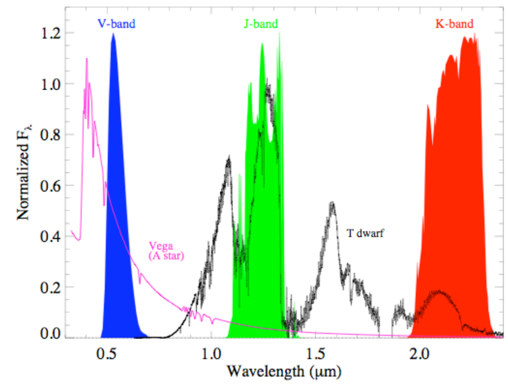
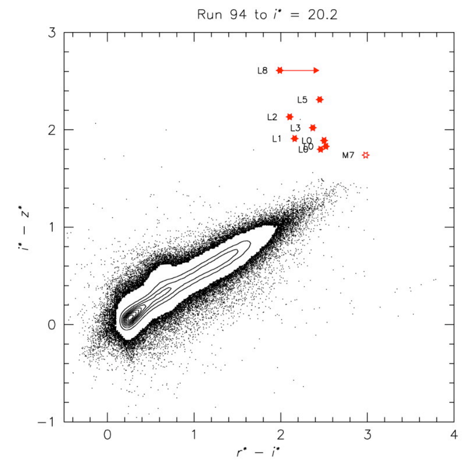
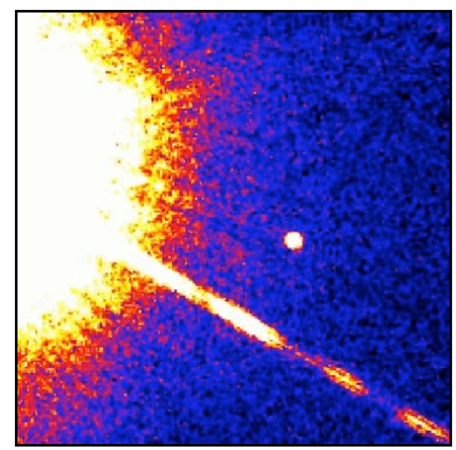
previously in 8.972…

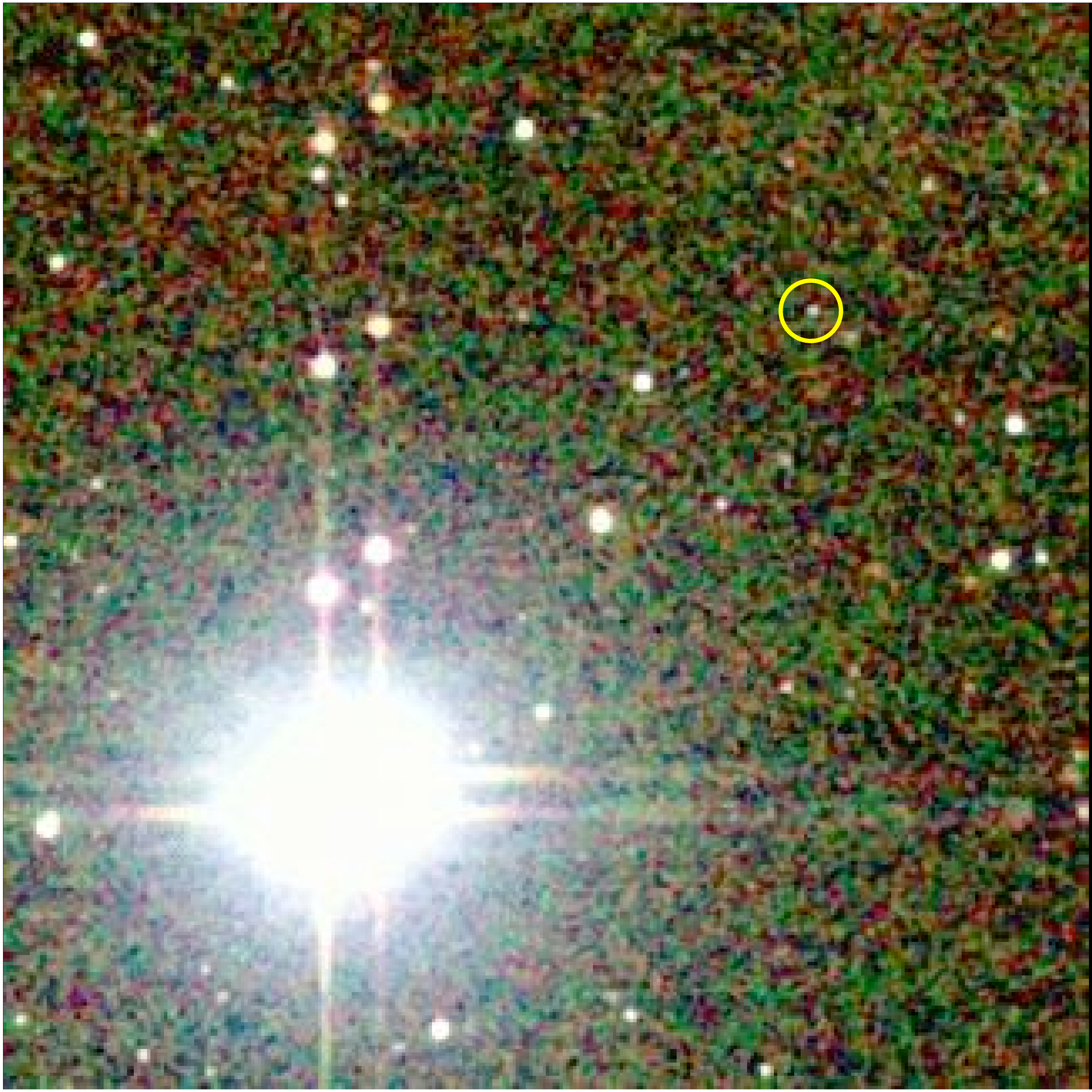
Finding Brown Dwarfs made easy:

- Look in the infrared
- Look for sources with weird (red) colors
- Look for moving sources
- Look in young clusters
- Look around nearby stars







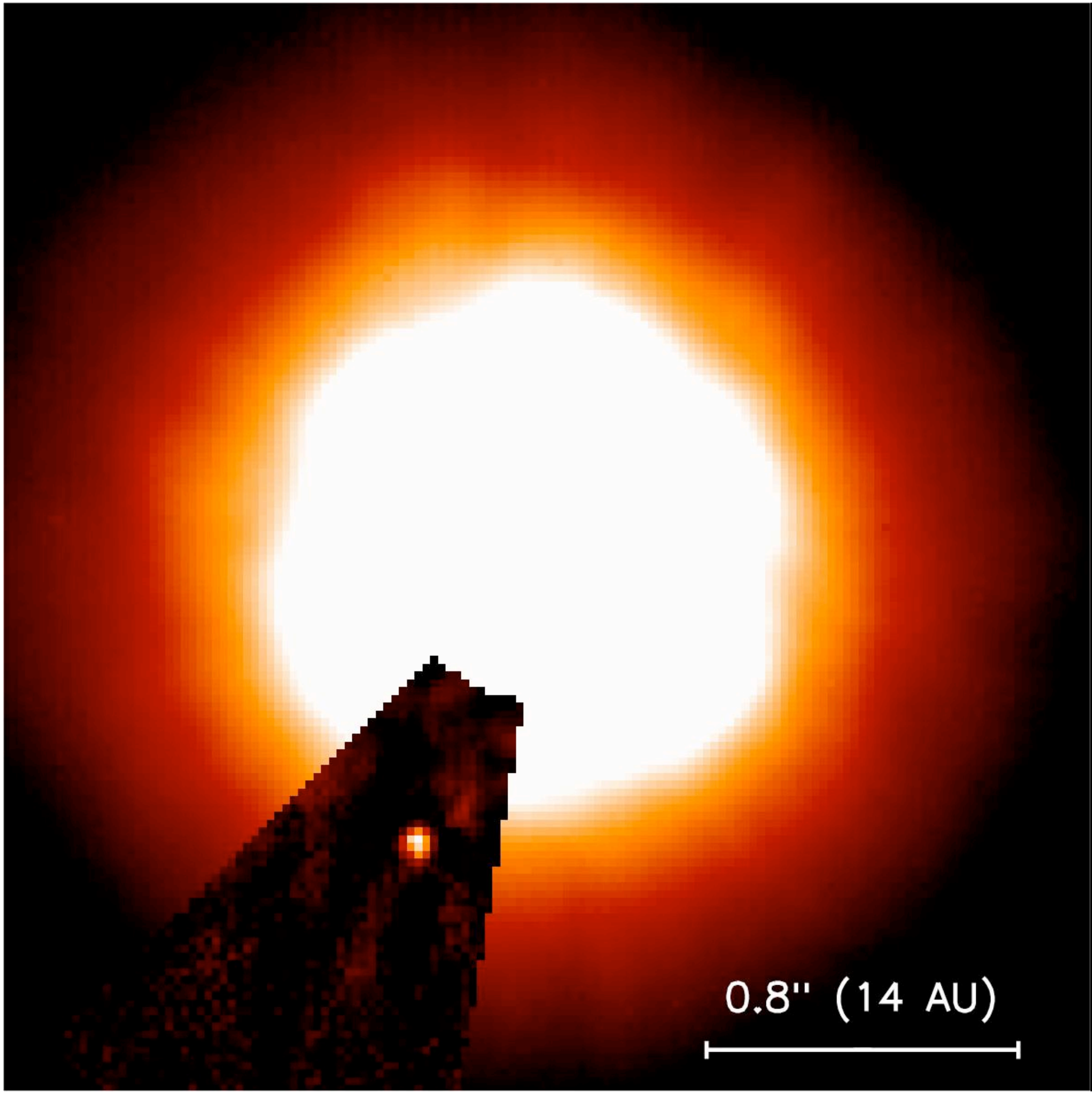


An easy case: Gliese 570D

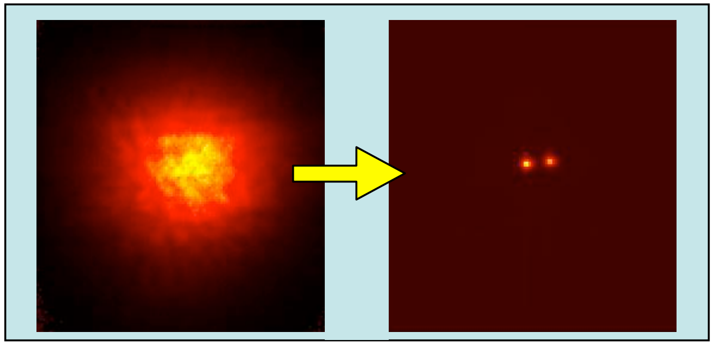
(Burgasser et al. 2000)

