Physical and chemical characterization of Galactic Hot Molecular Cores with APEX telescope

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USP

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Outline

- High-mass star formation
- Hot molecular cores: search for candidates

  Identification of dense clumps

  Tools to identify sources in advanced stages of evolution

- Follow-up studies with APEX and ALMA

  G331 and G332

  Identification of good candidates for astrochemical studies

High-mass star formation

- How do massive stars (M > 8 Msun) form?

  1) Strong feedback: accretion vs. radiation pressure (e.g. Kahn 1974; Wolfire & Casinelli 1986)

  2) Large distances (~kpc) and short lifetimes (~ 10^5 yrs)

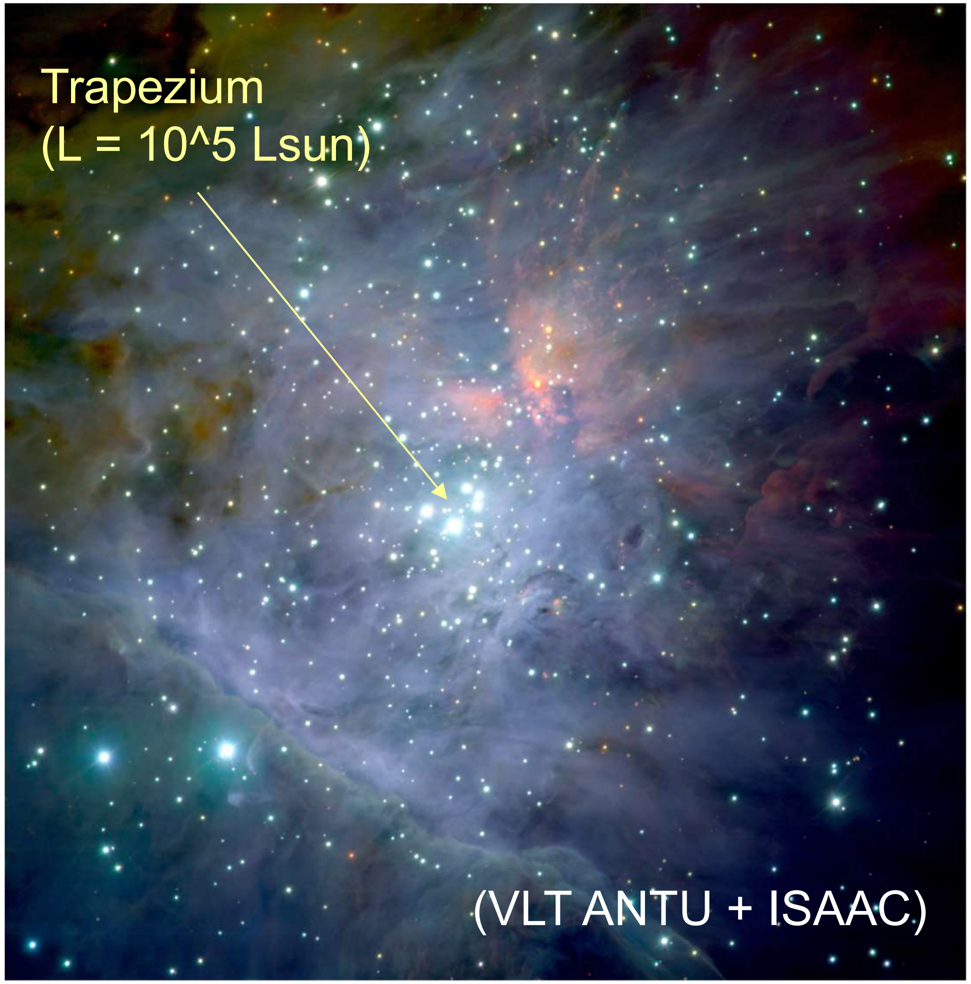
  3) Massive stars form in clusters, embedded in regions of high dust opacity

Proposed theories:

- Turbulent core (e.g., McKee & Tan 2003):
  - Scaled version of low-mass scheme

- Competitive accretion (e.g., Bonell+2001):
  - Stellar embryos of equal mass, gathering mass through Bondi-Hoyle accretion

Orion Nebula

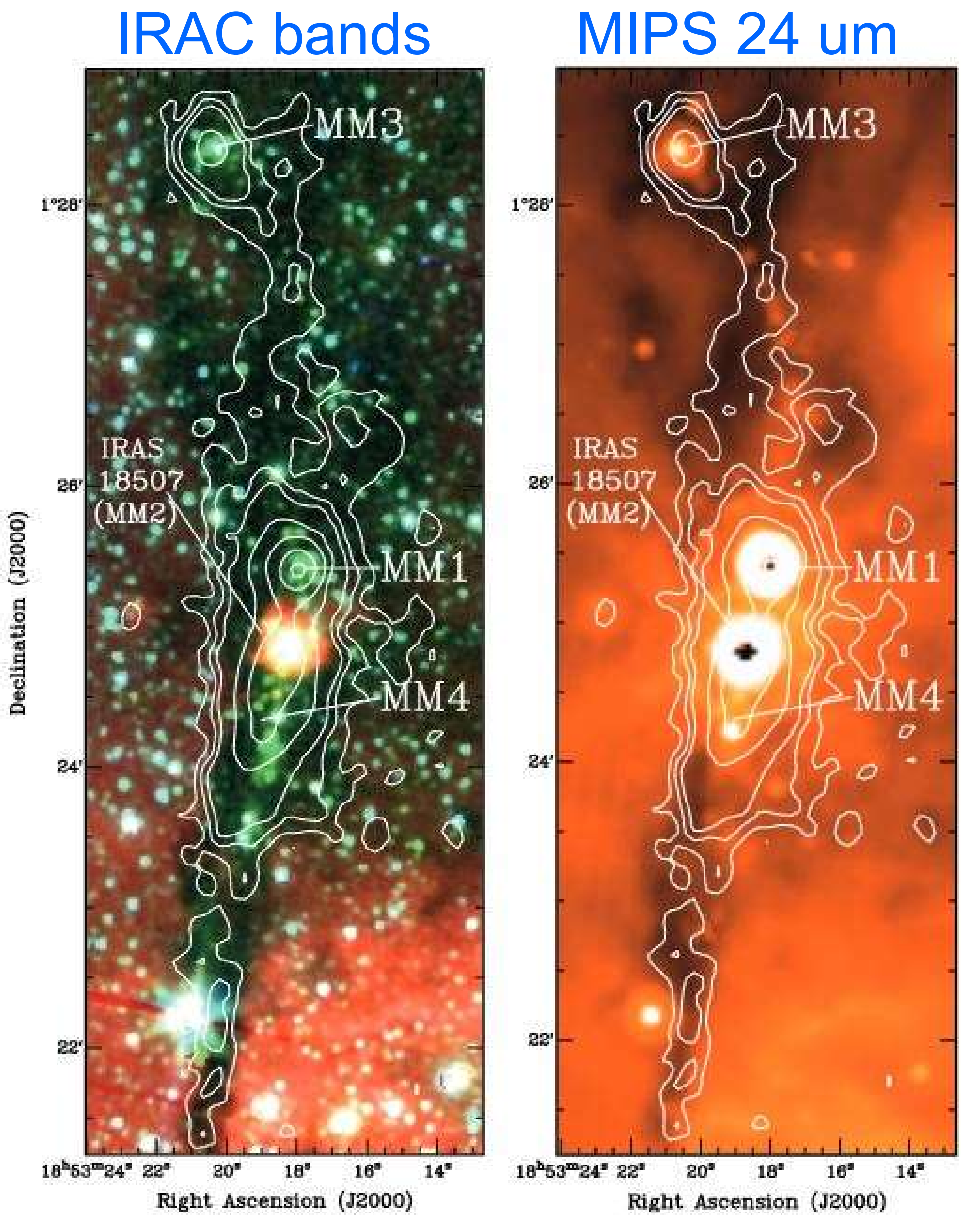


Credit: ESO/M.McCaughrean et al. (AIP)

Massive star forming regions

- High-mass stars form in clumps observed in mm continuum or molecular lines
- Properties (Bergin & Tafalla 2007):
  - Clumps:
  - Temp < 30 K
  - Surface densities ≥ 0.1 g cm^-2
  - Sizes of 0.1 - few pc
  - Cores:
  - Temp ~ 10 K
  - Sizes of 0.03 - 0.2 pc

