Observational perspective of the youngest phases of intermediate-mass stars

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What are intermediate-mass protostars?

- Intermediate-mass protostars are:
  - defined observationally through their bolometric luminosity: 50 L☉< Lbol < 2000 L☉
  - YSOs that will form stars with masses in the range 2 M☉< Mstar < 8 M☉
- Intermediate-mass protostars are:
  - precursors of Herbig Ae and Herbig Be stars (for L > 103 L☉)
  - precursors of Vega-type systems
- Intermediate-mass protostars are an important component of the UV interstellar radiation field in our Galaxy
- Intermediate-mass protostars provide a bridge between low- and high-mass protostars

Low- or high-mass star-formation?

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

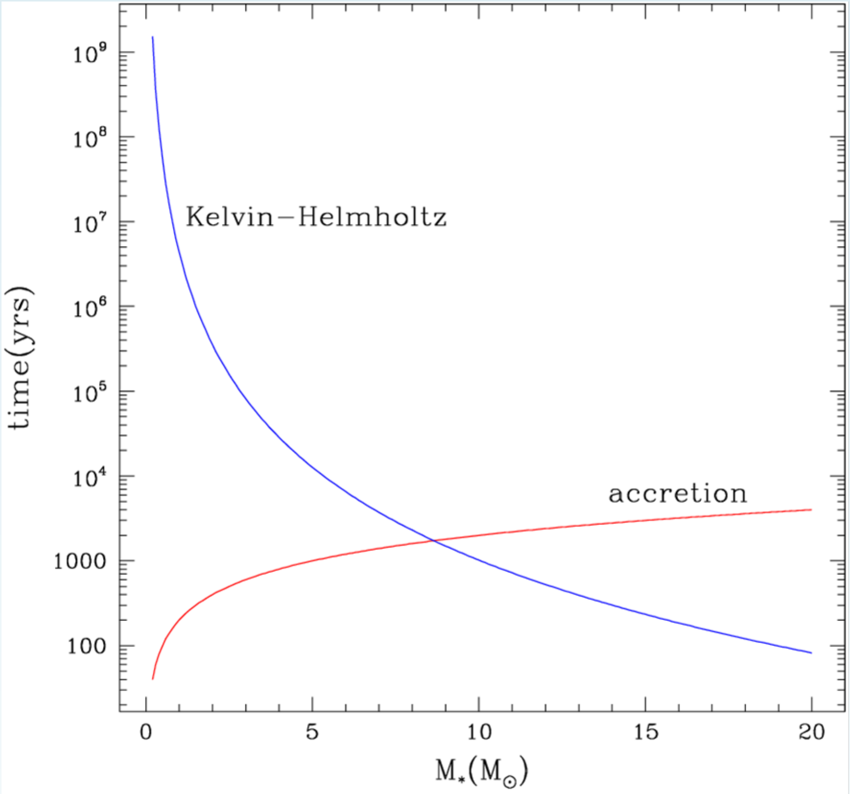
- Low-mass (< 8 M⊙): evolution dominated by accretion timescale: tacc < tKH

➡ Pre-main sequence

- High-mass (> 8 M⊙): evolution dominated by the KH timescale: *tacc* > *t*KH

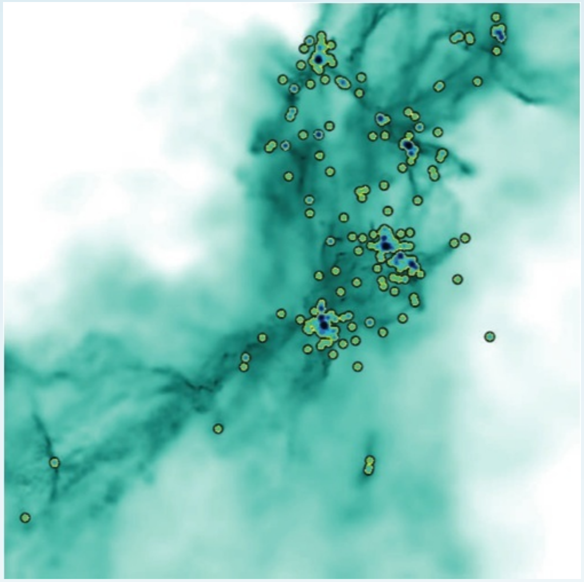
➡ No pre-main sequence, accretion on ZAMS

Radiation pressure acting on dust grains become large enough to reverse the infall of matter



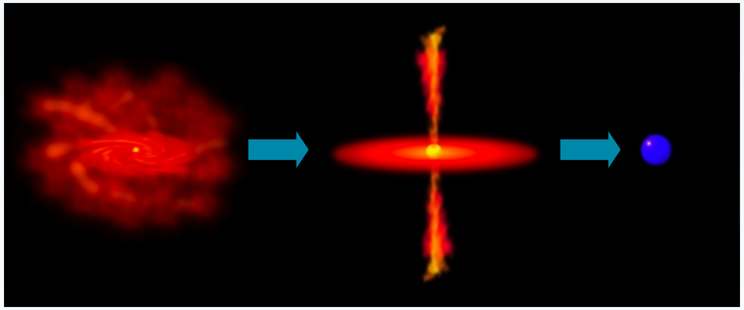
Low- or high-mass star formation?

- **COMPETITIVE ACCRETION**: Bonnell & Bate (2002) predict that clouds fragment initially into cores of a Jeans mass of ~0.5-1 M⊙. These cores subsequently form low-mass stars that compete to accrete the distributed gas in the molecular clump. This models predicts that massive stars should form exclusively in clustered environments. A special case of interaction is that causing a merging between low-mass stars giving rise to a high-mass star, which is only predicted for unusually high stellar densities (Bonnell & Bate 2005)



Adapted from Bonnell et al. (2004)

- **CORE ACCRETION**: McKee & Tan (2002, 2003) propose a turbulent accretion model, in which stars form via a monolithic collapse of a molecular cloud: a massive star forms from a massive core and gathers its mass from this massive core alone. Given the non-zero angular momentum of the collapsing core, this model predicts the existence of protostellar accretion disks around massive stars.



Courtesy of Luca Carbonaro

Low- or high-mass star-formation?

- Two relevant timescales in SF:
  1. accretion *tacc* = *M**/(d*M*/dt)
  2. contraction *t*KH = *GM**/*R***L**
- Low-mass (< 8 M☉): evolution dominated by accretion timescale: tacc < tKH
  - ➡ Pre-main sequence
- High-mass (> 8 M☉): evolution dominated by the KH timescale: *tacc* > *t*KH
  - ➡ No pre-main sequence, accretion on ZAMS

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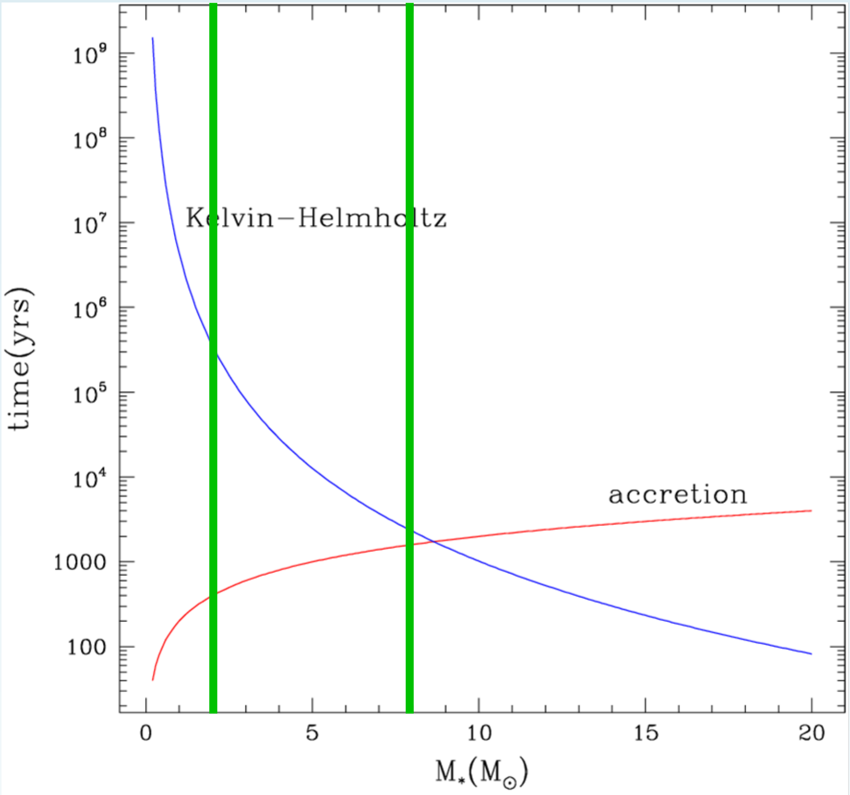


Properties of IMs protostars

1. Formation mode: isolated versus clustered
2. Disks: yes or not?
3. Outflows: ordered versus chaotic
4. Chemistry: rich or not?

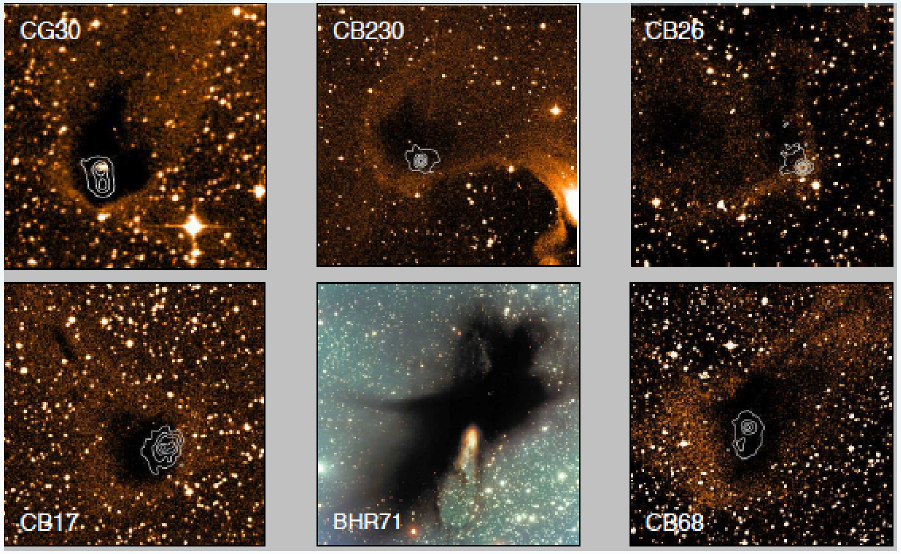
1. Formation mode: isolated versus clustered

- Low-mass star formation:
  - Low-mass YSOs form in isolation or in loose stellar aggregates
  - Low-density aggregates of < 10 stars pc-3 (Gómez+ 1993)
  - Single core

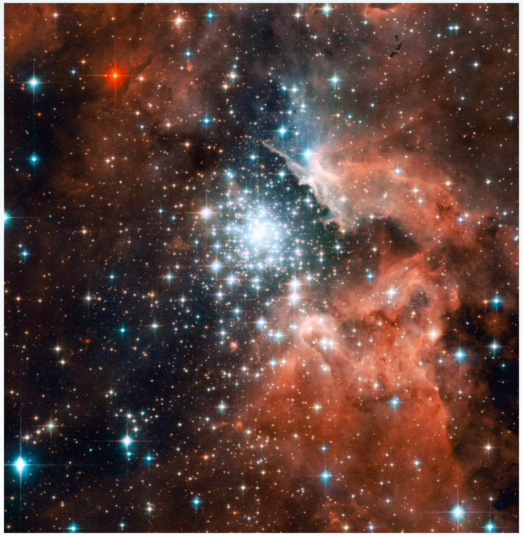
- High-mass star formation:
  - High-mass YSOs form in clusters
  - Very large stellar densities > 103 stars pc-3 (Hillenbrand & Hartmann 1998)
  - ⚠ de Wit+ (2006) only ~4% of O-field stars might have an origin outside of a young cluster
  - Core fragmentation

Bok Globules

Launhardt (2005)



