MASSIVE MOLECULAR OUTFLOWS TOWARD 6.7 GHz METHANOL MASERS

By Eye and Machine Learning

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BACKGROUND: Outflows and 6.7 GHz Masers

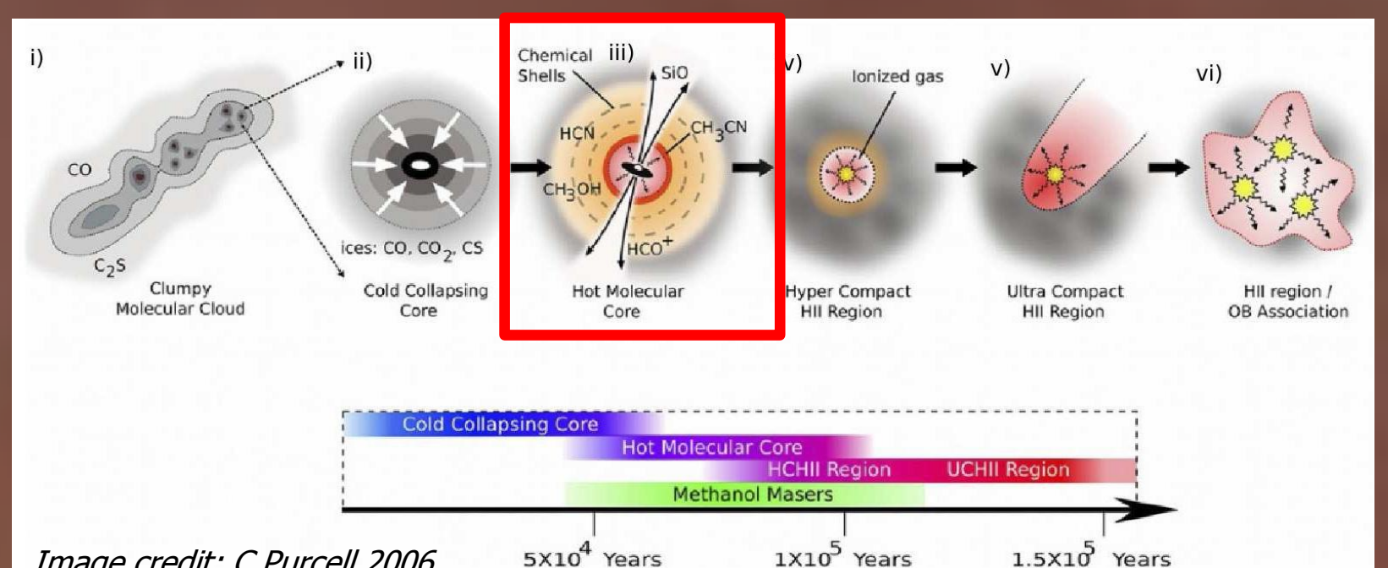


Image credit: C.Purcell,2006

Our current understanding of the evolutionary sequence of massive stars is shown on the right. Our study involves the Hot Core (HC) phase, age ~10^4-10^5 yr, prior to the UC HII region.

- High detection rates of outflows observed toward massive YSOs[1,2] (probable mechanism for removal of angular momentum[3,4] from accretion) → suggests formation via direct accretion like low mass stars.

- Many uncertainties remain which motivates studying outflows:
  ~ the association between outflows and their embedded driving sources in complex cluster environments[5]
  ~ the correlation between outflows' morphology, physical parameters and central source conditions[6].
  ~ the applicability of low-mass outflow theories to high mass scenarios[7].
- Advantage: outflows are large scale structures → much more visible than smaller YSOs → earliest observable signatures of star formation[5].

- 6.7 GHz methanol masers also detected[8,9] → uniquely associated with massive YSOs → important sign posts for YSOs in the HC phase[10,11].
- An association has been seen in the occurrence of methanol masers and outflows[8,9].
  Investigating such association contributes toward understanding details of HC phase, and on a bigger scale, the evolutionary time scale.

PHYSICAL PARAMETERS

- Target distances mainly obtained from Green[13] and Roman-Duval[15]. Unknown distances computed from the Galactic Rotation curve[16] using $C^{18}O$ peak velocity.

- Physical parameters calculated following the approach of Beuther[17], with corrections for use of ^{13}CO instead of ^{12}CO.
- Parameter averages - Table 1 (56 spectra, including sources with distance ambiguities and those with offsets from masers).
- Histograms showing comparisons with other authors[5,6,7,17] shown in Fig. 3 – all ambiguities and offset sources excluded.
- Results:

~ mass distribution similar between 100-300M_o but depleted for < 50M_o and heavier at >300M_o.
~ dynamical time scales have similar distribution with unique sharp turn-over at $4x10^4$ yr.

