Observational Frontiers of High-Mass (Proto)star Formation

R. S. Furuya
Subaru Telescope, NAOJ

Special thanks to
R. Cesaroni (Arcetri/INAF)
N. Ikeda (ISAS/JAXA)

Outline of Talk

- Introduction: study of high-mass star forming regions
- Disks and Toroids around young OB stars
- Gas Infall in hot molecular core
- Core mass function: a hint for stellar cluster formation
- Giant HII regions, *i.e.*, “starburst”
- Summary

High-Mass Star Forming Regions Observational Problems

- IMF: high-mass stars are **rare**
- Formation in clusters → **confusion**
- **Large distance**: > 350 pc (σ Ori), typically a few kpc
- **Rapid evolution**: $t_{acc} = 20\ M_{sun} / 10^{-3}\ M_{sun}\ yr^{-1} = 2\ 10^4 yr$
- Parental environment profoundly **altered**

Observational Frontiers

1) Initial conditions, including origin of IMF
2) Identification of "real" high-mass (proto)stars
3) The earliest phase of massive young stellar objects (YSOs) e.g., hyper compact HII regions
4) Accretion process
5) Formation of Giant HII regions, "starburst"

(1) and (2) require wide-field imaging spectroscopy, while (3), (4) and (5) require high-angular resolution, *i.e.*, interferometer

This talk deals with

M_{star}/M_{sun}	Designation
approx. 8 - 15	Early B
approx. 15 - 30	Late O
approx. 30 - 65	Early O

Very often misused terminology

"PROTOSTAR" should be reserved exclusively for:

A gaseous object in hydrostatic equilibrium
AND
Has NOT yet begun hydrogen burning

Almost all the objects should be called

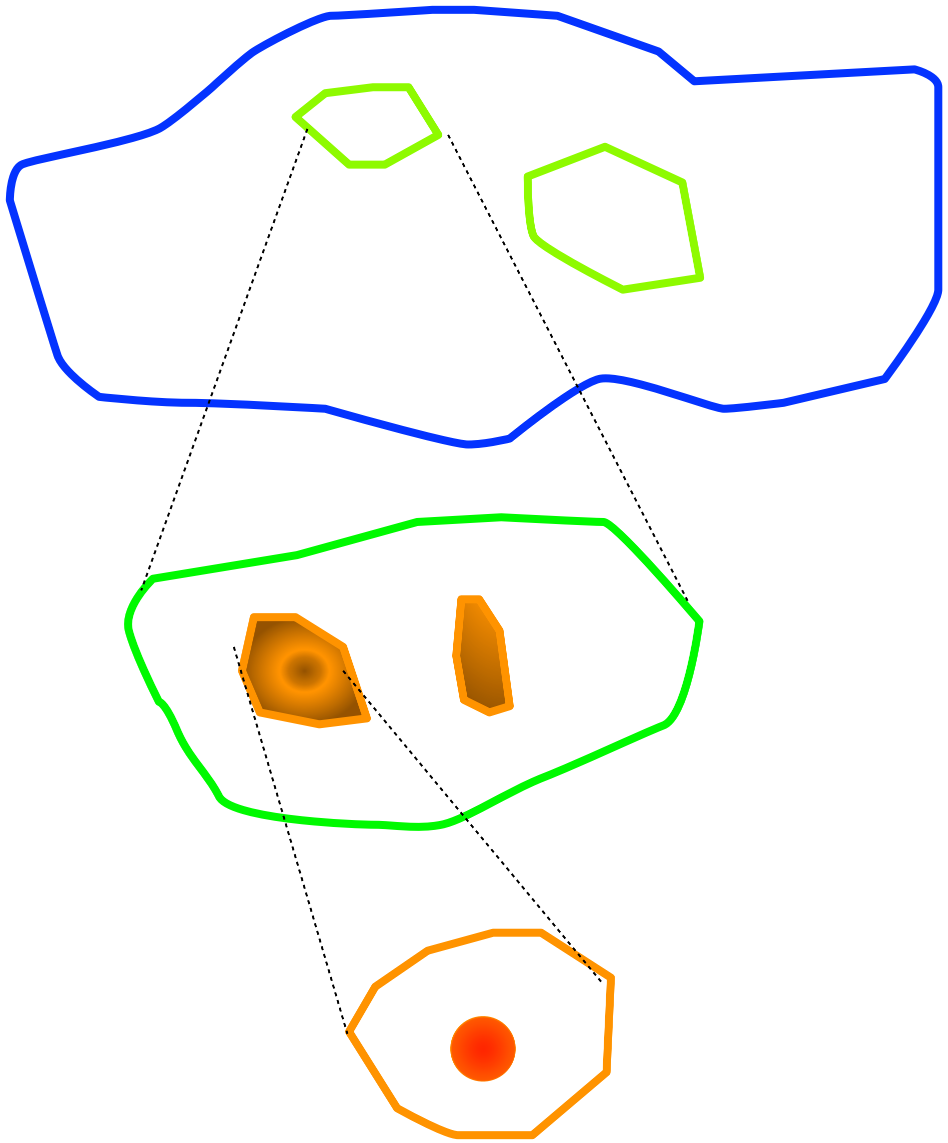
either

HIGH-MASS (PROTO)STAR

OR

MASSIVE YSO

Environment of High-Mass Star Forming Regions



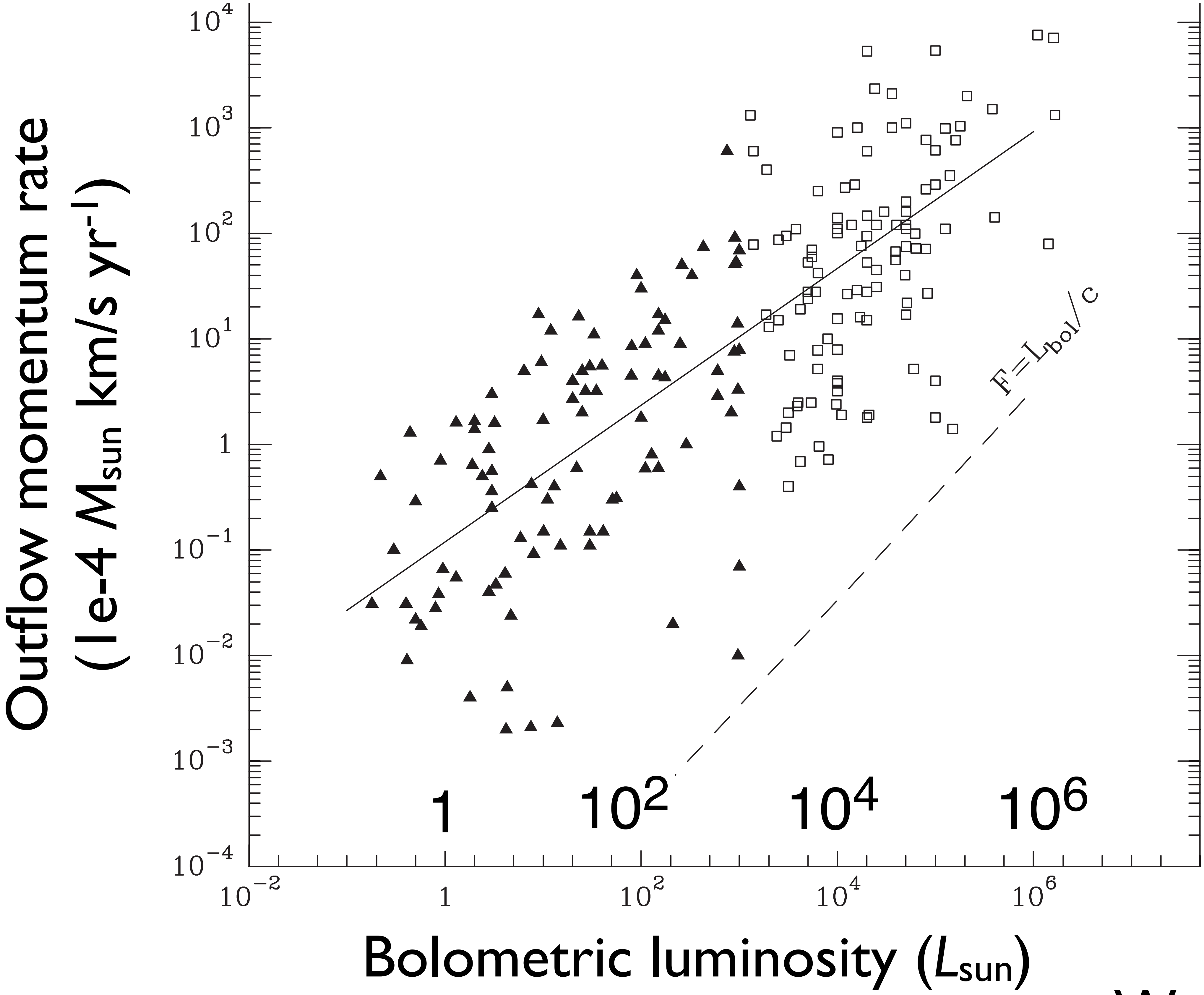
Clouds: 10–100 pc; 10 K; 10^3 cm^{-3}; ^{13}CO, $C^{18}O$, etc

Clumps: 1 pc; 30 - 50 K; 10^5 cm^{-3}; CS, $C^{34}S$ etc

Hot Molecular Cores: 0.1 pc; 50 -100 K; 10^7 cm^{-3}; CH_3CN, CN, etc

Massive YSOs: signposts: compact IR source, masers, Ultra Compact HII regions

Outflow properties, e.g., momentum rate, vary continuously as a function of source luminosity ...



Wu et al. 2004

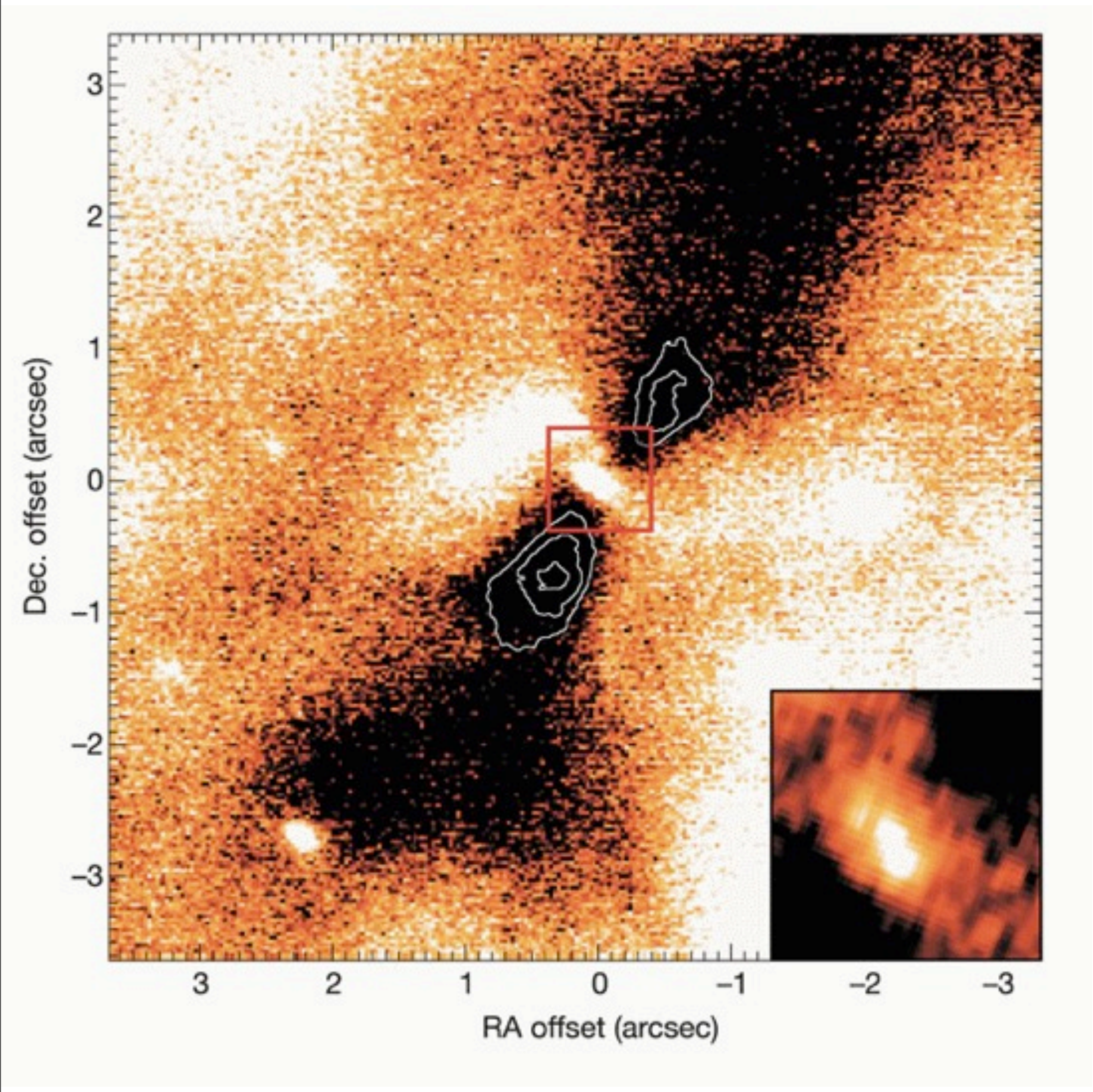
Search for Rotating “disks”

