Outflows and Jets in High-Mass Star Formation

SOUL OF HIGH-MASS STAR FORMATION

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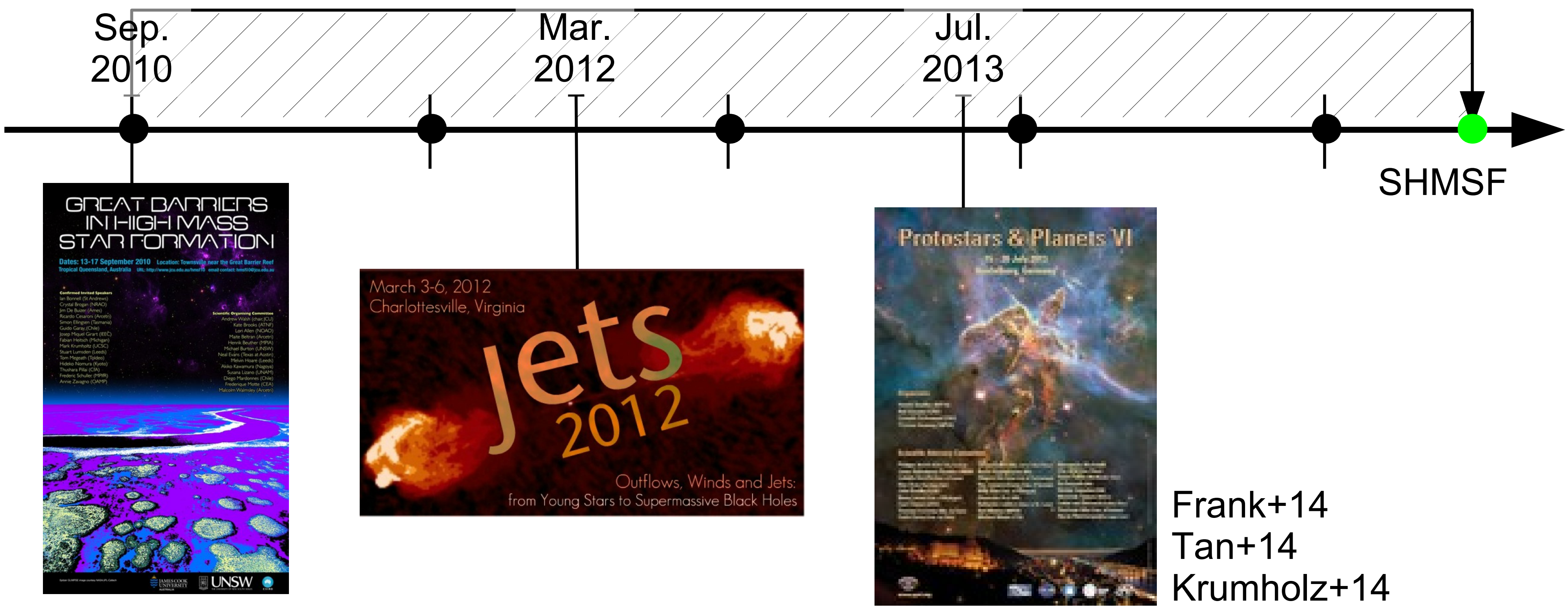
Puerto Varas, Chile

19 March 2015

Focus of this review



Outline

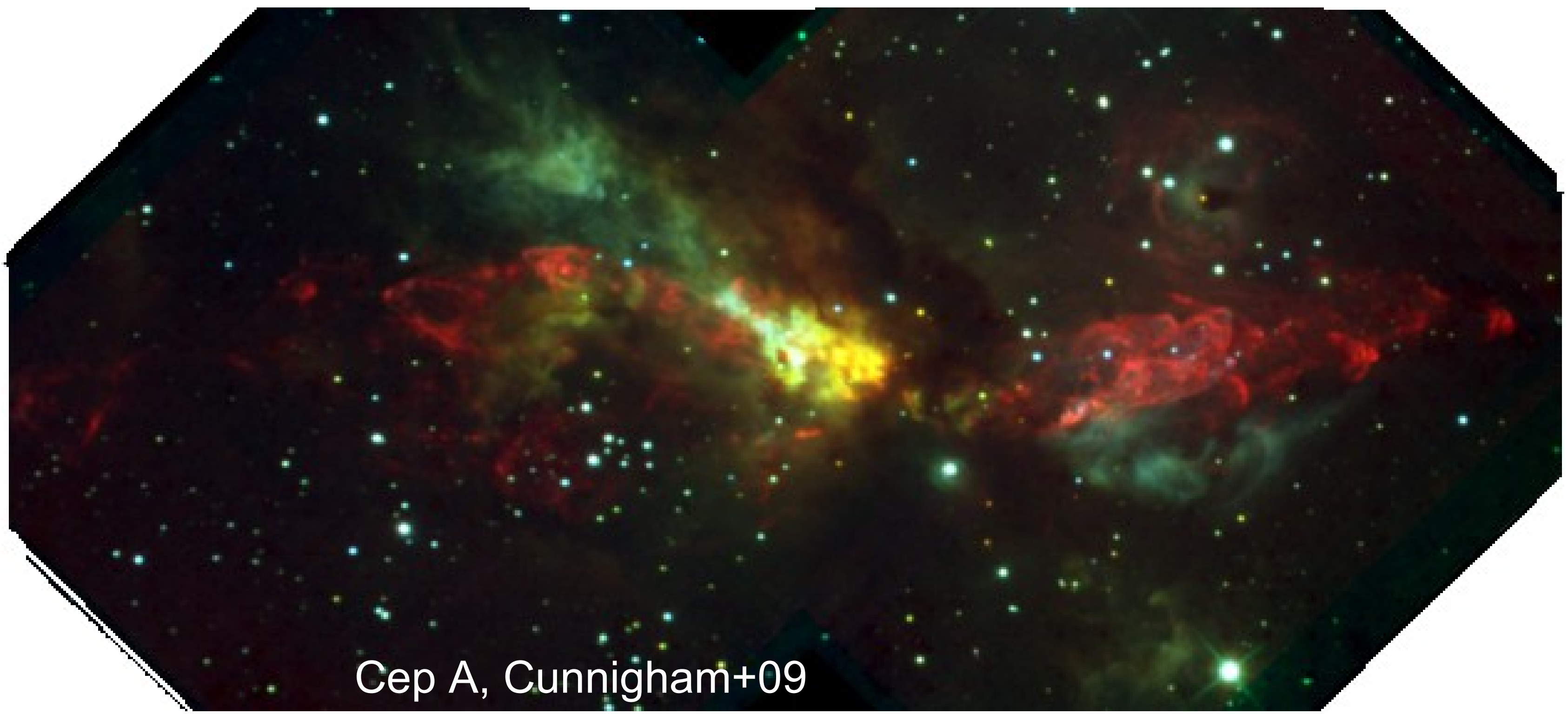
1. **Introduction**
2. **Observational tracers**
3. **Are high-mass outflows jet driven?**
4. **Simulations and theory**
5. **Summary and Conclusions**

1.1 Introduction: Definitions

Outflow: Matter pushed away from high-mass star formation regions
Definition leaves out:

- stellar winds
- expansion of developed HII regions

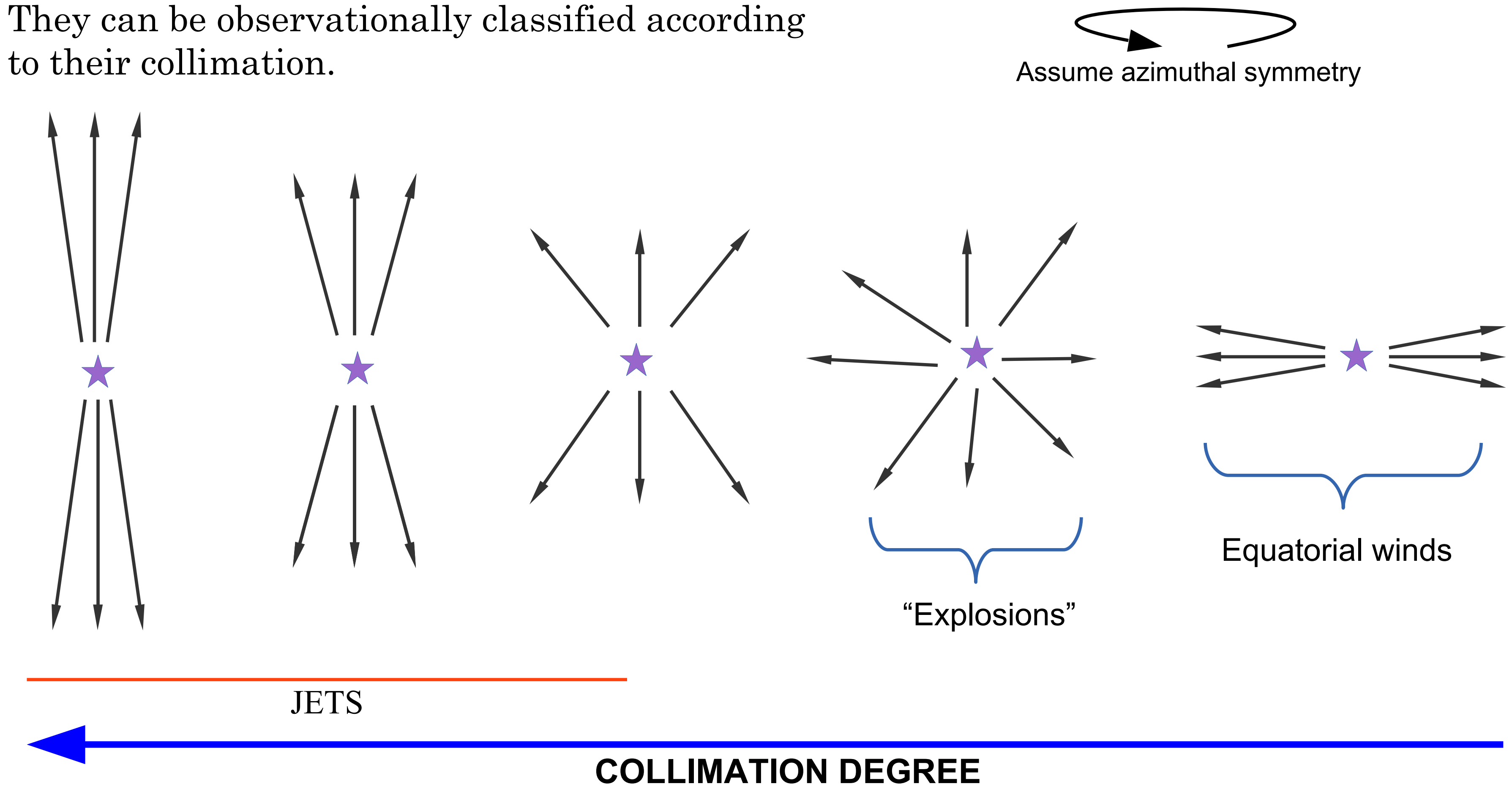
Jet: Very collimated outflow. Collimation factors ❾10.



Cep A, Cunnigham+09

1.1 Introduction: Morphology

HMYSO outflows have a very rich morphology. They can be observationally classified according to their collimation.



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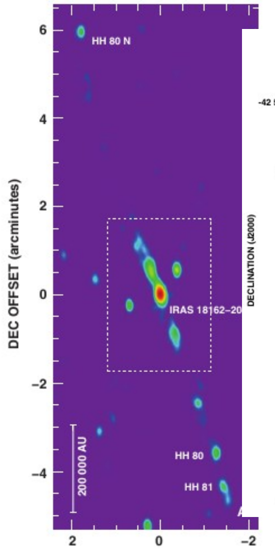
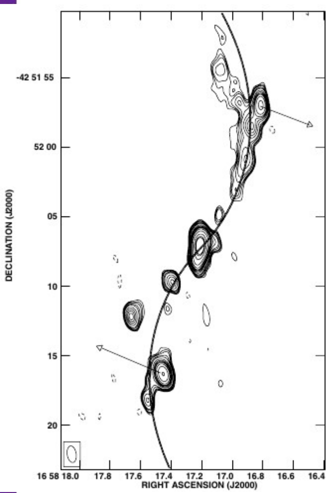
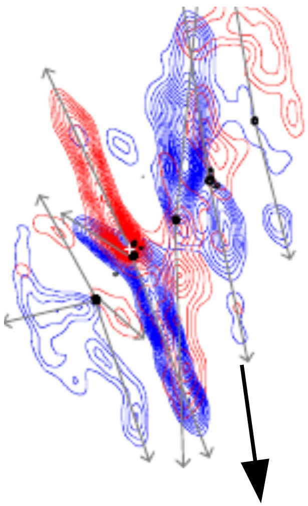


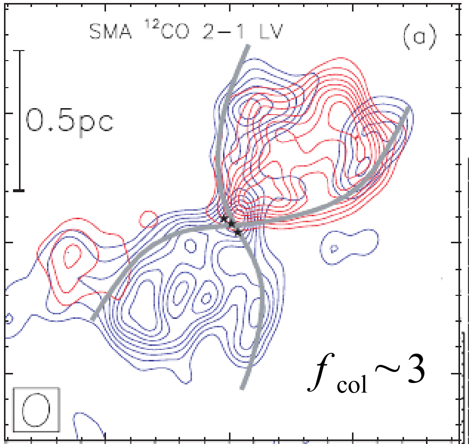
$f_{col} > 20$



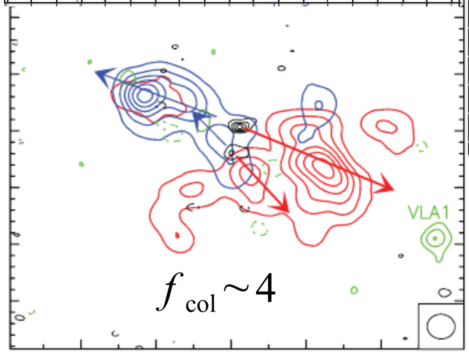
$f_{col} > 10$



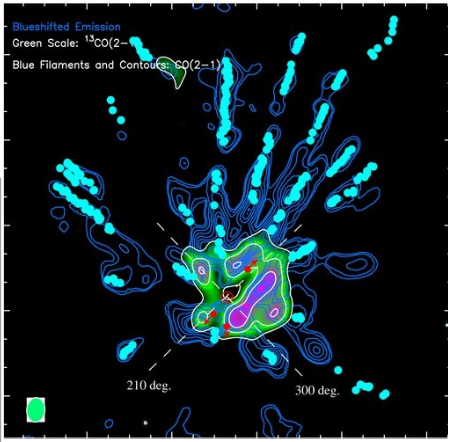
$f_{col} \sim 7$



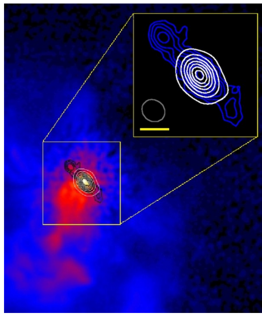
$f_{col} \sim 3$



$f_{col} \sim 4$



"Explosions"



Equatorial winds(?)

JETS

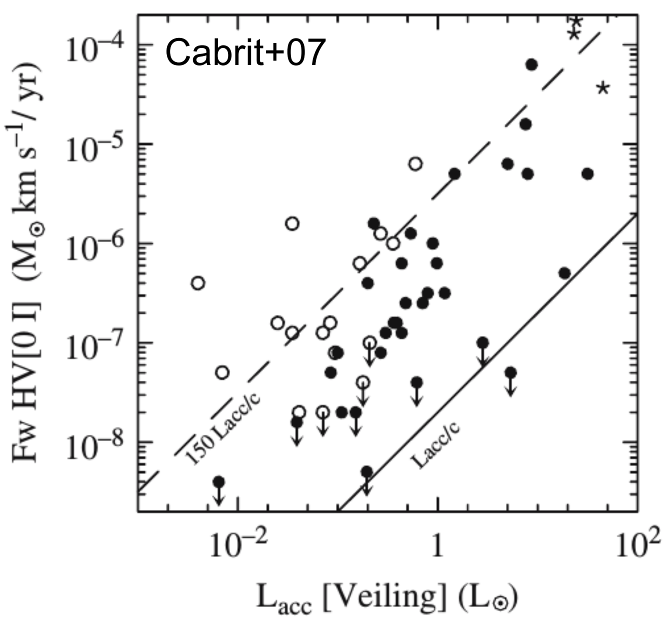
COLLIMATION DEGREE

1.2 The Disk-Jet-Outflow connection

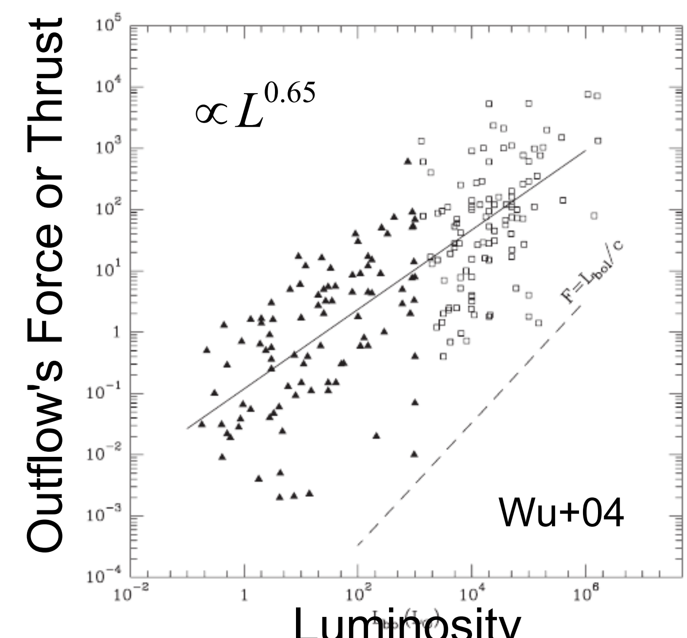
An observationally inspired hypothesis:

<u>Jets ^ Accretion Disks</u>

"Jet activity" ~ "Accretion activity"
However, there are not direct accretion activity tracers in high mass star formation.



Surrogates



Our Tools of Exploration

1. Introduction
2. Observational tracers
3. Are high-mass outflows jet driven?
4. Simulations and theory
5. Summary and Conclusions

2.1 Observational Tracers

Typical outflow tracers rely on detecting any subset of features that we classify in the following categories:

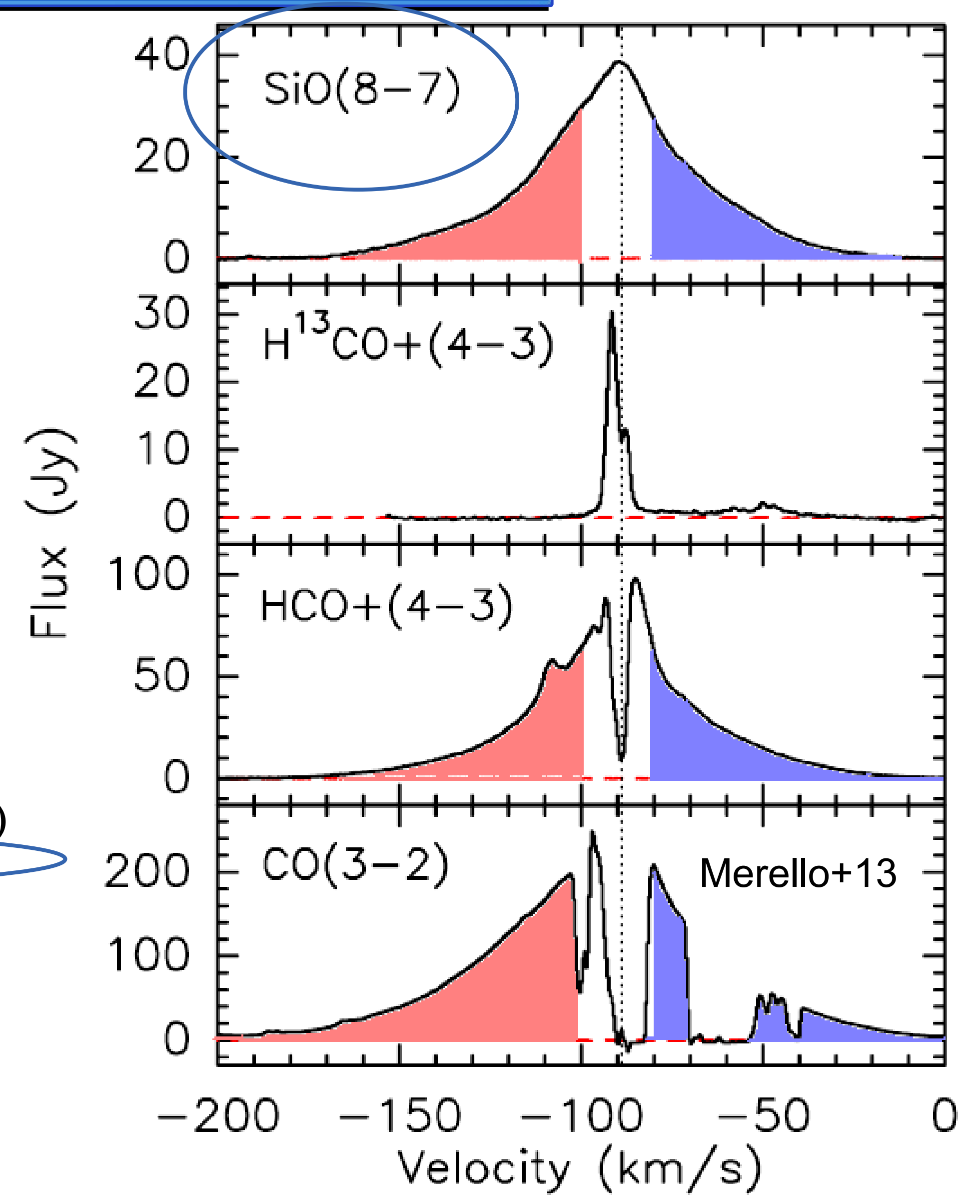
1) Kinematics: Directly observe the motion of material being expelled.

2) Shock tracers: Detecting continuum or line emission consistent with high-velocity shocks.

3) Morphology: Outflows cavities, jets, bow-shocks, and explosions.
   ^ Collimated vs. Uncollimated

2.1 Observational Tracers

1. Kinematics
   - Molecular and Atomic Lines
     - Line wings ($V_{\square}$)
     - Spectro-astrometry ($V_{\square}$)
     - P-Cygni type ($V_{\square}$)
   - Proper motions
     - Masers (V_{3D})
     - Ionized gas continuum ($V_{\square}$)
2. Shock tracers
   - Continuum (Radio, X, □ -rays?)
   - Narrow & wide band filter imaging
   - Line emission from shock tracers ($V_{\square}$)
3. Morphology
   - Bipolarity, cavities.
   - Resolved ionized jets
   - Illuminated jets. Explosions.



