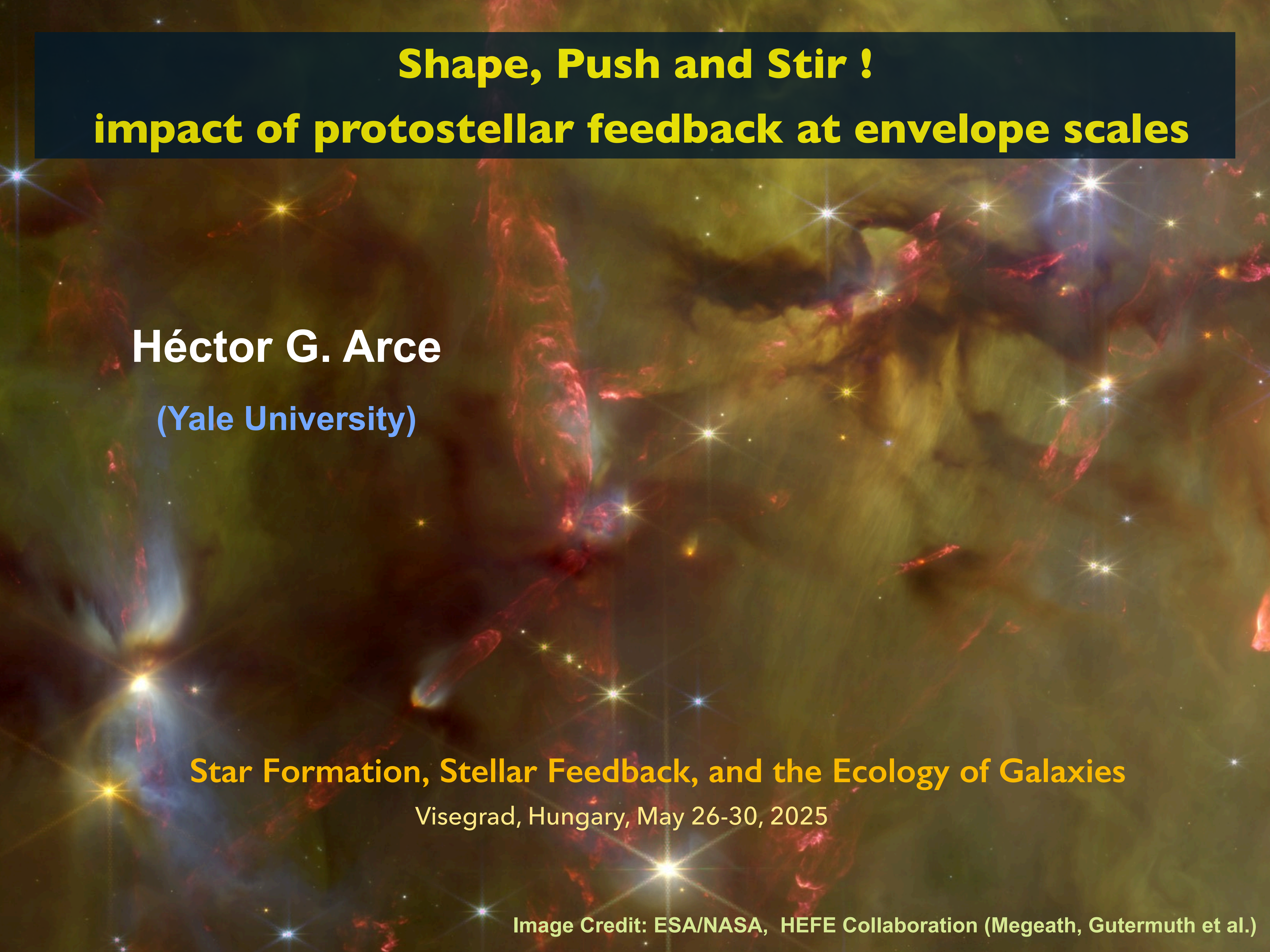


Shape, Push and Stir !
impact of protostellar feedback at envelope scales

Héctor G. Arce

(Yale University)

Star Formation, Stellar Feedback, and the Ecology of Galaxies

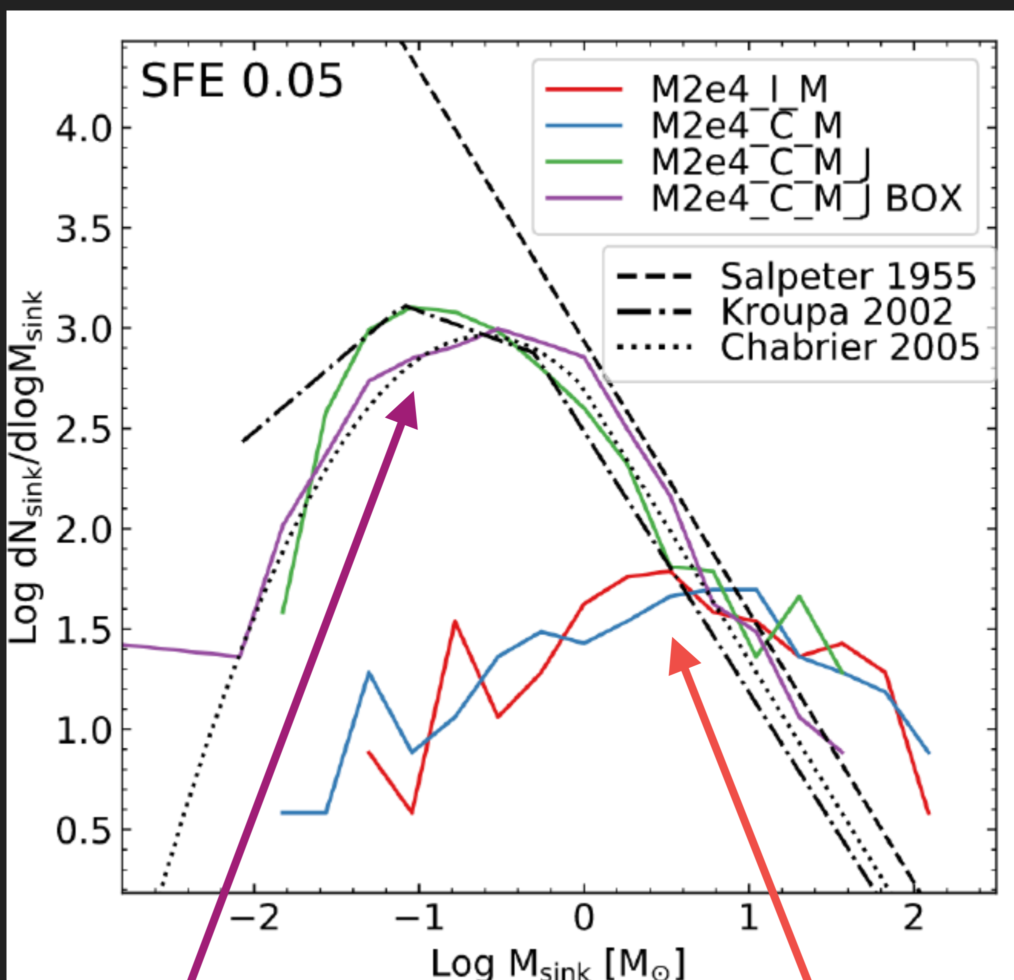
Visegrad, Hungary, May 26-30, 2025

Image Credit: ESA/NASA, HEFE Collaboration (Megeath, Gutermuth et al.)

OUTFLOW FEEDBACK DRIVES TURBULENCE, REDUCES STAR FORMATION RATE

SIMULATIONS SHOW STELLAR FEEDBACK IMPORTANT TO IMF + CLOUD EVOLUTION

Simulations with jet feedback recover observed IMF



Guszejnov et al. (2021)

Simulations **with** jet feedback

Simulations **without** jet feedback

STARFORGE simulation

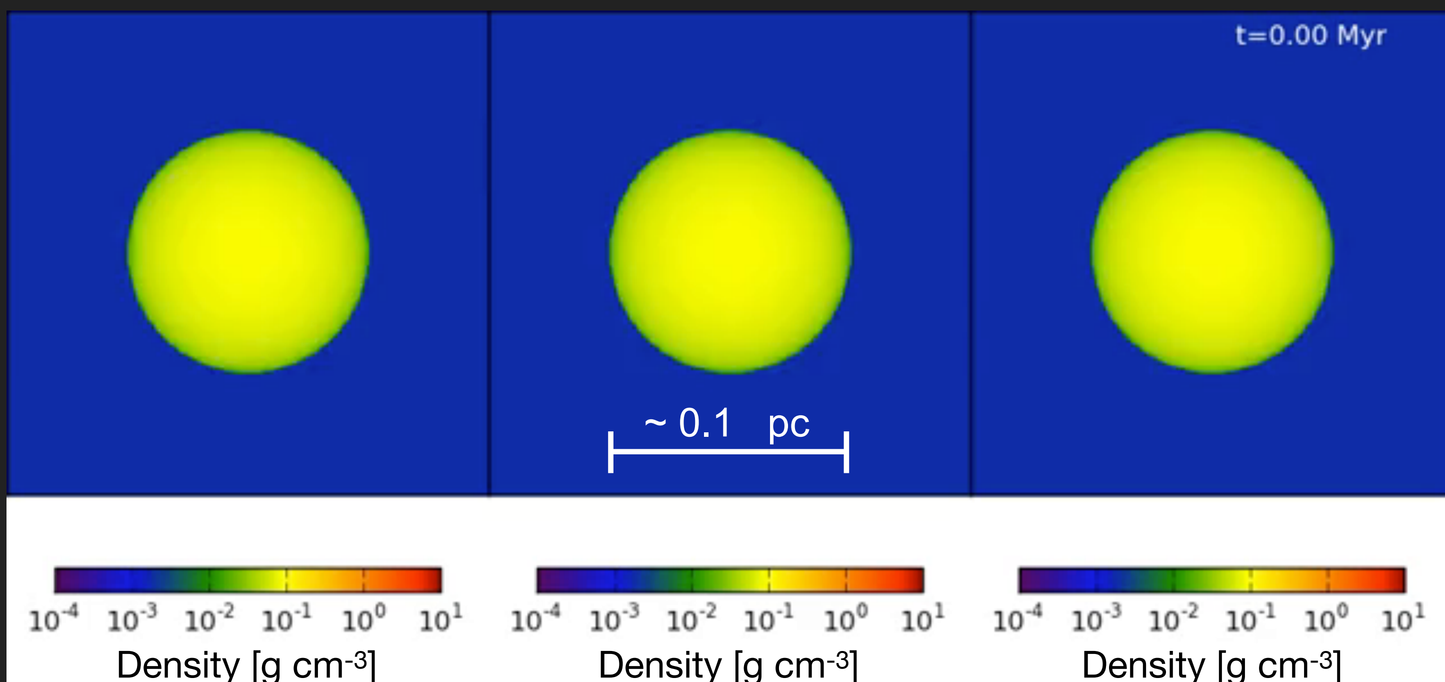
Simulation of star formation with feedback in $2 \times 10^4\ \mathrm{M}_\odot$ cloud

Grudić et al. (2022)

OUTFLOW-CORE INTERACTION MAY DETERMINE STAR FORMATION EFFICIENCY

SIMULATIONS SHOW THAT OUTFLOWS PERTURB CORE (MAIN MASS RESERVOIR OF FORMING STAR)

