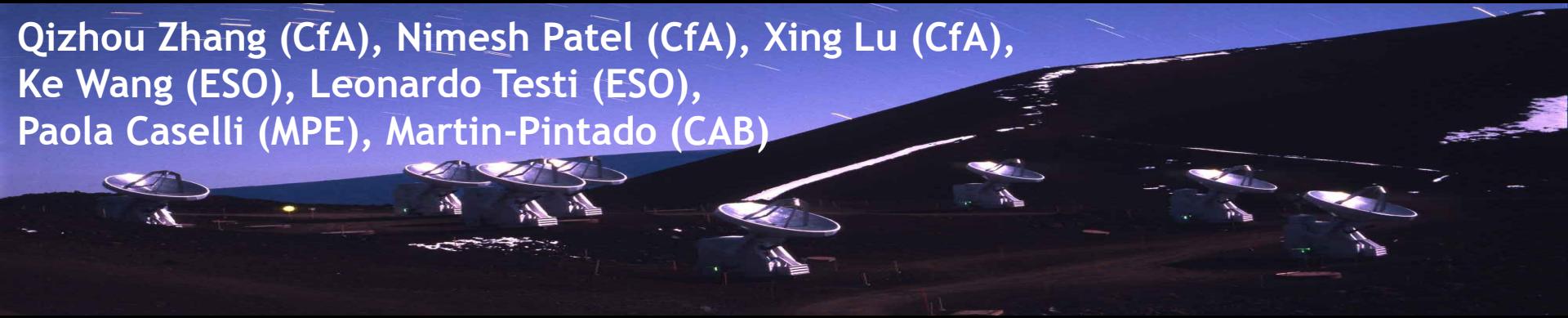


Chemistry and Star Formation: A Love-Hate Relationship

Izaskun Jimenez-Serra

IIF Marie Curie Fellow (ESO)

Qizhou Zhang (CfA), Nimesh Patel (CfA), Xing Lu (CfA),
Ke Wang (ESO), Leonardo Testi (ESO),
Paola Caselli (MPE), Martin-Pintado (CAB)



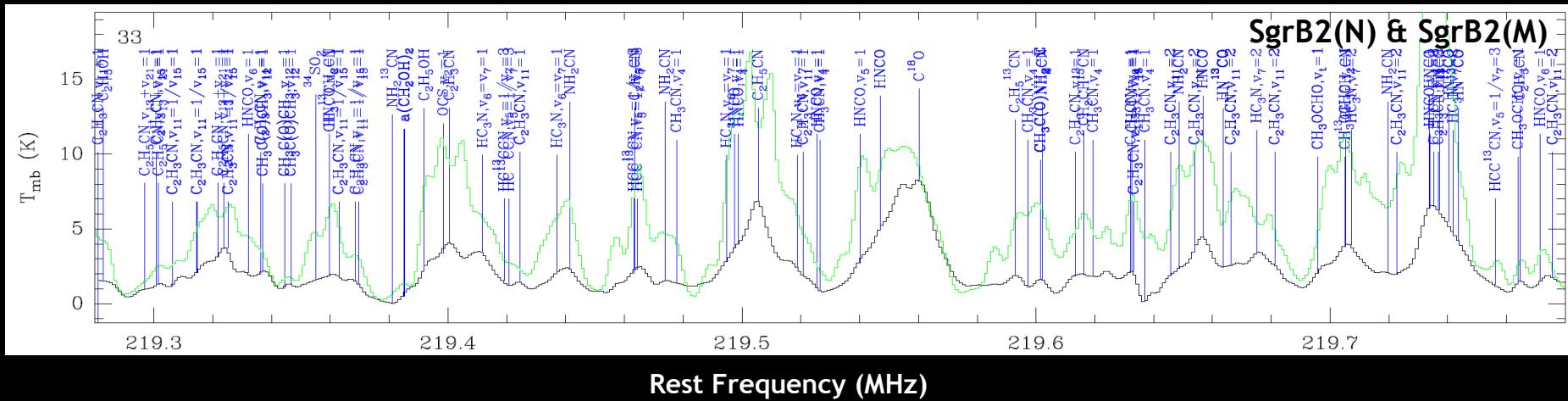
Chemistry: a Love-Hate Relationship

- **Love:**
- Key species for which chemistry is relatively well-constrained.
- Discriminate between different physical mechanisms.
- The more tracers, the better!!

Chemistry: a Love-Hate Relationship

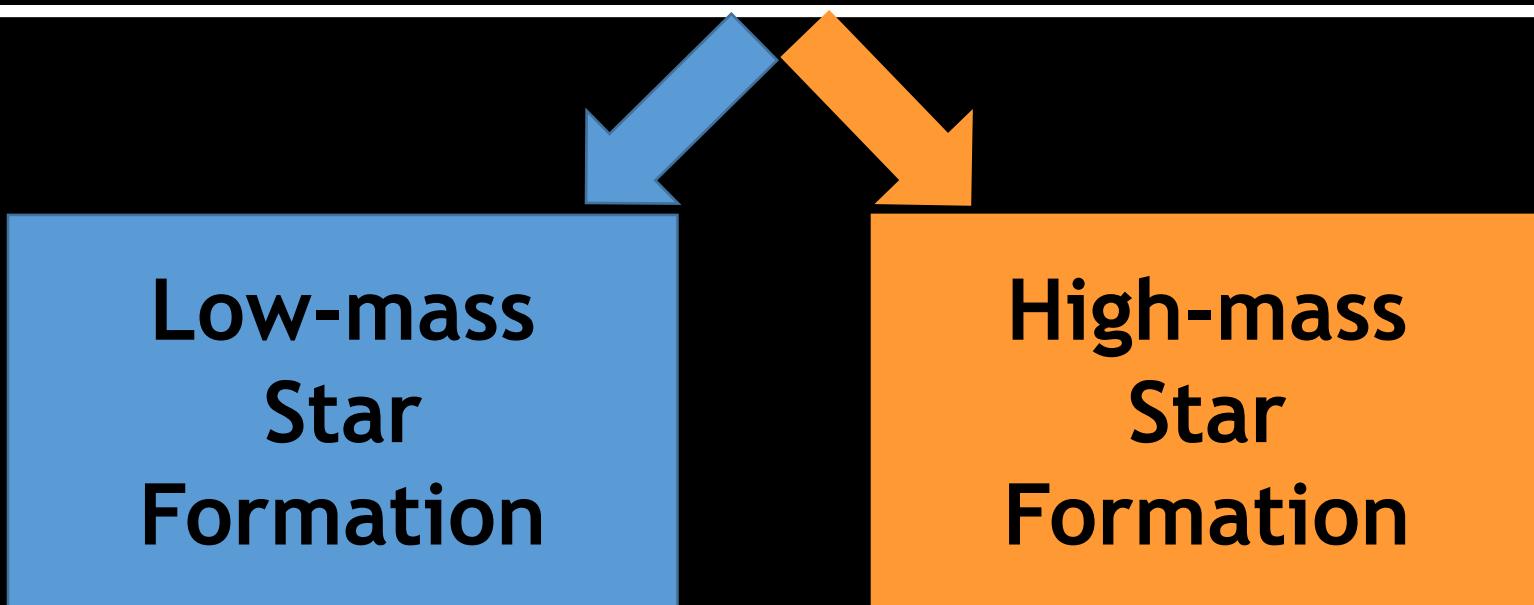
- **Love:**
- Key species for which chemistry is relatively well-constrained.
- Discriminate between different physical mechanisms.
- The more tracers, the better!!
- **Hate:**
- Chemical richness \Rightarrow Analysis of data is not trivial

Belloche+2013



Outline

- Introduction: Pathways to chemical complexity in SF
- Chemistry of the initial conditions and pre-stellar cores
- Chemistry in Protostellar Envelopes: Warm and Hot cores, disks
- Chemistry in Outflows



Pathways to Chemical Complexity

- Cold Chemistry: Initial Conditions and Pre-stellar Cores

Low T (<20 K) and high H₂ densities (>10⁵ cm⁻³) \Rightarrow Freeze-out

Only He, H₂, H₃⁺ and H₂D⁺ are left in the gas phase

High levels of deuteration \Rightarrow

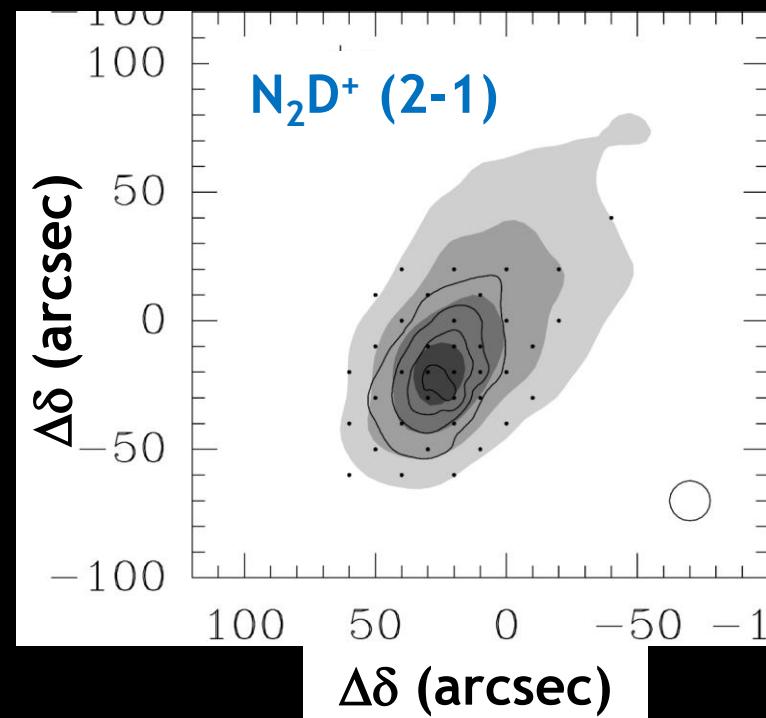


(Millar+1989, Roberts & Millar 2001)

Back reaction not possible at T<20 K

N₂D⁺/H₂D⁺/N₂H⁺
excellent probes of cold gas

Caselli+2002



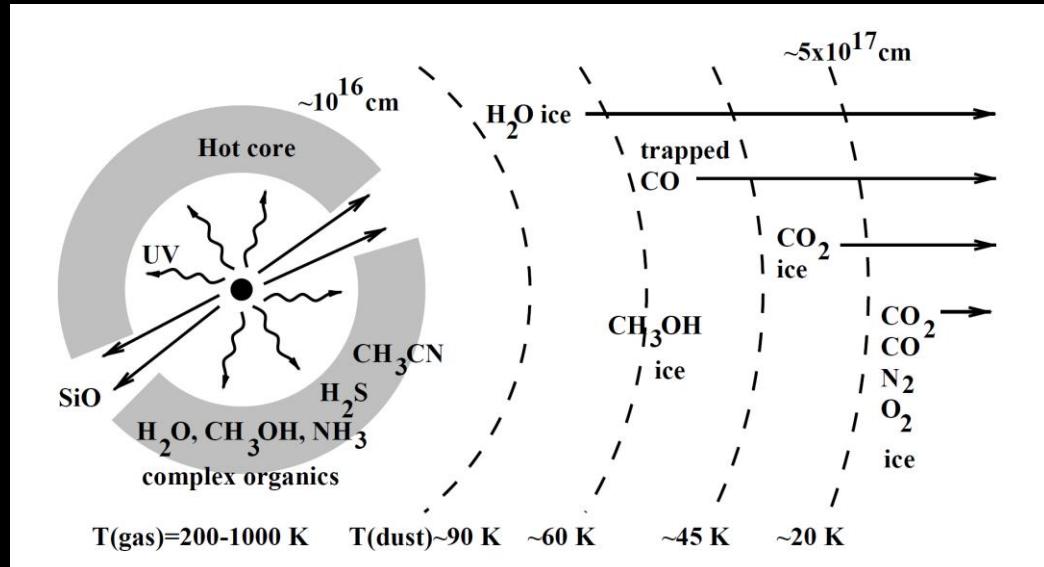
Pathways to Chemical Complexity

- Warm and Hot Chemistry: Proto-stellar heating

Thermal evaporation (desorption) of the ices at T>100 K

followed by

High T gas-phase chemistry (+UV photo-chemistry)

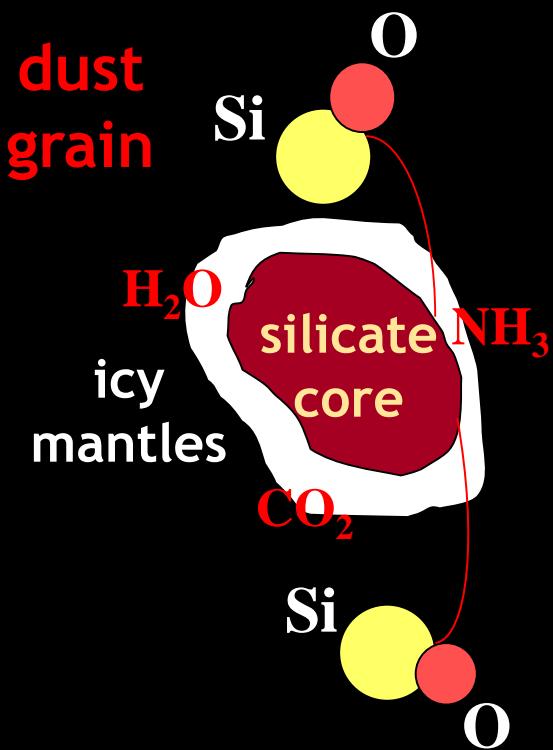


Active chemistry:

- i) Saturated molecules
(H₂O, H₂S, NH₃, CH₃OH)
- ii) COMs
(C₂H₅OH, CH₃OCH₃, HCOOCH₃)

Pathways to Chemical Complexity

- Shock chemistry: Grain Sputtering + high-T chemistry



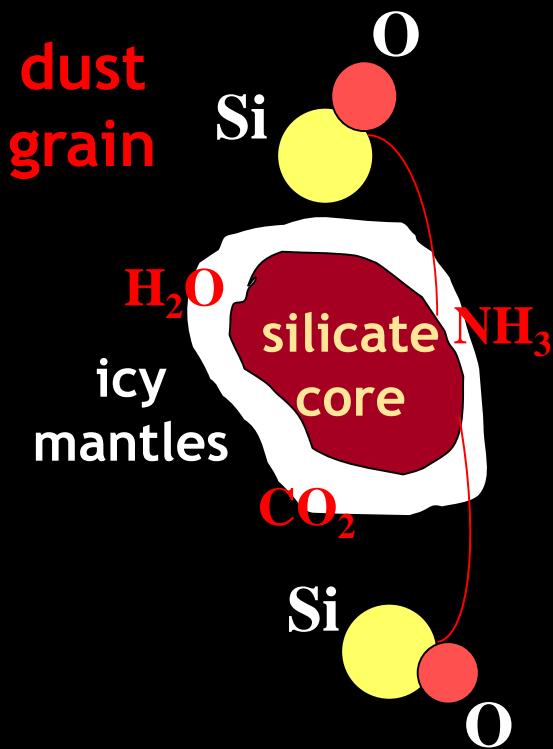
Ion-neutral velocity drift in shocks ⇒
Sputtering of ices and cores
(Schilke+1997, Caselli+97, Gusdorf+2008,
Jimenez-Serra+08, van Loo+12)

Production/destruction at high T
(e.g. H_2O vs. NH_3 in L1157)
(Viti et al. 2011)

Fontani+2014: Deuterated molecules HDCO , D_2CO found in shocks (L1157)

Pathways to Chemical Complexity

- Shock chemistry: Grain Sputtering + high-T chemistry



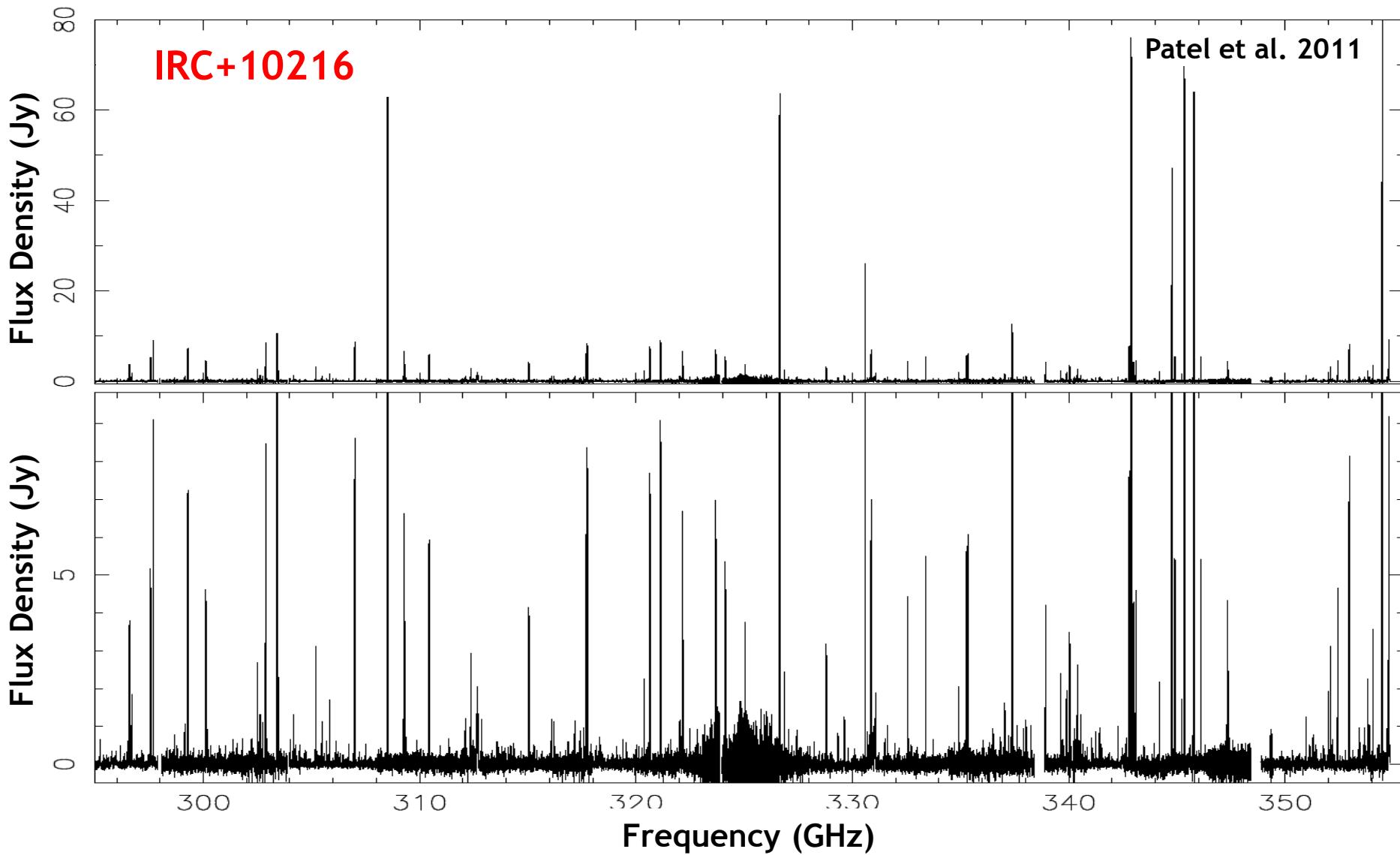
Ion-neutral velocity drift in shocks ⇒
Sputtering of ices and cores
(Schilke+1997, Caselli+97, Gusdorf+2008,
Jimenez-Serra+08, van Loo+13)

Production/destruction at high T
(e.g. H_2O vs. NH_3 in L1157)
(Viti et al. 2011)

SiO unique probe
(Martin-Pintado et al. 1992)

Fontani+2014: Deuterated molecules HDCO , D_2CO found in shocks (L1157)

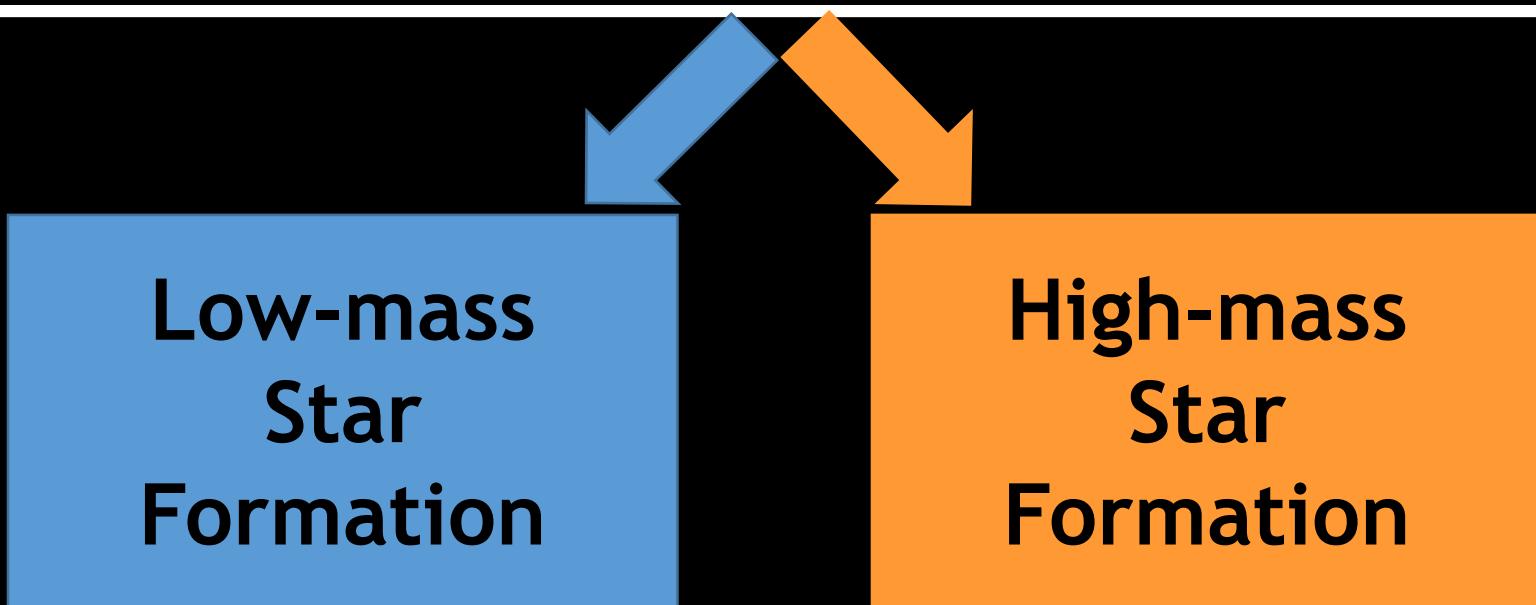
SMA a pioneering instrument



Very broad simultaneous bandwidth!!!

