Unveiling the physics of star formation with the SMA:

a decade's restrospective

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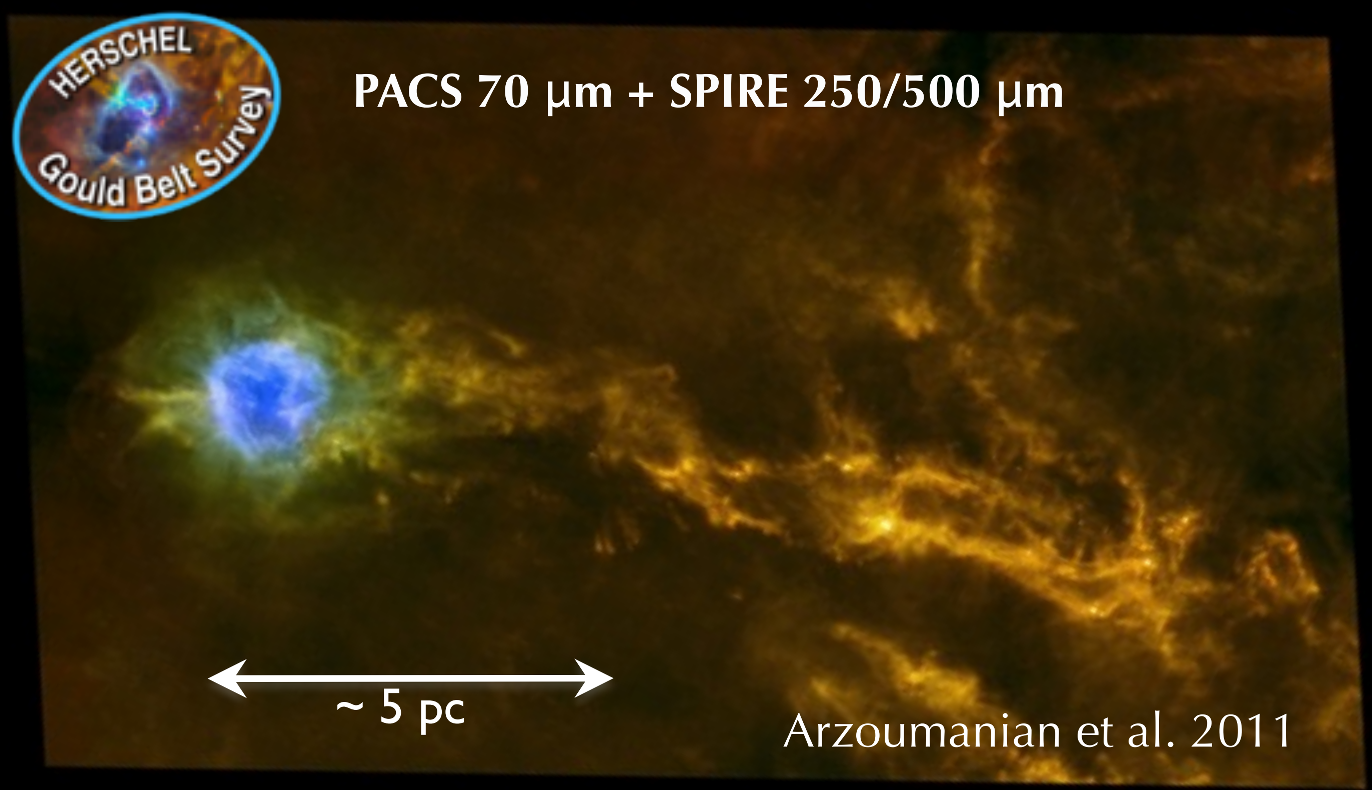
Star formation & Filaments: the Herschel view

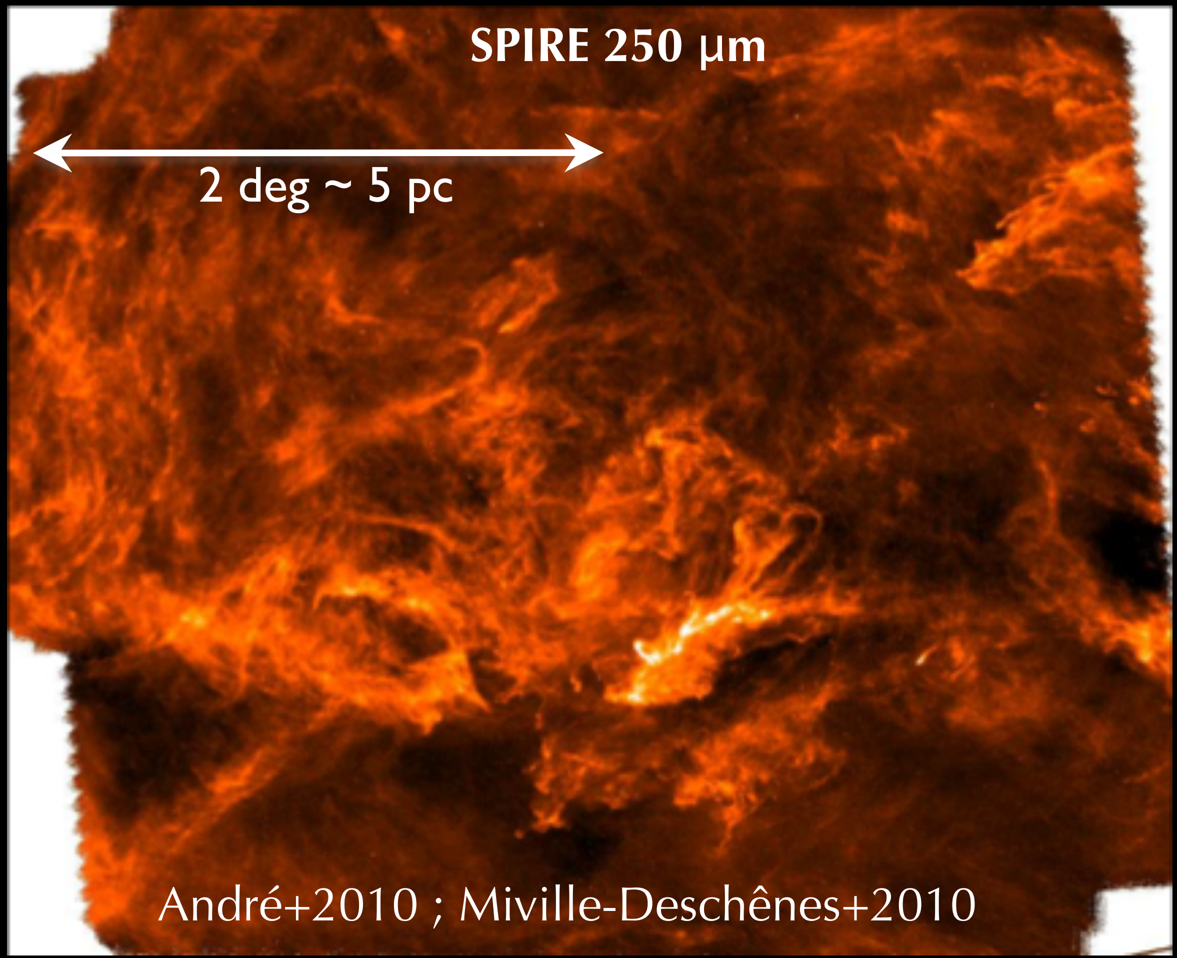
Herschel has revealed a "universal" filamentary structure in the cold interstellar medium

"Universal" = Ubiquitous + quasi-universal properties (e.g width)

IC5146 : Actively star-forming cloud



Polaris : Non-star-forming "cirrus" cloud



~ 75 % of prestellar cores form in filaments, above a (column) density threshold $\Sigma \gtrsim 150\ M_{\odot}/pc^2$

<=>

$M / L \gtrsim 15\ M_{\odot}/pc$

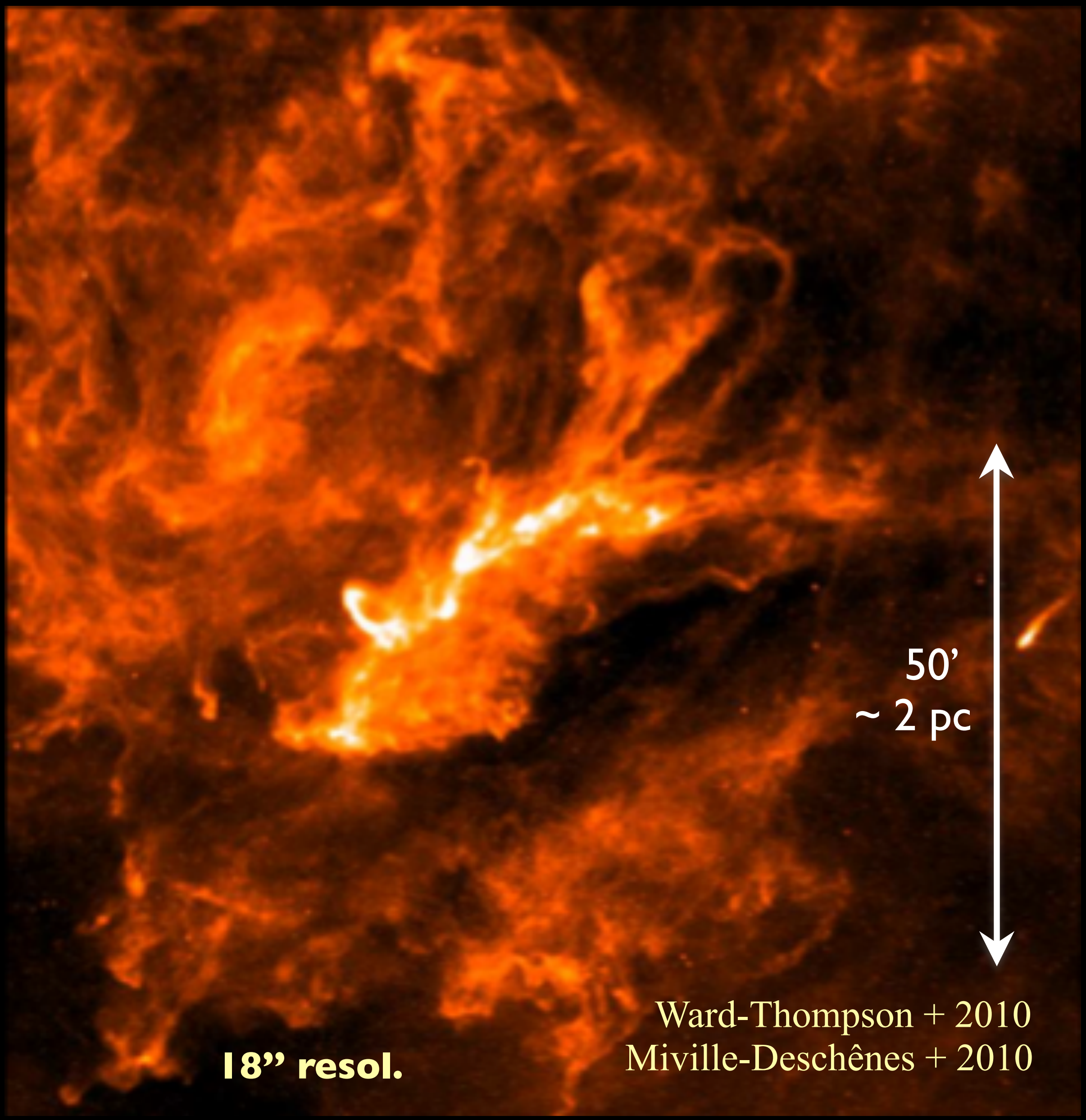
Star formation & Filaments: the Herschel view

Toward a 'universal' scenario for star formation ?

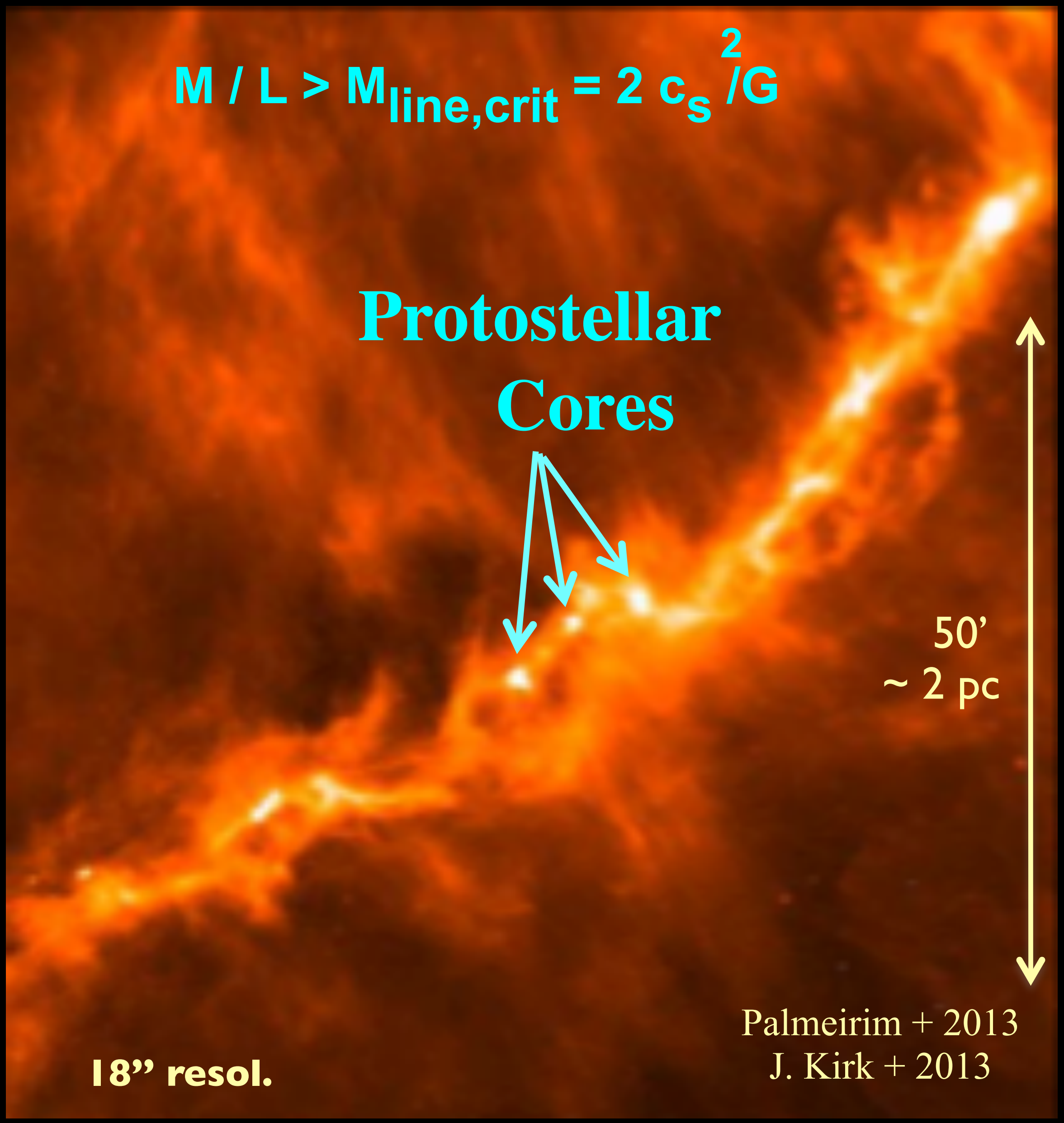
See related chapter for « Protostars & Planets VI »
by André, Di Francesco, Ward-Thompson, Inutsuka, Pudritz, Pineda

1) The dissipation of large-scale MHD 'turbulence' generates filaments

2) Gravity fragments the densest filaments into prestellar cores



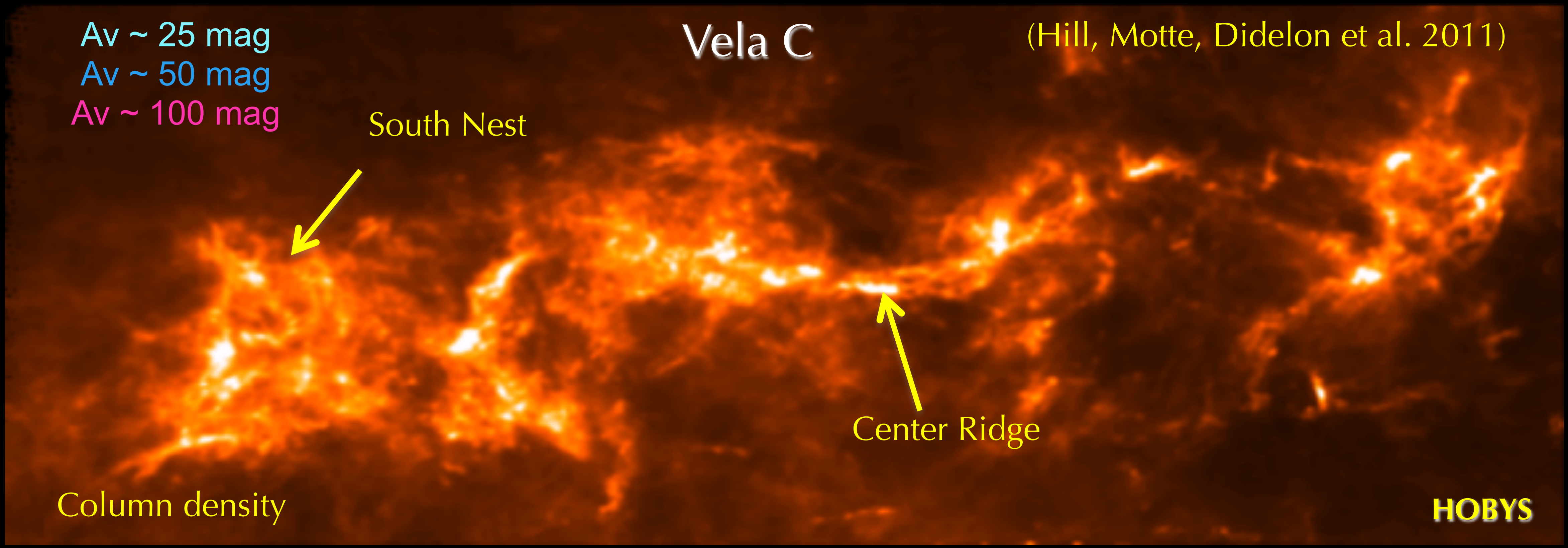
Polaris – *Herschel*/SPIRE 250 μm



Taurus B211/3 – SPIRE 250 μm

Star formation & Filaments: the Herschel view

Role of filaments in massive star formation ?



Tracing filamentary networks with the DisPerSE algorithm (Sousbie 2011)

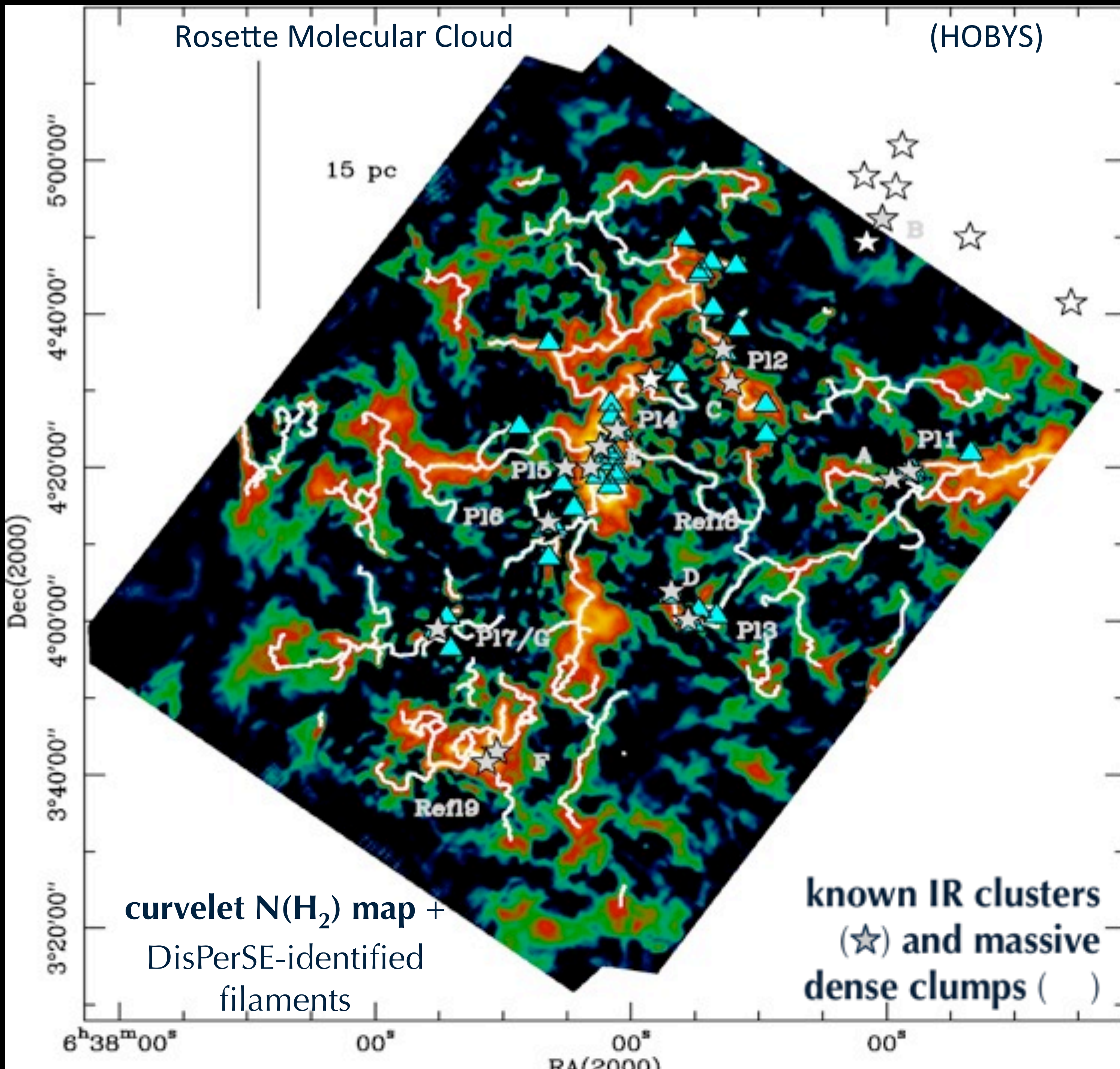
Hill et al. 2011; Minier et al. 2013

Disorganized networks ('nests') and dominating 'ridges'

Showing relative importance of turbulence vs. gravity (?)

Star formation & Filaments: the Herschel view

Role of filaments in massive star formation ?



HOBYS
PI: F. Motte

- massive star formation and star clusters found in dense "ridges" (Av > 100) at the junctions of (supercritical) filaments
- massive accretion flows into junction regions -> more clustered, more massive star formation ?