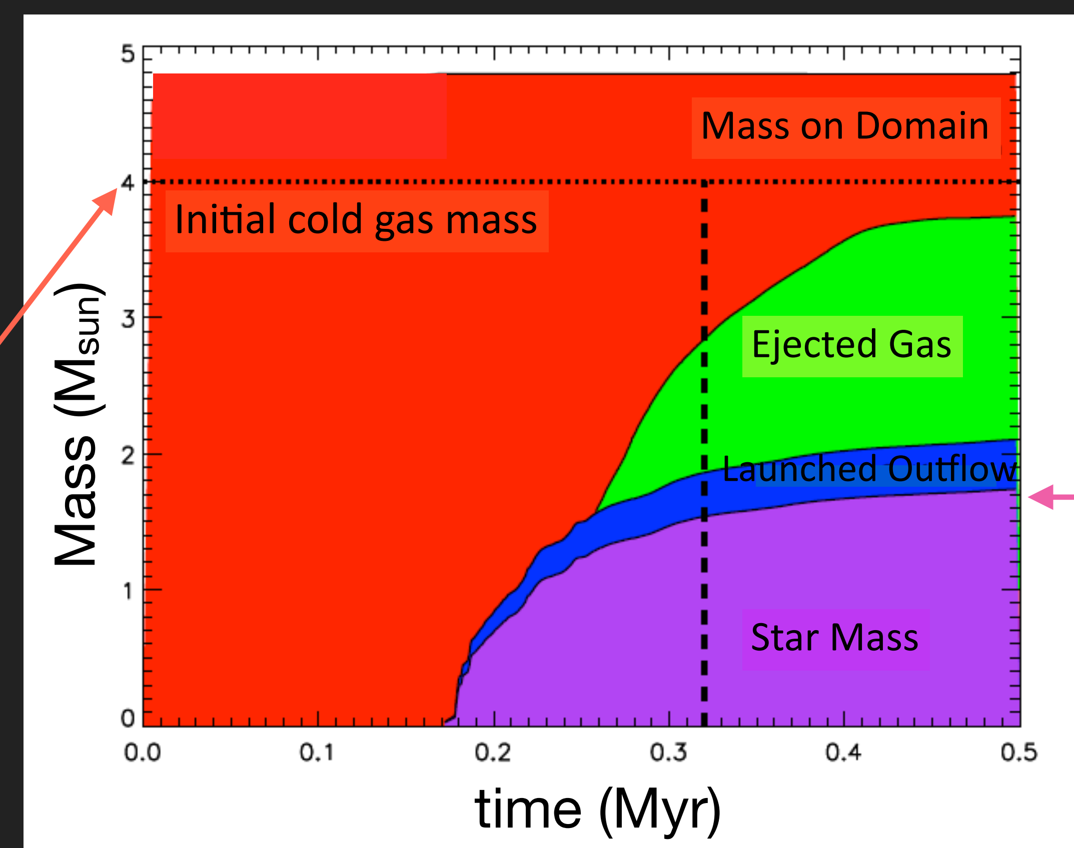
Simulation of outflow in core
(color show density of core gas):



slices of log density through *x*, *y* and *z* planes

Offner & Arce (2014)

Evolution of mass in domain



Offner & Arce (2014)

initial core mass
= 4 M_{sun}

final star mass
~1.7 M_{sun}

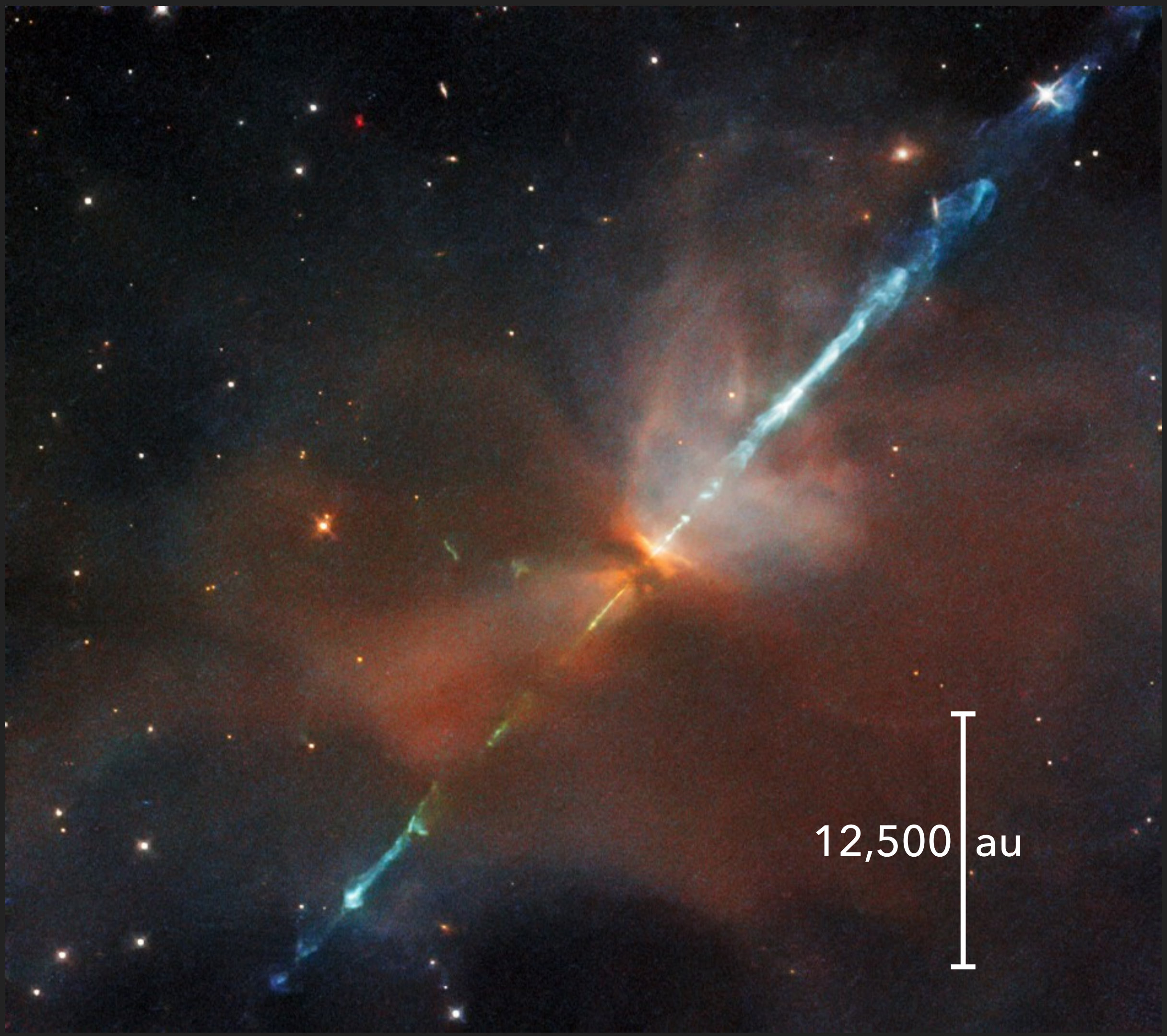
Core Star formation Efficiency (SFE) = $(M_{star}/M_{core}) \sim 0.4$

See also: numerical simulations by Machida & Hosokawa (2013); Offner & Chaban (2017); Grudić et al. (2021)

FEEDBACK OBSERVED AT DIFFERENT WAVELENGTHS

OPTICAL / IR PROVIDE SOME (BUT NOT ALL) INFORMATION ON FEEDBACK

HH 111



HST WFC3 IR ~1.3–1.6 μm narrow band filters

Credit: ESA/Hubble & NASA, B. Nisini

HOPS 84 / IRAS 05329-0505

JWST NIRCam Image (~1.6 – 4.7 μm)

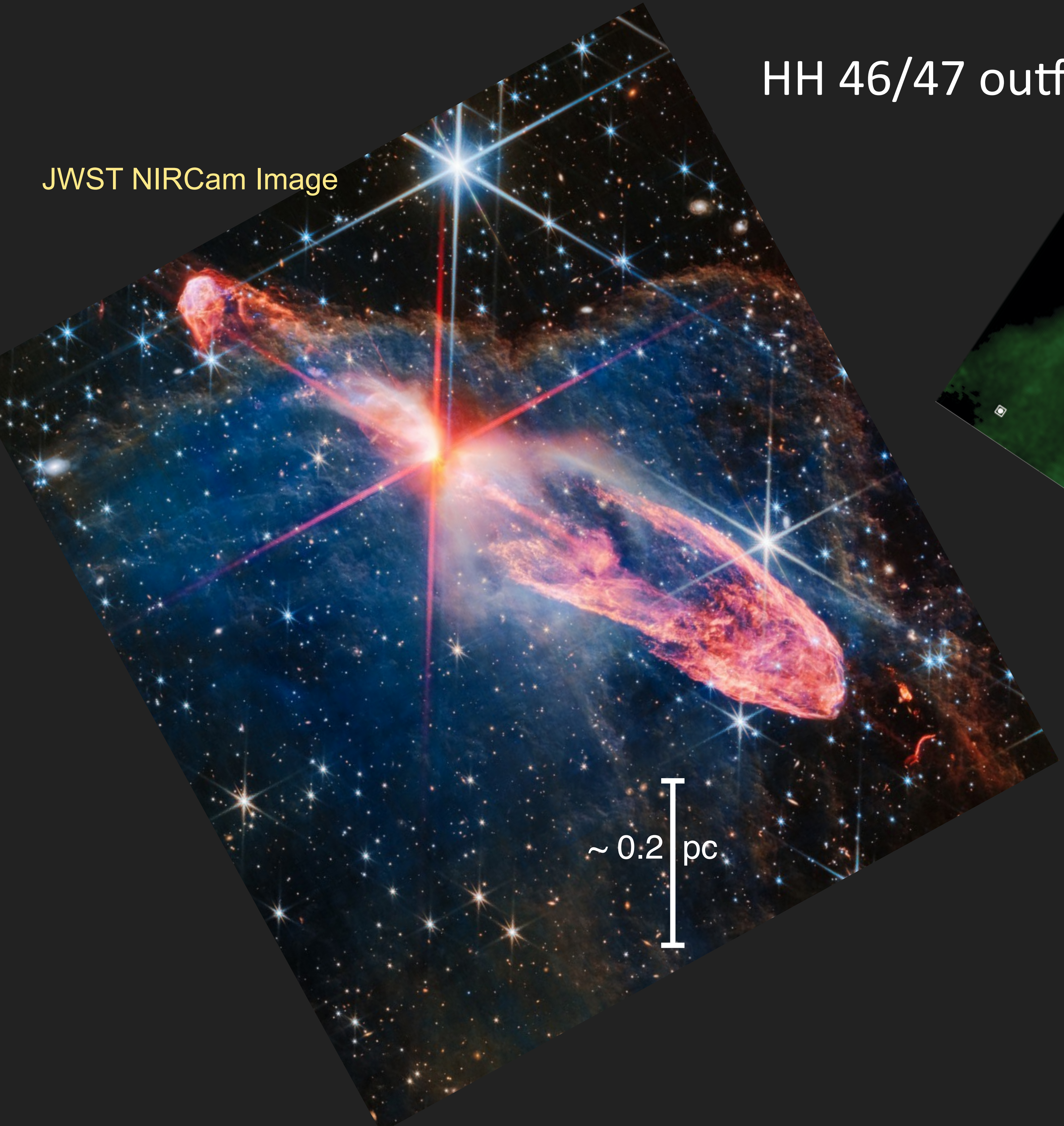
Credit: ESA/NASA, HEFE Collaboration (Megeath, Gutermuth et al.)

