Outflows and Jets: Theory and Observations

Summer term 2011

Henrik Beuther & Christian Fendt

15.04 Today: Introduction & Overview (H.B. & C.F.)
29.04 Definitions, parameters, basic observations (H.B.)
06.05 Basic theoretical concepts & models (C.F.)
13.05 Basic MHD and plasma physics; applications (C.F.)
20.05 Radiation processes (H.B.)
27.05 Observational properties of accretion disks (H.B.)
03.06 Accretion disk theory and jet launching (C.F.)
10.06 Outflow interactions: Entrainment, instabilities, shocks (C.F.)
17.06 Outflow-disk connection, outflow entrainment (H.B.)
24.06 Outflow-ISM interaction, outflow chemistry (H.B.)
01.07 Outflows from massive star-forming regions (H.B.)
08.07 Observations of extragalactic jets (C.F.)
15.07 Theory of relativistic jets (C.F.)

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ss11.html
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Last week: outflow-ISM interaction

Large-scale turbulence is likely driven by supernovae.

Smaller-scale turbulence can also be significantly driven by molecular outflows.

Outflows affect the envelopes of star-forming regions significantly. Early-on, they move large gas masses along with them. Lateron, they evacuate the core, and the gas can only fall in perpendicular to the outflow.

The outflows cause shocks with high temperatures and pressures.

In these high-T and high-P regions, distinctively different chemical networks are observed compared to the unperturbed gas.

Chemical properties may be used for (relative) age dating.

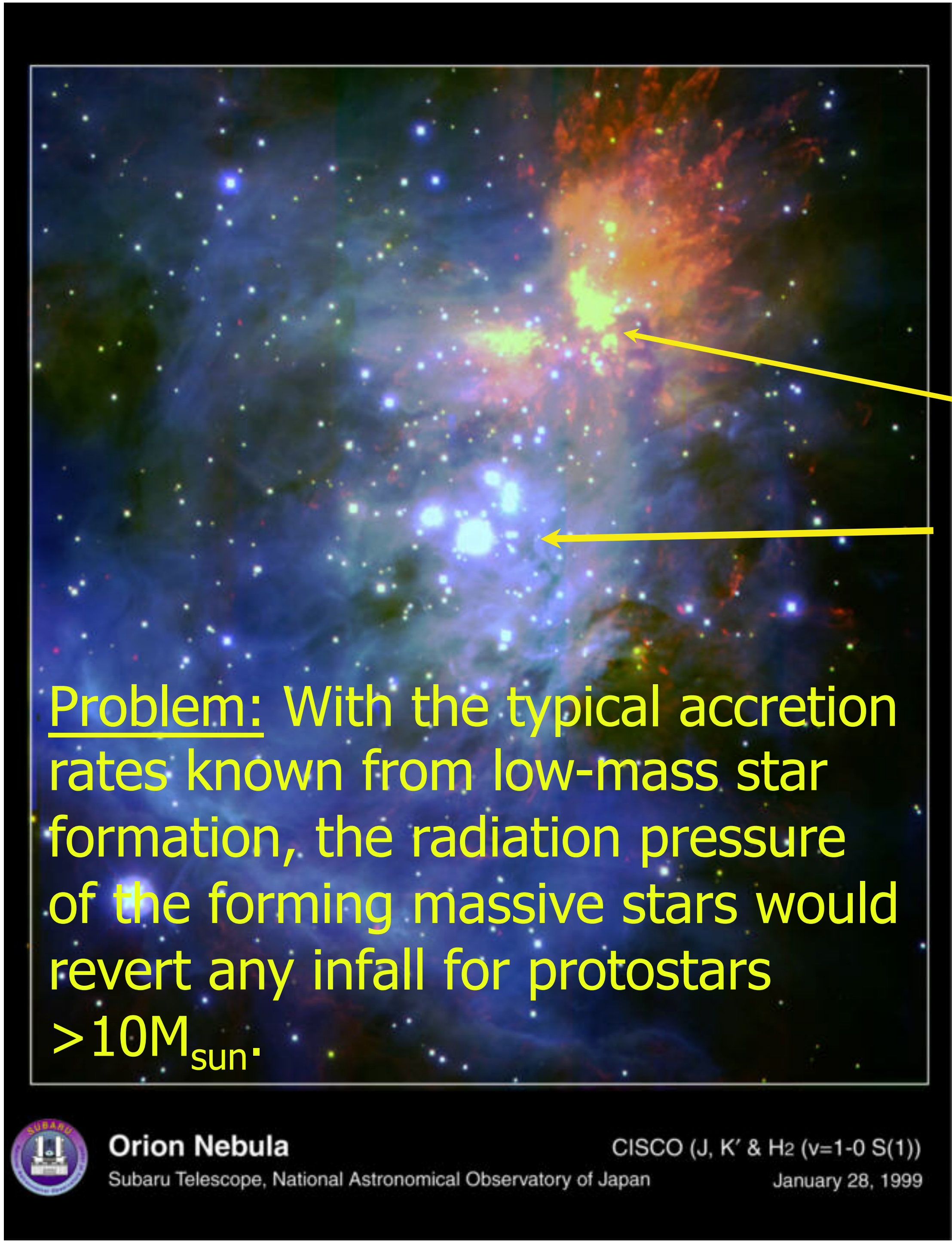
Topics today

- Importance, difficulties, potentials & early observational claims

- Single-dish results at relatively low spatial resolution

- Interferometric high-spatial resolution observations
  and their implications

- Infall and outflow around ultracompact HII regions



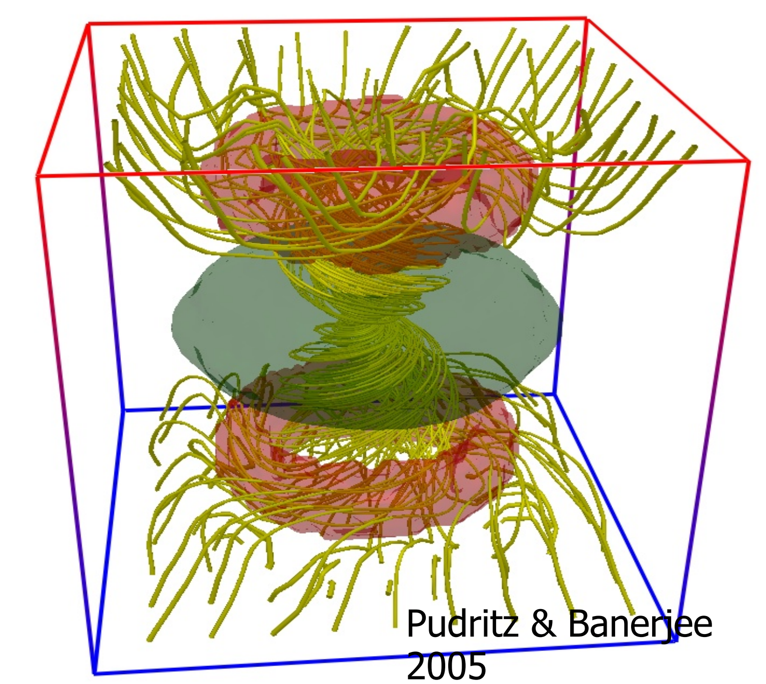
Problem: With the typical accretion rates known from low-mass star formation, the radiation pressure of the forming massive stars would revert any infall for protostars $>10M_{sun}$.

Importance of massive stars

Great impact on ISM and star clusters, $L \propto M^3$

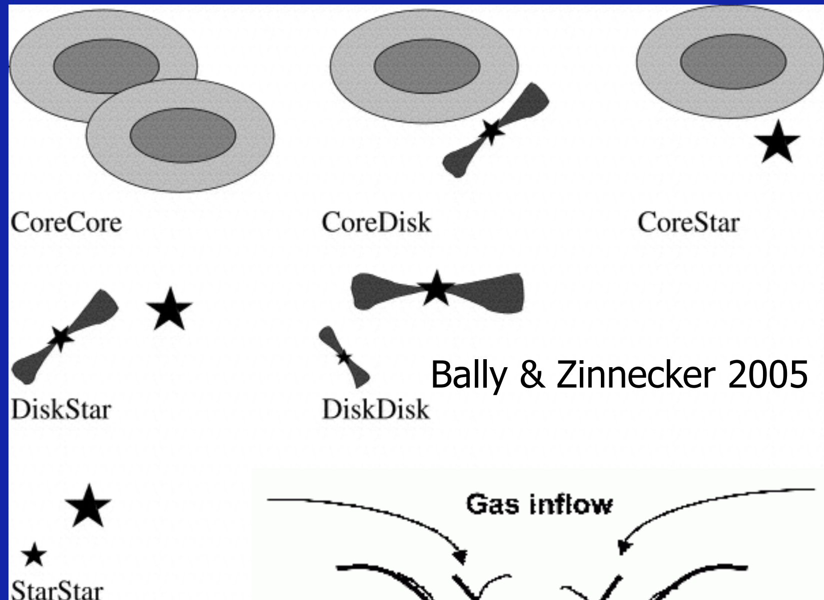
- Outflows and Jets
- UV-radiation
- Supernovae
- The majority of all stars form in clusters, massive stars exclusively.
- They produce all heavy elements
- Only star formation at high-Z that is observable.

