An Movie of Accretion/Ejection of Material in a High-Mass Young Stellar Object in Orion BN/KL at Radii Comparable to the Solar System

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High-Mass Star Formation: An Unsolved Problem

Addressing open questions: How do stars of ~ 10 $M_{\odot}$ form?

- Mass Accretion Process (Disk-mediated or competitive accr.? Coalescence?)
- Acceleration and Collimation of (proto-)Stellar Outflows?
- Sizes/Structures of Disks? Role of Magnetic Fields?
- Physical Properties of the Disk/Outflow interface?
- Multiplicity and distribution of massive YSOs within protoclusters

Why is high-mass star formation poorly understood?

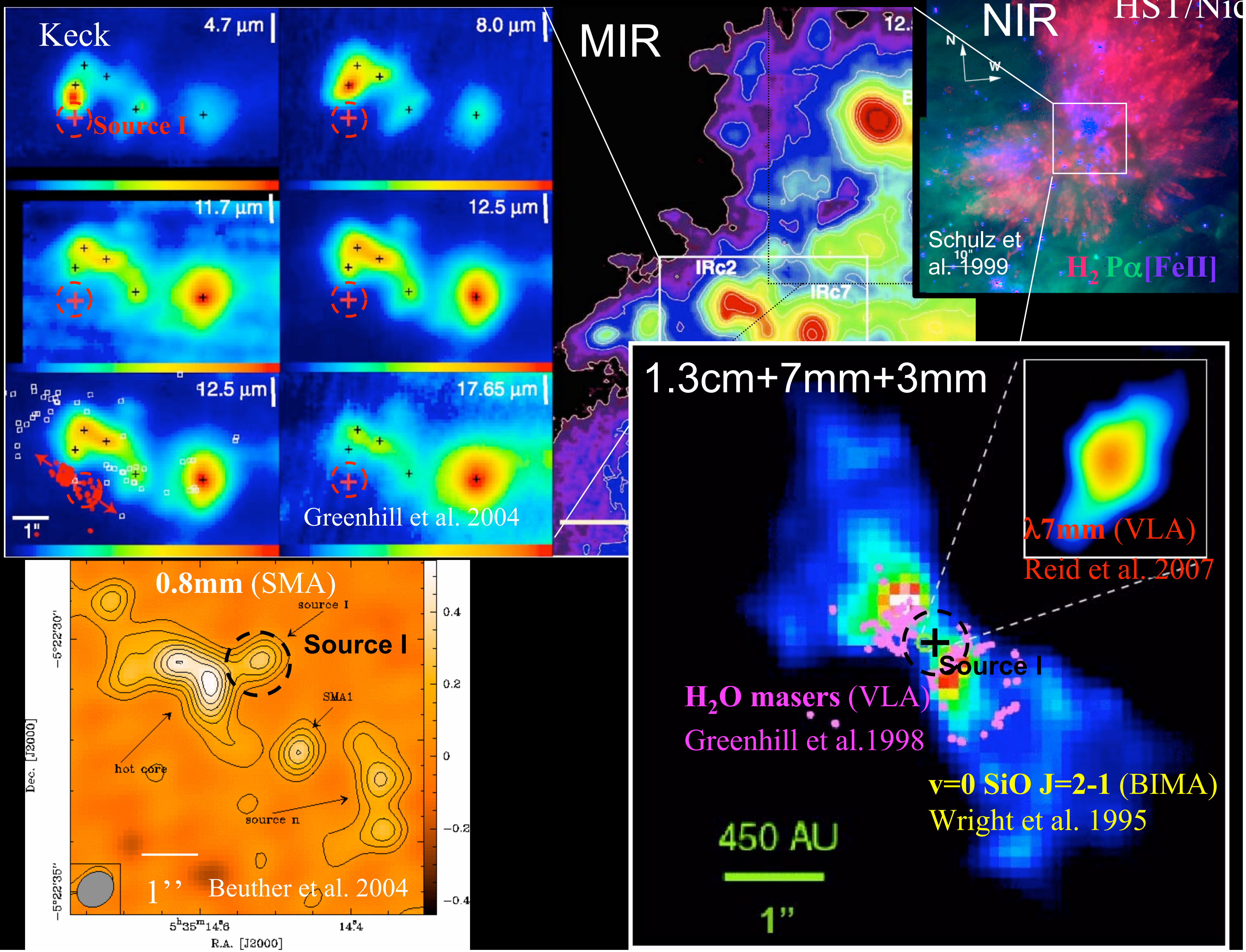
Good examples of accreting massive YSOs are rare.

- Declining IMF and Rapid evolution => Distance (> 500 pc)
- Formation in clusters => Confusion/crowding
- High extinction => radio and mm-wavelengths
- Thermal tracers generally unable to probe inside 10-1000 AU from a massive YSO

Talk Objective

Dynamics and physical conditions of circumstellar gas at radii 20-1000 AU from the high mass YSO Radio "Source I" in Orion BN/KL

The case of Radio "Source I" in Orion BN/KL



The KaLYPSO Project

A documentary of massive star formation: Probing the dynamical evolution of Orion Source I on 10-1000 AU scales using interferometric observations of molecular masers

Observational Dataset

Transition	Instrument	Observations	Resolution
^{28}SiO (v=1,2 J=1-0)	VLBA	40 epochs over 2001-03	0.1 AU
^{28}SiO (v=0 J=1-0)	VLA	5 epochs in 10 yrs	25-100 AU
$^{29/30}SiO$ (v=0 J=1-0)	VLA	2 epochs sep. by 9 yrs	100 AU
H_2O (6_{16}-5_{23})	VLA	3 epochs in 25 yrs	25 AU
7 mm continuum	VLA	3 epochs in 8 yrs	25 AU

A multithreaded observational and modelling study of radio Source I:

I. Mapping of the time-varying distribution of ~1000 SiO maser spots at radii 10-100 AU (v=1,2) and 100-1000 AU (v=0) from source I

II. A movie documenting the 3-D evolution of a disk/outflow “connection” within 100 AU from a massive protostar over 30% of the outflow crossing time

