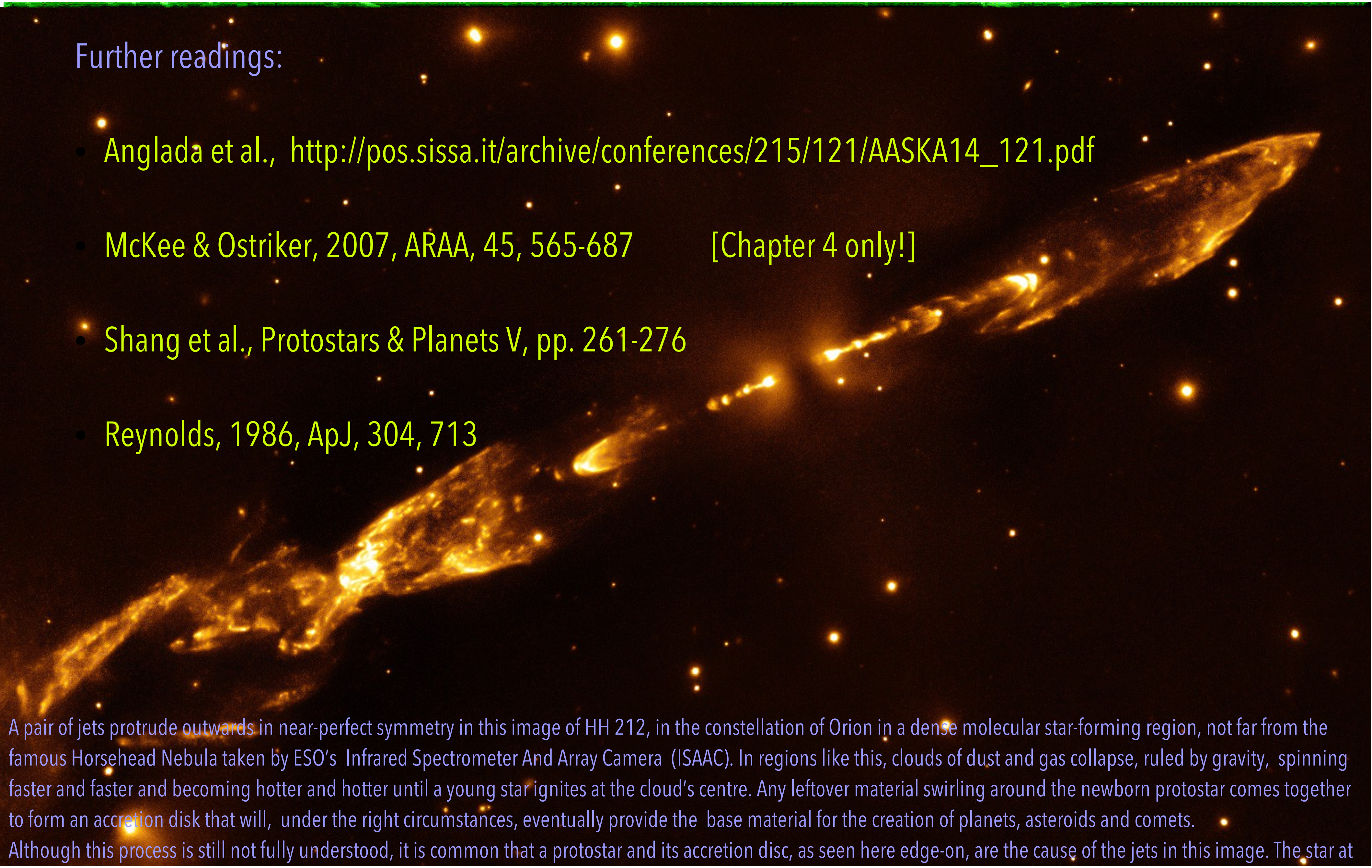
Young Stellar Objects in Star Forming Regions

Further readings:

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



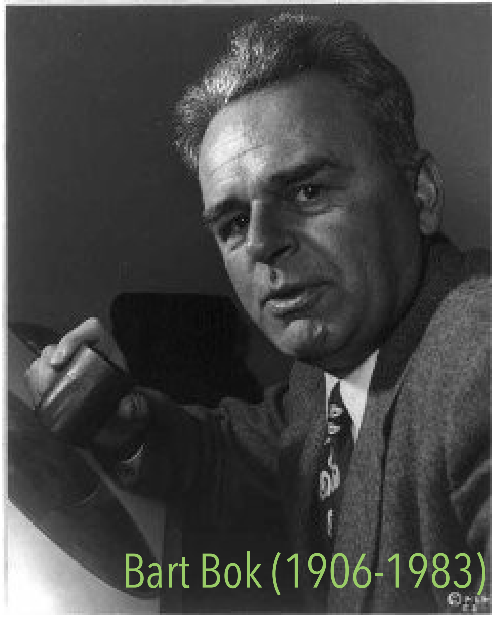
A pair of jets protrude outwards in near-perfect symmetry in this image of HH 212, in the constellation of Orion in a dense molecular star-forming region, not far from the famous Horsehead Nebula taken by ESO's Infrared Spectrometer And Array Camera (ISAAC). In regions like this, clouds of dust and gas 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


Bart Bok (1906-1983)

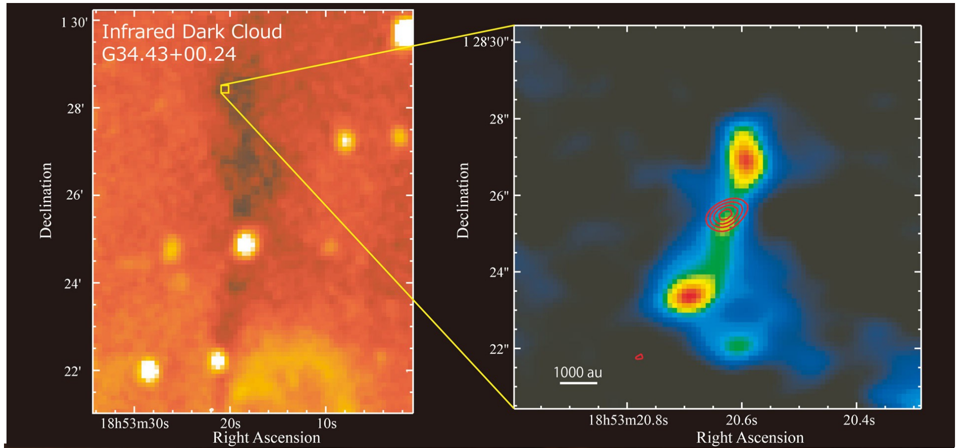
Star forming regions

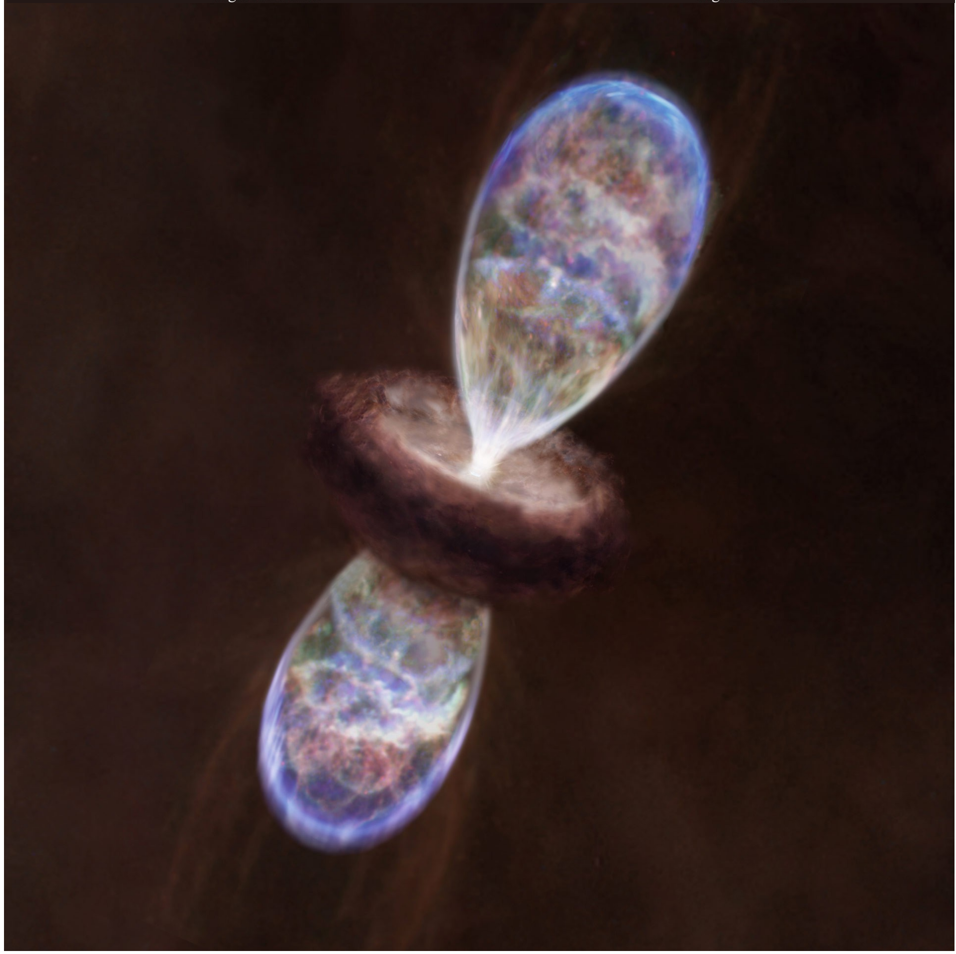
Ingredients:

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**

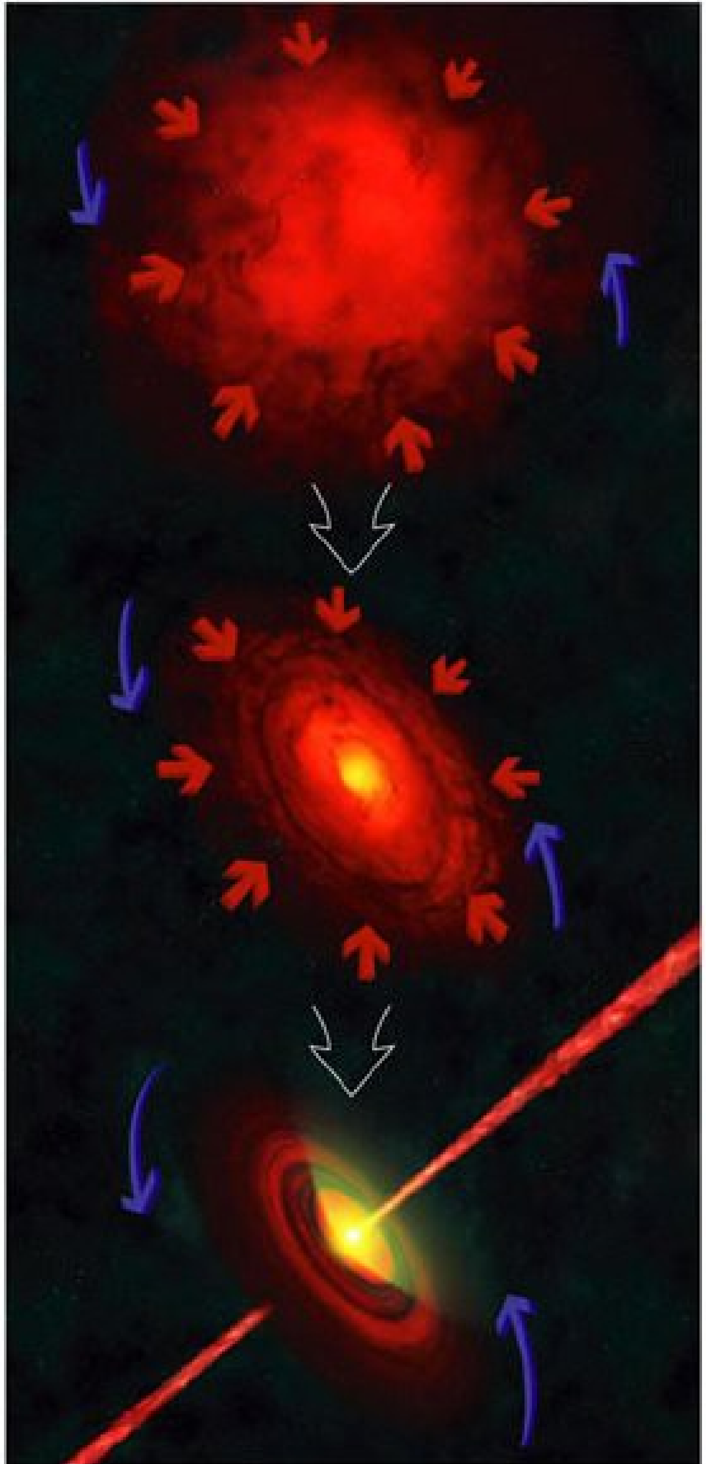
Gravitational collapse takes place if the size of the cloud exceeds the Jeans' Length J_L

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

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

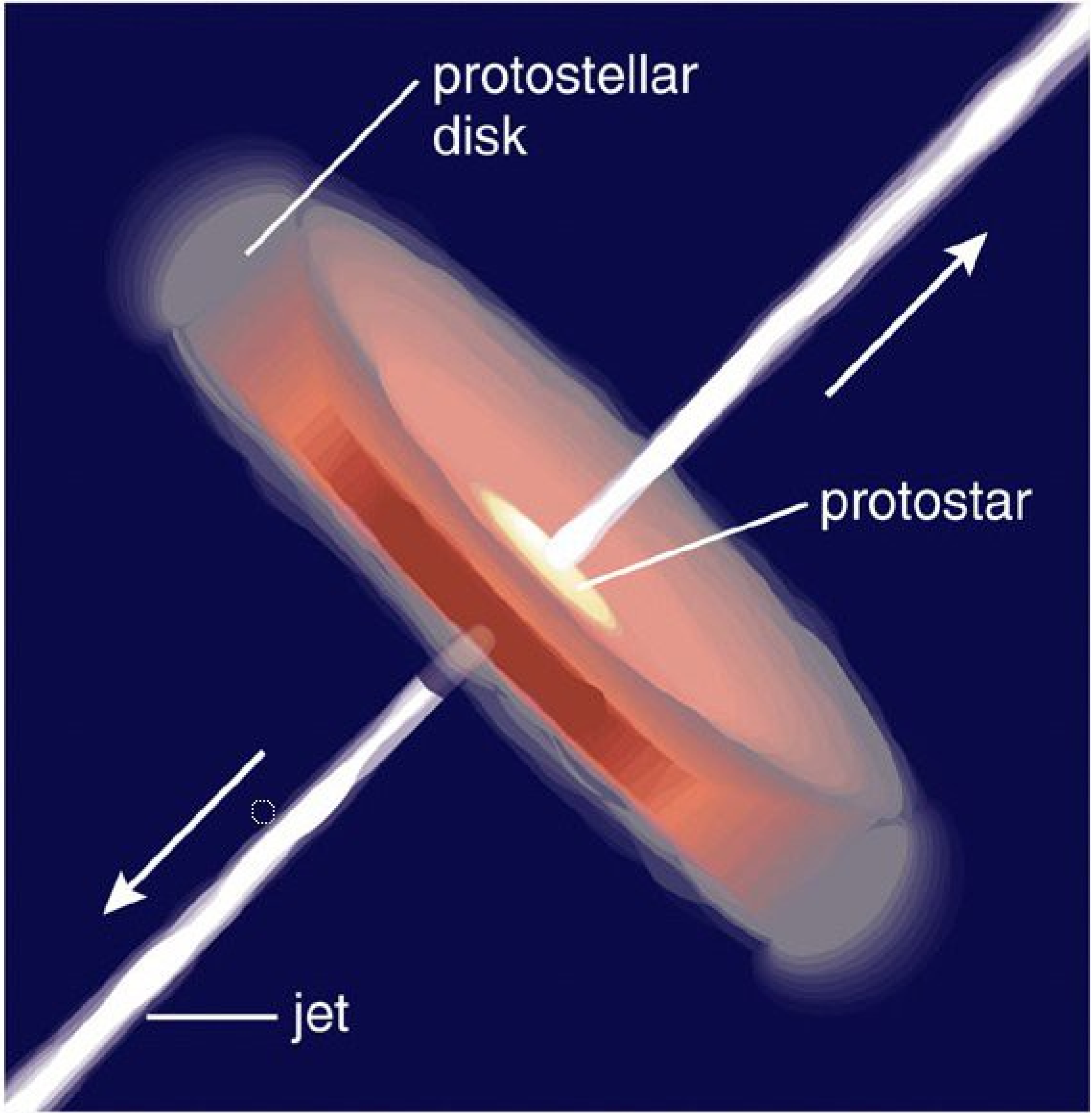
At a given point, feedback from the protostar may inject further perturbations into the GMC

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

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

⇒ 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

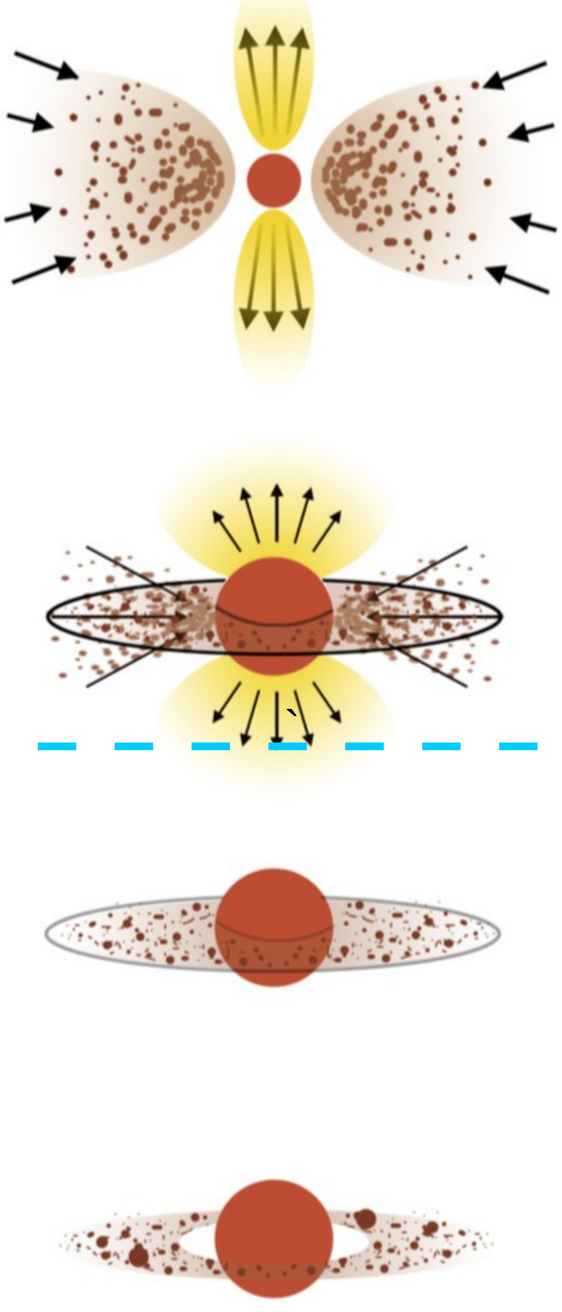
Class 0:
Main Acceleration phase?
Age≤10^5 years
M~0.5 $M_\odot$

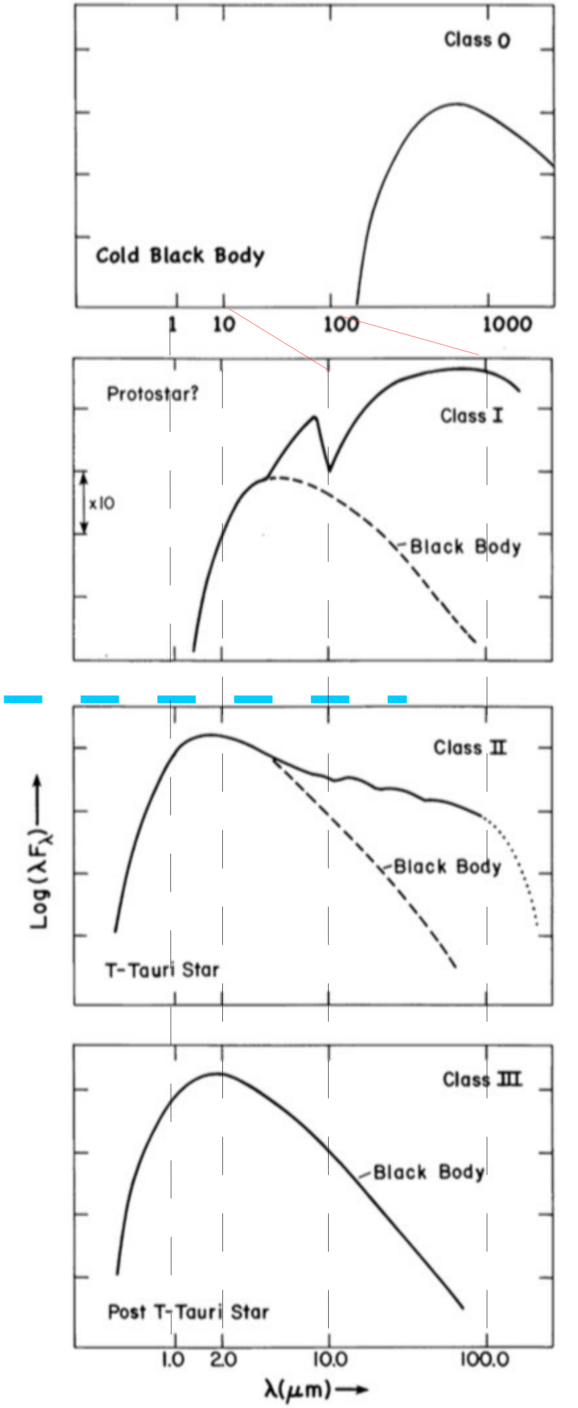
Class I:
Late accretion phase?
Age~10^5 years
M~0.1 $M_\odot$

Birth line for pre-main sequence stars

Class II:
Optically thick disk
Age≤10^6 years
<M_{disk}>~0.01 $M_\odot$

ClassIII:
Optically thin disk
Age≥10^6 years
<M_{disk}>~0.003 $M_\odot$
Planetary System





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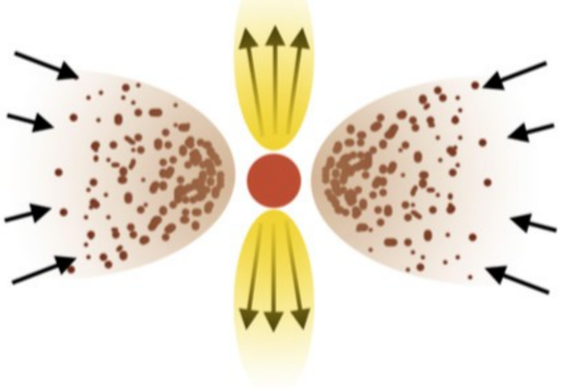
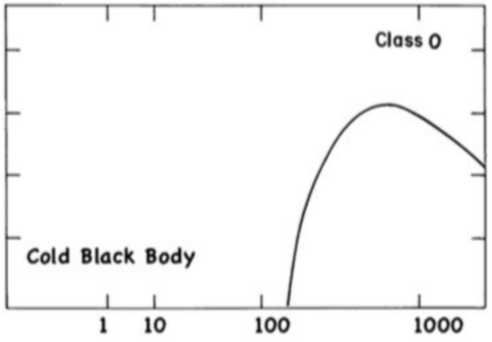




Class 0: Cold condensations of in-falling molecular gas

Hydrostatic low-luminosity proto-stellar object

Thermal emission mostly in the mm-sub-mm region (ALMA) by cold dust (< 20°K)

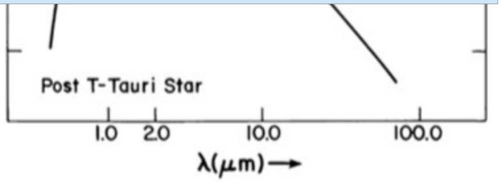
Detections in the radio at cm-wavelengths sensitive to the presence of a proto-stellar core

