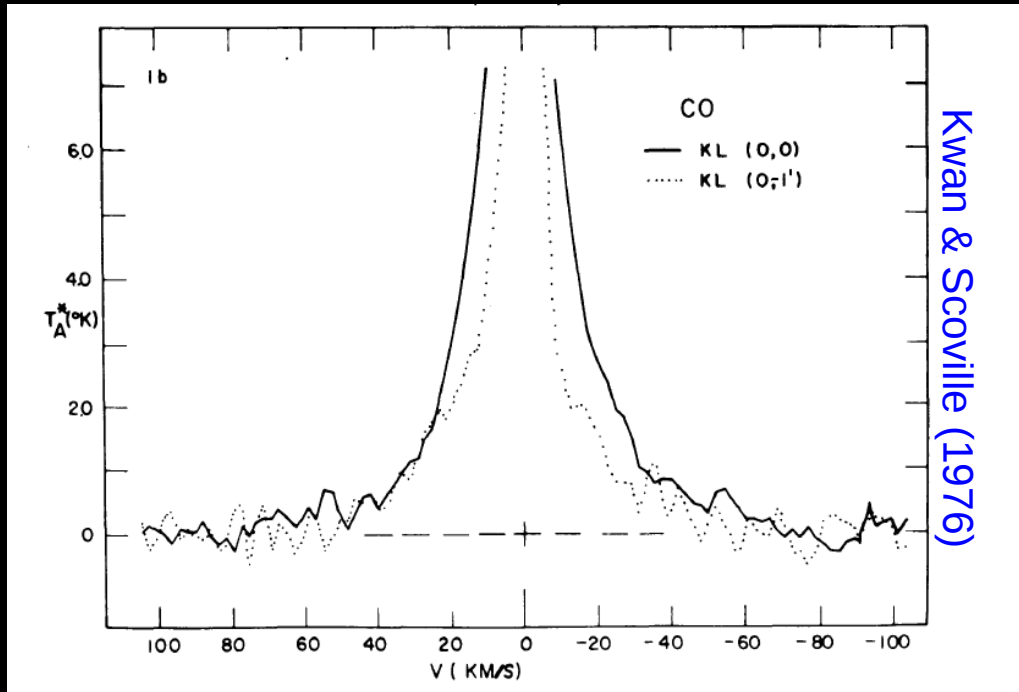


Outflow chemistry

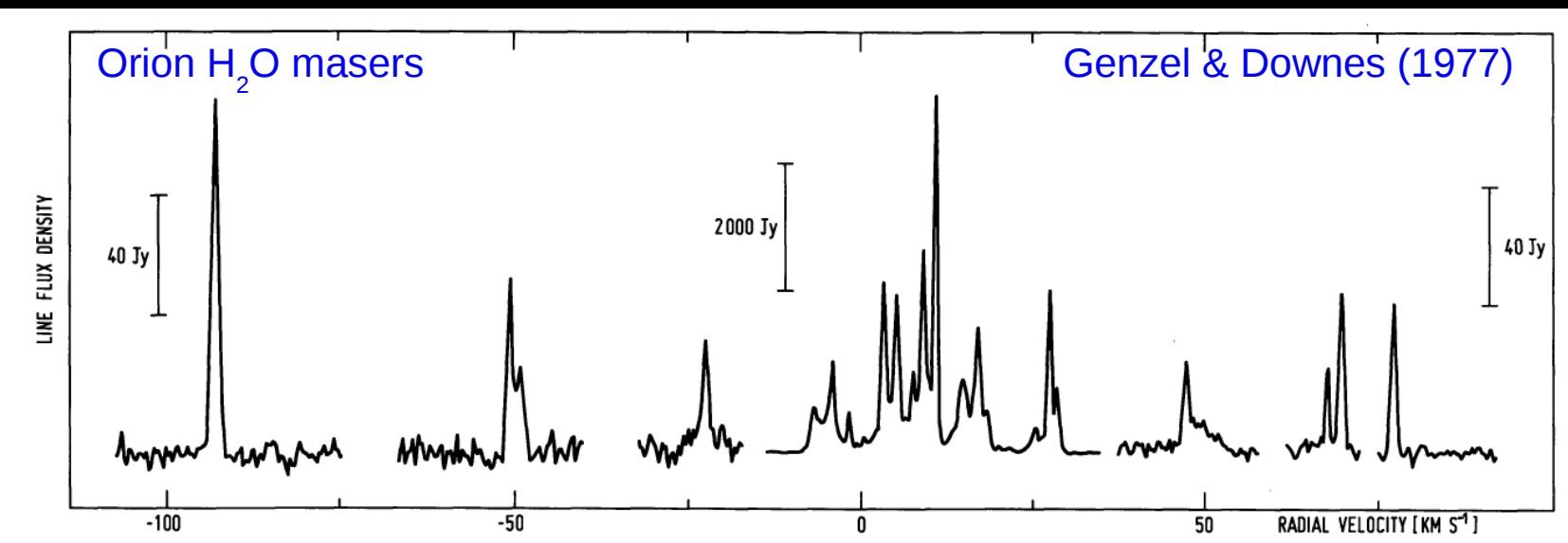
Mario Tafalla

Observatorio Astronomico Nacional (IGN) Spain

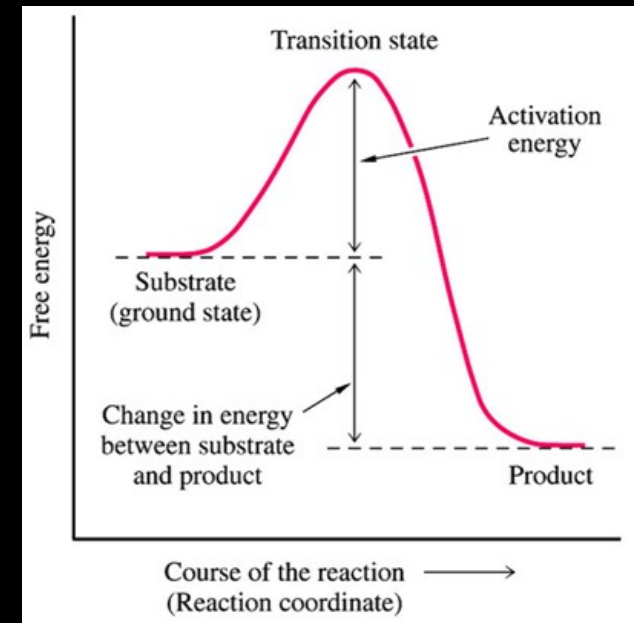
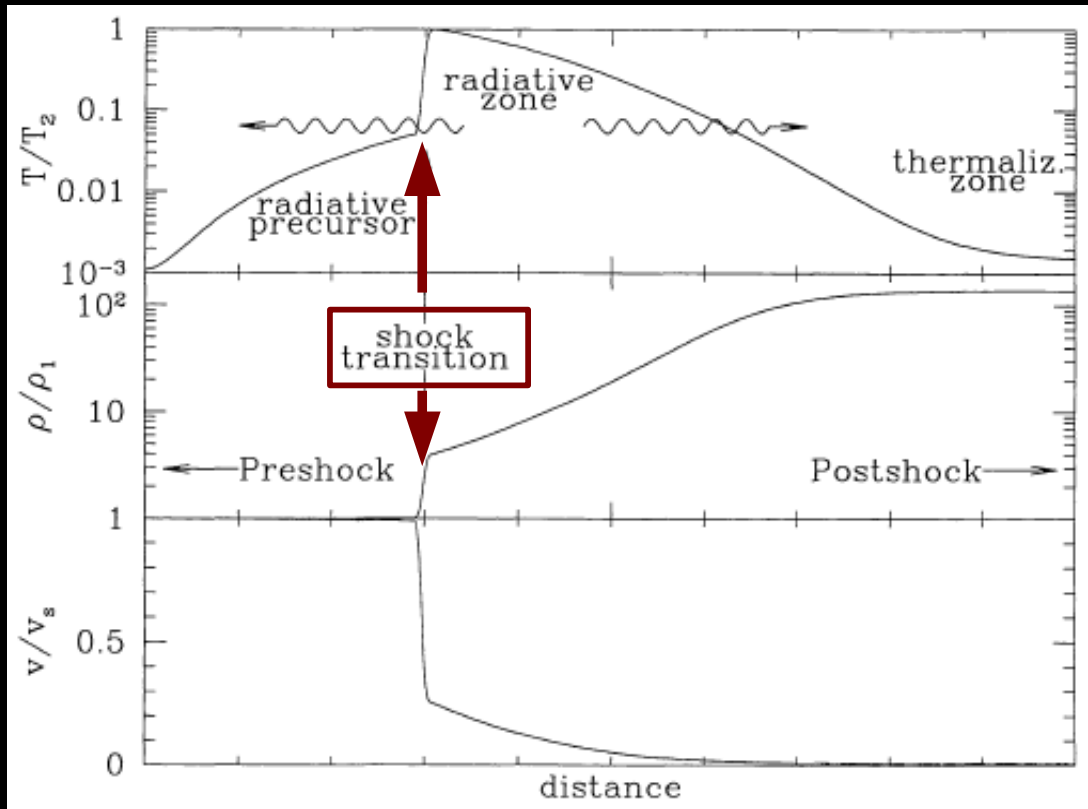
“Know your tracers”



- Youngest outflows: **molecules**
- CO **wings** up to 40 km/s
- H₂O **masers** up to 100 km/s
- sound speed @ 10 K is 0.2 km/s
- $M_A = 200 - 500$
- **How did molecules get to those velocities ?**

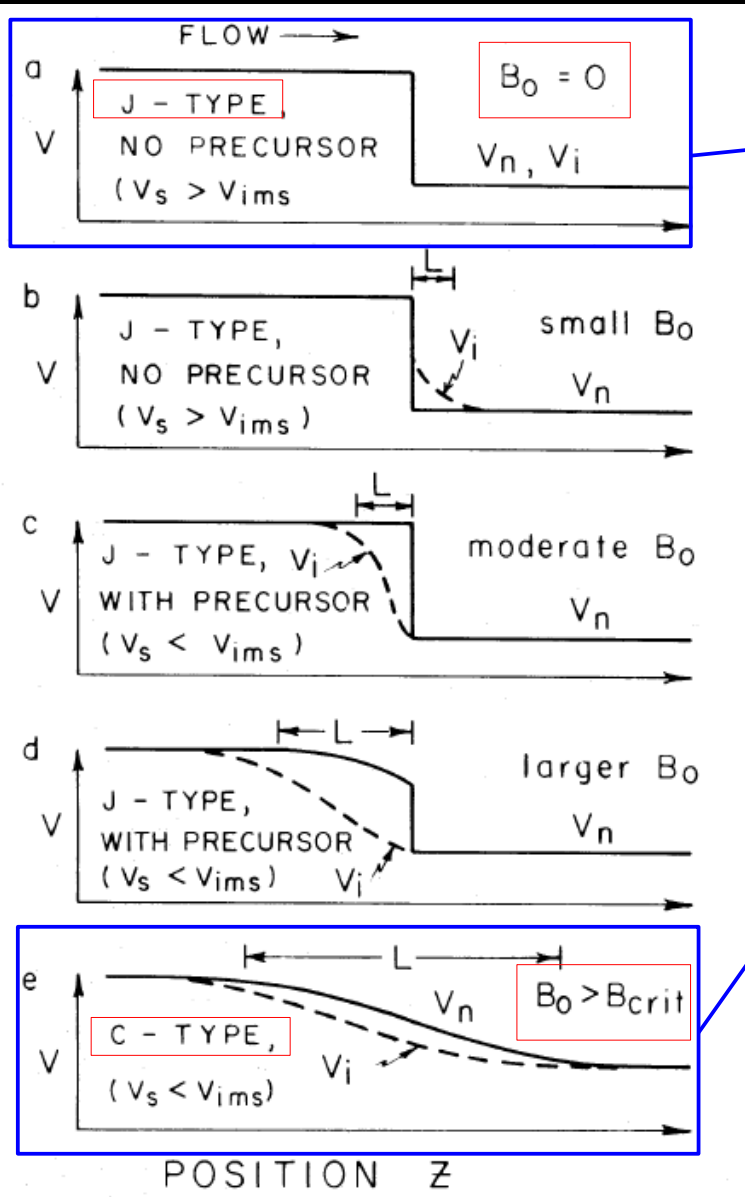


Outflow chemistry is shock chemistry

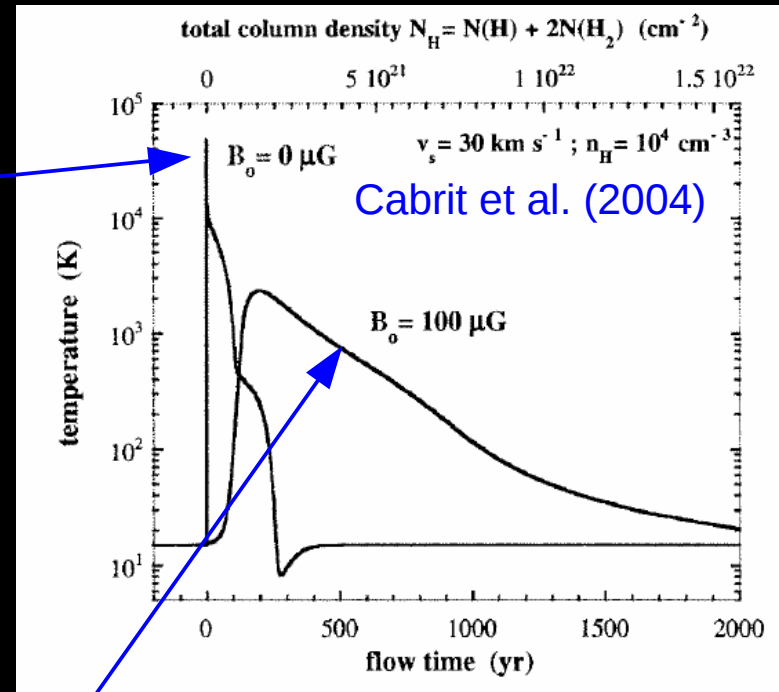


- Sudden acceleration and **temperature increase** in gas
 - open **new reaction channels** by overcoming activation energies (esp. neutral-neutral). **Complex chemistry**
- Dust grain disruption (via grain-grain coll. & sputtering)
 - release of molecules from **ice mantles**

Shock types: J(ump) and C(ontinuous)

