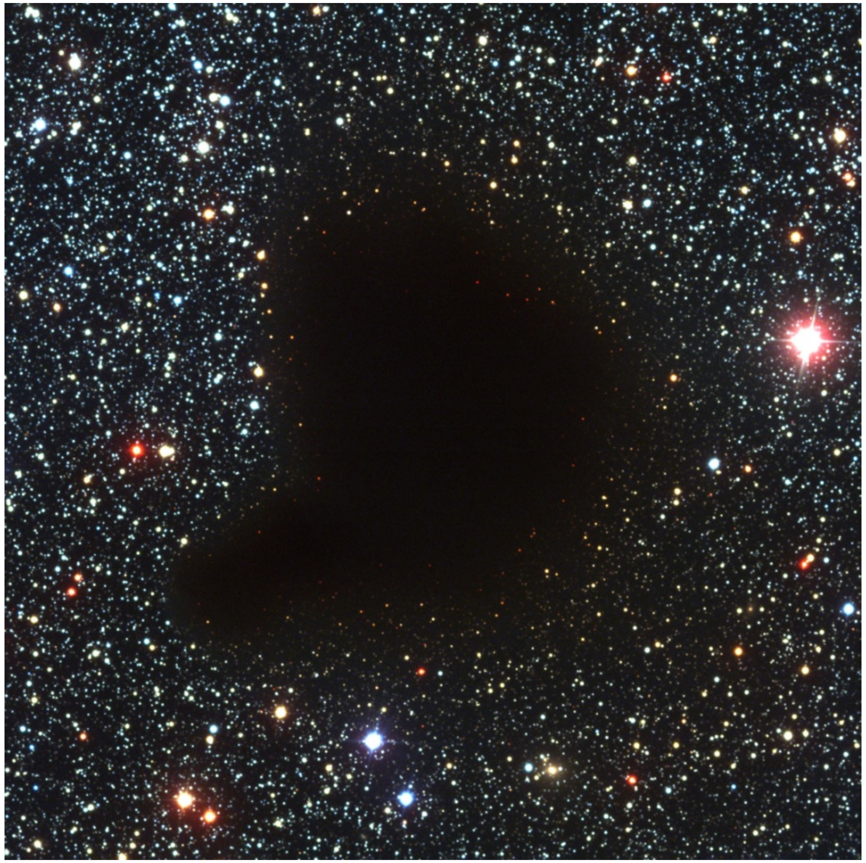
Star Formation

- 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

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

where U is the total thermal (kinetic) energy of the cloud and Ω 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

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

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.

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

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

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 Ω 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 $F_G = \dfrac{GMm}{r^2}$ the centrifugal force will eventually win out.

Centrifugal Radius

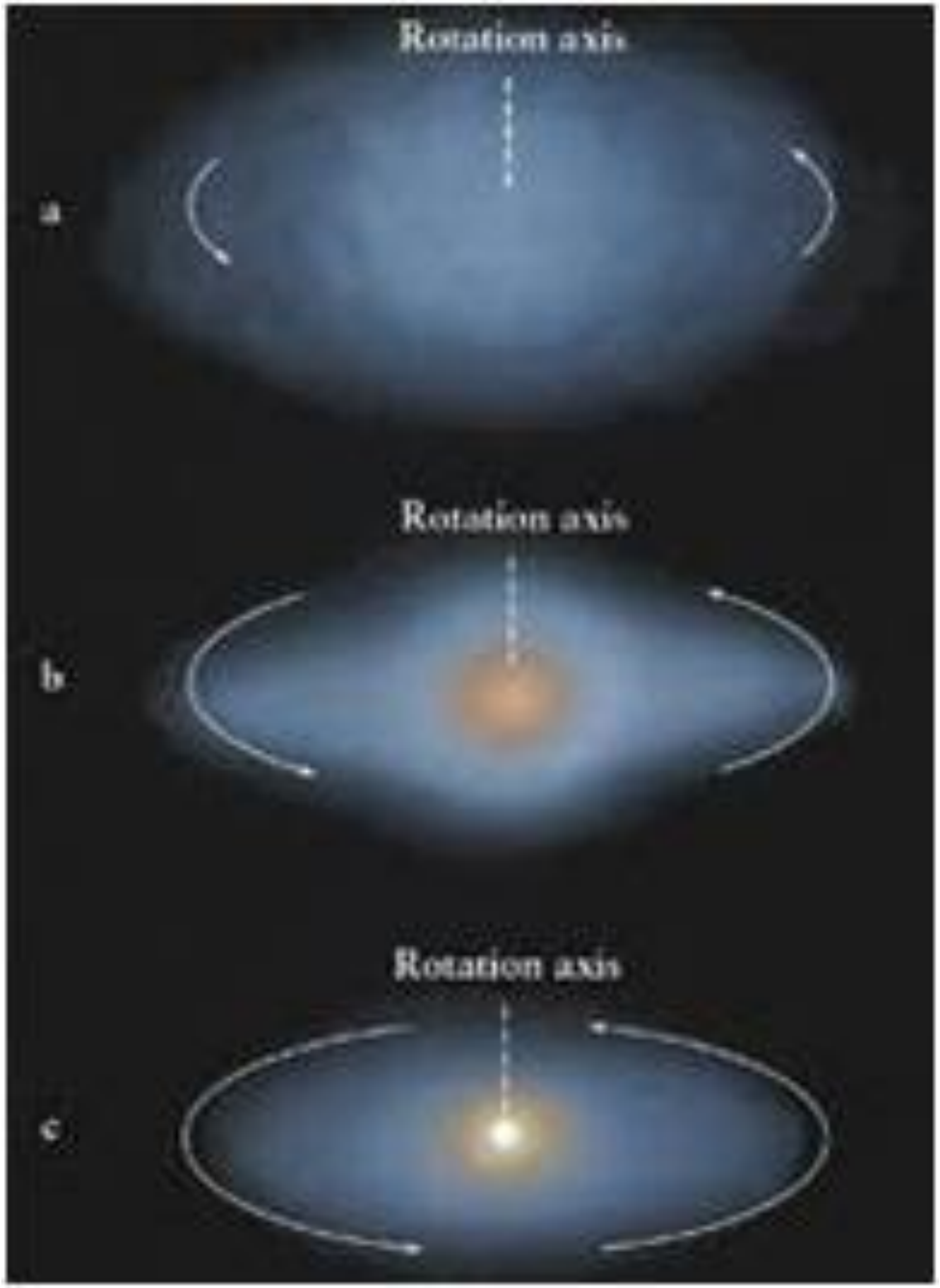
- Radius where $F_C = F_G$ is called the centrifugal radius