Hill et al. 2011
Schneider et al. 2012
Hennemann et al. 2012

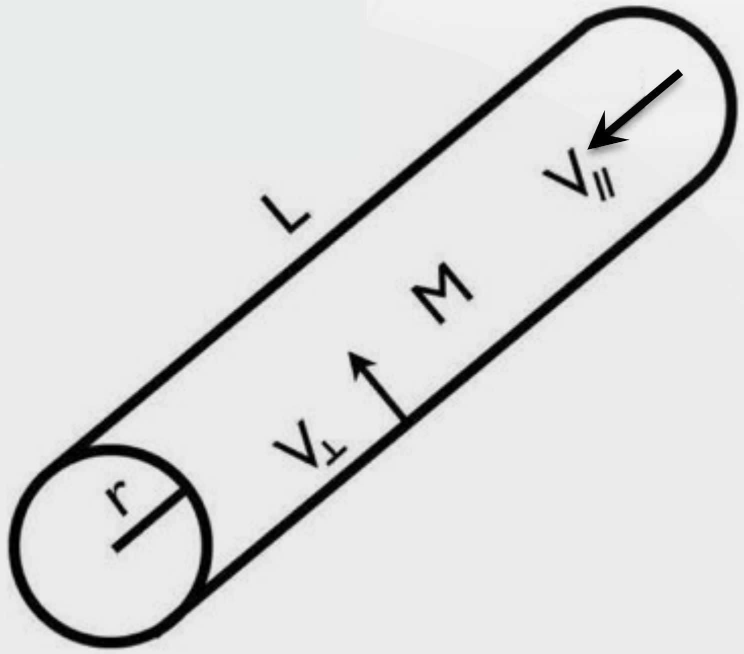
How do SMA observations help understanding the properties of:

- Filaments and clumps
- Embedded protostars

Star-formation related publications
=45% of SMA papers !


Clumps & Filaments
Disclaimer:
I won't discuss
chemistry (see Jimenez-Serra's review)
the galactic center (see Johnston's talk)
magnetic fields (see Qiu's talk)
... but might still exceed my allocated time !

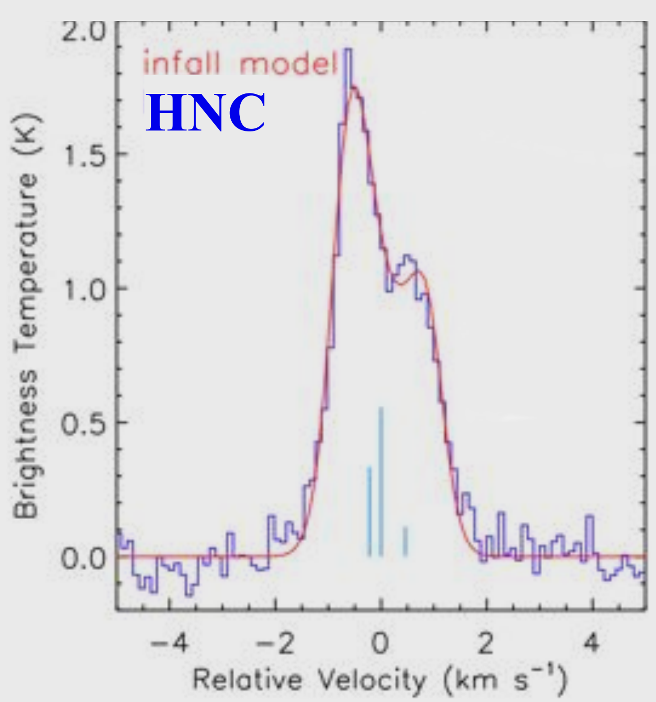
Low mass star formation : kinematics of filaments

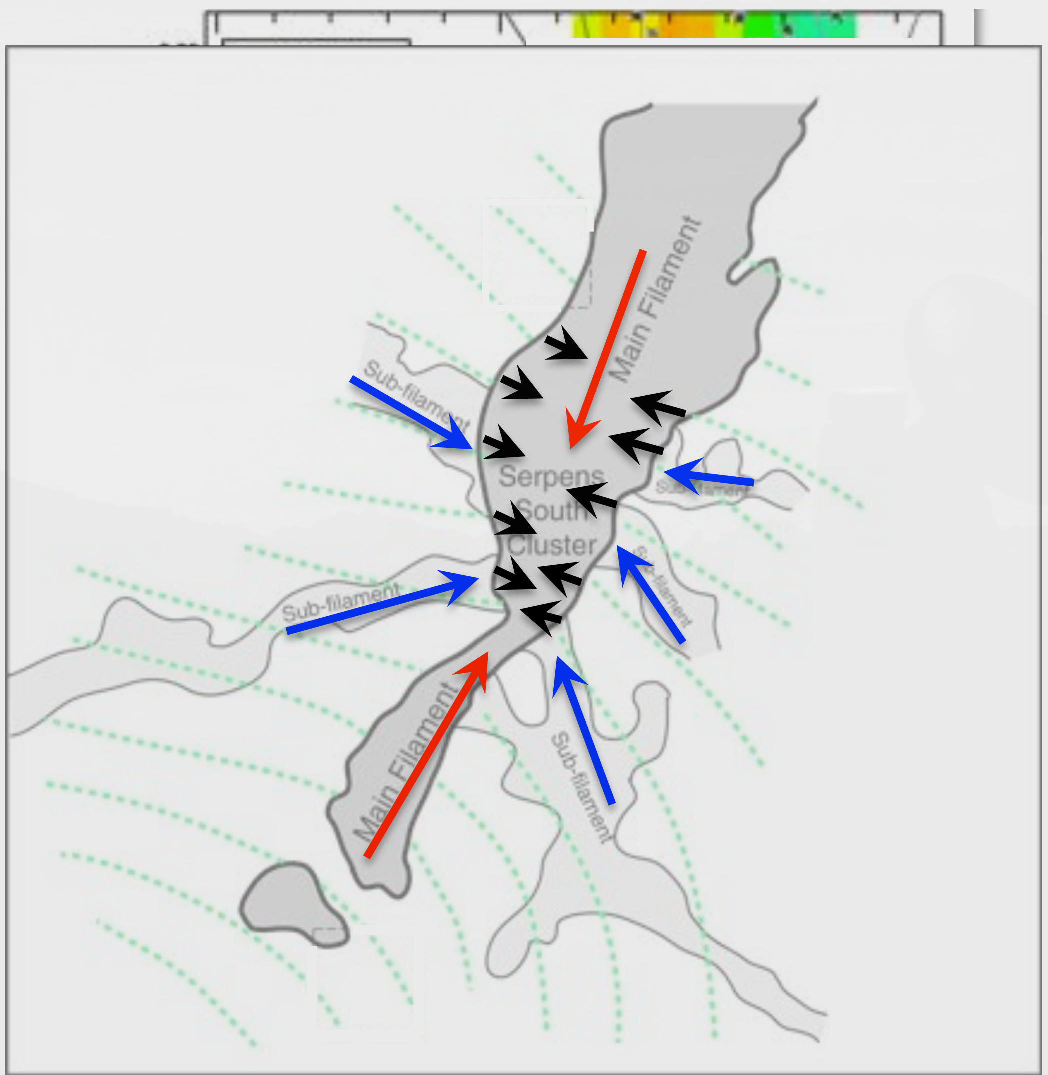


In Serpens-South:

- **infall along main filament**
- **radial contraction of main filament**
  Accretion of background material through subfilaments

Evidence of infall motions

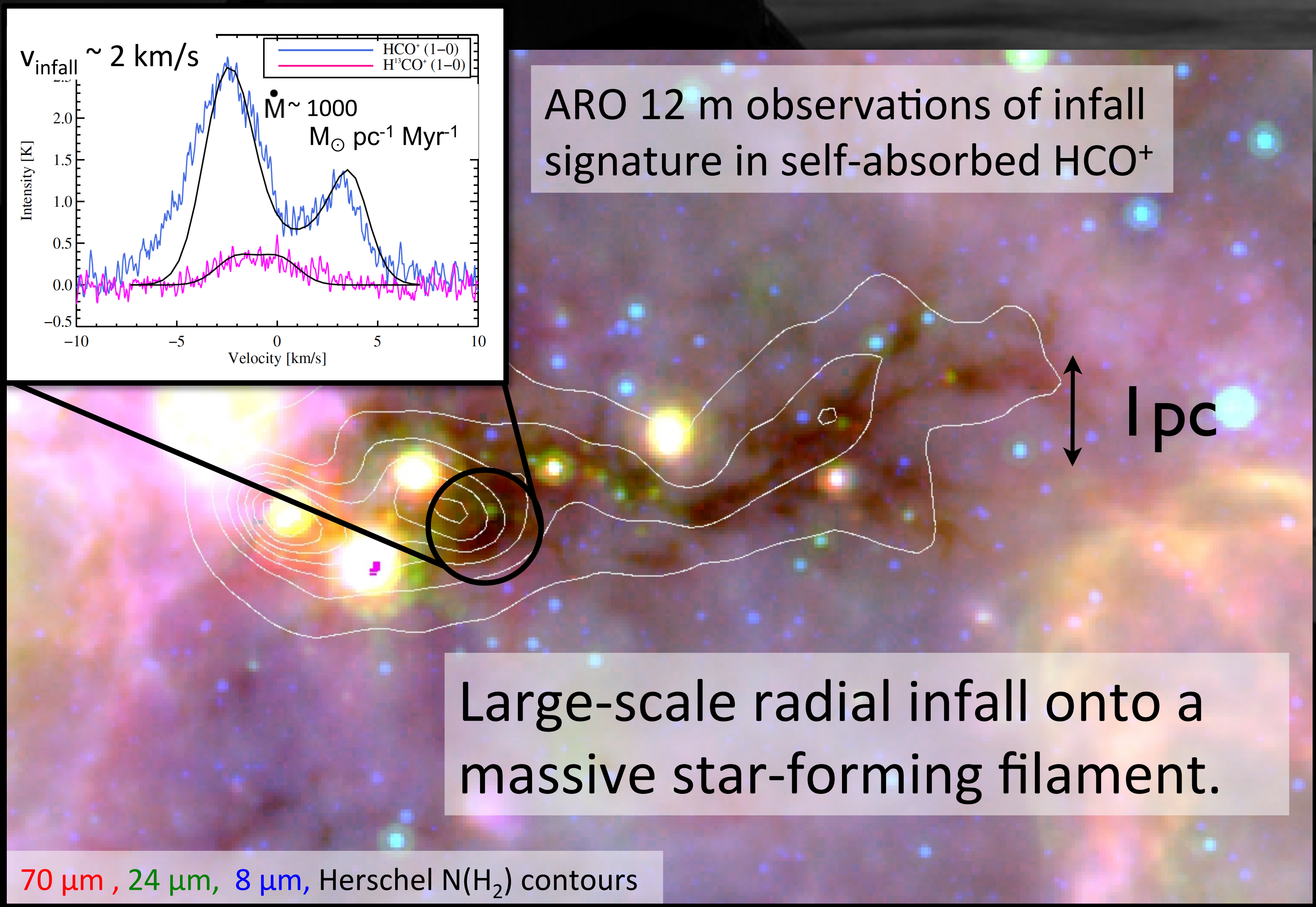


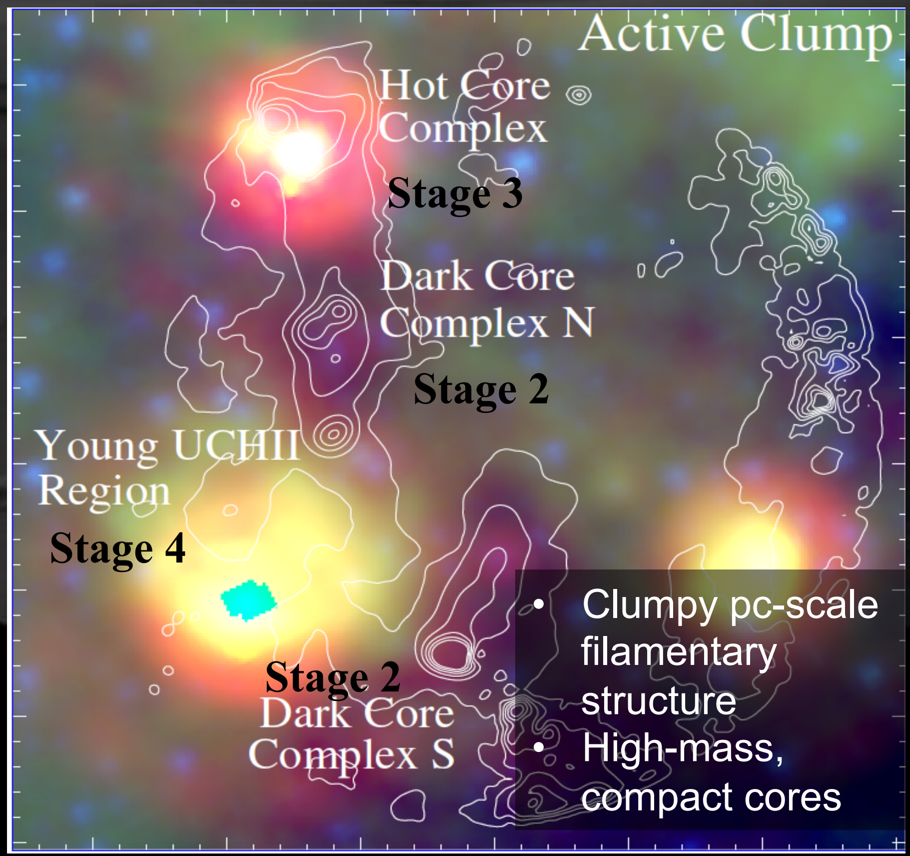


H. Kirk, P. Myers et al. 2013, ApJ, 766, 115

See also Tanaka et al. (2013)
SMA data under analysis: Nakamura, Kristensen, Maury, Chen +

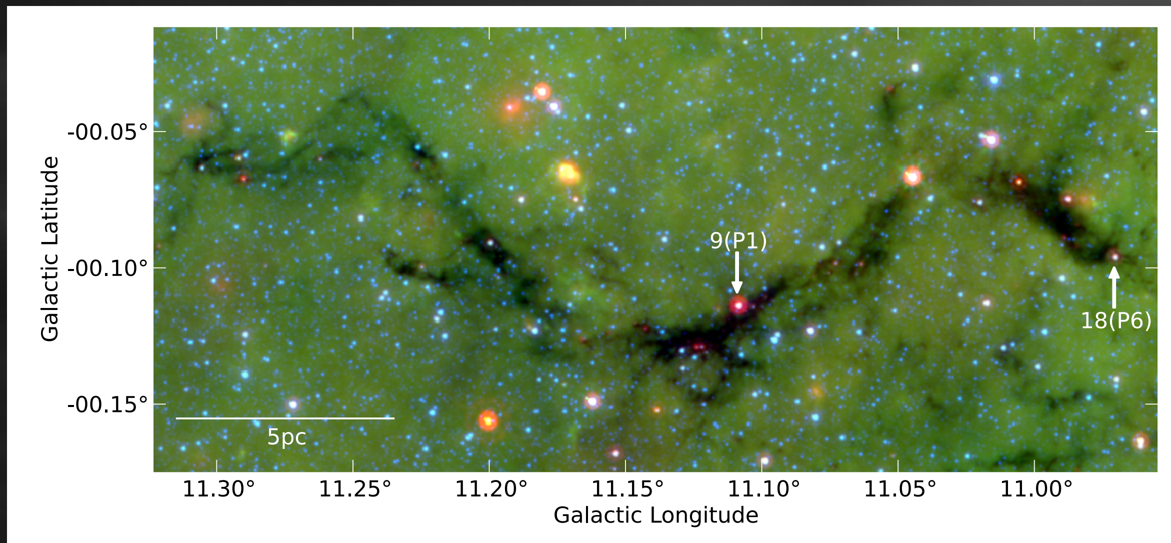
Massive star formation in massive star forming filaments

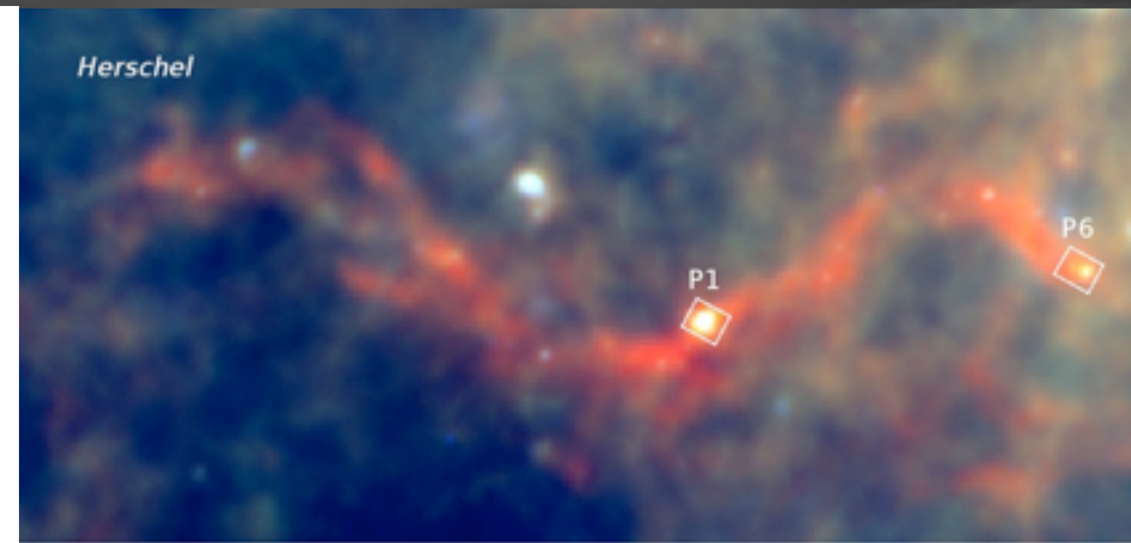




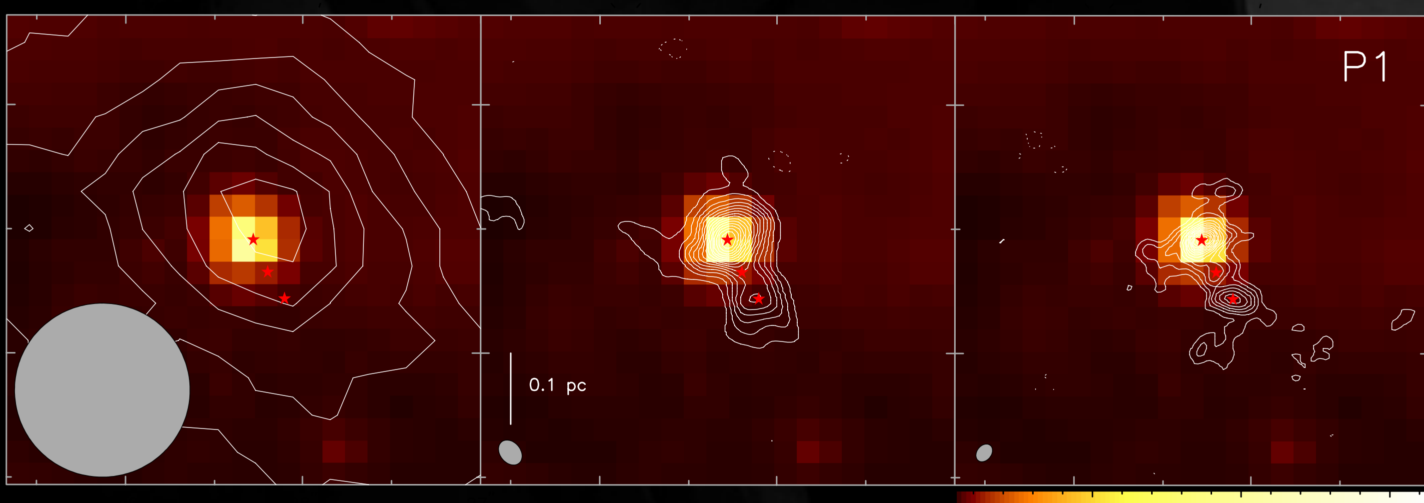
G32.03+0.05, Battersby, Myers, Keto, et al. in prep

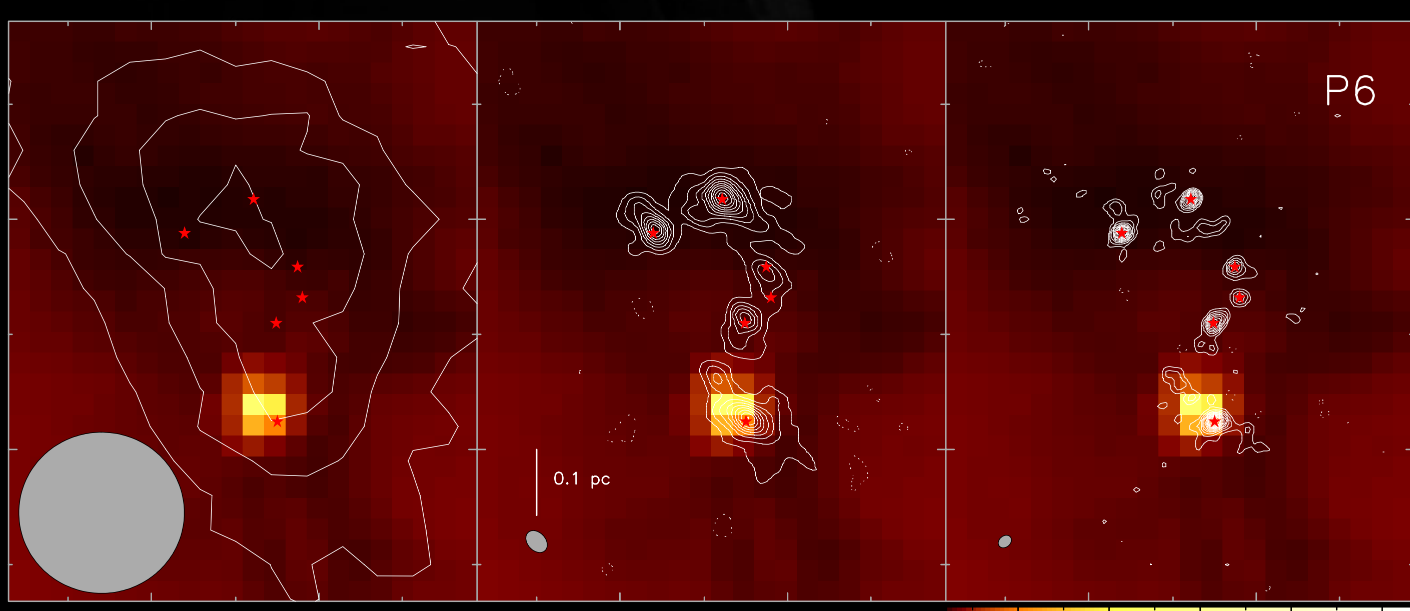
Hierarchical Fragmentation in the Snake IRDC





Wang et al. (2013)





Detection limit of 1-3.5 $M_\odot$: 23 condensations.

