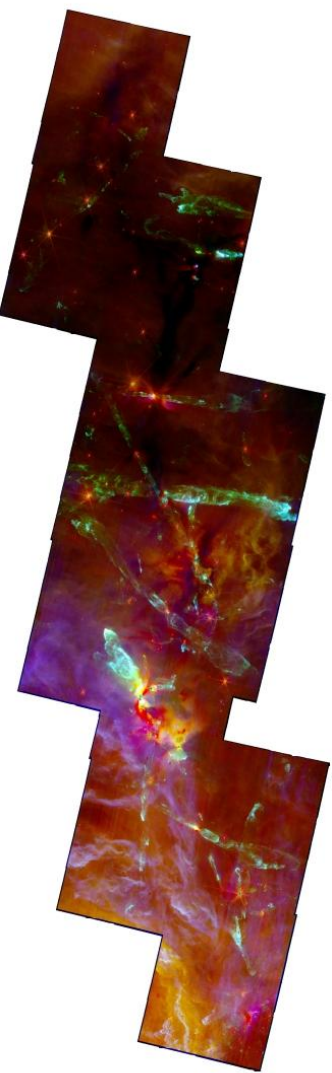


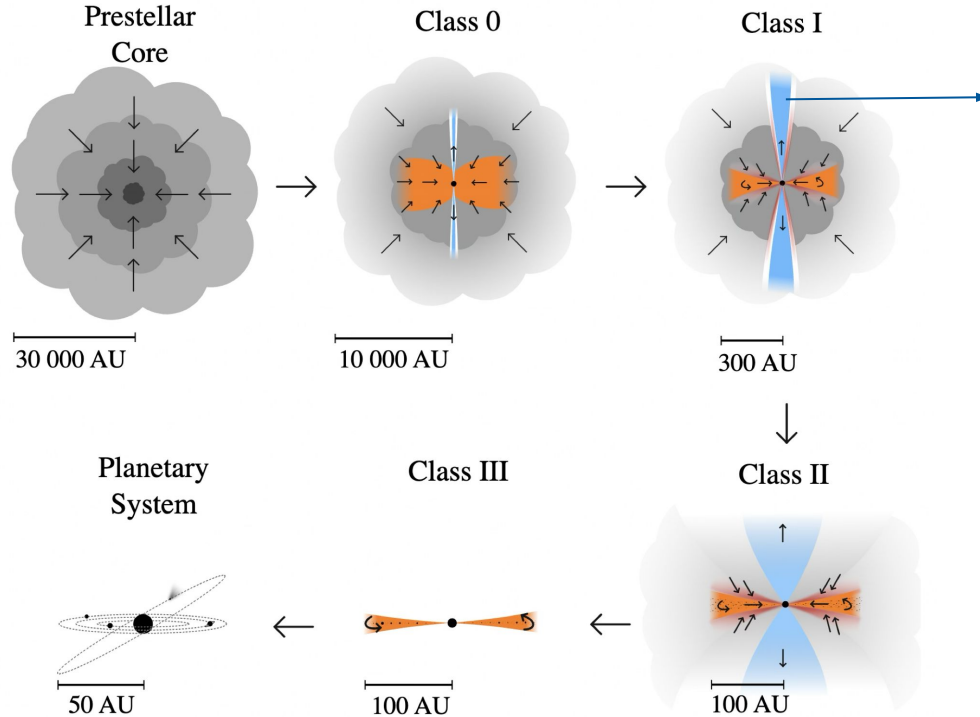
Why Do Some Protostars have Molecular Jets?

Insights from JWST IFU Spectroscopy

Manya Arora, Manoj Puravankara,
HEFE+IPA collaboration



What are Protostars ?



These outflows are important because?

Drive accretion by carrying away angular momentum from the disk

Regulate star formation in molecular clouds and shape the IMF through feedback processes

Credit: Magnus Vilhelm Persson

Driving Mechanisms & Morphology



The Protostellar Wind

Wide-angle, lower-velocity outflows that carve out the initial bipolar cavities in the parent molecular cloud core.



High-Velocity Jets

Highly collimated streams of ionized and atomic gas that drive shocks into the surrounding medium.

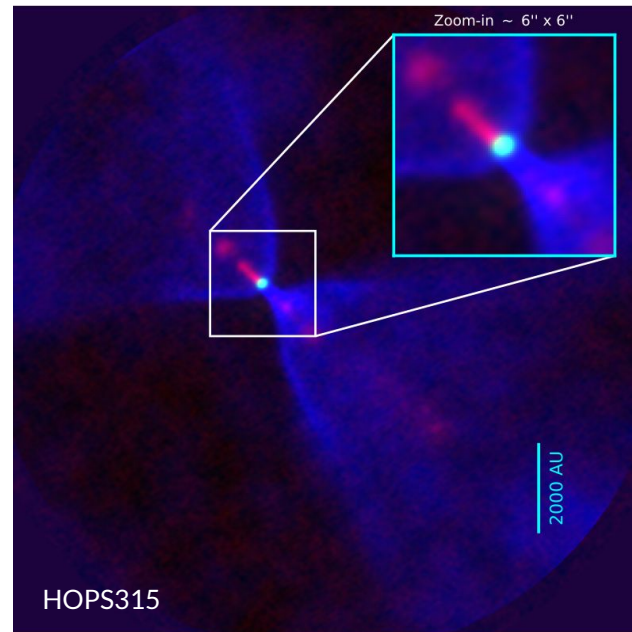


Molecular Entrainment

Ambient gas swept up by the jet/wind interaction, forming the bulk of the observable molecular outflow mass.

Sub-millimeter Tracers: ALMA

- ✓ **CO rotational lines:** trace the total mass and energetics of the entrained molecular outflow of cold (10–50K) gas.
- ✓ **SiO rotational lines:** Since silicon is normally locked in dust grains, shocks exceeding ~ 25 km/s, grains are shattered via sputtering, releasing Si into the gas phase. SiO highlights the ultra-fast jet knots near the source.

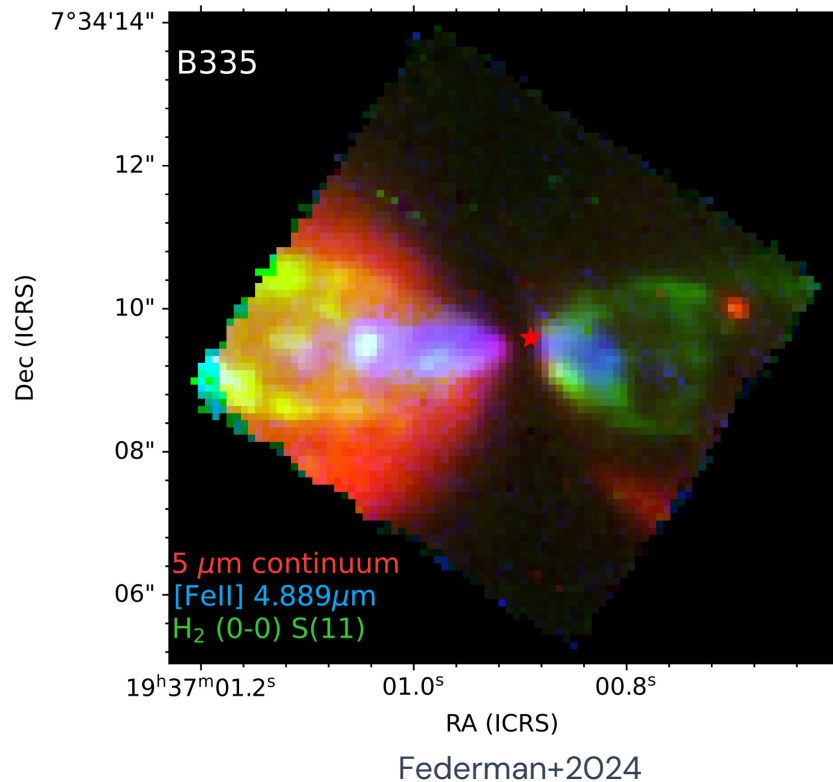


^{12}CO (2–1) @ 230.53800 GHz in blue
1.3 mm continuum in green
SiO(5–4) @ 217.10498 GHz in red
Dutta+2025