Massive Star Formation



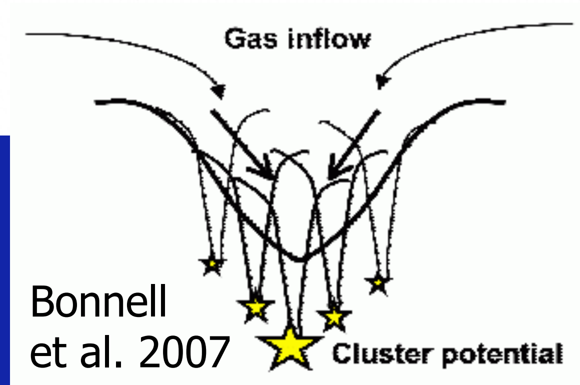
Pudritz & Banerjee 2005

<u>Modified classical scenario:</u>
Wolfire & Cassinelli 1987
Jijina & Adams 1996
Yorke & Sonnhalter 2002
Norberg & Maeder 2002
Keto 2002, 2003
Krumholz et al. 2005, 2006
Banerjee & Pudritz 2005



Bally & Zinnecker 2005

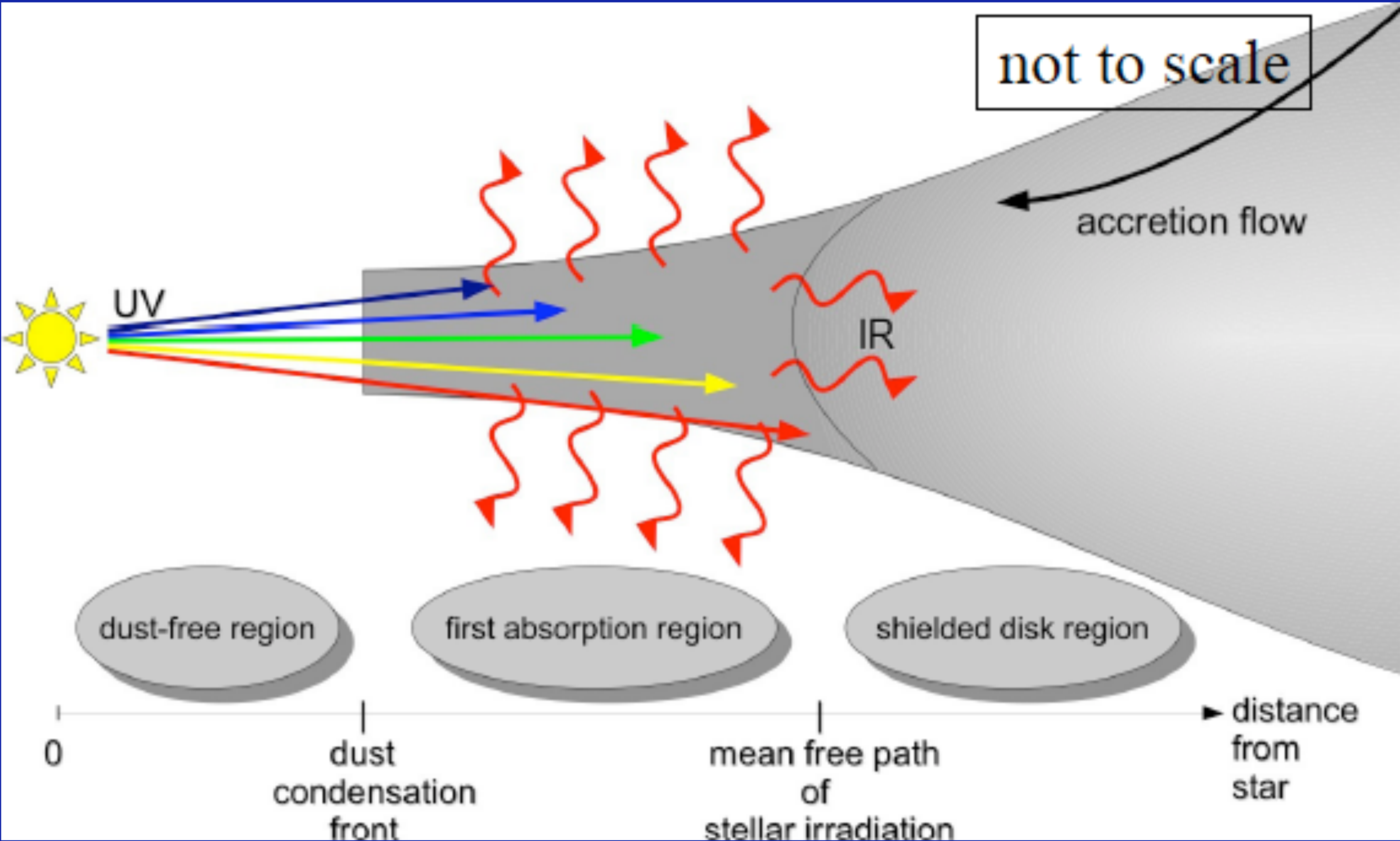
<u>Coalescence and competitive accretion scenario:</u>
Bonnell et al. 1998, 2004, 2004
Stahler et al. 2000
Bally & Zinnecker 2005



Bonnell et al. 2007

<u>How to differentiate between both scenario?</u>
- Molecular outflows and accretion disks
- Fragmentation and global collapse
- ...

Conceptual ideas



Courtesy of Rolf Kuiper

Results of early massive outflow research

Seem to be ubiquitous phenomena

Very massive and energetic

Seemingly less collimated than low-mass flows

Different entrainment scenarios proposed (deflection, winds...)

However, these results were based on small samples and poor angular resolution (between 21" and 60")

Shepherd et al. 1996a,b, Churchwell et al. 1997

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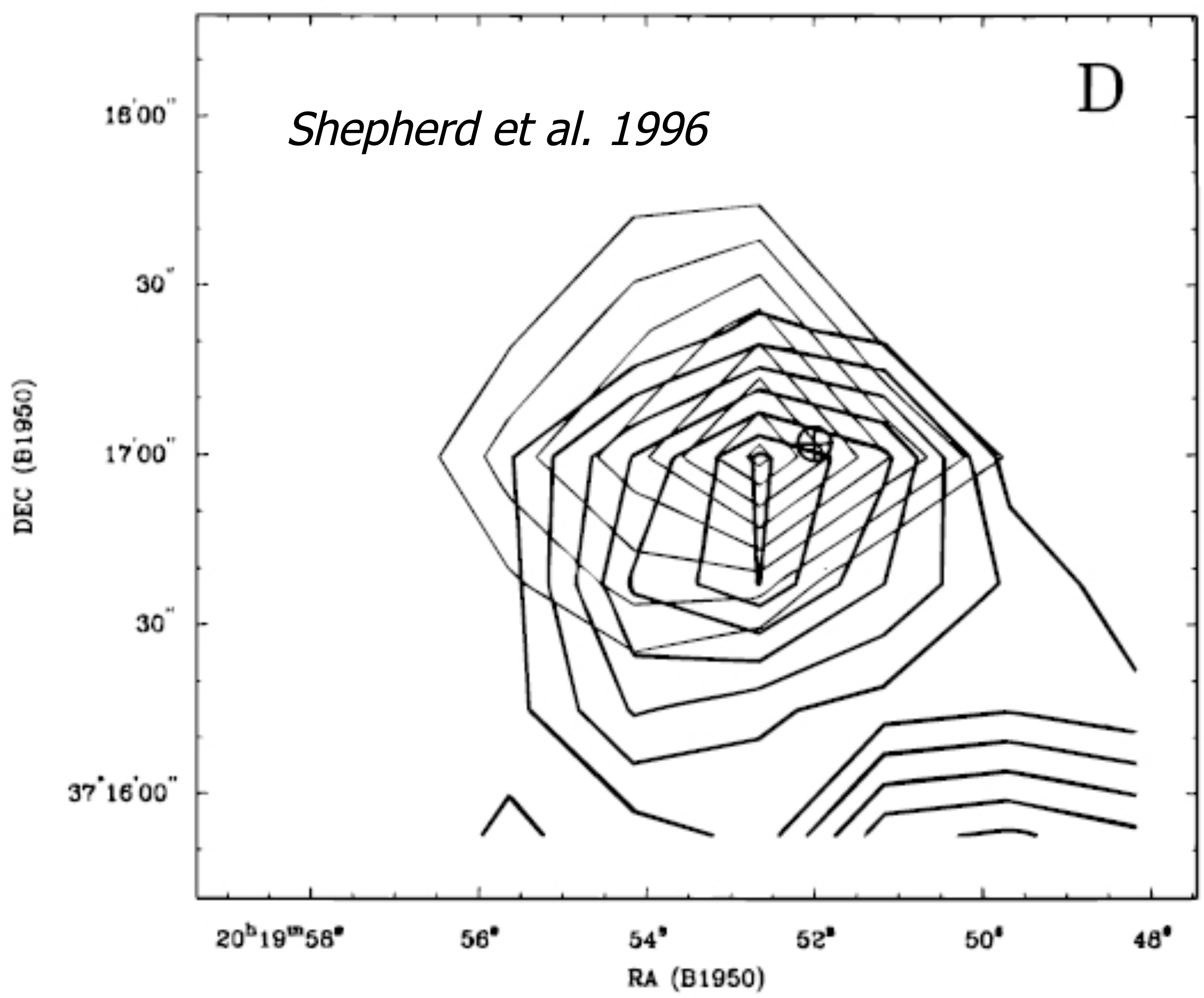

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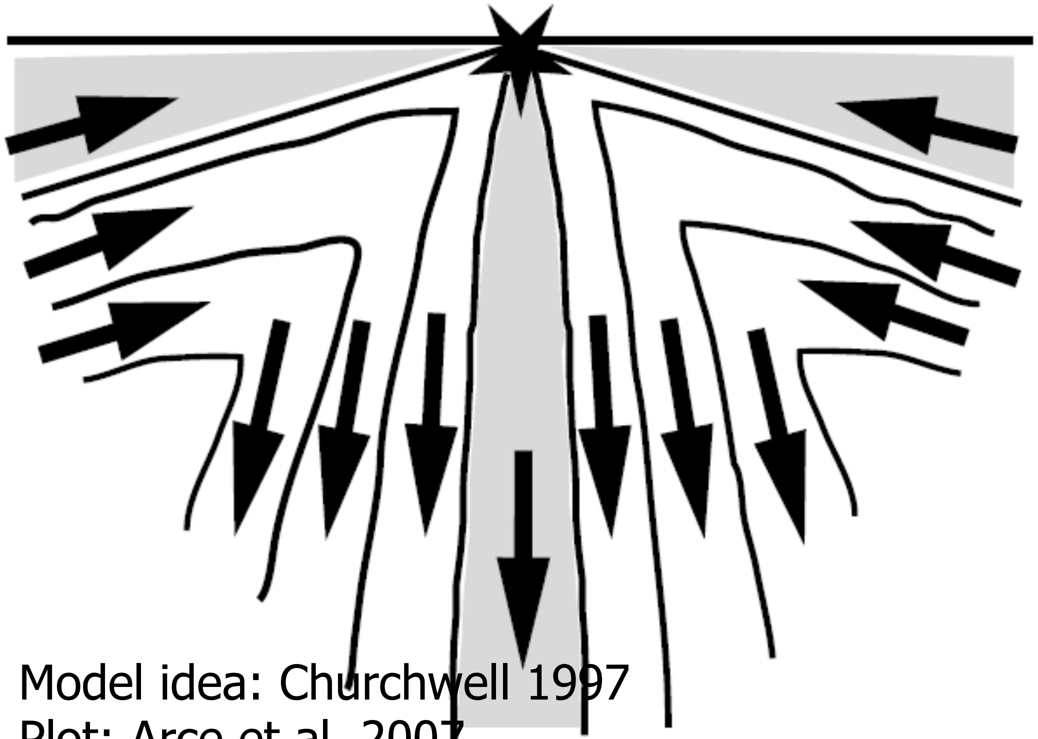

Model idea: Churchwell 1997
Plot: Arce et al. 2007

However, these results were based on small samples and poor angular resolution (between 21" and 60")

