The Most Detailed Picture Yet of a Massive Star in Formation

L. Greenhill (CfA/Kavli Inst./Berkeley)

How do high-mass stars ($M_* \gg 1\ M_\odot$) form?

- What lies < 200 AU from high-mass YSOs?
- Do magnetic fields drive and collimate their outflows?
- Are outflows turbulent?
- Ramifications for pop-III stars?

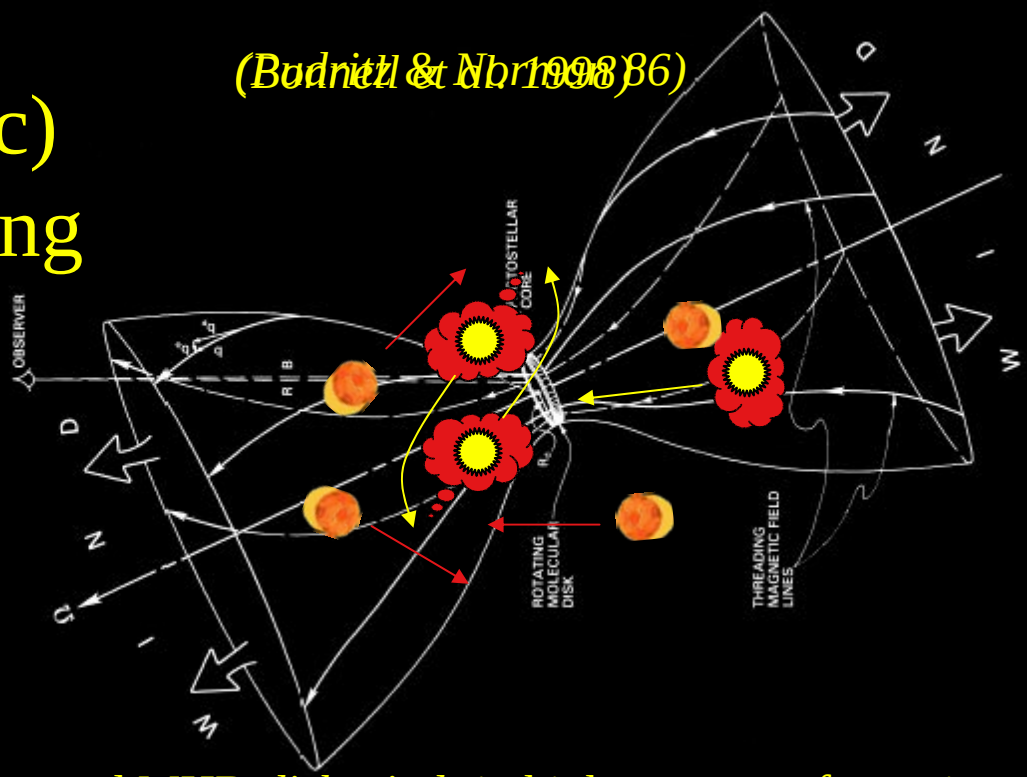
What is going on in Orion BN/KL?

Why is high-mass star formation poorly understood?

Good examples of accreting massive YSOs are rare.

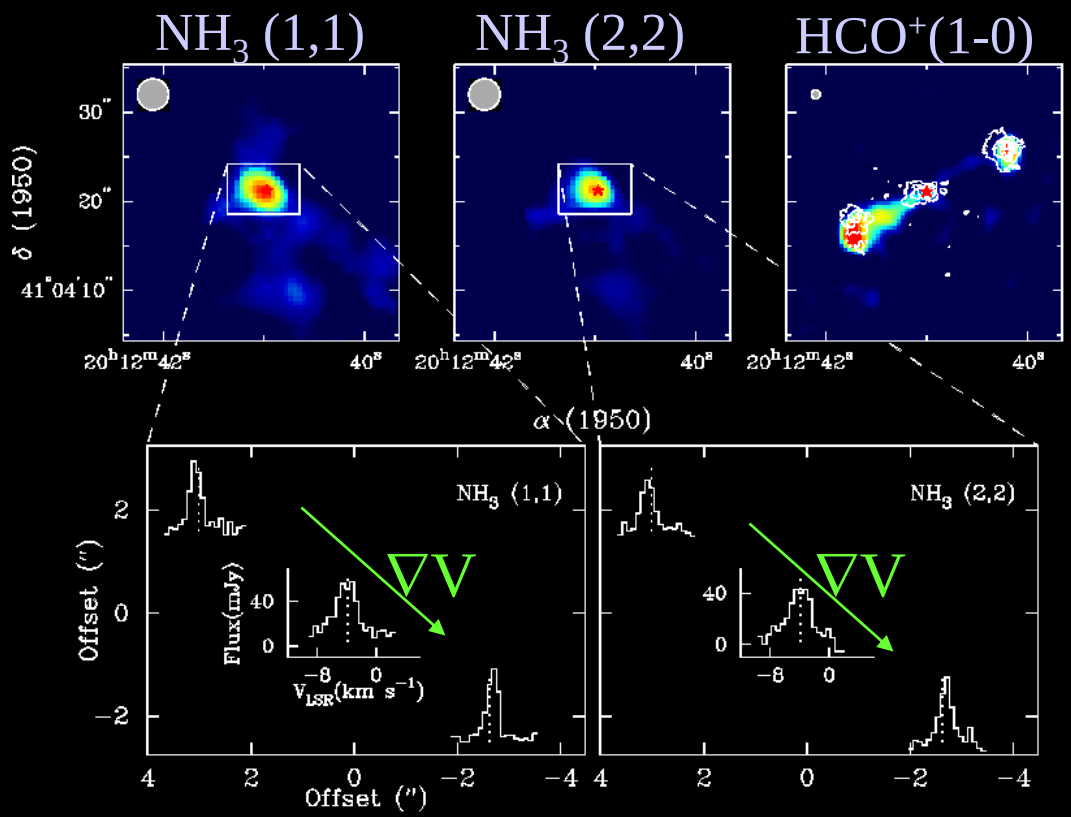
- Declining IMF
- Distance (> 500 pc)
- Confusion/crowding
- Rapid evolution
- Obscuration
- Poor thermal tracers of gas

(Burrell & Norman 1998)



Proposed MHD *disk winds* in high-mass star formation

A Typical Best Case - High-Mass Star Formation via Accretion



Few examples of disks known

- Zhang, Hunter, & Sridharan 1998,
- Shepherd & Kurtz 1999,
- Cesaroni et al. 1999.