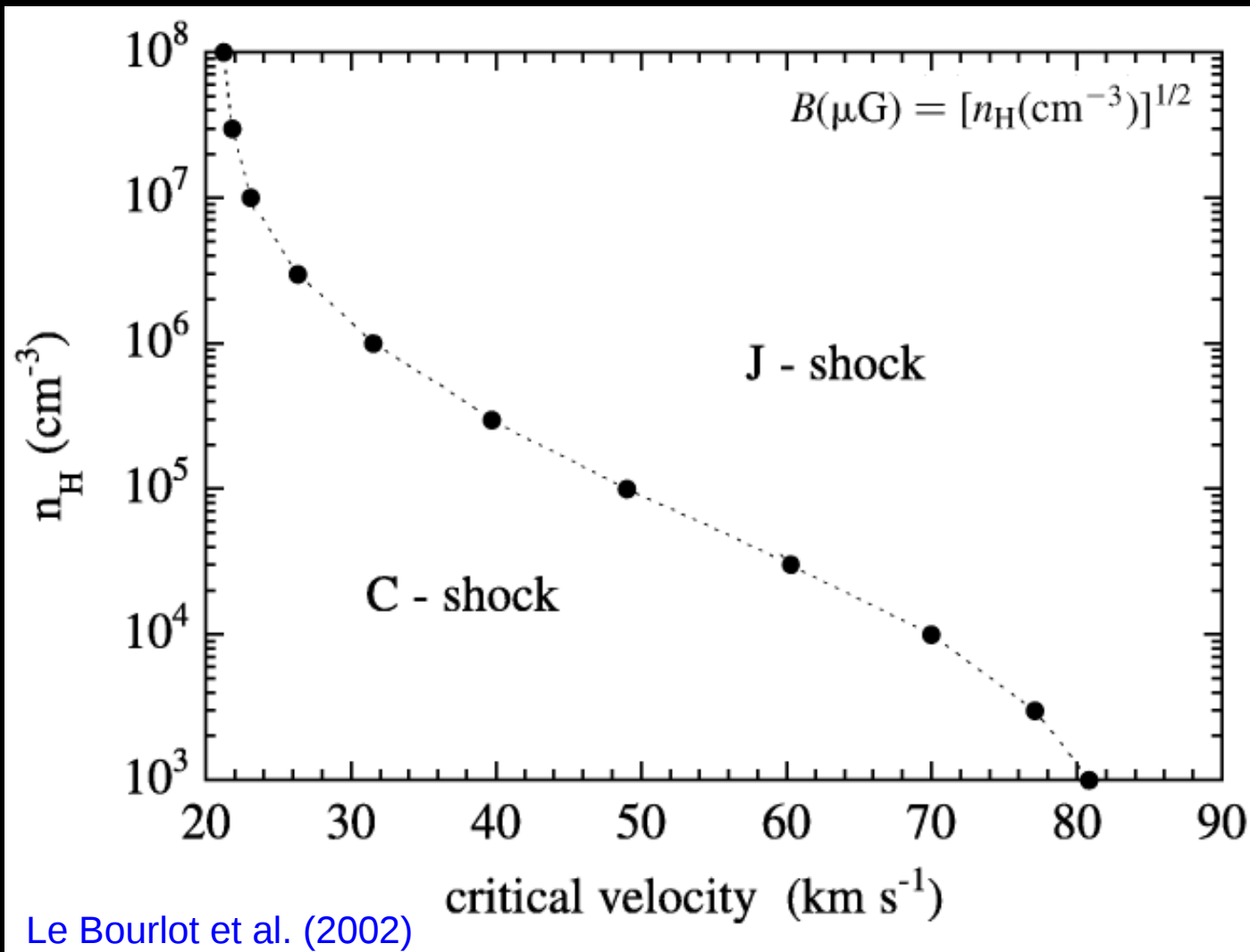


Draine (1980)



- **J-type**: sharp increase, high T , narrow post-shock. **Molecule destruction**
- **C-type**: gradual increase, lower T , broad post-shock. **Molecule survival**

J-shock / C-shock transition

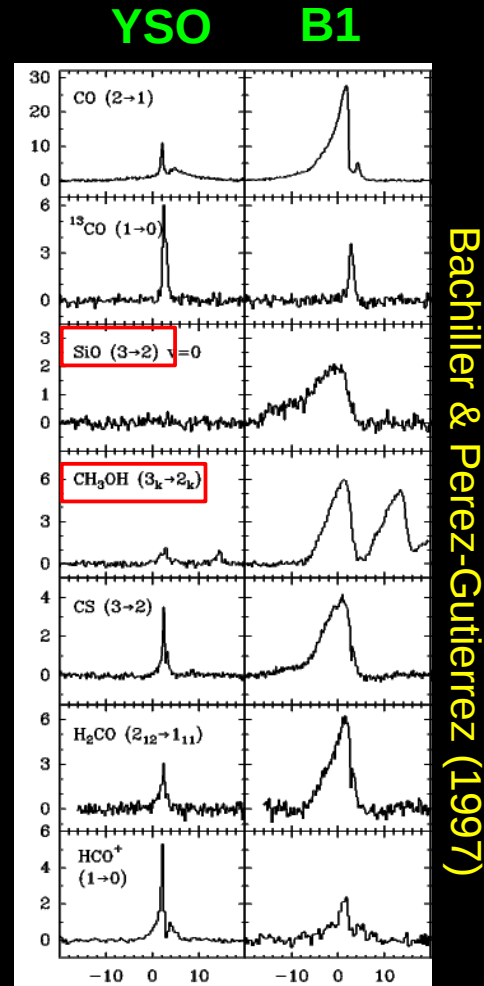
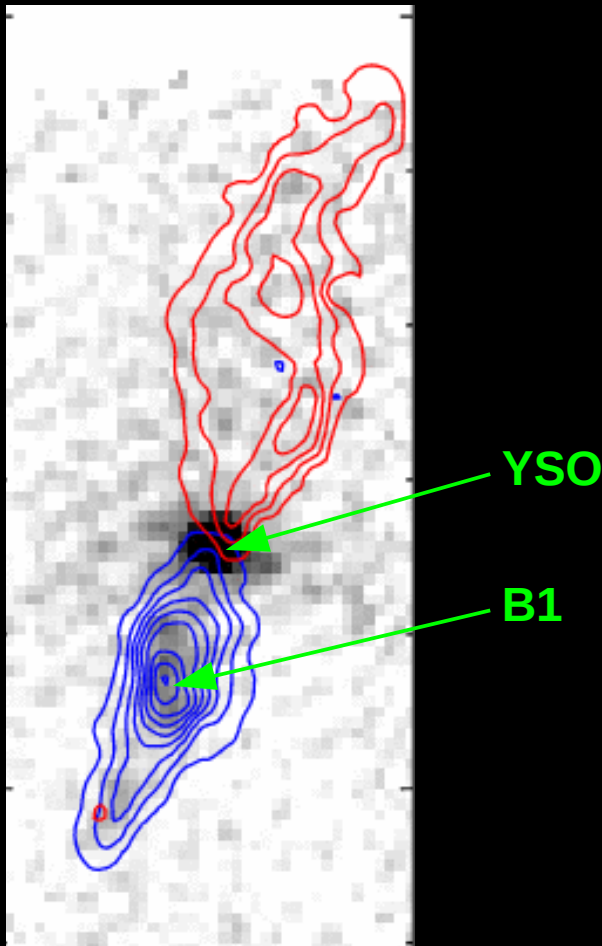


- **C-J transition** depends on collisional **dissociation** of H_2
- Shock physics and chemistry are **coupled**
- Molecule **survival** to high speeds

“Chemically active” outflows

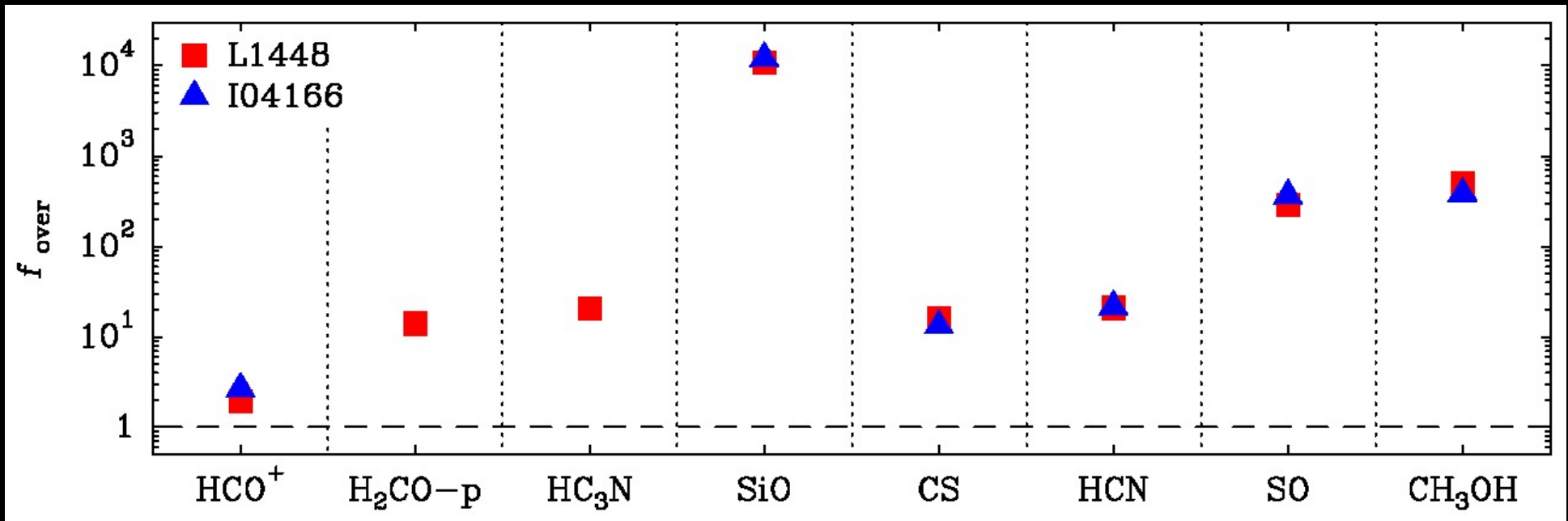
- **Most** outflows: emission dominated by **CO**
 - Supersonic but $T = 10\text{-}20\text{ K}$ (radiative post-shock)
 - No (detectable) emission from “exotic” species
- **Small group** of outflows
 - Strong lines of **SiO**, **CH₃OH**, etc. (at some spots)
 - “Chemically active”
 - Class 0 driving engine
- Chemical memory is **short** (-er than kinematic)
[or most acceleration is chemically inactive]

Chemically active L1157 outflow



- Powered by **Class 0** source IRAS 20386+6751
 - $L = 11 L_{\odot}$
- Several “chemical spots”
 - **B1**, B2, R
- **Prototype** of chemical studies
 - target for searches
- **Line surveys** on-going (Nobeyama, IRAM 30m, Herschel)

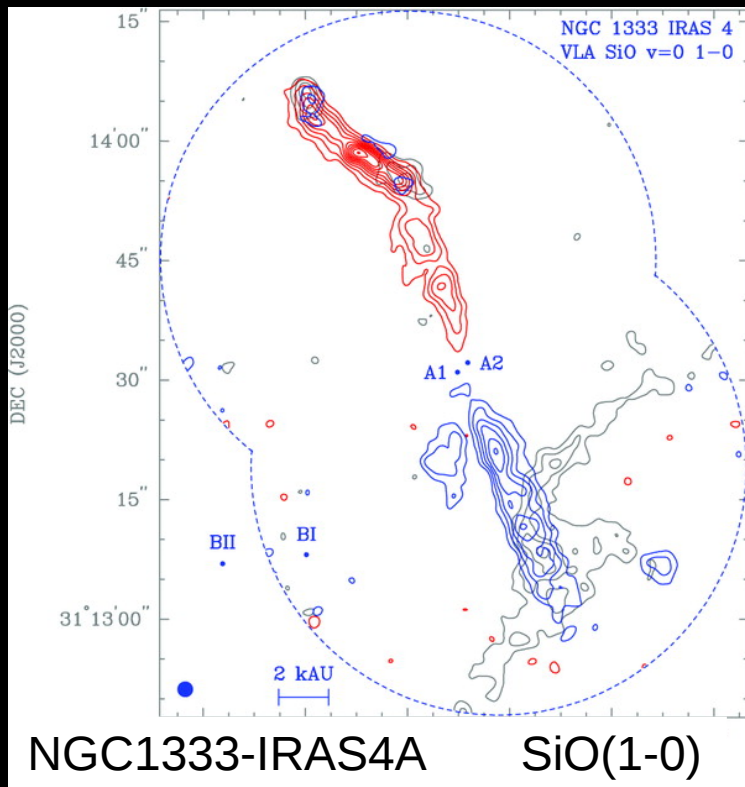
Large abundance enhancements



Tafalla et al. (2010)

- L1448 & IRAS 04166: Class 0
- Most molecules are enhanced
- CH_3OH & SO : ~ 300
- $\text{SiO} > 10^4$

SiO

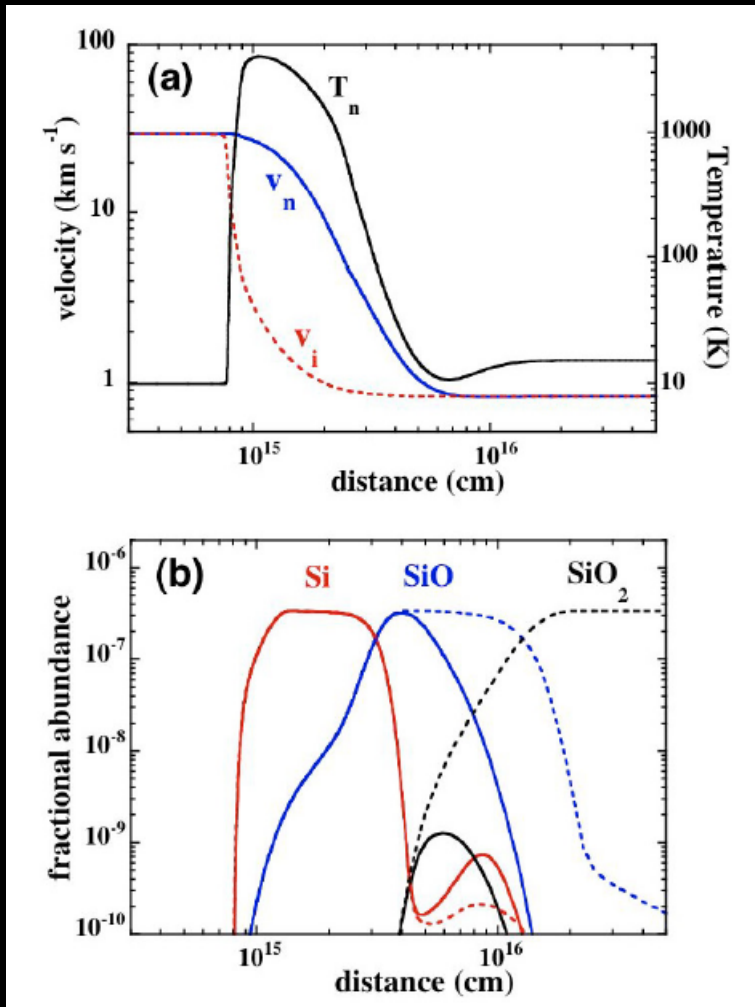


Choi et al. (2005)

- **Most selective** shock tracer
 - mm-wavelength lines (obs. ground)
 - $X(\text{SiO})_{\text{amb}} < 5 \cdot 10^{-12}$ (Ziurys et al. 1989)
 - observed enhancements $> 10^4$
- Detection guarantees abundance enhancement

