The Wonderous 3D World of Protostellar Shocks in NGC 2071 IR

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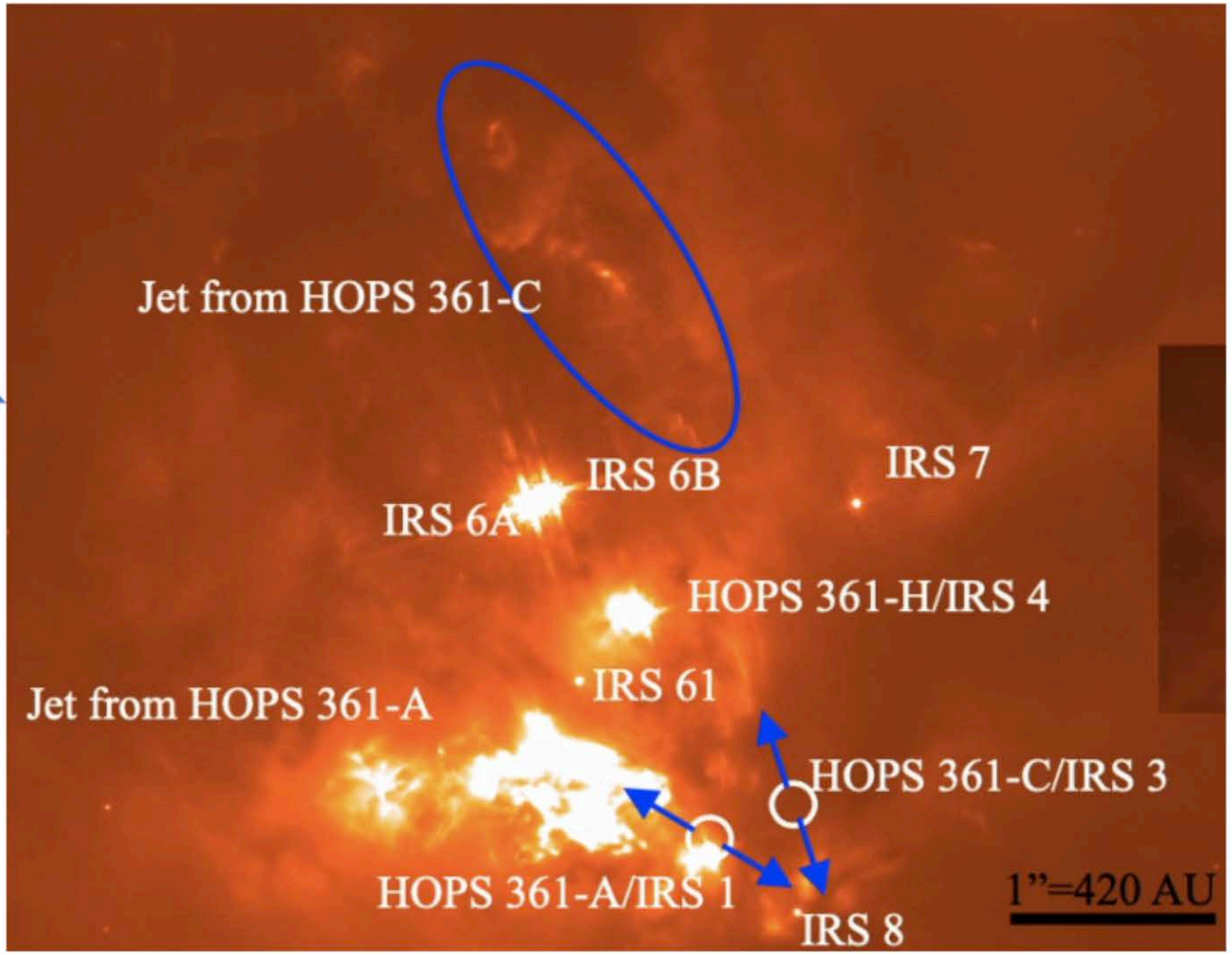
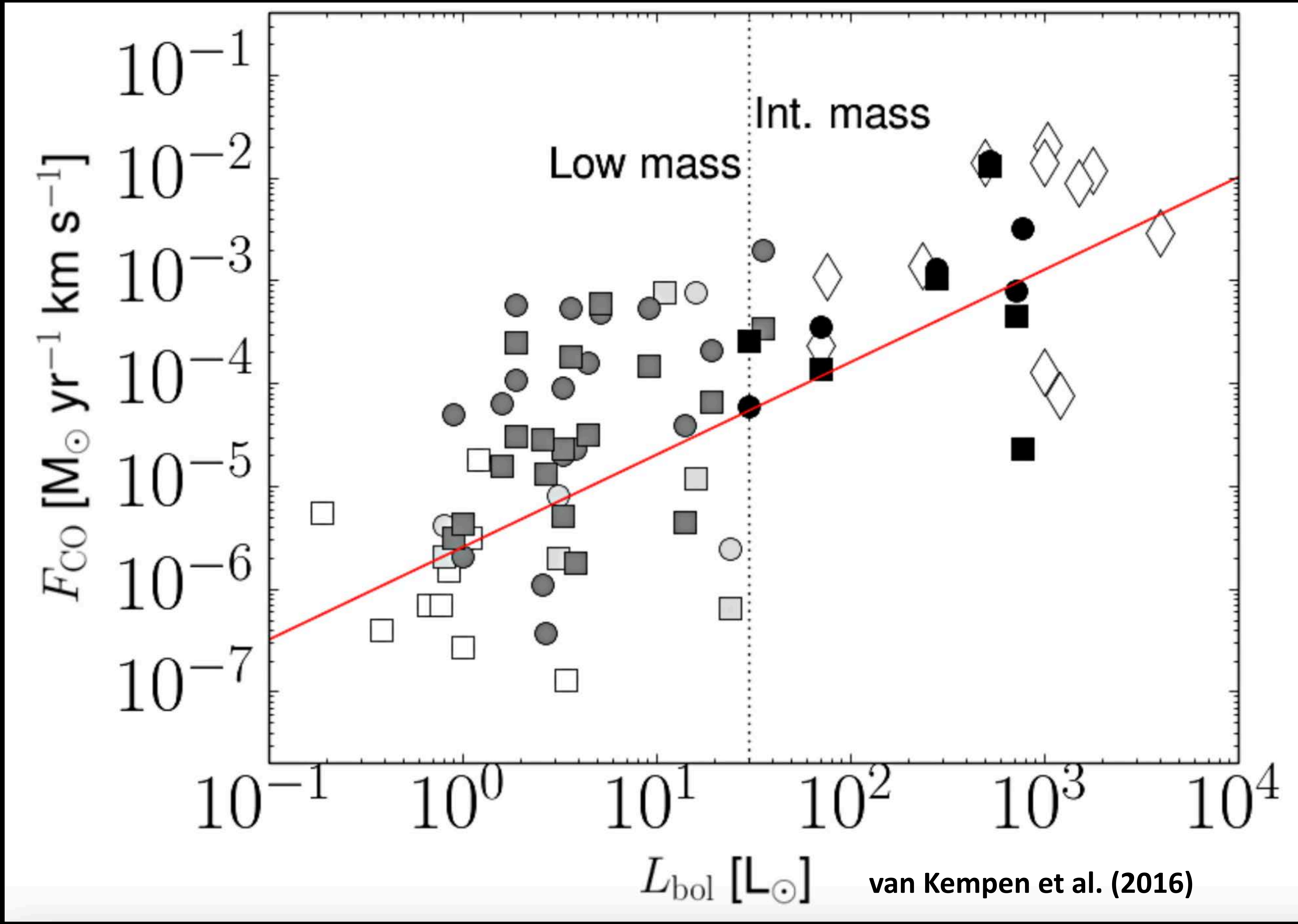
NGC 2071 IR hosts seven YSOs within 2000 AU with a total luminosity of $500L_{\odot}$.