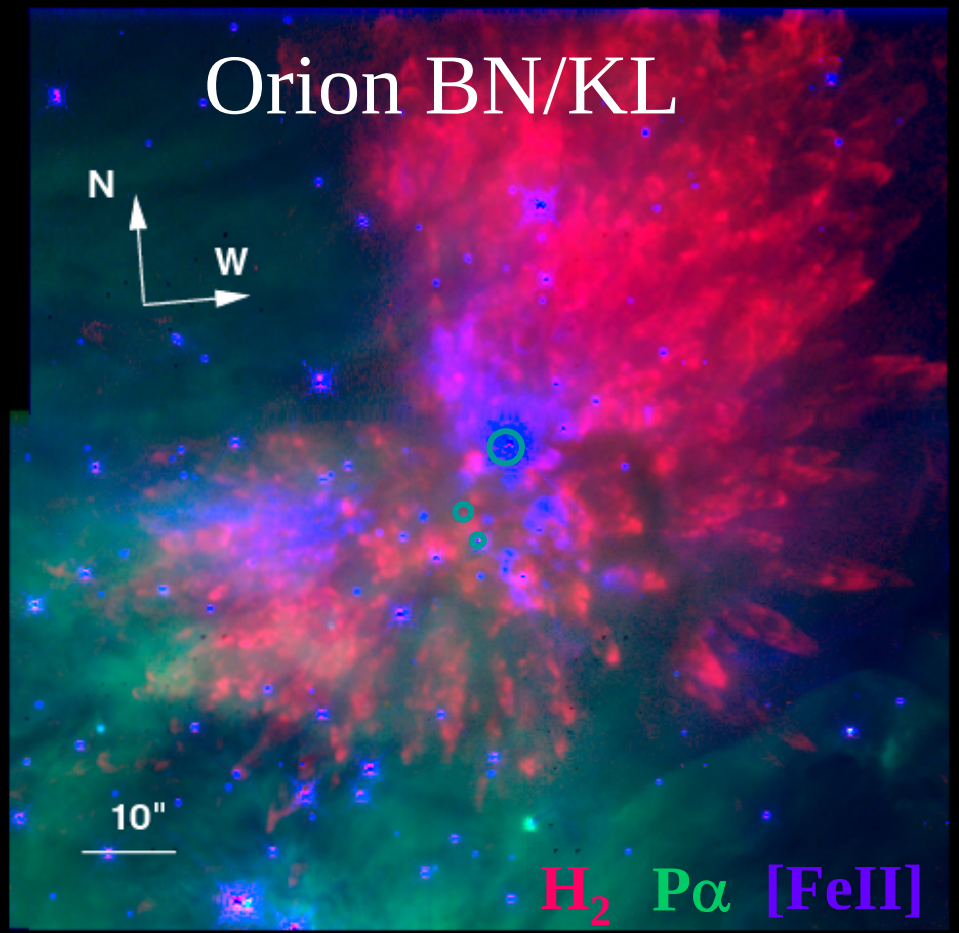
None resolved below 10^3 AU.

- A lot can hide in 10^3 AU

Limit of imaging thermal gas.

What Drives the Closest Example of High Mass Star Formation?

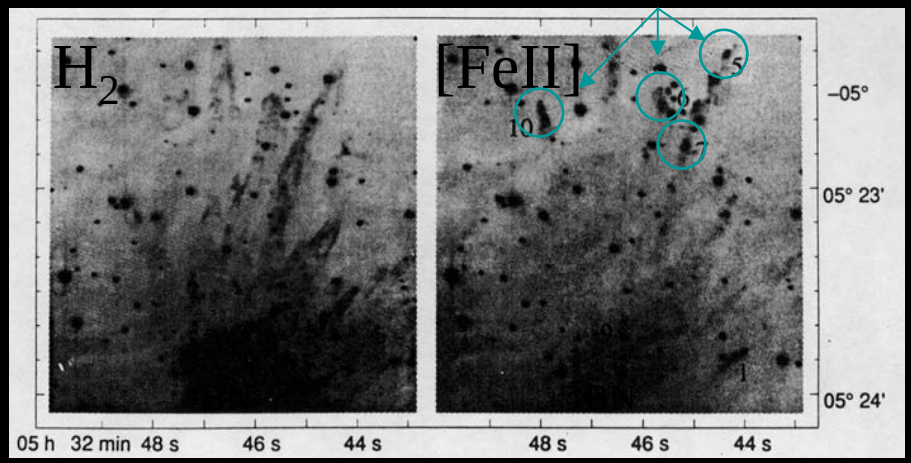
- Complex outflow structures
- Large variations in reddening
- No center of expansion identified
  - Remnant of explosion? ($\tau \sim 10^3$ yr)
  - Fragmenting stellar wind?



Schultz et al. 1999

(See also O'Dell et al.1997, Xu 1996, etc)

(HH-objects)



Allen & Burton 1993

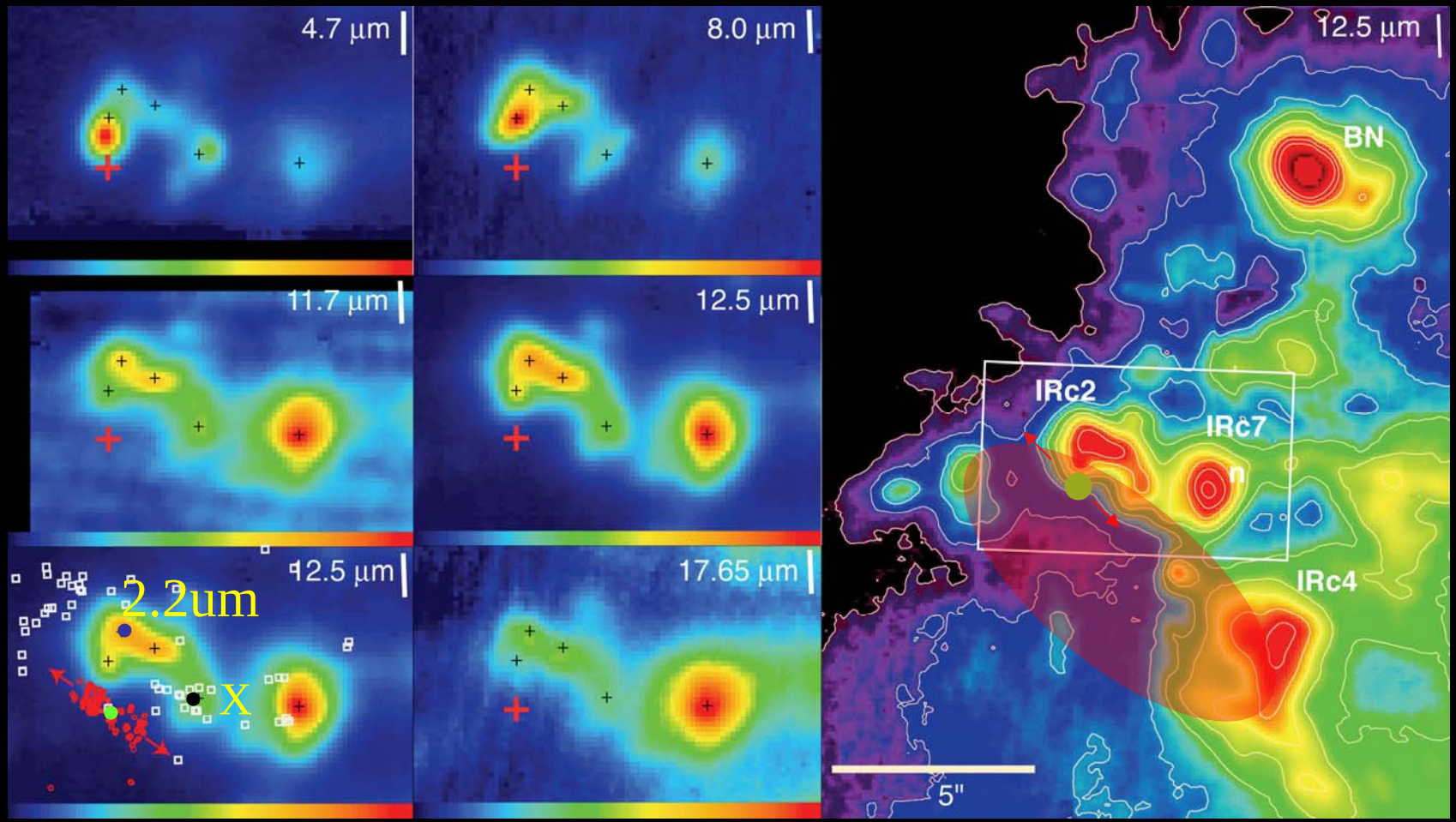
Means

- sub-″ mid-infrared continuum imaging (Keck)
- cm/mm-wave continuum imaging (VLA)
- cm/mm-wave line imaging (VLBA & VLA)
  - H_2O maser
  - SiO maser (v=0, 1, 2; J=1→0)
- moving pictures