Tracers: Advantage & Shortcoming

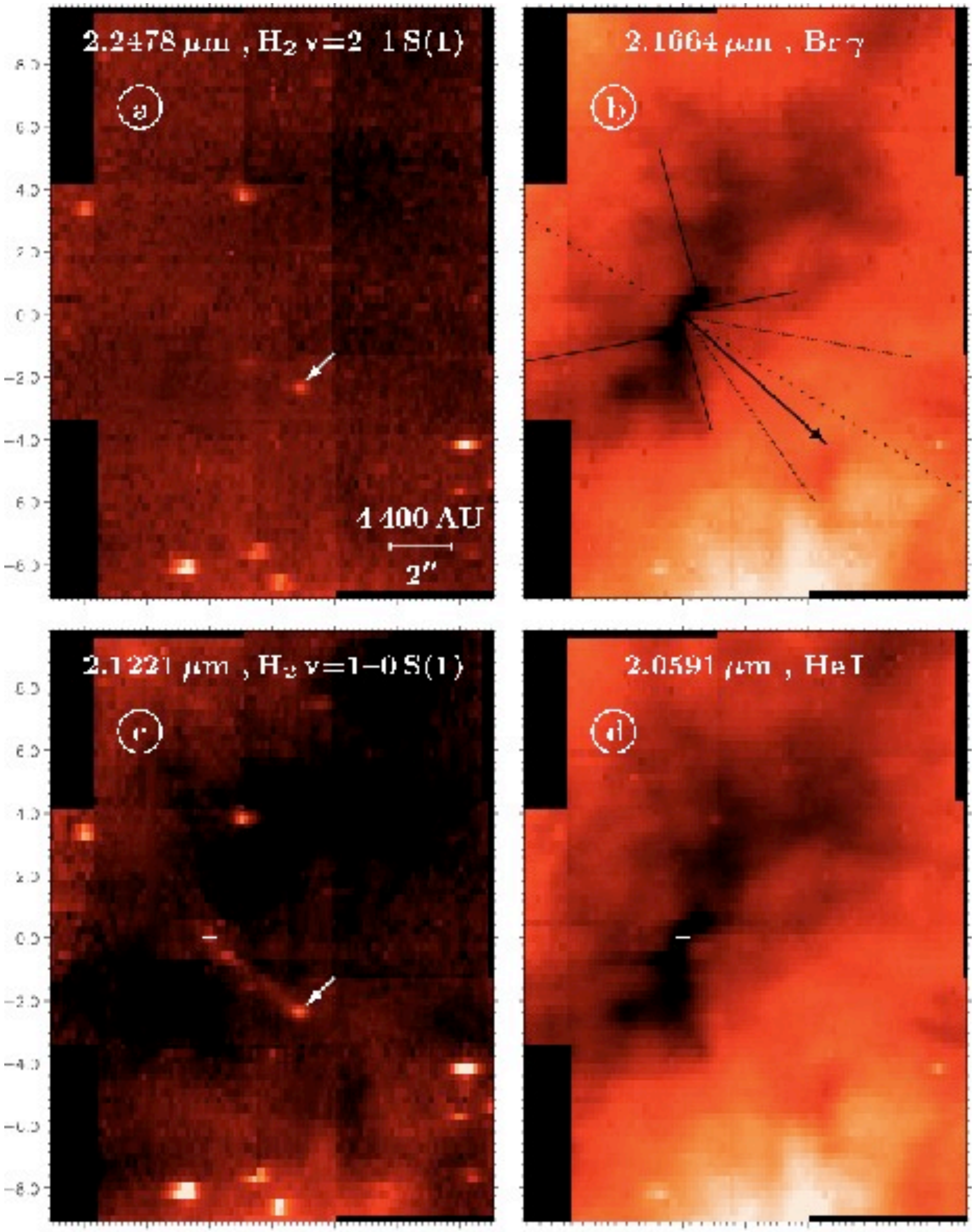
Continuum: IR, (sub)mm & cm	❖ High sensitivity in mass, esp, at submm (Detectable 0.1 M_{sun})	○ Confusion between disk and wind emission ○ No velocity info.
CH_3OH masers	❖ High angular resolution possible ❖ Very Common	○ Derived stellar mass too low; ○ H_2 jet parallel to CH_3OH masers ○ Sensitive to variety of factors ○ No column density info.
OH, H_2O & SiO masers	❖ High angular resolution possible ❖ H_2O:Very Common	○ Tracing outflow as well ○ OH & SiO: Very few examples ○ Sensitive to variety of factors ○ No column density info.
Thermal Molecular Lines	❖ Possible to trace both outflow & disk ❖ Column density	○ Poor angular resolution ○ Ambiguity in abundance

M17

Chini et al. (2004)

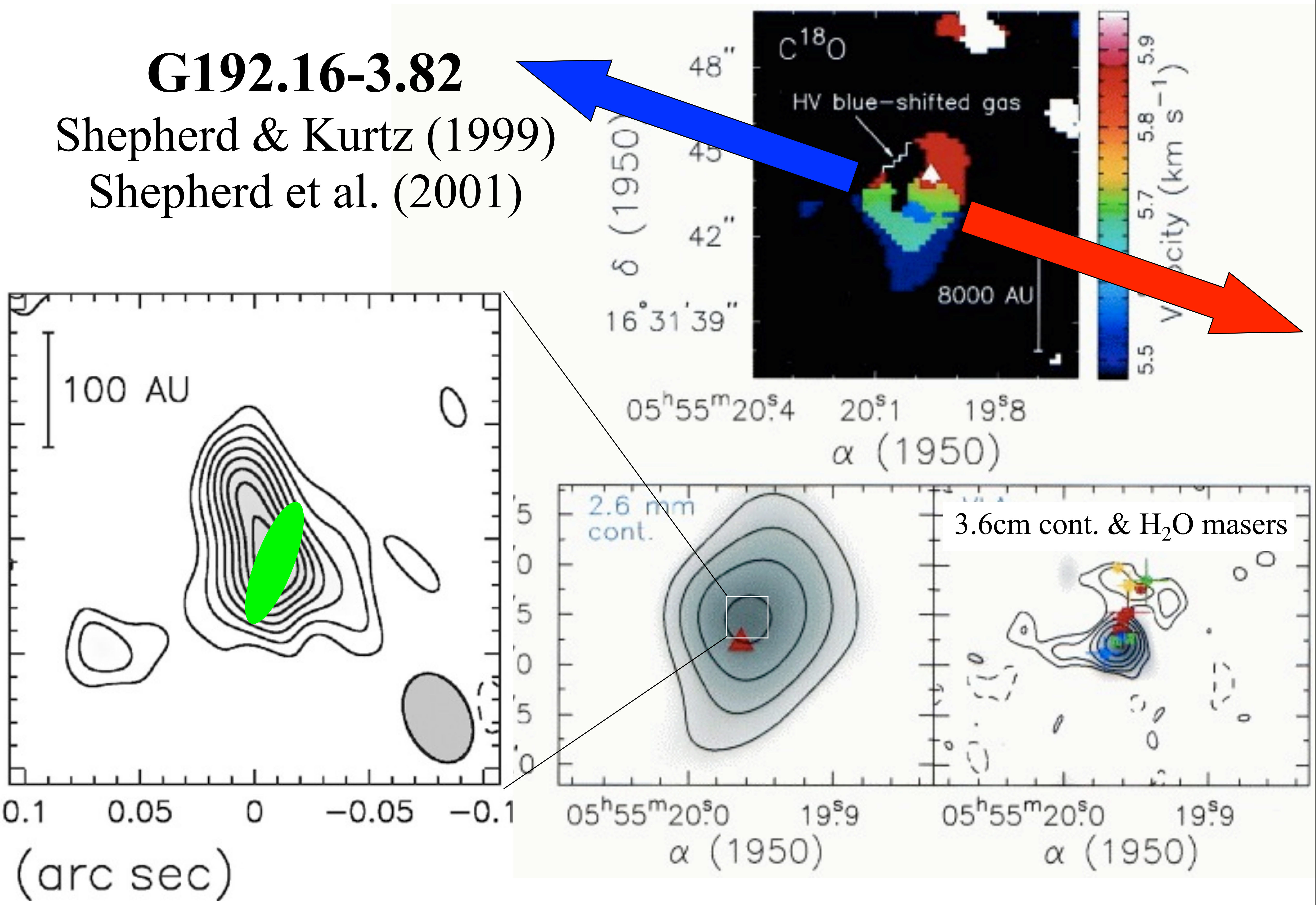


Nuerberger et al. (2007)



G192.16-3.82

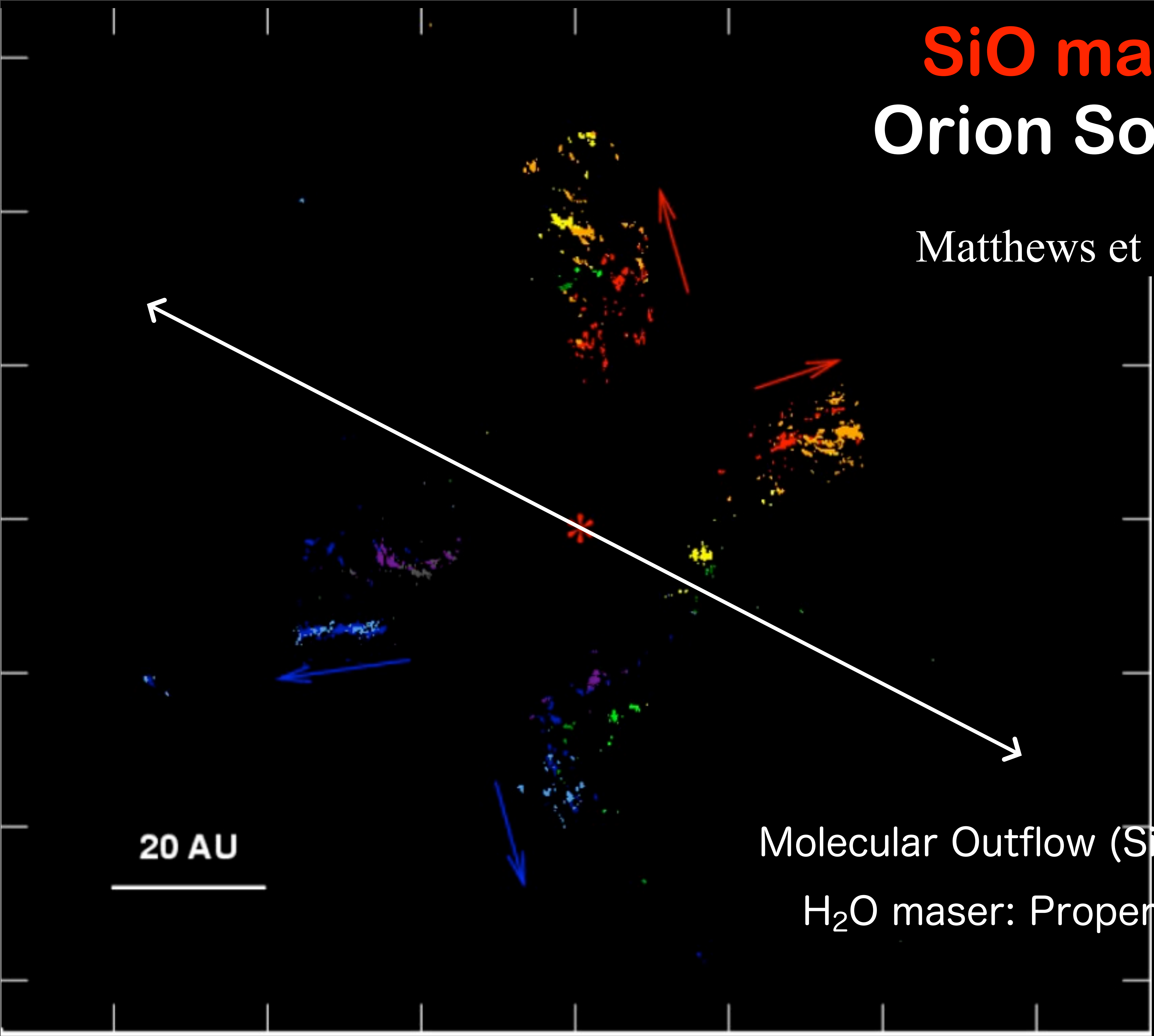
Shepherd & Kurtz (1999)
Shepherd et al. (2001)