HST/WFC3 IR (2009); Habel+21

Intermediate-mass protostellar outflows have significant impact in molecular clouds



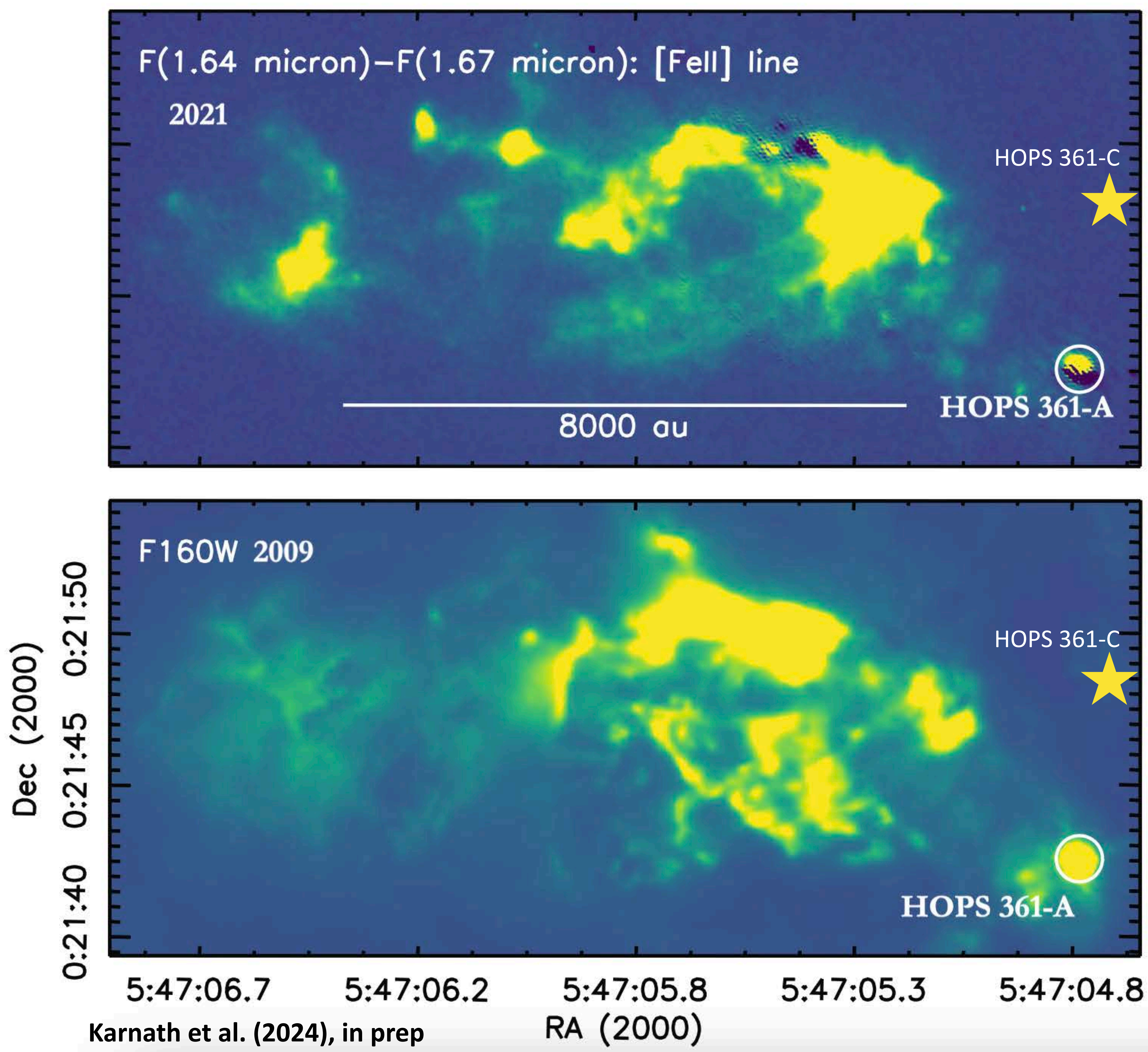
van Kempen et al. (2016)

- Fewer intermediate-mass protostars have been studied in the literature
- Critical component of star formation process, bridges low- to high-mass star formation
- More common than high-mass stars but more powerful than low-mass stars
- Need to assess the driving of turbulence and lowering SF efficiency
- 3D kinematics are difficult to obtain
- ***SOFIA-HST provides the 3D information***

Our team proposed an HST near-IR and SOFIA far-IR study in NGC 2071 IR focussing on the outflows and their impact on the surrounding cloud

1. Determine 3D velocities of shocked knots
2. Using models, constrain shock velocities, mass, and momentum flows through shocks
3. Constrain velocities and mass flow rates of jets/winds launched by intermediate mass stars