Parameter	Average
Mass	240 M_o
Momentum	3.7×10^3 M_o km/s
Energy	6.9×10^{34} J
Dynamical time scale	1.4×10^5 yr
Outflow mass flux	23×10^{-4} M_o/yr
Mechanical force	$4x10^{-2}$ M_o km/s yr
Mechanical Luminosity	76 (L_o)

Table 1

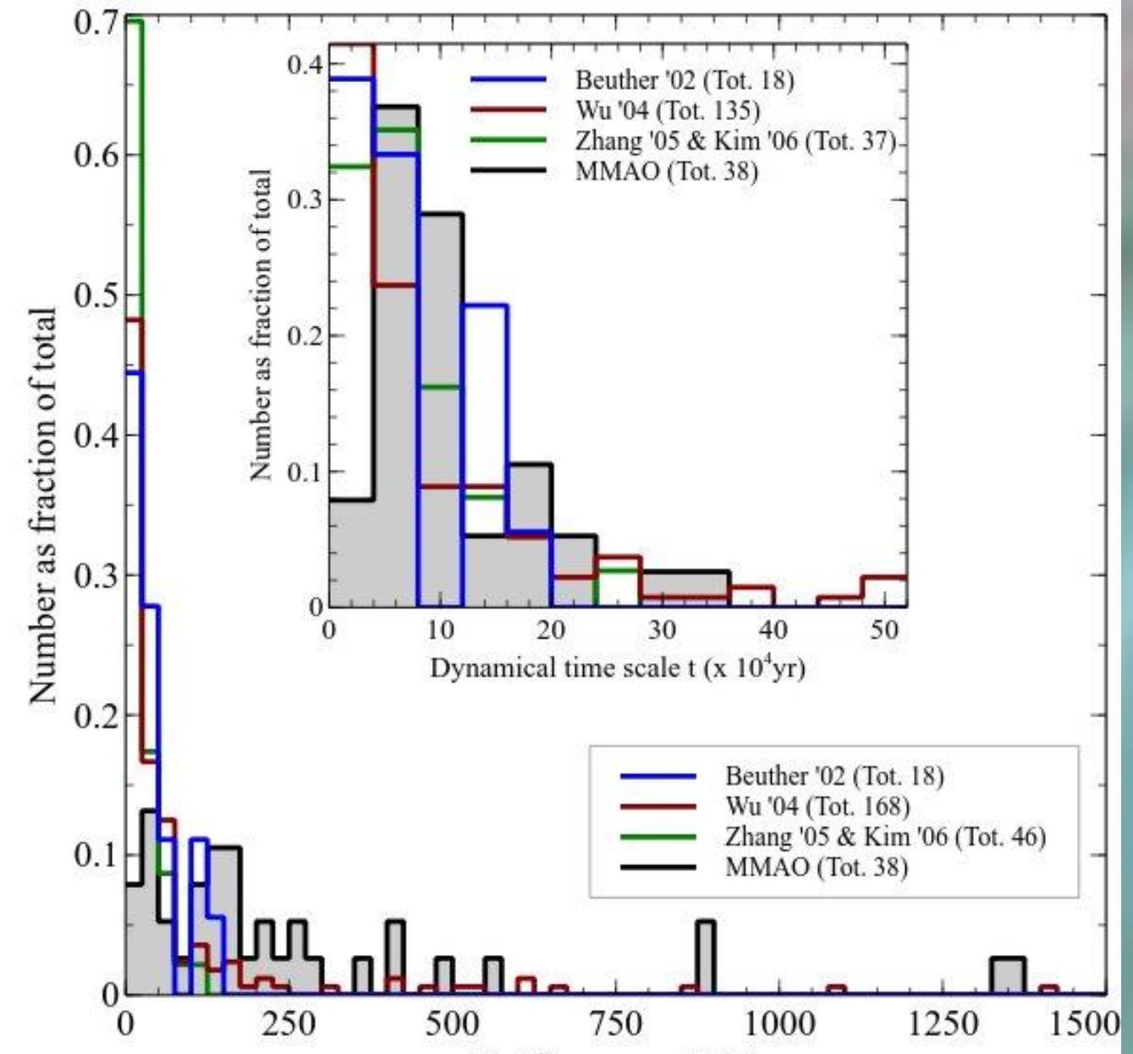


Fig .3: Comparisons of outflow mass and time scales with other surveys.

- Possible explanation:

Our data have a <u>selection bias</u>: every <u>flow</u> is associated with a 6.7 GHz <u>maser</u>. Both distributions suggest our <u>population is older</u> than the unbiased surveys of others.
Seems as if outflows associated with these masers are slightly more evolved[18].

Propose following time line of HC phase as opposed to Codella[19] :

Outflow on Maser off

Outflow on Maser on (sufficient methanol)

Outflow on Maser off

Outflow off Maser off (UCHII region)

OUTFLOW-MASER RELATIONS

- No strong correlation between L_{out} and L_{maser} exist but we flagged targets according to their L_{bol} range (Fig. 6) and saw:
  brighter maser and outflow luminosities → show association with brighter cores.
- Significant positive relation exists between L_{maser} and M_{core}.