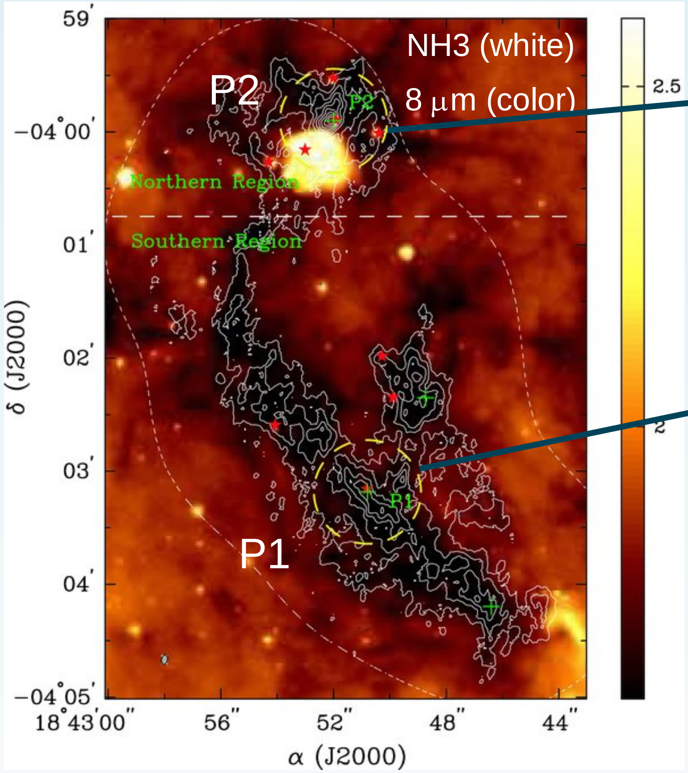
NGC 3603



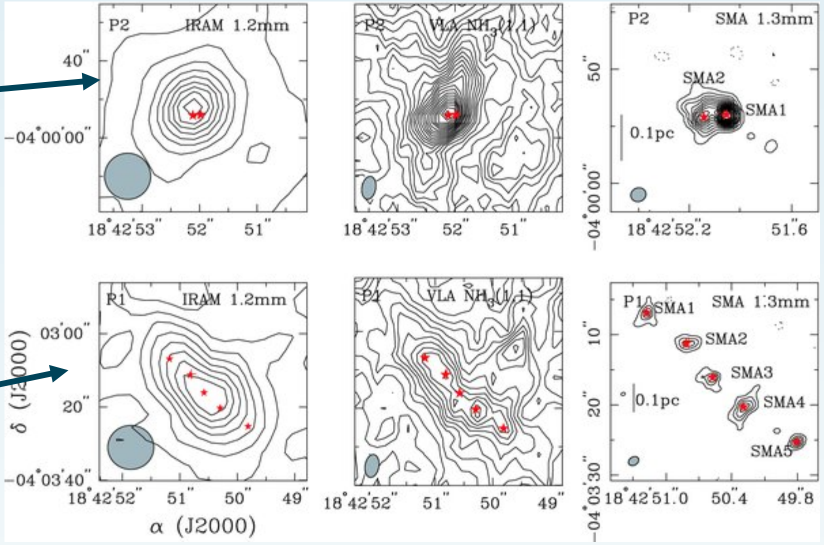
1. Formation mode: isolated versus clustered

- High-mass cores show evidence of fragmentation at very early evolutionary stages (IRDCs)

G28.24+0.06



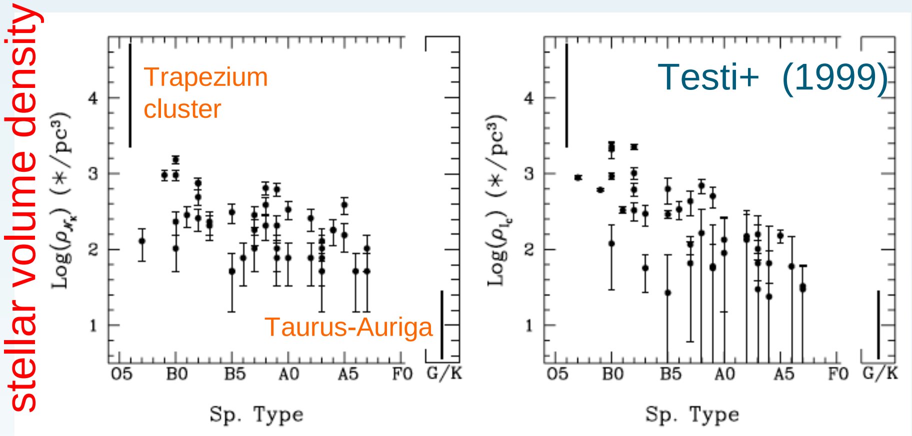
Zhang+ (2009)



- IRDCs fragmented in cores with masses of 22 to 100 $M_\odot$, and projected separation of 0.19 pc.
- For an average Tgas of 16 K, the thermal Jeans mass and length are 1 $M_\odot$ and 0.05 pc
- Mgas a factor 10 larger MJeans ➔ The large masses indicate that turbulence and/or magnetic fields play an important role in fragmentation.

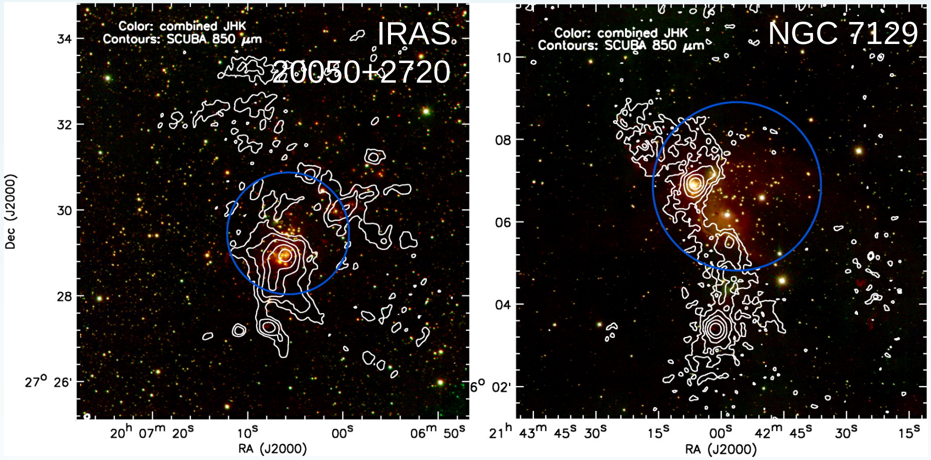
1. Formation mode: isolated versus clustered

- IMs protostars are found either in loose aggregates and in clusters.
- IMs protostars mark the transition from low-density aggregates to rich clusters, with a smooth transition for star masses around 3.5 M⨀ (Testi+ 1999)



NK = # of stars in K-band within 0.21 pc from Herbig star

Ic = integral over distance of the source surface density profile subtracted by the average source density measured at the edge of each field



Gutermuth+ (2005)

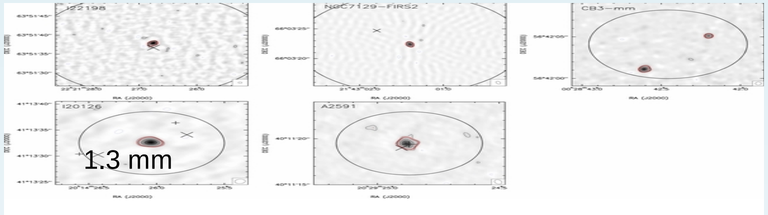
1. Formation mode: isolated versus clustered

- no fragmentation

I22198+6336 (370 $L_\odot$)

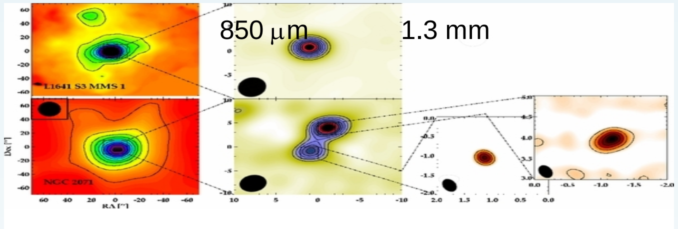
NGC 7129 FIRS2 (500 $L_\odot$)

CB3-mm (1000 $L_\odot$)



Palau+ (2013)

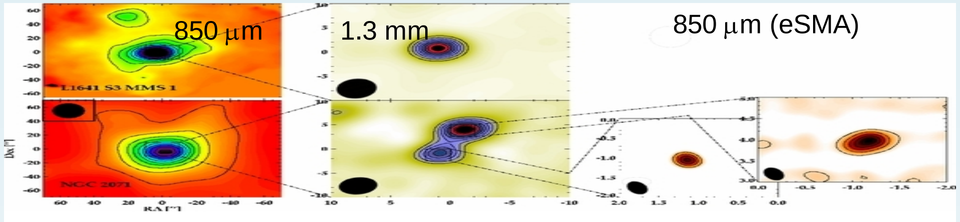
L1641 S3 MMS 1 (70 $L_\odot$)



van Kempen+ (2012)

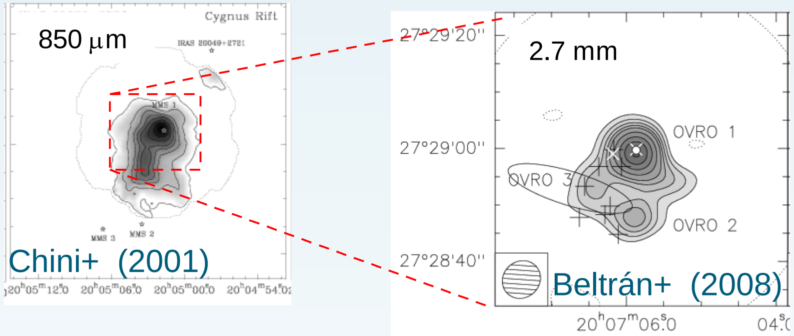
- small proto-clusters

NGC 2071 (520 $L_\odot$)



van Kempen+ (2012)

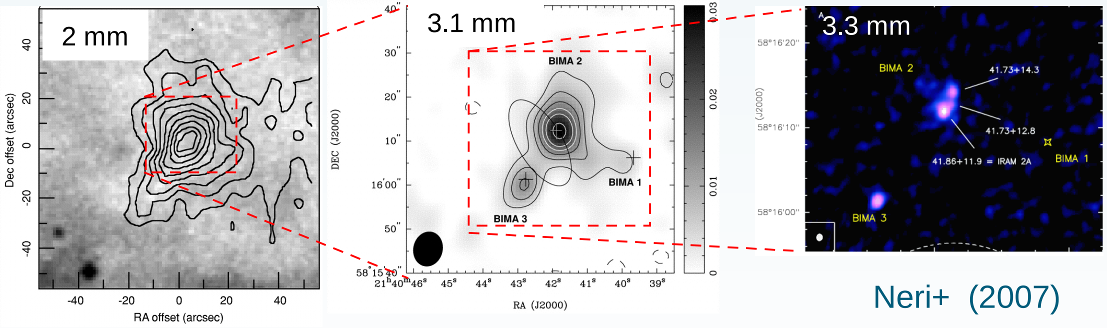
IRAS 20050+2720 (280 $L_\odot$)



Chini+ (2001)

Beltrán+ (2008)

IC1396N BIMA 2 (235 $L_\odot$)



Sugitani+ (2000)