Infrared Tracers: JWST

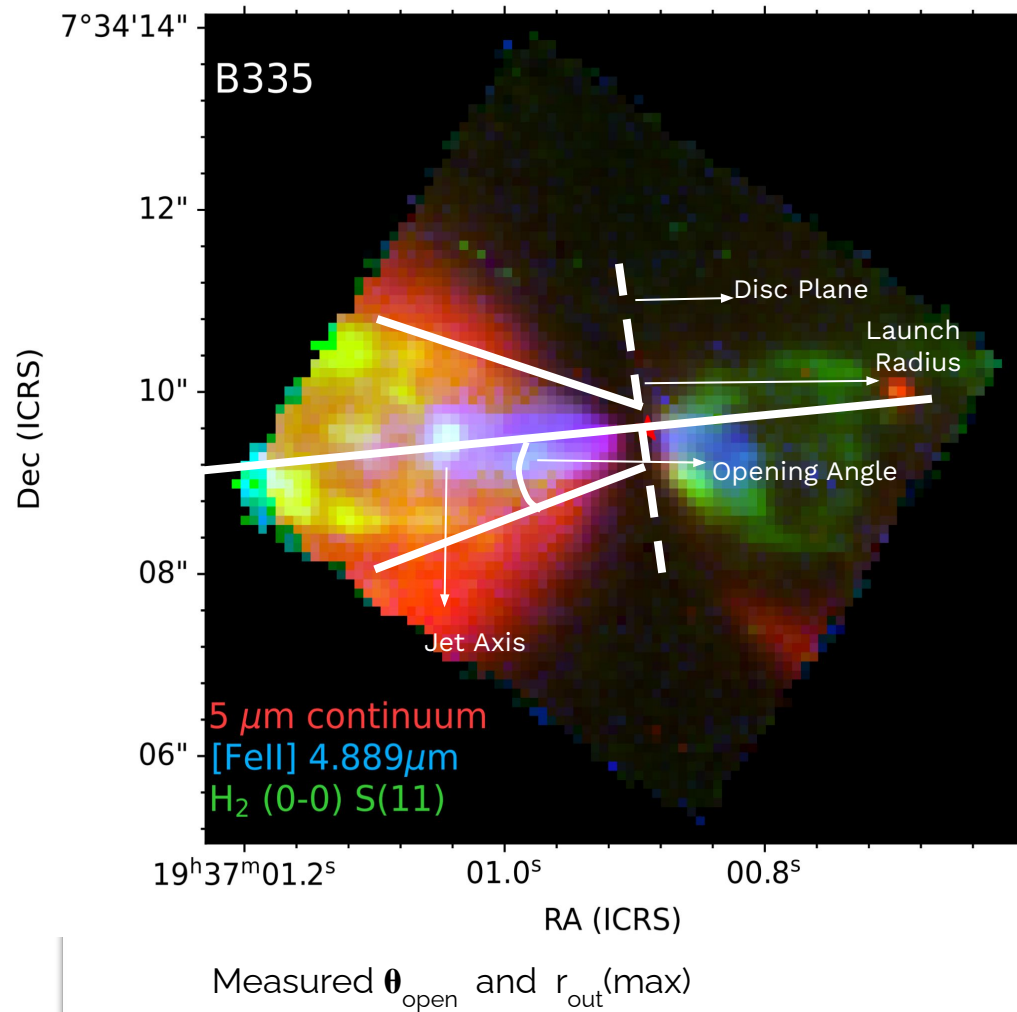
Shock-Heated Gas

- ✓ **Metallic FS Lines:** [FeII] traces the fastest, most ionized components of the jet.
- ✓ **Molecular Hydrogen:** H_2 lines trace the slower, shock-excited molecular wind.



How to quantify the morphology?

- Opening angle, θ_{open}
- Maximum Launch Radius, $r_{\text{out}}(\text{max})$
- Length
- Curvature



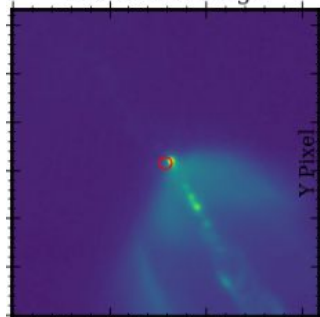
Rotating the image

Sobel Filter

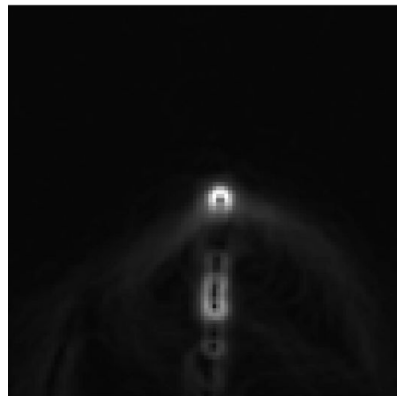
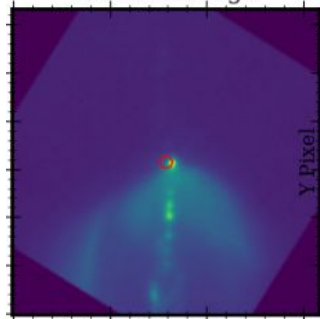
Hysteresis
Thresholding

Detecting the edges

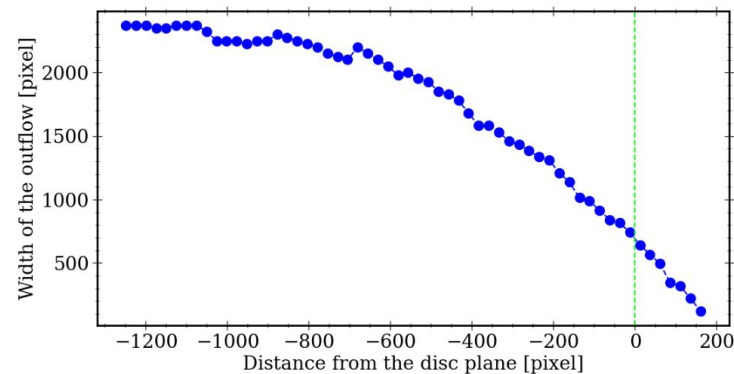
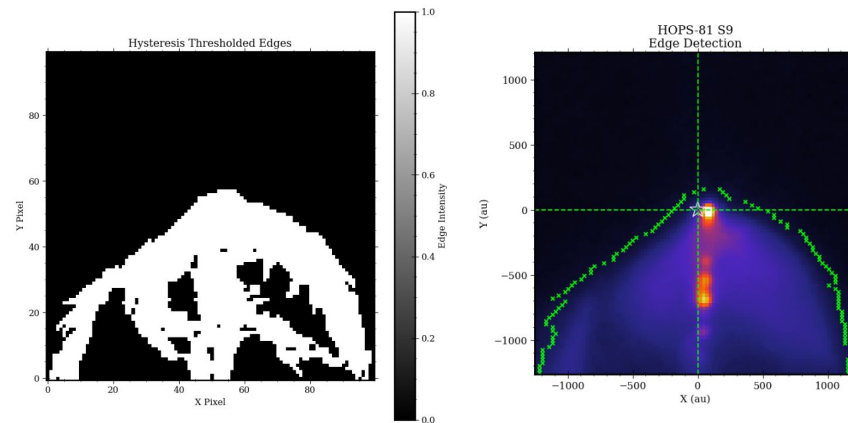
Observed Image



