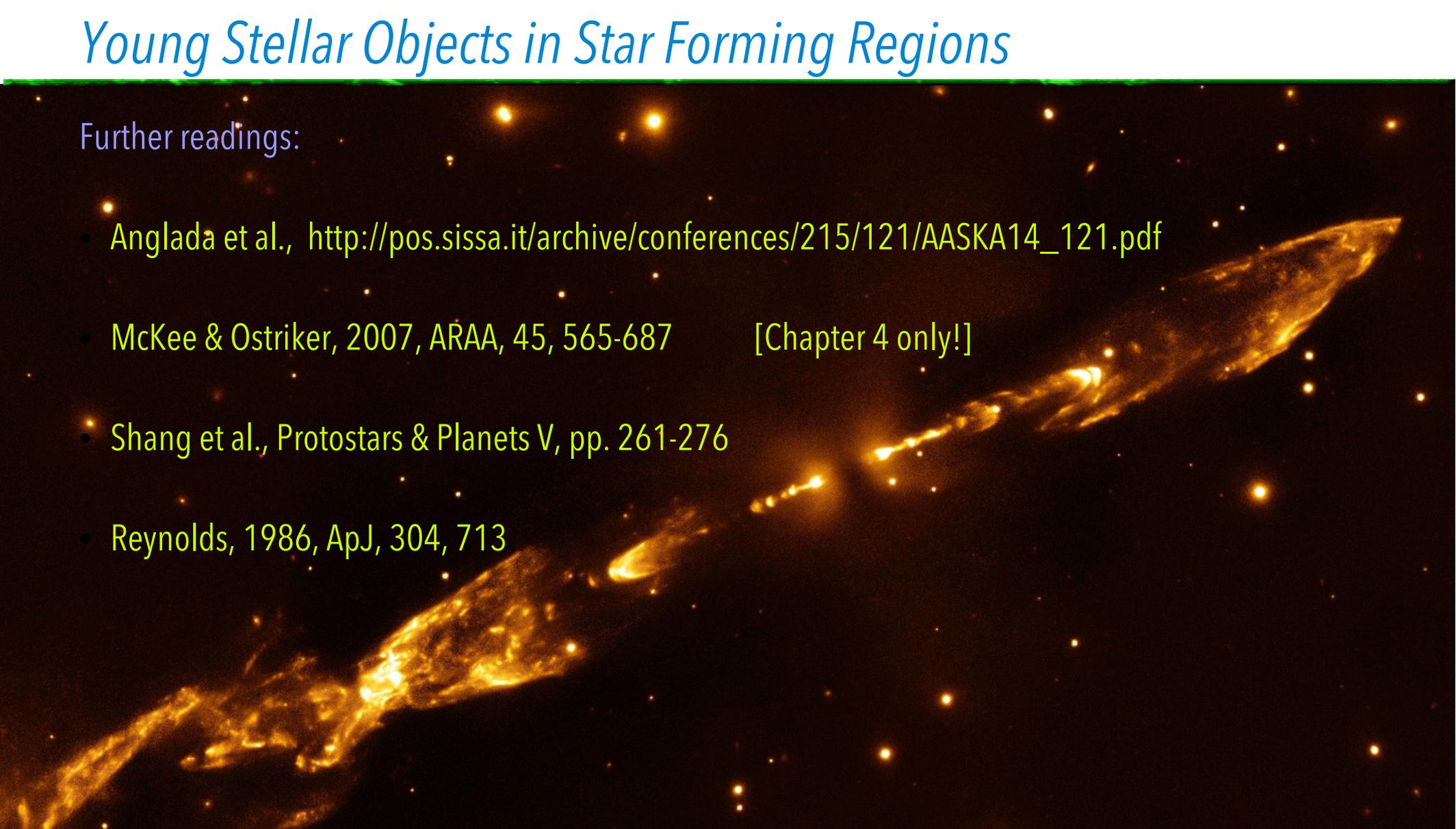


# Young Stellar Objects in Star Forming Regions

Further readings:

- Anglada et al., [http://pos.sissa.it/archive/conferences/215/121/AASKA14\\_121.pdf](http://pos.sissa.it/archive/conferences/215/121/AASKA14_121.pdf)
- McKee & Ostriker, 2007, *A&A*, 45, 565-687 [Chapter 4 only!]
- Shang et al., *Protostars & Planets V*, pp. 261-276
- Reynolds, 1986, *ApJ*, 304, 713



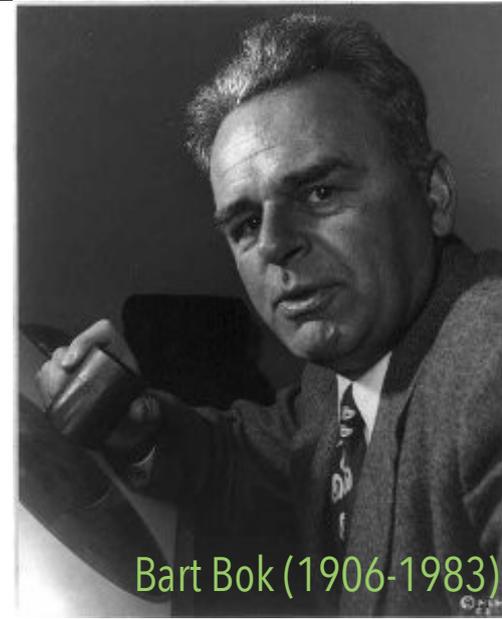
A pair of jets protrude outwards in near-perfect symmetry in this image of HH 212, in the constellation of Orion in a dense molecular star-forming region, not far from the famous Horsehead Nebula taken by ESO's Infrared Spectrometer And Array Camera (ISAAC). In regions like this, clouds of dust and gas collapse, ruled by gravity, spinning faster and faster and becoming hotter and hotter until a young star ignites at the cloud's centre. Any leftover material swirling around the newborn protostar comes together to form an accretion disk that will, under the right circumstances, eventually provide the base material for the creation of planets, asteroids and comets.

Although this process is still not fully understood, it is common that a protostar and its accretion disc, as seen here edge-on, are the cause of the jets in this image. The star at the centre of HH 212 is indeed a very young star, only a few thousand years old. Its jets are remarkably symmetric, with several knots appearing at relatively stable intervals. This stability suggests that the jet pulses vary quite regularly, and over a short timescale – maybe even as short as 30 years! Further out from the centre, large bow shocks spread out into interstellar space, caused by ejected gas colliding with dust and gas at speeds of several hundred km per second.

## Young Stellar Objects

Where do they form?

- Bok globules (low mass star forming regions)
- GMC



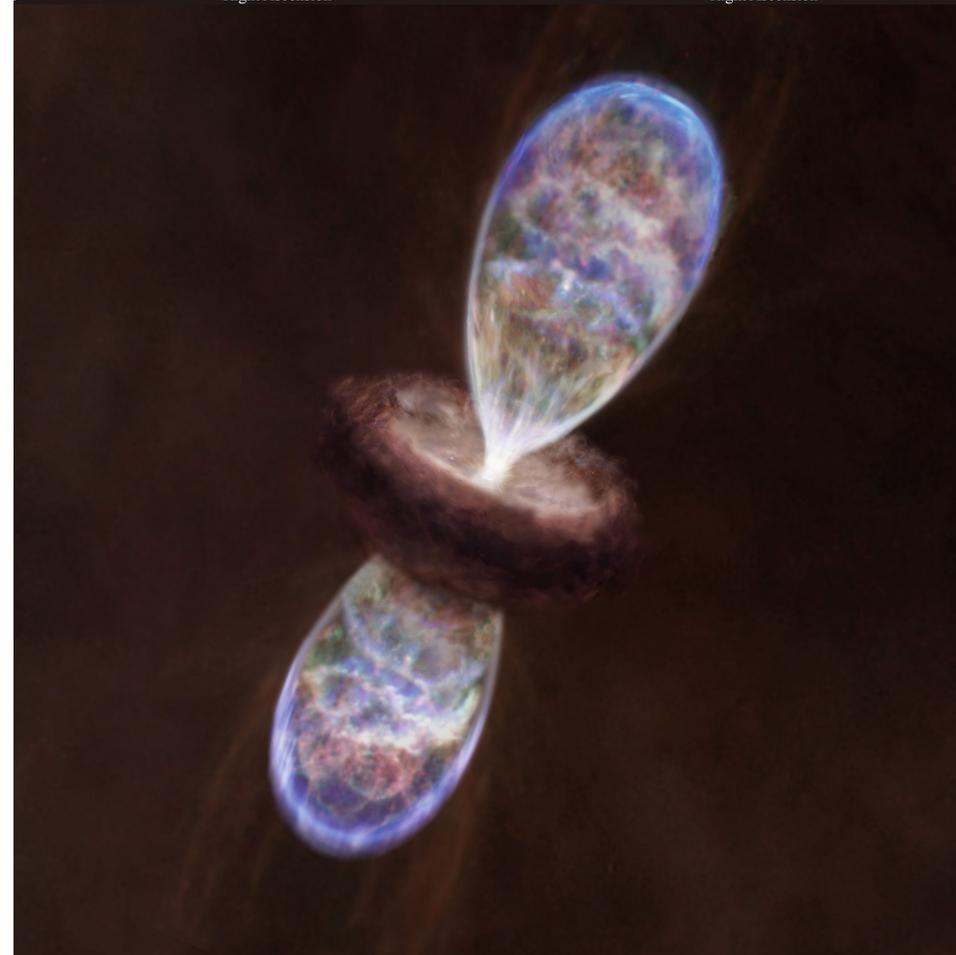
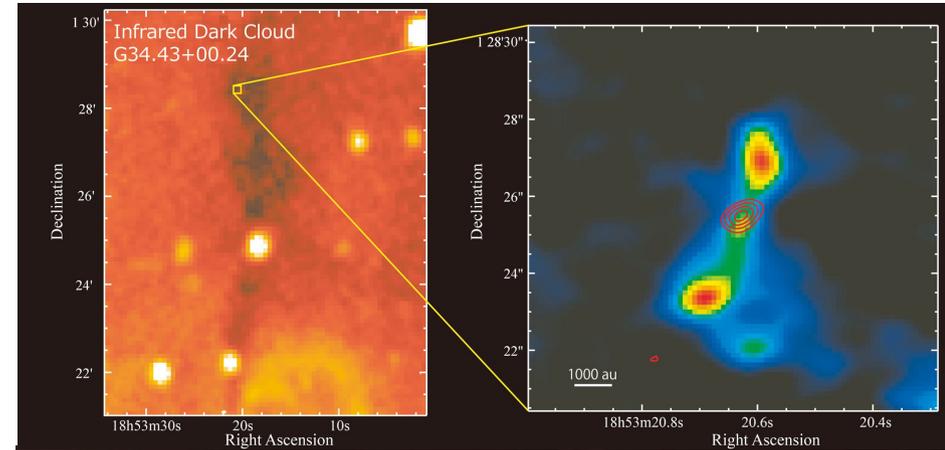
# Star forming regions

## Ingredients:

CNM (dust & molecules) + seeds (perturbations)

## Prescription:

- Gravitational collapse & (slow) accretion
- Bipolar outflows carry away angular momentum
- Start as molecular outflows
- Then become atomic & develop jets
- Influence / interaction with the parent cloud
- Radiation from line emission (molecules) & continuum when shocks set up (non - t!) and/or massive stars ionize surrounding medium



**Starting model:** spherical, static (self-gravitating, no rotation), homogeneous, isothermal cloud with no B field

Gravitational (dynamical) collapse: **INSIDE – OUT**

Gravitational collapse takes place if the size of the cloud exceeds the **Jeans' Length**  $J_L$

$$J_L = \sqrt{\frac{15 kT}{4 \pi G m \rho}}$$

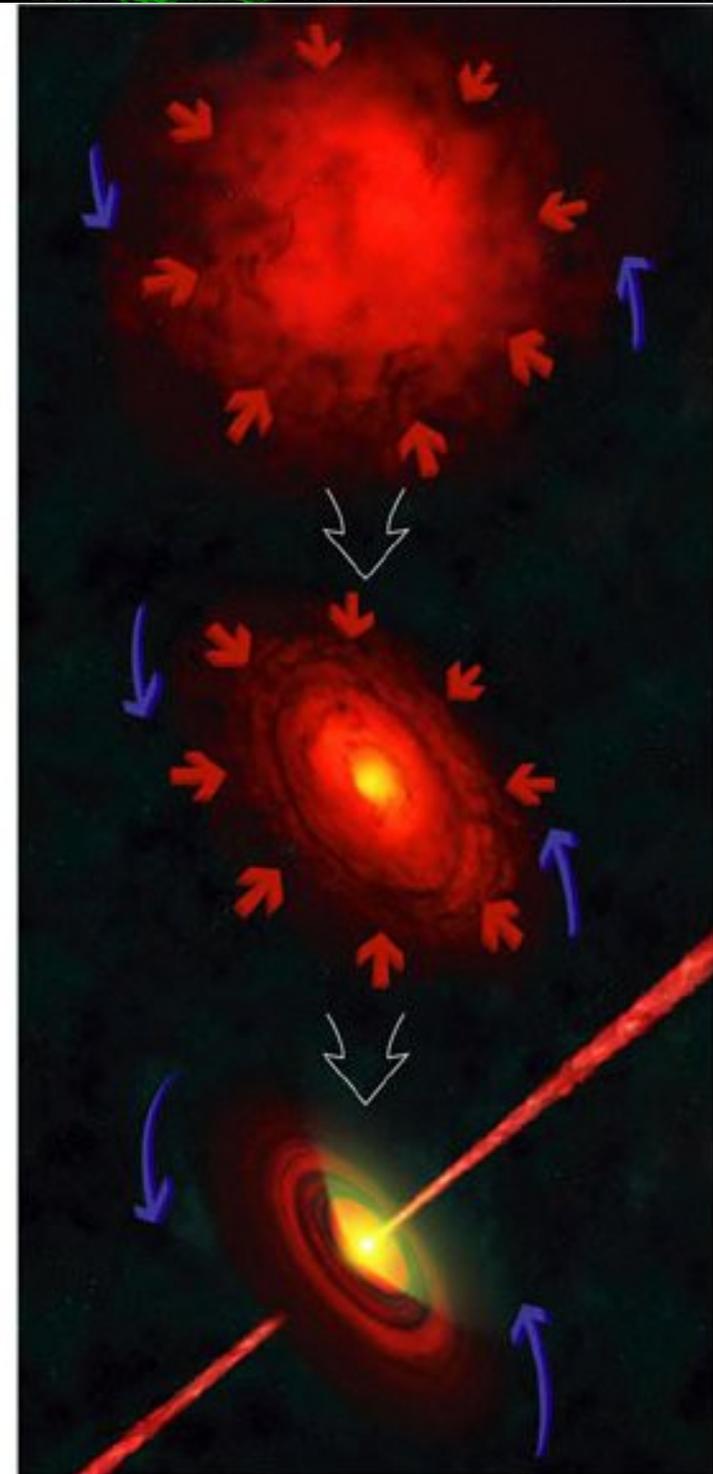
A cloud that is smaller than its Jeans length will not have sufficient gravity to overcome the repulsive gas pressure forces and condense to form a star

**Starting model:** spherical, static (self-gravitating, no rotation), homogeneous, isothermal cloud with no B field

Gravitational (dynamical) collapse: **INSIDE – OUT**

a more realistic case:

1. a relatively uniform cloud (molecular gas, dust) with some rotation and B field start to collapse
2. accretion to the condensed object is more efficient in a plane perpendicular to the rotation axis; as the mass assembly proceeds the rotation of the whole structure speeds up
3. the main accretion phase takes place from an equatorial disk; rotation has increased, and needs to be slowed down; outflows and jets of matter are created and angular momentum is brought away from the system



Fragmentation of a molecular cloud into a number of gravitationally bound cores initially supported by a combination of thermal, magnetic and turbulent pressures

Then, turbulence, magnetic fields and self-gravity proceed in a highly non-linear way



### Brief initial phase:

- gravitational energy released is mostly radiated away mainly by dust
- the fragment is isothermal
- strong central condensation  $\rho(r) \sim r^{-2}$

formation of a hydrostatic (adiabatic) proto-stellar object at the centre of each condensation

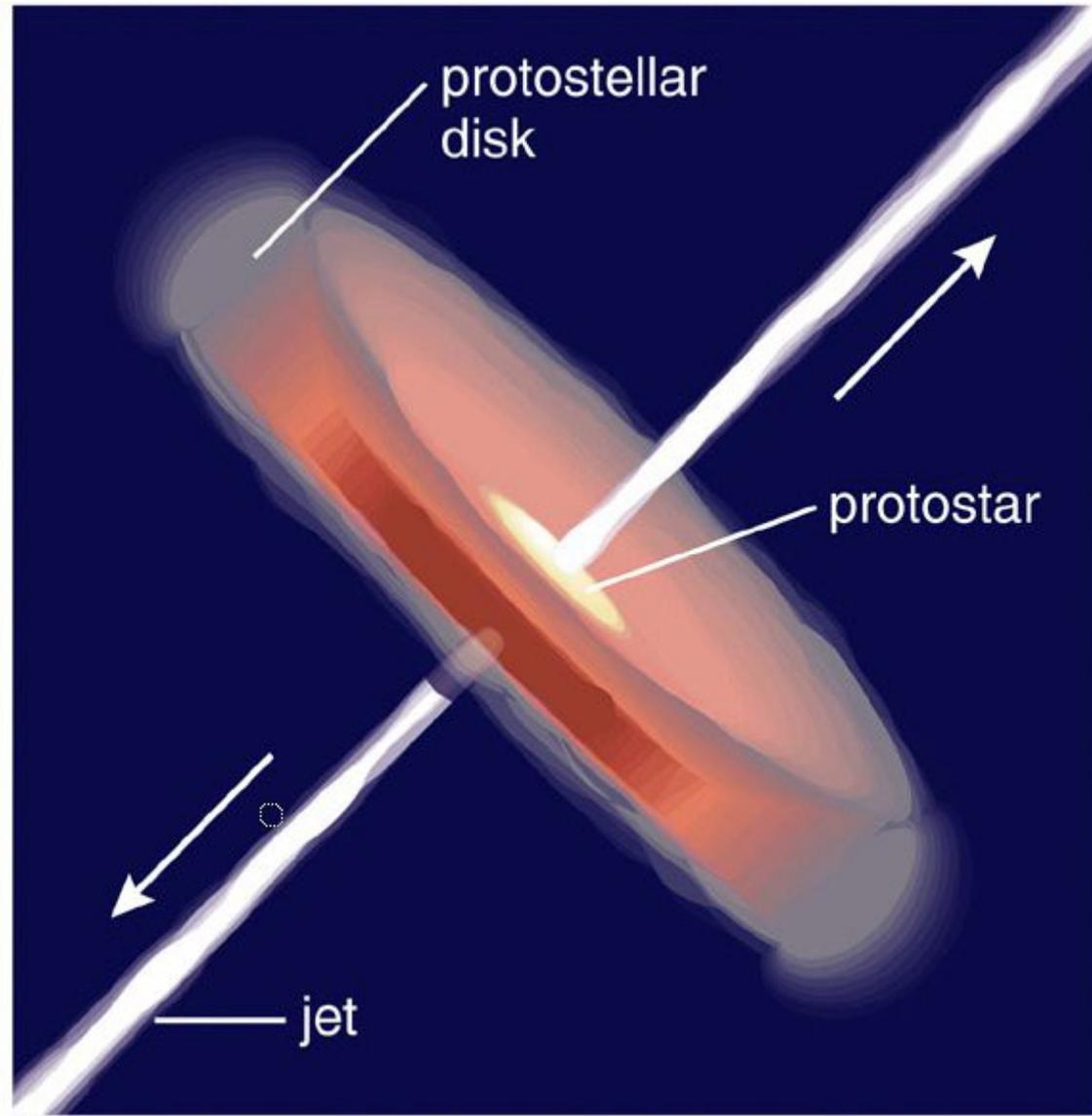
At a given point, feedback from the protostar may inject further perturbations into the GMC

## Main accretion phase:

- Mass from the in-falling envelope deposited onto an accretion disk, progressively warming up
- Angular momentum has to be dissipated, otherwise the rotation

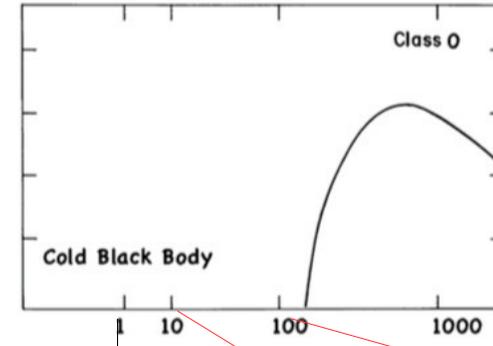
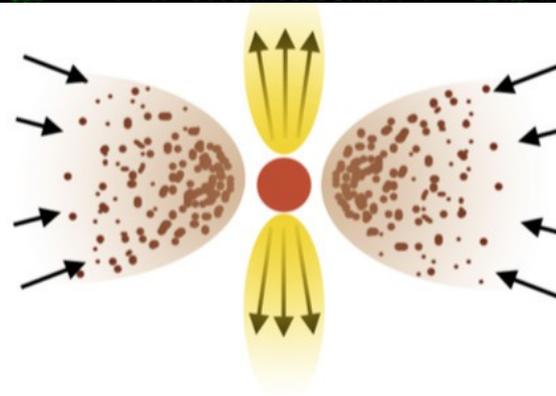
$$v_r = \omega \cdot r \leq v_{esc} = \sqrt{\frac{2GM}{r}}$$

- ⇒ will get to the **breakup** (i.e. match the escape velocity from the body surface) of the central object preventing any further accretion

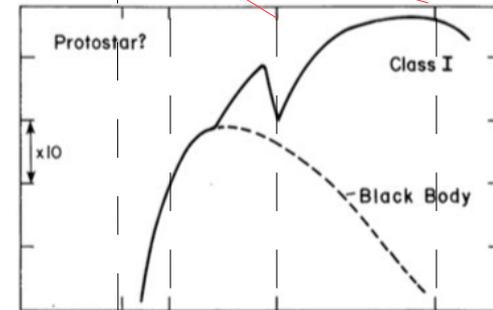
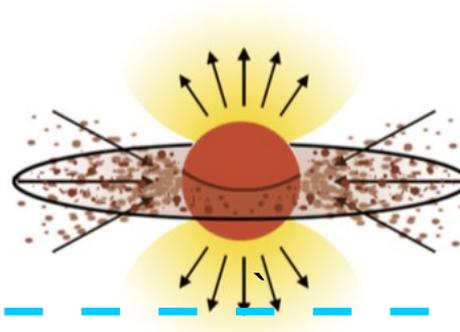


# Young Stellar objects Class 0-I-II-III

**Class 0:**  
Main Acceleration  
phase?  
Age  $\leq 10^5$  years  
 $M \sim 0.5 M_{\odot}$

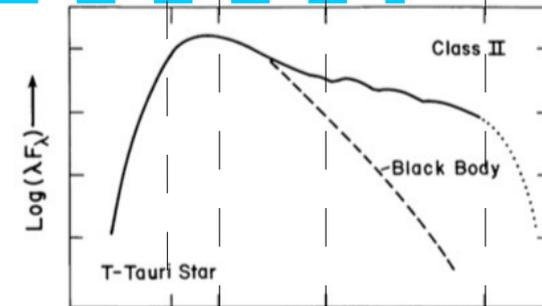
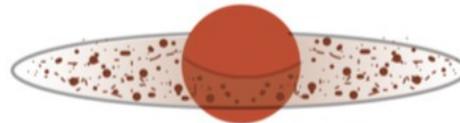


**Class I:**  
Late accretion  
phase?  
Age  $\sim 10^5$  years  
 $M \sim 0.1 M_{\odot}$

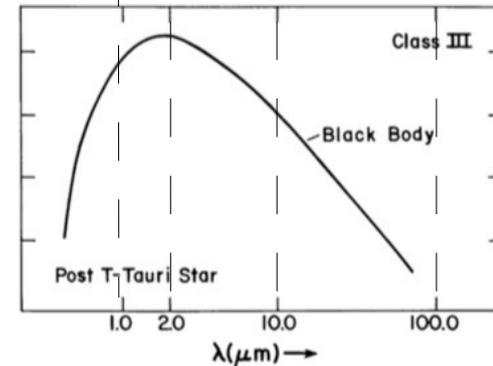


## Birth line for pre-main sequence stars

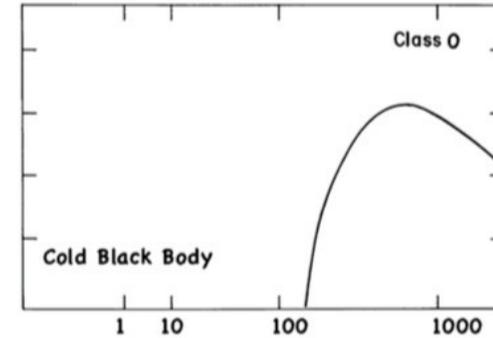
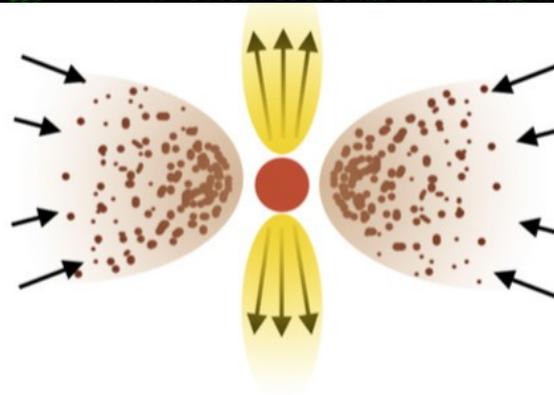
**Class II:**  
Optically thick disk  
Age  $\leq 10^6$  years  
 $\langle M_{\text{disk}} \rangle \sim 0.01 M_{\odot}$



**Class III:**  
Optically thin disk  
Age  $\geq 10^6$  years  
 $\langle M_{\text{disk}} \rangle \sim 0.003 M_{\odot}$   
Planetary System



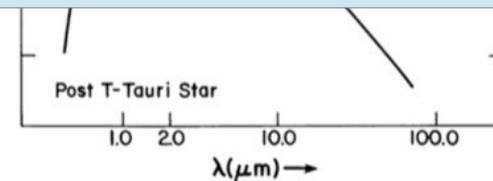
Class 0:  
Main Acceleration  
phase?  
Age  $\leq 10^5$  years  
M  $\sim 0.5 M_{\odot}$



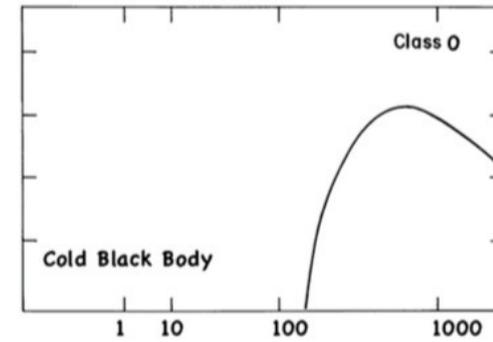
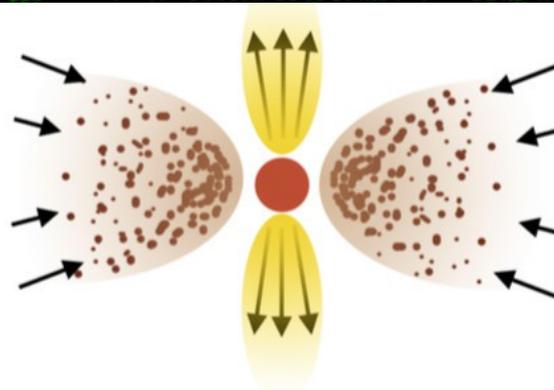
Class 0: Cold condensations of in-falling molecular gas  
Hydrostatic low-luminosity proto-stellar object

Thermal emission mostly in the mm-sub-mm region (ALMA) by cold dust ( $< 20^{\circ}\text{K}$ )  
Detections in the radio at cm-wavelengths sensitive to the presence of a proto-stellar core  
Responsible of a jet/collimated wind

