Why is Massive Star Formation so Unconstrained?

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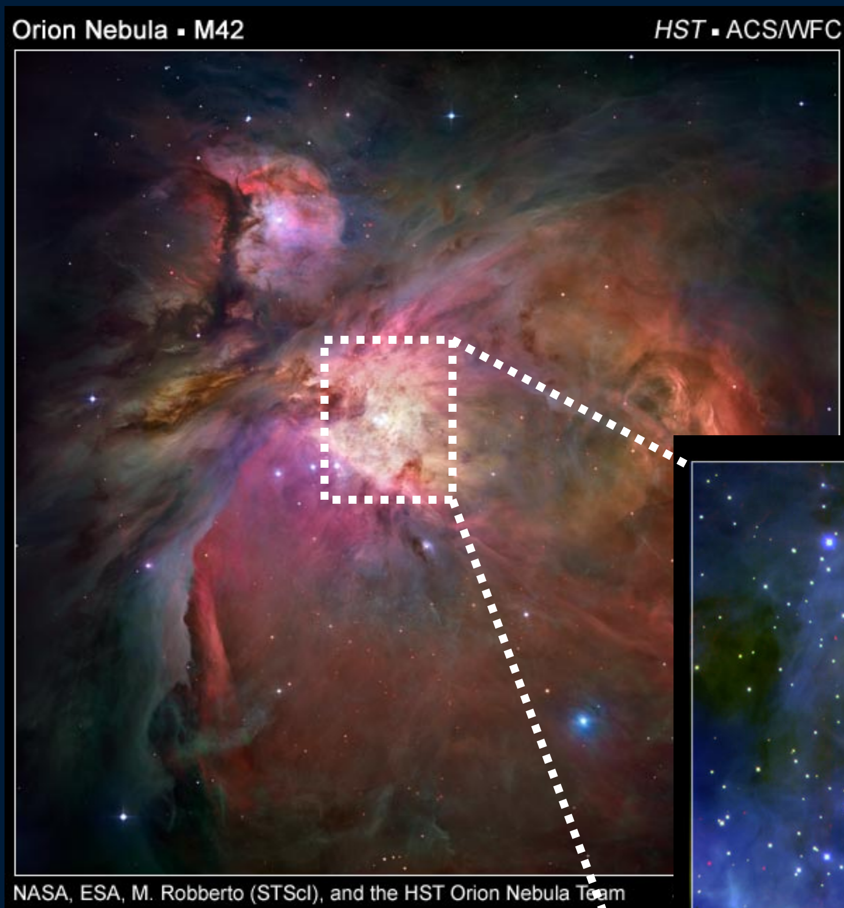
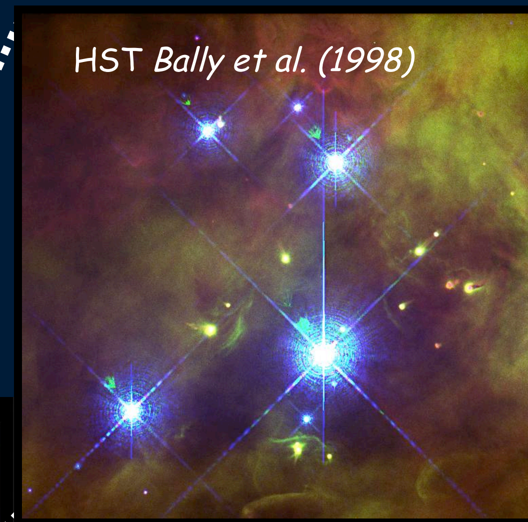
The Birth and Feedback of Massive Stars, Sept. 27, 2008

Outline: Why is Massive Star Formation so Unconstrained?

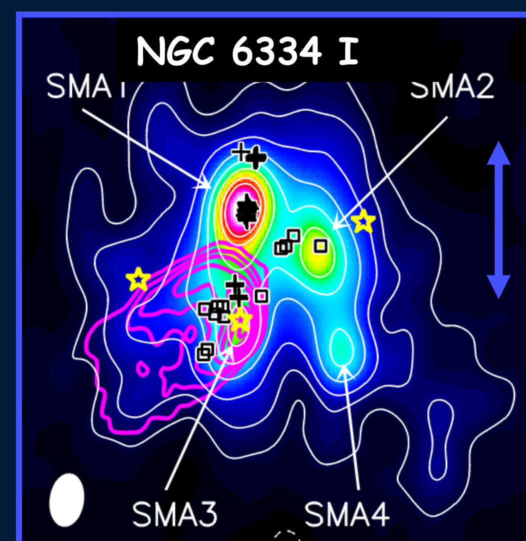
- Incredible clustered complexity
- Where's the disk? ⇨ superposition of line excitation, chemistry, complex kinematics, and optical depth
- Dynamical timescales are a tricky business
- Need larger sample…
- Looking toward the future

Orion: An Evolving Massive Cluster





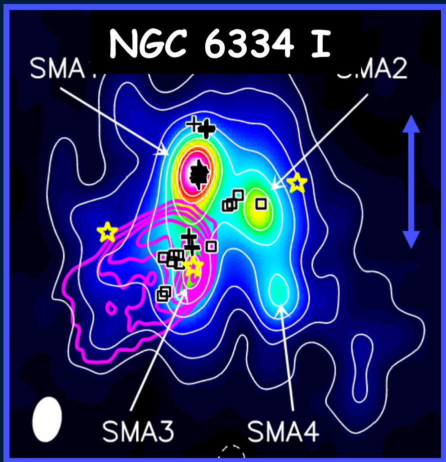
10,000 AU

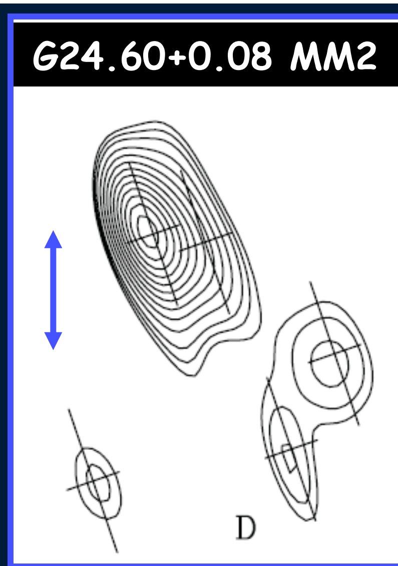


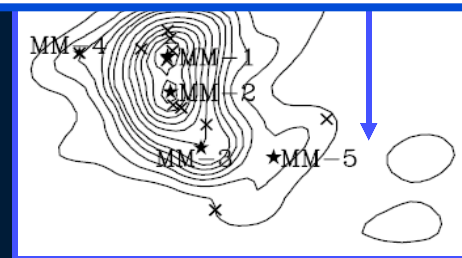
Are Trapezium-like systems the norm?

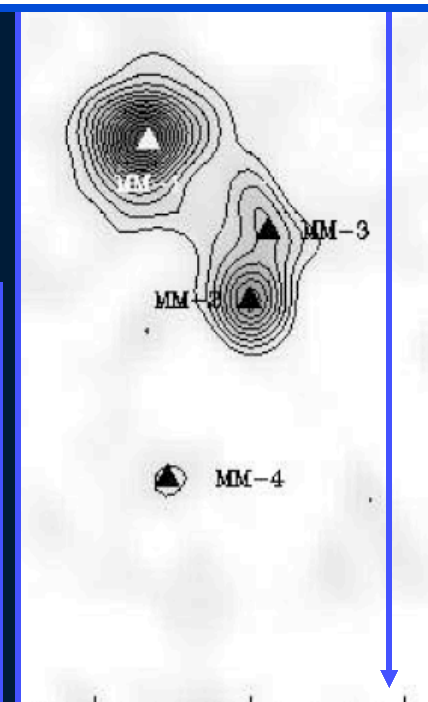
Most protoclusters show a range of evolutionary state:

