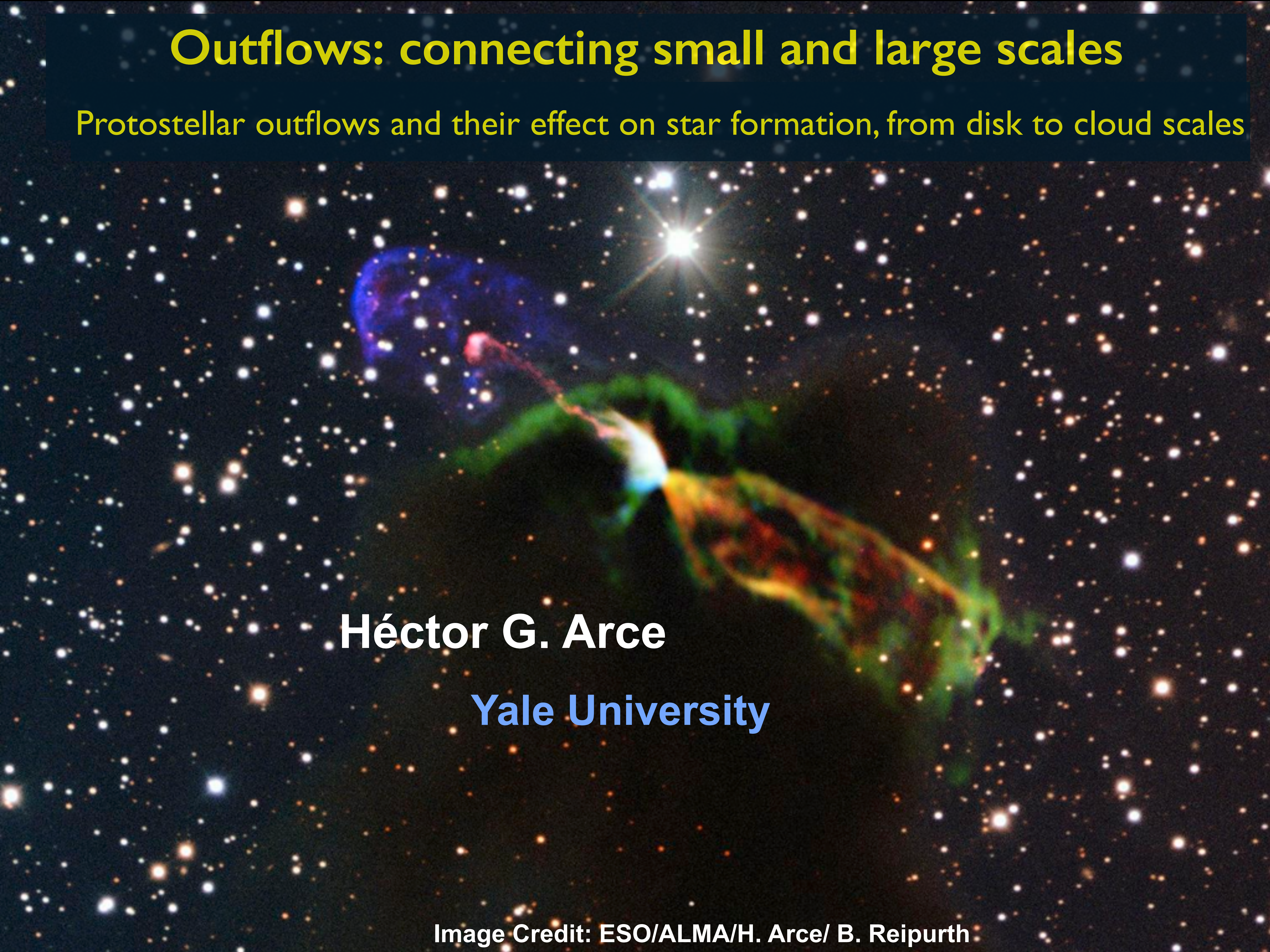
Outflows: connecting small and large scales

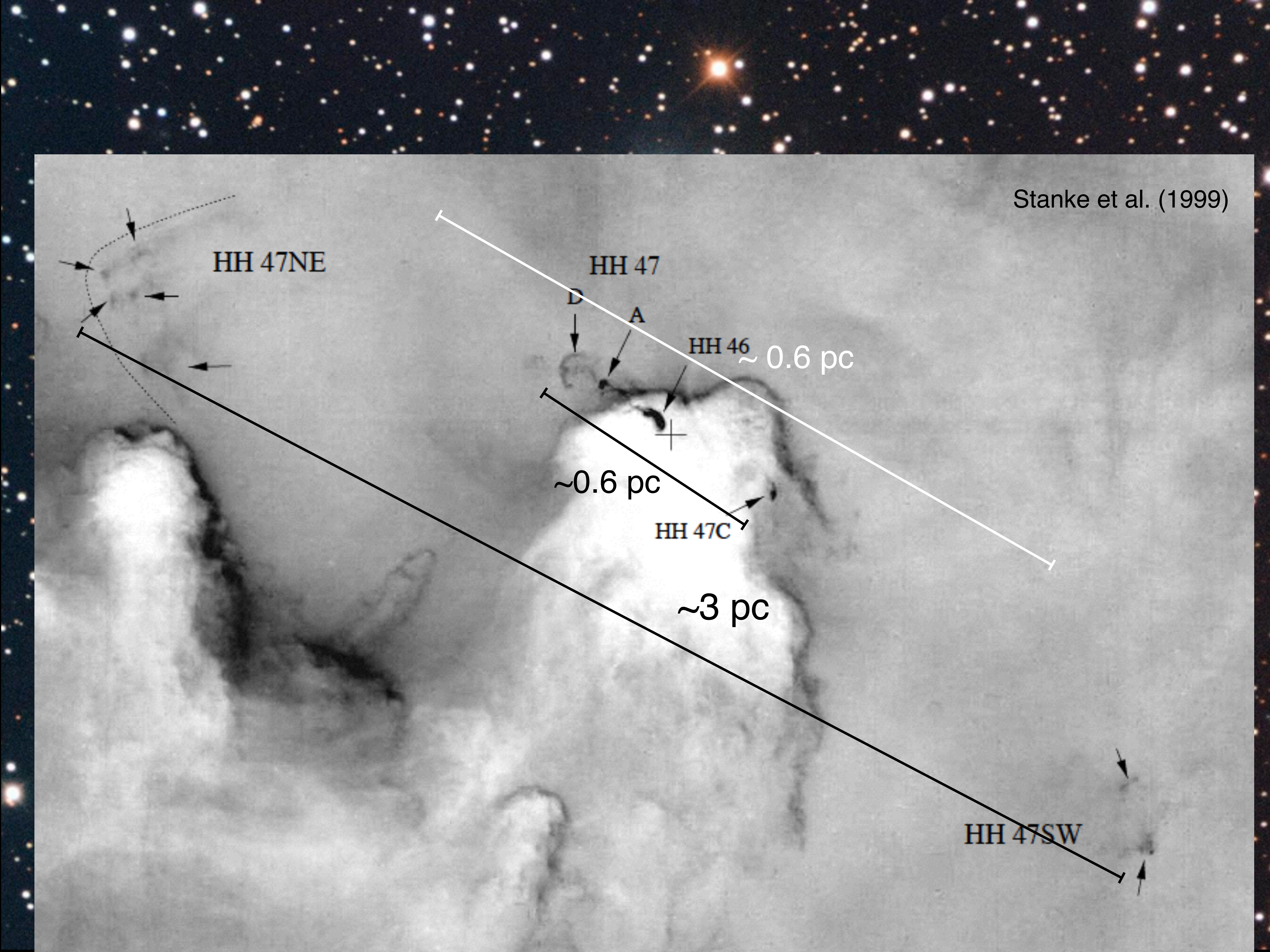
Protostellar outflows and their effect on star formation, from disk to cloud scales



Héctor G. Arce

Yale University

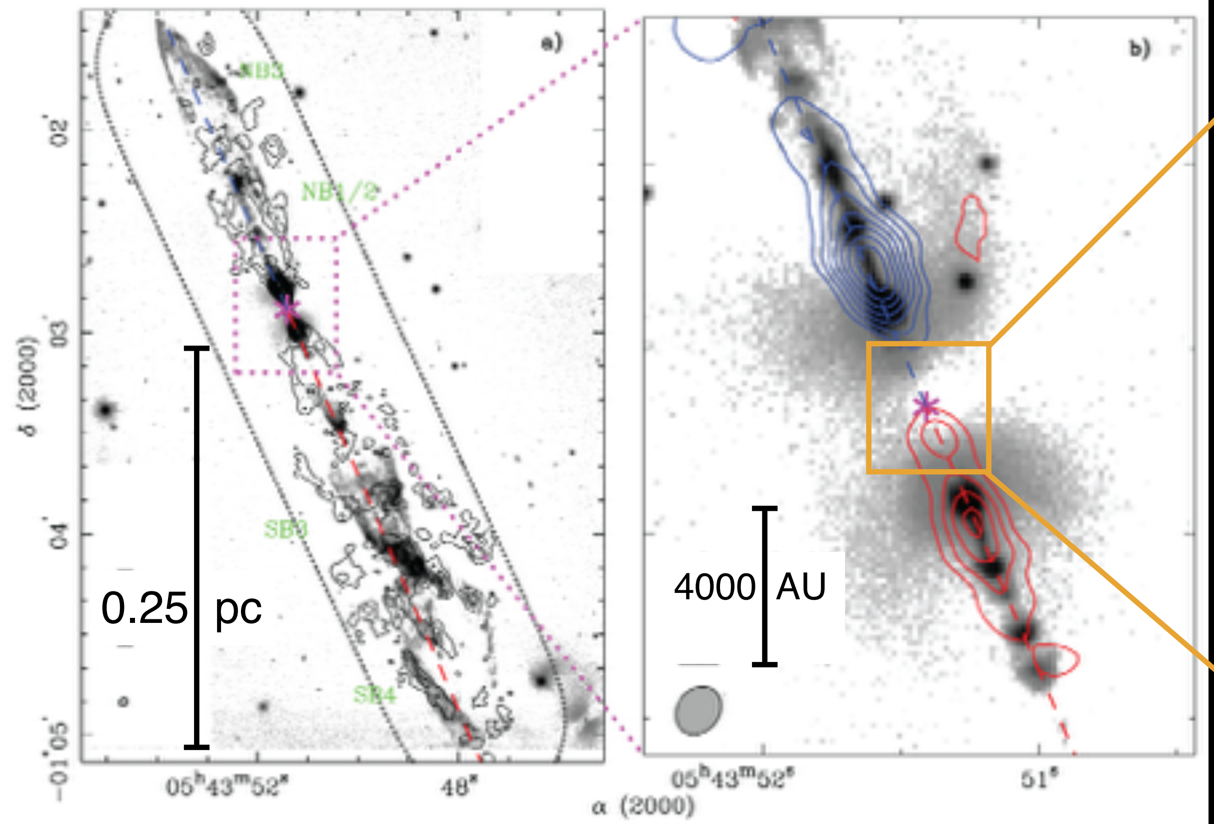
Image Credit: ESO/ALMA/H. Arce/ B. Reipurth


Stanke et al. (1999)
HH 47NE
HH 47
D
A
HH 46
~ 0.6 pc
~0.6 pc
HH 47C
~3 pc
HH 47SW

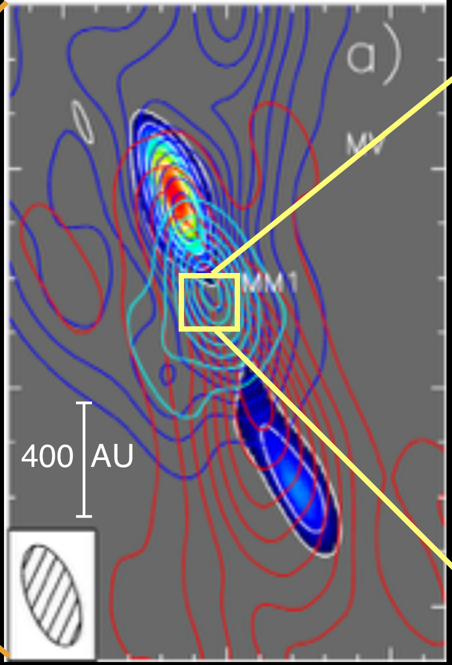
Outflows: *connecting small and large scales*

Outflows are one of the best examples of the connection between small and large scales

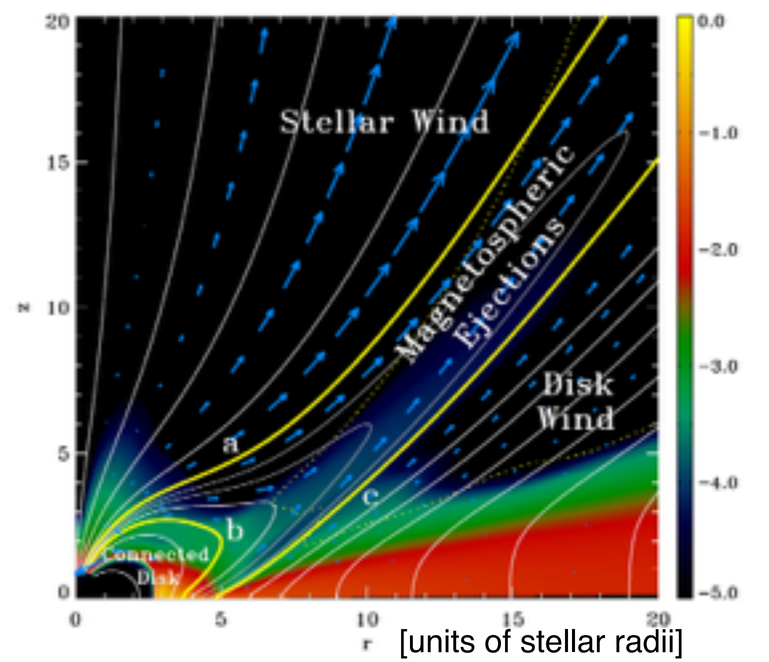
Example: HH 212



^{12}CO(2-1) Lee et al. (2006)



CO(2-1) + SiO(5-4)
Cabrit et al. (2012)



MHD simulations
Zanni & Ferreira (2013)

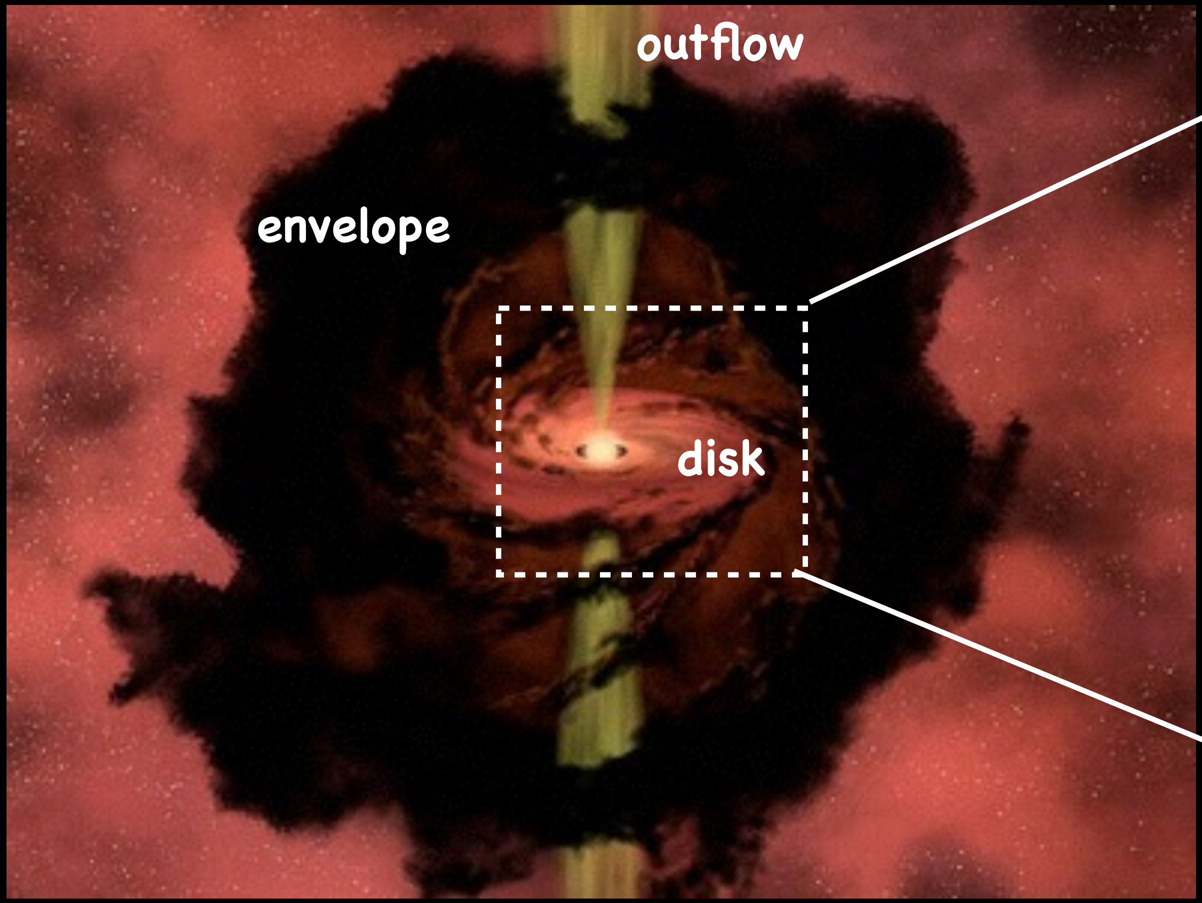
Outflows: an important aspect of star formation

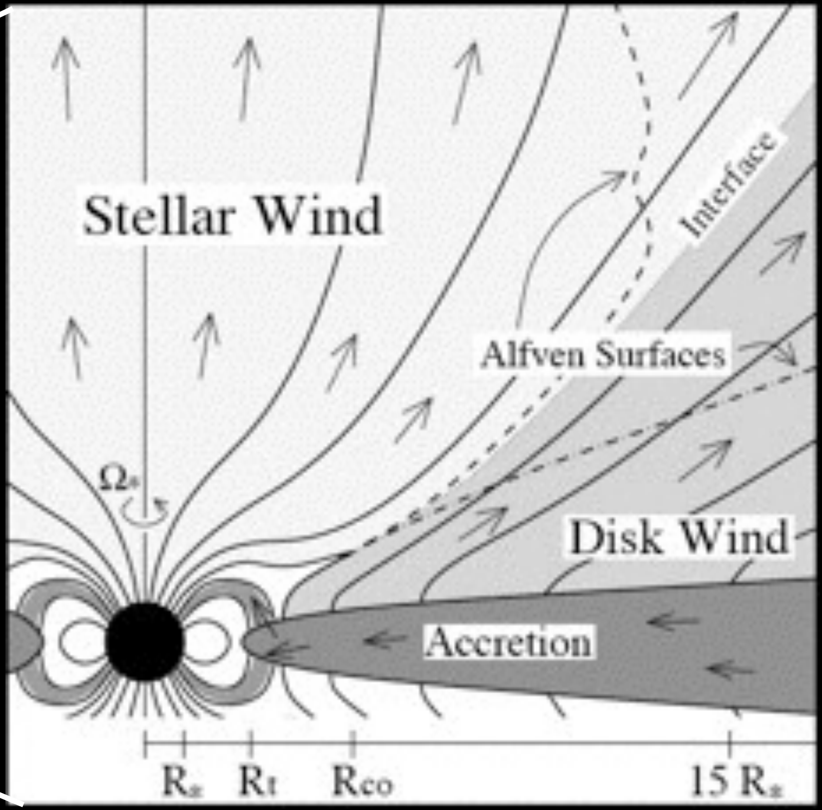
Outflows are thought to:

- Carry excess angular momentum from rotating disk, allowing material to accrete onto star
- Disperse circumstellar envelope material, cause low core-to-star efficiency
- Drive turbulence in clusters which results in low SFR and SFE

Outflows also key to studying different aspects of star formation:

- Outflows are accretion-driven and can be used as fossil record of accretion
- Allow us to derive/estimate certain source properties (e.g., age, i, binarity, etc.)





From Matt & Pudritz

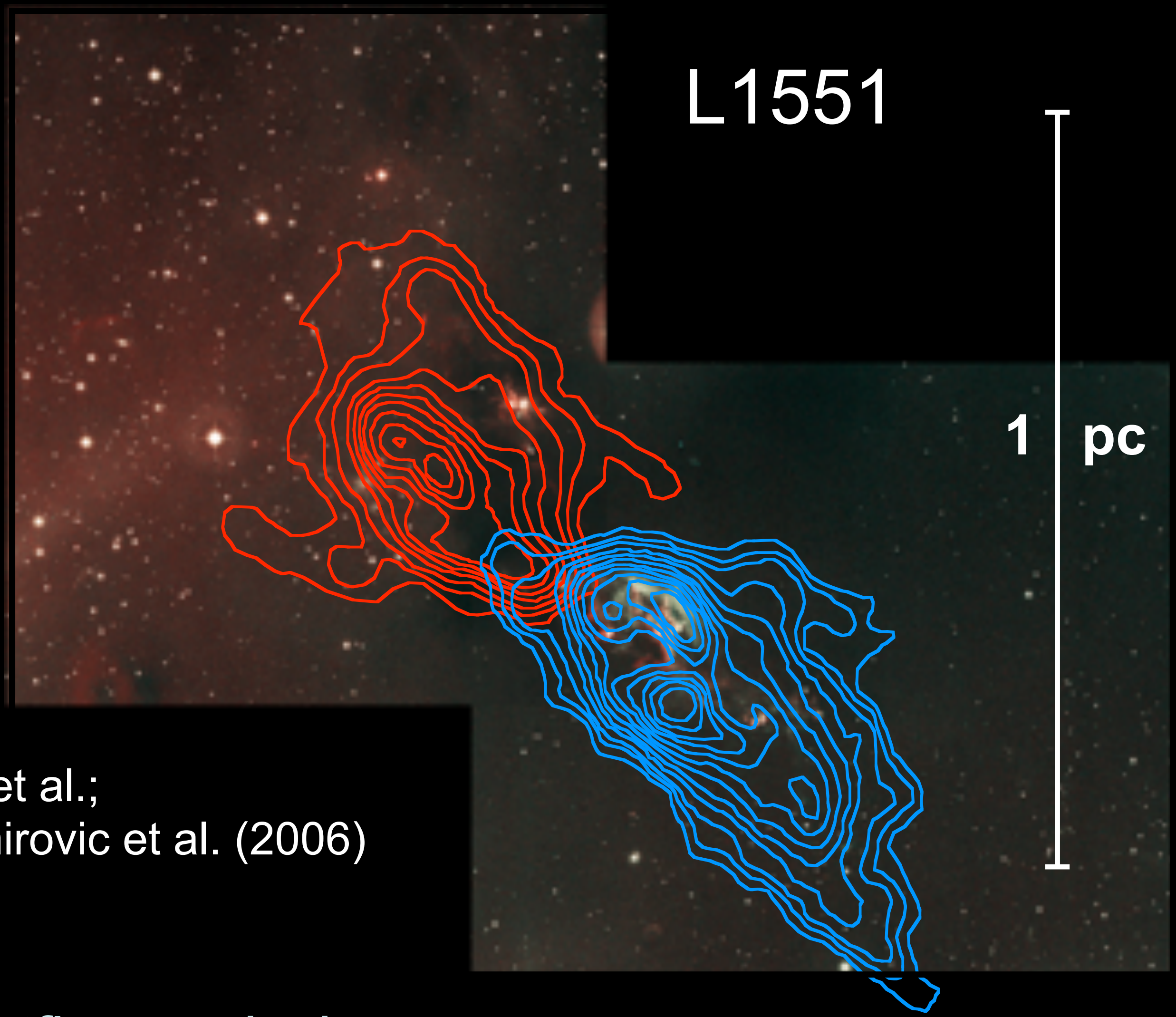
Different outflow manifestations

Optical emission (shock excited atomic lines)

IR emission (mostly shock-heated H_2 lines)

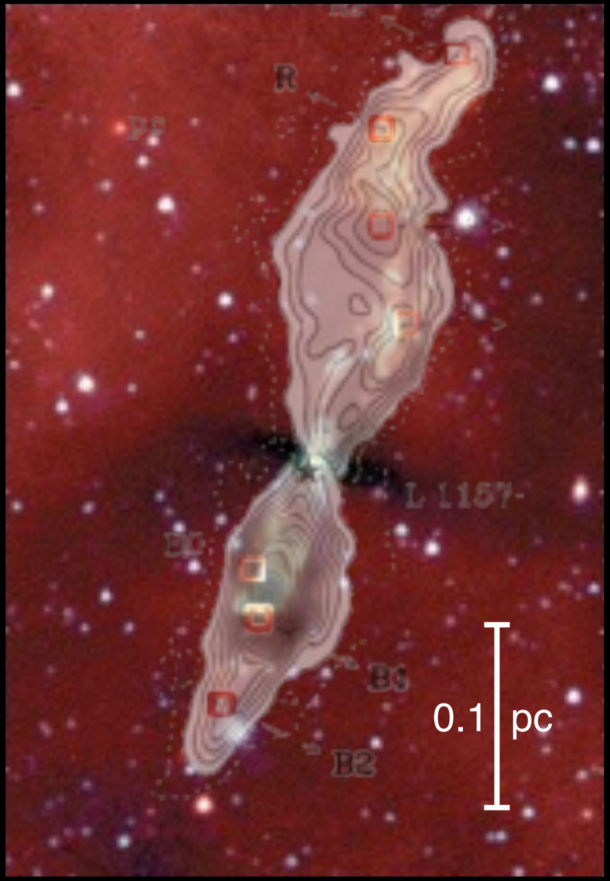
(both trace recently shocked gas)

L1551



Bally et al.;
Stojimirovic et al. (2006)

