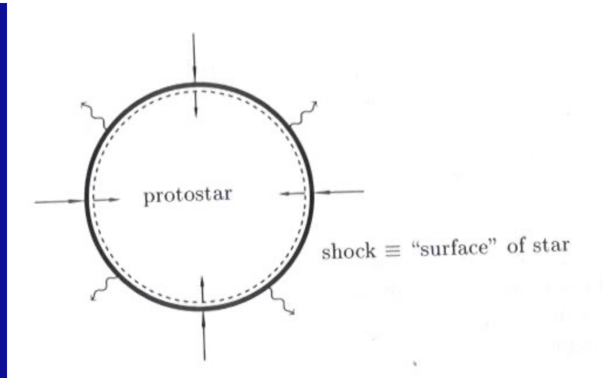
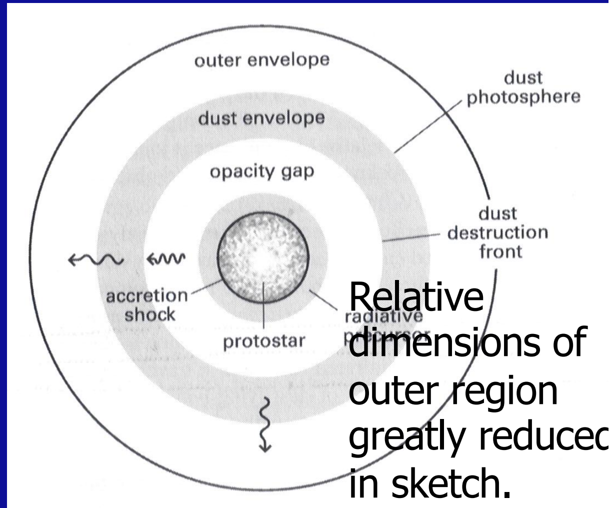
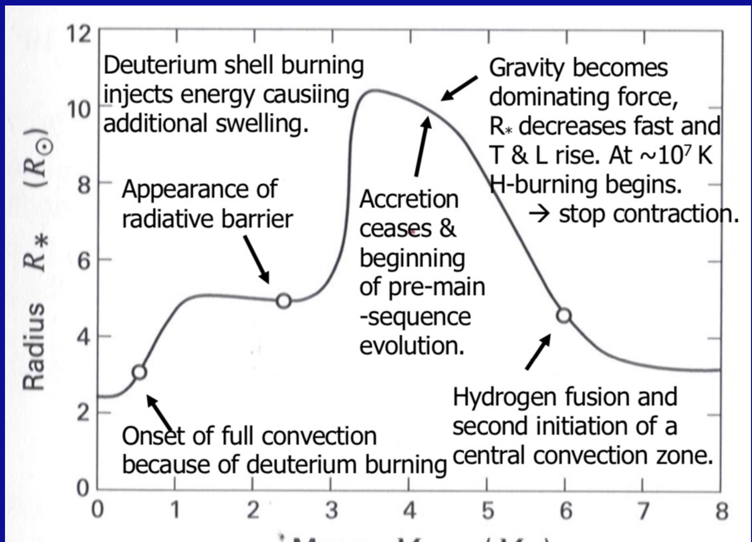
Summary last week I

- Protostellar evolution, 1st and 2nd core, accretion luminosity, definition of protostar
- Envelope structure
- Convection, entropy profile of protostar
- Structure of protostar
- Definition: protostar vs. pre-main sequence star

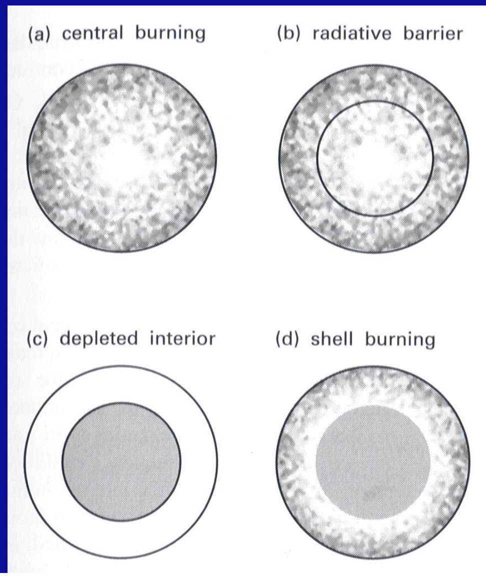




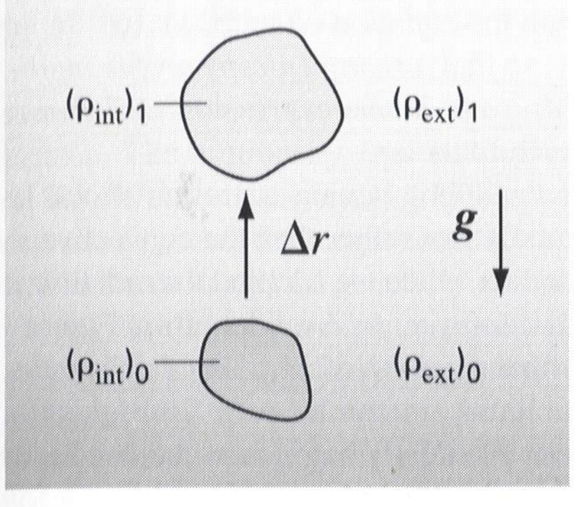
Relative dimensions of outer region greatly reduced in sketch.



Stahler & Palla 2004



Stahler & Palla 2004



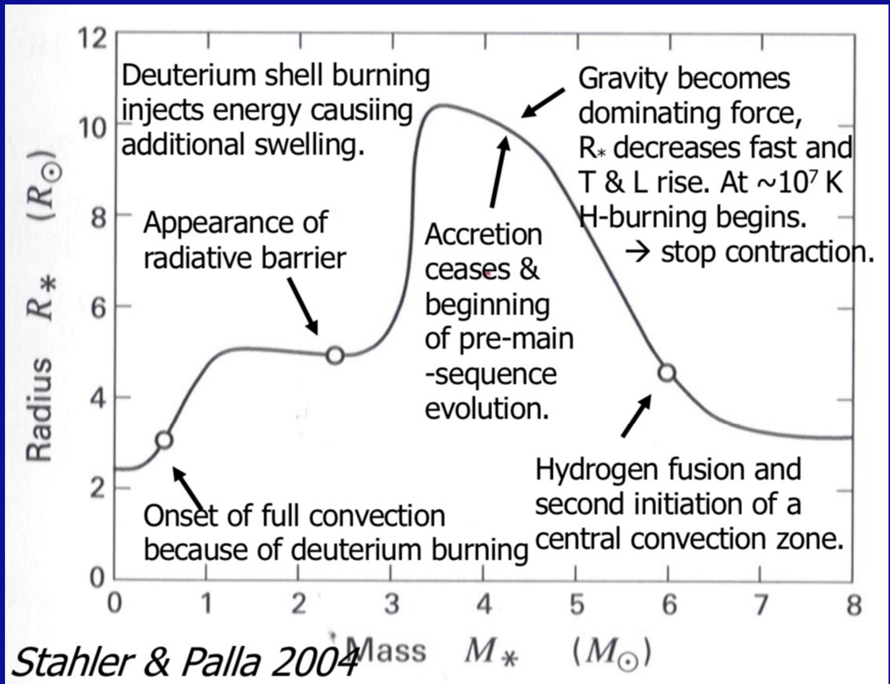
Summary last week II

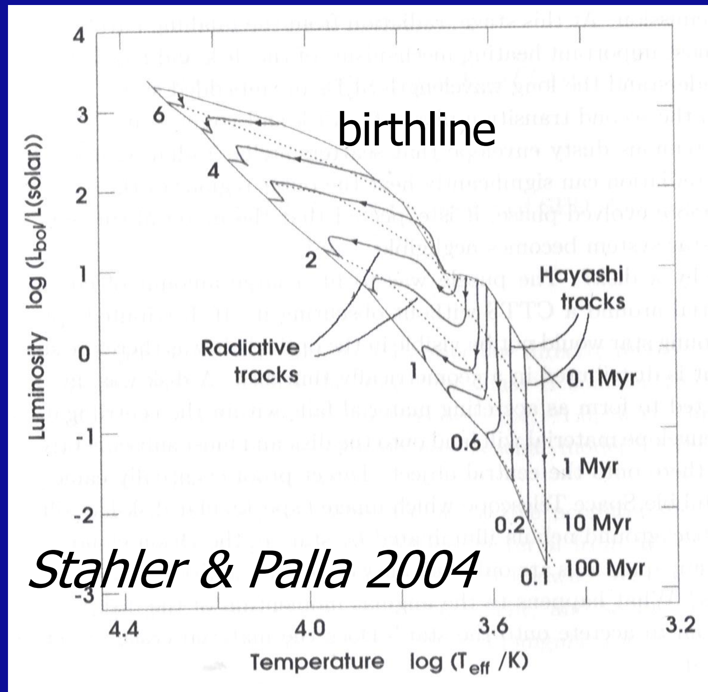
- Pre-main sequence evolution,
  → accretion stops, energy mainly by grav. contraction

