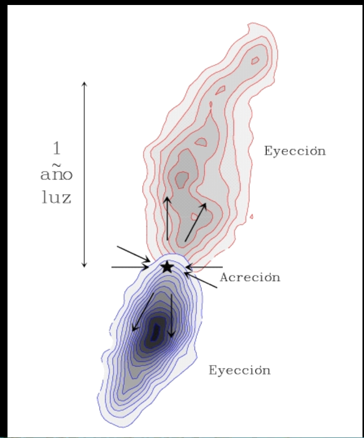
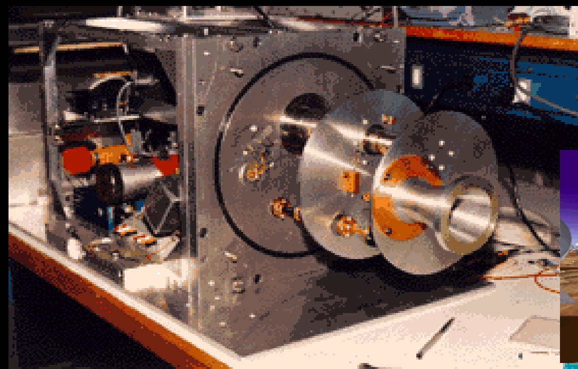
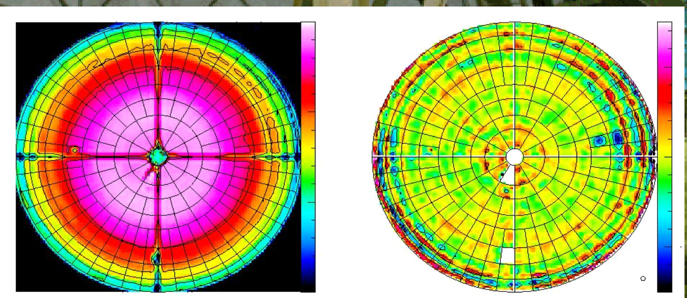
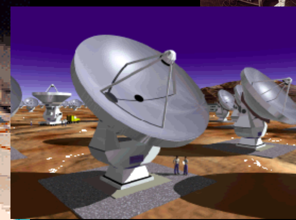
Observatorio Astronómico Nacional





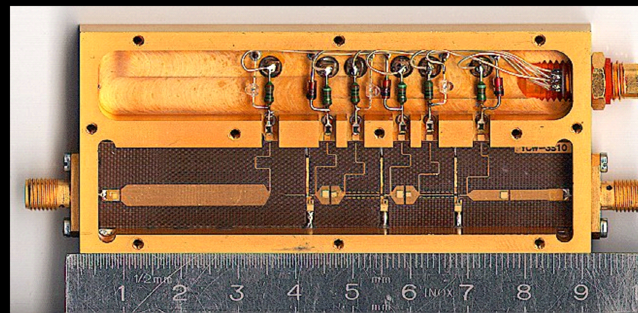


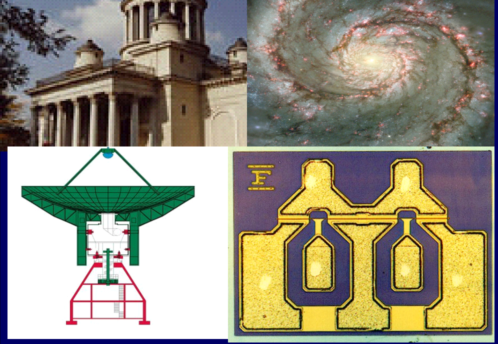


MINISTERIO
DE FOMENTO

DIRECCIÓN GENERAL
DEL INSTITUTO
GEOGRAFICO
NACIONAL

OBSERVATORIO
ASTRONÓMICO
NACIONAL





Observatorio Astronómico Nacional

Molecular outflows
observations

Rafael Bachiller

Protostellar jets in context, Rhodes,
July 2008

Outline

1.- CO outflows

2.- molecules other than CO

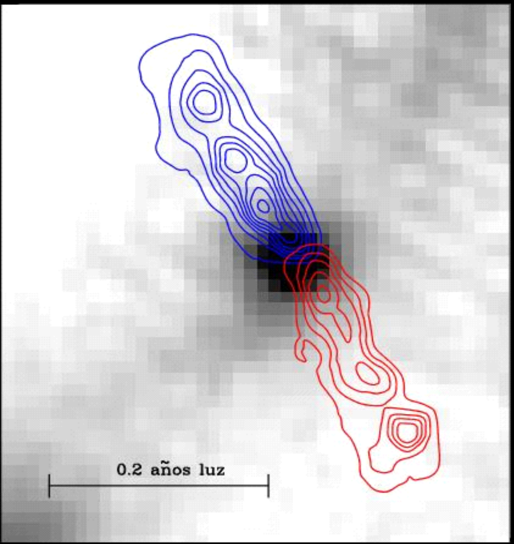
3.- chemical evolution of young (Class 0/I) outflows

4.- outflow structure and micro-structures (jets, shells, bullets, internal working surfaces)

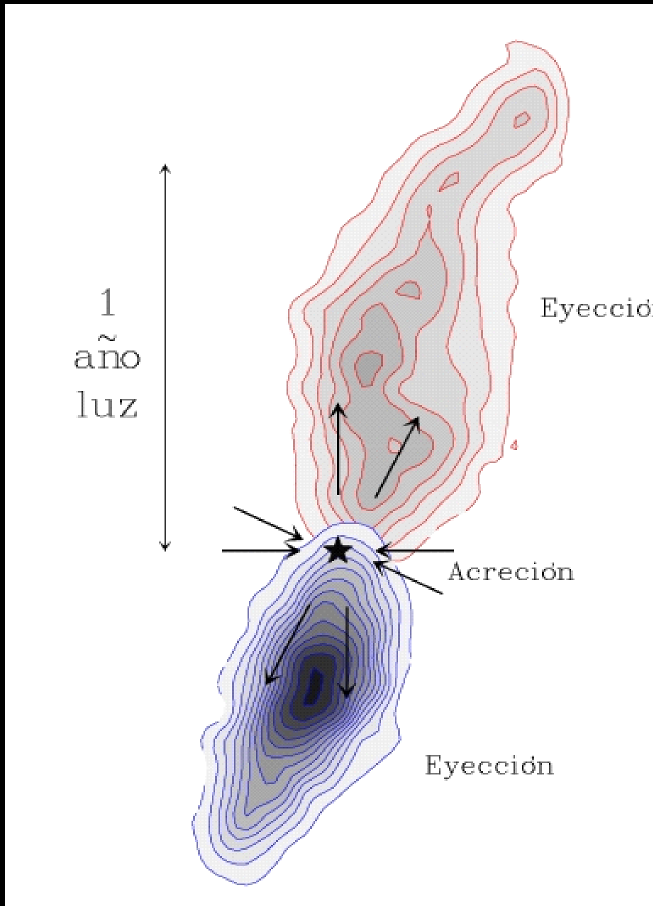
the nature of the primary wind

[5.- prospects with ALMA (J. Richer’s talk)]

Molecular outflows are CO outflows



- Present in all YSOs ($t < 10^5$ yr)
- Supersonic gas (10-100 km/s)
- The ejecta from the very internal region of the star/disk system sweeps up the ambient material



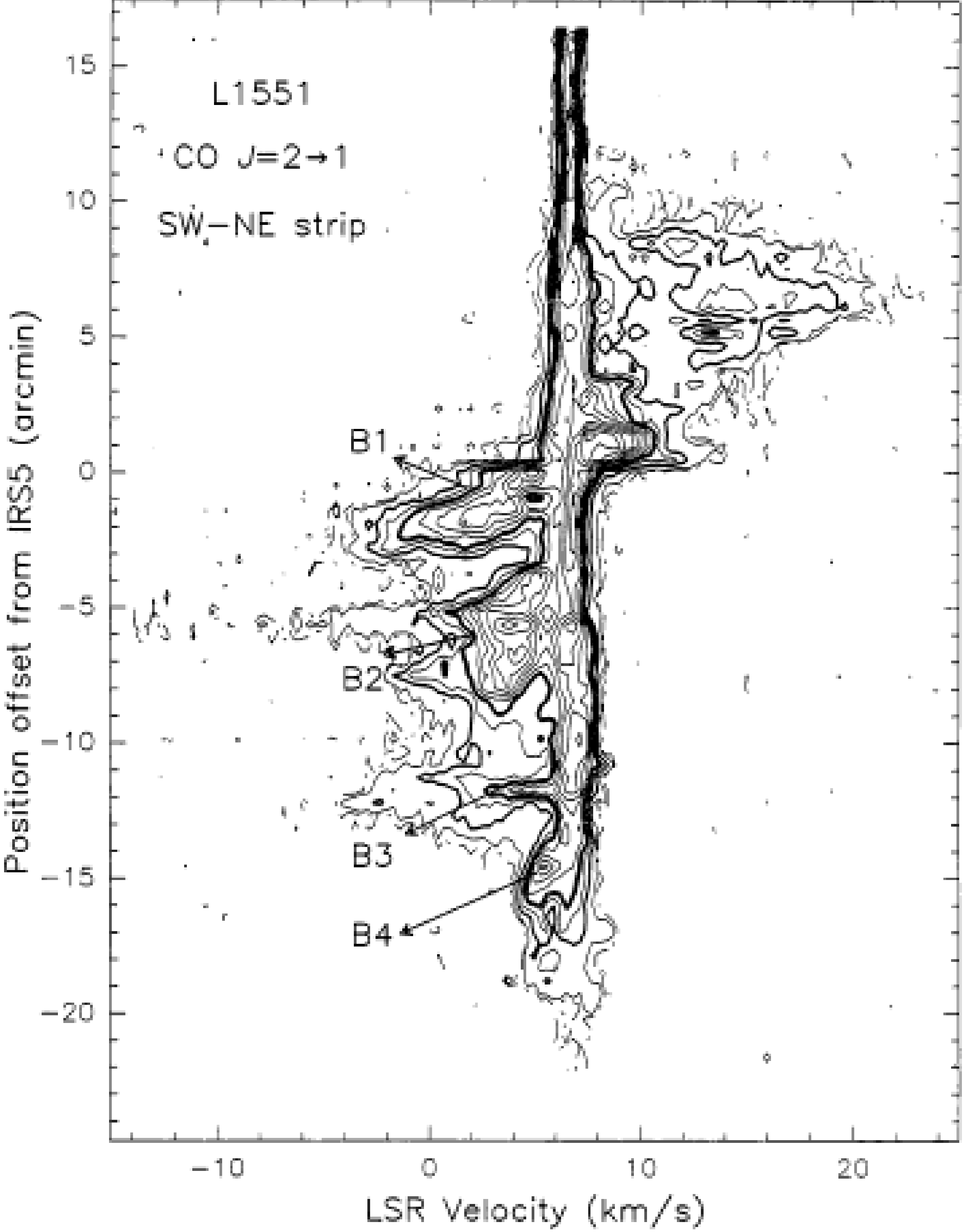
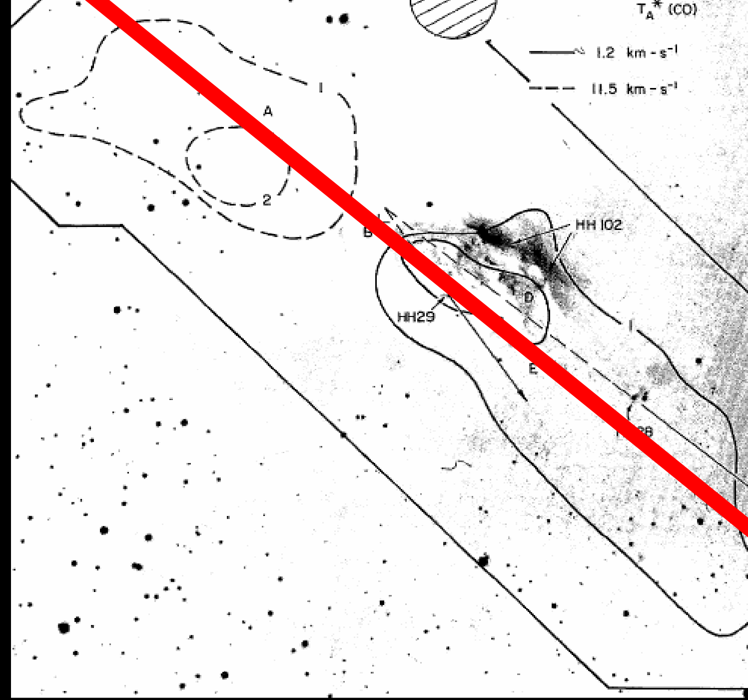


FIG. 1.—Velocity-position diagram along a SW-NE line, i.e., close to the main L1151 outflow axis, in the CO 2 → 1 line. Position offsets are in arcseconds with respect to IRS 5, which is 04ʰ28ᵐ40ˢ.1, 18°01′41″.2 (1950.0). Contours are at 1 K (*dash*), 1.5, 3 (*thick*) 4.5, 6 (*thick*), ... etc. B1, B2, B3, and B4 are the high-velocity features discussed in the text.



Bachiller, Tafalla & Cernicharo 1994

Advantages of CO spectroscopy

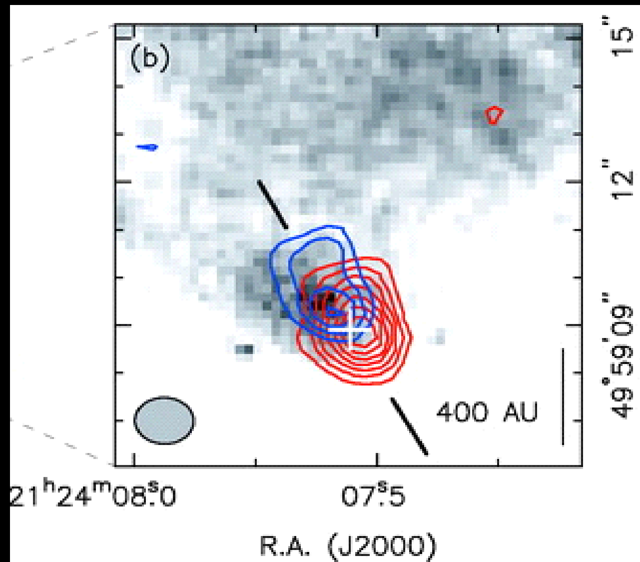
- CO traces swept-up material (outflow history)
  - CO very abundant
  - CO easy to thermalize (dipole moment = 0.1 Debye):
    - $T_{ex} = T_K$
  - Observing 2 lines (ex. 2-1 and 1-0) ==> T_{ex}
  - And adding one 13CO line ==> opacity
  - T_{ex}, τ ==> CO column density
  - Assuming CO abundance ==> H_2 column density
  - Mass
- The velocity field can be directly obtained from the profiles. This provides the Momentum, Kinetic Energy, and Mechanical Power of the flow
- Observational biases mainly come from projection effects (sizes and velocities need to be de-projected)
  - Uncertainties: factor 2 in mass, 10 in momentum, 60 in mechanical power (see ex. Cabrit & Bertout 1990)
  - Other biases: CO abundance, flow/ambient boundary
- Low mass objects are easier to study

Parameters of CO flows

- Size < 0.1 pc to a few pc
- Terminal velocity <1 to 100 km/s
- Timescales: $<10^3$ to 10^5 yr
- Mass $< 10^{-4}$ to few 10^2 Mo
- Energy: up to 10^{48} erg
- Force: 10^{-7} to 1 Mo km/s yr^{-1}
- Mechanical power: 10^{-5} to 10^4 Lo

Bachiller (1996, ARAA

Very weak outflows



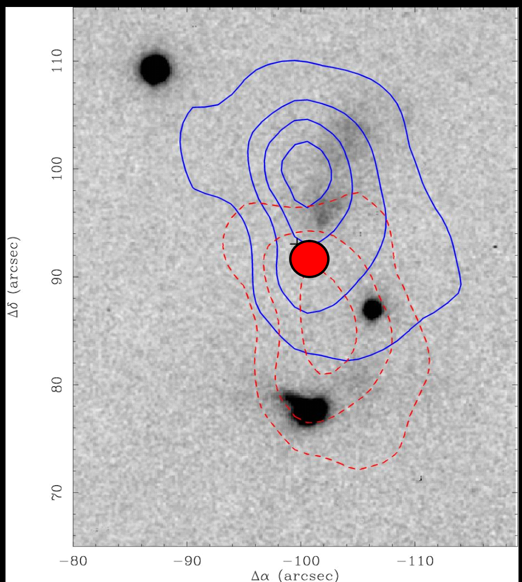
L1014-IRS

low luminosity source: L~0.09 L_{solar} M~20M_{Jup} -45M_{Jup}

bipolar molecular outflow: one of the smallest known

size ~500 AU, mass <10^{-4} M_{solar}

Bourke et al. (2005)



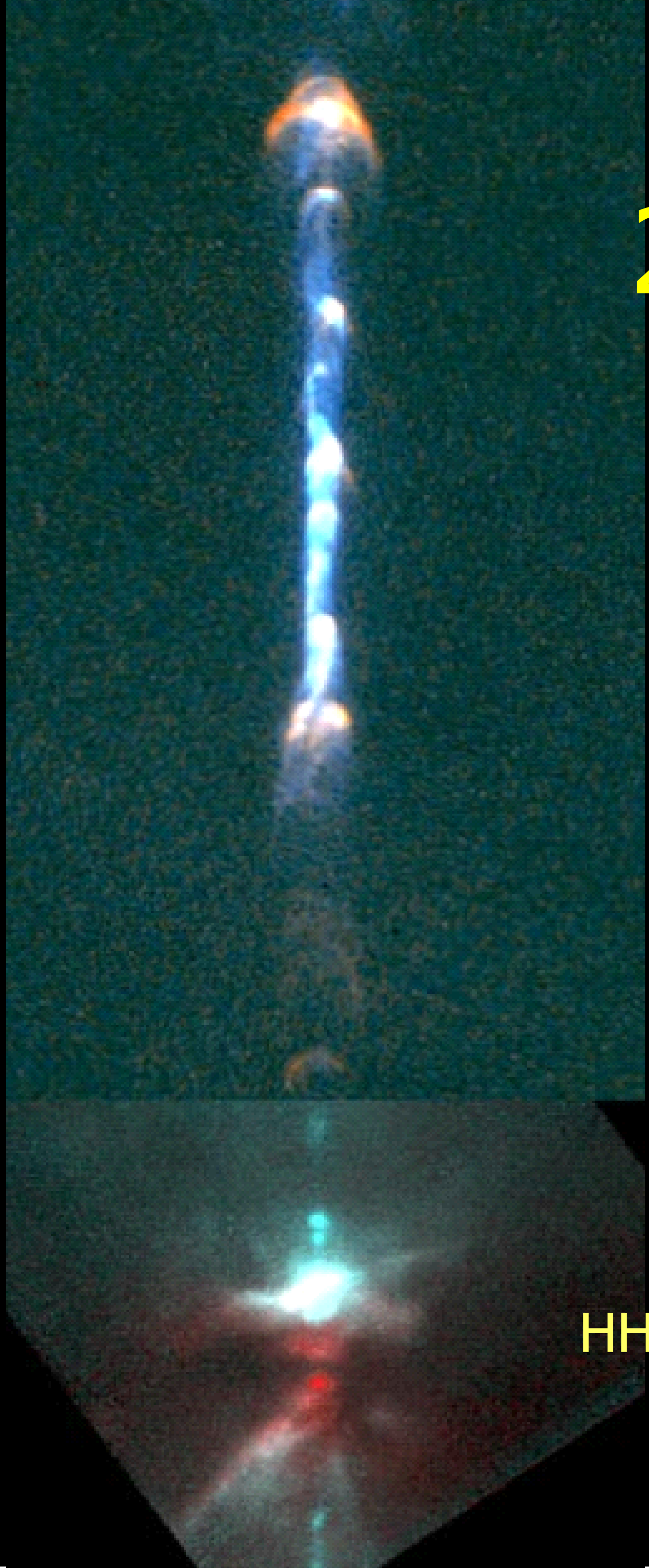
IC348 MMS2

size ~ 0.04 pc, mass ~10^{-3} M_{solar}

(Tafalla, Kumar & Bachiller 2006)

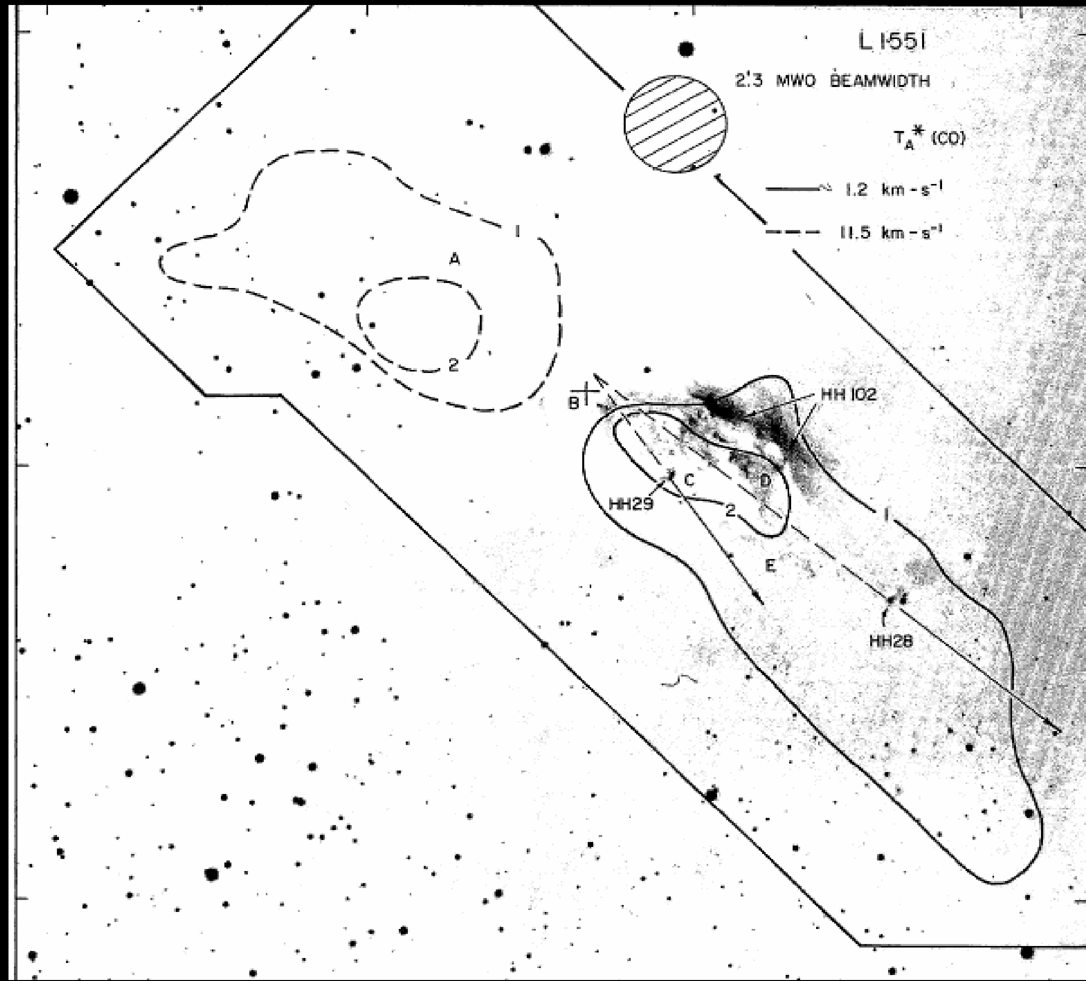
Brown dwarfs: cf. work by E. Whelan, T. Ray, et al.: Rho Oph 102, 2Mass 1207, etc

2 kinds of ejecta ?

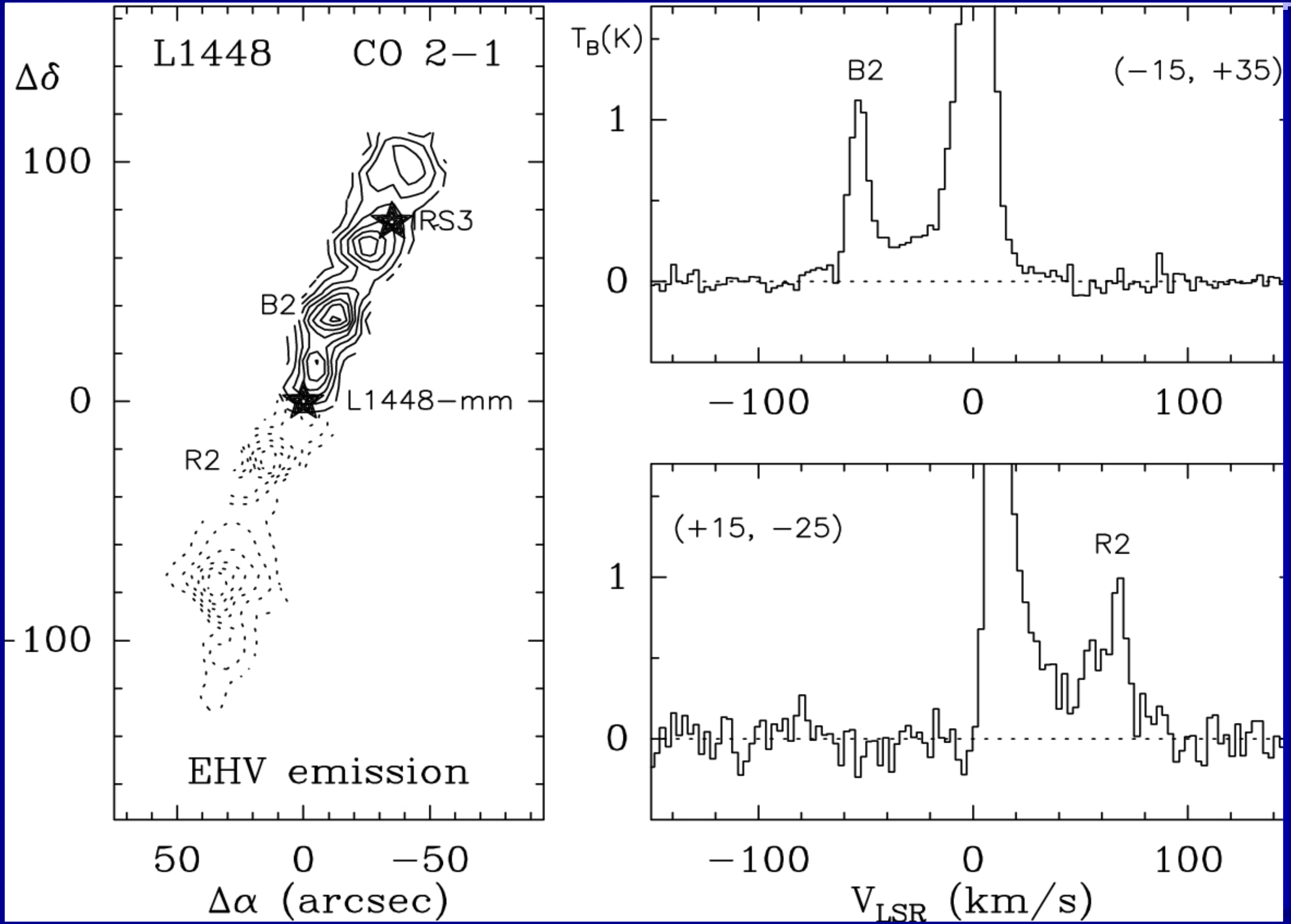


HH111

L1551

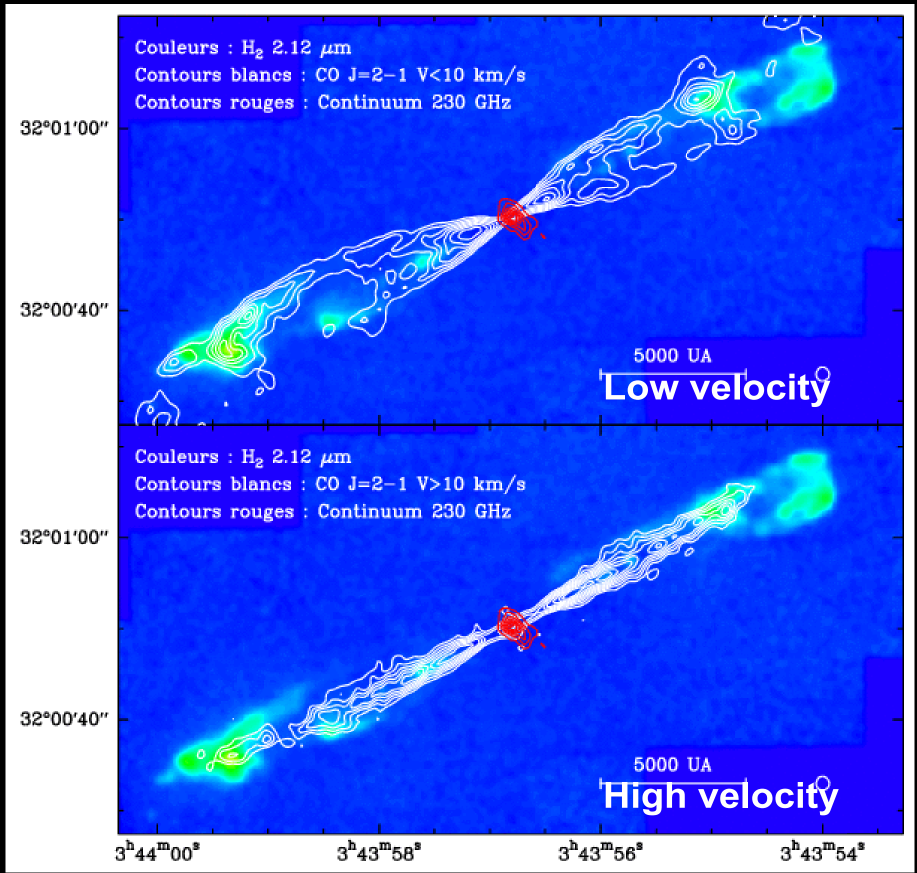


Class 0 outflows provide a link between optical/IR jets and molecular flows

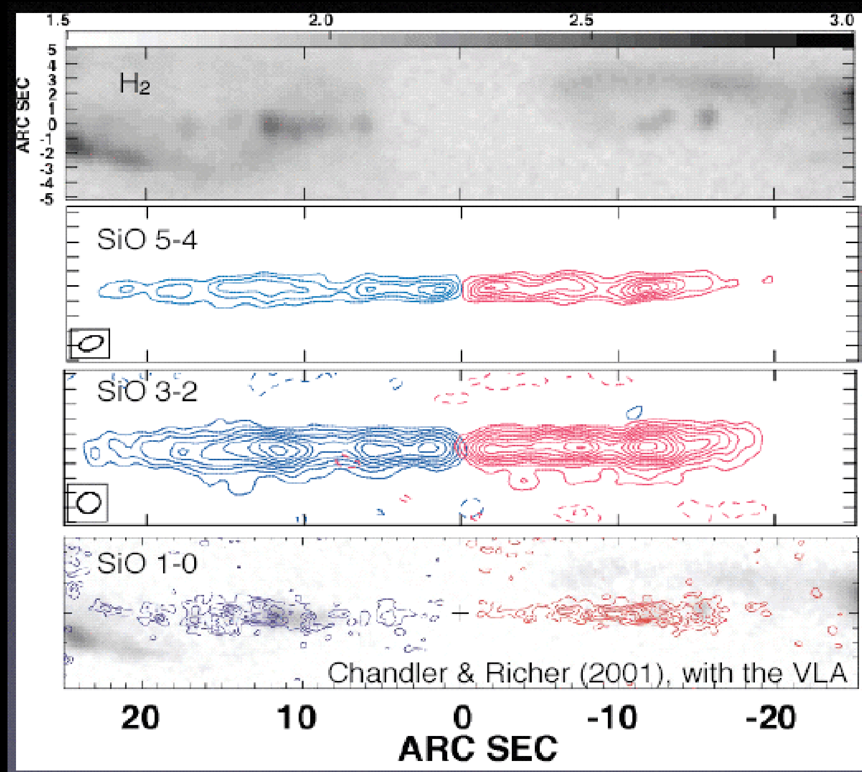


Bachiller et al. (1990)

HH211



Higher transition SiO more highly collimated (Hirano 2005 Chandler & Richer 2001)

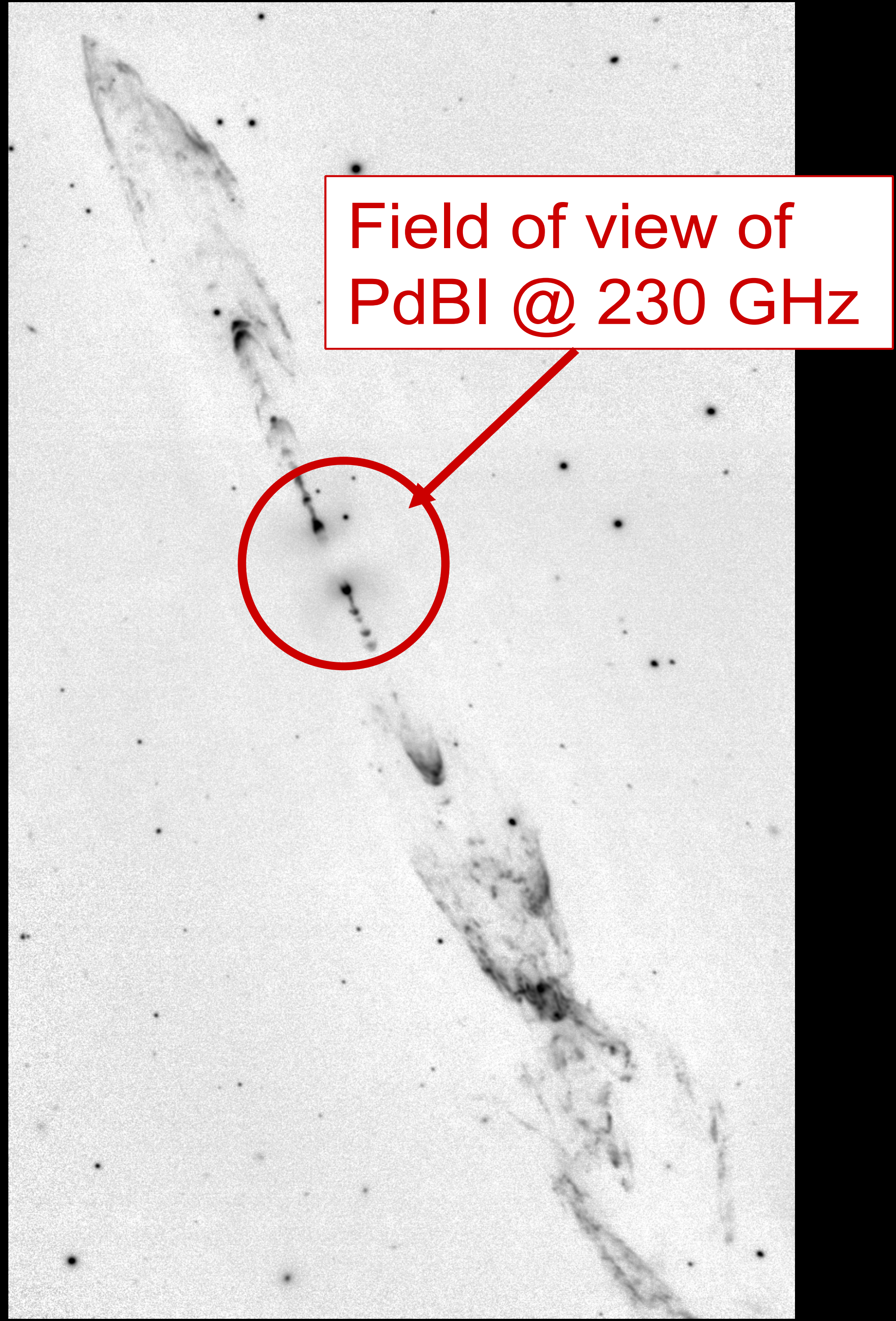


Very young molecular flows are as highly-collimated as optical jets.