Responsible of a jet/collimated wind

Bi

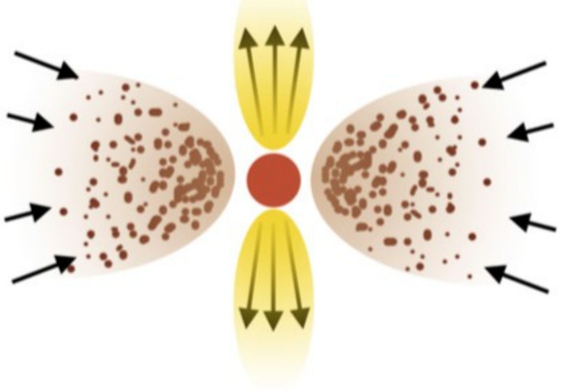
pre-mai

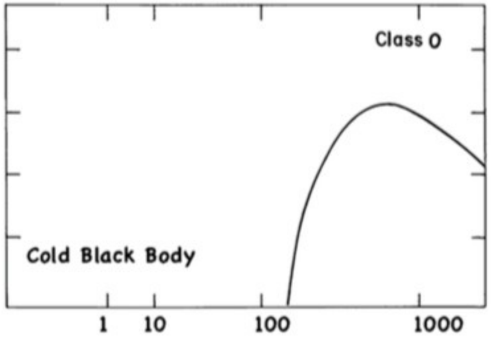
<M_{disk}>~0.003 $M_\odot$
Planetary System



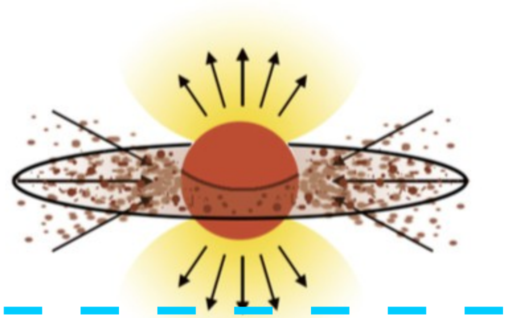
Young Stellar objects Class 0-I-II-III

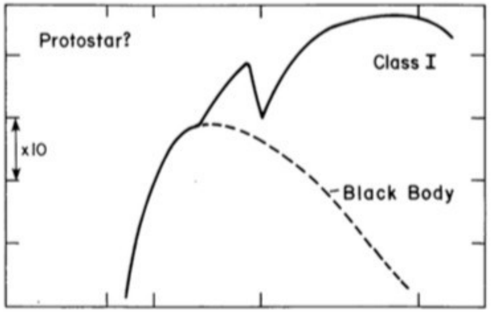
Class 0:
Main Acceleration phase?
Age≤10^5 years
$M \sim 0.5\, M_\odot$





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





Birth line for

pre-ma

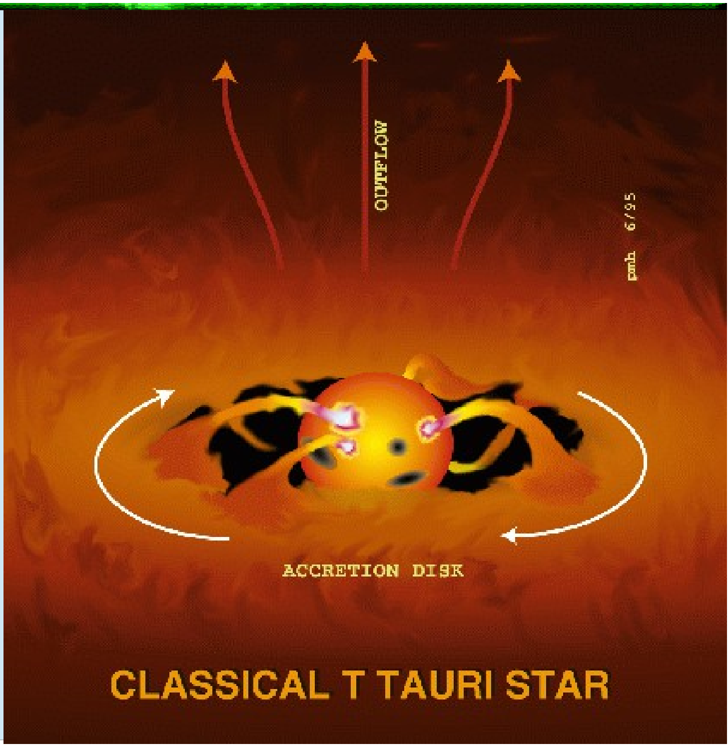
Class I: protostar still enshrouded by optically thick material

Emission from collimated thermal winds/jets ionized by neutral winds impacting the ambient medium (with polarization!)

Aligned to the molecular outflows

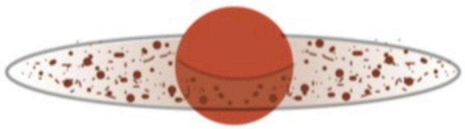
Young Stellar objects Class 0-I-II-III

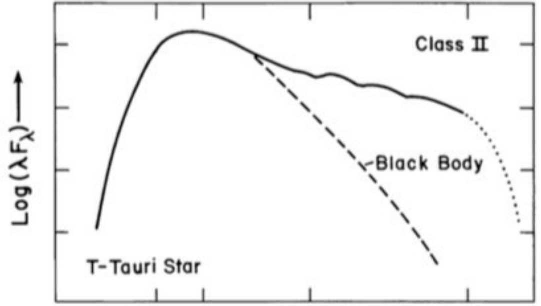
Class II: T Tauri phase: optical (reddened!) emission starts to come out along with a weak outflow and a wind



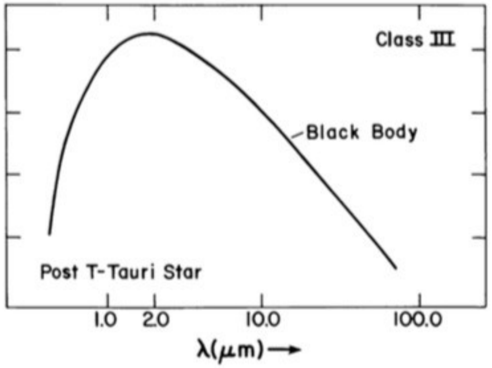
Birth line for pre-main sequence stars

Class II:
Optically thick disk
Age≤10^6 years
$<M_{disk}>\sim 0.01\ M_\odot$



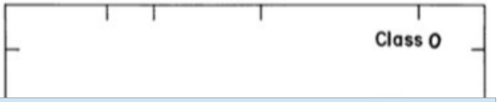


ClassIII:
Optically thin disk
Age≥10^6 years
$<M_{disk}>\sim 0.003\ M_\odot$
Planetary System



Young Stellar objects Class 0-I-II-III

Class 0:
Main Acceleration

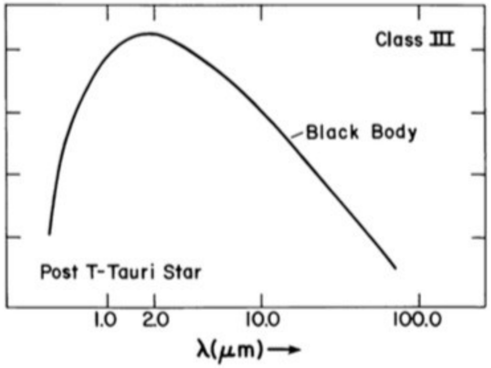


Class III: Evolved T Tauri, the star approaches the main sequence
Accretion substantially halted, proto-planetary disks may be present

Bi

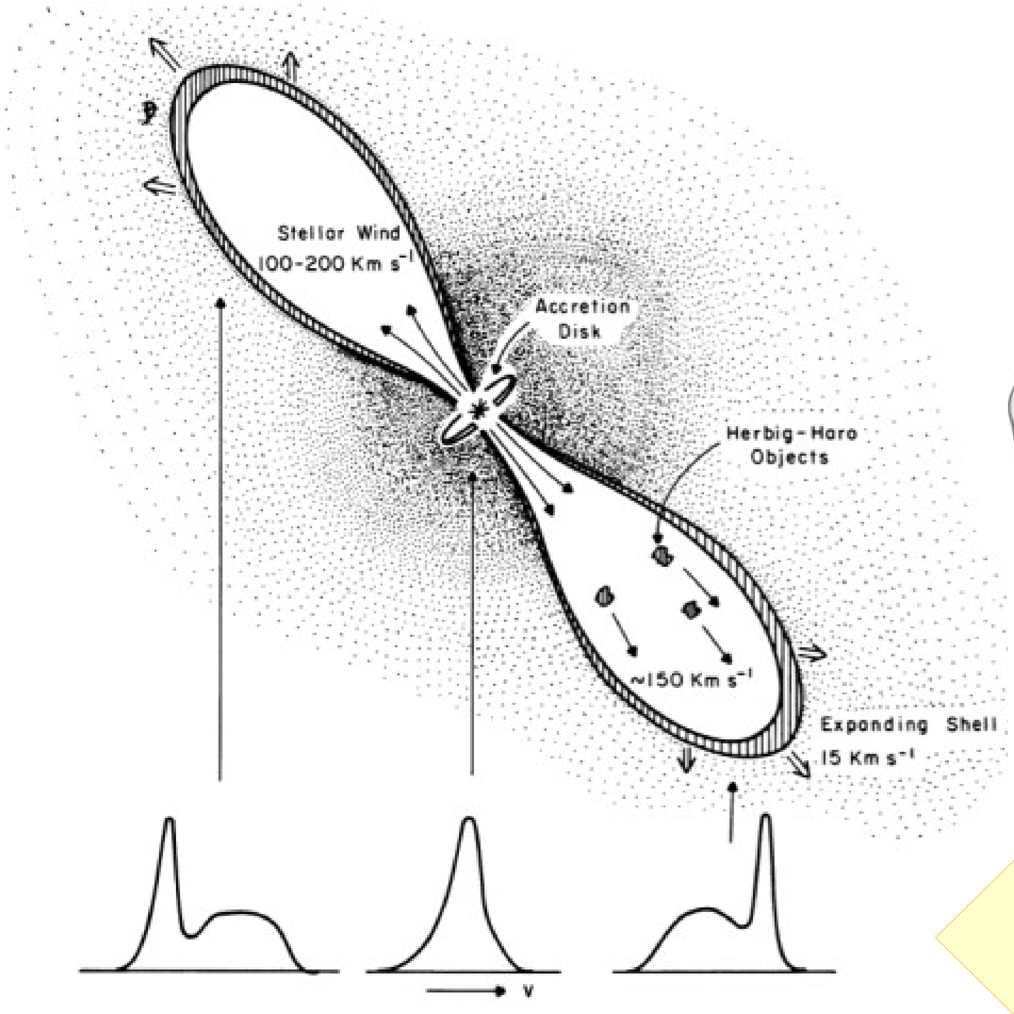
pre-mai

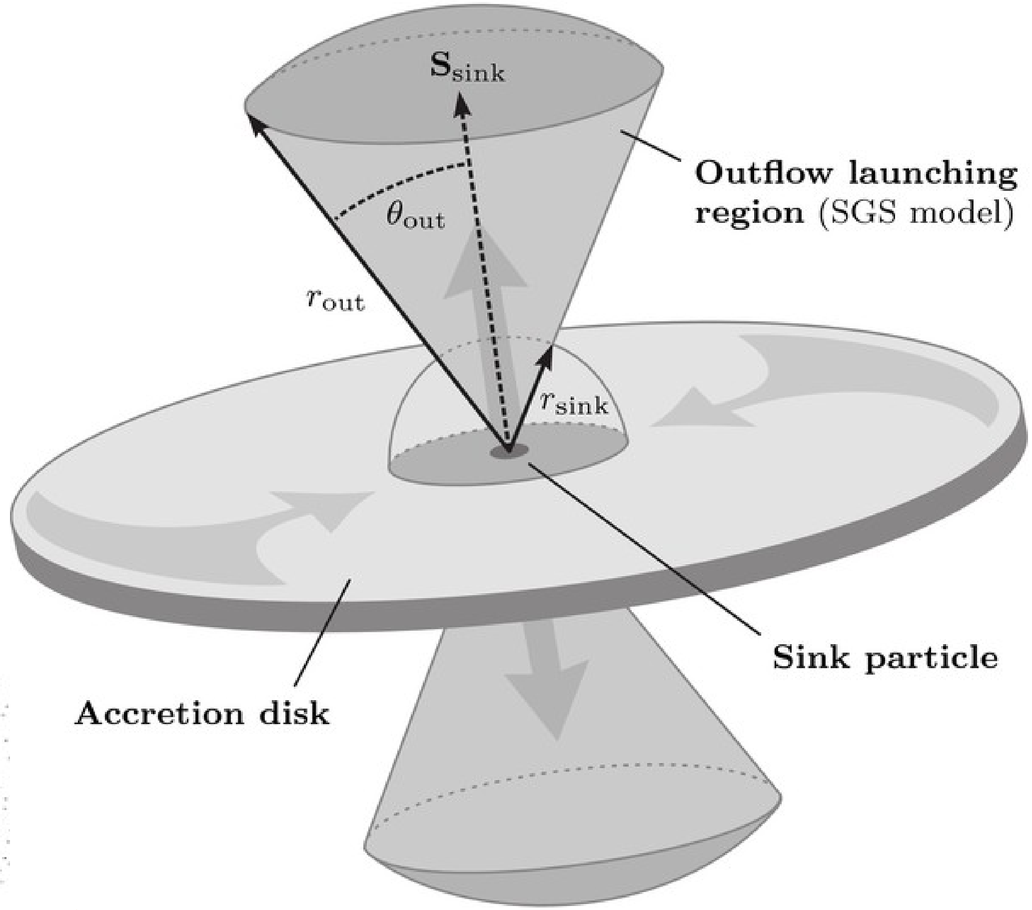
ClassIII:
Optically thin disk
Age≥10^6 years
<M_{disk}>~0.003 $M_\odot$
Planetary System



Young Stellar objects: Bipolar (molecular) outflows

Outflows: Snell+, 1980





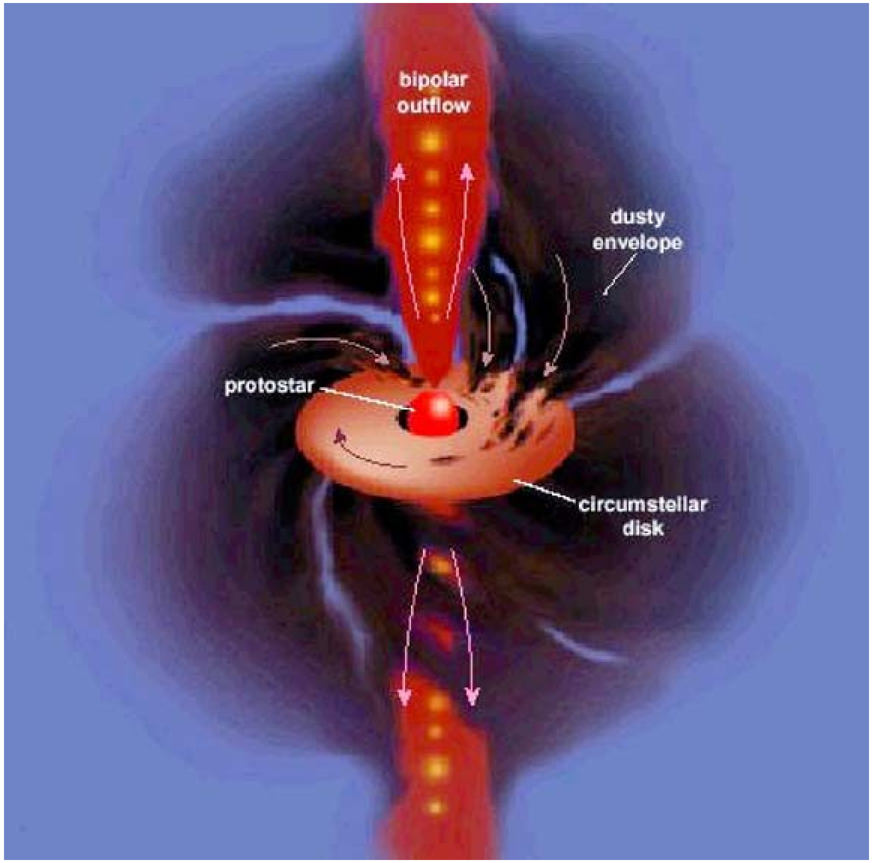
Line emission is Doppler shifted (broad)

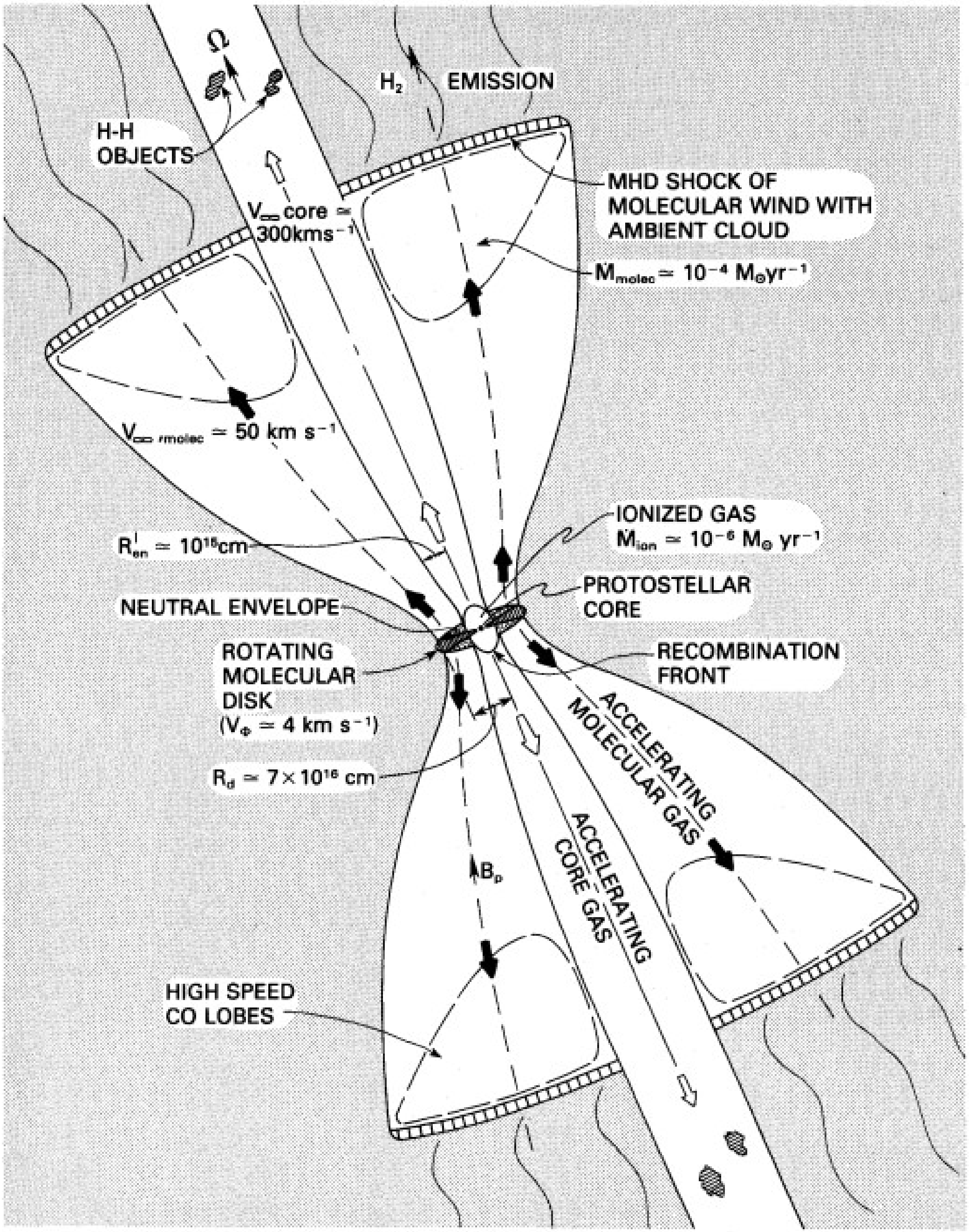
GMC

GMC+ Expanding bubble

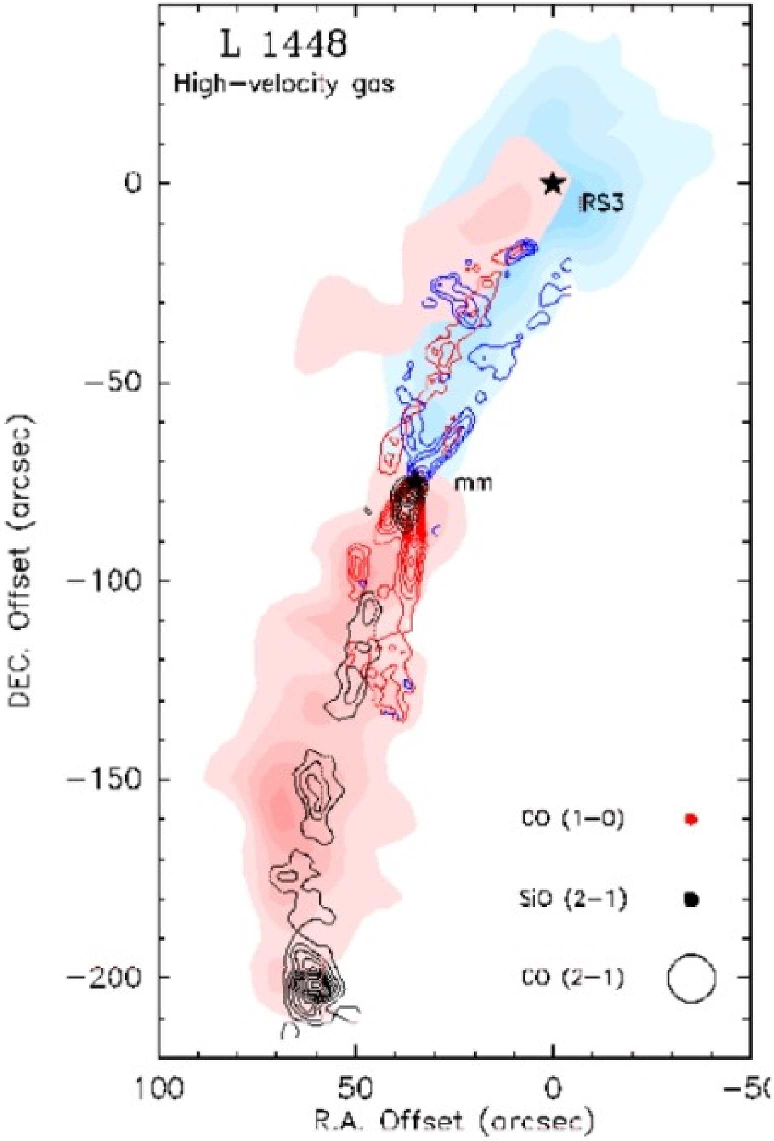
Bipolar outflows: Molecular stage

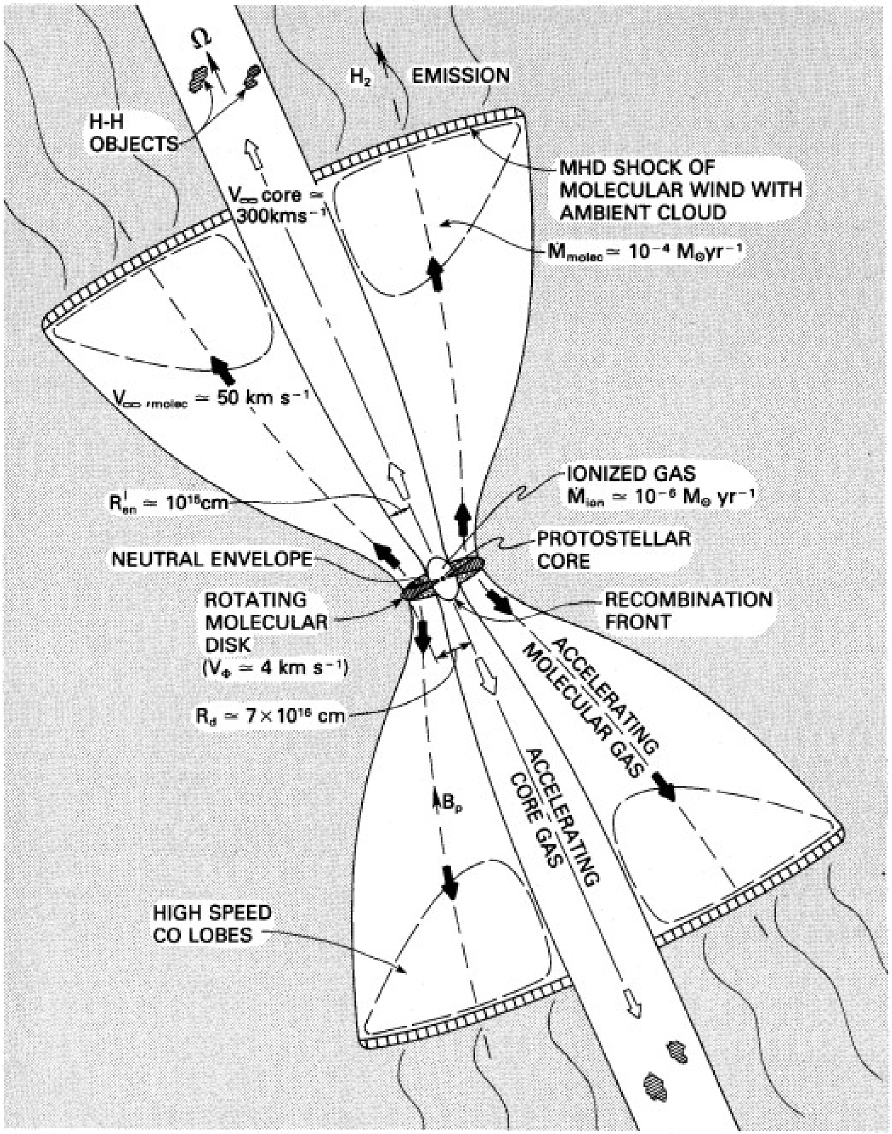
- Pudritz (1986): various components at work
- Their relative importance determines the protostellar class
- N.B. Consider the relative scales