L1157



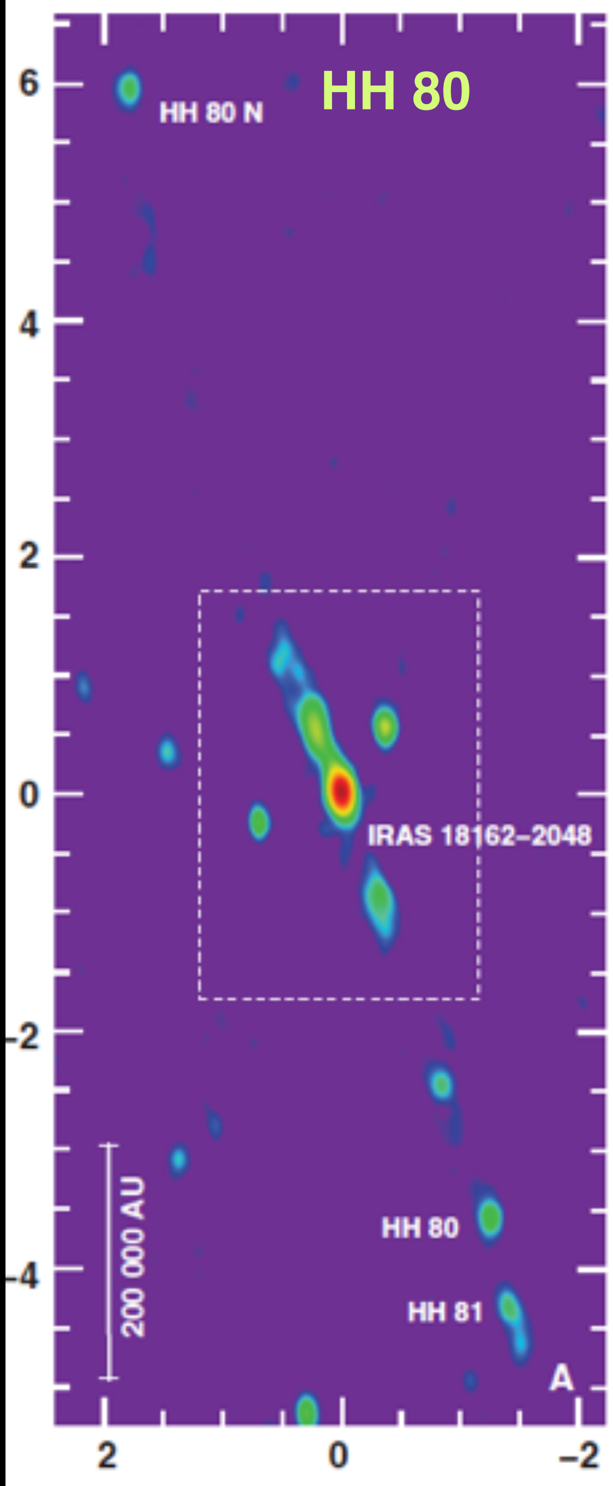
Looney et al. (2007); Bachiller et al. (2001)

Contours: CO outflow emission
($\lambda \sim 1 - 3$ mm)

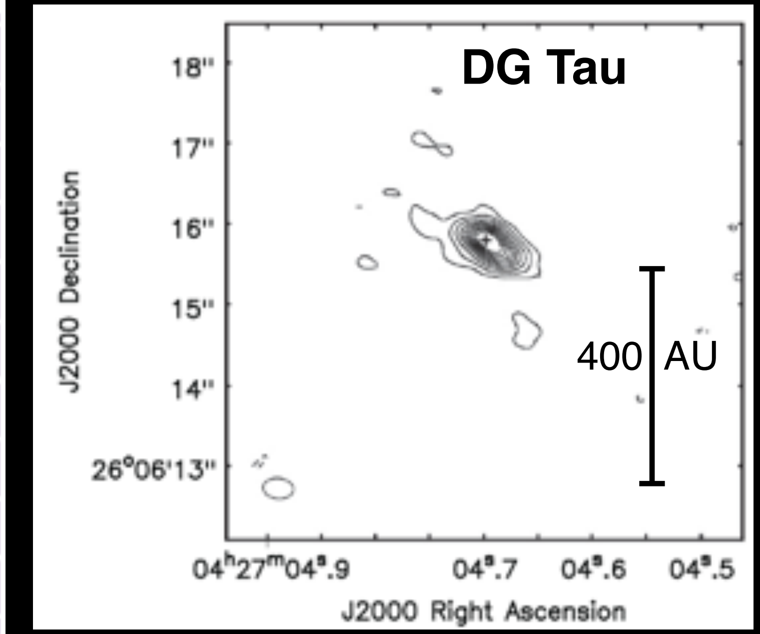
low-J CO (mostly) trace entrained gas

Other outflow manifestations

Radio Jets



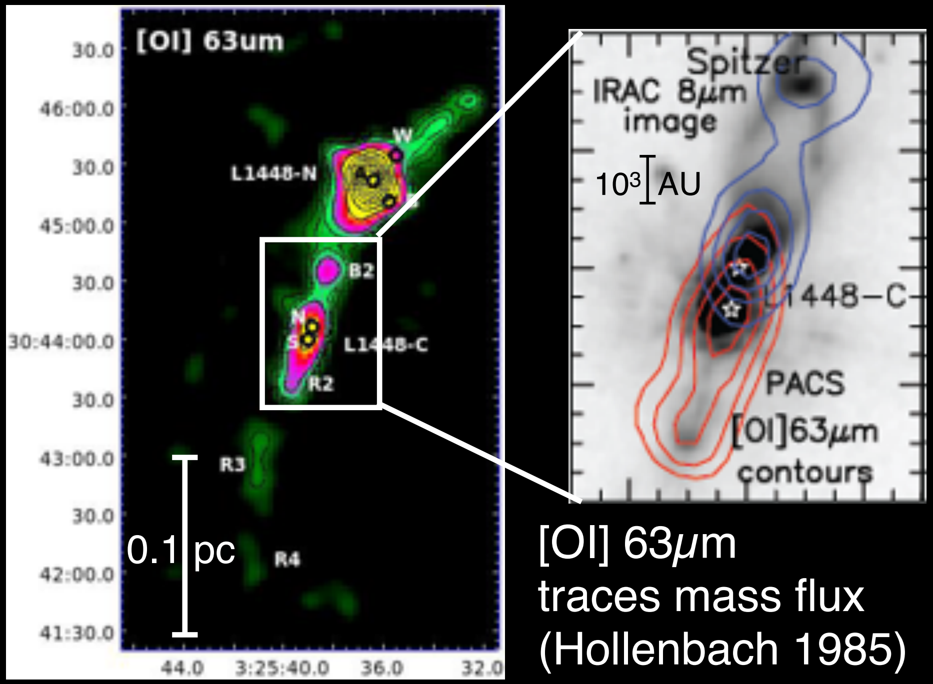
Carrasco-González et al. (2010)



mostly from thermal free-free emission from shock-heated gas

see Viviana Rosero's talk for more info on radio jets

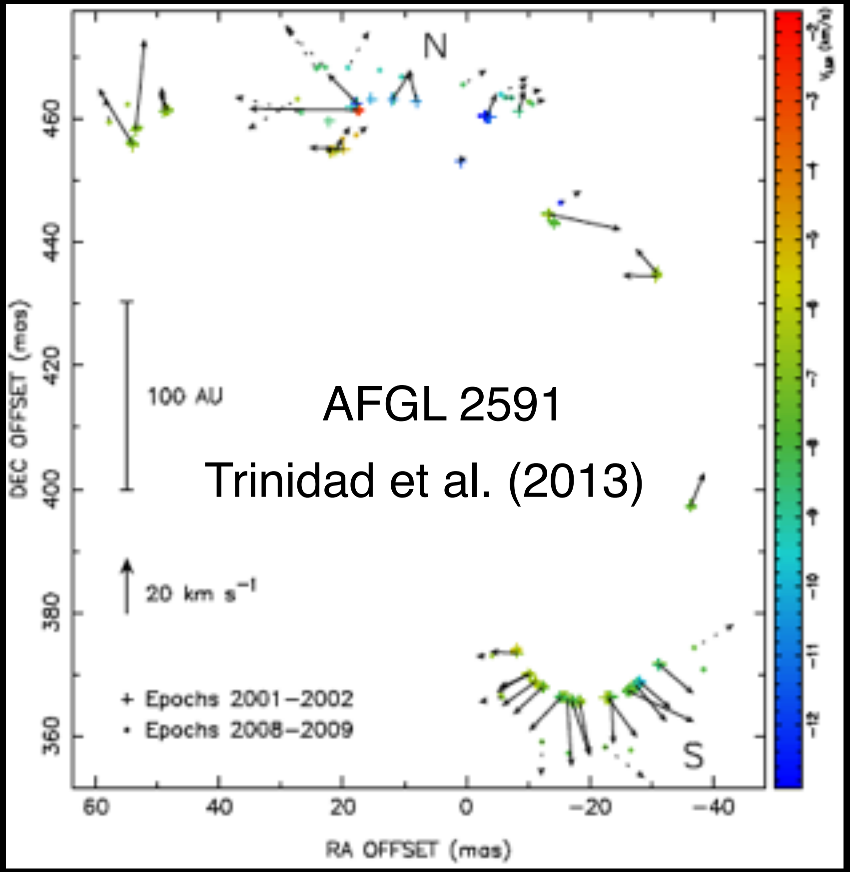
Atomic jet in [OI] 63μm



[OI] 63μm traces mass flux (Hollenbach 1985)

Santangelo et al. (2013)

Water masers

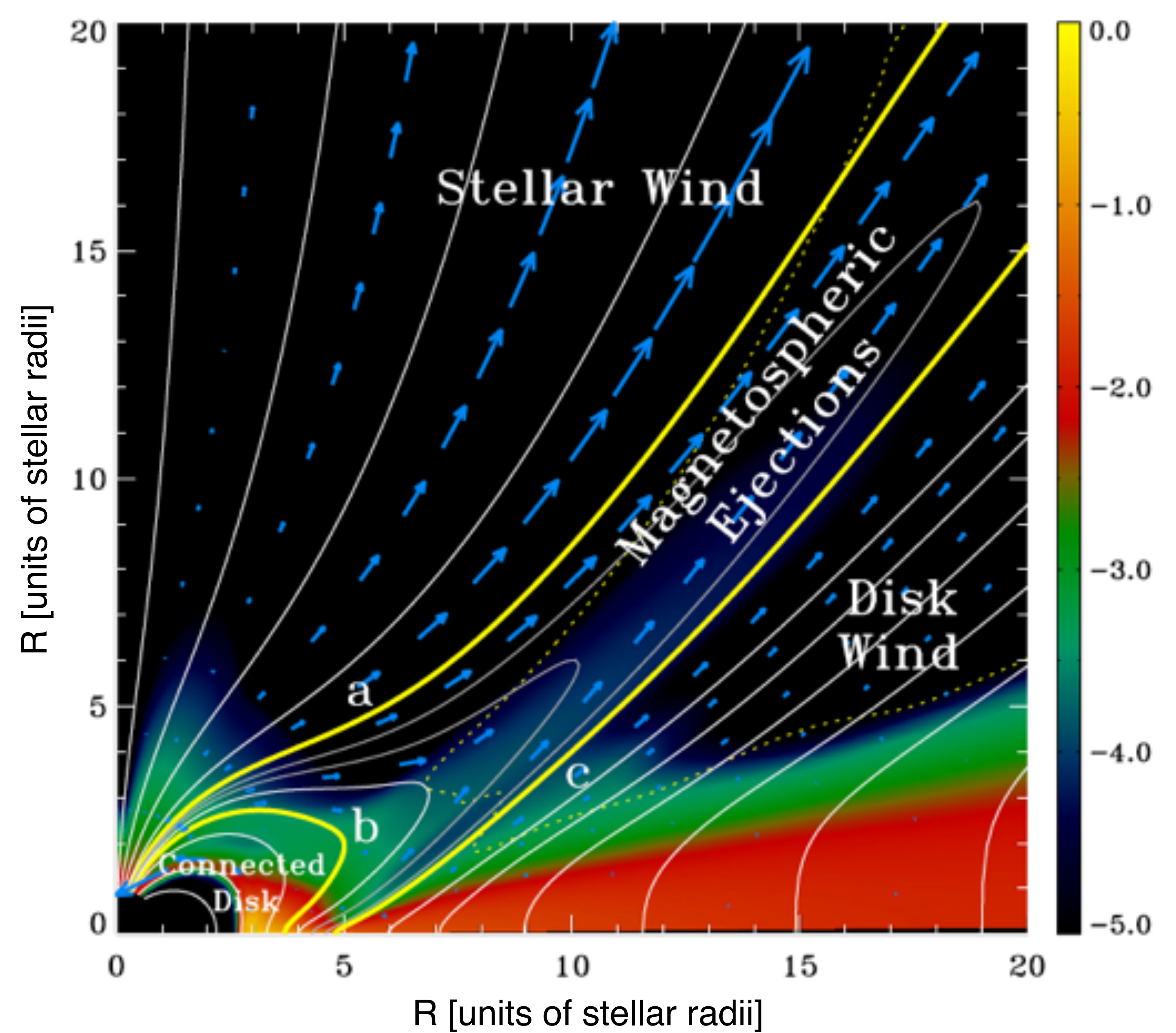


AFGL 2591

Trinidad et al. (2013)

trace dense shocks

The innermost scales: Jet Launching and collimation (models)

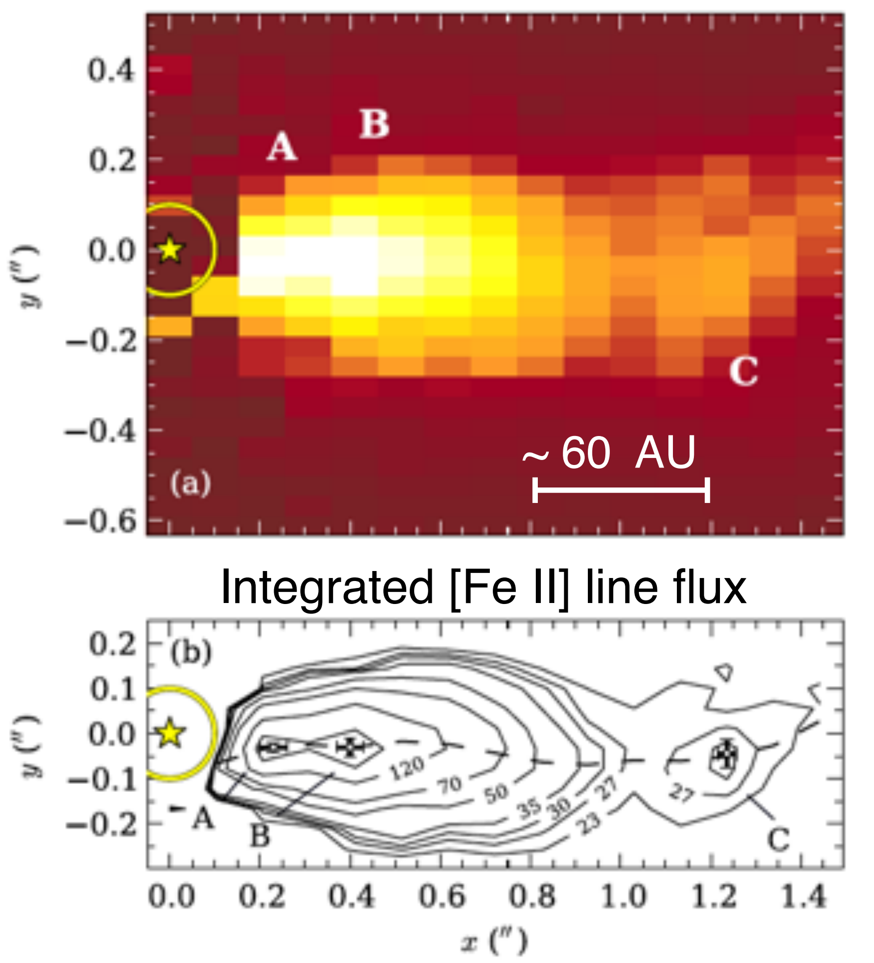


Zanni & Ferreira (2013)

For more on jet launching simulations, see next talk by Christian Fendt

The innermost scales: Jet Launching and collimation (observations)

DG Tau (Class II)



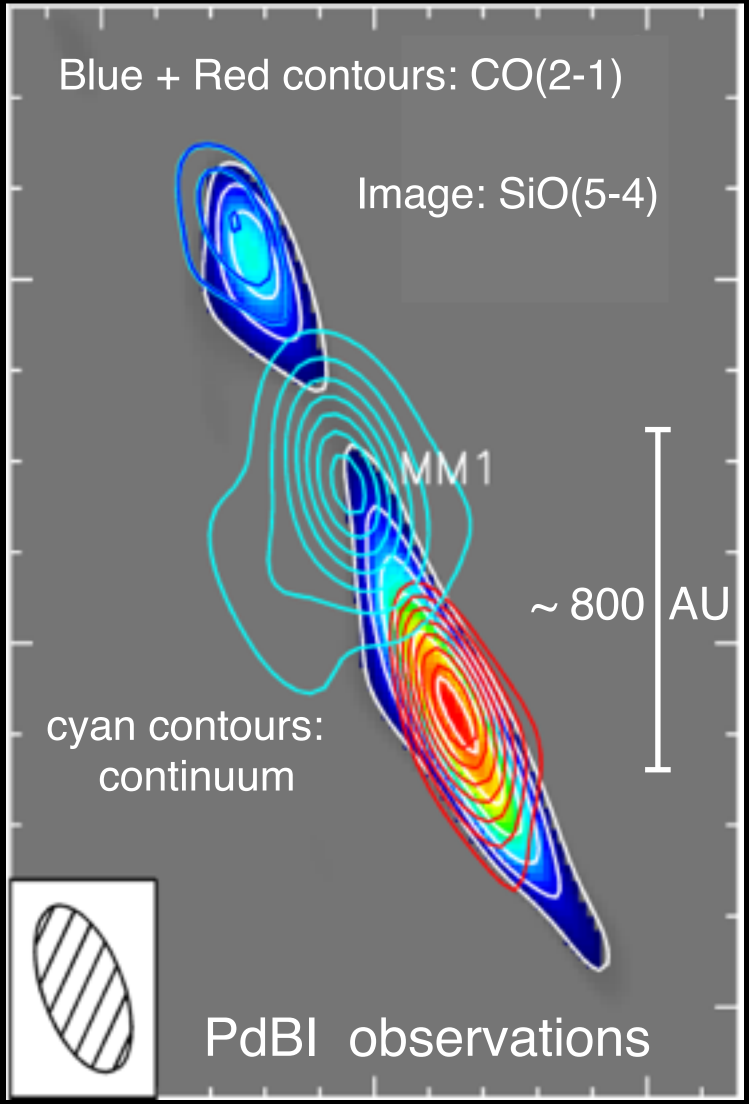
Integrated [Fe II] line flux

Observations using NIFS
on Gemini North (with AO)
res. ~0.1”

jet width ~0.2” ~ 30 AU
(~orbit of Neptune)

White et al. (2014)

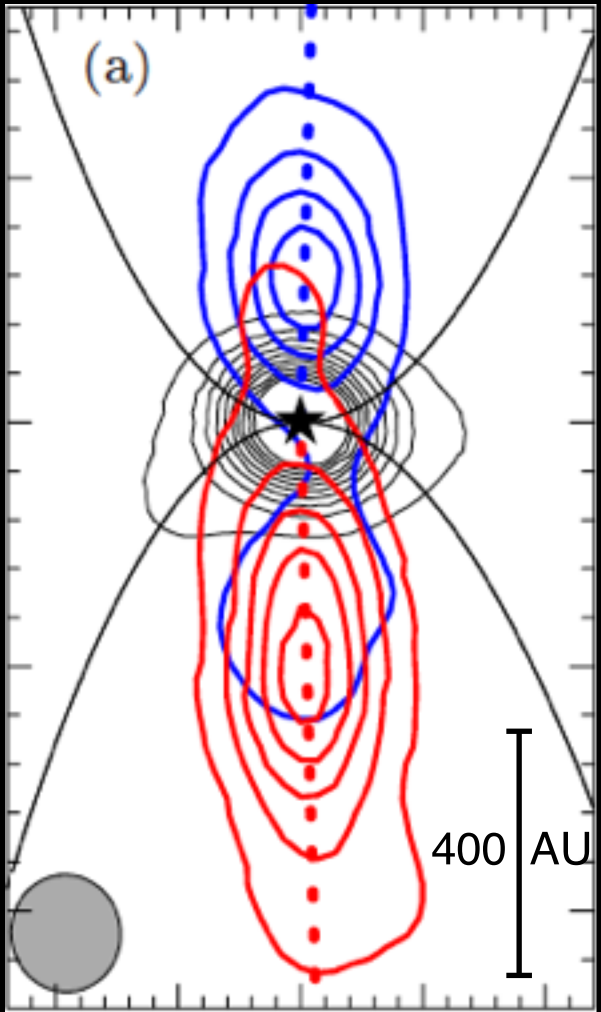
HH 212 (Class 0)



Cabrit et al. (2012)

HH 212

Blue + Red contours: HCO$^+$ (4-3)



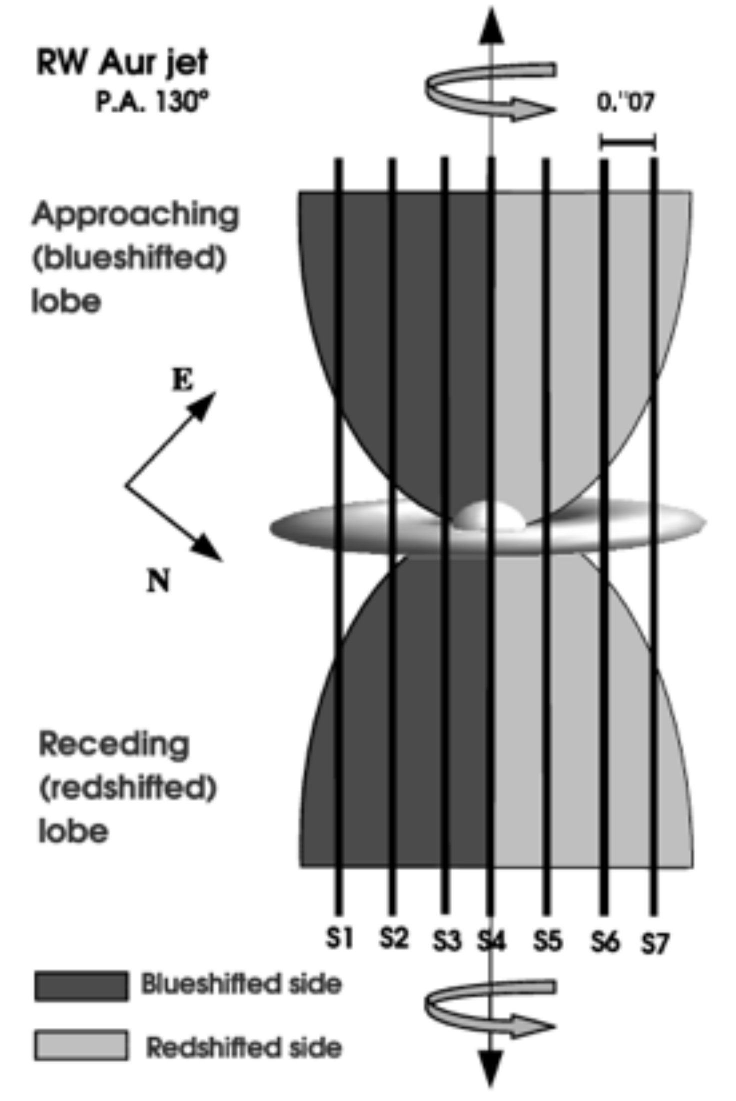
ALMA (Cycle 0)
observations

Lee et al. (2014)

jet width ~0.2” ~ 80 – 90 AU
(within a few 100 AU of source)

Collimation must be do to magnetic fields

Using jet rotation to investigate launching mechanism and angular momentum transport



Woitas et al. (2005)

Jets / winds launched by (rotating) star+disk B field are expected to rotate

poloidal velocity component

$$v_\mathrm{p} \approx v_z = (v_\mathrm{rad1} + v_\mathrm{rad2})/(2\cos i)$$

$v_{rad1,2}$ = measured radial velocities at positions on either side of flow axis
i = inclination angle w.r.t. line of sight

toroidal velocity component

$$v_\phi = (v_\mathrm{rad1} - v_\mathrm{rad2})/(2\sin i)$$

From conservation of total specific energy and ang. mom., and for $v_\phi \ll v_p$, and far enough from source that $KE_\mathrm{jet} \gg E_\mathrm{grav}$, then one can estimate launching radius using:

$$R_0 \approx 0.7\ \mathrm{AU} \left(\frac{R}{10\ \mathrm{AU}}\right)^{2/3} \left(\frac{v_\phi(R)}{10\ \mathrm{km\ s^{-1}}}\right)^{2/3} \left(\frac{v_p(R)}{100\ \mathrm{km\ s^{-1}}}\right)^{-4/3} \left(\frac{M_\star}{1\ M_\odot}\right)^{1/3}$$