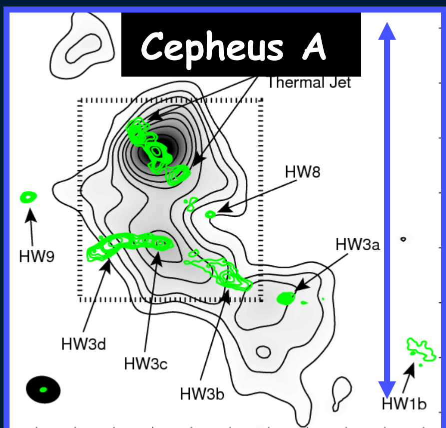
Feedback must be important

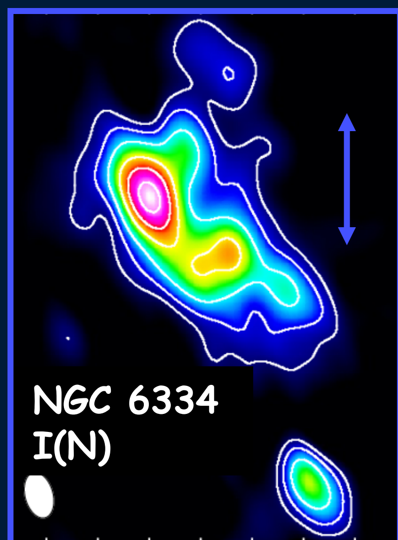


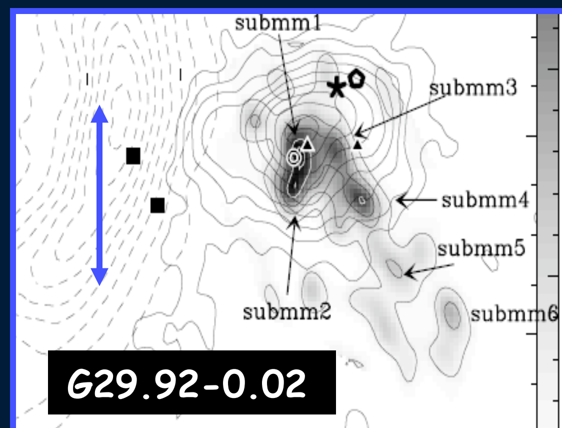


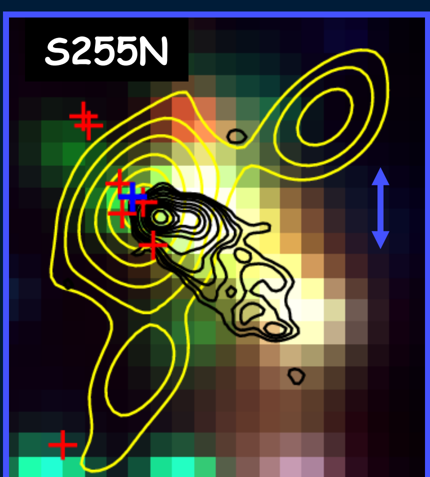


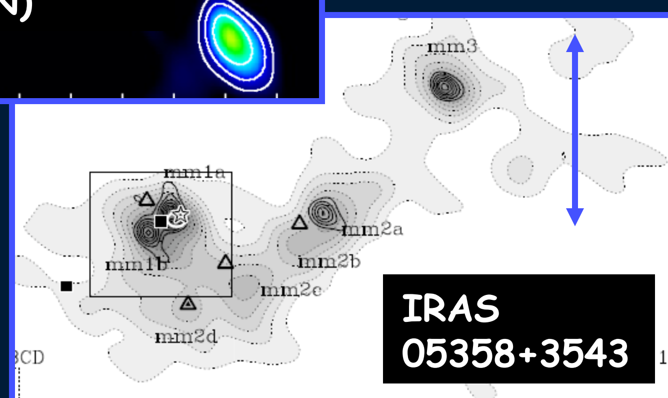


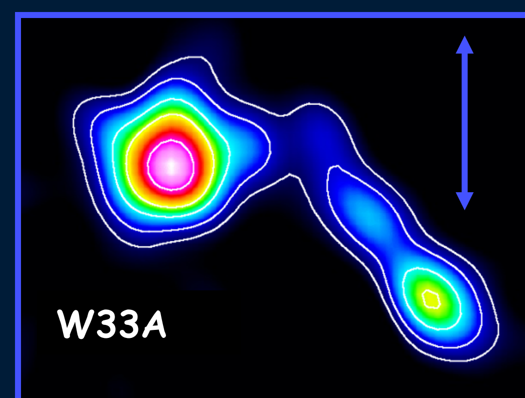












Massive Protocluster Properties

*By no means an exhaustive list…

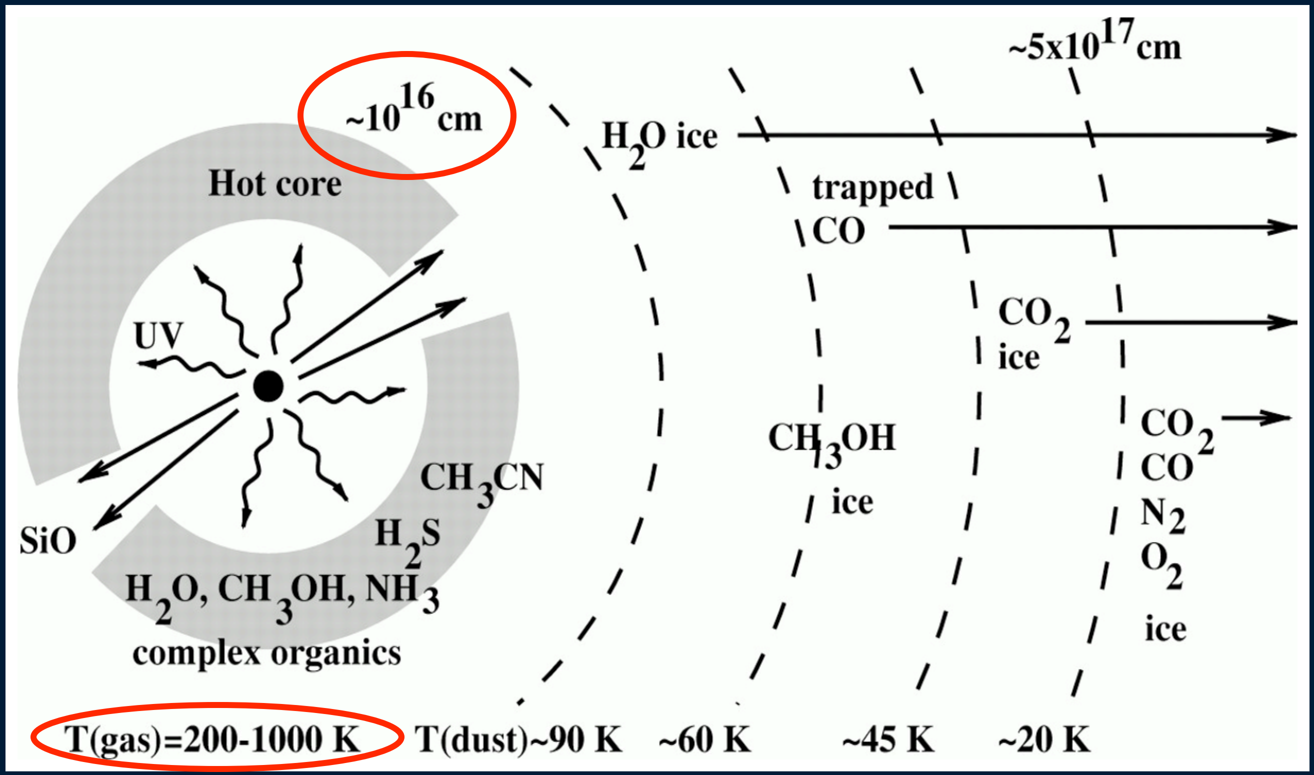
Source	Distance (kpc)	Luminosity ($L_\odot$)	Multiplicity (≥)	≈ΔVcores (km/s)	MM/Submm Reference
G29.96-0.02	6.0	10^{6}	6	4.0	(Beuther et al. 2008)
NGC 6334 I	1.7	$10^{5.4}$	4	4.0	(Hunter et al. 2006)
W3 IRS5	2.0	$10^{5.3}$	4	5.0	(Rodin et al. 2008)
W33a	4.0	10^{5}	3	only 1 with lines	(Brogan et al. in prep)
S255N	2.6	10^{5}	4	3.0	(Cyganowski et al. 2007)
Cepheus A-East	0.7	$10^{4.3}$	6	4.5	(Brogan et al. 2006)
G24.60+0.08	6.5	10^{4}	5	?	(Rathborne et al. 2007)
IRAS 05358+3543	1.8	$10^{3.8}$	4	?	(Beuther et al. 2008)
AFGL 5142	1.8	$10^{3.4}$	5	2.5	(Zhang et al. 2007)
~~NGC 6334 I(N)~~	~~1.7~~	~~$10^{3.4}$~~	~~6~~	~~2.5~~	~~(Brogan et al. in prep)~~

If you use Δv= 4 km/s, and a separation of 4000 AU and derive "Keplerian" centripetal mass ⇨ 35 $M_\odot$ } Sound familiar?

- Typical crossing time ~ 10^4 years ≤ Typical outflow timescales ~10^5 years
- Does this velocity dispersion prevent monolithic collapse?

"Hot Cores" around Massive Protostars

Van Dishoeck & Blake (1998)



1″ = 10^{16} cm (1,000 AU) at 1kpc

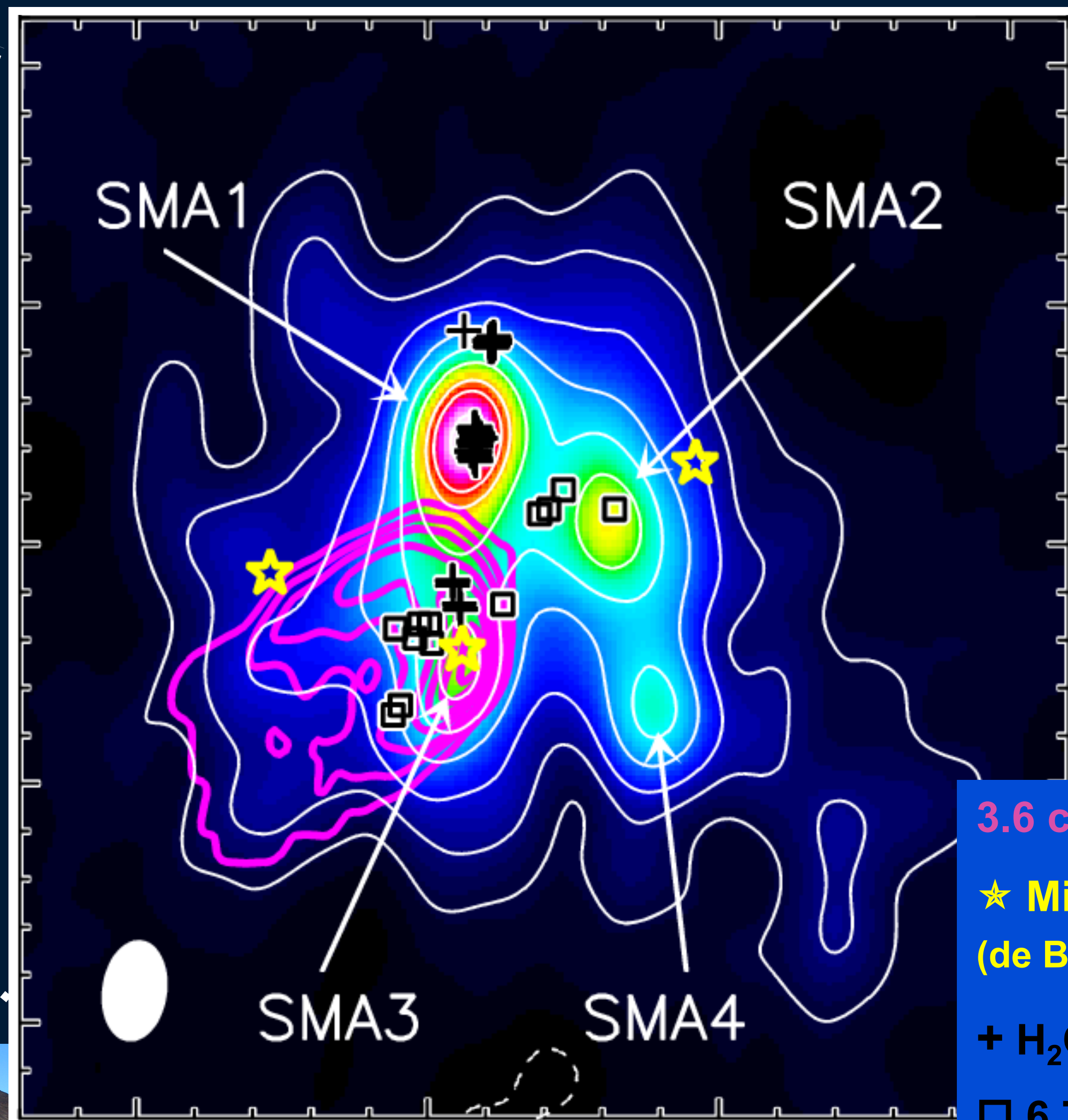
- Dust grain ice mantles melt
- High temperature combined with newly liberated atoms and molecules drive copious organic chemistry
- Can only be observed at small spatial scales (beam dilution)

NGC6334I: 1.3mm SMA Continuum

D= 1.7 kpc

L = $10^{5.4}$ $L_{\odot}$

SCUBA
850 μm



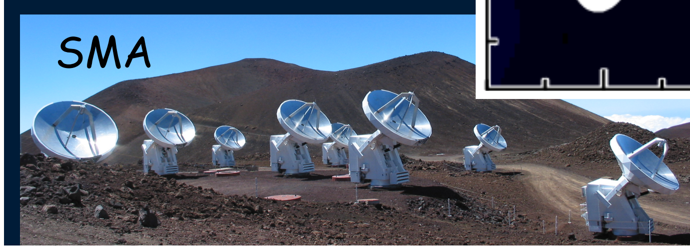
10,000 AU

3.6 cm continuum

☆ Mid-IR sources
(de Buizer et al. 2002)

+ H_2O masers

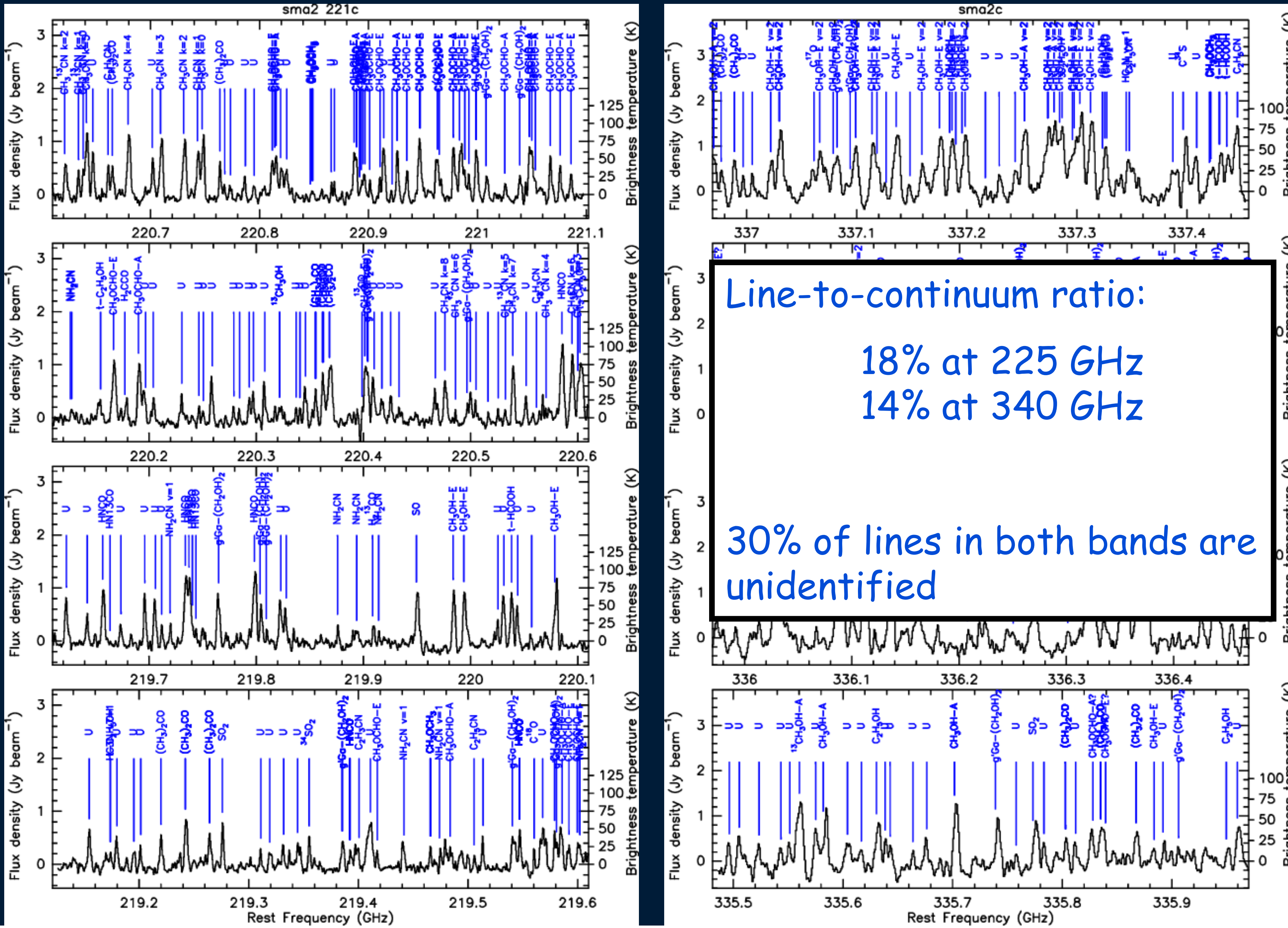
☐ 6.7 GHz methanol masers (Norris et al. 1993)



Hunter, Brogan, et al. (2006)

Now That's a Hot Core!

