Massive Protoclusters:
Keys to Understanding Massive Star Formation

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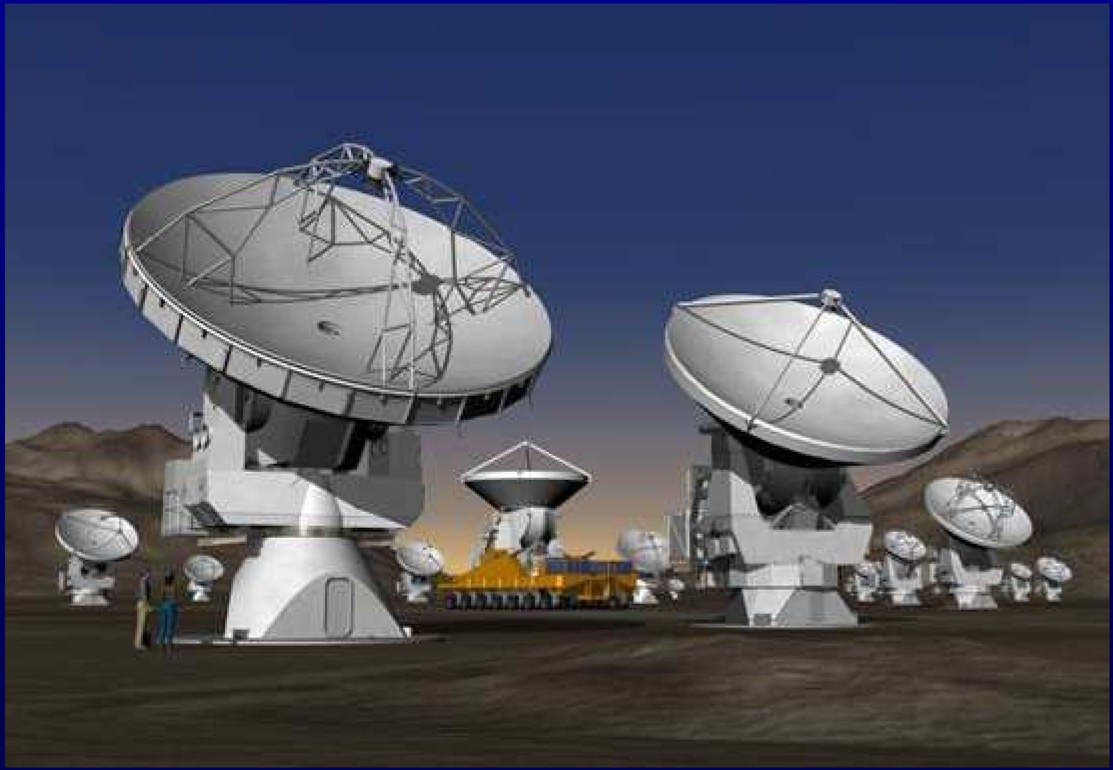
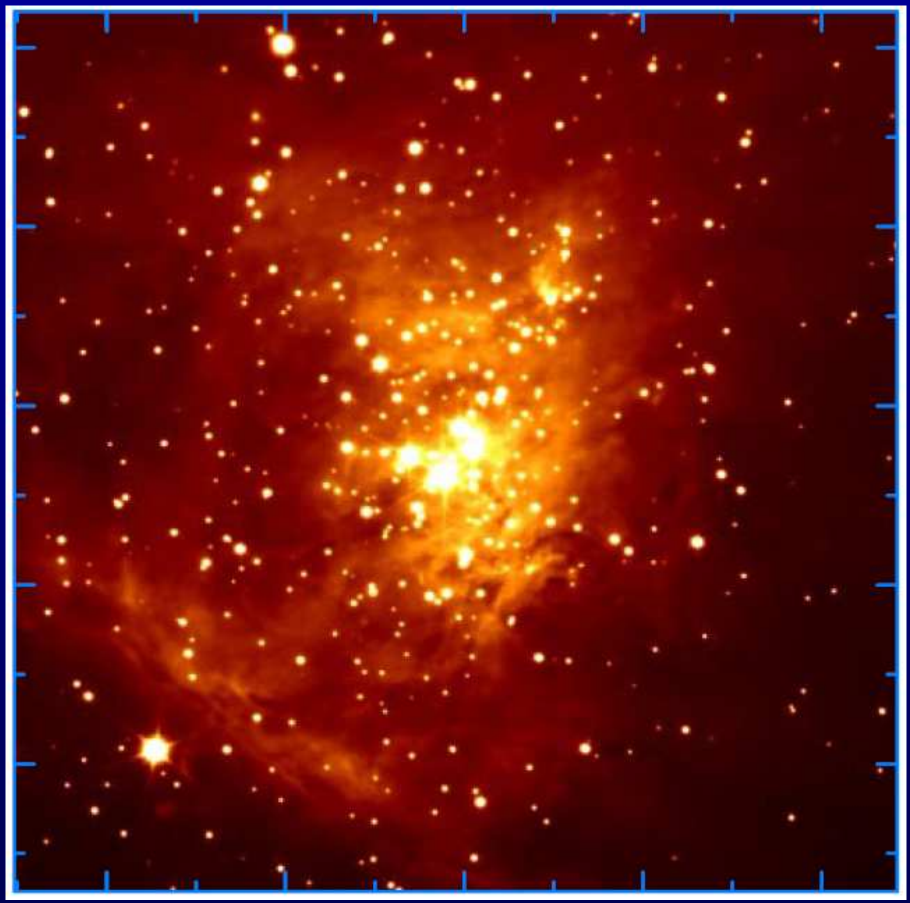


"Transformational Science with ALMA", Charlottesville, VA (June 22, 2007)

Some important features of clusters

- Mass segregation
- Rapid formation ~ 10^6 yr (small age spread)
- Common metallicity
- All massive stars form here



Not enough observational information for a unique theory

If we could examine clusters at earlier stages of formation, (i.e. “protoclusters”), we could add stronger constraints on SF theory.