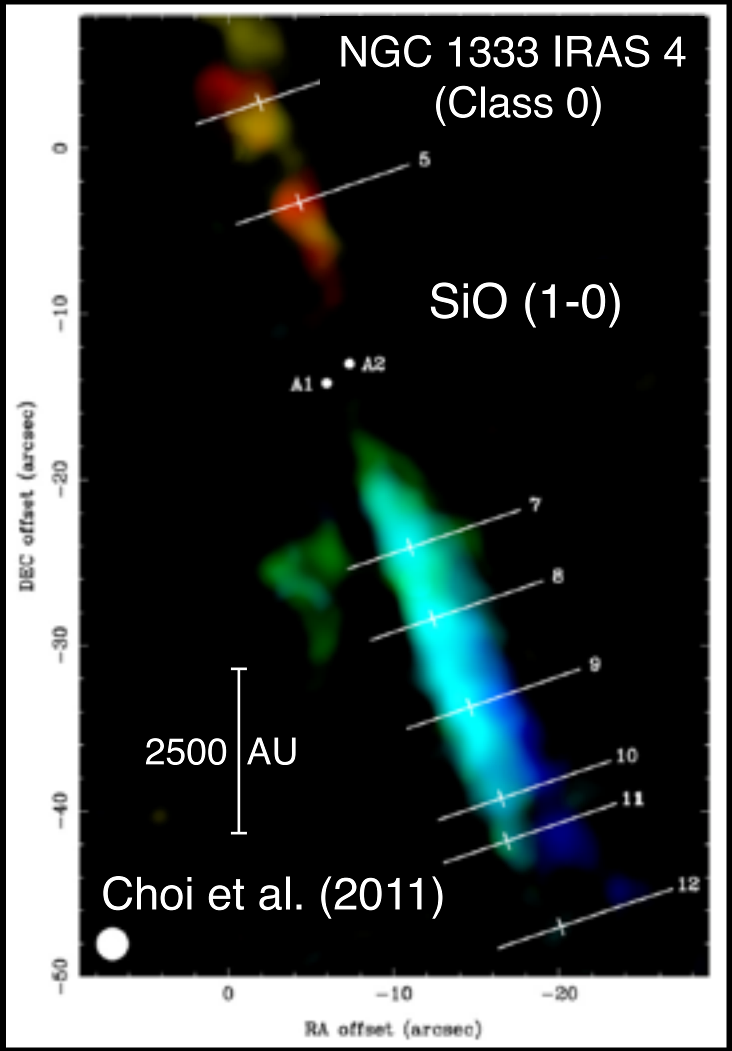
Anderson et al. (2003)

see also Chrysostomou et al. (2008); Belloche (2013)

Angular momentum transport:

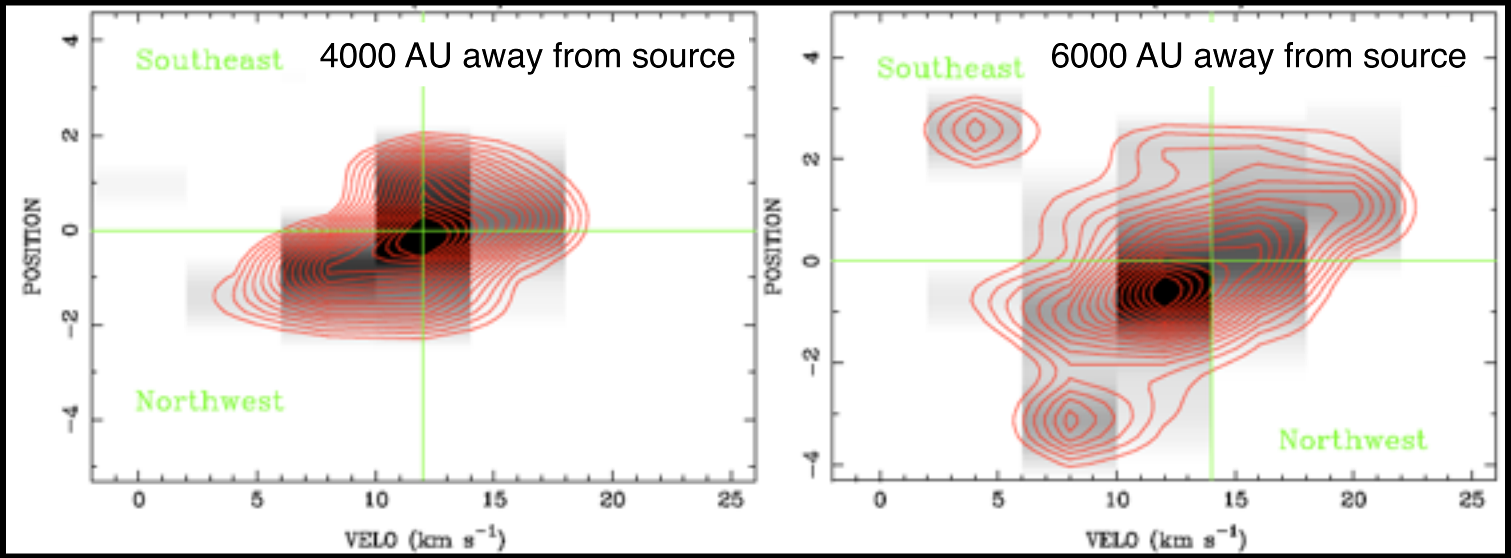
- Estimate jet angular momentum using estimates of $(dM/dt)_\mathrm{jet}$, v_ϕ, etc.
- Compare with angular momentum that has to be extracted from disk to allow accretion

Claims of jet/outflow rotation using different tracers (and in sources at different evolutionary stages)



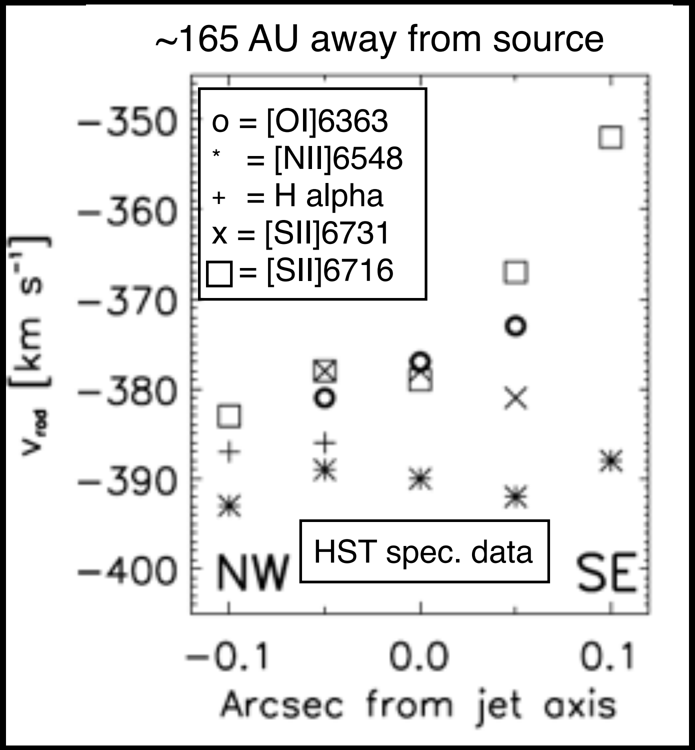
Choi et al. (2011)

Ori -S6 protostar (Zapata et al. 2010)

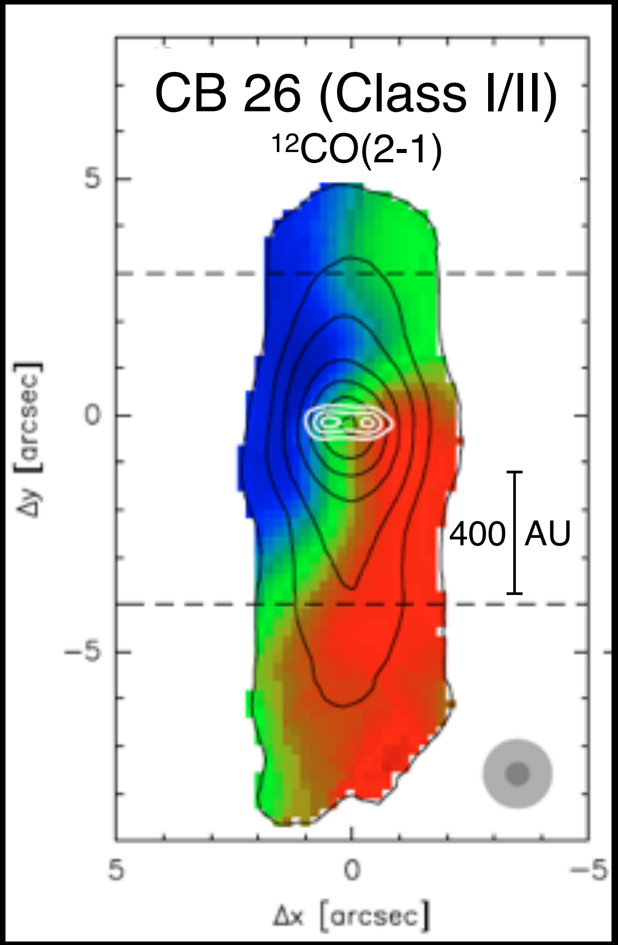


position-velocity diagram of cut perpendicular to SO (6_5-5_4) jet axis

LkHa 321 (Class II)



Coffey et al. (2004)



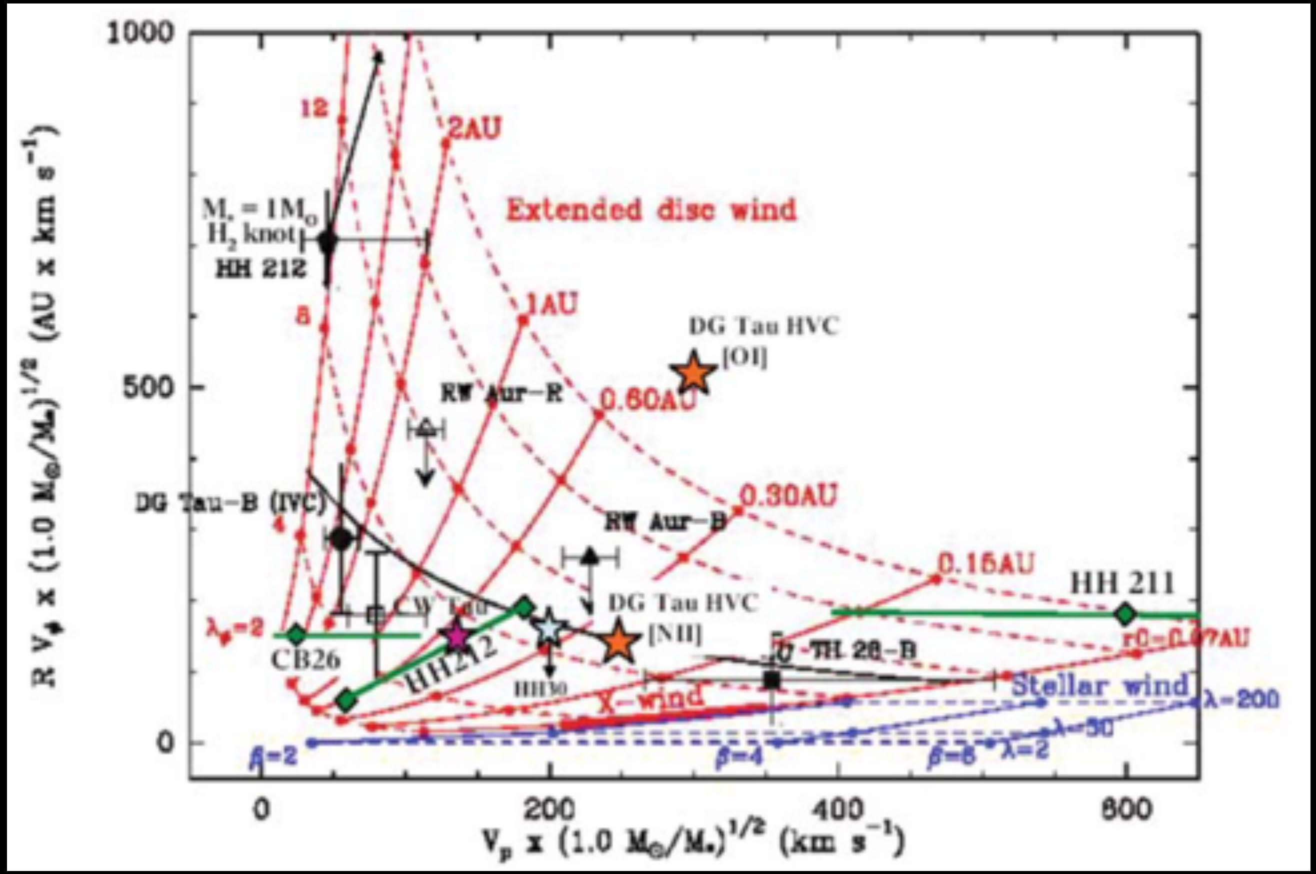
Launhardt et al. (2009)

A number of sources show possible signatures of rotation, consistent with those expected in MHD centrifugal models for jet launching.

However….
observed velocity gradients not necessarily due to rotation
(e.g., Soker 2005; Cerqueira et al. 2006; Fendt 2011)

Observations can be used to constrain launching radius/radii

(assuming observed velocity gradient is due to jet rotation)



Specific Angular Momentum

Poloidal Velocity

Comparison of predicted specific angular momentum vs. poloidal velocities with observations of jet/outflow rotation

Cabrit (2009), see also Ferreira et al. (2006)

Assuming observed kinetic signatures are from steady jet rotation, we see that jets are mostly consistent with extended disk wind, launched between 0.1 AU to few (~3-5) AU

If true outflows could have affect on disk, in region of planet formation

fast radial accretion —> planet migration
thermal processing and transportation of dust —> form and redistribute condrules
dusty disk winds —> screen disk against stellar FUV and X-rays

Outflow-core interaction may lead to low core SFE

Recent studies interpret observed similar shape in IMF and CMF as evidence that IMF may be set during the early stages of core formation

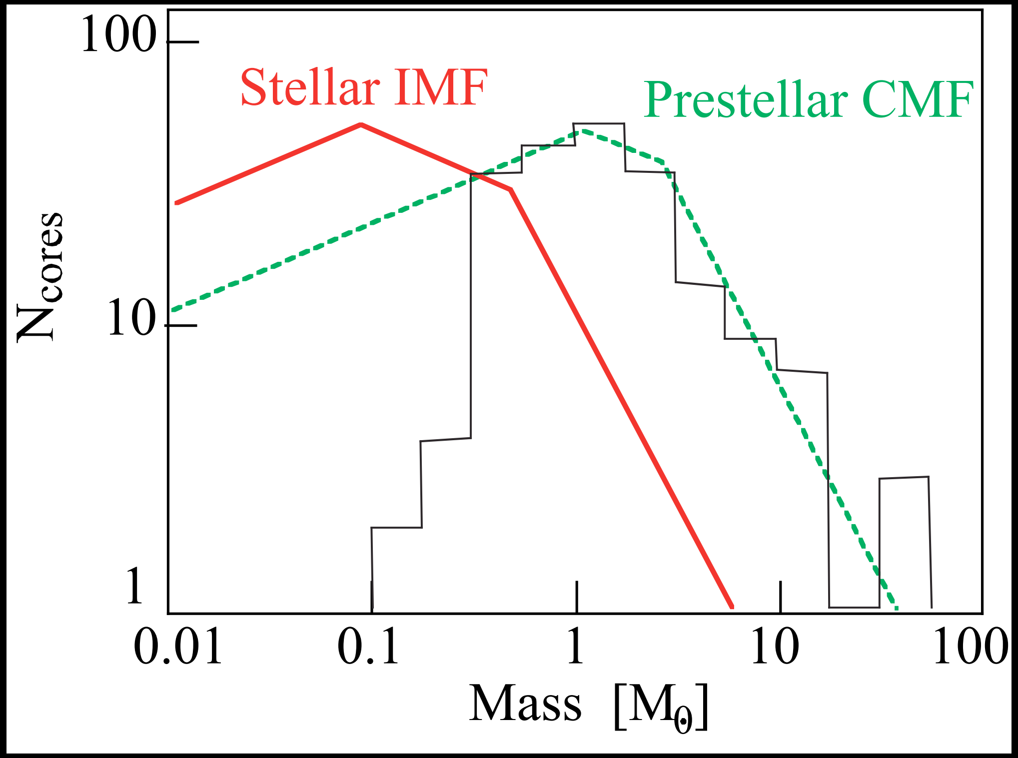
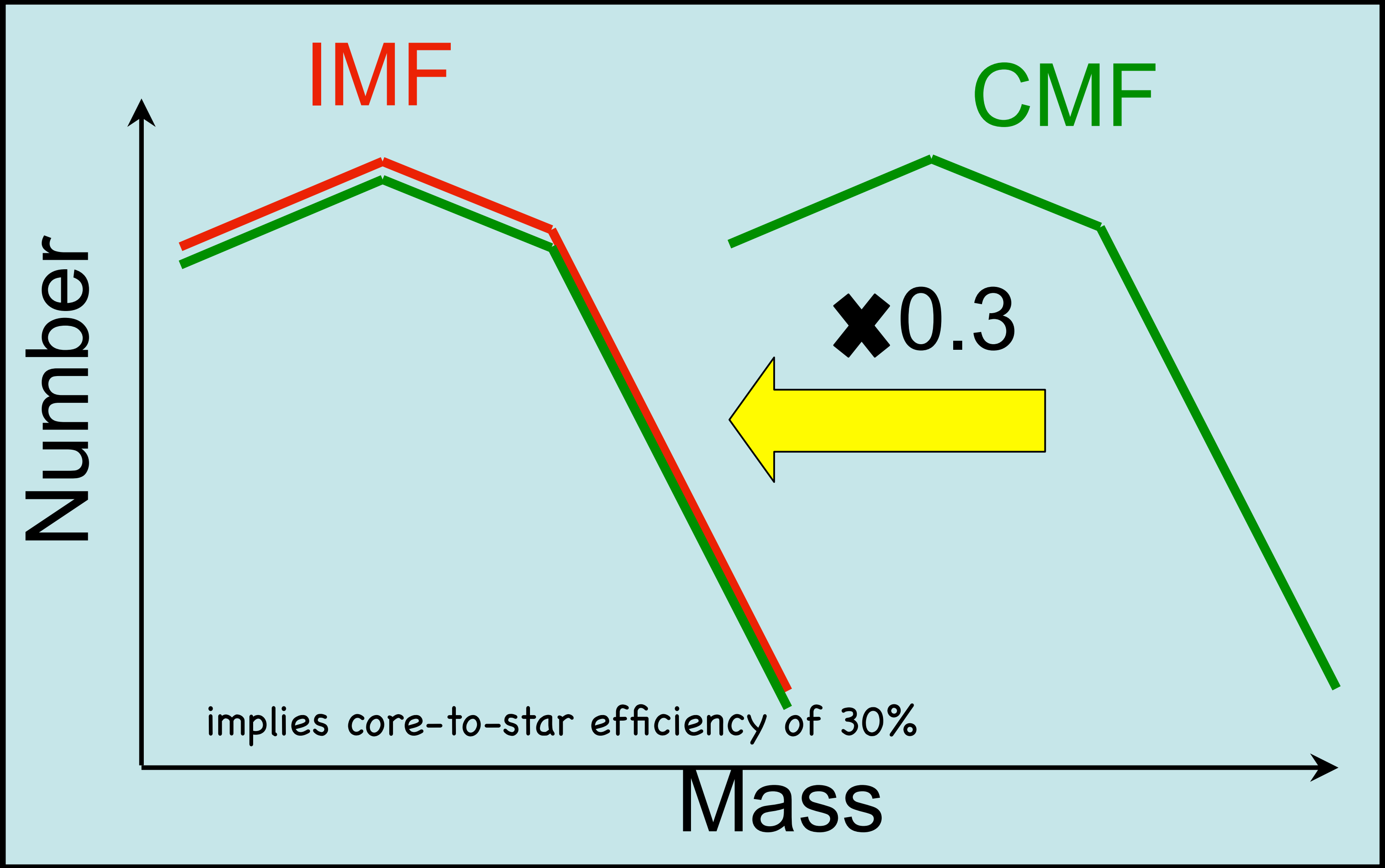


Figure from Nutter & Ward-Thompson (2007)
See also:
Alves et al. (2006)
Enoch et al. (2008)
Rathborne et al. (2009)
André et al.
and others…



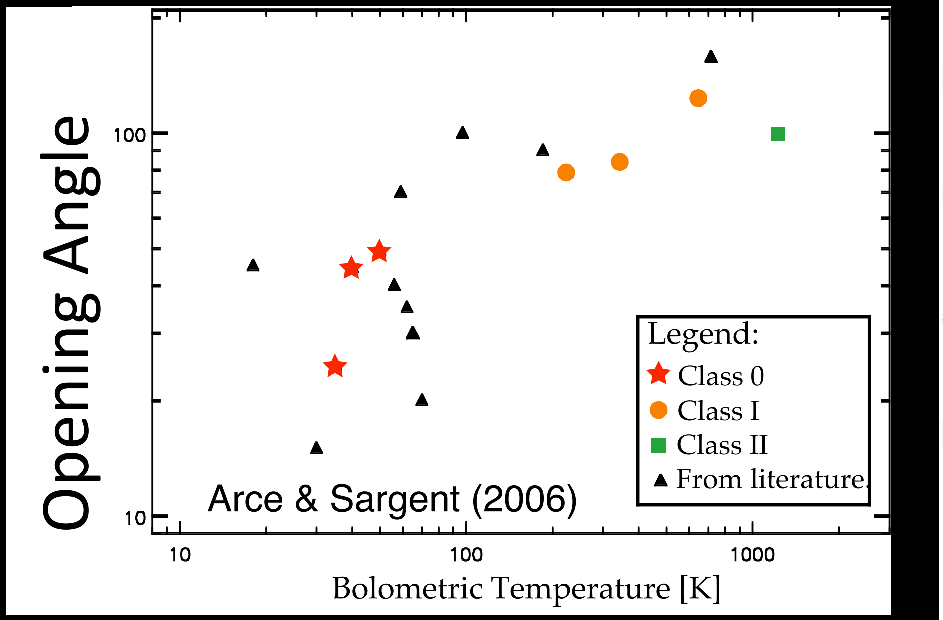
implies core-to-star efficiency of 30%

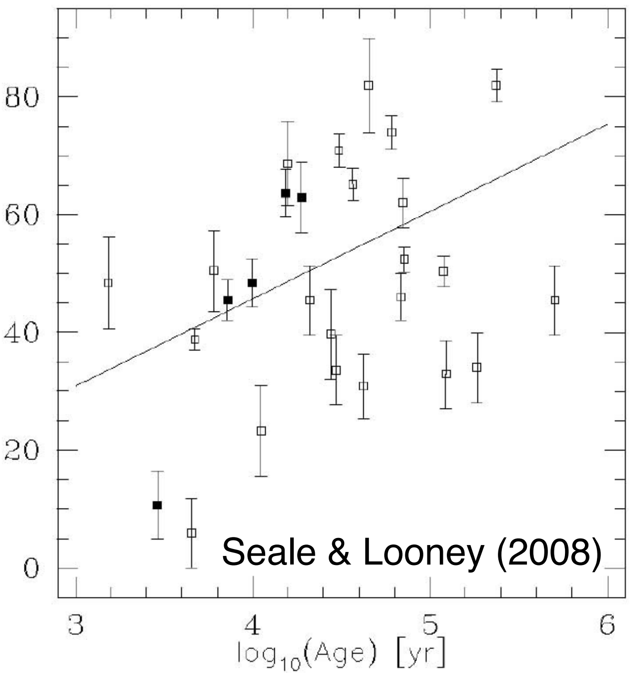
Many claim that core gas dispersal by outflows is the main mechanism for the low SFE (i.e., outflows disperse ~70% of core gas) <— one way large scales connect to small scales

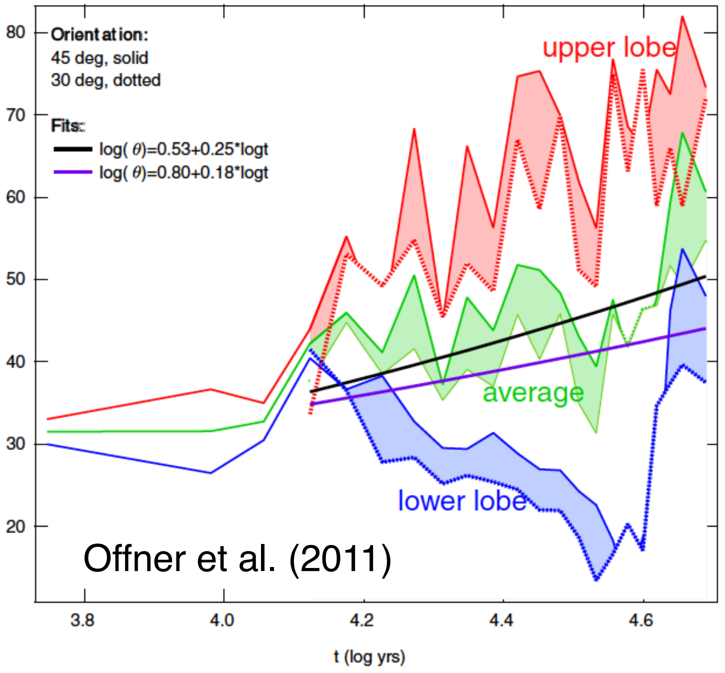
However, there are no observational studies that prove this