- Differences between low- and high-mass protostars

- Concept birthline

- SED observational signatures of the sequence

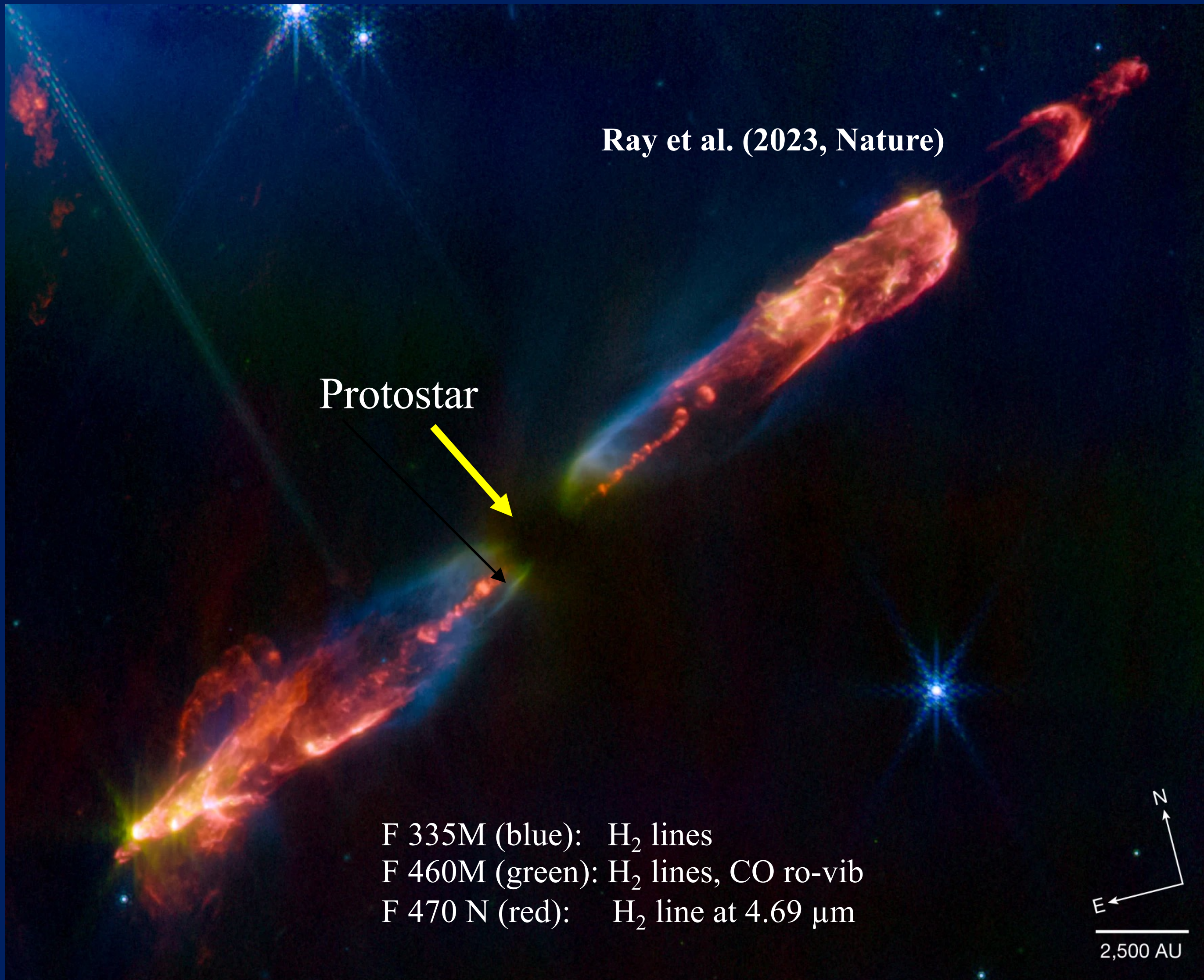




Topics today

- General outflow properties
- Jet launching
- Outflow entrainment

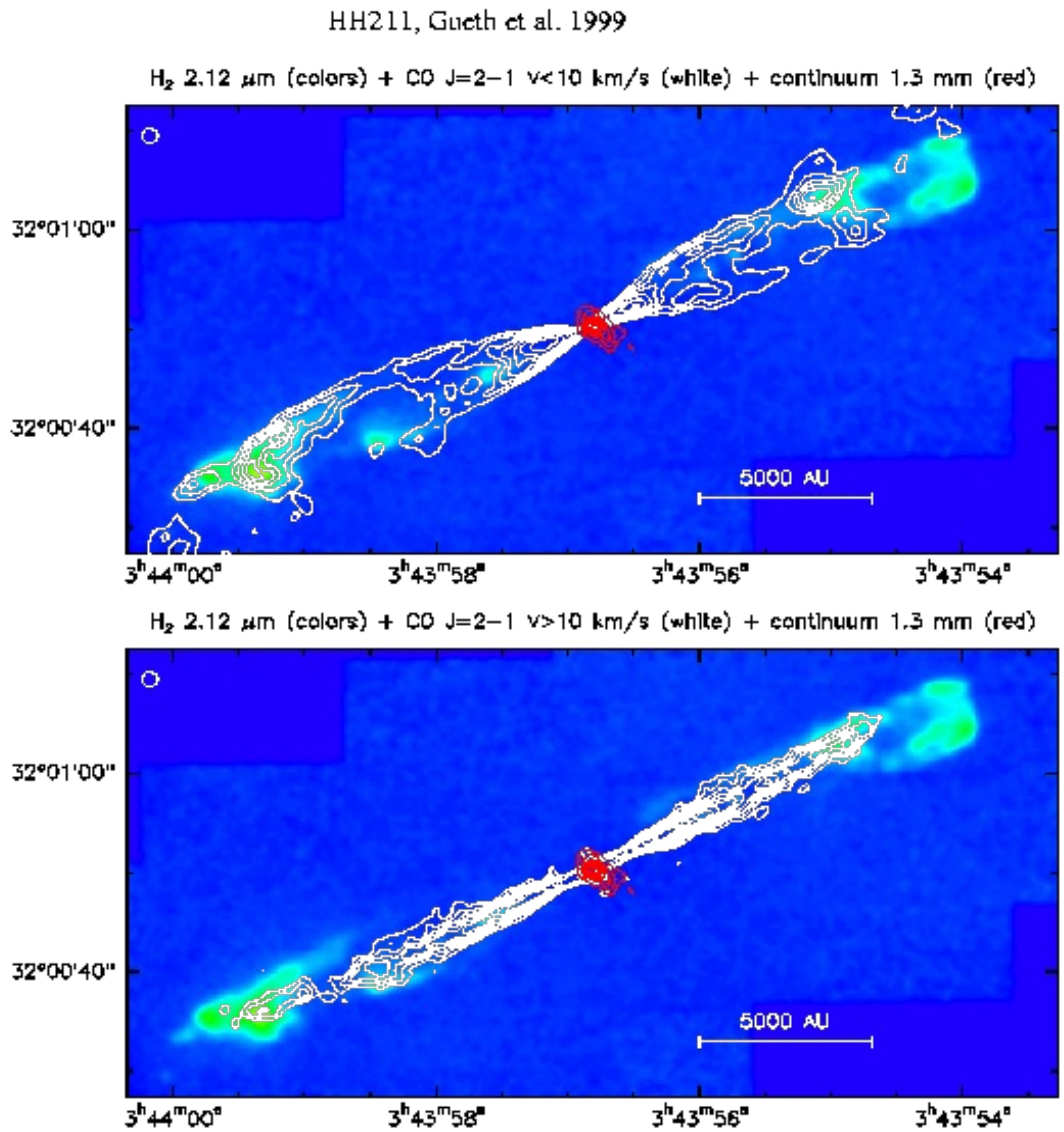
A Jet from a Protostar: Herbig Haro 211



Caratti o Garatti et al. (2024) – Detailed analysis

Jet is mostly molecular (H_2/HD) with an inner atomic structure

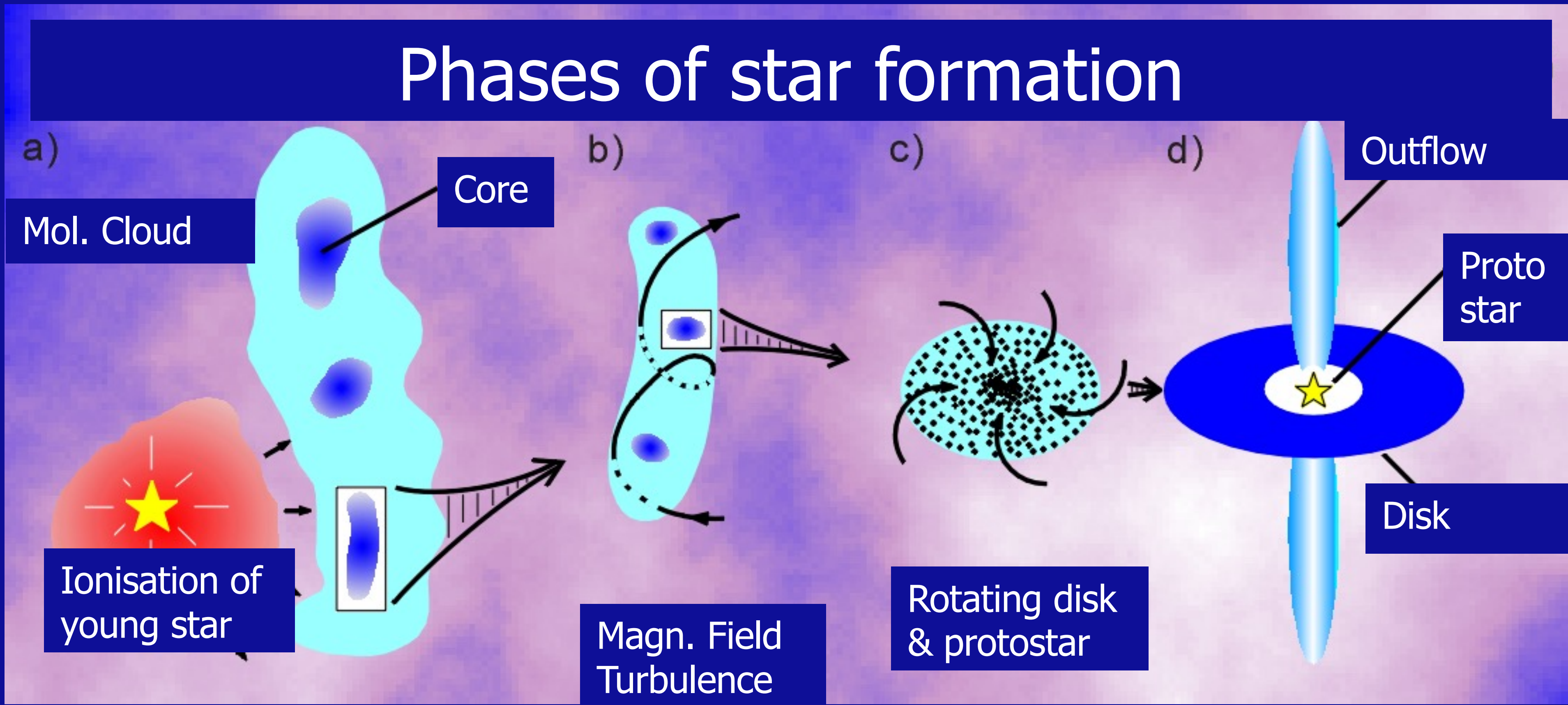
The Prototypical Molecular Outflow HH211



Entrained component

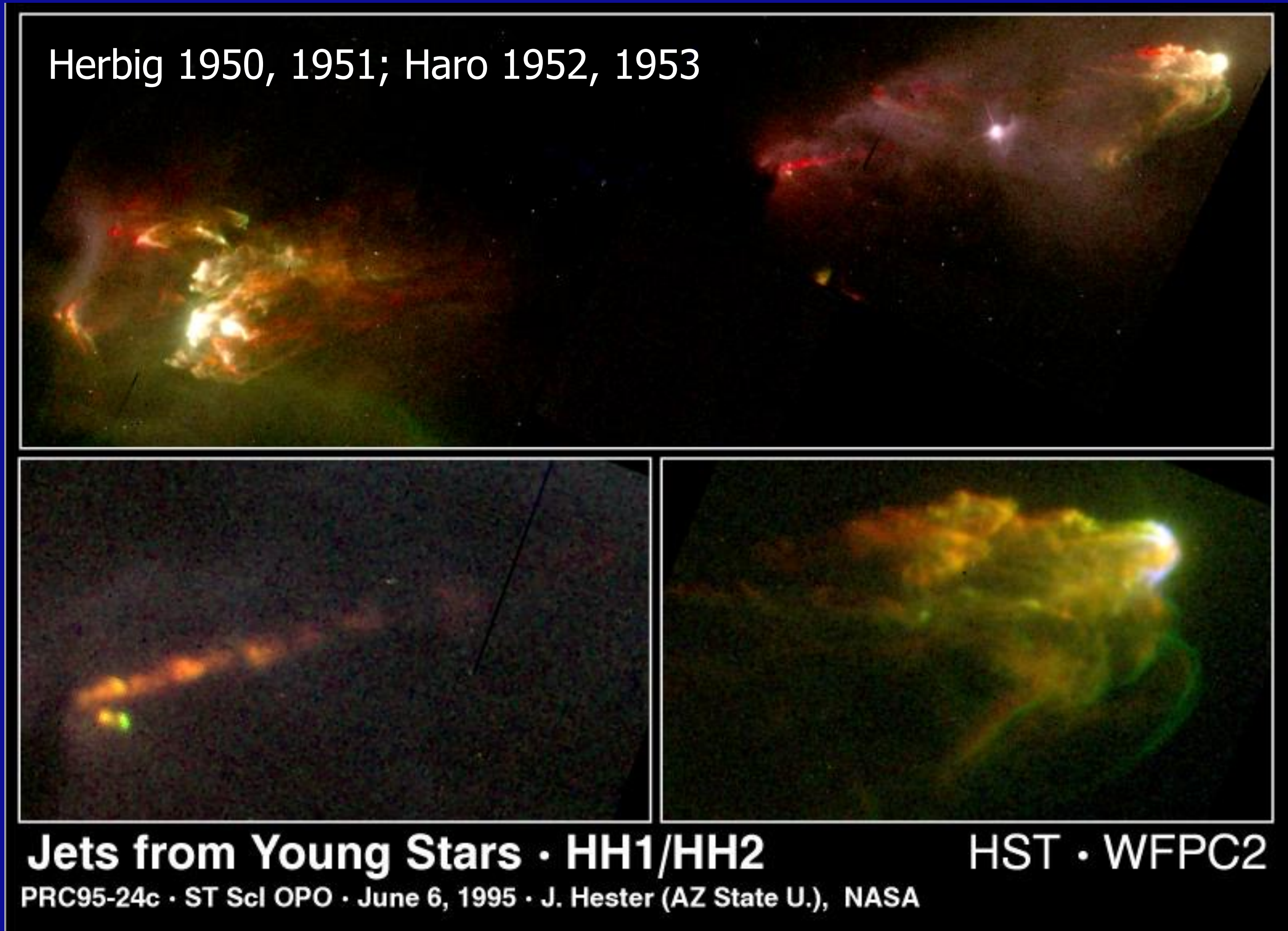
CO jet with linear velocity increase („Hubble law) Max: 80 km/s

Star Formation Paradigm



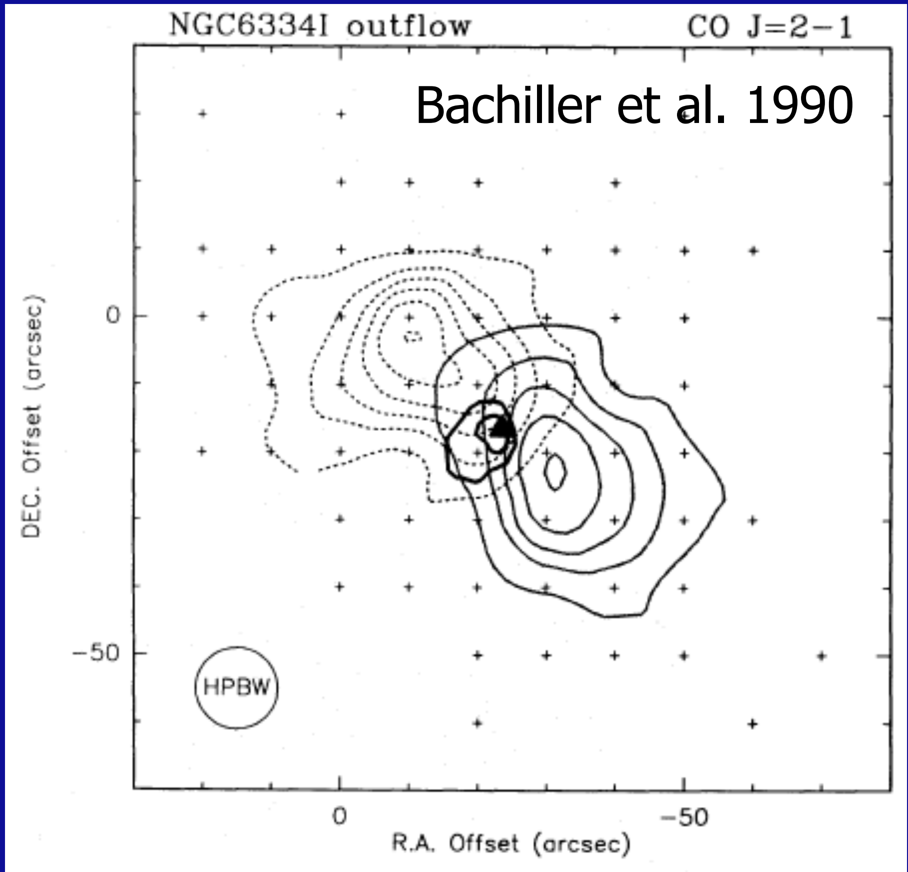
https://www.mpifr-bonn.mpg.de/473576/starform

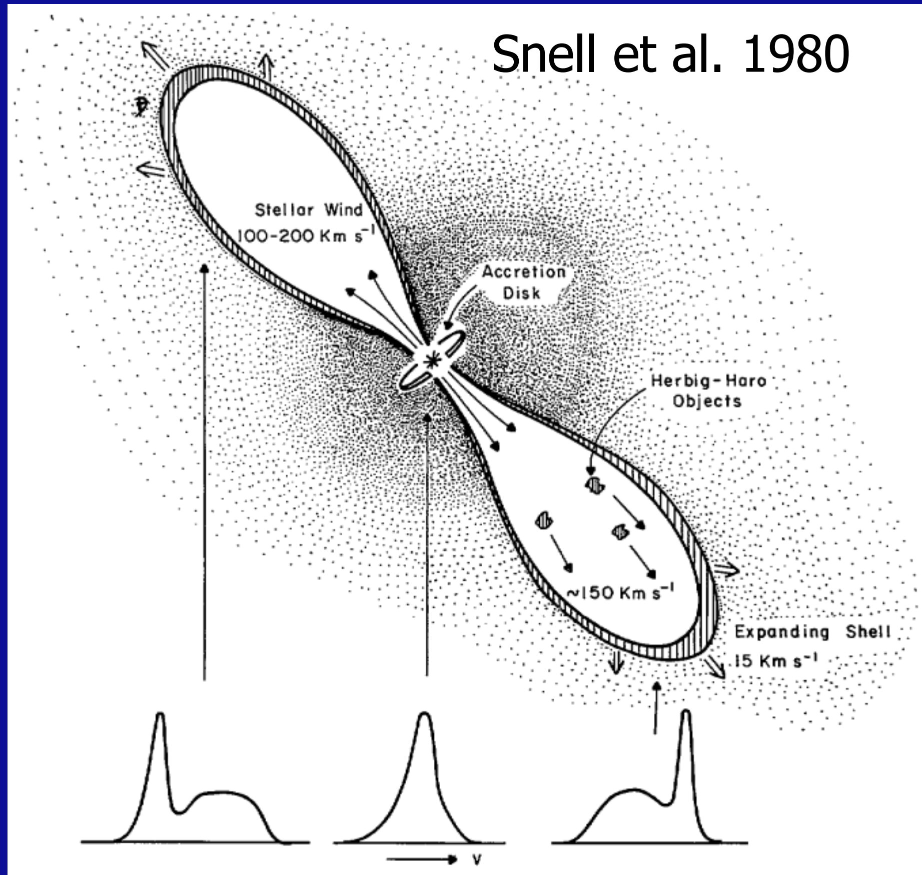
Discovery of Outflows I



Initially thought to be embedded protostars → soon spectra recognized as caused by shock waves → jets and outflows

Discovery of Outflows II

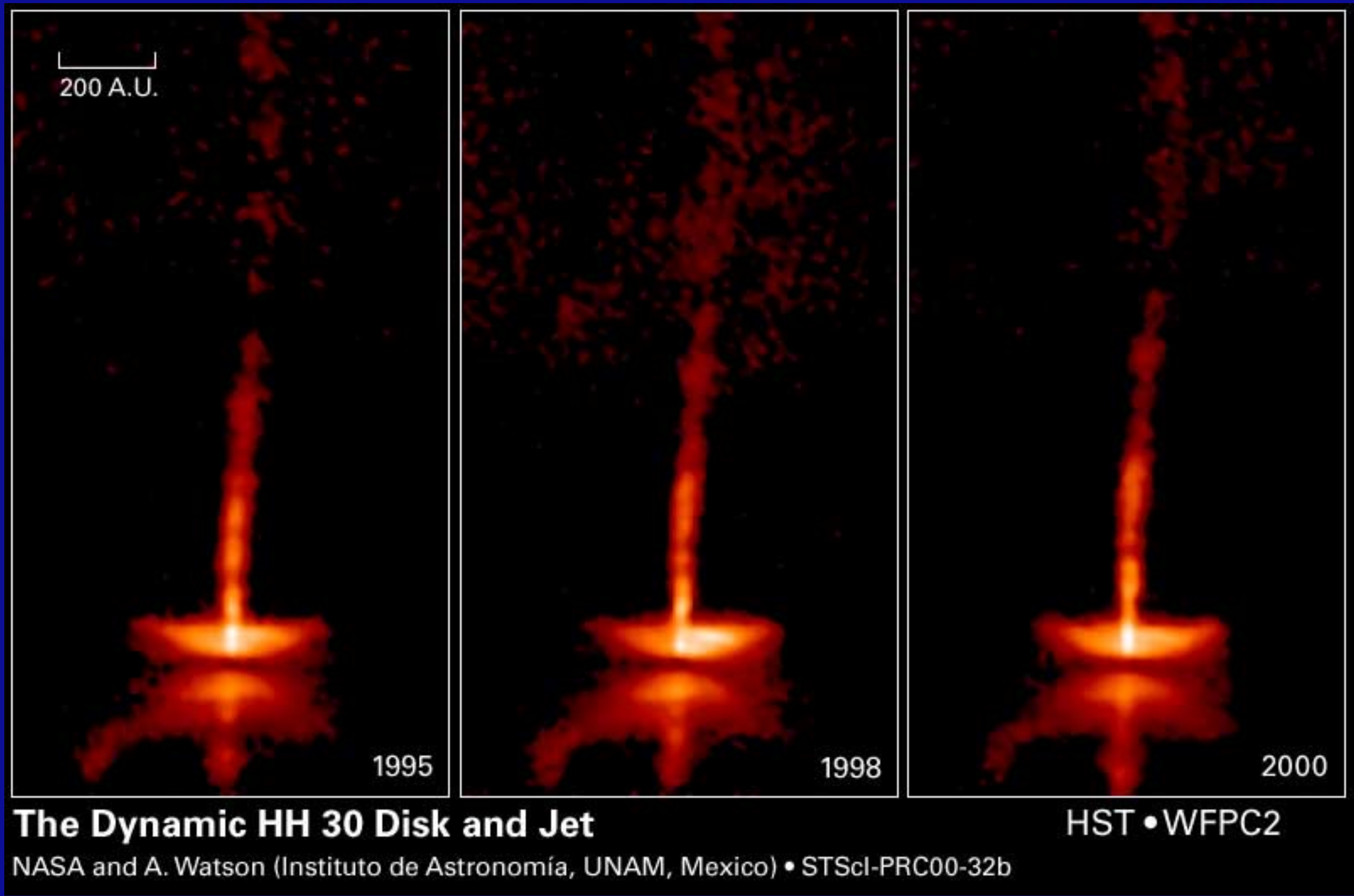




- Mid to late 70th, first CO non-Gaussian line wing emission detected (Kwan & Scoville 1976).