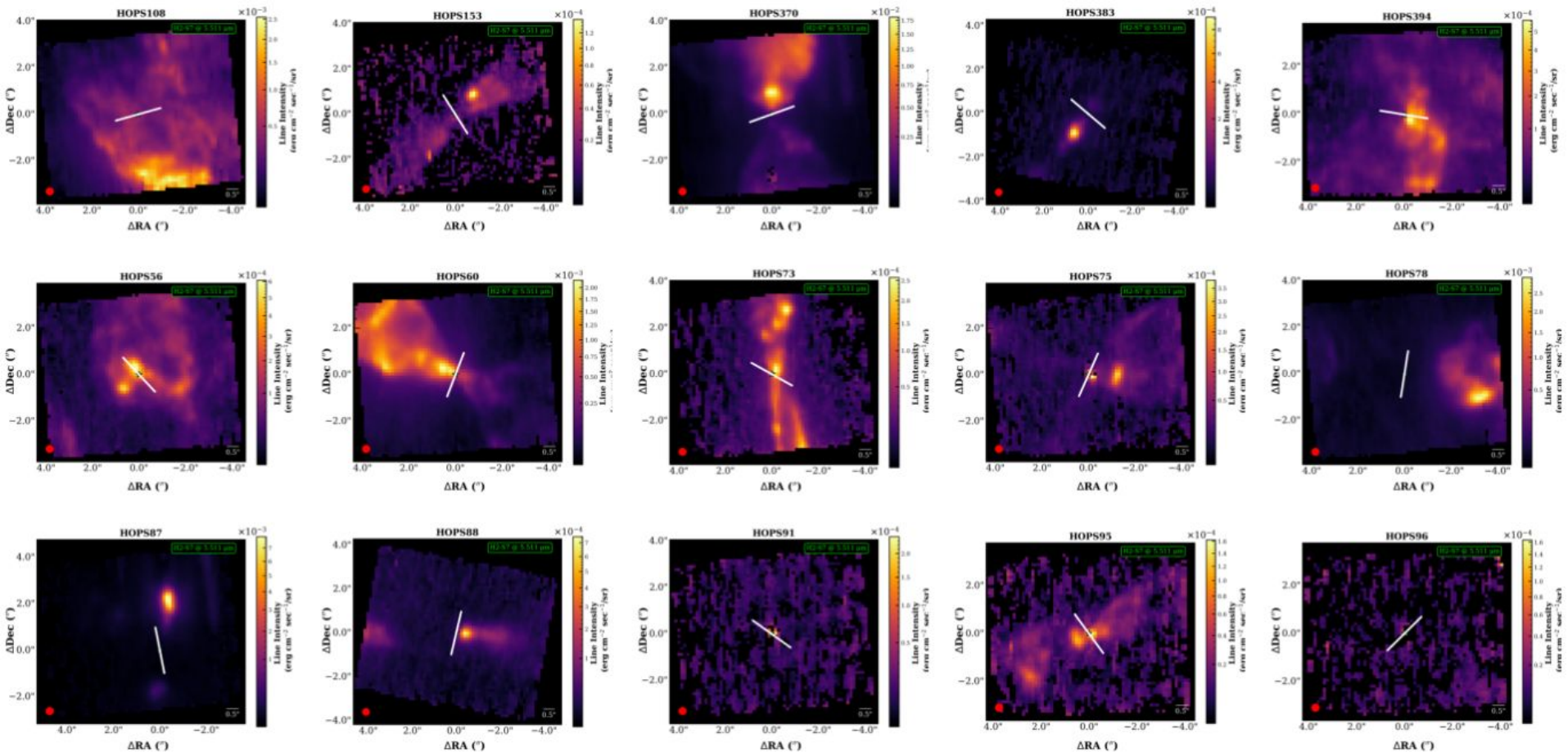
Rotated Image



shown for HOPS-81

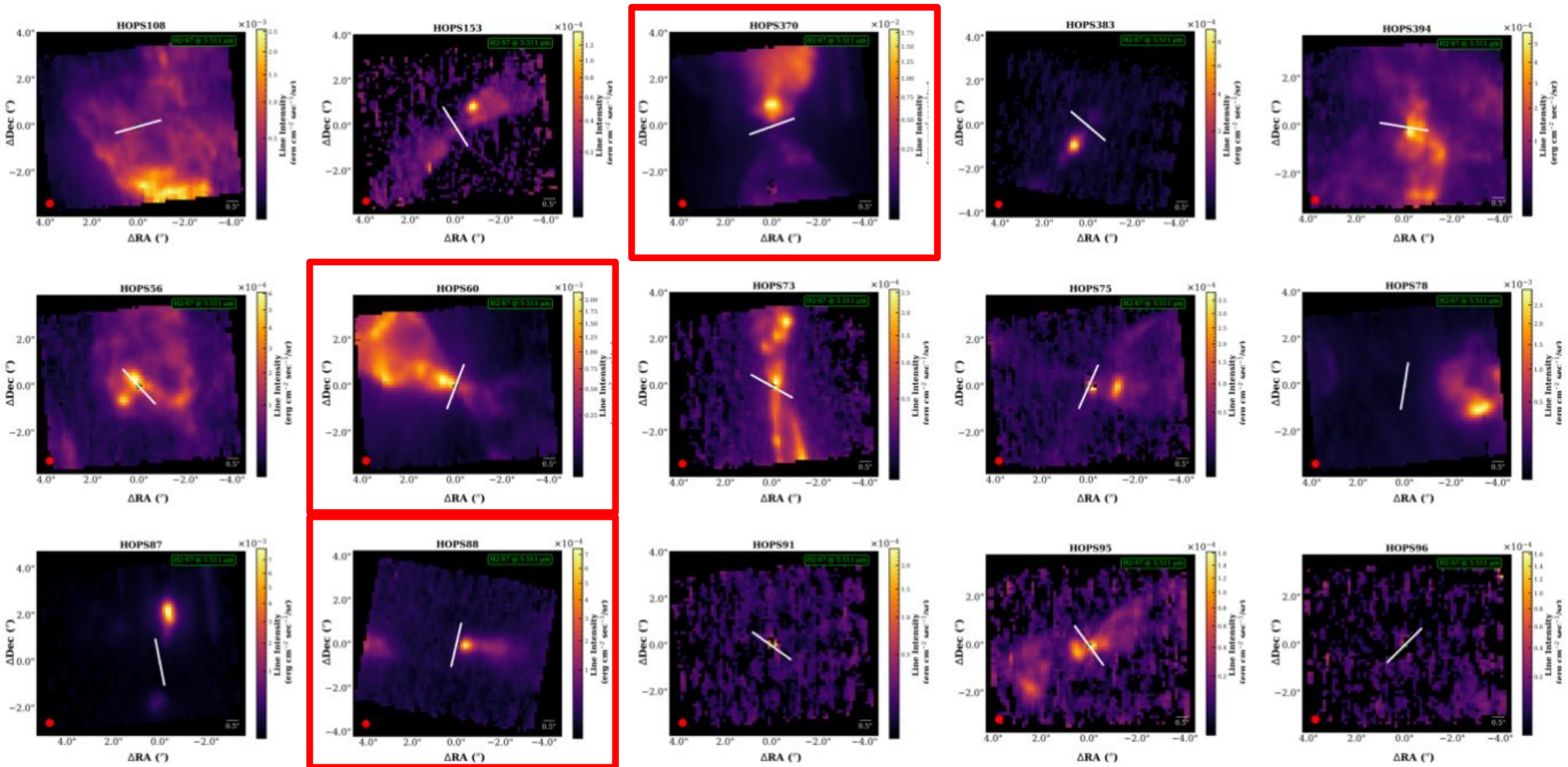


$\text{H}_2(\nu = 0-0)$ S(7) continuum subtracted line intensity maps



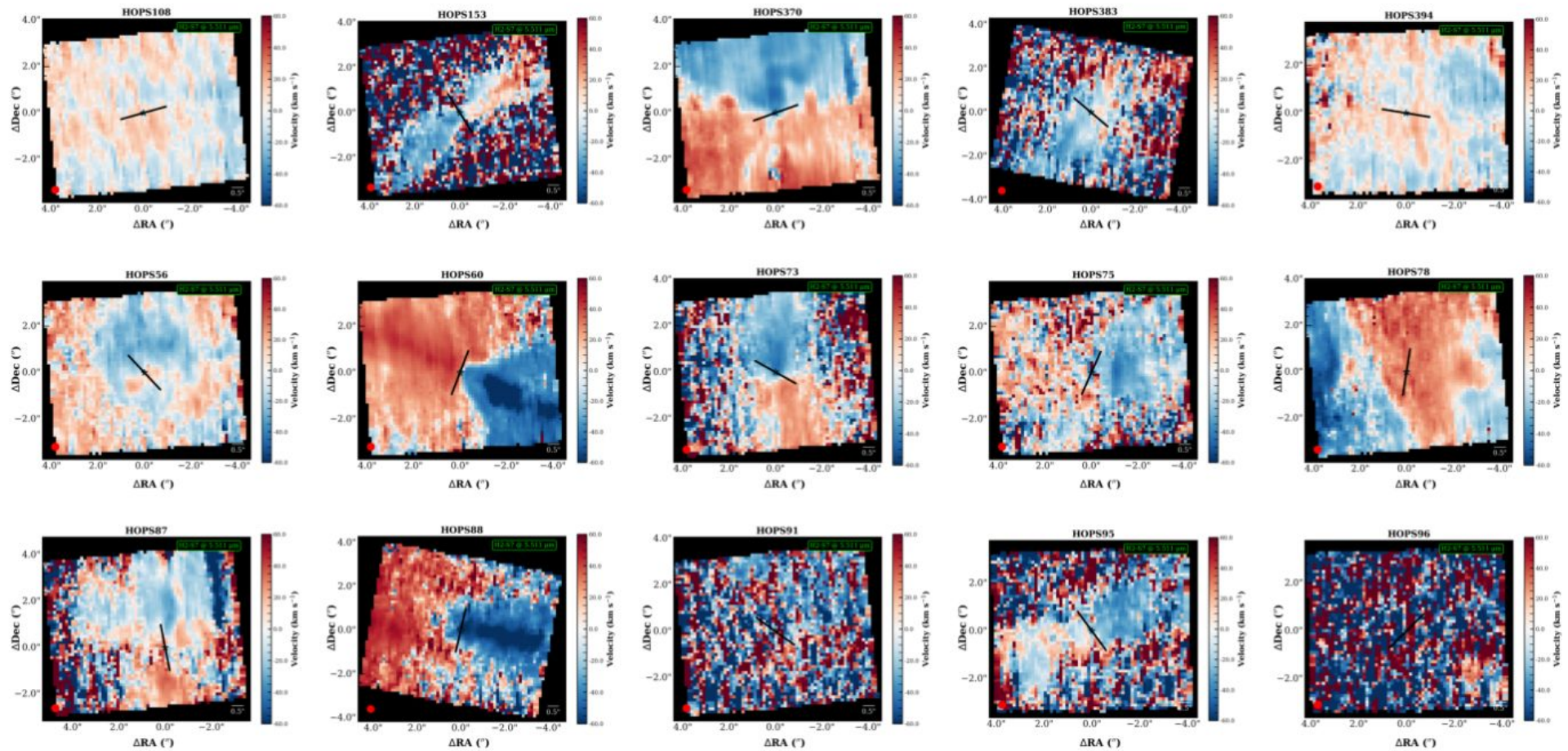
White line: Disk PA from VANDAM 2020

$\text{H}_2(\nu = 0-0)$ S(7) continuum subtracted line intensity maps



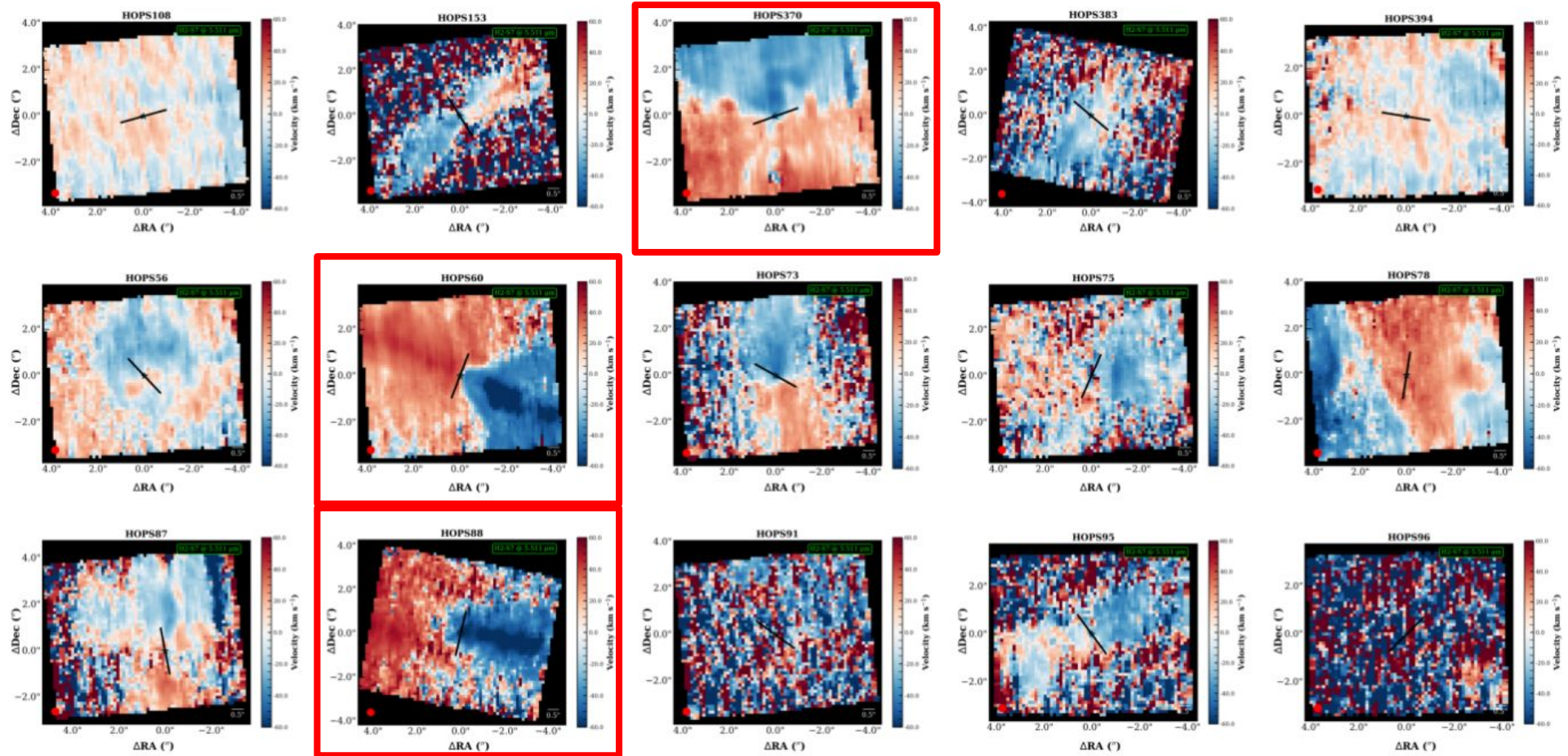
White line: Disk PA from VANDAM 2020

$\text{H}_2(\nu = 0-0)$ S(7) velocity shift maps



Black line: Disk PA from VANDAM 2020