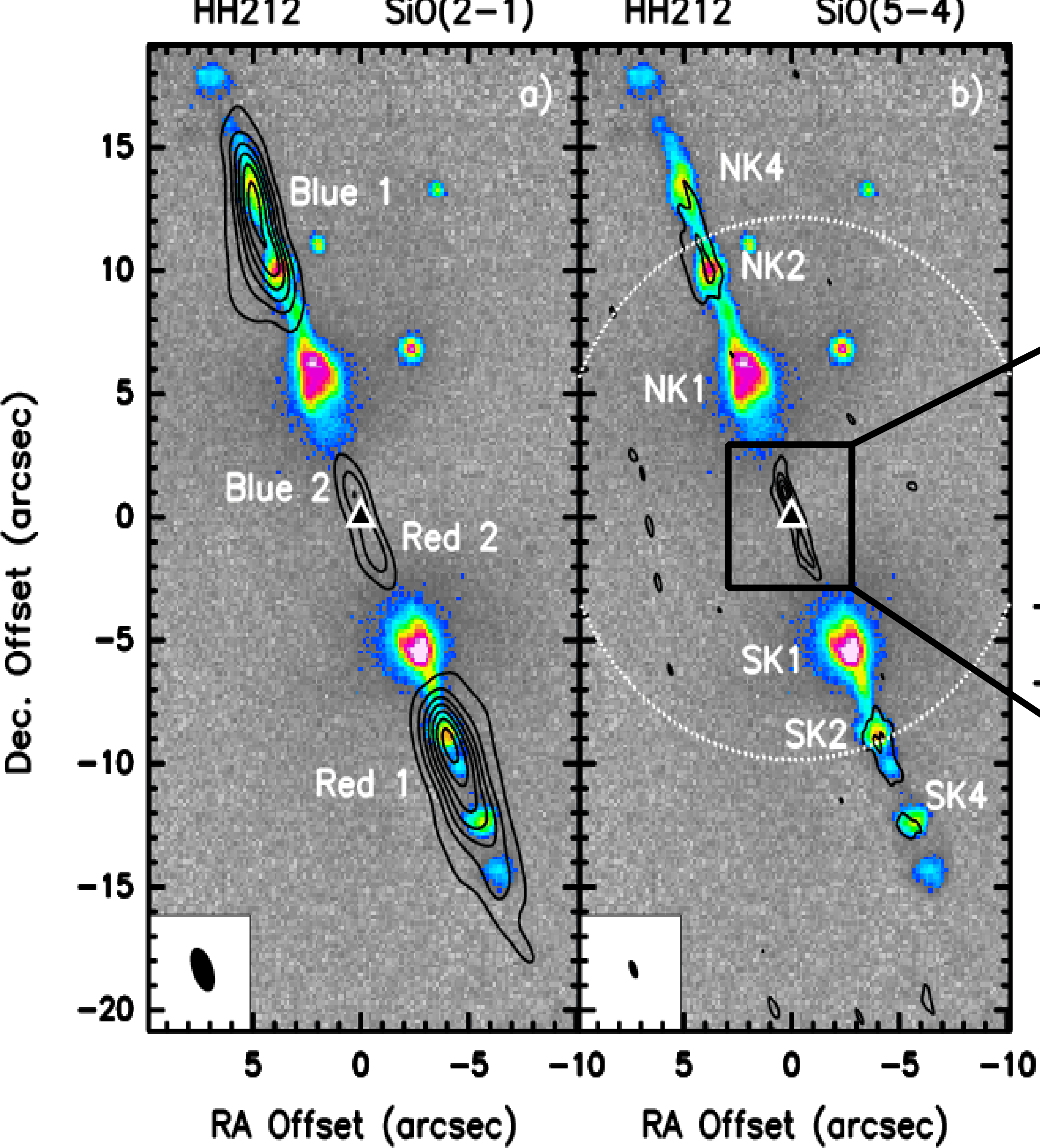
HH 211(age ~ 10^3 years). Compare CO (white contours), H_2 (color), & 1 mm continuum (red contours) (McCaughrean et al. 1994, Gueth & Guilloteau 1999).

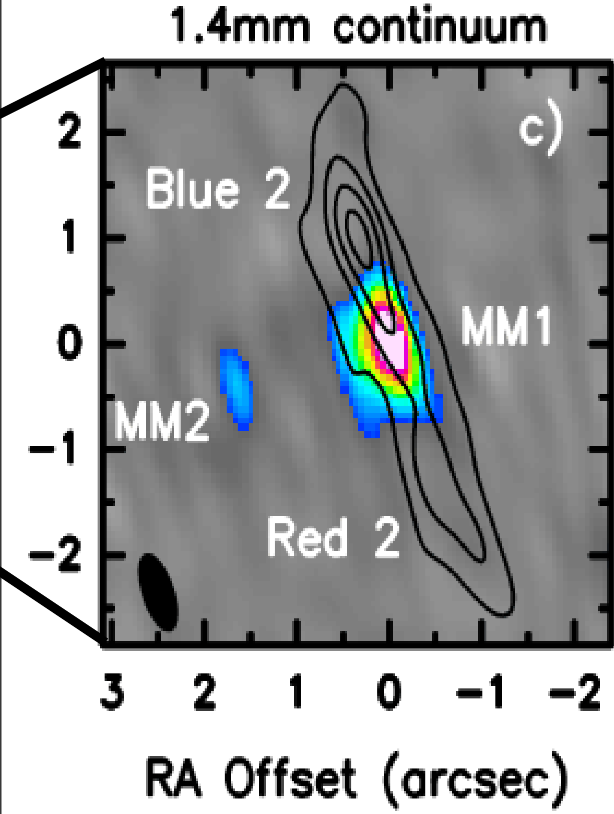
HH212

- IRAS05413-0104 low mass Class 0 source in Orion
- Only 4 deg from plane of sky
- **Highly symmetric H2 jet** (Zinnecker et al. 1998)

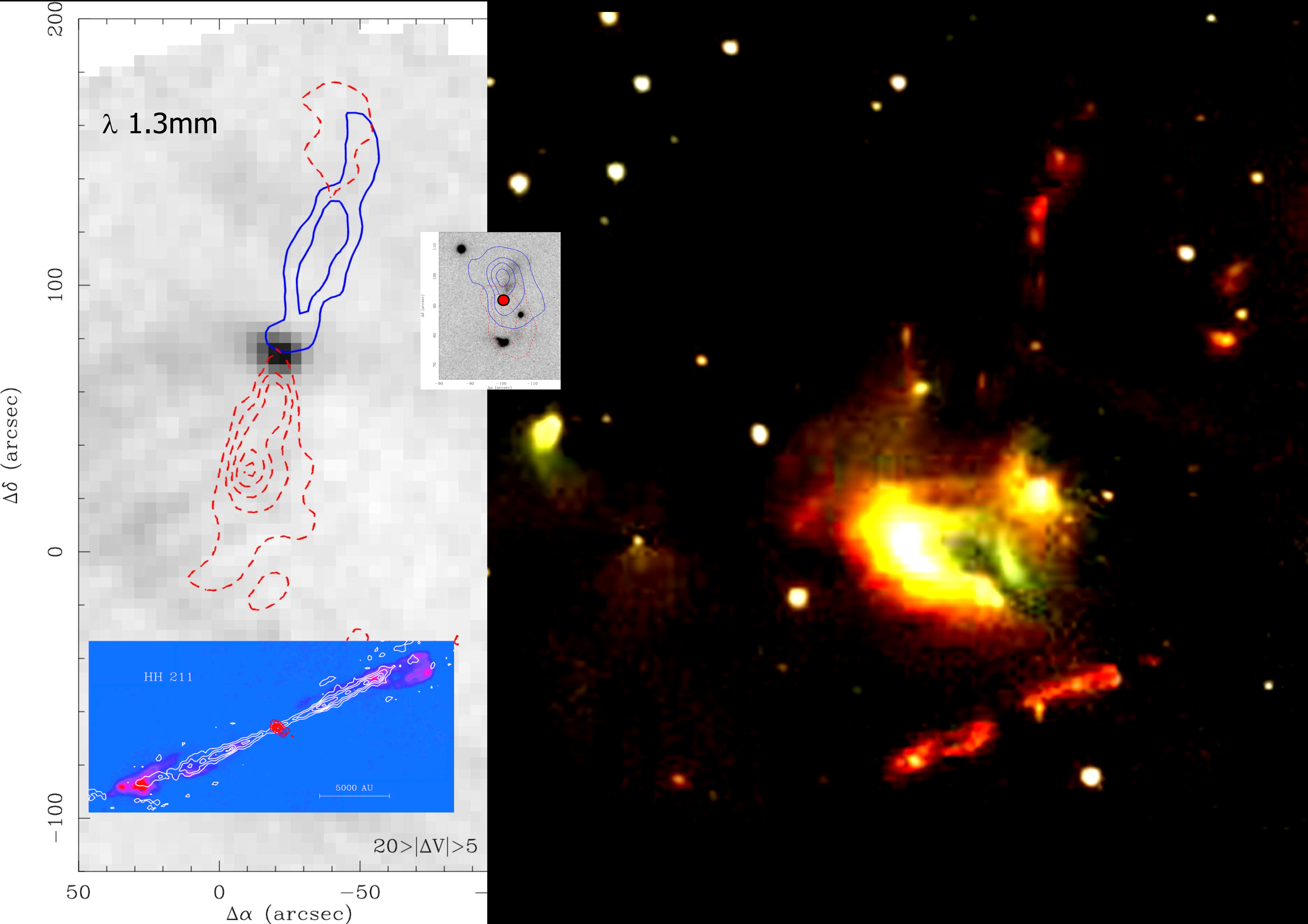


Contours: SiO (PdBI)
False colors: H2 (VLT)
(Codella et al. 2007)





SiO and H2 images with same angular resolution


λ 1.3mm
HH 211
5000 AU
20>|ΔV|>5
Δδ (arcsec)
Δα (arcsec)
200
100
0
−100
50
0
−50

Unification of mass loss mechanisms

- Some molecular flows can be as highly collimated as optical/IR jets
- When both phenomena coexist: optical jets and molecular flows have the same direction and orientation
- Bow shocks and precession (and lower resolution in the observations !) can explain the low collimation of many molecular flows
- Wide angle wind component (if it exists) eludes detection

<u>The properties of bipolar molecular outflows can only be explained with **jets**</u>

Purely jet-driven models can explain outflow width in very young sources (L1448, HH 211, HH212, HH 111,...) but have difficulty re-producing momentum distribution

✸ wide angle wind component seems to be needed.

Molecular outflows are not only made of CO

- Shock waves with high Mach number (~10- 1000)
- 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

C- and J- shocks

C shocks

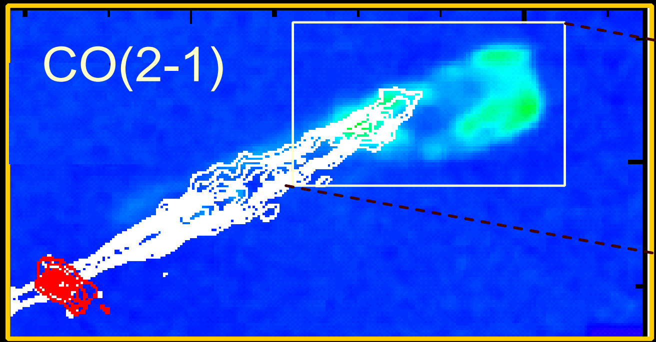
- Slow (< 50 km/s)
- T ~ 2000 – 3000 K
- Non- dissociative

J shocks

- Fast (~ 100 km/s)
- T ~ 10^5 K
- Dissociative
- (but molecules could re-form as the gas cools)

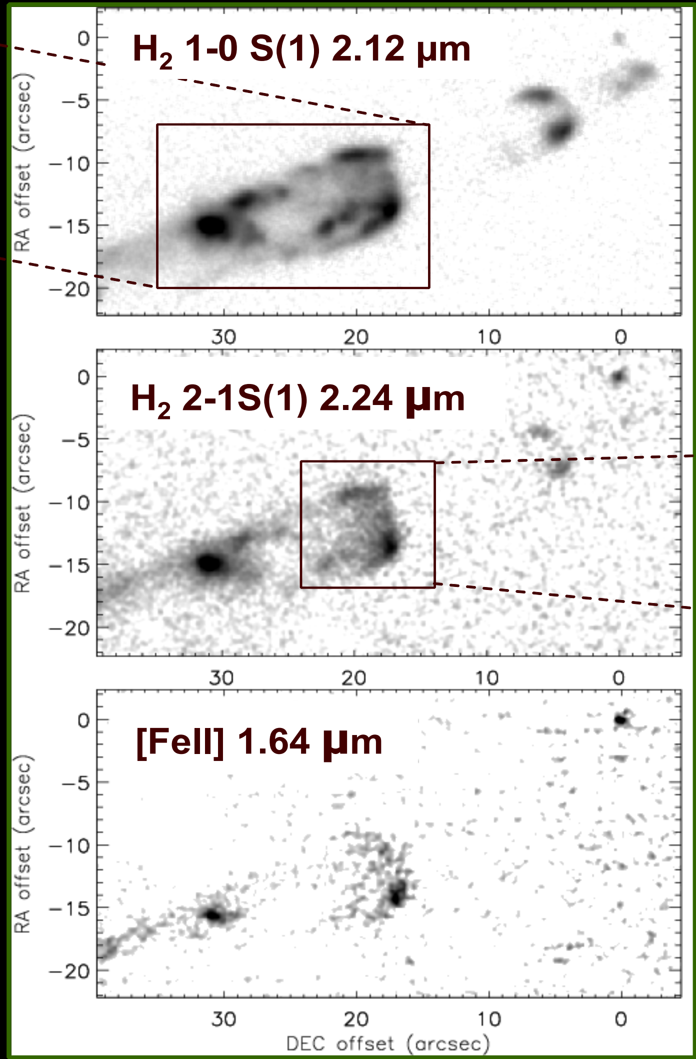
A combination of C and J shocks (associated with episodic outflow ejection) is needed to interpret observations (H_2, CO, H_2O, van Dishoeck 2004)

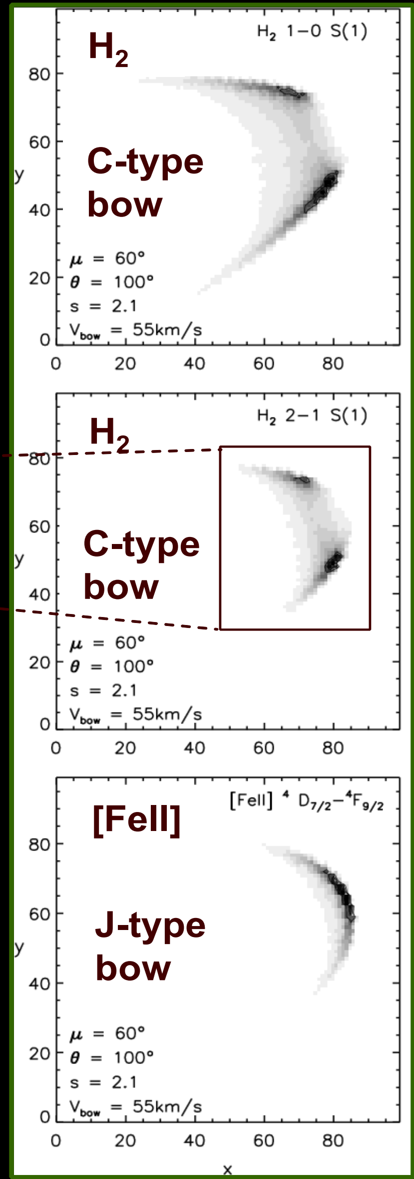
Shocks: HH 211 (Connell et al. 2005)



H2 & [FeII] found in the bows

Morphology similar on large scales but details differ (different physical conditions of the emission regions are traced by different lines)

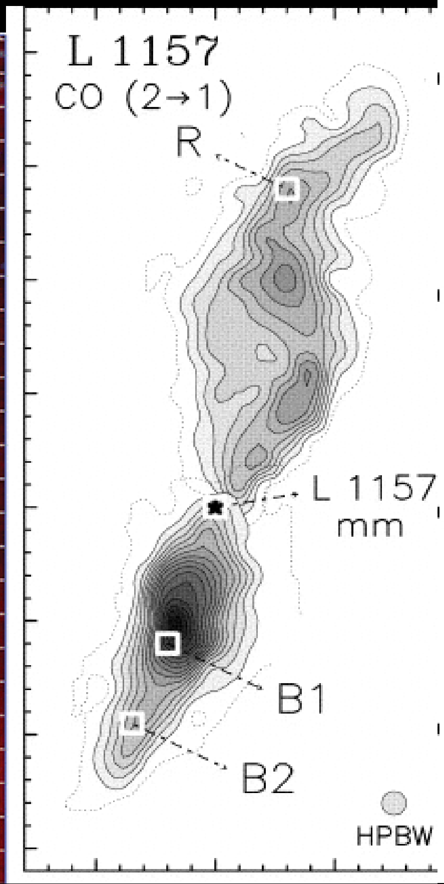




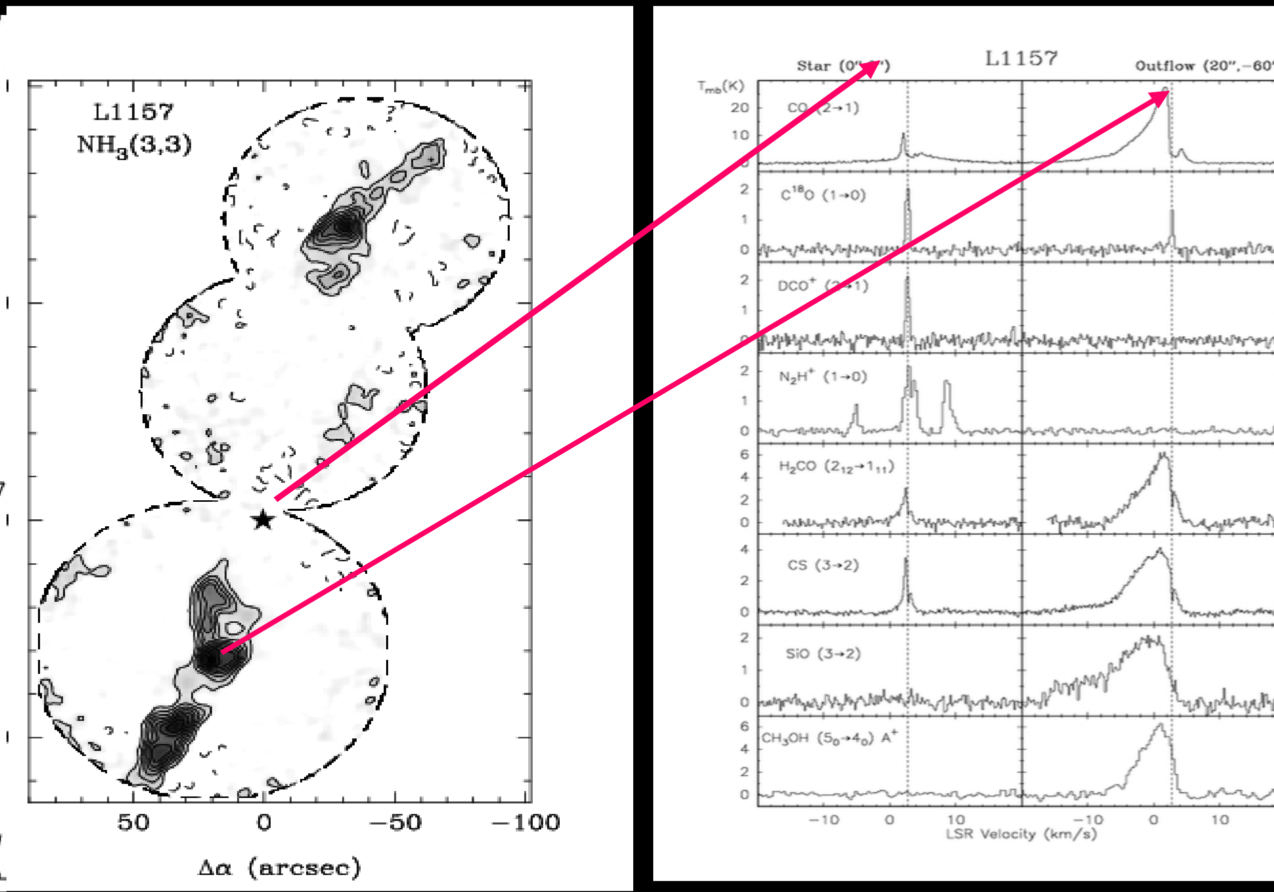
Class 0 outflows with favourable orientation in the sky are good target to study shock chemistry (opportunity to disentangle from other shock effects, e.g. collapsing envelope, Cecarelli et al. 2000)

Spitzer composite
3.6-4.5-8 μm image

Looney et al. (2007)



Bachiller et al. (2001)



Bachiller & Pérez Gutiérrez (1997)

Chemical surveys of Class 0 sources

- L1157: Bachiller & Pérez Gutiérrez 1997, Bachiller et al. 2001
- BHR71: Garay et al. 1998
- NGC1333 IRAS2: Joergensen et al. 2004
- NGC1333 IRAS4: Choi et al. 2004
- NGC2071: Garay et al. 2000
- Cep A: Codella et al. 2005
- …

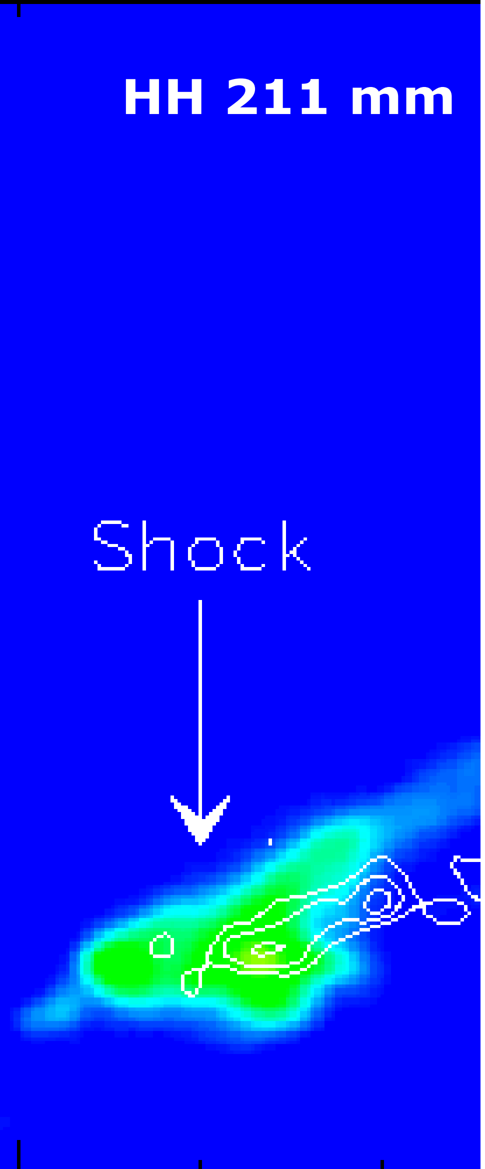
Spatial chemical segregation

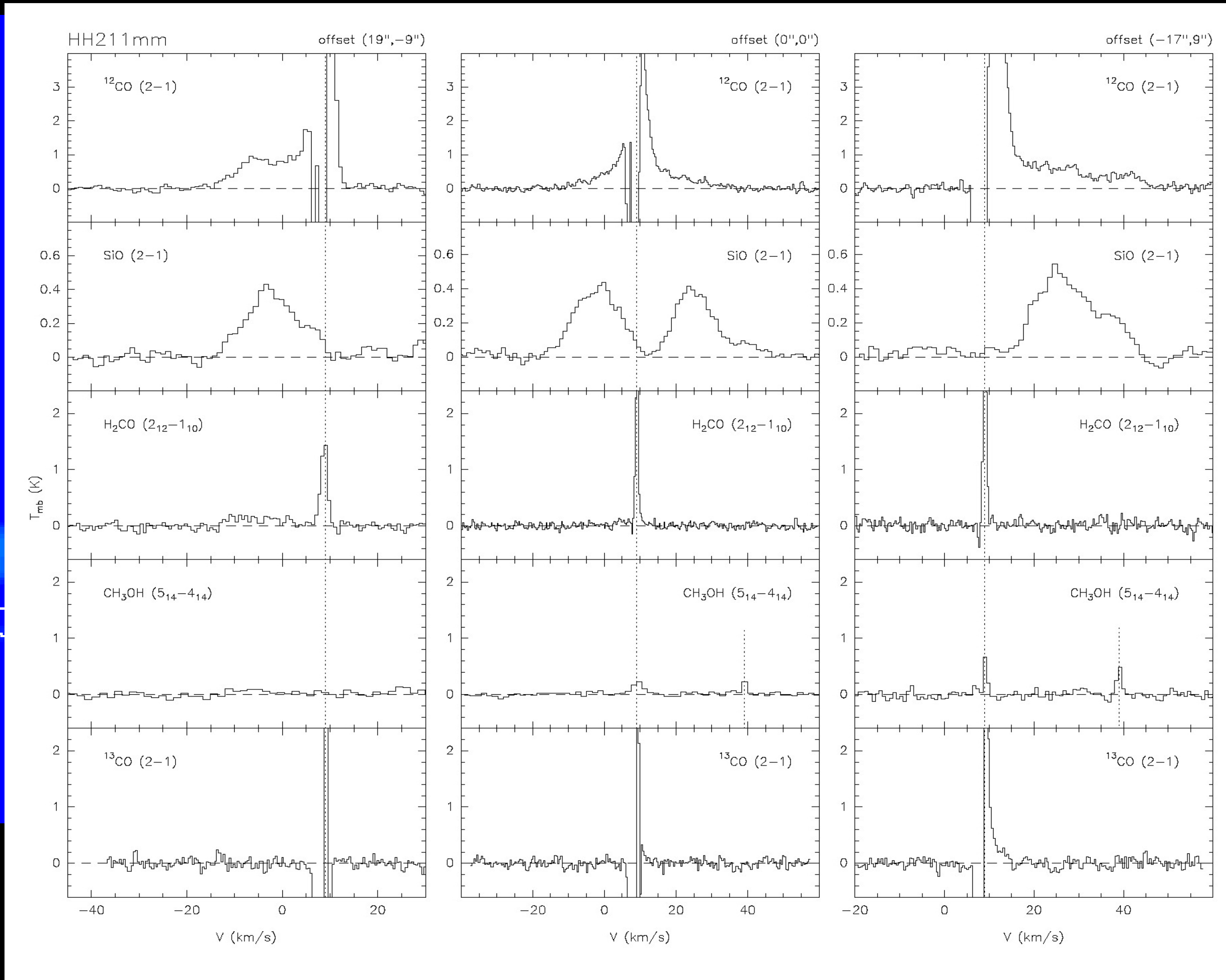
- Strong spatial gradients in molecular abundances
- Linked to the rapidly evolving chemistry (Bachiller et al. 2001)
- Could be also related to strong gradients in the abundance of atomic carbon (Joergensen et al. 2004)

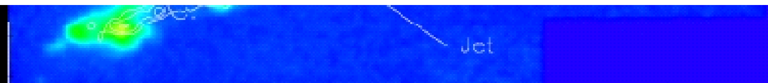
- See poster by Nomura & Millar on chemical models to reproduce different abundances in the shocked regions

SiO

- Extreme enhancement factors (up to 10^6) with respect to the ambient unperturbed medium (e.g. Bachiller 1996, ARAA)
- Extreme values found close to the heads (bow shocks) and axes of outflows
- Broad wings (> 25 km/s)
  - In agreement with high velocities needed for sputtering atomic Si from grains and/or grain-grain collisions (Schilke et al. 1997 ; Casselli et al. 1997)
- Detections up to J = 11-10 (Nisini et al. 2006): high excitation conditions T ~ few 100 K, n ~ 10^5 – 10^6 cm^{-3}

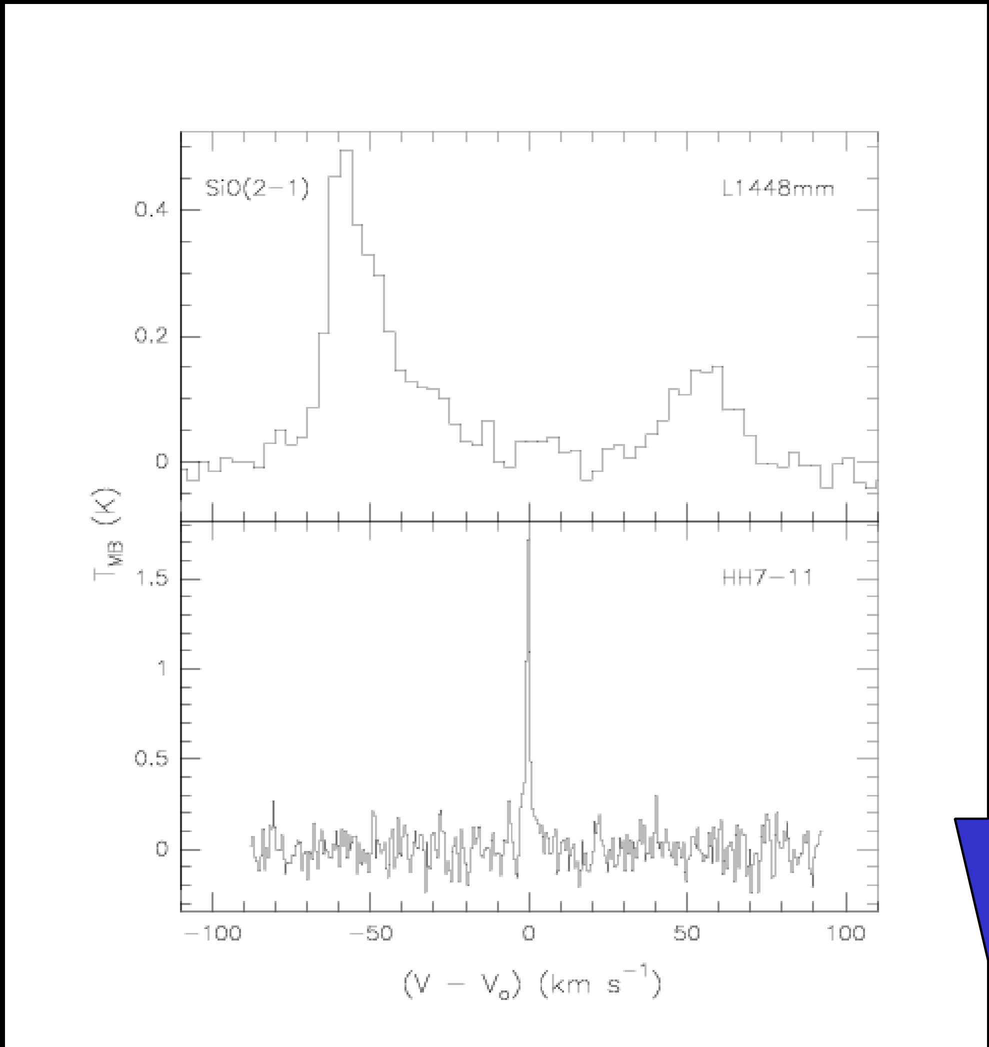






Gueth & Guilloteau 1999

Narrow (< 1km/s) SiO components



Codella et al. (1999)

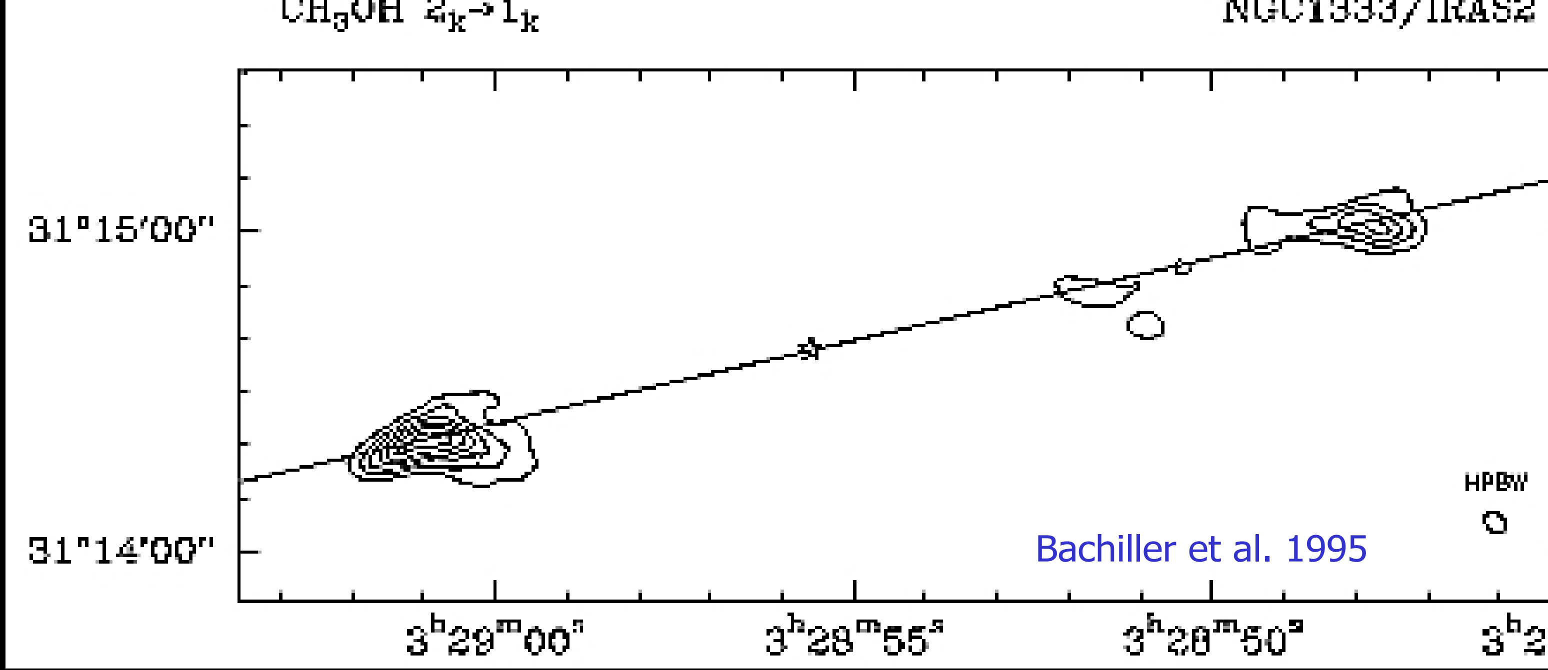
Uncertain origin

Codella, Bachiller & Reipurth (1999): SiO created at high velocities and slowed down as outflow evolves (~in 10^4 yr)

Jiménez-Serra et al. (2004, 2005): interaction of shock-precursors with the ambient gas

Time ?

