Massive star formation with the SMA

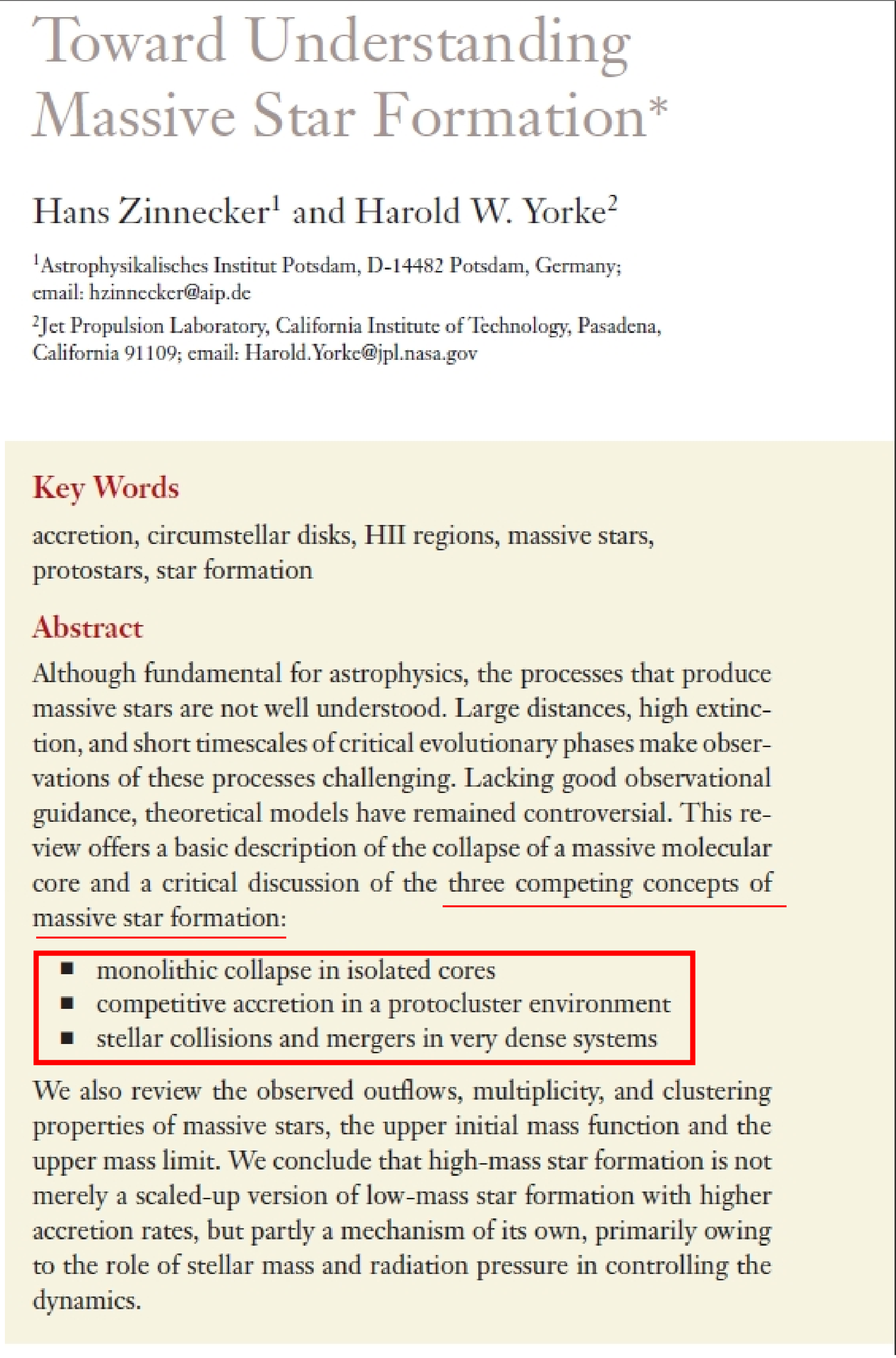
The SMA’s impact in studies of massive star formation since the last SAC meeting in 2007

Steve Longmore

Massive star formation: 2007

ARA&A review

- 3 competing concepts
  - Turbulent core
    - Predicts ➔Monolithic collapse of 100 Msun cores
  - Competitive accretion
    - Predicts ➔Initial Jeans fragmentation to cores of 1 Msun
  - Collisions/mergers
    - Predicts ➔ Dynamical interactions



Toward Understanding Massive Star Formation*

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Key Words

accretion, circumstellar disks, HII regions, massive stars, protostars, star formation

Abstract

Although fundamental for astrophysics, the processes that produce massive stars are not well understood. Large distances, high extinction, and short timescales of critical evolutionary phases make observations of these processes challenging. Lacking good observational guidance, theoretical models have remained controversial. This review offers a basic description of the collapse of a massive molecular core and a critical discussion of the three competing concepts of massive star formation:

- monolithic collapse in isolated cores
- competitive accretion in a protocluster environment
- stellar collisions and mergers in very dense systems

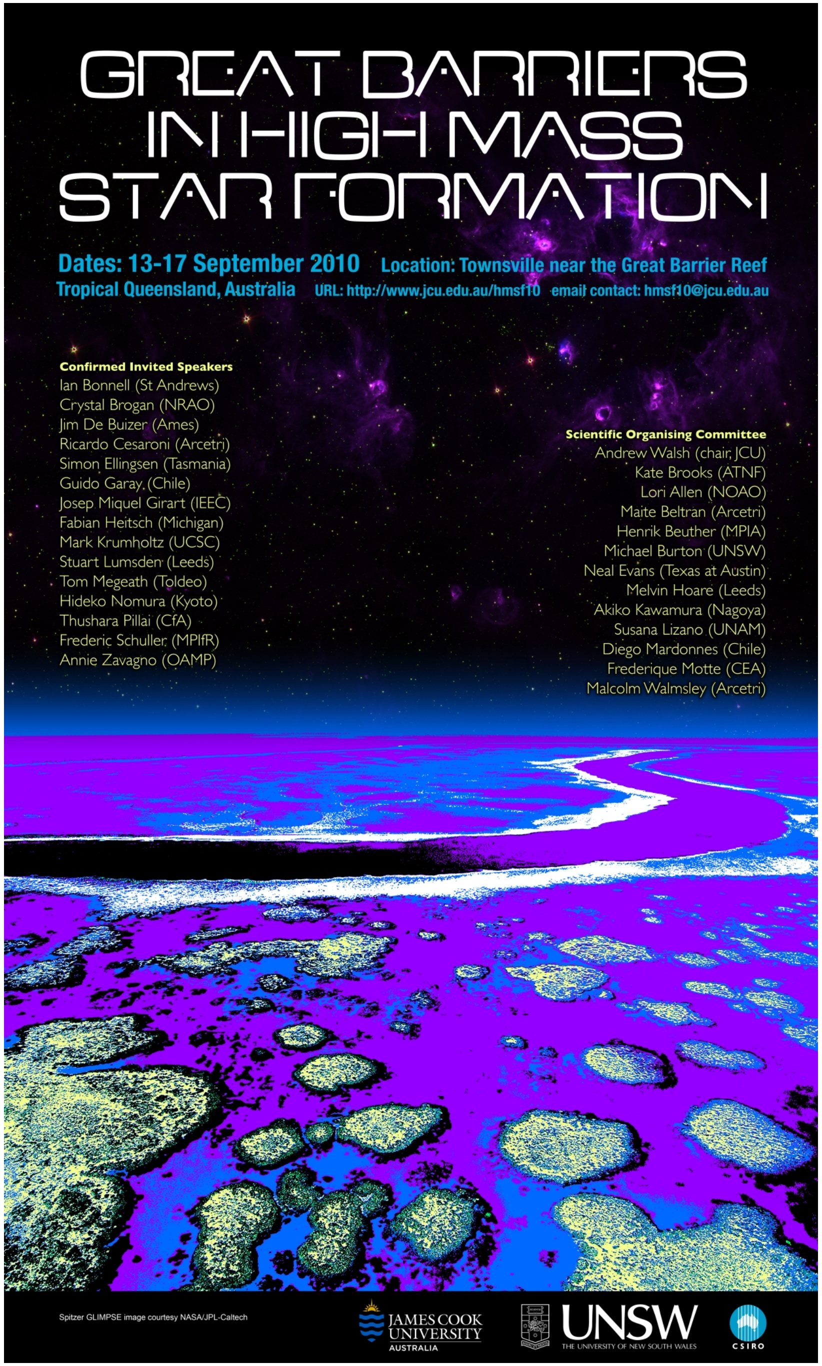
We also review the observed outflows, multiplicity, and clustering properties of massive stars, the upper initial mass function and the upper mass limit. We conclude that high-mass star formation is not merely a scaled-up version of low-mass star formation with higher accretion rates, but partly a mechanism of its own, primarily owing to the role of stellar mass and radiation pressure in controlling the dynamics.

Massive star formation: 2010

Conference 3 weeks ago

- Different picture emerging
  - Summarize key developments in this talk
- SMA observations played a lead role in developing new picture
  - ~20% (13/81) talks based on SMA data

- Why has SMA had such large impact?



GREAT BARRIERS IN HIGH MASS STAR FORMATION

Dates: 13-17 September 2010 Location: Townsville near the Great Barrier Reef
Tropical Queensland, Australia URL: http://www.jcu.edu.au/hmsf10 email contact: hmsf10@jcu.edu.au

Confirmed Invited Speakers
Ian Bonnell (St Andrews)
Crystal Brogan (NRAO)
Jim De Buizer (Ames)
Ricardo Cesaroni (Arcetri)
Simon Ellingsen (Tasmania)
Guido Garay (Chile)
Josep Miquel Girart (IEEC)
Fabian Heitsch (Michigan)
Mark Krumholtz (UCSC)
Stuart Lumsden (Leeds)
Tom Megeath (Toldeo)
Hideko Nomura (Kyoto)
Thushara Pillai (CfA)
Frederic Schuller (MPIfR)
Annie Zavagno (OAMP)

Scientific Organising Committee
Andrew Walsh (chair, JCU)
Kate Brooks (ATNF)
Lori Allen (NOAO)
Maite Beltran (Arcetri)
Henrik Beuther (MPIA)
Michael Burton (UNSW)
Neal Evans (Texas at Austin)
Melvin Hoare (Leeds)
Akiko Kawamura (Nagoya)
Susana Lizano (UNAM)
Diego Mardonnes (Chile)
Frederique Motte (CEA)
Malcolm Walmsley (Arcetri)

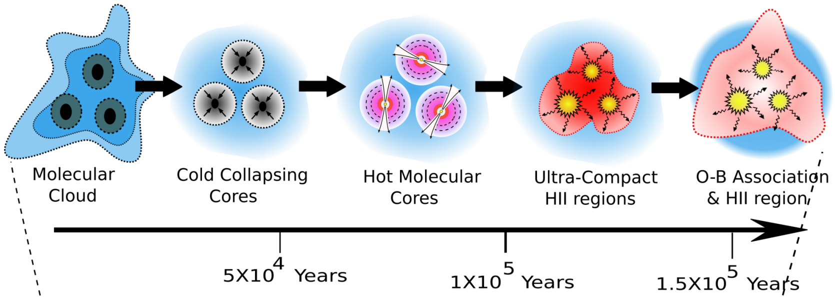
Spitzer GLIMPSE image courtesy NASA/JPL-Caltech