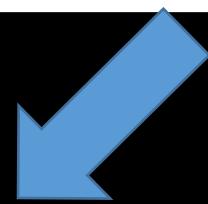
Outline

- Introduction: Pathways to chemical complexity in SF
- Chemistry of the initial conditions and pre-stellar cores
- Chemistry in Protostellar Envelopes: Warm and Hot cores, disks
- Chemistry in Outflows



Outline

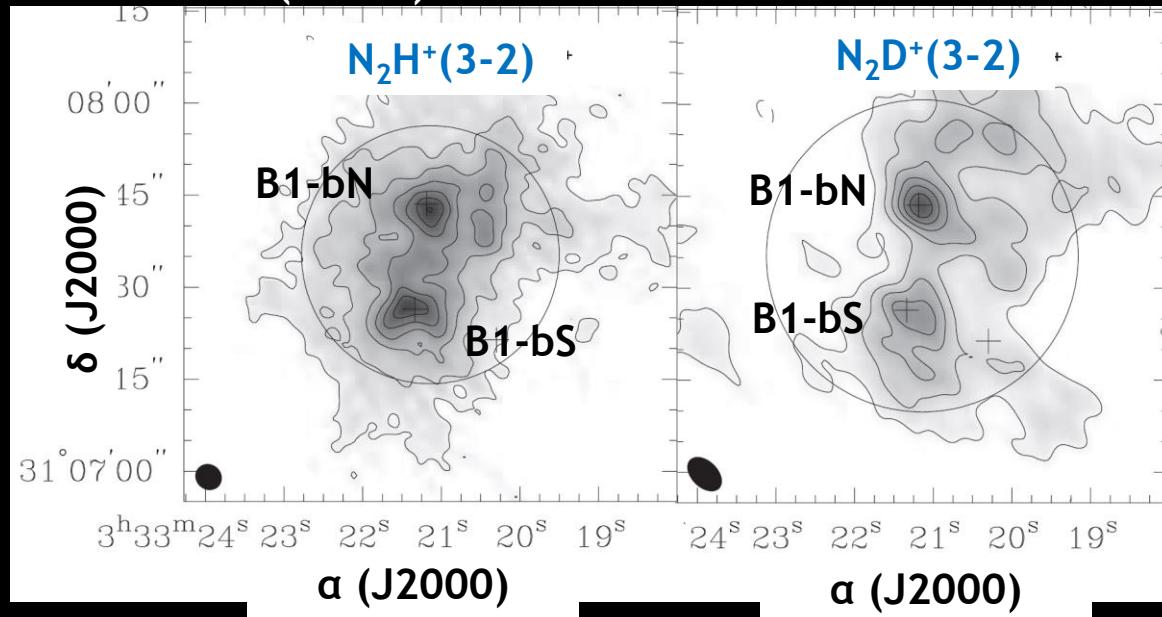
- Introduction: Pathways to chemical complexity in SF
- Chemistry of the initial conditions and pre-stellar cores
- Chemistry in Protostellar Envelopes: Warm and Hot cores, disks
- Chemistry in Outflows



Low-mass
Star
Formation

Cold Chemistry: Initial Conditions in Low-mass SF

Barnard 1b (N & S)



Huang & Hirano 2013

Inside Dark Clouds (B1b):

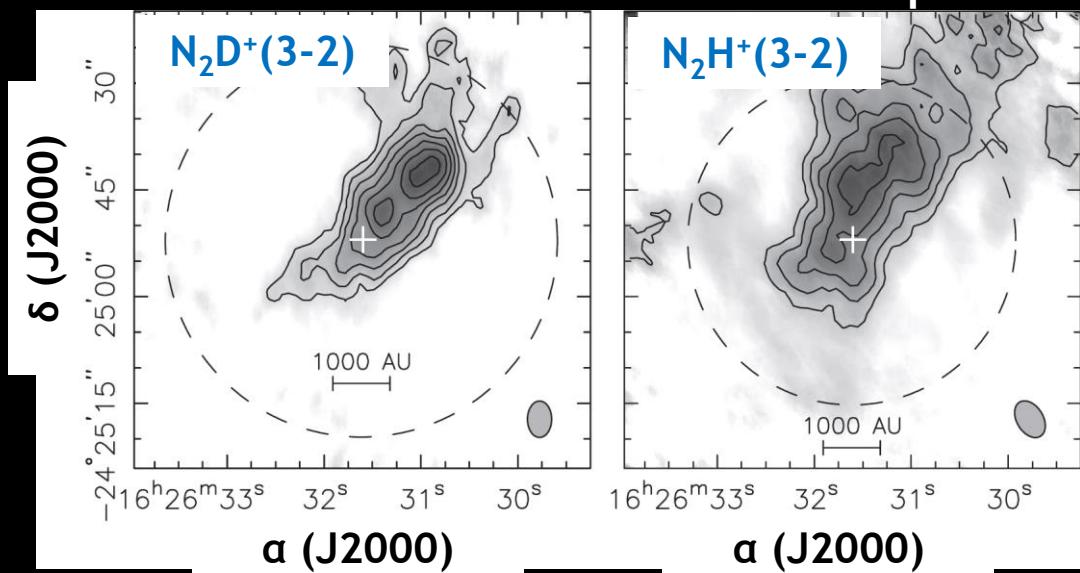
- Two first core candidates
- D/H~0.2
- B1-bS shows $H^{13}CO^+$

Bourke+2012

Oph A-N6

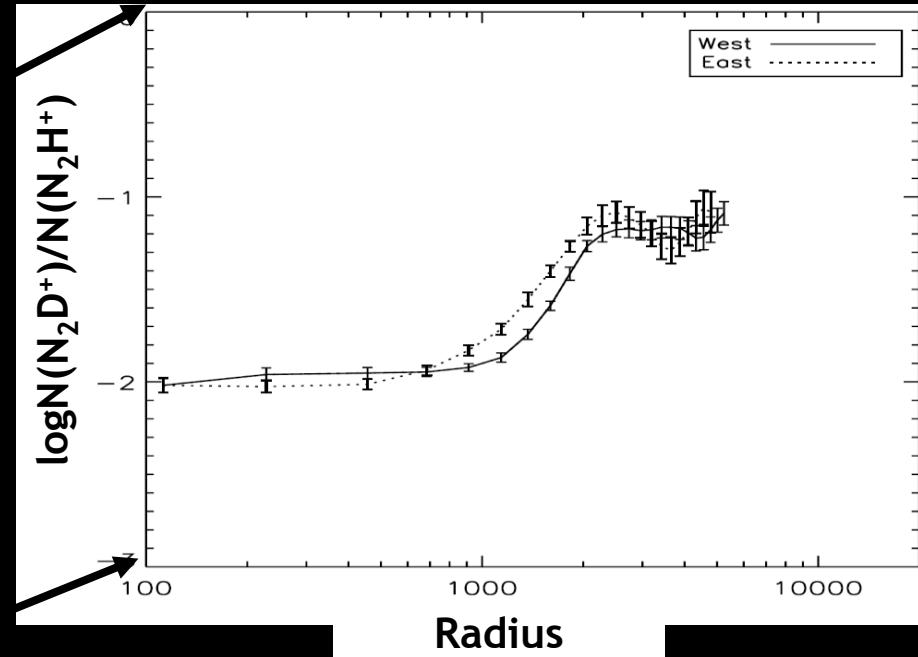
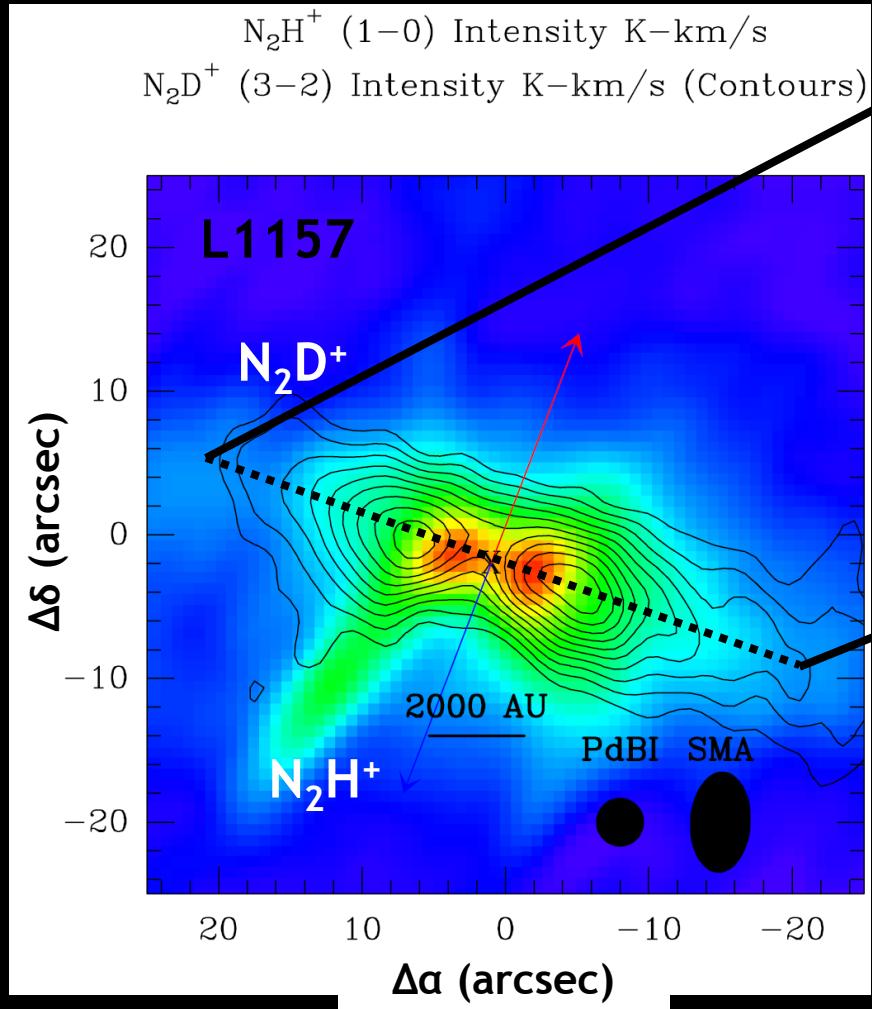
Cluster Cores:

- Resolved structure (~1400-3000 AU)
- Similar to isolated cores
- D/H~0.15



Warm Chemistry in Protostellar Envelopes

Tobin et al. 2013



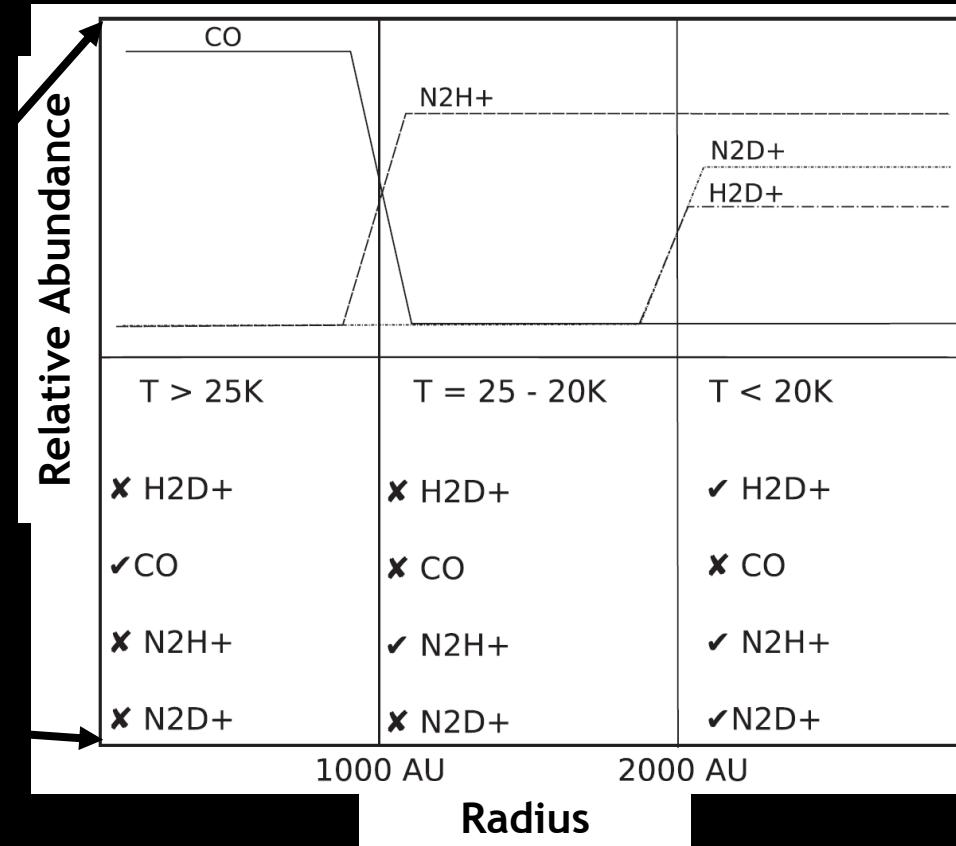
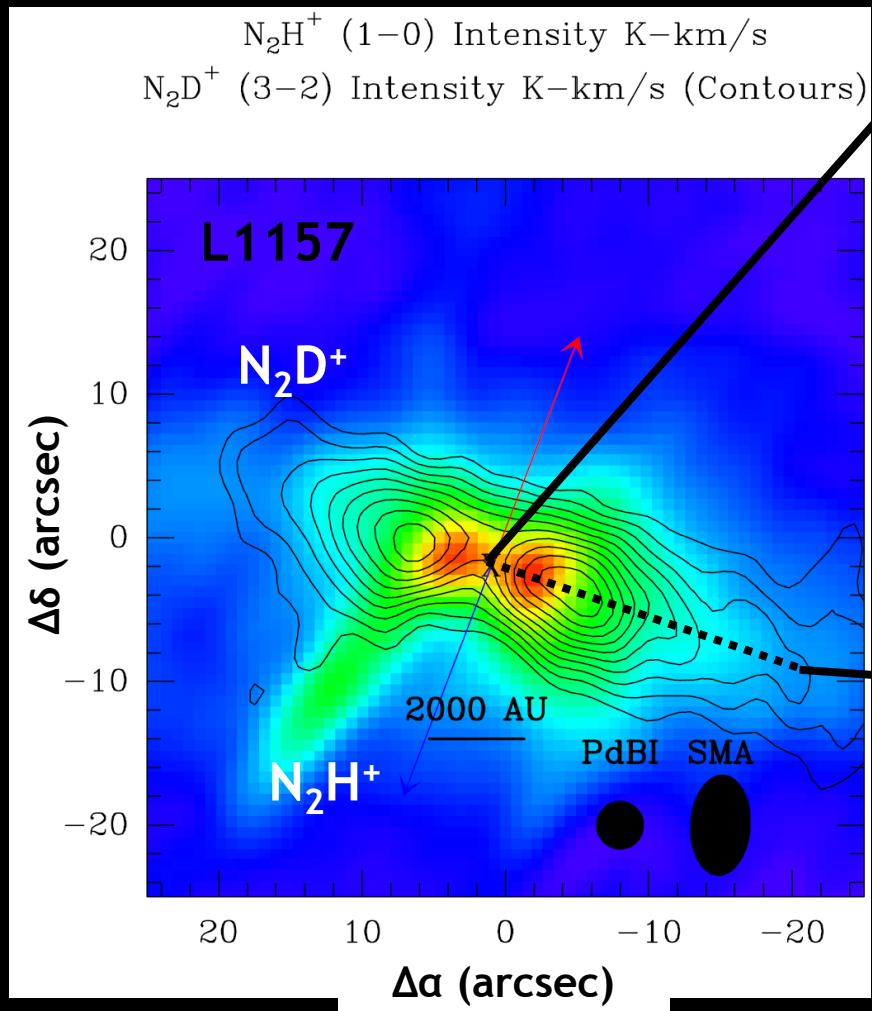
N_2D^+ and N_2H^+ depleted @ $r < 2000$ AU

Heating by the central protostar!

However, clear N_2D^+ and N_2H^+ emission offsets

Warm Chemistry in Protostellar Envelopes

Tobin et al. 2013

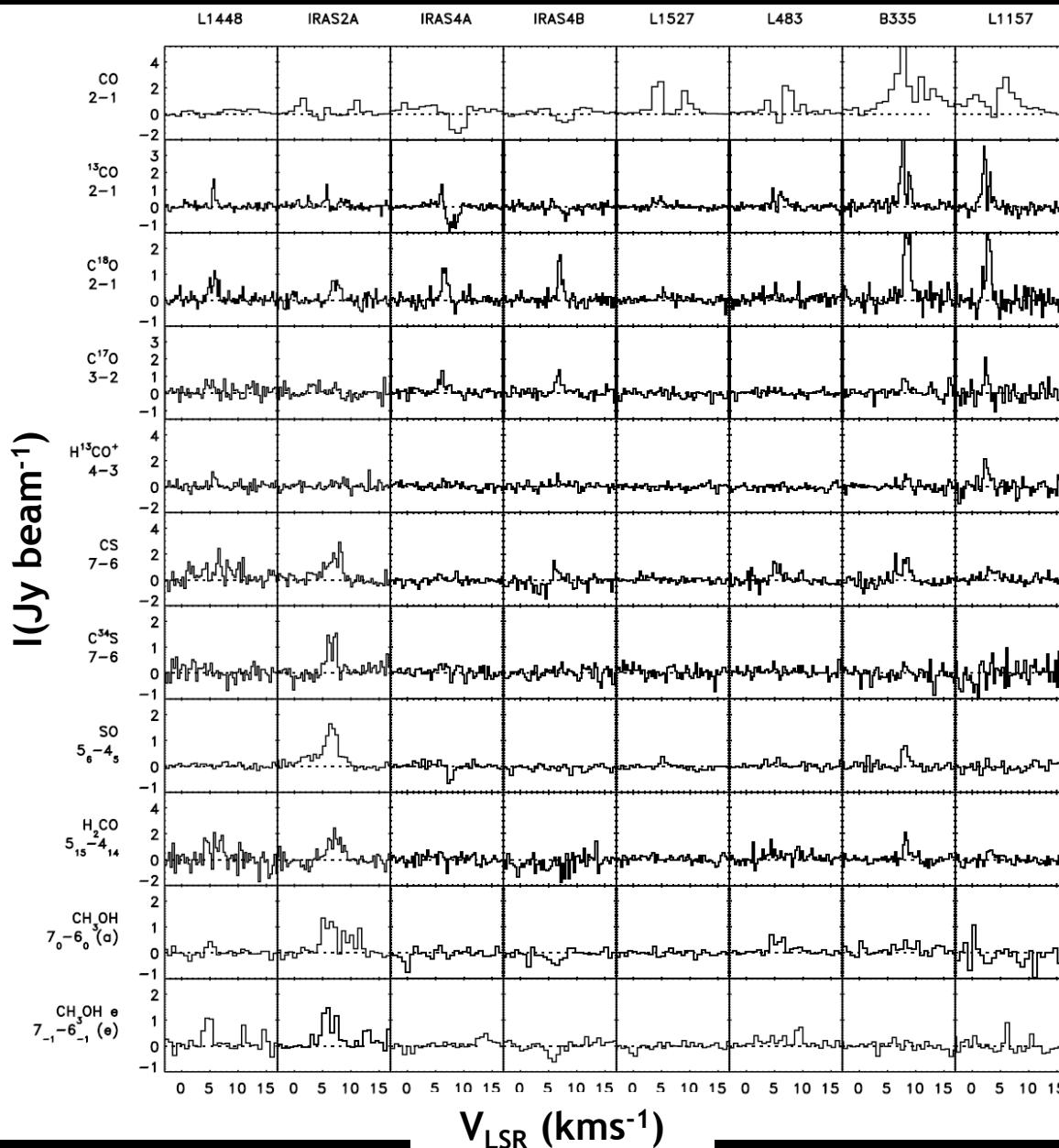


Emission offsets due to:

- CO depletion
- $T \sim 20-25\text{ K}$ at intermediate shell allowing destruction of H_2D^+