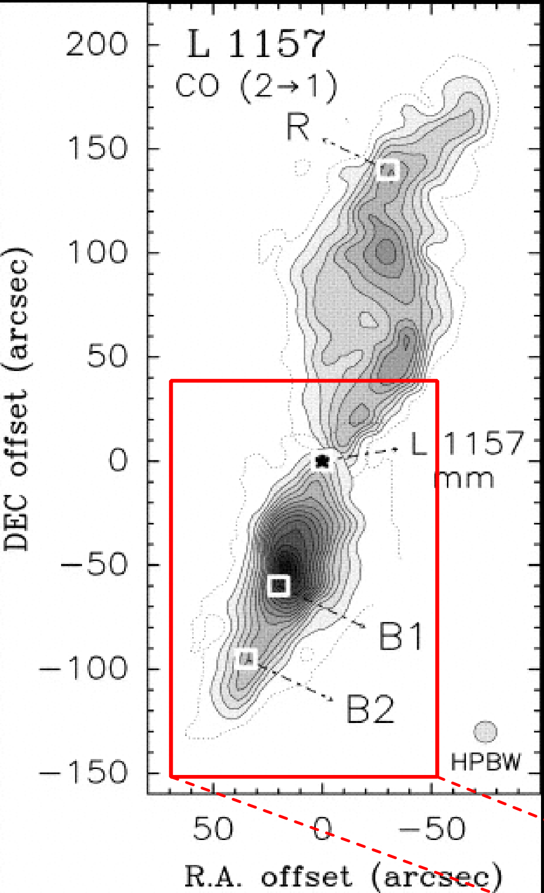
CH_3OH
H_2CO

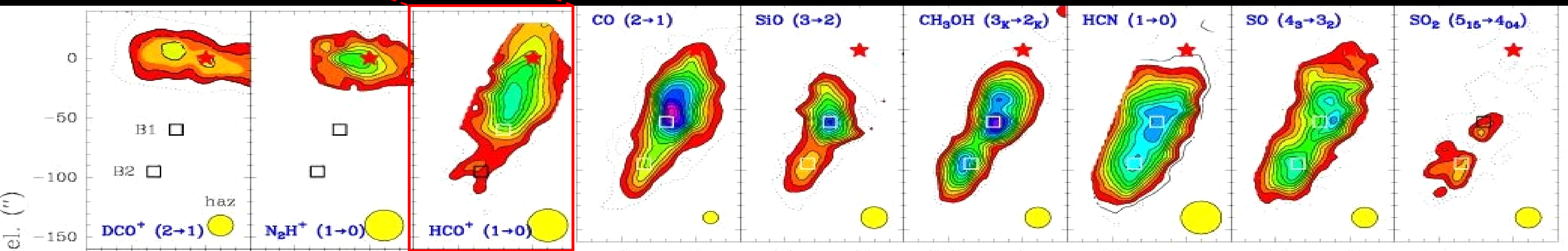


- Significantly enhanced (~100) in several outflows:
  - L1157, IRAS2, N2071, several objects (Garay et al. 2002, also Maret et al. 2005)
- Terminal velocities < than for SiO (do not survive at higher v ?)
- Directly evaporated from icy dust mantles
- See poster by Kalenskii et al. : some CH3OH lines can be masers

HCO^+

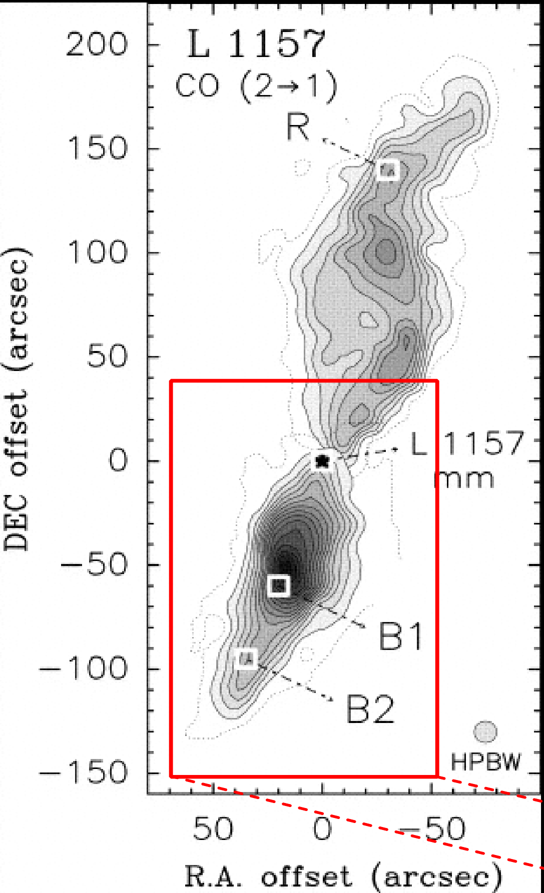
- high velocity emission prominent en regions close to the YSO
- enhancement ~ 20
- anticorrelated with CH_3OH (Joergensen et al. 2004)
- destroyed by
  - reaction with H_2O (Bergin et al. 1998)
  - dissociative recombination
- enhanced near HHs (e.g. HH2, Girart et al. 2002)
  - UV irradiation: Viti & Williams (1999), also NH_3
  - but shocks needed anyway, Girart et al. (2005)

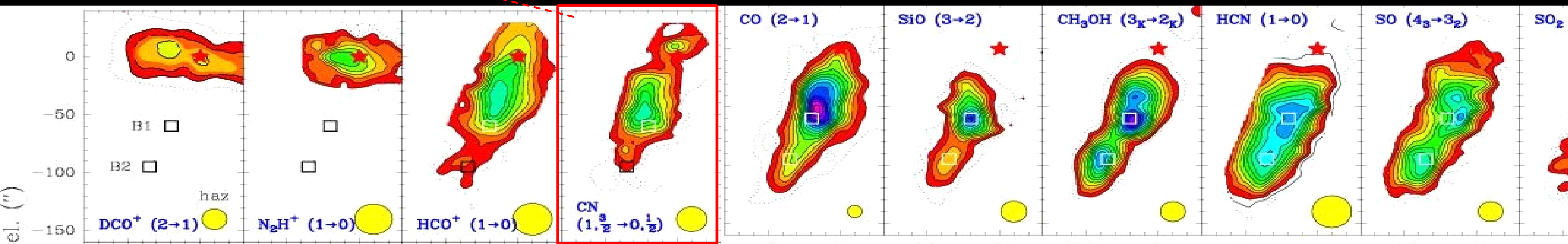




CN

- high velocity emission prominent in regions close to the YSO
- destroyed by
  - reaction with O (activation barrier ?)





Sulfur

Sulfur chemistry is seriously affected by grain surface reactions:

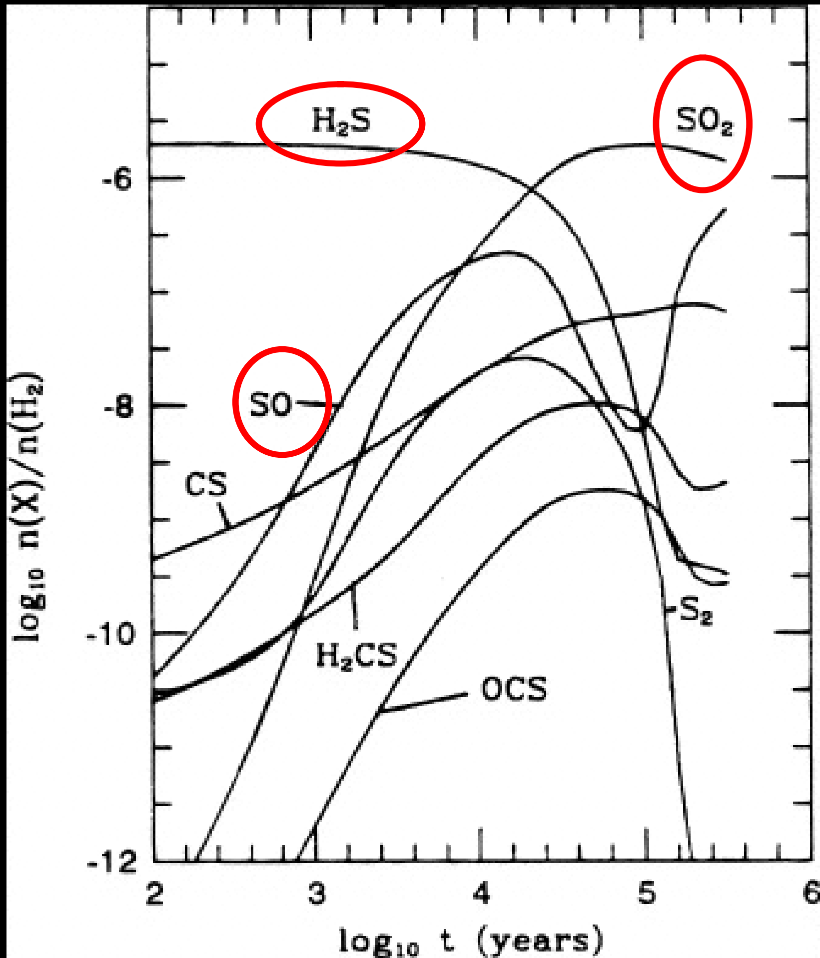
H_2S forms on grains $\rightarrow$ shocks inject H_2S in the gas phase (e.g. Pineau des Forêts et al. 1993)

$H_2S \rightarrow SO \rightarrow SO_2$

But

Lack of H_2S feature in the ISO spectra (van Dishoeck & Blake 1998; Gibb et al. 2000; Boogert et al. 2000)

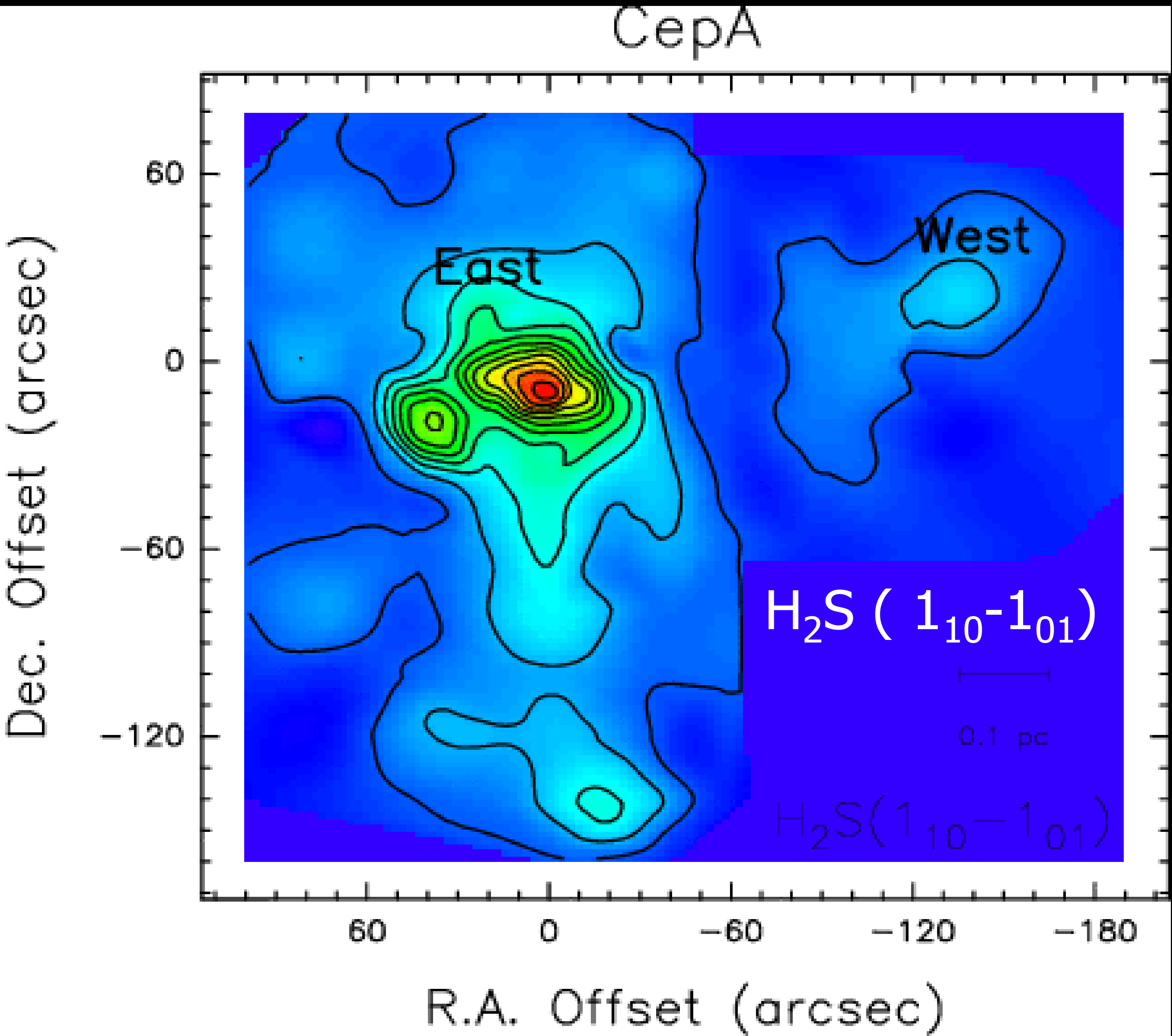
Detection of OCS on grains (Palumbo et al. 1997, see also van der Tak et al. 2003)



Is OCS a major carrier in ices?

Charnley (1997)

Codella et al. (2003)



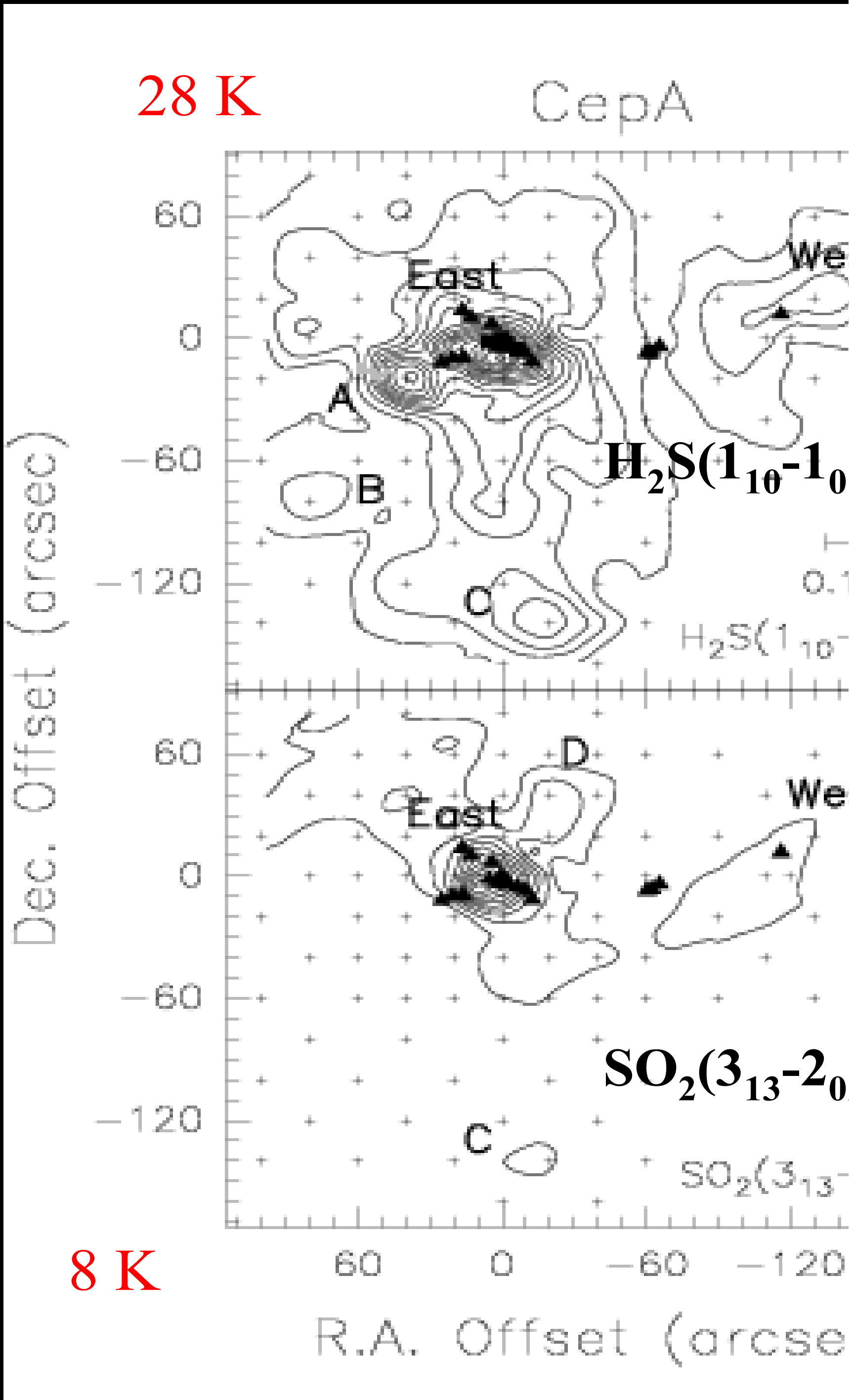
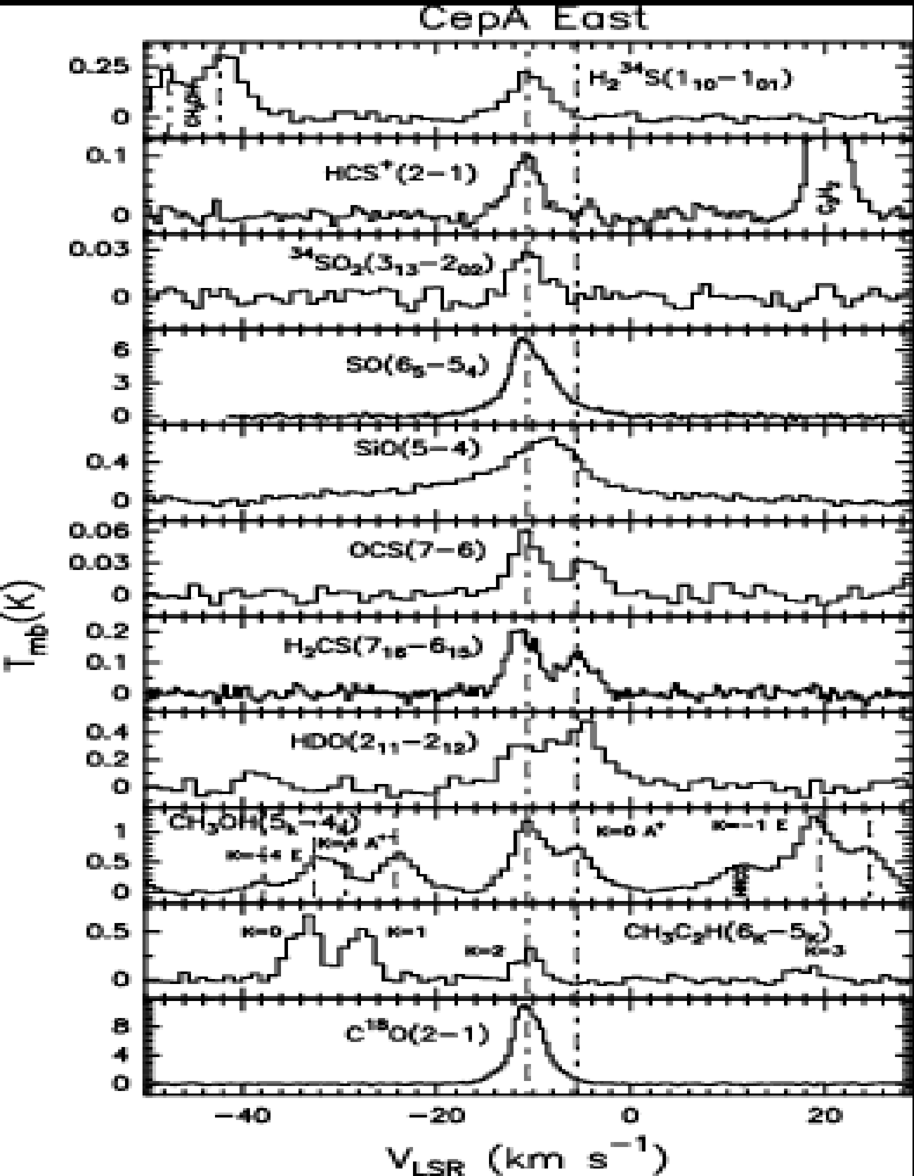


Table 1. LIST OF MOLECULAR SPECIES, TRANSITIONS AND OBSERVING PARAMETERS

Transition	ν_0 (MHz)	E_u (K)	$HPBW$ (″)	T_{sys} (K)	dv(AC) (km/s)	dv(1MHz) (km/s)
Selected transitions						
HDO($J_{K_-K_+} = 1_{10}$–1_{11})	80578.30	47	31	150	0.15	3.72
OCS($J = 7$–6)	85139.12	16	29	110	0.14	–
HCS^+($J = 2$–1)	85347.88	6	29	110	0.14	3.51
CH_3C_2H($J_K = 5_K$–4_K)	85457.30[a]	12[a]	29	150	0.27	3.51
$C^{34}S$($J = 2$–1)	96412.98	7	26	220	0.24	3.11
CS($J = 2$–1)	97980.97	7	25	180	0.24	3.06
SO($J_K = 3_2$–2_1)	99299.88	4	24	150	0.24	3.02
H_2CS($J_{K_-K_+} = 3_{13}$–2_{12})	101477.75	23	24	187	0.12	2.95
$^{34}SO_2$($J_{K_-K_+} = 3_{13}$–2_{02})	102031.91	8	24	130	0.11	2.94
CH_3C_2H($J_K = 6_K$–5_K)	102547.98[a]	17[a]	24	200	0.23	2.90
SO_2($J_{K_-K_+} = 3_{13}$–2_{02})	104029.414	8	24	120	0.23	2.88
SO_2($J_{K_-K_+} = 16_{214}$–15_{313})	104033.582	138	24	120	0.23	2.88
SO($J_K = 4_3$–3_2)	138178.64	9	17	370	0.17	2.17
CH_3OH($J_K = 3_K$–2_K)	145103.23[a]	14[a]	17	280	0.08	2.07
$H_2{}^{34}S$($J_{K_-K_+} = 1_{10}$–1_{01})	167910.52	28	14	480	0.07	1.79
H_2S($J_{K_-K_+} = 1_{10}$–1_{01})	168762.781	28	14	440	0.14	1.78
H_2CS($J_{K_-K_+} = 6_{16}$–5_{15})	202923.55	47	12	460	0.06	1.48
CH_3C_2H($J_K = 12_K$–11_K)	205080.73[a]	64[a]	12	600	0.11	1.46
HCS^+($J = 5$–4)	213360.64	31	12	330	0.04	1.41
$H_2{}^{34}S$($J_{K_-K_+} = 2_{20}$–2_{11})	213376.92	84	12	330	0.04	1.41
H_2S($J_{K_-K_+} = 2_{20}$–2_{11})	216710.437	84	11	550	0.11	1.38
SiO($J = 5$–4)	217104.94	31	11	450	0.43	1.38
$C^{18}O$($J = 2$–1)	219560.33	16	11	580	0.43	1.36
SO($J_K = 6_5$–5_4)	219949.39	24	11	580	0.11	1.36
CO($J = 2$–1)	230537.98	17	10	1100	0.10	1.30
$C^{34}S$($J = 5$–4)	241016.17	34	10	990	0.10	1.24
HDO($J_{K_-K_+} = 2_{11}$–2_{12})	241561.53	95	10	68	0.05	1.24
SO_2($J_{K_-K_+} = 5_{24}$–4_{13})	241615.797	24	10	670	0.10	1.24
CH_3OH($J_K = 5_K$–4_K)	241791.44[a]	35[a]	10	678	0.05	1.24
H_2CS($J_{K_-K_+} = 7_{16}$–6_{15})	244047.75	60	10	890	0.05	1.23
CS($J = 5$–4)	244935.61	34	10	1100	0.10	1.22
SO($J_K = 7_6$–6_5)	261843.72	35	9	1300	0.09	1.15
Serendipity detections						
$HC^{18}O^+$($J = 1$–0)	85162.21	4	29	110	0.14	–
C_3H_2($J_{K_-K_+} = 2_{12}$–1_{01})	85338.91	6	29	110	0.14	3.51
$C^{13}CH$($J_{K_-K_+} = 1_{11}$–0_{11})	85307.69	4	29	110	–	3.51
CH_2CO($J_{K_-K_+} = 5_{14}$–4_{13})	101981.43	23	24	130	0.11	2.94
CH_3OH($J_K = 10_{-3}$–10_1 E)	102122.70	154	24	130	–	2.94
CH_3OH($J_K = 9_1$–9_0 E)	167931.13	126	14	480	0.07	1.79
CH_3OH($J_K = 13_6$–14_5 E)	213377.52	390	12	330	0.04	1.41
CH_3OH($J_K = 1_1$–0_0 E)	213427.12	13	12	330	0.04	1.41
$^{34}SO_2$($J_{K_-K_+} = 16_{115}$–15_{214})	241509.05	131	10	670	–	1.24
HNCO($J_{K_-K_+} = 11_{011}$–10_{010})	241774.09	58	10	678	0.05	1.24
$^{34}SO_2$($J_{K_-K_+} = 18_{117}$–18_{018})	243935.88	163	10	890	–	1.23

[a] For CH_3OH, it refers to the J_0–J–1_0 A^+ line, while for CH_3C_2H it refers to the $K=$

Shock tracers: SiO, HDO, CH_3OH
Ambient medium: $C^{18}O$, CO, CS, CH_3C_2H
S-bearing species: H_2S, SO, SO_2
HCS^+, H_2CS, OCS



- **H_2S, SO, and SO_2 preferentially trace more quiescient regions than SiO**
- **HCS^+, H_2CS, OCS exhibit a well-defined red-shifted peak ("I-feature")**

Interpretation

- Shocks injecting (or producing) slow moving H_2S molecules in the gas phase

- Fast conversion of H_2S into SO and SO_2 in agreement with the Pineau des Forêts et al. (1993) and Charnley (1997) models (~ 10^3 yr)

- Lack of H_2S extended wings: H_2S is not the major sulphur carrier on grain mantles
(van der Tak et al. 2003). T(H_2S) ~ 27 K.

