Star Formation and Interstellar Medium studies with ALMA

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What will ALMA bring us?

- ALMA will do much better what current interferometers do
- It will also explore “terra incognita”
- It will have an effect on fields which have not needed to bother about mm astronomy so far

Some problems to be attacked with ALMA

- Initial conditions of star formation
- Outflow and jets
- Circumstellar disks
- Interstellar and pre-biotic chemistry
- Extragalactic SF (in particular LMC SMC) but also nearby starbursts

Some problems to be attacked with ALMA

- Initial conditions of star formation:
  - formation of massive stars and clusters
  - origin of the stellar IMF
- Outflow and jets:
- Circumstellar disks
- Interstellar and pre-biotic chemistry
- Extragalactic SF (in particular LMC SMC) but also nearby starbursts

Some problems to be attacked with ALMA

- Initial conditions of star formation:
- Outflow and jets:
  - ejection mechanism and launching point
  - proper motions
  - precession
- Circumstellar disks
- Interstellar and pre-biotic chemistry
- Extragalactic SF (in particular LMC SMC) but also nearby starbursts

Some problems to be attacked with ALMA

- Initial conditions of star formation:
- Outflow and jets:
- Circumstellar disks:
  - map dust emission
  - gas kinematics
  - disk evolution: gas and dust dispersal, debris disks, planet formation
- Interstellar and pre-biotic chemistry
- Extragalactic SF (in particular LMC SMC) but also nearby starbursts

Some problems to be attacked with ALMA

- Initial conditions of star formation:
- Outflow and jets:
- Circumstellar disks:
- Interstellar and pre-biotic chemistry:
  - protoplanetary chemistry
  - pre-biotic molecules formation and abundances
- Extragalactic SF (in particular LMC SMC) but also nearby starbursts

Some problems to be attacked with ALMA

- Initial conditions of star formation:
- Outflow and jets:
- Circumstellar disks:
- Interstellar and pre-biotic chemistry
- Extragalactic SF (in particular LMC SMC) but also nearby starbursts:

  - study of ISM in MW and Local Group
  - detection of CO and [CII] (main gas cooling of atomic ISM) at z=3

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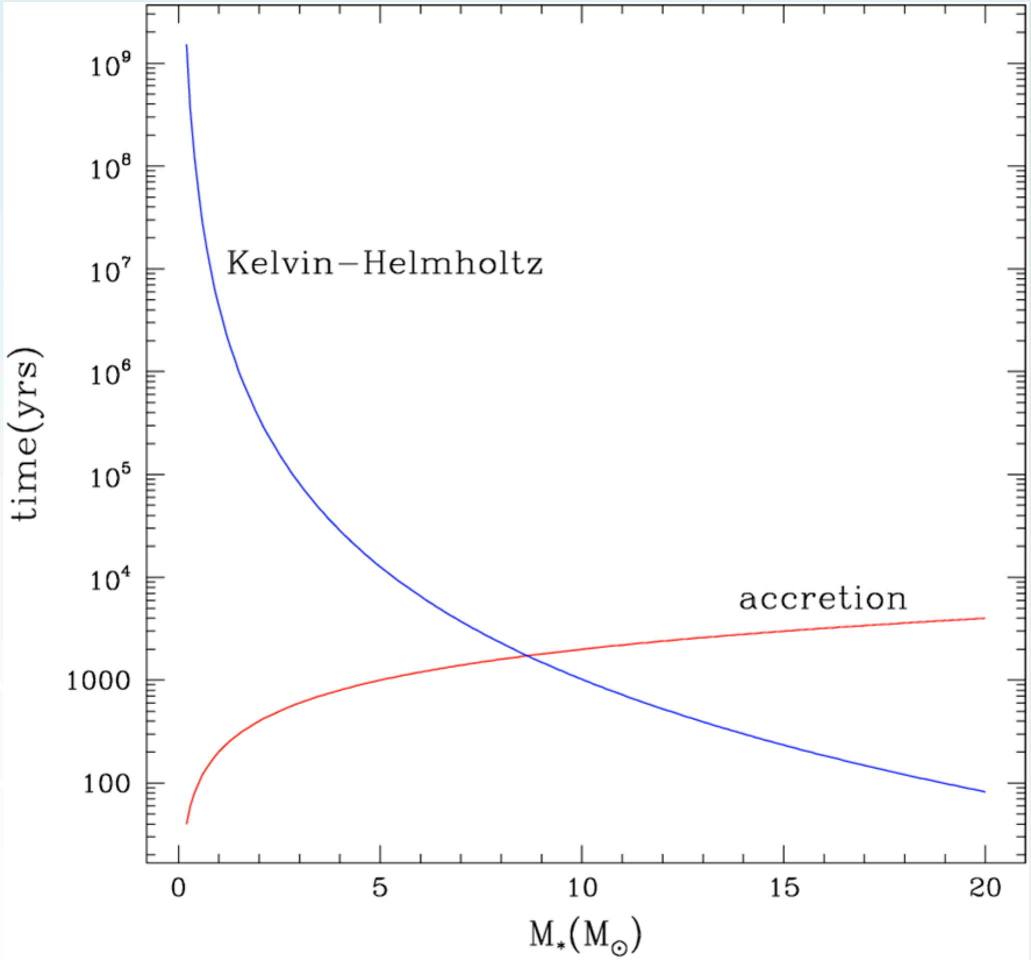
Massive star formation: theoretical challenge

- Two relevant timescales in SF:
  i. accretion $t_{acc} = M_*/(dM/dt)$
  ii. contraction $t_{KH} = GM_*/R_*L_*$

- Low-mass (< 8 $M_\odot$): $t_{acc} < t_{KH}$
  ➡ Pre-main sequence

- High-mass (> 8 $M_\odot$): $t_{acc} > t_{KH}$
  ➡ No pre-main sequence
  accretion on ZAMS

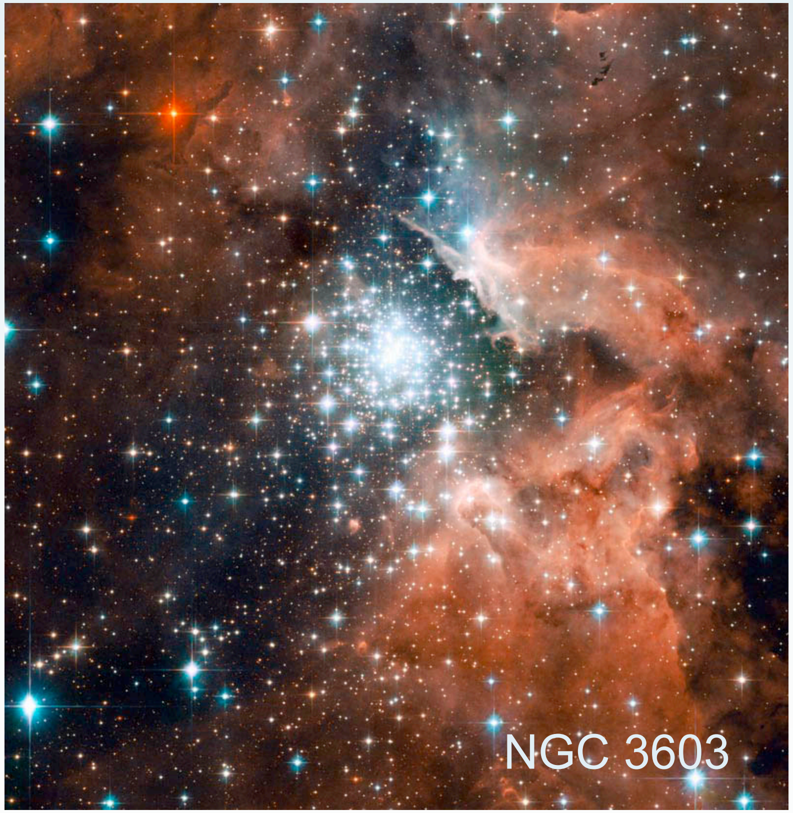


Massive star formation: theoretical challenge

- COMPETITIVE ACCRETION: a molecular cloud initially fragments in mainly low-mass cores of a Jeans mass ~0.5-1 $M_{\odot}$, which form stars which compete to accrete mass from the common reservoir of gas. At the same time, the gas (and low-mass stars) funnels down to the central part of the cluster (Bonnell & Bate 2002). Protostars located near the center of the gravitational potential accrete at a higher accretion rate because of a stronger gravitational pull, and thus experience a faster mass growth.

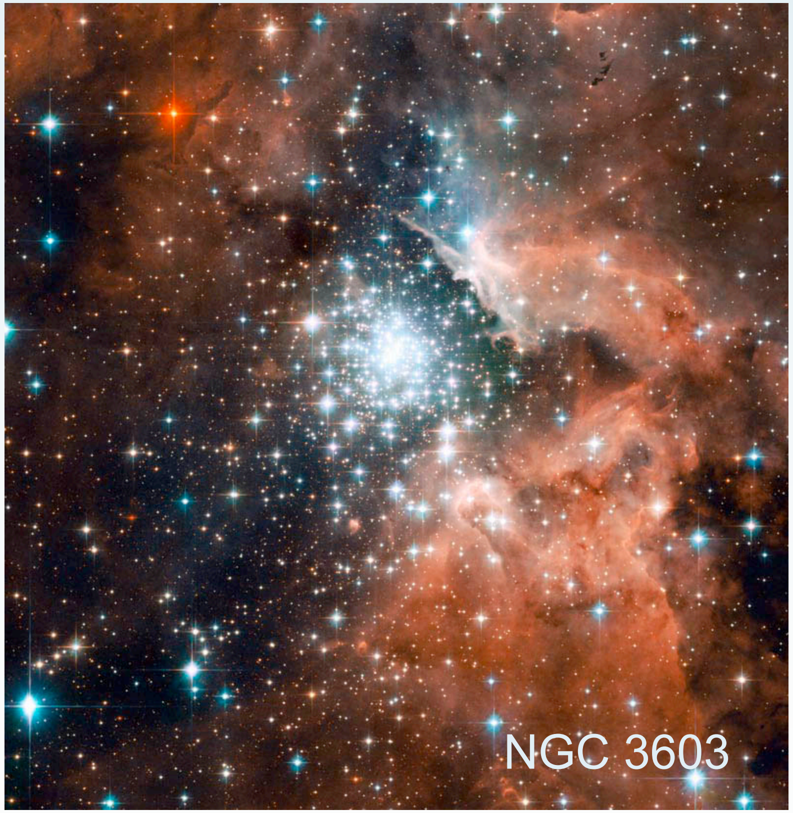
- CORE ACCRETION: a massive star is formed from a massive core which was fragmented from the natal molecular cloud and gathers its mass from this massive core only (McKee & Tan 2002; 2003). The heating from the embedded protostars increases the gas temperature, and thus the Jean mass (100 $M_{\odot}$: Krumholz et al. 2007).