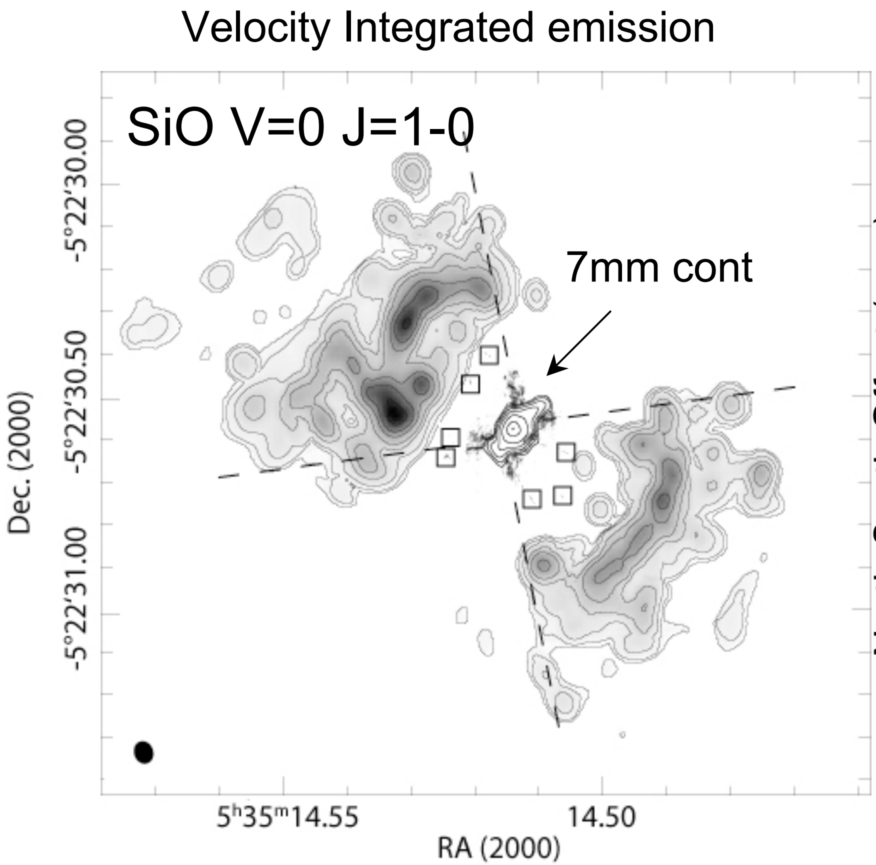
III. 3-D dynamics of the circumstellar gas via measurements of proper motions of individual SiO v=0,1,2 maser spots

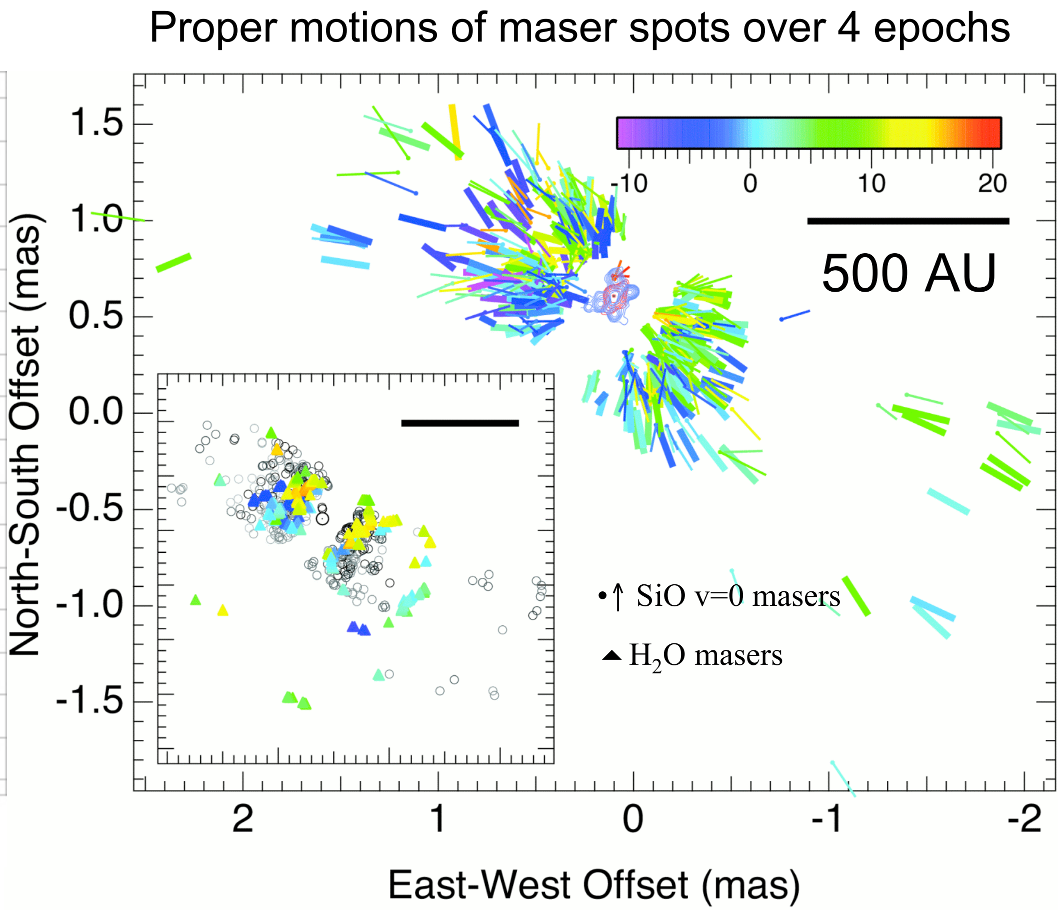
IV. Geometric, dynamical, and radiative transfer models of the molecular masing gas