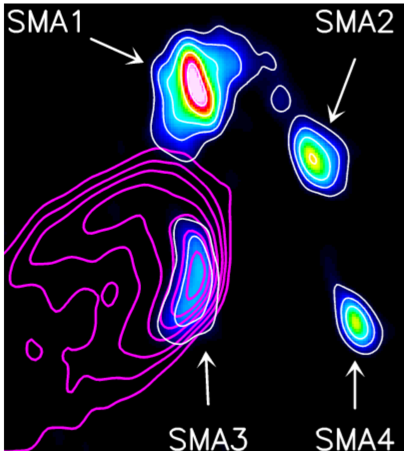
Brogan, Hunter, Indebetouw, in prep.;



Line-to-continuum ratio:

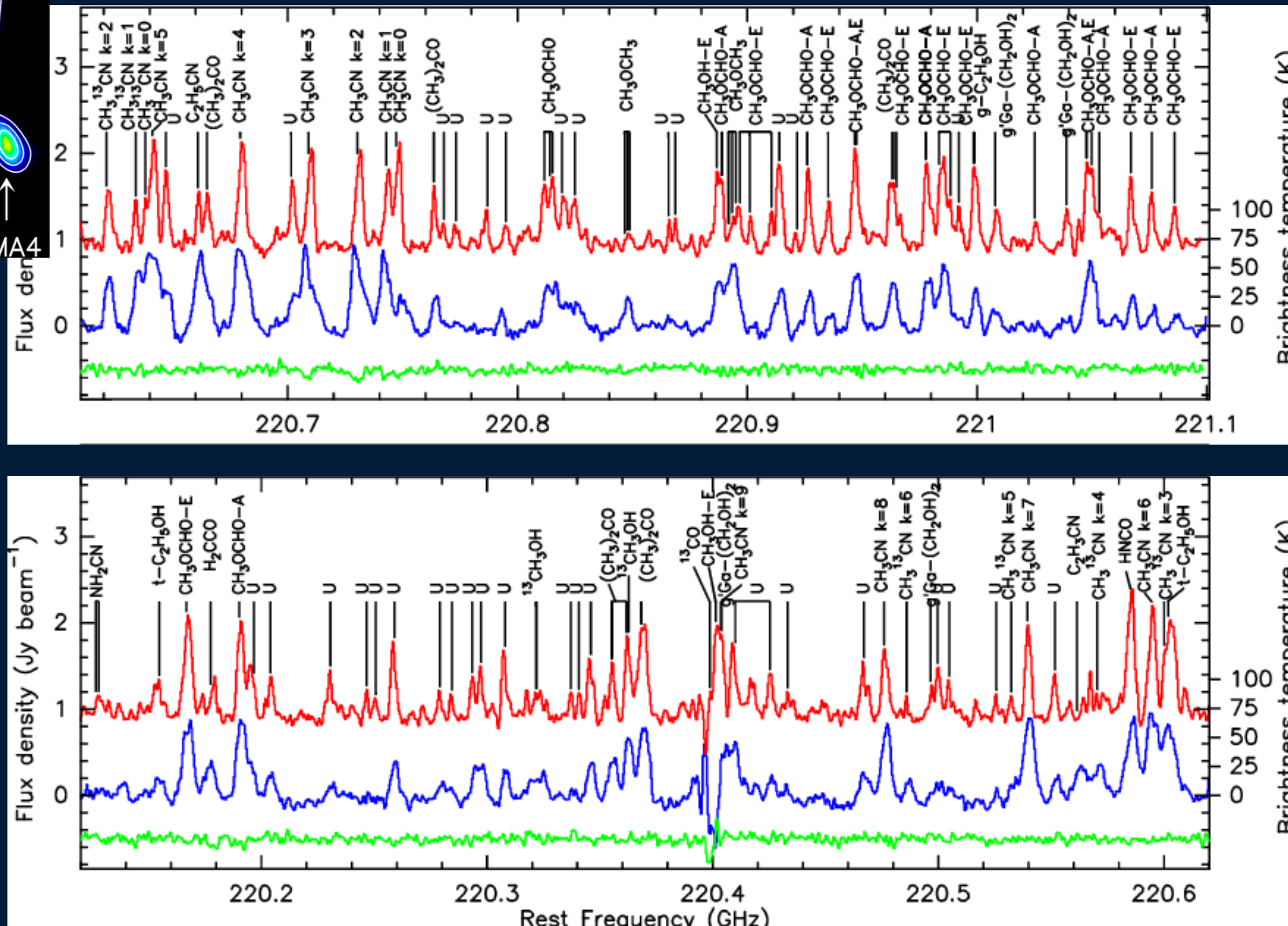
18% at 225 GHz
14% at 340 GHz

30% of lines in both bands are unidentified



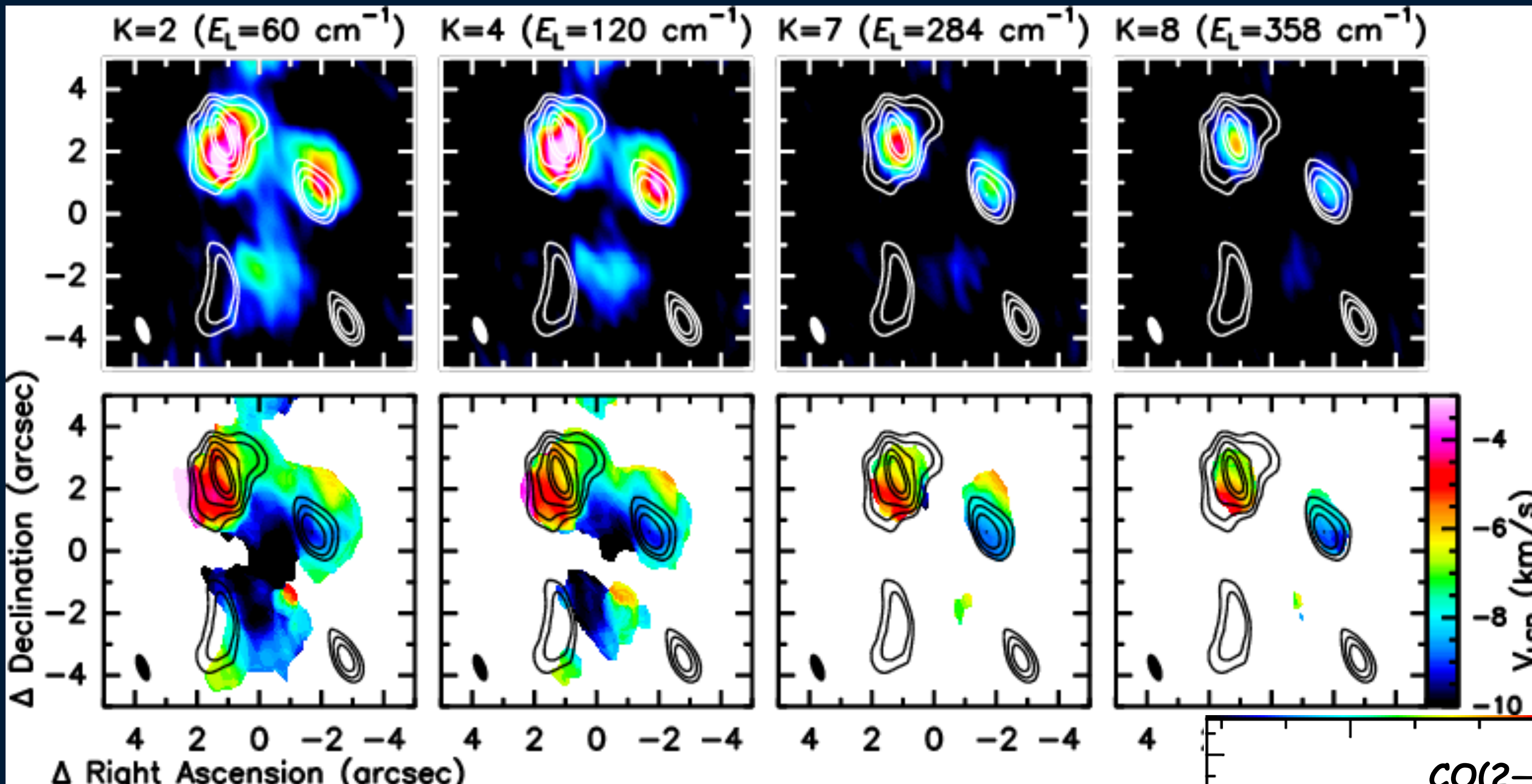
1.3 mm

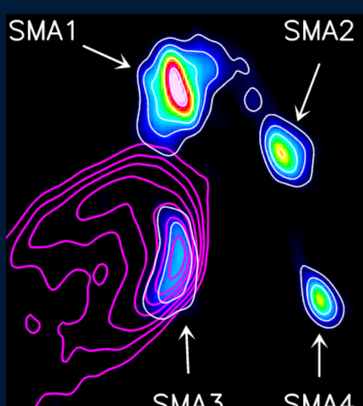
Line Comparison: SMA1 SMA2 SMA4



- Remarkable chemical variation between SMA1 and SMA2, only 4000 AU apart
- Why is SMA 4 line-free? Is it in a pre-hot core stage?

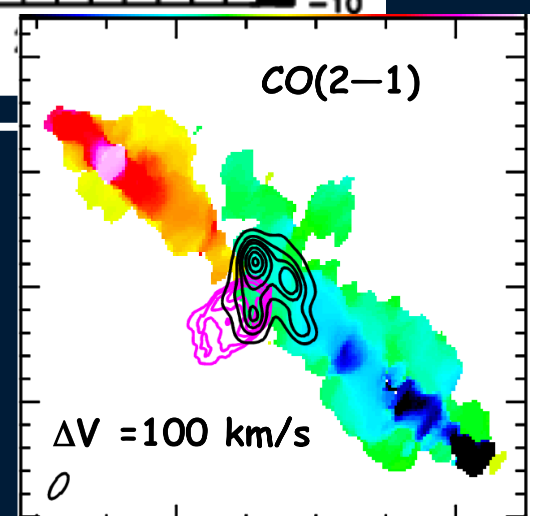
Methyl Cyanide (CH_3CN): The Perfect Disk Tracer… Right?