How to detect a "protocluster"?

Phenomenological definition of protocluster stages

Klein et al. 2005

Stage	Morphology	Detectable at
0: PPclCs (pre-proto cluster core)	massive cloud core without collapse	mm
1: early protocluster	massive stars have begun to form deeply embedded in the cluster	mm
2: protocluster	the forming massive stars begin to clear a cavity, an HII region begins to evolve	mm, FIR, radio
3: evolved protocluster	the cluster starts to emerge, but is still embedded	mm, FIR, MIR, radio
4: young cluster	the cluster has emerged from its parental cloud	mm, FIR, MIR, NIR
5: cluster	the cluster has dispersed its parental cloud	MIR, NIR

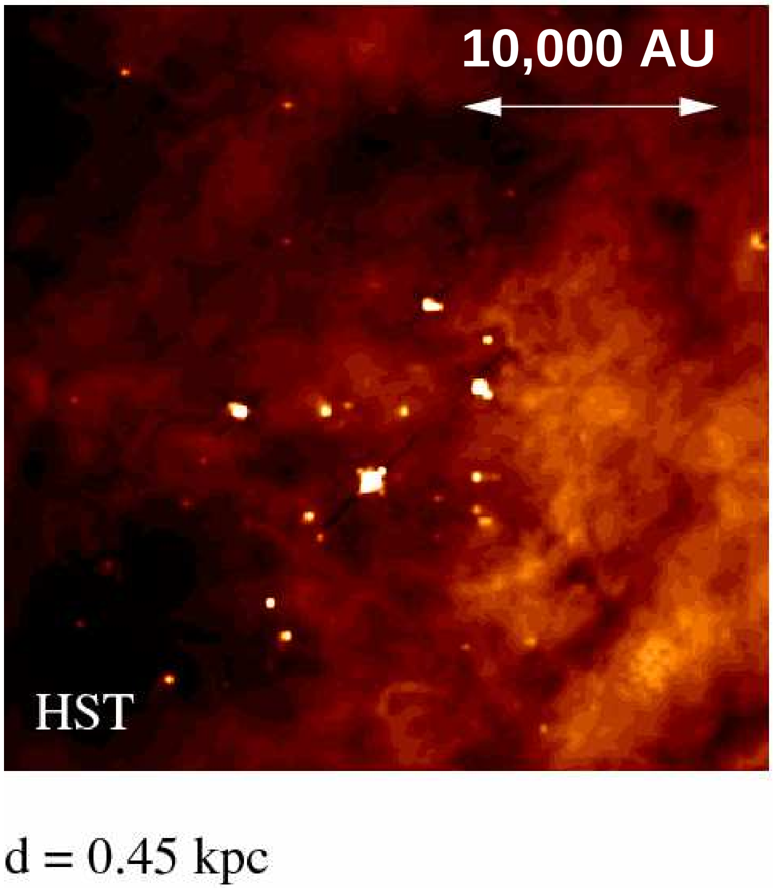
What does a massive protocluster look like?

A compact group of millimeter dust continuum sources with:

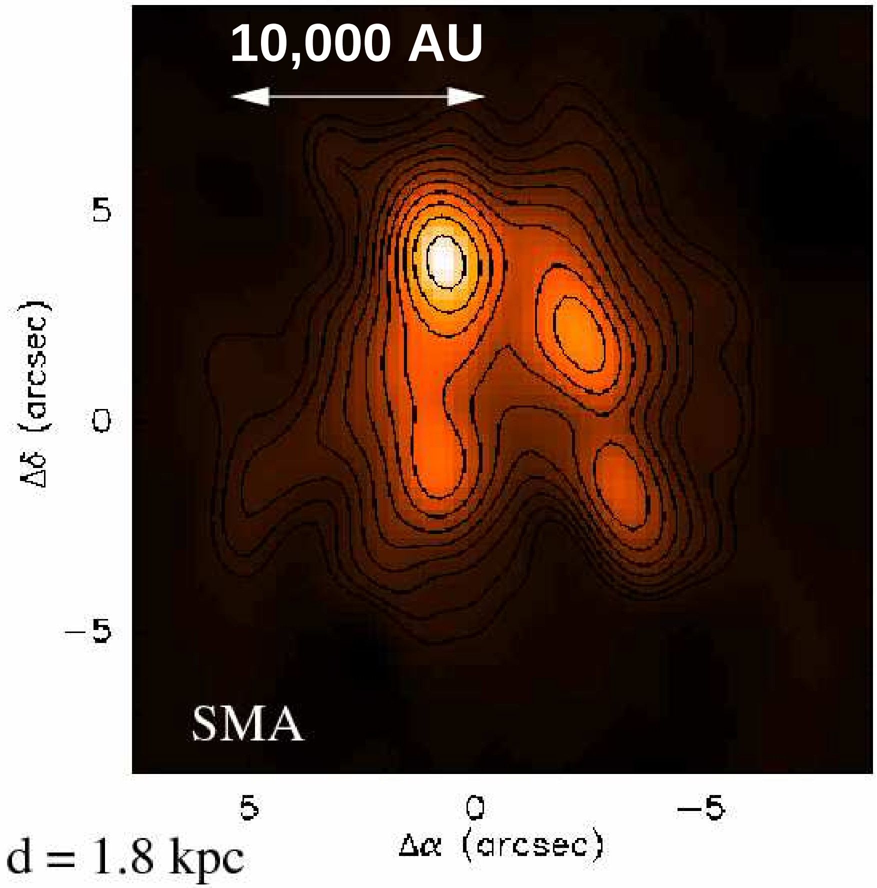
- Far-IR luminosity > 1000 $L_{\odot}$ (massive)
- Multiplicity ≥ 3 within 0.10 pc i.e. 3000 pc^{-3} (~Orion) < 10'' at 2 kpc (cluster)
- Majority of components lacking near-IR and mid-IR counterparts (proto)

What will a massive protocluster look like?