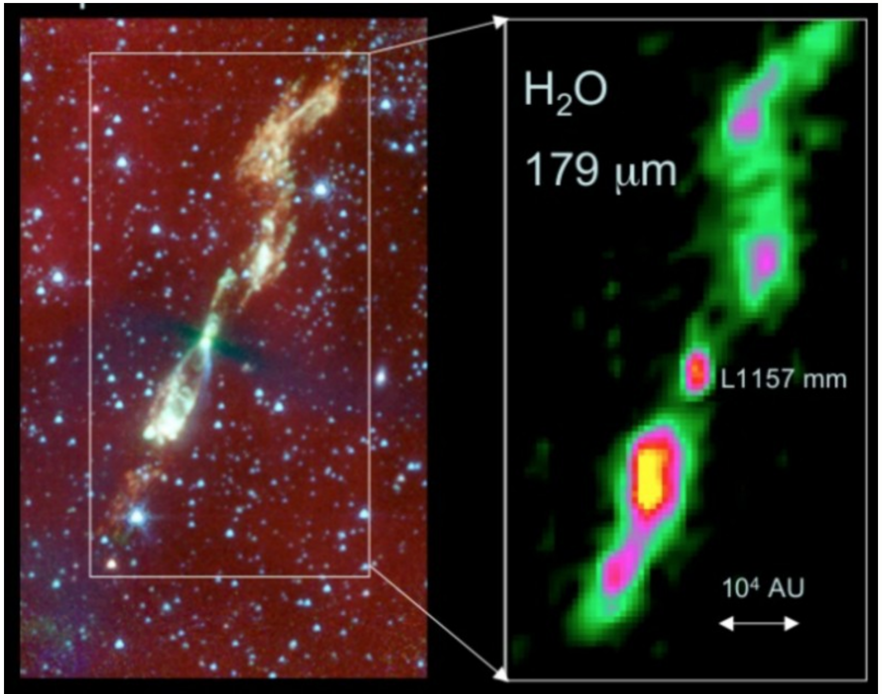
Outflows & Jets : model .vs. observation

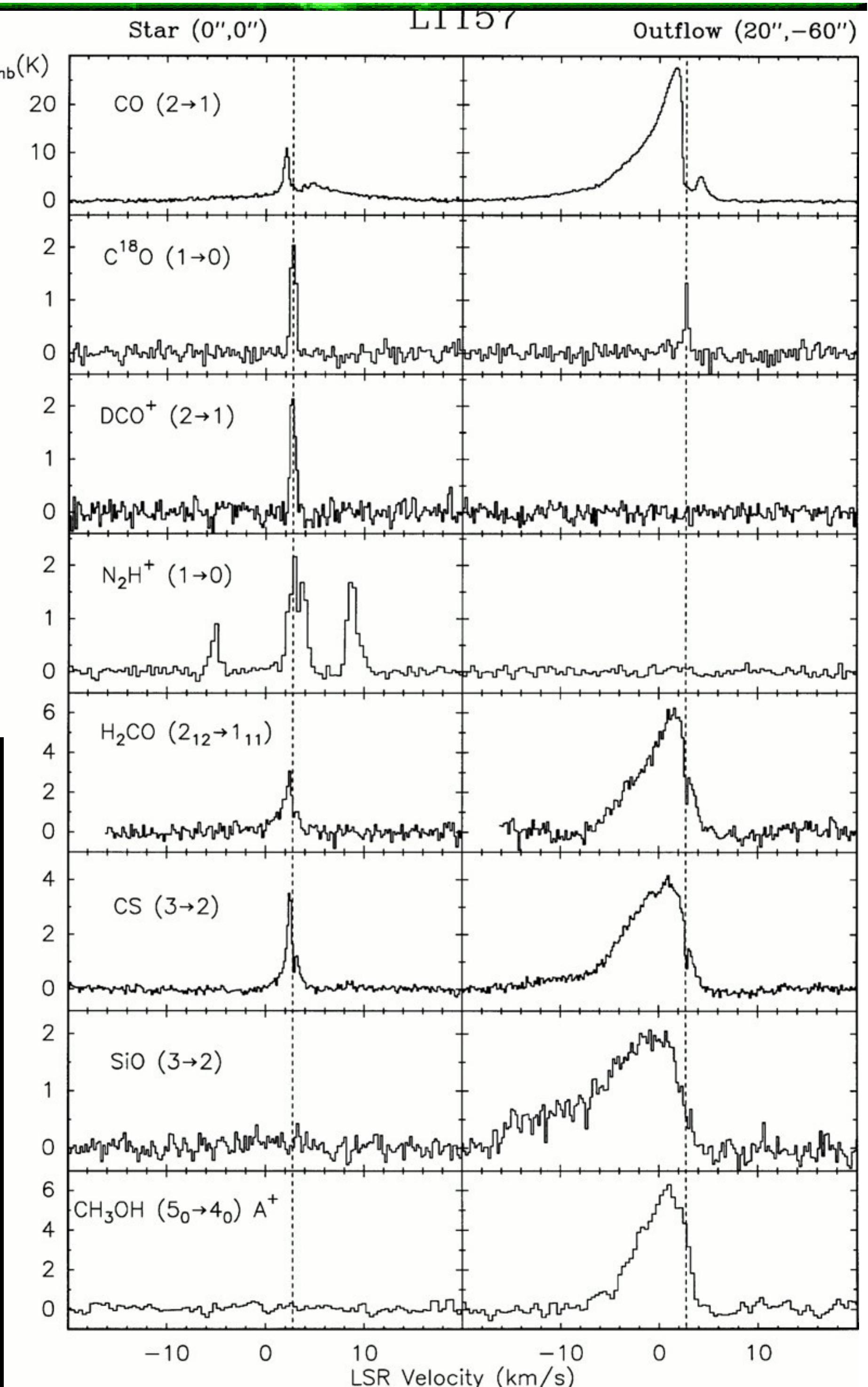




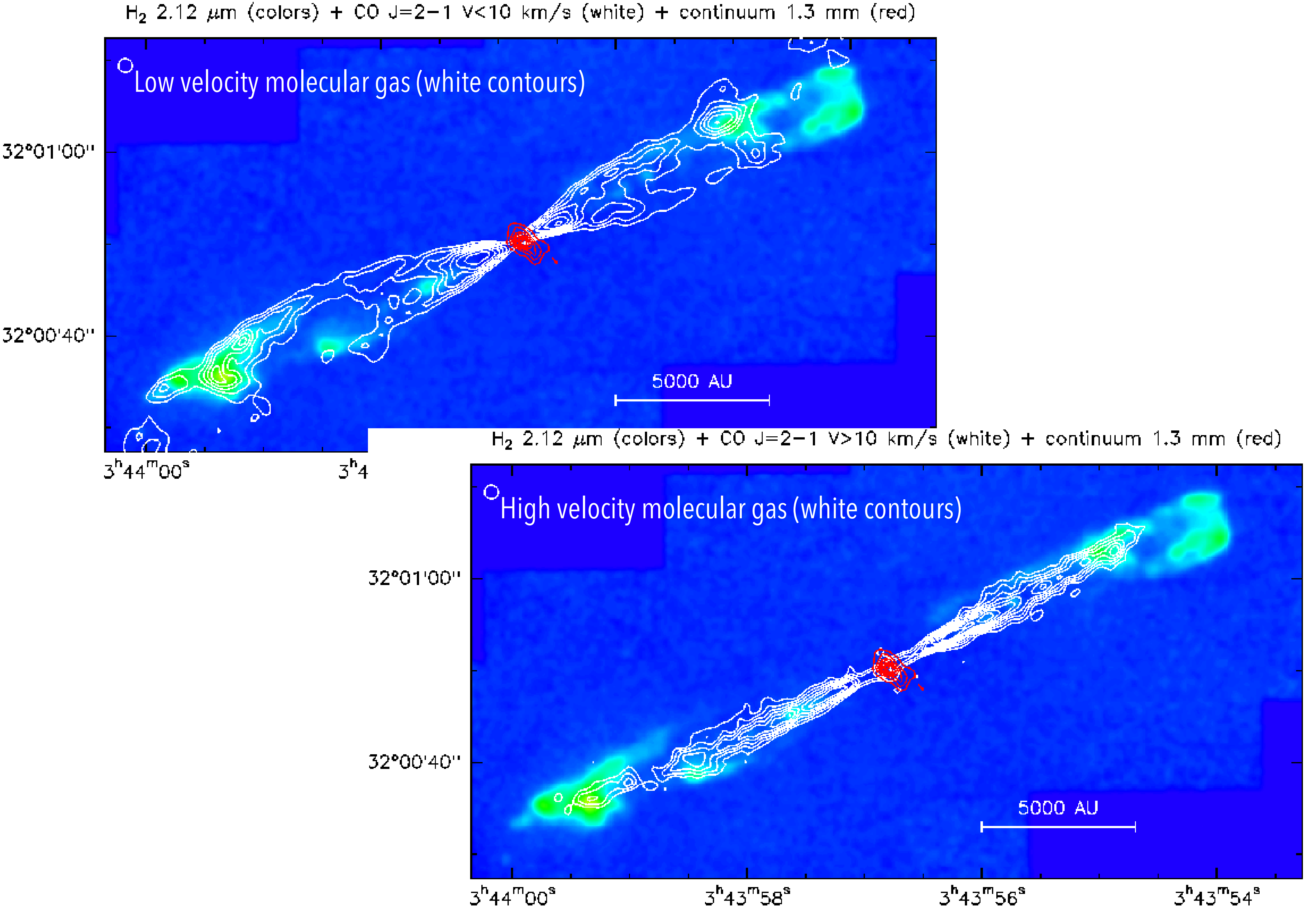
Young Stellar Objects: various ingredients

- *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*





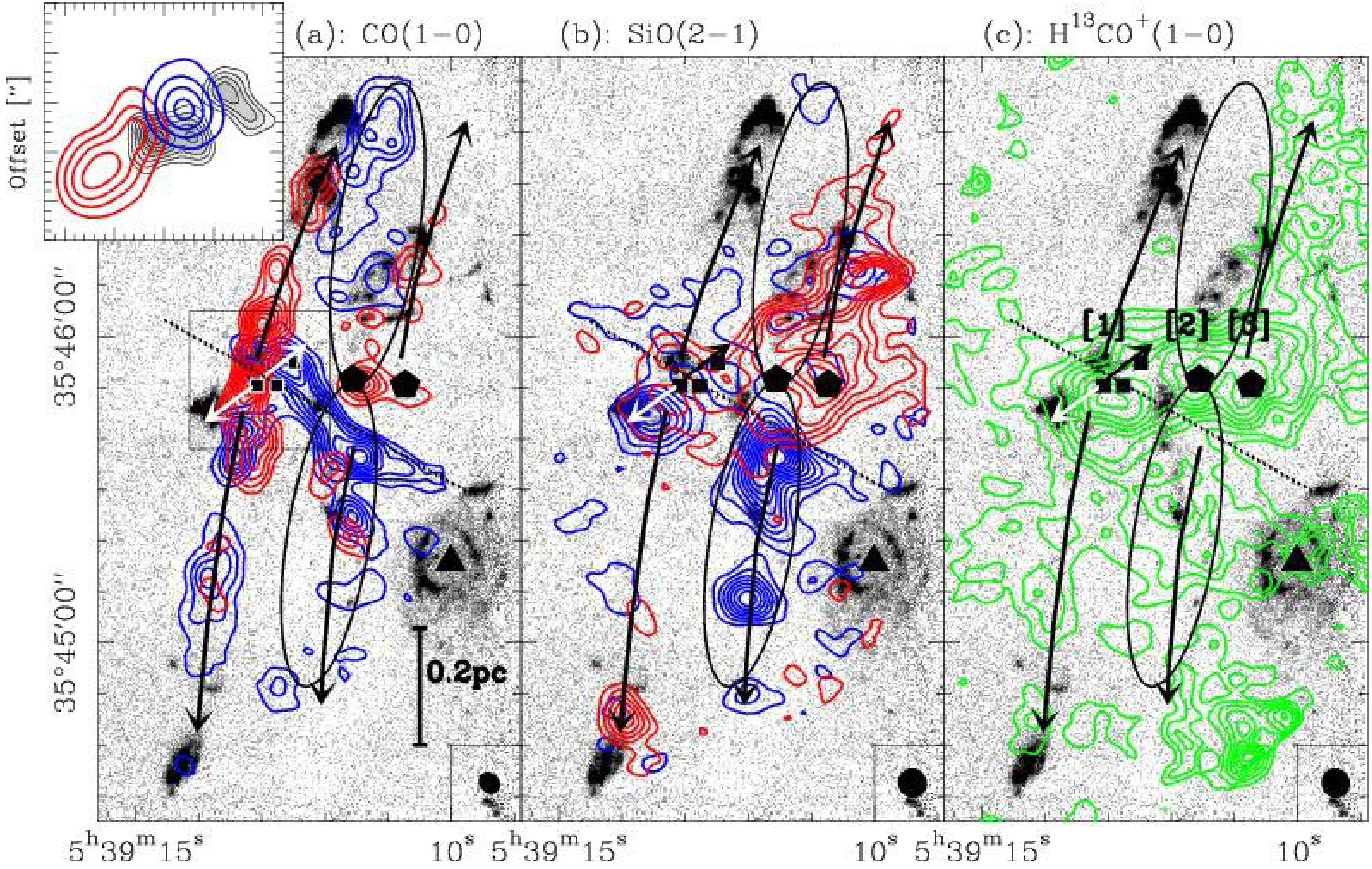
Young Stellar objects: various ingredients



Low velocity molecular gas (white contours)

High velocity molecular gas (white contours)

Interaction between outflows: gray scale optical (NIR)

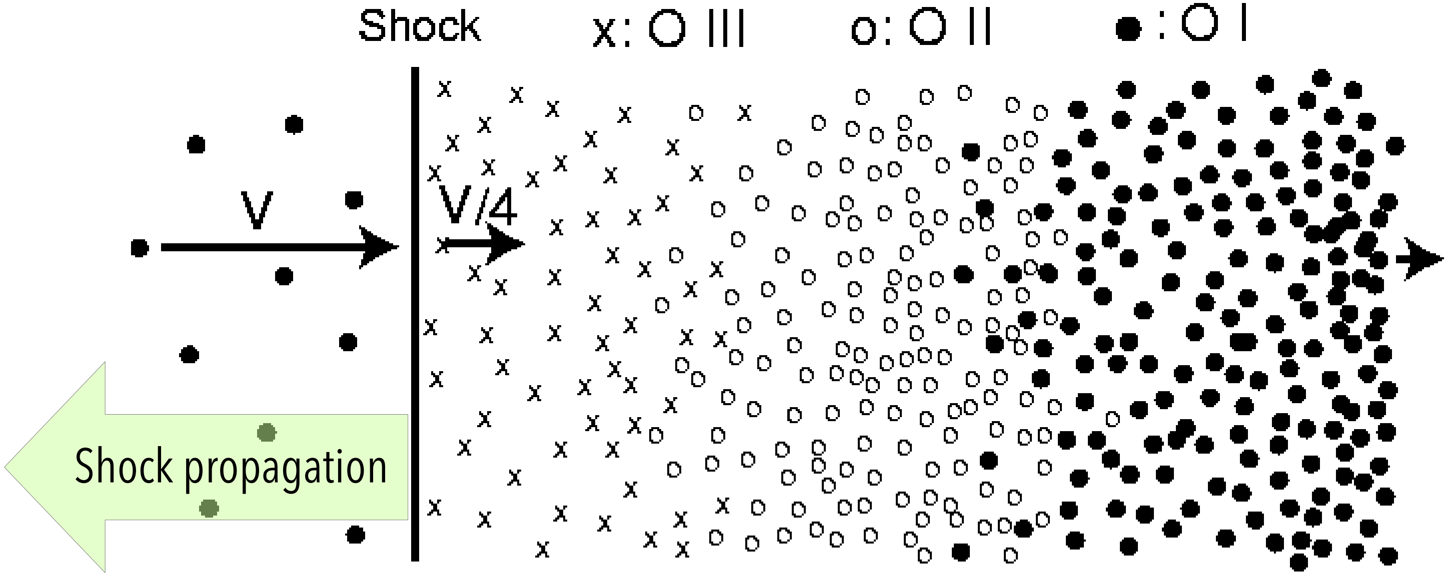


Young Stellar Objects: Herbig – Haro objects

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

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

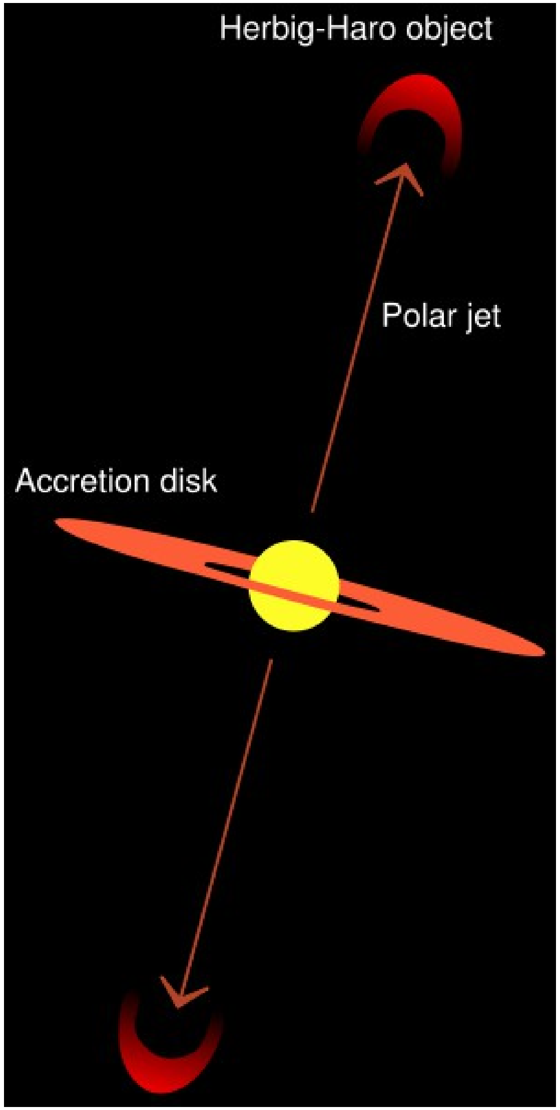
- The main emission mechanism of the radio emission is thermal bremsstrahlung (shock-ionized plasma) of a cooling plasma, created by outflow/jet heating of the ambient medium

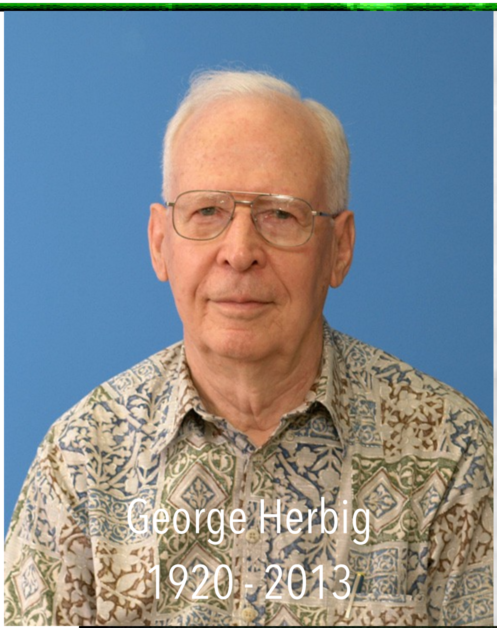


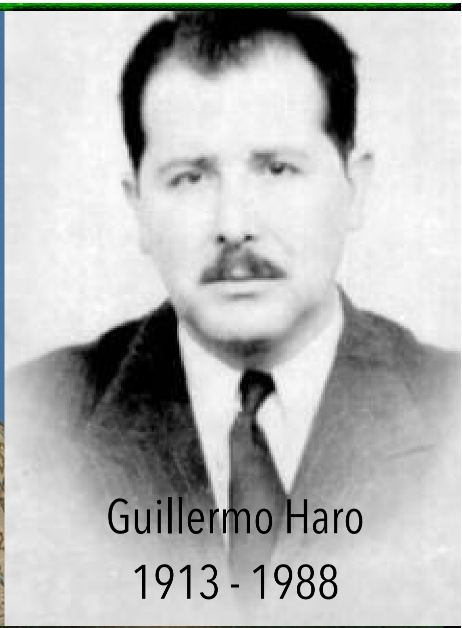
- In a few objects, also non-thermal emission from a population of relativistic electrons has been detected
- The cartoon shown above imply also (optical) line emission of recombination of cooling elements (ionized / neutral). Protostars with optical jets are known as Herbig-Haro objects.