Outflow-envelope interaction

Observations and models show widening of outflow cavity with time







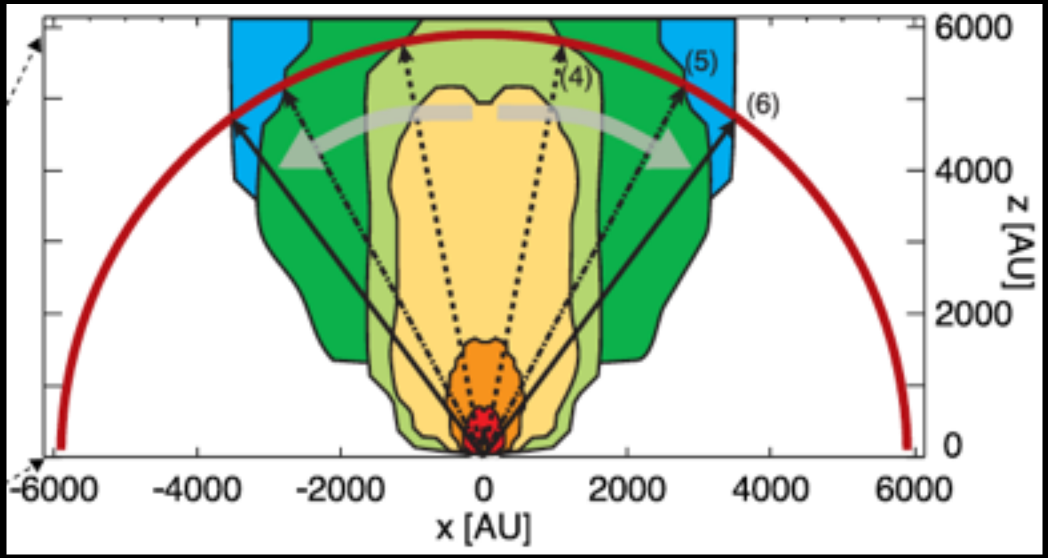
Time →

Arce & Sargent (2006): Using interferometer CO maps of molecular outflows from protostars at different evolutionary stages

Seale & Looney (2008): Using IRAC images of scattered-light from outflow cavities around protostars at different evolutionary stages

Offner et al. (2011): Numerical simulations of outflow in turbulent core show cavity widens with time

Machida & Hosokawa (2013): MHD simulations of outflow in core show cavity widens with time

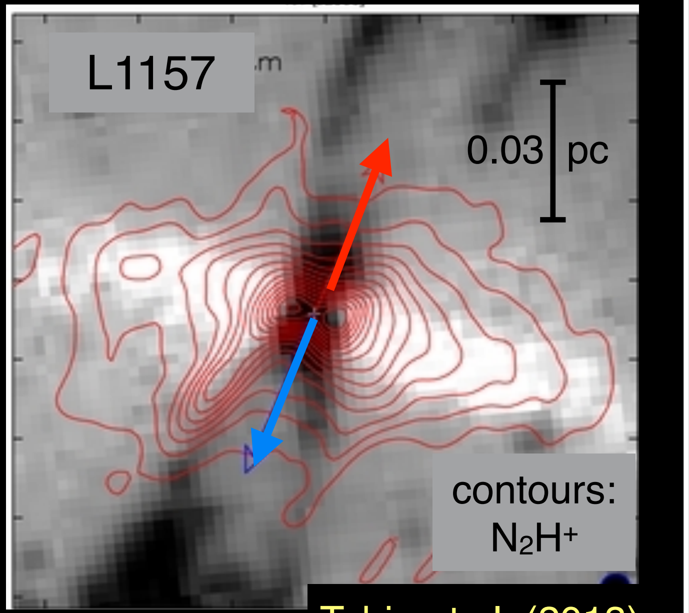


Outflow-envelope interaction

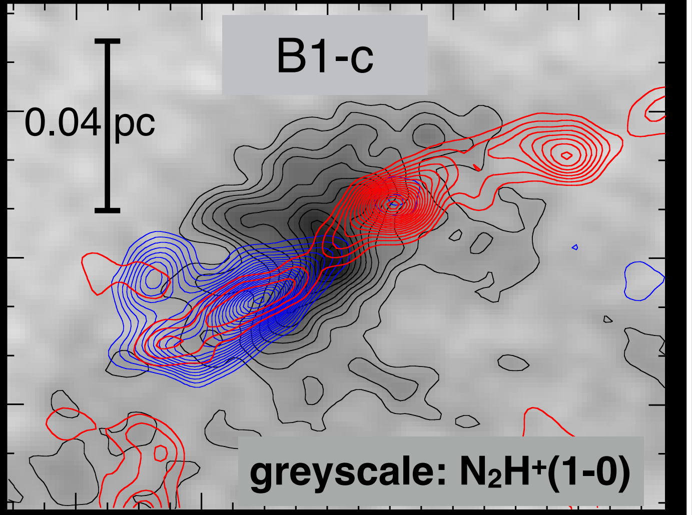
Observational evidence for widening of outflow cavity with time

Time →

Class 0



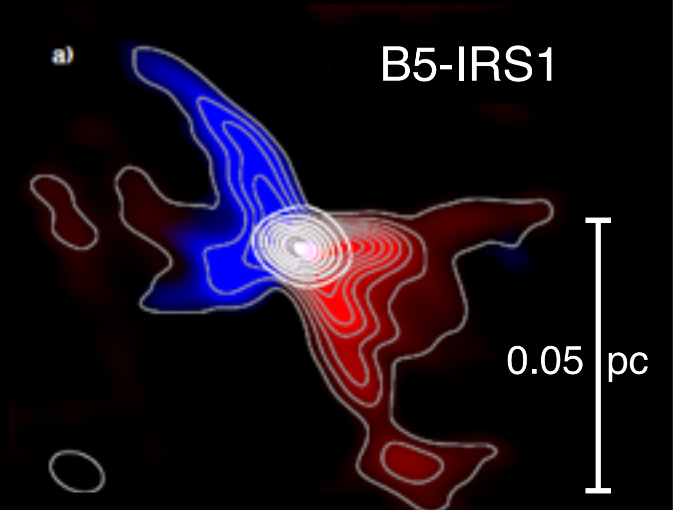
Tobin et al. (2013)



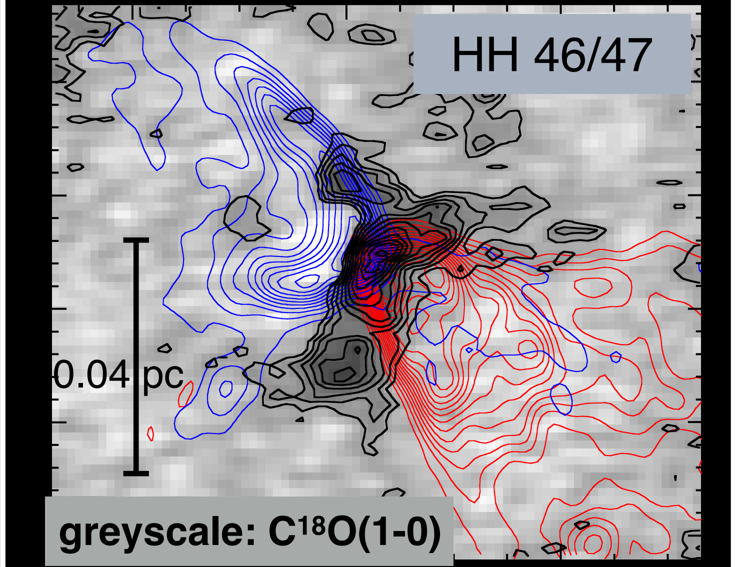
Storm et al. (2014)

Jet-like outflow at high vel. + cavity at low-vel. with o.a. ~ 20-50°.
Outflow starts entraining dense env.

Class I



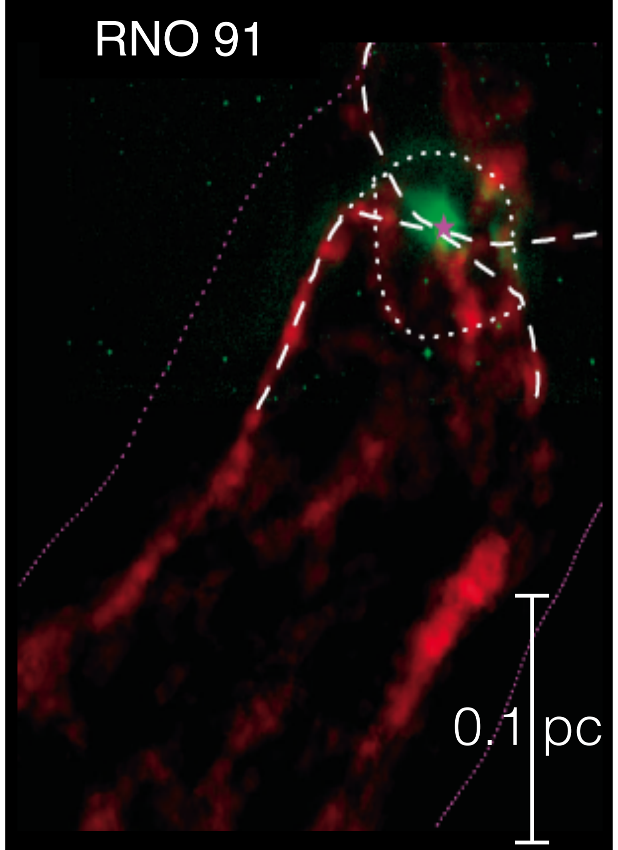
Zapata et al. (2014)



ALMA Cycle 1 data (Arce et al., in prep.)

Wide-angle outflow cavity with o.a. ~ 50-120°. Envelope constrained to volume outside outflow

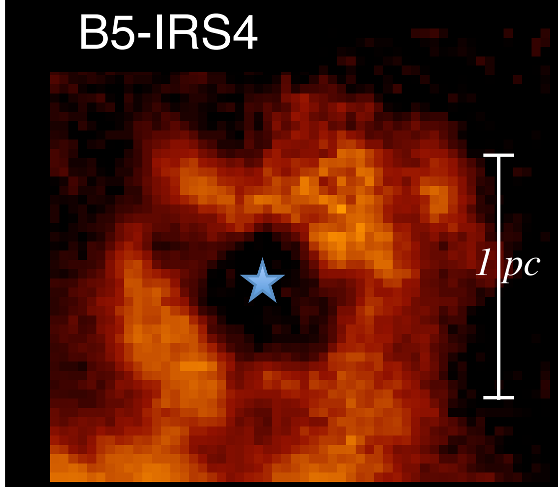
early Class II



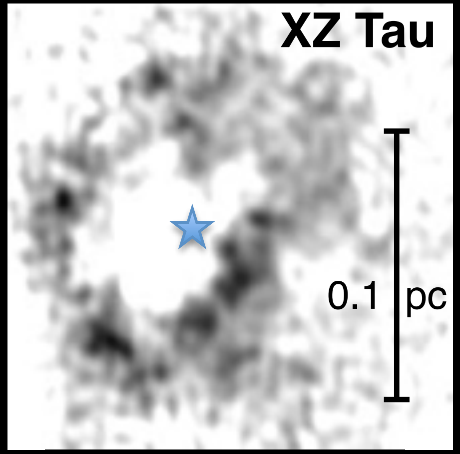
Lee et al. (2005)

Very wide-angle cavity with opening angle (o.a.) > 100 -130 °
Low-mass / low-density (or no envelope) left

late Class II



Arce et al. (2011)



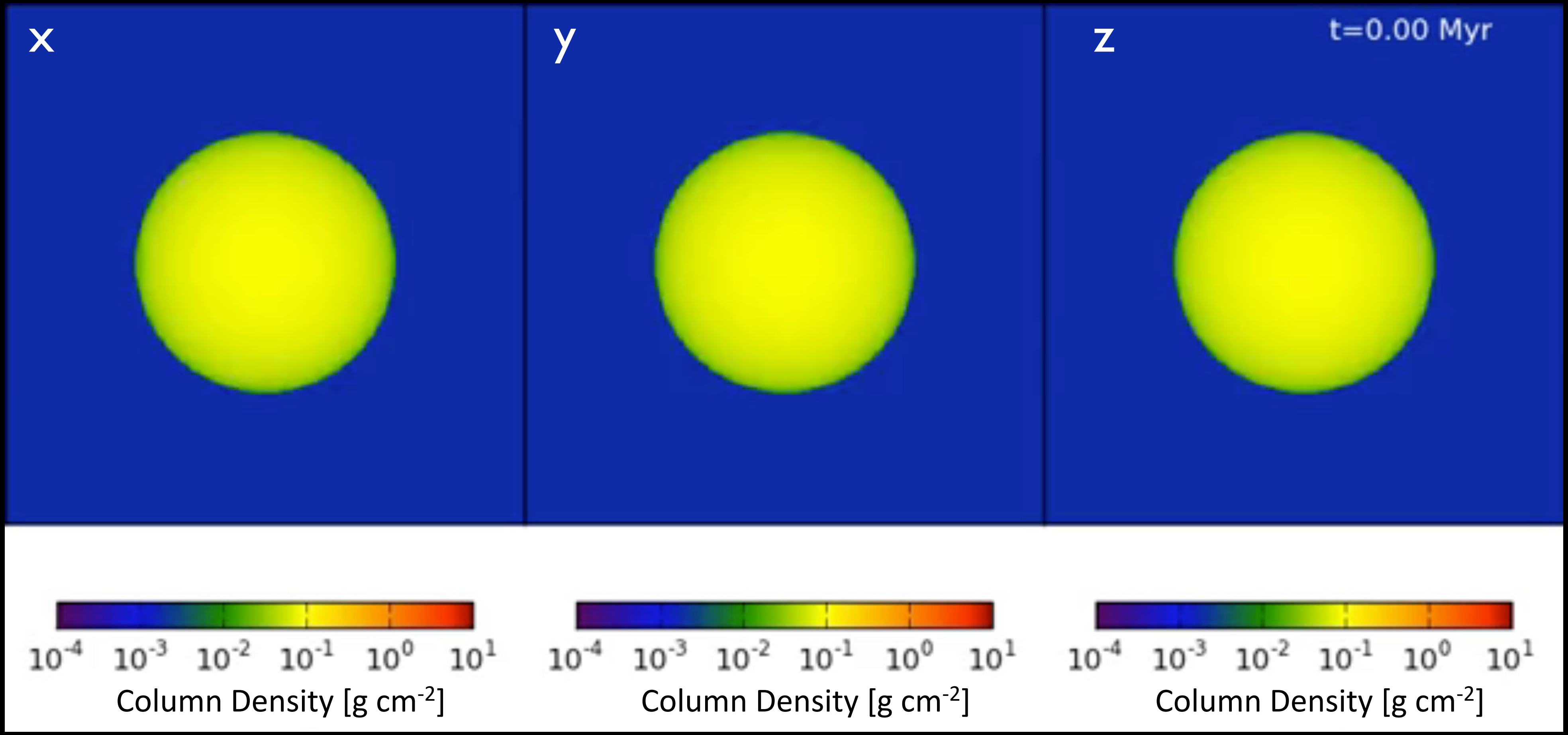
Welch et al. (2000)

Quasi-spherical wind observed in a few late Class II sources (with disk, but no envelope).
Not clear how common this is.

Using simulations to study outflow-driven gas dispersal

Simulations allows to estimate Star Formation Efficiency and Rate

Movie of density in the x, y and z planes



Simulations with ORION (AMR code) include:

- mass of core = 4 M_{sun}
- self-gravity
- seed turbulence
- Δx_{min} = 26 AU
- T = 10 K
- sub-grid stellar evolution model
- sub-grid outflow launching model
- run for 0.5 Myr

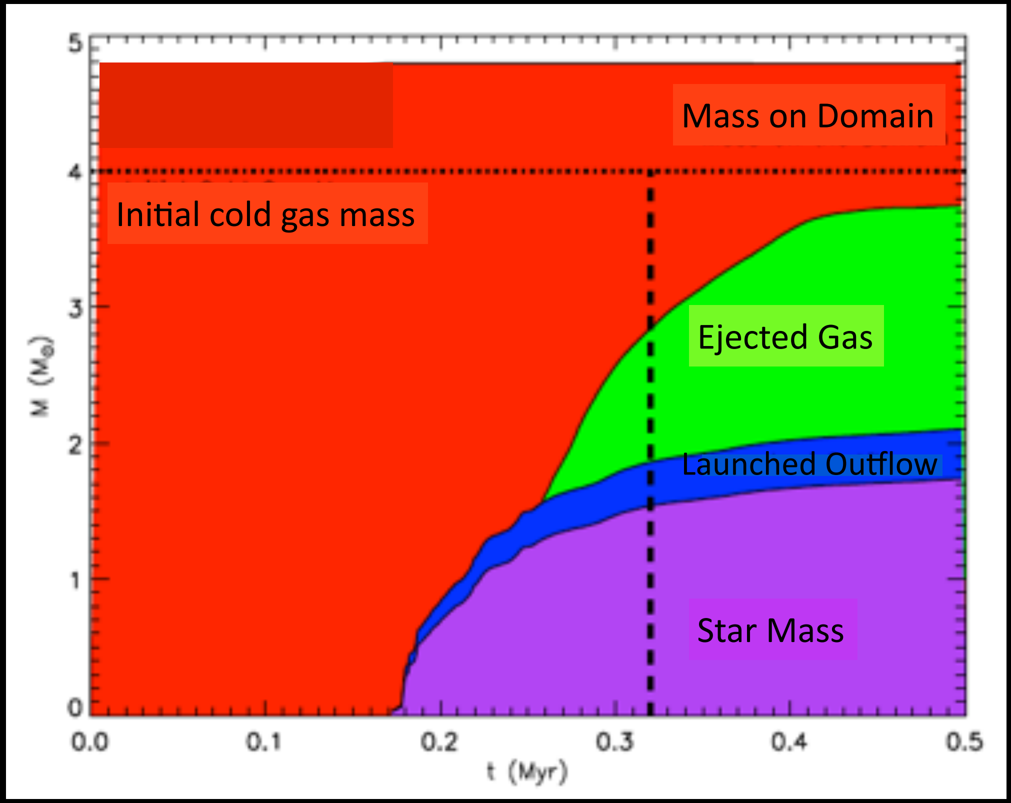
~ 0.1 pc

Results:

SFE (M_{star}/M_{core}) ~ 0.4

SFR per ff time (SFR_{ff}) ~ 0.15
(outflow feedback and core turbulence contribute
an order of mag to global SF inefficiency)

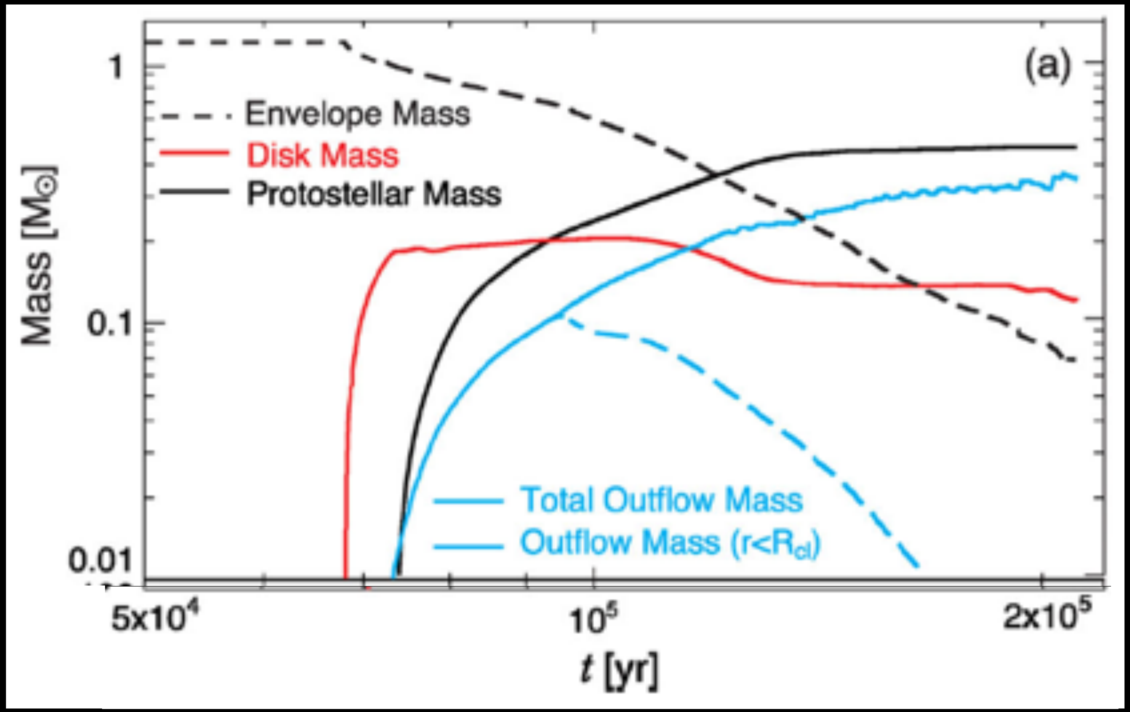
Offner & Arce (2014)

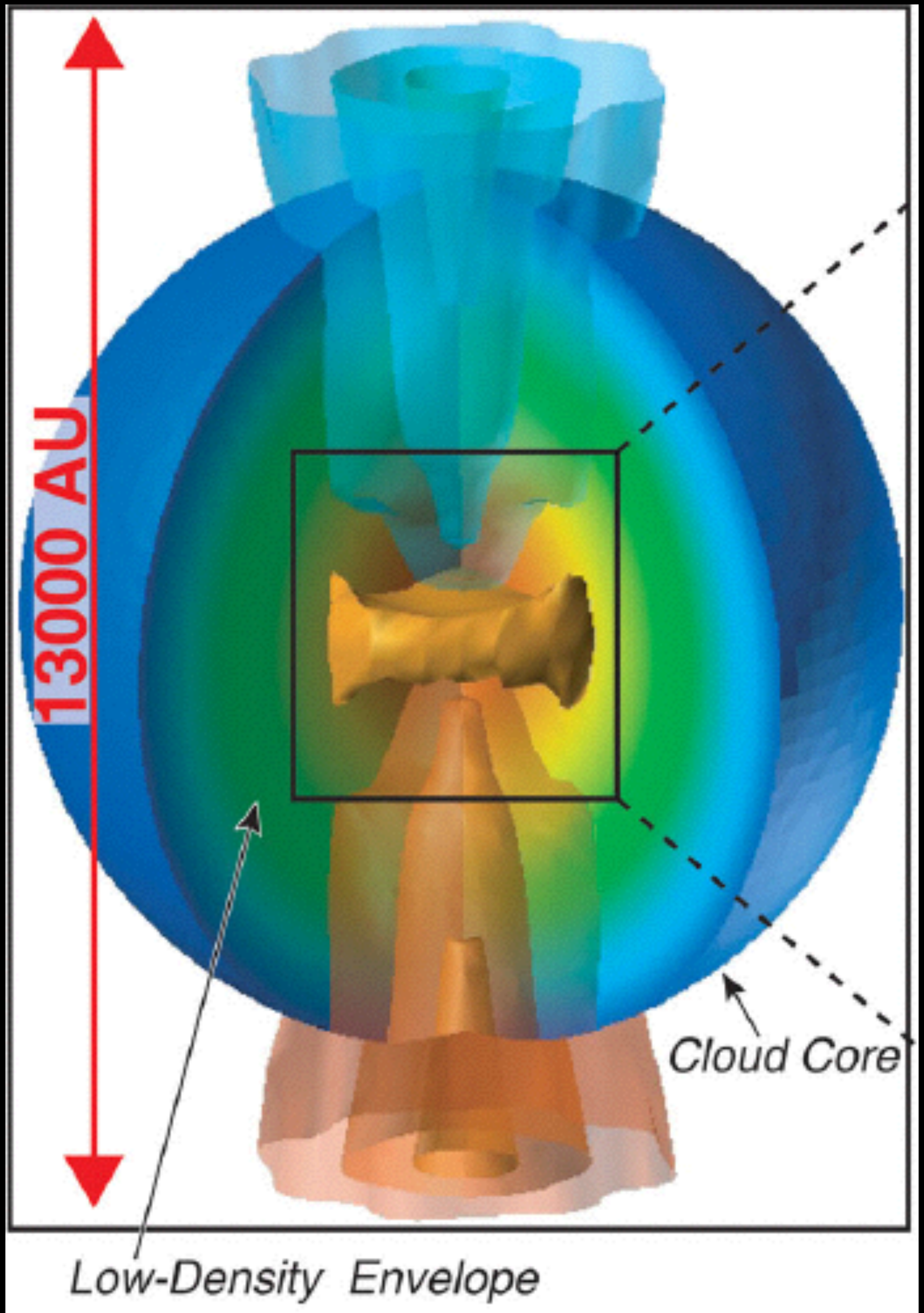


Simulations of evolution of protostar and outflow in core

MHD simulations show SFE ~50%

Large fraction of core mass is ejected by outflow





Machida & Hosokawa (2013)

Outflow-envelope interaction

However, some observational studies indicate outflow not enough to disperse envelope/core

core destruction time scale $t_{des} = M_{env}/(dM_{out}/dt)$

$< t_{des} > =$ 2.5 ± 0.8 Myr (Class 0)
$< t_{des} > =$ 1.6 ± 0.4 Myr (Class I)

(from sample of cores and outflows in Perseus)

Curtis et al. (2010)
(see also Hatchell et al. 2007)

core destruction time scale > mean lifetime of protostellar stage (~0.5 Myr)

Other possible explanations:

Heating of gas by UV radiation from star can help dissipate gas
(UV from protostars heats gas along outflow cavity walls and near protostar, see, e.g. Yildiz et al. 2013; van Kempen et al. 2010)

Mass is used up to form more than one star per core (instead of being dispersed)
(multiplicity very common in early stages of SF ,see, e.g., Chen et al. 2013, see talk by M. Dunham)

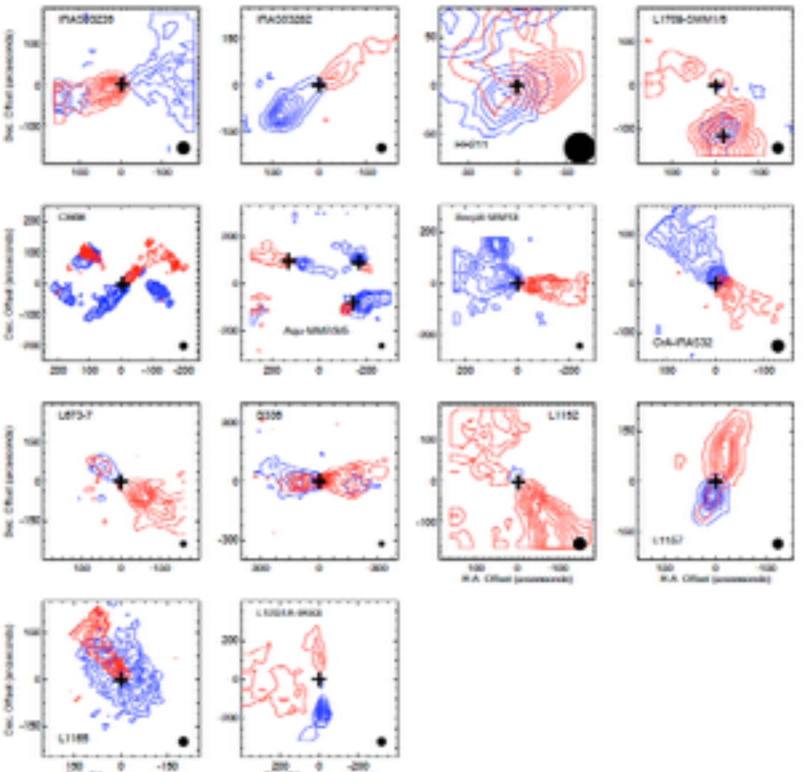
Also:

