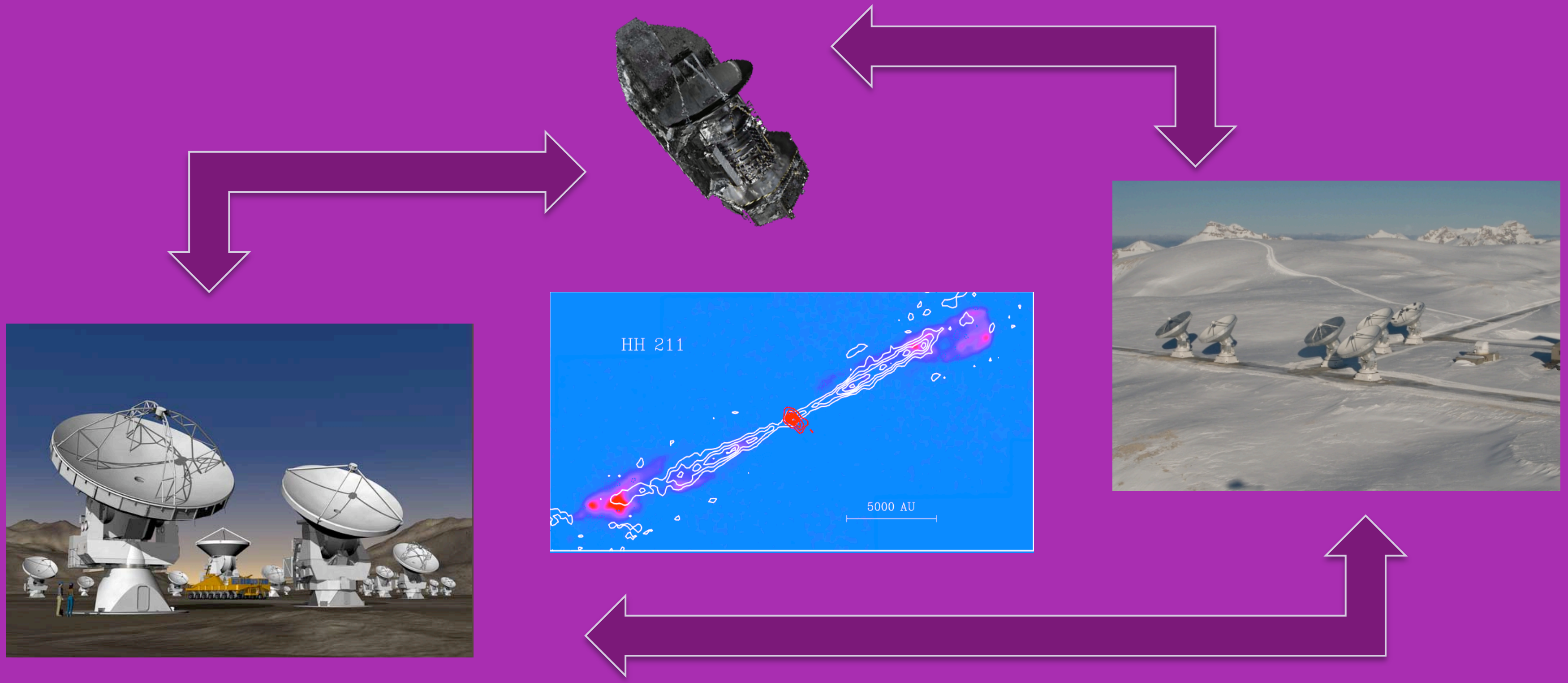
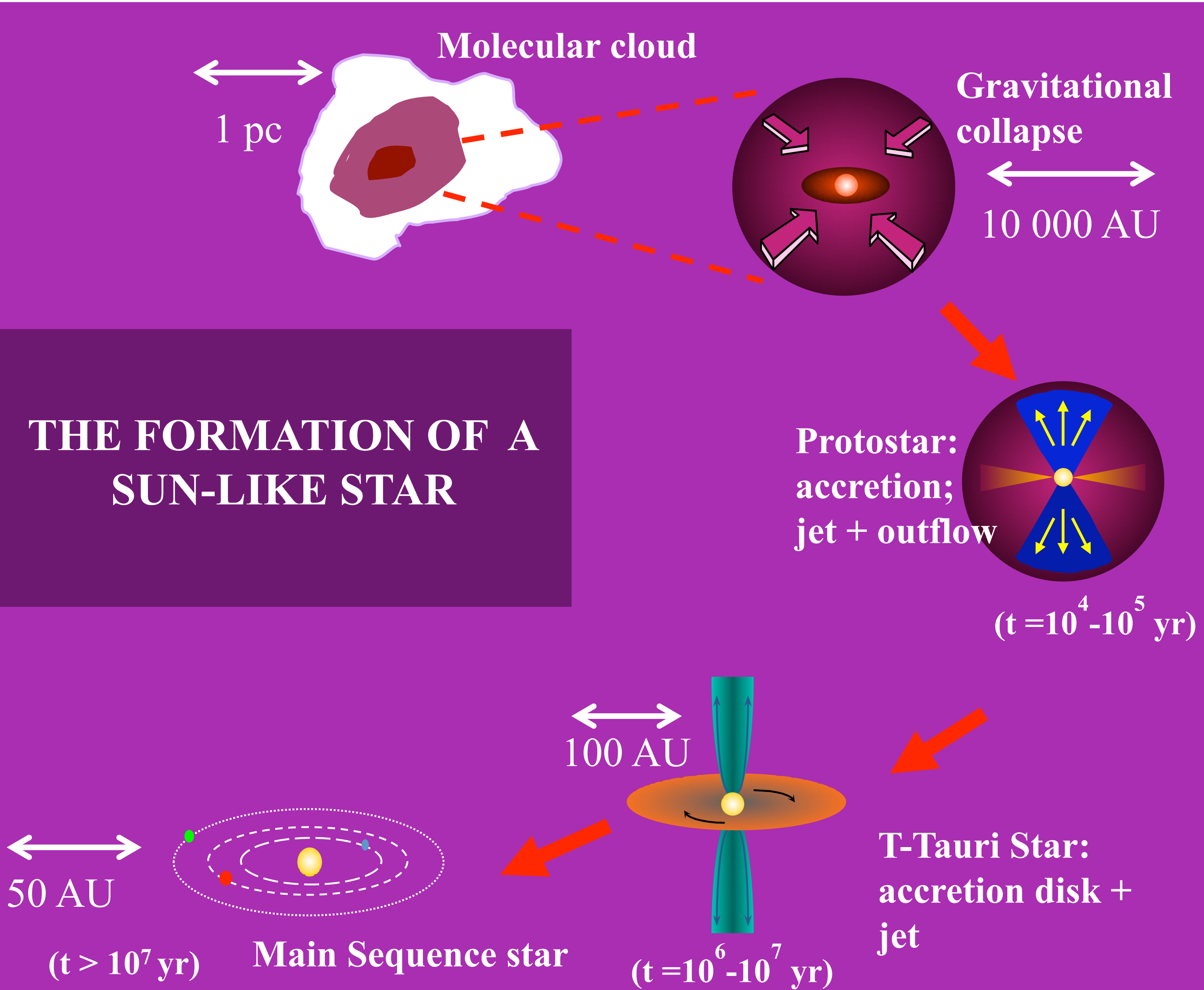
FROM THE ALPS TO ANDES:
PROTOSTELLAR JETS AS OBSERVED AT SUBMM-WAVELENGTHS

C. Codella (INAF, OAA)



THE FORMATION OF A SUN-LIKE STAR



Molecular cloud

1 pc

Gravitational collapse

10 000 AU

Protostar: accretion; jet + outflow

(t =10^4-10^5 yr)

100 AU

T-Tauri Star: accretion disk + jet

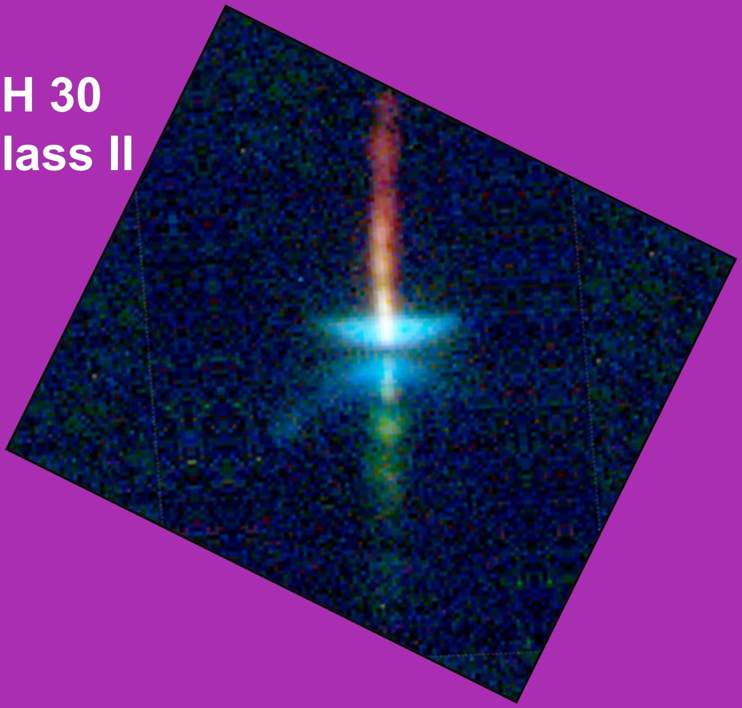
(t =10^6-10^7 yr)

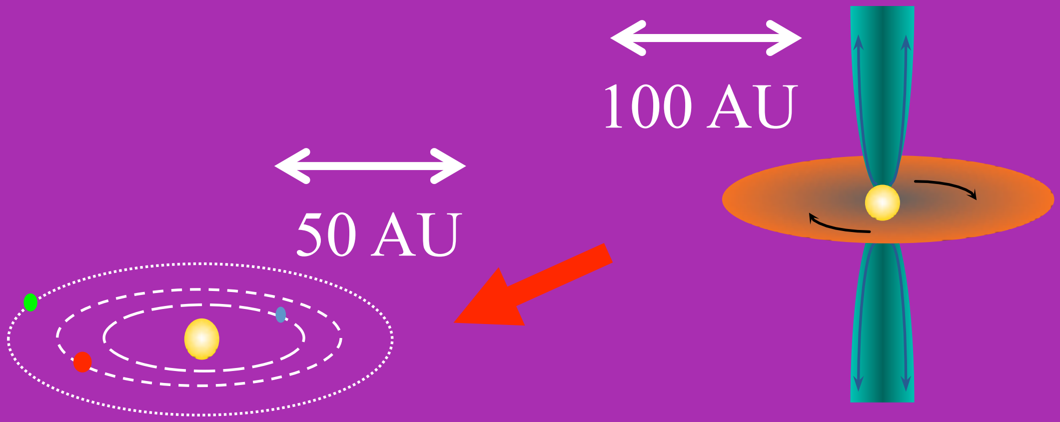
50 AU

(t > 10^7 yr)

