

# Star Formation

- Gravitational collapse
- Accretion discs
- Outflows

# Gravitational collapse

- stars form due to the gravitational collapse of interstellar gas clouds
- coldest, densest clouds are those most likely to collapse
- these are the molecular clouds



# Virial Theorem

- For a self-gravitating system in equilibrium the virial theorem states that

$$2U + \Omega = 0 \quad \text{or} \quad U = -\frac{1}{2}\Omega$$

where  $U$  is the total thermal (kinetic) energy of the cloud and  $\Omega$  is the total gravitational potential energy

# Jeans Mass

- In order for contraction of the cloud to occur we require the gravitational term to overcome the pressure term i.e.

$$- \Omega > 2U$$

- For constant density cloud this gives

$$M_c > \left( \frac{5kT}{G\mu m_H} \right)^{\frac{3}{2}} \left( \frac{3}{4\pi\rho_c} \right)^{\frac{1}{2}}$$

- Critical mass known as the Jeans Mass

# Fragmentation

- Initially when a cloud collapses its temperature remains cold so that the Jeans mass drops as the density increases
- Hence, smaller mass fragments can become unstable to collapse – leads to star clusters
- Eventually fragments heat up and a hydrostatic core will form

# Free-fall time

$$\frac{d^2 r}{dt^2} = -\frac{GM(r)}{r^2} = -\frac{4\pi GR_C^3 \rho_C}{3r^2}$$

since  $M(r)$  the mass internal to  $r$  will remain constant.

- Approximate solution can be obtained by assuming acceleration stays constant at the initial value ie.

$$\frac{d^2 r}{dt^2} = -\frac{4\pi GR_C^3 \rho_C}{3R_C^2} = -\frac{4\pi GR_C \rho_C}{3}$$

giving free-fall time  $t_{ff} = \sqrt{\frac{3}{2\pi G \rho_C}}$

# Infalling Cloud

- If assumed in free-fall – no pressure

$$\frac{1}{2} m v_{ff}^2 = \frac{GMm}{r}$$

$$v_{ff}(r) = \sqrt{\frac{2GM}{r}}$$

and  $\dot{M}$  is the mass infall rate where

$$\dot{M} = 4\pi r^2 \rho v$$

- So if constant  $\dot{M}$  then  $\rho \propto r^{-\frac{3}{2}}$

# Cloud Rotation

- If initial cloud of radius  $R$  has a uniform rotation rate  $\Omega$  then conservation of specific angular momentum along the equator means

$$\omega r^2 = \Omega R^2 = \text{constant}$$

- Therefore the centrifugal force for a mass  $m$

$$F_c = m\omega^2 r \propto r^{-3}$$

- Since gravity  $F_g = \frac{GMm}{r^2}$  the

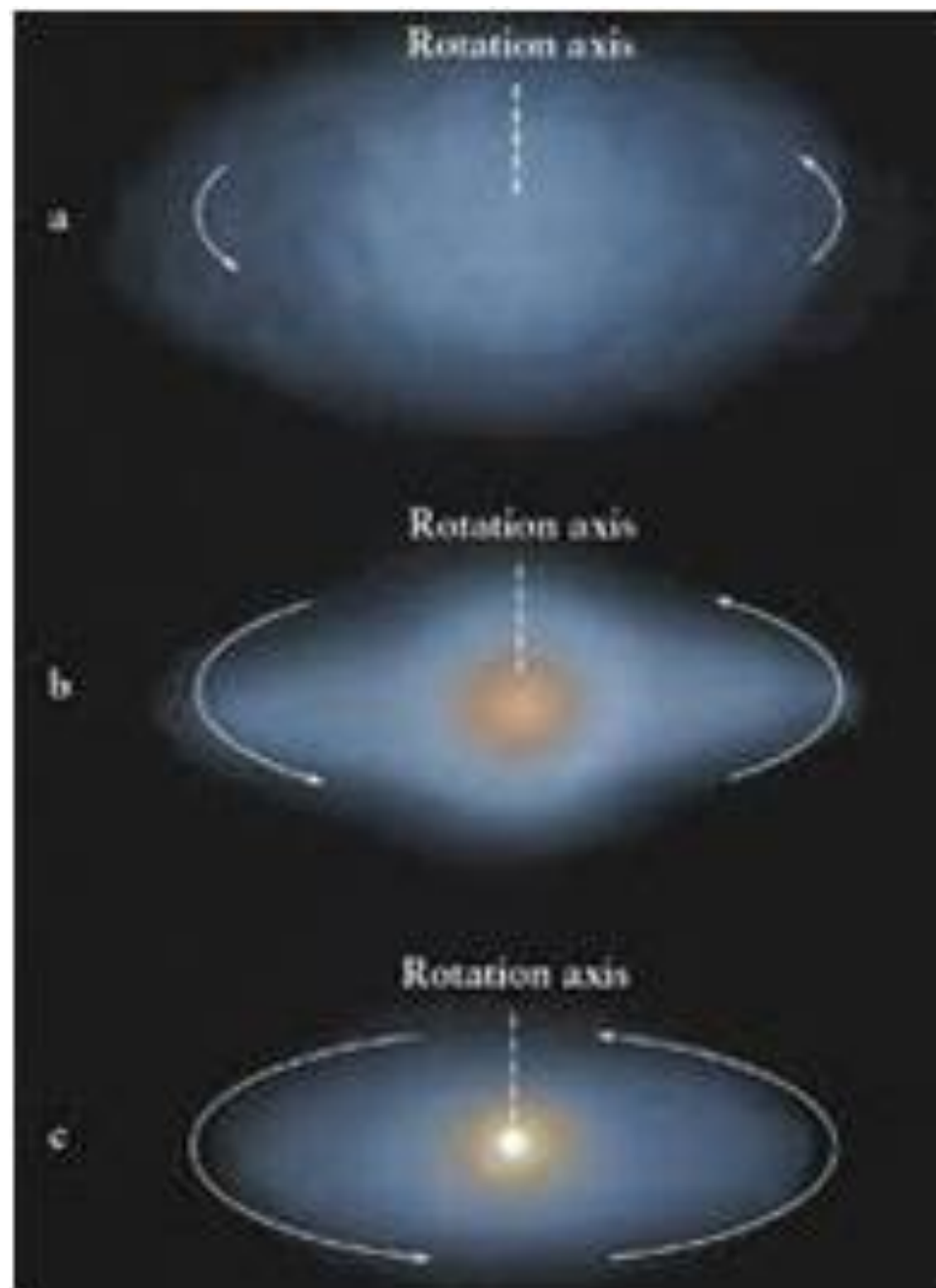
centrifugal force will eventually win out.