Massive star formation: observational challenge



- Massive stars are rare objects: for each 10 $M_\odot$ formed, a hundred 1 $M_\odot$ stars are formed.
- Rare objects than statistically form at large distances ➔ 4 kpc
- Massive stars form in clusters: only 4±2% of O-field stars are formed outside clusters (de Wit et al. 2006)
- Difficult to trace the primordial configuration of the molecular cloud

Massive star formation: observational challenge



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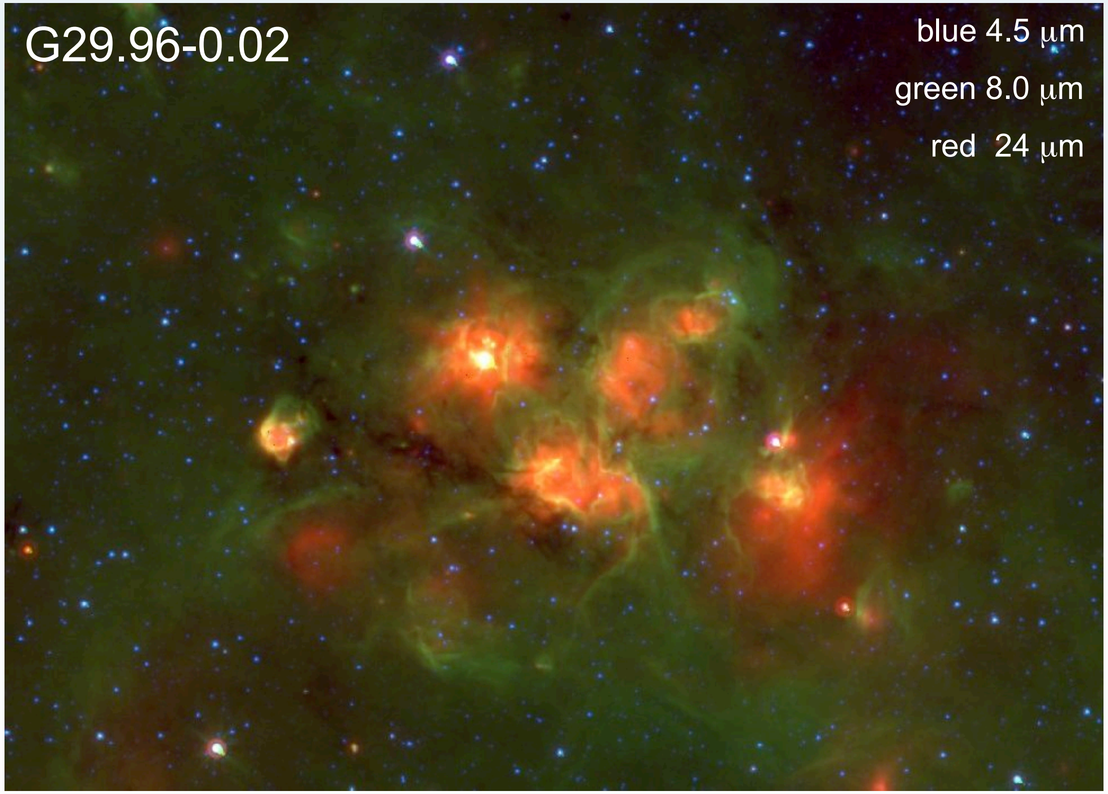
HIGH ANGULAR RESOLUTION AT (SUB)MM λ's IS A PRE-REQUISITE

Initial conditions of massive stars and cluster formation

• Formation sites: parsec scale high-density clumps (10^4 to 10^5 cm^{-3}) within Giant Molecular Clouds (GMCs) (density of order 100-1000 cm^{-3}) ➔ IR-Dark Clouds (IRDCs)



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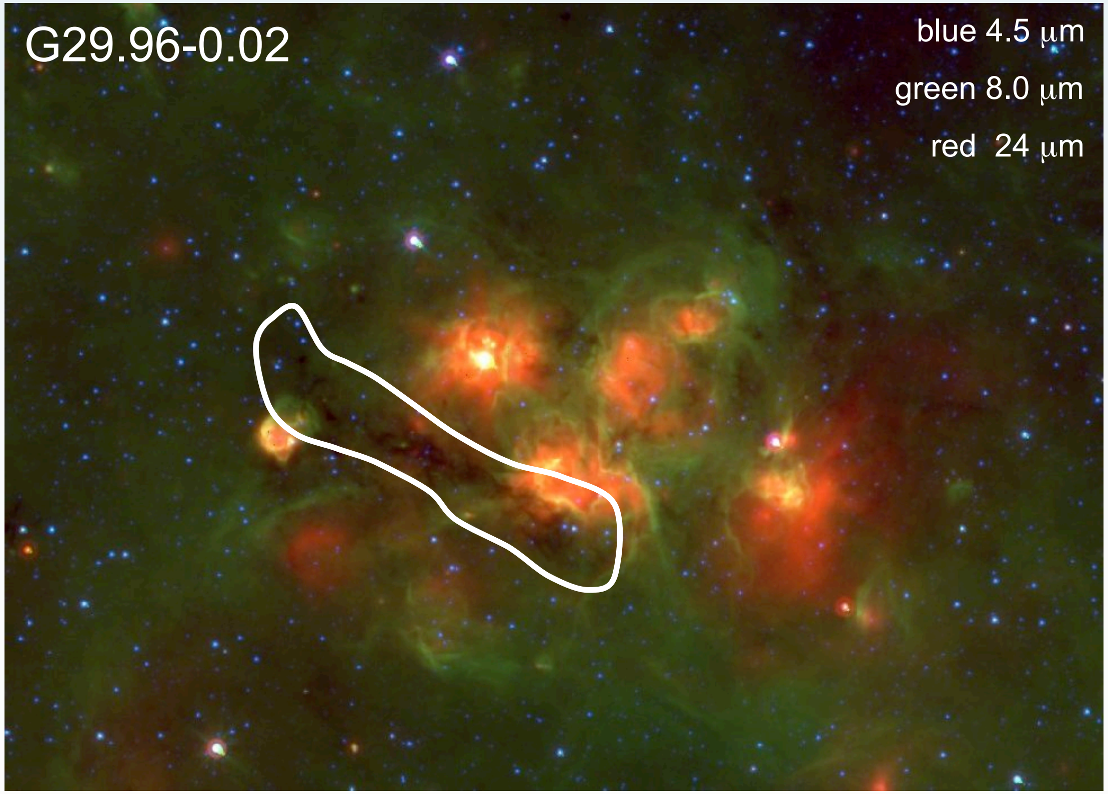
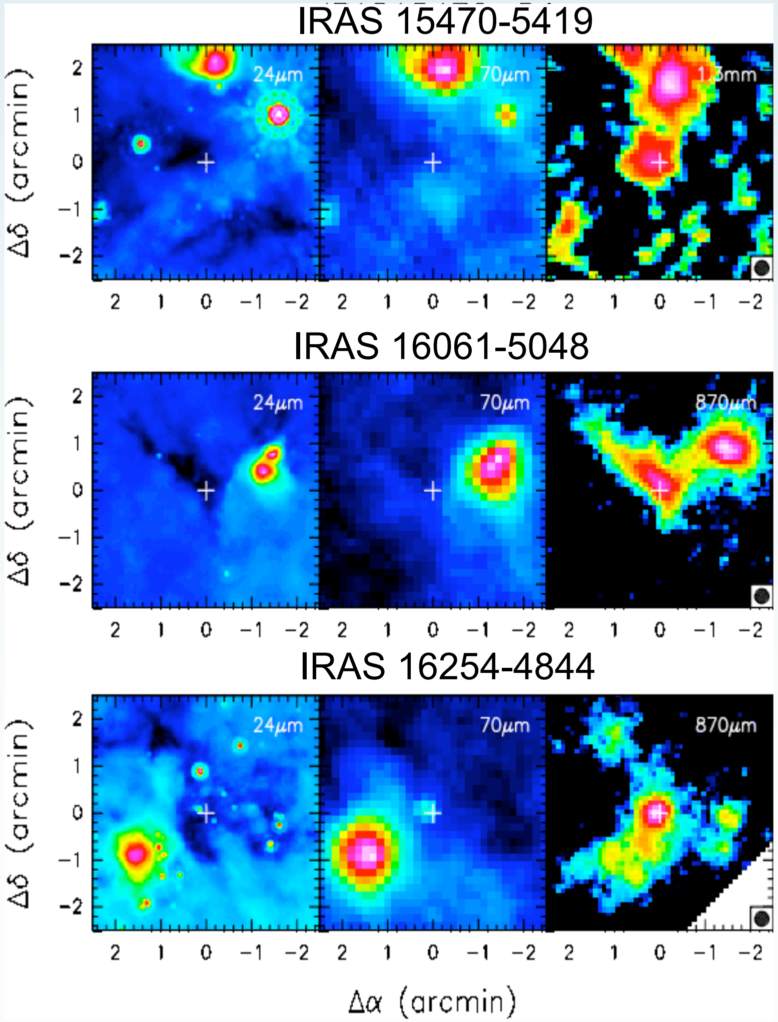
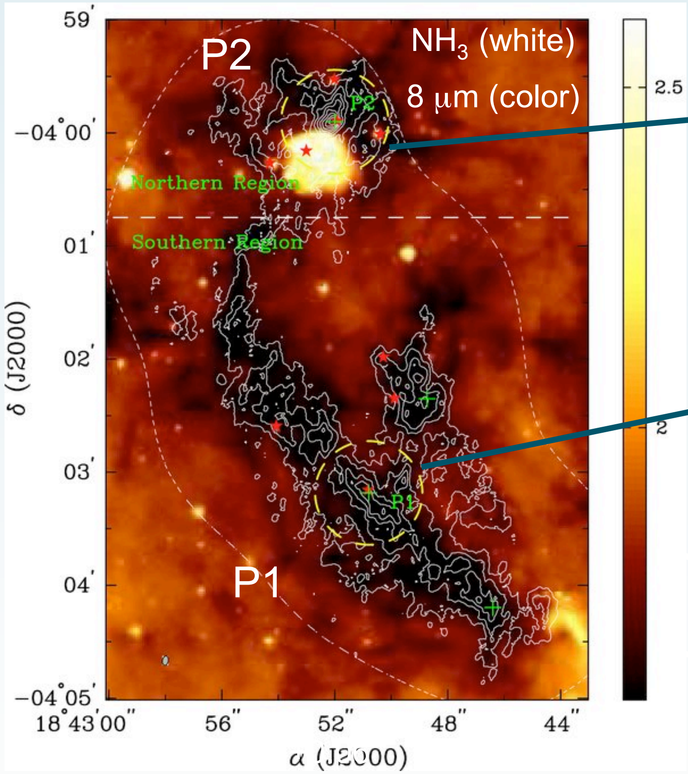


Initial conditions of massive stars and cluster formation

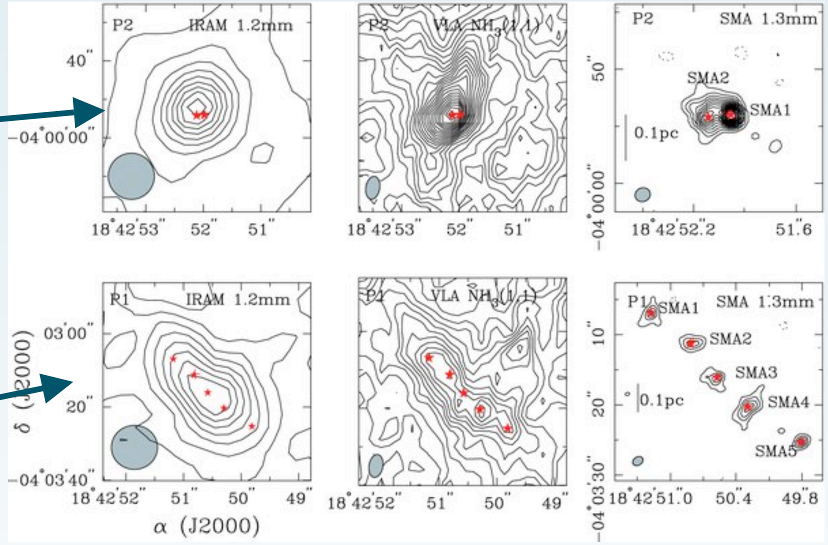


- IRDCs are detected in absorption at 8 μm and up to 24 μm (70 μm) with ISO, Spitzer, MSX, Herschel (Egan et al. 1998, Carey et al. 1998)
- At submillimeter and millimeter λ's are seen in emission.
- Physical properties: 10^3-10^4 $M_\odot$, 1-5 pc, 10^5 cm^{-3} , < 20 K

Initial conditions of massive stars and cluster formation



Zhang et al. (2009)