Main Sequence star

HH 30
Class II





100 AU

50 AU

T-Tauri Star:
accretion disk + jet

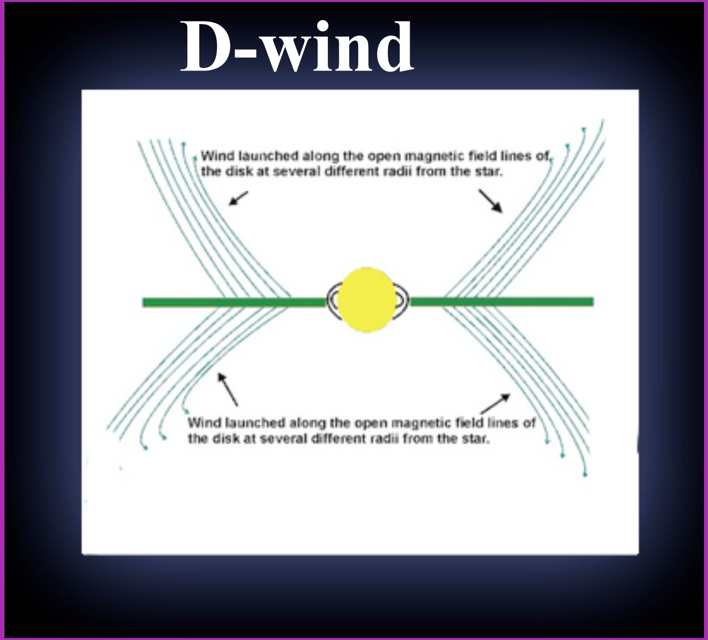
(t > 10^7 yr) **Main Sequence star**

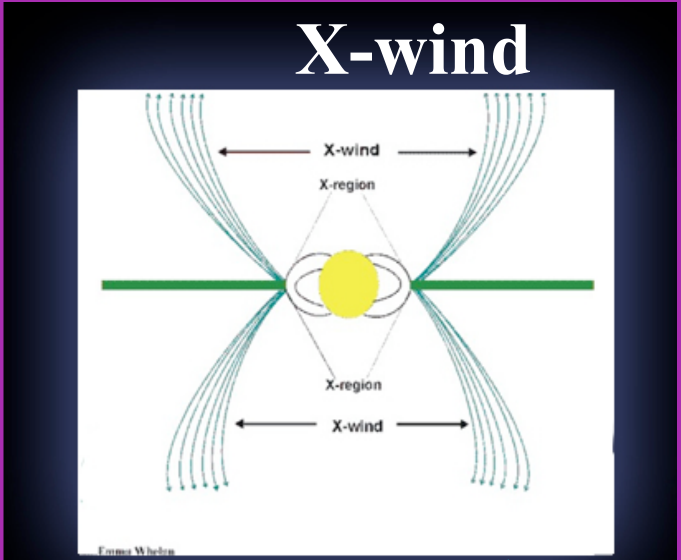
(t =10^6-10^7 yr)

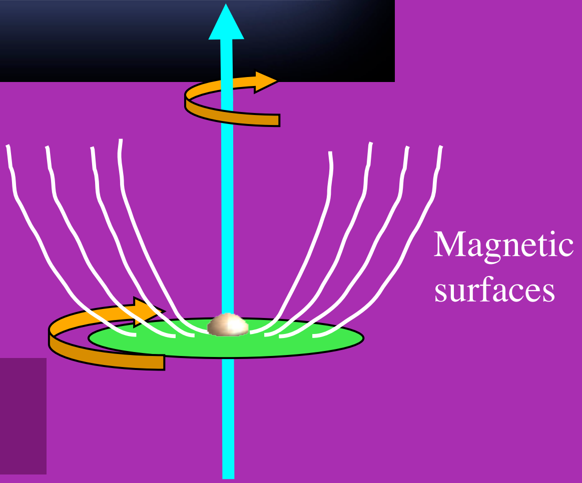
The launching and collimation of jets

Jets from protostars are launched centrifugally along magnetic field lines, although the precise mechanism is still hotly debated

MHD models predict that jets extract excess angular momentum from the star/disk system


D-wind


X-wind



Origin of the jet in the disk plane: 0.03 to a few AU

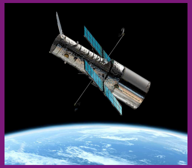
Acceleration and collimation of jet: within 20-100 AU above the disk

Rotation is transferred to the jet from the disk

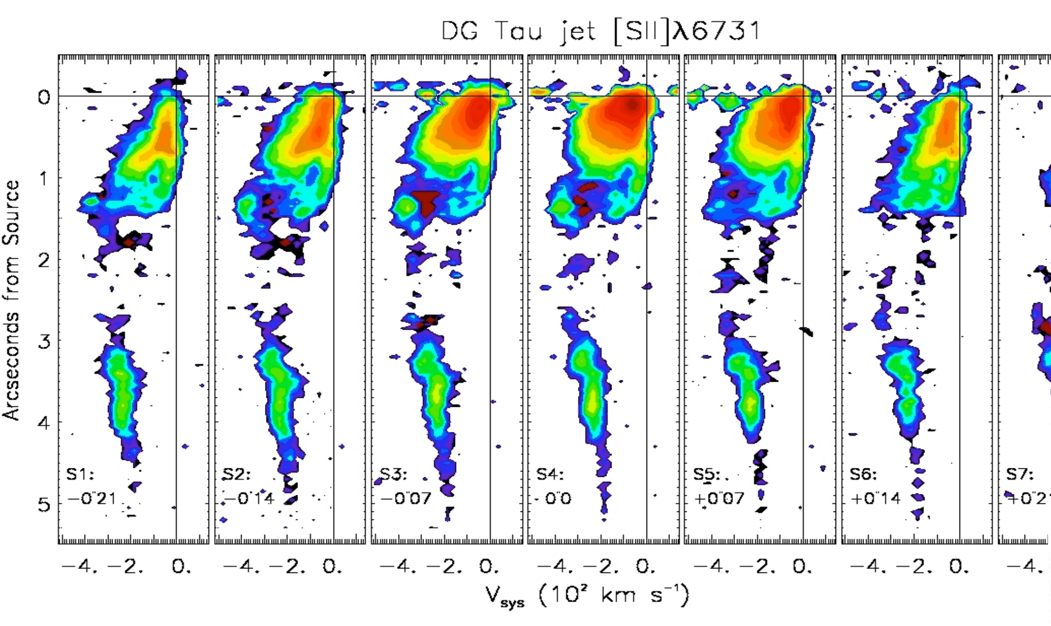
Anatomy of spectral jets

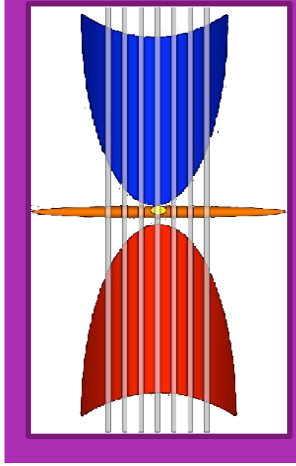
Main goal: to constrain launch mechanism

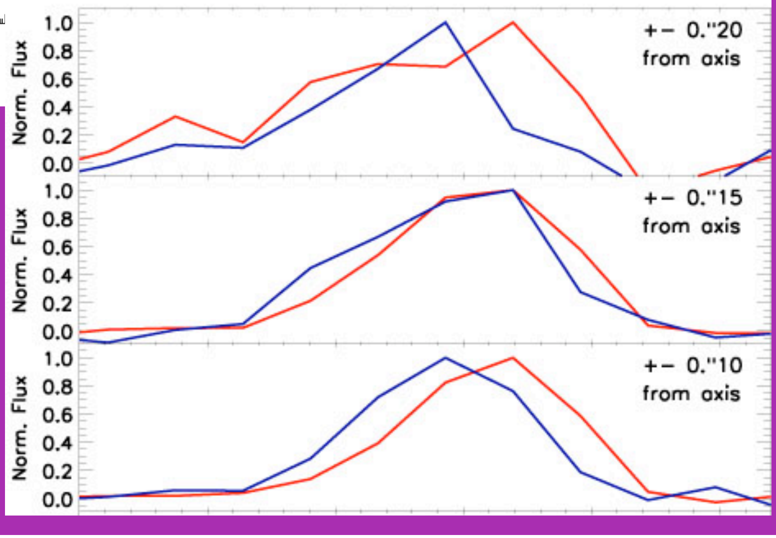
High spectral resolution with HST !



JeTseT



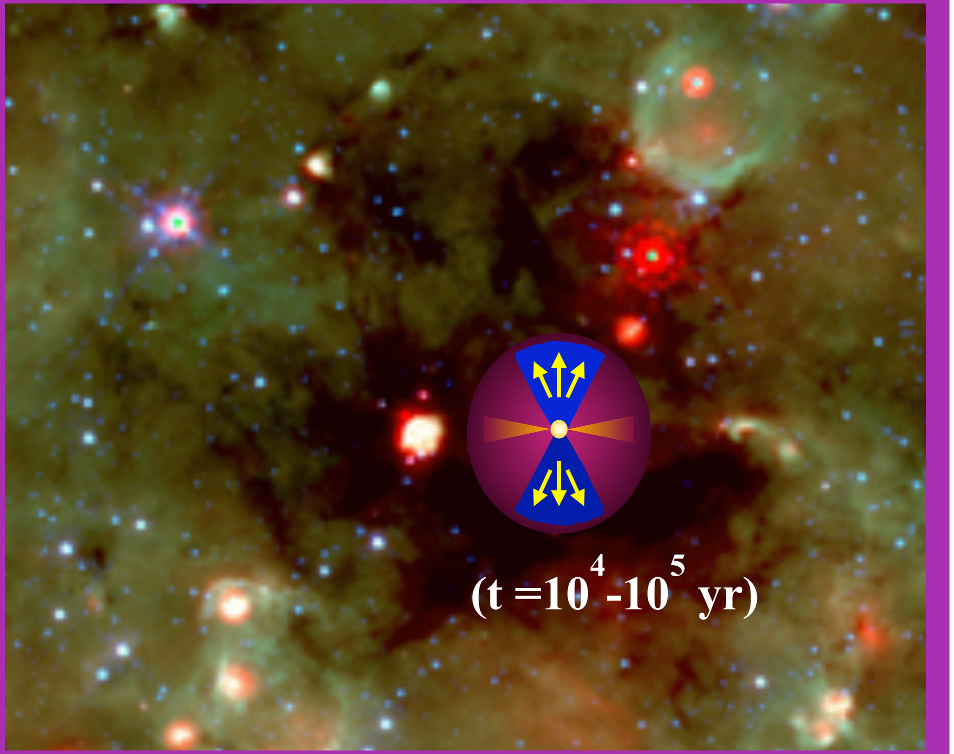




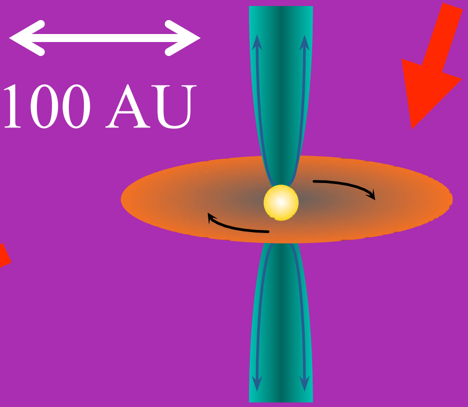
Jet rotation !

