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.)
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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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- Definitions
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- Jet rotation and precession
- Maser observations and one particular outflow → Orion
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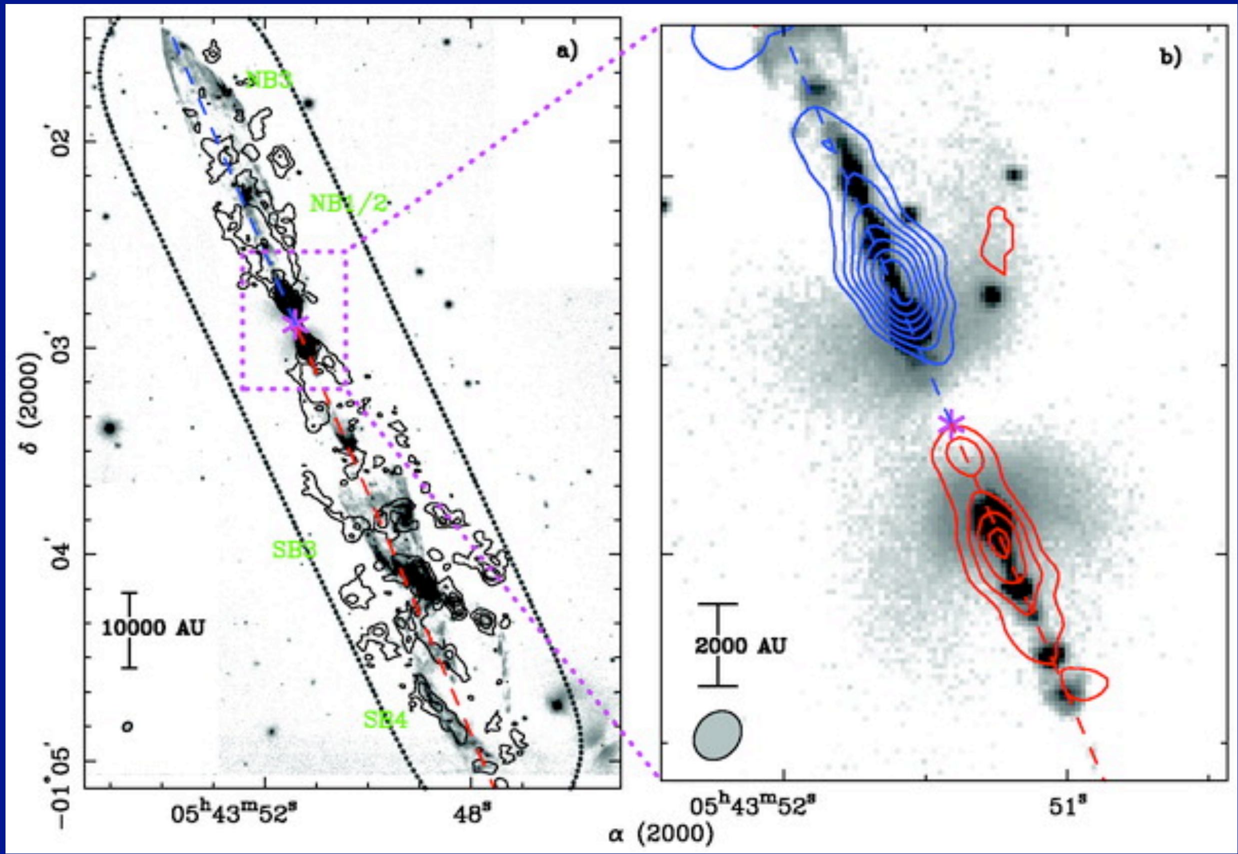
Jet/Outflow definitions



- Primary jet: Gas ejected directly from the protostar-disk interface: very collimated, usually v>150km/s, observable in H_2, [SII], [NII], cm cont.
- Jet-like molecular outflows: still very collimated, usually v<100km/s, entrained gas
- Molecular outflows: less collimated, usually v<50km/s, entrained gas

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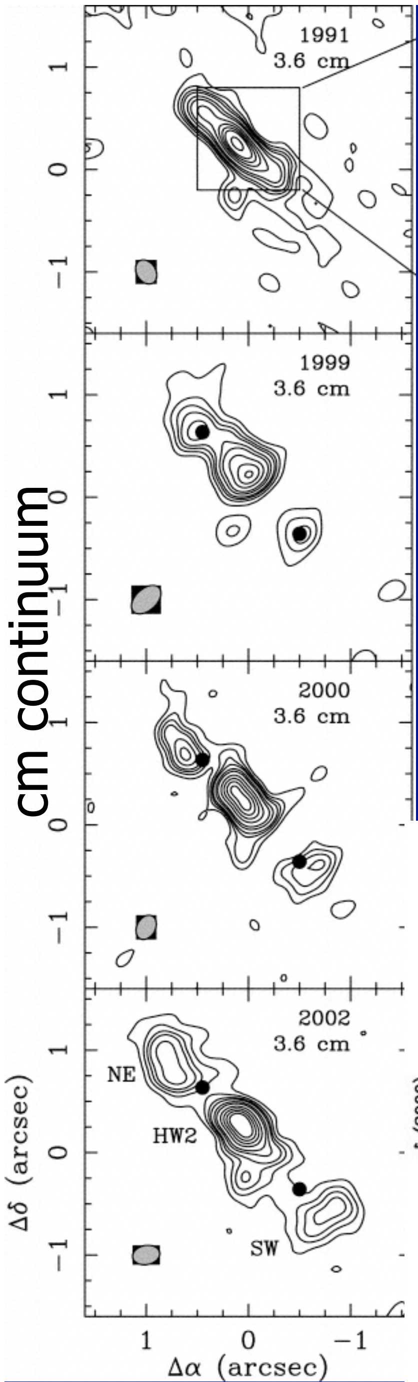
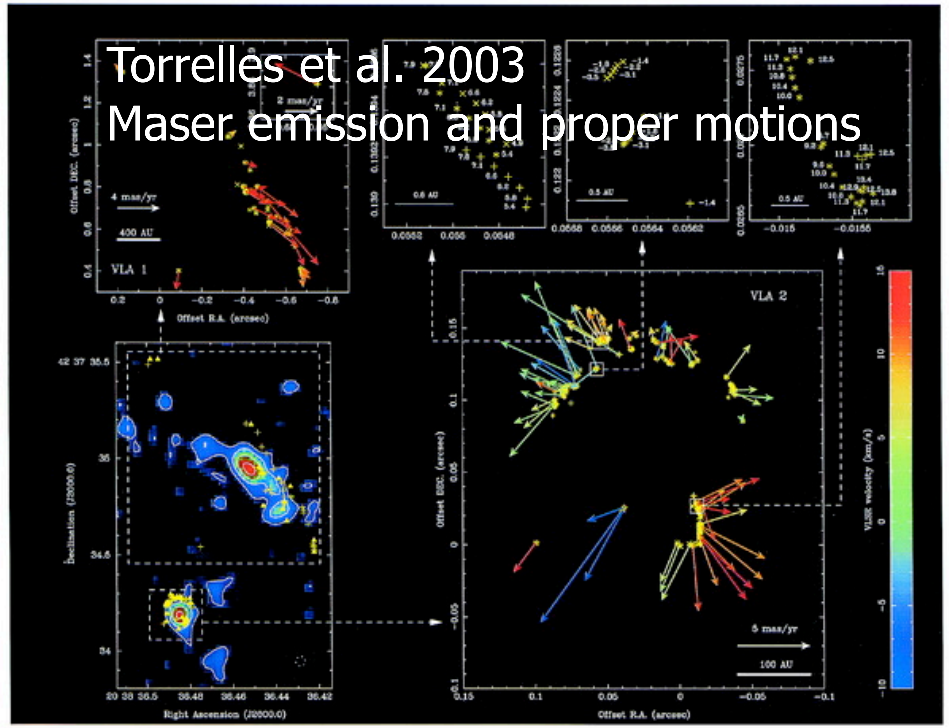
Various outflow tracers