$\text{H}_2(\nu = 0-0)$ S(7) velocity shift maps



Black line: Disk PA from VANDAM 2020



So to recap

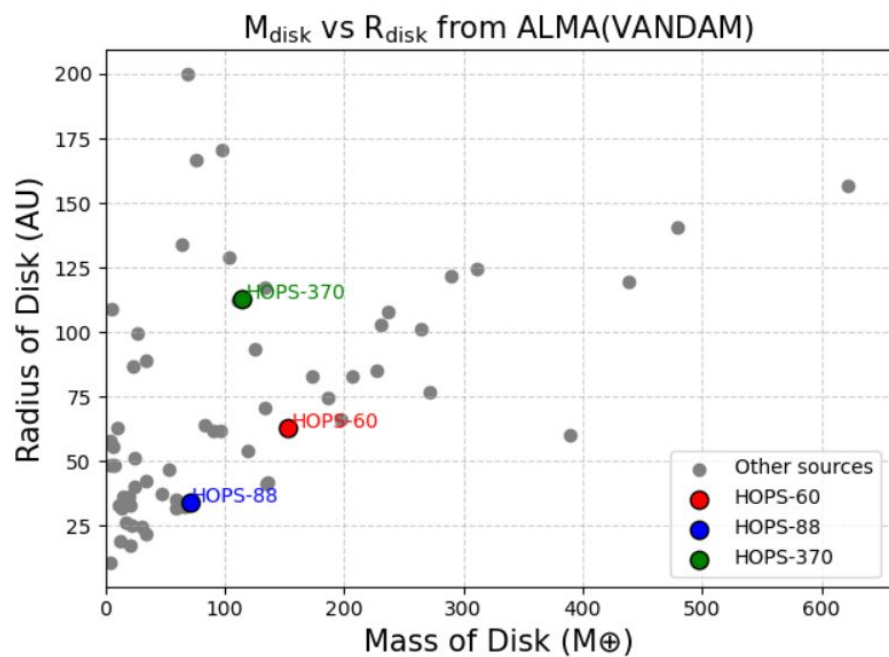
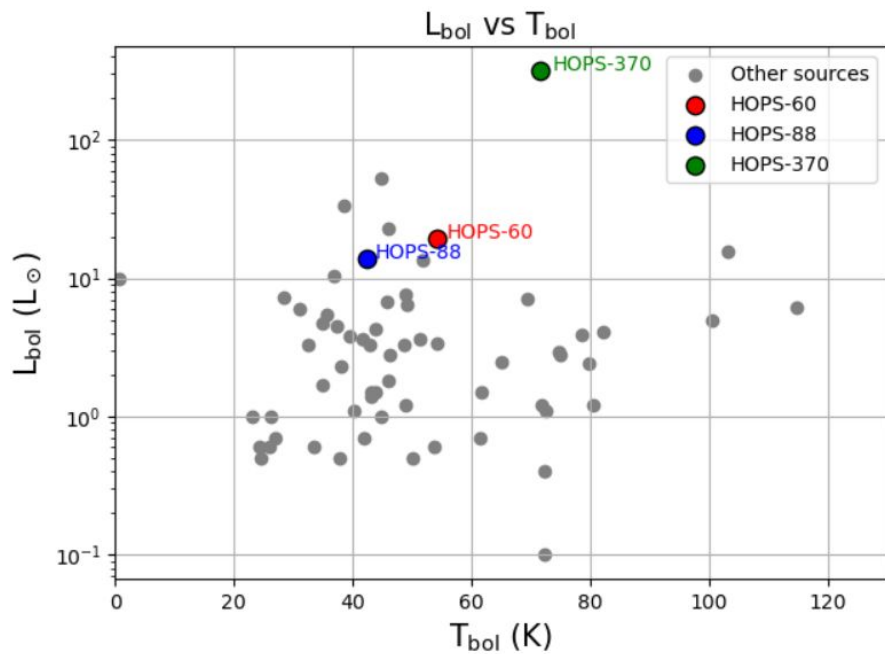
Most sources show biconical or wide angle H_2 flows

HOPS-60, HOPS-88 and HOPS-370 show a collimated molecular spine

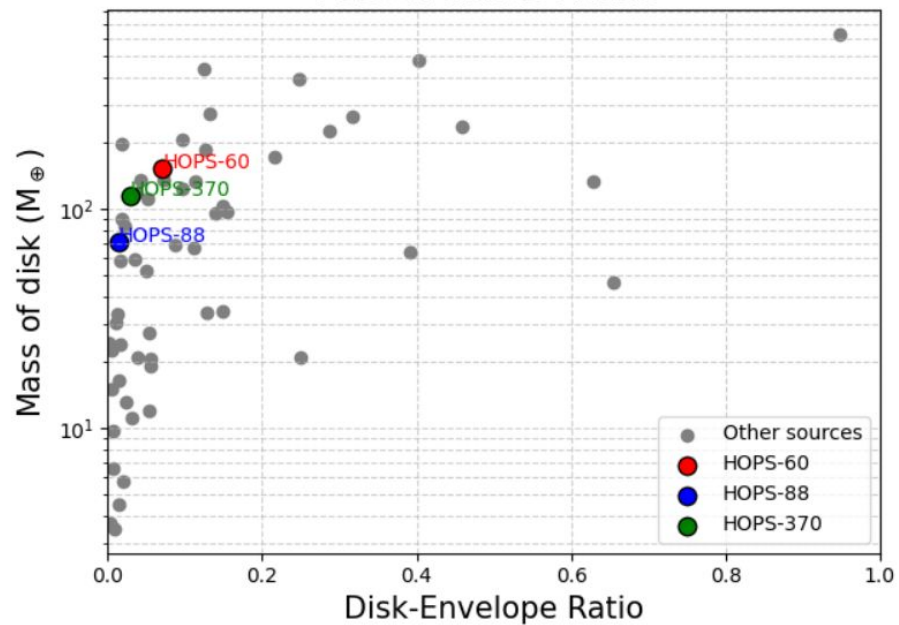
- **Why do these specific sources show this behavior**
- **Could it be that these three have some distinct parameters?**

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some distinct
parameters?

