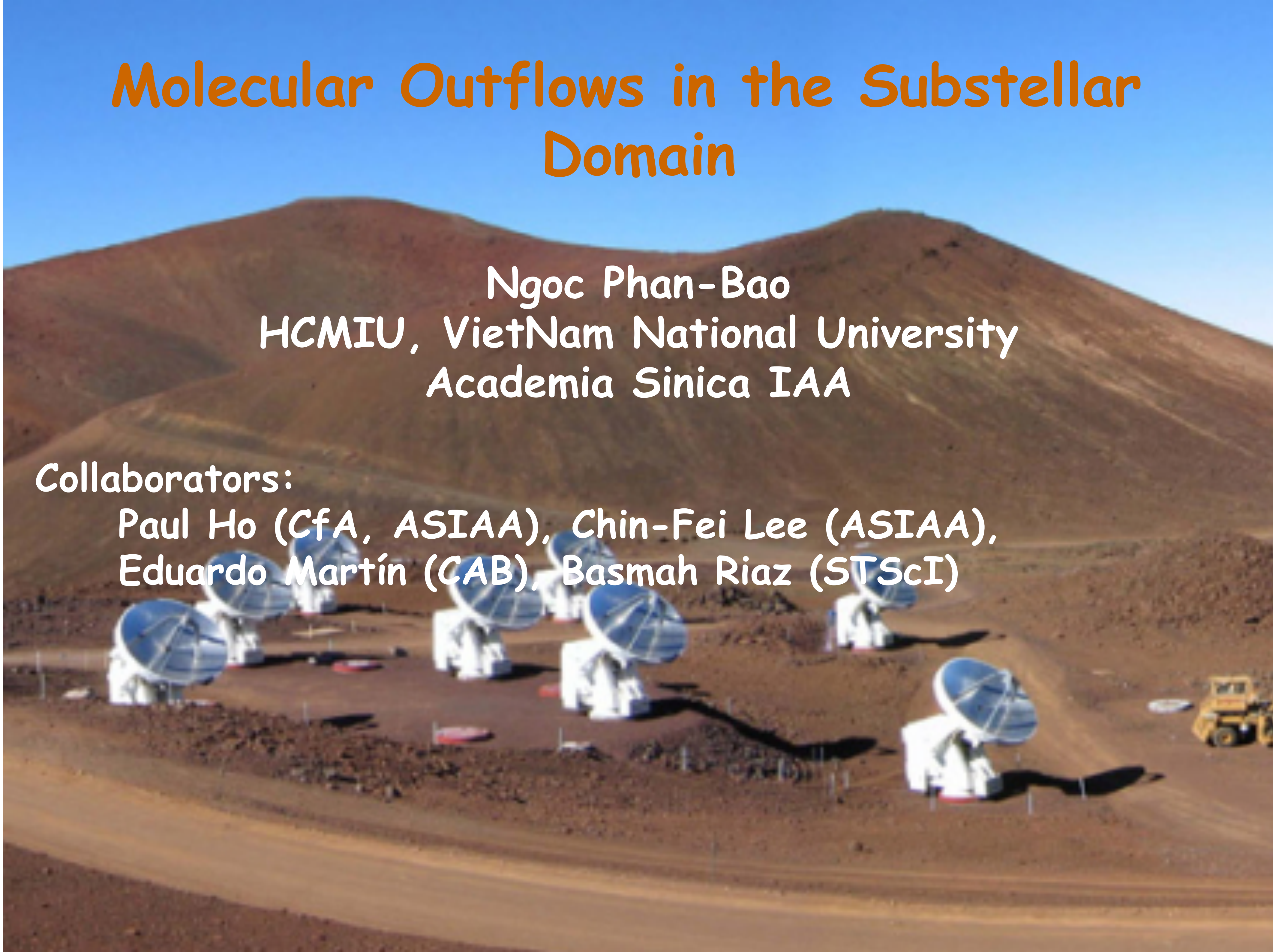

# Molecular Outflows in the Substellar Domain

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# Outline

- Motivation
- SMA and CARMA arrays.
- $^{12}CO$ $J=2 \rightarrow 1$ observations of young brown dwarfs in rho Ophiuchus and Taurus.
- Observations of proto-brown dwarfs with ALMA.

# Motivation

Molecular outflows provide a key piece of information on the earliest phase of brown dwarf formation: outflow morphology and properties (velocity, scale, mass, mass loss rate), *giving* some constraints on:

- star formation in the substellar domain
- the origin of brown dwarfs

# Submilimeter Array and Combined Array for Research in Millimeter-Wave Astronomy

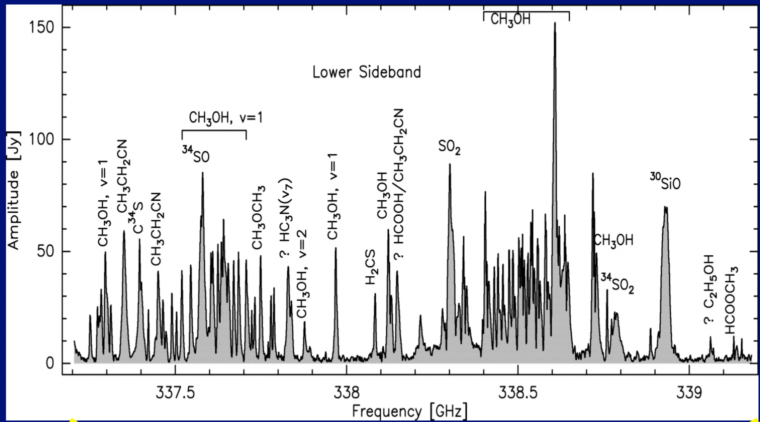
**SMA** (Ho, Morran & Lo 2004)

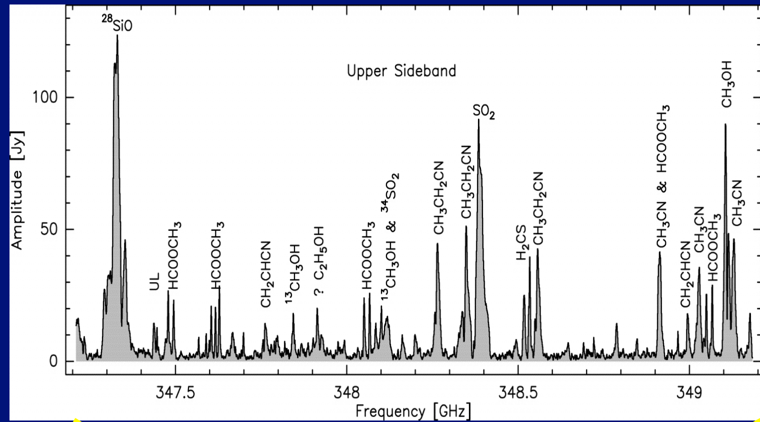
- A joi
- Eight

- 4 receiver bands: 230, 345, 400 and 690 GHz
- Bandwidth: 2 GHz and 4 GHz
- Configurations: subcompact, compact, extended, very extended
- Angular resolutions: 5"-0.1" (at 345 GHz)