- Bipolar structures, extremely energetic flow; but not (!) stellar winds

HH30 - A Disk-Outflow System in L1551



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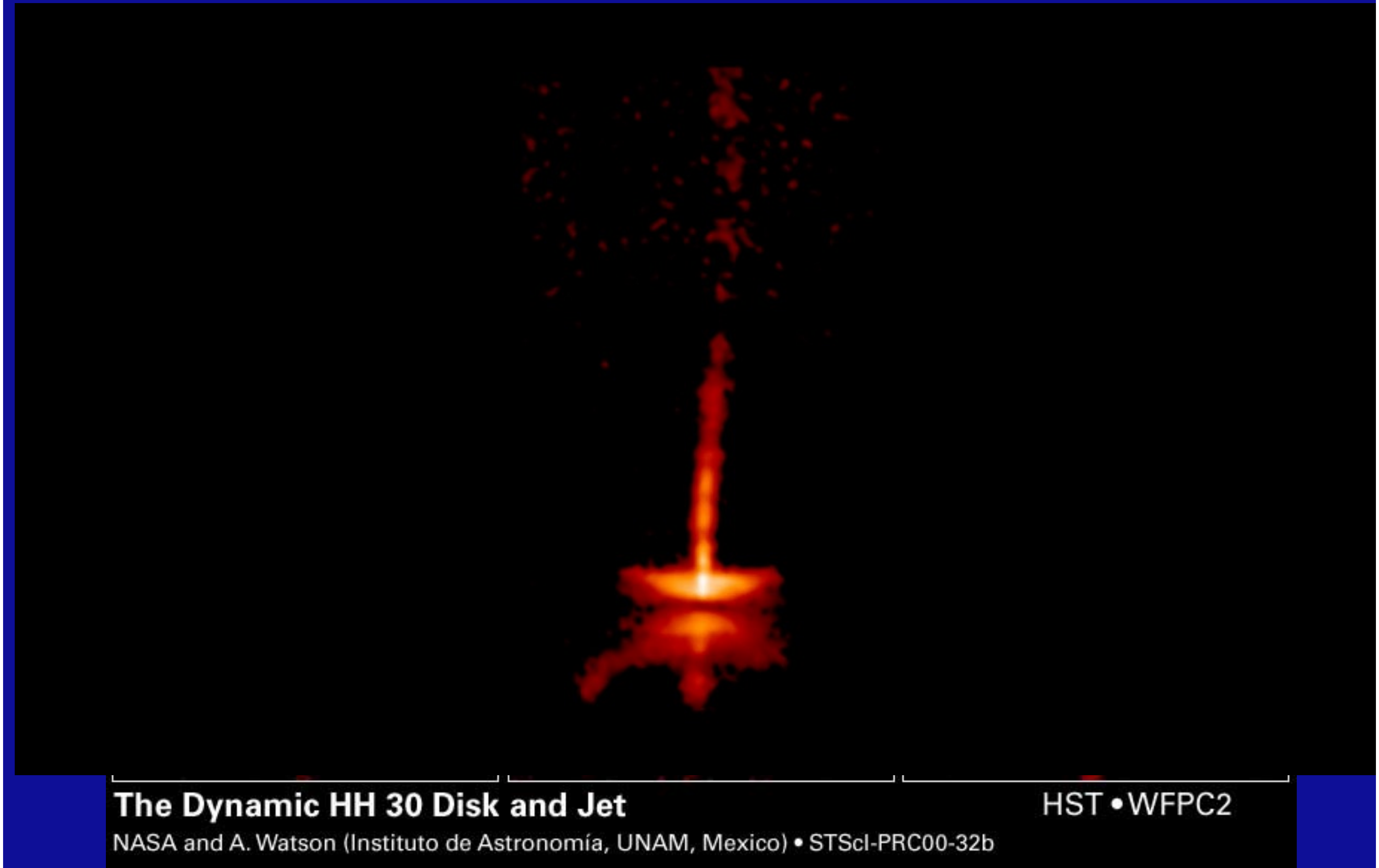
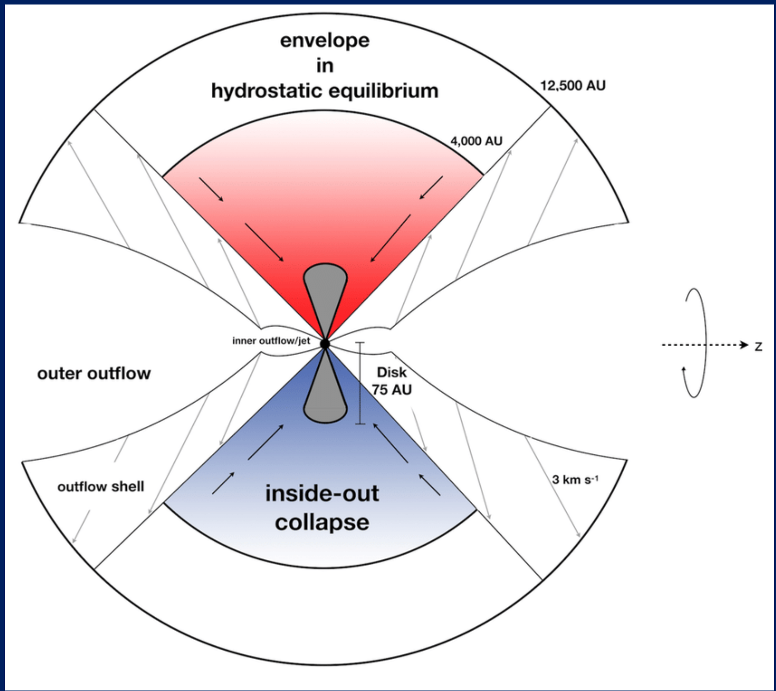
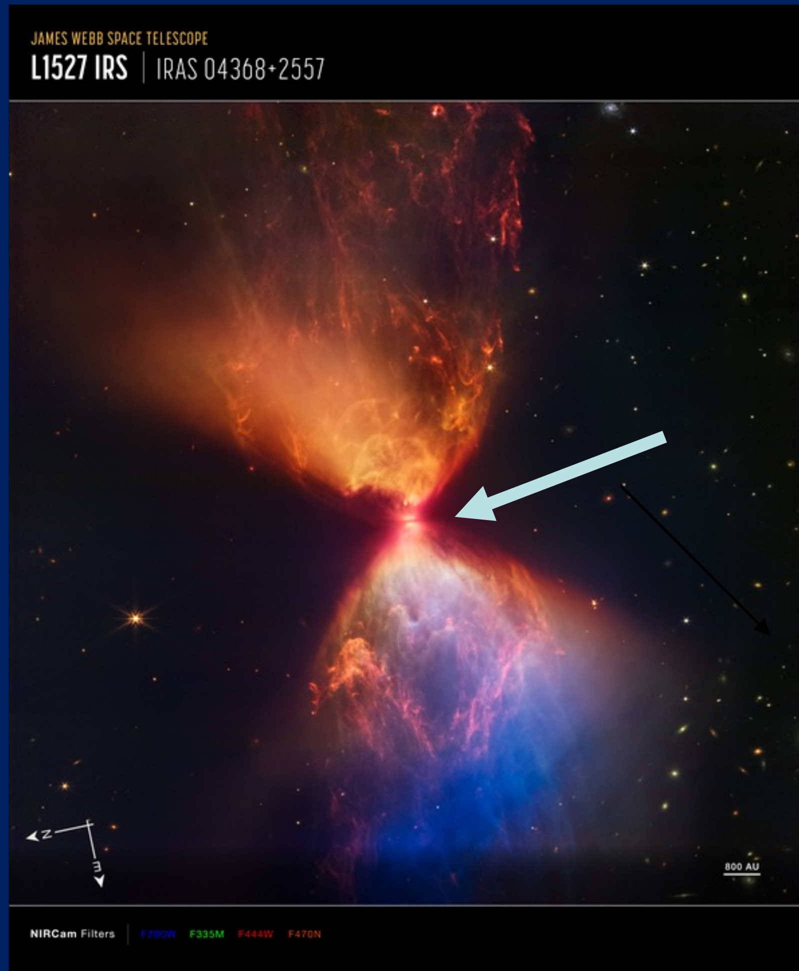


NIRCAM Image of the Class 0/I Protostar L 1527 in Taurus

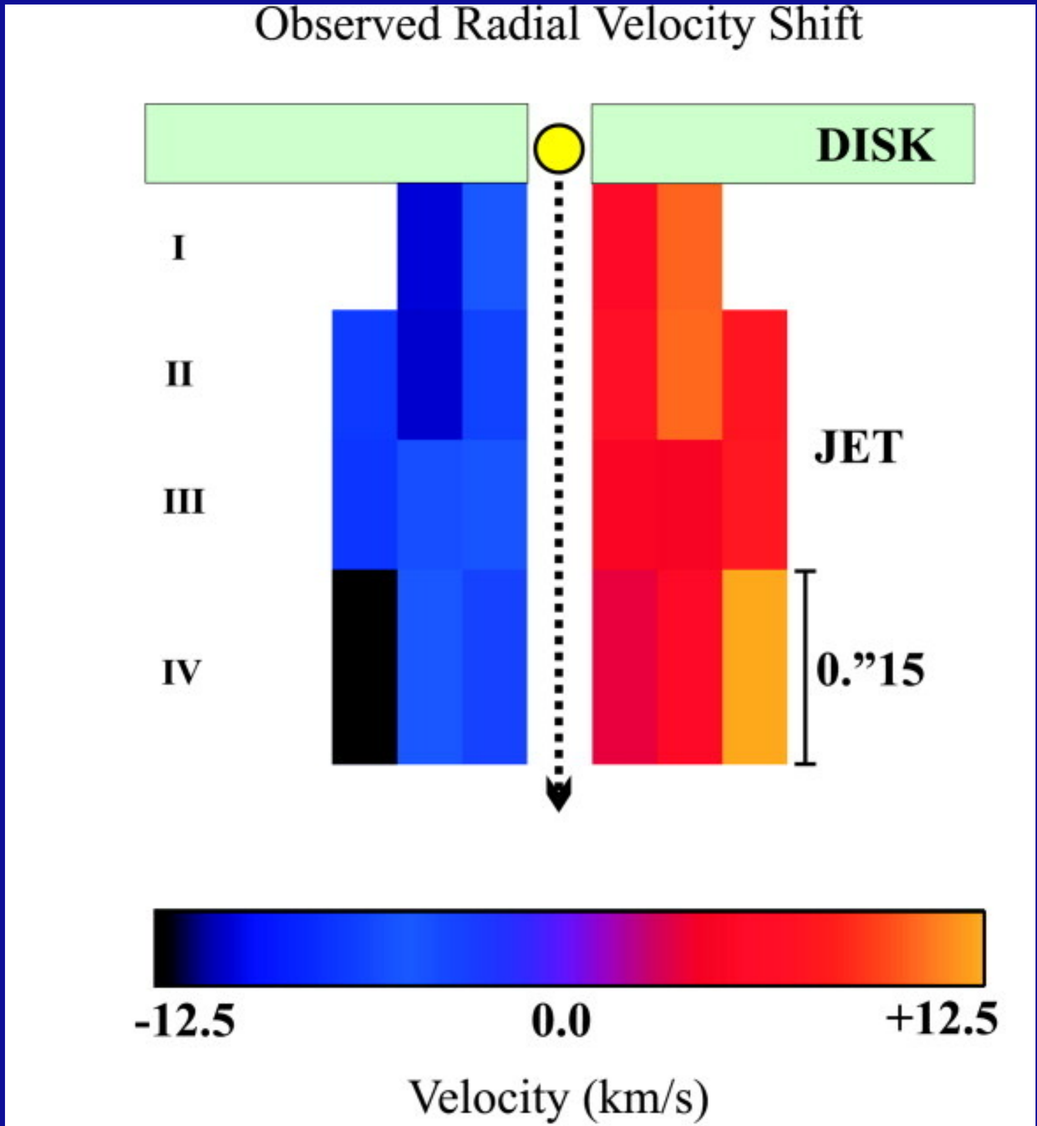


Lizxandra Flores et al. (2021): Spitzer/CARMA

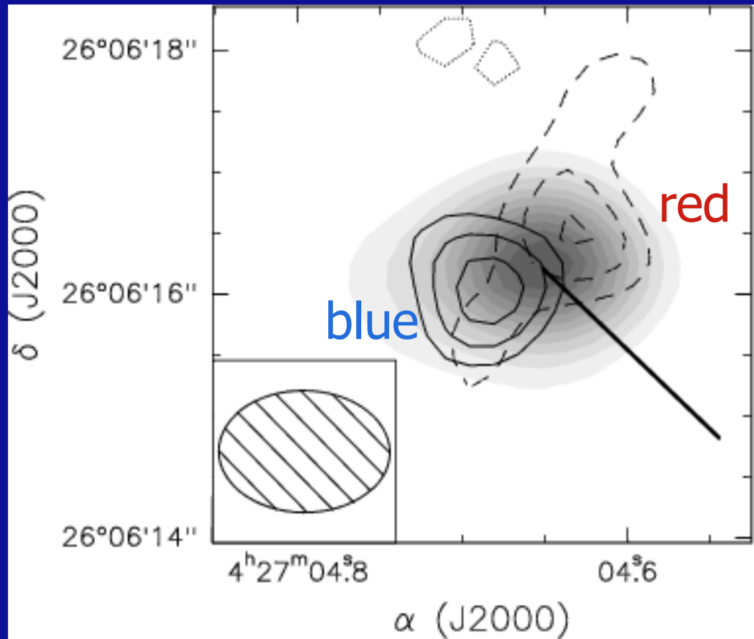
Disk + Infalling Envelope + Outflow + Jet



