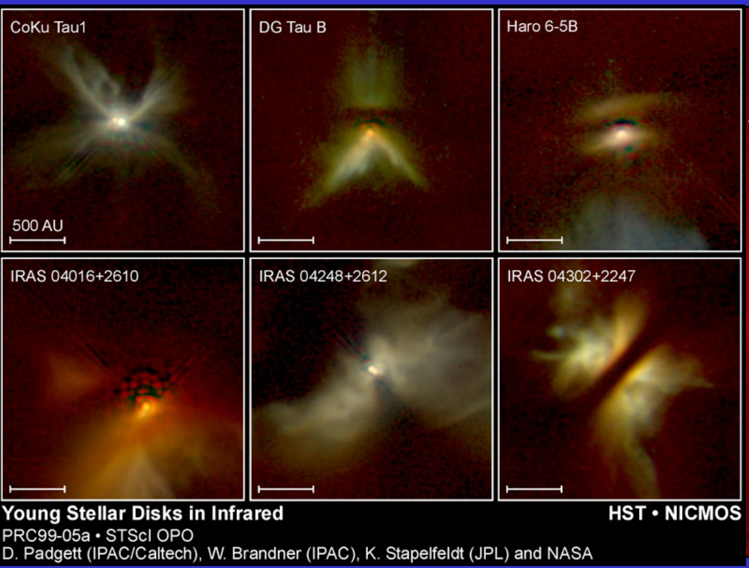
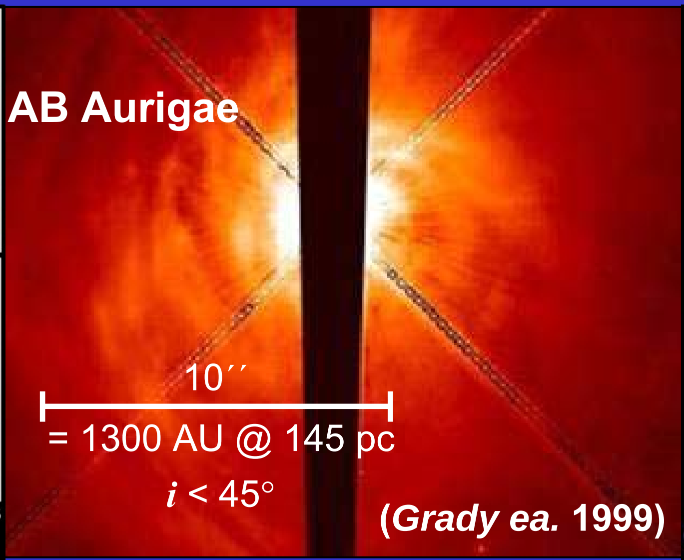
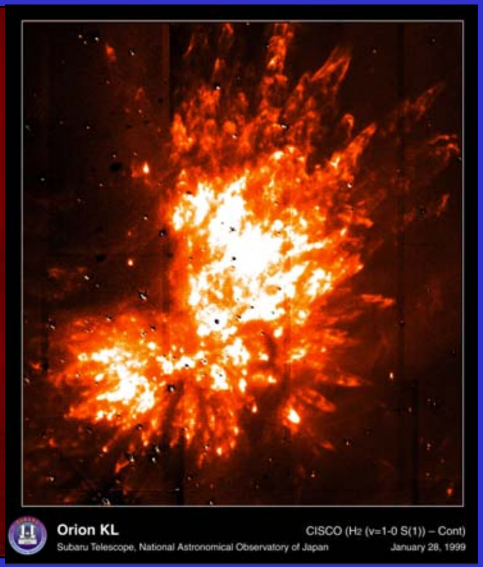
Thomas Henning
Max Planck Institute for Astronomy – Heidelberg

Disk around very young massive stars





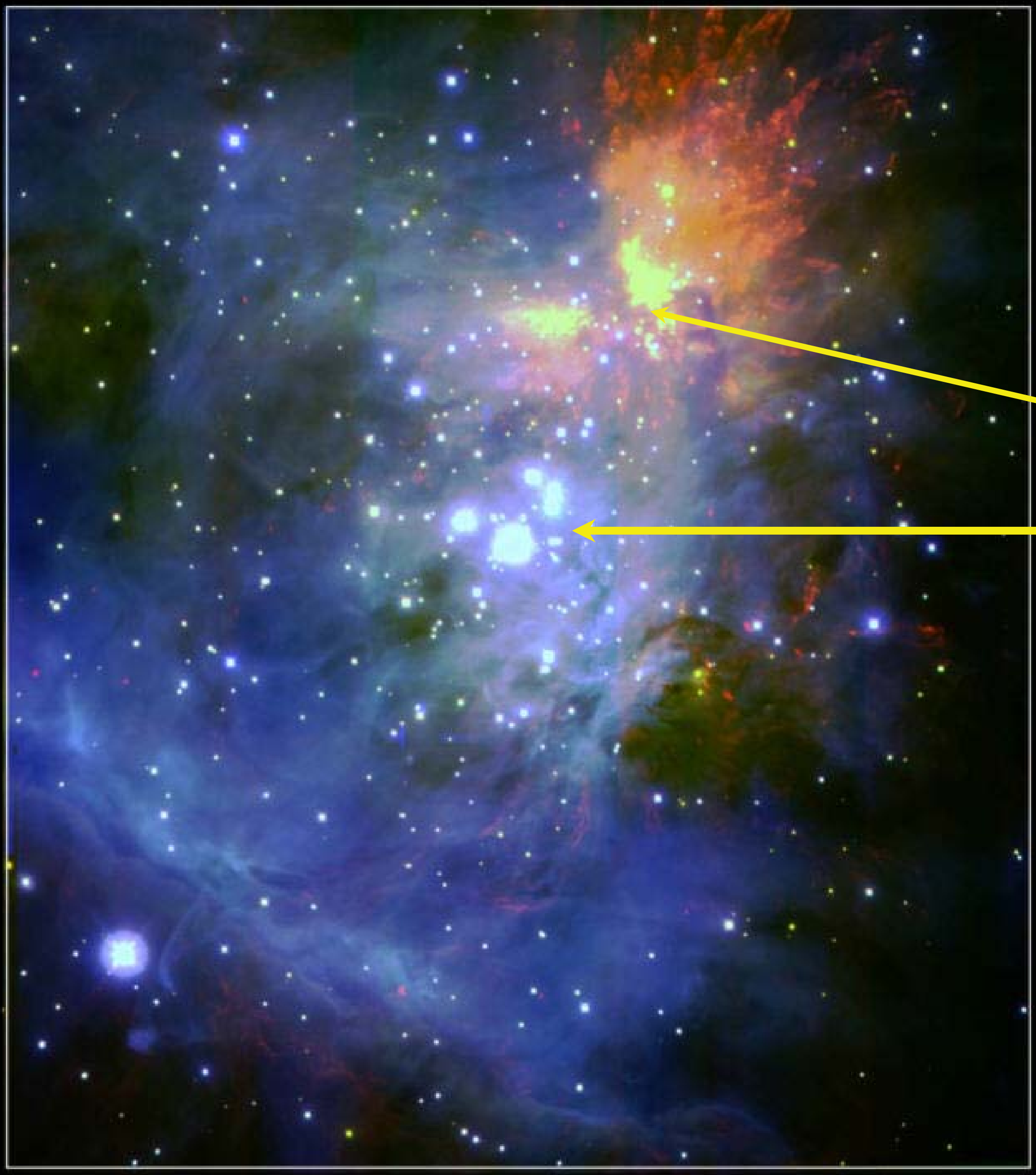


T Tauri stars ☺ ☺ ☺

Herbig Ae stars ☺ ☺ ☺

mYSOs ???

Importance of massive stars



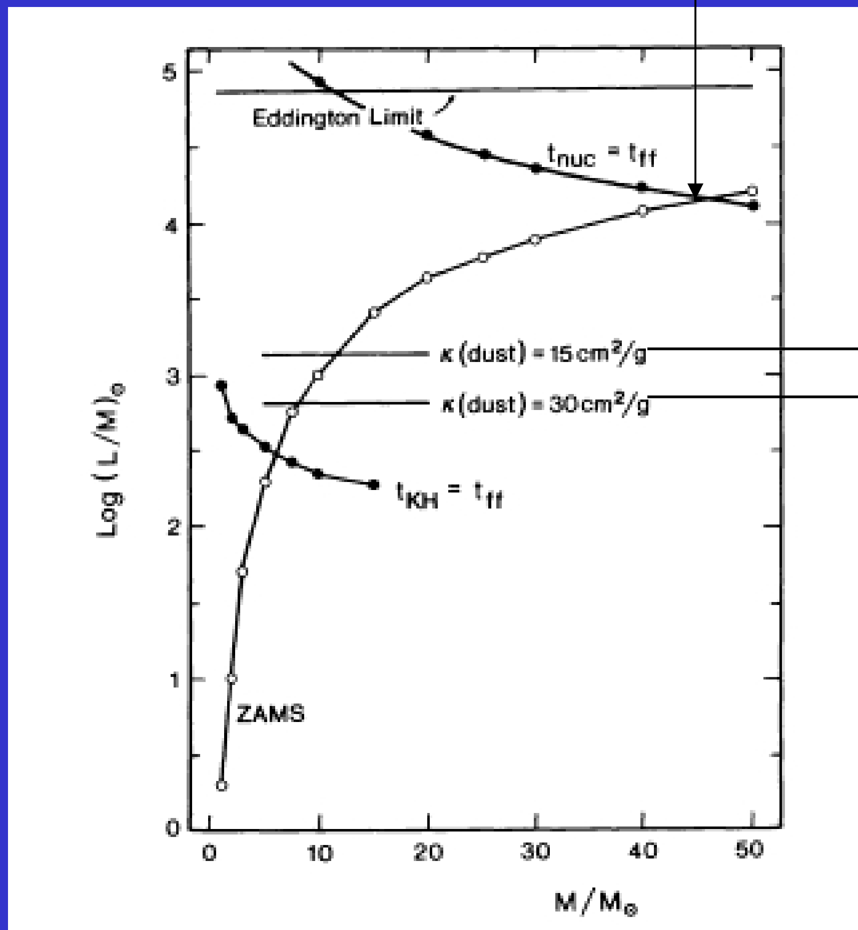
Orion Nebula
Subaru Telescope, National Astronomical Observatory of Japan
CISCO (J, K′ & H_2 (v=1-0 S(1))
January 28, 1999

Enormous impact on ISM and star clusters

- Outflows and jets
- UV radiation
- Nucleosynthesis
- Supernovae

Massive star formation is the only star formation mode observable in extragalactic systems.

Luminosity-to-mass ratio



Beech and Mitalas (1994)

High-mass stars: Mass larger than 8 M_{sun} – ZAMS B4 – 10^3 L_{sun}

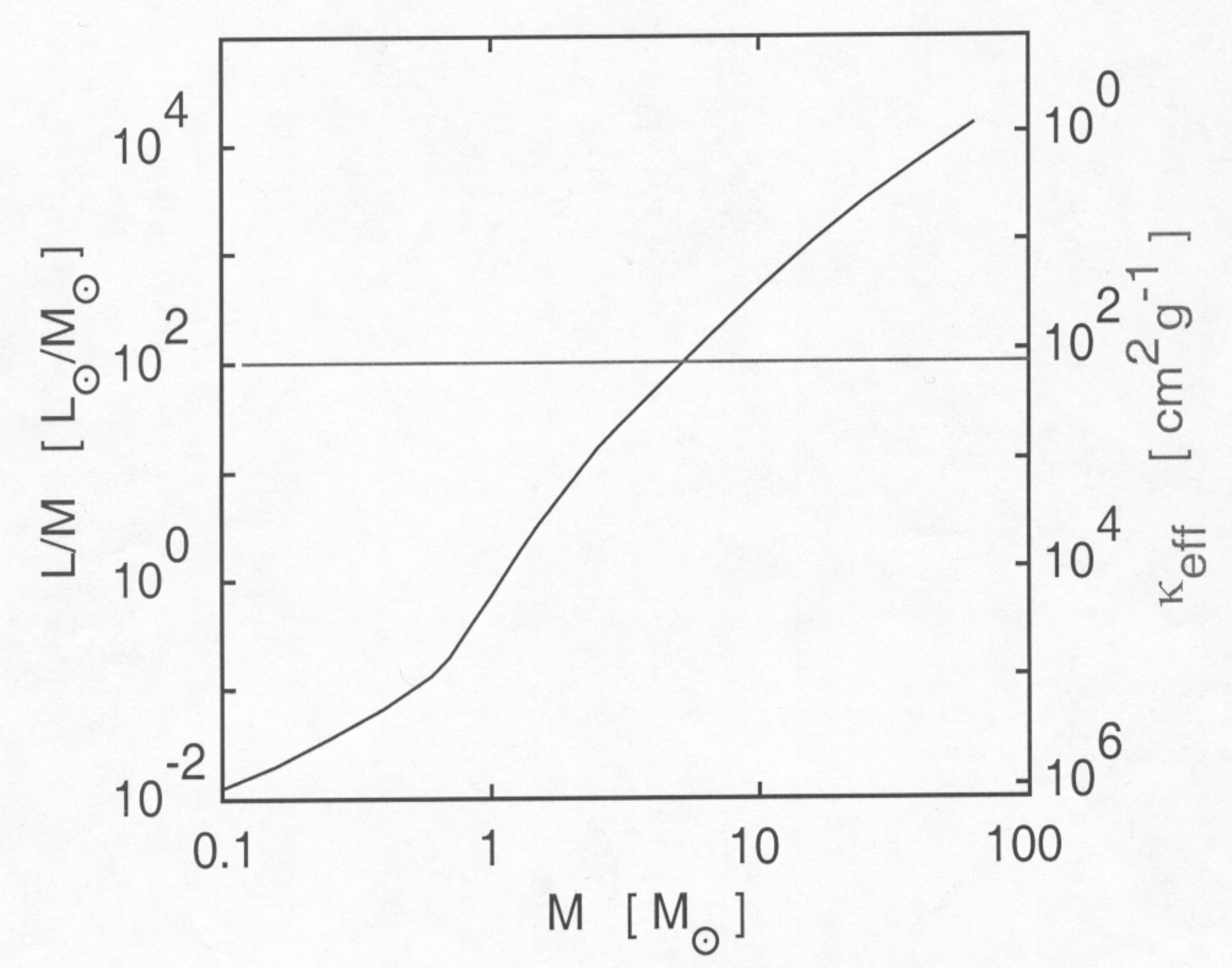
Accretion Limit - Spherical Symmetry

(Kahn 1974, Yorke & Krügel 1977, Wolfire & Cassinelli 1987)

Gravity exceeds radiative acceleration

$$\frac{GM}{r^2} > \frac{\kappa_{eff} L}{4\pi r^2 c}$$

with $L = L_* + L_{acc}$



$$\Rightarrow \kappa_{eff} < 130\ \mathrm{cm^2 g^{-1}} \left[\frac{M}{10M_\odot}\right]\left[\frac{L}{1000L_\odot}\right]^{-1}$$

Possible Solutions (2D)

- Formation of accretion disks: Ongoing accretion due to ram pressure for lower accretion rates than in 1D spherical case
  (Nakano 1989, Nakano, Hasegawa & Norman 1995, Jyjina & Adams 1996, Yorke & Sonnhalter 2002)
- Anisotropic radiation field - "flashlight effect" (Yorke & Sonnhalter 2002)
- Increased flashlight effect by wind-driven cavities (Krumholz, McKee & Klein 2005a)

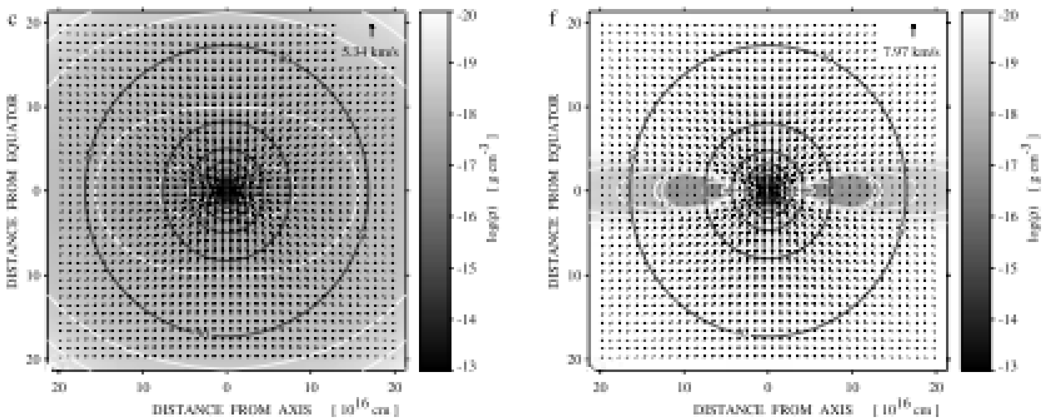


Fig. 9.—Distribution of density, velocity, and grain temperature for case G60 at evolutionary times as indicated in Table 4. Symbols and lines are as in Fig. 8.

Yorke & Sonnhalter (2002)

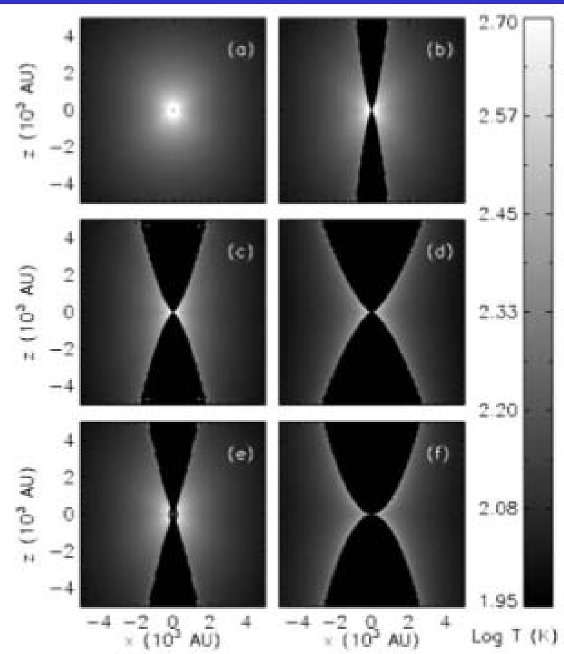
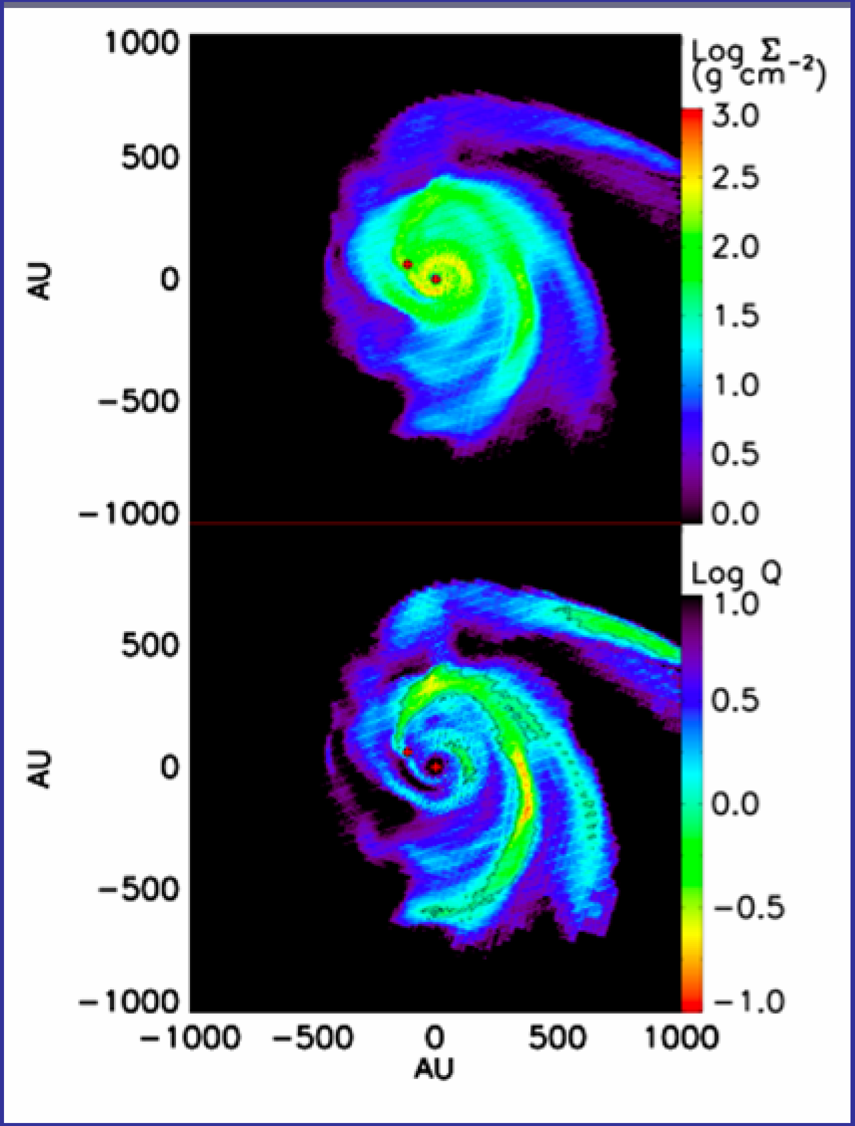


Fig. 1.—Color maps show the gas temperatures for each of our models. The models are (*a*) no wind cavity, (*b*) $\theta_o = 5°$, $b = 1.5$, (*c*) $\theta_o = 10°$, $b = 1.5$, (*d*) $\theta_o = 15°$, $b = 1.5$, (*e*) $\theta_o = 10°$, $b = 1.25$, and (*f*) $\theta_o = 10°$, $b = 2.0$. The white dots inside the cavity in panel *c* are the result of a minor code bug. [*See the electronic edition of the Journal for a color version of this figure.*]

Krumholz, McKee & Klein (2005a)

Disks, Accretion, Binaries

- $M_{disk} / M_* \approx 0.2 – 0.5$
- Global GI creates strong m = 1 spiral pattern
- Disks accrete very rapidly; $\alpha_{eff} \sim 1$
- Disks reach Q ~ 1, form fragments that migrate inward. Tight binaries likely result.