JAMES COOK UNIVERSITY AUSTRALIA
UNSW THE UNIVERSITY OF NEW SOUTH WALES
CSIRO

SMA's strengths

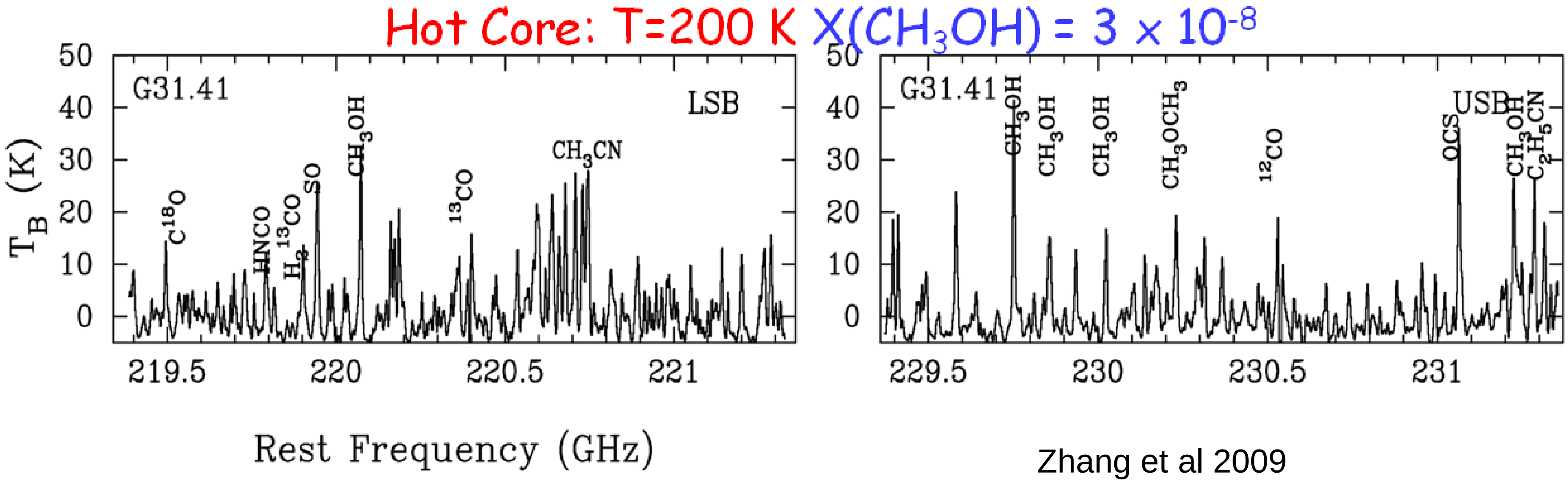
- Wide bandwidth ➔ many spectral lines simultaneously
  - Chemical clock
  - Deriving physical conditions
    - Specific "tracers": cold gas/high-densitygas/shocks/outflows/disks
    - Full chemical modelling

Evolutionary stages of high mass star formation



SMA chemistry papers

Chen et al 2010, accepted ApJ: Shi et al 2010, accepted ApJ: Palau et al 2009, accepted A&A: Wang et al 2010, ApJ, 713, 1192: Qin et al 2010, ApJ, 711, 399: Takahashi et al 2009, ApJ, 704, 1459: Beuther et al 2009, AJ, 137, 406: Qin et al 2008, ApJ, 686, L21: Rathborne et al 2008, ApJ, 689, 1141:Beuther et al 2008, ApJ, 675, L33: Fontani et al 2008, A&A, 477, L45

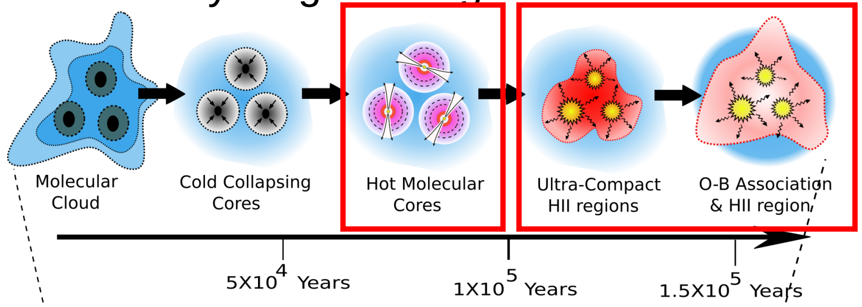


Zhang et al 2009

SMA’s strengths

- Wide bandwidth ➔ many spectral lines simultaneously
  - Chemical clock
  - Deriving physical conditions
    - Specific “tracers”: cold gas/high-densitygas/shocks/outflows/disks
    - Full chemical modelling

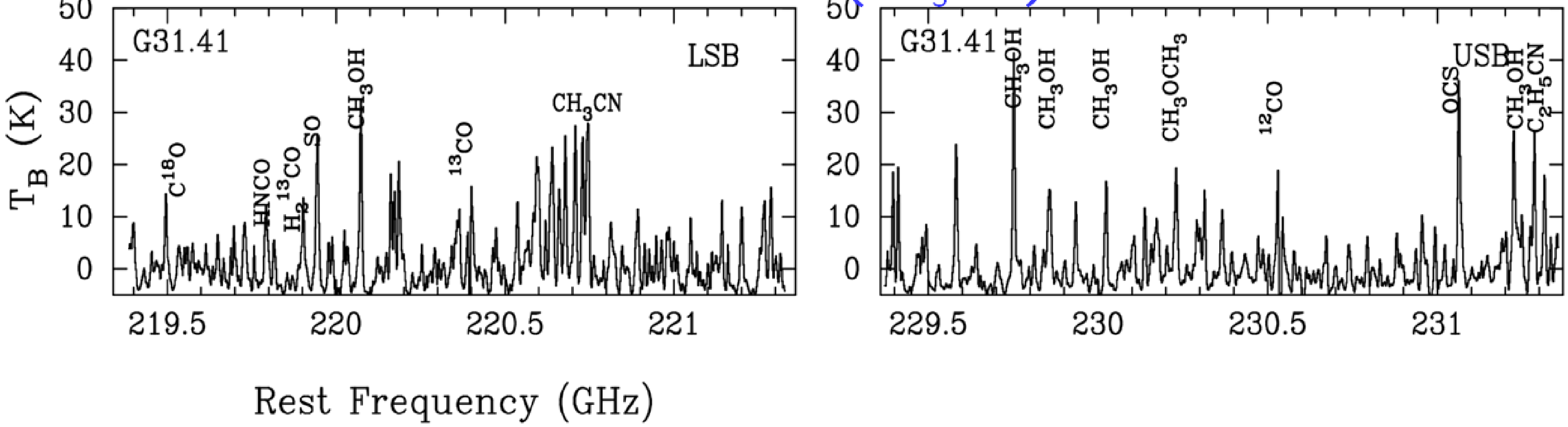
Evolutionary stages of high mass star formation



Izaskun (next talk): chemical modeling of hot molecular core

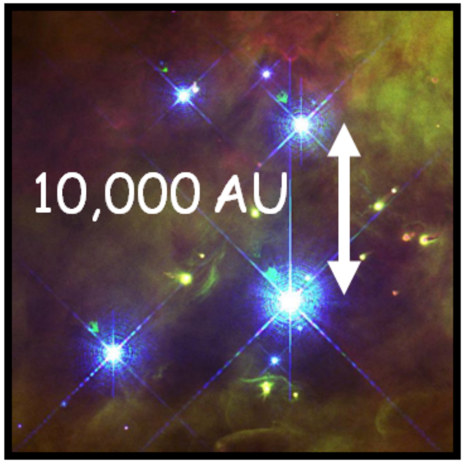
Roberto (subsequent talk): physics of massive star formation once massive star begun ionizing surrounding environment

Hot Core: T=200 K $X(CH_3OH) = 3 \times 10^{-8}$



SMA's strengths

- Wide bandwidth ➔ many spectral lines simultaneously
  - Chemical clock
  - Deriving physical conditions
    - Specific "tracers": cold gas/high-densitygas/shocks/outflows/disks
    - Full chemical modelling
- Flexible and high spectral resolution correlator
  - Detailed gas kinematics
- Polarization
  - Magnetic fields
- High frequency (345GHz is unique at present!)
  - High energy molecular transitions
    - Probe densest/hottest gas closest to protostars
  - Radio recombination lines
    - not pressure broadened
    - optically-thin
    - trace ionised gas dynamics close to protostar



1. Trapezium stars separated by ~10,000AU

2. Ambipolar diffusion scale ~2mpc (~400AU)

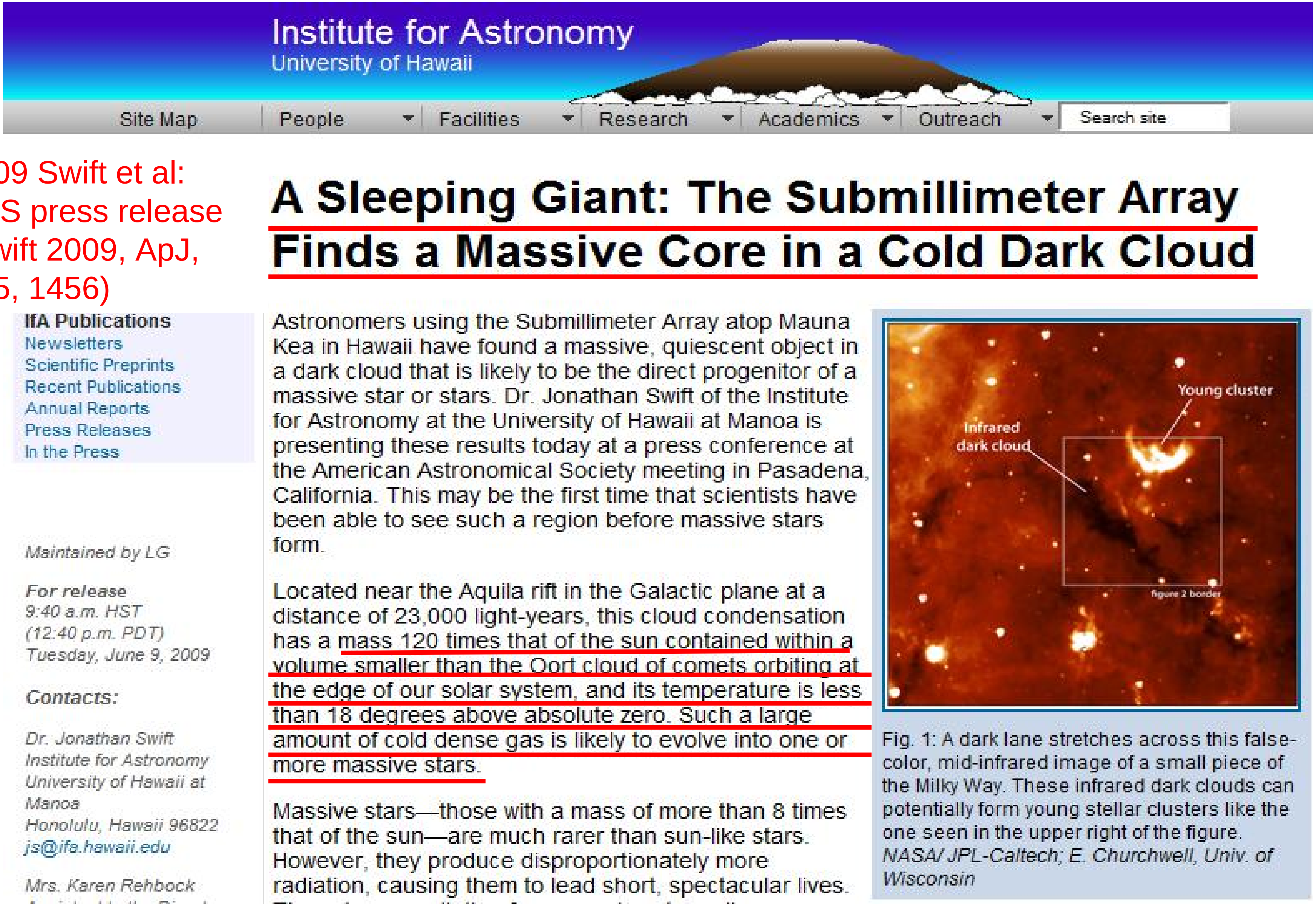
HIGH ANGULAR RESOLUTION IS KEY!!

