A New Sample of Massive Young Stellar Object Outflow Candidates:

Extended Green Objects from the GLIMPSE Survey

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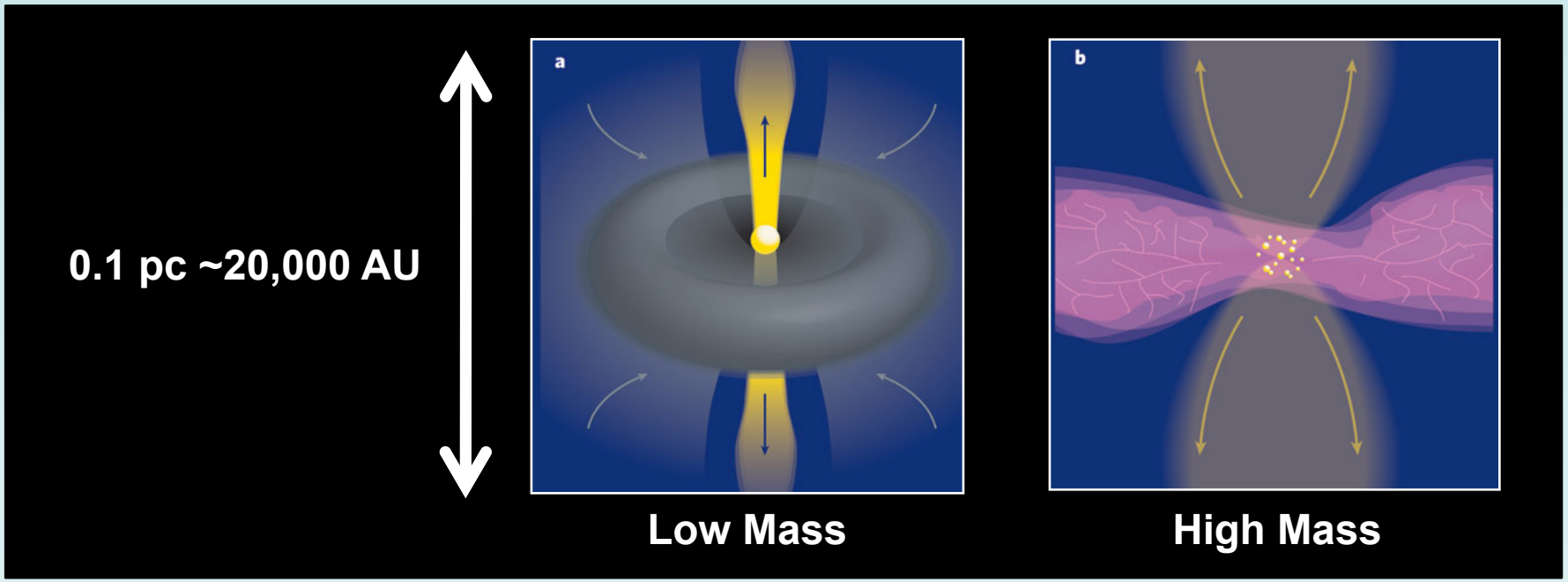
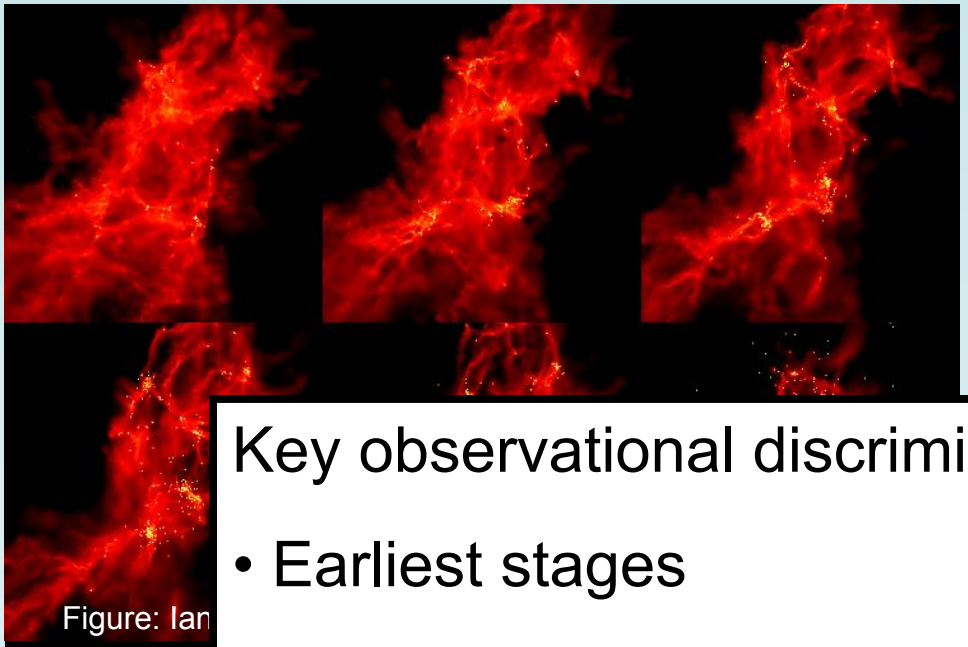
How do massive stars form?

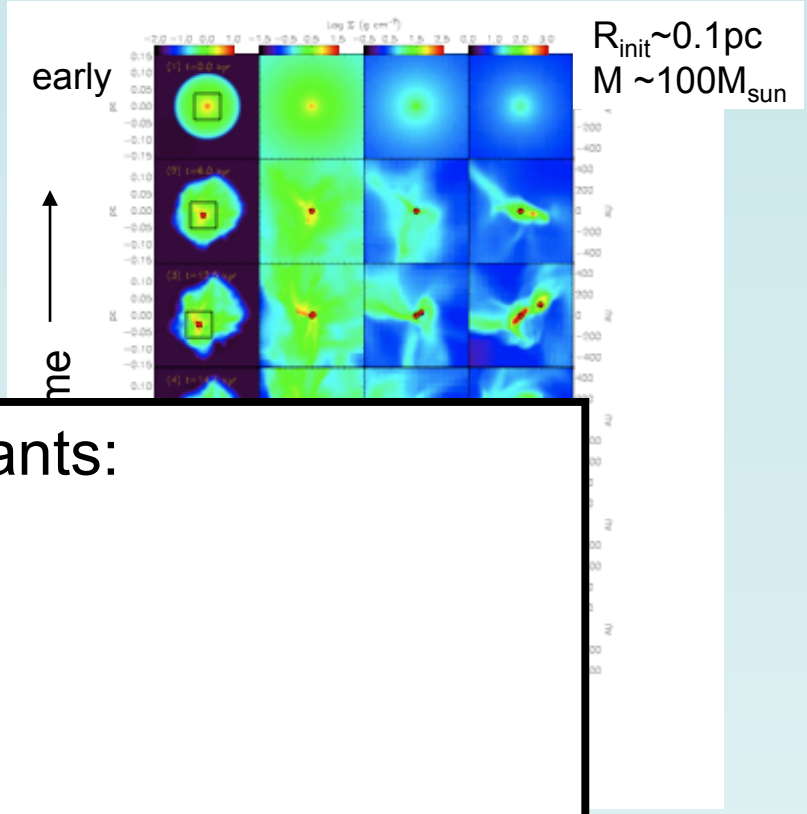


Observational difficulties:

- Distant (> 1 kpc)
- Deeply embedded (obscured shortward of MIR)
- Clustered

How do massive stars form?