# Centrifugal Radius

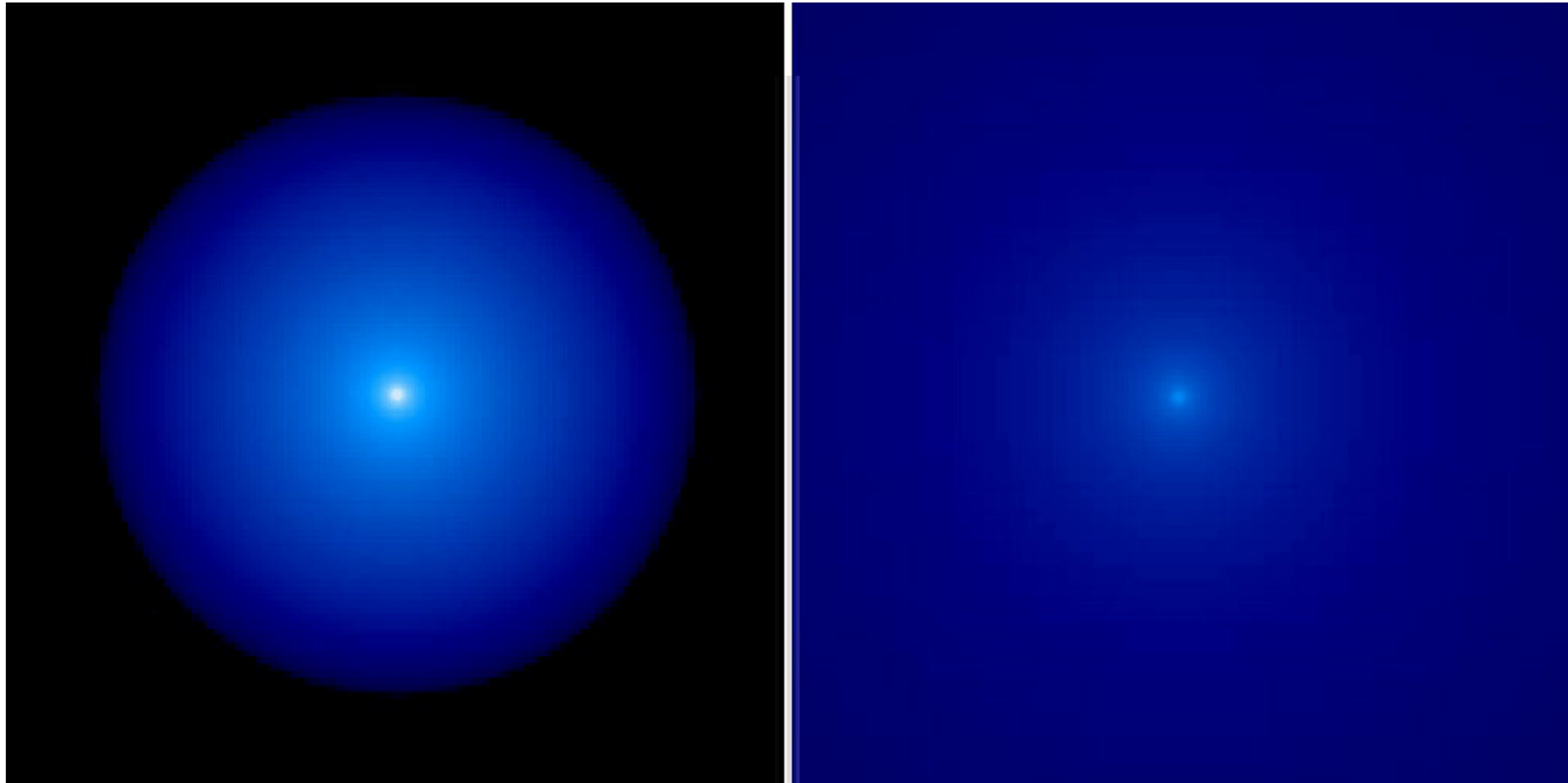
- Radius where  $F_c = F_g$  is called the centrifugal radius

$$R_c = \frac{\Omega^2 R^4}{GM}$$

- Cloud can still contract parallel to rotation axis
- This leads to flattened rotating structures
  - accretion discs
- But need to lose a lot of angular momentum



# Numerical simulation



Krumholz et al. (2007)