(Kratter & Matzner 2006, Krumholz ea. 2007, Kratter ea. 2008)

Surface density (upper) and Toomre Q (lower)

The Challenges

- Very massive objects are rare

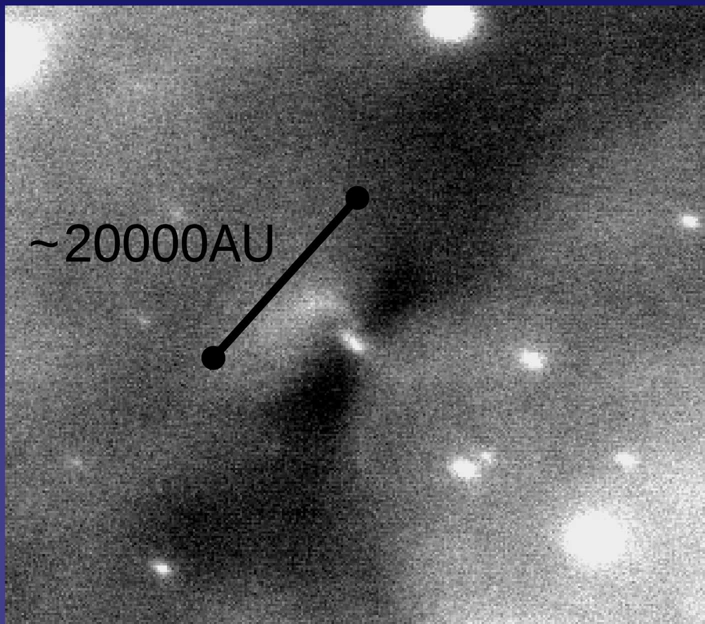
- Regions are at large distances
  (<1000AU gives <1´´ for > 1kpc)

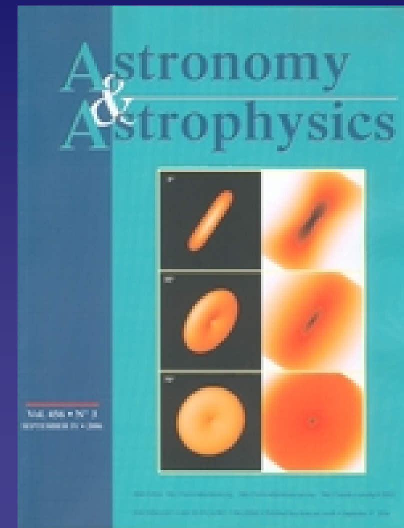
- Evolution is presumably fast
  (High accretion rates upward
  of 10^{-4} M_{sun}/yr over timescales of 10^5 yrs)

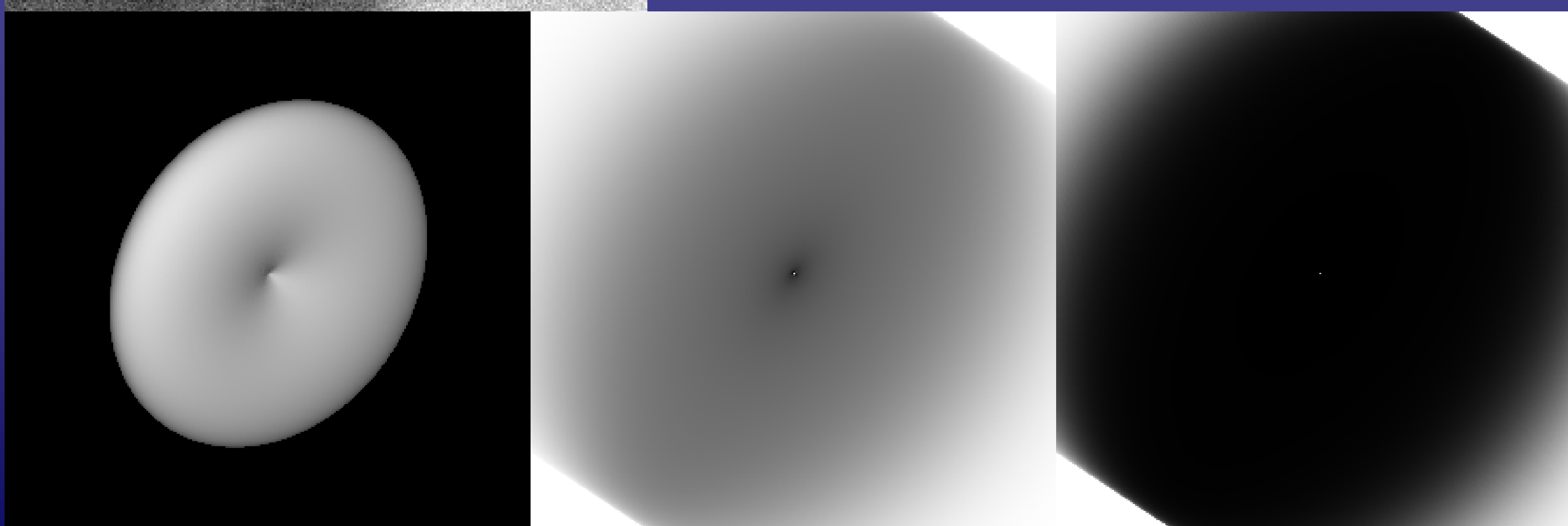
- MSF regions have complex structure

- Luminosity determination
  (Resolution, External radiation fields, Non-spherical radiation fields,
  Underluminous objects (?))

The SO-1 disk candidate in M17

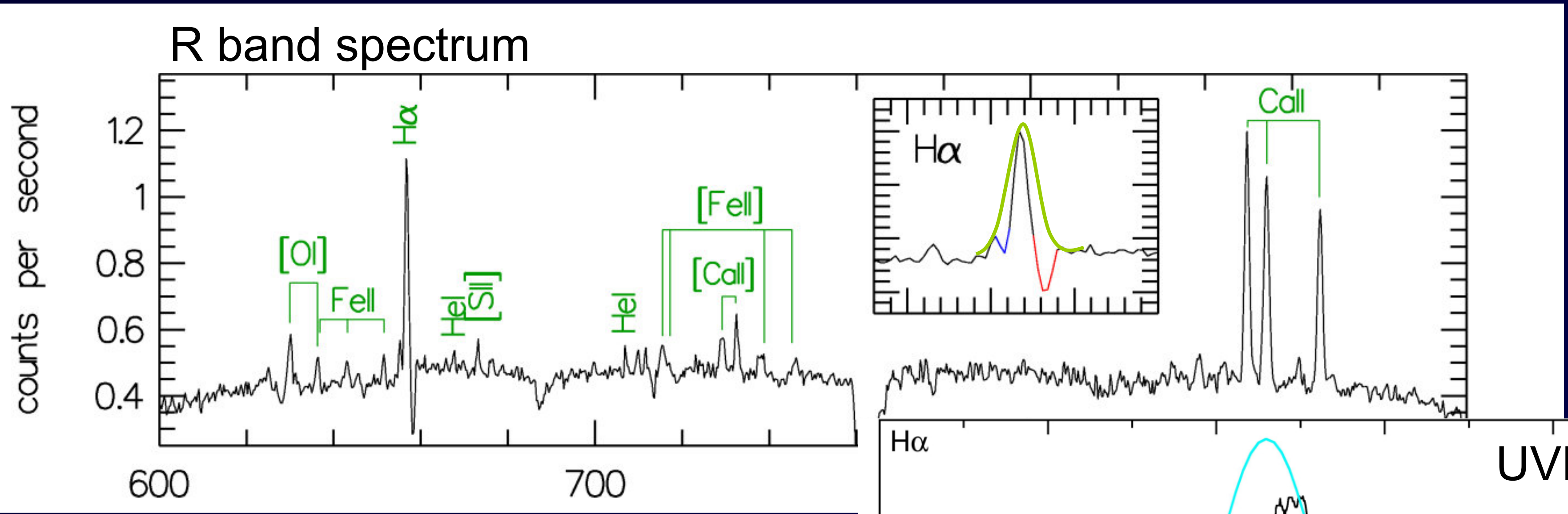


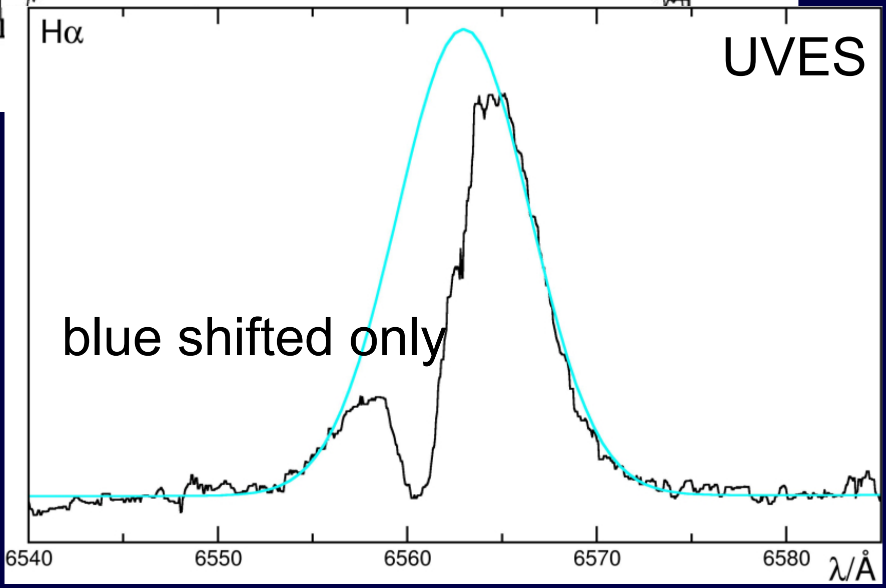




Chini et al. 2004, Steinacker et al. 2006

M17-SO1 – An Accretion Disk





Signatures typical of accretion:

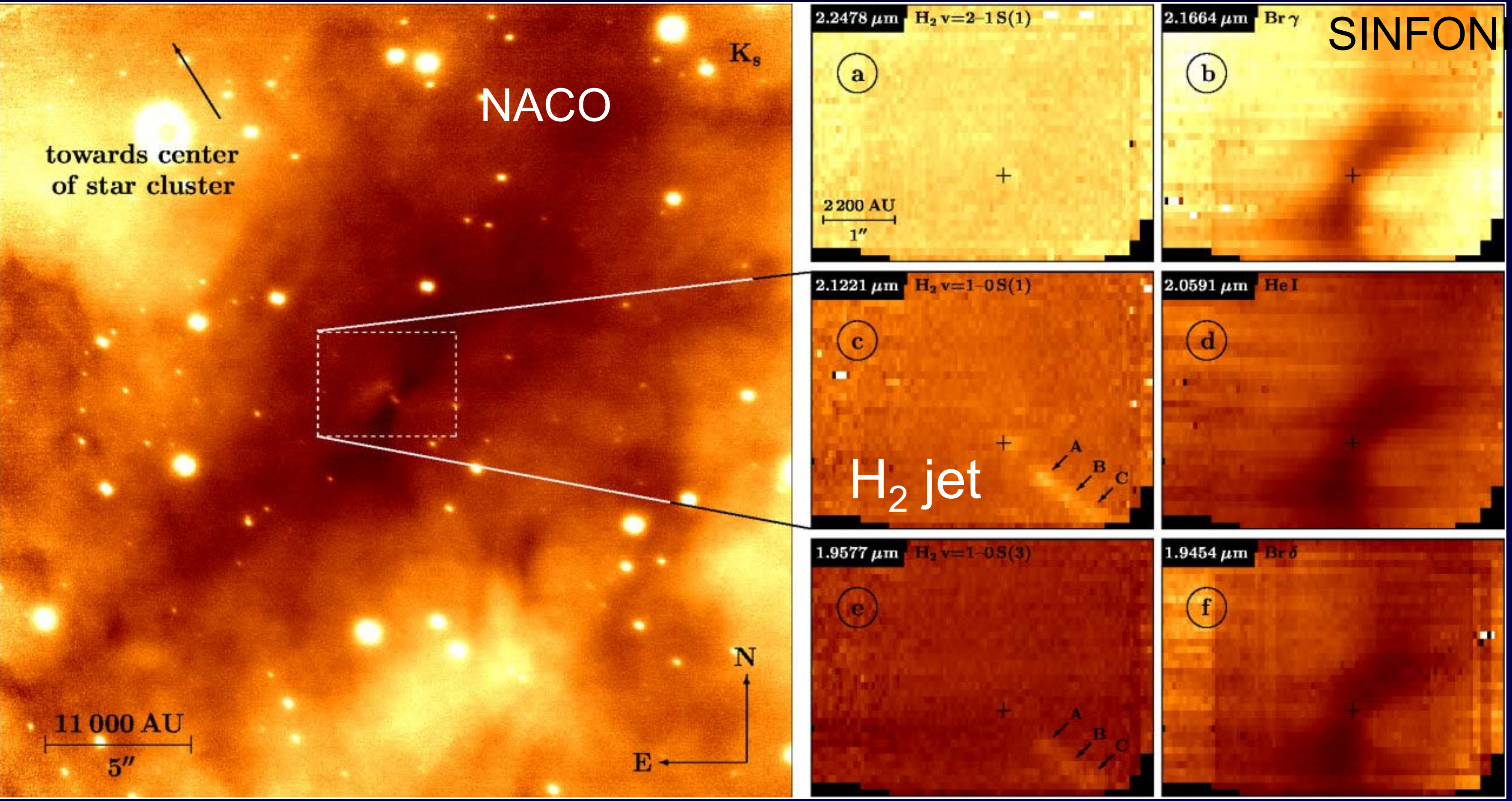
Forbidden lines ([OI], [SII], [FeII])

Further diagnostic lines (HeI, CaII)

Variable P Cyg profile (normal and inverse) at Hα

$\Rightarrow$ Outflow and infall

M17-SO1 – An Accretion Disk



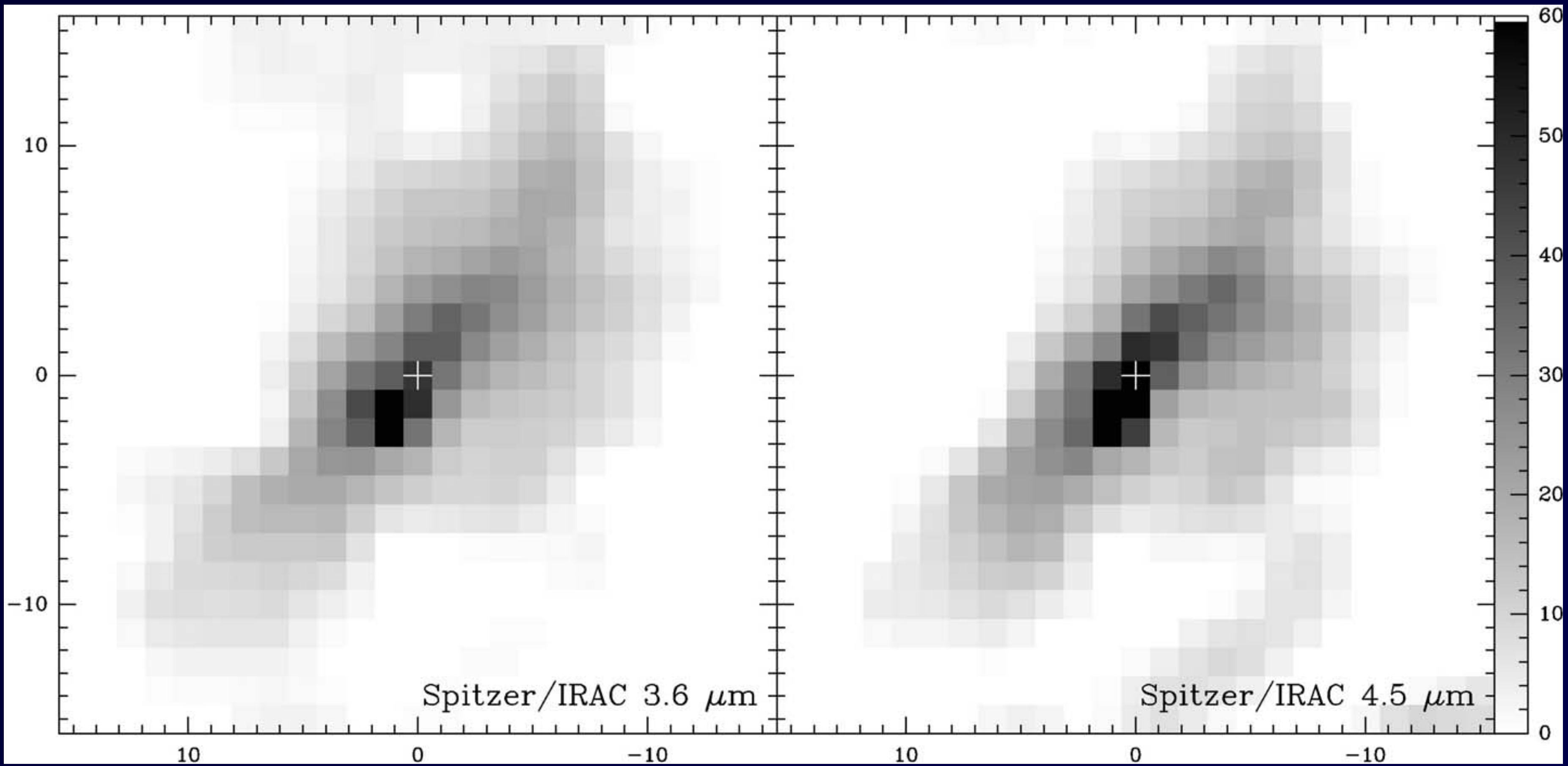
Nürnberger et al. (2007)

H_2 jet up to 7200 AU to SW, but no counter-jet (extinction)

$\dot{M}_{acc} \approx 9.3\times10^{-5} M_{\odot} yr^{-1}$

Too high for low-mass ⇒
High-mass protostar or FU Ori?

Do we really see a massive star + disk ?



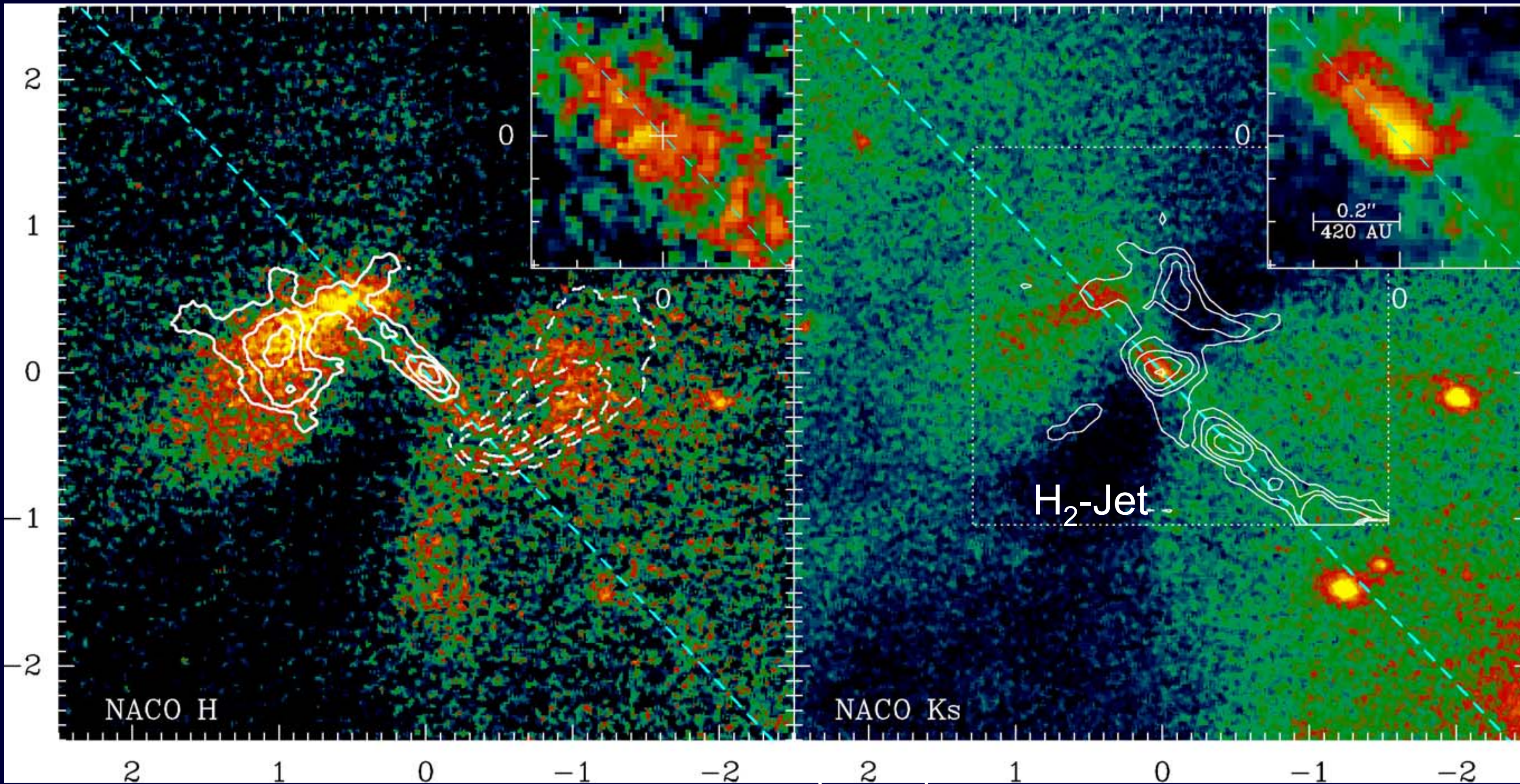
Photometry: > 2.8 $M_\odot$

Extinction from modelling (Steinacker et al. 2006) and Spitzer MIR data:

Lower limits (A_V > 60 mag)