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

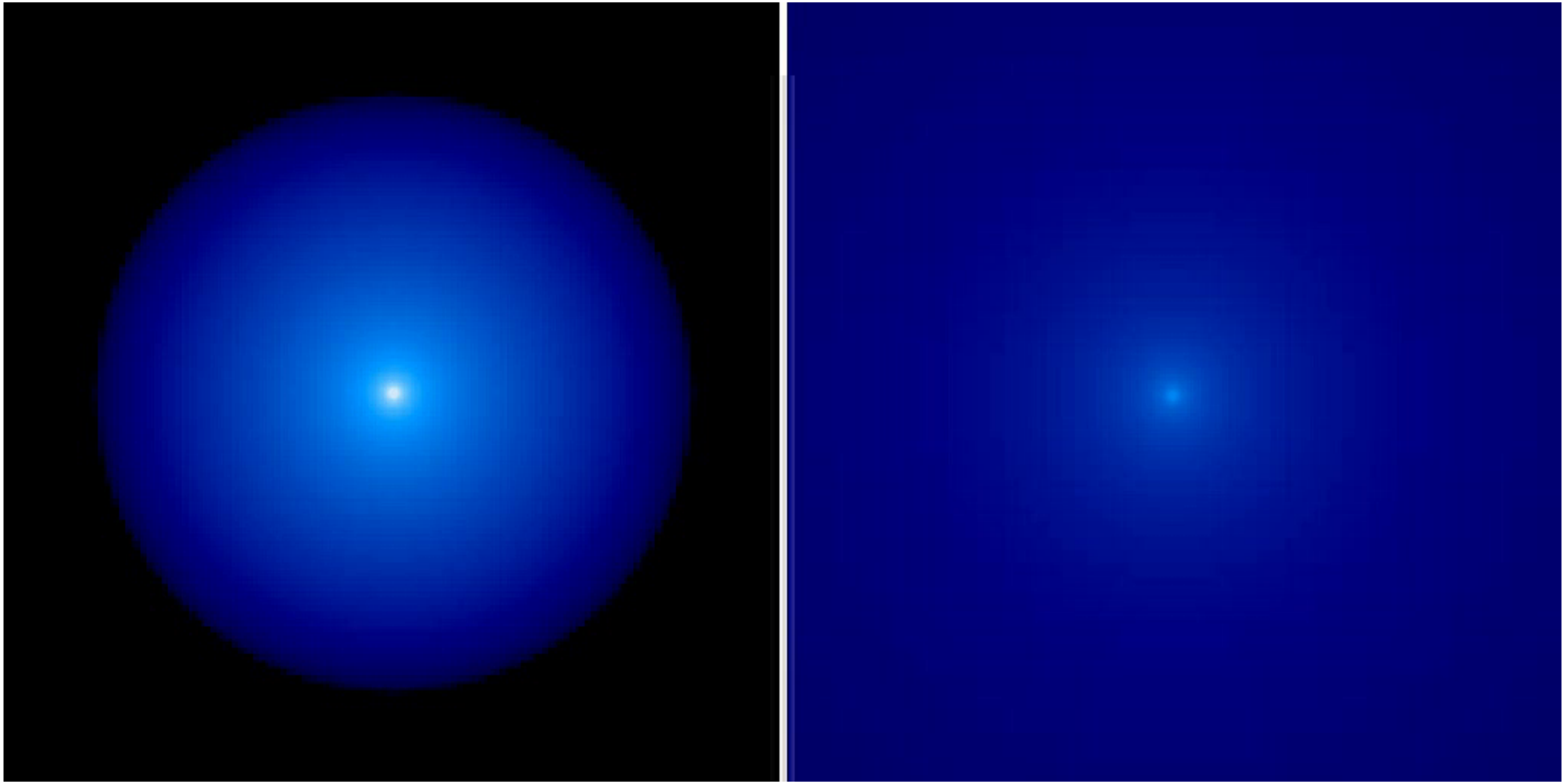
- Cloud can still contract parallel to rotation axis
- This leads toflattened rotating structures

- accretion discs

- But need to lose a lot of angular momentum


Rotation axis
a
Rotation axis
b
Rotation axis
c

Numerical simulation



Krumholz et al. (2007)