# Magnetic field during collapse

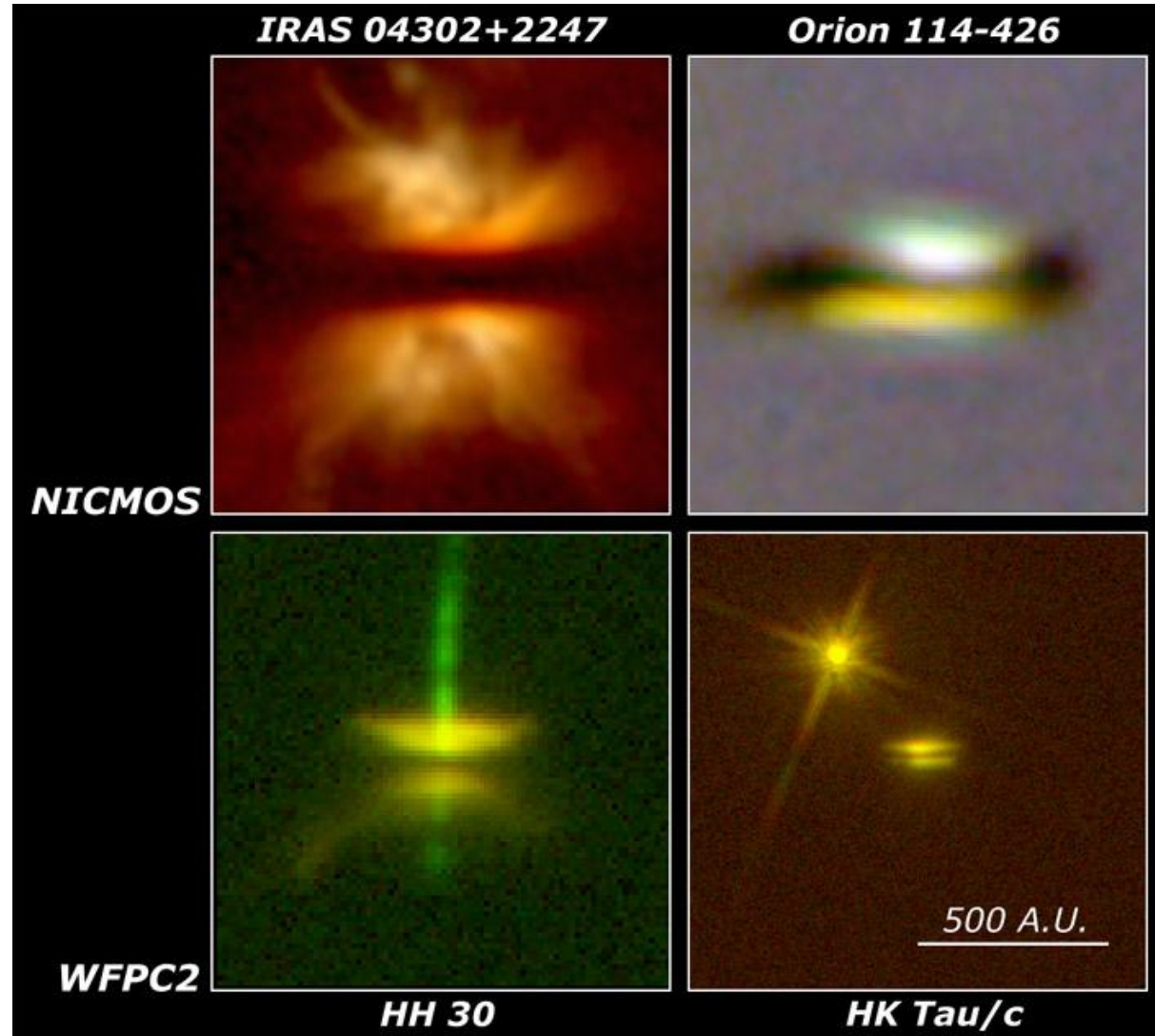
- Molecular clouds always have some level of ionization due to passage of energetic particles – cosmic rays
- Hence the initial magnetic field in the cloud will get dragged in during the collapse
- Need to lose a lot of magnetic flux too

# Accretion Discs

- Infalling, rotating material forms a disc around the proto-star
- Viscous forces allow mass to accrete inwards whilst transferring angular momentum outwards
- Material heats up and radiates with luminosity