Disk mass: 0.02 – 5 M_{sun}

Detection of a point source and jet

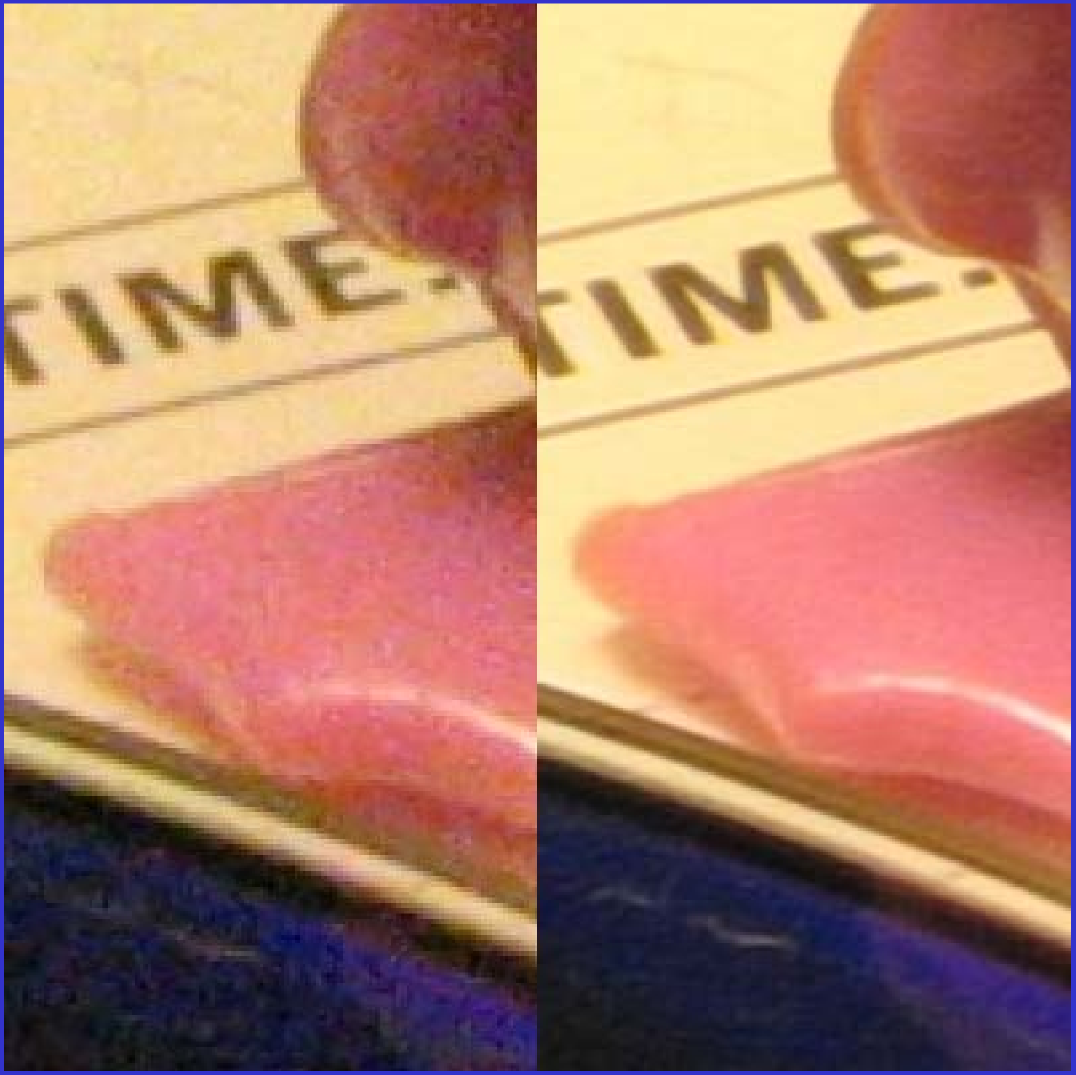


New data: Point source and jet structure

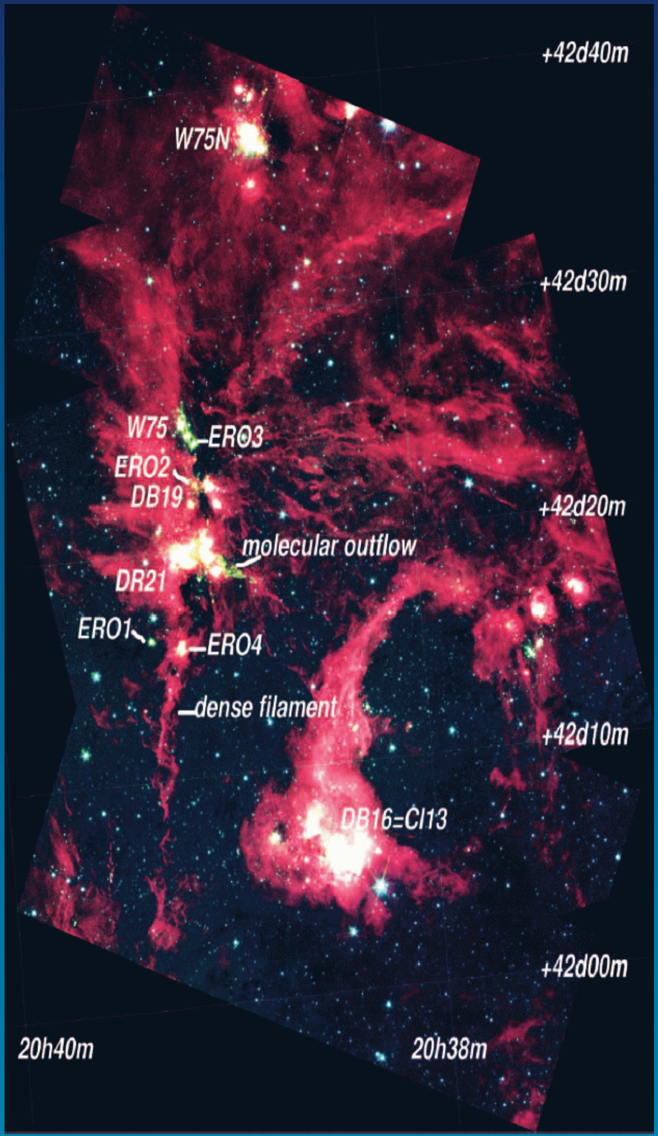
Nielbock et al. (2008)

Star > 2.8 M_{sun} Disk > 0.02 - 5 M_{sun}

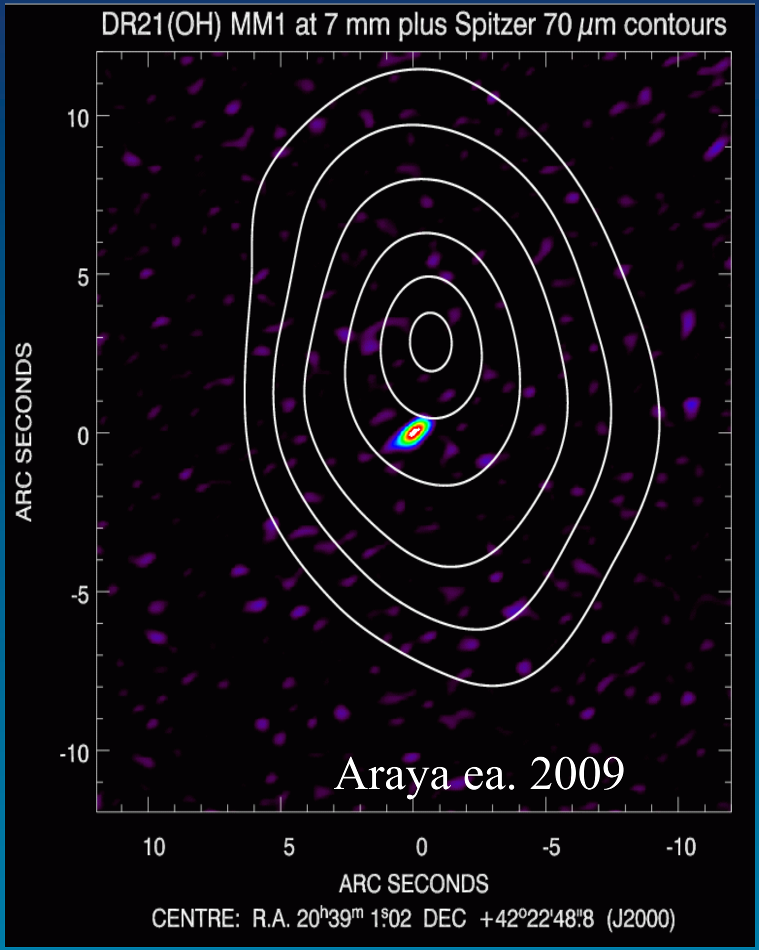
Resolution, Resolution, Resolution



DR21(OH) MM1: Spitzer and VLA in concert



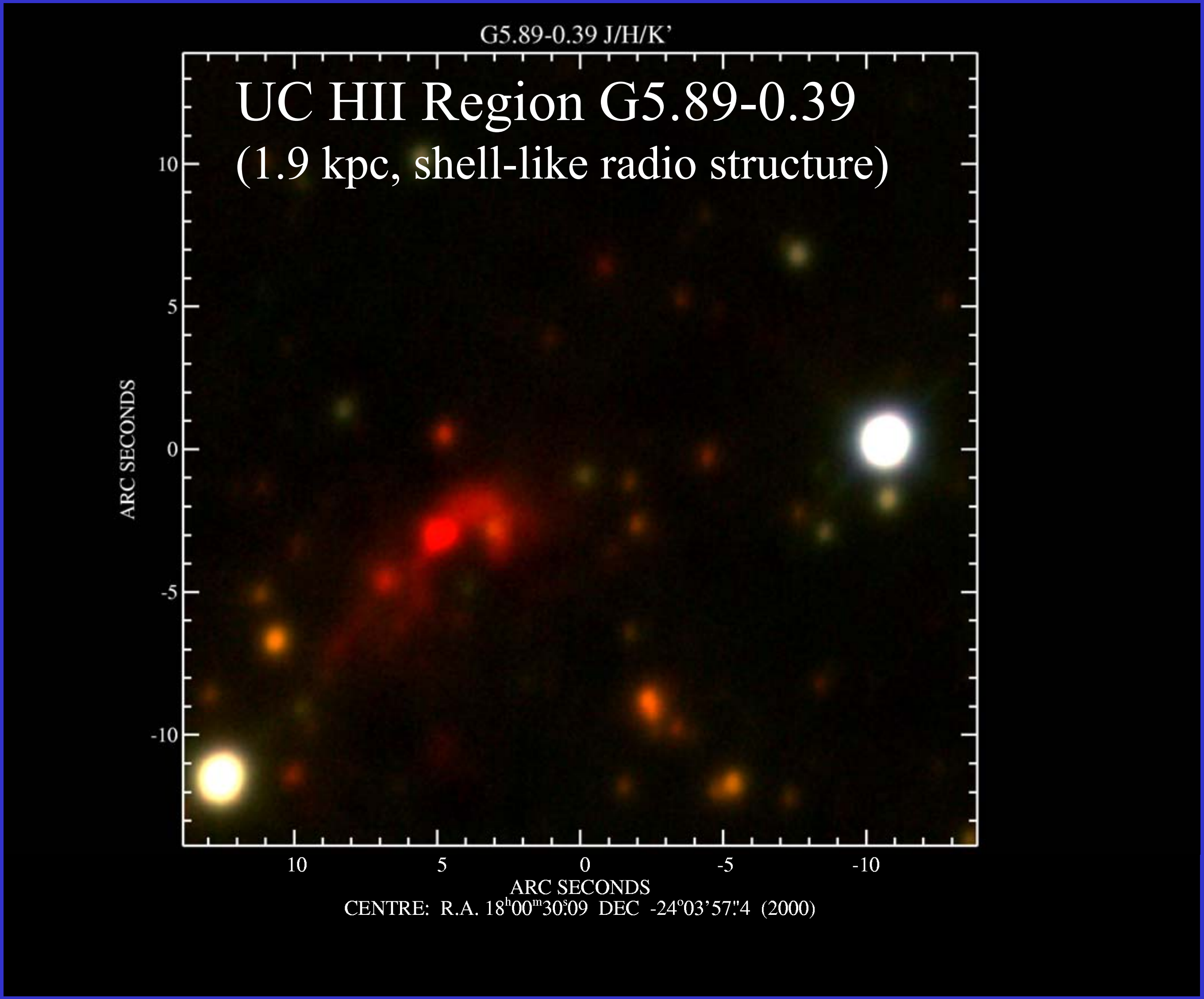
VLA 7 mm image vs MIPS 70 µm contours



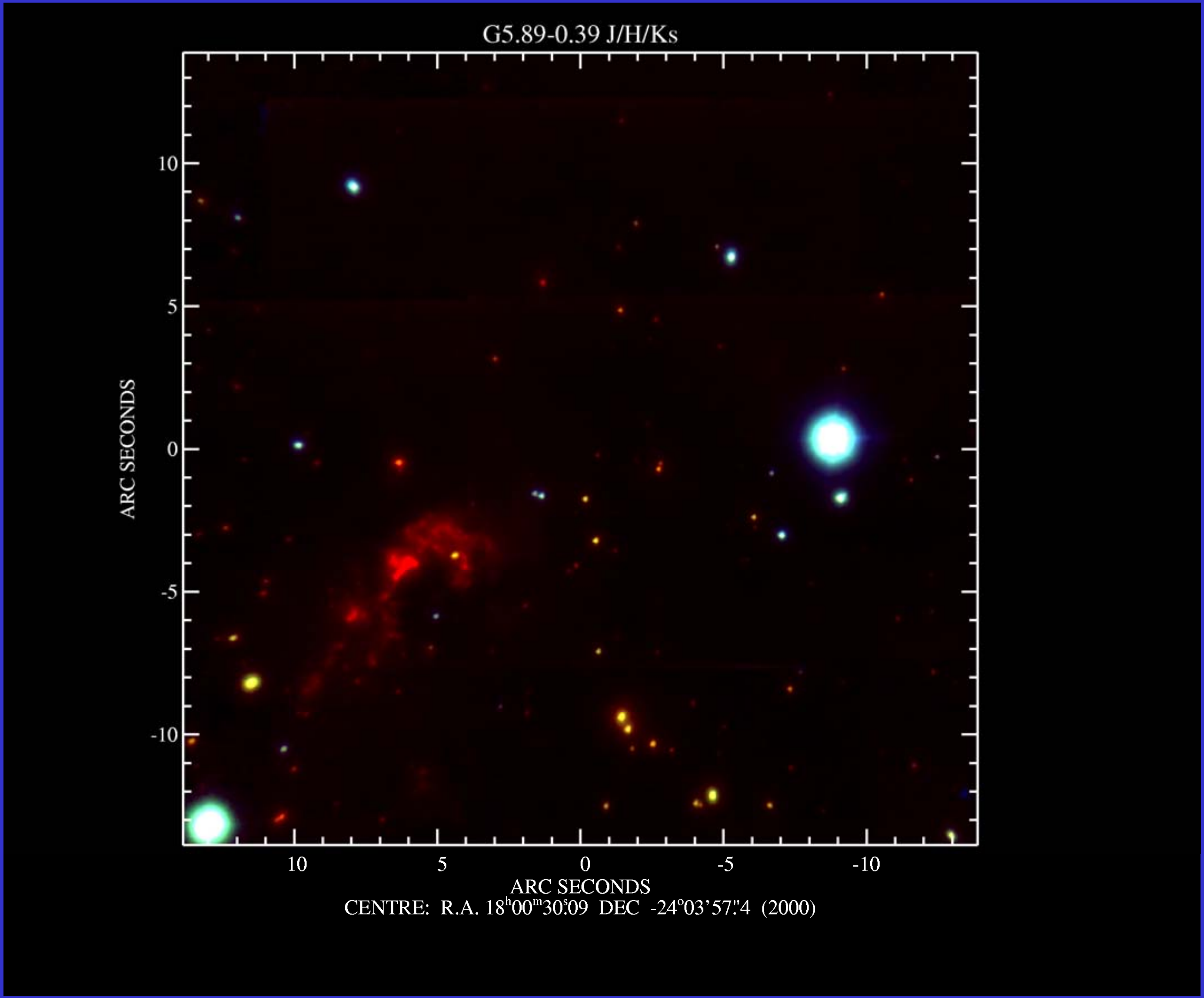
DR21 structure - IRAC (Marston et al. 2004)

Disclaimer: This is not a Spitzer talk!

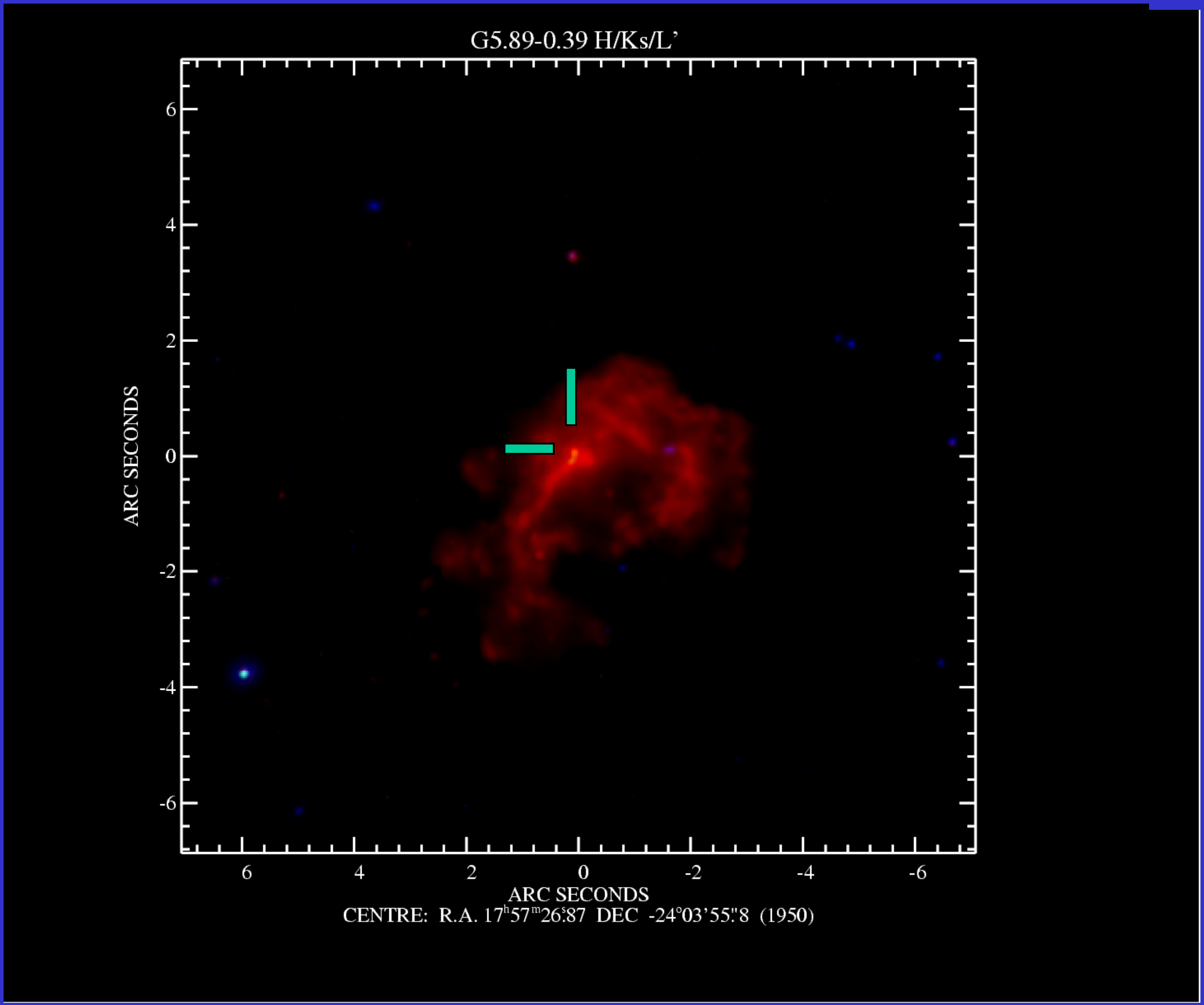
1999: ALFA / OMEGA @ 3.5m Calar Alto



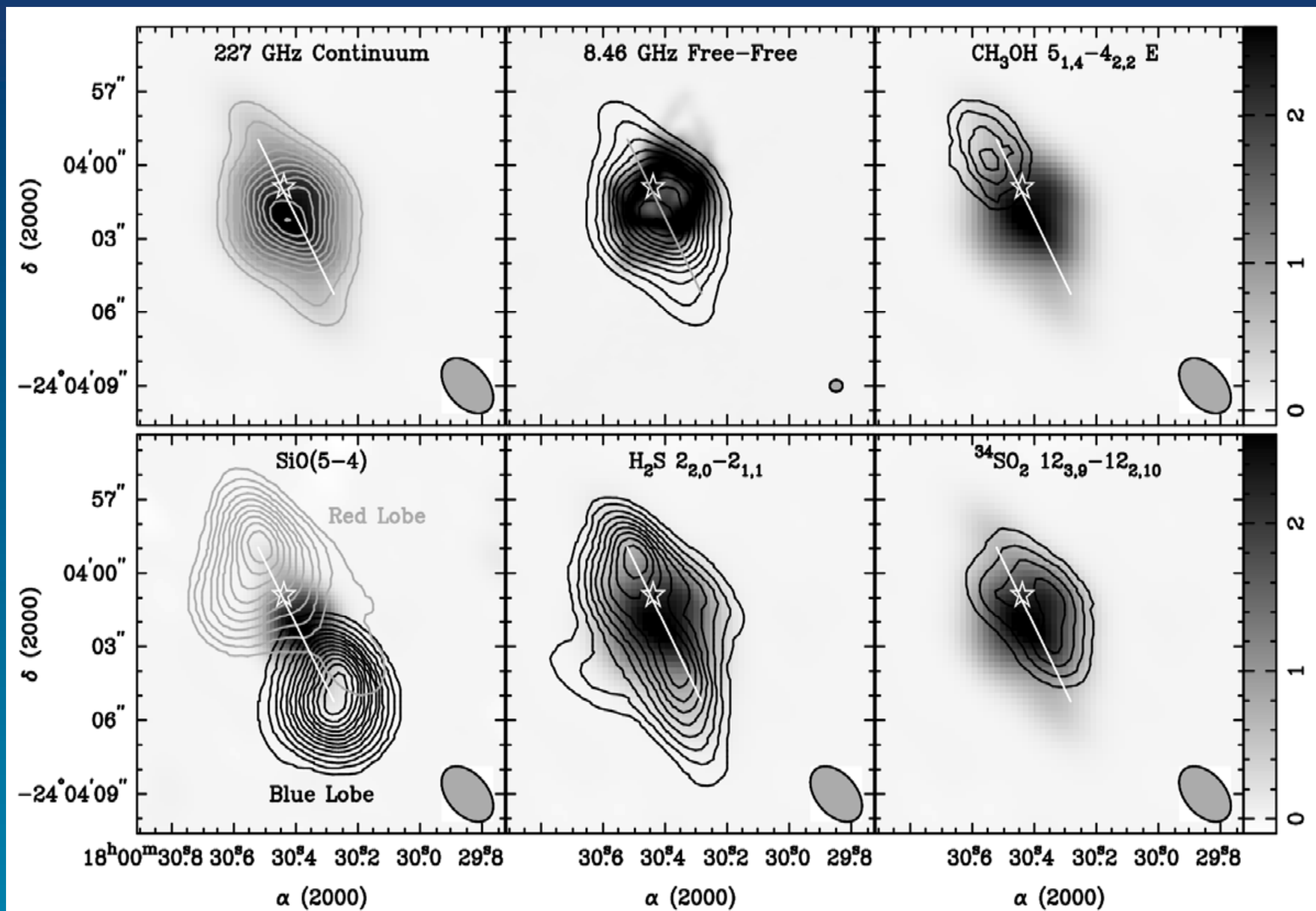
2002 NAOS-CONICA@ESO 8.0 m VLT UT4 „Yepun“



2002 NACO – New Wavelengths at sub-arcsecond scales



SMA Observations

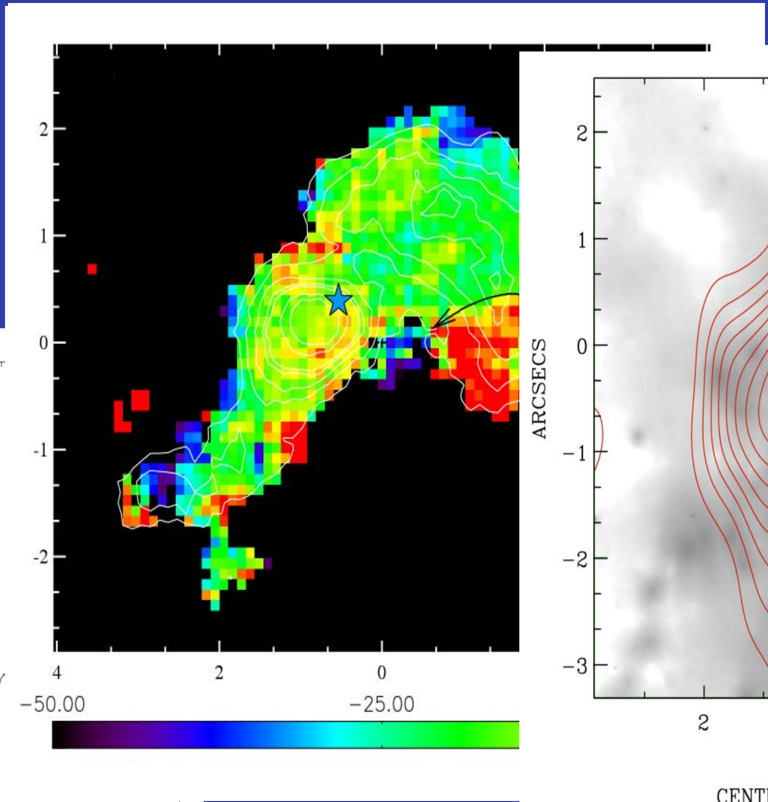


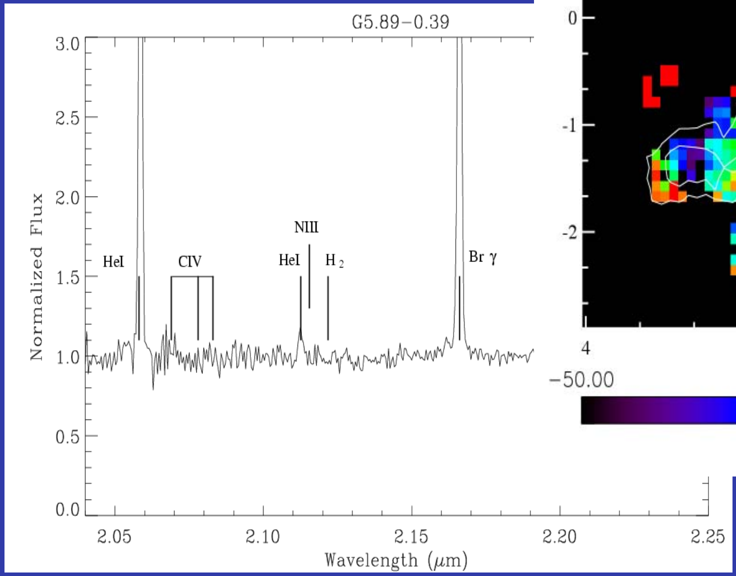
Sollins et al. (2004)

G5.89-0.39: More than just a spherical UCHII region

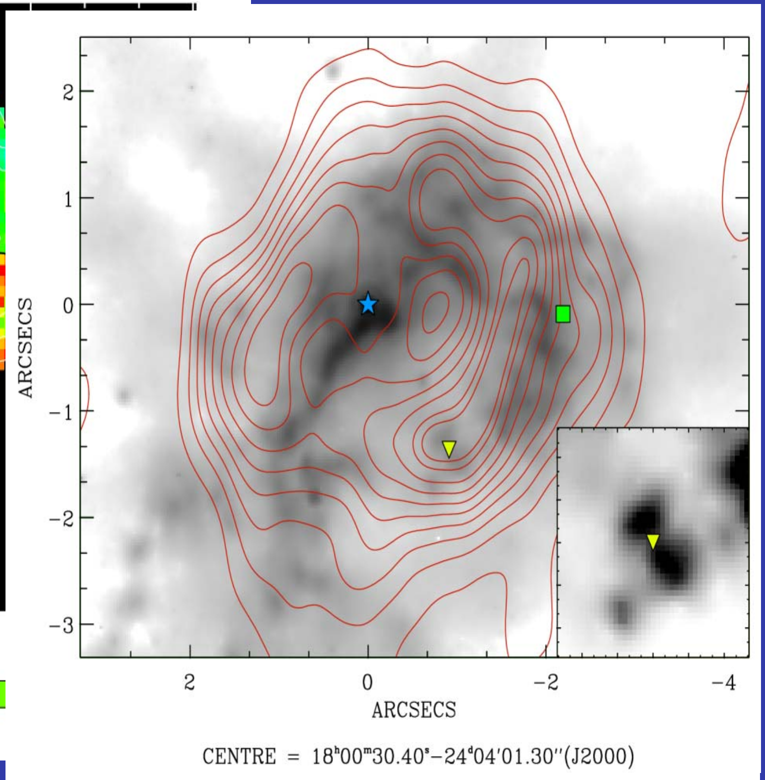
Puga, Feldt, Henning, et al. 2006
D=1.9 Kpc

ADONIS/GraF Fabry-Perot spectroscopy revealing the Br gamma velocity structure of the UCHII region (colour-coding in km/s).