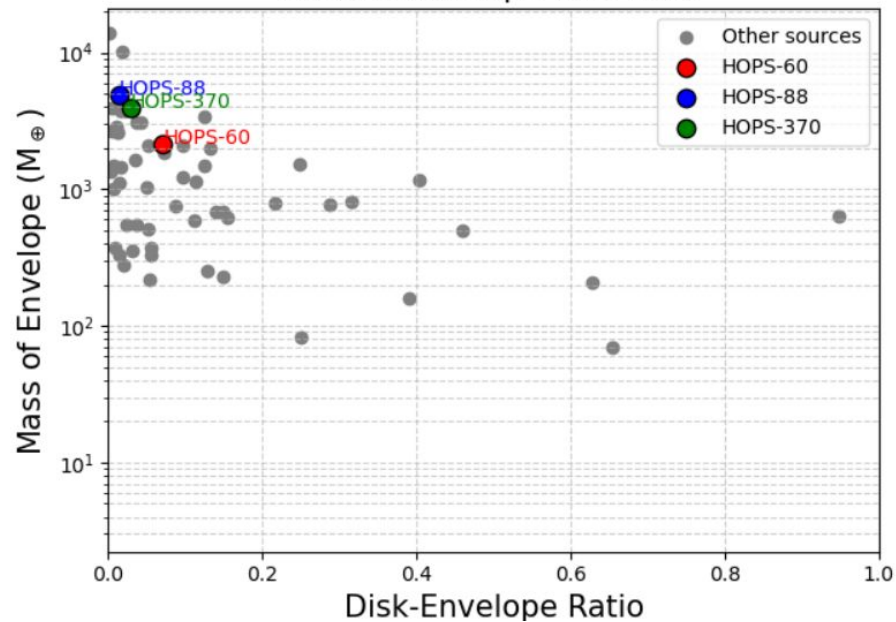
- 
- Bolometric Luminosity
 - Bolometric Temperature
 - Mass of Disk
 - Radius of Disk
 - Mass of envelope (upto 2500 AU)
 - Ratio of disk-envelope mass
(Calculated from ALMA survey,
Federman+2023)



Mass of disk vs M ratio



Mass of envelope vs M ratio



Why do these specific sources show this behavior

They don't show any distinction in bulk parameters

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High mass loss rate $\Rightarrow$ collimation?

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Molecular wind is launched from beyond the dust sublimation radius making the primary jet driven from the disk is molecular.

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Molecular wind is launched from beyond the dust sublimation radius making the primary jet driven from the disk is molecular.

Could Accretion Rate be a reason?

High mass loss rate $\Rightarrow$ collimation?

Molecules can reform around the shocked gas if density is high enough.



We need to
measure mass loss
rate which is a
good proxy for
accretion itself.

- Rotational Diagrams
- Kinematics
- Measure Dynamics of the flow

Rotational Diagrams

For a population of molecules in LTE,
number of molecules in each upper
state is given by

$$N_u = \frac{N}{Z} g_u \exp \left(-\frac{E_u}{k_B T_{\text{rot}}} \right)$$

For optically thin emission

$$N_u = \frac{N}{Z} g_u \exp \left(-\frac{E_u}{k_B T_{\text{rot}}} \right) = \frac{4\pi F_u}{h\nu_u \Omega A_u}$$
$$\ln \frac{N_u}{g_u} = \ln \frac{4\pi F_u}{h\nu_u \Omega g_u A_u} = -\frac{E_u}{kT} - \ln \frac{Z(T)}{N}$$

Rotational Diagrams

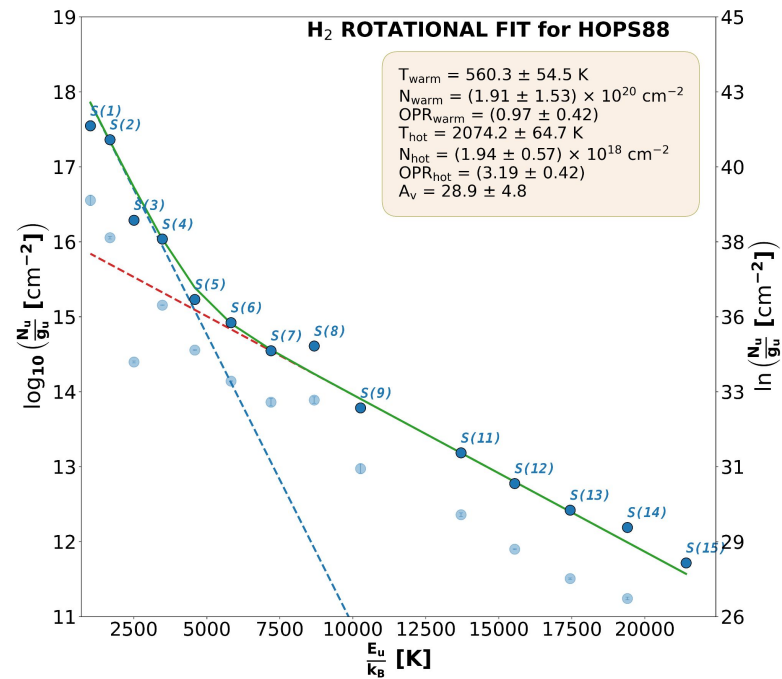
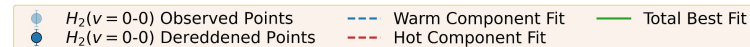
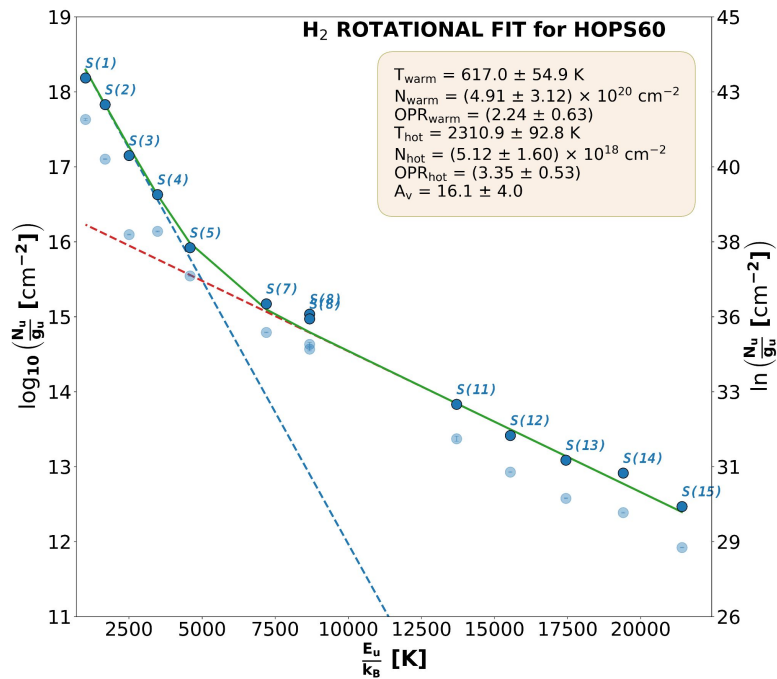
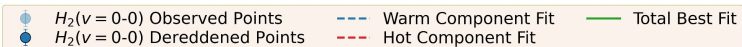
Spectra extracted from a 0.67" circular aperture centered around 870 μ m peak (Tobin+2020)

Lines used : Rotational lines ($v=0-0$) from S(1) to S(15)

Gaussian profiles were fitted to these lines post continuum subtraction

We perform extinction correction using KP5 law [Pontoppidan et al. 2025]

We plot $\ln \frac{N_u}{g_u}$ and E_u/k for all the levels



Rectangular aperture centered around $870\mu\text{m}$ peak in the IFU that covers the spatial extent of the jet. This is divided narrow strips (1-2 pixels each).

Lines used : Rotational lines ($v=0-0$) from $S(7)$, $S(5)$, $S(2)$ and $S(1)$

The velocity is derived from the measured wavelength shift in the spectra of each strip relative to the rest wavelength of each transition.