V. Dynamical Scenarios for BN/KL: proper motions of the radio continuum sources

Radio "Source I" drives a "Low-Velocity" NE-SW outflow

VLA maps of SiO V=0 J=1-0



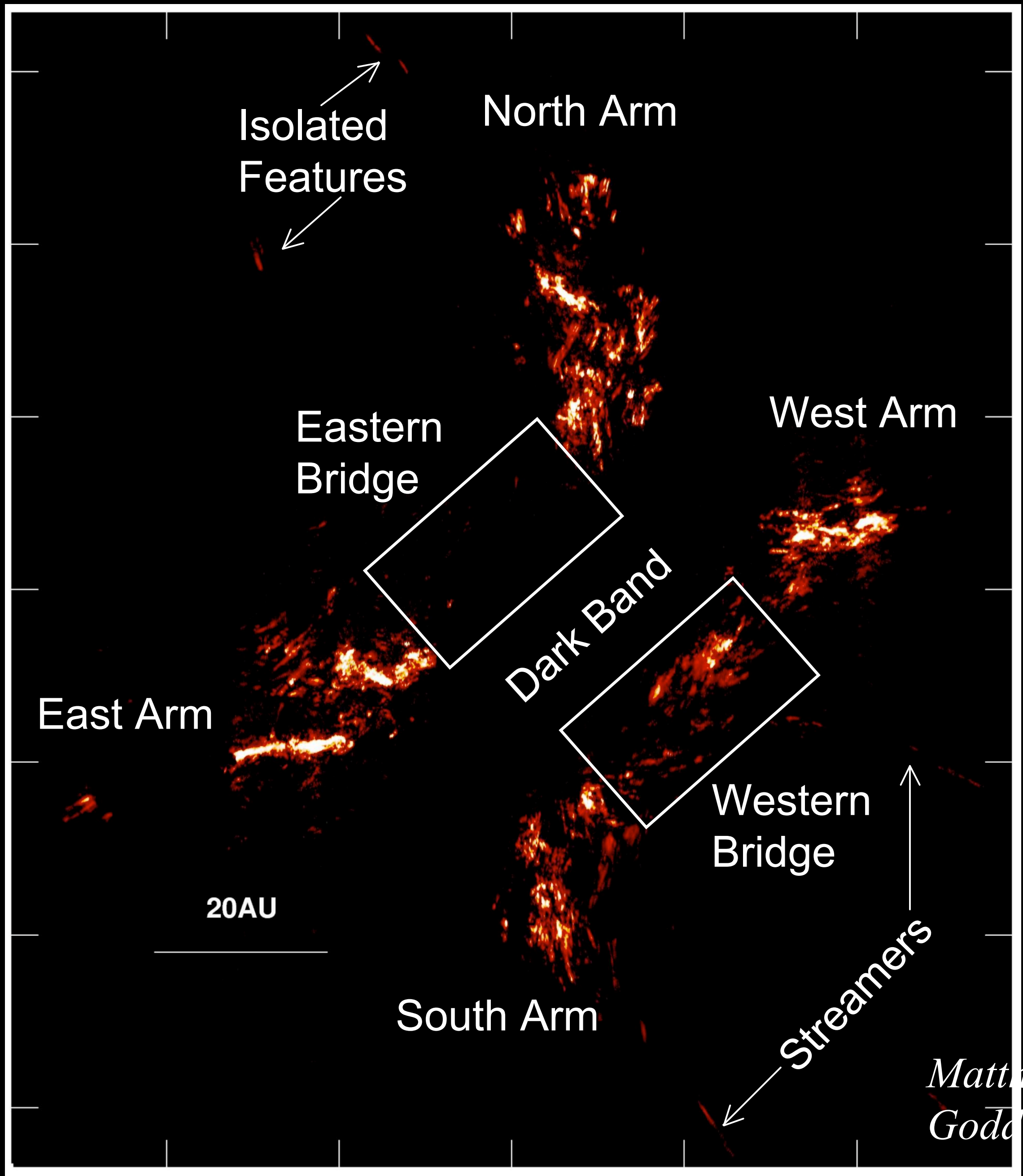


Outflow properties inferred from maser proper motions:

- Characteristic speed ~ 20 km/s
- Size < 2000 AU
- Dynamical crossing time <500 years
- Mass-loss rate $\sim 5\times10^{-6}\ M_{\odot}$/yr

Greenhill, Goddi, et al., in prep.