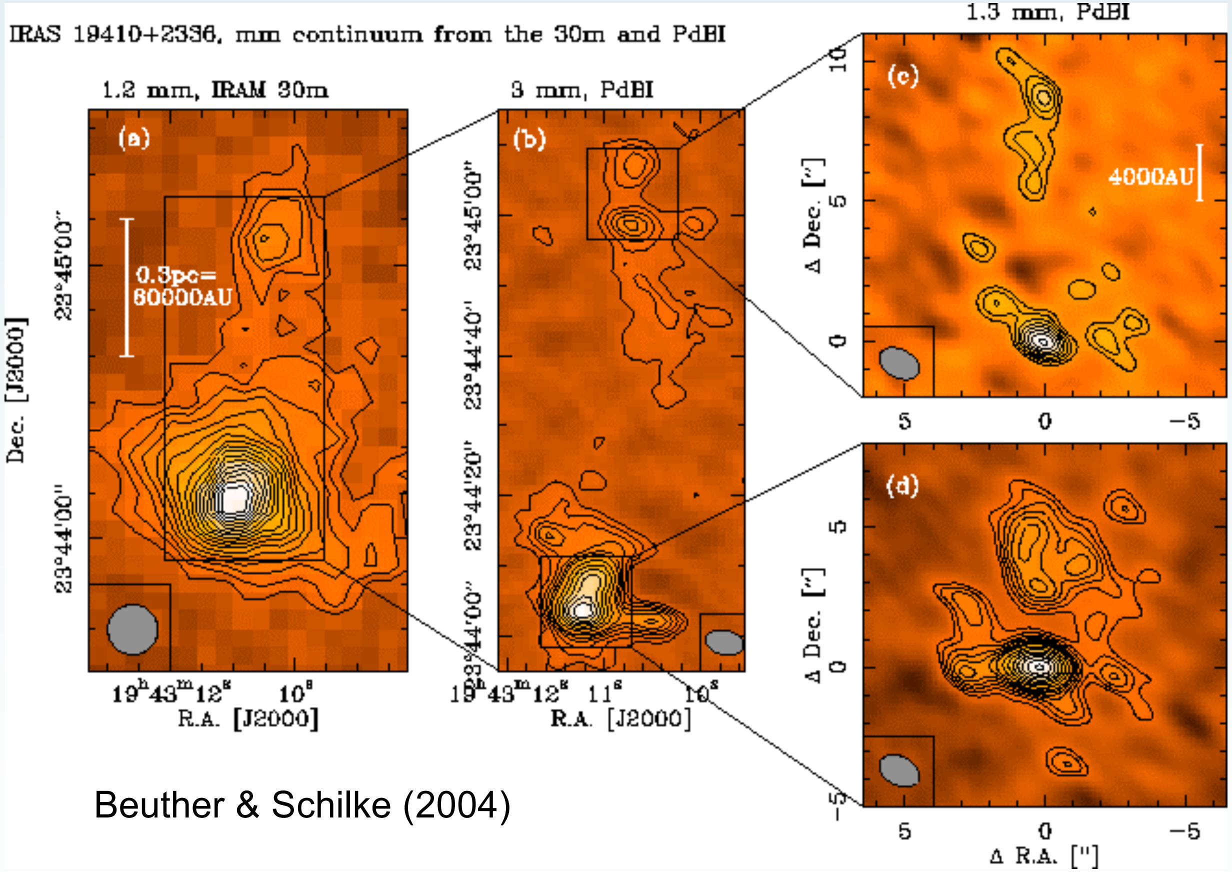
- SMA obs: IRDCs fragmented in cores with masses of 22 to 100 $M_{\odot}$, and projected separation of 0.19 pc. Resolution 1”
- For an average T of 16 K, the thermal Jeans mass and length are 1 $M_{\odot}$ and 0.05 pc.
- M_{gas} a factor 10 larger M_{Jeans} ➔ cloud fragmentation may not be controlled solely by the thermal pressure and gravity ➔ turbulence/magnetic field??

IMF and Theoretical Models

- High-angular resolution millimeter and submillimeter observations start to allow to study origin of stellar IMF at the earliest phase of star formation.
- This will have an impact on studies of core structure: core mass function versus stellar mass function → test predictions theoretical models on massive star formation and simulations
- The number of cores in protoclusters is a good diagnostic of massive star formation theories

IMF and Theoretical Models

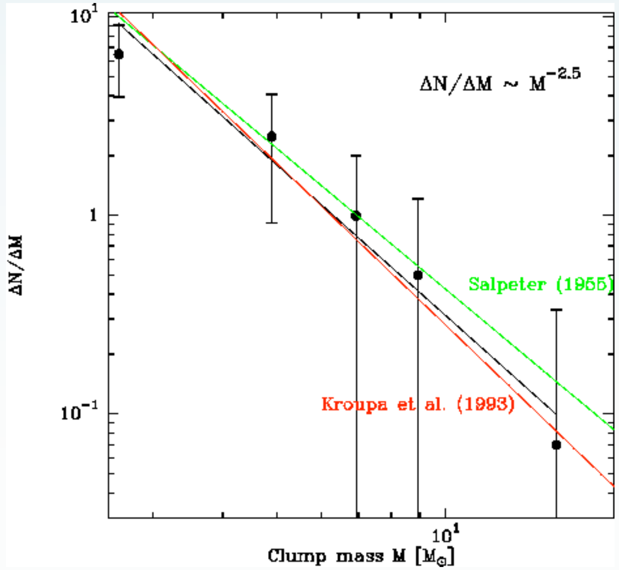
- Fragmentation of a massive protocluster:



Beuther & Schilke (2004)

- Core masses
  1.7 $M_\odot$ to 25 $M_\odot$

  (80 to 90% filtered out)



- CMF = Stellar IMF ➡ support for the core accretion scenario

IMF and Theoretical Models

- Beuther & Schilke (2004) study has some caveats:

  - spatial resolution: > 1” at 1.3 cm (0.01 pc at 2 kpc)
  - 80-90% emission filtered out
  - same temperature for all clumps (46 K, IRAS)
  - poor statistics (24 clumps)

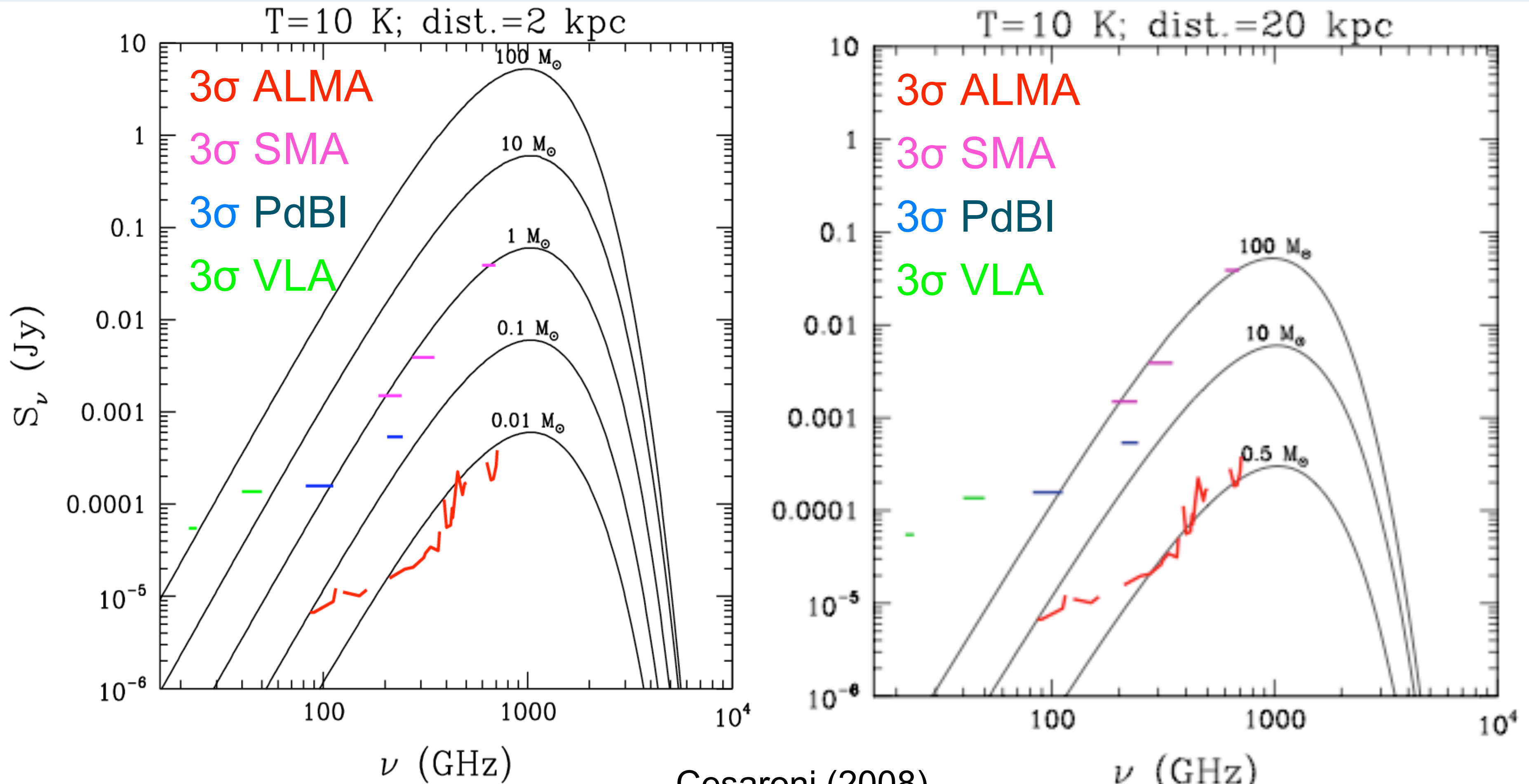
ALMA contribution

- The resolution achieved up to know is ~1”, which at typical distances of 4-5 kpc is 0.019 - 0.024 pc, and sensitivity to detect ~1.7 $M_{\odot}$.

➡ ALMA will resolve cloud structure on all scales from 500 AU to >1 pc (at 10 kpc, a resolution of 50 mas means 0.002 pc or 500 AU), and will allow to detect cold cores of > 0.1 $M_{\odot}$ up to 10 kpc and 0.5 $M_{\odot}$ up to 20 kpc

• Continuum spectrum of cold core (sensitivity estimates for 5 hr ON-source)

• Note: **$M_{Jeans} \approx 0.5\ M_O$**



Cesaroni (2008)

