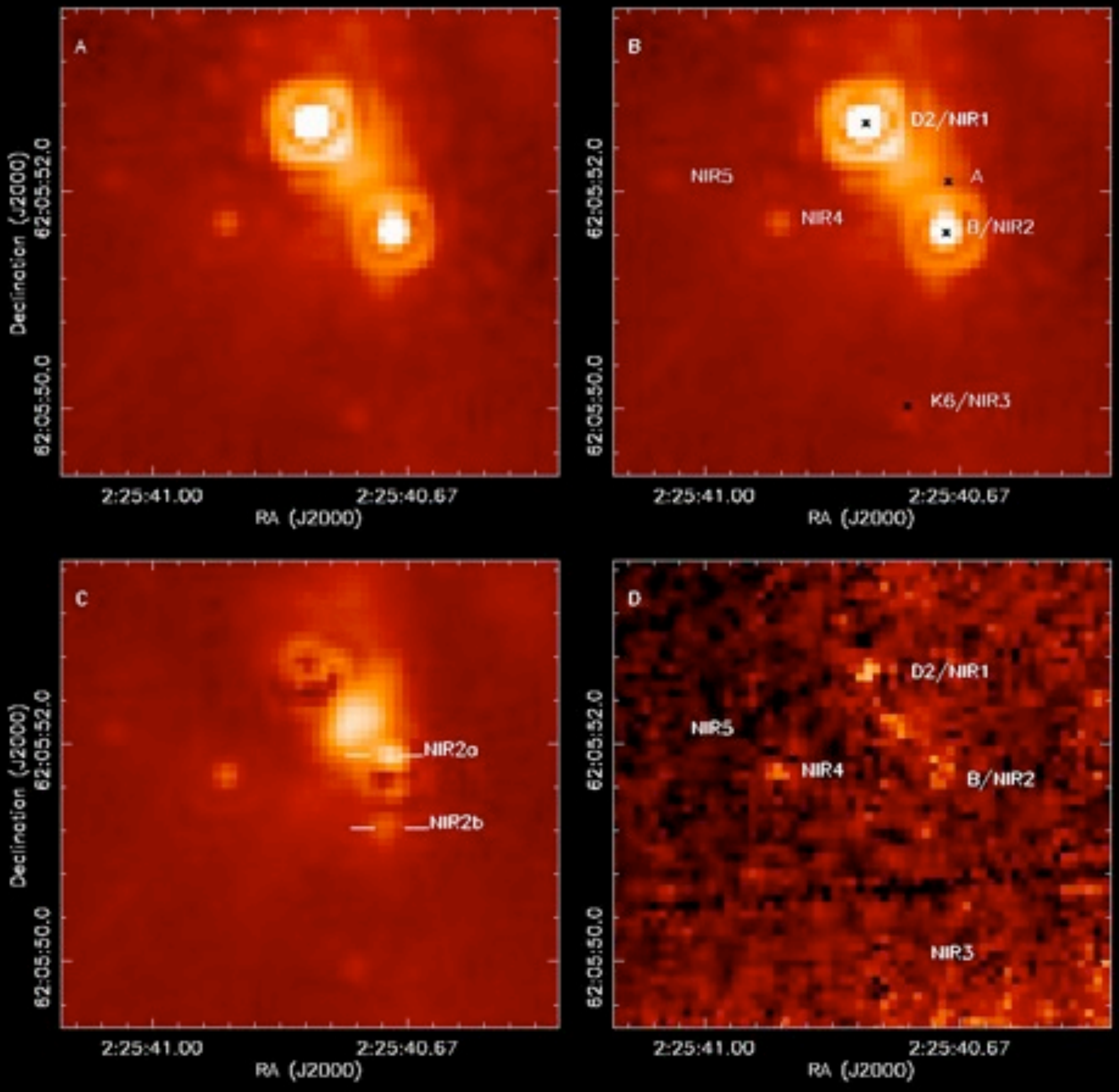
- 240 low mass stars
- Nebulae illuminated by massive stars



In the center is the very red, very luminous source, IRS 5 (InfraRed Source 5).

This source is 100,000 as luminous as our own sun.

It is one of the most obscured and young objects in this region.



HST data show five very red stars and one nebula.

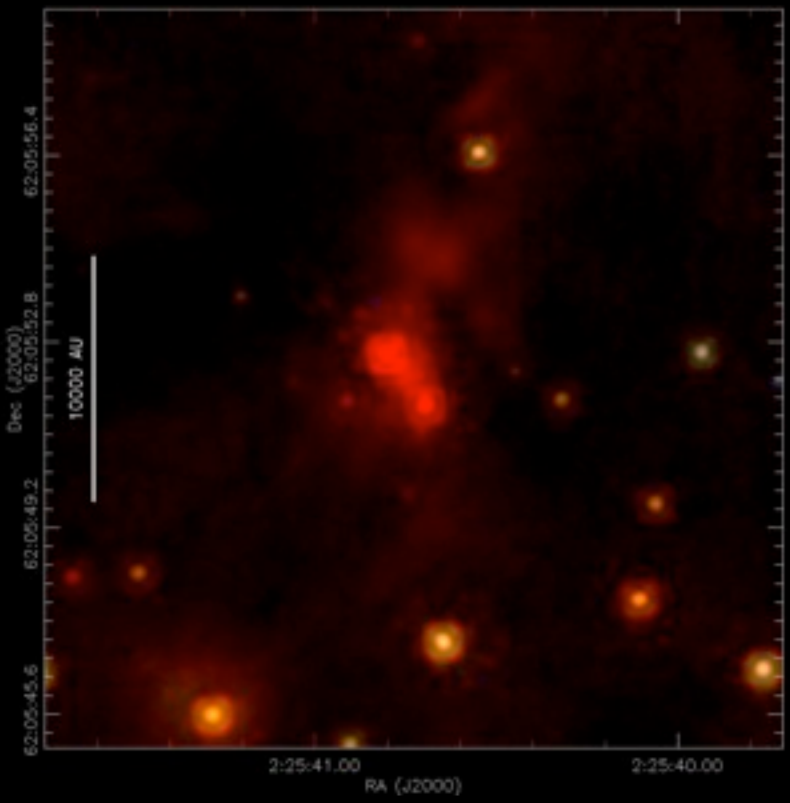
Very Large Array radio images show that three stars are surrounded by bubble of ionized gas.

