Filament fragmentation and the youngest star formation within OMC

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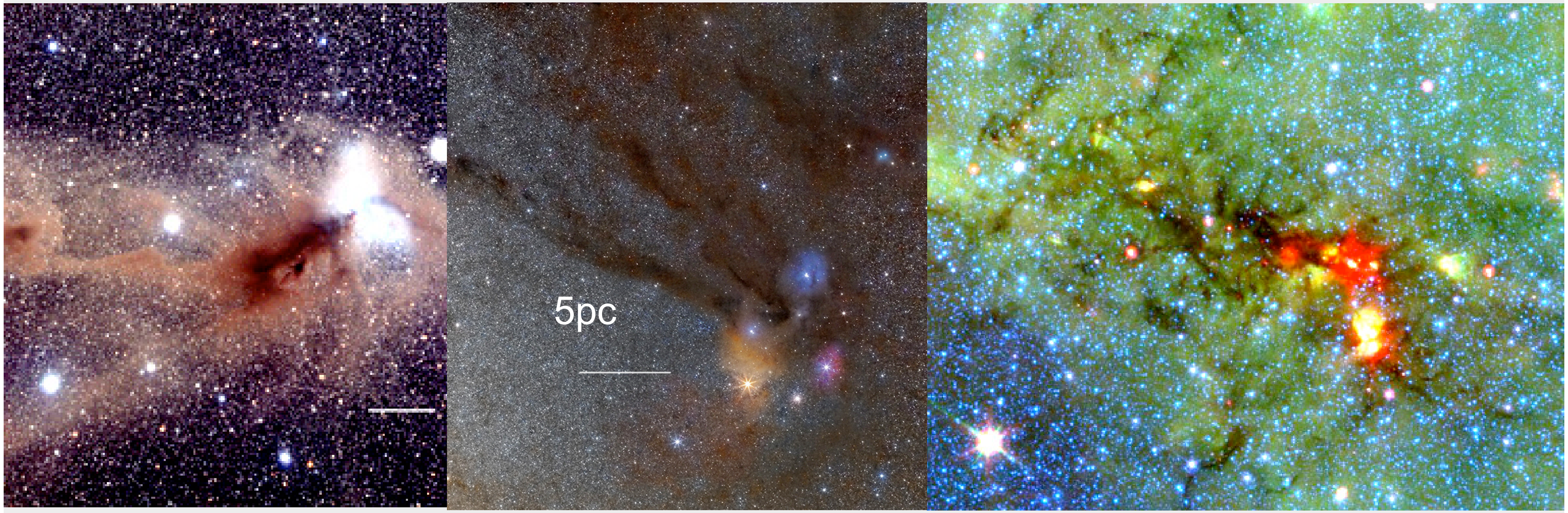
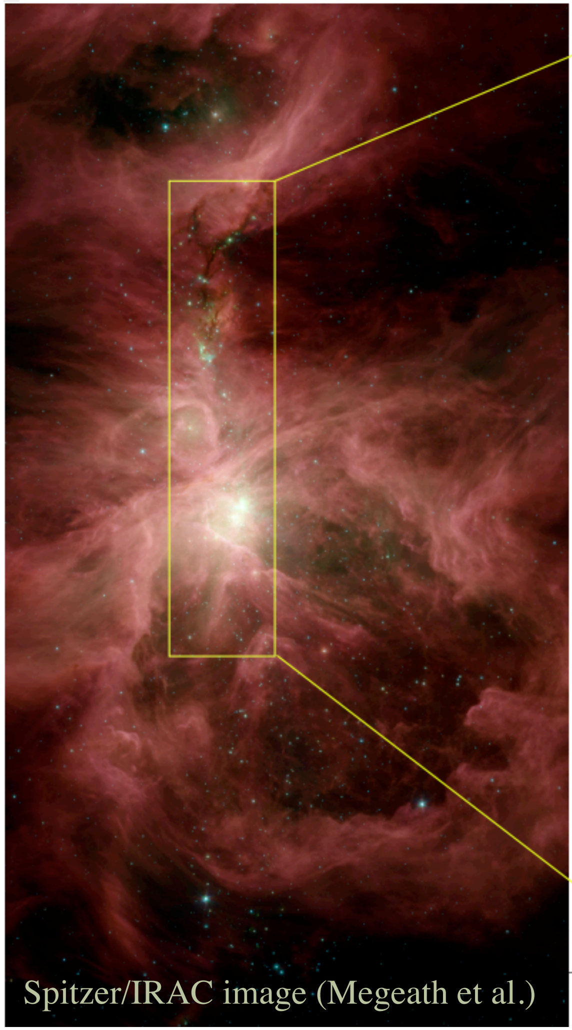
Introduction & Motivations

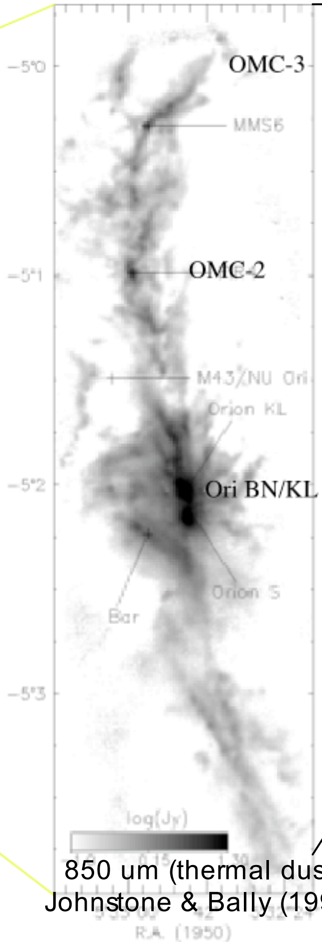


- Majority of stars (90%) form as members of young stellar clusters (e.g., Lada & Lada 2003; Parras et al. 2003).
- Young star-clusters are always associated with filamentary structures ($N_{H2}>10^{22}$ cm^{-2}; e.g.,Taurus, Serpens, Ophucus, Orion, NGC 1333, IRDCs; Myers 2009)
- Physical relation between large-scale filamentary structure and individual starformation/protocluster forming sites is important to understand I.Cs. of SFs
- Orion Giant Molecular Clouds A is one of the nearest targets (d~414 pc)