Mass spectrum of condensations :
power law with slope α = 2.0±0.2
turnover at 2.7 $M_\odot$ condensation mass.

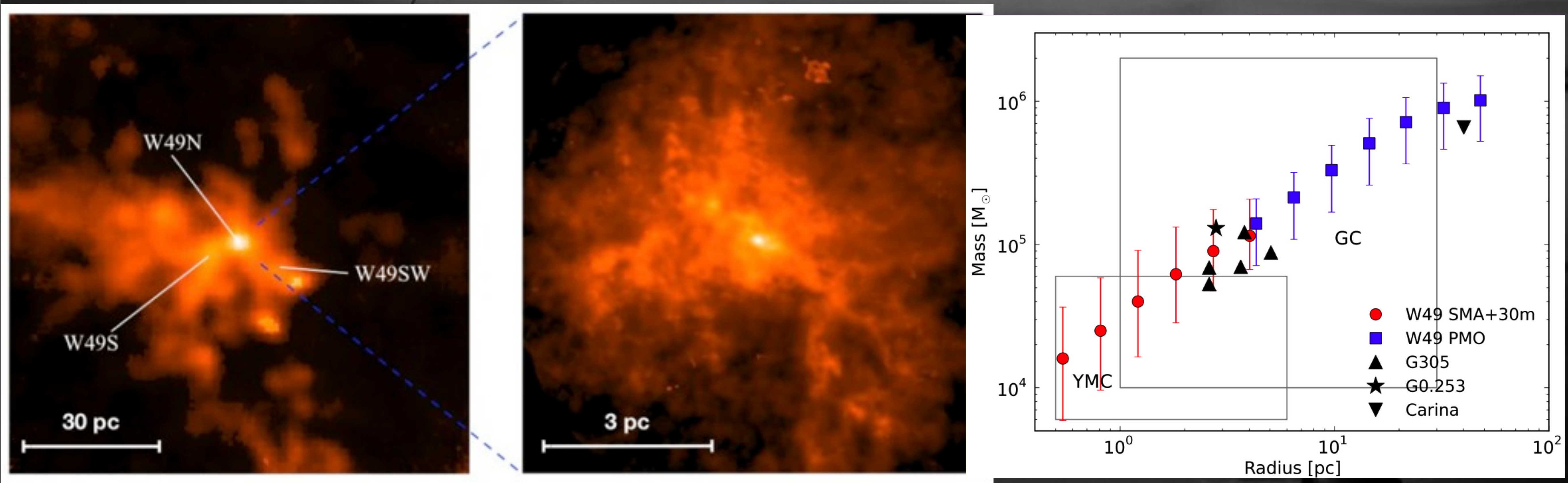
First study of the CMF.

Hierarchical fragmentation
Clump masses are much larger than the thermal Jeans mass, indicating the importance of turbulence and/or magnetic fields in cloud fragmentation
- or sub-fragmentation at smaller scales.

Similar to what is found in IRDC clumps G28.34-P1 and G30.88-C2

Chemical differentiation : see Jimenez-Serra's talk

RESOLVING THE NATAL MOLECULAR CLOUD OF A FORMING YOUNG MASSIVE CLUSTER



Projected multi-scale mass maps of the Giant Molecular Cloud (left) and central clump (right) in W49A, obtained from CO-isotopologue line ratios.

In total, the W49 complex contains about 10^6 Msun in 60pc

-

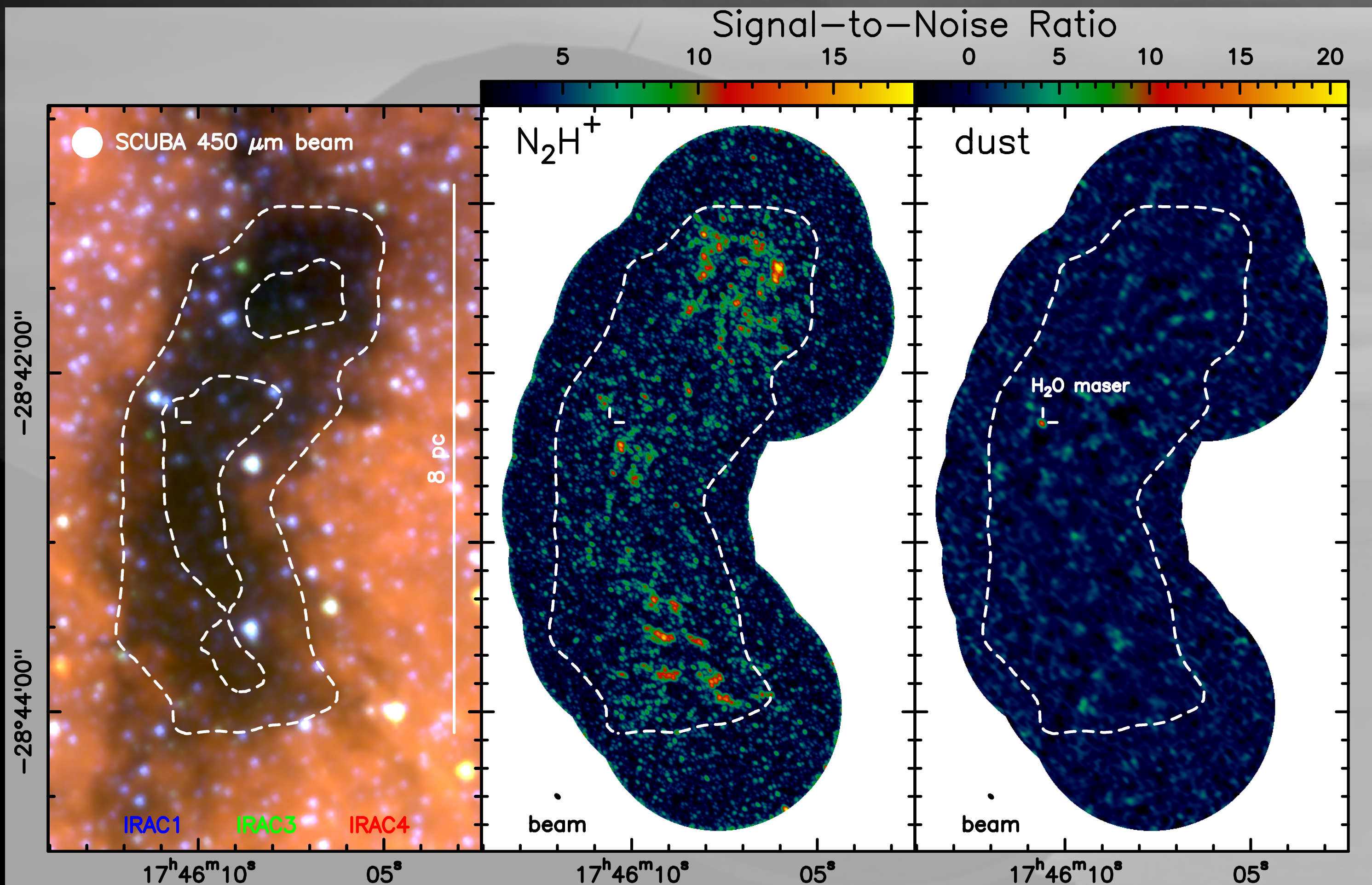
50000 Msun in central 3pc

SMA reveals an intricate network of filaments feeding star-building material inward at 2 km/s.
Global gravitational contraction with localized collapse in a "hub-filament" geometry.
Potential to form a gravitationally bound massive star cluster

See also SMA observations of W33A by Galvan-Madrid et al. (2010)
... G28.34 by Zhang et al. (2009)

Galván-Madrid, R. et al. (2013)

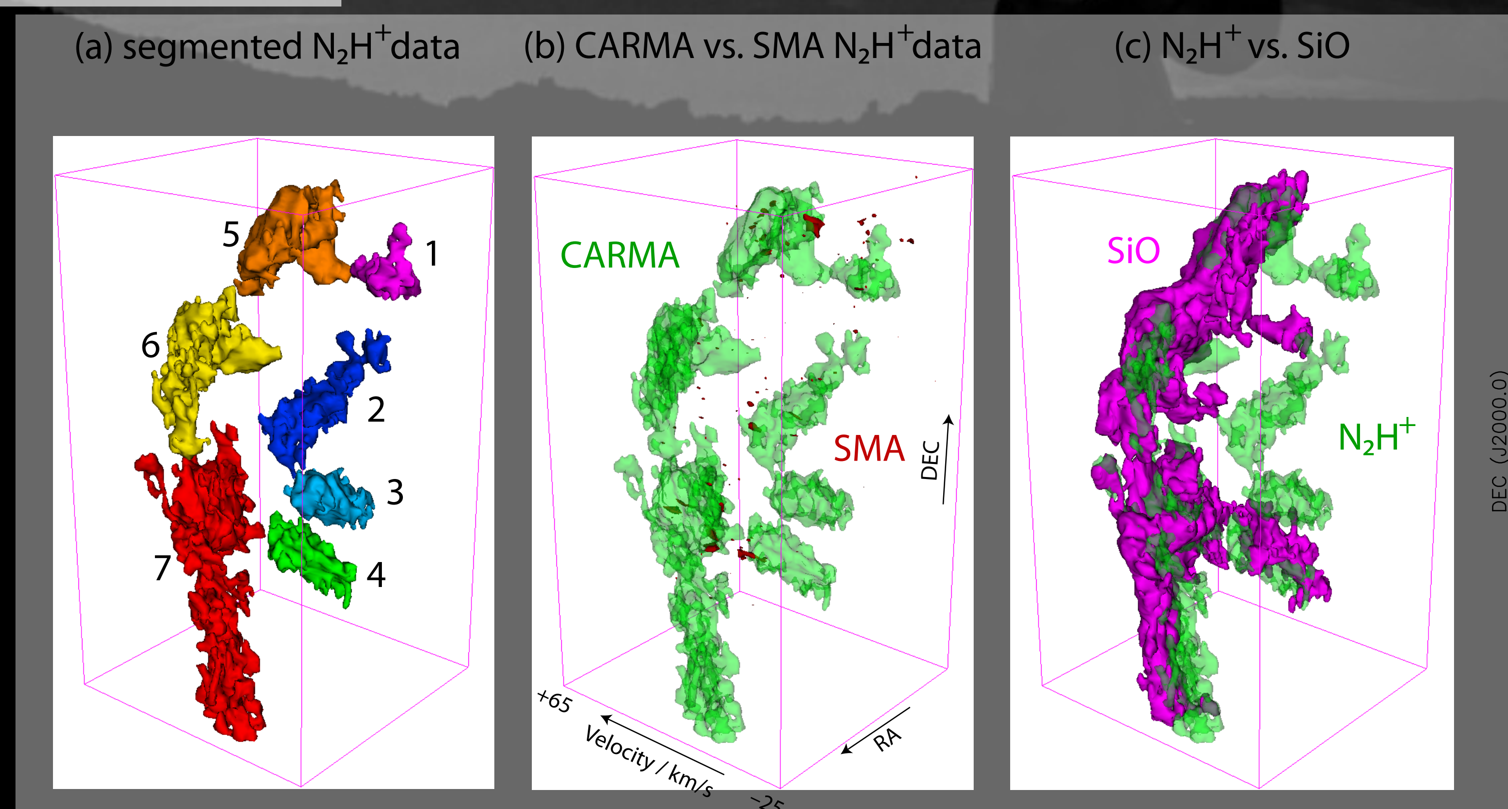
THE GALACTIC CENTER CLOUD G0.253+0.016: A DENSE CLOUD WITH LOW STAR FORMATION POTENTIAL



Kauffmann, Pillai & Zhang (2013)

25 times denser than Orion

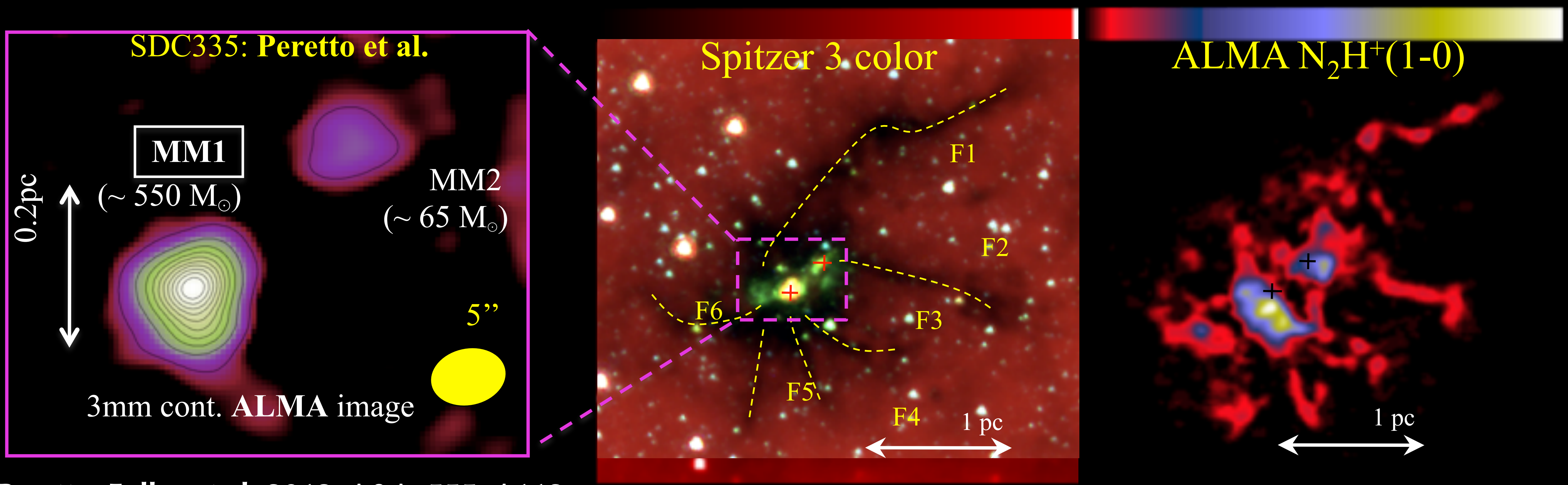
Star-formation rate 45 times lower than expected from such cloud densities



Widespread SiO emission suggests that the cloud is currently forming in a collision of several clouds, thus implying a low cloud age

See also Longmore et al. (2012)
and
Johnston's talk

ALMA identification of a massive protostellar core at the center of a converging network of filaments

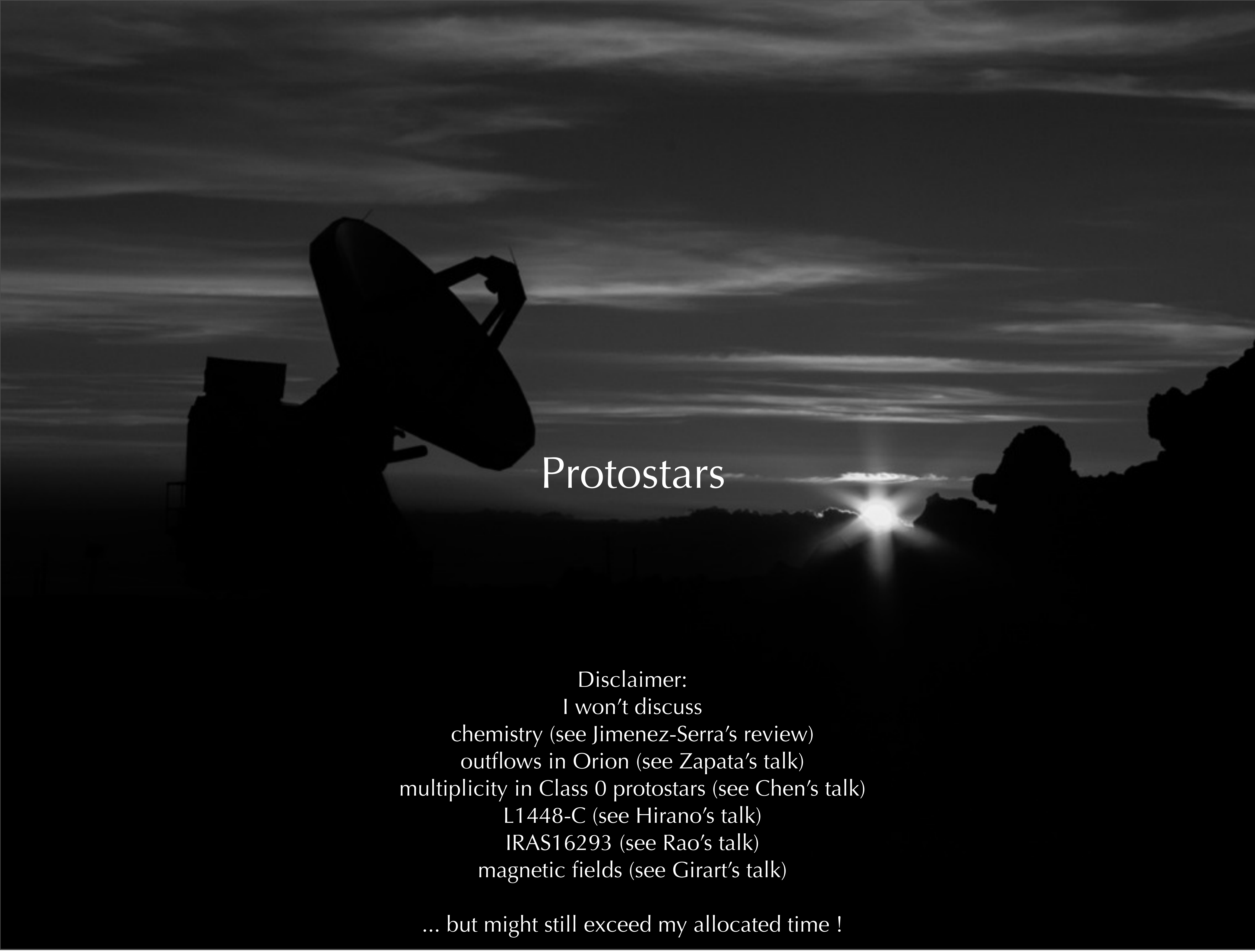


Peretto, Fuller et al. 2013, A&A, 555, A112

M_{H2}(MM1) ~ 550 M$_\odot$ in D=0.05 pc:

One of the most massive protostellar core ever observed in the Galaxy !

A possible progenitor of an OB cluster similar to the Trapezium cluster in Orion



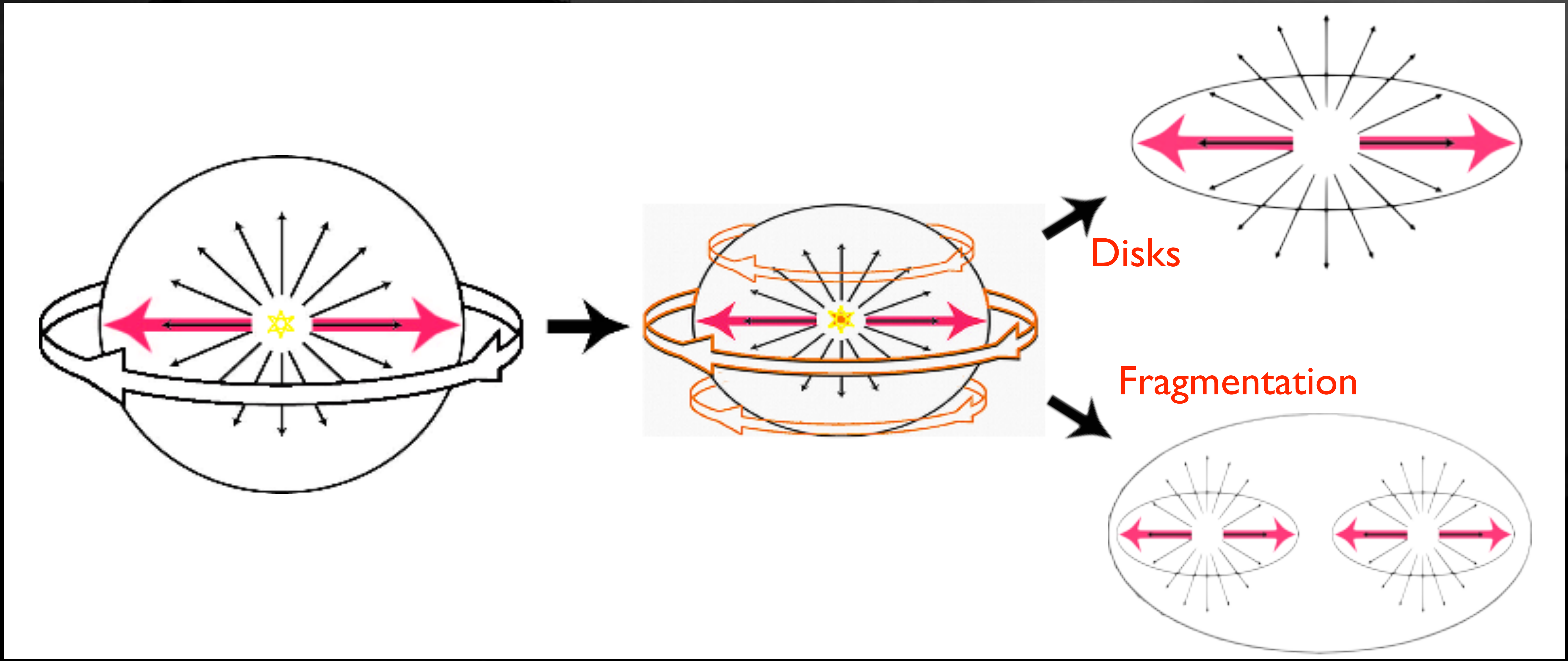
Protostars

Disclaimer:
I won't discuss
chemistry (see Jimenez-Serra's review)
outflows in Orion (see Zapata's talk)
multiplicity in Class 0 protostars (see Chen's talk)
L1448-C (see Hirano's talk)
IRAS16293 (see Rao's talk)
magnetic fields (see Girart's talk)

... but might still exceed my allocated time !