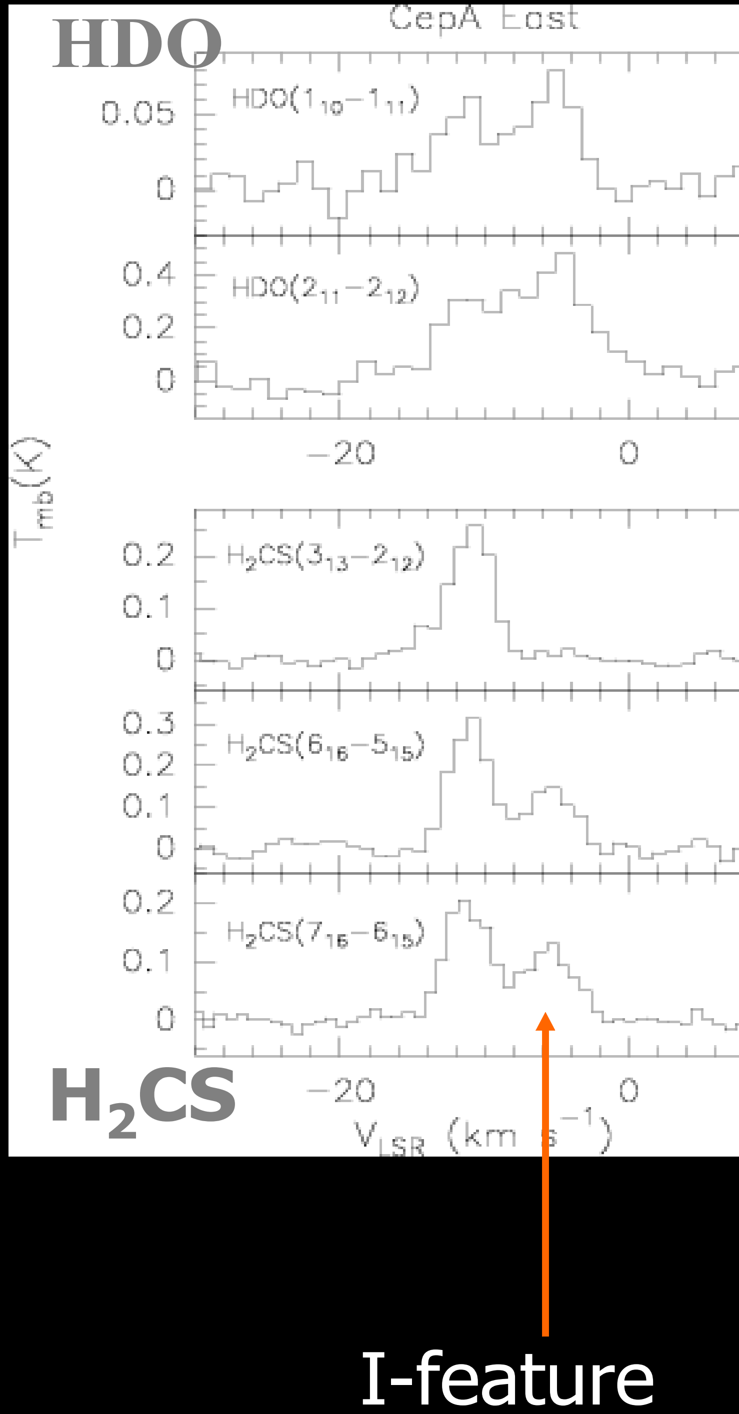
"I-feature"

OCS and H_2CS emit at moderate high velocities (where SiO starts to dominate) and where also the CH_3OH abundance increases (released at about 220 K)

SO, SO_2, CS, H2S not prominent

HDO increases the abundance at such velocities, as expected in regions heated above 200 K (Hartquist et al. 1980)

Shock models (e.g. Wakelam et al. 2004) do not explain well this behavior



Model calculations in Codella, Viti, Williams & Bachiller (2006, ApJ Lett)

The I-feature (at –5.5 km/s) is consistent with a turbulent interface between the outflow and the ambient cloud if

(i) 100 % of Sulfur in grains is assumed to be in form of OCS

(ii) Sufficient material is entrained into the interface on 10-50 yr.

Iron

Iron is a refractory element similar, in many respects, to Silicon (depleted on grains).

Lines of Fe II are well observed in many jets (shocked regions)

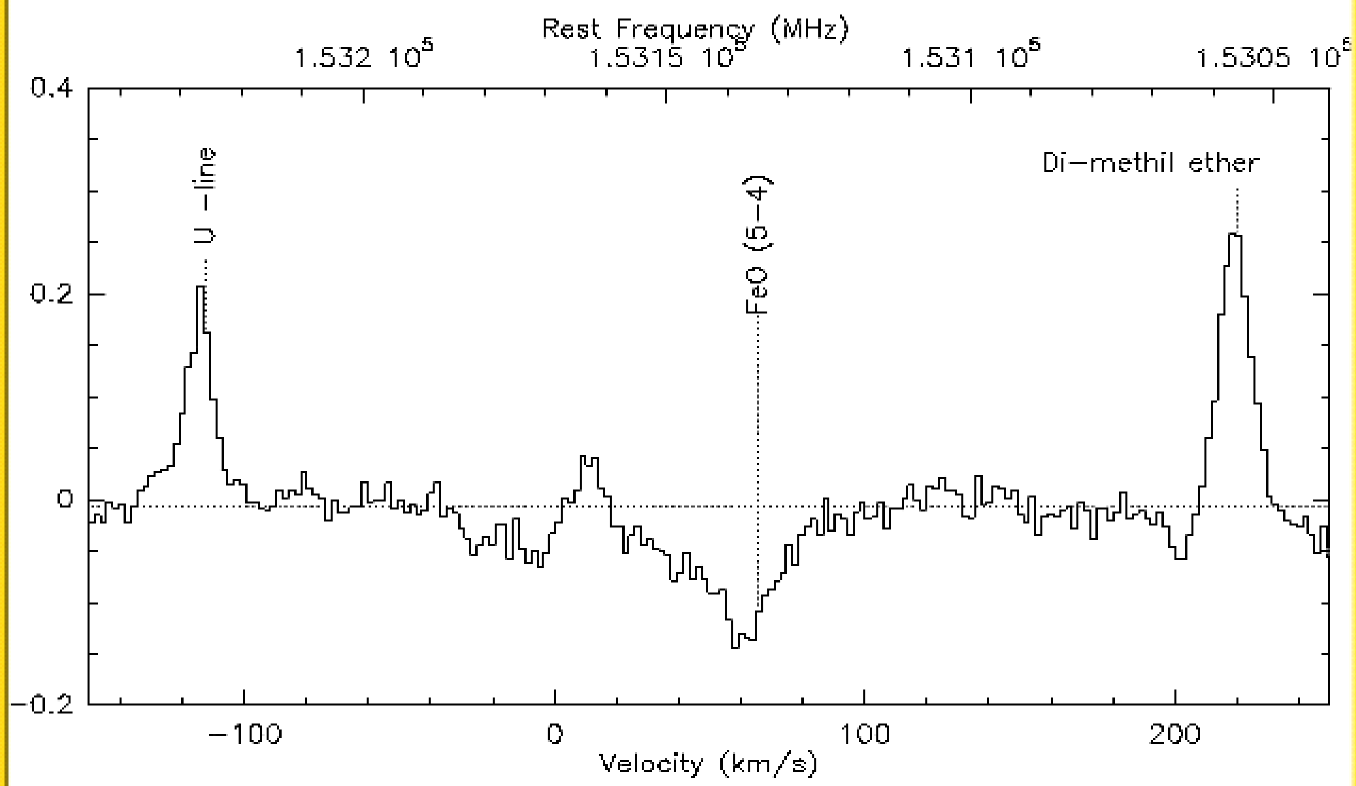
→ Similarly to SiO, one should expect to find FeO emission from molecular shocks.

Observations of FeO (5-4), FeC (6-5), and MgOH (3-2)

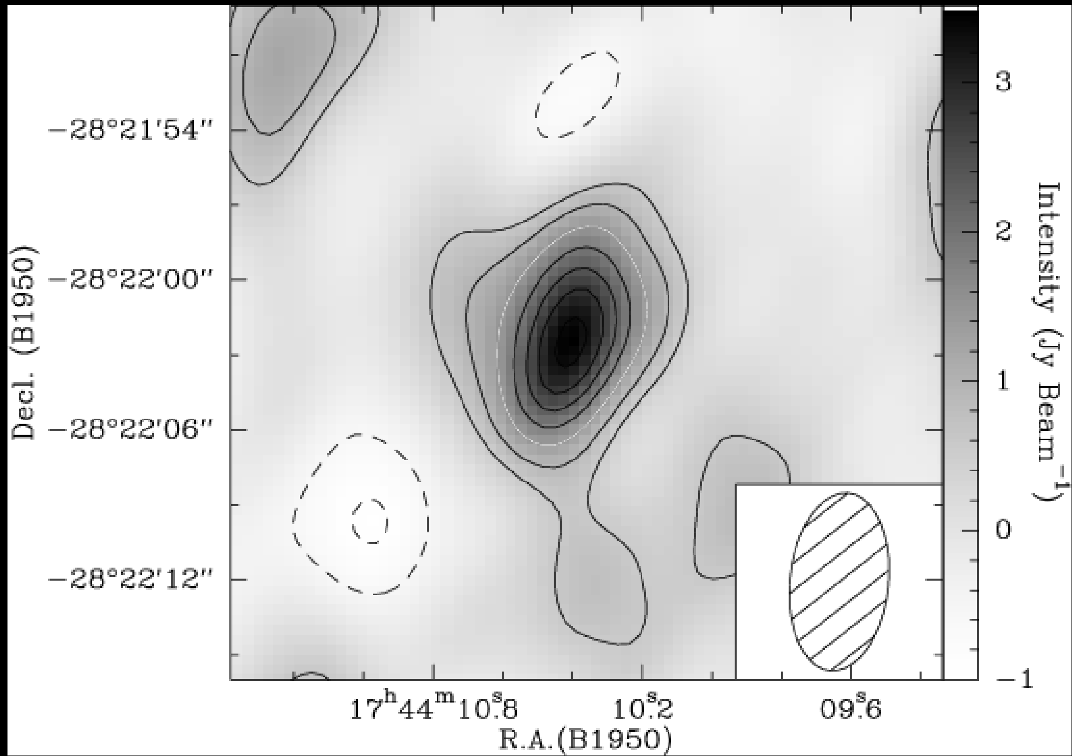
Source (1)			Velocity (LSR) (km s^{-1}) (4)	rms (FeO)[a] (mK) (5)	rms (FeC)[a] (mK) (6)	rms (MgOH)[a] (mK) (7)
W3(OH)			-45	21	52	17
OriIRC2			7	10	40	7
IC443G1			-10	12	26	7
IRC10216			-27	9	16	5
I16293E2			7	8	25	6
Sgr B2M			65	13	30	17
Sgr B2N[b]			65	70	...	26
L1157B			1	5	10	3

Notes. *The rms noise values in cols. (5) (7) are for FeO (5 4), FeC (6 5), and MgOH (3 2), respectively.* [a] *Noise values for 1 MHz resolution.* [b] *Sgr B2N spectrum is so crowded that the "rms" given for FeO is a measure of confusion because of the blended U lines rather than noise, and FeC (6 5) is completely blended with U lines.*

Tentative detection of FeO in the ISM (towards Sgr B2 M)
Walmsley, Bachiller, Pineau des Forêts & Schilke (2003)



Nobeyama map of FeO (153 GHz) towards Sgr B2
Furuya et al. (2003)



higher column density of FeO towards the UCHII regions associated with Sgr B2 M
[FeO]/[SiO] between 0.02 and 0.05.
shocks responsible for the ejection of a small amount of iron into the gas phase are caused by the stars associated with the HII region Sgr B2 M itself.

L1157 B1

N(FeO) < 6×10^{11} cm^{-2} , [FeO]/[SiO] < 0.01

Sgr B2

[FeO]/[SiO] ~ 0.02-0.05 in 5″ region , [FeO]/[H_2] ~ 3×10^{-11} in 15″ region
(could be 10x higher in central 5″)
compatible with negative results in other sources

Interpretation

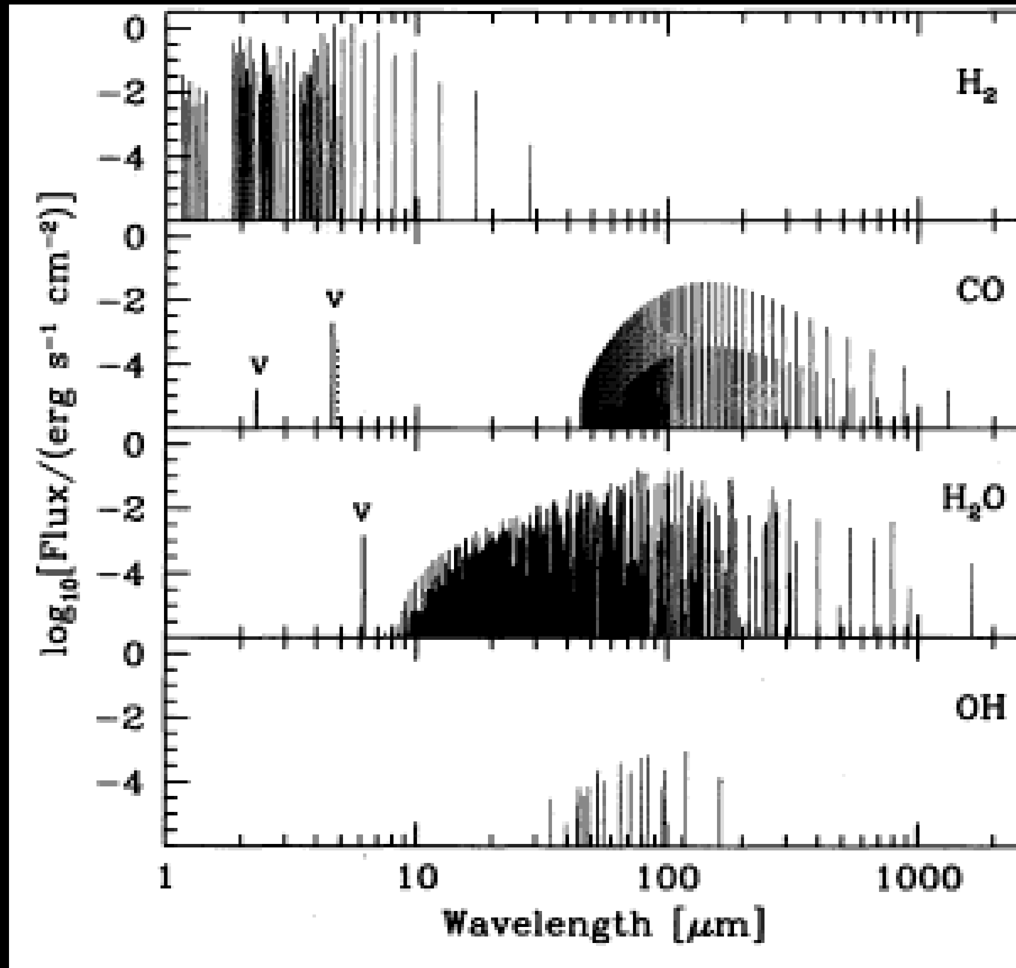
The iron liberated from grains in the shocks remains atomic and is not processed into molecular form (FeII emission is indeed well known is shocks)

While the erosion rates are similar for iron and silicon, gas-phase iron is much less reactive in the shock and in the postshock gas than atomic silicon:

- atomic silicon can react at low temperatures with species such as OH and O
- the analogous reactions for atomic iron (endothermic by 10,200 K for Fe+O_2 and 1550 K for Fe+OH) only occur under high-temperature conditions in a shock.

Water

- Expected to be one of the main coolants
- Thermal emission is difficult to observe



Rotational lines of H_2O from a MHD shock wave
40 km/s, preshock n = 10^5 cm^{-3}, preshock B = 447 μG
Kaufman & Neufeld (1996)

Bergin, Melnick & Neufeld (1997): 3-stage chemistry

- Low T

  $H_3O^+ + e^- \rightarrow H_2O + H$ (branching ratios ?)

  $OH + H_2$

  $OH + H + H$

  $O + H + H_2$

- T > 400 K

  $O + H_2 \rightarrow OH + H$ 3160 K

  $OH + H_2 \rightarrow H_2O + H$ 1660 K

- Very High T

  $O_2 + H_2 \rightarrow OH + OH$ 28190 K

  $OH + H_2 \rightarrow H_2O + H$ 1660 K

  - after the passage of the shock, water molecules quickly deplete on grains

- ISO observations towards L1448, L1157
  - High excitation conditions, similar to those traced by SiO (Giannini et al. 2001)

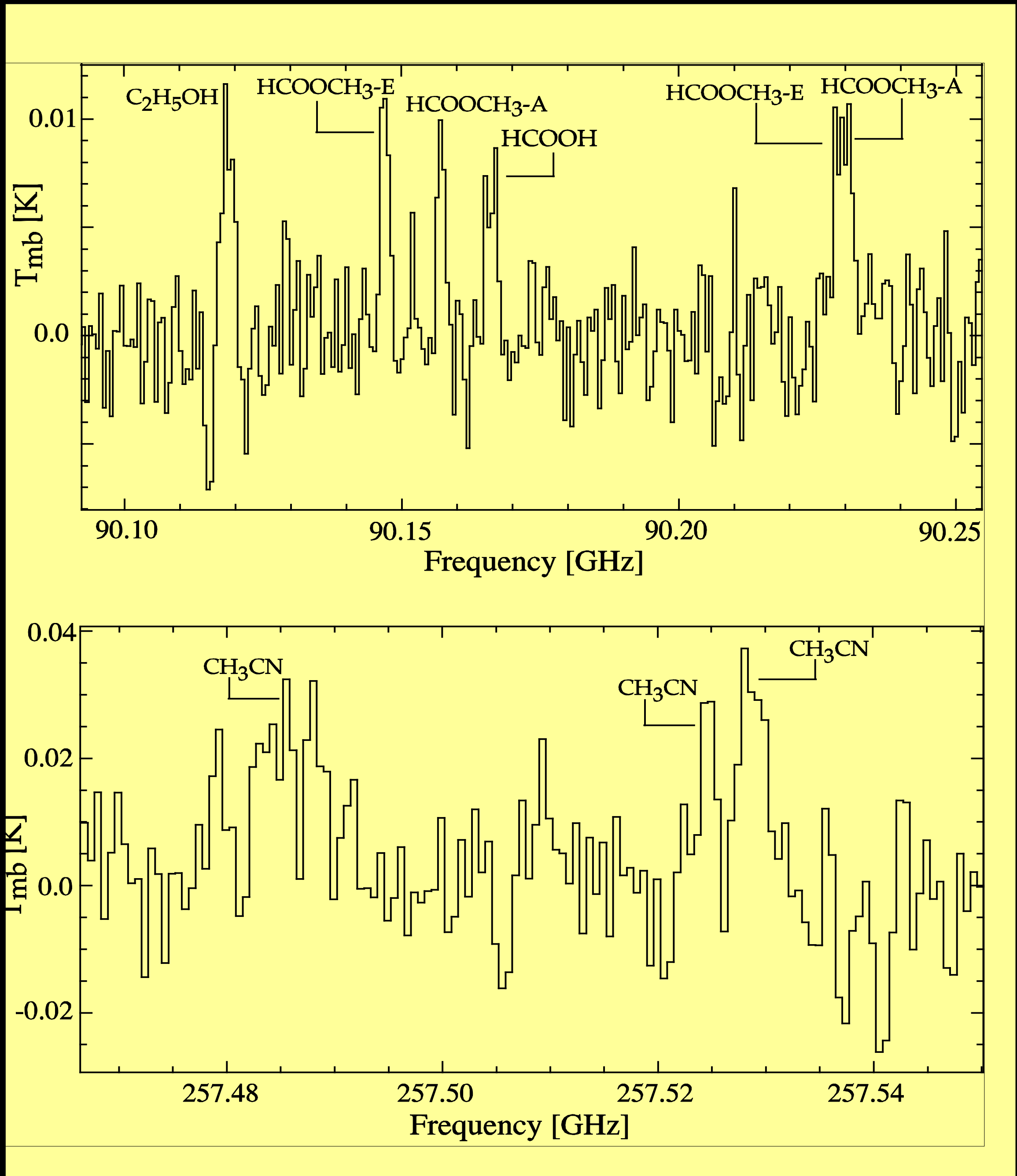
    T ~ few 100 K, n ~ $10^5 - 10^6$ cm^{-3}
- Column density ratio (Nisini et al. 2006)

  $SiO/H_2O \sim 2\ 10^{-4}$ to 10^{-3}

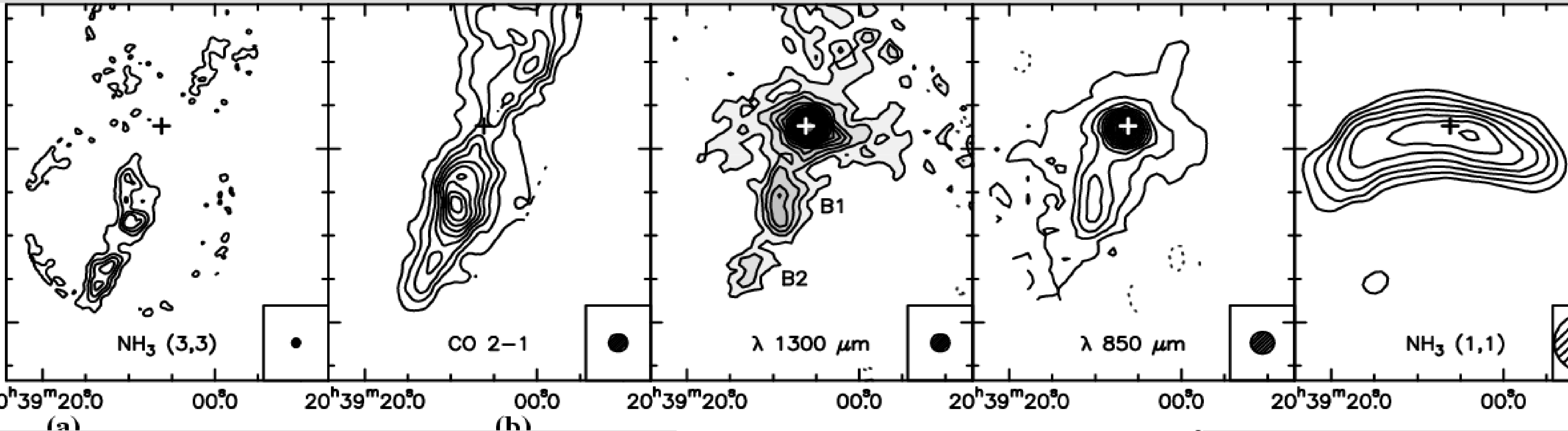
- Important lines to be observed with HERSCHEL
  - Low excitation: 752, 900, 1113 GHz
  - High excitation: 1090- 1300 GHz

(Even more) complex molecules

- Arce, Santiago, Joergensen, Tafalla, Bachiller (2008) ApJ Lett – L1157 B1
  - $HCOOCH_3$
  - CH_3CN
  - $HCOOH$
  - C_2H_5OH
- Probably ejected from the grain mantles (formation time scale >> kinematical time scales)
- Abundances (relative to CH_3OH) similar to hot cores and GC => universal dust composition

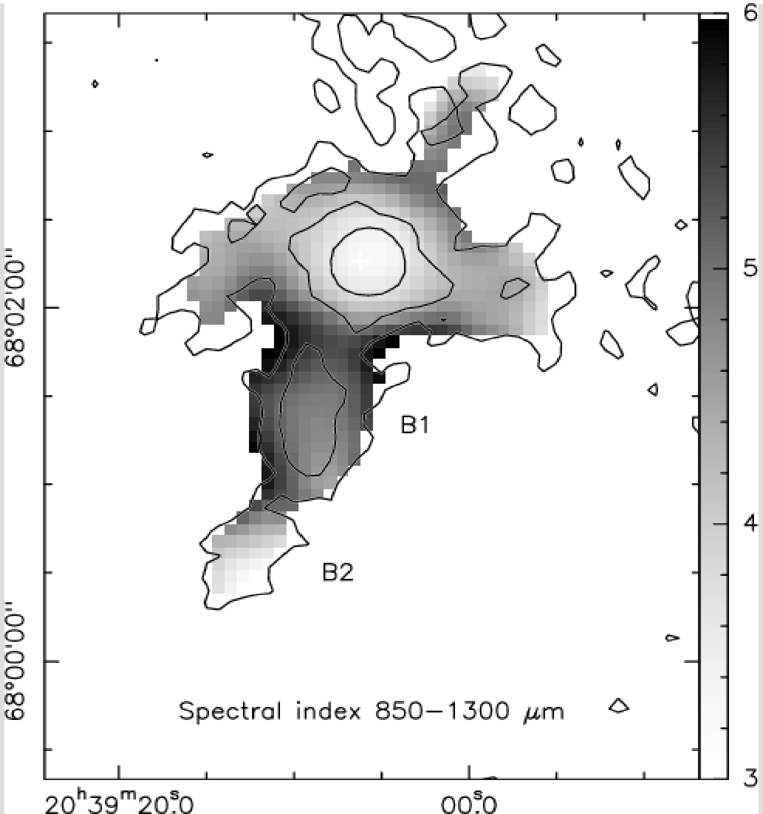


Dust in the shocked region (Gueth, Bachiller & Tafalla 2003)



Spectral index (1.3 mm/ 0.85 mm) ~5 in the shock

$\beta \sim 3$ ($\kappa \sim \nu^{\beta}$) small grains ?



Early evolution of outflows

Systematic study of young outflows: evolution from Class 0 to Class I

Homogeneous observations at the IRAM 30-m telescope

Work with Joaquín Santiago (Ph.D.)

Several lines:

- ^{12}CO, ^{13}CO, $C^{18}O$
- SiO
- H_2CO
- CH_3OH

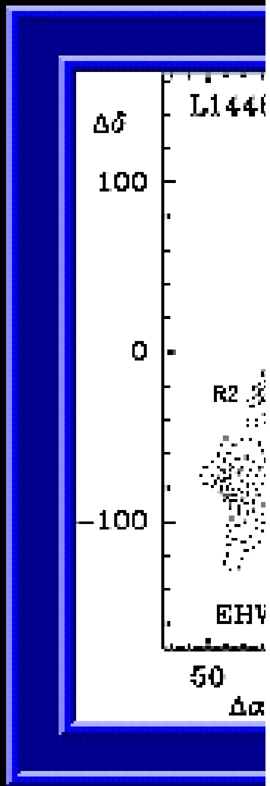
16 outflows:

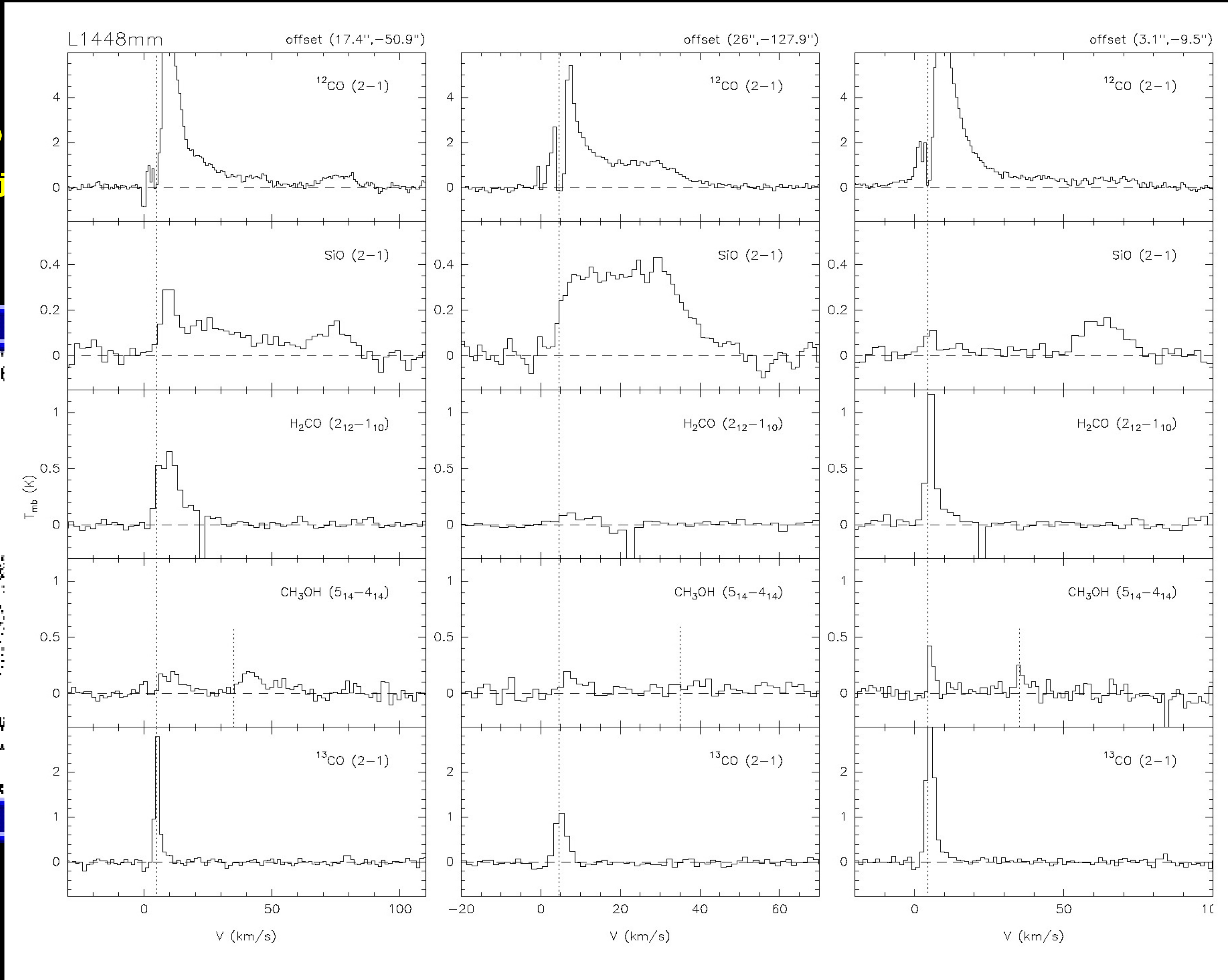
Source	Lbol
Class 0	
L1448 mm (+IRS3)	8.3/11
IRAS 03282	1.3
HH211 mm	10
L1157 mm	11
IRAS 16293-2422	21
SERP S68-N	5
N1333 - IRAS4A	17
N2264 - G	10
L1527	1.4
L483	14
B335	2.7
VLA 16293	1.0
Class I	
L1551 IRS5	3.8
B5-IRS1	9.4
L1228	3.4
TMR1	3.8

More massive objects: Caratti o Garatti et al. (2008), Beuther et al. (outflow survey), Codella et al. (S-chemistry), Kumar et al. (work on Onsala 1),...