A 3D picture of outflow structures is key to best understand molecular clouds



Karnath et al. (2024), in prep

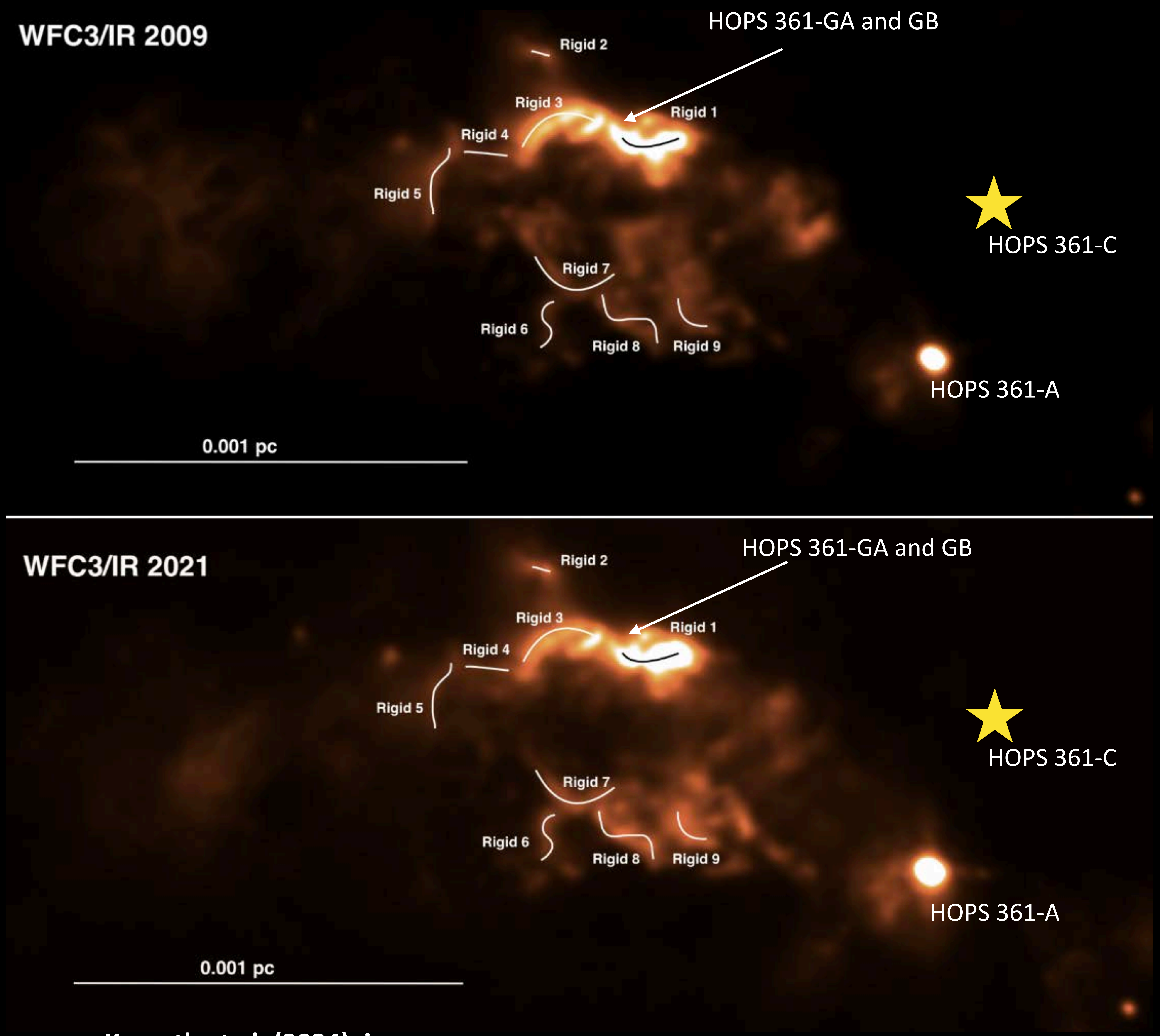
- Split the study into two parts:
  - HOPS 361-A
  - HOPS 361-C