Conserving the angular momentum during collapse: consequences

Opposing forces to gravity during collapse:
Outward pressure in all directions / Centrifugal force in the equatorial plane



Natural results:

- flattening of the envelope ie formation of disk with keplerian motions (viscosity)
- fragmentation of the envelope in components taking away their own angular momentum
- if magnetized: launching of a high-velocity jet

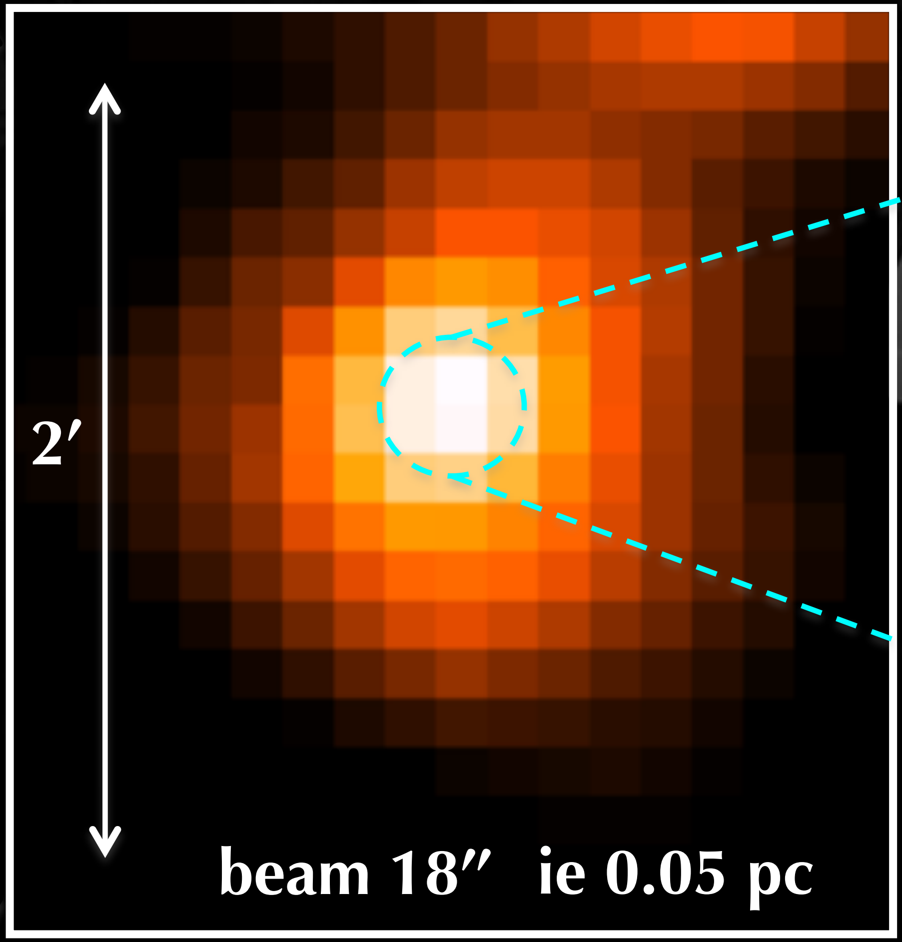
The early stages of star formation: properties of embedded protostars

At most limited sub-fragmentation within the cores identified with *Herschel* in nearby clouds

Progenitors of individual stars or binary systems, not "clusters"

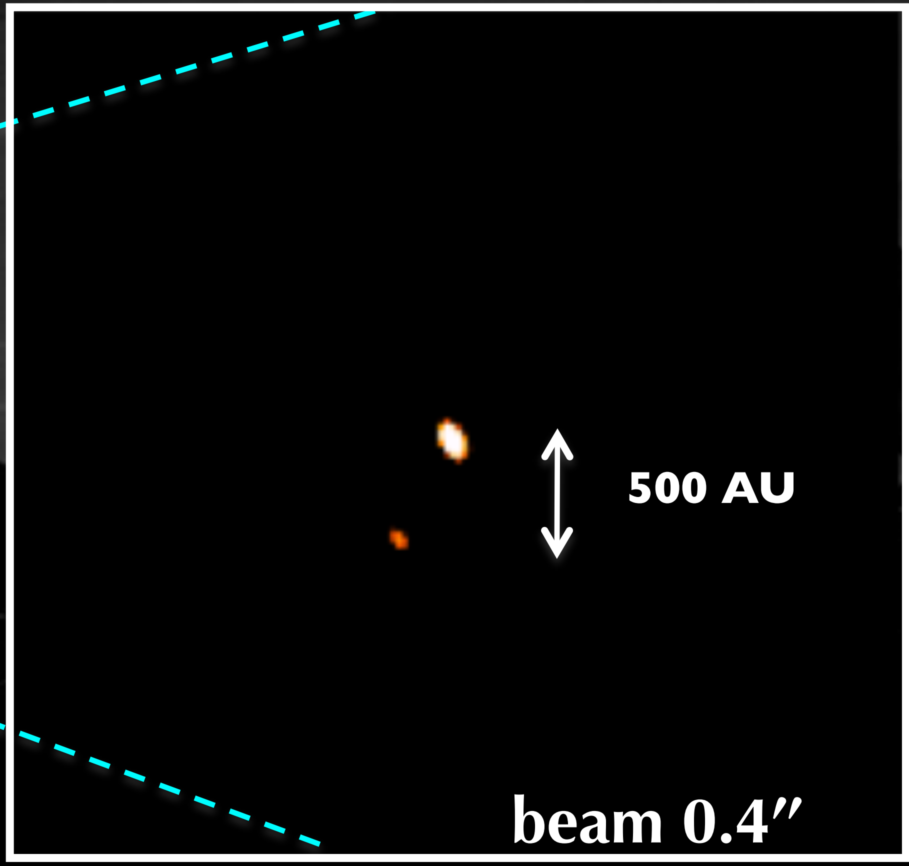
Herschel **~ 15" resolution at λ ~ 200 μm ⇔ ~ 0.02 pc < Jeans length @ d = 300 pc**

L1448-C: Herschel/SPIRE 250 μm



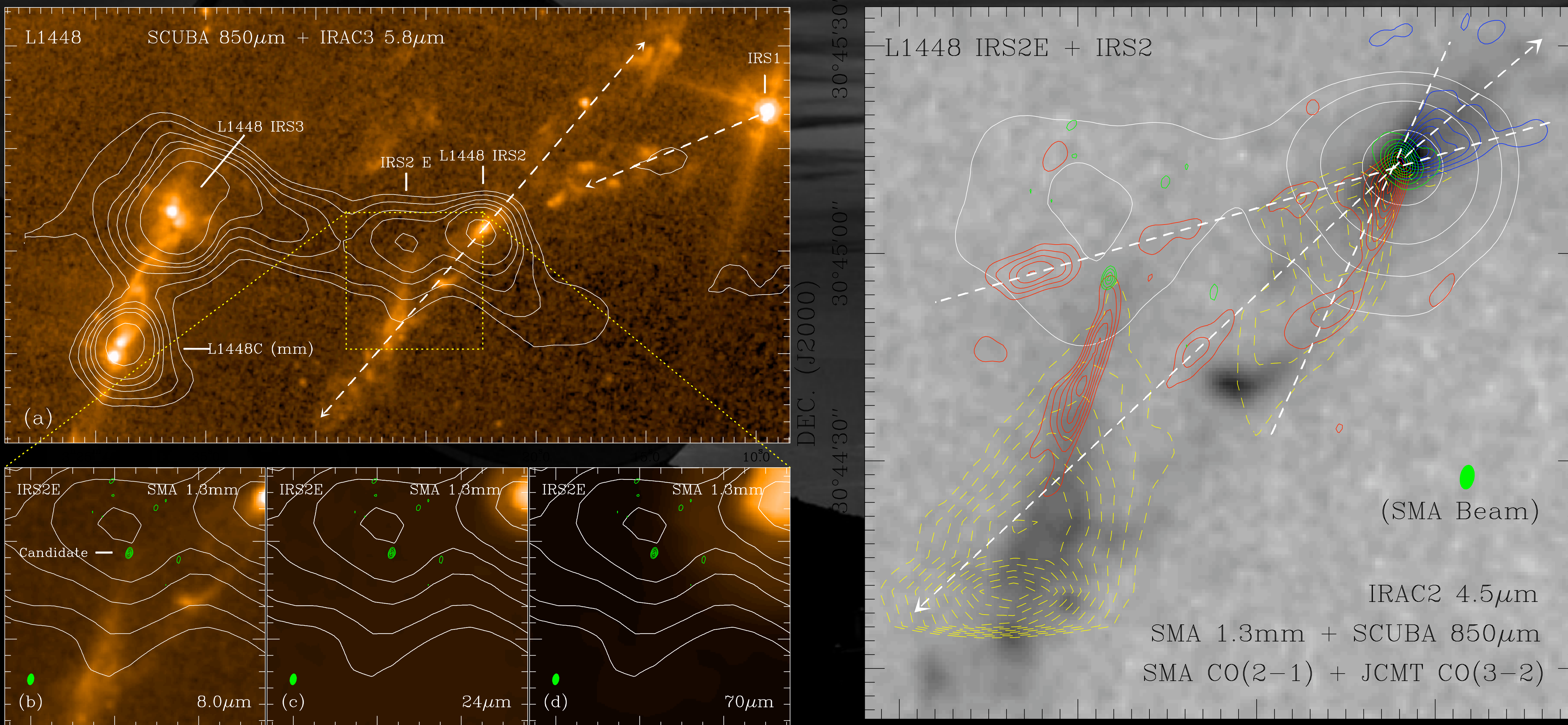
Pezzuto, Sadavoy et al., in prep.

L1448-C: IRAM-PdB interferometer 1.3mm



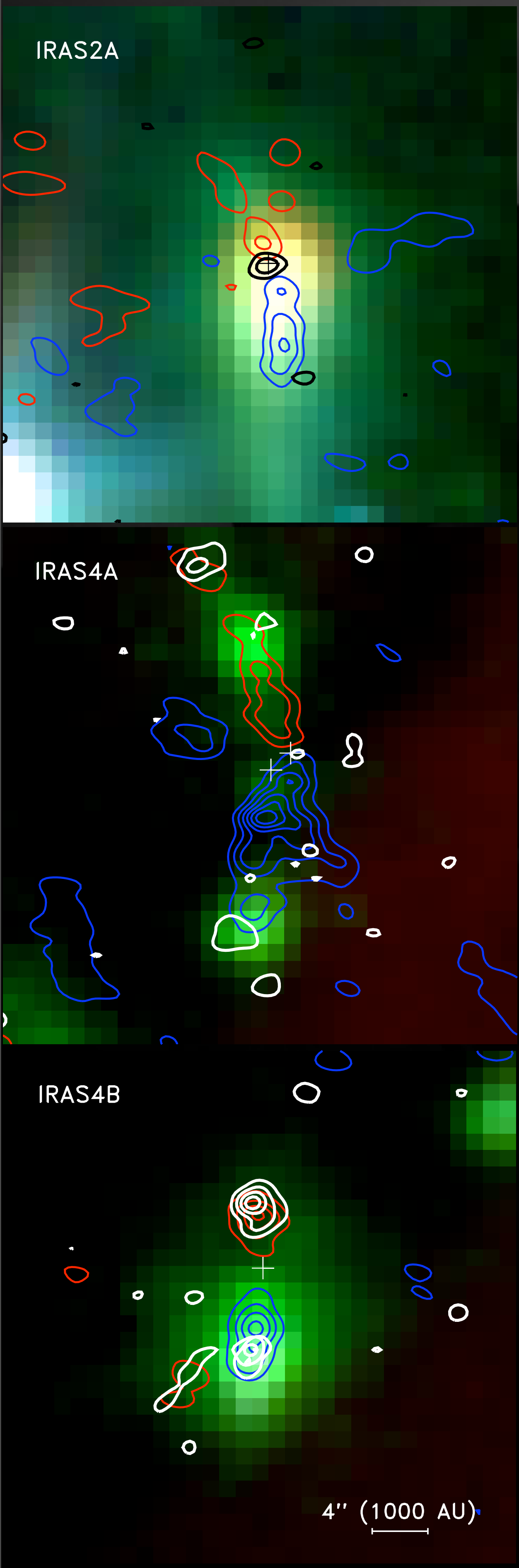
Maury et al. 2010

Candidate First Hydrostatic Cores

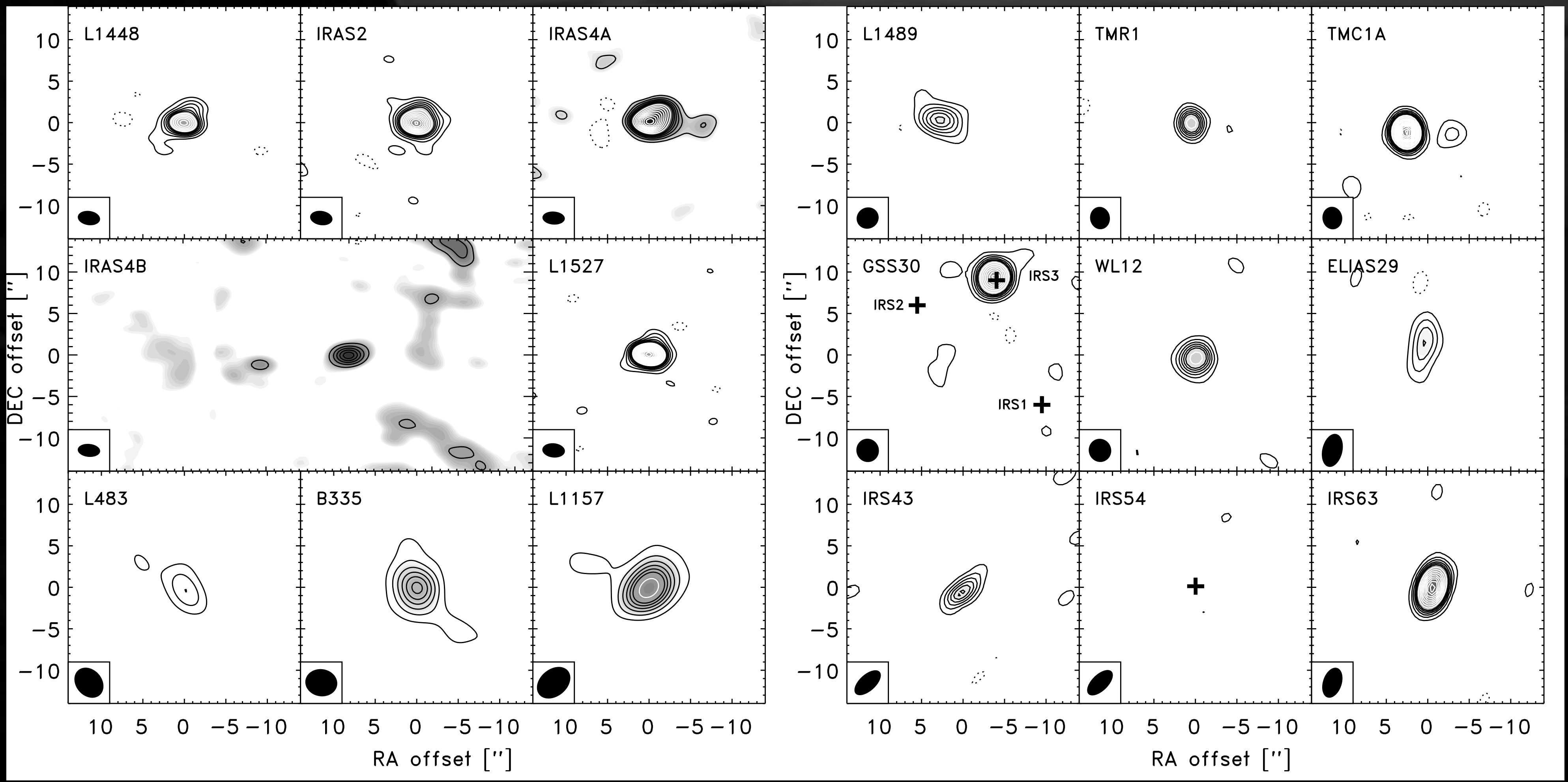


See also SMA observations of L1451-mm by Pineda et al. (2008)
SMA observations of B1-bN by Hirano & Liu (2014)

The PROSAC survey (Jes Jørgensen, Tyler Bourke, Chin-Fei Lee, Philip Myers, David Wilner, Qizhou Zhang, James Di Francesco, Nagayoshi Ohashi, Fredrik Schöier, Shigehisa Takakuwa and Ewine van Dishoeck)