Warm Chemistry in Protostellar Envelopes

Jorgensen+2007



PROSAC: SMA Survey
of low-mass Protostars

Wider outflows \Leftrightarrow less
disk/envelope ratio

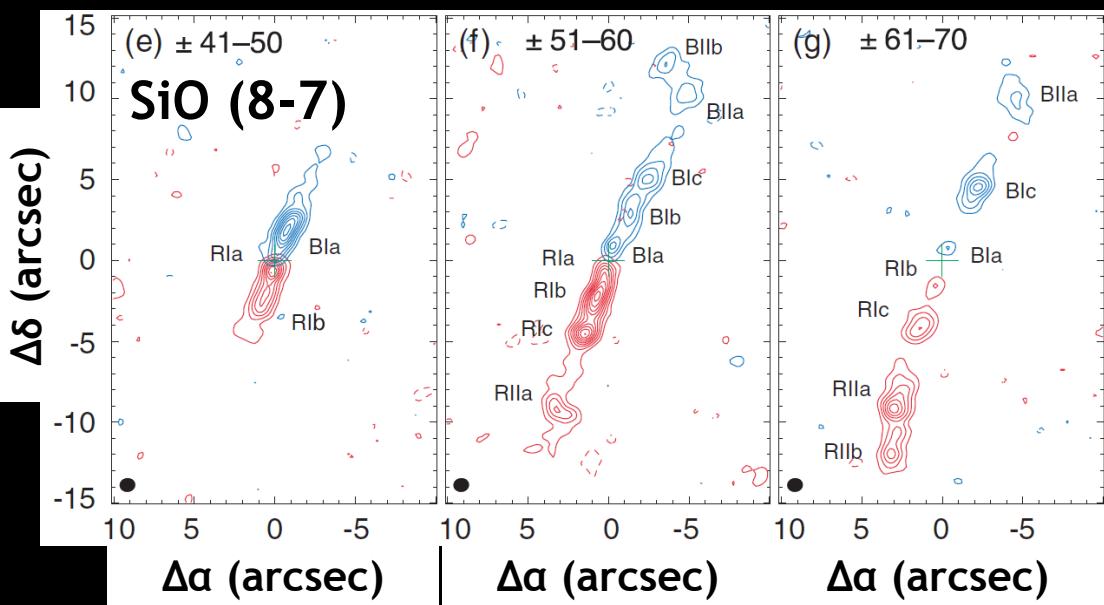
Inverse P-Cygni
profiles \Rightarrow infall
motions

H₂CO/CH₃OH
participate of
outflows

SMA spectral survey
toward IRAS16293-2422
(Jorgensen+2011)

Outflows in Low-mass SF regions

Hirano+2010



L1448

SiO: Ejection period~15–20 yrs

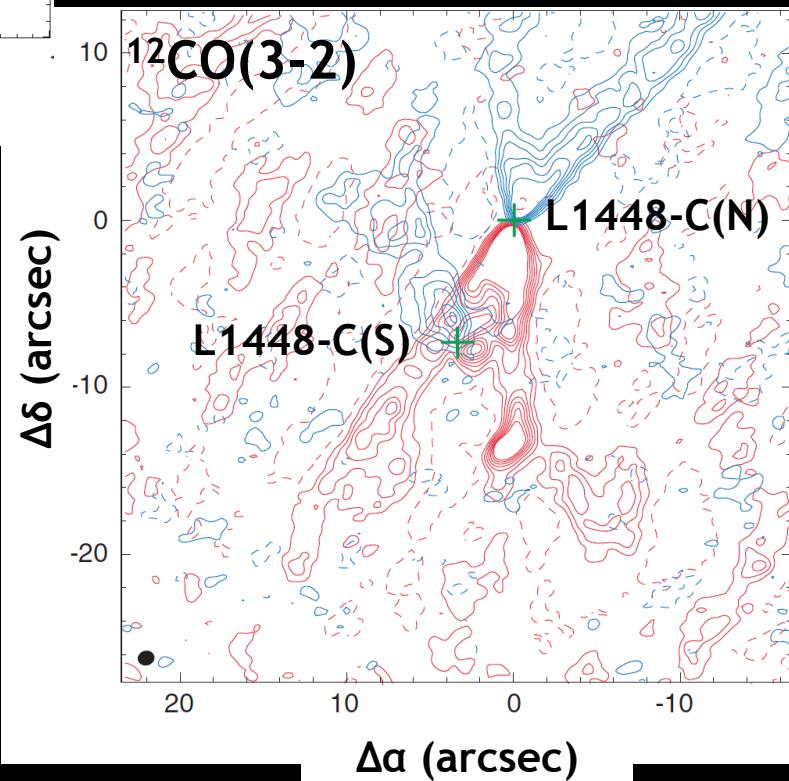
$$L_{\text{mech}} \sim L_{\text{bol}}$$

Acretion rate~ $10^{-5} M_{\odot}/\text{yr}$

CO: Wide-opening angle wind + high velocity jet

consistent with **unified X-wind model**

[Secondary outflow powered by L1448-C(S)]



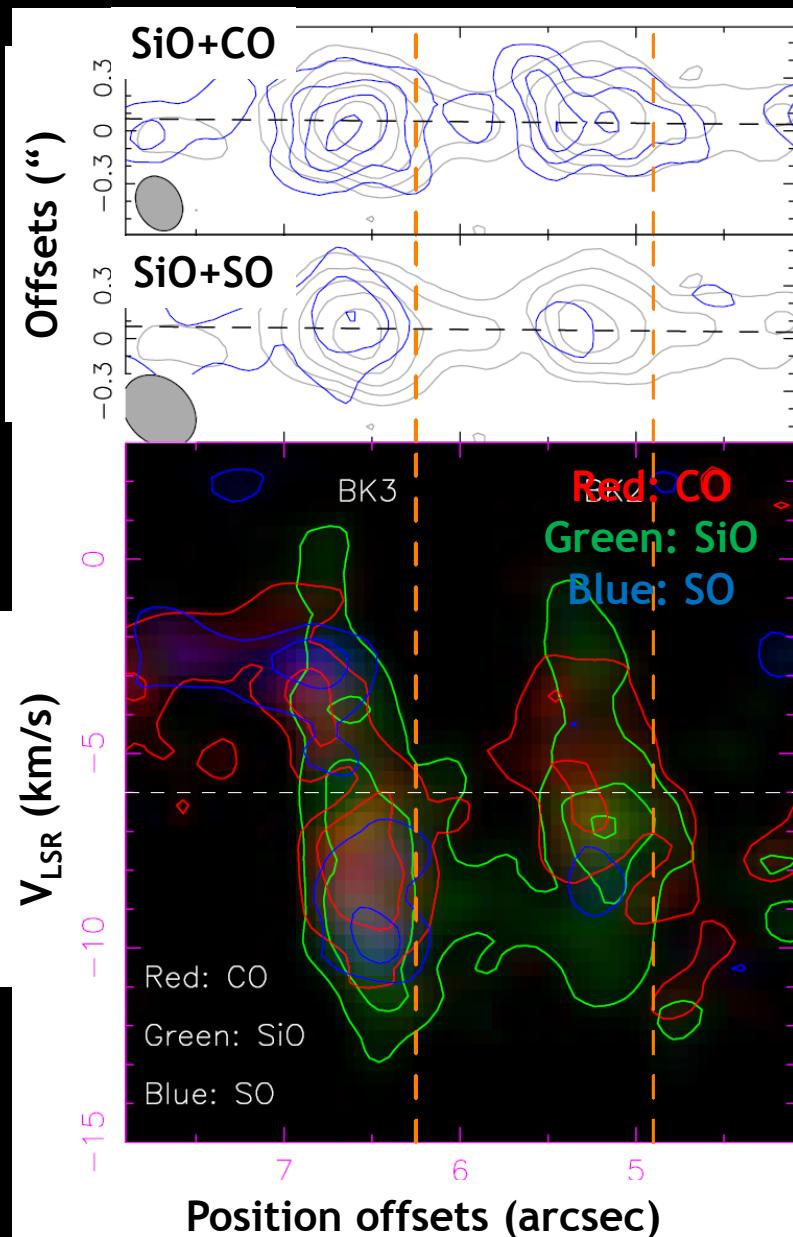
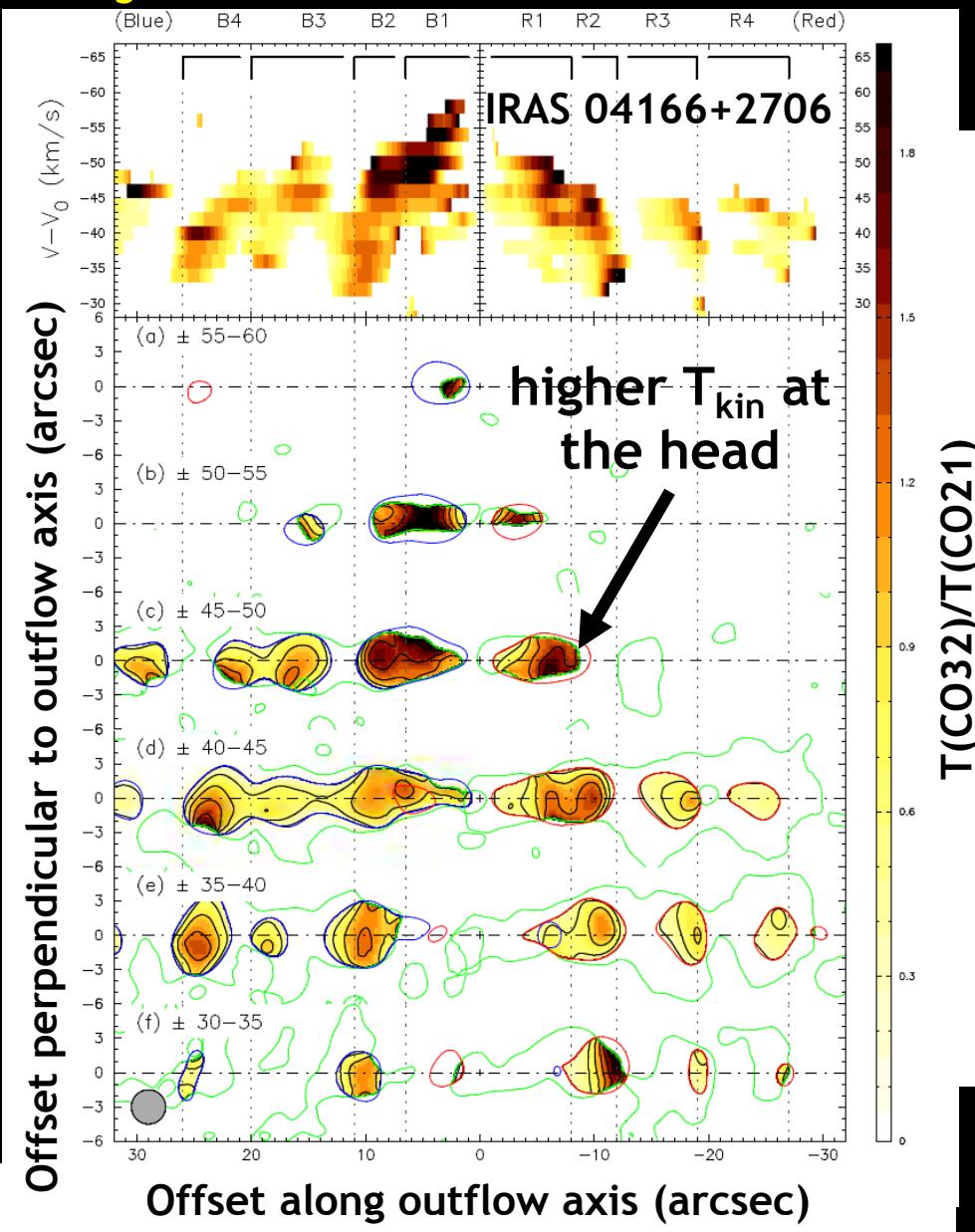
Outflows in Low-mass SF regions

Wang+2013

Internal structure of the knots

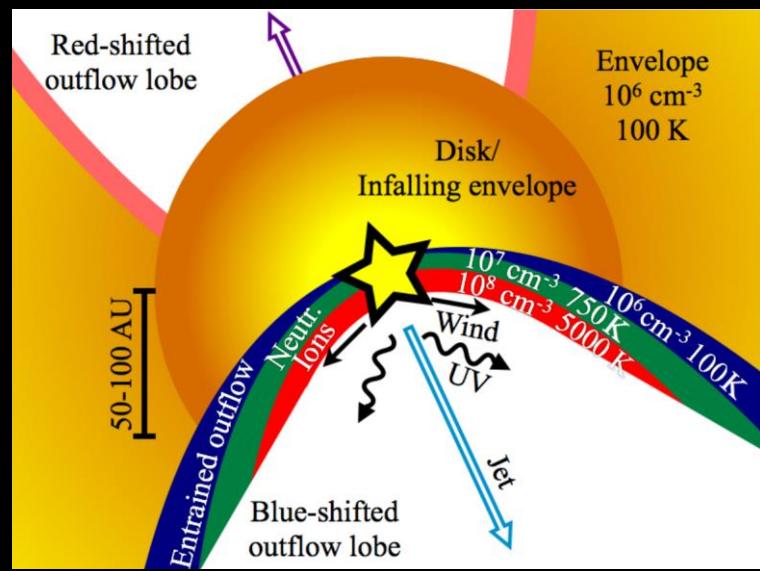
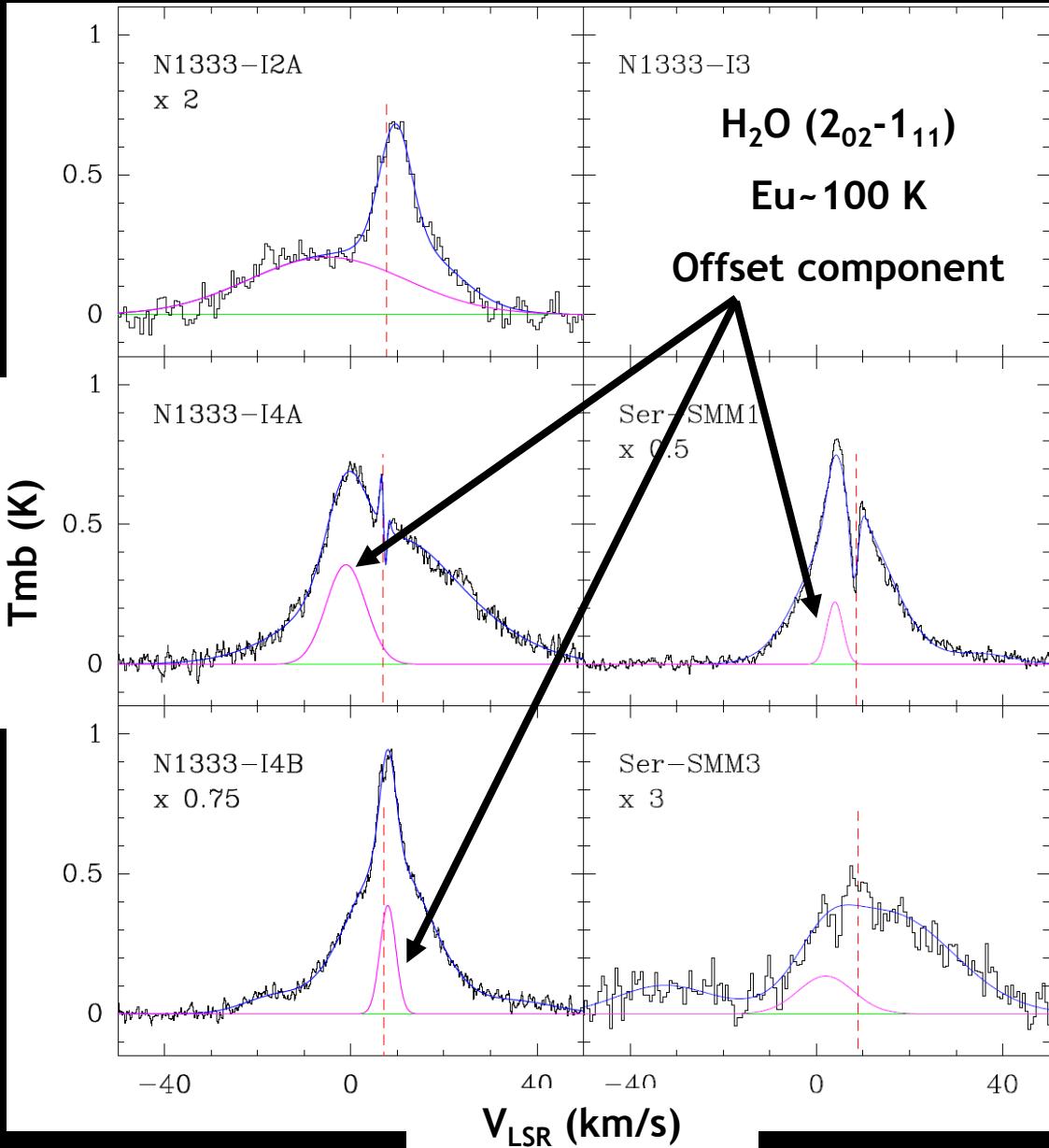
HH211

Lee+2010



Outflows in Low-mass SF regions

Kristensen+2013



$$n(H_2) \sim 5 \times 10^6 - 10^8 \text{ cm}^{-3}$$

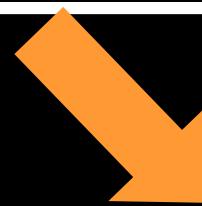
$$T \sim 750 \text{ K}$$

OH⁺, CH⁺, OH detected at
the same velocities

Dissociative shocks in the
inner 100 AU

Outline

- Introduction: Pathways to chemical complexity in SF
- Chemistry of the initial conditions and pre-stellar cores
- Chemistry in Protostellar Envelopes: Warm and Hot cores, disks
- Chemistry in Outflows