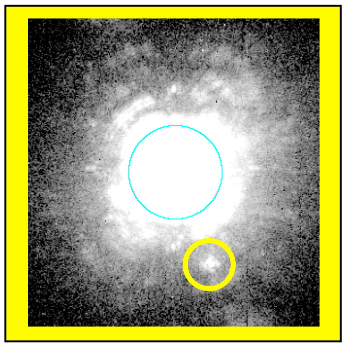
2MASS JHK_s

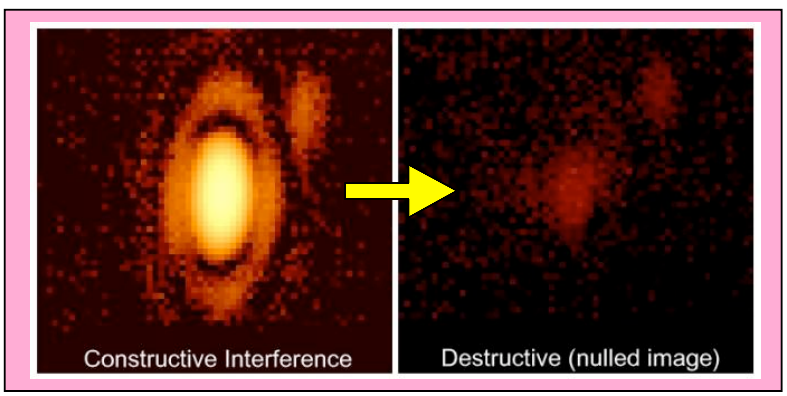
A hard case: HR 7672B
(Liu et al. 2002)



Gemini AO







Techniques for finding BD companions

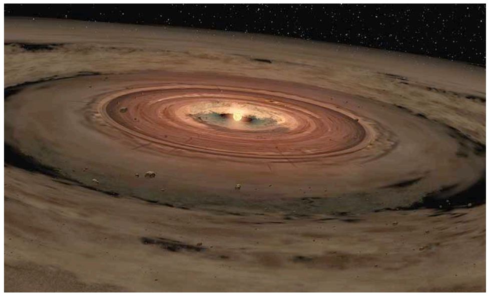
- Direct imaging (wide companions)
- Radial Velocity (rare!)
- Speckle Interferometry
- Adaptive Optics
- Coronagraphy
- Spectral Difference Imaging
- Interferometric nulling
- Combinations of the above!*

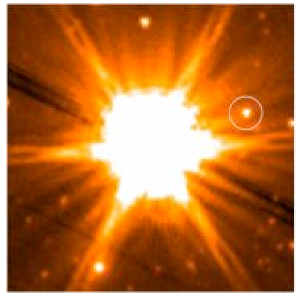
Correct for atmospheric blurring

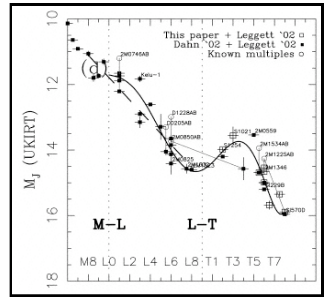
***See Thursday's Physics Colloquium by Ben Oppenheimer**

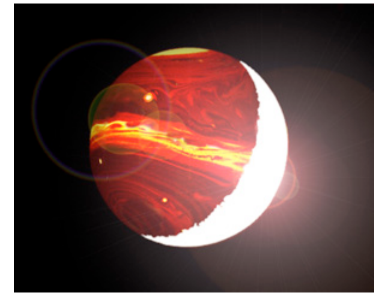
Searching for BD companions

- Pros:
  - Can target nearby stars to find faintest companions
  - Distance, composition and age constraints from primary
  - No selection bias from colors
- Cons:
  - Close in companions hard to see in glare of star
  - Brown dwarf companions to stars are rare (~1-5%)
  - Must confirm companionship (e.g., common proper motion)

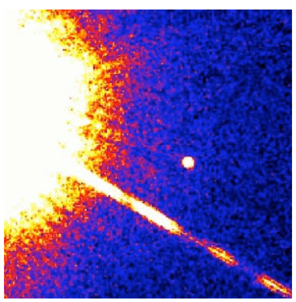


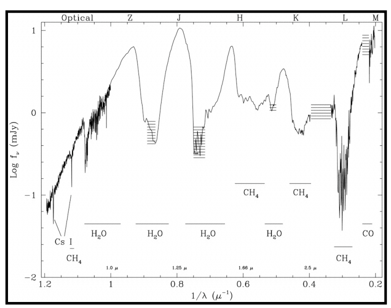


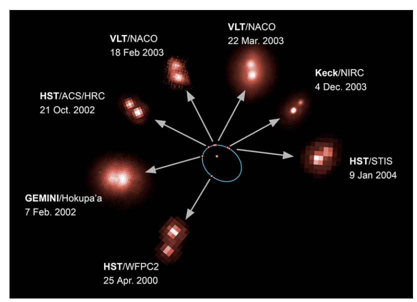


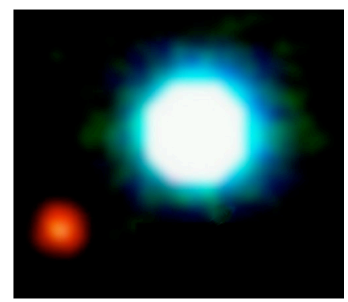


Lecture 3:
Star and Brown Dwarf Formation







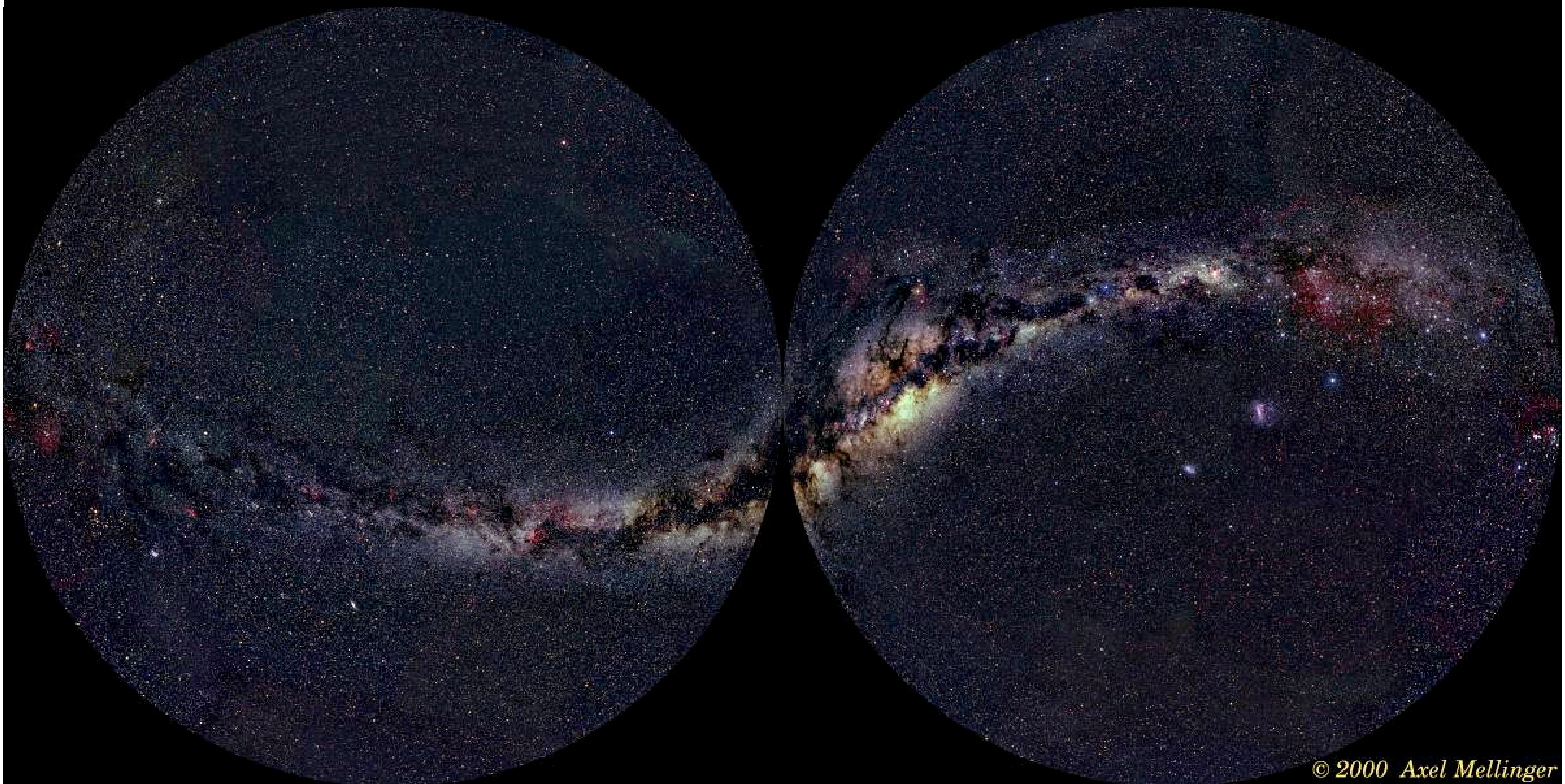


Do brown dwarfs form in the same manner as stars, as planets, or both?