Magnetic field during collapse

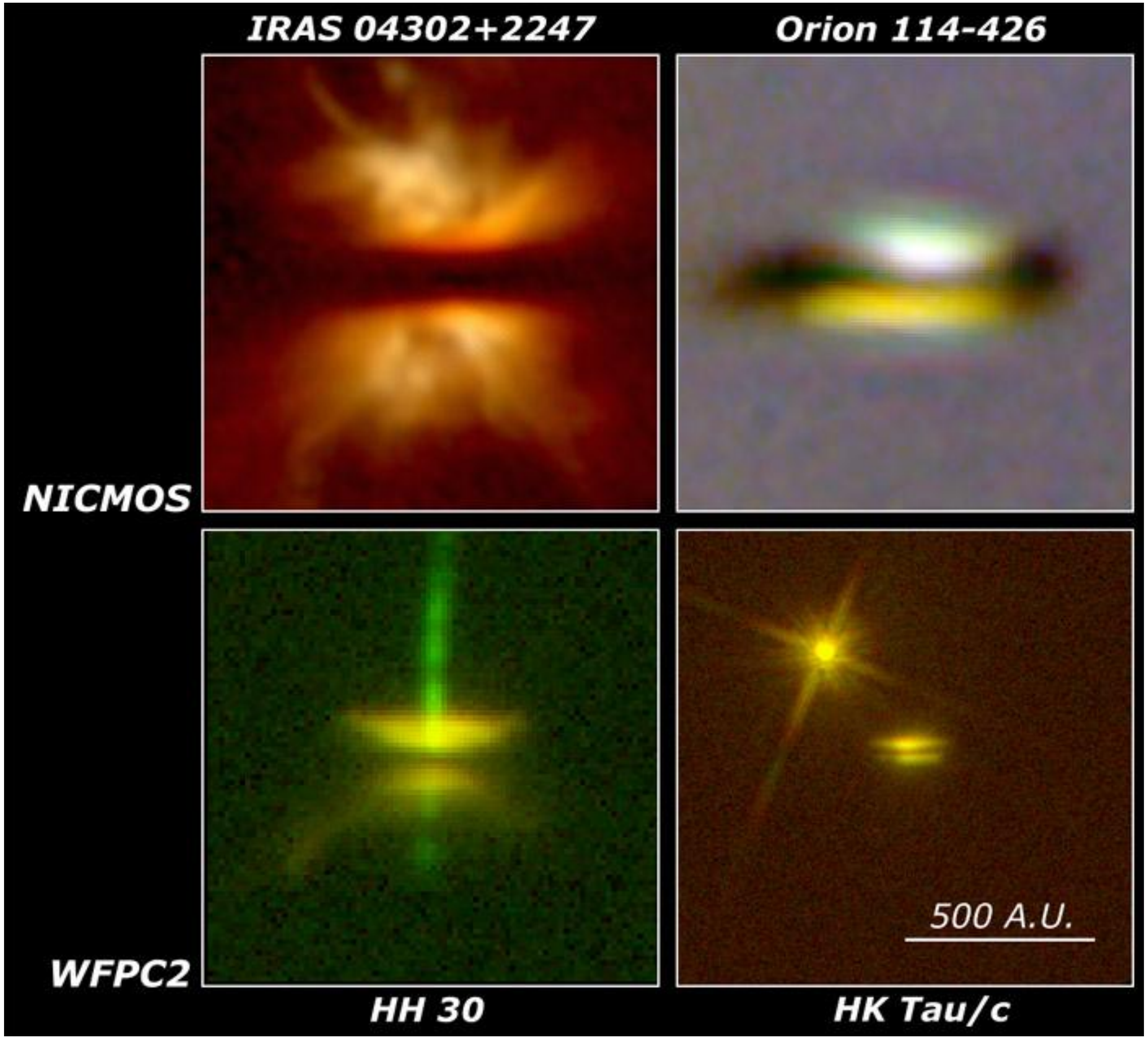
- Molecular clouds always have some level of ionization due to passage of energetic particles – cosmic rays
- Hence the initial magnetic field in the cloud will get dragged in during the collapse
- Need to lose alot of magnetic flux too