Directors' Discretionary Time programs (PI: N. Karnath)

HST (16493) - continuum, [Fe II] 1.64 um, HI, Pa B

SOFIA Cy9 (2021) – [OI] 63 um

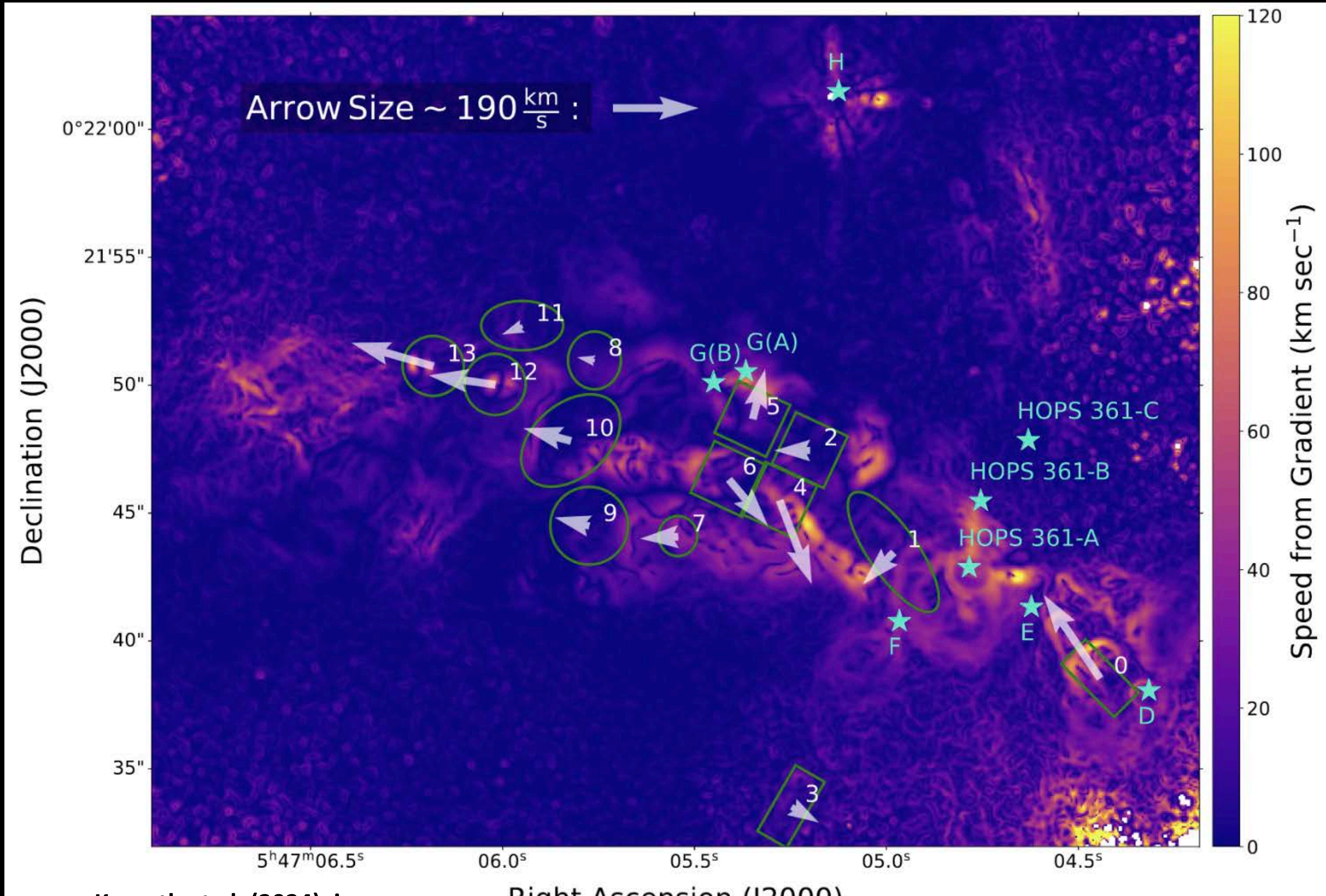
HOPS 361-A has a compact, complex outflow