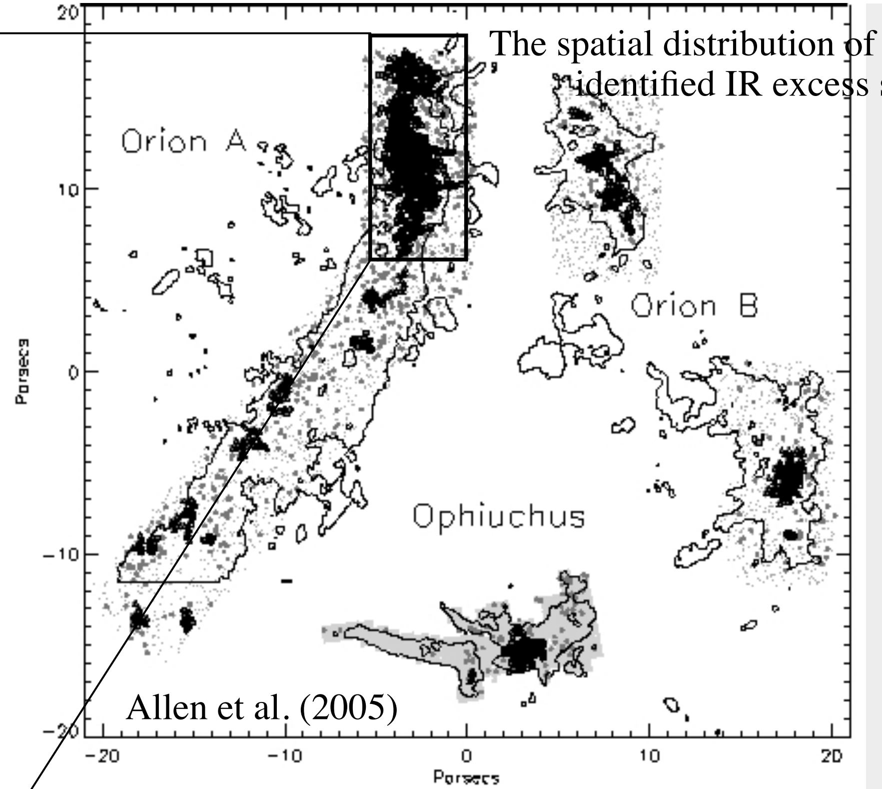
Orion Molecular Cloud (OMC)

• Remarkable filamentary structures (e.g., Johnstone & Bally 1998)
• Number of IR excess sources and submm continuum sources
(e.g., Chini et al. 1997;Lis et al. 1998;Nielbock et al. 2003;Allen et al. 2004;Williams et al. 2003;Peterson & Megeath 2008; etc.)


Spitzer/IRAC image (Megeath et al.)



850 um (thermal dust)
Johnstone & Bally (1999)

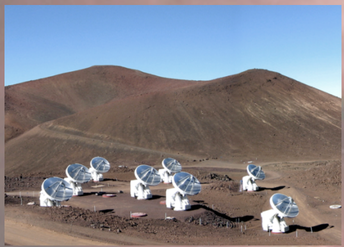


The spatial distribution of Spitzer identified IR excess sources
Allen et al. (2005)

- Orion A contains M_{gas}~5x10^4 Mo (Bally et al. 1989)
- 208 infrared excess sources in the OMC-2/3 region (Nielbock et al. 2003; Allen et al. 2005; Peterson et al. 2003)