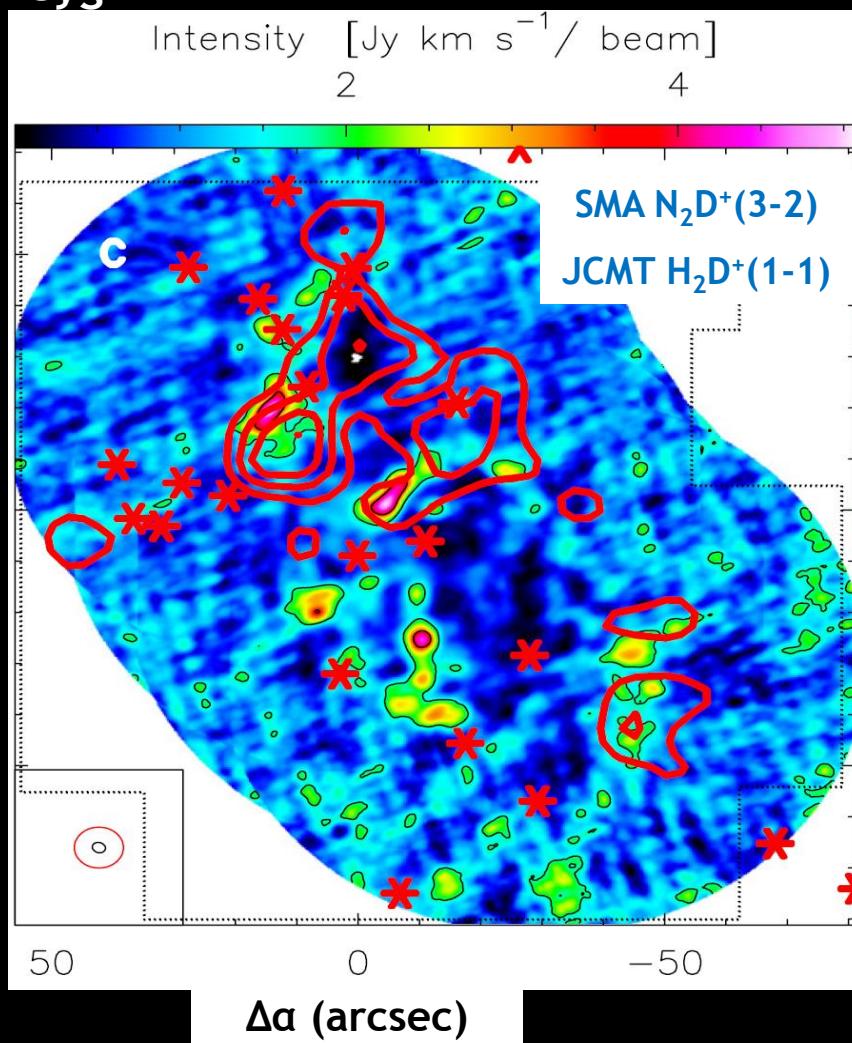


High-mass
Star
Formation

Cold Chemistry: Initial Conditions in High-mass SF

Cygnus X

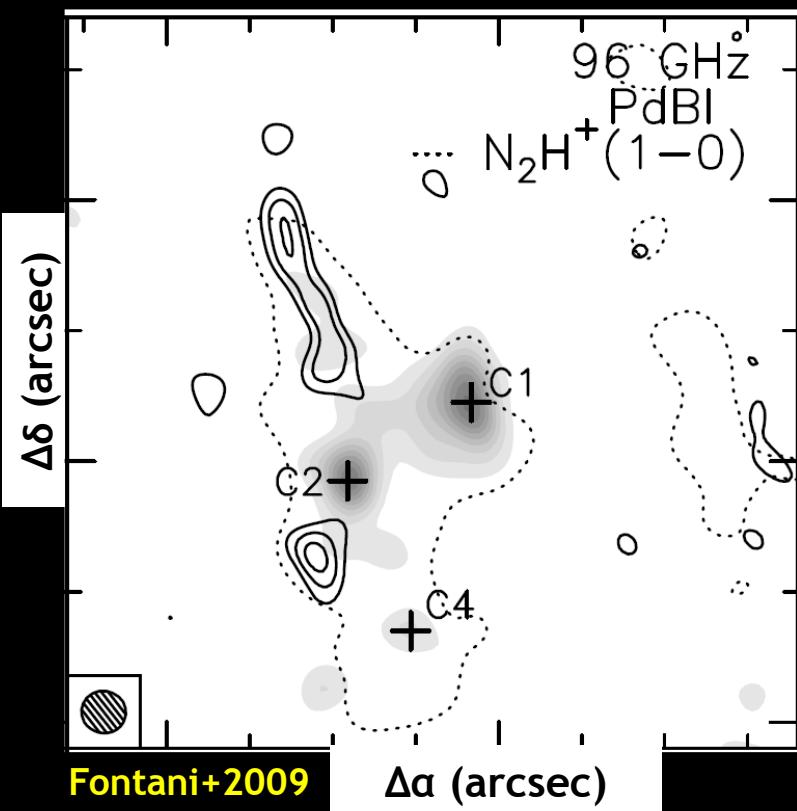
Pillai+2012



- N₂D⁺ also unveils pre-stellar objects in massive/intermediate SF regions



IRAS05345+3157

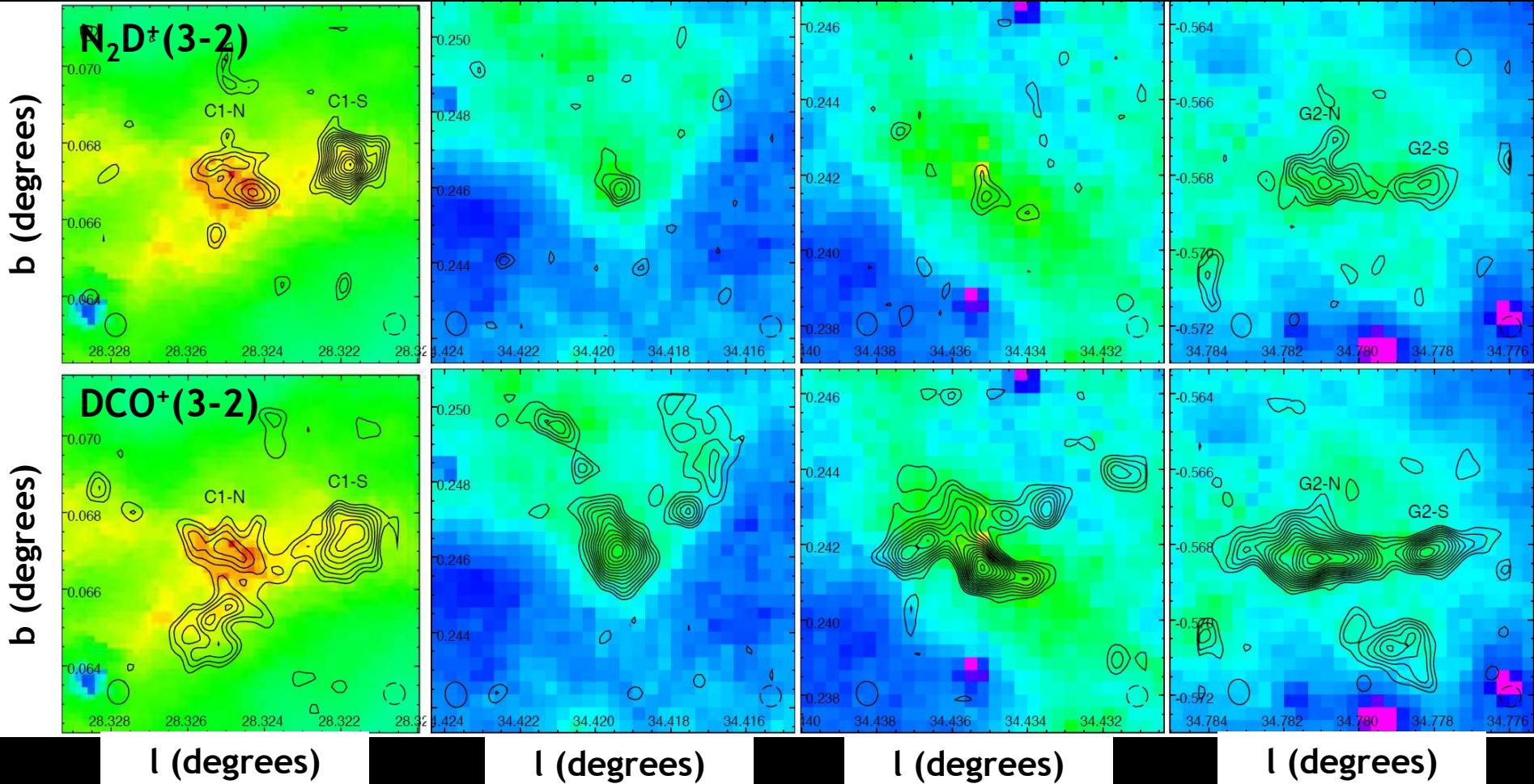


- N₂D⁺ does not provide a complete census of pre-stellar gas in clusters

Initial Conditions in Infrared-Dark Clouds

ALMA Cycle 0

Tan+2013

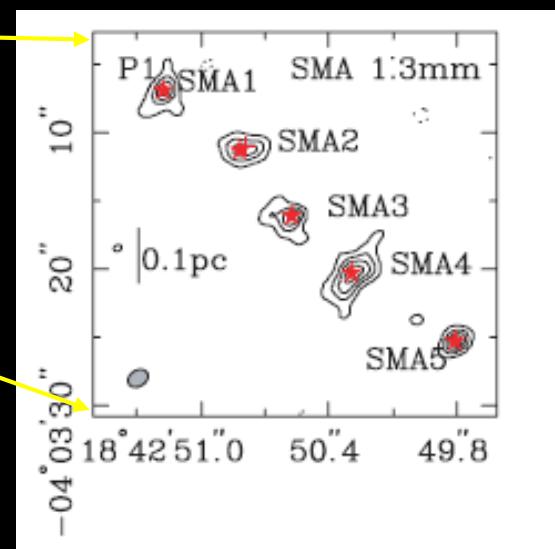
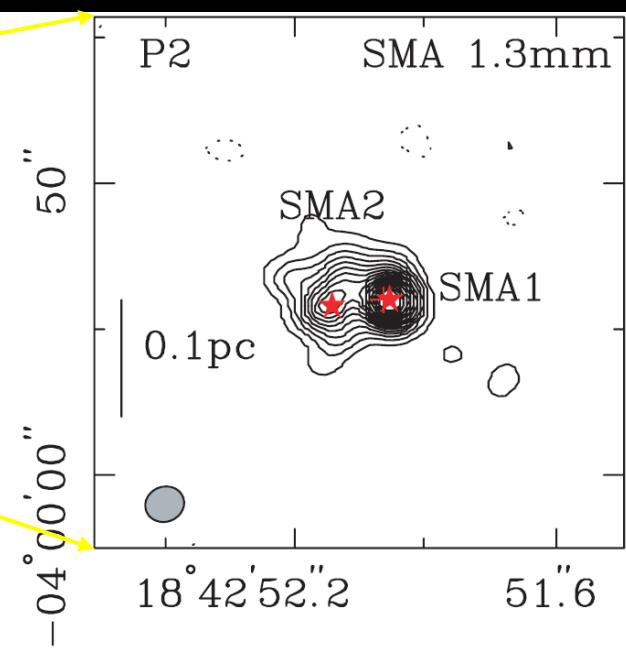
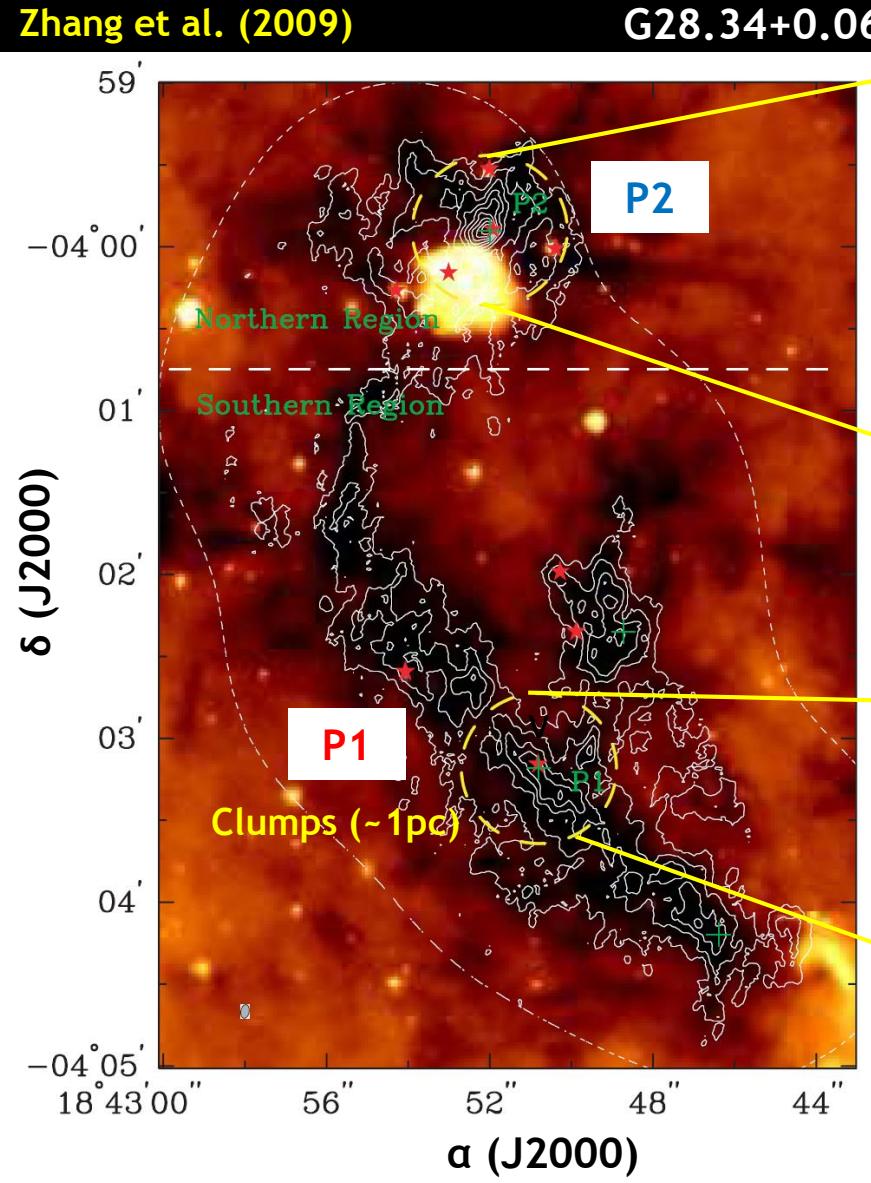


- N_2D^+ detections in IRDCs with ALMA → Very faint emission

Initial Conditions in Infrared-Dark Clouds

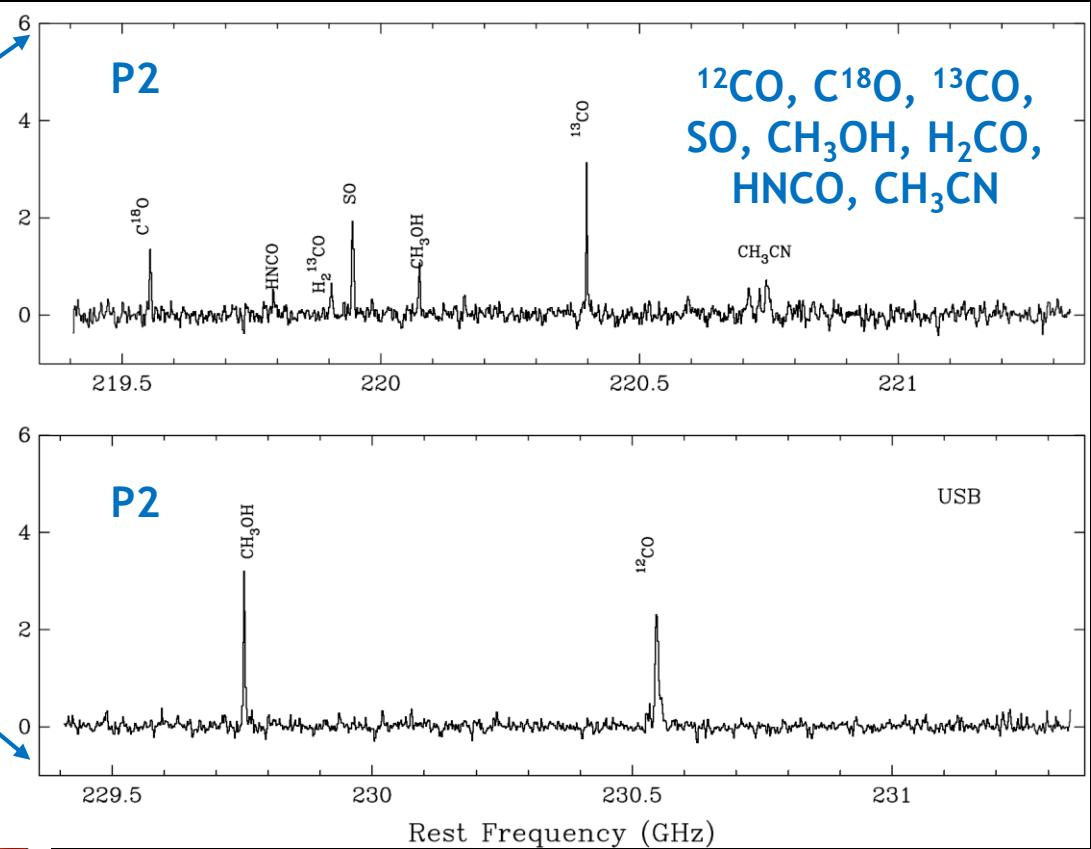
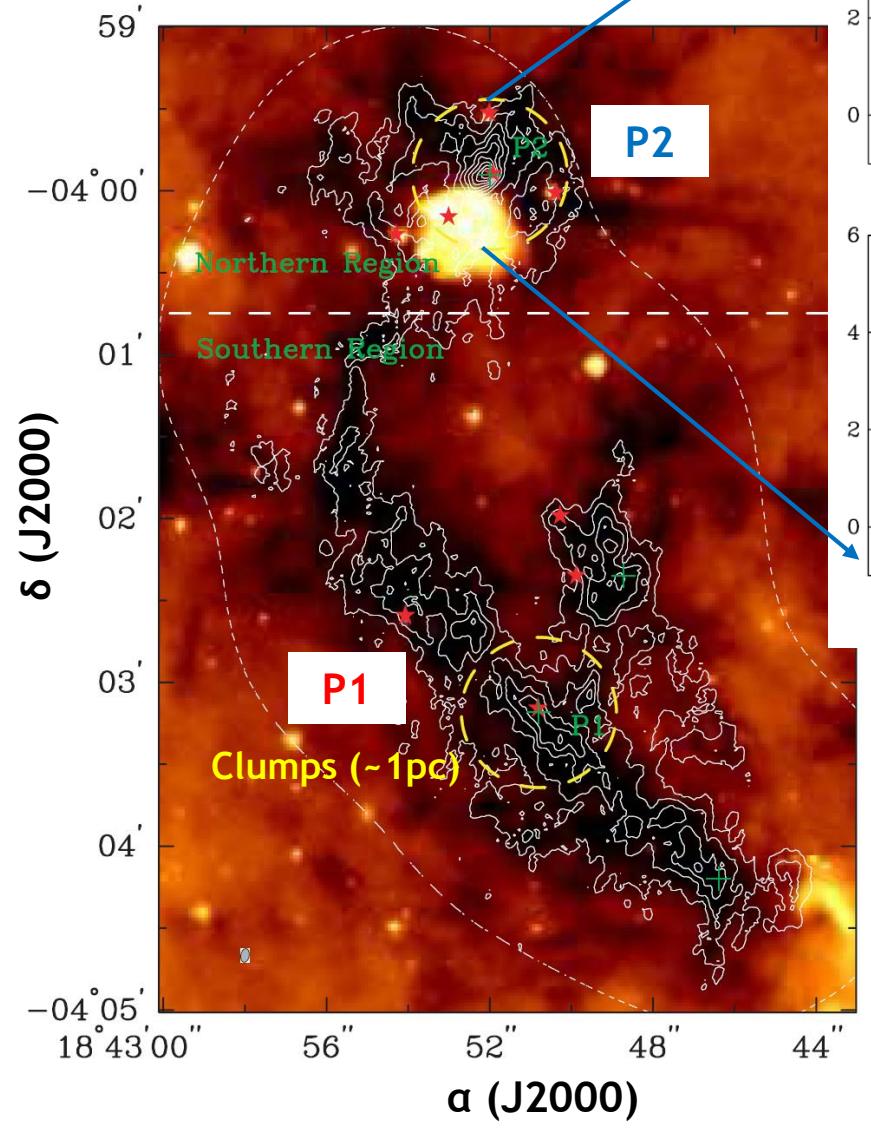
Zhang et al. (2009)

G28.34+0.06



Initial Conditions

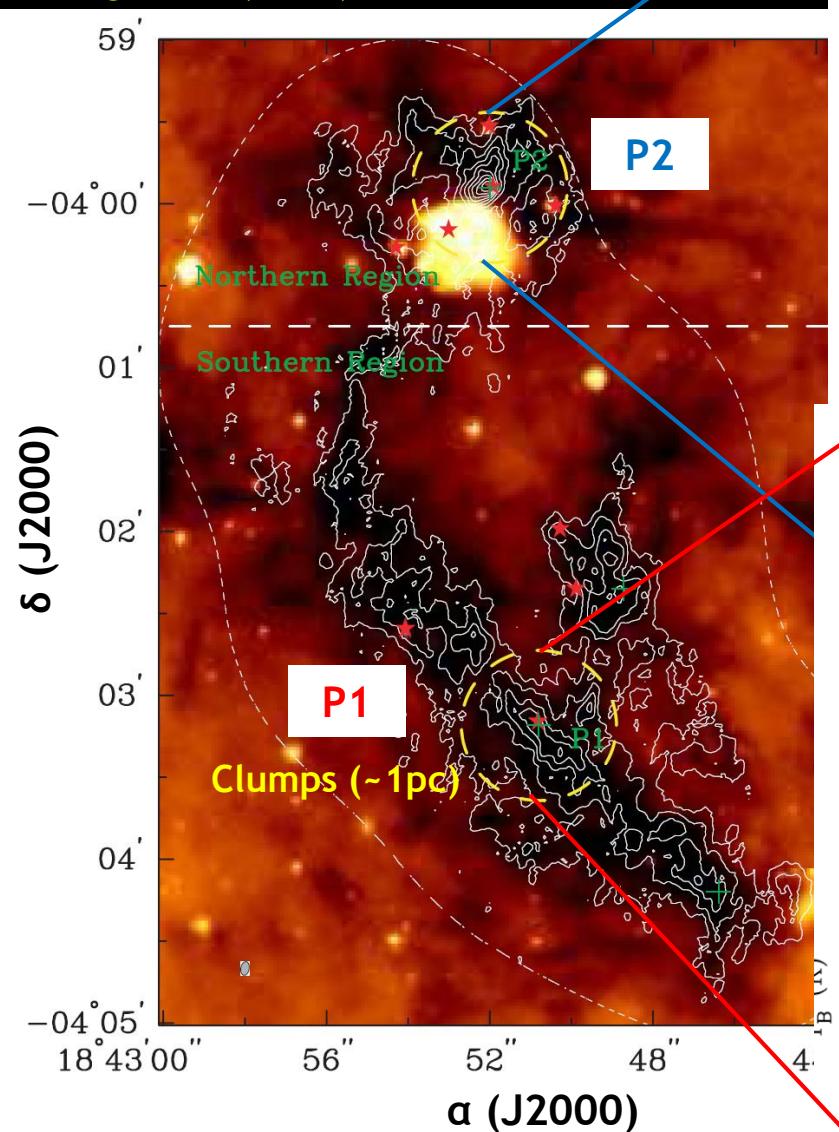
Zhang et al. (2009)