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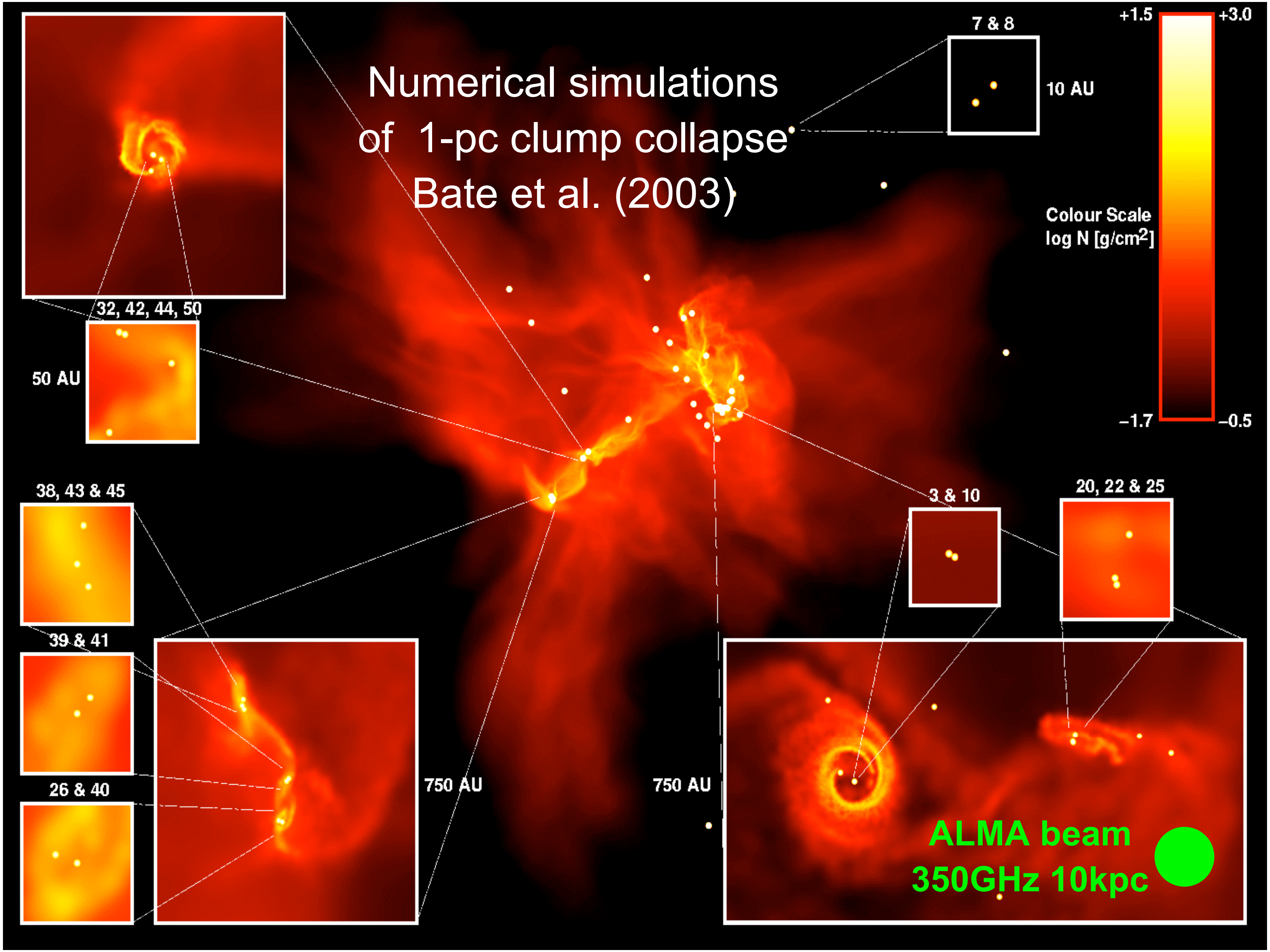
➡ ALMA will perform CMF studies for many more embedded clusters and will substantially improve the statistics of the studies.

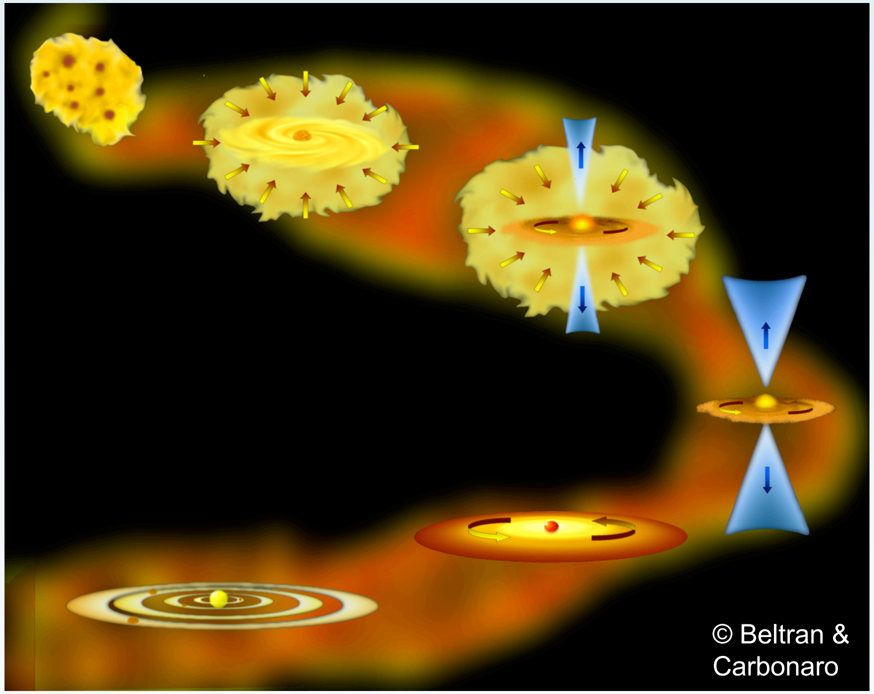
• Information about multiplicity in protostellar systems (quite a few proto-binaries already)

➡ Predictions of massive star formation theories and simulations will be tested with ALMA


Numerical simulations
of 1-pc clump collapse
Bate et al. (2003)
7 & 8
10 AU
+1.5
+3.0
Colour Scale
log N [g/cm2]
−1.7
−0.5
32, 42, 44, 50
50 AU
38, 43 & 45
39 & 41
26 & 40
750 AU
750 AU
3 & 10
20, 22 & 25
ALMA beam
350GHz 10kpc

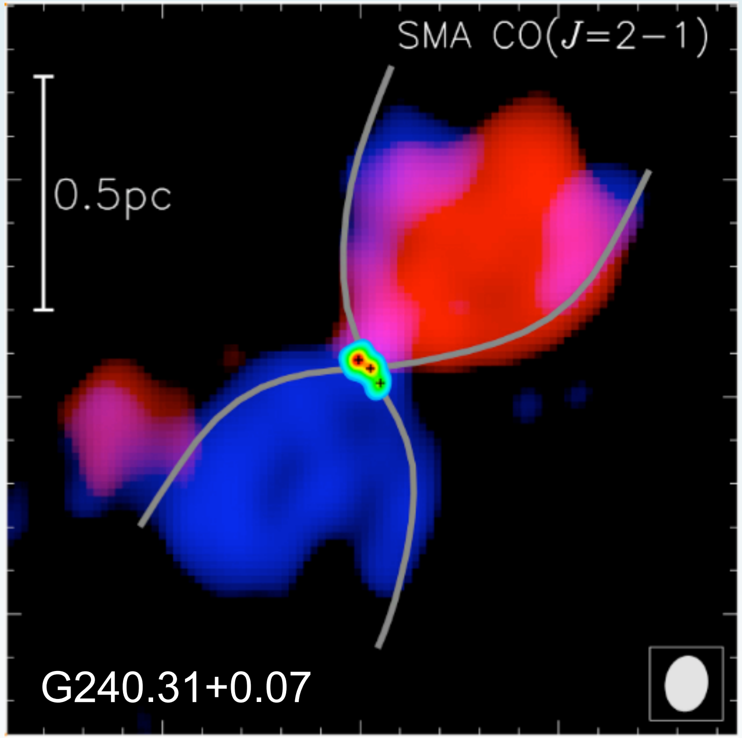
Outflow, rotation, and infall

- The core accretion model proposes the formation of a massive star via monolithic collapse of a molecular cloud ➔ similar to Sun-like stars, with very high accretion rates
- Another way to discriminate between theoretical models is to search for rotating disks, outflows, and infall around massive YSOs



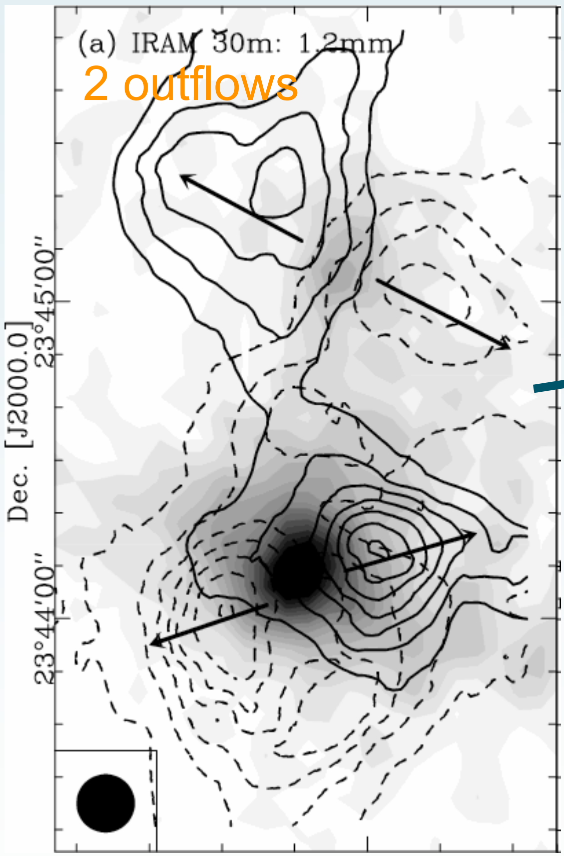
Outflow

- Outflows trace the earliest phase of protostellar evolution when extinction is high
- Outflow rate is proportional to accretion rate and hence provides a rough measure of this important parameter
- Outflow is thought to be perpendicular to a circumstellar disk and is crude evidence for its existence
- A cluster of protostars produces a cluster of outflows and one requires very high angular resolution to make out individual features

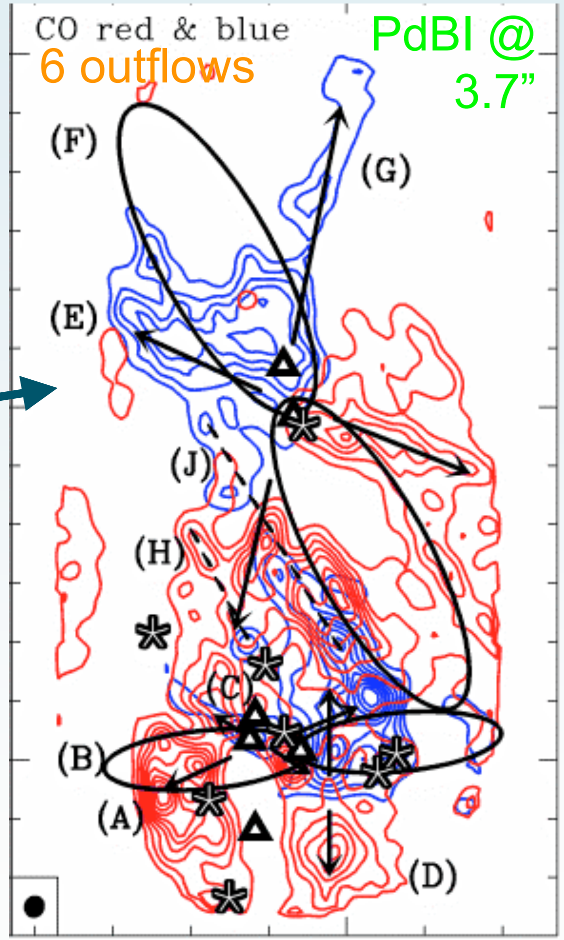


Qiu et al. (2009)

Outflow: IRAS 19410+2336



Beuther et al. (2003)



OAA

Outflow

• High angular resolution needed to resolve multiple outflows, *not* to image single outflow. Requirements:

- ❑ star separation in cluster ≈ 0.05 pc = 0.5"-10"
- ❑ line wings >> 1 km/s
- ❑ line intensity = few K

➔ very easy for ALMA! e.g. 1" resolution, 1 hr ON-source, 1 km/s resol.➔ 1σ = 0.1 K ➔ can image any outflow in the Galaxy

• Other advantages of ALMA for outflow studies:

➔ Measurement of proper motions: 100 km/s @ 1 kpc imply 20 mas/yr (@ 90 GHz, 1/3 beam ≈ 15 mas) → outflow inclination wrt l.o.s. from Vl.o.s./Vp.m. → deprojected outflow parameters → OUTFLOW RATE

➔ Imaging from 0.01 pc to 1 pc (in different tracers) → possible outflow precession

Rotation

- The searches for disks around massive YSOs have revealed an ever growing number of disks candidates.
- The main discriminating feature between these disks and those in low-mass pre-main sequence stars is the ratio M_{disk} versus M_{star}