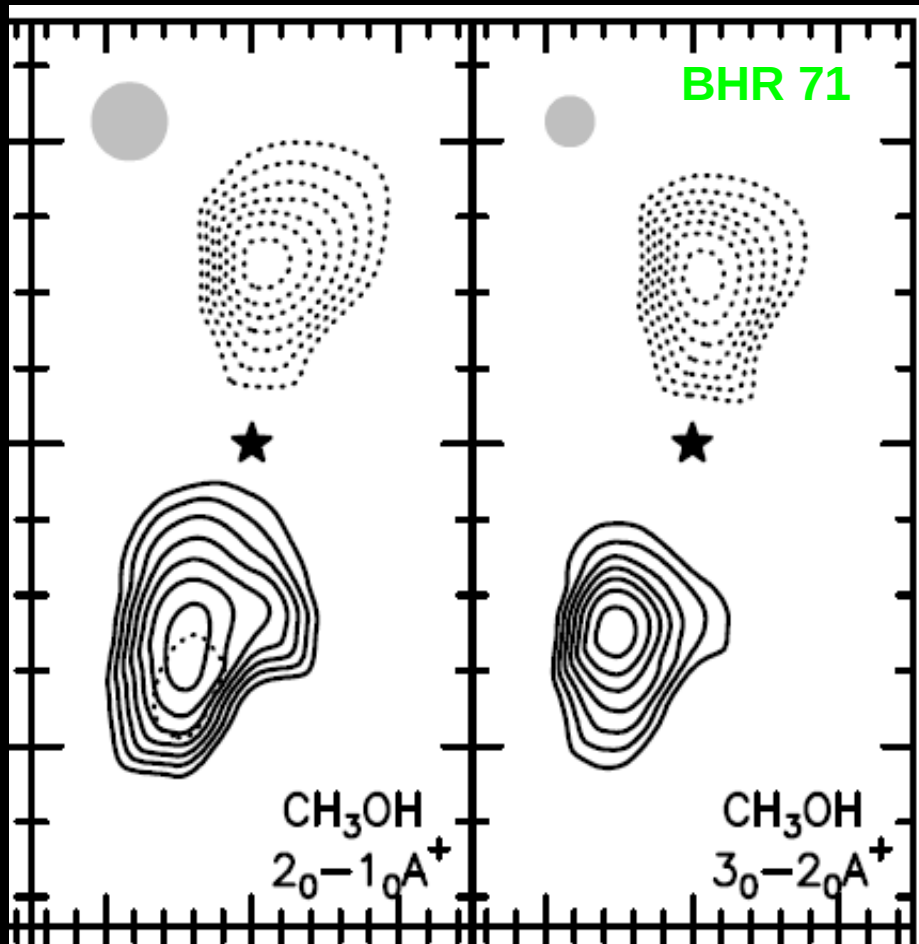
SiO

- Si released from core grains
- C-shocks
 - sputtering of (charged) grains by heavy neutral particles (Schilke et al. 1997, Gusdorf et al. 2008a)
 - grain-grain collisions (Caselli et al. 1997)
- J-shocks
 - dust vaporization (Guillet et al. 2009)
- SiO released from mantles (Gusdorf et al. 2008b)
- Overall
 - models explain abundances
 - problems with line shapes (later)

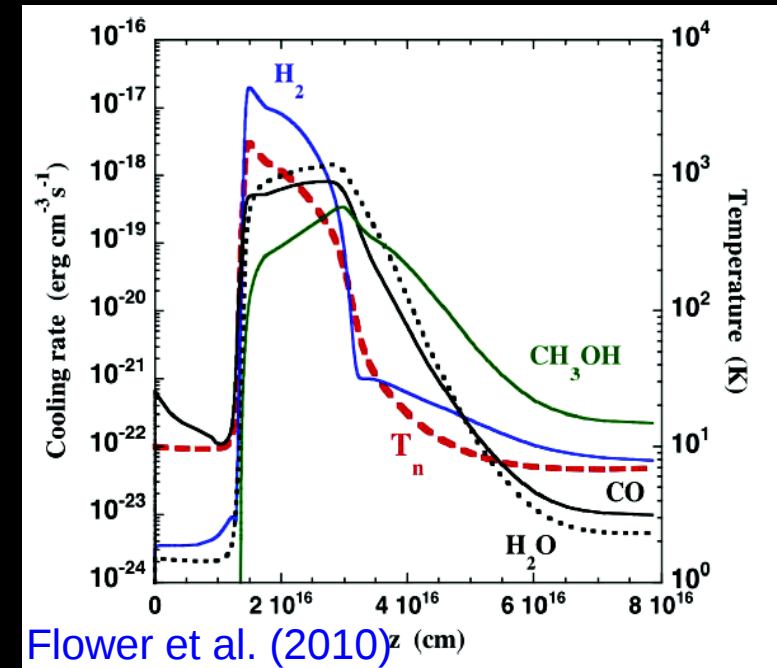


Gusdorf et al. (2008)

CH₃OH

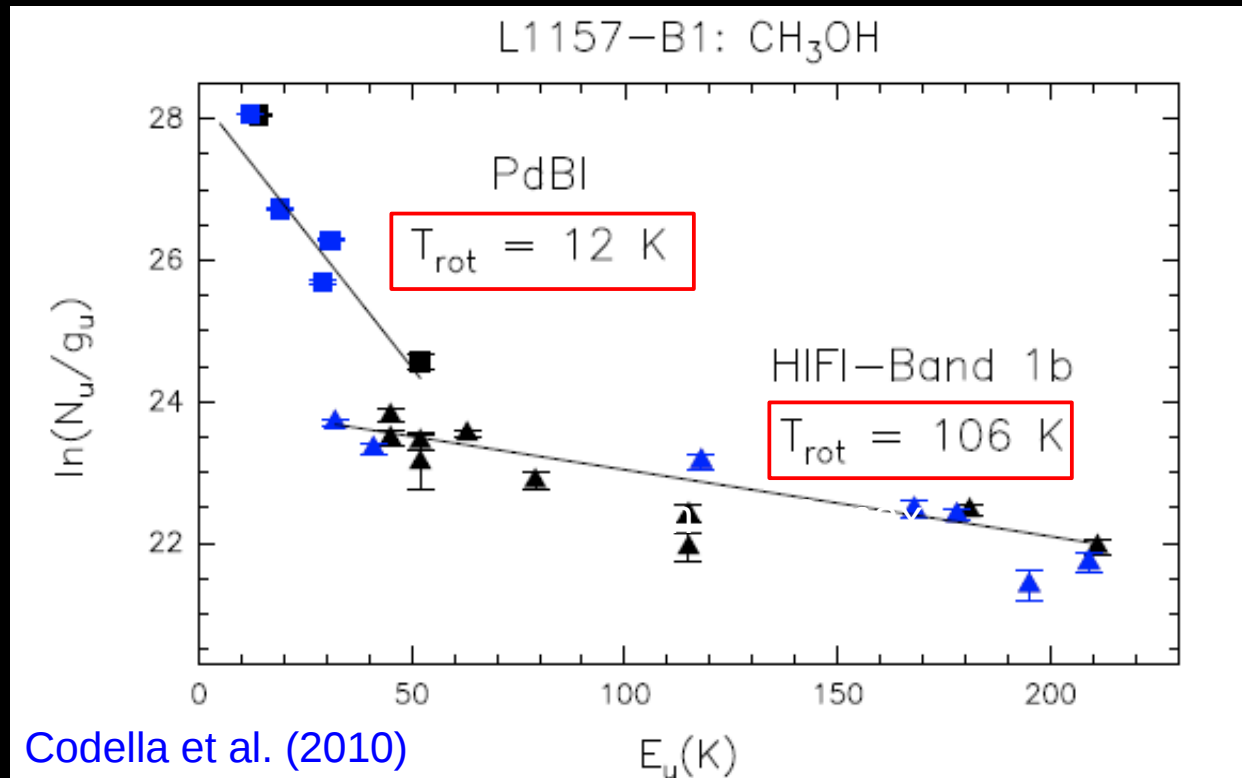


Garay et al. (1998)

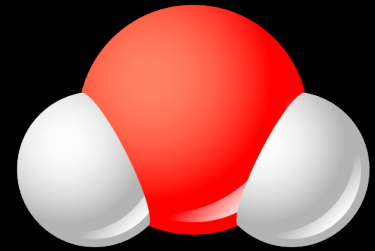
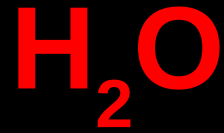


- Released **directly** from grain mantles
 - main ice component
- Threshold $v_s = 15$ km/s (Flower et al. 2010)

Warm CH₃OH



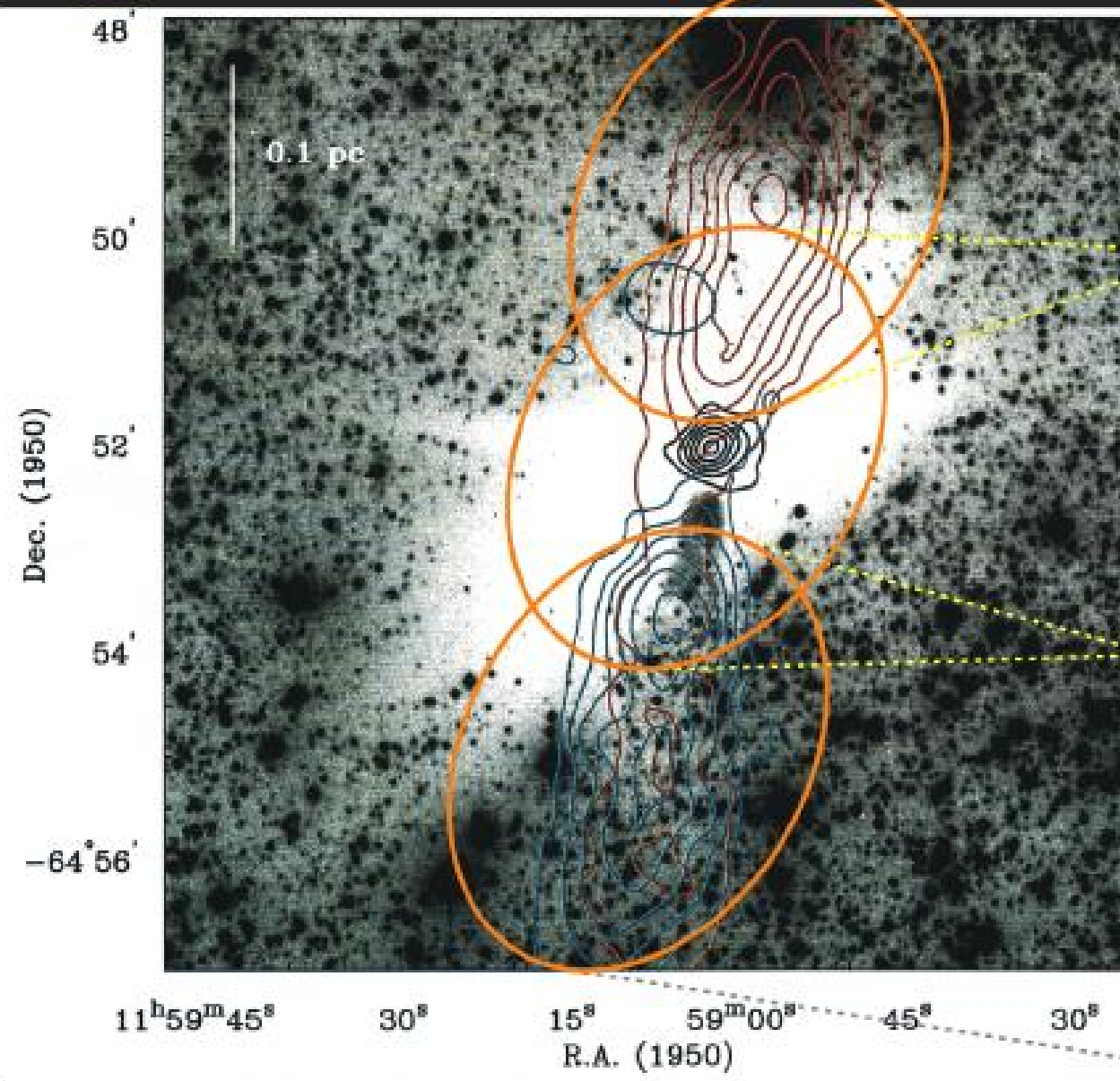
- **Cold** ($T_{\text{rot}} = 12$ K) component known from ground observations
- **Warm** ($T_{\text{rot}} = 106$ K) component identified with **Herschel**



- Sensitive **outflow** tracer
- **Low** ambient abundance ($< 7 \times 10^{-8}$, Snell et al. 2000)
- Strong shock **enhancement**
 - evaporation from mantles (main ice)
 - gas-phase production (all O to H_2O for few 100 K)
- Well known **maser** emission (Cheung et al. 1969)
- **Thermal** emission: ISO, SWAS, Odin