After subtracting out one the bright sources, two additional companions are found.

Seven sources total, at least three are massive stars.

These observations support the formation of trapezia in the centers of clusters. These stars eventually blow out their dusty birth clouds - and may form a trapezium in a visible nebula like the Orion nebula.

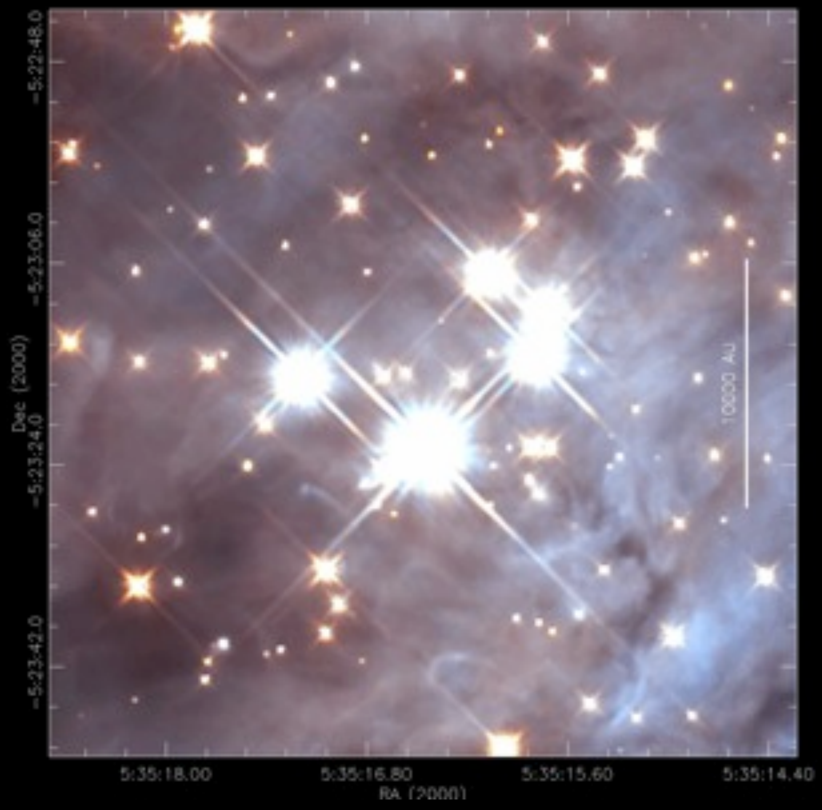
W3 Proto-Trapezium



HST Nicmos: Megeath et al. 2005)