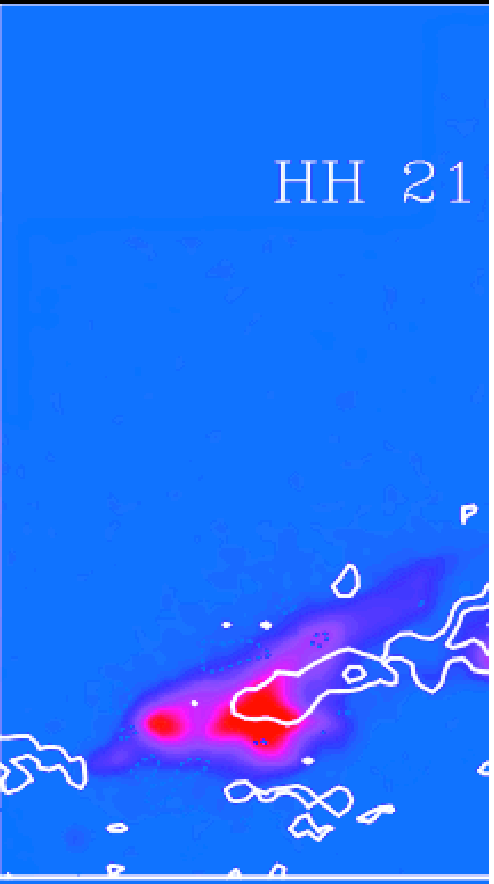
Class 0 o

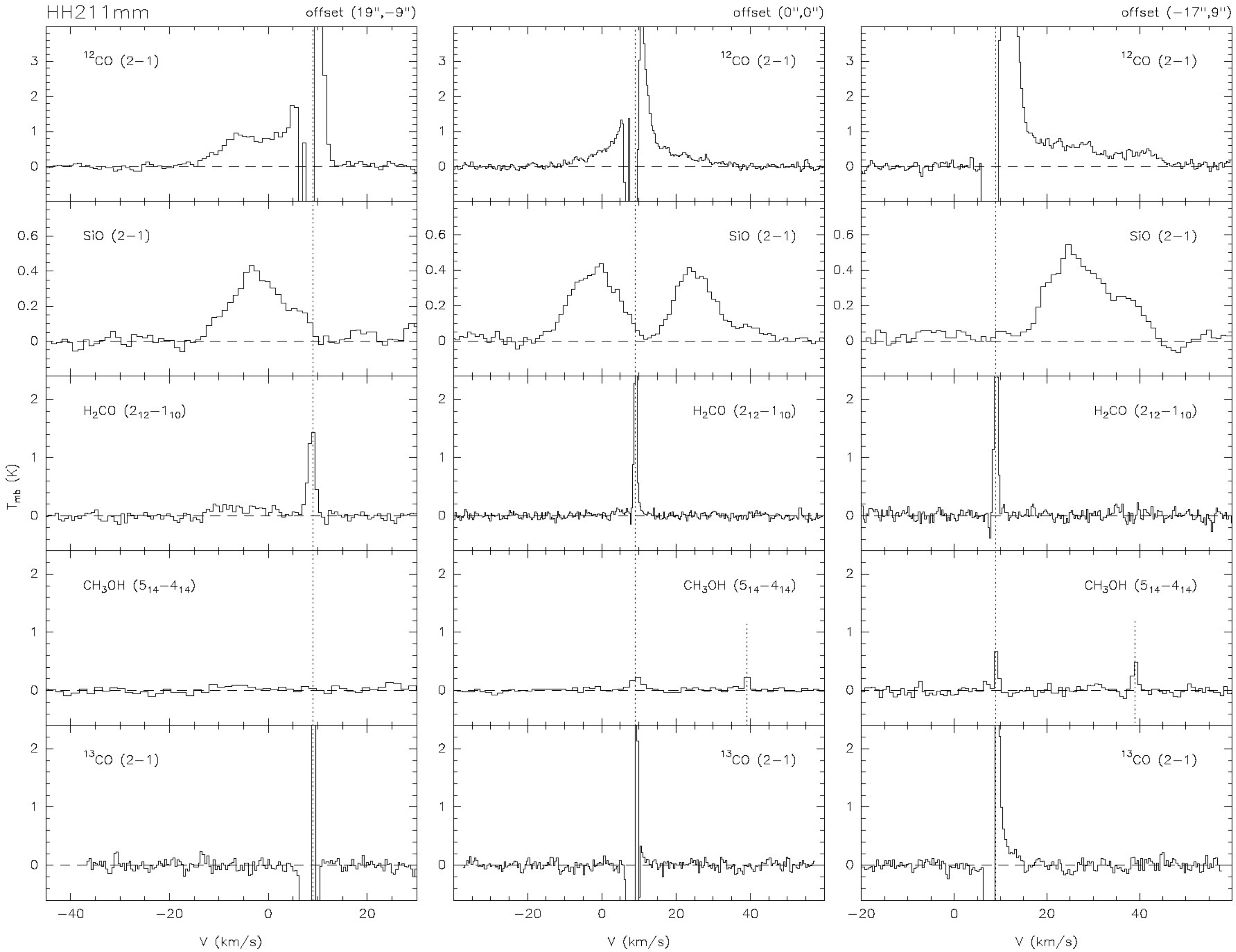
Molecular ej

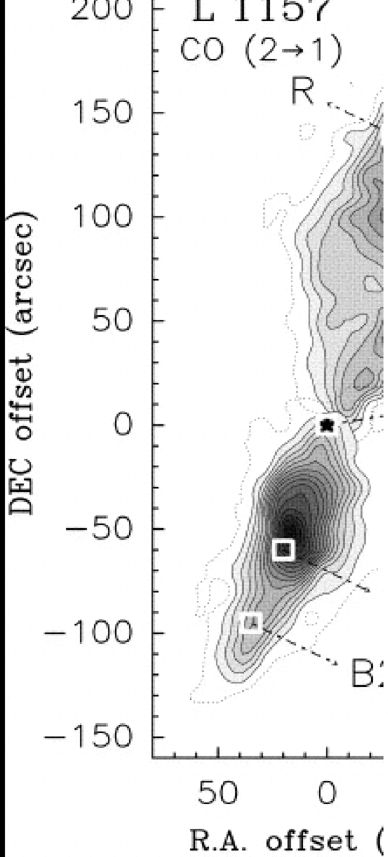


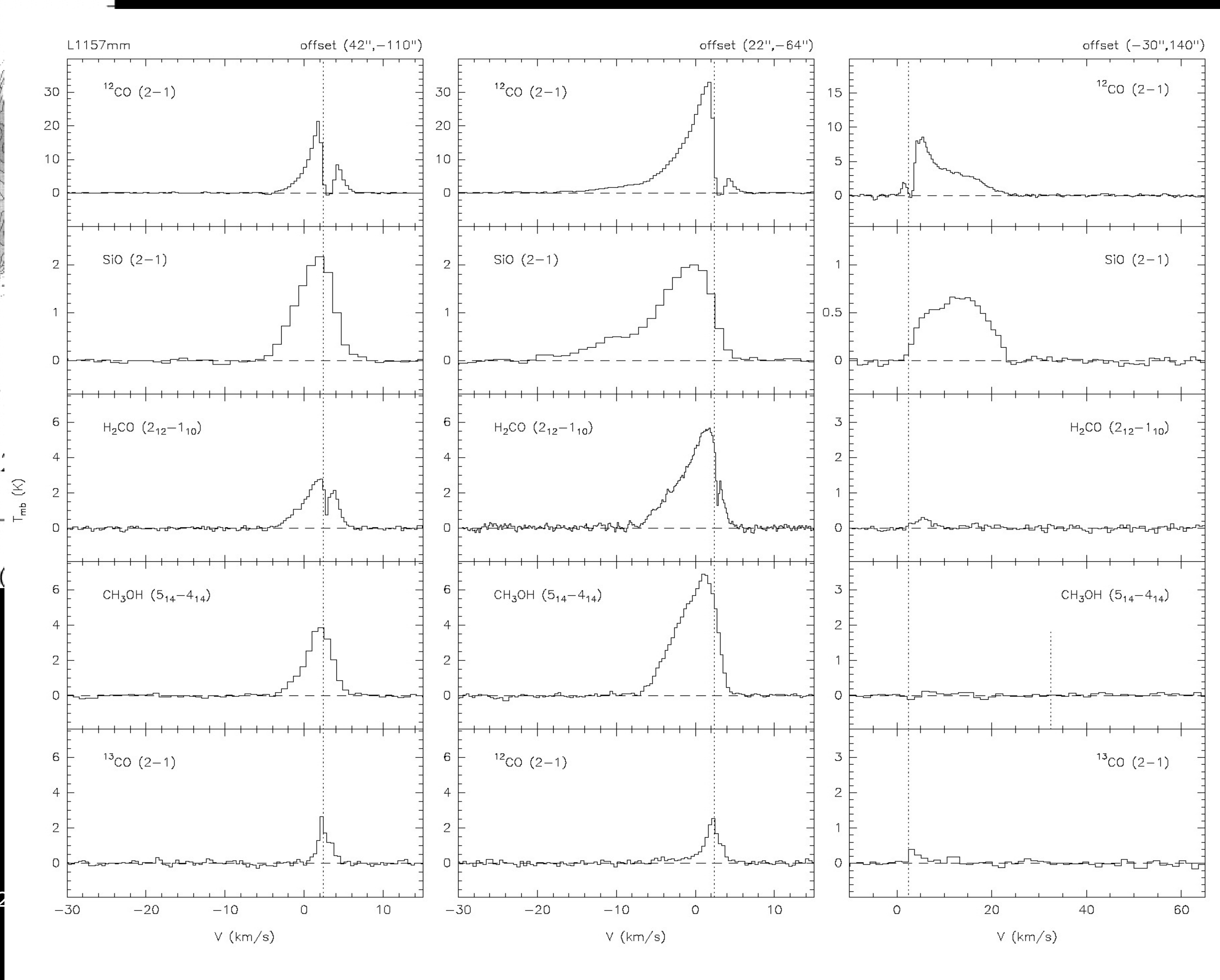


HH 211 mm


HH 21

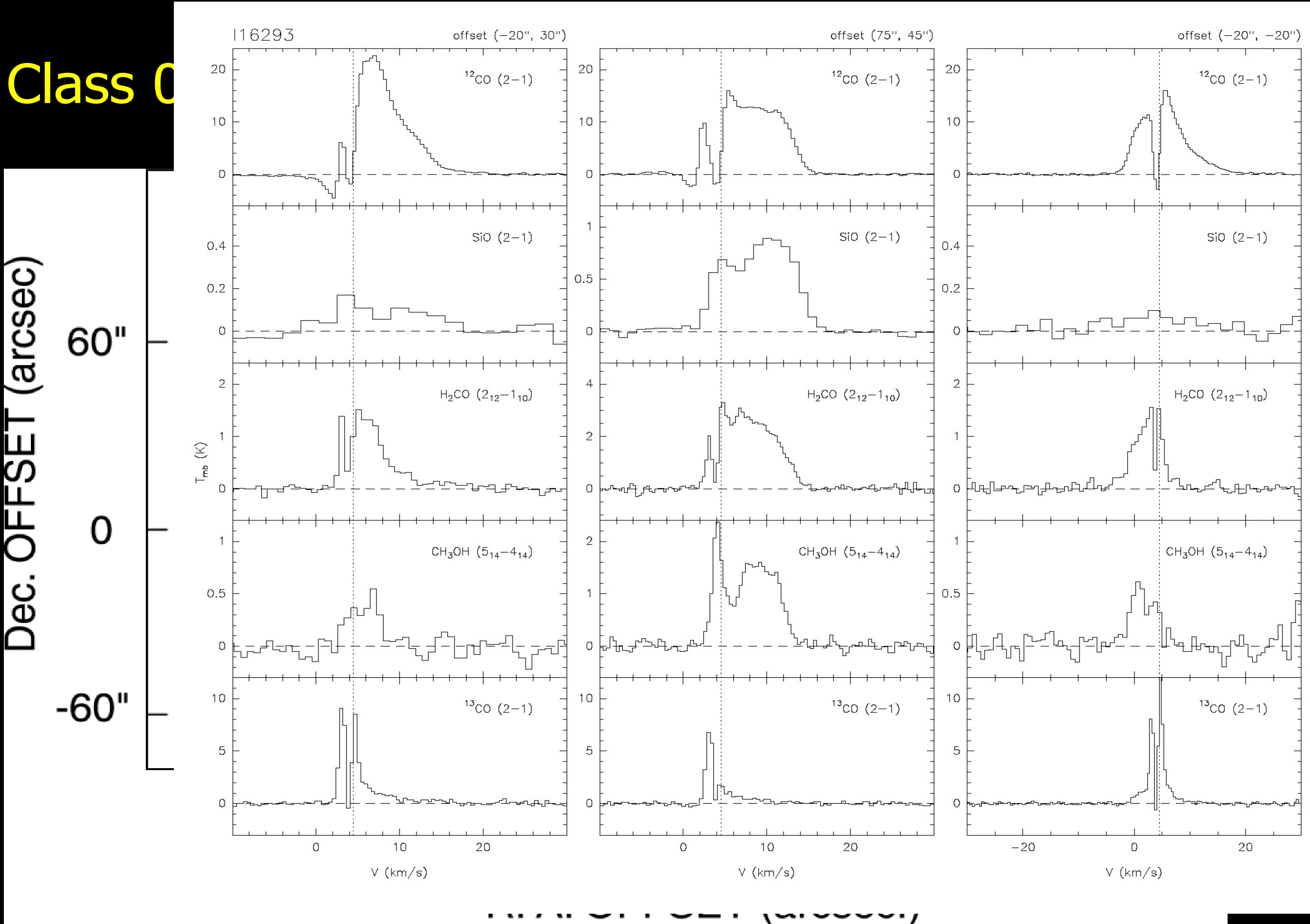

HH211mm
offset (19",-9")
offset (0",0")
offset (-17",9")
^{12}CO (2−1)
SiO (2−1)
H_2CO $(2_{12}-1_{10})$
CH_3OH $(5_{14}-4_{14})$
^{13}CO (2−1)
T_{mb} (K)
V (km/s)





Bachiller et al. 1997, 2

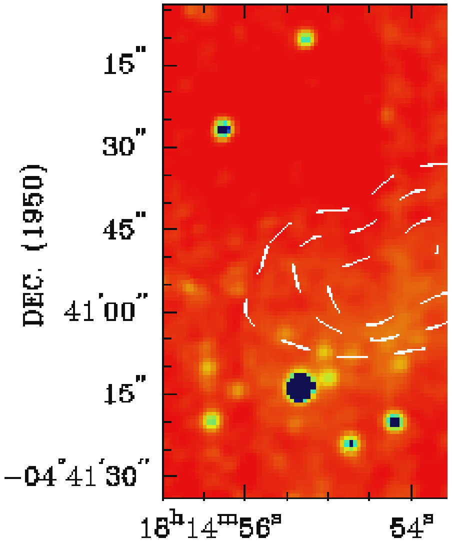
Class 0

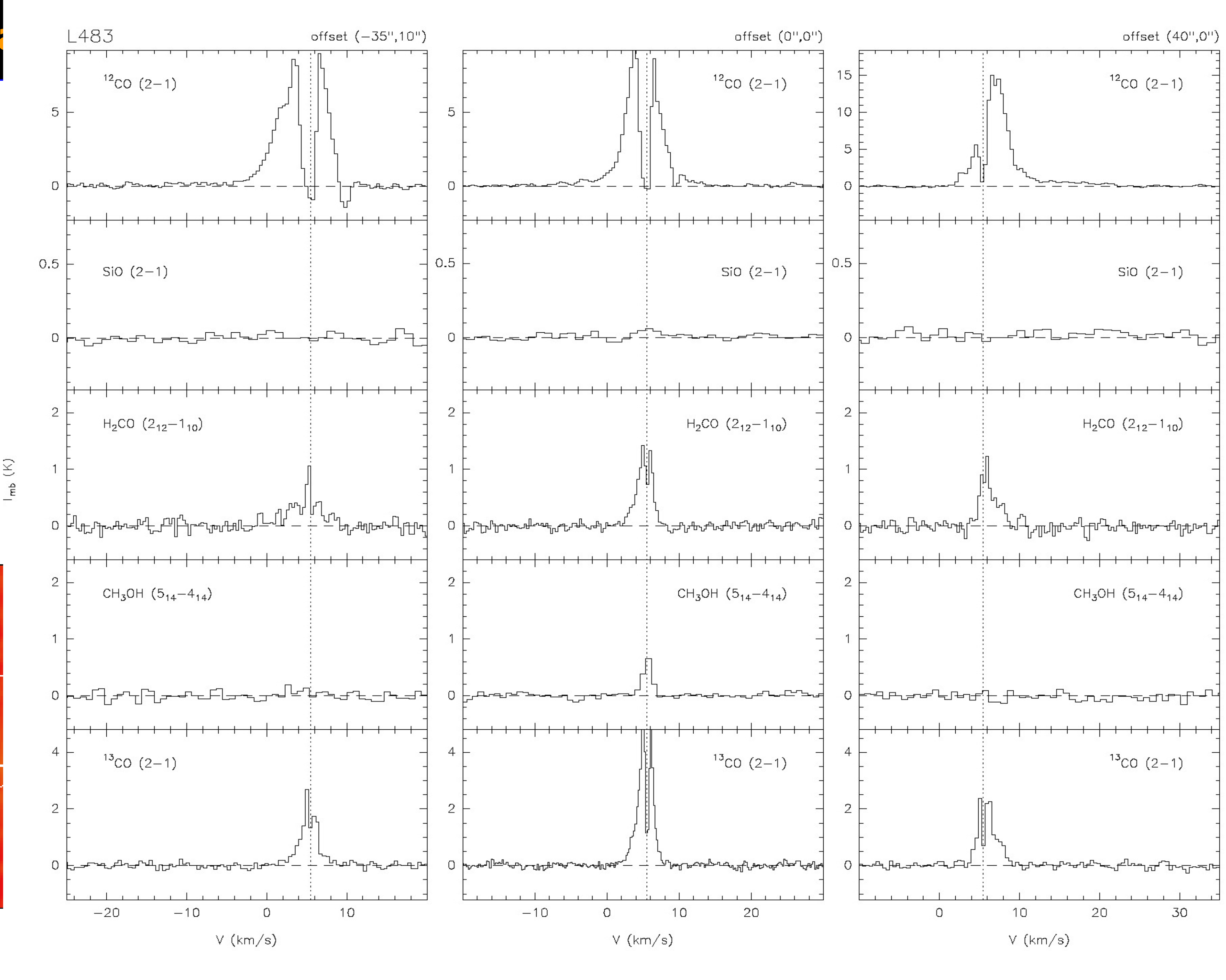


I16293
offset (−20", 30")
offset (75", 45")
offset (−20", −20")
^{12}CO (2−1)
SiO (2−1)
H_2CO ($2_{12}-1_{10}$)
CH_3OH ($5_{14}-4_{14}$)
^{13}CO (2−1)
T_{mb} (K)
V (km/s)
Dec. OFFSET (arcsec)
60"
0
-60"

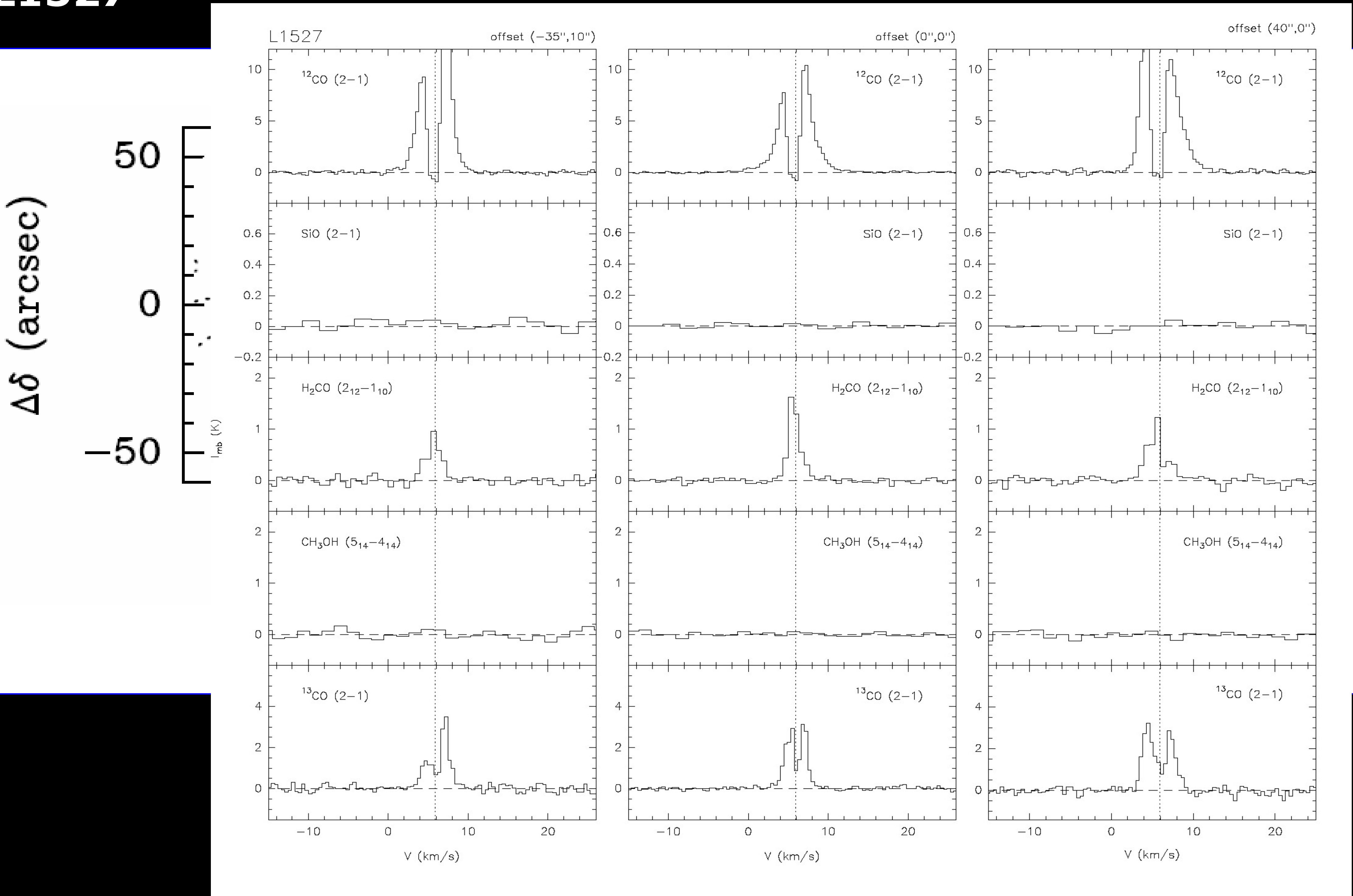
Class 0 to Cla

^{12}CO





L1527

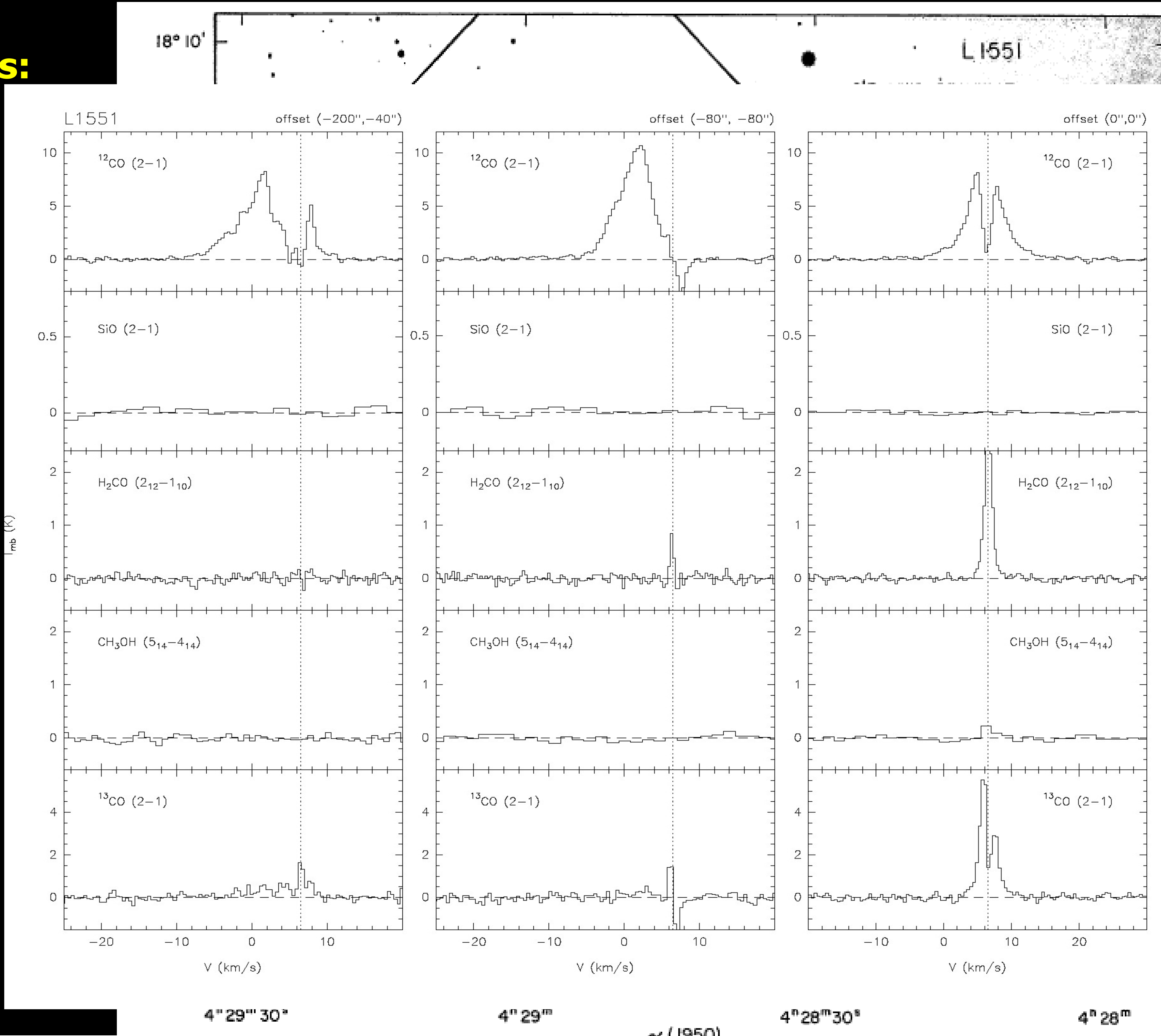


Δδ (arcsec)
50
0
−50
L1527
offset (−35'',10'')
offset (0'',0'')
offset (40'',0'')
^{12}CO (2−1)
SiO (2−1)
H_2CO ($2_{12}-1_{10}$)
CH_3OH ($5_{14}-4_{14}$)
^{13}CO (2−1)
T_{mb} (K)
V (km/s)

Class I outflows:

L1551 IRS5

Snell et al. 1990



Outflow chemical classification: based on SiO, H_2CO and CH_3OH behaviour

- Group 1 Extremely high velocity outflows: high velocity SiO emission (although some SHV emission can be present)

HH211mm, L1448mm, IRAS 04166,...

- Group 2 Chemically active outflows (SiO, H_2CO and CH_3OH low velocity wings dominate the spectra, although some EHV can be present)

L1157mm, IRAS 16293-2422, N1333-I4A,...

- Group 3 Transition outflows: only low velociy H_2CO wings (not always present)

L483, L1527

- Group 4 Class I outflows: wings only seen in CO

L1551, ...

The chemical evolution is linked to other evolutionary trends:

- **increasing Tbol**
- **increasing opening angle**
- **decreasing outflow efficiency (Lmech/Lbol)**

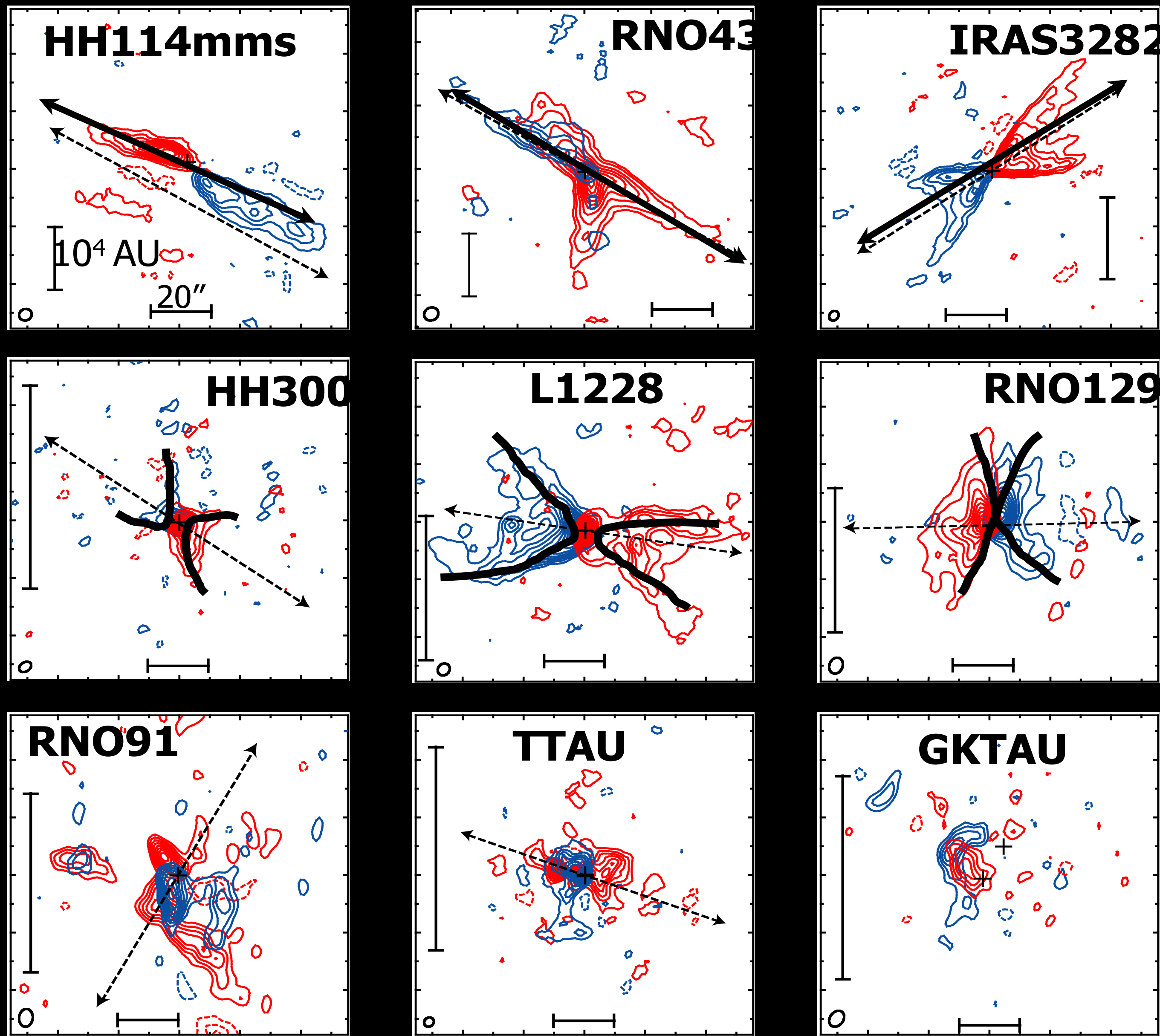
^{12}CO(1-0) outflow survey

(Arce & Sargent 2006)

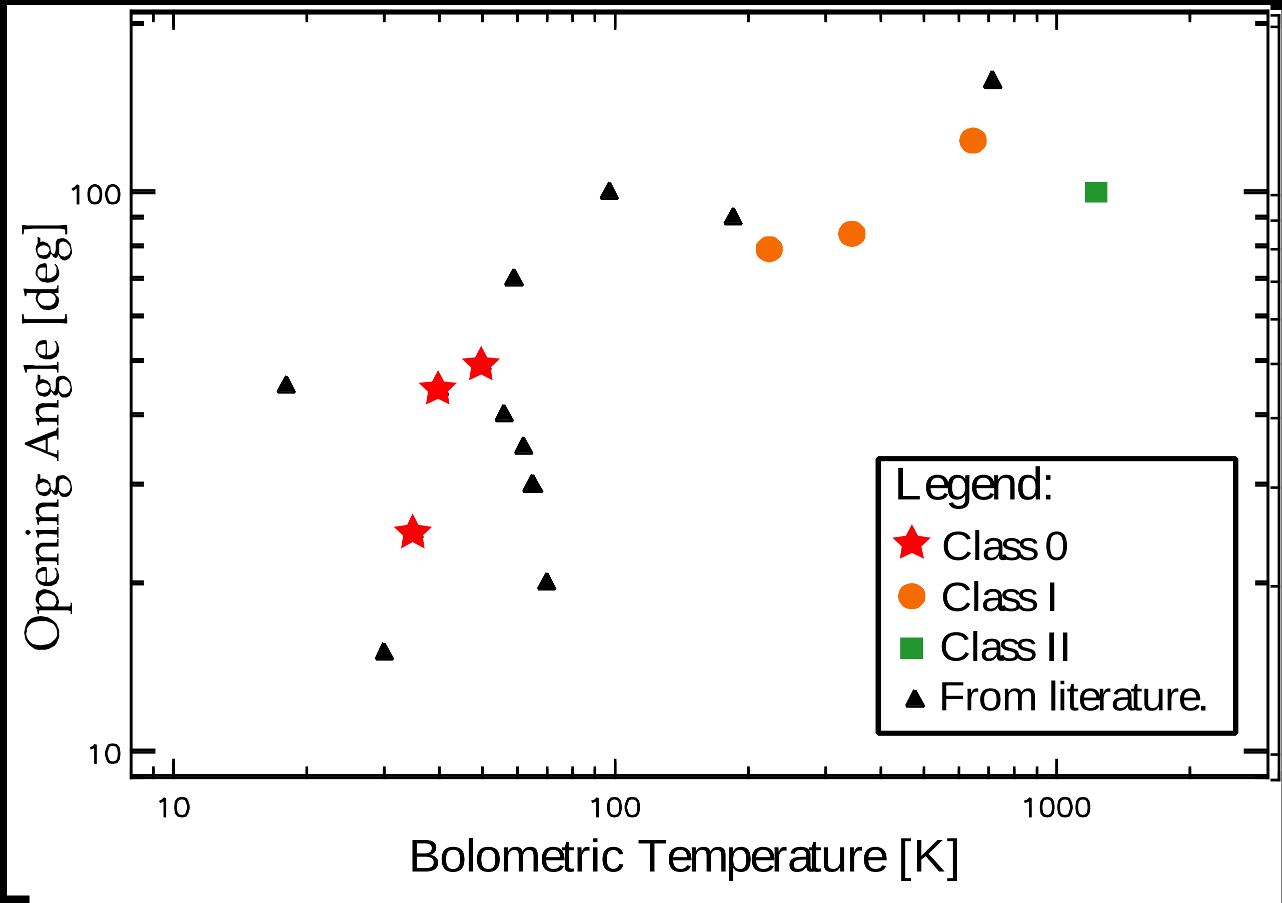
Class 0

Class I

Class II



Opening angle vs. time



Time →

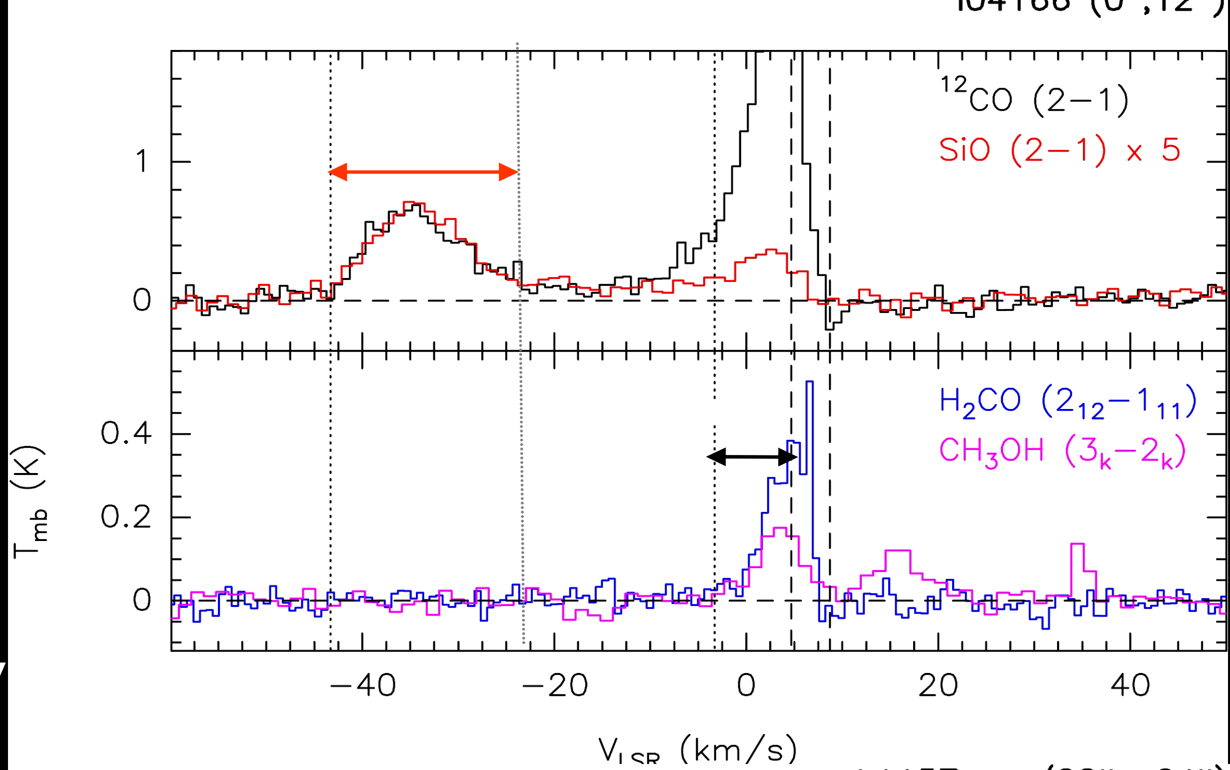
Arce & Sargent (2006)