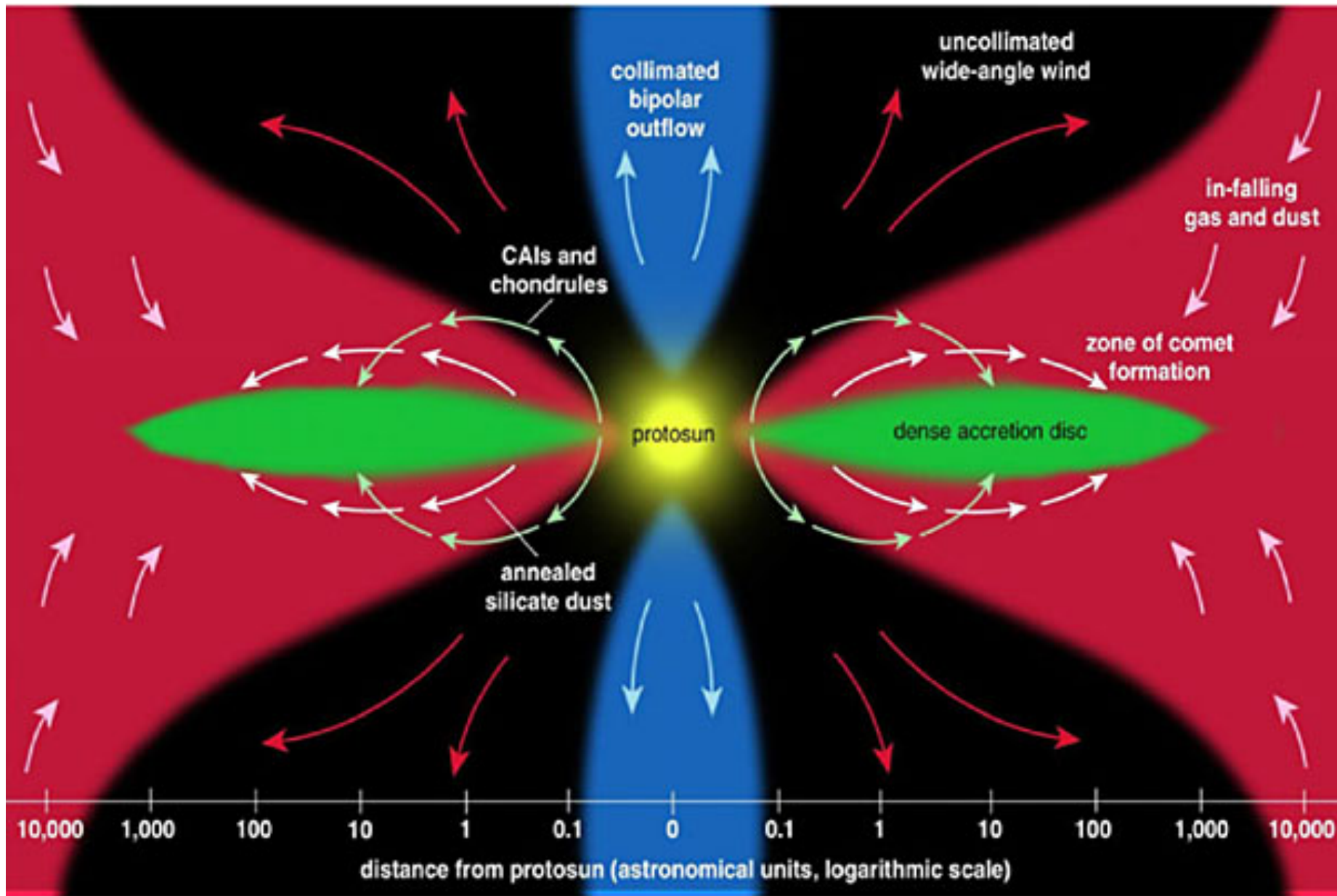
$$L_{\text{acc}} \sim \frac{GM \dot{M}}{R_s}$$

- Can see discs indirectly in absorption against nebulae or scattered light in the optical