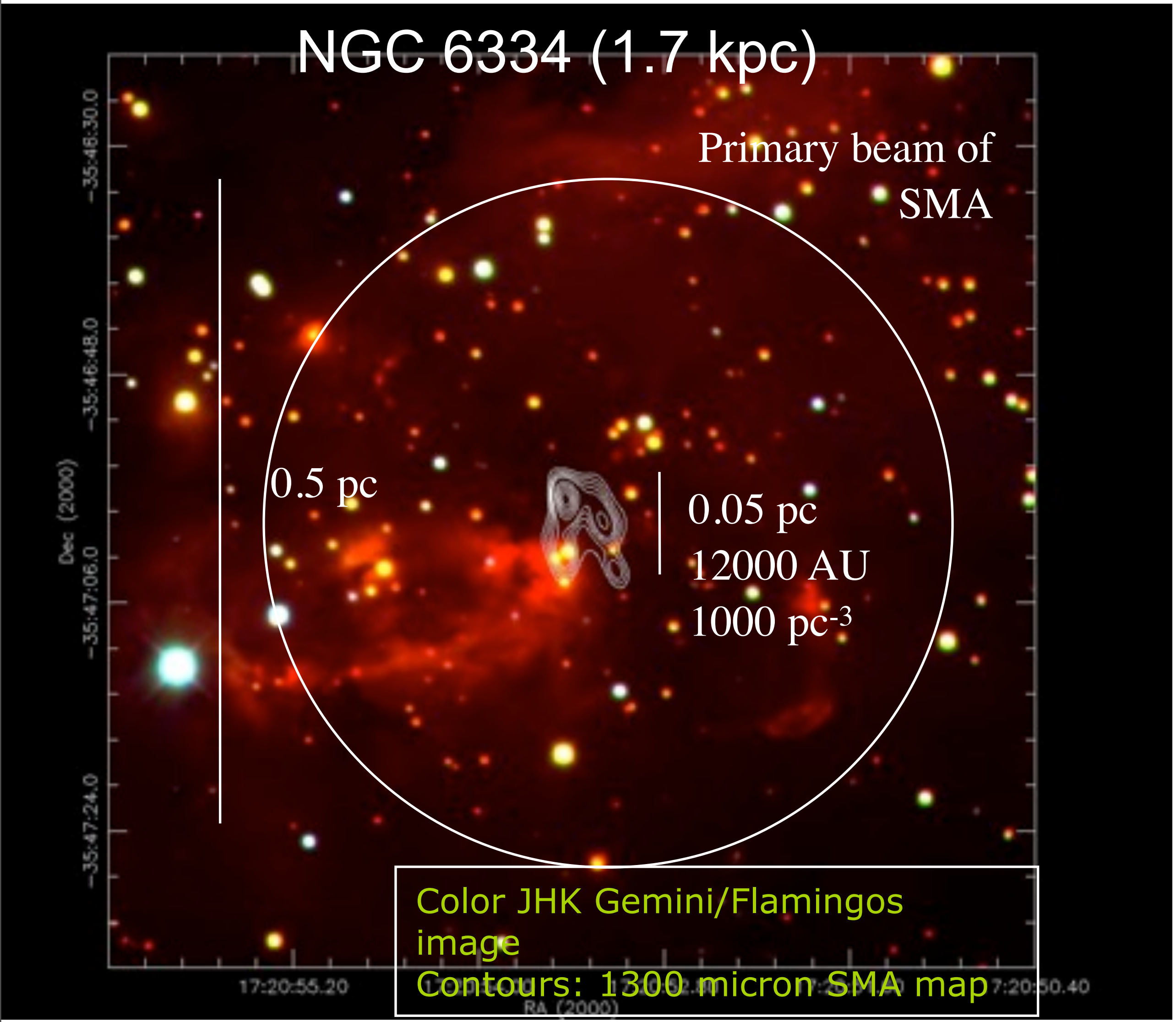
100,000
years

Orion Trapezium



HST Nicmos: Luhman et al.. 2001)

Multiplicity of Young High Mass Stars