# SMA Correlator

Orion KL, Beuther et al. 2005



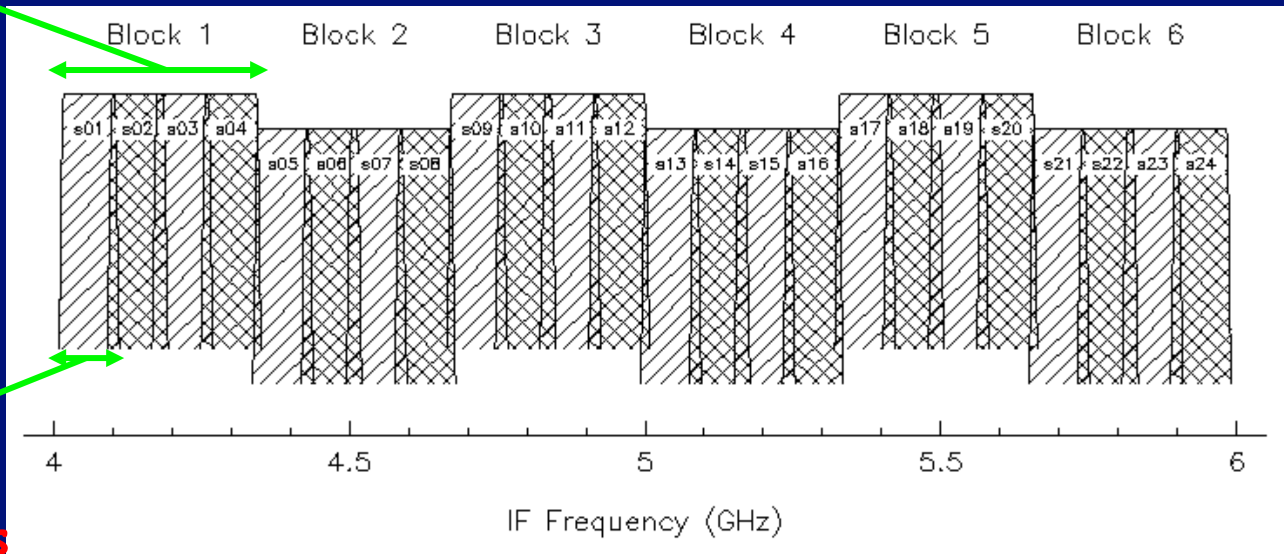




2 GHz

10 GHz

2 GHz

328 MHz




chunk: 104 MHz

32-4096 channels

2.8-0.02 km/s

1.968 GHz

# CARMA

- A university-based millimeter array at Cedar Flat (US)
- six 10.4-meter, nine 6.1-meter, and eight 3.5-meter antennas

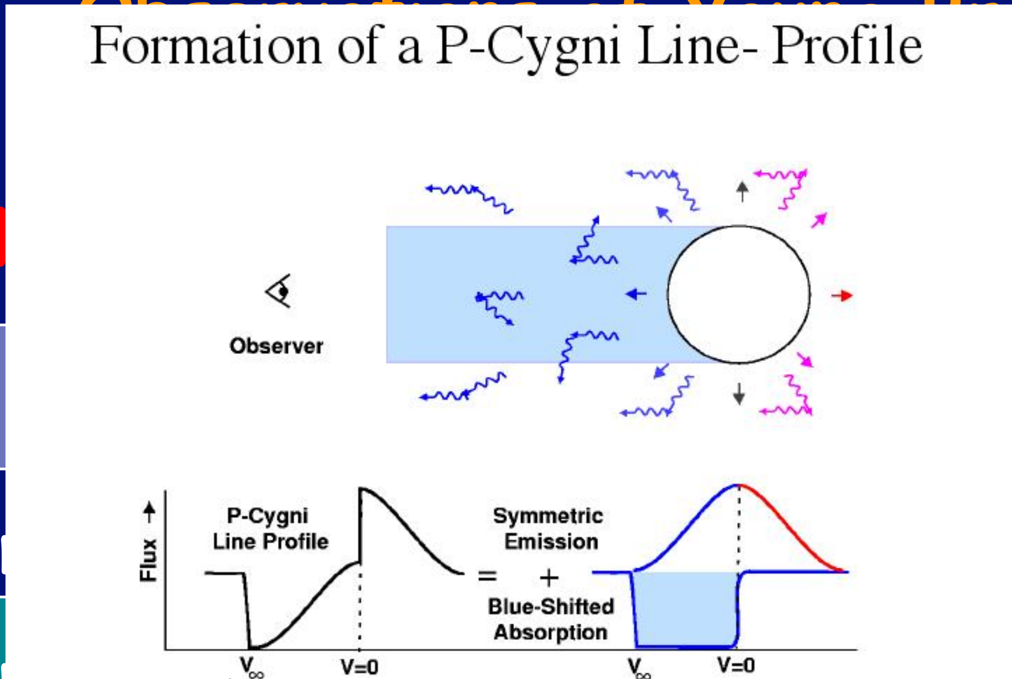

- 3 receivers: 27-35 GHz (1 cm), 85-116 GHz (3 mm) and 215-270 GHz (1 mm); 8 bands available.
- Configurations: A, B, C, D, E
- Angular resolutions: 0.3", 0.8", 2", 5", or 10" at 100 GHz

| Bandwidth (MHz) | Channels (per sideband) | Chan. width (MHz) | dV [1mm] (km/s) |
|---|---|---|---|
| 500 | 96 | 5.21 | 5.2 |
| 250 | 191 | 1.31 | 1.3 |
| 125 | 319 | 0.392 | 0.39 |
| 62 | 383 | 0.161 | 0.16 |
| 31 | 383 | 0.081 | 0.081 |
| 8 | 383 | 0.021 | 0.021 |
| [illegible] | [illegible] | [illegible] | [illegible] |

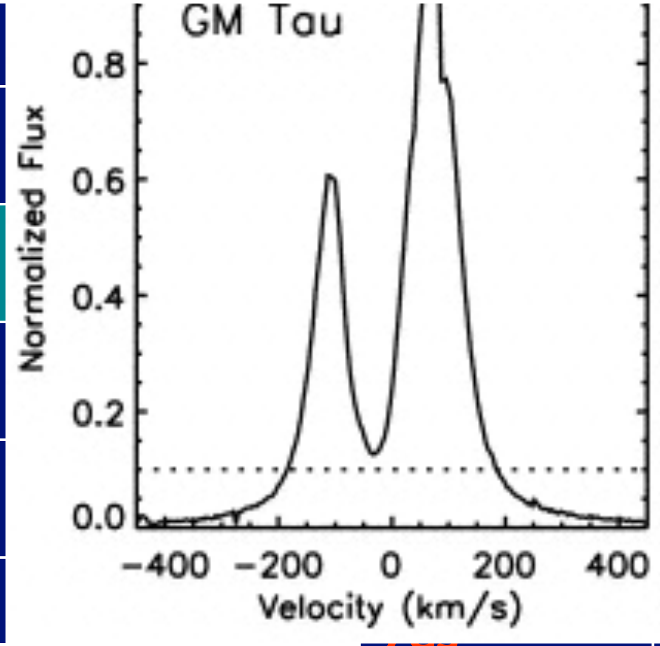
# ...own Dwarfs
# ...aurus

**Sampl...** ...rus: 140 pc, <1-3 Myr

| Target | | | FELs? | P Cygni? | Array |
|---|---|---|---|---|---|
| ISO-O... | | | Yes | --- | SMA |
| ISO-O... | | | Yes | Yes | SMA |
| 2M 0441 | 35 | | --- | --- | CARMA |
| 2M 0439 | 50 | | --- | --- | CARMA |
| MHO 5 | 90 | | Yes | --- | SMA |
| 2M 0414 | 75 | | --- | Yes | CARMA |
| 2M 0438 | 70 | | Yes | --- | CARMA |
| GM Tau | 75 | | --- | Yes | SMA |