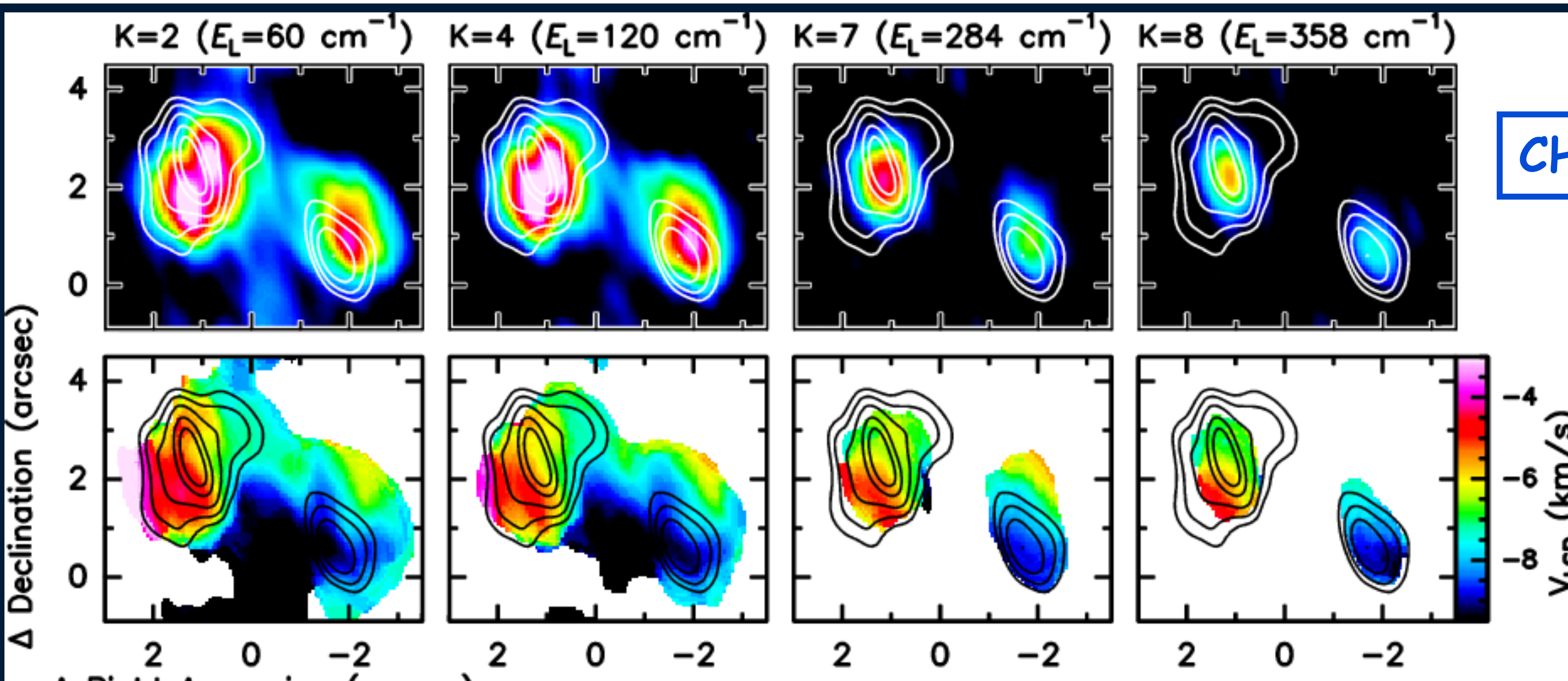




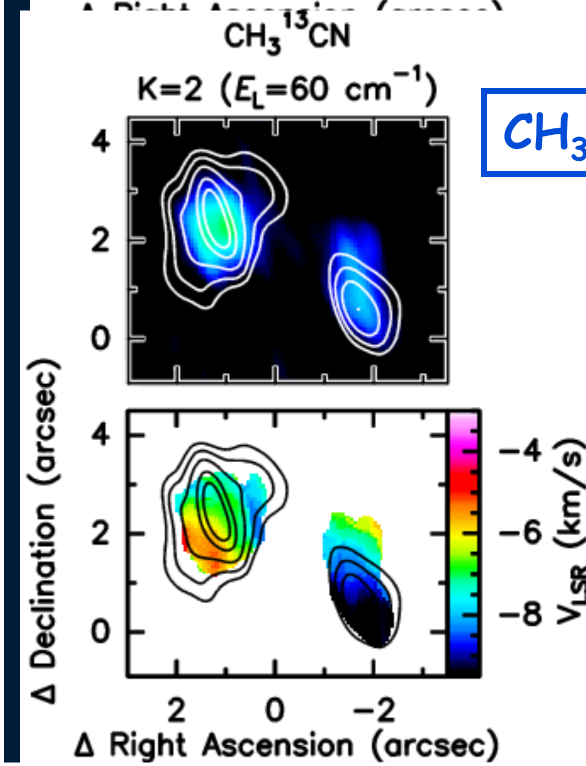
Increasing temperature

Lower lying transitions reveal tremendous kinematic complexity





CH_3CN



$CH_3{}^{13}CN$

Zooming in on SMA1 and SMA2:

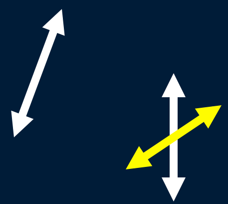
- Morphology vs. line excitation temperature could suggest a central heating effect
- But… comparison with isotopologue of K=2 reveals that lower lying transitions are also very optically thick (assuming C^{12}/C^{13}=55)

CH_3CN K=2: τ_{SMA1}=90 τ_{SMA2}=50

For both sources T_b (K=2) =80 K

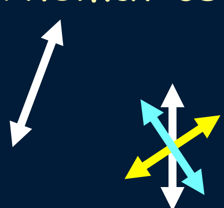
HNCO

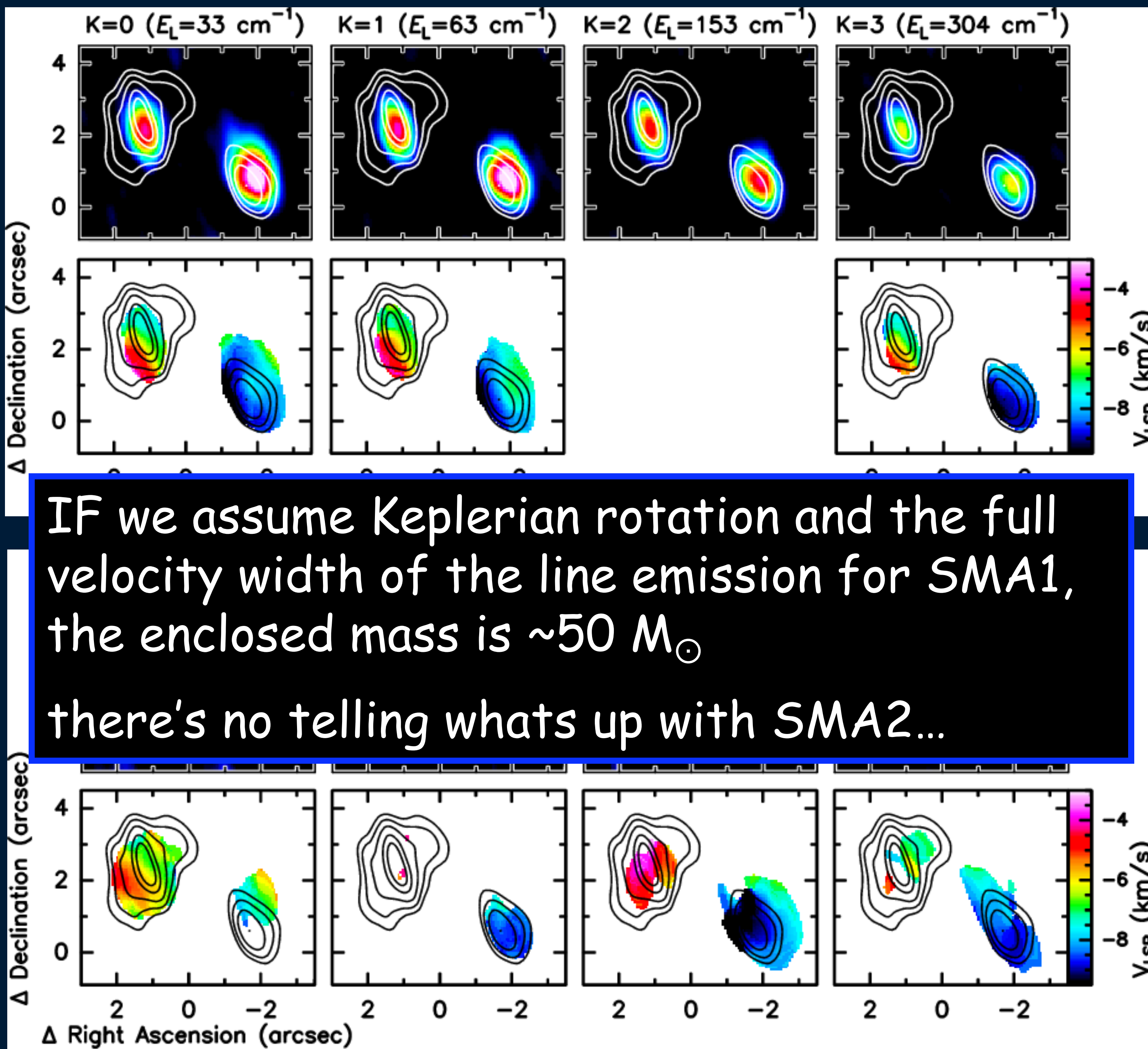
dominated by radiative processes not collisions



Various organic species

Note widely different distributions and kinematics



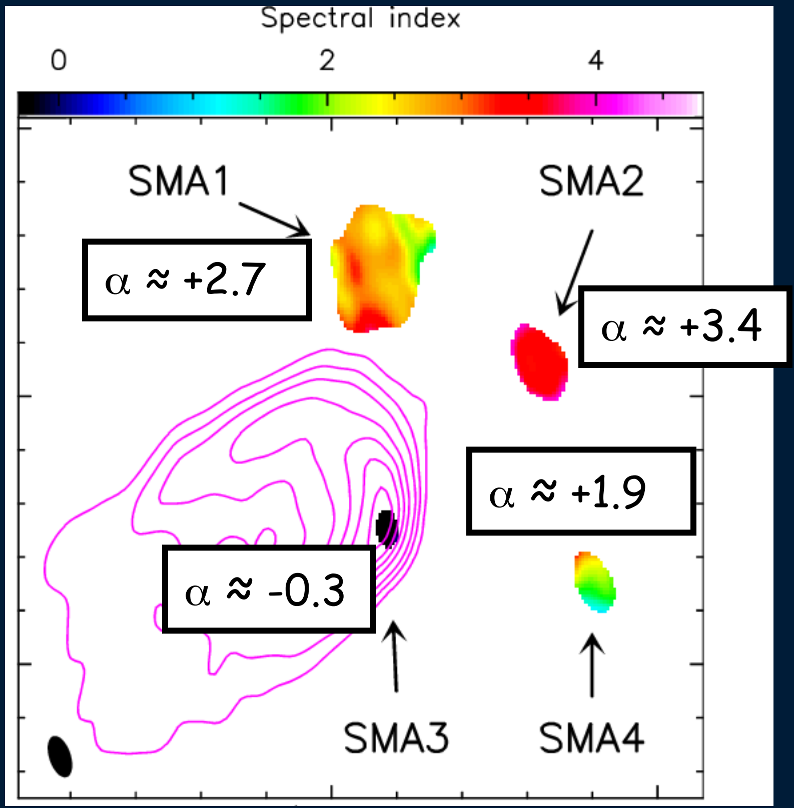


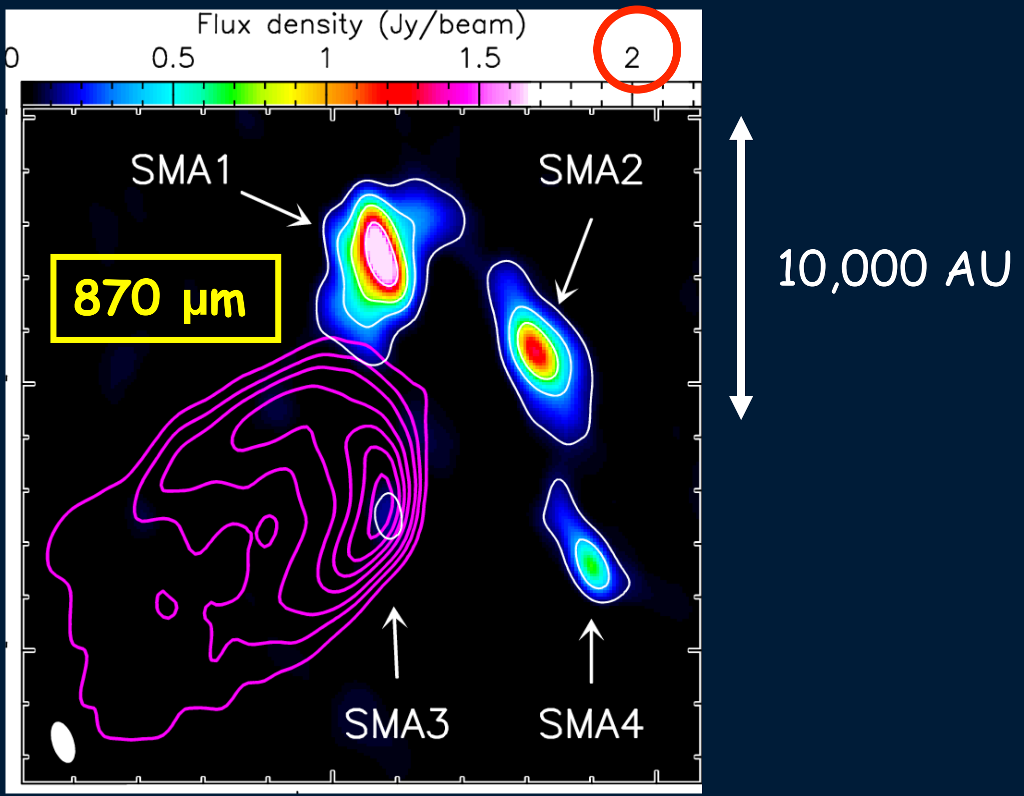
IF we assume Keplerian rotation and the full velocity width of the line emission for SMA1, the enclosed mass is ~50 $M_{\odot}$

there's no telling whats up with SMA2…

Dust emission from NGC 6334 I (Beam 0.8"x 0.4")

- It is crucial to observe with high spectral resolution to remove the lines!