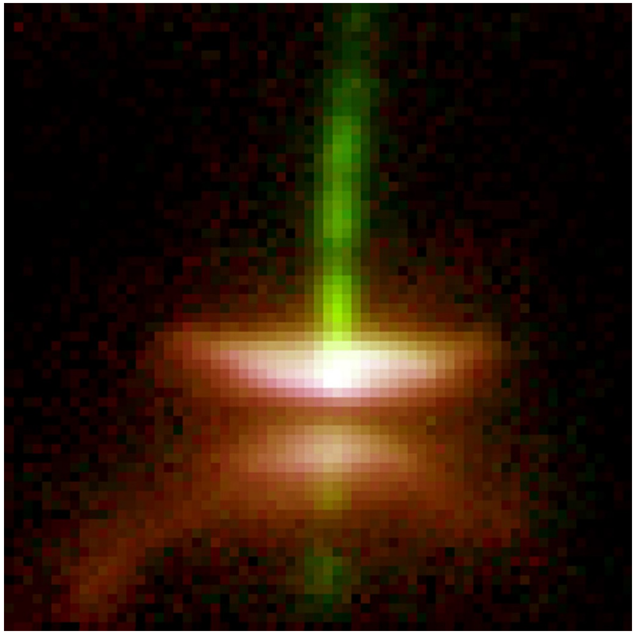
Young Stellar Objects: Herbig – Haro objects

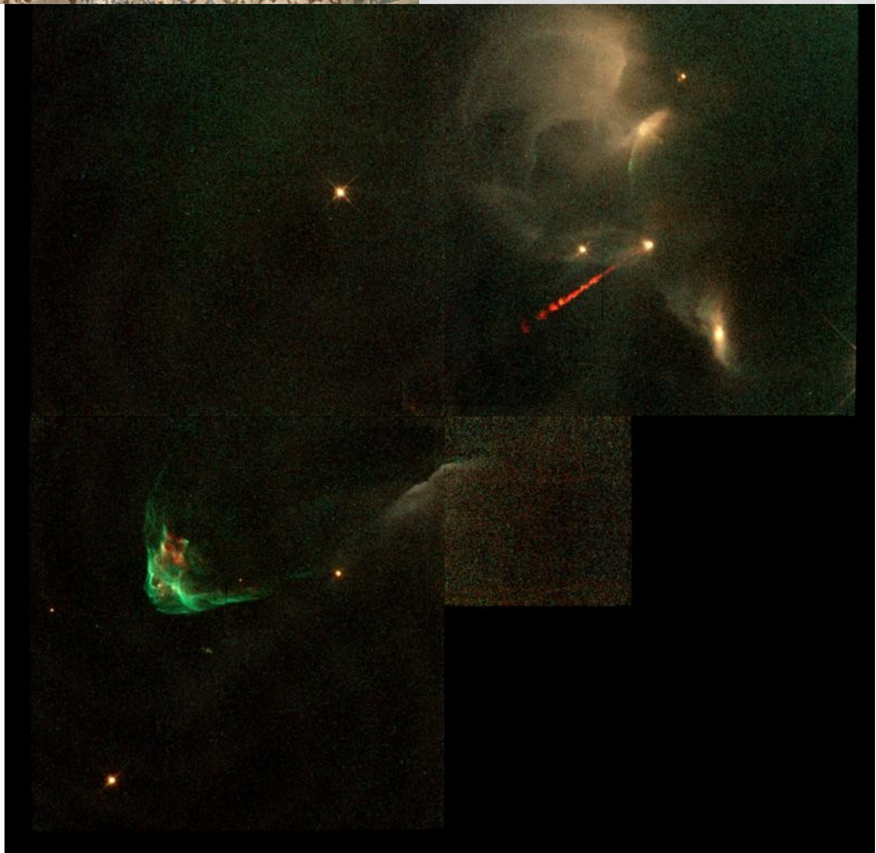
Herbig – Haro objects: spectacular signature of SF




George Herbig
1920 - 2013


Guillermo Haro
1913 - 1988



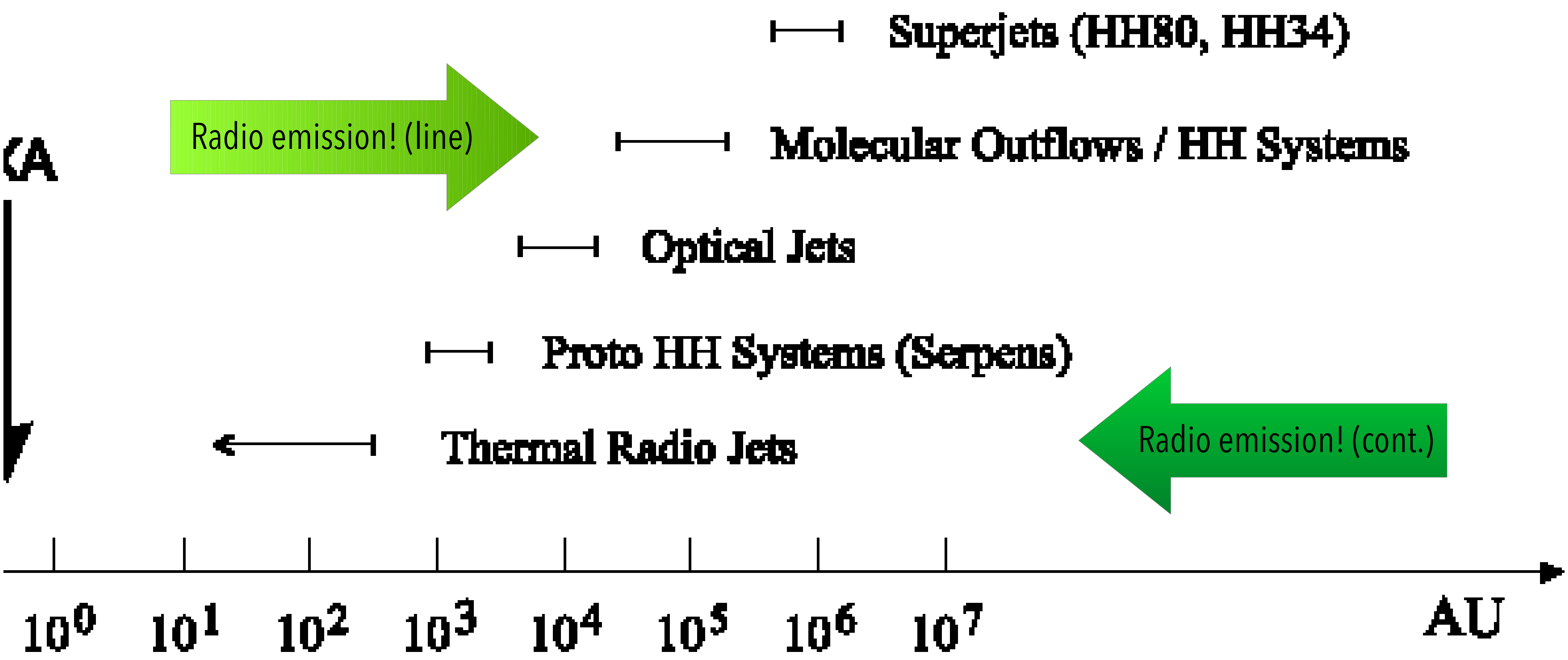


Young Stellar objects: the role of radio emission

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

Masers in SFR are ubiquitous and variable point-like sources (many species are known)

(see later on)



Superjets (HH80, HH34)

Radio emission! (line)

Molecular Outflows / HH Systems

Optical Jets

Proto HH Systems (Serpens)

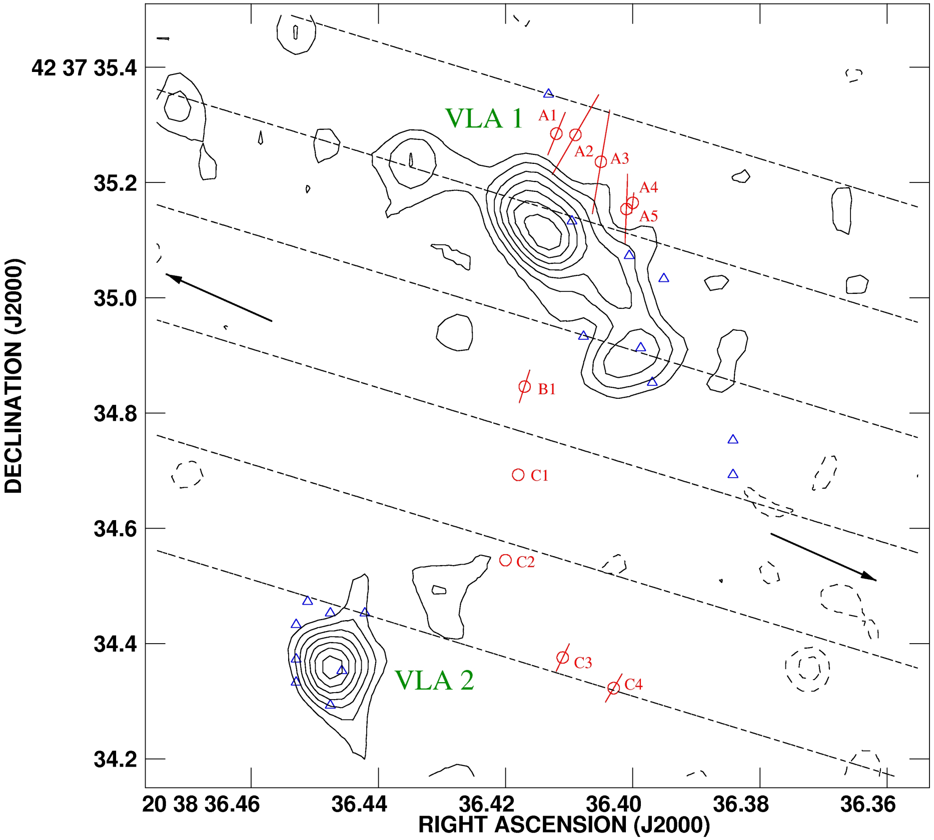
Thermal Radio Jets

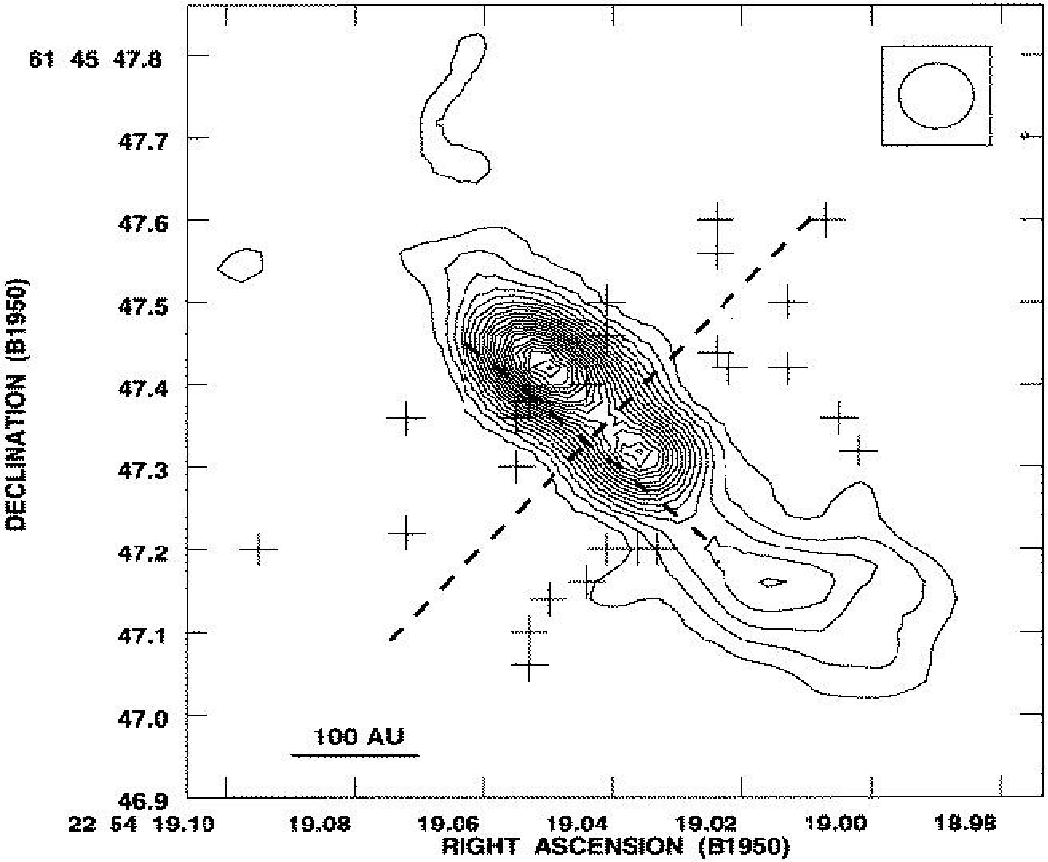
Radio emission! (cont.)

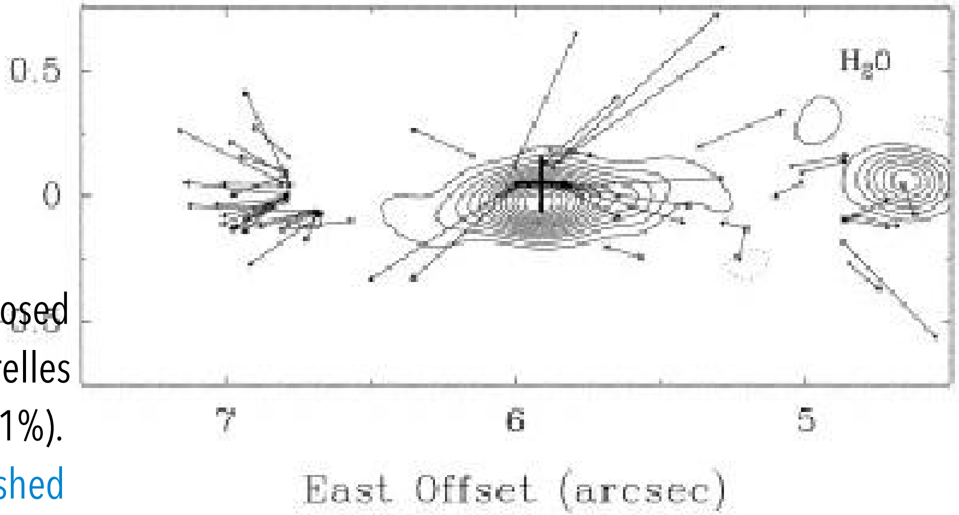
Bipolar outflows: atomic/ionized stage

Thermal & Non – Thermal Jets:

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



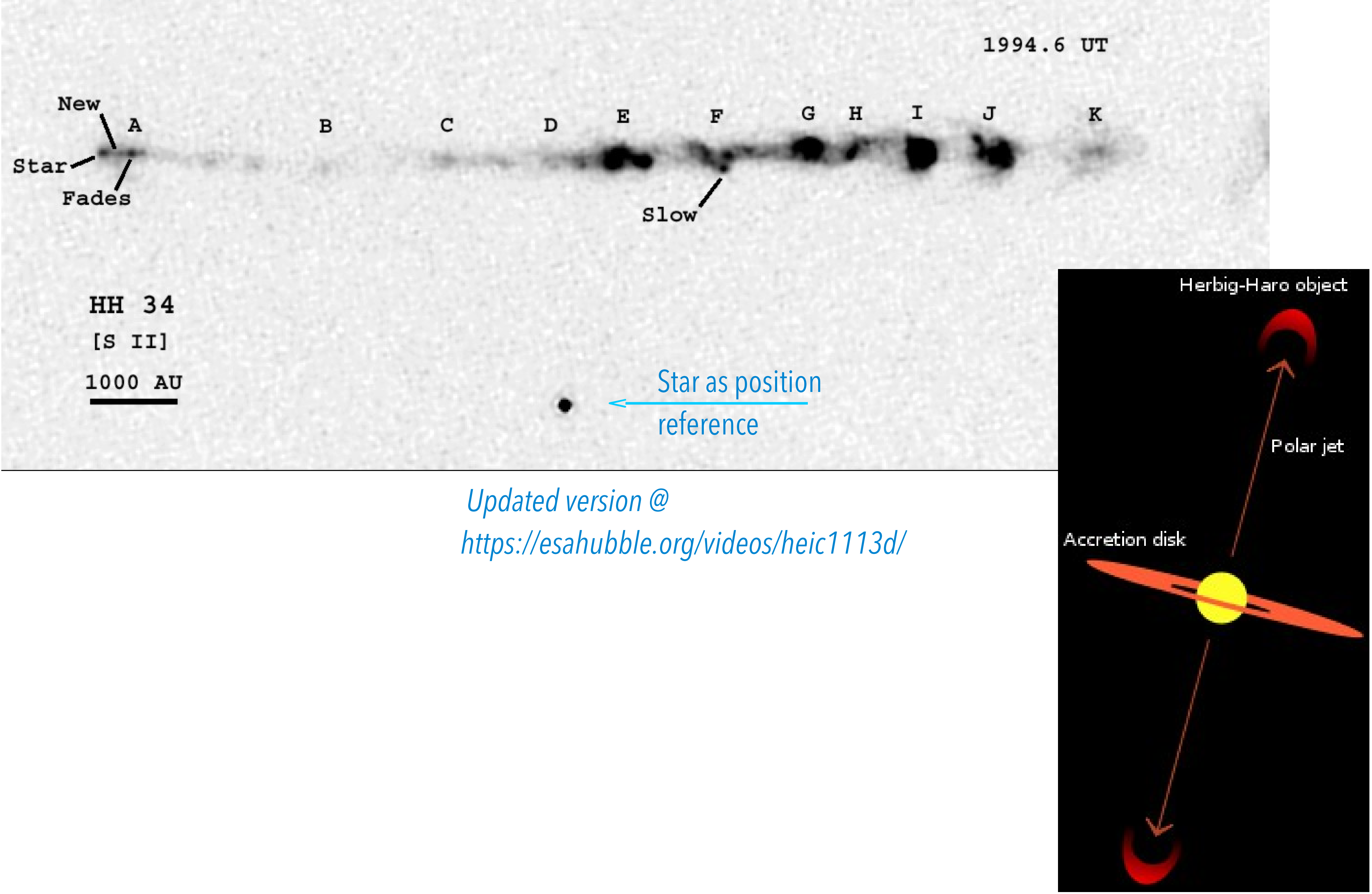




Surcis +, 2009: Positions of methanol (o) and water (Δ) masers superimposed on 1.3cm continuum contour map of the VLA 1 thermal jet and VLA 2 (Torrelles +,1997). The red segments indicate linear polarization vectors (40mas = 1%). Arrows show the direction of the bipolar outflow (66d) and the parallel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

Bipolar outflows: atomic stage

Velocity measurements More movies at http://sparky.rice.edu/movies.html



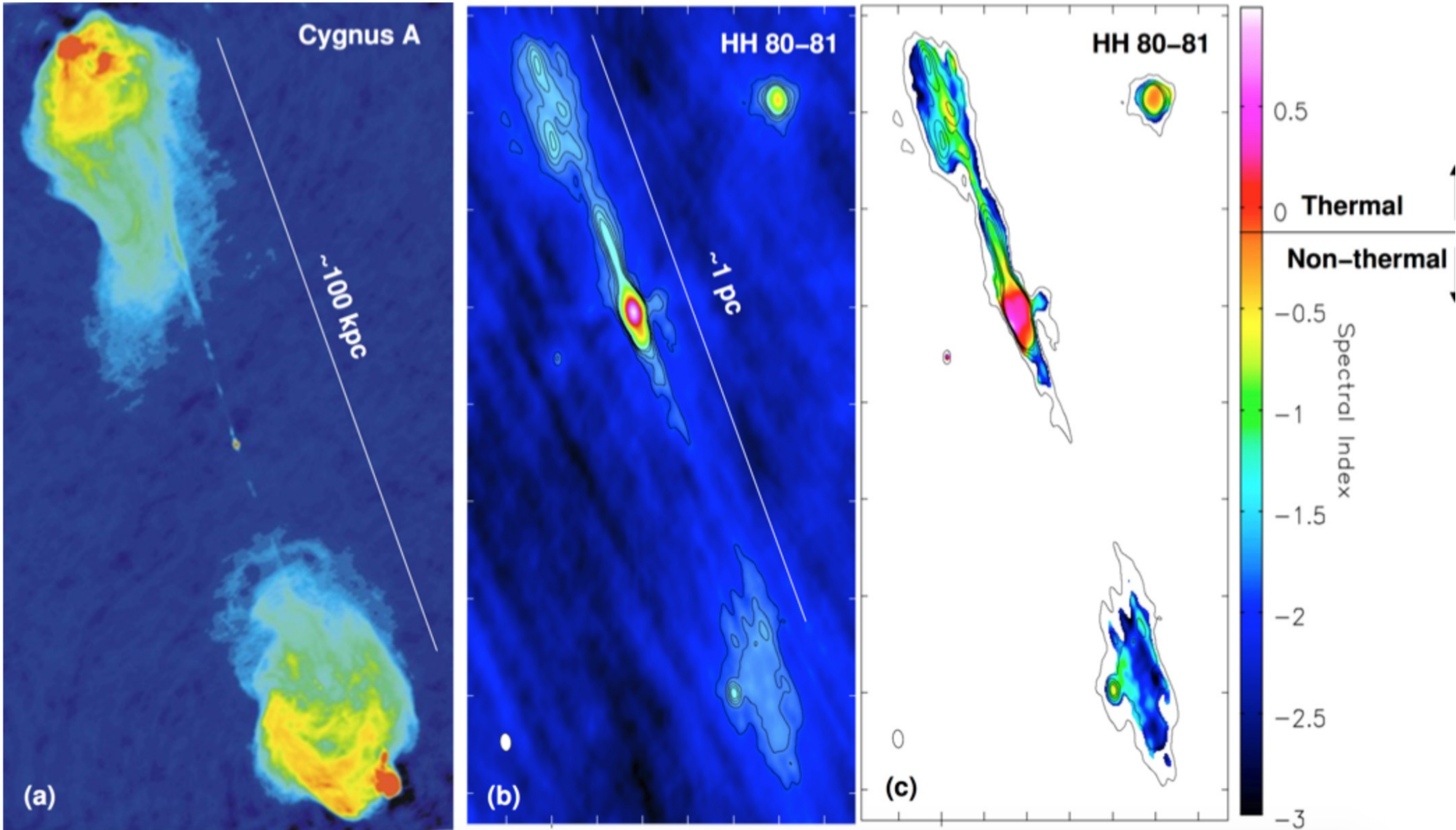
Star as position reference

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

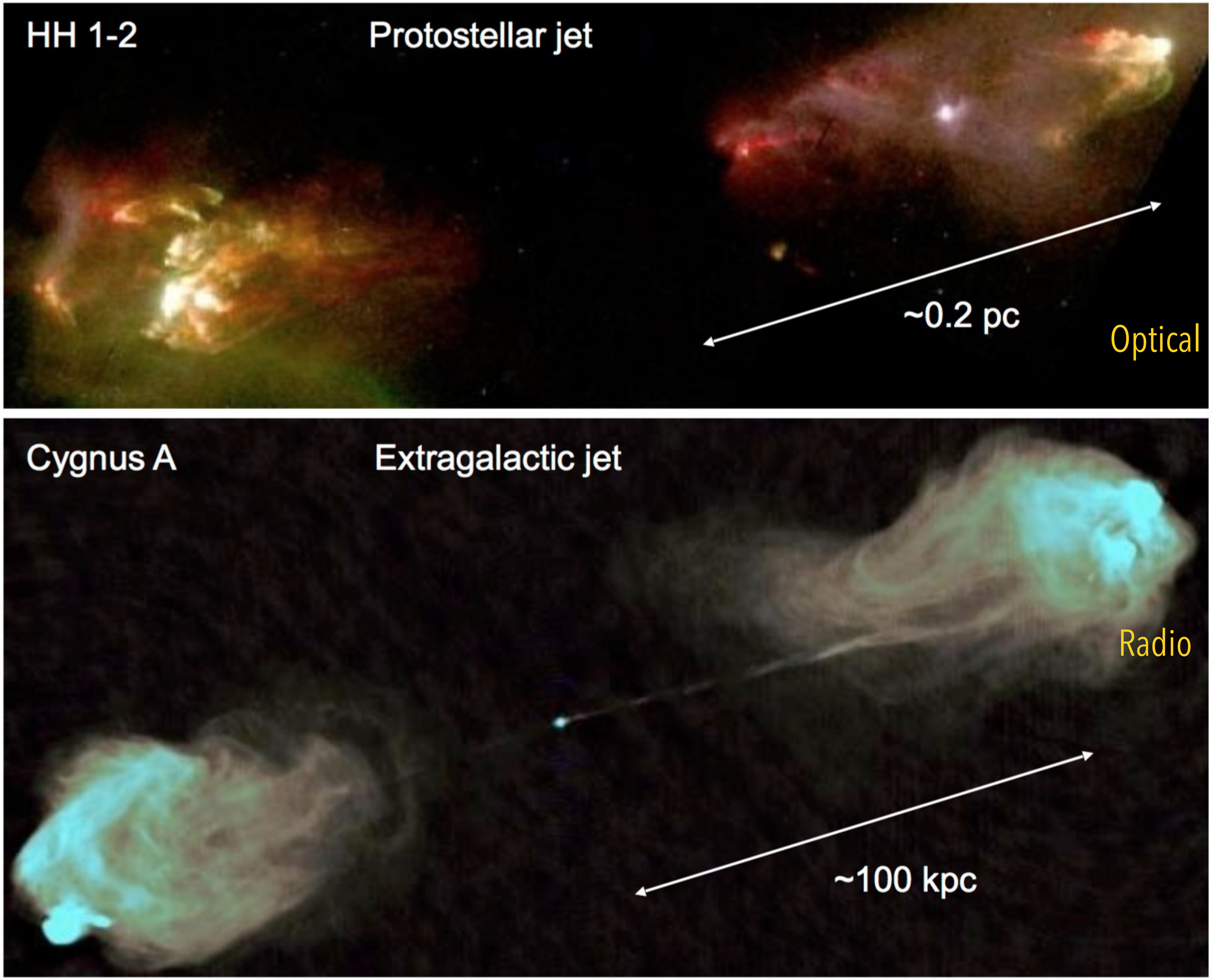
Young Stellar objects: the role of radio emission

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*

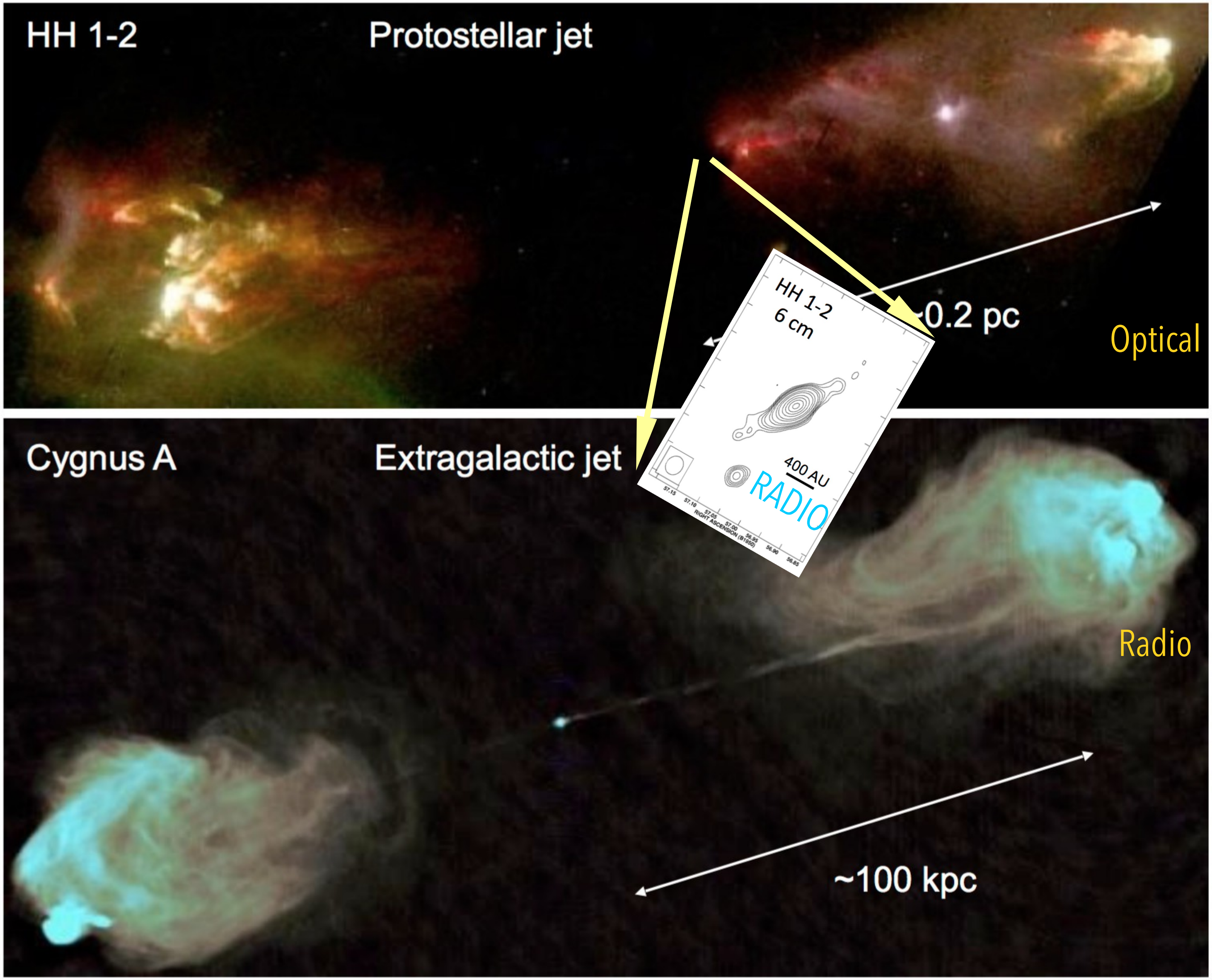


Similarities with radio galaxies?