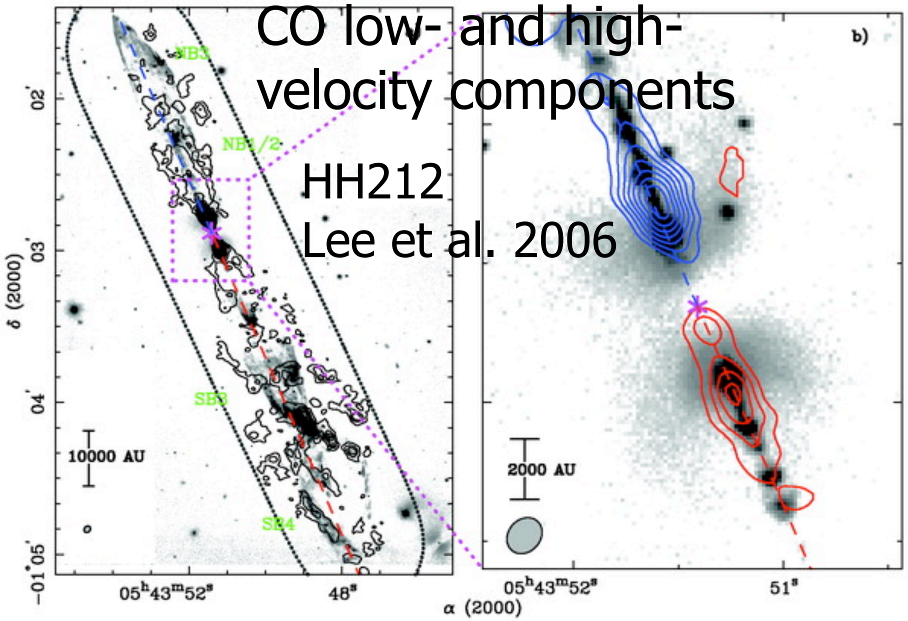


cm continuum

Curiel et al. 2006

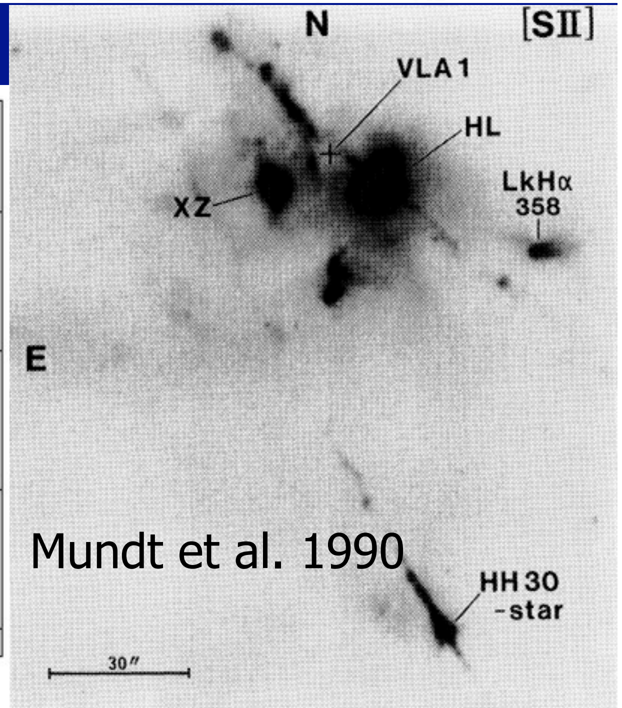


Torrelles et al. 2003
Maser emission and proper motions



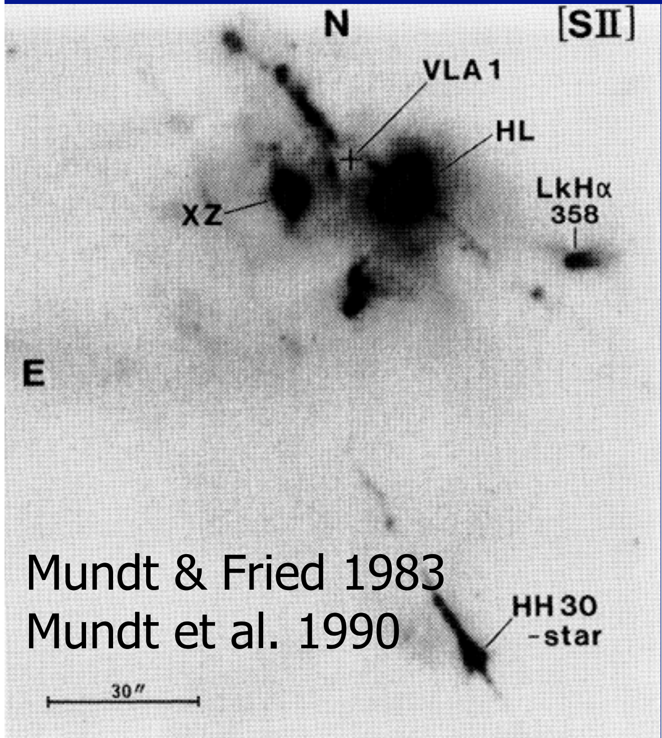
CO low- and high-velocity components

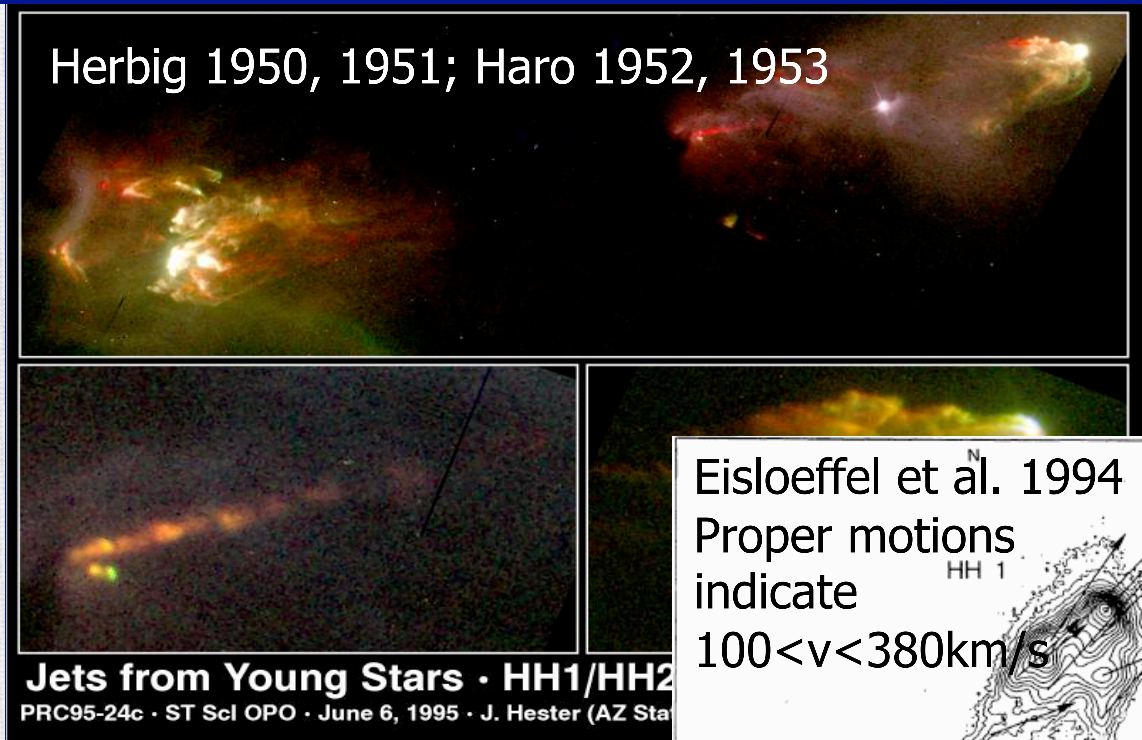
HH212
Lee et al. 2006

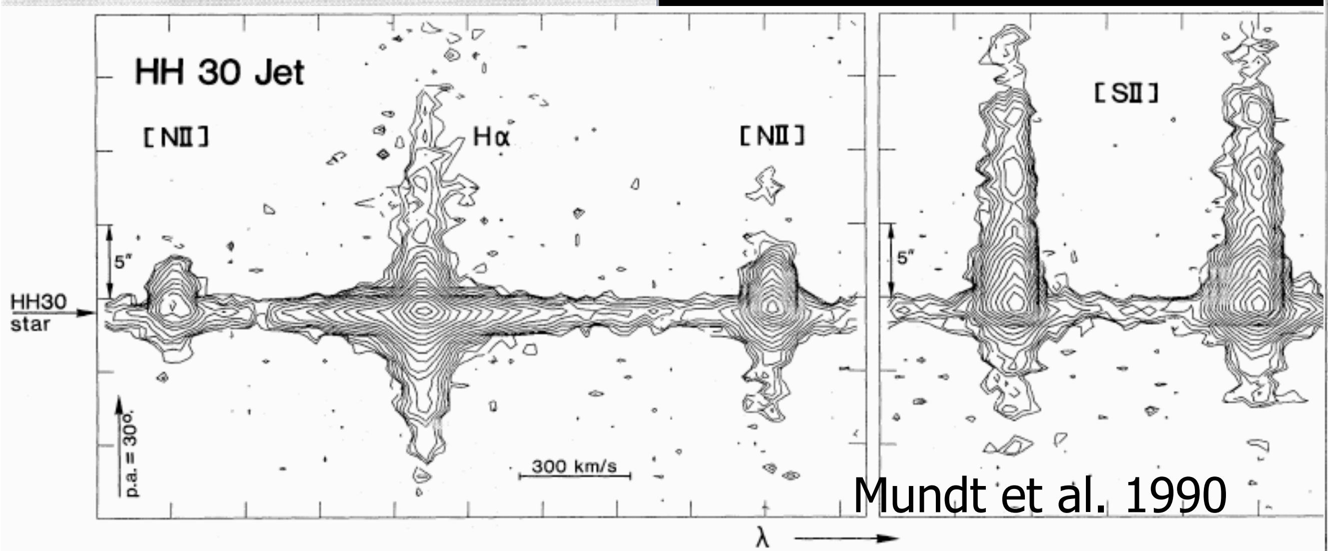