Key observational discriminants:

- Earliest stages
- Role of cluster feedback (outflows,ionization,heating)
- Demographics of YSO populations

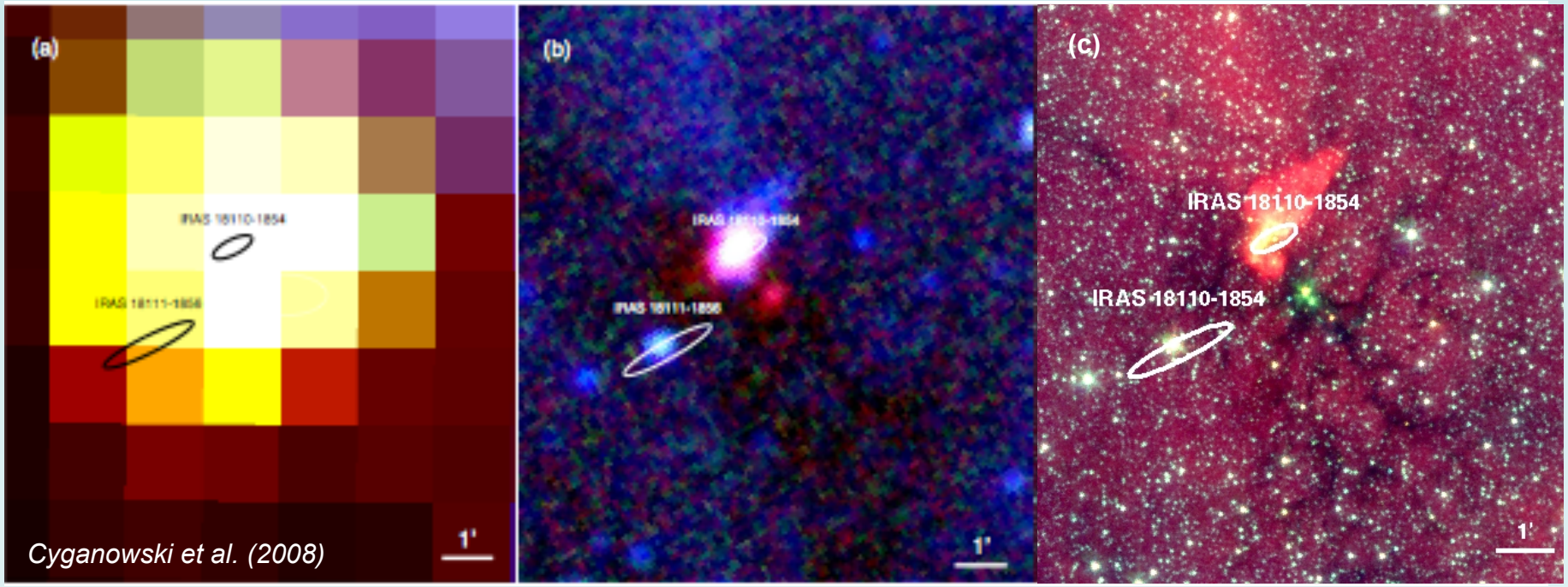
- Fragm
  protostars
- Competitive accretion
- Dynamics and interactions matter
- Sum of above factors -> IMF

surpresses fragmentation
- Majority of mass →1 object
- Core mass maps directly to stellar mass

(Core IMF=stellar IMF)

The Evolution of IR-selected MYSO samples…

IRAS *MSX* *Spitzer (IRAC)*

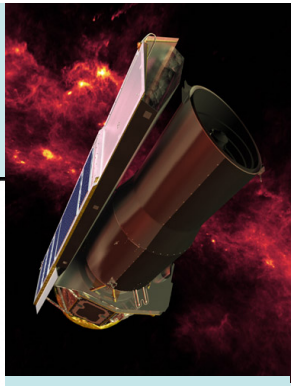


RGB: 100, 25, 12 μm
Resolution ~ 0.5'-2'

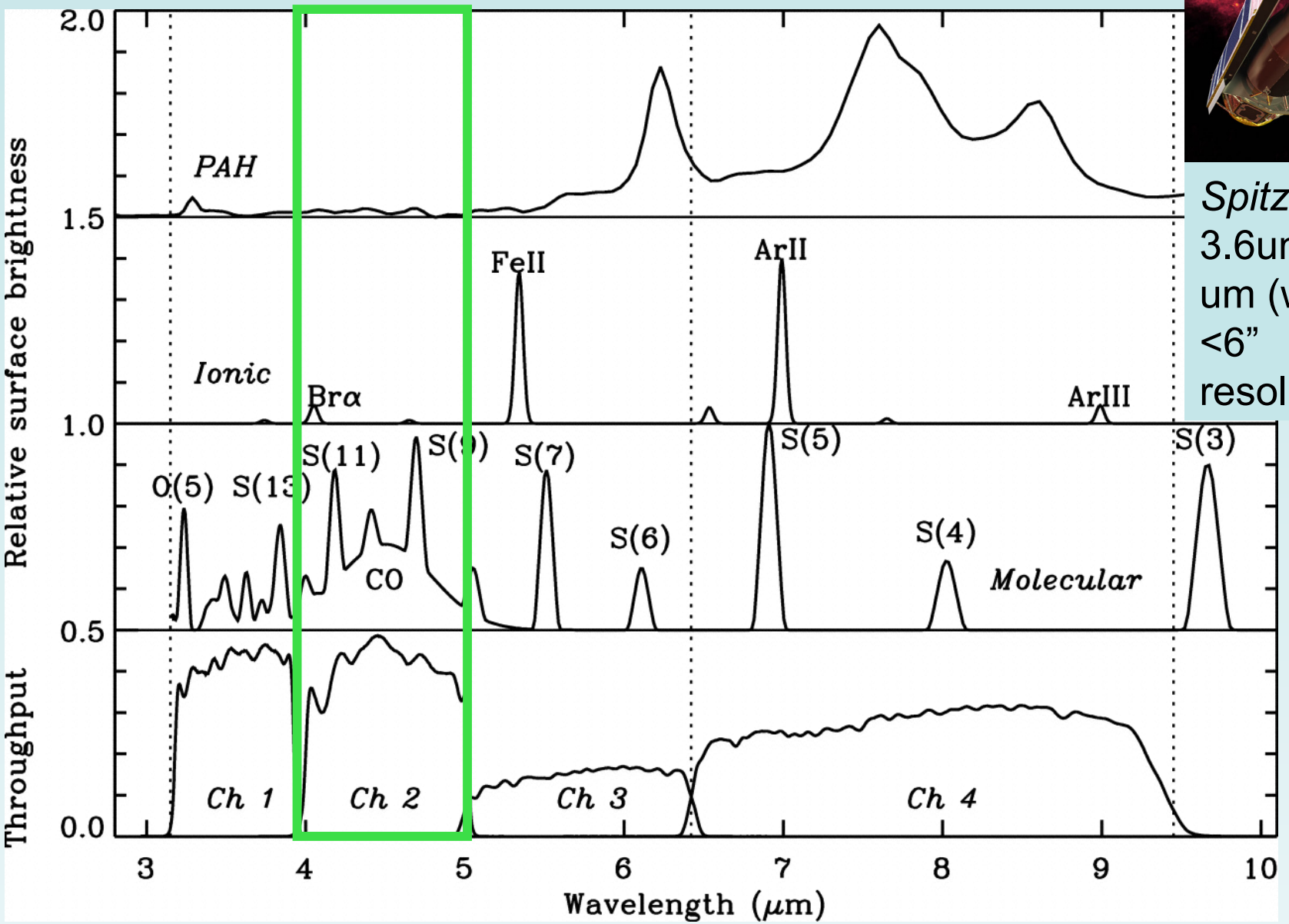
RGB: 21.4, 12.1, 8.3 μm
Resolution ~ 18"