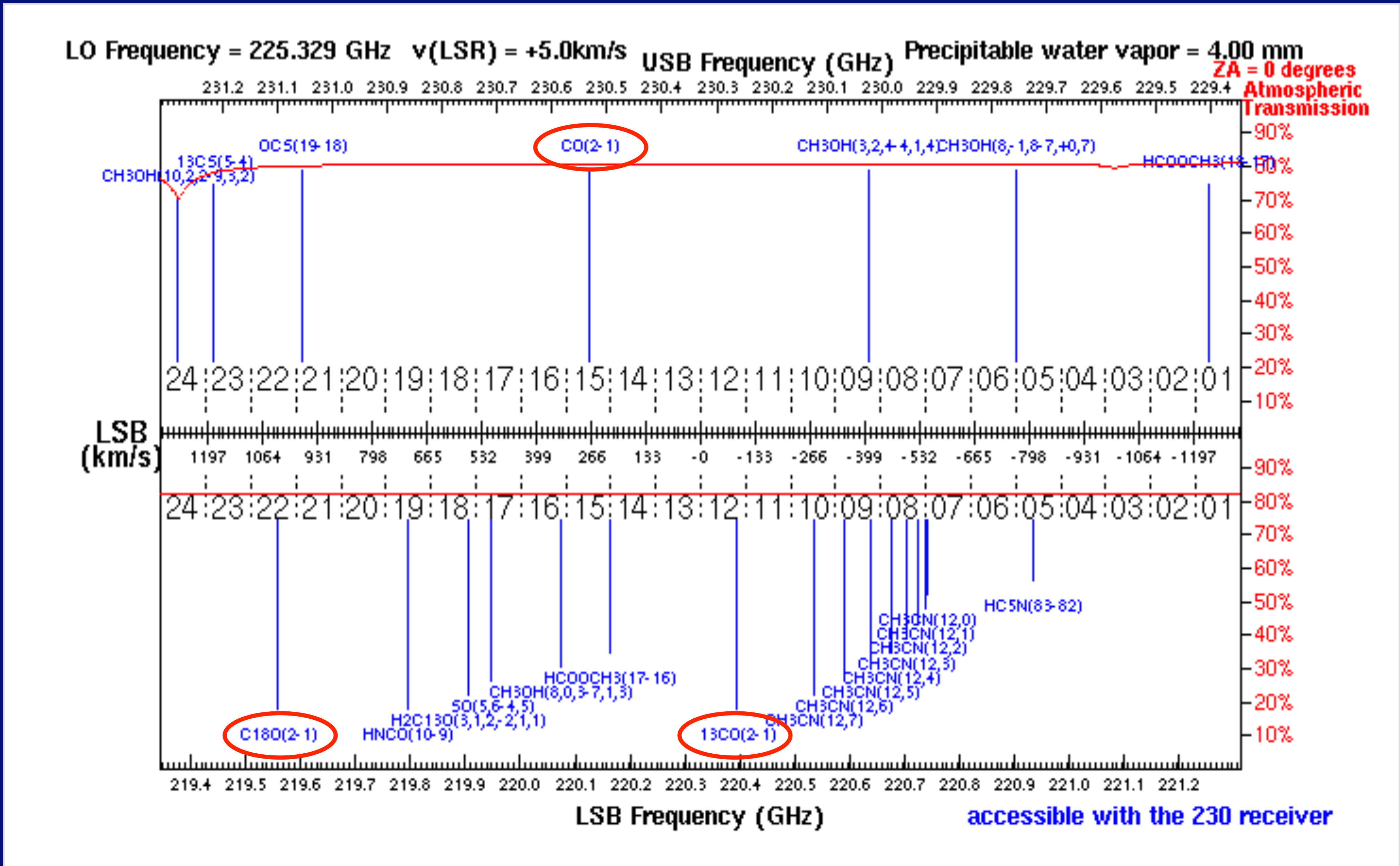
Stan Owocki



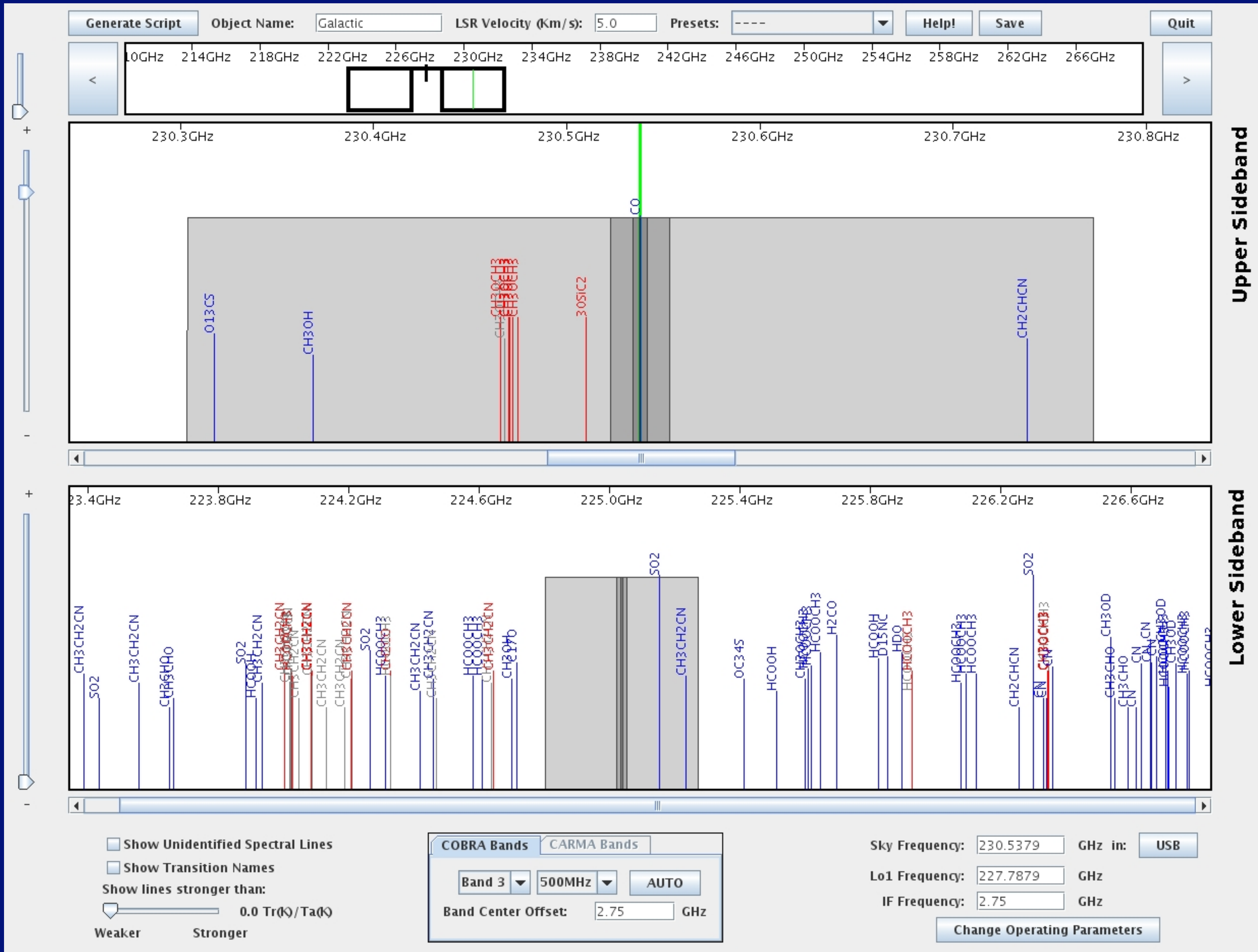
White & Basri

# $^{12}CO$ J=2→1 observations ($C^{18}O$ and $^{13}CO$ 2-1)

SMA: compact, synthesized beam of 3.6" x 2.5", 0.25 km/s

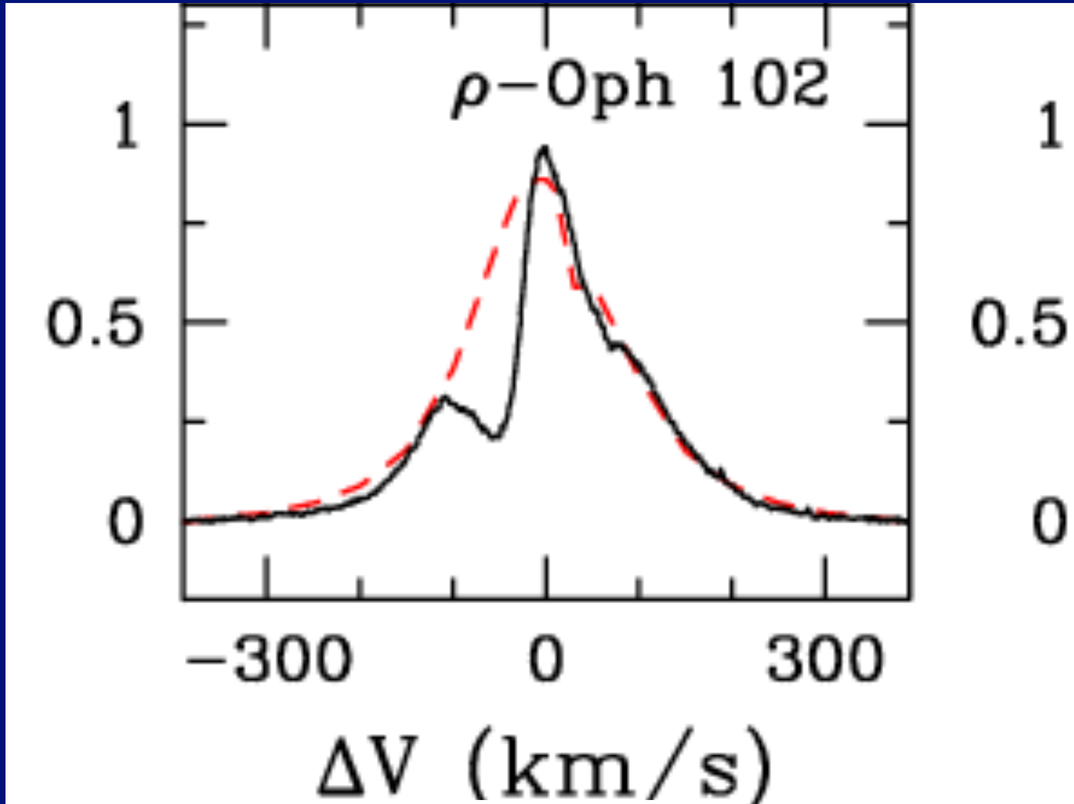


# CARMA: D configuration, 2.8" x 2.5 ", 0.18, 0.39, 0.74, and 1.3 km/s



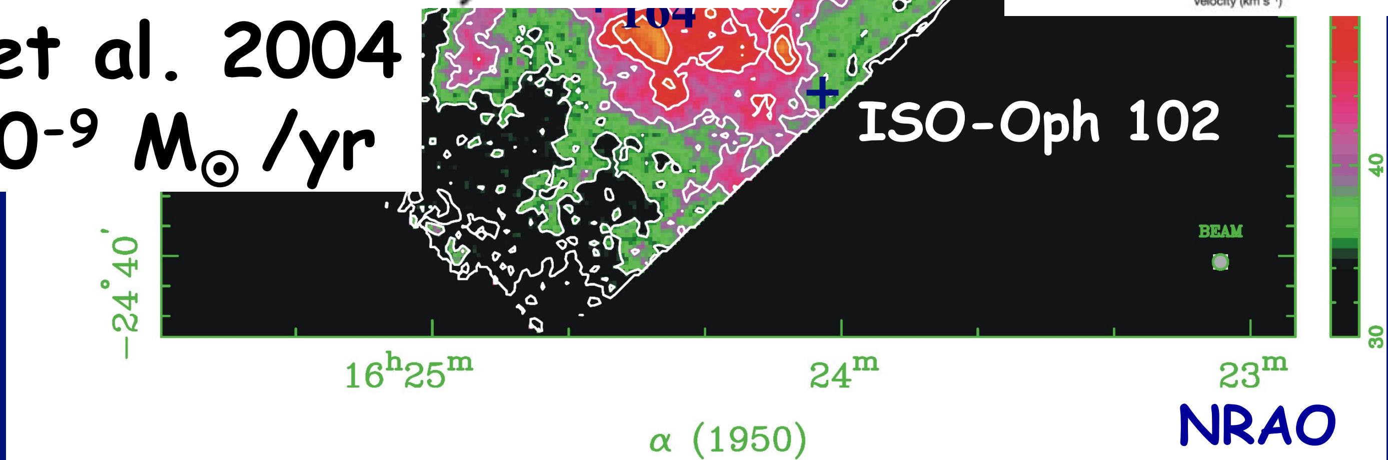