Jet Rotation in DG Tau



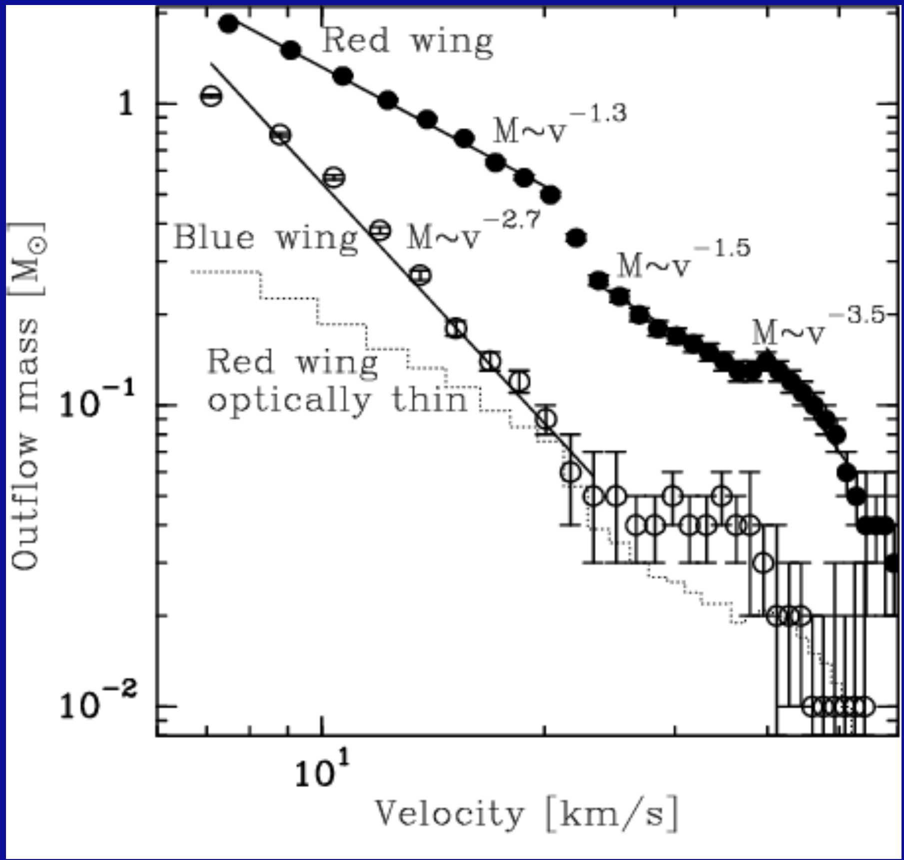
Bacciotti et al. 2002



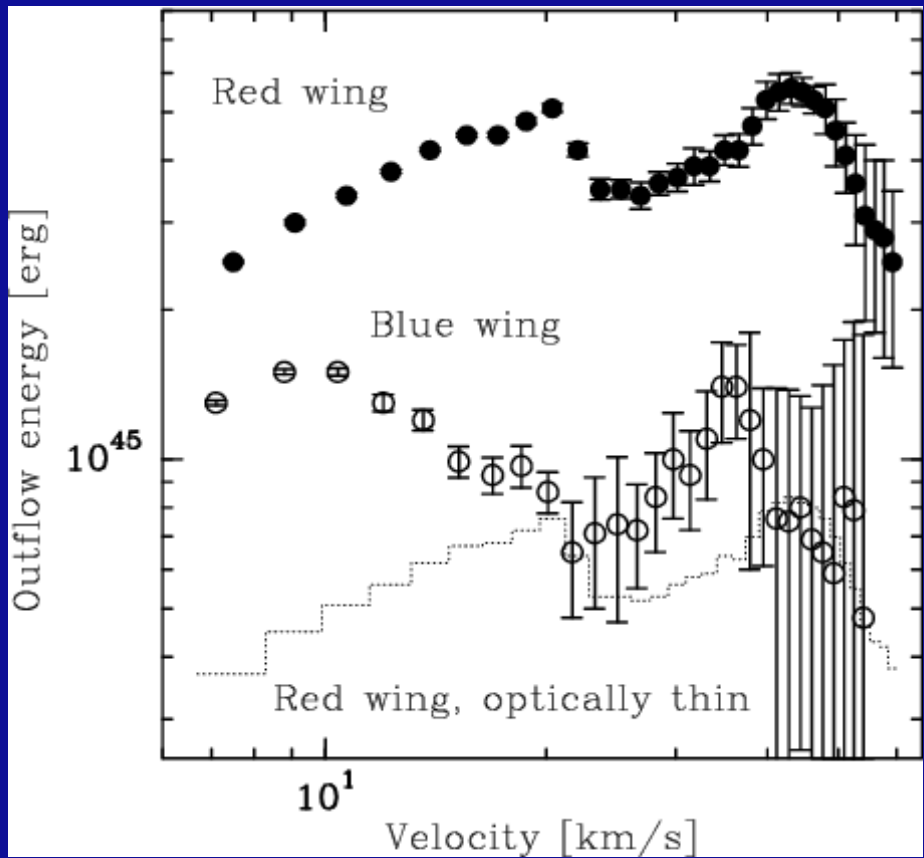
Testi et al. 2002

→ Corotation of disk and jet

Mass vs.Velocity & Energy vs. Velocity



$E \sim v^2$

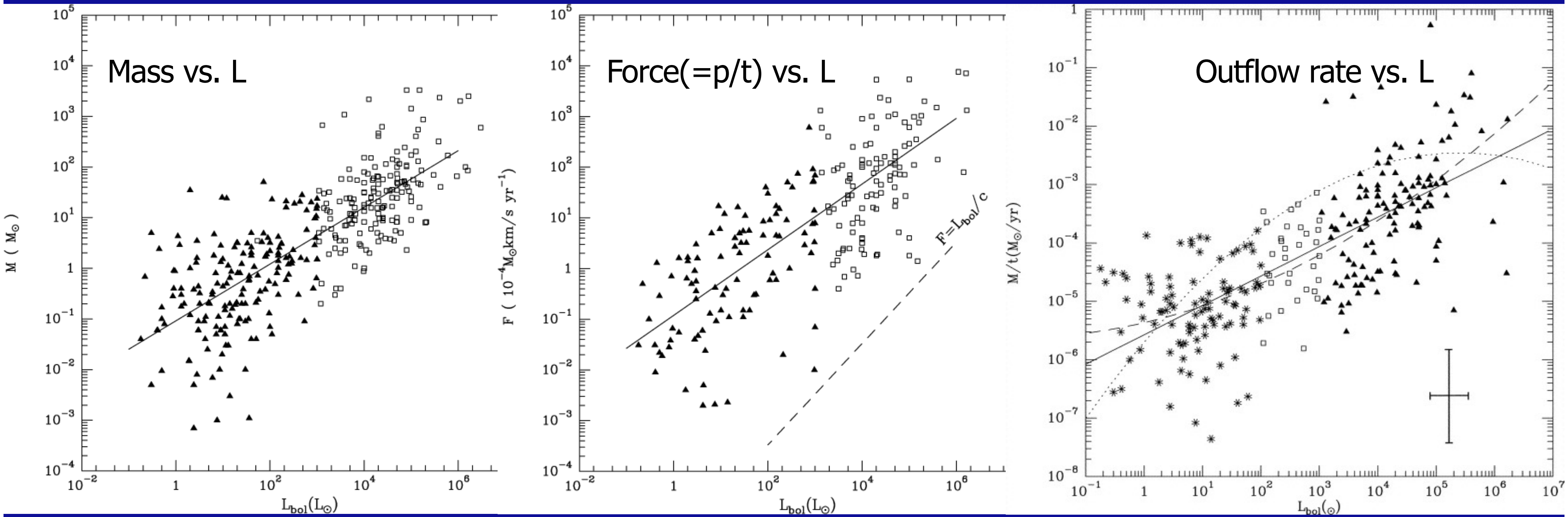


- Mass-velocity relation exhibits broken power-law, steeper further out.
- Energy at high velocities of the same magnitude than at low velocities.

Lebron et al. 2006

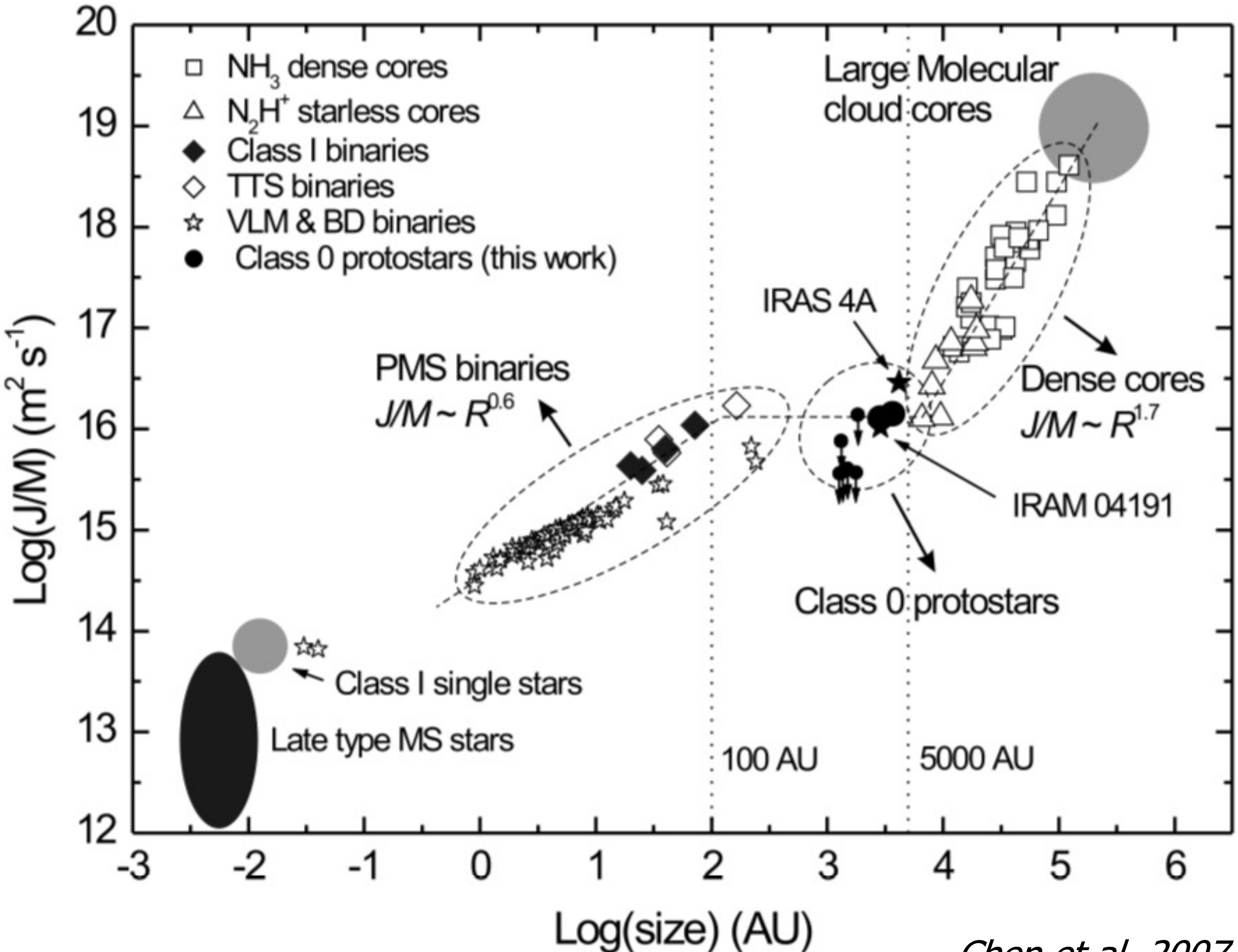
General Outflow Properties

- Jet velocities 100-500 km/s <==> Outflow velocities 10-50 km/s
- Estimated dynamical ages between 10^3 and 10^5 years
- Size between 0.1 and 1 pc
- Force provided by stellar radiation too low (middle panel)
  → non-radiative processes necessary!



Wu et al. 2004, 2005

Specific Angular Momentum



Chen et al. 2007

Impact on Surrounding Cloud

- Entrain large amounts of cloud mass with high energies.

- Partly responsible to maintain turbulence in cloud.

- Can disrupt the cores to stop any further accretion.

- May trigger collapse in neighboring cores.

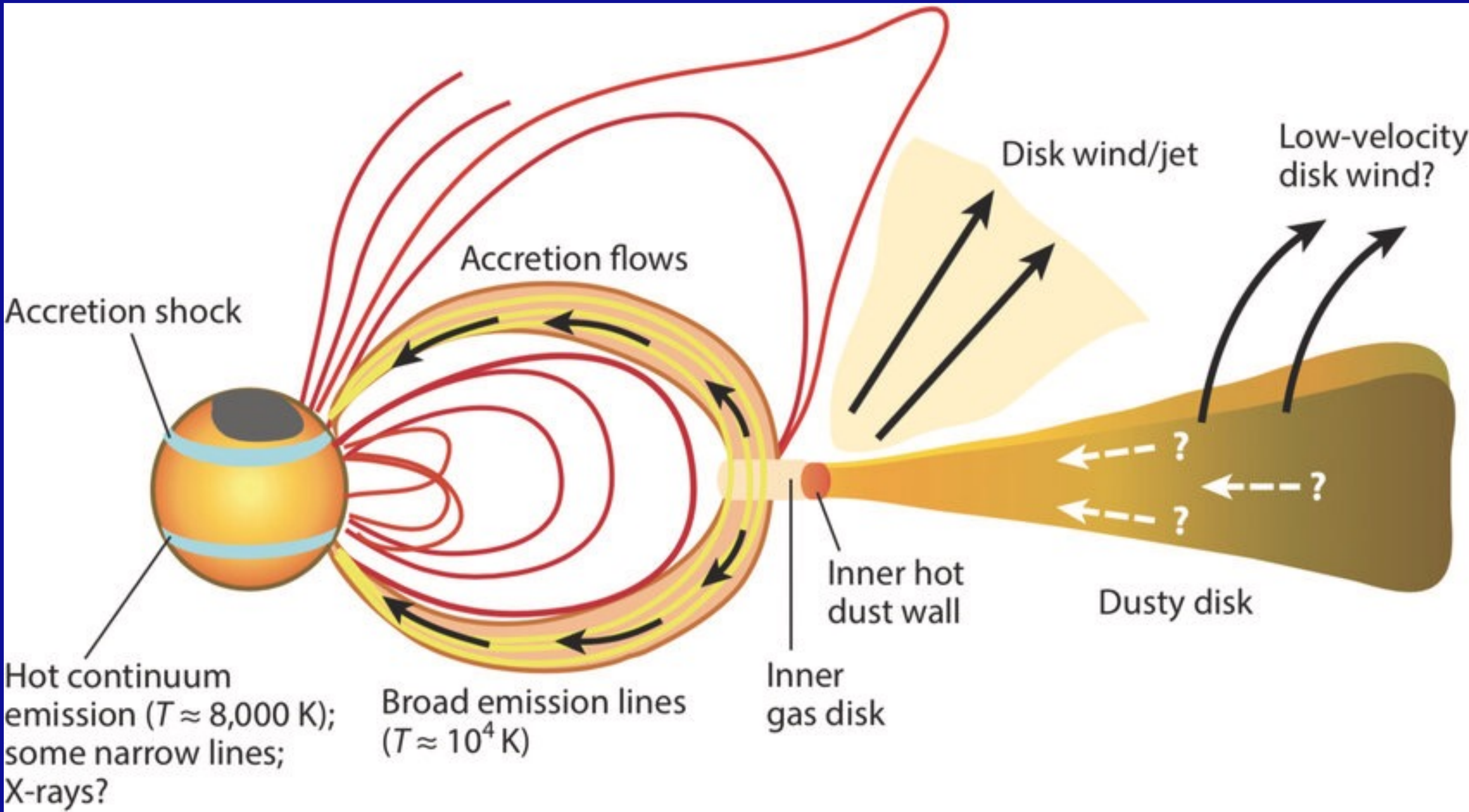
- Via shock interactions heat the cloud.

- Alter the chemical properties.

Topics today

- General outflow properties
- Jet launching
- Outflow entrainment

Schematic View of Jet/Wind Launching

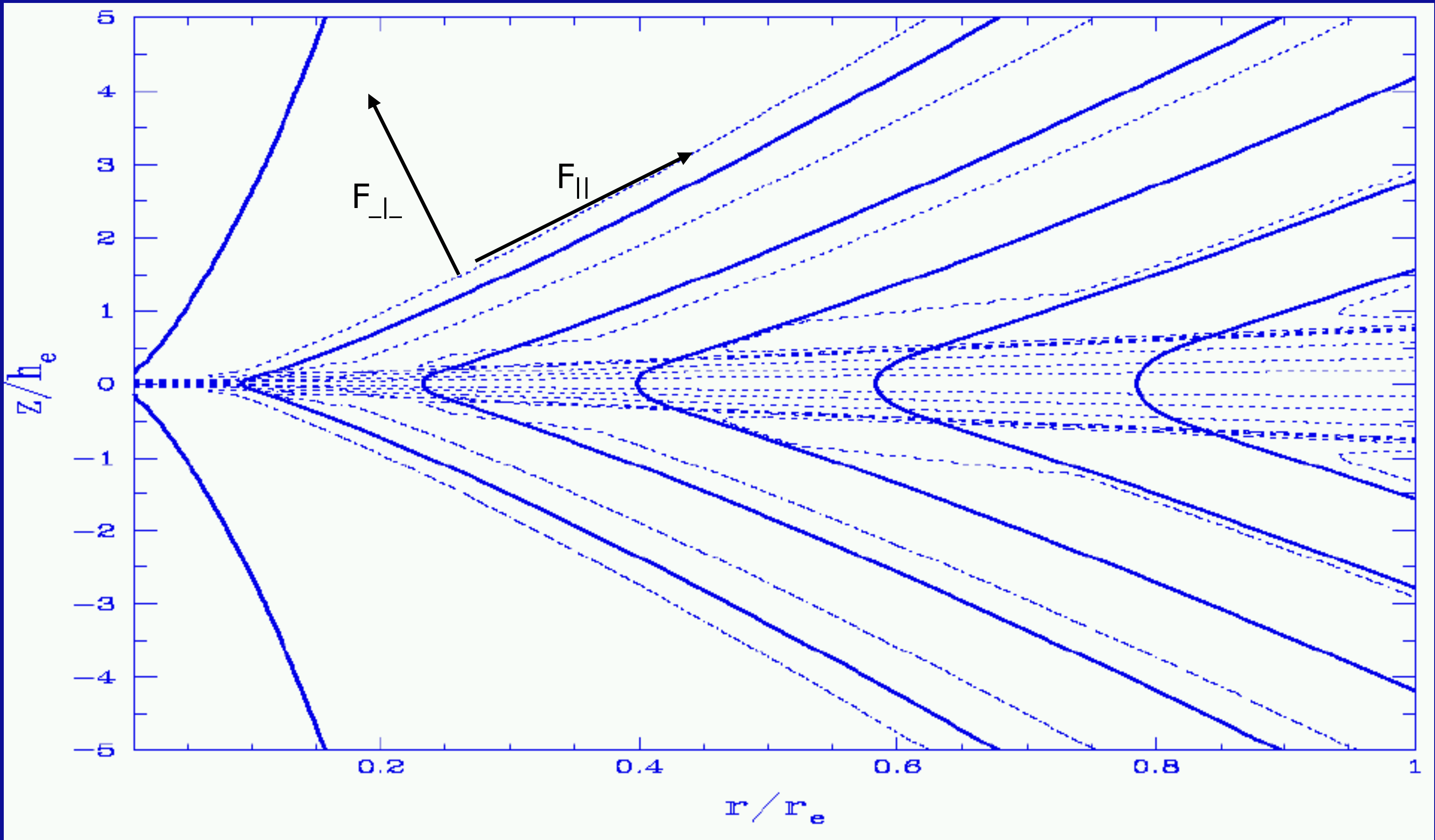


Kuruwita et al. (2024)

Jet launching from Accretion Disks

"magnetic accretion-ejection structures" (Ferreira et al 1995-1997):

1) disk material diffuses across magnetic field lines, 2) is lifted upwards by MHD forces, then 3) couples to the field and 4) becomes accelerated magnetocentrifugally and 5) collimated



Magnetic field lines (thick) and streamlines (dashed)

Jet launching

General consensus:

Jets are driven by magnetocentrifugal winds from magnetic field lines anchored in rotating circumstellar disks.