Contour: 1.3 mm SIMBA



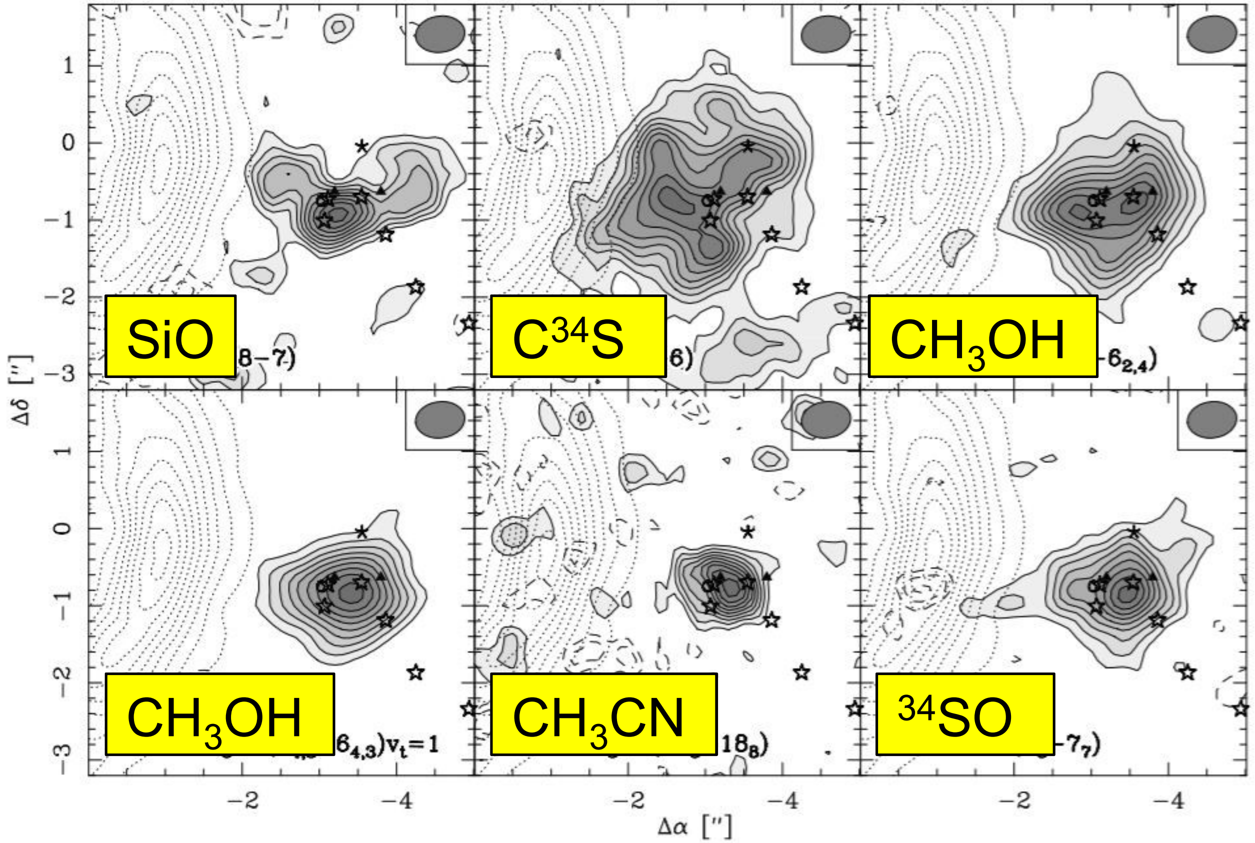
Rathborne+2005

Hot molecular cores

HMC G29.96, SMA observations

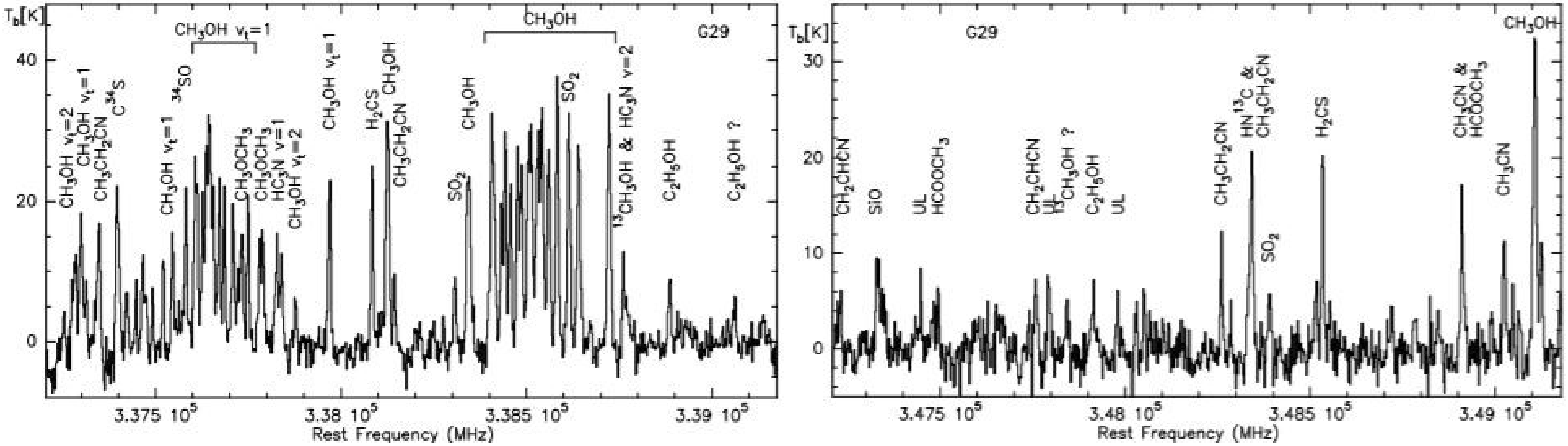
- Massive young star forming regions → produce HMCs
- Early evolutionary stage, protostar still actively accreting and prior to formation of UCHII regions (**)
- Gas temperatures > 100 K
- Rich chemistry in molecular line emission

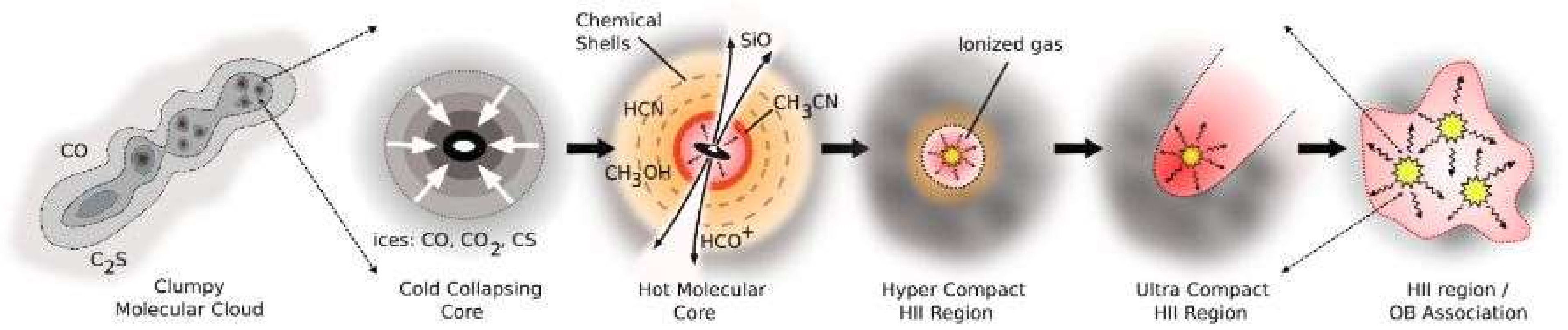
→ Complex Organic Molecules (COMs)



Beuther+2006

337.5 – 349.5 GHz





- Grain-surface chemistry (Bisshop+2007, Herbst & van Dishoeck+2009):

  First generation (T>100 K):

  H2CO, CH3OH, C2H5OH, HNCO, NH2CHO, CH3CN, C2H5CN, HCOOCH3, CH3OCH3

  Cold molecules (T<100 K):

  CH2CO, CH3CHO, HCOOH, CH3CCH

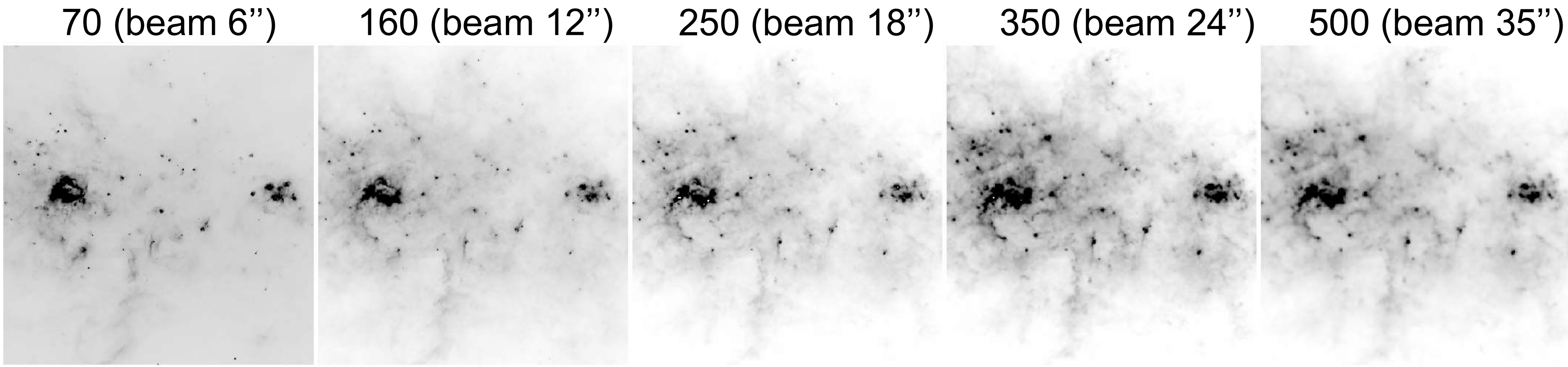
- Several well-studied HMCs in the northern sky (e.g., Kurtz+2000) with IRAM-30m, SMA, etc.
- Large COMs studied mostly in Sgr B2 HMC (see review of McGuire 2018): 8-12 atoms

- **Is it possible to obtain a sample of HMC candidates in the southern sky?**
  Can we find large COMs in regions outside the Galactic center?

What do we need?

- Sample of dense clumps (III – IV Galactic Quadrants)
- Determination of physical properties → Mass, luminosity
- Advanced evolutionary stages of massive star formation
- Molecular line observations at sub-mm wavelengths

Hi-GAL:
The Herschel infrared Galactic Plane Survey



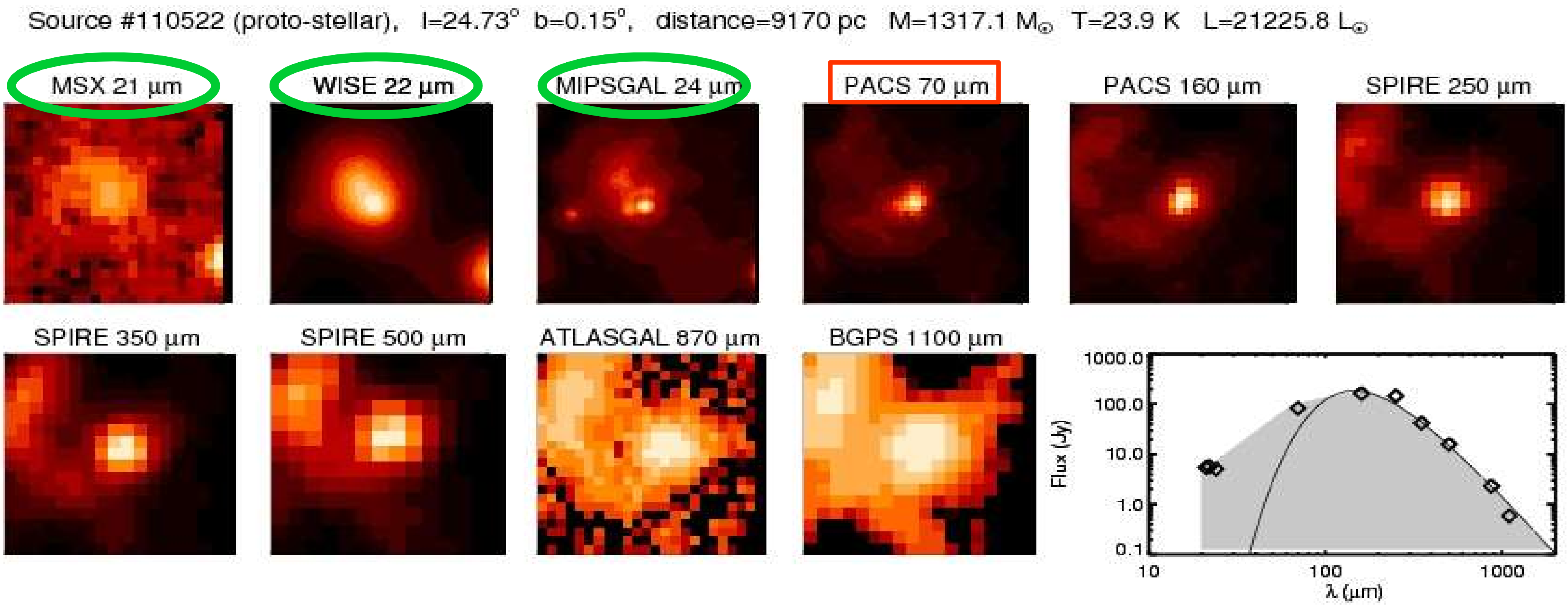
Simultaneous 5-bands (*70-160-250-350-500 μm*) continuum mapping of 720 sq. deg. of the Galactic Plane (|*b*|≤1°)