Karnath et al. (2024), in prep

- HOPS 361-A has:
  - Has consistent knot speeds
  - Shock speeds are ~50 km/s via MAPPINGS model (Sutherland + 2018)
  - Proper motions range from 90 - 275 km/s
  - Rigid structures that remain unchanged between epochs
    - The cavity is not as cleared as HOPS 361-C => less evolved?

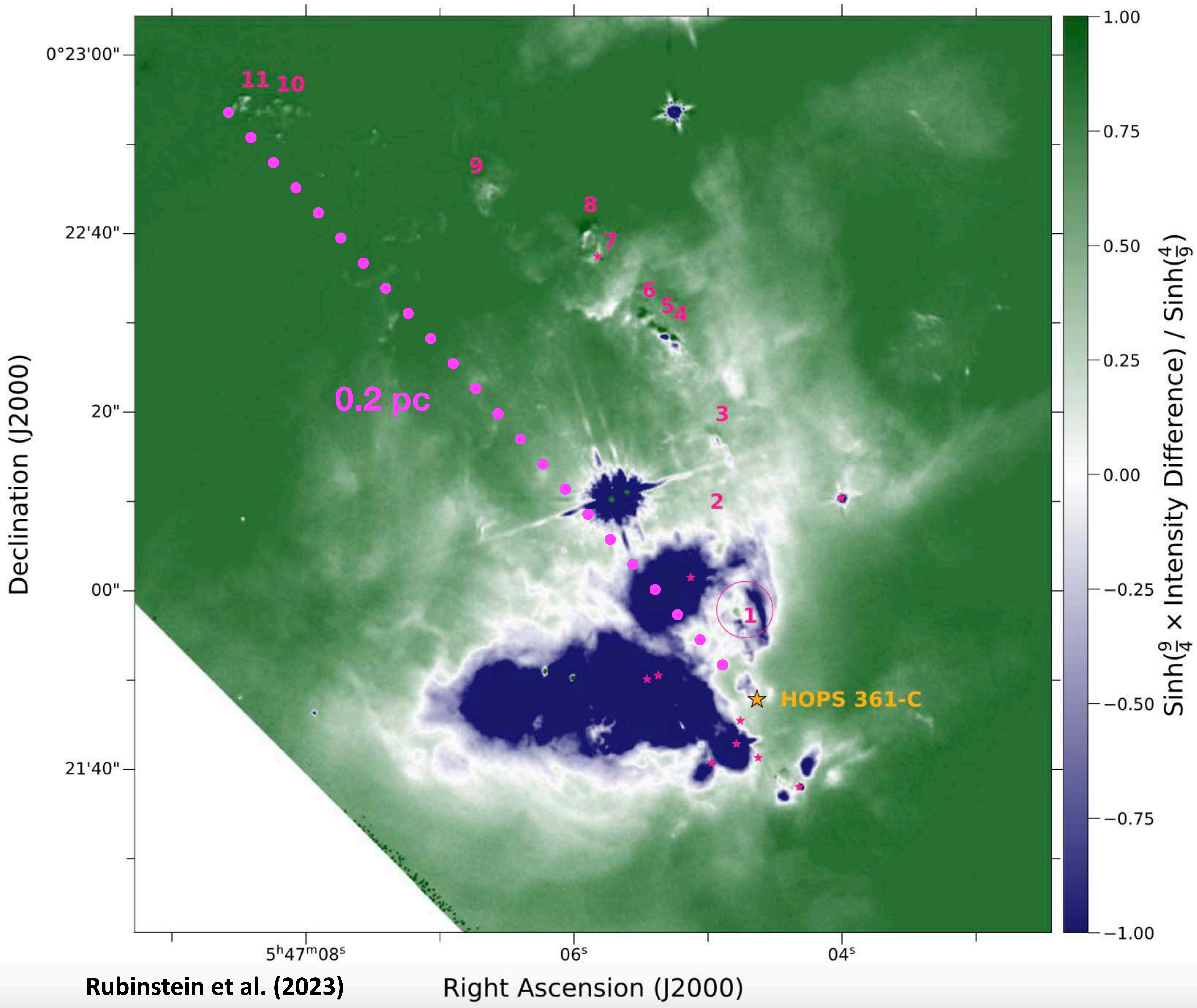
HOPS 361-A has a much more complex outflow