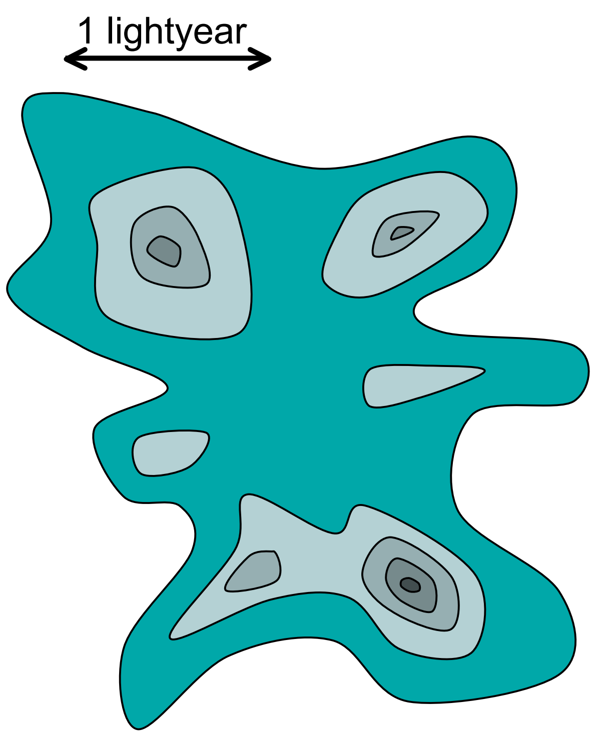
What is the minimum mass of a brown dwarf?

How many brown dwarfs are likely to be present in the Galaxy or the immediate vicinity of the Sun?

