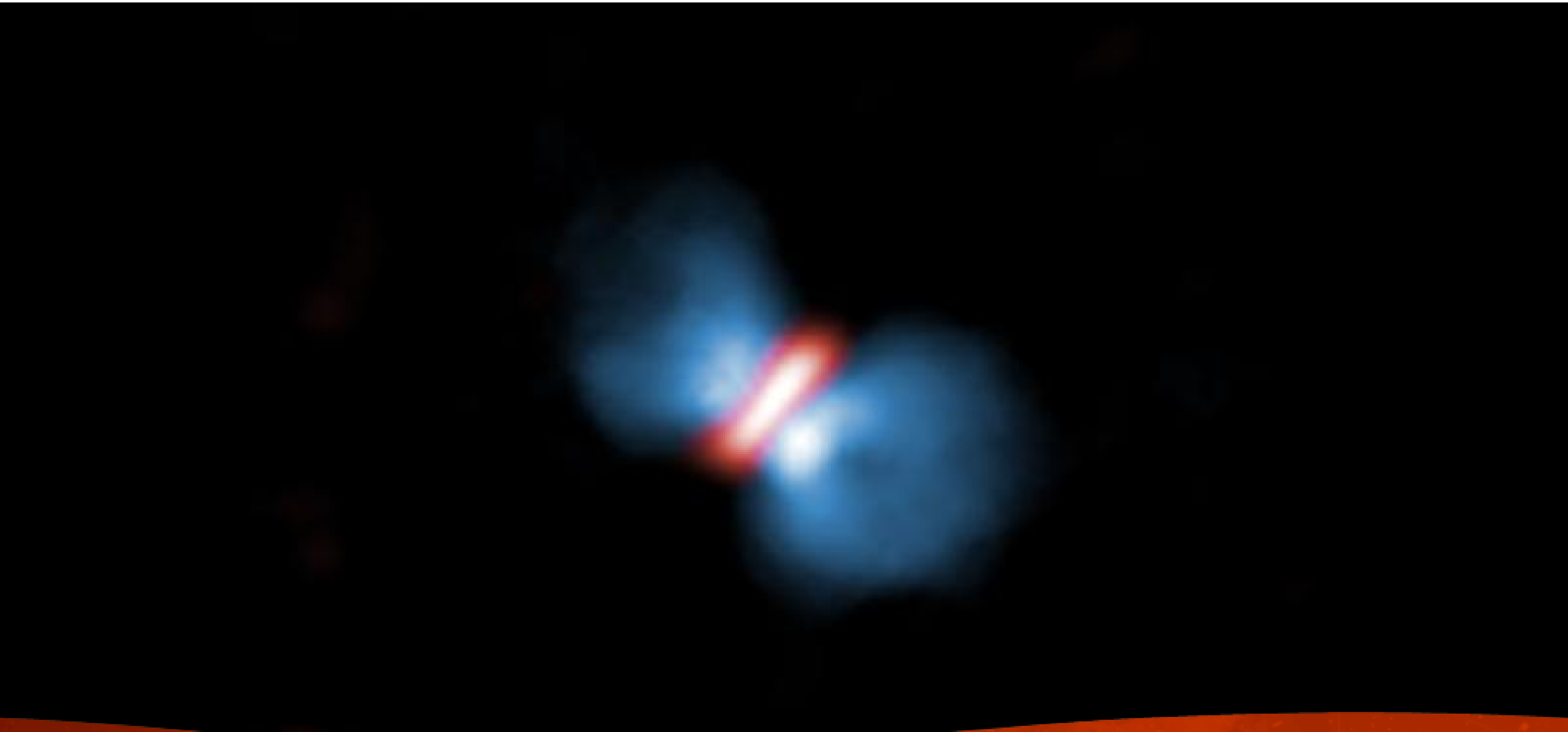


# Star Formation/ISM


**A. Wootten, NRAO**

# Advantages of GBT/Total Power

- New instruments may be outfitted more easily on a TP telescope
  - Provides access to new technology
  - Nimbleness
- Interpretation, particularly of extended regions, requires total flux recovery
- Wide field of view: Molecular emission generally is extended and may occur at just about any frequency
  - ALMA has had requests for 1000s of pointings!