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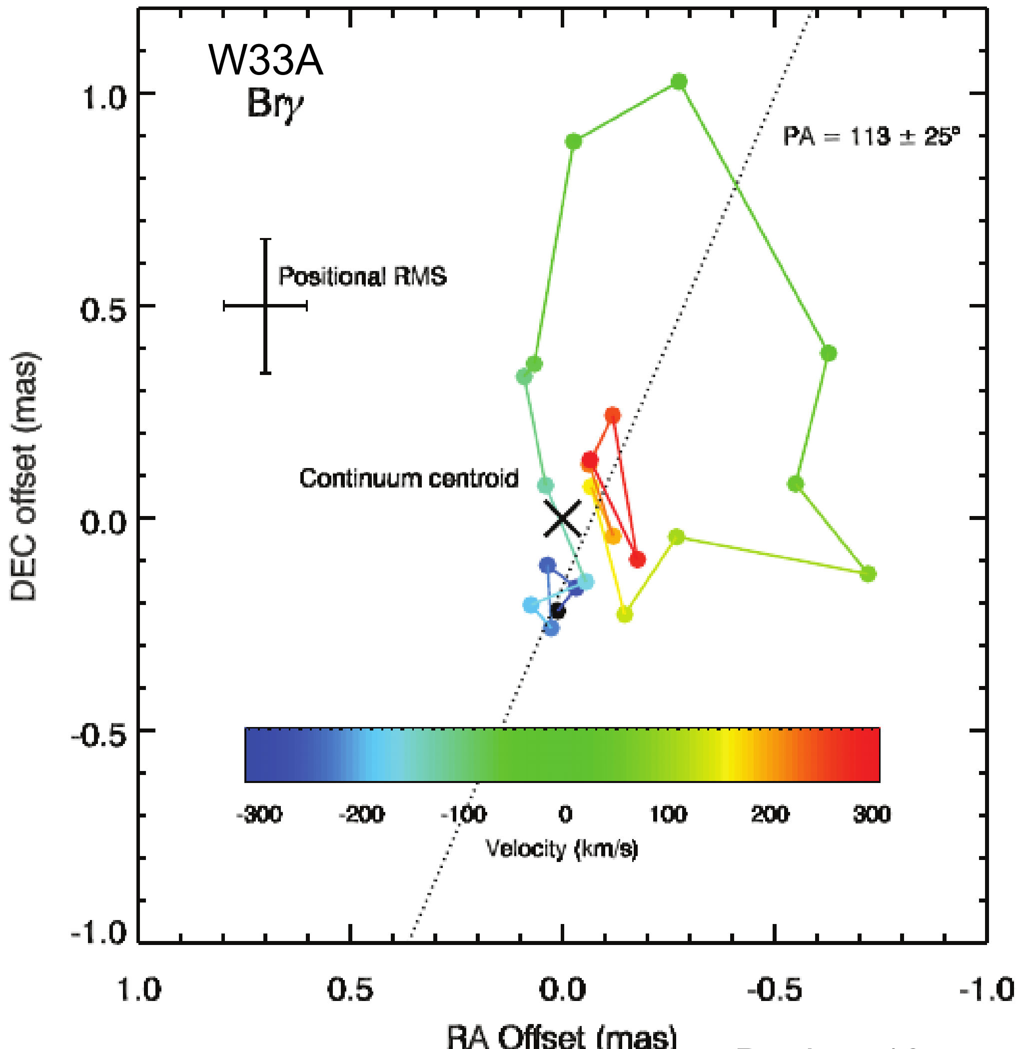

Davies+10

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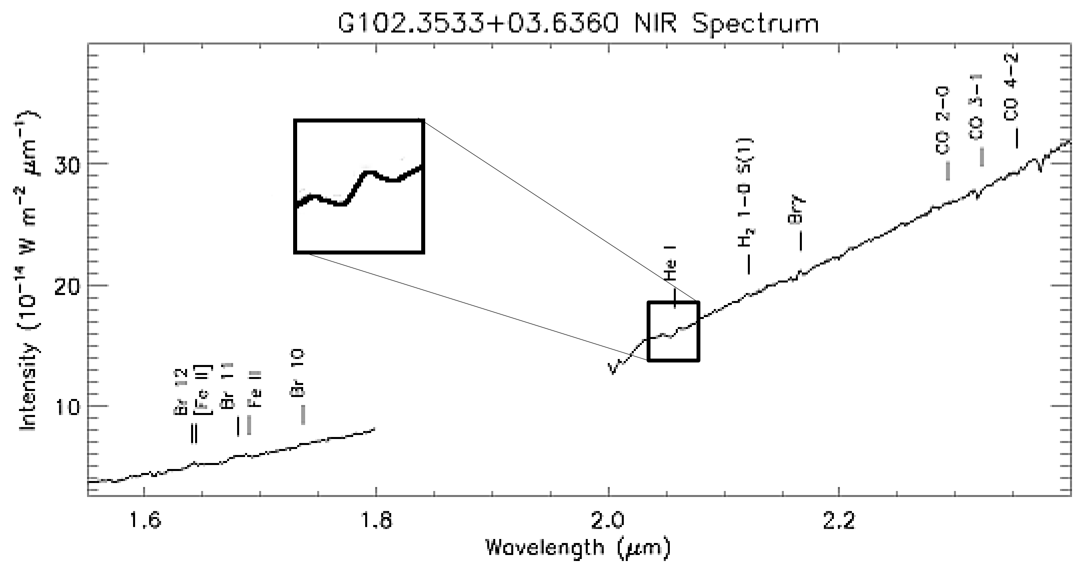

Cooper+13

See the poster by Pomohaci et al. showing nicer examples.

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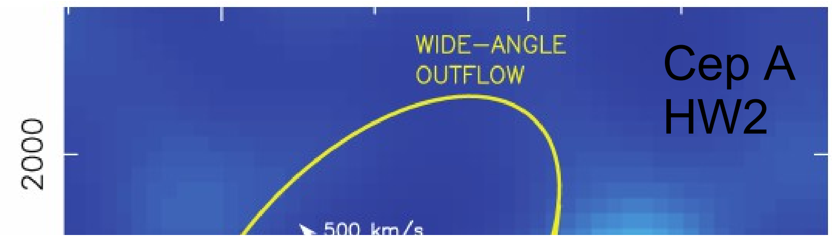

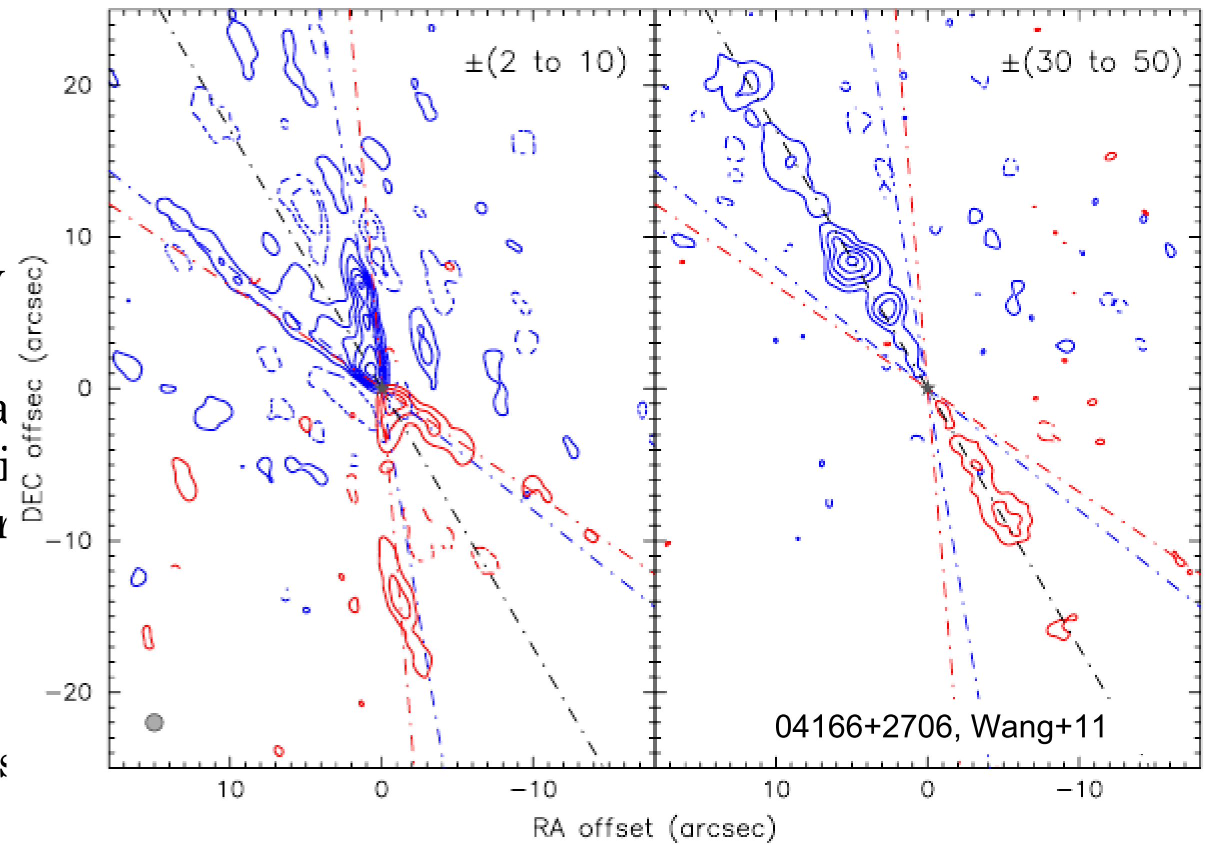

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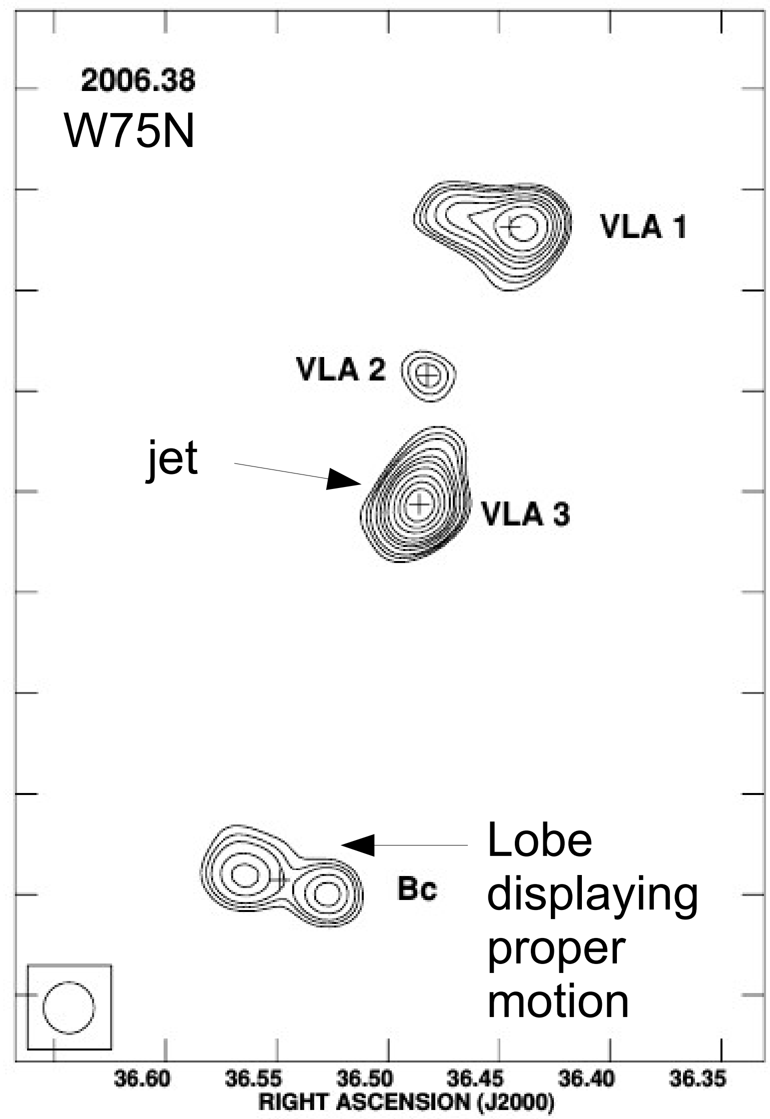

Carrasco-Gonzalez+10

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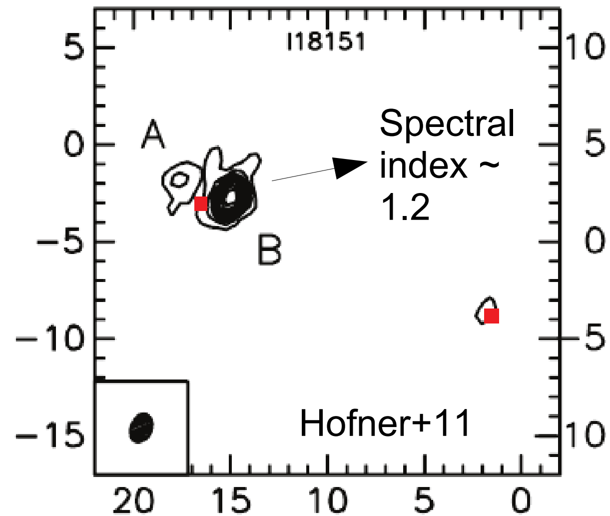
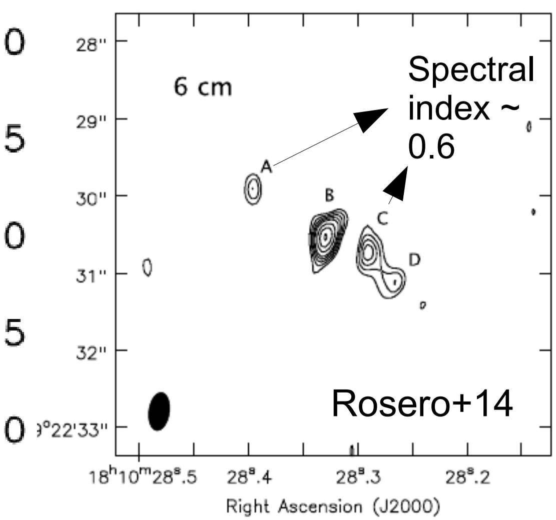
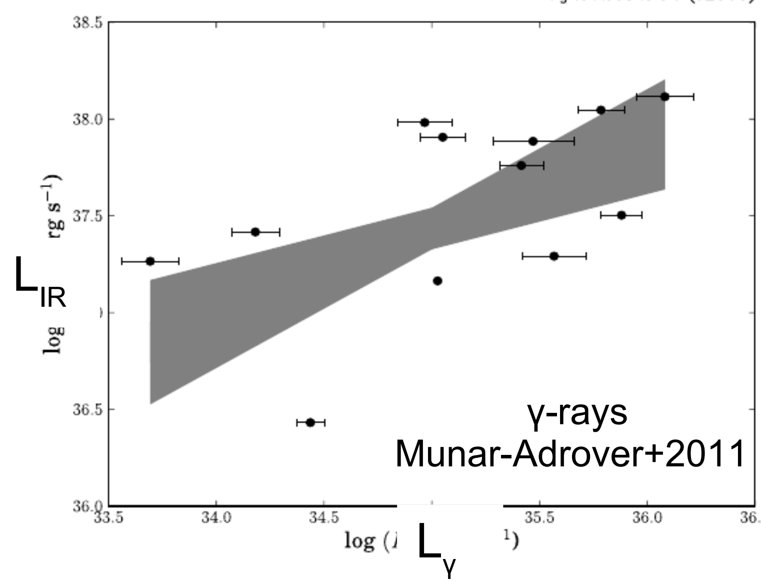
Thermal free-free shock emission







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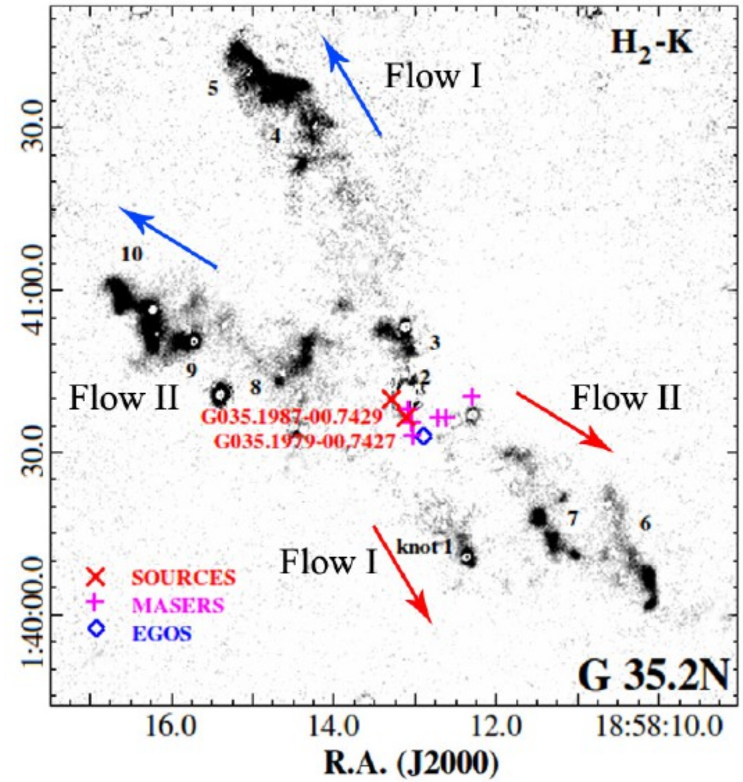

Caratti o Garatti+15

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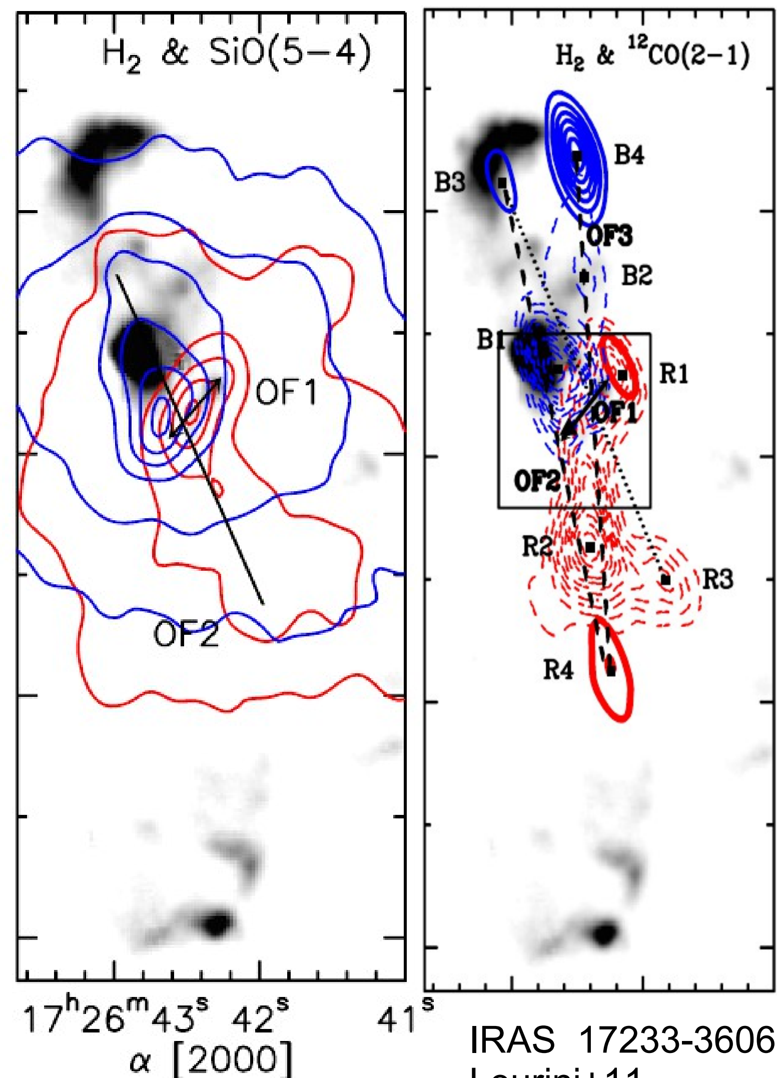

IRAS 17233-3606
Leurini+11
Leurini+13

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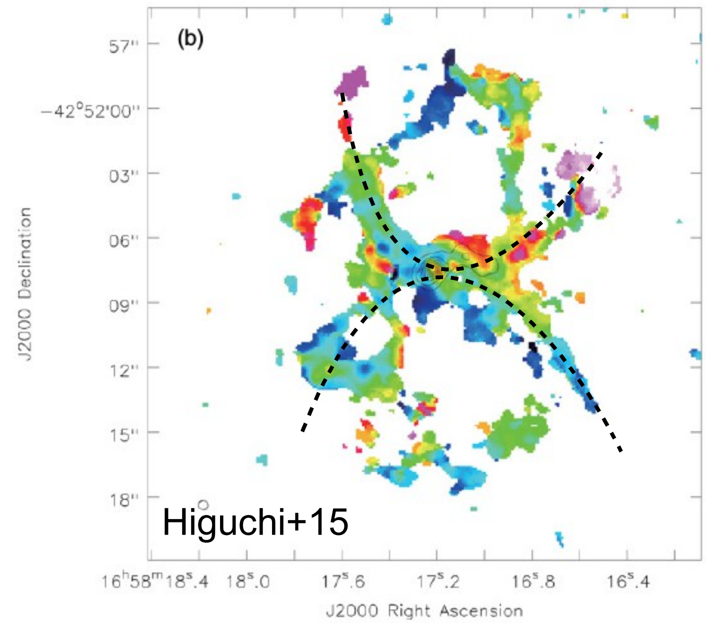
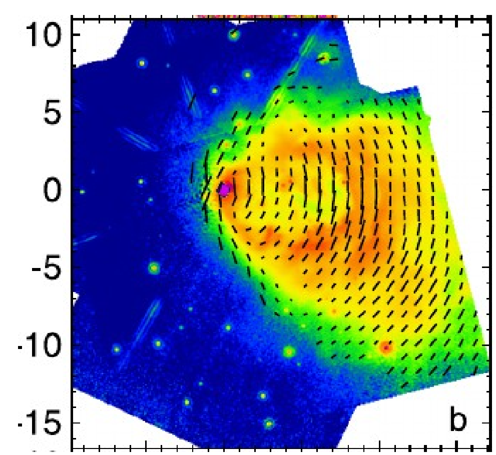
IRAS 16547-4247