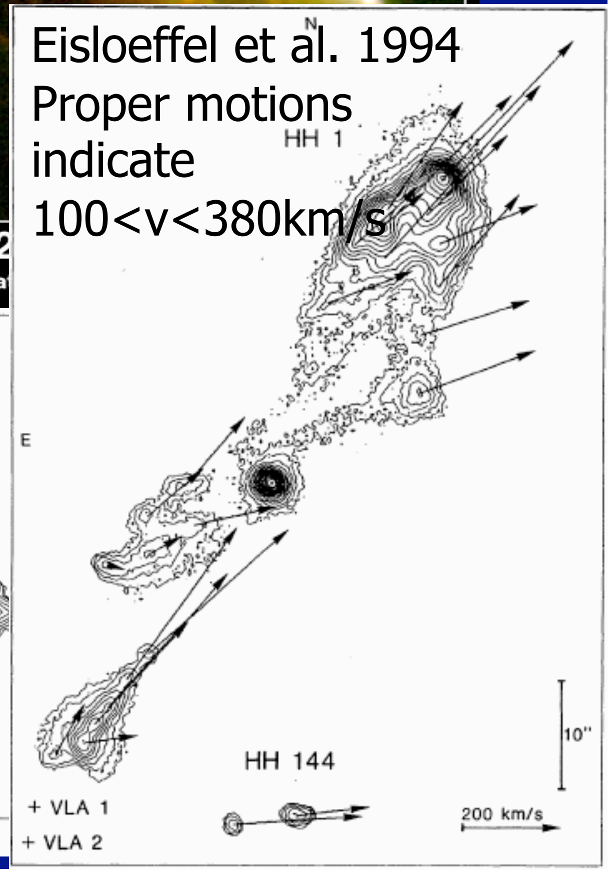
Mundt et al. 1990

Optical jet observations

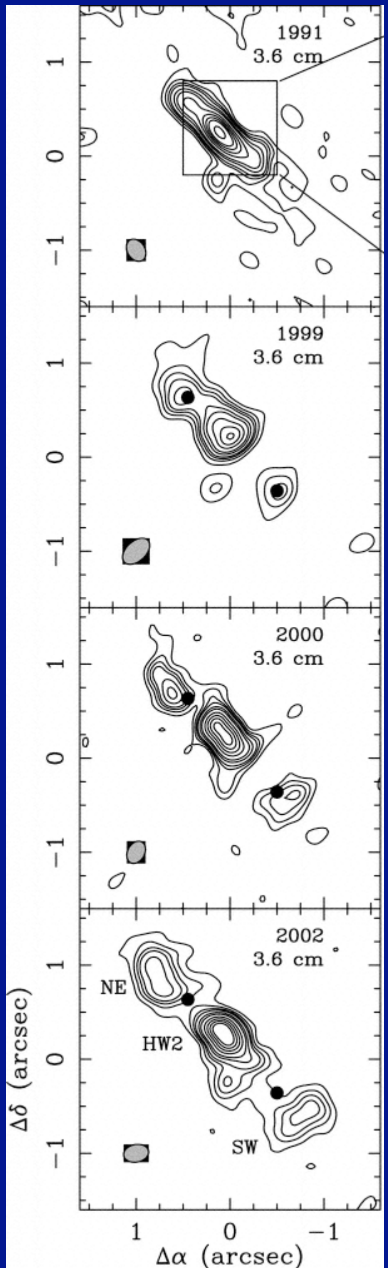




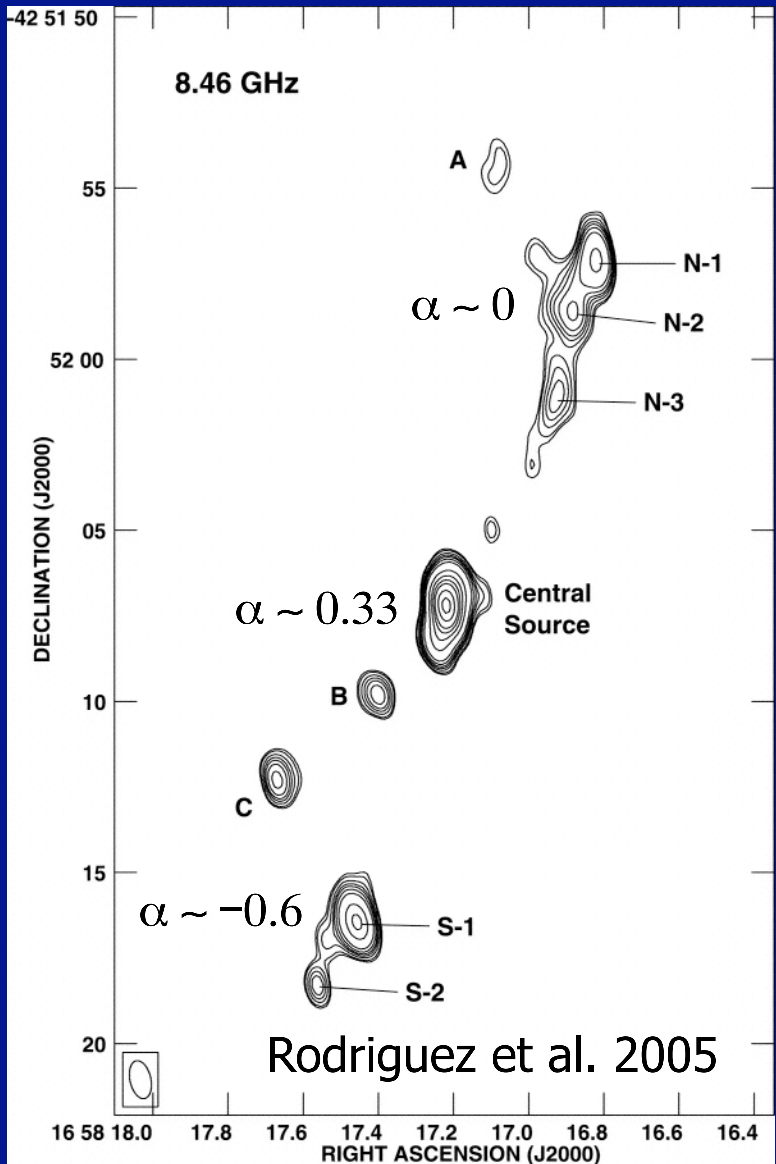




Free-free cm emission from ionized jet component



Curiel et al. 2005

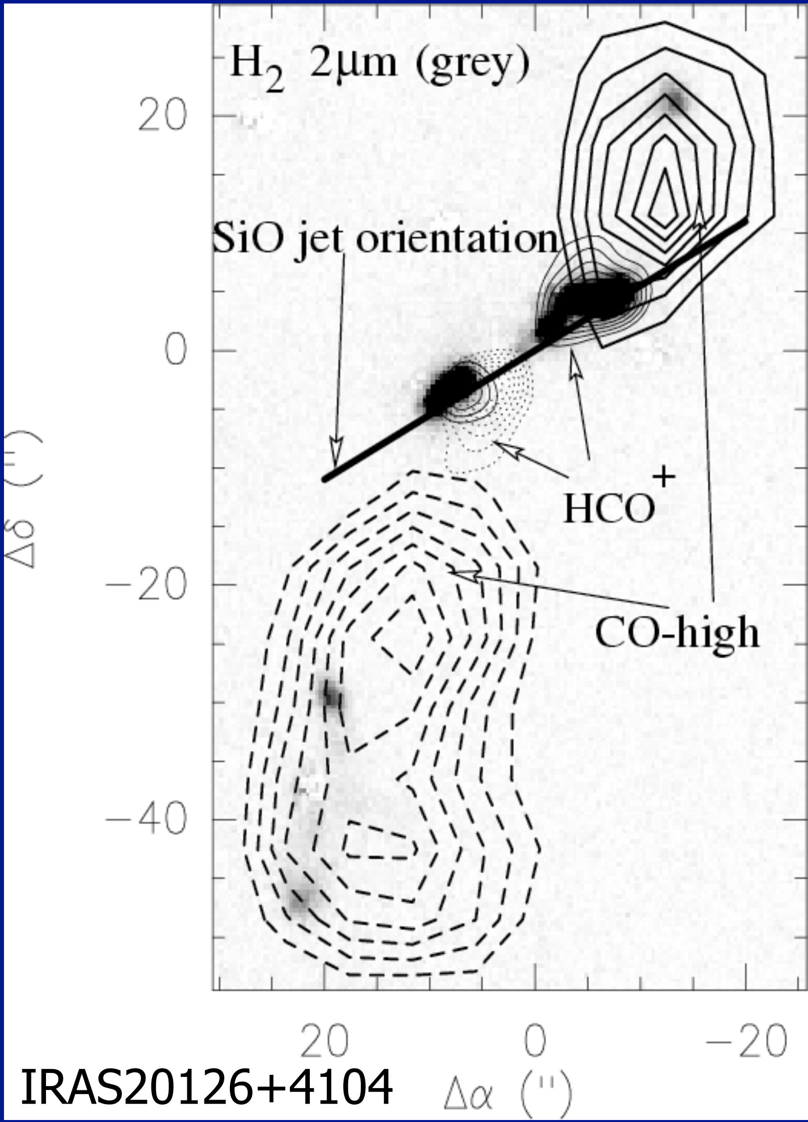


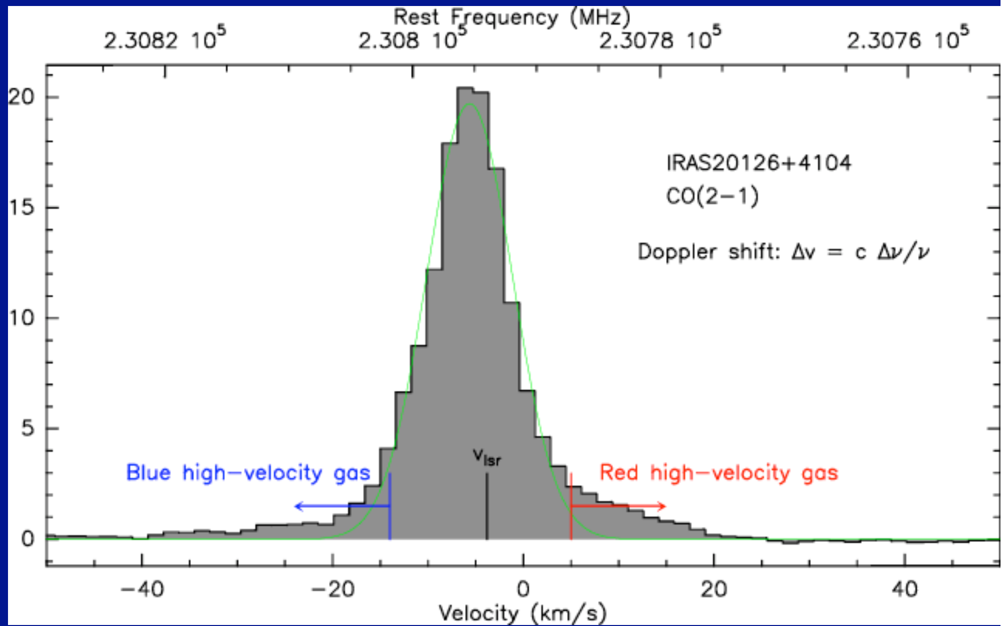
Spectral indeces (α) give information about jet:

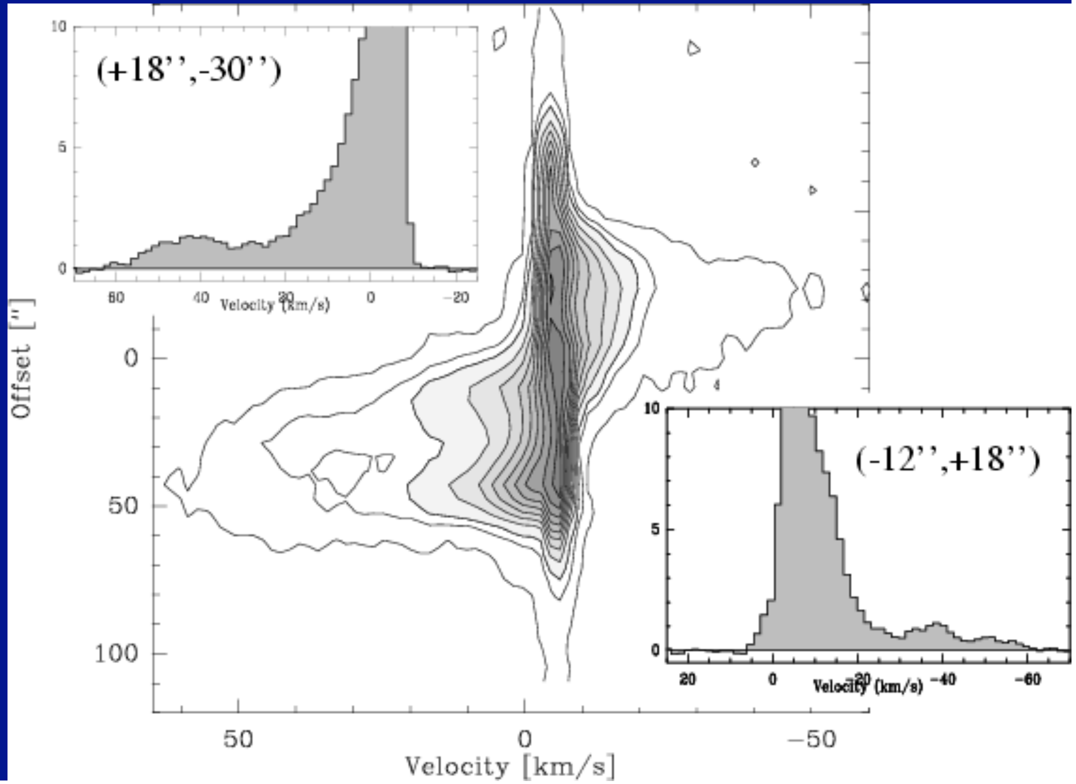
- Between 2 and -0.1 thermal ionized wind (Reynolds 1986)
- Typical spherical wind α~0.6
- Collimated jets, even lower values of α
- Optically thin thermal emission → α around 0
- Synchrotron emission → α negative

Different jet components may be produced by shock waves that can accelerate some e^- to relativistic speed, whereas most remain thermal.

Molecular outflows

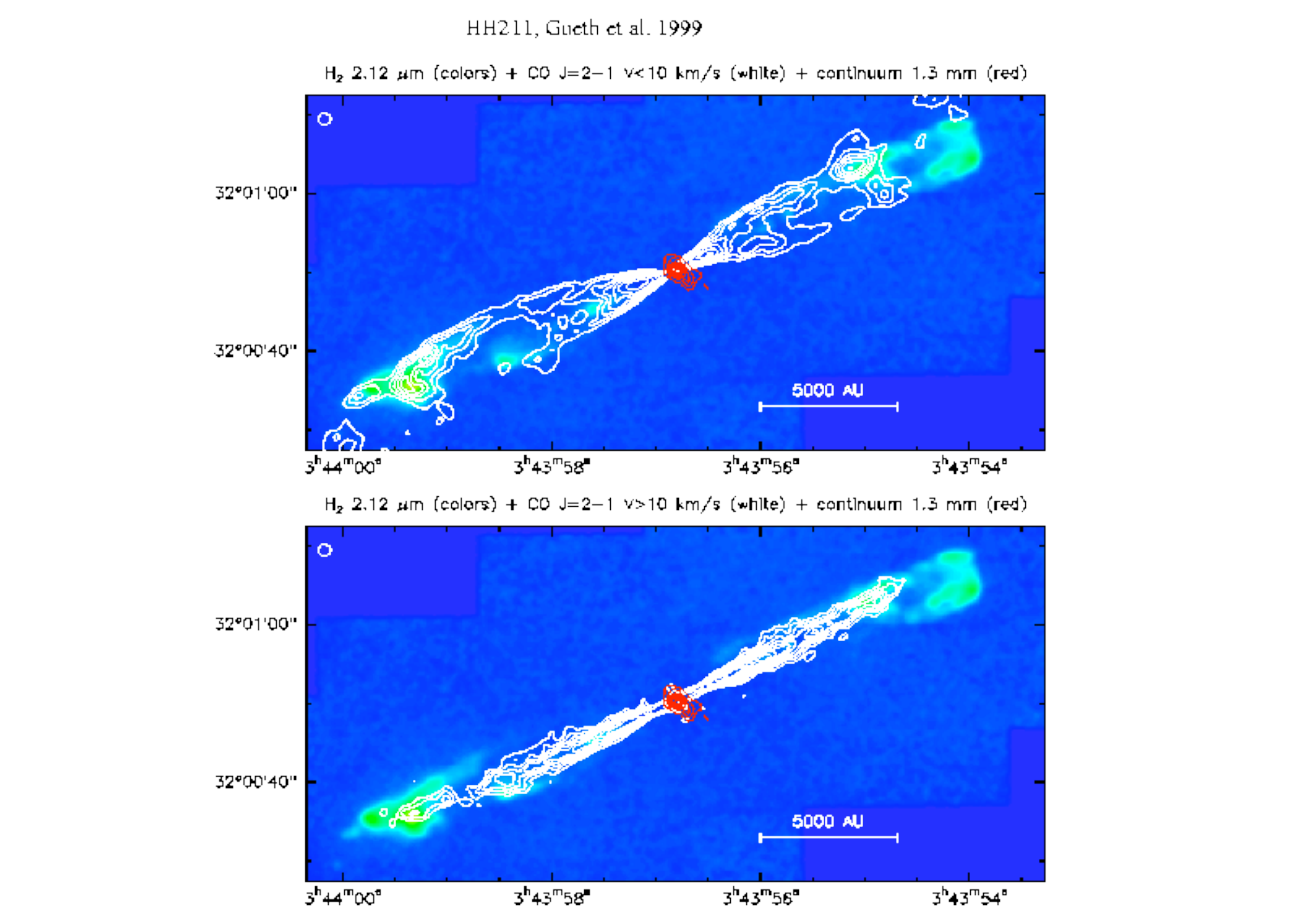




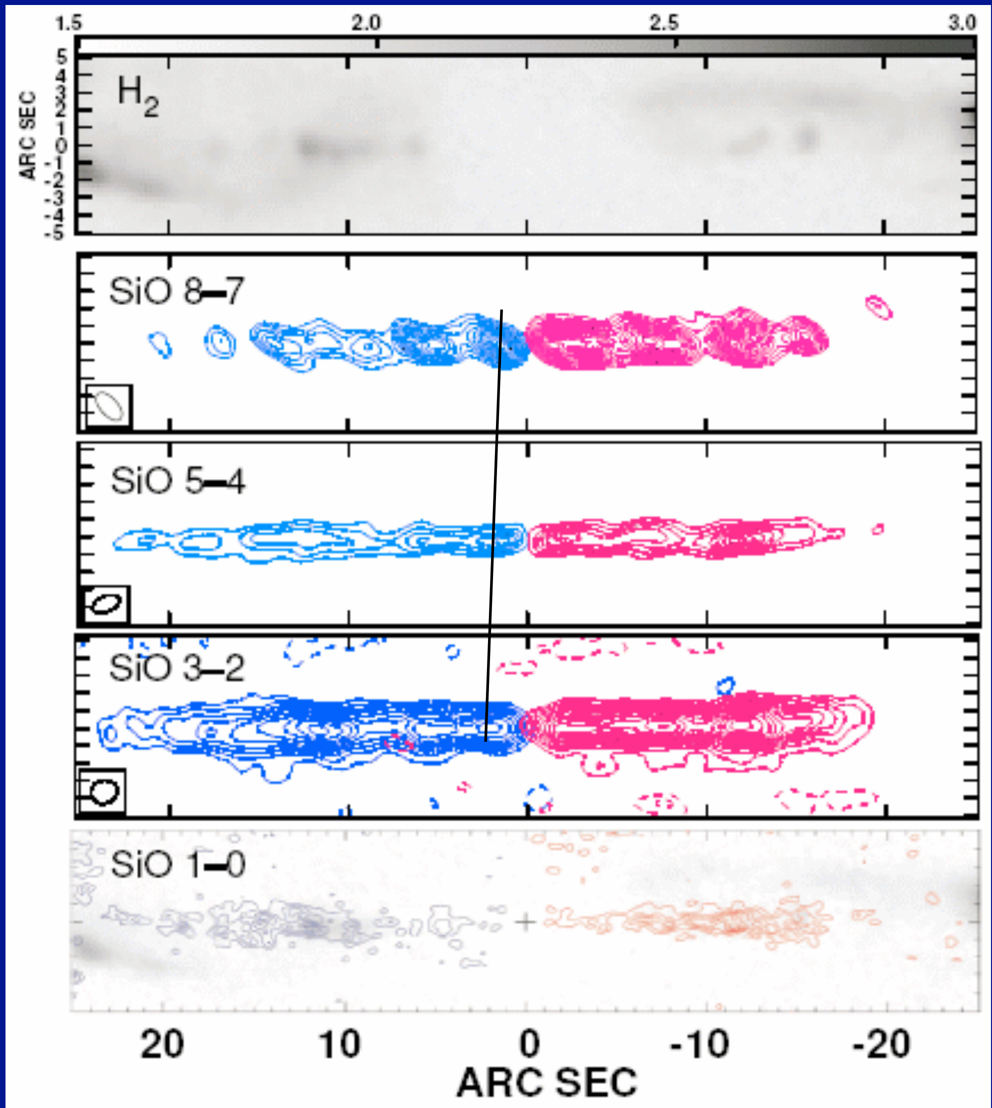


Lebron et al. 2006

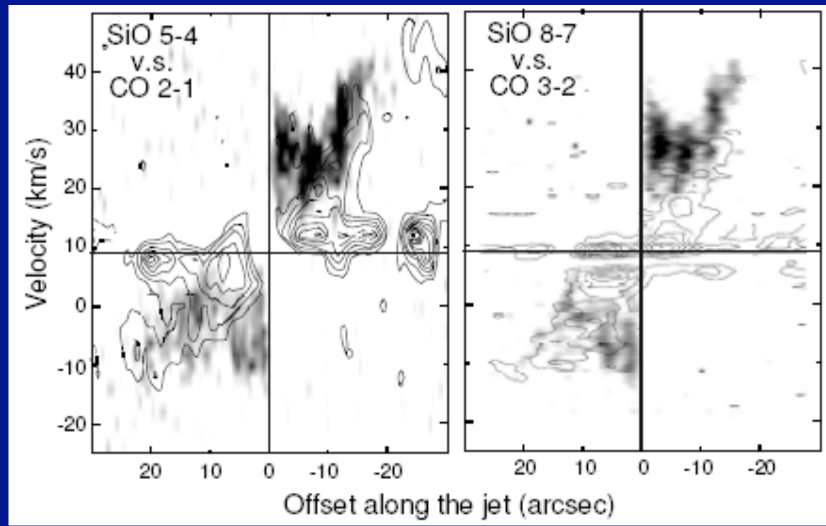
The prototypical molecular outflow HH211



Jet entrainment in HH211



From Hirano et al. 2006, Palau et al. 2006, Chandler & Richer 2001, Gueth et al. 1999, Shang et al. 2006



- Warmer gas closer to source
- Jet like SiO emission has always larger velocities than CO at the same projected distance from the driving protostar