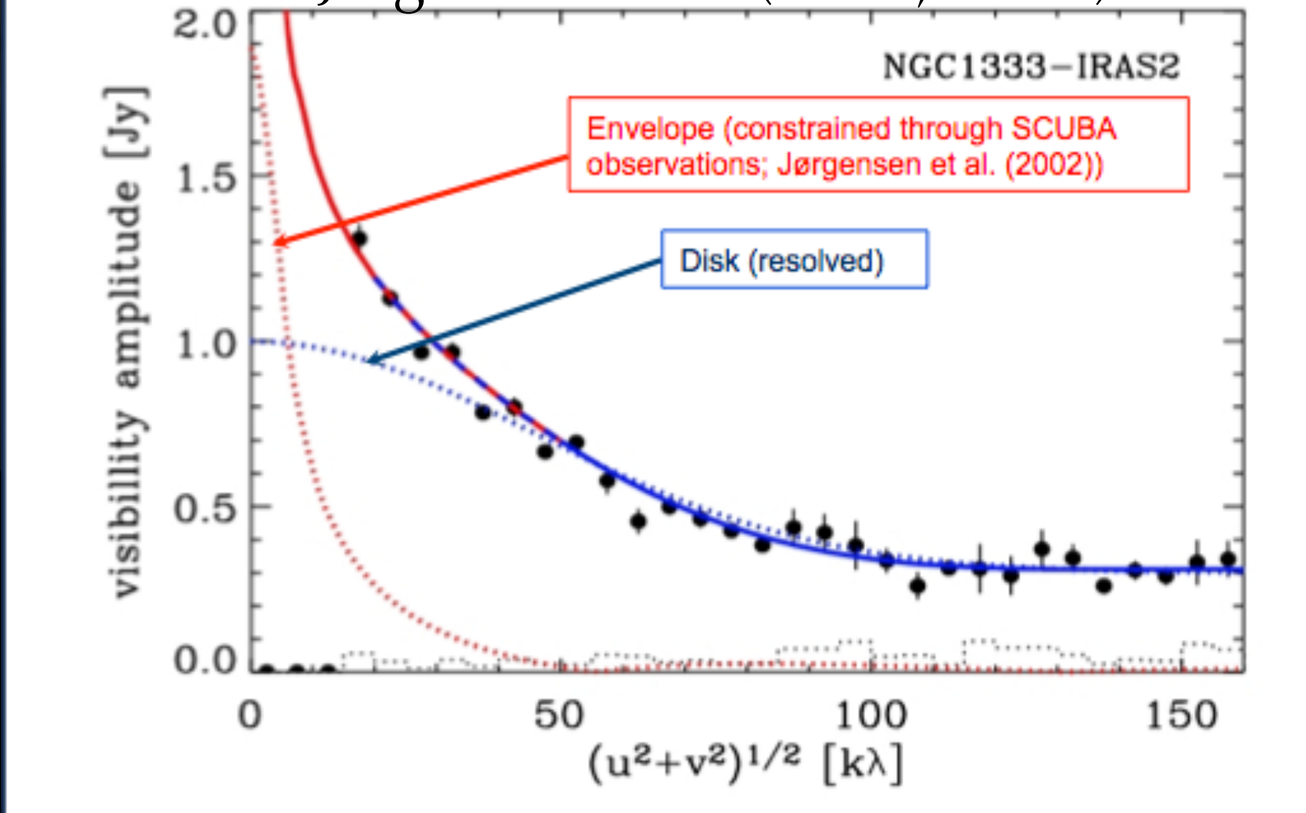


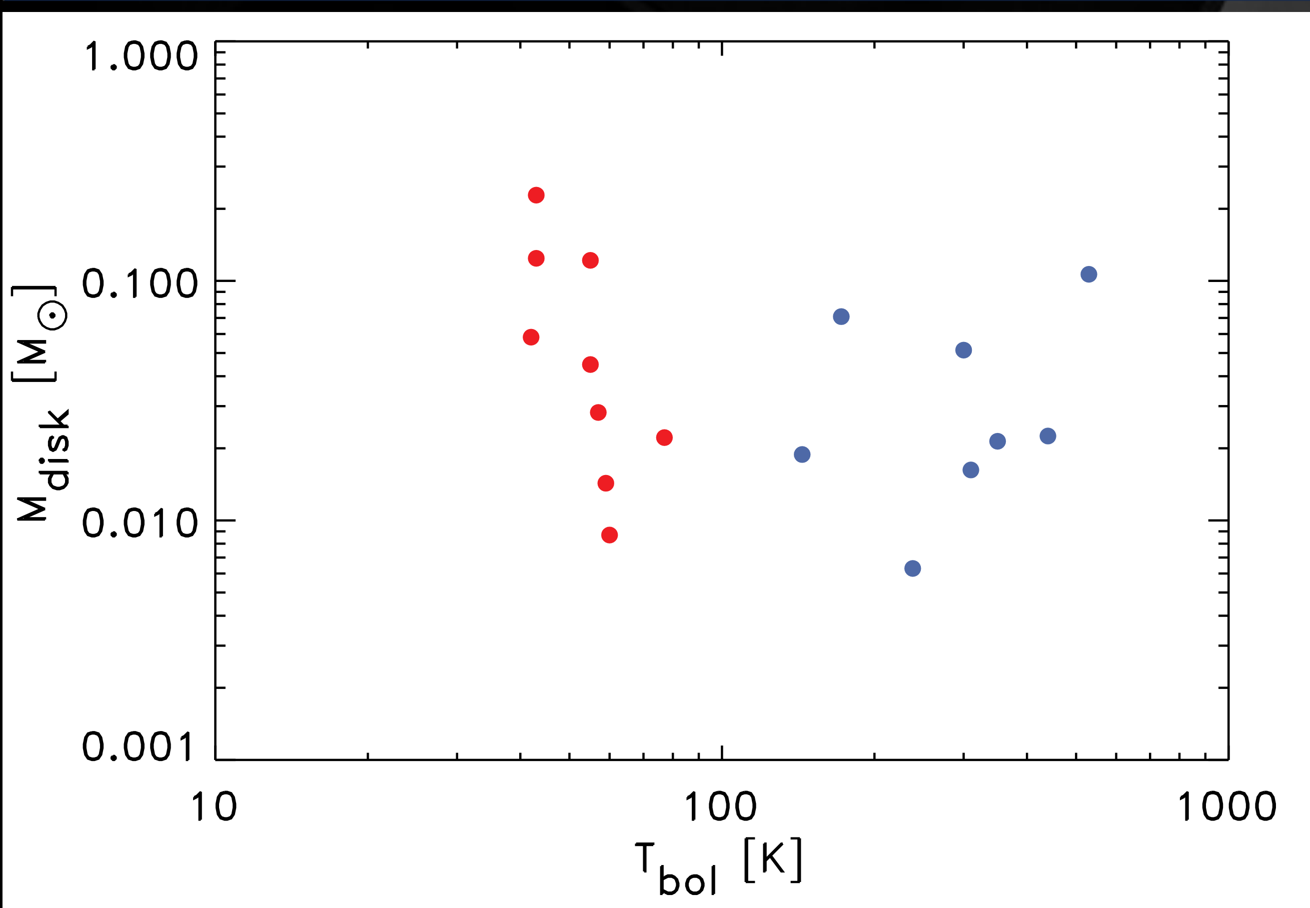
PROBING THE INNER 200 AU OF LOW-MASS PROTOSTARS WITH THE SUBMILLIMETER ARRAY



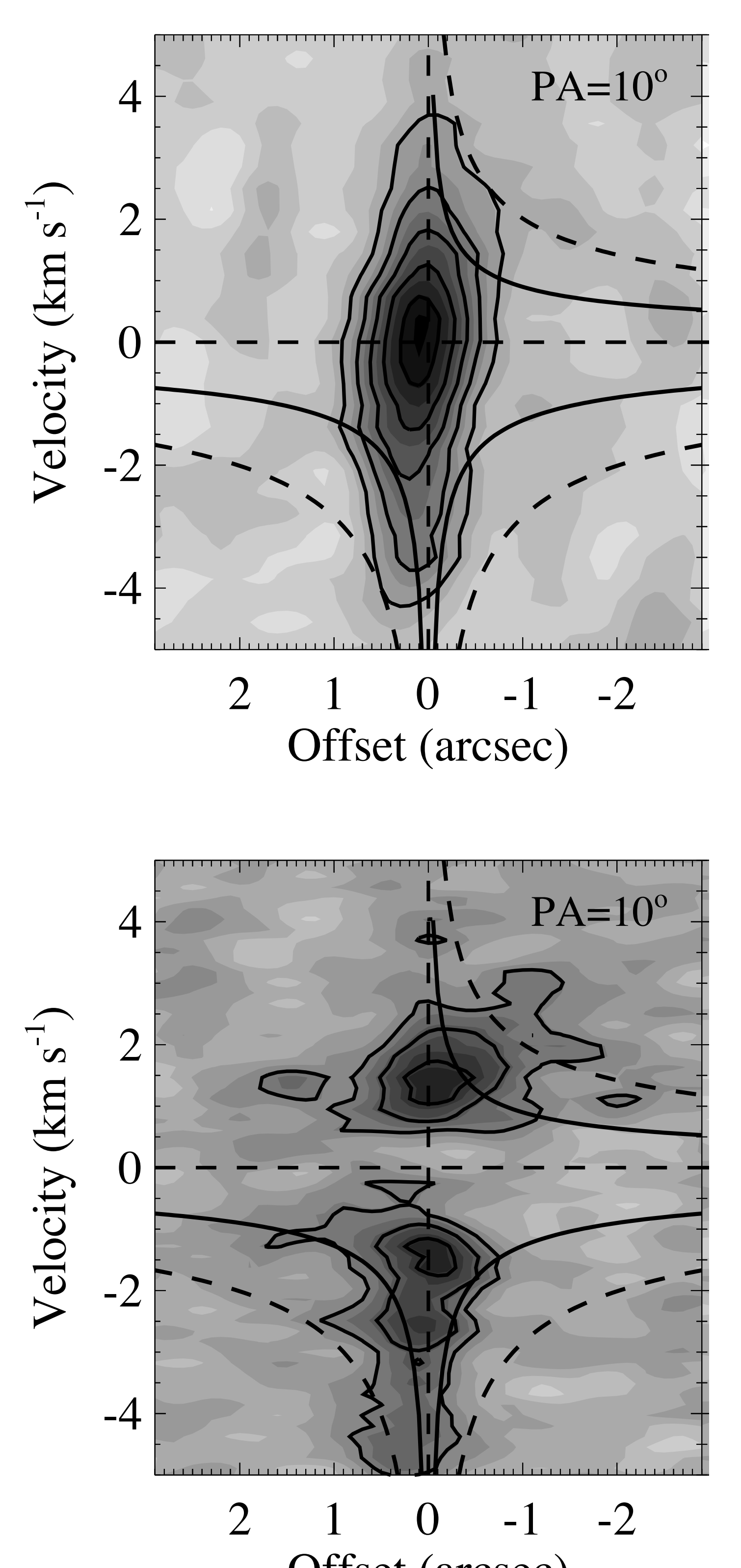
The PROSAC survey

Jorgensen et al. (2007, 2009)





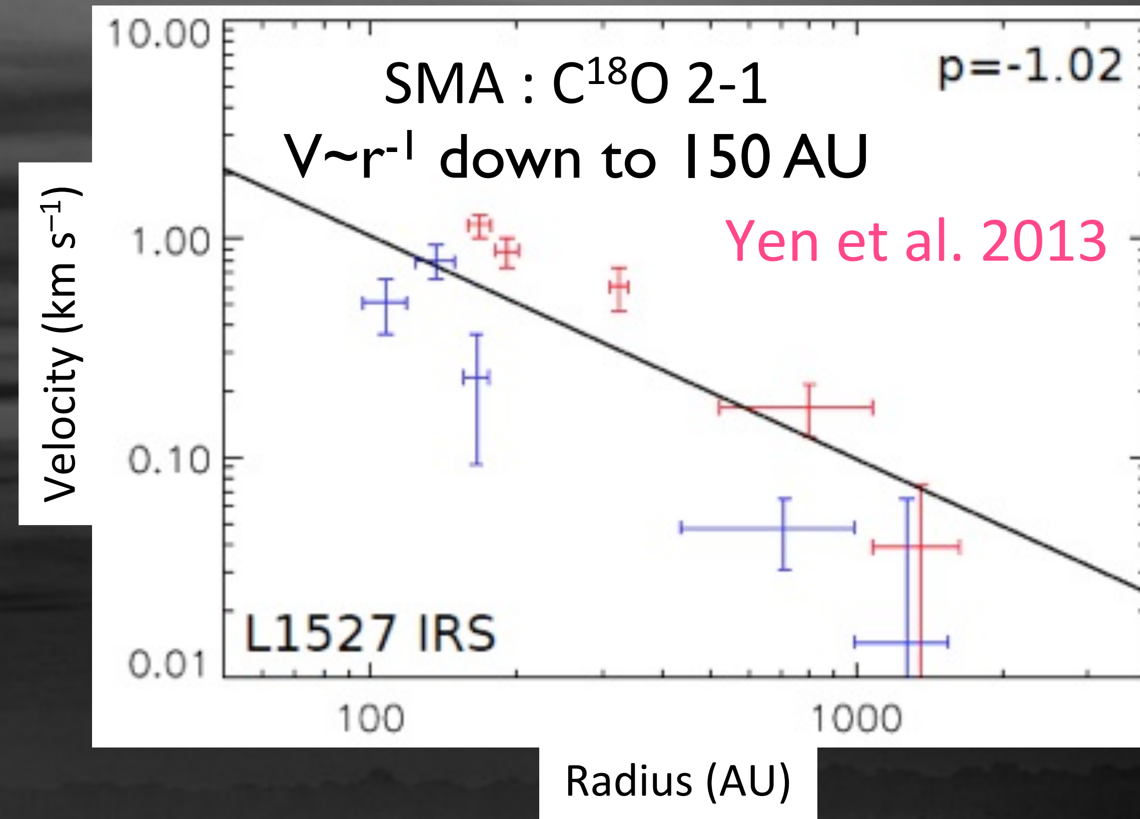
In Class 0 protostars:
no keplerian rotation detected



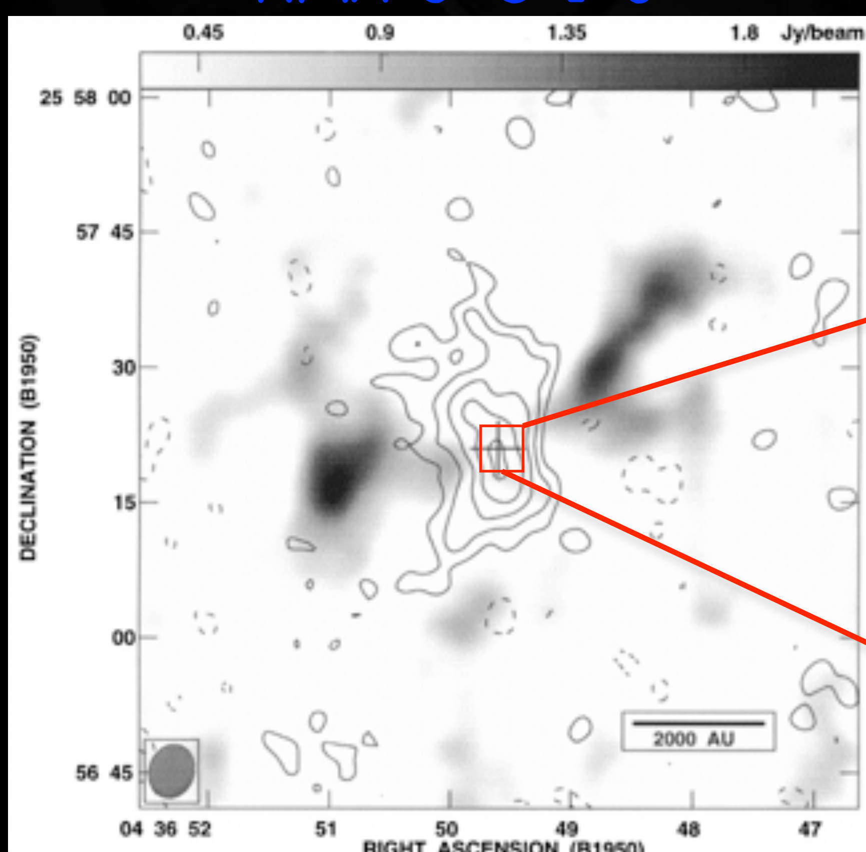
Brinch et al. (2009)

A keplerian disk around the Class 0 Protostar L1527

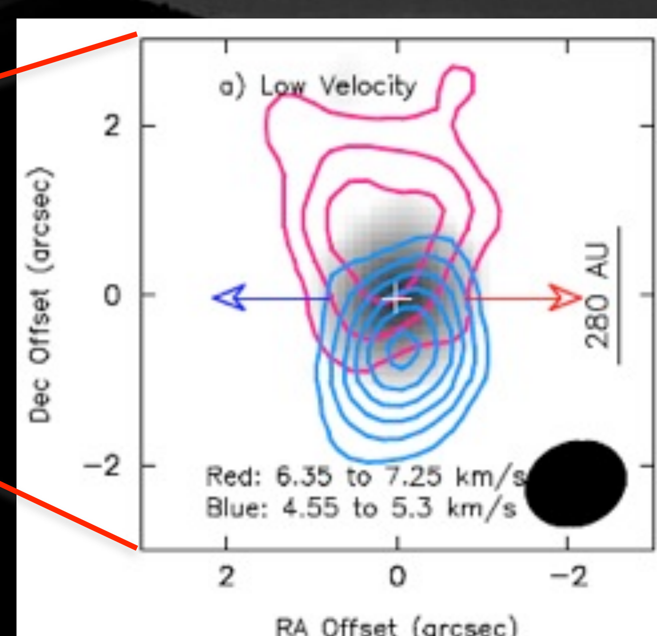
L1527: Class 0/I protostar
Lbol ~ 2.6 Lsol
Menv ~ 1-2Msol



NMA C18O 1-0

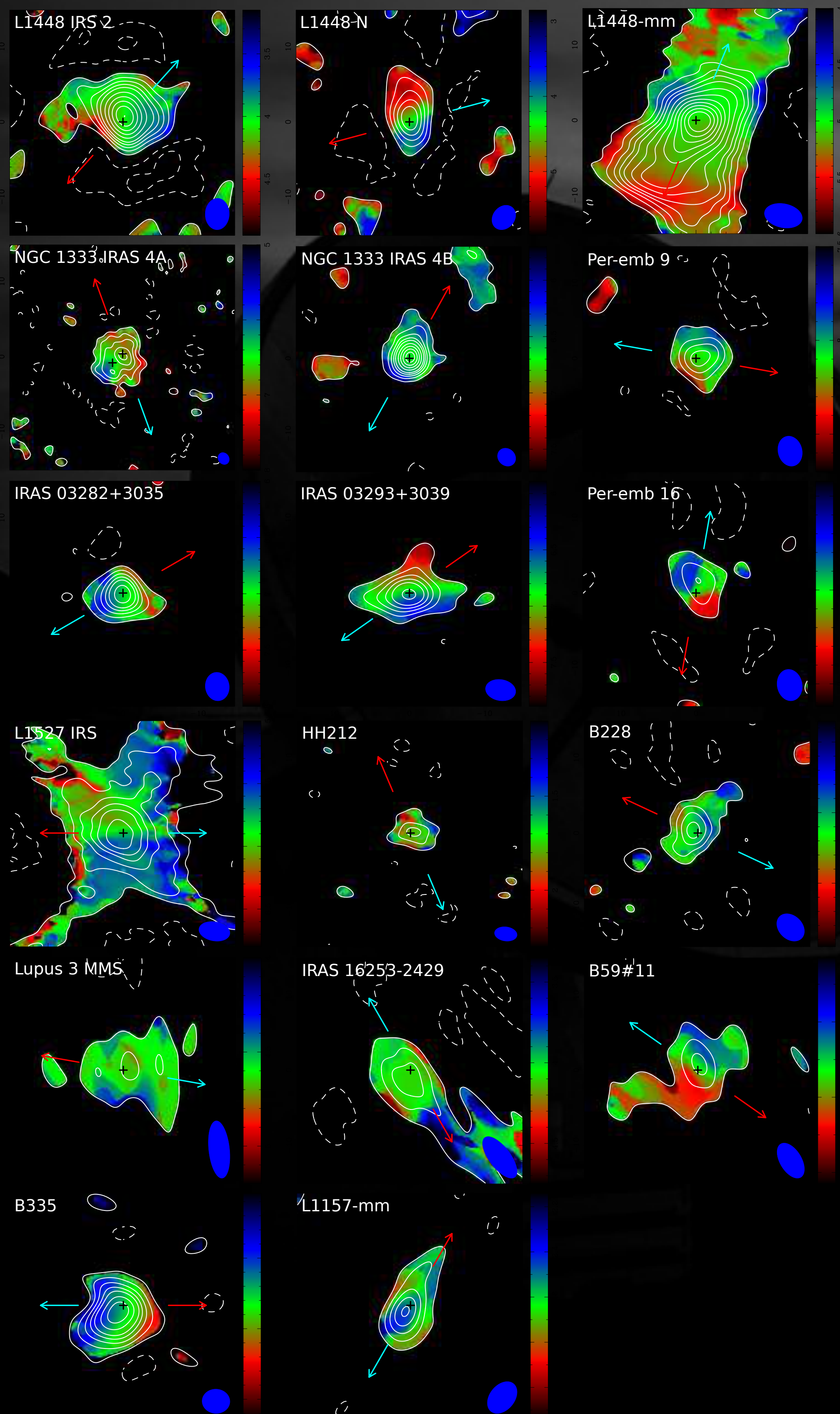


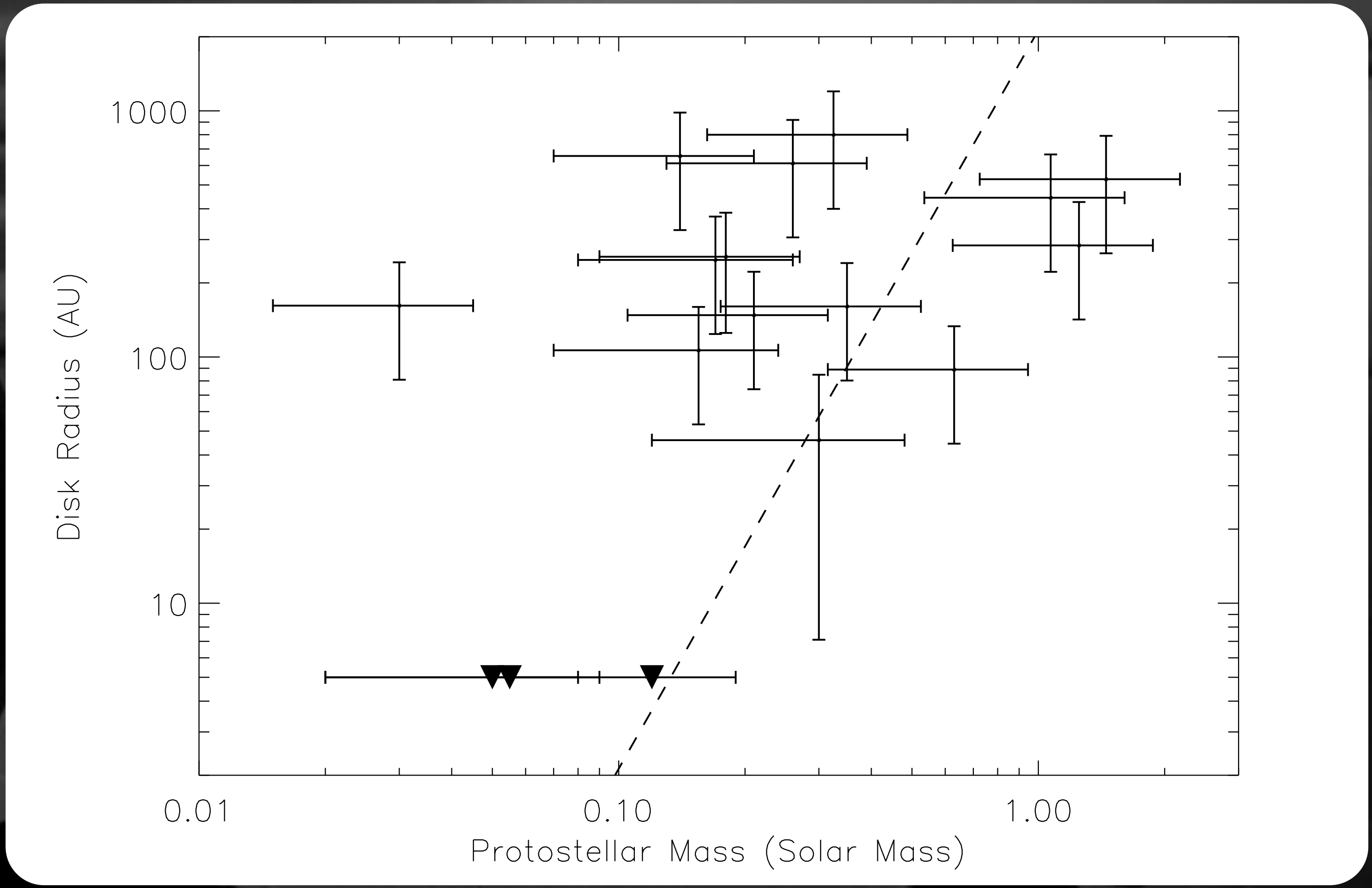
CARMA 13CO 2-1



Tobin+ (2012,2013):
CARMA 13CO and SMA 850mu continuum
Edge-on disk with r=125AU
Protostellar mass 0.19 Msol
Disk mass 0.0075 Msol

Class 0 envelopes: conservation of angular momentum ?

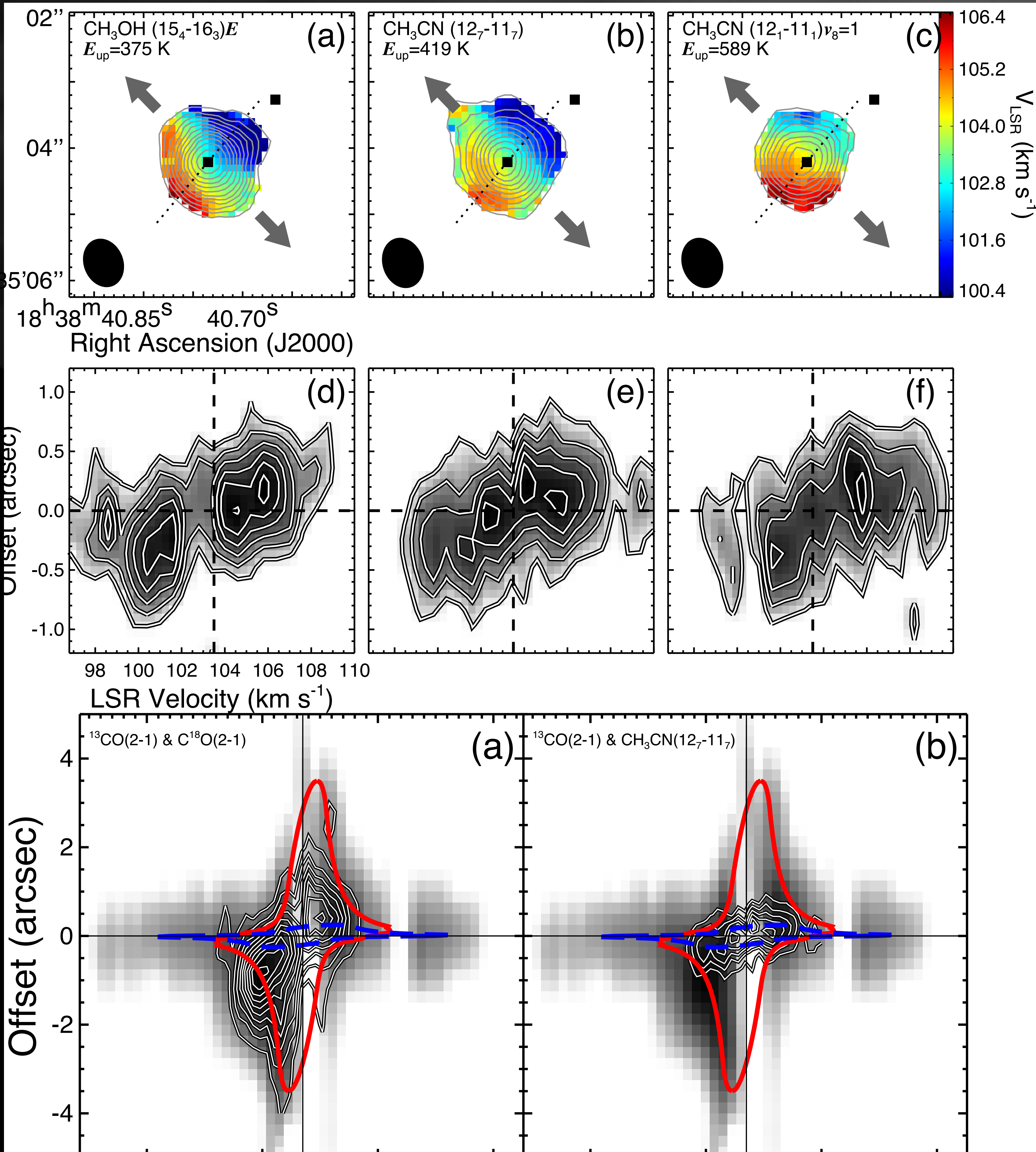




Inferred disk sizes ranging over two orders of magnitude from <5 AU to >500 AU. (Yen et al. (2013)

Infall and outflow around HH 212 (Lee et al. 2005):
Envelope is dynamically infalling with slow rotation : the kinematics is found to be roughly consistent with a free fall toward the source plus a rotation of a constant specific angular momentum.