Accretion Discs

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

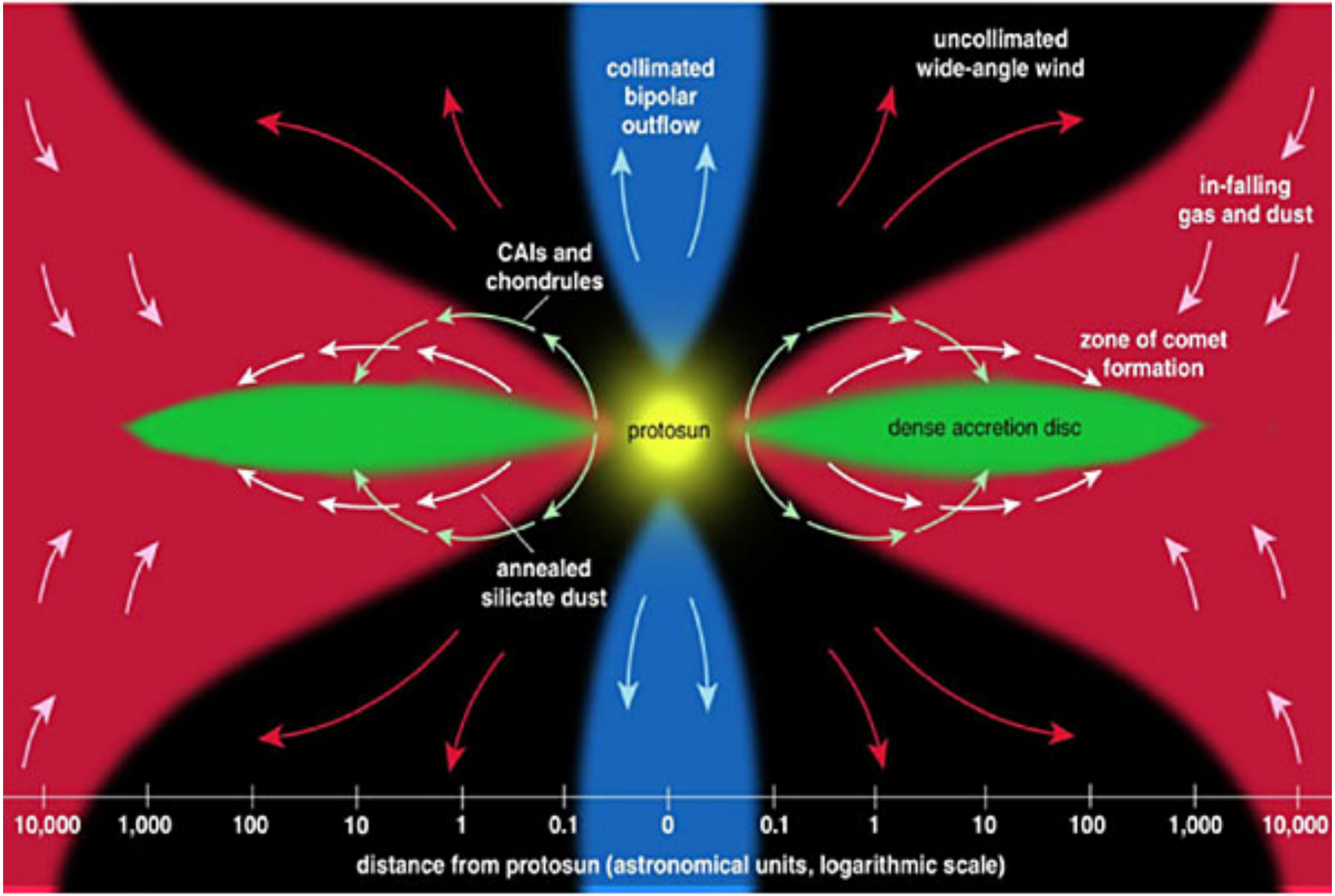
$$L_{acc} \sim \frac{GM\dot{M}}{R_S}$$

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

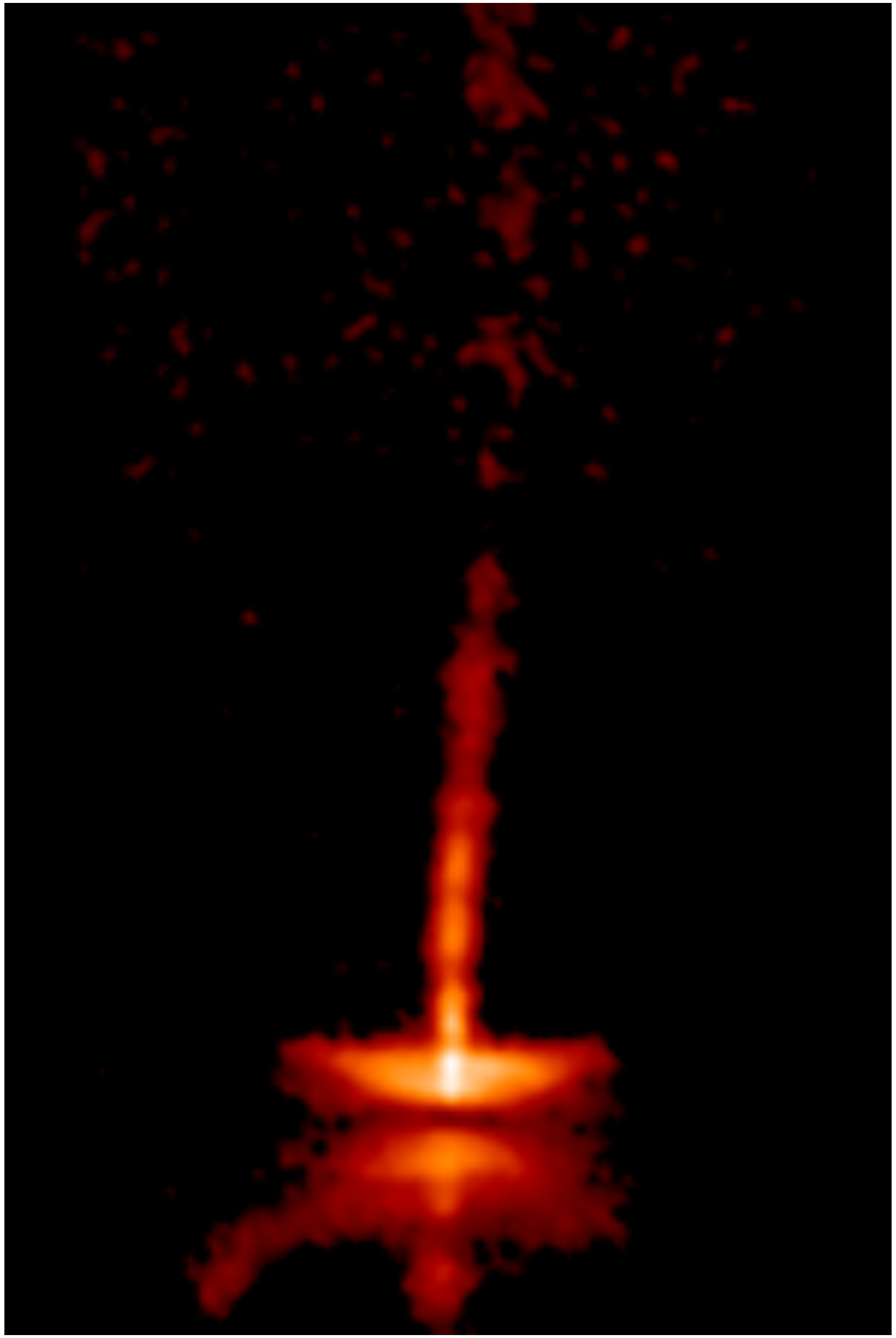


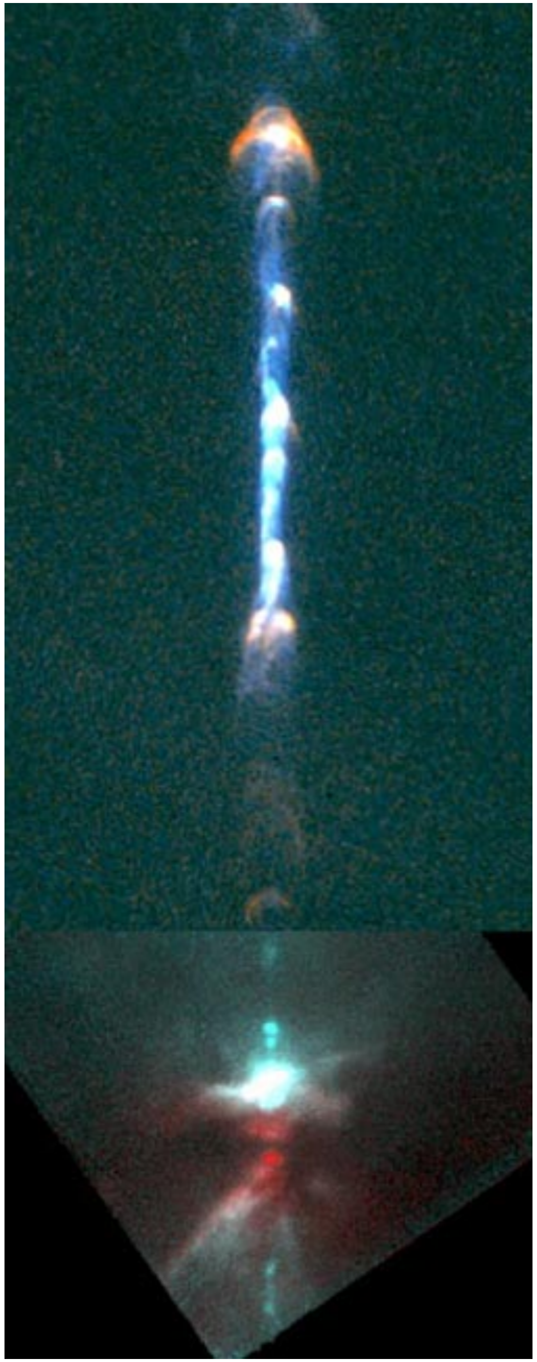