Karnath et al. (2024), in prep

- HOPS 361-A has:
  - Knot speeds are more consistent
  - Shock speeds are ~50 km/s via MAPPINGS model (Sutherland + 2018)
  - Proper motions range from 90 - 275 km/s
  - Rigid structures that remain unchanged between epochs
    - The cavity is not as cleared as HOPS 361-C => less evolved?

HOPS 361-C is less luminous and the outflow knots are more distinct

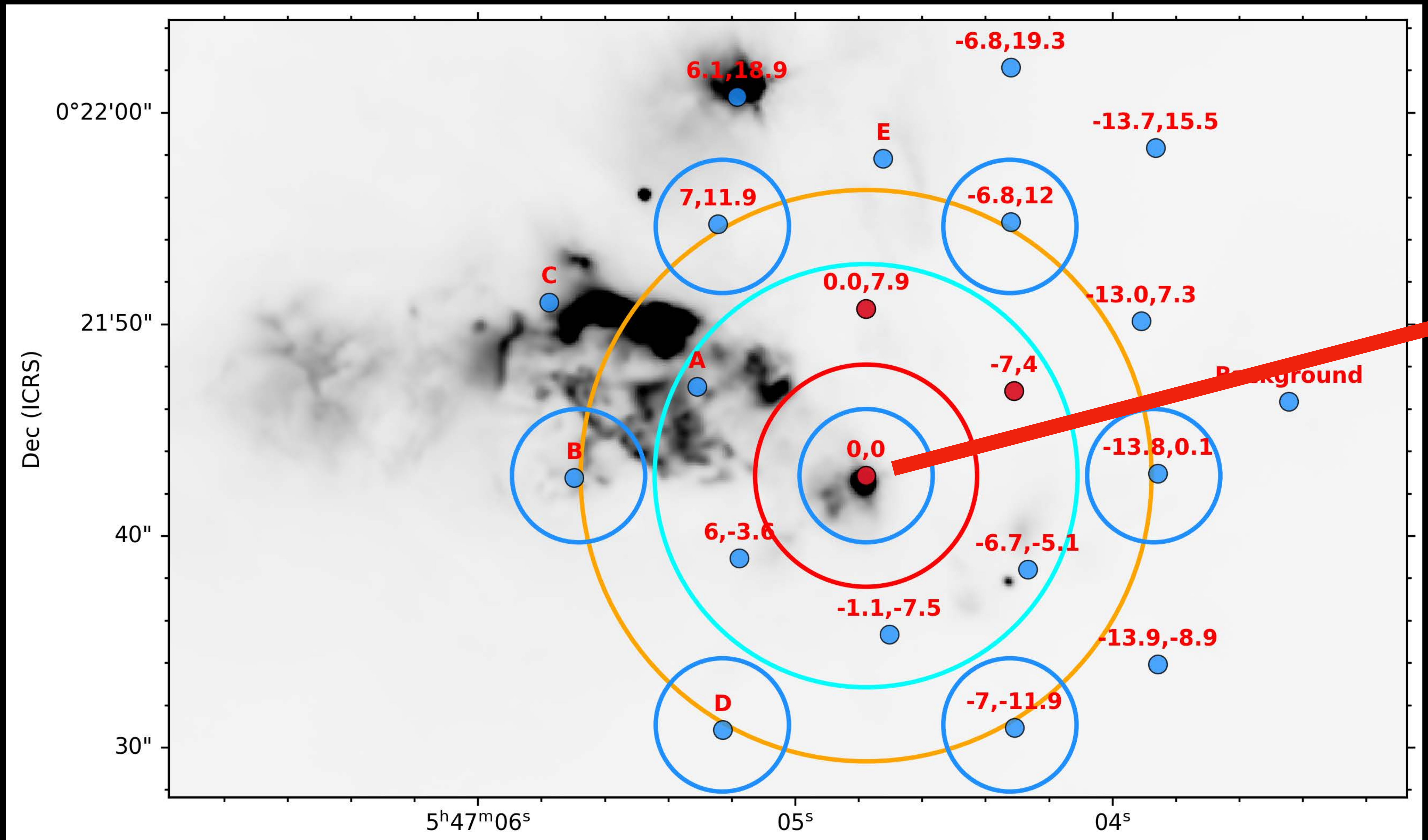


Rubinstein et al. (2023)