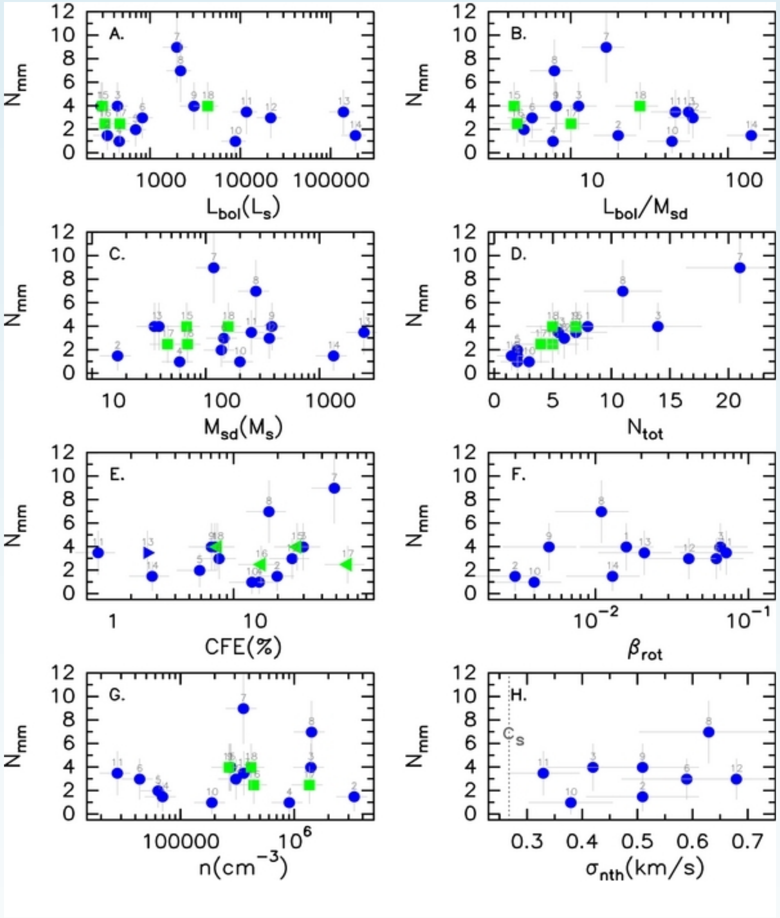
Beltrán+ (2002)

Neri+ (2007)

1. Formation mode: isolated versus clustered

- Palau+ (2013) studied fragmentation (~1000 AU) in a sample of 18 IM-HM embedded cores with luminosities ranging from 300 to 2×105 L⊙
- 30% no signs of fragmentation (5 cores)
- 50% split in ≳ 4 fragments (9 cores)
- Mean separation between sources ~3000 AU
- No correlation of physical properties of the cores with fragmentation level

Palau+ (2013)



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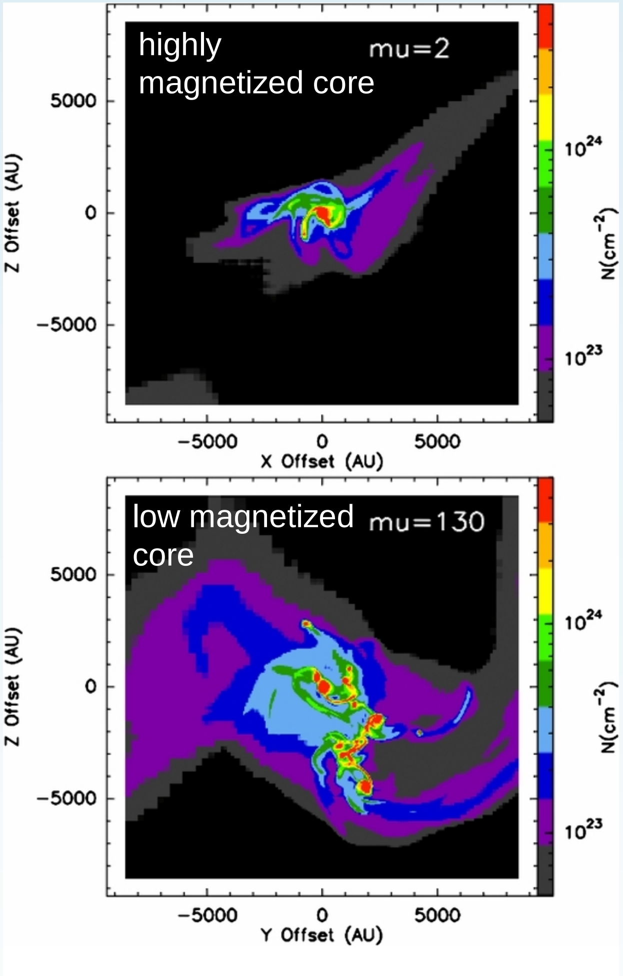
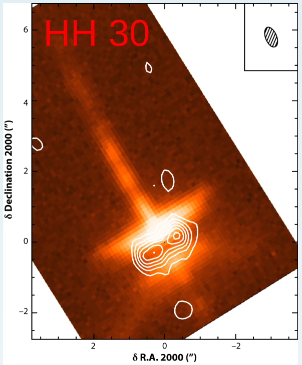
➡ fragmentation could be controlled by the magnetic field (MHD simulations of Commerçon+ 2011): highly magnetized cores would show a low level of fragmentation while cores where turbulence dominates over magnetic field would show high level of fragmentation

Palau+ (2013)

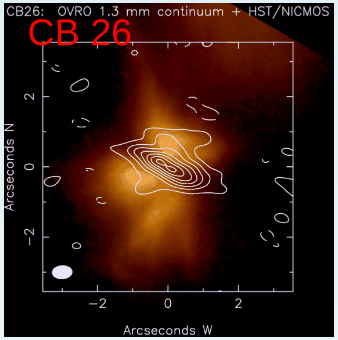


2. Disks: yes or not?

- low-mass disks



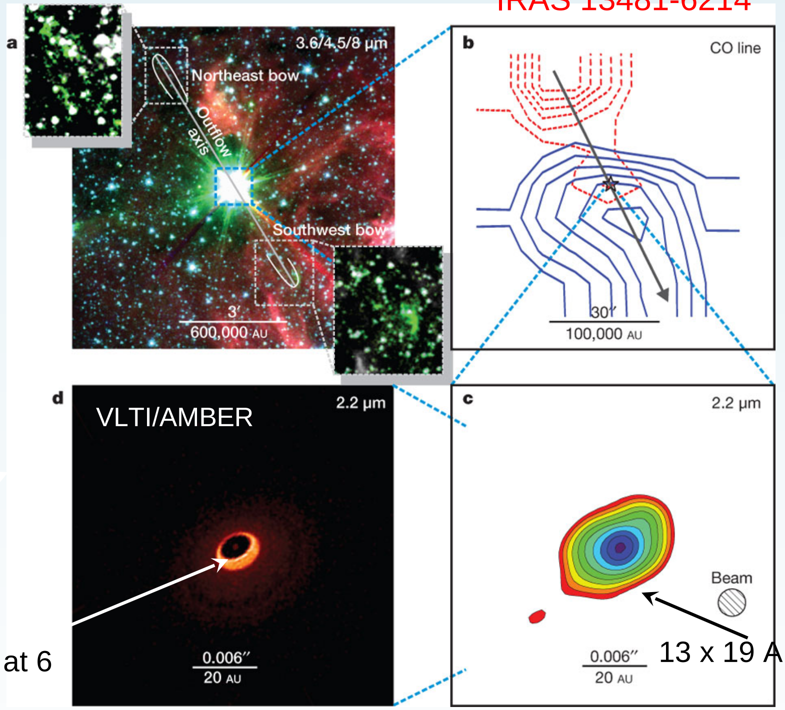
Chiang & Youdin (2010)



Sauter+ (2009)

- early B-type (late O-type) disks
  - At least for Mstar $\lesssim$ 20 M$\odot$: IRAS 20126+4104 (Cesaroni+ 2005), Cepheus A (Patel+ 2005), NGC 7538S (Sandell+2033), IRAS 13481-6214 (Kraus+ 2010), CRL2136 (de Wit+ 2011), G35.20-0.74N (Sánchez-Monge+ 2013) and many more ….

IRAS 13481-6214



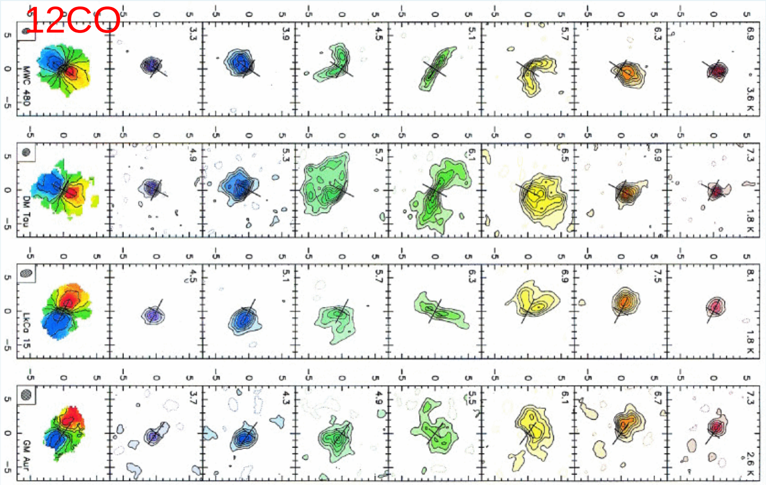
truncated at 6 AU

13 x 19 AU

Kraus+ (2010)

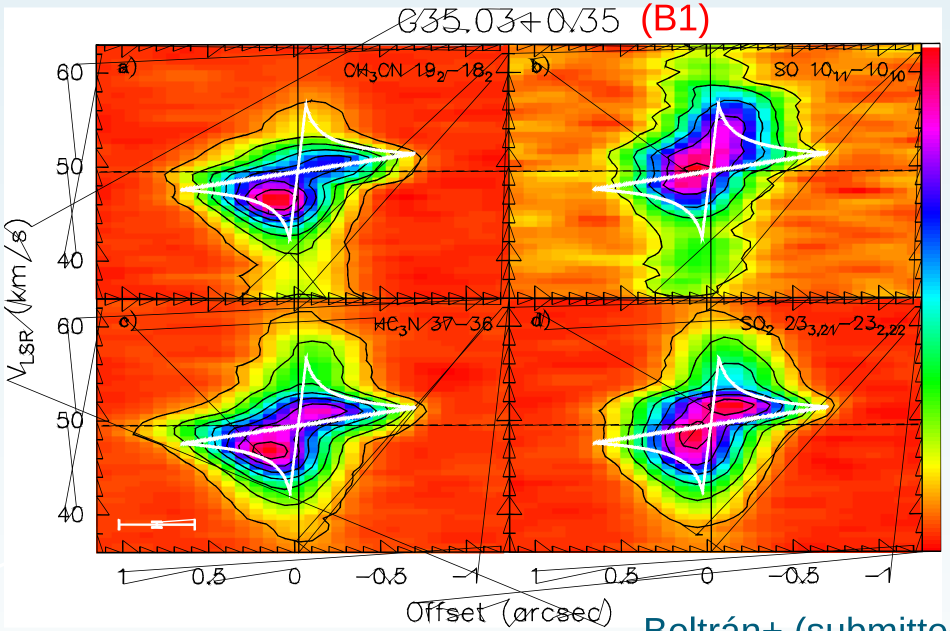
2. Disks: yes or not?

- low-mass disks
  - Mdisk < Mstar
  - Sizes ~ 100 AU
  - Keplerian rotation



Simon+ (2000)

- early B-type (late O-type) disks
  - Mdisk < Mstar
  - Sizes = a few 100 AUs
  - Keplerian rotation



Beltrán+ (submitted)

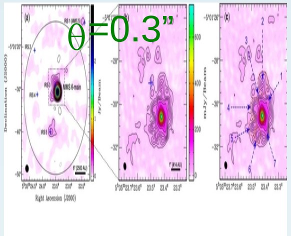
Keplerian rotation about a 9 $M_\odot$ star

2. Disks: yes or not?

- intermediate-mass disks

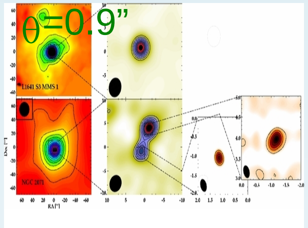
Source	Mstar (M⊙)	Mdisk (M⊙)	Radius (AU)
L1641 S3	> 3.5	< 3.9 (0.45)	< 300
NGC 2071 A	0.9	0.35	~200
NGC 2071 B	0.5	0.29	~200
MMS 6/OMC3	3 (?)	0.29	< 100

MMS 6/OMC3 (< 60 L⊙)



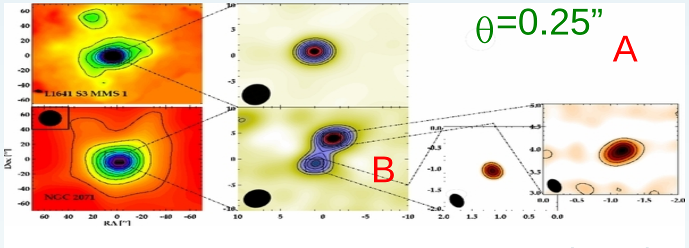
Takahashi+ (2012)

L1641 S3 MMS 1 (70 L⊙)



van Kempen+ (2012)

NGC 2071 (520 L⊙)

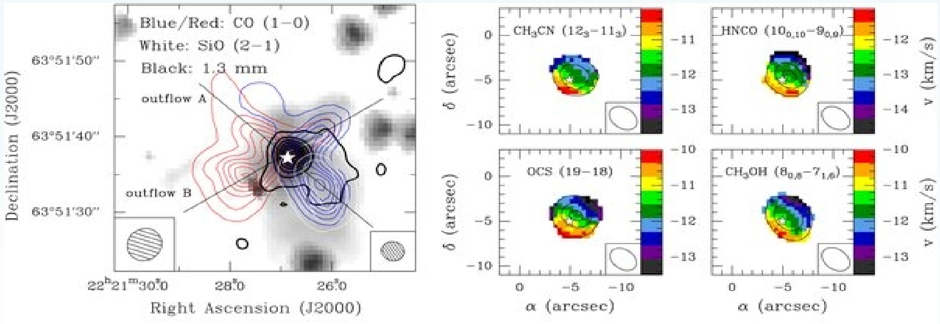


van Kempen+ (2012)

- Keplerian rotation ?