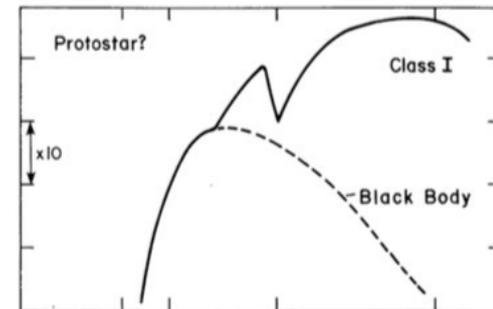
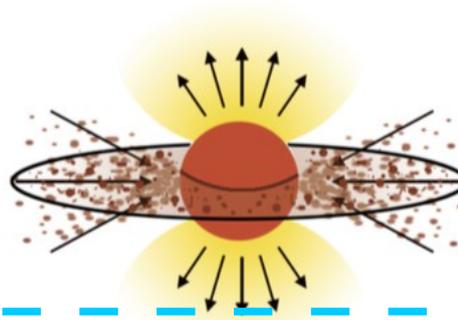
$\langle M_{\text{disk}} \rangle \sim 0.003 M_{\odot}$   
Planetary System



Class 0:  
Main Acceleration  
phase?  
Age  $\leq 10^5$  years  
M  $\sim 0.5 M_{\odot}$



Class I:  
Late accretion phase?  
Age  $\sim 10^5$  years  
M  $\sim 0.1 M_{\odot}$

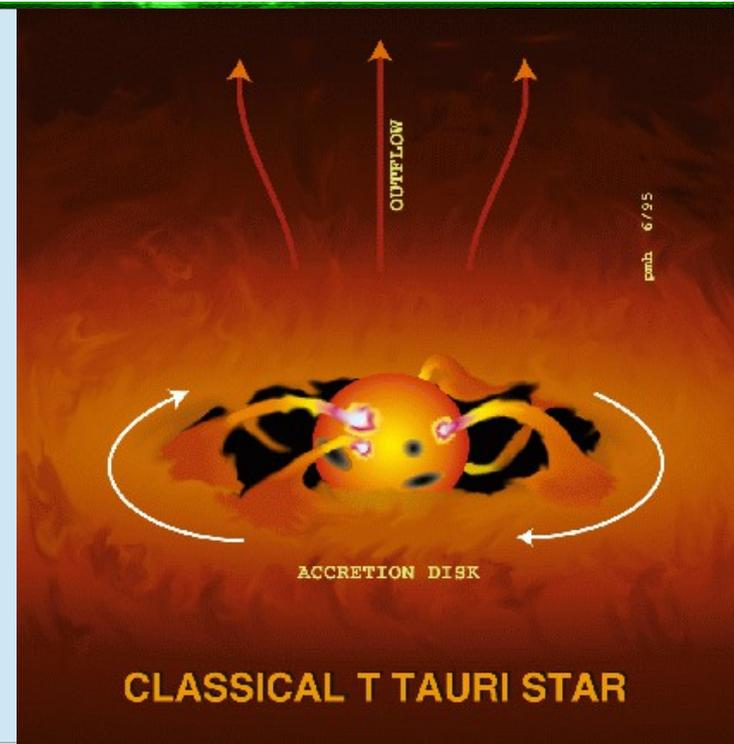


Birth line for

pre-main

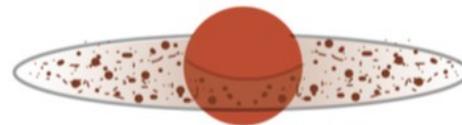
Class I: protostar still enshrouded by optically thick material  
Emission from collimated thermal winds/jets ionized by neutral winds impacting the ambient medium  
(with polarization!)  
Aligned to the molecular outflows

Class II: T Tauri phase: optical (reddened!) emission starts to come out along with a weak outflow and a wind

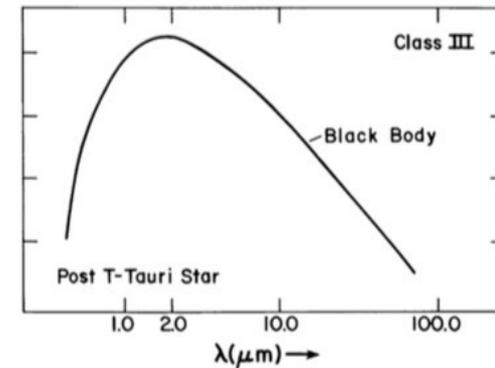
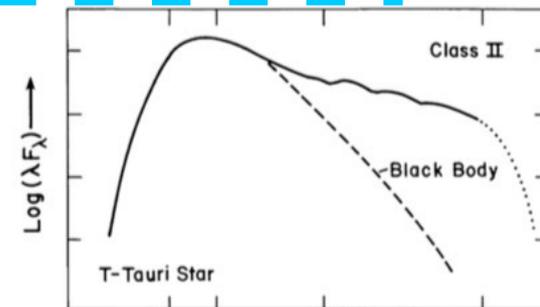


Birth line for pre-main sequence stars

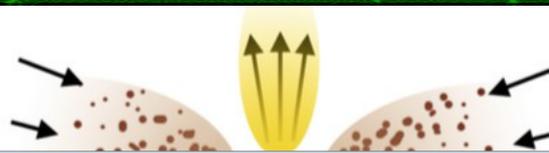
Class II:  
 Optically thick disk  
 Age  $\leq 10^6$  years  
 $\langle M_{\text{disk}} \rangle \sim 0.01 M_{\odot}$



Class III:  
 Optically thin disk  
 Age  $\geq 10^6$  years  
 $\langle M_{\text{disk}} \rangle \sim 0.003 M_{\odot}$   
 Planetary System



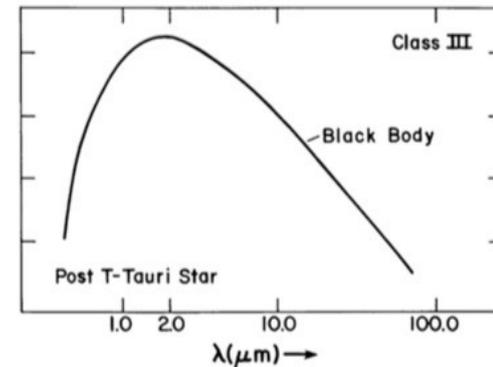
Class 0:  
Main Acceleration



Class III: Evolved T Tauri, the star approaches the main sequence  
Accretion substantially halted, proto-planetary disks may be present

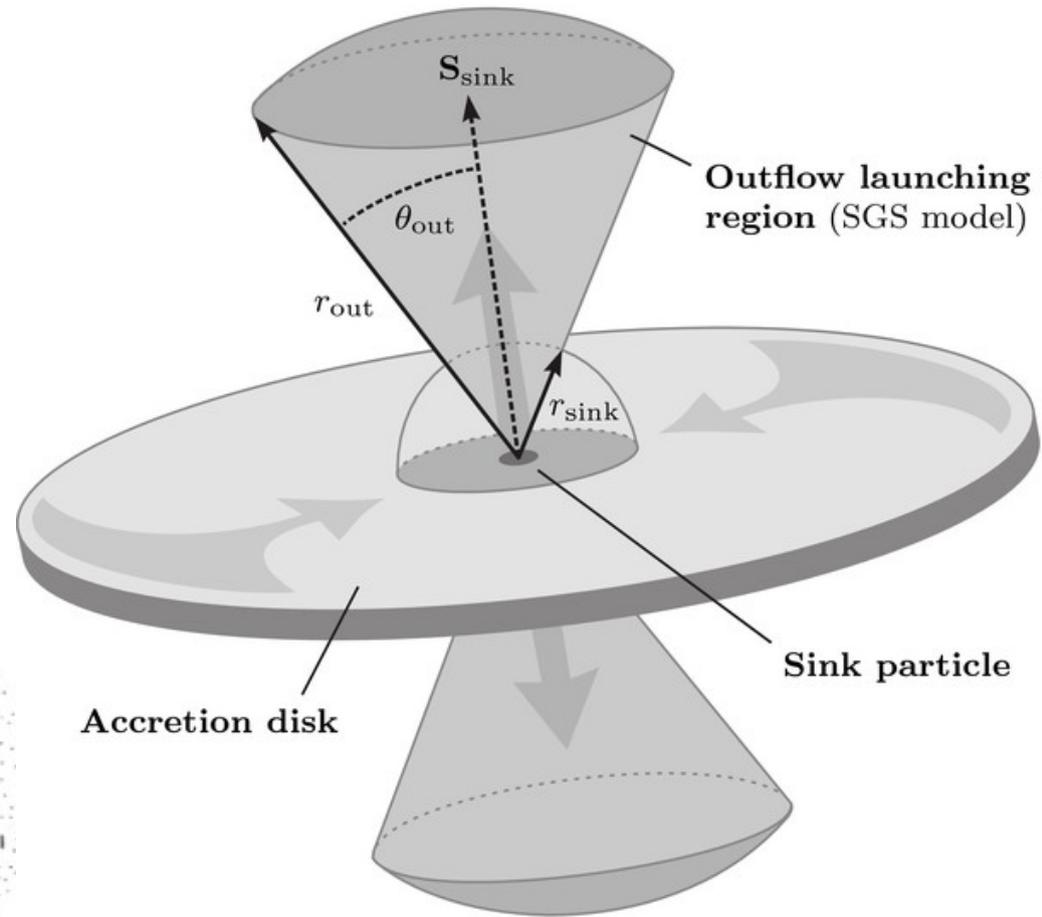
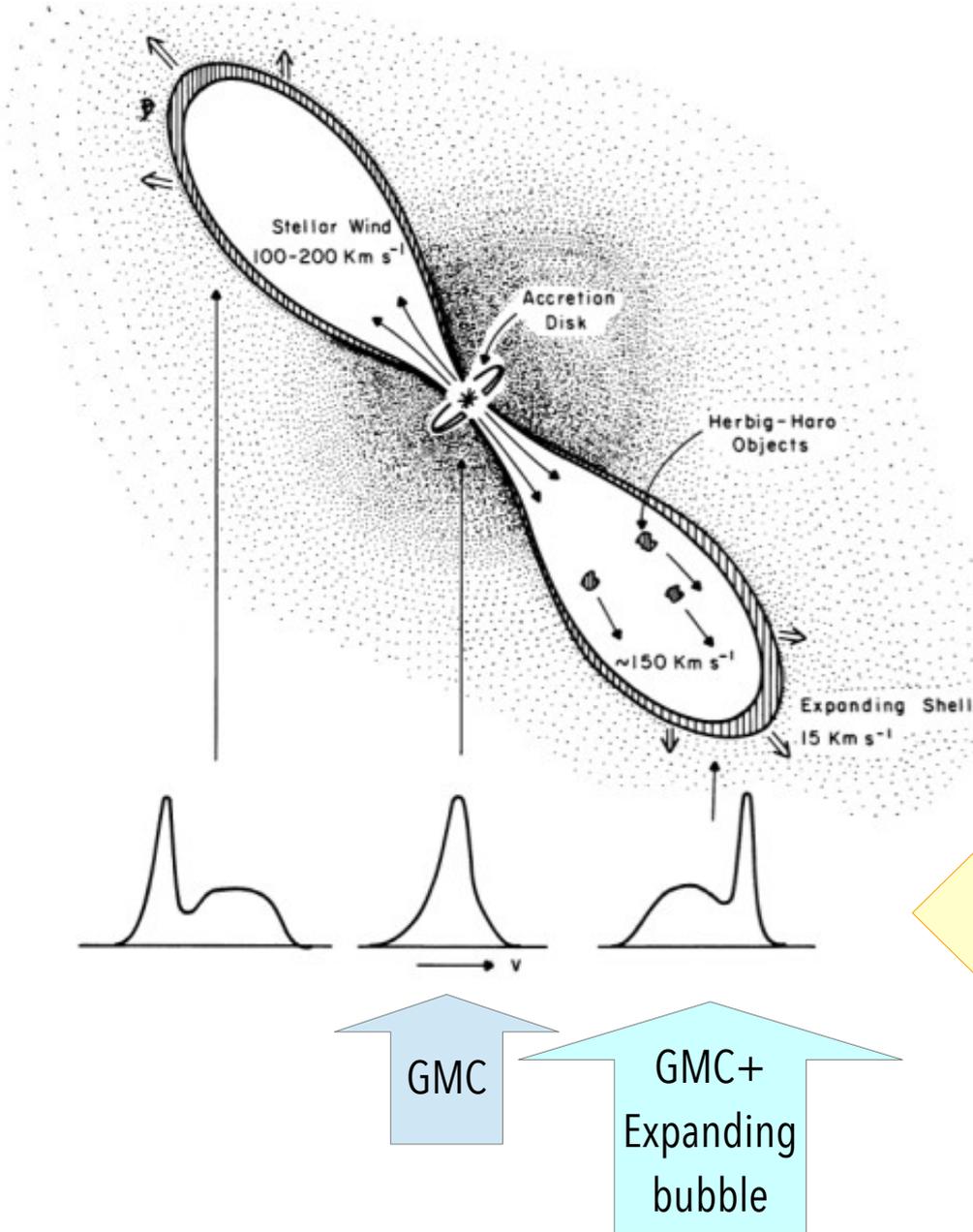
— — Bi  
pre-mai

Class III:  
Optically thin disk  
Age  $\geq 10^6$  years  
 $\langle M_{\text{disk}} \rangle \sim 0.003 M_{\odot}$   
Planetary System



# Young Stellar objects: Bipolar (molecular) outflows

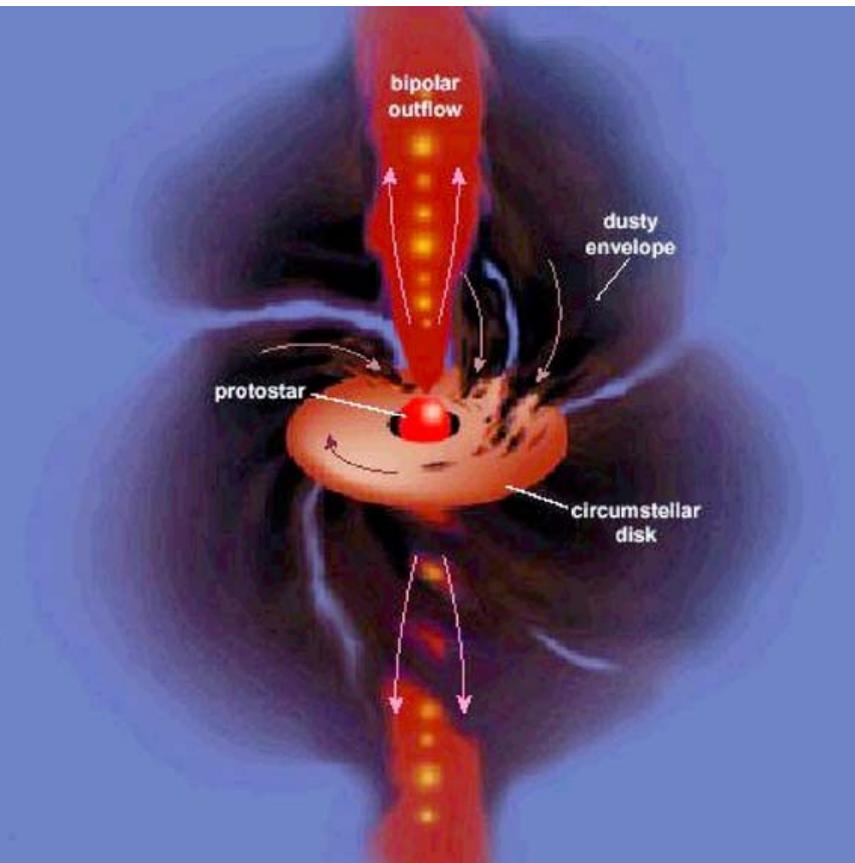
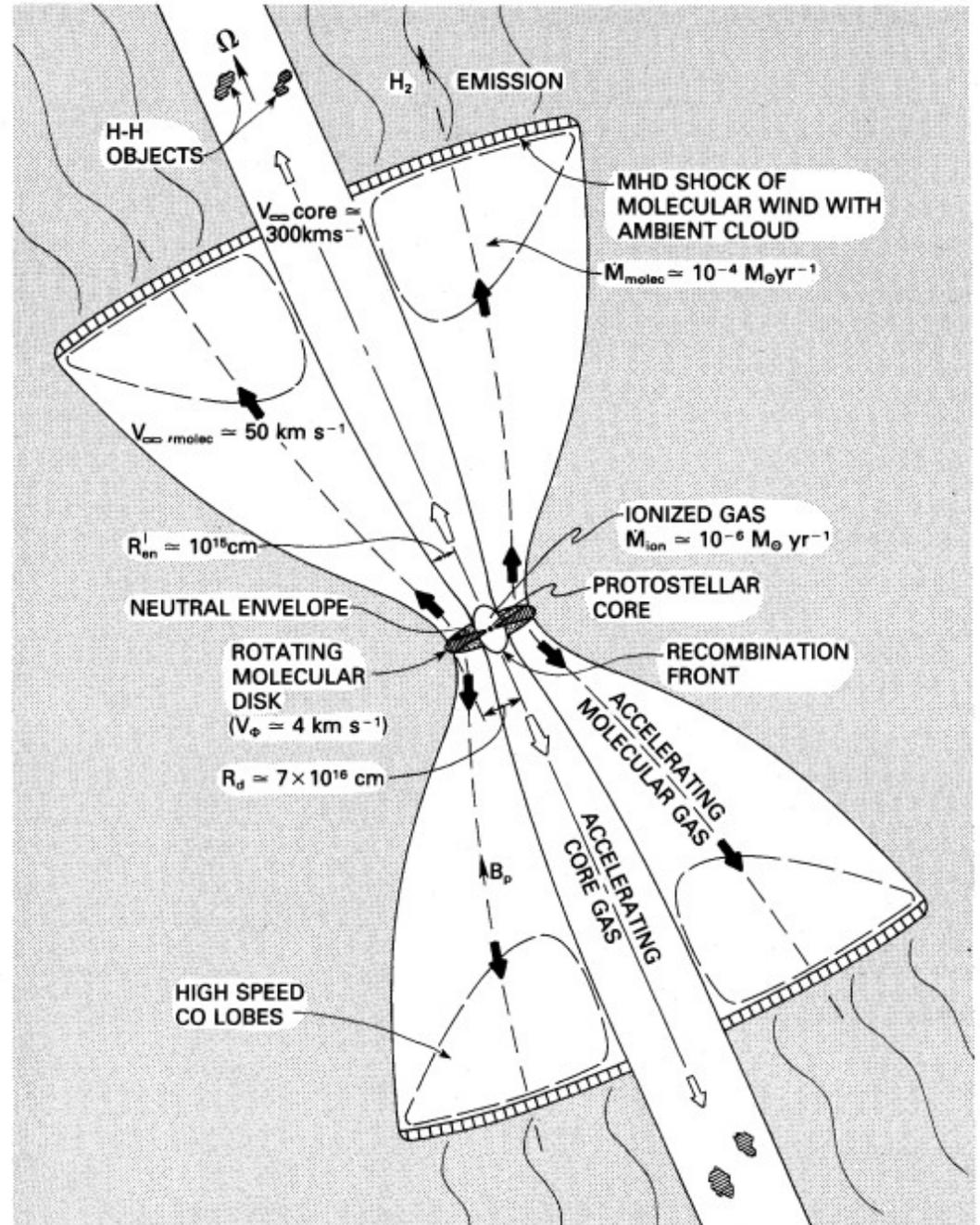
Outflows: Snell+, 1980



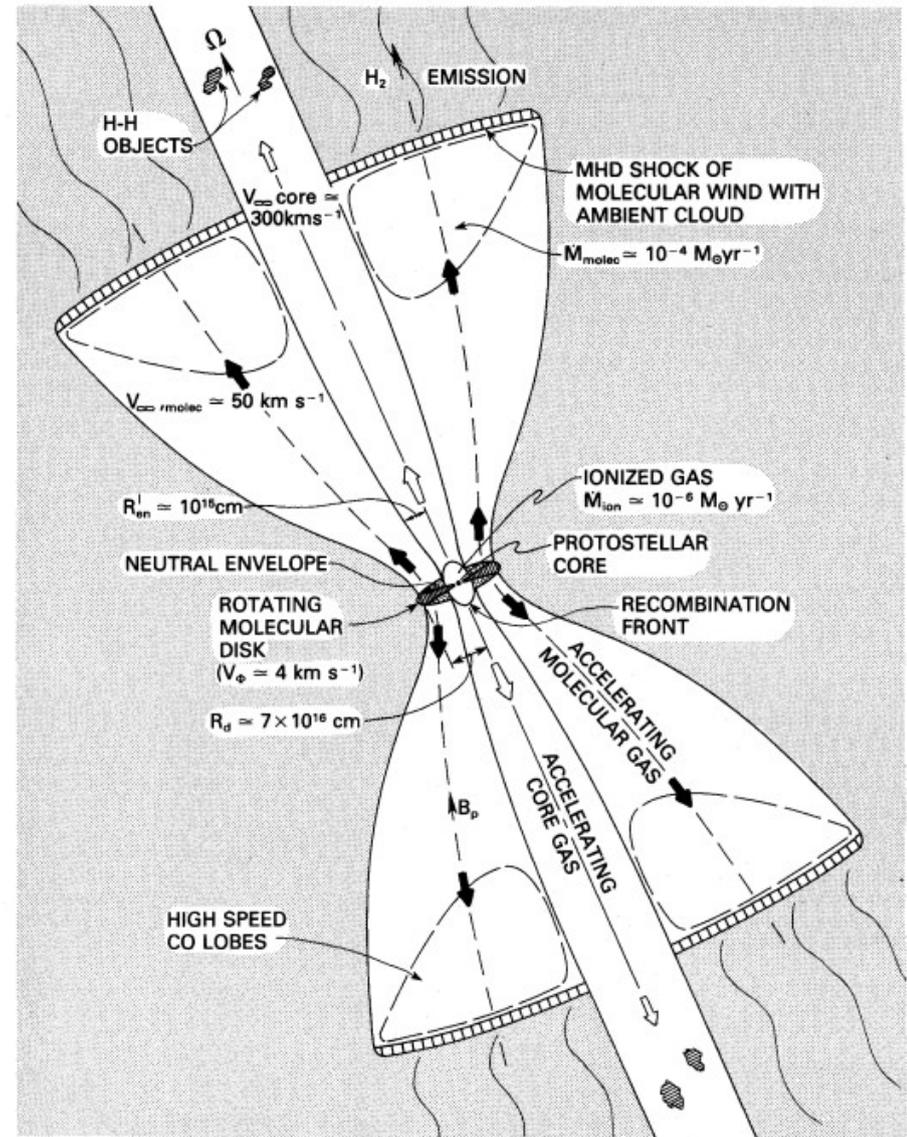
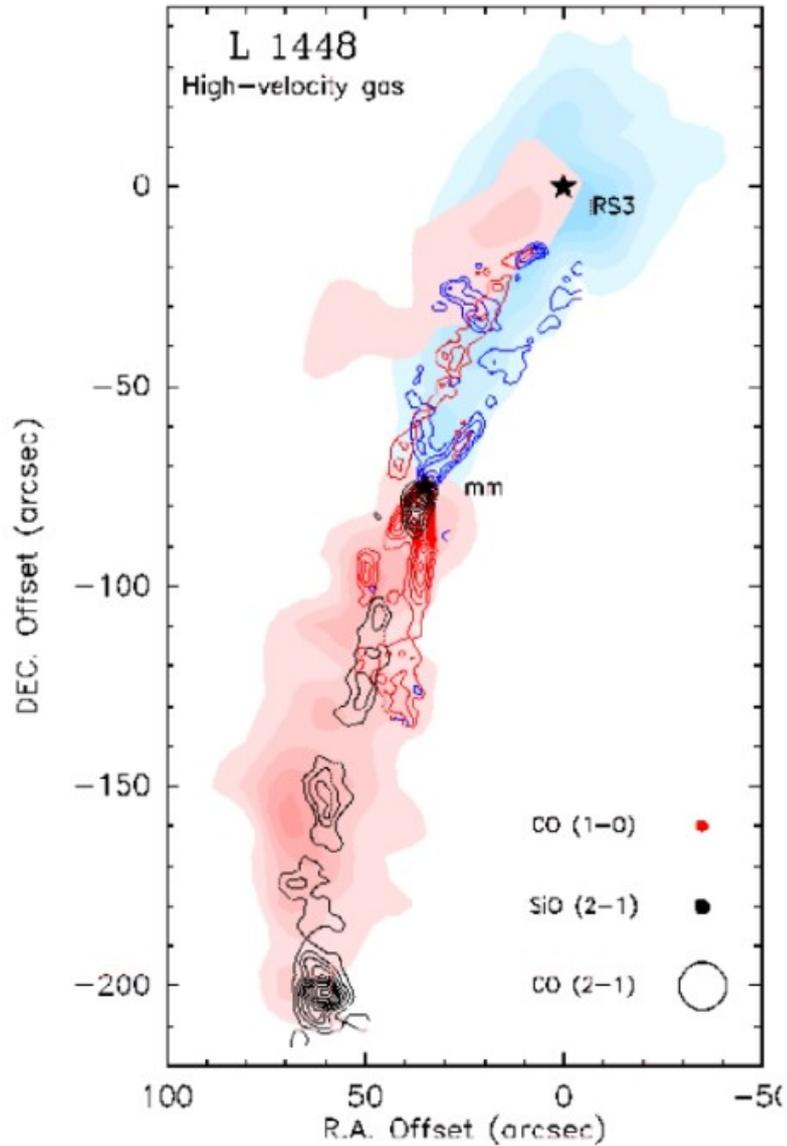
Line emission is Doppler shifted (broad)

## Bipolar outflows: Molecular stage

- Pudritz (1986): various components at work
- Their relative importance determines the protostellar class
- N.B. Consider the relative scales