AFGL 2591
Simpson+13

2.1 Observational Tracers

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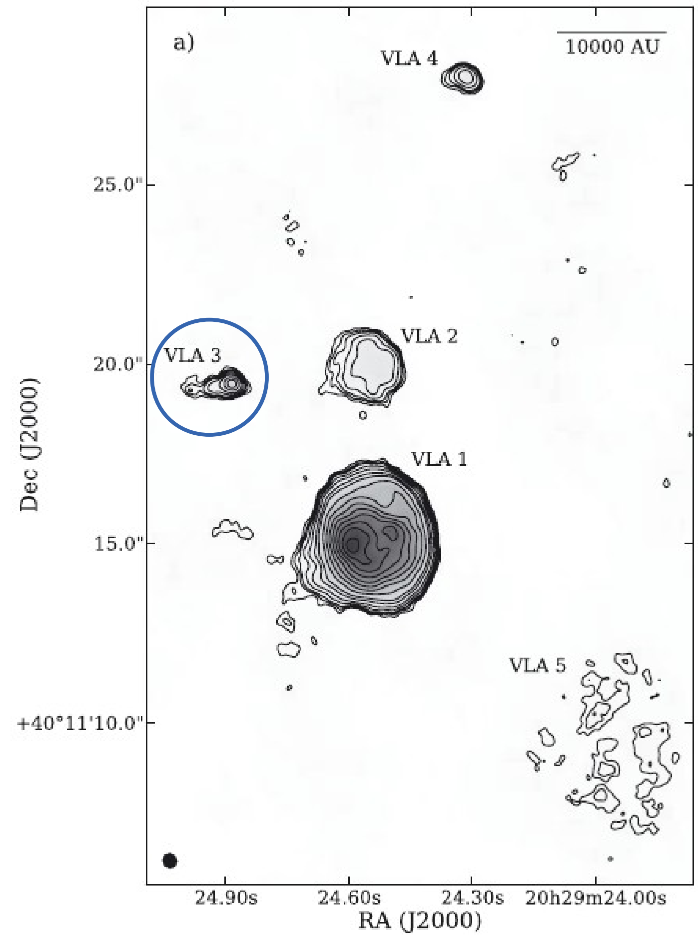
AFGL 2591 VLA3



Johnston+13

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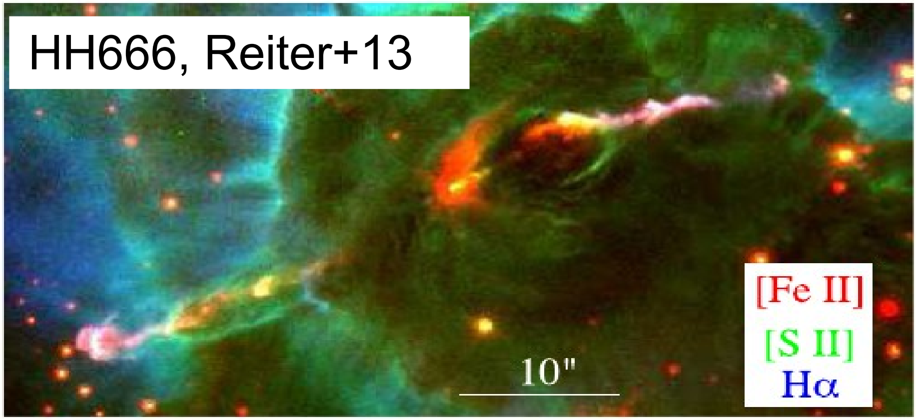
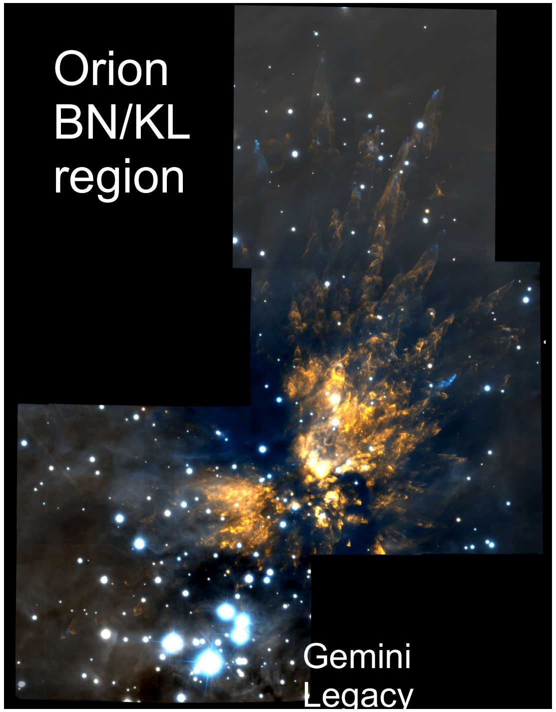


Reiter's talk

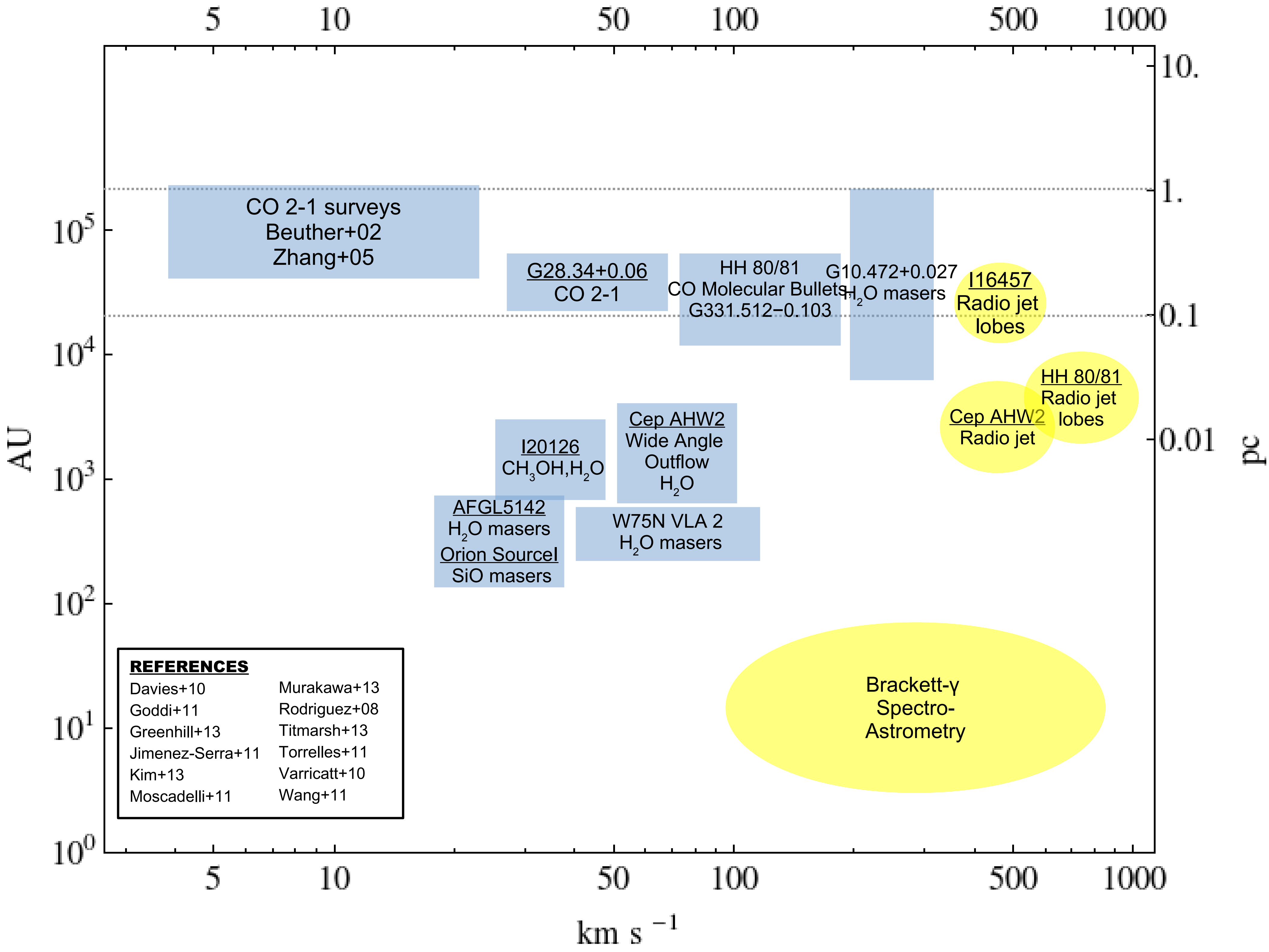


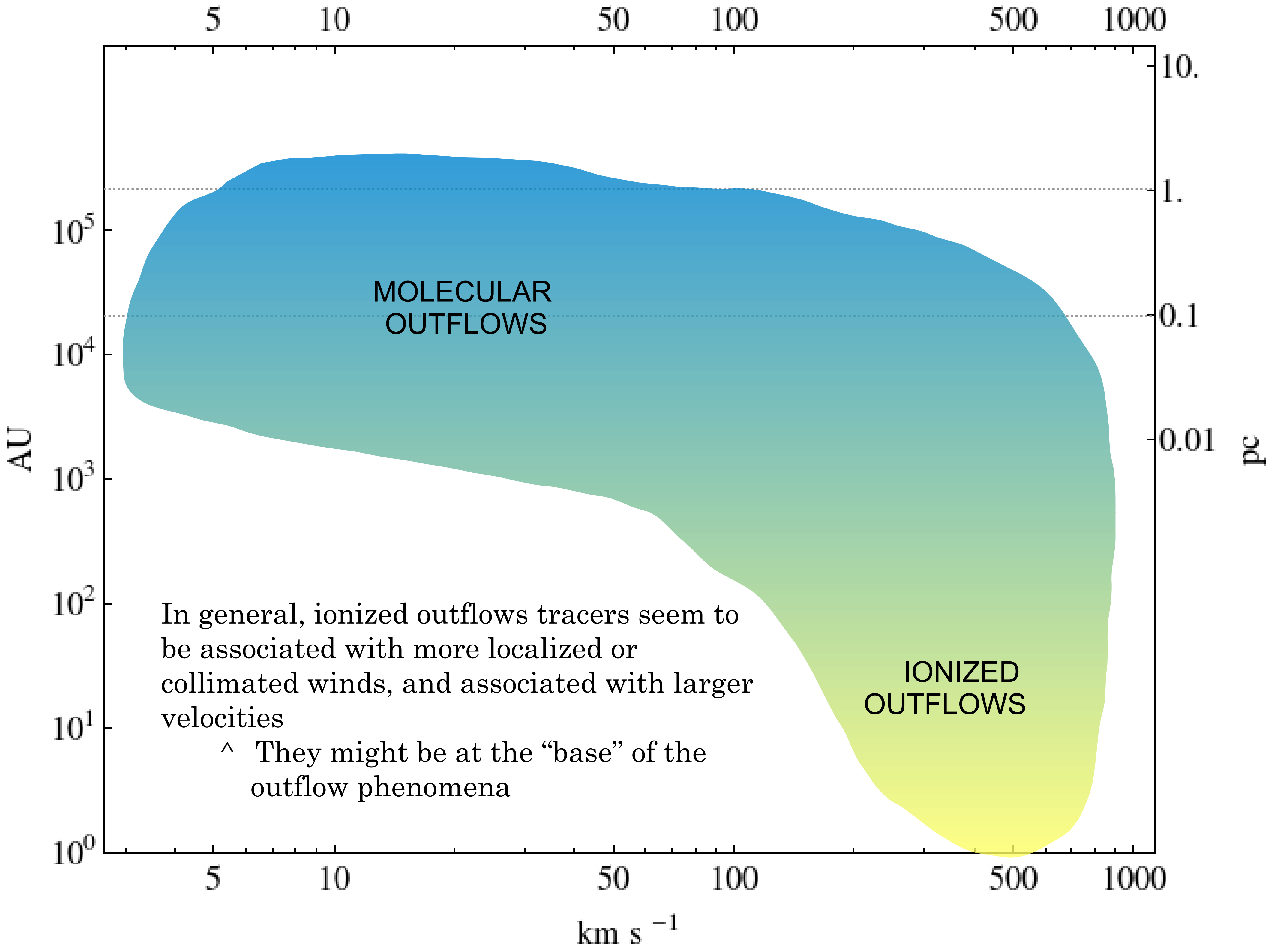
2.2 Ionized and Molecular

Most of the tracers are either of ionized or molecular gas, possibly not because outflows and jets not having an atomic component, but because of an observational bias.

Besides this distinction, there are other systematic differences between the molecular and ionized outflow phenomena. They are different in

- Velocities
- Physical scale

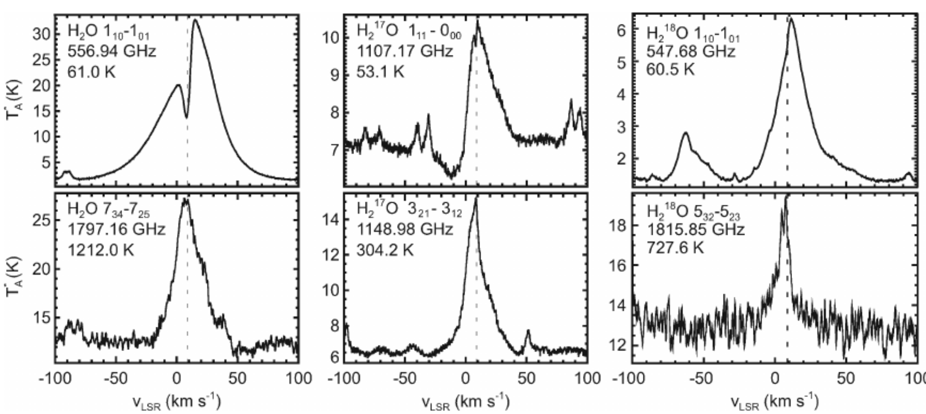

CO 2-1 surveys
Beuther+02
Zhang+05
G28.34+0.06
CO 2-1
HH 80/81
CO Molecular Bullets
G331.512−0.103
G10.472+0.027
H2O masers
I16457
Radio jet
lobes
HH 80/81
Radio jet
lobes
Cep AHW2
Radio jet
I20126
CH3OH,H2O
Cep AHW2
Wide Angle
Outflow
H2O
AFGL5142
H2O masers
Orion SourceI
SiO masers
W75N VLA 2
H2O masers
Brackett-γ
Spectro-
Astrometry
REFERENCES
Davies+10
Goddi+11
Greenhill+13
Jimenez-Serra+11
Kim+13
Moscadelli+11
Murakawa+13
Rodriguez+08
Titmarsh+13
Torrelles+11
Varricatt+10
Wang+11
AU
pc
km s −1

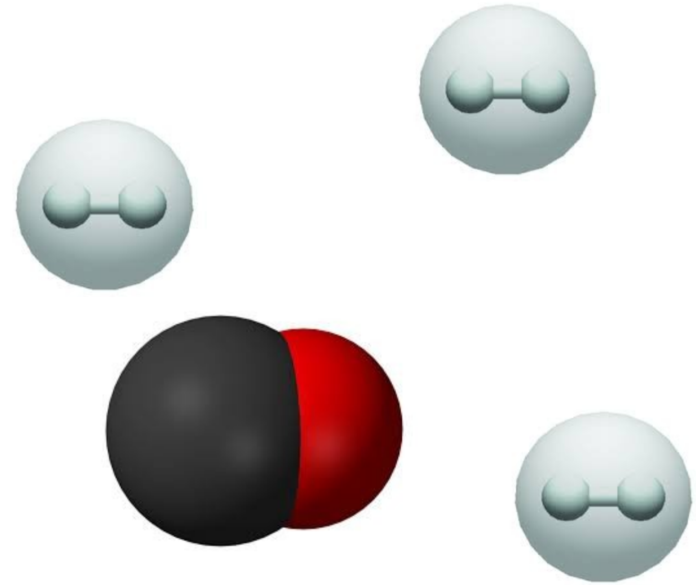

MOLECULAR
OUTFLOWS
IONIZED
OUTFLOWS
In general, ionized outflows tracers seem to
be associated with more localized or
collimated winds, and associated with larger
velocities
^ They might be at the "base" of the
outflow phenomena
AU
pc
km s −1
5
10
50
100
500
1000
10.
1.
0.1
0.01
10^5
10^4
10^3
10^2
10^1
10^0

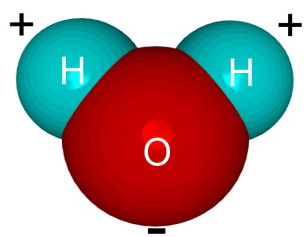
2.3 Chemistry: Water in High-mass Outflows

Re-evaluation of **the role of water as a gas coolant** in high-mass star formation. H_2Oabundance usually lower than compared with older models' predictions ($[H_2O/H_2] \sim 10^{-5}$ - 10^{-4}, van Dishoek+11).

- W3 IRS5 (10^{-8} - 10^{-10}, Chavarría+10)
- AFGL 2591 (10^{-10}, Choi+15)
- Orion BN/KL (10^{-6}, Goicoechea+15)
- DR21 (10^{-6}, van der Tak+10)
- W43-MM1 (10^{-7} envelope, 10^{-4} hot core, Herpin+12)
- IRAS 17233-3606 (10^{-5}, Leurini+14)







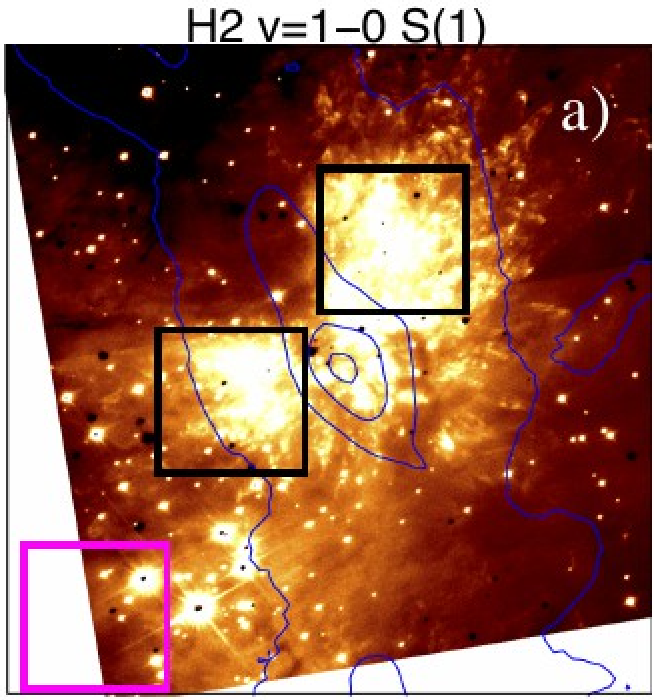
van Dishoek+13, Orion KL water spectra

2.3 Chemistry: Orion's Water

Orion BN/KL Outflows

Confirmation by Herschel of the attenuated role of water in gas line cooling.

- H_2O **Increase in the fastest shocks** ^ ice mantle sputtering
- Less water than expected ^ UV dissociation? Grain mantle locking?



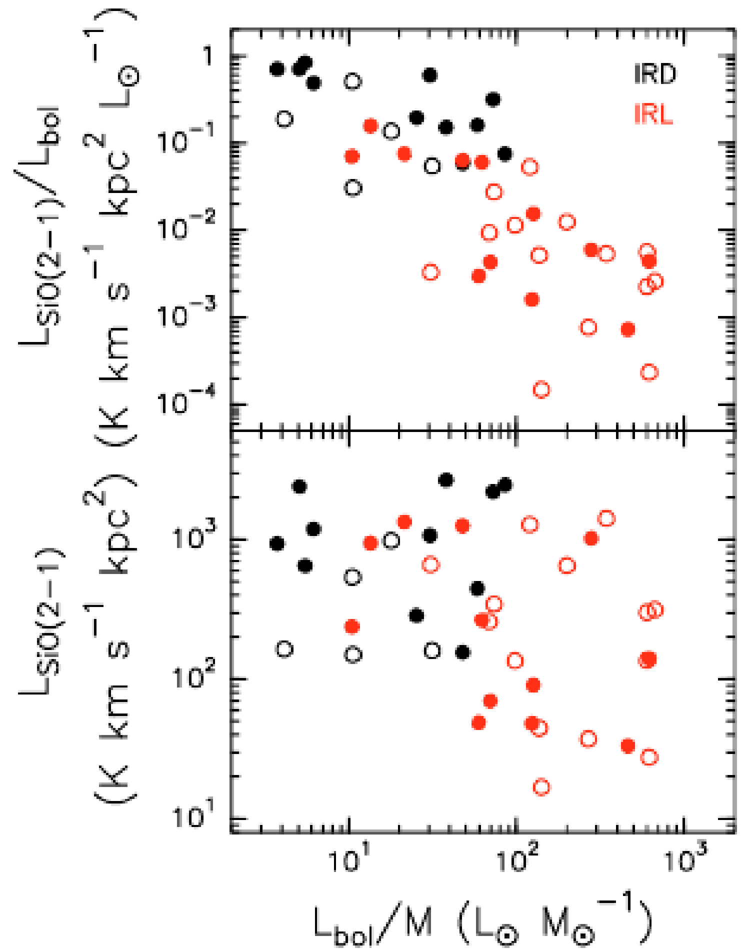
Goicoechea+15

Line Cooling Budget

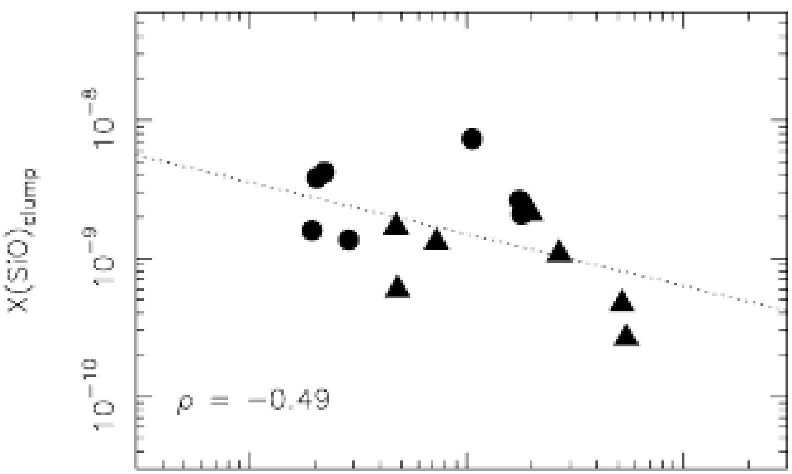
- H_2 ~ 50% (see also Caratti o Garatti+15)
- CO (v=0,1) ~ 30%
- H_2O ~ 10%
- OH, OI, CII, ~ 10%

2.3 Chemistry: Shock Tracers

- SiO(2-1) single dish survey towards 57 mm-selected high-mass molecular clumps (López-Sepulcre+11)
- 90% detection rate of a mm-based selected sample of young clumps
  ^ possibly not only outflows
- Evidence of chemical evolution and decrease in SiO abundance and excitation with time (Sánchez-Monge+13, Miettinen+06)



López-Sepulcre+11



Sánchez-Monge+13

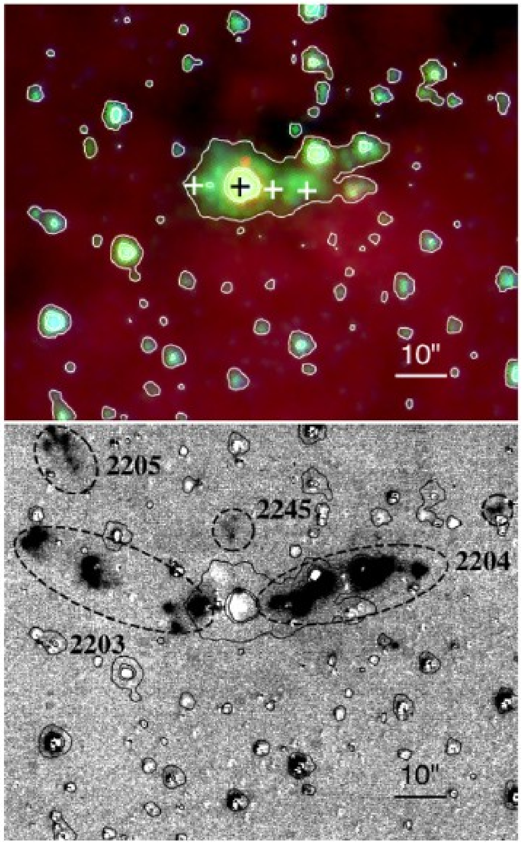
2.3 Shock Tracers: EGOs
What causes the Green Color?