The entire Plane has been observed. Images access (with registered astrometry and absolute flux calibration) and compact source catalogues for longitudes between 65° and 290° (Molinari+16, Elia+17). Survey completed for the outer-Galaxy.

→ **Nearly 150000 clumps across the Galactic plane**

Proto-stellar sources

Mid-IR



- Properties: T(dust), surface density
  If distance available: Mass, Luminosity
- Distance estimation using line emission
  (Kinematic distances)

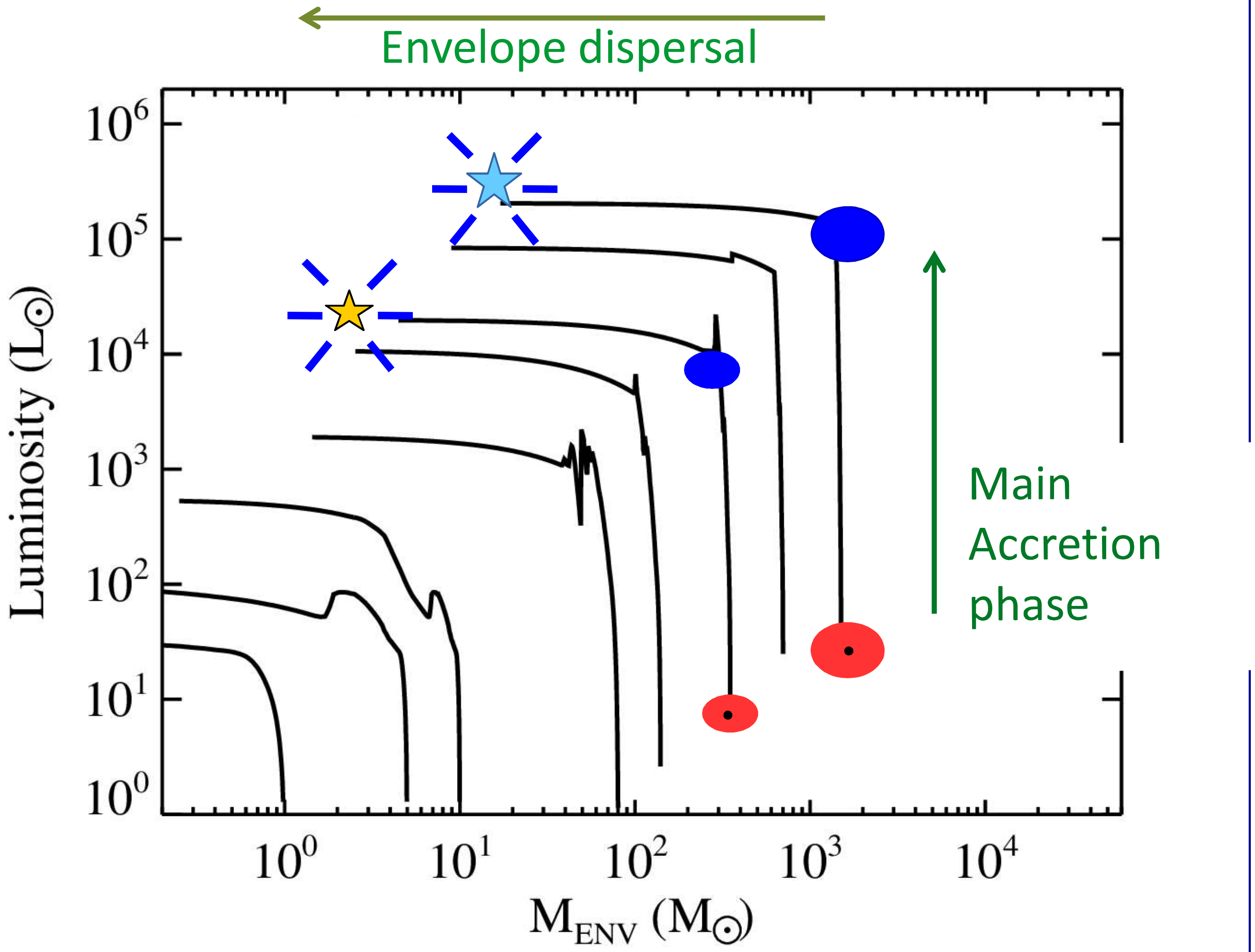
Elia+ 2017

Clump evolution: tools

- **Luminosity – envelope mass diagram:**
  Ratio between the bolometric luminosity and clump mass
  (e.g. Molinari+2008)

High-mass protostellar tracks following models of turbulence collapse (McKee & Tan 2003)

Low-mass protostellar sources: Saraceno+1996



Clump evolution: tools

- **Luminosity – envelope mass diagram:**
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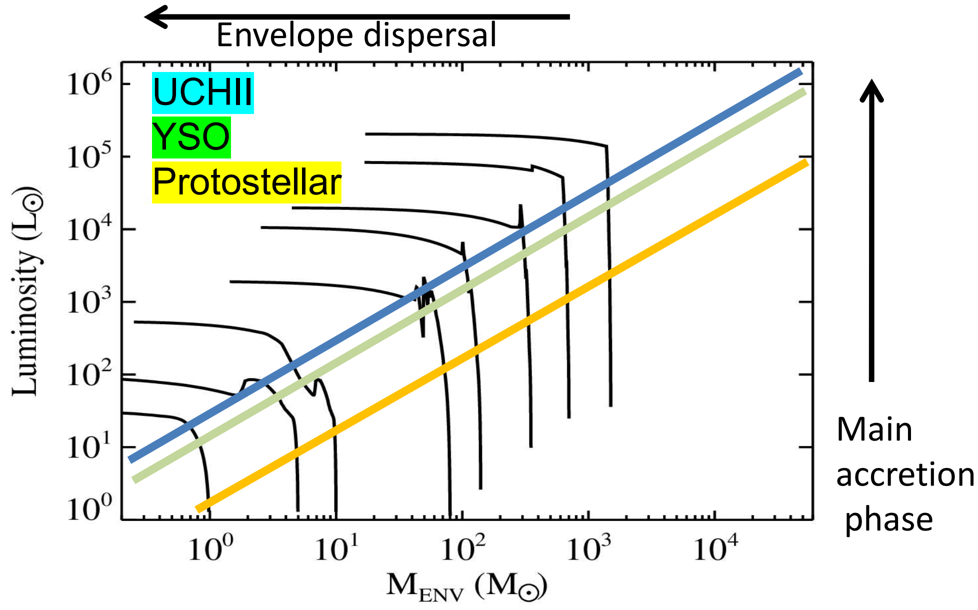


- **Defining sequence in L-M diagram**
  Sample of ~1000 Hi-Gal clumps associated to NH3 emission (Merello+2019)
  Protostellar L/M~1
  YSO L/M~10
  UCHII L/M~30

- **Time-scale of clumps:**
  Mclump = 700 Msun → UCHII stage reached in ~ 10^5 yrs

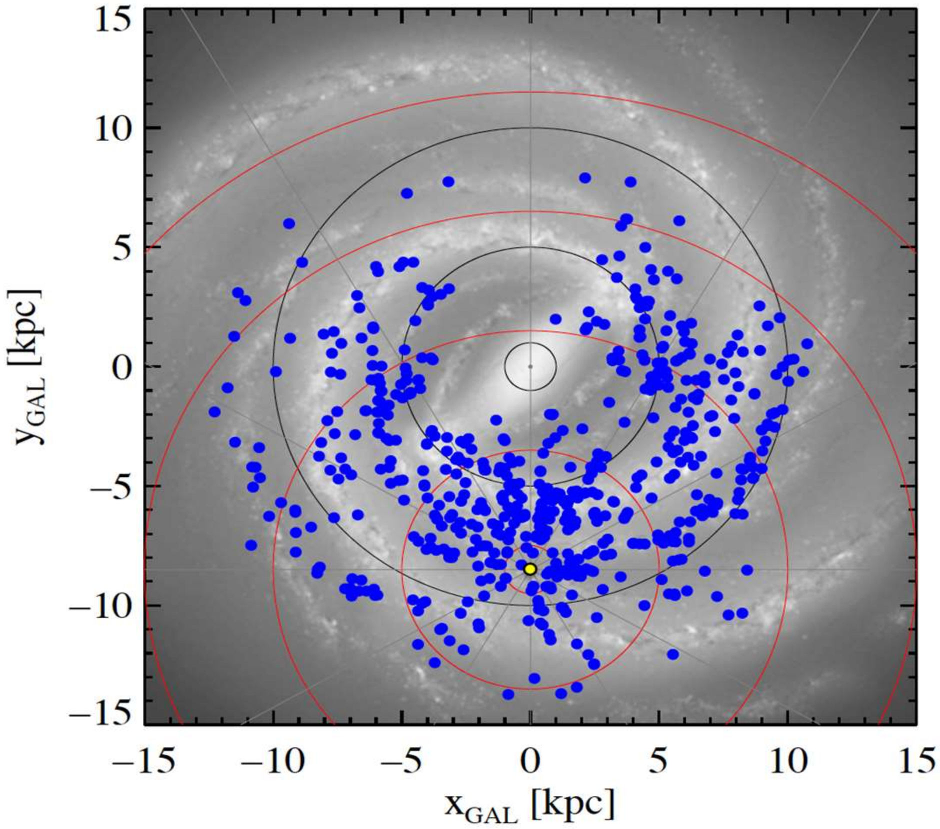
- In agreement with chemical models of several species (Gerner+2014):
  SiO, CH3CN, CH3OH, SiO, OCS, …