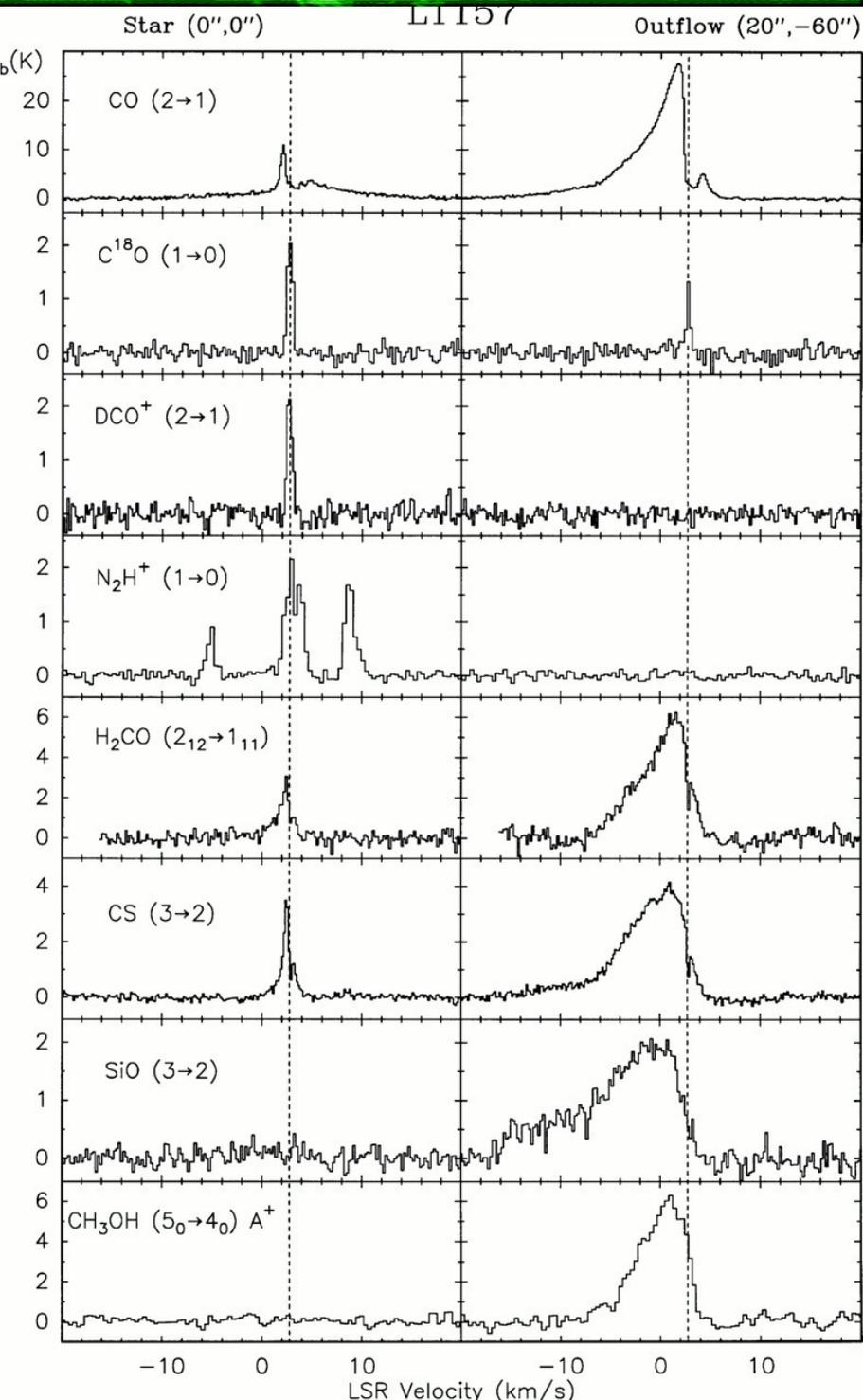
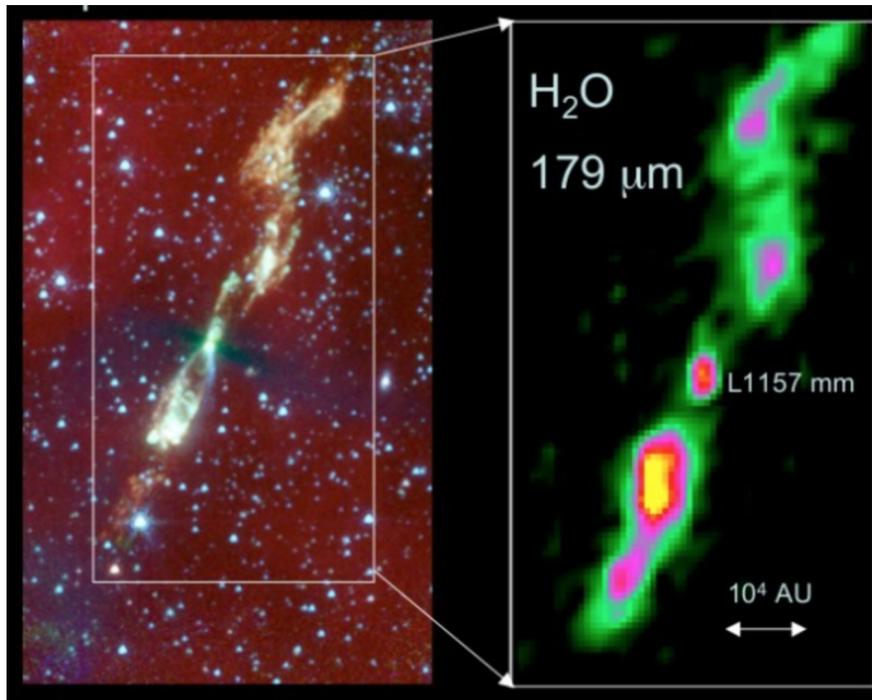


Outflows & Jets : model .vs. observation



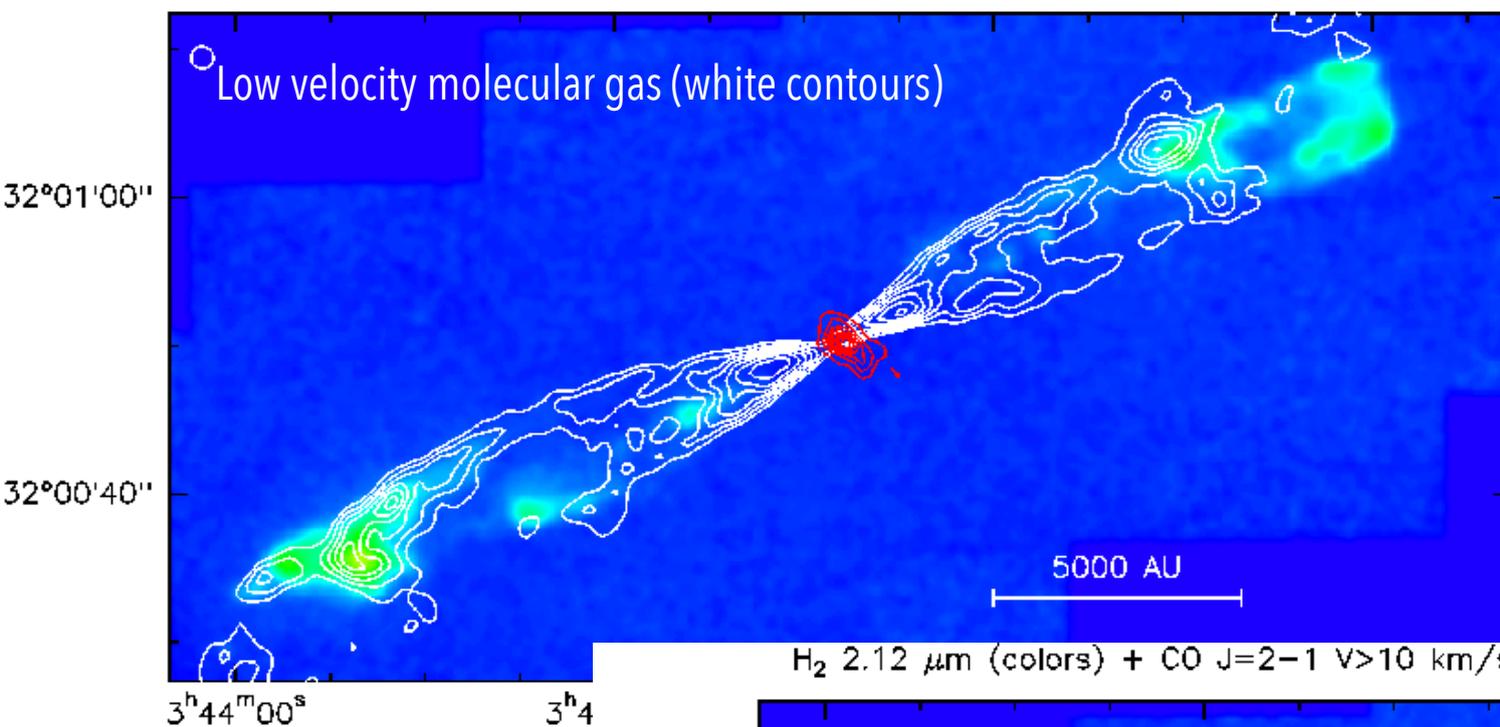
# Young Stellar Objects: various ingredients

- Various molecules trace different cloud components with various optical depths, densities, etc.
- All this generates a multilayer model of the SFR and of its outflow-jet structure
- In SFR where multiple cores are developing their gravitational instability, the mutual interaction may generate new perturbations/instabilities leading to further collapses

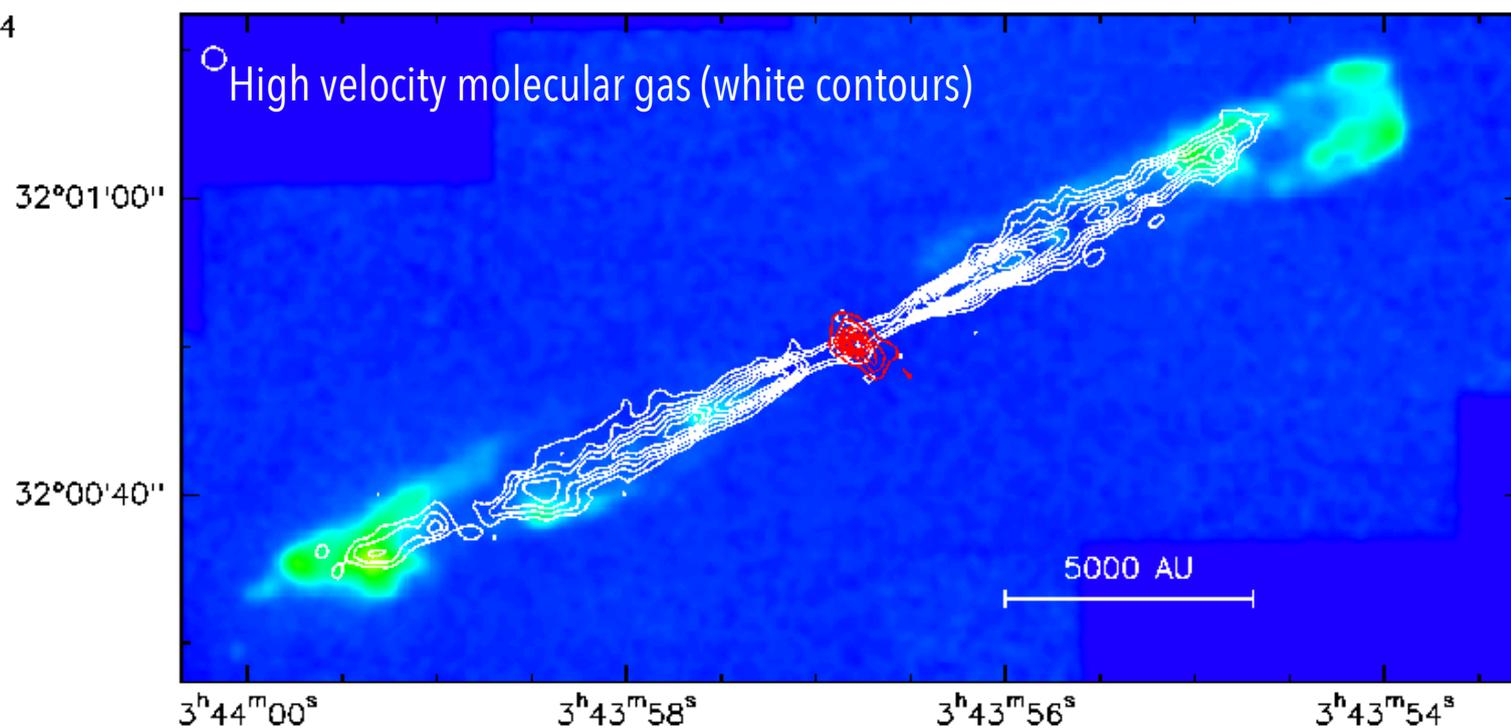


# Young Stellar objects: various ingredients

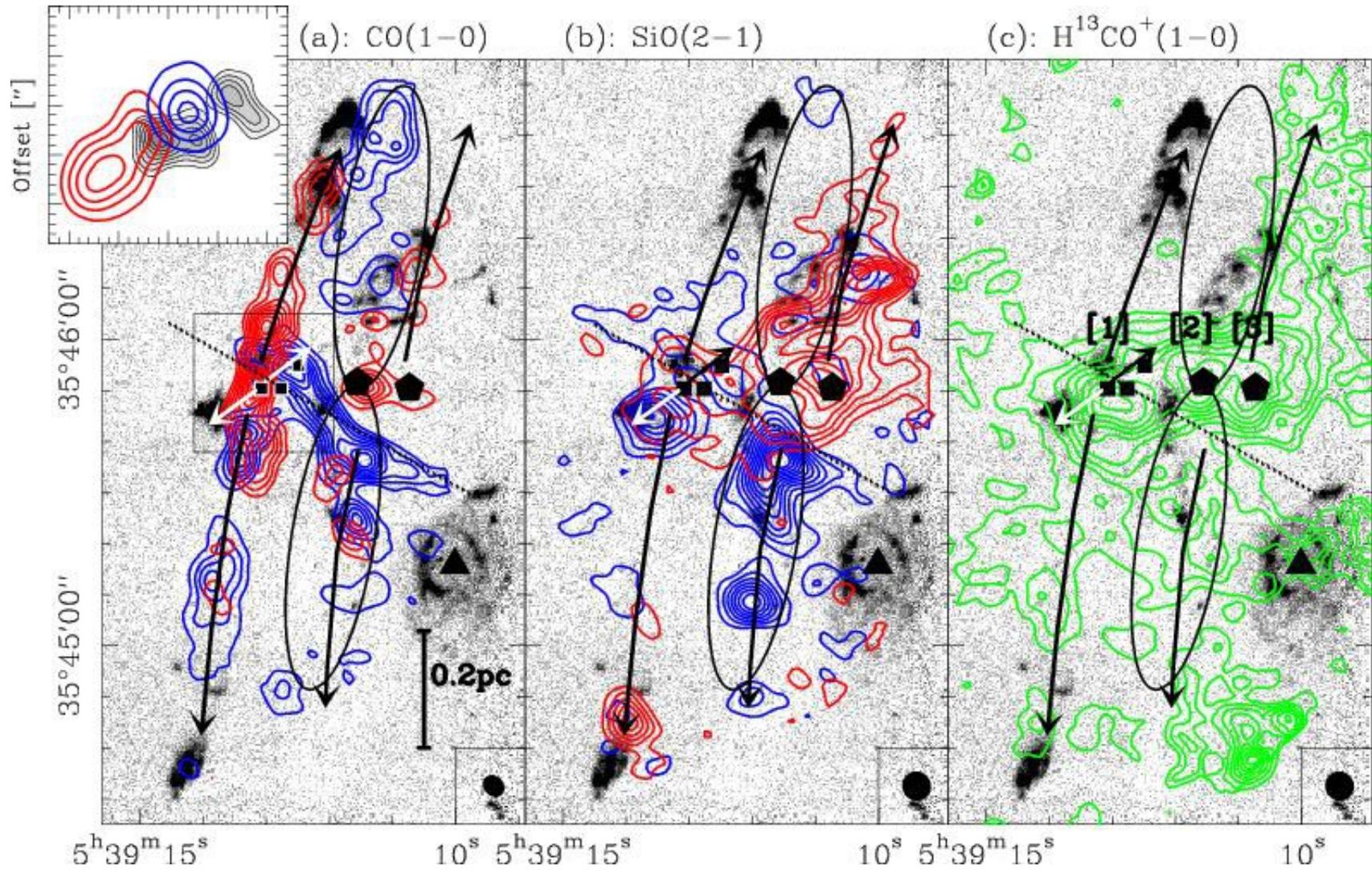
H<sub>2</sub> 2.12 μm (colors) + CO J=2-1 V<10 km/s (white) + continuum 1.3 mm (red)



H<sub>2</sub> 2.12 μm (colors) + CO J=2-1 V>10 km/s (white) + continuum 1.3 mm (red)



Interaction between outflows



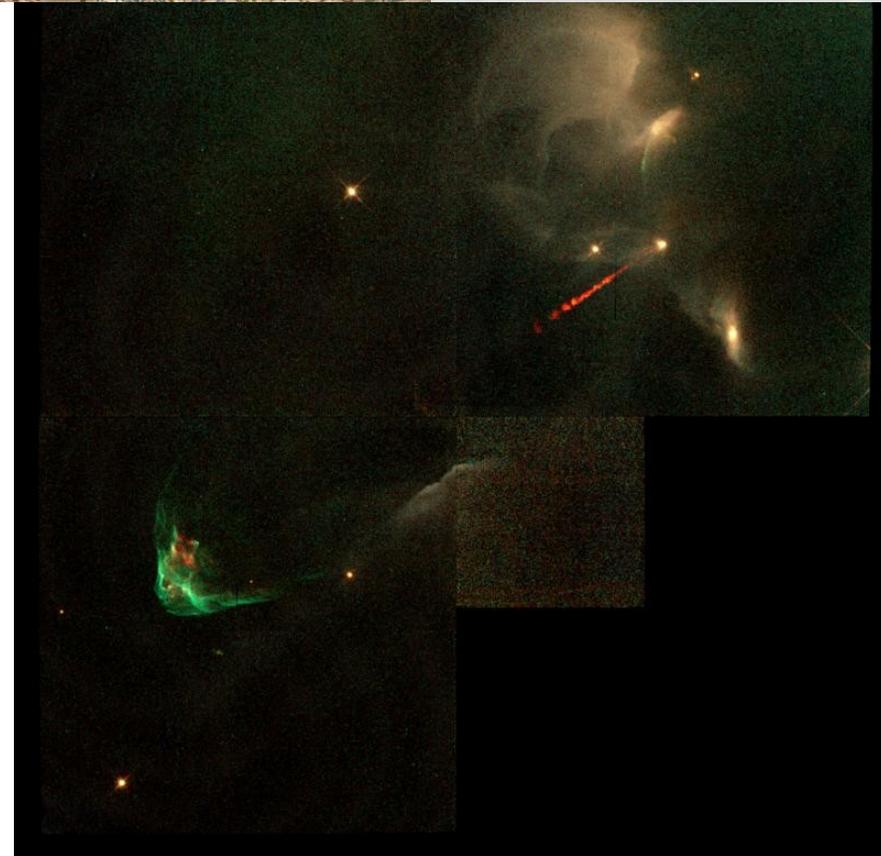
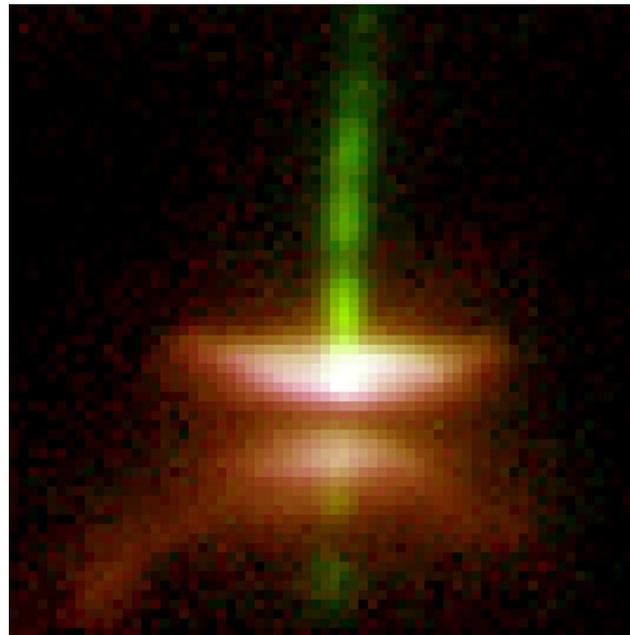
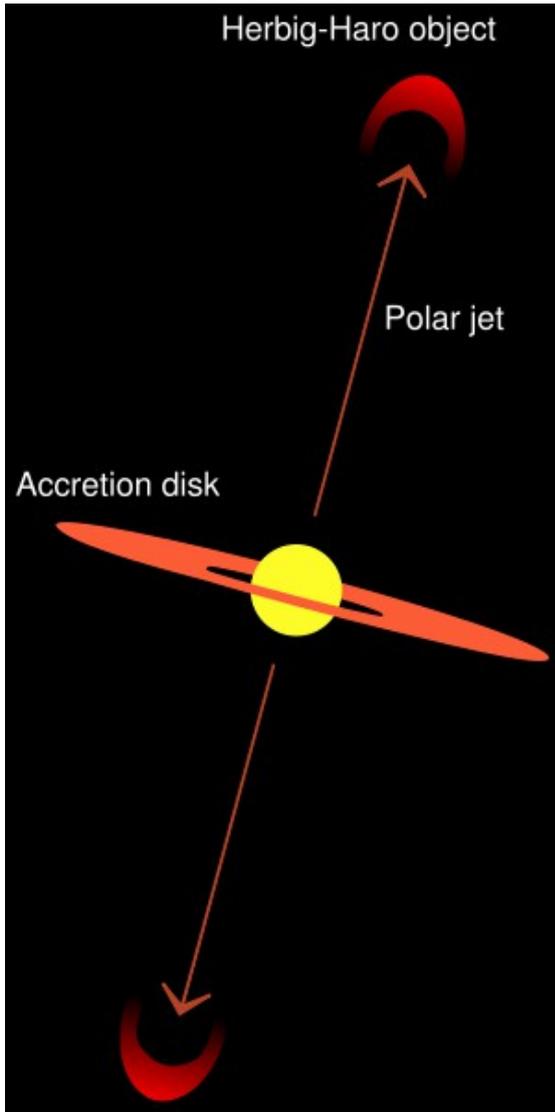
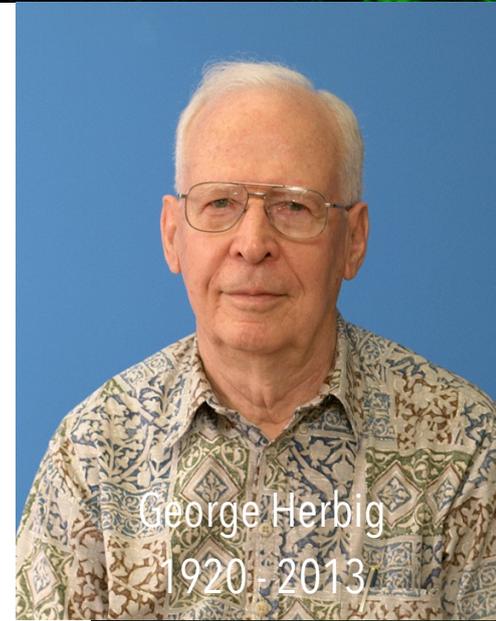
## *Young Stellar Objects: Herbig – Haro objects*

*Spectacular (thanks HST!) beacons of star formation: HH901 & HH 902  
However, lots of dust & cold gas absorb many photons!*



# Young Stellar Objects: Herbig – Haro objects

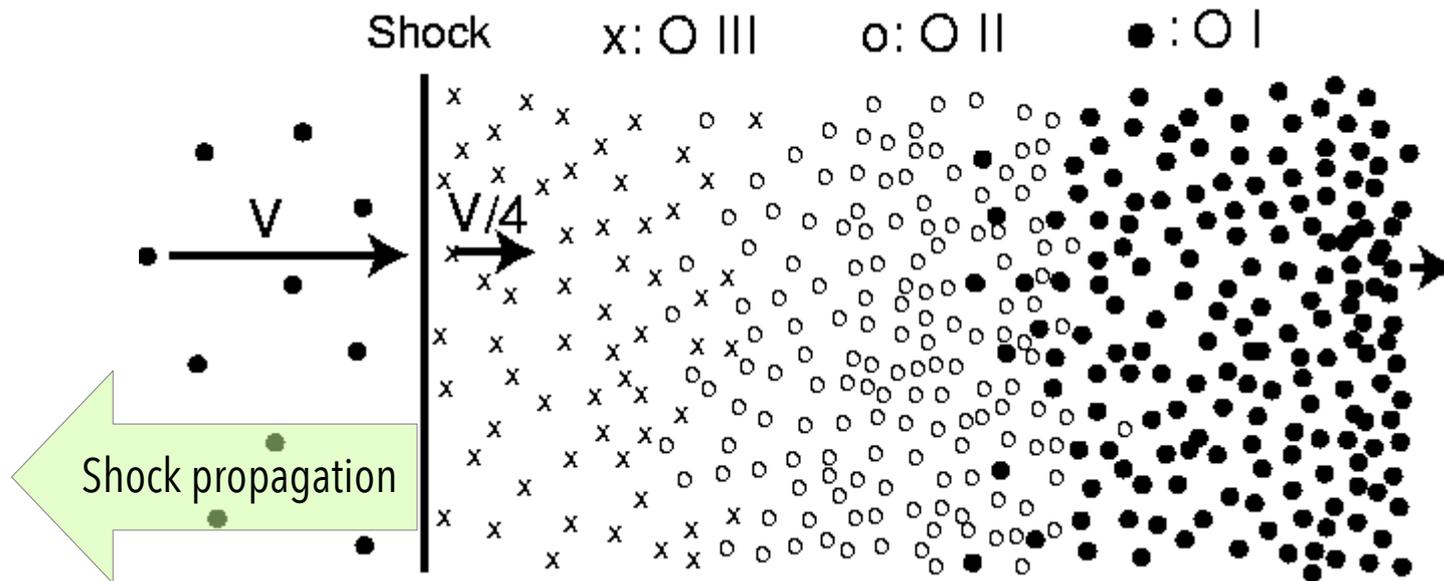
*Herbig – Haro objects: spectacular signature of SF*



*Radio emission:*

*Effective tool to investigate the earliest phases (the dense core region is still optically thick!)*

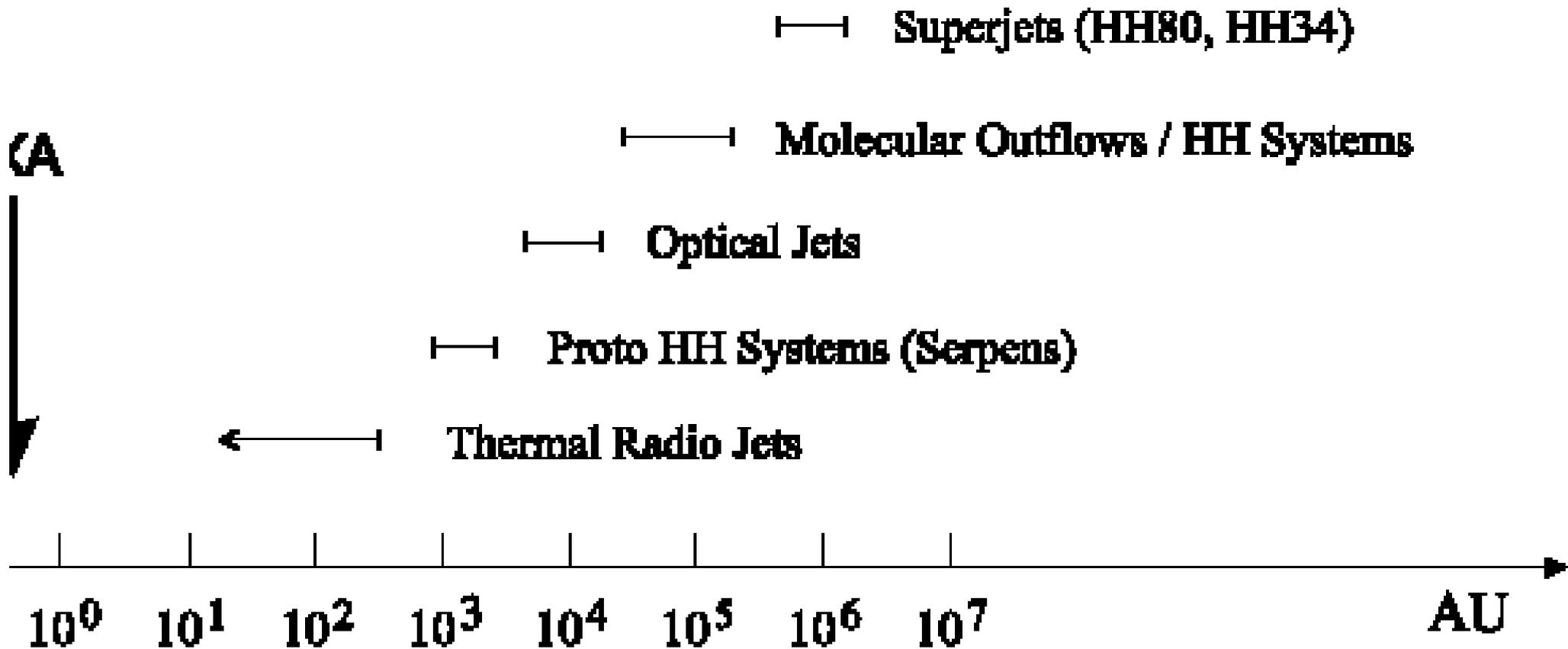
- The main emission mechanism of the radio emission is thermal bremsstrahlung (shock-ionized plasma) of a cooling plasma, created by outflow/jet heating of the ambient medium*



- In a few objects, also non-thermal emission from a population of relativistic electrons has been detected*
- The cartoon shown above imply also (optical) line emission of recombination of cooling elements (ionized / neutral). Protostars with optical jets are known as Herbig-Haro objects.*

*The kinetic energy of the ejected material can be transferred to produce a population inversion of the impacted ambient, and generate maser emission.*