Collaborators

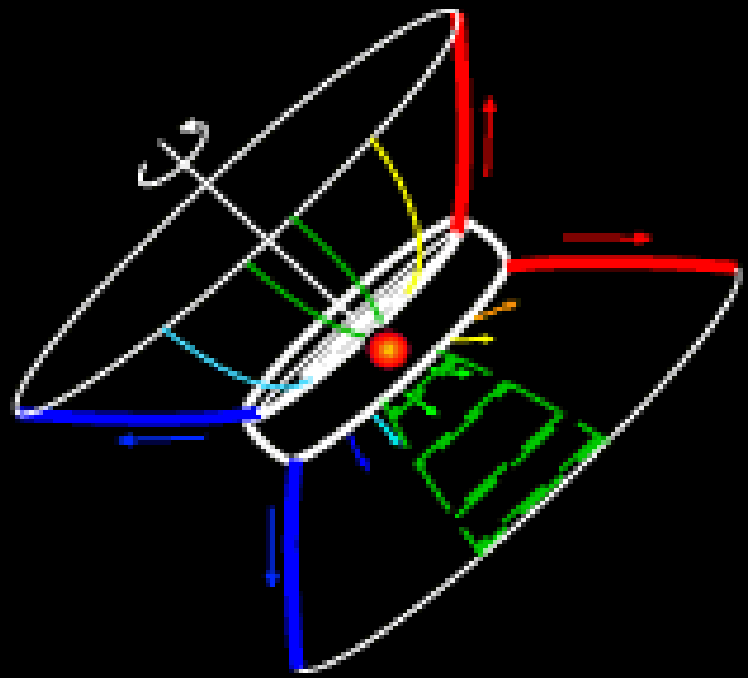
Chandler, Danchi, Diamond, Elitzur, Gezari,
Menten, Moran, Najita, Reid

A High Density Cluster Core?