Cumulative VLBA Moment 0 images of SiO (v=1,2) masers over *2 years*

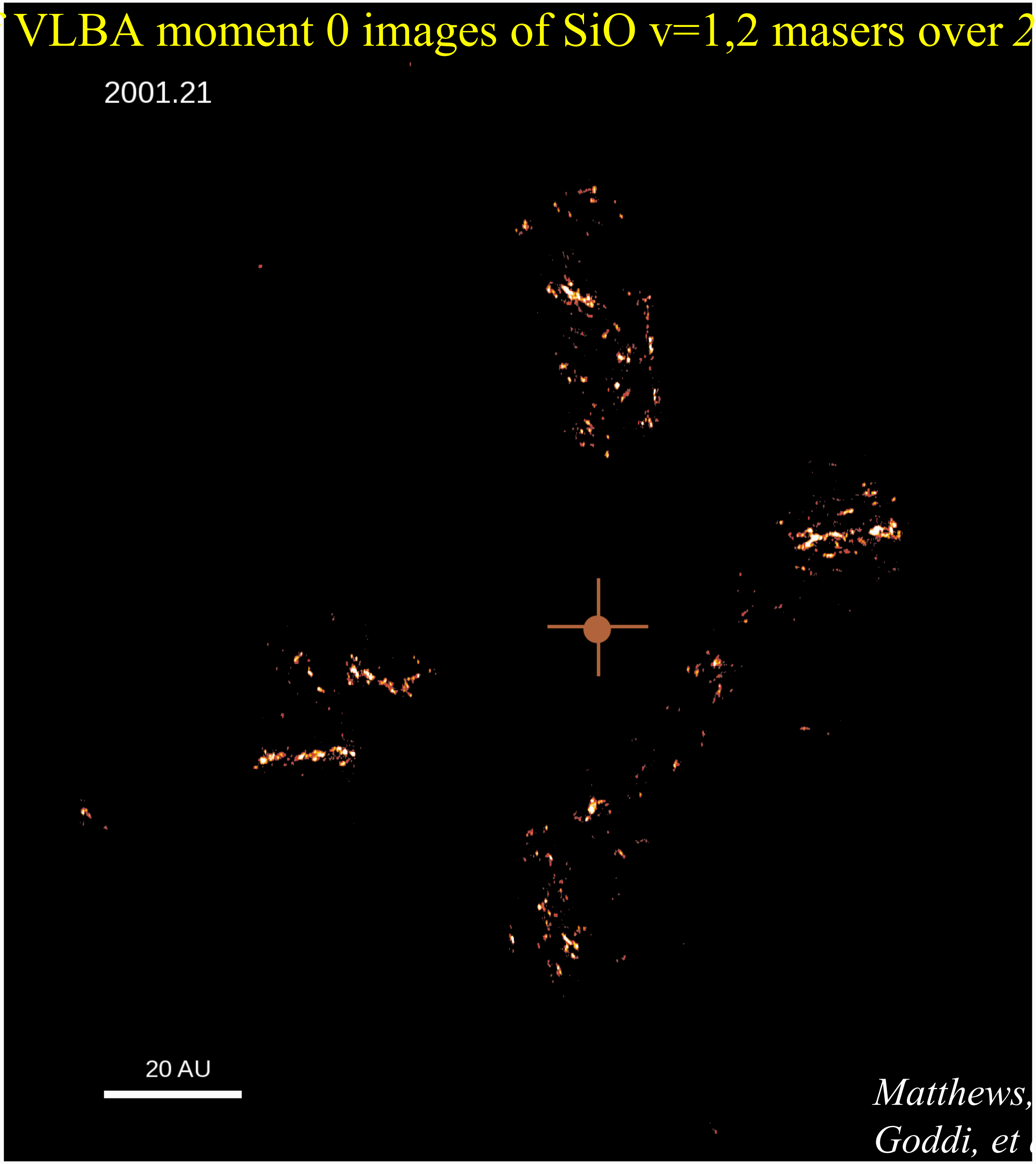


R<100 AU

Matthews, Greenhill, Goddi, et al. submitted

Time-series of VLBA moment 0 images of SiO v=1,2 masers over 2 *years*

Integrated Intensity

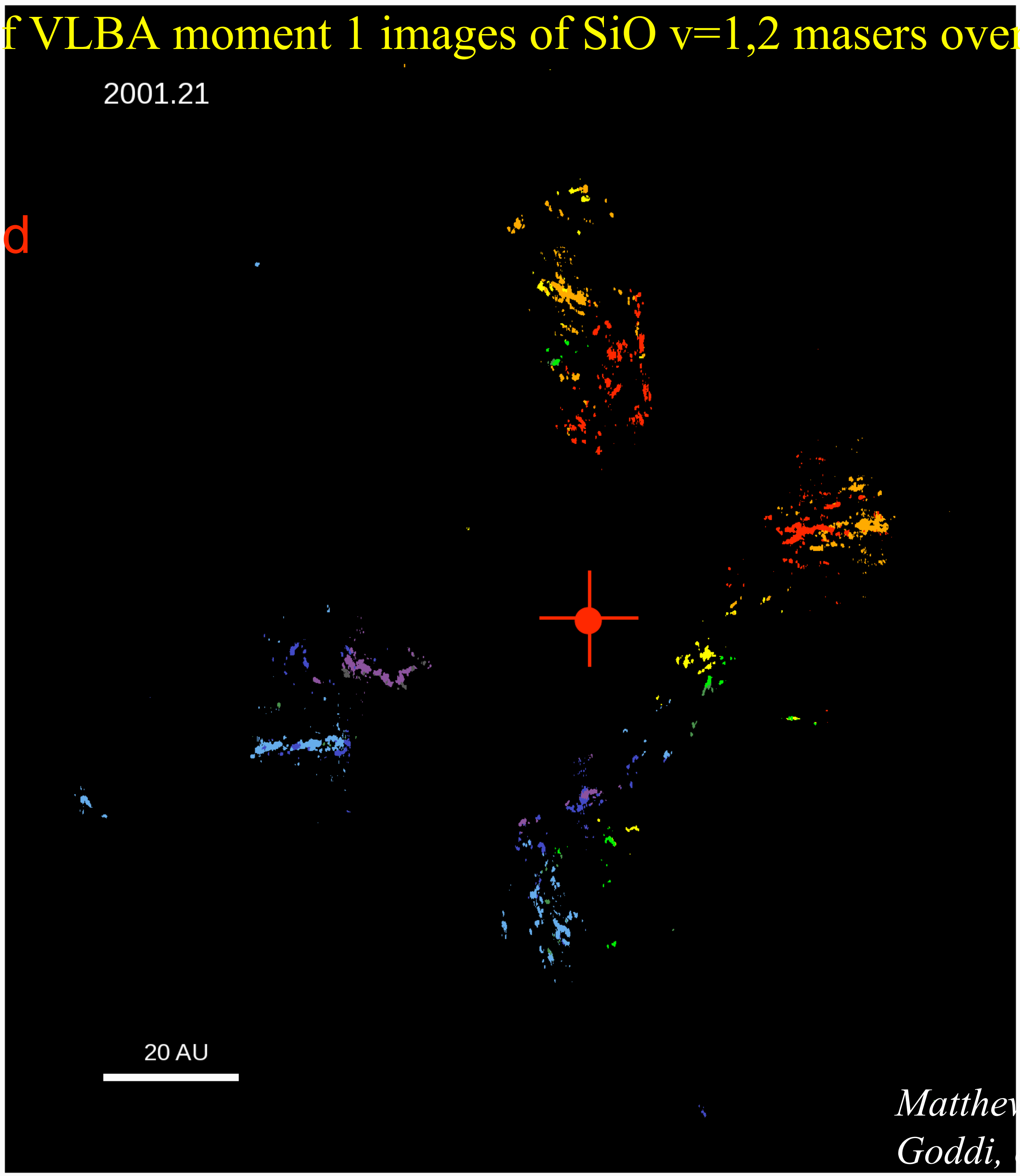


R<100 AU

Matthews, Greenhill, Goddi, et al. submitted

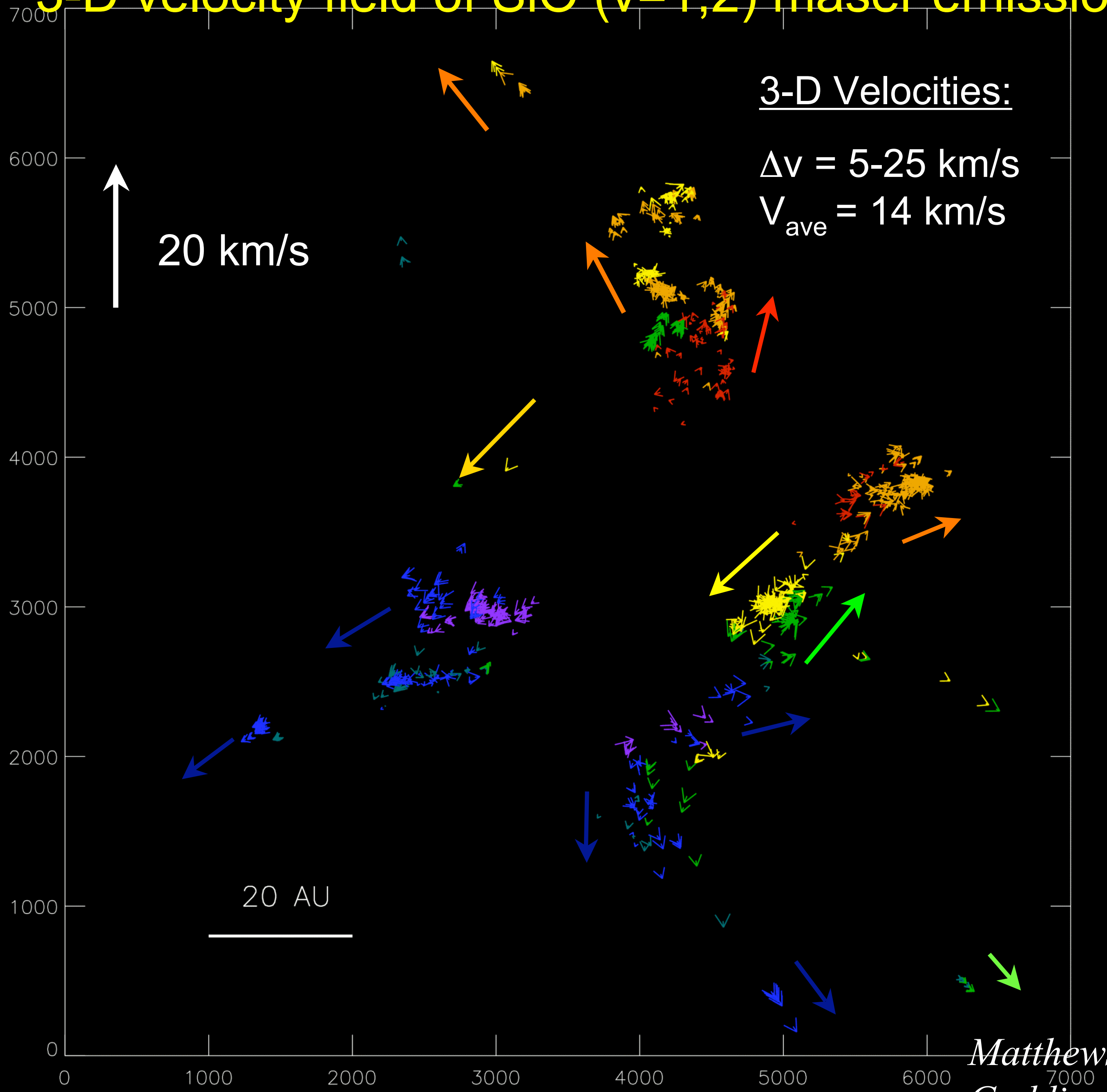
Time-series of VLBA moment 1 images of SiO v=1,2 masers over *2 years*