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



Young Stellar objects: the role of radio emission

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

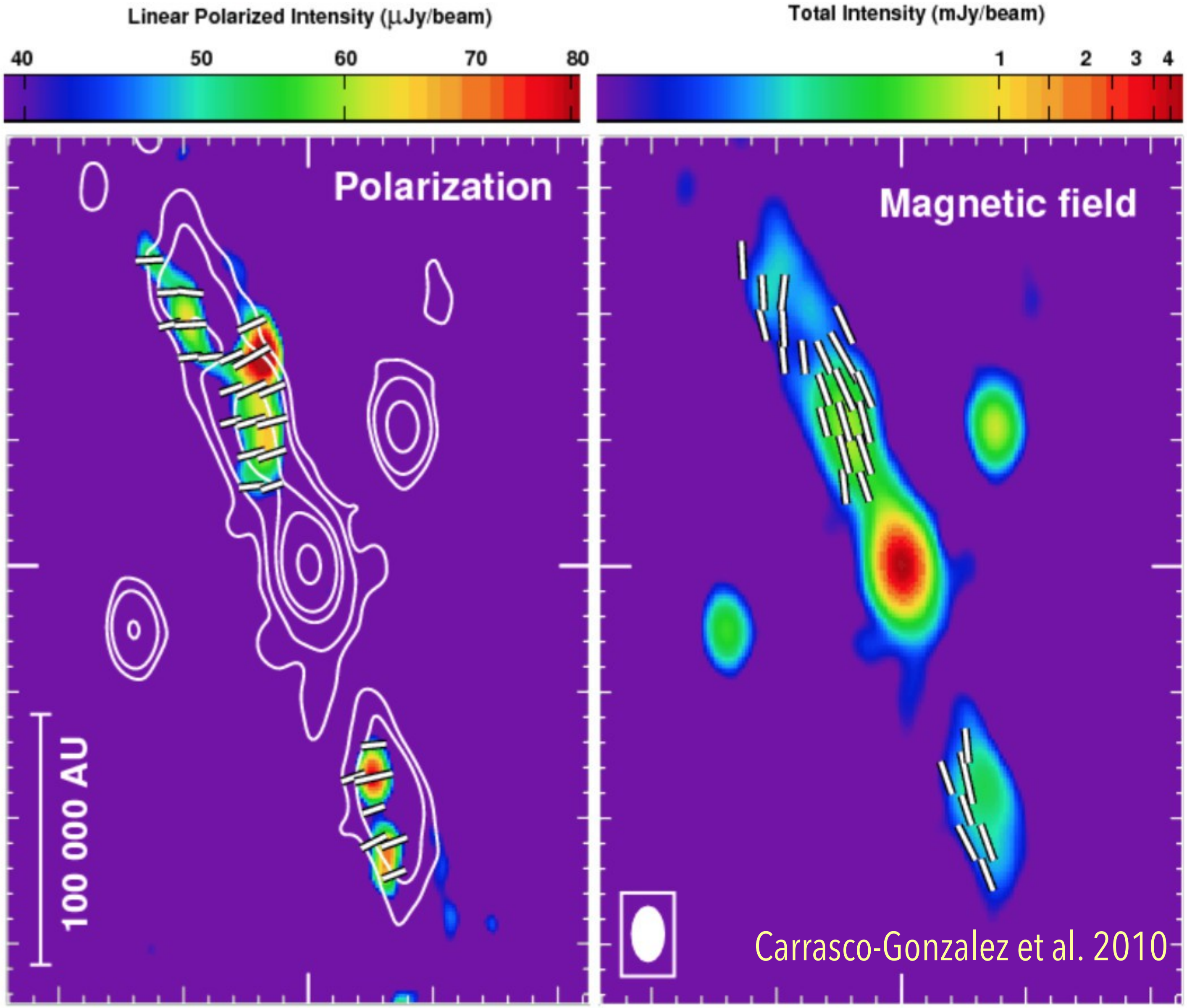
- Radio ⍰ ionized gas, base of the jet, velocity
  (mostly) optically thin, continuum emission, quite weak (mJy level)
  (maser emission in local high brightness spots!)

- 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 μG in HH 80-81 (Carrasco -Gonzalez et al. 2010)



Carrasco-Gonzalez et al. 2010

Summary (?) of Thermal jets

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 of 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*

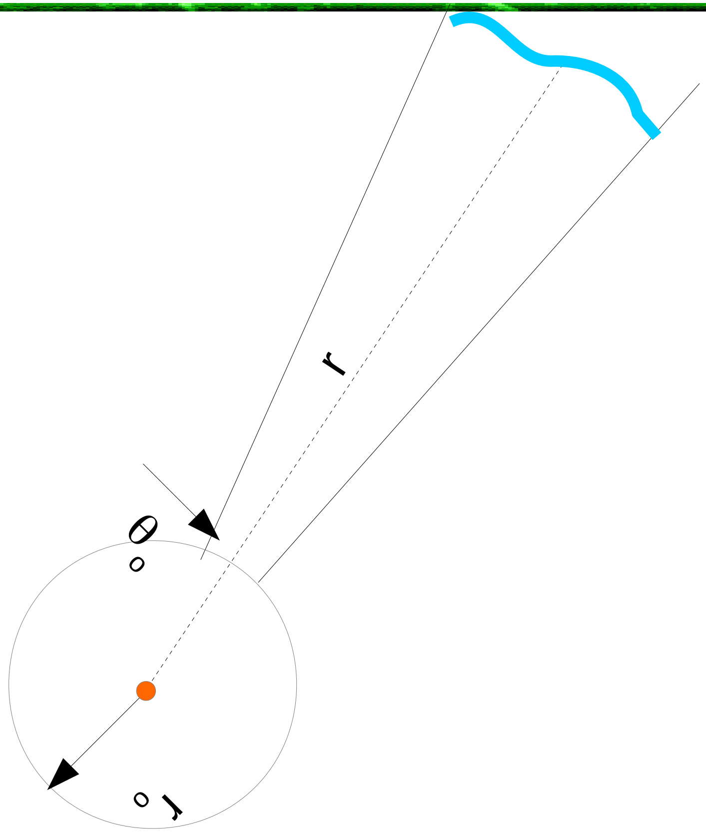
$$r \;=\; 0.56\left(S_{mJy}\,\nu_{10}^{-\alpha_{op}}\right)^{1/2}\theta_o^{-1/2}\left(\nu_{10m}\right)^{\alpha_{op}/2-1}D_{kpc}\left(T_4\right)^{-1/2}(\sin i)^{-1/2}F^{-1/2}\qquad[10^{15}\,cm]$$

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

where $v_8 = \dfrac{v}{10^8\,cm\,s^{-1}}$; $S_{mJy}=$ flux density in mJy ; $\nu_{10}=\dfrac{\nu}{10\,GHz}$; $\nu_m=$ peak frequency in 10GHz units ;

α_{op} = optically thick spectral index ; $T_4=$ temperature in units of $10\ ^{o}K$; $F=$ 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_o = core (collimation) radius*
- *$\dot{M}$ is the ouflow mass loss rate*

See Reynolds (1986) for a proper description

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

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where $v_8 = \dfrac{v}{10^8\,cm\,s^{-1}}$; S_{mJy} = flux density in mJy ; $\nu_{10} = \dfrac{\nu}{10\,GHz}$; ν_{10m} = peak frequency in 10GHz units ;

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

α_{op} = optically thick spectral index ; T_4 = temperature in units of $10\ {}^oK$; F = Function of optically thick/thin spix

Young Stellar objects: the role of radio emission

718 REYNOLDS Vol. 304

Combination of

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

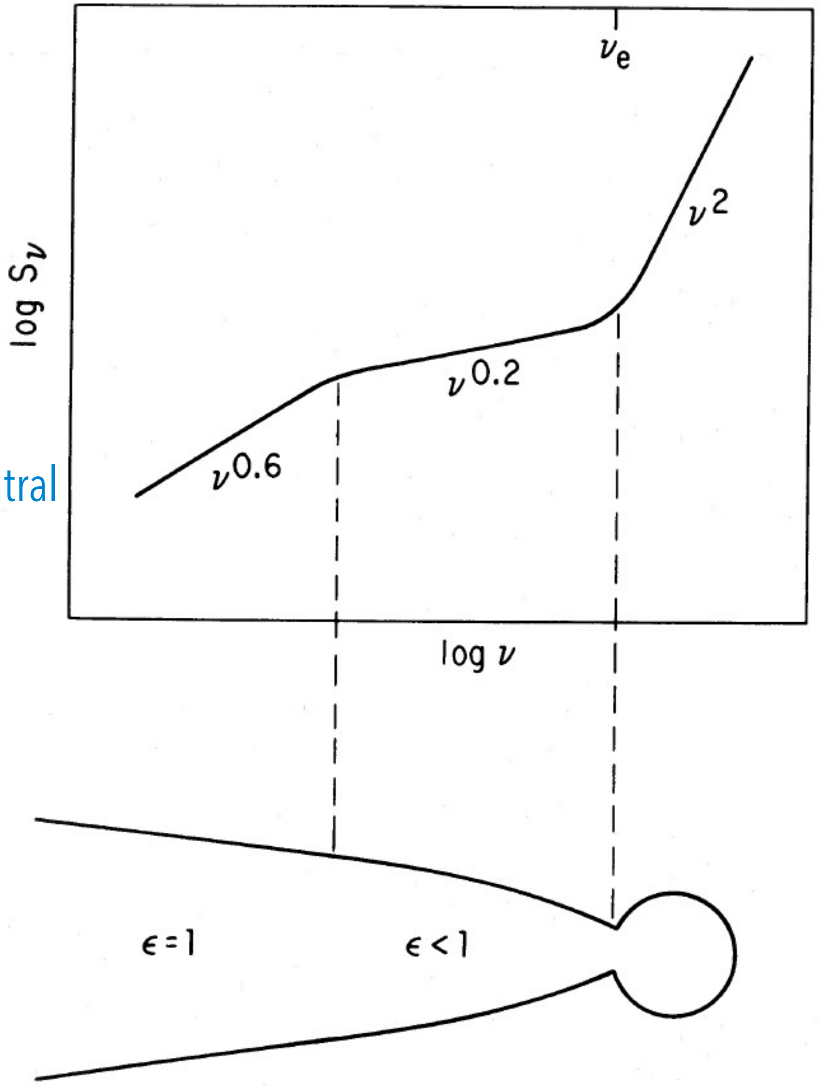


FIG. 2.—Schematic core-jet spectrum, showing an example of the mapping between spatial structure in a flow and spectral structure in the integrated radio flux (the source is assumed unresolved). The homogeneous core dominates the emission at high frequencies; descending in frequency, one observes first 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.

Young Stellar objects: the role of radio emission

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

- *1. YSO jets (non-relativistics) 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.*

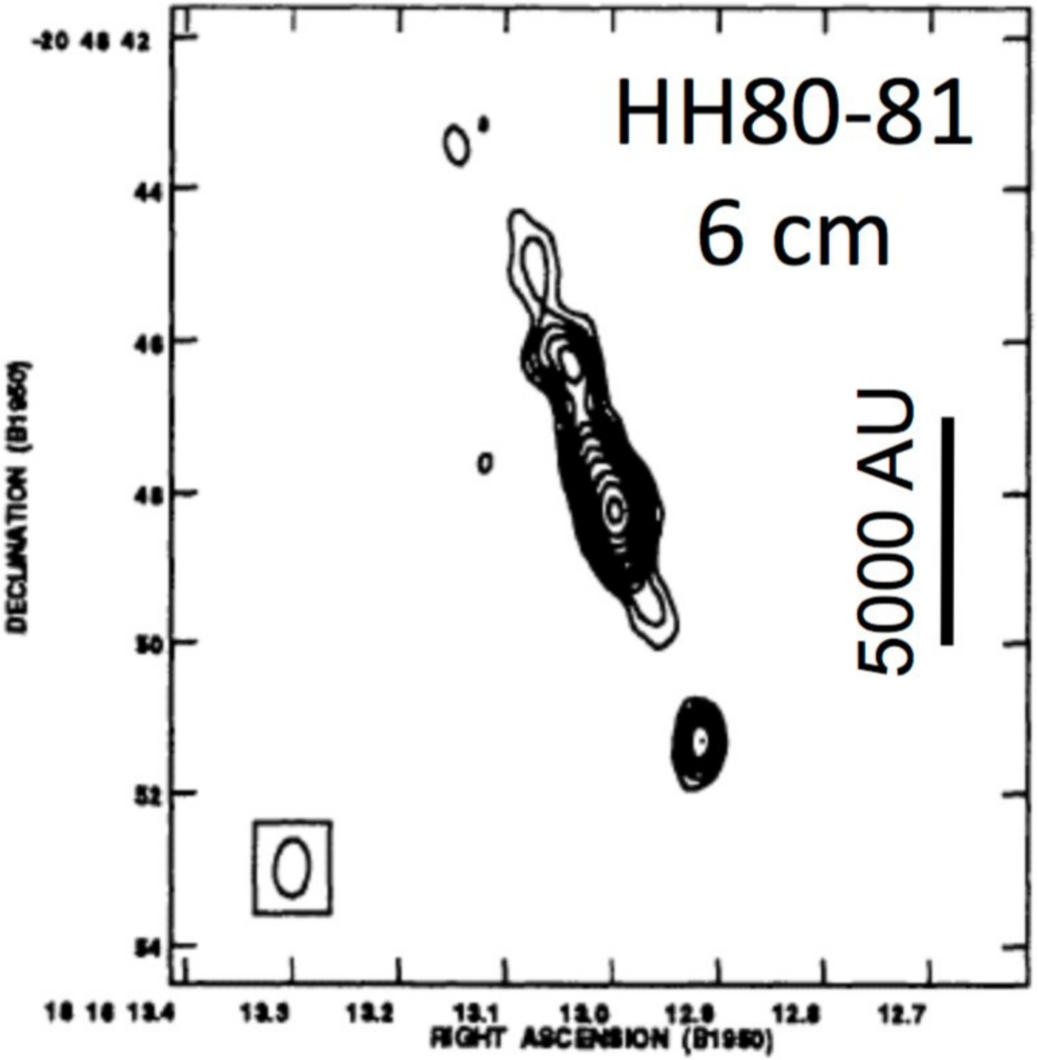
- *4. YSO jets CAN accelerate particles up to relativistic velocities (synchrotron emission)*

- *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* yr^{-1} *and v ~ 100-200 and 200-500 km* s^{-1} *. In high mass stars, disks are confused by the presence of HII region emission*

Young Stellar objects: the role of radio 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

Young Stellar objects: the role of radio emission

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,

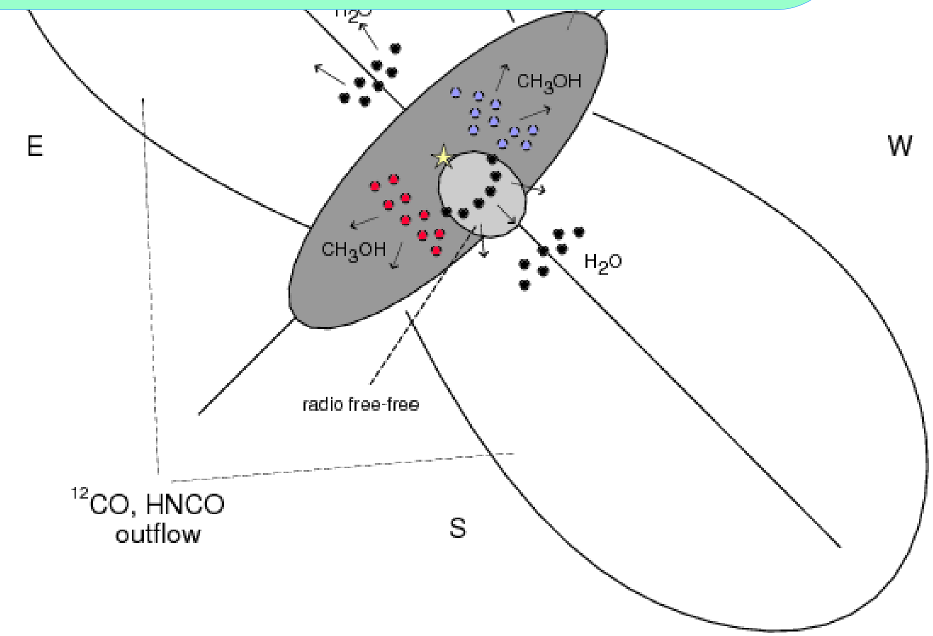
*and *then* generate* **Maser emission**

Molecules a

line radiatio

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 ~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.

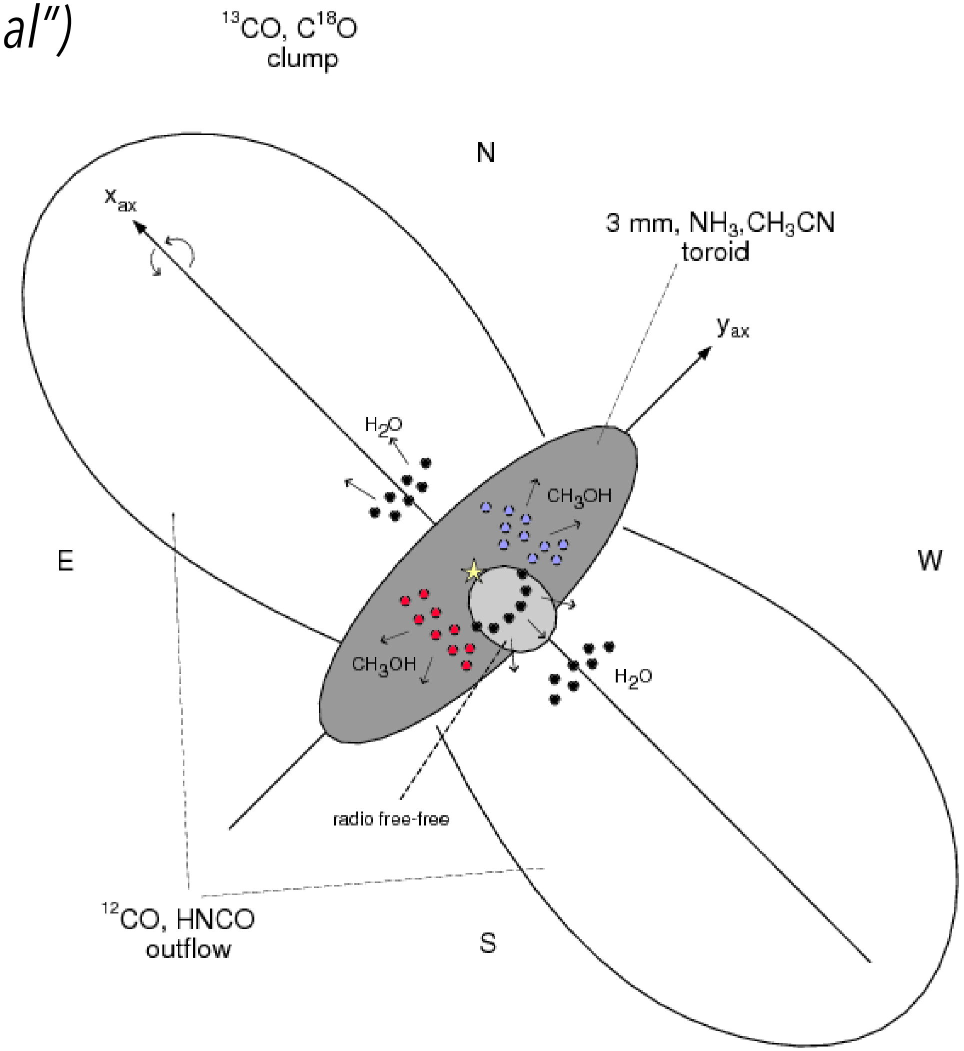
Summary of star formation and Young Stellar Objects (YSOs)

- Massive, luminous stars ionize their surroundings into HII regions. The expansion of these regions into ambient gas at ~ 10 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,

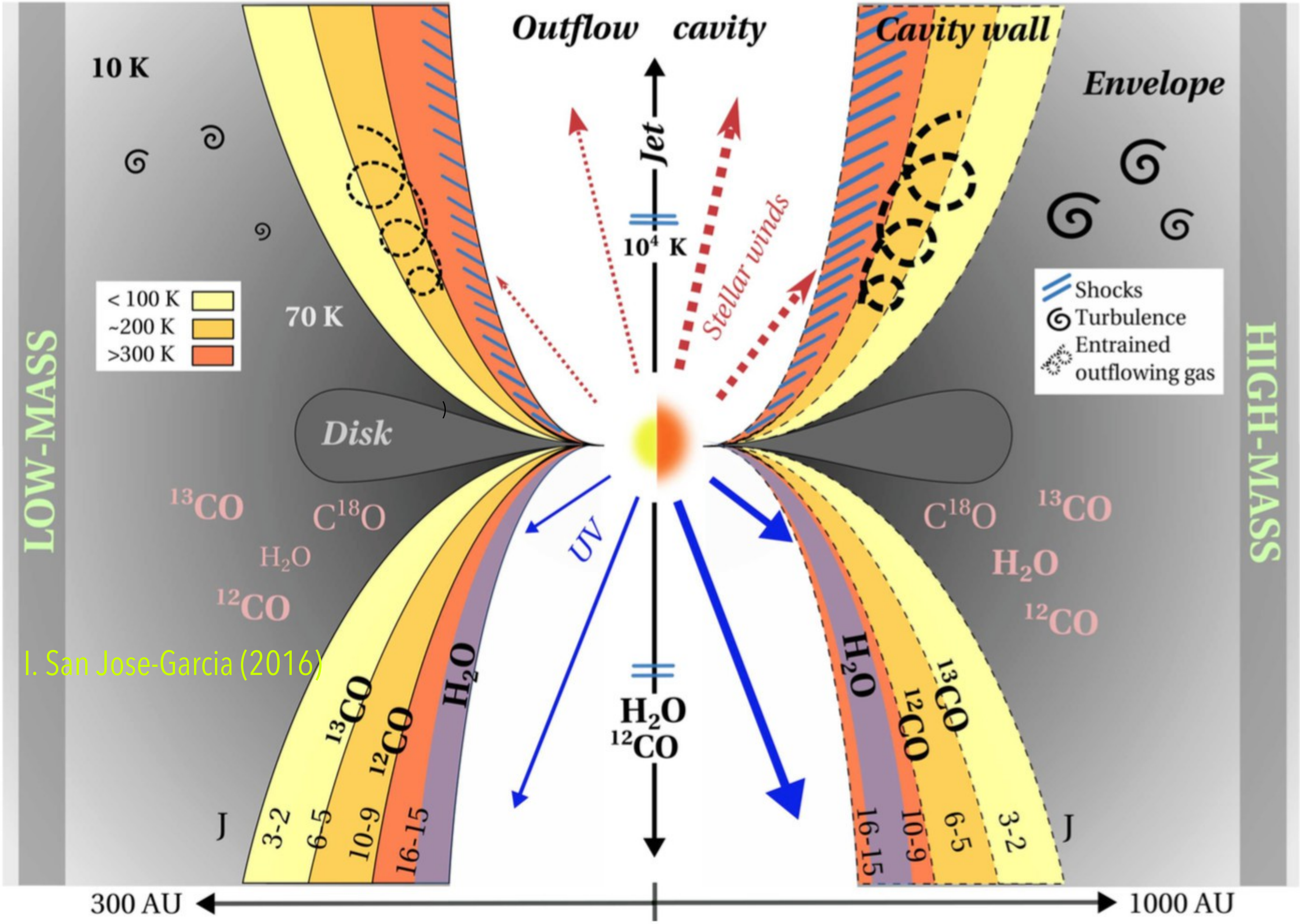
*and *then* generate* **Maser emission**