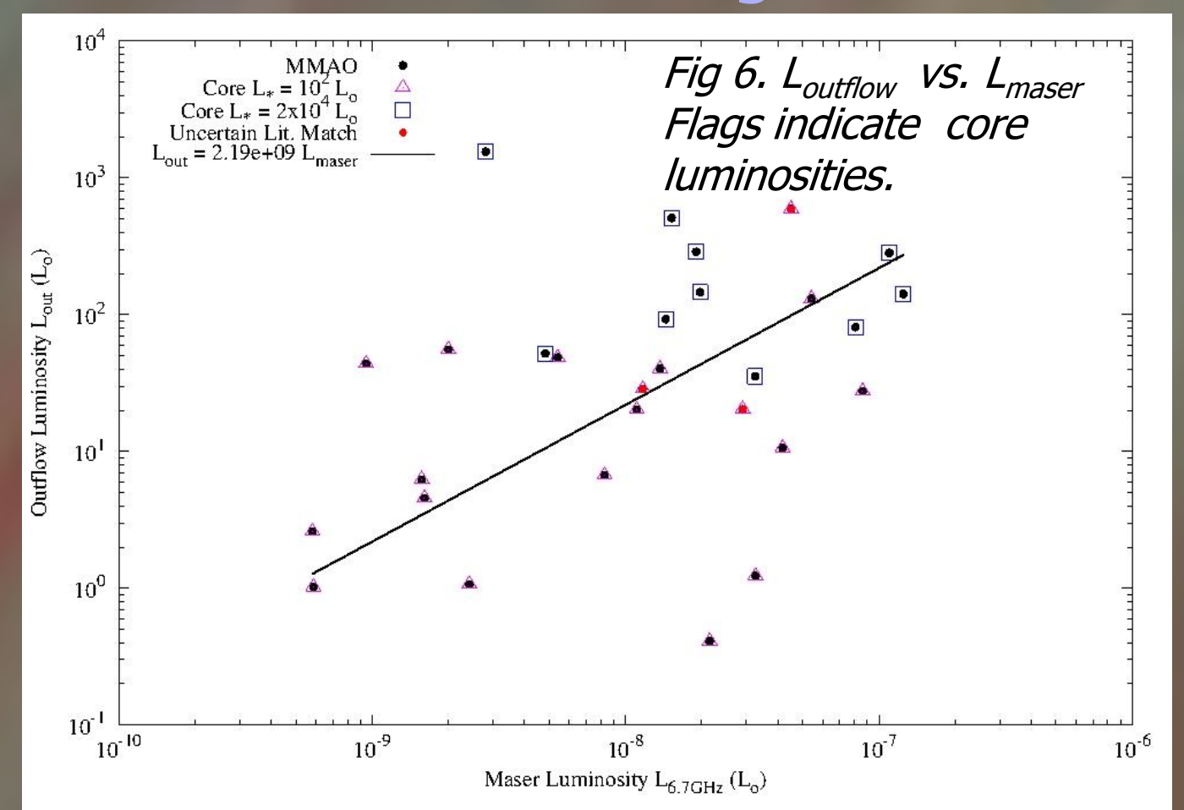


Fig 6. $L_{outflow}$ vs. L_{maser} Flags indicate core luminosities.

Above results agree with suggestion that the <u>mass</u> and <u>brightness</u> of a <u>massive YSO</u> has an effect on the <u>luminosity</u> of the <u>outflow</u> it generates, as well as the <u>maser</u> it pumps.

Appears as if

pumping source of maser = driving source of outflow → supports the theory that massive stars form via direct accretion with a single star powering its outflow.

REFERENCES

1. Shepherd, et al., ApJ, 472, 225.
2. Xu, Y., et al. 2006, AJ, 132, 20.
3. Klaassen, P.D., 2007, ApJ 663:1092.
4. Snell, R.L. et al., 1980, ApJ 239, L17.
5. Zhang, Q. et al., 2005, ApJ, 625, 864.
6. Kim, K.T. & Kurtz, S. E. 2006, ApJ, 643, 978.
7. Wu, Y. et al., 2004, A&AS, 426, 503.
8. Walsh, A. J. et al., 1998, MNRAS 301, 640.
9. Minier, V., 2005, A&AS 429, 945.
10. Menten, K.M., 1991, ApJ 380, L75.
11. Minier, V., 2003, et al. VizieR Online Data Catalog, 3403, 31095.
12. Pestalozzi, M. R. et al.,. 2005, A&AS,432, 737.
13. Green, J. A. & McClure-Griffiths, N. M., 2011, MNRAS,417, 2500.
14. Williams, J. P. et al., 1994, ApJ, 428,693.
15. Roman-Duval, J. Et al., ApJ, 699, 1153.
16. Brand, J. & Blitz, L. 1993, A&AS, 275, 67.
17. Beuther, H. et al., 2004, ApJ 608:330.
18. Viti, S. et al., 2004, MNRAS, 354, 114.
19. Codella, C. 2004, A&AS 417, 615.
20. Churchwell, E. 1999, in NATO ASIC Proc. 540, 515.