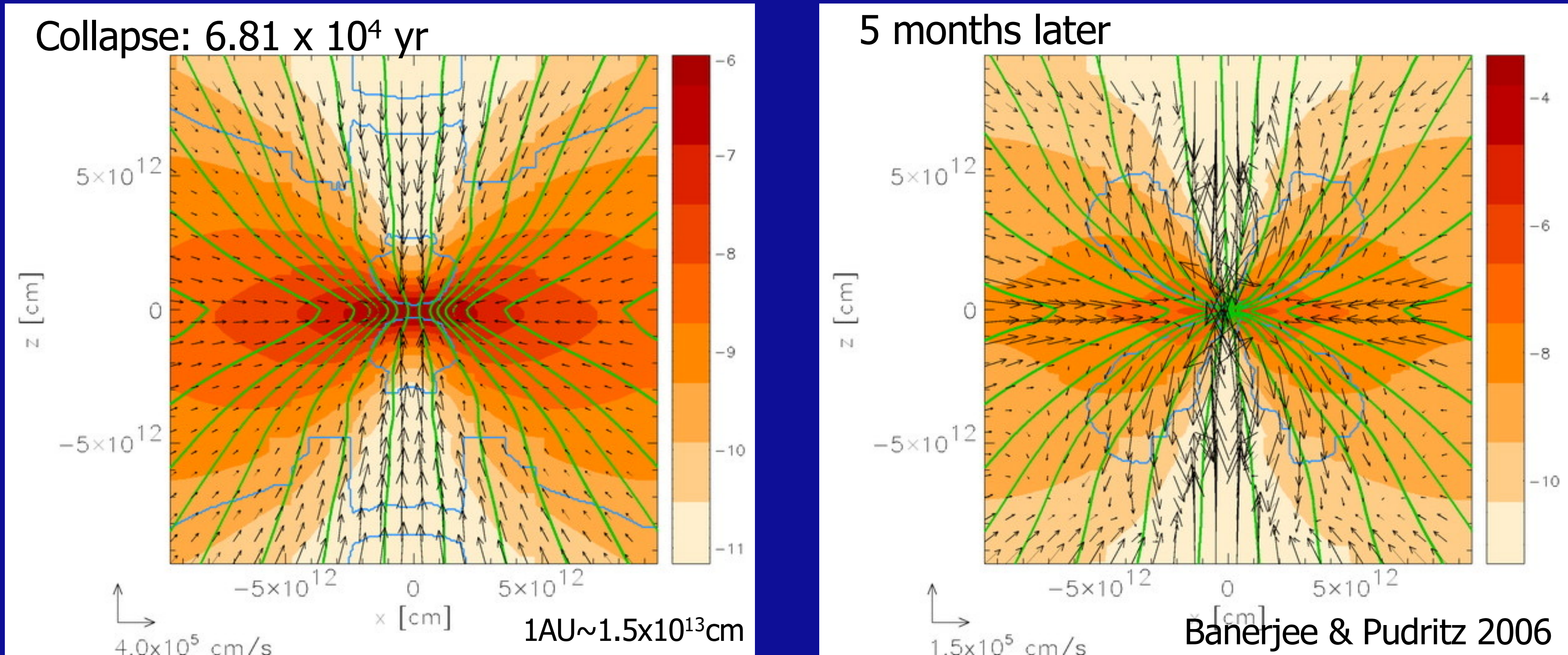
Close to disk: $B^2/8\pi < \rho v^2$ (magnetic field anchored in the disk)

Outside of disk: Density is low → Magnetic energy dominating

Disk winds ← → X-winds

Launching over larger disk area? ← → Launching from a small area close to disk truncation?

Jet-launching: Disk winds I



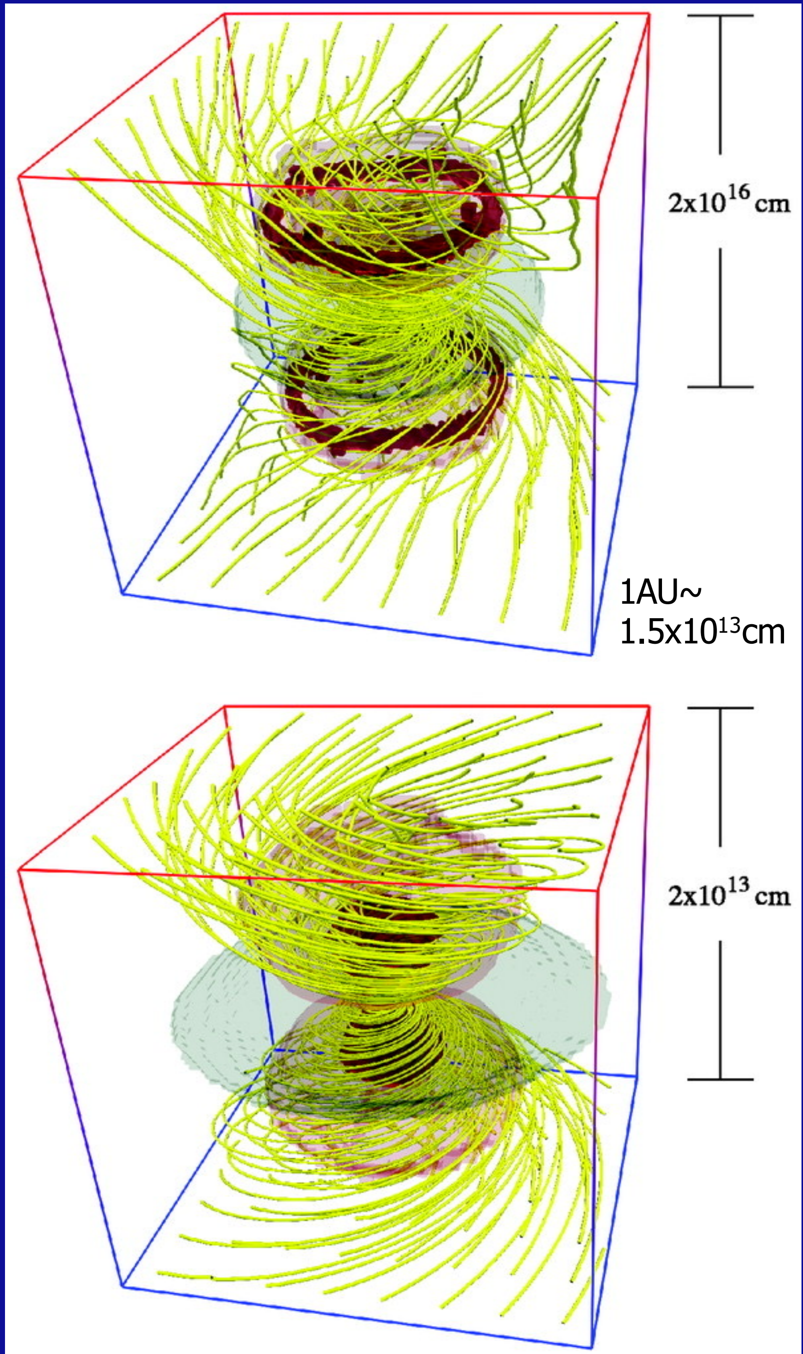
- Infalling core pinches magnetic field.

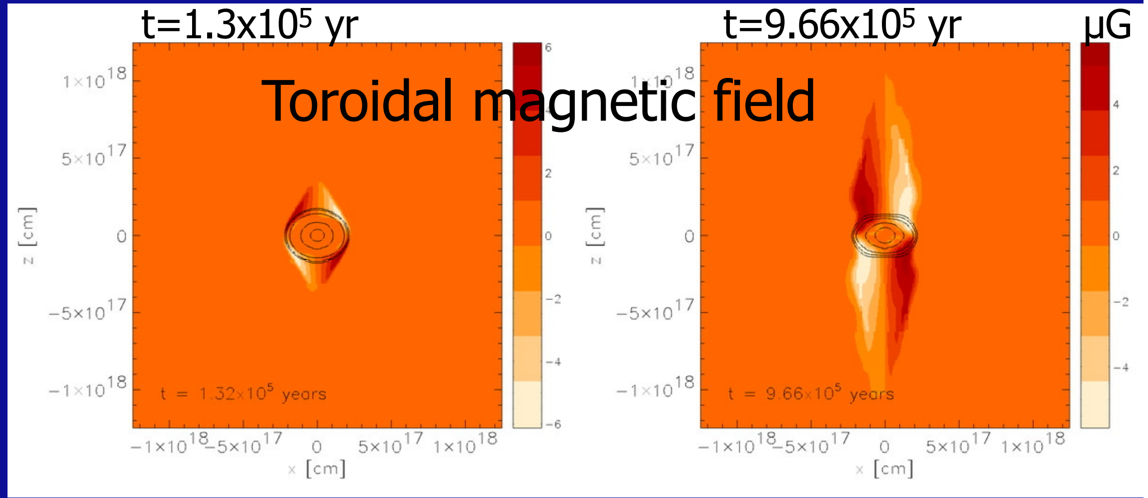
- If poloidal magnetic field component B_p has angle larger 30° from vertical
  → centrifugal forces launch matter-loaded wind along field from disk

- Wind transports away from 60 to 100% of disk angular momentum.

Review: Pudritz et al. 2006

Jet-launching: Disk winds II



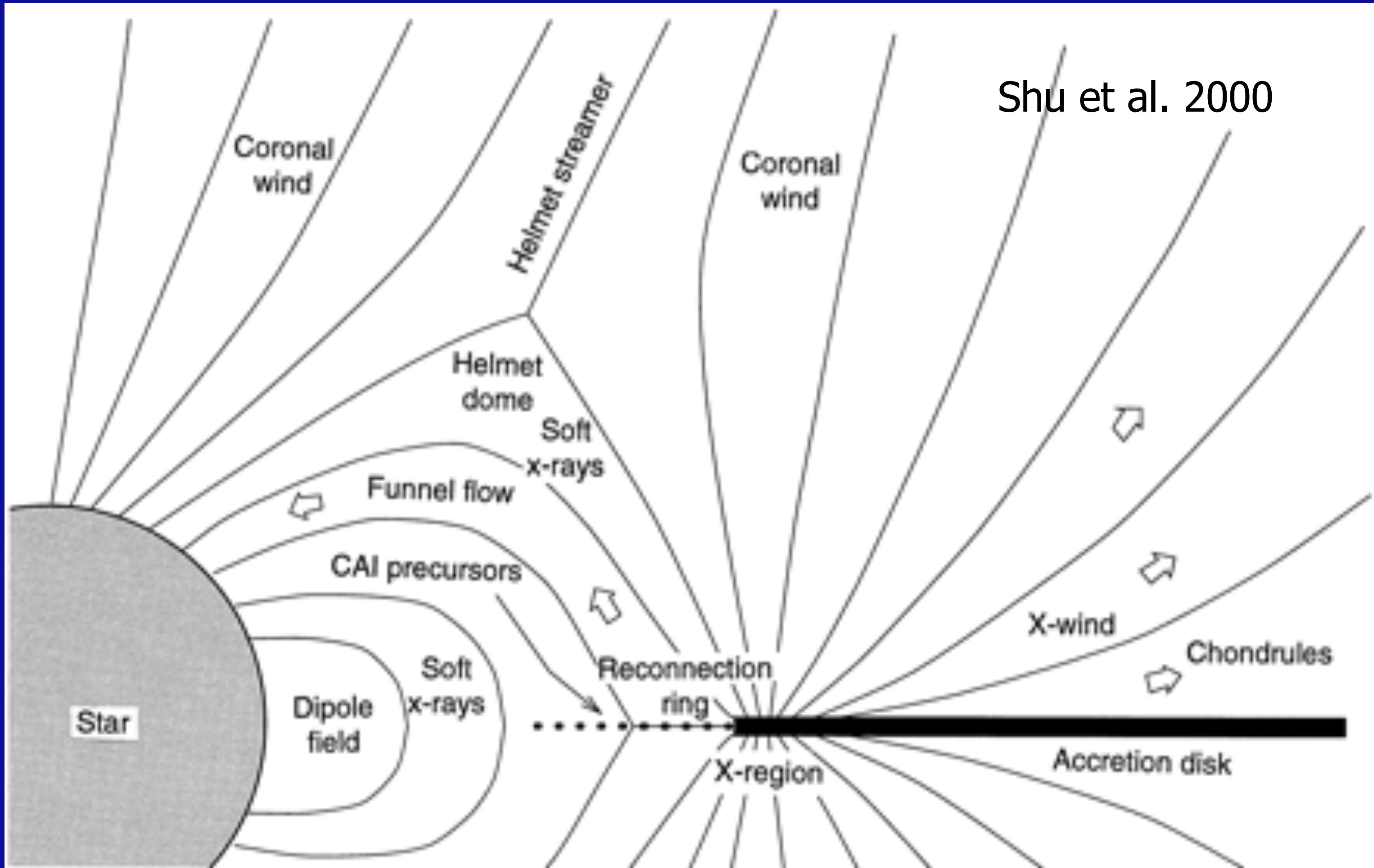


- On larger scales, a strong toroidal magnetic field B_t builds up during collapse.

- At large radii (outside Alfven radius r_A, the radius where kin. energy equals magn. energy) B_t/B_p much larger than 1
  → collimation via Lorentz-force $F_L \sim j_z B_t$