Bacciotti et al. (2000), Coffey (2012)

Protostar:
main accretion phase;
jet + outflow

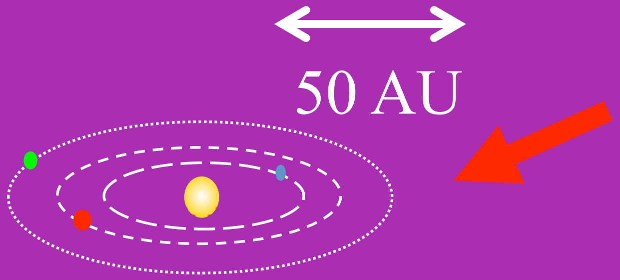


(t =10^4-10^5 yr)



T-Tauri Star:
accretion disk + jet

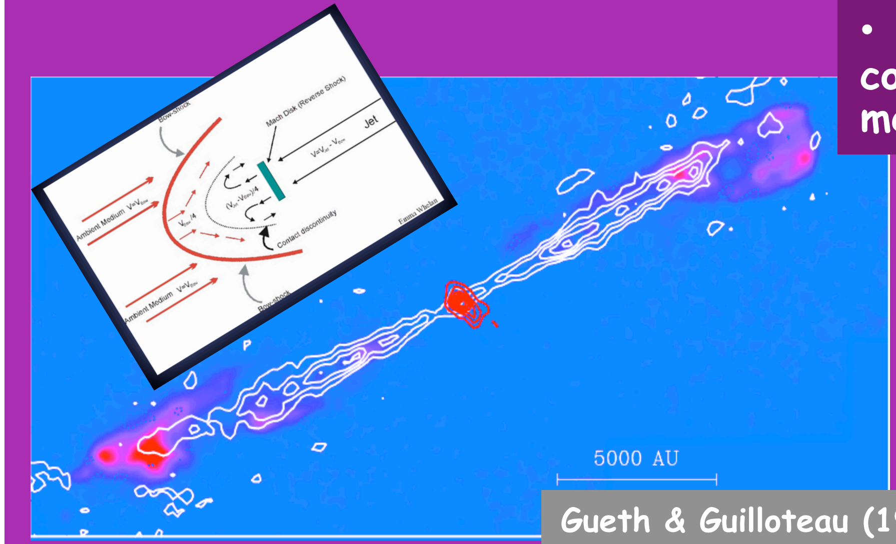
(t =10^6-10^7 yr)



(t > 10^7 yr) **Main Sequence star**

Propagation of (jet-driven) outflows

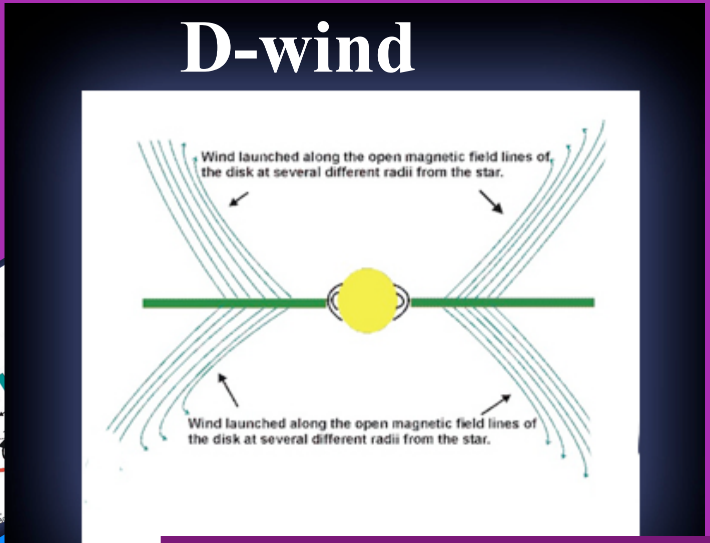
- Rapid heating (from ~10 to a few 1000 K) and compression of the gas → "Shock chemistry"
- High-T chemistry: endothermic reactions
- Ice sublimation & Grain disruption
- The shocked gas acquires a chemical composition distinct from that of the unperturbed medium

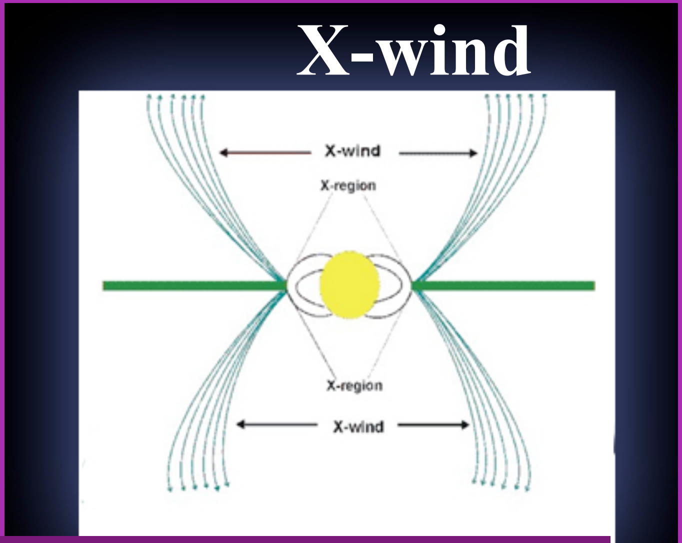


Gueth & Guilloteau (1992)

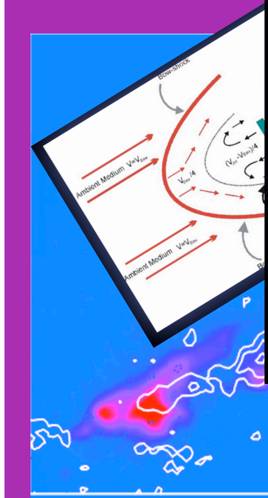
SiO production along jets:
due to shock reprocreleases silicon in the gas phase (sputtering of Si atoms from grains in shocks with speeds essing of dust, which > 25 km/s), allowing a quick formation of SiO through reactions involving OH (e.g. Schilke et al. 1997)

Propagation of (jet-driven) outflows





SiO formed inside or outside the dust sublimation radius?
SiO abundance constrains models!



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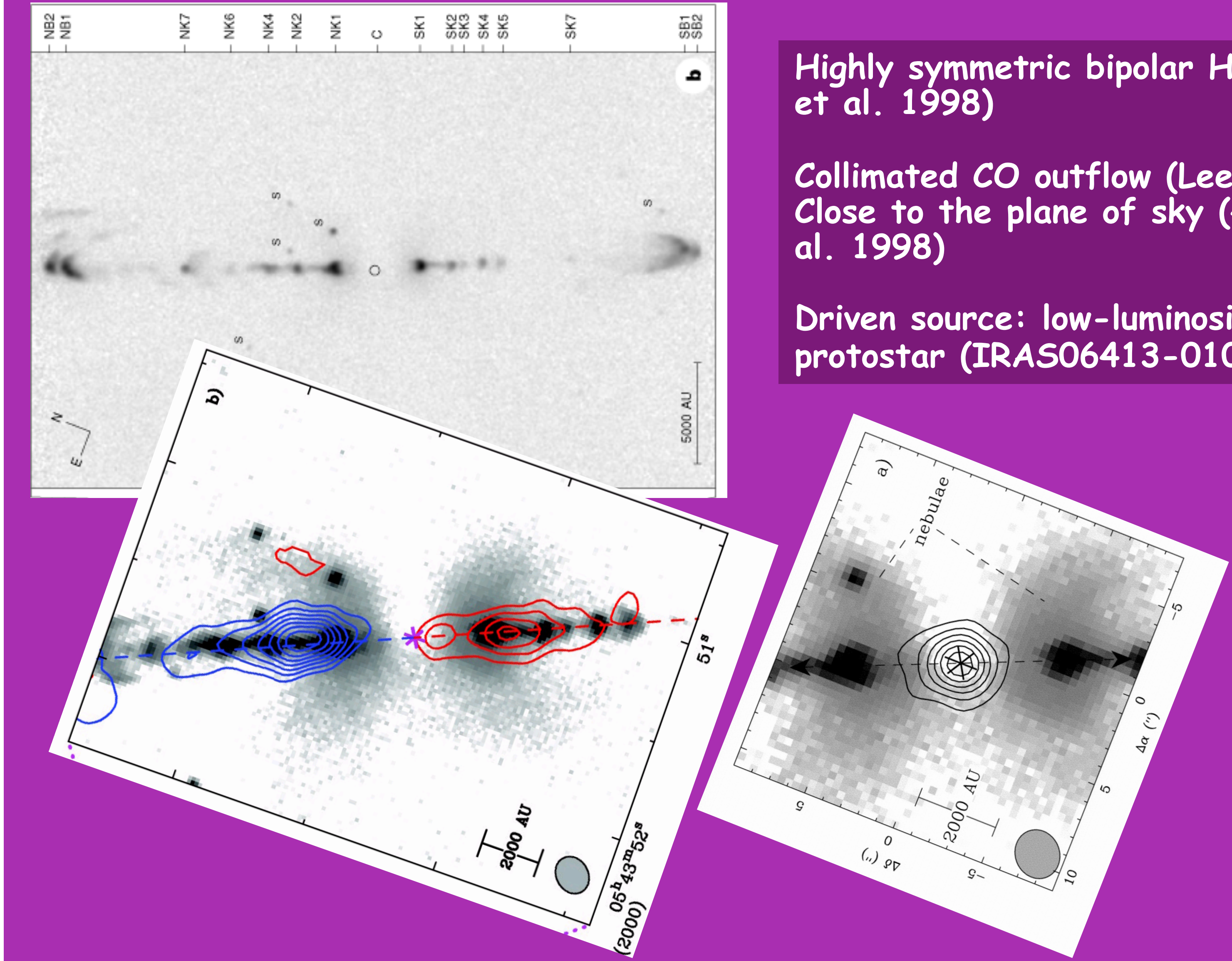
The HH212 star forming region (Orion)

Highly symmetric bipolar H_2 jet (Zinnecker et al. 1998)

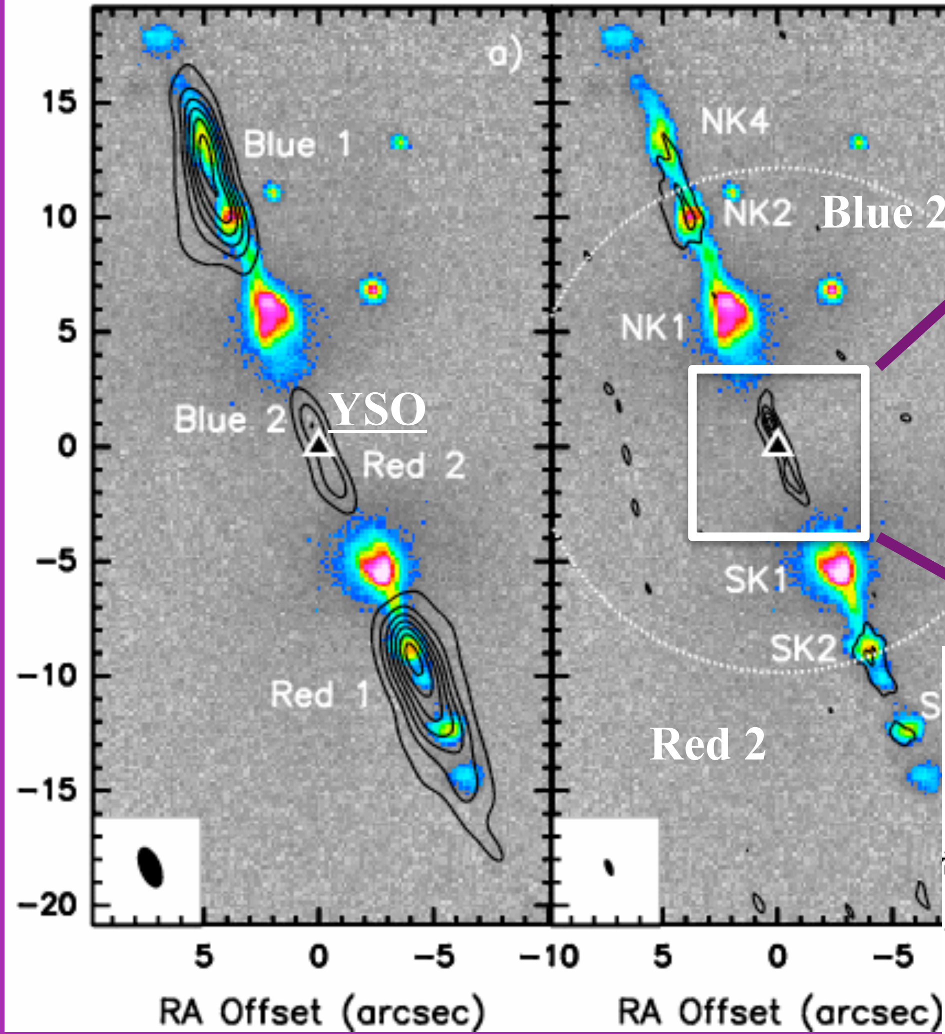
Collimated CO outflow (Lee et al. 2006)
Close to the plane of sky (4°; Claussen et al. 1998)

Driven source: low-luminosity Class 0 protostar (IRAS06413-0104)