25 AU

Goals of Our OMC Project



- *SMA*

1.3mm/0.85mm
Angular resolution: ~5"
mass sensitivity: 0.1 Mo

- *EVLA*

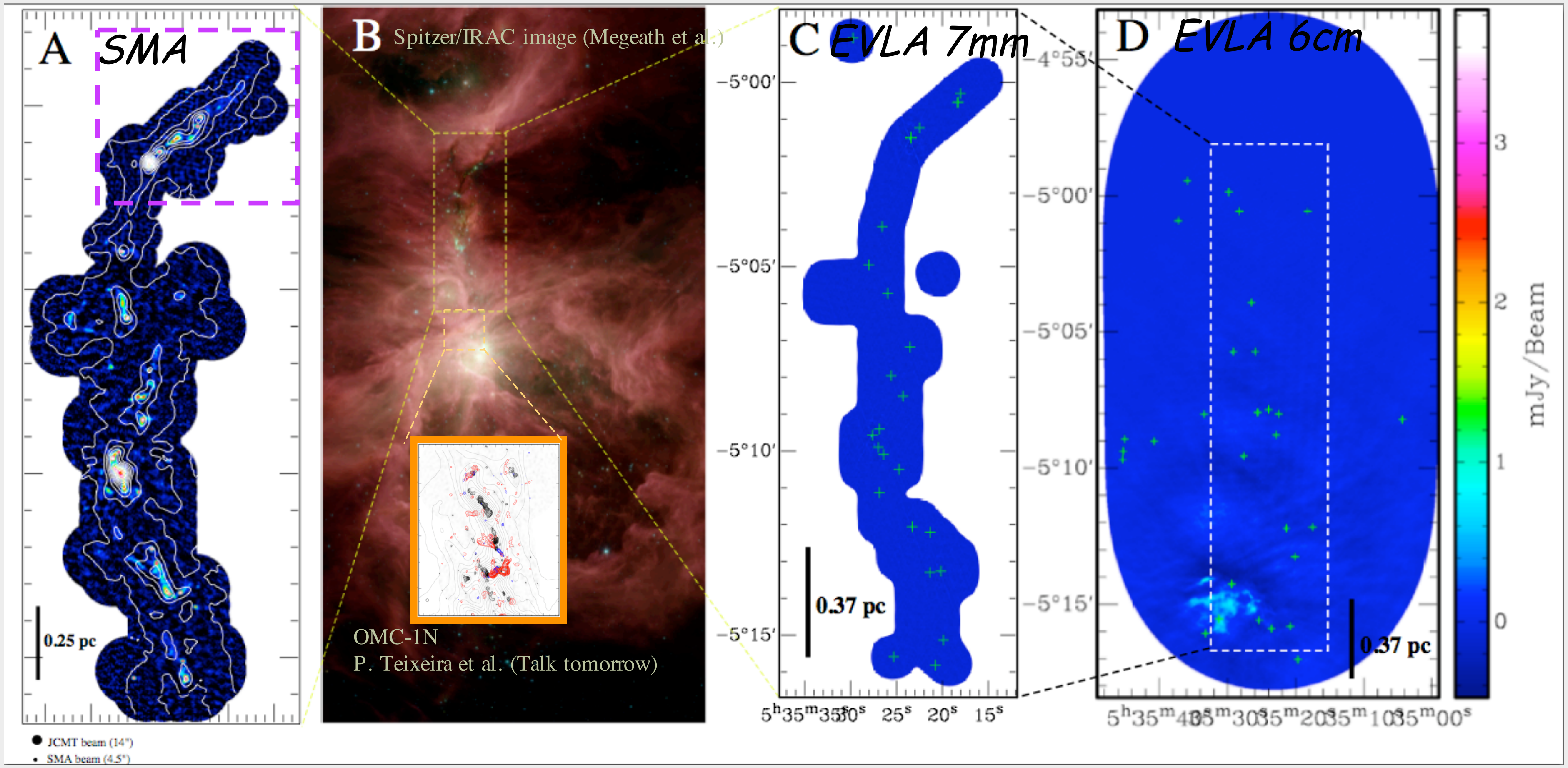
7mm/4cm/6cm
Angulr resolution: ~0.5"
mass sensitivity: 0.07 Mo

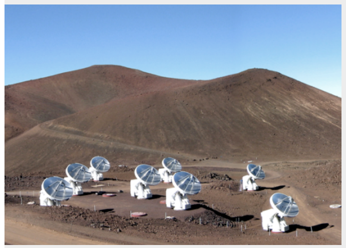
(1) Large Scale: Fragmentation properties within molecular filaments
- Resolving protocluster member with a few 100 AU scale
- Hierarchical fragmentation from 10 pc down to 100 AU scale
- ICMF ⇄ IMF, Star formation Efficiency
- Stellar evolution along the filaments

(2) Individual source: physical properties of pre-/proto-stellar cores
- Initial physical conditions of embedded star/protocluster member (density structure, size, mass, spatial distribution etc..)
- Multiplicity in the protostellar phase & their nature
- Dust properties within envelopes/circumstellar disks

Ongoing OMC projects

Resolving Protostars within filaments





- *SMA (197 fields)*

1.3mm/0.85mm

Angular resolution: ~4.5"