For typical distance (~4kpc) need resolution better than 2-3"

Testing the “three competing concepts”:

The hunt for ~100 Msun, monolithically-collapsing cores

2009 Swift et al: AAS press release (Swift 2009, ApJ, 705, 1456)



A Sleeping Giant: The Submillimeter Array Finds a Massive Core in a Cold Dark Cloud

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For release
9:40 a.m. HST
(12:40 p.m. PDT)
Tuesday, June 9, 2009

Contacts:

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Mrs. Karen Rehbock

Astronomers using the Submillimeter Array atop Mauna Kea in Hawaii have found a massive, quiescent object in a dark cloud that is likely to be the direct progenitor of a massive star or stars. Dr. Jonathan Swift of the Institute for Astronomy at the University of Hawaii at Manoa is presenting these results today at a press conference at the American Astronomical Society meeting in Pasadena, California. This may be the first time that scientists have been able to see such a region before massive stars form.

Located near the Aquila rift in the Galactic plane at a distance of 23,000 light-years, this cloud condensation has a mass 120 times that of the sun contained within a volume smaller than the Oort cloud of comets orbiting at the edge of our solar system, and its temperature is less than 18 degrees above absolute zero. Such a large amount of cold dense gas is likely to evolve into one or more massive stars.

Massive stars—those with a mass of more than 8 times that of the sun—are much rarer than sun-like stars. However, they produce disproportionately more radiation, causing them to lead short, spectacular lives.

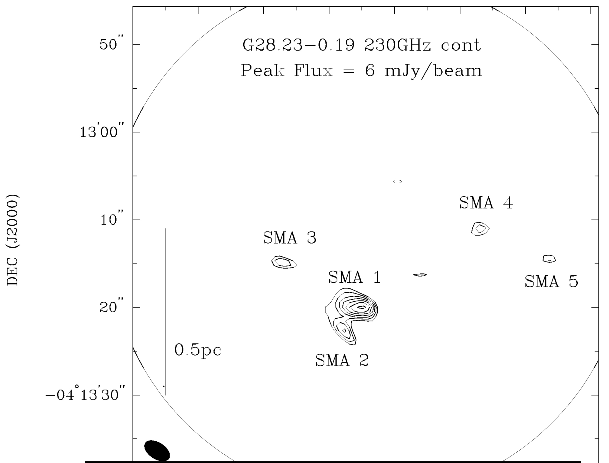
Fig. 1: A dark lane stretches across this false-color, mid-infrared image of a small piece of the Milky Way. These infrared dark clouds can potentially form young stellar clusters like the one seen in the upper right of the figure. *NASA/ JPL-Caltech; E. Churchwell, Univ. of Wisconsin*

Contours = 1.2mm continuum emission

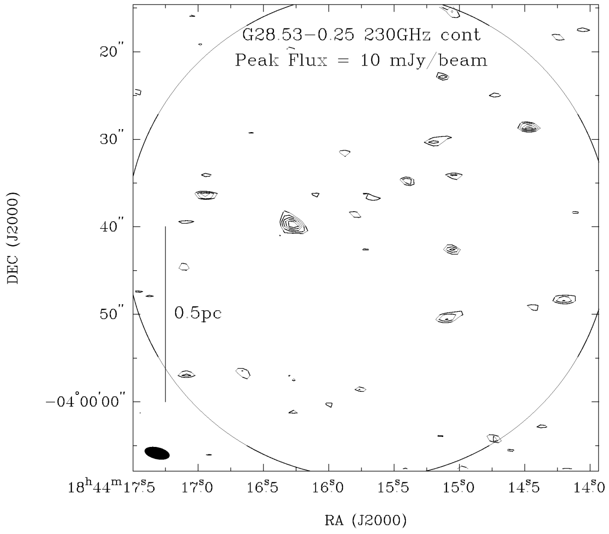
Longmore et al submitted ApJ

Time

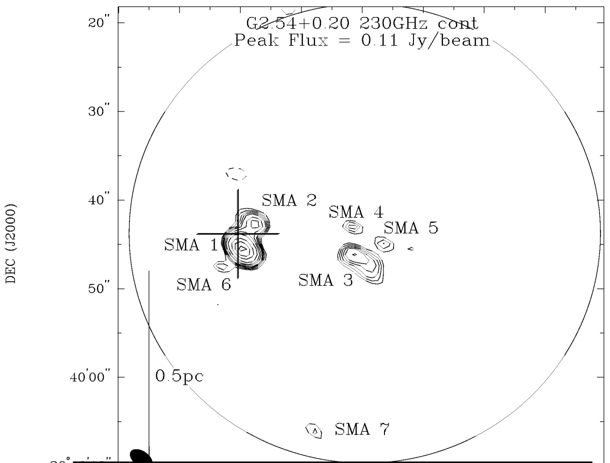
Youngest (Group 1)



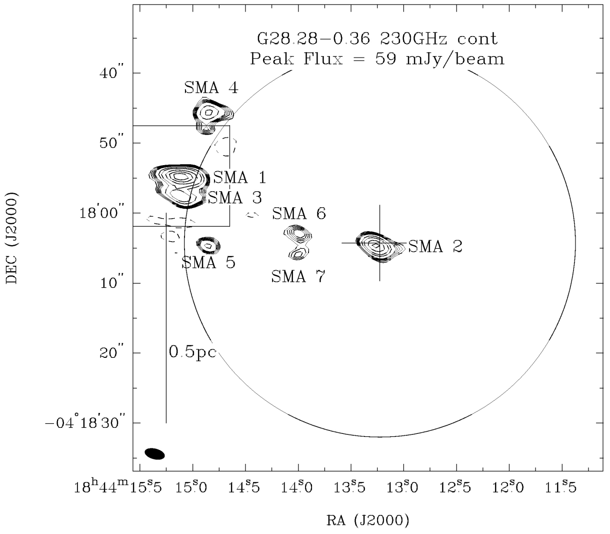
Core mass ~ 2-10 Msun



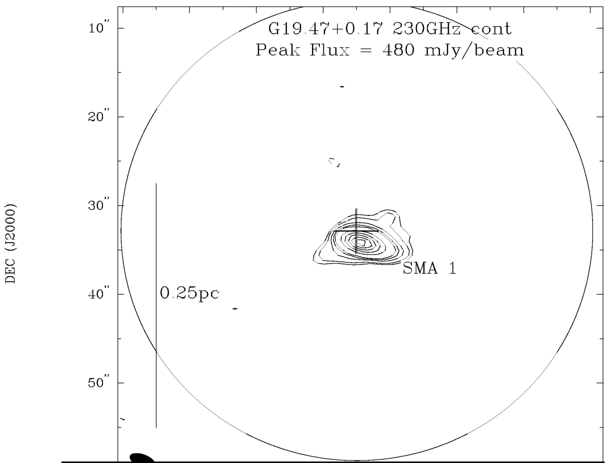
Intermediate (Group 2)



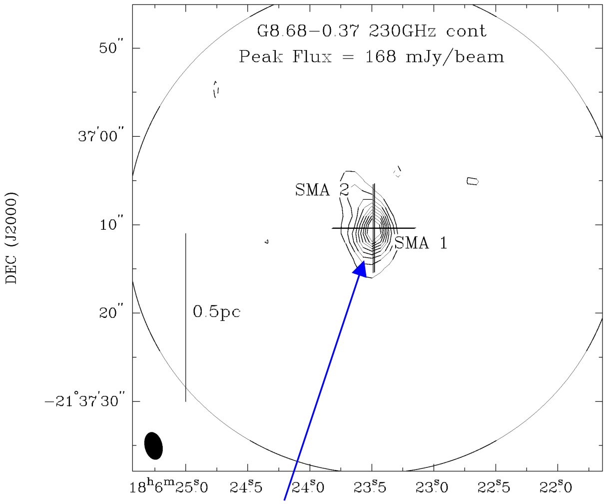
Core mass ~ 10-30 Msun



Oldest (Group 3)

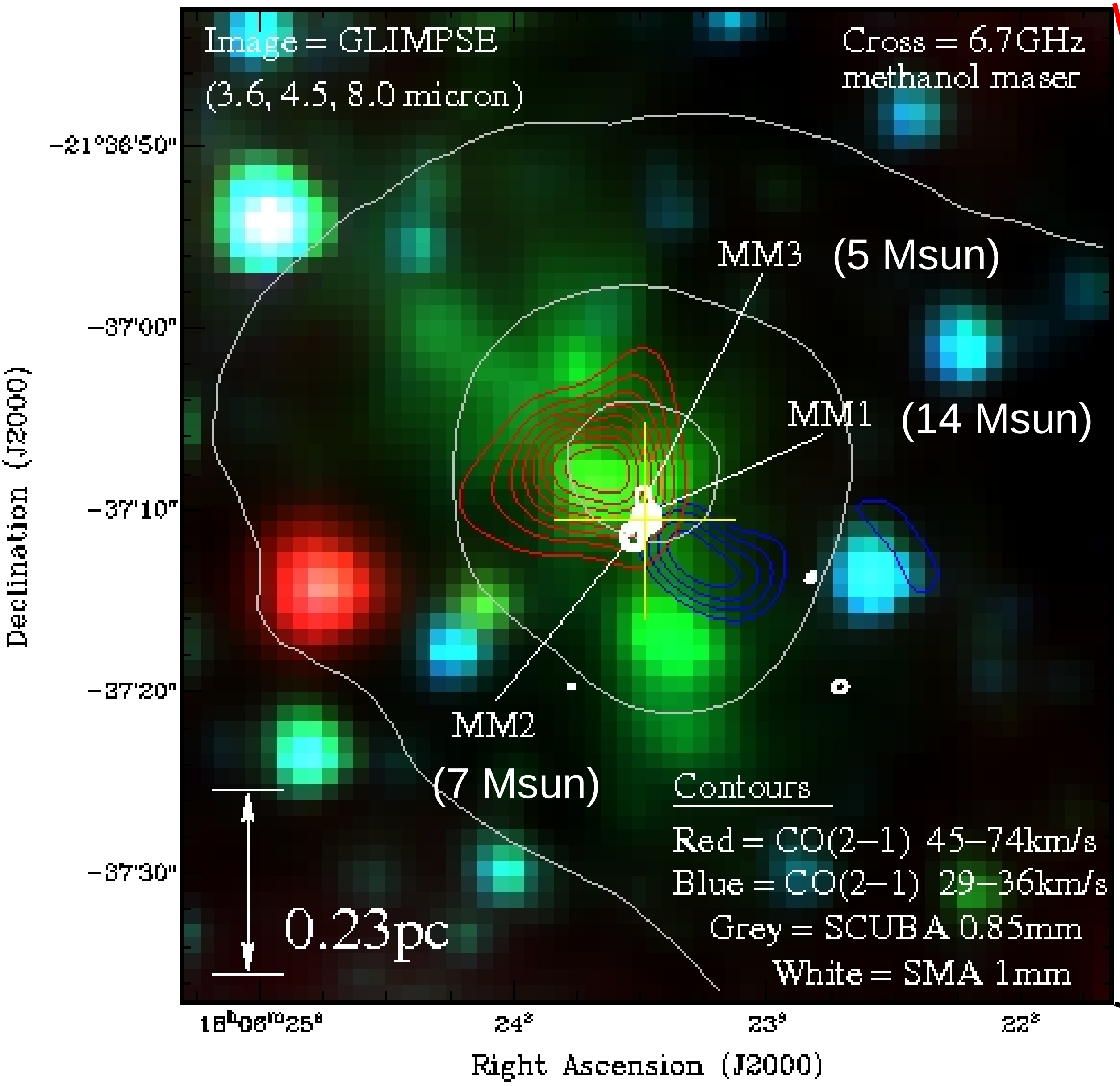


Core mass ~ 50-100 Msun



100Msun core ➔ massive star forming through monolithic collapse?