Water in BHR71



T_A^*

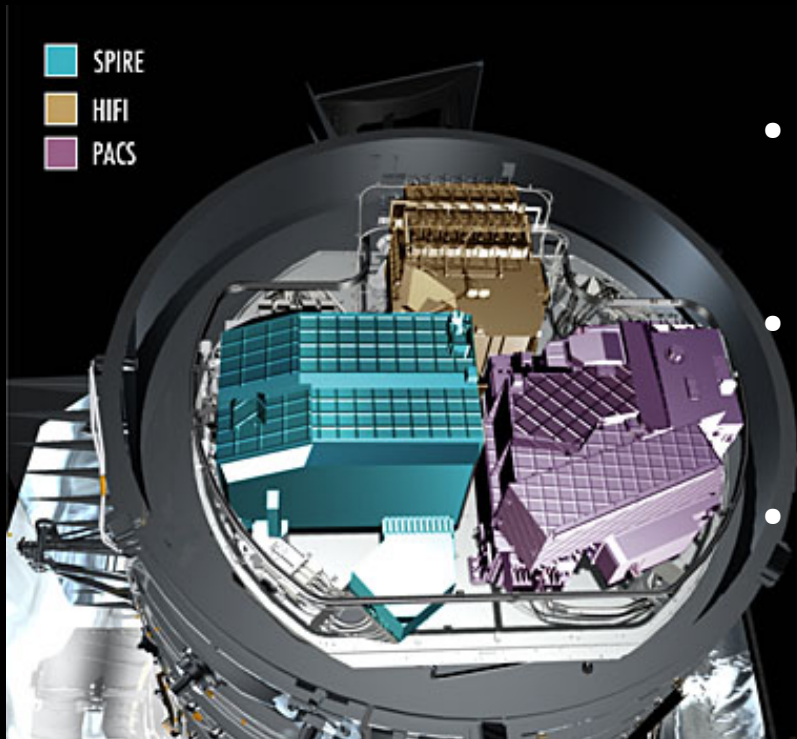
T_A^*

T_A^*

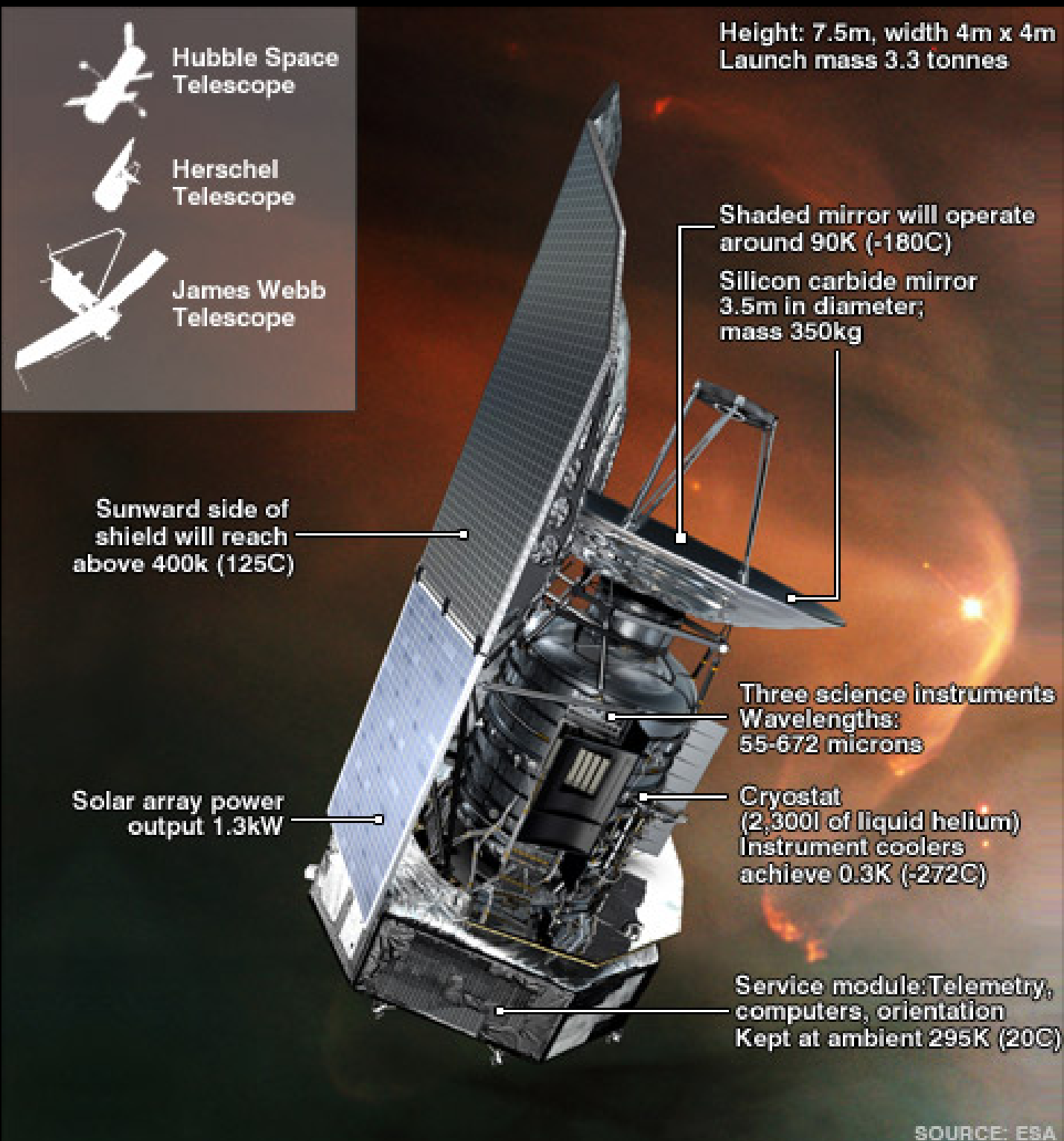
Velocity (km/s)

H₂O & Herschel Space Observatory

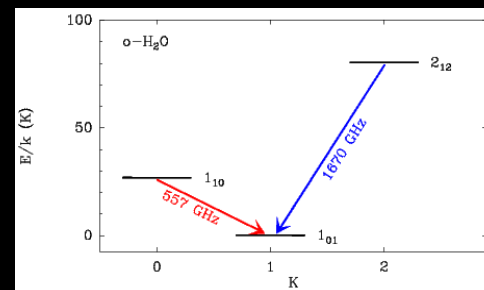
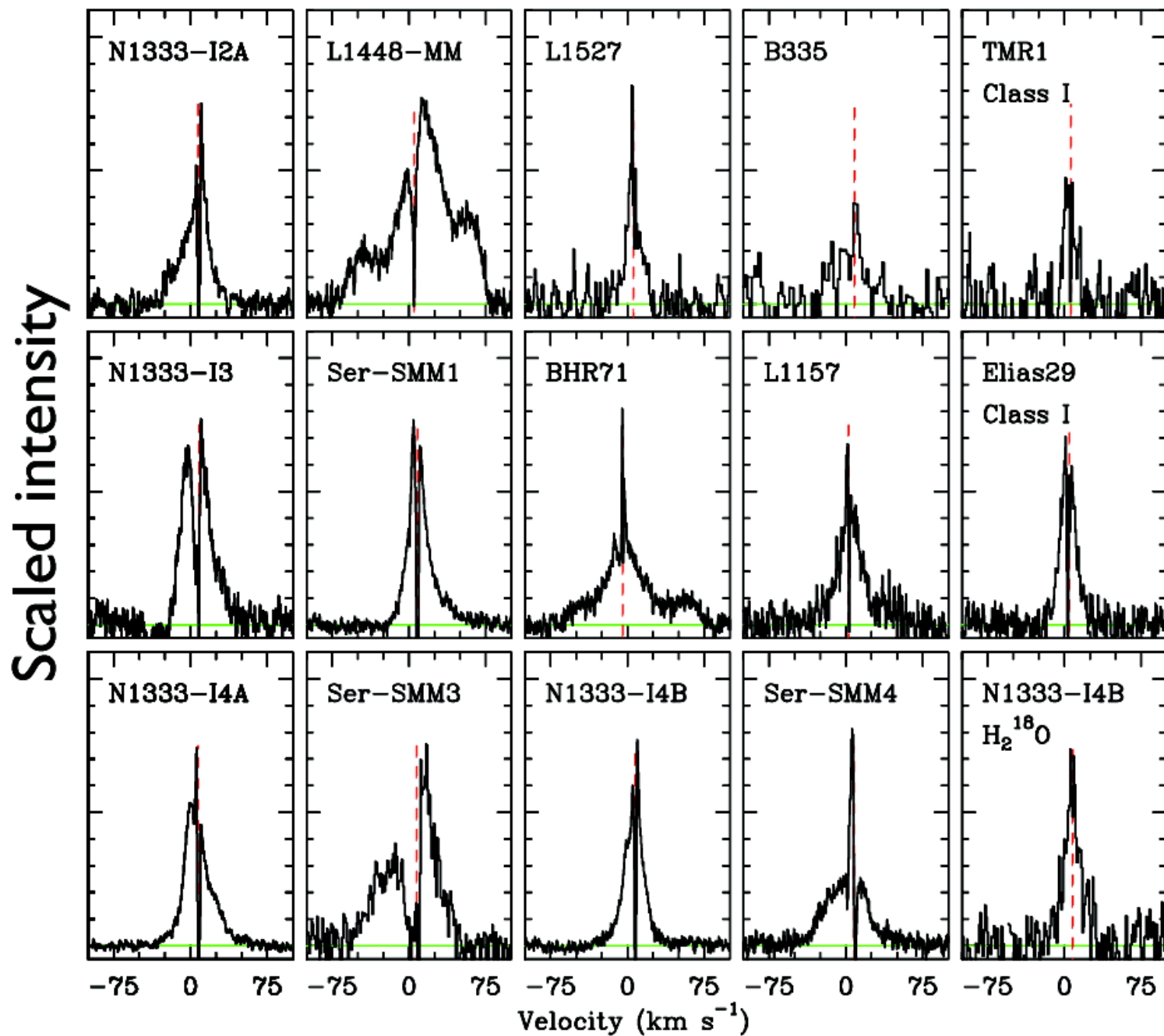
- **PACS**
 - 60-200 μ m / R=1500
- **SPIRE**
 - 200-670 μ m / R=1000
- **HIFI**
 - 150-600 μ m / R=10⁷



- **CHESS**
 - Chemical HERSchel Surveys of SF regions
- **HEXOS**
 - Herschel/HIFI Obs. of EXtraOrdinary Sources
- **WISH**
 - Water in Star forming regions with Herschel



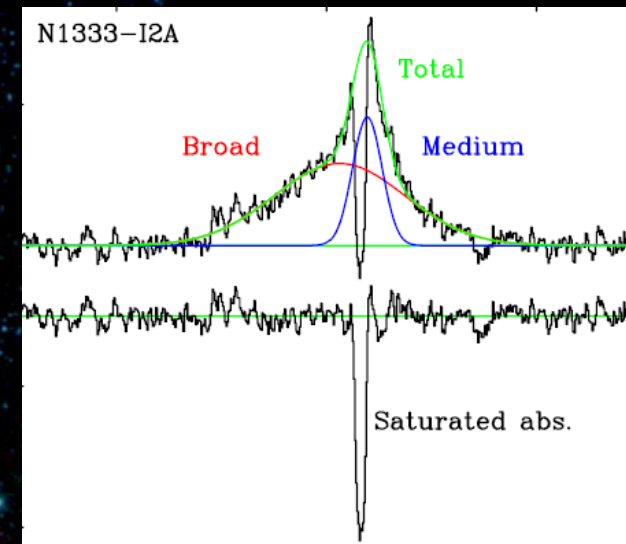
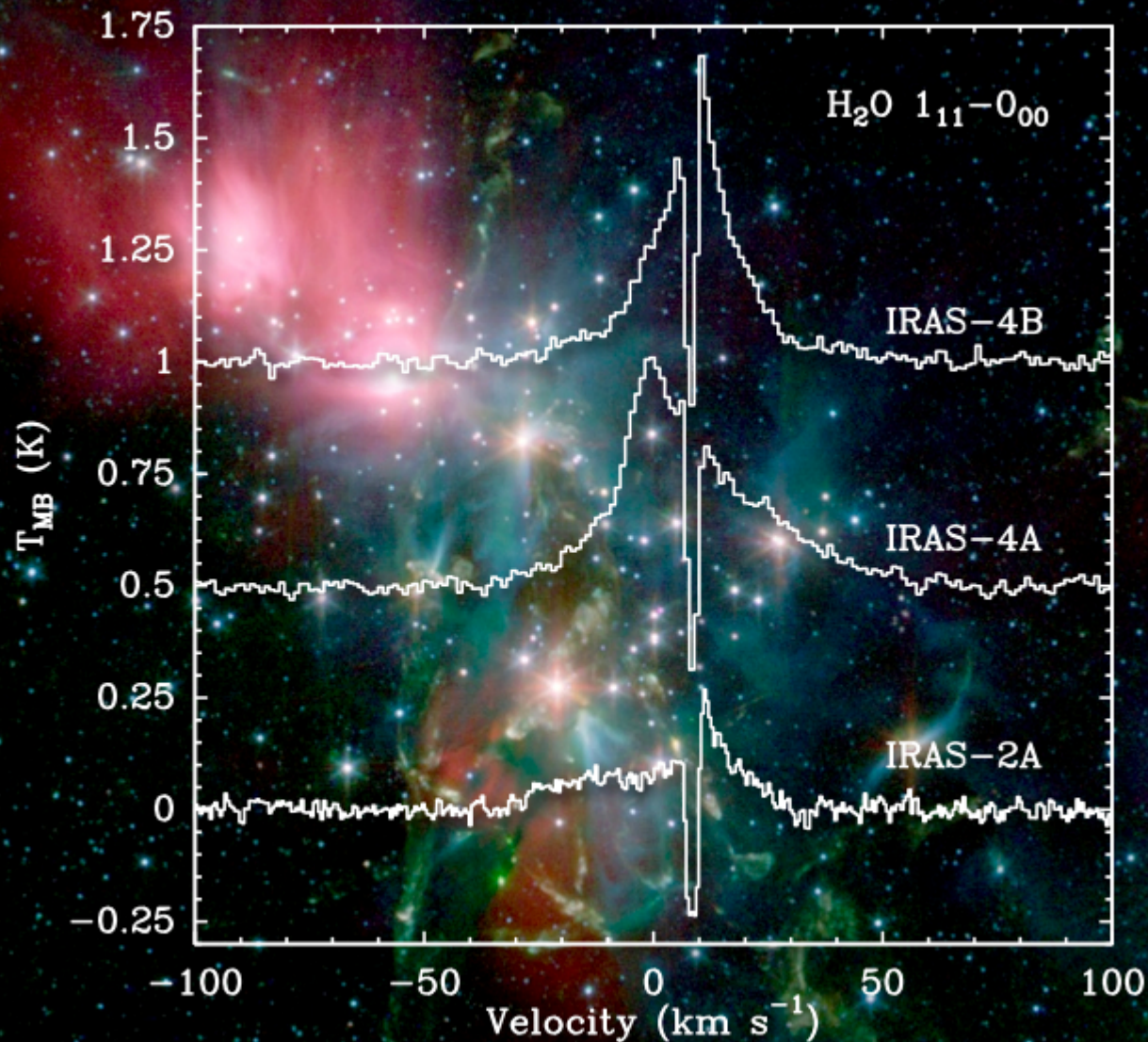
$\text{H}_2\text{O}(1_{10}-1_{01})$ survey of low-mass YSOs