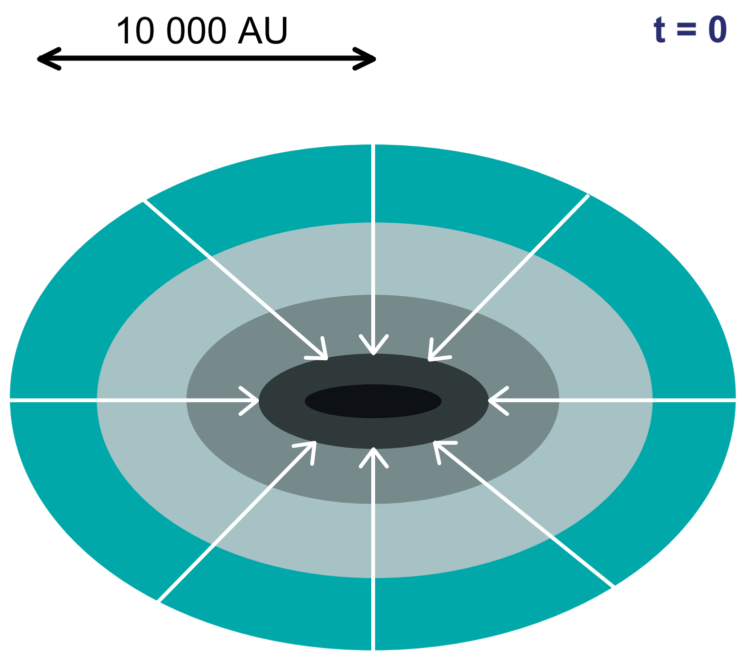
Molecular clouds in the Milky Way



Phases of star formation



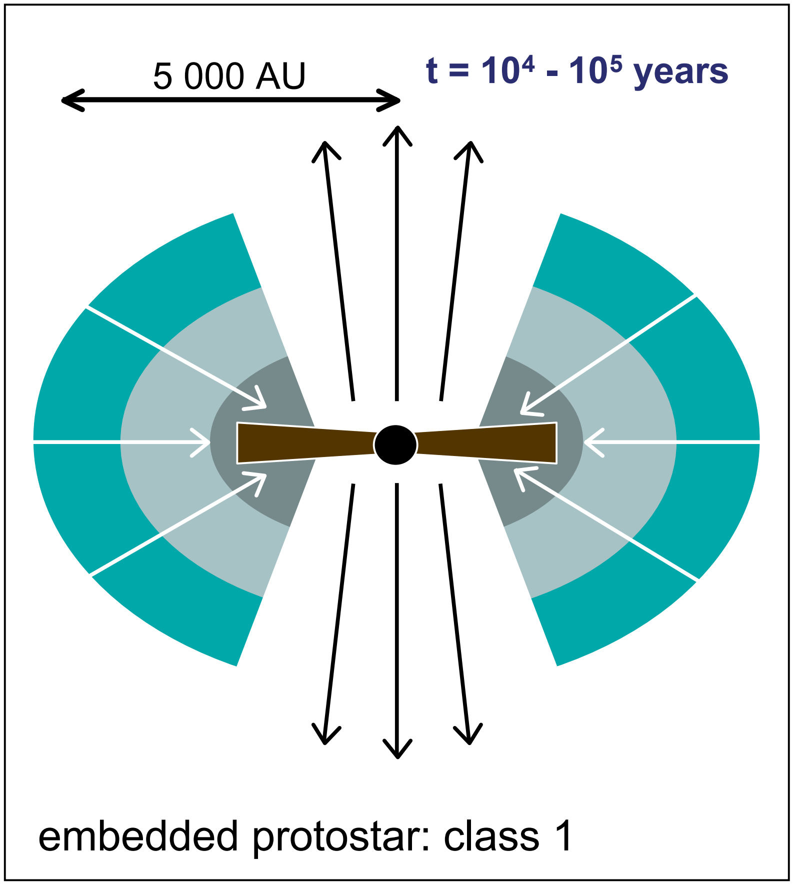
prestellar cores in dark clouds

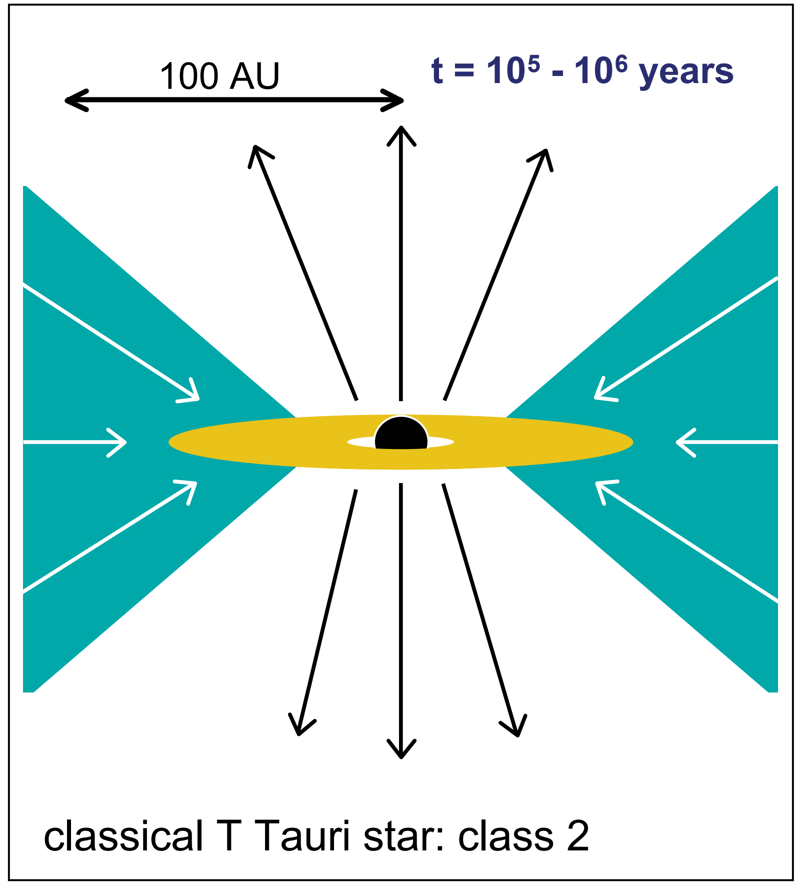


gravitational collapse: class 0 object

Illustrations by Ralf Klessen

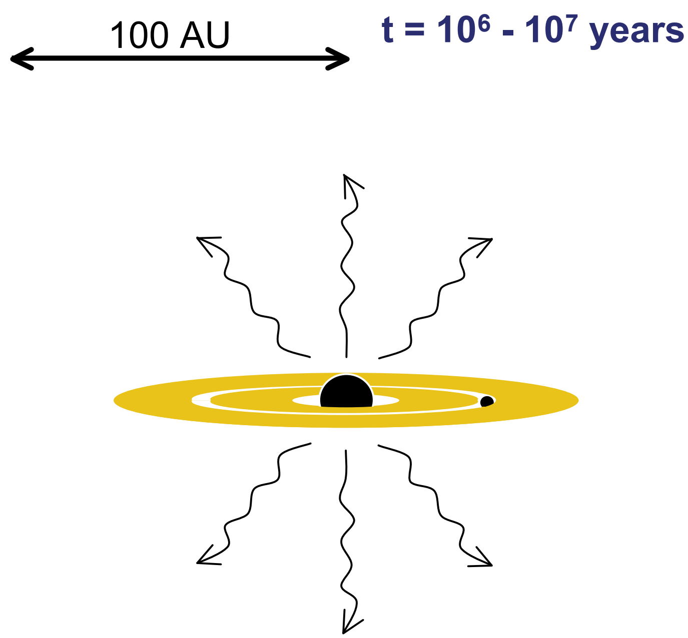
Phases of star formation



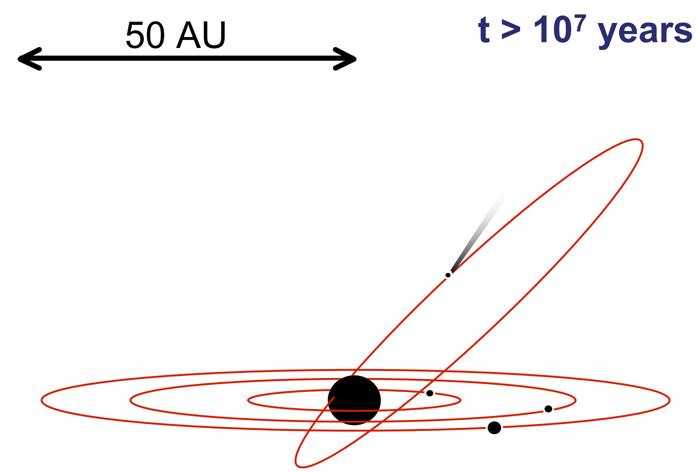


Illustrations by Ralf Klessen

Phases of star formation

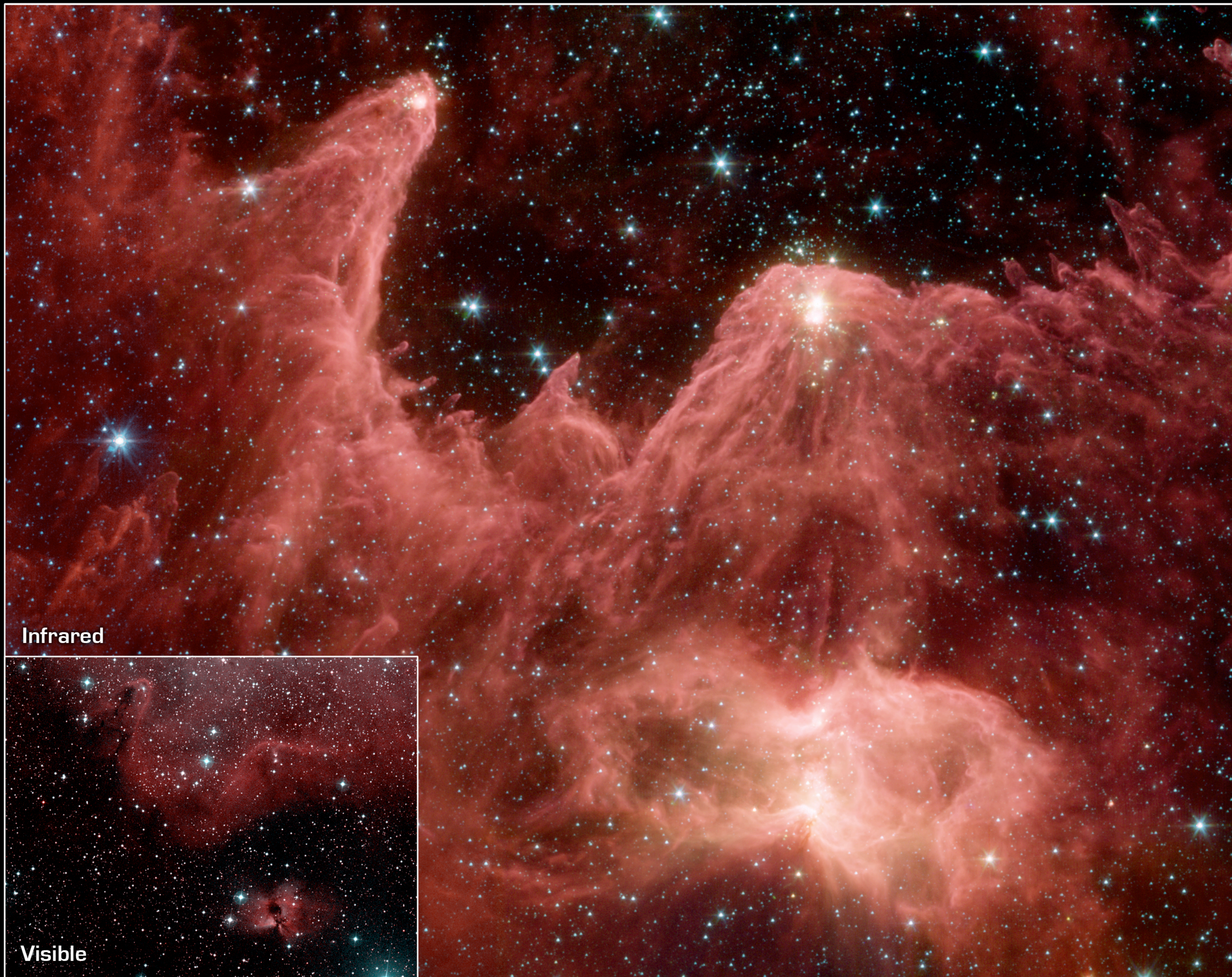


pre-main sequence star, debris disks, visible at optical wavelengths



star on main sequence (nuclear fusion) with planetary system

Illustrations by Ralf Klessen



“Mountains of Creation” in W5 Star-Forming Region

Spitzer Space Telescope • IRAC

Visible: DSS

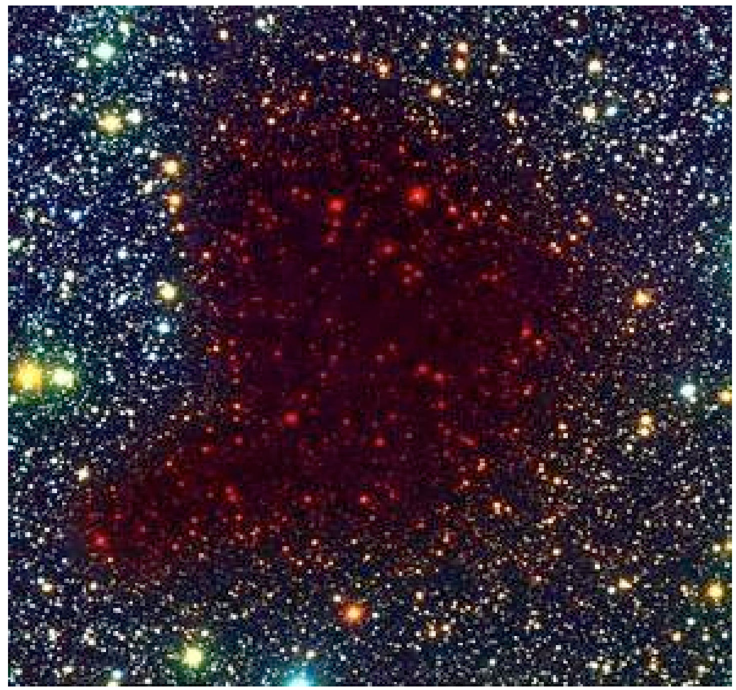
NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)

ssc2005-23a

← Optical

Prestellar Cores

Infrared →



Alves, Lada, Lada (2001)