mass sensitivity: 0.1 Mo

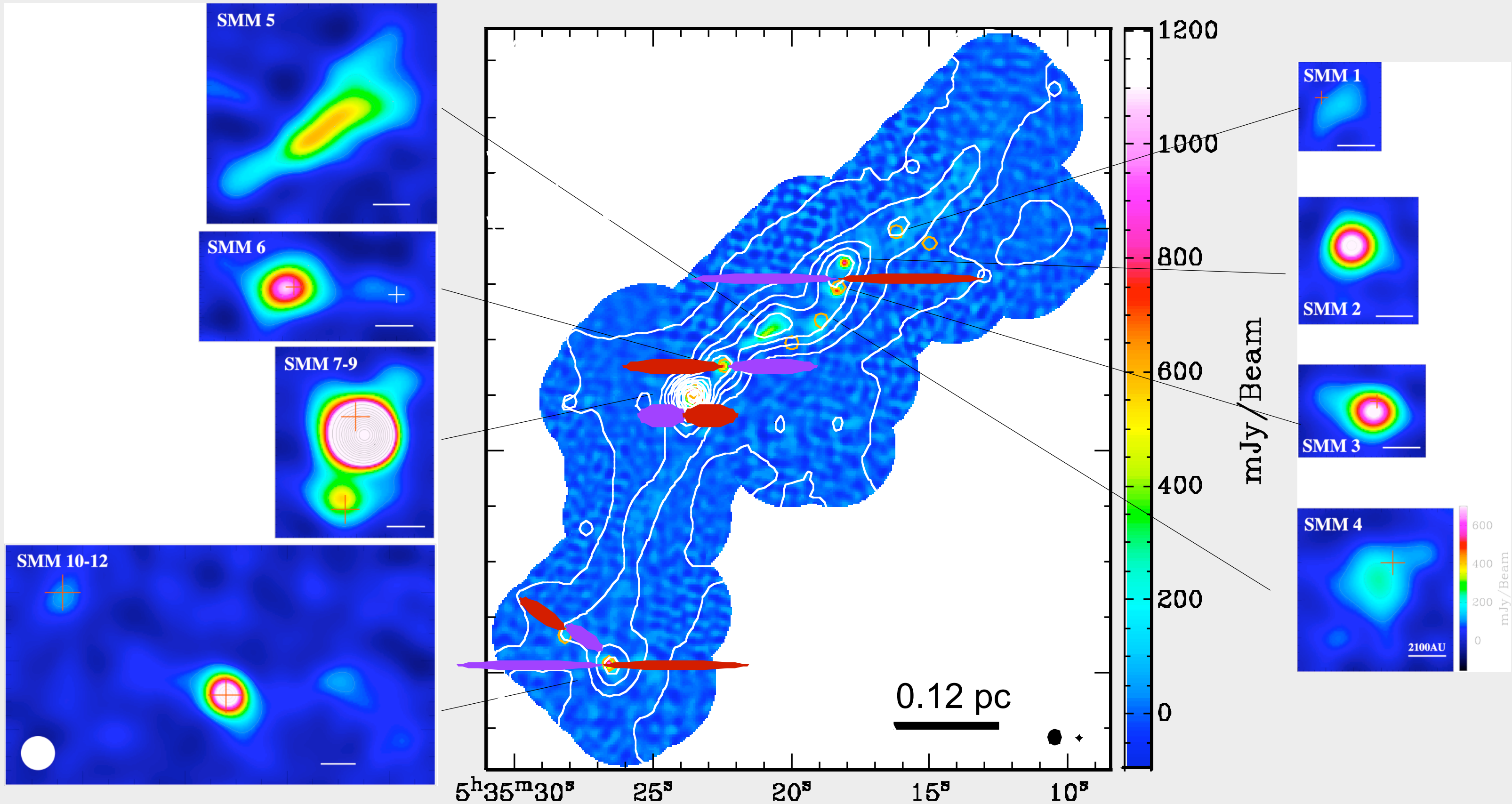
- *EVLA (68/5 fields)*

7mm/4cm/6cm

Angular resolution: ~0.5"

mass sensitivity: 0.07 Mo

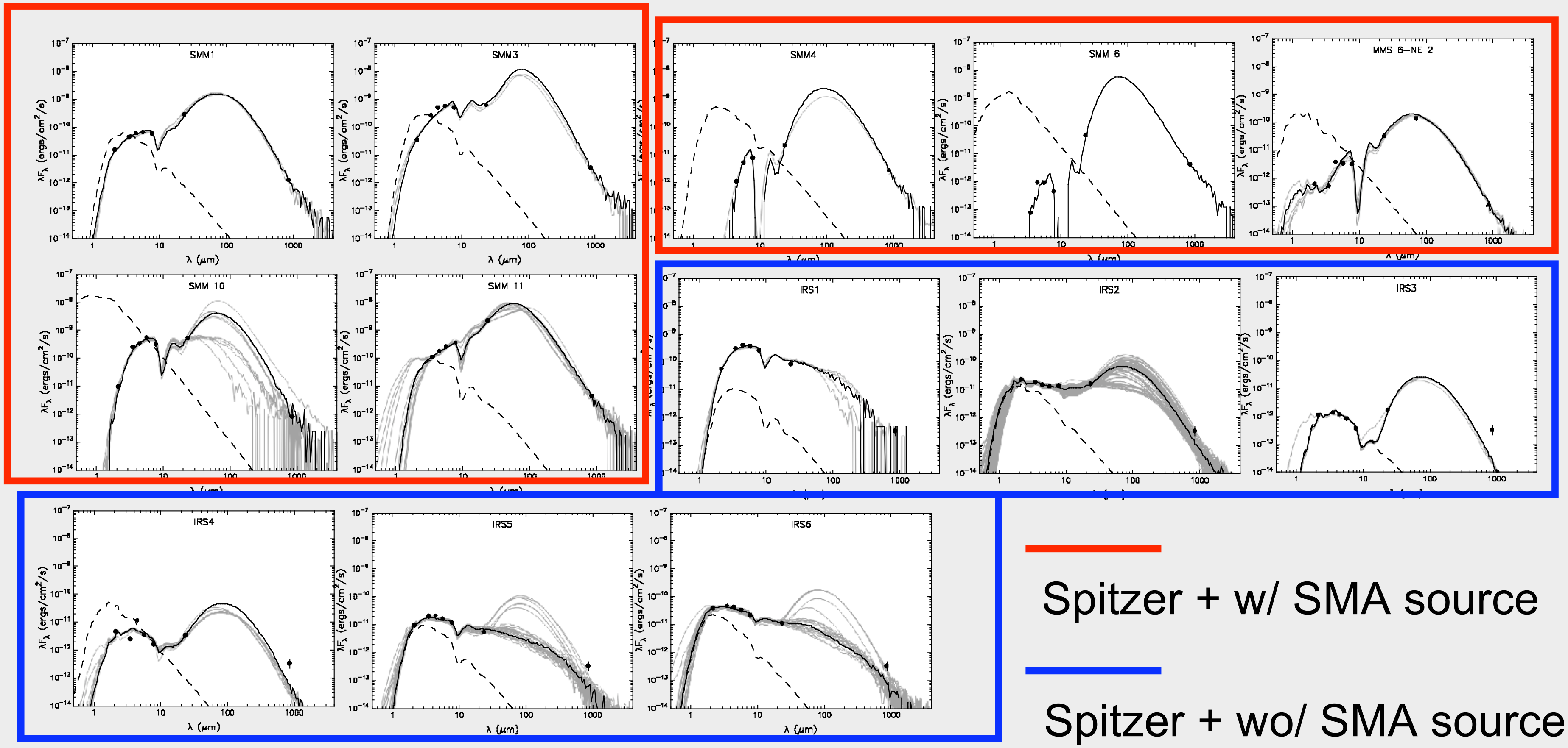
Embedded Sources in OMC3



- 12 continuum sources were detected and spatially resolved at SMA 850 um.
- 16 % recovering flux compared with JCMT/SCUBA data
- There are 16 infrared sources;(detected by Spitzer observations; Peterson & Megeath 2008)
    - 8/12 (67%) sources: w/ Spitzer sources (c.f. Takahashi et al. 2008; Peterson & Megeath et al.2008)
    - 5/12 (42%) sources: w/ Molecular outflows (c.f., Takahashi et al. 2008)