See poster by Stecklum

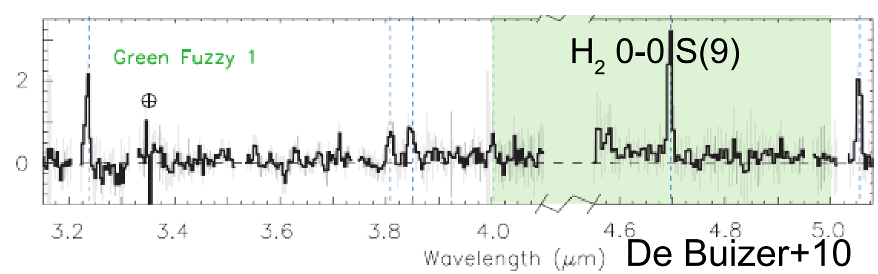
There is good evidence of EGOs being HMYSO, but what causes the 4.5 □ m excess?

	# EGOs	Notes
Cyganowsky+09	20	64% and 89% association with Class II and I CH_3OH masers. 90% with SiO
Chen+10	69	Blue excess asymmetry 0.15 ~ $(29_B\text{-}19_R)/69$
Lee+12	12	Only 3/12 outflows have H_2 emission morphology similar to 4.5 □ m excessThe rest are possibly due to scattered light.
De Buizer+10	2	One with H_2 lines, the other with green color artificially enhanced
Cyganowsky+11	2	Associated with molecular outflows and SiO

G19.88−0.53



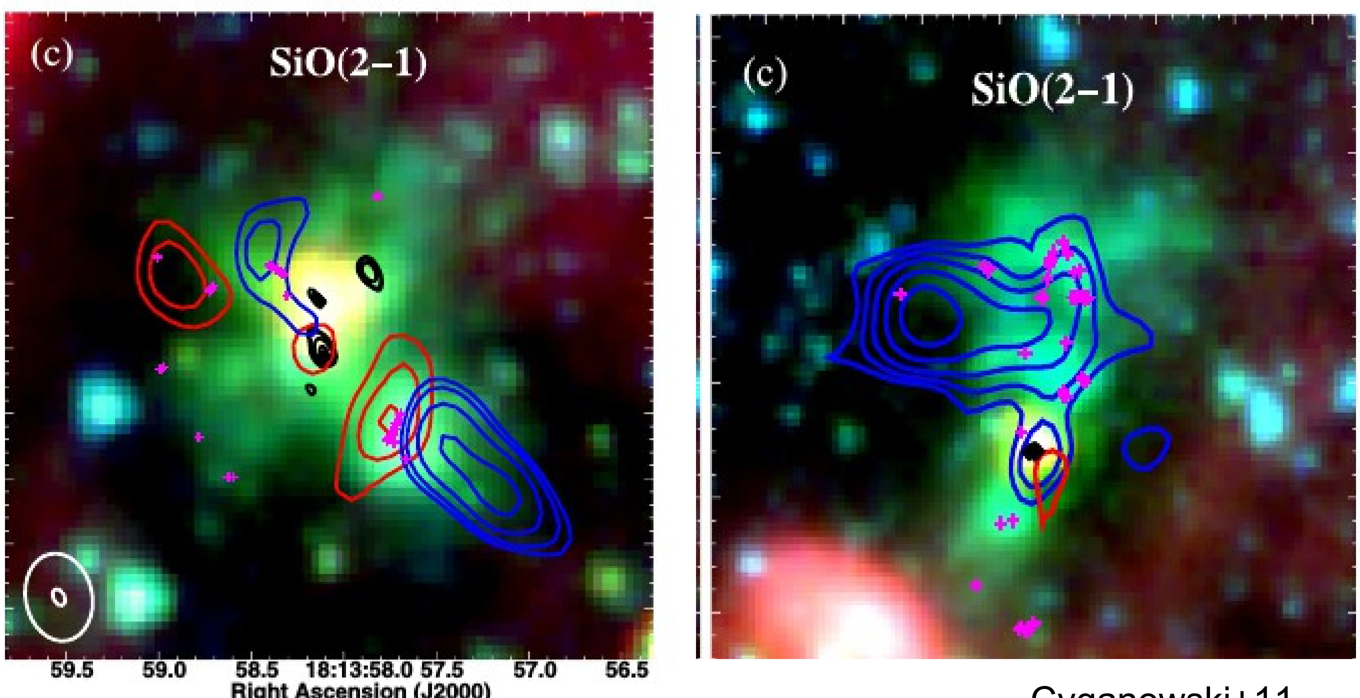
Lee+12



De Buizer+10

2.3 Shock Tracers: EGOs
What causes the Green Color?

- Most EGOs are young HMYSOs ✔
- Not clear the 4.5 □ m excess is a robust and specific shocked gas tracer



Cyganowski+11

A Key Question

1. Introduction
2. Observational tracers
3. Are high-mass outflows jet driven?
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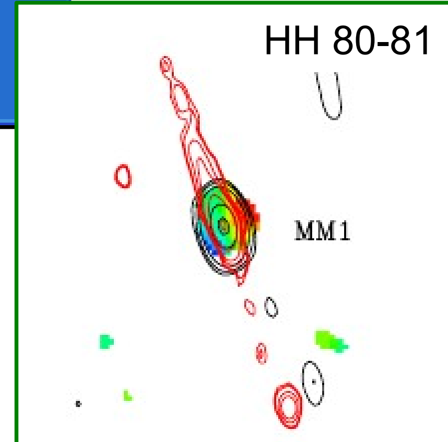
Related Questions

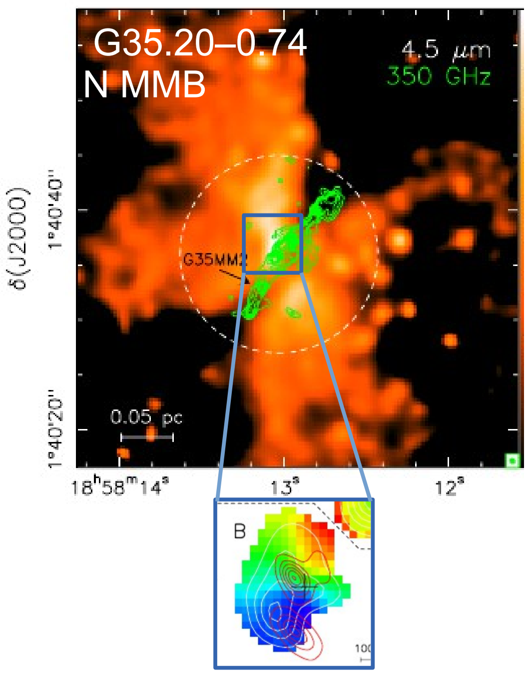
3.1 Disk-like structures perpendicular to outflows?
3.2 How collimated are outflows associated with HMSF?
3.3 How far from the star are they collimated? Are MHD winds necessary to explain the characteristics of high-mass outflows?
3.4 Energetics of ionized jets `   Energetics of molecular outflows `   Mass of central objects? Are there different relations between the high- and low-mass case? Are all jets ionized?
3.5 What is the relation between magnetic fields and outflows?
3.6 Can (precessing) jets explain all type of outflows? What about those than are not excited by jets?

3.1 Morphology: Disk-outflow relation

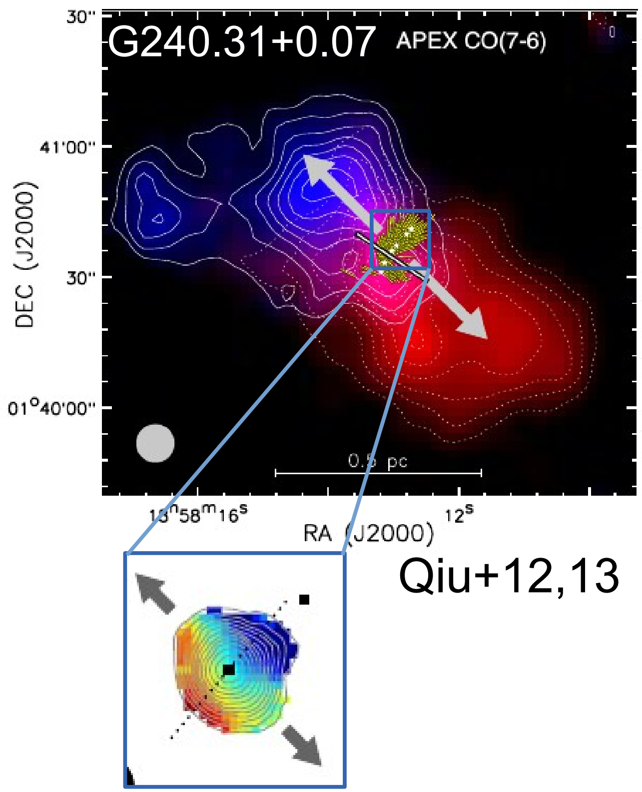
Apparently, it is common that the disk-like structures associated with HMYSOs have angular velocity aligned with the outflow.



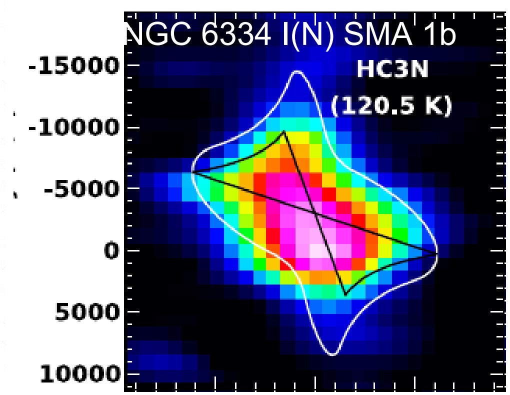
Fernández-López+11



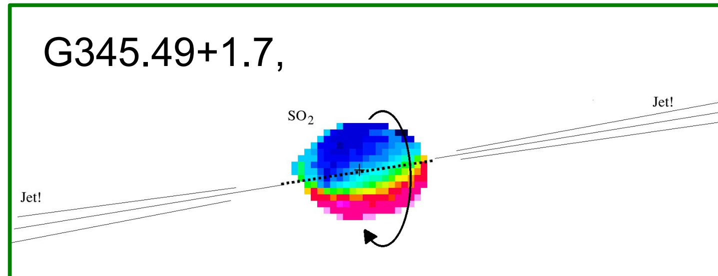
Sánchez-Monge+13



Qiu+12,13



Hunter+14

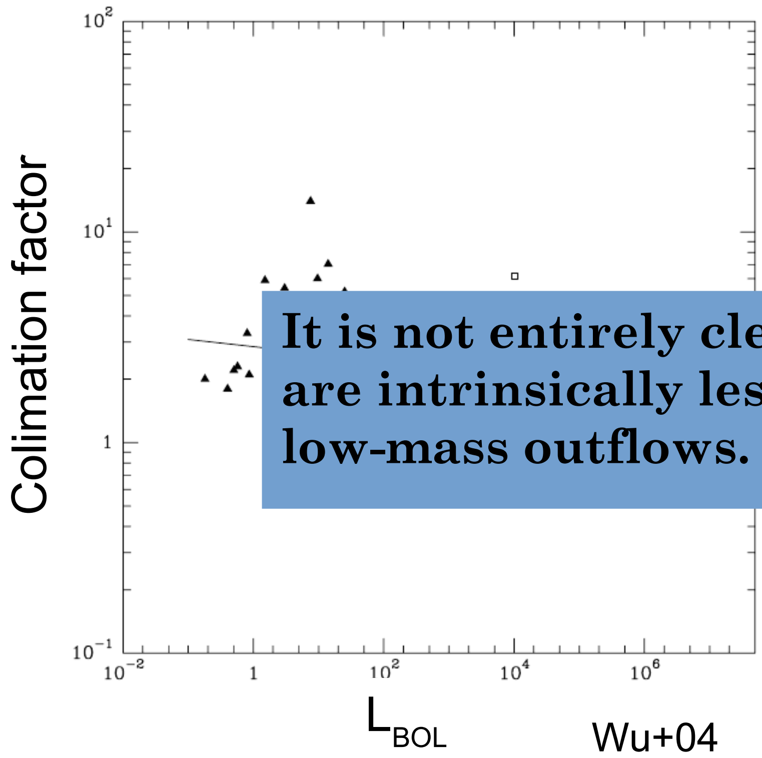


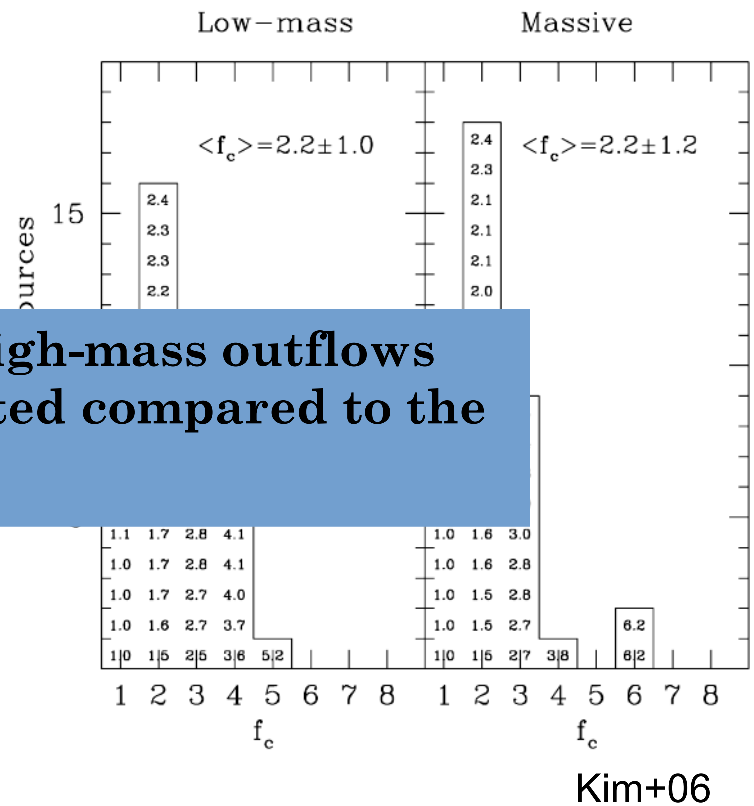
Guzman+14

3.2 Morphology: Collimation

<u>The most straightforward way to address this question</u>

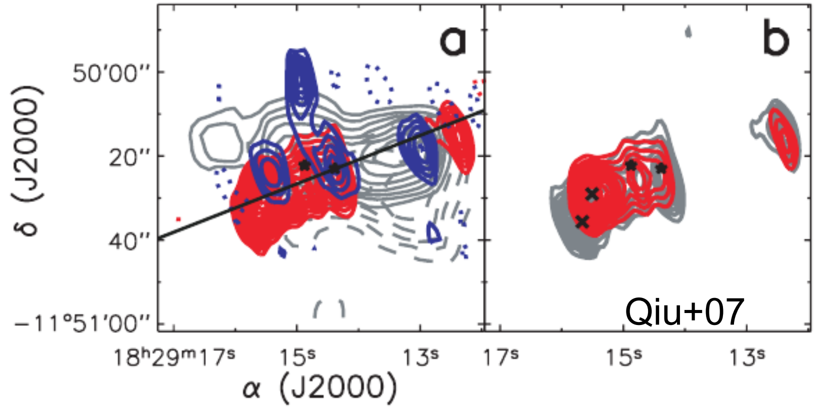
Are outflows associated with high-mass star formation less collimated compared to that associated with low mass SF?





It is not entirely clear that high-mass outflows are intrinsically less collimated compared to the low-mass outflows.

3.2 Morphology: C



Lets analyze in more detail an example of a molecular outflows sample

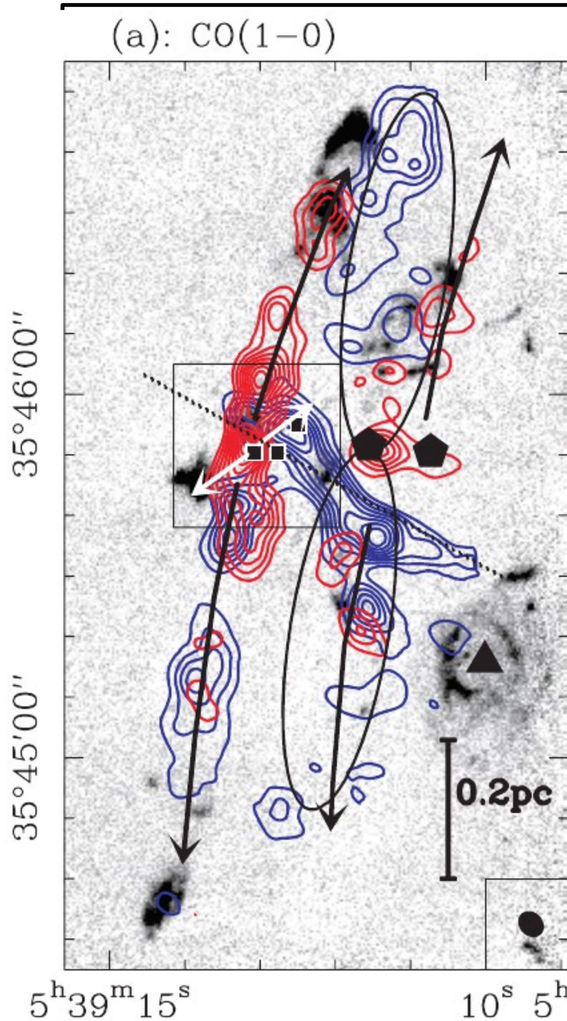
^ Beuther+02 sample

^ CO(2-1)@IRAM-30m

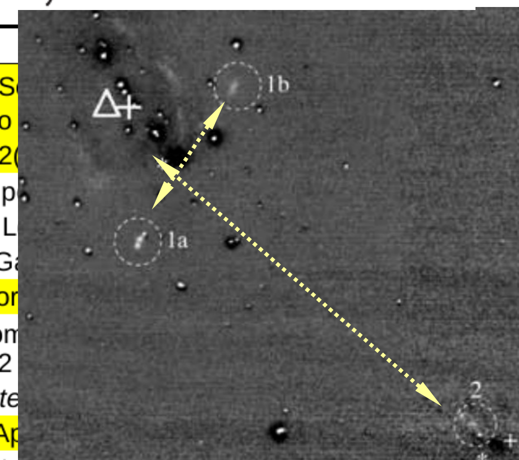
Which ones are associated with more collimated outflows than those determined with single dish?

More than half of those that were followed. In most cases, *there are more than one outflow.*

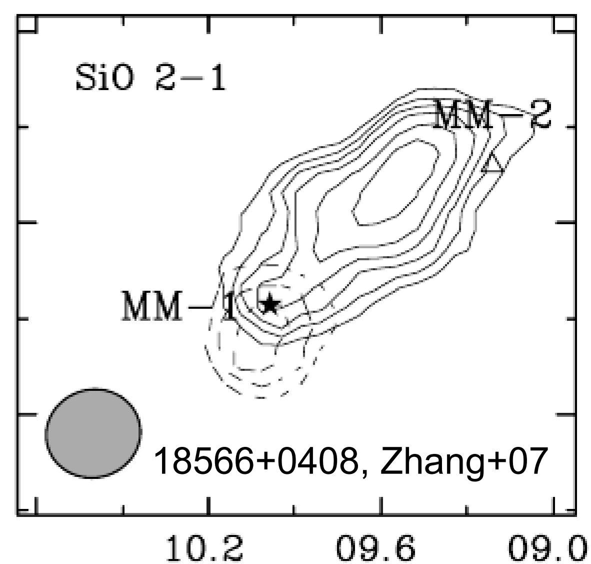
Confusion, blending, and low-angular resolution need to be taken into account.