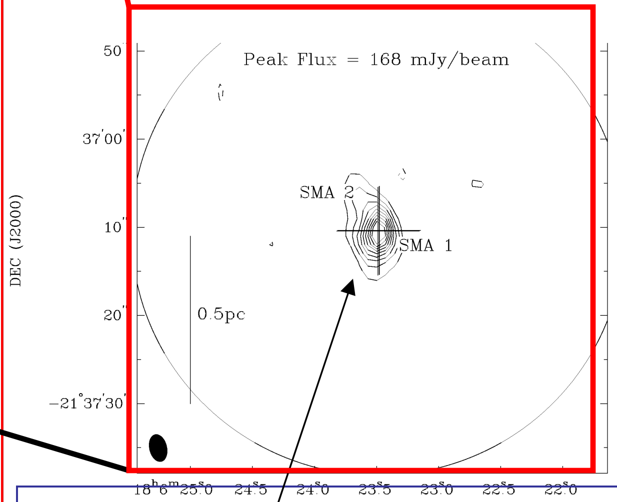
Fragments more massive and closer together with time?



RA (J2000)

Longmore et al accepted ApJ

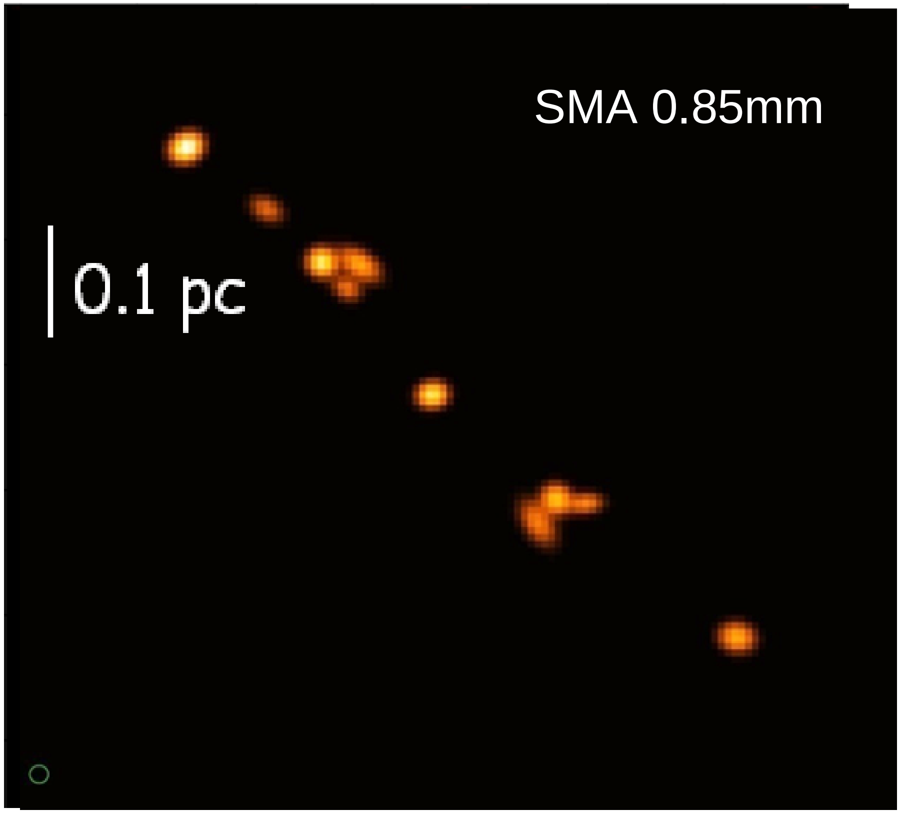
At θ < 1” resolve 100Msun core into 3 much less massive sub fragments



100Msun core ➔ massive star forming through monolithic collapse?

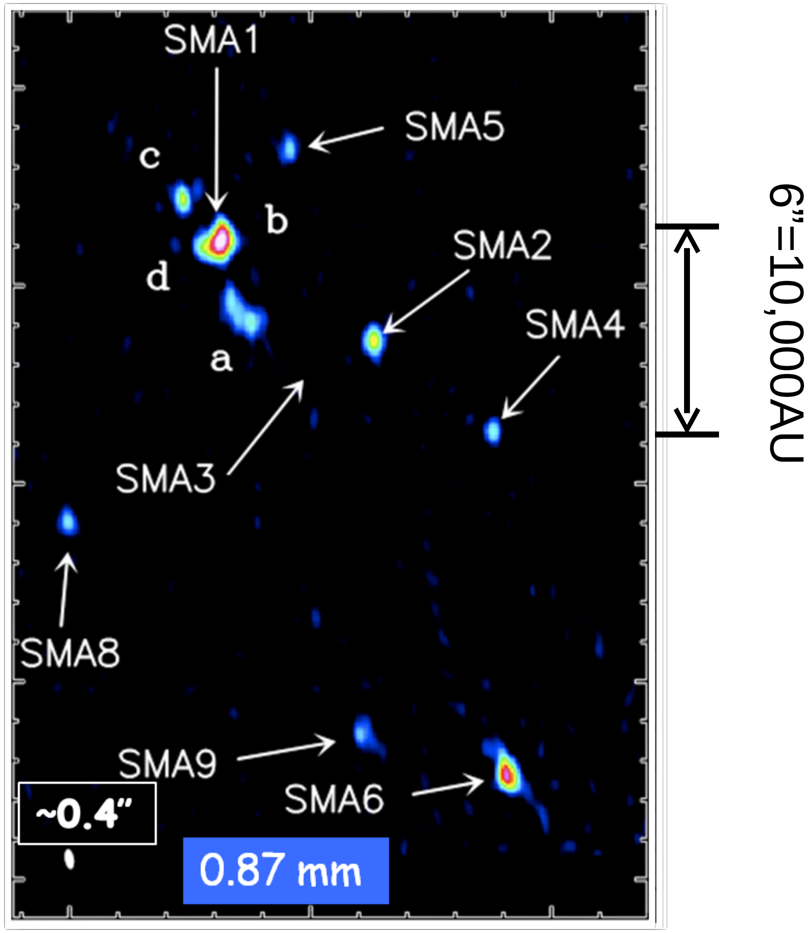
All ~100 Msun monolithic collapse candidates fragment at higher resolution

Zhang et al 2009, ApJ, 696, 268



At 1” resolution core mass = 22 – 64 Msun

At 0.5” resolution core mass= 2 – 8 Msun



Brogan et al 2009, ApJ, 707, 1

Testing three-competing concepts: conclusions

Predictions

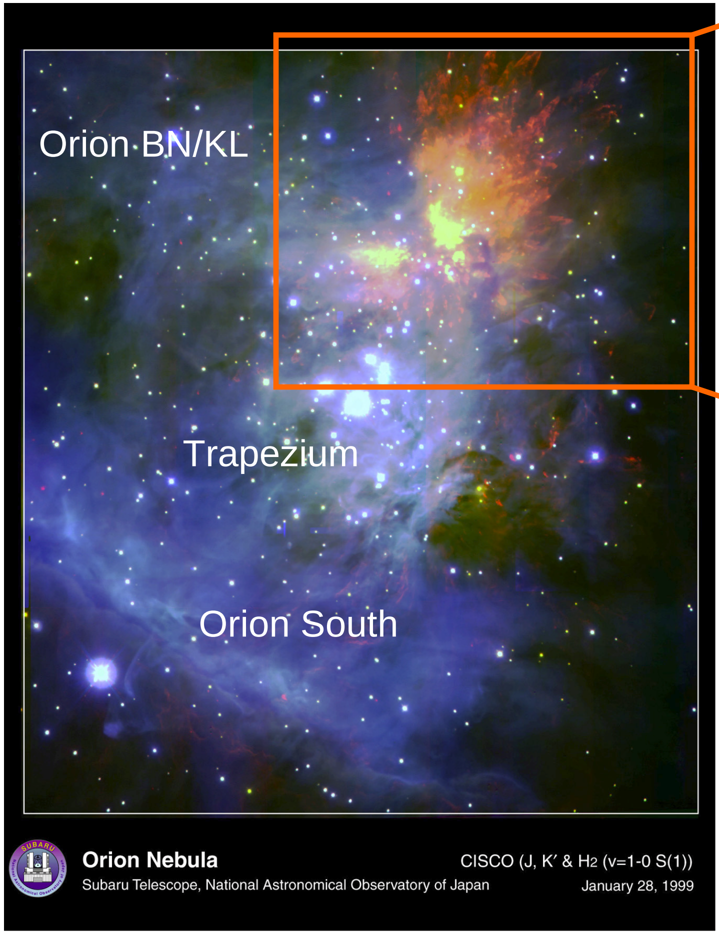
~~100 M sun monolithically collapsing core?~~

~~Hundreds of 1 M sun fragments?~~

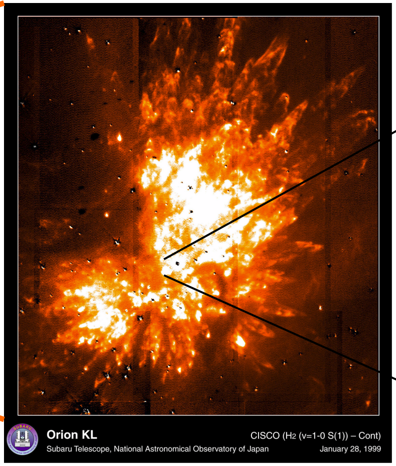
Mergers or dynamic interactions?