- $L < 10^4 L_\odot$ ($M < 20 M_\odot$) ➡ $M_{\text{"disk"}} < M_{star}$

  ➡ DISKS

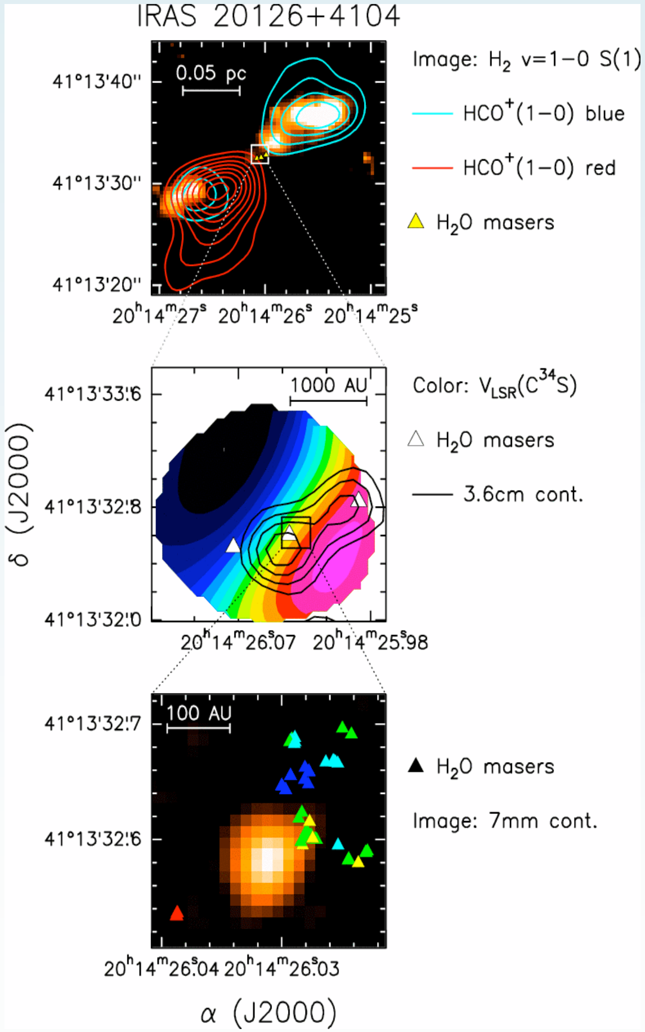
- $L > 10^5 L_\odot$ ($M > 20 M_\odot$) ➡ $M_{\text{"toroid"}} >> M_{star}$
  ➡ TOROIDS

LIST OF TRACERS USED TO SEARCH FOR DISKS IN HIGH-MASS YSOs

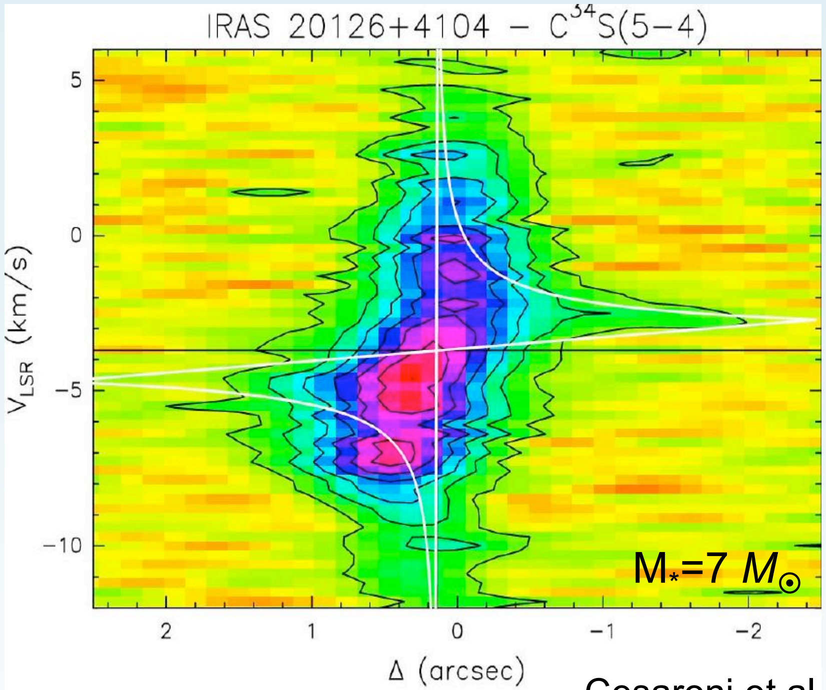
Tracer	References
CH_3OH masers	*Norris et al.* (1998); *Phillips et al.* (1998); *Minier et al.* (1998, 2000); *Pestalozzi et al.* (2004) *Edris et al.* (2005)
OH masers	*Hutawarakorn and Cohen* (1999); *Edris et al.* (2005)
SiO masers	*Barvainis* (1984); *Wright et al.* (1995) *Greenhill et al.* (2004)
H_2O masers	*Torrelles et al.* (1998) ; *Shepherd and Kurtz* (1999)
IR, mm, cm continuum	*Yao et al.* (2000); *Shepherd et al.* (2001); *Preibisch et al.* (2003); *Gibb et al.* (2004a); *Chini et al.* (2004); *Sridharan et al.* (2005); *Jiang et al.* (2005); *Puga et al.* (submitted)
NH_3, $C^{18}O$, CS, $C^{34}S$, CH_3CN, $HCOOCH_3$	*Keto et al.* (1988); *Cesaroni et al.* (1994, 1997, 1998, 1999a, 2005); *Zhang et al.* (1998a, 1998b, 2002); *Shepherd and Kurtz* (1999); *Olmi et al.* (2003); *Sandell et al.* (2003); *Gibb et al.* (2004b); *Beltrán et al.* (2004, 2005); *Beuther et al.* (2004b, 2005)

Cesaroni et al. (2007)

Rotation



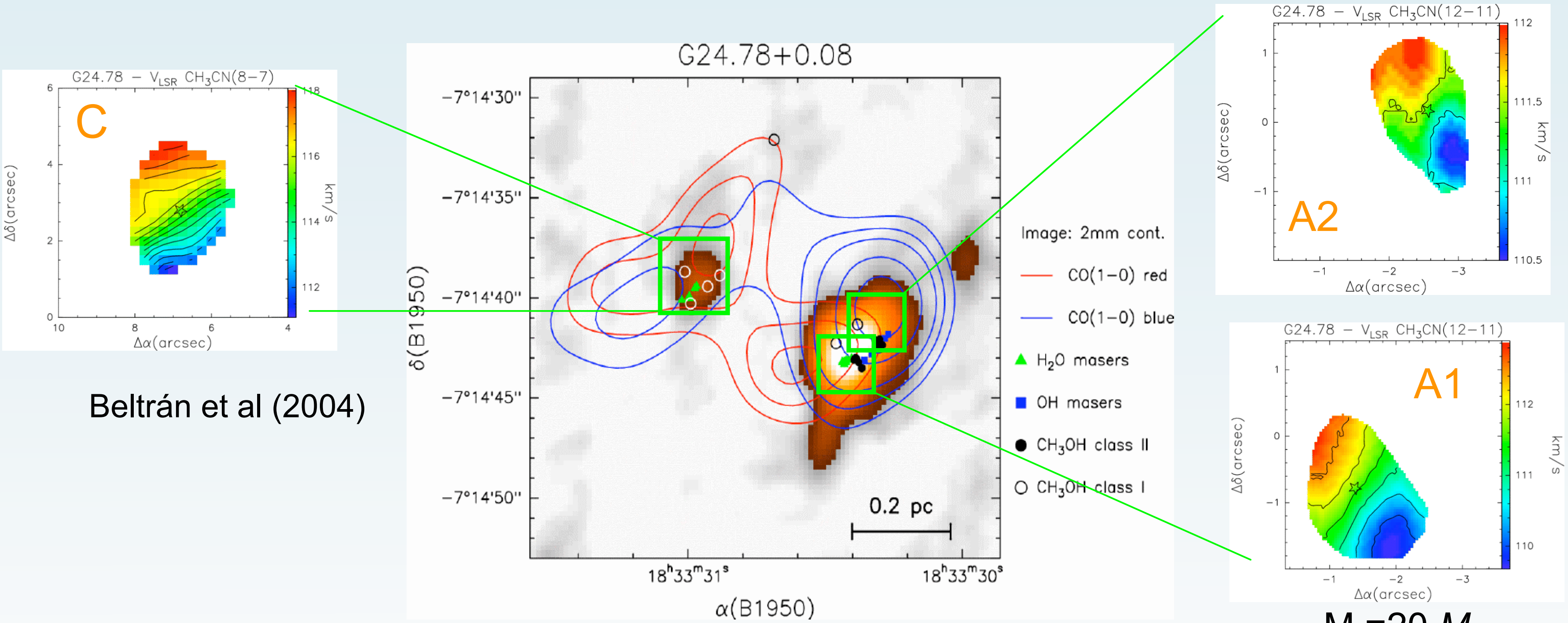
Cesaroni et al. (2007)



Cesaroni et al. (2005)

- B-type star with L~10^4 $L_\odot$
- Disk of mass 0.65-3.6 $M_\odot$ and radius 0.037 pc (7600 AU)
- Keplerian rotation around a M_*=7 $M_\odot$
- Mass accretion rate = 2 x 10^{-3} $M_\odot$/yr

Rotation



Beltrán et al (2004)

$M_* = 20\ M_\odot$

- O-type stars with L~ 7x10^5 $L_\odot$
- Toroids of mass 80-250 $M_\odot$!!! and radius 0.02-0.04 pc (4000-8000 AU)
- NO Keplerian rotation ➡ gravitational potential of the system dominated by the toroid ➡ self-gravitating structures
- Mass accretion rate = ~10^{-2} $M_\odot$/yr

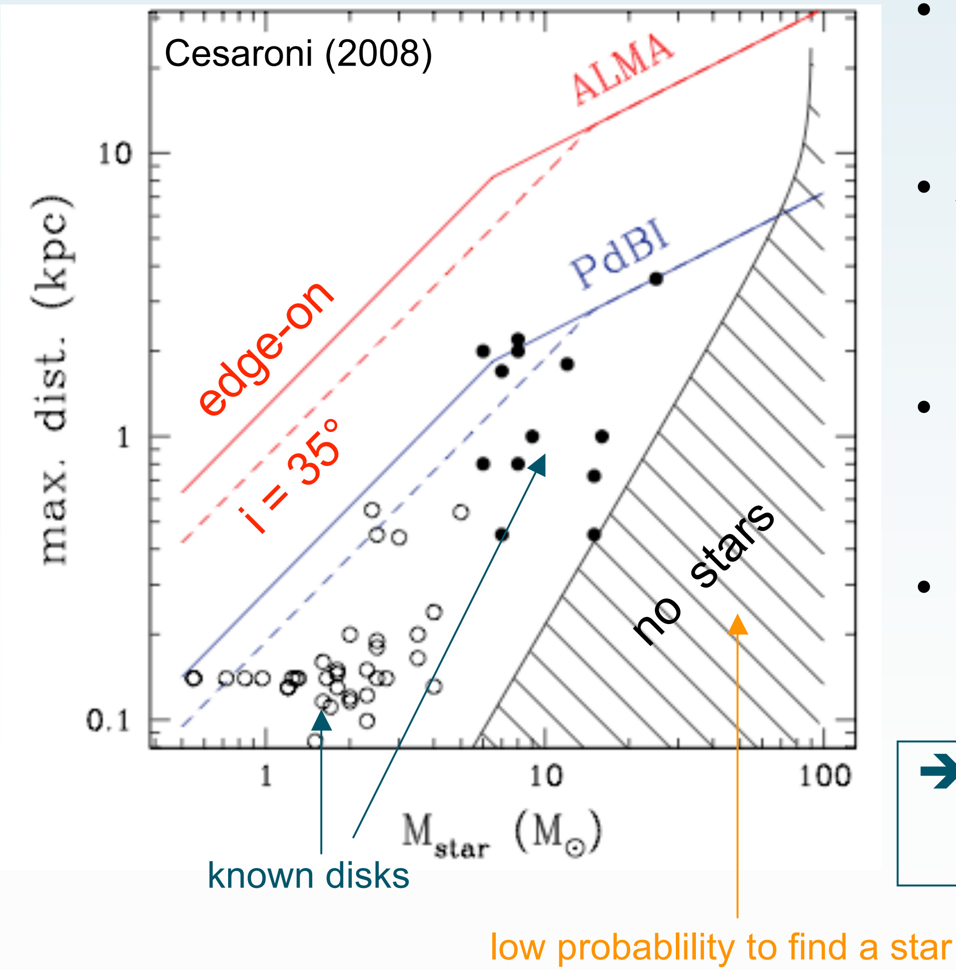
Rotation

- NO “true” disks have been found towards O-type stars:
- Hypothesis:
    - ❑ observational bias: disks could be heavily embedded inside the toroids and its emission difficult to disentangle from that of the large-scale rotating structure
    - ❑ disks could be destroyed or truncated at small radii (~30 AU) by interactions with stellar companions in the cluster or by the ionizing radiation of the early-type star (photo-evaporated disks: Hollenbach et al. 2000)
    - ❑ disks could never be created. Alternative formation models needed such as merging or competitive accretion (Bonnell et al. 2004; 2005).