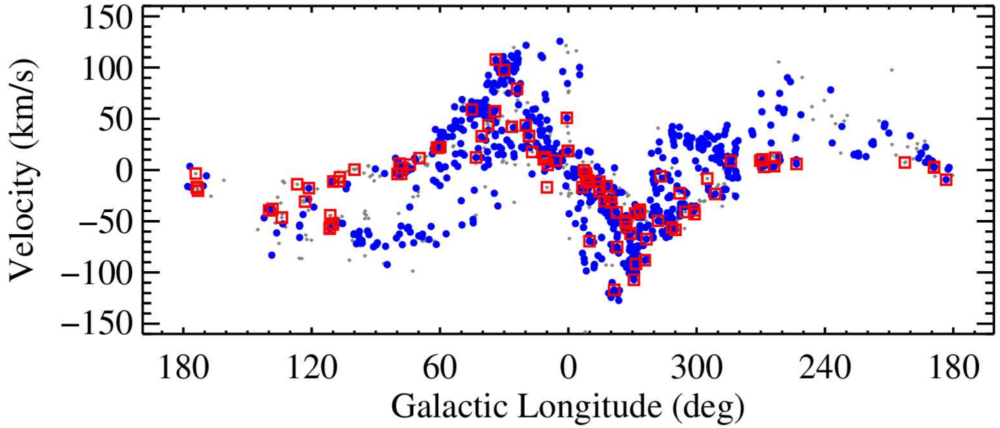
HMC candidates: Hi-GAL clumps associated with CS observations.

- CS(2-1) data from Bronfman et al. (1996,2018)
- IRAS point sources with colors characteristics of UCHII regions (Wood & Churchwell 1989)

874 CS observations, associated with ~1000 dust clumps from catalogue (Merello+, in prep)

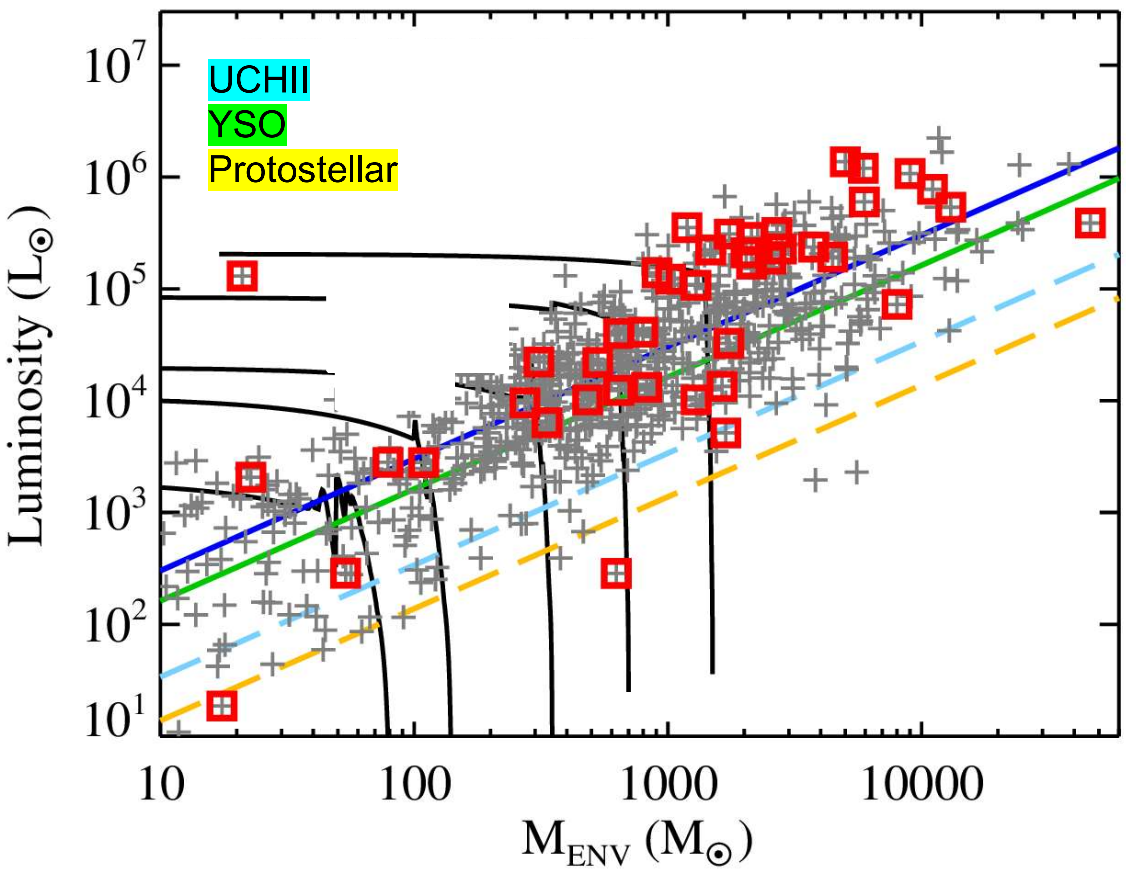
- The L/M parameter works as an independent diagnostic of the evolutionary stage of clumps.





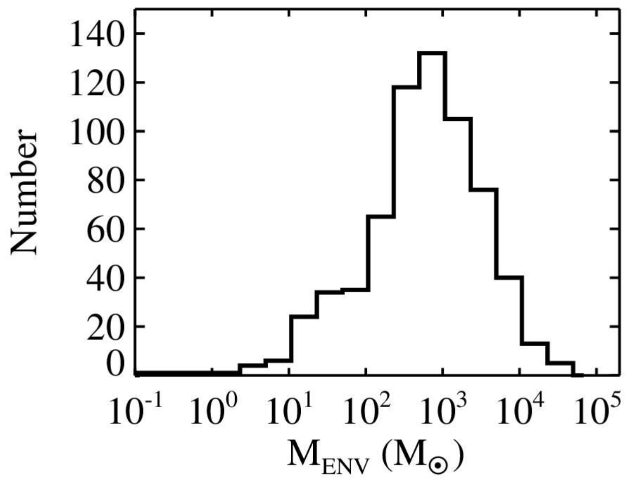
- Reliable sample: **661** clumps with CS detections.
- **277** clumps (43%) in the UCHII region stage with M>100 Msun
- **114** clumps in YSO stage, M>100 Msun

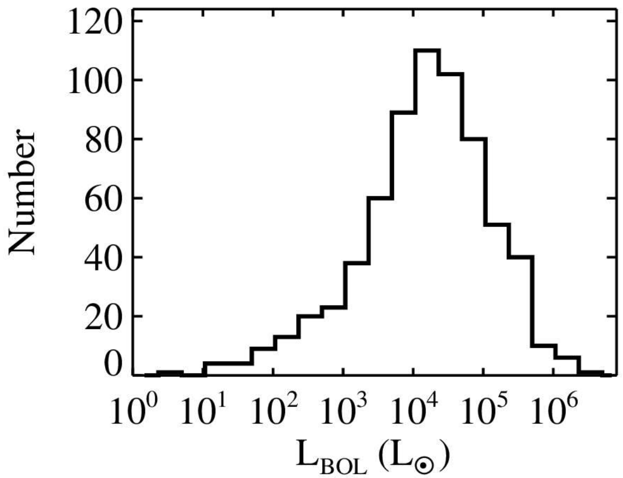
(Merello+, in prep)

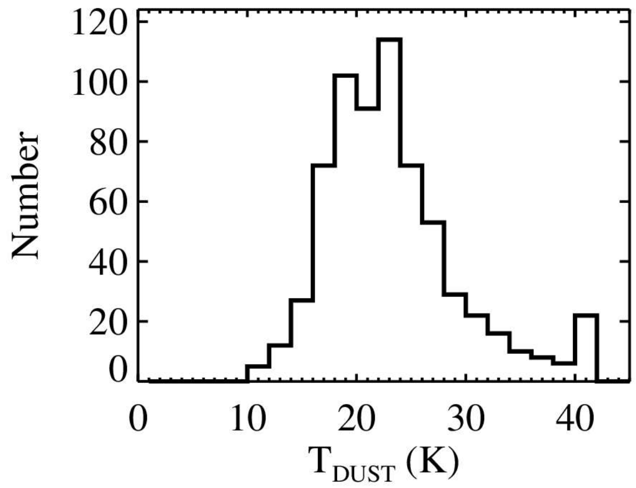


- From Hi-GAL sources in the UCHII region locus:

T_{DUST} ~ 26 K (β = 2.0)
M ~ 830 M_{SUN}
L = 5.4 10^4 L_{SUN}
Σ ~ 0.9 g cm^{-2}







Follow-up studies: mm line emission

LLAMA:
- 12 m antenna
- Alto Chorrillos, Argentina
- 4820 m. altitude
- Intially Band 5 (163-211 GHz) and Band 9 (602-720 GHz)

APEX:
- 12 m antenna
- Llano Chajnantor, Chile
- 5100 m. altitude
- Observations in
- Band 5 (163-211 GHz)
- Band 6 (211-275 GHz)
- Band 7 (275-373 GHz)