RGB: 8.0, 4.5, 3.6 μm
Resolution ~ 2"

A New Diagnostic: *Spitzer*'s 4.5μm band

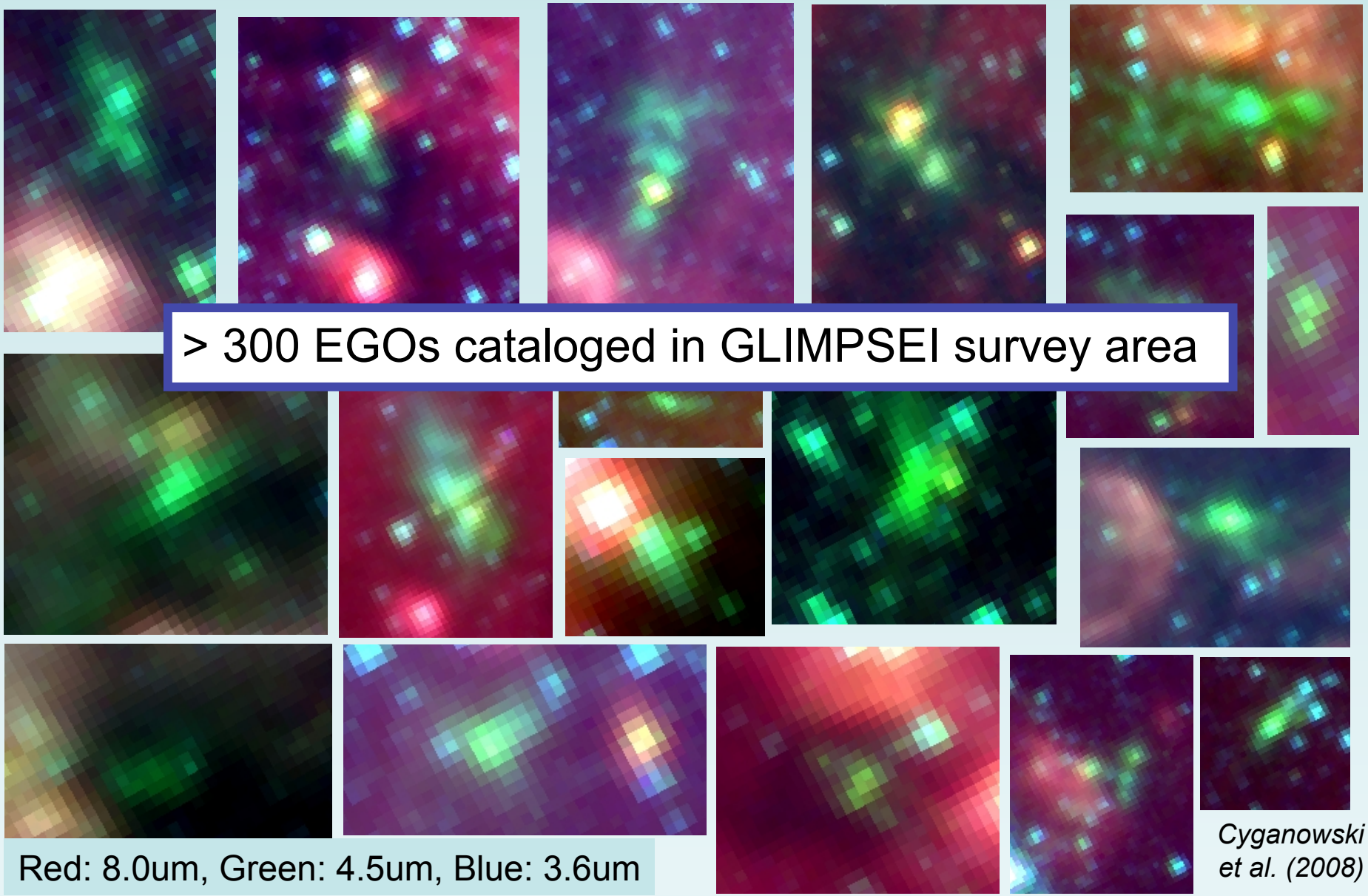


Spitzer, 3.6um-24 um (with <6" resolution)



Reach et al. (2006)

A New MYSO Outflow Sample:
GLIMPSE Extended Green Objects (EGOS)



> 300 EGOs cataloged in GLIMPSEI survey area

Red: 8.0um, Green: 4.5um, Blue: 3.6um

Cyganowski et al. (2008)