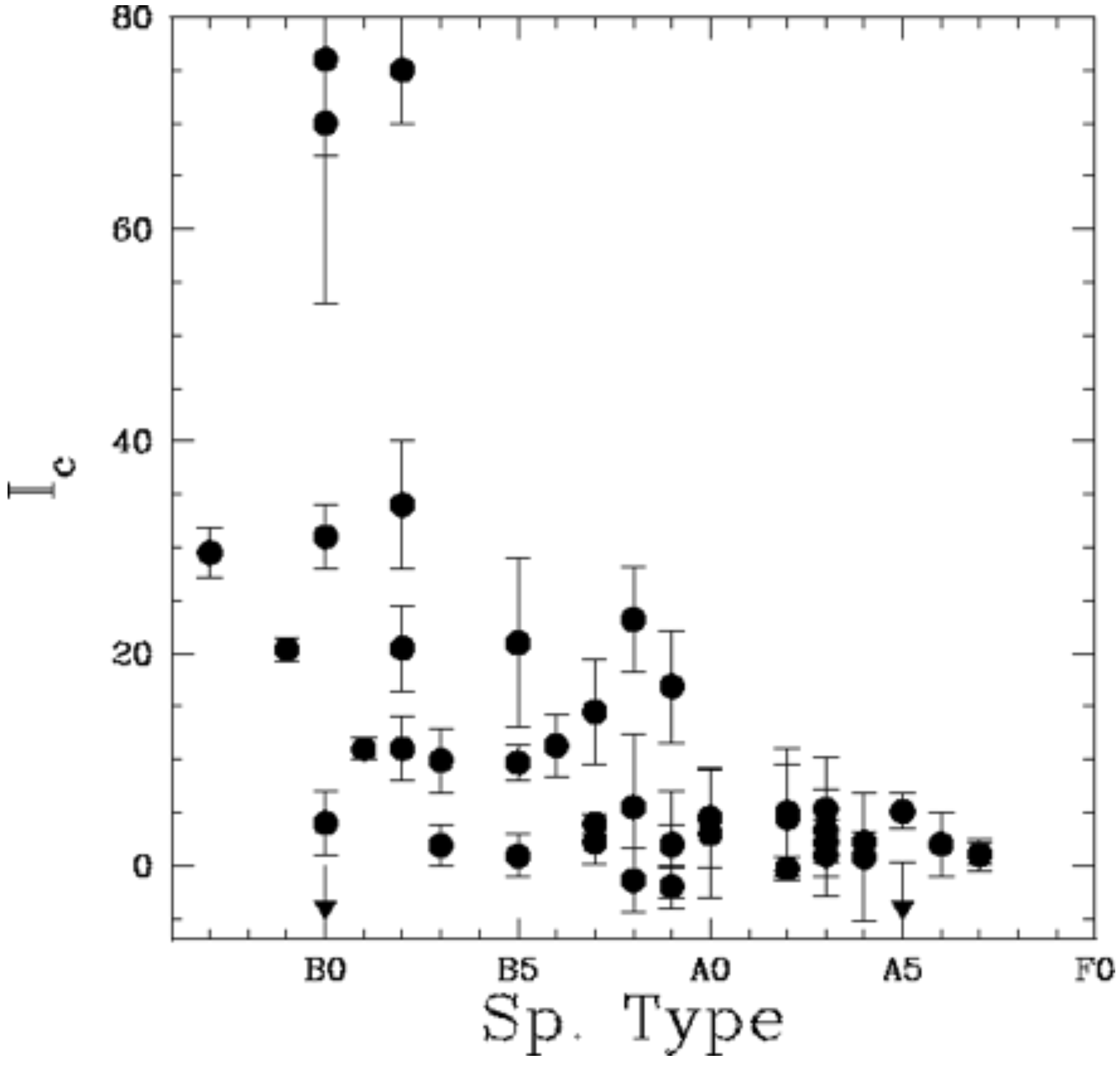
Massive sub-mm sources found in compact groups in centers of clusters: **primordial mass segregation.**