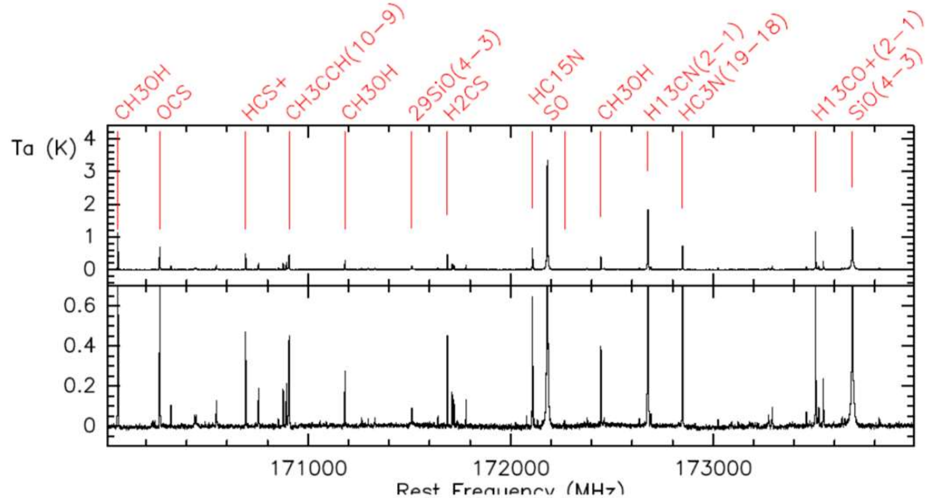
APEX observations:

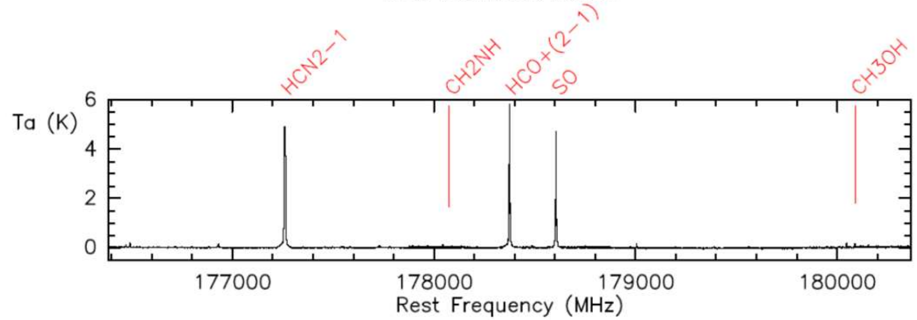
1. Study of two energetic sources:
   G331
   G332

2. 46 Candidates at a distance <6 kpc:
14 sources outer Galaxy, 32 inner Galaxy
With 7 Additional known HMCs:
18032-2137
13079-6218
15278-5620
16562-3959
17258-3637
17233-3606
16547-4247

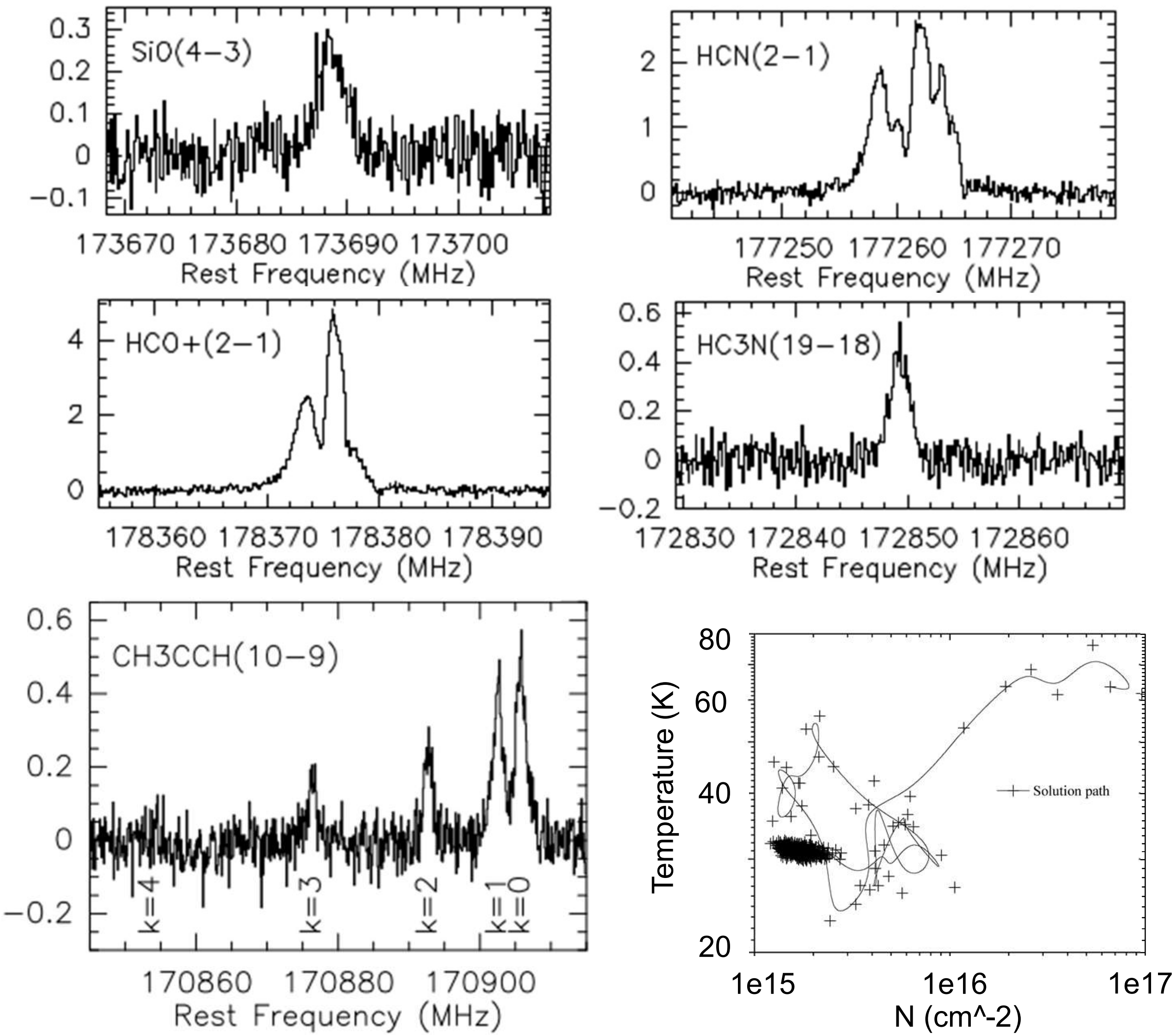
- SEPIA B5 (170-174, 177.4-180.4 GHz)
- Diagnostic of temperature (CH3CCH), shocked gas (SiO) and dense gas
- Tracers of hot cores (HC3N)

Species	SEPIA B5 Transition	Frequencies
$HC^{18}O^+$	J=2-1	170.3227
CH_3CCH	J=10-9,K=0	170.9056
$H^{13}CN$	J=2-1	172.6778
HC_3N	J=19-18	172.8493
$H^{13}CO^+$	J=2-1	173.5067
SiO	J=4-3	173.6883
HCN	J=2-1	177.2612
HCO^+	J=2-1	178.3750



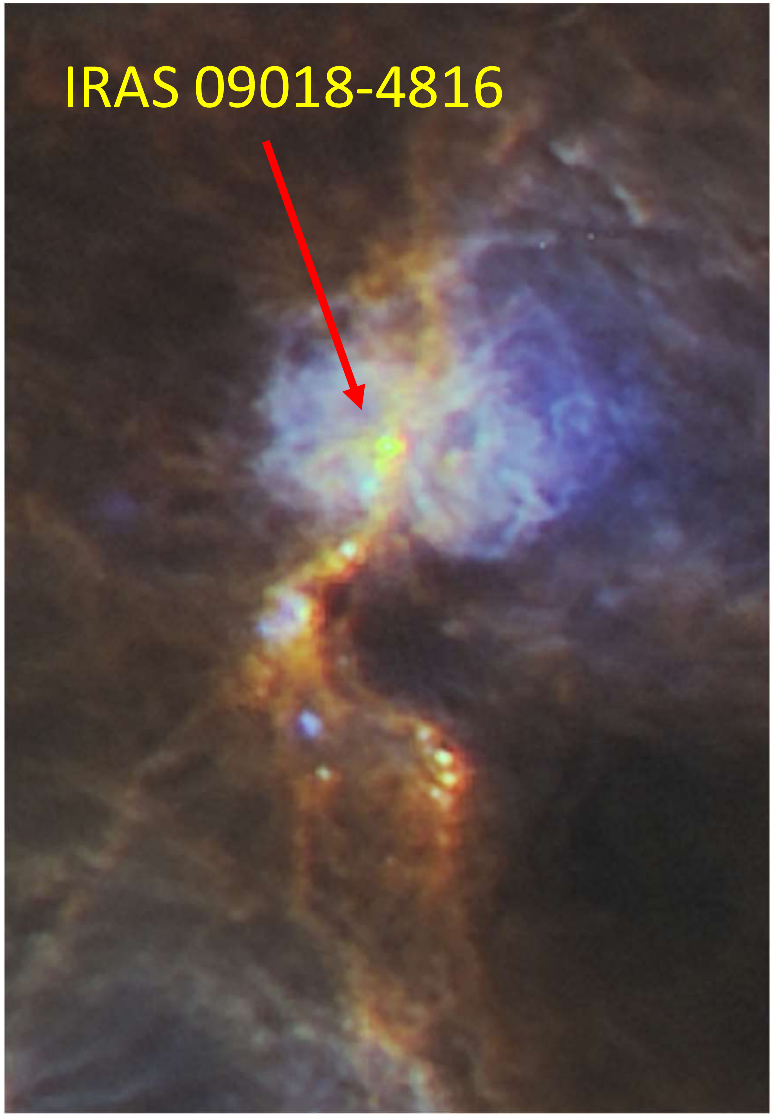


Band 5



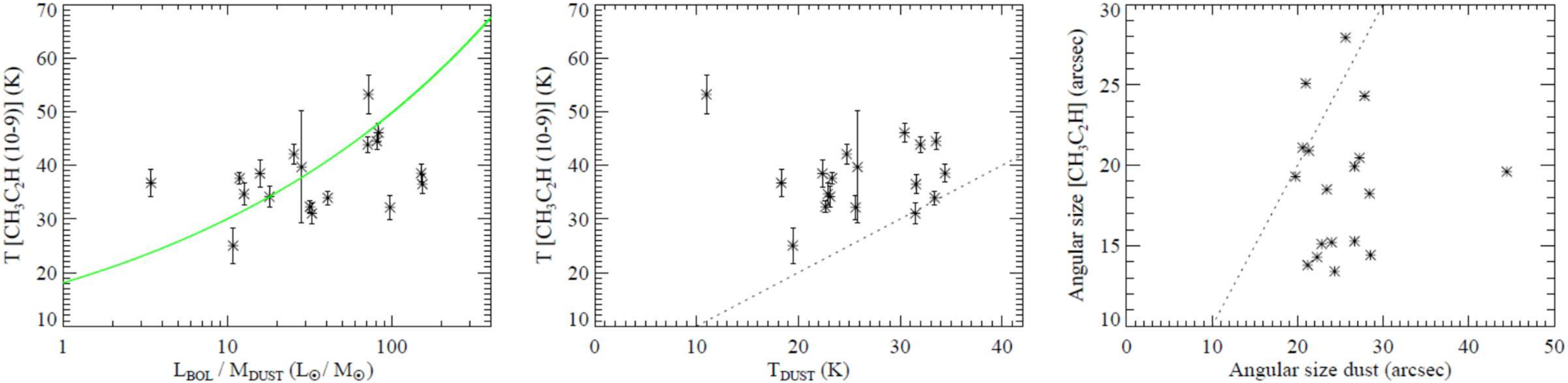
- MCMC fit of the CH3CCH line:
- Tex = 31.12 (0.58) K
- Nmol = 1.7047 (0.28) e+15 cm^-2
- Size = 10.76 (0.71) arcsec