Trapezium in H Alpha



NGC 6334 I at 1.3 mm

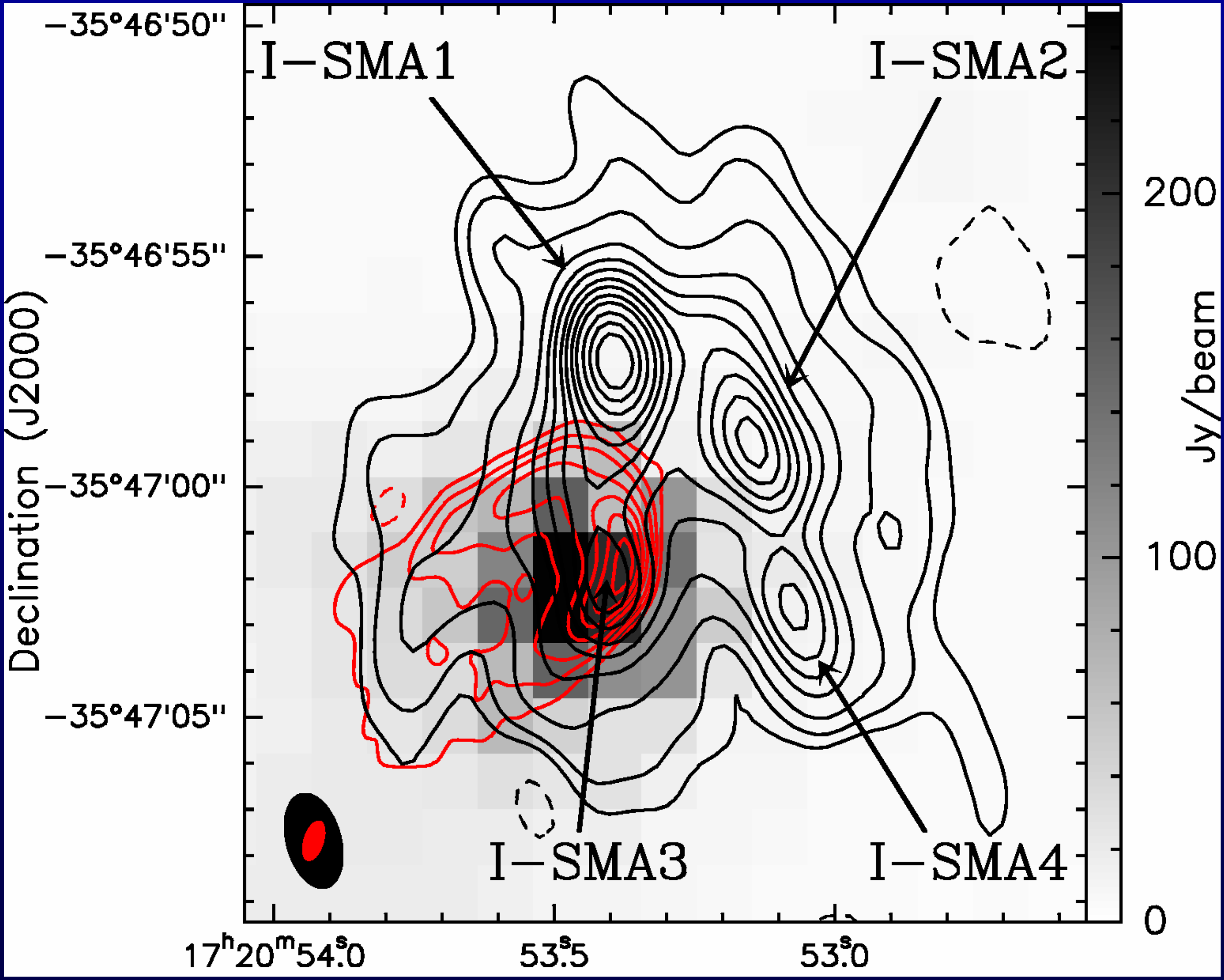


Comparable linear scale

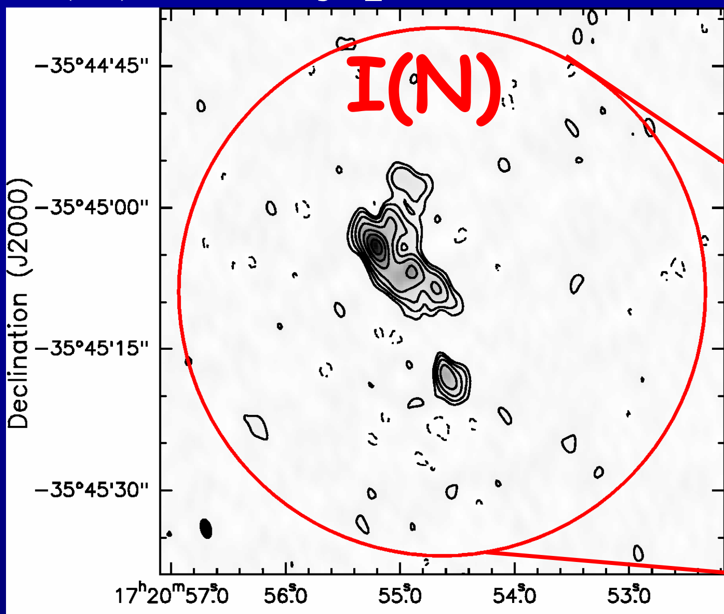
Comparable luminosity