SMA unveils the structure of massive protostellar cores



IRAS18360: Qiu et al (2012)

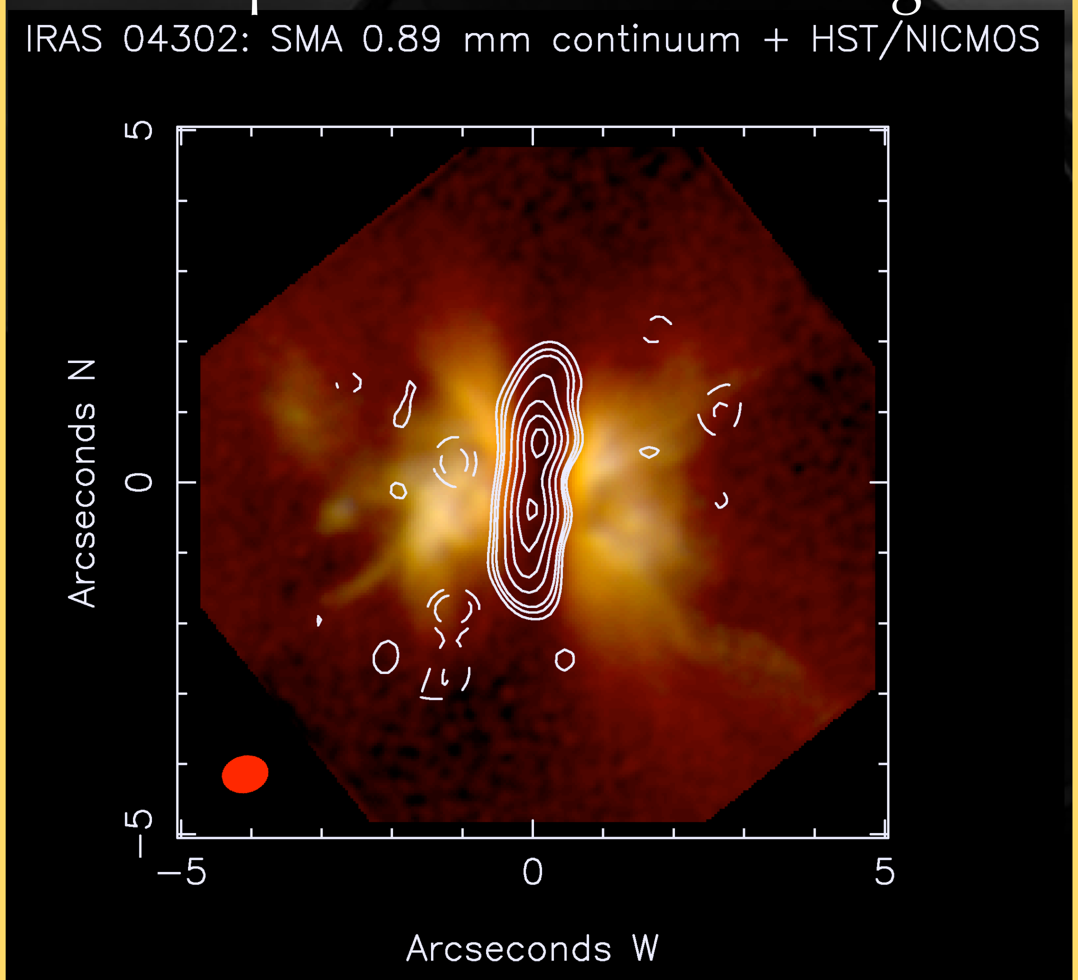
See also :
Beuther et al. 2006 in IRAS18089
Keto & Zhang (2009) in IRAS20126

Some rotation signatures but not many.

Difficulties to observationally isolate massive accretion disks from the surrounding dense gas envelopes and the molecular outflows

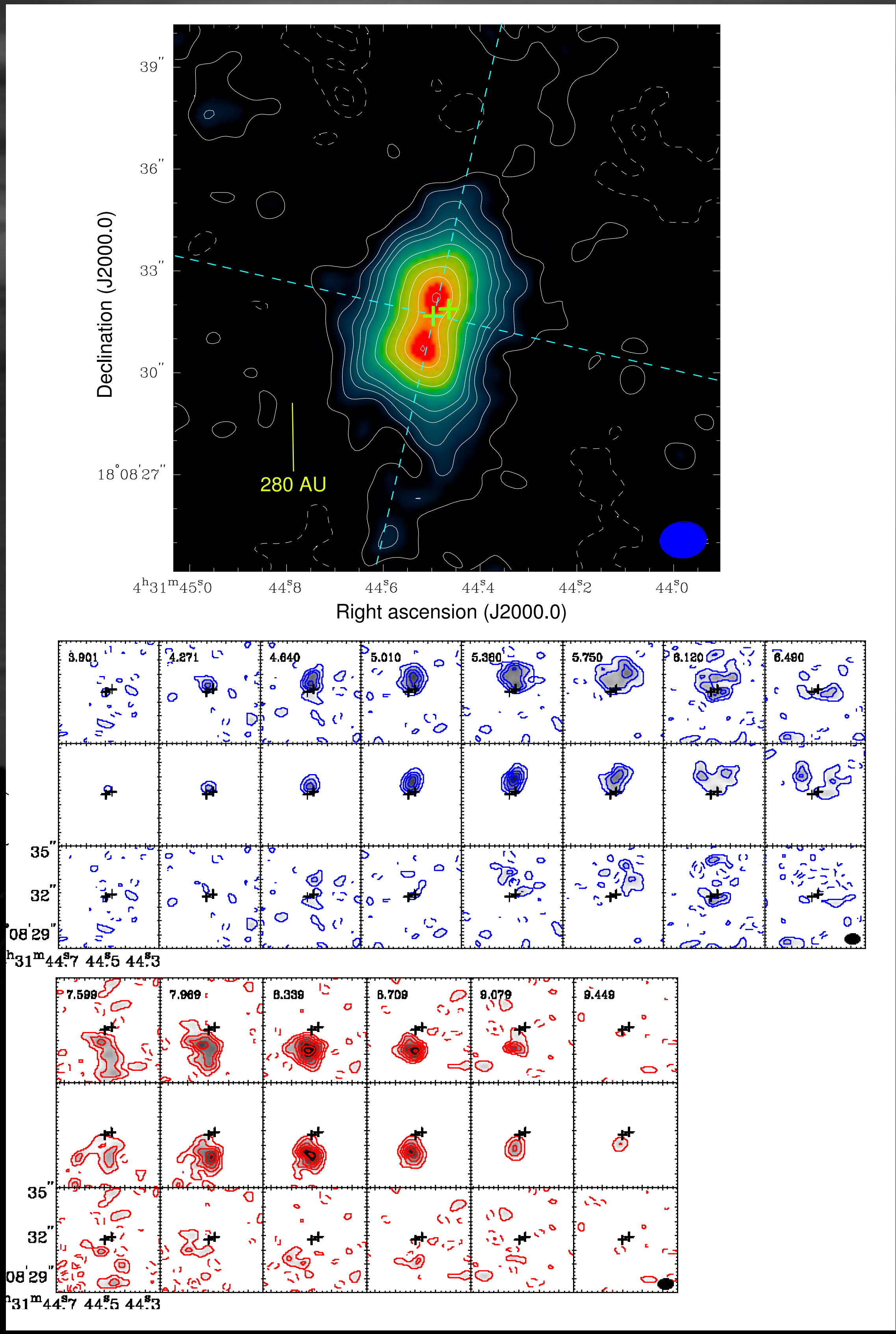
Circumstellar Disks in Class I protostars

IRAS 04302+2247: Class I protostar in Taurus-Auriga



Wolf et al. (2008)

L1551: Takakuwa et al. (2013)

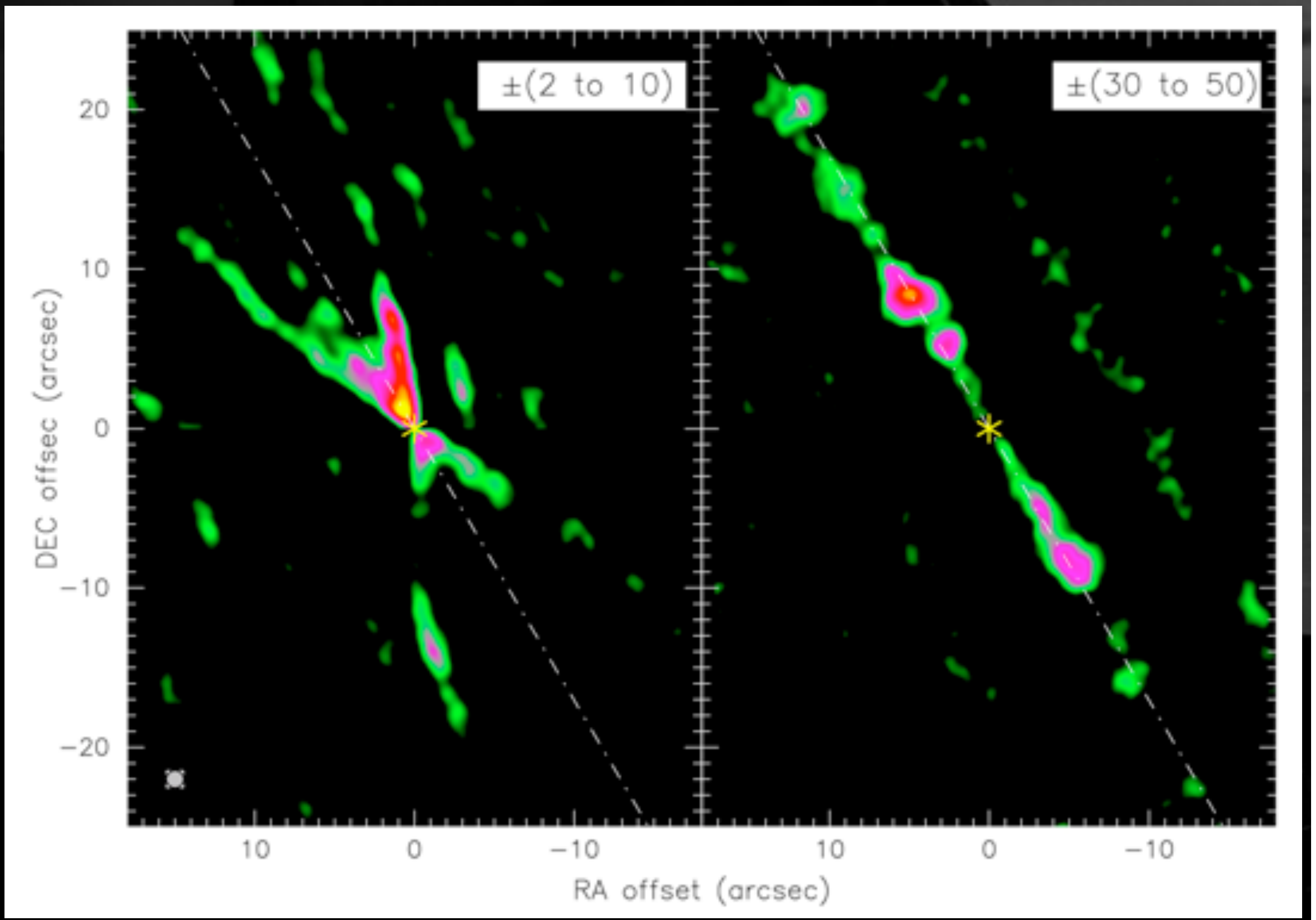


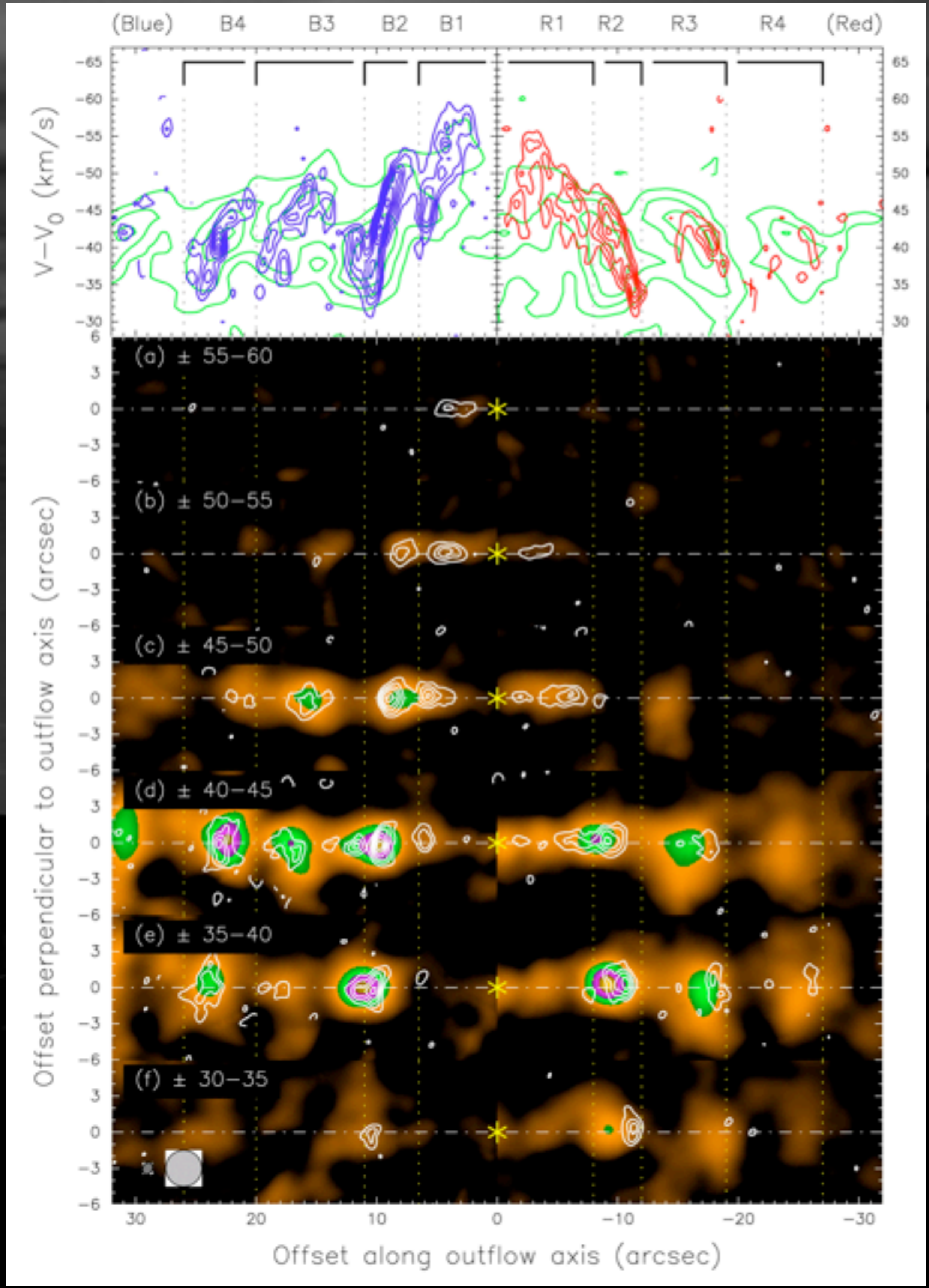
High Vel. (> 0.5 km s^{-1}) Component
Keplerian Disk around 0.8 M_{sun}

Low Vel. (< 0.5 km s^{-1}) Component
Outer Infalling Envelope with the Decelerated Infalling Velocity ?

Resolving protostellar jets and outflows

IRAS04166

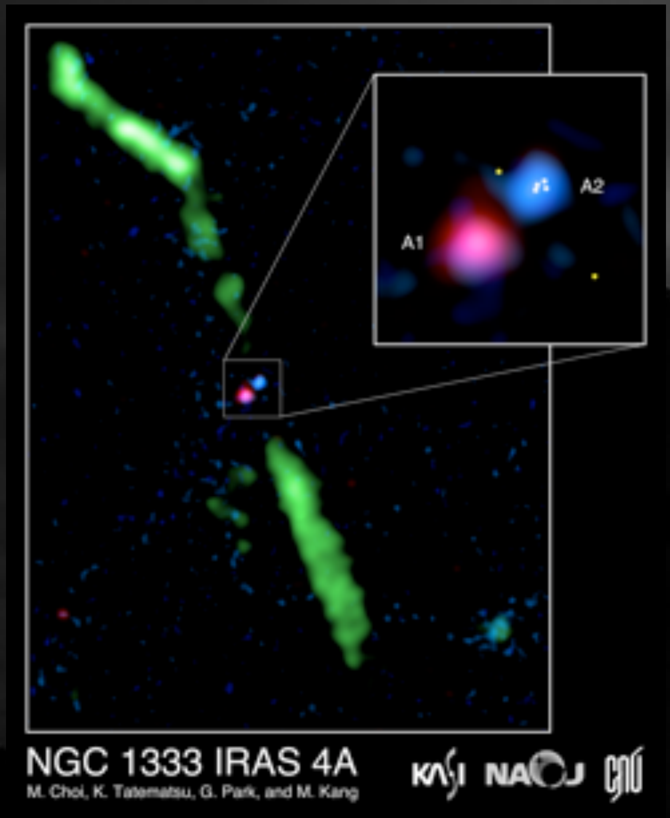




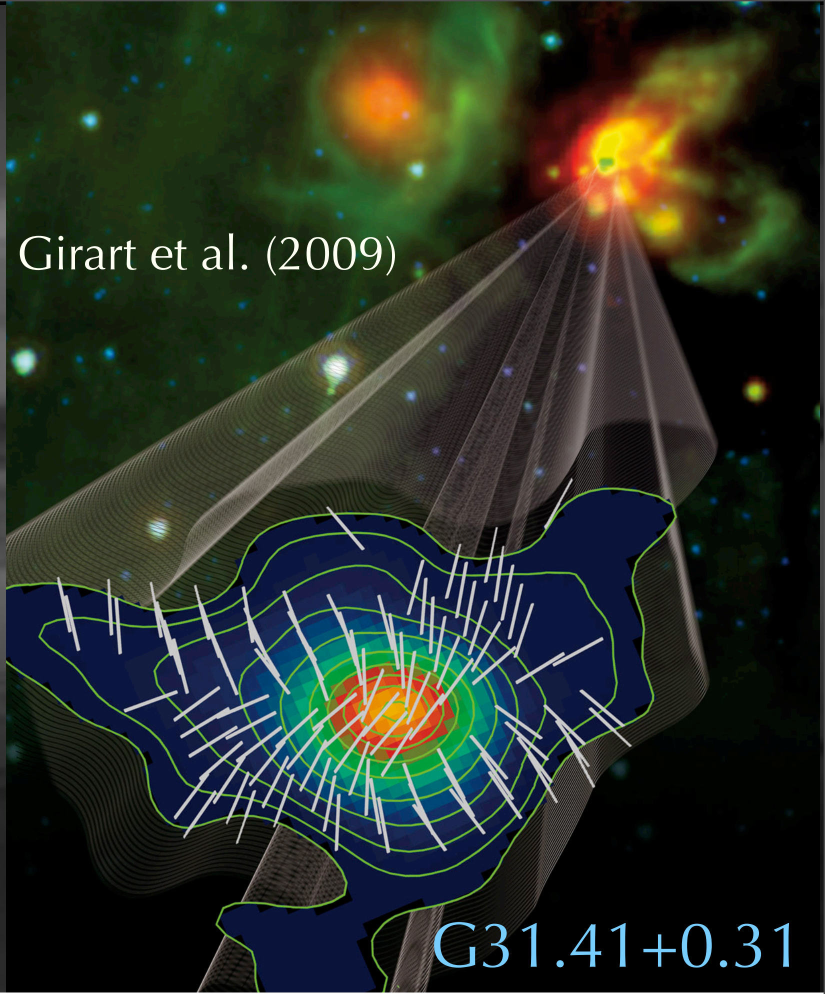
Wang et al. (2013)

See also Bourke et al. (2005) in L1014, Palau et al. (2005) in HH211. Lee et al. (2007, 2008) in HH212 + Hirano's talk

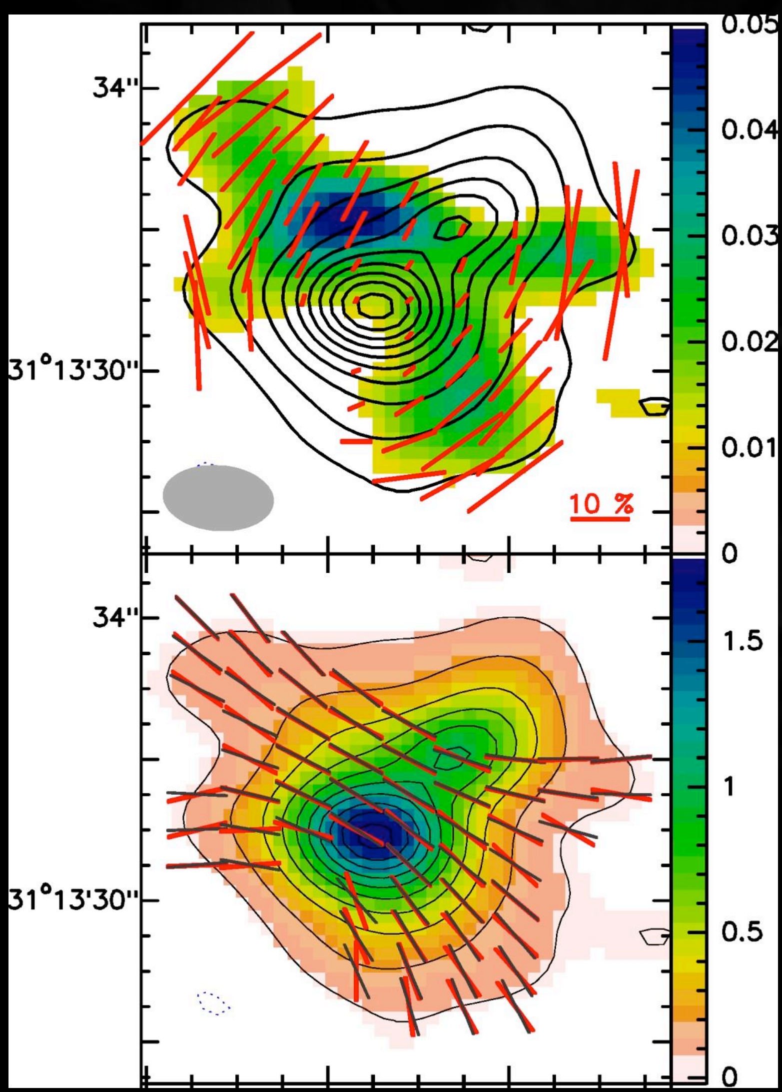
Magnetic Fields



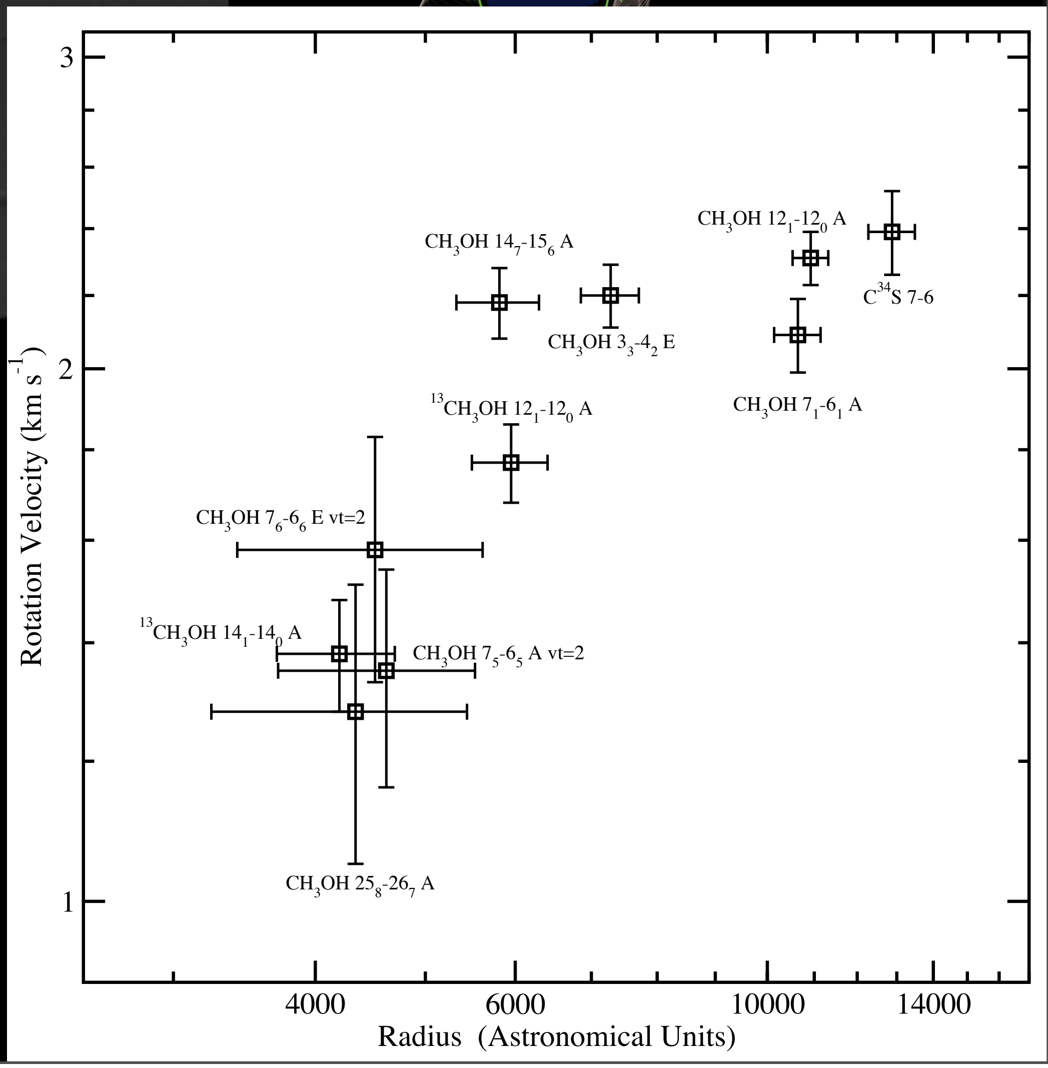
Angular momentum not conserved during collapse ?