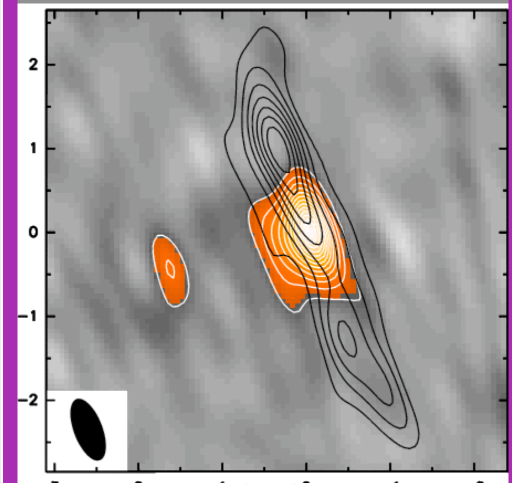
Digging in the dark

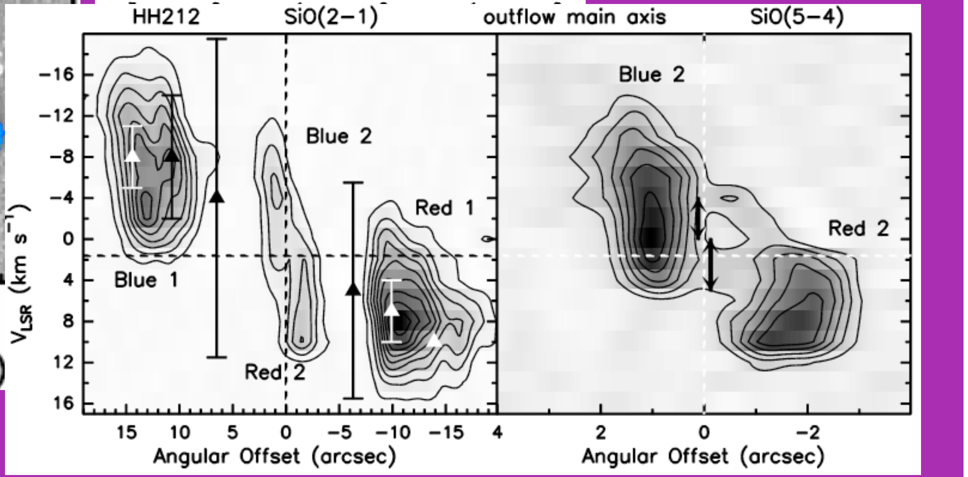
SiO(2-1) & SiO(5-4) vs. (IR) H_2



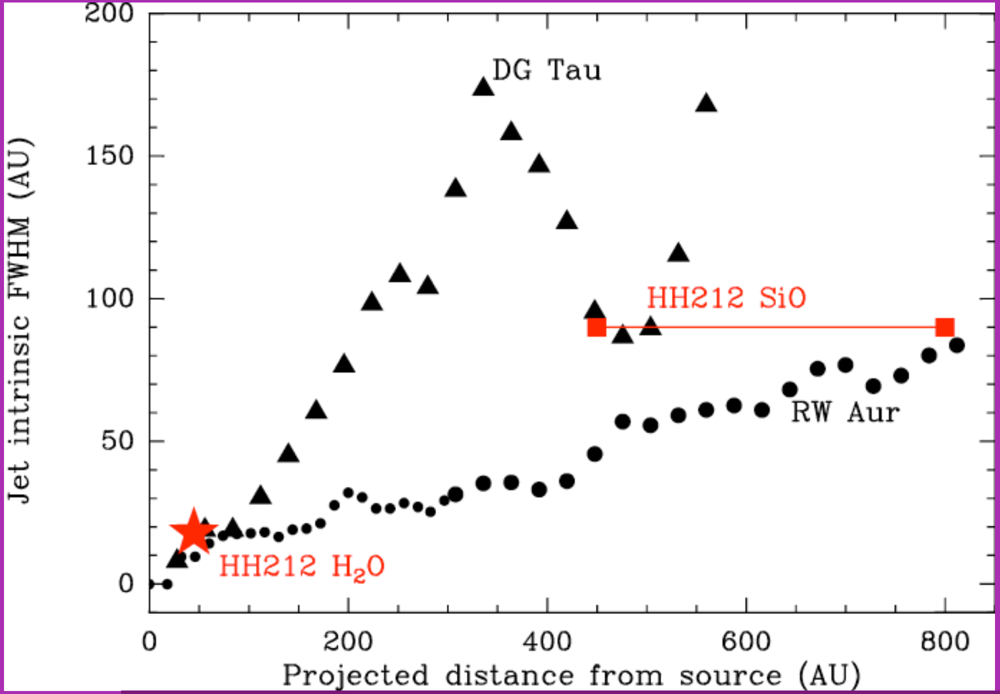
Protostellar system: primary jet from a Class 0 protostar (Codella et al. 2007, 2012)

SiO(5-4) vs.1.4mm





Digging in the dark



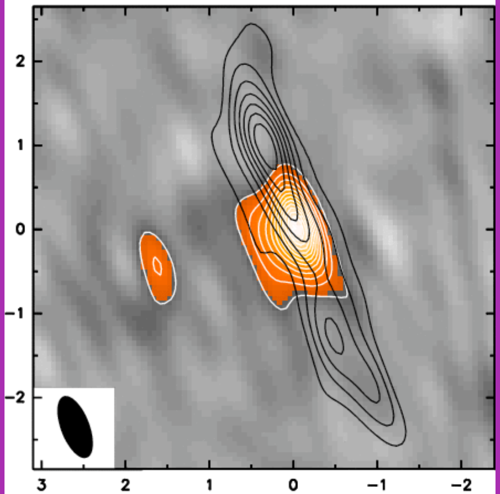
Typical transversal (beam deconvolved) size: 0.2" = 90 AU.

No evidence of higher jet collimation in Class 0 sources.

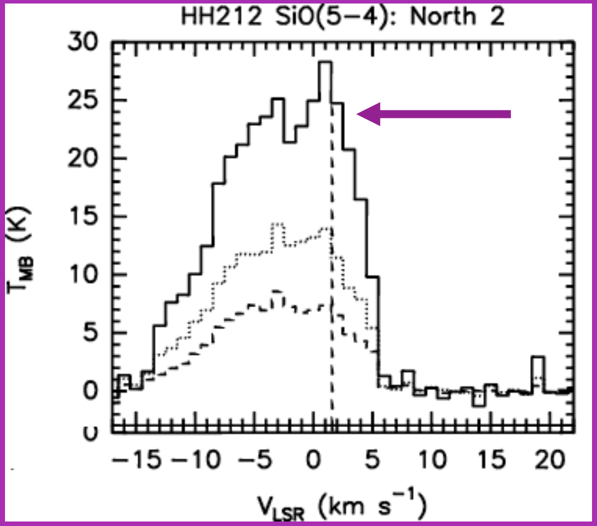
This rules out collimation by external pressure gradients. Jets are self-collimated by internal magnetic stresses.

Protostellar system: primary jet from a Class 0 protostar (Codella et al. 2007, 2012)

SiO(5-4) vs.1.4mm

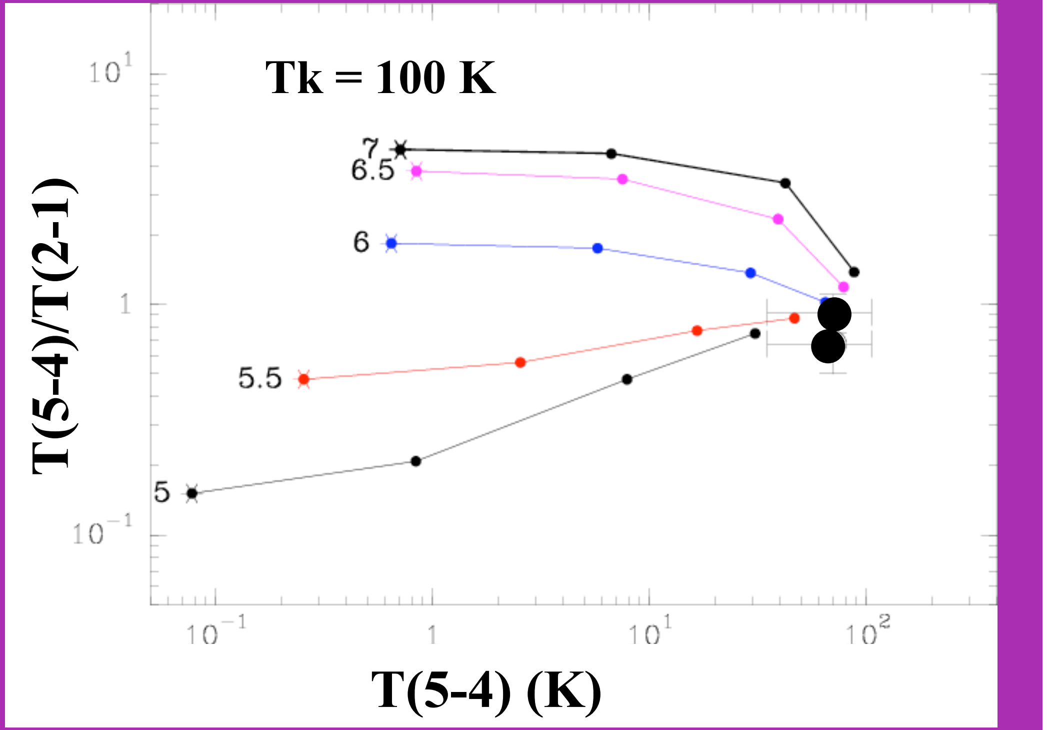


Size matters…….



In the HH212, we need to assume optically thick gas:
values ~ 1 for both ratios are achieved ONLY when approaching the LTE thick regime

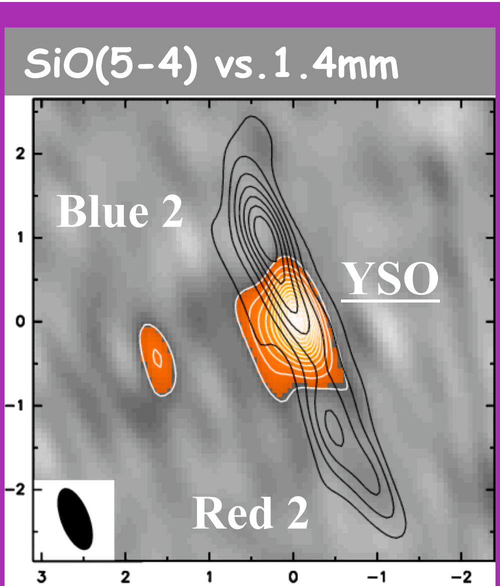
Codella et al. (2007)