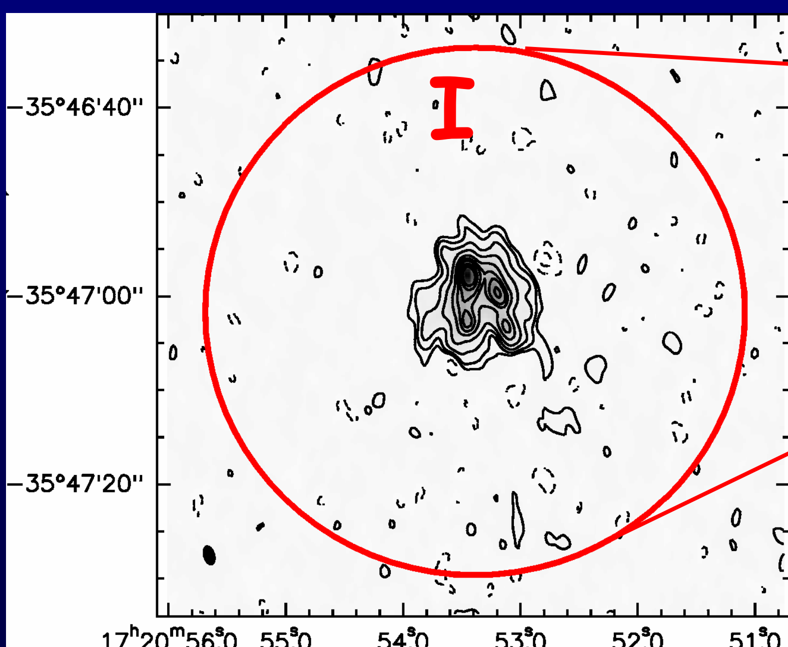
“An HII region begins to evolve”

Grayscale: Spitzer 3.6μm, Red contours: UCHII region



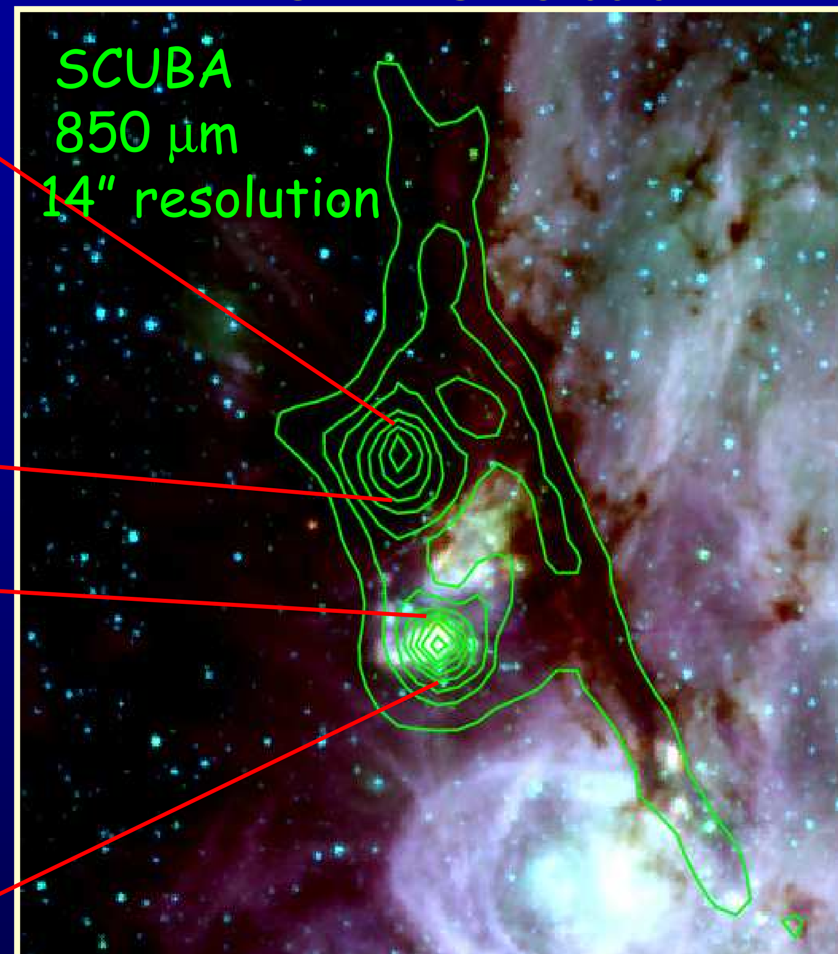
I(N): “early protocluster”