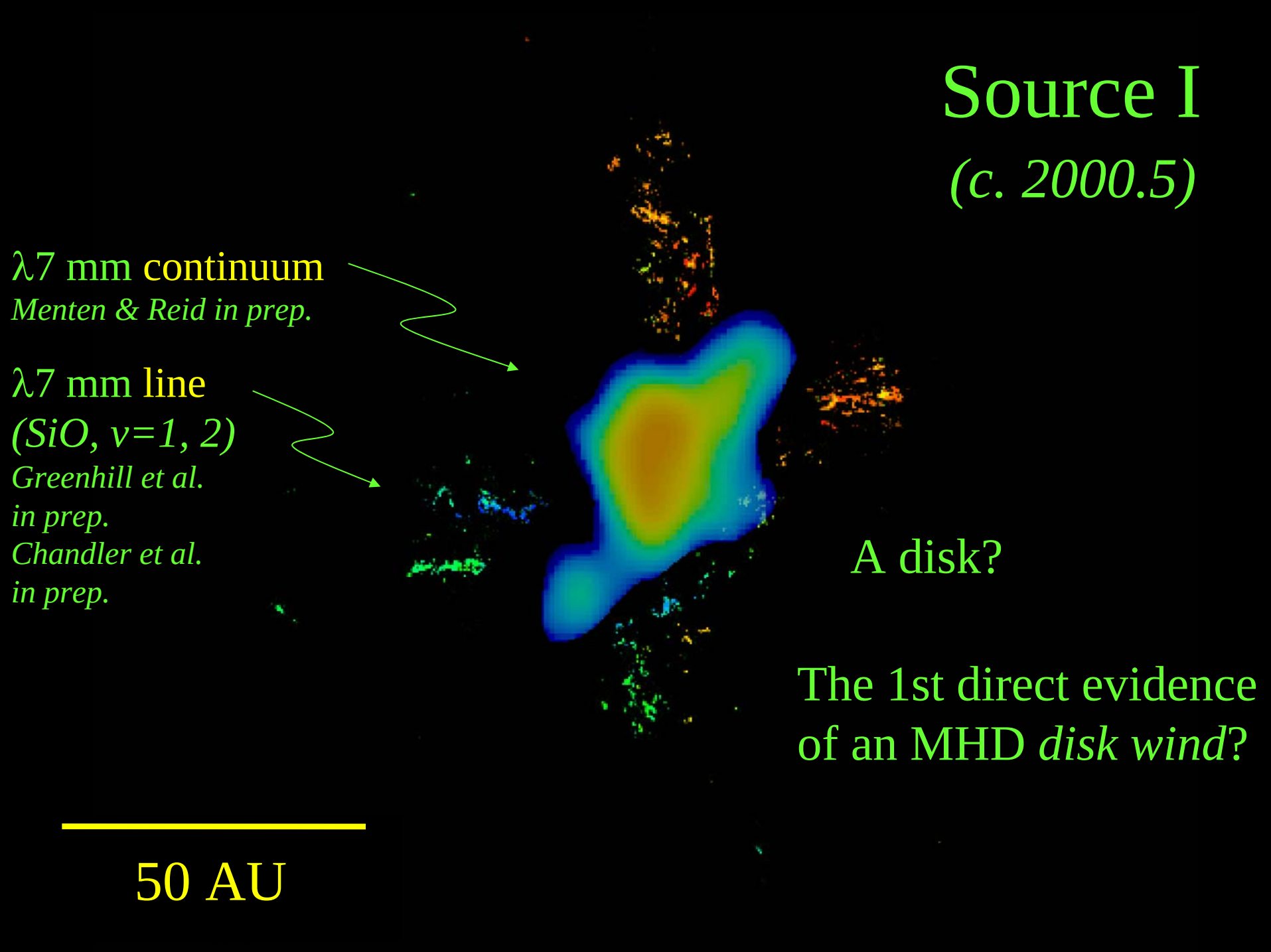


Greenhill et al. 04; see also Shuping et al. 04

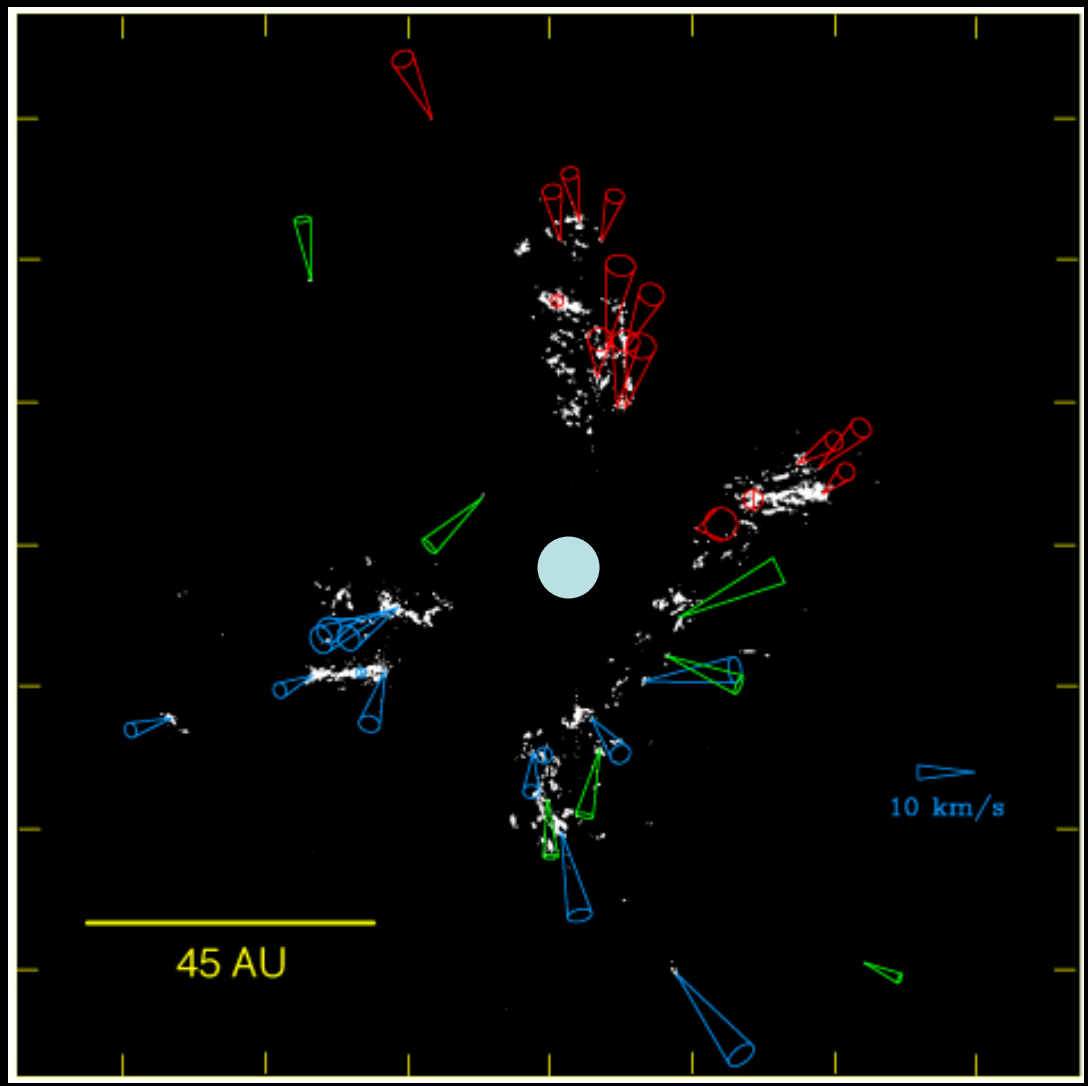
Keck LWS mid-IR images of BN/KL



What lies < 200 AU from this high-mass YSO?


Source I
(c. 2000.5)
λ7 mm continuum
Menten & Reid in prep.
λ7 mm line
(SiO, v=1, 2)
Greenhill et al.
in prep.
Chandler et al.
in prep.
A disk?
The 1st direct evidence
of an MHD disk wind?
50 AU

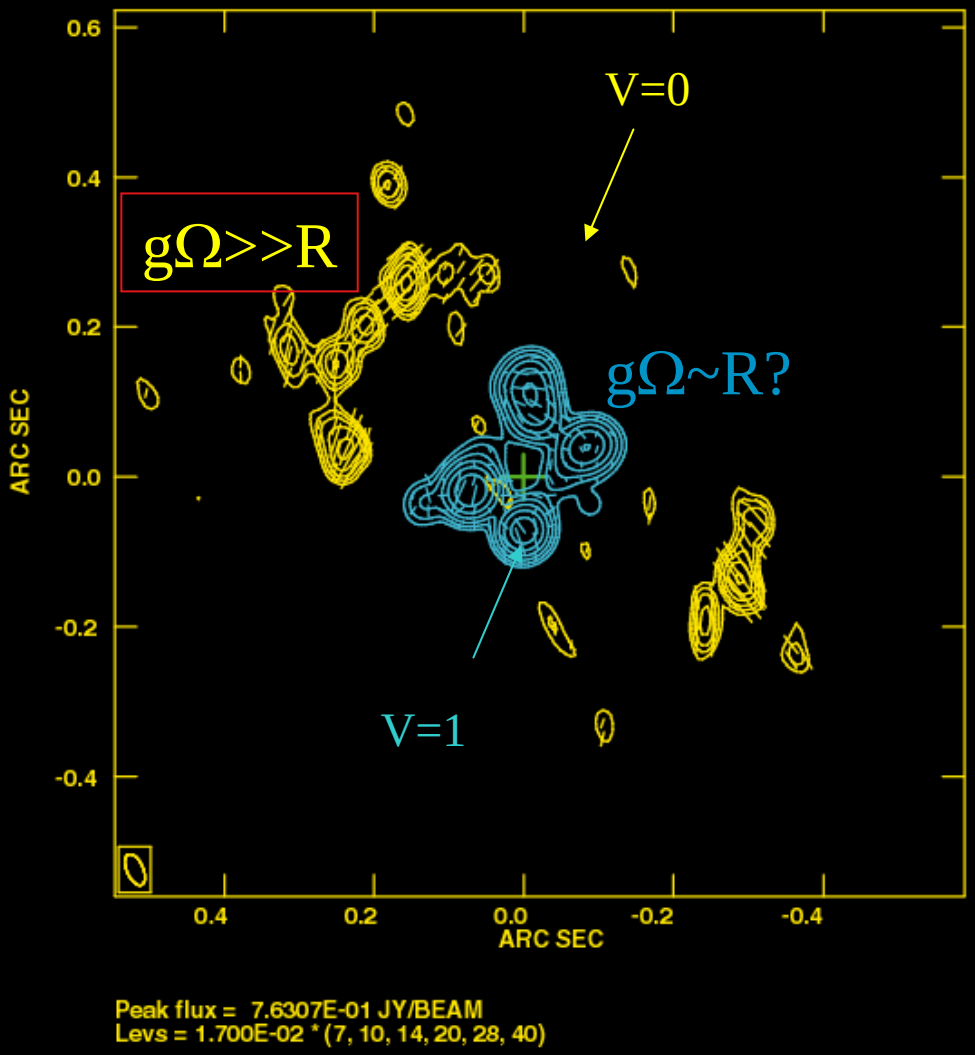
Proper Motion of Molecular Gas



SiO (v=1,2) motion
over *4 months*

25 AU

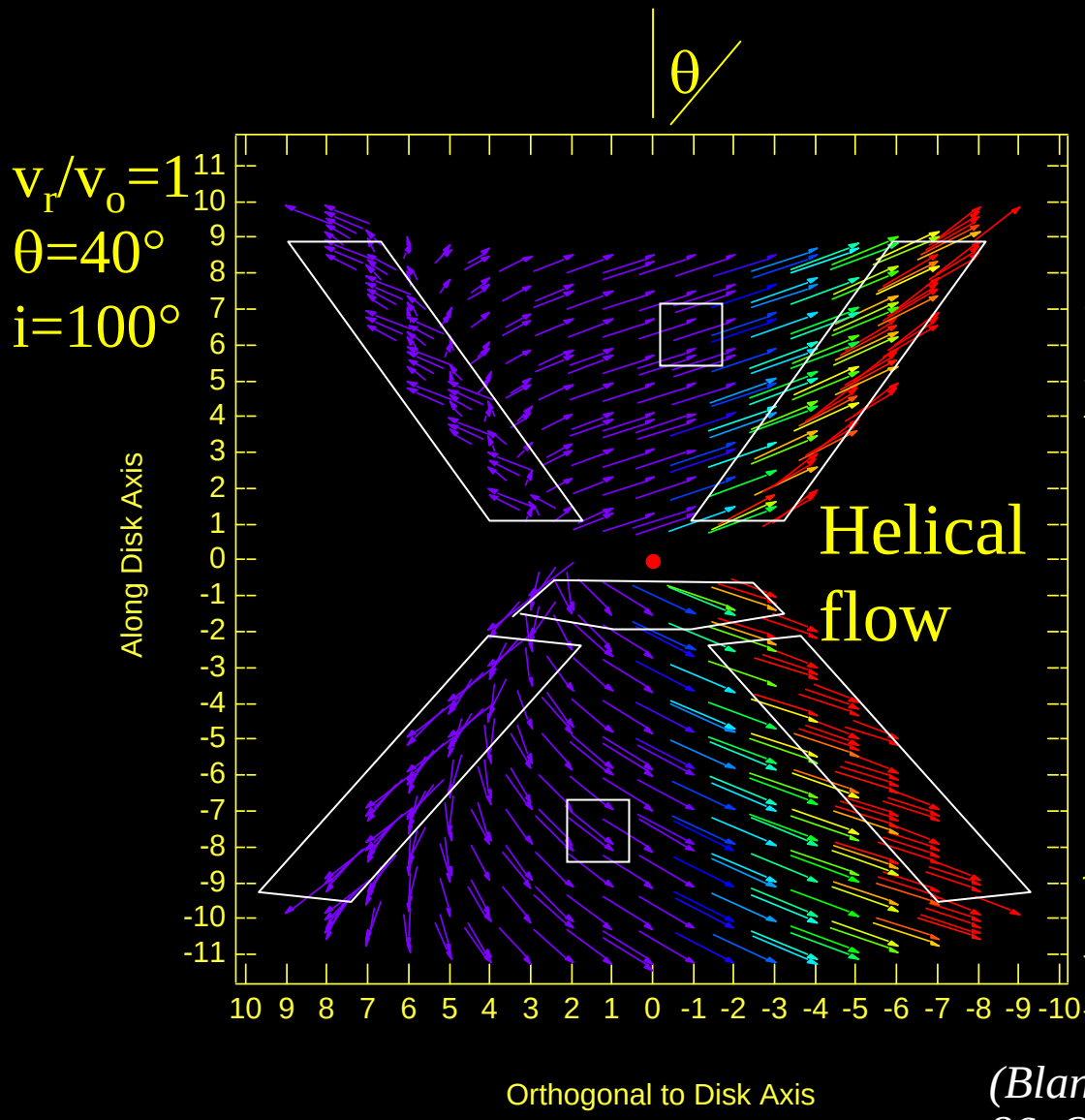
Is there a detectable magnetic field?