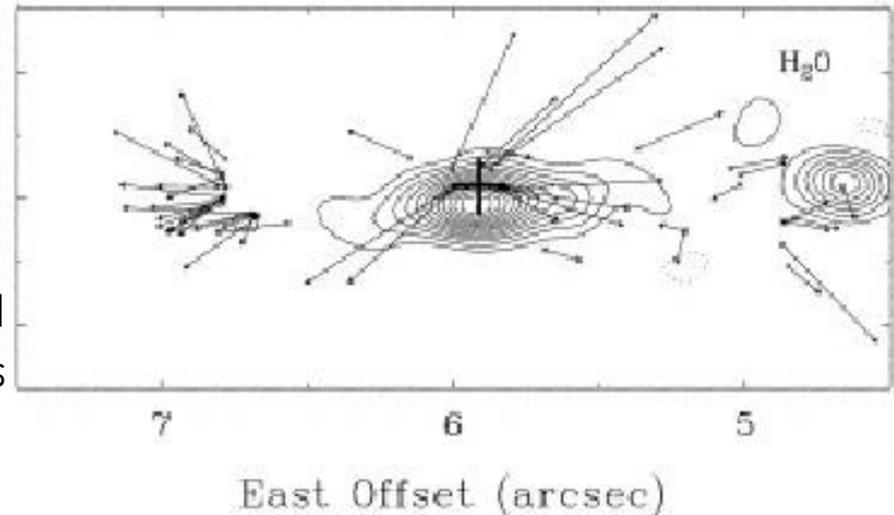
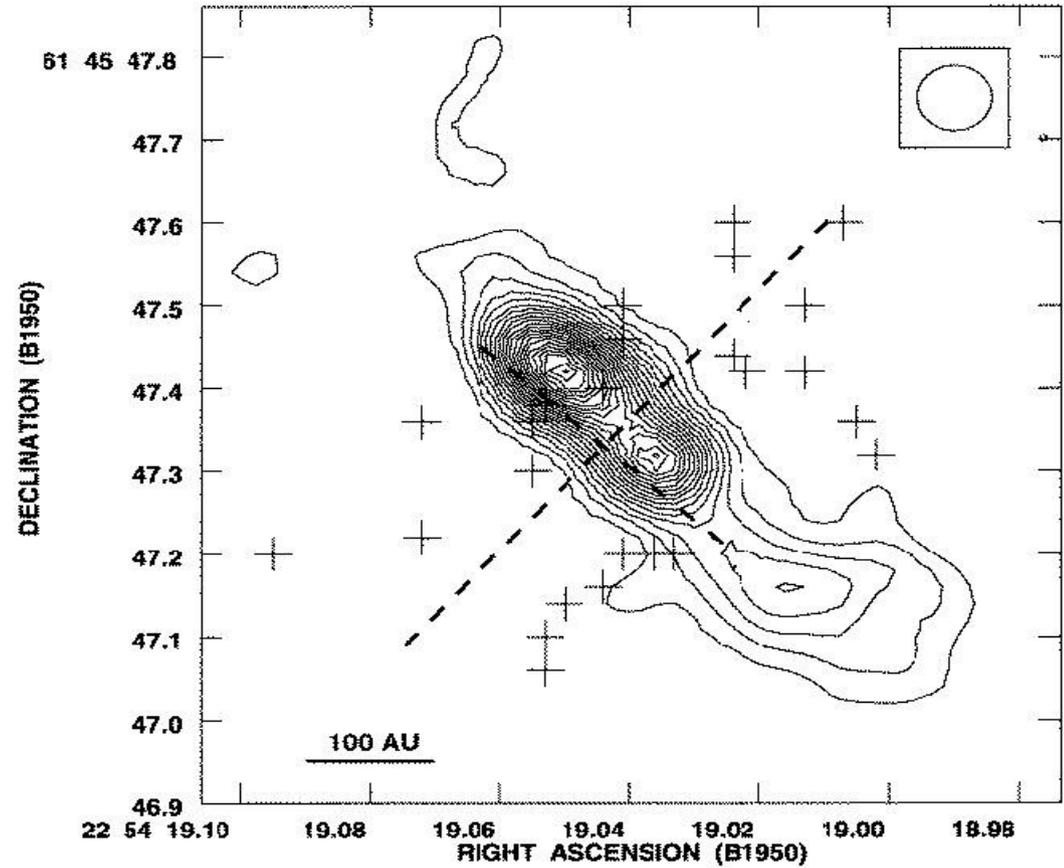
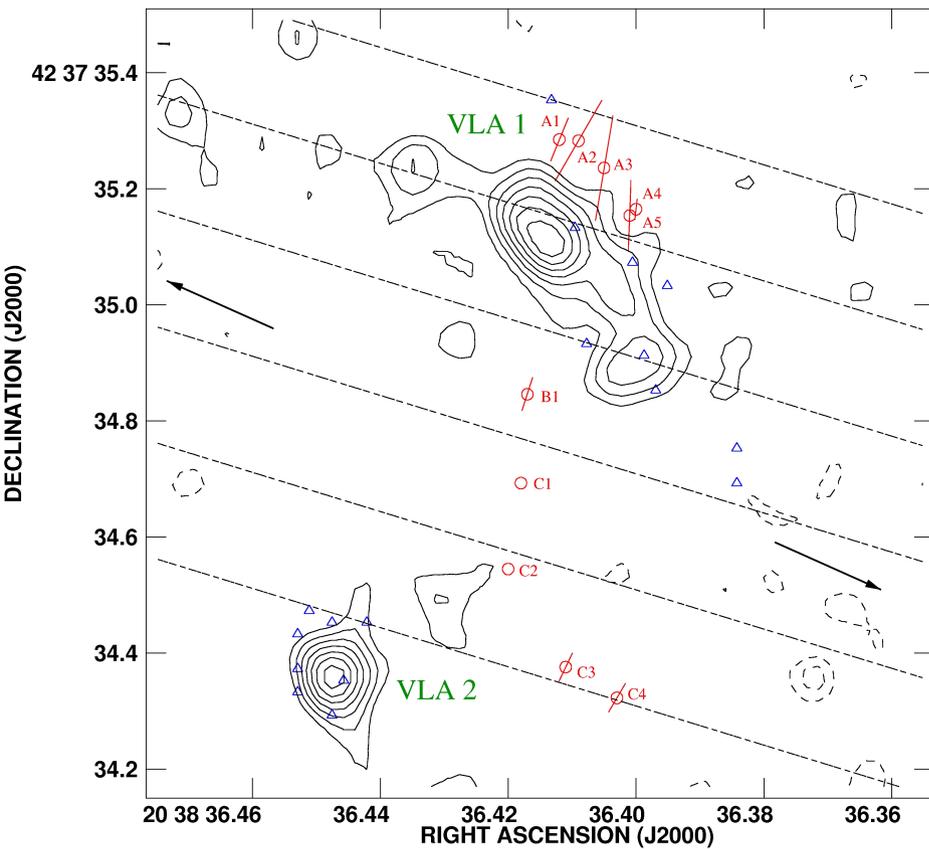
*Masers in SFR are ubiquitous and variable point-like sources  
Many species*



# Bipolar outflows: atomic/ionized stage

## Thermal & Non-Thermal Jets:

The spectrum is the key for determining which of the two mechanisms is at work

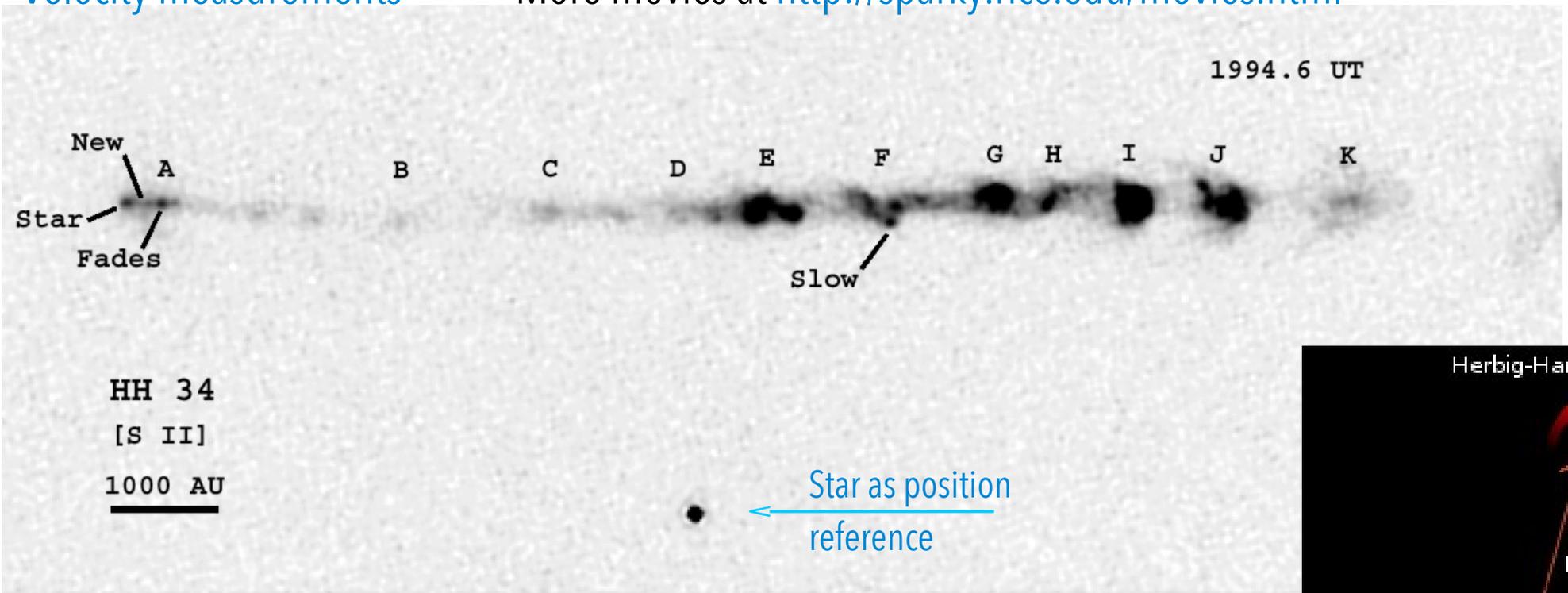


Surcis +, 2009: Positions of methanol (o) and water ( $\Delta$ ) masers superimposed on 1.3cm continuum contour map of the VLA 1 thermal jet and VLA 2 (Torrelles +, 1997). The red segments indicate linear polarization vectors (40mas = 1%). Arrows show the direction of the bipolar outflow (66d) and the parallel dashed lines the B field lines ( $73 \pm 10d$ ) as derived from the linear polarization.

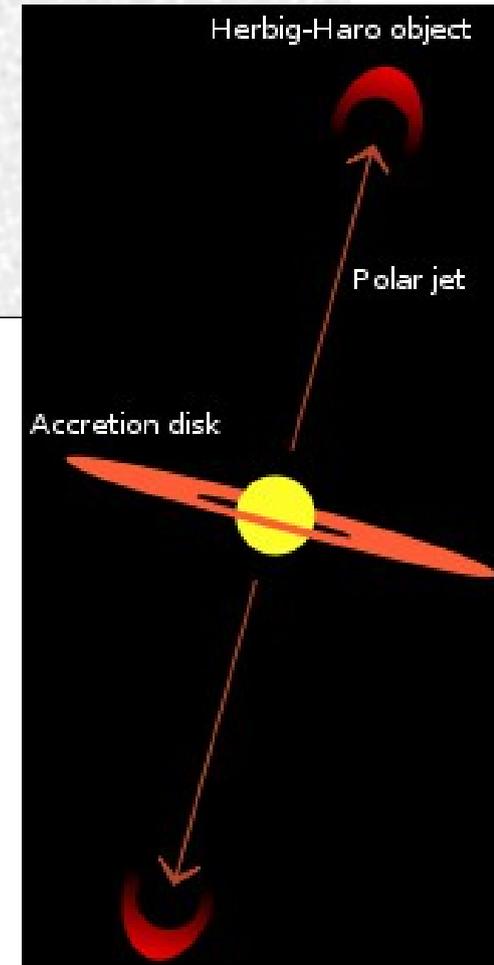
# Bipolar outflows: atomic stage

Velocity measurements

More movies at <http://sparky.rice.edu/movies.html>



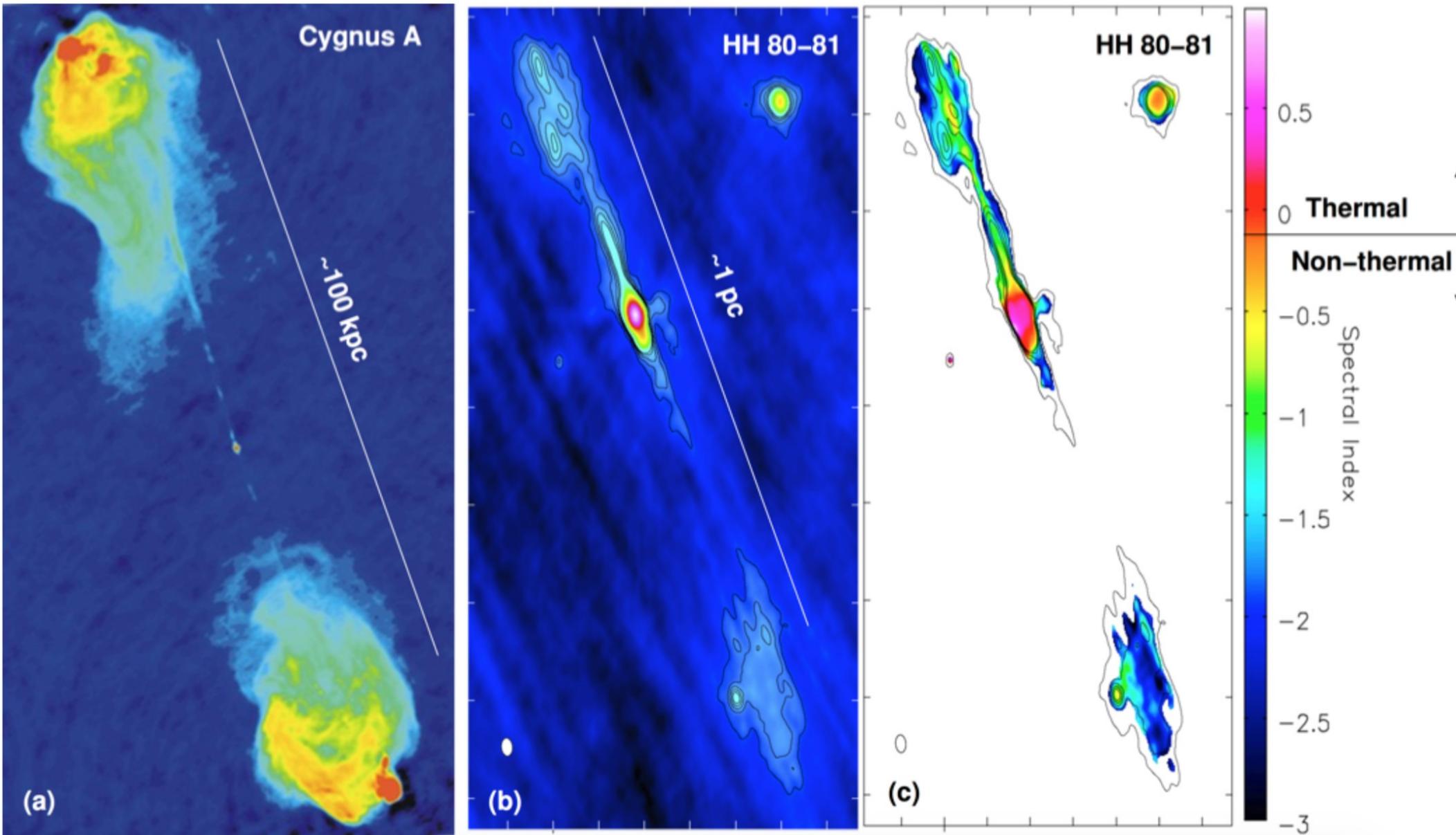
Updated version @  
<https://esahubble.org/videos/heic1113d/>



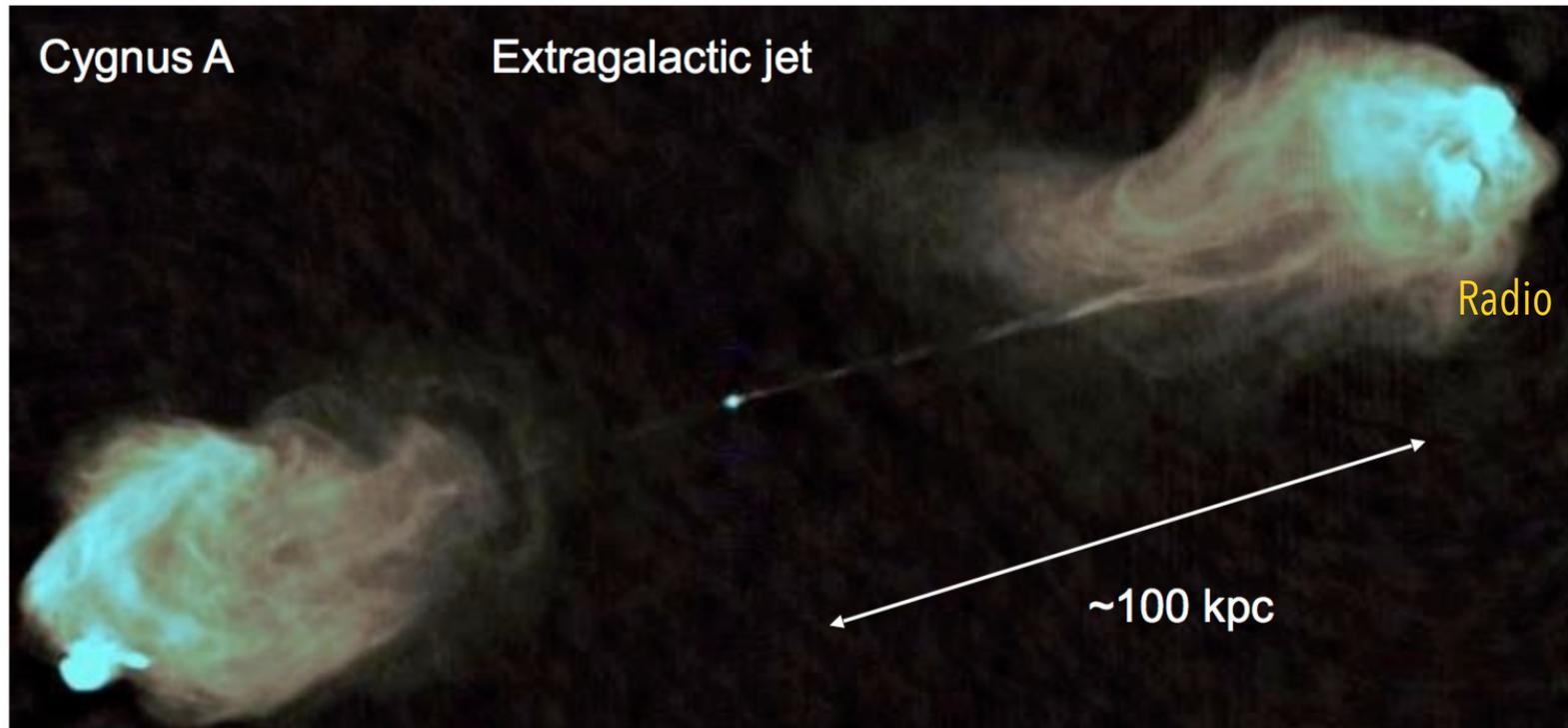
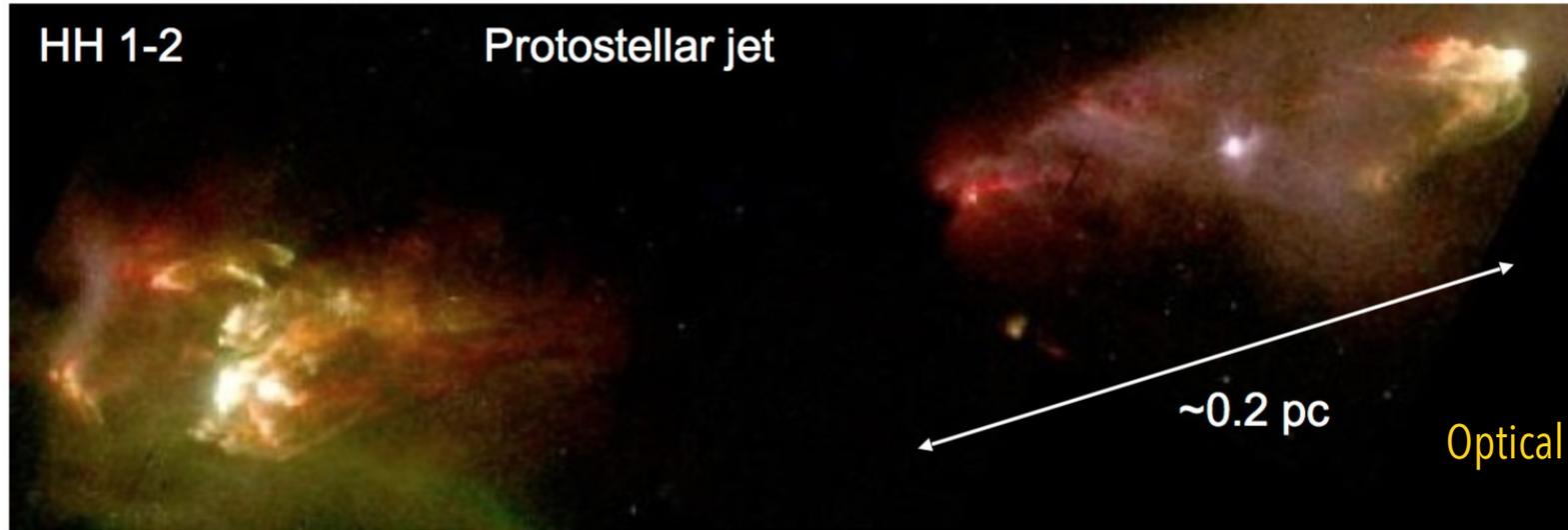
## Young Stellar objects: the role of radio emission

Effective tool to investigate the earliest phases (the dense core region is still optically thick!)

- *The main emission mechanism is thermal bremsstrahlung (shock-ionized plasma)*
- *GMC (line) emission*

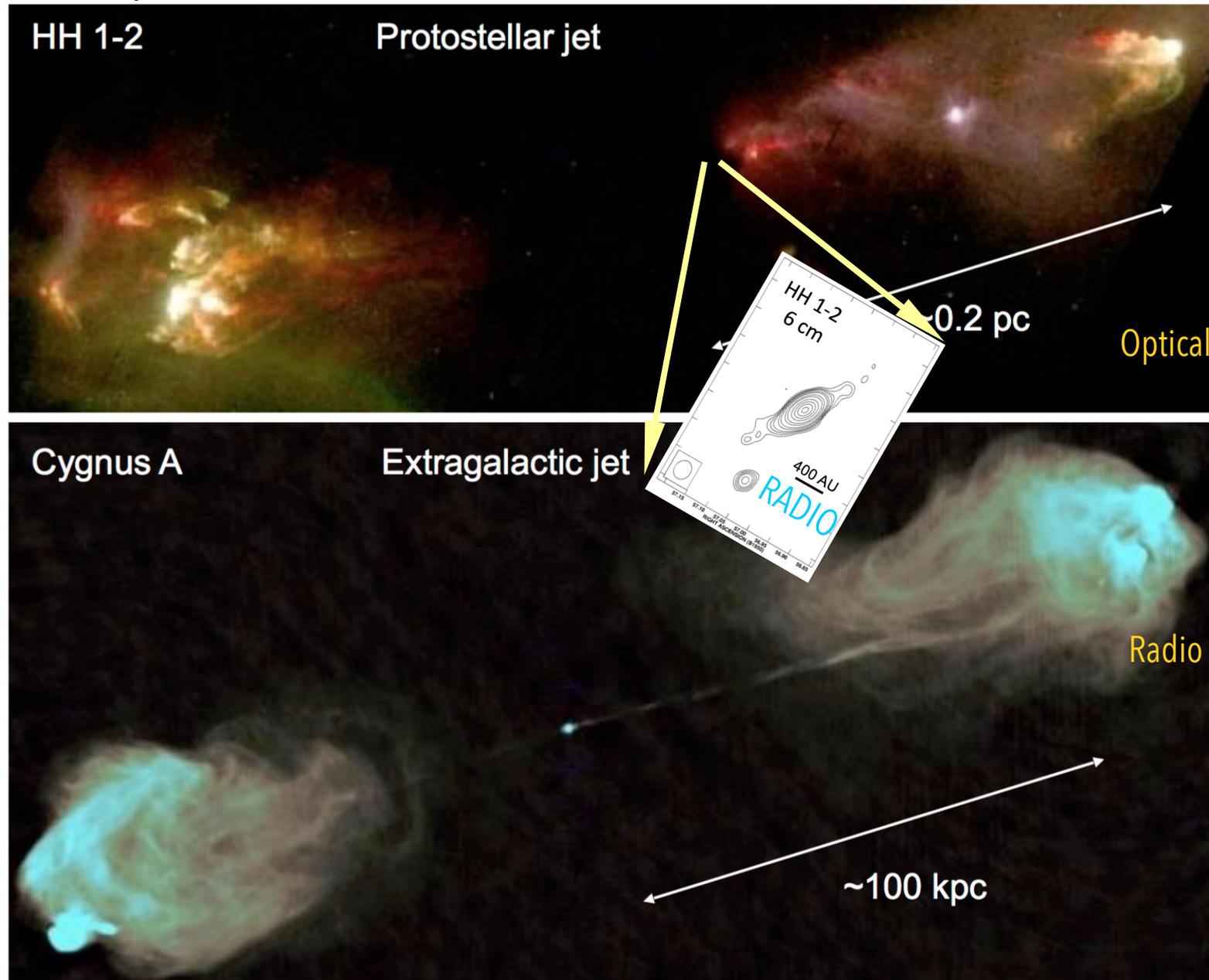


*Similarities with radio galaxies?*



## Young Stellar objects: the role of radio emission

The radio emission traces the base of the jets, where other emission is optically thick: HH 1-2 is a low mass object



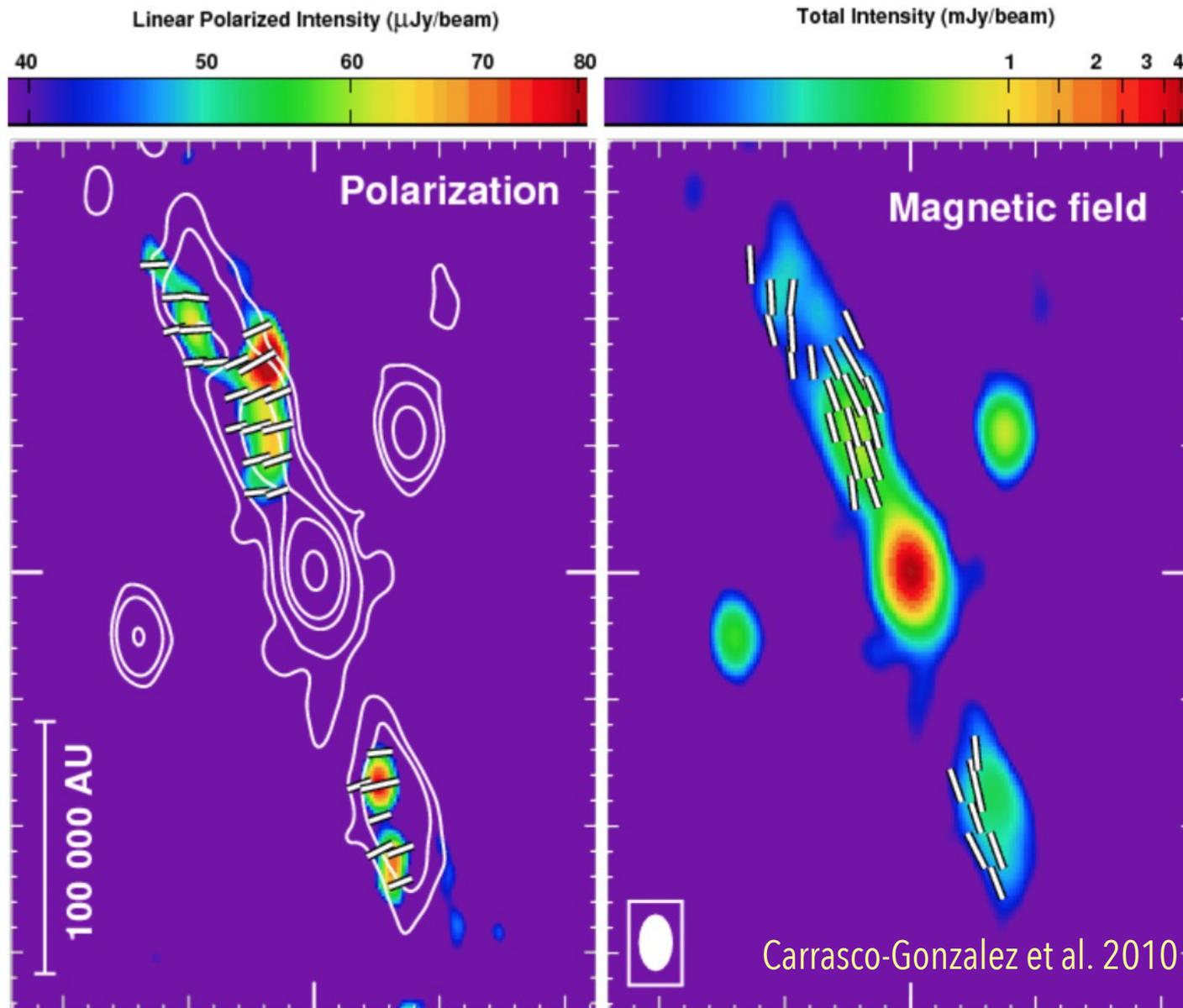
*Large number of known YSOs, nearby and lot of information can be obtained from observations at different wavelengths*