NACO long-slit spectrum of „central" star confirms SpT ``earlier than O7V´´



NACO L' image + VLA 2cm contours.
The symbols denote the central O5-O7 star, the centre of the Brγ bipolarity, and the bipolar L' band structure related to the Sollins mm source (inset with more extreme L' cut levels for clarity)

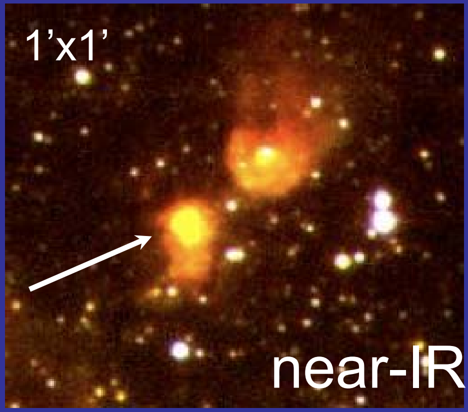
The Toolbox

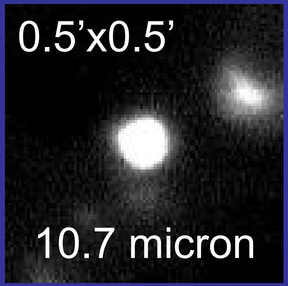
Disk Tracers

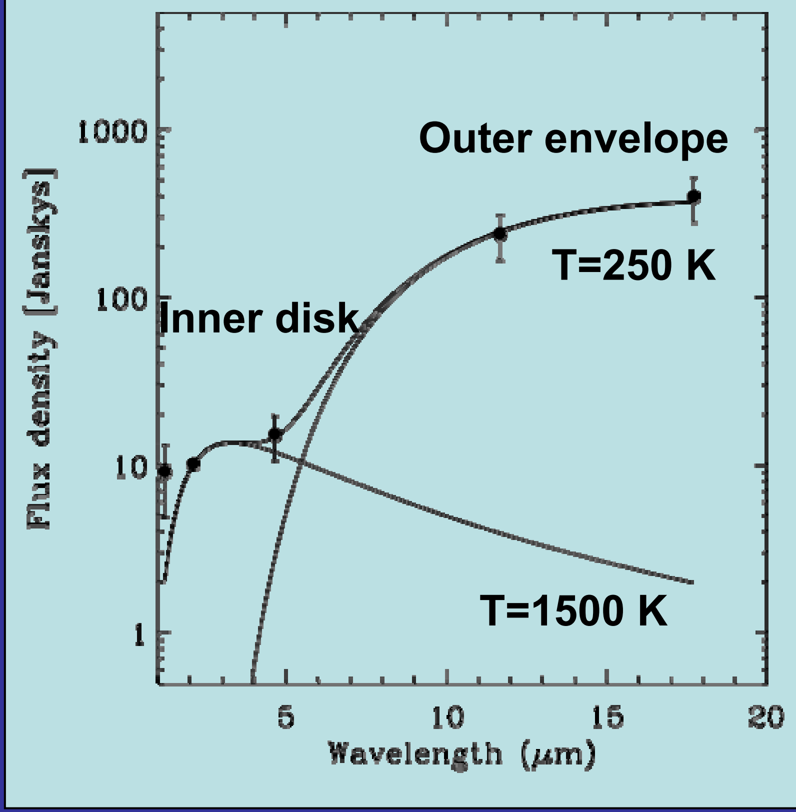
- Extinction lanes, thermal infrared emission
- Infrared interferometry (e.g. MIDI @ VLTI)
- NIR gas emission lines (CO)
- Millimeter continuum observations (incl. polarimetry)
- Non-thermal lines (SiO, CH_3OH, H_2O, OH, H rec. lines)
- Thermal lines (e.g. NH_3, CS, $C^{18}O$, SO_2, CH_3CN, $HCOOCH_3$, H rec. lines)

Recent reviews: Cesaroni et al. (2006, 2007)

IRAS 16164-5046



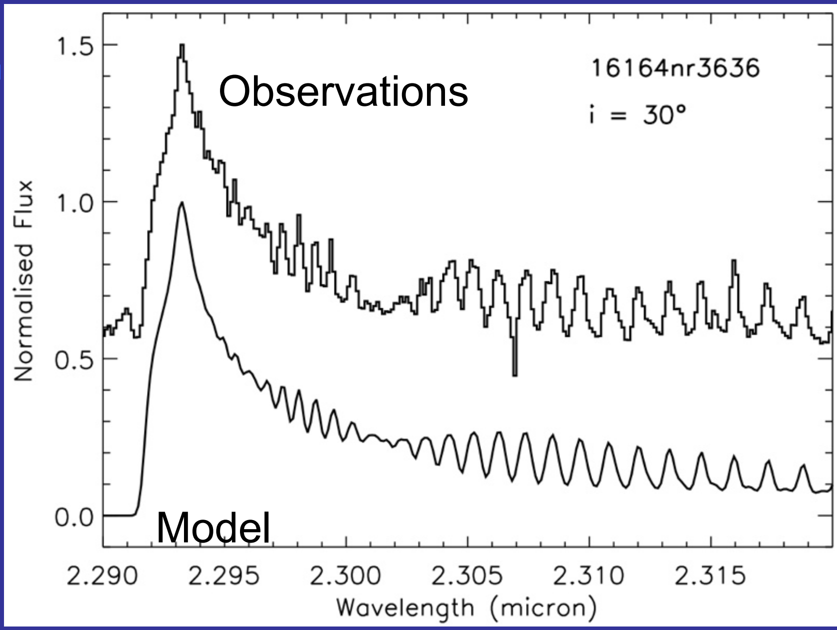




- Near-IR observations show the presence of a hot inner disk
- Mid-IR (TIMMI2) observations trace dust of a few 100 K and show an extended source (1.8"= 6500 AU).
- An envelope is detected in the sub-mm (Karnik et al. 2001).
- Near- and mid-IR SED can be fitted by a 2 temperature blackbody, representing the inner disk and the outer envelope (Bik et al. 2008)

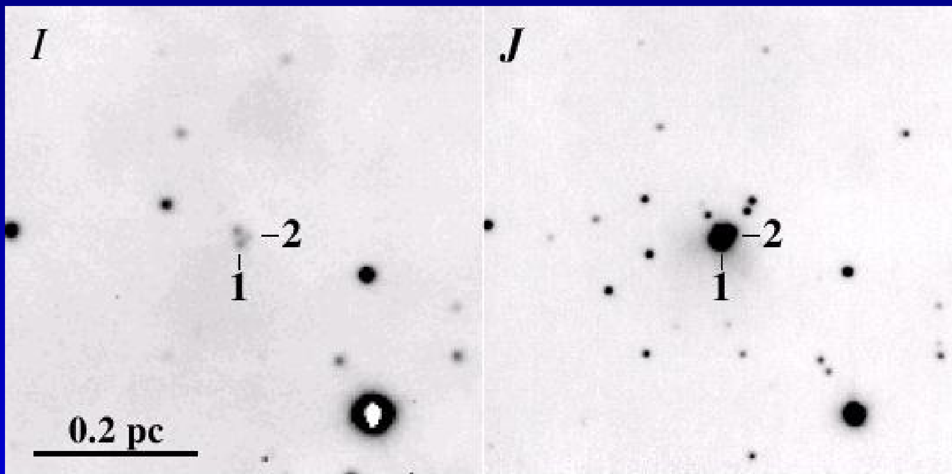
IRAS 16164-5046

- VLT ISAAC spectra (R=10,000) of CO bandheads (Bik & Thi, 2004)
- CO bandheads: Spectral profile can be explained with a Keplerian velocity profile
- Central star: ~O7 based on ratio HeI/Br gamma (Hanson et al. 2002) in the small HII region surrounding this source

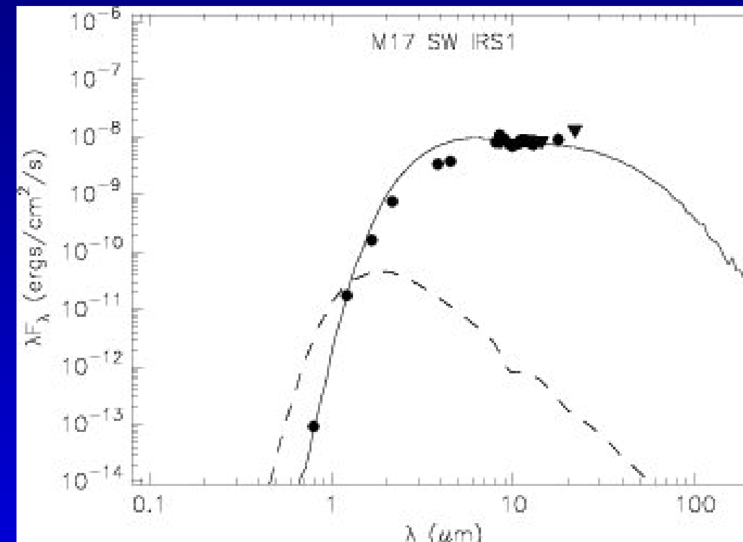


- Distance: 3.6 kpc
- Central star: ~30 Msun (O7)
- $T_{ex}(CO)$: ~4000 K
- N(CO): ~4 10^{20} cm^{-2}
- R (CO):~ 3AU

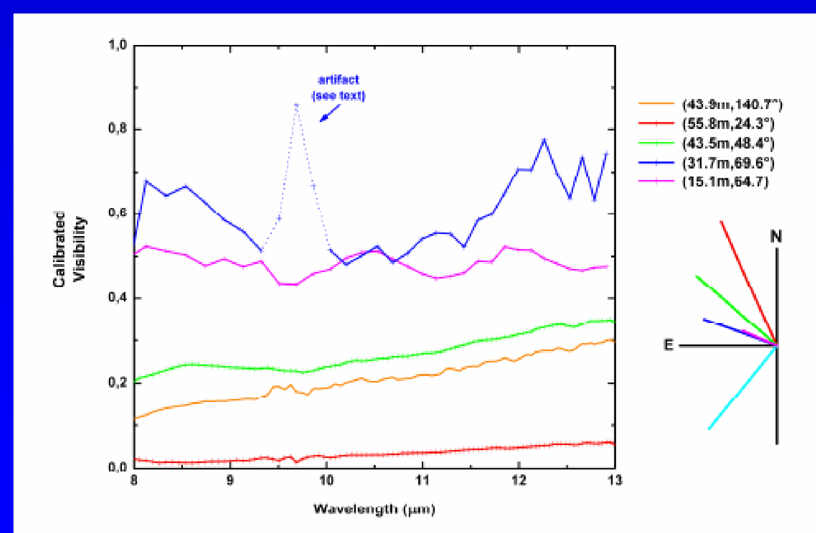
The Kleinmann & Wright Object (KWO, M17 IRS 1)



VLT-ISAAC (J band, Chini 2004)

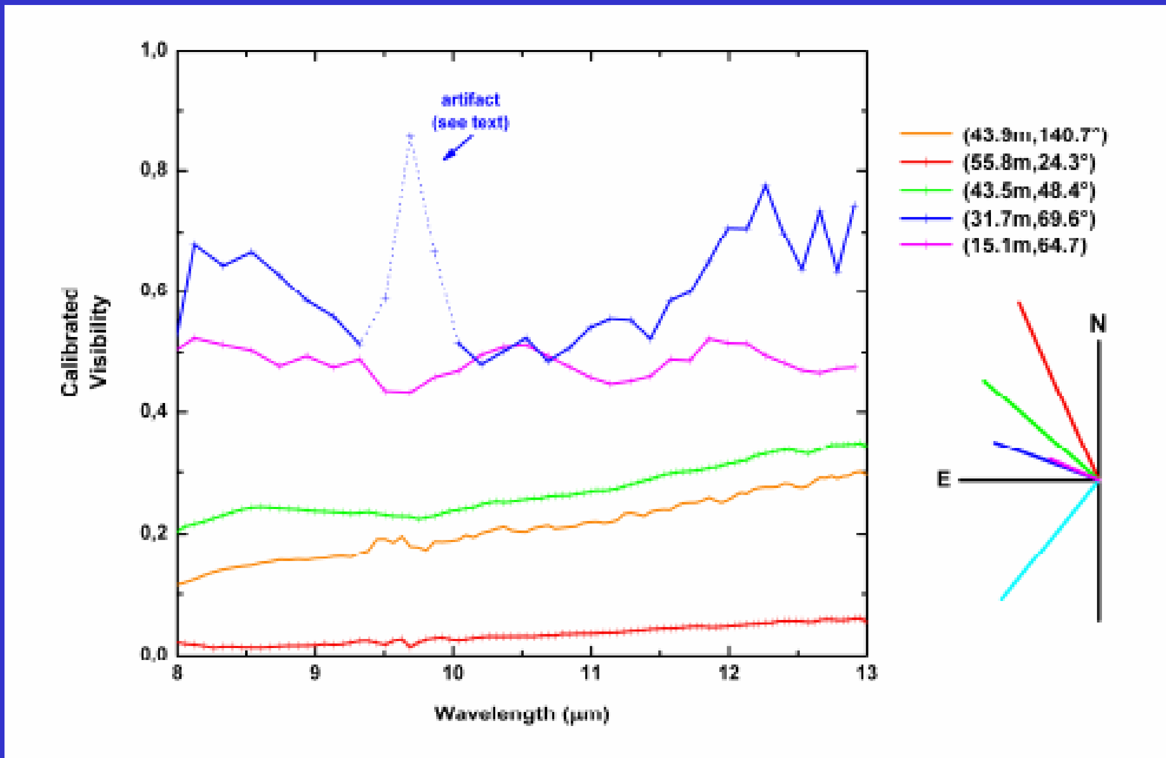


(D=2.2 kpc, L=2x10^4 L_{sun})



Follert ea. 2009

Combination of SED fitting and interferometric data

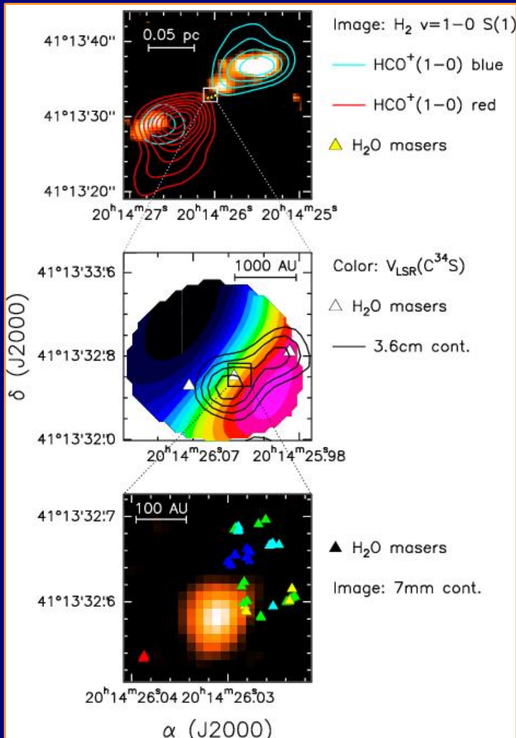


parameter	value
stellar mass	15.0 $M_{\odot}$
stellar radius	4.9 $R_{\odot}$
stellar temperature	31350 K
disk mass	9 x 10^{-2} $M_{\odot}$
disk outer radius	506 AU
disk inner radius	26 AU ($\cong$ 2.2 R_{SUB})
scale height factor	0.903
disk flaring power	1.153
disk accretion rate	7.8 x 10^{-8} $M_{\odot}$/yr
inclination angle	75.5°

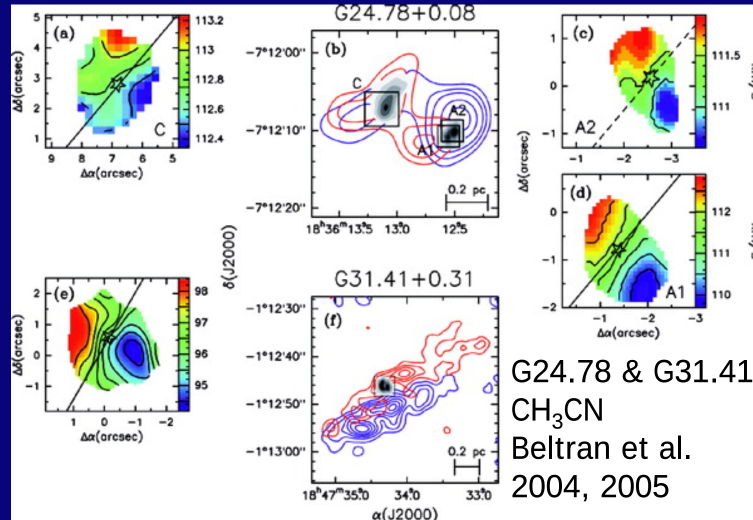
Comparison between synthetic and observed visibility curves

Synthetic image for best fitting model (smoothed) - RT code by B. Whitney ´03, Fitting tool – Robitaille ea. 2006, 2007

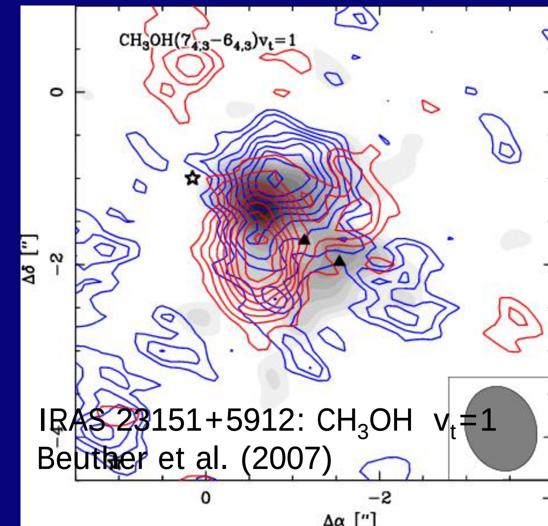
Potentially disk-tracing molecules



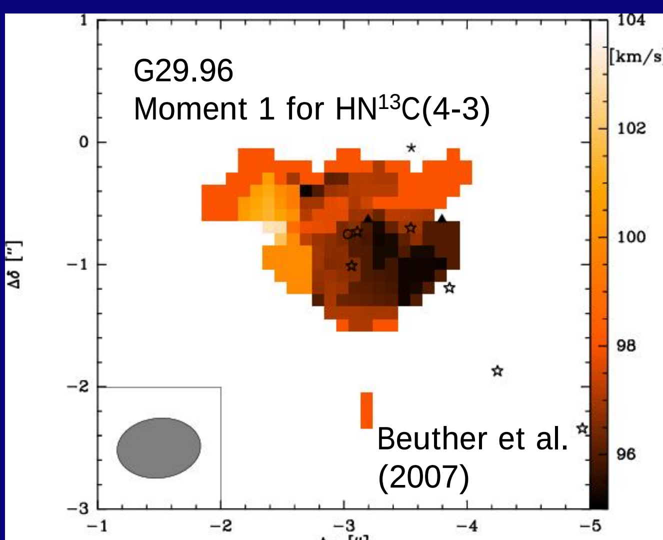
IRAS 20126+4104: CH_3CN & $C^{34}S$
Cesaroni et al. 1997, 1999, 2005



G24.78 & G31.41
CH_3CN
Beltran et al.
2004, 2005

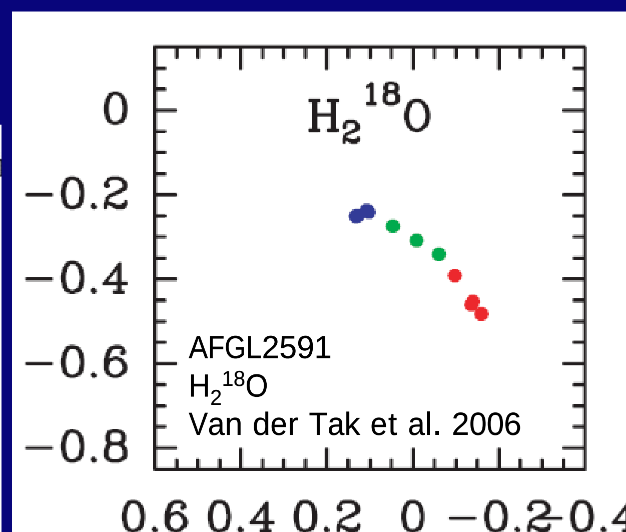


IRAS 23151+5912: CH_3OH $v_t=1$
Beuther et al. (2007)