05358+3543, Beuther+02



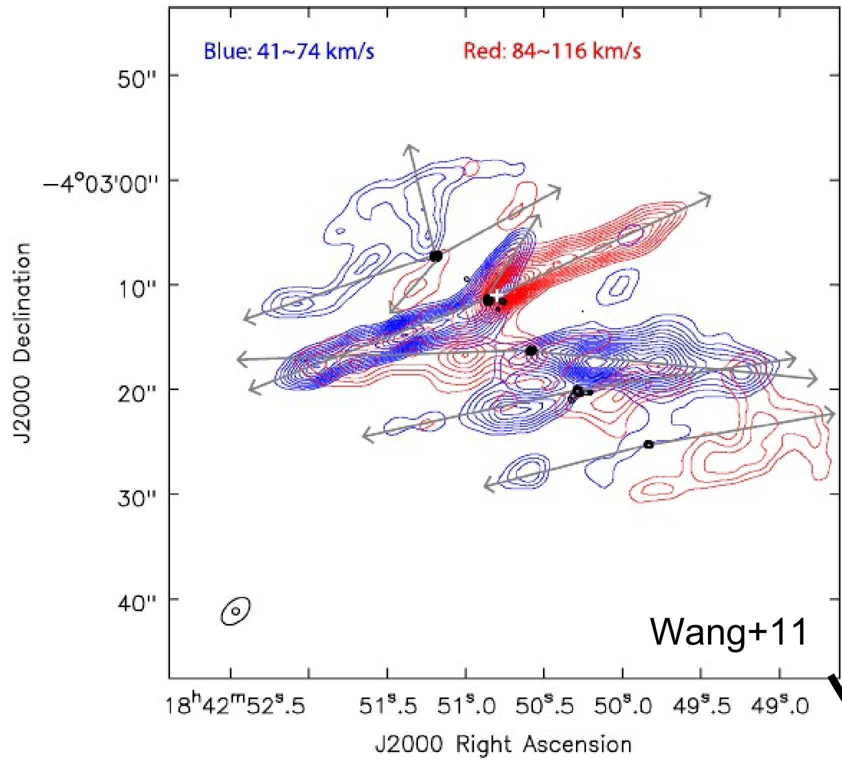
22570+5912, Varricatt+10



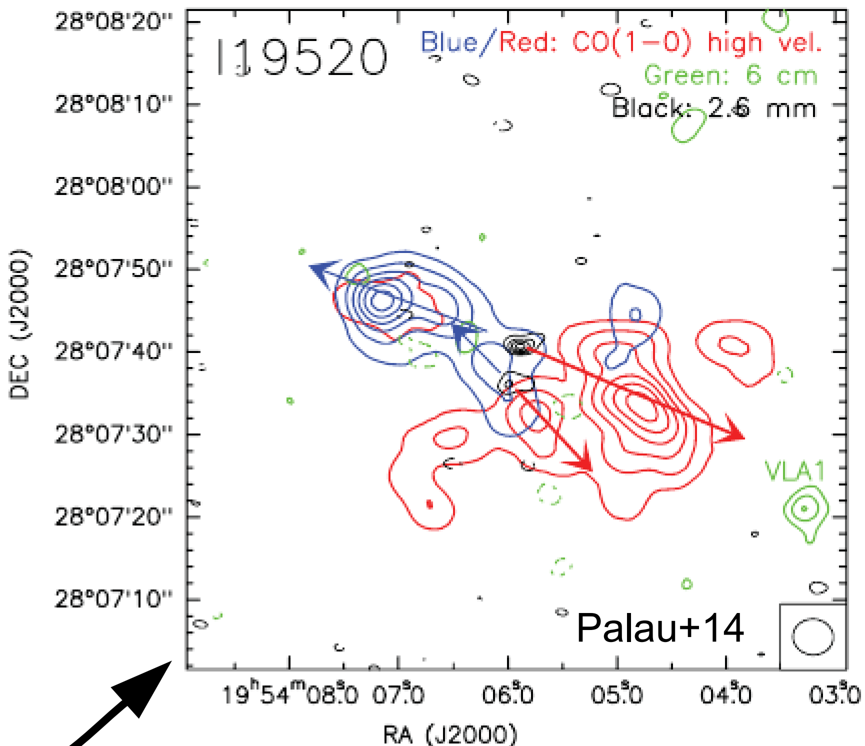
18566+0408, Zhang+07

3.2 Morphology: Collimation

Very collimated flows.
At least in the beginning!!



10^5 L☐ HMYSO

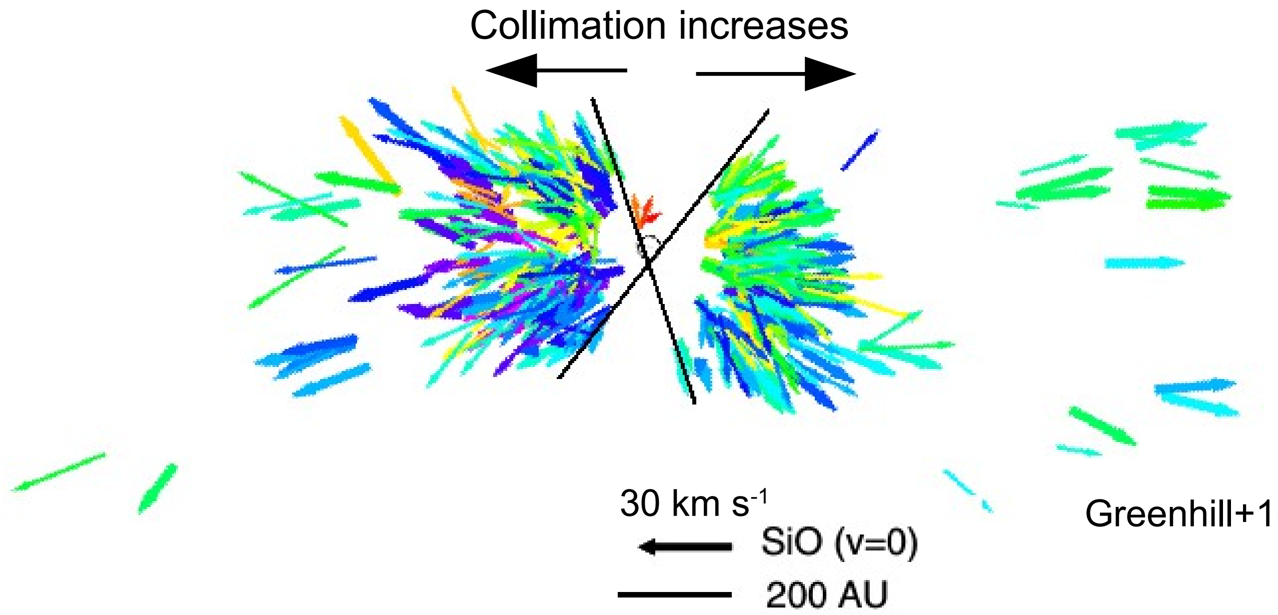


Evolution, confusion, or
fundamental difference?

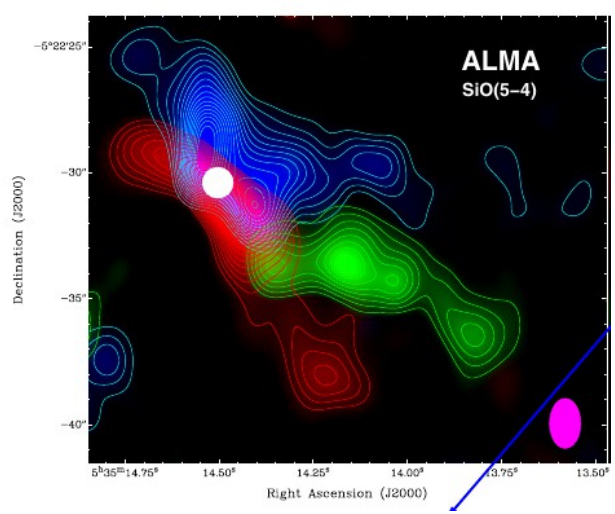
3.3 Morphology: Where does the collimation occur?

Furthermore, collimation seems to be act at ~ 100 AU scales from the star. Greenhil+13 presented evidence in for this in Orion Source I

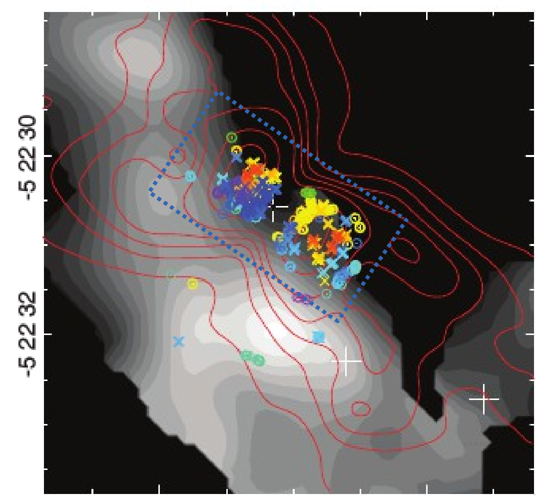
- SiO (1-0) masers
- Conical wind becomes more collimated at 120 AU from the source
- There is also evidence of rotation in the flow, but unfortunately not very consistent.



Greenhill+13



Zapata+12



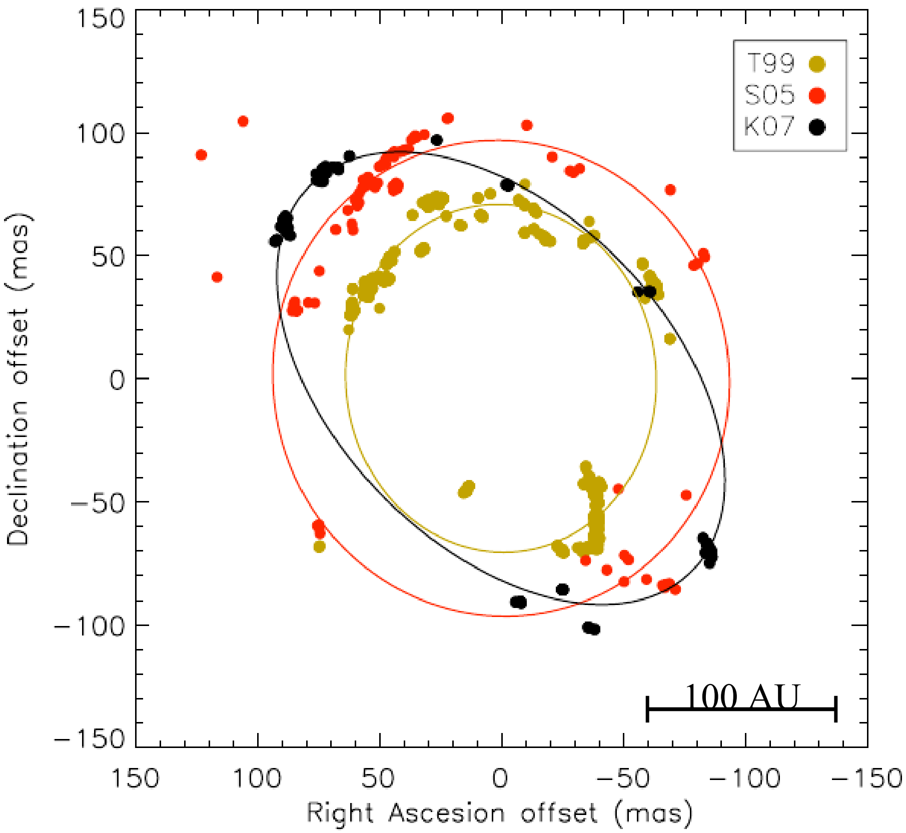
3.3 Morphology: Where does the collimation occur?

Similar evidence was presented by Kim+13, showing an H_2O maser outflow that apparently has accelerated and become more collimated. The collimation mechanism acts on a ~200 AU scale.

<u>Summarizing</u>

We are starting to see evidence that evidence of re-collimation occurring on 100 AU scales, similar to the low-mass case

^ MHD collimation



Kim+13

See Kim's talk

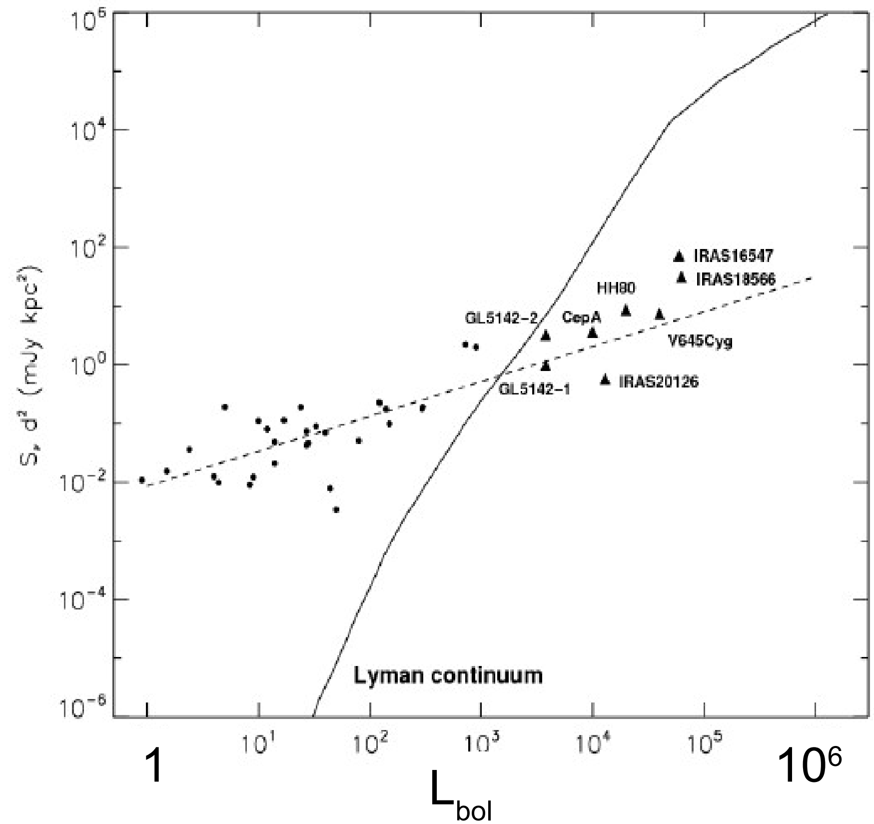
3.4 Dynamics: Jet – Outflows correlations

$$\left(\frac{S_\nu d^2}{\mathrm{mJy\ kpc^2}}\right) = 0.008\left(\frac{L_{\mathrm{bol}}}{L_\odot}\right)^{0.6},$$

<u>Ionized jets</u>

- At the base of many outflows
- With maser, our best chance to probe very near the star

Their energy and momentum is correlated with the luminosity of the central object, with the same type of relation extending from low- to high-mass young stars.

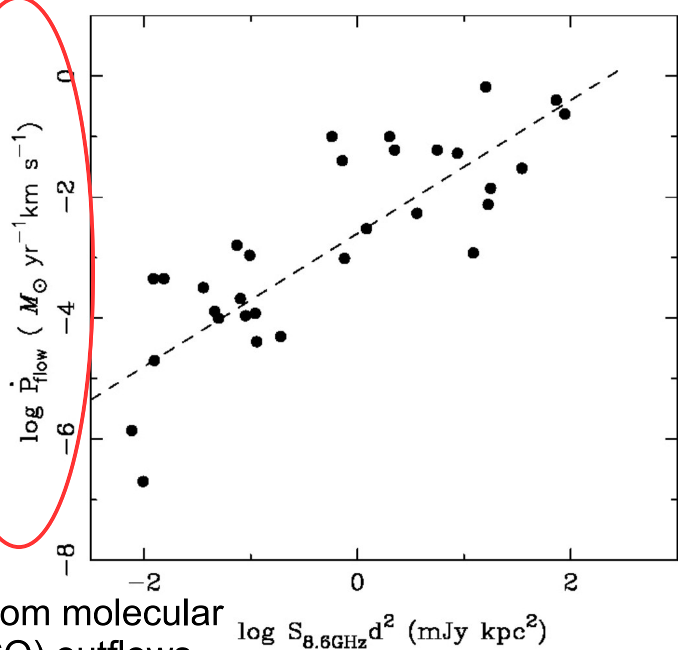


Anglada+14

3.4 Dynamics: Jet – Outflows correlations

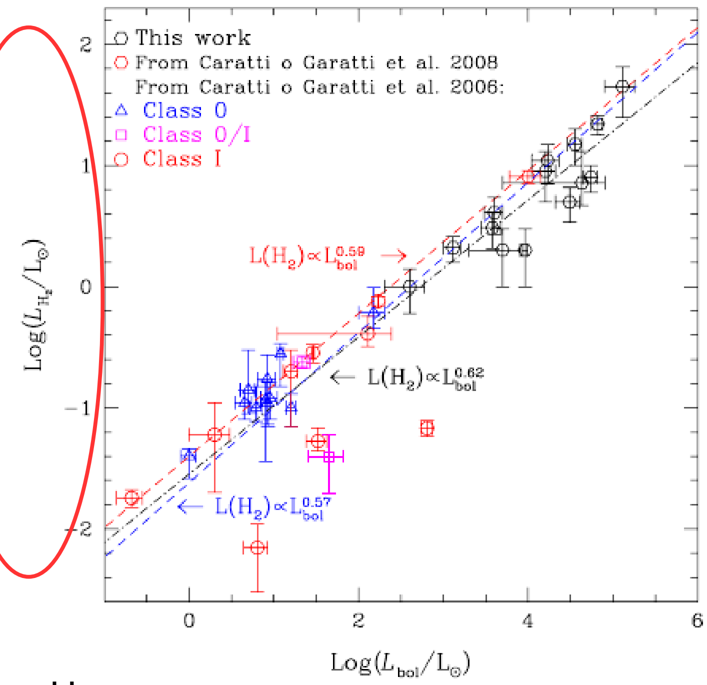
Other correlations related to $F_{CO} \alpha L_{bol}^{0.65}$

$\dot{P}_{flow} \alpha (S_{8.6GHz} d^2)^{1.1}$



From molecular (CO) outflows

$L_{H_2} \alpha (L_{bol})^{0.62}$



From H_2 outflows

Caratti o Garatti+15

See poster by Caratti o Garatti and poster+talk by Maud

3.4 Dynamics: Jet – Outflows correlations

Summarizing:

$$\dot{M}\,V \simeq \dot{P} \propto S_\nu\, d^2 \propto L_{H_2} \propto L_{\rm bol}^{0.6} \propto M^2$$

This seems to imply:

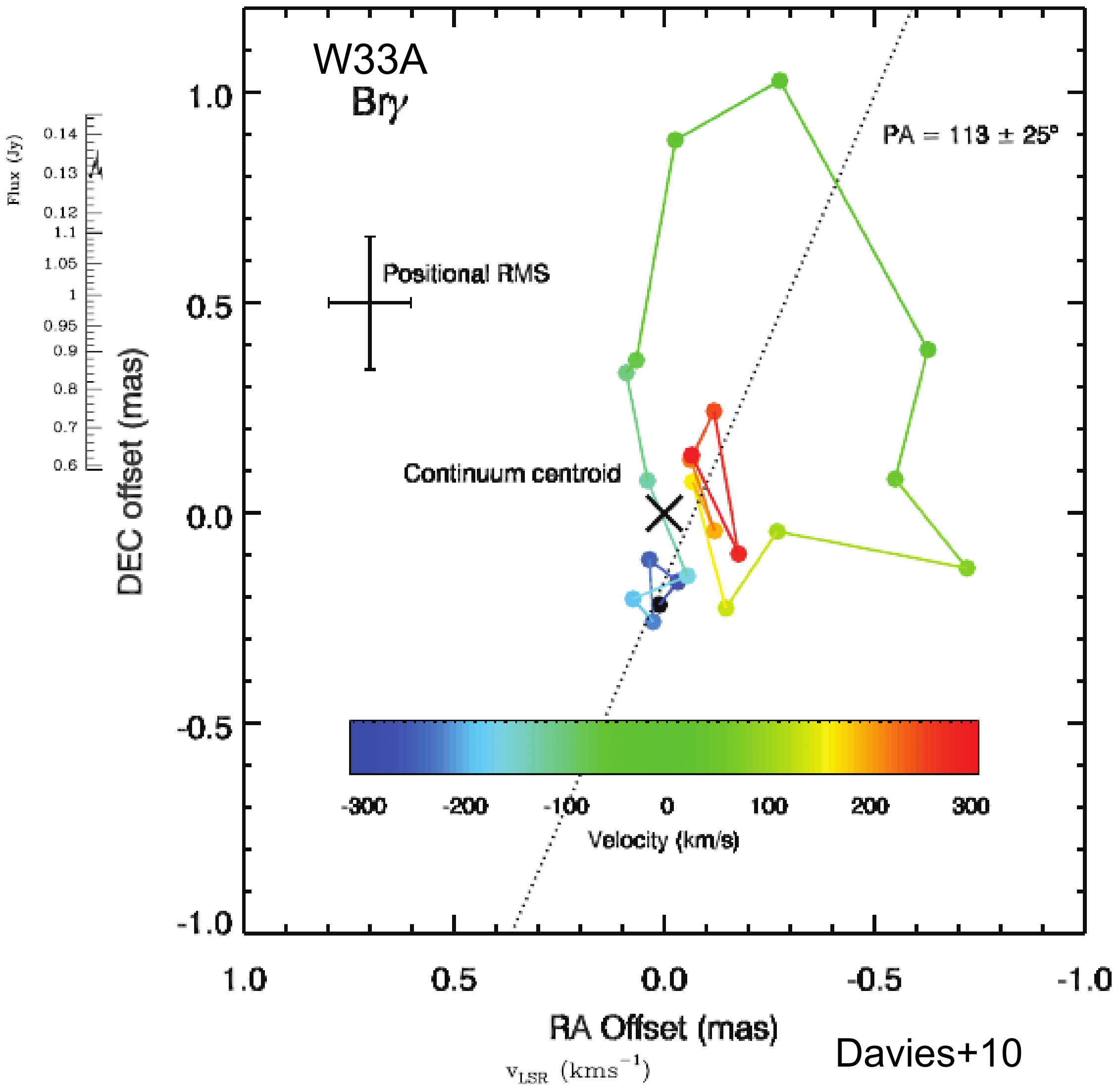
- That the radio emission detected toward the central part of outflows is related to shock excitation from a jet
- Similar low- high-mass star processes

3.4 Dynamics: Jet – Outflows correlations

The few direct measurements of the velocity of the ionized gas – not from proper motions of lobes – indicate high-velocities for the ionized gas

- Direct measurement of very wide HRLs in Cep A HW2
- Br-□ Spectro-astrometric results in W33A

However, explaining the momentum of the molecular outflows from the ionized jets is problematic (Guzman+12)

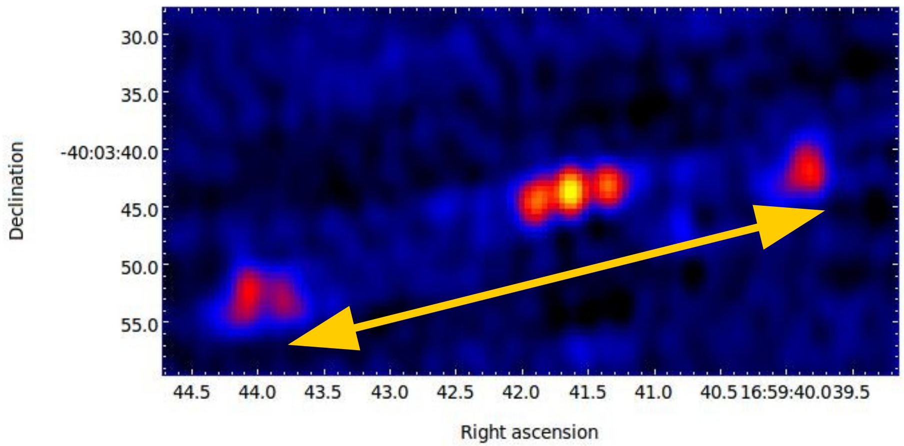


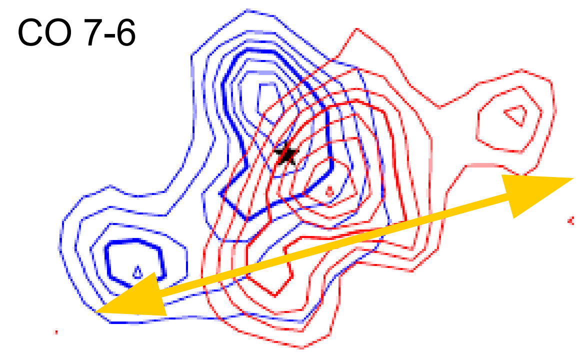
Davies+10

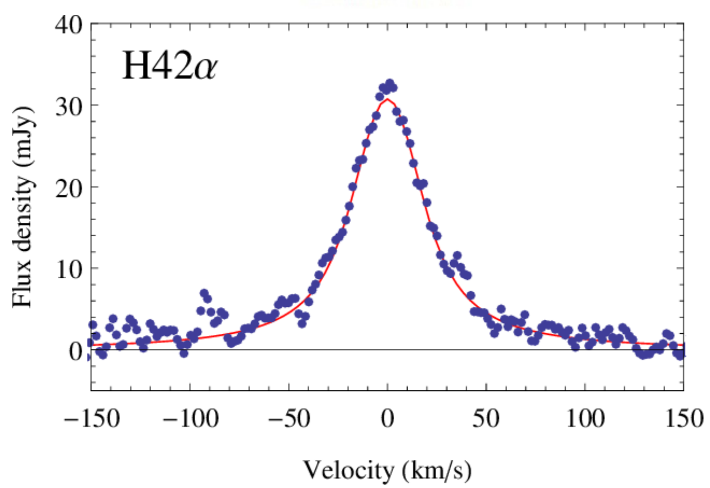
3.4 Dynamics: Jet – Outflows correlations

In some cases the radio emission may arise from an hyper-compact HII region (ALMA result!)