Systemic velocity subtraction

Inclination correction

We also get dynamical timescale

Kinematics

Kinematics

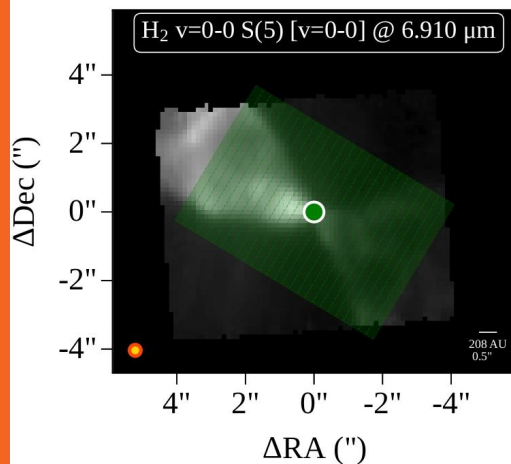
Strip wise Spectral
Extraction

Central Wavelength
using Gaussian profiles

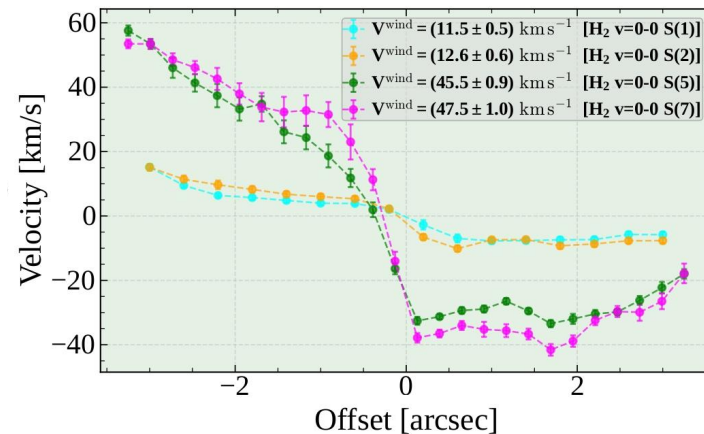
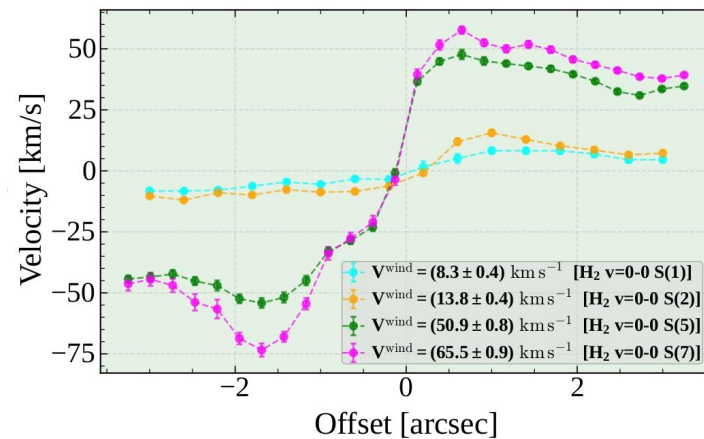
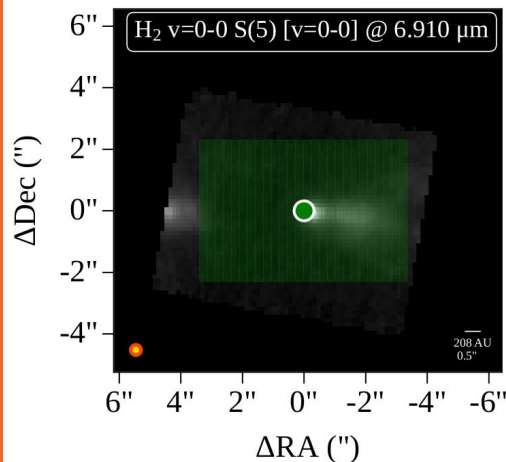
Removing Systemic
Velocity

Inclination Correction

HOPS-60



HOPS-88





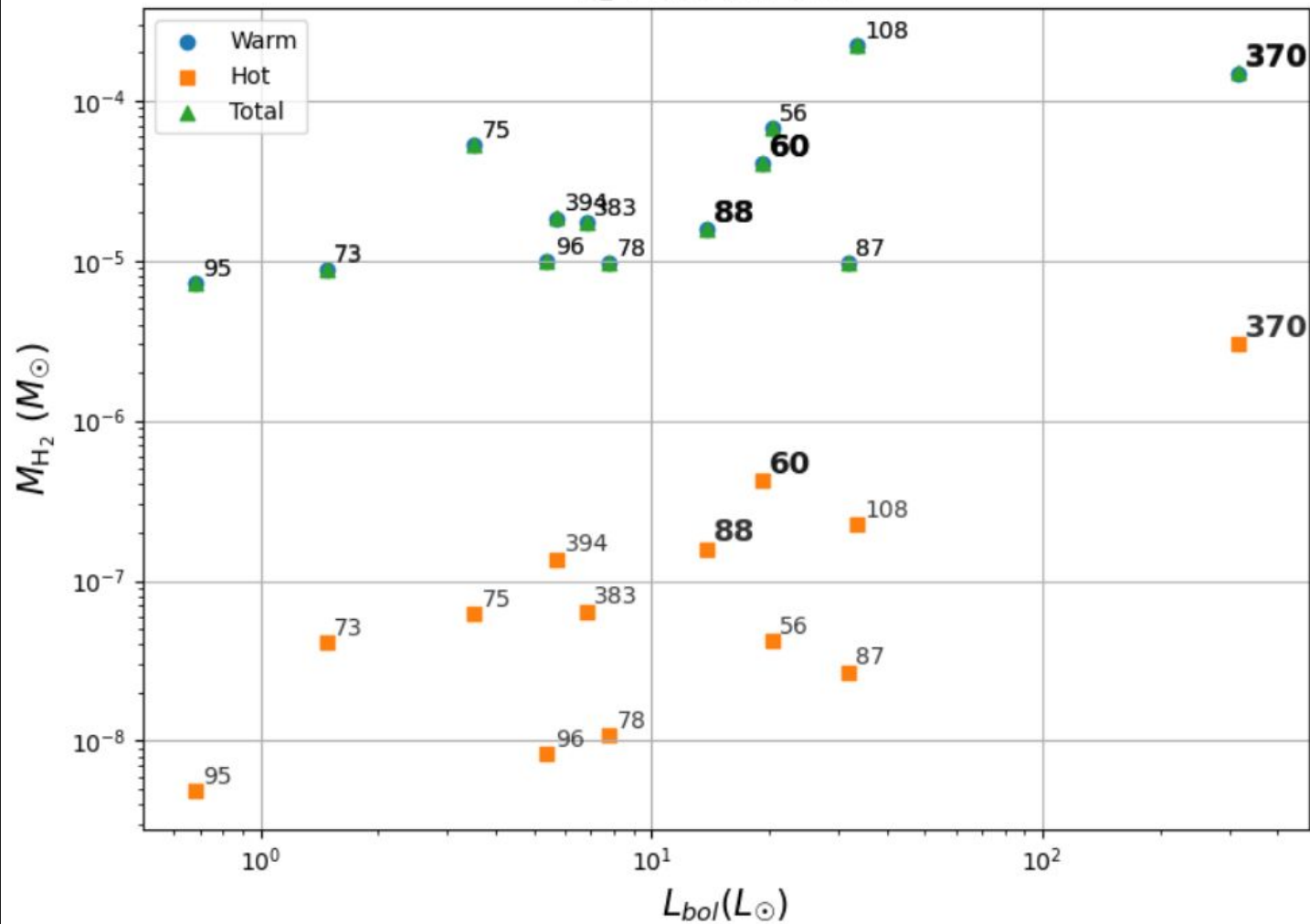
Dynamics of H₂

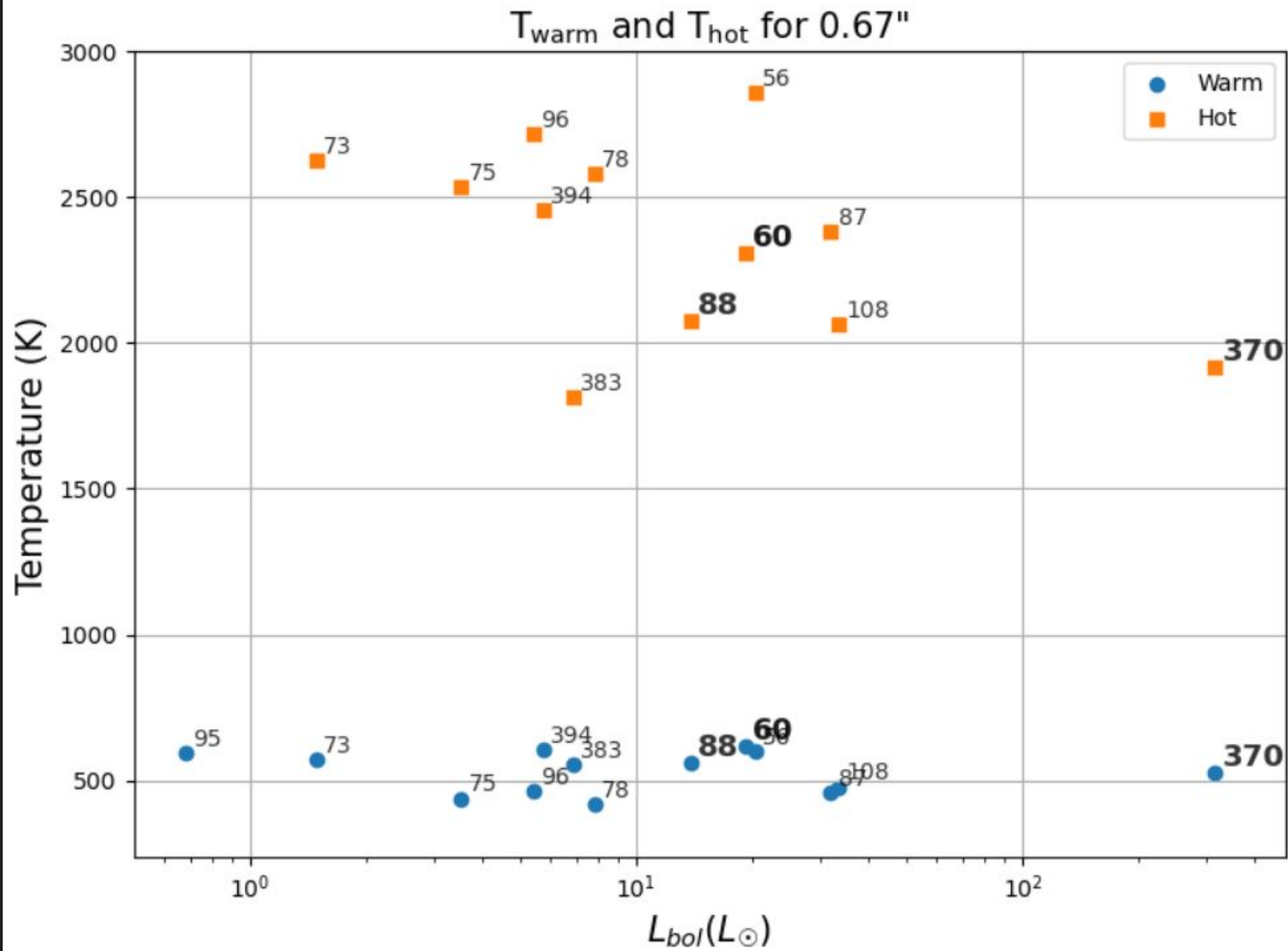
$$M_{\text{H}_2}(\text{warm/hot}) = N_{\text{warm/hot}} * \Omega * \mu_{\text{H}} * m_{\text{H}}$$