VLTI/AMBER

IRAS 22198+6336 (370 L⊙)



Sánchez-Monge+ (2010)

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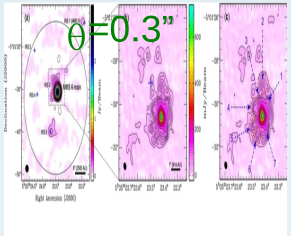
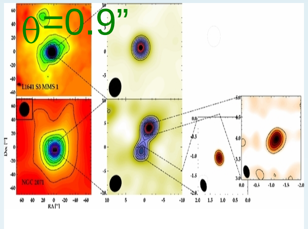


θ=0.3"

Takahashi+ (2012)

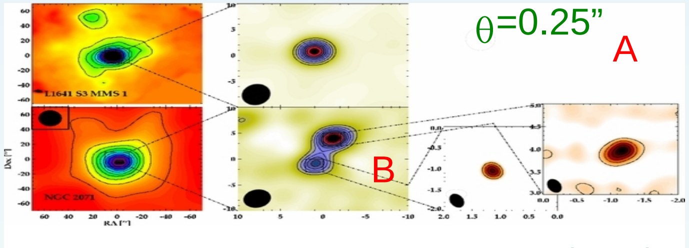
L1641 S3 MMS 1 (70 L⊙)



θ=0.9"

van Kempen+ (2012)

NGC 2071 (520 L⊙)

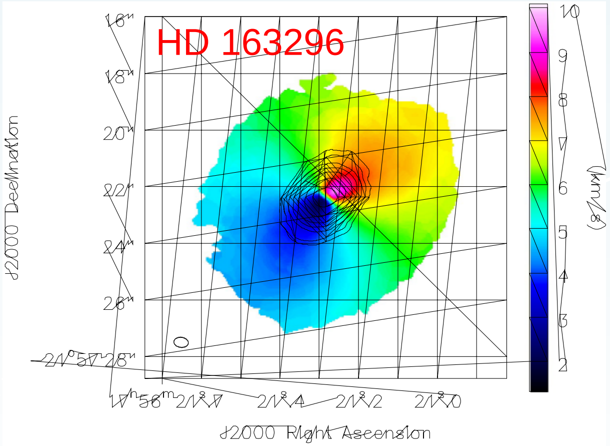


θ=0.25"

A

B

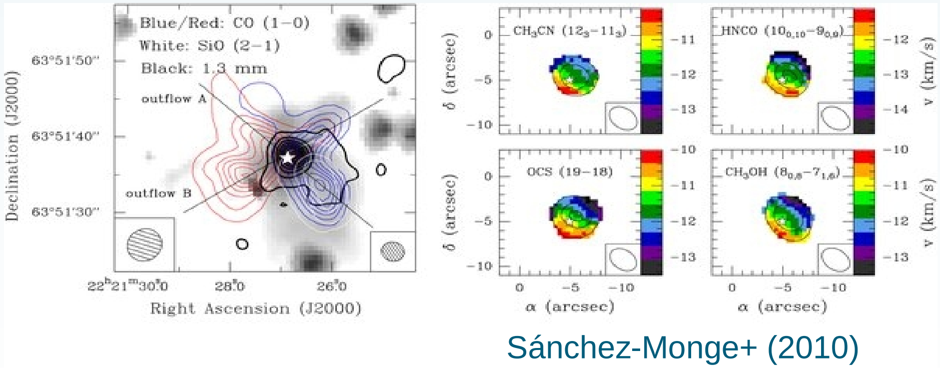
van Kempen+ (2012)



HD 163296

de Gregorio-Monsalvo+ (2013)

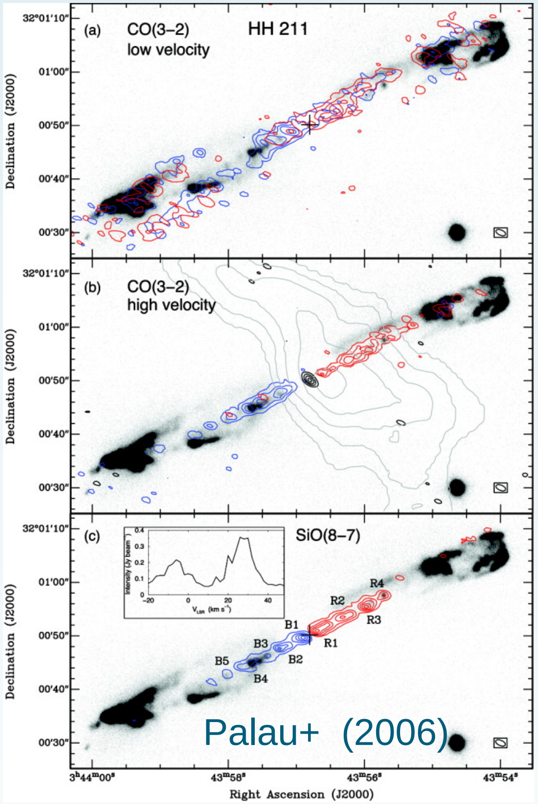
IRAS 22198+6336 (370 L⊙)



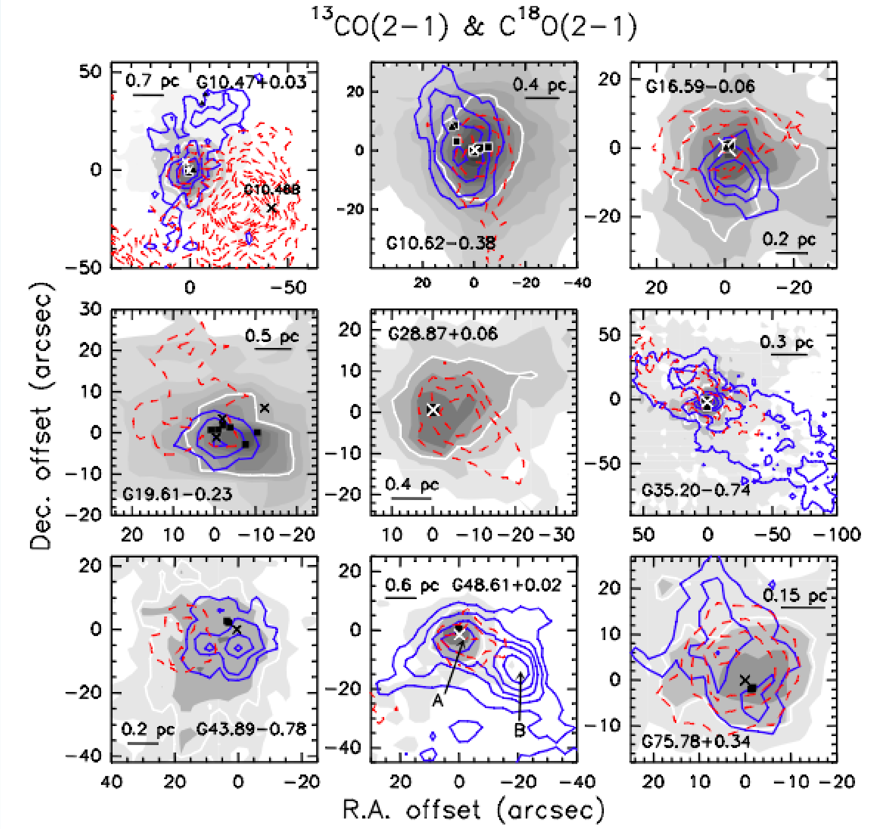
Sánchez-Monge+ (2010)

3. Outflows: ordered versus chaotic

- low-mass molecular outflows
- high-mass molecular outflows



Palau+ (2006)



López-Sepulcre+ (2009)

3. Outflows: ordered versus chaotic

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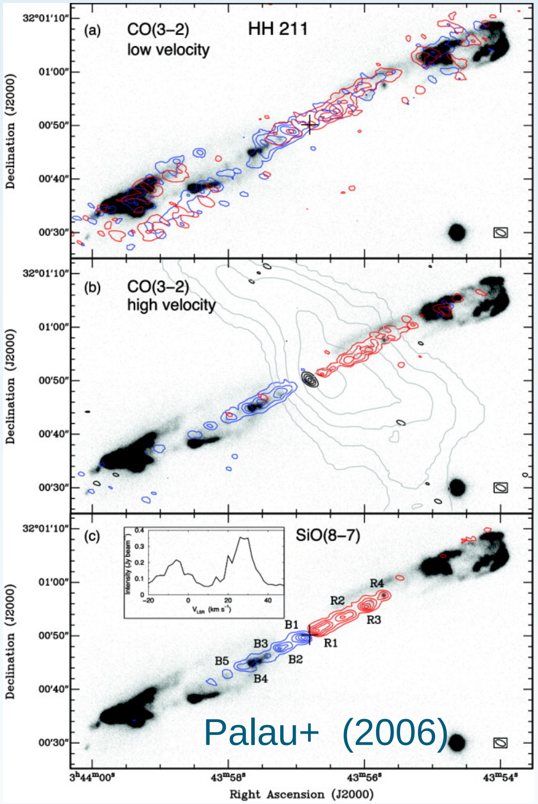
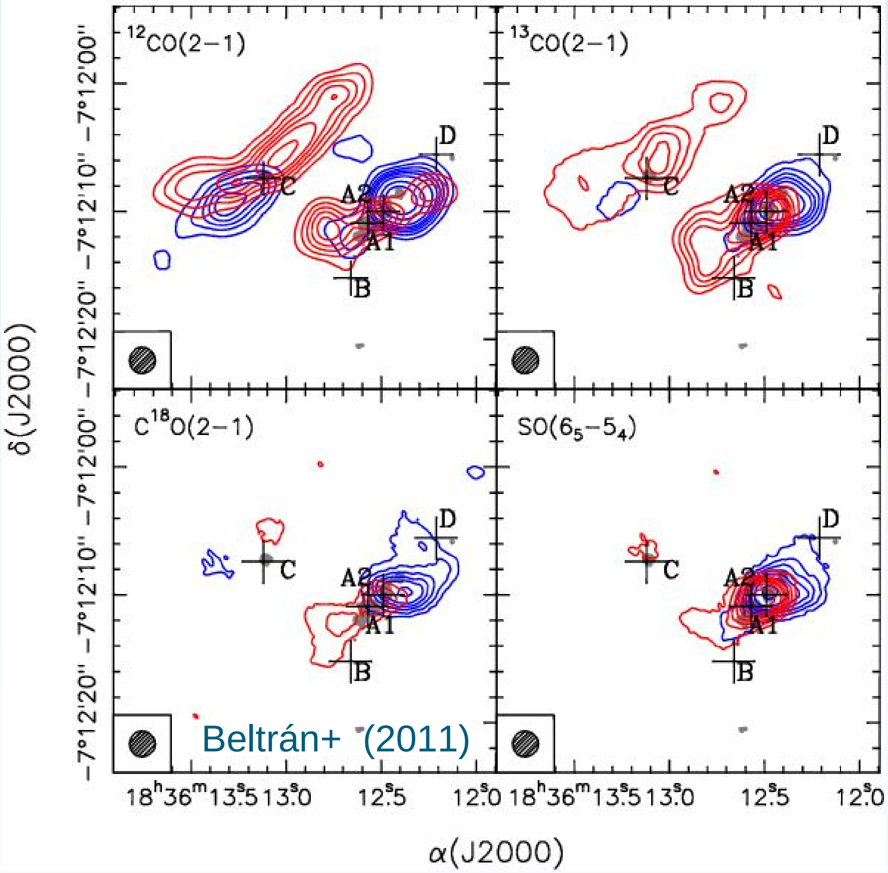