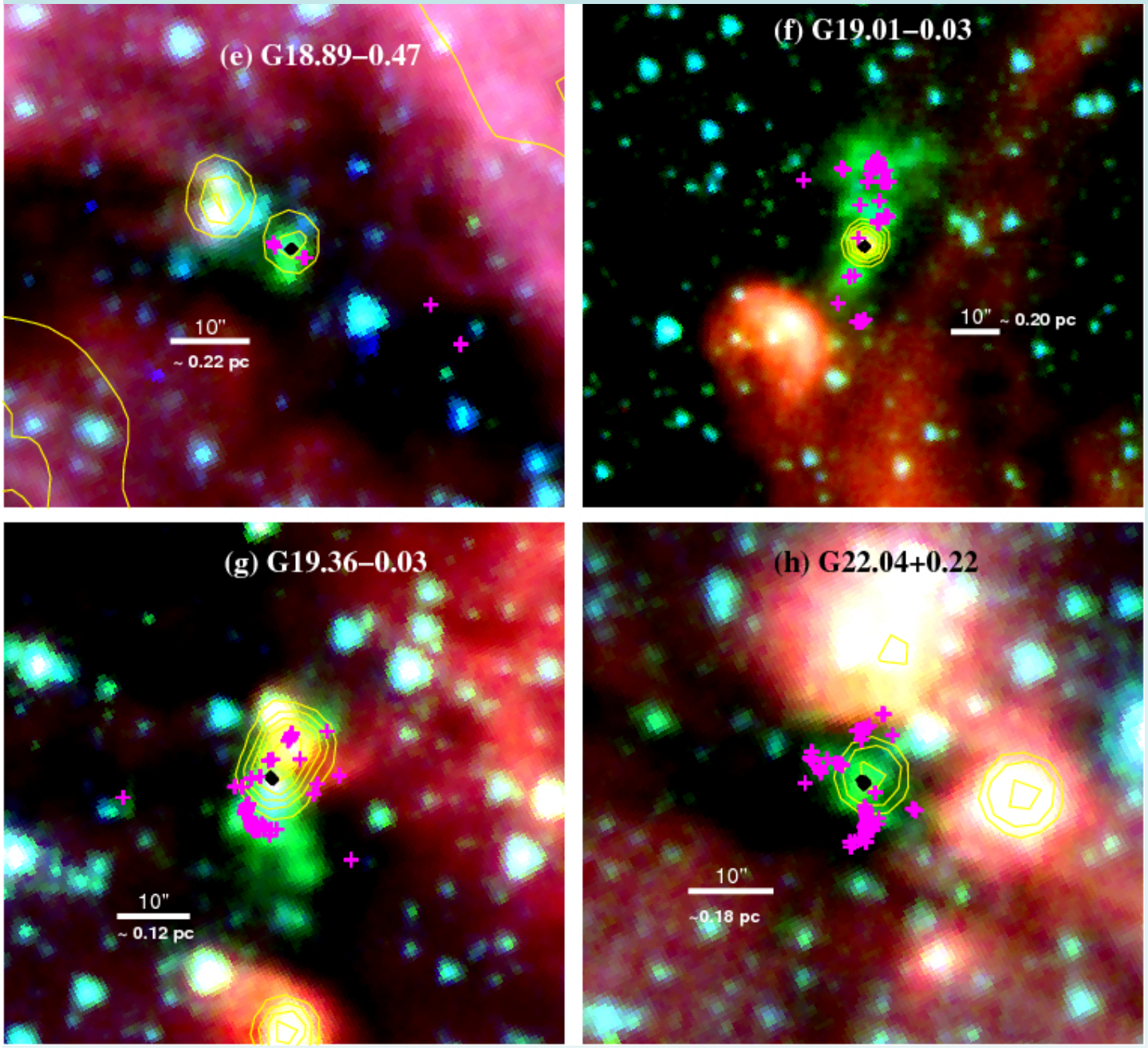
Are EGOs *Massive* YSOs with Outflows?

Observational Tests:

- EVLA survey for 6.7 GHz CH_3OH masers (associated exclusively with *massive* YSOs; Minier et al. 2003)
- VLA survey for 44 GHz CH_3OH masers (associated with molecular outflows; Kurtz et al. 2004)
- JCMT survey for SiO, HCO^+, $H^{13}CO^+$, thermal CH_3OH emission

- Sample of ~28 EGOs, selected to:
  - Cover range of MIR properties (8/24um counterparts, morphology, angular extent of 4.5um emission)
  - Be visible from northern hemisphere

EGO Survey Results: Spatial Distribution of CH_3OH Masers



GLIMPSE Images:
Red: 8um
Green: 4.5um
Blue: 3.6um

Yellow contours:
MIPS 24 um

+ 44 GHz Class I CH_3OH masers

◊ 6.7 GHz Class II CH_3OH masers

Cyganowski et al. (2009)

EGO Survey Results: Summary

- 6.7 GHz CH_3OH maser detection rate >64%
  - Nearly 2x detection rate of other MYSO samples
  - Centrally concentrated, coincident with 24μm emission
- 44 GHz CH_3OH maser detection rate ~ 89%
  - Spatially distributed, coincident with 4.5μm emission
  - Velocities near systemic
- HCO^+ (3-2) line profiles indicative of outflows (broad line wings)
- SiO (5-4) detection rate 90% → recent shocks, *active* outflows
- 95% *non*detection rate for bright 44 GHz continuum emission → most EGOs are *not* UC HII regions

Bottom line: Surveyed EGOs are young MYSOs with active outflows, and hence presumably ongoing accretion

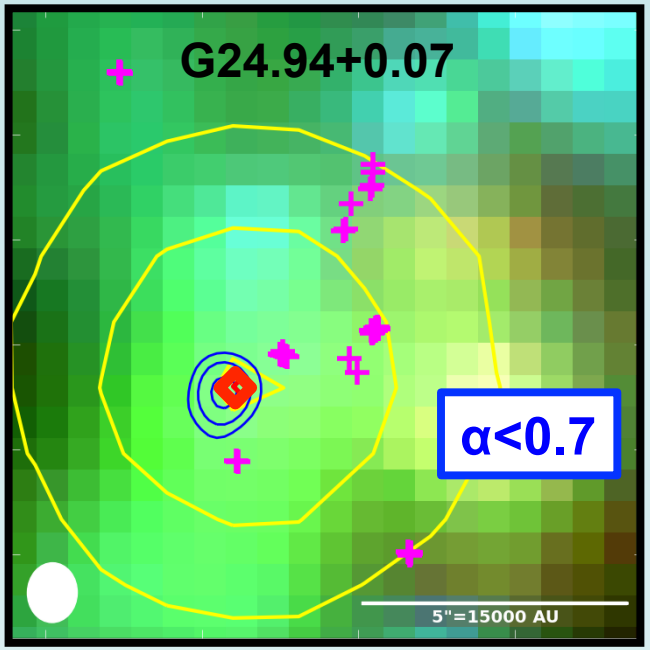
How evolved are EGOs?