NGC 6334I

GLIMPSE 3-color



At 1.7 kpc, 2″ = 3400 AU

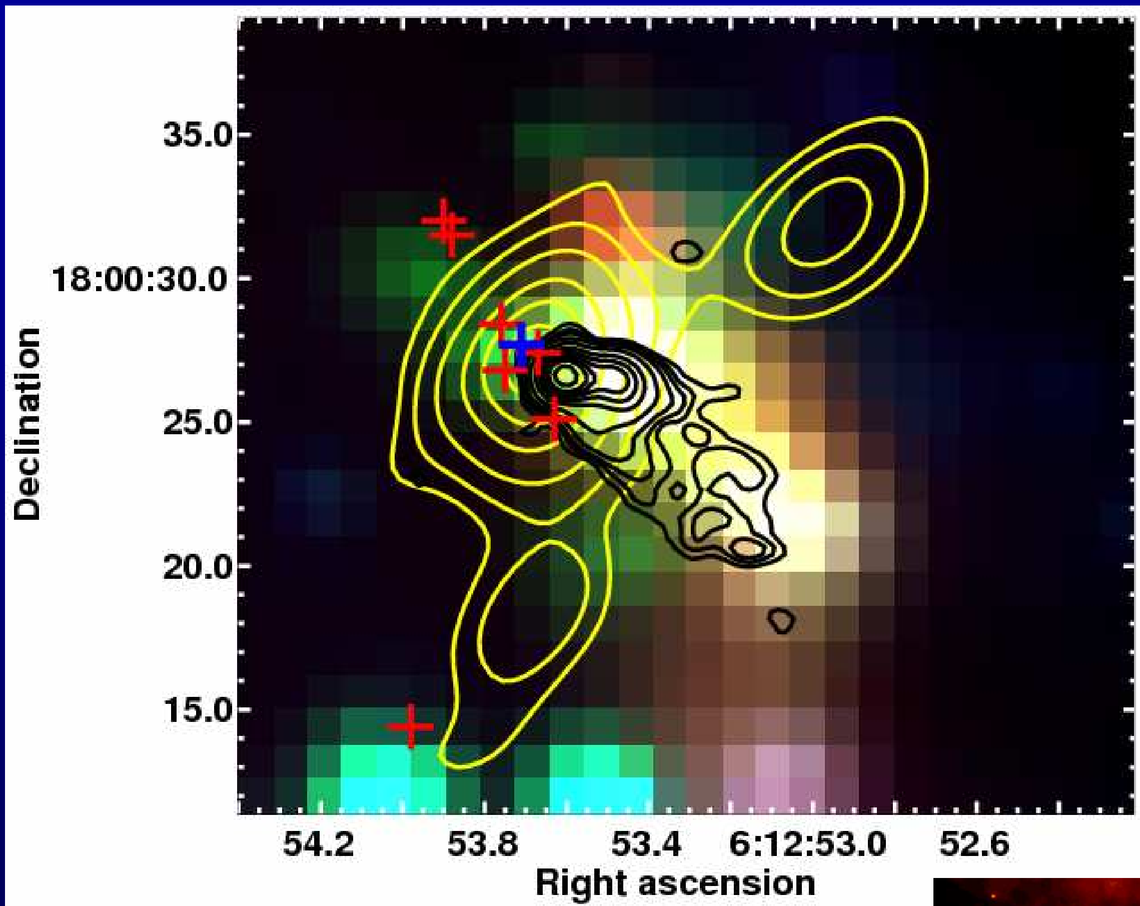
Hunter et al. (2006)

Recently-found protoclusters at 1.3mm

Field	Multiplicity	Luminosity	Paper
NGC 6334 I	4	$10^{5.4}$ $L_{\odot}$	Hunter et al. 2006
S 255 N	3	$10^{5.0}$	Cyganowski et al. 2007
Ceph-A East	5	$10^{4.3}$	Brogan et al. 2007
IRDC G24.60+0.08	5	$10^{4.0}$	Rathborne et al. 2007
IRAS 05358+3543	4	$10^{3.8}$	Beuther et al. 2007
NGC 6334 I(N)	6	$10^{3.4}$	Hunter et al. 2006
AFGL 5142	5	$10^{3.4}$	Zhang et al. 2007
IC 1396 N	3	$10^{2.5}$	Fuente et al. 2007

This is a rapidly-advancing field and this is by no means an exhaustive list!

Another example: S255N (d=2.6 kpc)