- *Optical & IR*  *Temperature, density, mass*  
*partially obscured, line (optical) and continuum (IR) emission*
- *Radio*  *ionized gas, base of the jet, velocity*  
*(mostly) optically thin, continuum emission, quite weak (mJy level)*  
*(maser emission in local high brightness spots!)*
- *mm/submm*  *Disk, molecular outflow*  
*wealth of molecular lines and dust continuum*

*Magnetic field* very difficult to observe, specially in the jet. We do not know very much about it since the jet is weak and different from those typically found in AGN

Magnetic field detected via polarization of radio emission

Signature of synchrotron emission, with a field of  $200 \mu\text{G}$  in HH 80-81 (Carrasco-Gonzalez et al. 2010)



Collimated outflows present in YSO from O-type (*quite rare*) to brown dwarf (*very common*) proto-stars (disk-jet scenario)

- 1. Often exhibit a central weak cm emission source
- 2. Resolved on the sub-arcsec scale, elongated in the same p.a. of the large scale outflow and  
 → trace the region where the outflow is originated
- 3. The spectrum is flattish or slightly inverted, sometimes complex, → thermal origin
- 4. Found in all stages of star formation, from class 0 onwards
- 5. *Model of thermal jets in Reynolds (1986)* from which some parameters can be inferred from observations

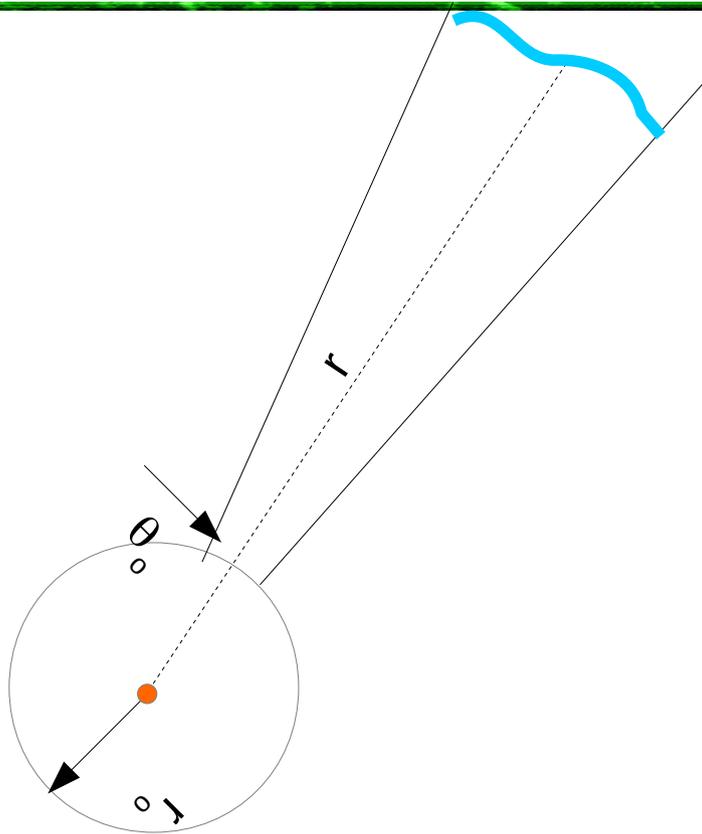
$$r = 0.56 \left( S_{mJy} v_{10}^{-\alpha_{op}} \right)^{1/2} \theta_o^{-1/2} \left( v_{10m} \right)^{\alpha_{op}/2-1} D_{kpc} \left( T_4 \right)^{-1/2} (\sin i)^{-1/2} F^{-1/2} \quad [10^{15} \text{ cm}]$$

$$\dot{M} = 0.938 v_8 x_o^{-1} \left( \frac{\mu}{m_p} \right) \left( S_{mJy} v_{10}^{-\alpha_{op}} \right)^{3/4} \left( D_{kpc} \right)^{3/2} \left( v_{10m} \right)^{-0.45+3\alpha_{op}/4} \theta_o^{3/4} \left( T_4 \right)^{-0.075} (\sin i)^{-1/4} F^{-3/4} \quad [10^{-6} M_{\odot}]$$

where  $v_8 = \frac{v}{10^8 \text{ cm s}^{-1}}$ ;  $S_{mJy}$  = flux density in mJy ;  $v_{10} = \frac{v}{10 \text{ GHz}}$ ;  $v_m$  = peak frequency in 10GHz units ;

$\alpha_{op}$  = optically thick spectral index ;  $T_4$  = temperature in units of  $10^4 \text{ K}$  ;  $F$  = Function of optically thick/thin spix

$x_o$  = ionization fraction



- 5. Model of thermal jets in Reynolds (1986) from which some parameters can be inferred from observations
- $r_0$  = core (collimation) radius
- $\dot{M}$  is the outflow mass loss rate

See Reynolds (1986) for a proper description

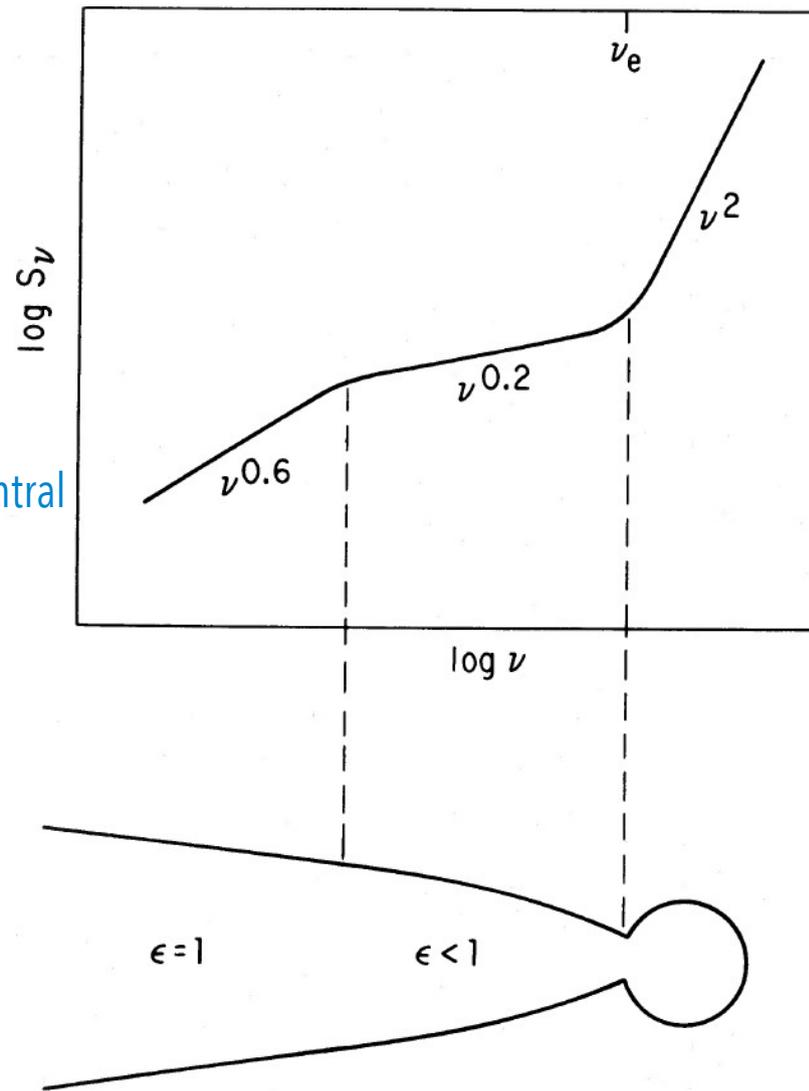
$$r = 0.56 \left( S_{mJy} v_{10}^{-\alpha_{op}} \right)^{1/2} \theta_0^{-1/2} \left( v_{10m} \right)^{\alpha_{op}/2-1} D_{kpc} \left( T_4 \right)^{-1/2} (\sin i)^{-1/2} F^{-1/2} \quad [10^{15} \text{ cm}]$$

$$\dot{M} = 0.938 v_8 x_0^{-1} \left( \frac{\mu}{m_p} \right) \left( S_{mJy} v_{10}^{-\alpha_{op}} \right)^{3/4} \left( D_{kpc} \right)^{3/2} \left( v_{10m} \right)^{-0.45+3\alpha_{op}/4} \theta_0^{3/4} \left( T_4 \right)^{-0.075} (\sin i)^{-1/4} F^{-3/4} \quad [10^{-6} M_{\odot}]$$

where  $v_8 = \frac{v}{10^8 \text{ cm s}^{-1}}$ ;  $S_{mJy}$  = flux density in mJy ;  $v_{10} = \frac{v}{10 \text{ GHz}}$ ;  $v_{10m}$  = peak frequency in 10GHz units ;

indeed,  $v_{10m}$  is the frequency at which the extrapolations of asymptotically optically thick and thin spectra meet.

$\alpha_{op}$  = optically thick spectral index ;  $T_4$  = temperature in units of  $10^4 \text{ K}$  ;  $F$  = Function of optically thick/thin spix



Combination of

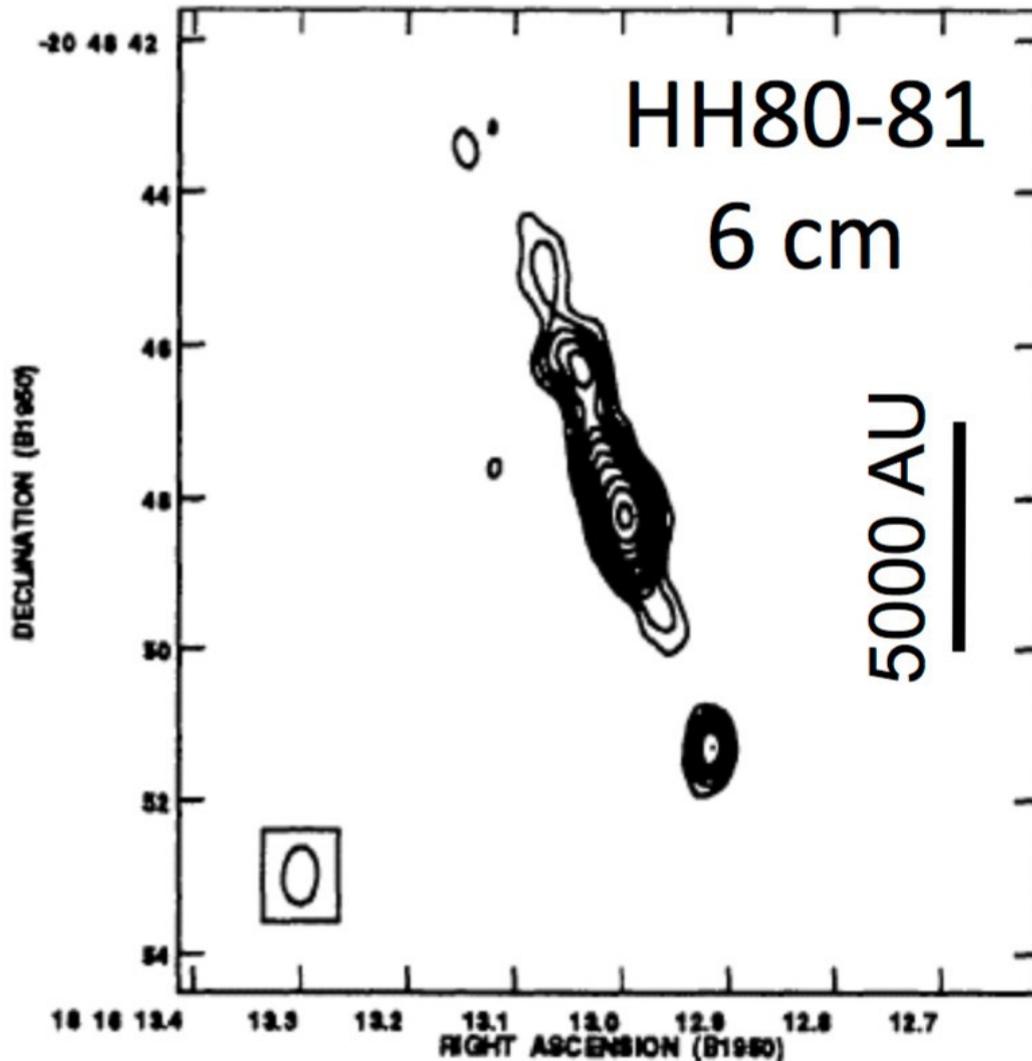
1. Optically thick emission of the central  $\nu^2$  (densest/hottest) region
2. Optically thin emission ( $\nu^{-0.1}$ )
3. Density gradients along the jet (decreasing the emission)

FIG. 2.—Schematic core-jet spectrum, showing an example of the mapping between spatial structure in a flow and spectral structure in the integrated radio flux (the source is assumed unresolved). The homogeneous core dominates the emission at high frequencies; descending in frequency, one observes first the inner jet where it is confined ( $\epsilon < 1$ ), then the outer jet where it is free ( $\epsilon = 1$ ). The quoted spectral indices of 0.2 and 0.6 could be achieved with a variety of source gradients as described in the text.

*Effective tool to investigate the earliest phases (the dense core region is still optically thick!)*

- *1. YSO jets (non-relativistic) are morphologically very similar to relativistic jets.*
- *2. Magnetic fields are also thought to play a fundamental role in the YSO jet phenomenon, similar to relativistic jets. But magnetic fields are very difficult to observe in YSOs.*
- *3. Radio observations suggest the presence of non-thermal emission in some YSO jets.*
- *3B. High sensitive radio observations of HH 80-81 confirmed presence of linearly polarized synchrotron emission in HH 80-81.*
- *4. YSO jets CAN accelerate particles up to relativistic velocities (synchrotron emission)*
- *5. With high sensitive radio observations, we can study the magnetic field in YSO jets in a similar way as in relativistic jets.*
- *Disks are often present with sizes 30-300 AU, 0.1 M and 300-1000 AU a few M and clumpy in low/high mass proto stars. Jets have  $10^{-5} - 10^{-6} M \text{ yr}^{-1}$  and  $v \sim 100-200$  and  $200-500 \text{ km s}^{-1}$ . In high mass stars, disks are confused by the presence of HII region emission*

The *kinetic energy of the ejected material (outflow/jet)* can be transferred to the ambient medium produce a *population inversion* of the impacted ambient, and generate **maser emission**

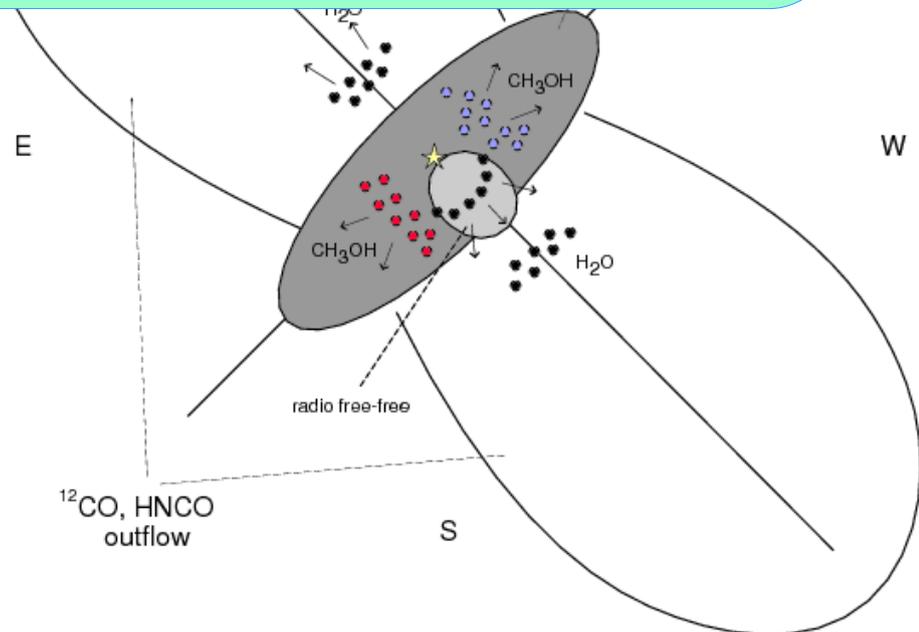


Martí et al. 1993: non thermal jet in a high mass object

The kinetic energy of the ejected material, *as well as radiative energy from the [proto-]star* can be transferred to produce a *population inversion* of the impacted ambient, and *\*then\** generate **Maser emission**

Molecules and  
line radiation

Prior of going to Maser Emission,  
Let's make a summary of star formation processes



## Summary of star formation and Young Stellar Objects (YSOs)

- The road to star formation in a disk galaxy like the Milky Way begins when massive ( $\sim 10^7 M_{\odot}$ ) bound structures condense out of the diffuse ISM as a result of gravitational instabilities, frequently initiated within spiral arms.
- The most massive structures (GMAs or HI superclouds) inherit high levels of internal turbulence from the diffuse ISM, and this combines with self-gravity to cause fragmentation into GMCs of a range of masses, as well as clumps within the GMCs.
- The turbulence within GMCs is highly supersonic and approximately Alfvénic. It imposes a log-normal distribution of densities and creates a spectrum of gas condensations over a wide range of spatial scales and masses. This structure is hierarchical.
- This turbulence damps in about one crossing time, and as yet it is not understood exactly how, and for how long, the highly intermittent sources of energy in the ISM (including within GMCs themselves) can maintain the observed universal level of turbulence in GMCs.
- Spatially defined structures within GMCs tend to have internal velocity dispersions that increase with size as  $\sigma \propto \ell^{0.5}$ , which is understood to reflect the underlying power spectrum scaling expected for supersonic turbulence.

## Summary of star formation and Young Stellar Objects (YSOs)

- Some of the densest regions created by turbulence become self-gravitating cores with masses that are typically on the order of the Bonnor-Ebert mass. The distribution of core masses appears to be similar to the IMF for stars, and turbulence appears to be important in defining this distribution.
- These cores are frequently clustered, owing to the dominance of large scales in the turbulent flow. Forming cores sample from the local vorticity of the turbulence to determine their spins. The rate of core formation can be estimated based on the turbulent properties of a GMC.
- Dense cores that begin or become magnetically supercritical undergo collapse, first becoming strongly stratified internally. Observations show that magnetic fields in cores are roughly critical, and this is consistent with inferred core lifetimes.
- Continued accretion after the collapse of a core can occur if the surrounding ambient medium has a sufficiently low level of turbulence, but it is not yet known how much this can increase the masses of stars.
- The collapse of a core leads to the formation of a rotating disk interior to an accretion shock; significant magnetic flux is lost in this collapse process, although based on current results this is not enough to account for the small fluxes observed in stars.

## Summary of star formation and Young Stellar Objects (YSOs)

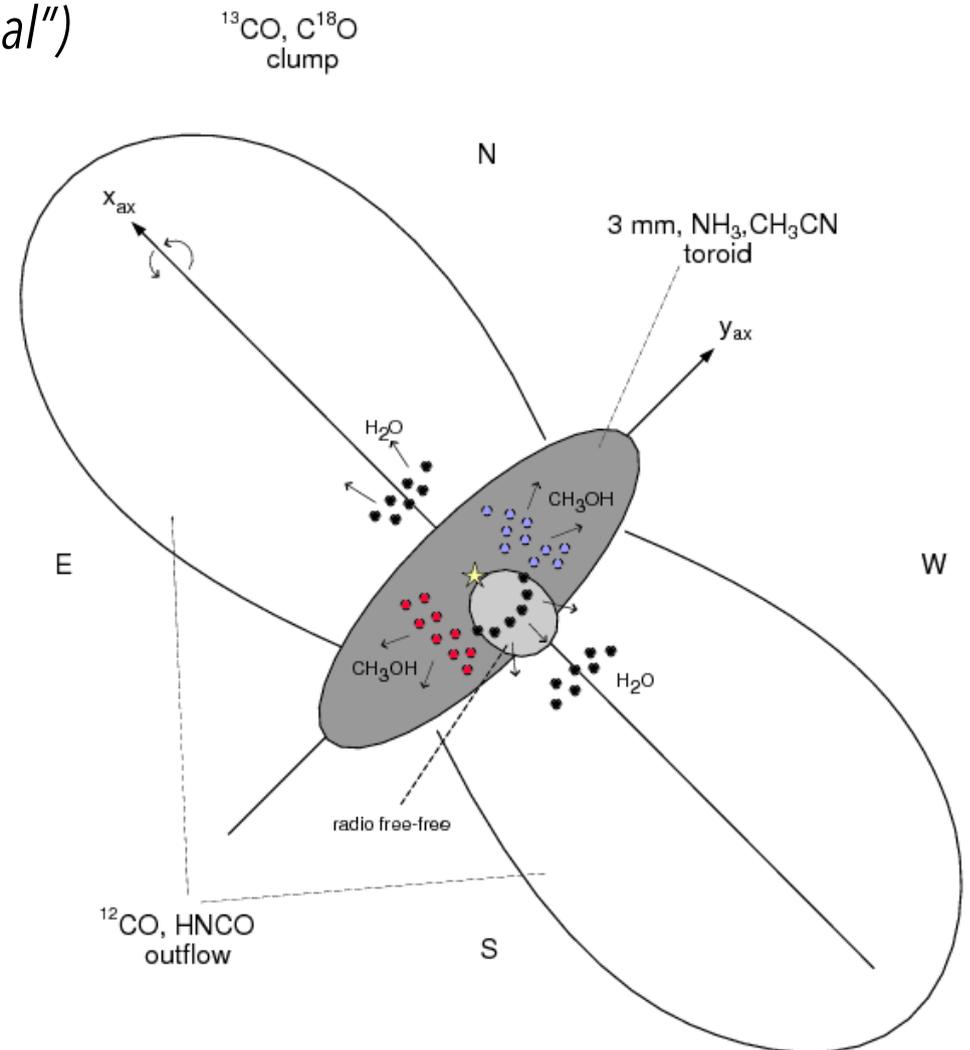
- Disks accrete owing to a combination of processes that transport angular momentum outward; these transport mechanisms include gravitational stresses when the surface density is high enough, and magnetic stresses when the ionization is high enough.
- Powerful winds are magnetocentrifugally driven from the surface of circumstellar disks at a range of radii. The inner portion of the wind, which arises nearest the central star, becomes collimated into a jet-like flow owing to magnetic hoop stresses.
- The impact of a wide-angle, stratified disk wind on the protostellar core sweeps up much of the ambient gas into a massive molecular outflow. This reduces the net efficiency of star formation to  $\sim 1/3$ . The combined action of many outflows also helps to energize dense, star-cluster-forming clumps.
- Massive stars form from cores that are considerably more massive than a Bonnor-Ebert mass, and are most likely highly turbulent. Radiation pressure strongly affects the dynamics of massive star formation, but can be overcome by the combined action of disk formation, protostellar outflows, and radiation-hydrodynamic instabilities in the accreting gas. It is not clear whether protostellar feedback determines the maximum mass of the stars that form.

- Massive, luminous stars ionize their surroundings into HII regions. The expansion of these regions into ambient gas at  $\sim 10 \text{ km s}^{-1}$  energizes GMCs, contributing to the large-scale turbulent power. However, this process is difficult to regulate and can unbind GMCs within a few dynamical crossing times. By the time they are finally destroyed, GMCs may have lost much of their original mass by photoevaporation.
- The destruction of GMCs returns almost all of the gas they contain to the diffuse phase of the ISM, with a mean star-formation efficiency over the cloud lifetime of  $\sim 5\%$ . This low efficiency can be understood as a consequence of the small fraction of mass that is compressed into clumps dense enough that turbulence does not destroy them before they collapse.
- The return of GMC gas to the diffuse ISM completes the cycle of star formation, which then begins anew.