Higher frequency = increased Flux $\propto \nu^{2 \text{ to } 4}$

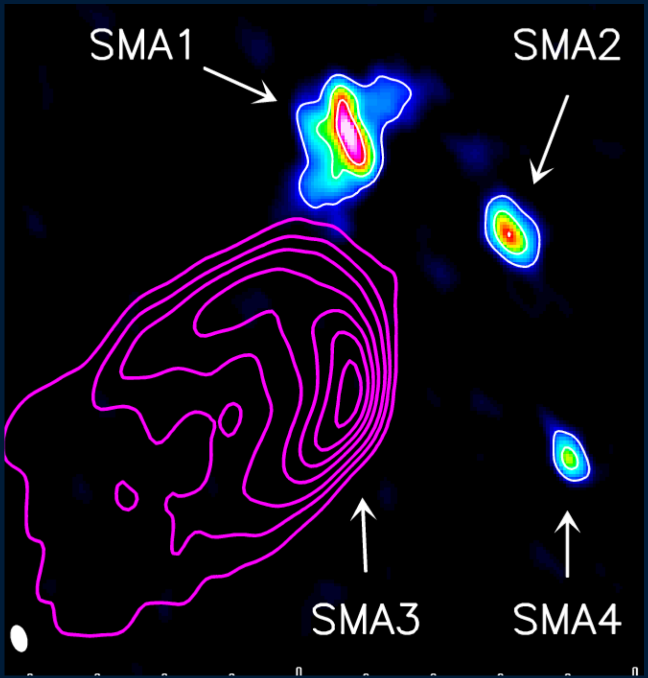
thick (2) thin (4)

Dust emissivity
$\beta = \alpha - 2$

Result: Optical depth or composition of dust varies from source to source.

The Brightness Temperature measured at High Resolution is a powerful probe of Luminosity

Beam 0.5″x 0.3″ (850 x 510 AU)



$$T_b\,(K) = \frac{1.224\times10^6 * S_\nu(Jy)}{\nu^2\,(GHz) * [\theta_{beam}\,('')]^2}$$

$$L_b \geq 4\pi R_{beam}^2\,\sigma T_b^4$$

$$L_{b,fit} \geq 4\pi R_{fit}^2\,\sigma T_{b,fit}^4$$

	T_b(K)	$T_{b,fit}$(K)	R_{fit}(AU)	$L_{b,fit}(L_\odot)$
SMA 1	72	78	930	> 4100
SMA 2	44	77	500	> 1200
SMA 4	23	83	320	> 620

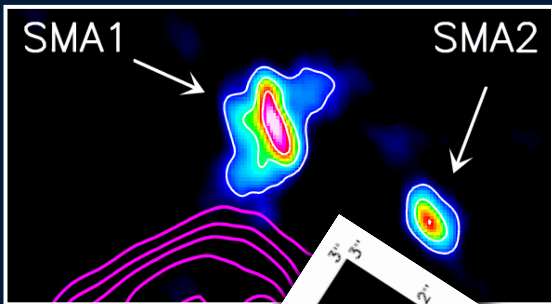
With its higher resolution and range of frequencies, ALMA will enable assumption free luminosity measurements of protocluster members

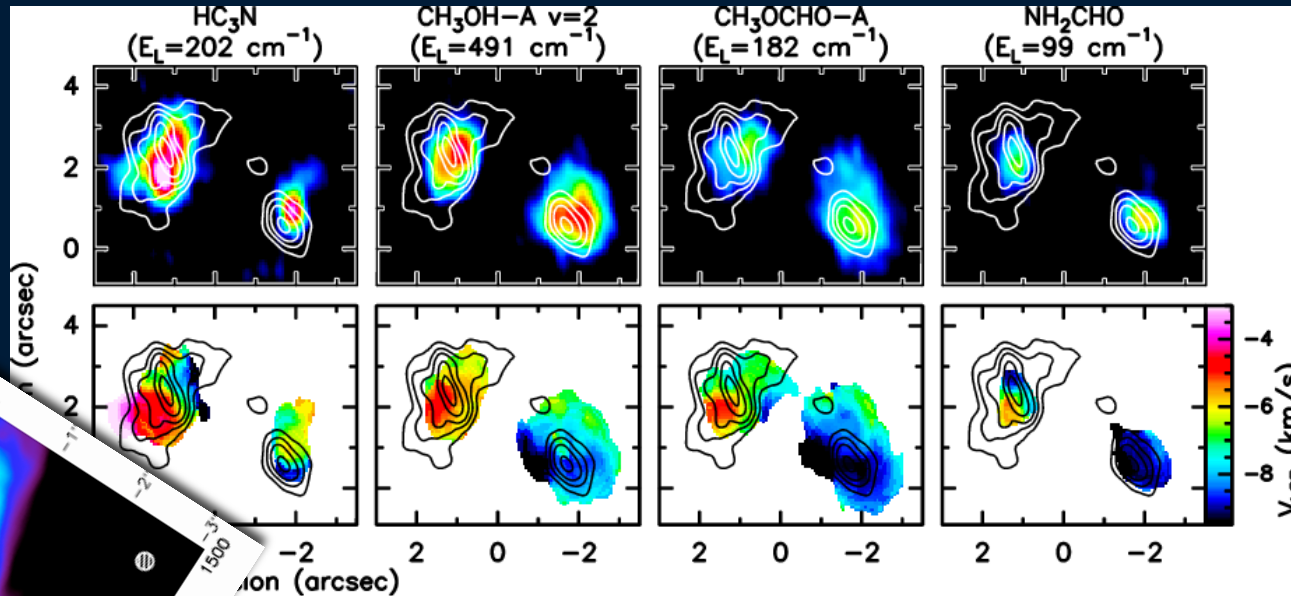
But for SMA1 and SMA2 brightest lines have T_b ~ 125 K

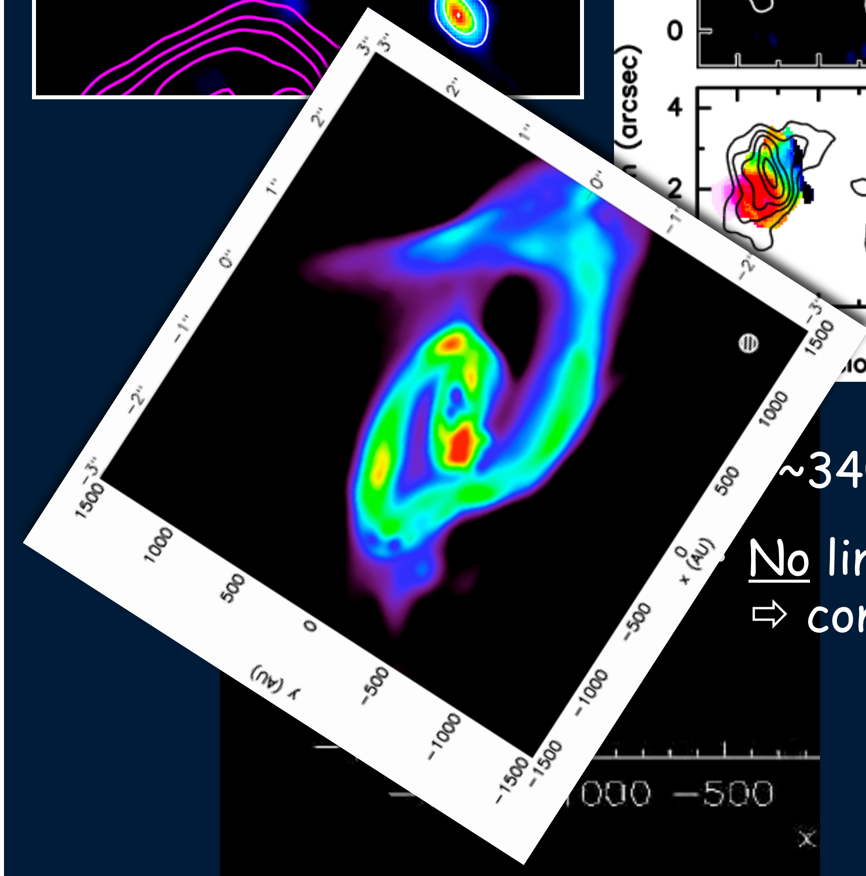
⇨ Luminosities at least 7x larger than lower limits

For T_{dust}=125 K, τ_{dust} ~ 1 at 340 GHz

So What's up with the Crazy Morphology?







~340 GHz data:

- No lines peak on SMA1 or SMA2 continuum peak
  ⇨ continuum opacity is simply too high

ALMA simulation of m=1 spiral: of disk at 0.5 kpc in CH_3CN (K=0) 220.747 GHz, T_{upper} = 69 K

Could something like this work? We need very high resolution at a frequency where the emission is optically thin in BOTH continuum and lines

(Krumholtz, Klein, & McKee 2007)

How to Get the Most Bang for your Buck

- T > 100 K innermost regions ⇒ use high temp. lines to avoid envelope contamination
- Inner disk column density ~ 10^3 g cm^{-2} ⇒ dust optical depth ~ 1 at 100 GHz (3mm)
  - Outer parts of disk continuum very easy to image with ALMA
  - Outer parts of disks have strong lines, very easy to image kinematics with ALMA (but only if unblended)
    - 25x greater sensitivity than SMA shown here
  - Kinematics and continuum morphology in the central few hundred AU challenging with ALMA due to high dust optical depth