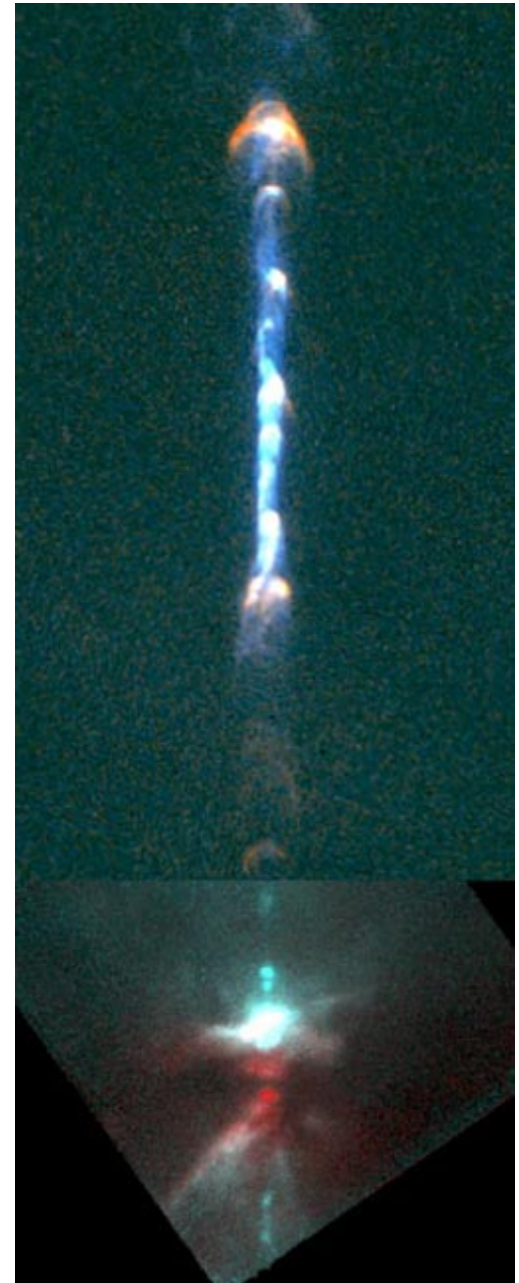
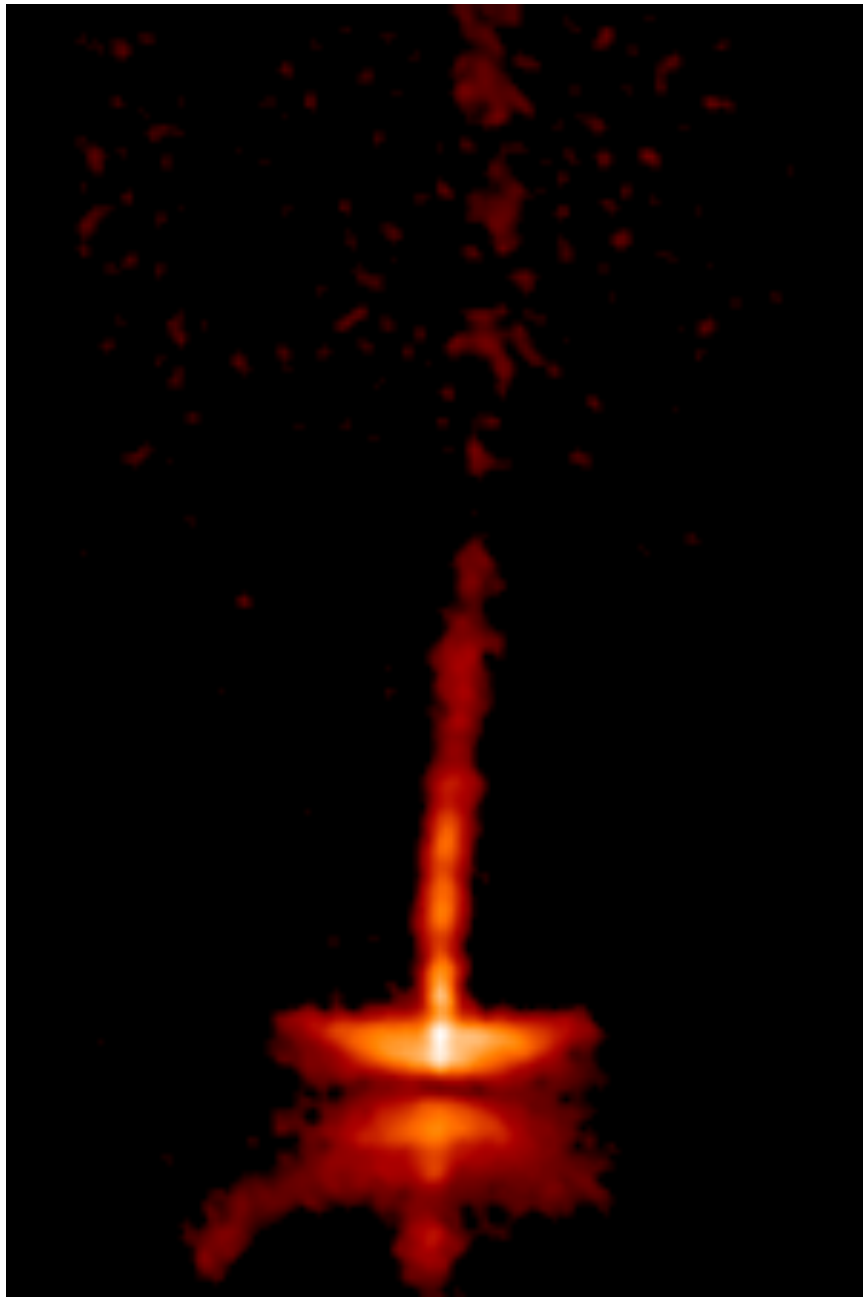


# Jets and bipolar outflows

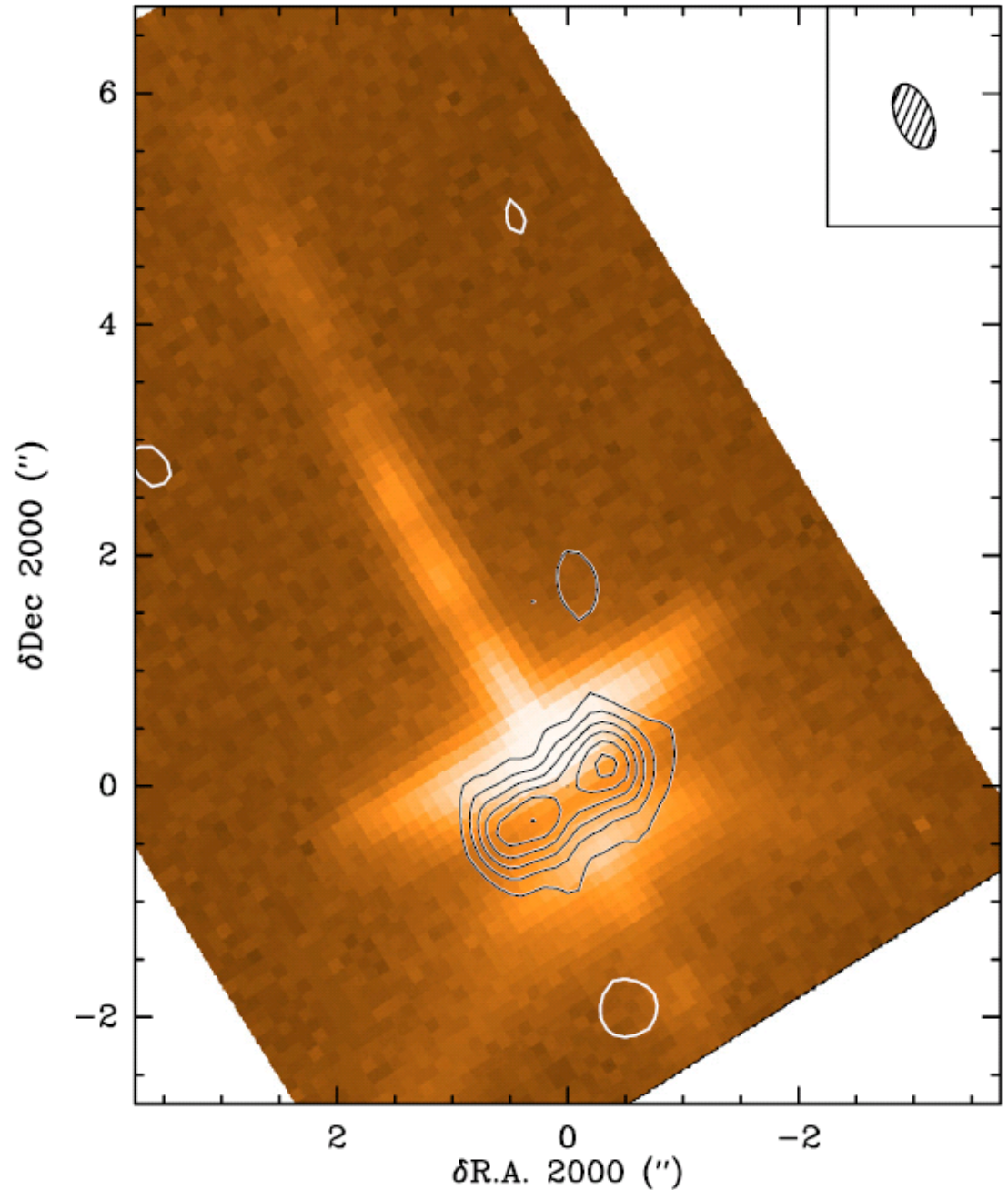
- Rotating magnetic fields in the star-disc system act to drive material out along the rotation axis
- Jets of ionized material are seen moving at several hundreds of km/s
- Bipolar molecular outflows moving at several tens of km/s that clear cavities