FEEDBACK FROM YOUNG STAR OBSERVED AT MANY WAVELENGTHS

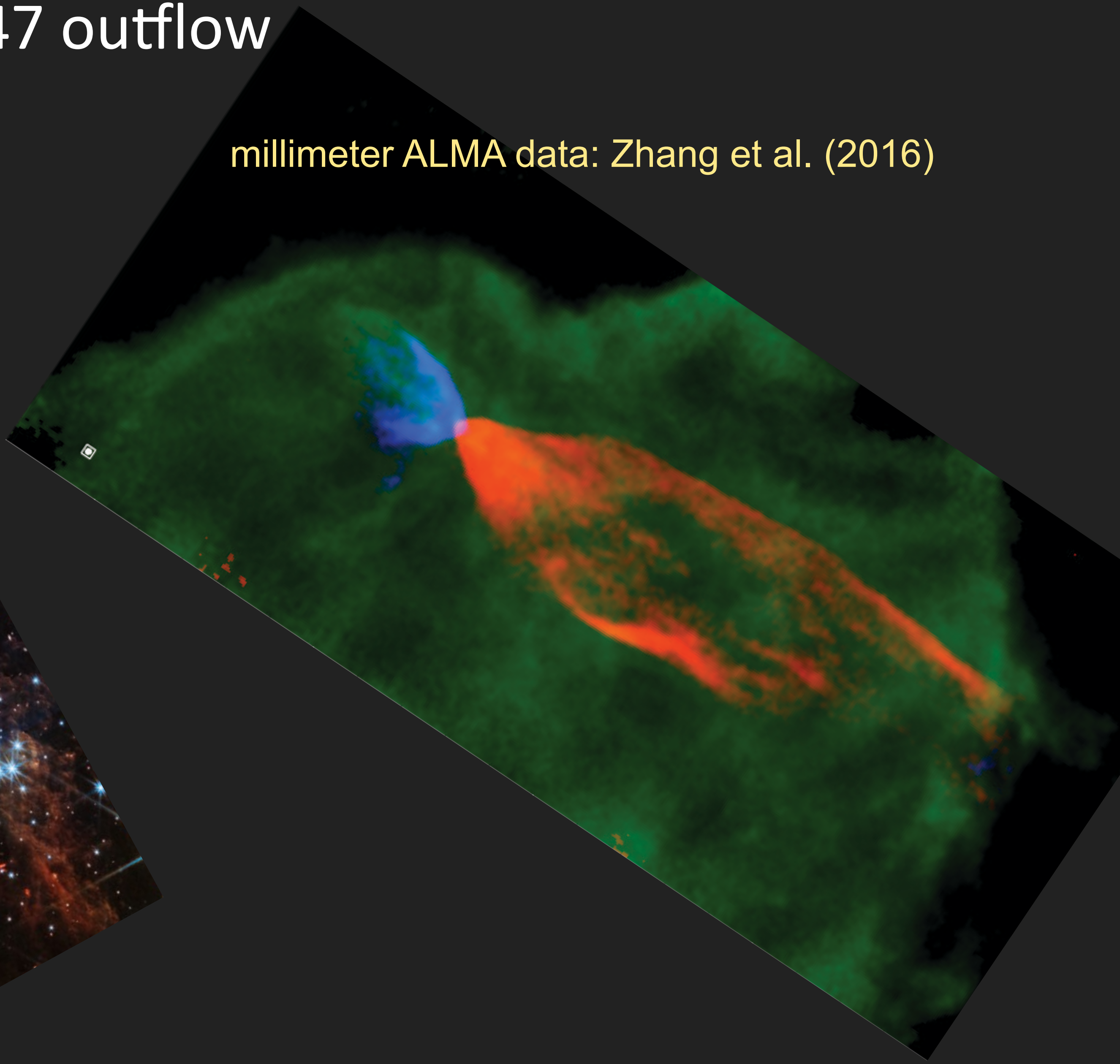
JWST GREAT FOR STUDYING SHOCKS, BUT NEED TO PROBE GAS TO DETERMINE FEEDBACK IMPACT ON CLOUD

HH 46/47 outflow

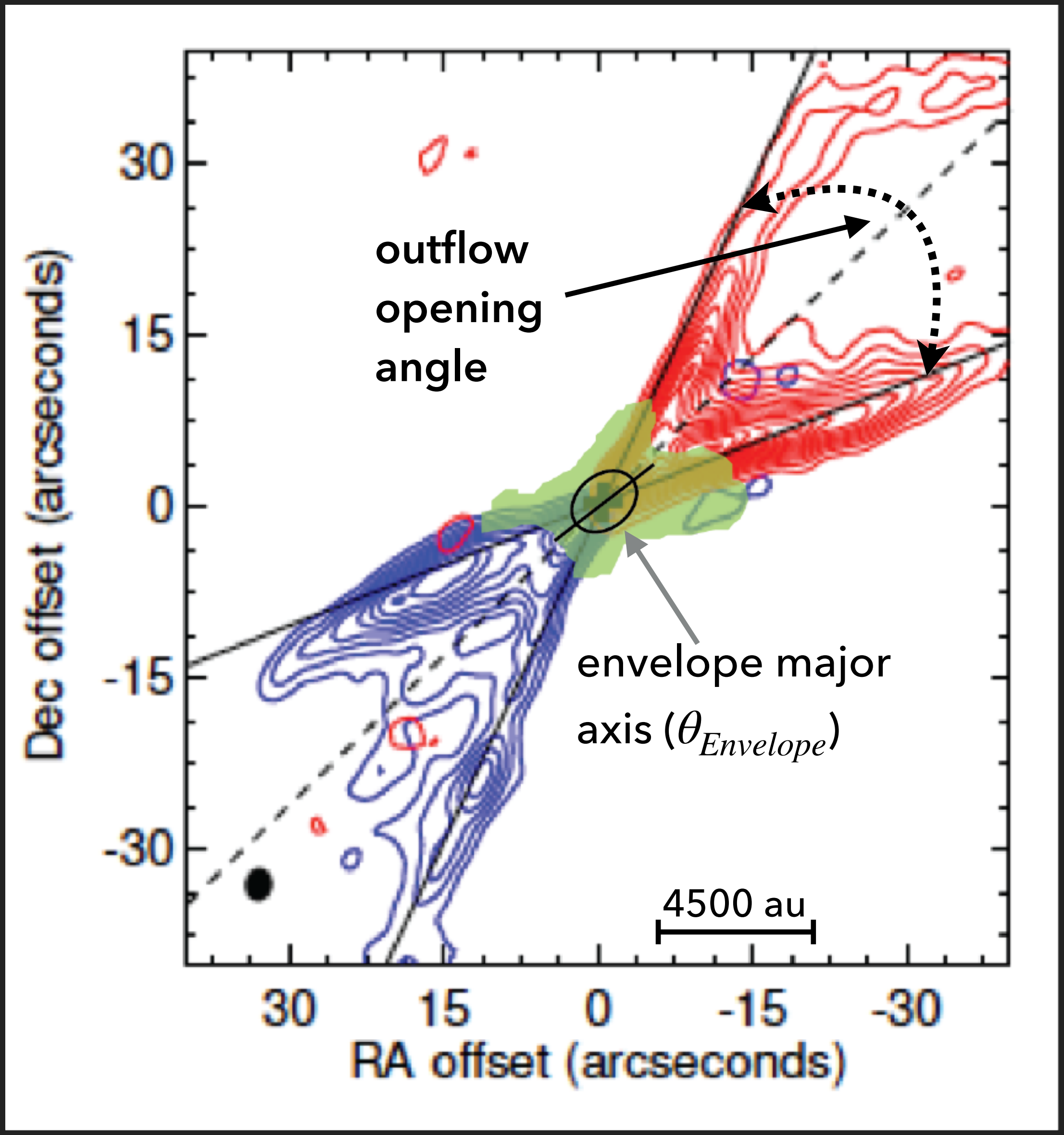
JWST NIRCam Image



millimeter ALMA data: Zhang et al. (2016)



OUTFLOWS PUSH ENVELOPE MATERIAL CREATING CAVITIES



Molecular outflow in Perseus from Class 0 source

outflow opening angle provides first order assessment of outflow impact on core/envelope:

wider outflow --> larger core volume / more mass swept-up

red contours: ^{12}CO red-shifted lobe

blue contours: ^{12}CO blue-shifted lobe

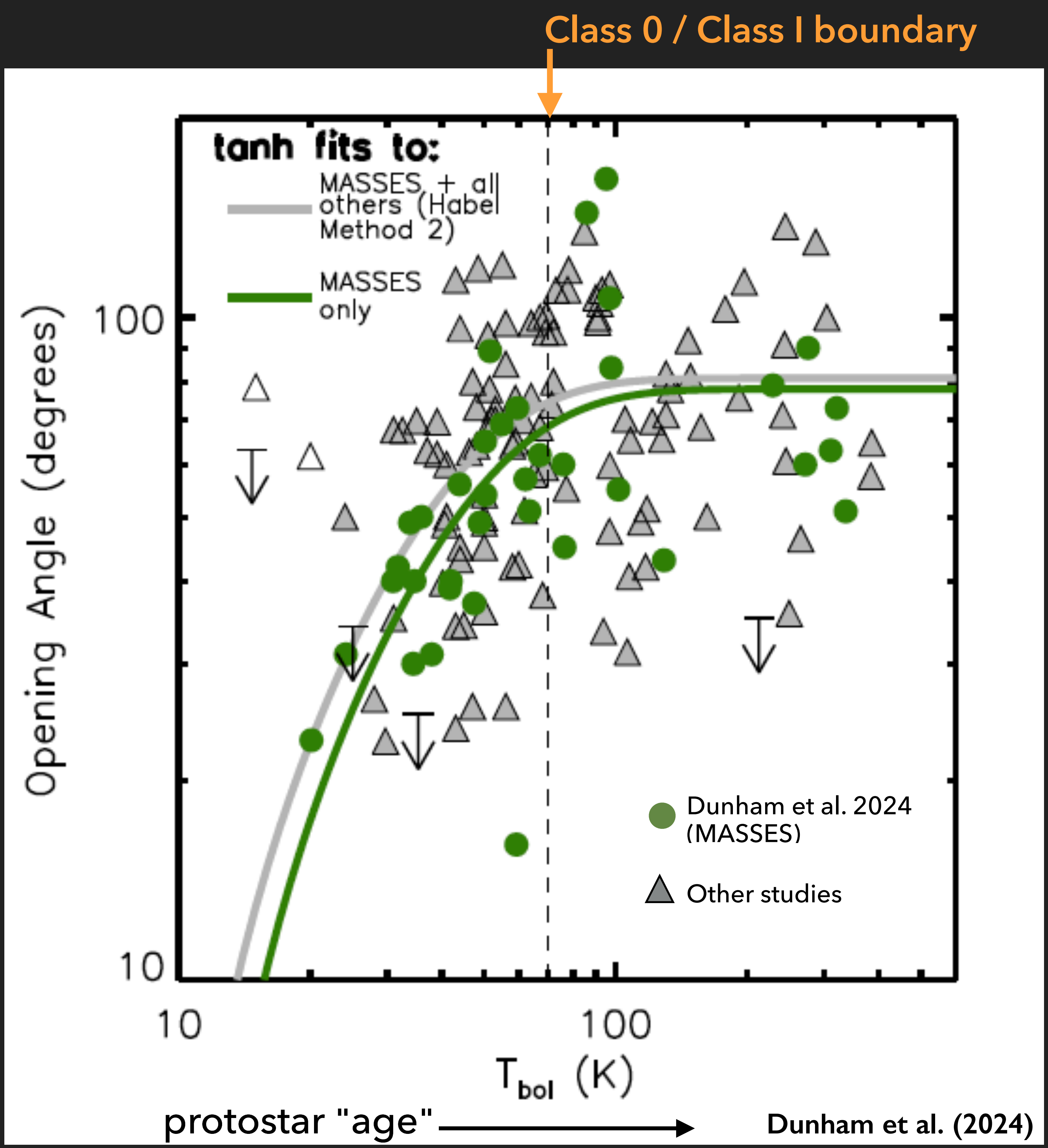
green: envelope traced by $C^{18}O$

Envelope shape and kinematics may show impact of outflow on dense gas around protostar

part of Mass Assembly of Stellar Systems and their Evolution with the SMA (MASSES) survey

Stephens et al. 2018, 2019 Dunham et al., 2024

SMA SURVEY OF PERUSES PROTOSTARS SHOW INCREASE INCREASE IN OUTFLOW OPENING ANGLE



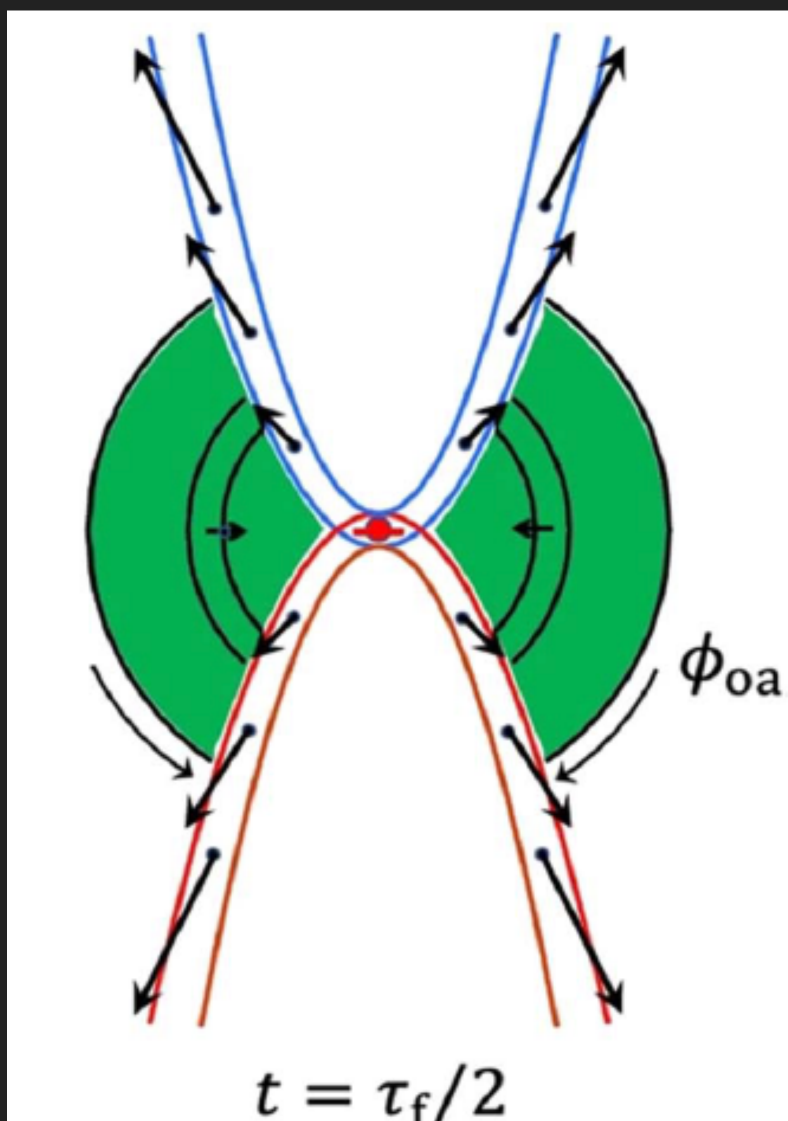
Dunham et al. (2024), using SMA (MASSES data) and other studies see a general where older protostars have wider cavities.