Greenhill et al., in prep

- Polarization maps trace **B** at 200 AU.
- **B** is ∥ or ⊥ to polarization.
- Where would the field come from?
  - Presumably not stellar.
  - Sweeping up of ambient field?
    - –Ambipolar diffusion
- Does anisotropic pumping contaminate the polz?
  - –Nedoluha & Watson 1994
  - – Wiebe & Watson 1998…

Another way to trace magnetic field



- 3-D velocity and accel of gas inside 100 AU.
  - helical flow
  - ballistic flow
- 3-yr VLBA time monitoring will lay out 3-D dynamics.

(Blandford & Payne 82, Pudritz & Norman 86, Ouyed, Pudritz & Stone 97)

Summary I

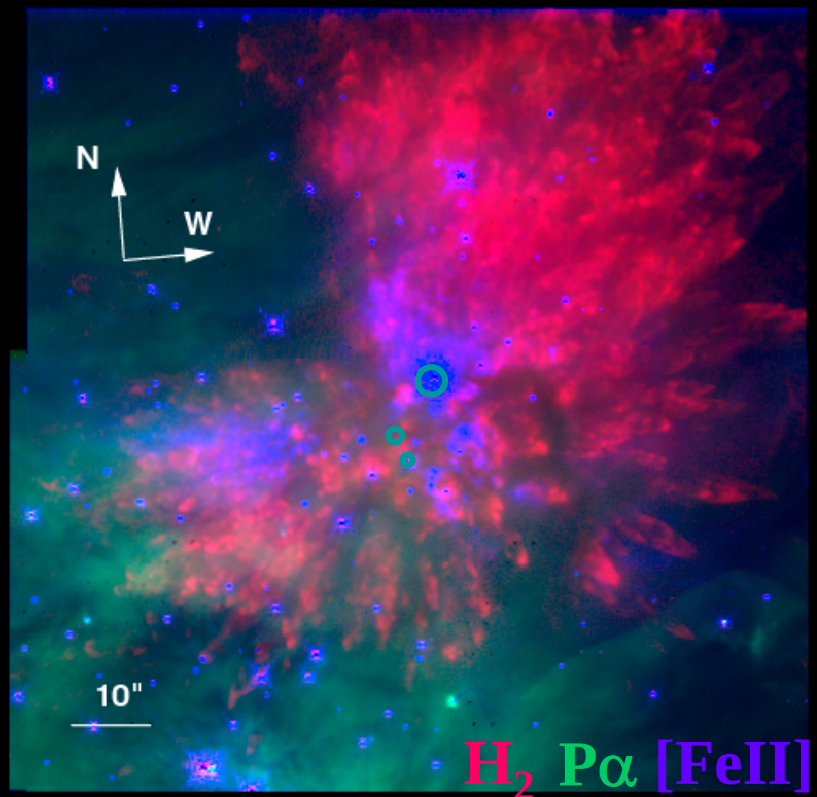
- Organized accretion/outflow structure in rotation.
- Bipolar, funnel-like geometry
- Indirect evidence for a disk (R>20 AU).
- Time scales are short.
  - Period ~ 30 yr
  - Outflow ~ 20 yr (r = 0→60 AU)
- YSO mass is large.
  - max $|V_{3D}|^2 \sim 2GM/r$ $M_* \sim 10\ M_\odot$

Summary II

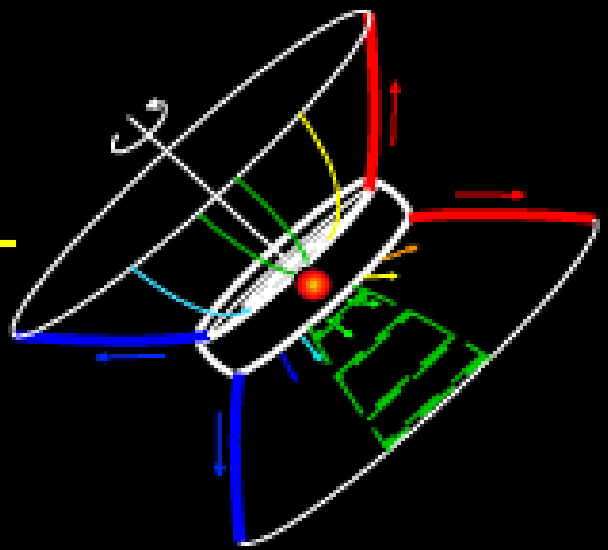
- Large inferred mass loss rate.
  - $3\times10^{-(4\pm1)}\alpha$ $M_\odot$ yr^{-1} (SiO v=1, 2)
  - $7\times10^{-(4\pm1)}\alpha$ $M_\odot$ yr^{-1} (H_2O)
  - Low-ρ, high-v wind / High-ρ, low-v limb?
- Orion BN/KL provides perhaps the *only* case to directly test whether massive YSO disks drive MHD winds.
  - Test via measurement of v_{3D} and a_{3D} fields.
- And are we any closer to answering the 30 year old question, what powers Orion BN/KL? NO!

(cf. Tan/McKee & Tan)