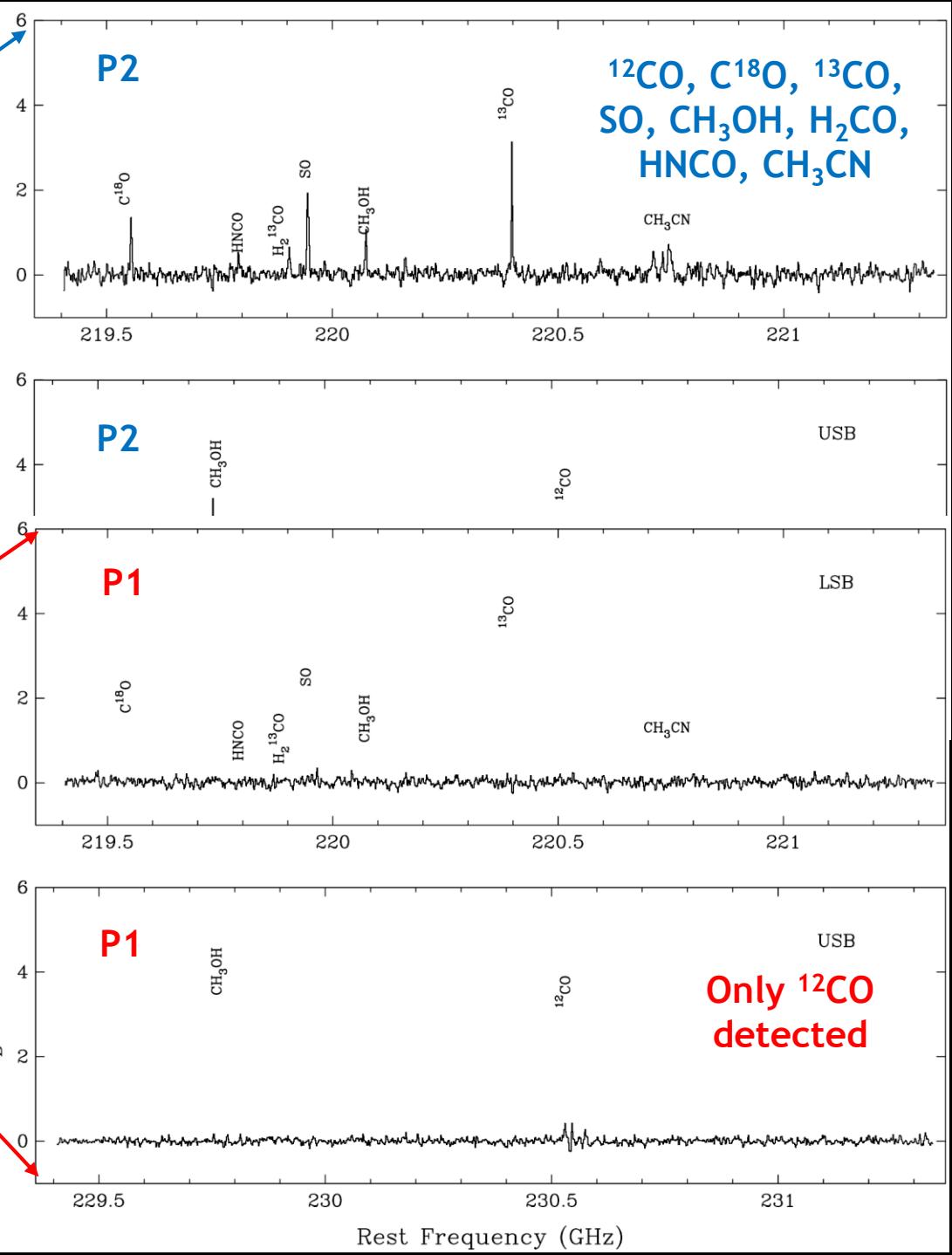
^{12}CO , C^{18}O , ^{13}CO ,
SO, CH_3OH , H_2CO ,
HNCO, CH_3CN

Initial Conditions

Zhang et al. (2009)



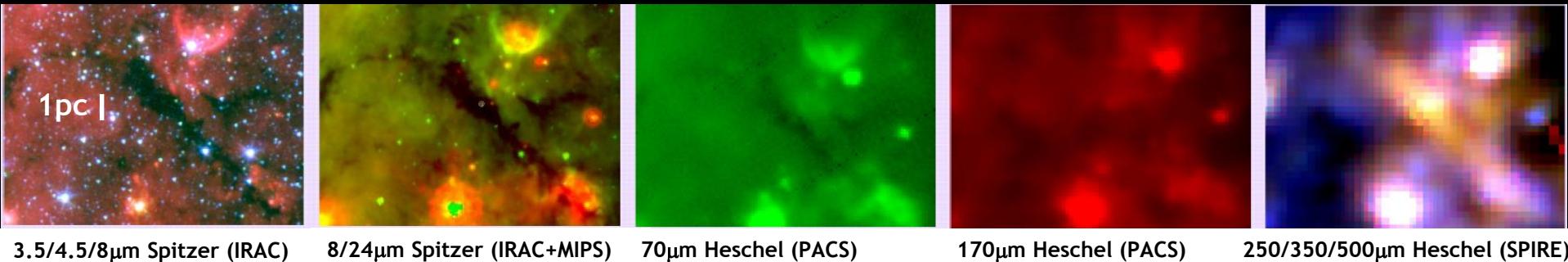
Wang et al. (2014) in G11.11-0.12



Hot Chemistry: Proto-stellar heating

- IR-bright at $\lambda \geq 250 \mu\text{m}$ 
- $T_{\text{dust}} < 25 \text{ K}$

Her4



Large chemical survey with the SMA

Collaborators:

Q. Zhang, H. Smith, P. Myers (Harvard)

J. Jackson (Boston U.)

J. Foster (Yale U.)

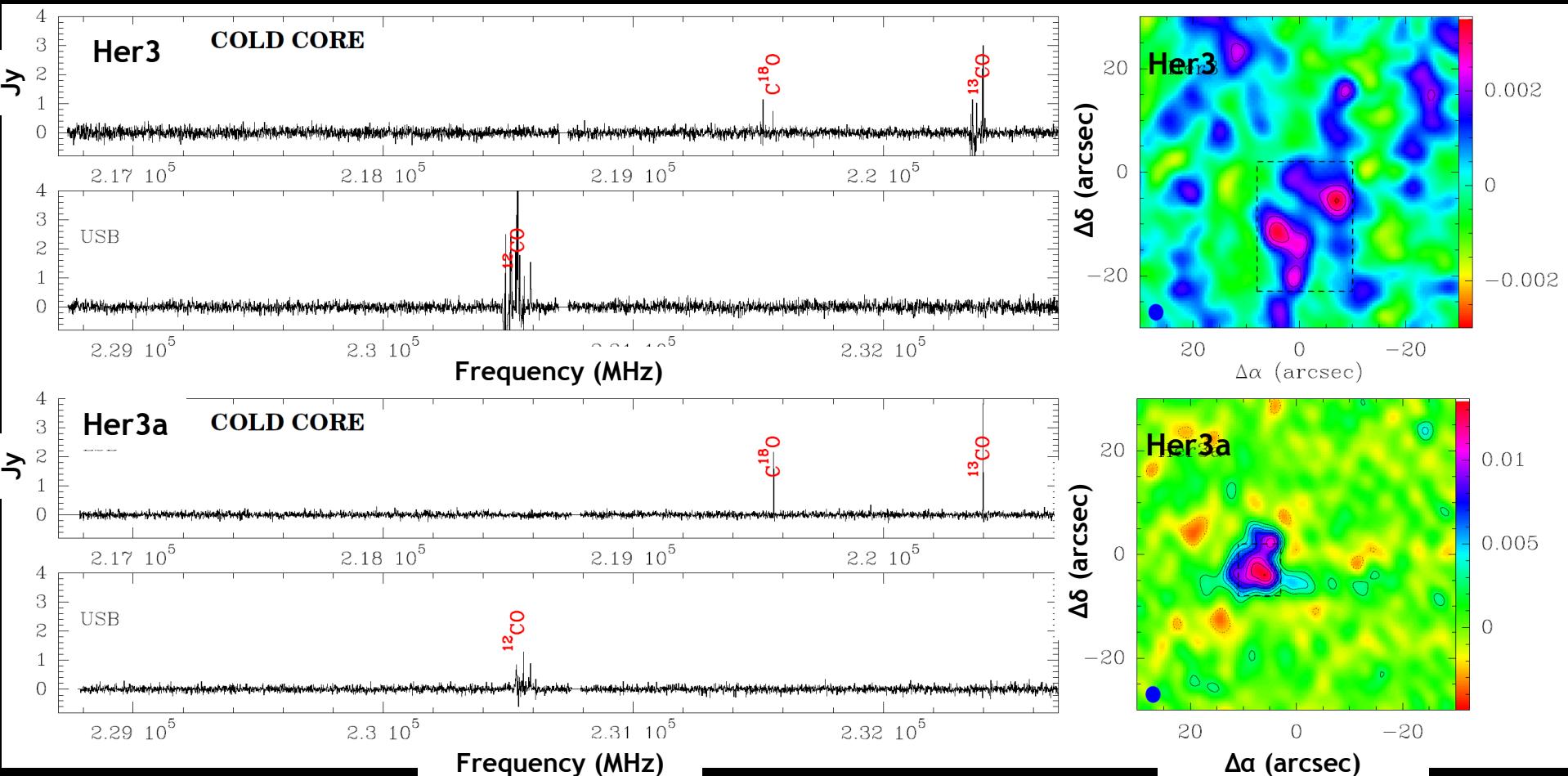
Clump chemical variations correlated with: 

- T_{dust}
- Clump's physical structure



Chemical Evolution in IRDC cores

Herschel Cold Clump sample: a) far-IR bright at $\lambda > 250\mu\text{m}$ and b) $T_{\text{dust}} \sim 15-25\text{ K}$

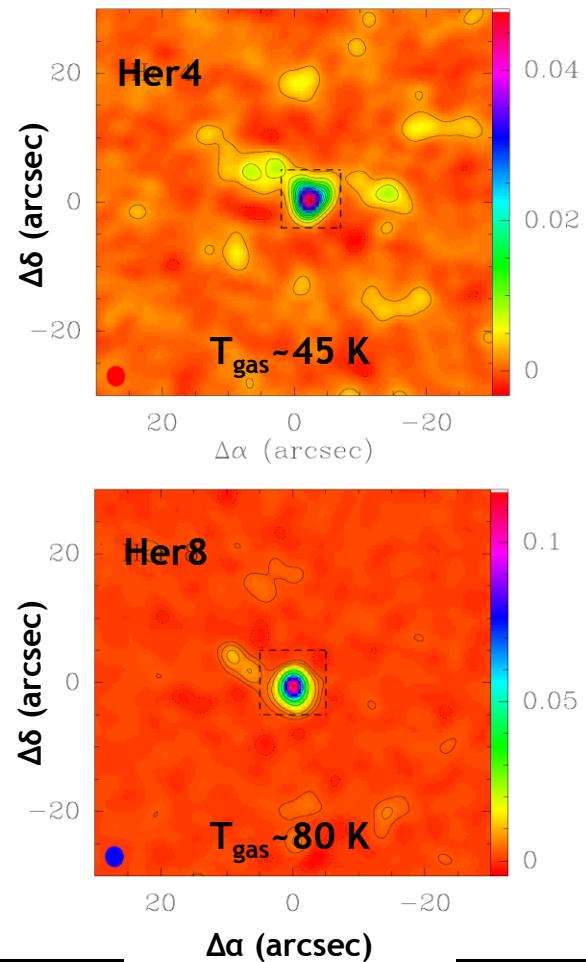
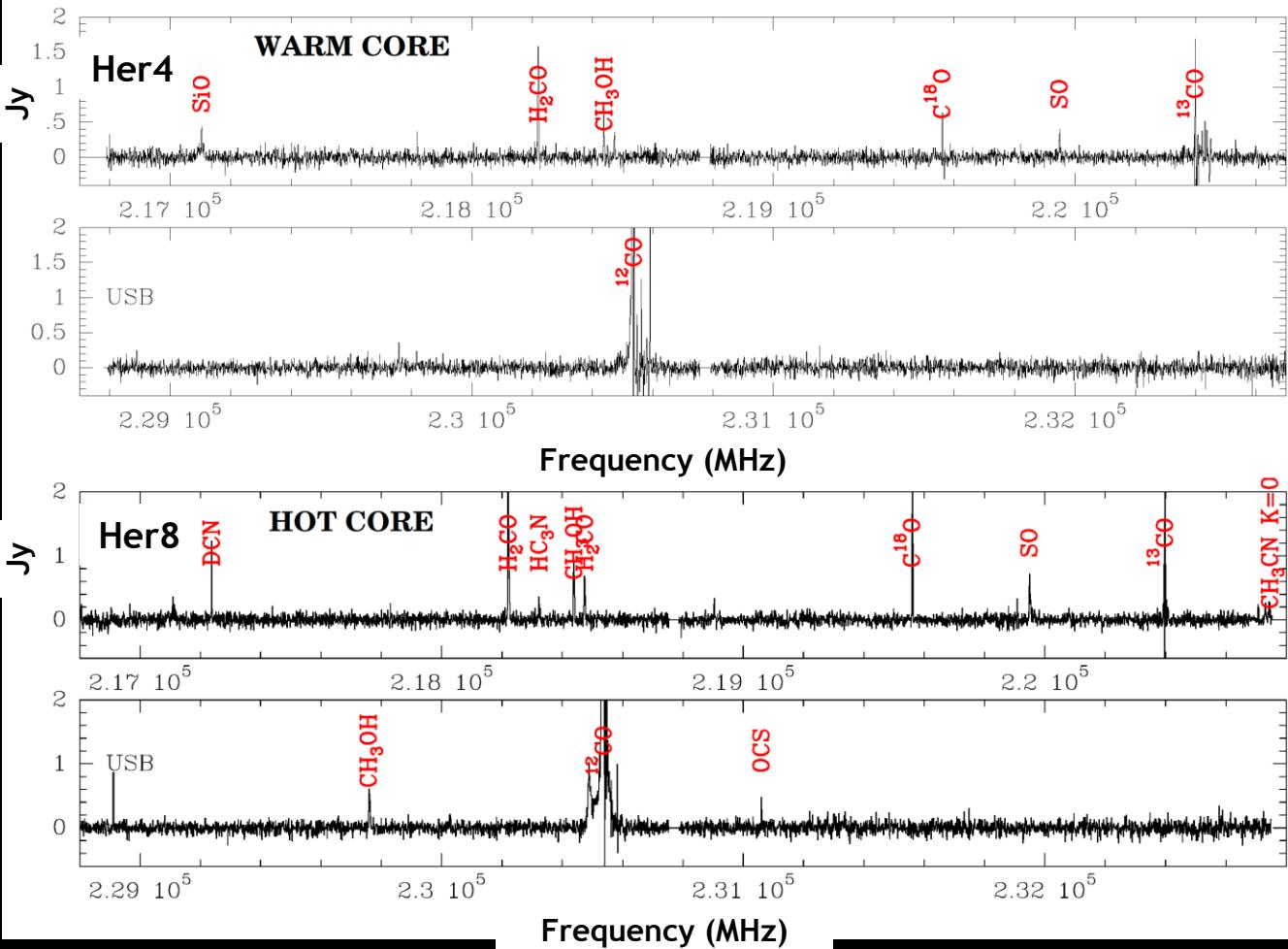


^{12}CO , ^{13}CO and C^{18}O only detected

Jimenez-Serra et al. in prep

Chemical Evolution in IRDC cores

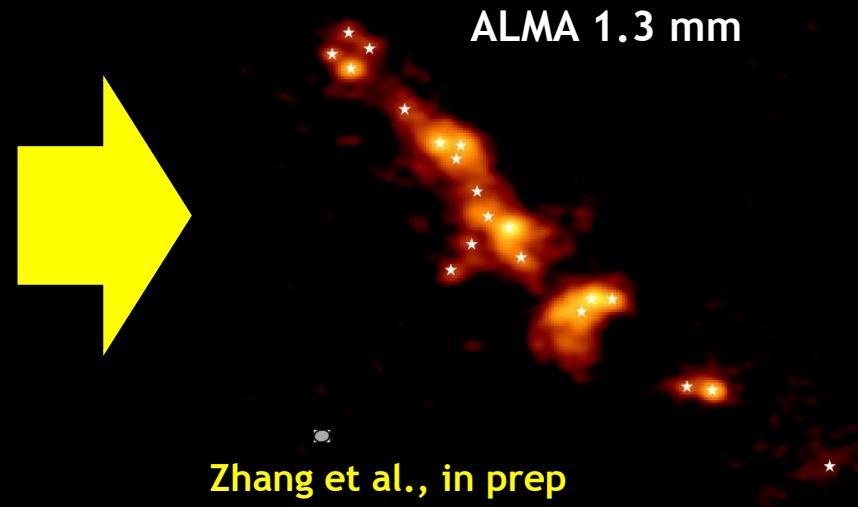
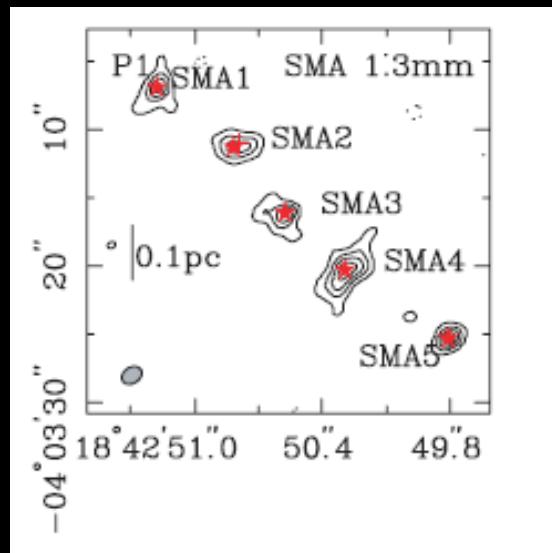
Herschel Cold Clump sample: a) far-IR bright at $\lambda > 250\mu\text{m}$ and b) $T_{\text{dust}} \sim 15-25\text{ K}$



Progressive thermal desorption of ices as the core evolves!!!

Chemical Evolution in IRDC cores

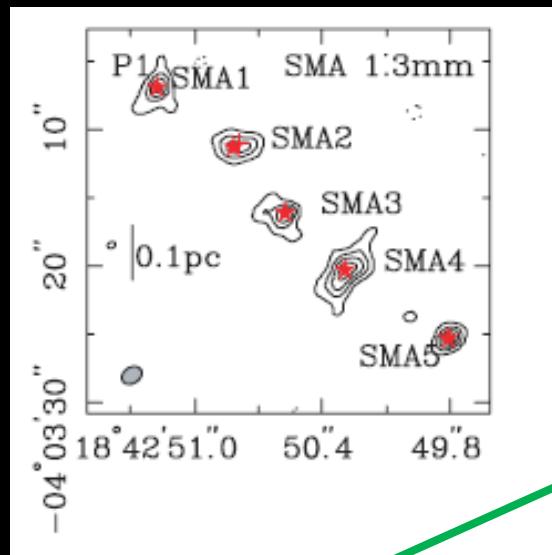
G28.34+0.06



Zhang et al., in prep

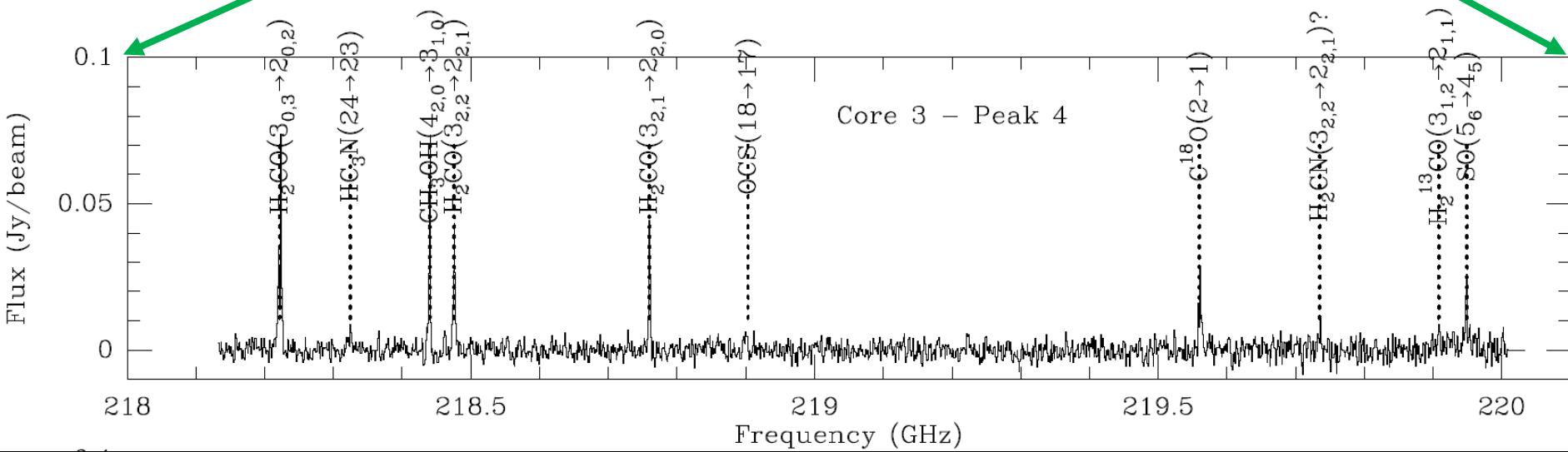
Chemical Evolution in IRDC cores

G28.34+0.06



Zhang et al., in prep

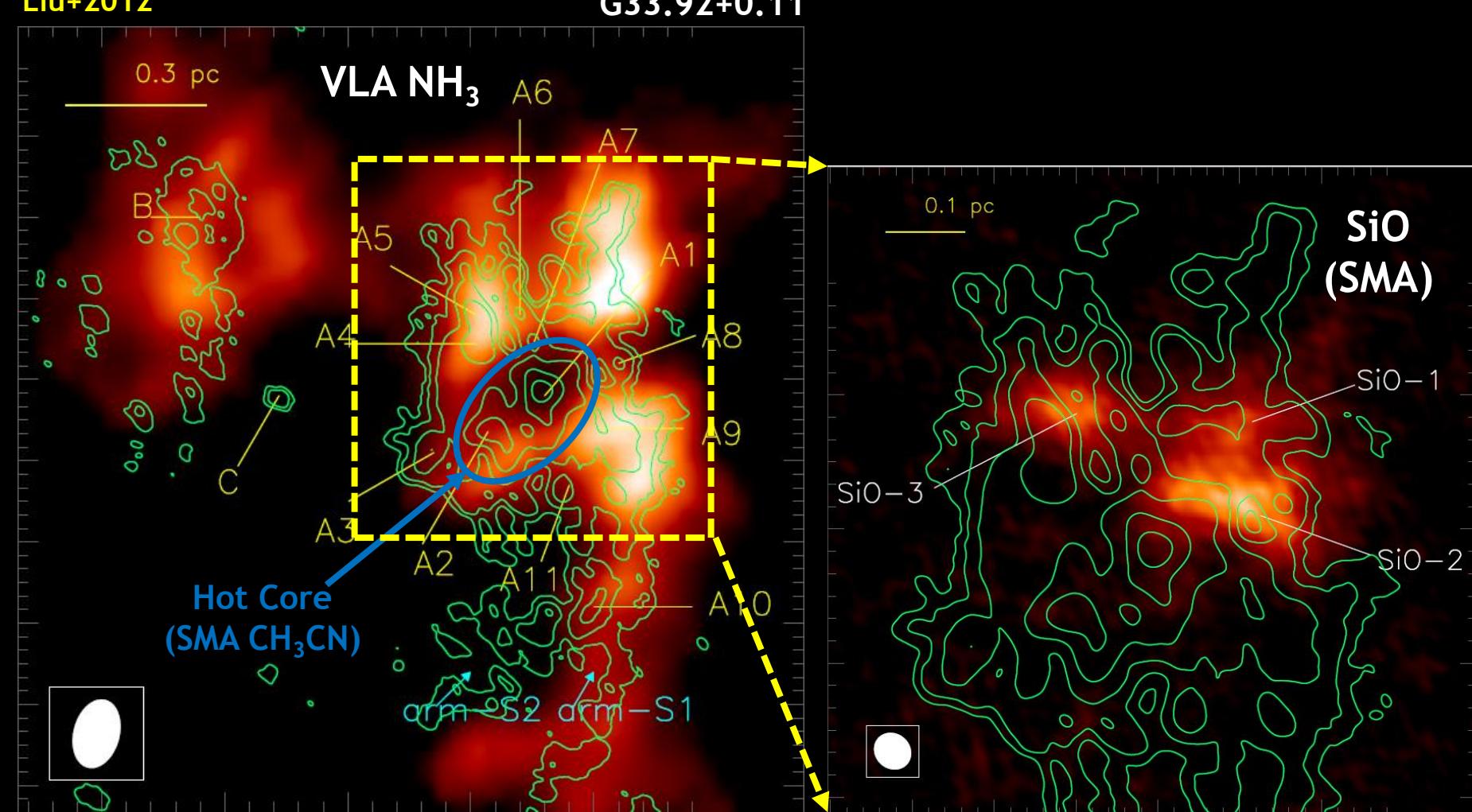
H_2CO , CH_3OH
and SO
detected
(with lower
abundances)