Visible

Infrared

"Starless" Core L1014

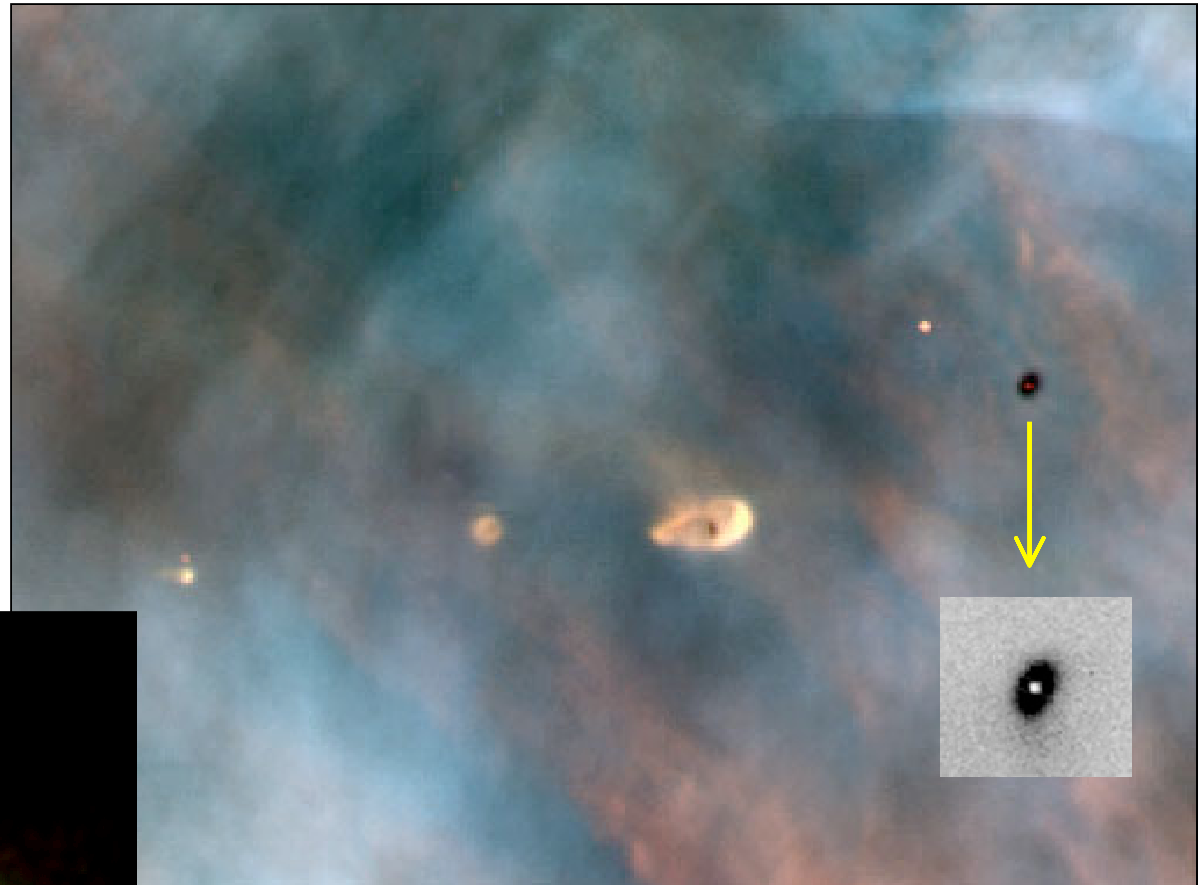
Spitzer Space Telescope • IRAC • MIPS

Visible: DSS

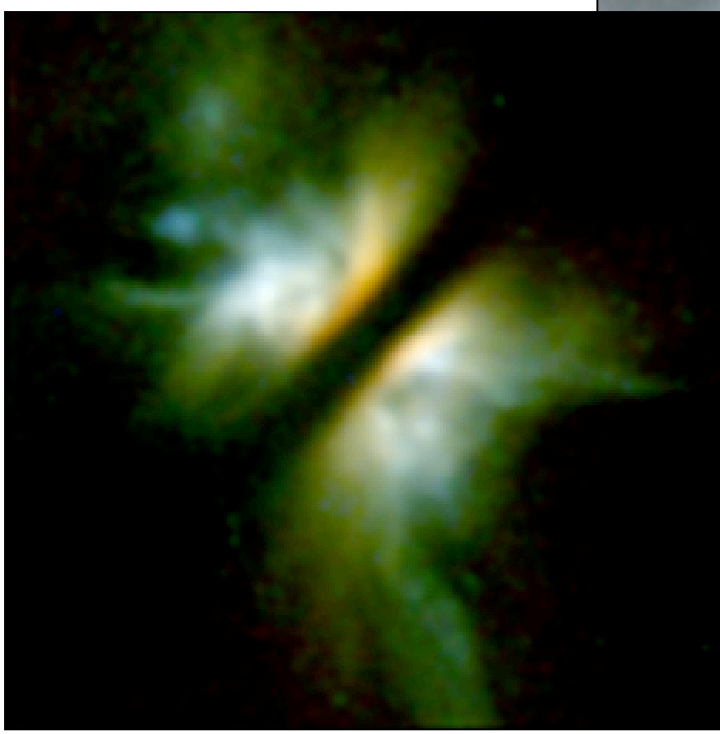
NASA / JPL-Caltech / N. Evans (Univ. of Texas at Austin)

ssc2004-20a

Circumstellar disks

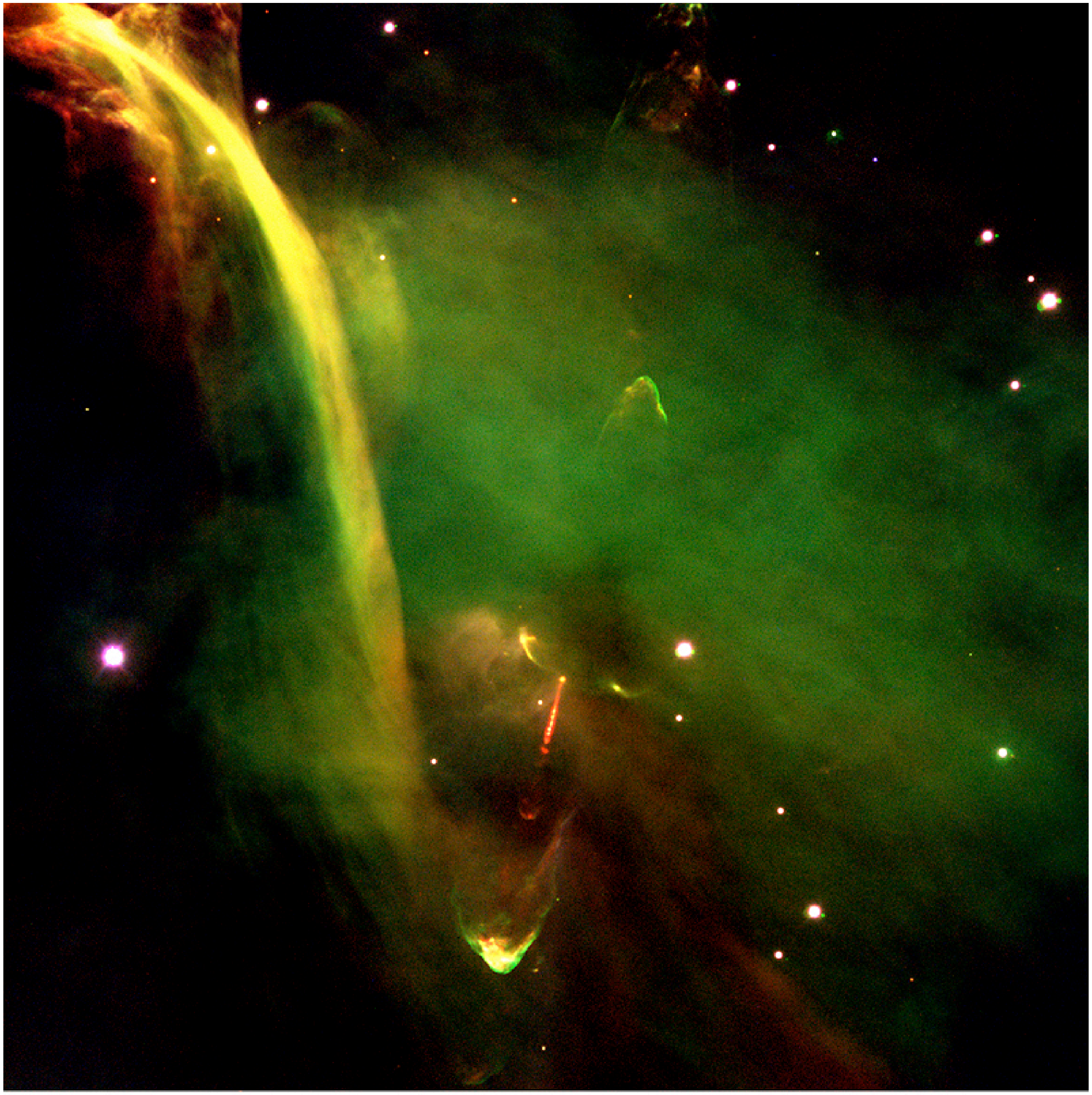


McCaughrean et al.



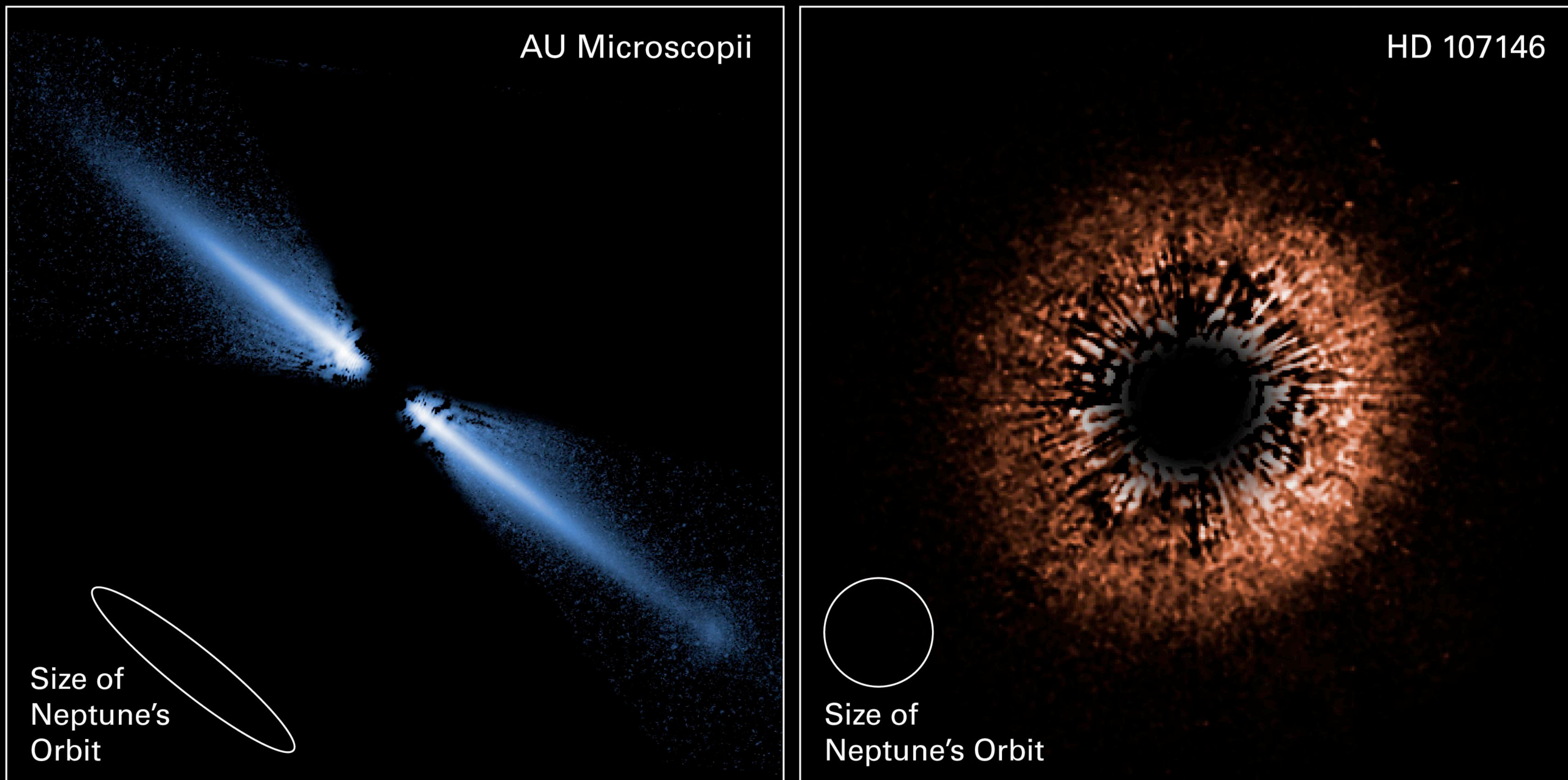
Padgett et al. (1999)