OBSERVATIONS AND OUTFLOW DETECTIONS

- Observed ^{13}CO and $C^{18}O$ *p-p-v* maps toward a sample[12,13] of 70 6.7 GHz methanol masers between 20° < *l* < 33.8° with JCMT-HARP.
- Detect 58 ^{13}CO clumps (*Starlink ClumpFind*[14]); 47 were closely associated with the masers.

- Analysed associated spectra for Doppler broadened line wings.
  <u>**Criteria:**</u> (1) Up-scale $C^{18}O$ spectrum to ^{13}CO peak. (2) Fit a Gaussian to the $C^{18}O$ peak. (3) Subtract this Gaussian from ^{13}CO to get residue.
  Wings = points where (residual > 0) <u>and</u> (^{13}CO T_A > 3σ on noise).
- Wing detection frequency = 98% (Fig 1.).
- With wings' velocity ranges → create blue and red velocity integrated maps.
- Plotted blue and red maps as contours on the peak integrated ^{13}CO background (Fig 2.).

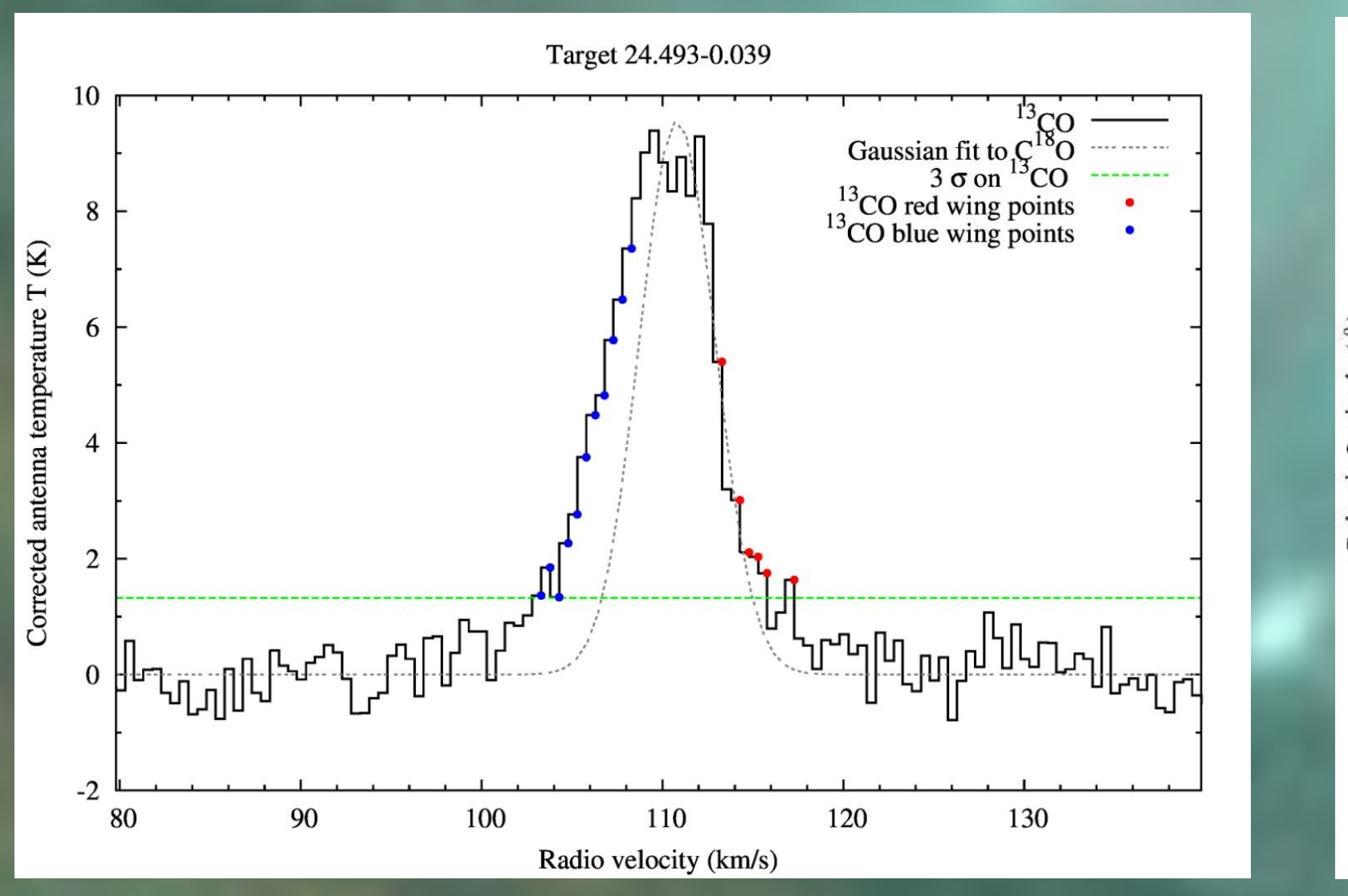


Fig. 1 : Wing selection criteria.