Chemistry, Large-scale Structure and Feedback

Chemistry reveals how funneled gas impacts onto central clump

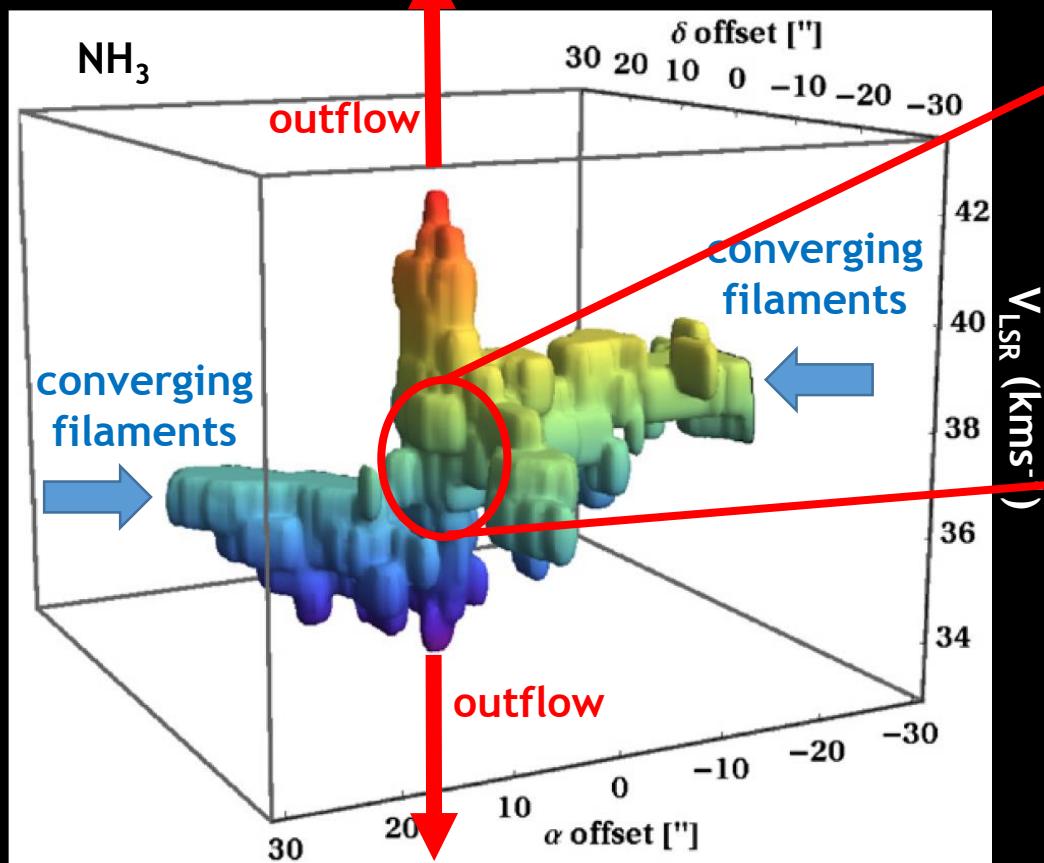
Liu+2012



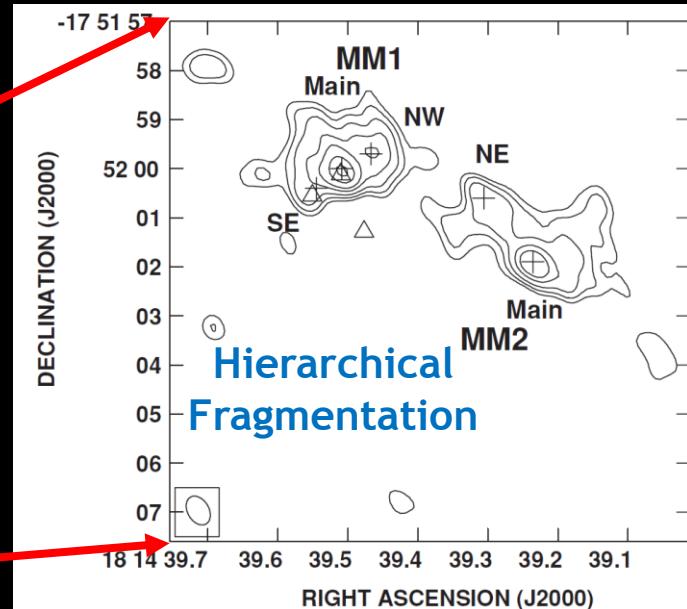
Chemistry, Large-scale Structure and Feedback

NH₃ reveals convergence of cold filaments triggering SF

Galvan-Madrid+2010



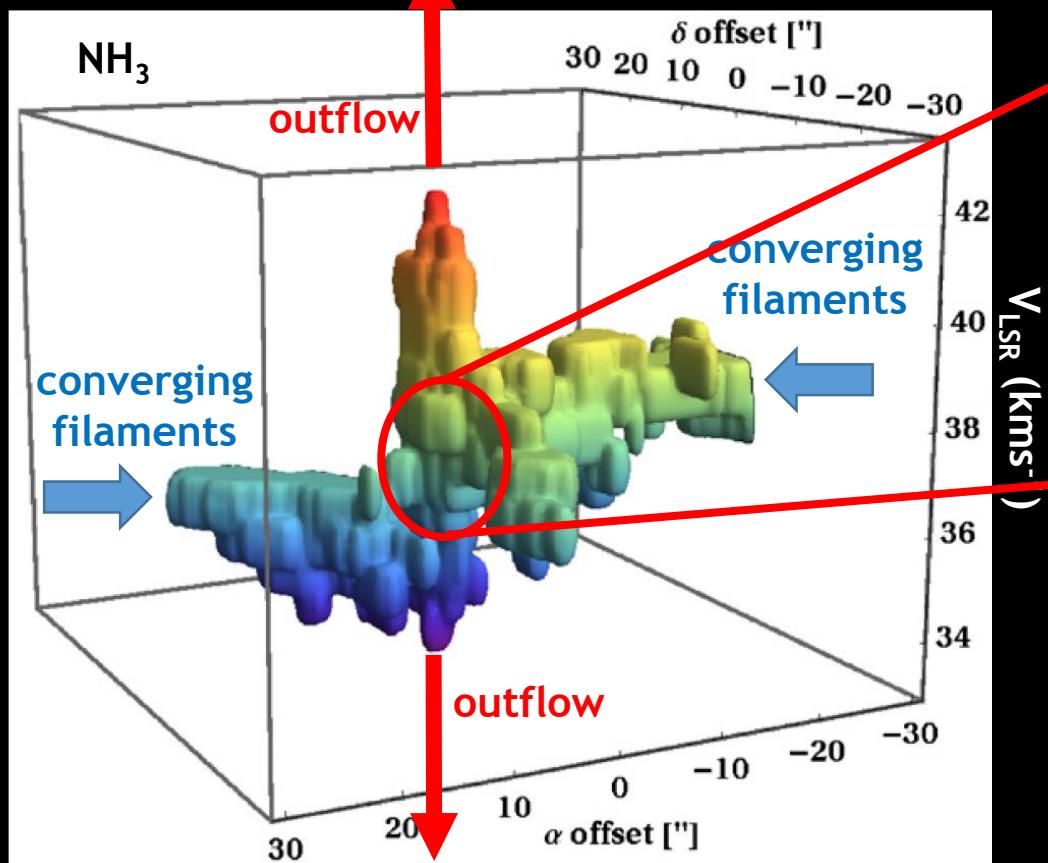
W33A



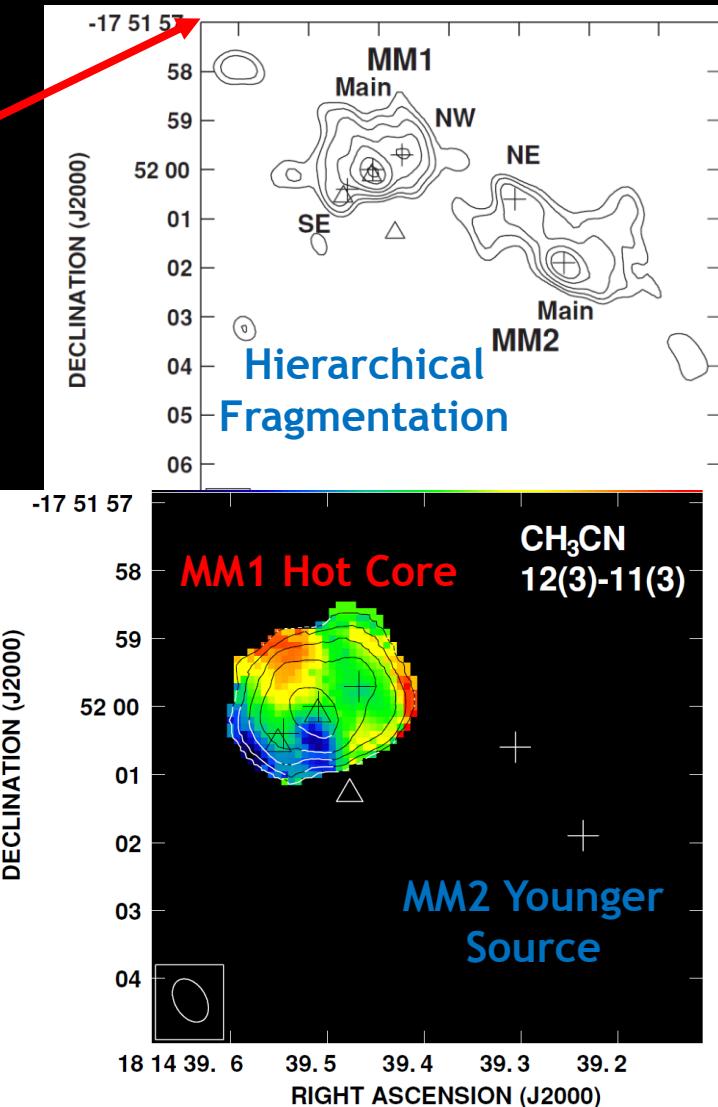
Chemistry, Large-scale Structure and Feedback

NH₃ reveals convergence of cold filaments triggering SF

Galvan-Madrid+2010

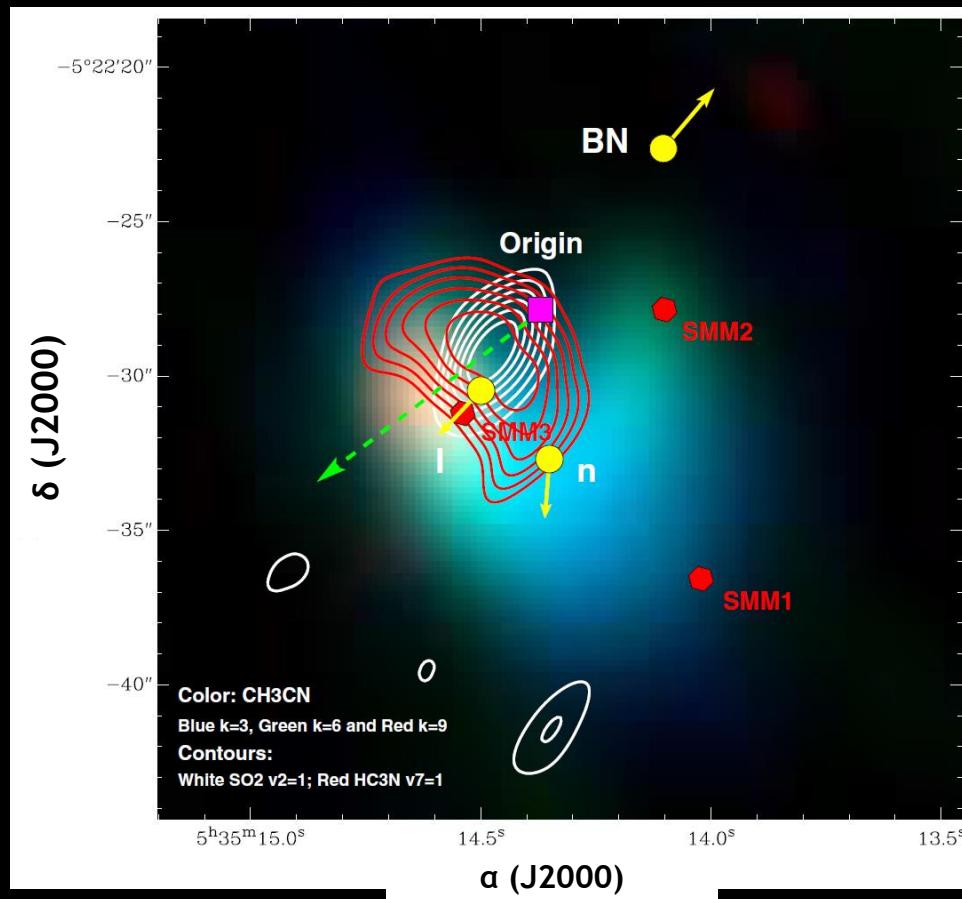
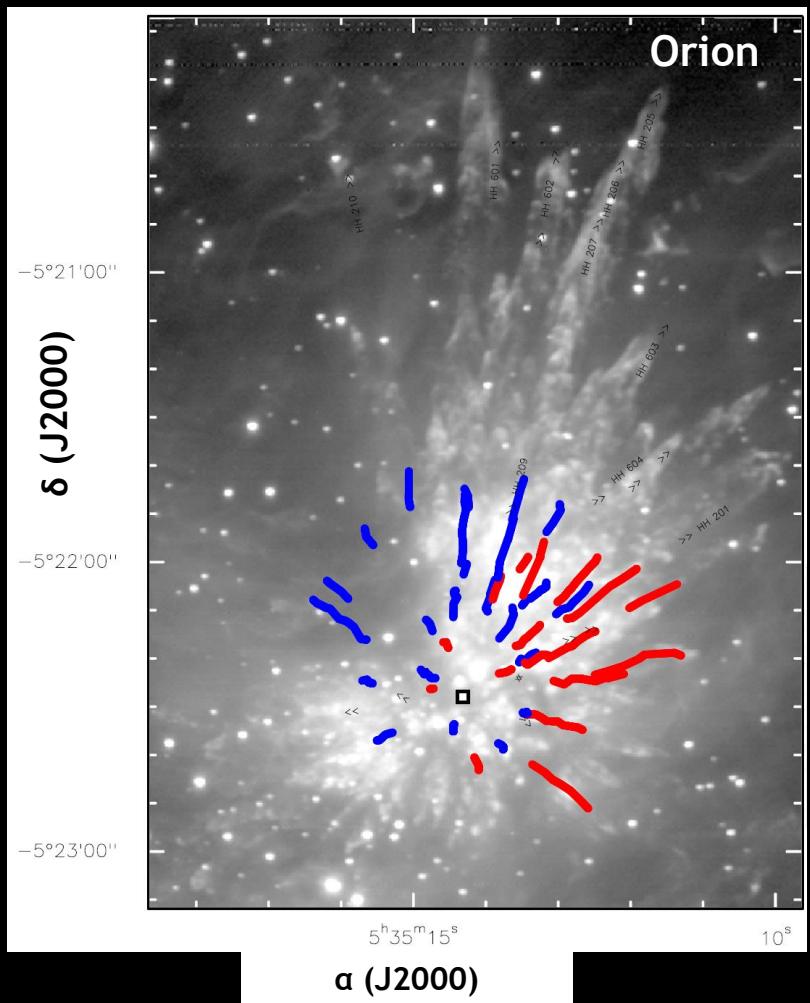


W33A



Large-scale explosive outflows

Orion Hot Core not a Hot Core: Result of the explosive event?
Zapata+2009



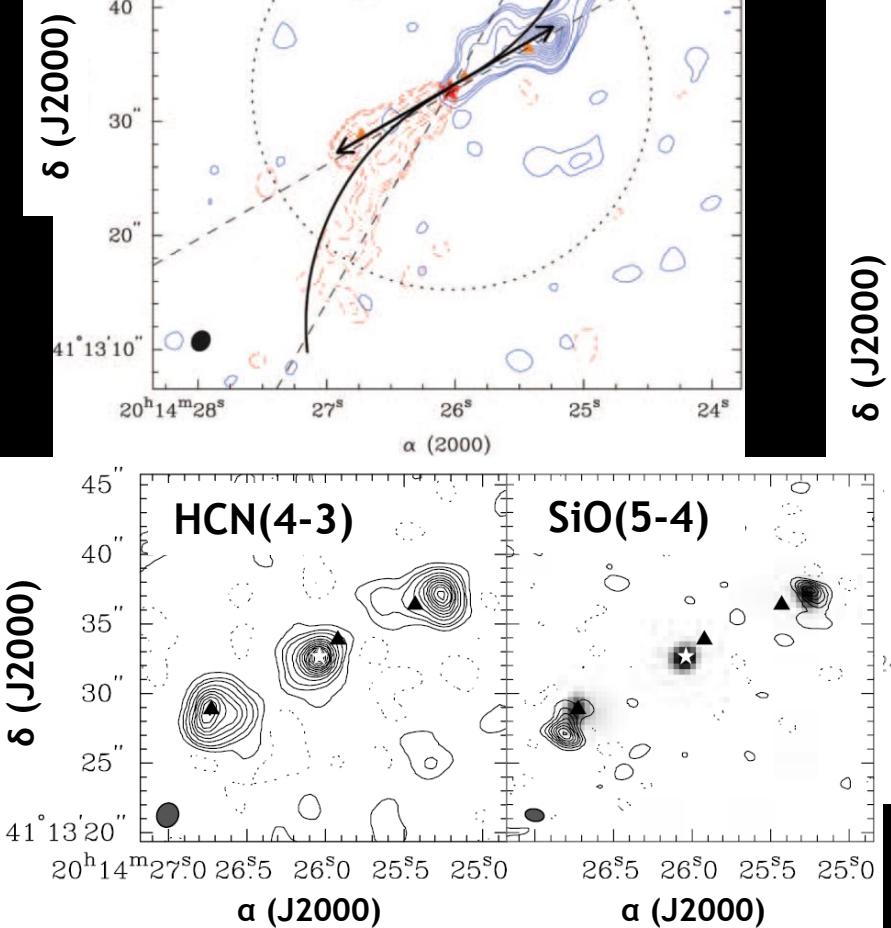
No sub-mm, radio or IR source: Hot Core externally heated?

Outflows driven by High-mass Protostars

Orion Hot Core not a Hot Core: Result of the explosive event?