SiO masers

Orion Source I

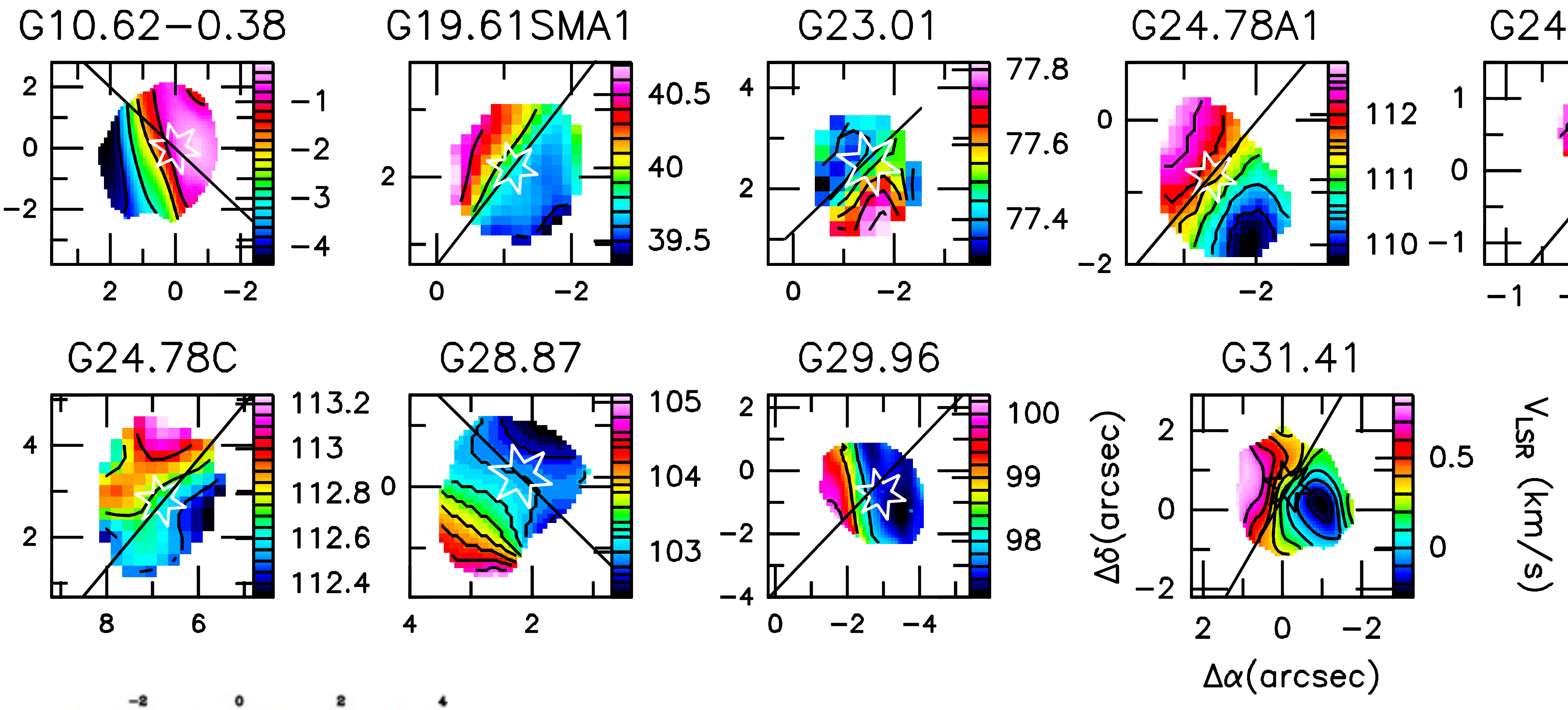
Matthews et al. 2010

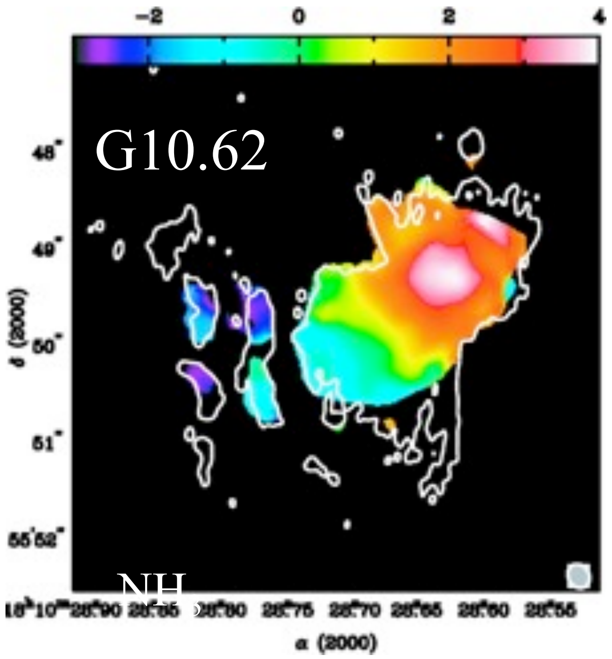


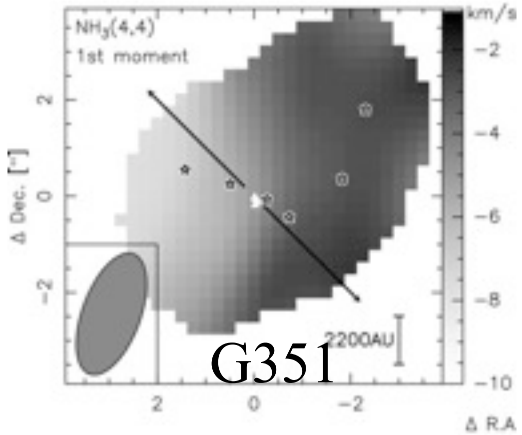
Molecular Outflow (SiO thermal)

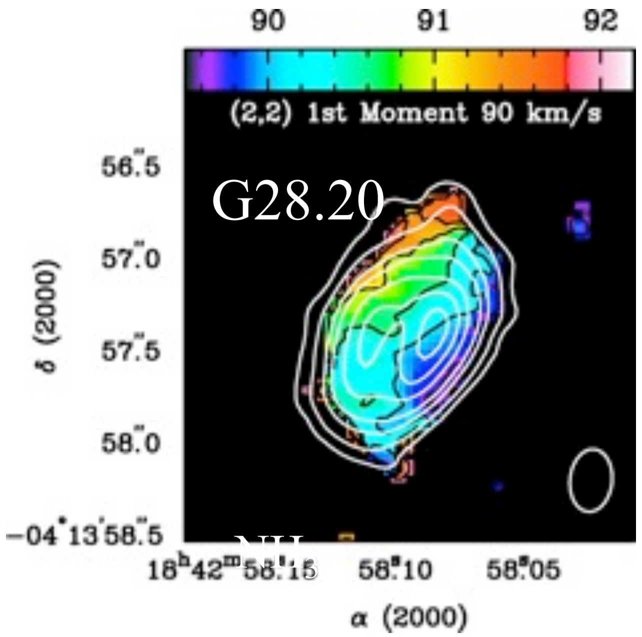
H_2O maser: Proper Motion

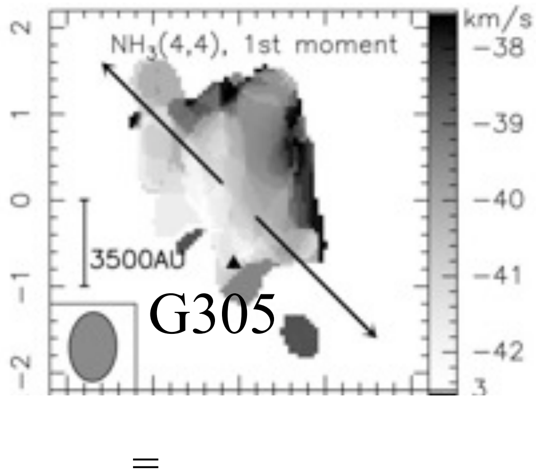
Velocity fields of HMCs, rotating toroids











The Growing Evidence for “Disks” around Massive YSOs

CH_3OH masers	ATCA, EVN	Norris et al. Ellingsen et al., Walsh et al. Minier et al., Edris et al., Pestalozzi et al.
OH masers	Merlin	Outflow sources: Cohen et al., Edris et al., Hoare et al.
SiO & H_2O masers	Hat Creek, VLA, VLBA	e.g. Orion source I Plambeck et al.Doleman et al., Greenhill et al., Torrelles et al.
Continuum: NIR, mm & cm	BIMA, Pt-link	Jet/outflow plus Disk system, Hoare et al., Gibb et al., Shepherd et al.
Molecular Lines: **NH_3, $C^{18}O$, CS, $C^{34}S$, CH_3CN,…**	VLA, SMA OVRO, BIMA PdBI, SMA NMA	UC HIIs, Hot Cores Shepherd et al., Shepherd and Kurtz, Bernard et al., Sandel et al. Olmi et al. Beltran et al. Cesaroni et al., Zhang et al. Furuya et al. etc. etc…..

Disks

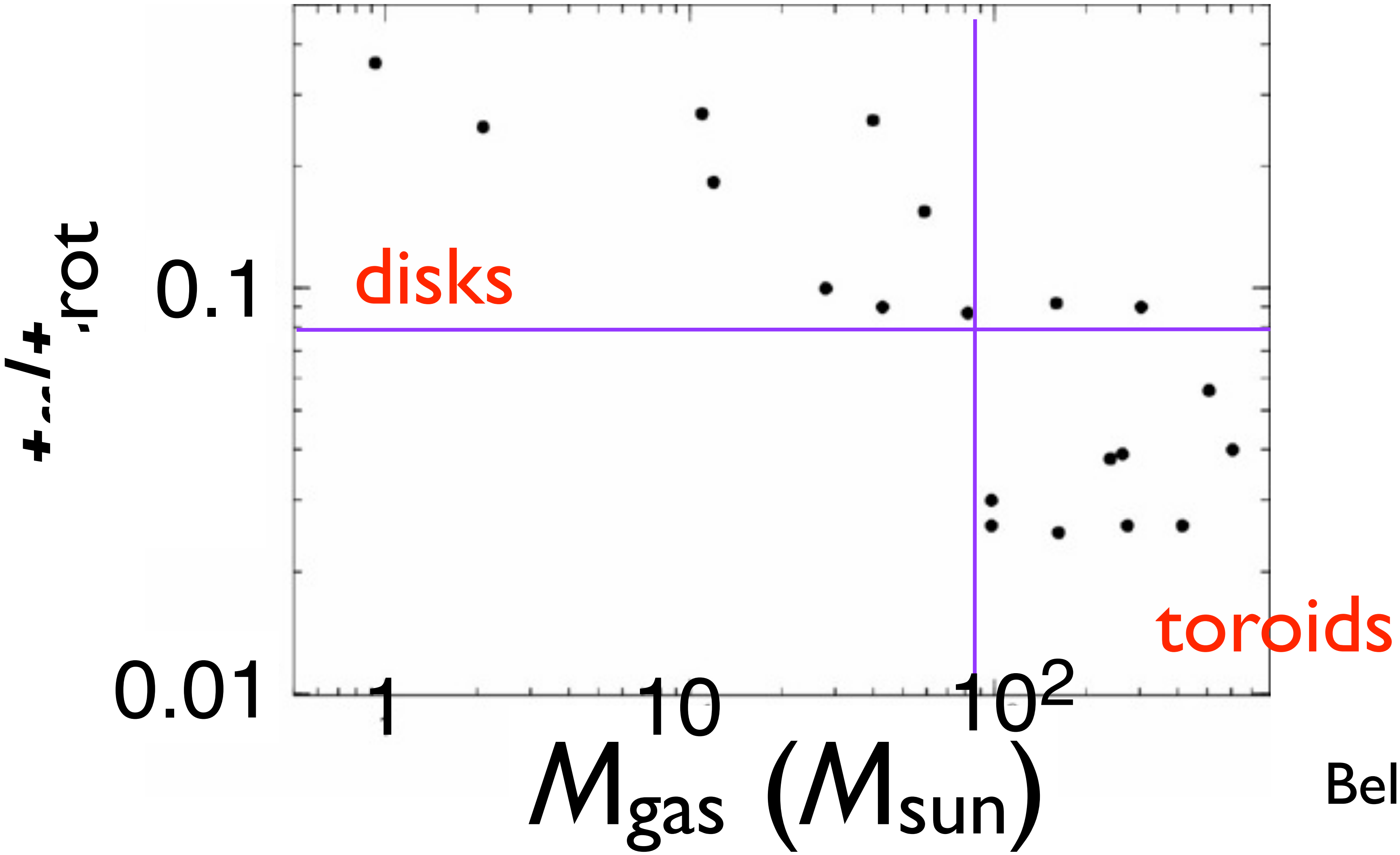
- Mass < a few 10 M_{sun}
- Radius ~ 1000 AU
- $L \sim 10^4 L_{sun}$ → B (proto)stars
- Large t_{ff}/t_{rot}

→ Equilibrium, circumstellar structures

Toroids

- Mass > 100 M_{sun}
- Radius ~ 10000 AU
- $L > 10^5 L_{sun}$ → O (proto)stars
- Small t_{ff}/t_{rot}

→ Eon-equilibrium, circum-cluster structures



Beltran et al. (2010)

Disks/Toroids around O/B stars

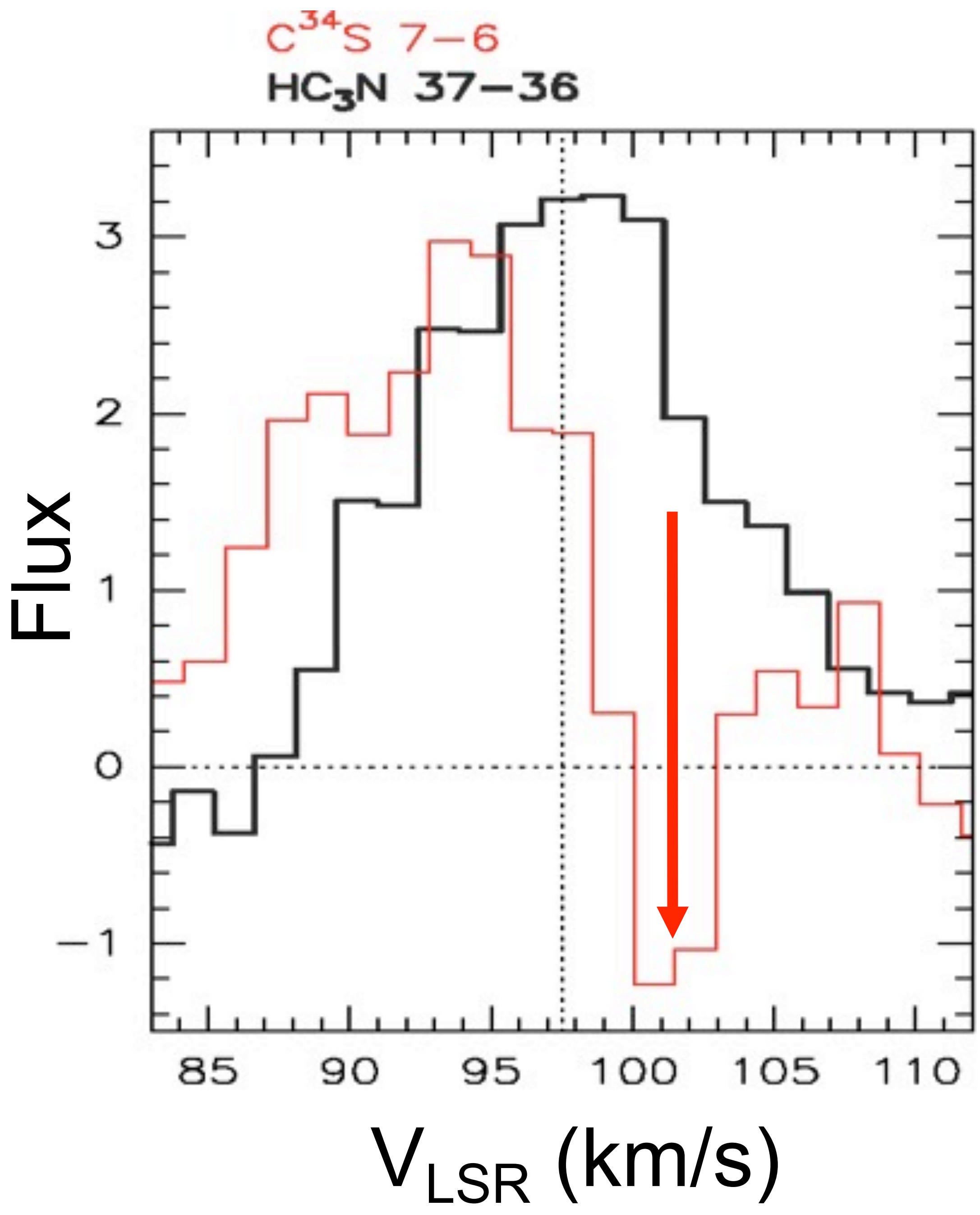
- Disks are widely found around B (proto)stars → Star formation by disk-mediated accretion, like in low-mass stars