Palau+ (2006)

- distance = 0.315 kpc
- Angular resolution < 2” (< 650 AU)

- high-mass molecular outflows

G24.78+0.08 (O9.5 ▯ 20 M⊙)

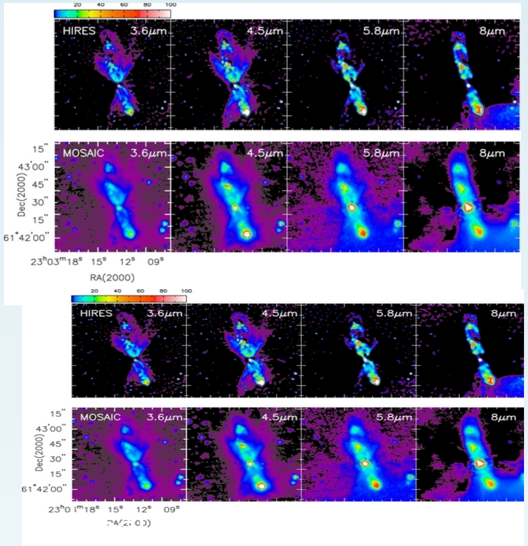


Beltrán+ (2011)

- distance = 7.7 kpc
- Angular resolution < 1” (< 8000 AU)

3. Outflows: ordered versus chaotic

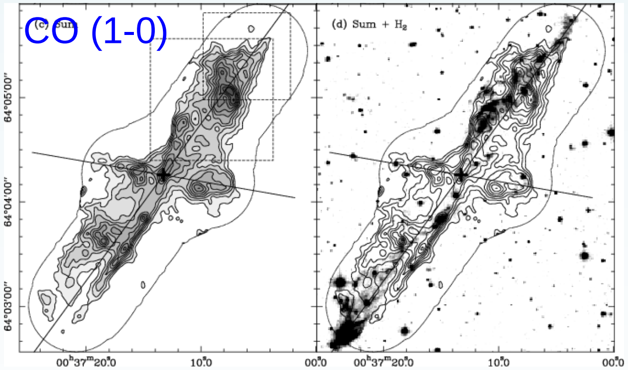
CepE-mm (Lbol= 80 $L_\odot$)



(2011)

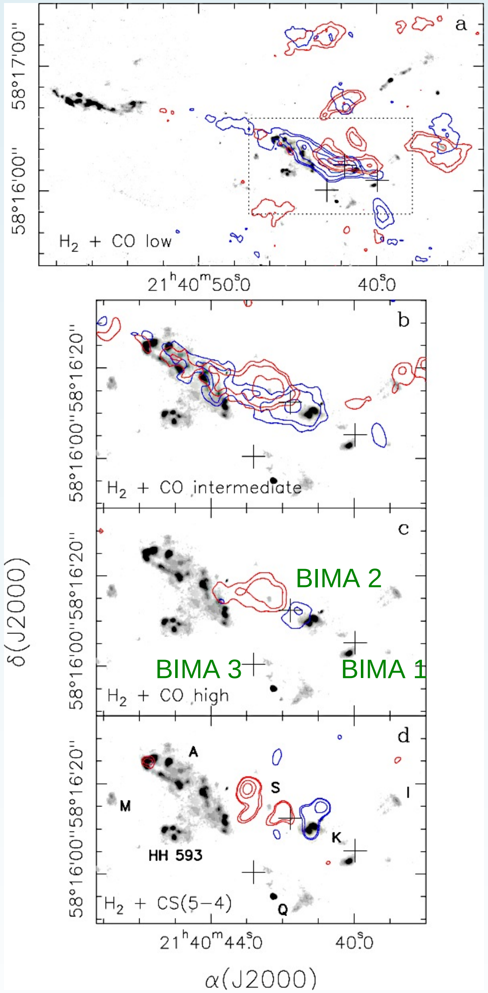
HH288 (Lbol= 500 $L_\odot$)

CO (1-0)



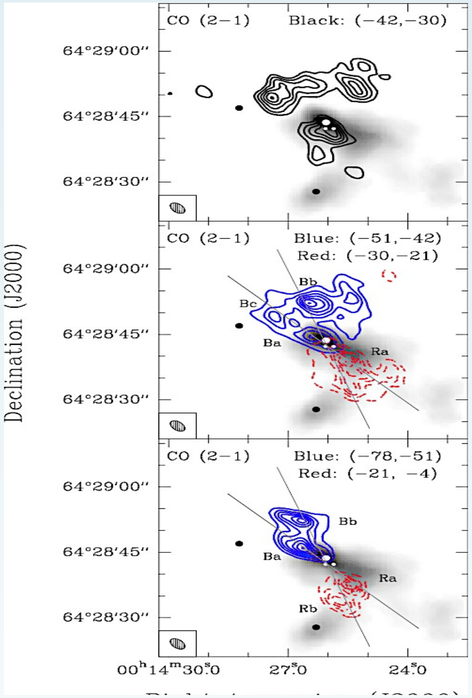
Gueth+ (2001)

IC1396N –BIMA2 (Lbol= 235 $L_\odot$)



Beltrán+ (2009)

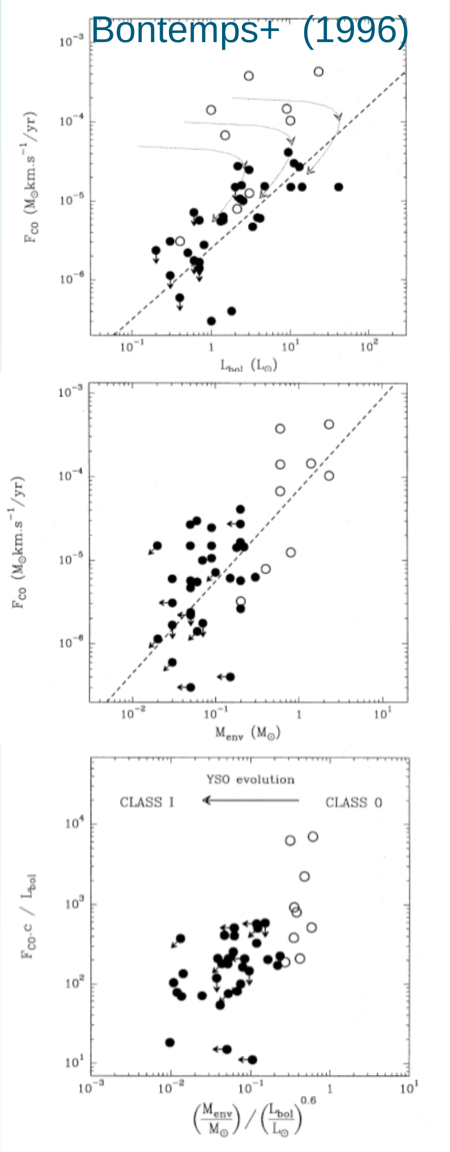
IRAS 00117+6412 (Lbol= 1400 $L_\odot$)



Palau+ (2010)

3. Outflows: properties

- Low-mass molecular outflows
  - well ordered and collimated outflows
  - outflow momentum flux is proportional to the bolometric luminosity of central object
  - outflow momentum flux is proportional to the circumstellar envelope mass
  - decline of outflow activity phase and decrease of mass accretion/infall rate with evolutionary phase accretion

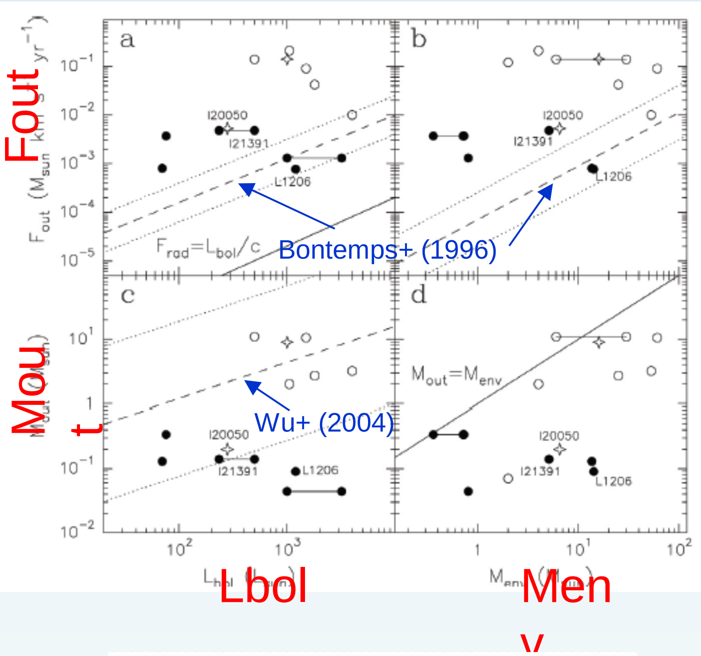


Bontemps+ (1996)

3. Outflows: properties

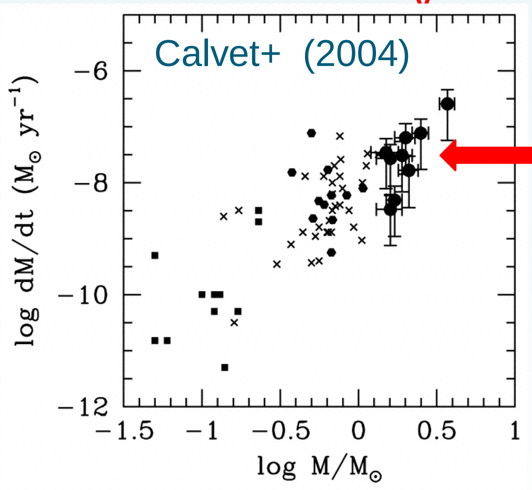
- Intermediate-mass molecular outflows
  - IMs YSOs have higher Fout than low-mass objects.
  - $F_{out} = f_{ent} \times (\dot{M}_w/\dot{M}_{acc}) \dot{V}_w \times M_{acc}$ (Bontemps+ 1996)
  - IMs have higher mass accretion rate, higher entrainment efficiency, or higher outflow driving engine efficiency
  - Calvet+ (2004) found that $\dot{M}_{acc}$ for IMTTs was 5 times higher that for low-mass CTTs
  - IMs accrete material faster. Consistent with dispersal time of circumstellar material < 105 yrs (Fuente+ 2001)

Beltrán+ (2008)