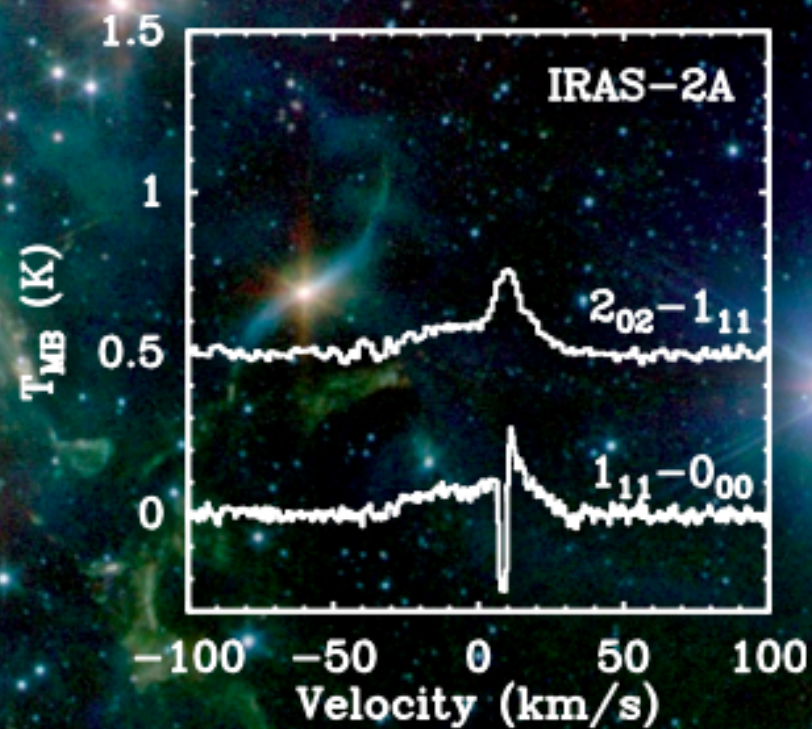
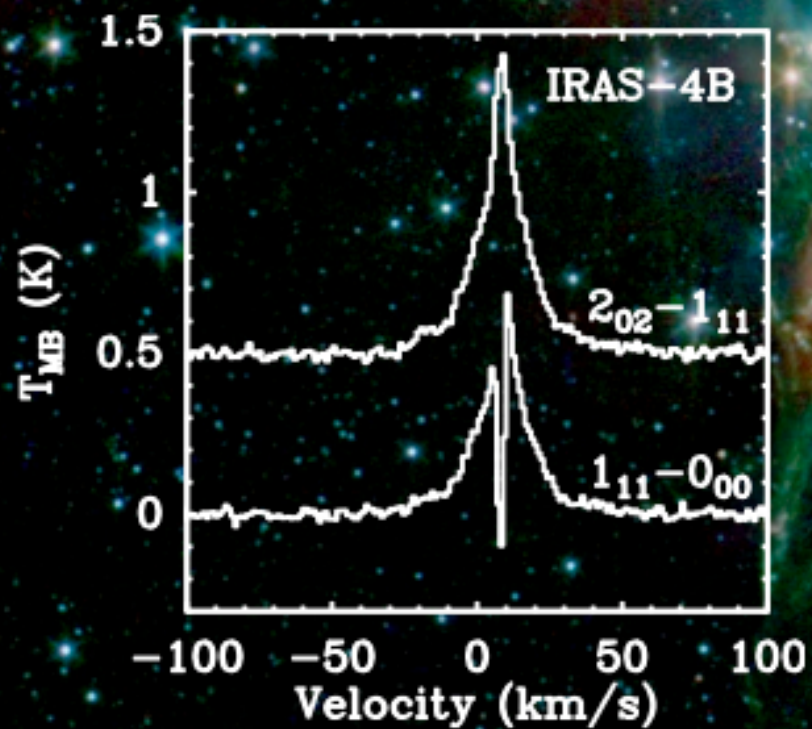
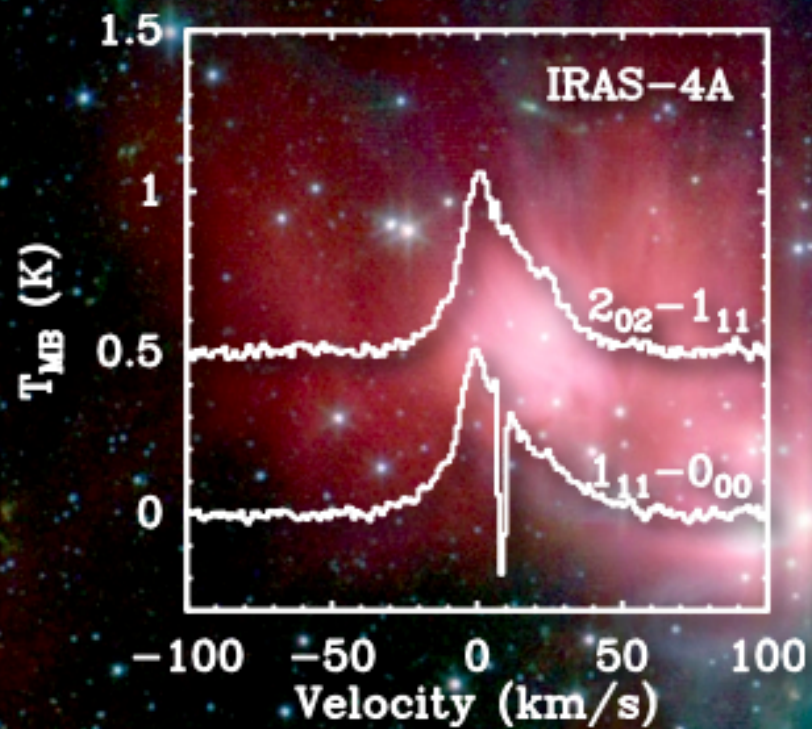
Kristensen et al. (2012)



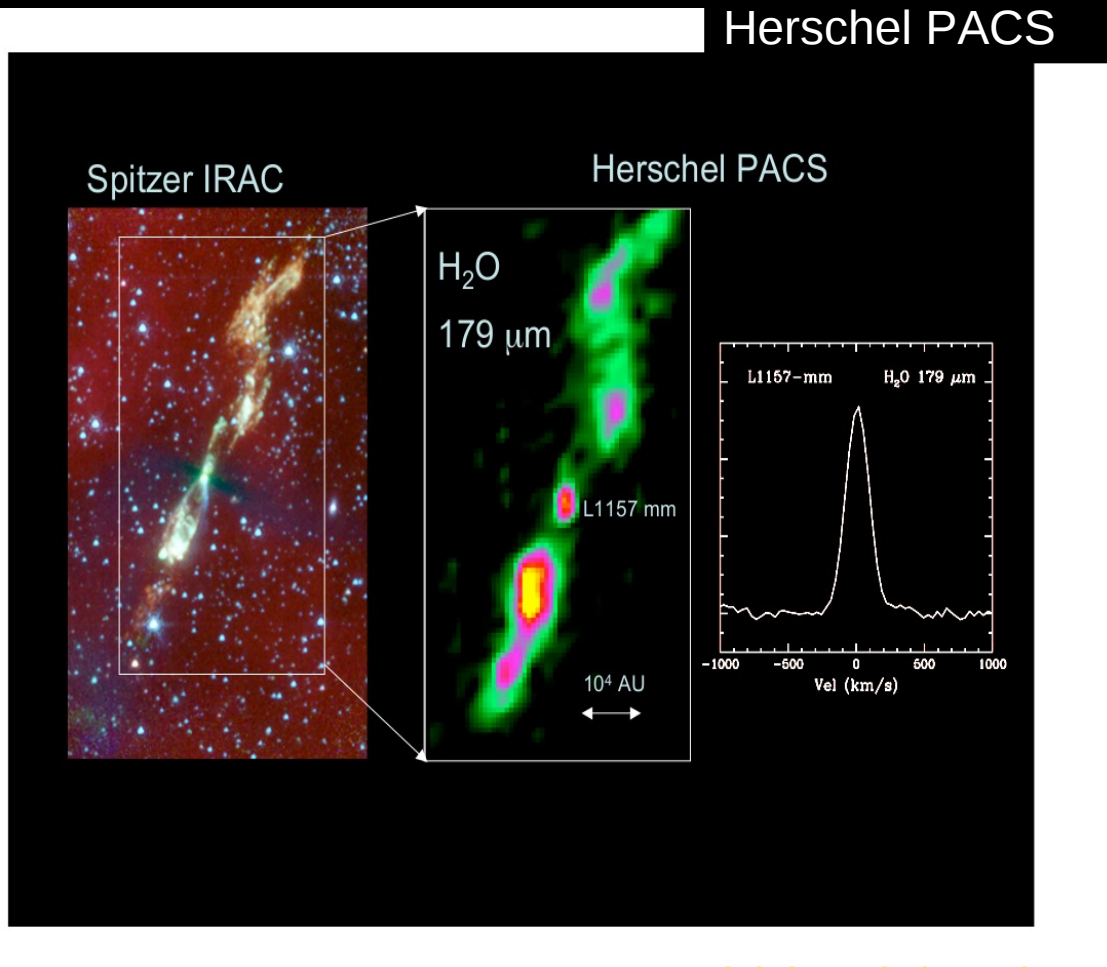
Multiple outflow components?



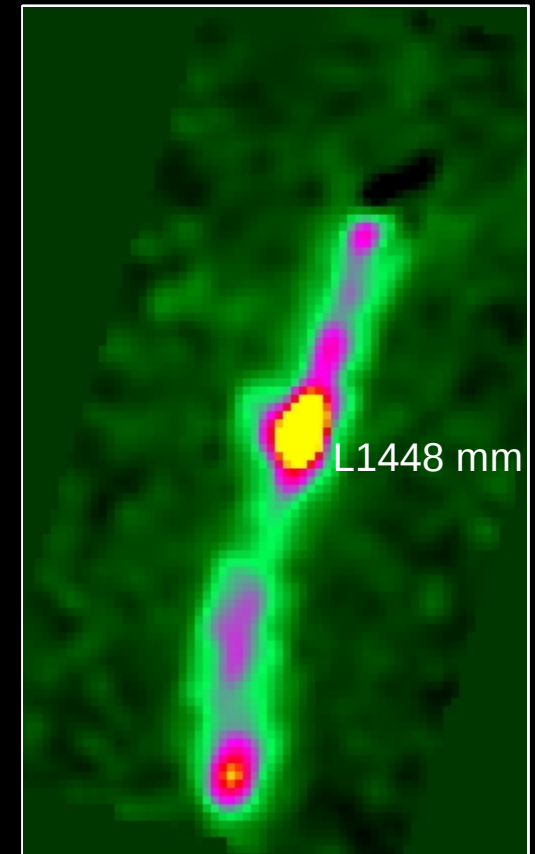
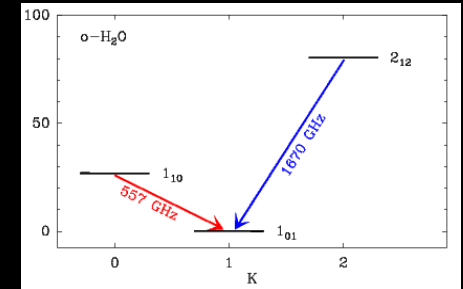
Kristensen et al. (2010)



$\text{H}_2\text{O}(2_{12}-1_{01})$ maps of L1157 & L1448



Nisini et al. (2010)

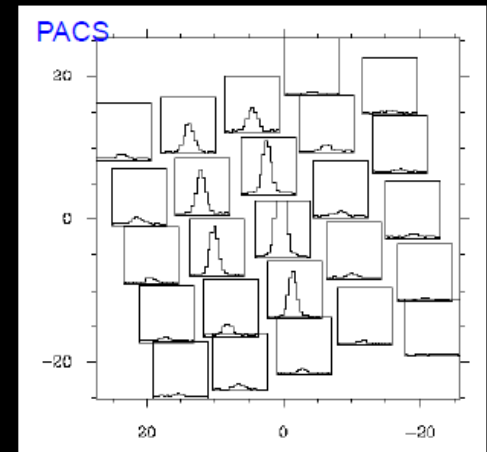
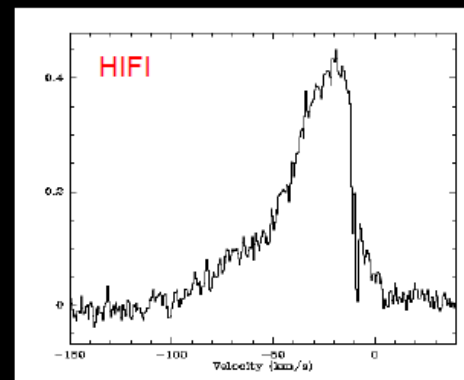
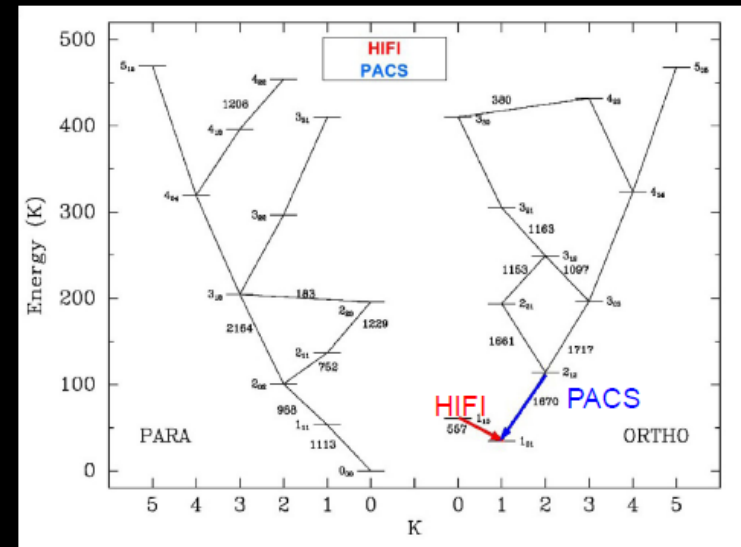


Nisini et al. (2012)

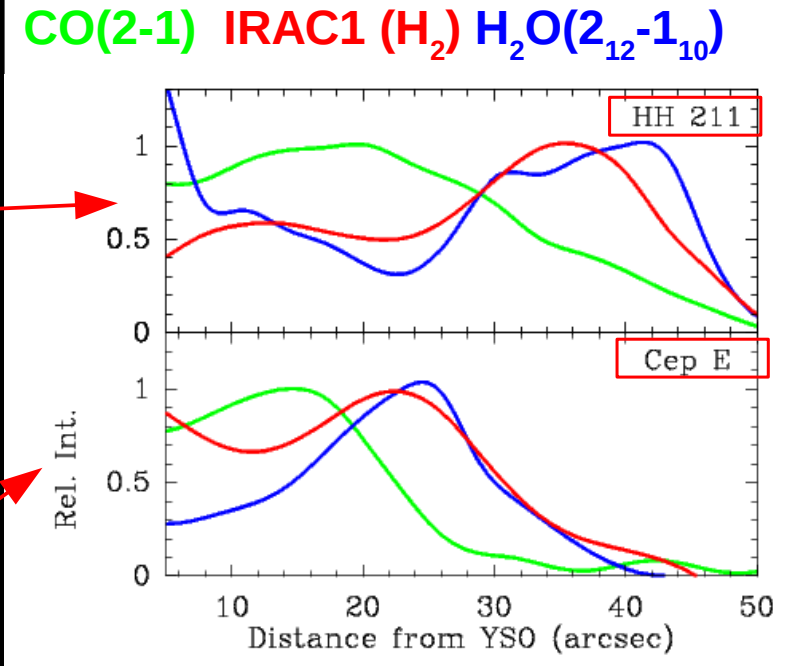
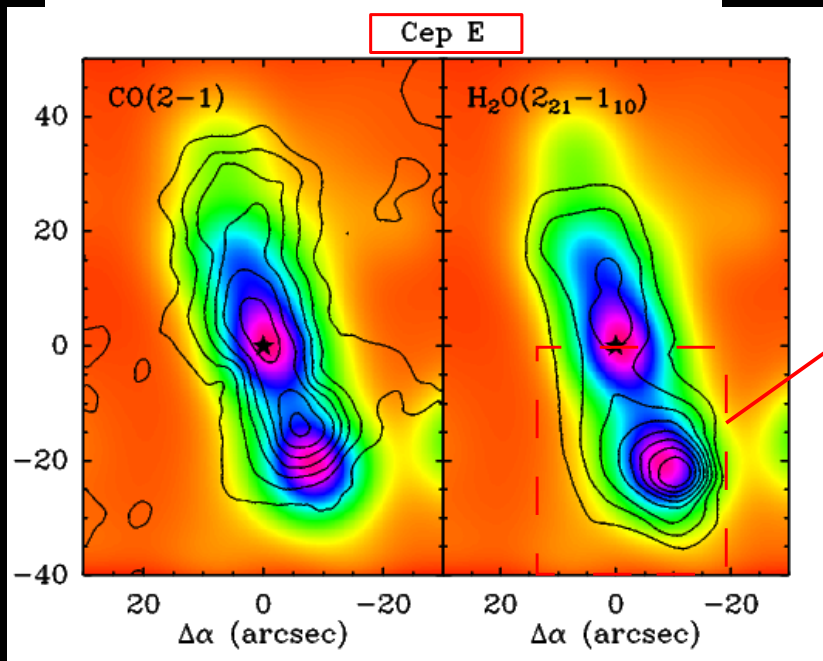
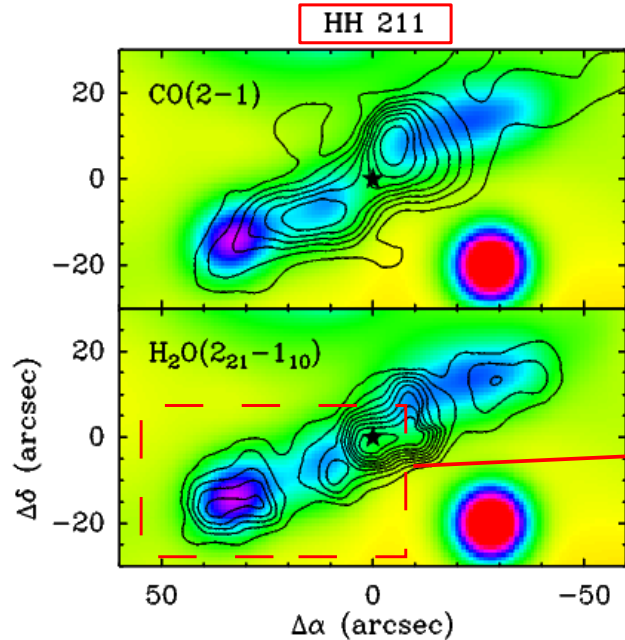