Jets and bipolar outflows

- 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

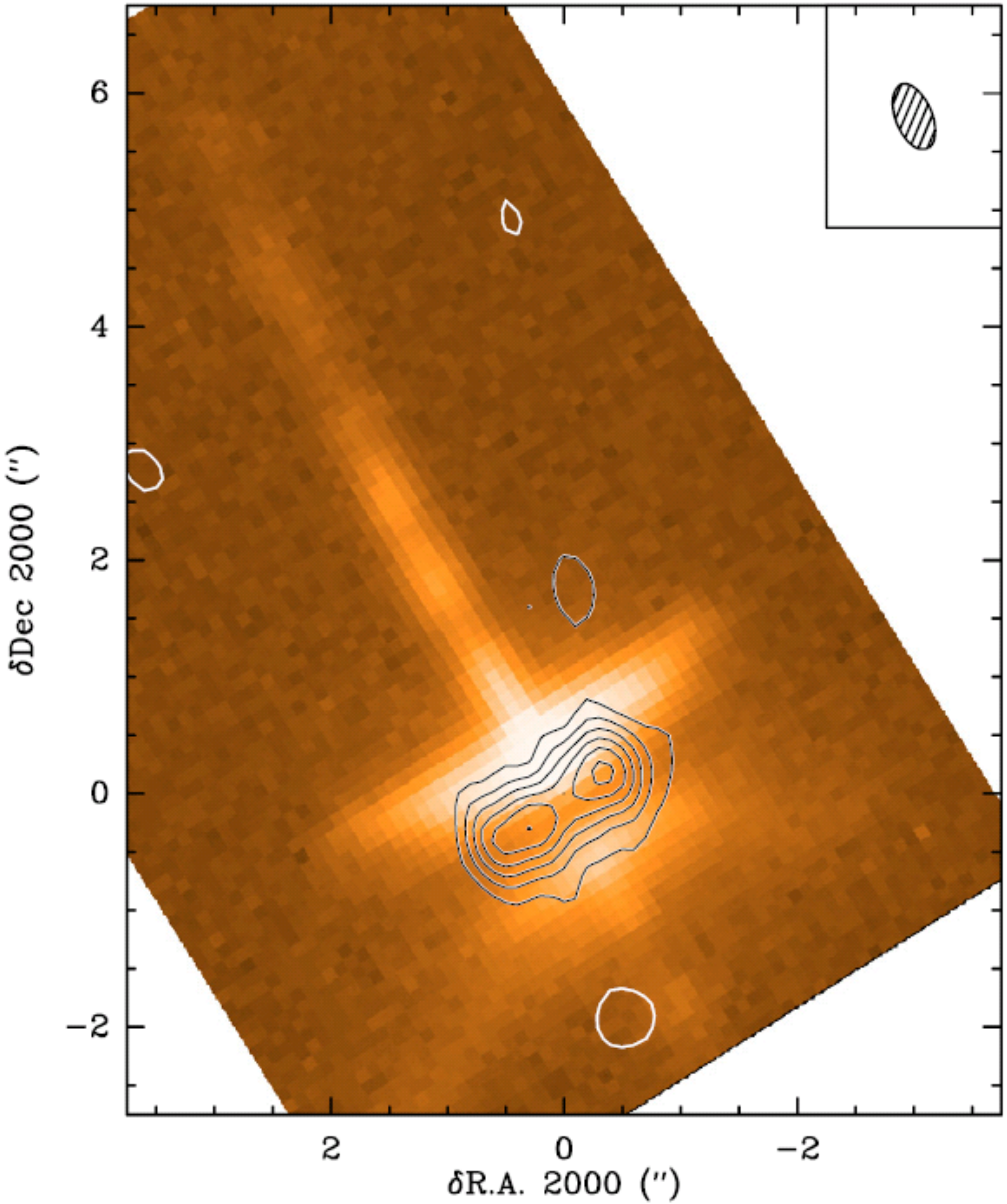


(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

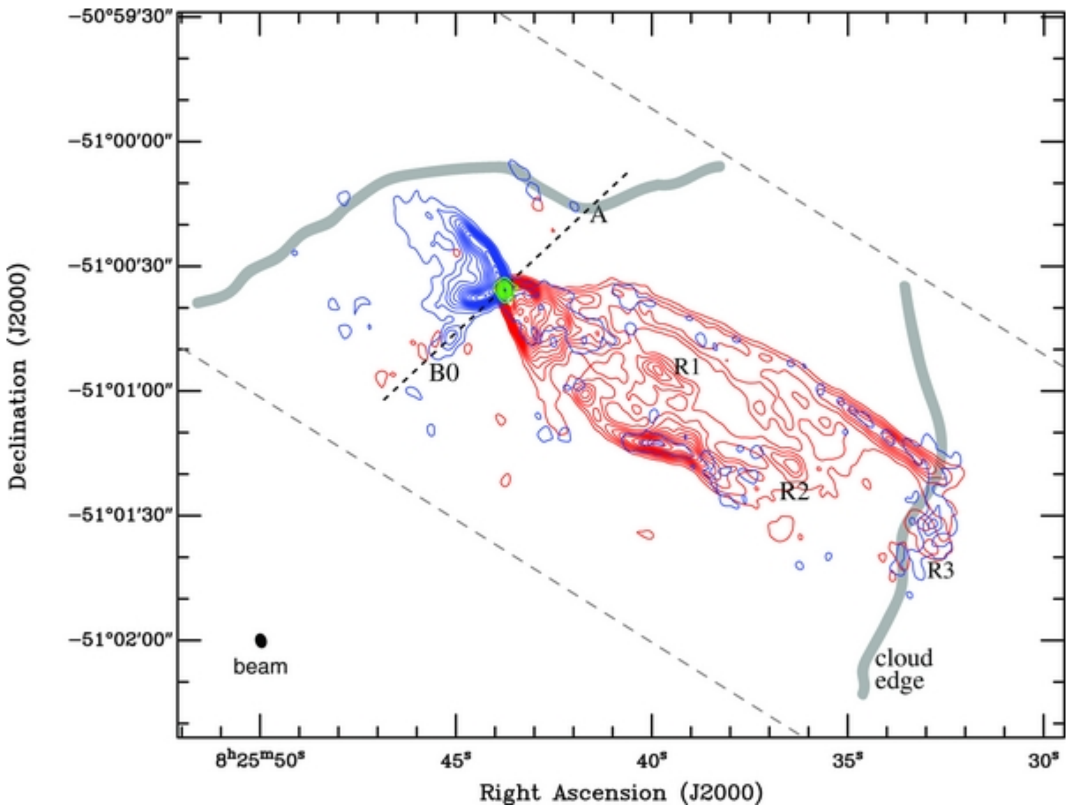




- Can see disc directly in molecular gas (CO)



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

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

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

• For massive stars $\tau_{\text{K-H}} << \tau_{ff}$ 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_2O, CH_3OH
- 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