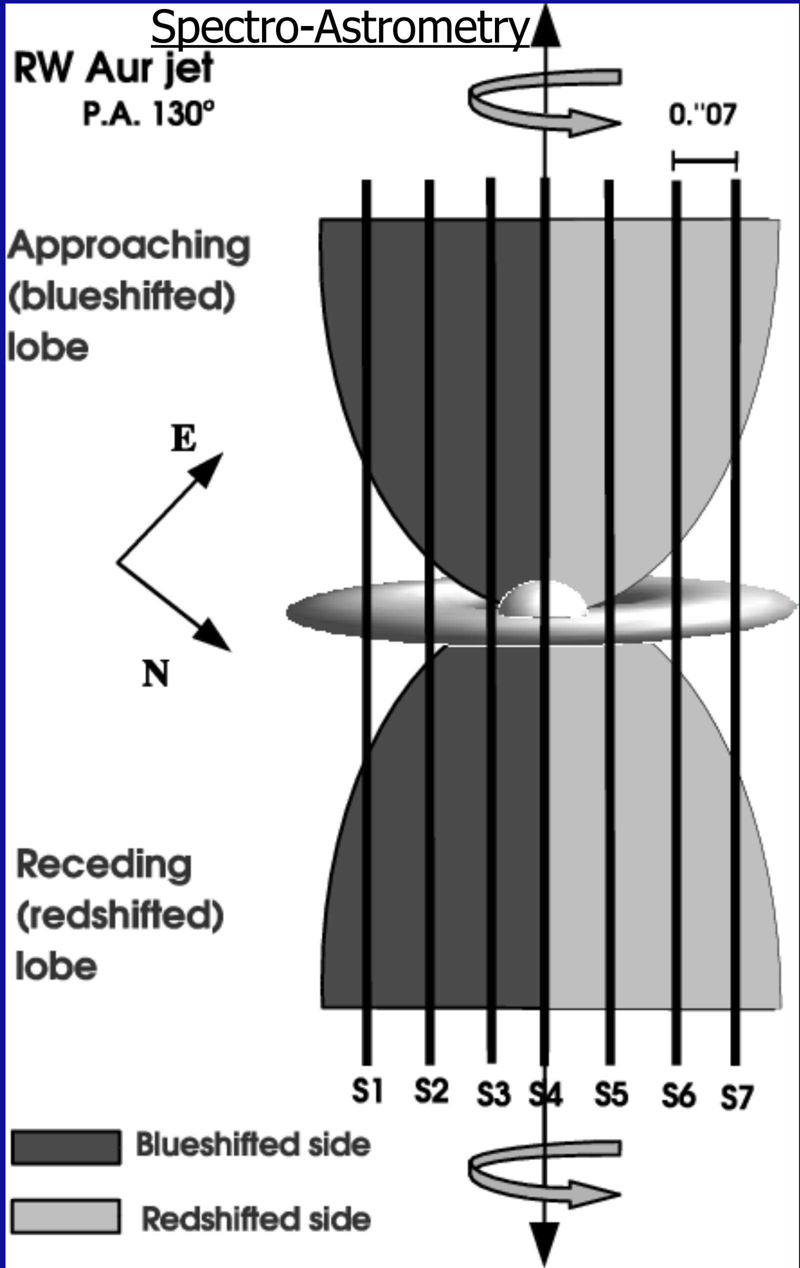
Banerjee & Pudritz 2006

X-Winds

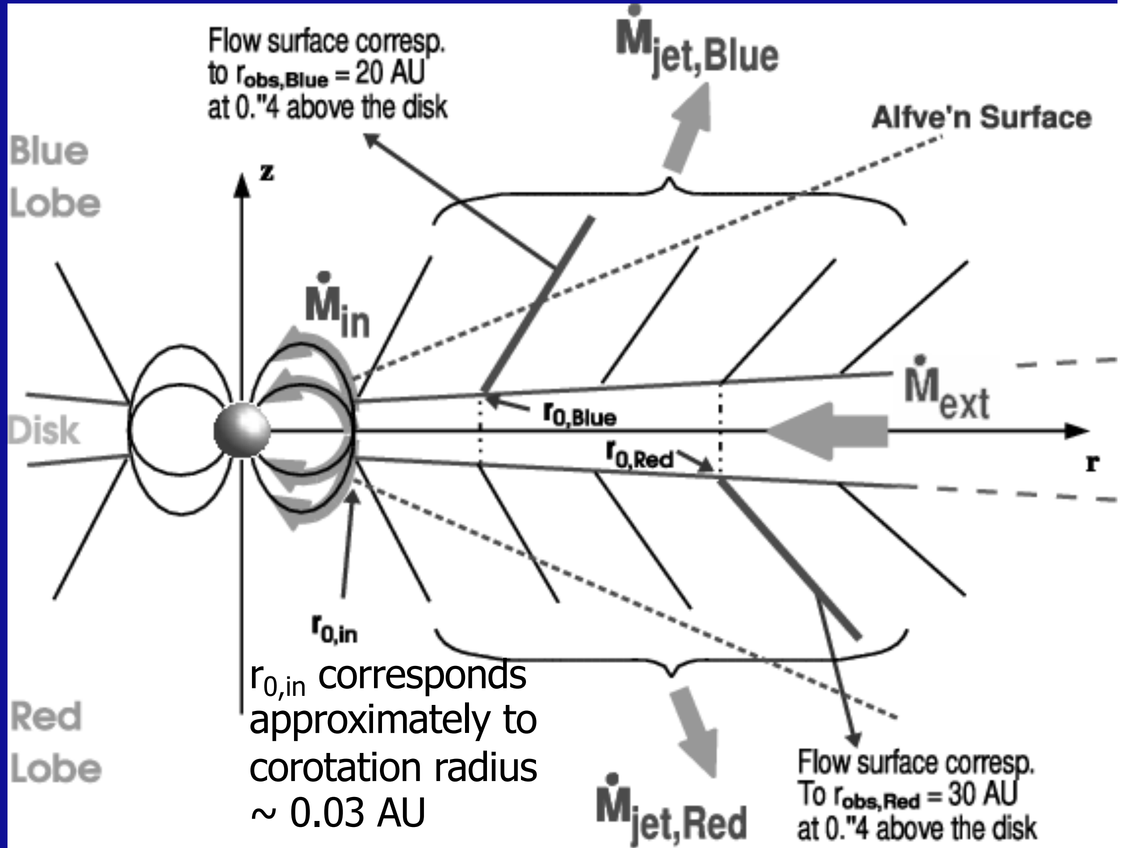


The wind is launched magneto-centrifugally from the inner co-rotation radius of the accretion disk (~0.03AU)

Jet-launching Points and Angular momenta



Woitas et al. 2005



- From toroidal and poloidal velocities
  → footpoints r_0, where gas comes from
  → outer r_0 for the blue and red wing are about 0.4 and 1.6 AU (lower limits)
  → consistent with disk winds
- About 2/3 of the disk angular momentum may be carried away by jet.

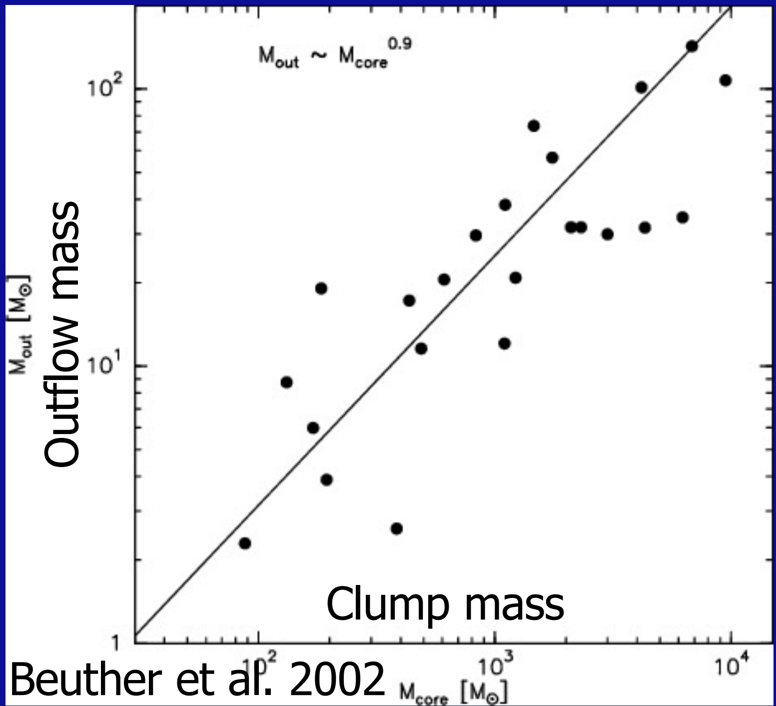
Topics today

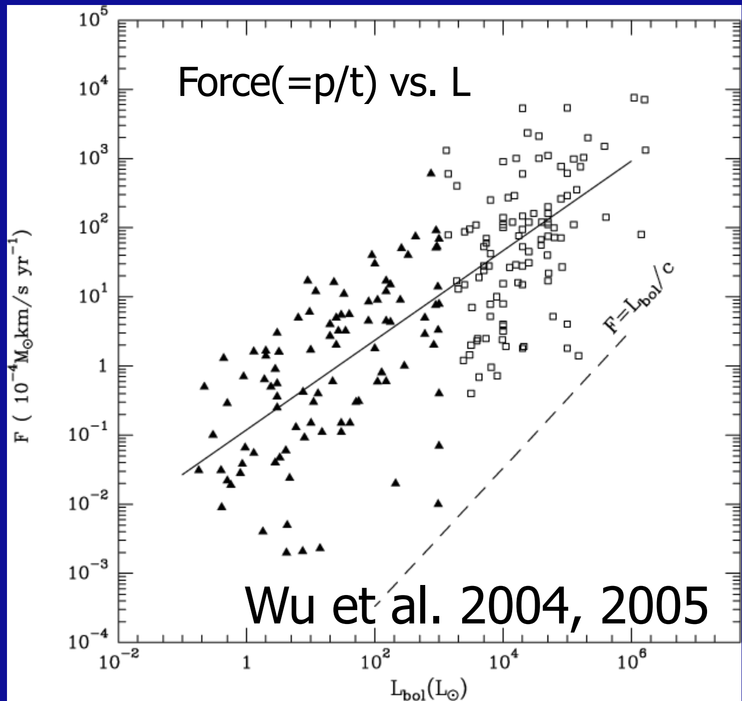
- General outflow properties
- Jet launching
- Outflow entrainment

Outflow Entrainment I

- Molecular outflow masses much larger than stellar masses
  → Outflow mass not directly from star-disk but swept-up entrained gas.

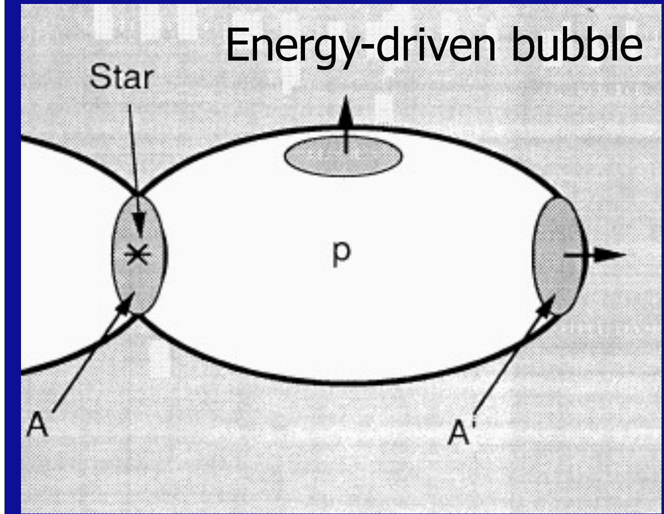
- Force in outflow cannot be explained just by force excerted from
  central object → other outflow driving and entrainment processes required.





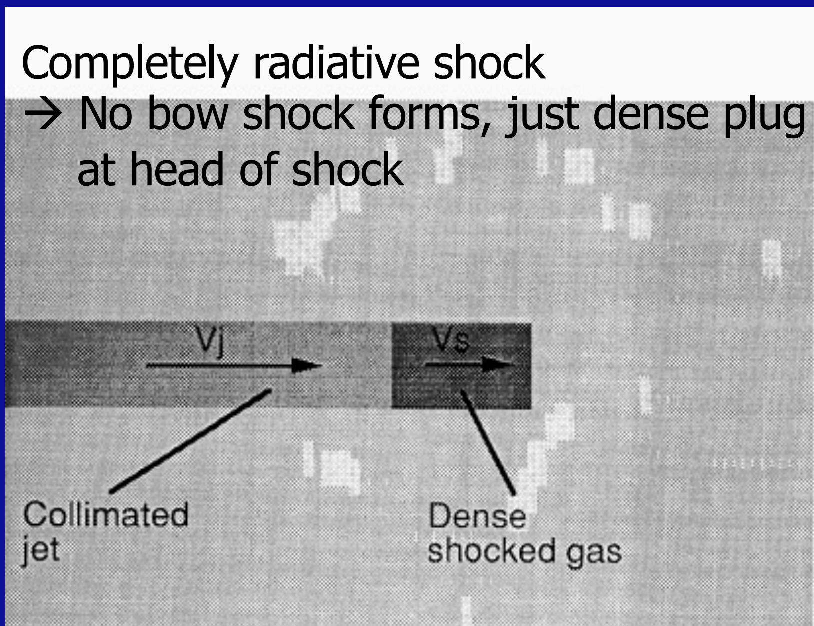
Outflow driving II

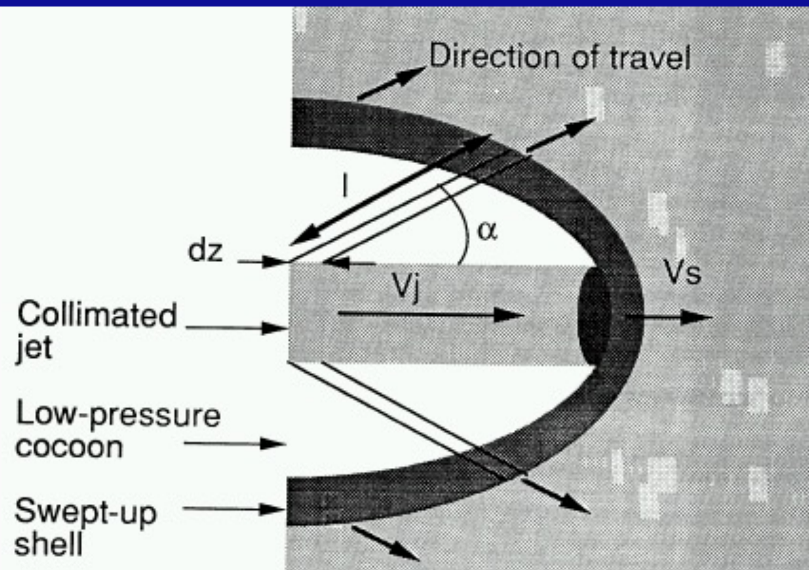
Momentum-driven vs. energy-driven molecular outflows



- Energy-driven: jet-energy conserved in pressurized bubble that gets released adiabatically as the bubble expands.
  → large transverse velocities which are not observed
  → momentum conservation better

- Completely radiative shock → only dense plug at front
- Completely adiabatic shock → large bow shocks with mainly transverse motions
- Both wrong → intermediate solution with highly dissipative shock required → forward motion & bow shock
  → accelerate the ambient gas





Highly dissipative shock: Forward motion AND bow-shock for gas entrainment.

Masson et al. 1993

Outflow entrainment models I

Basically 4 outflow entrainment models are discussed in the literature:

Turbulent jet entrainment model

- Working surfaces at the jet boundary layer caused by Kelvin-Helmholtz instabilities form viscous mixing layer entraining molecular gas.
  → The mixing layer grows with time and whole outflow gets turbulent.

- Broken power-law of mass-velocity relation is reproduced, but velocity decreases with distance from source → opposite to observations

Jet-bow shock model

- Jet impacts on ambient gas → bow shocks are formed at head of jet.
  → High pressure gas is ejected sideways
  → broader bow shock entraining the ambient gas.
  → Episodic ejection produces chains of knots and shocks.

- Numerical modeling reproduces many observables, e.g. Hubble-law (outflow velocity increases with distance).

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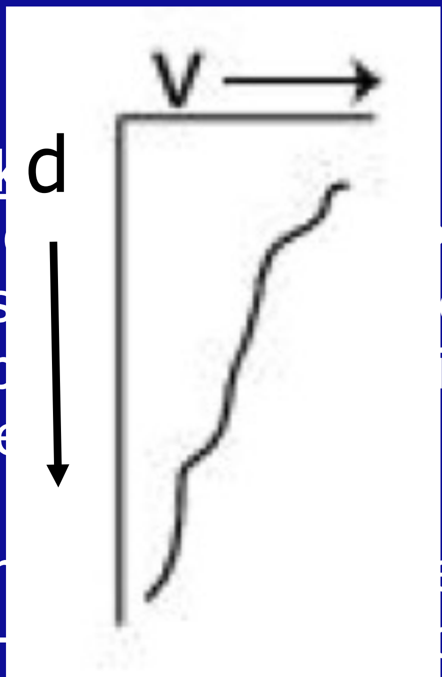
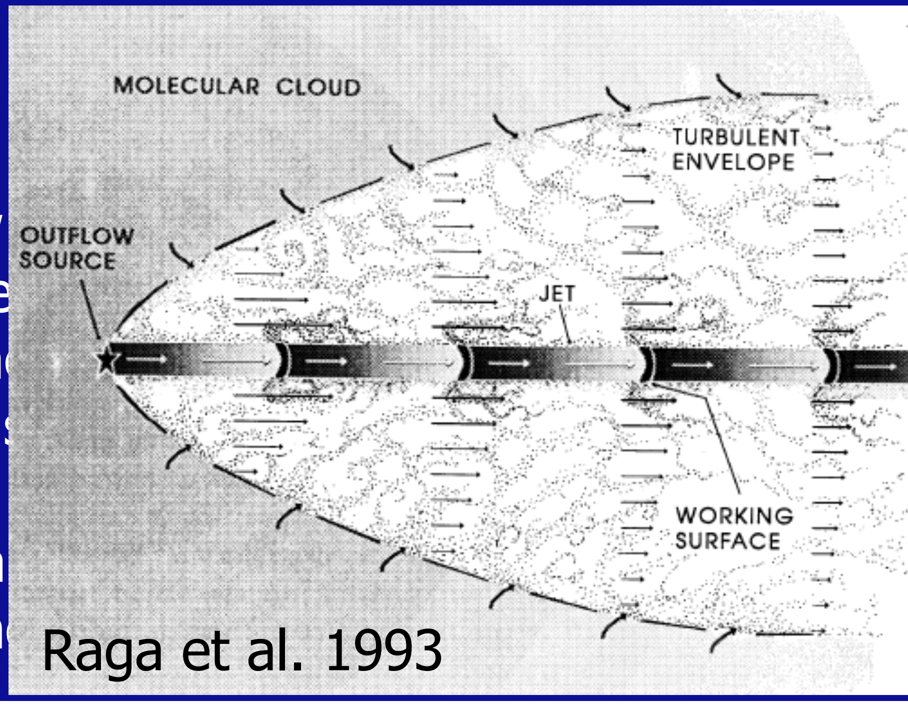
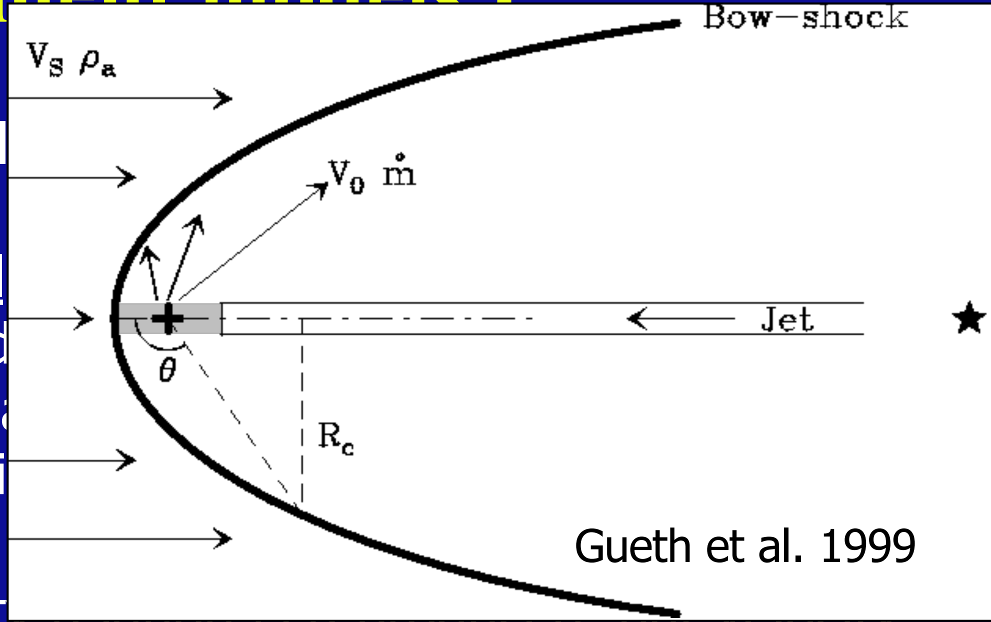