Dynamical interactions

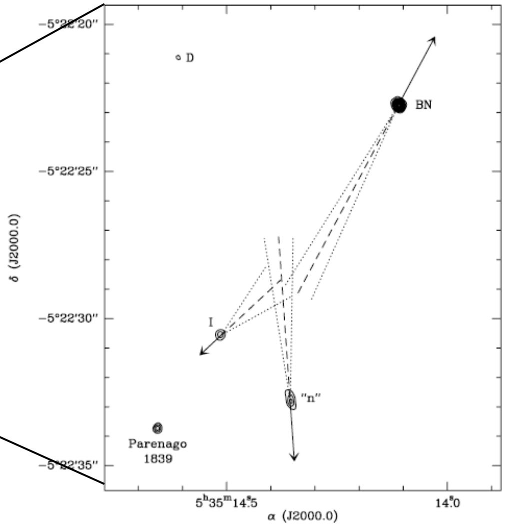
- One stunning example: Zapata et al 2009, ApJ, 704, L45



H_2 Bullets

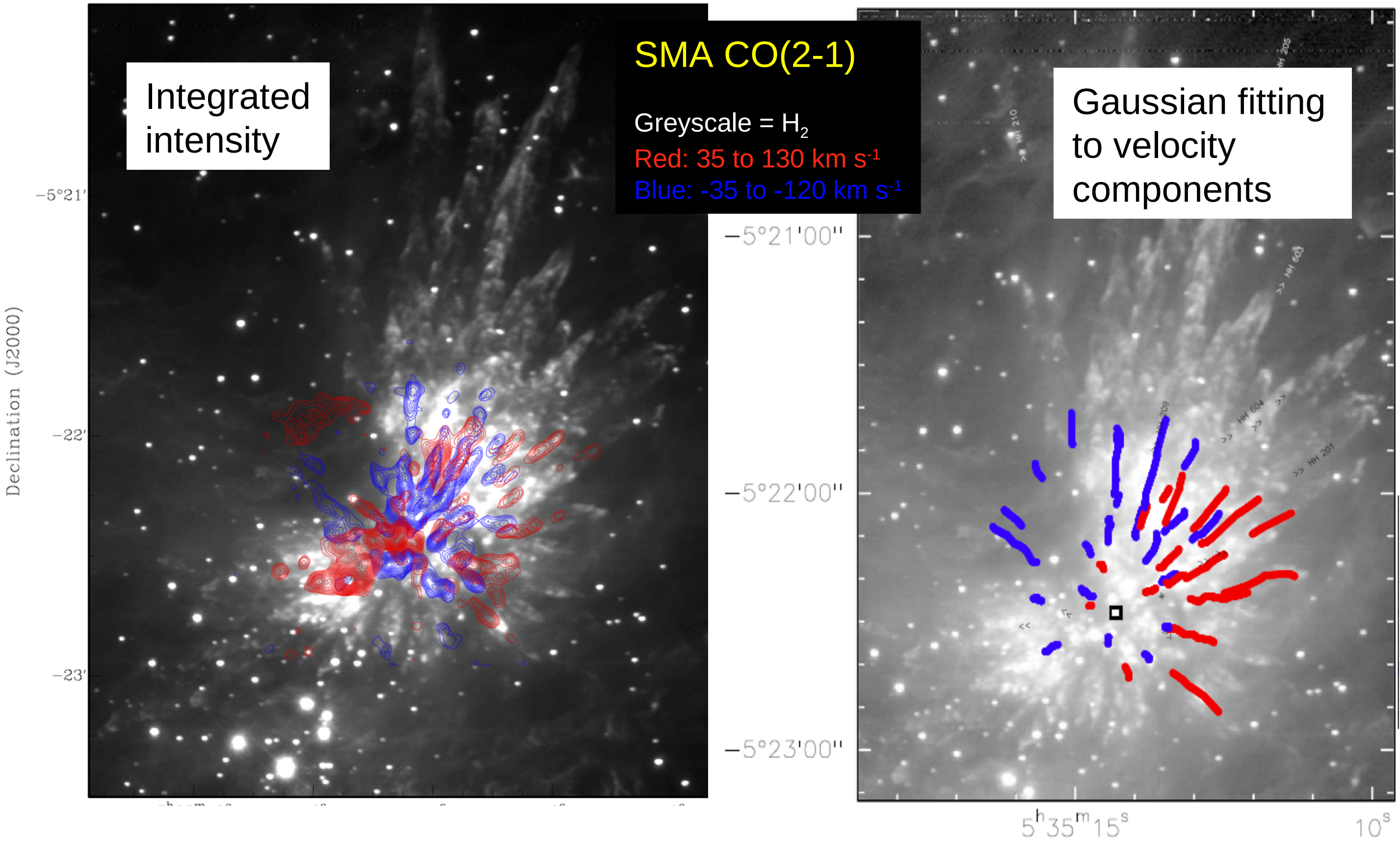


Gómez et al 2005,2008

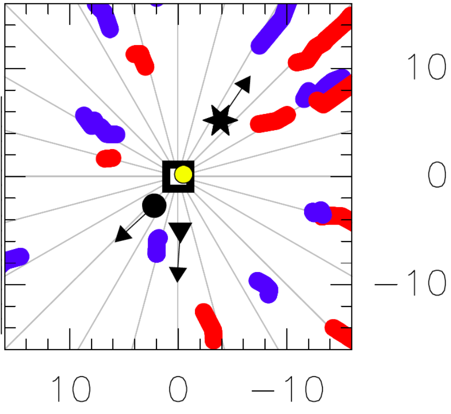


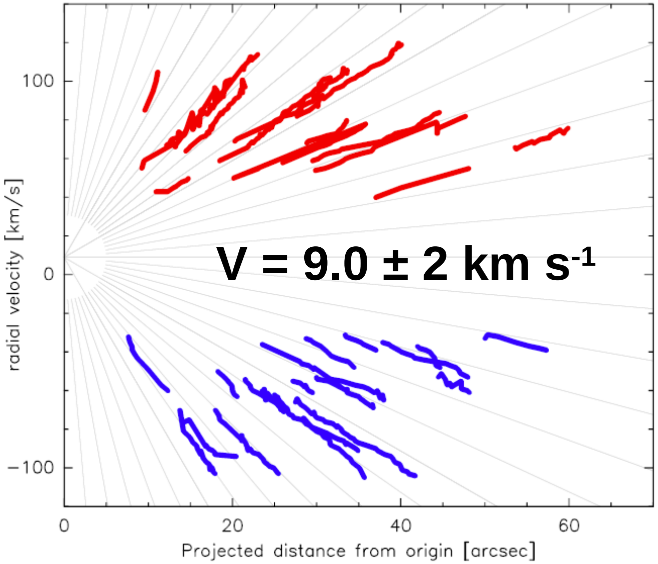
L_{bol} ~10^5 L_{sun} (Orion BN/KL)
M ~ 10 M_{sun}
E ~ 10^{47} Erg
High vel. >100 km s^{-1}
Very poor collimated (degree of collimation 200° – 300°)
Bright in optical and infrared bands

Proper motion of three massive stars at center of outflow suggest common spatial location ~500 years ago



A Common center





Origin of the CO filaments:
Zapata et al. (2009)
05h 35m 14.37s, -05◦ 22′ 27.9″ ± 1.5″

Dynamical disintegration:
Rodríguez et al. (2005)
05h 35m 14.35s, -05◦ 22′ 27.7″ ± 1″

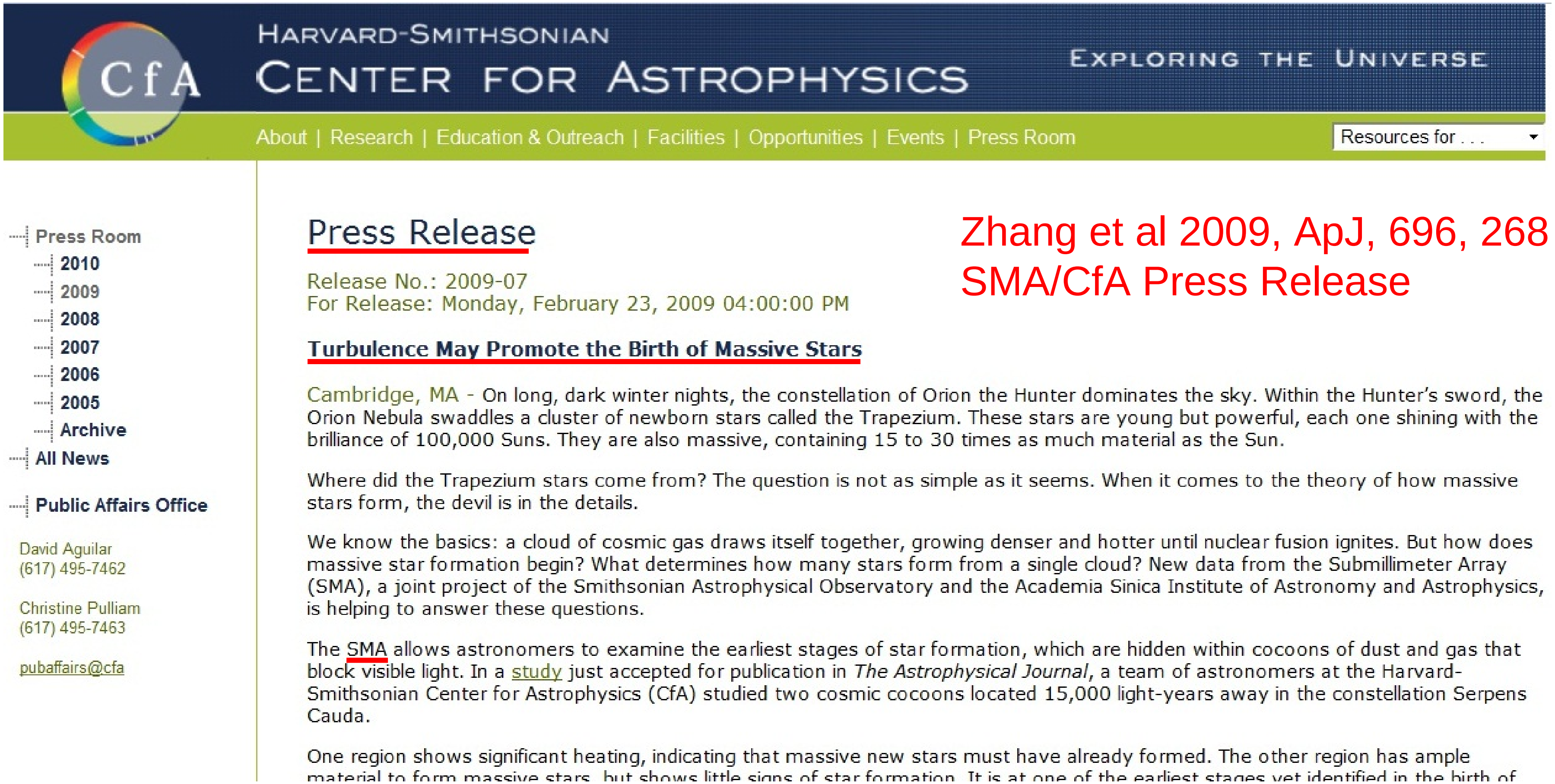
Very strong evidence that outflow in Orion BN/KL was generated by the disintegration of a massive triple stellar system ~500 years ago

Moving forward: developing the picture of massive star formation

KEY QUESTIONS

How do cores with M ~10’s Msun form O-stars
- coupling of parsec-scale gas ➔ cores

What is providing support for cores?
1. Magnetic field or turbulence dominated?
2. Evolution with time/size-scale?



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Zhang et al 2009, ApJ, 696, 268
SMA/CfA Press Release

Press Release

Release No.: 2009-07
For Release: Monday, February 23, 2009 04:00:00 PM

Turbulence May Promote the Birth of Massive Stars

Cambridge, MA - On long, dark winter nights, the constellation of Orion the Hunter dominates the sky. Within the Hunter’s sword, the Orion Nebula swaddles a cluster of newborn stars called the Trapezium. These stars are young but powerful, each one shining with the brilliance of 100,000 Suns. They are also massive, containing 15 to 30 times as much material as the Sun.

Where did the Trapezium stars come from? The question is not as simple as it seems. When it comes to the theory of how massive stars form, the devil is in the details.

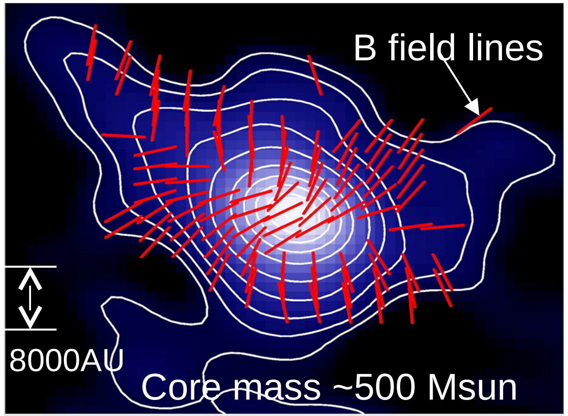
We know the basics: a cloud of cosmic gas draws itself together, growing denser and hotter until nuclear fusion ignites. But how does massive star formation begin? What determines how many stars form from a single cloud? New data from the Submillimeter Array (SMA), a joint project of the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, is helping to answer these questions.