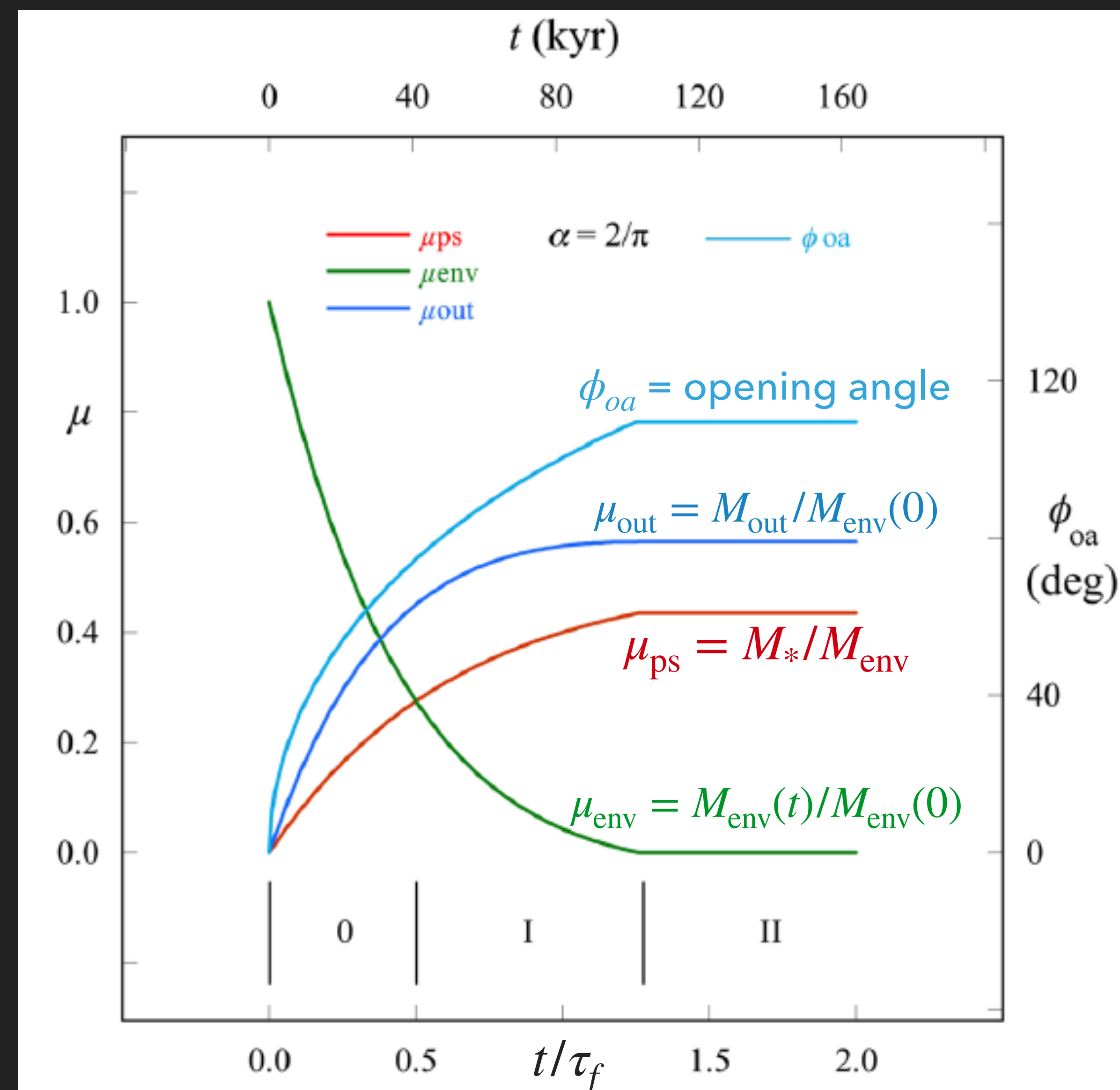
Combining results from MASSES and others, it seems that while cavities widen at early (Class 0) stages, they then remain ~constant at later (Class I) stages

Mass Assembly of Stellar Systems and their Evolution with the SMA (MASSES) Survey (Stephens et al. 2018; 2019)

PARABOLIC CAVITIES DISPERSE ENOUGH CORE GAS TO RESULT IN SFE ~ 0.4

Even if cavity opening angle (ϕ_{oa}) stalls at ~ 110 deg at end of Class I



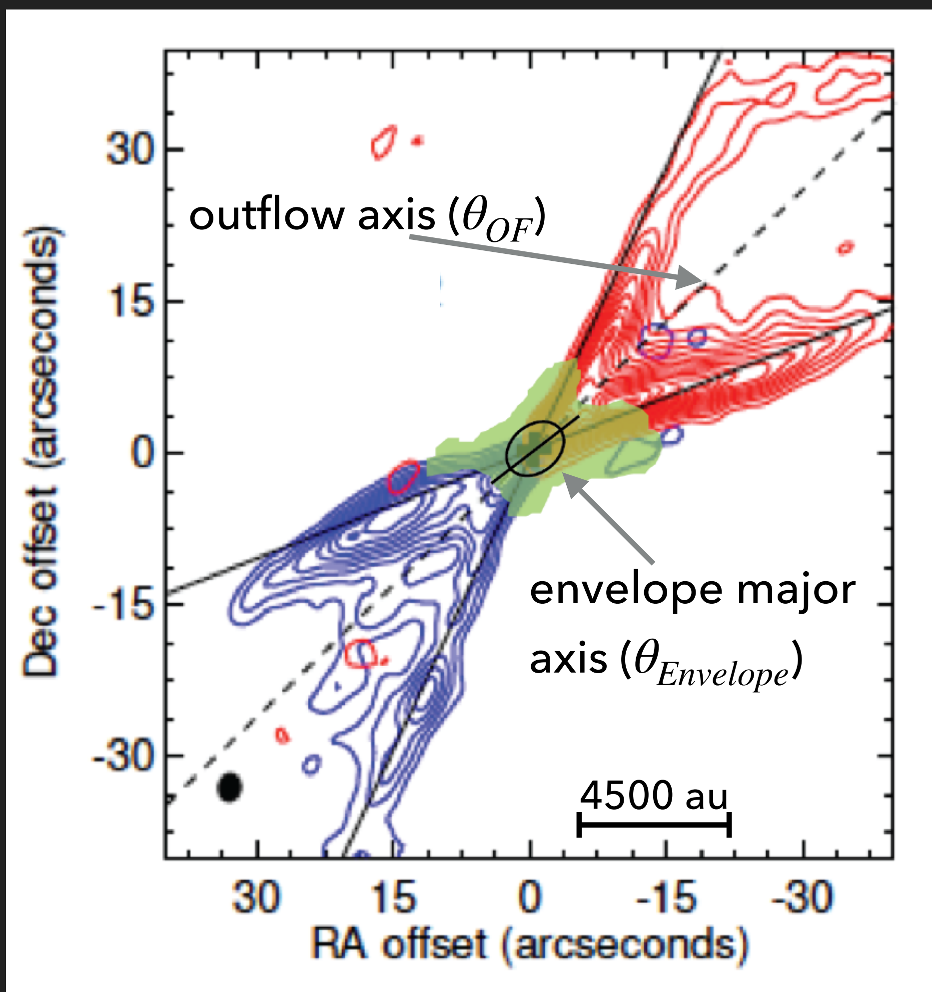


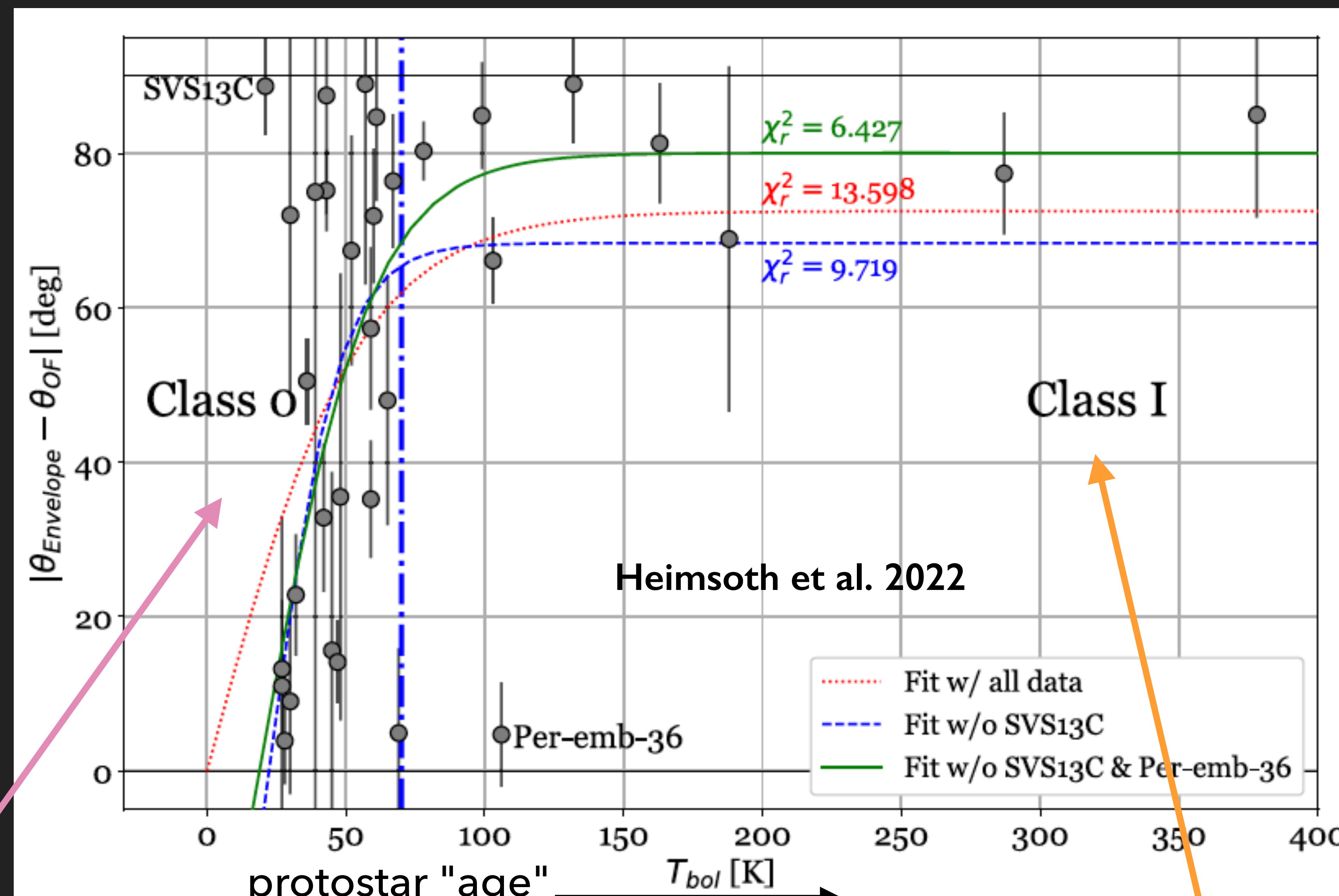
(t/τ_f = accretion age/core free fall time)