Abundances analysis

1.- Relative abundances from column density ratios

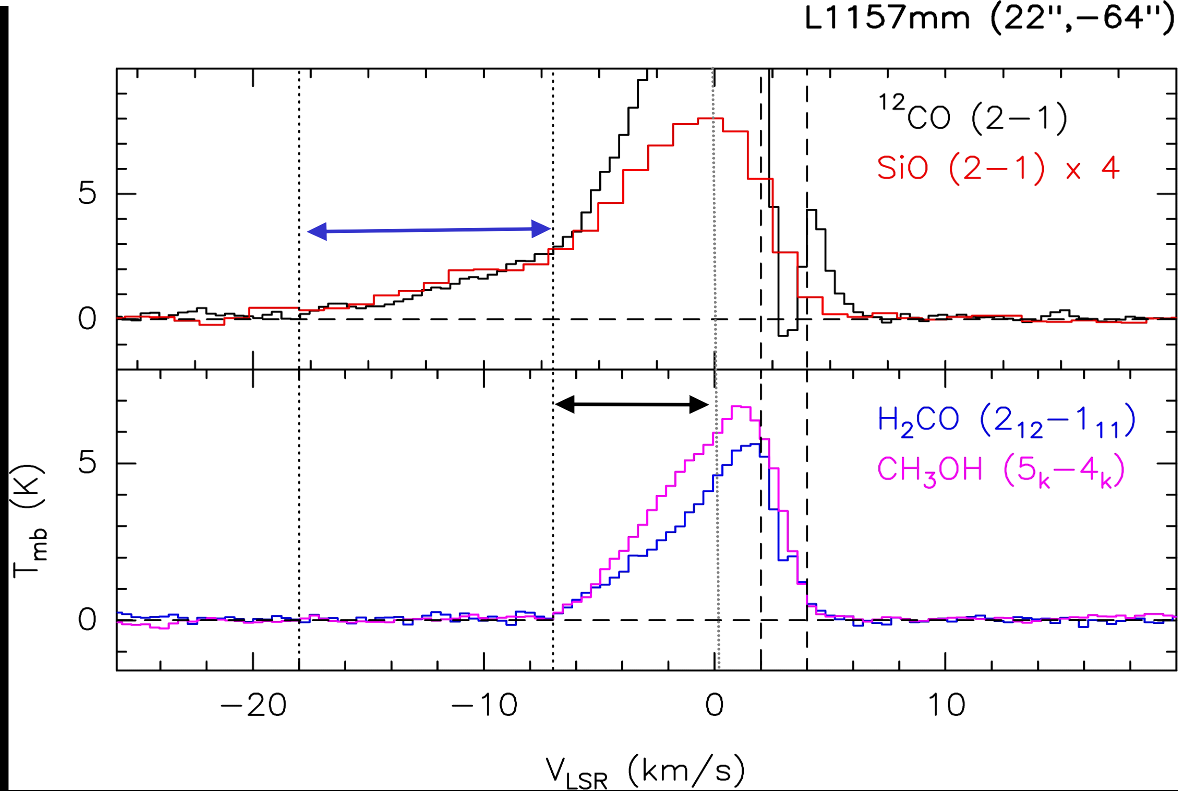
X(SiO)/X(CO) = N(SiO)/N(CO)

N from LTE methods
(uncertainties < factor 2)



2.- Analysis separation in two velocity ranges

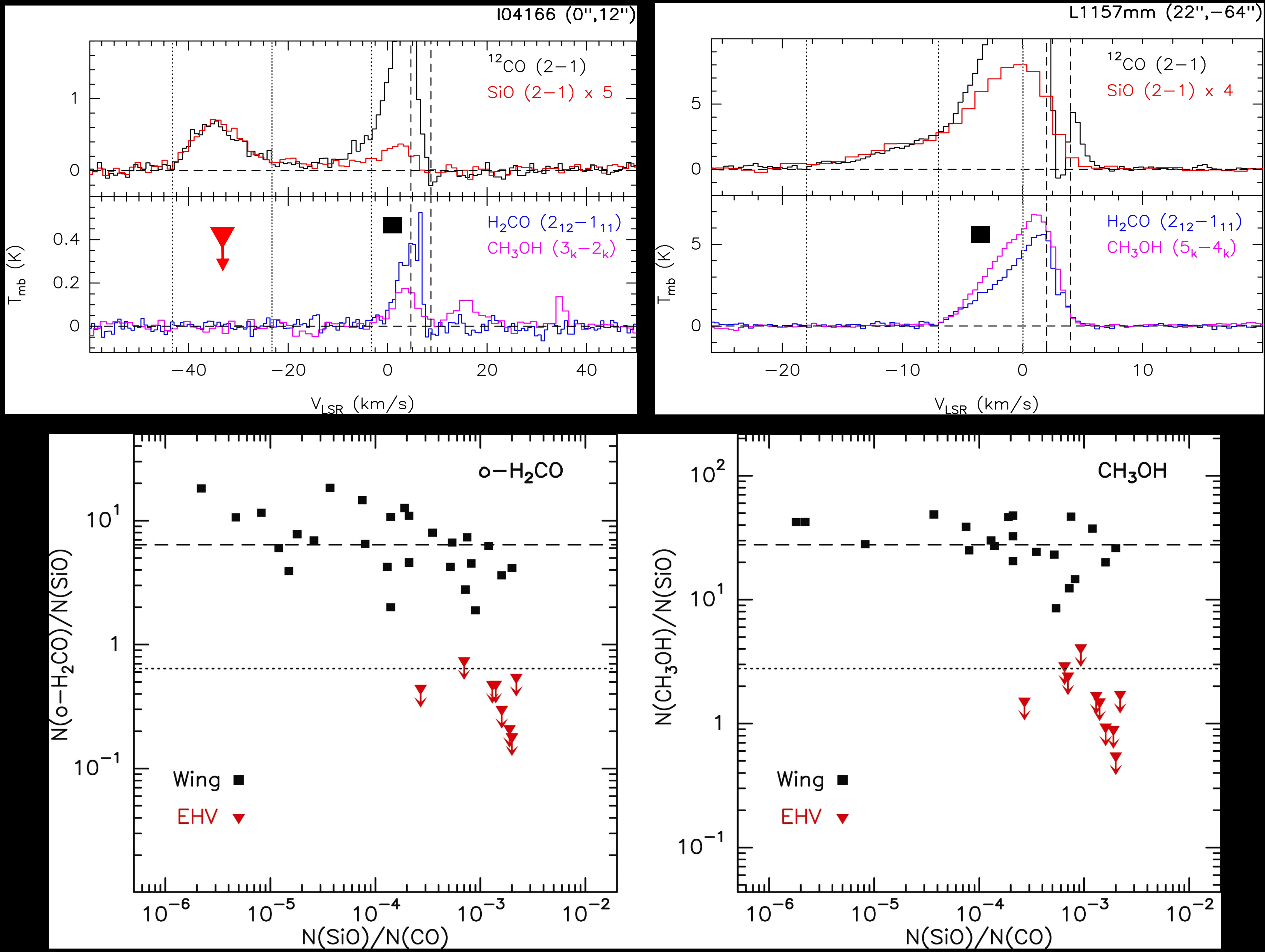
- As systematic as possible



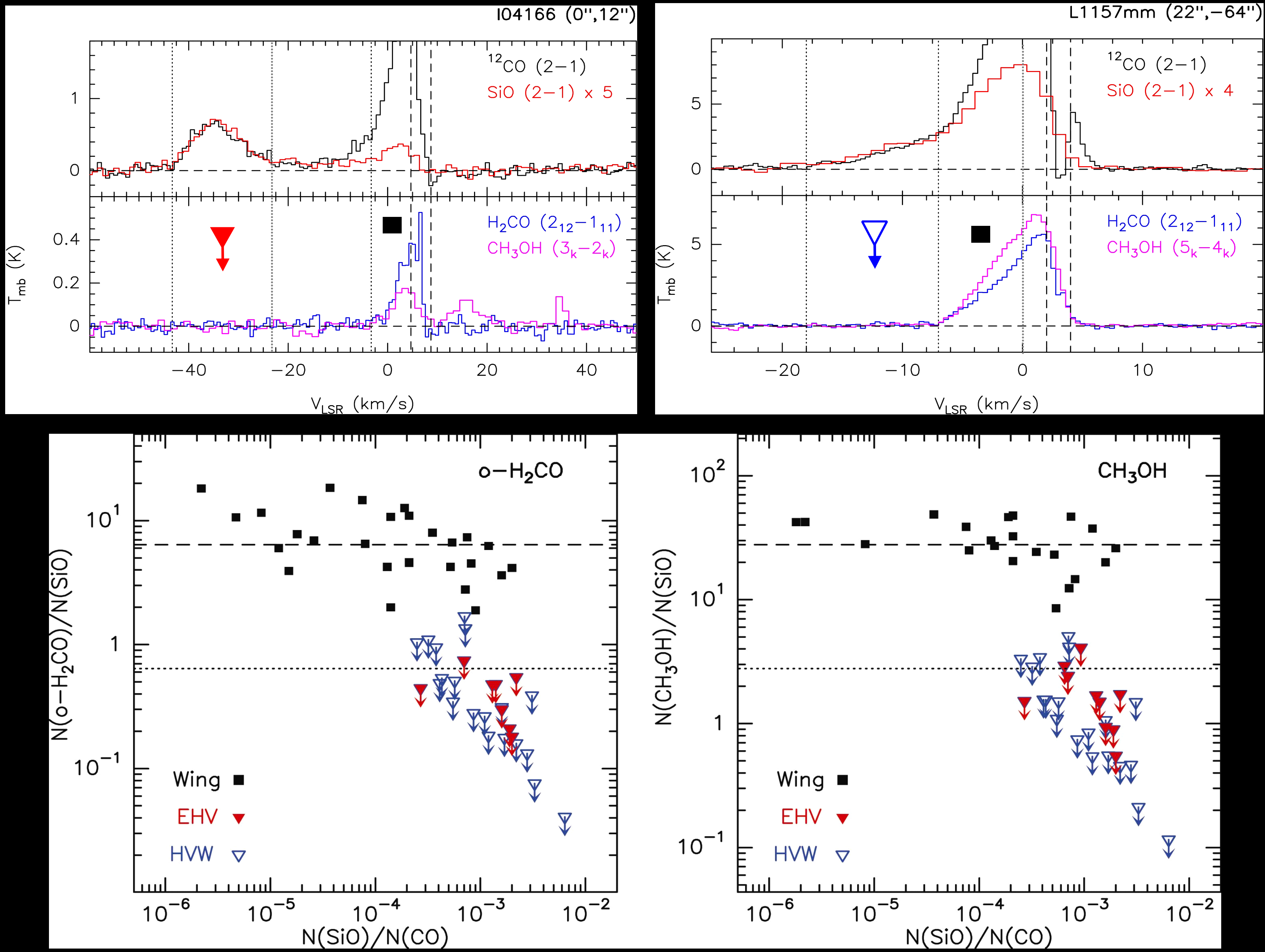
- N ratios obtained for similar line profiles
- **Three emission types:**

EHV : Extremely-***High-Velocity*** peaks
HVW : ***High-Velocity*** Wings
Wings : **Low velocity** Wings

EHV presents a different chemical composition than low v. Wings



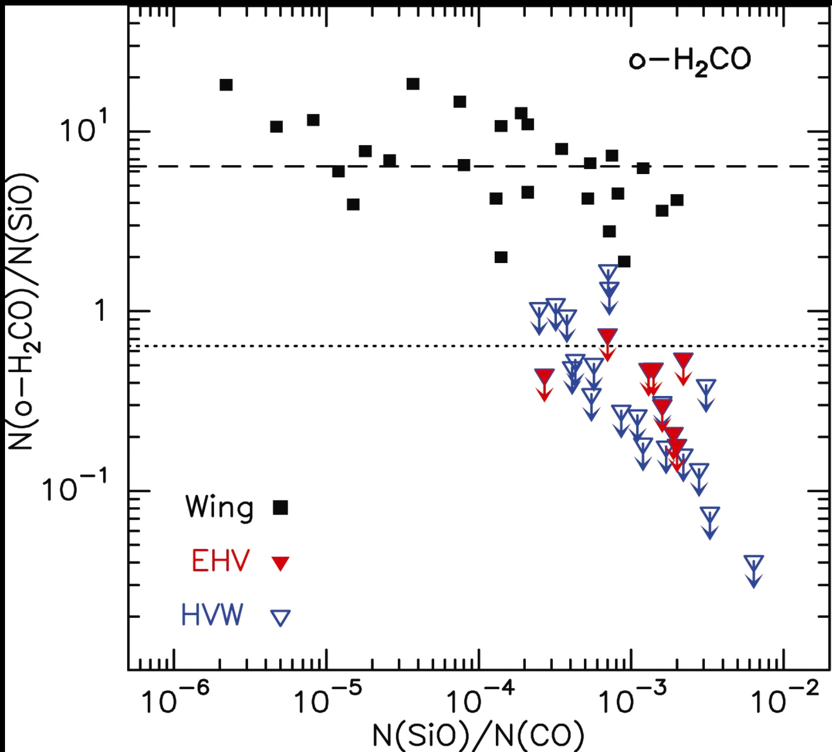
HVW is more similar to EHV than to low v. Wings

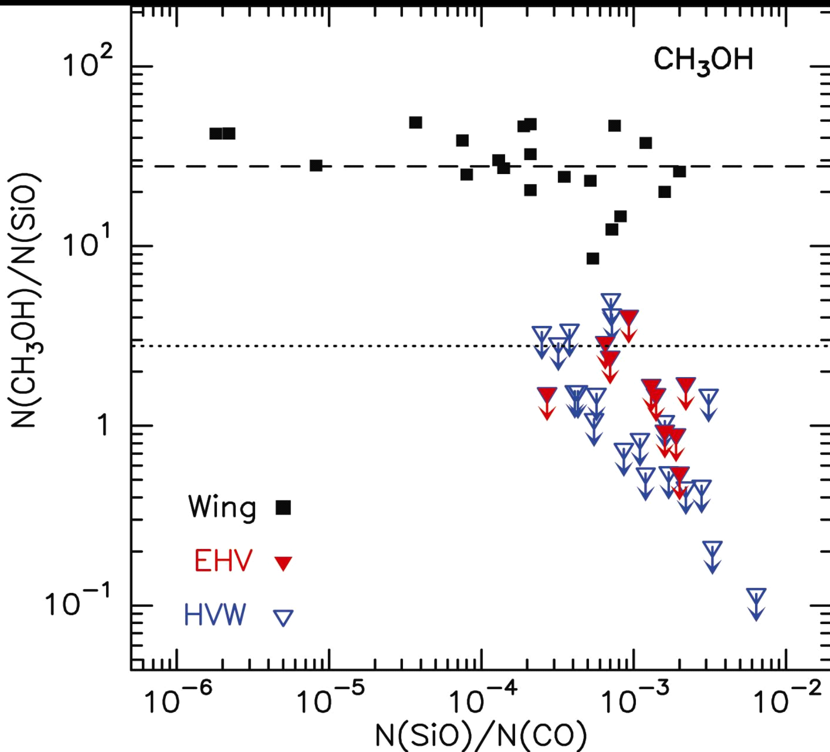


Two outflow components with distinct chemistries

- A **Low-velocity (Wing) component** where for a factor 100 in X(SiO)
  - X(o-H_2CO)/X(SiO) ~ 6 (± factor <10)
  - X(CH_3OH)/X(SiO) ~ 30 (± factor <10)
- A **high-velocity (EHV-HVW) component** where, **X(H_2CO)/X(SiO) & X(CH_3OH)/X(SiO) are at least 10 times lower than in Wings for a similar X(SiO)**

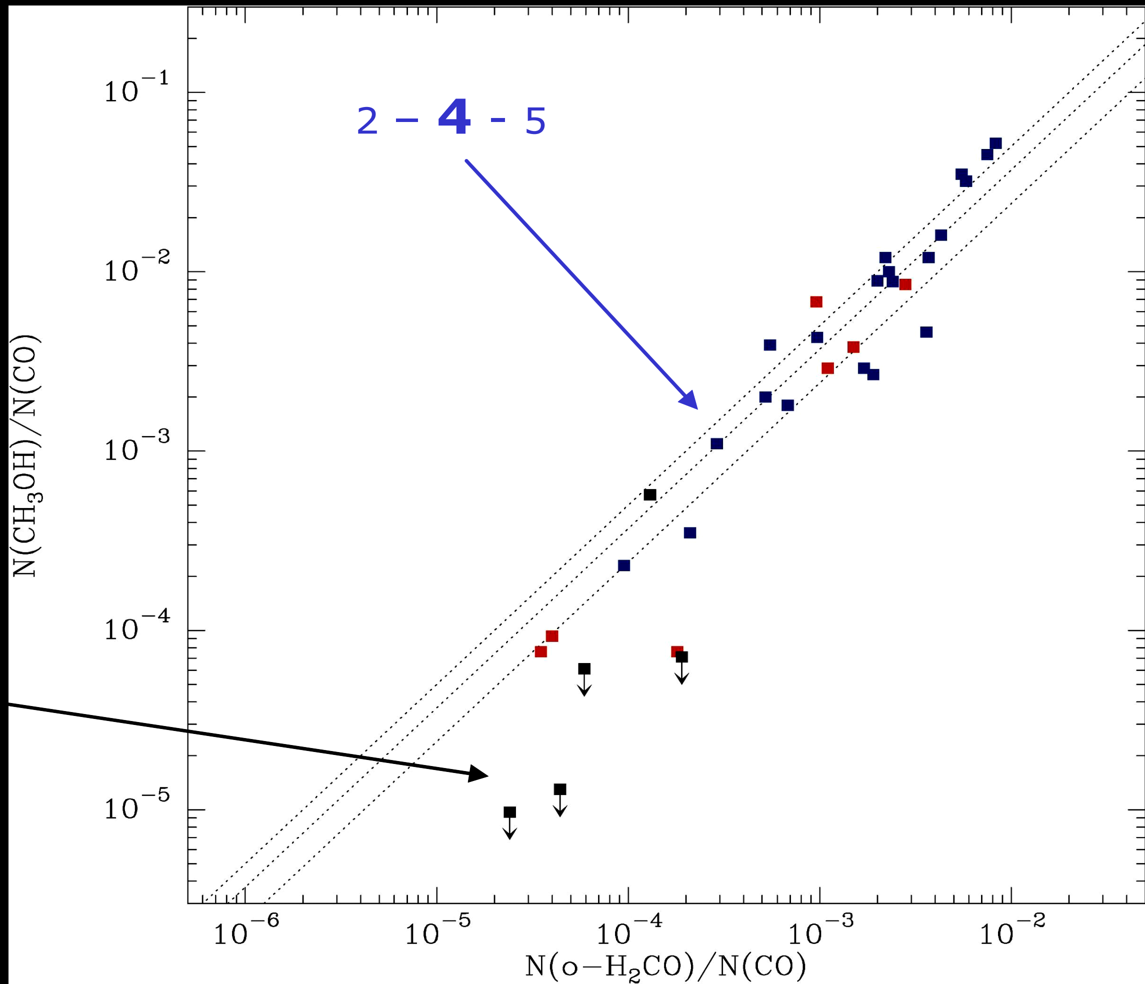
These two components also have different morphology and velocities, so they seem to have different physical origins





Low velocities (wings) trace entrained/shocked ambient material

- **SiO** from the **Si released by the shock from dust grains cores** *(eg. Schilke et al. 1997)*
- **CH_3OH/o-H_2CO ratio ≈ 4** points to a **common origin in ice mantles of grains** *(Watanabe et al. 2003):* CO hydrogenation at 15 K
- *Purely pulled material could have abundance ratios similar to non-depleted outer parts of starless cores*



The high velocity component (EHV & HVW) could directly trace the primary protostellar wind

This may not to be a chemistry based on grain-destruction!

-H2 molecules can well survive in MHD winds launched at a few AU from the YSO (Panoglou et al. 2008) which could be mainly neutral

- CO & SiO can be produced at high abundances in the primary winds from protostars (Glassgold et al. 1991): High-temperature chemistry

- similar to Oxigen-rich chemistry in evolved stars, where there is a lack of H2CO & CH3OH

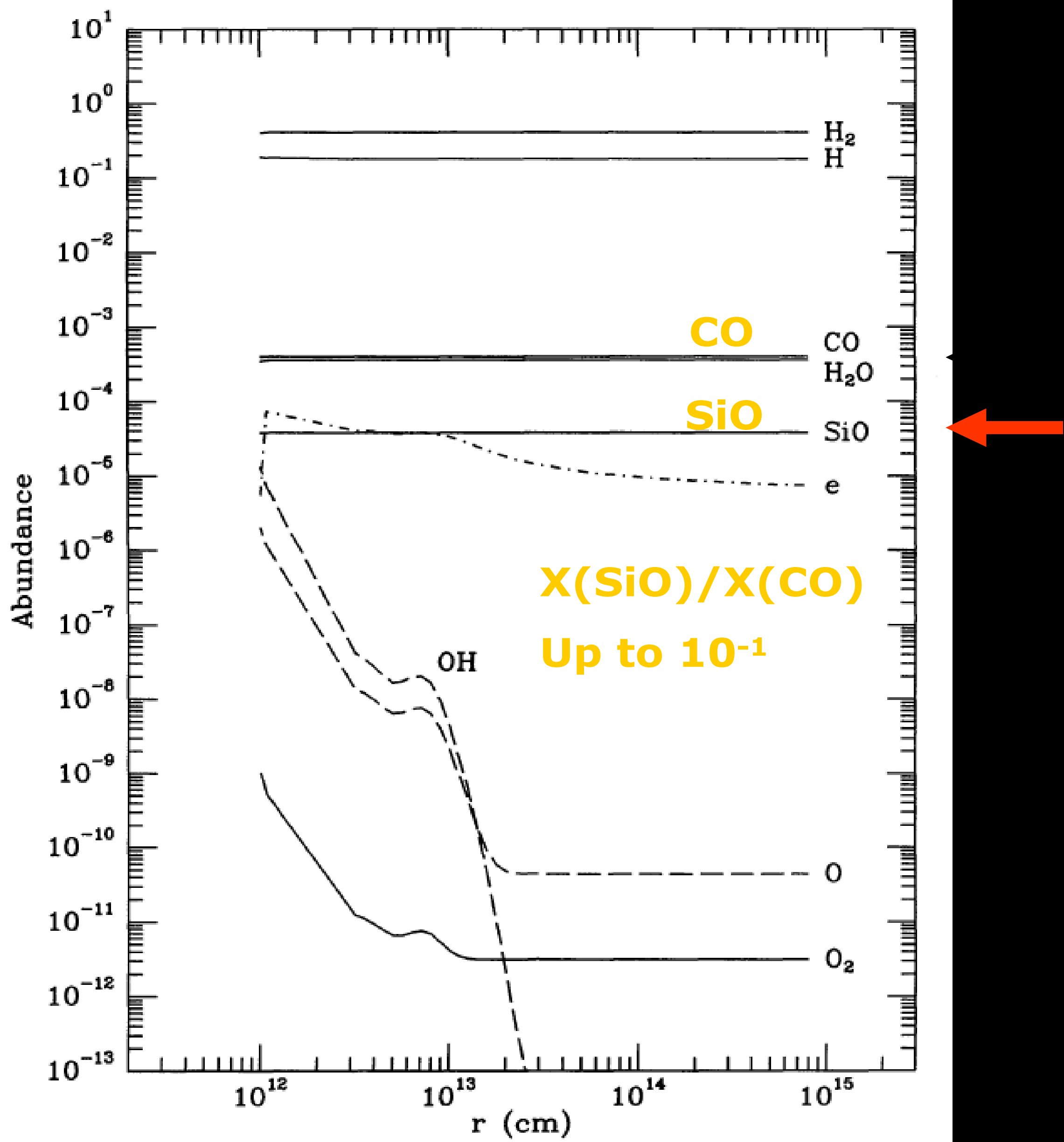
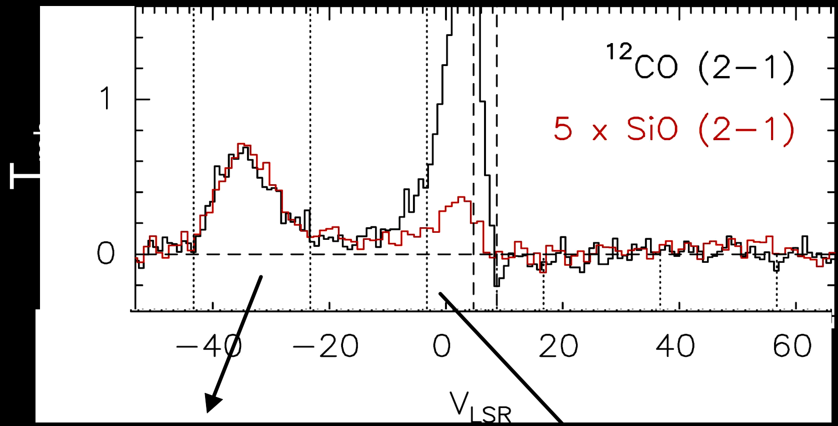
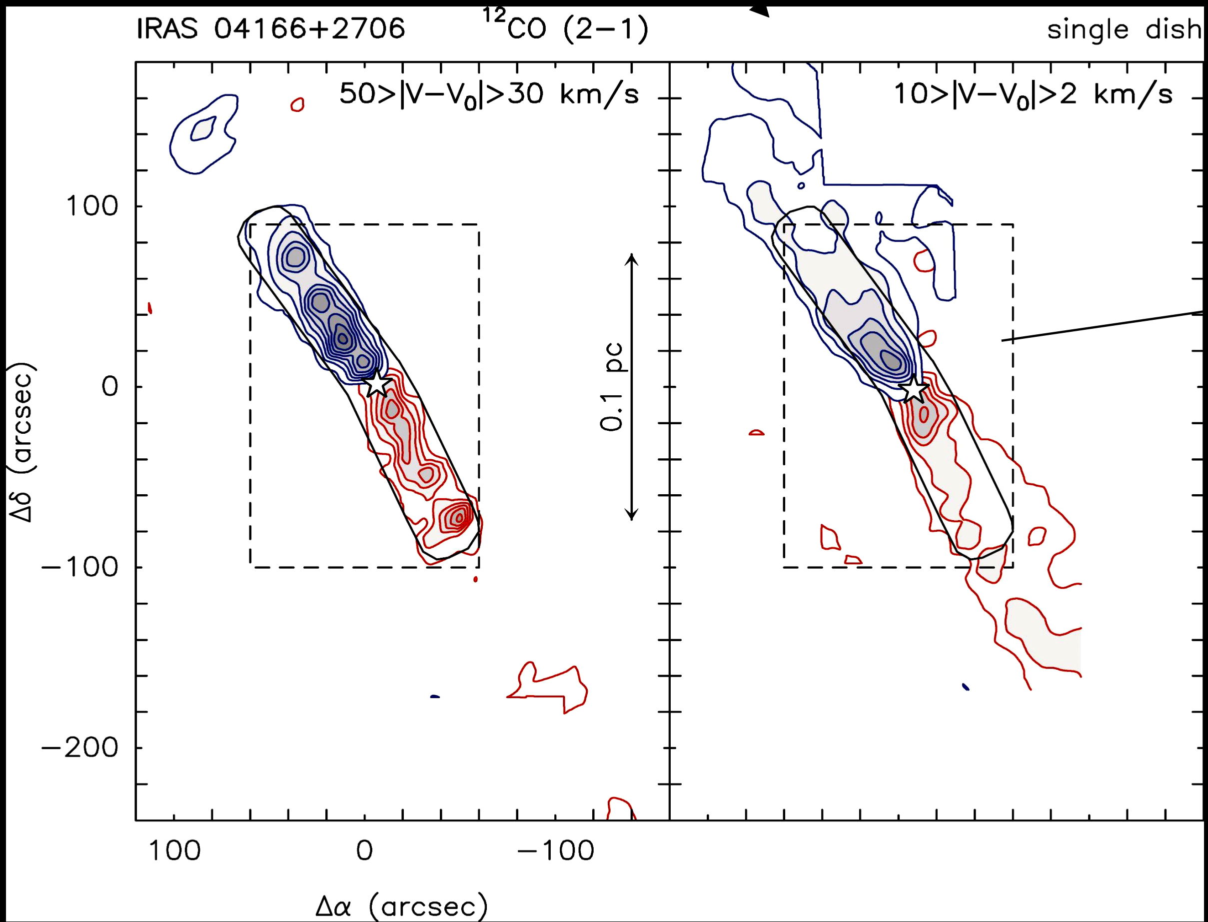


FIG. 9.—Chemical abundances for Case 3 and $\dot{M} = 3 \times 10^{-5}\ M_{\odot}\ yr^{-1}$

Glassgold et al. 1991

IRAS 04166+2706 (I04166) is a unique target for high spatial resolution observations of EHV outflows





- Protostar 0.4 Lsun
- First EHV in Taurus, at only 140 pc
- Scaled version of other EHV in further and more active clouds, i.e. Perseus *(Tafalla et al. 2004)*
- Clean propagation trough the environment and favorable orientation + the closest EHV = the best target for high resolution observations

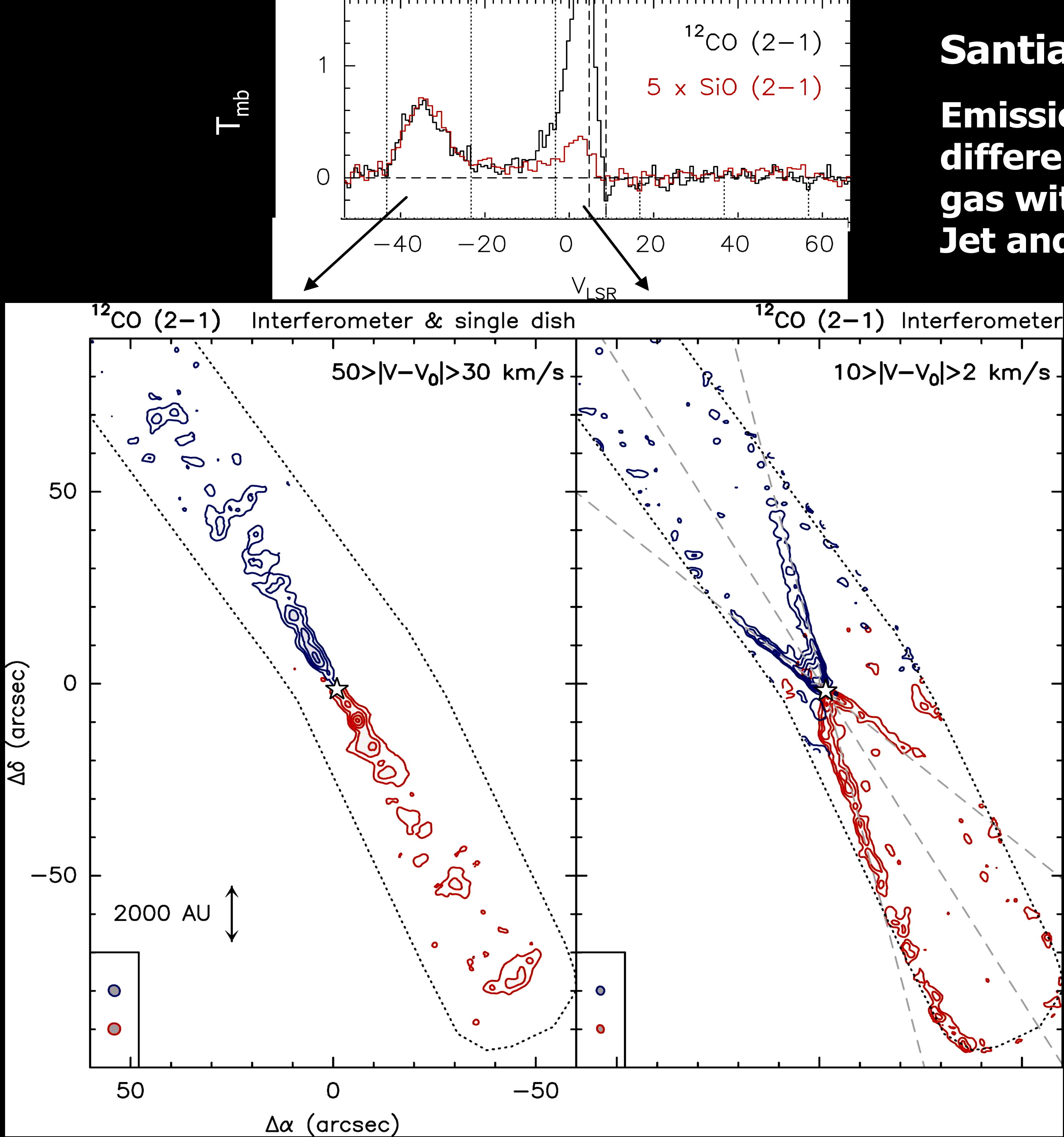
IRAM PdBI

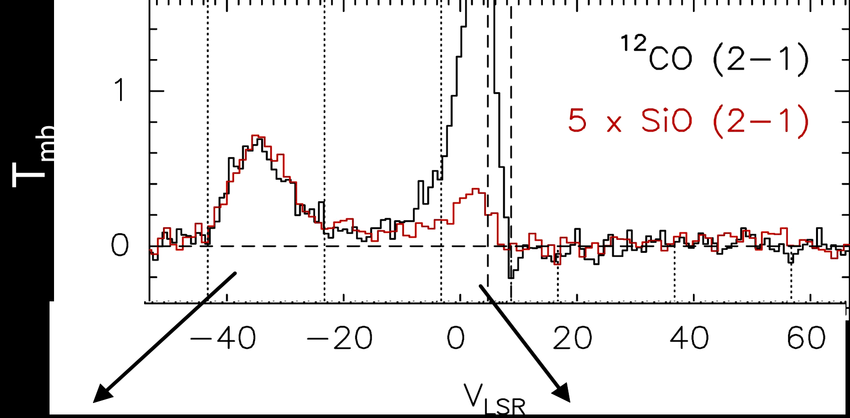
2" @ 1.3 mm (280 AU)
4.5" @ 3 mm (600 AU)