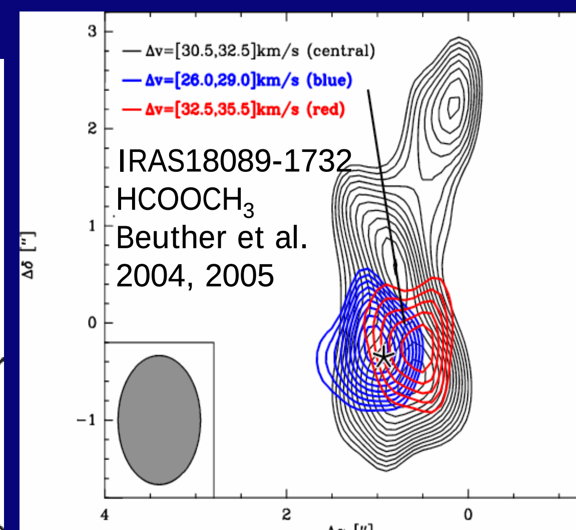


G29.96
Moment 1 for $HN^{13}C(4-3)$

Beuther et al.
(2007)



AFGL2591
$H_2{}^{18}O$
Van der Tak et al. 2006

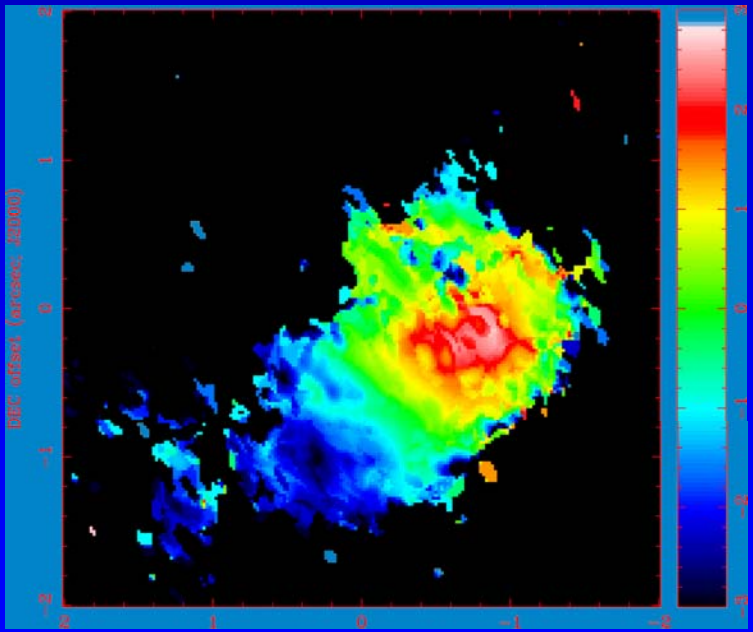


IRAS18089-1732
$HCOOCH_3$
Beuther et al.
2004, 2005

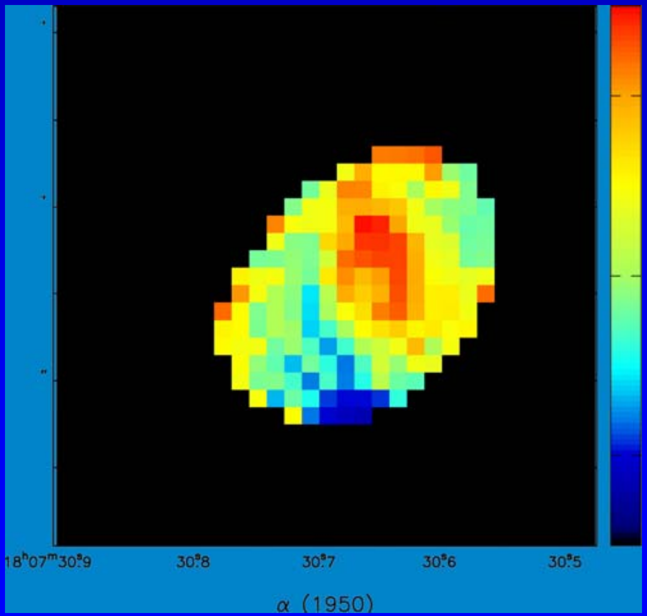
Not all massive stars are the same!

Objects with luminosities larger than ~10^5 L_{sun} are often characterized by large (~0.1 pc), massive (few hundred M_{sun}) rotating structures („circumcluster toroids“ – Cesaroni et al. 2006)

G 10.62-0.38 (Keto et al. 1998), G 24.78+0.08 (Beltran et al.2004, 2005)



Mean velocity of molecular gas (NH_3)
Sollins et al. (2005)

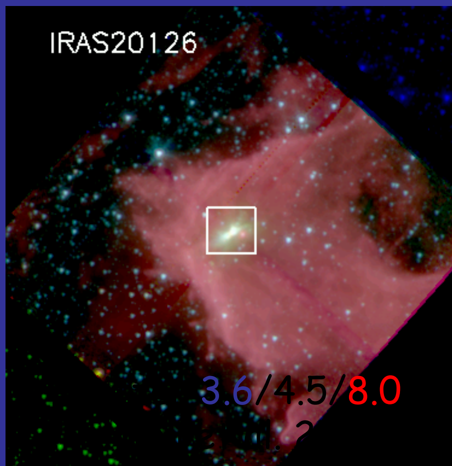


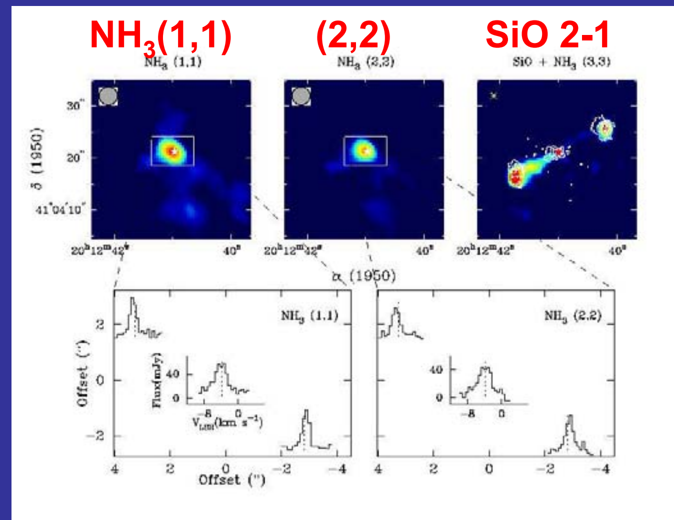
Mean velocity of ionized gas (H66a)
Keto (2002)

Disks around Massive Young Stellar Objects?

- **IRAS 20126 + 4104**; L = 1.3 × 10^4 $L_\odot$; d = 1.7kpc
  CH_3CN, NH_3 (1,1), (2,2), $C^{34}S$(5-4), 3.6cm continuum, …
  (Cesaroni et al. 1997, 1999, 2005; Zhang et al. 1998, 2001)
  Disk diameter: 3200 AU, Mass: 4 $M_\odot$
- **G 192.16 – 3.82**; L = 3 × 10^3 $L_\odot$ (B2); d = 2kpc
  ^{13}CO, $C^{18}O$, H_2O maser line; 2.6mm, 7mm, and 3.6cm continuum
  (Shepherd & Kurtz 1999, Shepherd et al. 2001)
  Disk diameter: 130AU; Mass: ~ few $M_\odot$
  Flattened rotating structure (H_2O) ~ diameter of 1000AU
- **AFGL 490**; L ≈ 3 × 10^3 $L_\odot$ (B2); d = 1kpc
  CS(2-1), $C^{17}O$, 3mm continuum, …
  (Schreyer et al. 2002, 2006)
  Disk diameter: < 250AU; Mass ~ few $M_\odot$
  Flattened rotating structure 22000AU × 6000AU

IRAS 20126+4104





Zhang et al. 98, 01

SED: 1.3×10^4 L_{sun}

M_*=7-15 M_{sun}

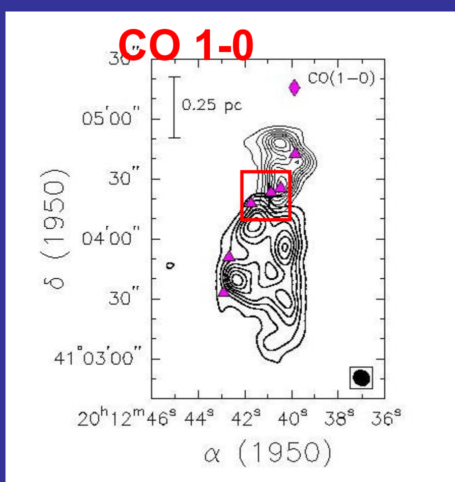
D=1.7 kpc

Evidence:

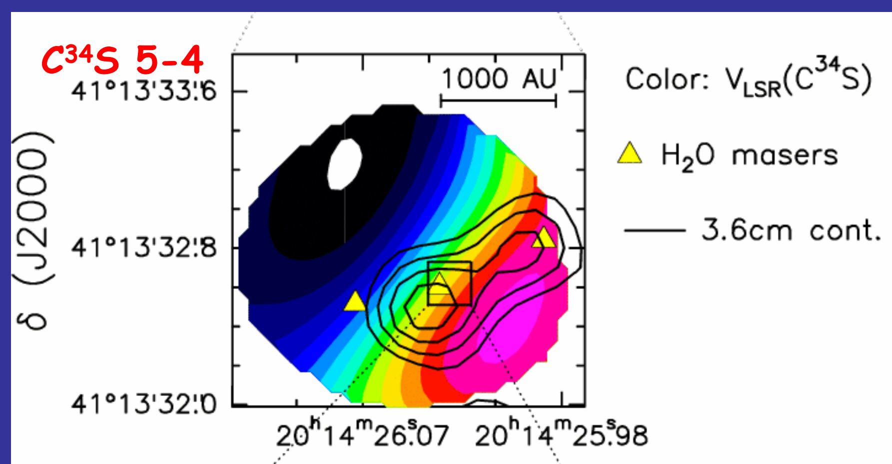
Keplerian-like rotation

Flattened Structure

Jet-like outflow



Shepherd et al. 99



Cesaroni et al.
97,99,05

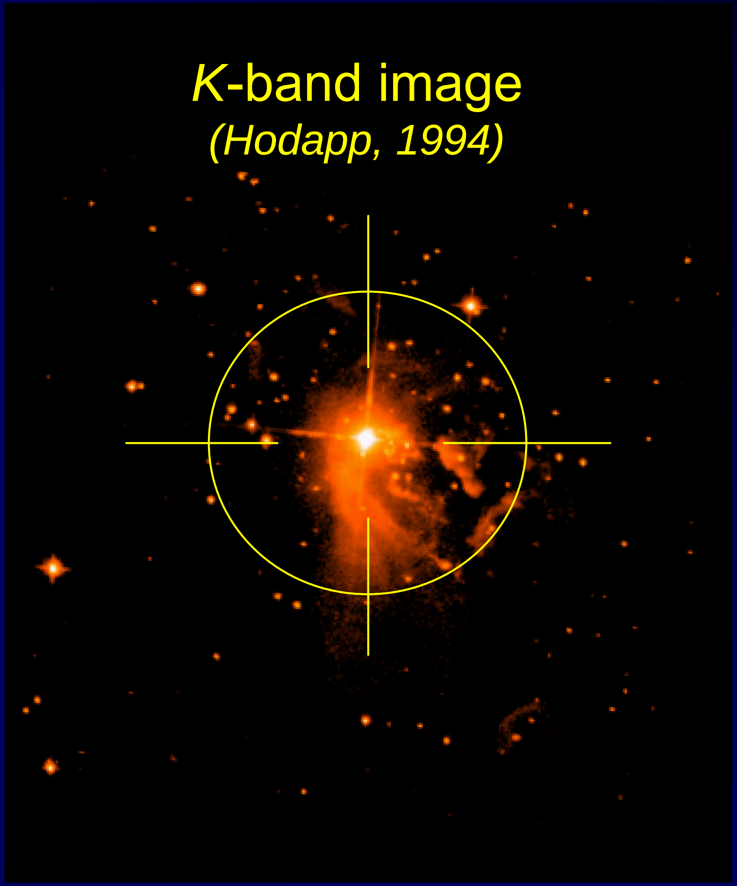
AFGL 490 – Our example

- Optical: diffuse nebulosity,
  NIR: luminous source
  (Allen, 1972)

- $D \approx 1$ kpc, $L = 1.4 – 4 \times 10^3\ L_{sun}$
  Spectral type B3-B2, $M_\star = 8\text{-}10\ M_{sun}$

- Typical properties of a
  Becklin Neugebauer Object:
  - weak continuum flux at l≥1cm
  - broad & strong Bra and Brg
  (Bunn et al. 1995)

- Ionized region $R \leq 100$ AU
  (Simon et al. 1981, 1983)



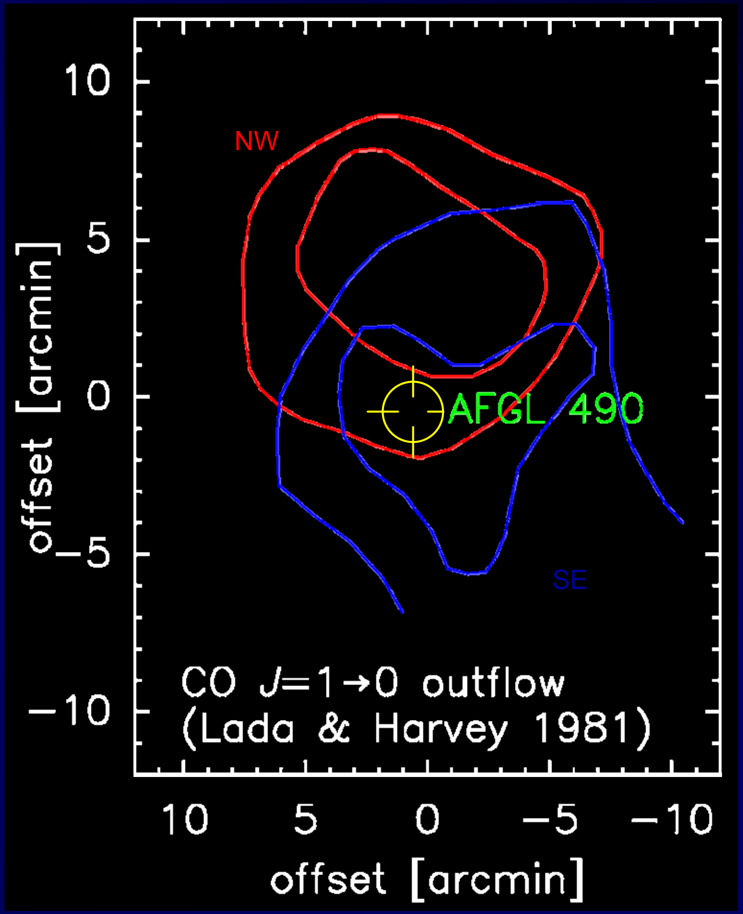
K-band image
(Hodapp, 1994)

AFGL 490 – What has been known before?

- Embedded in a dense cloud core
  (Hodapp 1994, Kawabe et al. 1984, Snell et al. 1984)

- Poorly collimated high-velocity outflow *(Lada & Harvey, 1981)*
  $t_{dyn} \approx 2 \times 10^4$ yr *(Churchwell, 1999)*

- Previous interferometer studies: presence of a huge disk with a diameter ≈ 25 000 AU
  (Mundy & Adelmann, 1988, Nakamura et al. 1991)

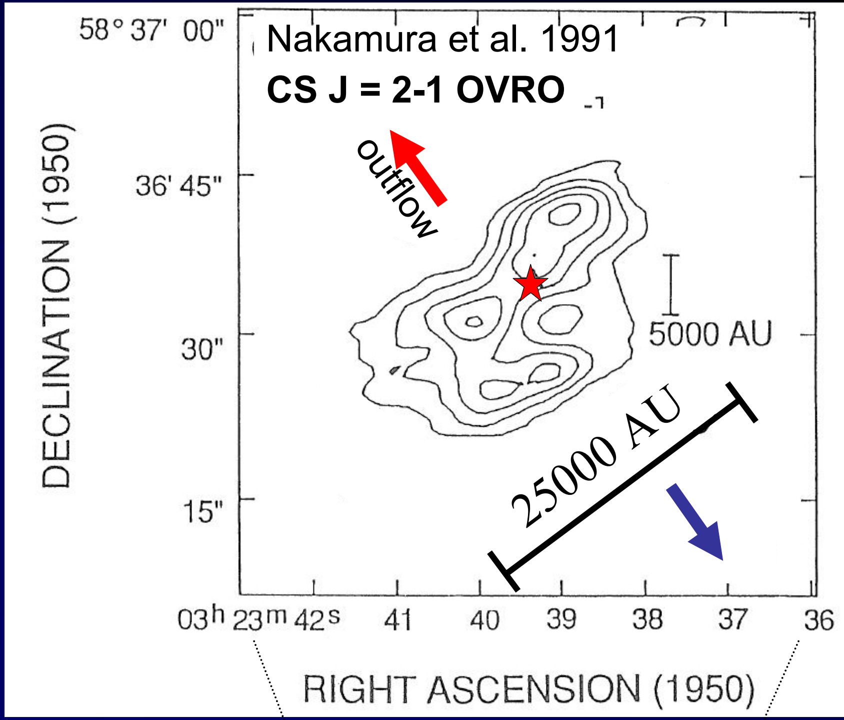


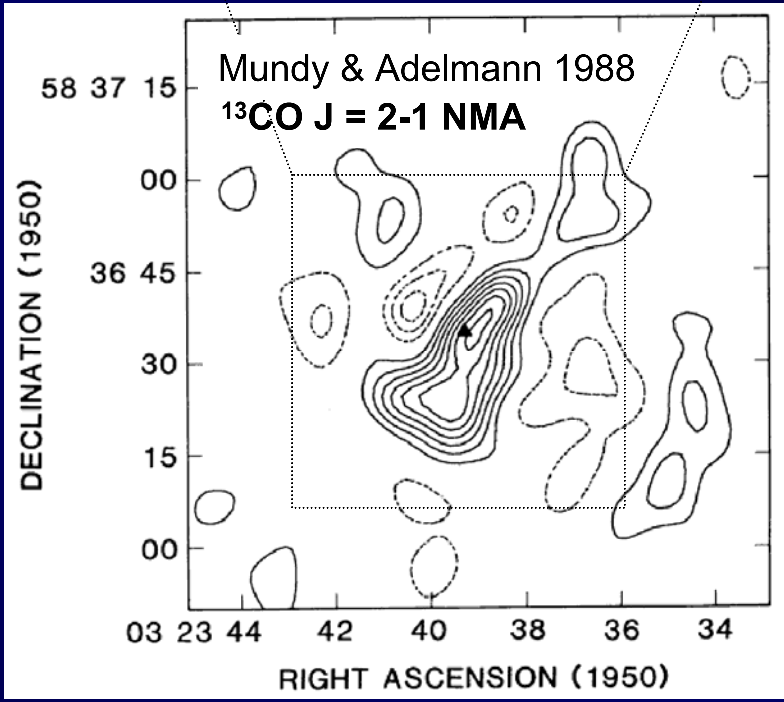
AFGL 490

- Embedded in a dense cloud core
  (Hodapp 1994, Kawabe et al. 1984, Snell et al. 1984)

- Poorly collimated high-velocity outflow *(Lada & Harvey, 1981)*
  $t_{dyn} \approx 2\text{x}10^4$ yr *(Churchwell, 1999)*

- Previous interferometer studies:
  Huge disk-like structure with a diameter ≈ 25 000 AU
  (Mundy & Adelmann, 1988, Nakamura et al. 1991)





Observational data for AFGL 490

JCMT & IRAM 30m Observations

Mapping in :

- CS J = 2-1, 3-2, 5-4, 7-6, $C^{18}O$ J = 2-1: IRAM 30m, JCMT
- Continuum SCUBA 450μm, 870μm; 1.3mm MAMBO

Plateau de Bure Interferometer Observations

Mapping in:

- CS J = 2-1 + λ3mm (2.7″ x 2.2″)
- $C^{34}S$ J = 2-1, CH_3OH (1.8″ x 1.4″)
- $C^{17}O$ J = 2-1 + λ1mm (0.9″ x 0.8″)

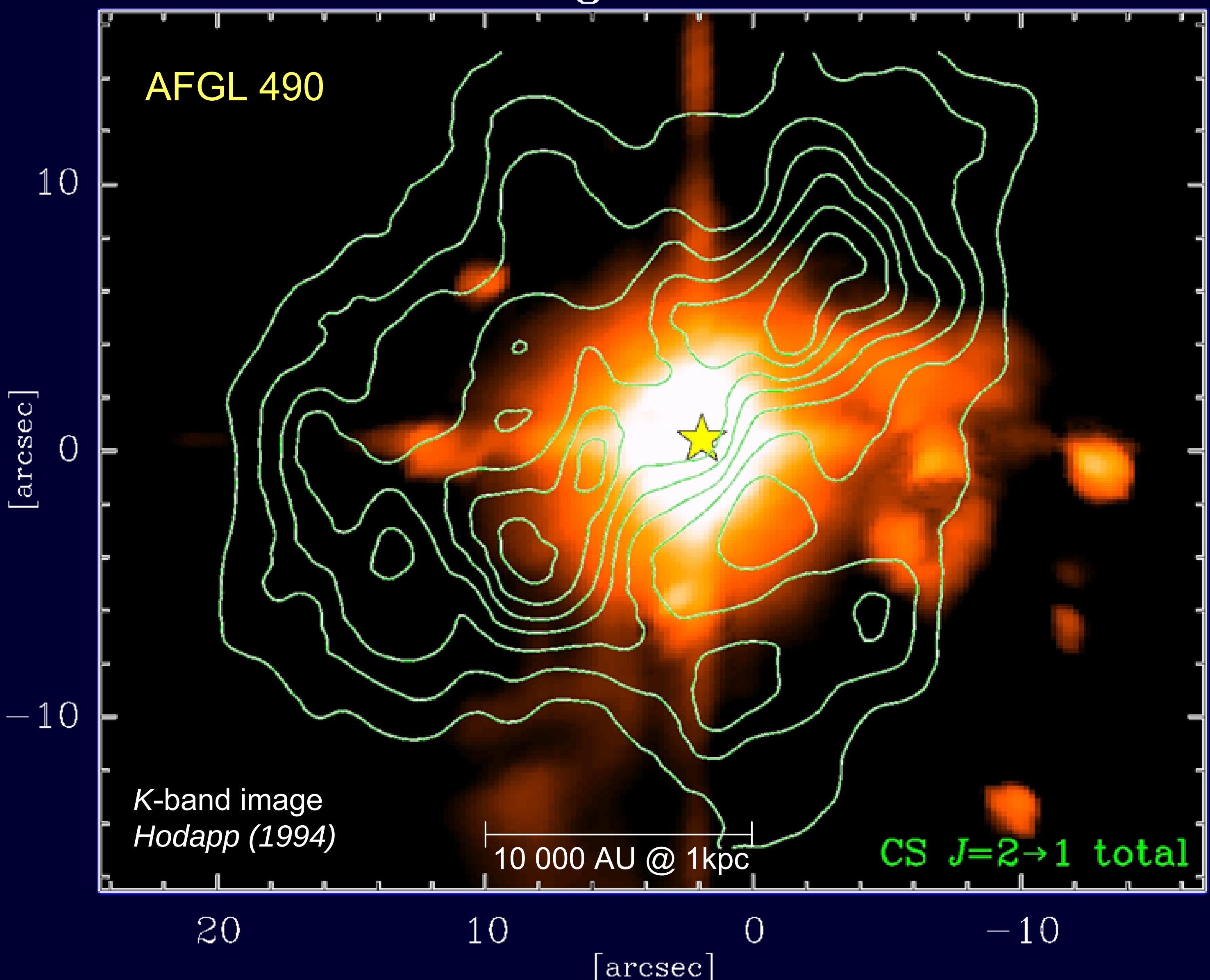
VLA-CD Observations

Mapping in:

- CS J = 1-0 + λ7mm

Our observational results

Plateau de Bure Interferometer Observations in CS J = 2-1

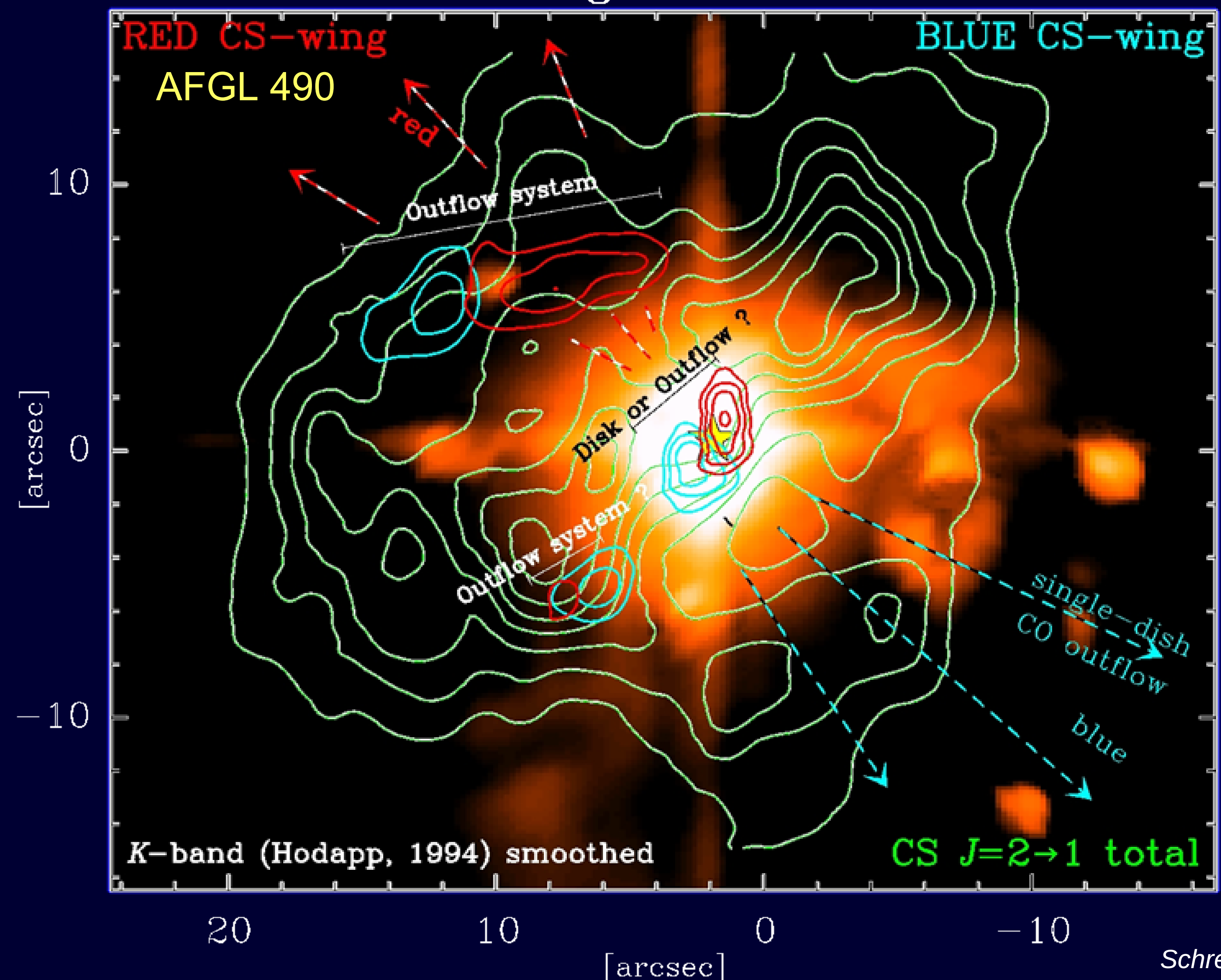


- Embedded in a dense cloud core
- Bar-like dense structure (25 000 AU)

Schreyer et al. (2002)

Our observational results

Plateau de Bure Interferometer Observations in CS J = 2-1

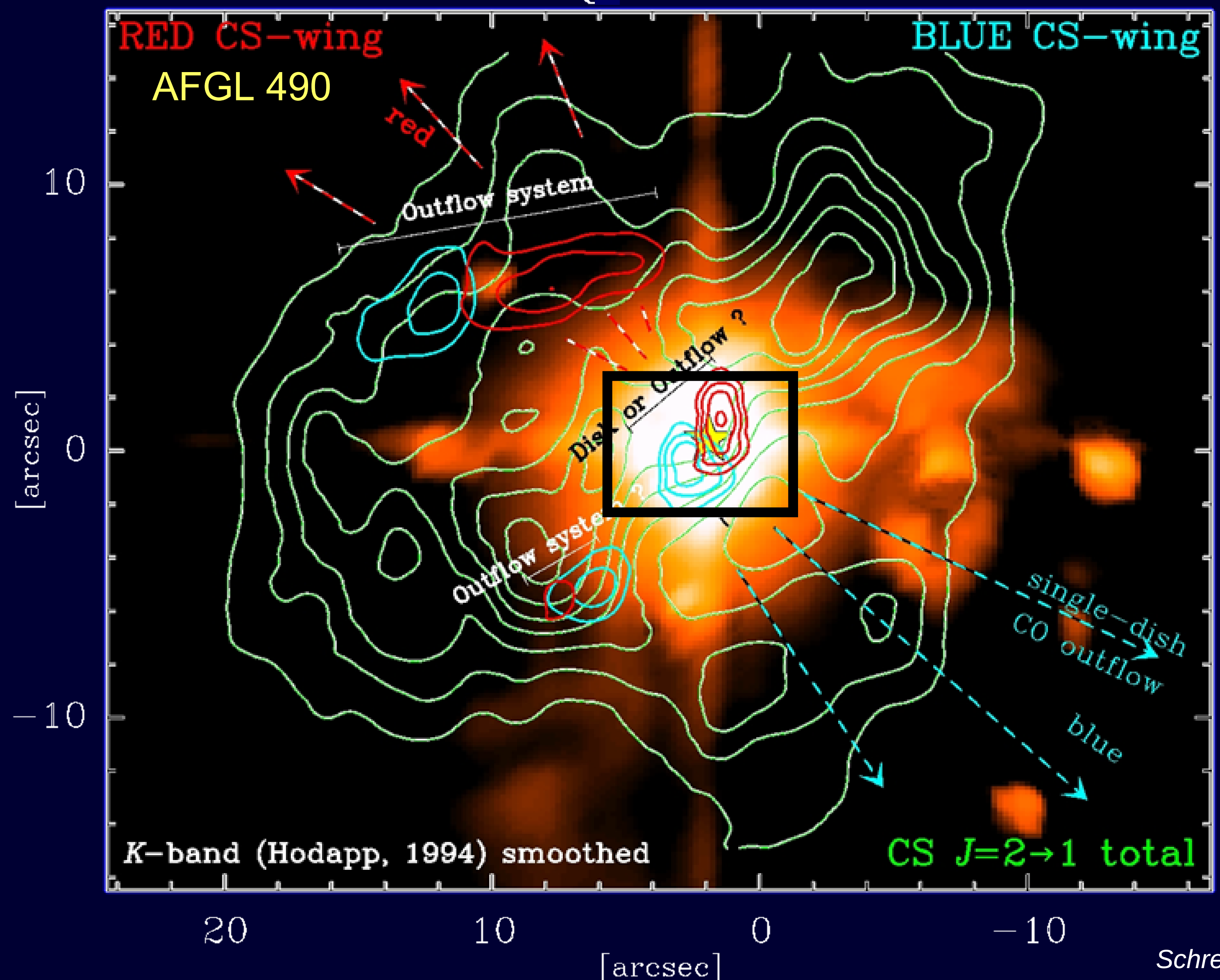


- Embedded in a dense cloud core
- Disk-like system around AFGL 490
- Mass inside R = 4000 AU $M_{disk} \approx M_{\star} \approx 8\ M_{\odot}$

Schreyer et al. (2006)

Our observational results

Plateau de Bure Interferometer Observations in CS J = 2-1



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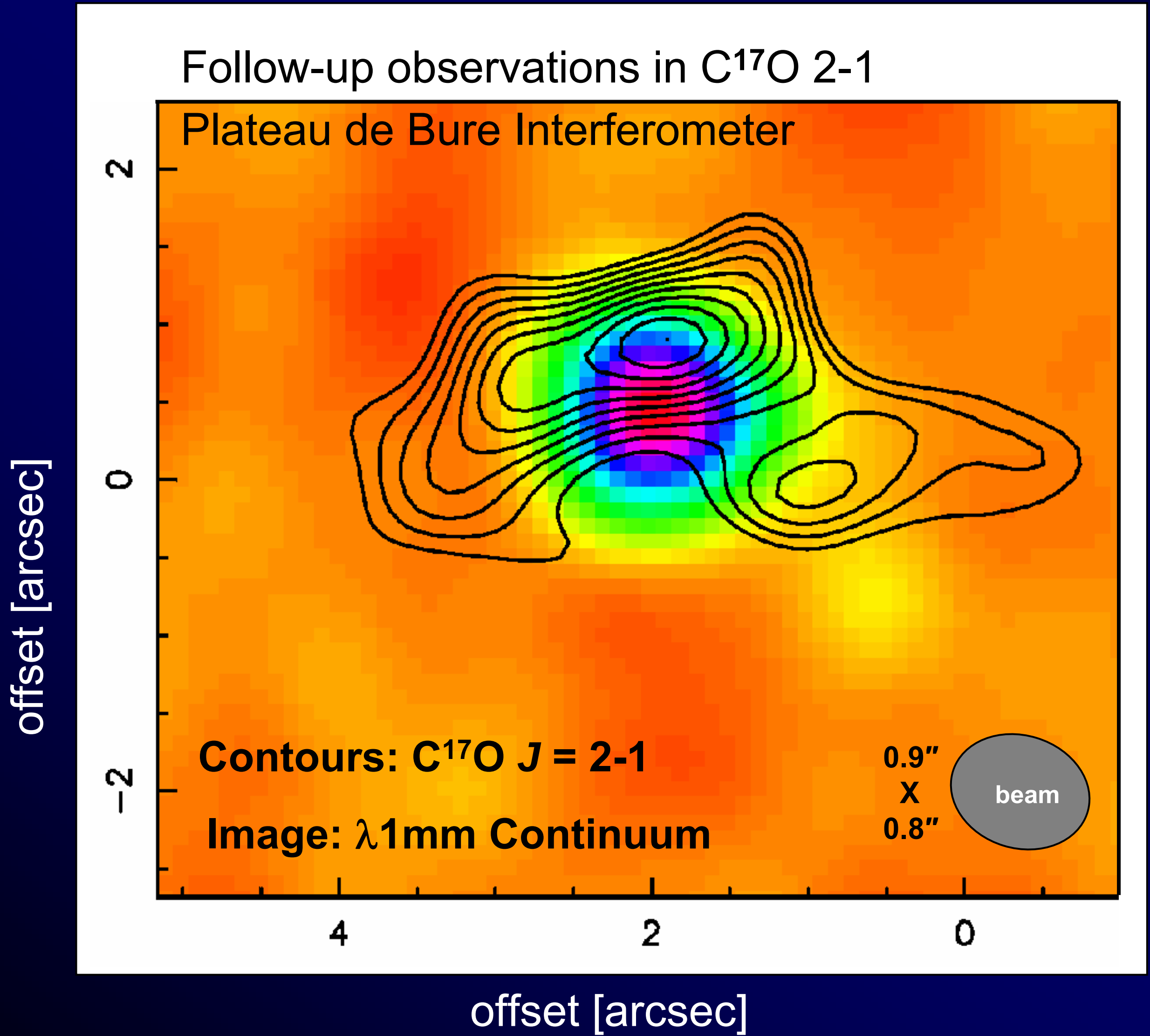
Schreyer et al. (2006)

Our observational results

AFGL 490



- Clumpy gas ring centered at the 1mm continuum point source

←

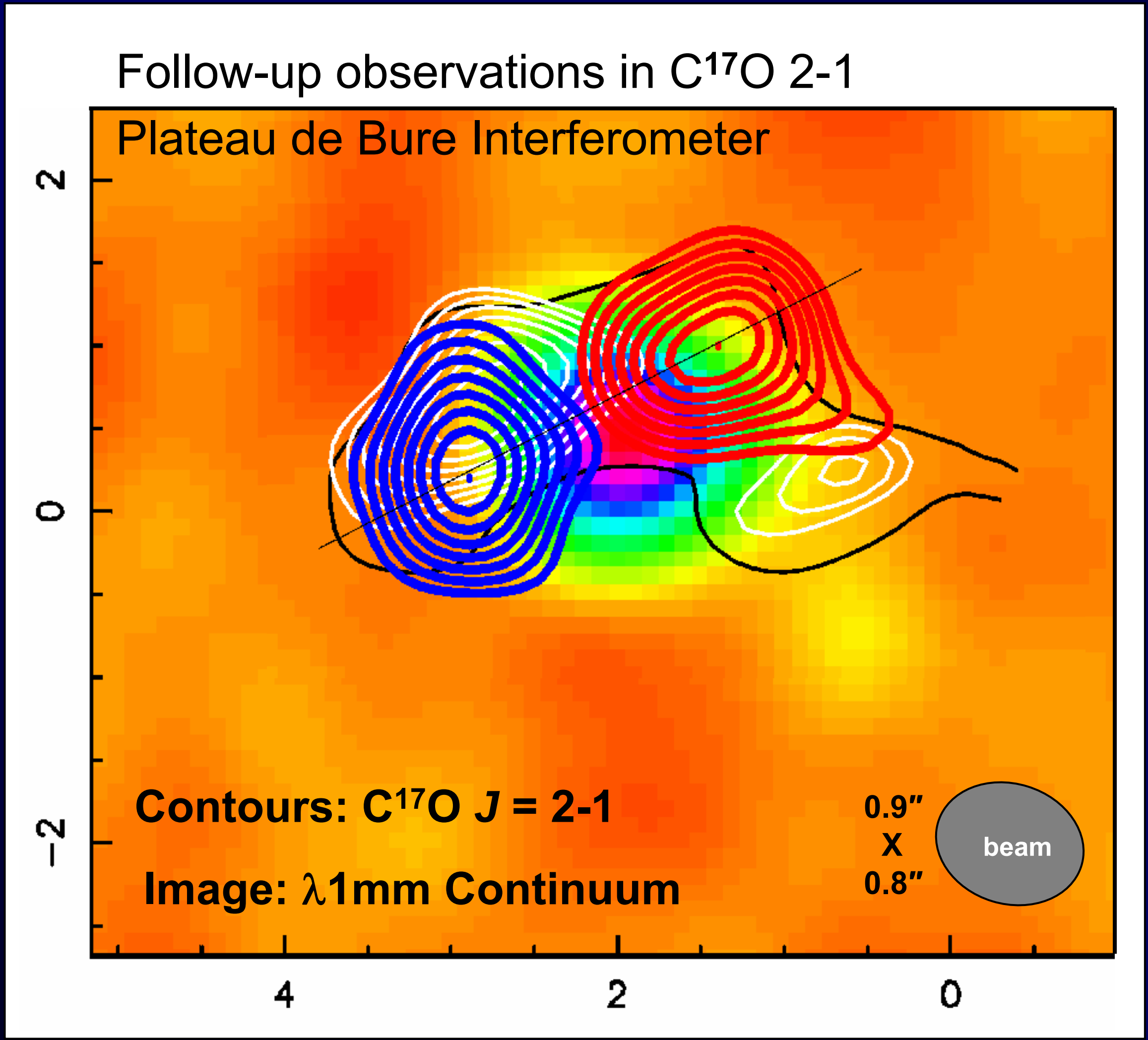
$C^{17}O$ contour levels: 20%-90% of the peak emission 10% = 1σ

Color-coded image: 1mm continuum point source, peak intensity = 0.6 Jy $beam^{-1}$

Schreyer et al. (2006)

Our observational results

AFGL 490



- Clumpy gas ring centered at the 1mm continuum point source
- Well separated **red-** and **blue-**shifted $C^{17}O$ emission

Red & blue $C^{17}O$ contour levels:
30%-90% of the peak emissions

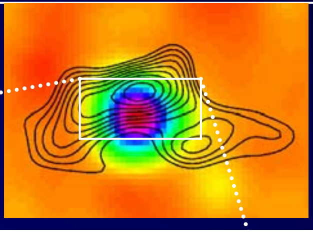
V_{lsr}-Red: -12.5…-9.5 km/s
V_{lsr}-Blue: -15.5…-13.4 km/s

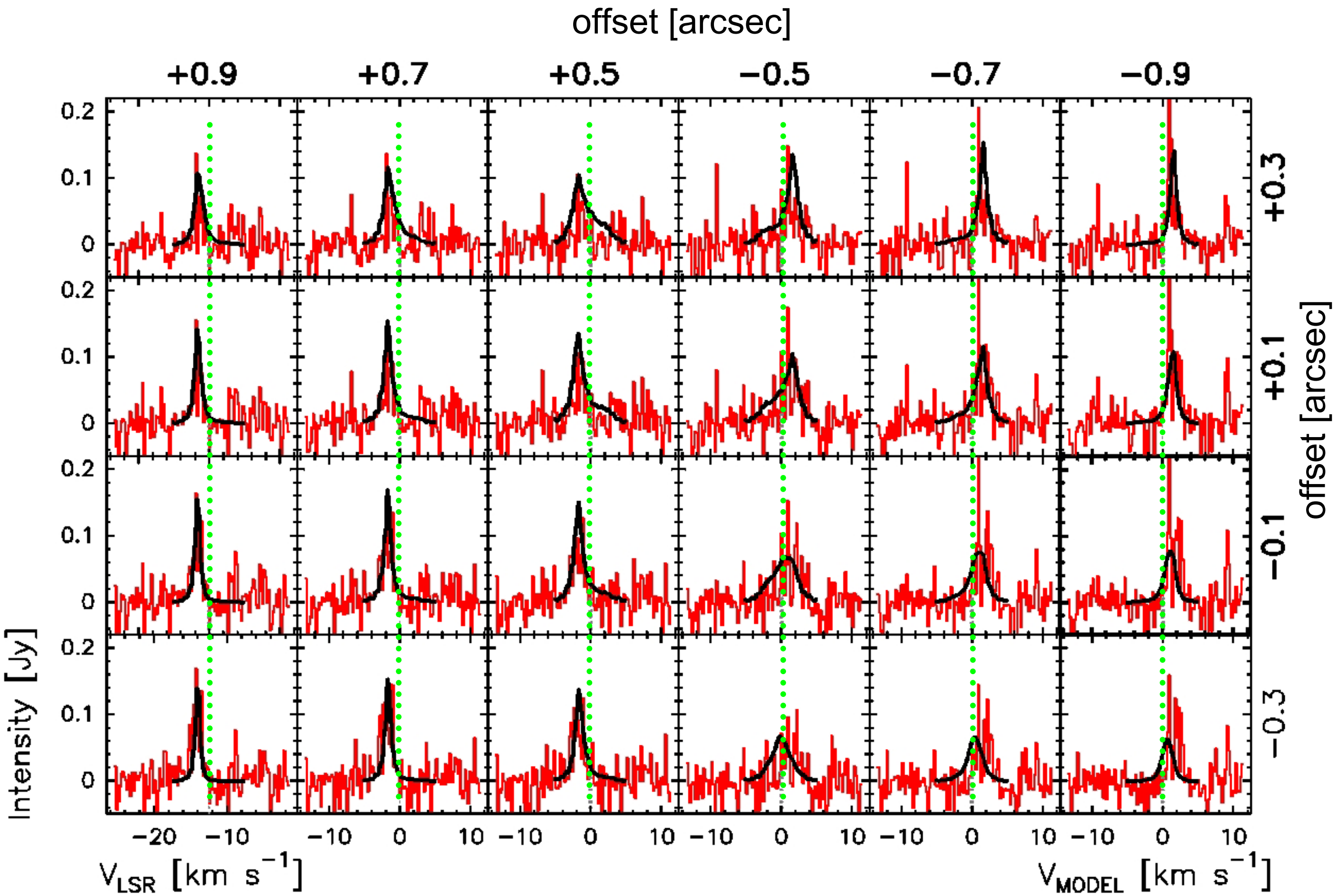
Schreyer et al. (2006)

Modelling of the $C^{17}O$ emission

AFGL 490

Iterative Modelling of the $C^{17}O$ 2-1 line profiles





Observed spectra - **Simulated line profiles**

Complete cycle:

Step I
2D model for the continuum emission

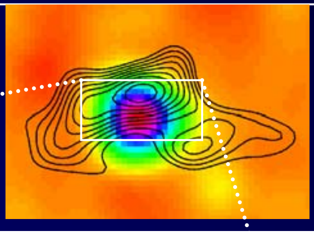
Step II
1+1D modelling of the chemistry in the disk