LOS
Velocity field



Matthews, Greenhill, Goddi, et al. submitted

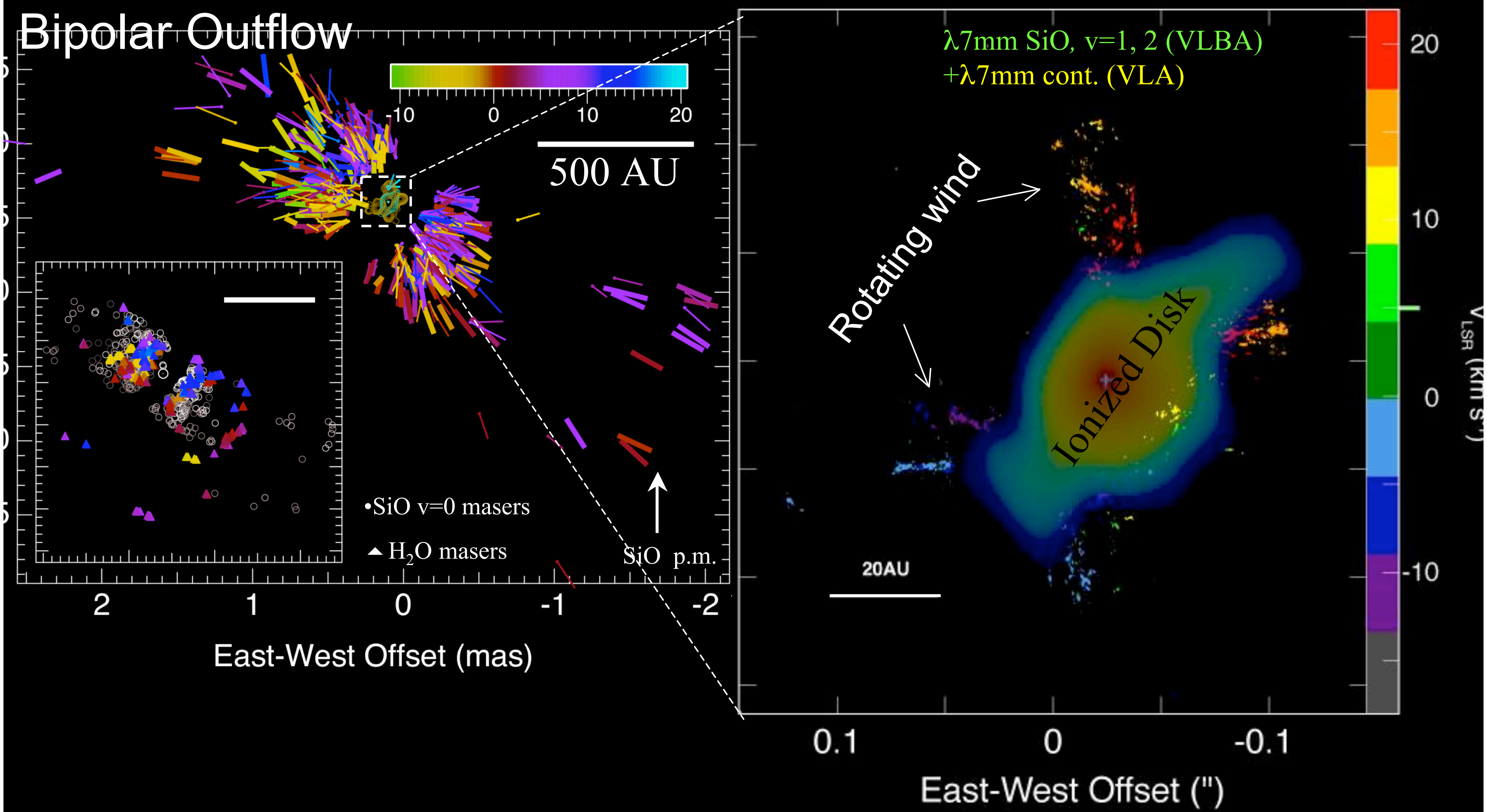
3-D velocity field of SiO (v=1,2) maser emission



Matthews, Greenhill, Goddi, et al. submitted

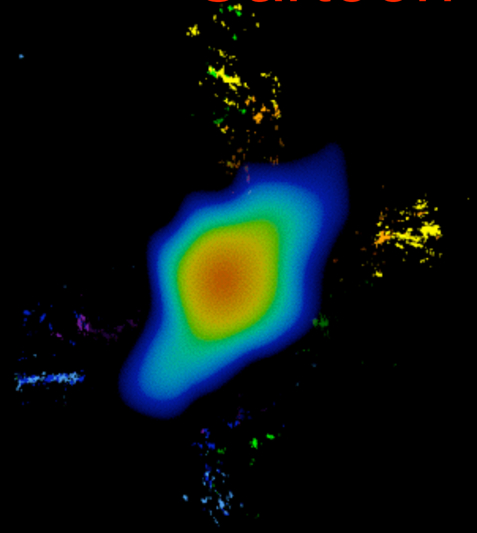
Distribution of molecular masers in Orion Source *I*