Shepherd et al. 1996a,b, Churchwell et al. 1997

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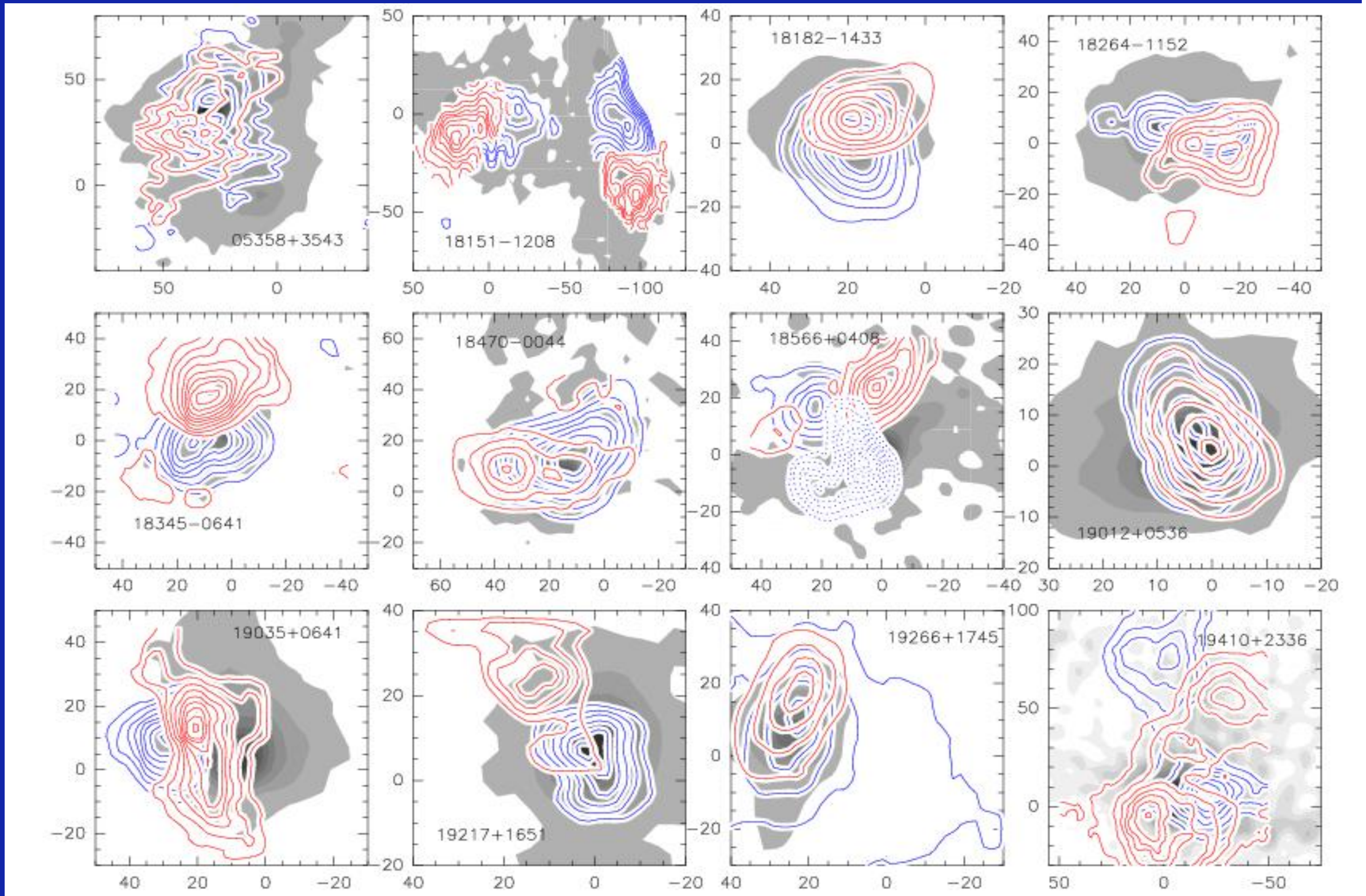
Massive molecular outflow maps

Grey: 1.2mm cont., Contours: CO(2-1)

IRAM 30m, Beam 11"

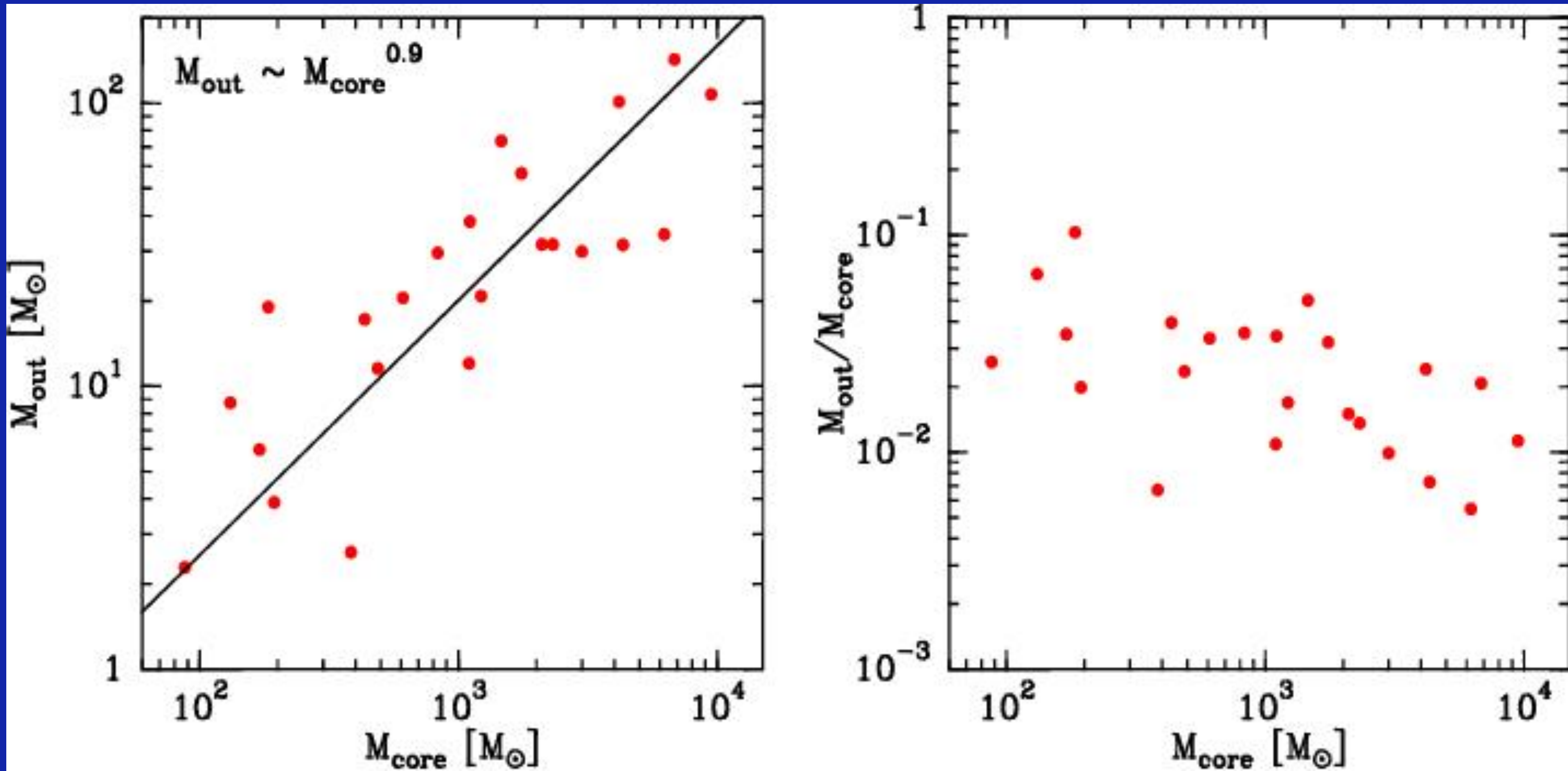


- Assuming momentum conservation: $p_{out} = M_{out}v_{out} = M_{jet}v_{jet} = dM_{jet}/dt\ v_{jet}t = p_{jet}$
- With a jet/outflow velocity ratio v_{jet}/v_{out}~20 and a ratio of jet-flow rate to the accretion rate of ~0.3, one can estimate accretion rates:

→ Mean accretion rate 10^{-4} M_{sun}/year
high enough to overcome radiation pressure

Beuther et al. 2002

Outflow masses versus core masses



Accretion rate: $\dot{M}_{acc} = f_{acc} M_{core}/t_{ff}$ deflection efficiency: $f_r = \dot{M}_{jet}/\dot{M}_{acc}$

Multiply both equations and assume momentum conservation

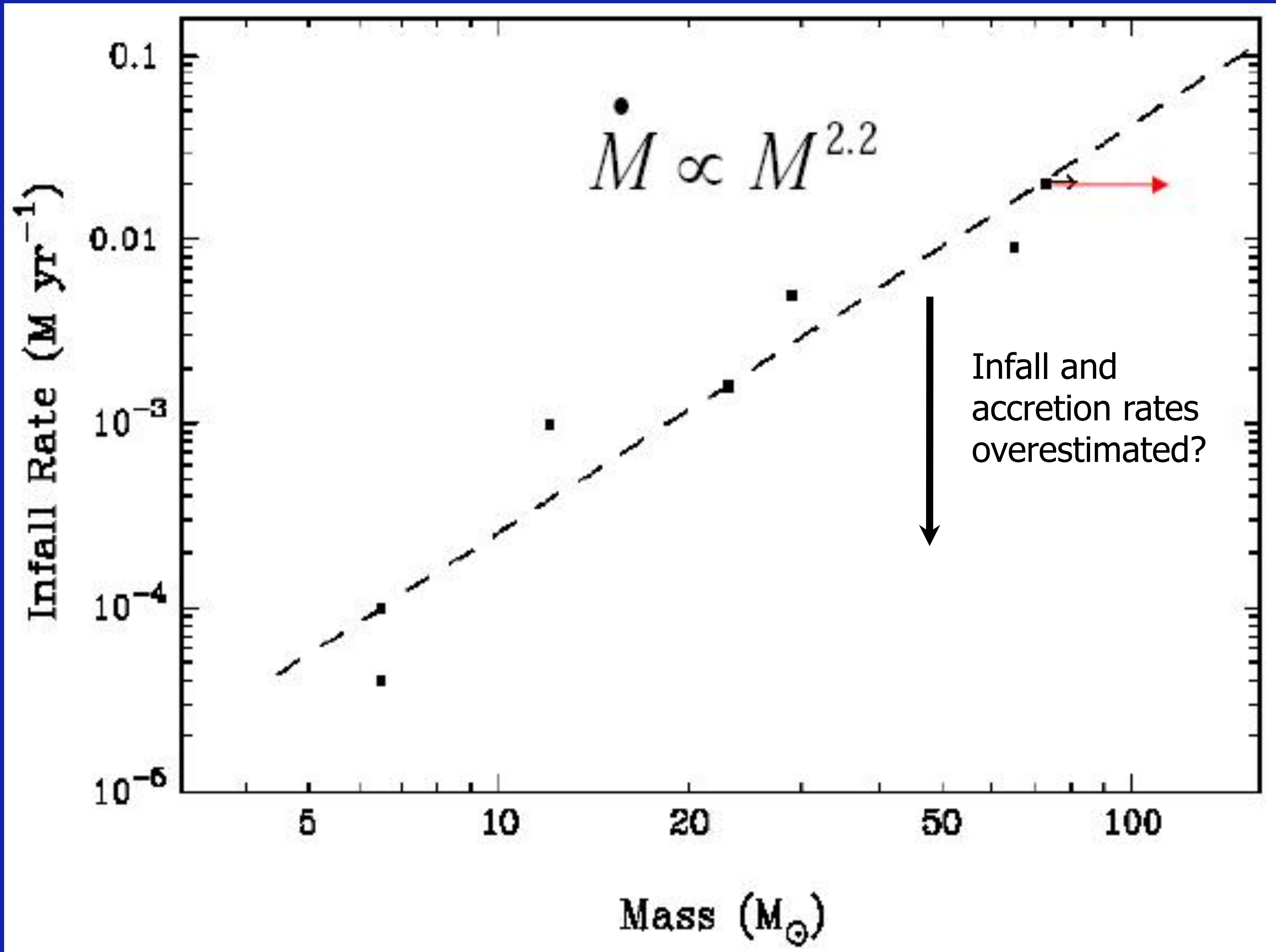
$f_r f_{acc} = M_{jet}/M_{core}$ (= v_{out}/v_{jet} x M_{out}/M_{core}) = constant → M_{jet} = constant x M_{core}