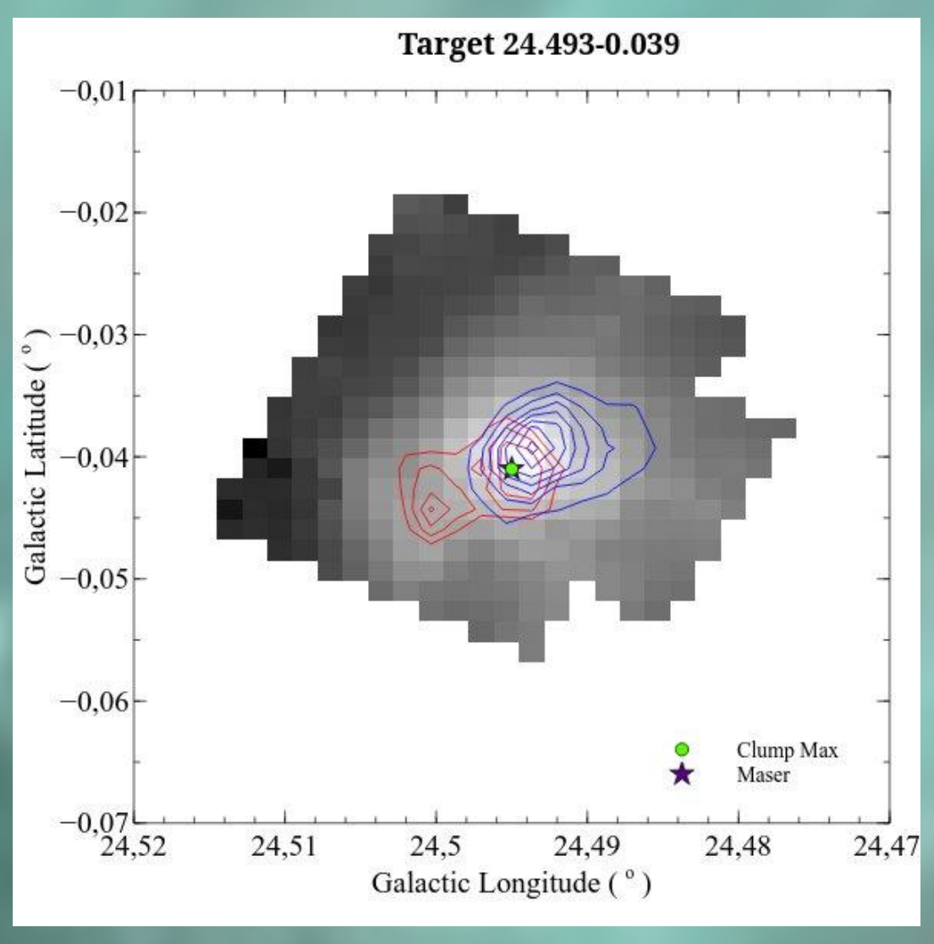


Fig. 2: Mapped red and blue contours, increasing in steps of 10% of peak int . until 90%

PARAMETER RELATIONS

- Calculated a mean accretion rate from our mean outflow mass flux[17]:
  $\dot{M}_{out} = 31 \times 10^{-4} M_{\odot}/yr$ leads to $M_{accr} \sim 10^{-3} M_{\odot}/yr$
  which is sufficient to overcome radiation pressure in direct accretion[20].
- A statistical significant relation exists between outflow and core masses (derived from $C^{18}O$) over three orders of magnitude with $M_{out} = 0.24\, M_{core}^{0.96}$ (Fig.4)
- Also a significant relation between F_{co} and M_{core} with $F_{CO} = 1.4 \times 10^{-4} M_{core}$
- Luminosity divisions from Shepherd[1] on a M_{out} vs t relation show that higher luminosity (hence more massive) YSO's entrain higher mass outflows (Fig.5, blue & red lines).