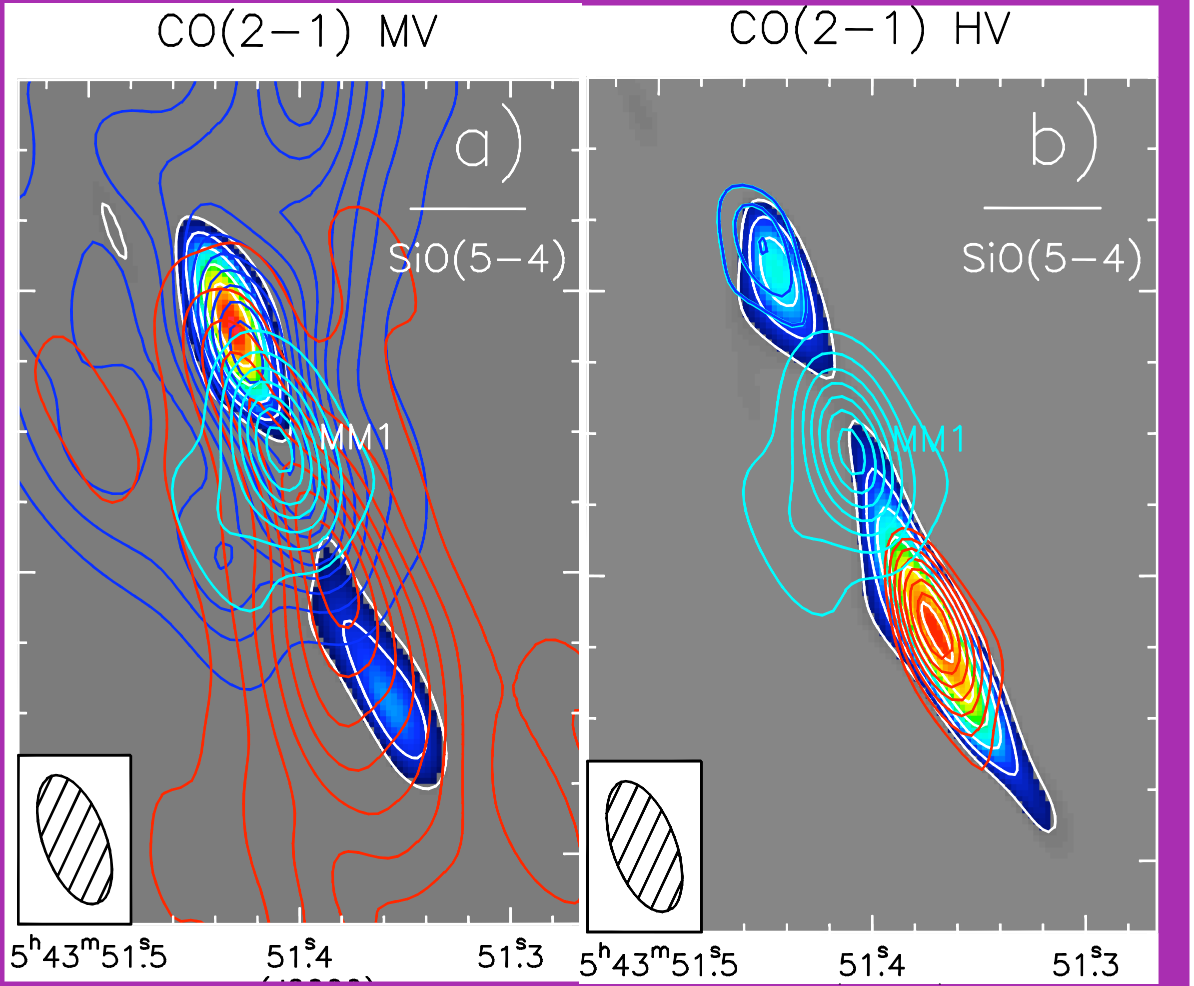
Previous conclusions that SiO was optically thin were due to strong beam dilution in single-dish data (< 1 K…)

WE NEED CO TO INFER ABUNDANCES…………

Limits of the PdBI observations



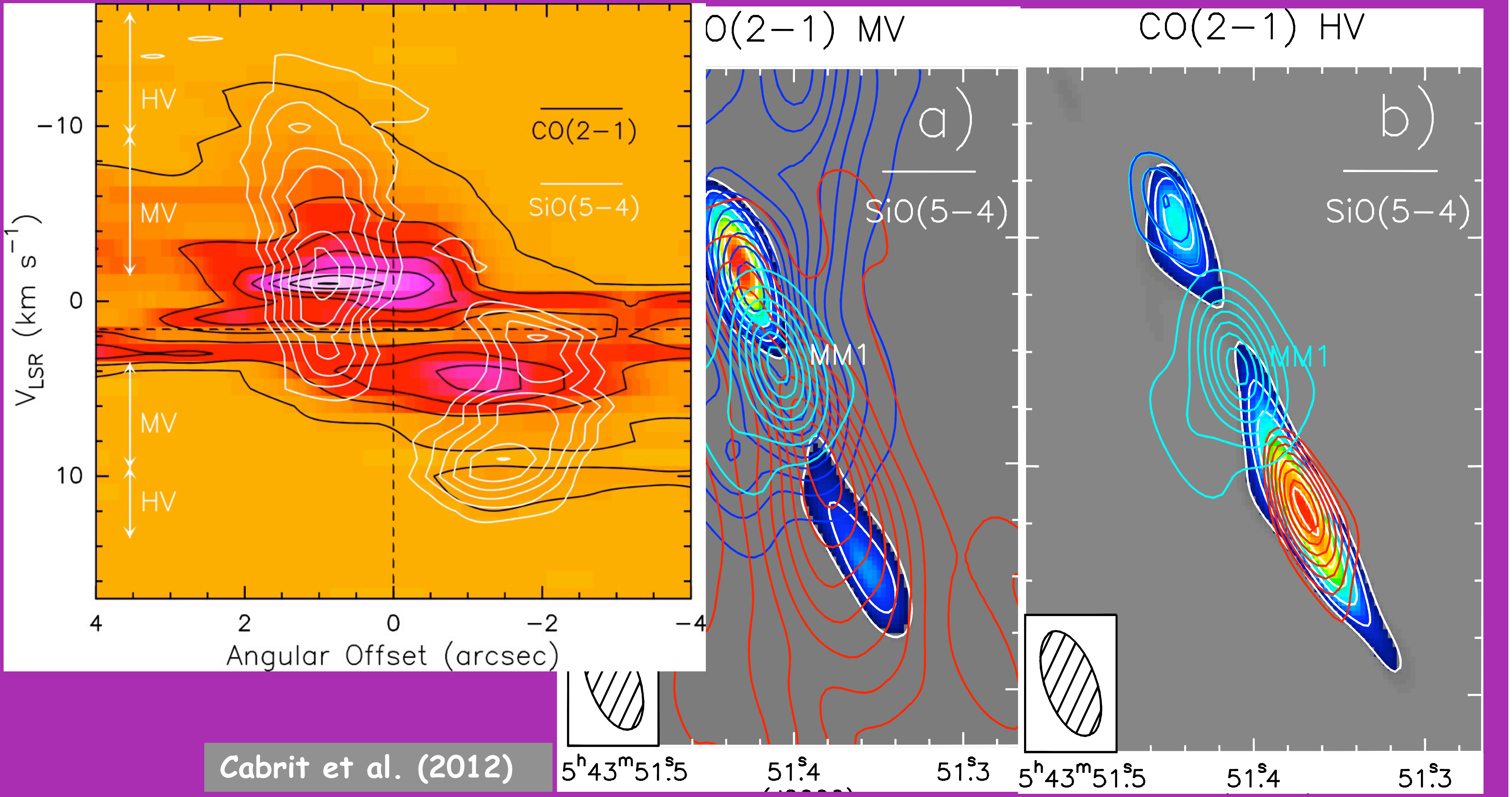
SiO(5-4) vs.1.4mm



Cabrit et al. (2012)

The low-velocity CO(2-1) is due to entrained gas at the base of the outflow cavity, and traces the jet only at the highest velocities……

Limits of the PdBI observations of HH212

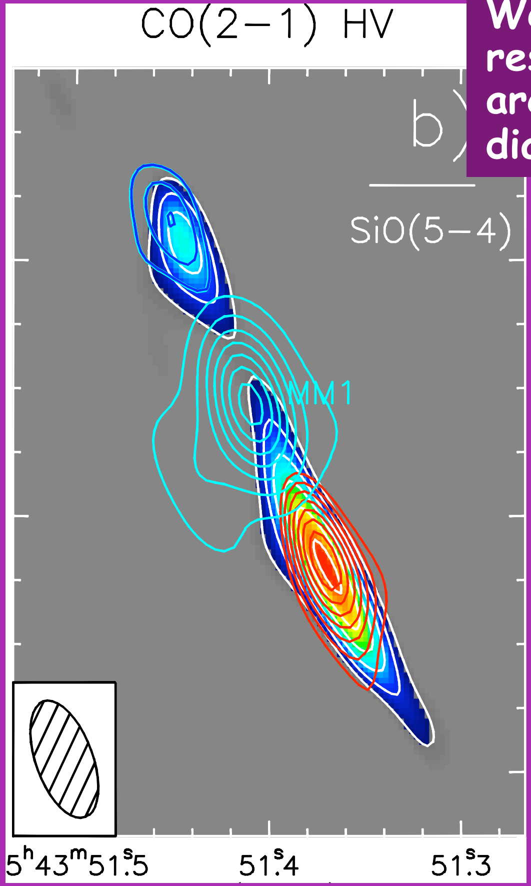


Cabrit et al. (2012)

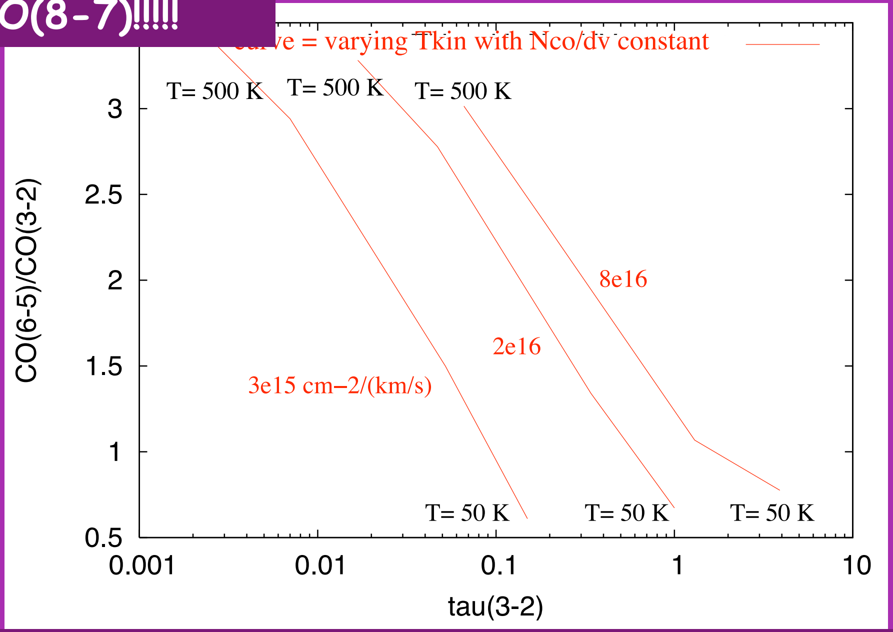
The low-velocity CO(2-1) is due to entrained gas at the base of the outflow cavity, and traces the jet only at the highest velocities…… we need higher J CO lines!

Note also the elongated PdBI beam.

ALMA, HELP !