It is very likely that outflow mass, momentum, energy are generally underestimated (next slide)
(e.g., Downes & Cabrit 2007; Offner et al. 2011; Dunham et al. 2014)

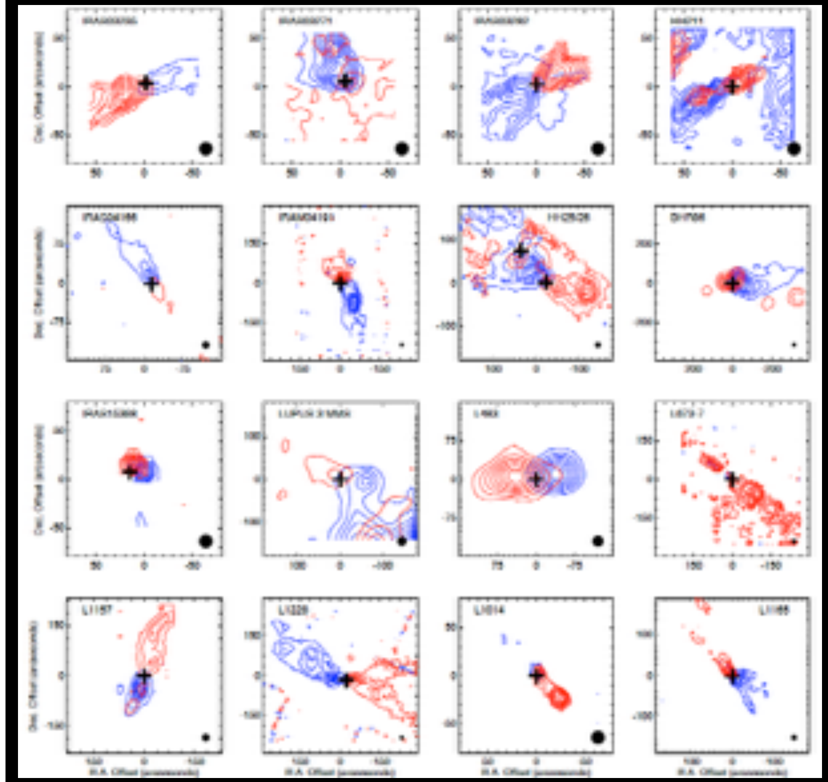
Correcting for underestimates in CO Outflow properties

Survey of 28 molecular outflows driven by low-mass protostars
Data used to explore how different assumptions affect estimate of outflow properties

CO(2-1) outflow maps



CO(3-2) outflow maps

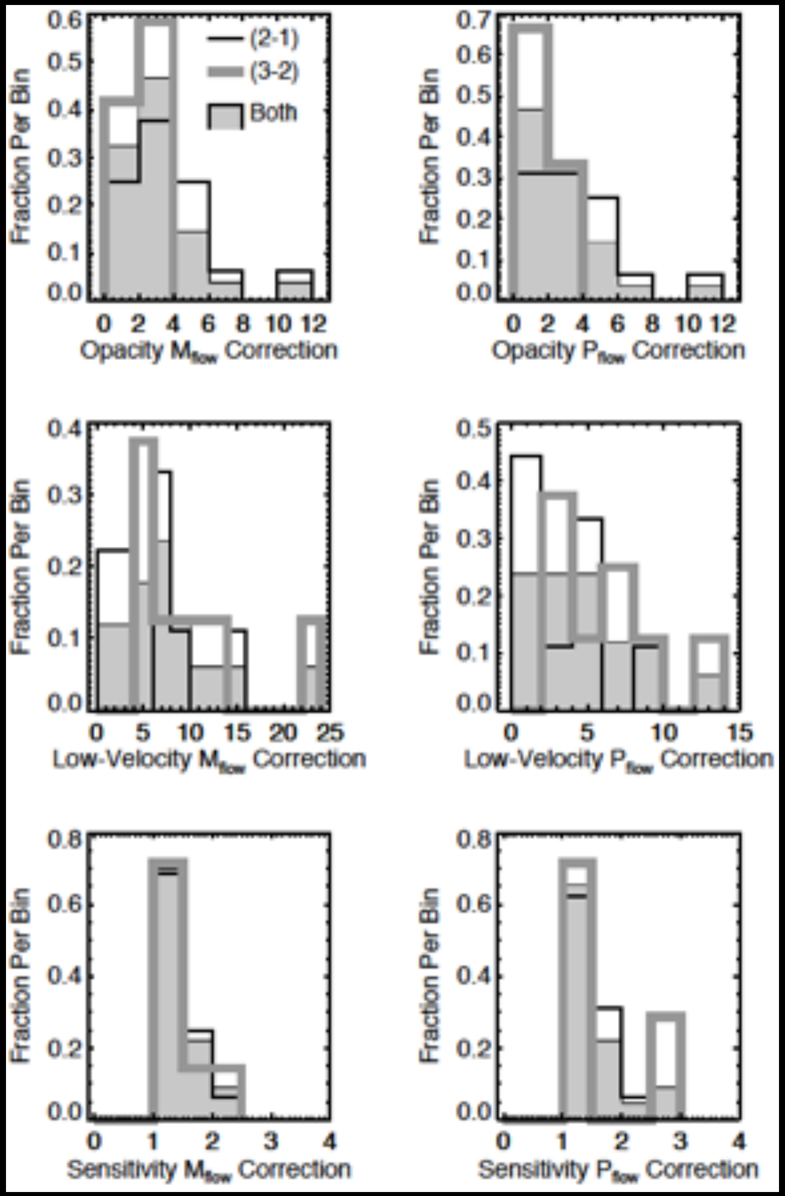


Dunham et al. (2014)

Survey of 28 molecular outflows driven by low-mass protostars, sufficiently isolated spatially and/or kinematically to fully separate into individual outflows:
-Study of outflow properties using different assumptions shows that different effects not normally taken into consideration (e.g., opacity, outflow emission at low velocities, emission below the sensitivity of the observations) increase outflow masses and dynamical properties by an order of magnitude, on average, and factors of 50–90 in the most extreme cases

Correction in

Mass **Momentum**



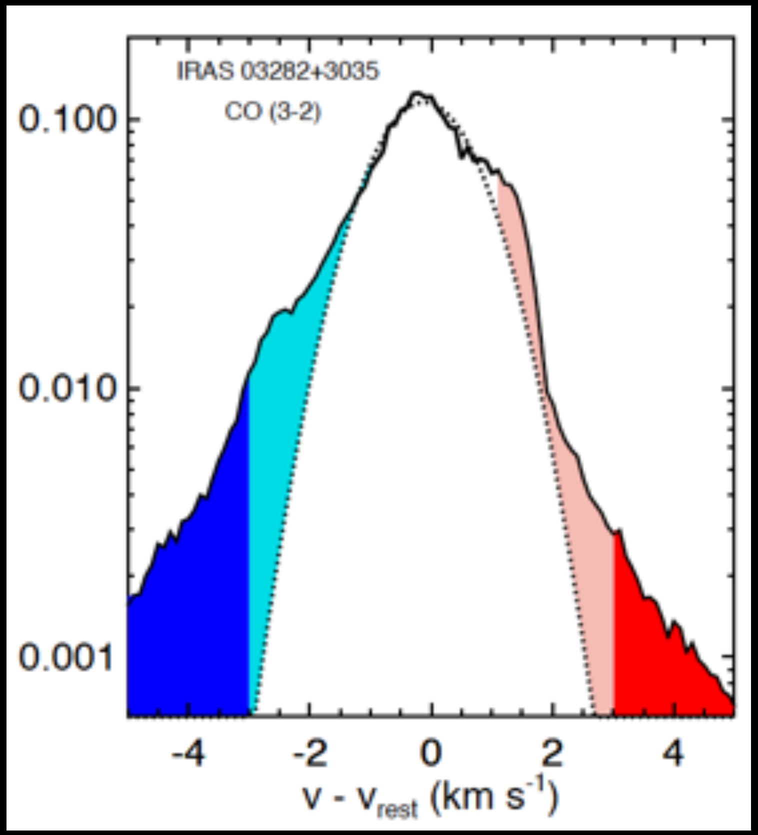
Dunham et al. (2014)

Outflow mass and dynamical properties typically underestimated by an order of magnitude (or more)

Outflows may still the potential to be the main cause for low SFE in cores, but further observational surveys are needed.

Importance of low-velocity outflow

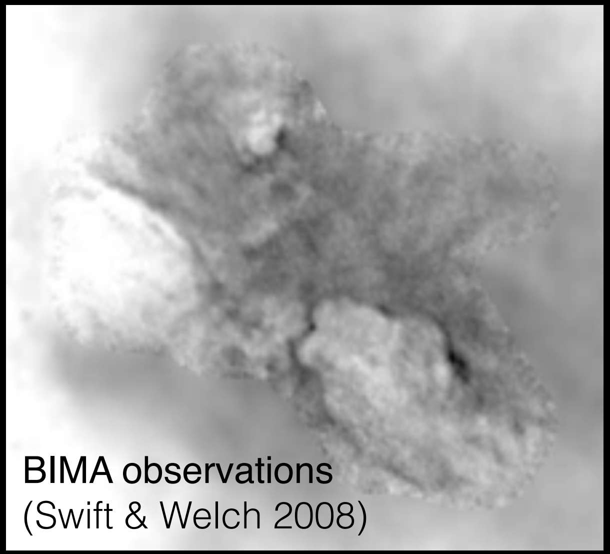
IRAS 03282+3035



Dunham et al. (2014)

A factor of a few to an order of magnitude of mass (compared to mass at $V_{out} > 2$-3 km/s) may be “hidden” in low-velocity outflow untraceable by ^{12}CO

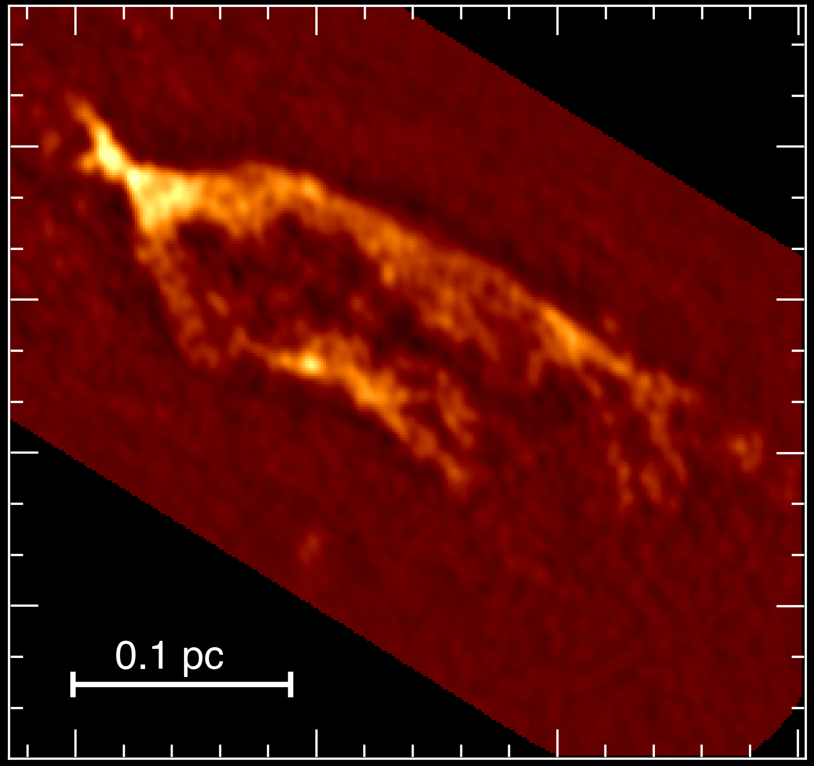
L1551 ^{13}CO(1-0)
near cloud velocity



BIMA observations
(Swift & Welch 2008)

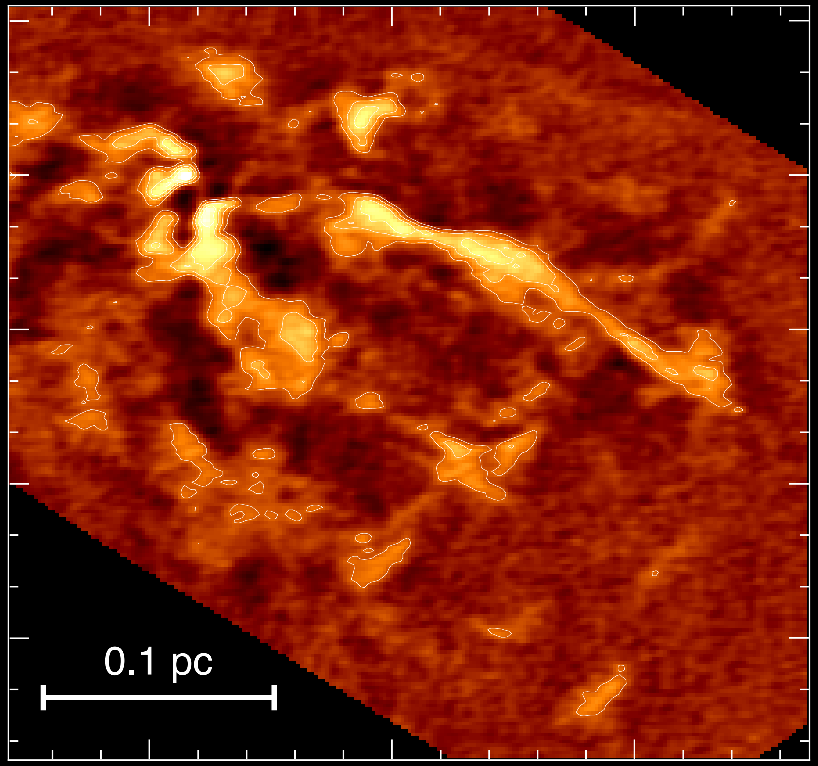
Example: red lobe in HH 46/47 molecular outflow

^{12}CO(1-0) [$v_{out} \sim 1$ km/s]



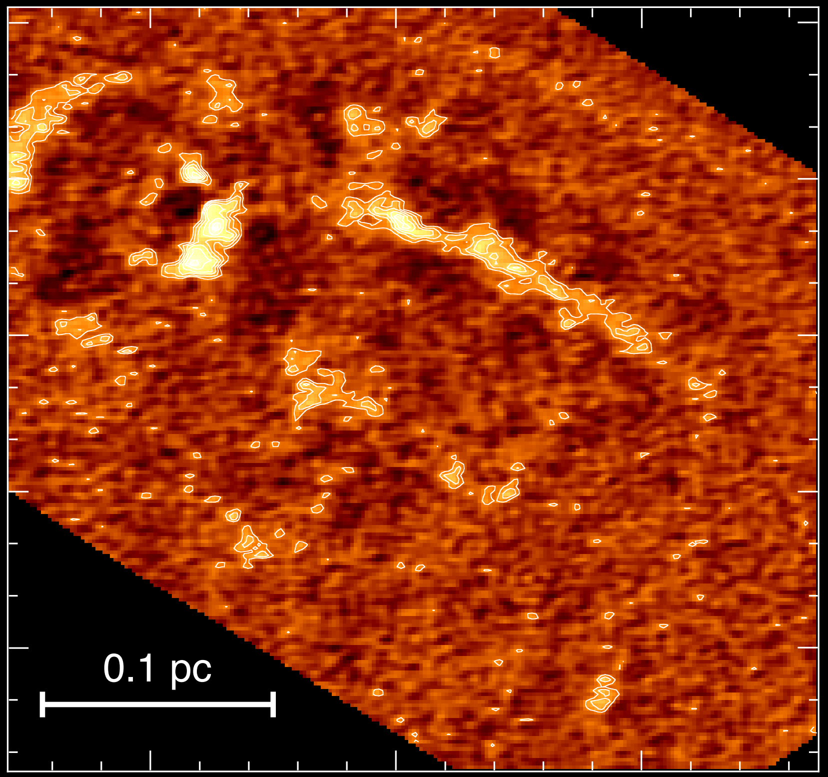
ALMA Cycle 0 data (Arce et al. 2013)

^{13}CO(1-0) [$v_{out} \sim 0.7$ km/s]



ALMA Cycle 1 data (Arce et al., in prep.)

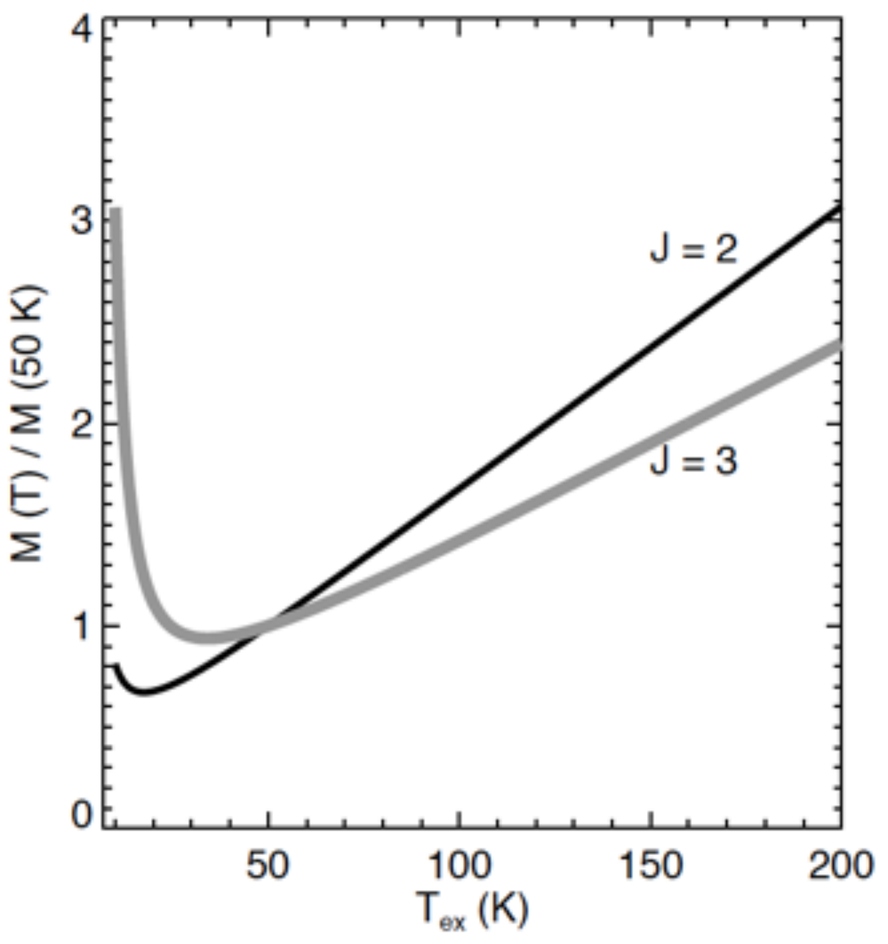
$C^{18}O$(1-0) [$v_{out} \sim 0.4$ km/s]



ALMA Cycle 1 data (Arce et al., in prep.)

Excitation temperature also important for outflow mass estimate

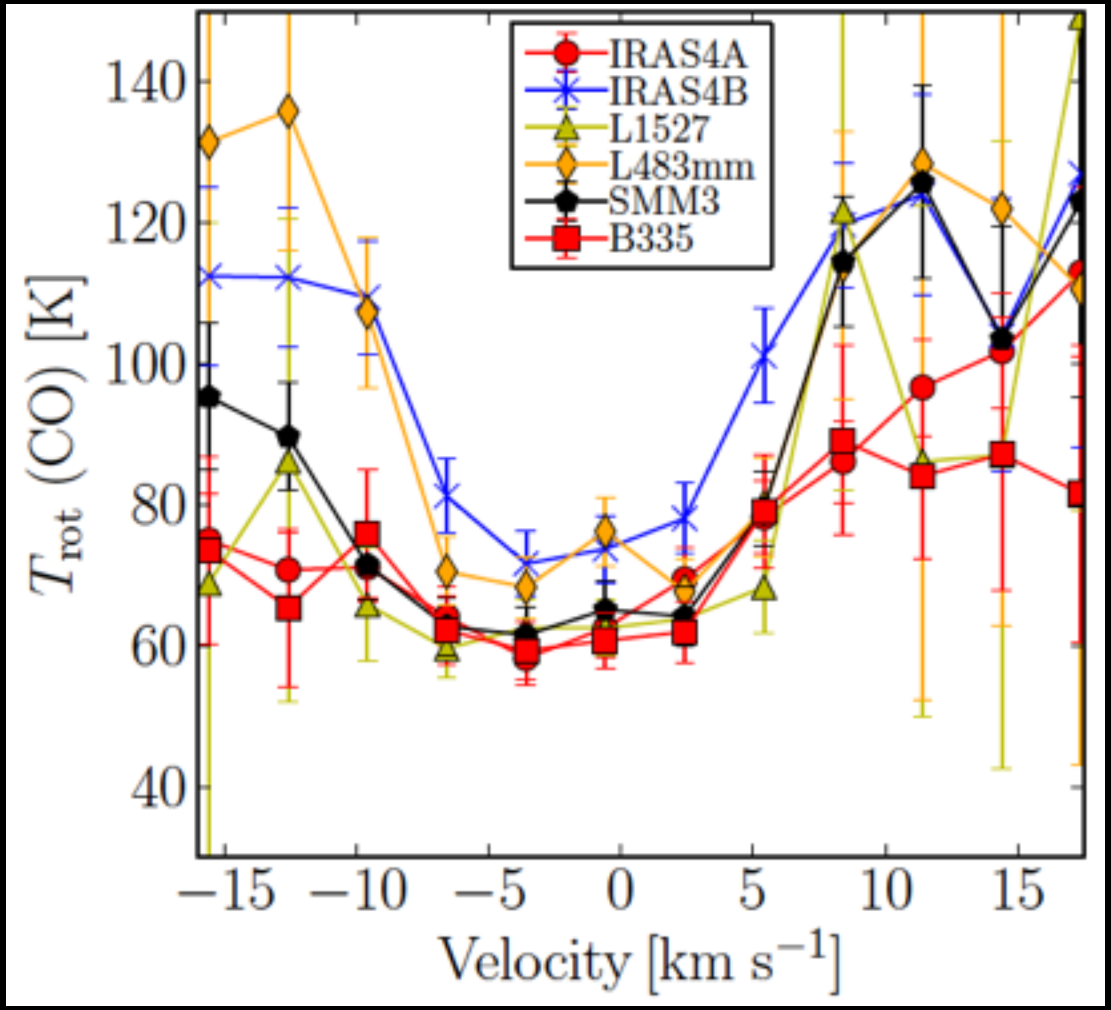
assuming “low” T_{ex} may underestimate mass



correction factor for CO outflow mass for different assumed T_{ex}, compared to mass using T_{ex}=50K

Dunham et al. (2014)

temp. typically > 50 K, and increases with velocity



Trot as a function of outflow velocity for different outflows
Trot obtained from rotational diagram, using 4 to 6 transitions

Yildiz et al. (2013)

This is further indication that outflow mass, momentum, energy are usually underestimated
(more pronounced for momentum/energy because of increase in temp. with velocity)

(see also Hatchell et al. 1999; Downes & Cabrit 2007)

Connecting small and large scales: outflow-driven turbulence

simulations indicate that outflows can easily replenish (drive) turbulence in core

color represents gas velocity

Volume rendering of gas in simulation

(Same AMR simulations using ORION as shown before)

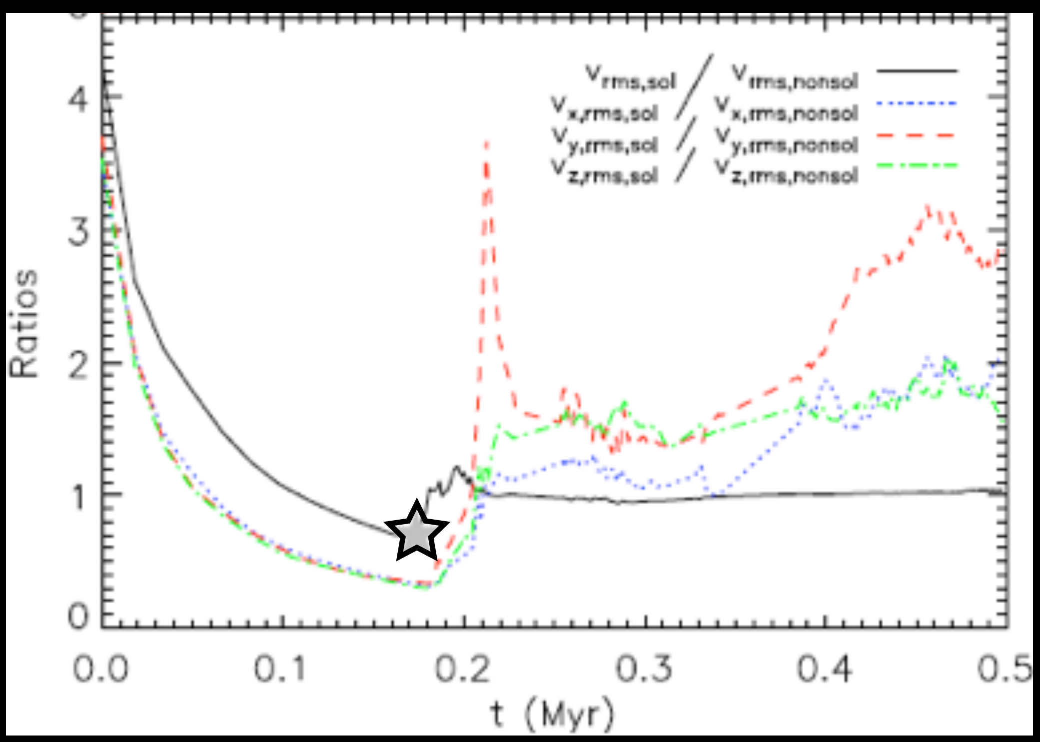
Offner & Arce (2014)