- No disk found around O (proto)stars, while theory predicts their presence (Krumholz et al. 2009)
  - Disks might be "hidden" inside toroids
  - O-star disk lifetime might be too short to detect?
  - Photo-evaporation by O stars? (Hollenbach+ '94)
  - Tidal destruction by stellar companions (Hollenbach+ '00)

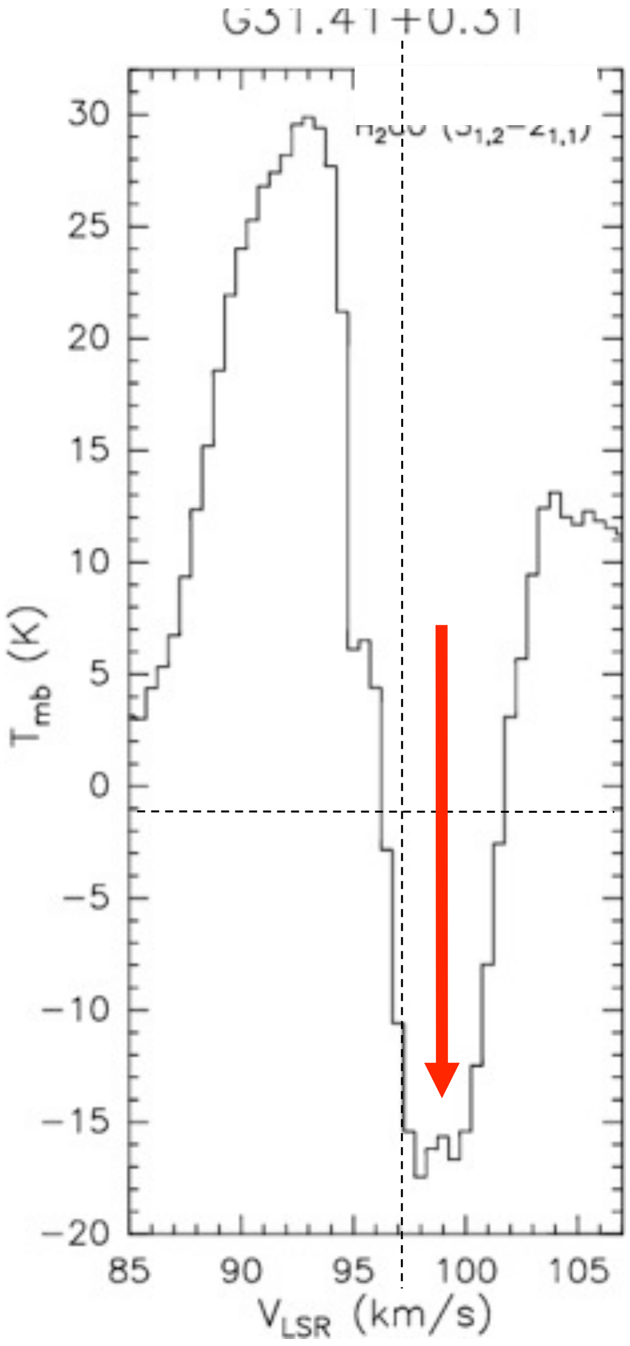
Search for Infall
in
Hot Molecular Cores

Inverse P Cyg profiles towards O-type (proto)star: Evidence for infall in HMC

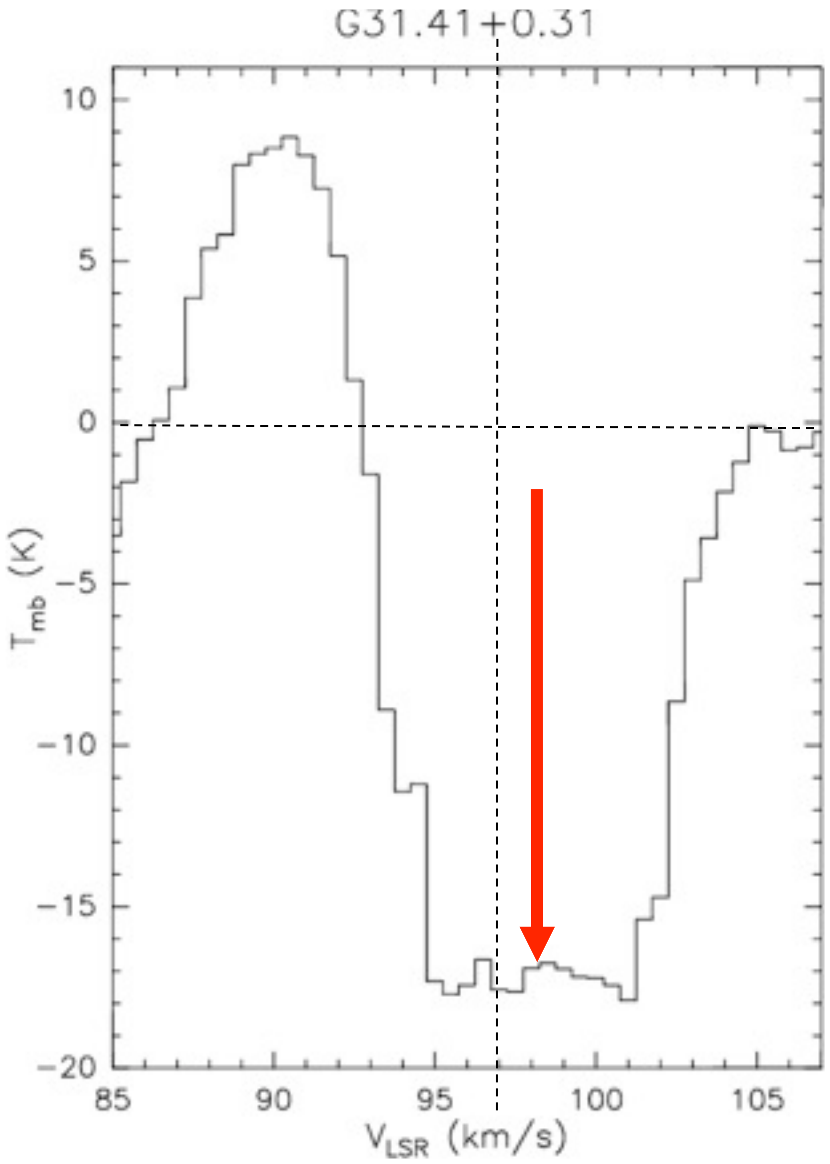
(Girart et al. 2009)



$H_2CO(3_{12}$-$2_{11})$



CN(2-1)



Growing Evidence for Infall in HMCs

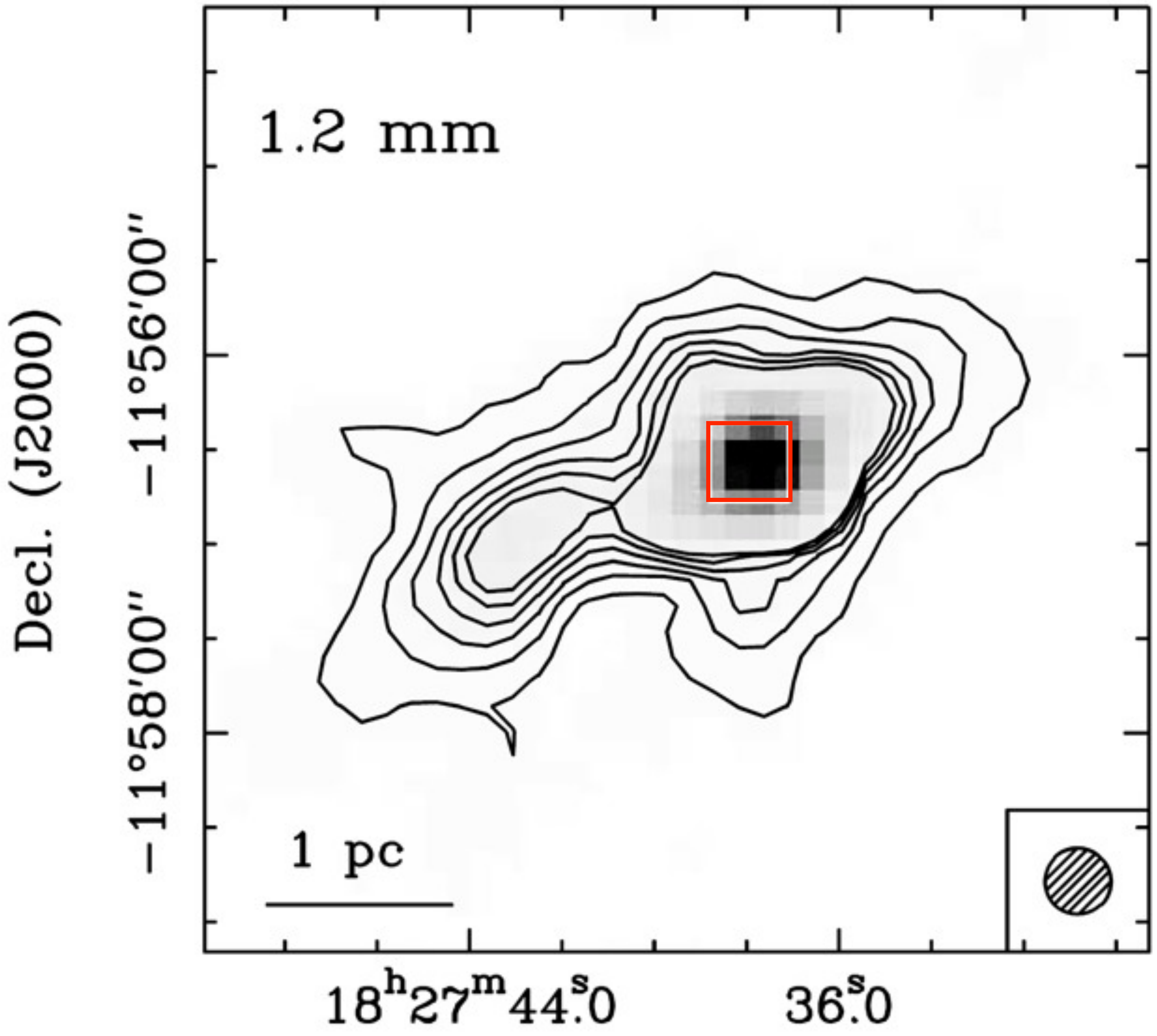
HMC	M_{gas} (M_{sun})	R (mpc)	**d*M*/d*t*** (M_{sun}/yr)
G10.62	82	20	$3\ 10^{-2}$
G24.78 A1	130	20	$4\ 10^{-4} \sim 10^{-2}$
W51 N	90	70	$5\ 10^{-2}$
W51 e2	140	10	$6\ 10^{-2}$
G31.41	490	40	$3\ 10^{-3} \sim 3\ 10^{-2}$
G19.61	100-420	30	$>3\ 10^{-2}$

Ref. Keto+88, Beltran+06, 11, Zapata+08, Zhang & Ho 97, Shi+10, Girart+09, Furuya+11