The SMA allows astronomers to examine the earliest stages of star formation, which are hidden within cocoons of dust and gas that block visible light. In a study just accepted for publication in *The Astrophysical Journal*, a team of astronomers at the Harvard-Smithsonian Center for Astrophysics (CfA) studied two cosmic cocoons located 15,000 light-years away in the constellation Serpens Cauda.

One region shows significant heating, indicating that massive new stars must have already formed. The other region has ample material to form massive stars, but shows little signs of star formation. It is at one of the earliest stages yet identified in the birth of

Magnetic fields towards G31.41+0.31

[Girart et al 2009, Sci., 324, 1408]



Magnetic field strength: **B ≈ 10 mG**

Magnetic energy > Turbulent energy

Mass-to-flux ratio (wrt critical value): **2.7**

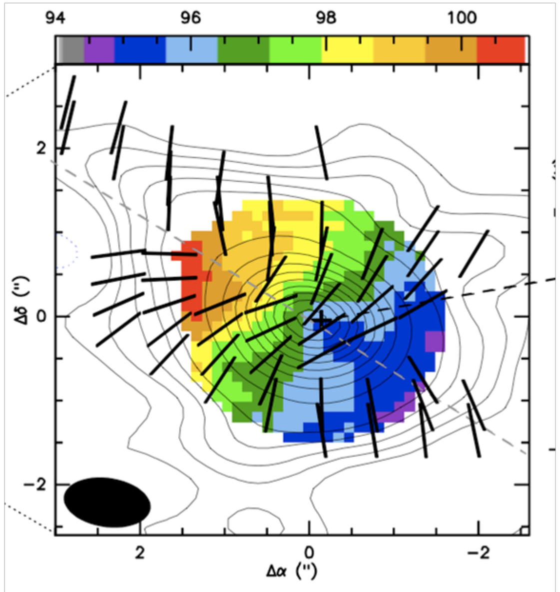
Alfvenic velocity: **$v_A \approx$ 8 km/s**

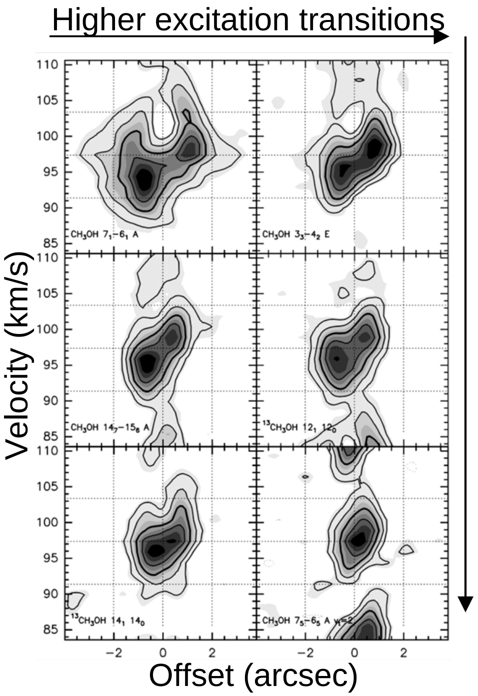
Dust polarization shows classic “hourglass” B field morphology perpendicular to major axis of core

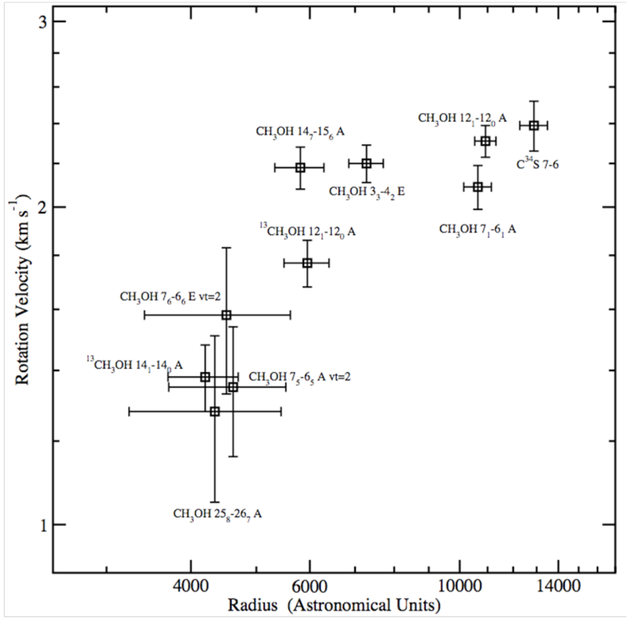
Rotation perpendicular to major axis

Optically-thick methanol lines with highest energy levels have smallest angular size

Decrease in measured spin velocity with radius so angular momentum not conserved ➔ **MAGNETIC BRAKING**







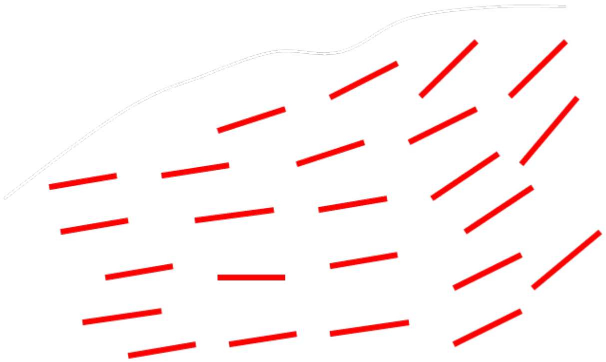
A cure for “hour-glass-itis*”!

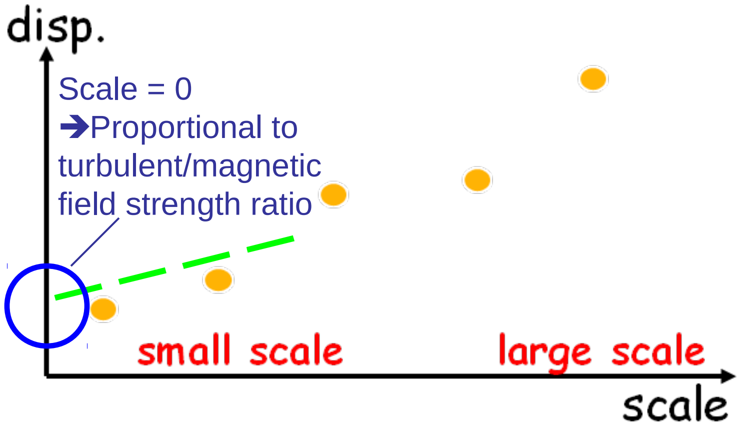
Koch et al 2010, accepted ApJ, Tang et al 2009a, 2009b, 2010

- Science results from polarization observations been hampered by lack of quantitative analysis tools for interpreting magnetic fields which do not have hour-glass morphologies
- Dispersion function
  - 2nd-order structure function
  - Scale-dependent measure of change in orientation of field lines
  - Scale = 0 limit gives ratio between turbulent/magnetic field strengths

$$\langle \Delta\phi^2(l_k)\rangle^{1/2} \equiv \left\{ \frac{1}{N(l_k)} \sum_{l_k \leqslant r_{ij} < l_{k+1}}^{N(l_k)} \left(\phi_i(r_i) - \phi_j(r_j)\right)^2 \right\}^{1/2}$$

Φ: position angle





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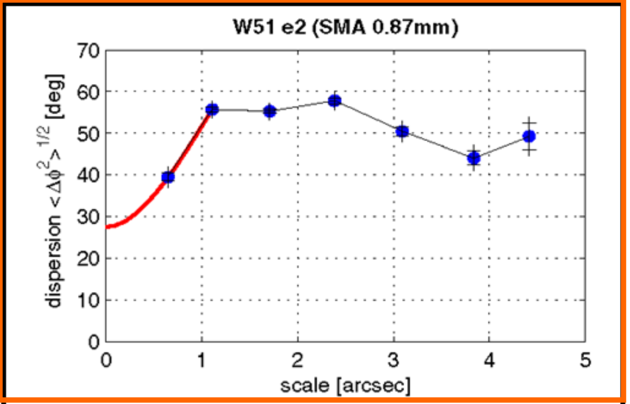
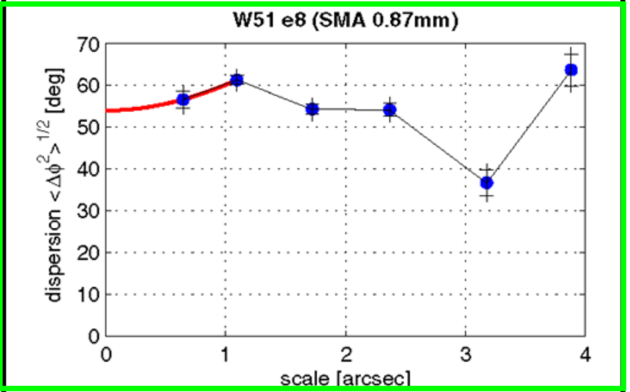
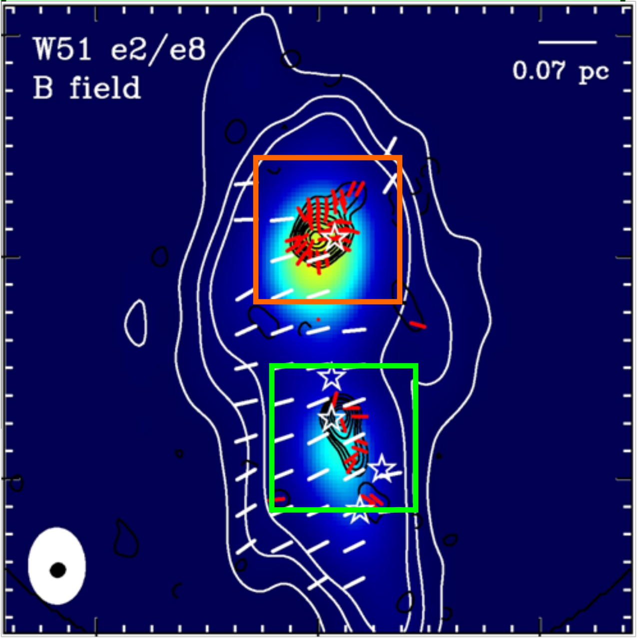
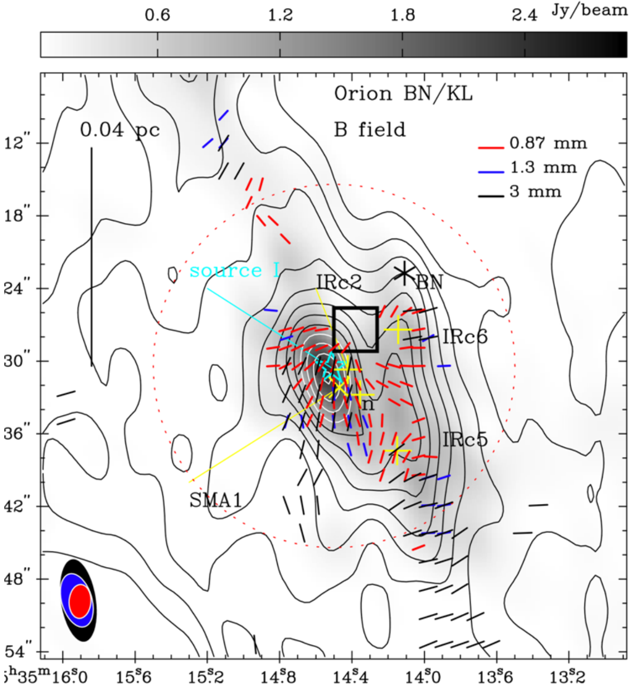
* “hour-glass-itis” – an affliction that affects astronomers when confronted with non-hour-glass polarization morphologies