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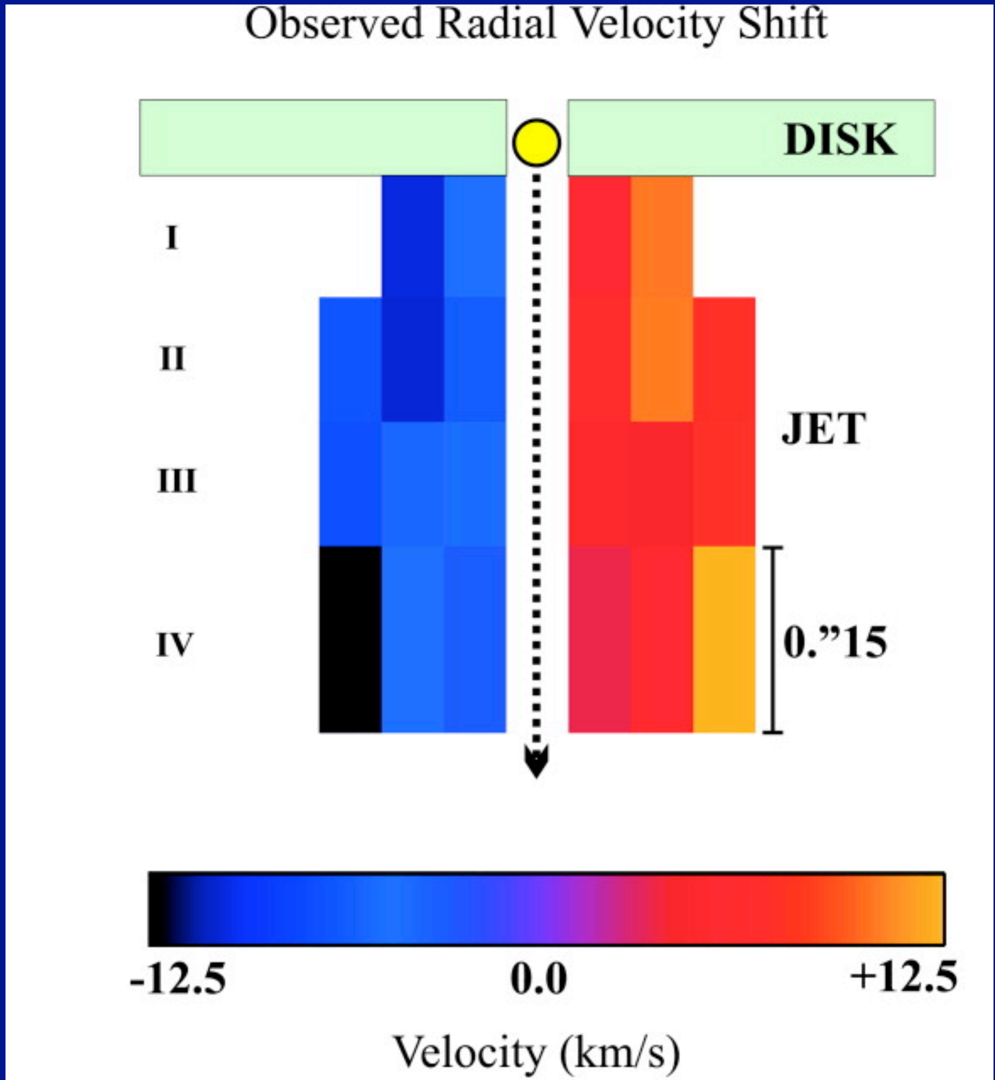
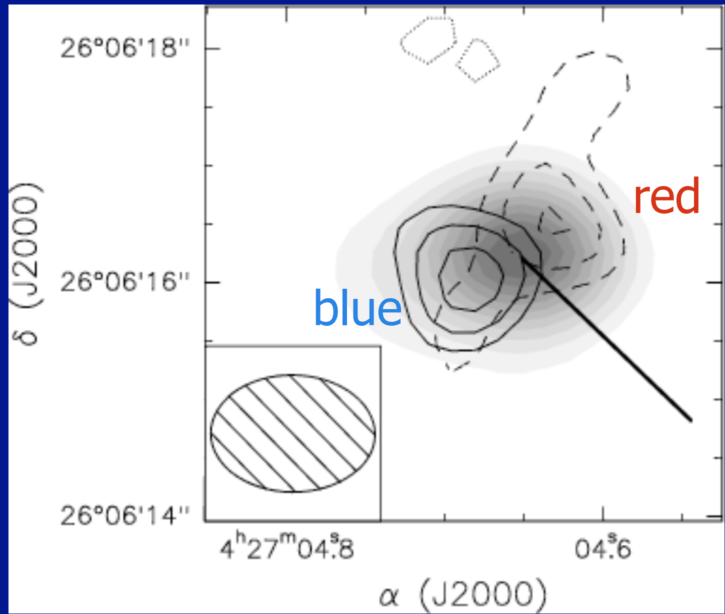
Jet rotation in DG Tau



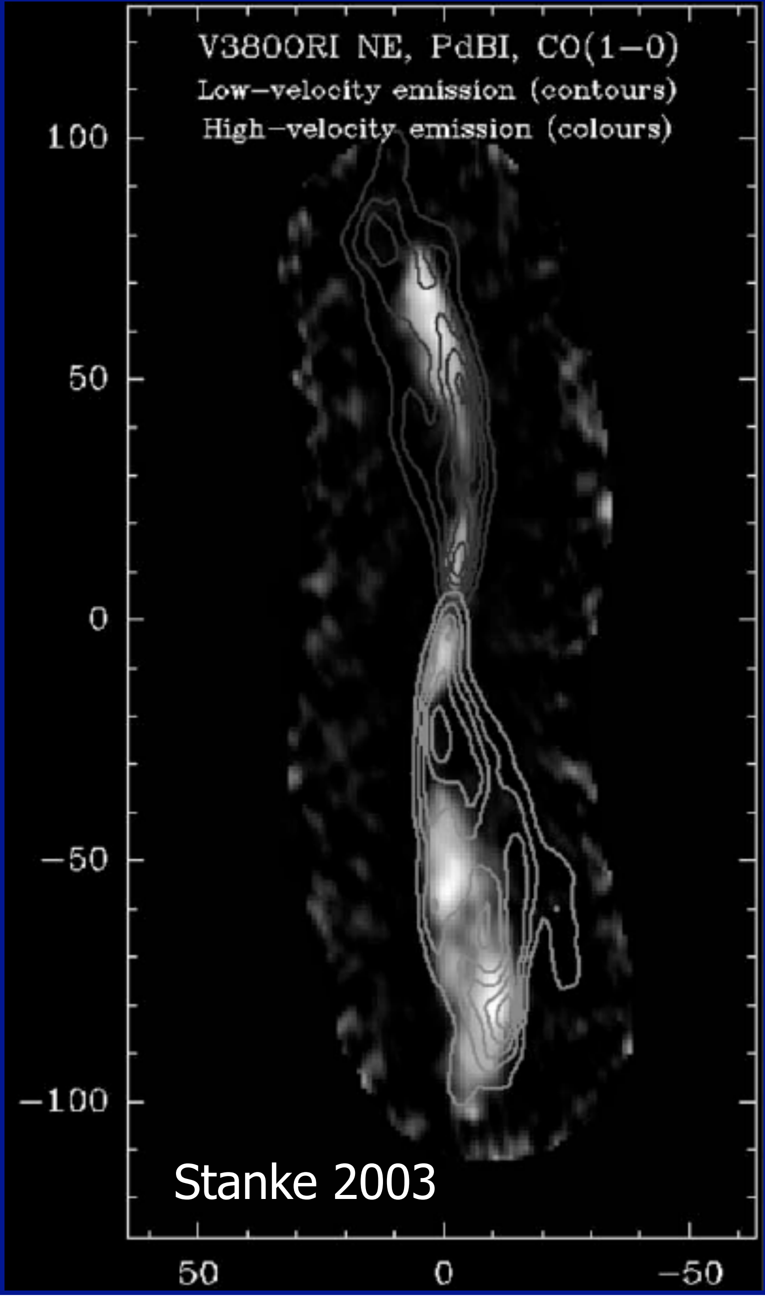
Bacciotti et al. 2002

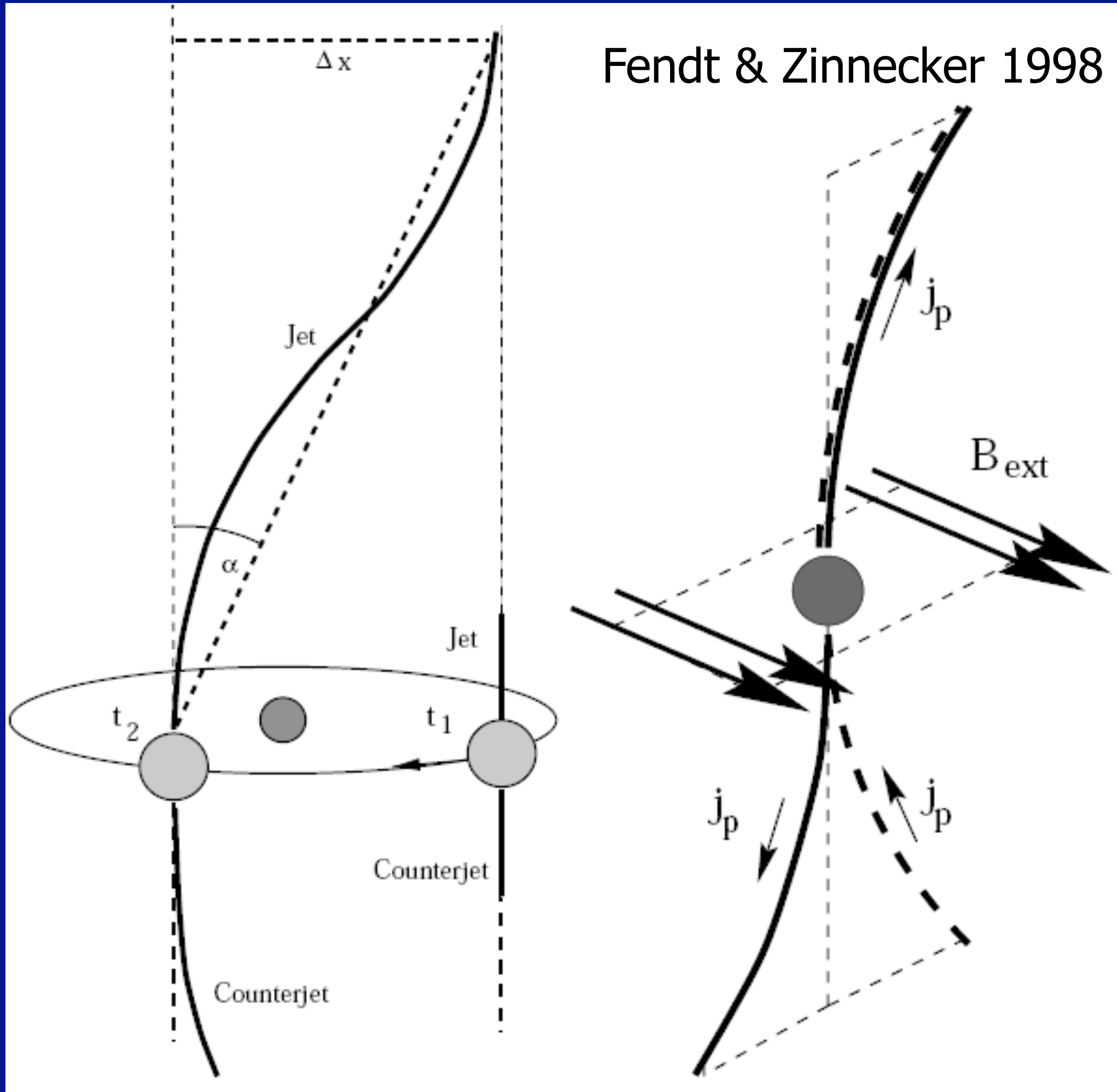


Testi et al. 2002

Corotation of disk and jet

Outflow/jet precession





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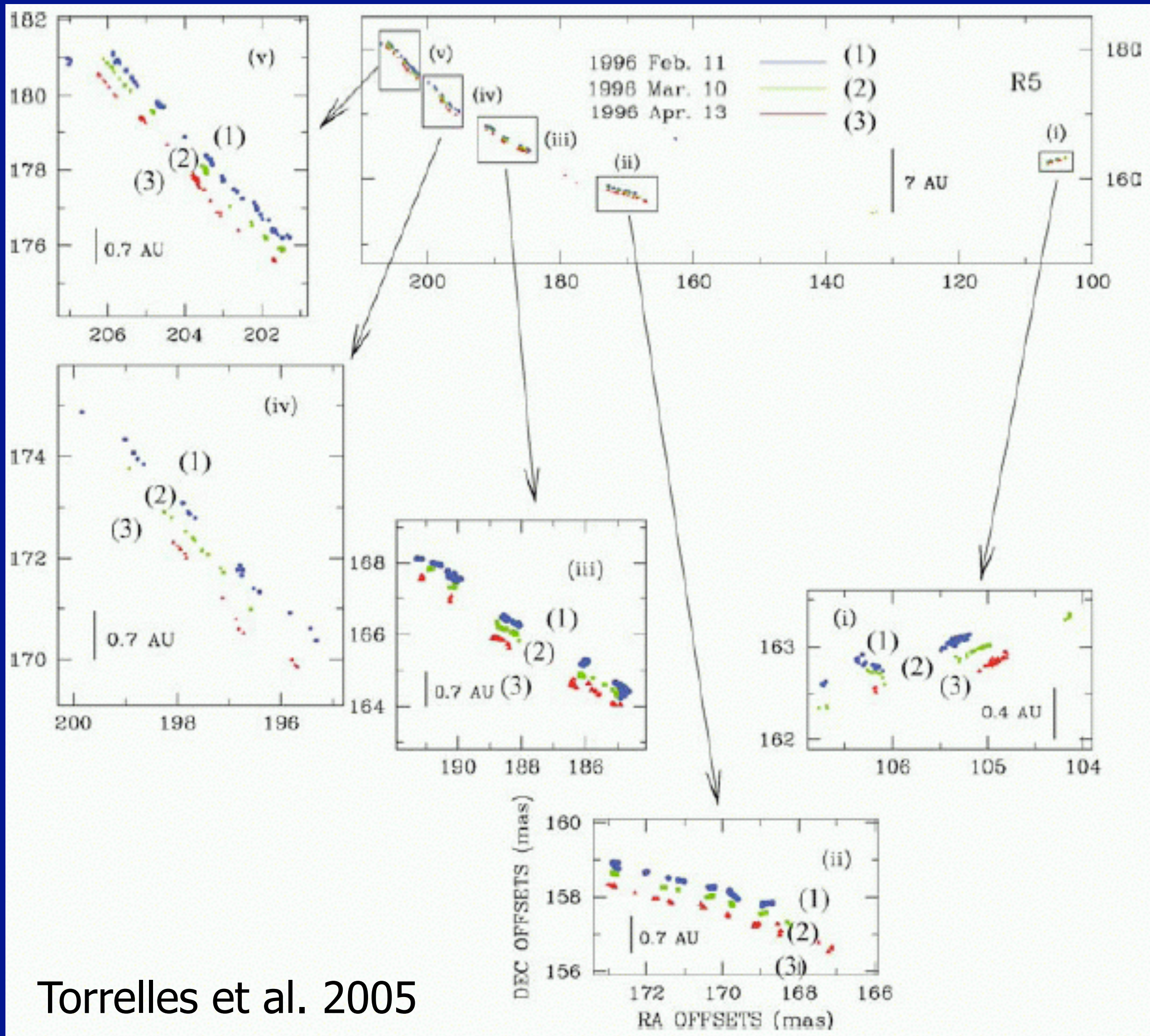
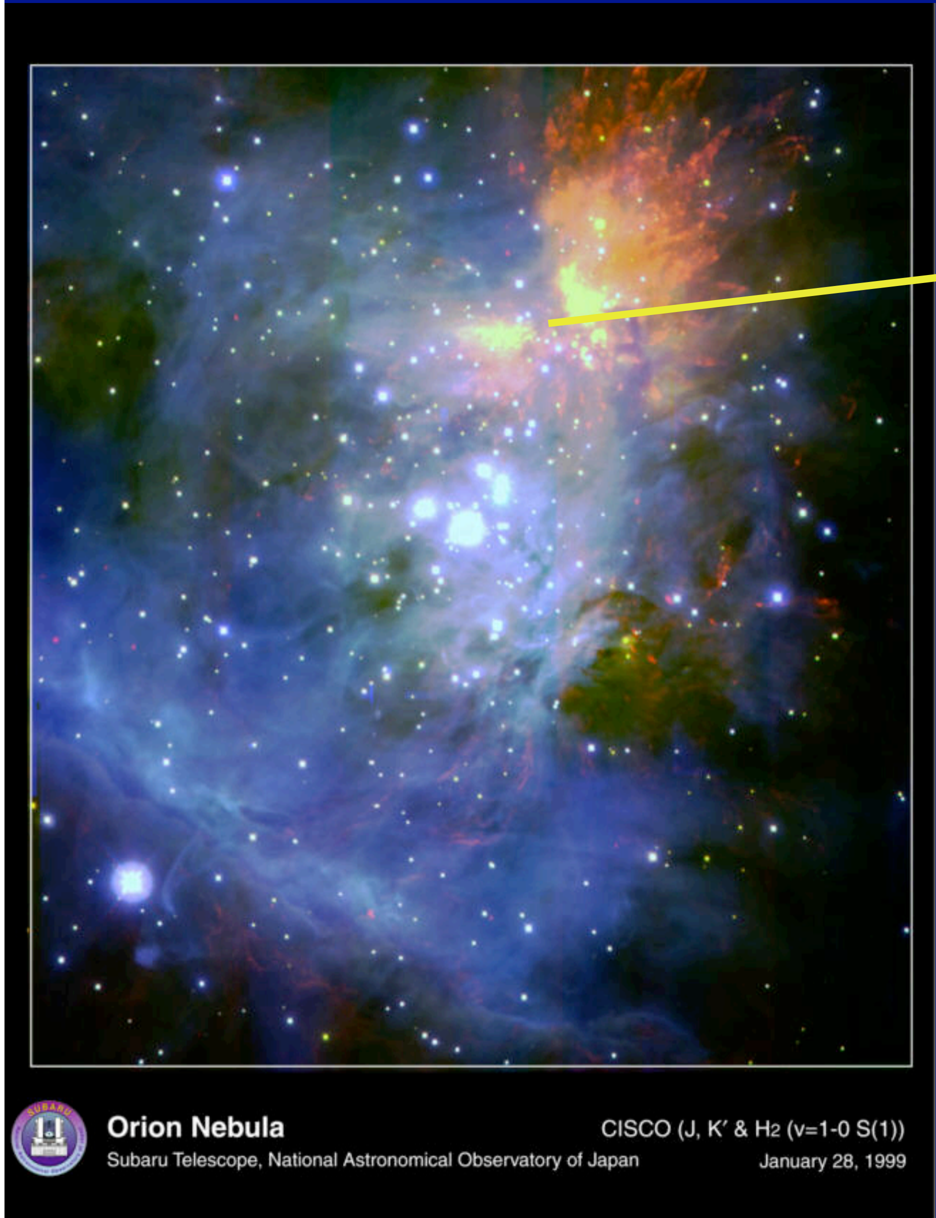
Maser observations