Girart et al. (2009)



Girart et al. (2006)



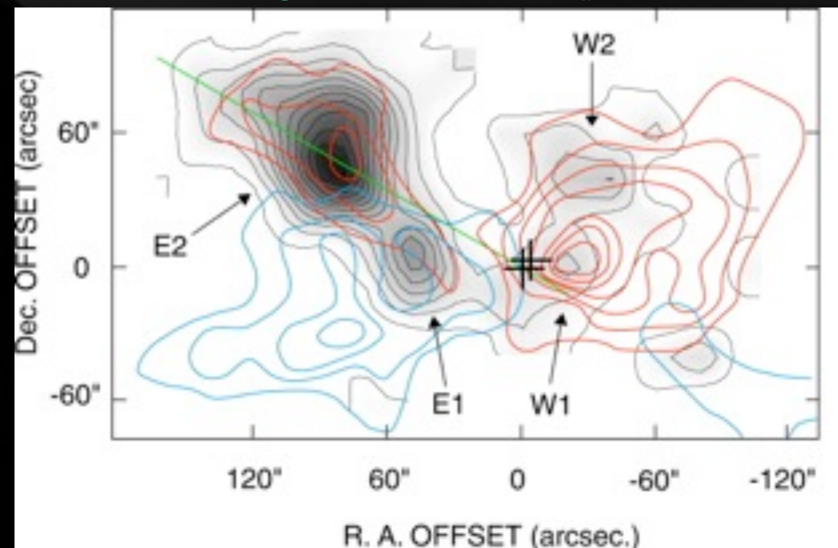
ALMA vs SMA


15 ant (105 baselines – 1700 m^2)
ALMA
Science Verification
8 ant (28 baselines – 226 m^2)
SMA

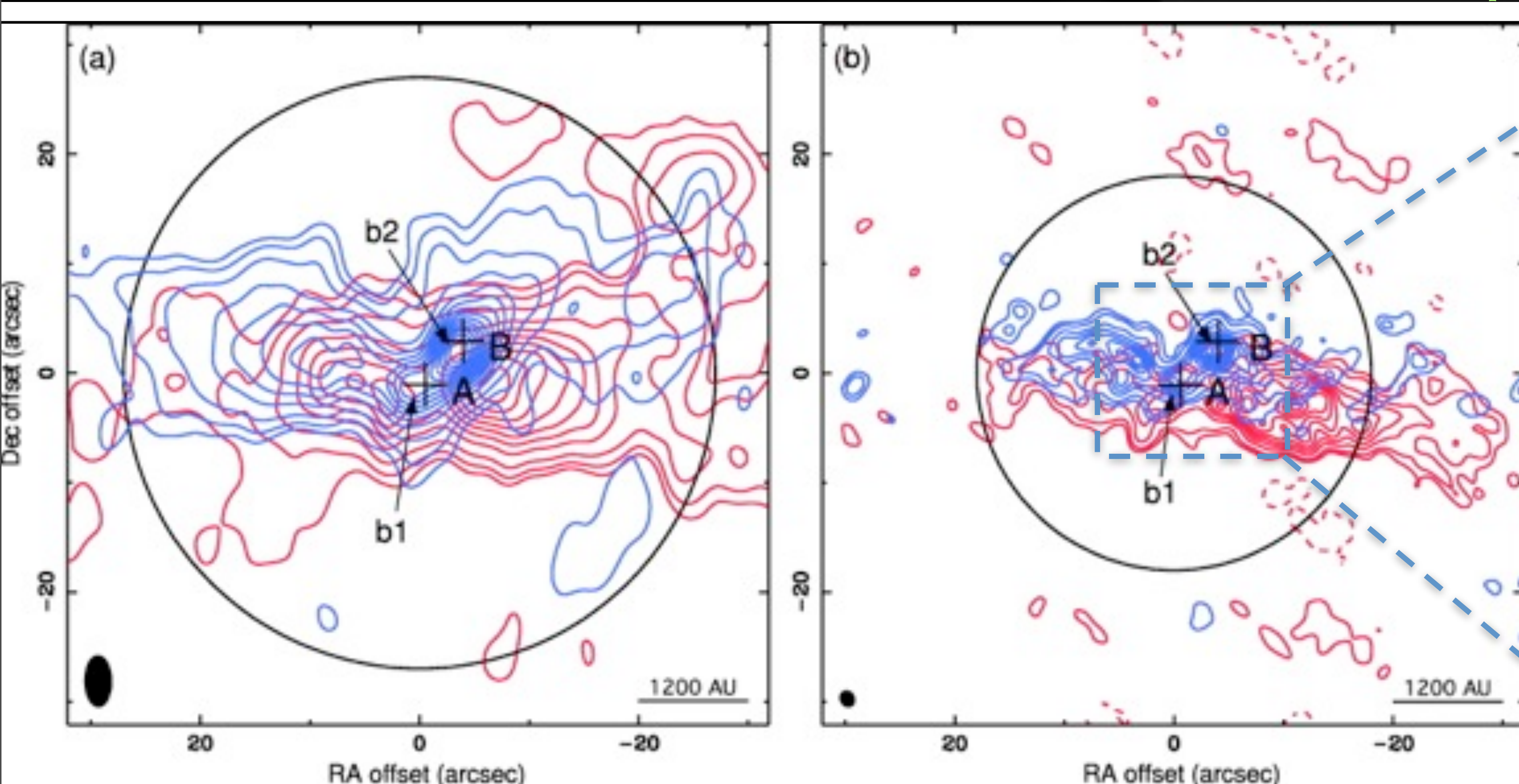
Complexity of Molecular outflows in IRAS 16293-2422

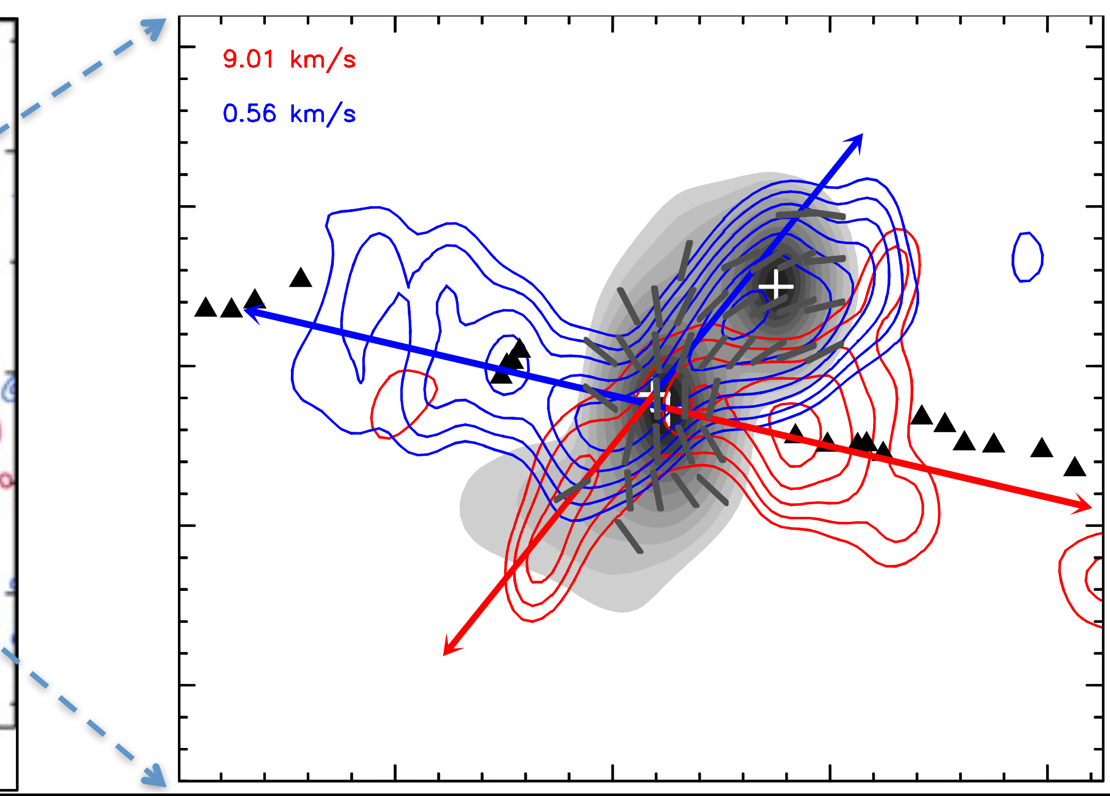
(Mizuno et al. 1990, Yeh et al. 2008; Rao et al. 2009)

CO 1-0
Quadrupolar outflow at large scales ~0.1 pc,

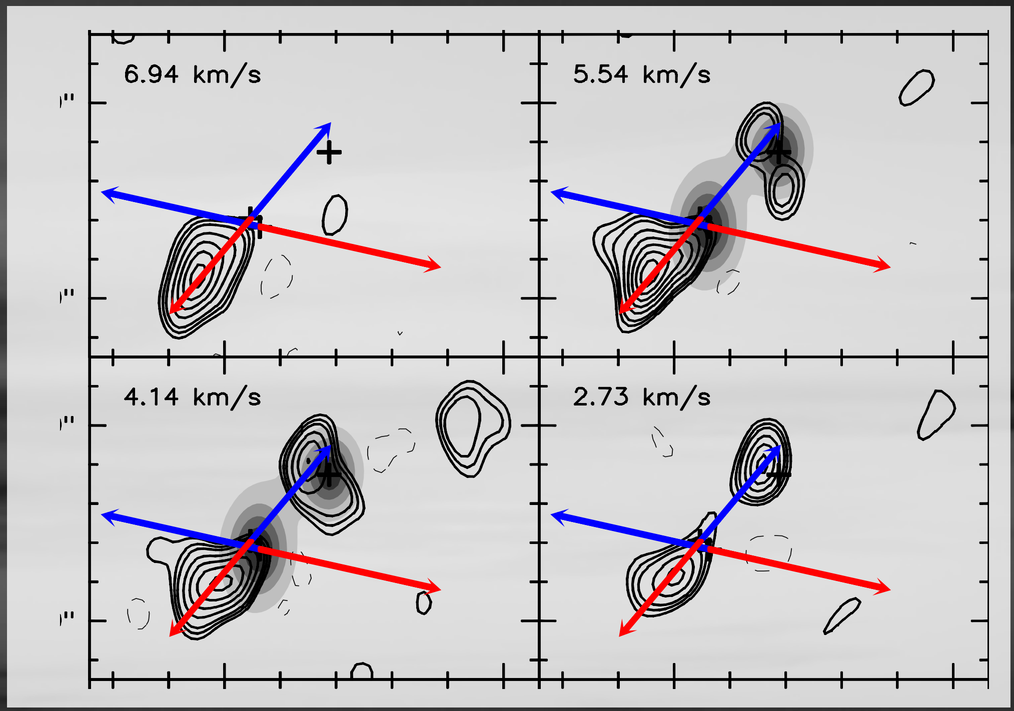


CO 2-1, 3-2
Bipolar/Quadrupolar outflow at scales of 0.01 pc



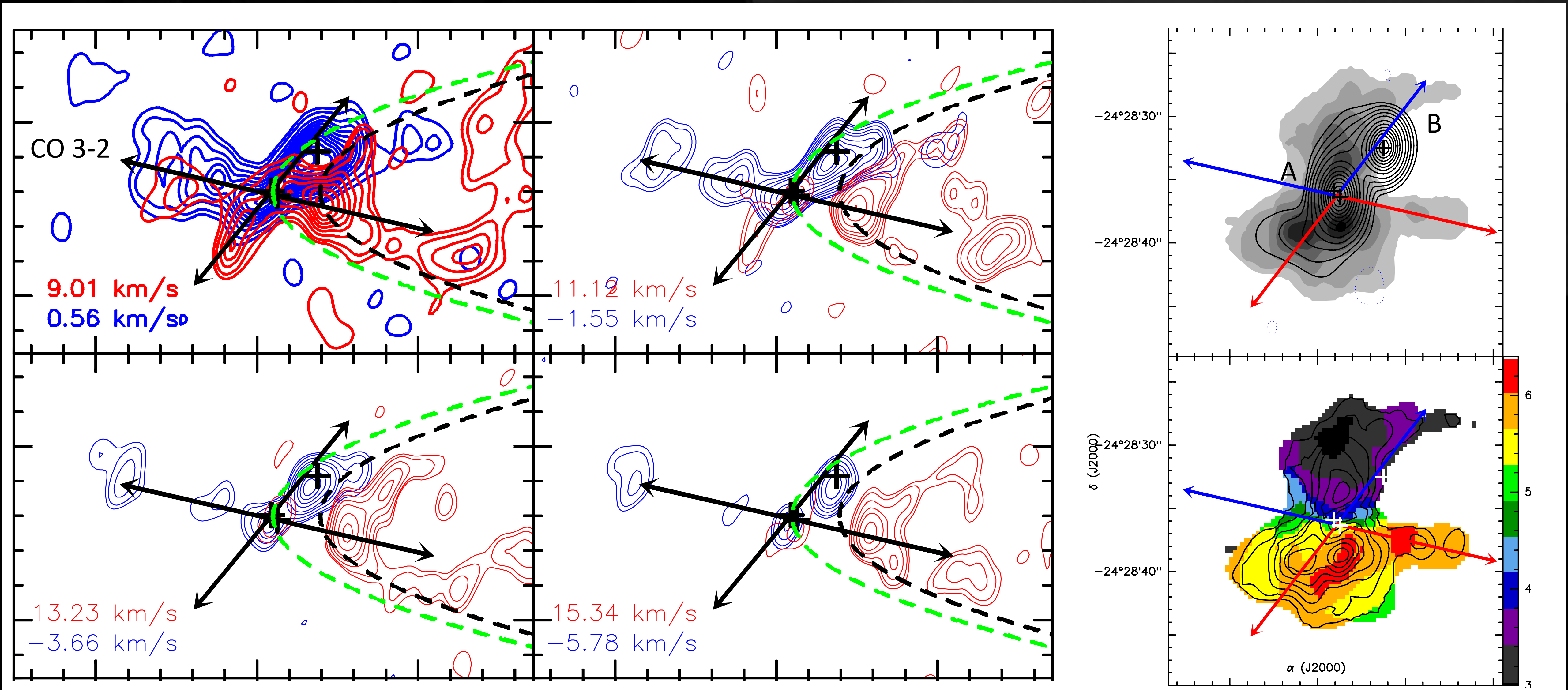


IRAS 16293-2422
SMA
Rao, Girart et al 2009



SiO 8-7 & 870µm

CO 3-2
Quadrupolar outflow
at scales of 0.005 pc

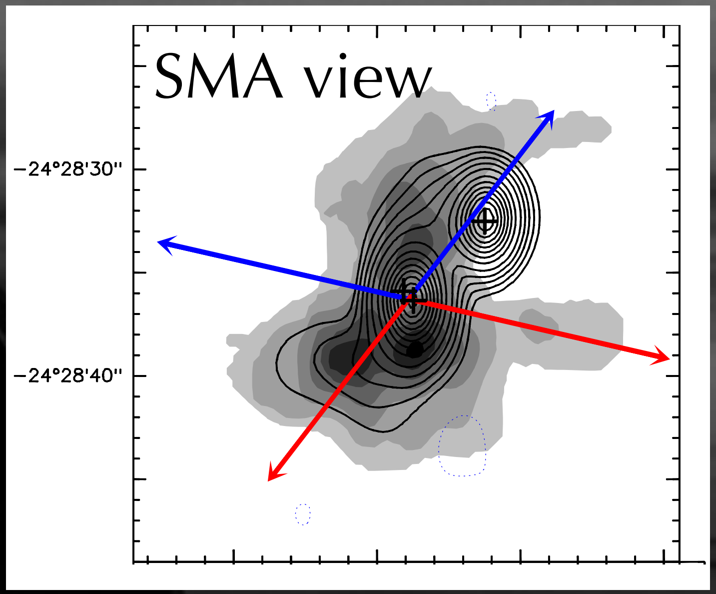


H13CO+ 3-2 & 870µm

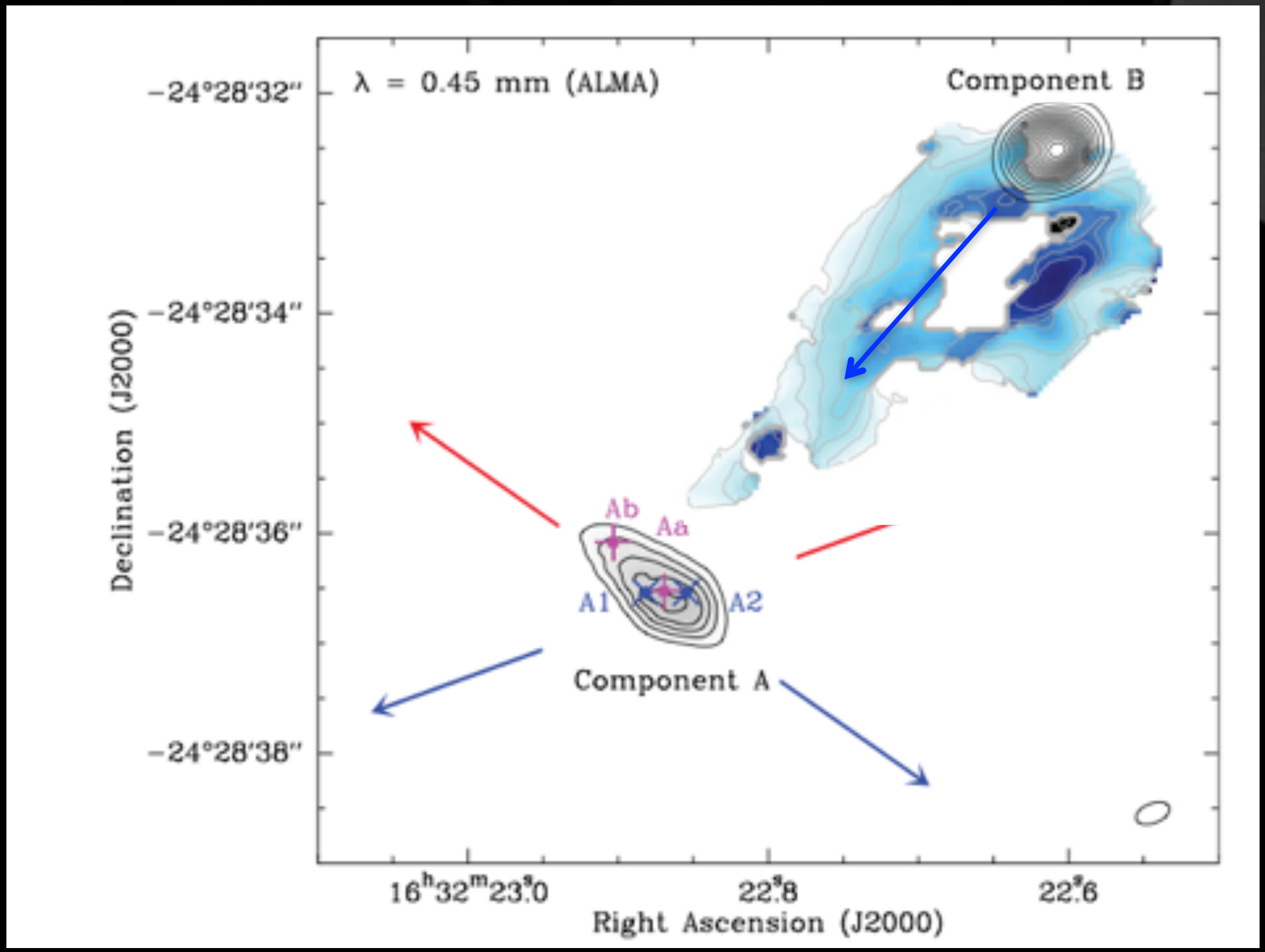
CO 3-2 & 870µm

ALMA Science Verification observations of IRAS 16293-2422

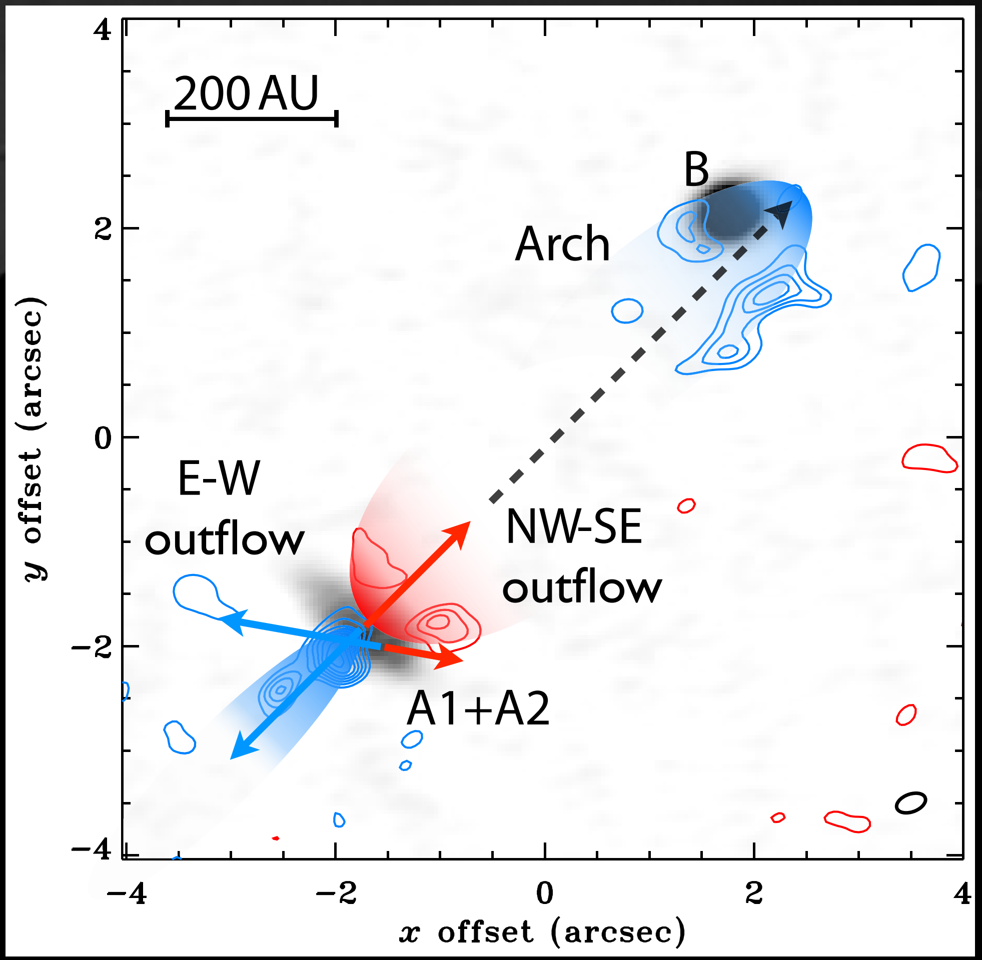
Same data but different interpretation!!!