Infall, Rotation, and Jet towards B-type (proto)star

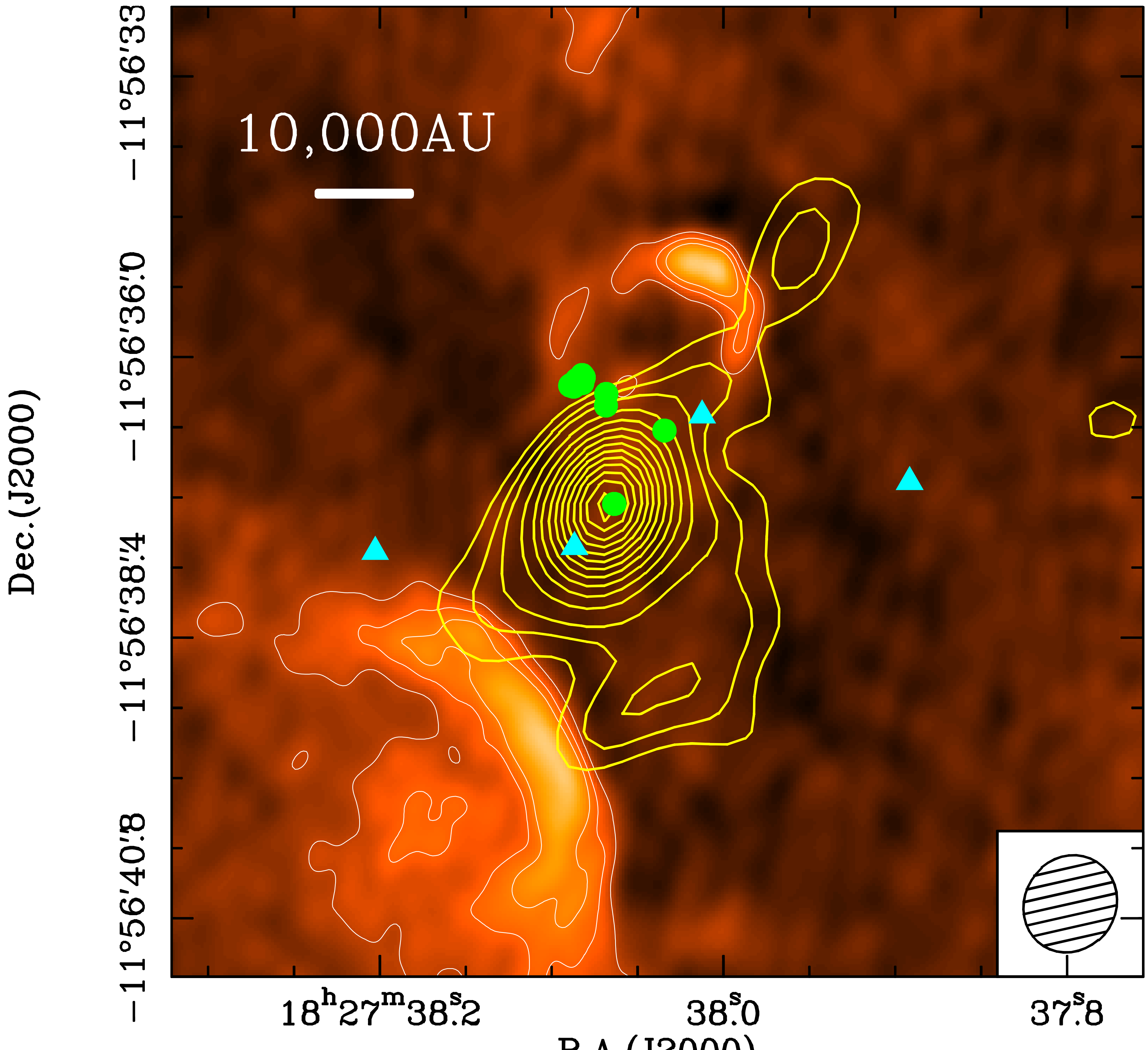
Furuya et al. 2005a, 2011

A pc-scale Clump:
1.2 mm Cont. towards G19.61-0.23



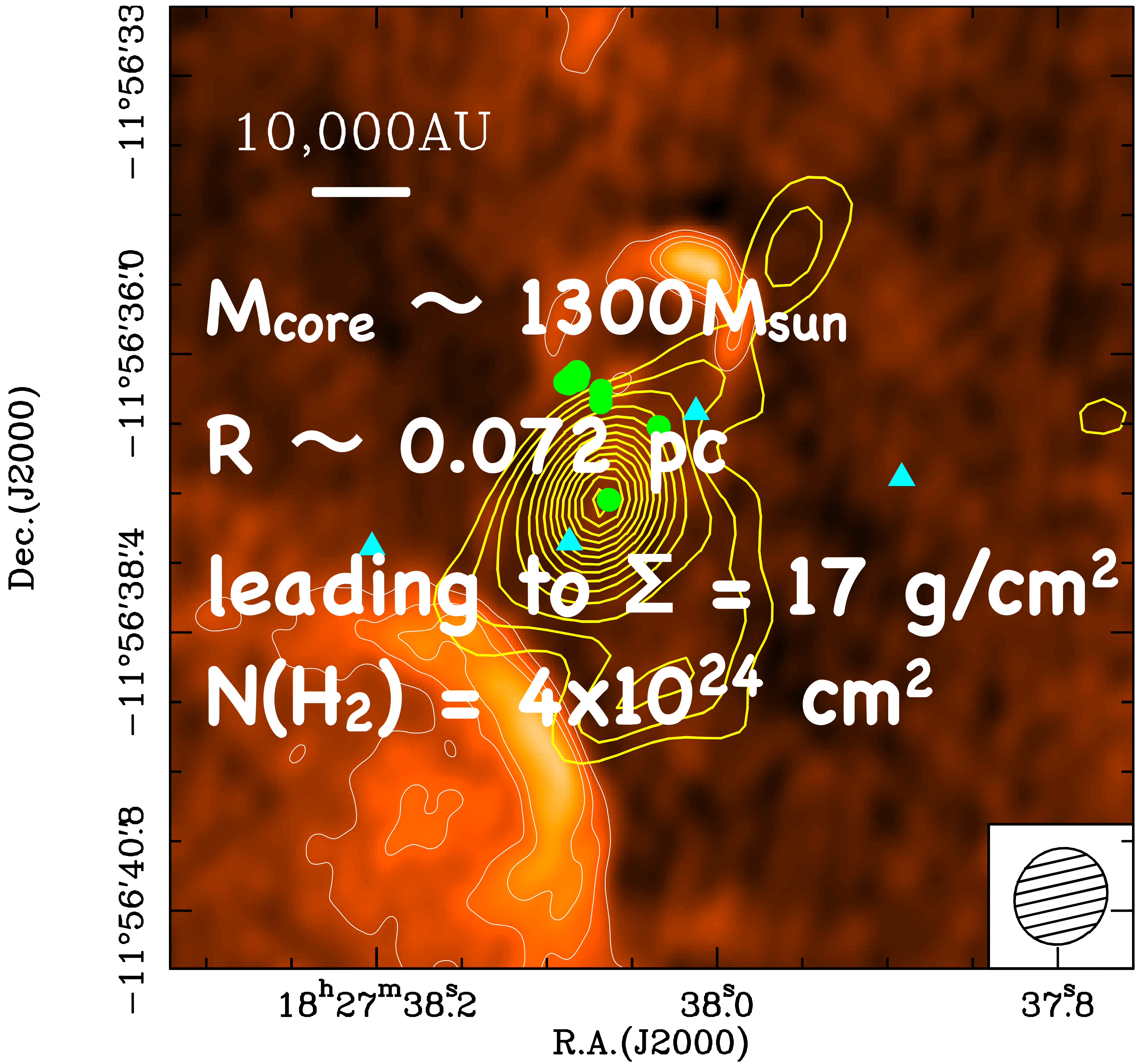
Clump mass = 2800 +/- 100 M_{sun};T_d = 42 K; Size = 4.1 x 1.7 pc (Furuya et al. 2005a)

Image: 1.3 cm cont. ● : OH maser ▲ : H_2O maser



Yellow Contour: 890 μm Continuum

Image: 1.3 cm cont. ● : OH maser ▲ : H_2O maser



$M_{core} \sim 1300 M_{sun}$

$R \sim 0.072$ pc

leading to $\Sigma = 17$ g/cm^2

$N(H_2) = 4 \times 10^{24}$ cm^2

Yellow Contour: 890 µm Continuum

nature

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LETTERS

A minimum column density of 1 g cm^{-2} for massive star formation

Mark R. Krumholz[1,2] & Christopher F. McKee[3]

Massive stars are very rare, but their extreme luminosities make them both the only type of young star we can observe in distant galaxies and the dominant energy sources in the Universe today. They form rarely because efficient radiative cooling keeps most star-forming gas clouds close to isothermal as they collapse, and this favours fragmentation into stars of one solar mass or lower[1–3]. Heating of a cloud by accreting low-mass stars within it can prevent fragmentation and allow formation of massive stars[4,5], but the necessary properties for a cloud to form massive stars—and therefore where massive stars form in a galaxy—have not yet been determined. Here we show that only clouds with column densities of at least 1 g cm^{-2} can avoid fragmentation and form massive stars. This threshold, and the environmental variation of the stellar initial mass function that it implies, naturally explain the characteristic column densities associated with massive star clusters[6–9] and the difference between the radial profiles of Hα and ultraviolet emission in galactic disks[10,11]. The existence of a threshold also implies that the initial mass function should show detectable variation with environment within the Galaxy, that the characteristic

effective adiabatic index $\gamma \approx 1.4$ throughout its volume. As even $\gamma \approx 1.1$–1.2 is sufficient to suppress fragmentation[5], equation (1) implicitly defines a critical light-to-mass ratio η_{halt} above which fragmentation will halt in a cloud with a given Σ, δ and T_{b}. We describe our procedure for solving this equation in the Supplementary Information.

We approximate the infrared dust opacity as $\kappa = \delta\kappa_0(\lambda_0/\lambda)^2$, where δ is a dimensionless number that we define to be unity at solar metallicity, λ is the radiation wavelength, and $\lambda_0 = 100\,\mu\mathrm{m}$. Observations in the Milky Way indicate[13,17] that, in cold regions where dust grains are coated with ice mantles, $\kappa_0 \approx 0.54\,\mathrm{cm}^2\,\mathrm{g}^{-1}$. Under Milky Way conditions the minimum temperature for interstellar gas is $T_{\mathrm{b}} \approx 10\,\mathrm{K}$, with a weak density dependence that we ignore for simplicity. In addition to the Milky Way case, we also consider $\delta = 0.25$, $T_{\mathrm{b}} = 10\,\mathrm{K}$, appropriate for a low-metallicity galaxy today, and $\delta = 0.25$, $T_{\mathrm{b}} = 15\,\mathrm{K}$, typical of a galaxy at $z \approx 6$ that has low metallicity but a temperature floor of 15 K imposed by the cosmic microwave background. Figure 1 shows the value of η_{halt} calculated for the three cases. We find that η_{halt} declines with Σ because at higher Σ a cloud of fixed mass has a smaller radiating area and remains

Interferometric Spectra towards the Hot Molecular Core

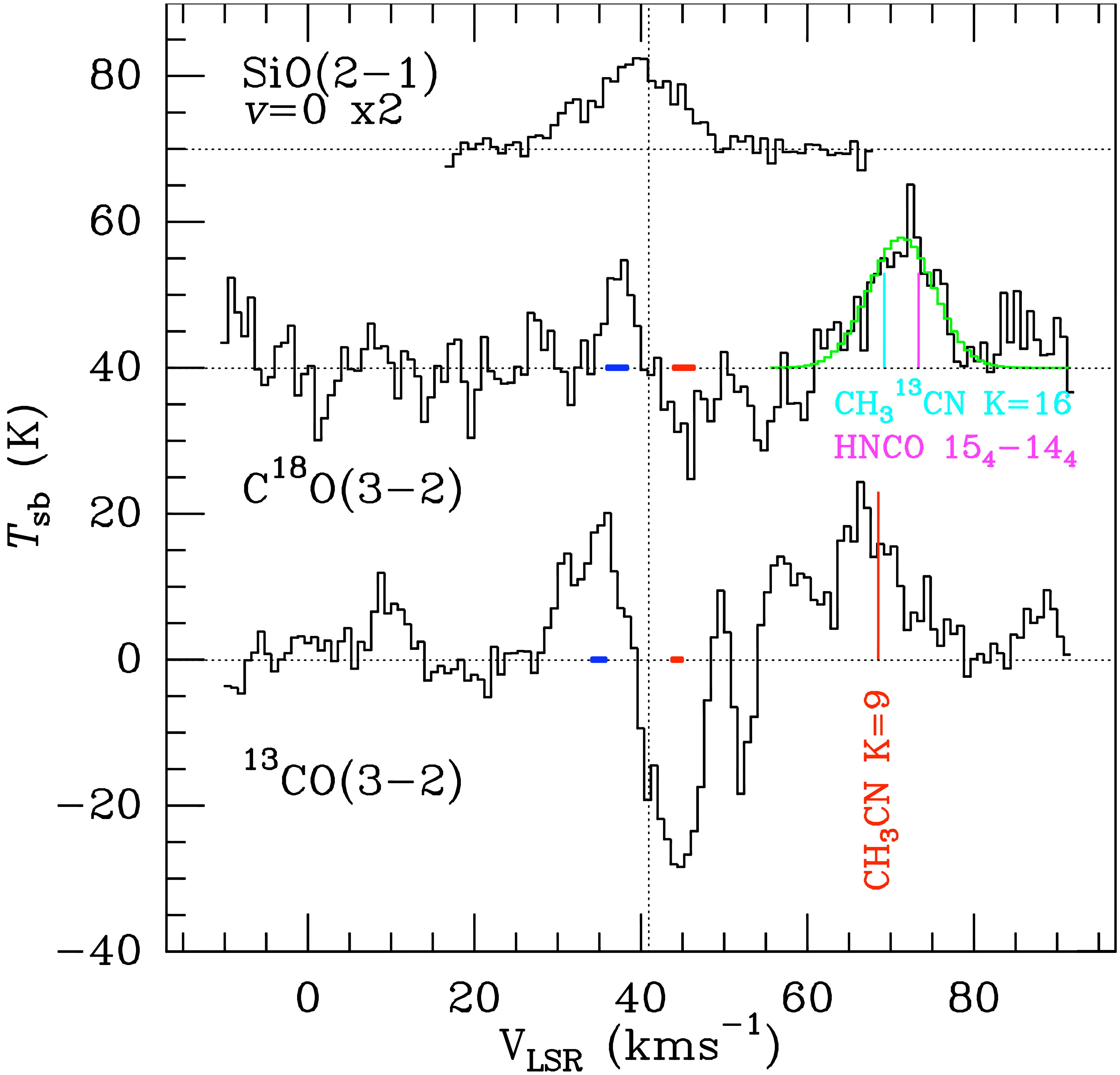
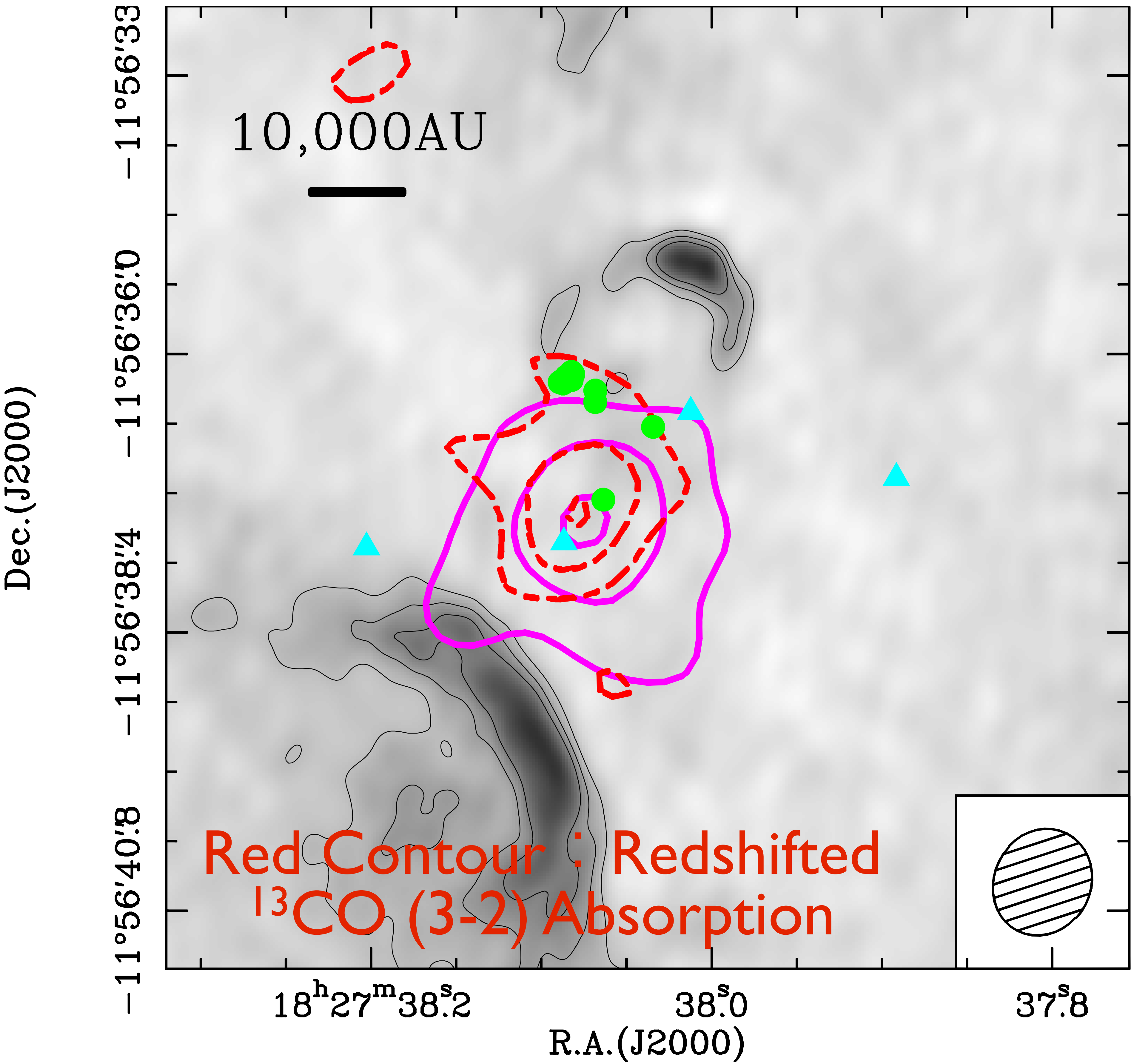