$$\dot{M}_{\text{loss}}(\text{warm/hot}) = M_{\text{H}_2}(\text{warm/hot})/t_{\text{dyn}}$$

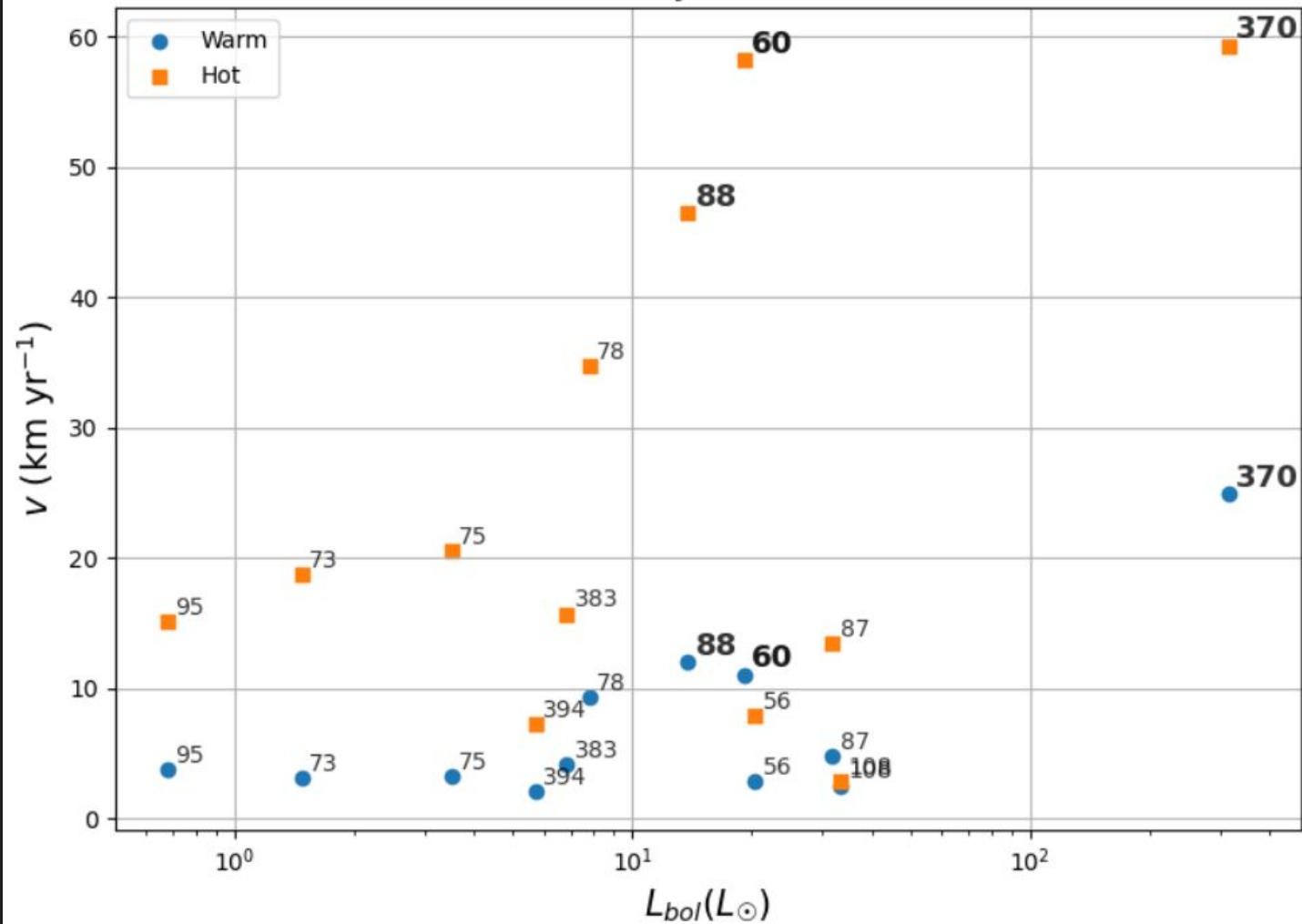
$$\dot{p} = \dot{M}_{\text{loss}} < v >$$

H₂ Mass for 0.67"