H₂O survey of outflows

- **Goal:** sample a large number of outflows
- Sample of **25 objects**
- ~ 2 positions each
- 2 ortho-H₂O lines
 - **557 GHz (HIFI)**
 - **1670 GHz (PACS)**



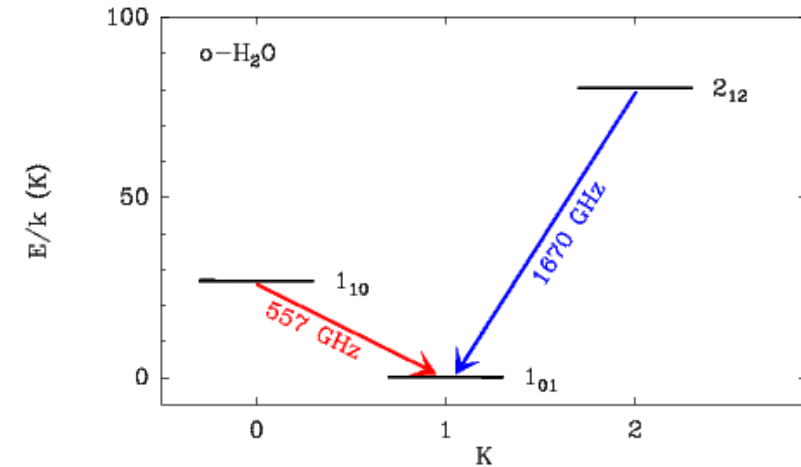
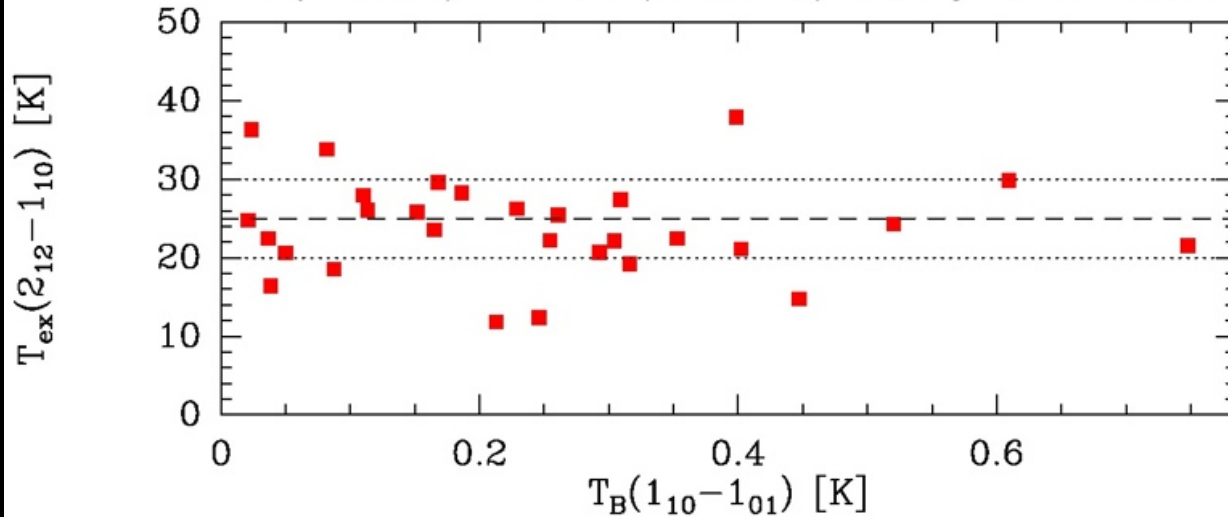
What gas is traced with H₂O?



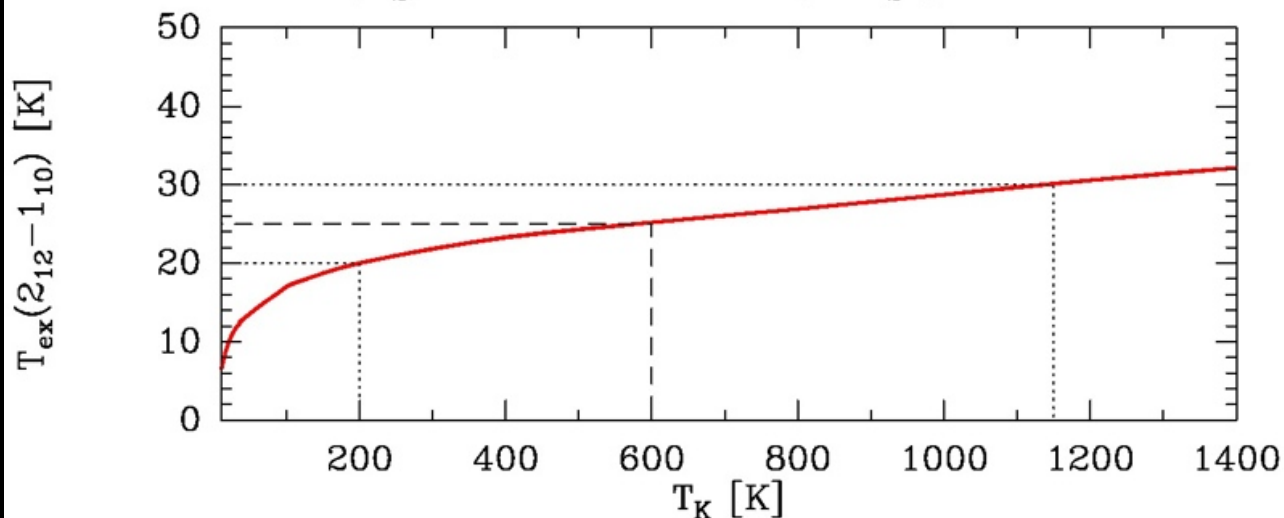
- H₂O emission
 - **different** from CO(2-1)
 - **similar** to H₂
- H₂O traces hot/warm gas

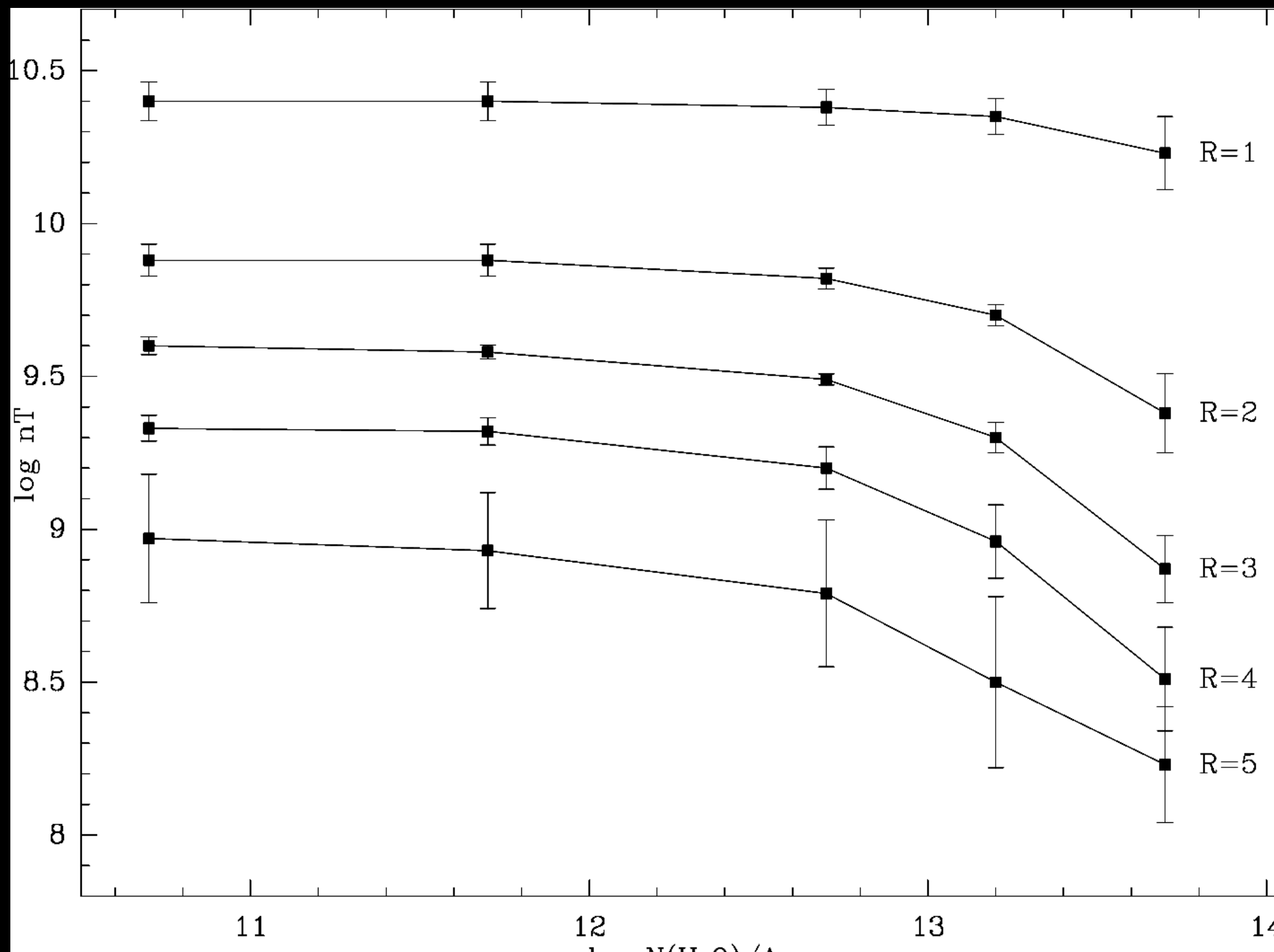
High pressure H₂O

HIFI (557GHz) & PACS (1670GHz) survey of 25 outflows



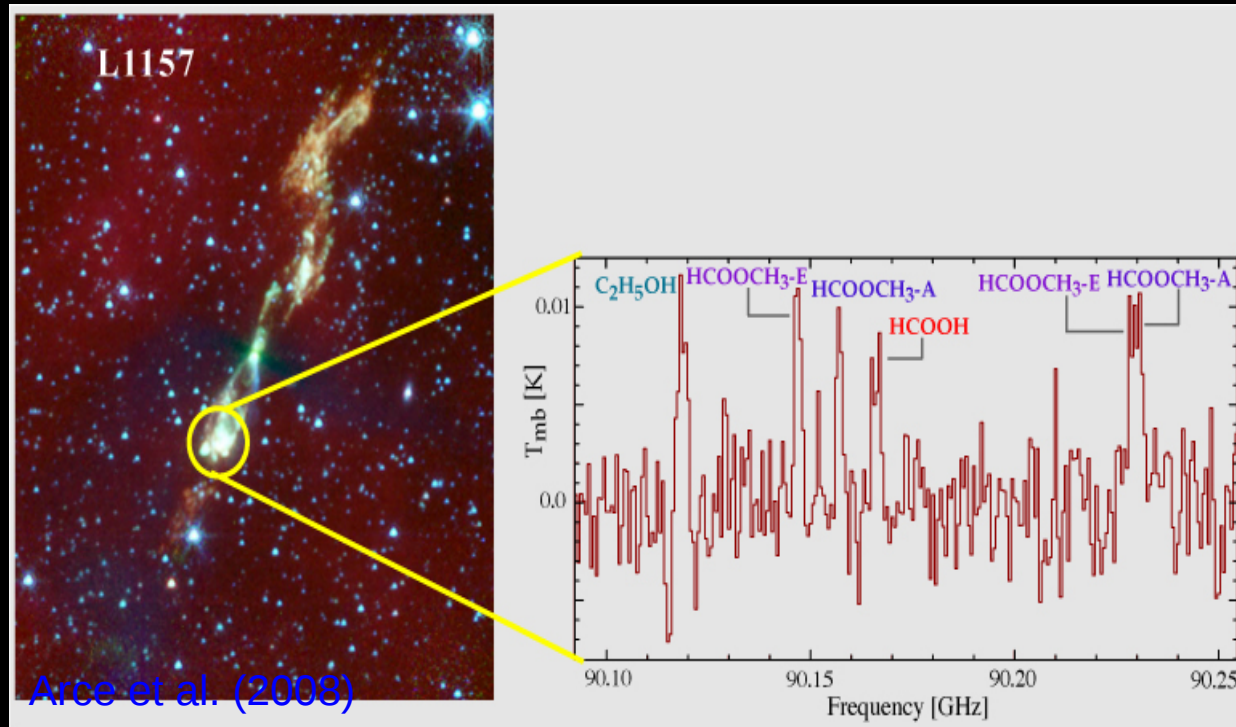
LVG: $n(\text{H}_2) = 5 \cdot 10^6 \text{ cm}^{-3}$ & $N(\text{o-H}_2\text{O}) = 10^{14} \text{ cm}^{-2}$