These may be proto-trapezia

40% of emission nebulae contain trapezia (Sharpless 1953)

Left: Submillimeter Array map of NGC 6334 show group of massive (> 10 solar mass) protostars in the center of a cluster of low mass stars (Hunter et al. 2006).

Is There a Connection Between High Mass Star Formation and Clusters?

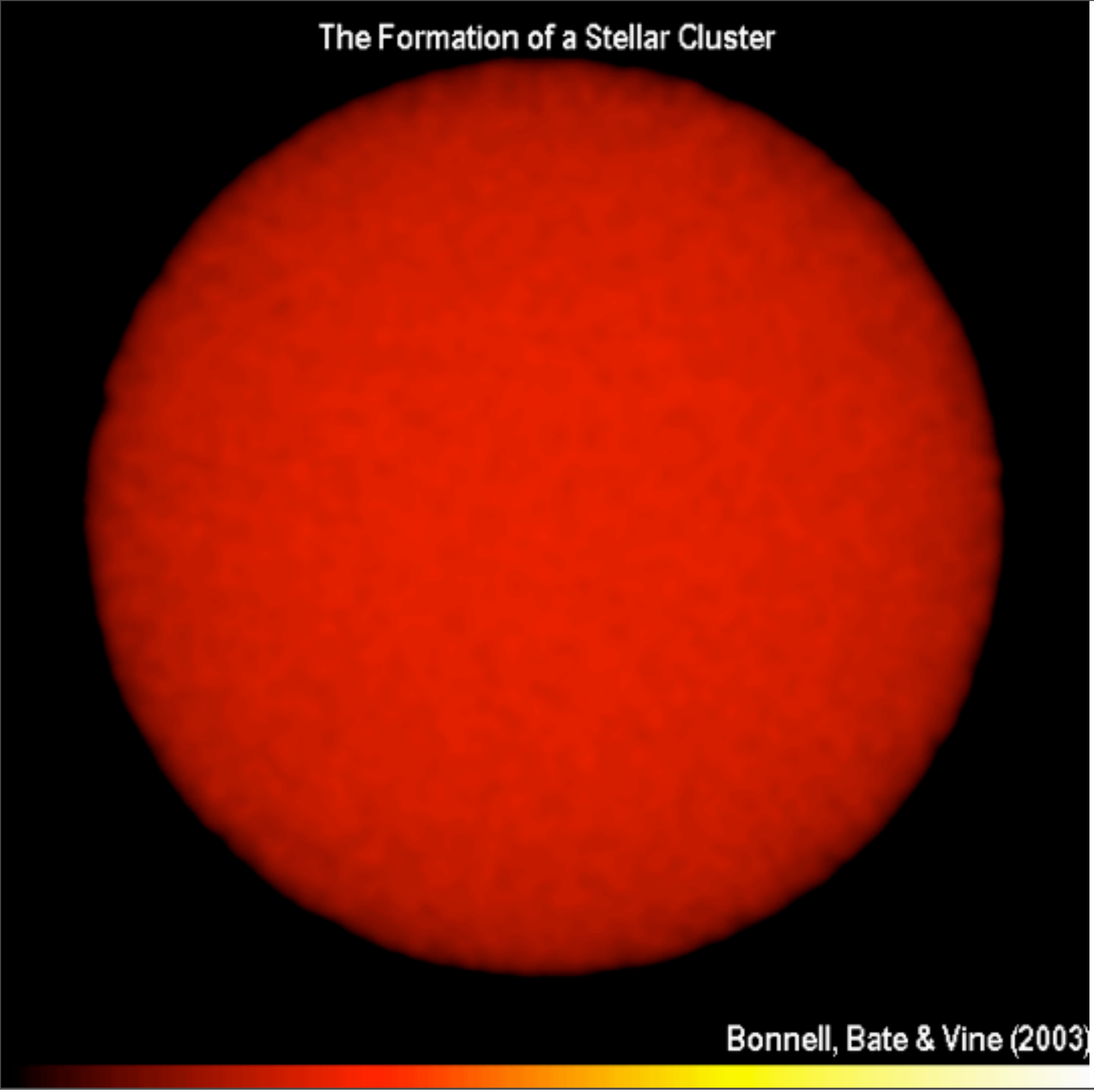


Testi et al. 1998

From a survey of 44 Herbig Ae/Be stars

1000 solar
mass core

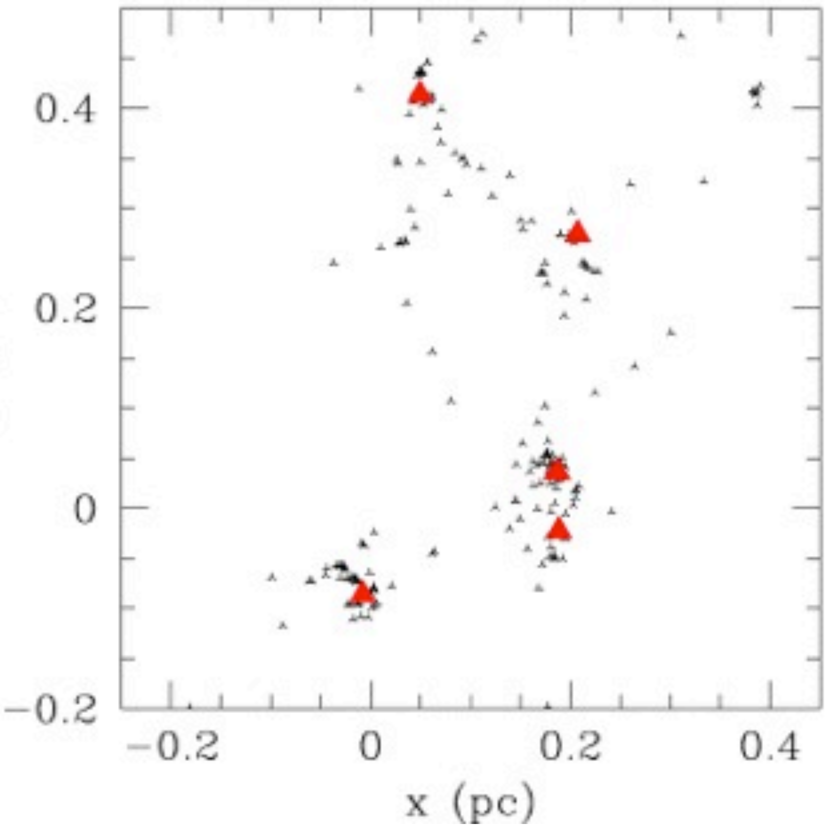
Jeans