Spectral Energy Distributions

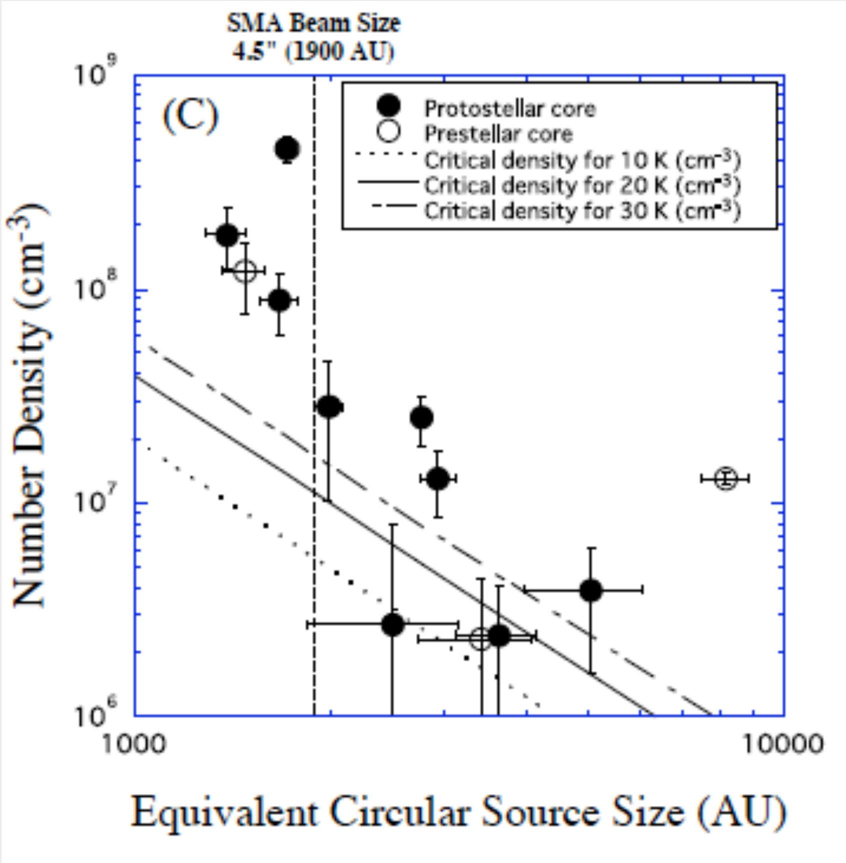
- SMA 850um continuum detected sources vs. non-detected sources



Spitzer + w/ SMA source

Spitzer + wo/ SMA source

Properties of Continuum Sources



Jeans Length:

$$\lambda_{\text{frag.}} = \sqrt{\frac{\pi c_s^2}{G\rho_0}}$$

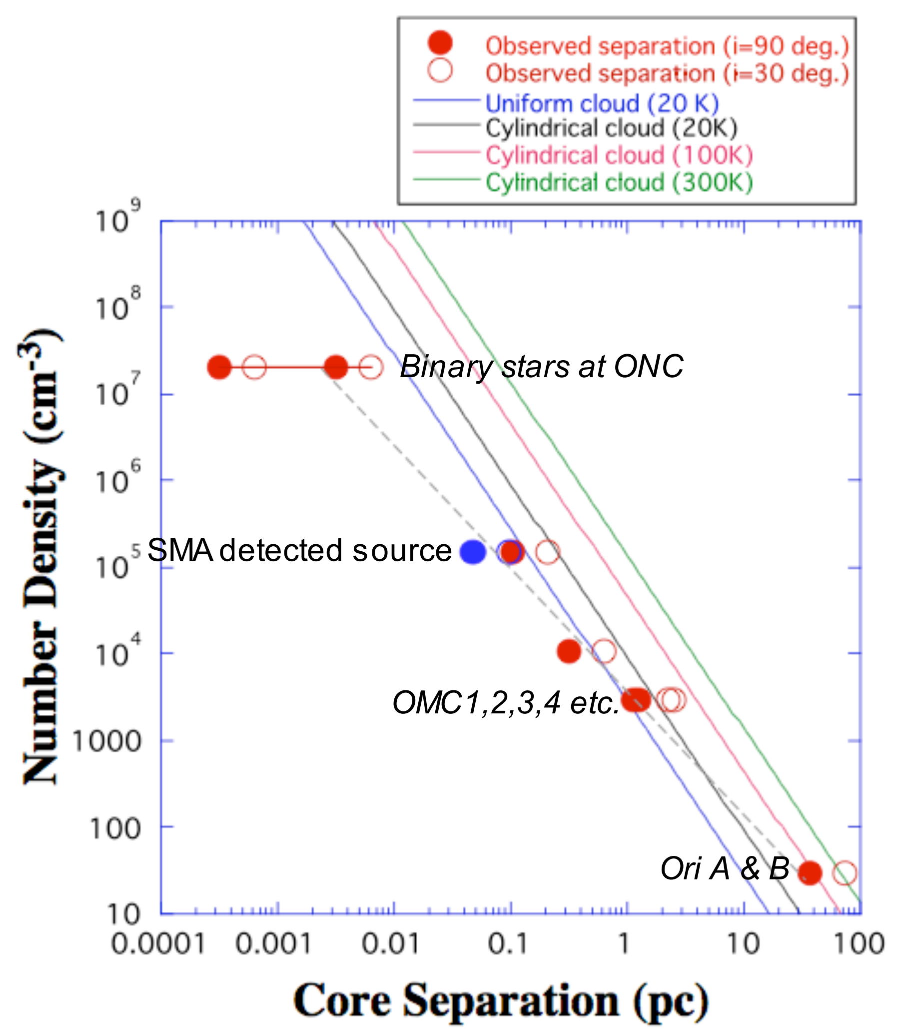
$$c_s = \sqrt{\frac{kT_{\text{gas}}}{\mu m_H}}.$$