The kinetic energy of the ejected material, *as well as radiative energy from the [proto-]star* can be transferred to produce a *population inversion* of the impacted ambient,

and *\*then\** generate **Maser emission**

(in this case, the excitation is termed "collisional")



*N.B. Molecules also emit substantial line radiation*

Cartoon of the inner region in ◁ low/high ▷ mass objects: stratification of jet/outflows

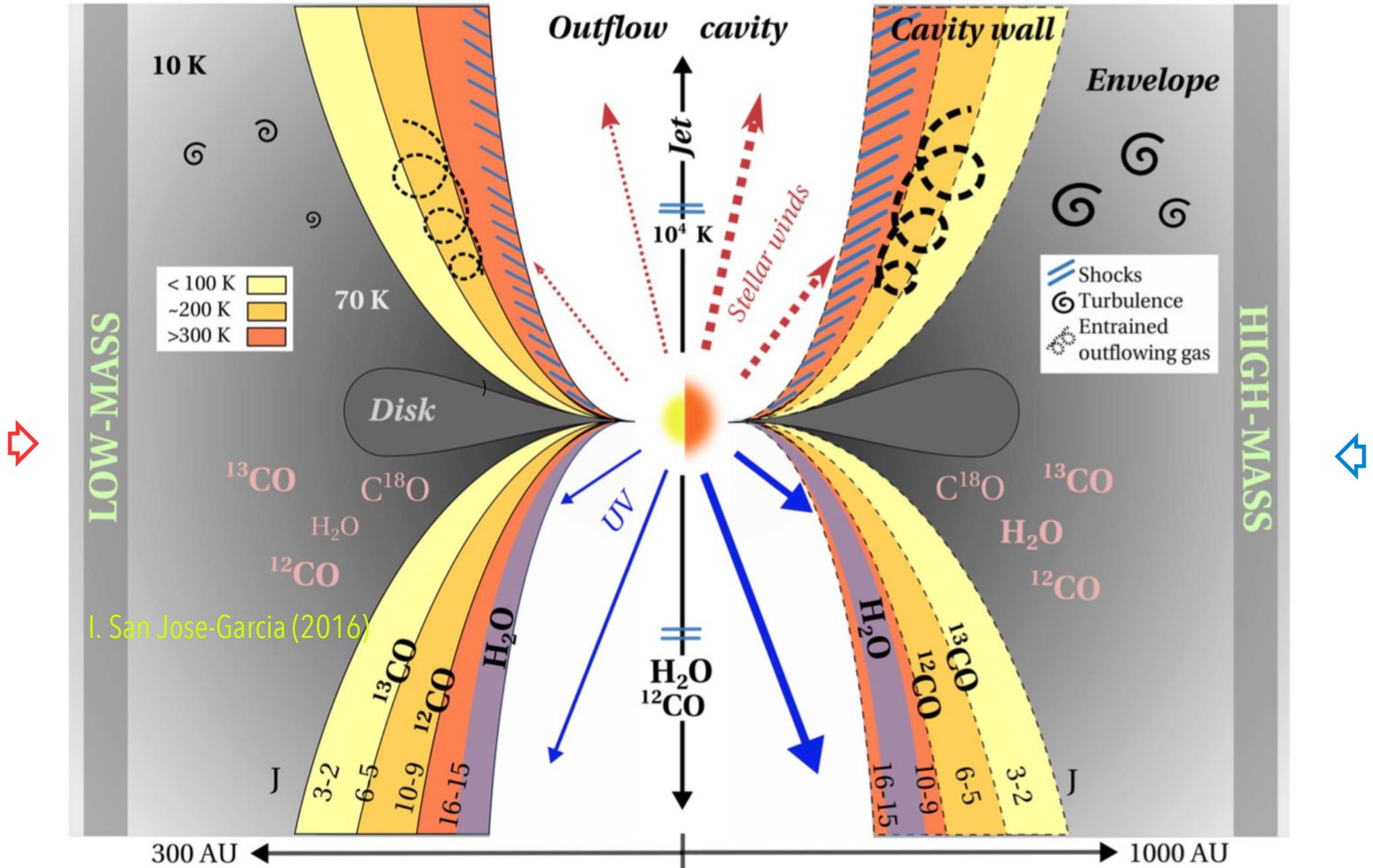


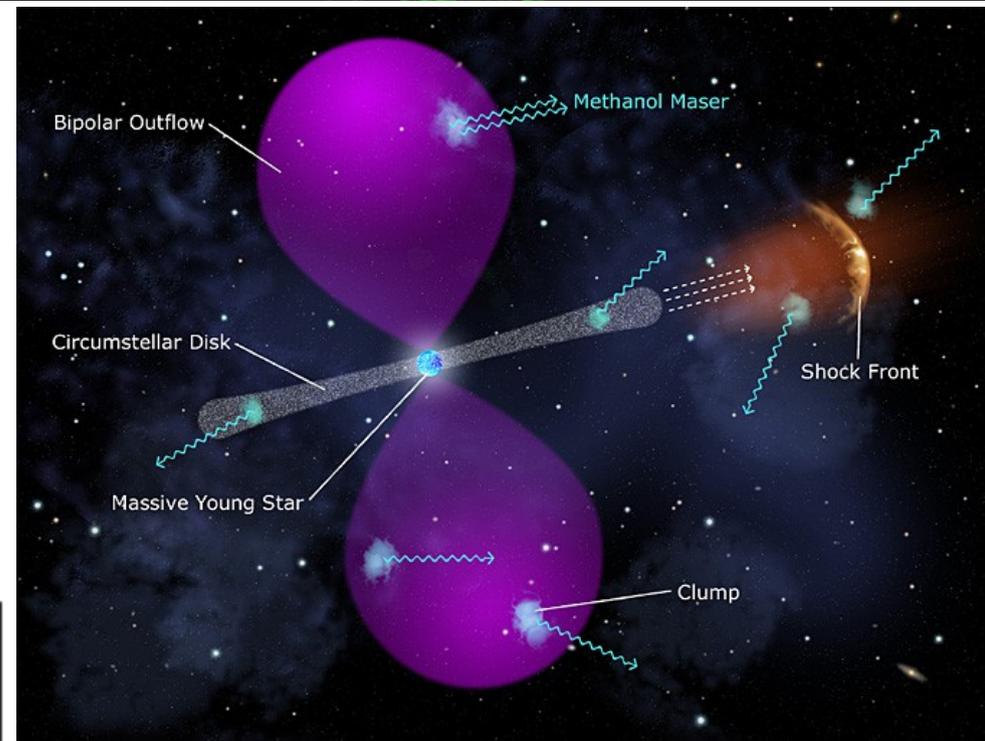
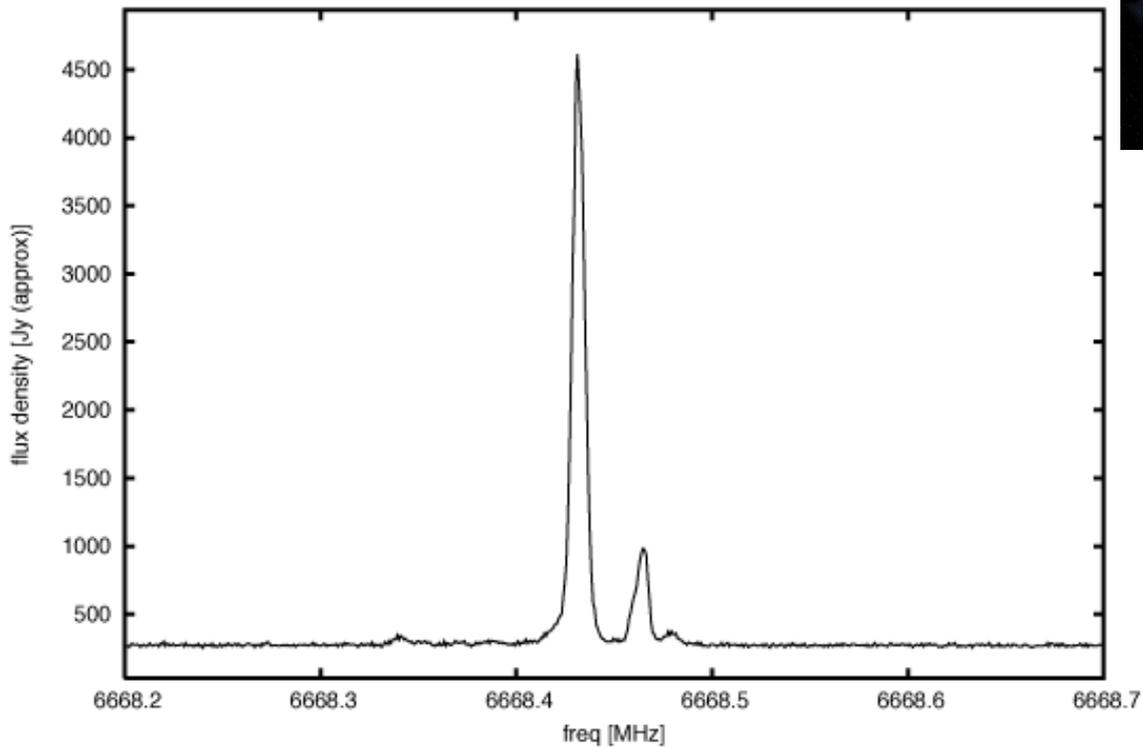
Figure 1.1: Cartoon illustrating the different components within the outflow, together with the temperature

# Masers

Further readings:

- Reid & Moran, 1981, ARAA, 19, 231-276
- Lo, 2005, ARAA, 43, 625-676

9.62+0.19 CH<sub>3</sub>OH 800 Hz resolution 19 seconds of data Pie Town 2011 Nov 22



# Masers

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Occur when LTE does not hold

First detected in the ISM in the '60s

**OH** (1965), **H<sub>2</sub>O** (1969), **CH<sub>3</sub>OH** (1970), **SiO** (1974)

[CH, H<sub>2</sub>CO, **NH<sub>3</sub>**, HCN]

Found in both *SFR* (best in HM objects) and *in evolved stars* (LPV and supergiants, OH/IR stars)

Also mega-masers (1982) are nowadays known

All have very small linear and angular size (maser spots, often broadened by interstellar scattering)

Transitions of the fine/hyperfine structure of **molecules**

→ trace (relatively) **cold (& dense) regions of the ISM**

# Masers

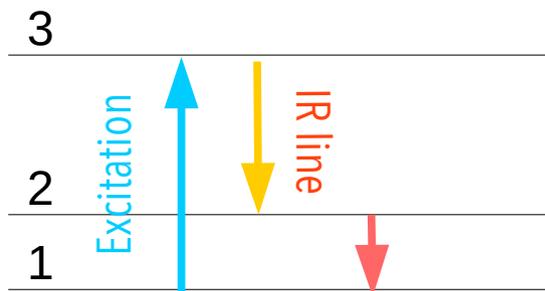
Trace a particular range of densities:  $n \sim 10^5 - 10^{11} \text{ cm}^{-3} \gg$  than in ISM even in GMC  
 $\Rightarrow$  Condensations in the ISM

A source of energy for the inversion of the population is necessary (**pumping**)

Different conditions/manifestations in SFR and in evolved stars

Interstellar masers: in SFR – associated with ultracompact HII regions,  $\text{H}_2\text{O}$  always present likely lasting for  $10^5$  years, OH not found in the largest condensations

Circum – stellar masers: in OH/IR associations (evolved stars)



Regardless its origin, the pumping works like aside  
A molecule is excited to 3, than it decays to 2 where  
 $A_{21}$  is very small, i.e. population inversion!!!

# Interstellar Masers

Molecule	Wavelength (cm)	n (cm <sup>-3</sup> )	T (K)
OH	18	10 <sup>5</sup> -10 <sup>7</sup>	100-200
H <sub>2</sub> O	1.35	10 <sup>7</sup> -10 <sup>9</sup>	300-1000
CH <sub>3</sub> OH	0.83	10 <sup>4</sup> -10 <sup>5</sup>	20-100
	4.49	10 <sup>4</sup> -10 <sup>5</sup>	20-100
SiO	0.35	10 <sup>9</sup> -10 <sup>10</sup>	700-1000
NH <sub>3</sub>	1.25	10 <sup>4</sup> -10 <sup>5</sup>	60-150
H <sub>2</sub> CO	6.3	10 <sup>4</sup> -10 <sup>5</sup>	20-40

## Masers: radiative transfer (from Reid & Moran 1981)

Standard radiative transfer equation:

$$\frac{dI}{dr} = -\kappa I + \varepsilon \quad \text{where}$$

$$\kappa = \frac{h\nu}{4\pi\Delta\nu} (n_1 - n_2) B_{21} \quad \varepsilon = \frac{h\nu}{4\pi\Delta\nu} n_2 A_{21}$$

At equilibrium, neglecting spontaneous emission and collisions...

$$n_2 - n_1 = (n_2 + n_1) \frac{\Delta R}{R} \frac{\Gamma}{\Gamma + 2B_{21}I(\Omega/4\pi)}$$

where  $\Gamma$  = rate of population redistribution throughout the pump cycle and  $R$  and  $\Delta R$  are sum and difference of the pump rates into masing levels,  $\Omega$  is the beam solid angle of the microwave emission.

Assuming  $\kappa, \varepsilon$  constant (i.e.  $\Gamma \gg 2B_{21}I(\Omega/4\pi)$ )

$$I(r) = I_0 e^{-\kappa r} + \frac{\varepsilon}{\kappa} (1 - e^{-\kappa r})$$

If the optical depth  $\tau = \kappa r$  is negative, then an exponential amplification occurs!

## Masers: radiative transfer (from Tools of Radio Astronomy, ALTERNATIVE to previous slide)

More appropriately:

$$\frac{dI}{dr} = -\kappa I + \varepsilon \quad \text{where}$$

$$\kappa = \frac{h\nu}{4\pi\Delta\nu} (n_1 B_{12} - n_2 B_{21}) \quad \varepsilon = \frac{h\nu}{4\pi\Delta\nu} n_2 A_{21}$$


At equilibrium, neglecting spontaneous emission and collisions...

$$n_2 - n_1 = (n_2 + n_1) \frac{\Delta R}{R} \frac{\Gamma}{\Gamma + 2[B_{12} - B_{21}]I(\Omega/4\pi)}$$

where  $\Gamma$  = rate of population redistribution throughout the pump cycle and  $R$  and  $\Delta R$  are sum and difference of the pump rates into masing levels,  $\Omega$  is the beam solid angle of the microwave emission.

Assuming  $\kappa, \varepsilon$  constant (i.e.  $\Gamma \gg 2[B_{12} - B_{21}]I(\Omega/4\pi)$ )

$$I(r) = I_0 e^{-\kappa r} + \frac{\varepsilon}{\kappa} (1 - e^{-\kappa r})$$

If the optical depth  $\tau = \kappa r$  is negative, then an exponential amplification occurs!

## Masers: radiative transfer

Standard radiative transfer equation:

$$I(r) = I_0 e^{-\kappa r} + \frac{\epsilon}{\kappa} (1 - e^{-\kappa r})$$

can be rewritten in terms of temperature

$$T_B(r) = (T_{B_0} - T_x) e^{-\kappa r} + T_x$$

where  $T_x$  is the excitation temperature:

$$\frac{n_2}{n_1} = e^{-h\nu/kT_x}$$

$T_x$  is  $< 0$  for population inversion

The population inversion is reduced by  $B_{21}$  when  $2B_{21}/\Omega/4\pi > \Gamma$

under this condition the maser is **saturated** and this occurs when

$$T_s = \frac{h\nu}{2k} \frac{\Gamma}{A_{21}} \frac{4\pi}{\Omega}$$

### Unsaturated maser:

small changes in the pump ( $\kappa$ ) result in dramatic changes in the emission  $\approx e^{\kappa r}$

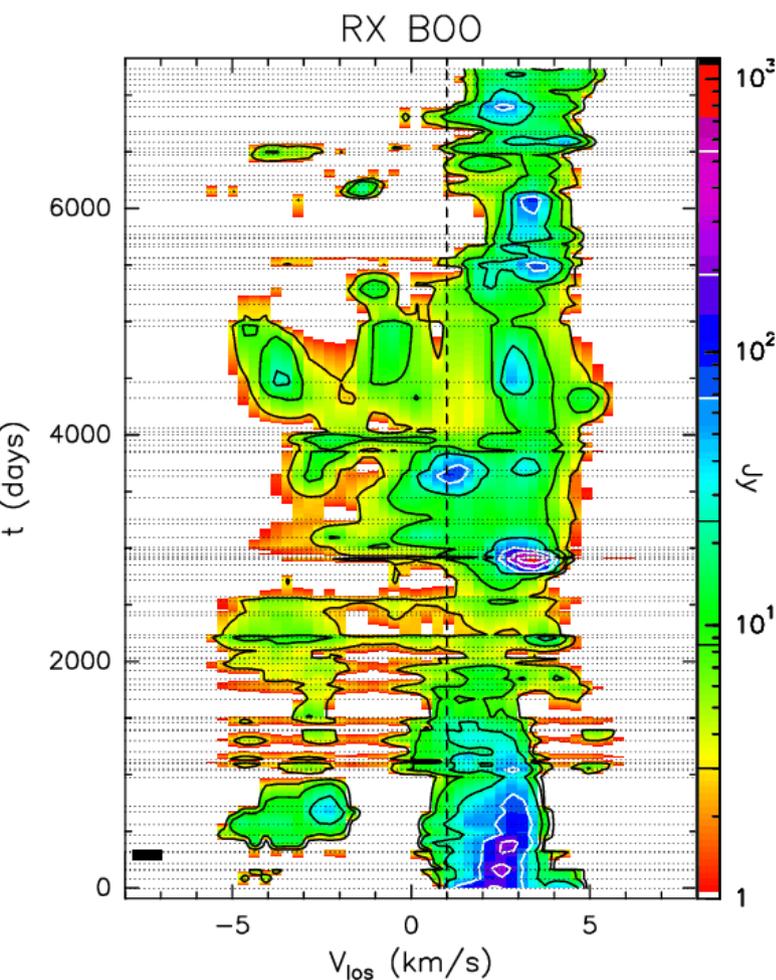
### Saturated maser:

changes are proportional to  $\kappa r$  less sensitive indicator of pump variations

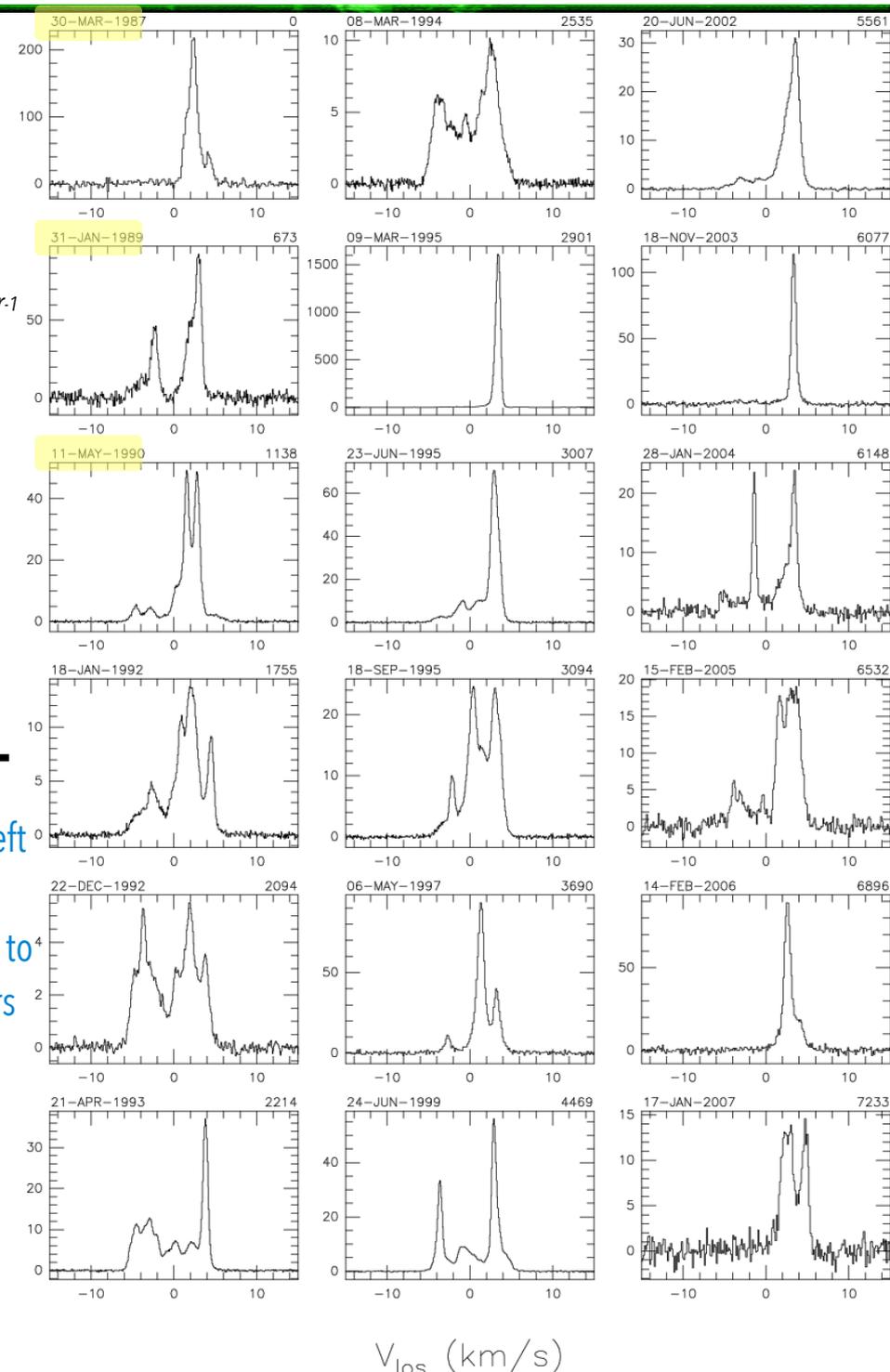
# Interstellar Masers

Water maser: **variability** in RX Boo as observed with the 32m dish in Medicina (Winnberg et al. 2008)

RX Boo is a 9-11 mag SRV with a mean spectral type of M 7.5 and a period varying between 340 and 400 days (Kukarkin et al. 1971). Olofsson et al. (2002) in their model fit involving several CO transitions estimated a mass-loss rate of  $6 \cdot 10^{-7} \text{ Msun yr}^{-1}$  and an expansion velocity of  $9.3 \text{ km s}^{-1}$ , whereas Teysier et al. (2006), as a result of another model fit, obtained  $2 \cdot 10^{-7} \text{ Msun yr}^{-1}$  and  $7.5 \text{ km s}^{-1}$ , respectively

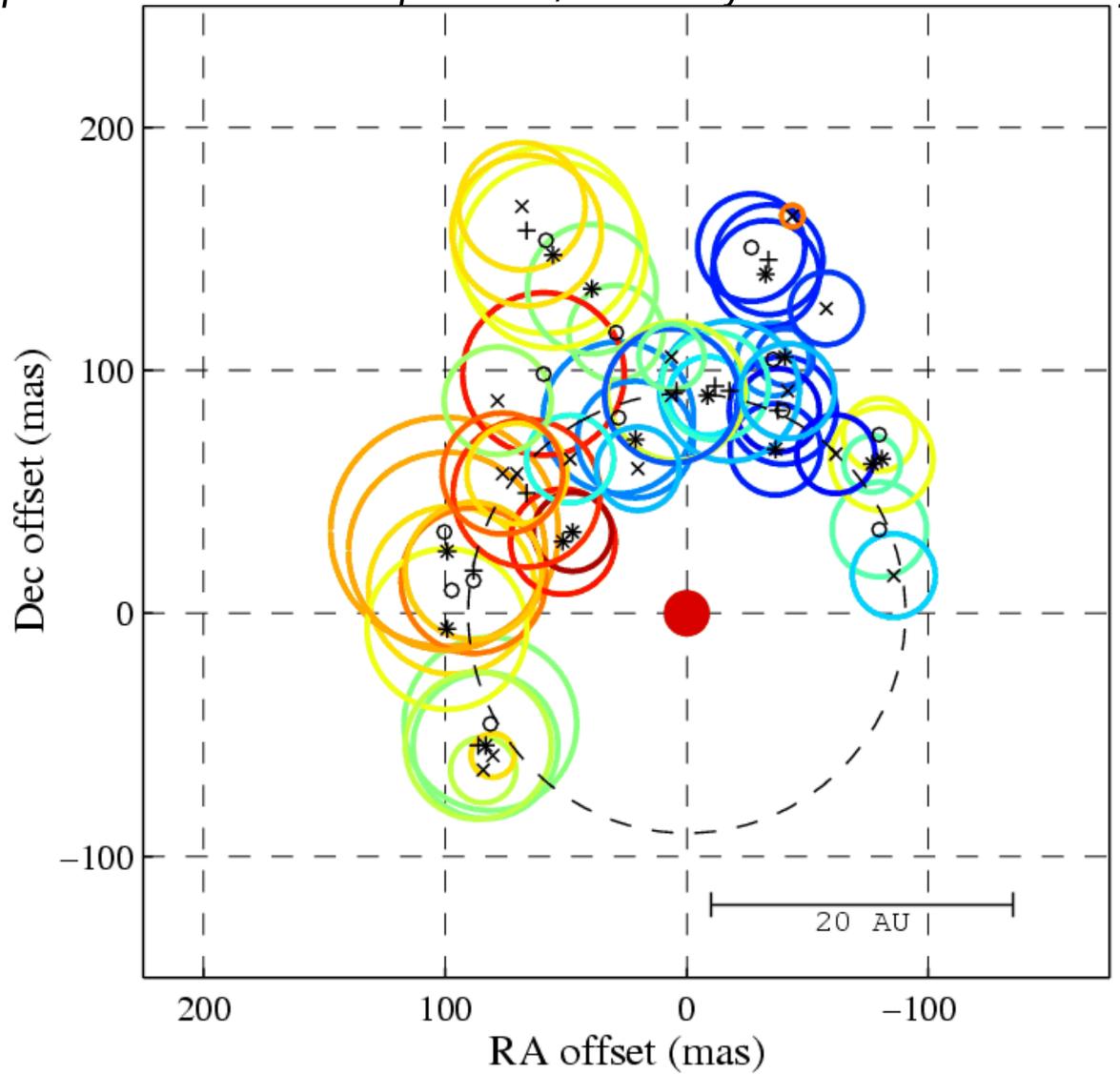


Each spectrum (right) is a line in the figure on the left (dotted horizontal lines). Times are then smoothed to obtain what we see. Colors represent line intensity



# Interstellar Masers

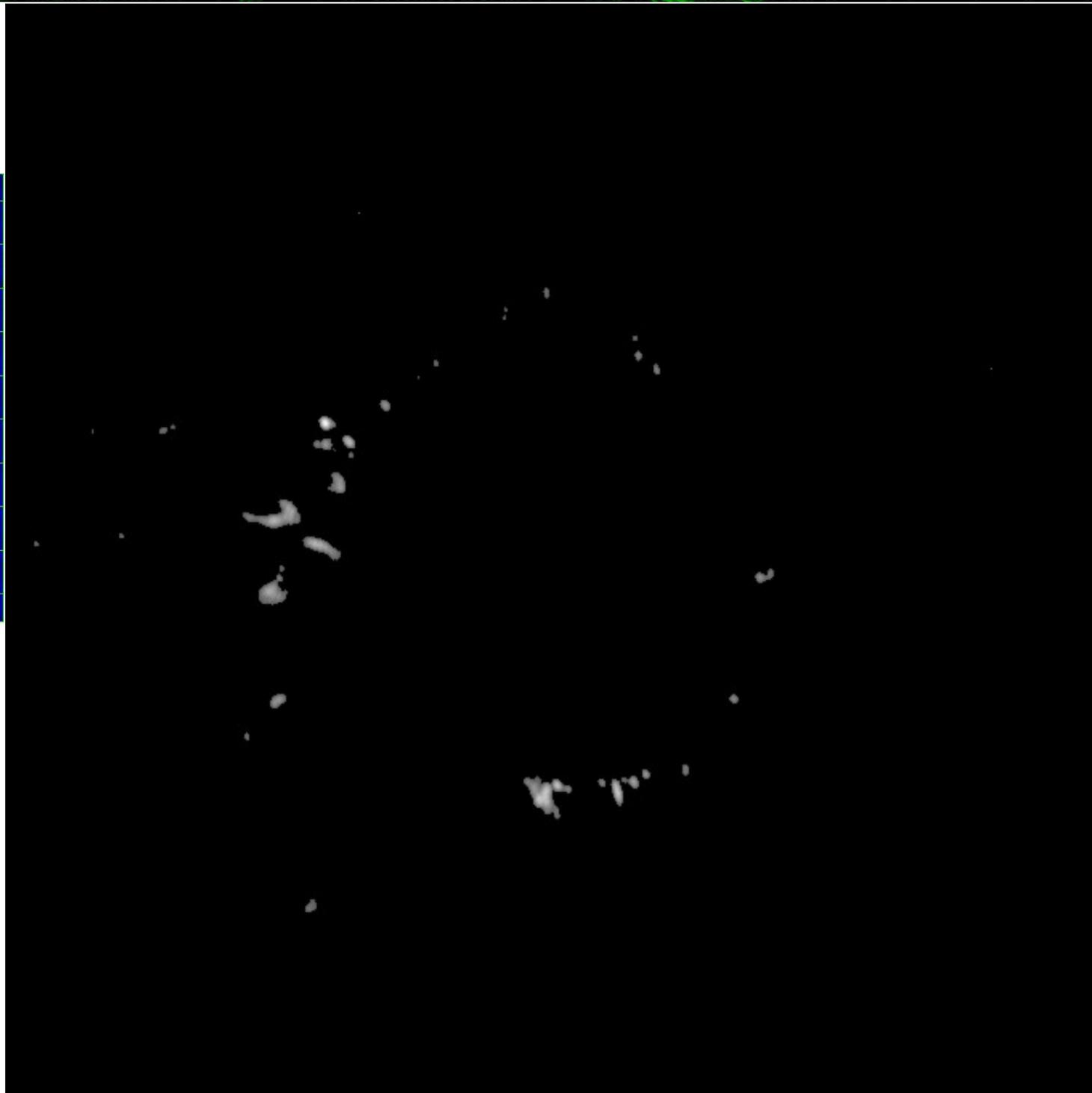
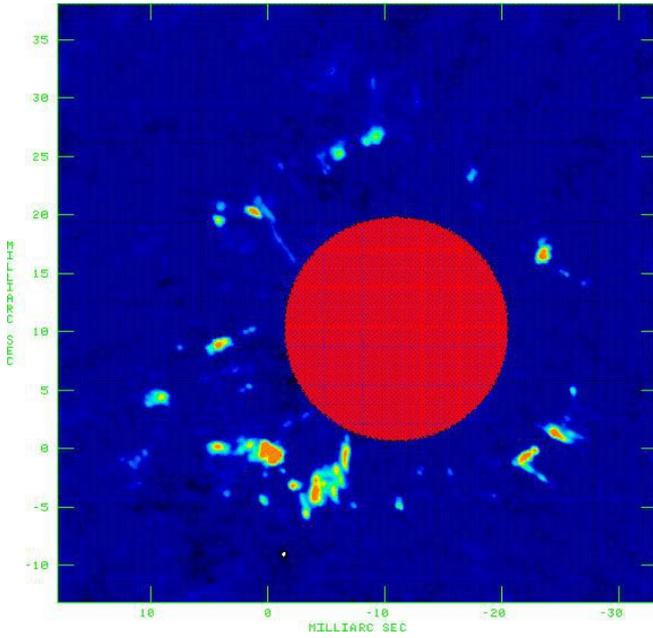
*RX Boo: maser spots as a function of position, intensity and relative velocity*



-5 -4 -3 -2 -1 0 1 2 3 4 5 6  
Line-of-sight velocity (km/s)