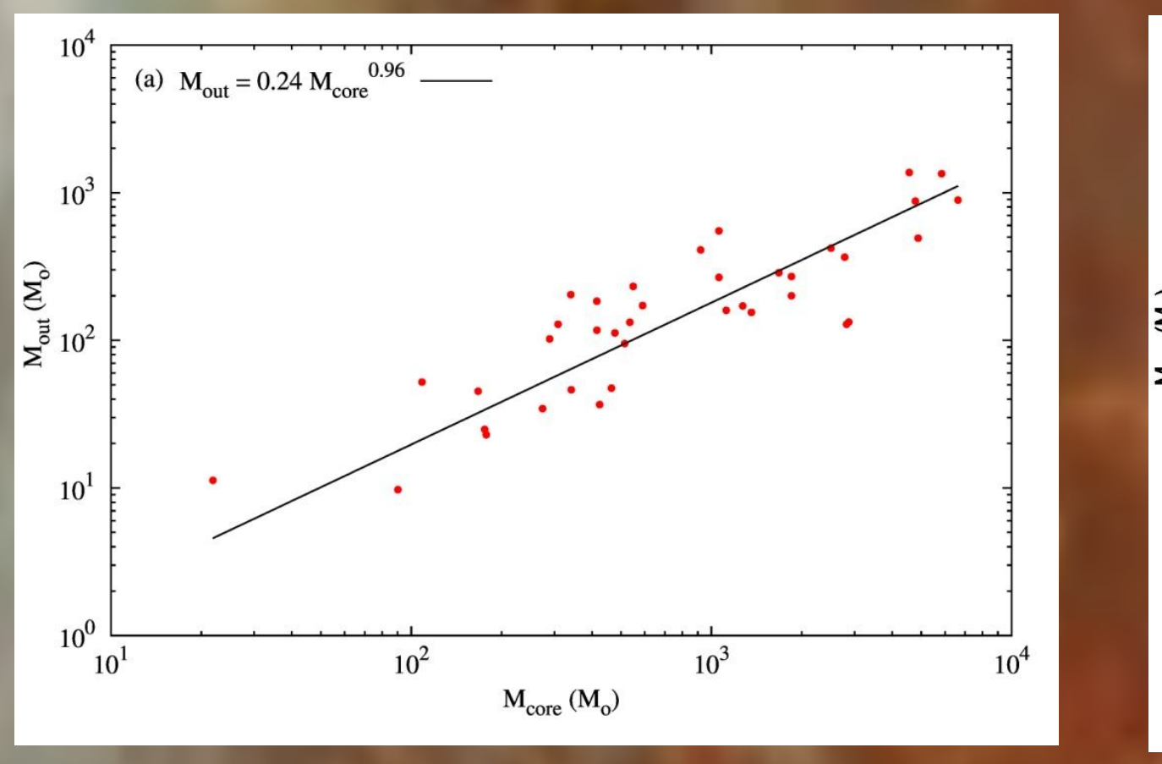


Fig. 4: Outflow vs. H_2 core masses as derived from $C^{18}O$.