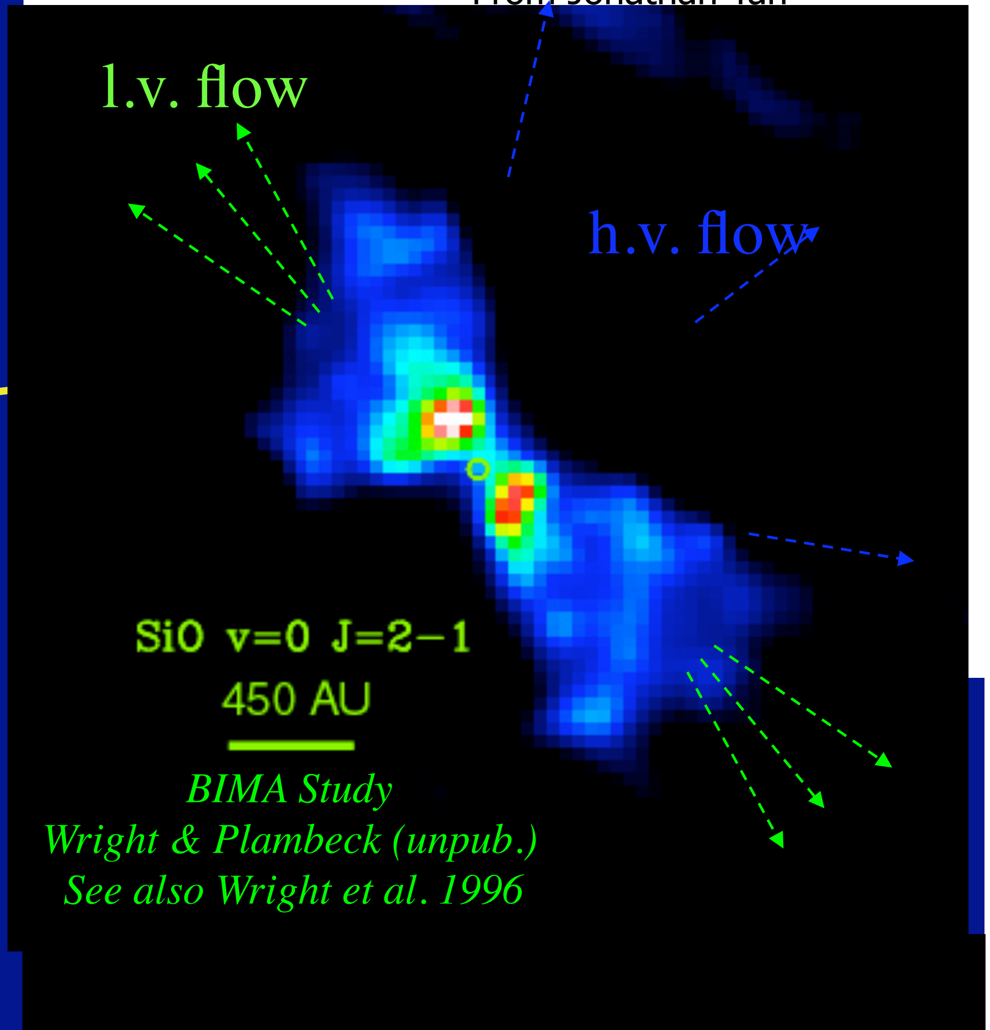


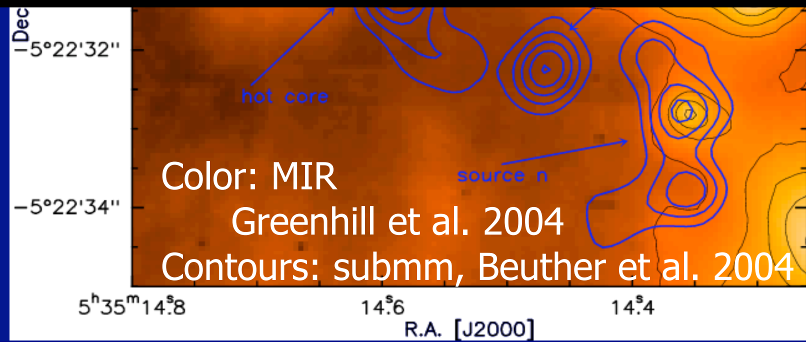
Torrelles et al. 2005

The masers in Orion-KL

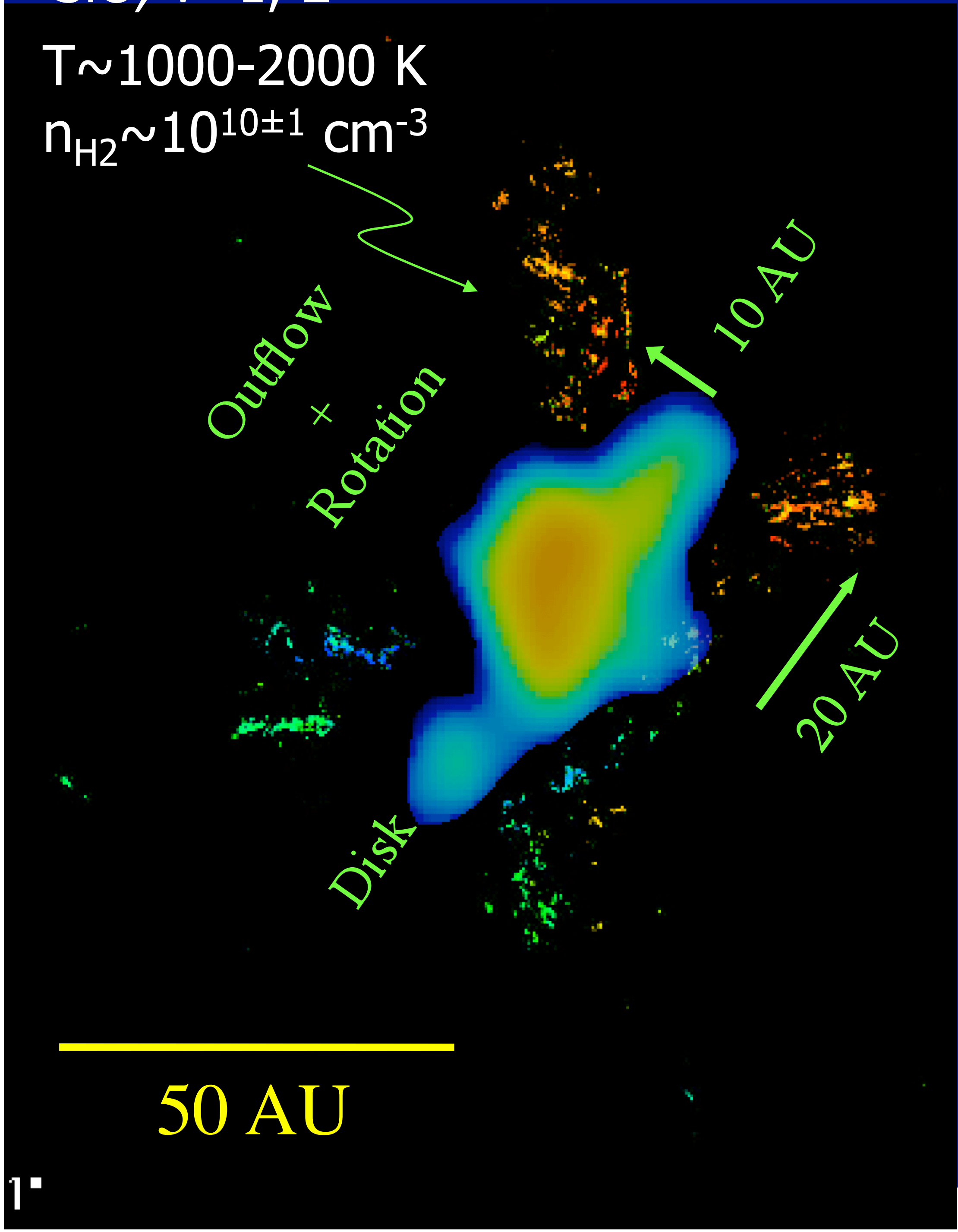
From Jonathan Tan





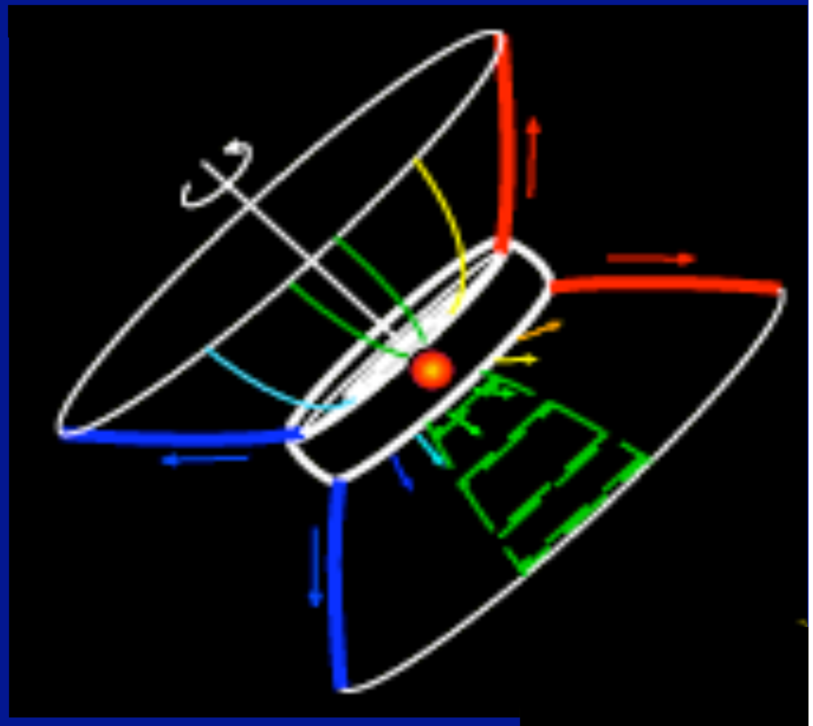


SiO, v=1, 2



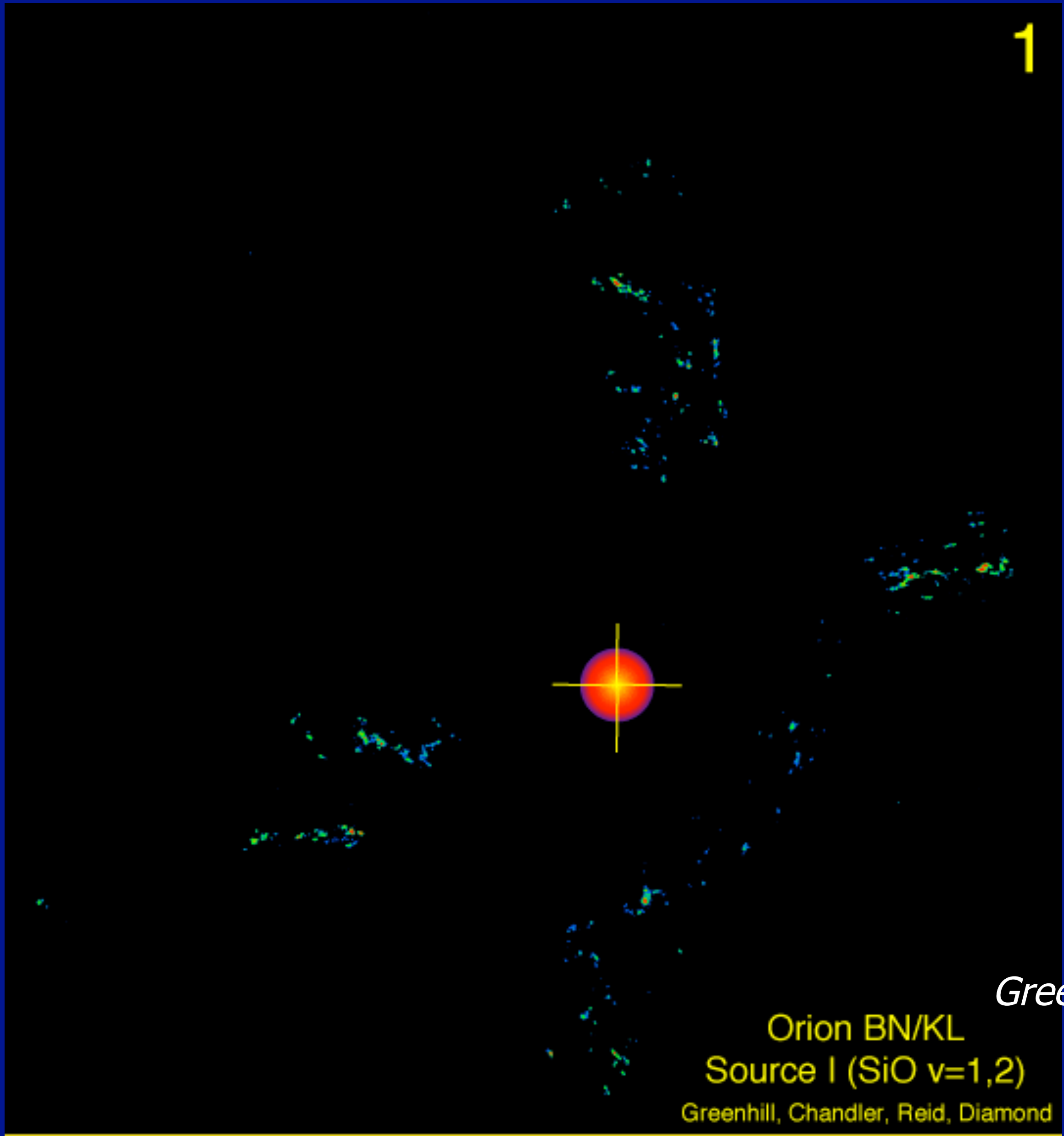
Source *I*

R<100 AU



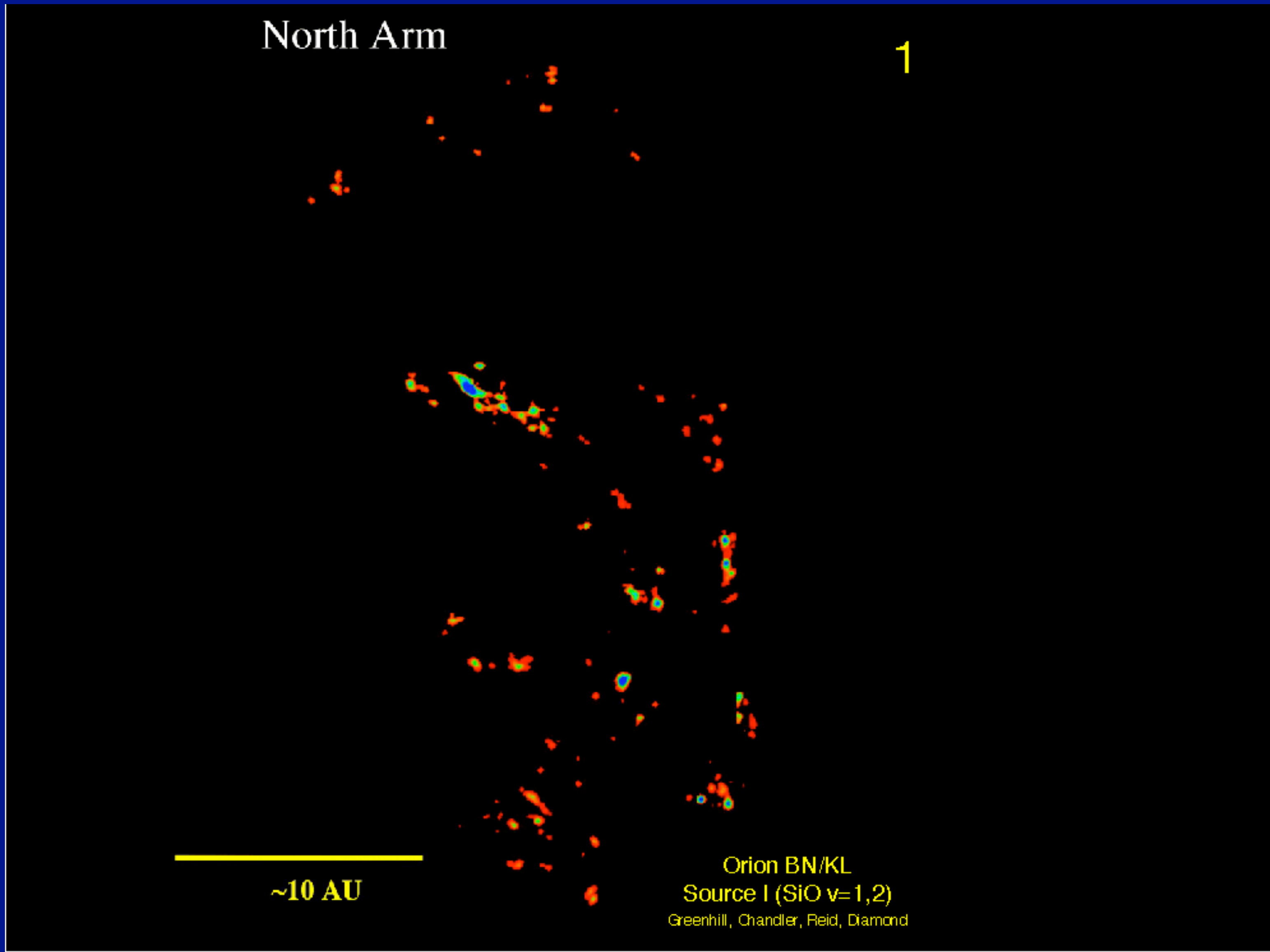
Greenhill and collaborators

Proper motions of the source I maser spots



Greenhill and collaborators

Proper motions of the source I maser spots



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Spatial scales and spatial resolution

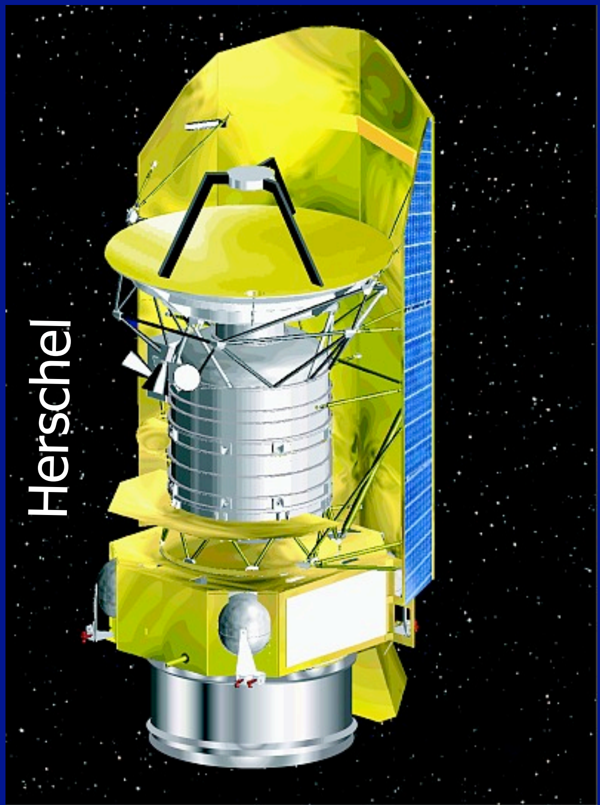
- Stellar radius: R(sun) ~ 6.96×10^8 m ~ 4.7×10^{-3} AU
- Inner disk truncation radius of order 10 AU
- Low-mass disk size ~ a few 100 AU
- High-mass disk size of the order 1000 AU
- Jet and outflow length between a few 1000 AU and of the order parsec

1pc ~ 200 000 AU
~ 3.1×10^{16}m

- Telescope resolution is defined by $\Theta \sim \lambda/D$
  Optical: Θ of order 0.1" with AO and Hubble. If seeing limited rather 1".
  Infrared: similar to optical
  Far-Infrared: of the order 10"
  cm wavelengths: single-dish of order arcmin,
  interferometer of order arcsec
  mm wavelengths: single-dish of order 20"
  interferometer of order 1"
  Very large Baseline Interferometry (cm/mm VLBI): of order mas