(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

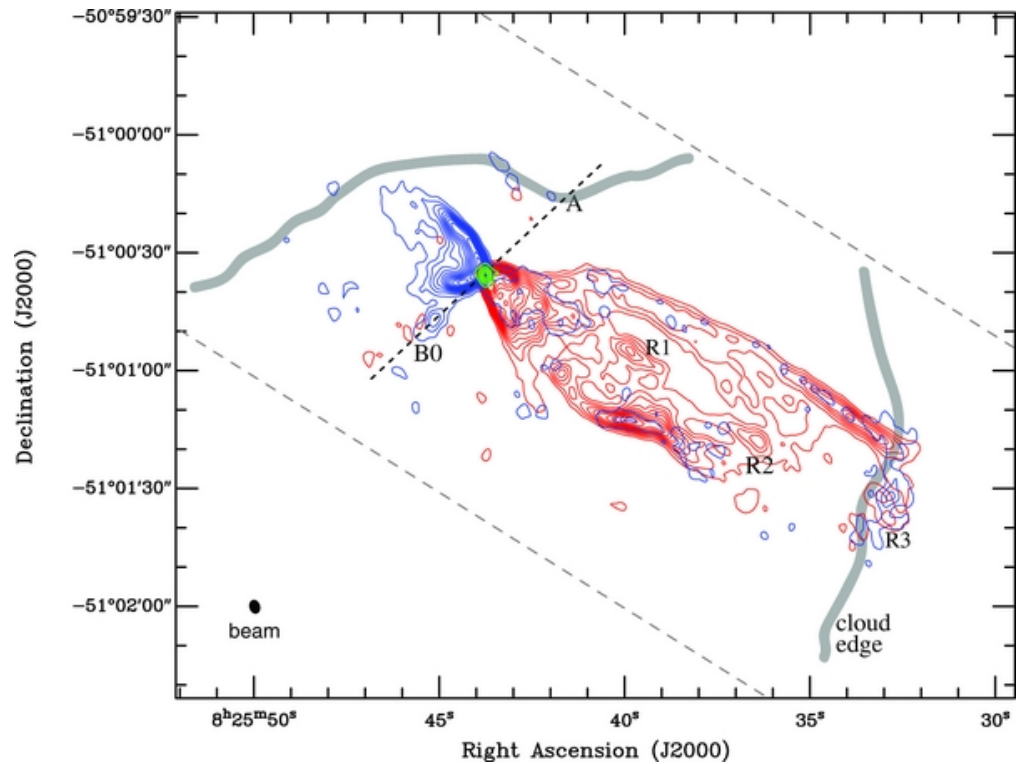


- Can see disc directly in molecular gas (CO)





Optical picture showing jet



Mm-wave picture showing molecular outflow (ALMA telescope)

# Summary

- Stars form in cold, dense cores of molecular clouds
- Angular momentum leads to formation of accretion discs
- Magnetic fields drive outflows perpendicular to the discs

# Massive star formation

- Timescale for contraction of the protostellar hydrostatic core to the H burning main sequence is

$$\tau_{\text{K-H}} \sim \frac{GM^2}{R} / L$$

and for MS stars  $L \propto M^{3.3}$  so  $\tau_{\text{K-H}} \propto M^{-1.3}$

- For massive stars  $\tau_{\text{K-H}} \ll \tau_{\text{ff}}$  and they arrive on the MS whilst still deeply embedded in their molecular cloud

# Masers

- A combination of dense molecular gas and either
  - strong IR radiation field
  - or collisions in outflows
- Leads to pumping of excited levels and a population inversion in certain molecules such as OH, H<sub>2</sub>O, CH<sub>3</sub>OH
- This leads to maser emission