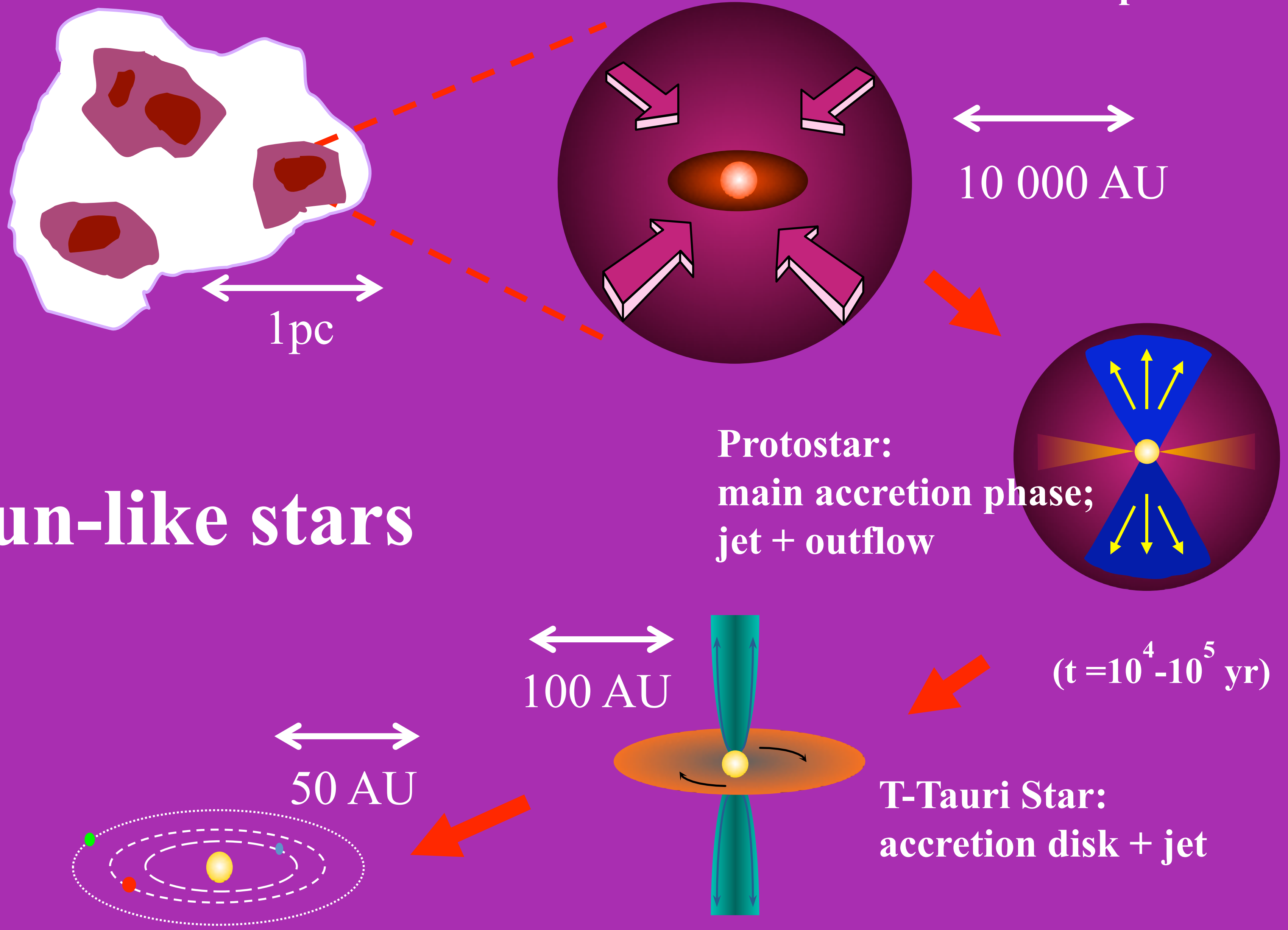
We need angular resolutions less than 0.2 arcsec to infer jet diameter. SiO(8-7)!!!!!



The CO(6-5)/CO(3-2) is a sensitive tracer of Tkin. High-J and high angular resolution needed to minimise contamination due to cavities.

Kinematics, physical properties, and chemical composition of protostellar jets: EARLY SCIENCE ALMA project (PI Codella) + Large Program IRAM PdBI CALYPSO

Sun-like stars



Molecular cloud and high-density cores

1pc

Gravitational collapse

10 000 AU

Protostar:
main accretion phase;
jet + outflow

($t = 10^4$-10^5 yr)

100 AU

T-Tauri Star:
accretion disk + jet

($t = 10^6$-10^7 yr)

50 AU

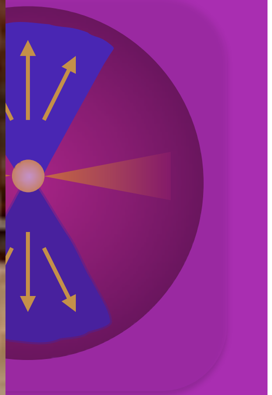
Main Sequence star

($t > 10^7$ yr)

Molecular cloud and high-density cores

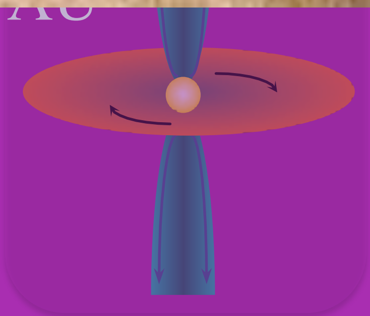
Gravitational collapse

U



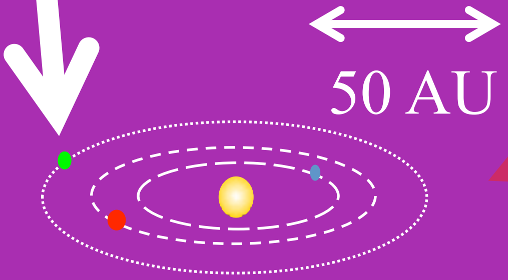
0^{4}-10^{5} yr)

100 AU



T-Tauri Star:
accretion disk + jet

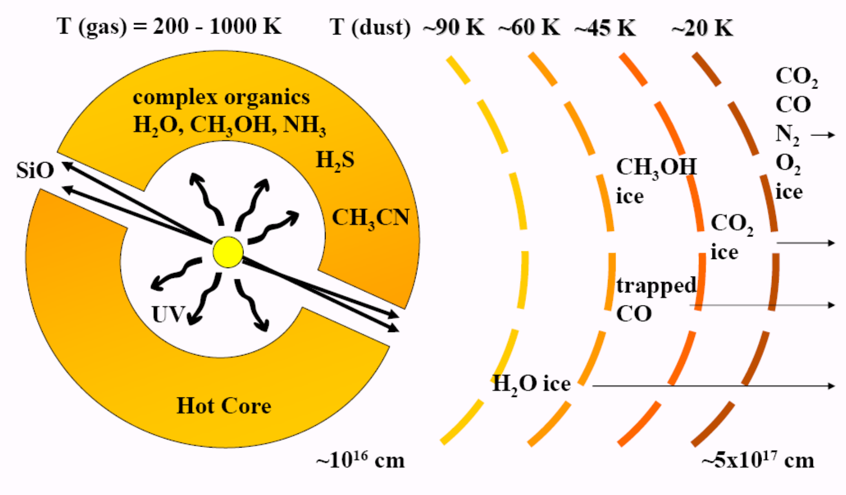
(t =10^{6}-10^{7} yr)



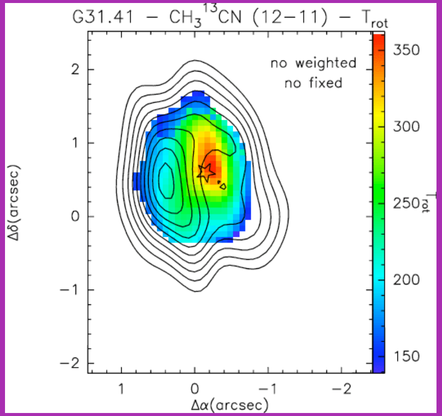
Main Sequence star

(t > 10^{7} yr)

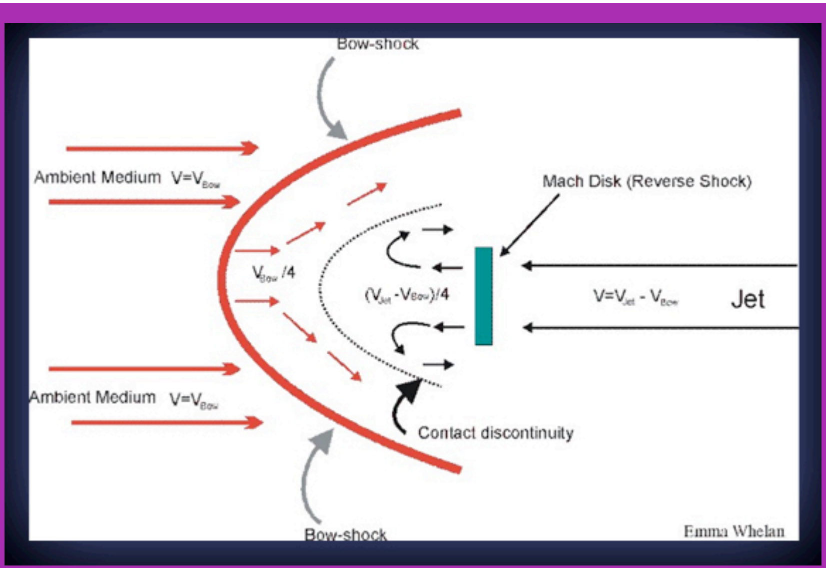
Our Chemical Origins



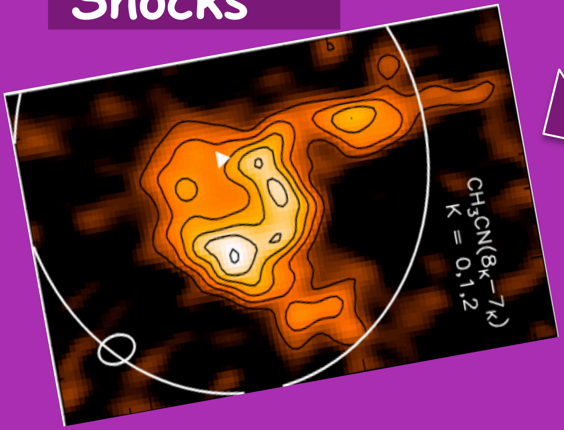
Hot cores



CH_3CN



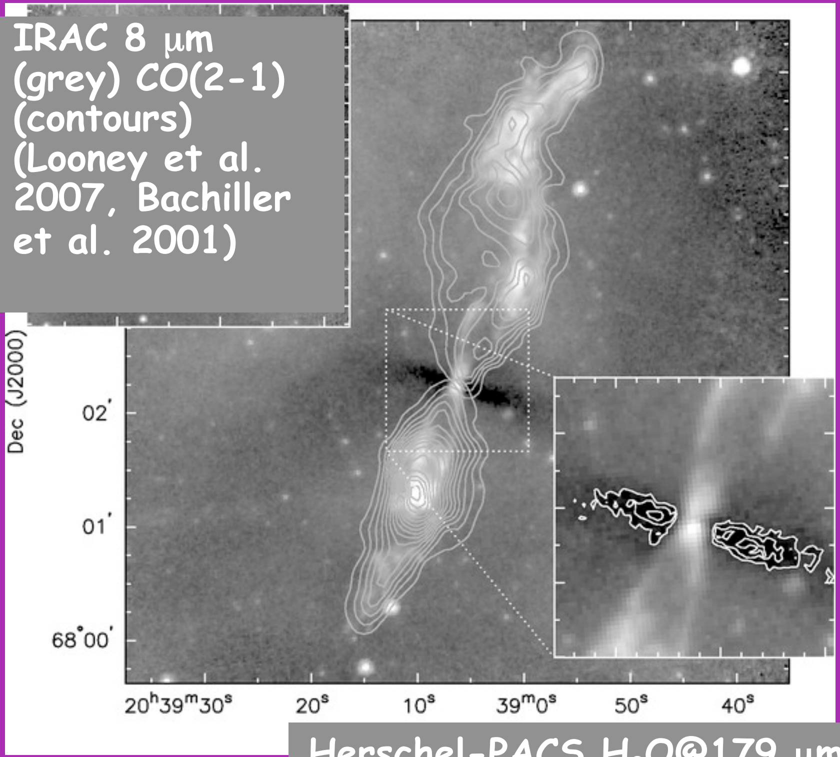
Shocks



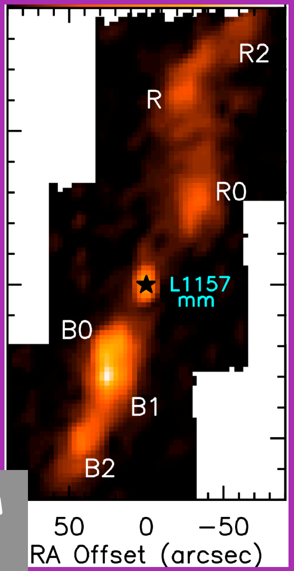
Complex Organic Molecules !