→ $\dot{M}_{acc}$ is approximately a linear function of M_{core}

(assuming that free-fall time t_{ff} and f_{acc} are approximately constant)

Beuther et al. 2002

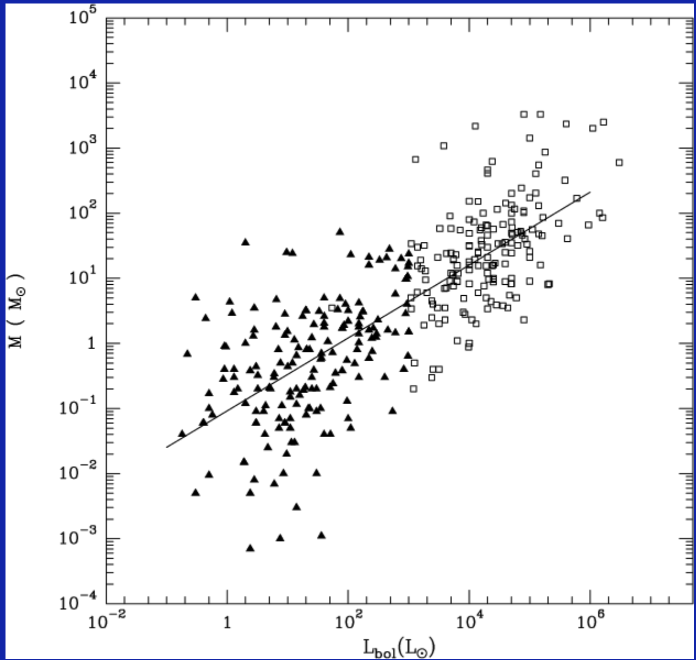
Accretion rates vs protostellar mass



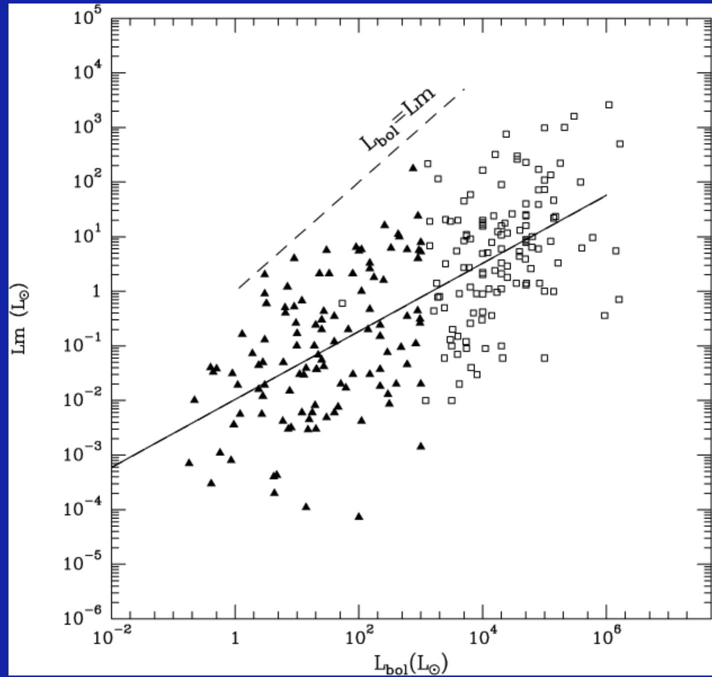
Zhang 2005

Outflow properties

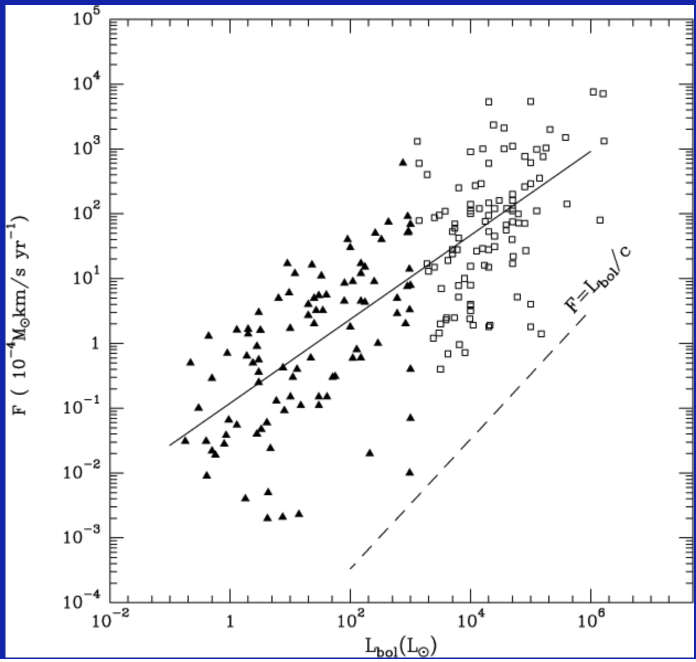
Mass



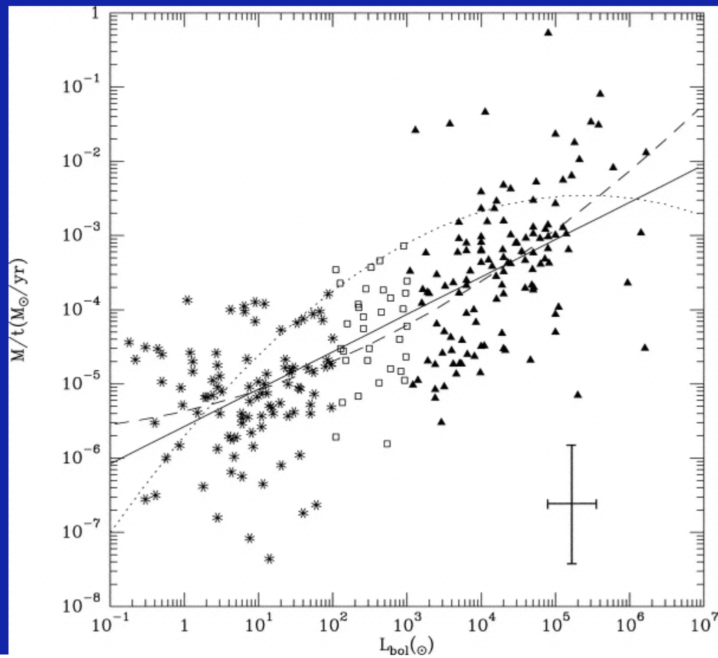
Mechanical L



Mechanical Force



Outflow rate



Wu et al. 2004, 2005