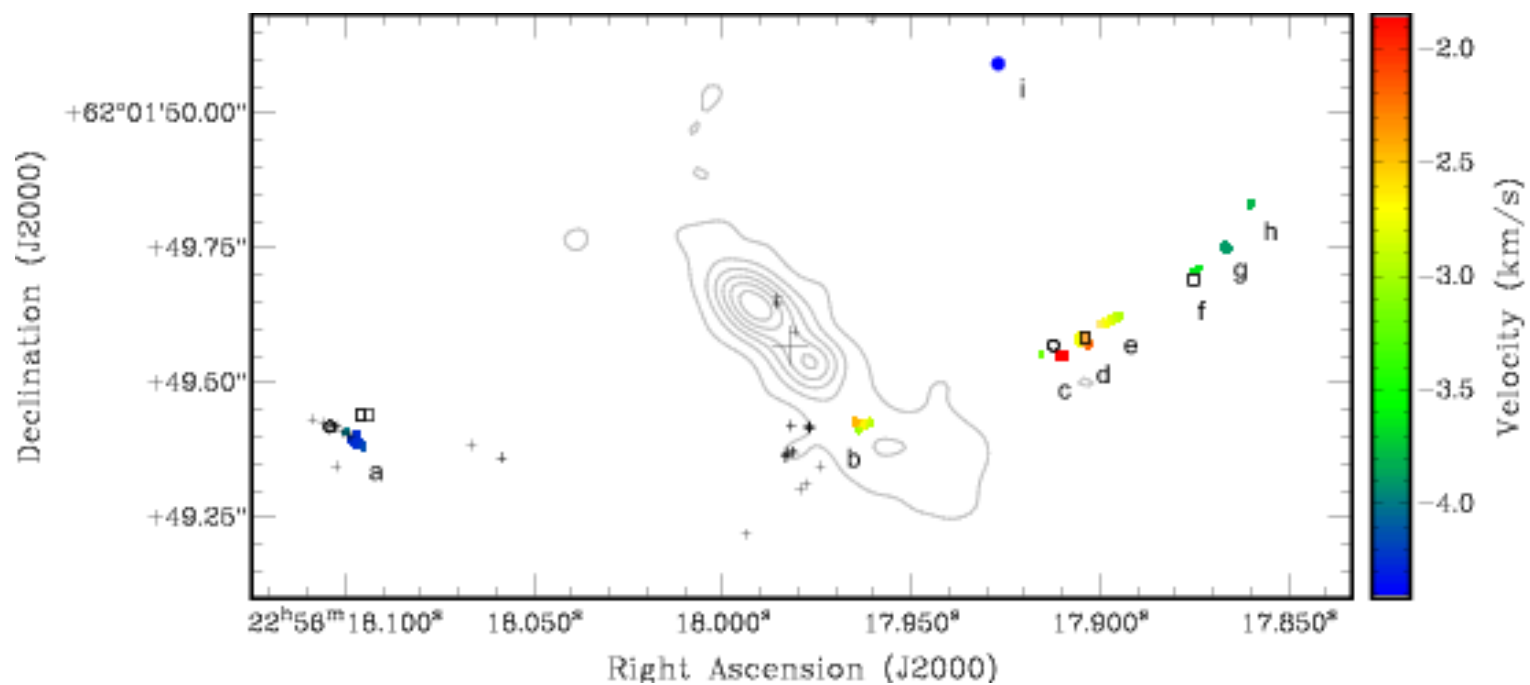
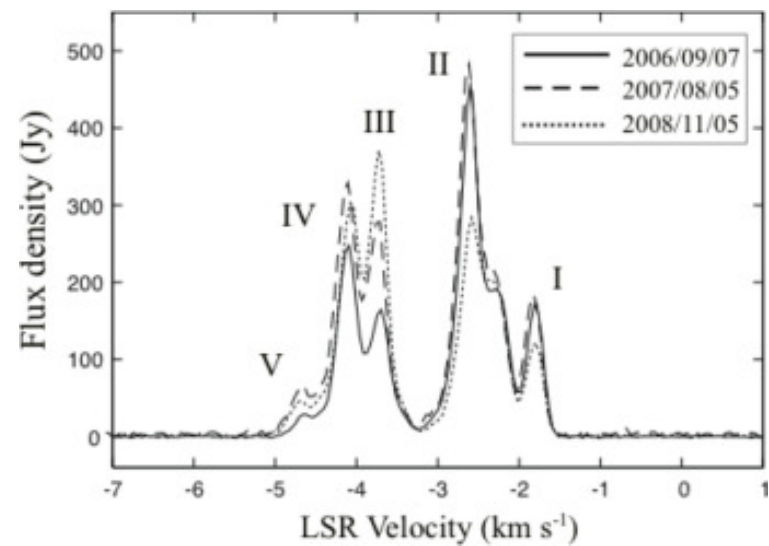
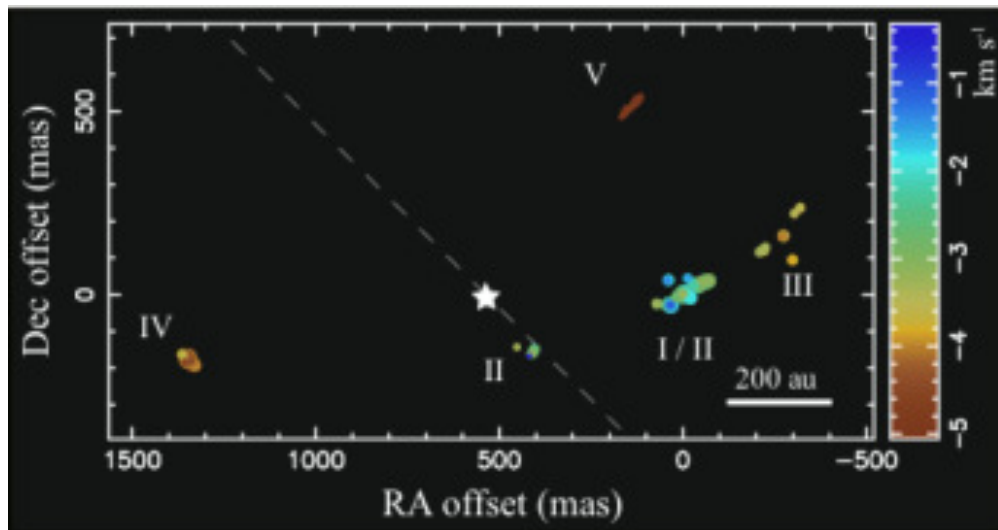
# Stimulated Emission