Herbig Haro objects: protostars with jets



Protostar HH-34 in Orion (VLT KUEYEN + FORS2)

ESO PR Photo 40b/99 (17 November 1999)



Circumstellar Debris Disks

Hubble Space Telescope • ACS HRC

NASA, ESA, J. Krist (STScI/JPL), D.R. Ardila (JHU), D.A. Golimowski (JHU), M. Clampin (NASA/Goddard), H. Ford (JHU), G. Hartig (STScI), G. Illingworth (UCO-Lick) and the ACS Science Team

STScI-PRC04-33a

What are the relevant scales for star formation?

- Densities
  - $n_{H2} \sim 10\ cm^{-3}$ (GMC)
    $\sim 10^{2\text{-}3}\ cm^{-3}$ (clump)
    $\sim 10^{5\text{-}10}\ cm^{-3}$ (core)
    $\sim 10^{20}\ cm^{-3}$ (embryo)
- Temperatures
  - $T \sim 10$ K (GMC $\rightarrow$ core)
    $\sim 10^{6}$ K (H ignition)
- Velocities
  - $c_s = (kT/m)^{1/2} \sim 10^{4}$ cm/s

$n_{H2}\ (cm^{-3}) = 3\times10^{23}\ \rho\ (g\ cm^{-3})$
$\rho \sim 1.4\ M_{\odot}/R_{\odot}^{3}\ g\ cm^{-3}$

What are the relevant scales for star formation?

- Time
  - $t_{dynamical} \sim (G\rho)^{-1/2} \sim 10^6$ yr (clump)
  - $t_{cross} \sim L/c_s \sim 10^7$ yr $> t_{dynamical}$
- Length
  - $\lambda_{Jean} \sim c_s/(G\rho)^{1/2} \sim 0.2$ pc (clump)
- Mass
  - $M_{Jean} \sim \rho\lambda^3_{Jean} \sim 0.5\ M_\odot$ (clump)
  - $M_{OL} \sim 0.001\text{-}0.01\ M_\odot$

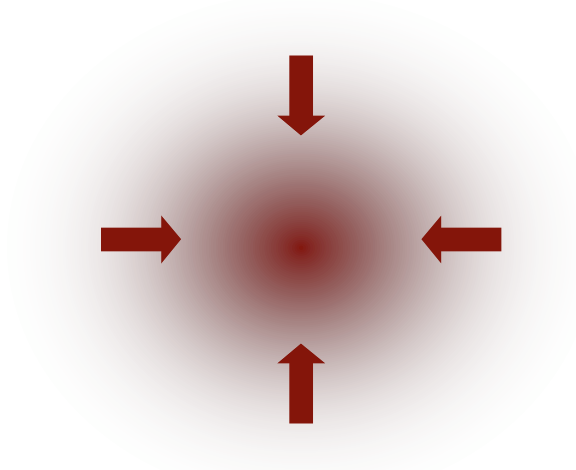
What is the Jean's length/mass?

Runaway growth of gravitational collapse; gravity beats gas thermal pressure support.

Collapse is on a dynamical timescale

Always occurs at large scales (gravity is a large-scale force)

Similar to Bonner-Ebert length/mass scale (externally driven cloud)

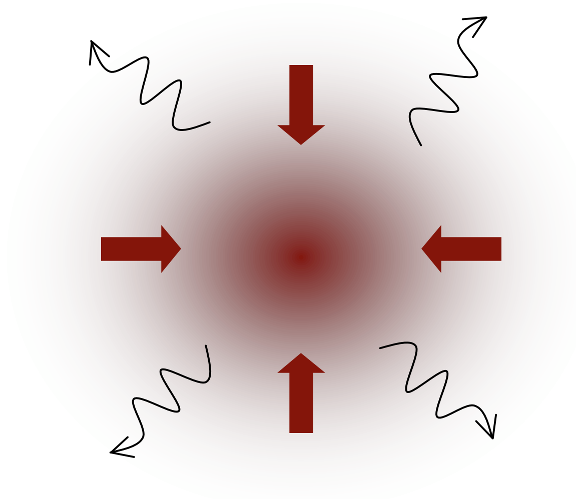


What is the opacity limit mass?

Balance of work done to compress object ($\Delta W = PdV$) and energy loss through radiation ($L \approx 4\pi R^2 \sigma T^4$) over dynamical timescale.

For efficient radiation, $T \sim 10$ K (applicable for $n < 10^{10}$ cm^{-3})

$M_{OL} \sim 0.001\text{-}0.01\ M_{\odot}$ for various geometries.



What is the "minimum" stellar mass?

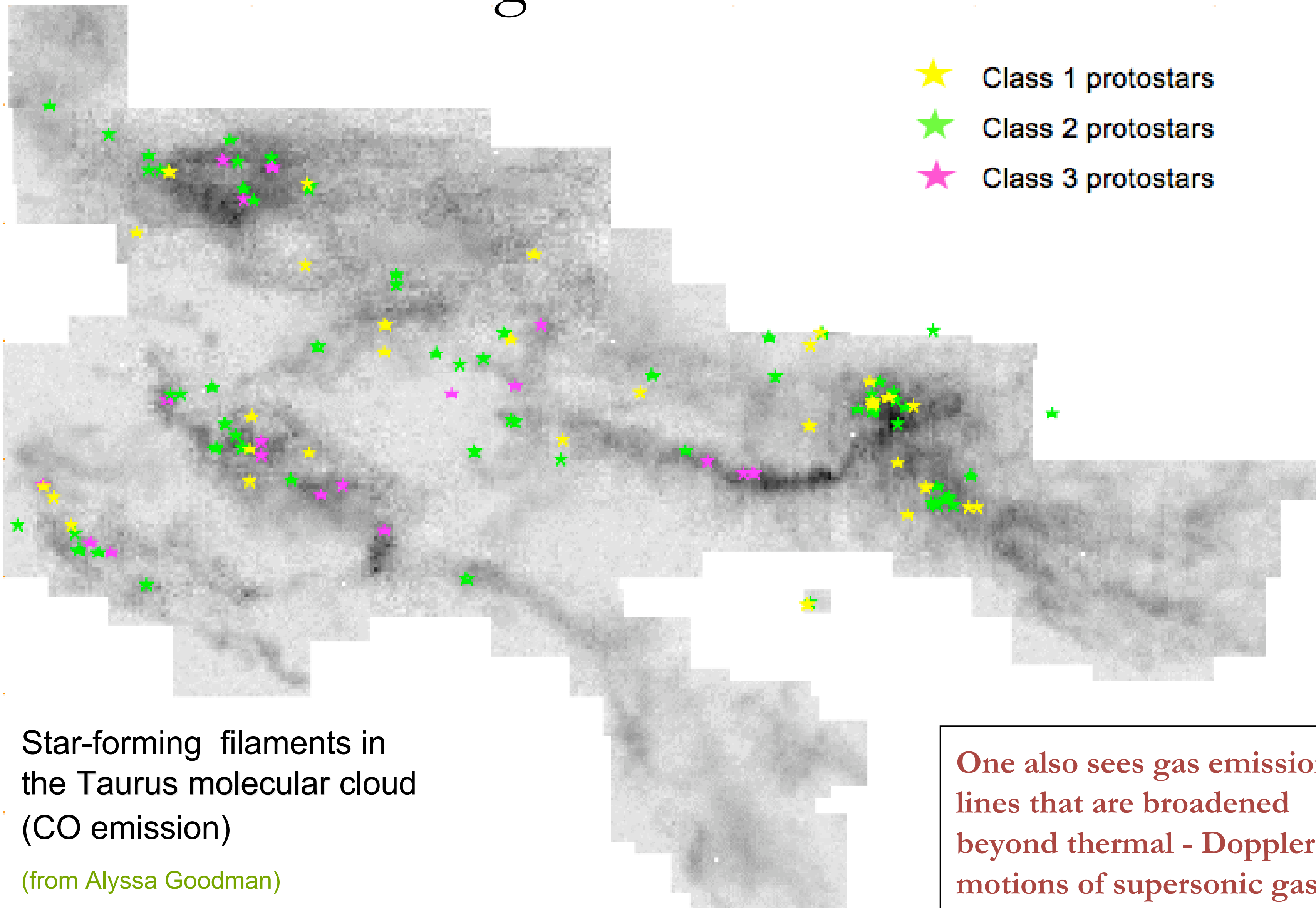
- Jean's mass is the minimum mass for gravitational instability
  - BUT fragmentation can occur in the collapsing cloud
  - $M_{Jean} \propto \rho^{-1/2}$ and $t_{dyn} \propto \rho^{-1/2} \Rightarrow$ smaller masses can collapse faster
- Below opacity limit, a core cannot compress
  - BUT remaining accretion of gas is 99% of star building

The primary difficulty in making a brown dwarf is balancing the requirement for a dense gas environment to make a low mass stellar embryo but preventing subsequent accretion of gas once the embryo is formed.