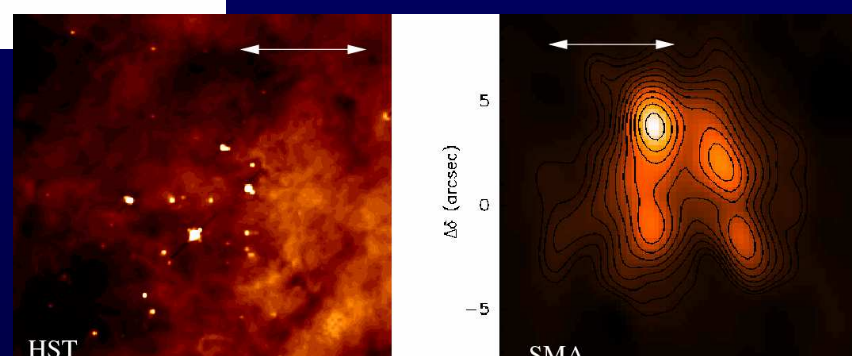
IRAC 3-color image

Black = UCHII region

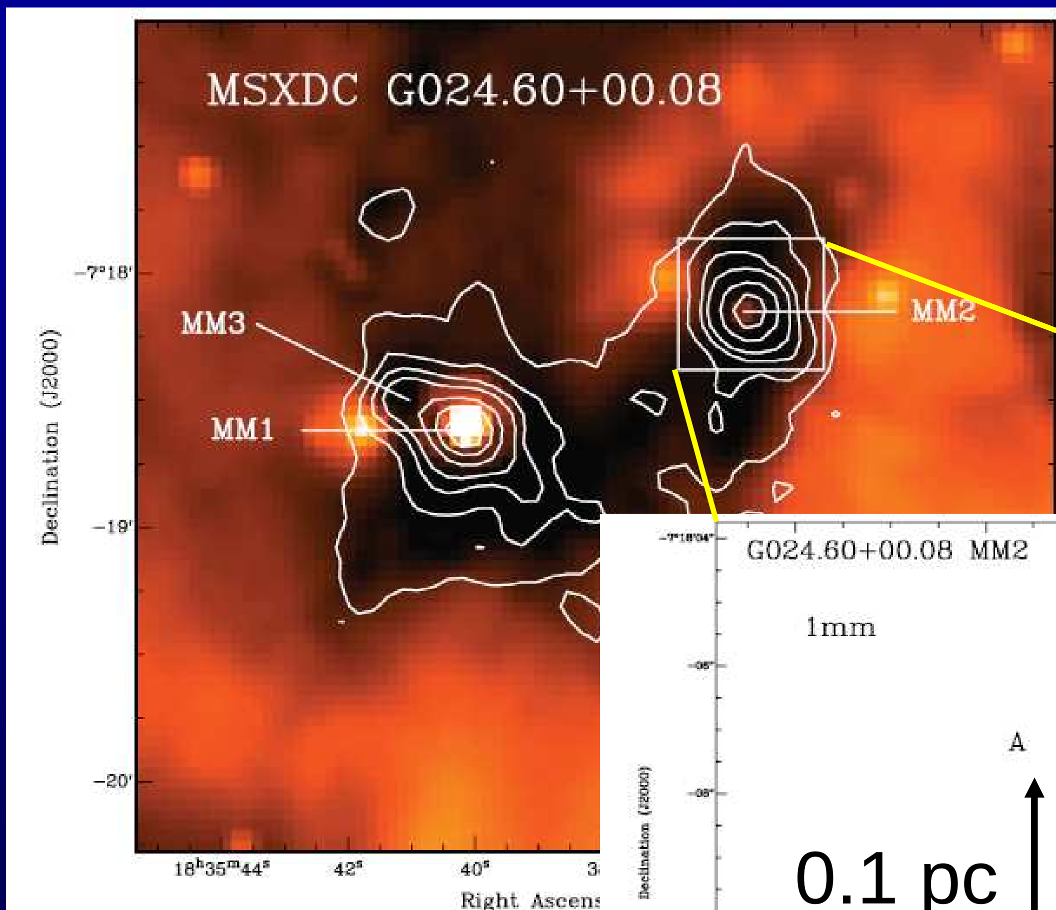
Yellow = 1.3mm dust

(Cyganowski, Brogan, & Hunter, 2007)

Trapezium & NGC 6334 I images shrunk to the same physical scale



IRDC G24.60+0.08, L ~ $10^{4.3}$ $L_\odot$

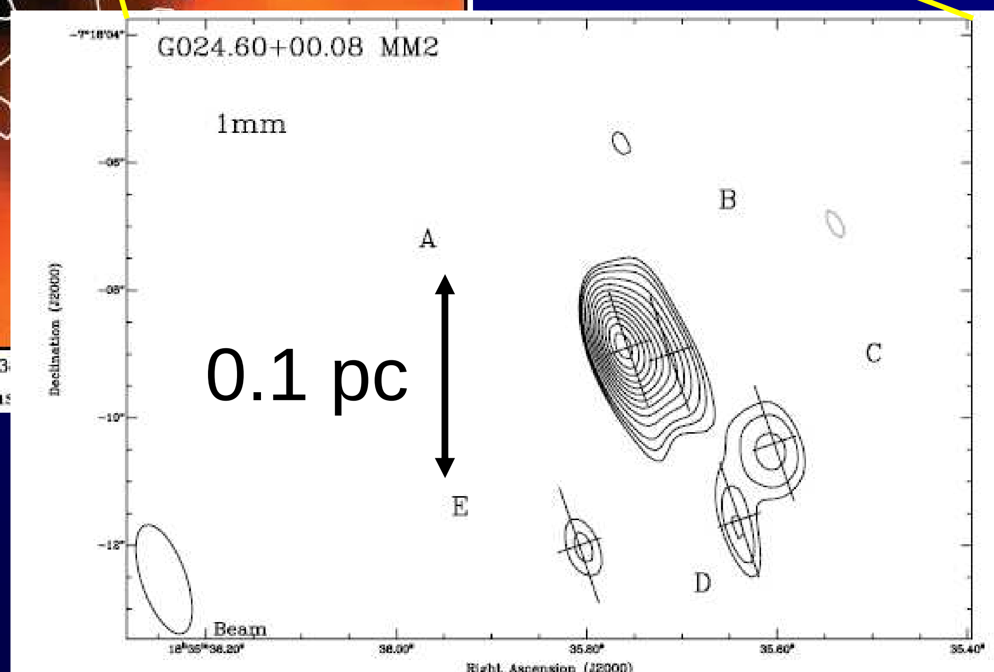


PdBI observations

6.5 kpc, 1.9” x 0.7”

12000 x 5000 AU

(Rathborne et al. 2007)