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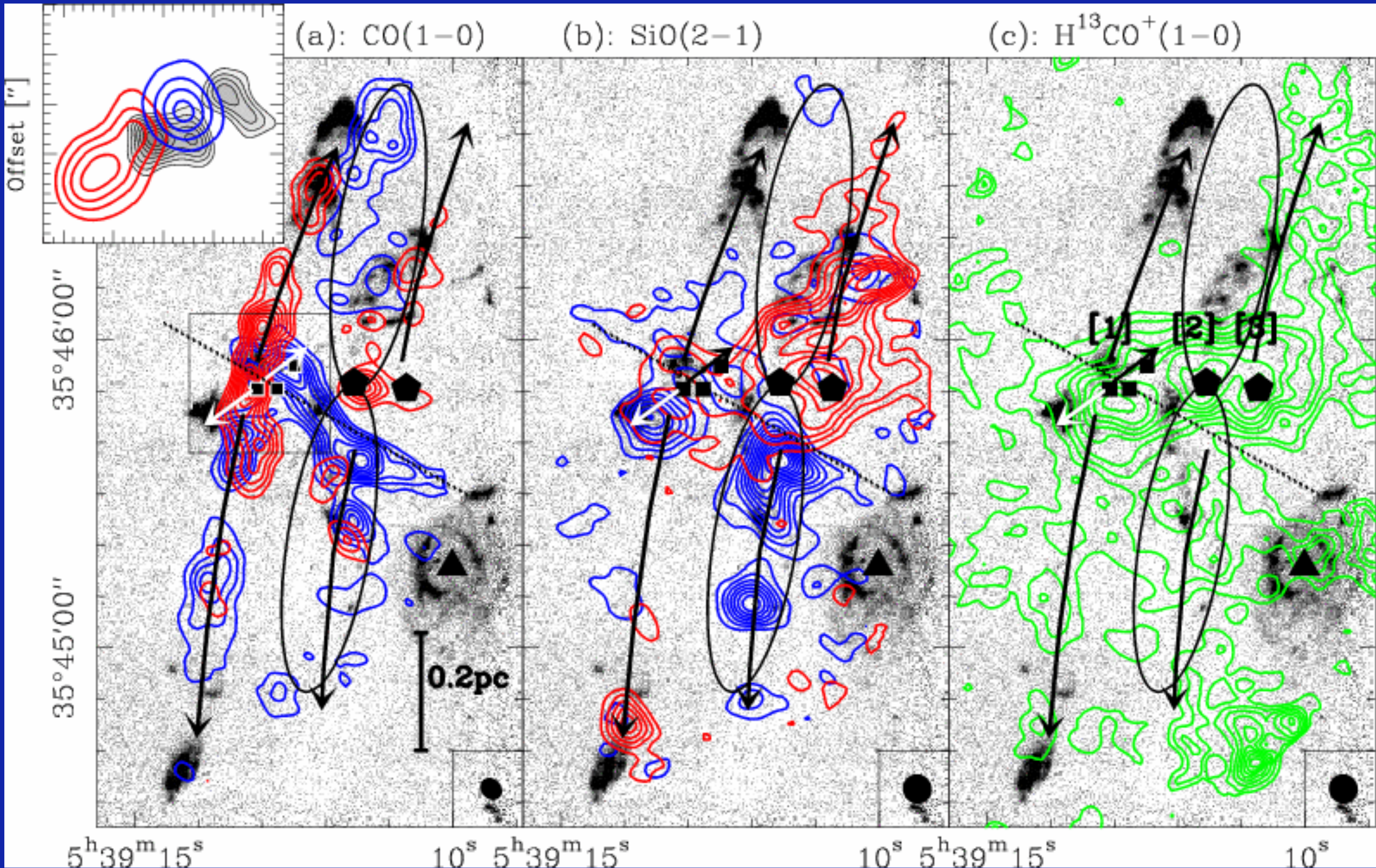
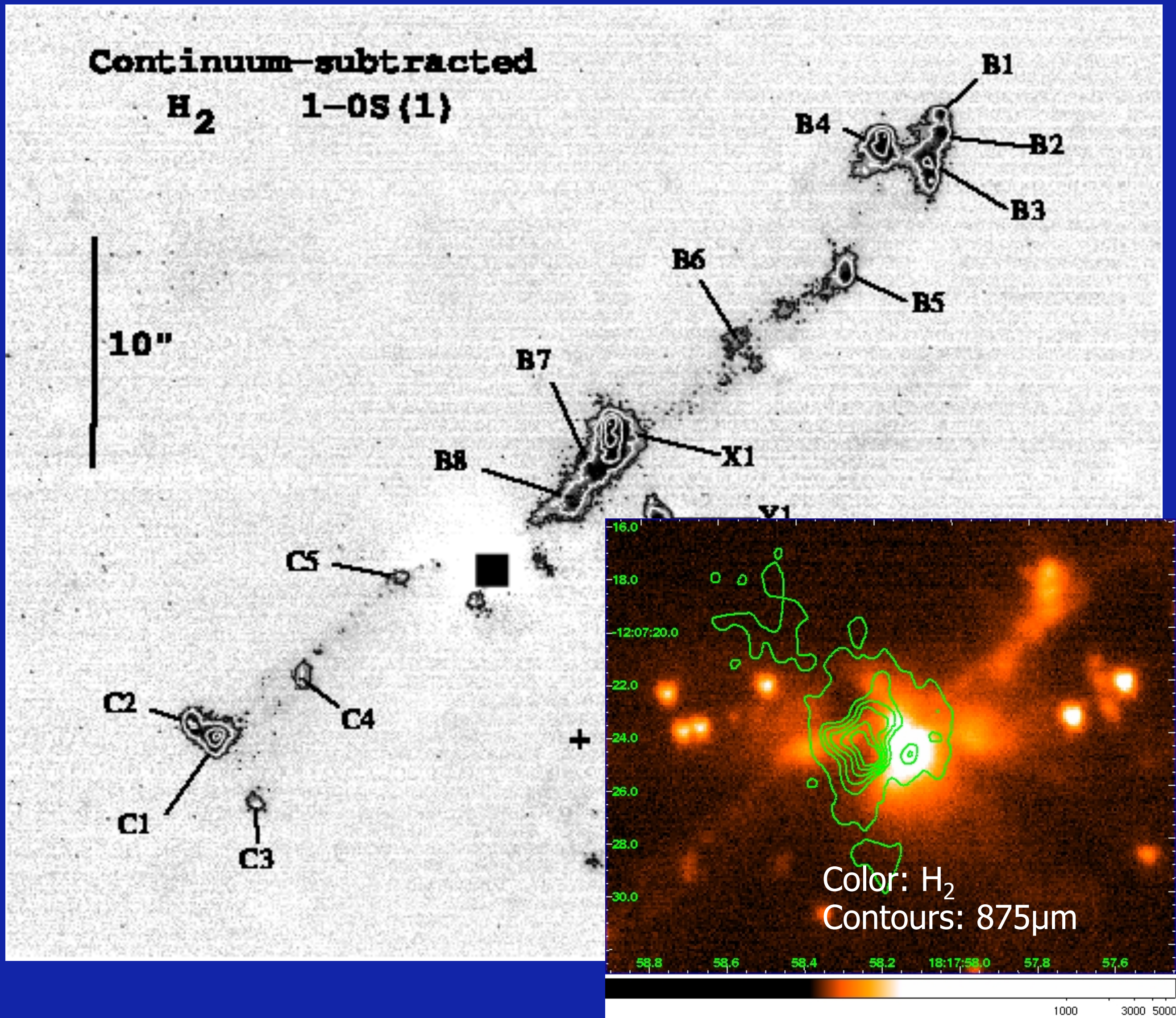
The pre-UCHII region IRAS05358+3543



L_{bol} ~ 6.3x10^3 L_{sun}; no cm emission → pre-UCHII region

Beuther et al. 2002

Shocked H_2 emission in IRAS 18151-1208

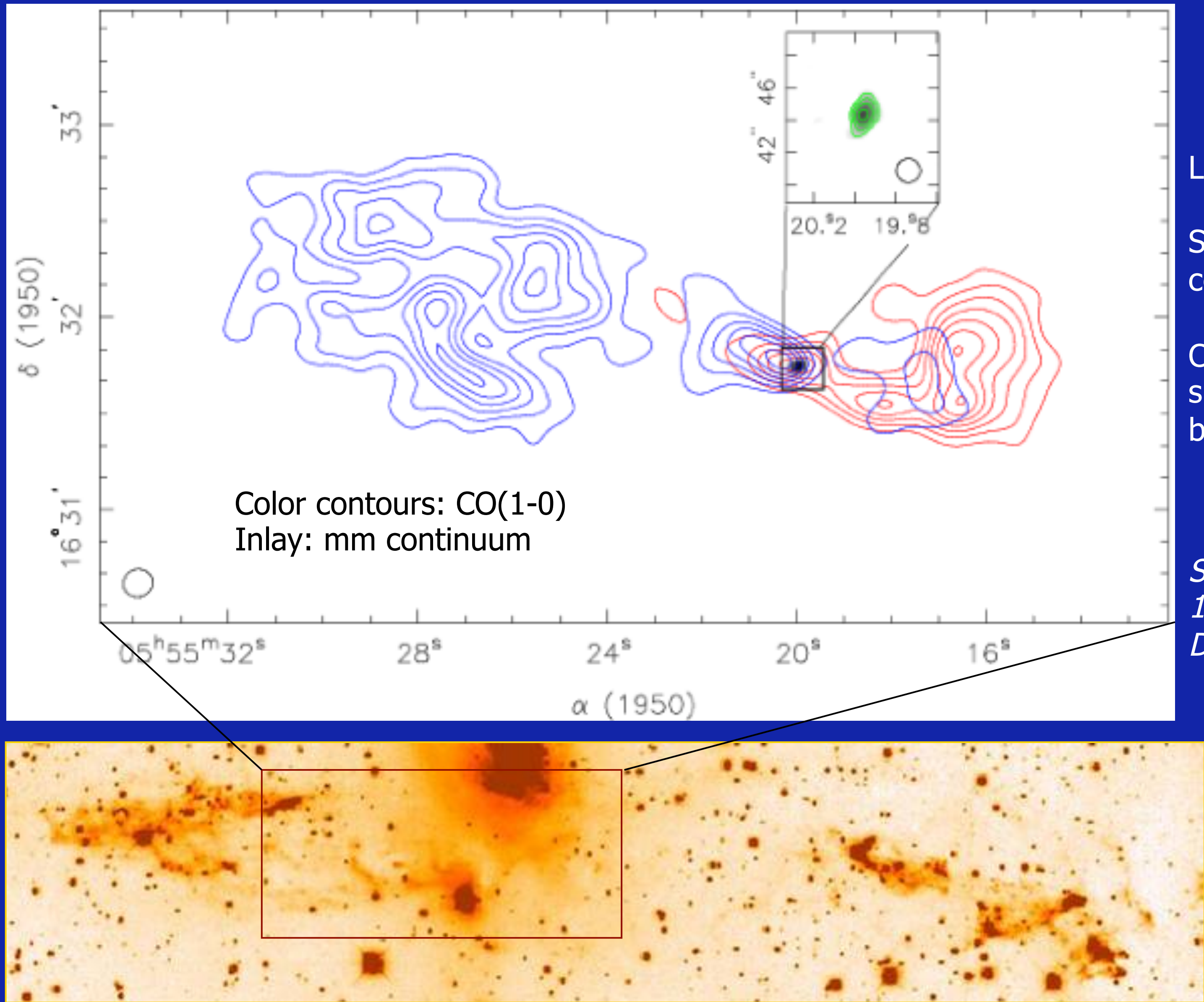


L_{bol} ~ $2x10^4$ L_{sun}
no cm emission
→pre-UCHII region

Spectroscopy of the H_2 features reveals similar characteristics to low-mass outflows