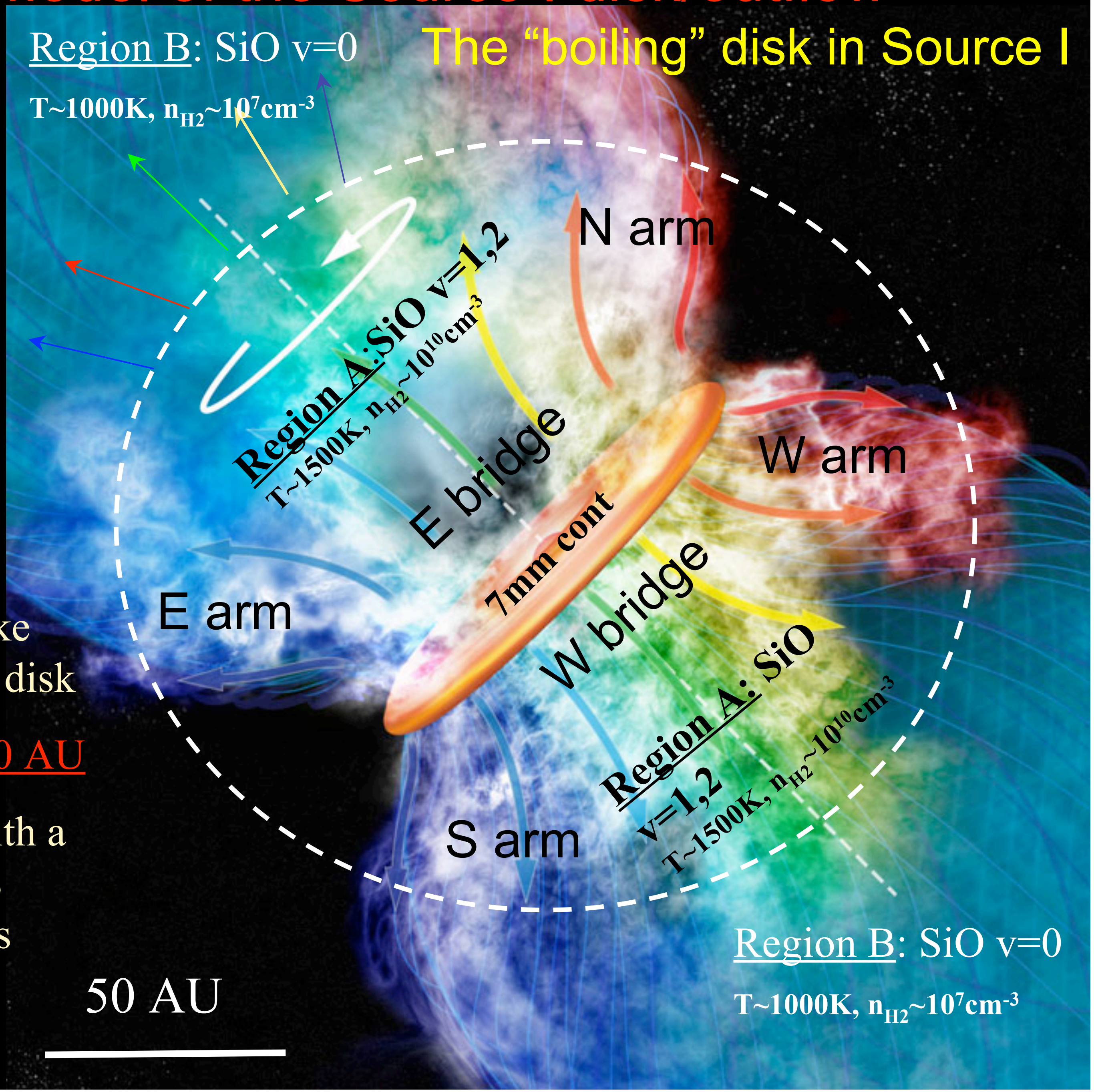
R=100-1000 AU | *R =10-100 AU*



Resolving an outflow launch/collimation region from a compact disk in a high-mass YSO => evidence of disk-mediated accretion

Cartoon Model of the Source I disk/outflow





➢Region A: R<100 AU

Material is driven into a bipolar rotating funnel-like outflow from an edge-on disk

➢Region B: 100<R<1000 AU

Material is outflowing with a characteristic speed of 18 km/s along a NE-SW axis

Summary

- Bipolar, wide-angle outflow along a NE-SW axis at radii 100-1000 AU
  - ➢ T_{dyn} ~ 300 yr for R = 1000 AU; $dM_{out}/dt \sim 5\times10^{-6}\ M_\odot/yr$
- Organized accretion/outflow structure inside ~100 AU
  - ➢ Bipolar, funnel-like wind in rotation (T_{dyn} ~ 20 yr for R = 0-70 AU)
  - ➢ Rotating and expanding disk (T_{rot}~30 yr for R ~ 40 AU)

⇒ Good example of disk-mediated accretion in massive YSOs

- Source I is the best massive YSO known for testing how inflowing material is collimated to form an outflow
  - ➢ Photoionized wind? (e.g., Hollenbach et al.1995))
  - ➢ Equatorial line-driven wind? (e.g., Drew et al. 1998)
  - ➢ Equatorial wind driven by dust-mediated radiation pressure? (Elitzur 1982)
  - ➢ MHD disk wind? (e.g., Pudritz et al. 2007)

The Mass of Source I

The masing gas is not in purely Keplerian rotation, e.g. radiative and/or magnetic forces act against gravity (outward motions)

=> *Only a lower limit to the mass can be estimated* :

1. Keplerian rotation (<u>bridge</u>): R=35 AU, V_{3D}=14 km/s
   $|V_{bridge}|^2 \sim 2GM_*/R$ => $M_*>7\ M_\odot$

2. Wind at the escape velocity (<u>arms</u>): R=25 AU, V_{3D}=16 km/s
   $|V_{arm}|^2 \sim 2GM_*/R$ => $M_*>7\ M_\odot$

3. 7mm continuum luminosity (<u>HII region</u>): $L_* \sim 10^4\ L_\odot$
   => $M_* \sim 10\ M_\odot$