# ISO-Oph 102

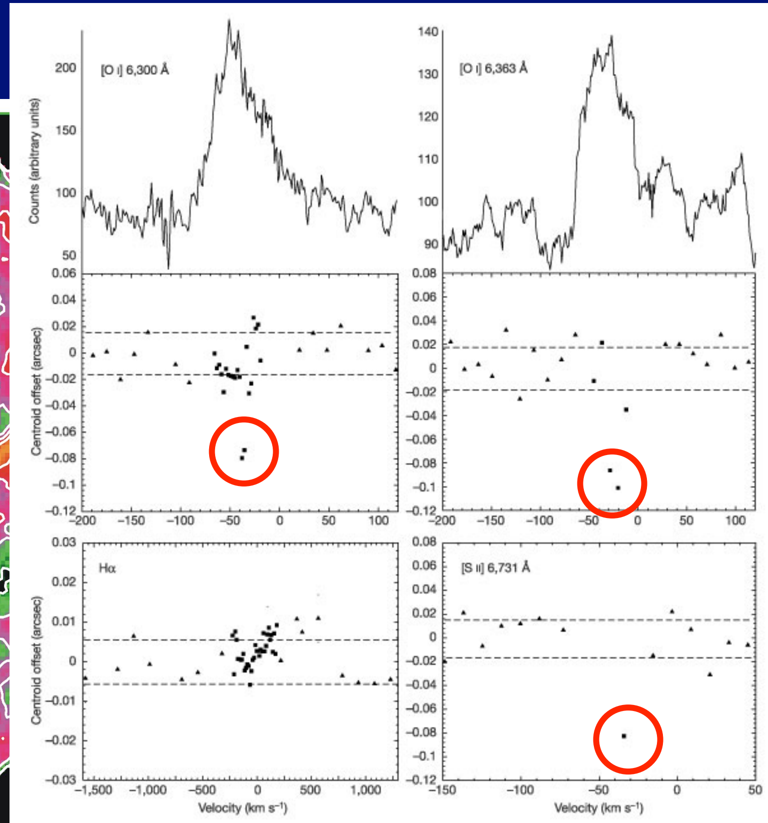
Whelan et al. 2005



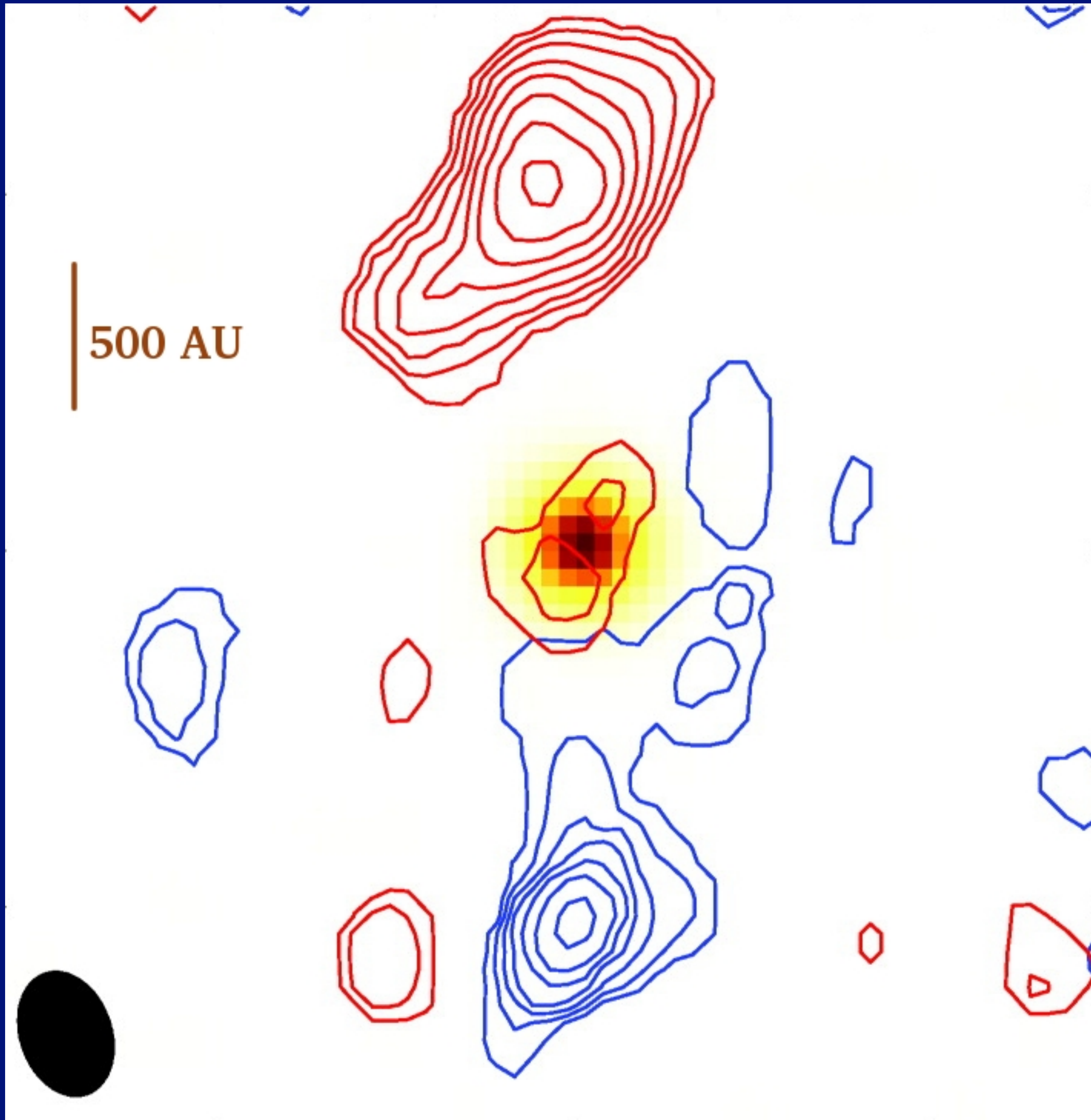

Natta et al. 2004

$\dot{M}_{acc}=10^{-9}\ M_\odot/yr$



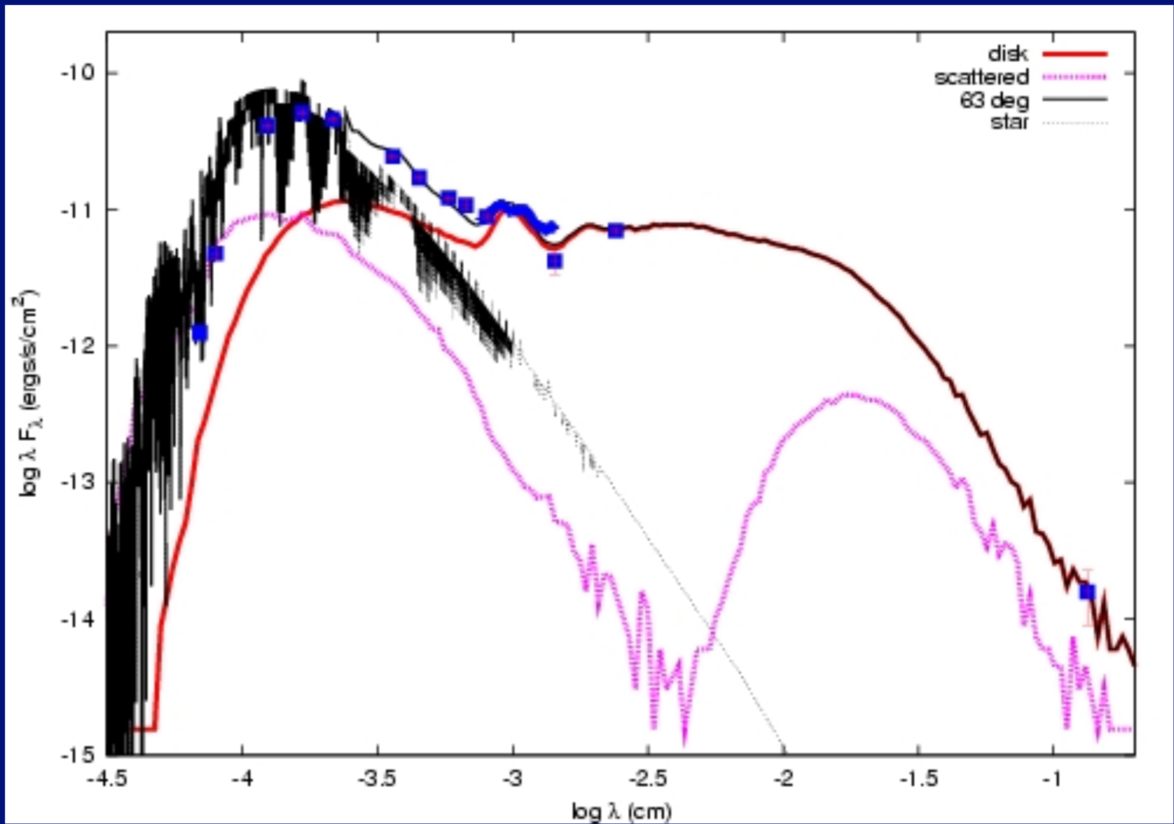
# CO J=2→1 MAP (230 GHz)




Phan-Bao et al. 2008

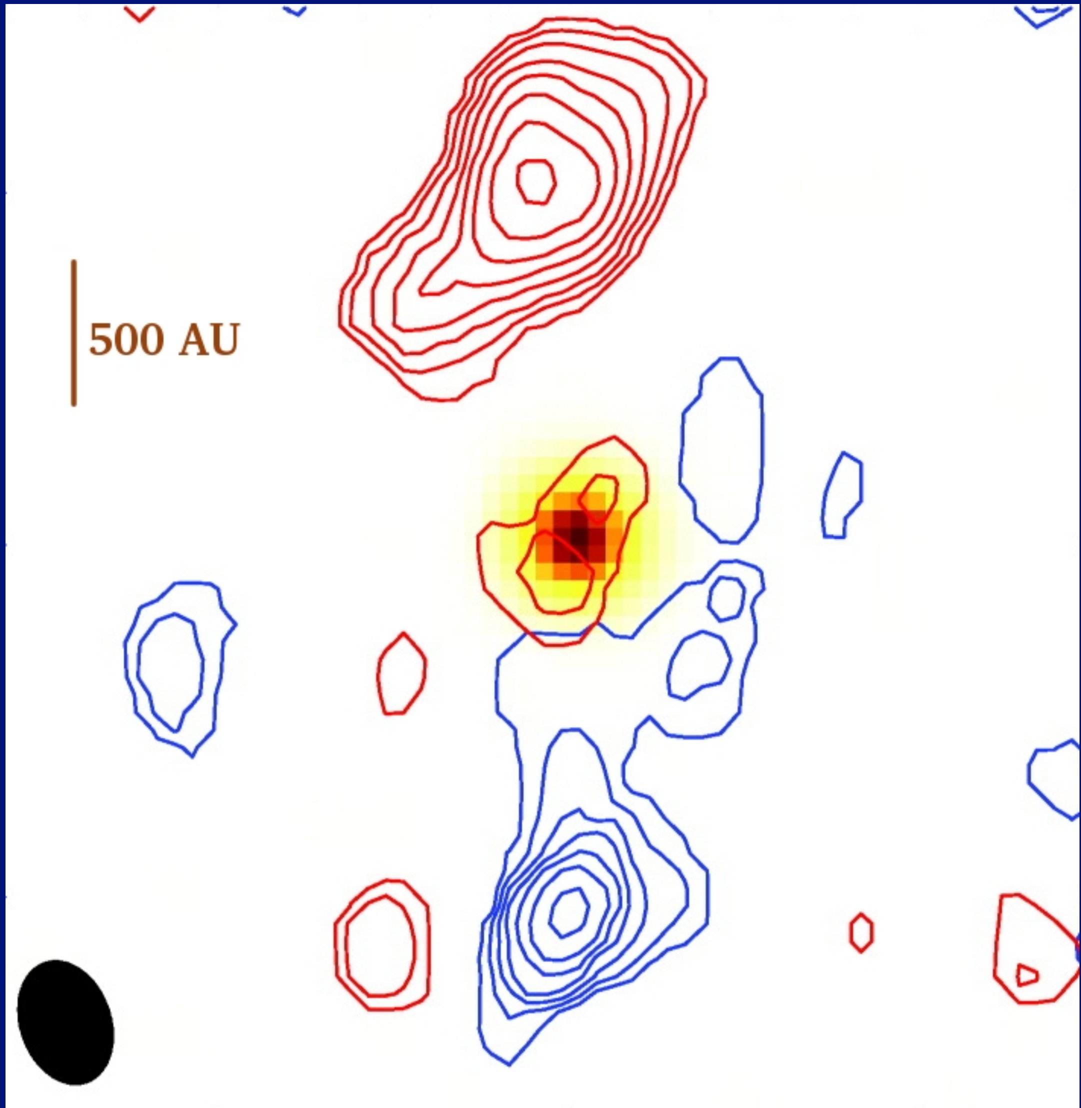
# Disk Parameters

## Spectral Energy Distribution




- Disk Mass:
  8 $M_J$
- Outer disk radius:
  80 AU
- Inclination:
  63°

# CO J=2→1 MAP (230 GHz)




- Outflow mass:
  $1.6 \times 10^{-4}\ M_{\odot}$
- Mass loss rate:
  $1.4 \times 10^{-9}\ M_{\odot}/yr$

→over 100 times smaller than the typical values for T Tauri stars!