(Myers, Dunham & Stephens 2023)

EVIDENCE OF OUTFLOW AFFECTING SHAPE OF ENVELOPE

Difference between envelope major axis and outflow axis appear to change over time (using MASSES data)

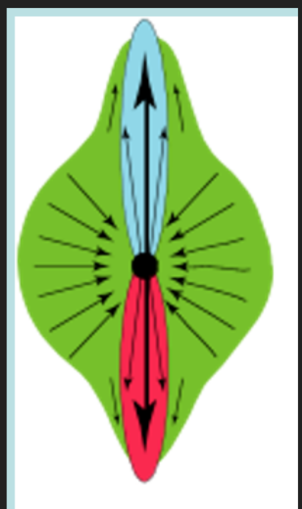




Class 0 : outflow carve out cavity in envelope; cavity walls seen in dense tracers

Class I : cavities are much wider and dense gas mostly is perpendicular to outflow

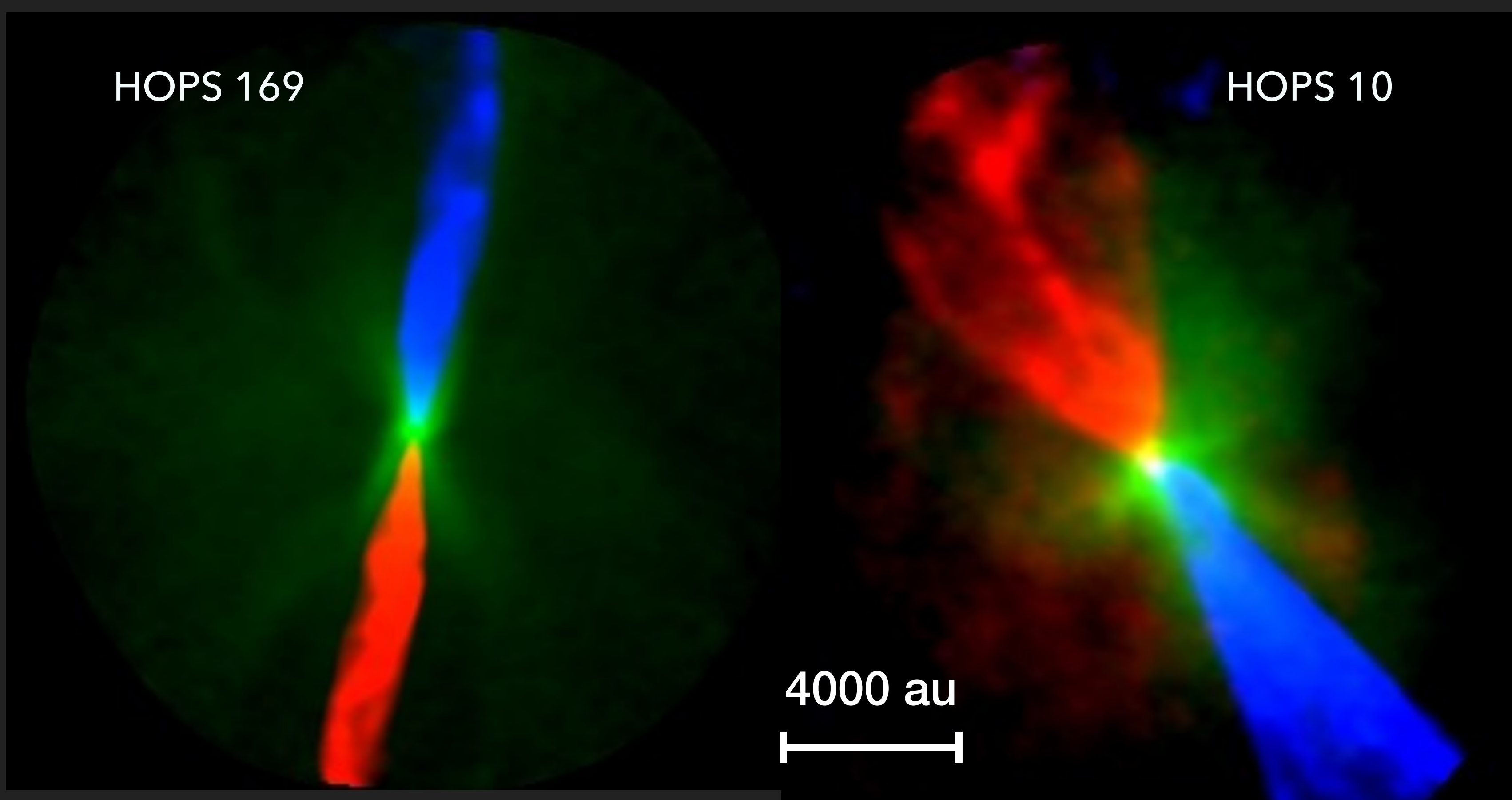
ALMA + TP DATA SHOW LOW-INTENSITY EXTENDED C180 EMISSION + CENTRAL BRIGHT EMISSION

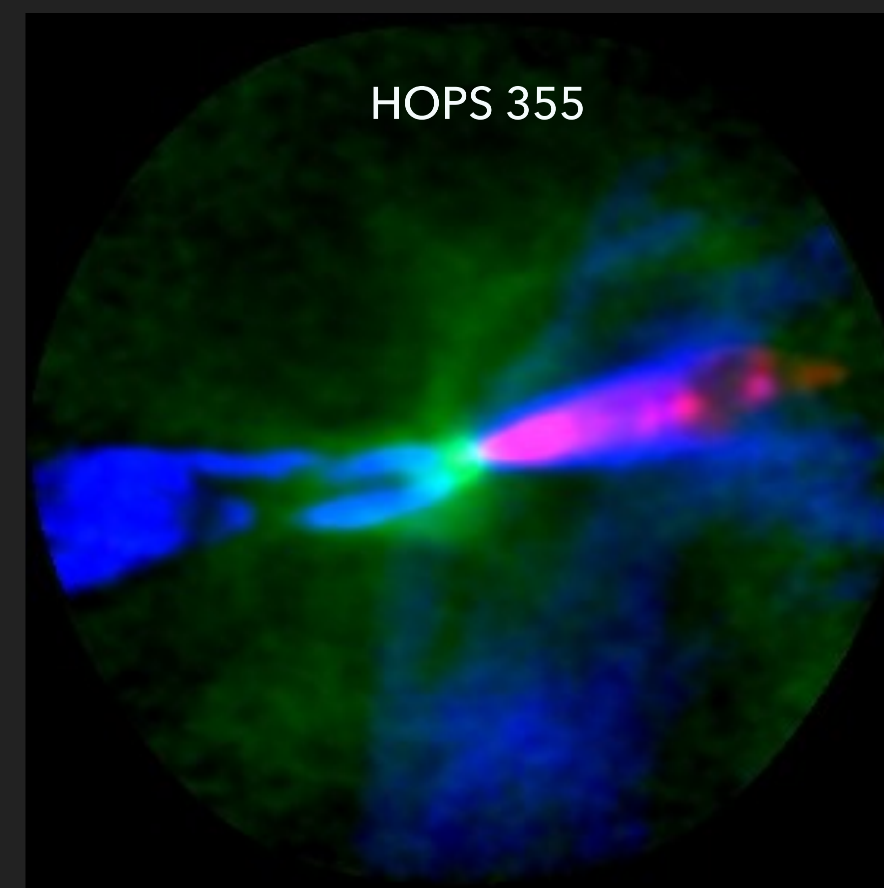


Bright emission extends (mostly) parallel to outflow in these Class 0 sources, tracing outflow cavity walls

Example of how outflows **shape** their surrounding envelope

Blue-shifted $^{12}CO(2-1)$ outflow   Red-shifted $^{12}CO(2-1)$ outflow   Envelope traced by $C^{18}O(2-1)$

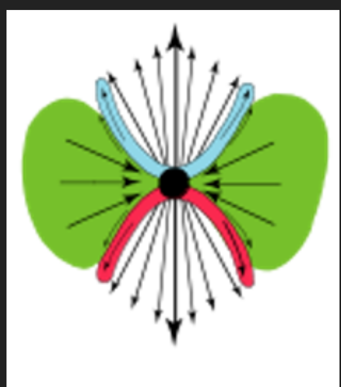




Essential to have ALMA 12m+7m+TP to probe range of structures

OUTFLOWS SHAPE THEIR PARENT ENVELOPE

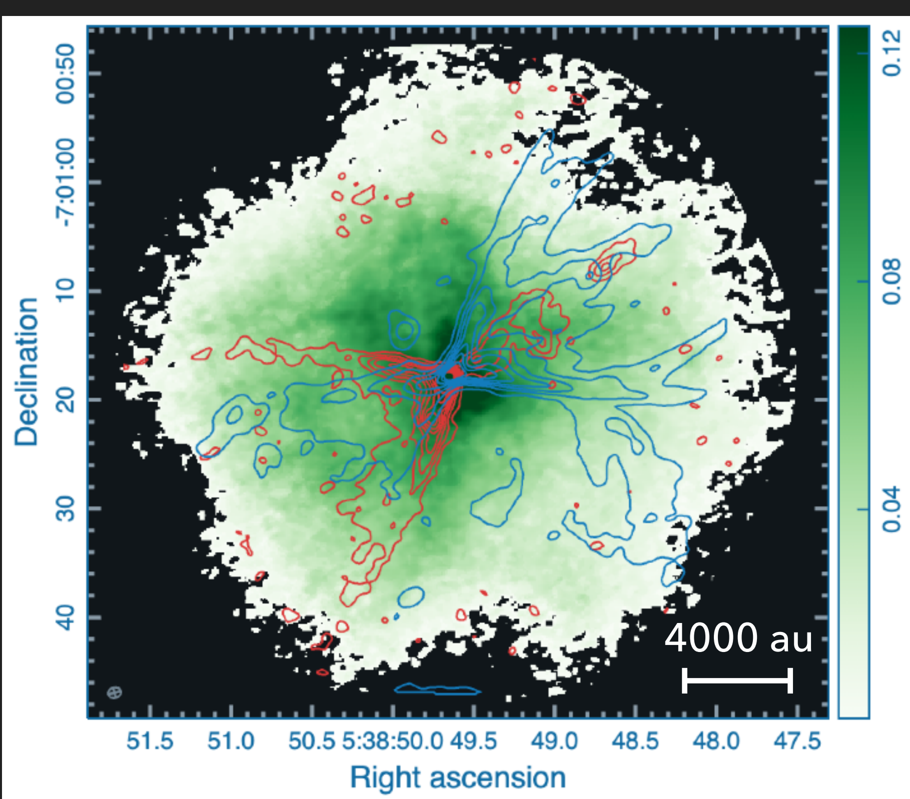
ALMA DATA SHOW MOST DENSE GAS PERPENDICULAR TO OUTFLOW & OUTFLOW-INDUCED CAVITIES