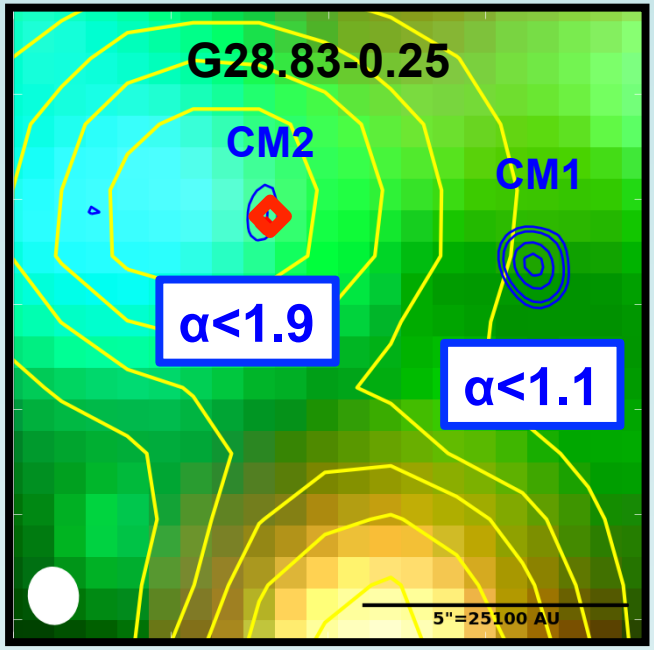
Search for cm continuum emission:

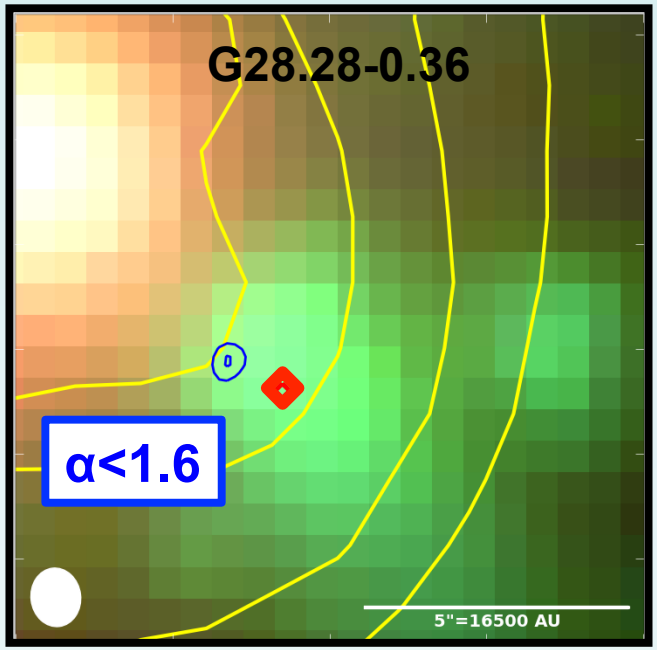
- Deep VLA surveys:
  - 3.6 cm (σ~30 μJy/beam)
  - 1.3 cm (σ~0.25 mJy/beam)
  - Resolution ~1”

- Sample of 14 EGOs:
  - Selected from maser survey sample
  - Associated with 6.7 GHz CH_3OH masers, 44 GHz CH_3OH masers, or both

Cm Survey Results: Detections







GLIMPSE Images:
Red: 8um
Green: 4.5um
Blue: 3.6um

Yellow contours:
MIPS 24 um

Blue contours:
3.6 cm continuum

+ 44 GHz Class I CH_3OH masers

◊ 6.7 GHz Class II CH_3OH masers

Cyganowski et al., in prep.

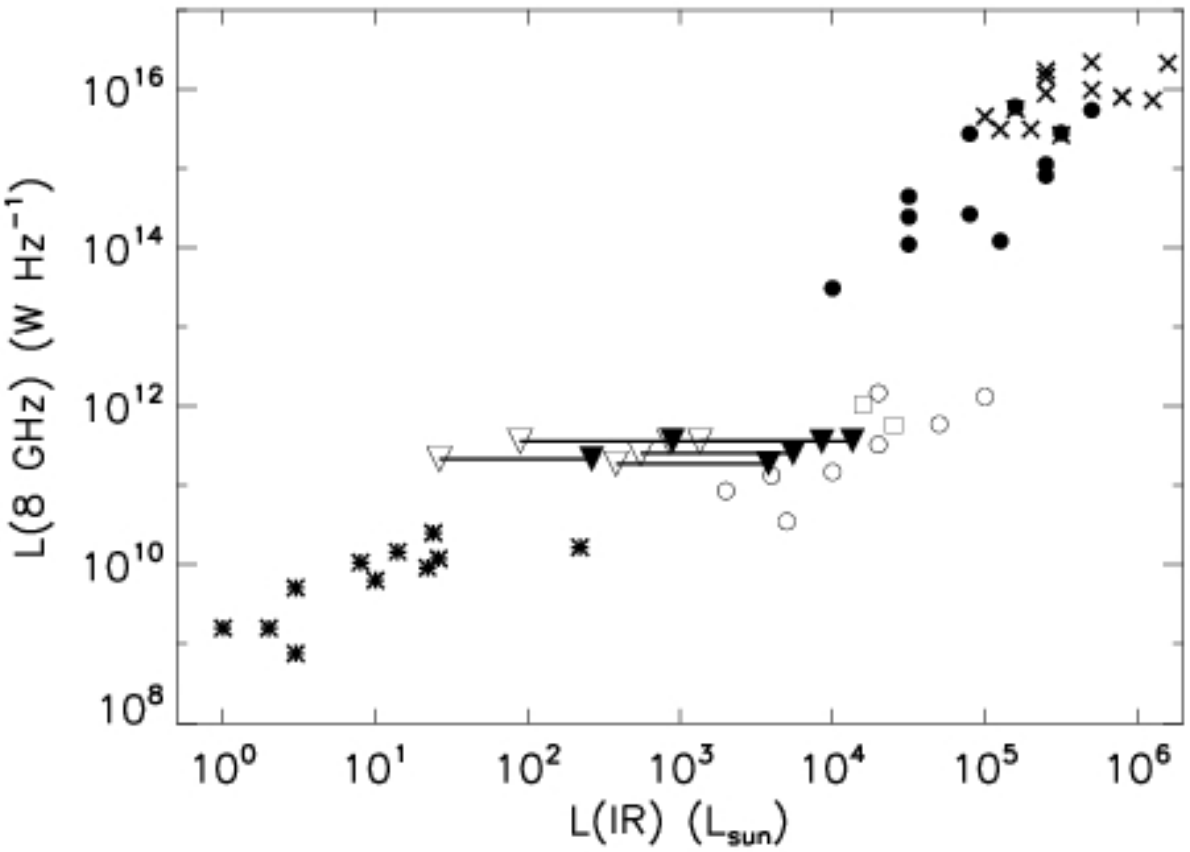
Cm Continuum Survey Results: Summary

- *Non*detection rate 57% (8/14)
  - Undetected at both 3.6 and 1.3 cm:
    - N_{lyc}< few x 10^{44} s^{-1} (optically thin)
    - Size < ~ 100 AU (optically thick)