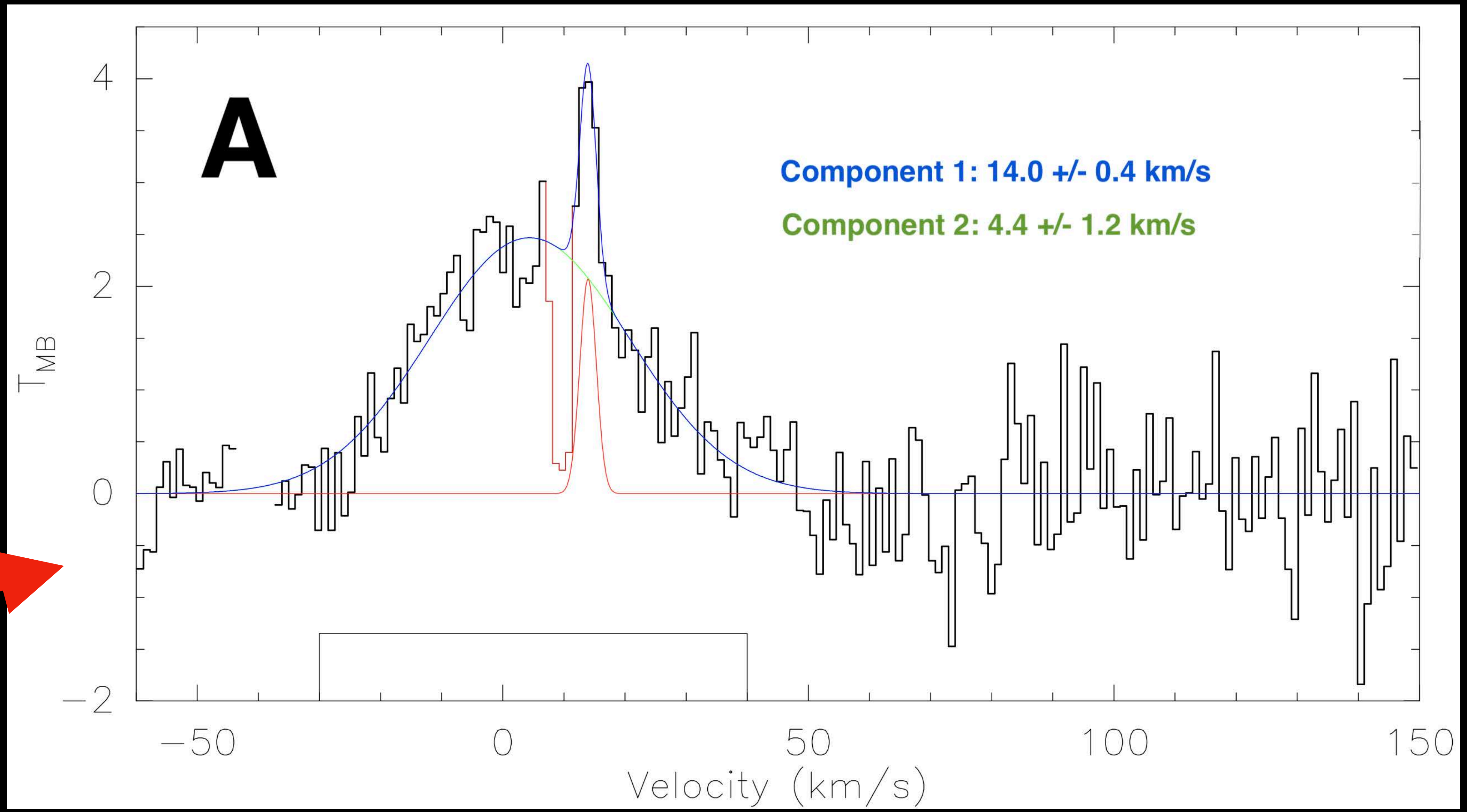
- HOPS 361-C has:
  - Deceleration of knot speed
  - The arc of the outflow is consistent with a binary (Tobin et al. 2020), precession of the outflow axis ~2000 yrs
  - An opening angle of 16°
  - Proper motions range from 100 - 350 km/s
  - Shock speeds are ~50 km/s via MAPPINGS model (Sutherland + 2018)

SOFIA GREAT measured the [OI] line at 63 microns

- Added the 3rd motion component, radial velocity
- The [OI] line is needed to determine pre shock densities and shock speeds in MAPPINGS model (Sutherland et al. 2018)