OAA

Rotation

➔ ALMA sensitivity and resolution ABSOLUTELY needed



- Maximum distance at which a Keplerian disk can be detected as a function of the mass of the star.
- Assuming HPBW= $R_{disk}/4$, $\Delta V=V_{rot}(R_{out})$, $M_{disk} \propto M_{star}$, same mean surface density in all disks, $T_B > 20$ K
- Observation frequency = 230 GHz, 5 hours ON-source, spectral resolution = 0.2 km/s, and S/N = 20
- It will be necessary to span the whole Galaxy to find a circumstellar disk associated with an early O star

➔ ALMA sensitive enough to detect a disk up to distances of 20 kpc.

Infall

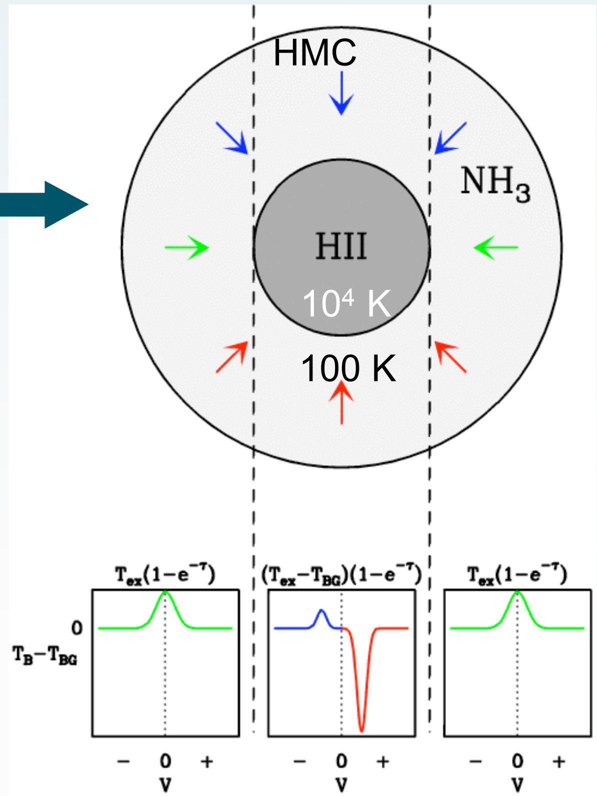
• Important to test models for OB star formation, but difficult to detect/recognize: e.g. line broadening towards star may be due to optical depth and/or turbulence

• Few direct detections of gas infall towards massive YSOs.

• Inverse P-Cygni profiles (or red-shifted absorption) towards bright embedded sources have been detected:

❑ hypercompact HII regions (very bright at cm λ's) as for G10.62 (Keto et al. 1988; Sollins 2005) or G24.78 A1 (Beltran et al. 2006)

❑ a strong compact millimeter source as for W51 North (Zapata et al. 2008), G31.41+0.31 (Girart et al. 2009; Frau et al., in preparation), G19.61-0.23 (Wu et al. 2009)



Infall

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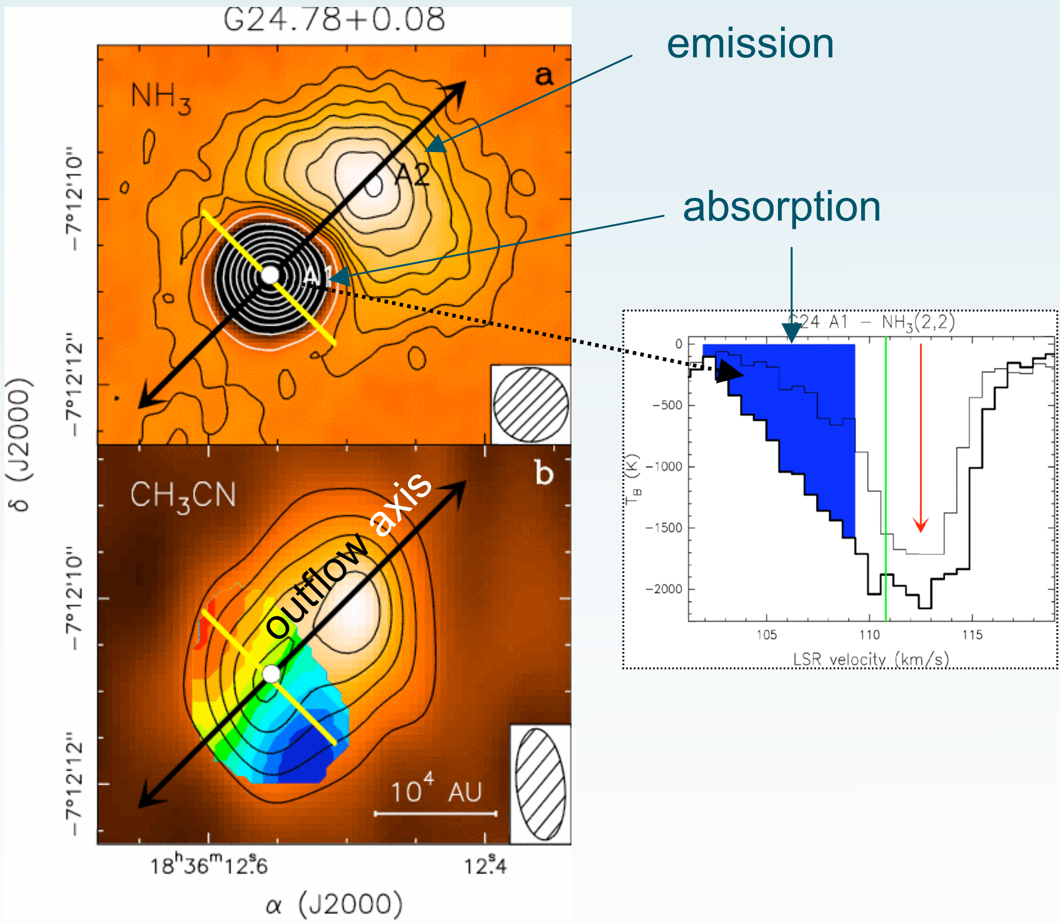
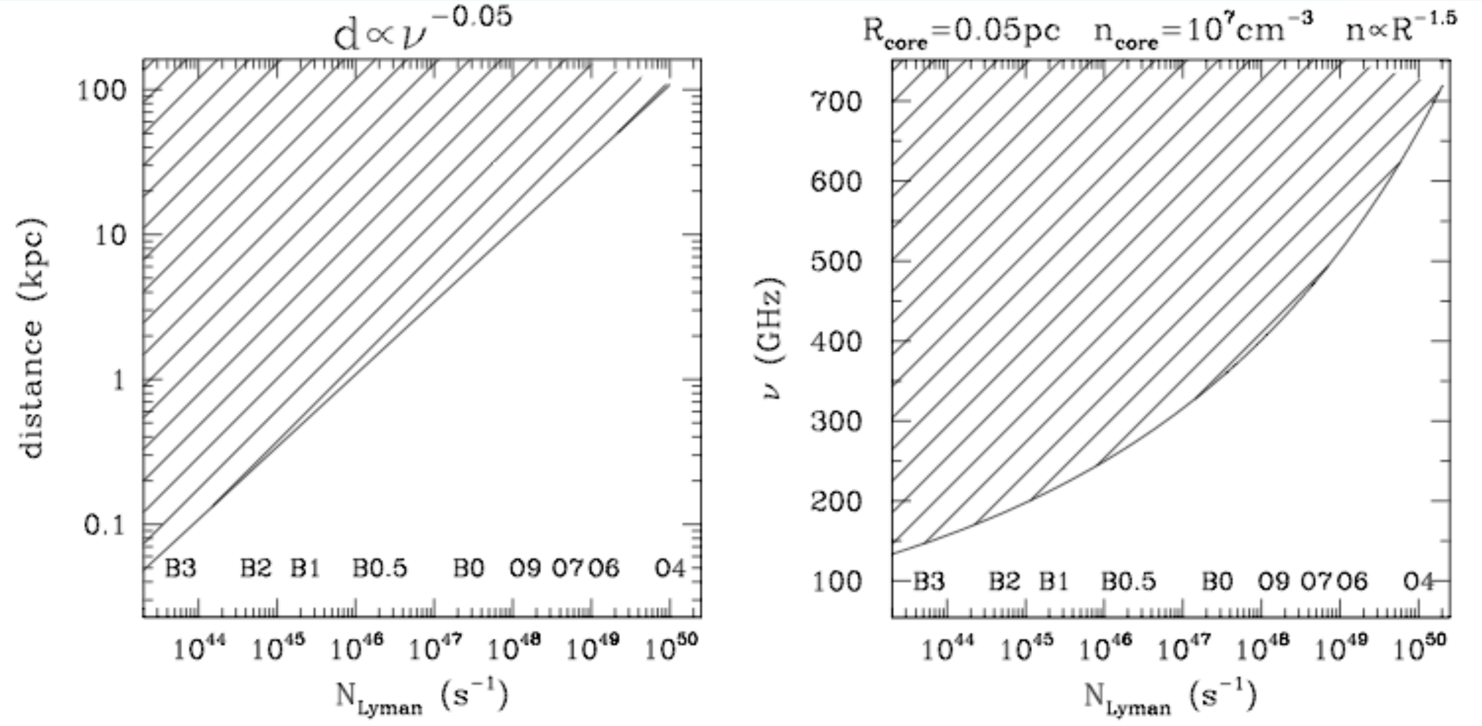
$NH_3(2,2)$ VLA B



Beltrán et al. (2006)

Infall

- Assuming 2 R_{HII} = HPBW(ν) 0.012” = [350/ν(GHz)], optically thick free-free emission, and dusty core optically thin, Cesaroni (2008) found a relationship between the spectral type of the ionizing star and the maximum distance and frequency at which the red-shifted absorption can be detected. R_{HII} = 50-1000 AU



➔ ALMA should detect infall up to the Galactic center

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Interstellar and pre-biotic chemistry

Known Interstellar and Circumstellar Molecules (July 2000)