Most probably Source I has a mass in the range **7-10 $M_\odot$**

Candidate physical mechanisms driving the disk-wind

- **Disk Photoionization** (Hollenbach et al.1994)
  For M_*~8 $M_\odot$, an *ionized* wind is set *beyond* the radius of the masers

- **Line-Driven winds** (Drew et al. 1998):
  $v_w \geq 400$ km/s, $\rho_w << 10^{-14}$ g cm^{-3} inconsistent with $v_{mas} < 30$ km/s, $\rho_{mas} > 10^{-14}$ g cm^{-3}

- **Dust-mediated radiation pressure** (Elitzur 1982):
  Dust and gas are mixed at R<100 AU: $L_{mod} = 10^5\ L_\odot$, $\dot{M}_{mod} = 10^{-3}\ M_\odot\ yr^{-1}$
  Inconsistent with: $L_{obs} \leq 10^4\ L_\odot$, $\dot{M}_{obs} = 10^{-5}\ M_\odot\ yr^{-1}$, T_{gas}~2000 K

- **MHD disk-winds** (Konigl & Pudritz 2000):

Maser features are detected along curved and helical filaments
=> Magnetic fields may play a role in launching and shaping the wind

Radiative transfer analysis of SiO maser emission

From a (constrained) LVG model with both radiative and collisional pumping

Species	n_{H2} (cm^{-3})	T (K)	R (AU)
^{28}SiO v=0	$< 10^7$	<1200	>100
^{28}SiO v=1	10^8 - 10^{10}	> 1500	<100
^{28}SiO v=2	10^9 - 10^{11}	> 2000	<100
^{29}SiO/^{30}SiO v=0	10^8 - 10^{11}	> 1500	<100

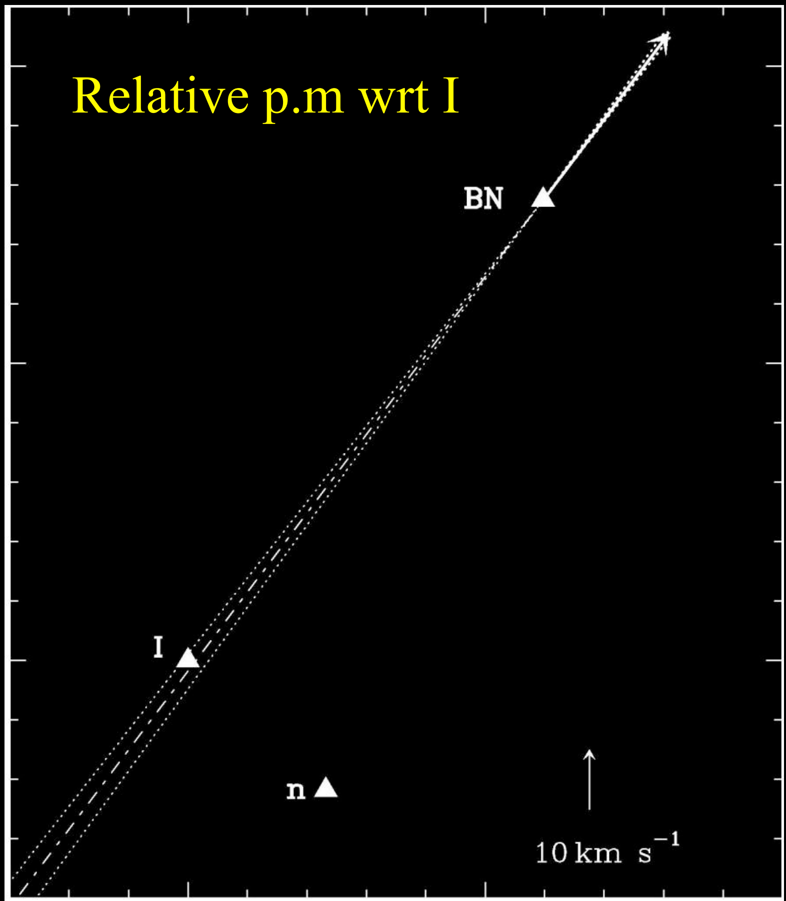
Doel et al. 1995

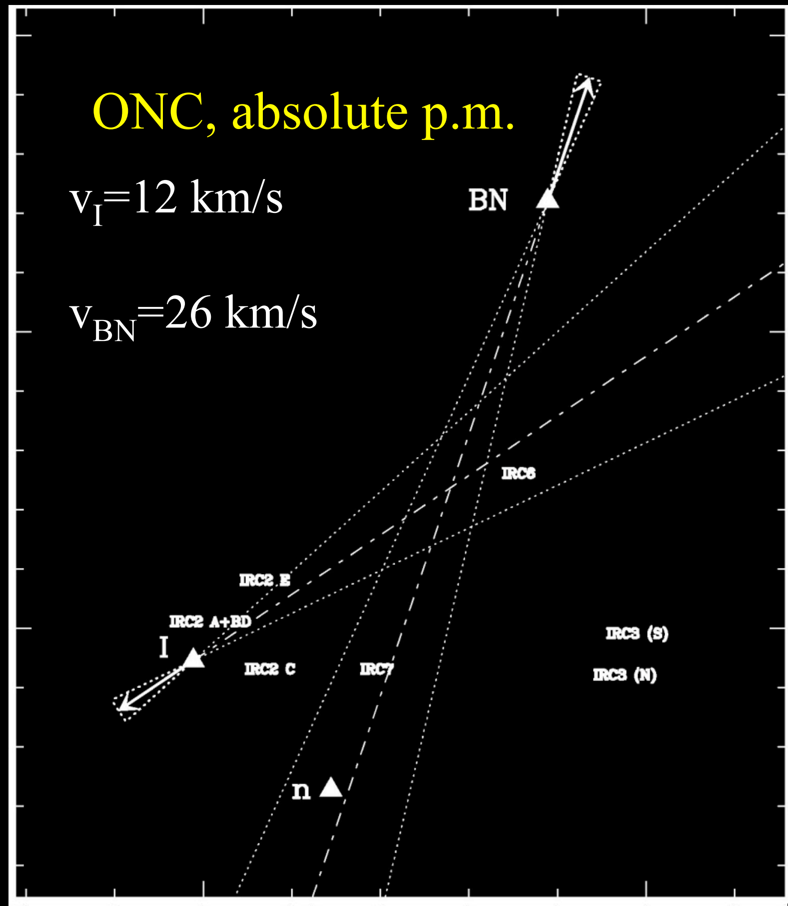
Goddi et al. 2009

Different maser species/transitions trace different portions of the molecular gas around Source I

Effects of maser saturation and line overlap will be included in a future paper (Humphreys et al. In prep.)