Santiago-Garcia et al. (2008)

Emission at velocity ranges with different chemistry comes from gas with different spatial origin: a Jet and a Shell

- **CO EHV** : traces a **jet**
  - non-precessing
  - symmetric peaks with bowshock apperance (widening ~10º)
  - no interaction with the shel
- **CO Wing** : traces a **shell**
  - rectilinear walls (> 5000 AU)
  - symmetric V shape
  - jet bisecting the shell

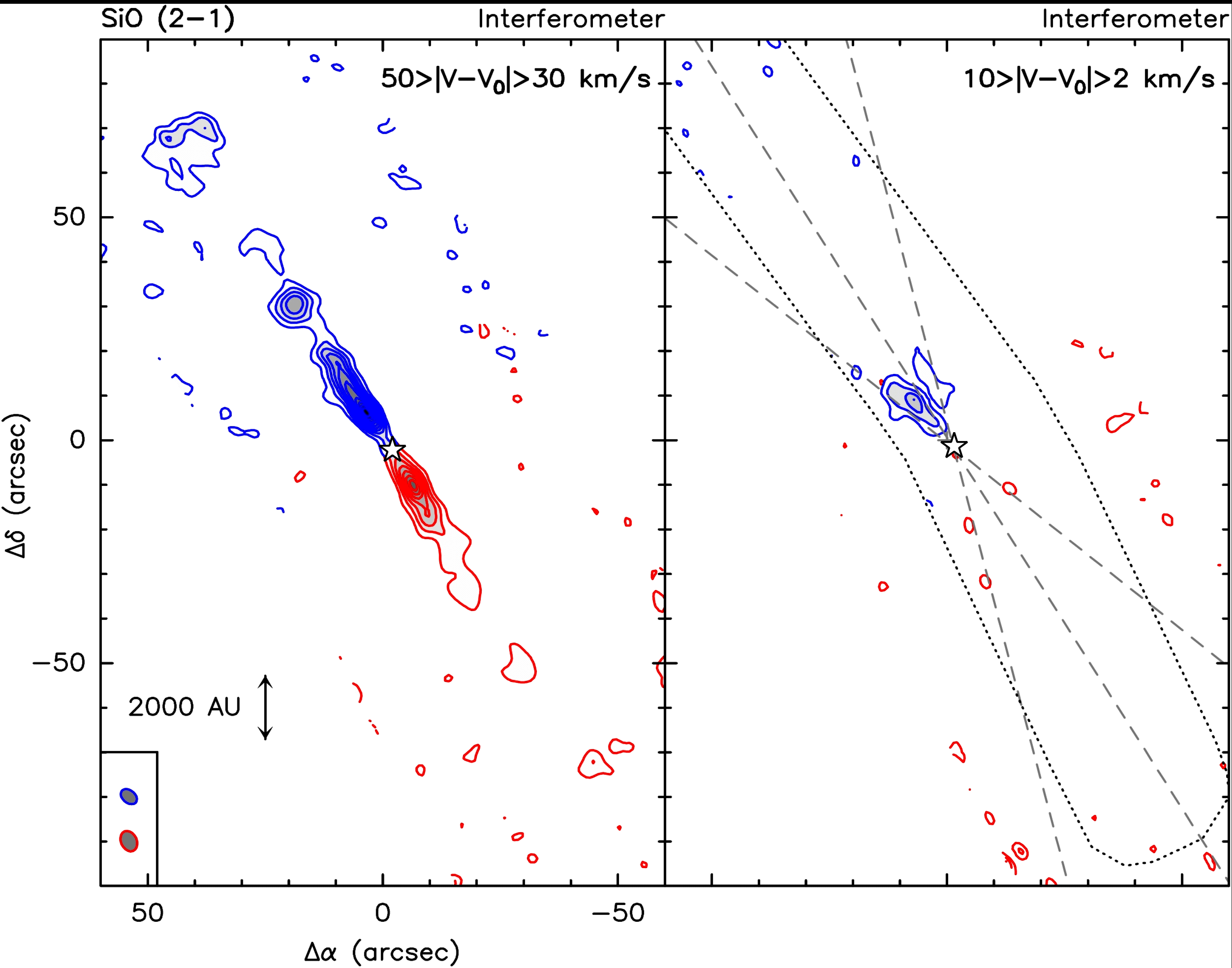




Santiago-Garcia et al. (2008)

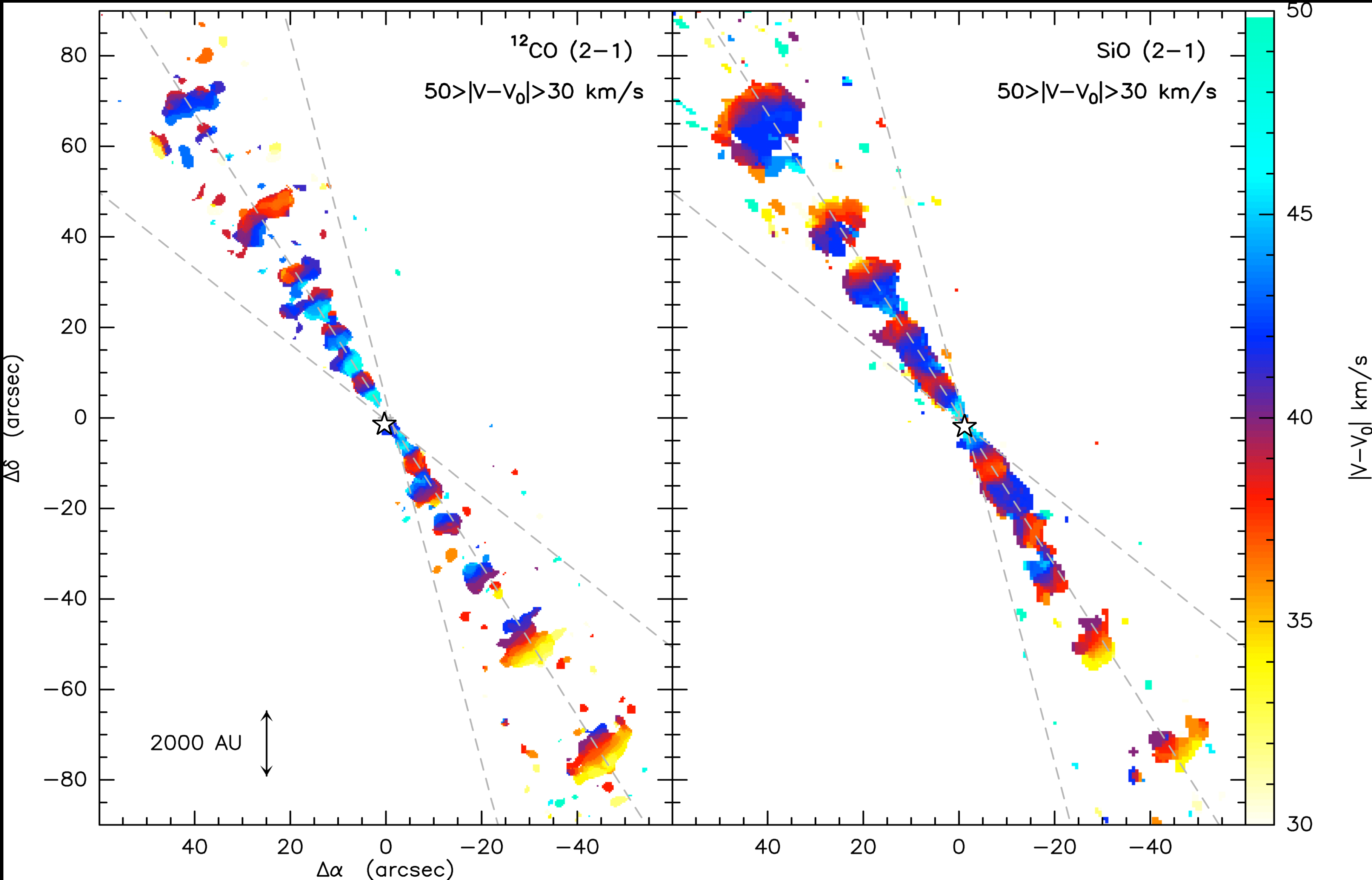
Emission at velocity ranges with different chemistry comes from gas with different spatial origin: a Jet and a Shell

- **CO EHV** : traces a **jet**
  - non-precessing
  - symmetric peaks with bowshock apperance (widening ~10º)
  - no interaction with the shel
- **CO Wing** : traces a **shell**
  - rectilinear walls (> 5000 AU)
  - symmetric V shape
  - the jet is bisecting
- **SiO EHV** : traces the **same jet** as CO
- **SiO Wing** : traces **a region of the shell**



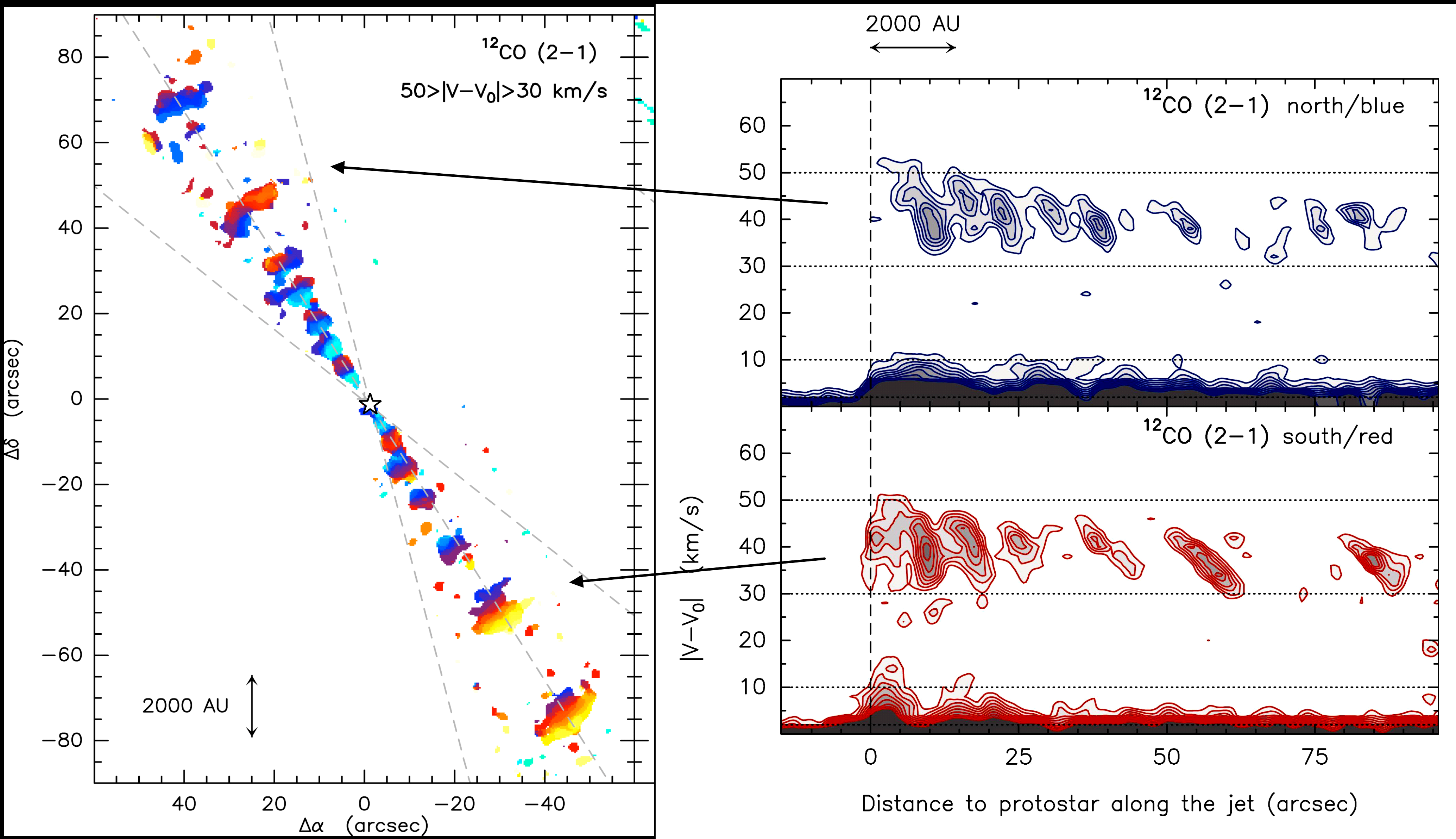
The jet exhibits a systematic structure in velocity

- **Both in CO and SiO**
- **Intermittency with 120 yr periodicity**
- **Similar velocity field in all bullets** : fastest gas closest to protostar
- No variations in **average velocity**



Saw-tooth pattern in PV diagram

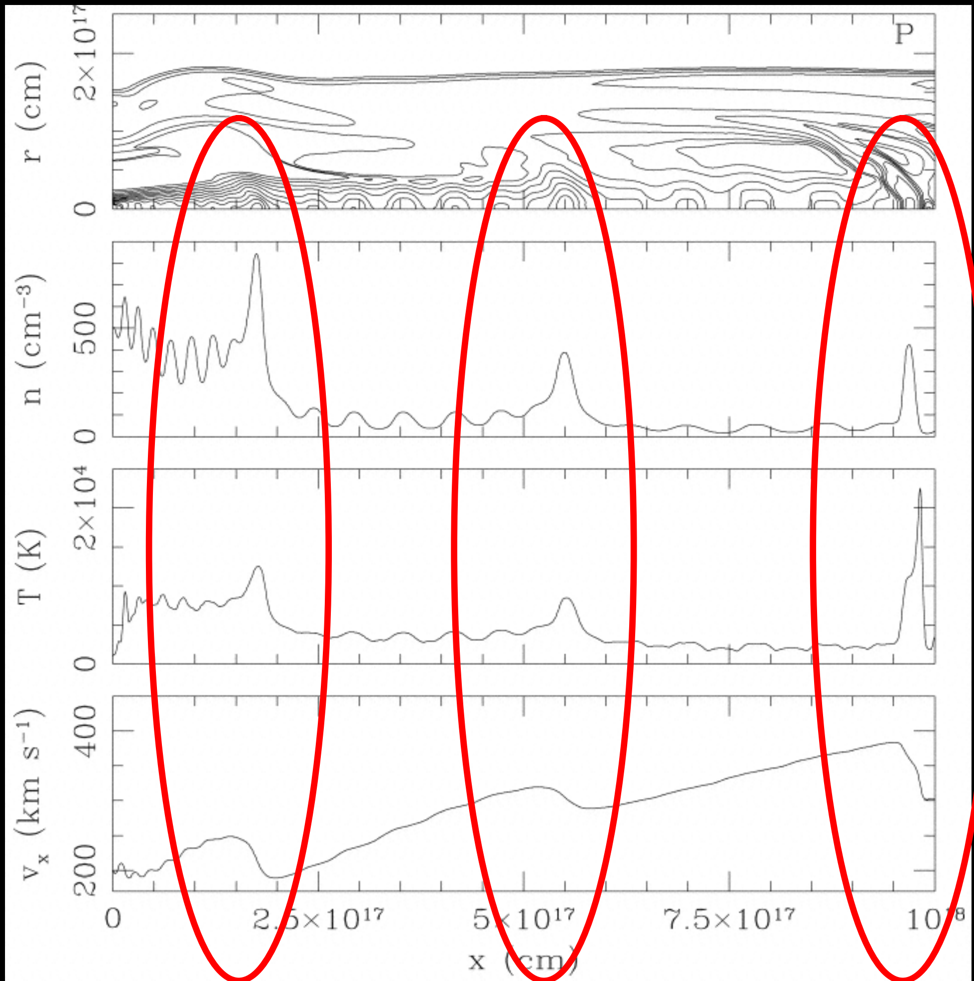
- Average velocity of bullets remains ~ constant (fastest gas close to YSO)
- No precession
- No rotation (at the level of our accuracy)

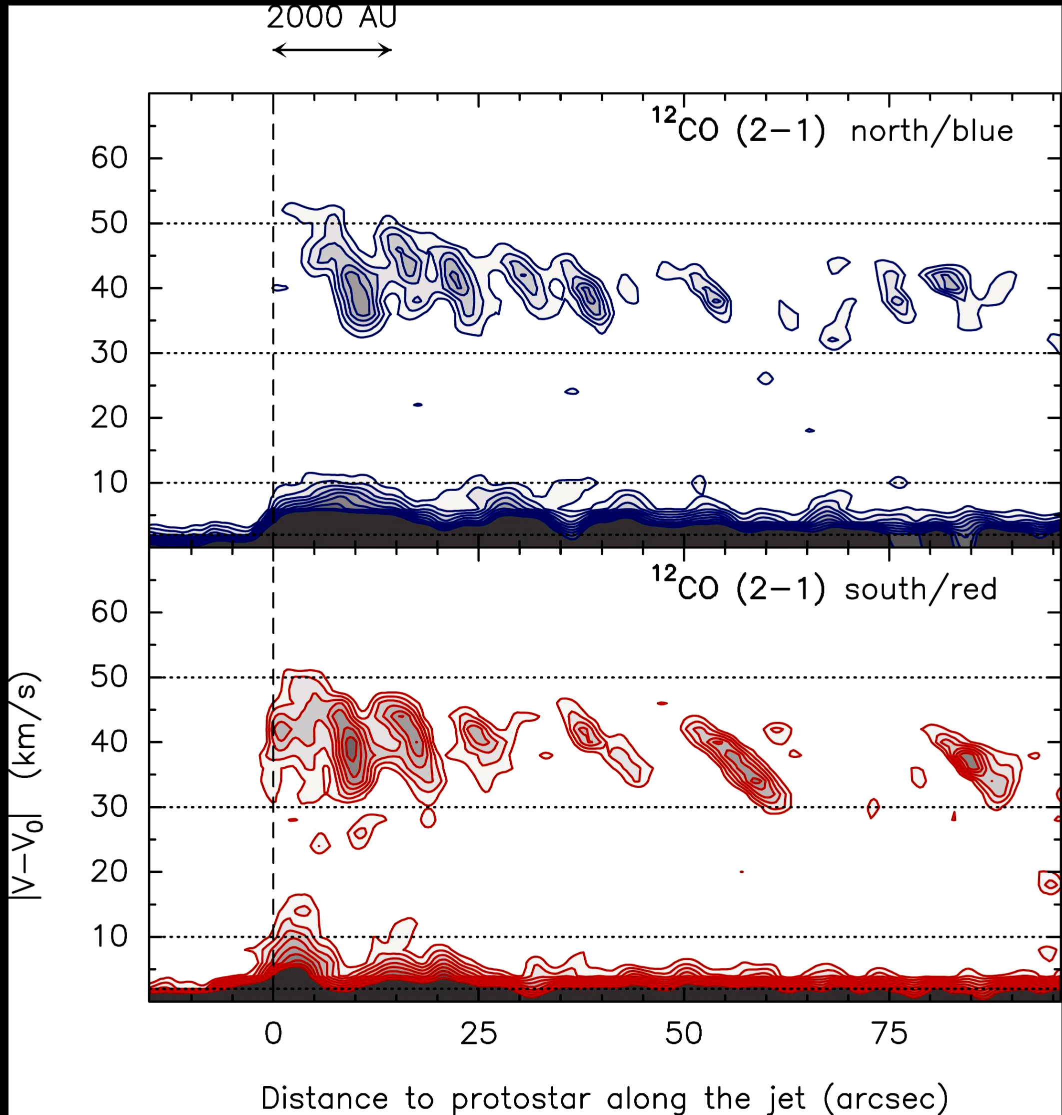


Raga & Noriega-Crespo (1998) noted similar behavior in HH objects of HH34

=> These are shocks generated by **time variations in launching velocity of the ejecta**

CO & SiO seen in the **density enhancements** (increasing average velocity is not essential in the model)



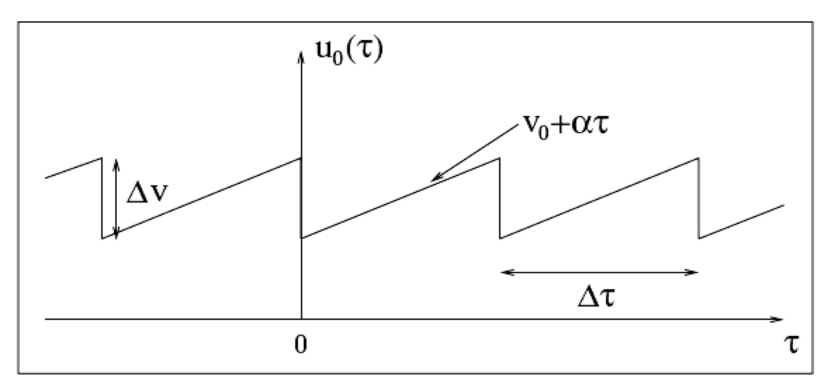


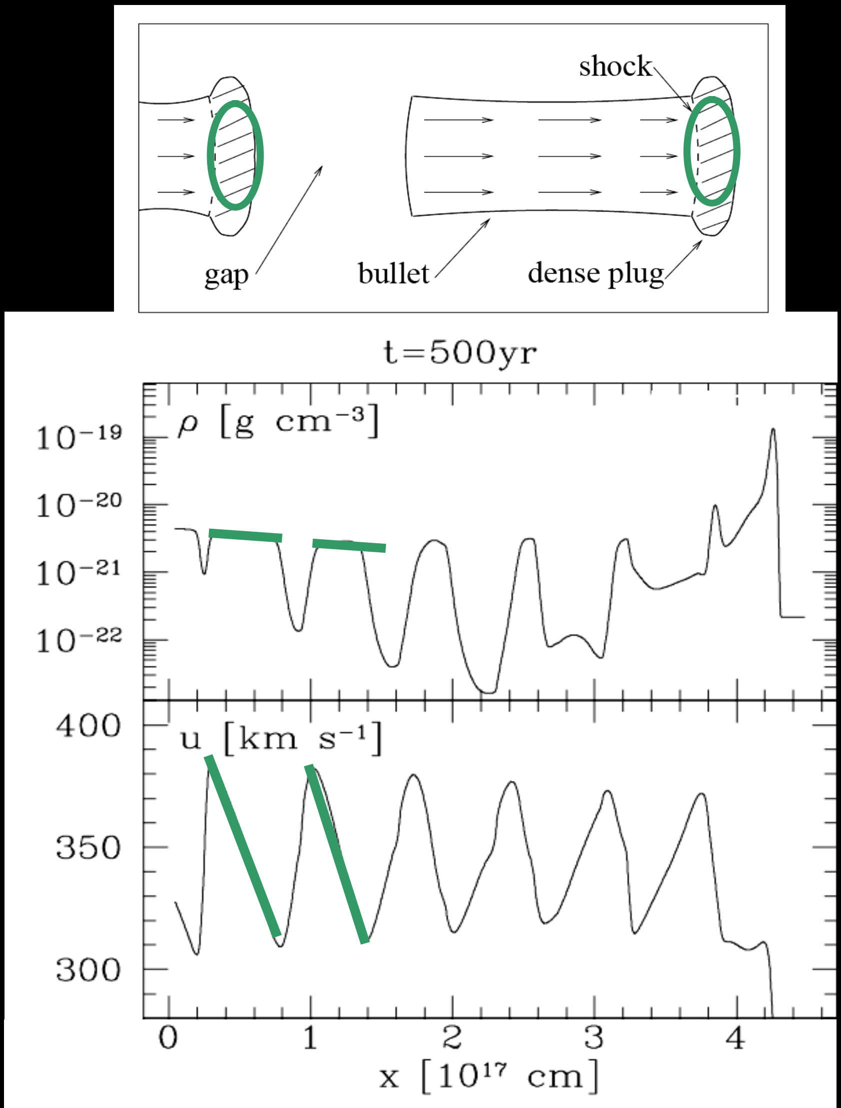
Masciardi et al. (2002) explained similar saw tooth pattern of HH objects in HH111

=> These are shocks generated by **time variations in launching velocity of the ejecta**

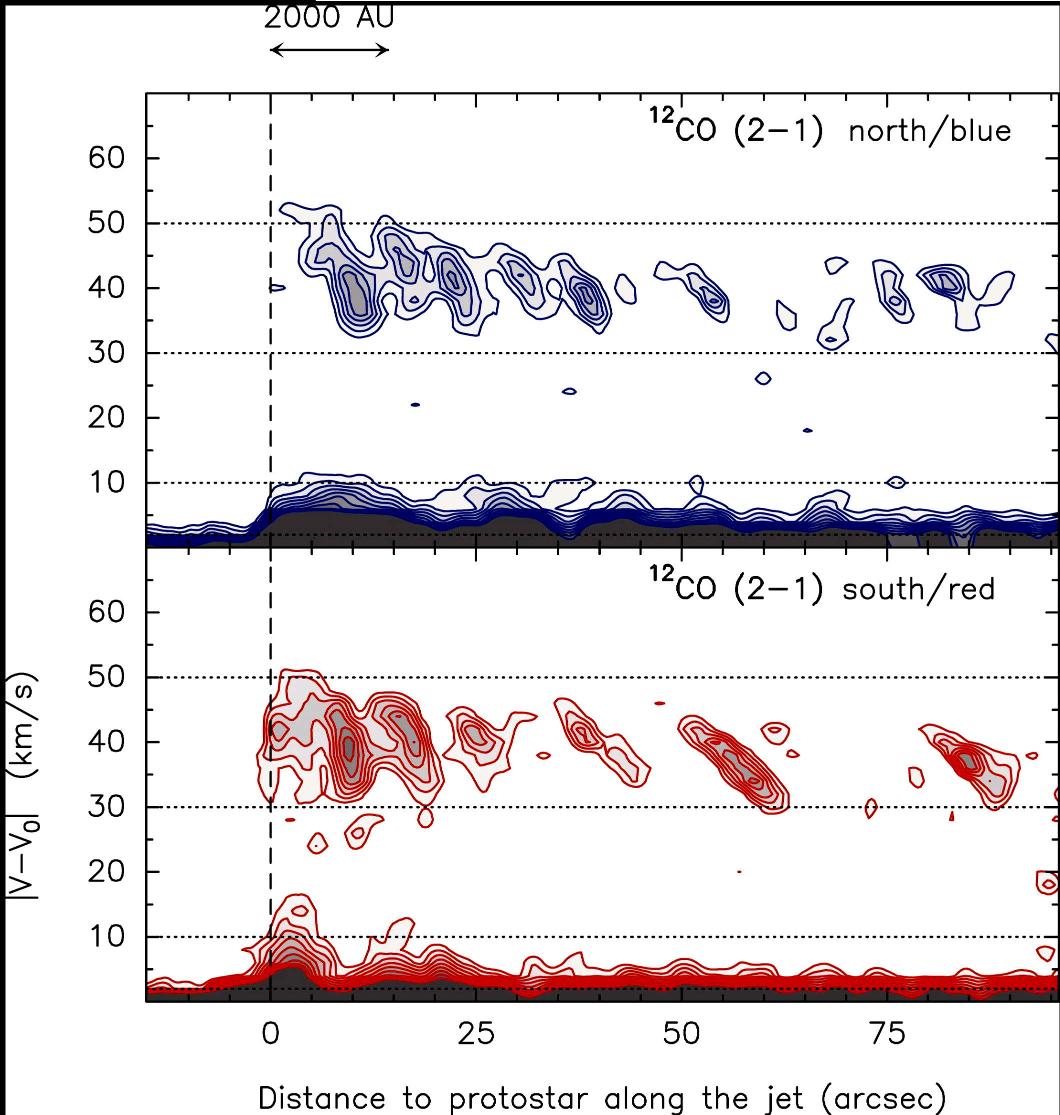
Molecular bullets are internal working surfaces within the primary jet