Phan-Bao et al. 2008

This first detection provides molecular outflow properties to constrain modeling works on brown dwarf formation (e.g., Machida et al. 2009)

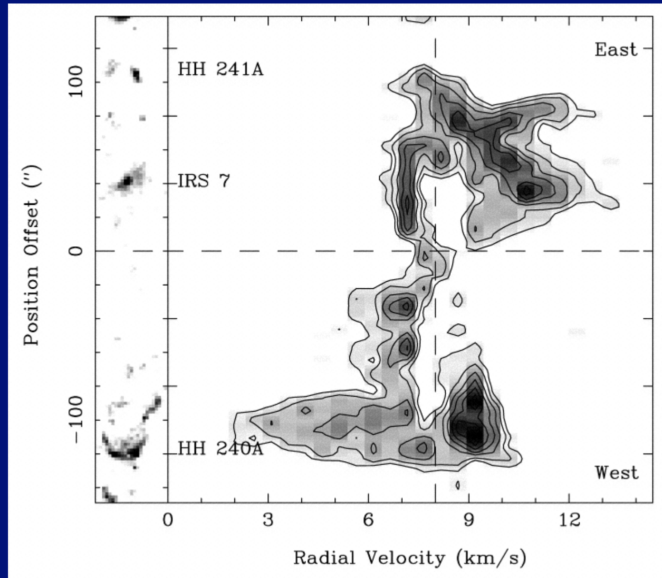
# Standard Models for Molecular Outflow Formation

- Jet-driven bow shock model

(e.g., Raga & Cabrit 1993) →

<u>Observation:</u>

Spur position-velocity structure

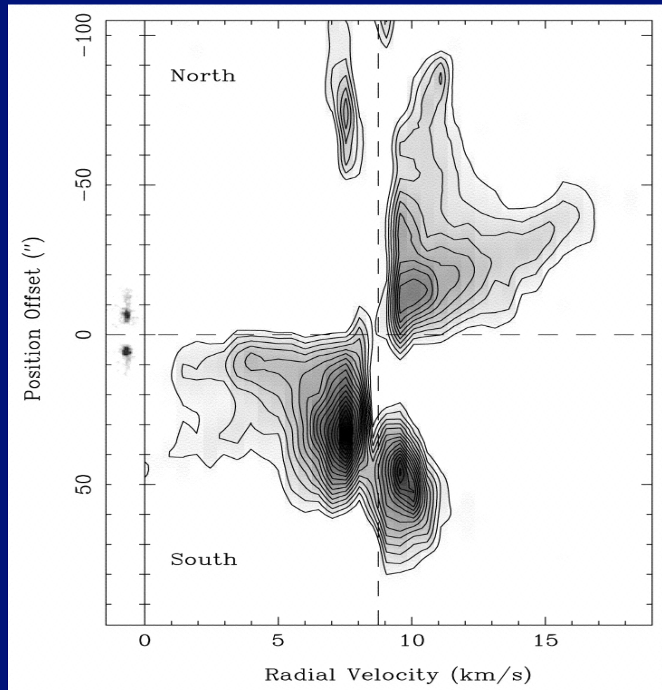



- Wind-driven-shell model

(e.g., Shu et al. 1991) →

<u>Observation:</u>

Parabolic position-velocity structure

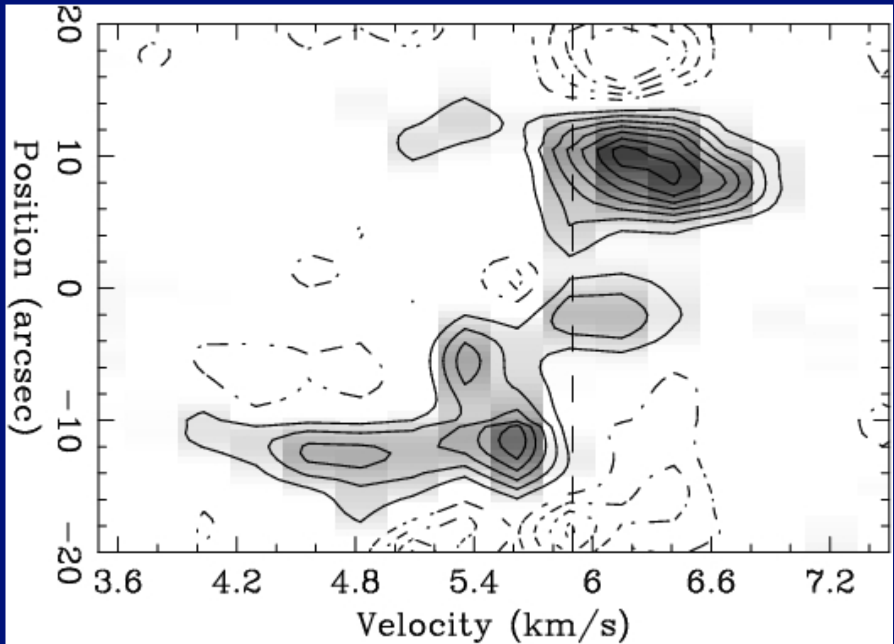


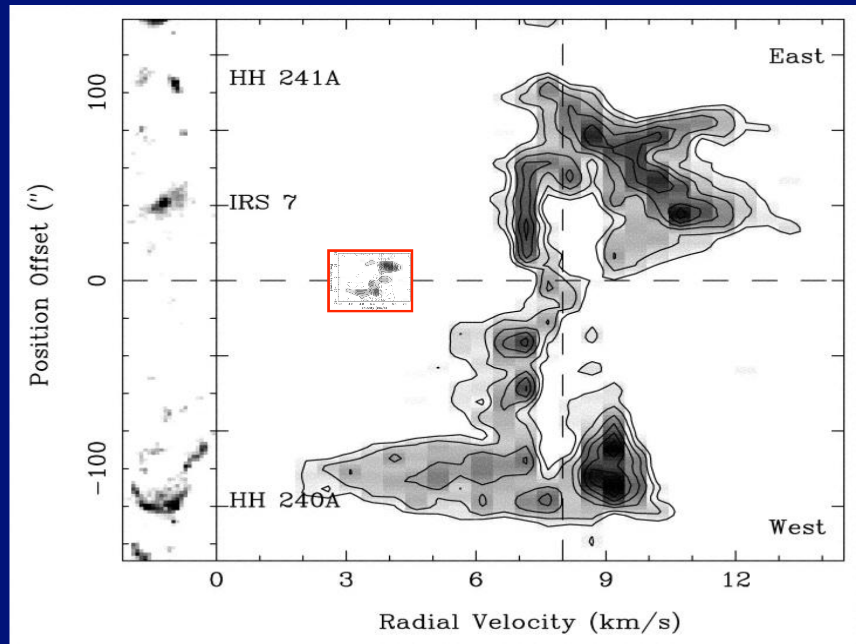

(Lee et al. 2000)