$S_\nu \sim \nu^\alpha$
α = -0.1 optically thin
α = 2 optically thick

- Most cm-λ EGO counterparts are:
  - Weak (< 1 mJy)
  - Detected only at 3.6 cm
  - Intermediate spectral indices
- One detected only at 1.3 cm, probable HC HII region
- Only 2 EGOs associated with UC/C HII regions:
  - Both show cm-λ multiplicity

Cm Survey Results: Nature of cm emission



EGOs: ▷ ◀

Hoare & Franco 2007:

UC HIIs: X

HC HIIs: ●

Winds: ○

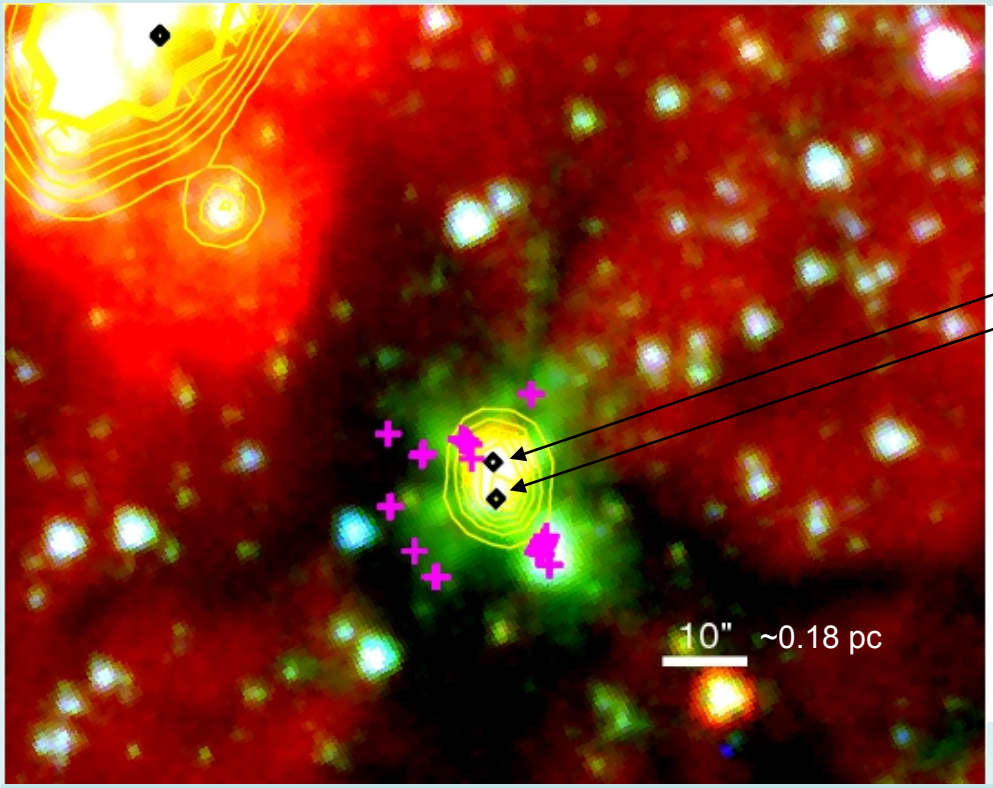
Jets: □

Anglada et al 1998:

Low mass jets: ✱

Cyganowski et al., in prep.

Feedback Mechanisms and (Proto)cluster Formation: Case Study G11.92-0.61



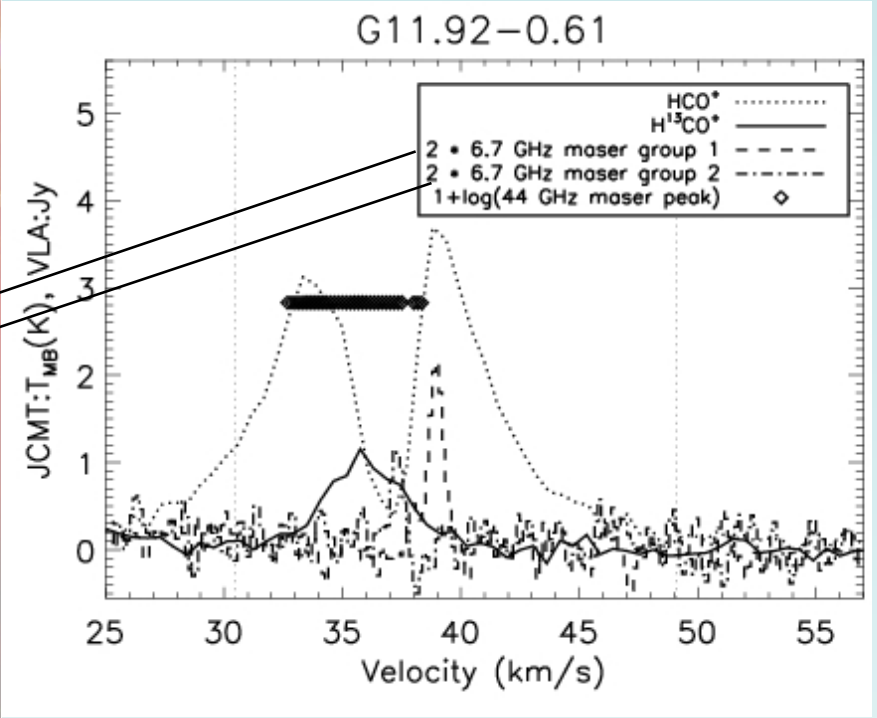
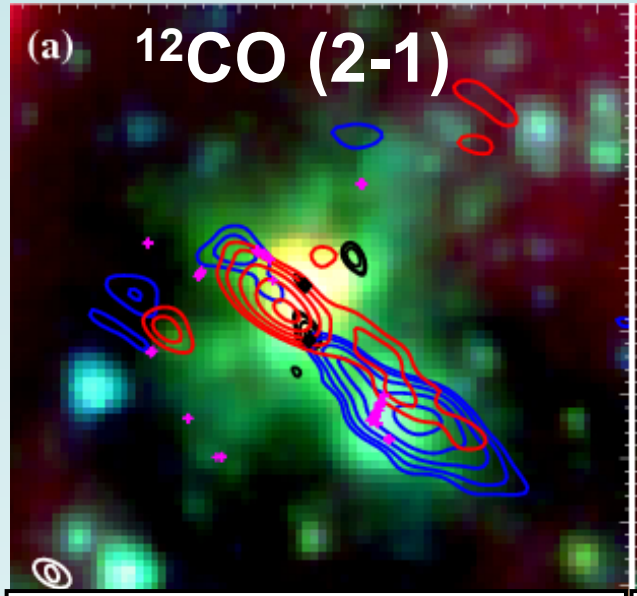


Image: Red: 8um, Green: 4.5um, Blue: 3.6um (GLIMPSE)
Yellow contours: MIPS 24 um
Magenta Crosses: 44 GHz Class I CH_3OH masers
Black Diamonds: 6.7 GHz Class II CH_3OH masers