Five Solutions for BD Formation

1. **Turbulent (supersonic) fragmentation**
2. Fragmentation of protostellar cores followed by competitive accretion
3. Fragmentation of circumstellar disks followed by competitive accretion
4. Ejection of stellar embryos
5. Photoevaporation of cores

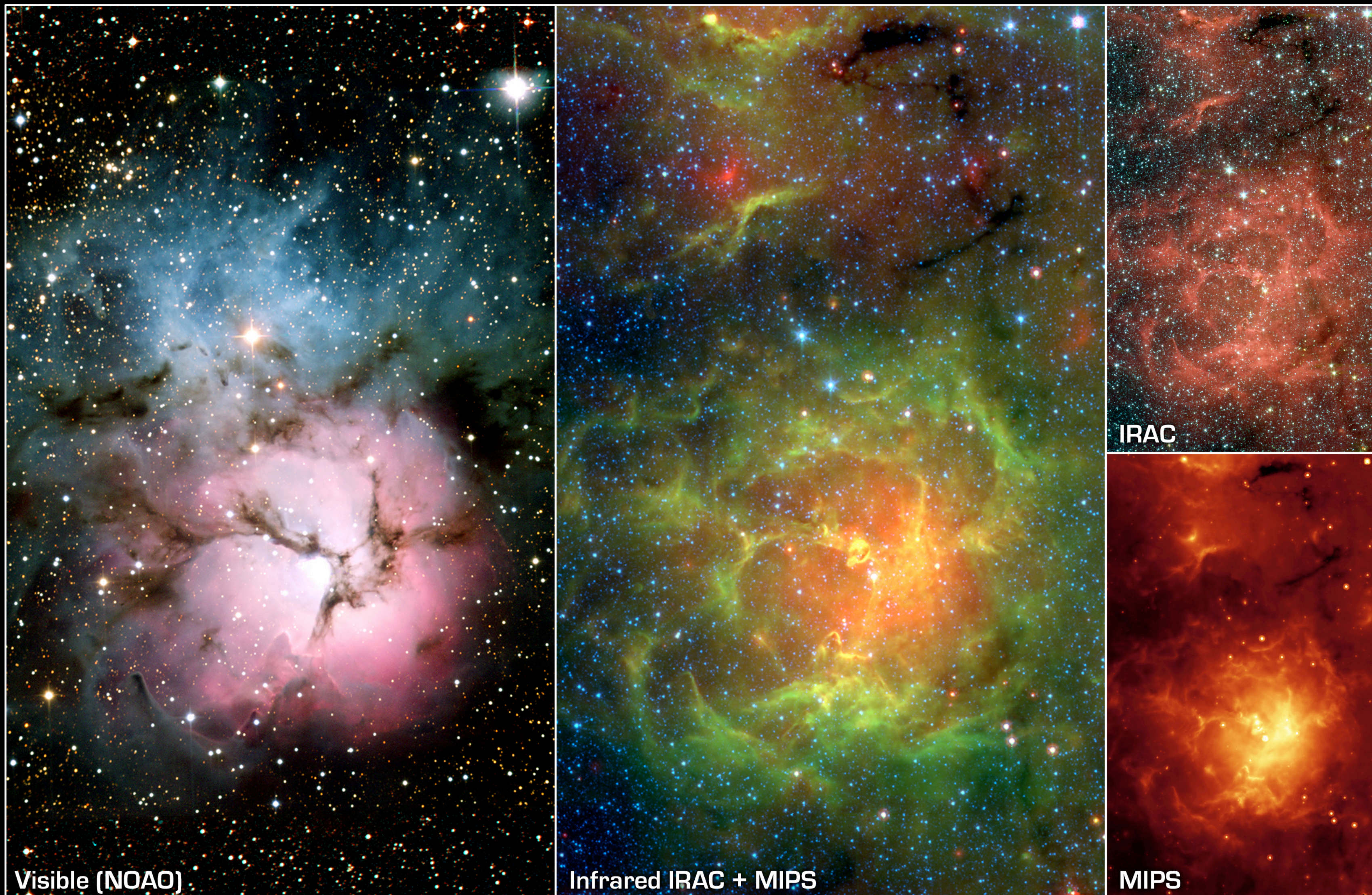
Star forming environments are turbulent



Star-forming filaments in the Taurus molecular cloud (CO emission)

(from Alyssa Goodman)

One also sees gas emission lines that are broadened beyond thermal - Doppler motions of supersonic gas



Trifid Nebula/Messier 20

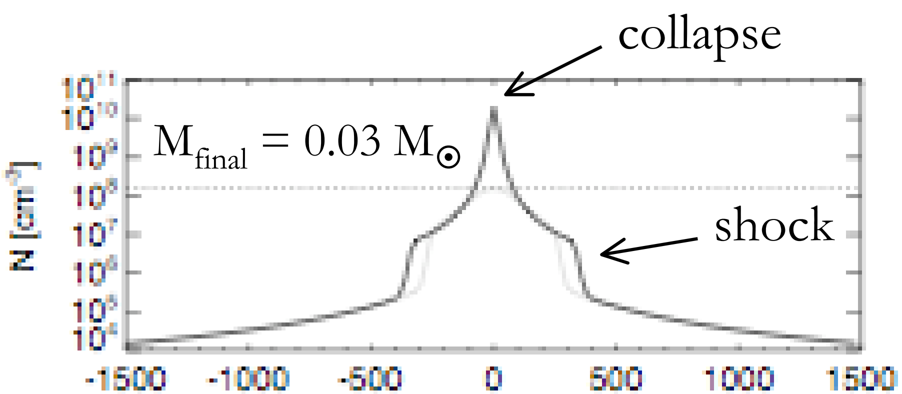
NASA / JPL-Caltech / J. Rho (SSC/Caltech)