⇨ Data longer than 3 mm will be essential

⇨ ALMA at 3 mm and EVLA 10 mm

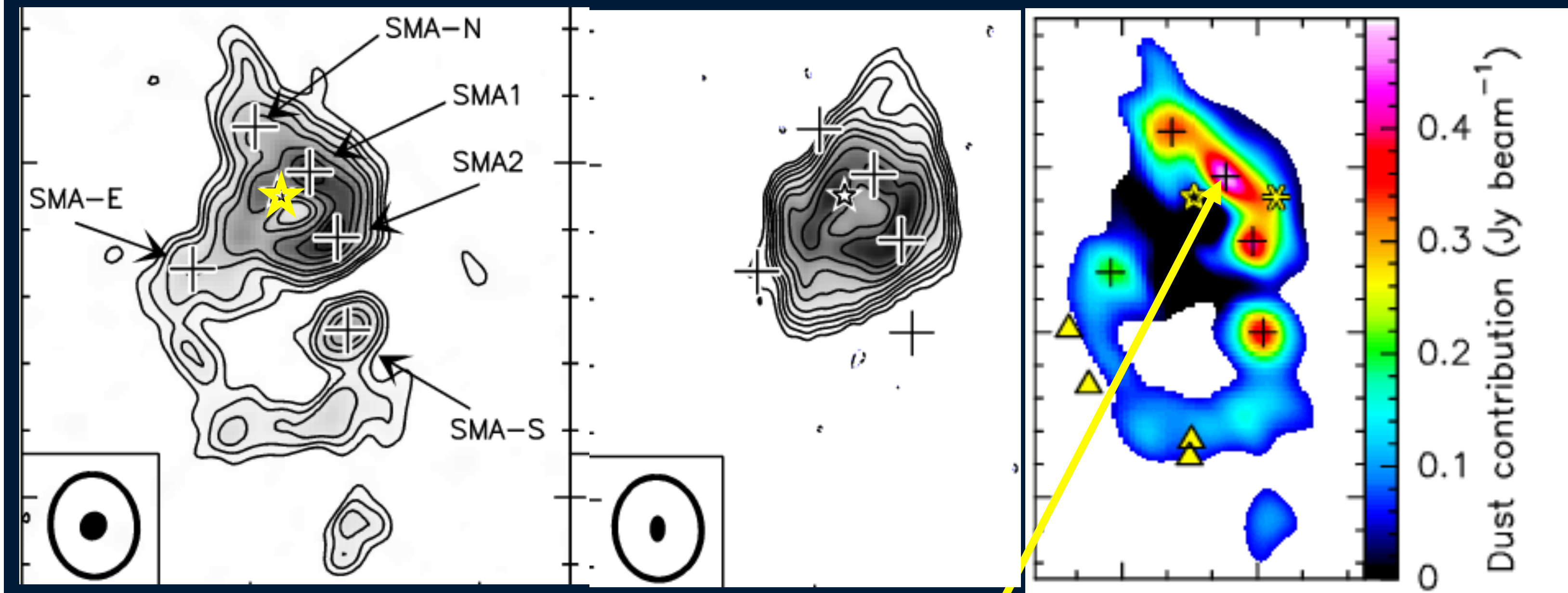
↑ ALMA Band 1

The Ultra Compact HII Region G5.89-0.39

D = 2 kpc

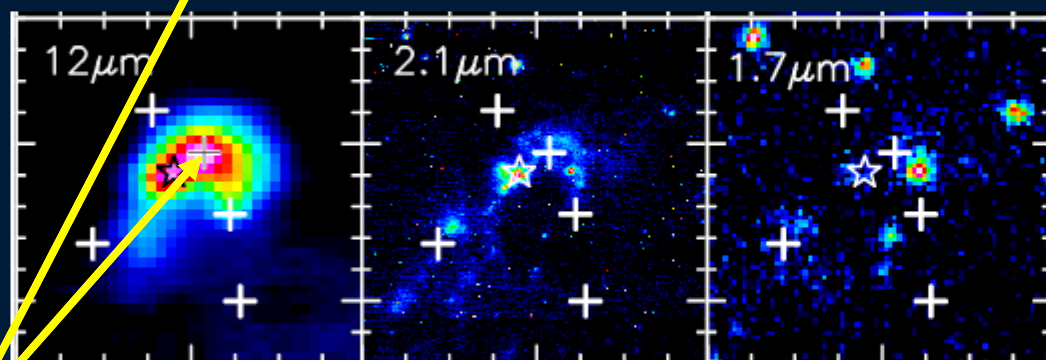
L = $10^{5.5}$ $L_\odot$

SMA 870 μm | VLA 3.6 cm | Dust Emission



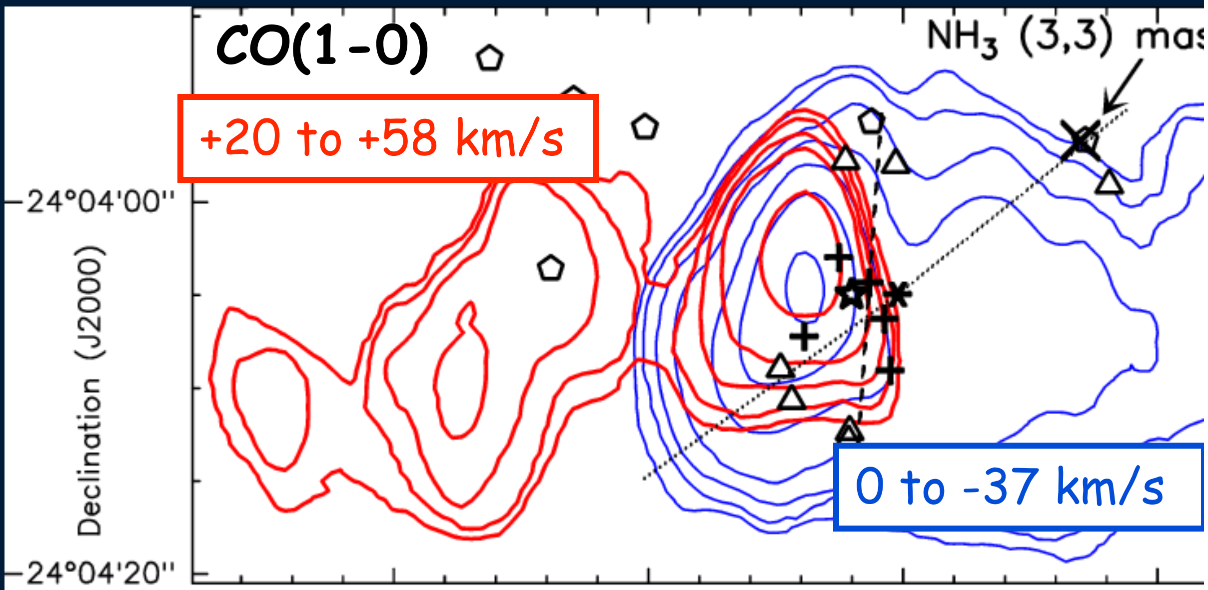
8,000 AU

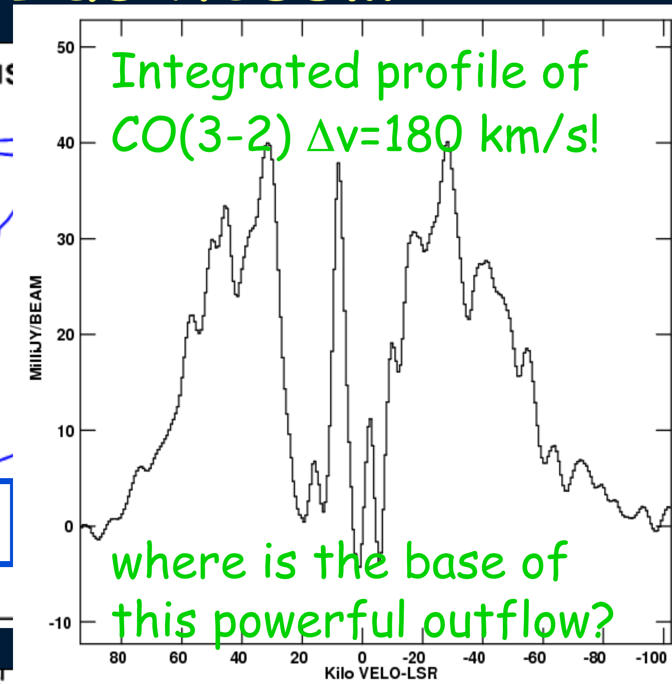
- Why is the only O star located on the shell (i.e. not at center)?
- Dusty clumps around periphery reveal new generation of protostars, plausibly triggered by the HII region
- At least one is internally heated

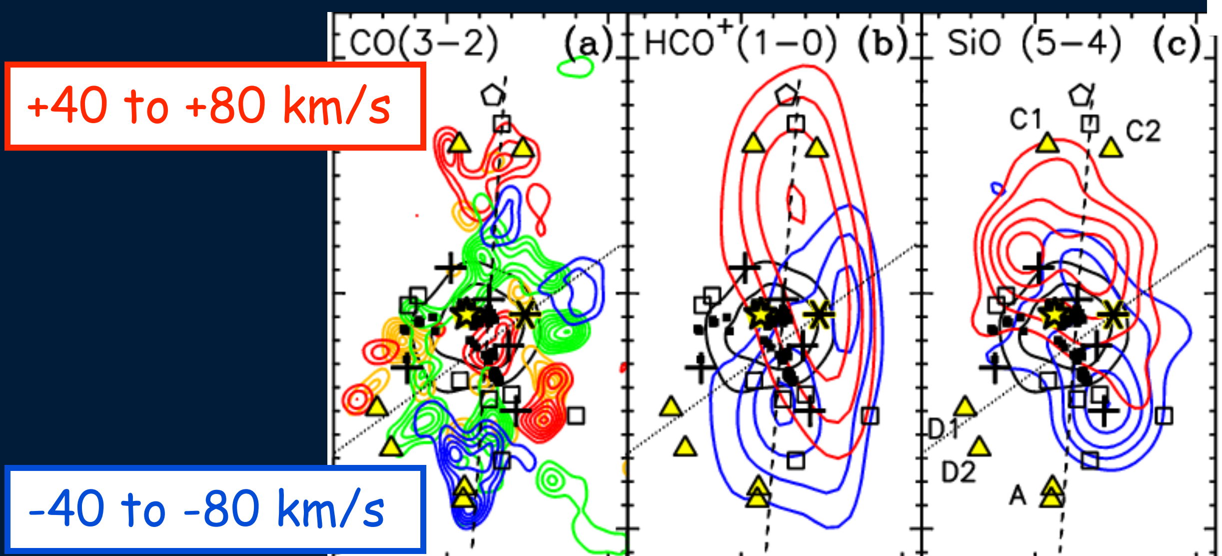


Hunter, Brogan et al. (2008)

Outflows Are a Tricky Business…







Hunter, Brogan et al. (2008)

Dynamical timescale estimates have been severely affected by assuming the E-W flow size scale, but the velocity extent of the N-S flow

⇨ Fossil outflows may dominate single dish data

A Sort of Sequence with Many Caveats

Increasing cm-wavelength emission

Increasing far-IR luminosity

Very Dense Cold Cores: Infrared Dark Clouds

+ ?

High Mass Protostellar Objects (HMPO)

Massive Young Stellar Object (MYSO)

+ ?

Hot Cores

Hypercompact HII region

+ ?