○ undetected λ < 8 μm

● detected λ < 8 μm

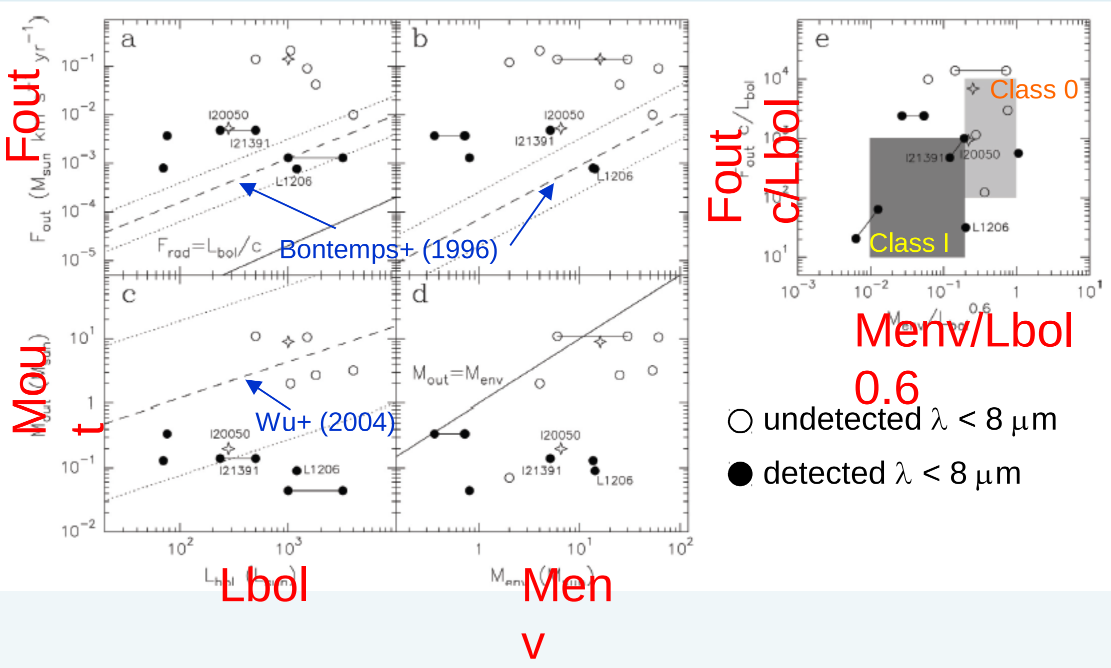


IMTTs

3. Outflows: properties

- Intermediate-mass molecular outflows
  - Fout and Mout is up to 2 orders of magnitude higher for YSOs not detected at $\lambda < 8\ \mu m$
  - More embedded sources are more efficient at driving their outflows, which are more powerful and massive
  - Undetected YSOs at at $\lambda < 8\ \mu m$ have higher outflow efficiency → decline in the outflow activity with evolutionary stage (Bontemps+ 1996)

Beltrán+ (2008)



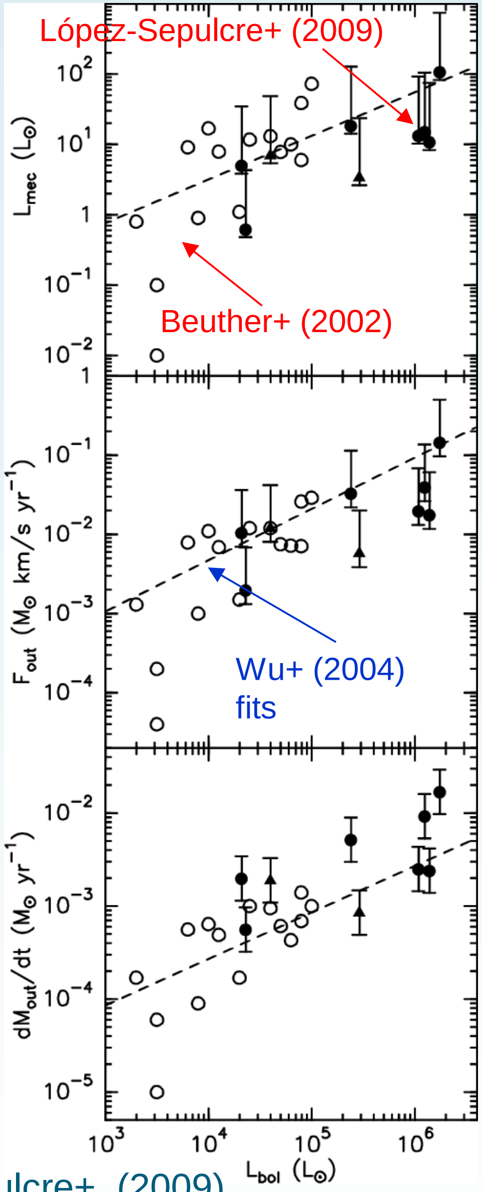
○ undetected $\lambda < 8\ \mu m$

● detected $\lambda < 8\ \mu m$

➡ IMs outflow properties similar to those of low-mass ones

3. Outflows: properties

- High-mass molecular outflows
  - Beuther+ (2002), Wu+ (2004), and López-Sepulcre+ (2009) show continuity in the correlation between mechanical luminosity, mechanical force, mass loss rate and bolometric luminosity from low-mass to high-mass
  - The luminosity of the powering source determines the outflow energetics, and the driving mechanisms are similar for all luminosities.


López-Sepulcre+ (2009)

Beuther+ (2002)

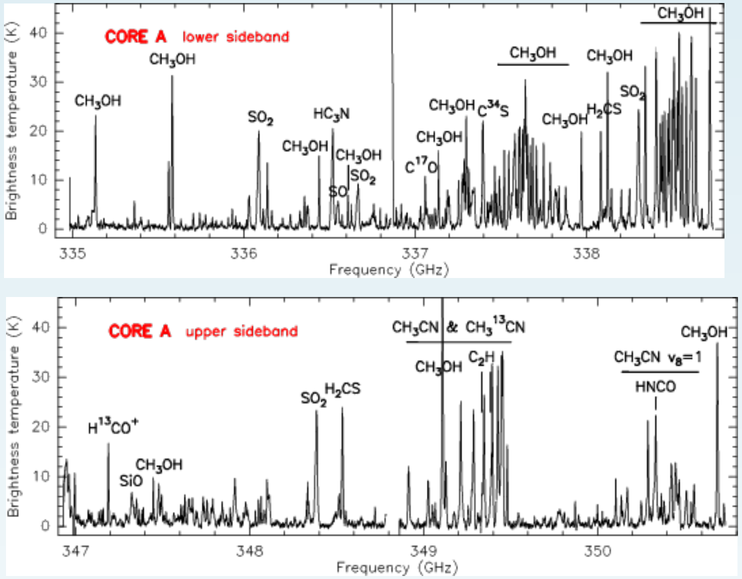
Wu+ (2004) fits

López-Sepulcre+ (2009)

4. Chemistry: rich or not?

- High-mass protostars
  - Hot molecular cores are the cradles of OB stars, with sizes < 0.1 pc (10,000 AU), T > 100 K and n~107 cm-3 present a very rich chemistry, especially of Complex Organic Molecules, due to the evaporation of dust grain mantles.
  - CH3CN, CH3OH, HNCO, HCOOCH3, CH2CO, C2H5CN, CH3OCHO, C2H5OH, D2CO with Eupper > 1500 K

G35.03+0.35 (B1)



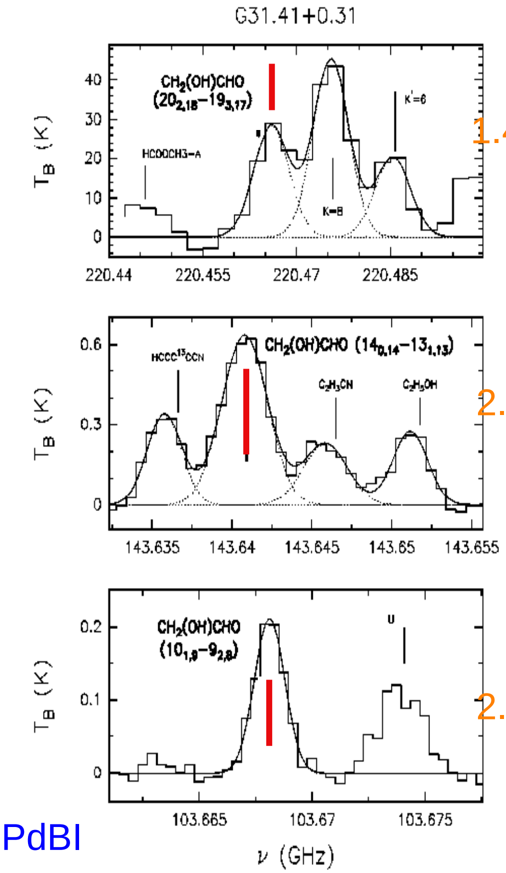
ALMA Cycle 0 - Band 7

Beltrán+ (submitted)

4. Chemistry: rich or not?

- High-mass protostars
  - Hot molecular cores are the cradles of OB stars, with sizes < 0.1 pc (10,000 AU), T > 100 K and n~107 cm-3 present a very rich chemistry, especially of Complex Organic Molecules, due to the evaporation of dust grain mantles.
  - CH3CN, CH3OH, HNCO, HCOOCH3, CH2CO, C2H5CN, CH3OCHO, C2H5OH, D2CO with Eupper > 1500 K
  - Prebiotic molecules: acetic acid (vinegar), formic acid, urea, interstellar antifreeze, acetone (the nail polish remover), ethyl formate (the chemical responsible for the flavor of berries), amino acetonitrile (direct precursor of glycine?), glycolaldehyde (simplest of monosaccharide sugars)

G31.41+0.31 (O5-O6)



1.4 mm

2.1 mm

2.9 mm

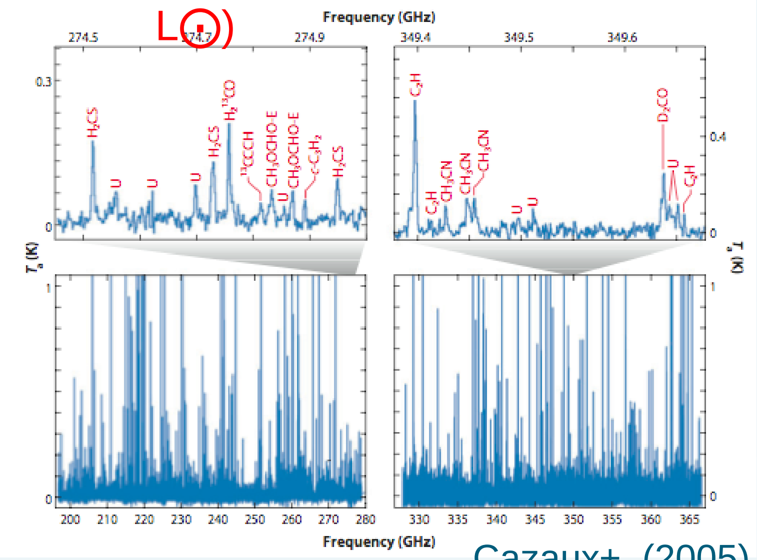
PdBI

Beltrán+ (2009)

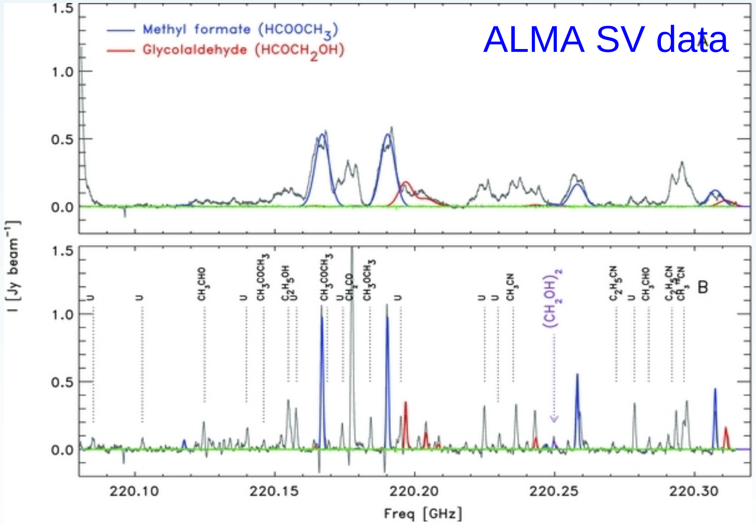
4. Chemistry: rich or not?