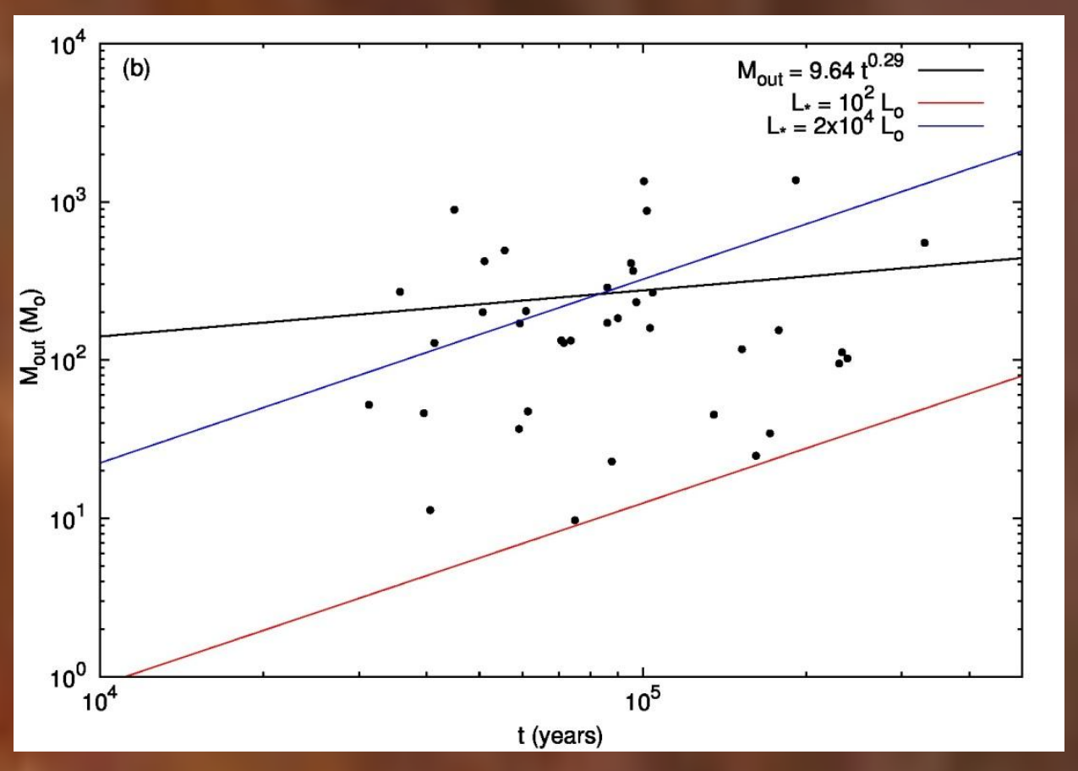
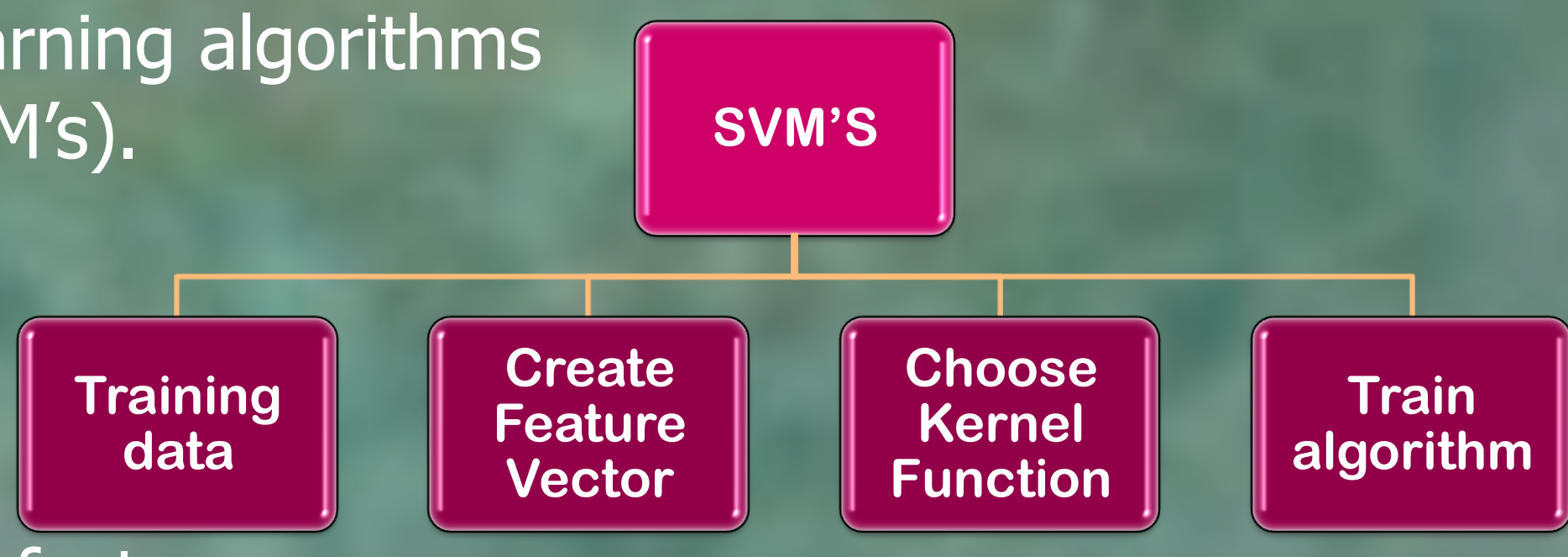