(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



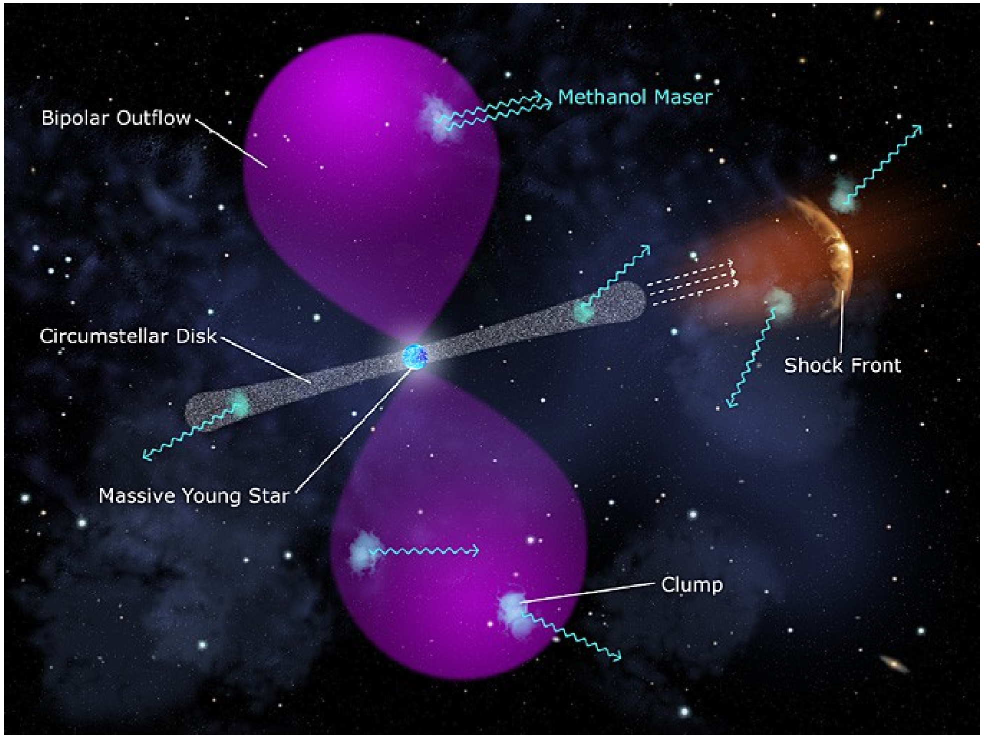
I. San Jose-Garcia (2016)

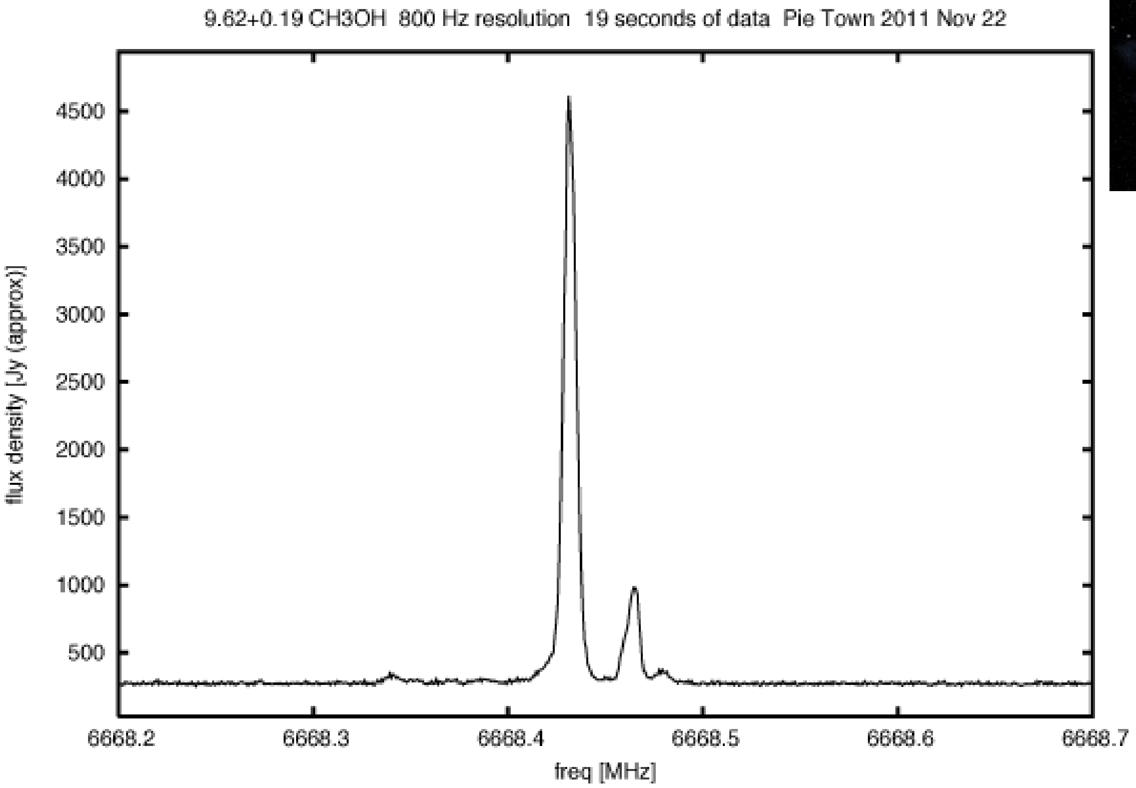
Figure 1.1: Cartoon illustrating the different components within the outflow, together with the temperature

Masers

Further readings:

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





Masers

Occur when LTE does not hold

First detected in the ISM in the '60s

***OH** (1965), $\boldsymbol{H_2O}$ (1969), $\boldsymbol{CH_3OH}$ (1970), **SiO** (1974)*

[CH, H_2CO, $\boldsymbol{NH_3}$, 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: $n \sim 10^5 - 10^{11}$ cm^{-3} >> than in ISM even in GMC

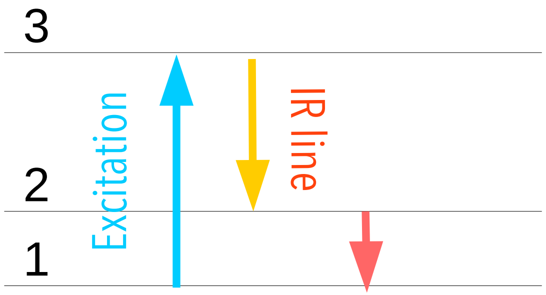
⇒ Condensations in the ISM

*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, H_2O 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^{-3})	T (K)
OH	18	10^5 -10^7	100-200
H_2O	1.35	10^7 -10^9	300-1000
CH_3OH	0.83 4.49	10^4 -10^5 10^4 -10^5	20-100 20-100
SiO	0.35	10^9 -10^{10}	700-1000
NH_3	1.25	10^4 -10^5	60-150
H_2CO	6.3	10^4 -10^5	20-40

Masers: radiative transfer (from Reid & Moran 1981)

Standard radiative transfer equation:

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

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

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 ΔR are sum and difference of the pump rates into masing levels, Ω is the beam solid angle of the microwave emission.

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

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

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:

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

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

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 ΔR are sum and difference of the pump rates into masing levels, Ω is the beam solid angle of the microwave emission.

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

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

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

Masers: radiative transfer

Standard radiative transfer equation:

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

can be rewritten in terms of temperature $T_B(r) = (T_{B_o} - T_x) e^{-\kappa r} + T_x$

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 $2B_{21} I \Omega / 4\pi > \Gamma$

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

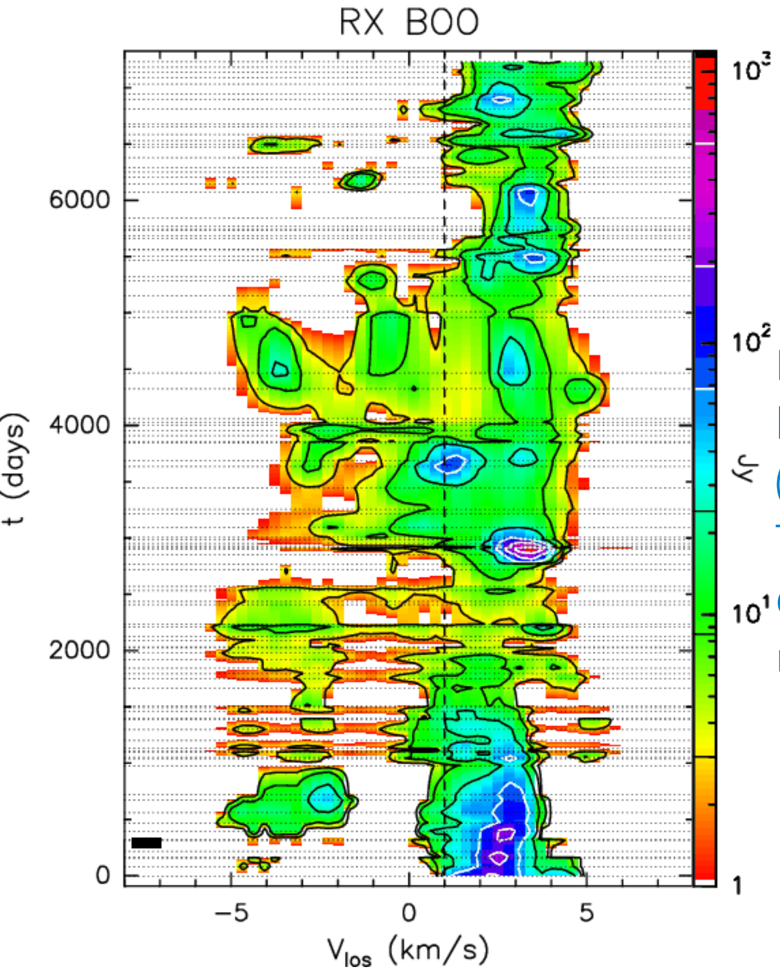
Saturated maser:

changes are proportional to κr less sensitive indicator of pump variations

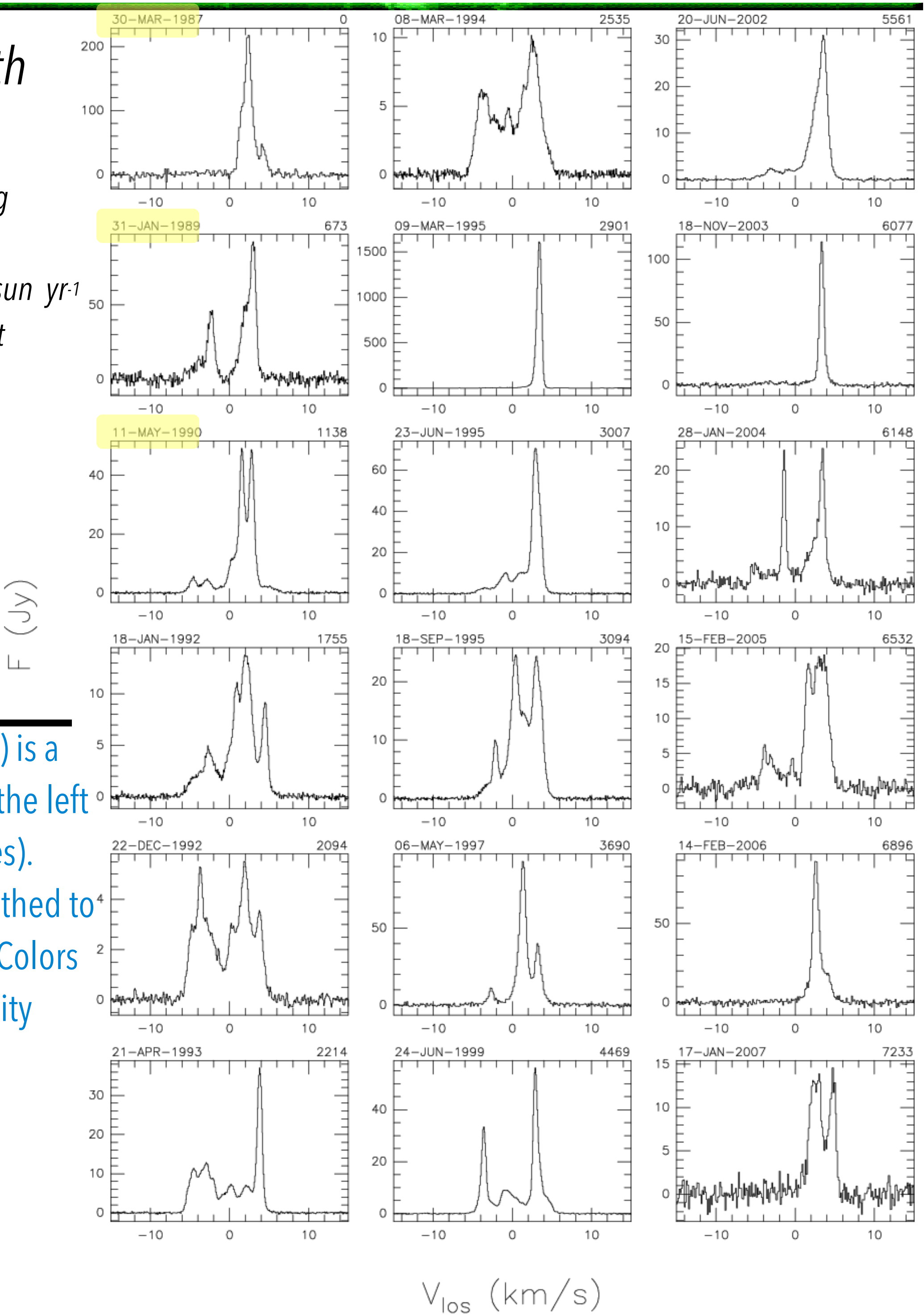
Interstellar Masers

*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 $6\ 10^{-7}$ Msun yr^{-1} and an expansion velocity of 9.3 km s^{-1}, whereas Teyssier et al. (2006), as a result of another model fit, obtained $2\ 10^{-7}$ Msun yr^{-1} and 7.5 km s^{-1}, respectively

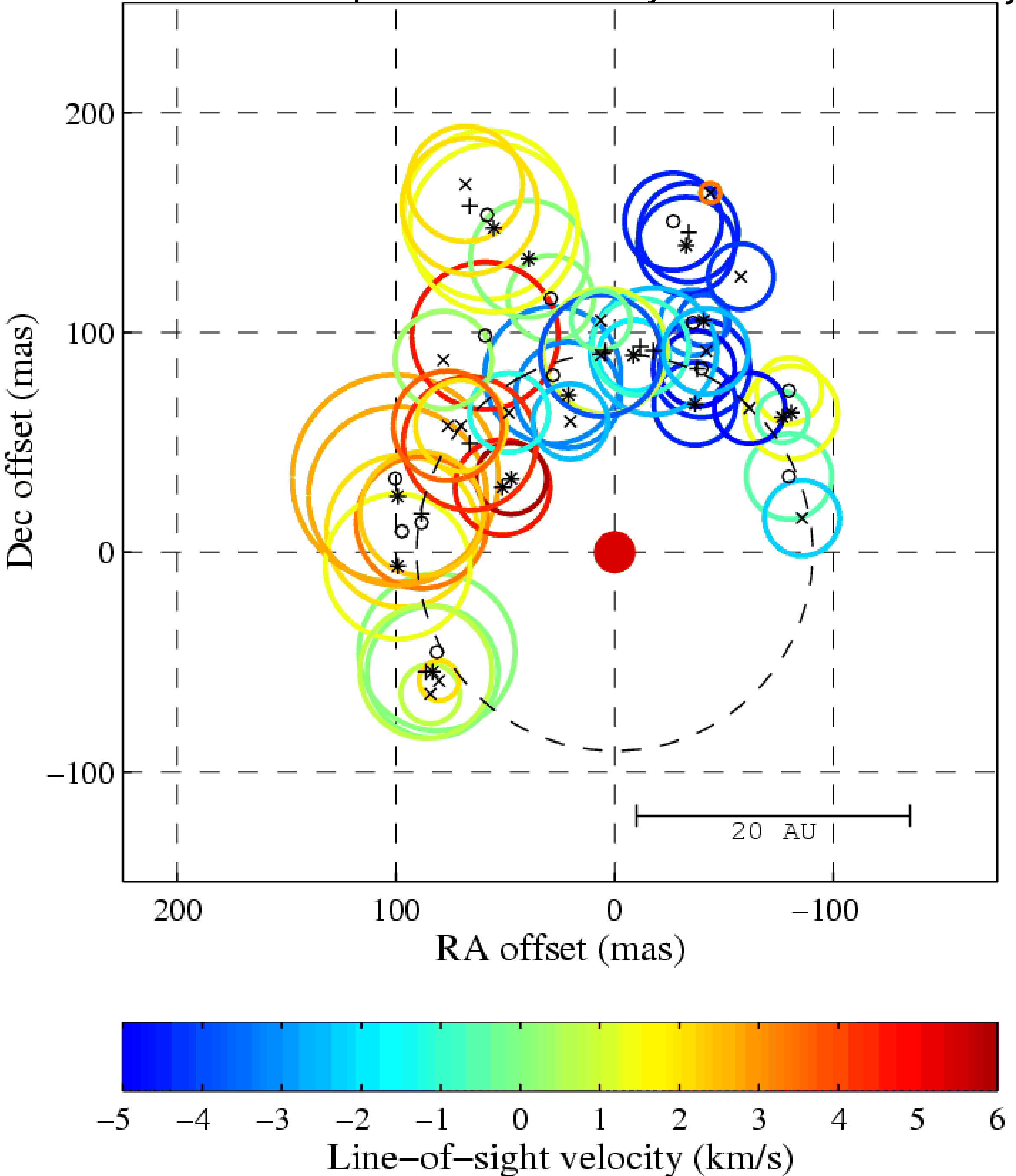


Each spectrum (right) is a line in the figure on the left (dotted orizontal lines). Times are then smoothed to obtain what we see. Colors represent line intensity



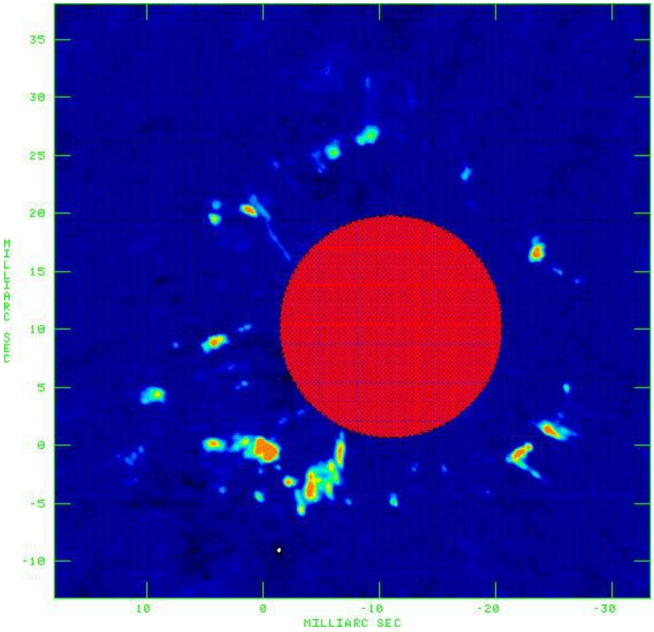
Interstellar Masers

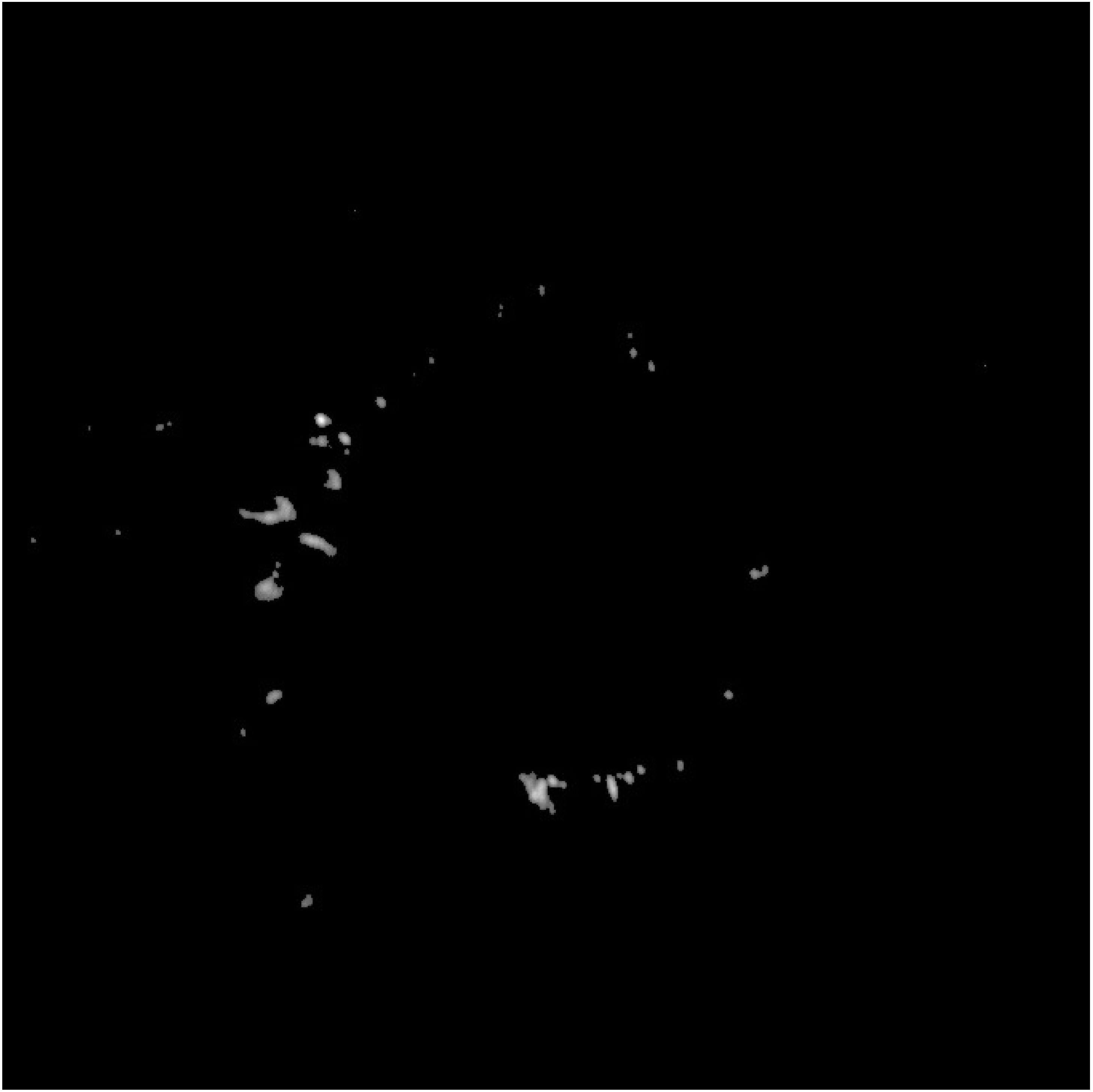
RX Boo: maser spots as a function of position, intensity and relative velocity