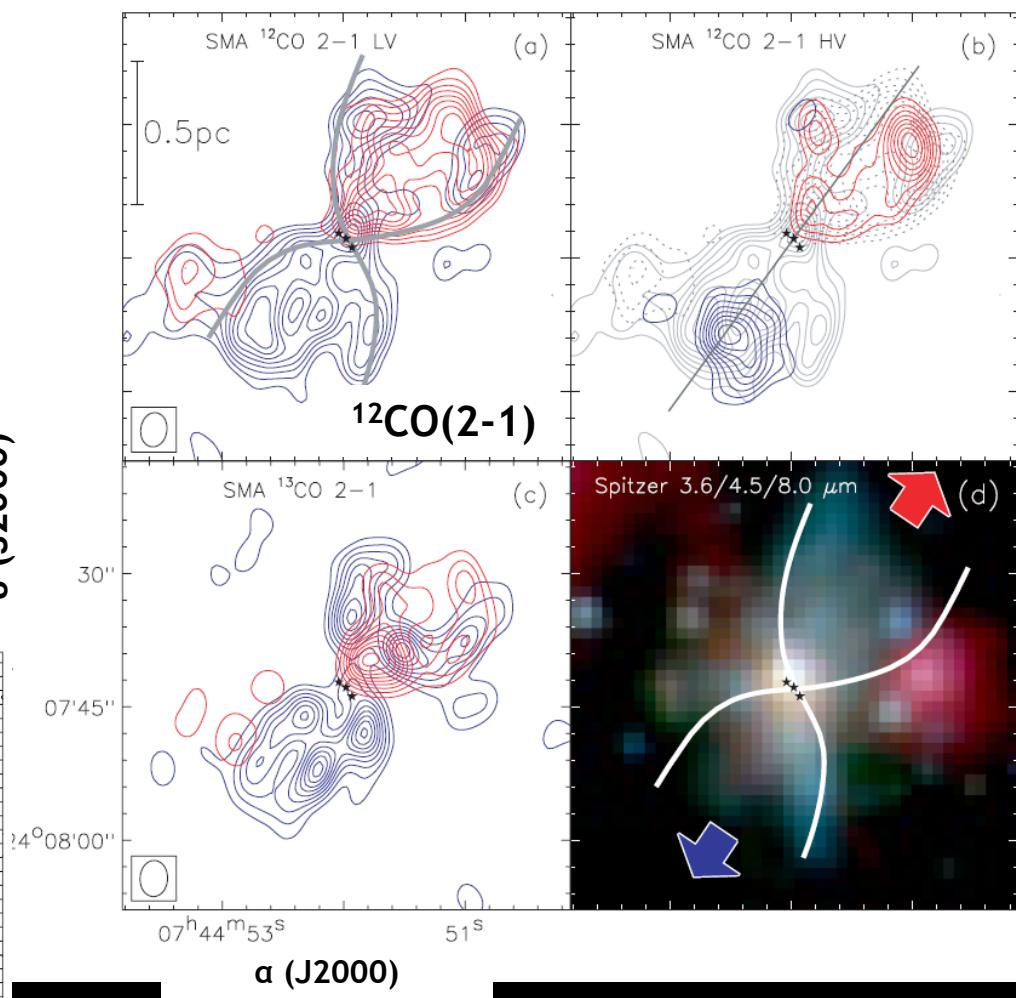
Su+2007

IRAS20126+4104



G240.31+0.07

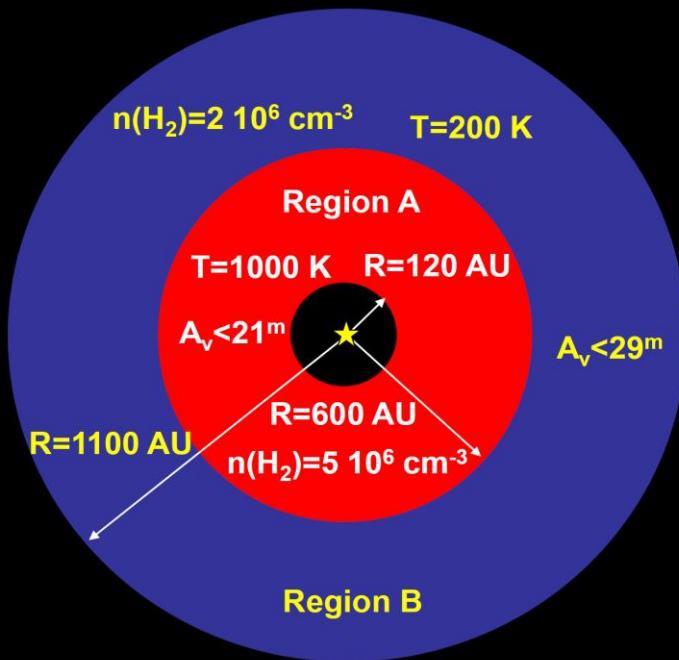
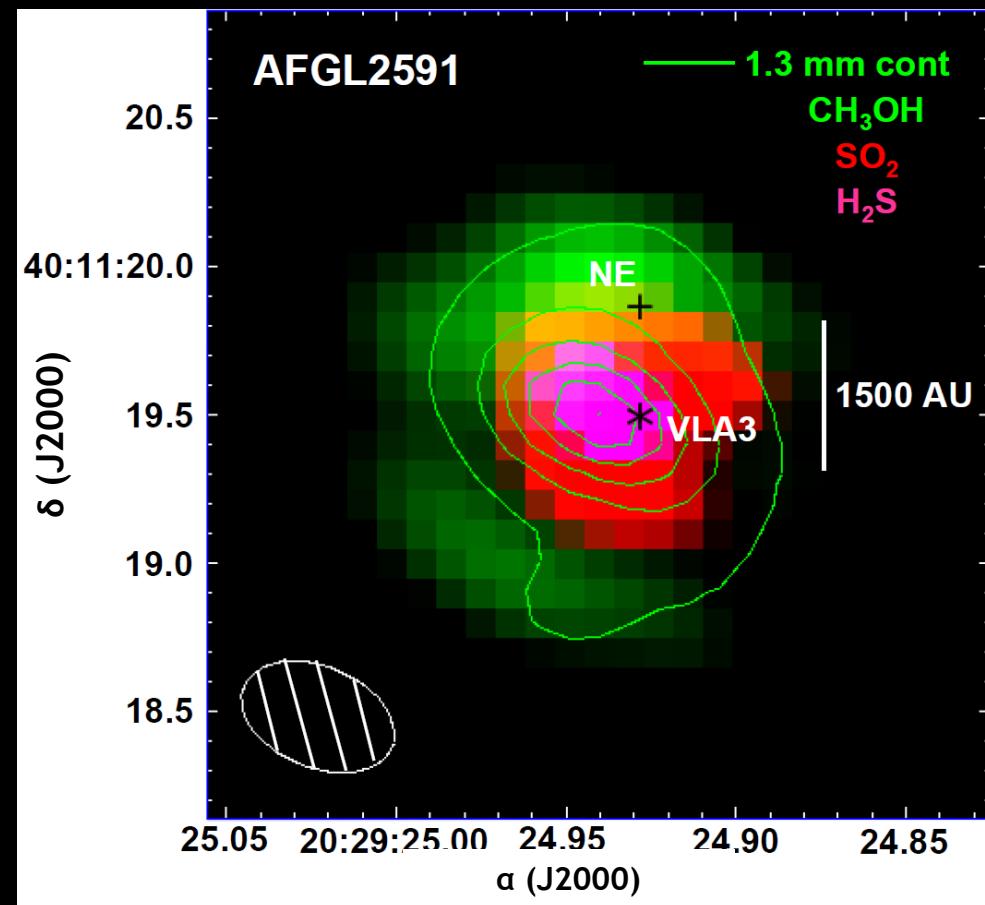
Qiu+2009



Smaller scales: High-mass Hot Cores

Chemical segregation in the AFGL2591 VLA 3 hot core

Jimenez-Serra+2012



i) strong UV photo-dissociation
+

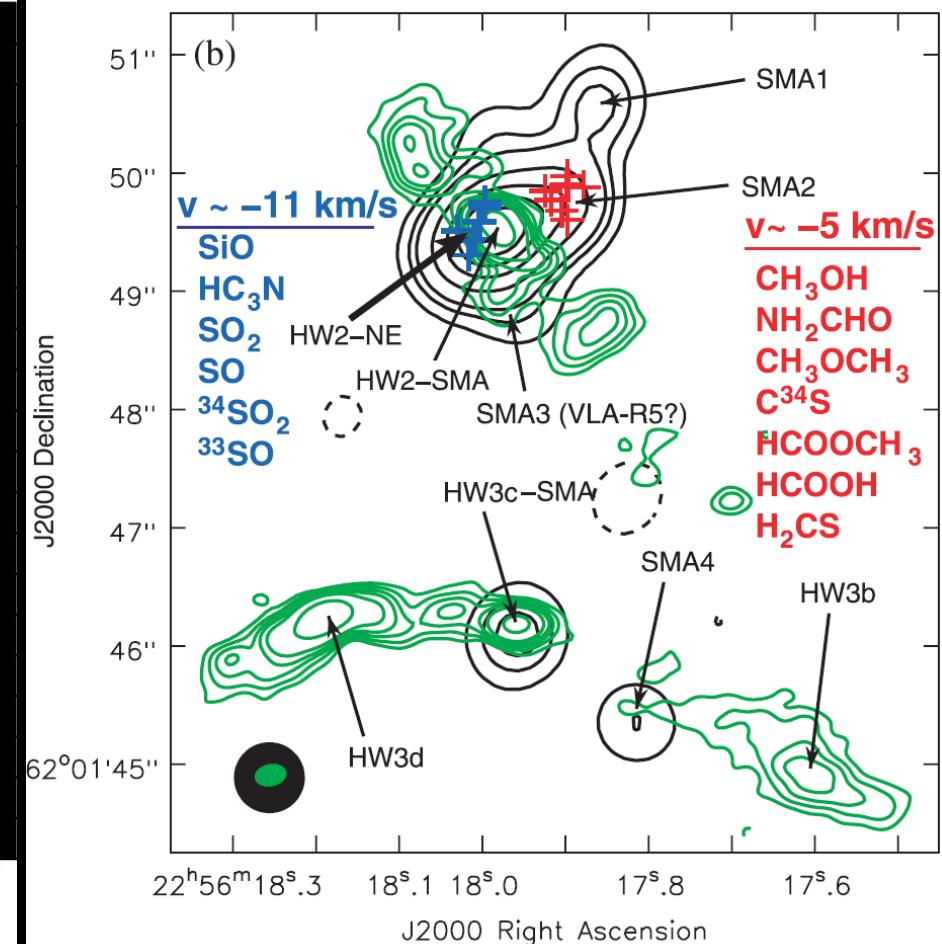
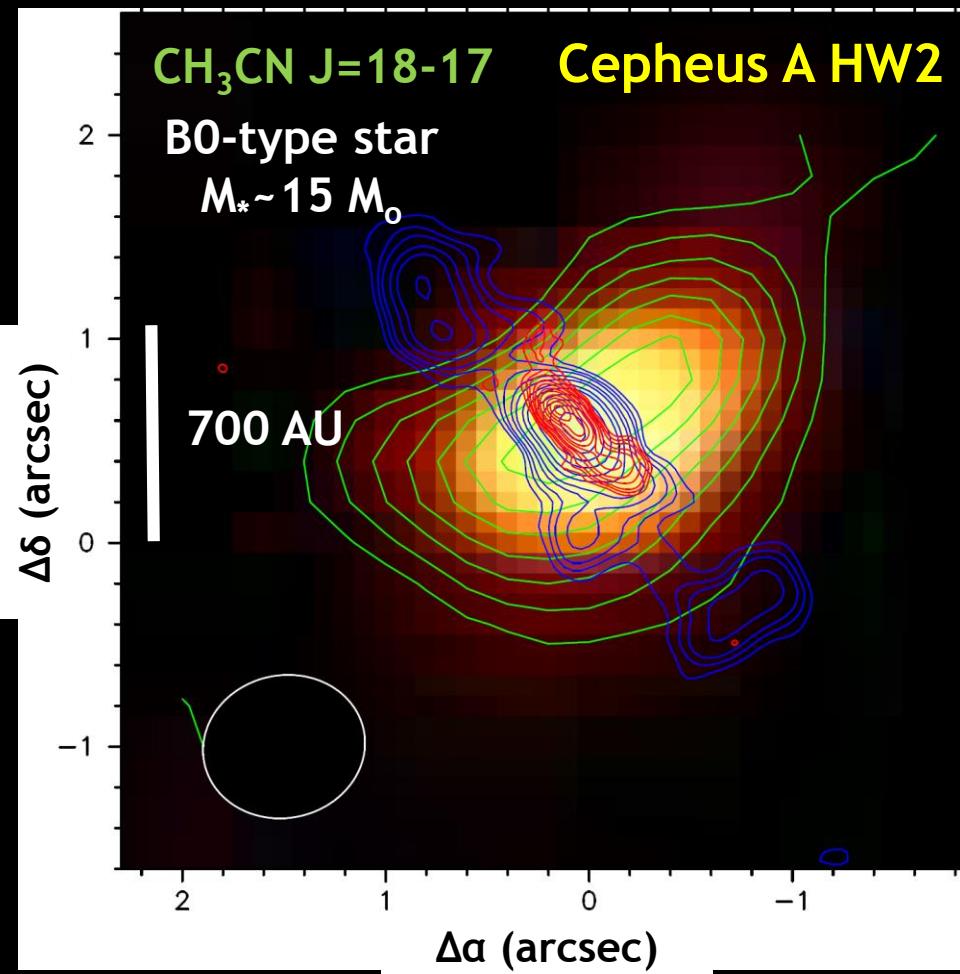
ii) high T gas-phase chemistry

Presence of a cavity
with $r < 120 \text{ AU}!!!$

Smaller scales: Disks around Massive Stars

Patel et al. (2005)

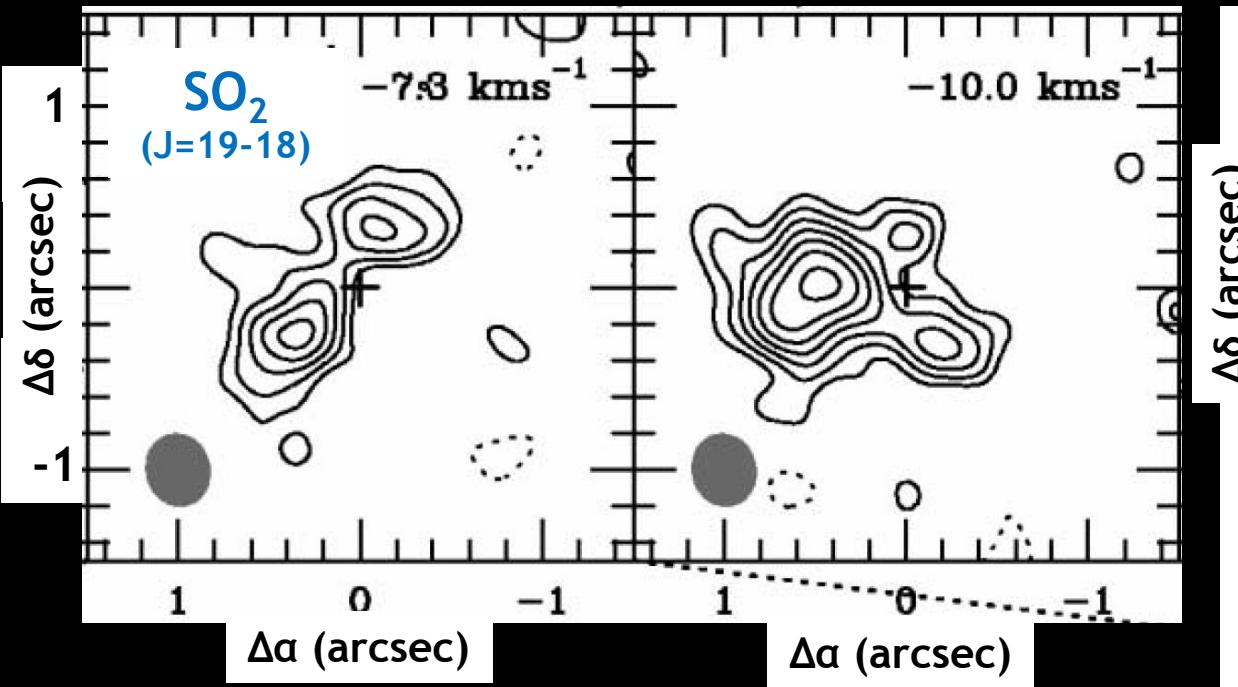
Brogan et al. (2007)



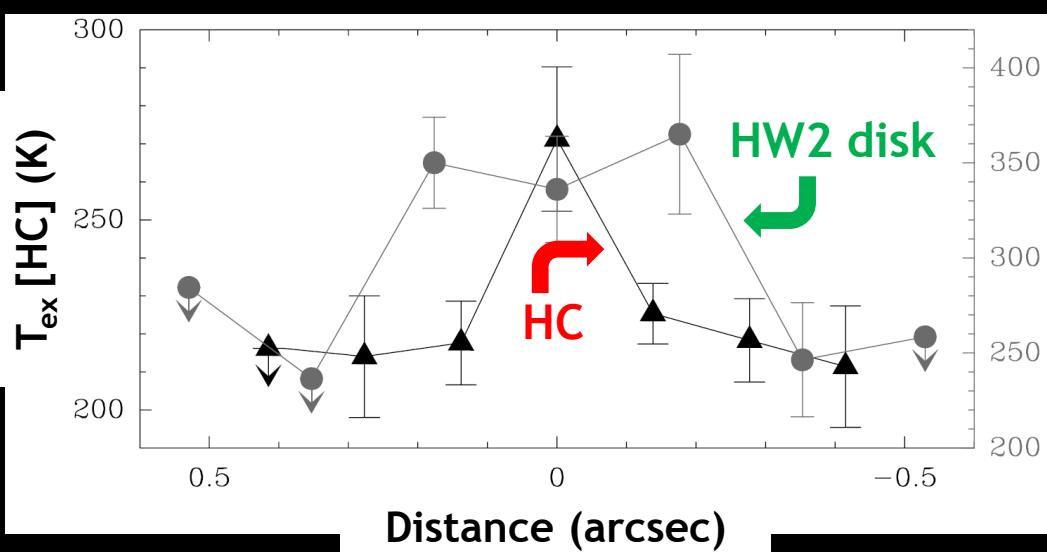
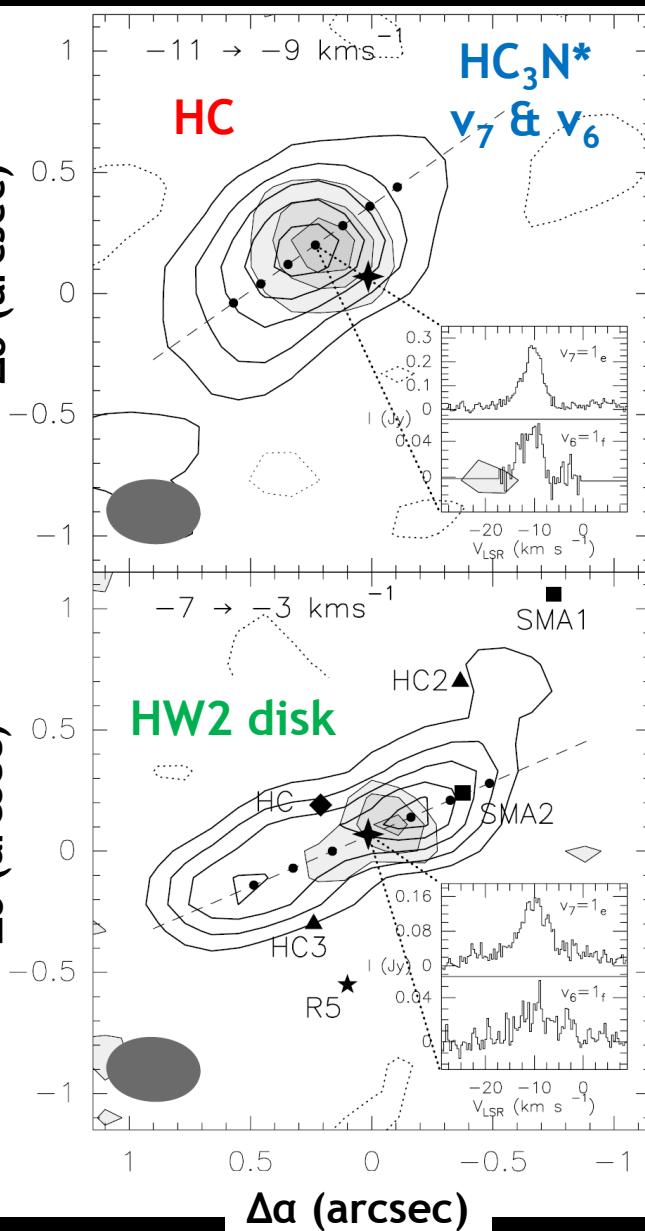
Circumstellar disk or superposition of several objects?