# Jet-Driven Bow-Shock Structure

## Position-Velocity Diagram

Lee et al. 2000

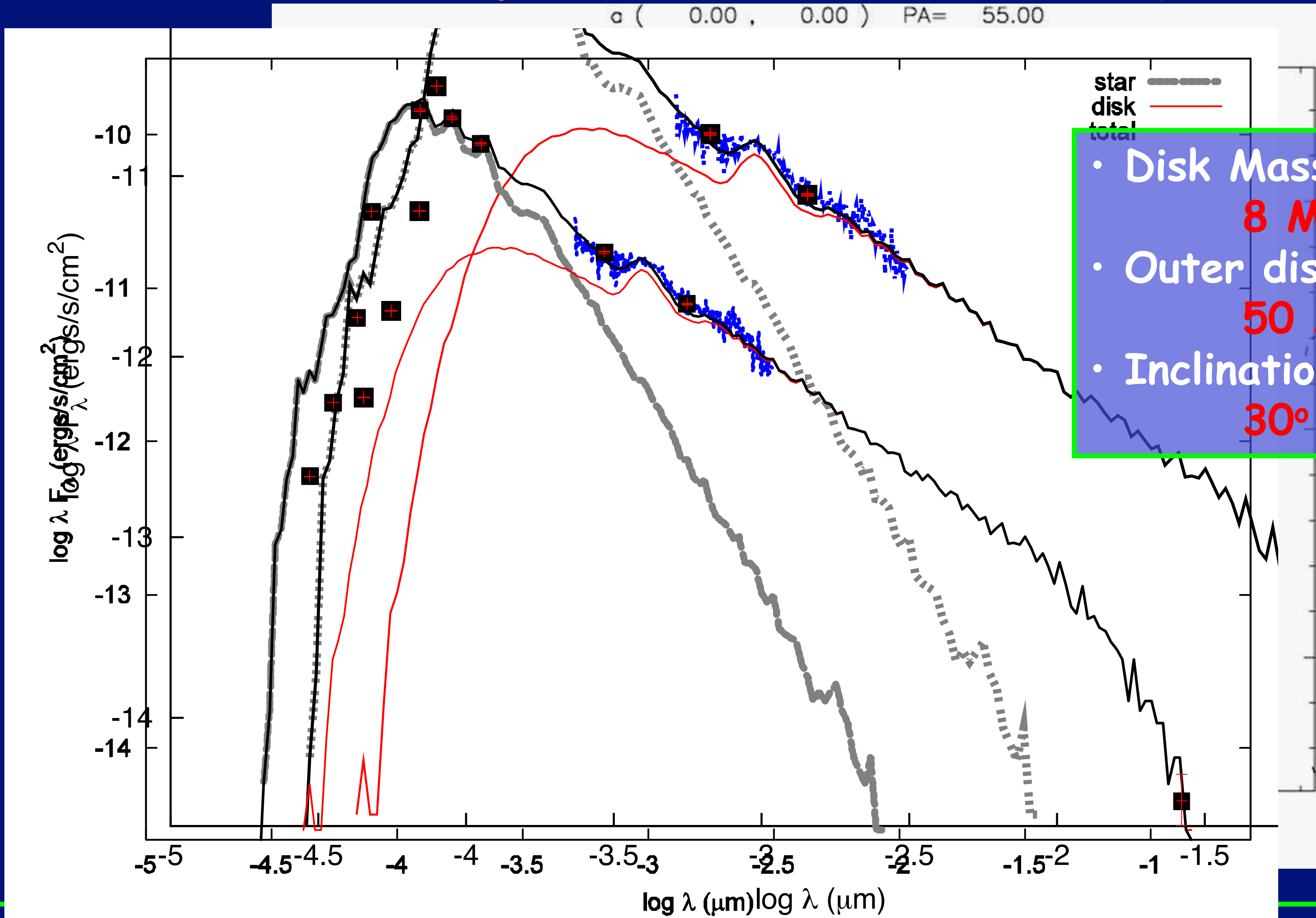



ISO-Oph 102 of 0.08 $L_{\odot}$ versus A more massive object of 17 $L_{\odot}$

Providing us an insight into the outflow morphology and the first case to test the star formation theory in the substellar domain.

# MHO 5 (90 $M_J$, $\dot{M}_{acc}=1.6\times10^{-11}$ $M_\odot$ /yr, Taurus)



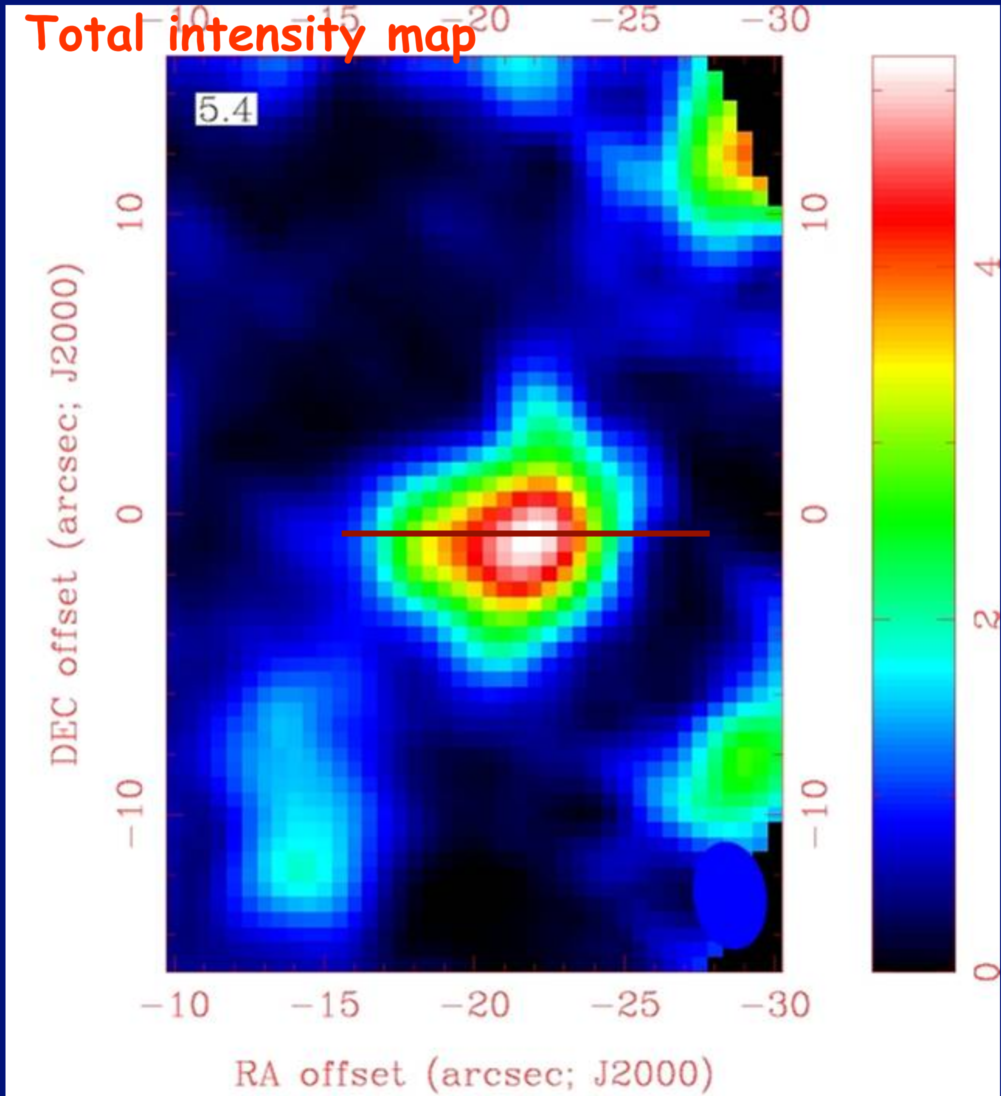

- Disk Mass:
  8 $M_J$
- Outer disk radius:
  50 AU
- Inclination:
  30°

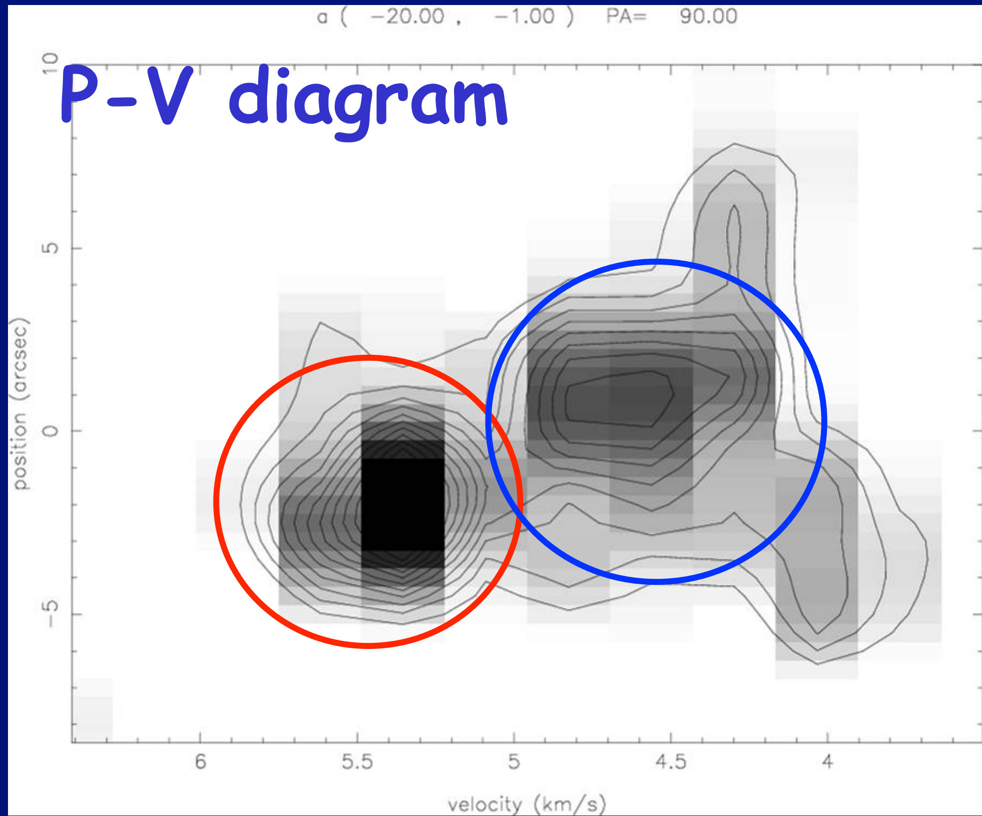
- Outflow mass:
  $6.5 \times 10^{-5}$ $M_\odot$
- Mass loss rate:
  $0.9 \times 10^{-9}$ $M_\odot$/yr