Velocity field deconstructed into two components:

$\nabla \times V$ = 0 : compressive field (squeezing motion)

$\nabla \cdot V$ = 0 : solenoidal field (stirring motion)

Ratio of solenoidal to compressive rms velocity in simulations



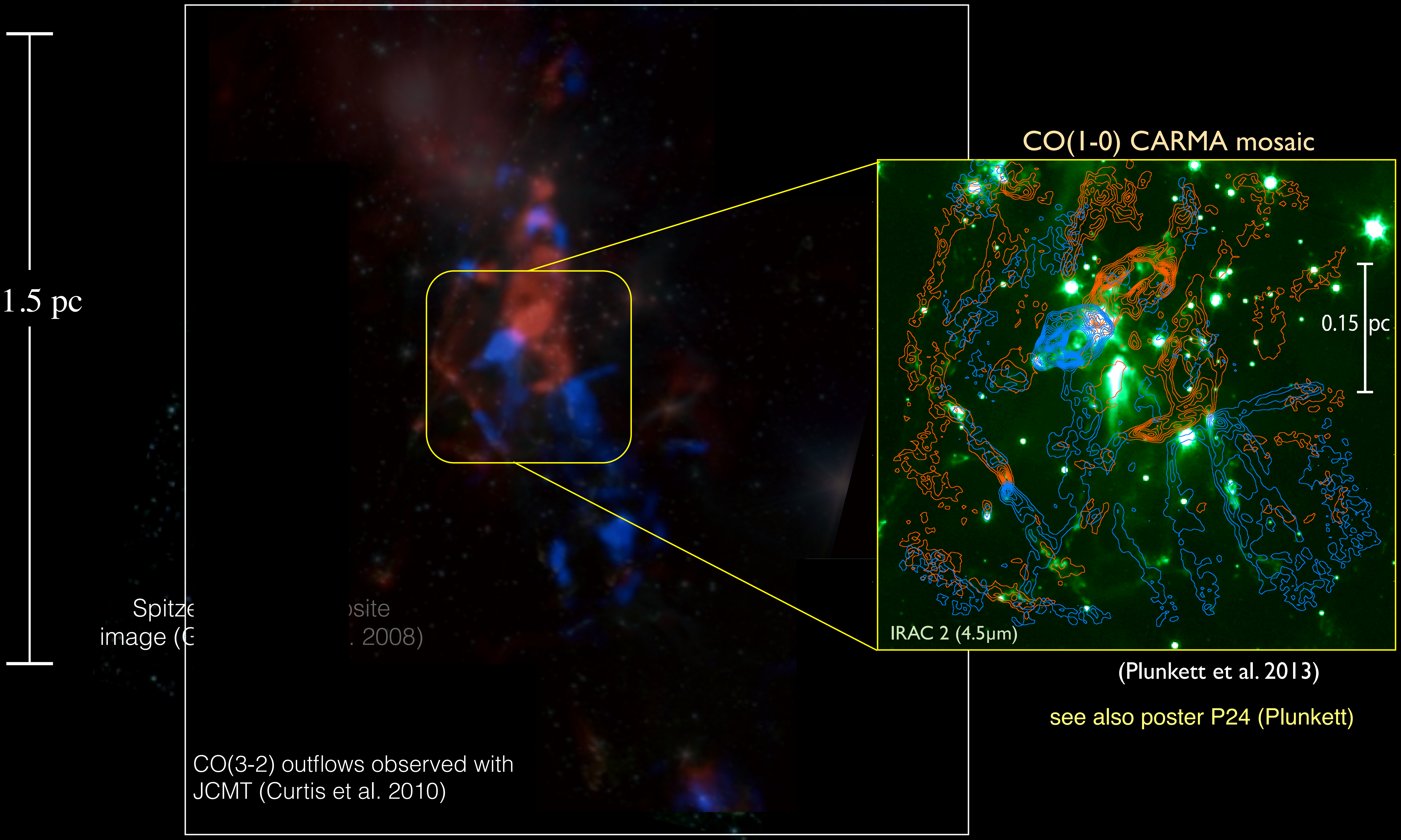
- Start with purely solenoidal random field
- It decays as gravity takes over (and compressive field increases)
- Protostar forms (t ~ 0.18 Myr) and drives outflow
- Solenoidal field increases again due to outflow
- Ratio of ~ 1 reached (due to outflow + gravity)
- Final total velocity dispersion is twice the initial value

--> **individual outflow able to replenish turbulent motions on core scales**

Outflows in protostellar clusters

Example: NGC 1333

NGC 1333 considered "prototypical" cluster by theorist modeling outflow-driven turbulence (e.g., Nakamura & Li 2007; Matzner 2007).



Spitze osite
image (G . 2008)

CO(3-2) outflows observed with JCMT (Curtis et al. 2010)

(Plunkett et al. 2013)

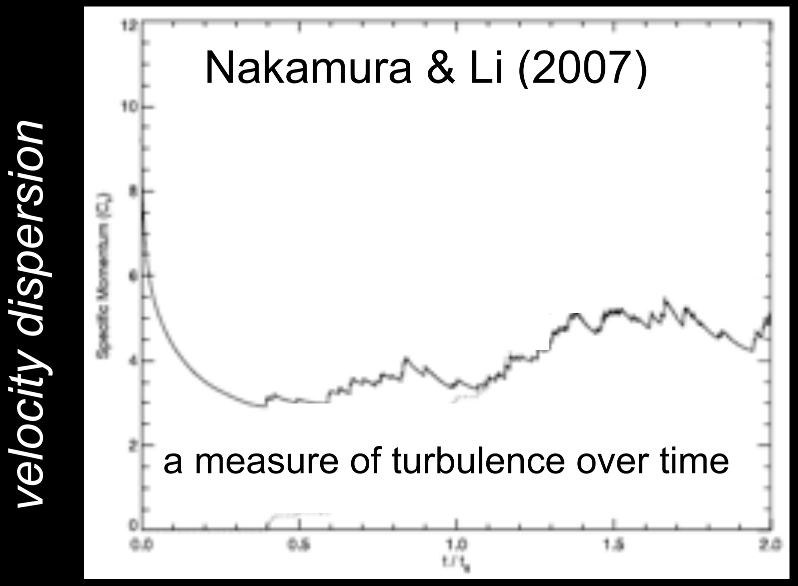
see also poster P24 (Plunkett)

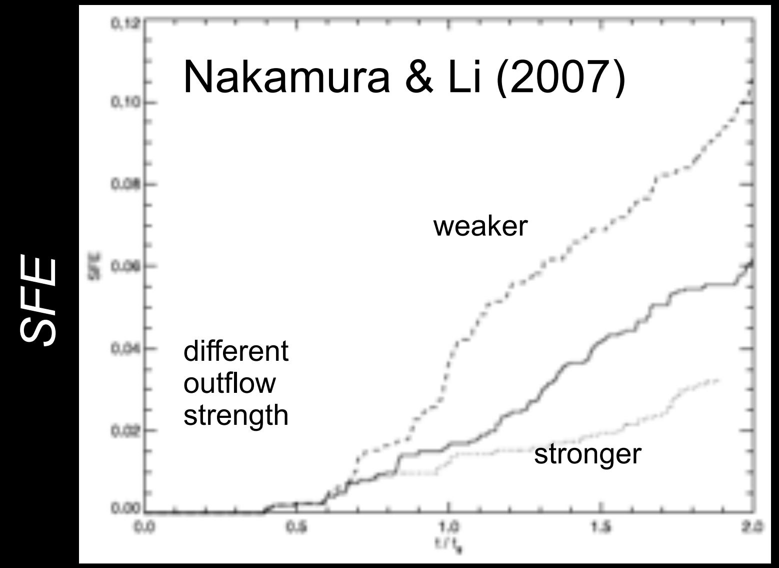
Outflows in clusters: simulations

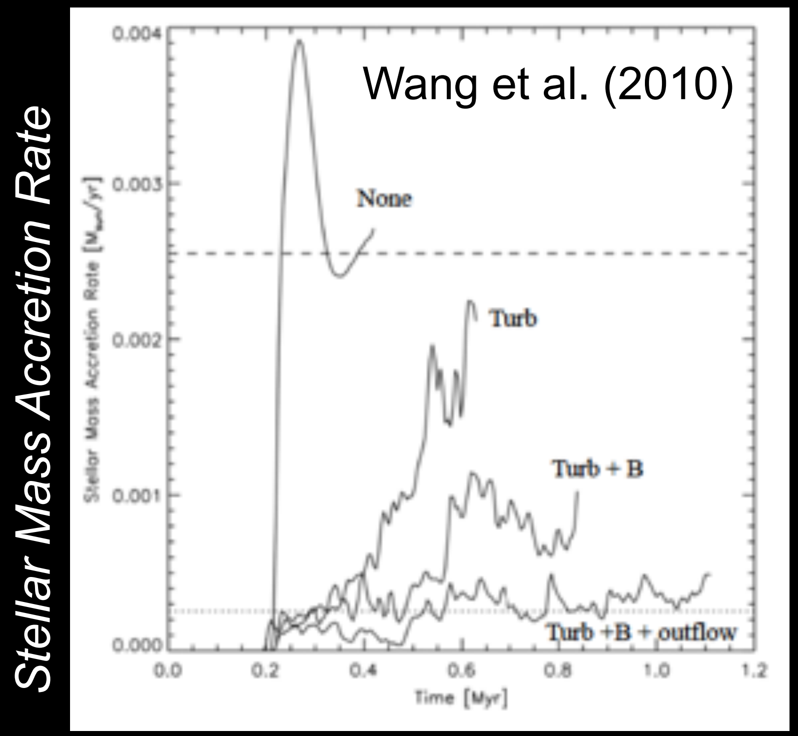
MOVIE from models by Wang, Li, Abel & Nakamura (2010)

MHD simulations show outflows important in clusters:

- outflows drive turbulence
- maintain low star formation efficiency
- maintain low accretion rate
- help maintain quasi-equilibrium state (outflow ~ infall)







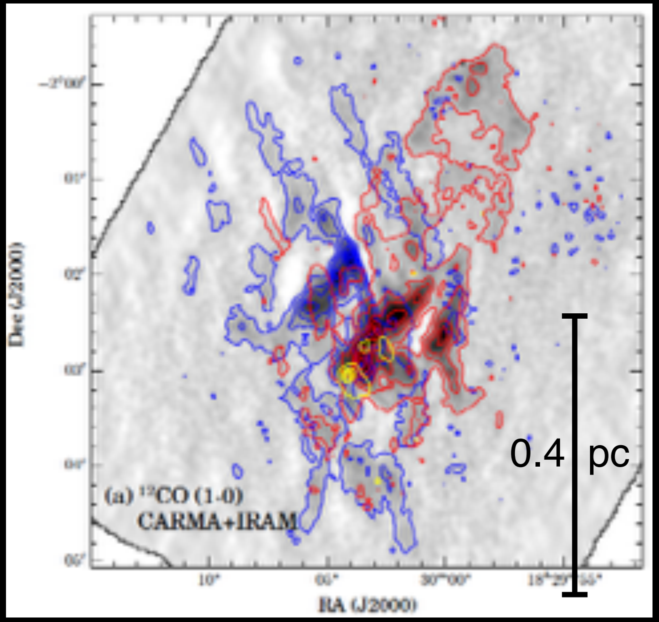
time →

Outflows in clusters: observations

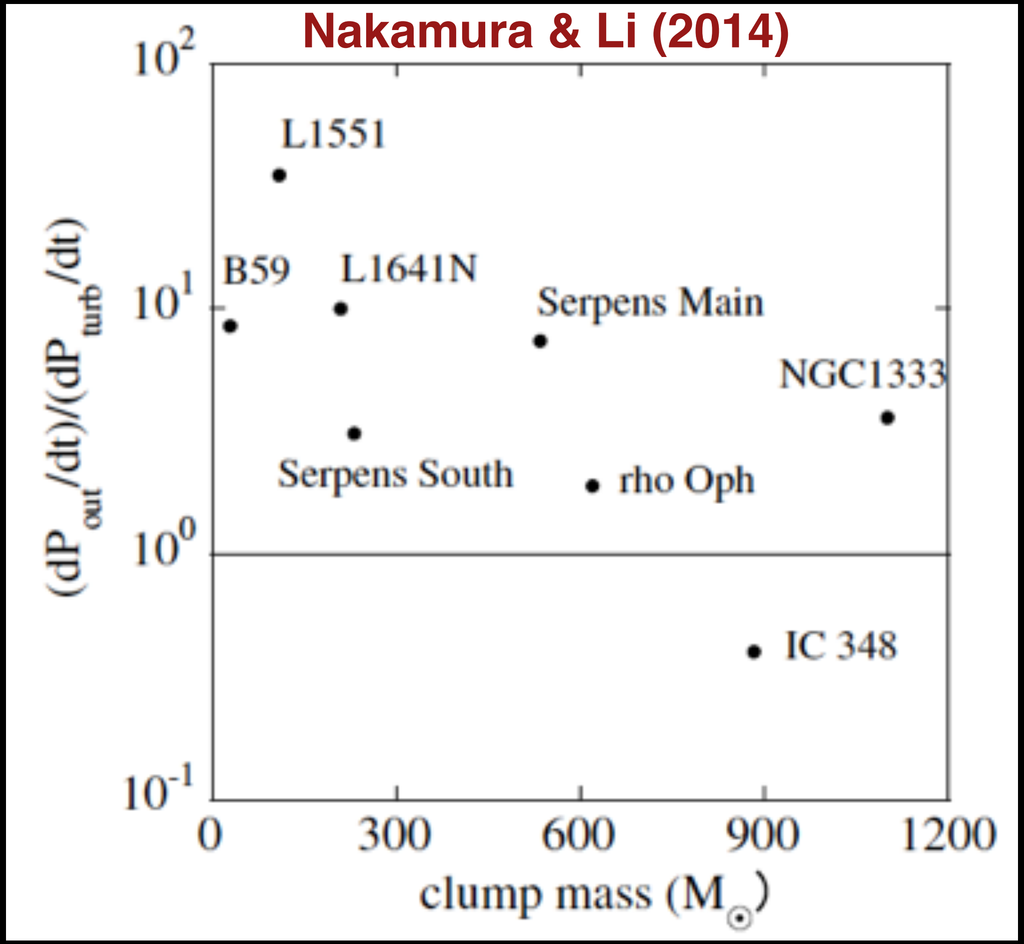
Comparing outflow momentum input rate with turbulence momentum dissipation rate

outflow inject enough momentum to maintain turbulence in clusters
(but not enough energy to totally disrupt cluster gas)

Serpens South

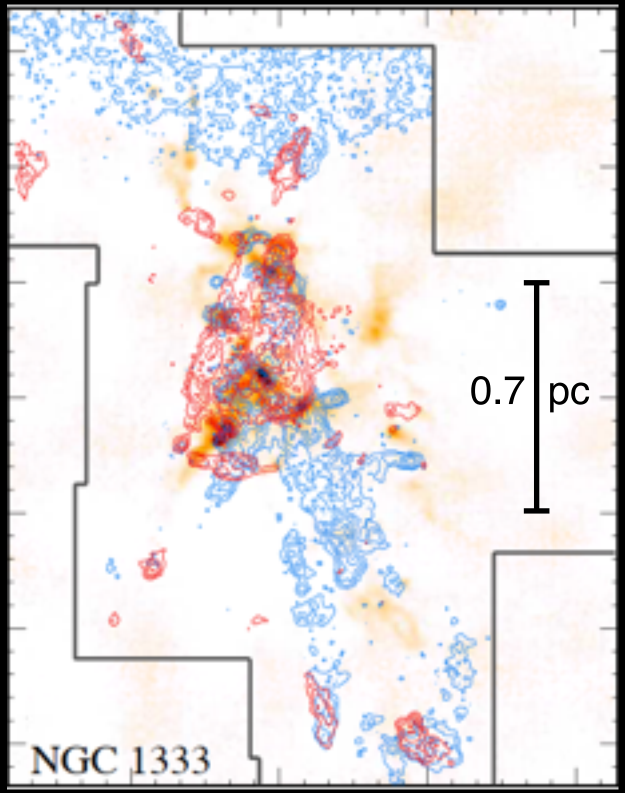


Plunkett et al. (2014)
see also poster P24 (Plunkett)



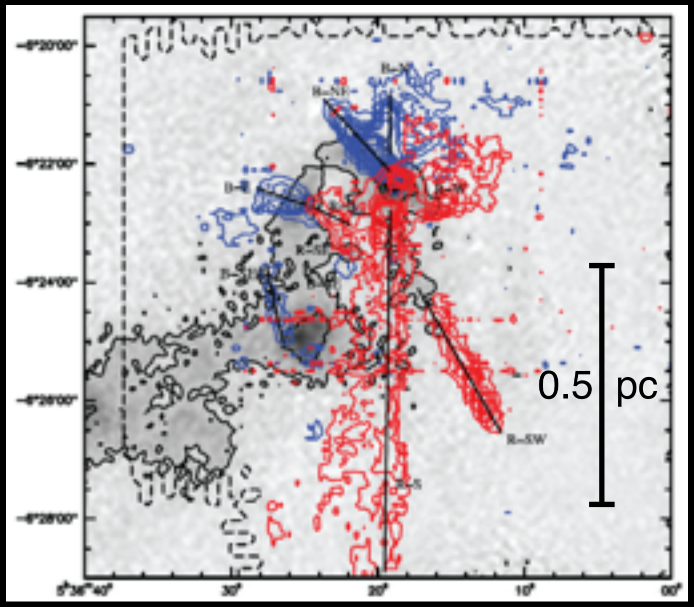
see also Arce et al. (2010)

NGC 1333



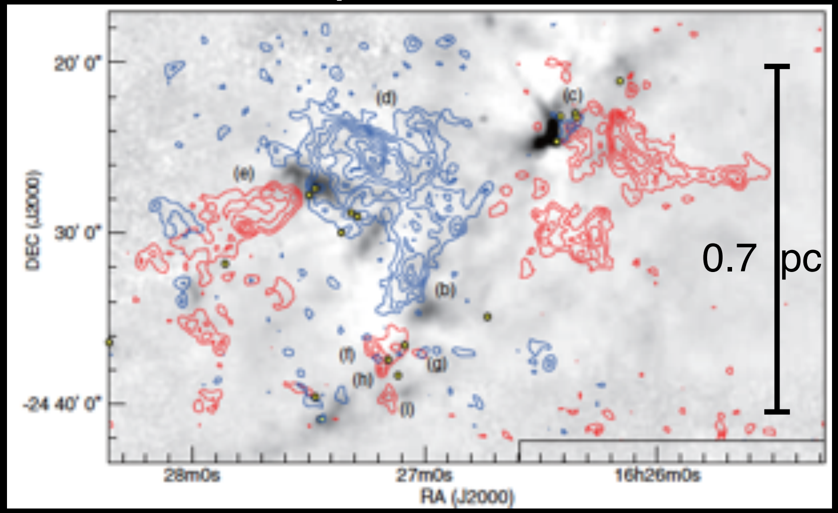
Curtis et al. (2010)

L1641N



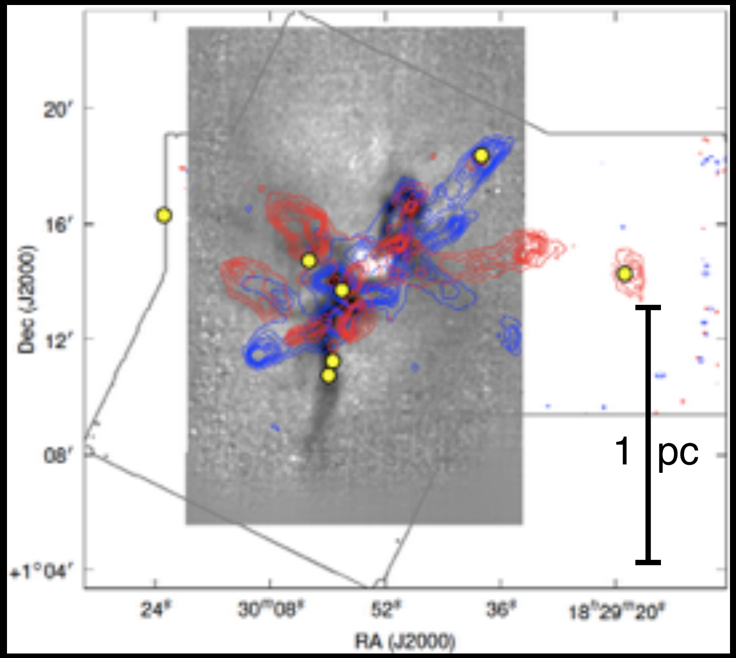
Stanke & Williams (2007)

rho Oph



Nakamura et al. (2011), see also poster P6 (Drabek-Maunder)

Serpens Main



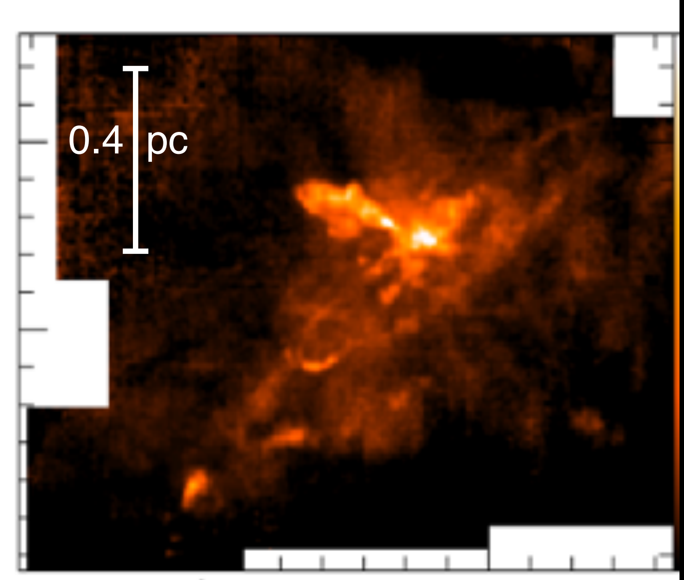
Graves et al. (2010)

Impact of outflows on cluster gas distribution and kinematics

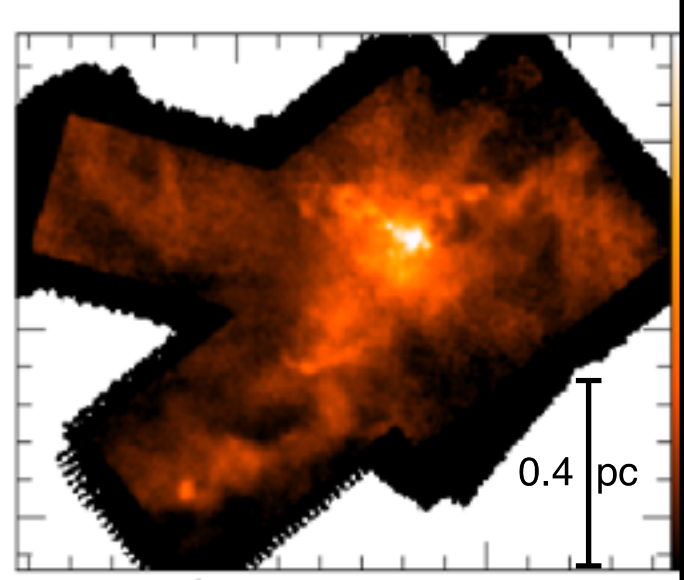
Example: B59

evidence for change in density disruption and turbulence driving by outflows

^{12}CO(3-2)

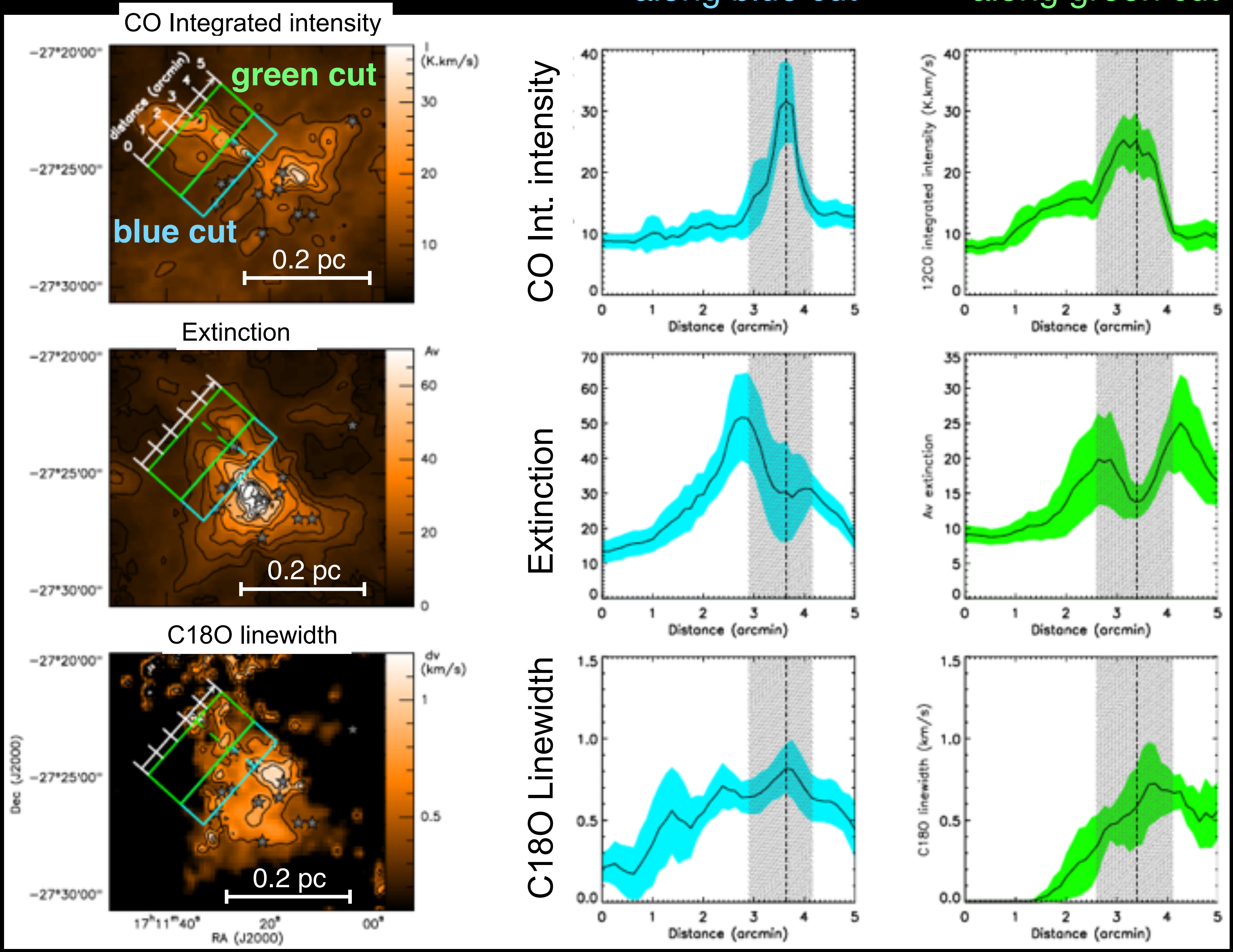


^{13}CO(3-2)



along blue cut

along green cut



direct evidence of outflow-generated turbulence?