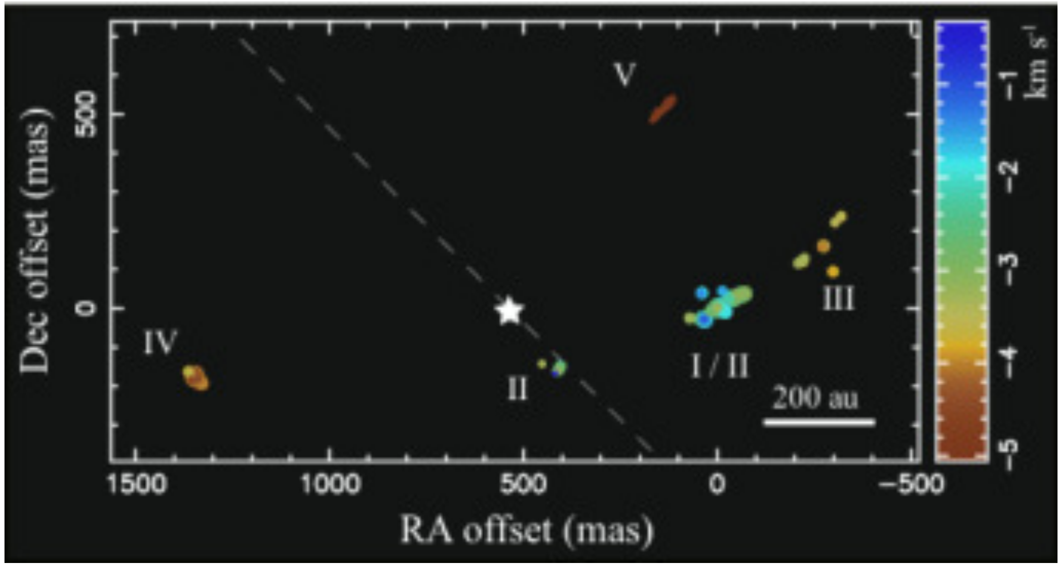
$\rightarrow$beaming

Amplification

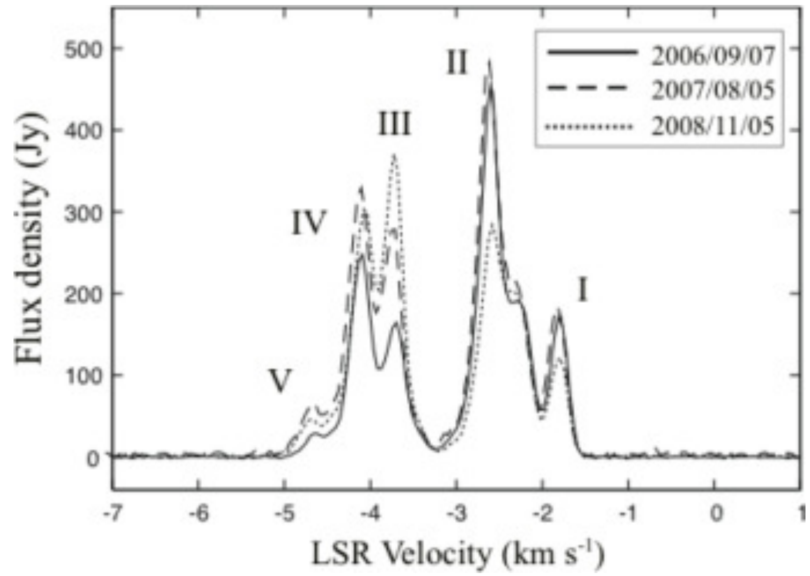
- photons can stimulate other molecules $\rightarrow$cascade as in a laser
- can also view phenomena as a negative optical depth:

  instead of attenuation $I_l \propto e^{-\tau}$

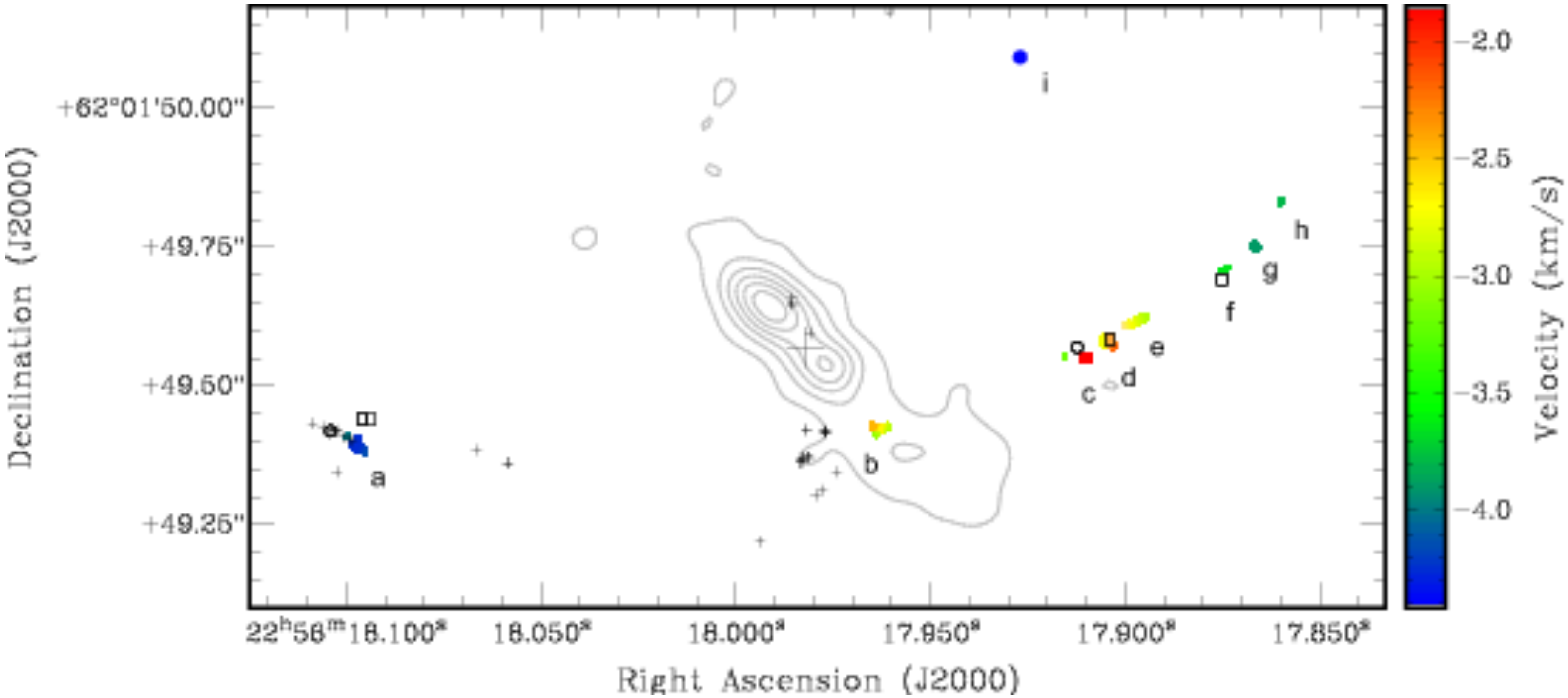
  you get amplification $I_l \propto e^{\tau}$
- intense spots of maser emission