The L1157 chemically rich outflow

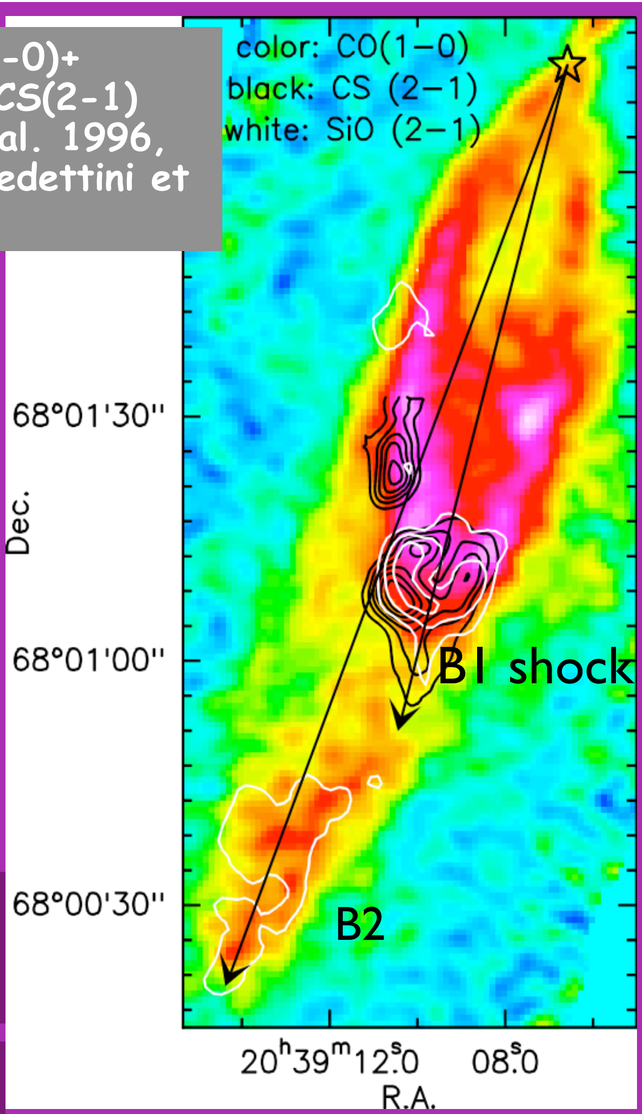
IRAC 8 µm (grey) CO(2-1) (contours) (Looney et al. 2007, Bachiller et al. 2001)



Herschel-PACS H_2O@179 µm (Nisini et al. 2010)



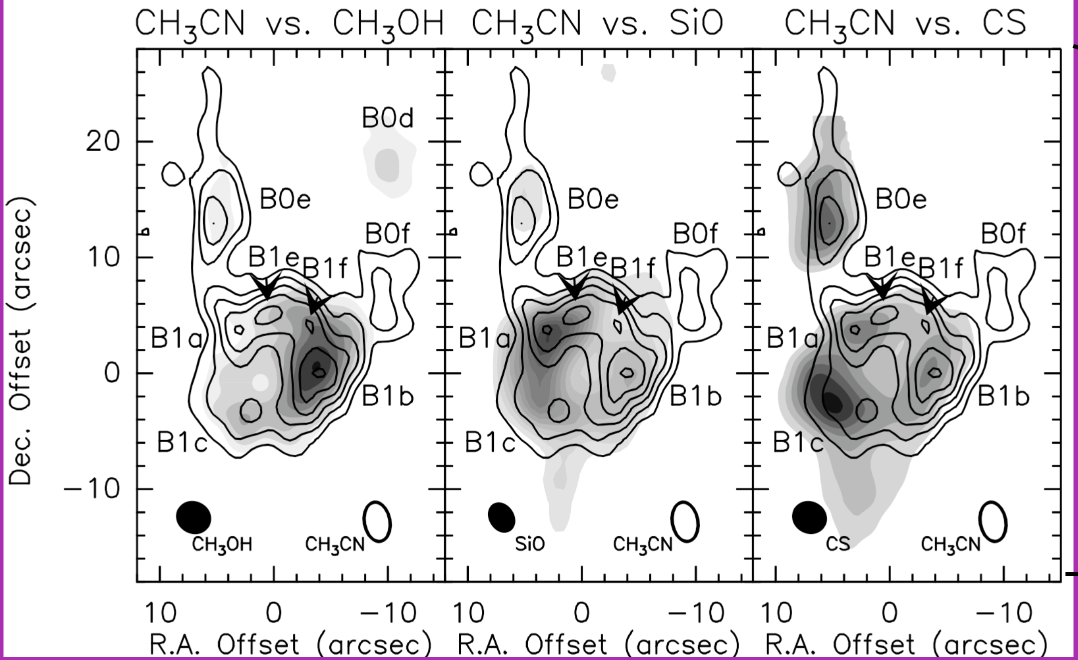
PdBI CO(1-0)+ SiO(2-1)+CS(2-1) (Gueth et al. 1996, 1998, Benedettini et al. 2007)

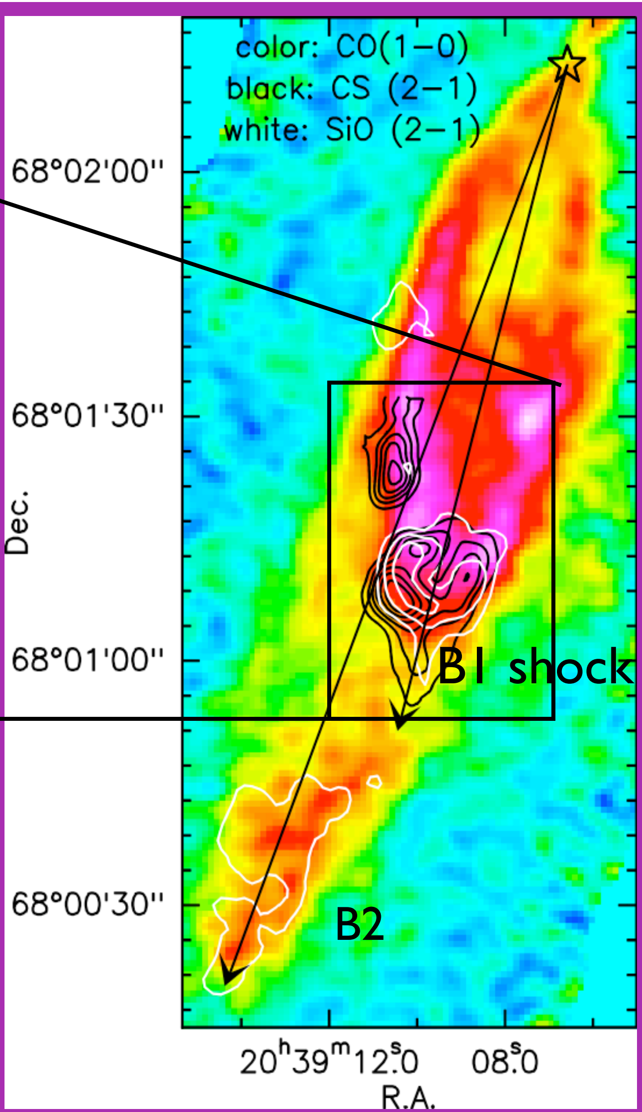


Powered by a Class 0 source (d = 250 pc)
Most chemically rich outflow know so far: SiO, SO, NH_3, CH_3OH, C_2H_5OH, H_2O, and many other molecules!

Precessing molecular outflow associated with bow shocks seen in CO (Gueth et al. 1996) and H_2 (Neufeld et al. 2009): B1 is the brightest shocked region.

The L1157 chemically rich outflow

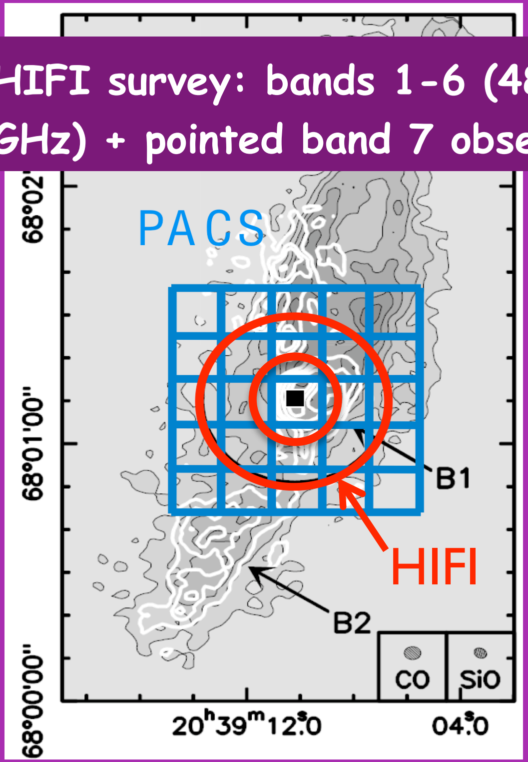




Gueth et al. (1998), Benedettini et al. (2007), Codella et al. (2009)

Complex and clumpy structure of the B1 shock, with typical shock tracers peaking at different positions

The Herschel lesson: different excitation regimes



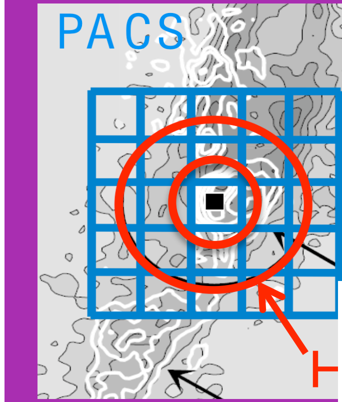
HIFI survey: bands 1-6 (488-1670 GHz) + pointed band 7 observations

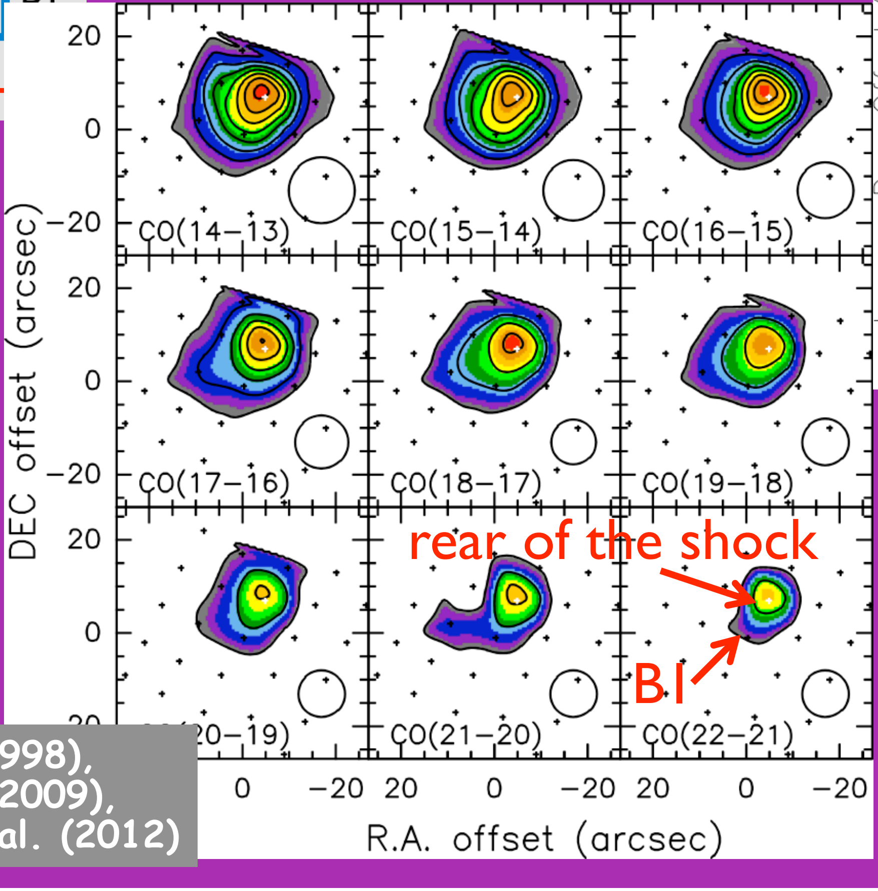
PACS: full spectrum
55-95 μm + 101-210 μm
SPIRE: full spectrum
190-672 μm