Relation between critical number density vs. source size:

$$\rho(\lambda_{\text{frag.}}) = \frac{\pi k}{G\mu m_H}\frac{T_{\text{gas}}}{\lambda_{\text{frag.}}^2}$$

- Most detected sources likely gravitationally unstable
- Some may be collapsing <-> support multi-wavelength results

Fragmentation Properties



References-- Myers P.C., (1978); Maddalena et al. (1986); Dutrey et al. (1991); Dutrey et al. (1994); Hanawa et al. (1993); Wiseman & Ho (1998); Cesaroni & Wilson (1994); Johnstone & Bally (1999); Reipurth et al. (2007)

❖ *Maximum Instability Size* *(Nakamura et al. 1992)*

$$\lambda_{\rm frag.} \sim \frac{20 c_s}{\sqrt{4\pi G \rho_c}}$$

for cylindrical clouds

❖ *Shallower slope than thermal fragmentation*
→ $N \propto R^{-1.4}$ (c.f., $\propto R^{-2}$ for Jeans length)
→ Cloud temperature effect or Turbulence?

❖ *Fragmentation ~ most unstable mode (or slightly smaller than λ_{frag})*

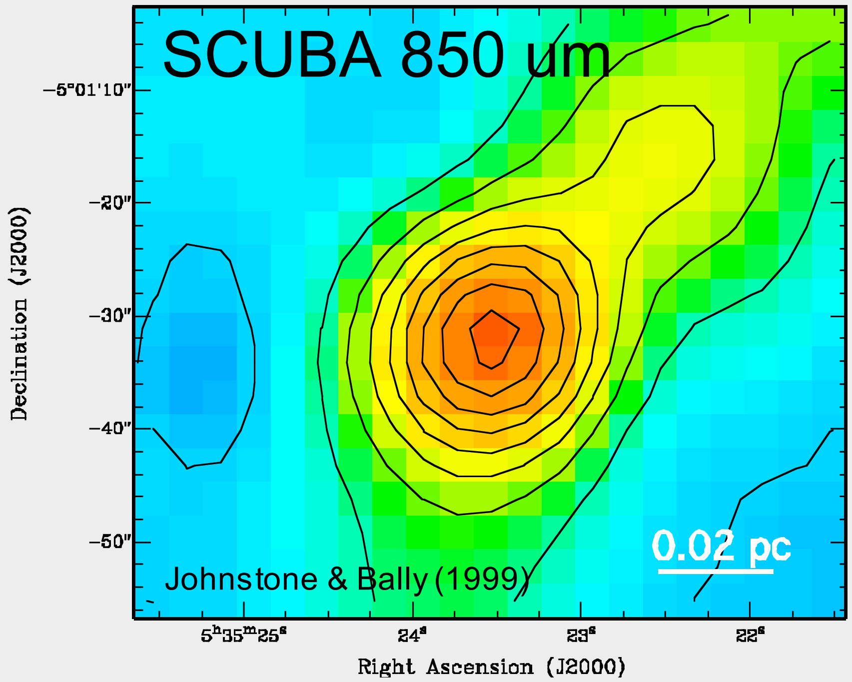
❖ *Most unstable mode might be shorter than λ_{frag} when the magnetic field and/or rotation are strong (e.g., Nakamura et al. 1992)*

❖ *Rotation Wide-scale binary separation ~ same trend as the hierarchical structure*
--> Related to next fragmentation scale?

Brightest continuum source in OMC-3/MMS6

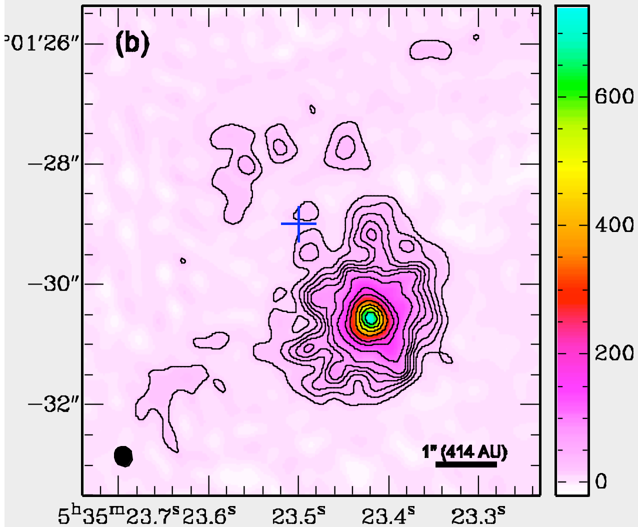
- Intermediate mass source: (>60Lo, 36 Mo; Chini et al. 1997)
- MMS 6-main: no IR source, large-scale jet/outflow ⇄ Starless?
- Brightest & compact continuum among OMC-2/3 sources
- p=-2 at outer radius ⇄ density structure of the prestellar phase