Davis et al. 2004, Fallscheer et al. 2011

A young UCHII region: G192



$L_{bol} \sim 3x10^3 L_{sun}$

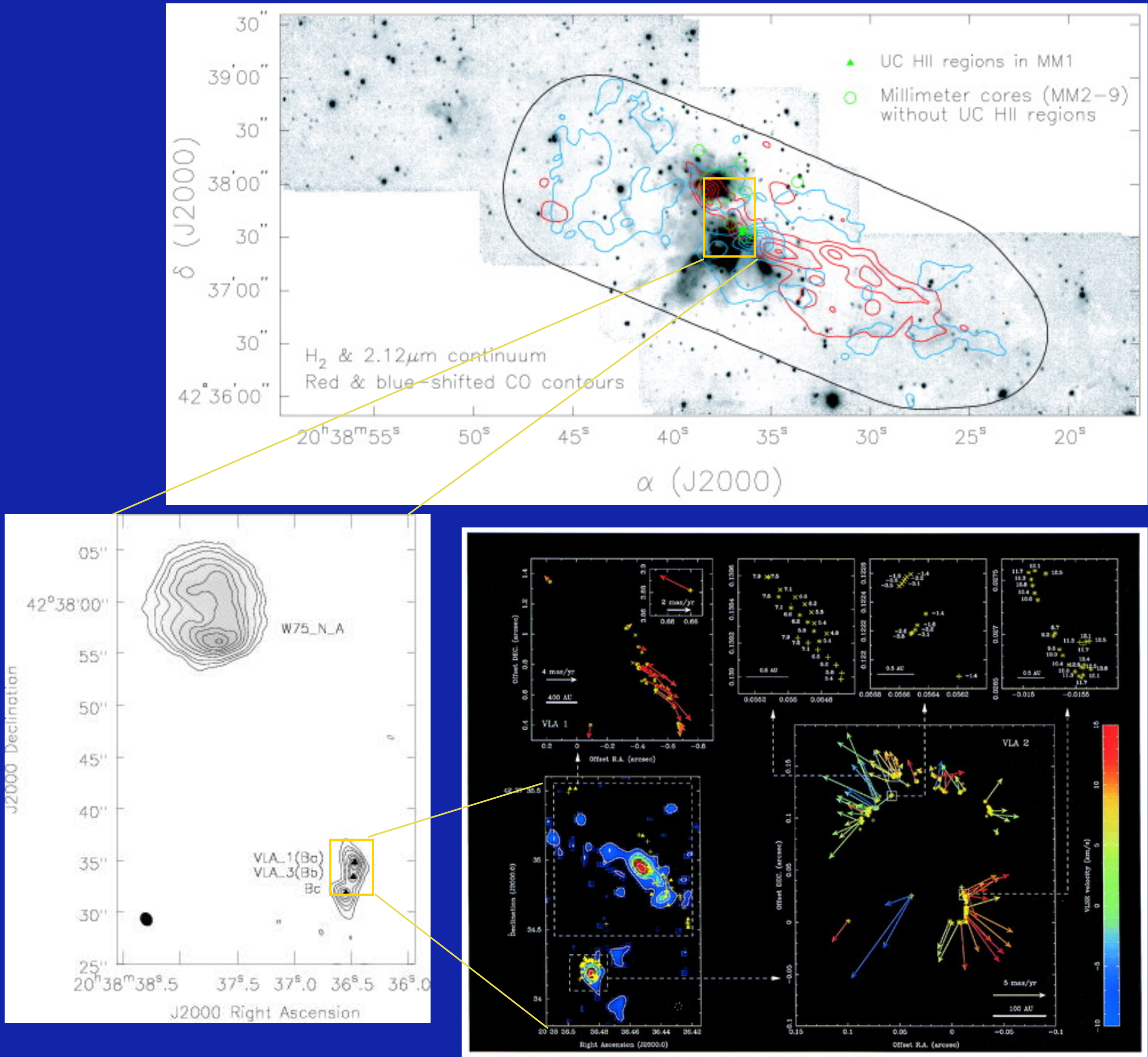
Small UCHII at center

Collimation consistent with wind-blown bubble

Shepherd et al. 1998, 1999
Devine et al. 1999

[SII]

The UCHII region W75



Cluster of B0.5 to B2 stars associated with UCHIIs

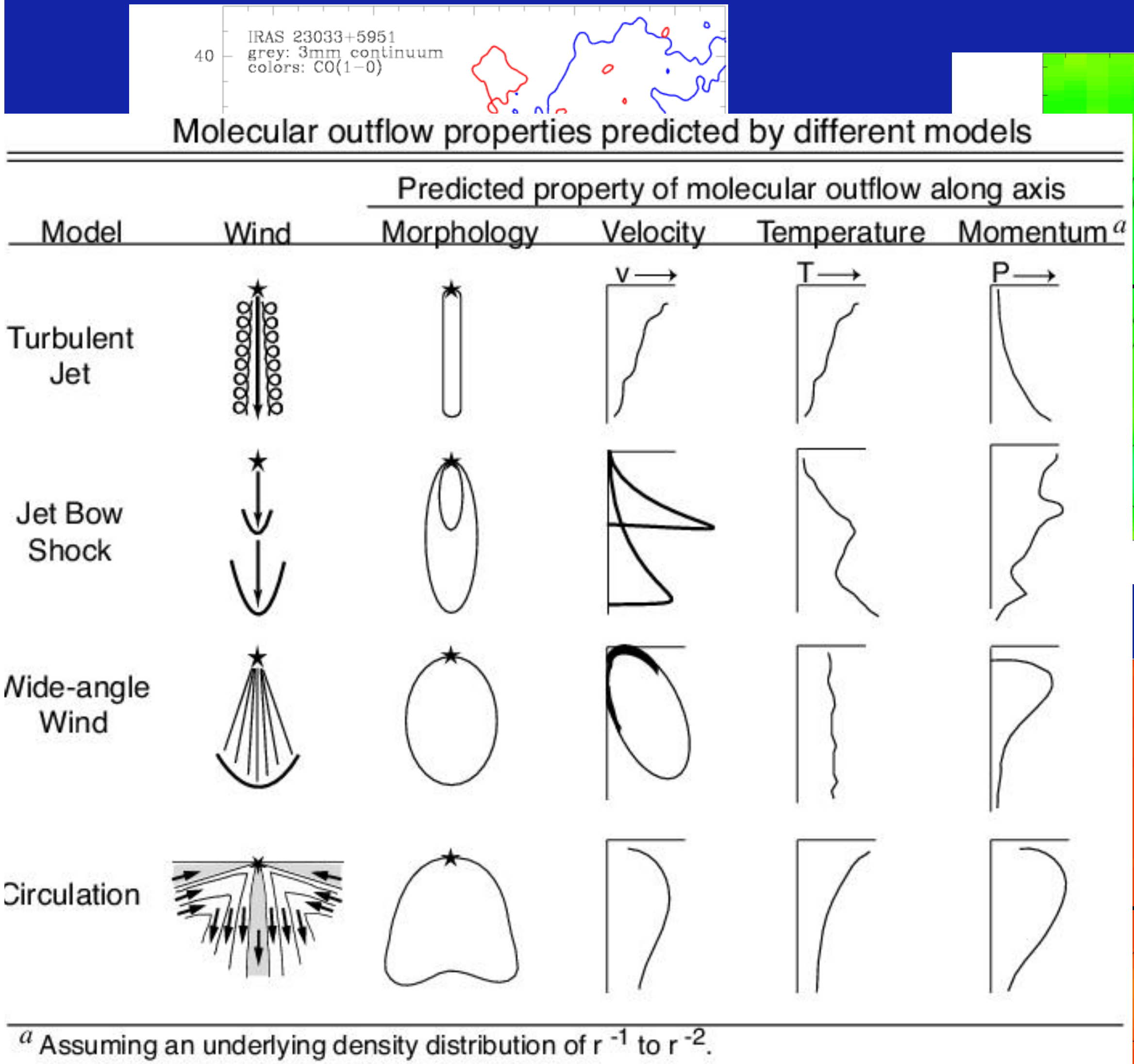
$L_{bol} \sim 4x10^4 L_{sun}$

Wide-angle large-scale outflow, is that associated with the small-scale maser outflows?

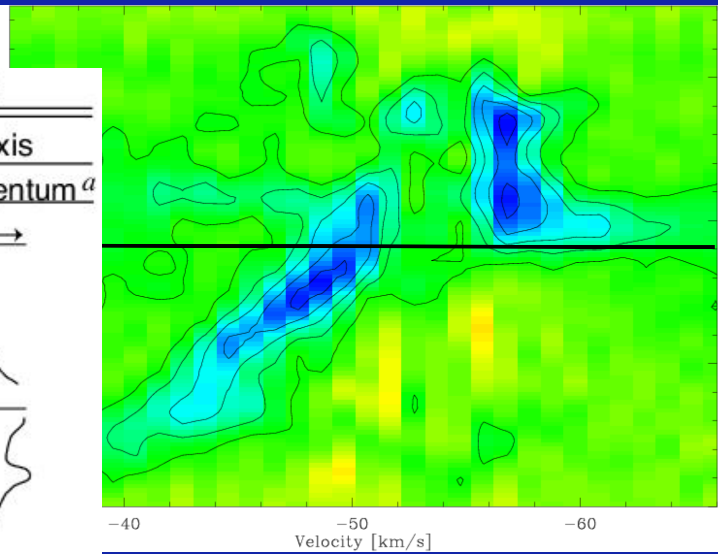
Shepherd et al. 2003, 2004

Torrelles et al. 2003

Position velocity diagrams



23033+5951



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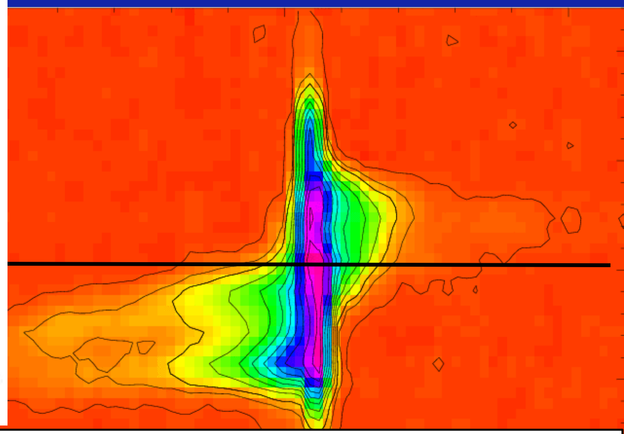
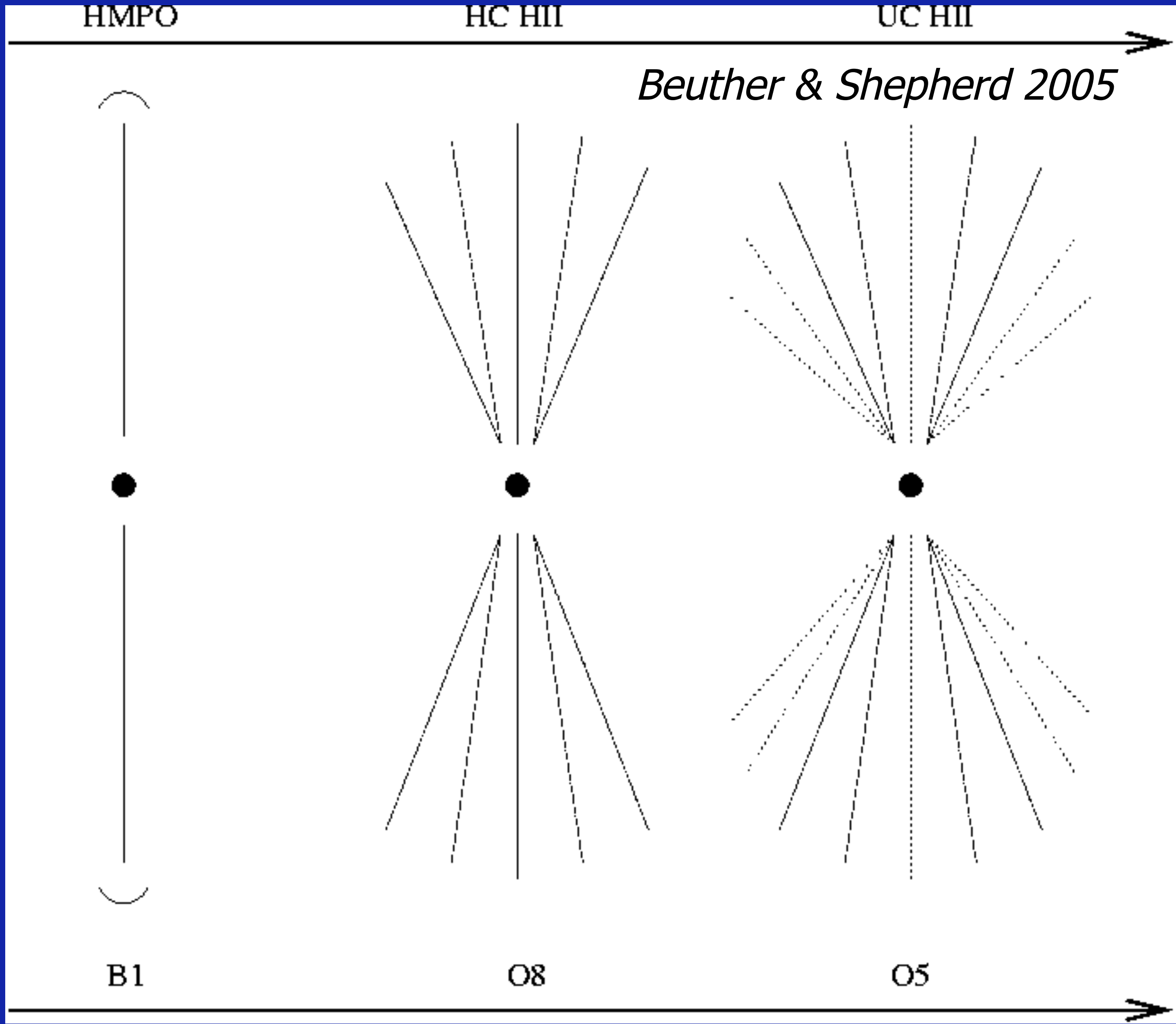