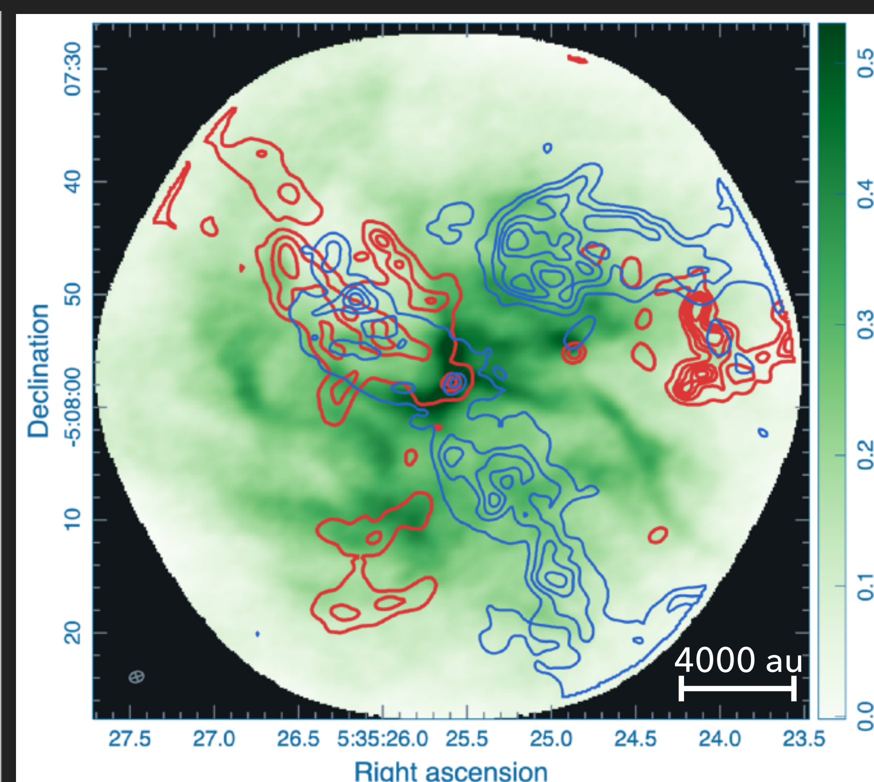
Bright emission extends (mostly) perpendicular to outflow in these Class I sources
+ maps show clear cavities coincident with molecular outflow

Blue-shifted ^{12}CO(2-1) outflow | Red-shifted ^{12}CO(2-1) outflow | Envelope traced by C^{18}O(2-1)

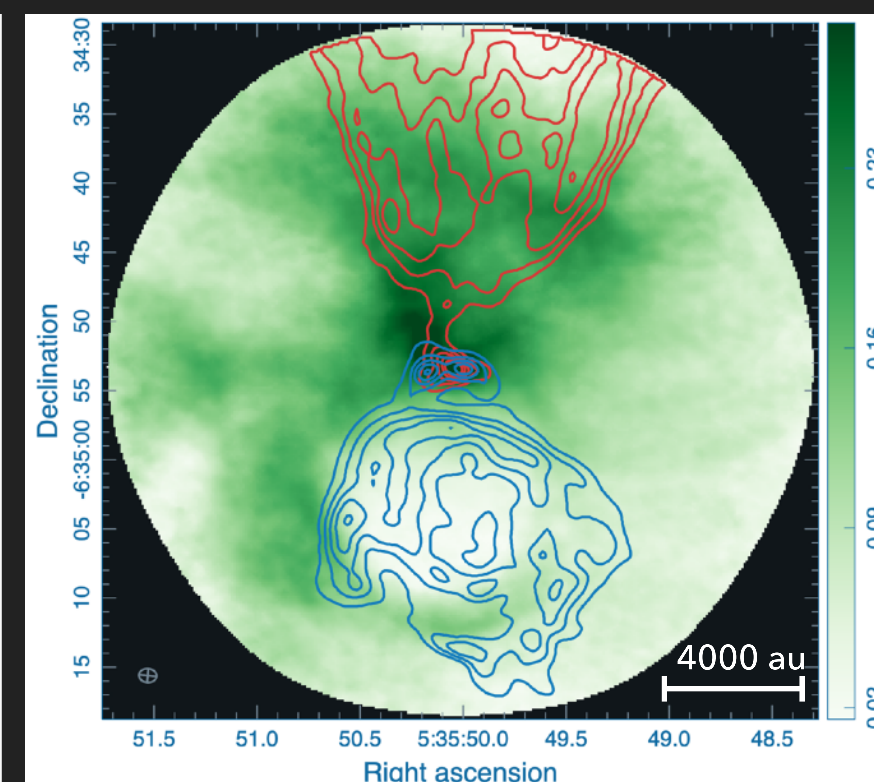
HOPS 139



HOPS 71



HOPS 177

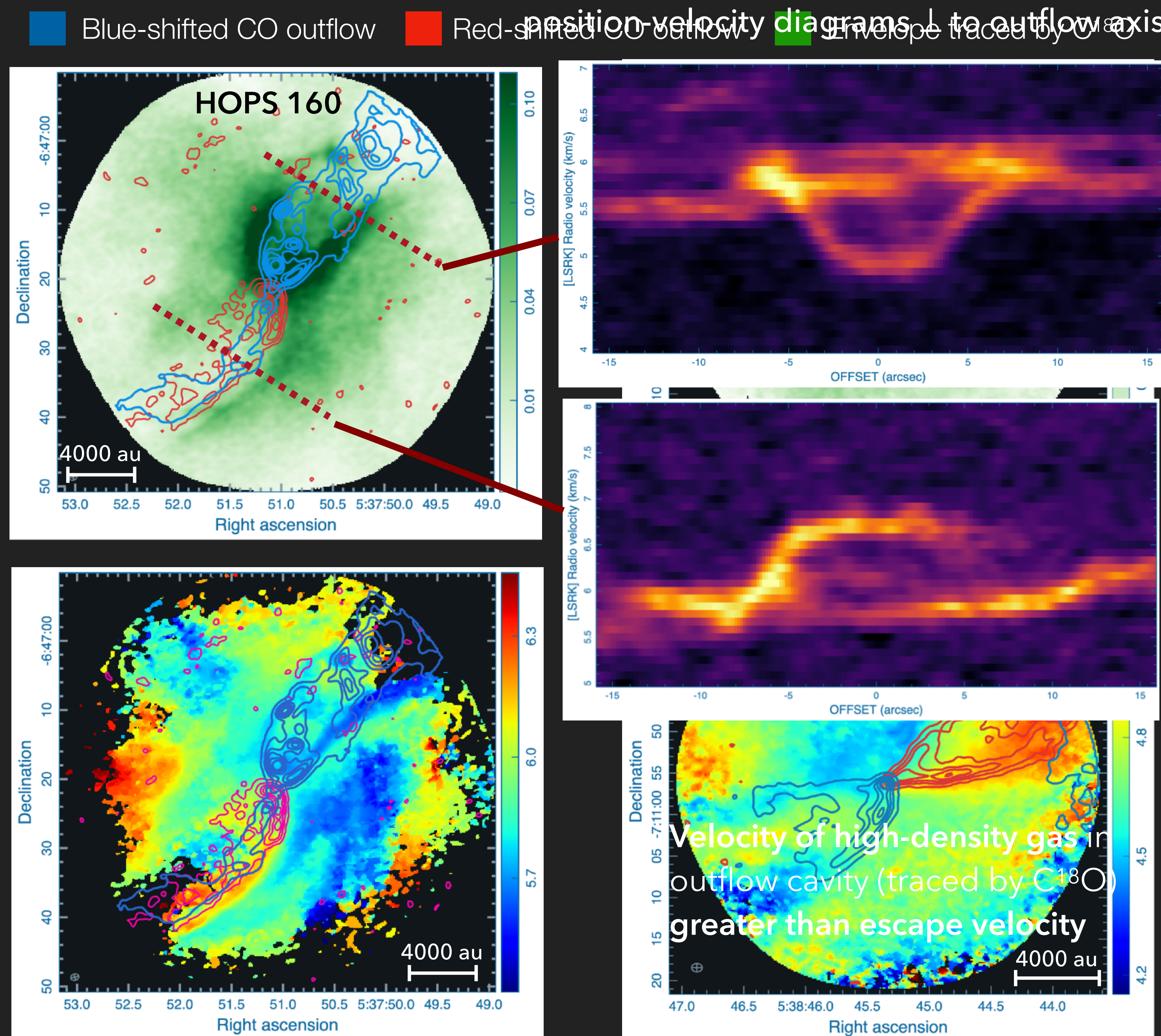


Outflows clearly **shape** the structure and density distribution of envelopes

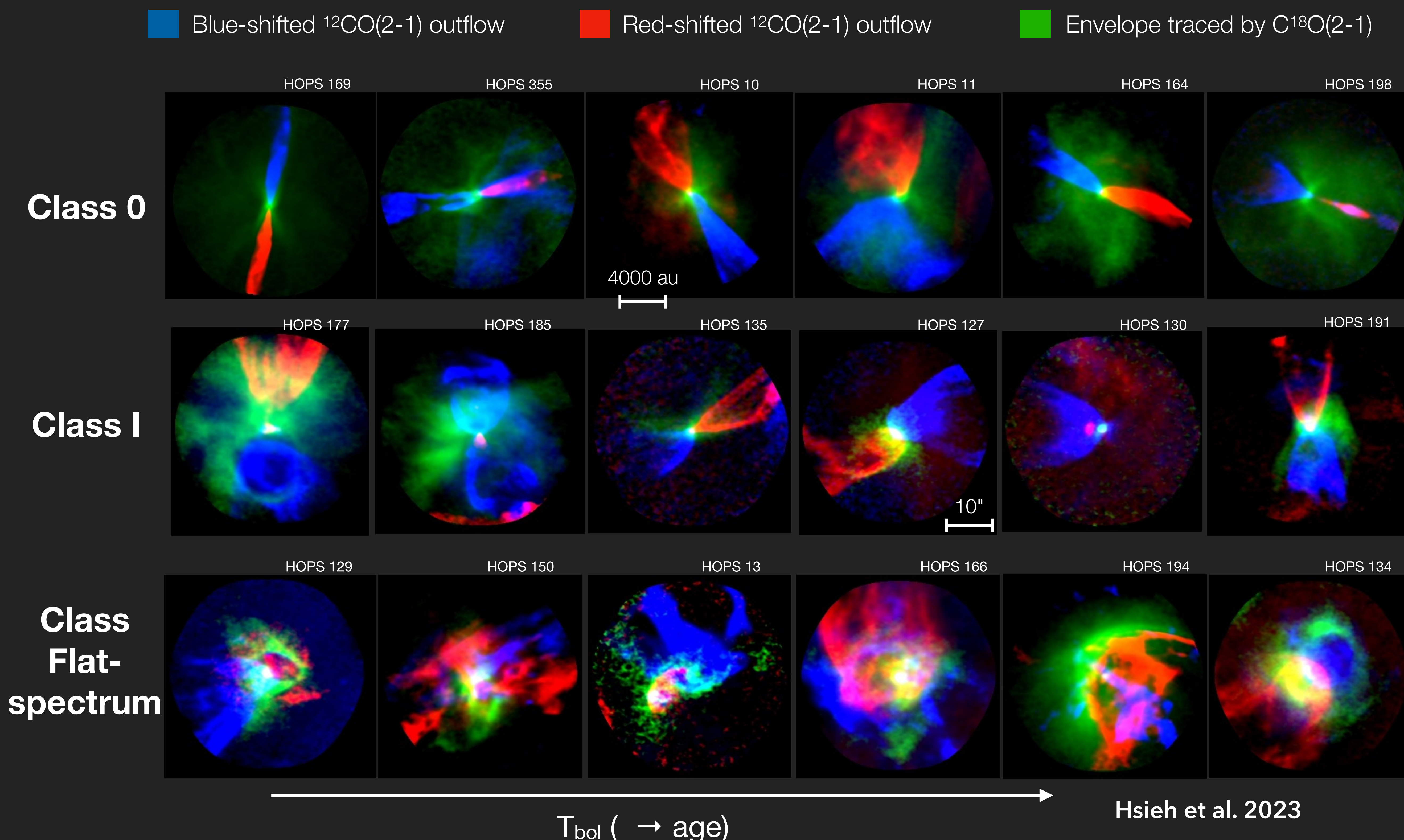
DATA SHOW VELOCITY GRADIENT IN DENSE GAS ALONG OUTFLOW

$C^{18}O$ integrated intensity maps + outflow contours show outflow-induced cavity in envelope

$C^{18}O$ velocity maps + outflow contours show outflow-generated velocity gradients in envelope



ALMA MULTI-LINE SURVEY OF PROTOSTARS AT DIFFERENT EVOLUTIONARY STAGES



Hsieh et al. 2023

SIGNIFICANT TOTAL MASS-LOSS DURING PROTOSTELLAR STAGE

Evolutionary Class	duration of stage [Myr]	$\dot{M}_{out}$ [$M_\odot$ Myr^{-1}]	total M_{out} [$M_\odot$]
0	~ 0.1 – 0.3	2.6	0.3 – 0.7
I	~ 0.3 – 0.5	4.4	1.2 – 2.3
Flat-spectrum	~ 0.3 – 0.5	0.5	0.2 – 0.3
Total during protostellar phase:	~ 0.5 – 1.3	––	1.7 – 3.3