- Low-mass protostars
  - Organic molecules including CH3OH, CH3CN and CH3C2H have also been detected in the inner envelopes (≲150 AU) of low-mass deeply embedded Class 0 protostars called hot corinos
  - Hot corinos have T > 100 K and n>108 cm-3 and sizes < 150 AU
  - As with hot cores, COMs synthesized on grain surfaces during pre-stellar phase grain mantles sublimation by radiation released by gravitational energy
  - Prebiotic molecules: glycolaldehyde (simplest of monosaccharide sugars) towards IRAS 16293-2422 (Jørgensen+ 2012)
  - Hot corinos only found in a handful of sources (e.g. NGC 1333: Bottinelli+ 2004, 2007; Jørgensen+ 2005)

IRAS 16293-2422 (27 L☉)



Cazaux+ (2005)



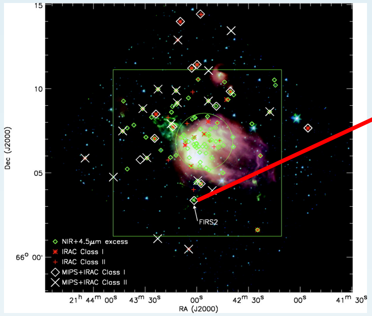
ALMA SV data

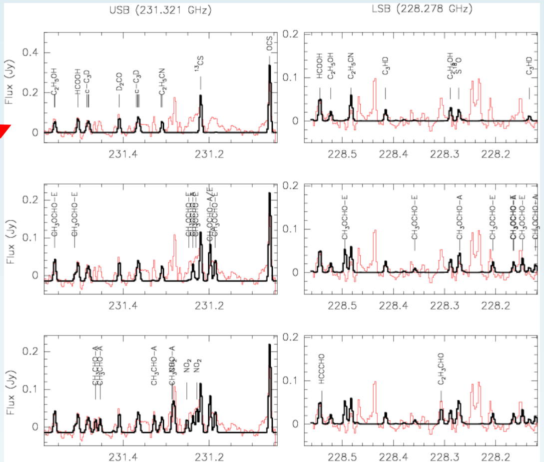
Jørgensen+ (2012)

4. Chemistry: rich or not?

- Intermediate-mass protostars

NGC 7129 FIRS2 (500 L⊙)

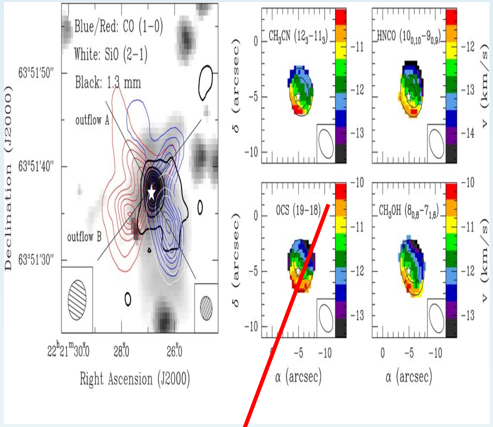


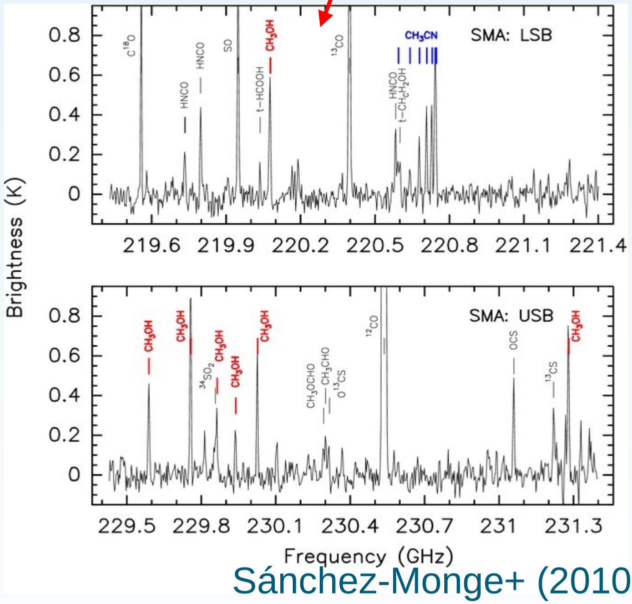


Fuente+ (2005)

- C2H3COH, HCOOH, CH3CHO, C2H5OH, CH3OCHO, C2H5CN, D2CO, CH3CN

IRAS 22198+6336 (370 L⊙)

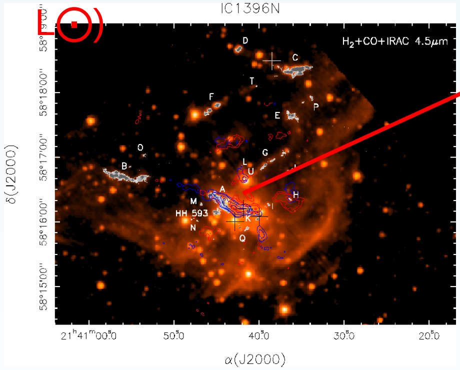


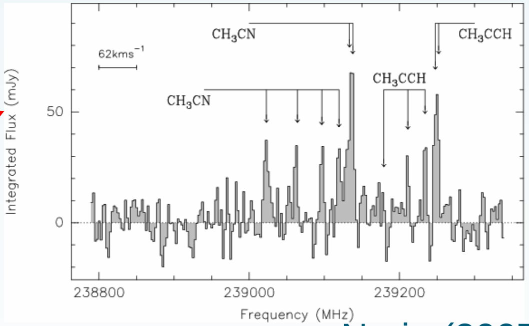


Sánchez-Monge+ (2010)

- CH3CN, CH3OH, HNCO, HCOOH

IC1396N - BIMA 2 (235 L⊙)



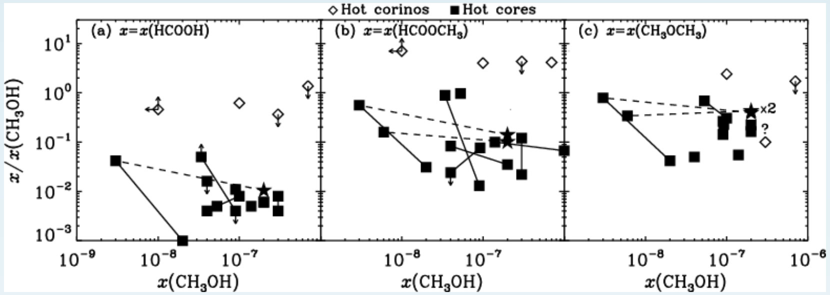


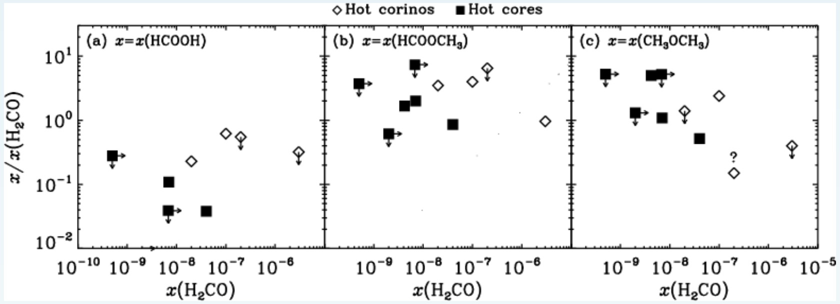
Neri+ (2007)

- CH3CN, CH3CCH

4. Chemistry: rich or not?

- Intermediate-mass protostars
  - IMs hot cores are less massive and smaller <1000 AU (e.g. OMC2-FIR4: Kama+ 2010) than HMs
  - CH3CN abundances ~10-9 (Fuente+ 2005; Sánchez-Monge+ 2010) similar to that found towards hot corinos and hot cores (Bottinelli+ 2004)
  - Bottinelli+ (2007) found abundance ratios with respect to CH3OH in hot cores lower than in hot corinos by 1-2 orders of magnitude and abundance ratios with respect to H2CO comparable (or relatively lower) for hot cores and hot corinos
  - ➡ Complex molecules in hot corinos are relatively more abundant than in hot cores. Possible differences in the grain mantle composition caused by different physical conditions (gas density and dust temperature) during the pre-stellar and accretion phase



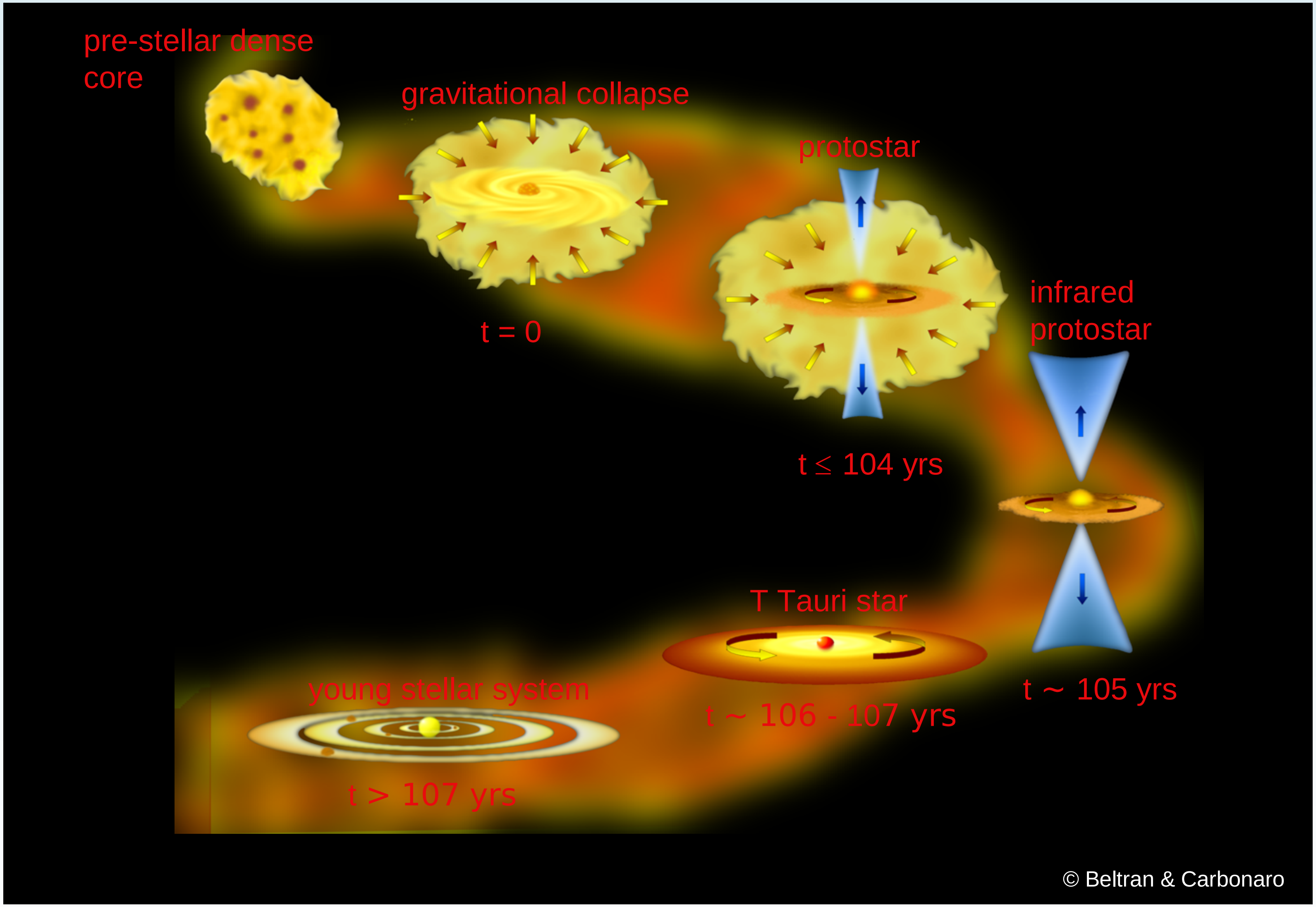


Bottinelli+ (2007)

Conclusions

- Intermediate-mass protostars represent in fact a bridge between low- and high-mass protostars
- IMs would share the formation mechanism with low-mass protostars, and likely with early B-type (late O-type) protostars
- IMs protostars mark the transition from low-density aggregates to rich clusters, and present different degrees of fragmentation
- IMs have circumstellar disks with properties similar to those of low-mass and early B-type prostostars
- IMs outflows are intrinsically more energetic but no more complex, are collimated even at low velocities, and have properties similar to those of low-mass (and high-mass) ones
- IMs have chemistry rich in complex molecules, similar to what observed in hot cores and hot corinos.

Low- or high-mass star-formation?