Raga et al. 1993

Outflow entrainment models I



Gueth et al. 1999

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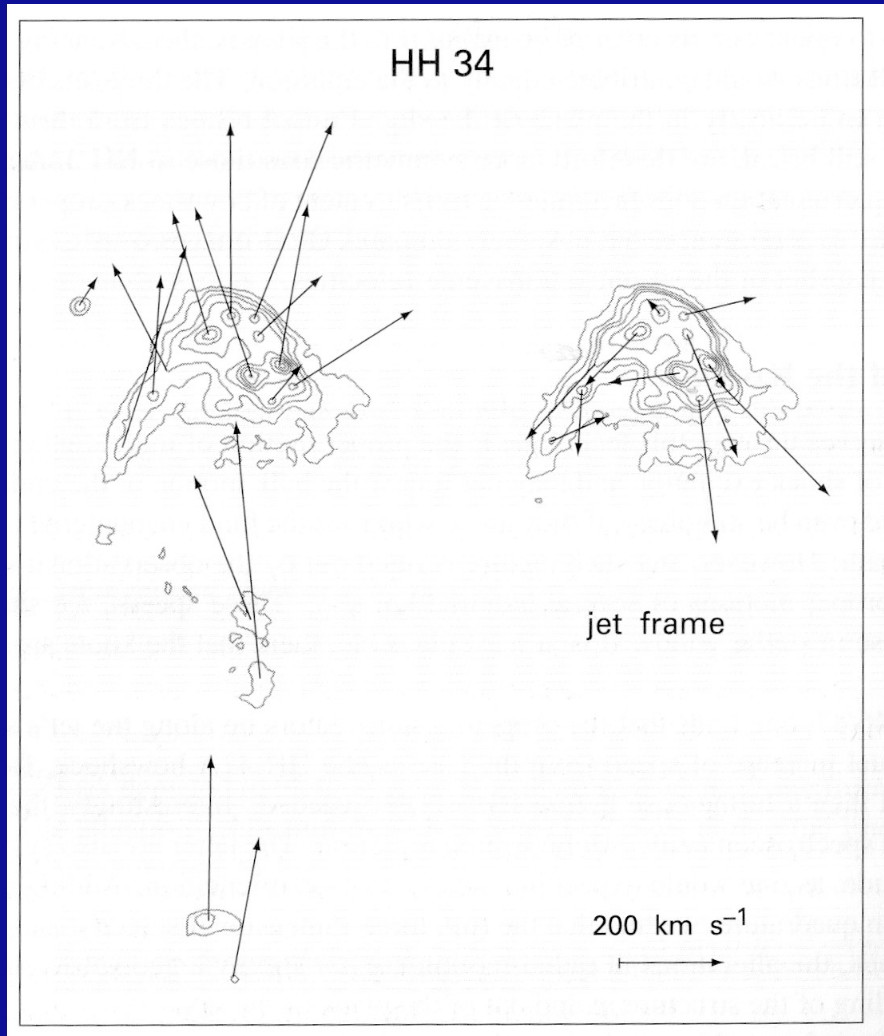
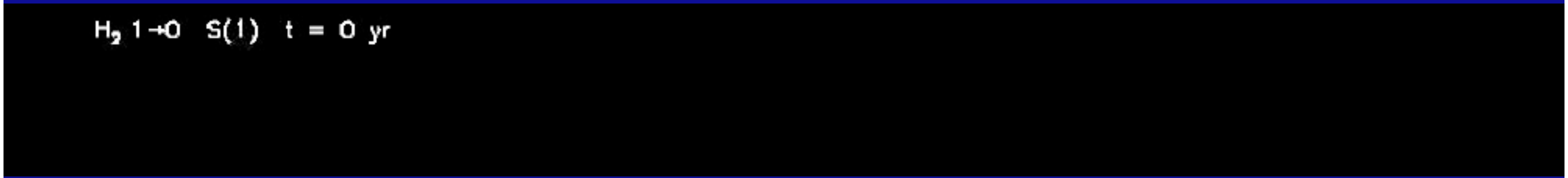
The Case of the HH34 Bow Shock



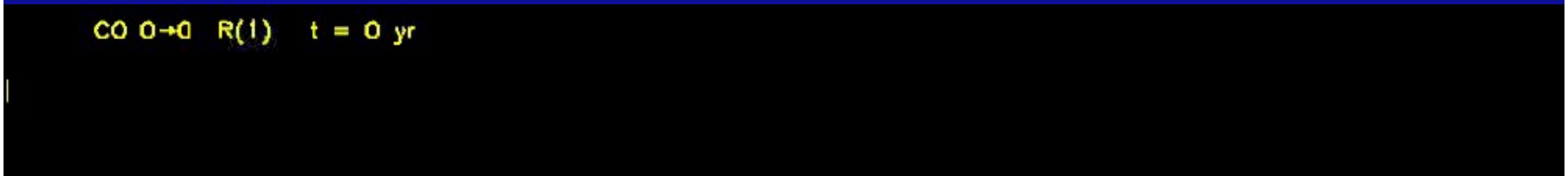
In the jet-frame, after subtracting the velocity of the mean axial flow, the knots are following the sides of the bow shock.

Reipurth et al. 2002

Jet simulations I



3-dimensional hydrodynamic simulations, including H, C and O chemistry and cooling of the gas, this is a pulsed jet.



Rosen & Smith 2004

Outflow Entrainment Models II

Wide-angle wind model

- Wide-angle wind blows into ambient gas forming a thin swept-up shell.

- Different degrees of collimation can be explained by different density structures of the ambient gas.

- Attractive models for older and low collimated outflows.

Circulation model

- Molecular gas not entrained by underlying jet/wind, but infalling gas is deflected from the central protostar by high MHD pressure.

- Proposed to explain massive outflows because originally considered difficult to entrain large amounts of gas. … not necessary anymore …

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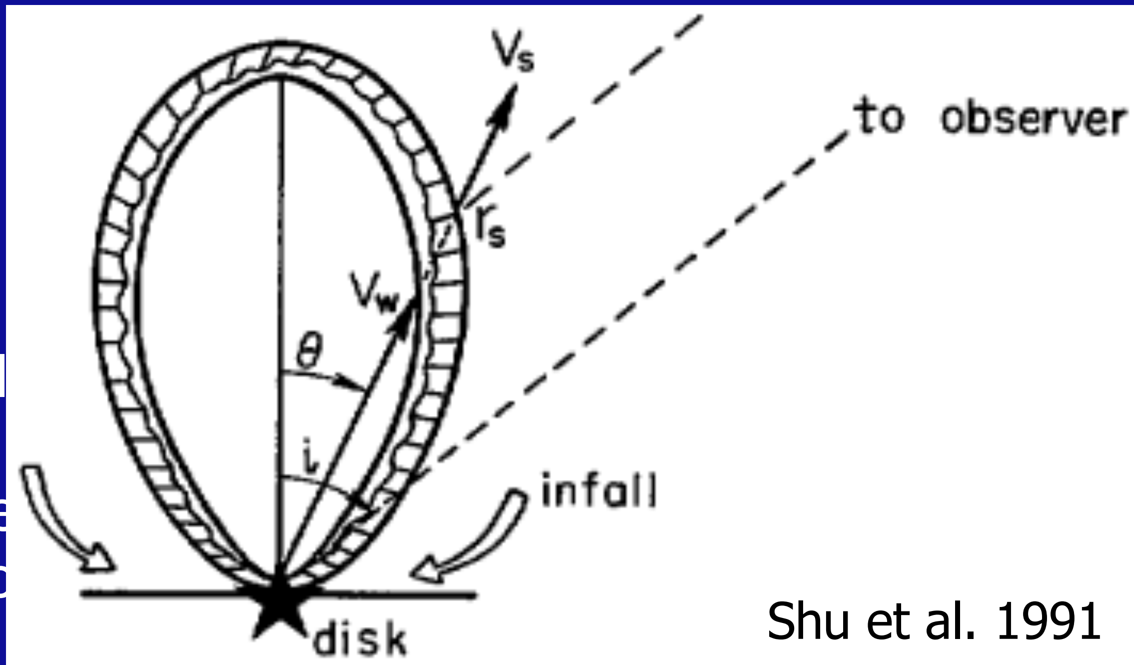
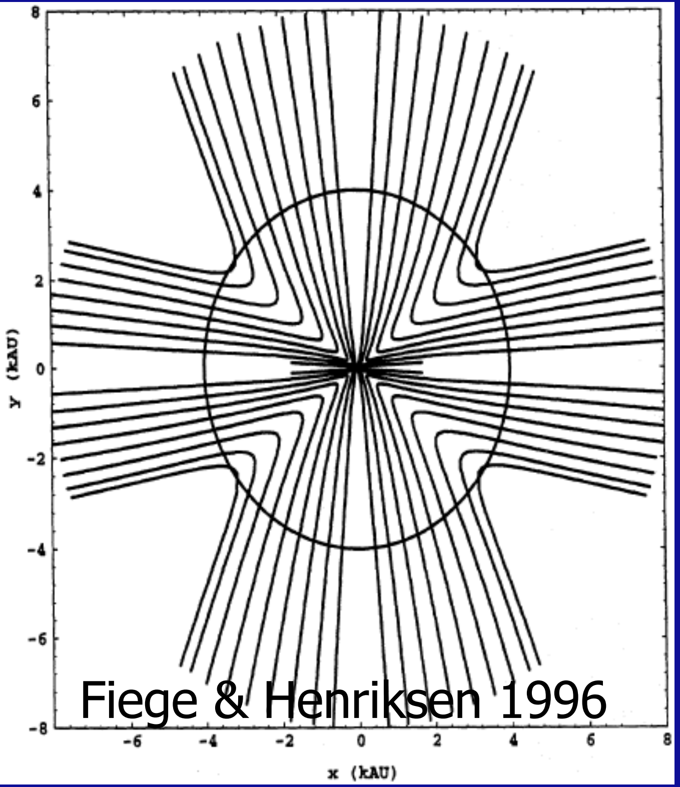