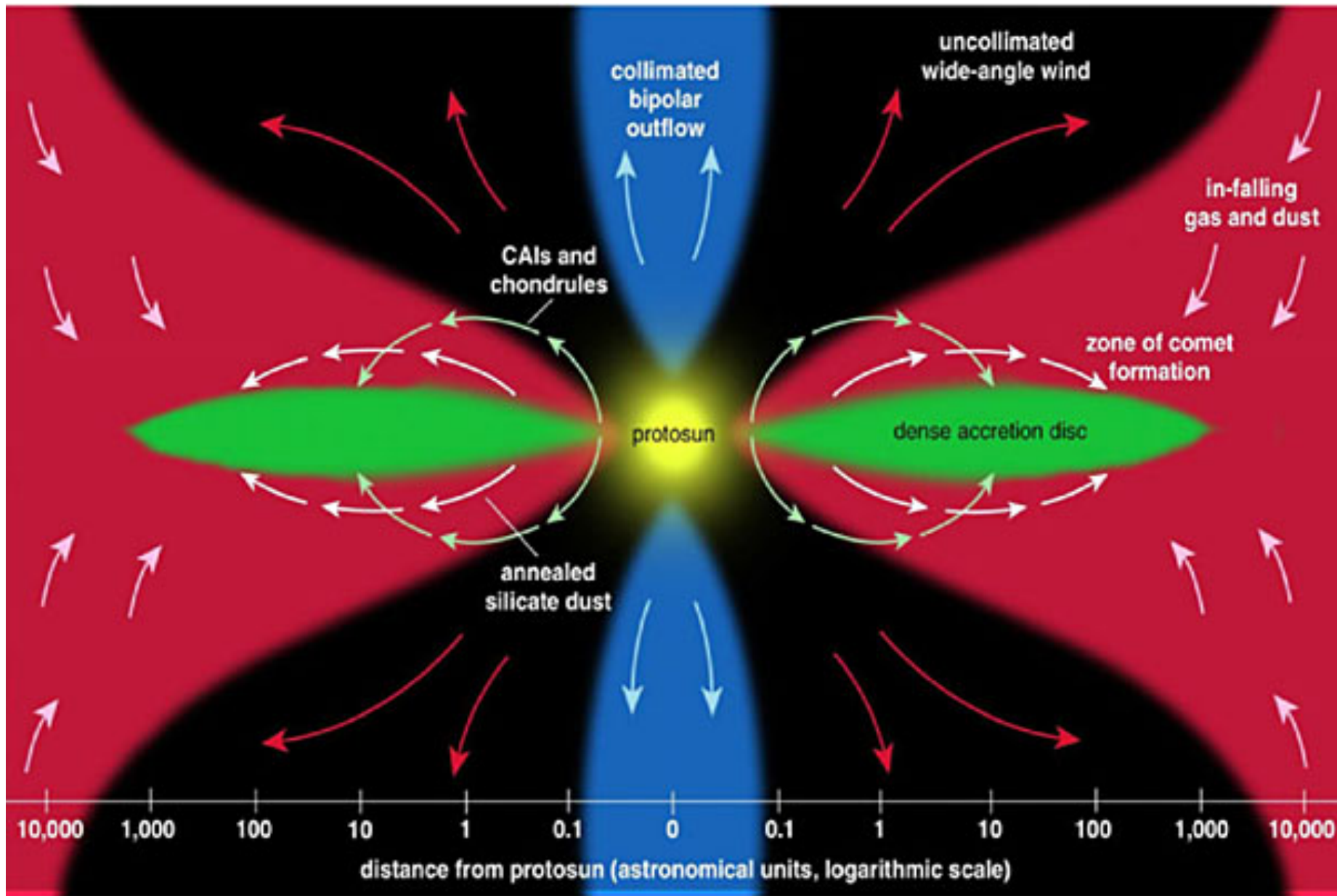
- passing photon with same frequency as the maser transition can stimulate a radiative de-excitation
- emitted photon has same direction as stimulating photon

→beaming

# Amplification

- photons can stimulate other molecules  
→ cascade as in a laser
- can also view phenomena as a negative optical depth:
  - instead of attenuation  $I_l \propto e^{-\tau}$
  - you get amplification  $I_l \propto e^{\tau}$
- intense spots of maser emission





(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

# Periodic Methanol Masers

- Some methanol masers exhibit periodic flaring of the intensity of some components
- May be caused by colliding winds in an eccentric massive young binary system