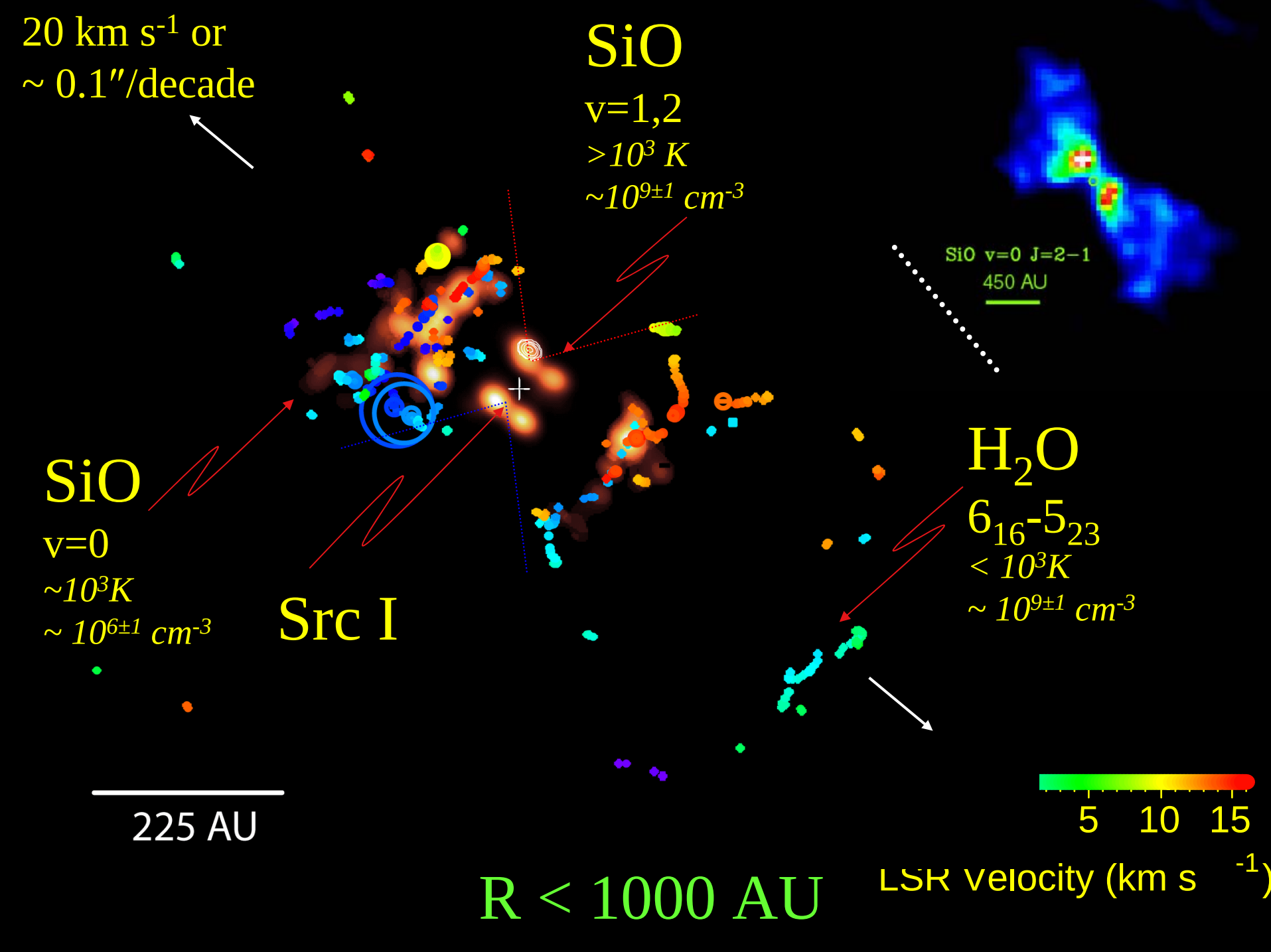
What Drives the Closest Example of High Mass Star Formation?