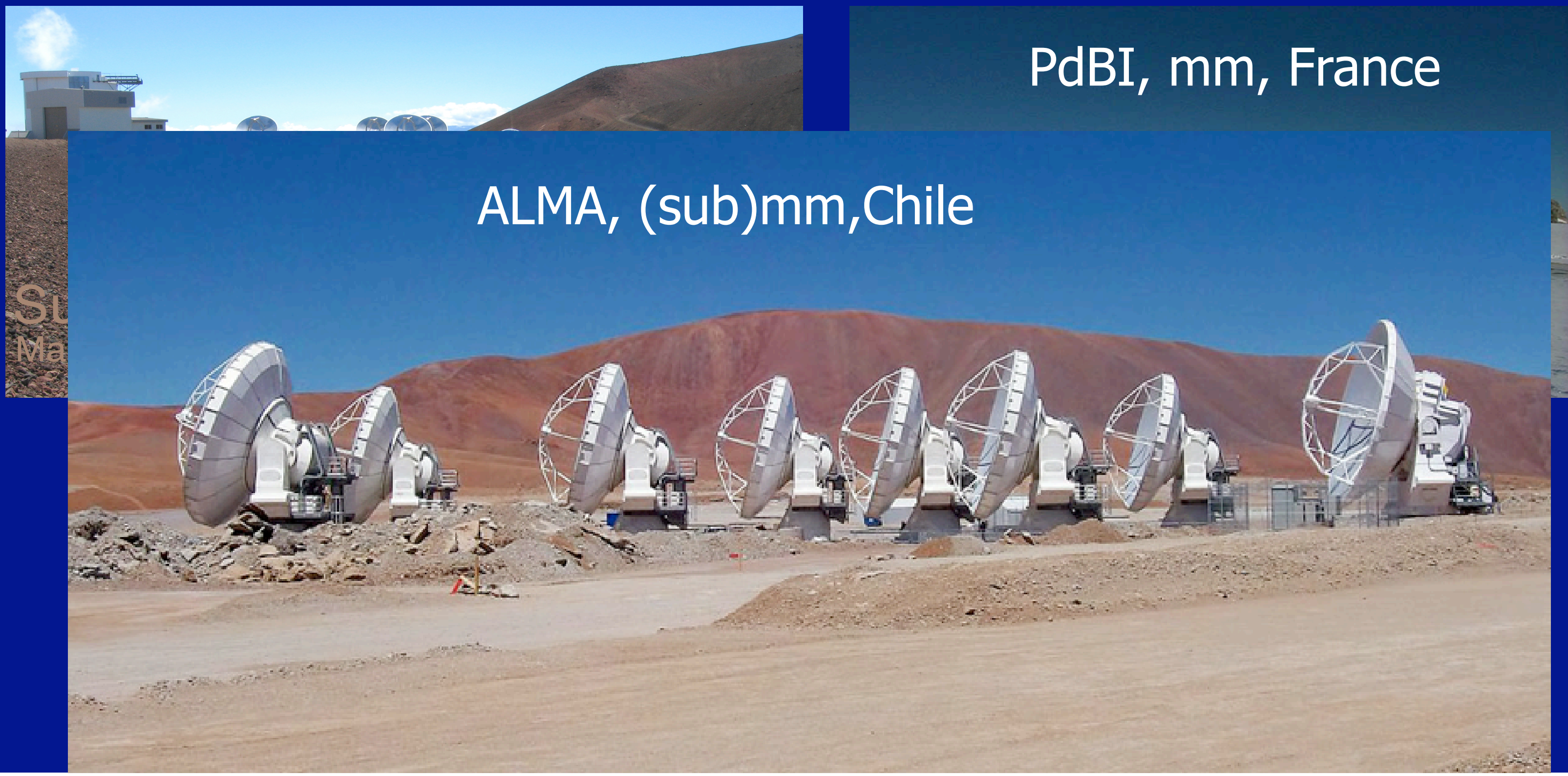
Optical telescopes

Far Infrared



cm and mm single-dish telescopes

cm and mm interferometer



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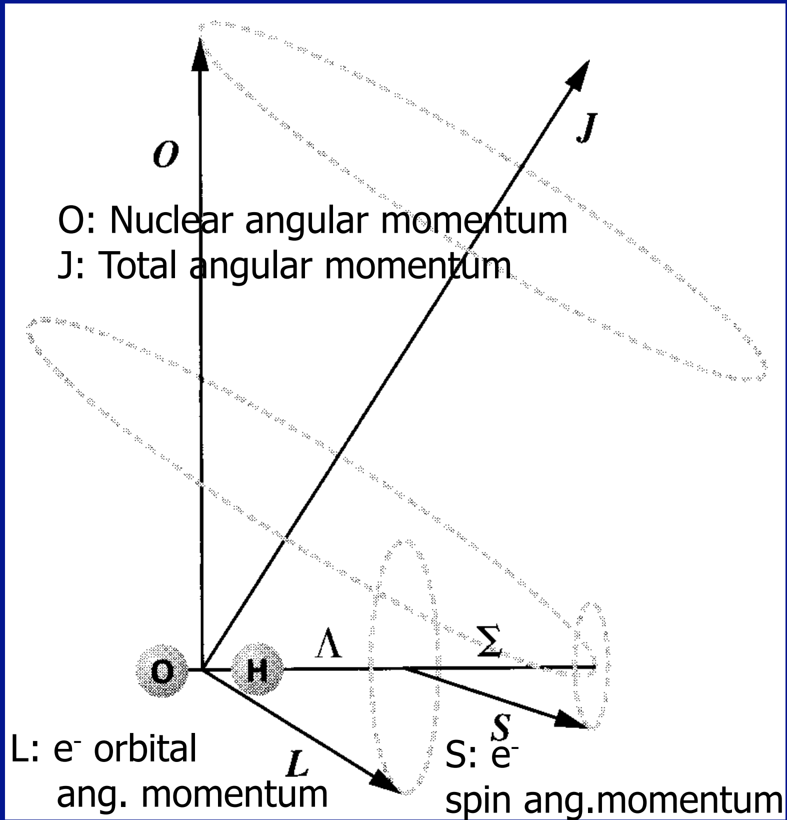
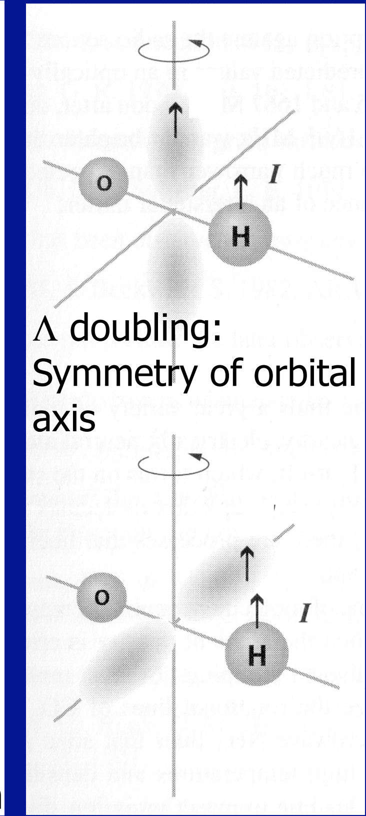
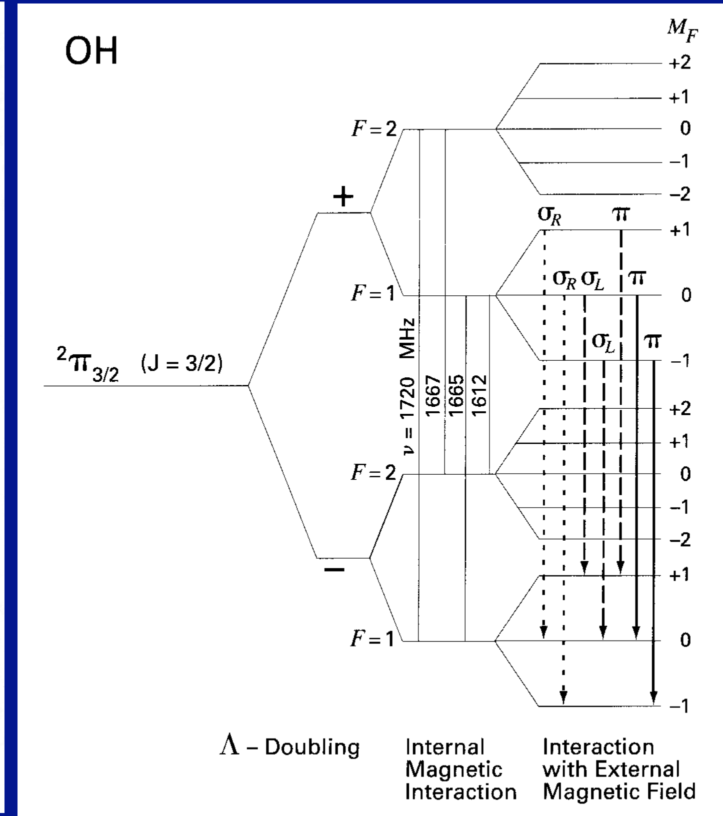
The Zeeman effect and magnetic fields I

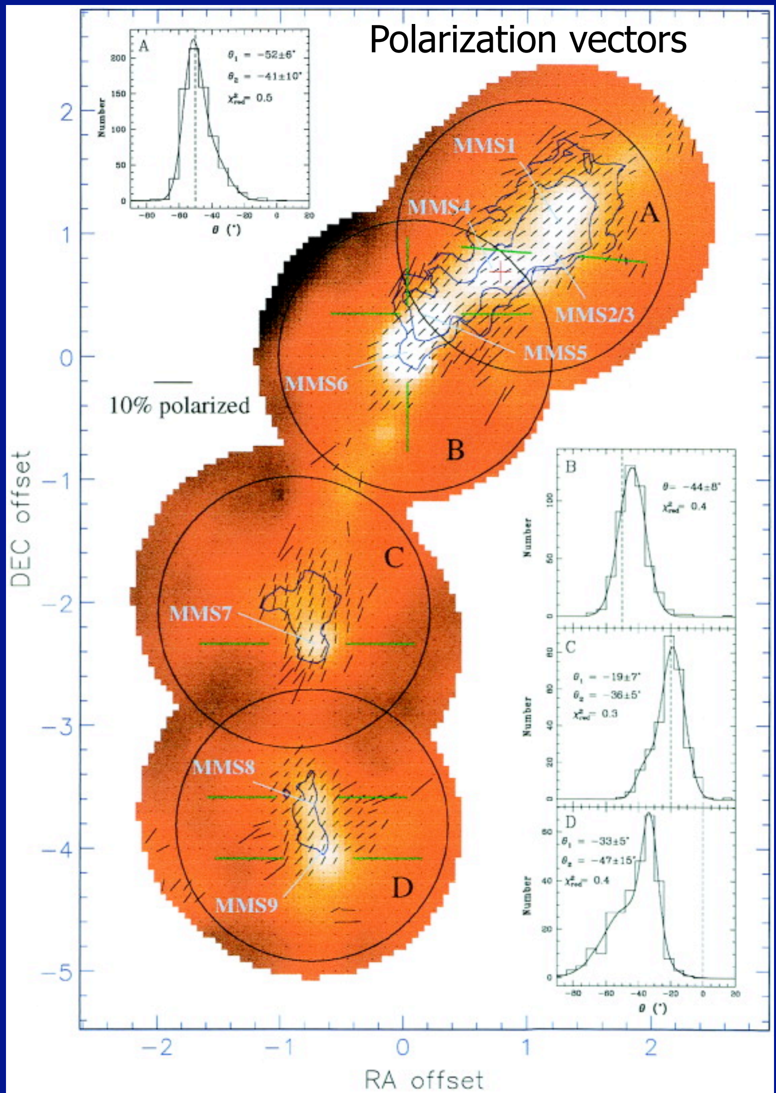






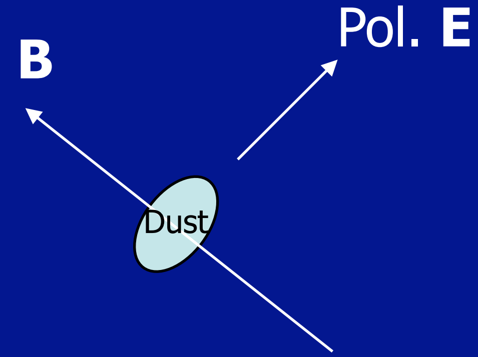
- OH is a free radical with one unpaired free electron and hence non-zero electronic angular momentum. Highly reactive in lab, but can survive in space.
− Λ doubling, which is caused by symmetry difference of the e⁻ orbital with respect to the rotation axis, produces energy splitting.
- Interaction between spins of e⁻ and H nucleus causes additional magnetic hyperfine splitting.
- And external magnetic fields then produces the Zeeman splitting.

Dust polarization and magnetic fields



Polarized submm continuum emission

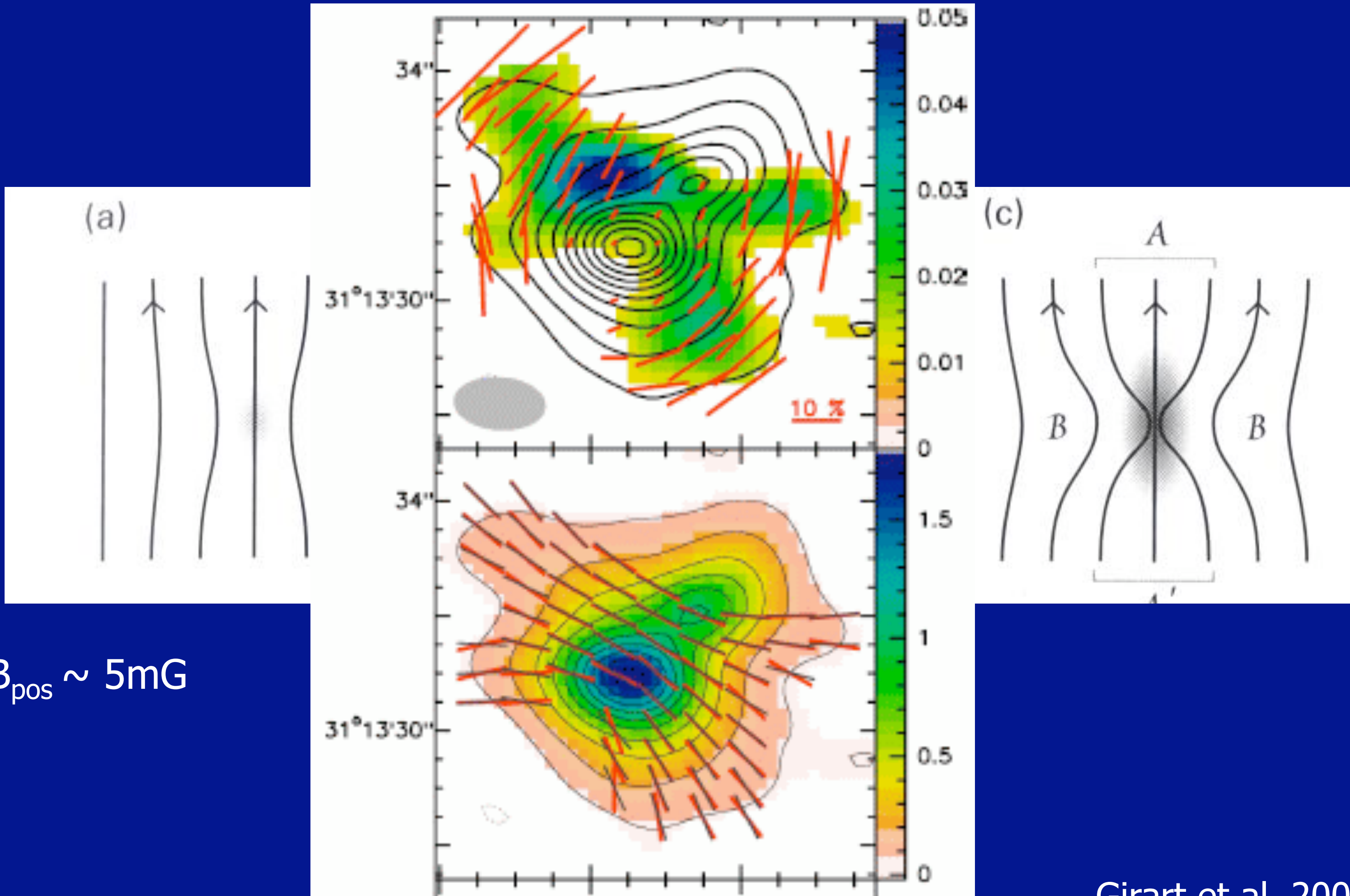
Thermal dust emission
at (sub)mm wavelengths
perpendicular to magnetic field!



Molecular filaments can collapse
along their magnetic field lines.