Shu et al. 1991

Outflow Entrainment Models II



Fiege & Henriksen 1996

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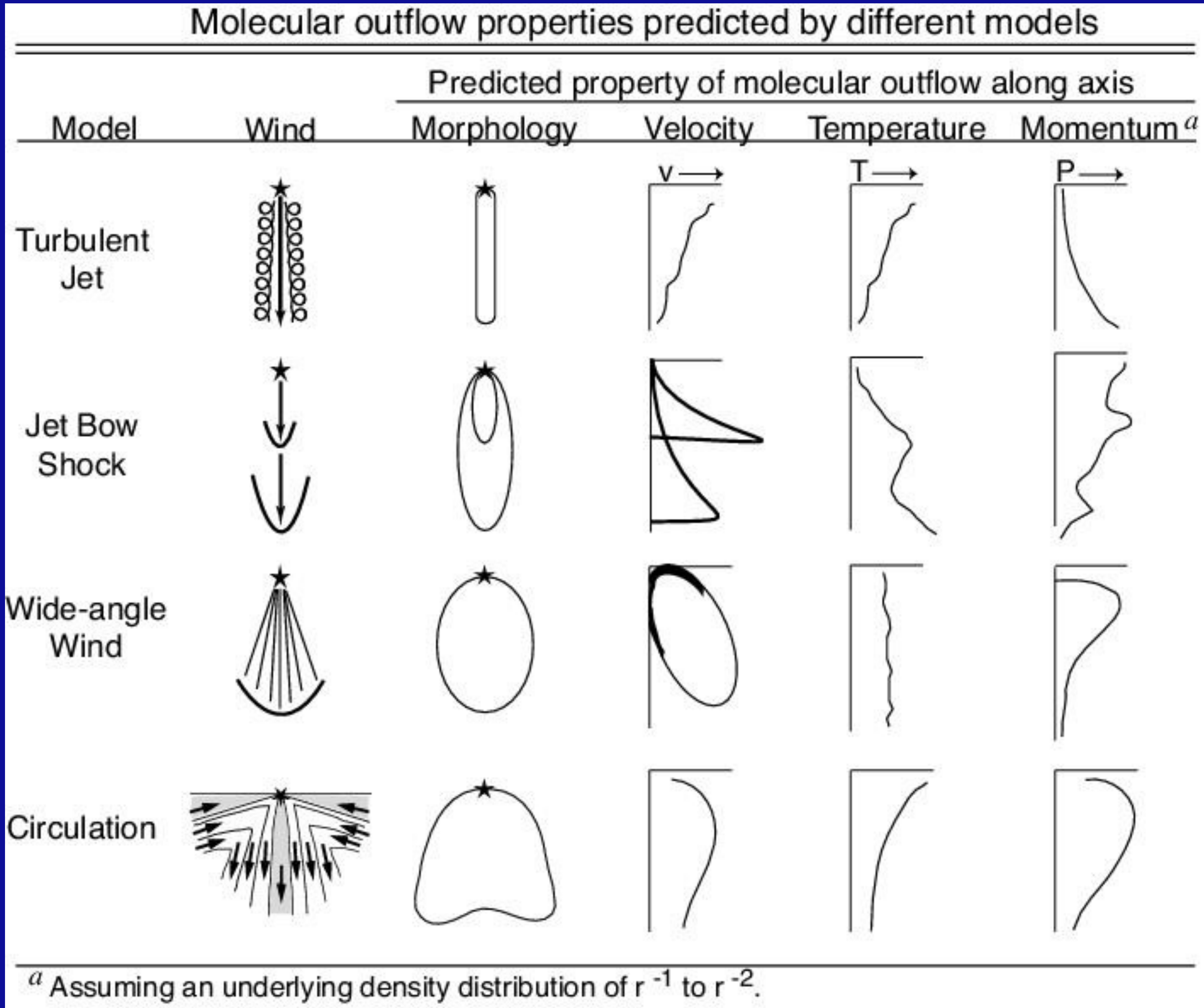
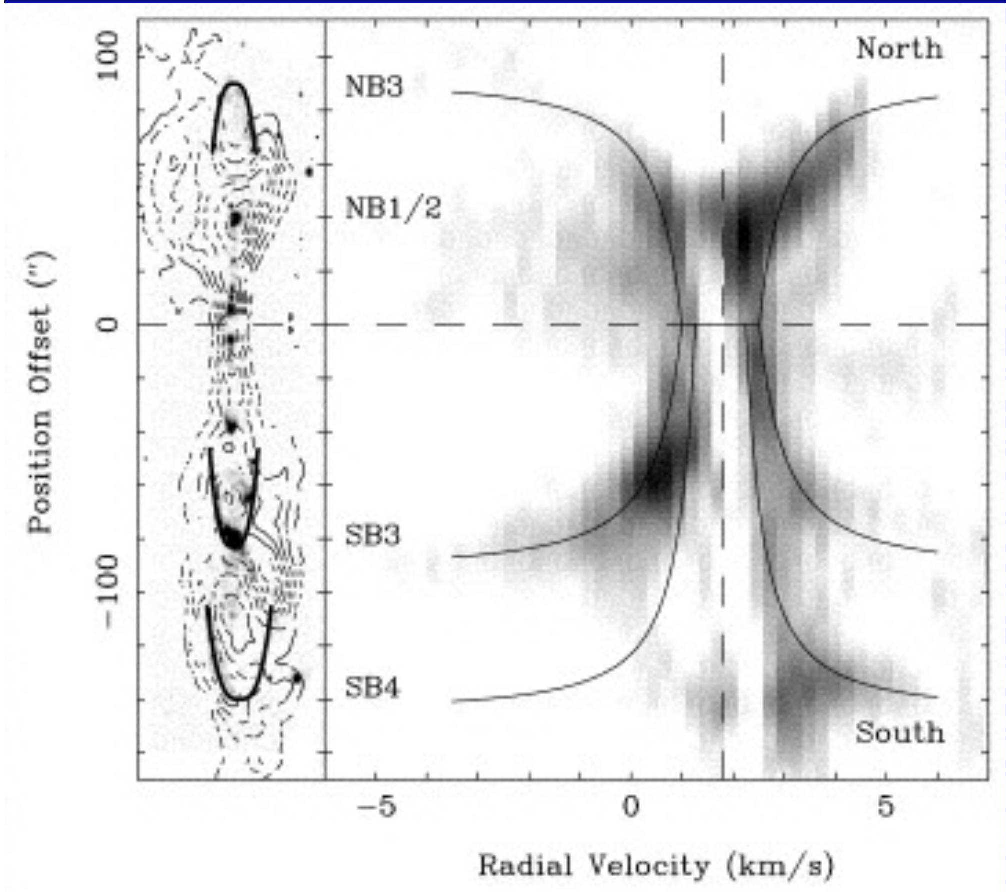
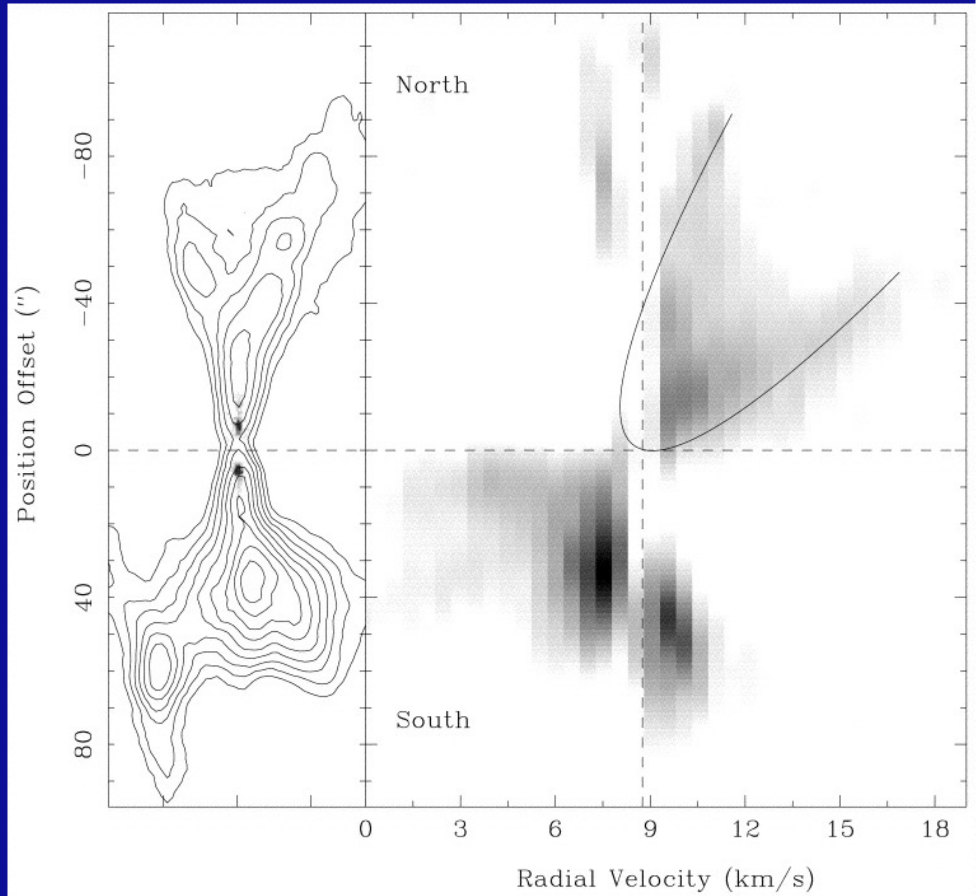
Outflow Entrainment Models III



Arce et al. 2007

Collimation and Position-Velocity Structure





HH212: consistent with jet-driving

VLA0548: consistent with wind-driving

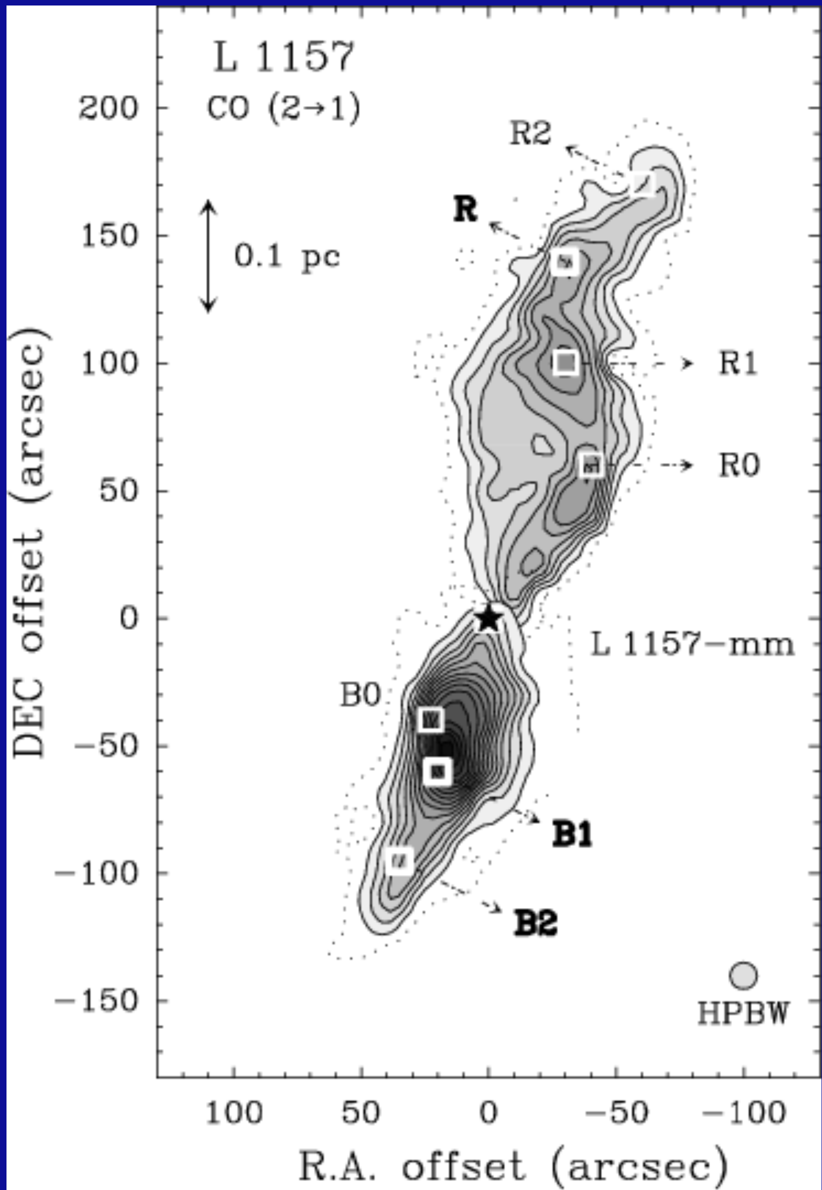
- pv-structure of jet- and wind-driven models very different
- Often Hubble-law observed → increasing velocity with increasing distance from protostar

Lee et al. 2001

Topics today

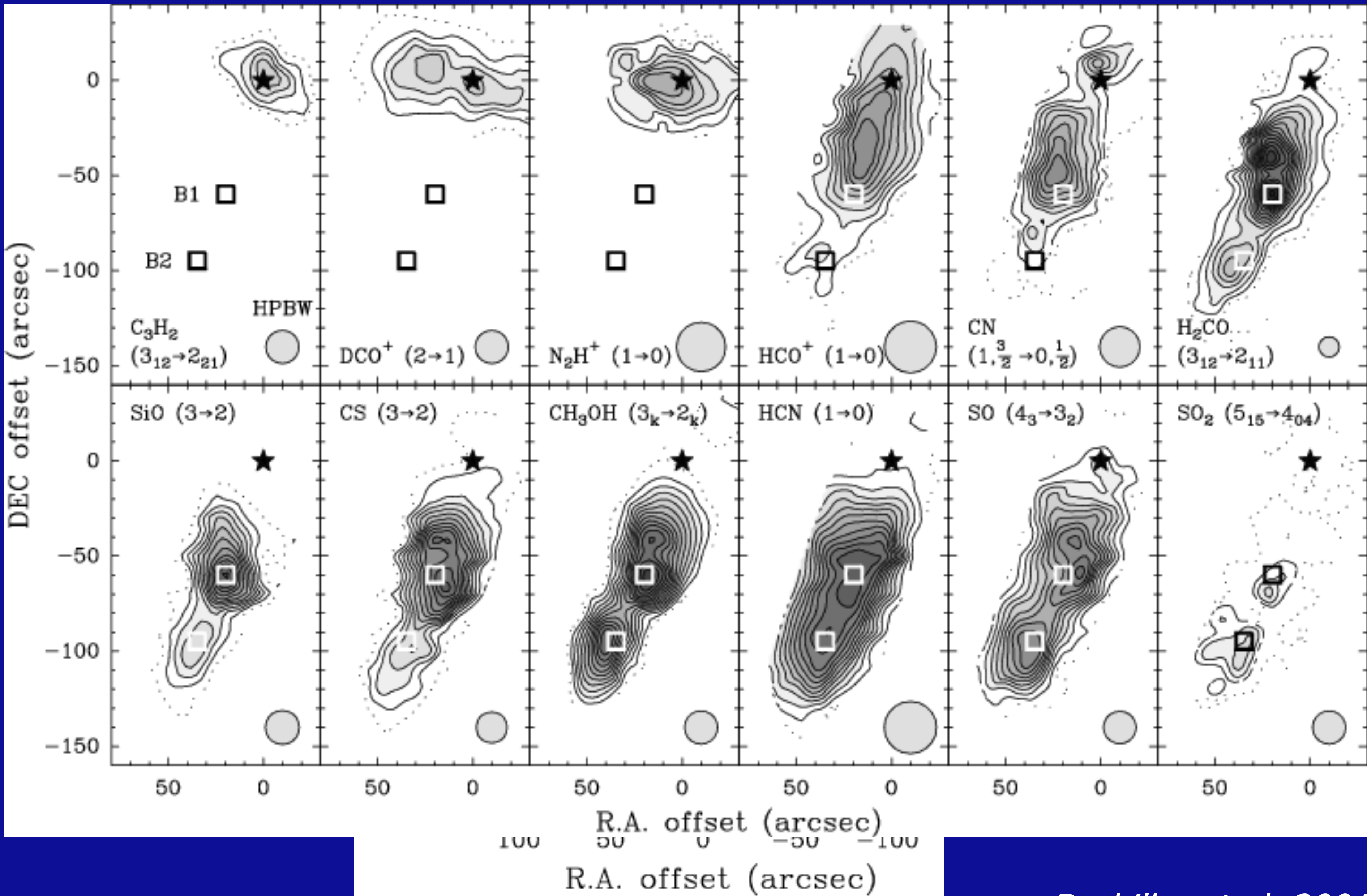
- General outflow properties
- Jet launching
- Outflow driving and entrainment
- Effects on the environment

Outflow Chemistry



Bachiller et al. 2001

Outflow Chemistry



Bachiller et al. 2001

Summary

- Outflows and jets are ubiquitous and necessary phenomena in star formation.

- Transport angular momentum away from protostar.

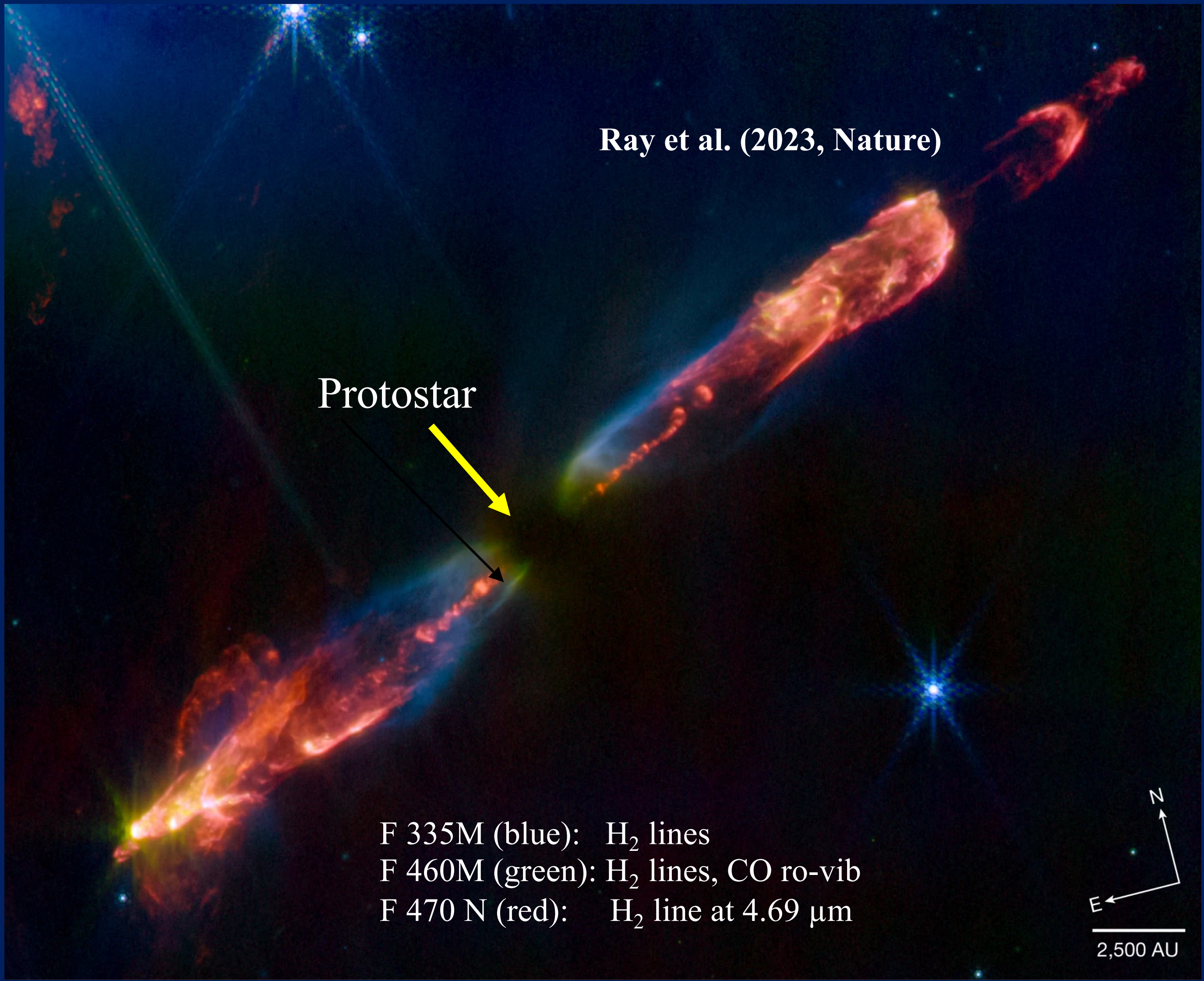
- They are formed by magneto-centrifugal disk-winds.

- Collimation is caused by Lorentz forces.

- Gas entrainment can be due to various processes: turbulent entrainment, bow-shocks, wide-angle winds, circulation …

- They inject significant amounts of energy in the ISM, may be important to maintain turbulence and disrupt their maternal clouds.

A Jet from a Protostar: Herbig Haro 211



Caratti o Garatti et al. (2024) – Detailed analysis

Jet is mostly molecular (H_2/HD) with an inner atomic structure