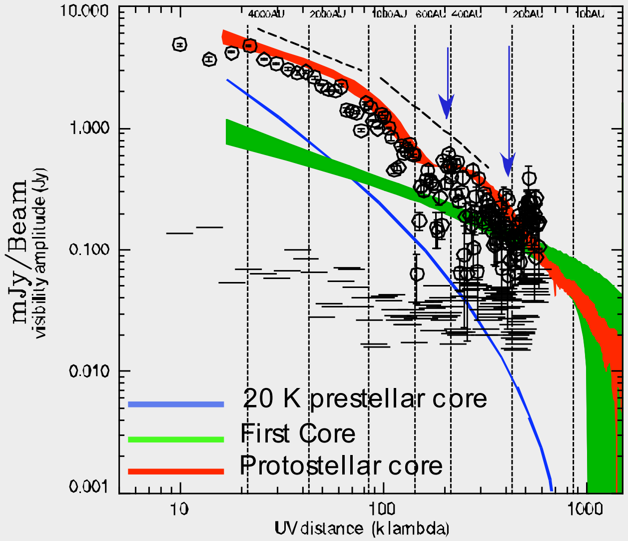
Takahashi et al. (2009) ApJ, 704,1459

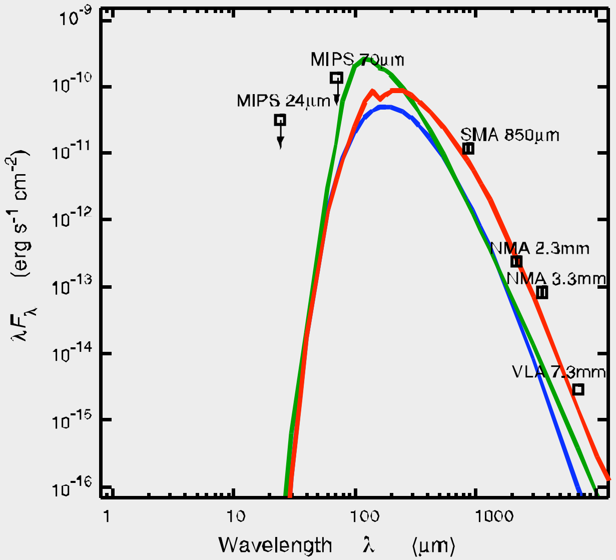


Youngest intermediate-mass protostellar core?