Number of Atoms

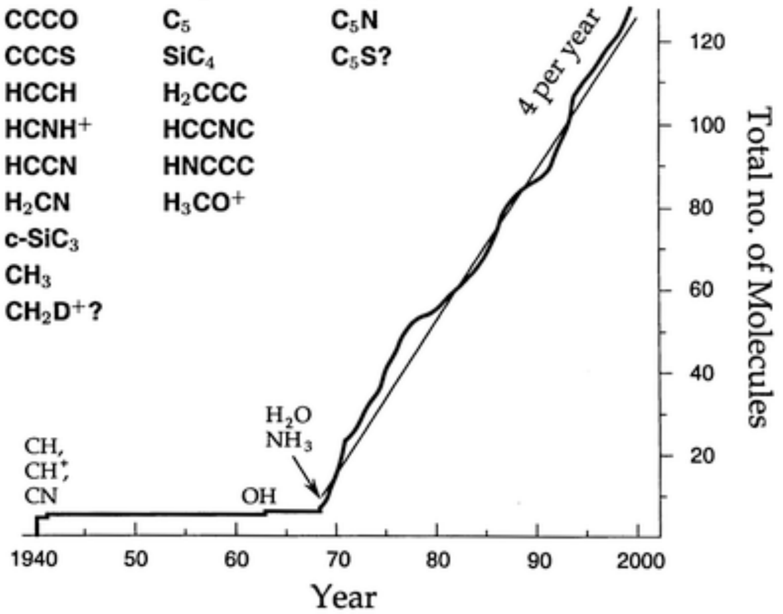
2	3	4	5	6	7	8	9
H_2	H_2O	NH_3	SiH_4	CH_3OH	CH_3CHO	CH_3CO_2H	CH_3CH_2OH
OH	H_2S	H_3O^+	CH_4	NH_2CHO	CH_3NH_2	HCO_2CH_3	$(CH_3)_2O$
SO	SO_2	H_2CO	$CHOOH$	CH_3CN	CH_3CCH	CH_3C_2CN	CH_3CH_2CN
SO^+	HN_2^+	H_2CS	$HC{\equiv}CCN$	CH_3NC	CH_2CHCN	C_7H	$H(C{\equiv}C)_3CN$
SiO	HNO	$HNCO$	CH_2NH	CH_3SH	HC_4CN	H_2C_6	$H(C{\equiv}C)_2CH_3$
SiS	SiH_2?	$HNCS$	NH_2CN	C_5H	C_6H		C_8H
NO	NH_2	$CCCN$	H_2CCO	HC_2CHO	c-CH_2OCH_2		
NS	H_3^+	HCO_2^+	C_4H	$CH_2=CH_2$	C_7^-?		
HCl	NNO	$CCCH$	c-C_3H_2	H_2CCCC			
$NaCl$	HCO	c-$CCCH$	CH_2CN	HC_3NH^+			
KCl	HCO^+	$CCCO$	C_5	C_5N			
$AlCl$	OCS	$CCCS$	SiC_4	C_5S?			
AlF	CCH	$HCCH$	H_2CCC				
PN	HCS^+	$HCNH^+$	$HCCNC$				
SiN	c-$SiCC$	$HCCN$	$HNCCC$				
NH	CCO	H_2CN	H_3CO^+				
CH	CCS	c-SiC_3					
CH^+	C_3	CH_3					
CN	$MgNC$	CH_2D^+?					
CO	$NaCN$						
CS	CH_2						
C_2	$MgCN$						
SiC	HOC^+						
CP	HCN						
CO^+	HNC						
HF	$SiCN$						
	KCN?						

10
CH_3COCH_3
$CH_3(C{\equiv}C)_2CN$?

11
$H(C{\equiv}C)_4CN$

13
$H(C{\equiv}C)_5CN$

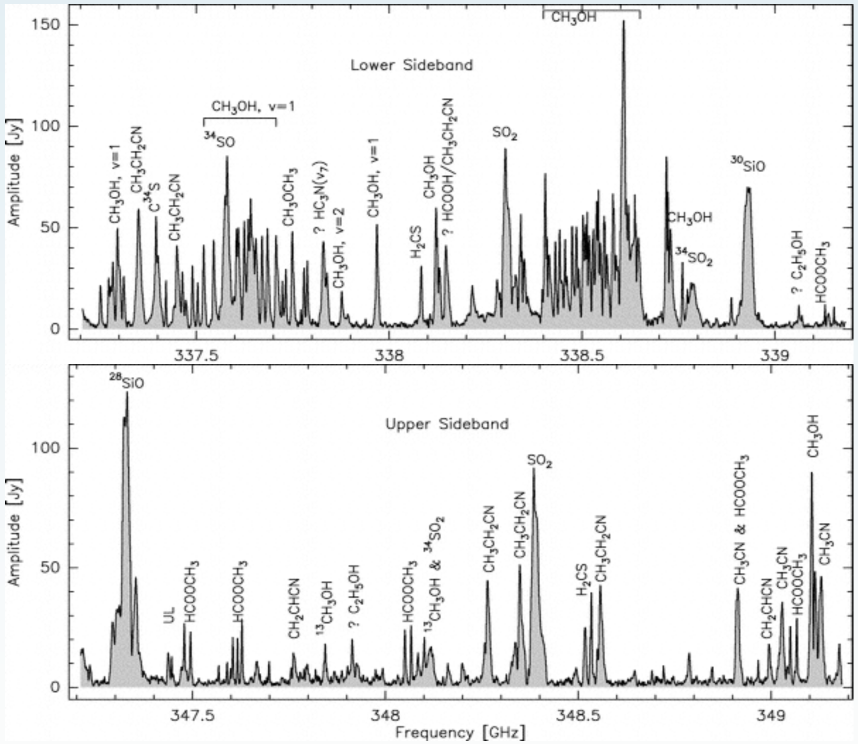
Total: 123



Interstellar and pre-biotic chemistry

- ALMA will see hundreds of Orion-like sources, including the warm gas around young protostars and protoplanetary disks.
- ALMA, with its gain in sensitivity and angular resolution with respect to any available facility, will unveil a real forest of lines in all spectral observations.
- Spanning the survey over the whole frequency range of ALMA will cover a large range of excitation conditions.
- Most of the emission will arise from isotopic species and vibrationally excited states of already known molecules.

Orion KL survey at 865 μm with SMA



Beuther et al. (2005)

Interstellar and pre-biotic chemistry

• For high column densities, the dust becomes optically thick at the highest frequencies, which will cause some lines to show up in absorption.

➔ This will complicate the interpretation

• In order to fully explore the potential of these lines for studies of the physical structure and chemical complexity of star forming regions, protoplanetary disks, interstellar and circumstellar clouds, galaxies, etc

➔ a complete and accurate molecular line database will be required

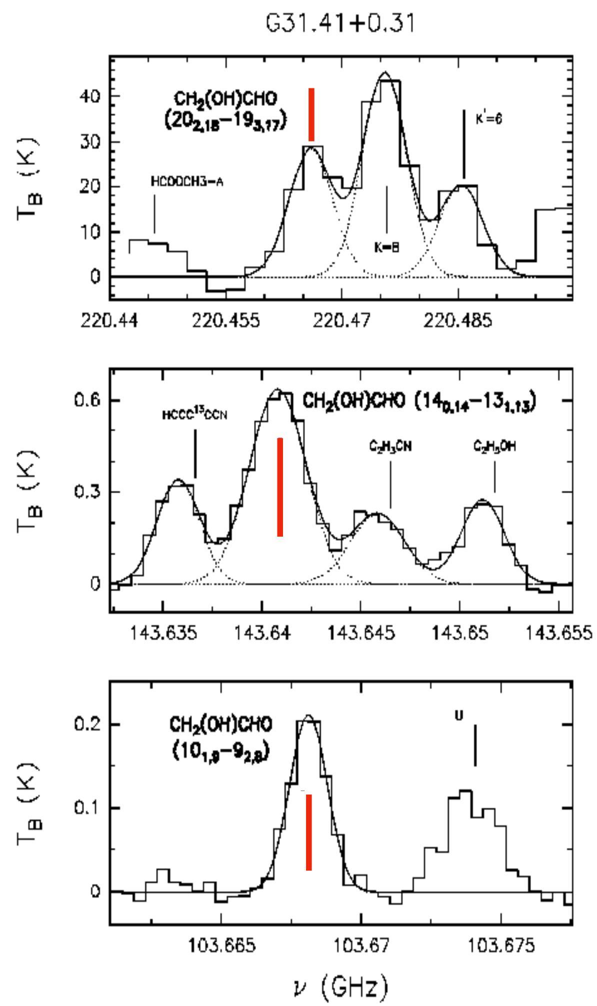
➔ The interpretation of molecular ALMA data will also need additional molecular physics information, like collisional rates, quantum chemistry calculations, etc.

Interstellar "large organic" and pre-biotic detections in space

- First discoveries: formaldehyde (H_2CO) in 1969 and methanol (CH_3OH) in 1970
- Some "exotic" molecules in interstellar clouds (most towards the Galactic Center):
  - ❑ formic acid (HCOOH)
  - ❑ urea (H_2NCONH_2)
  - ❑ interstellar antifreeze (a.k.a ethylene glycol) ($HOCH_2CH_2OH$)
  - ❑ acetone (CH_3COOCH_3)
  - ❑ ethanol (CH_3CH_2OH)
  - ❑ methanol (CH_3OH)
  - ❑ acetic acid (CH_3COOH) (1996)
  - ❑ glycolaldehyde (CH_2OHCHO): simplest of monosaccharide sugars (2000)
  - ❑ glycine (NH_2CH_2COOH) ???, the simplest amino acid: there was a claim for the detection but its detection has been rejected

Building blocks of life in space

- Glycolaldehyde has been detected for the first time towards a hot molecular core (G31.41+0.31: Beltrán et al. 2009).
- Complex organic molecules are YET to be detected in proto-planetary disks.
- The chemistry in the inner few 100 AU is distinctly different from that of the outer colder envelope.
- Complex organic molecules could be formed in-situ in proto-planetary disks or find their way to proto-planetary disks during the collapse.
- High-angular resolution and sensitivity studies will have consequences for pre-biotic chemistry in proto-planetary disks (and planets) and chemistry models.



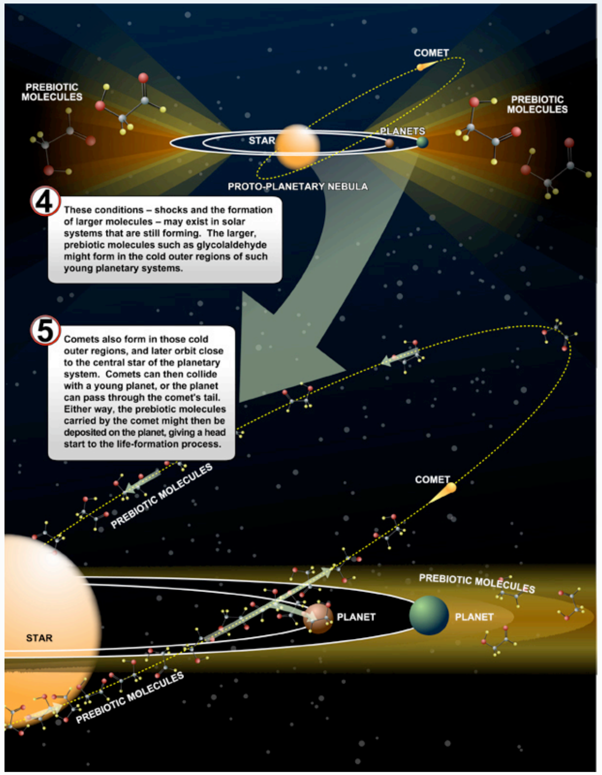
Beltrán et al. (2009)

Building blocks of life in space

➔ ALMA will resolve these hot core regions and map the distribution of molecules

➔ The data will be used to test models of complex organic molecule formation (thermal evaporation vs. liberation of icy mantles in shocks), models of hot core chemistry and dynamical effects

➔ Systematic search of pre-biotic molecules (glycine, adenine, and other DNA bases) will constrain astro-biological theories: could comets have 'seeded' the primordial Earth with water and other chemical ingredients required to kick start life?