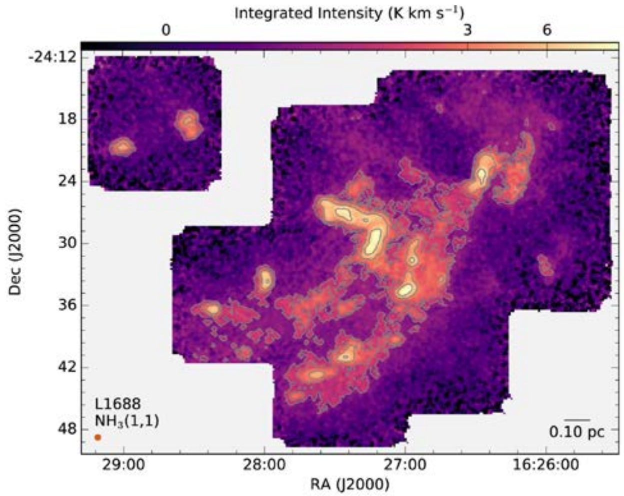
# Some SF/ISM Questions

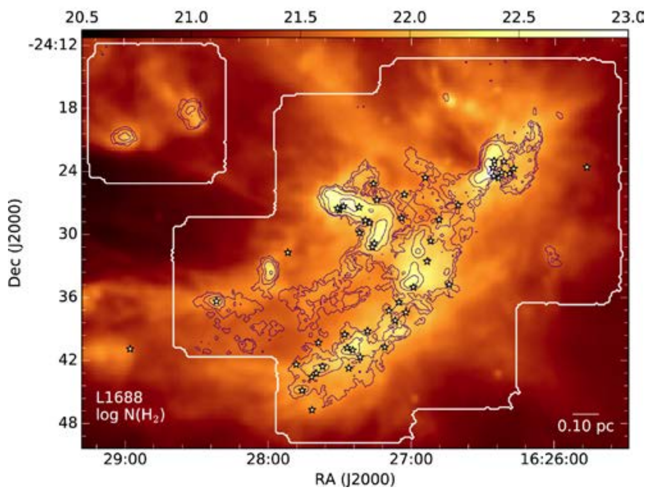
- What is the relation between hydrocarbon molecules and carbon grains and PAHs?
- How are complex organic molecules formed? Is the disk chemical composition inherited from the dense core?
- How do grains evolve? How do grain mantles grow? What is the role of mantles in increasing molecule complexity?
- What is the role of magnetic field in the collapse ?
- When do protoplanetary disks form? At what size?
- How is the ionization fraction regulated? What is the impact on the chemistry & on the coupling with B field?
- How does $H_2$ form? Is the $H_2$ Ortho to Para ratio at thermal equilibrium?