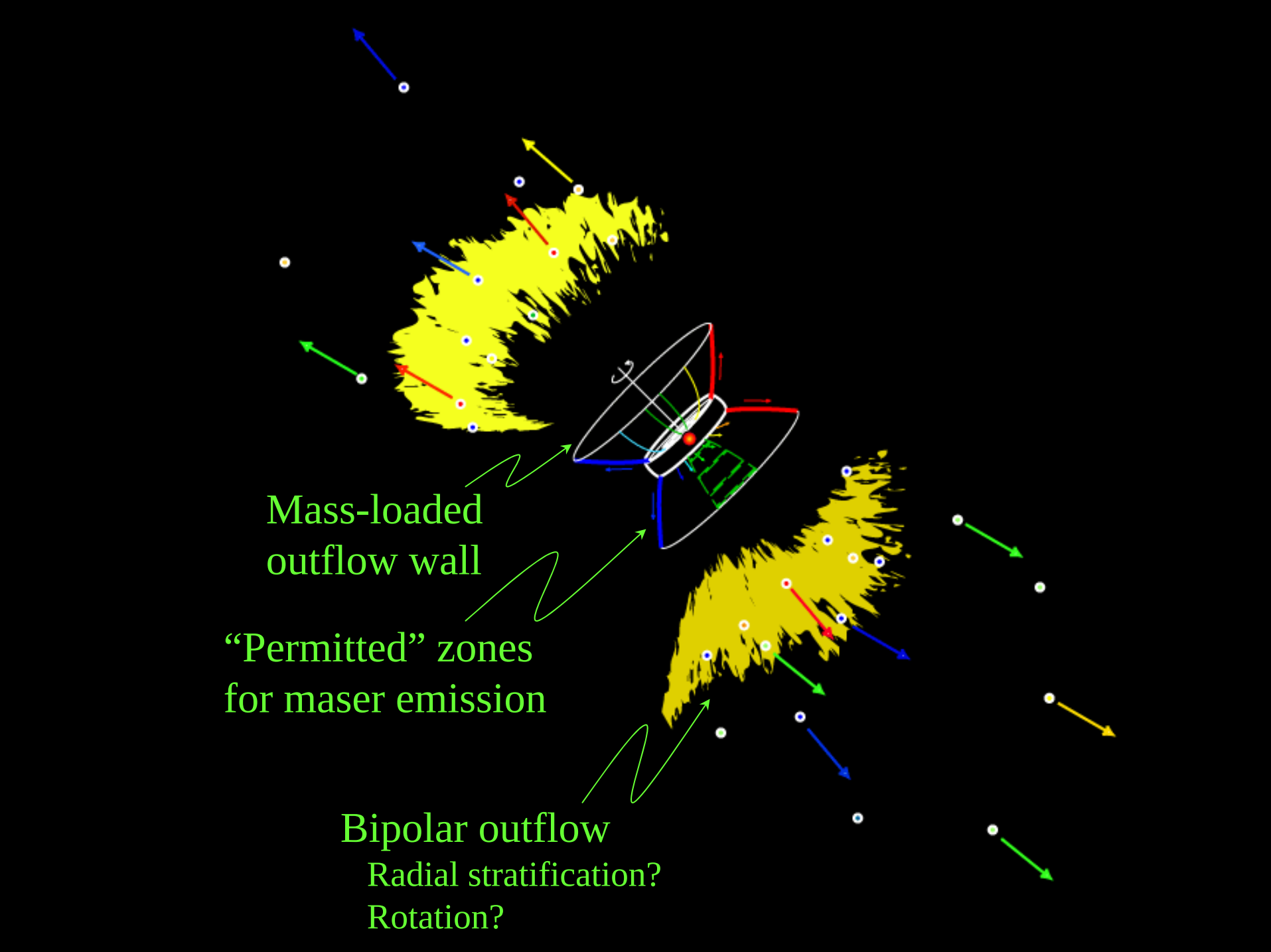


Schultz et al. 1999



…probably a cluster

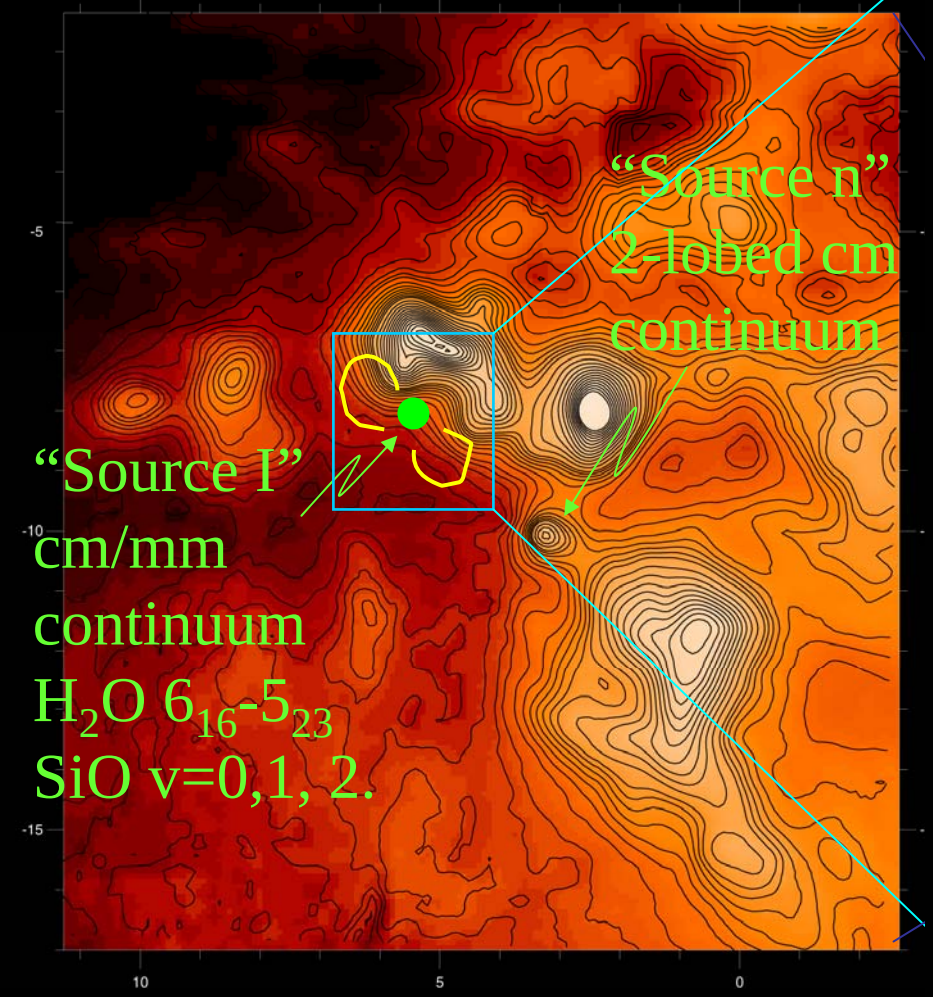

20 km s-1 or
~ 0.1″/decade
SiO
v=1,2
>10³ K
~10⁹±¹ cm⁻³
SiO v=0 J=2−1
450 AU
SiO
v=0
~10³K
~ 10⁶±¹ cm⁻³
Src I
H2O
6₁₆-5₂₃
< 10³K
~ 10⁹±¹ cm⁻³
225 AU
5
10
15
LSR velocity (km s-1)
R < 1000 AU

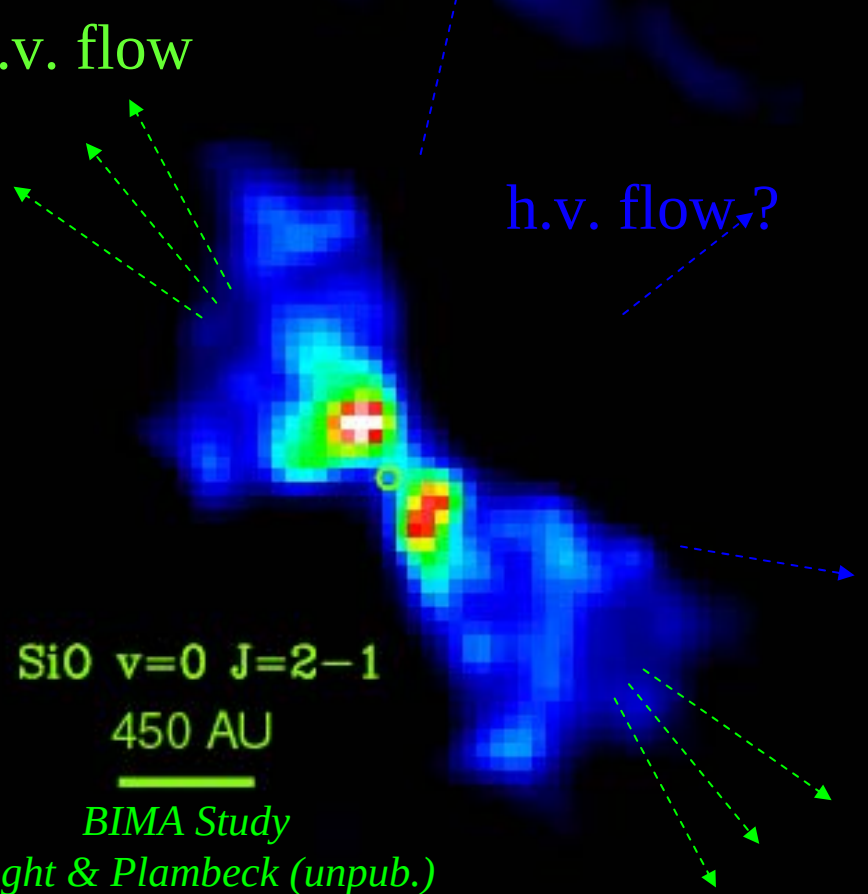

Mass-loaded
outflow wall
“Permitted” zones
for maser emission
Bipolar outflow
Radial stratification?
Rotation?

Masers trace hot, dense gas…

- H_2O
  - $n_{H2} \sim 10^9 - 10^{10}\ cm^{-3}$
  - T ~ 300 - 800 K
    - *Dusty regions. Collisional pump (shocks).*
- SiO (v=1, 2)
  - $n_{H2} \sim 10^9 - 10^{11}\ cm^{-3}$; $N_{SiO} \sim 10^{19} - 10^{20}\ cm^{-2}$
  - T > 1200 K
    - *Dust-free regions. Collisional and radiative pumps.*
- SiO (v=0)
  - $n_{H2} \sim 10^5 - 10^6\ cm^{-3}$; $N_{SiO} \sim 10^{16}\ cm^{-2}$
  - T ~ 800 - 1600 K

• Close association with young stars.
• Quiescent gas.





BIMA Study
Wright & Plambeck (unpub.)
See also Wright et al. 1996

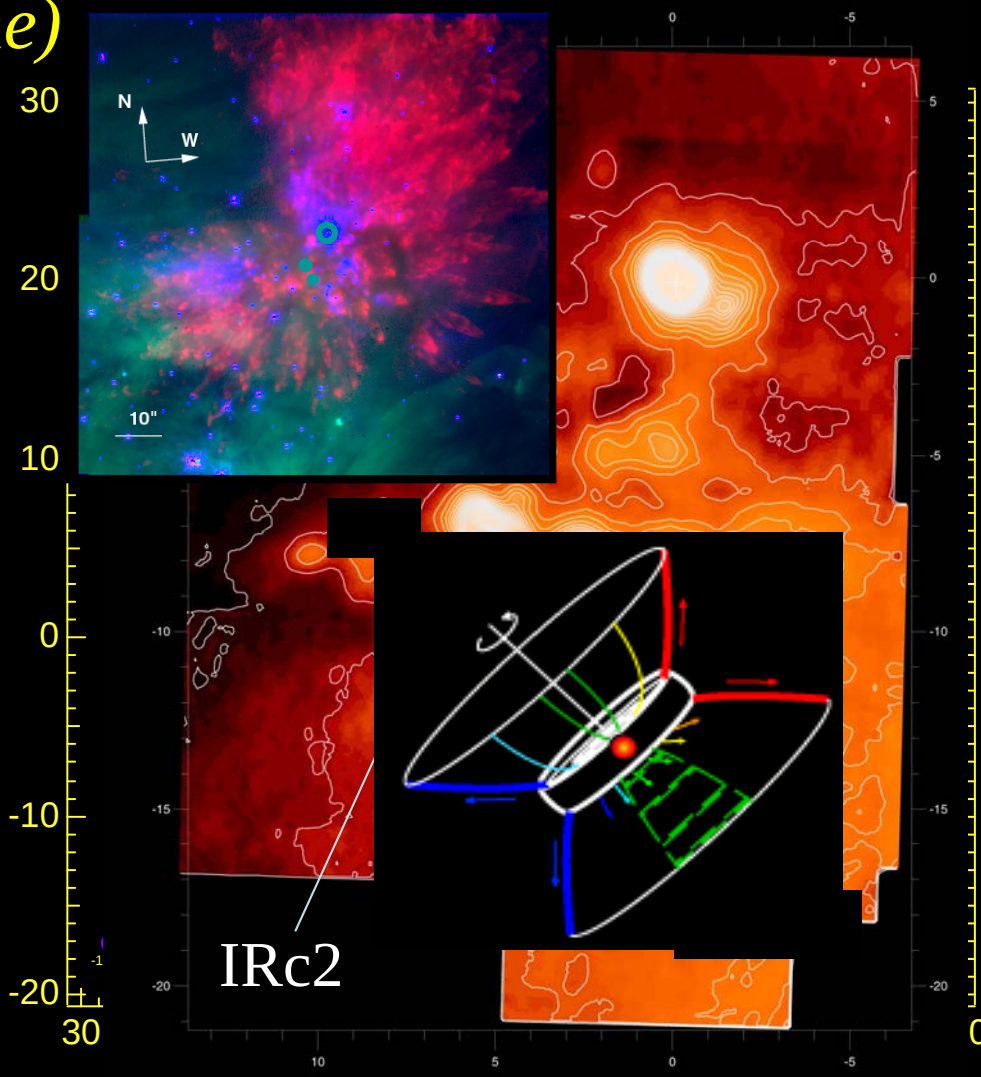
Gezari et al. in prep.