G345.49+1.7, Guzman+12,+14





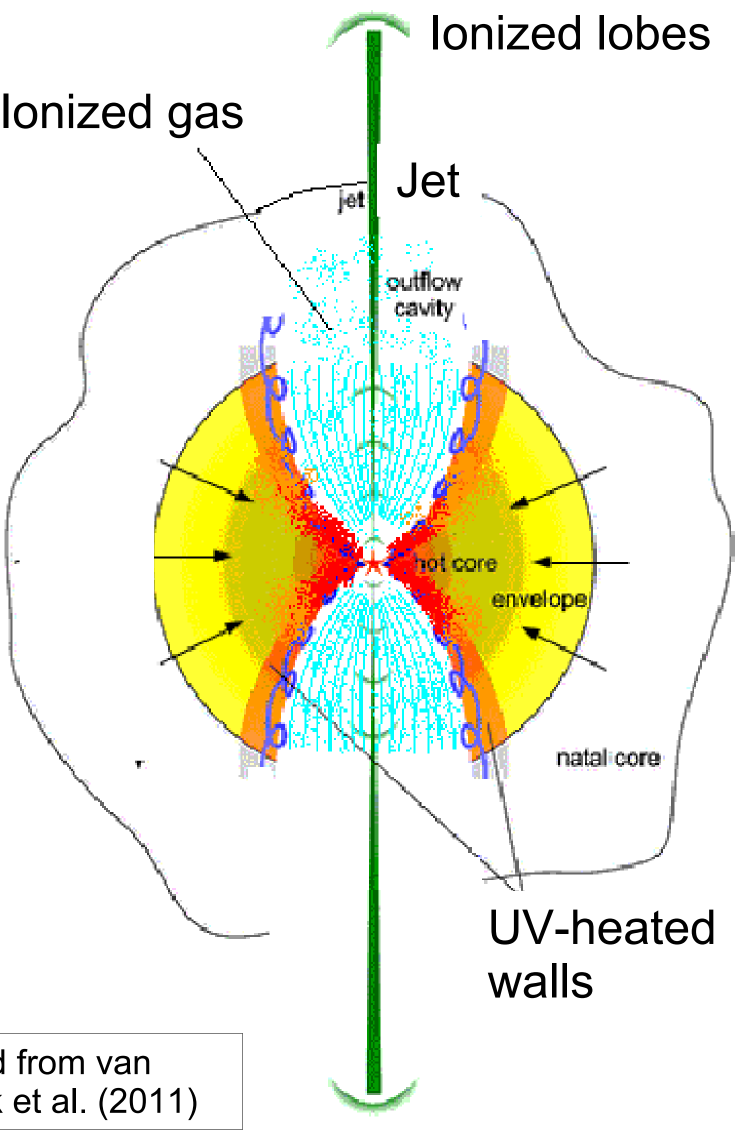


We do not detect EHV ionized gas, but what would is better described as a gentle photo-ionized wind

A jet inside a HC HII region?

But there are ionized lobes nevertheless!

- Maybe the jet is inside the HC HIIR
- In combination with a slow ionized wind ^ similar and different compared to the low mass case
- Other possible cases:
  - G353.273+0.641 (Motogi+13)
  - AFGL 5142 (Goddi+11)



Adapted from van Dishoek et al. (2011)

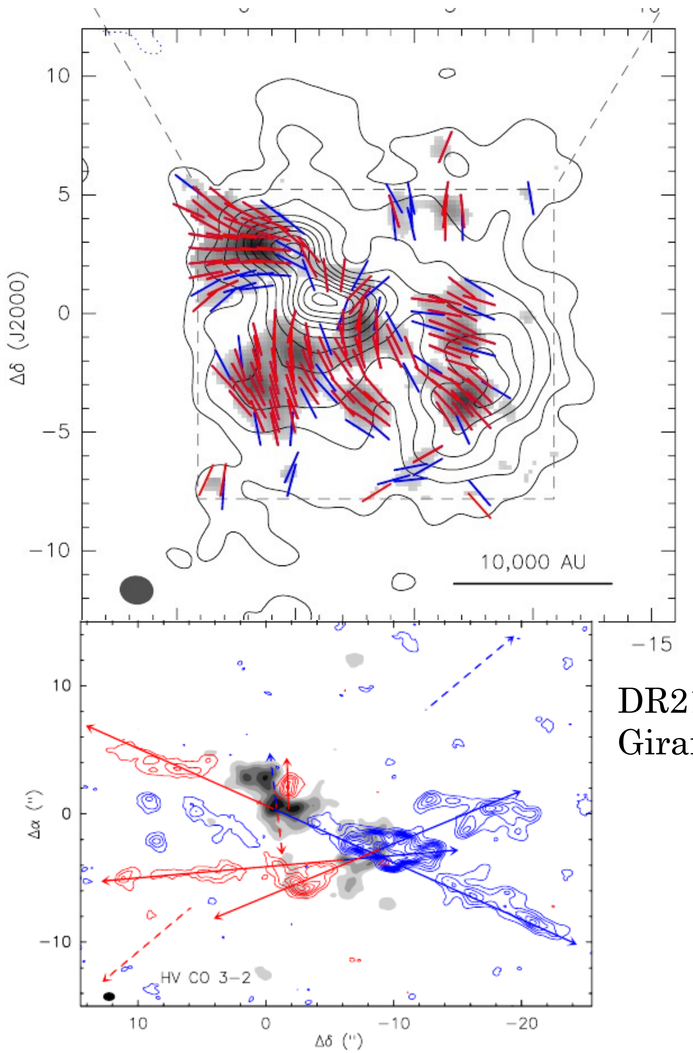
3.5 Magnetic Fields Alignment with Outflows/Jets

<u>Magnetic field direction</u>

- Dust polarization
- Molecular lines, maser polarization and synchrotron polarization ^ more difficult

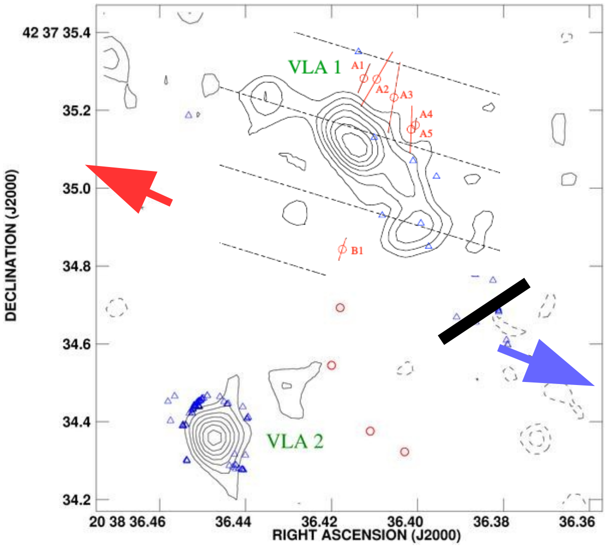
RESULTS

1) Generally a complicated morphology
   Example: DR21(OH)

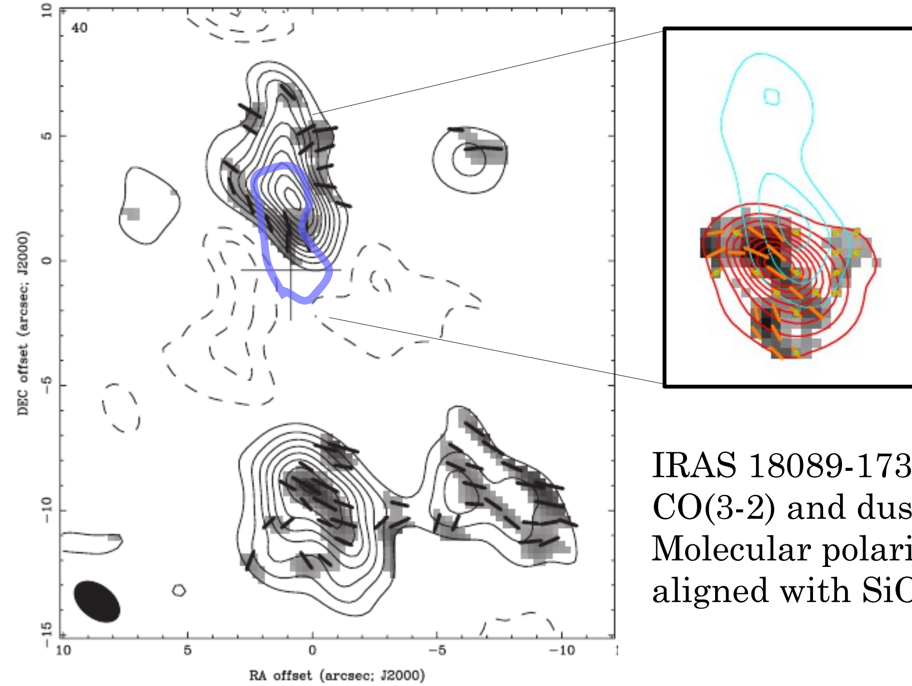


DR21(OH)
Girart+13

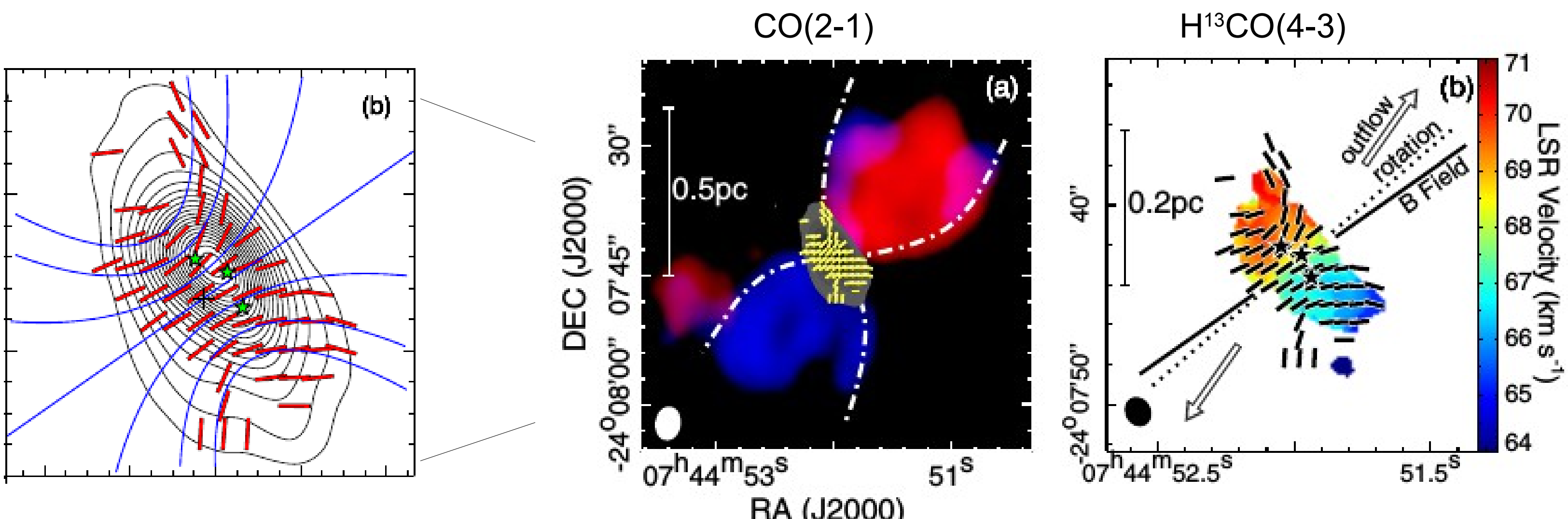
See poster by Dall'Olio



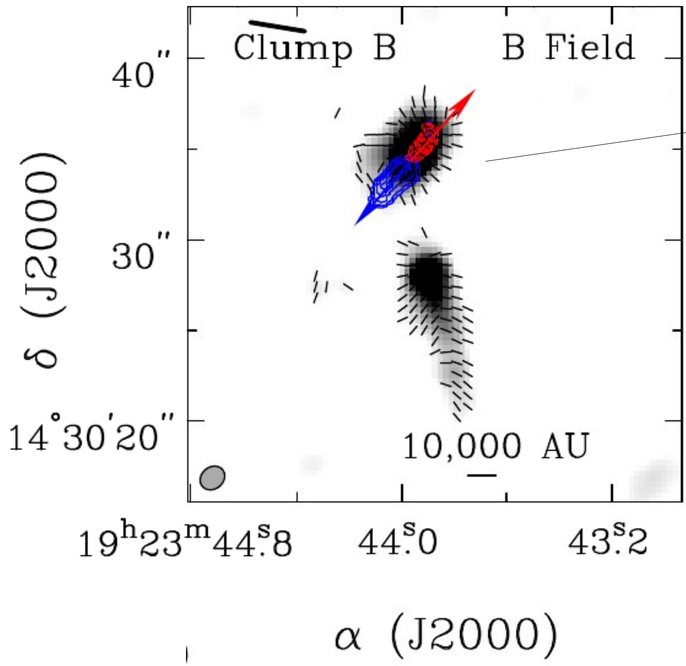
W75N VLA1 (Surcis+11,+09)
Water and methanol masers polarization
Apparent alignment small scale

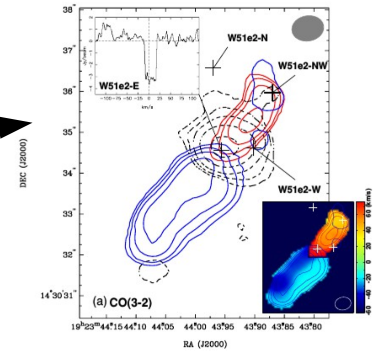


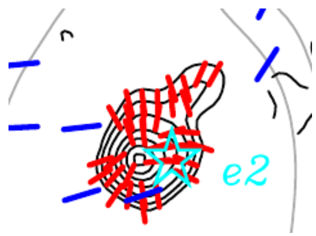
IRAS 18089-1732 (Beuther+10)
CO(3-2) and dust polarization
Molecular polarization somewhat aligned with SiO outflow.



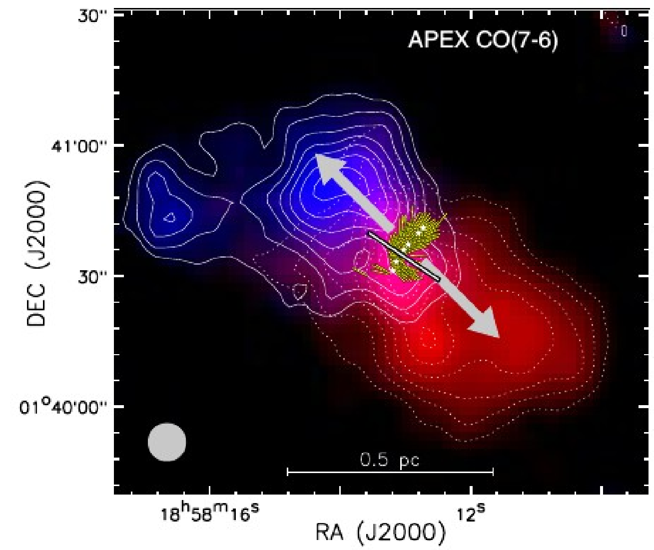
G240.31+0.07 (Qiu+14)
Hourglass shape. Alignment with outflow



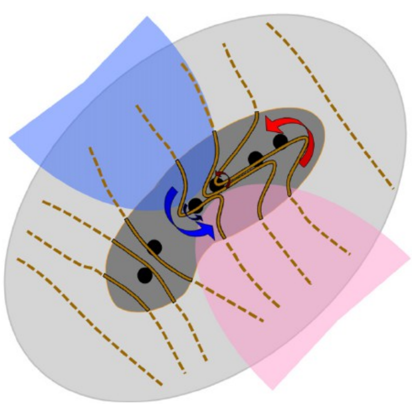


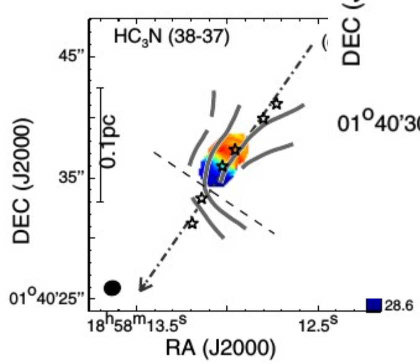


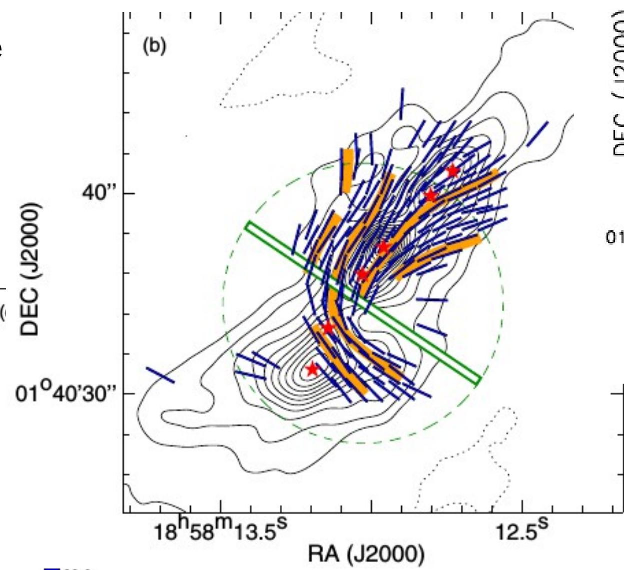
W51e2-E (Zhang+14, Shi+10, Tang+09)
Hourglass type of shape.
More "radial" than aligned



G35.2N (Qiu+13)
One part of the clump aligned, the other perpendicular.
Interpretation: From poloidal to toroidal due to rotation (see also Liu+13).

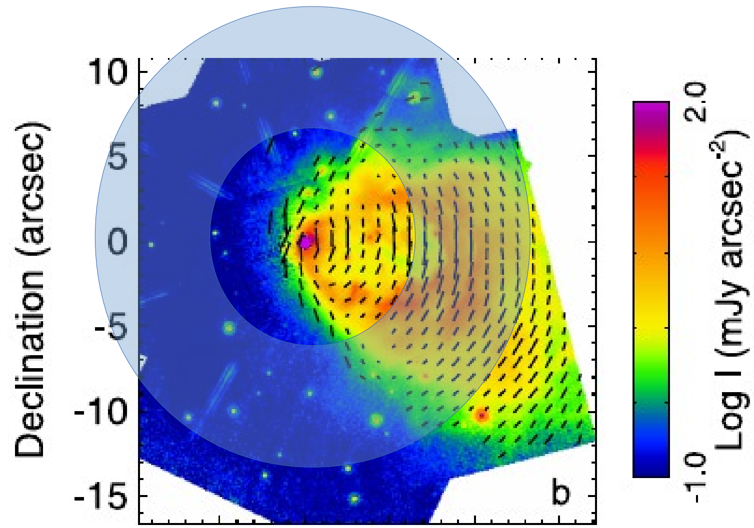


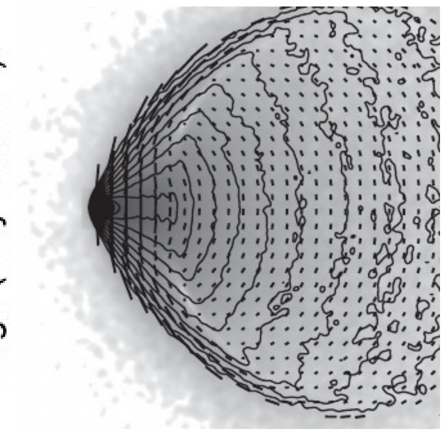


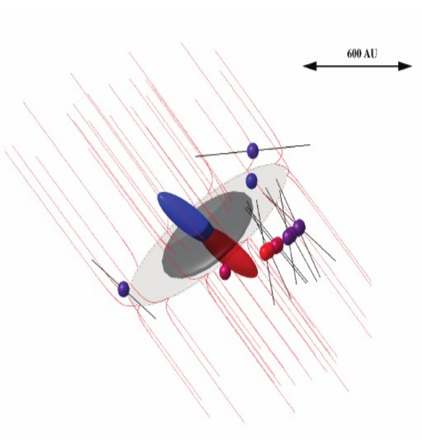


AFGL 2591 and S140-IRS1 (Simpson+13)

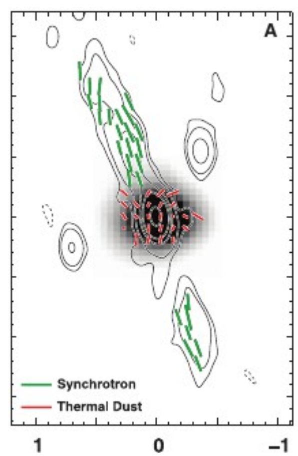
- 2□ m polarimetry (HST)
- Best reproduced with elongated grains aligned in a toroidal field respect to the direction of the outflow's cavities.







Cepheus A HW2
Vlemmings+10
Maser polarization



HH 80-81 (Carrasco-González+10)
Ionized jet (+molecular+atomic jet) and molecular outflow.
Synchrotron emission polarization, poloidal field in the lobes.