850 um continuum image with ~0.”3 angular resolution



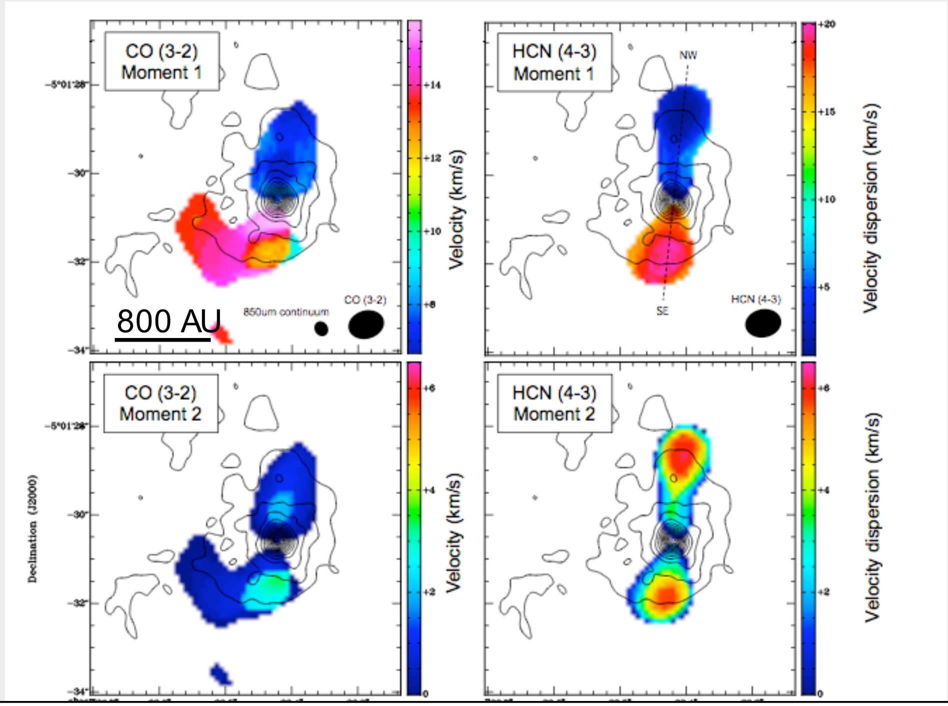


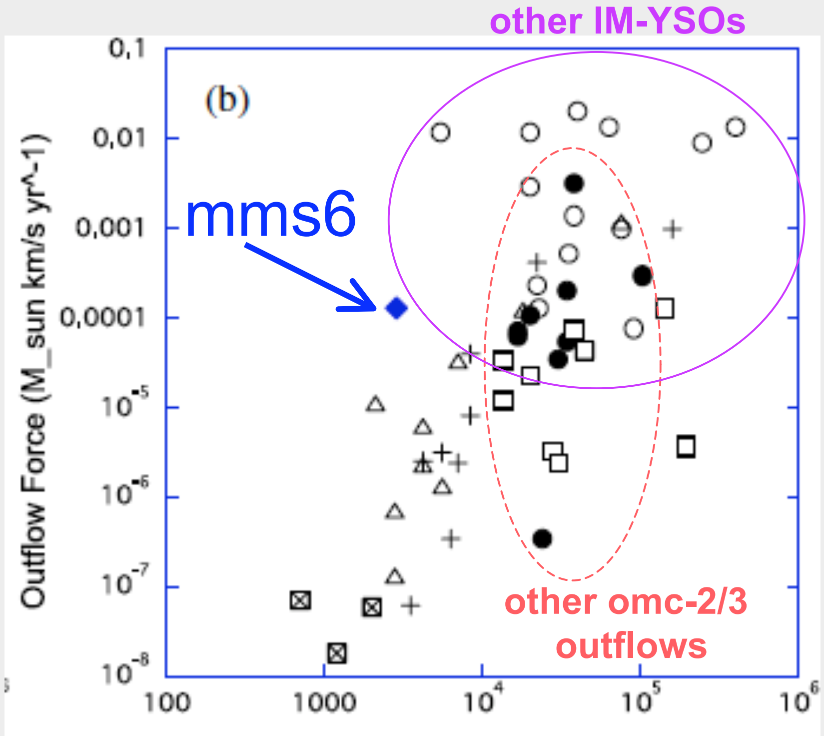


Takahashi et al. (2012), ApJ, 752, 10

- MMS 6-main peak: 132×120 AU; M=0.29 Mo; n=1.5×10^{10} cm^{-3}
- Gas temperature on 100 AU scale is at least 52 K (likely optically thick)
- Core models with radiative transfer calculation (e.g., Tomida et al. 2010)
  - 20 K Prestellar core (LP), First adiabatic core (BE), and Protostellar core (LP+disk+central heating source)
  - A self luminous source is necessary to explain the observed flux density at 850 um

Compact & Dense molecular outflow



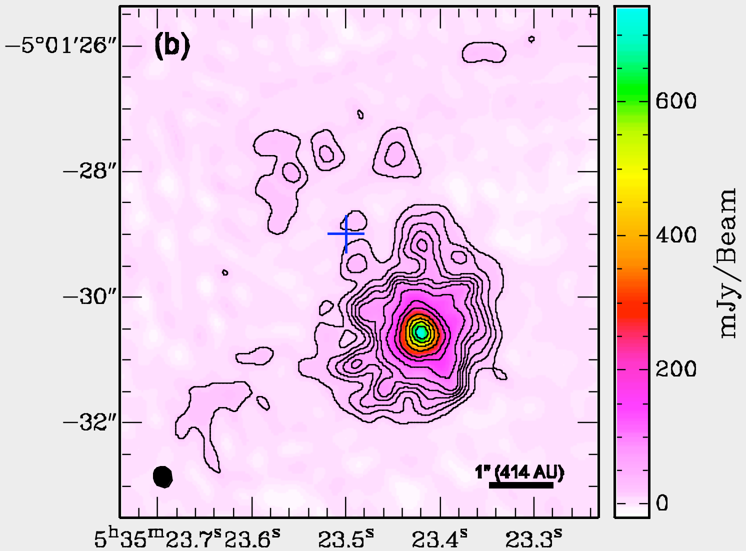


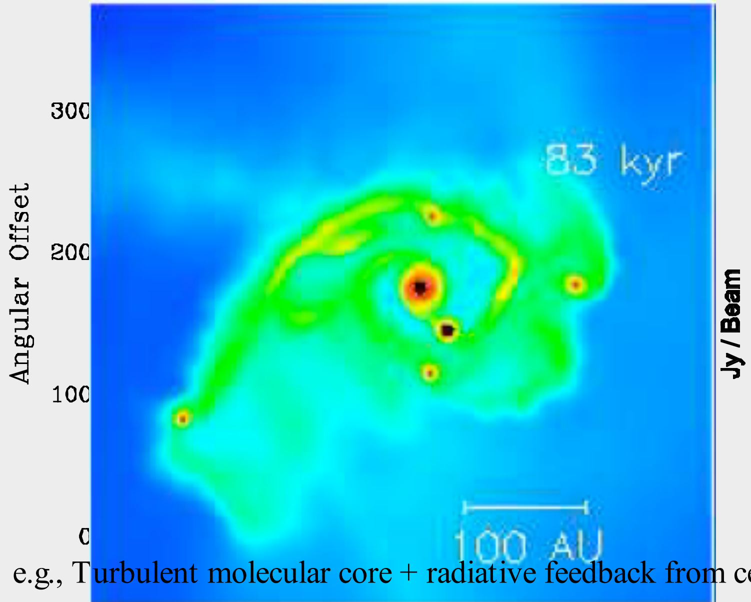
- Extremely compact and young, but the outflow velocity and momentum rate are comparable to other IM Class 0/I outflows in the OMC-2/3 region

- MMS 6-main is a phase right after protostar formation?

Sub-clumps within the massive envelope?

- Substructures (spikes + sub-clumps); M=0.066-0073 Mo
- Separation of the clumps: 0”.6-1”.4 (250-580 AU)
- Jeans length : 0”.87 (360 AU) with T=20 K, n=3x10^{9} cm^{-3}
- Gravitationally unstable disk: $M_{disk}/(M_{*}+M_{disk})$>~24% (Shu et al. 1990)
  - ~45 % for MMS 6-main case
- Fragmentation within pseudo disk disturb the mass accretion process onto the central star (e.g., Kratter et al. 2006; 2008)





e.g., Turbulent molecular core + radiative feedback from center

Stamatellos et al. 2011

Summary

- Wide field continuum imaging with SMA & EVLA (4.5”/2000 AU--> 0.5”/200 AU)

- Star formation within OMC-3 through thermal dust emission
  - Detections of the Class 0/I like sources with a mass range from $0.3 < M < 5.8$ Mo within 1400-4100 AU structure ($2.3E+06 < n_{H2} < 4.5E+08$ cm^{-3})
  - Molecular outflows (42%), Infrared sources (67%), and free free jets (25%)

- Fragmentation properties are investigated
  - Hierarchical fragmentation processes are suggested (5deg/37pc down to 25”/0.05 pc)
  - Consistent with the thermal Jeans length/shorter than the maximum unstable mode.
  - Magnetic field/ rotation might be important for the fragmentation in Orion?

- The youngest IM protostellar core; MMS 6
  - Heating source at the center + extremely compact outflow
  - Substructure within the massive envelope