L/M=18



Preliminary results (Merello, Bronfman, Mendoza, Lépine+, in prep)

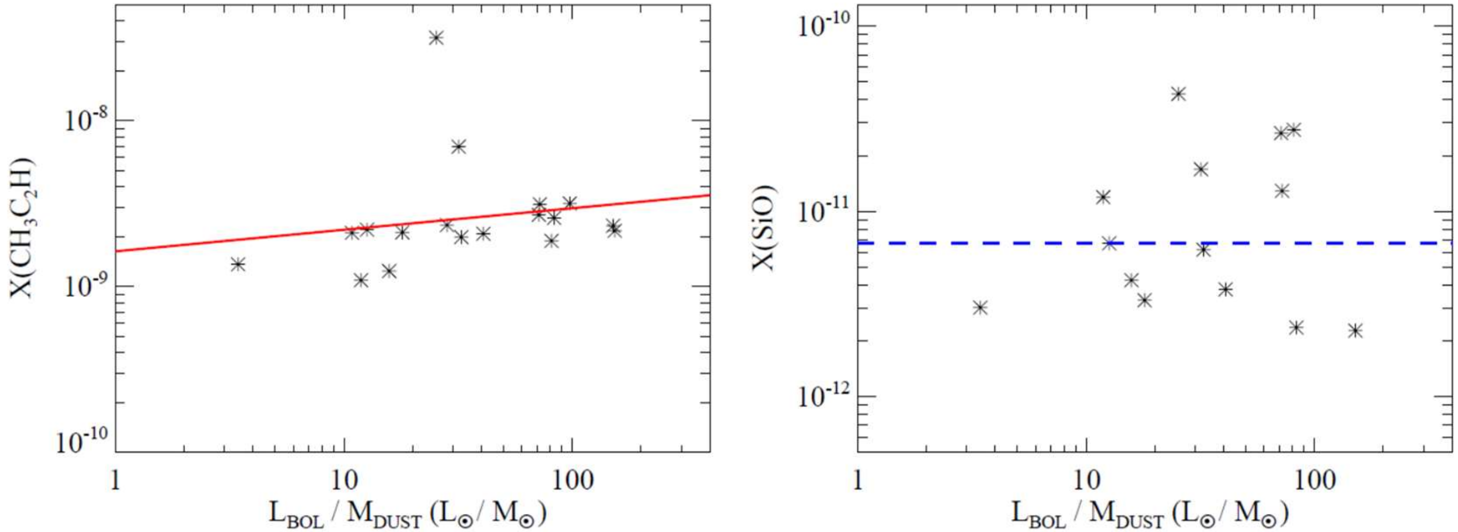
CH3CCH line and MCMC fit



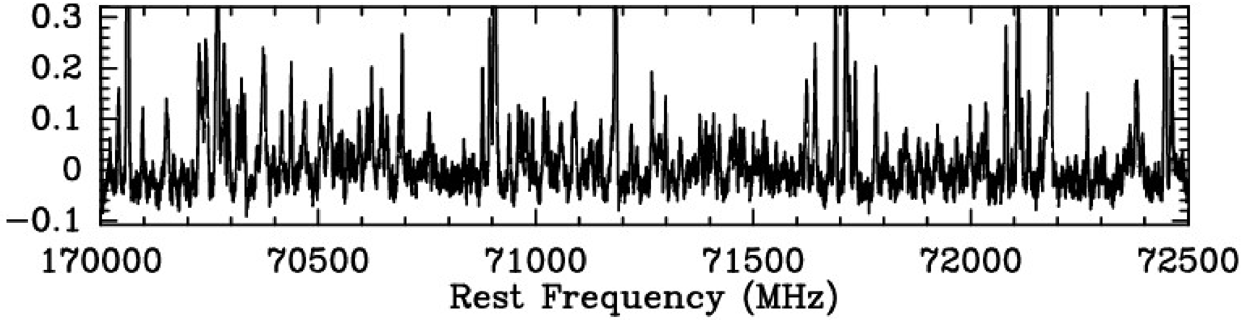
Fractional abundances

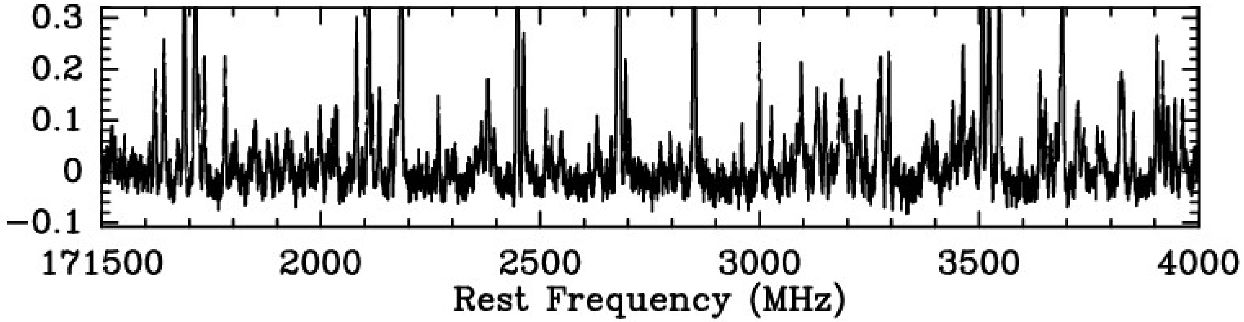
X(CH3CCH)

X(SiO)



HMC candidate 04: 18056-1952





- Discovery of several new sources with rich spectra:
  - e.g. 18056-1952, 16272-4837
- Detection of NH2CHO in new sources:
  - 1 known HMCs
  - 3 HMC candidates

Chemisty of HMC candidates

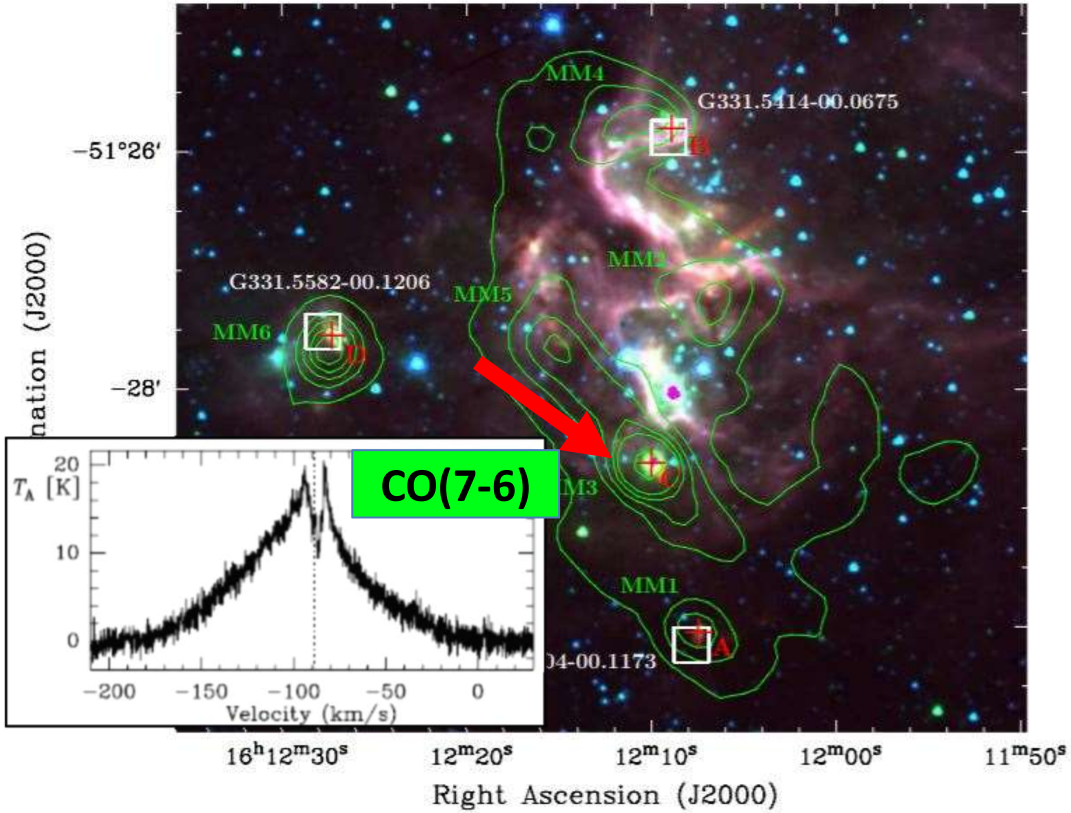
(1) G331

- Source G331.512-0.103 in Norma spiral arm tangent (dist= 7.5 kpc)
- M=5.6E3 Msun, L=7E5 Lsun