Masciardi et al. 2002



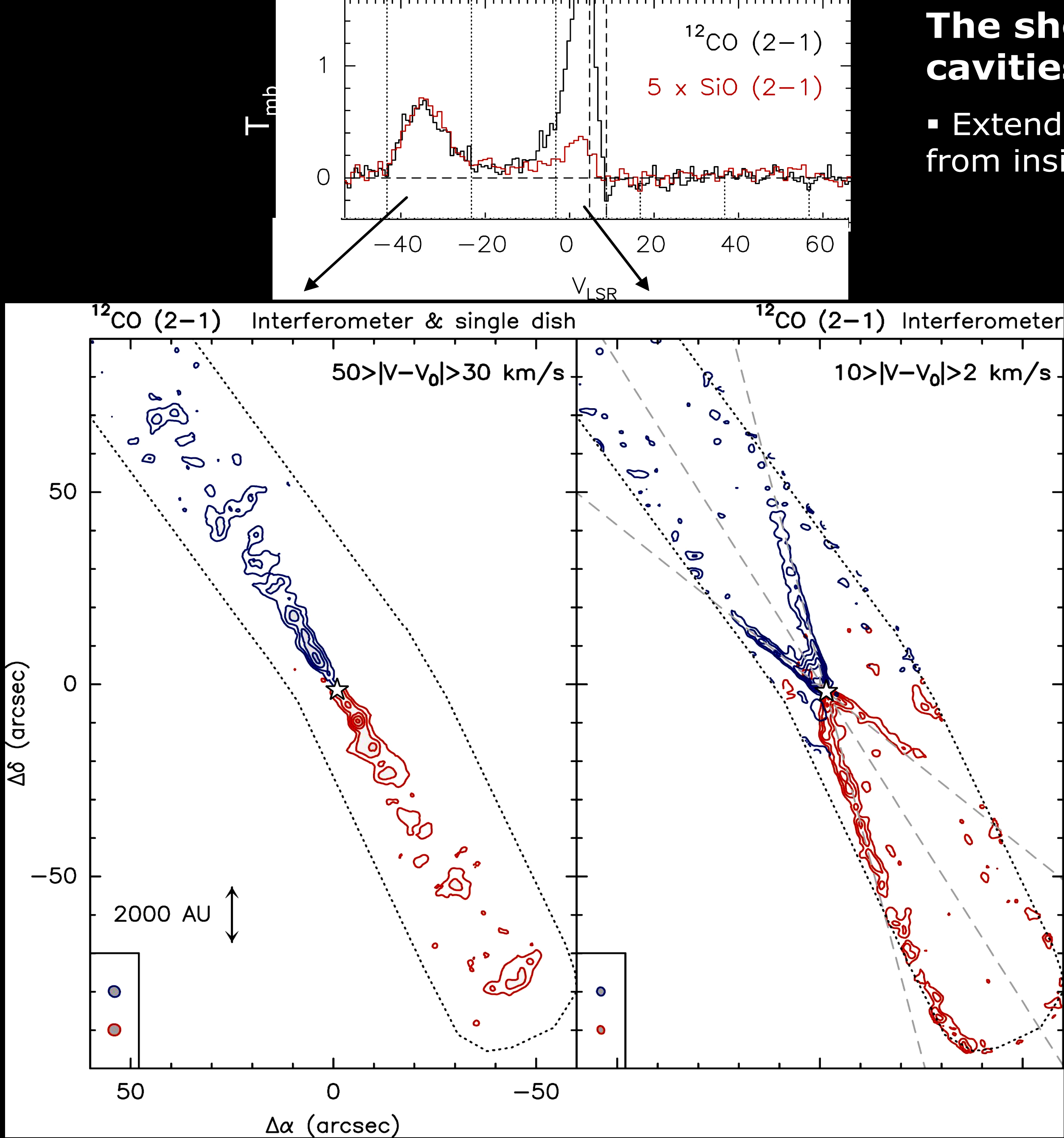


Masciardi et al. 2002



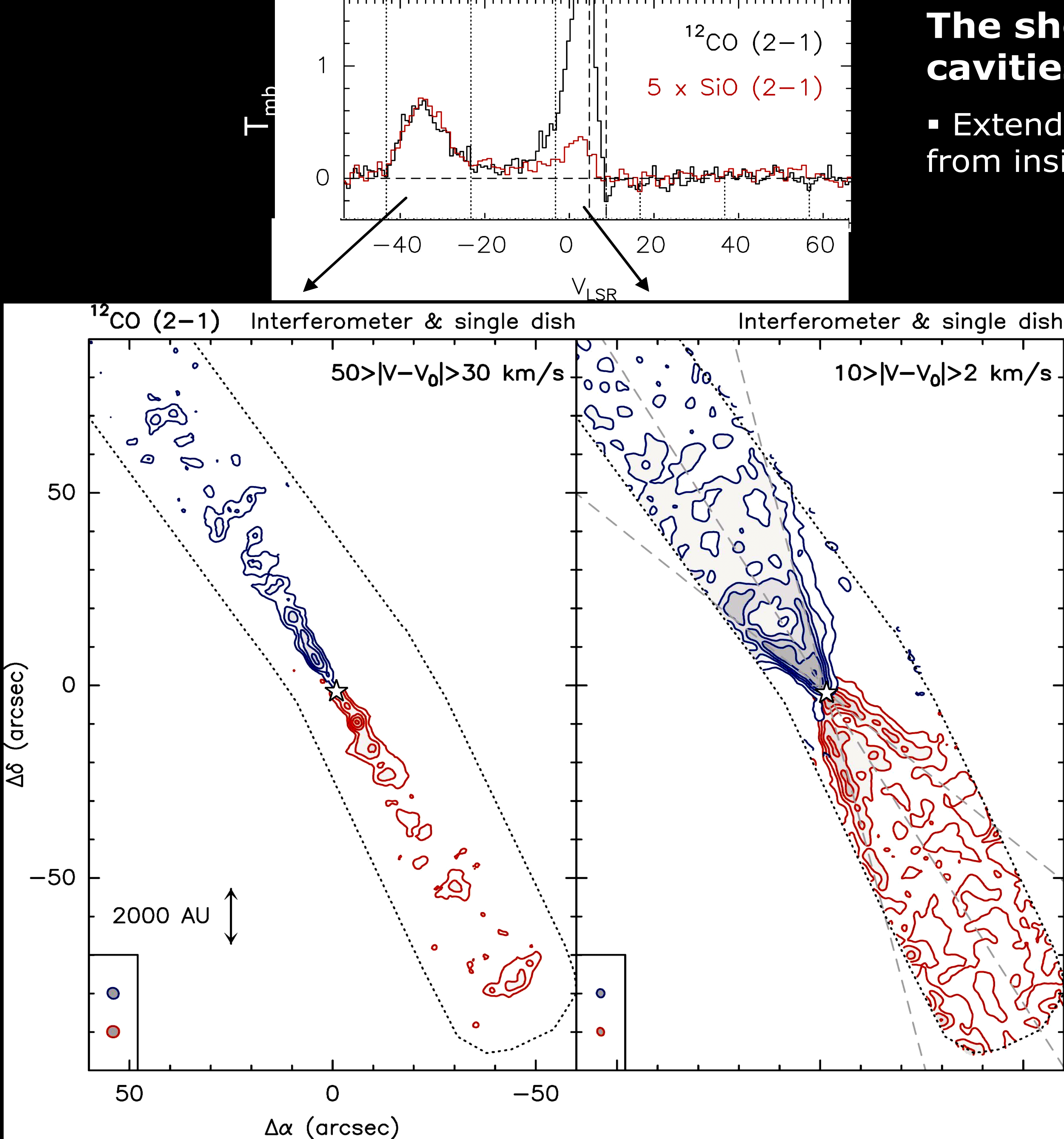
The shells are the walls of empty cavities

- Extended emission filtered out comes from inside the V-shell



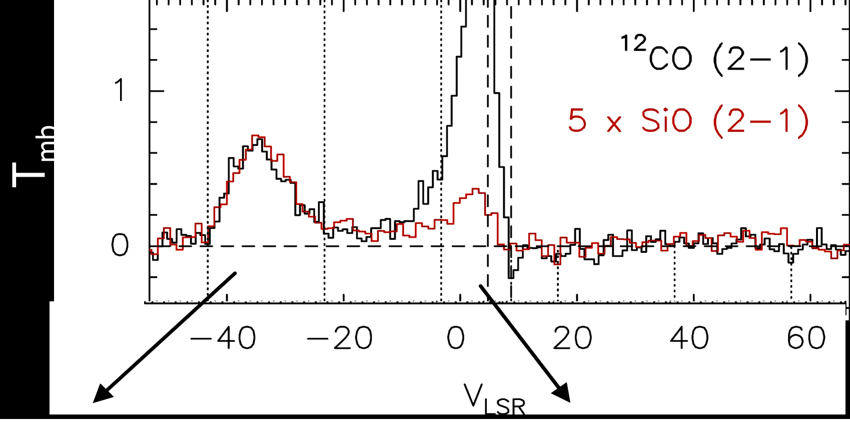
The shells are the walls of empty cavities

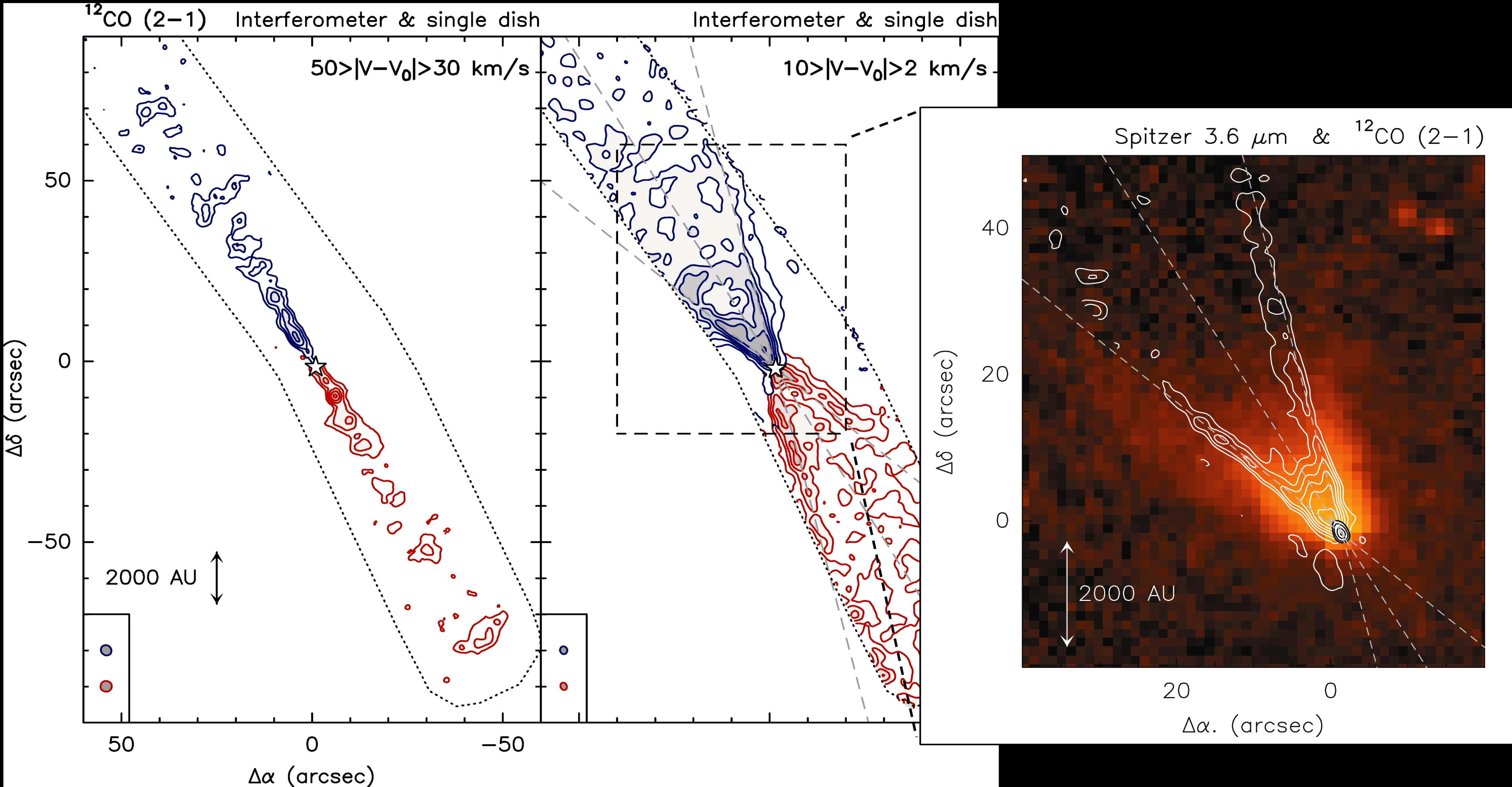
- Extended emission filtered out comes from inside the V-sell



The shells are the walls of empty cavities

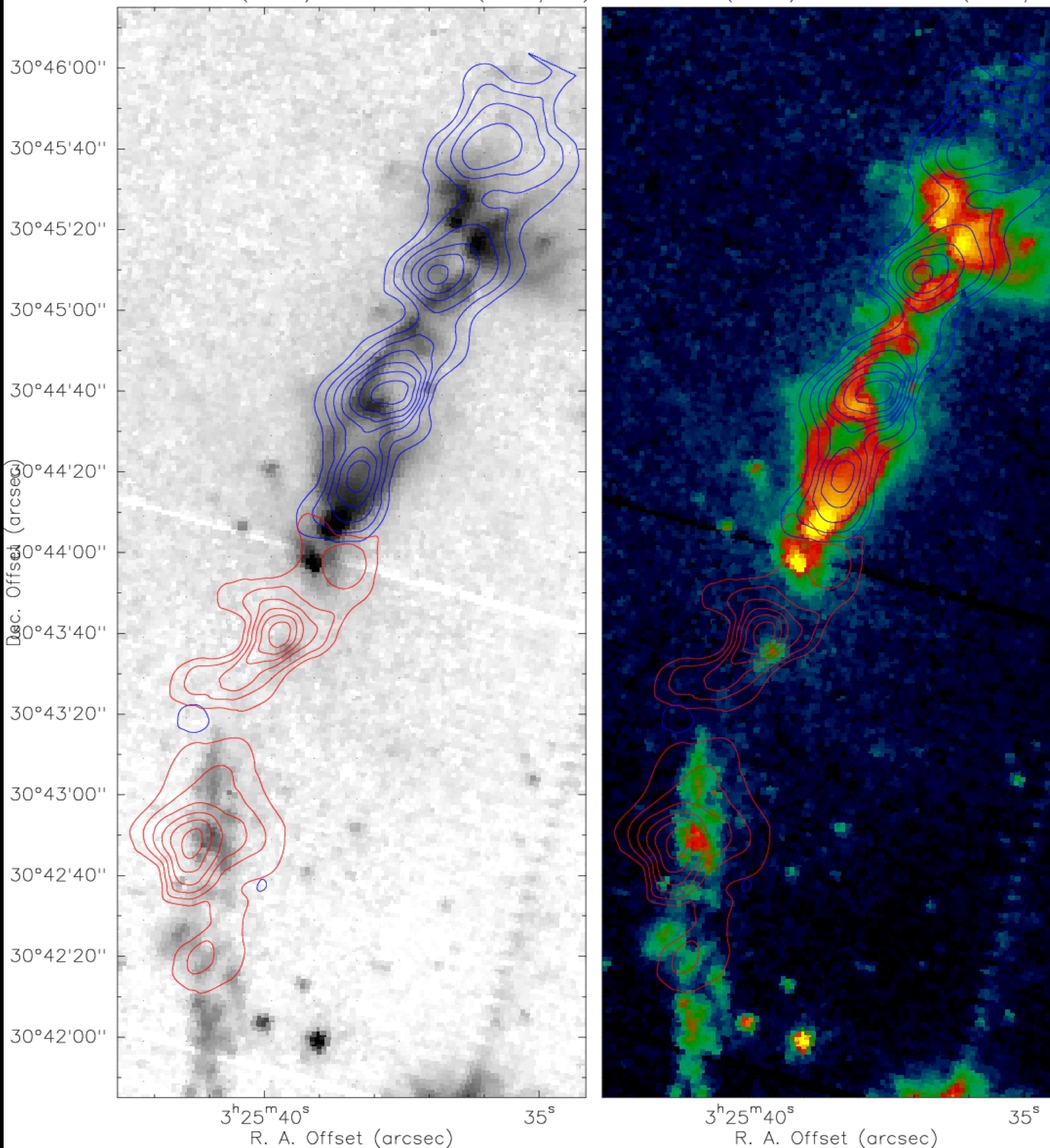
- Extended emission filtered out comes from insid the V-shell
- **IR cometary nebula** seen by Spitzer
- No interaction jet/shell ? What is inflating the shell ?



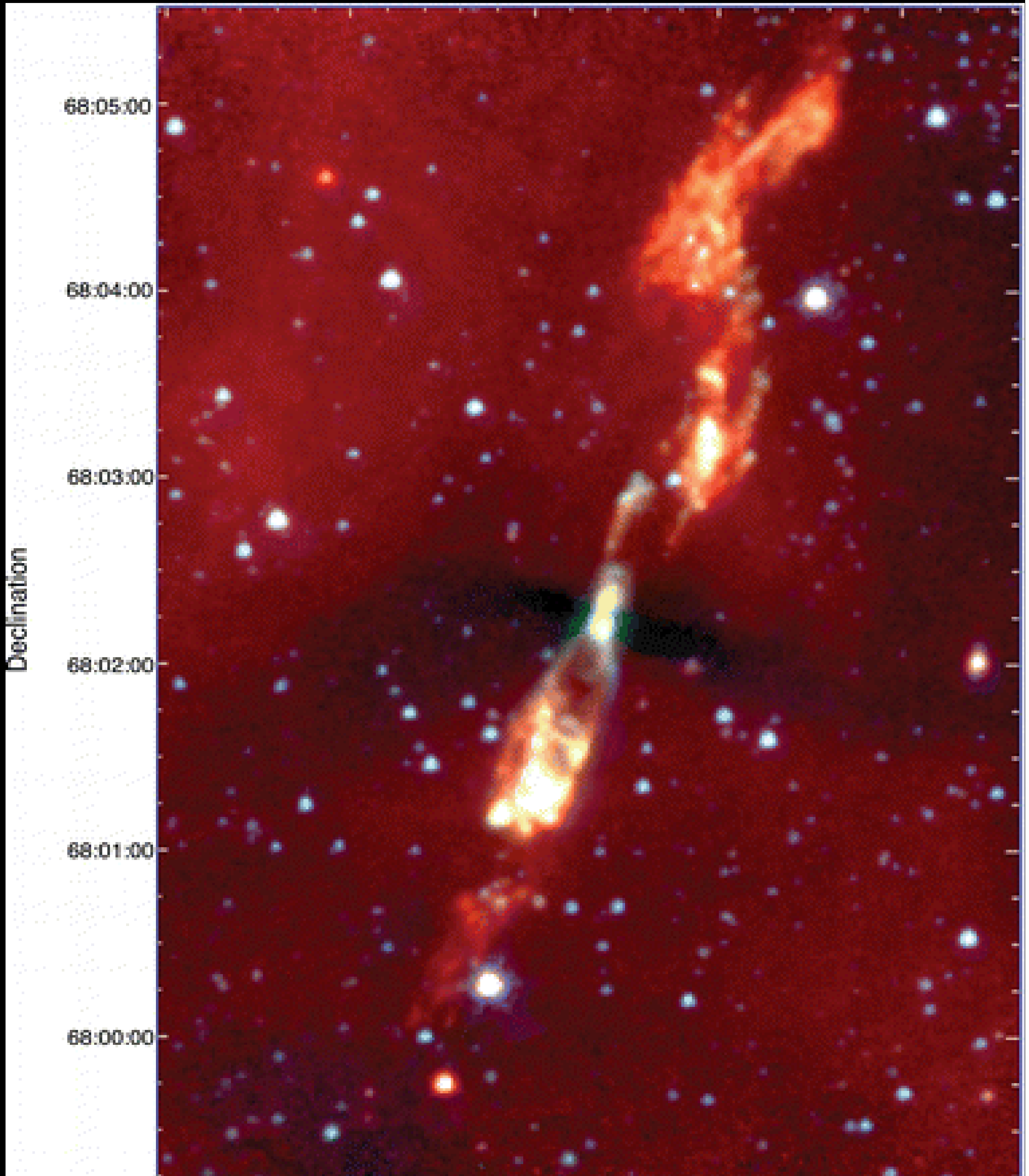


L1448

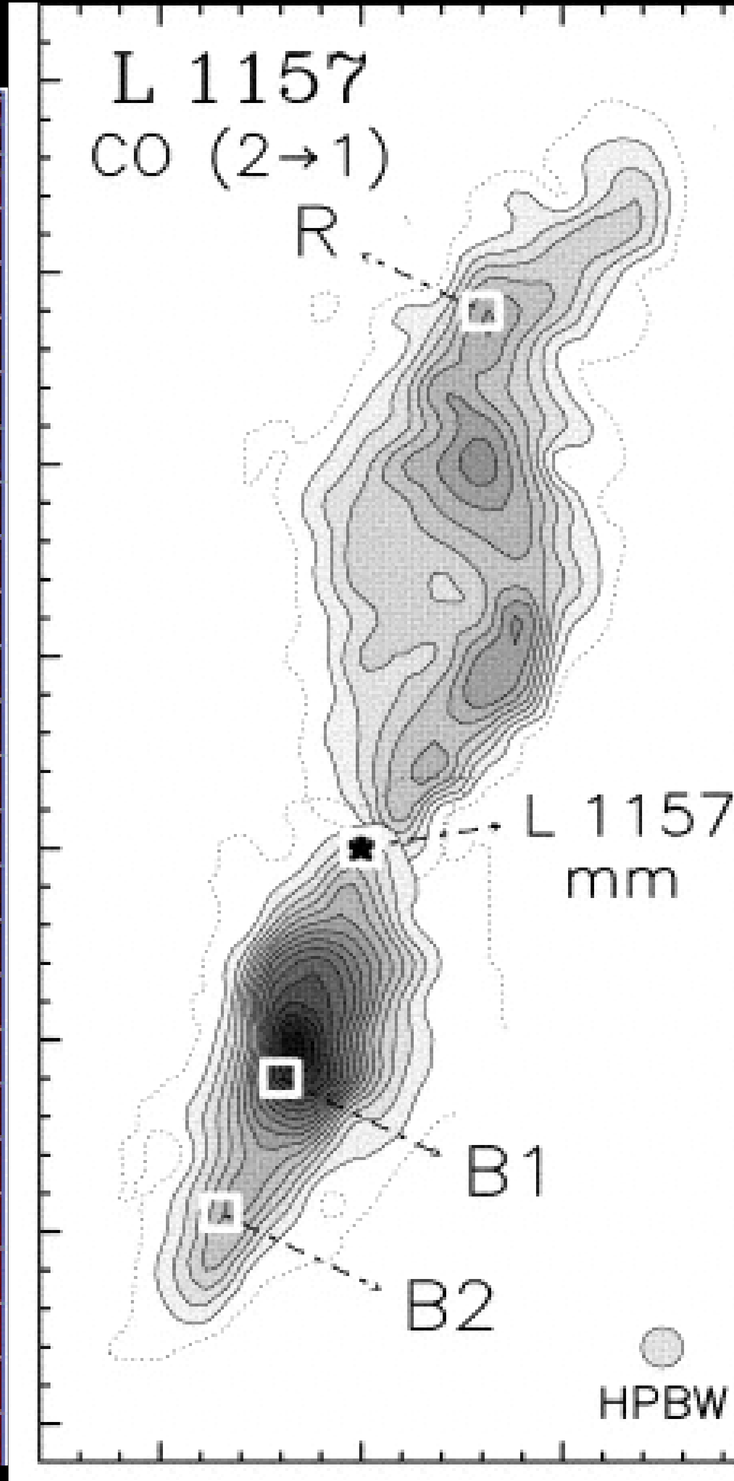
outflow widening by bow shocks



Precession



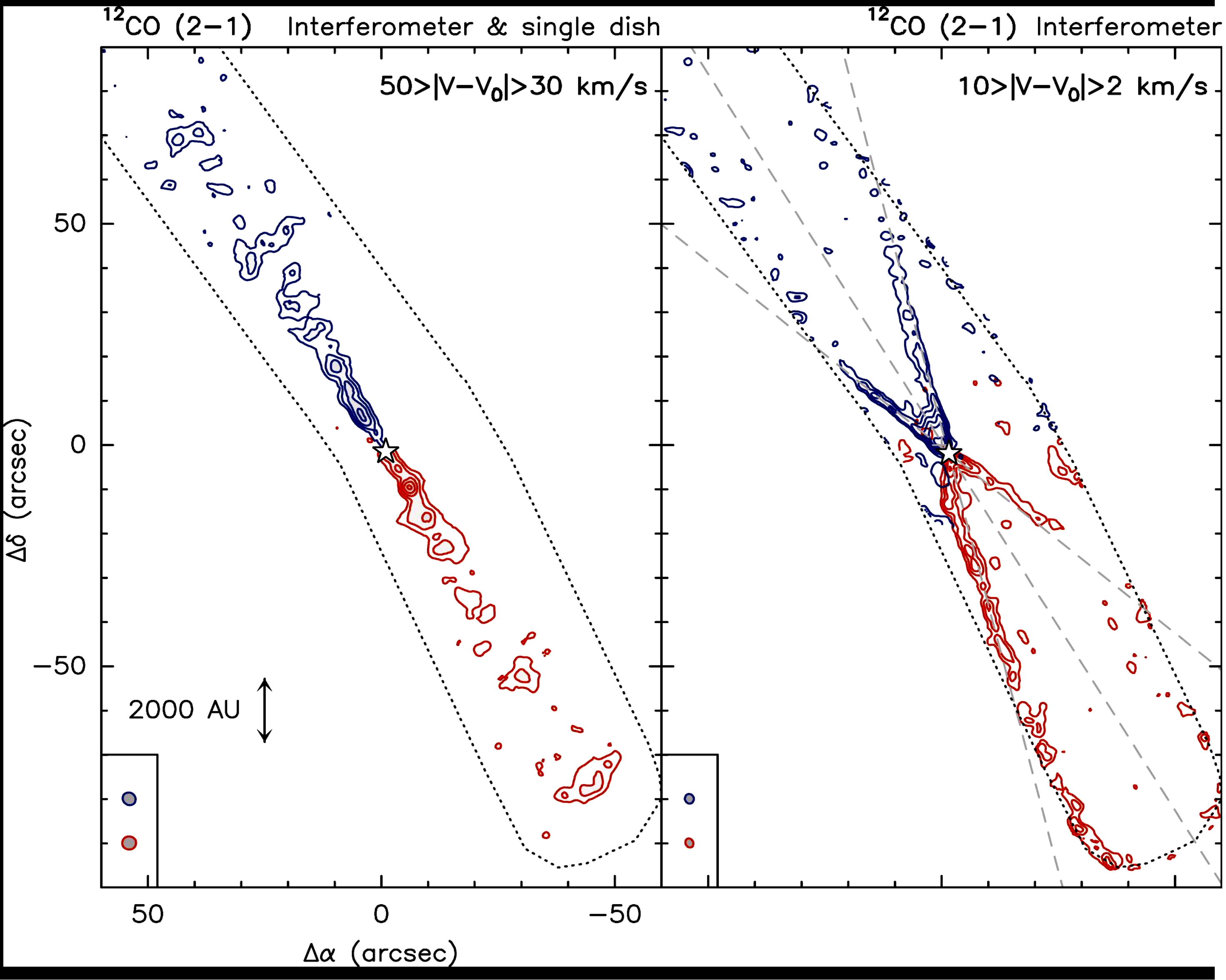
Looney et al. (2007)

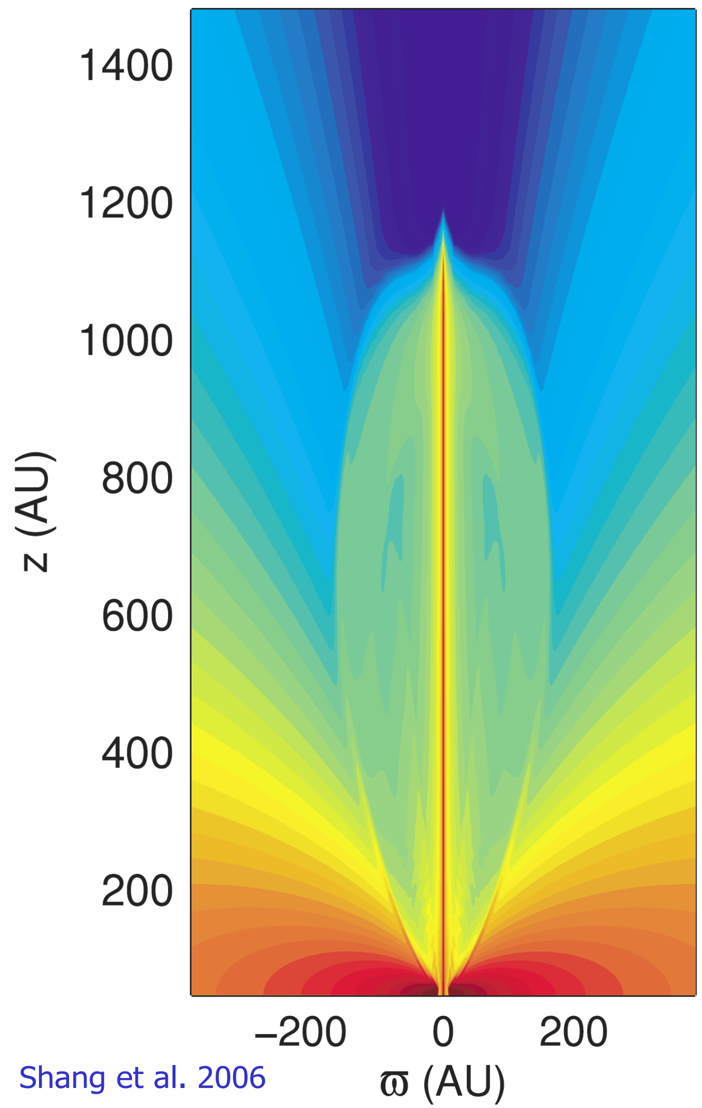


Bachiller et al. (2001)

Cavity opened by a wide-angle component of the primary wind ?

- **EHV** jet as the **densest part of a collimated primary wind** (time-variable)
- **Shell** as ambient material **entrained by a wide-angle/low-density component of the primary wind**
- Compare to recent simulations of **two components wind** ***(Shang et al. 2006)***





Shang et al. 2006

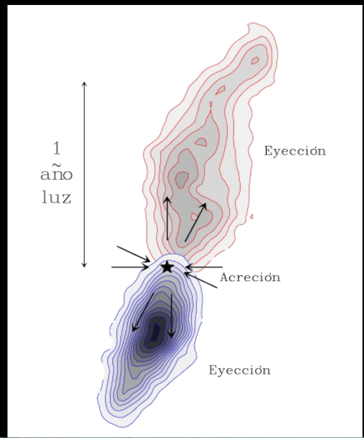
Conclusions

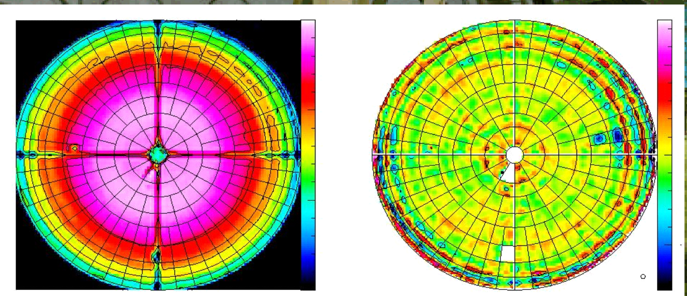
- Molecular (CO) observations are a powerful tool to study outflows
- Rapidly evolving chemistry
  - Creation / destruction of chemical species SiO, CH_3OH, H_2CO, Sulfur molecules, more complex (pre-biotic) species, etc…

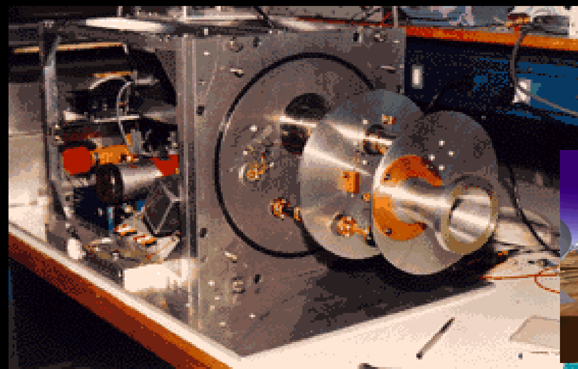
➔ Evolution of young (Class 0- Class I- Class II) bipolar outflows
  - As T_{bol} increases ::Terminal velocity decreases, Opening angle at the base increases, Outflo efficiency (L_{mech}/L_{bol}) decreases, chemical activity evolves.

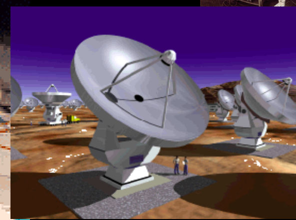
- Class 0 outflows: two chemical components in the gas
  - A high velocity component (SiO) : the primary wind
  - A low velocity component (H2CO & CH3OH & SiO) : shocked ambient material
- High spatial resolution: Two chemical components = Two spatial components
  - EHV : a CO & SiO jet, the dense part of the primary wind. EHV peaks ("bullets") are interna shocks due to variations in the launching velocity
  - Low-velocity wing : the rectilinear walls of an empty cavity opened in the ambient gas, perhaps by a wide (invisible) angle component of the primary wind
- ALMA will explore in detail regions of < 1" (gas & dust) and will very likely revolutioniz our knowledge of outflows (cf. J. Richer)
  - Collimation scale, study of two components (jets + wide-angle wind). Primary wind ?, relationship acretion/outflow (+ temporal changes), multiplicty: clusters will be resolved out (down to a few au), large variety of YSOs (low-mass, massive objects), shock structure: cooling lengths, stratification of conditions, chemical complexity, magnetic fields

Observatorio Astronómico Nacional





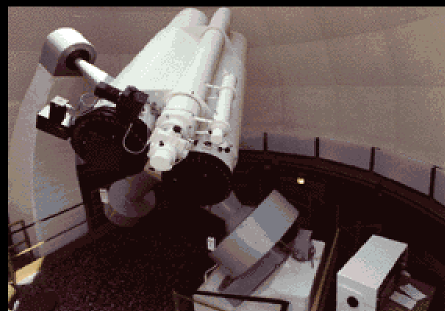


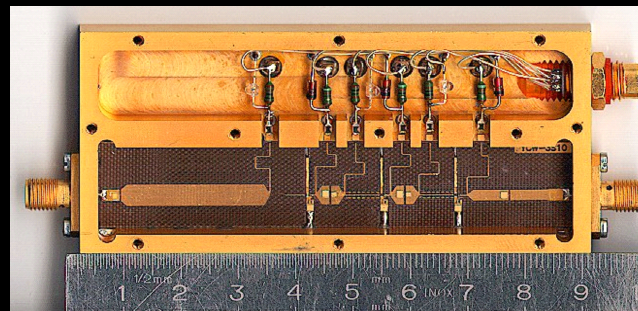


MINISTERIO
DE FOMENTO

DIRECCIÓN GENERAL
DEL INSTITUTO
GEOGRAFICO
NACIONAL

OBSERVATORIO
ASTRONÓMICO
NACIONAL





Summary of chemical behaviour

a) EHV outflows contain molecular bullets and display SiO enhancements by several orders of magnitude.

b) The SiO enhancement decreases as the outflow evolves, while the abundances of H_2CO and CH_3OH increase.

c) Transition objects only show residuals of this chemical activity, with low-velocity H_2CO wings.

d) This chemical behaviour is independent of the energetics involved, as shown by the chemical equivalence between L1448mm and IRAS 04166.

e) The high and “low” velocity regimes exhibit significant differences in their chemistry:

When the importance of the high velocity regime (related to SiO young shocks) decreases, the importance of the low velocity chemical regime (related to H_2CO and CH_3OH rich chemistry) increases.

Opening angle vs. time (Arce & Sargent 2006)