Summarizing, there are nice examples of magnetic fields:

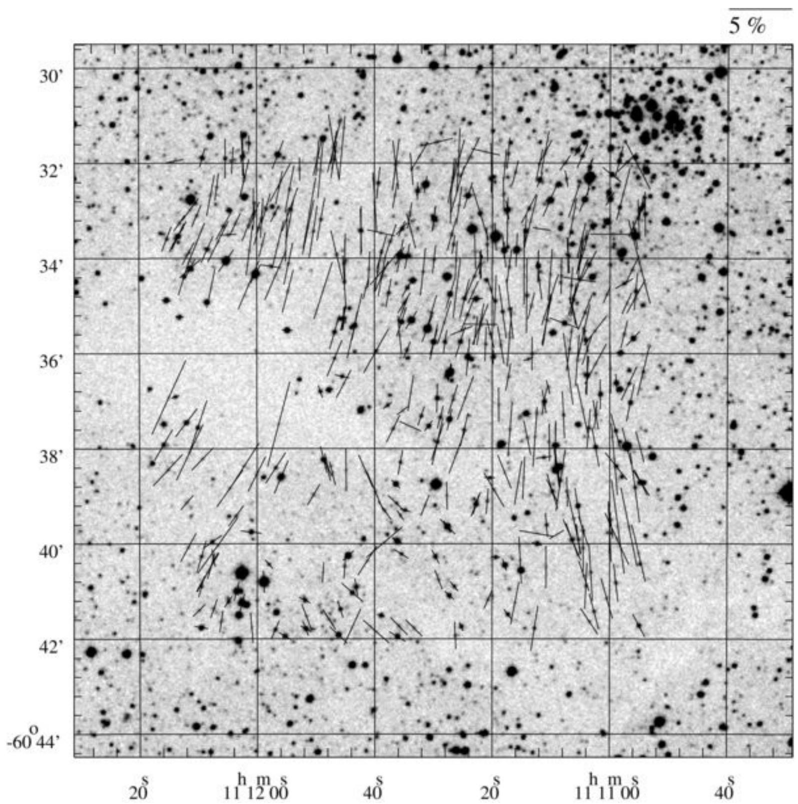
1) Aligned with the outflow direction
2) With an hourglass geometry
3) Perpendicular to the outflow direction

3.5 Magnetic Fields Alignment with Outflows/Jets

What do more systematic surveys tell us?

1)Large scale (~pc) magnetic field ^ uncorrelated with outflow direction

- High- and low mass YSOs (Optical polarimetry, Targon+11)

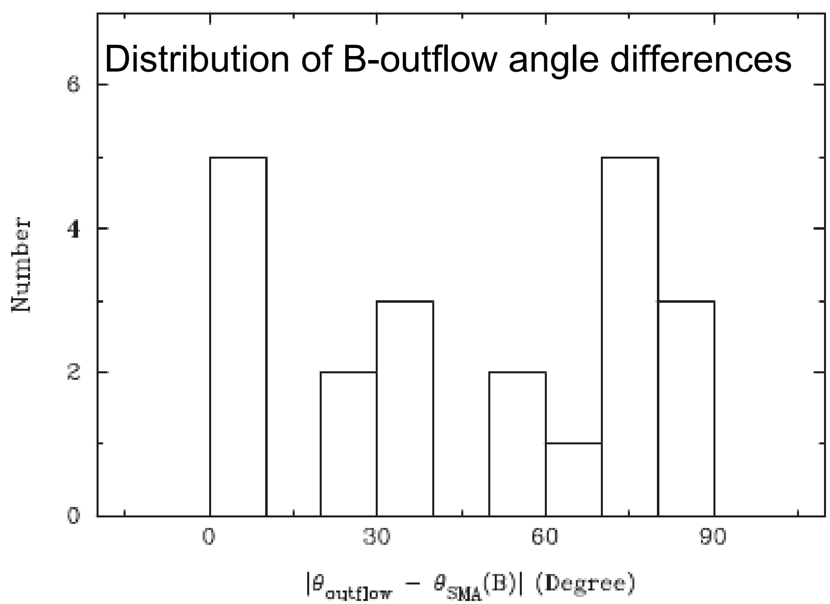


Field 15, one of of the 28 fields studied by Targon+11

3.5 Magnetic Fields Alignment with Outflows/Jets

What do more systematic surveys tell us?

1) Large scale (~pc) magnetic field ^ uncorrelated with outflow direction
2) Small scale (~0.01-0.05 pc) magnetic field ^ uncorrelated with outflow direction
   - Dust emission polarization (High-mass case, SMA, Zhang+14)
   - Dust emission polarization (High- and low-mass,CARMA, Hull+14)
   - Methanol maser polarization (Dodson+12), *but see recent results by Surcis et al. …*



Zhang+14

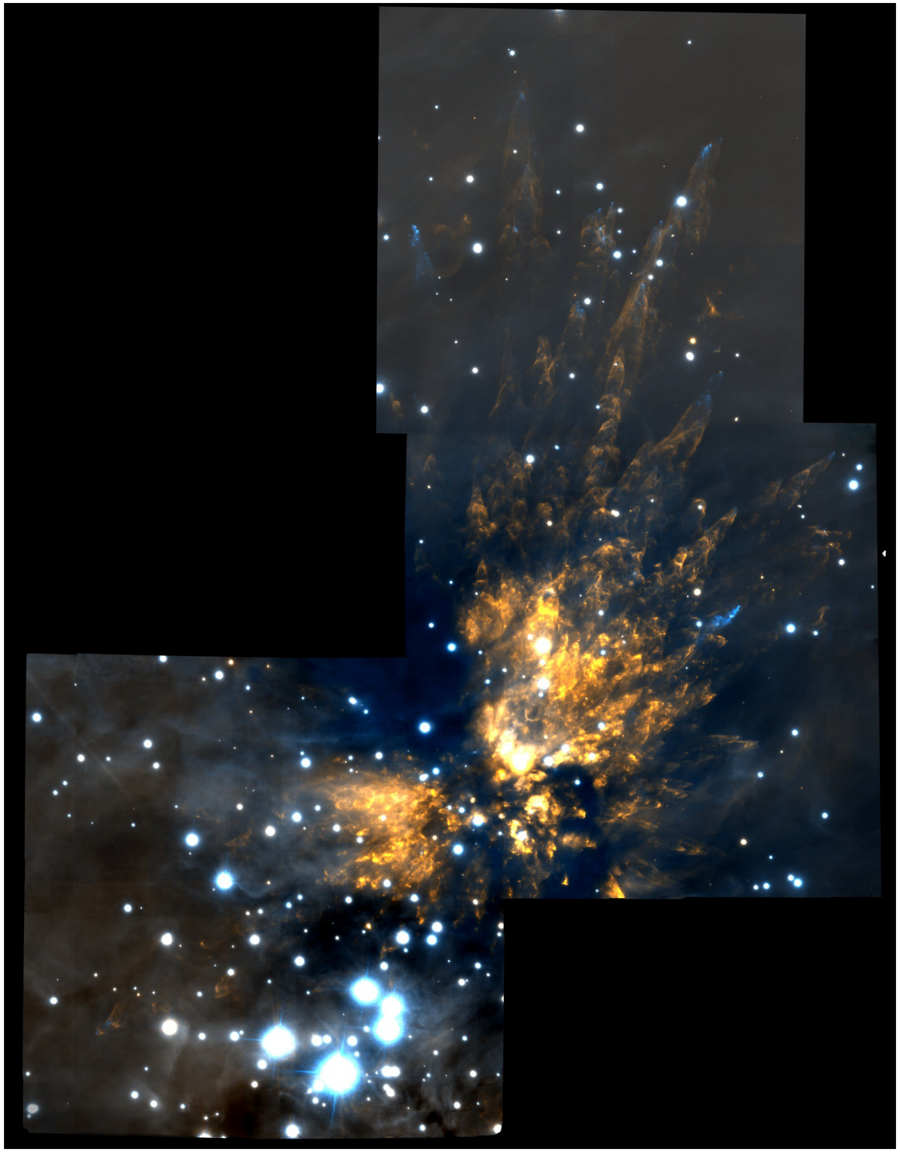
G35.2N, G240, and W51e2 are part of this sample. Are the physical processes that link the direction of the outflow and *B* necessary? Do they work sometimes? Are these fundamentally *chance* alignments?

3.6 Definitely Not Jets
Explosive Outflows: Orion BN/KL

It is important to study the high-mass outflows for which a jet excitation mechanism is highly unlikely.

Orion BN/KL "explosion"

- Excited and high velocity molecular gas (e.g., Kwan+76)
- H_2 "fingers" (Allen+93)

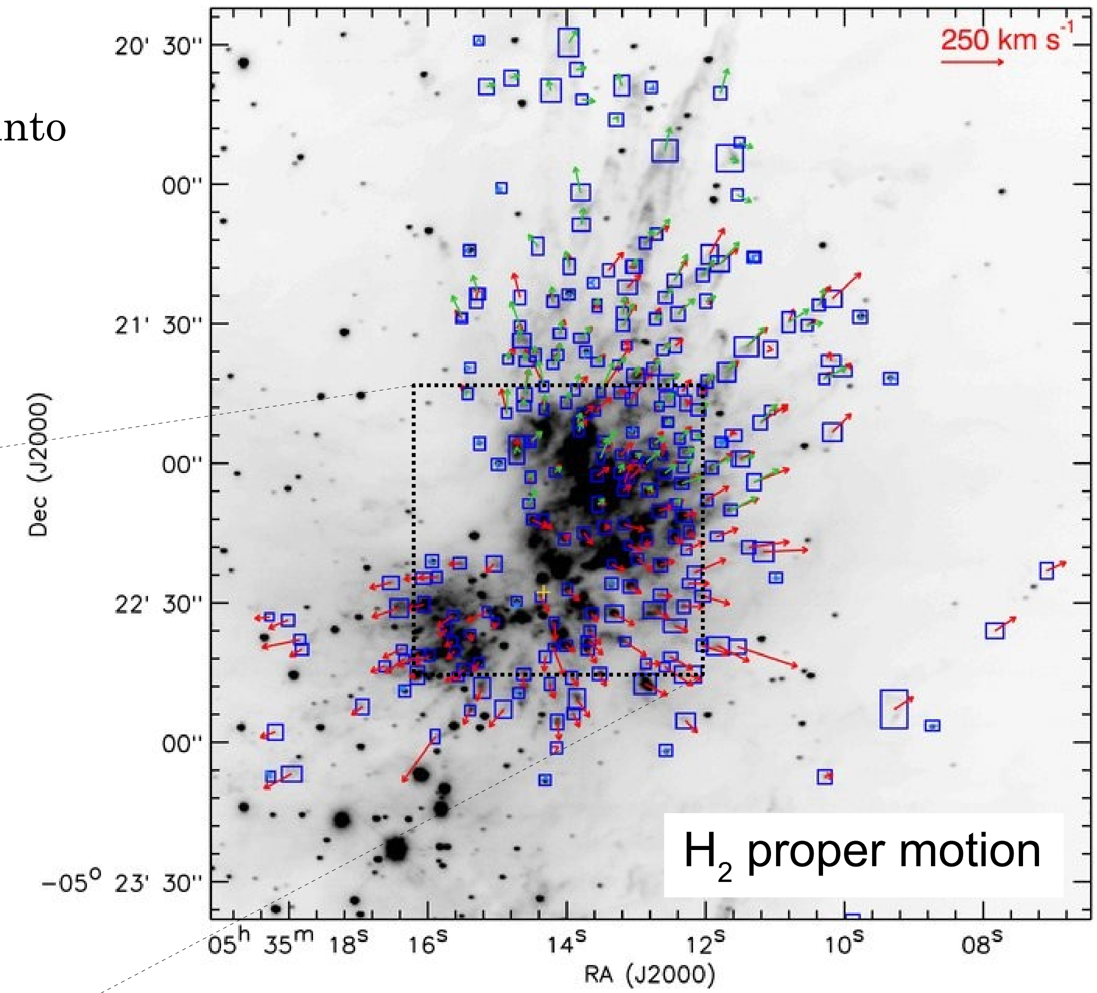


Modern picture of the fingers. Gemini Observatory Legacy

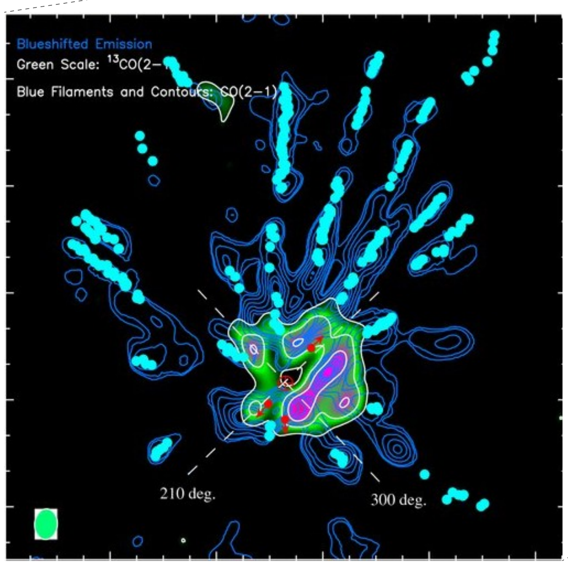
3.6 Definitely Not Jets
Explosive Outflows: Orion BN/KL

- H_2 proper motions ^ 500 yr
- Extended molecular outflow
- 2.6 x 10^{47} erg in the kinetic energy of stars + outflow
- Well defined center
- CO outflow of 15 km/s
  $M_{out} > 10\ M_{\odot}$

- Proposed decay could inject energy into the ISM in three ways:
  - Clamp rebound
  - Disk disruption
  - Liberation of magnetic stress

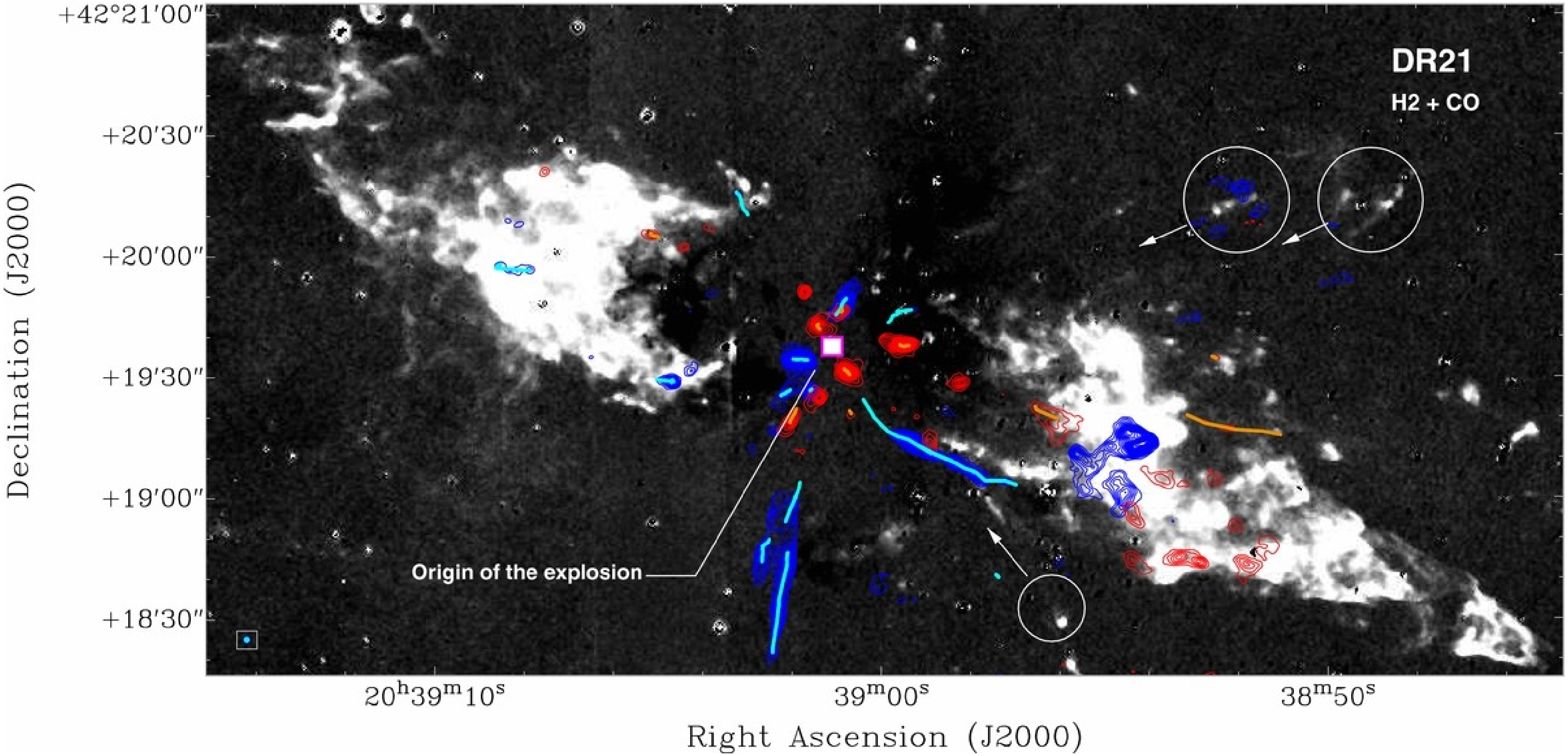


Bally+11



CO(2-1), Zapata+11

3.6 Definitely Not Jets: Explosive Outflows: DR21



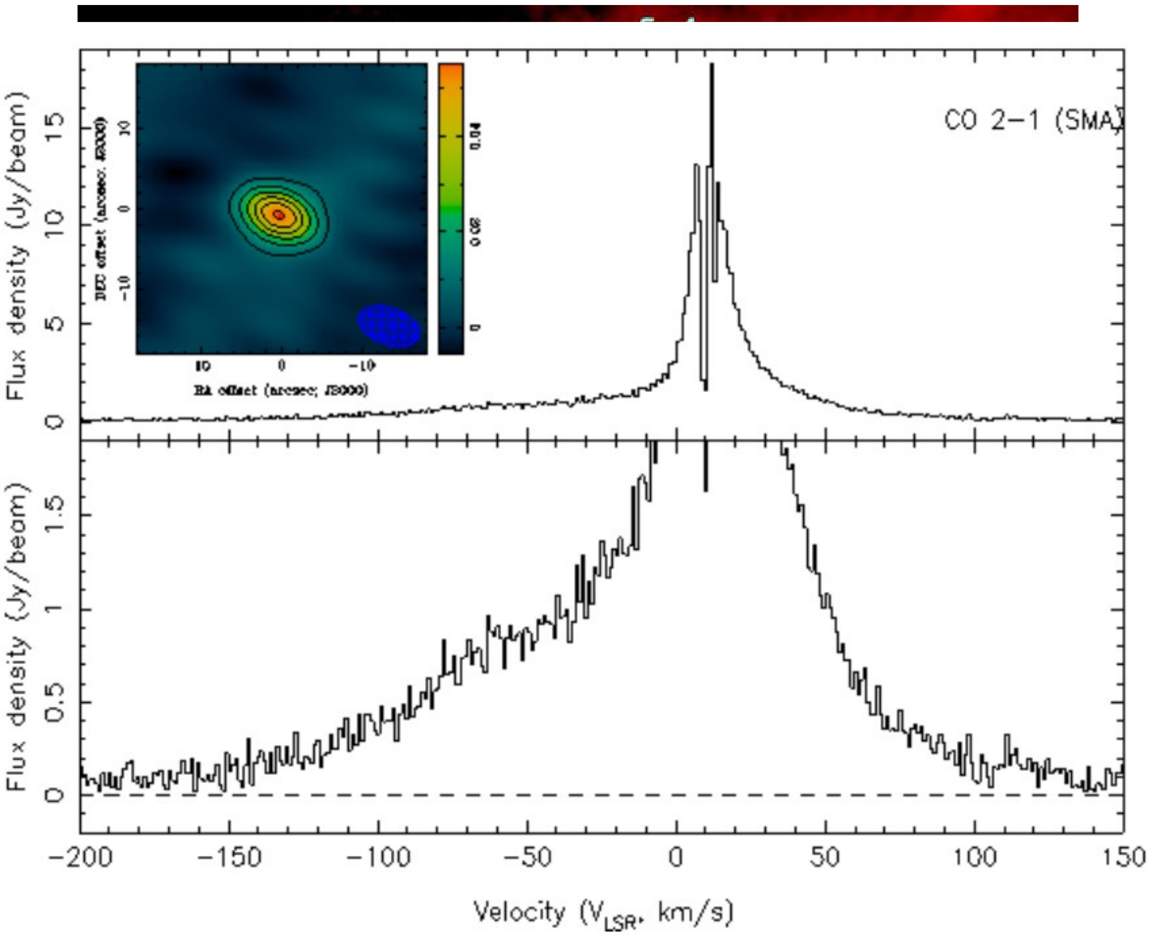
Zapata+13

- 10^{48} erg molecular outflow
- ~ 10,000 Kinematic Age

(Many outflows or explosion?, Peters+14)

3.6 Definitely Not Jets
Explosive Outflows: IRAS 05506+2414

- L_{bol} ~ 5000 $L_{\odot}$
- Kinematic Age ~ 200 yr
- Several "bullets"
- Strong CO(2-1) and SiO(5-4) wings (SMA) from central source



Sahai, "*Outflows, Winds and Jets: From Young Stars to Supermassive Black Holes*", Charlottesville, 2012

3.6 Non-collimated outflows feedback

	Distance(pc)	Timescale (yr)	Energy (erg)
Orion	414	500-1000	$2\text{-}6 \times 10^{47}$
DR21	1360	~ 10,000	$> 2 \times 20^{48}$
05506+2414	~ 2800	~ 200	$\sim 5 \times 10^{45}$

Explosive events are **energetic, uncollimated, nearby, and recent**.

^ **Important in the feedback budget**

^ Perhaps more than bipolar, collimated outflows?