mass = 1

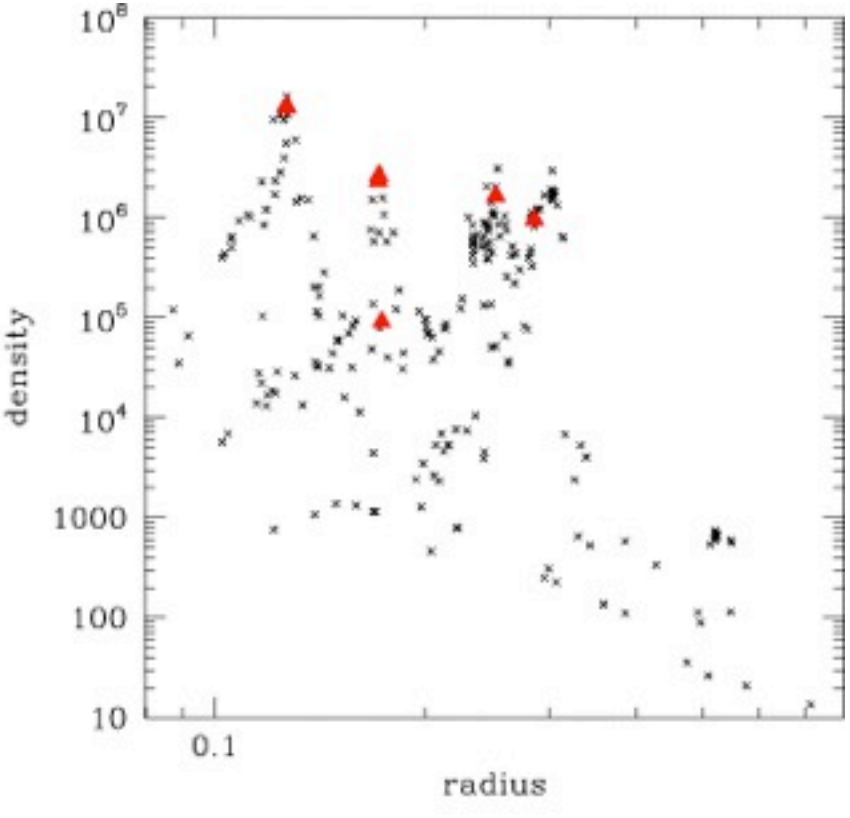


1000 solar mass core

Jeans mass = 1

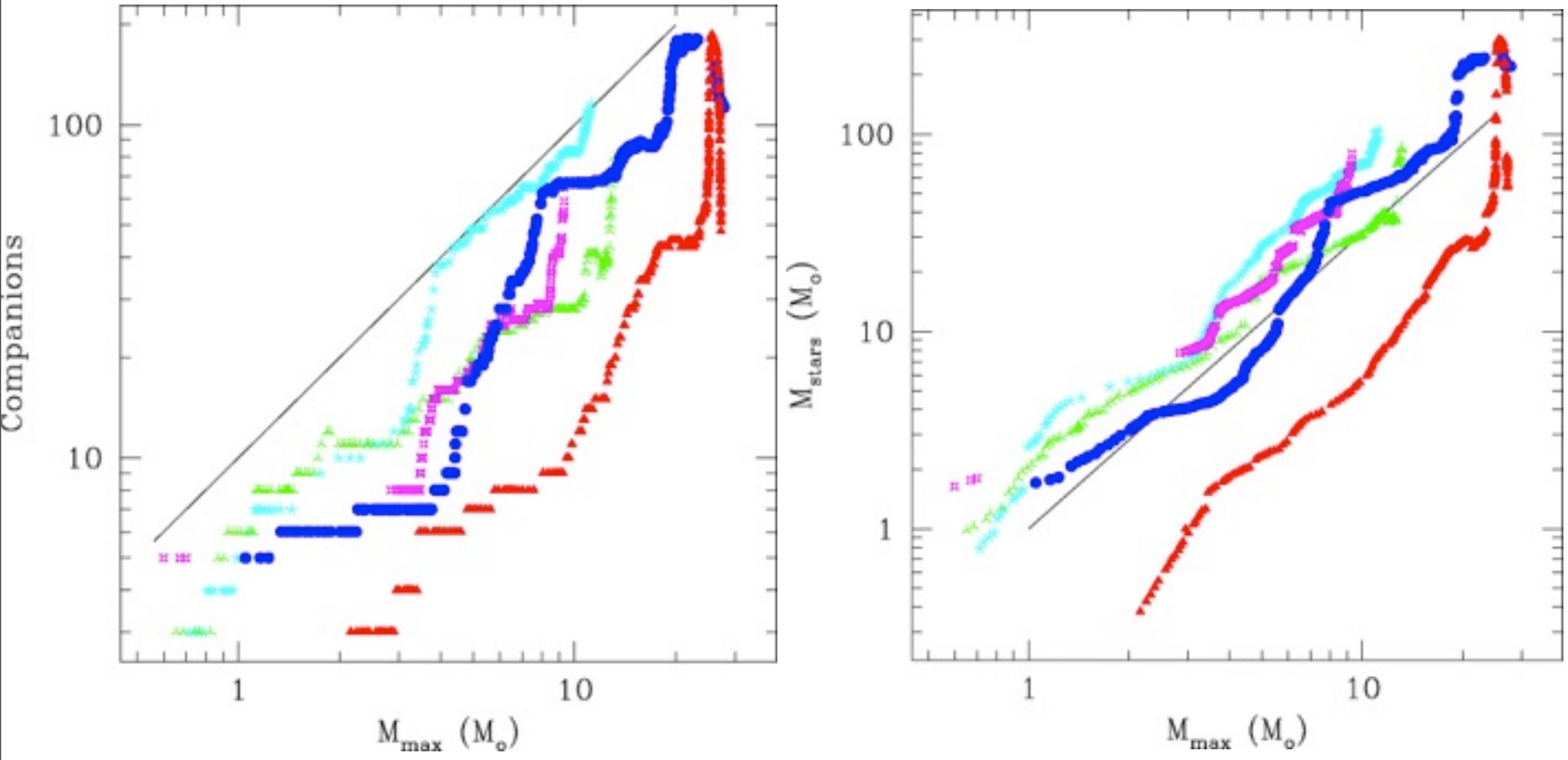
Competitive Accretion: Bate, Bonnell & Vine 2003





Red triangles are the most massive objects

Competitive Accretion: Bate, Bonnell & Vine 2003



Number of companions within a 0.1 pc subcluster and the total mass of the companions as a function of the most massive star in a sub-cluster.

Radiative Hydrodynamics Simulations (Krumholz, Klein & McKee 2007)