Conclusions

➔ ALMA will bring observations of high mass star forming regions to a point where comparison with theory is useful

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- ALMA will trace the initial conditions of massive stars and cluster formation: assess structure of IR-dark clouds in the Galaxy, perform statistically significant Core Mass Function studies of embedded clusters
- Resolve multiple outflows from clusters and measure their (3D) velocity → accurate estimate of outflow parameters
- Image circumstellar disks in OB stars up to Galactic center → discriminate between high-mass star formation theories
- Reveal infall in O stars up to Galactic center → This is important because direct measurement of accretion onto protostars is an essential part of understanding protostellar evolution

Conclusions

➔ ALMA will push astro-chemistry studies by searching pre-biotic molecules in proto-planetary disks

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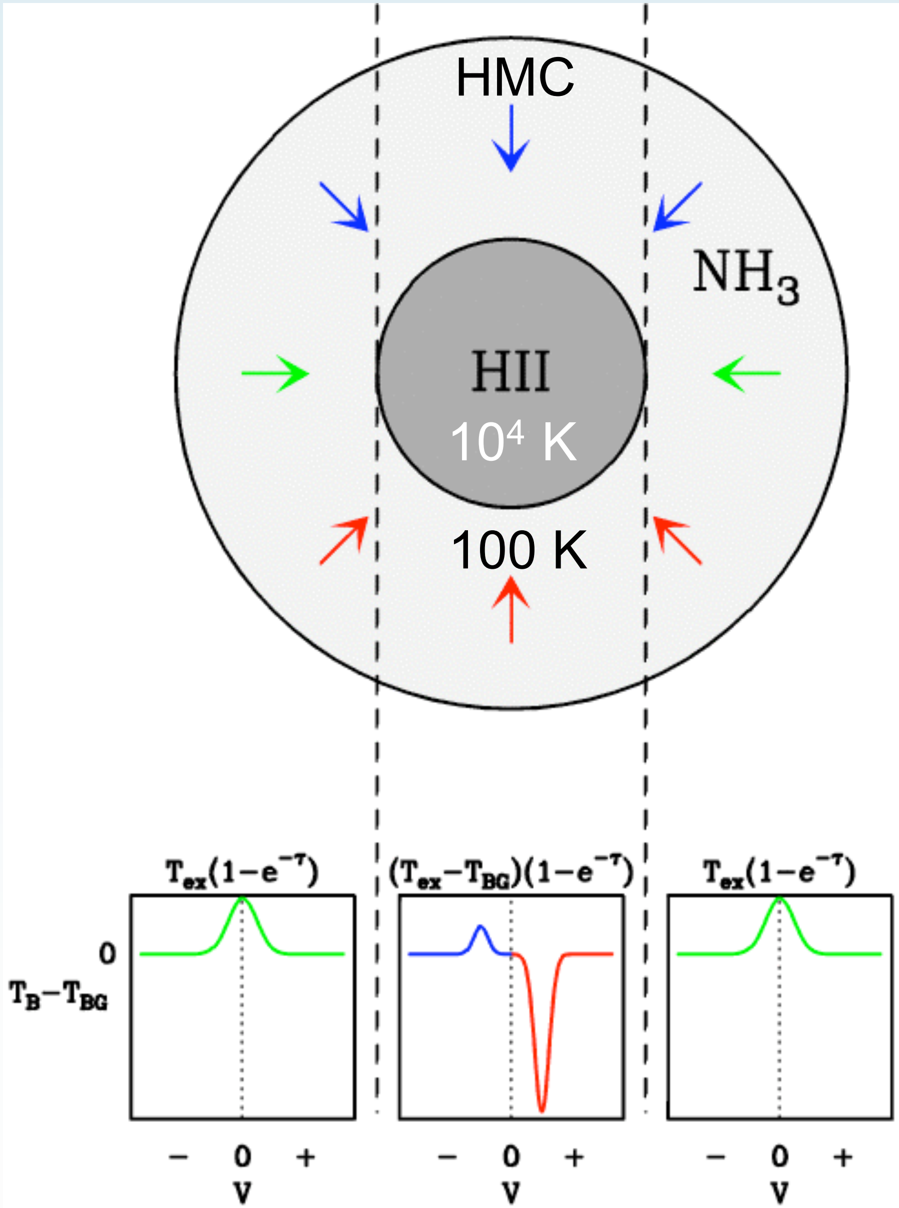
➔ ALMA will push astro-chemistry studies by searching pre-biotic molecules in proto-planetary disks

- ALMA will resolve hot core regions and map the distribution of molecules
- Allow searches of complex molecules two orders of magnitude deeper (to abundances of < 10^{-13} with respect to H_2) thanks to its much higher sensitivity to compact emission.
- Have important consequences in determining the chemical composition of the material from which future solar systems are made: boost our knowledge of the chemistry in proto-planetary disks, and of how complex molecules are incorporated into planetary systems (obviously complemented with IR studies: *Herschel*).
- Sophisticated analysis and modeling tools needed.

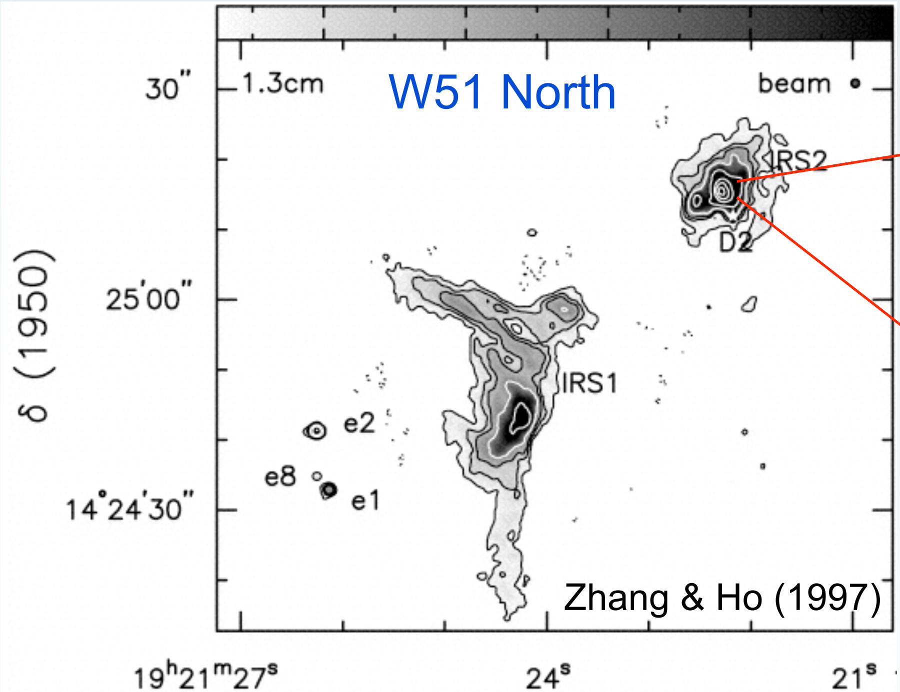
QAA

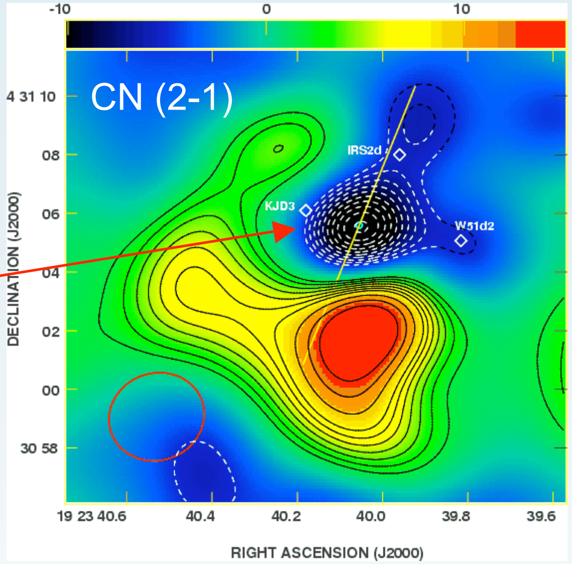
Thank you!

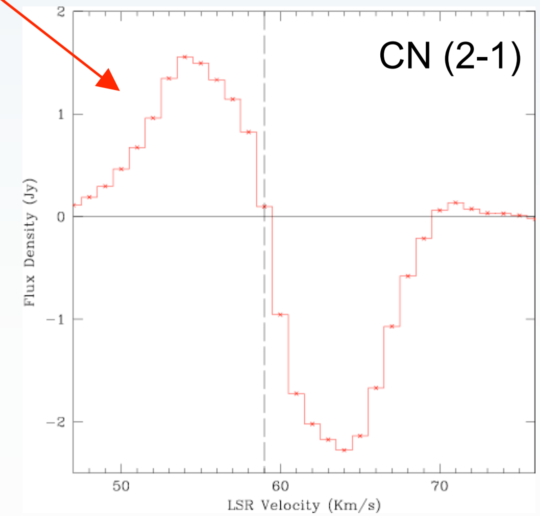
• Absorption line tracing infall in a core with embedded HII region



• Red-shifted absorption against a strong continuum millimeter source



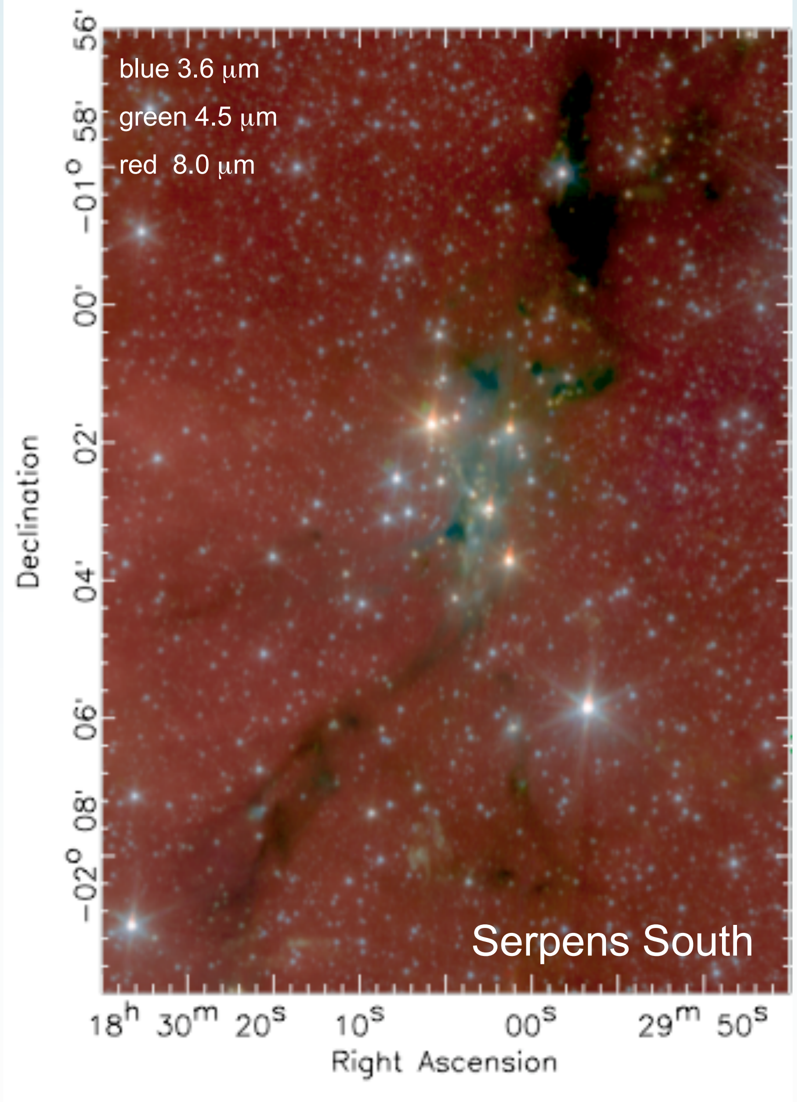




Zapata et al. (2008)

Initial conditions of massive stars and cluster formation

- Formation sites: parsec scale high-density clumps (10^4 to 10^5 cm^{-3}) within Giant Molecular Clouds (GMCs) (density of order 100-1000 cm^{-3}) ➔ IR-Dark Clouds (IRDCs)



Guthermuth et al. (2008)