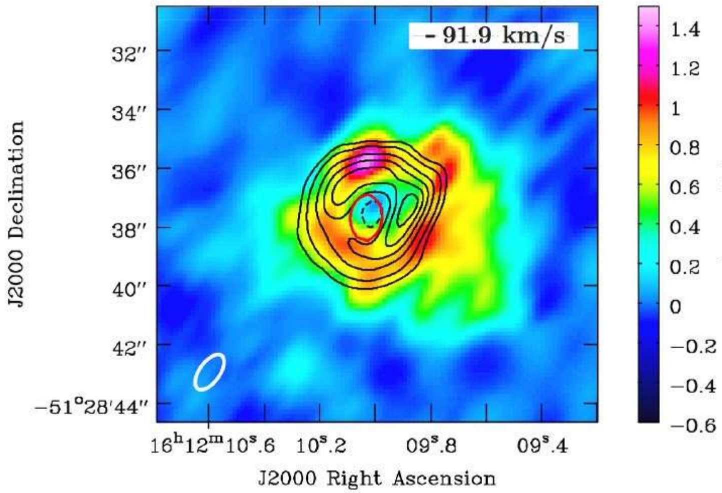
(Bronfman+2008; Merello+2013a)

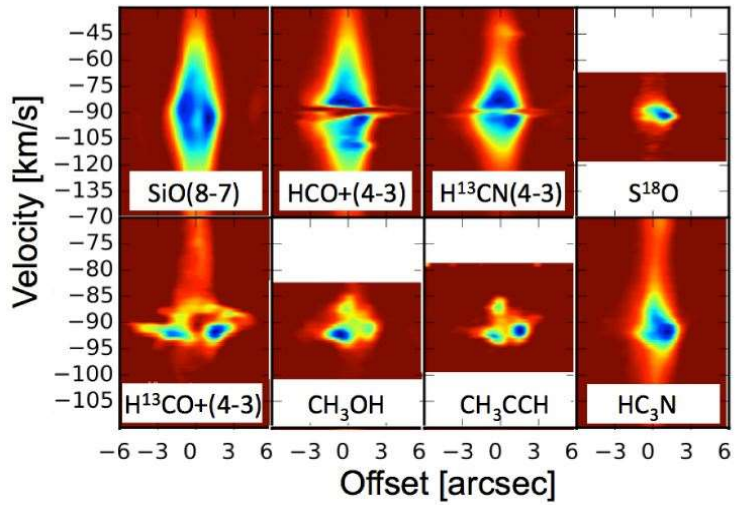
- Energetic, high velocity molecular outflow

- ALMA Band 7 observations: Merello+2013b; Hervias-Caimapo+2018



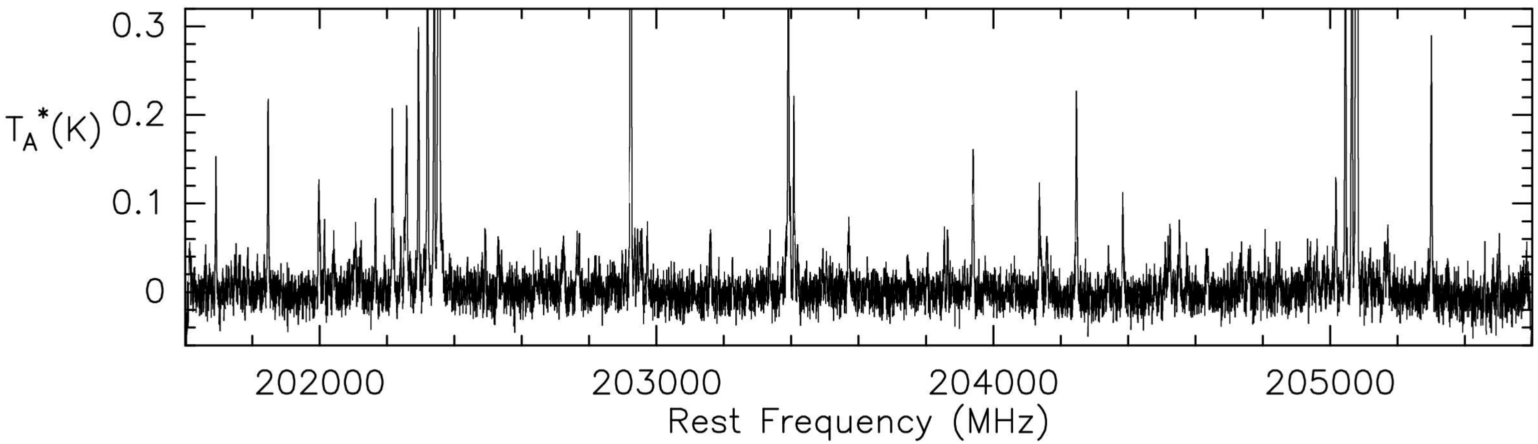
See talks of:
- N. Duronea
- E. Mendoza
- C. Canelo





(2) G332

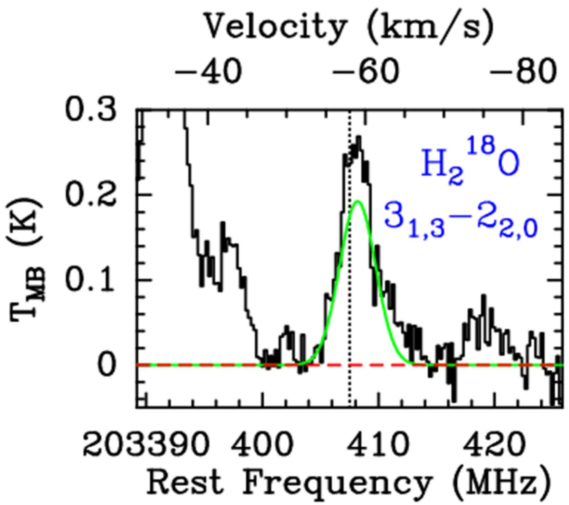
- Distance 3.85 kpc
- M = 6.2E3 Msun
  L = 4.2E5 Lsun
  n(H2) = 4.0E5 cm-3
- APEX observations:
  - B5 (201.6-205.6 GHz)
  - B5 (170.0-174.0)
  - B6 (224.8-228.8)
  - B6 (238.7-242.7)
  - B6 (253.0-257.0)
  - B6 (265.3-269.3)
  - B7 (363.1-367.1)

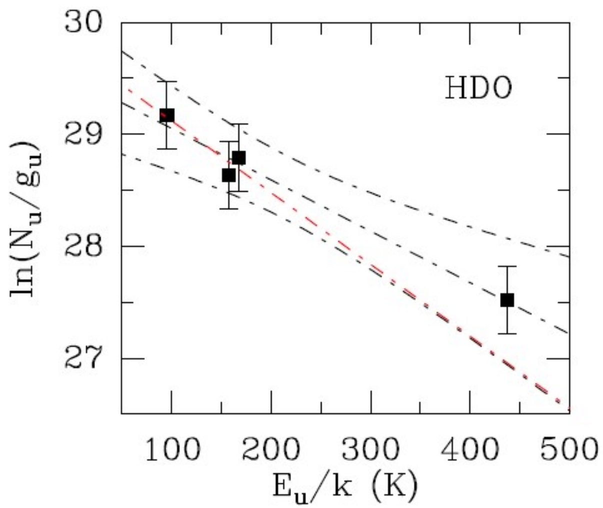


Preliminary results (Merello, Bronfman, Mendoza, Lépine+, in prep)

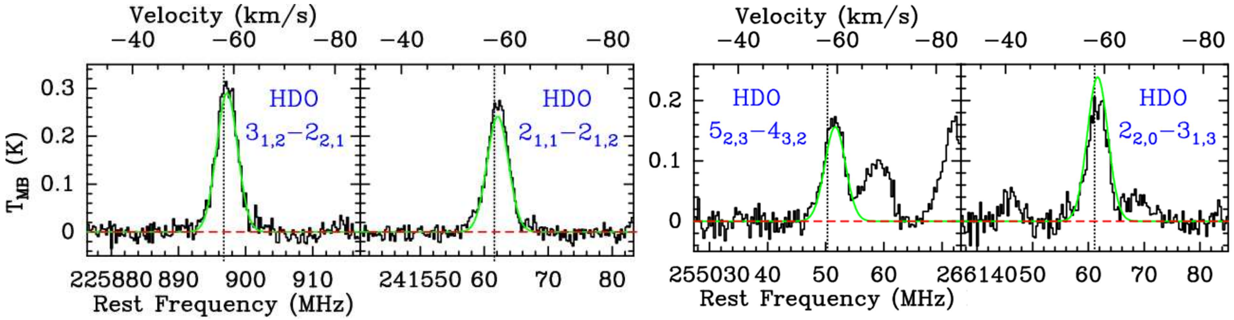
- **Detection of thermal water emission**
  p-$H_2^{18}O$ ($3_{1,3} - 2_{2,0}$)

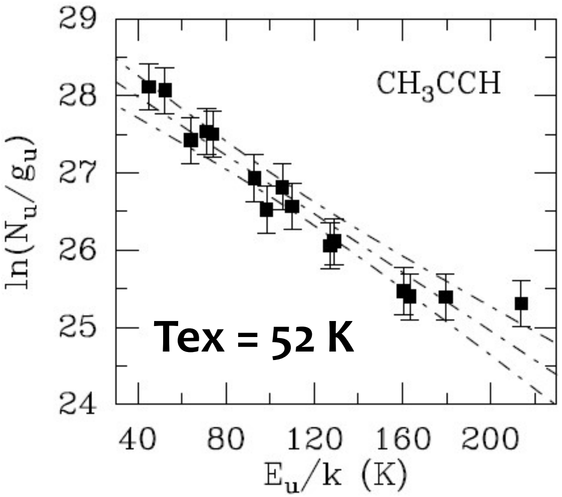
Tex = 218 K
$X(H_2O)$=2.42E(-6)
[HDO/H2O]=2.29E(-4)
Size = 23 arcsec

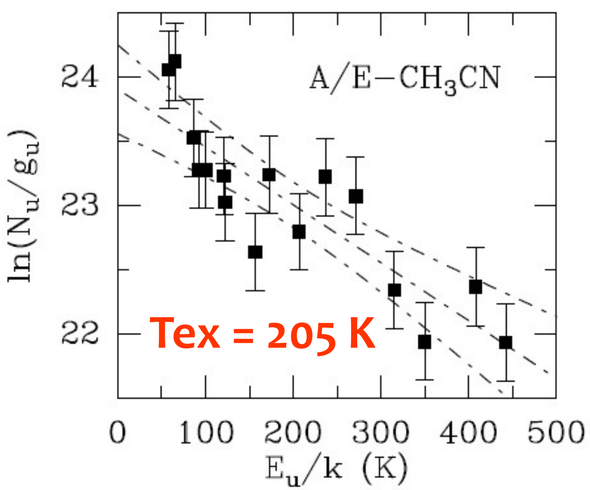




→ In agreement with other detections of water in HMCs:
- Liu+2013 (**G34.26+1.15**)
- van der Tak+2006 (**AFGL 2591 , W3 IRS5, NGC 7538 IRS1, W33A)**
- Gensheimer+1996 (**9 HMCs)**