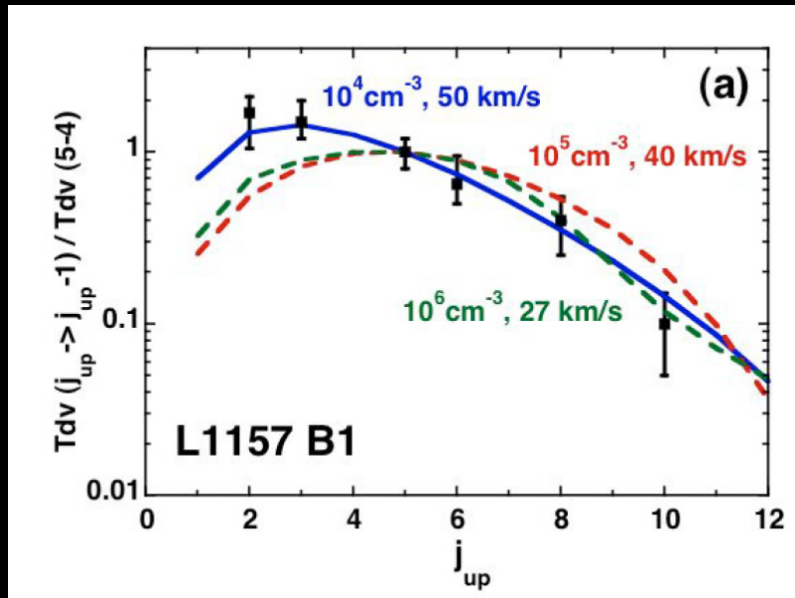
Complex organic molecules

L1157-B1



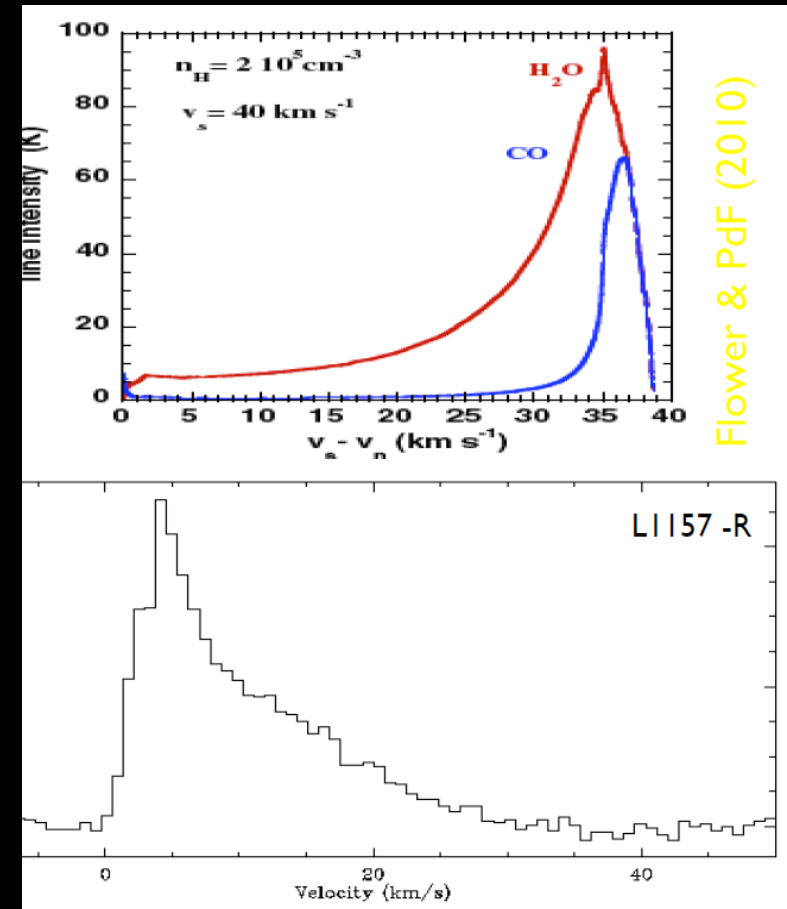
- Methyl formate, ethanol, formic acid in L1157-B1
- Imply **processing** of dust mantles
- Previously only detected in **hot cores/corinos**
- Lower ratio wrt to CH_3OH (Sugimura et al. 2011)

The “problem” with chemical models



Gusdorf et al. (2008)

- Plane parallel single velocity shock **models**
 - explain **abundance** enhancements
 - fit **integrated intensities**



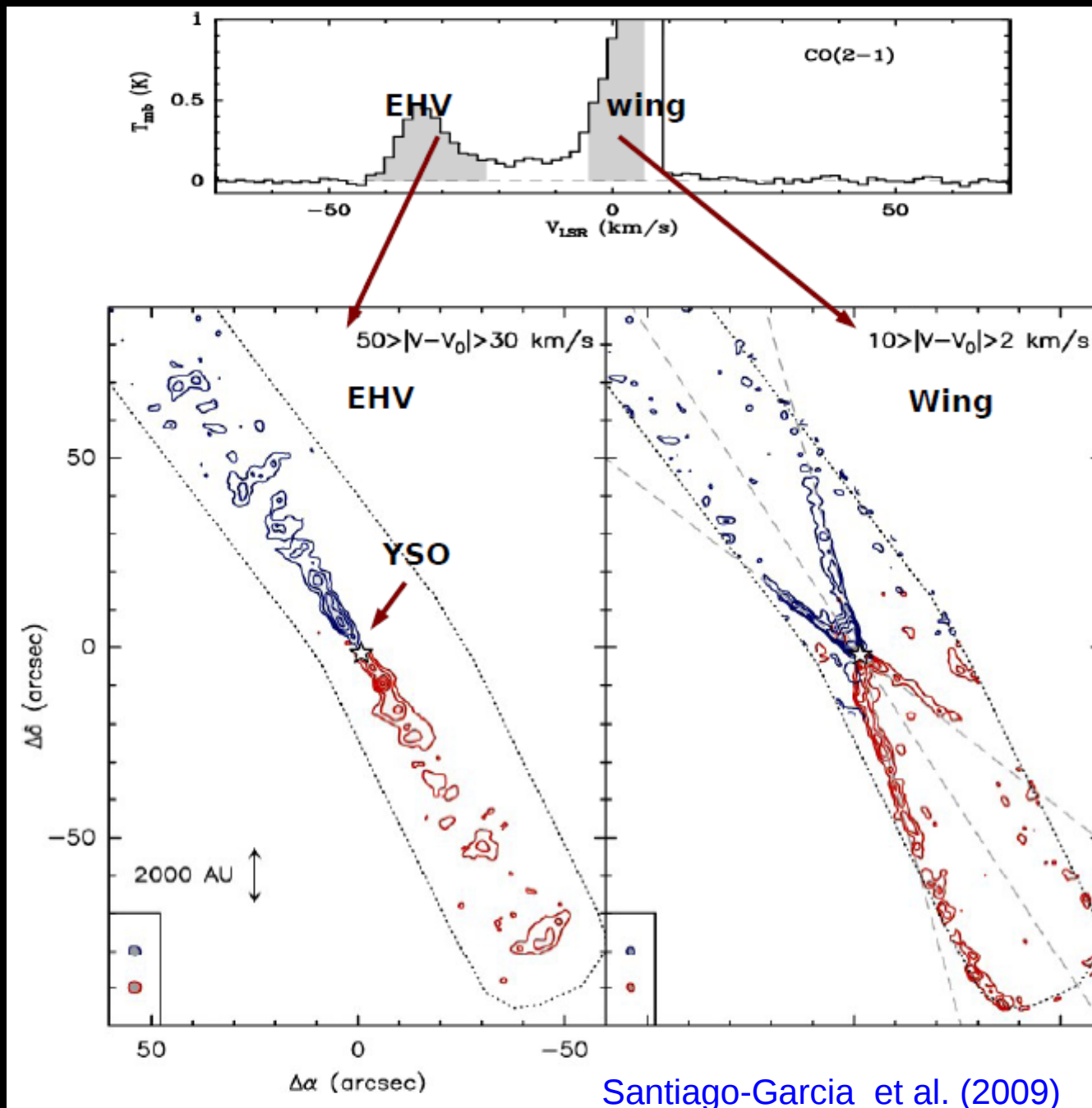
- Wrong **line profile**
 - no wing: spike at v_s
- Optical depth **overestimated** ($\sim \times 10$)

Why do outflows have “wings”?

- Molecular spectra characterized by “wing”
 - Most emission is at the lowest velocities
- Plane parallel shocks produce “spikes”
 - Post-shock gas piles up at v_s
 - Slower gas most recently shocked
- Bow shocks can mix velocities
 - But requires a bow shock at each position
- What is the kinematic history of outflow gas?

**Outflow chemistry
vs
jet chemistry**

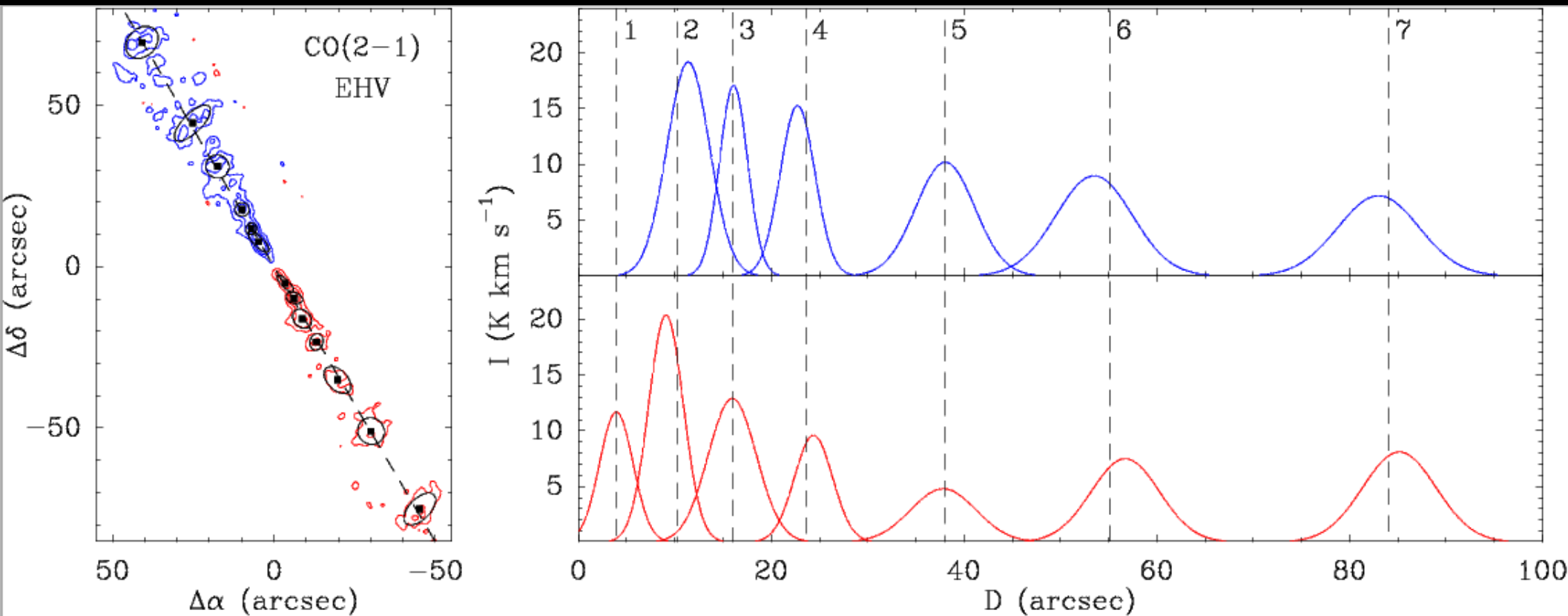
Extremely High Velocity component



Santiago-Garcia et al. (2009)

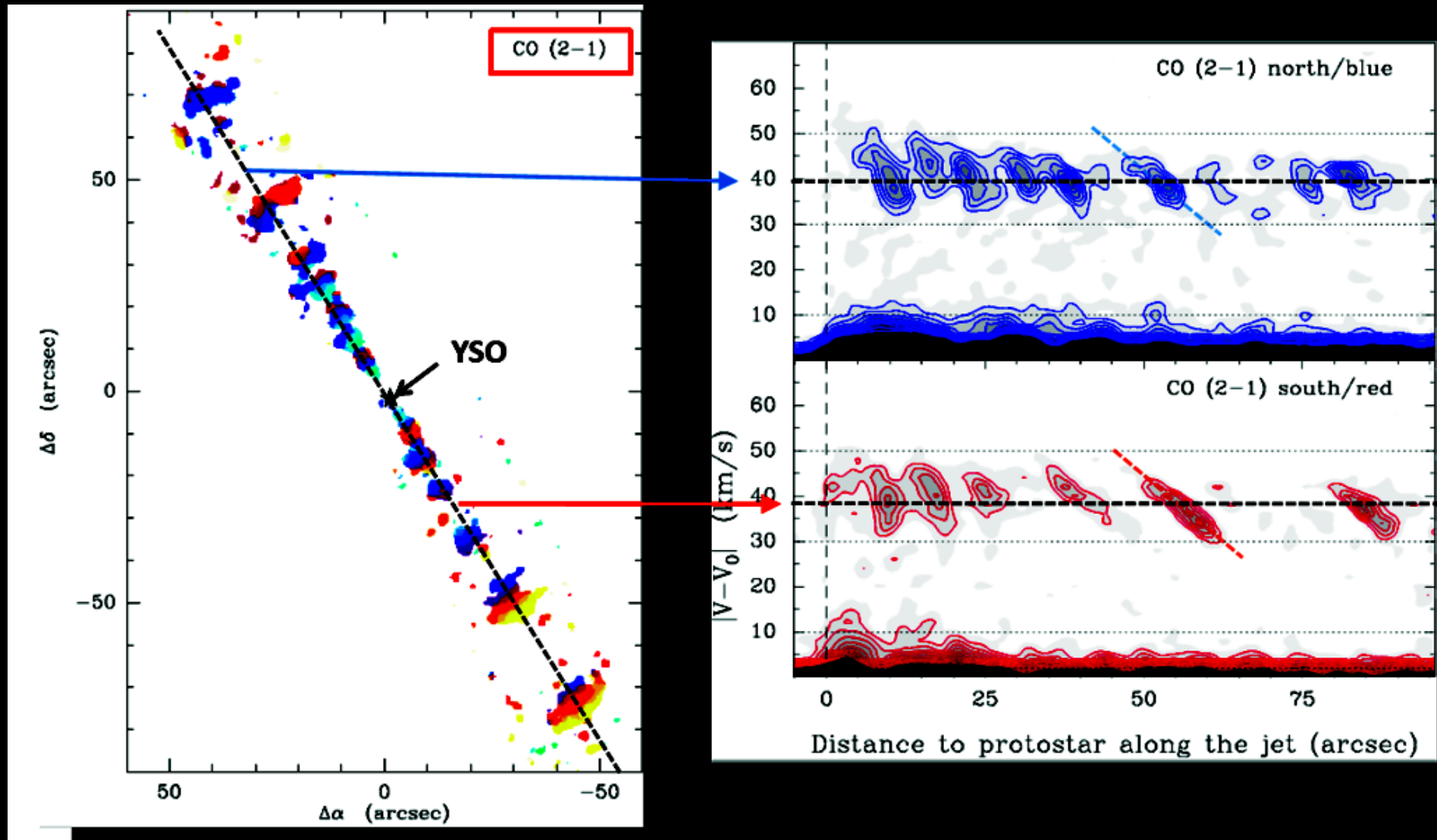
- **IRAS 04166+2706**
 - Taurus
 - class 0
 - 0.4 $L_{\odot}$
- **Wing**
 - ambient
 - accelerated
- **EHV**
 - jet
 - clumpy

Point symmetry: YSO origin



- EHV peaks are **symmetric** wrt to YSO
 - **location**, intensity, and width
- Too far apart and moving too fast to communicate
 - symmetry originates at **launching point**