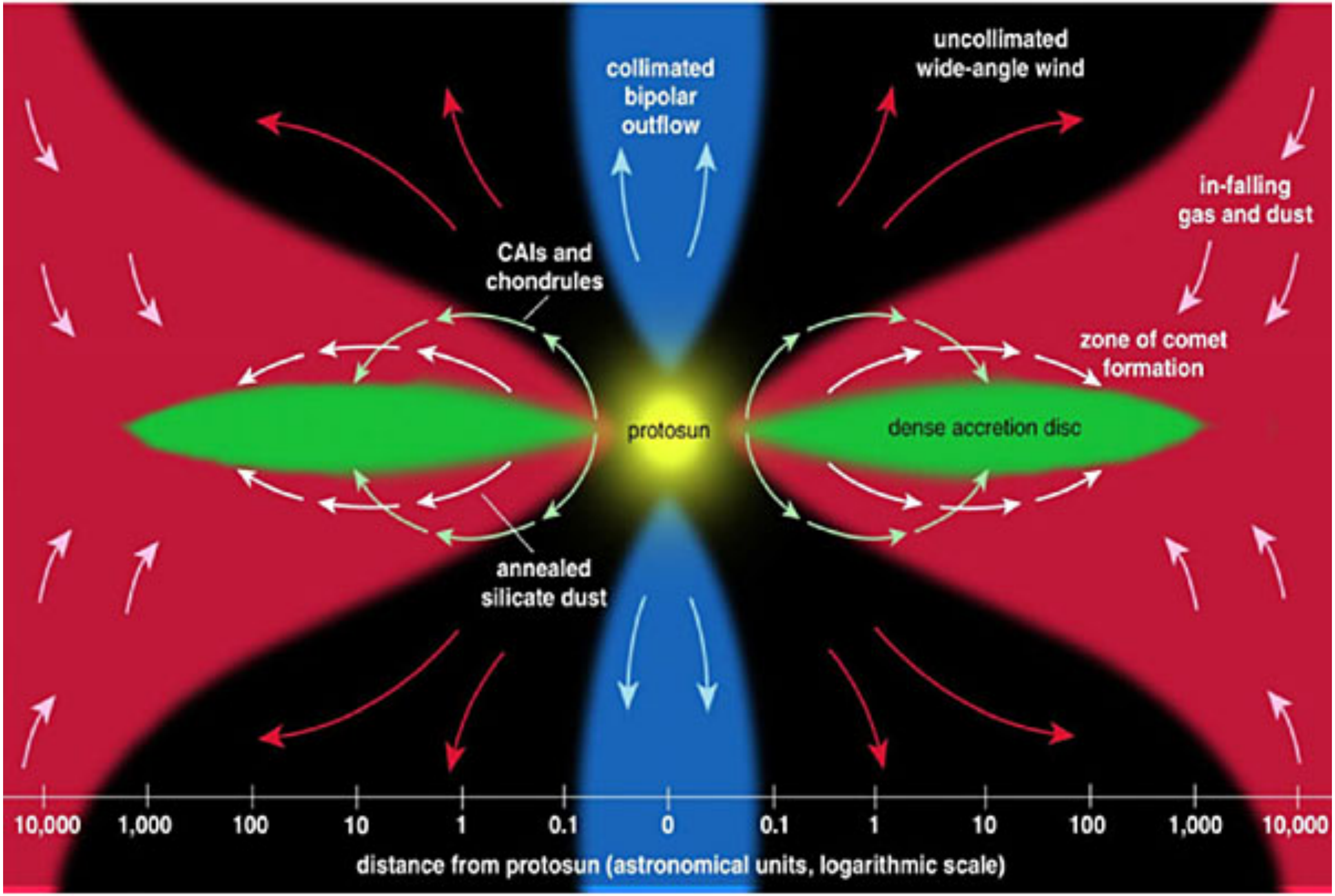
V
IV
II
I / II
III
200 au
Dec offset (mas)
RA offset (mas)
km s-1



2006/09/07
2007/08/05
2008/11/05
Flux density (Jy)
LSR Velocity (km s-1)
I
II
III
IV
V



Declination (J2000)
Right Ascension (J2000)
Velocity (km/s)
+62°01'50.00"
+49.75"
+49.50"
+49.25"
22h56m18.100s
18.050s
18.000s
17.950s
17.900s
17.850s
a
b
c
d
e
f
g
h
i



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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