In principle, all pv-diagrams appear reproducable via jet-entrainment and/or wide-angle winds, similar to the low-mass outflows.

An evolutionary scenario



Possible reasons: Stellar wind, magnetic diffusivity, (ionized) radiation?

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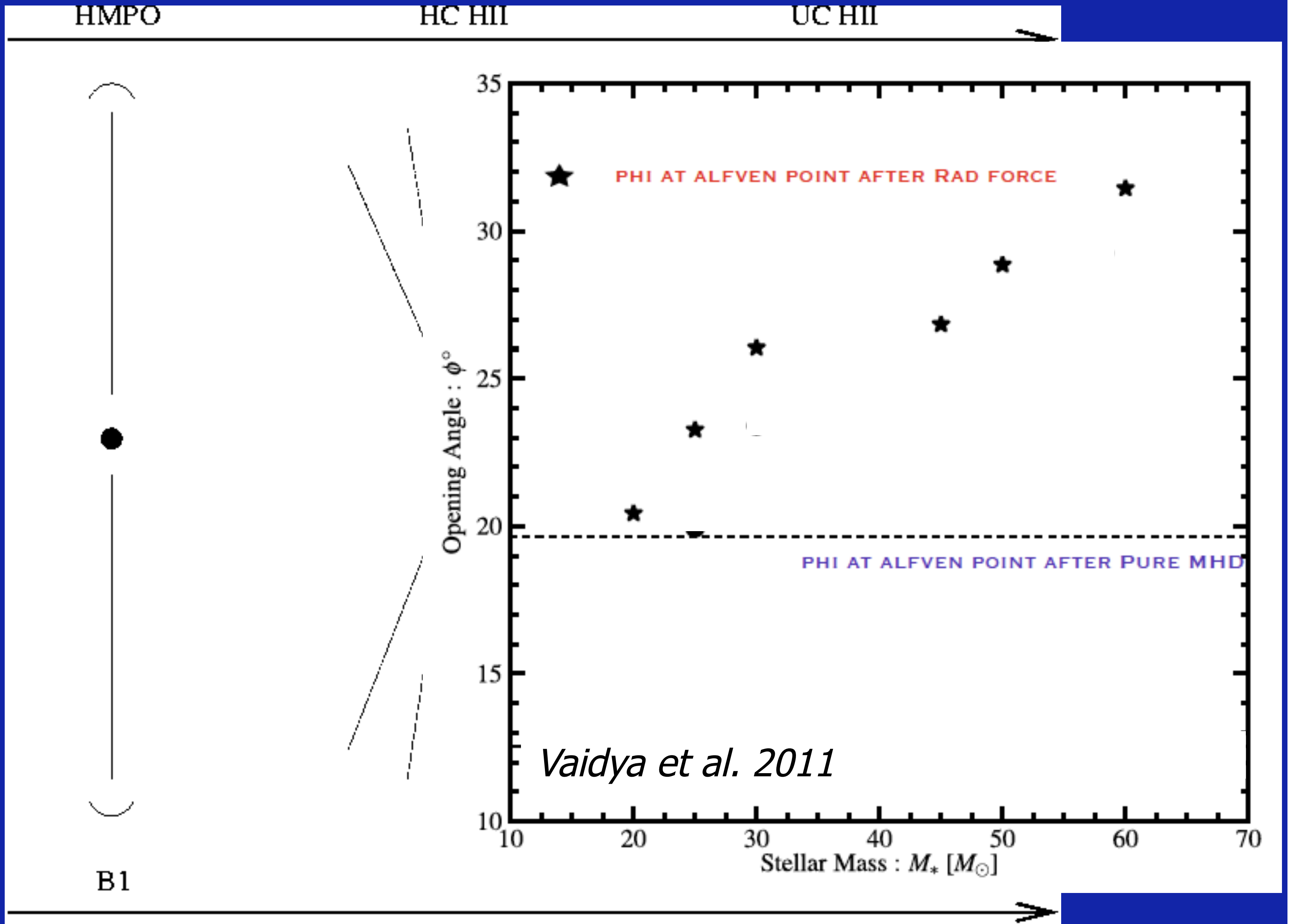

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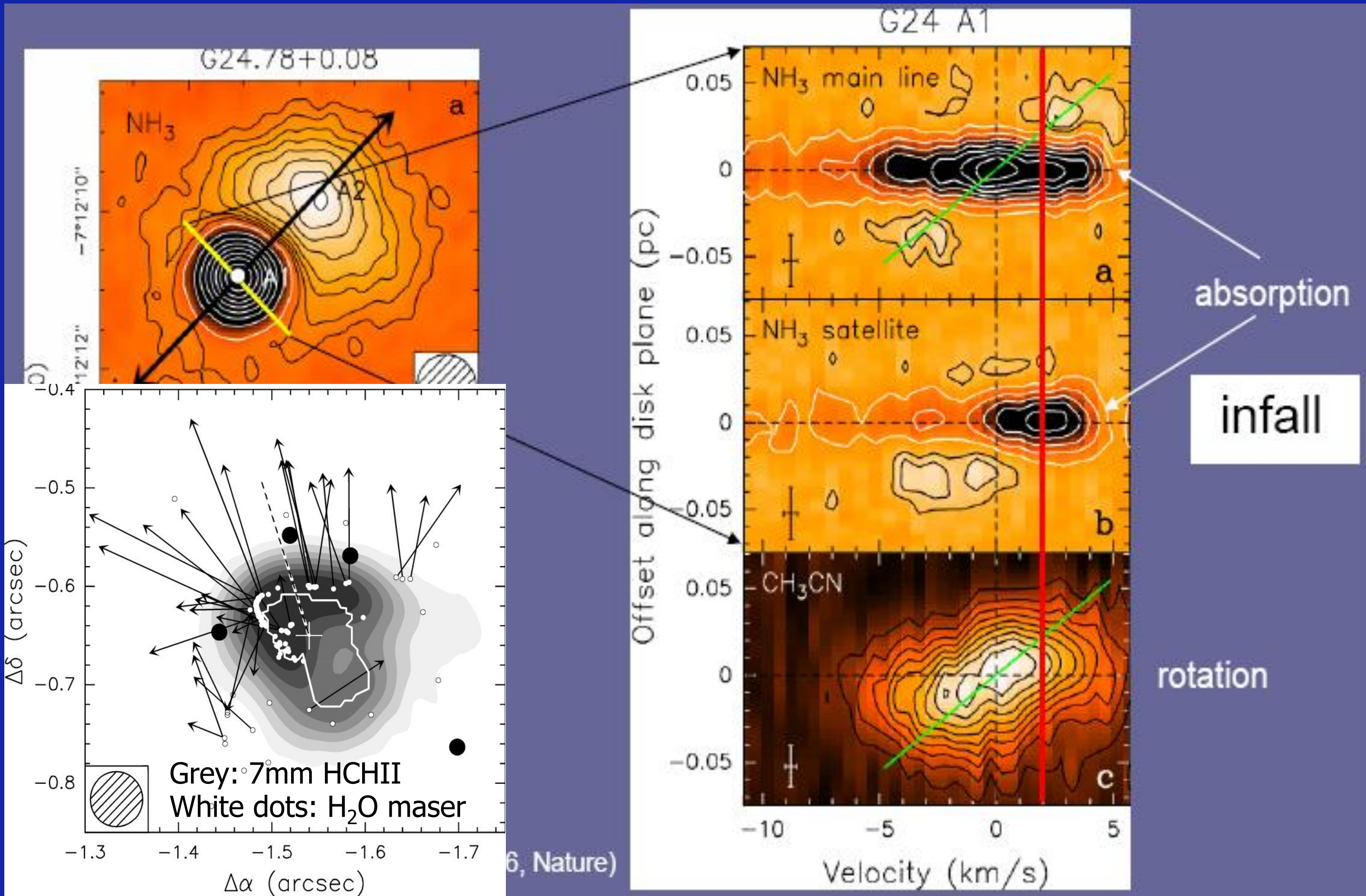
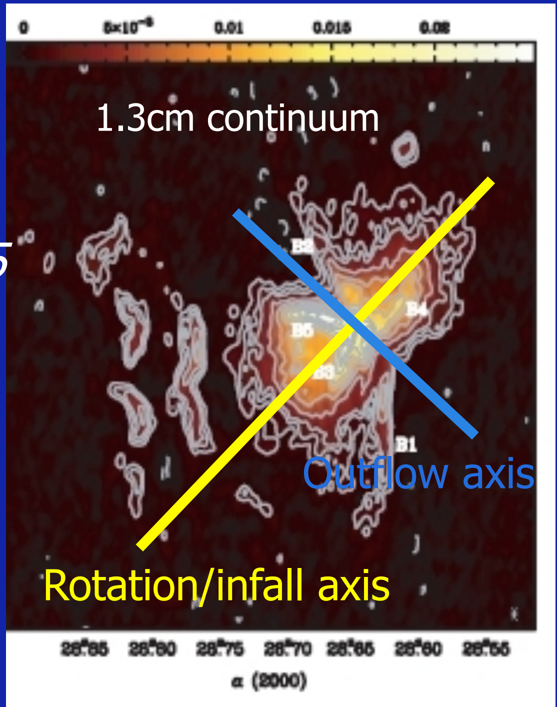
Rotation, Infall and Outflow motions