Dynamical interaction in BN/KL:
Proper Motions of Source I and BN (λ7mm cont. VLA)





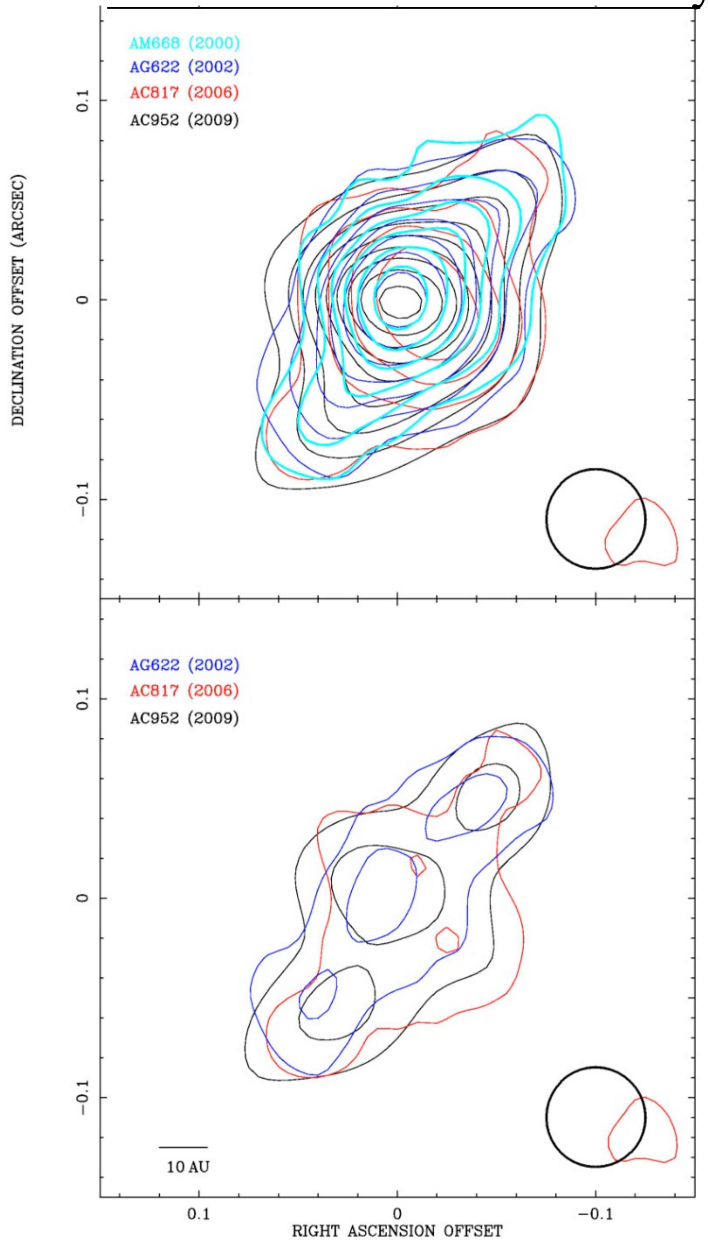
500 years ago BN and I might have been as close as 50-100 AU

I. The large motions of BN and I are the results of a triple-system decay 500 yrs ago

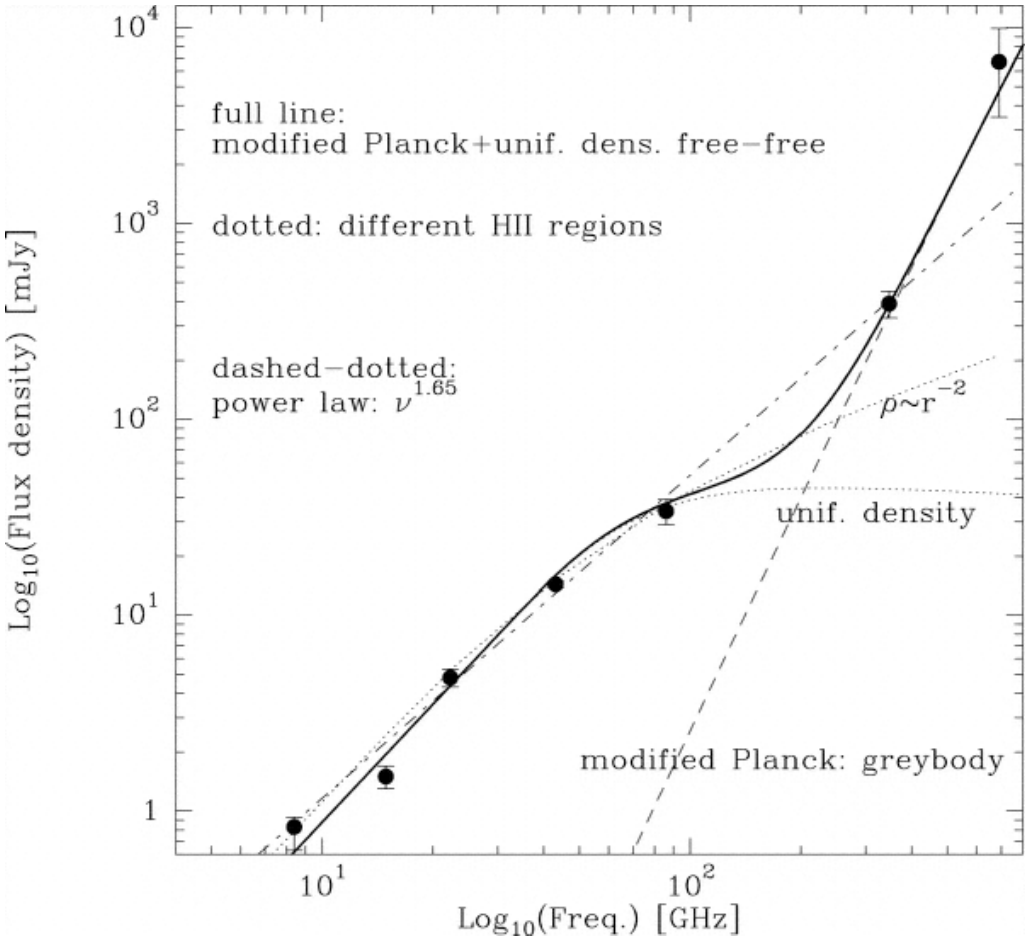
II. An entire protocluster decayed ejecting the radio and IR sources in BN/KL

Goddi et al. in prep.; see also Rodriguez et al. 2005 and Gomez et al. 2008

Morphological evolution of the 7mm continuum emission over 10 years



SED from 8.4 to 690 GHz



Morphological evolution of individual maser features over 2 yrs