→ similar to ISO-Oph 102 (Phan-Bao et al., submitted)

# Observations of Proto-Brown Dwarfs

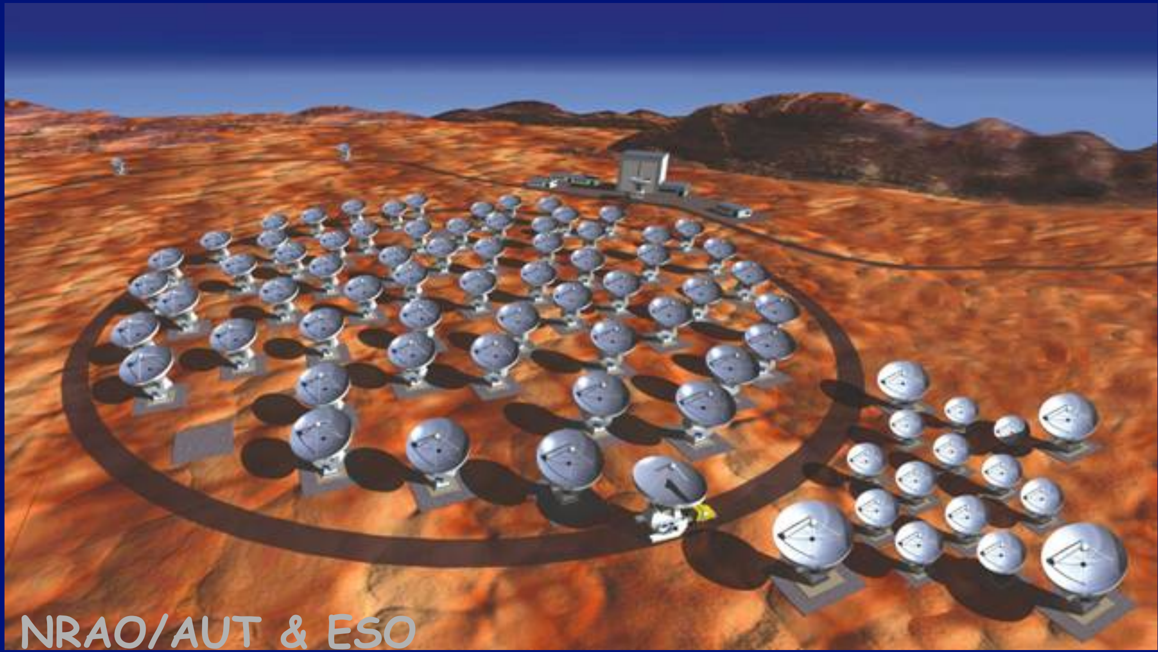
**Question:** Can we observe the formation of brown dwarfs (planetary mass objects) even at earlier phases?

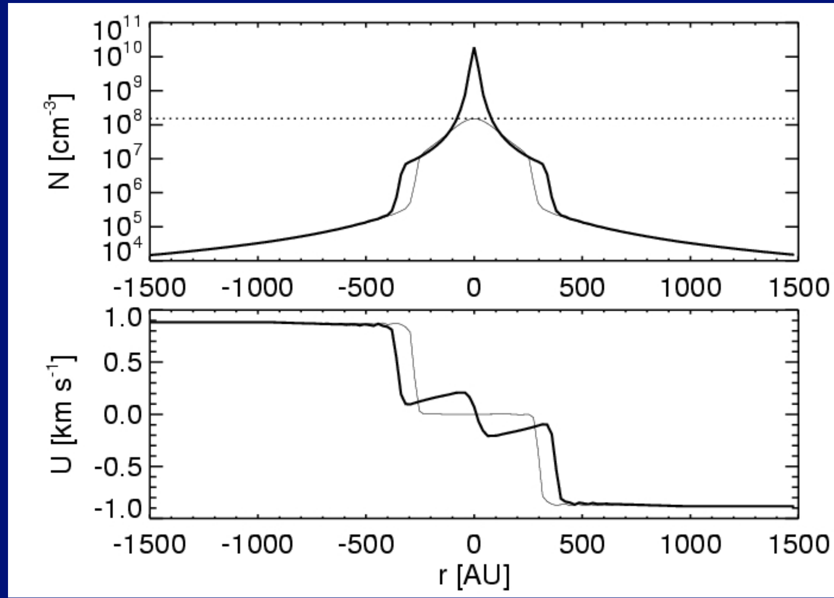



A proto-brown dwarf?

# ALMA




Whitworth et al. 2007

- ALMA is 10-100 times more sensitive and 10-100 times better angular resolution than the current mm/submm arrays.

To achieve the same continuum sensitivity, ALMA only needs 1 sec while SMA needs 8 hours.

→ An excellent instrument to search for proto-brown dwarfs /planetary mass objects class II, I, 0, BD-cores, and the BD disk structure.

# Summary

- Molecular outflow properties: compact and small-scale structures of ~200-500 AU; Low velocities: 1-3 km/s; Outflow mass: $10^{-4}$ $M_{\odot}$; Mass loss rate: $10^{-9}$ $M_{\odot}$/yr

➢ The molecular outflow in the substellar domain is a scaled-down version of that in low-mass stars.

➢ This suggests that very low mass stars and brown dwarfs form like low-mass stars in a version scaled down by a factor of over 100.

# SMA, CARMA, ALMA

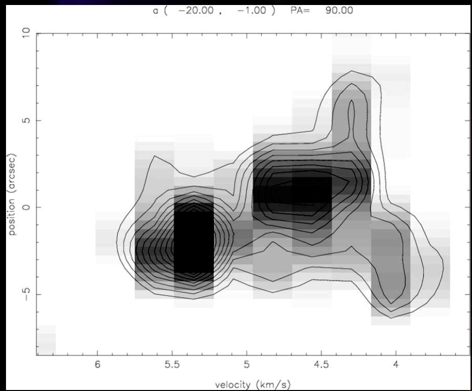
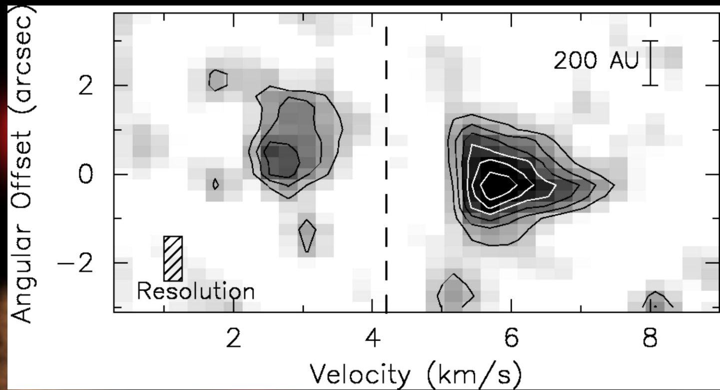
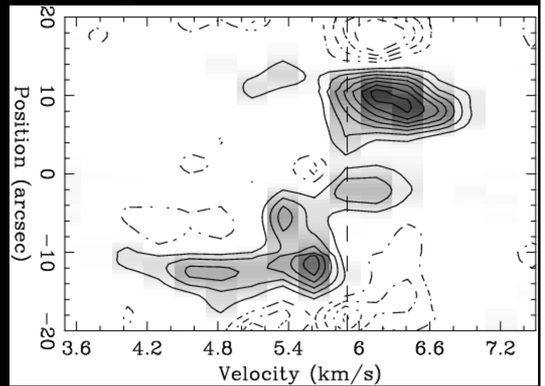
| Core | Class 0 (?) | Class I (?) | Class II BD |
|---|---|---|---|
| ? |  |  |  |
| | Phan-Bao et al., in prep. | Bourke et al. 2005 | Phan-Bao et al. 2008 |







Image Credit: ASIAA