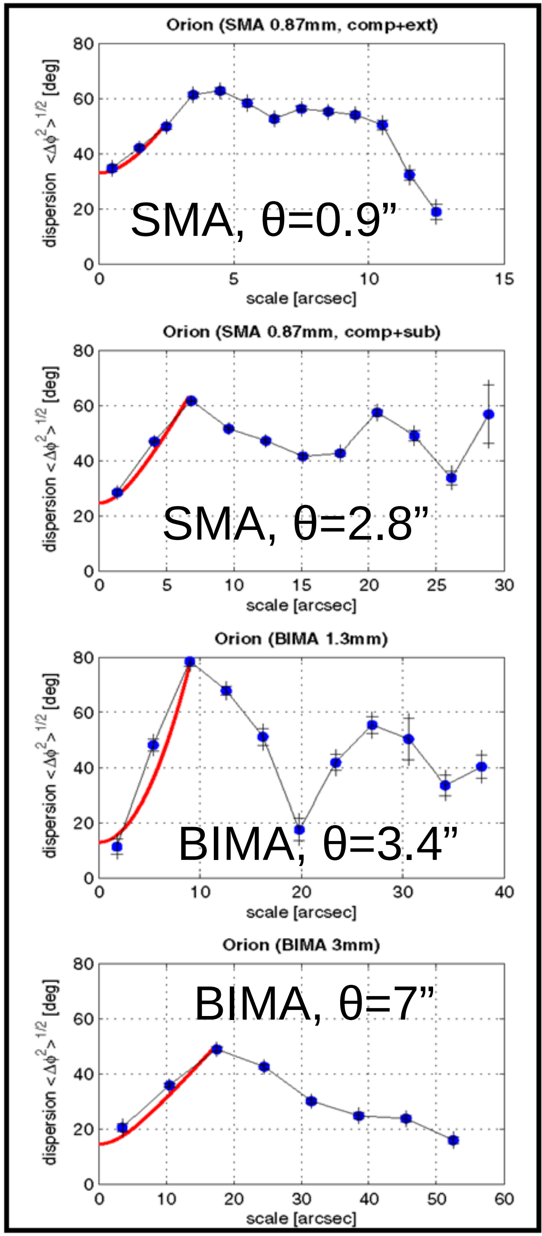






Orion BN/KL dispersion function down to 2mpc (400AU)

➔ **ambipolar diffusion scale**

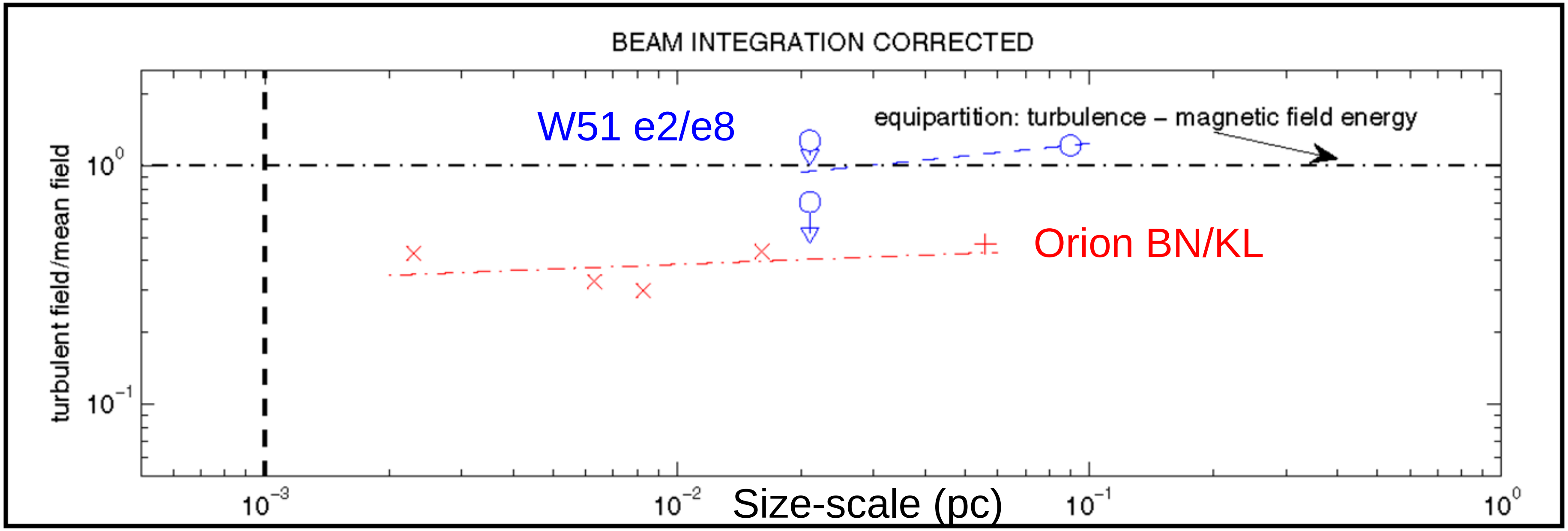


W51 e2 and e8 dispersion function:

2 observations

- θ ~ 2.3'' ➔ 69 mpc (14,000AU)
- θ ~ 0.7'' ➔ 21 mpc (4300AU)

Turbulence – magnetic field evolution



- close to constant turbulent / mean field ratio ➔ 0.4 (Orion) , ~ 1 (W51 e2 / e8)
- hint of a decrease toward smaller scales

Massive star formation + SMA + Magnetic Fields: Conclusions

1. MAGNETIC SUPPORT AT LEAST AS IMPORTANT AS TURBULENCE

2. NONE OF THE CURRENT SIMULATIONS/THEORY INCORPORATES MAGNETIC FIELDS…

KEY QUESTION 2: Where does material come from that eventually ends up on the high-mass star?

Facts:

1. Cores with M ~10’s of Msun do not have enough mass to form O-star through direct collapse ➔ to form O-stars, cores must be coupled to large reservoir of cluster-scale gas
2. Flattened rotating structures commonly observed towards massive star formation regions
   - Sizes range from pc to 100AU scales
3. Disks a notable common feature in all massive star formation simulations
4. Outflows are ubiquitous phenomena towards massive star formation regions

SMA infall/disk-related papers

Furuya et al., accepted A&A
Sascha et al. accepted ApJ
Keto et al. 2010, accepted MNRAS
Okamoto et al, 2009, ApJ, 706, 1036
Galvan-Madrid et al. 2009, ApJ, 706, 1036
Klaassen et al. 2009, ApJ, 703, 1038
Fallscheer et al. 2009, A&A, 504, 127
Franco-Hernandez et al. 2009, ApJ, 701, 974
Zapata et al. 2009, ApJ, 698, 1422
Keto et al. 2008, 678, L109
Eisner et al 2008, ApJ, 683, 304
Zapata et al 2008, A&A, 479, L25

SMA outflow-related papers

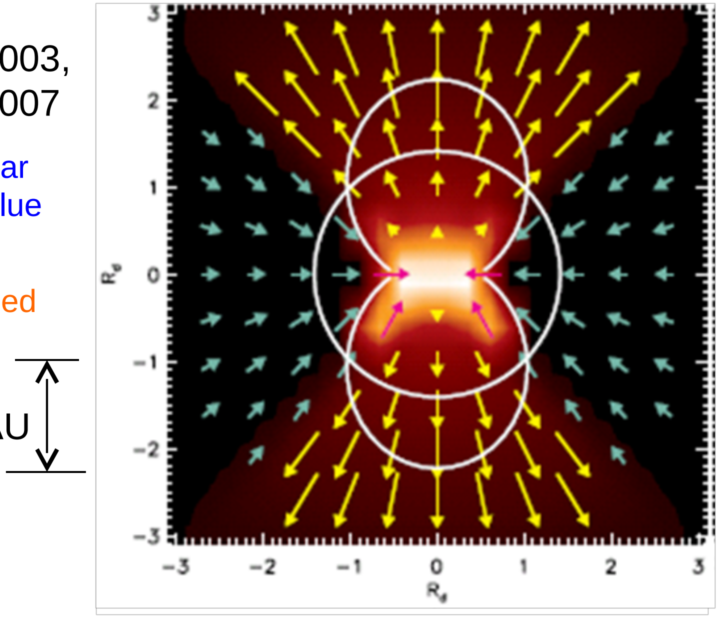
Shi et al., accepted ApJL
Zapata et al. 2010, A&A, 510, 2
Leurini et al. 2009, A&A, 507, L1443
Qiu et al. 2009, ApJ, 702, L66
Zapata et al. 2009, ApJ, 704, L45
Bruderer et al. 2009, A&A, 503, L13
Bruderer et al. 2009, ApJ, 700, 872
Qiu et al. 2009, ApJ, 696, 66
Beuther et al. 2008, ApJ, 679, L121

Parsec-scale accretion flows feeding massive accretion disks

Keto 2003,
Keto 2007

Molecular
gas = Blue

Ionized
gas = Red

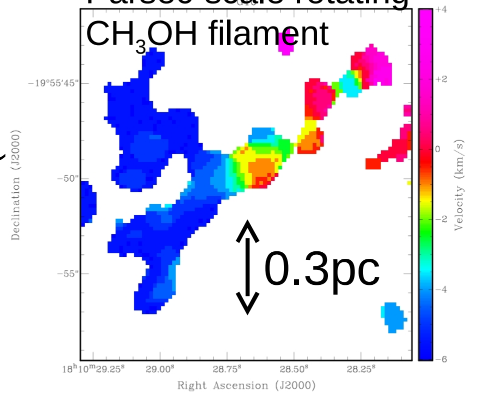


- Large, cloud-scale (pc) infalling, rotationally-flattened molecular gas feeds material to star forming accretion disk at core scale (1000's AU)

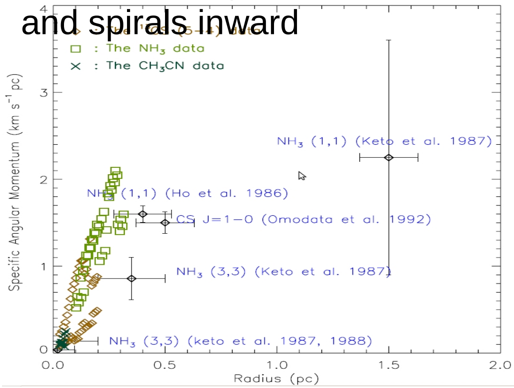
- Massive (potentially gravitationally-unstable) disk (100's AU) feeds central (proto)star and pressure-driven/photo-ionized outflow

- Large gravitational potential combined with high accretion rate and self-shielding in disk plane allows star to continue gaining mass via ionized accretion flow once star reaches ~O9

Baobab Liu (PhD Thesis)