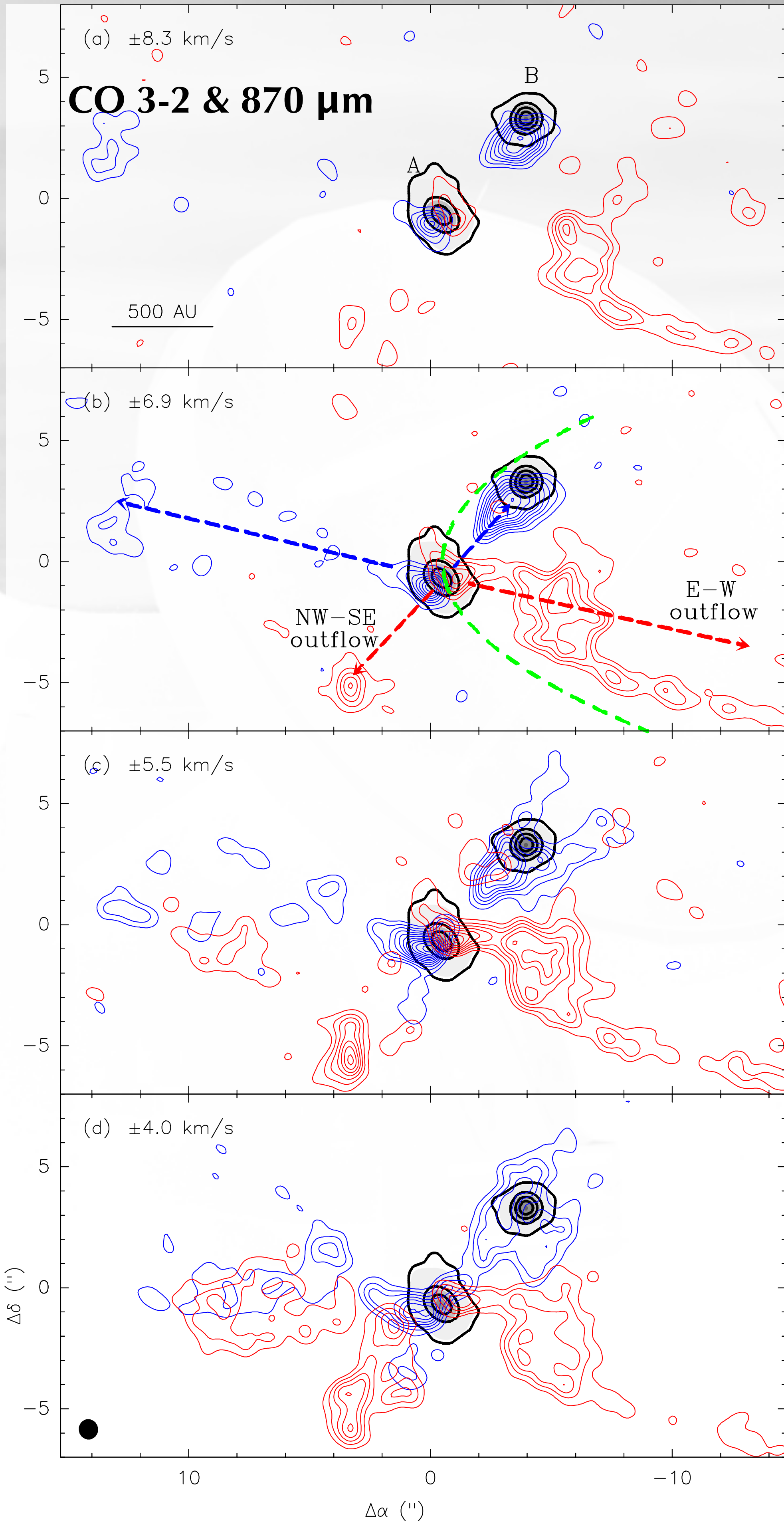
(Loinard et al. 2013)



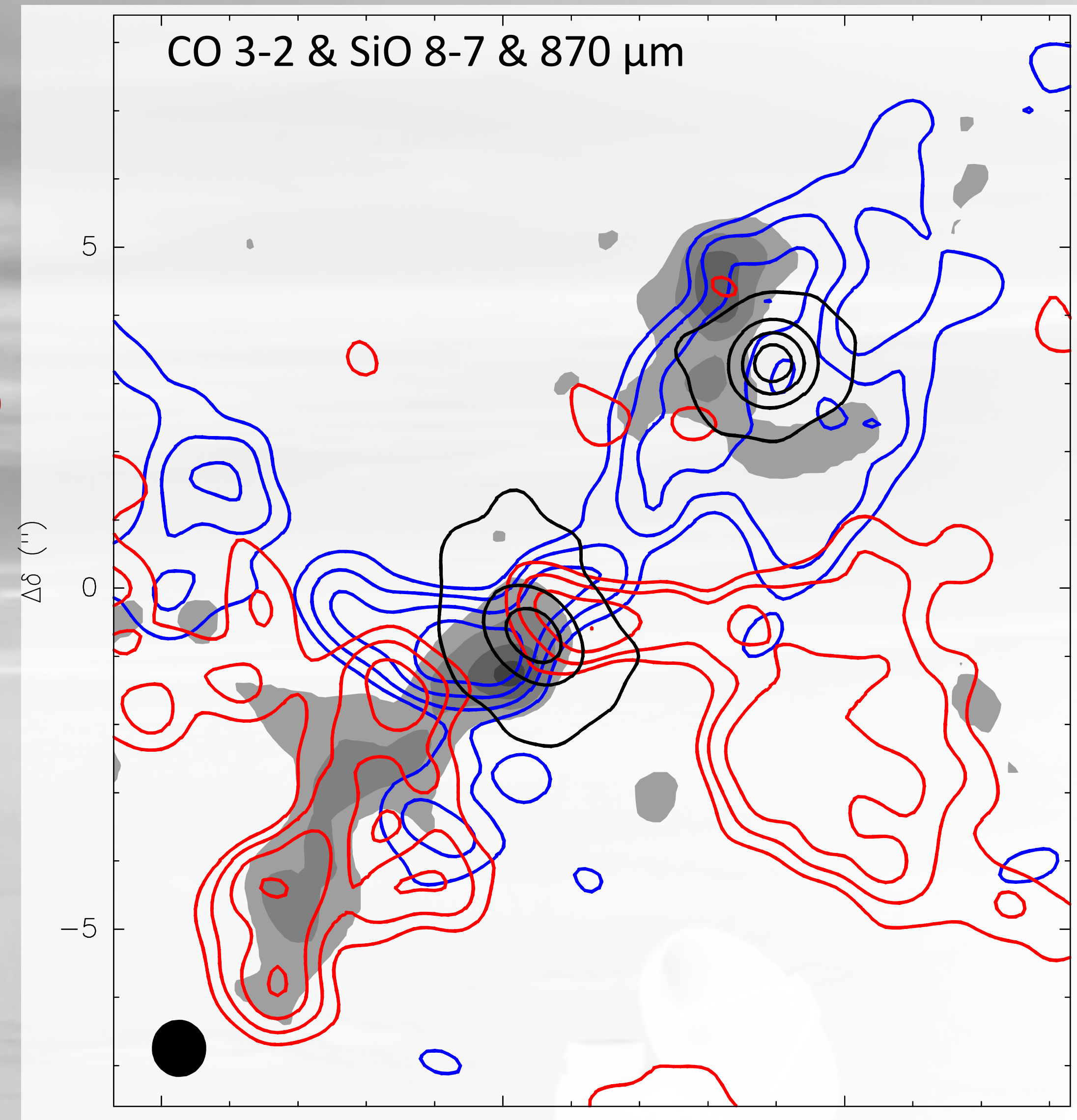
(Kristensen et al. 2013)



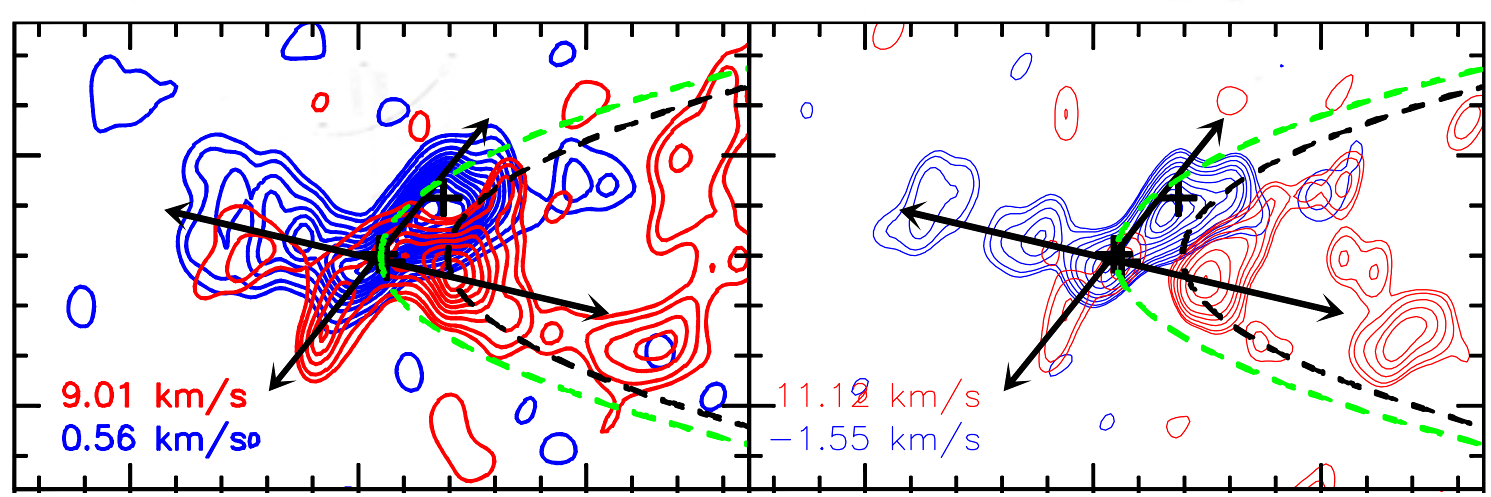
IRAS 16293-2422
SMA
Girart et al 2014



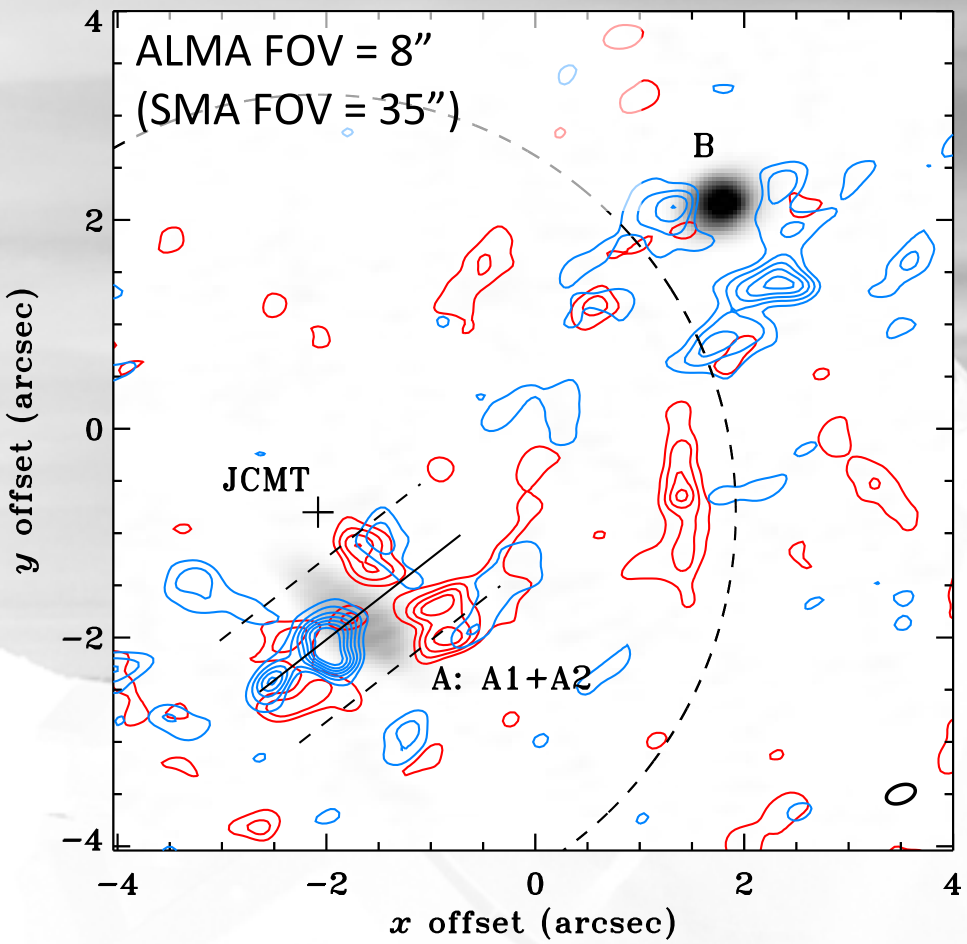
Two perpendicular CO outflows arising from source A



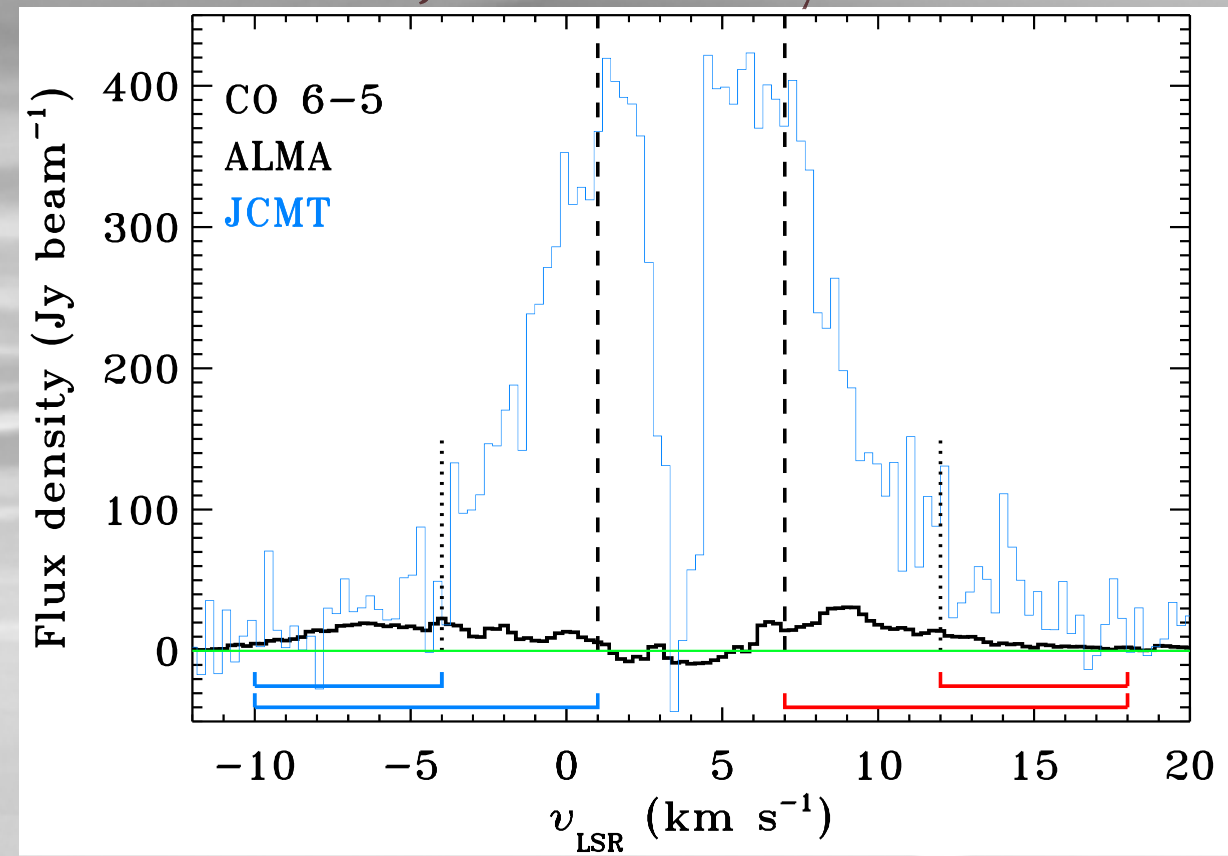
CO 3-2 compact only

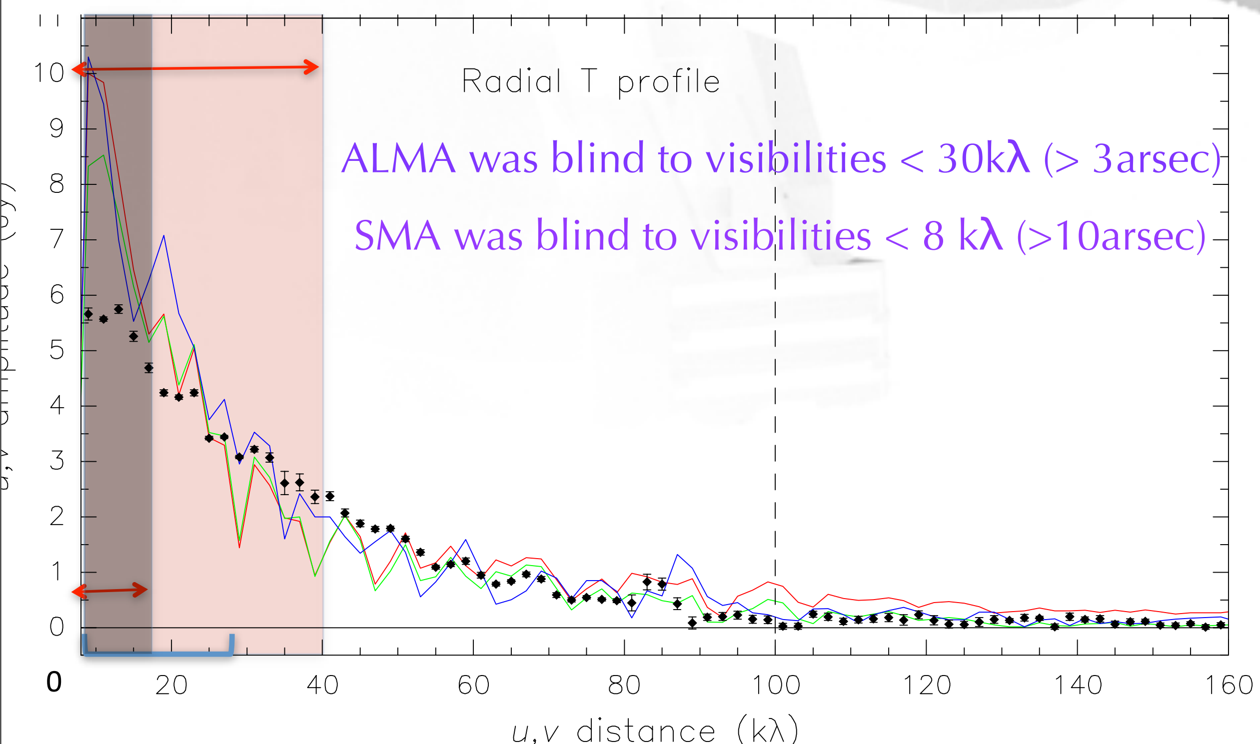


SMA (David) beats ALMA-Science Verification (Goliath) !! Why???



ALMA vs JCMT CO 6-5: they look so different!





SMA, ALMA measure the visibility function:
2-D Fourier transform of the sky brightness

$$V(u,v) = \int I(l,m) \cdot e^{j.2\pi.(ul + vm)} dl.dm$$

Open questions to be addressed in the next decade !

Connect the scales !

Statistics !

Dust properties !

What regulates the SFR ?

Role of magnetic fields in filaments and cores ?

Formation of disks: when and how in low-mass protostars ?

Accretion onto the protostars: episodic, rates ?

Role of galactic flows and turbulence ?

Are there any disks at all in massive protostellar cores ?

Massive star formation: dynamic or monolithic ?

Massive prestellar cores ?

(chemistry, ionization rates, etc ...)

SMA: sensitive to both small and large scales + polarization capacities !