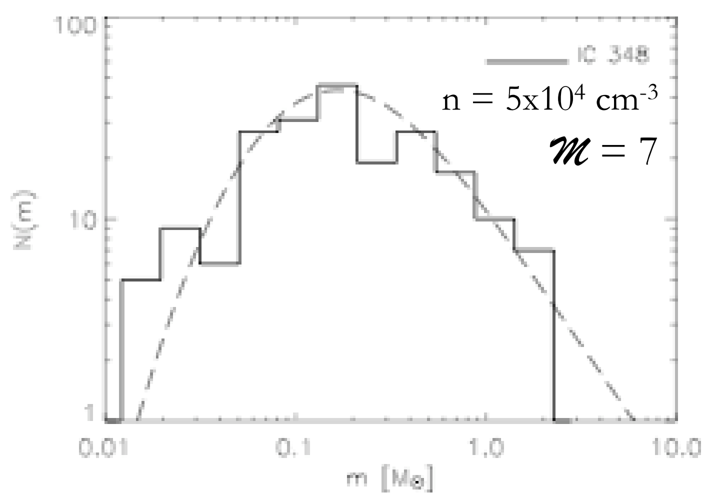
Spitzer Space Telescope • IRAC + MIPS

ssc2005-02a

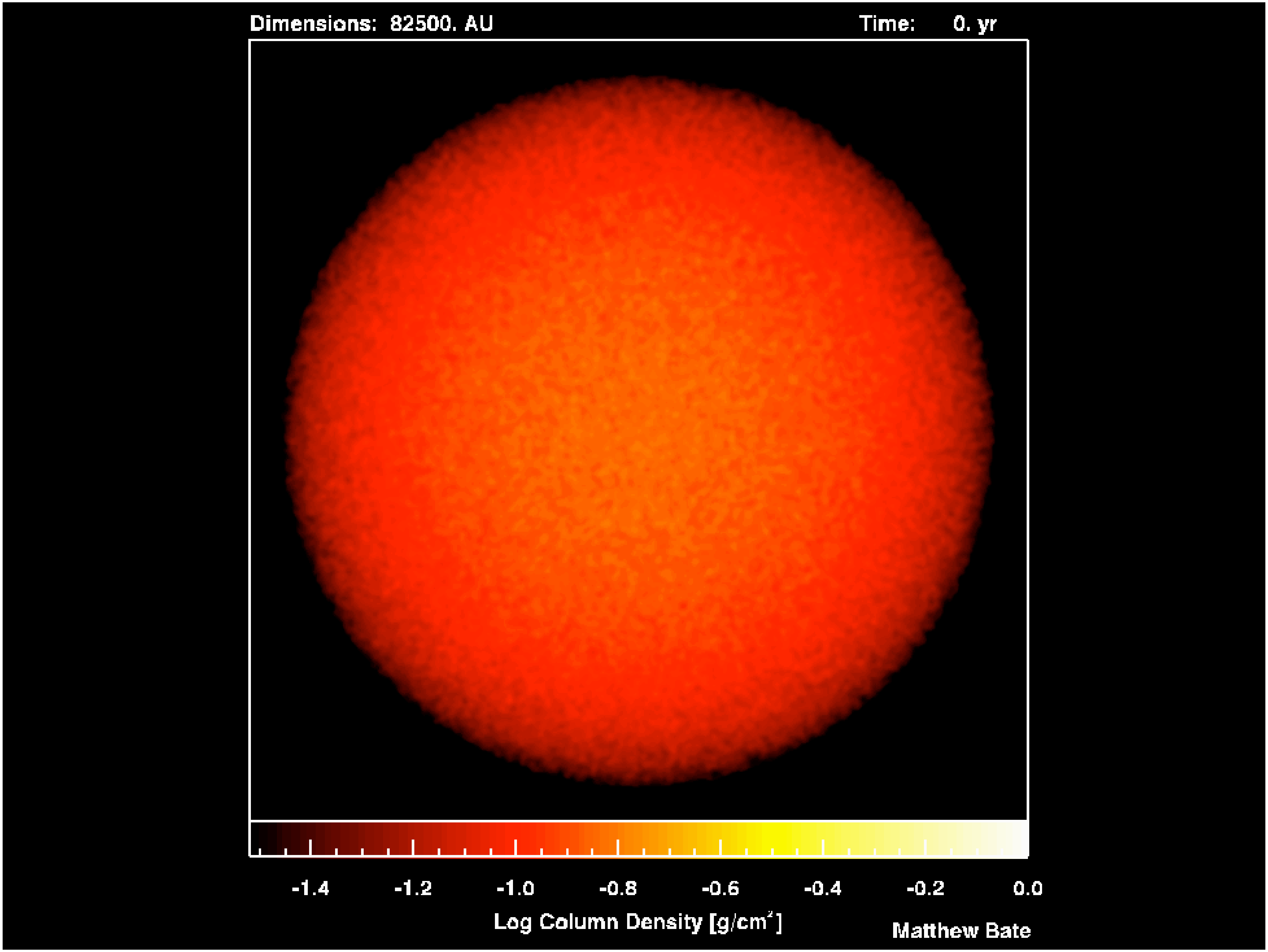
Turbulent Fragmentation

The requirement for high densities and low gas reservoirs can be solved by creating dense cores in converging supersonic flows.





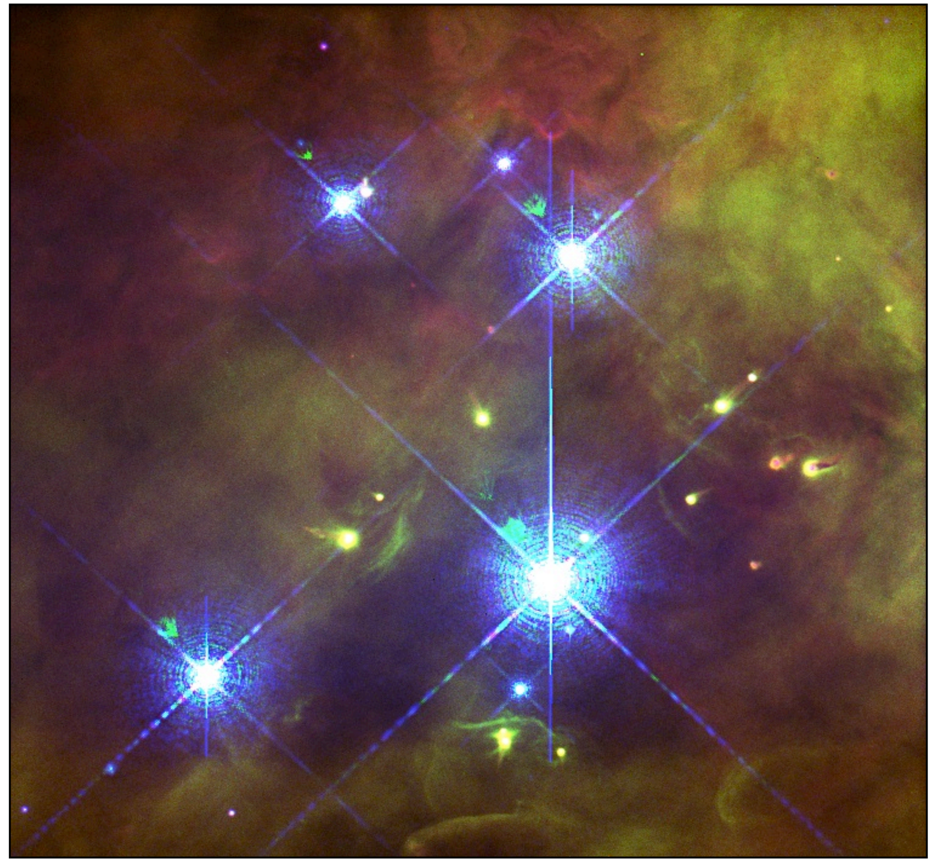
$$n_{core} \sim 14\mathcal{M}^2 n_{shock} > n_{BD} \sim 10^{6\text{-}7}\ cm^{-3} \Rightarrow n_{shock} > 10^{4\text{-}5}\ cm^{-3}$$



Dimensions: 82500. AU
Time: 0. yr
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
Log Column Density [g/cm^2]
Matthew Bate

Photoevaporation

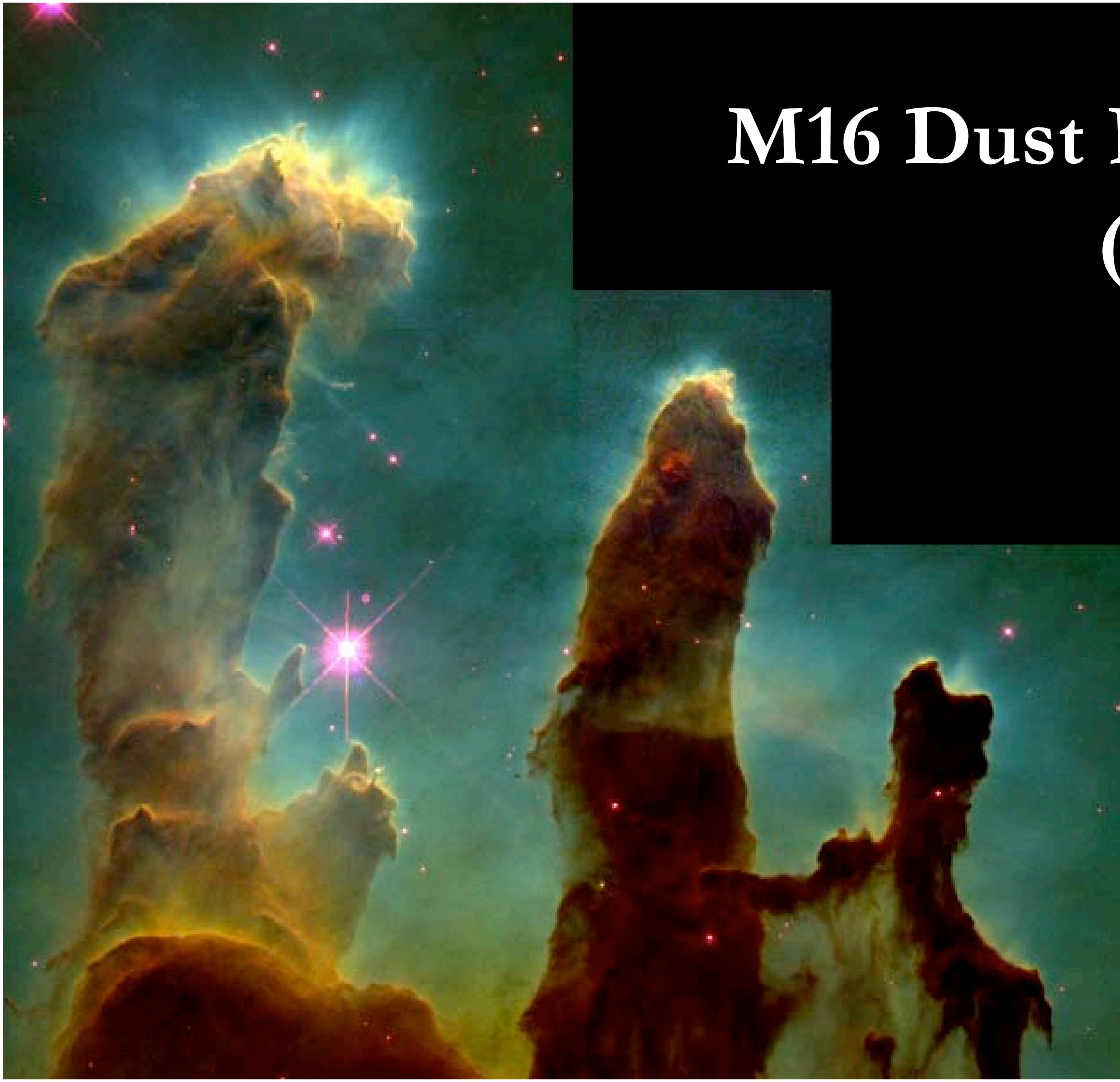
Ionizing radiation from central star
Θ1C Orionis



Proplyds: Evaporating ``protoplanetary´´ disks around young low-mass protostars

(images: Doug Johnstone et al.)

M16 Dust Pillars (HST)



Five Solutions for BD Formation

1. Turbulent (supersonic) fragmentation
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Discussion Points

1. What are some of the strengths and problems of turbulent fragmentation?
2. What is the best measure for ascertaining which mechanism is dominant?
3. Do you suspect different mechanisms to be dominant in different regions?
4. Given the observational evidence, does ejection seem to be a valid idea for brown dwarf formation?