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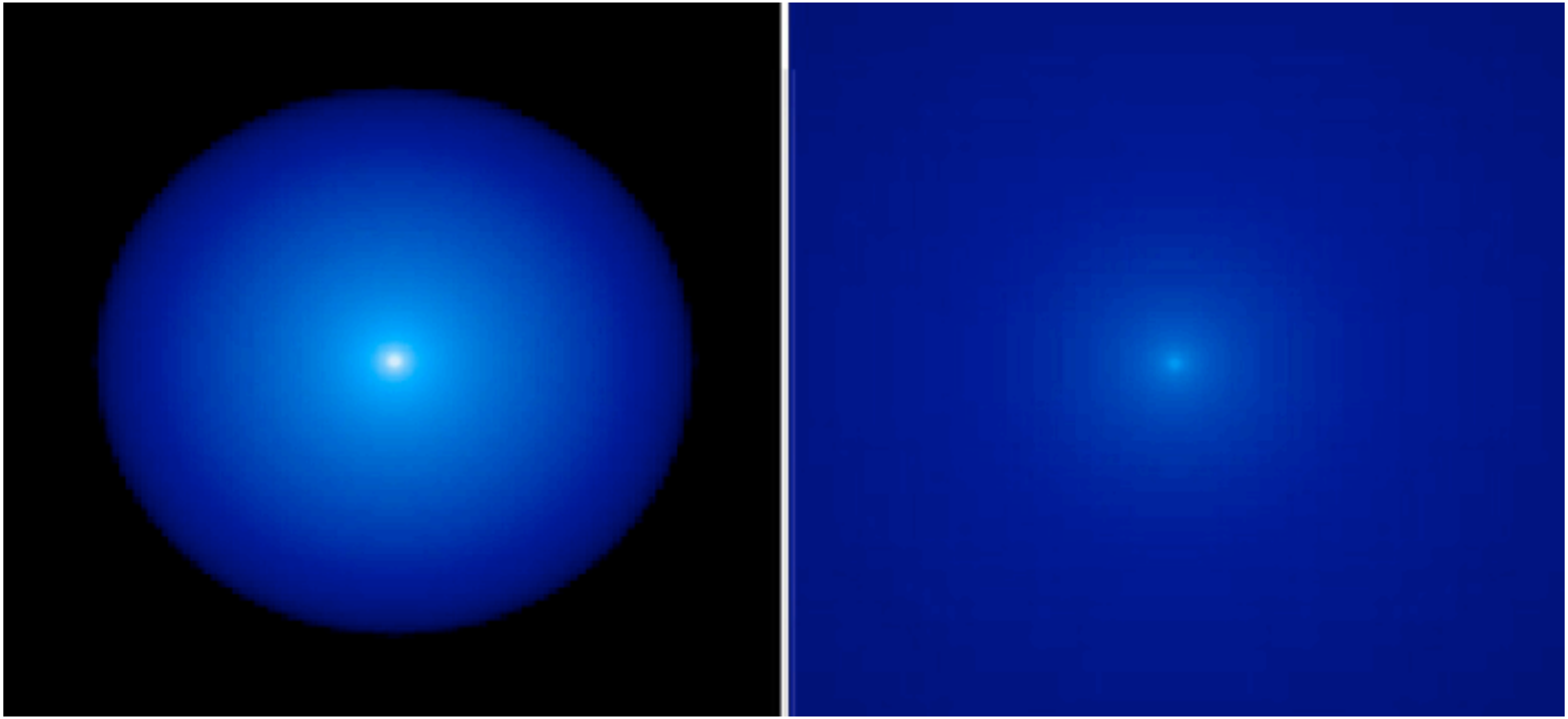

Radiative Hydrodynamics Simulations (Krumholz, Klein & McKee 2007)

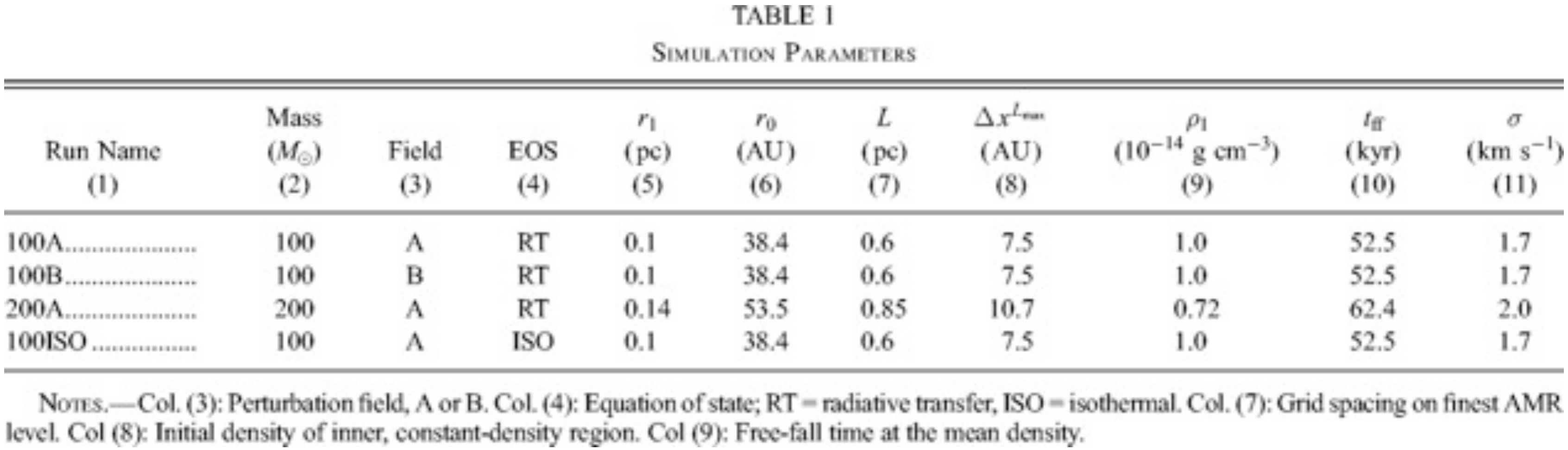

TABLE 1

SIMULATION PARAMETERS

Run Name (1)	Mass ($M_\odot$) (2)	Field (3)	EOS (4)	r_1 (pc) (5)	r_0 (AU) (6)	L (pc) (7)	$\Delta x^{L_{\rm max}}$ (AU) (8)	ρ_1 (10^{-14} g cm^{-3}) (9)	$t_{\rm ff}$ (kyr) (10)	σ (km s^{-1}) (11)
100A....................	100	A	RT	0.1	38.4	0.6	7.5	1.0	52.5	1.7
100B....................	100	B	RT	0.1	38.4	0.6	7.5	1.0	52.5	1.7
200A....................	200	A	RT	0.14	53.5	0.85	10.7	0.72	62.4	2.0
100ISO	100	A	ISO	0.1	38.4	0.6	7.5	1.0	52.5	1.7

NOTES.—Col. (3): Perturbation field, A or B. Col. (4): Equation of state; RT = radiative transfer, ISO = isothermal. Col. (7): Grid spacing on finest AMR level. Col (8): Initial density of inner, constant-density region. Col (9): Free-fall time at the mean density.