Ultracompact HII region

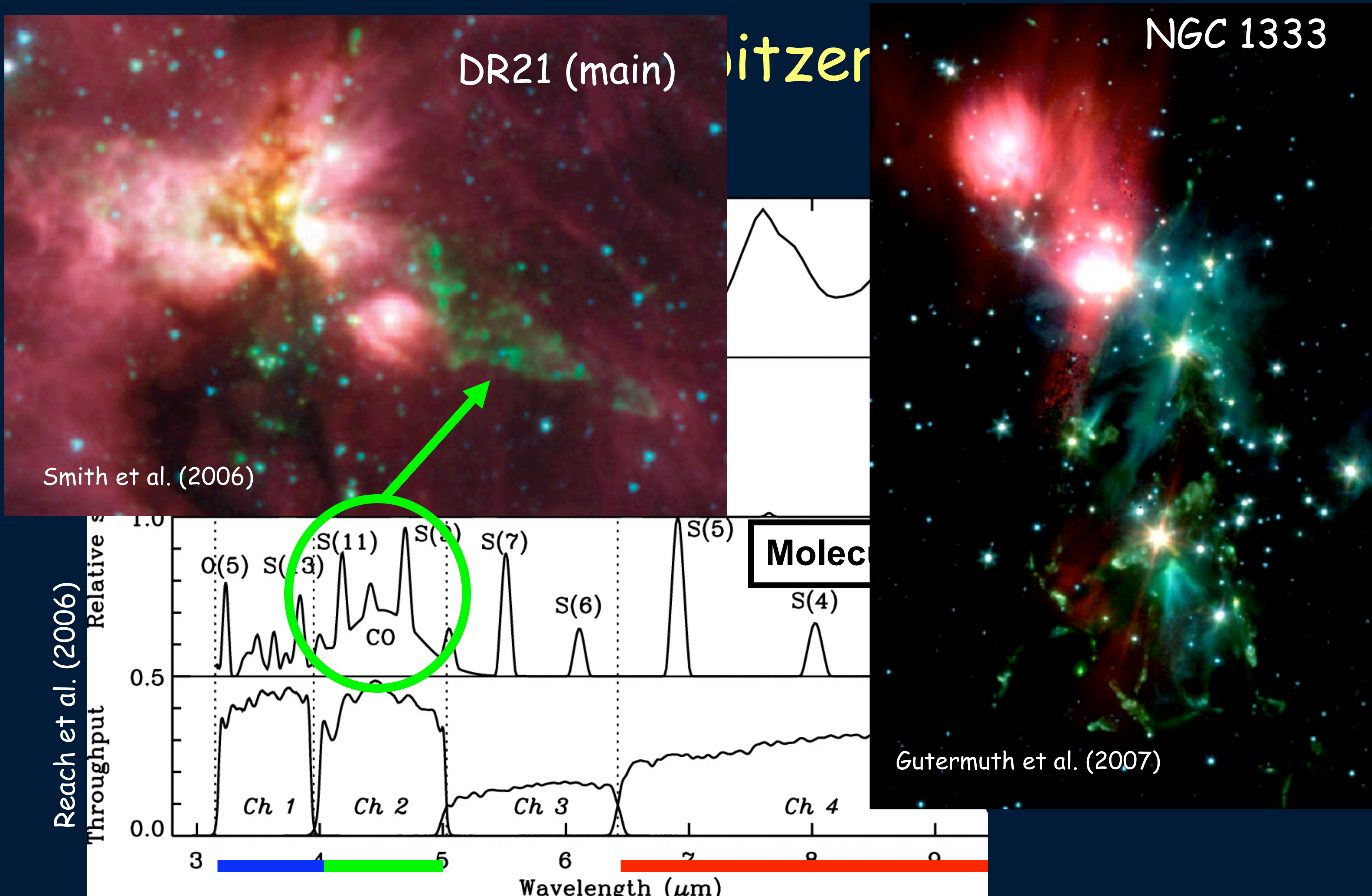
Large Diffuse Evolved HII region

IRAS

Masers

Molecular outflows

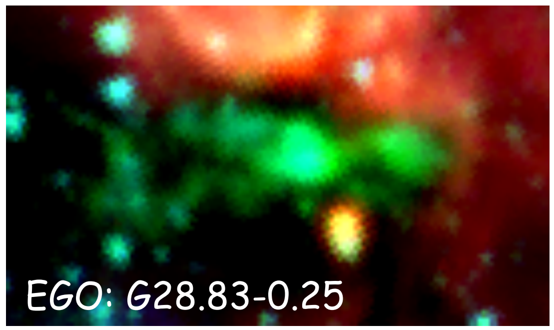
Flattened disk-like structures



⇨ Perhaps similarly colored "Extended Green Objects" (EGOs) would act as signposts for a new sample of massive young stellar objects

A Catalog of >100 EGOs from GLIMPSE
(Cyganowski et al. 2008)

- Mean offset from IRAS point source > 1′
- Many coincident with IRDCs
- Many coincident with MIPSGAL 24 μm emission
- Mid-IR colors consistent with young YSOs



⇨ Comprises a new pool of massive young stellar object candidates

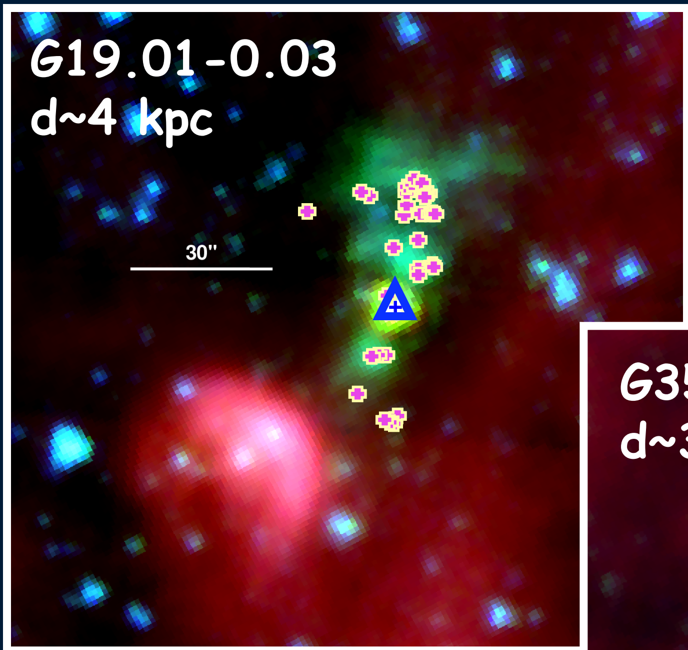
But how to efficiently confirm that the candidates are massive and 4.5 μm emission is due to outflow?

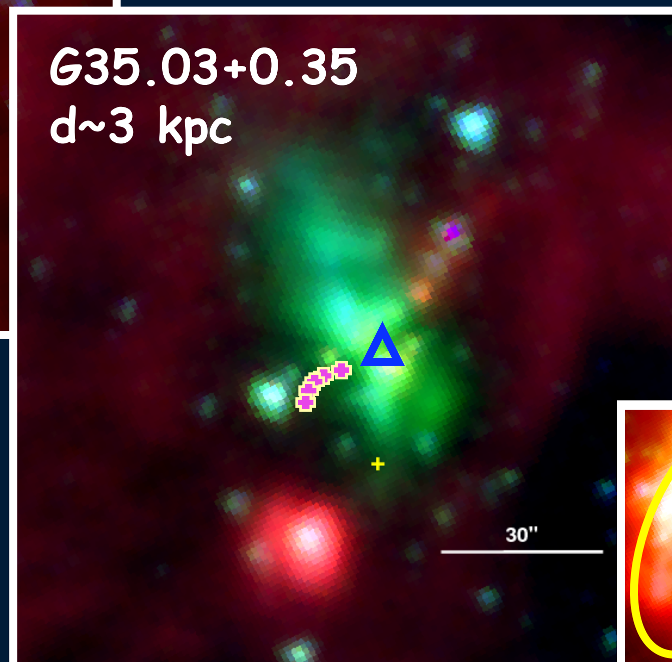
Methanol (CH_3OH) masers:

- 6.7 GHz (class II): Ubiquitous toward massive star forming regions, but not low mass (Minier et al. 2003; Ellingsen 2006; and many others)
- 44 GHz (class I): Massive outflows (Kurtz et al. 2004)

This search makes use of new capabilities of the EVLA ⇨ extended wavelength coverage!

Results from (E)VLA Maser Survey of EGOs

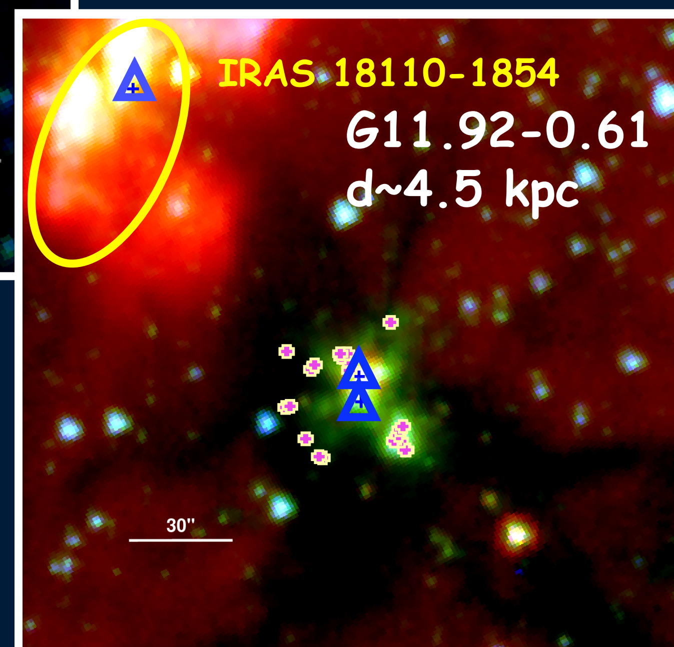




Maser Detection Rates:

- ▲ 6.7 GHz Class II: 64% (18/28)
- ✚ 44 GHz Class I: 89% (17/19)

⇨ Extended 4.5 μm emission is a signpost of MYSOs, with active outflows, likely powered by ongoing accretion



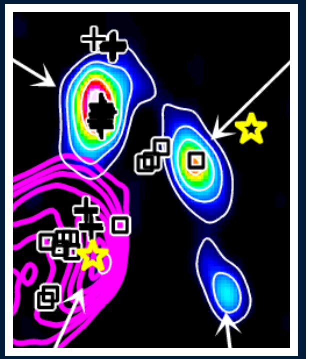
Next Step:

- MM follow-up to determine properties of protostars

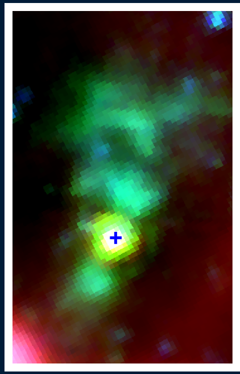
Cyganowski et al. in prep. (see poster)

Summary and Conclusions

- Massive stars form in protoclusters
  - Many massive star forming regions have the appearance of proto-trapezium
  - A multitude of dust cores – some with "hot core" emission indicating a star has ignited – others that are "lineless"



- The copious line emission from MYSOs is a powerful probe of the physical conditions
  - Making sense of kinematics is very tricky: must account for line excitation, line and continuum optical depth
  - Massive accretion does not happen through "Keplerian frisbees"
  - Watch out for fossil flows ⇨ dynamical timescales



- IRAS is a blunt tool in the inner Galaxy; need better sample
  - Spitzer/GLIMPSE EGOs have produced a new promising sample

ALMA will improve resolution and spectral sensitivity by more than 25x

EVLA will be essential to probe optically thick inner disk regions

- Extra slides

External heating? No!

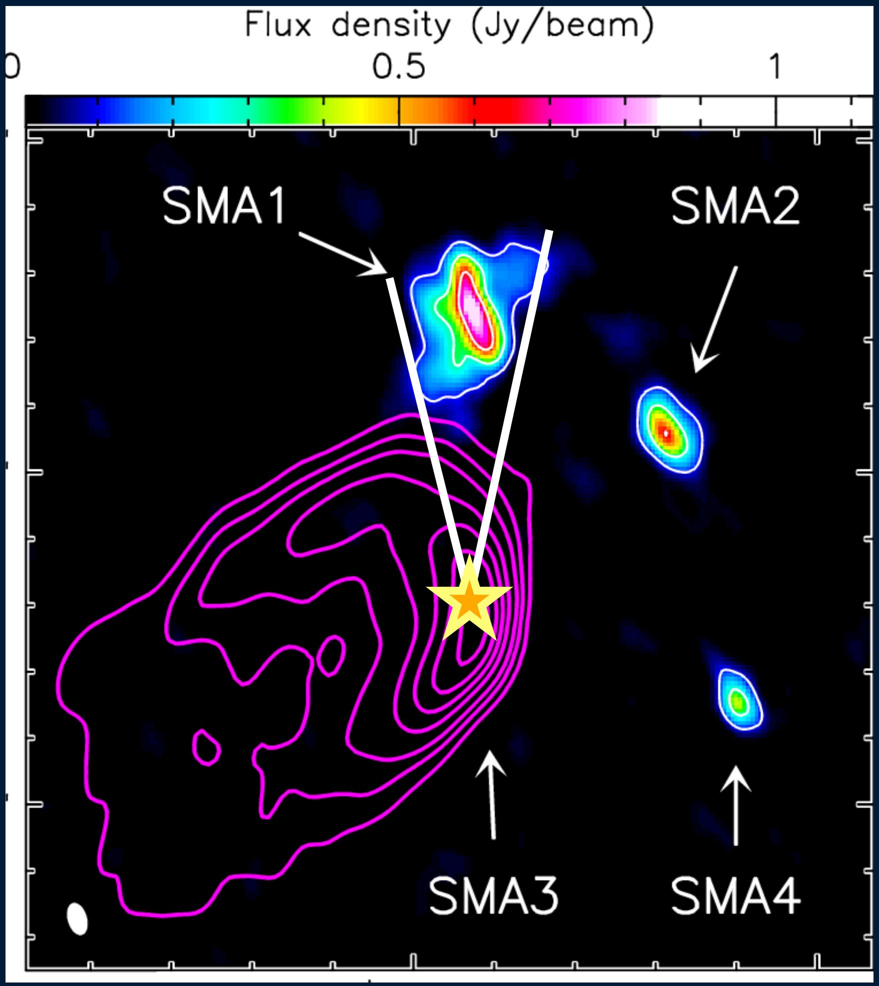
25° intercept angle ≤ 1.2% of a sphere (centered on the UCHII region exciting star)