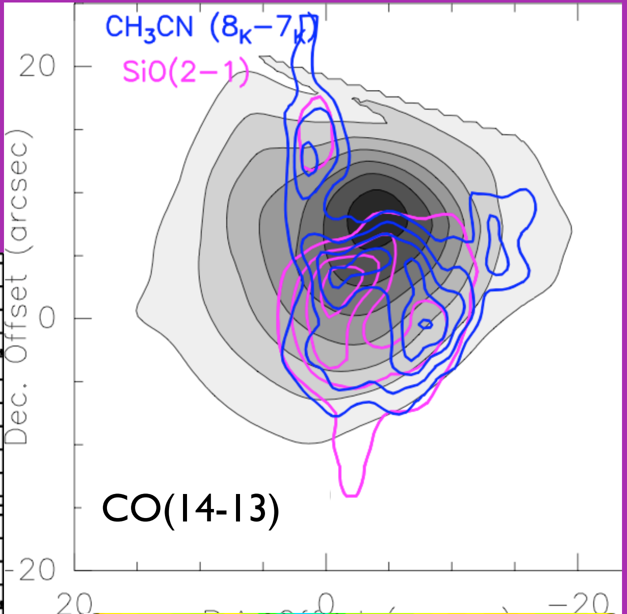
CHESS: Herschel
Key Project
\+ IRAM 30-m

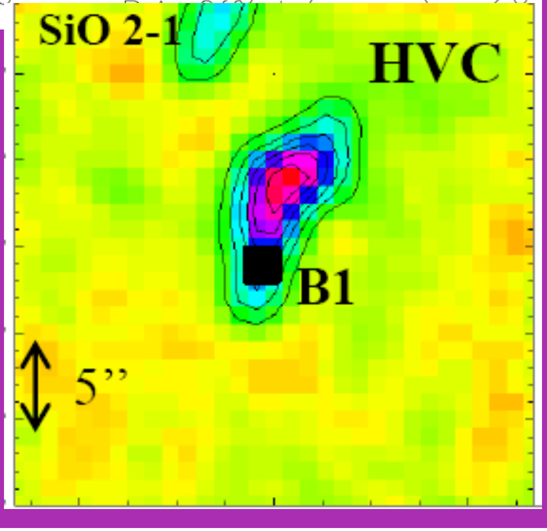
The Herschel lesson: different excitation regimes

Excellent match in the HV regime for high-Jup CO and SiO



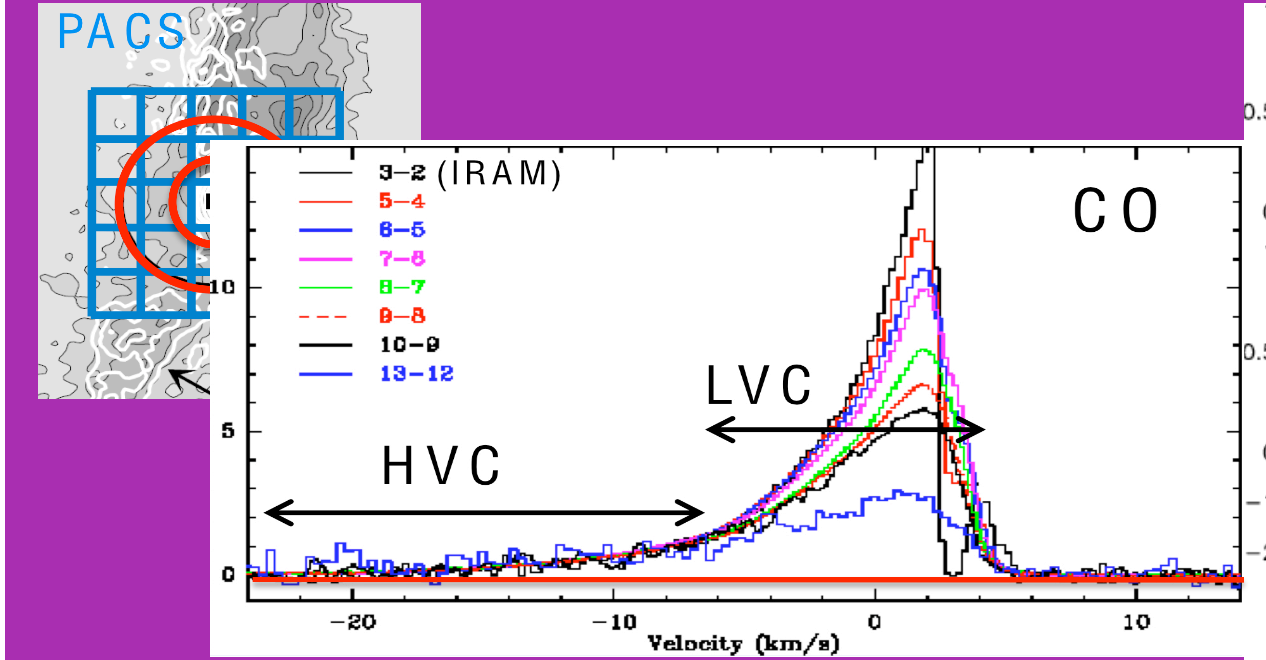


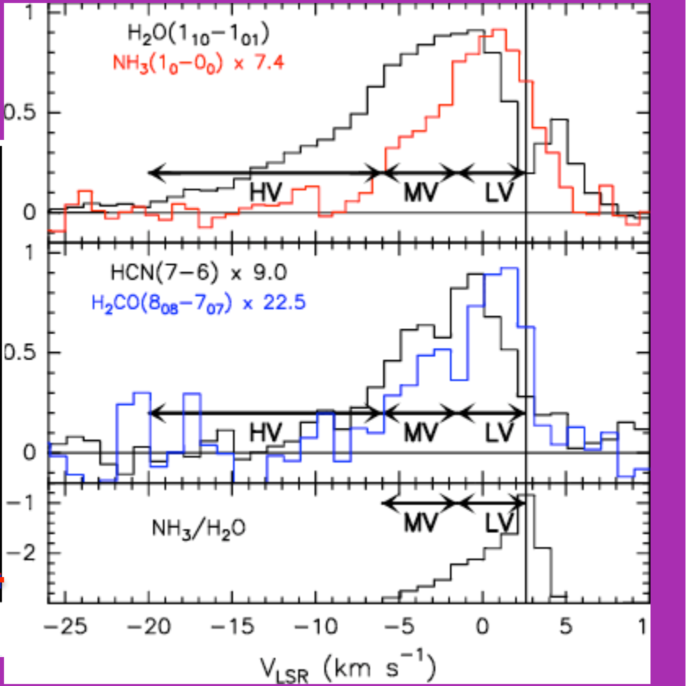




Gueth et al. (1998),
Codella et al. (2009),
Benedettini et al. (2012)

The Herschel lesson: different excitation regimes





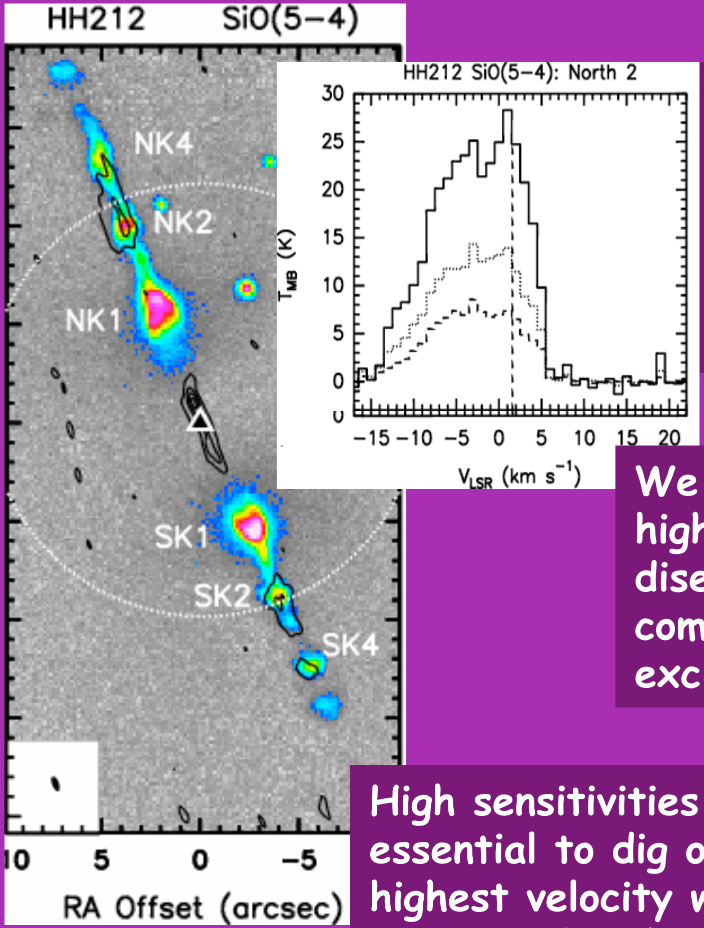
So far, two CO gas components are detected:

1. Hot gas at T ~ 400 K;
2. Warm (chemically rich) gas at T ~ 100 K;

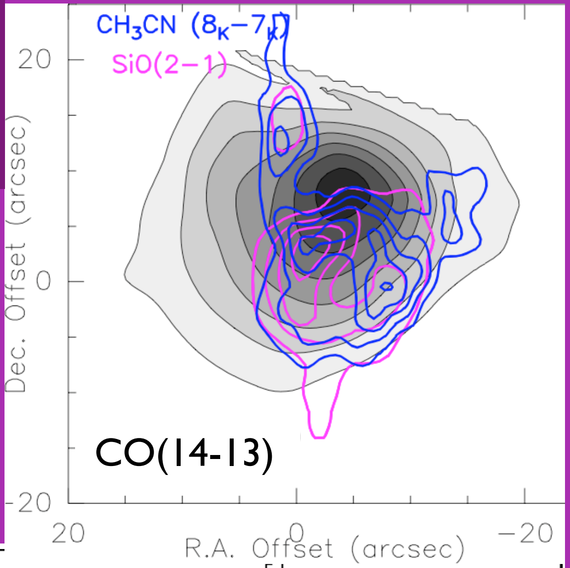
Shock models: the hot CO component, located at the rear of the bow shock, arises from a dissociative J-type shock.

Codella et al. (2010),
Lefloch et al. (2012)

Roundup

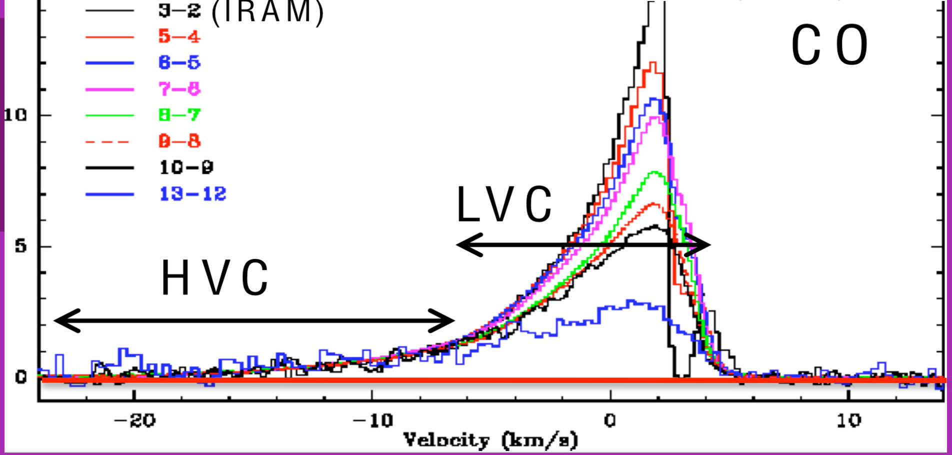


SiO allows us to unvail the deeply obscured protostellar environments. We need sub-arcsec angular resolutions.



We need to observe high-J CO lines to disentangle the different components at different excitation.

High sensitivities are essential to dig out the highest velocity wings, associated with the jet.



In other words… we need ALMA!