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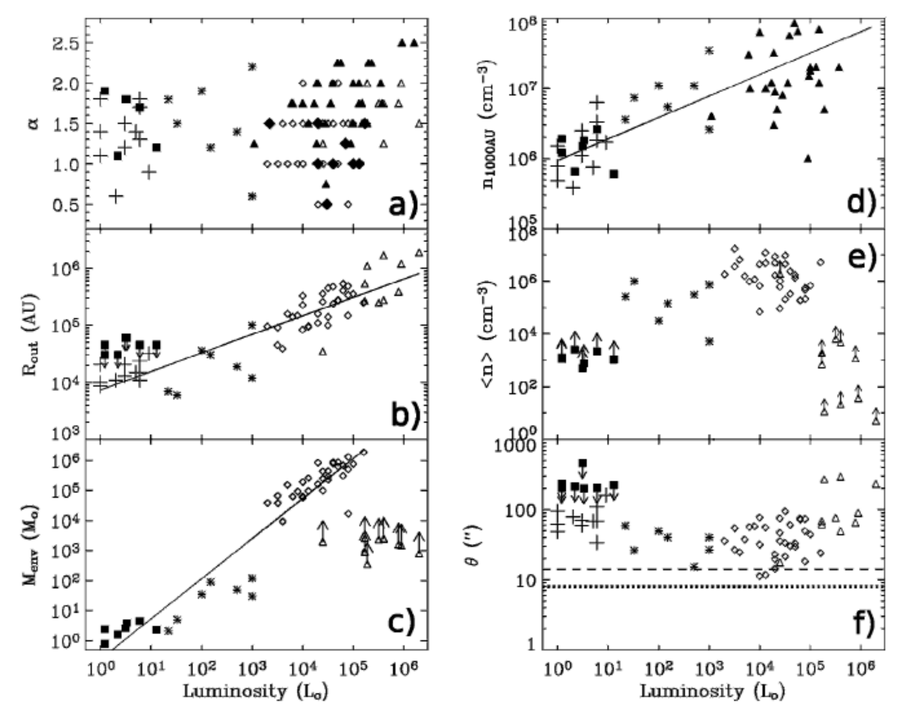
Low- or high-mass star formation?

- Crimier+ (2010) analyze the physical structure of IM envelopes with luminosities ranging from 30 to 1000 L⊙ by fitting the continuum brightness profiles with spherical, single index, power-law density models, with a power law that varies from 1.2 to 2.2
- Envelope radii range 6000 – 105 AU, and the masses range from 5 to 120 M⊙, and mass of central star between 0.1 and 6 M⊙
- There is a continuity in the parameters of the envelopes from low- to high-mass protostars
- IMs allow a bridge between low- and high-mass sources

➡ there are no important differences in the star-formation process between the two regimes

➡ 60% of the low- to high-mass protostars are consistent with the SIS inside out collapse model (Shu 1977) with similar power-law index : 1.5 ≲ α ≲ 2.0



Crimier+ (2010)

Results are based on single-dish observations, sensitive to the outer envelope (> 10")

Low- or high-mass star formation?

- Crimier+ (2010) analyze the physical structure of IM envelopes with luminosity ranging from 30 to 1000 L⊙
- Continuum brightness profiles can be reproduced by a spherical, single index, power-law density models, with a power law that varies from 1.2 to 2.2
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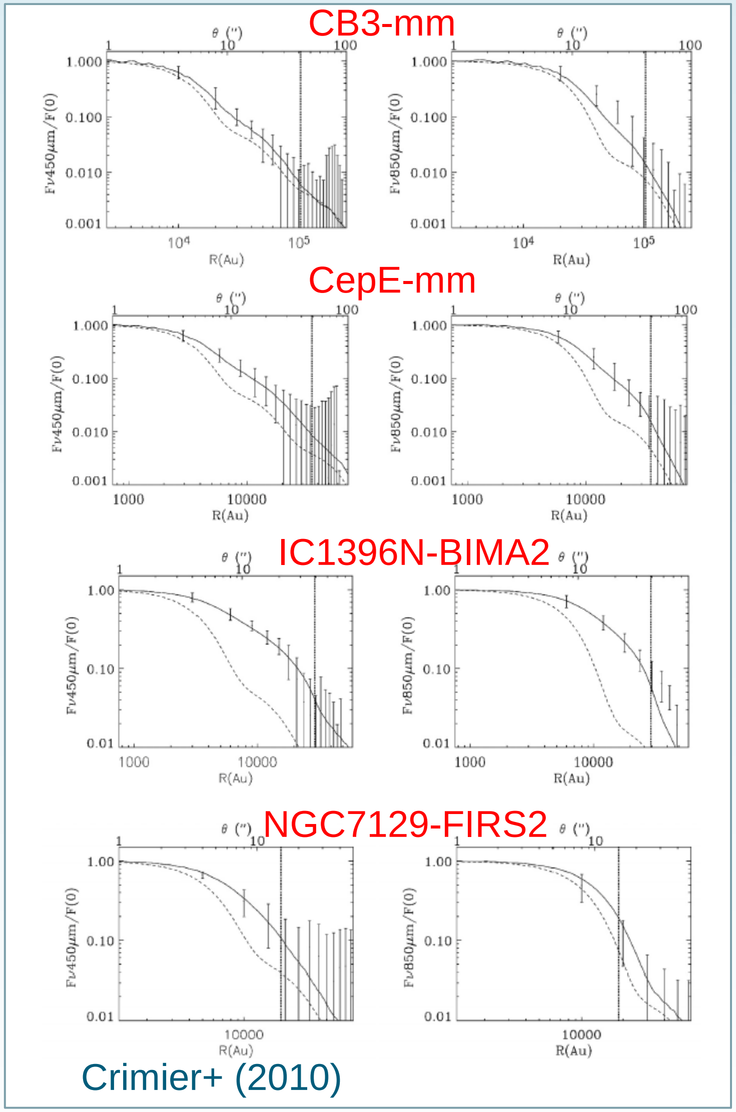


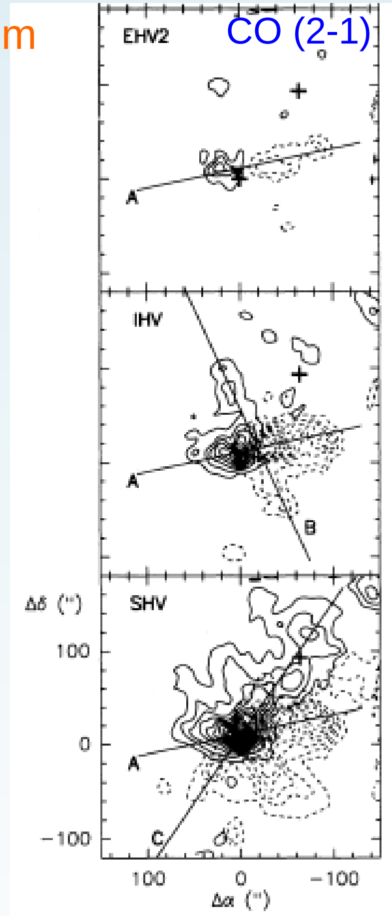
Crimier+ (2010)

3. Outflows: ordered versus chaotic

- IRAS 20050+2720 (Lbol= 280 $L_\odot$): distance 700 pc

IRAM 30-m

θ = 11”



Bachiller+ (1995)

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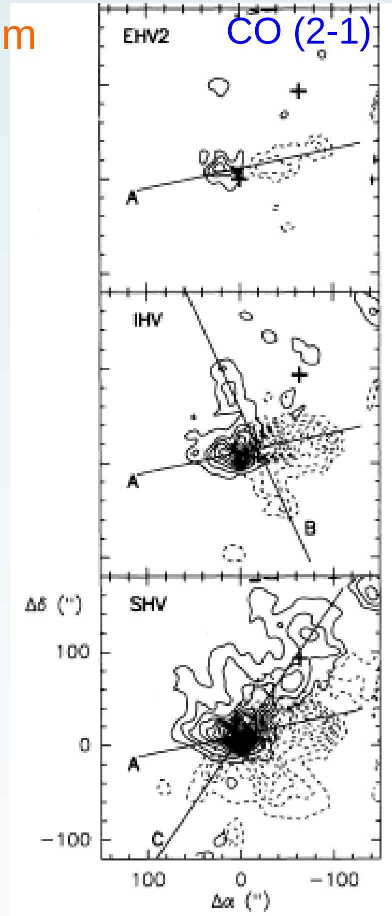
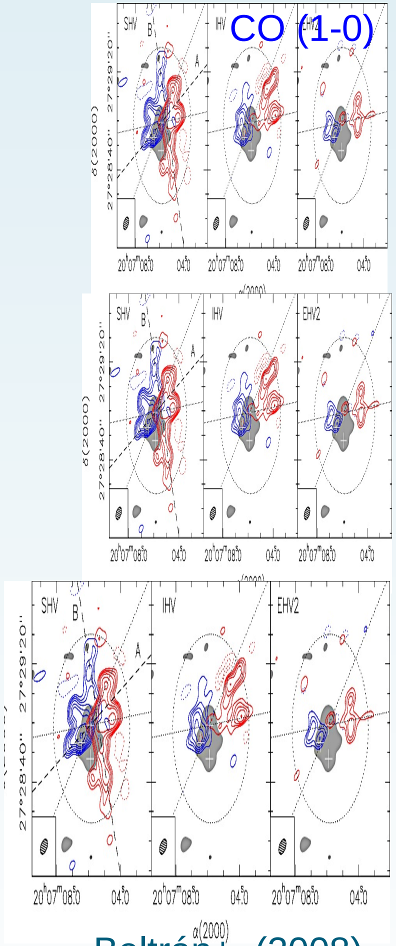


CO (2-1)

Bachiller+ (1995)

OVRO

θ = 4.3-6.7”



CO (1-0)

Beltrán+ (2008)

4. Chemistry: rich or not?

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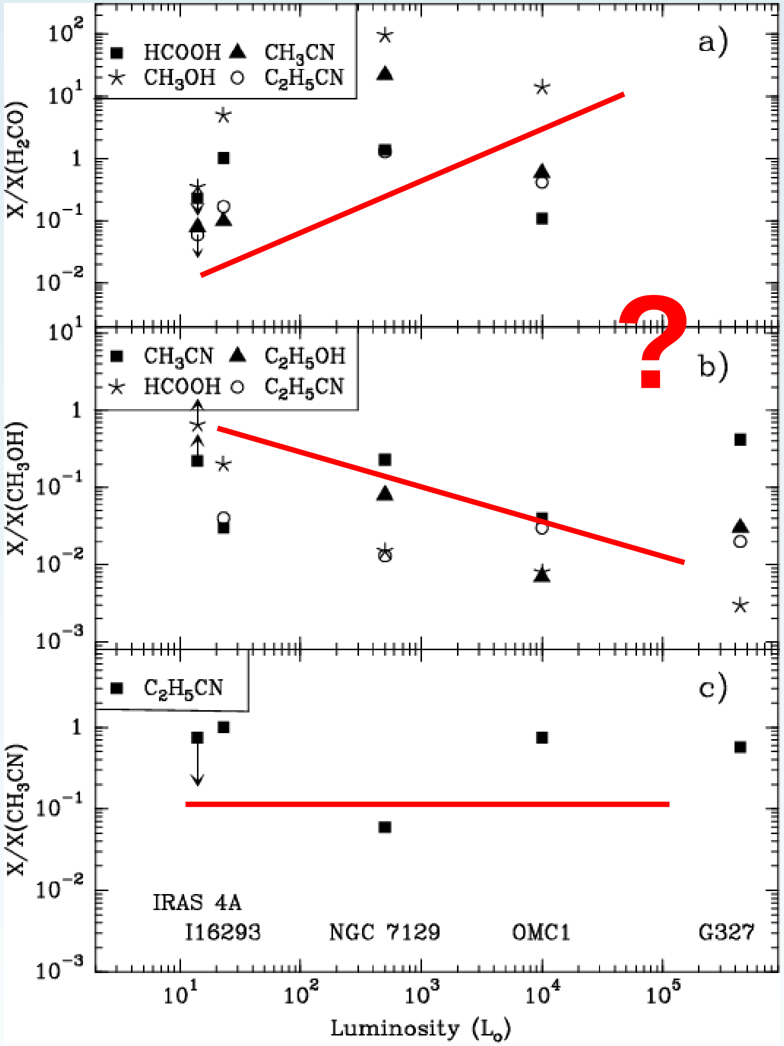
    - CH3CN abundances ~10-9 (Fuente+ 2005; Sánchez-Monge+ 2010) similar to that found towards hot corinos and hot cores (Bottinelli+ 2004)
    - Fuente+ (2005) found H2CO and HCOOH more abundant in low luminosity sources, while CH3OH more abundant in massive objects



Fuente+ (2005)