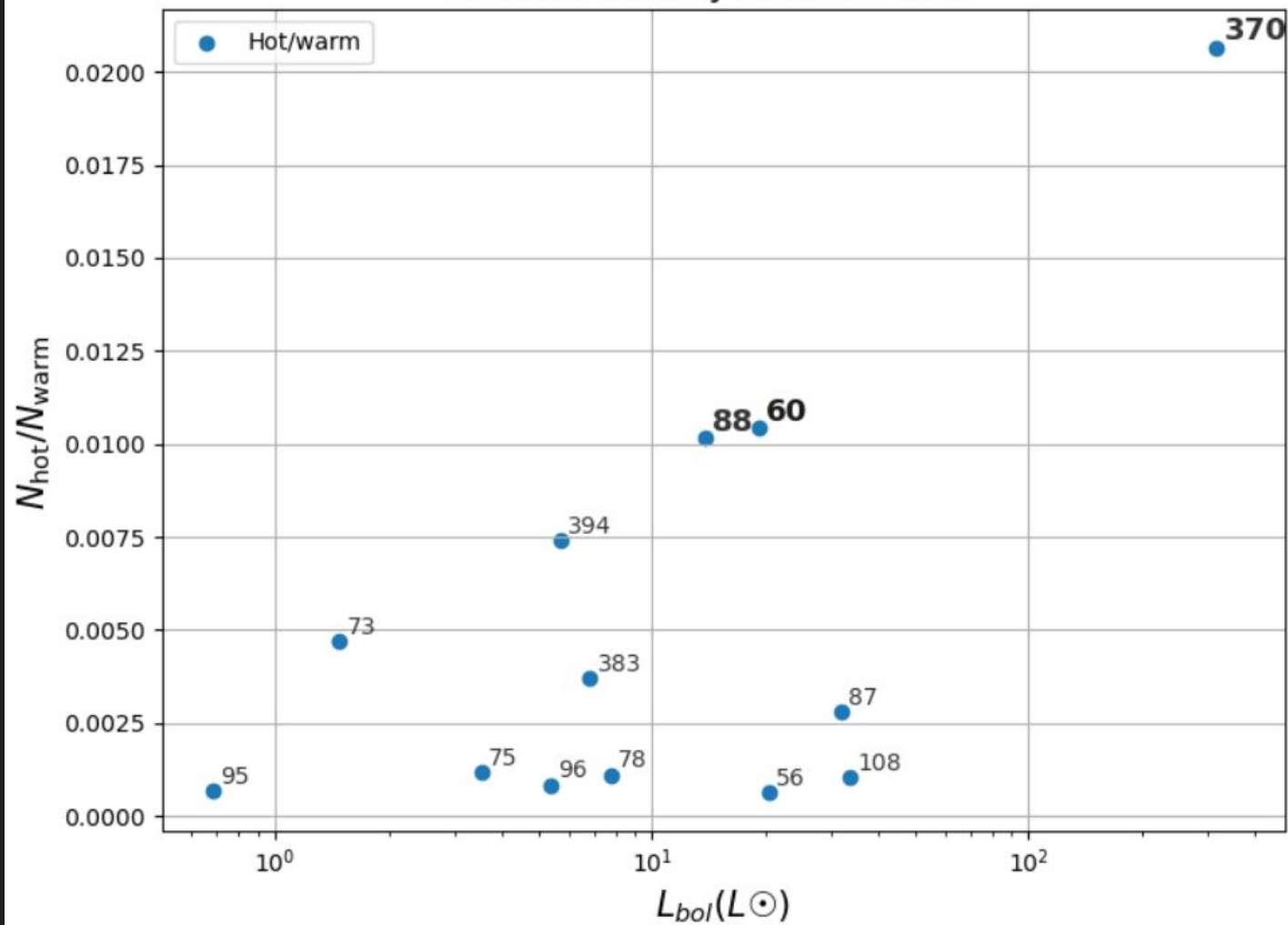




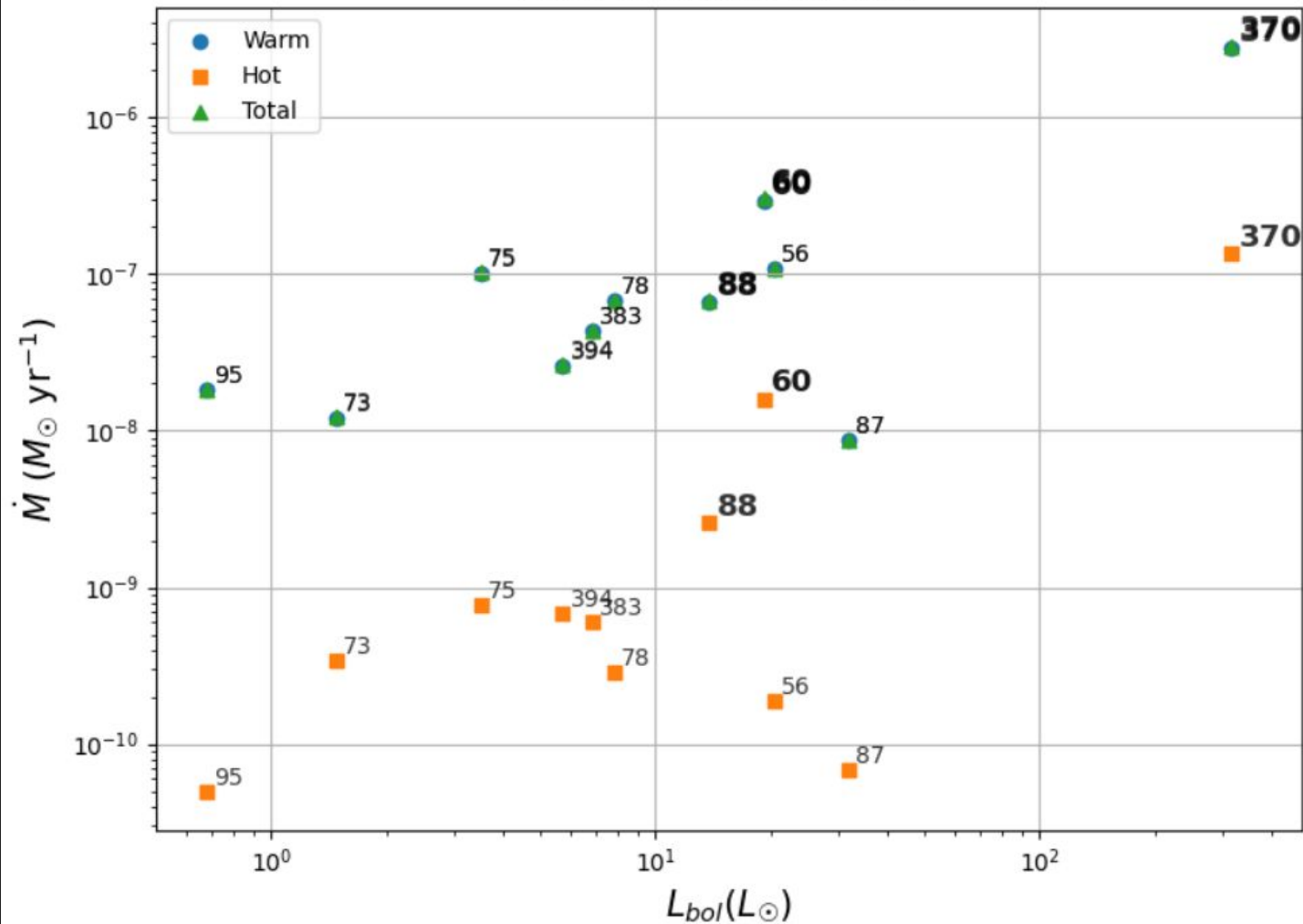
Velocity for 0.67"



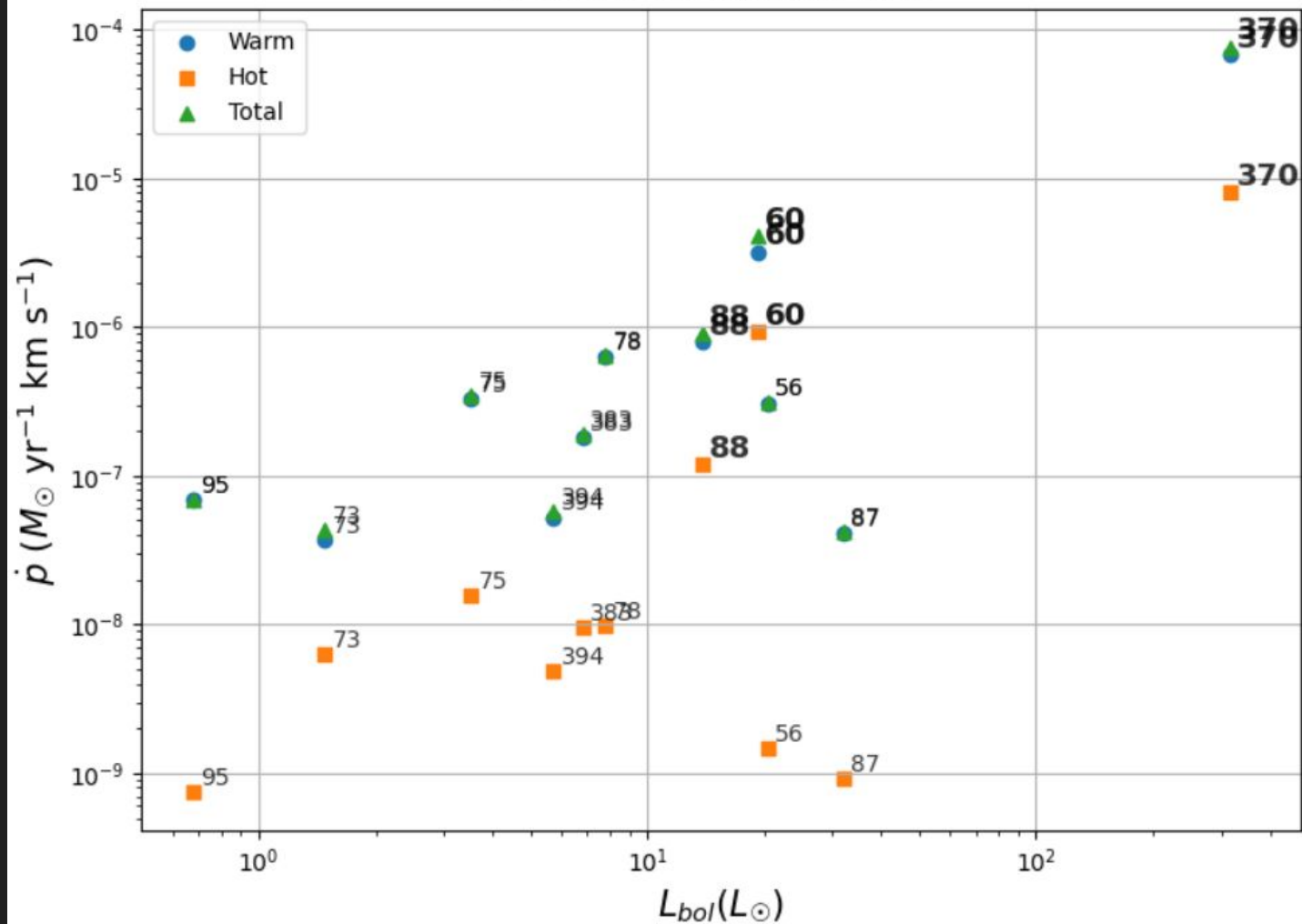
Column Density Ratio for 0.67"



Mass-loss Rate for 0.67"



Momentum Rate for 0.67"



Conclusion

Intrinsic protostellar properties (L_{bol} , T_{bol} , M_{env} , M_{disk} , R_{disk} , or M ratio) do not uniquely distinguish HOPS 60, HOPS 88 and HOPS 370 from the rest of the Class 0 population.

However, sources with collimated H_2 jets, in general, show higher velocity, mass-loss and momentum rates.

Mass fraction of hotter component for the 3 is also much larger and faster than others in the sample.

— Conclusion

Our analysis suggests that incidence of molecular jets in protostars is likely connected to higher mass accretion/ejection phase, and not just an evolutionary effect.

The exact details of how during a high accretion phase jets becomes molecular needs to be further investigated.

References

- [1] H. Tyagi, Phd dissertation, 2025
- [2] John J. Tobin et al, VANDAM, 2020
- [3] R. H. Hildebrand, 1983
- [4] S. Federman et al, 2023
- [5] John J. Tobin, Patrick D. Sheehan, 2024
- [6] John J. Tobin et al 2020 ApJ 905 162
- [7] K. M. Pontoppidan et al 2024 ApJ 963, 158
- [8] Tabone et al, A&A 636, A60 (2020)