Jet and Outflows Simulations

1. Introduction
2. Observational tracers
3. Are high-mass outflows jet driven?
4. **Simulations and theory**
5. Summary and Conclusions

4. High-Mass Outflow and Jet Simulations

Two types of simulations

1)Numerical simulations

2)Laboratory scaled experiments

4.1 High-Mass Outflow and Jet Simulations

1) <u>Numerical simulations</u>

 i. Core scales (≤ 10^2 M□)
   - Resolution from <0.1 AU to ~10 AU
   - Focus on a single star or a small stellar system
   - **Spontaneous formation of magnetically accelerated outflows** (e.g., Hennebelle+11, Seifried+12)
   - Study of the **effect of radiation in jet models** (e.g., Vaidya+11, Kuiper+15)

 ii. Clump scales(~10^3 M□) scales
   - Resolution from >10 AU to ~100 AU
   - Focus on a cluster level 10-100 stars
   - Study the **effect of outflows feedback** on the mass functions and SF efficiencies (Wang+10, Myers+14, Krumholz+12, Federrath+14)

4.1 High-Mass Outflow and Jet Simulations

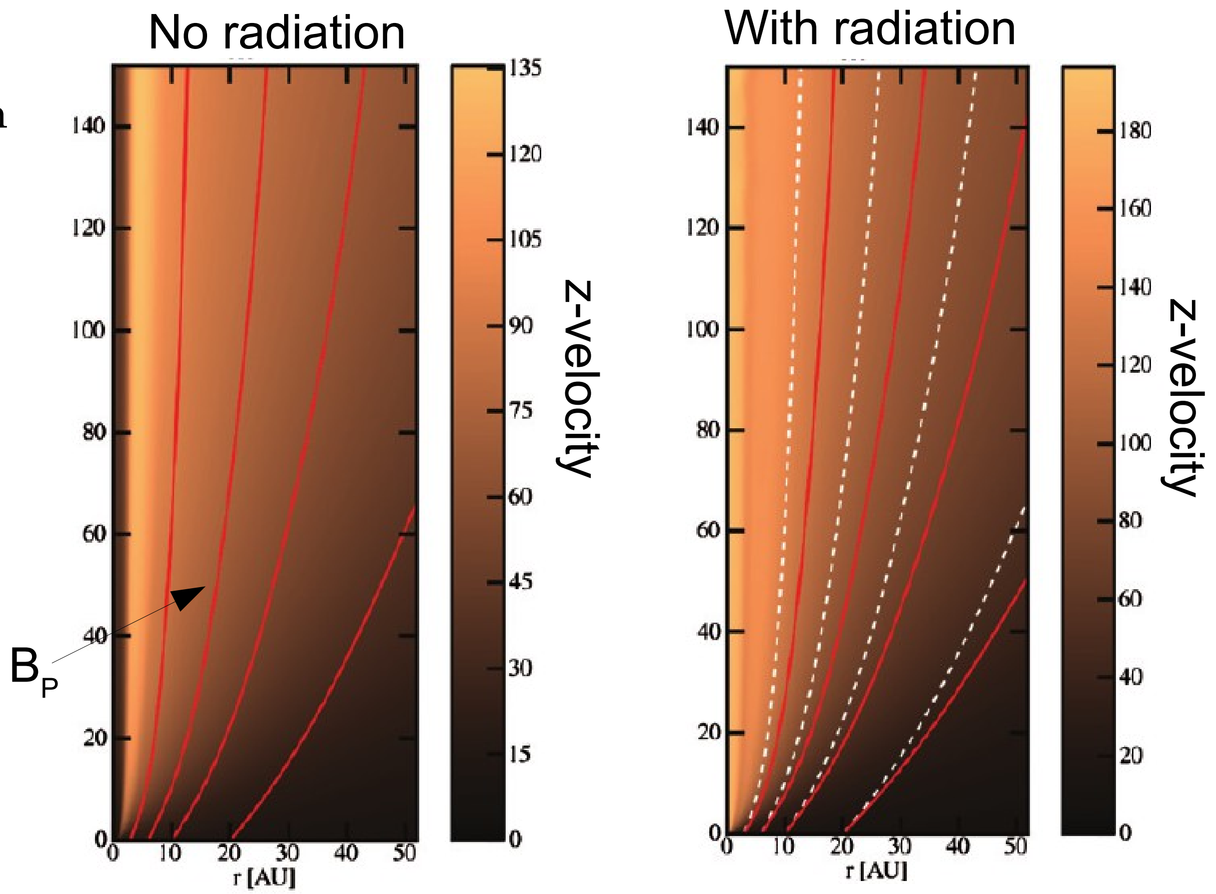
	Mass (M□	Res. (AU)	Turbulence (decay)	B fields	Radiation	Sink parts.	Rot.	Outflows "subgrid"
Vaidya+11	20-60*	<0.1*	N	Y	Y	n.a.	n.a.	n.a.
Henebelle+11	100	2	Y	Y	N	N	N	N
Seifried+12	100	4.7	N	Y	N	Y	Y	N
Kuiper+15	100	10	N	N	Y	n.a.	Y	Y
Cunningham+11	300	24	Y	N	Y	Y	N	Y
Federrath+14	500	60.4	Y	Y	N	Y	N	Y
Peters+14			N	N				Y
Peters+11	1000	98	N	Y	Y (ion)	Y	Y	N
Peters+10,+12			N	N				N
Krumholz+12	1000	23	Y	N	Y	Y	N	Y
Myers+14	1000	23	Y	Y	Y	Y		Y
Wang+10	1215	200	Y	Y	N	Y	N	Y

Initial temperatures between 10 and 30 K

4.1 High-Mass Outflow and Jet Simulations

Core scales and individual jets

- Radiation diminishes the collimation of magnetic jets (Vaidya+11)
- Radiation helps to create faster outflows (Vaidya+11)

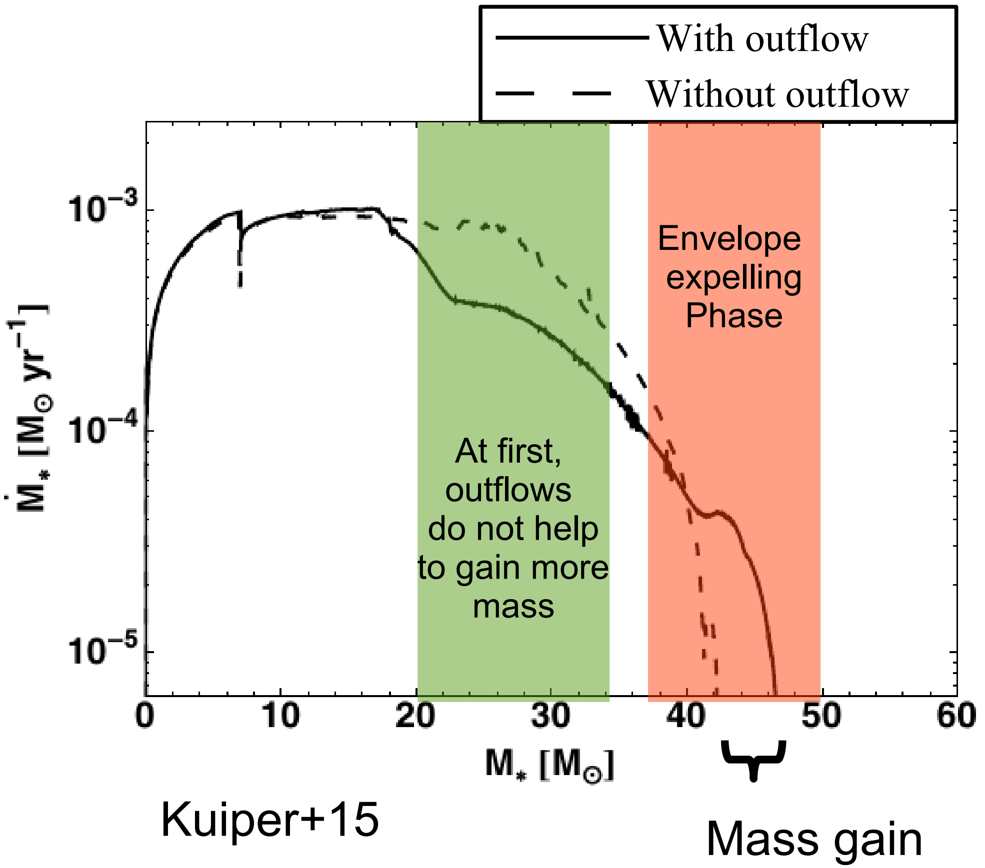


Vaidya+11

4.1 High-Mass Outflow and Jet Simulations

<u>Core scales and individual jets</u>

- Radiation diminishes the collimation of magnetic jets (Vaidya+11)
- Radiation helps to create faster outflows (Vaidya+11)
- Makes the flashlight effect more effective, delaying the expelling of the envelope and disk and increasing the accretion timescale and the accreted mass (Kuiper+15)



Kuiper+15

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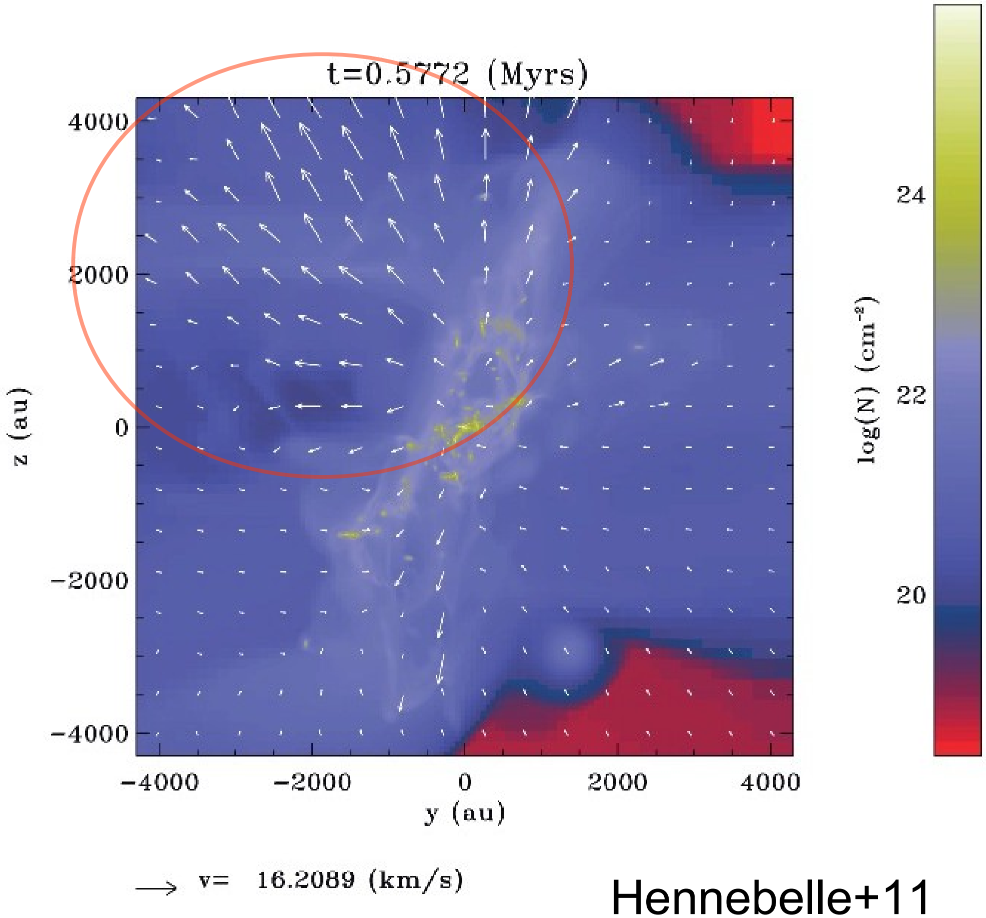
- Makes the flashlight effect more effective, delaying the expelling of the envelope and disk and increasing the accretion timescale and the accreted mass (Kuiper+15)
- Wide outflows naturally form during collapse of magnetized turbulent cores (Hennebelle+11)

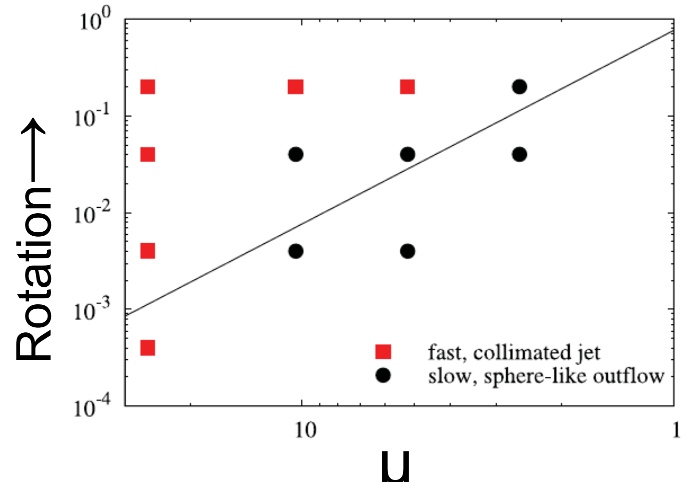


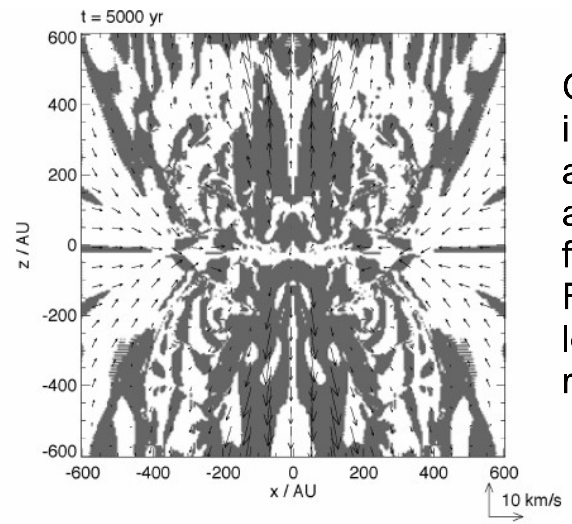
Hennebelle+11

4.1 High-Mass Outflow and Jet Simulations

<u>Core scales and individual jets</u>

- Radiation diminishes the collimation of magnetic jets (Vaidya+11)
- Radiation helps to create faster outflows (Vaidya+11)
- Makes the flashlight effect more effective, delaying the expelling of the envelope and disk and increasing the accretion timescale and the accreted mass (Kuiper+15)
- Wide outflows naturally form during collapse of magnetized turbulent cores (Hennebelle+11)
- Generation of fast, collimated jets needs a rotationally supported disk, and magneto-centrifugal seem to be the preferred acceleration mechanism (Seifried+12)





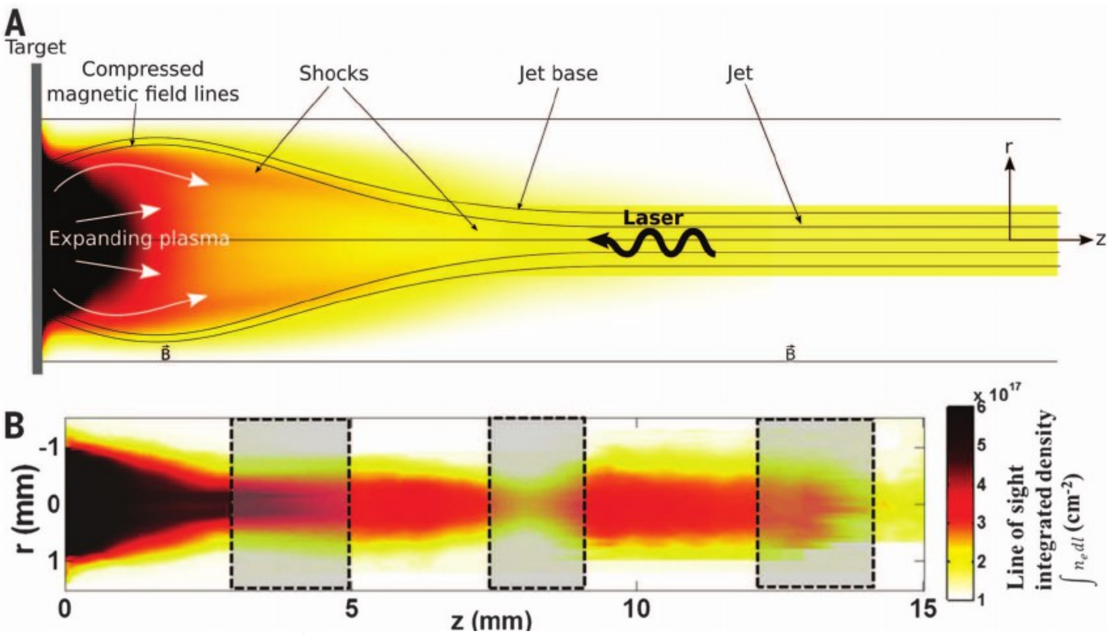
Grey areas indicate where acceleration is along poloidal field lines. Fastest gas is located in these regions.

Seifried+12

4.2 High-Mass Outflow and Jet Simulations

<u>Two types of simulations</u>

1) Numerical simulations
2) Laboratory scaled experiments
   i. Ideal MHD experiments
      - Similar sonic and Alfvénic Mach numbers
      - Velocity × Length >> thermal and magnetic diffusivity and kinematic viscosity



Albertazzi+14

5. Summary

1) Increasing evidence given by the morphological similarity and dynamical relations scaling from low- to high-mass stars up to several × 10^5 L□ YSOs indicate
    ^ jet excitation of outflows ^ disk accretion
  Morphological Similarity: Collimation, Wide-angle winds, disks.
  Dynamical Scaling: Ionized and molecular Jet tracers
2) Increasing evidence of collimation is occurring near the source
    ^ MHD wind (although magnetic field observational evidence not clear!)
3) Explosive outflows – not produced by jets – might be common
    ^ important for feedback

5. Future

1) Is there an **alternative** to disk accretion consistent with observations? Do high-mass stars of M>30M□ use the disk+jet accretion scenario during all of their formation process?

2) Relate instantaneously accretion and outflow activity directly

- NIR techniques?

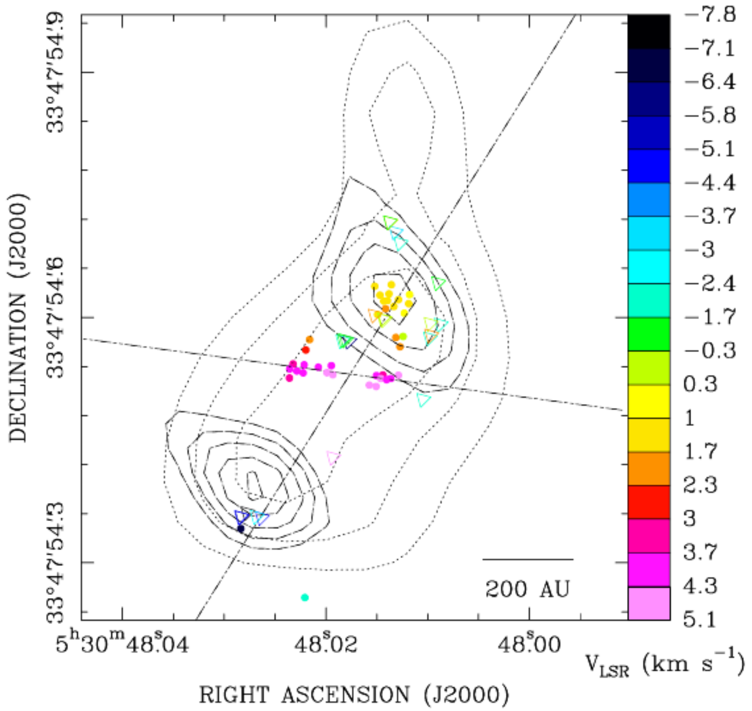
3) Magnetic fields and flows at ~ 100 AU scales and less

- ALMA, masers, spectro-astrometry

A jet inside a HC HII region?

But there are ionized lobes nevertheless!

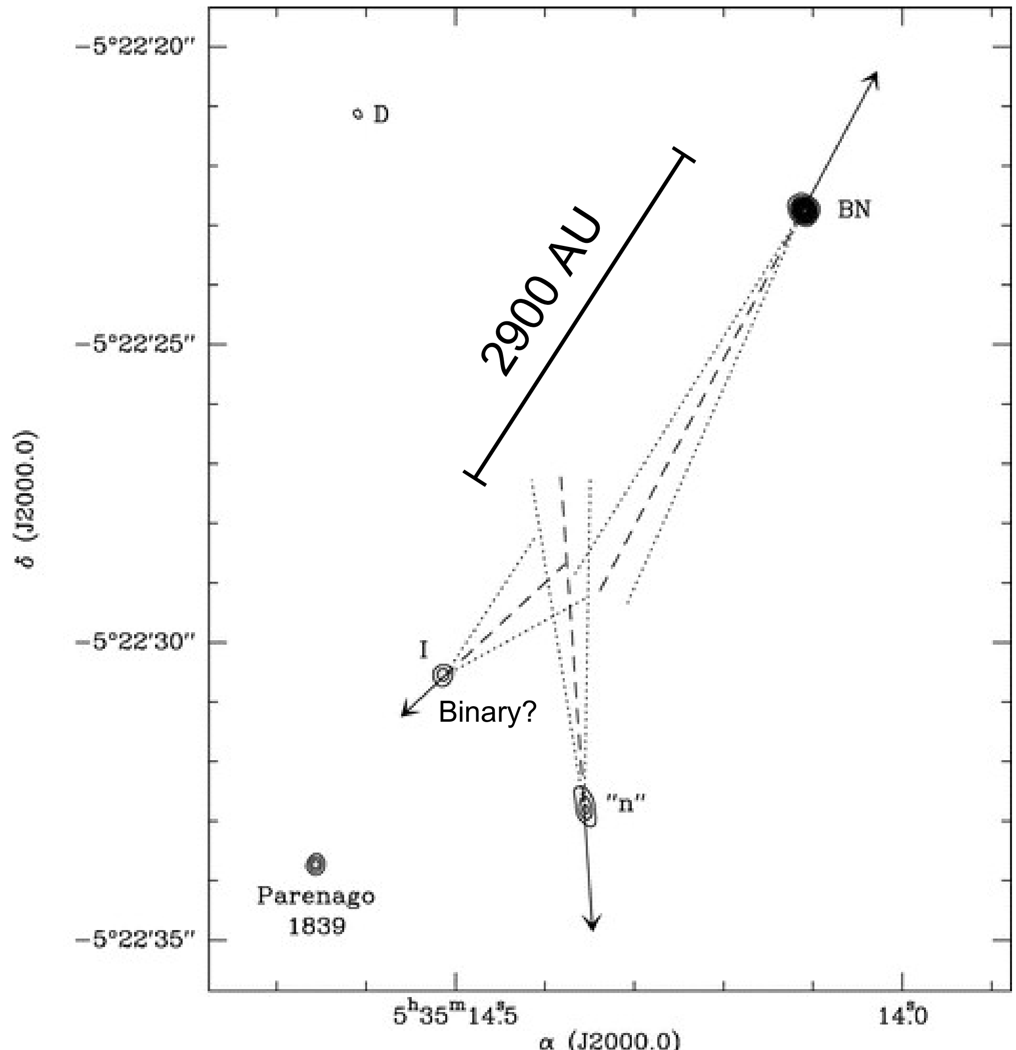
- Maybe the jet is inside the HC HIIR
- In combination with a slow ionized wind ^ similar and different compared to the low mass case
- Other possible cases:
  - G353.273+0.641 (Motogi+13)
  - AFGL 5142 (Goddi+11)



Goddi+11

3.6 Definitely Not Jets
Explosive Outflows: Orion BN/KL

- BN, Source I, and Source "*n*": runaway stellar objects of a former multiple non-hierarchical system decayed ~500 yr ago (Rodríguez+05, Gómez+08, Goddi+11)
- Alternatively, a close encounter between □^{1}C and BN ~5000 yr ago (Chatterjee+13) induced high accretion rates and outflow activity



Gómez+08