Danchi etal. in prep.
Greenhill et al. in "

- Crowded.
- Uncertain Ids of YSOs. Multiple outflows.
- Patchy obscuration, A_V of a few to 500.

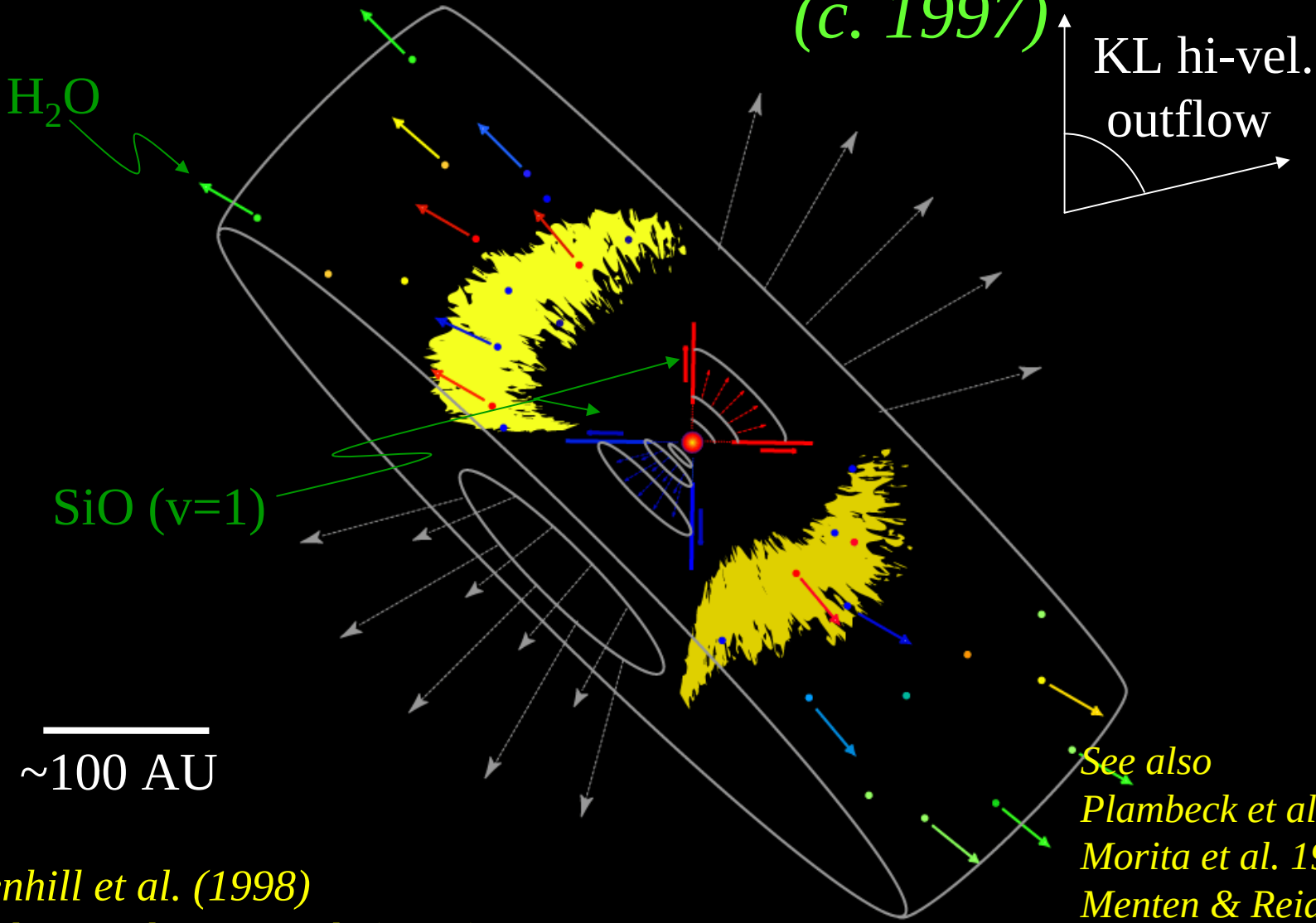
What powers Orion BN/KL?

- Probably not source I *(alone)*
  - The h.v. flow is shadowed.
  - Src I flows are “compact.”
  - There are many YSOs in the vicinity.
- However
  - Alignment with the 18 km/s flow is good, and
  - Mass loss may be eposodic



What is Source I?

(c. 1997)



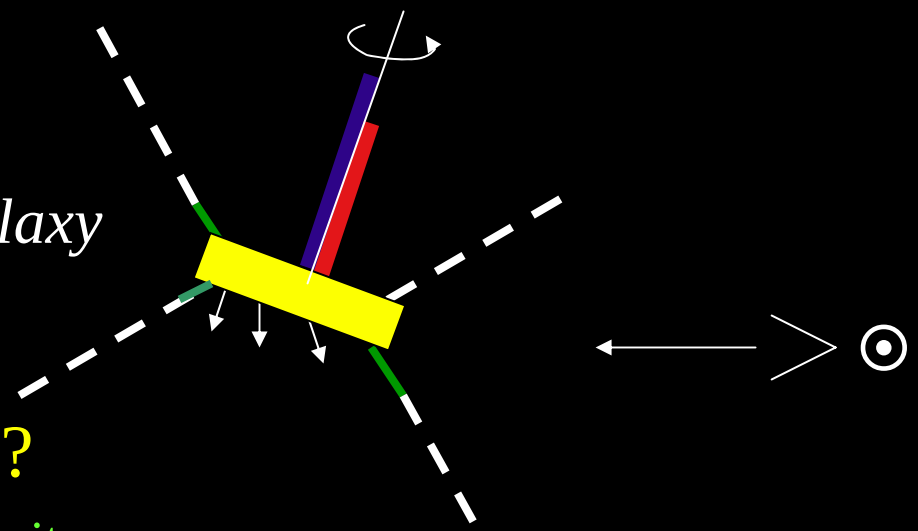
Greenhill et al. (1998)
See also Doeleman et al. (1999)

See also
Plambeck et al. 1990
Morita et al. 1992
Menten & Reid 1995
Genzel & Stutzki 1989

More Questions…

- Is the model antropocentric?

P.O.V. in outer galaxy



- Is Source I unique?
  - Yes, in terms of proximity.
  - But, possibly similar source in W51 IRS2 (Eisner et al.).
  - No reported southern sky surveys for interstellar SiO masers.
- An especially short evolutionary phase for massive YSOs?
- Maser emission can be a highly specific tracer.

  Is there danger here?

Are Magnetic Fields Important?

- Evaluate 3-D gas dynamics
  - v=1, 2 SiO masers @ R<10^2 AU
  - Radiation-driven disk winds?
  - Hydromagnetic disk winds?
    - Blandford & Payne 82, Pudritz & Norman 86, Ouyed, Pudritz & Stone 97
  - Where would the field come from?
    - Presumably not stellar.
    - Sweeping up of ambient field?
      - Ambipolar diffusion
- Measure linear polarization
  - v=0, 1, 2 SiO masers @ R<10^3 AU

Key Science Questions

- What does HMSF look like?
  - Structure @ R= 20-10^3 AU
  - 3-D gas dynamics @ R= 20-10^3 AU
- Are magnetic fields important?
- Is source I important (to BN/KL)?
- Are outflows turbulent?
- Can more massive stars form in the same way?