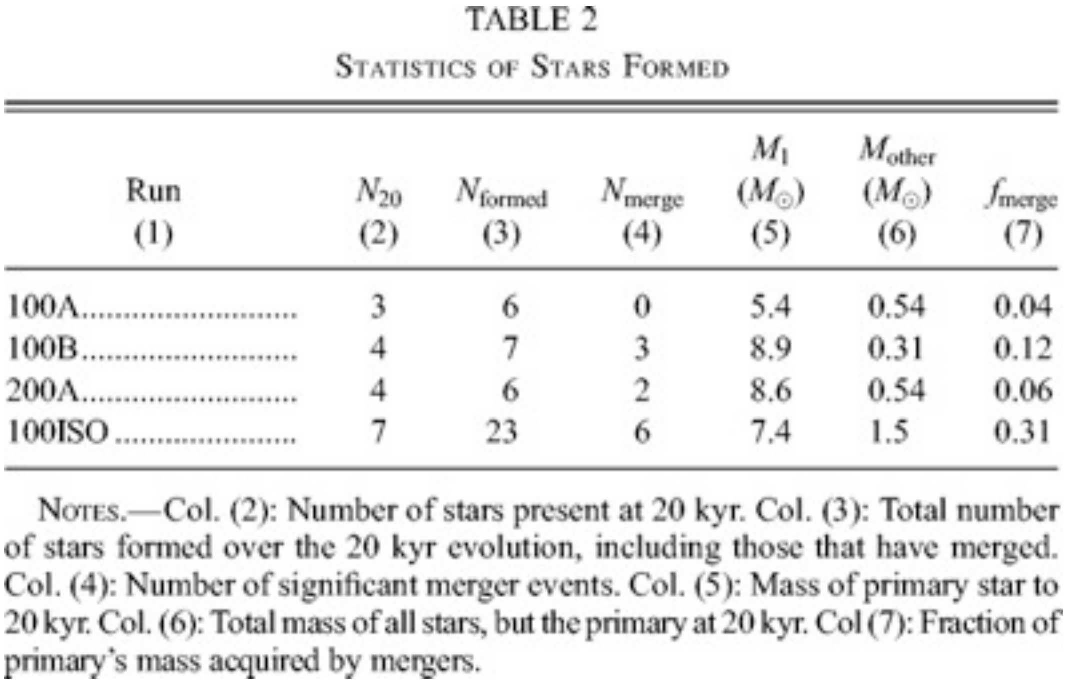

TABLE 2

STATISTICS OF STARS FORMED

Run (1)	N_{20} (2)	$N_{\rm formed}$ (3)	$N_{\rm merge}$ (4)	M_1 ($M_\odot$) (5)	$M_{\rm other}$ ($M_\odot$) (6)	$f_{\rm merge}$ (7)
100A..........................	3	6	0	5.4	0.54	0.04
100B..........................	4	7	3	8.9	0.31	0.12
200A..........................	4	6	2	8.6	0.54	0.06
100ISO	7	23	6	7.4	1.5	0.31

NOTES.—Col. (2): Number of stars present at 20 kyr. Col. (3): Total number of stars formed over the 20 kyr evolution, including those that have merged. Col. (4): Number of significant merger events. Col. (5): Mass of primary star to 20 kyr. Col. (6): Total mass of all stars, but the primary at 20 kyr. Col (7): Fraction of primary's mass acquired by mergers.

Radiative Hydrodynamics Simulations (Krumholz, Klein & McKee 2007)

Bonnell, Batte & Vine assume an isothermal gas. Higher gas densities leads to fragmetnation of less massive stars

$$m_j = \rho_0 \lambda_J^3 = \frac{c_s^3 \pi^{3/2}}{G^{3/2} \rho_0^{1/2}} = \left(\frac{\pi k T}{\mu m_H G}\right)^{3/2} \rho_0^{-1/2}$$

This may not be the case in dense cores forming massive stars:

1. Cores have high column density and thus have significant optical depth.

2. Accretion luminosity of massive stars will heat core

This may suppress fragmentation.

However, many of the stars in Bonnell, Bate and Vine form away from the massive stars and are transported inward. So the difference may really be that Krumholz starts with a dense core while Bonnell starts with a uniform density cloud.

Summary

The formation of stars greater than 10 solar masses distinctly different than that around low mass stars.

1.Massive stars evolve faster, can reach the main sequence during the protostellar phase.

3.High luminosity means that photon pressure can stop collapse (Luminosity exceeds Eddington Luminosity for dust opacity).

5.Dust forced down to sublimation radius by ram pressure of collapsing envelope.

7.Down-convert photons to IR wavelengths at dust sublimation radius. This lowers opacity of dust grains to light and lowers the momentum absorbed by the dust grains)

9.Flashlight effect in rotating envelope “beams” radiation along rotation axis while material can fall along disk.

11.HII regions may be confined by gravity.

Need to understand why dense clouds do not just fragment into clusters of low mass stars:

12.competitive accretion?

14.radiative feed back?