Total entrained molecular outflow mass loss of envelope/core during protostellar stage is ~ 1 – 3 $M_\odot$

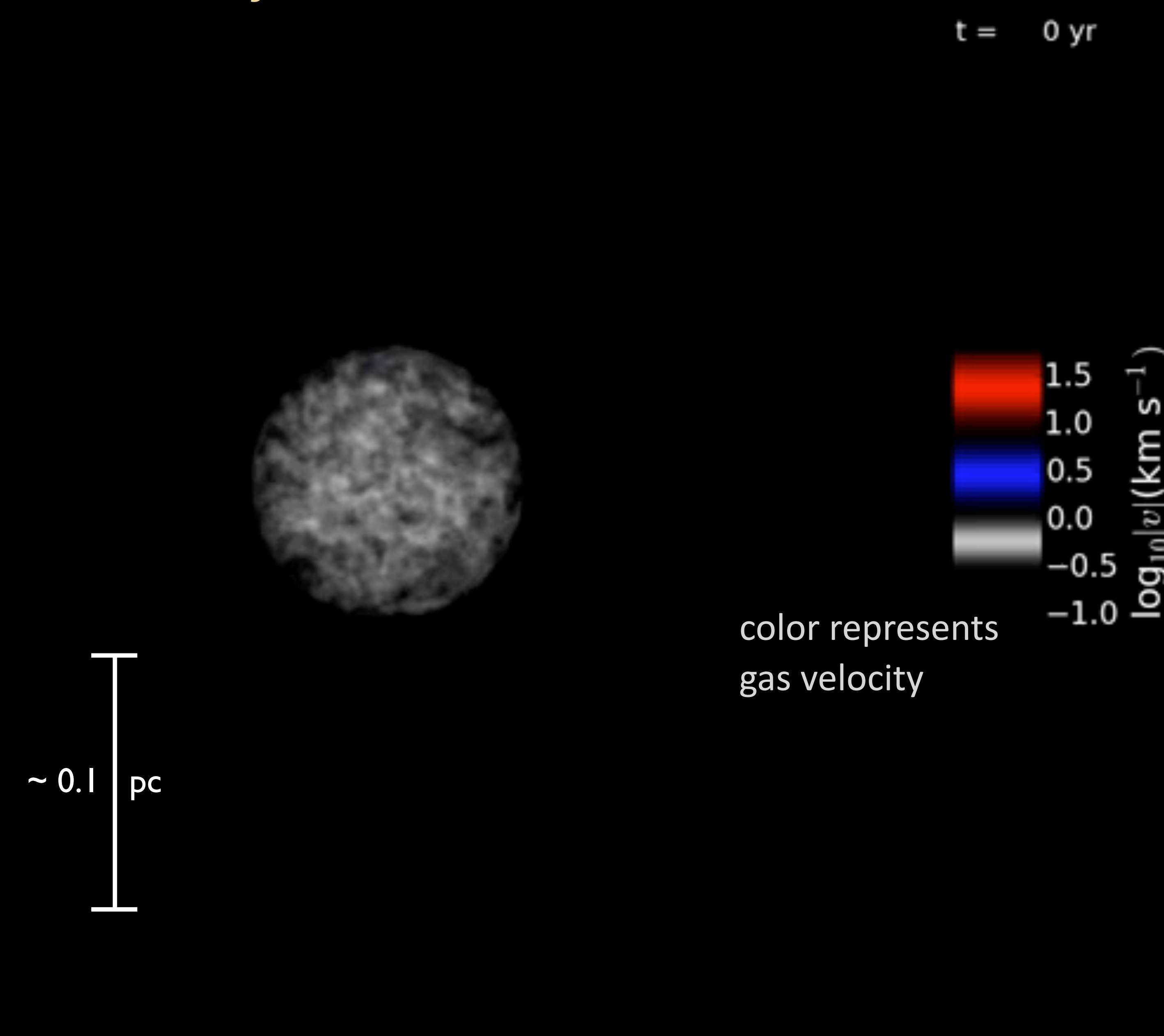
this is larger than current average mass of cores (out to ~6000 au)

––> implies ~continues replenishment of material from larger scales (cloud) to core

Hsieh et al. 2023

SIMULATIONS (OLD AND NEW) SHOW OUTFLOWS DRIVE TURBULENCE IN CORE

Old hydro (no B) simulations



Offner & Arce (2014)

More recent MHD simulations

Effects of stellar feedback on cores in STARFORGE

> "Cores strongly affected by feedback have a higher velocity dispersion on average than cores with less feedback… We attribute this to the injection of momentum into the dense gas via these feedback mechanisms"

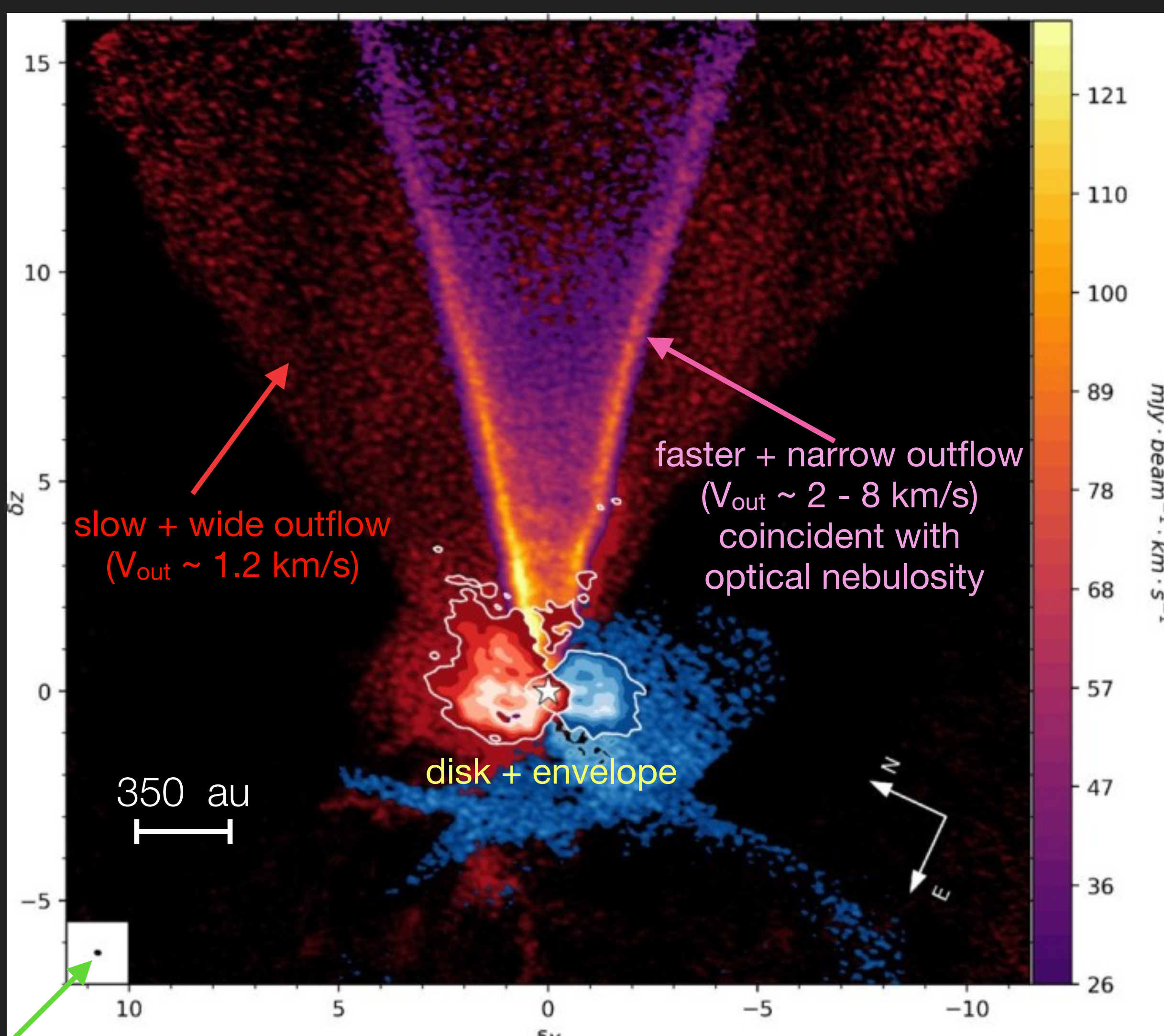
Neralawar et al. 2024

SLOW OUTFLOW AT ANGLES BEYOND OPTICAL NEBULOSITY

Previously undetected very wide-angle outflow in DG Tau B

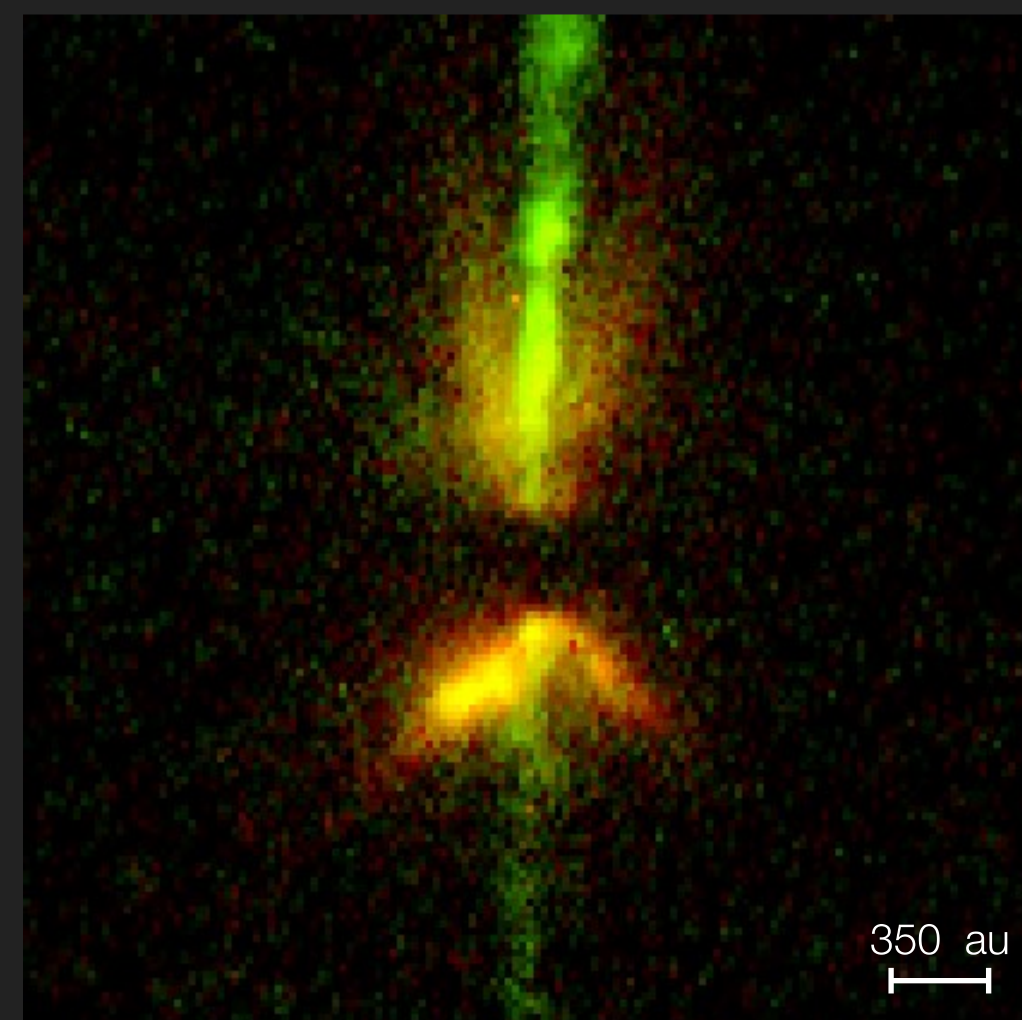
Wide outflow can drive turbulence and entrain envelope material beyond "classical" outflow walls

ALMA $^{12}CO(2\text{-}1)$



de Valon et al. (2020)