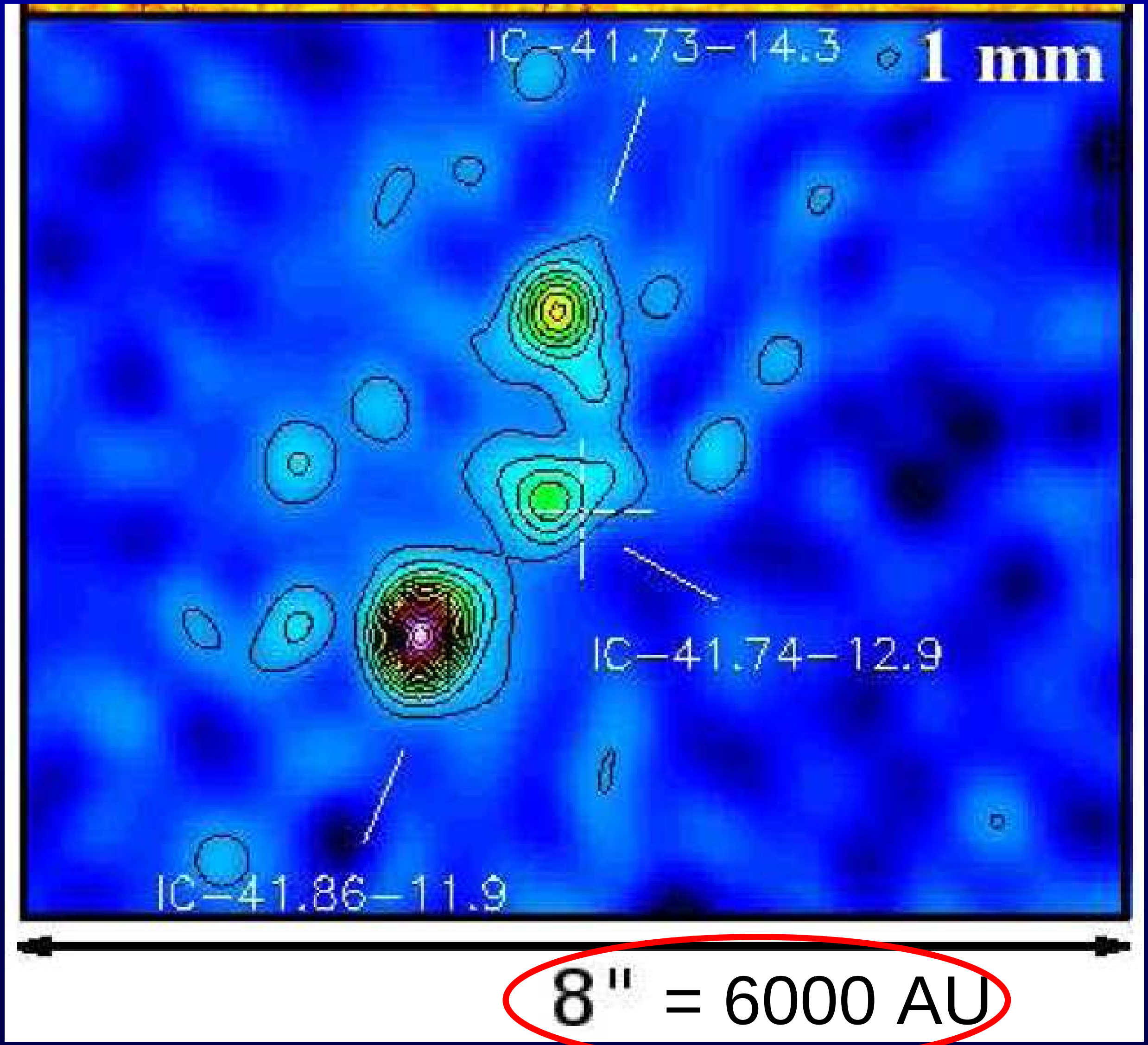


Lower mass example: IC1396N

PdBI
1.3 mm

L~300 $L_\odot$
Herbig Ae
0.75 kpc

Fuente
et al. (2007)



ALMA will reveal the Big Picture

1. Even low mass protostars & protostellar disks will be detectable out to several kpc ➔ more complete census of protoclusters, even if invisible in the IR

Low-mass disks in continuum:

~ 100 mJy at 345 GHz at 140 pc (SMA; Andrews & Williams 2007)

ALMA sensitivity ~ 0.045 mJy rms in 30 minutes:

10σ detection out to 2.0 kpc

In spectral lines, e.g. $H^{13}CN(4\text{-}3)$:

~ 1.4 Jy at 220 pc (NGC1333 IRAS2A, SMA; Jorgensen 2005)