Karnath et al. (2024), in prep



The two outflows in NGC 2071 IR are quite different

- HST/WFC3 multi-epoch observations allow us to measure knot sizes, gradients between epochs due to proper motions, and transverse velocity

- SOFIA/GREAT resolved [OI] allows us to understand radial motions resolved down to a few km/s

- HOPS 361-A is much brighter than HOPS 361-C (both are intermediate-mass protostars)

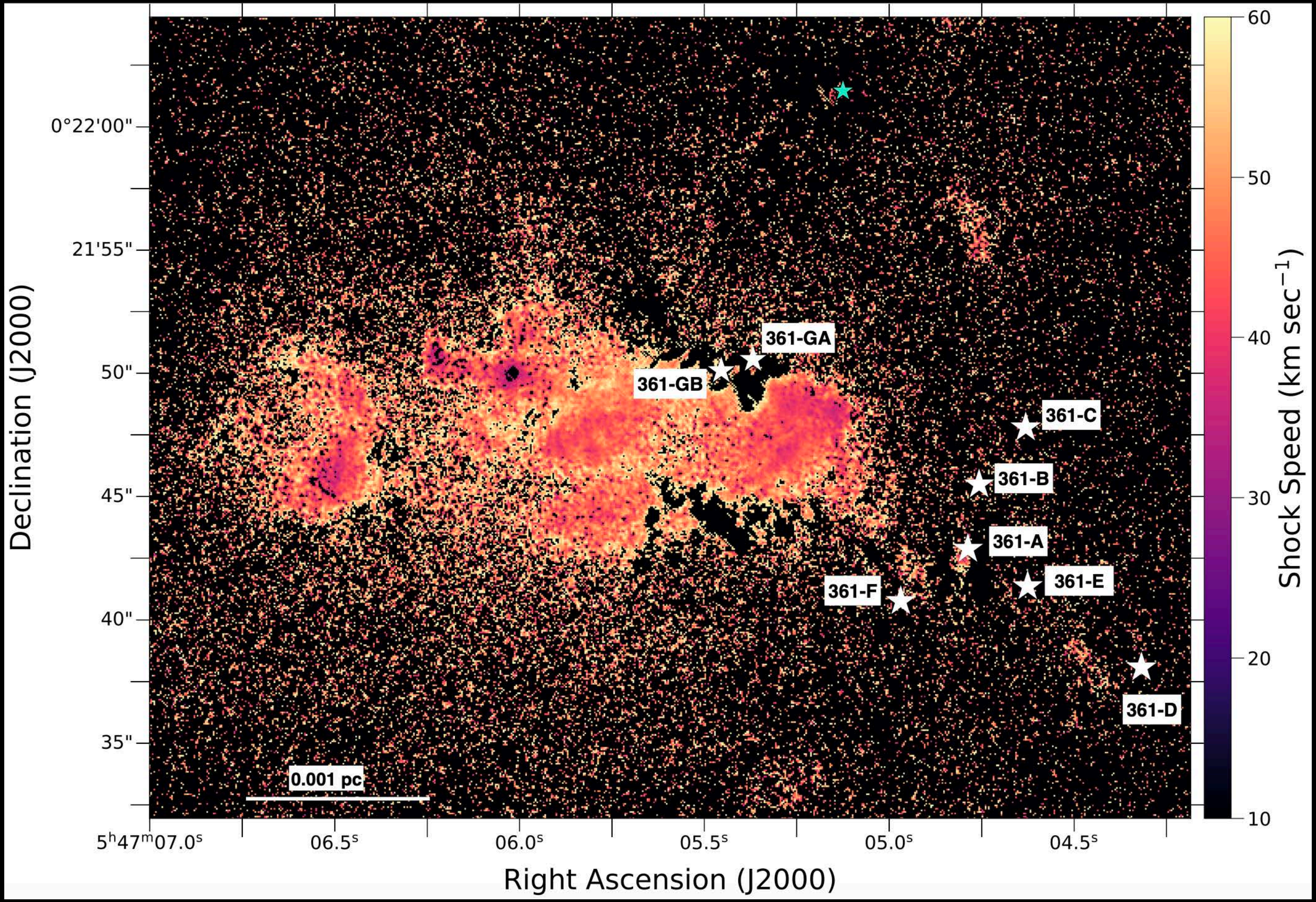
- The constant amount of material leaving each outflow are similar and have typical values (~5x10^{-6} $M_{\odot}$/yr)
  - HOPS 361-A has consistent momentum flux
  - HOPS 361-C has decreasing momentum flux

- ***The combination of HST and SOFIA enable a full understand the 3D flow!***

- ***The community needs more space-based high spectral resolution and FIR capability.***

Backup Slides

Shock Speed Map Karnath et al. (2024)



Extinction Map Karnath et al. (2024)