Duarte-Cabral et al. (2012)

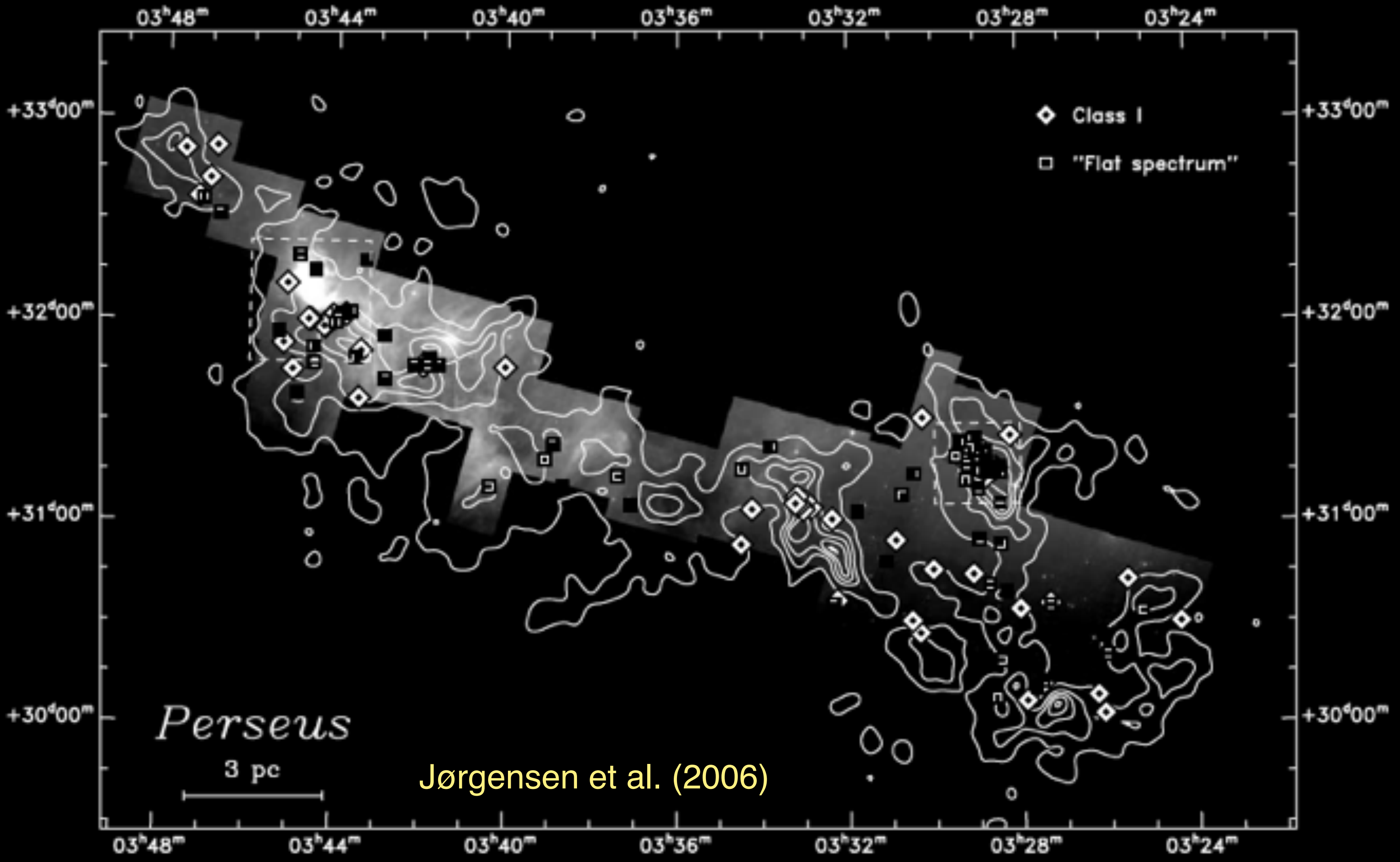
Outflow impact on cloud complexes and GMCs

Outflows have significant impact on cluster environment (sizes~1 - 4 pc), but lack power and energy to sustain turbulence or cause any major disruption on the scale of a molecular cloud complex or GMC (~10 pc).

(see Walawender et al. 2005; Dent et al. 2009; Arce et al. 2010; Ginsburg et al. 2011; Narayanan et al. 2012)

Protostars (and outflows) are mostly clustered in regions with size ~ 1 - 4 pc, large areas of cloud with few or now protostars (and outflows)

Example: Perseus

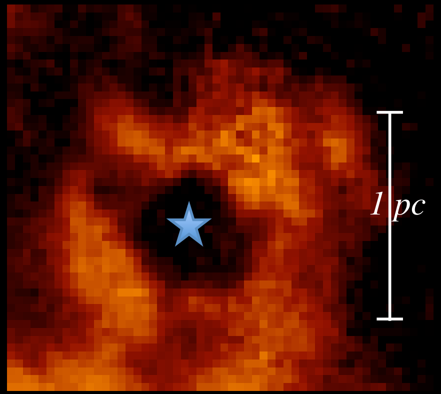


Jørgensen et al. (2006)

(see also Arce et al. 2010)

Additional energy source is responsible for turbulence on a global cloud scale.

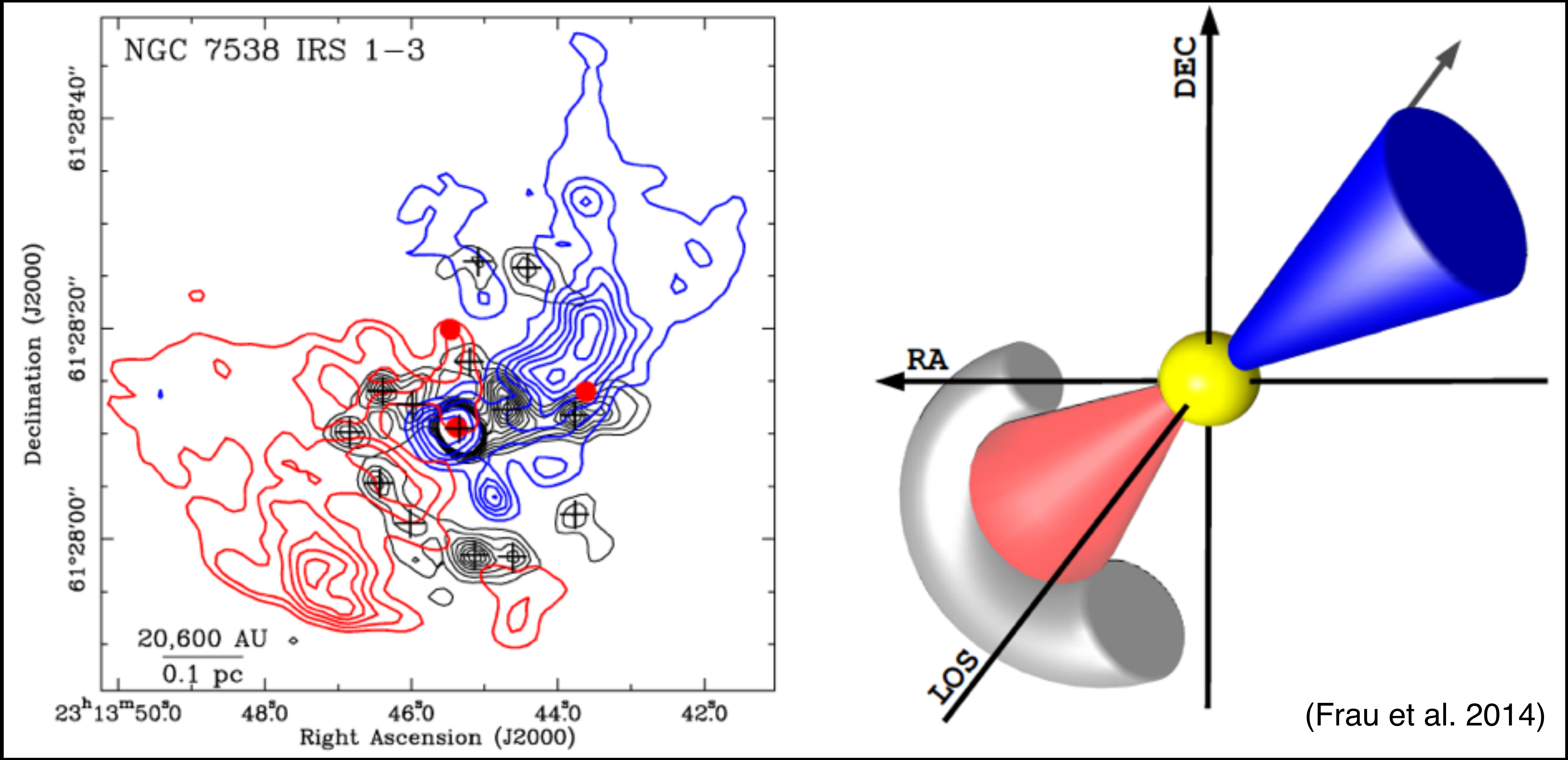
(spherical) winds from mid to high mass stars are good (internal) candidate in many regions
(e.g., Arce et al. 2011;
Nakamura et al. 2012)



shell in Perseus (B5)
(Arce et al. 2011)

Outflows can change density distribution of cloud

“Shaping a high-mass star-forming cluster through stellar feedback”
NGC 7538 IRS 1-3



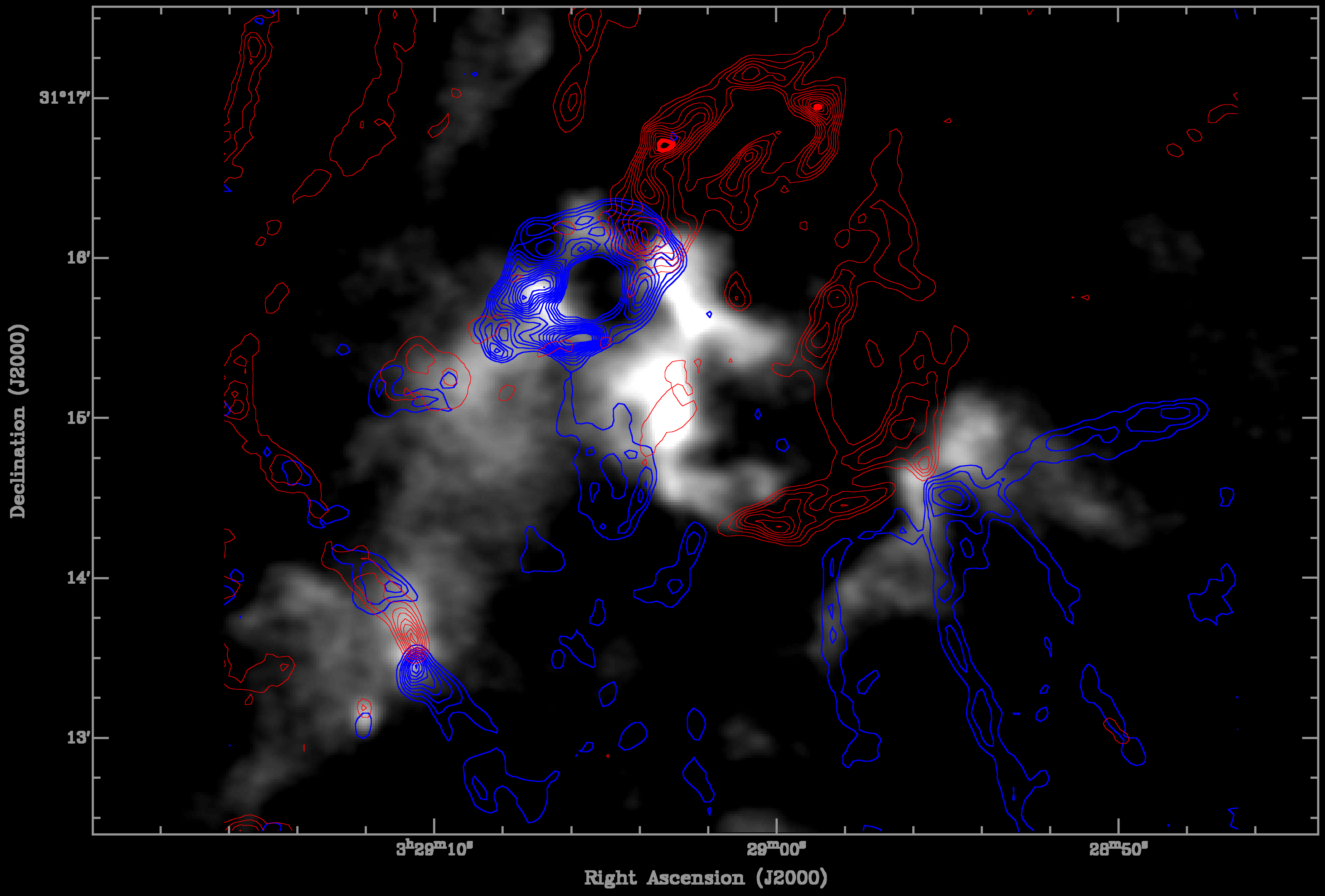
(Frau et al. 2014)

Evidence for dusty curved structure (with ~50 M_{sun}) formed by outflow from high mass star
also, possible evidence of (outflow)-triggered core formation

For more on outflows from massive stars see previous section,
poster P4 (Cunningham), and next talk by V. Rosero

Outflows affect dense gas

NGC 1333



Greyscale: N2H+ data from CARMA Large Area Star formation Survey (CLASSy) observations of NGC 1333 (Mundy et al.)

red and blue contours: red and blue-shifted CO(1-0) outflows (Plunkett et al. 2013)

Giant (parsec-scale) Outflows are common

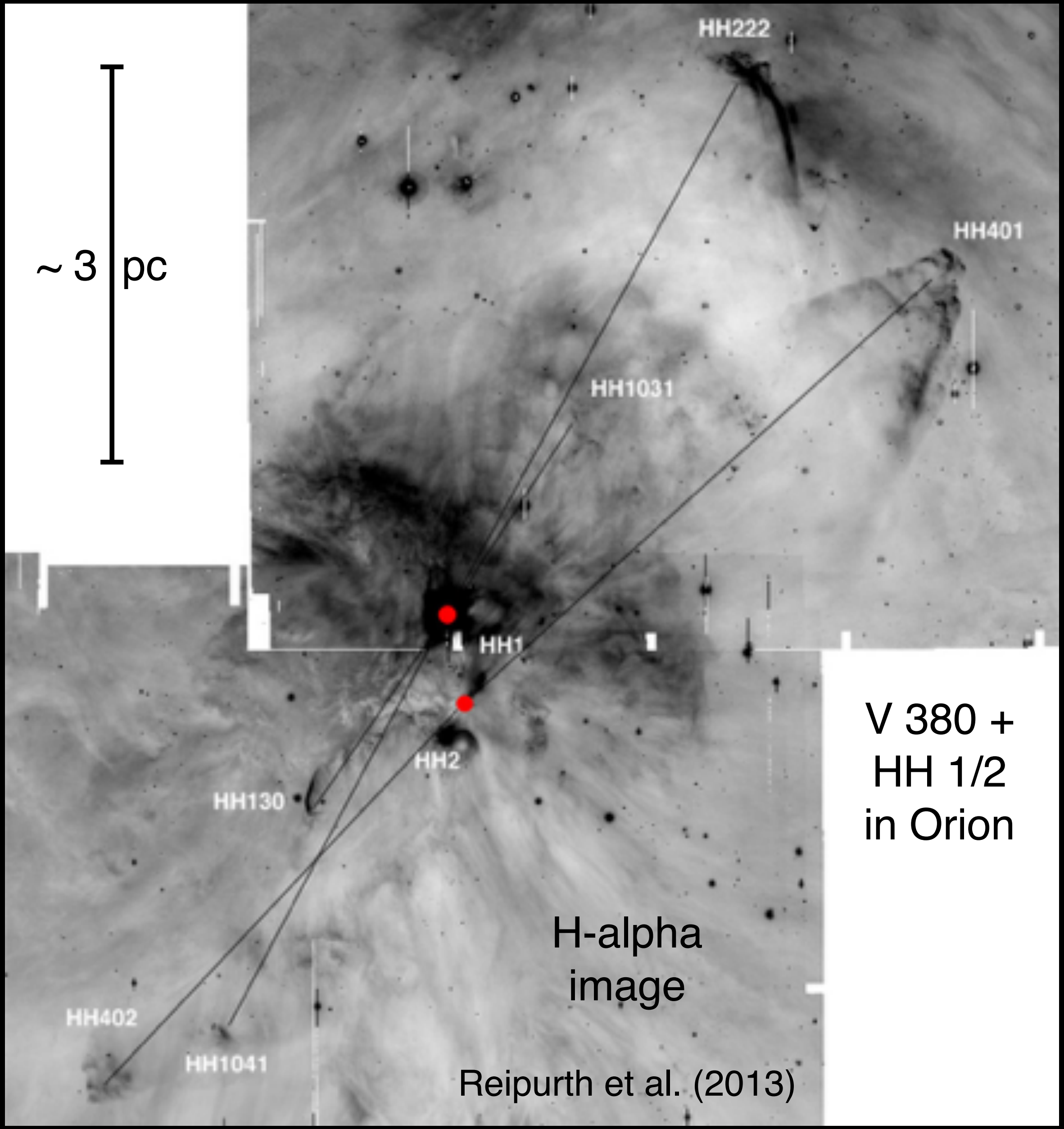
Discovery of many giant (pc-scale) outflows in the late 90’s

Existence of giant outflows should not be surprise, if assume constant jet velocities of ~100 km/s and timescales of 0.1 Myr. Outflows could reach ~10pc from source.

$d_{pc} \sim \tau_4 \, v_{100}$ pc ,
d_{pc} = distance from source in pc
v_{100} = velocity in units of 100 km/s
τ_4 = dynamical time units of 10^4 yrs

Even if take deceleration of ejecta in consideration, pc-scale outflows should be common

Recent cloud-wide surveys show that probably most outflows are much larger than previously thought, and can easily reach lengths of > 1 pc (e.g., Narayanan et al. 2012)

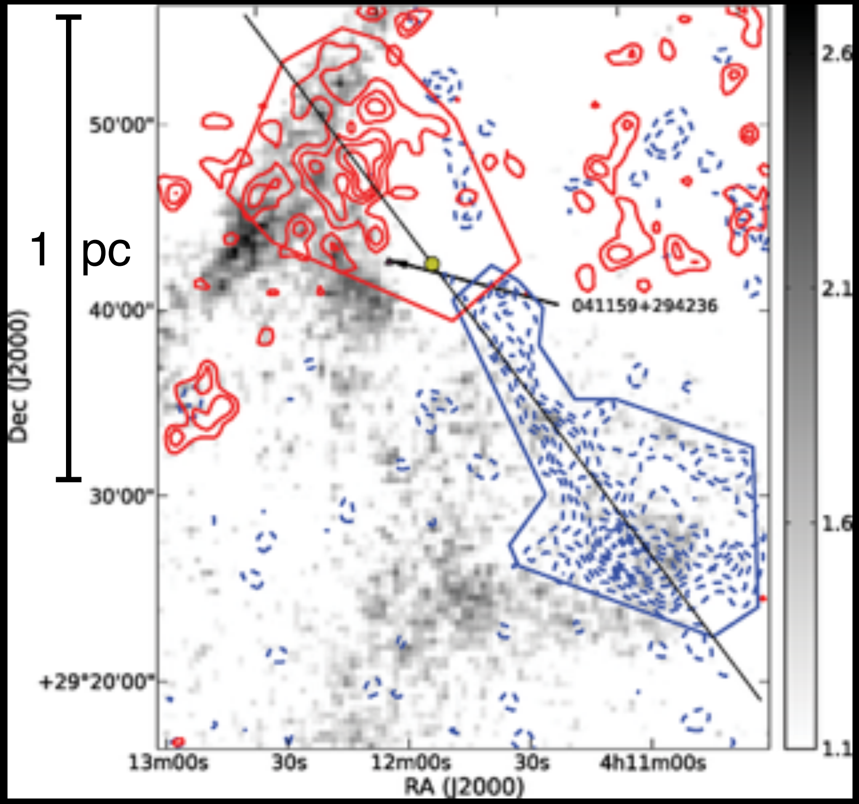


V 380 + HH 1/2 in Orion

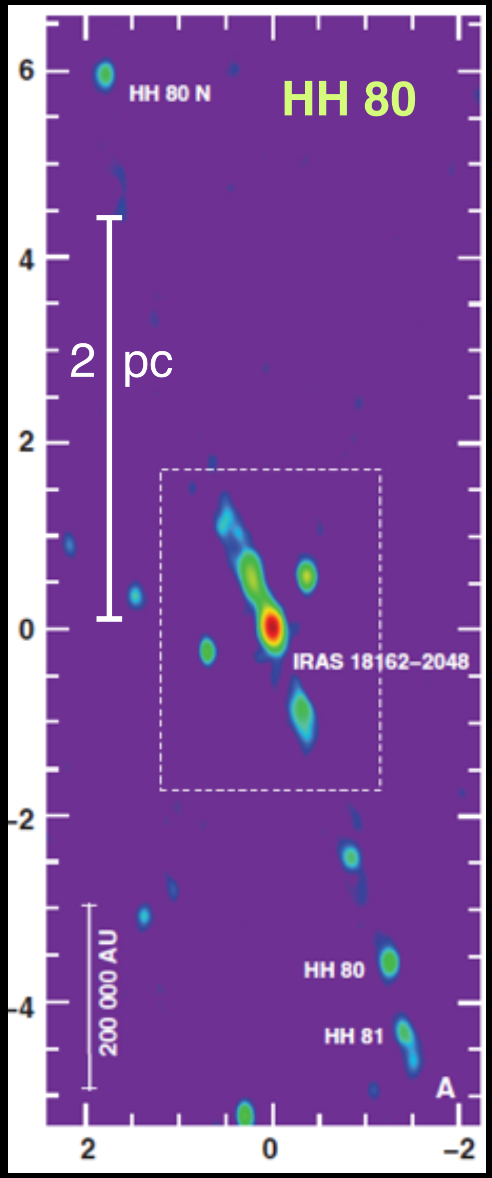
H-alpha image

Reipurth et al. (2013)

YSO 041159+294236



CO outflow in Taurus
(Narayanan et al. 2012)



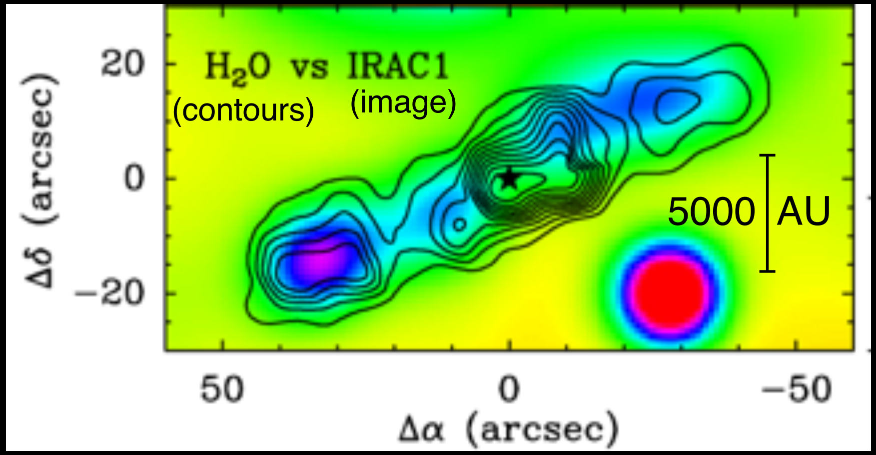
Radio jet
(Carrasco-González et al. 2010)