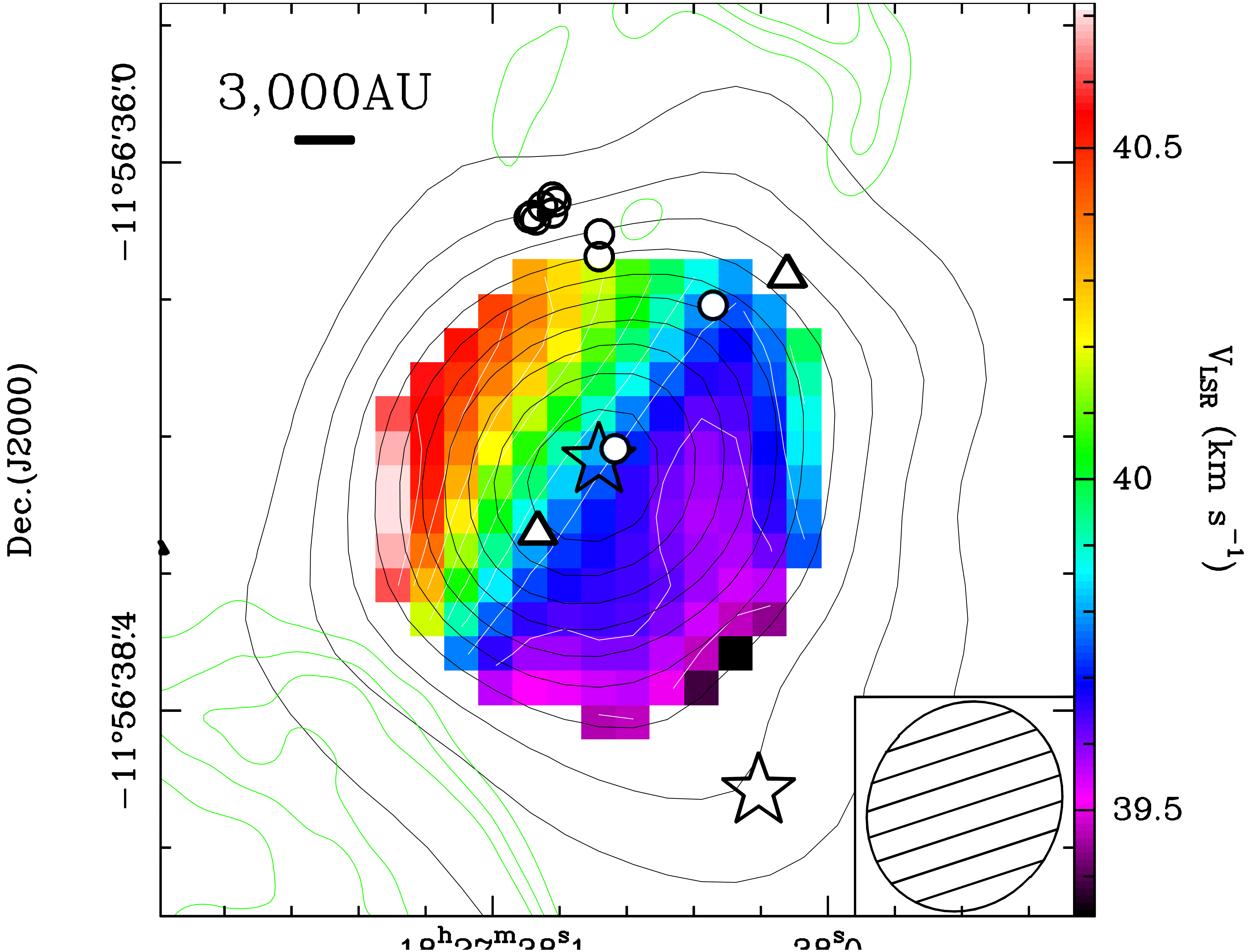
Image: 1.3 cm cont. ● : OH maser ▲ : H_2O maser



Red Contour : Redshifted ^{13}CO (3-2) Absorption

Magenta Contour: $CH_3{}^{13}CN$ (18-17) K=2

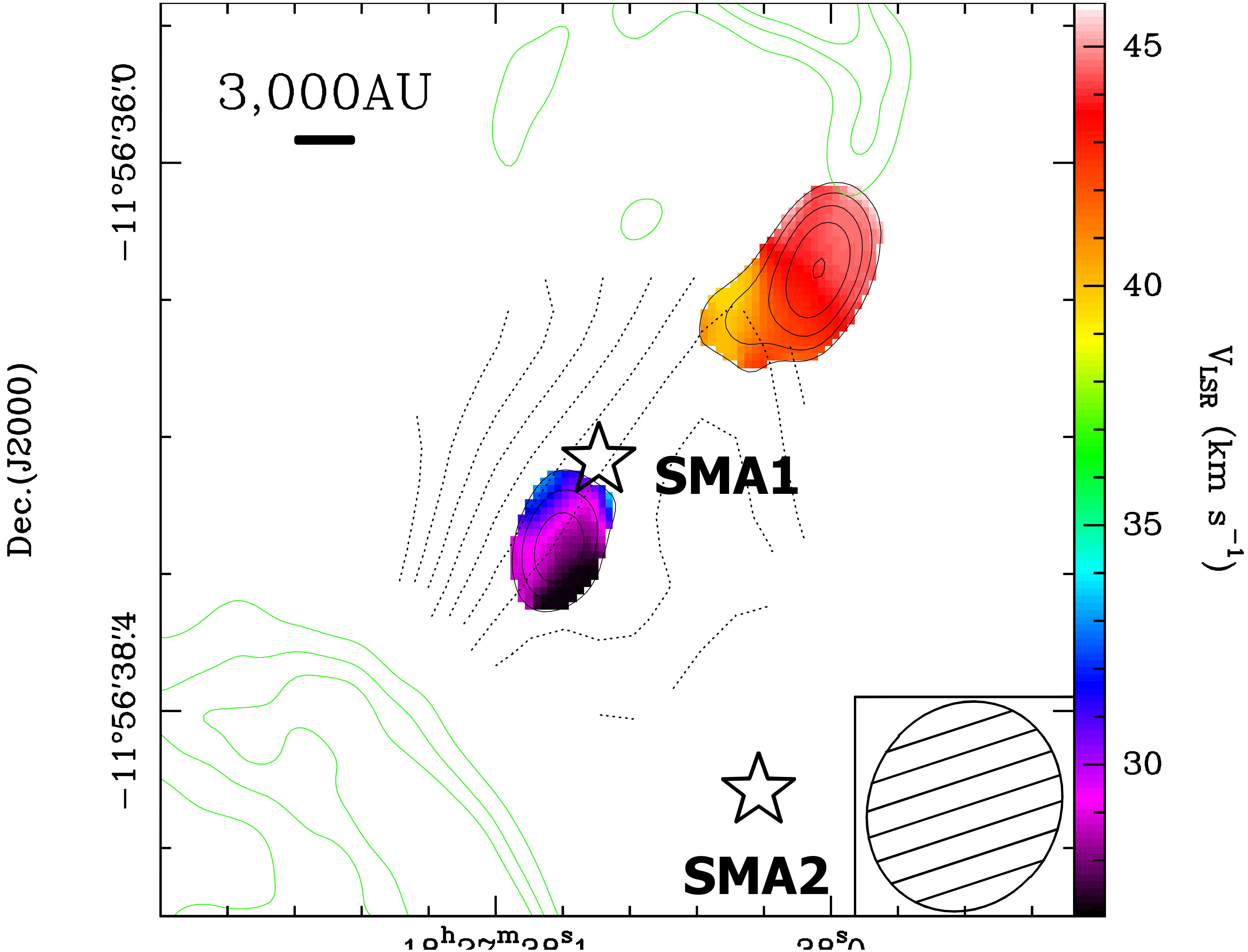
Green contour：1.3cm cont.　△：OH maser　○：H_2O maser



Color: Velocity field obtained from CH_3CN (18-17) K=7 and $CH_3{}^{13}CN$ (18-17) K=5

Dashed thin contour: Total integrated intensity

Green contour：1.3cm cont.



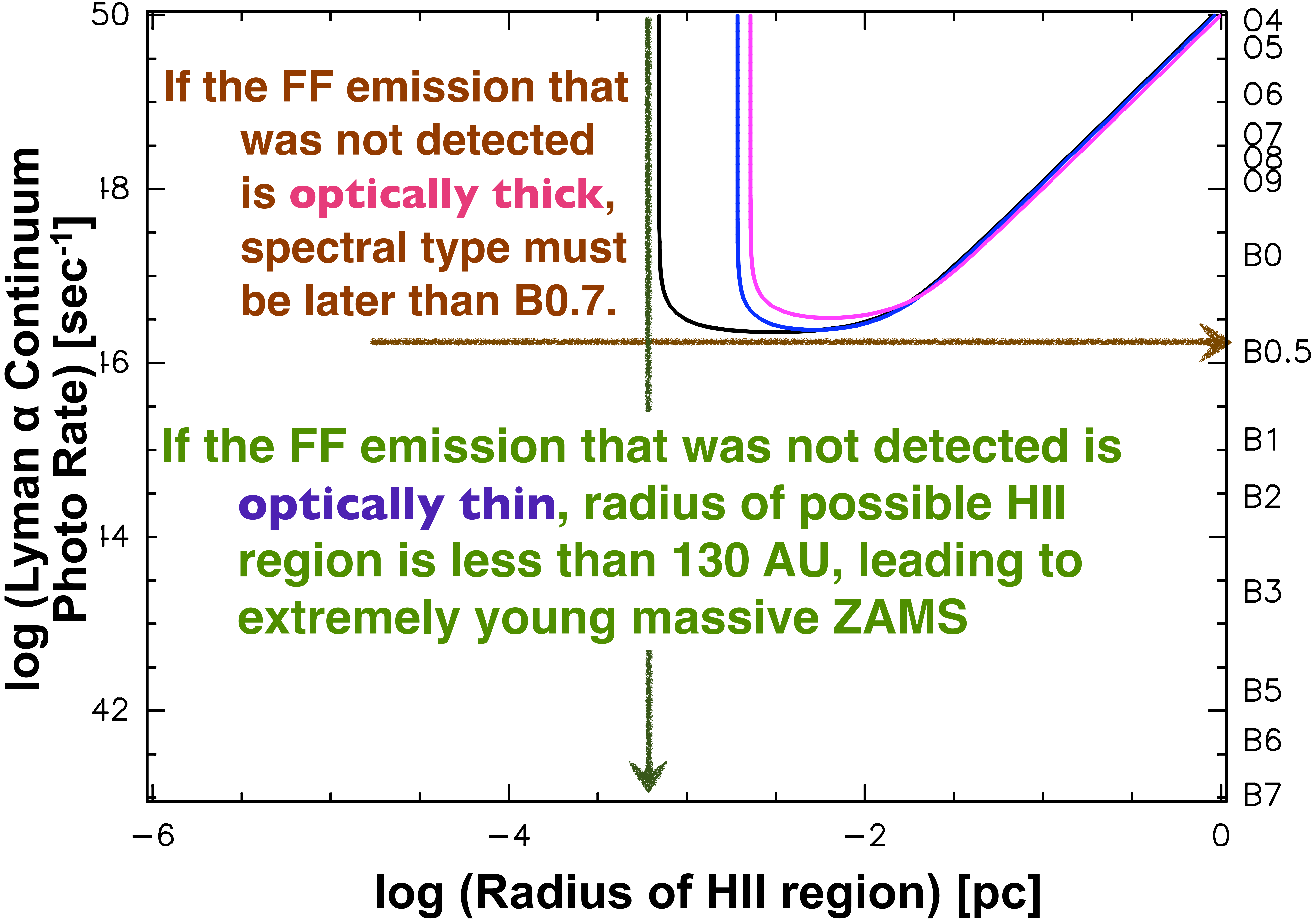
Color： Velocity filed of H_2O maser spots

Dashed contour：CH_3CN velocity field

☆：890 μm cont. peak

Assuming that central (proto)star is a single star, what does the negative detection of free-free emission tell us?