$50{,}000 L_\odot * 0.012 = 600\ L_\odot$

Core radius ~ 1" ~ 1700 AU

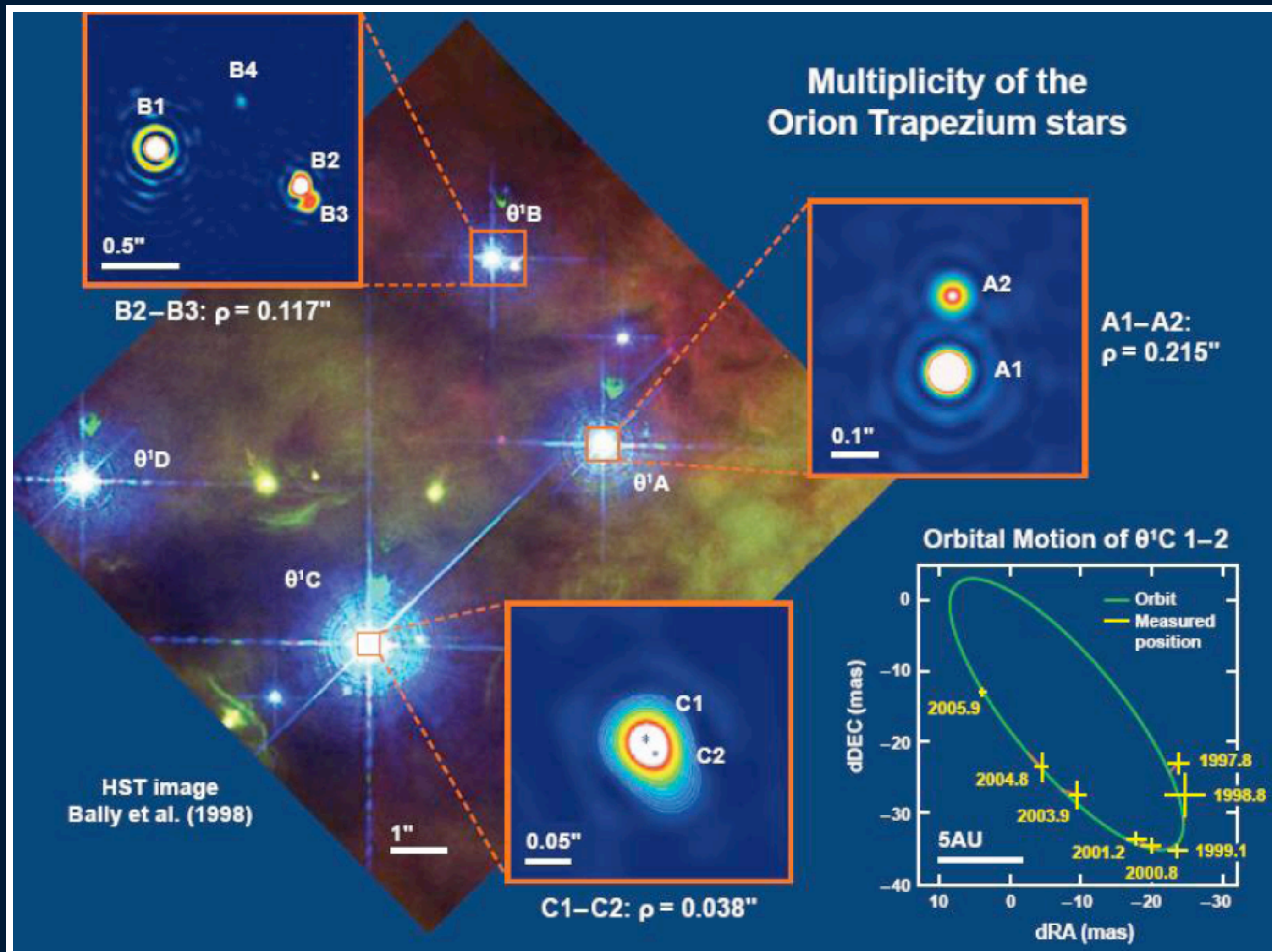
$L = 4\pi R^2 \sigma T^4 < 600\ L_\odot$

$T < 15$ K



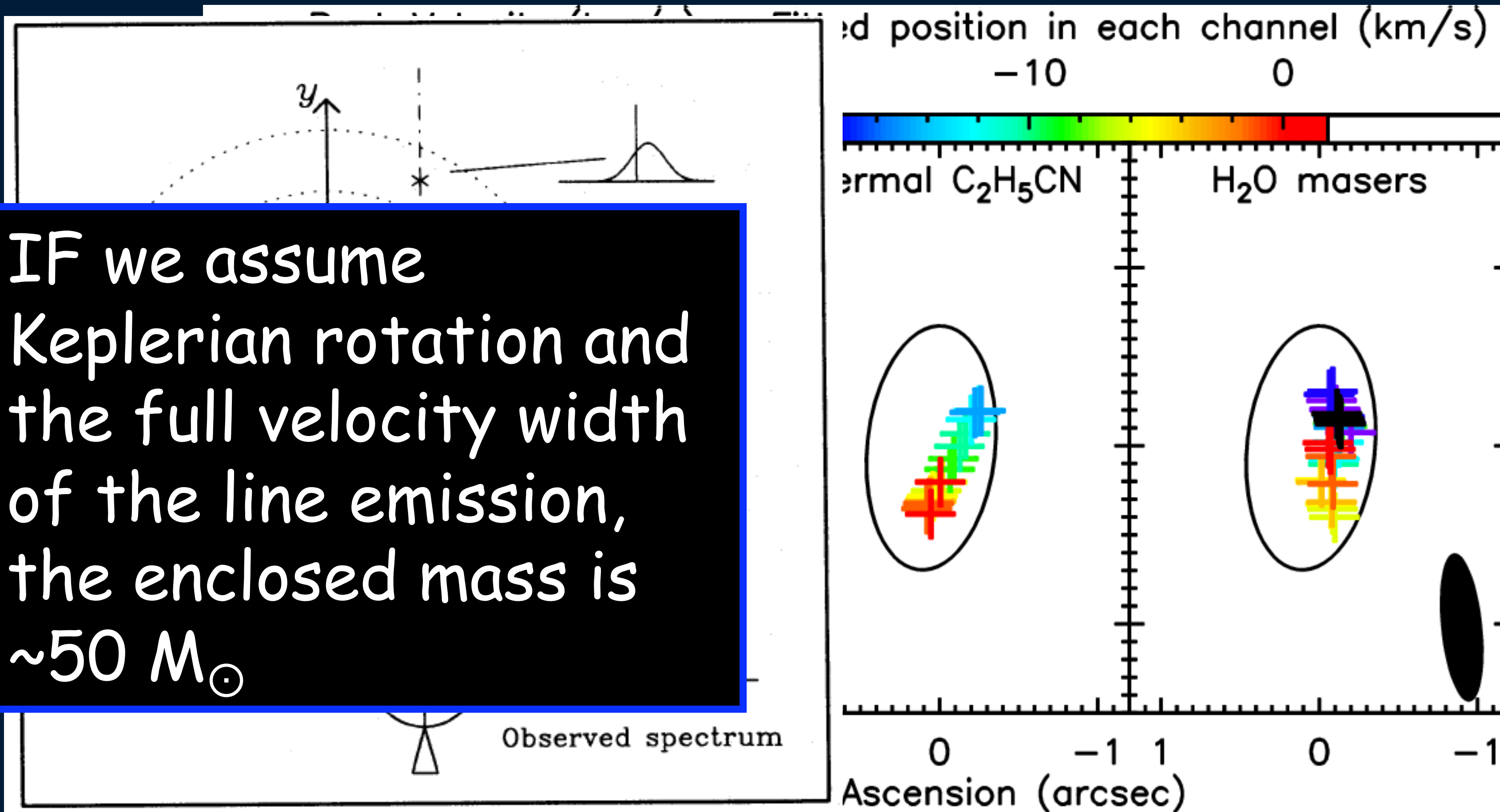
But....

Zinnecker & Yorke (2007)



At our current resolution, NGC6334I could harbor kinematically distinct multiple protostars within each core which can easily mimic a disk (see for example Brogan et al. 2006 for CepA-East)

A Closer Look at the Velocity Gradient



IF we assume Keplerian rotation and the full velocity width of the line emission, the enclosed mass is ~50 $M_\odot$

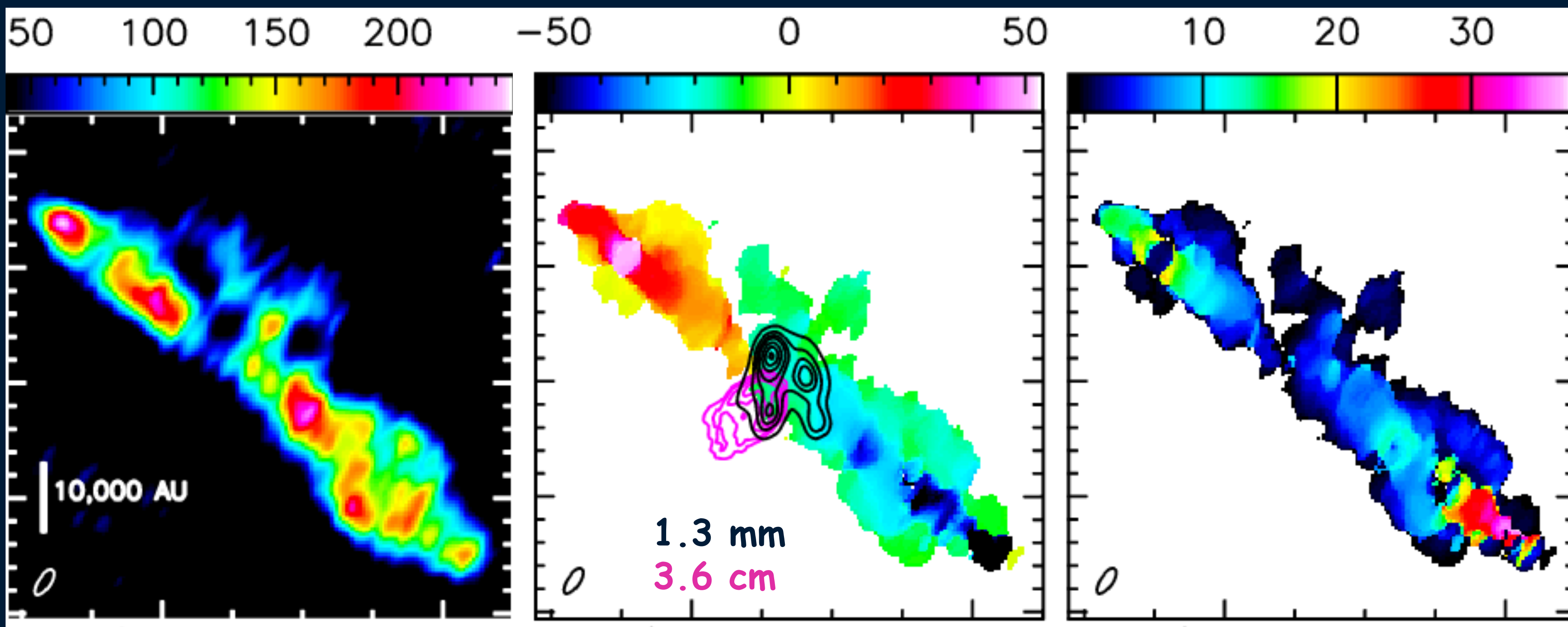
Highest velocities <u>not</u> seen toward center in optically thin lines

⇨ Likely high dust opacity attenuates emission from center of the disk

H2O masers do show highest velocities toward center but P.A. is slightly different (?)

An Incredibly Collimated Massive Outflow

Integrated Intensity (Jy * km/s) | Peak Velocity (km/s) | Line Width (km/s)



Using LVG analysis of multiple single dish (18″ resolution) high J CO lines observed with APEX, Leurini et al. (2006) find:

$M_{outflow}$ >3 $M_{\odot}$ and L_{mech}>1500 $L_{\odot}$ assuming an inclination of 45°