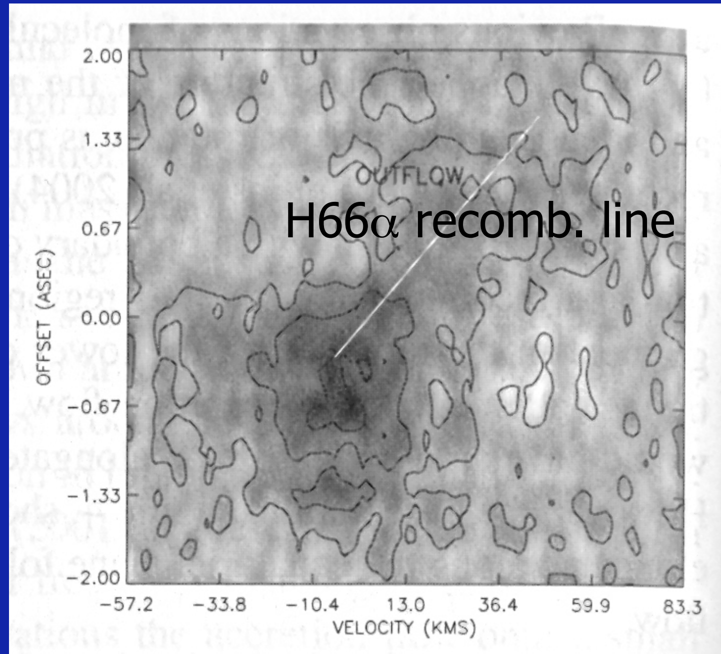


Beltran et al. 2006, 2007

The very luminous UCHII region G10.6-0.4

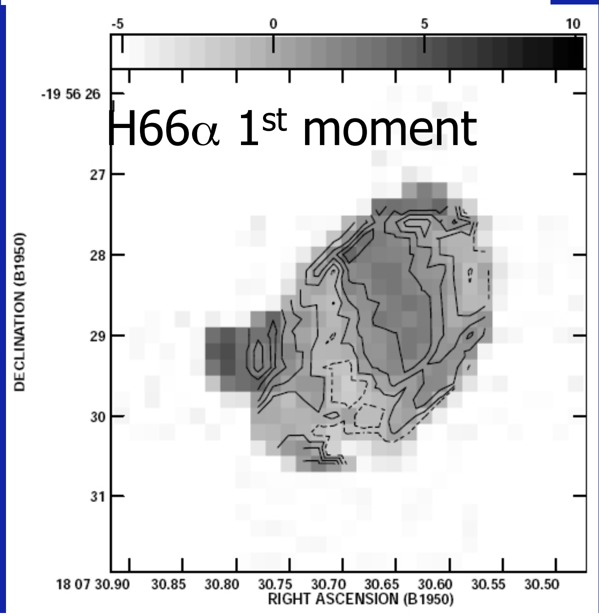
Keto 2002, 2005
Sollins et al. 2005

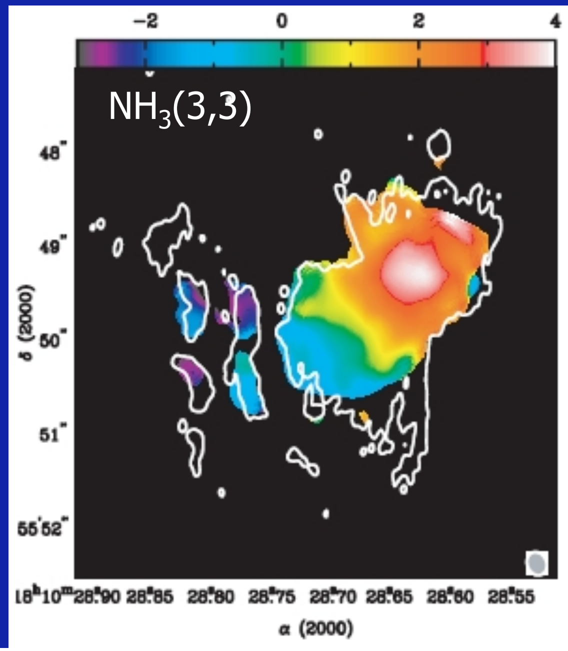




Infall in mol. and ionized gas.

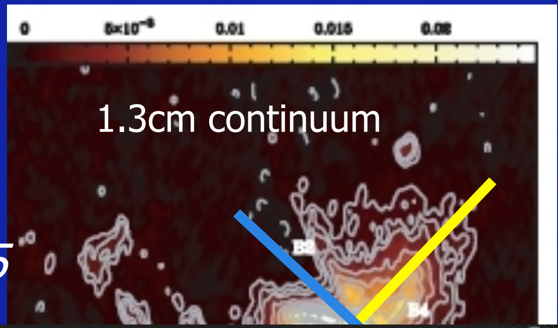
Outflow in ionized gas perpendicular.

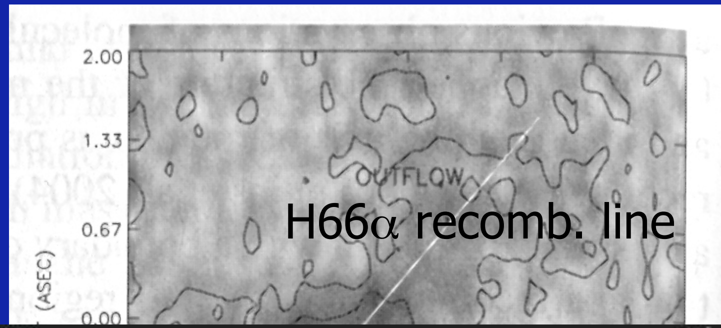


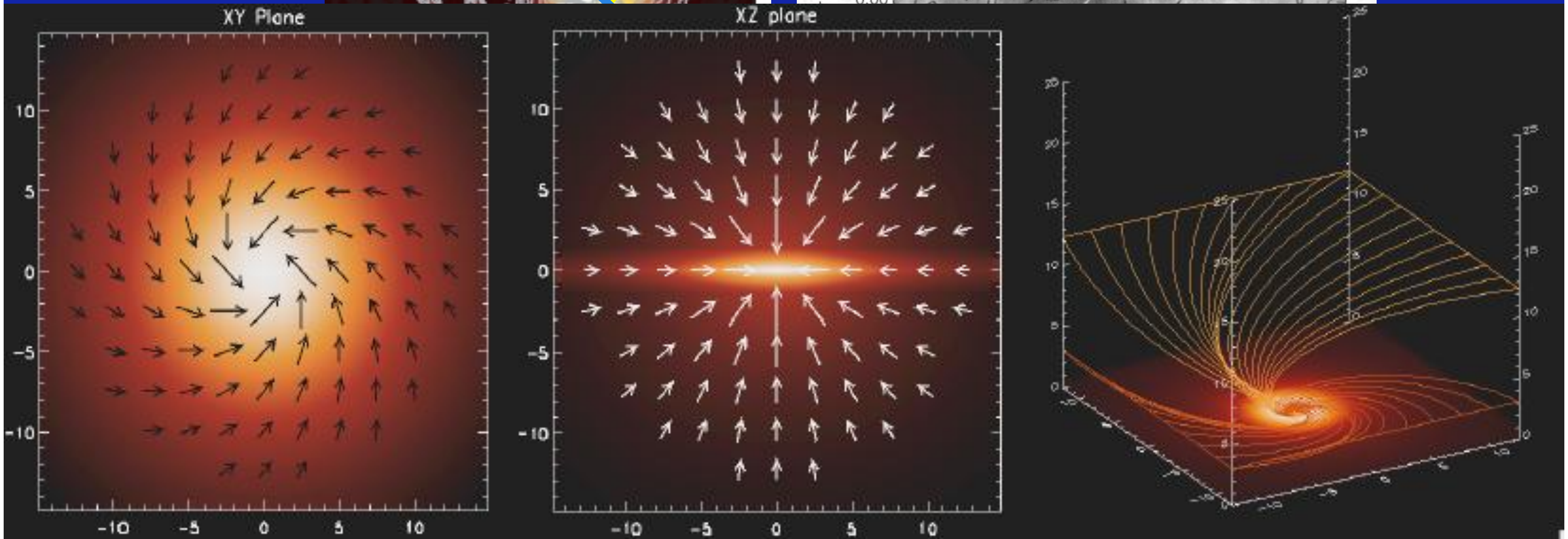


The very luminous UCHII region G10.6-0.4

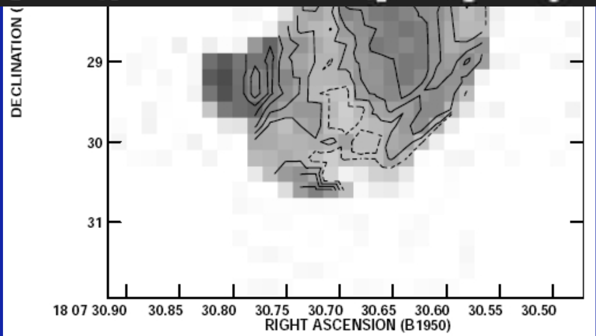
Keto 2002, 2005
Sollins et al. 2005

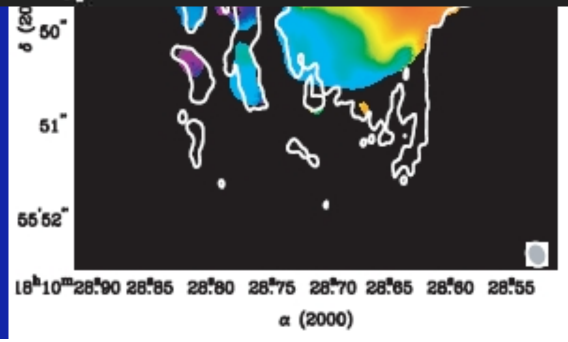






Outflow in ionized gas perpendicular.





Summary

Massive molecular outflows are ubiquitous phenomena.

Jet-like outflows exists at least up to early-B and late-O-type stars.

Like in low-mass star formation, some outflows are likely driven by jet-entrainment whereas others are consistent with wide-angle winds.

Estimated accretion rates are high enough to overcome radiation pressure.

Flashlight effect additional helps reducing radiation pressure in equatorial plane.

Hence the observations support the scenario that massive star formation proceeds similarly to low-mass star formation.

The observations suggests an evolutionary sequence.

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