Furuya et al. 2011



If the FF emission that was not detected is **optically thick**, spectral type must be later than B0.7.

If the FF emission that was not detected is **optically thin**, radius of possible HII region is less than 130 AU, leading to extremely young massive ZAMS

Summary: G19.61 SMA1

- Detected gas infall, rotation of HMC, and jet perpendicular to the rotation axis, the toroid is unstable
- The HMC shows extremely high column density of $\Sigma \sim 17$ g/cm^{-2} , corresponding to $N(H_2)$ ~4e24 cm^{-2}
- Negative detection of radio free-feee emission suggest that the putative (proto)star is either B0.7 or young massive YSO ($R_{HII} < 130$ AU).
- Considering all the results, the rotating gas is highly likely "circumcluster" toroid rather than "circumstellar" one.

Furuya et al. 2011

Fragmentation Process
and
Core Mass Function

Core Mass Function

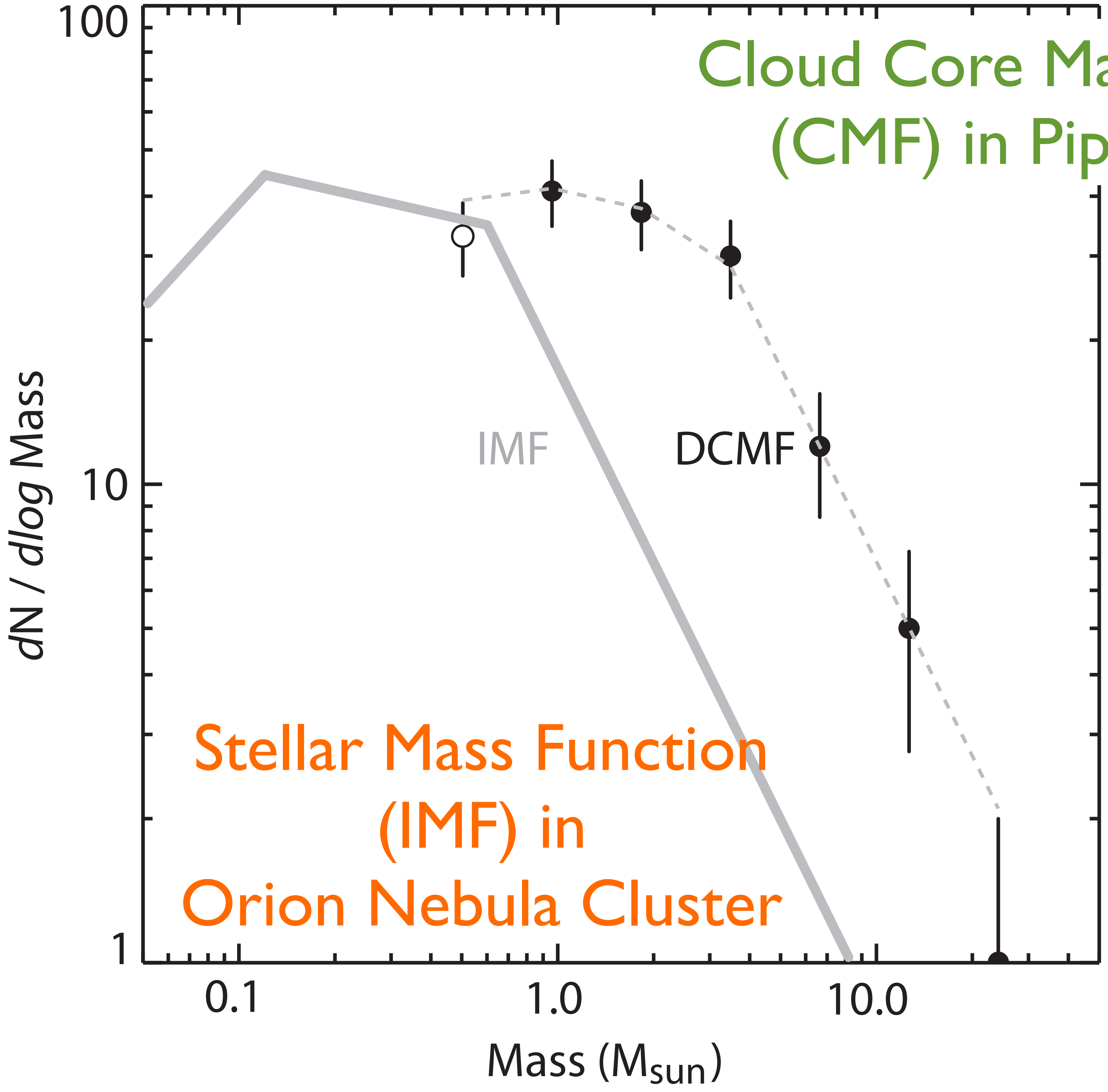
- Almost all star forming regions in solar neighborhood, e.g., Taurus, Perseus, Orion, Ophiuchus, Pipe, Chameleon, Serpens, S140, ... show **very similar** slope of,

$$\boxed{\frac{\Delta N}{\Delta M}_{\text{cloud core}} \propto M^{-2.3\sim-2.5}}$$

- The resemblance between CMFs (and with IMF) may be telling us that CMF is set in fragmentation process of (giant) molecular clouds

Comparison of CMF and IMF

(Pipe Nebular; CMF derived from NIR extinction)

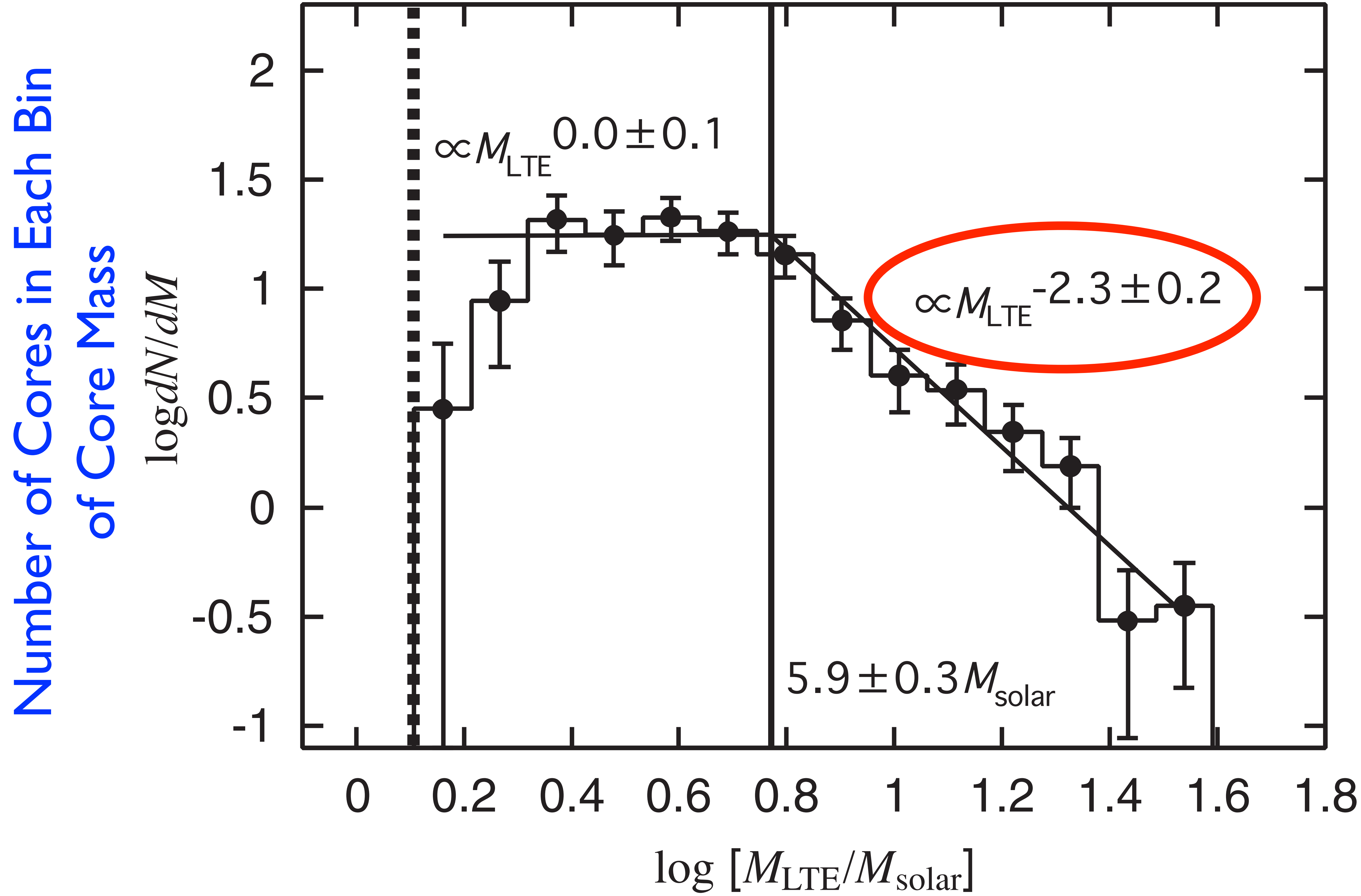


Cloud Core Mass Function (CMF) in Pipe Nebula

Stellar Mass Function (IMF) in Orion Nebula Cluster

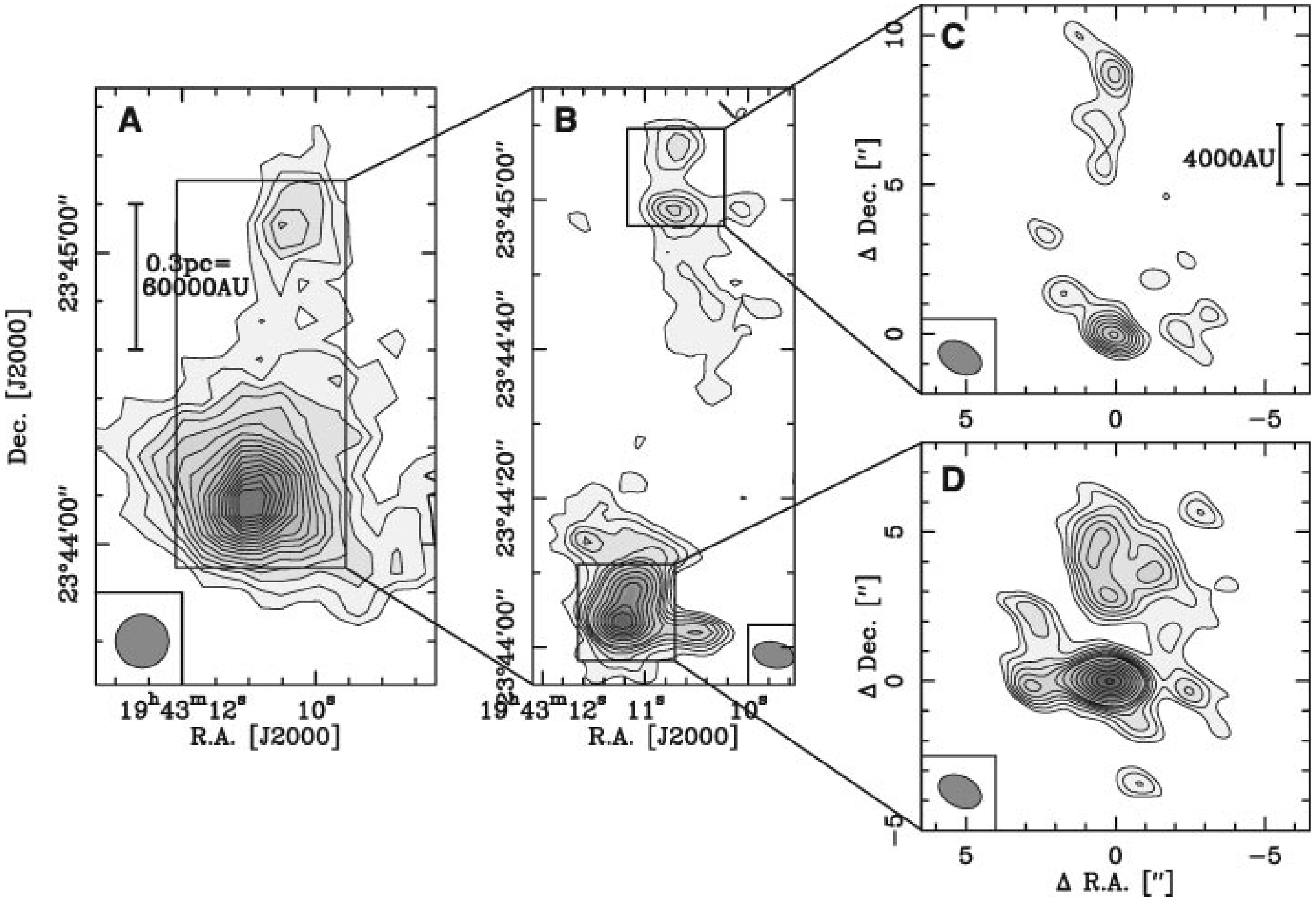
©Alves et al. 2007

Core Mass Function (Orion B; $H^{13}CO^+$ J=1-0)