Matthews & Wilson 2000

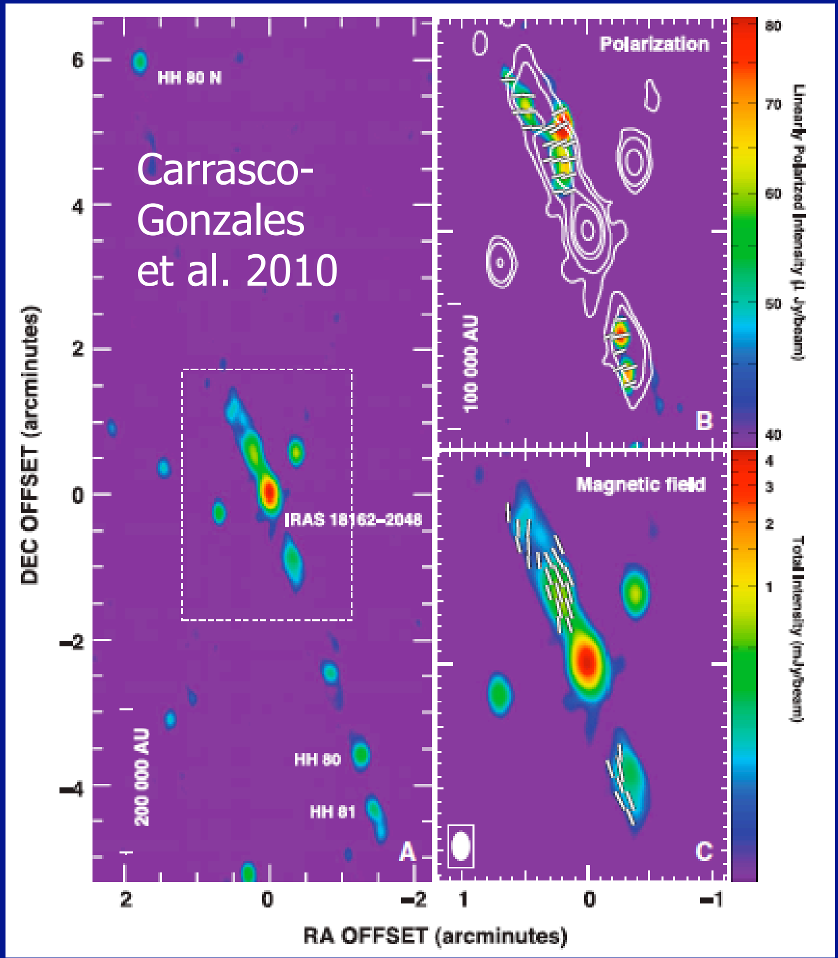
Ambipolar diffusion

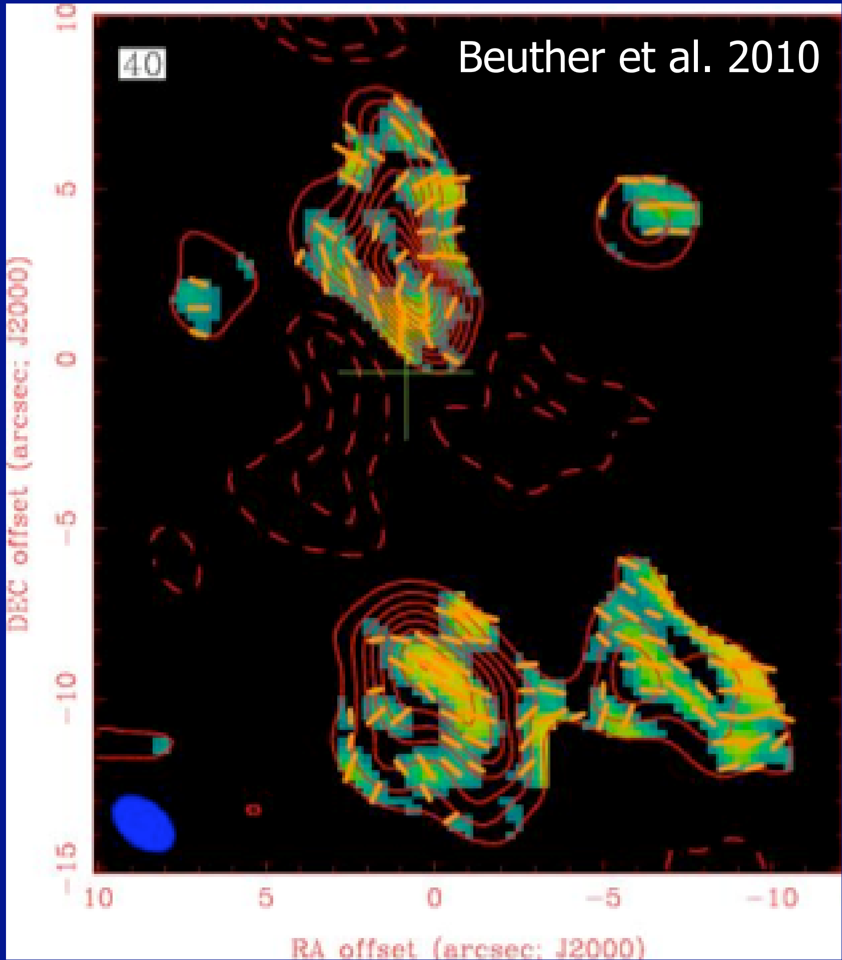


$B_{pos} \sim 5mG$

Girart et al. 2006

Magnetic fields in jets/outflows





- Measured magnetic fields in jets/outflows from polarized synchrotron as well as polarized CO emission

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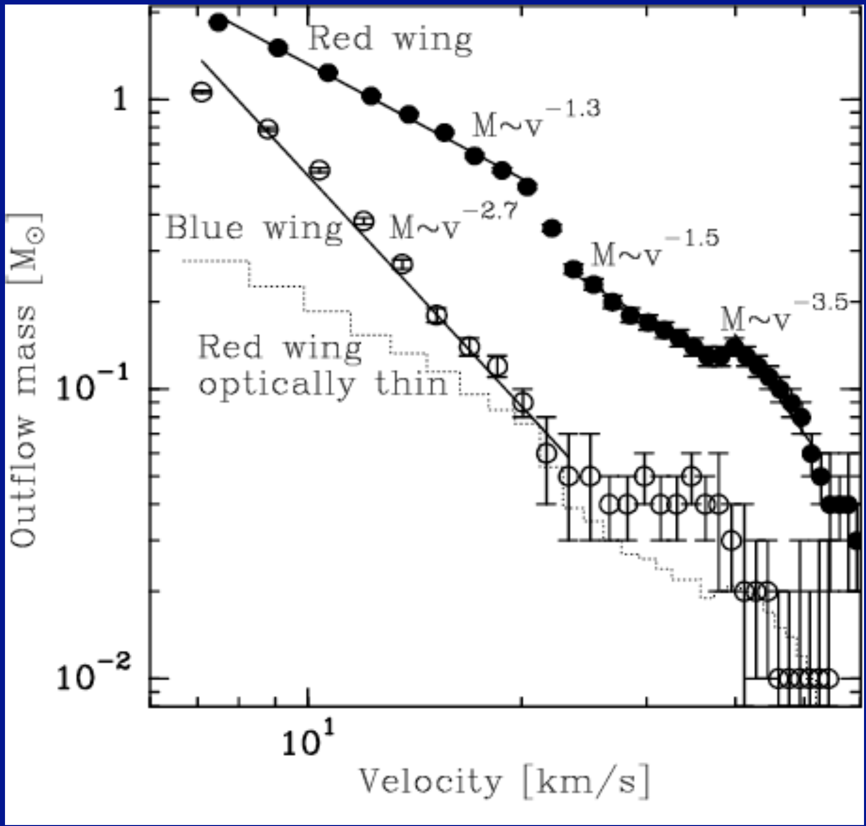
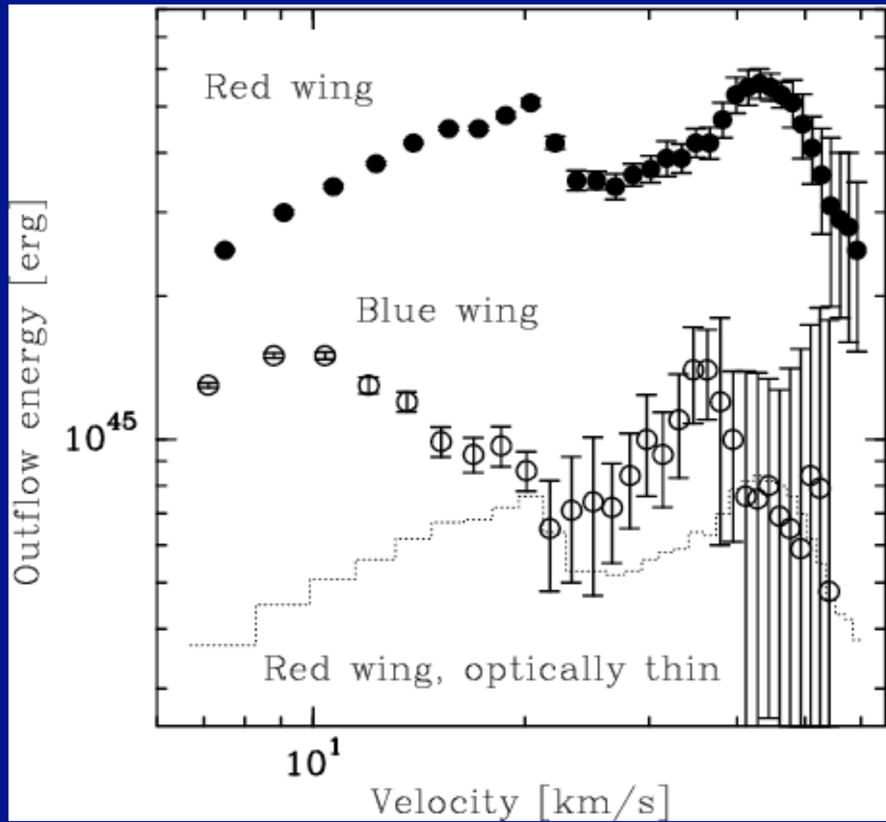
Mass vs.velocity, energy vs. velocity



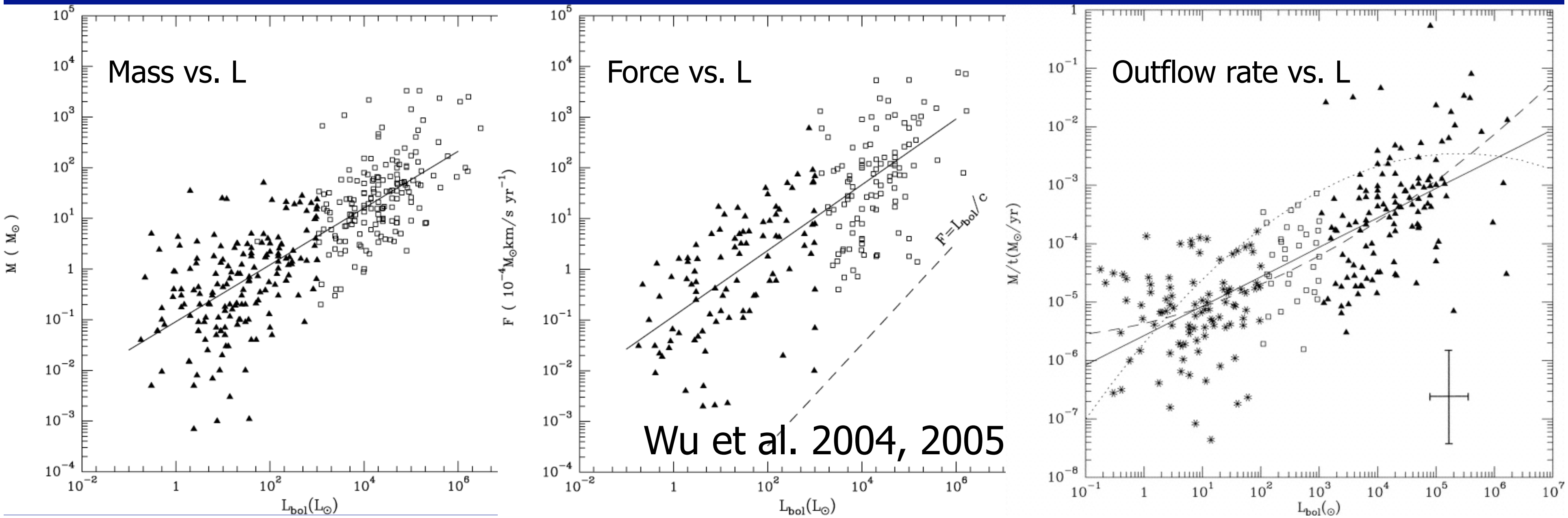


- Mass-velocity relation exhibits broken power-law, steeper further out
  → less mass at high velocities.
- Energy at high velocities of the same magnitude than at low velocities.

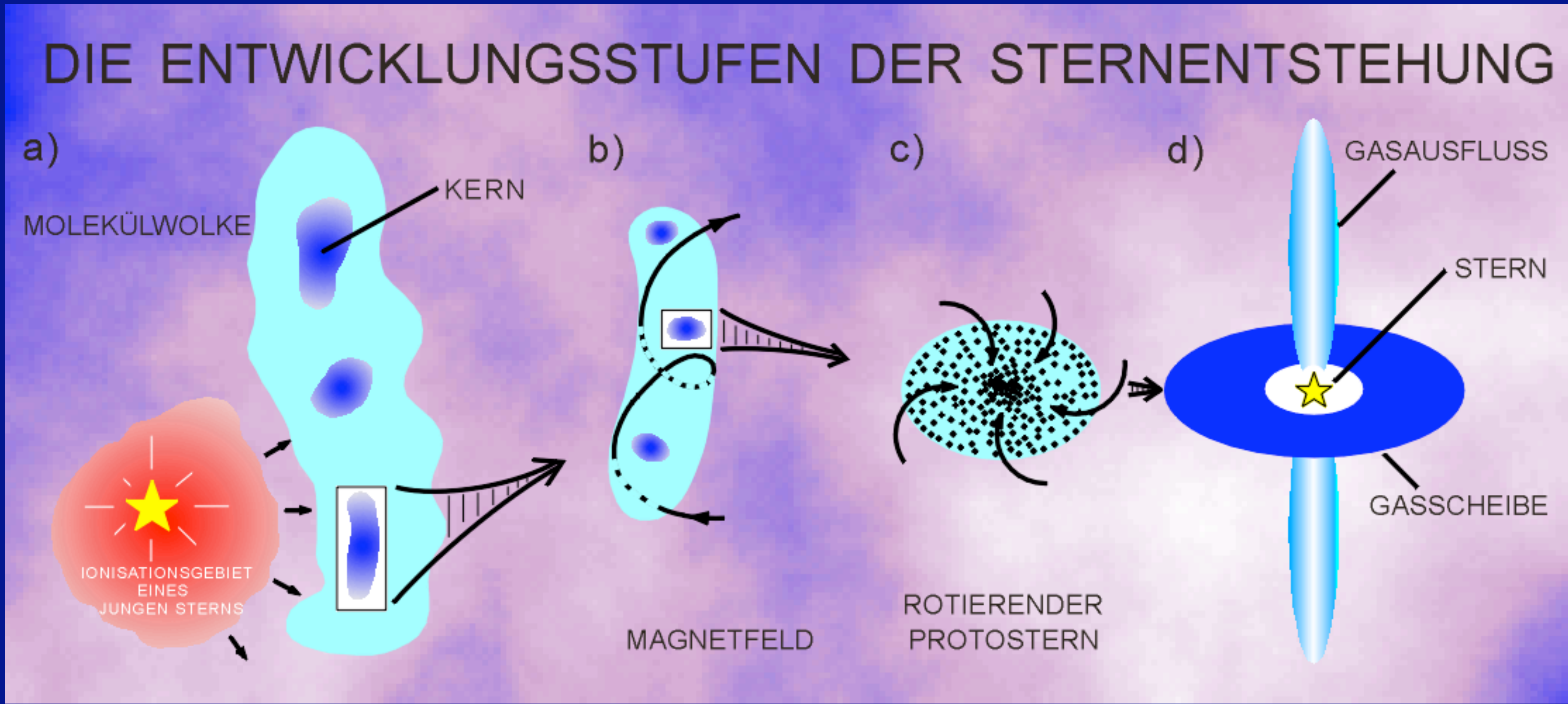
Lebron et al. 2006

General outflow parameters

- Jet velocities 100-500 km/s <=> entrained outflow velocities 10-50 km/s
- Jet opening angle θ a few degrees <=> outflow θ up to 90 degrees
- Estimated dynamical ages between 10^3 and 10^5 years
- Size between 0.1 and 1 pc.
- Force (F=p/t) provided by stellar radiation too low (middle panel)
  → non-radiative processes necessary!
- Largely neutral with ionization degree between 10^{-1} and 10^{-8}.
- Measured magnetic fields between a few µG and a few mG.



Star Formation Paradigm



Observable Spectral Energy Distributions (SEDs)