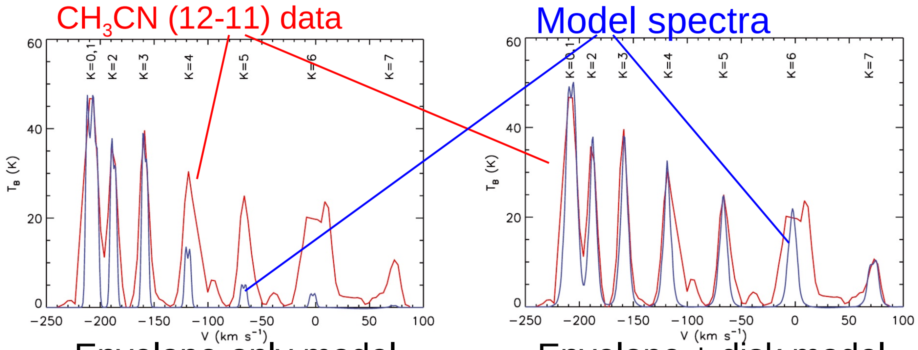


Parsec-scale rotating
CH_3OH filament



Gas loses angular momentum
and spirals inward

Keto & Zhang 2010



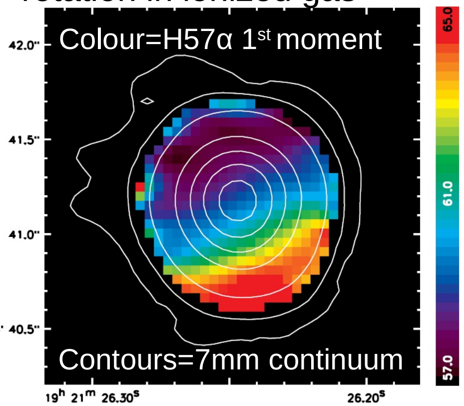
CH_3CN (12-11) data

Model spectra

Envelope-only model

Envelope + disk model

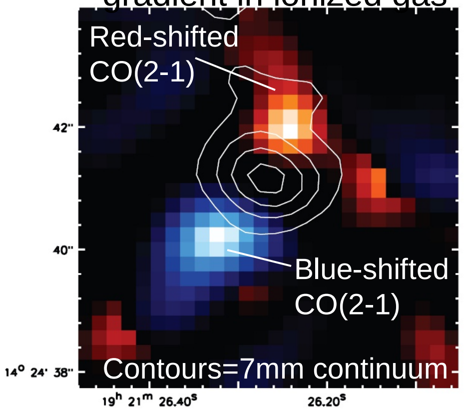
Keto & Klaassen 2008



H57α velocity gradient shows rotation in ionized gas

Colour=H57α 1st moment

Contours=7mm continuum



CO(2-1) outflow ⊥ to gradient in ionized gas

Contours=7mm continuum

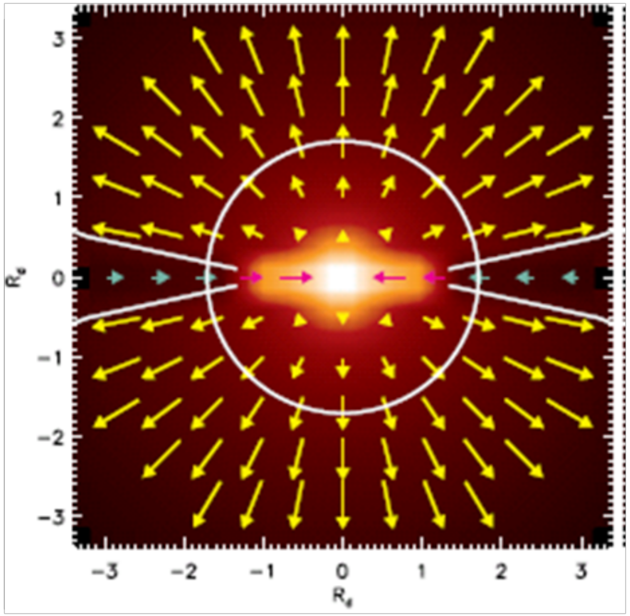
Parsec-scale accretion flows feeding massive accretion disks

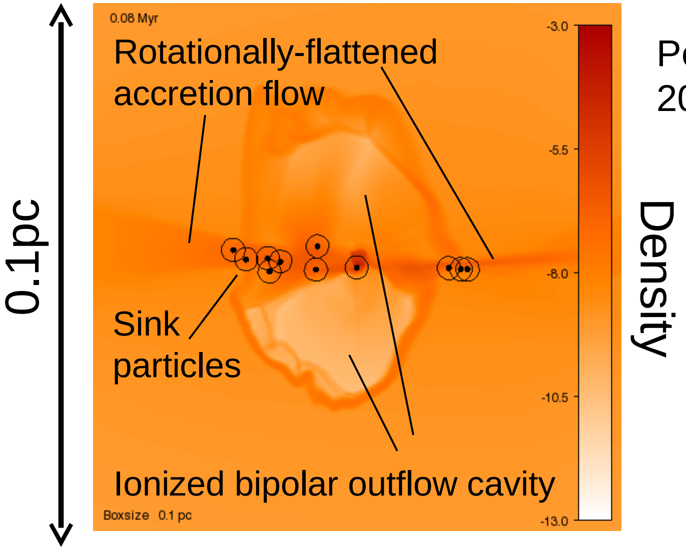
Keto 2003,
Keto 2007

Molecular
gas = Blue

Ionized
gas = Red

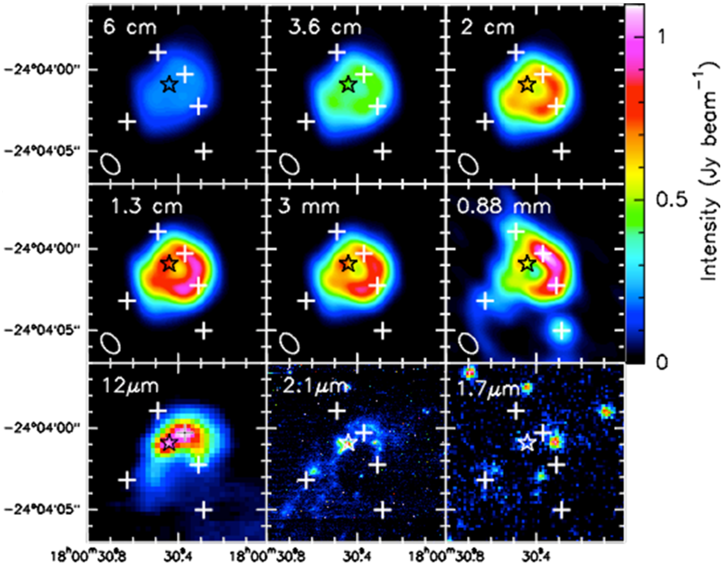
100 AU





Peters et al
2010

- •Large, cloud-scale (pc) infalling, rotationally-flattened molecular gas feeds material to star forming accretion disk at core scale (1000’s AU)
- •Massive (potentially gravitationally-unstable) disk (100’s AU) feeds central (proto)star and pressure-driven/photo-ionized outflow
- •Large gravitational potential combined with high accretion rate and self-shielding in disk plane allows star to continue gaining mass via ionized accretion flow once star reaches ~O9
- •Ionised gas and radiation pressure escape through outflow cavities



Hunter et al 2008

Morphological evolution of outflows traced by CO(2-1) [Keping Qiu's Thesis]

HH80-81
W3(H2O)
No free-free

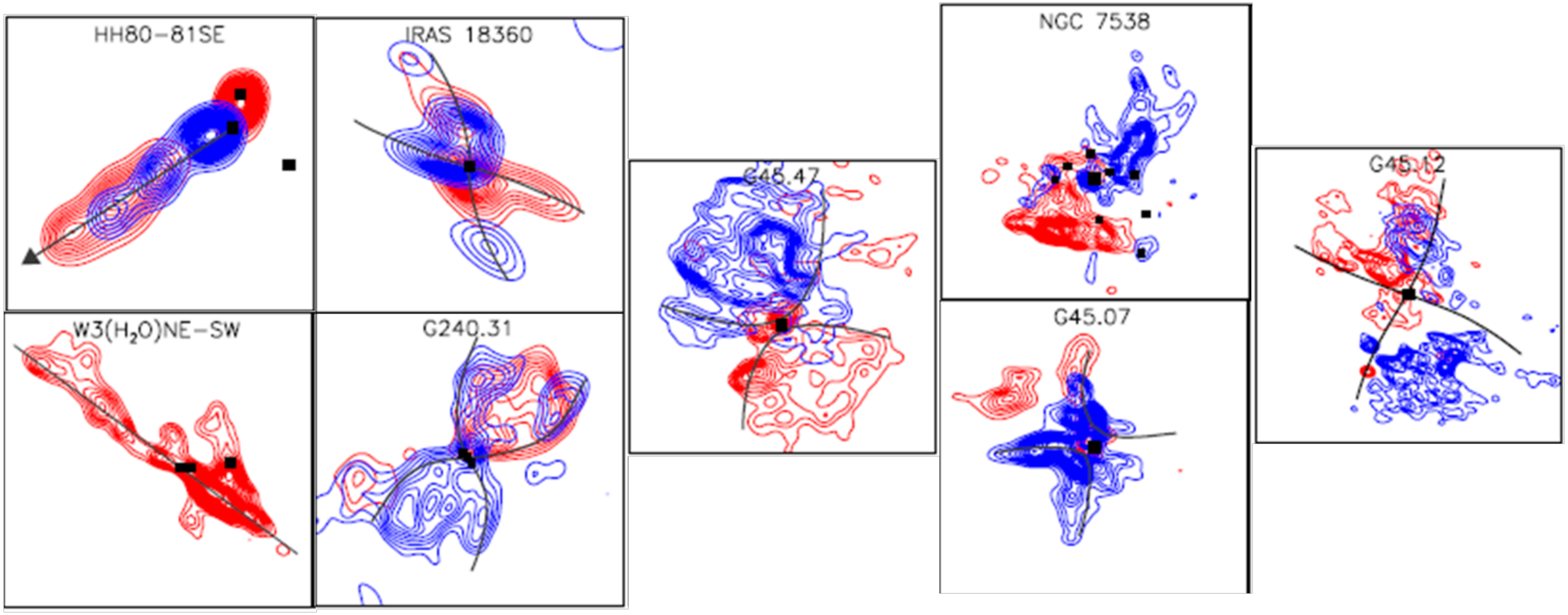
IRAS18360
G240.31
weak free-free

G45.47
HC HII

NGC7538
G45.07
Well-defined
HC/UC HII

G45.12
Expanding
UC HII

Evolution (or luminosity)



Jet-like Bi-conical Widely opened shells Remnant

Conclusions

- SMA’s impact on massive star formation studies since 2007
  - None of the “competing” models fully describe data
    - No cores with enough material to form massive stars through monolithic collapse
    - No Jeans-like thermal fragmentation to hundreds of 1Msun cores
    - Only one (albeit spectacular!) example of interactions/mergers
  - Magnetic fields important source of support. They are not currently incorporated into theoretical simulations.
  - In order for observed cores to form O-stars they must gain mass from surrounding reservoir of parsec-scale gas
    - Picture emerging where cores M ~ 10’s Msun fed by accretion from larger scales

The future

- Ultra-wide bandwidth
  - Increased continuum sensitivity
    - Where are the low-mass stars in high-mass star forming regions?
      - Current core mass functions from SMA observations appear top heavy compared to stellar IMF. Is this an observational bias or are we reaching a size scale at which IMF breaks down as predicted in some models?
    - Extend polarization observations to younger and larger samples of MSF regions
  - Transitions covering full range of excitiation conditions observed simultaneously
    - Build “complete” picture of cold, low-density gas + disk + outflow + shocks + ionised gas + …

The end