Disks around Massive Stars: Cepheus A HW2

Jimenez-Serra et al. (2007)



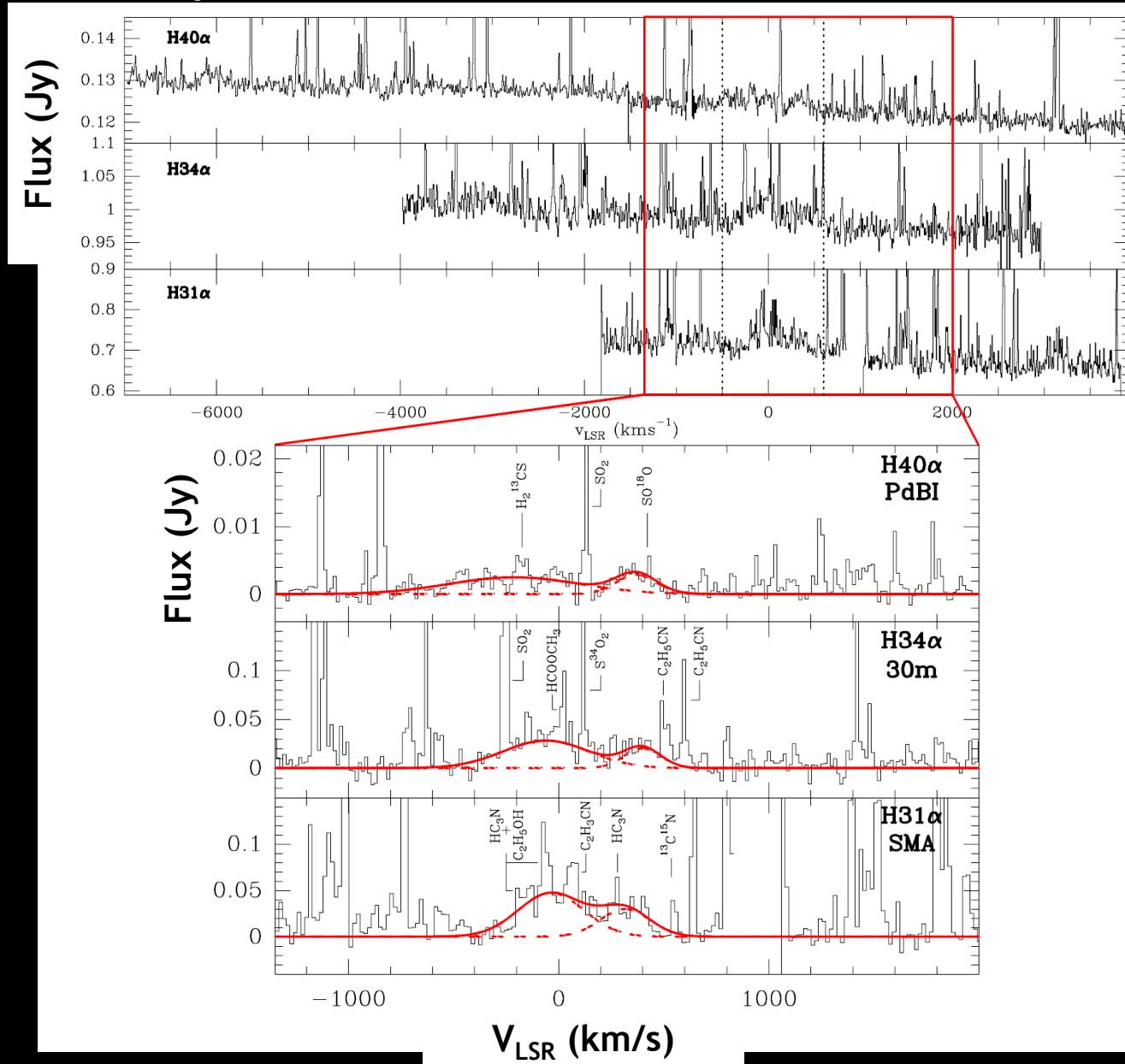
Jimenez-Serra et al. (2009)



Kinematics of Ionized Disks and Winds

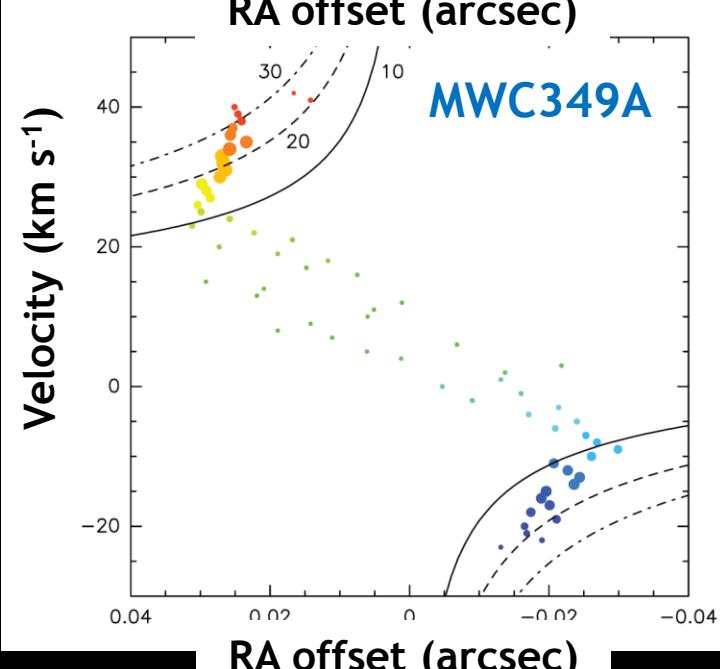
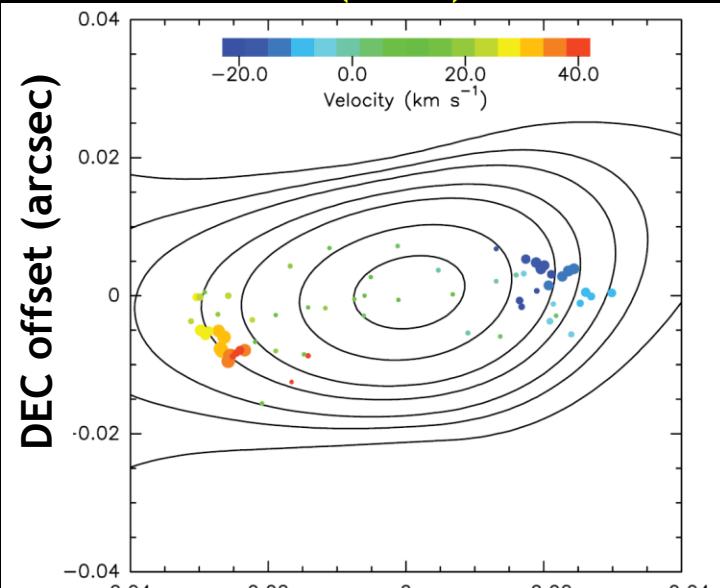
Cepheus A HW2

Jimenez-Serra et al. (2011)

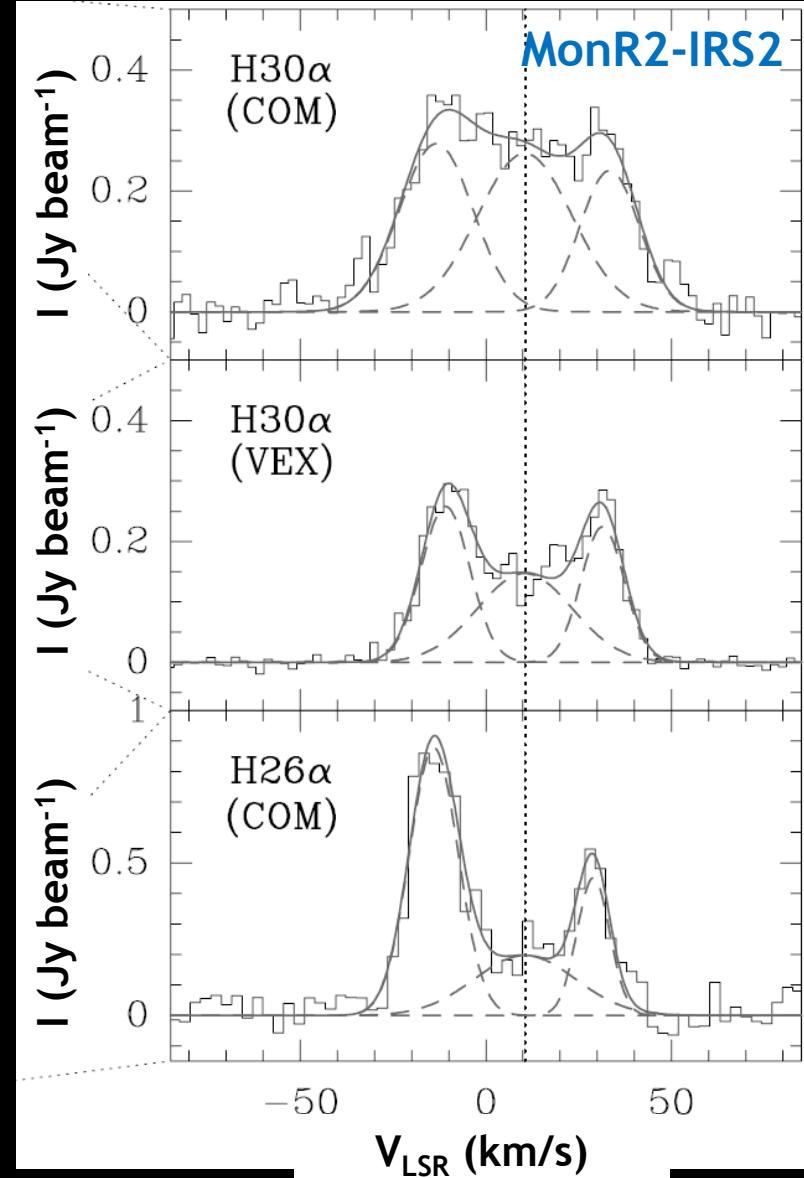


Kinematics of Ionized Disks and Winds

Weintraub et al. (2008)

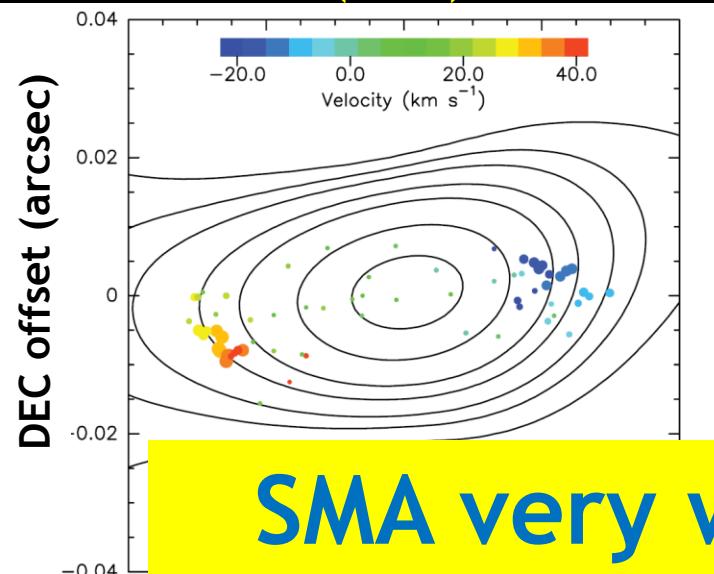


Jimenez-Serra et al. (2013)

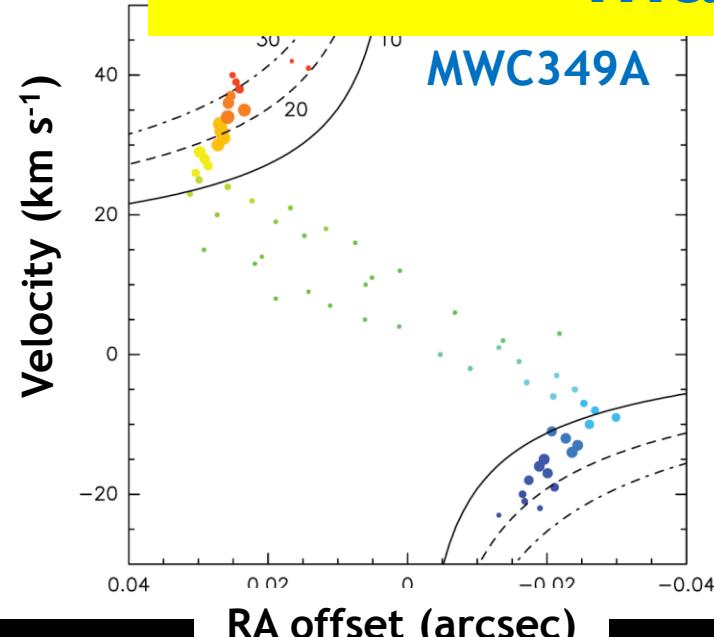


Kinematics of Ionized Disks and Winds

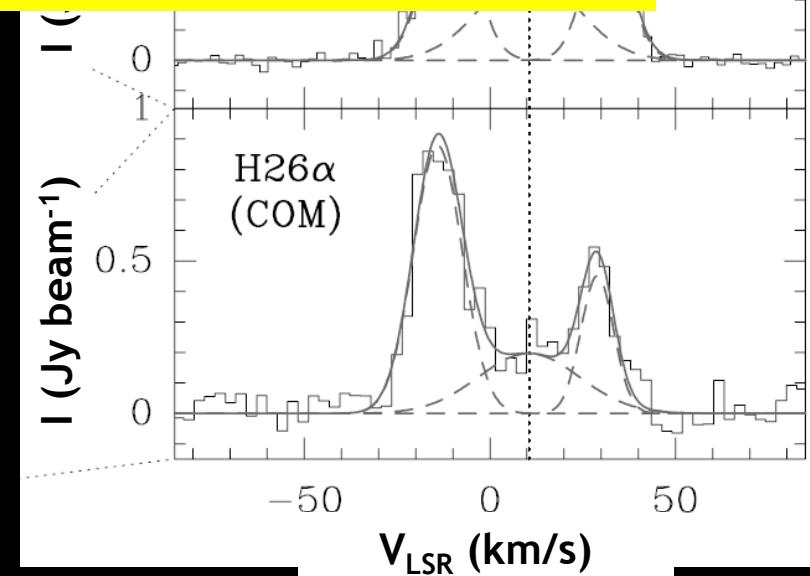
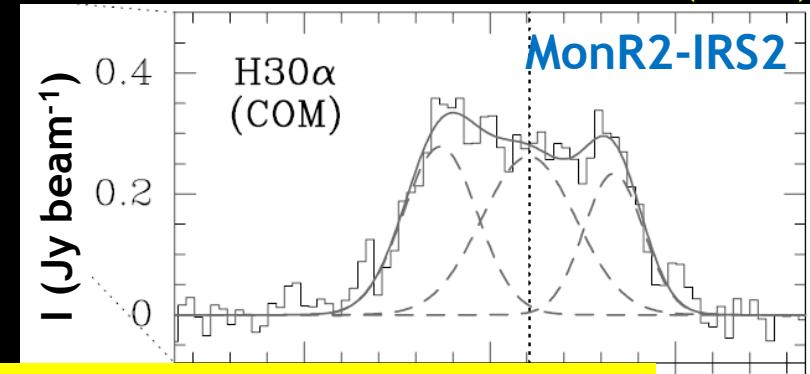
Weintraub et al. (2008)



SMA very well suited for RRL
maser studies



Jimenez-Serra et al. (2013)

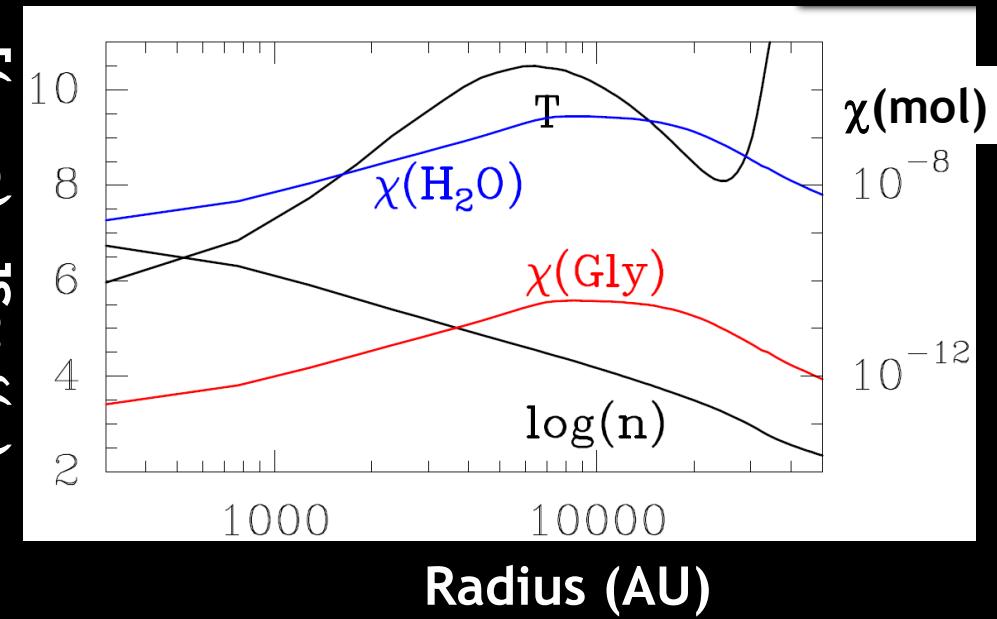
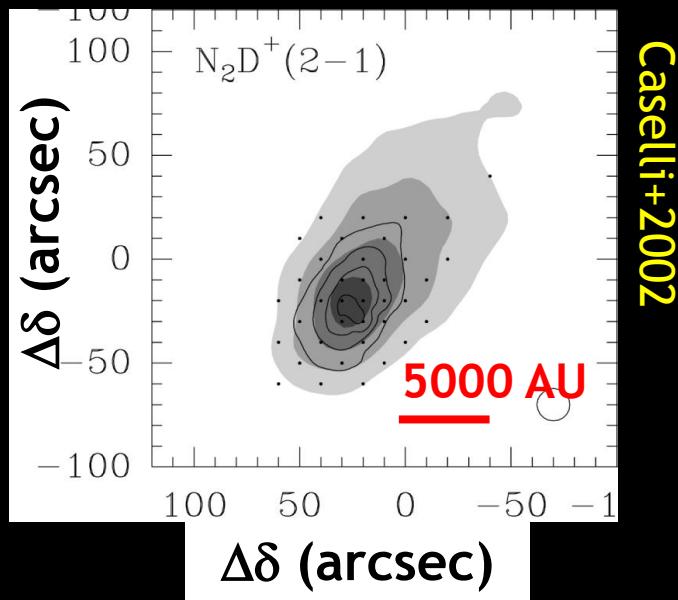
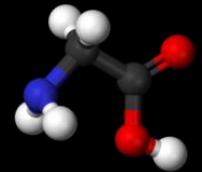


Challenges for the Next Decade

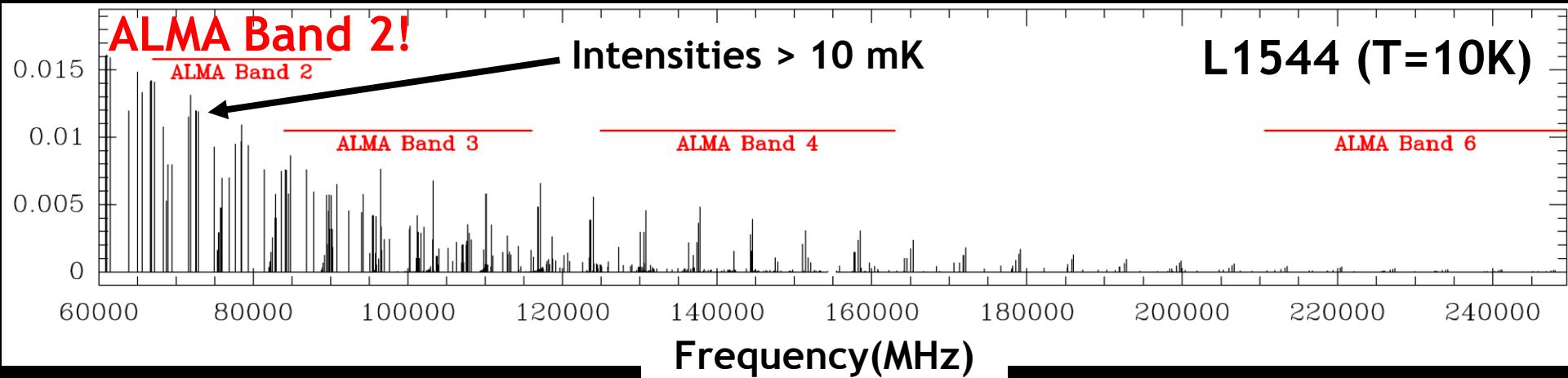
- Detection of COMs in all kinds of environments:
Low-mass Protostars (Jorgensen+2012), **Hot Cores**
(Belloche+2013), **Galactic Center** (Requena-Torres+2006), **PDRs**
(Guzman+2014), **pre-stellar cores** (Bacmann+2012)
- **Interferometry is key** \Rightarrow linewidths reduced \Rightarrow easier
line identification in crowded spectra
- **Broad bandwidth crucial!!!** \Rightarrow **SMA**
- **COM chemistry in low-mass objects** \Rightarrow
Advent of new instrumentation

Cold Glycine in Pre-stellar Cores

$(\text{NH}_2\text{CH}_2\text{COOH})$



Jimenez-Serra+2014



Conclusions

- SMA pioneering instrument for chemistry in SF regions.
- Advances in our understanding of physics in low-mass and high-mass SF through chemistry:
- Cold initial conditions of SF
- Protostellar heating: Warm and Hot Envelopes, Disks
- Chemistry in Outflows