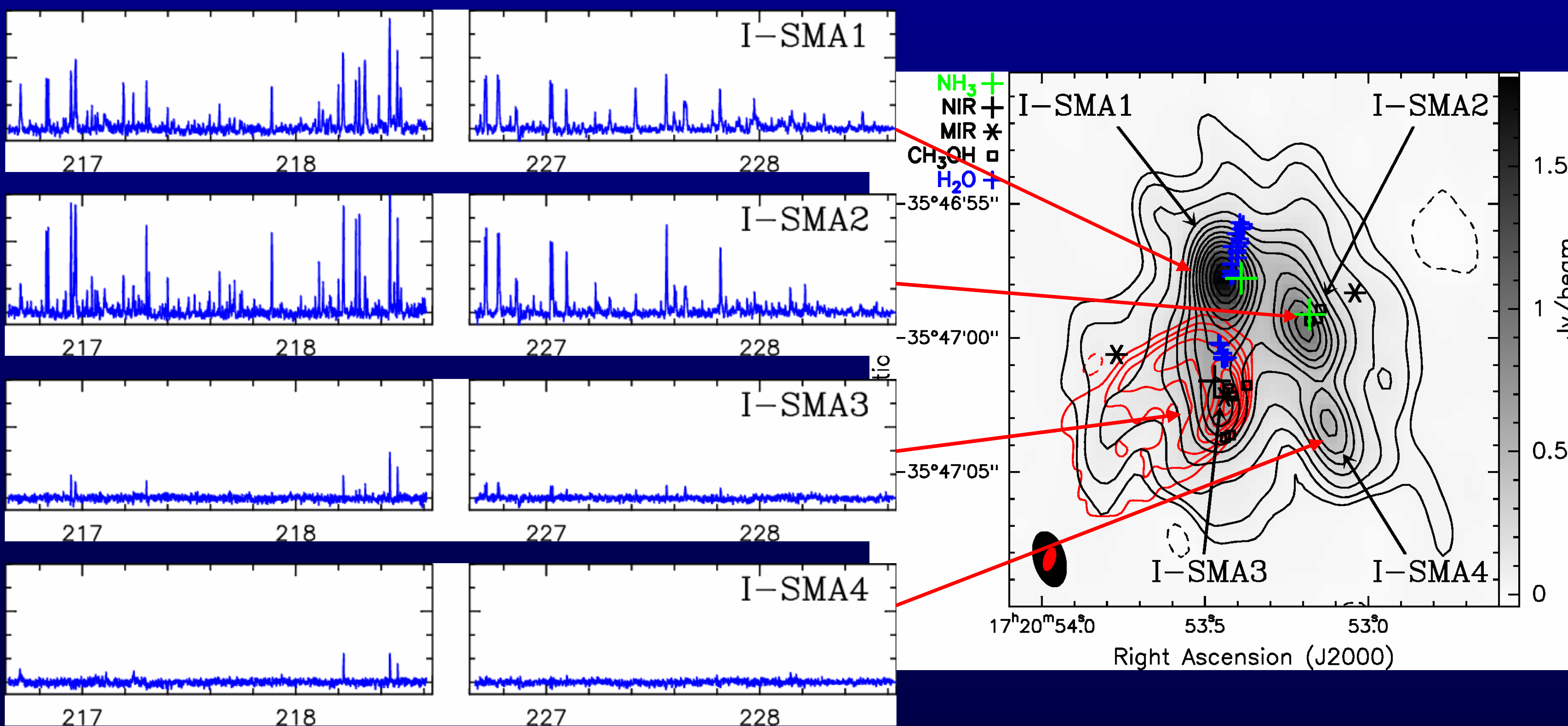
ALMA sensitivity ~ 3 mJy rms in 30 minutes (2km/s):

10σ detection out to 1.5 kpc

Challenges: sorting out the individual luminosities, masses, grain properties, and ages

ALMA will reveal the Big Picture

2. Line emission from dense, optically-thin gas will provide the velocity dispersion of the cluster and help pinpoint evolutionary state of members



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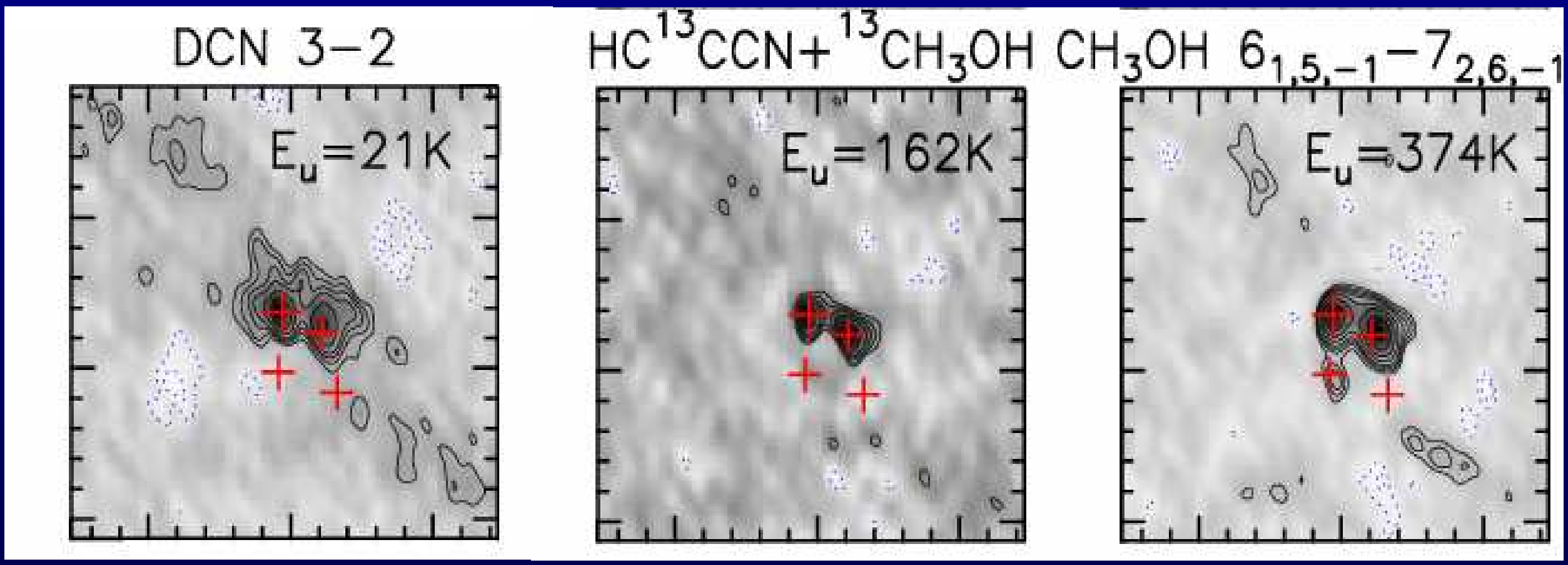

Summary

1. ALMA will provide an unprecedented census (IMF) of protoclusters, even while they are still invisible in the infrared

2. ALMA will measure the velocity dispersions which could be a key discriminator between SF theories

   - Protostars may retain velocity of progenitor core
   - Does velocity dispersion of cores affect IMF?
   - Are number densities high enough for mergers?

3. Comparative chemistry will also provide powerful diagnostics of evolutionary state