- Two different gas envelope regions, traced by gas temperatures of CH_3CCH and CH_3CN

→ **In agreement with grain surface chemistry of COMs** (Bisshop+2007)

CH_3CCH (10-9) [B5 ~ 170.9 GHz], (12-11) [B5 ~ 205.0 GHz]
(15-14) [B6 ~ 256.3 GHz]
CH_3CN(11-10) [B5 ~ 202.3 GHz], (14-13) [B6 ~ 257.5 GHz]

Preliminary results (Merello, Bronfman, Mendoza, Lépine+, in prep)

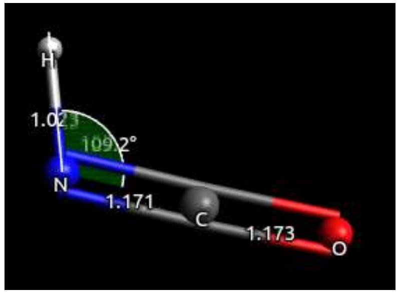
- **Detection of HNCO and NH2CHO**

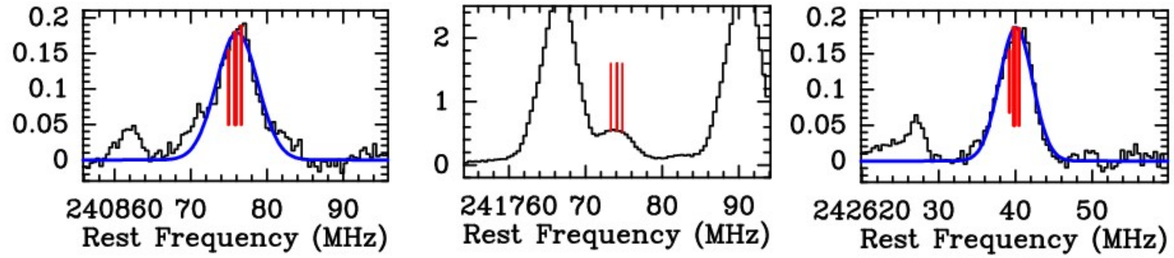
Peptide bond (Possible candidate for Acetamide CH3CONH2 ??).

- **Detection of sugar glycolaldehyde**

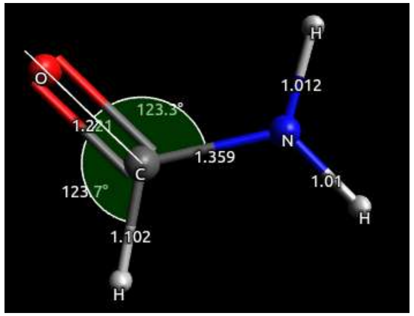
Found in low-mass protostar (Jørgensen+2012) and high-mass star forming region (McGuire+2018).

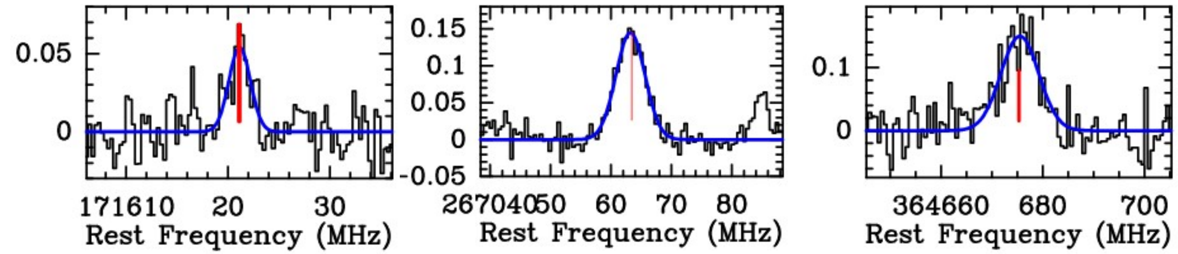
Isocyanic acid (HNCO)



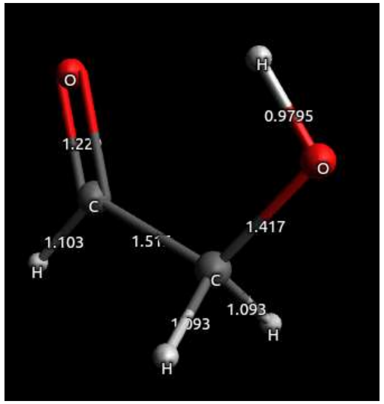


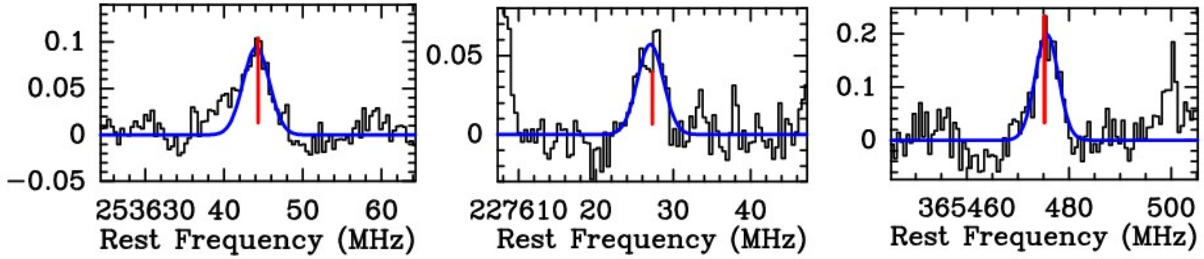
Formamide (NH2CHO)





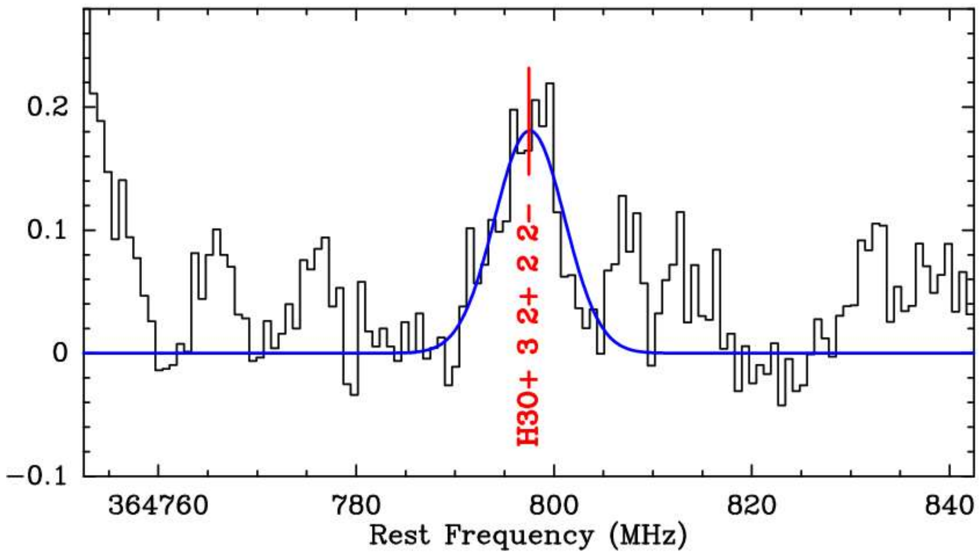
Glycolaldehyde (CH2OHCHO)





Preliminary results (Merello, Bronfman, Mendoza, Lépine+, in prep)

- **Detection of H3O+ in Band 7**



Phillips+1992

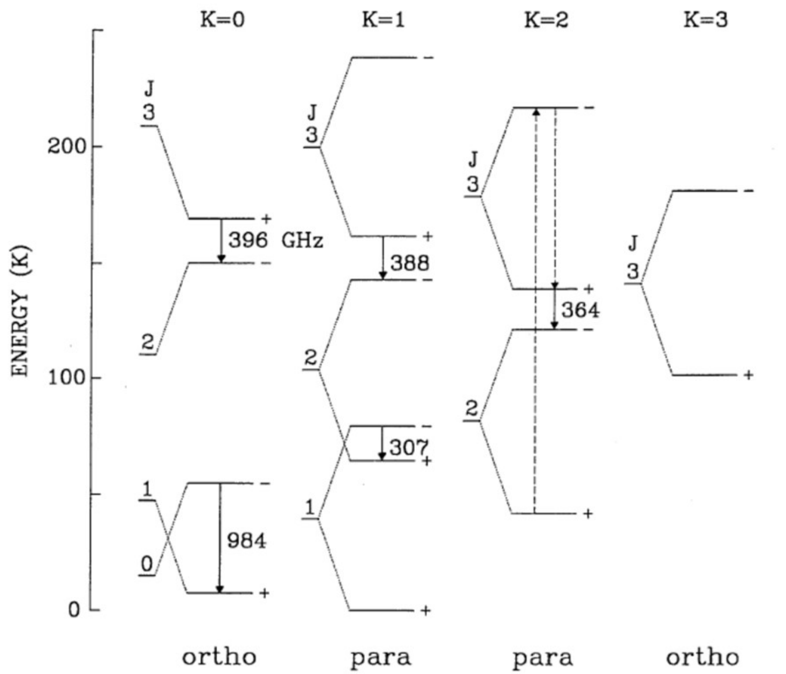


FIG. 1.—Energy level diagram of H_3O^+, illustrating the submillimeter transitions (*full lines*) and the possible radiative pumping of the 364 GHz line (*dashed lines*).

- Previous detections in Orion/KL, SgrB2, W3 IRS5
- H3O+ is importante in the chemistry of oxygen and water.
- Linked to HCO+

$$CO + H_3^+ \rightarrow HCO^+ + H_2$$
$$HCO^+ + H_2O \rightarrow H_3O^+ + CO$$

Summary

- Construction of sample of hot molecular core candidates across the Galactic plane
- Observations with single-dish telescopes → properties of dense gas toward these objects, with opportunities for astrochemical studies.
- Identification of G331 and G332 as "laboratories" for studies of COMs
- Identification of new sources only available in the southern sky → new studies with APEX, LLAMA and ALMA telescopes

Thank you