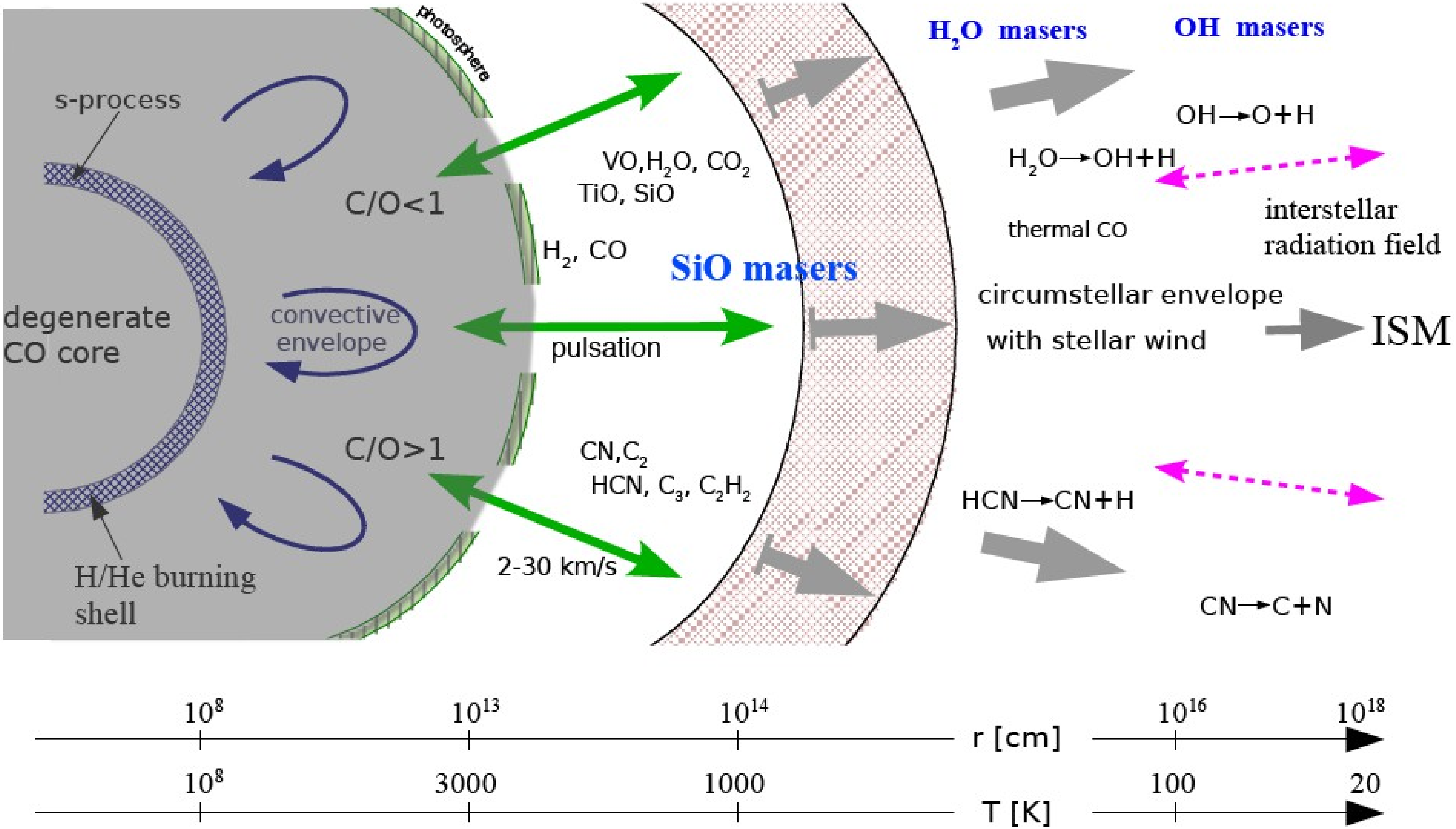
Interstellar Masers

TX Cam: VLBA movie





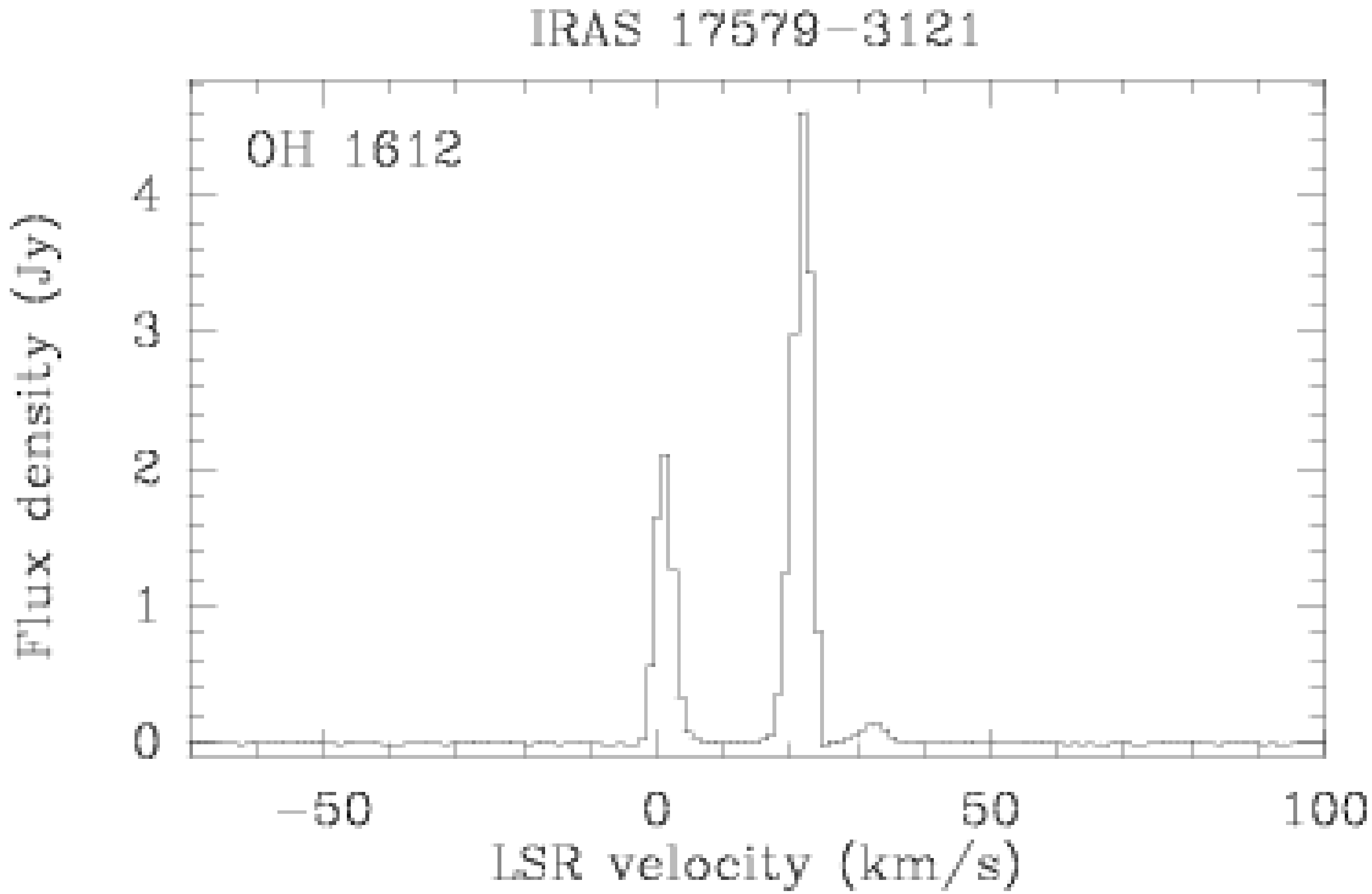
STAR **molecule formation** **dust formation** **photochemical reactions**



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

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

Masers (**OH** and **H_2O**) have been detected in external galaxies up to
z=0.265 (1.3 Gpc) and z=0.66 (4 Gpc) respectively

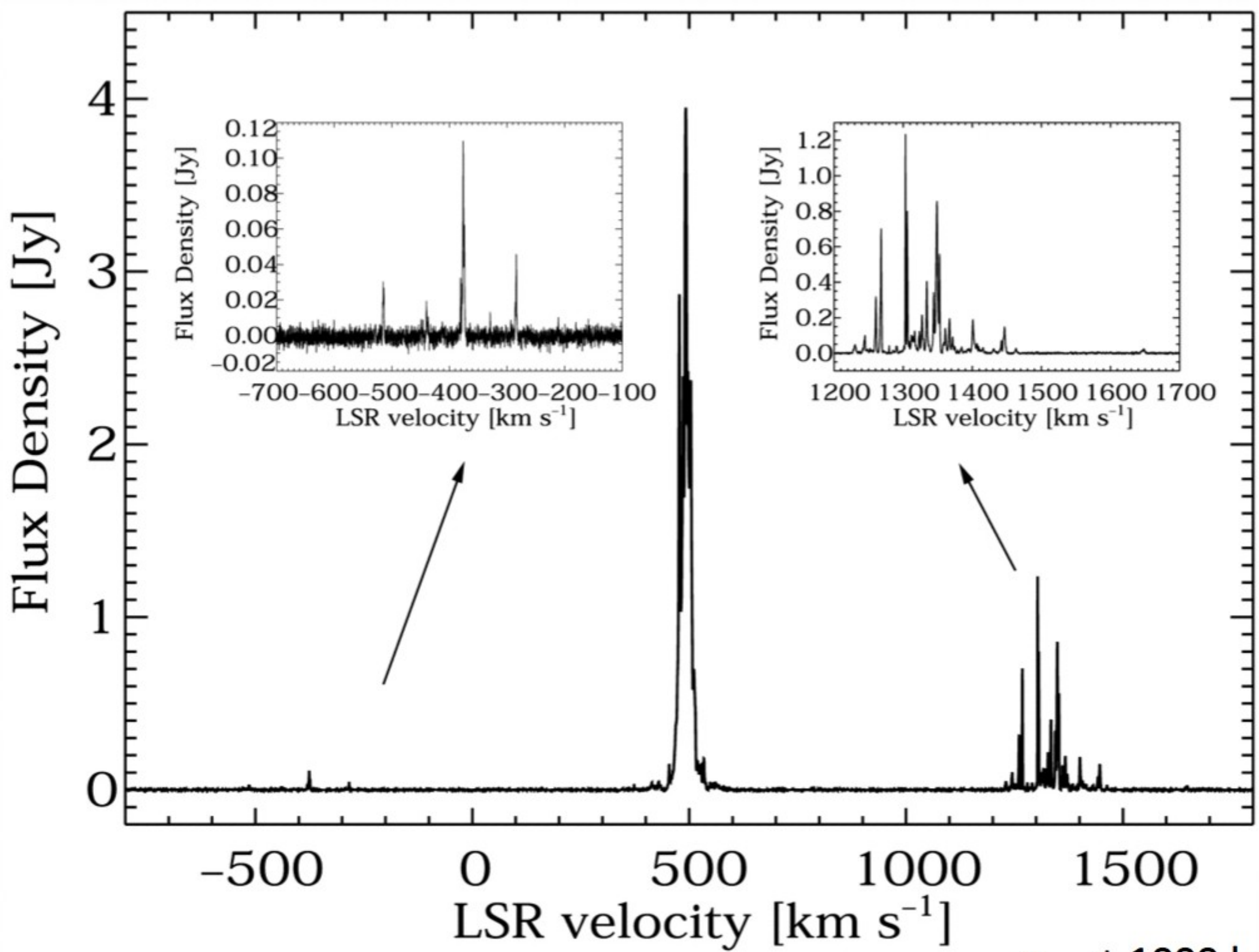
Their luminosities reach 10^6 times those of galactic masers and are then termed MEGAMASERS

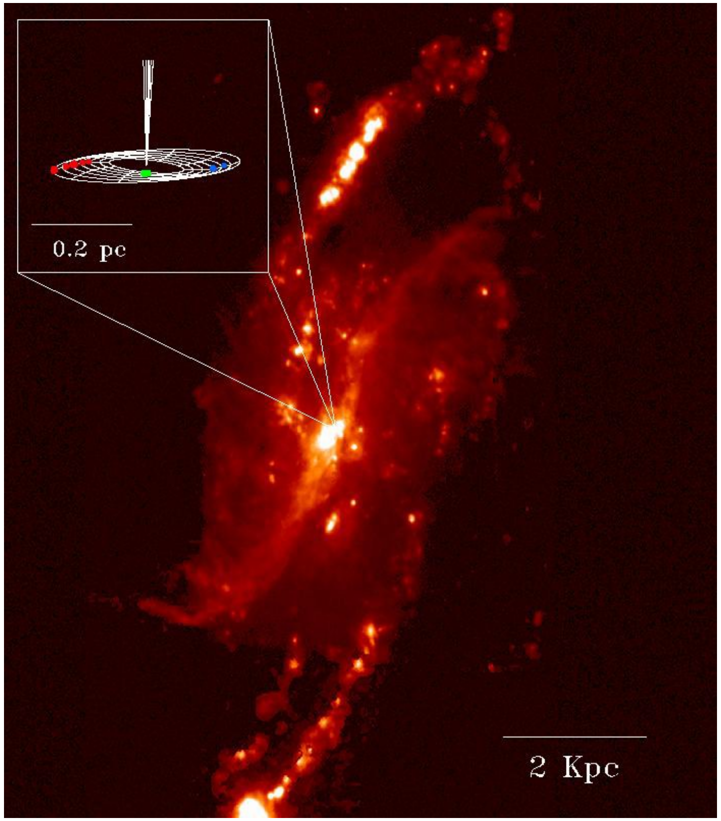
OH: found in the central 100 pc of ULIRGs, i.e. (nuclear) star bursting galaxies

H_2O: found within parsecs in AGNs (Sy2, Liners, ellipticals)

Megamasers: NGC4258

Strong nuclear water maser at 22 GHz





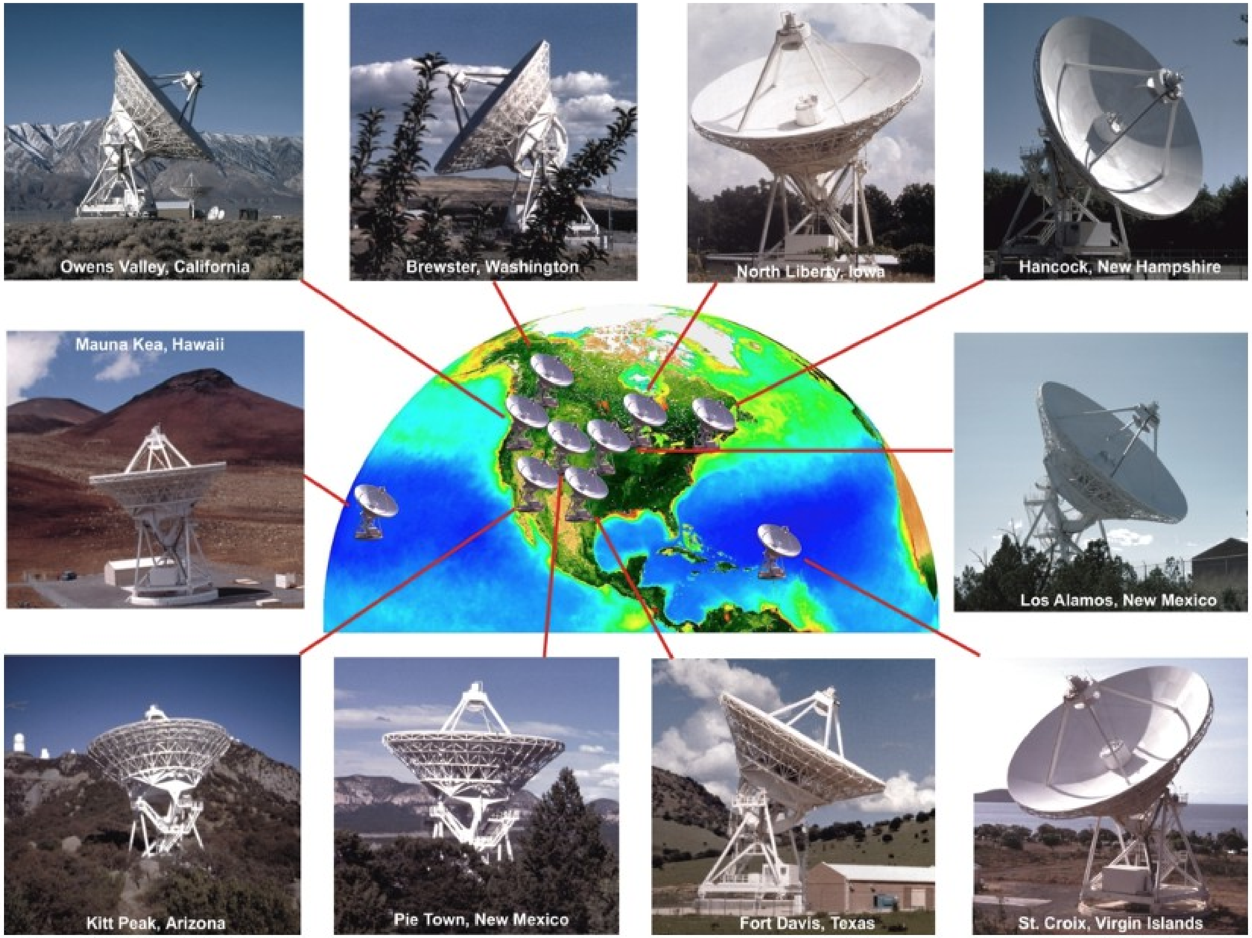
Single dish
Observation

v_{sys} ± 1000 kms^{-1}

GBT (Modjaz et al. 2005)

Megamasers: NGC4258

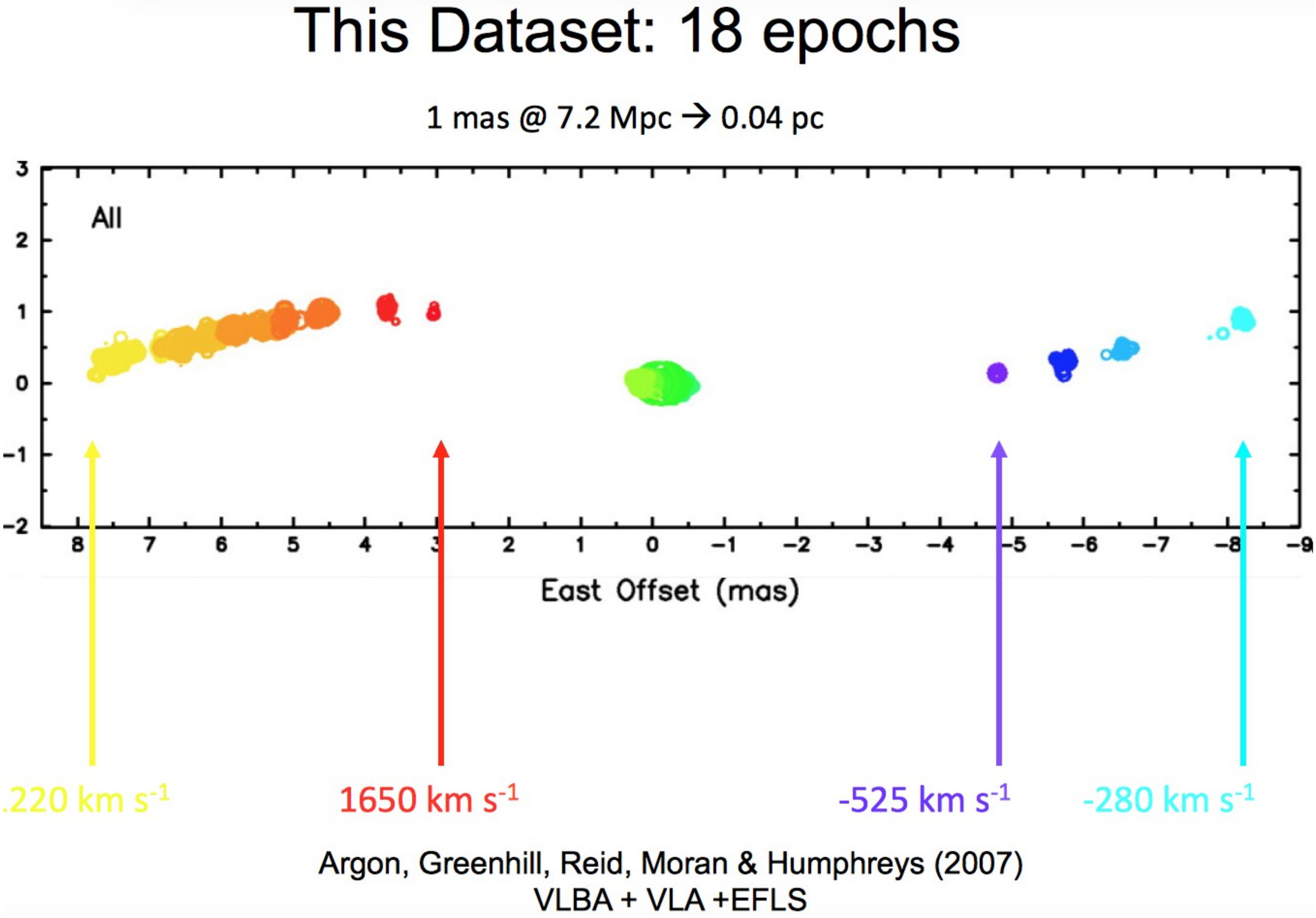
VLBA imaging and spectroscopy of NGC 4258



VLBA: Angular resolution = 200 μas (0.006 pc at ~ 7.0 Mpc)