# Interstellar Masers

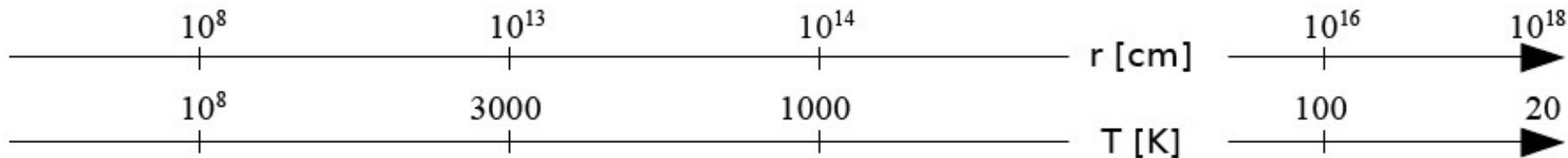
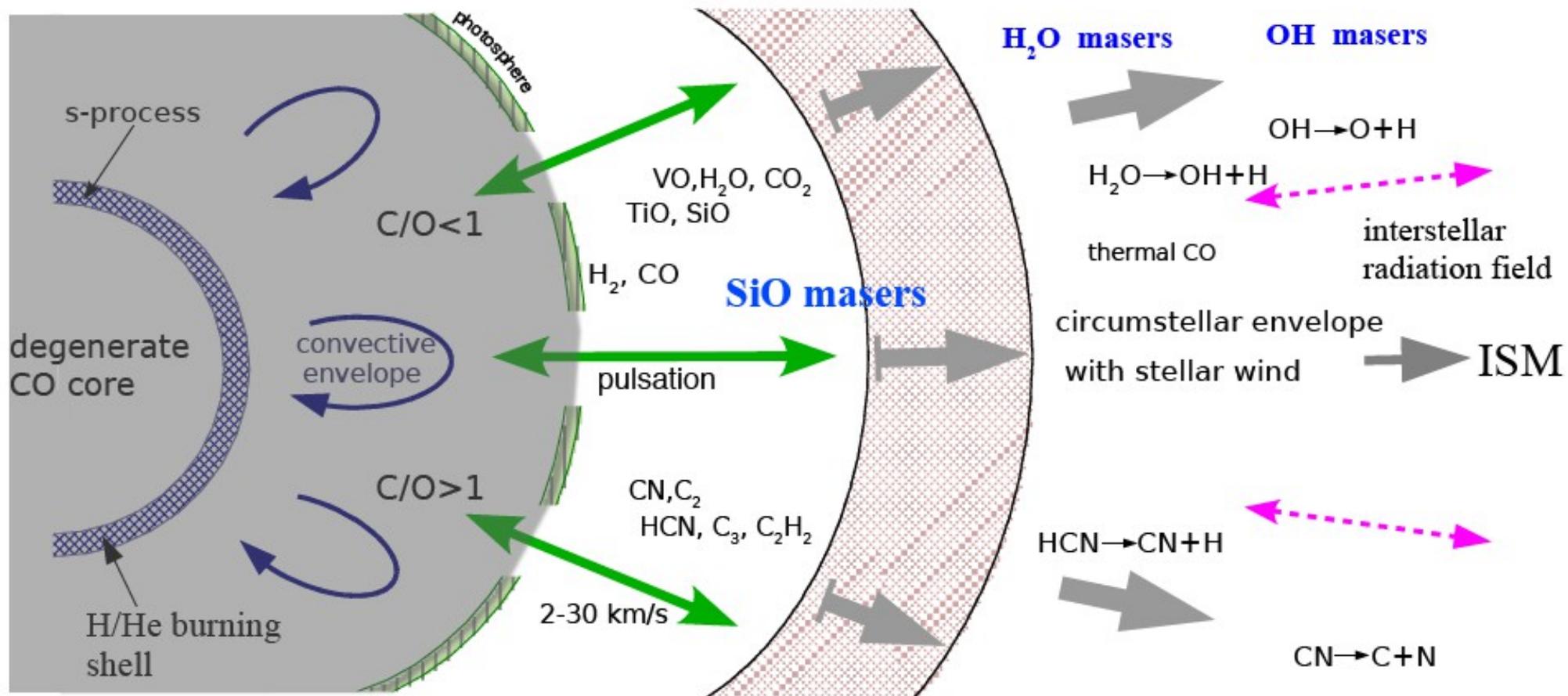
*TX Cam: VLBA movie*



# STAR

## molecule formation dust formation

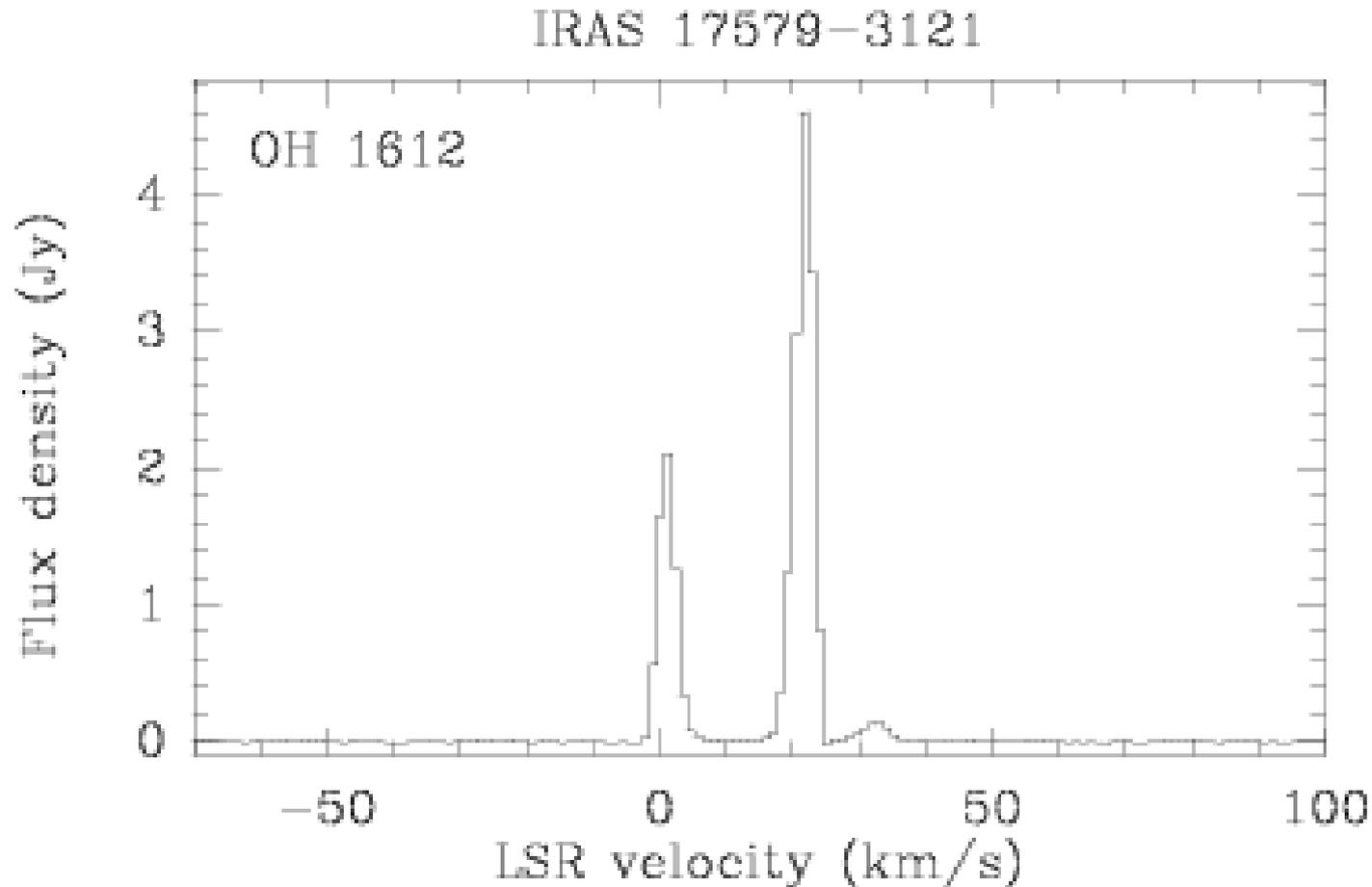
## photochemical reactions



# Interstellar Masers

Variability: red .vs. blue

Delay helps in determining the size of the envelope  $D = c \Delta t$



VLBI measures the angular size, and then the **distance** is obtained!



## Interstellar Masers.... and beyond

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Typical luminosities reach about 1 (a few)  $L_{SUN}$  at maximum

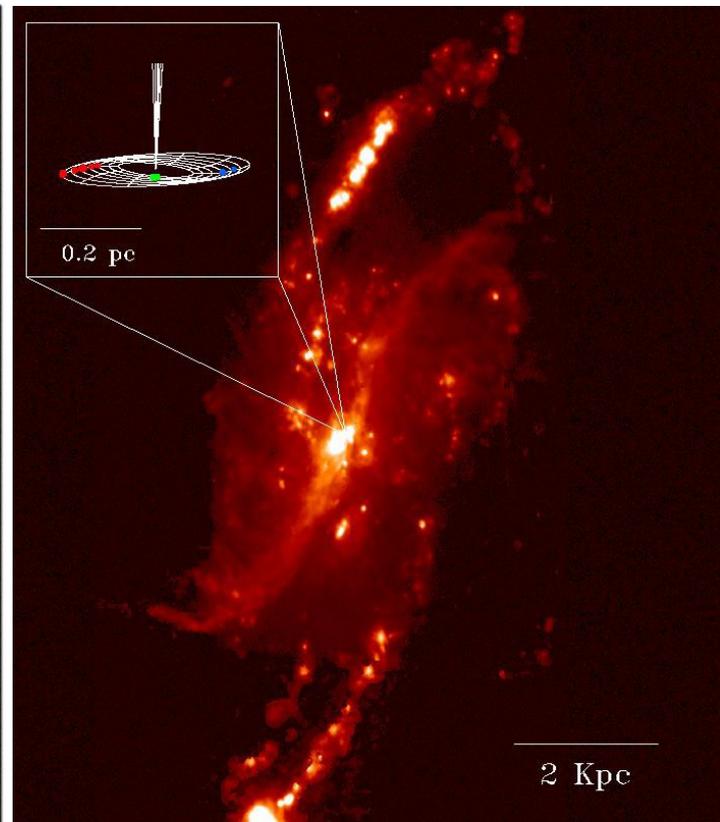
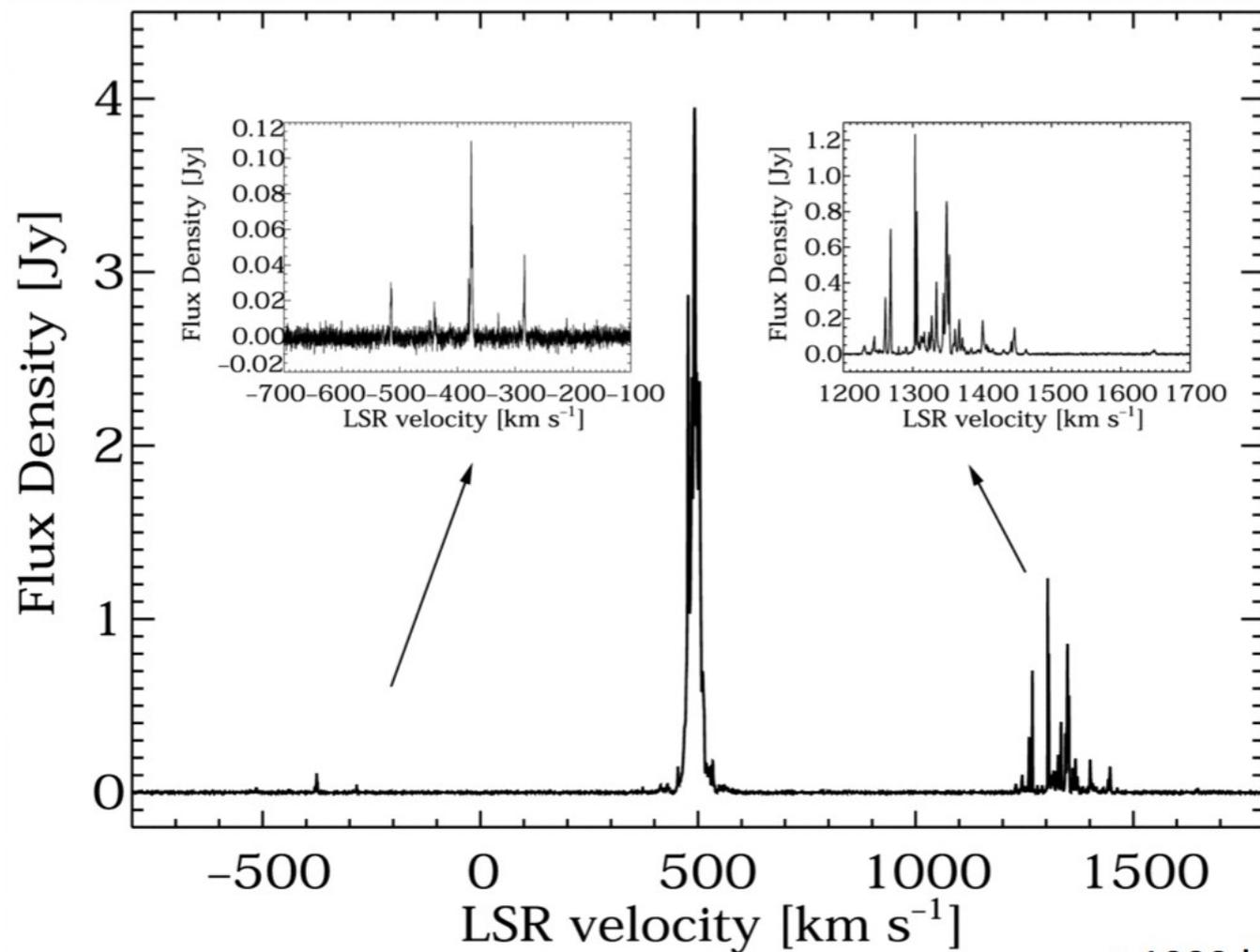
Masers (**OH** and **H<sub>2</sub>O**) have been detected in external galaxies up to  
 $z=0.265$  (1.3 Gpc) and  $z=0.66$  (4 Gpc) respectively

Their luminosities reach  $10^6$  times those of galactic masers and are then termed **MEGAMASERS**

**OH**: found in the central 100 pc of **ULIRGs**, i.e. (nuclear) star bursting galaxies

**H<sub>2</sub>O**: found within parsecs in **AGNs** (Sy2, Liners, ellipticals)

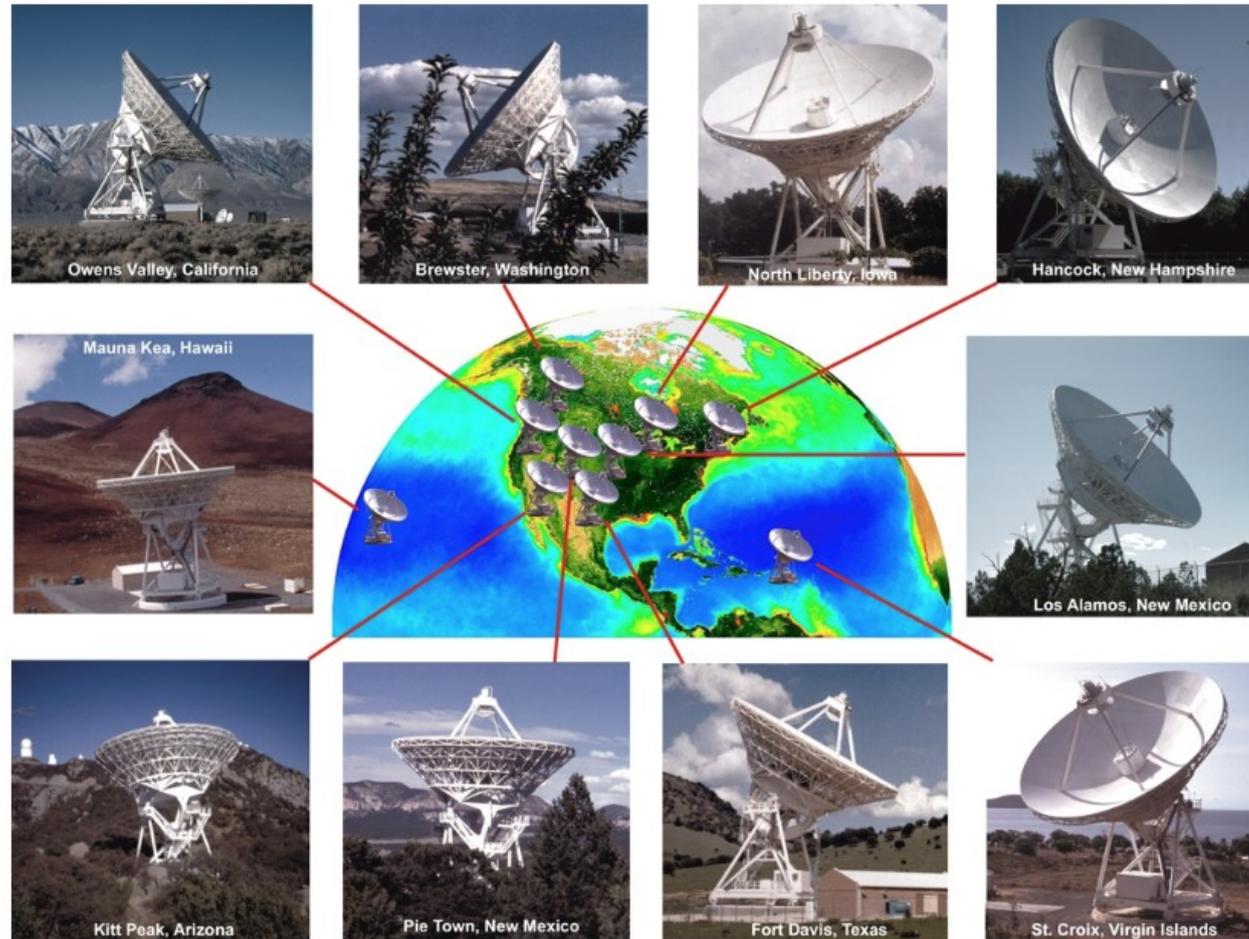
## Strong nuclear water maser at 22 GHz



Single dish  
Observation

$v_{\text{sys}} \pm 1000 \text{ km s}^{-1}$   
GBT (Modjaz et al. 2005)

## VLBA imaging and spectroscopy of NGC 4258

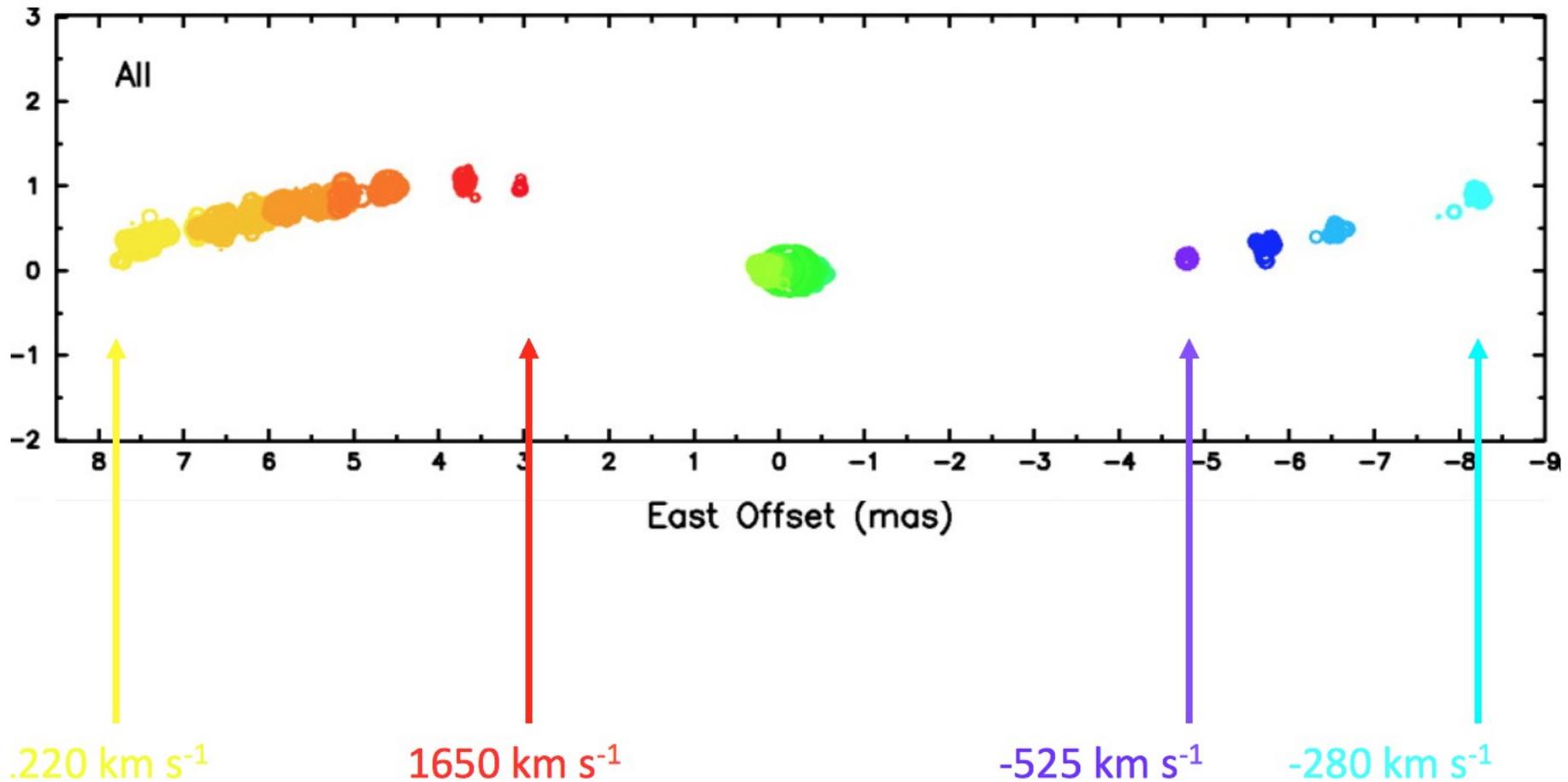


VLBA: Angular resolution =  $200 \mu\text{as}$  ( $0.006 \text{ pc}$  at  $\sim 7.0 \text{ Mpc}$ )

Spectral resolution  $< 1 \text{ kms}^{-1}$

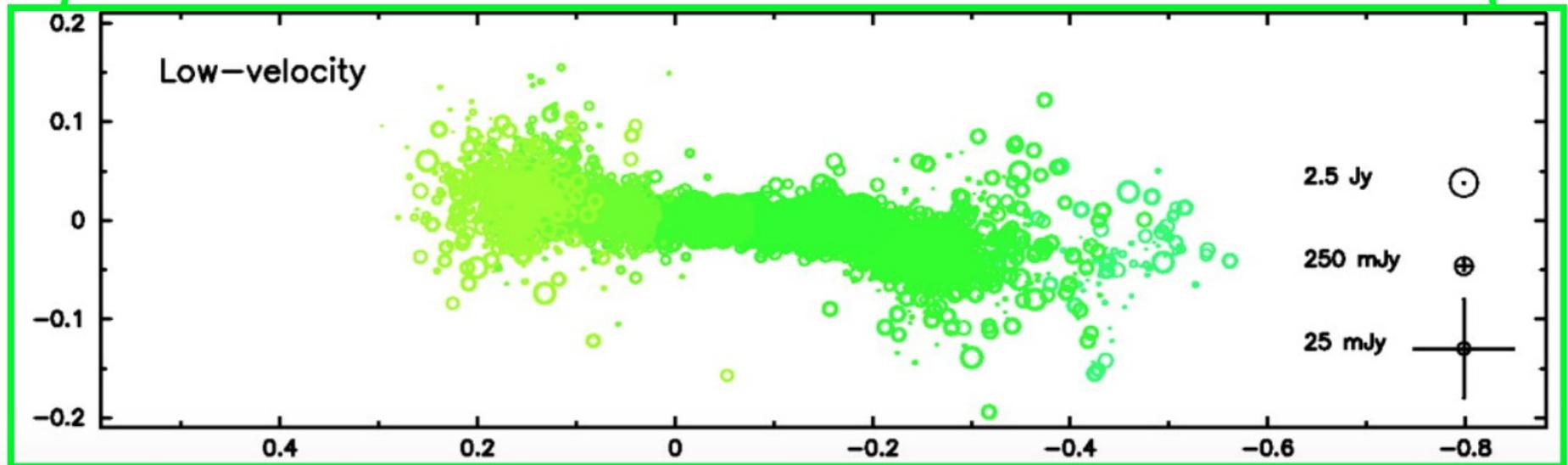
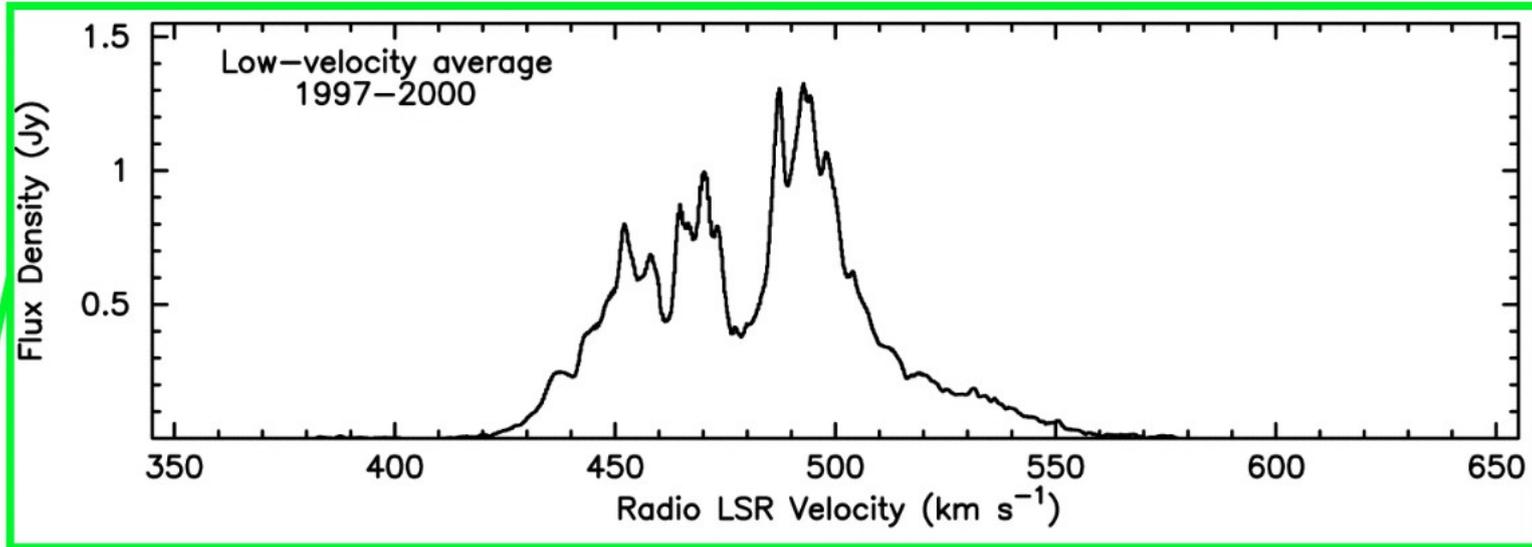
## This Dataset: 18 epochs