Saw-tooth velocity pattern

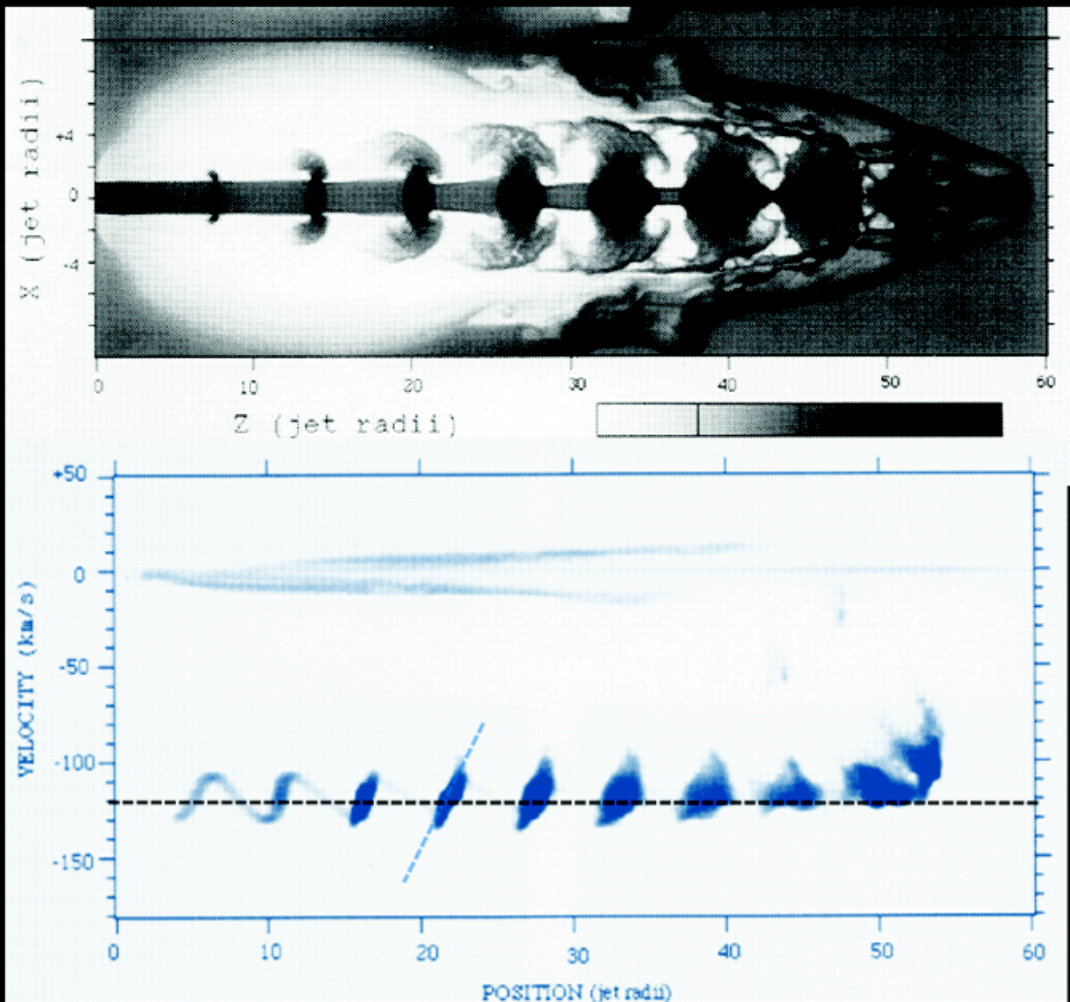


- EHV gas: constant mean 40 km/s + sawtooth
 - Each EHV peak: fastest gas lies upstream

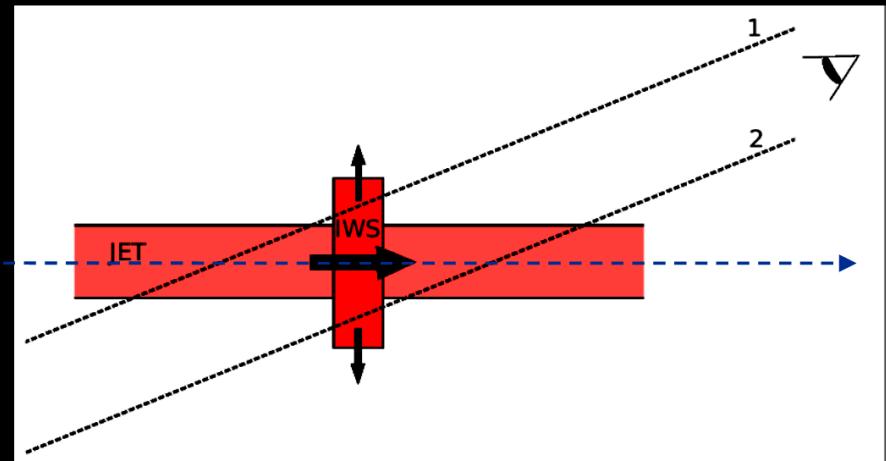
Internal working surfaces

Stone & Norman, (1993)

- Numerical **simulation** of pulsating jet
 - **Saw-tooth** velocity pattern

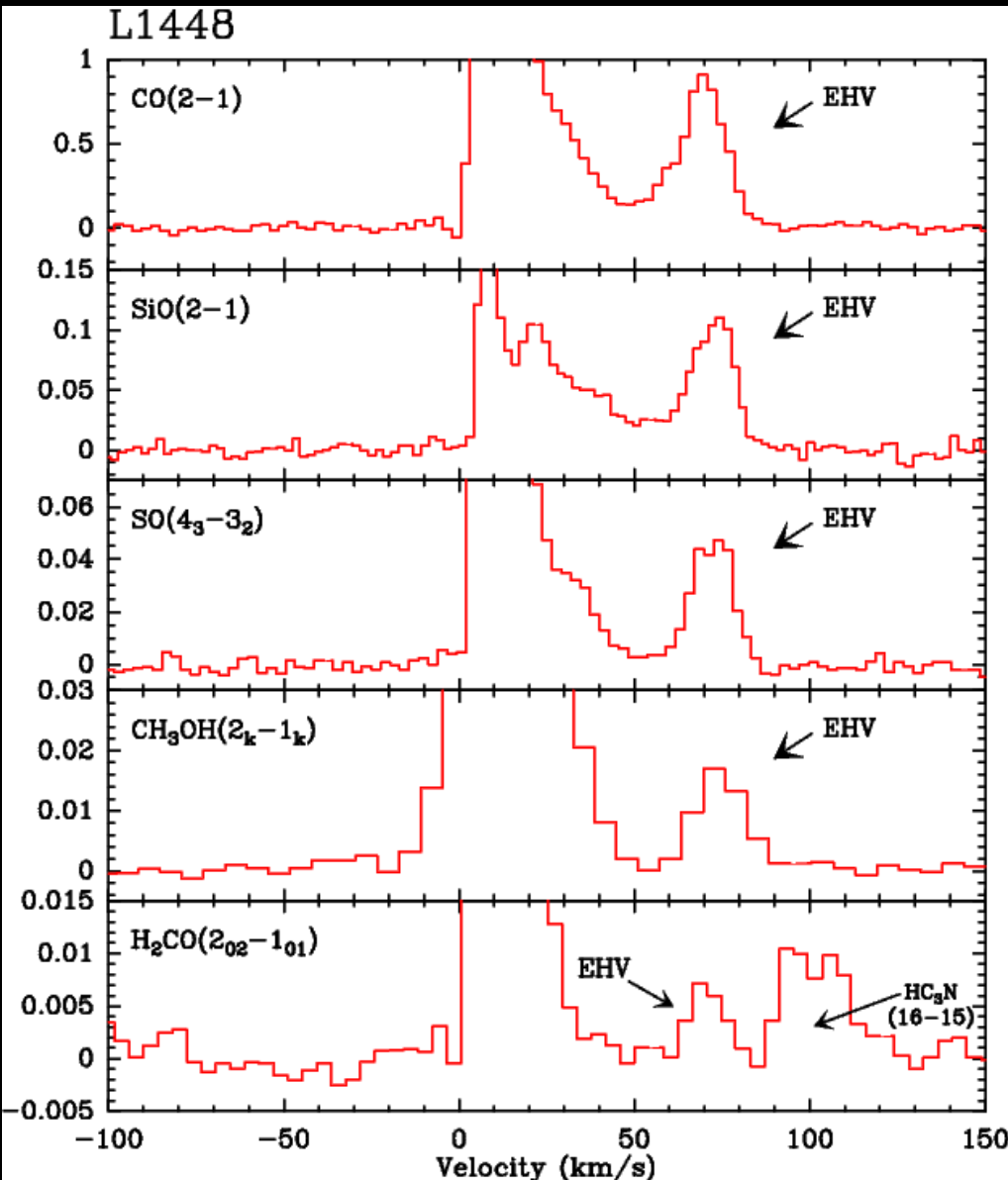


- Projection of **lateral expansion** with jet velocity



Chemical composition of EHV gas

- Is **jet composition** like “outflow” (shocked ambient) gas composition?
 - chemistry reflects **thermal history** of gas
 - clues on jet launching mechanism
- First survey of EHV gas
 - L1448 & IRAS 04166
 - CO, SiO, **SO**, **CH₃OH**, **H₂CO**
 - Large range of intensities



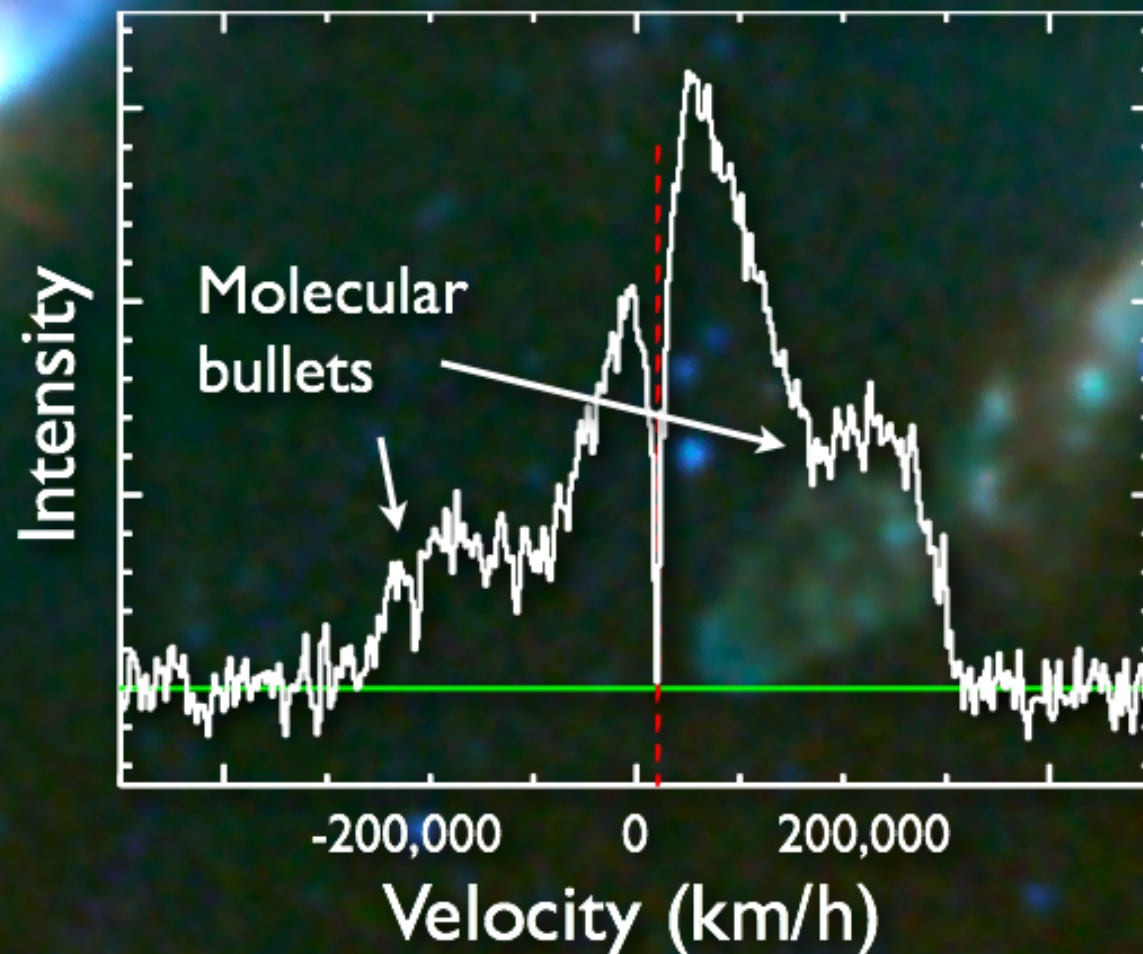
Tafalla et al. (2010)

H₂O in EHV gas with Herschel

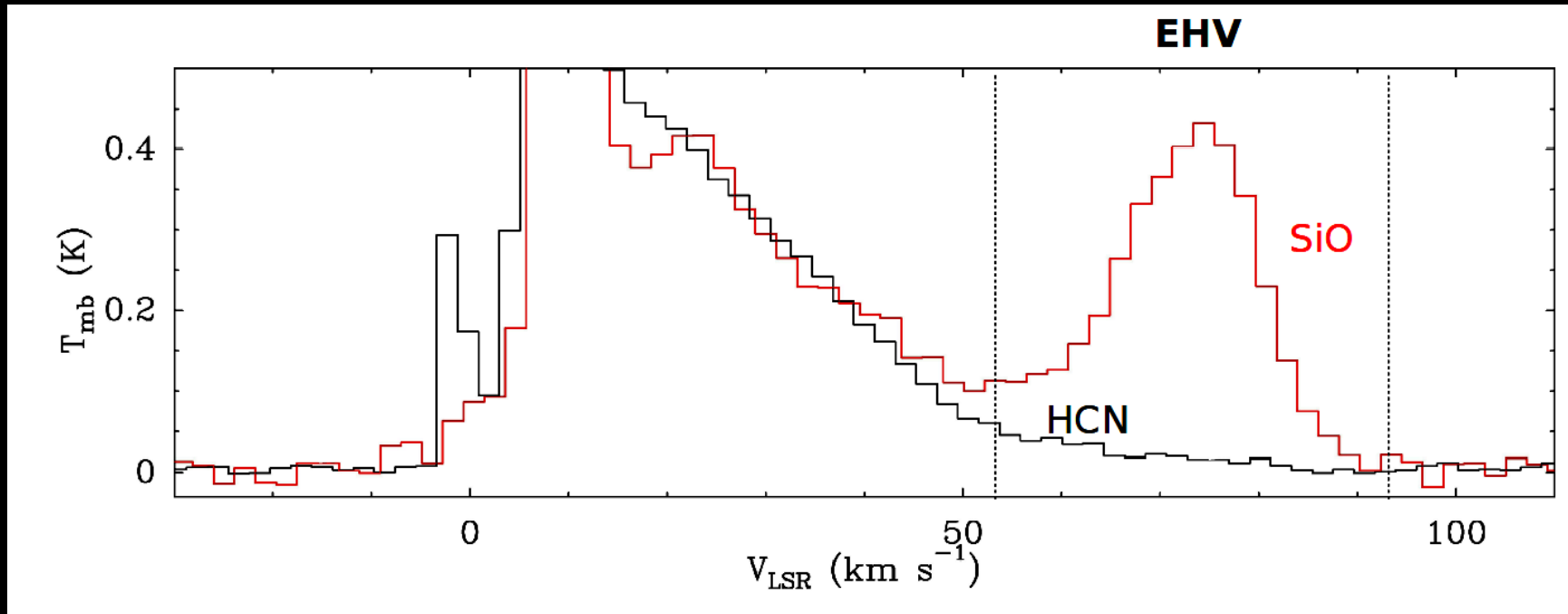
LI448-MM



H₂O I₁₀₋₁₀₁ (557 GHz)



EHV gas is oxygen-rich



Tafalla et al. (2010)

- All detected species in EHV gas are **oxygen-bearing**
- C-bearing molecules are significantly depleted
 - **HCN/SiO** ratio drops by 20 between wing and EHV
- **Atomic protostellar wind** (Glassgold et al. 1991)
 - C locked in CO
 - How do you produce CH₃OH? (needs grains)
- **Disk wind** (Panoglou et al. 2012)
 - No SiO production. Unclear C/O ratio

Conclusions

- **Chemical activity** is signature of **outflow youth**
- Boom in **molecular tracers** of outflow gas
 - chemical and thermal complexity
- Outflow **wing** composition: **shocked ambient gas**
 - **problems:** need for global models of chemistry plus better velocity structure
- New chemistry of **EHV gas** component
 - **differences** with wing chemistry
 - need for **jet/wind models**