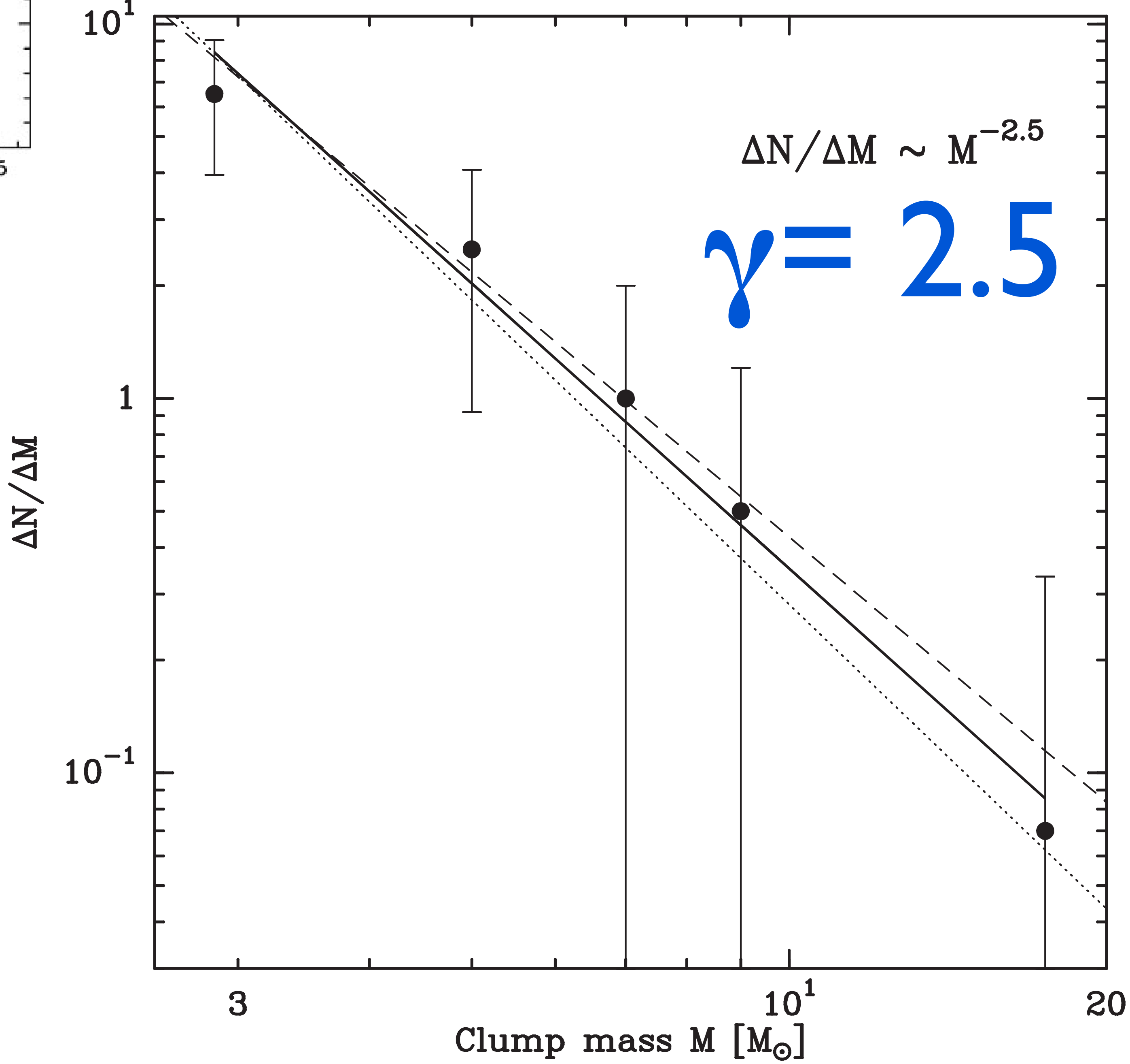


©Ikeda et al. 2009

Beuther & Shilke 2003



1.2 mm thermal dust continuum
in
IRAS 19410+2336



$\gamma = 2.5$

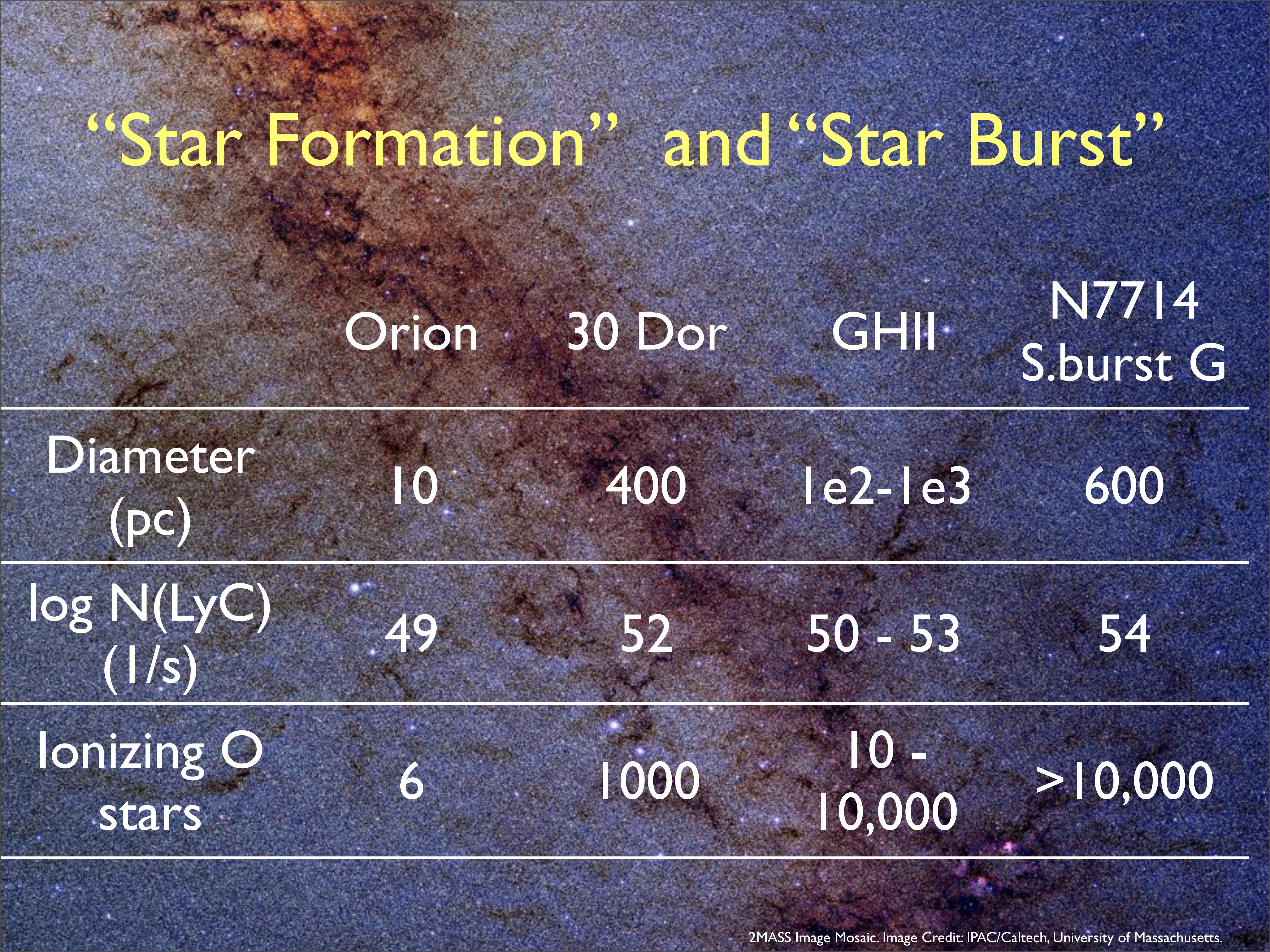
Core Mass Function

- Almost all star forming regions in solar neighborhood, e.g., Taurus, Perseus, Orion, Ophiuchus, Pipe, Chameleon, Serpens, S140, ... show **very similar** slope of,

$$\boxed{\frac{\Delta N}{\Delta M}_{\mathrm{cloud\ \ core}} \propto M^{-2.3\sim-2.5}}$$

- The resemblance between CMFs (and with IMF) may be telling us that CMF is set in fragmentation process of (giant) molecular clouds
- ALMA will resolve cloud structure scales down to 100 AU at d = 10 kpc, and would detect "lighter" cores.

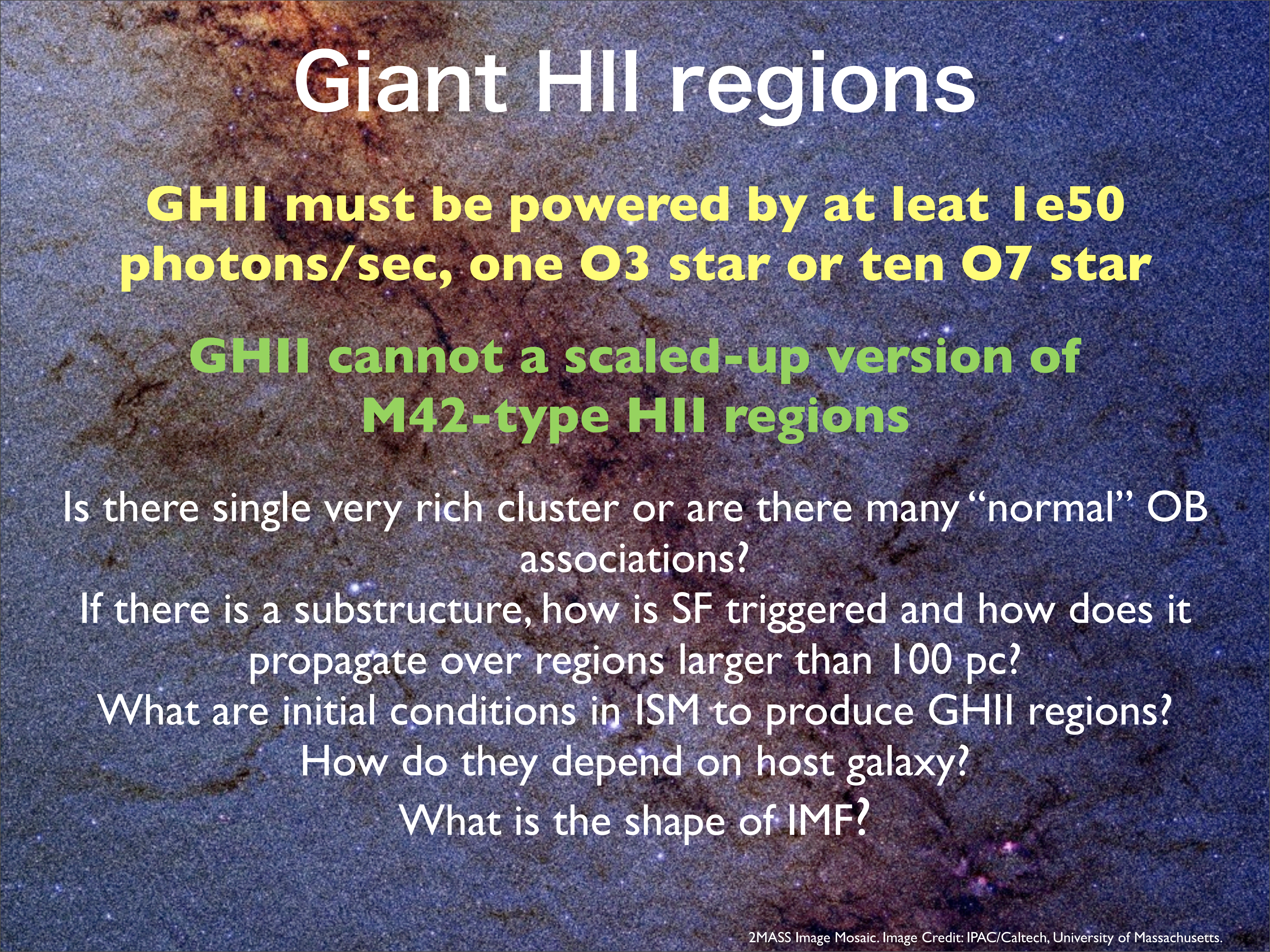
“Star Formation” and “Star Burst”



	Orion	30 Dor	GHII	N7714 S.burst G
Diameter (pc)	10	400	1e2-1e3	600
log N(LyC) (1/s)	49	52	50 - 53	54
Ionizing O stars	6	1000	10 - 10,000	>10,000

2MASS Image Mosaic. Image Credit: IPAC/Caltech, University of Massachusetts.

Giant HII regions



GHII must be powered by at leat 1e50 photons/sec, one O3 star or ten O7 star

GHII cannot a scaled-up version of M42-type HII regions

Is there single very rich cluster or are there many “normal” OB associations?
If there is a substructure, how is SF triggered and how does it propagate over regions larger than 100 pc?
What are initial conditions in ISM to produce GHII regions?
How do they depend on host galaxy?
What is the shape of IMF?

2MASS Image Mosaic. Image Credit: IPAC/Caltech, University of Massachusetts.

Keywords of Talk

- Disks and Toroids are commonly seen around young O and B stars, respectively.
- Growing evidence for gas infall in hot molecular cores
- Core mass function: a hint for stellar cluster formation
- Giant HII regions, *i.e.*, “starburst”