Outflow Chemistry: connecting large scales with (really) small scales

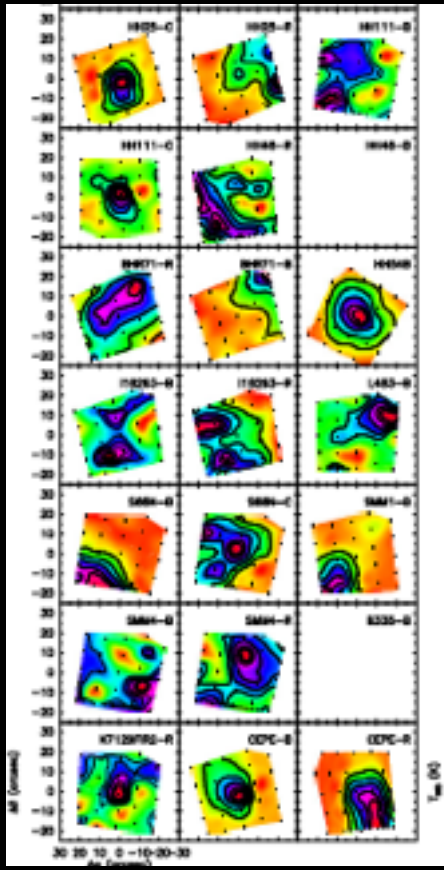
Shocks trigger physical processes (e.g., grain destruction) and chemical reactions (i.e., high-temperature gas-phase chemistry) not present in quiescent gas, affecting chemical abundance of molecules in cloud

Water, water everywhere…

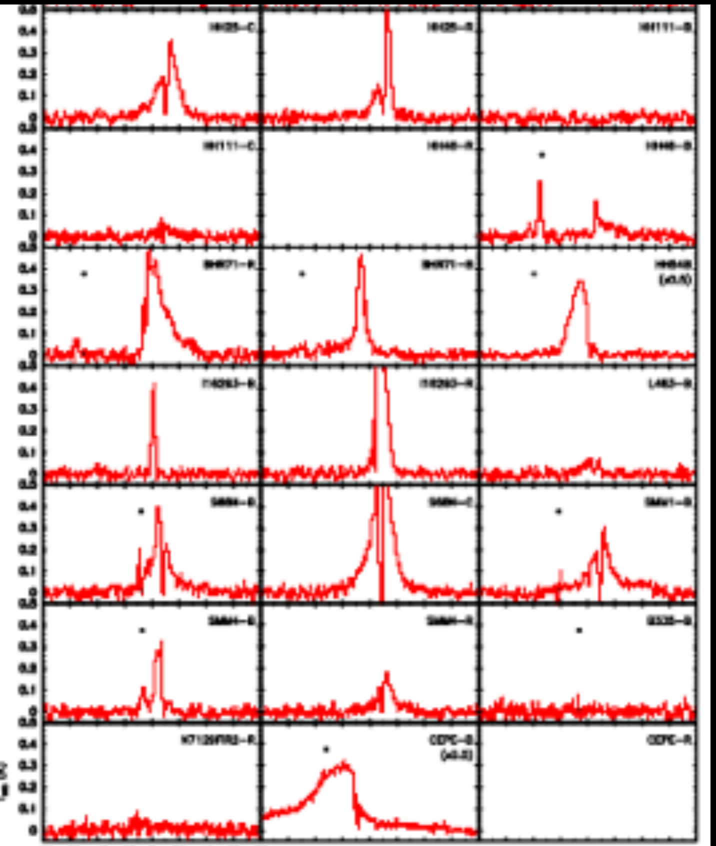
HH 211



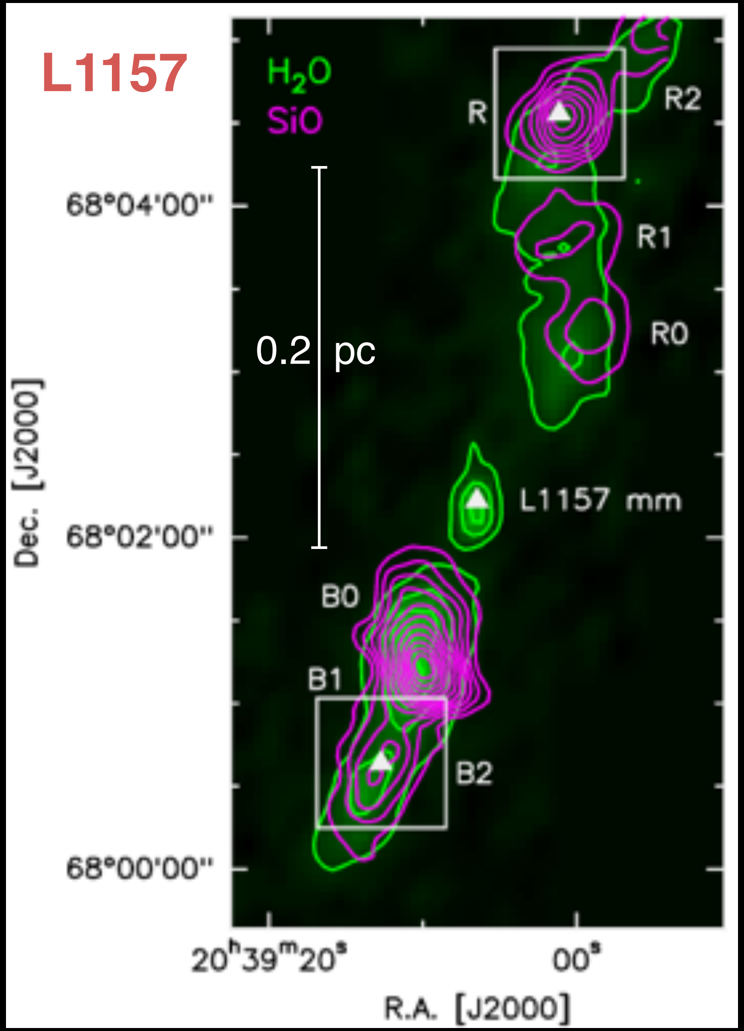
Tafalla et al. (2013)



PACS map of $H_2O(2_{12}-1_{01})$



HIFI spectra of $H_2O(1_{10}-1_{01})$



Santangelo et al. (2013)

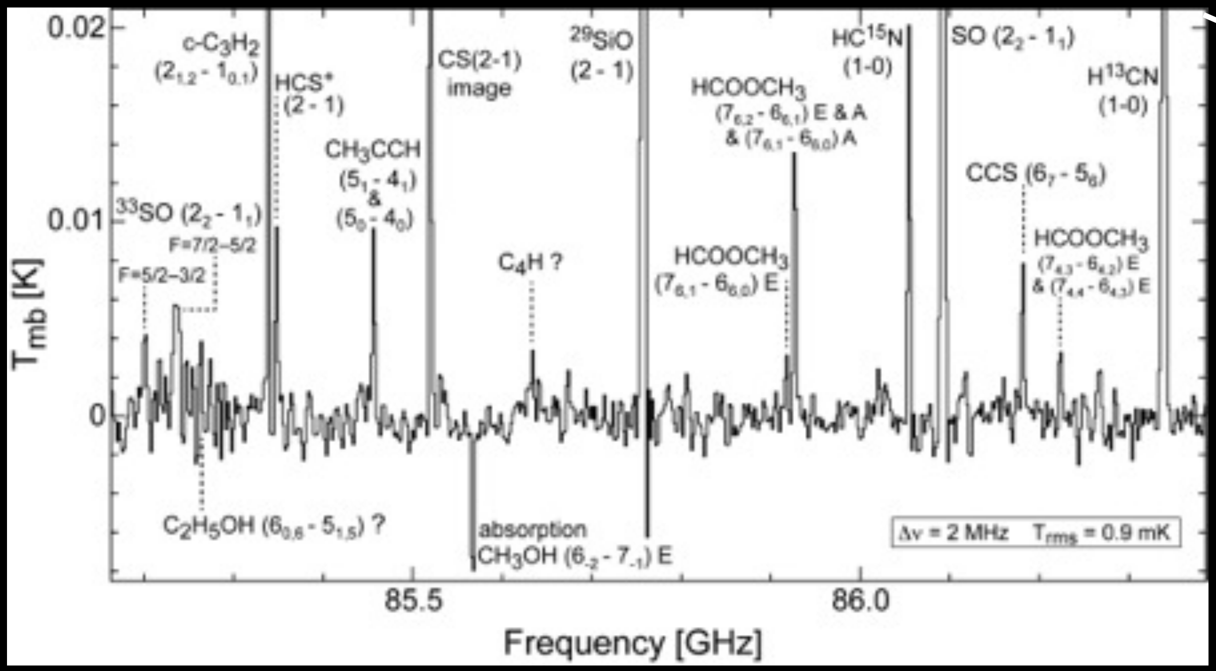
Spatial distribution of H_2O similar to shock tracers (e.g., H_2, SiO, high-J CO) —> H_2O traces currently shocked gas (different from entrained gas traced by low-J CO)

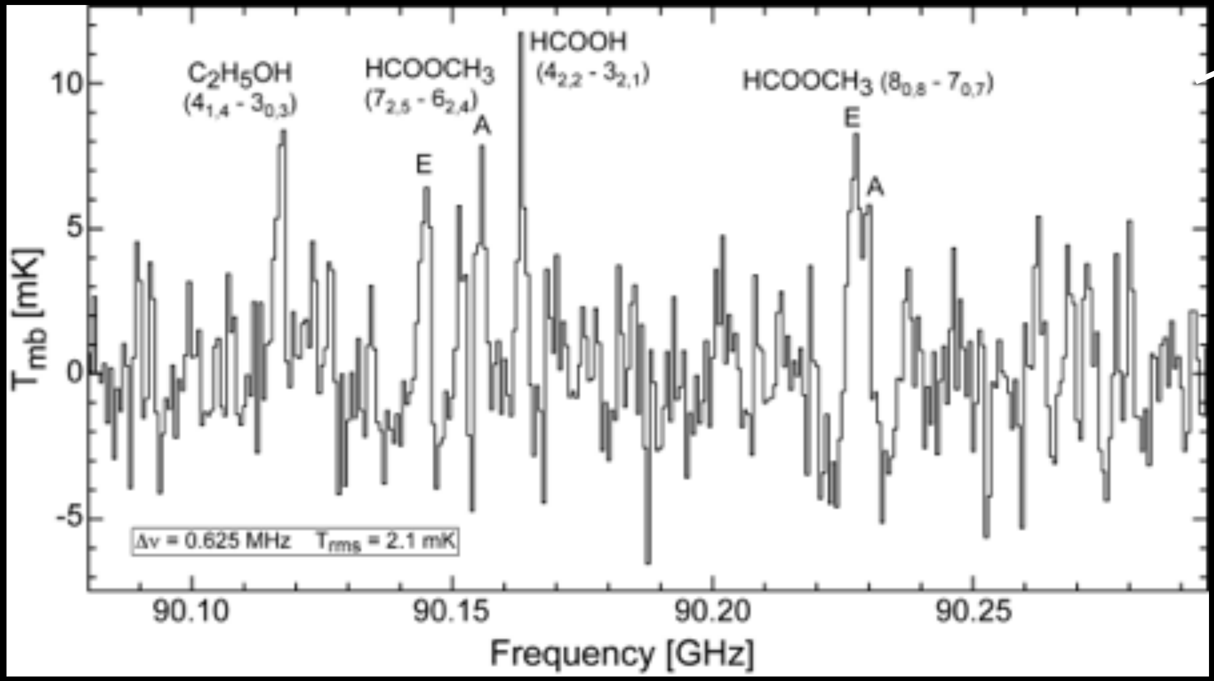
(see also Yildiz et al. 2013)

High-temp. chemistry and ice sputtering may both contribute to high H_2O abundance in outflows (van Dishoeck et al. 2013)

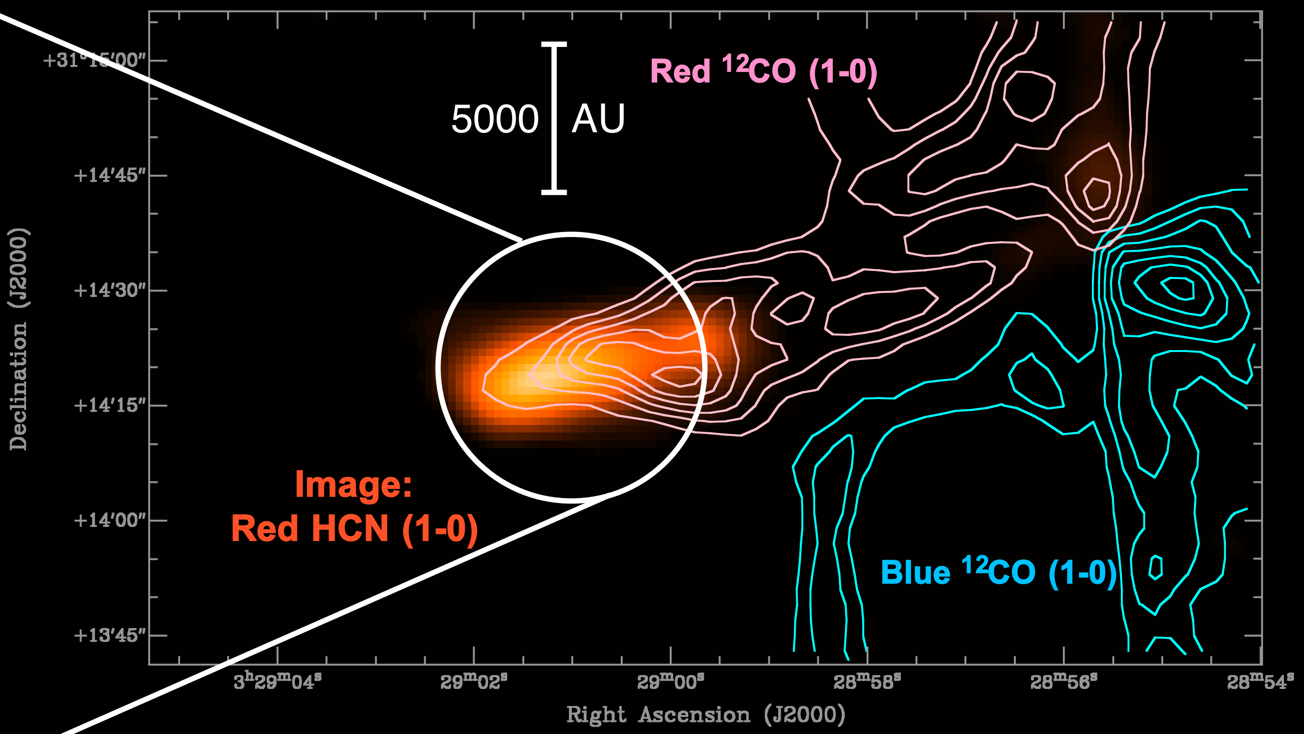
Connecting large and (really) small scales

Estimating composition of COMs in ice mantle with mm observations of shocked gas?





Arce et al., in prep.

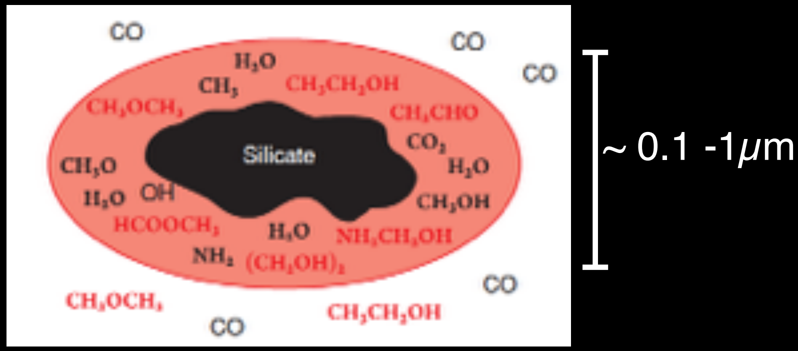


CO(1-0) from Plunkett et al. (2013)

HCN (1-0) data from CARMA Large Area Star formation Survey (CLASSy) observations of NGC 1333 (Mundy et al.)

Complex molecules form on grain mantle

molecules are released to gas phase by shocks, we can then observe rotational transition of complex molecules in mm



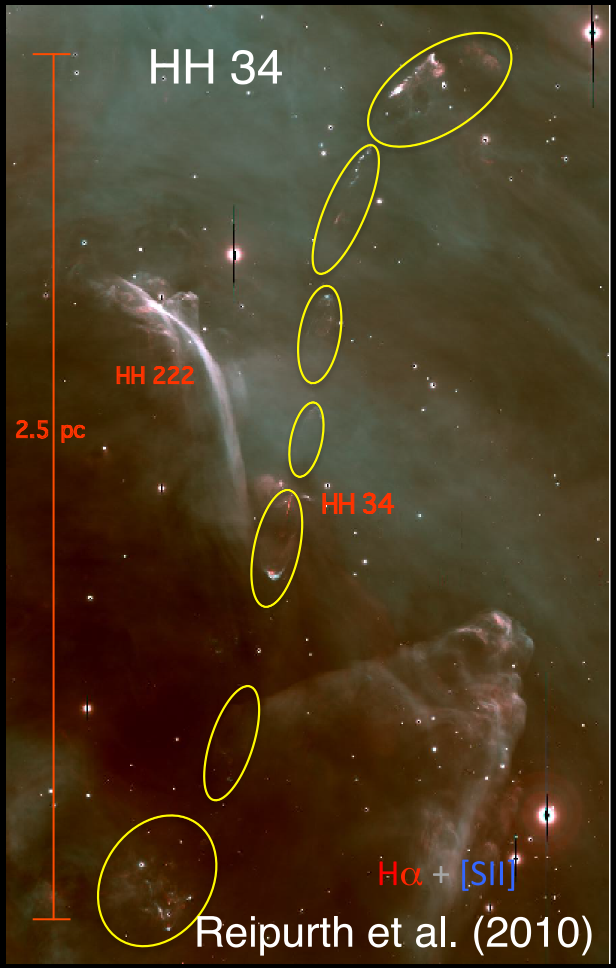
Öberg et al. 2010

(see also Arce et al. 2008, Öberg et al. 2011; Yamaguchi et al. 2012)
(… however, see talk by A. Bacmann and Bacmann et al. 2012)

Outflows: *connecting small and large scales*

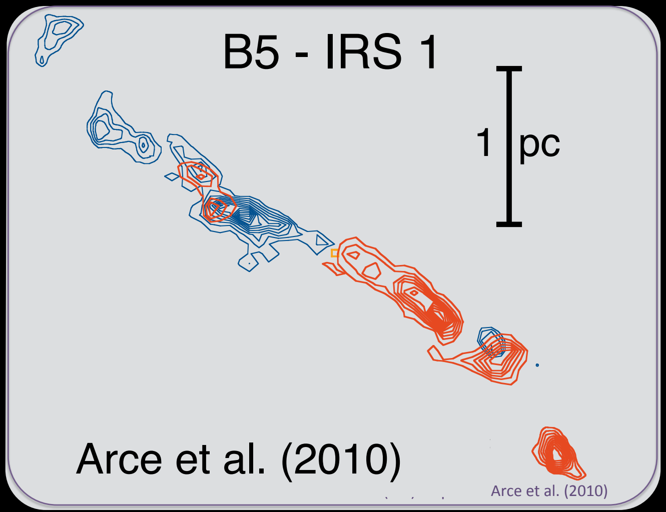
Estimating source properties using outflow ejection history

S-point symmetry = precession



Reipurth et al. (2010)

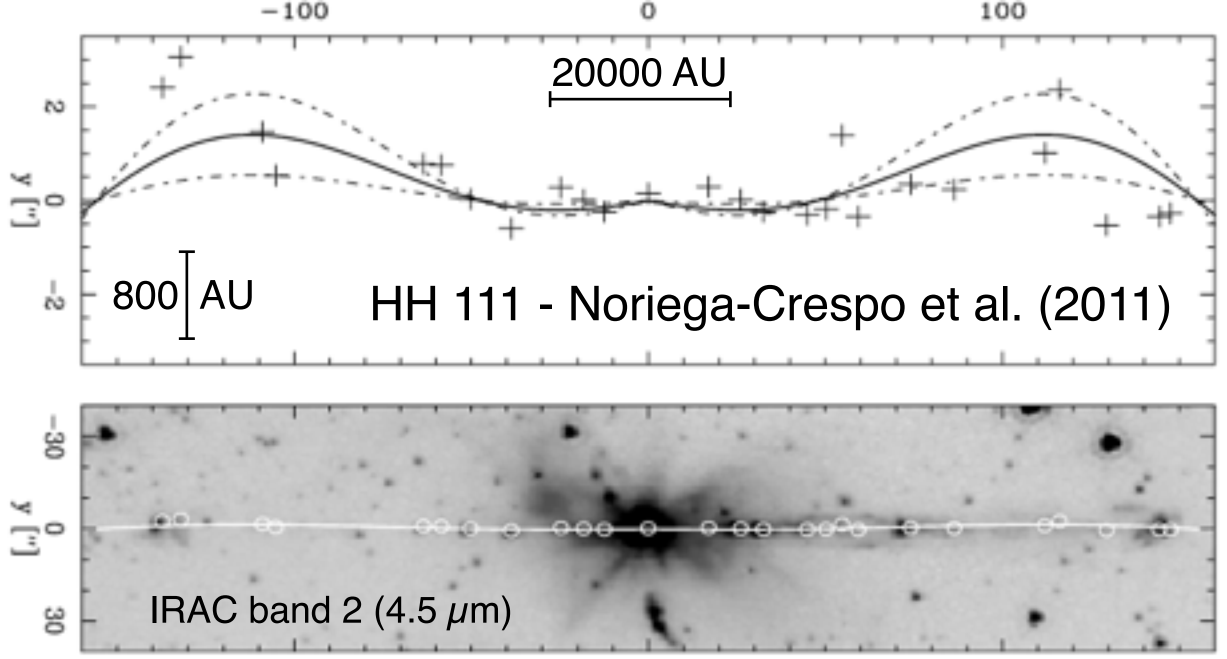
Precession could be due to binary/disk interaction



Arce et al. (2010)

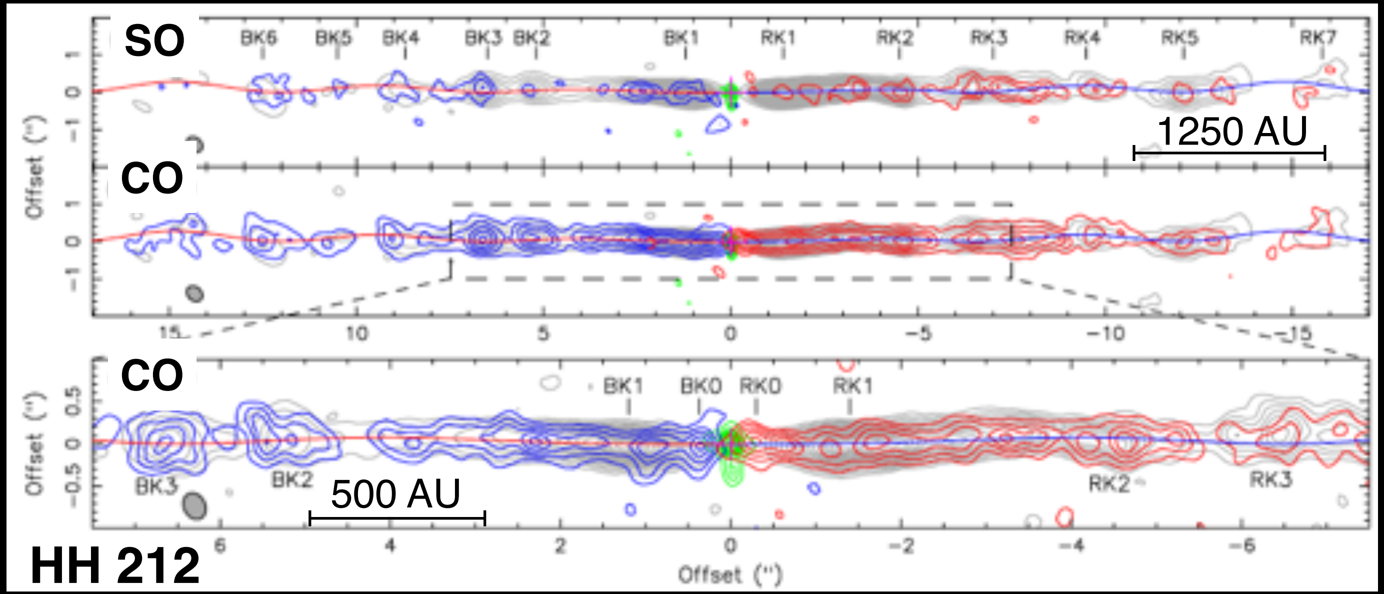
Also, episodic outflow can be used to study episodic accretion

Reflection symmetry = orbital motion of source



HH 111 - Noriega-Crespo et al. (2011)

estimated orbital motion of binary system with sep. ~186 AU



estimated binary separation ~5 AU, total mass in system ~ 60 M_{Jup}

Lee et al. (2010)

Summary

Outflows important for star formation process at scales from a few stellar radii to a few pc (ie. accretion, core-to-star formation efficiency, turbulence, low star formation rate)

at smallest scales (closer to the source), outflow could have impact on planet formation
—> important to deduce launching radius from observations (e.g., jet rotation)

Observations indicate that outflows impact their surrounding core/envelope, but it is still not clear if outflows are responsible for fully clearing core and for the presumed low SFE (~0.3)
- simulations show that outflows maybe responsible for SFE ~0.4-0.5, but still need the observational evidence

Current sample of observed clusters indicate that outflow momentum and energy input rate are enough to maintain turbulence in cluster-forming clump (~1–4 pc)
-consistent with simulations that indicate outflow-drive turbulence is important in clusters (maintains low SFR)

Outflows can change density distribution of host cloud (on scales of < 0.1 to ~ 1pc), but do not have enough energy to fully disrupt (gravitationally unbind) cloud.