Spectral resolution < 1 kms^{-1}

Megamasers: NGC4258



This Dataset: 18 epochs

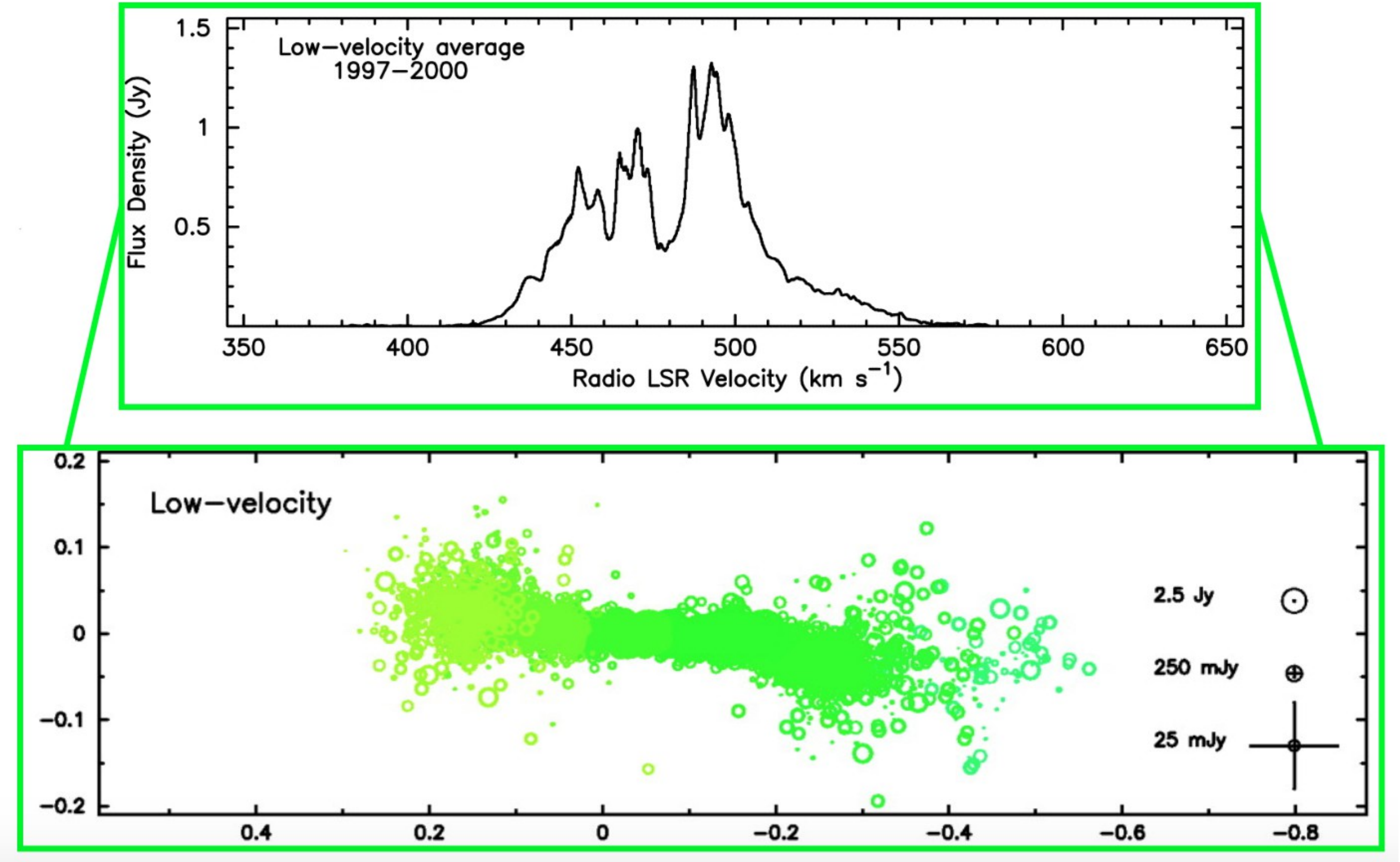
1 mas @ 7.2 Mpc → 0.04 pc

220 km s^{-1} 1650 km s^{-1} -525 km s^{-1} -280 km s^{-1}

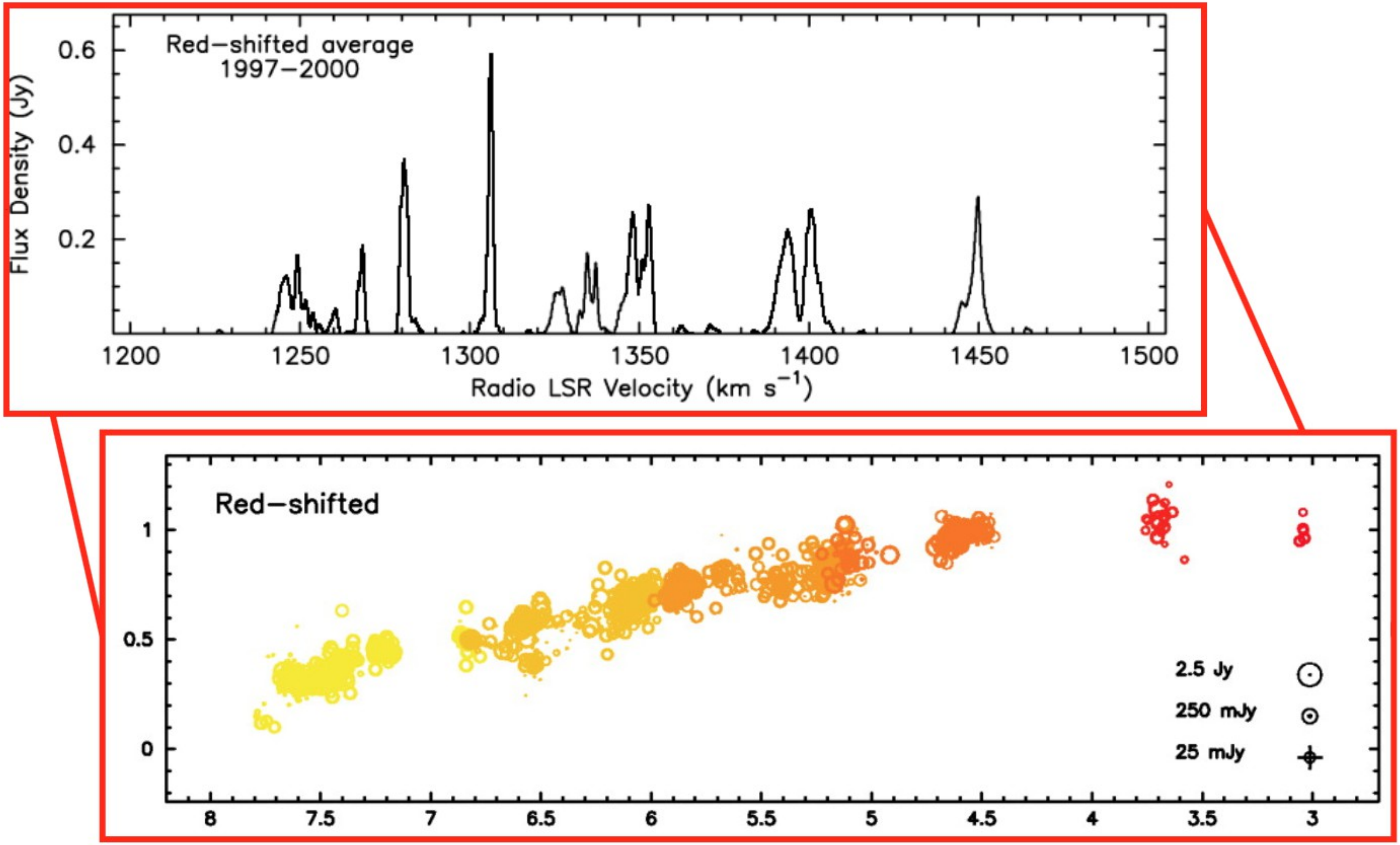
Argon, Greenhill, Reid, Moran & Humphreys (2007)
VLBA + VLA +EFLS

Megamasers: NGC4258

Systemic Maser Emission

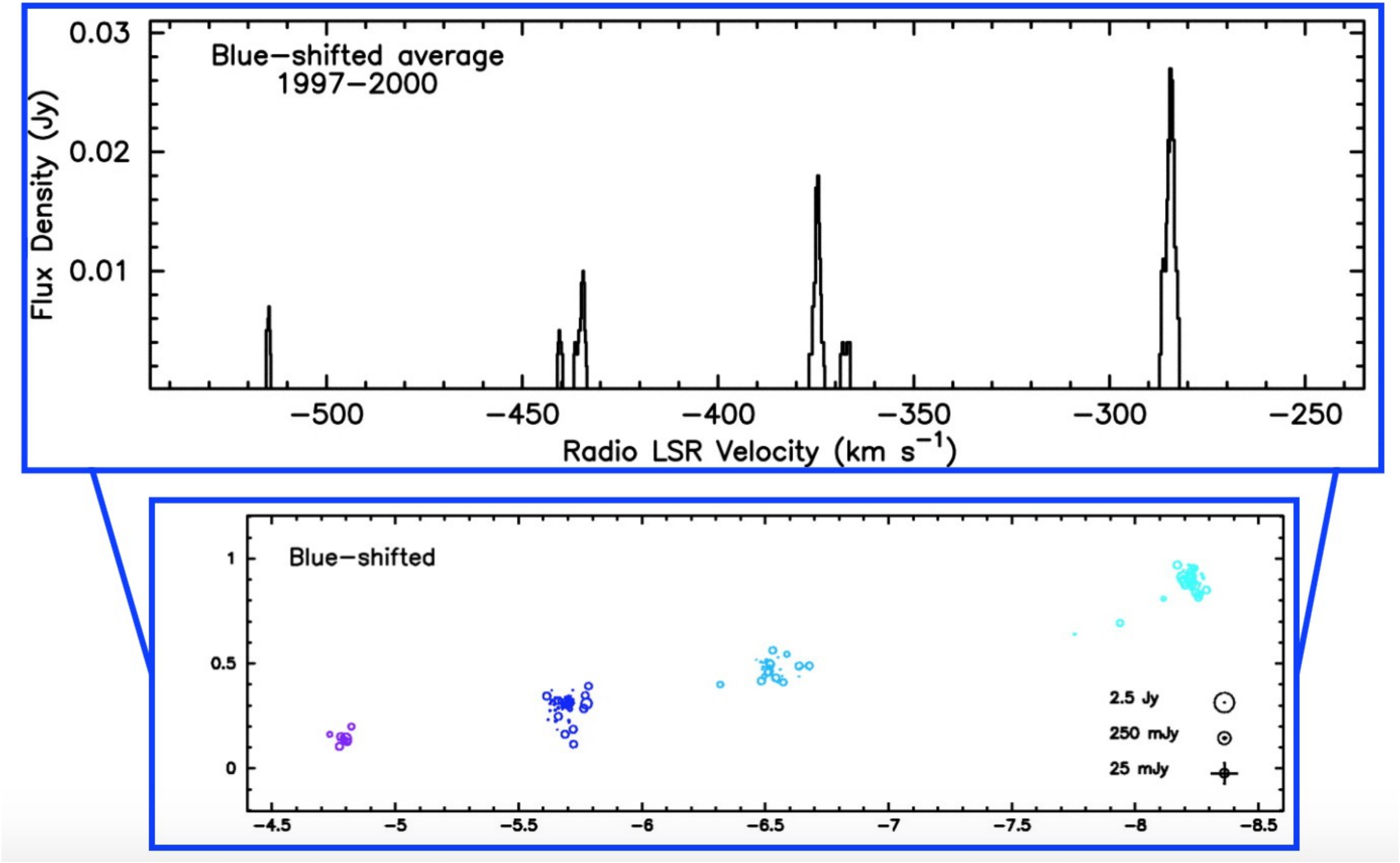


Red-shifted emission



Megamasers: NGC4258

Blue-shifted Emission



Megamasers: NGC4258

VLBA imaging and spectroscopy

- individual masers resolved and v_{rad} assigned to individual components
- objects in front of AGN have v_{rad} ~ 470 km/s (systemic velocity)

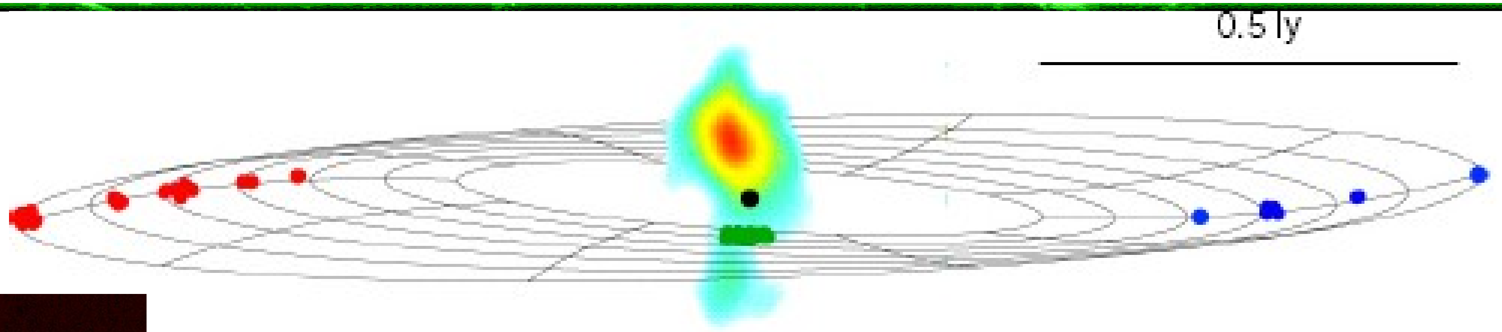
  the inclination angle relative to AGN is i ~ 82°
- objects at the edges have v_{rad} ~ 470 ± 1000 km/s (– blue and + red shifted)
- a rotating Keplerian disk provides a perfect fit to each individually observed components of the three radial velocity systems with an accuracy better than 1%

BH mass ~ 4.0 ± 0.1 10^7 M_{SUN}

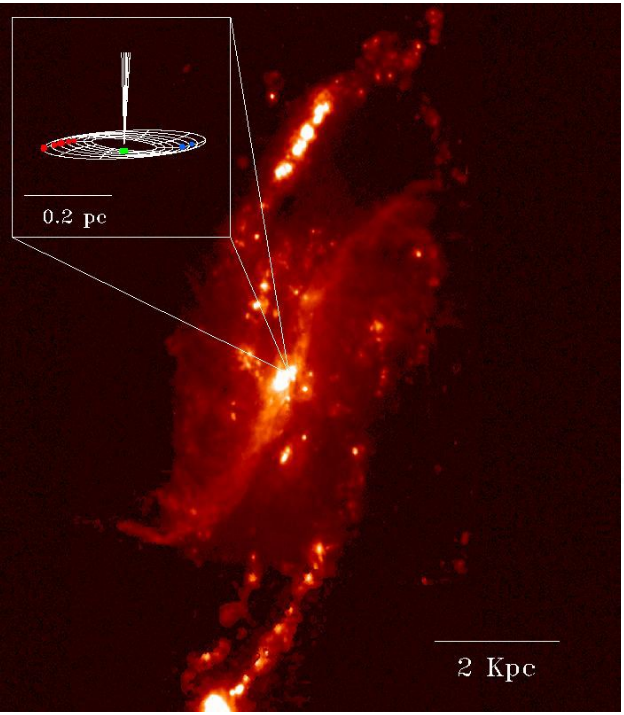
Distance ~ 7.6 ± 0.3 Mpc

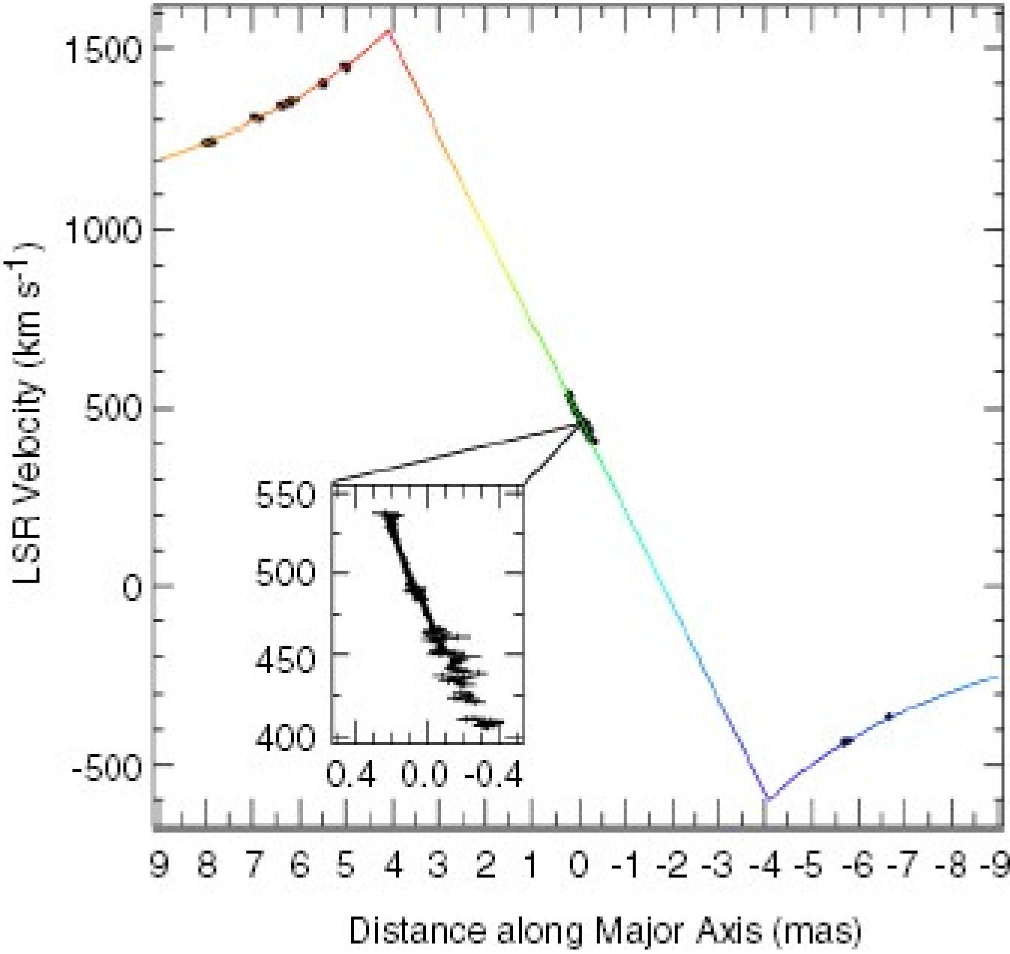
For details on Megamaser modelling and explanation on geomety, see:
http://www.ifa.hawaii.edu/users/kud/teaching_15/12_Megamasers.pdf

Megamasers: NGC4258 black hole mass $4.0 \pm 0.1\ 10^7\ M_{SUN}$



Based on Herrnstein, Greenhill et al. 1998





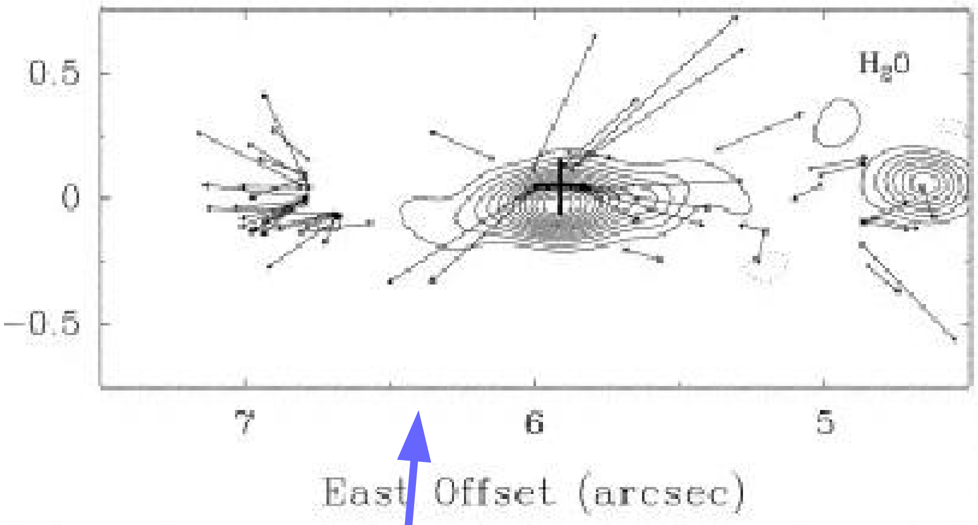
Miyoshi et al. 1995

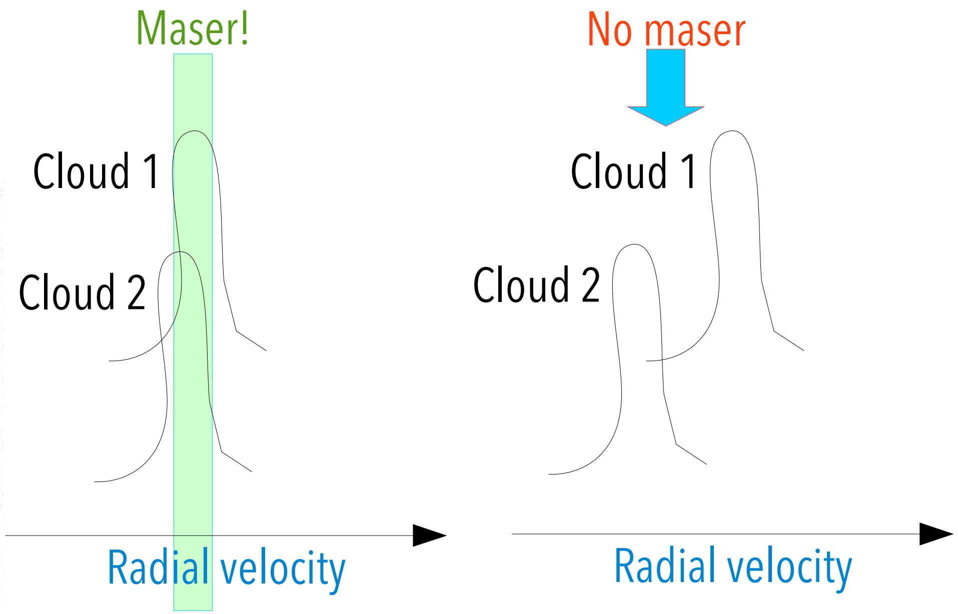
Arrangement : Greenhill

Interstellar Masers.... and beyond

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

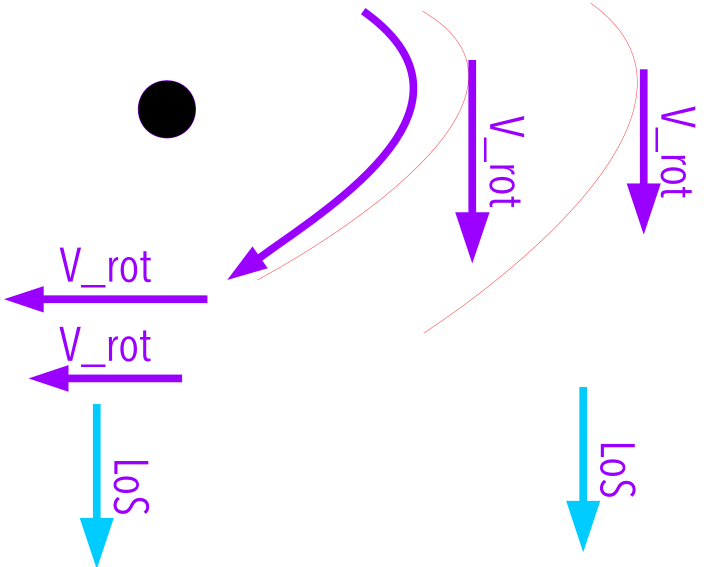
There is "velocity coherence" ⇨ *i.e. Masing molecules must be at the same radial velocity within the thermal width along the gain path*

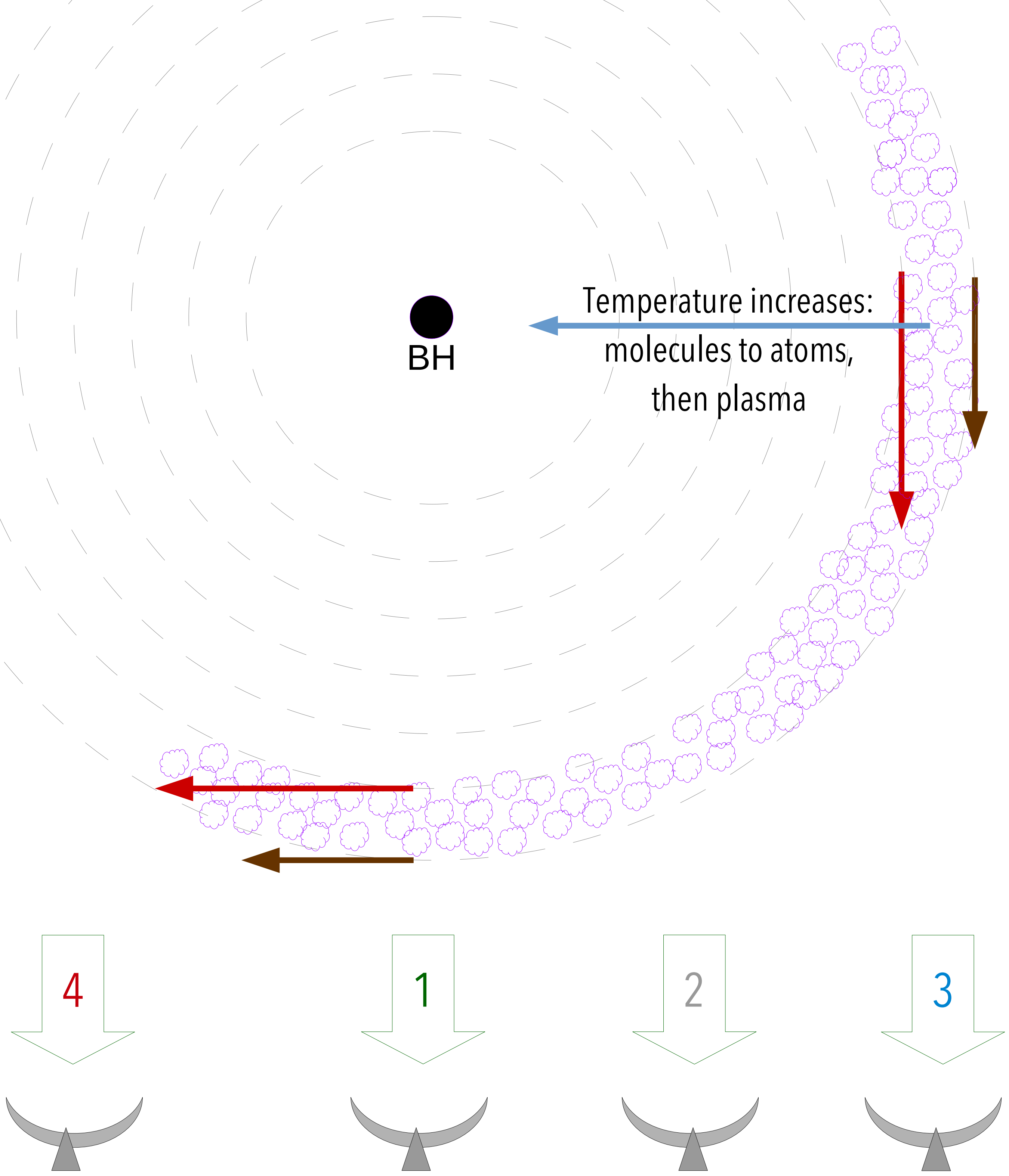




Pumping (2)

- *Radiative*
- *Collisional*





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

- 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