HST - WFPC2 (optical) image

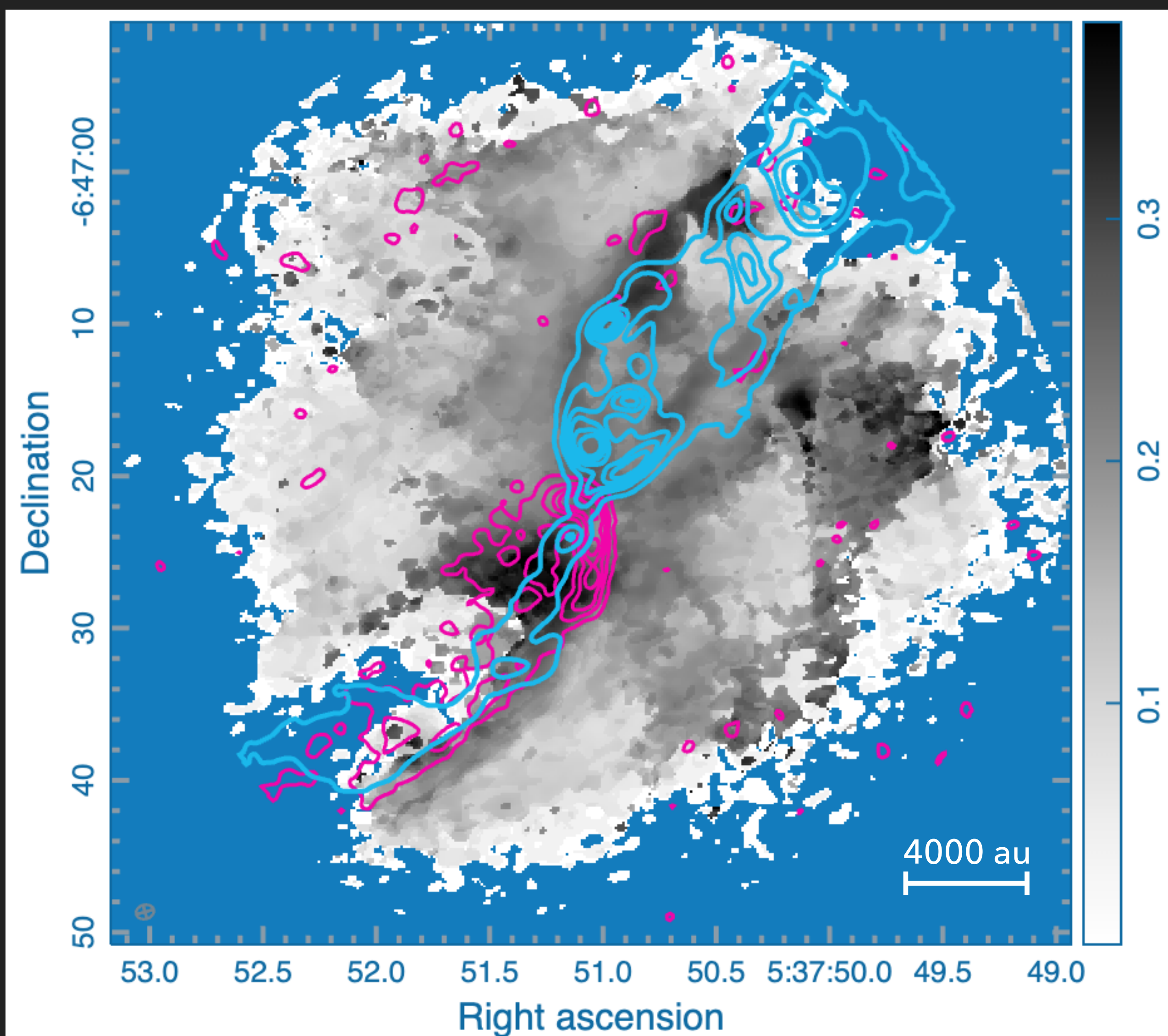


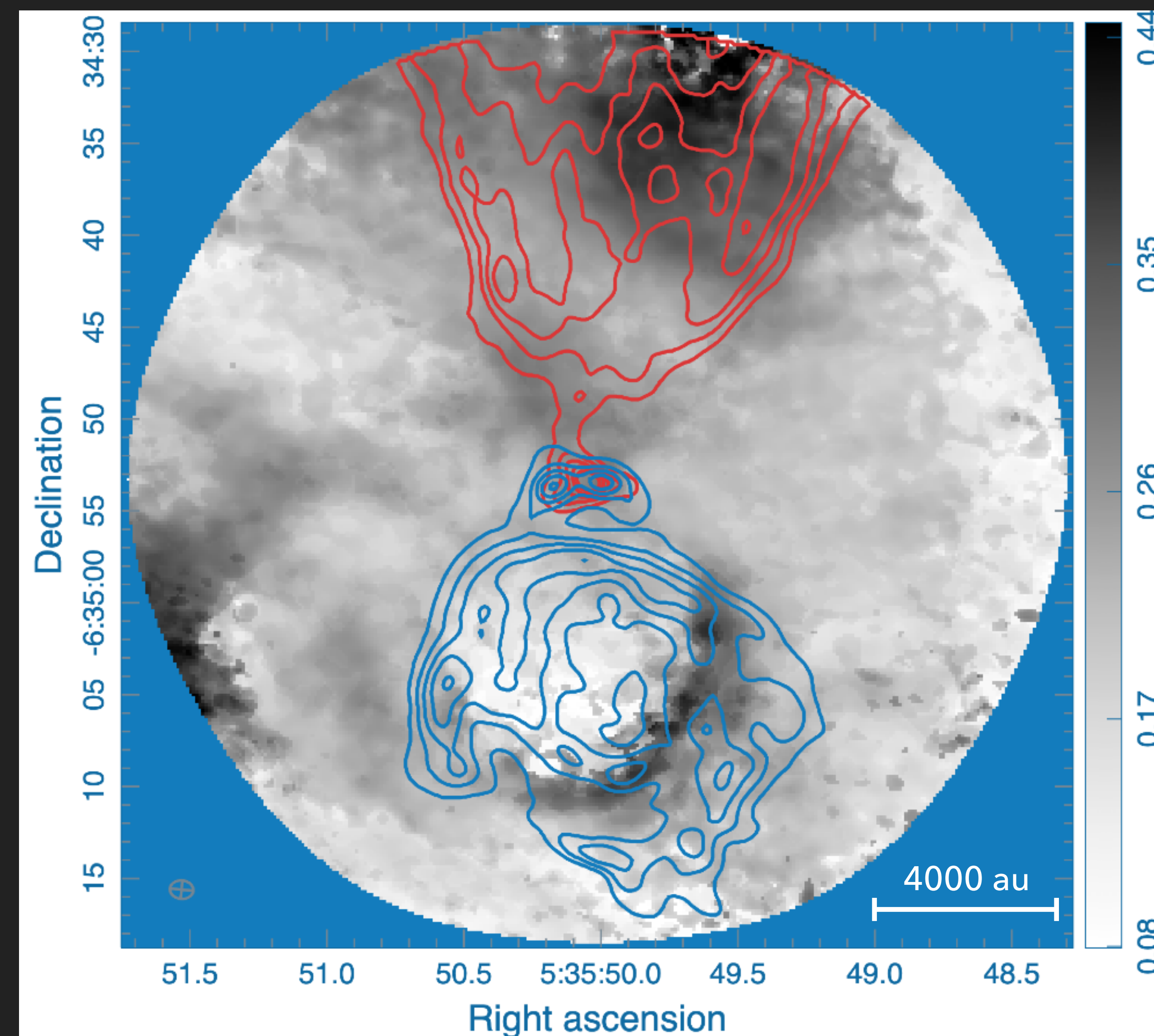
Stapelfeldt et al. (1997) + Padgett et al. (1999)

OUTFLOWS STIR THEIR PARENT ENVELOPE

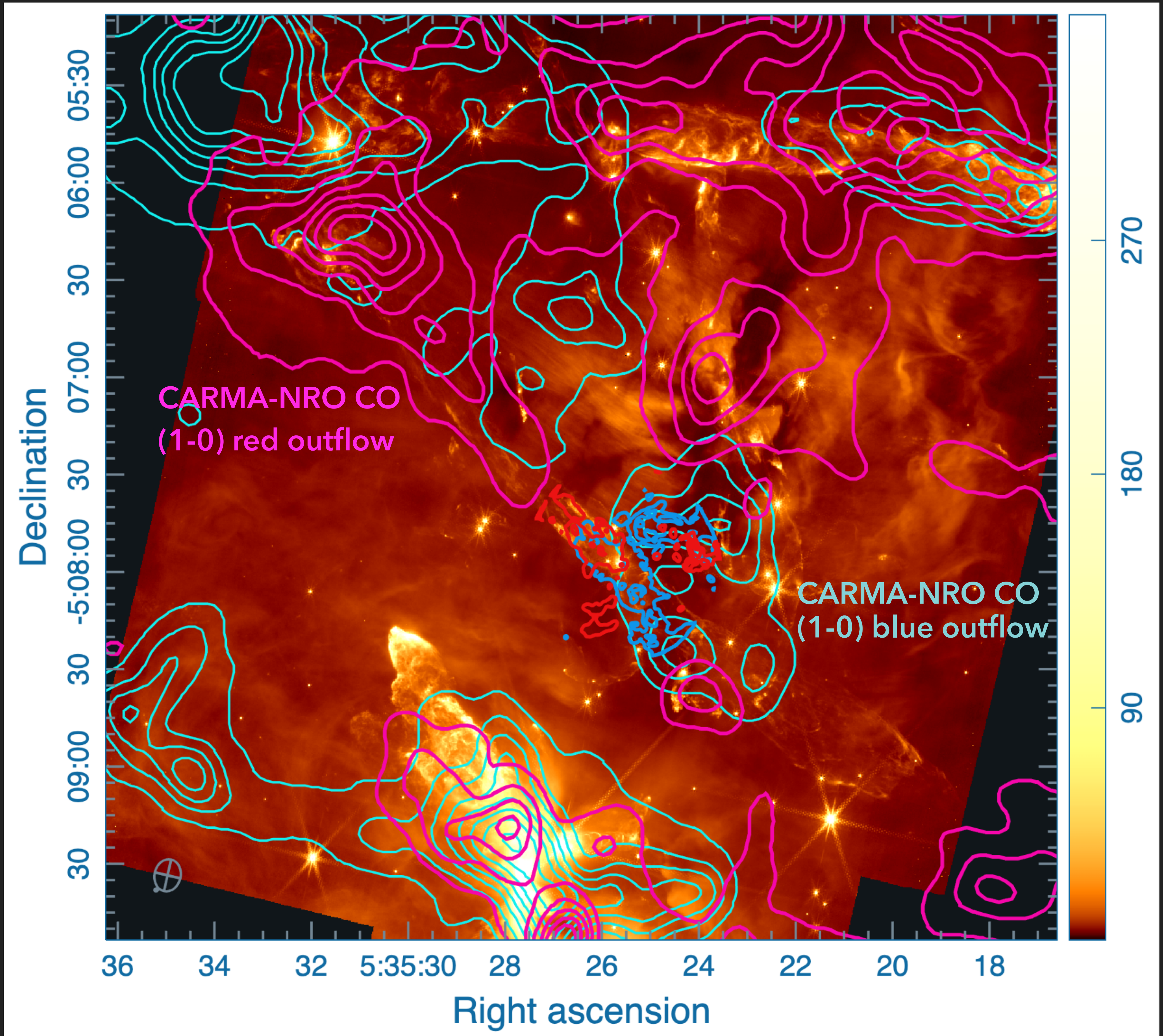
WIDE LINEWIDTH IN AND BEYOND OUTFLOW CAVITY — OUTFLOW-DRIVEN TURBULENCE ?

Blue-shifted $^{12}CO(2\text{-}1)$ outflow | Red-shifted $^{12}CO(2\text{-}1)$ outflow | $C^{18}O(2\text{-}1)$ linewidth





JWST (NIRCAM) AND ALMA OBSERVATIONS OF HOPS 71



SUMMARY

- Simulations and analytic models show outflow dispersal of core/envelope (dense) gas results in star-formation efficiencies of ~0.3 – 0.5.
- ALMA data clearly show that outflows shape and push their envelopes. There is evidence that they also stir (drive turbulence), as suggested by simulations.
- Outflows widen with time and entrain large amount of core/envelope mass (continuos replenishment from larger cloud scales needed to keep observed core masses)
- JWST and ALMA complementary for studying feedback impact at envelope and larger scales

Acknowledgments: research funded by National Science Foundation (AST-2407116)