Step III
2D modelling of the line profile

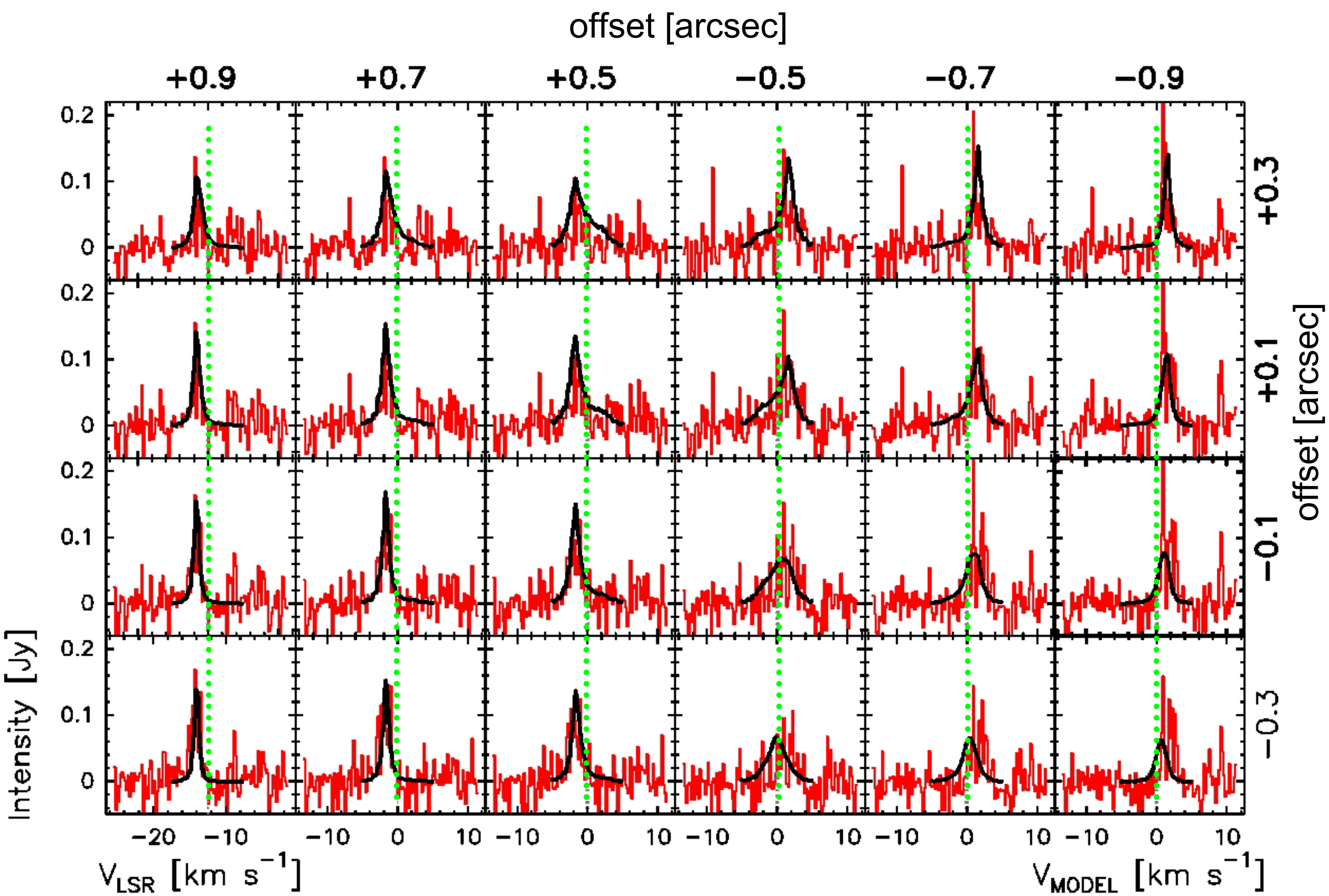
Schreyer et al. (2006)

Modelling of the $C^{17}O$ emission

AFGL 490



Iterative Modelling of the $C^{17}O$ 2-1 line profiles



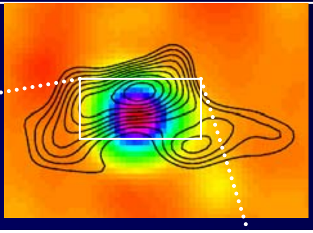
Observed spectra - **Simulated line profiles**

Assumptions for the model:

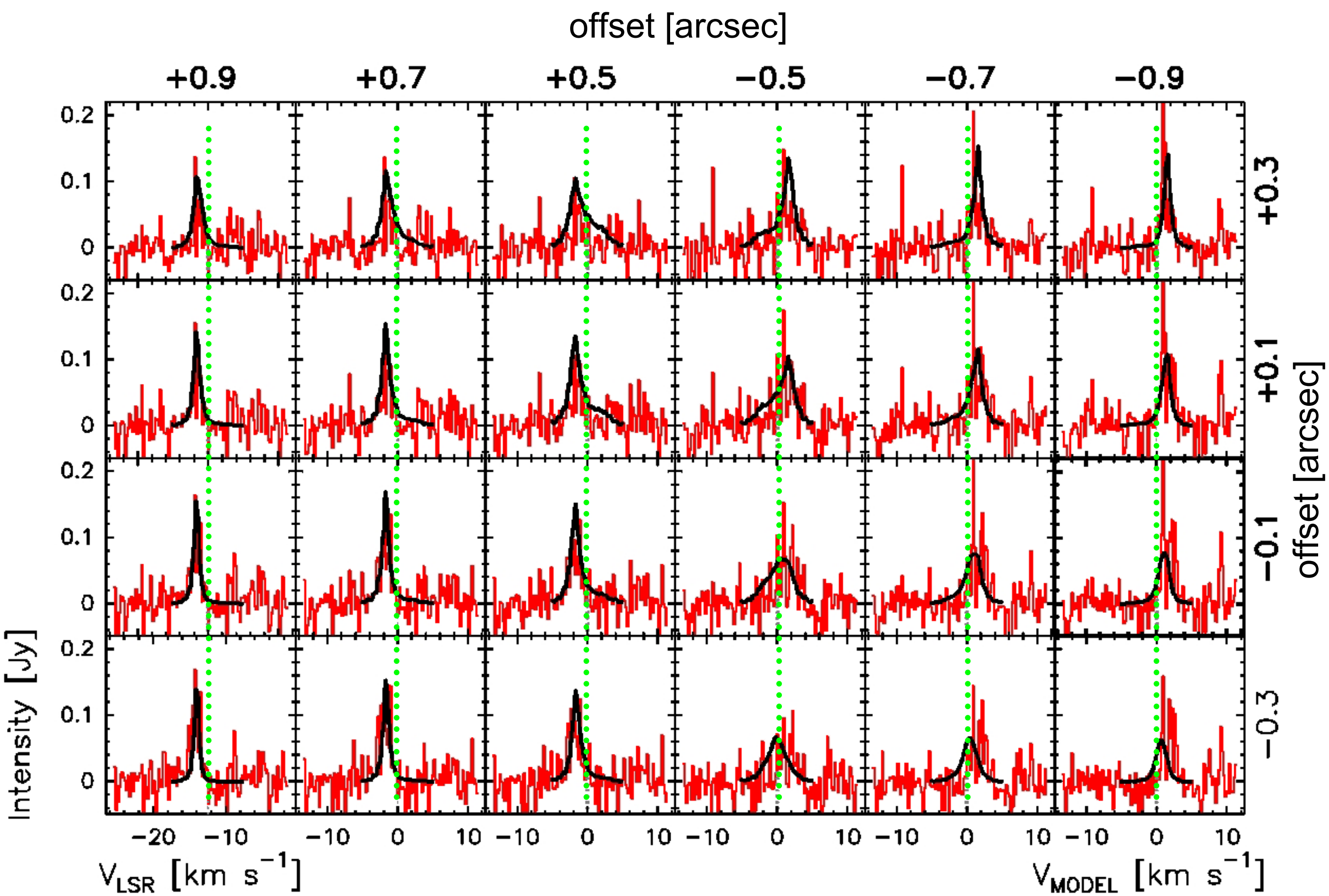
- Flared-disk model
- Velocity profile $V(r) = V_o(r_o/r)^{-s}$
- Surface density gradient $\Sigma(r) = \Sigma_o(r_o/r)^{-p}$
- Dust grains: MRN-like size distribution (Mathis et al. 1977)
- $M_{gas} : M_{dust} = 100$
- Age: 0.1 Myr

Modelling of the $C^{17}O$ emission

AFGL 490



Iterative Modelling of the $C^{17}O$ 2-1 line profiles



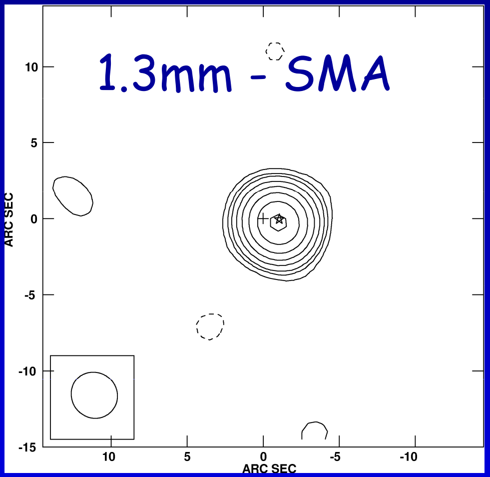
Observed spectra - **Simulated line profiles**

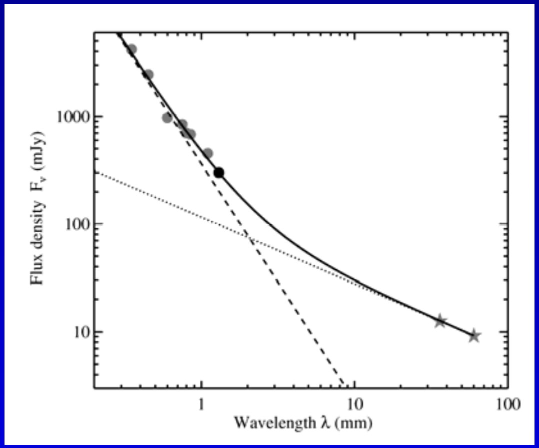
Best Fit Results:

- Inclination & position angle i = 30°±5°
- $M_\star$ = 8…10 $M_\odot$
- M_{disk} = 0.2…1 $M_\odot$
- Velocity profile $V(r) = V_o(r_o/r)^{-0.5}$
- Surface density gradient $\Sigma(r) = \Sigma_o(r_o/r)^{-1.5}$
- Optical depth $\tau < 0.01$
- R_{out} = 1500 AU

Schreyer et al. (2006)

MWC 297





B1.5, M_*=10 Msun

M_{disk}=0.07 Msun

Rdisk ~ 80AU

No detectable compact CO 2-1

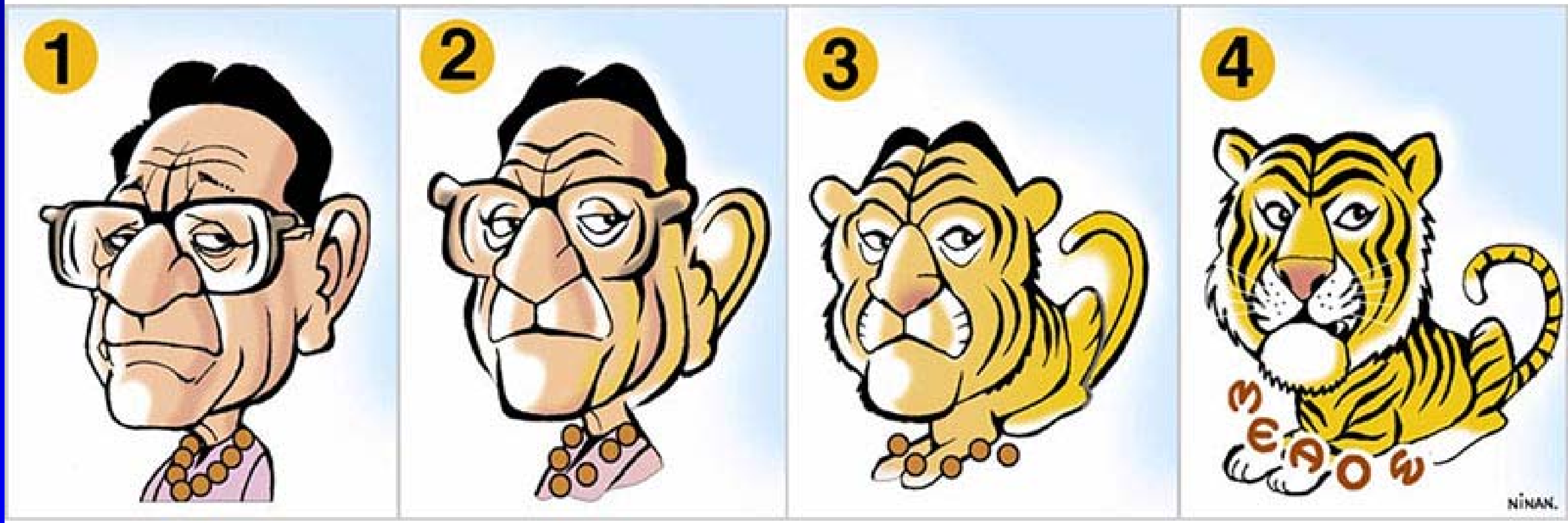
Dust mass requires a flattened disk to be optically visible

Manoj et al. 2007

VLTI interferometry study (Acke et al. 2008)
NIR/MIR emission including the 10 micron
Silicate emission comes from very compact region (FWHM 1.5 AU)
No evidence for inner emission-free gap

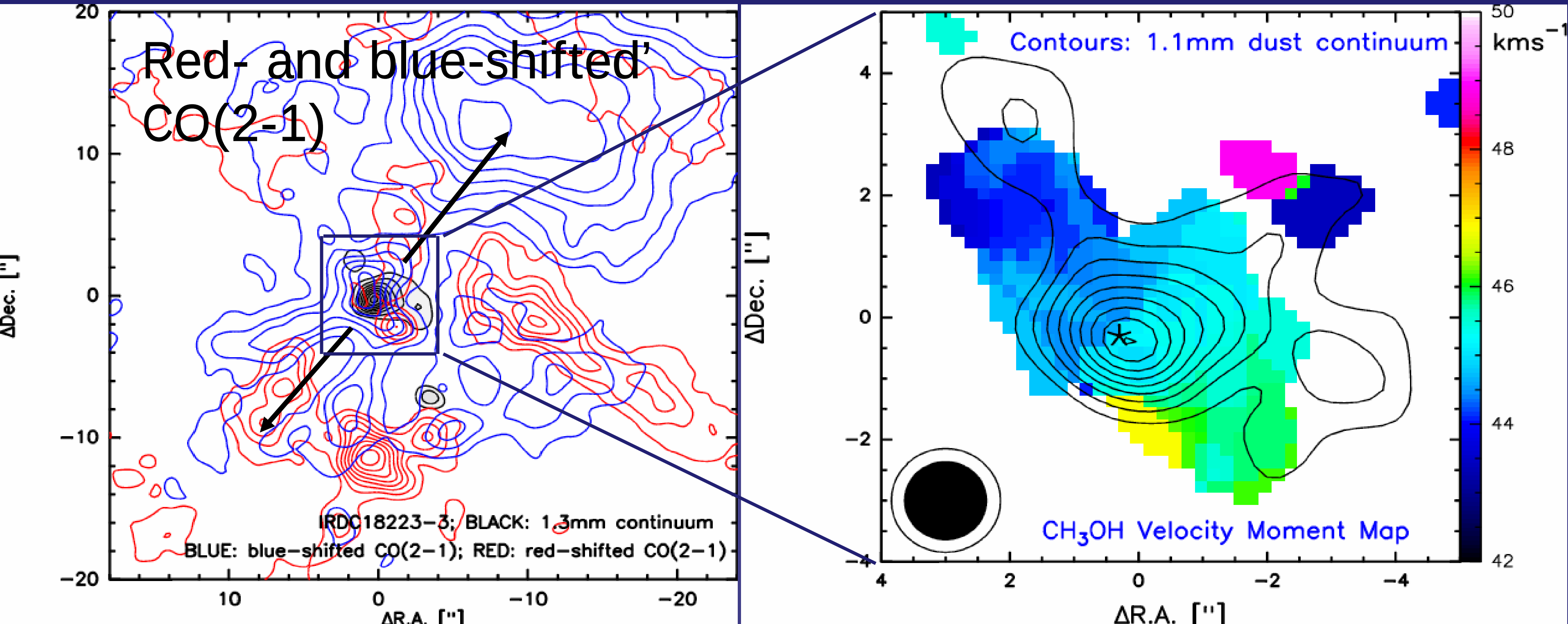
(see also the similar B0 star R Mon – Fuente ea. 03, 06; Alonso-Albi ea. 07)

Evolutionary Stages



Rotation and outflow at the onset of MSF

IRDC 18223-3, distance ~ 3.7kpc



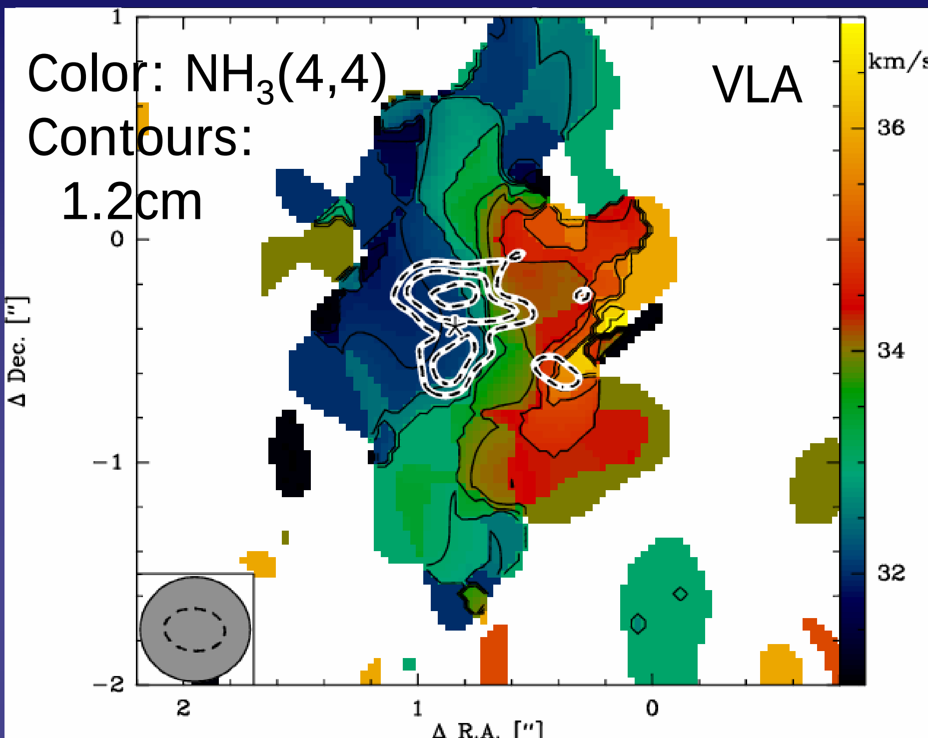
- Outflow wings +-15 km/s
- Outflow mass 13 M_{sun}
- Outflow rate 3.5×10^{-4} M_{sun}/yr
- Dynamical age ~3.7×10^{4} yrs

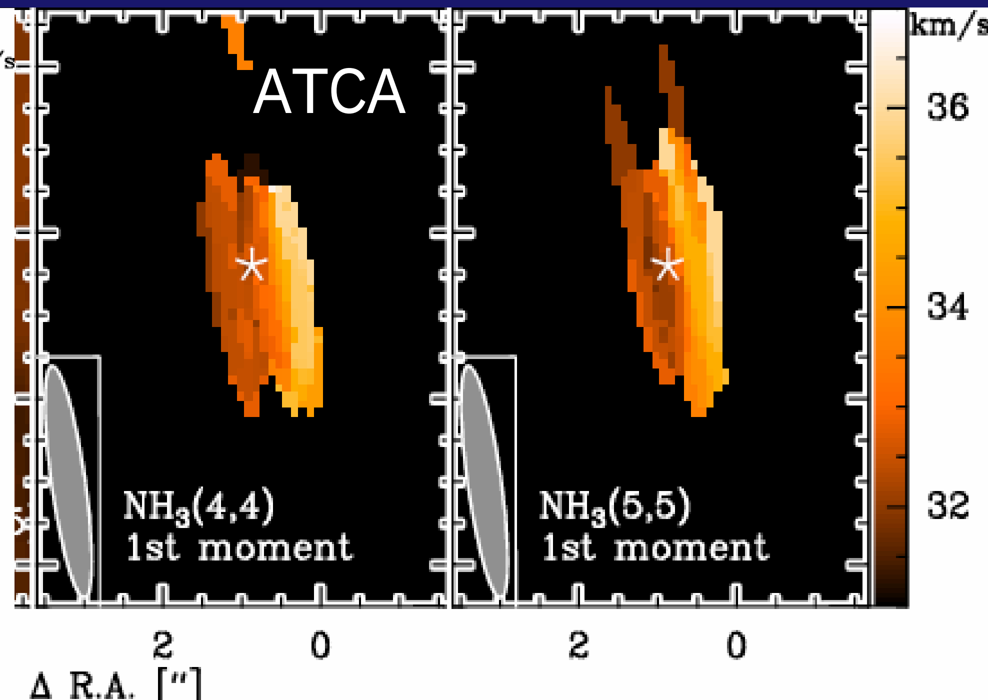
- Δv ~ 2.1 km/s
- Velocity spread ~ 2.5 km/s
- Structure size ~ 25000 AU
- Likely optically thick line?

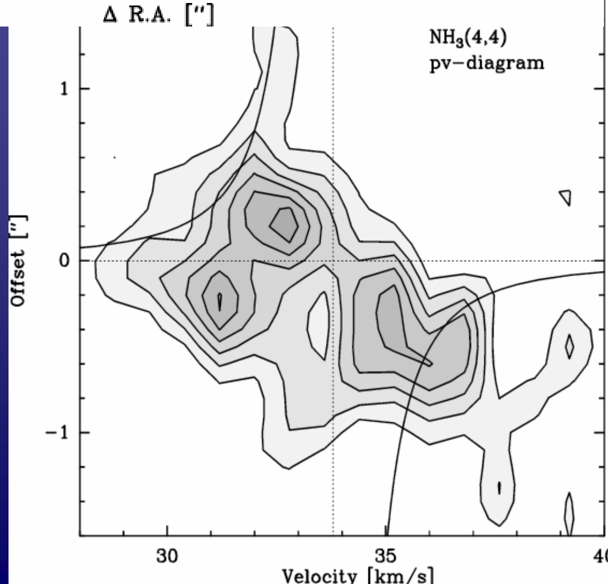
About 50 M_{sun} in gas vs total 500 M_{sun}

Fallscheer et al., in prep.