Fig. 5: L_{bol} divisions on M_{out} vs. t relation as by Shepherd[1].

These above results support the theory that a single YSO drives its own molecular outflow during accretion, as opposed to a cluster of less massive YSO's together producing a wide-angle flow.

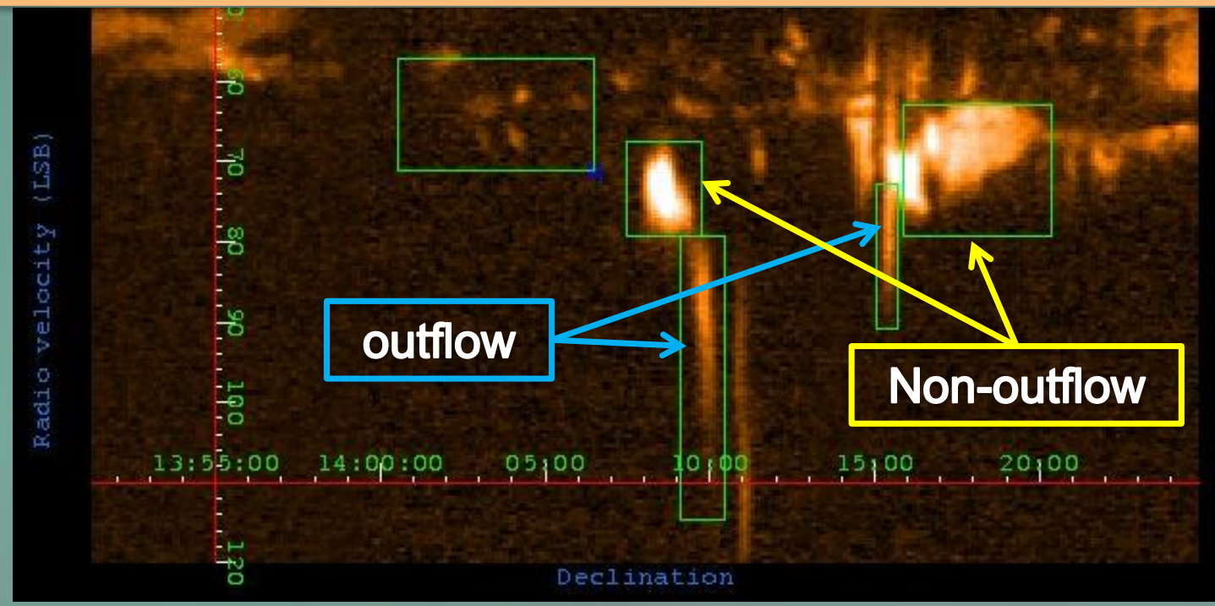
MACHINE LEARNING

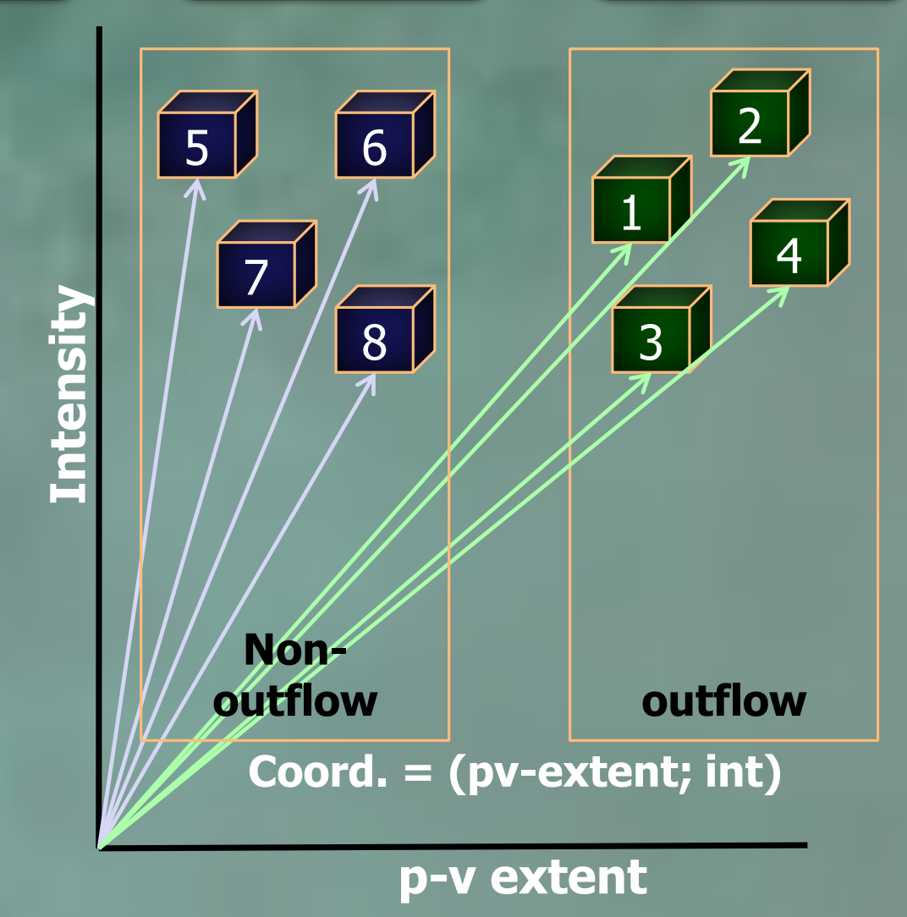
- This discussed study emphasized the need for automated outflow detection methods.
- Explore the use of machine learning algorithms
  - <u>Support Vector Machines</u> (SVM's).



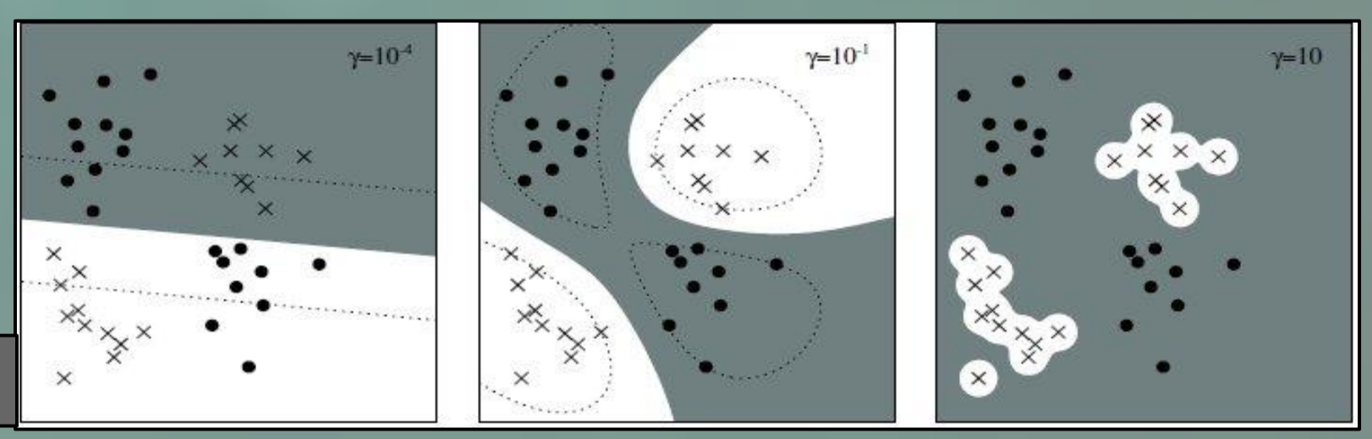
- <u>**T**raining data</u> →
  create feature vector per pixel. Property values are "coordinates" in N-dimensional feature-space.

<u>GMC W51:</u> Initial data set → manually classify training data regions.





- SVM trained.
- Optimise adjustable parameters C (curvature) and γ (boundary tightness).



Effect of Increasing γ