Cyganowski et al. (2009)

Molecular Bipolar Outflows: G11.92-0.61

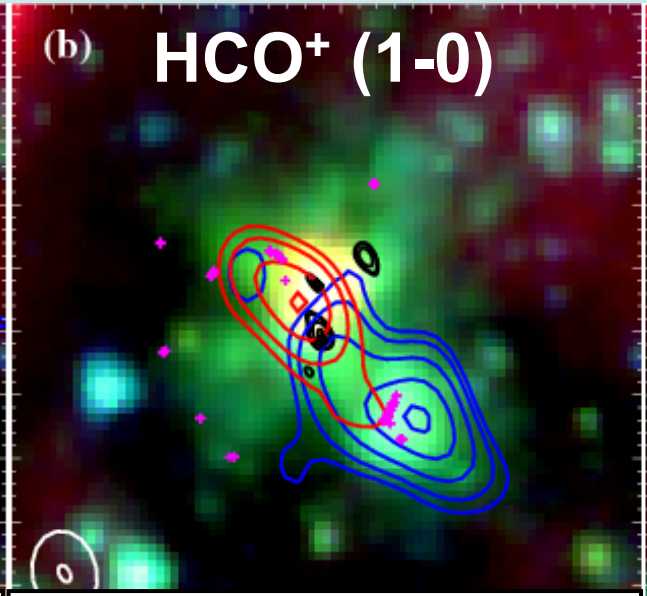
SMA



Outflow properties
M_{red}: 0.2 M_{sun}
M_{blue}: 0.6 M_{sun}
M_{total}: 0.8 M_{sun}
Length: 0.6 pc
t_{dyn}: ~ 5-6 x 10^3 yrs

Mass outflow rate:
~ 1.3 x 10^{-4} M_{sun}/yr

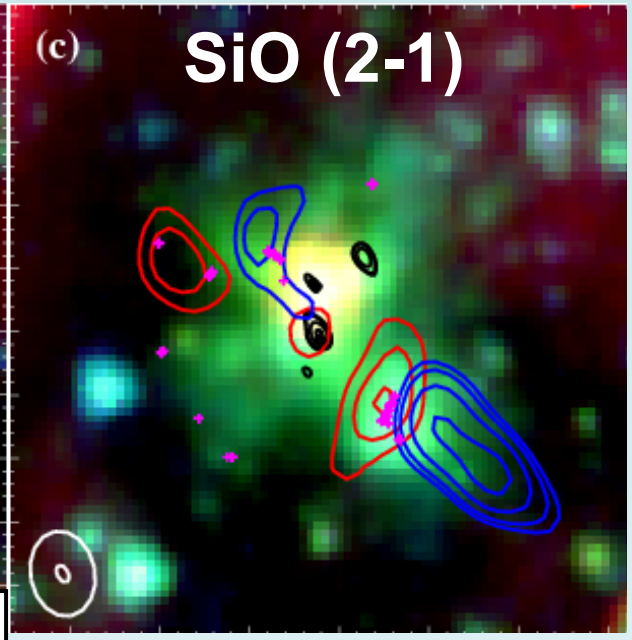
CARMA



Outflow properties
M_{red}: 2.6 M_{sun}
M_{blue}: 5.2 M_{sun}
M_{total}: 7.8 M_{sun}
Length: 0.6 pc

Mass outflow rate:
~ 1.4 x 10^{-3} M_{sun}/yr

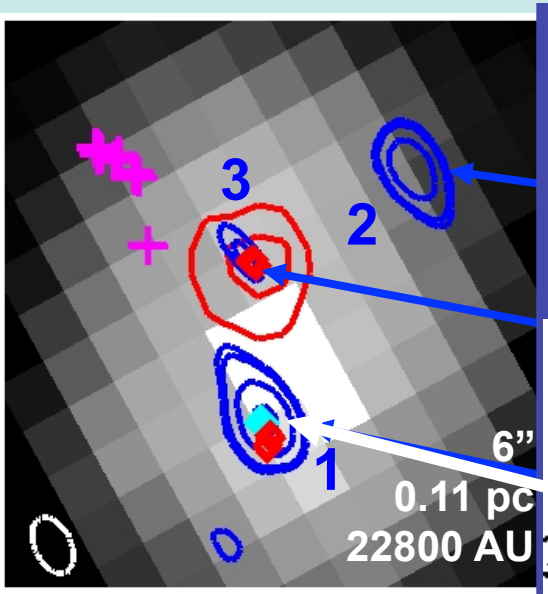
CARMA



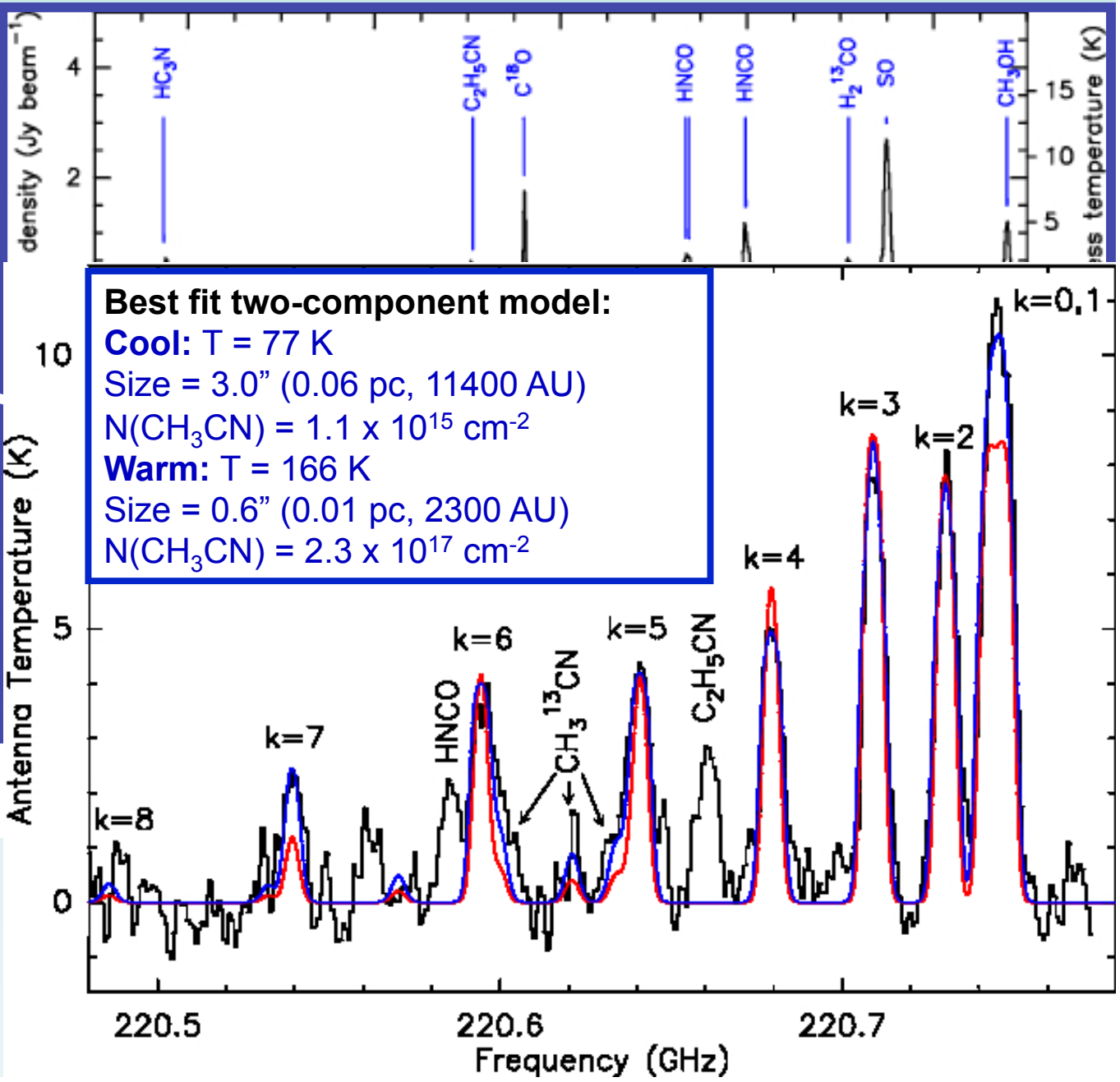
V_{LSR}~ 35 km/s
Red: v~ 45-54 km/s
Blue: v~ 8-25 km/s
~V_{LSR} ± 10 km/s