1 mas @ 7.2 Mpc  $\rightarrow$  0.04 pc

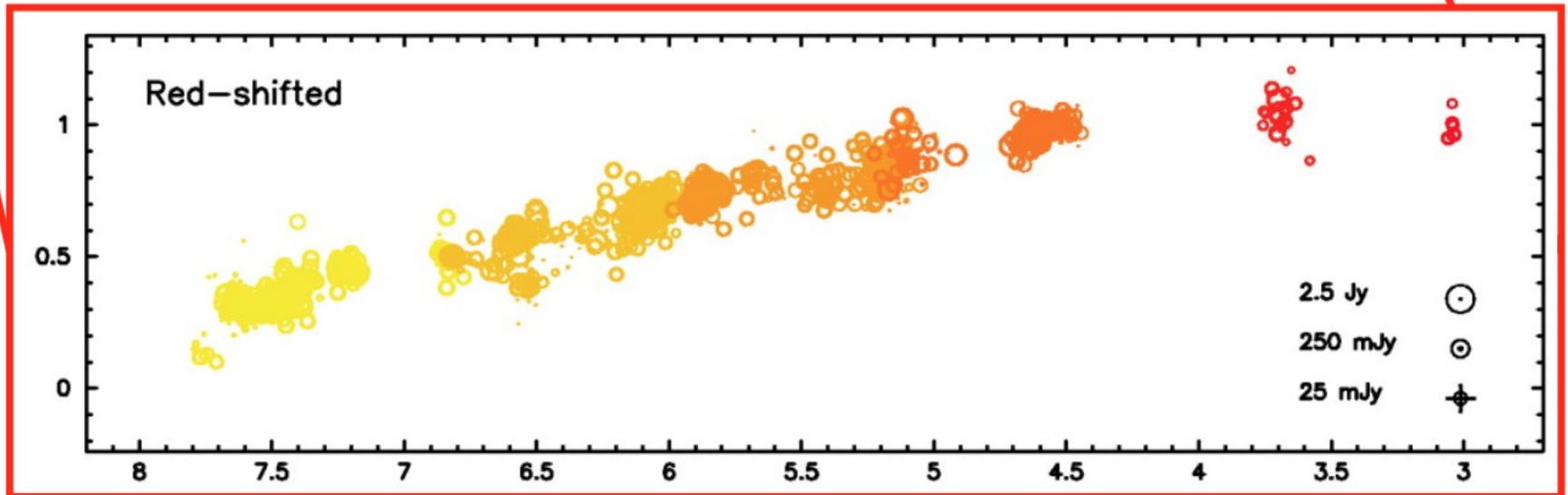
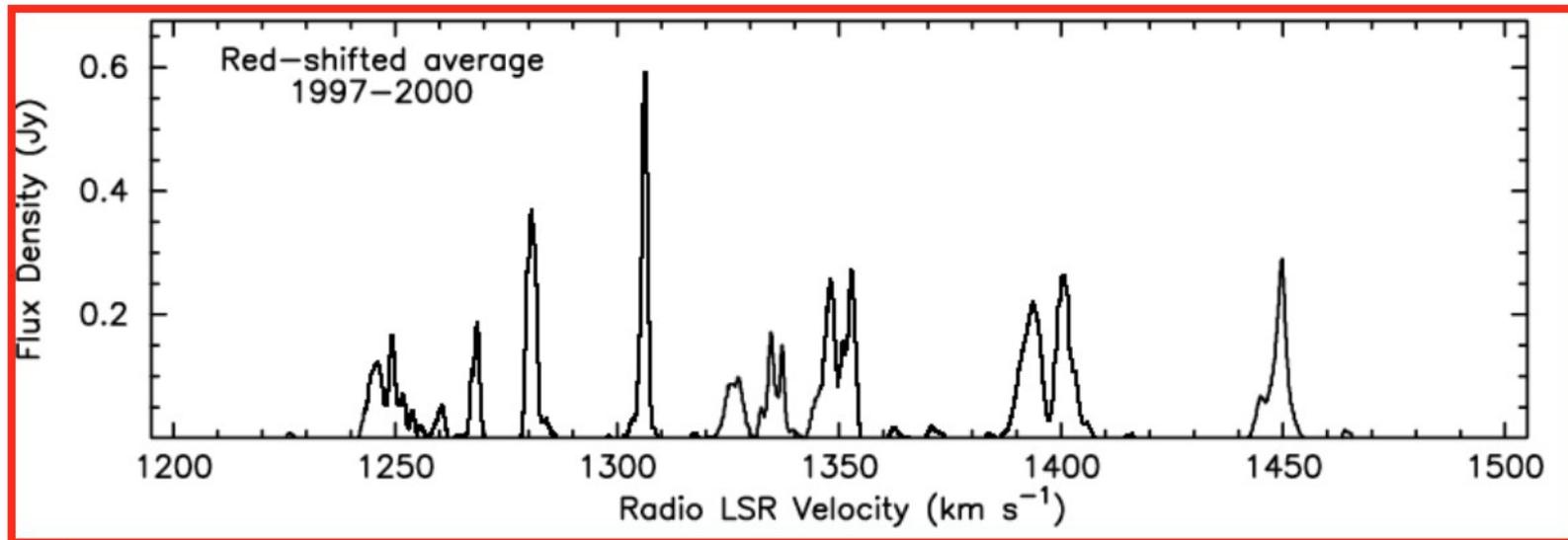


Argon, Greenhill, Reid, Moran & Humphreys (2007)  
VLBA + VLA + EFLS

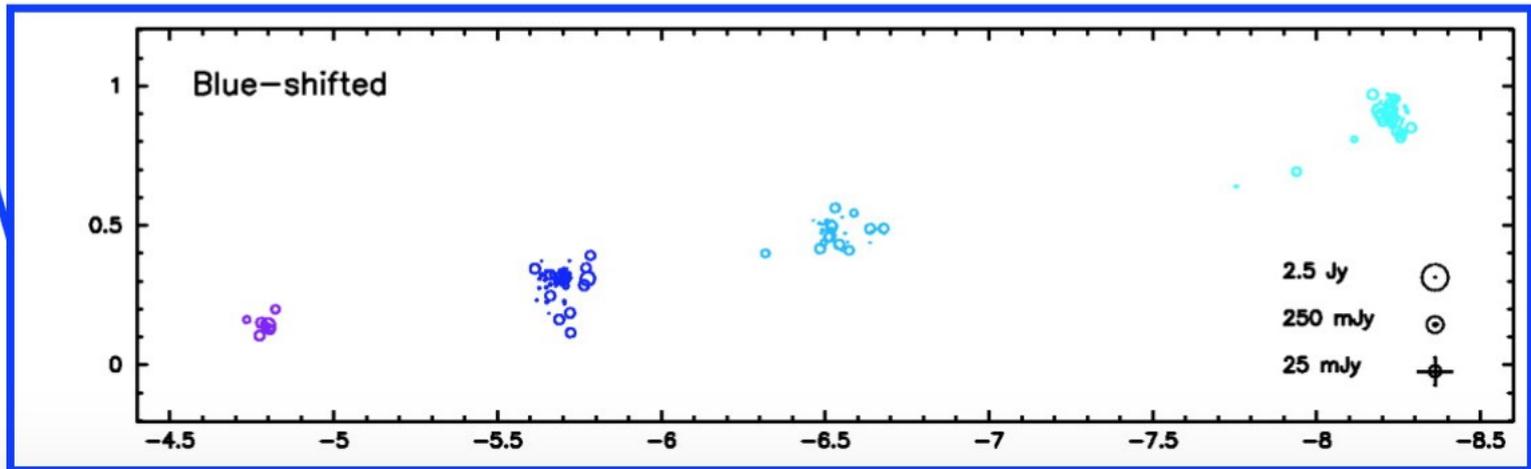
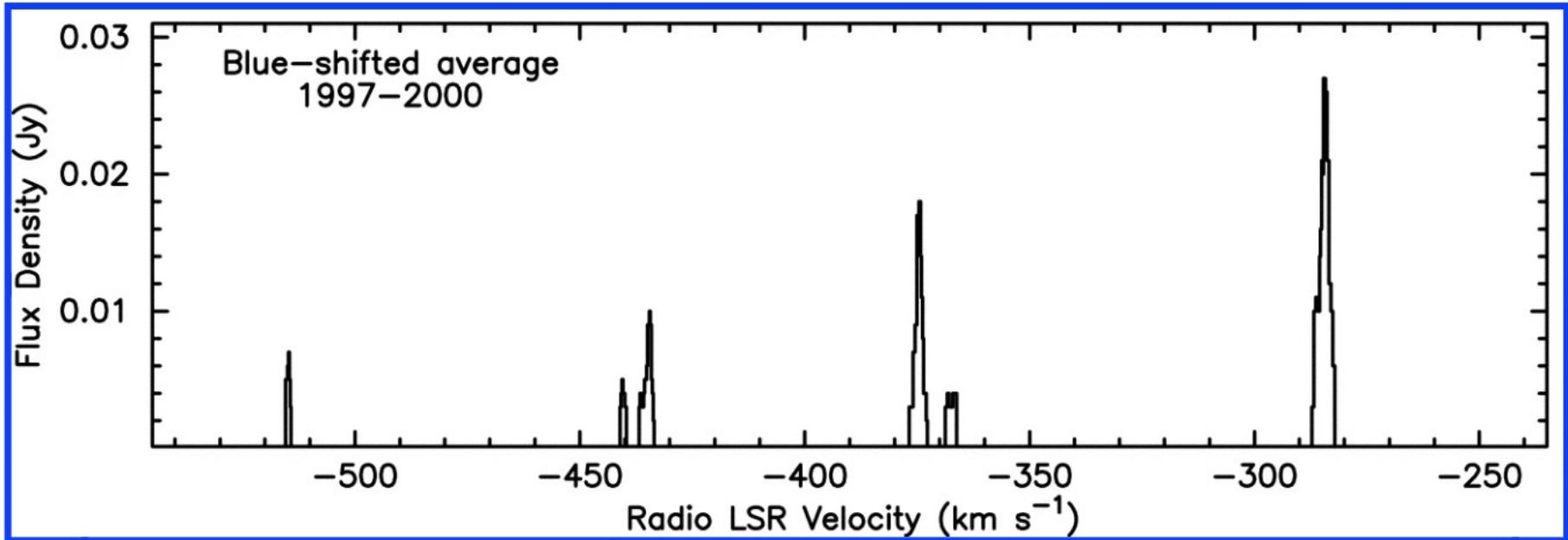
# Systemic Maser Emission



## Red-shifted emission



# Blue-shifted Emission



# Megamasers: NGC4258

## VLBA imaging and spectroscopy

- individual masers resolved and  $v_{\text{rad}}$  assigned to individual components
- objects in front of AGN have  $v_{\text{rad}} \sim 470$  km/s (systemic velocity)  
the inclination angle relative to AGN is  $i \sim 82^\circ$
- objects at the edges have  $v_{\text{rad}} \sim 470 \pm 1000$  km/s ( - blue and + red shifted)
- a rotating Keplerian disk provides a perfect fit to each individually observed components of the three radial velocity systems with an accuracy better than 1%

BH mass  $\sim 4.0 \pm 0.1 \cdot 10^7 M_{\text{SUN}}$

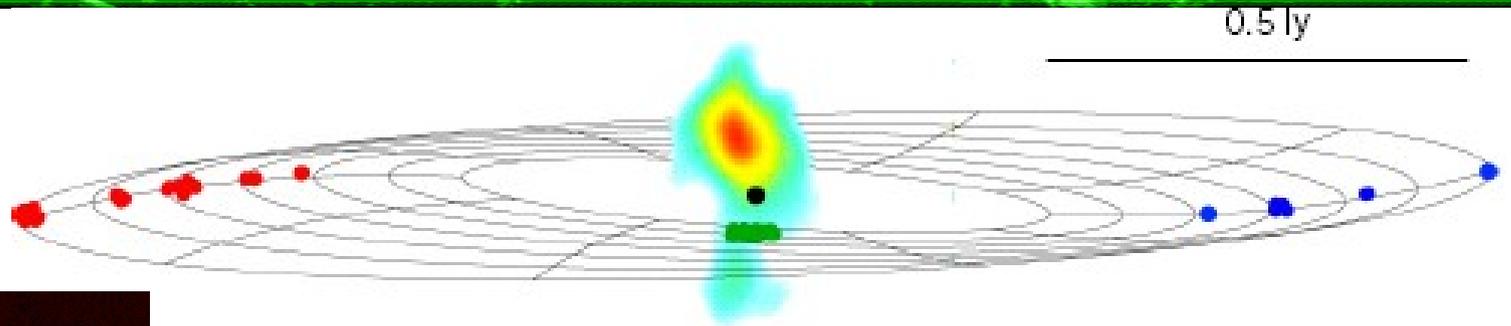
Distance  $\sim 7.6 \pm 0.3$  Mpc

For details on Megamaser modelling and explanation on geometry, see:

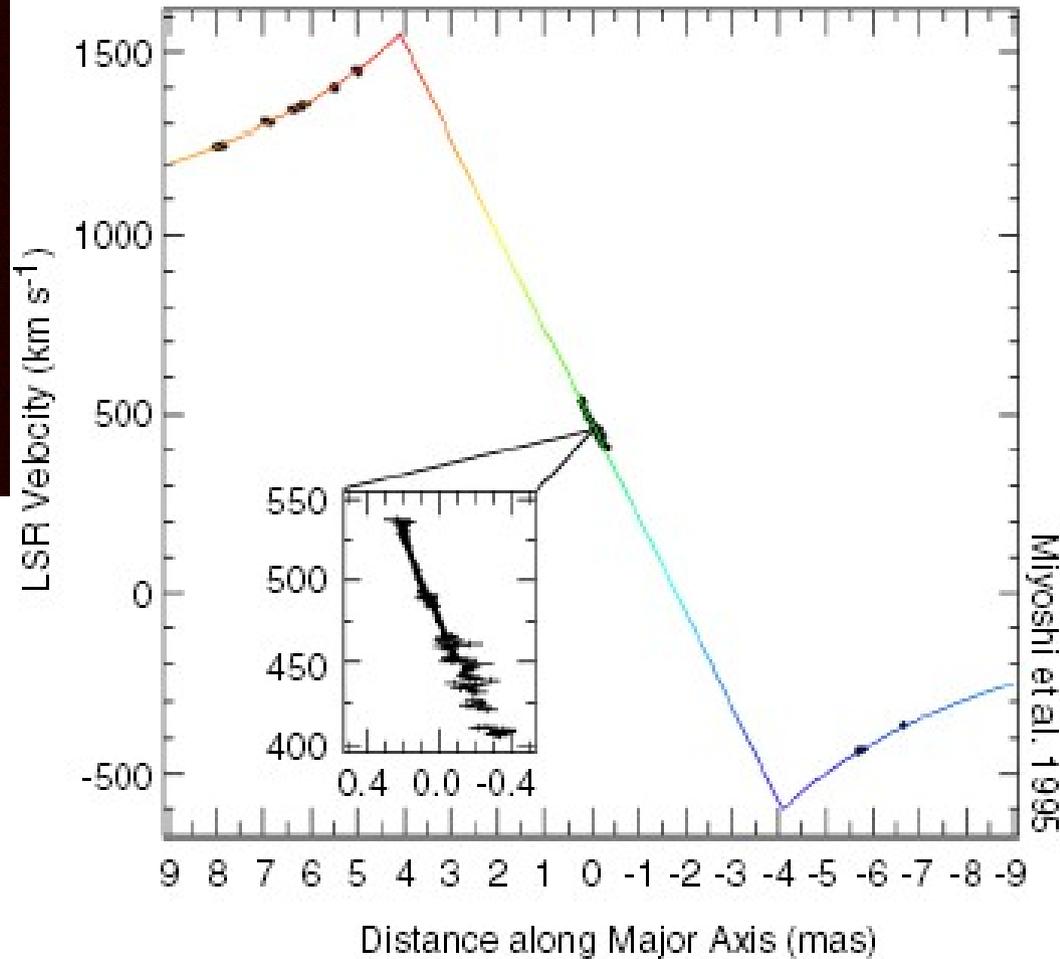
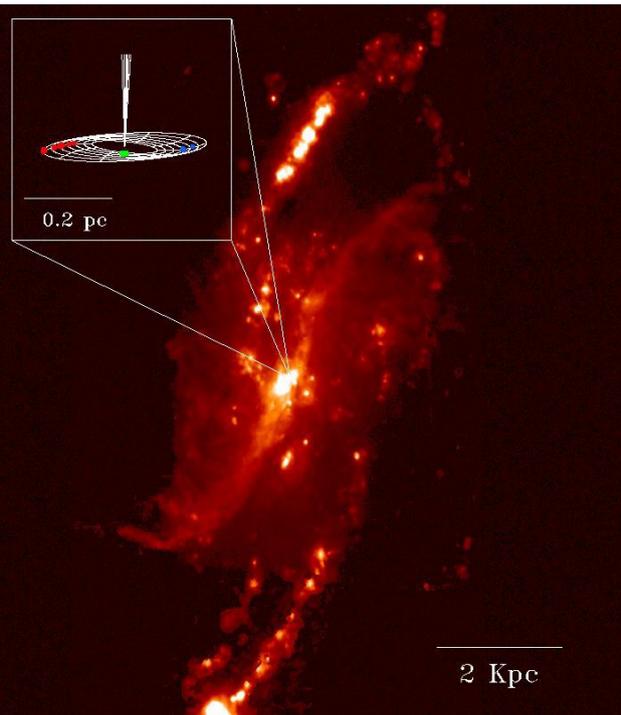
[http://www.ifa.hawaii.edu/users/kud/teaching\\_15/12\\_Megamasers.pdf](http://www.ifa.hawaii.edu/users/kud/teaching_15/12_Megamasers.pdf)

# Megamasers: NGC4258

black hole mass  $4.0 \pm 0.1 10^7 M_{SUN}$



Based on Herrnstein, Greenhill et al. 1998

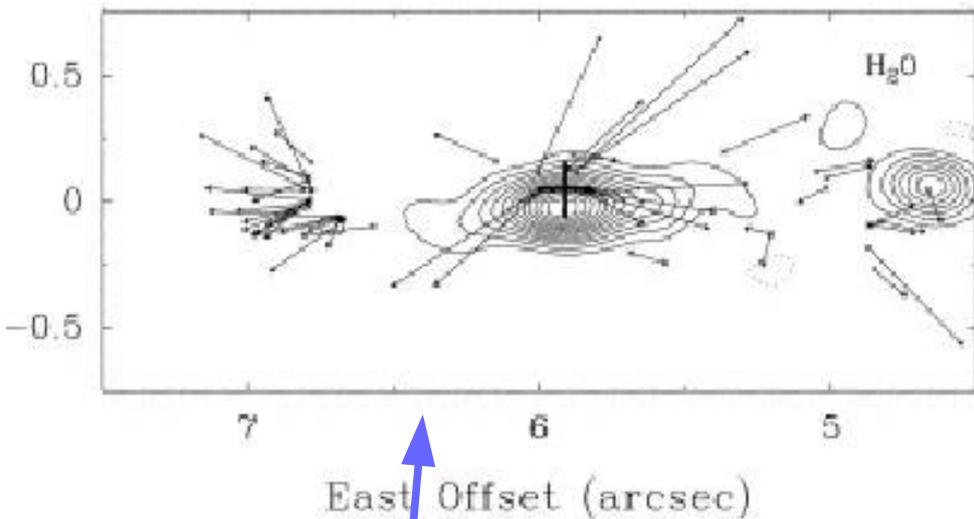


Arrangement : Greenhill

# Interstellar Masers... and beyond

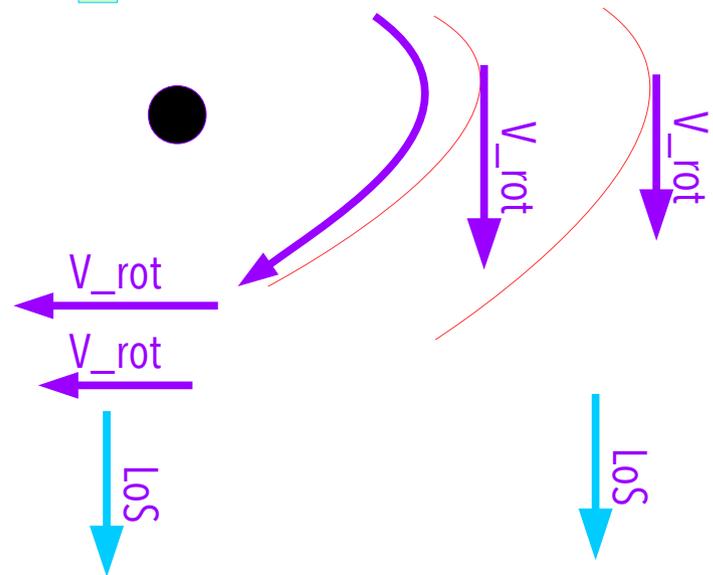
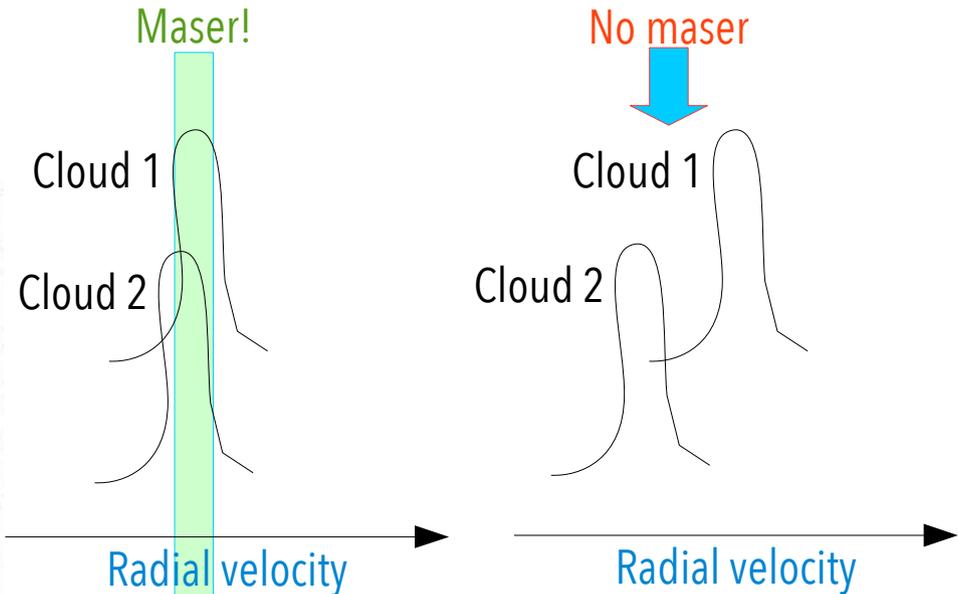
Pumping: Even in case of population inversion, we need that.....

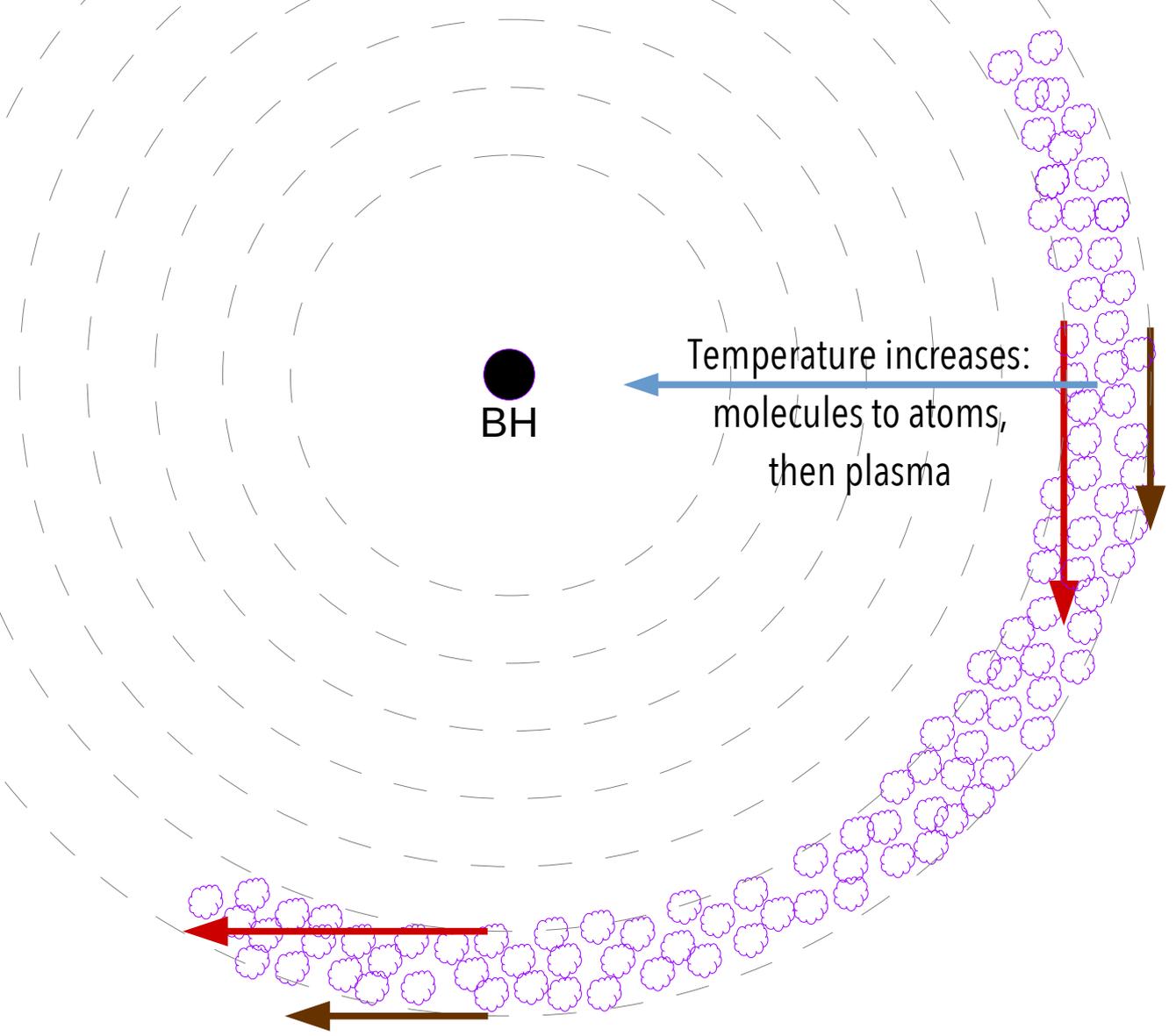
There is "velocity coherence"  $\Rightarrow$  i.e. Masing molecules must be at the same radial velocity within the thermal width along the gain path



Pumping (2)

- Radiative
- Collisional





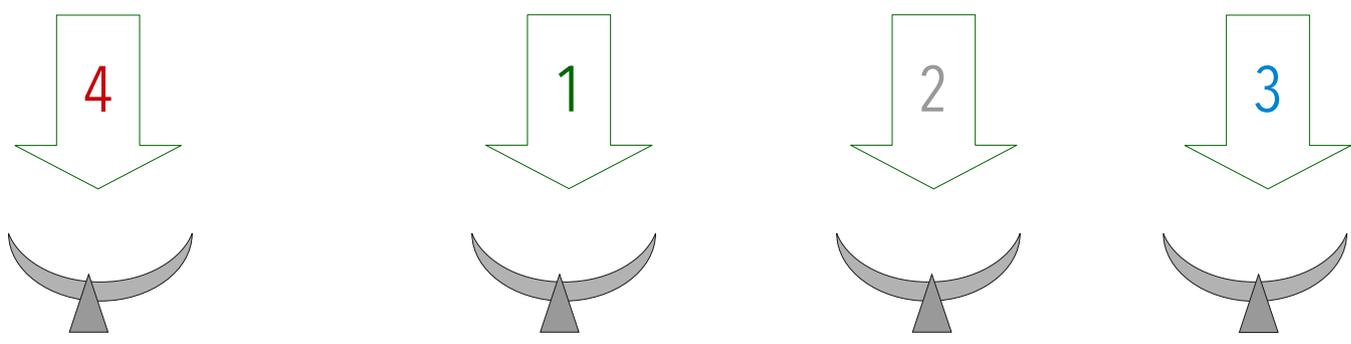
Masing clump

LoS 1: Clumps do not have radial velocities, and ALL the clouds participate to amplification, which is VERY EFFECTIVE  
Emission at the SYSTEMIC VELOCITY

LoS 2: Clumps have different radial velocities, and amplification can occur within each clump only.  
NO significant emission

LoS 3: There are MANY clumps aligned within the same LoS, BUT amplification works only for a few clumps with similar radial velocities  
Emission is BLUESHIFTED

Los 4: The same as Los 3, but the Emission is REDSHIFTED



## Maser & MegaMasers: Summary

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- Trace “clumps” of cold material (molecules)
- Amplification of incoming radiation in conditions of inversion (w.r.t. LTE) of level population
- “Pumping” is required
- Narrow features, very sensitive to Doppler effects, excellent kinematic probes
- Geometry is very important!
- Interstellar/Circumstellar Masers in SFR/Evolved stars (OH/IR)
- Megamasers in accretion disks around edge on AGNs
- Variability on short timescales