The Disk candidate in IRAS 18089-1732 (HMPO)





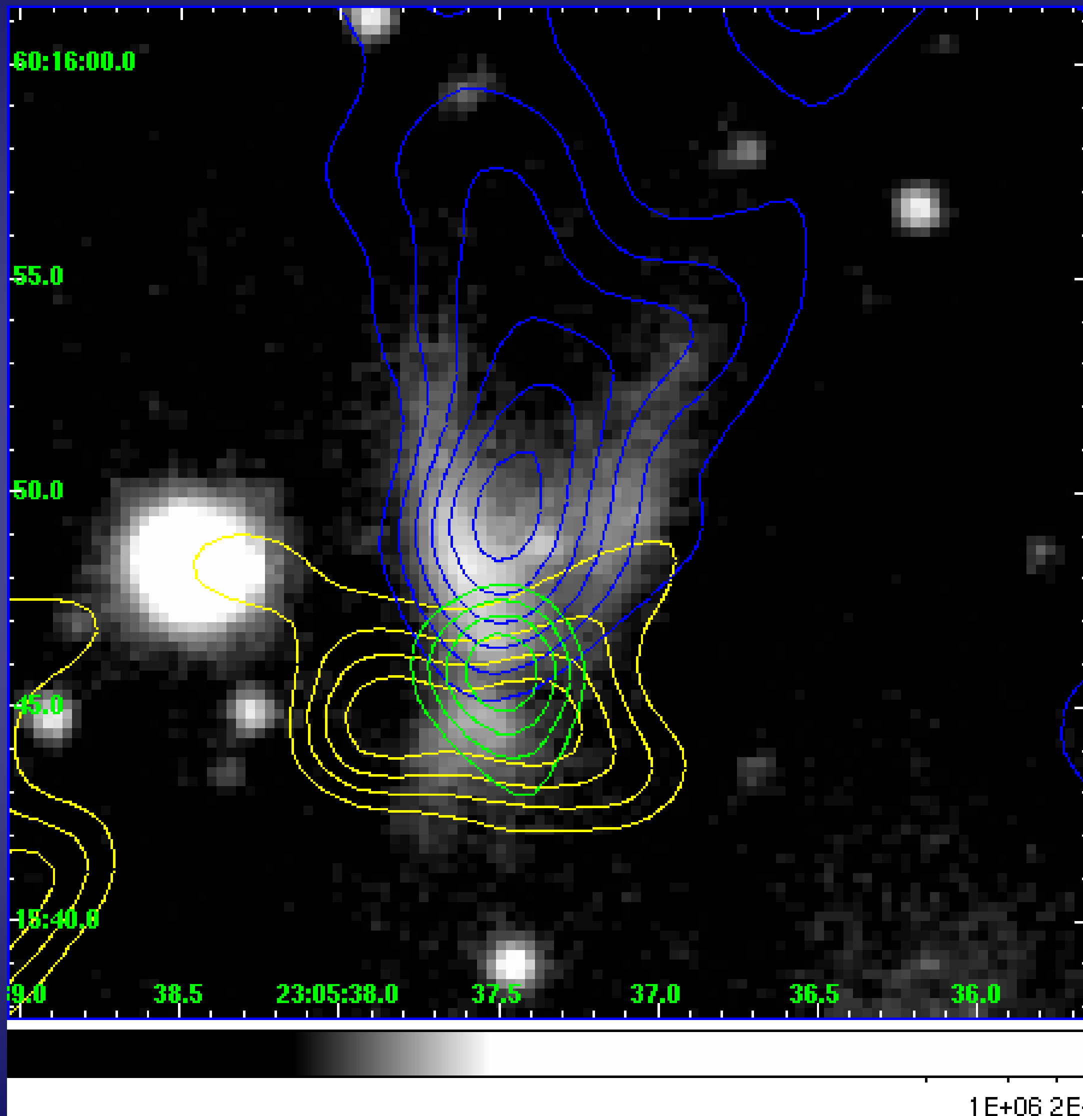


New high-excitation ammonia $NH_3(4,4)/(5,5)$ data

- Clear east-west velocity gradient.
- Non-Keplerian motions.
- T > 100K in rotating structure.
- $\Delta v(NH_3(5,5))$ ~ 4.7 km/s

Beuther & Walsh 2008

A more evolved disk in MSF?



SMA @ 1.3mm and about 5.6kpc

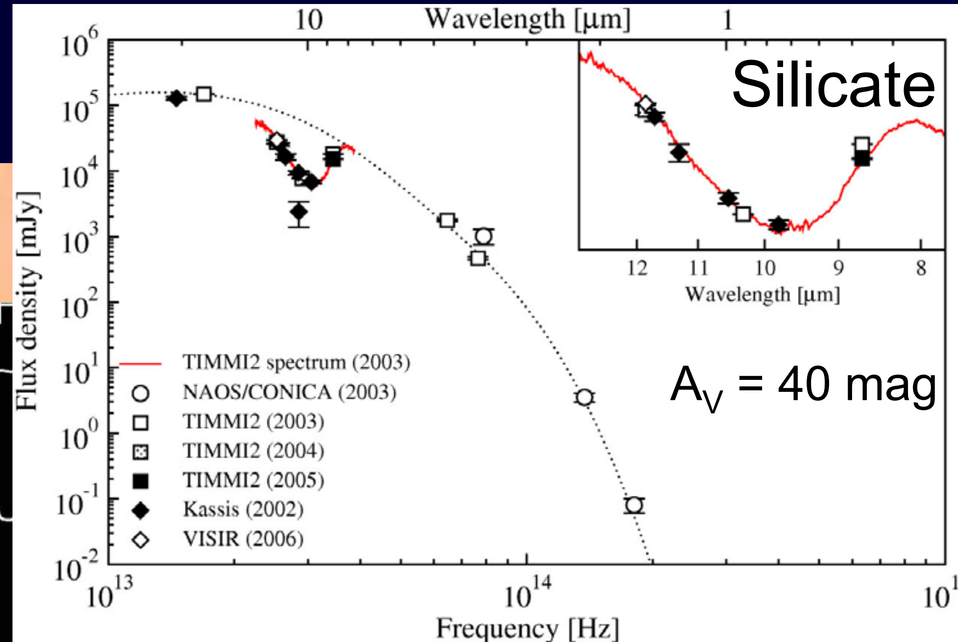
- Blue: CO(2-1)
- Green: 1.3mm continuum
- Yellow: $C^{18}O$(2-1)

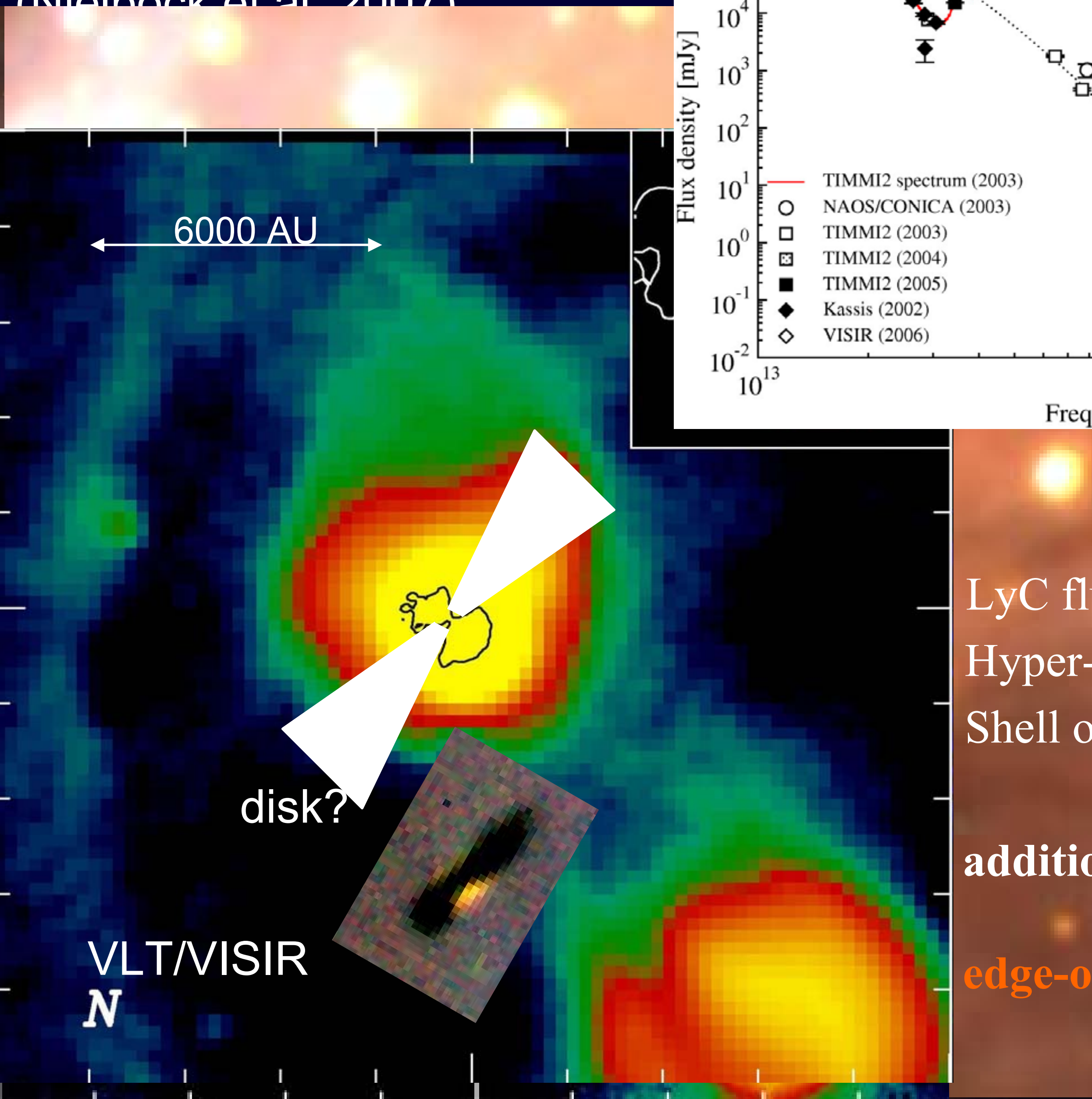
- No dust emission on large scales
- Gas mass ~ $5M_{sun}$
- $\Delta v(C^{18}O)$ ~ 0.8km/s
- Size ~ 20000 AU

Quanz et al. in prep.

M17-UC1

(Nielbock et al. 2007)





LyC flux: B0-B0.5 V star

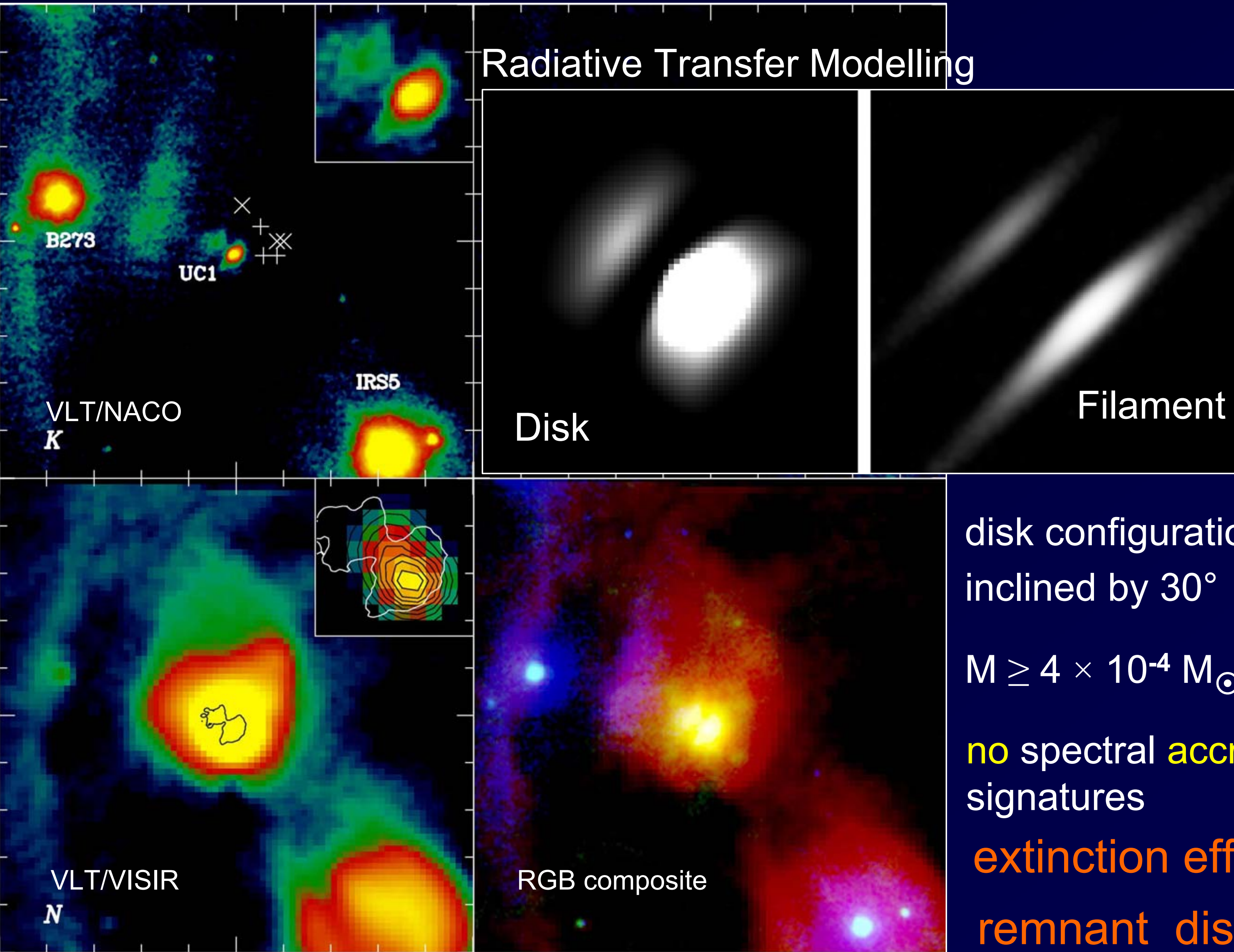
Hyper-compact HII region (?)

Shell of 0.6 – 3.4 $M_{\odot}$ (warm dust/gas)

additional cool dust

edge-on disk? (see Orion proplyd)

M17-UC1 – Disk or Filament?



disk configuration inclined by 30°

$M \geq 4 \times 10^{-4} M_\odot$

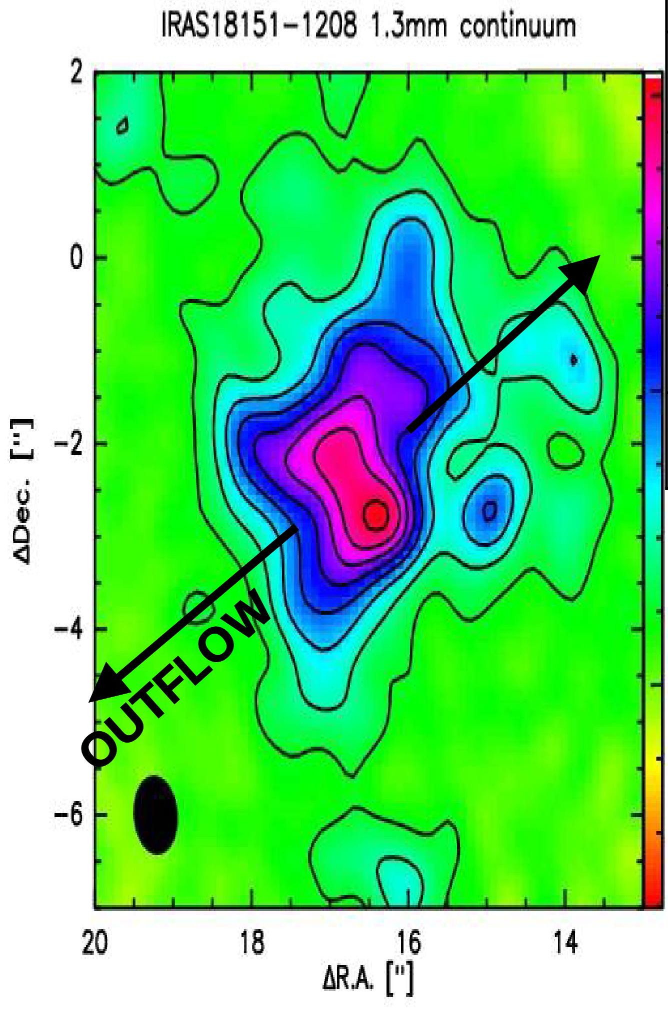
no spectral accretion signatures

extinction effect?

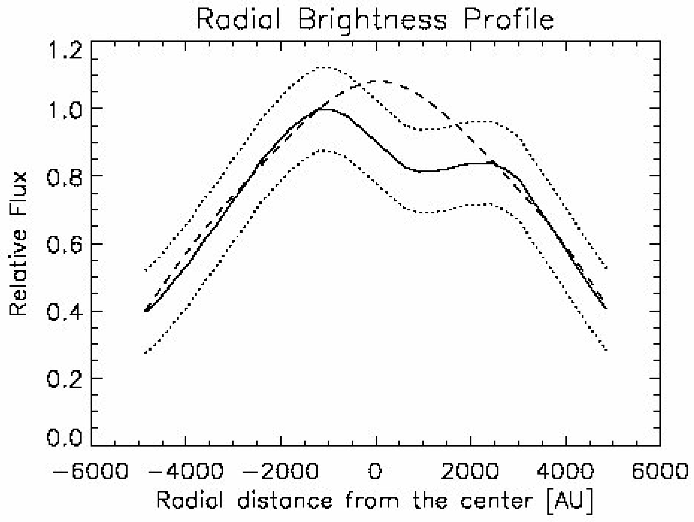
remnant disk?

RT modeling of a disk candidate in a high-mass protostellar object

Successful modeling of elongation detected orthogonal to the outflow orientation



	Low Mass: Butterfly Star	High mass: IRAS 18151-1208
α, radial density parameter	2.37	2.37
β, disk flaring parameter	1.29	1.29
M_{dust}	0.07 $M_\odot$	3 $M_\odot$
R_{out}, radius at density=0	300 AU	5000 AU
R_*, T_*, L_*	$2R_\odot$, 4000K, $0.92L_\odot$	$7.5R_\odot$, 22500K, $14000L_\odot$

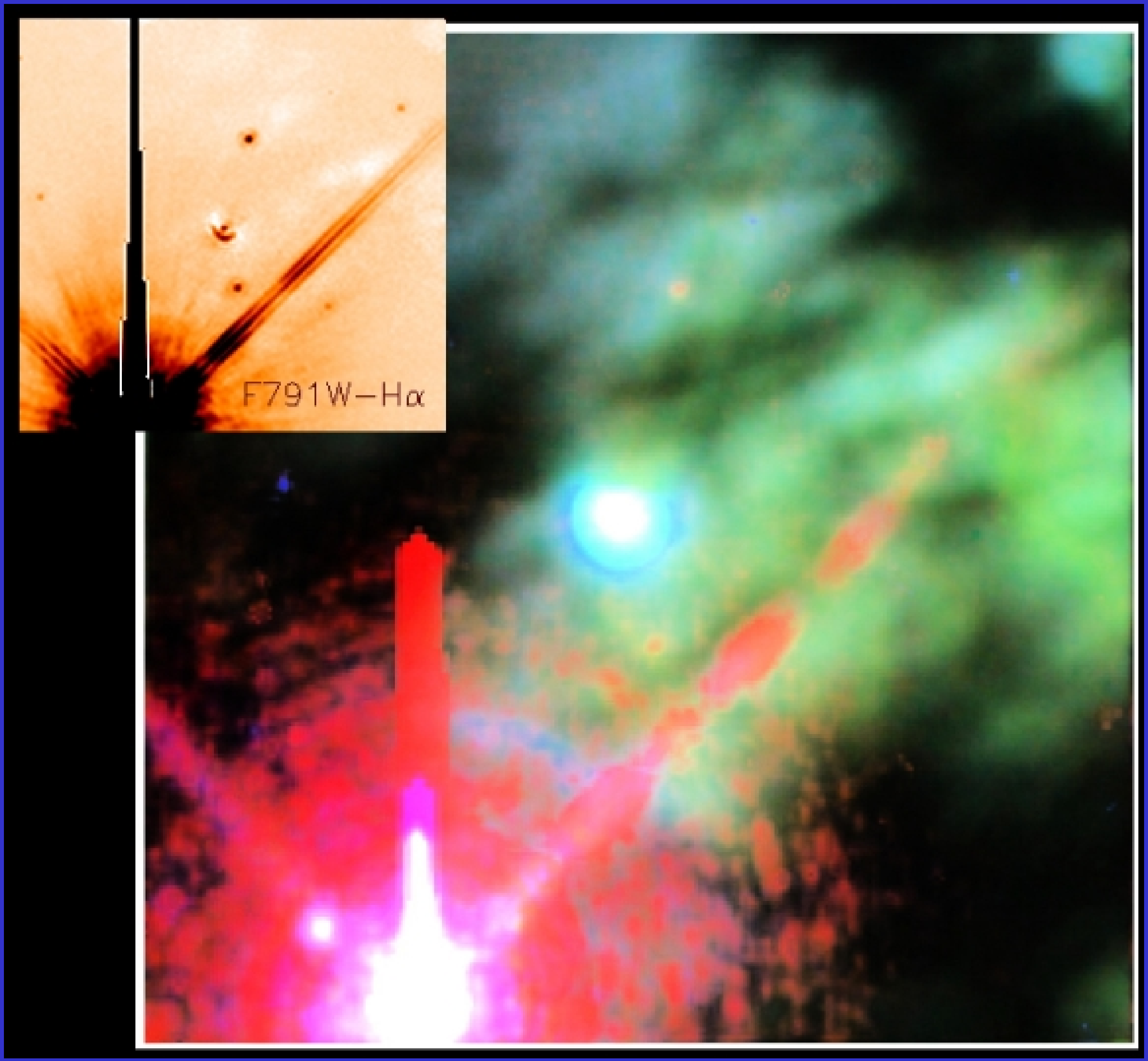


The Hourglass Close to Her 36 (O7 star in M8)

HST Image in [OIII], [SII], Hα

G5.97-1.17: The View of HST

Red: [SII]
Green: [Hα]
Blue: [OIII]



Her 36: O7 ZAMS
Dist: 2.7"/0.024pc

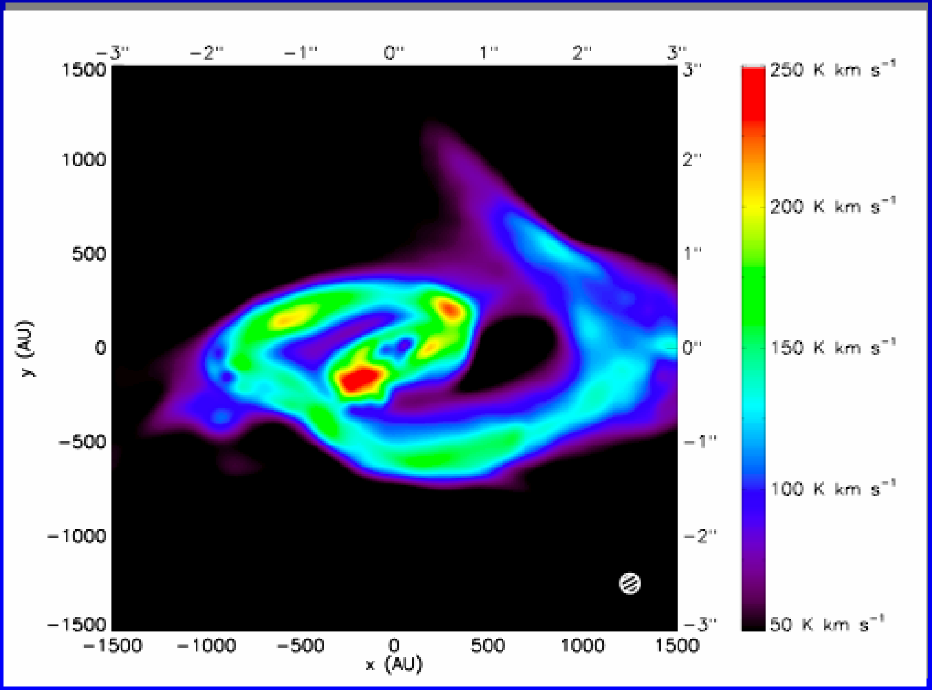
Ext.: $A_V = 5$ mag
$UV_{req} = 5.5 \times 10^{45}\ s^{-1}$
$UV_{prov} = 3.8 \times 10^{45}\ s^{-1}$

$\dot{M} = 7 \times 10^{-7}\ M_\odot\ yr^{-1}$

(Stecklum, Henning, Feldt ea. 1998)

Summary

- Disks around early B-type stars exist and disappear rapidly (Typical masses of a few M_{sun} and sizes of ~1000 AU)
- No strong evidence for disks around O-type stars (small disks seem to be present – CO)
- We need to determine disk/torus kinematics …



Integrated T_B in simulated 1000 s / pointing ALMA observation of disk at 0.5 kpc in CH_3CN 220.7472 GHz (Krumholz, Klein, & McKee, 2007, ApJ, 665, 478)