Cyganowski et al., 2011

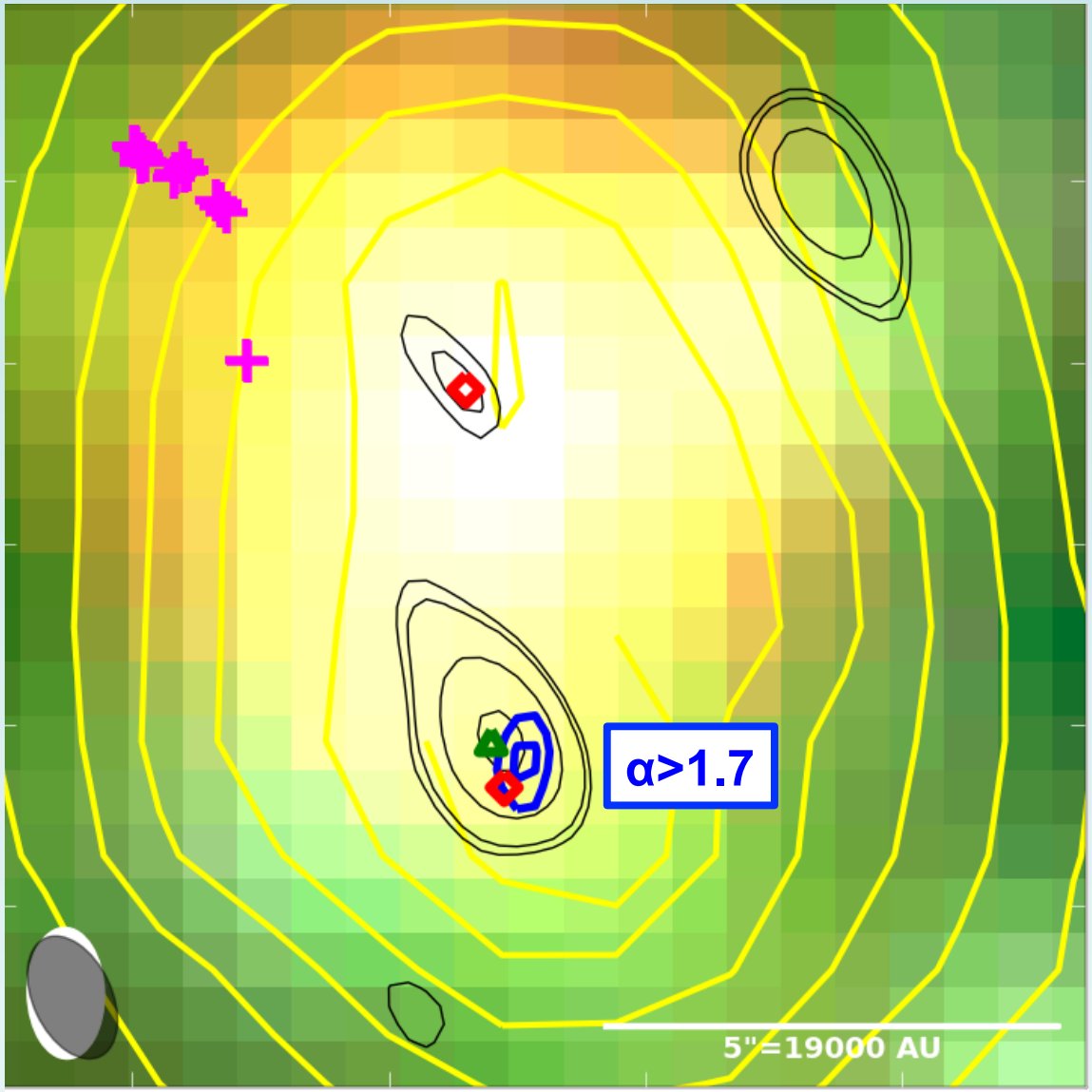
Compact Cores: G11.92-0.61



Greyscale: MIPS 24 um
Blue contours: CARMA 1 mm continuum
Red contours: GLIMPSE 8um
Filled ◊: H_2O maser
◊: 6.7 GHz CH_3OH masers
+: 44 GHz CH_3OH masers



Compact Cores and Cm Continuum: G11.92-0.61



GLIMPSE Images:
Red: 8um
Green: 4.5um
Blue: 3.6um

Yellow contours:
MIPS 24 um

Blue contours:
1.3 cm continuum

+ 44 GHz Class I CH_3OH masers

◊ 6.7 GHz Class II CH_3OH masers

△ H_2O maser

Cyganowski et al., in prep.

Summary and Conclusions:

- Catalog of >300 GLIMPSEI EGOs selects for *massive* young stellar objects *with outflows*
- High resolution surveys of indirect tracers (masers) confirm association of EGOs with *active* outflows and *massive* YSOs
- Case studies (high resolution observations of *direct* tracers) show:
  - outflow origin for extended 4.5 um emission
  - driving sources are hot cores and *NOT* UC HIIs
  - diversity in clustering properties and evolutionary state

EGOs are a promising new sample for studying (proto)stellar feedback during the crucial--and poorly understood--early active accretion phase