  - M. Gerin, IAU332

# Ammonia Surveys

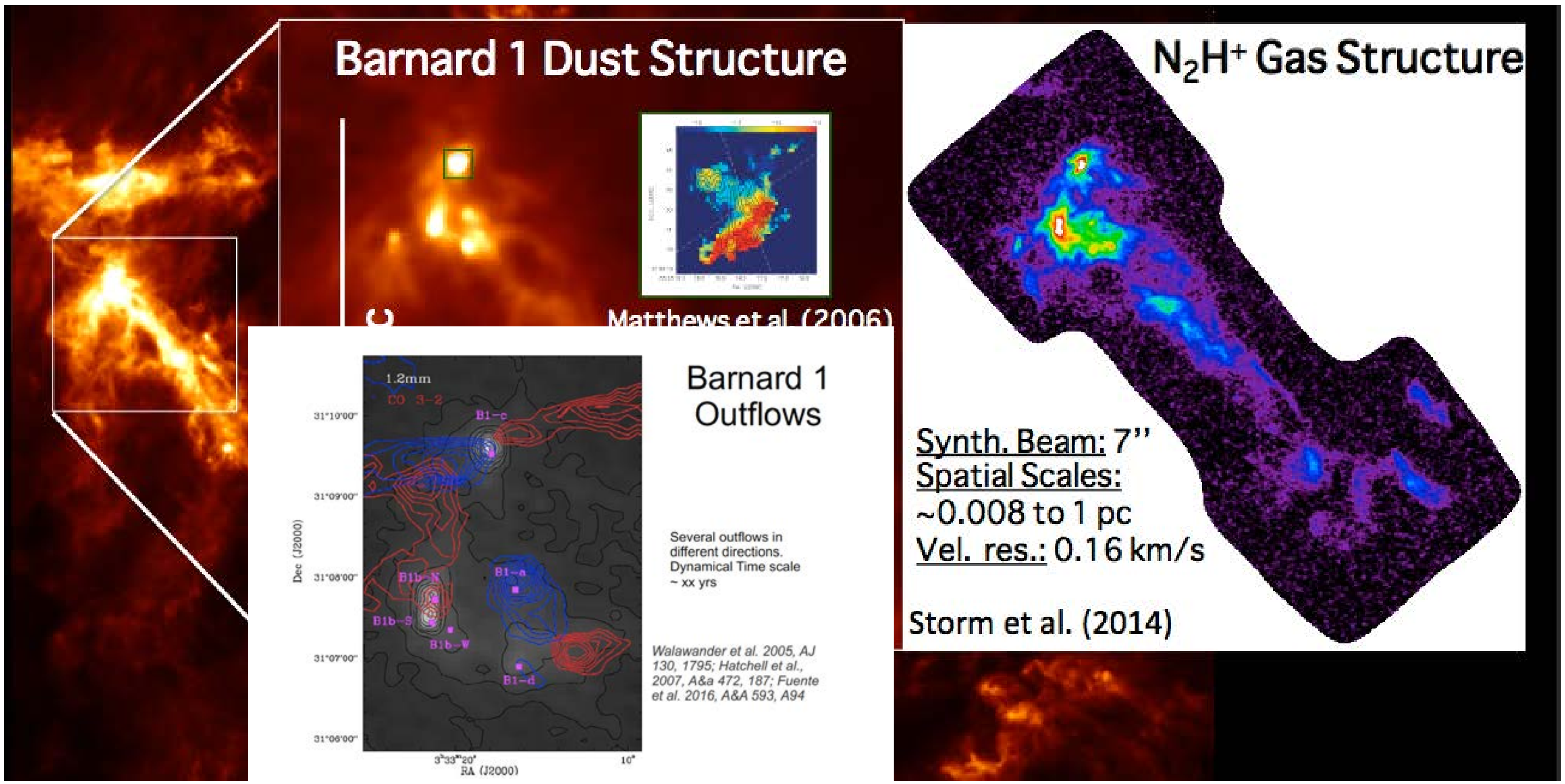
Friesen et al. 2017



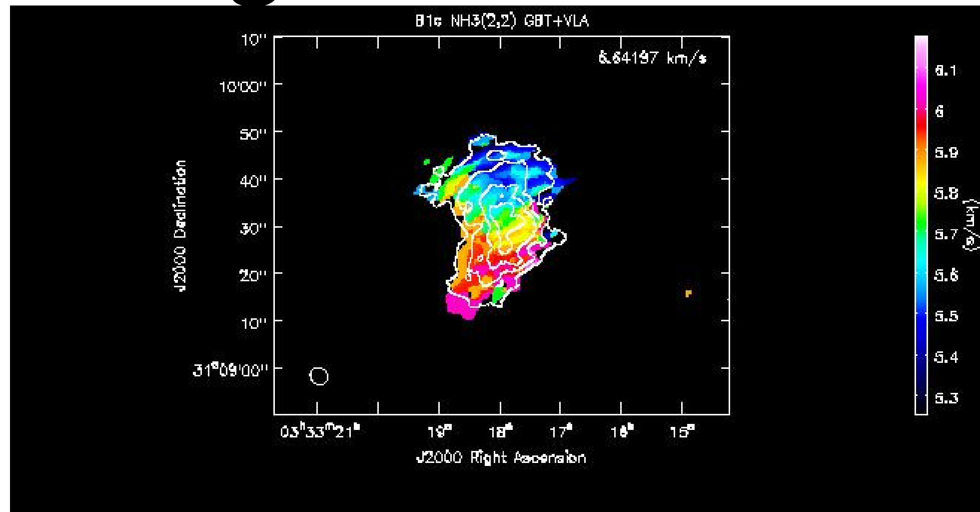

Extend to 3mm: higher resolution, with Argus, Argus+

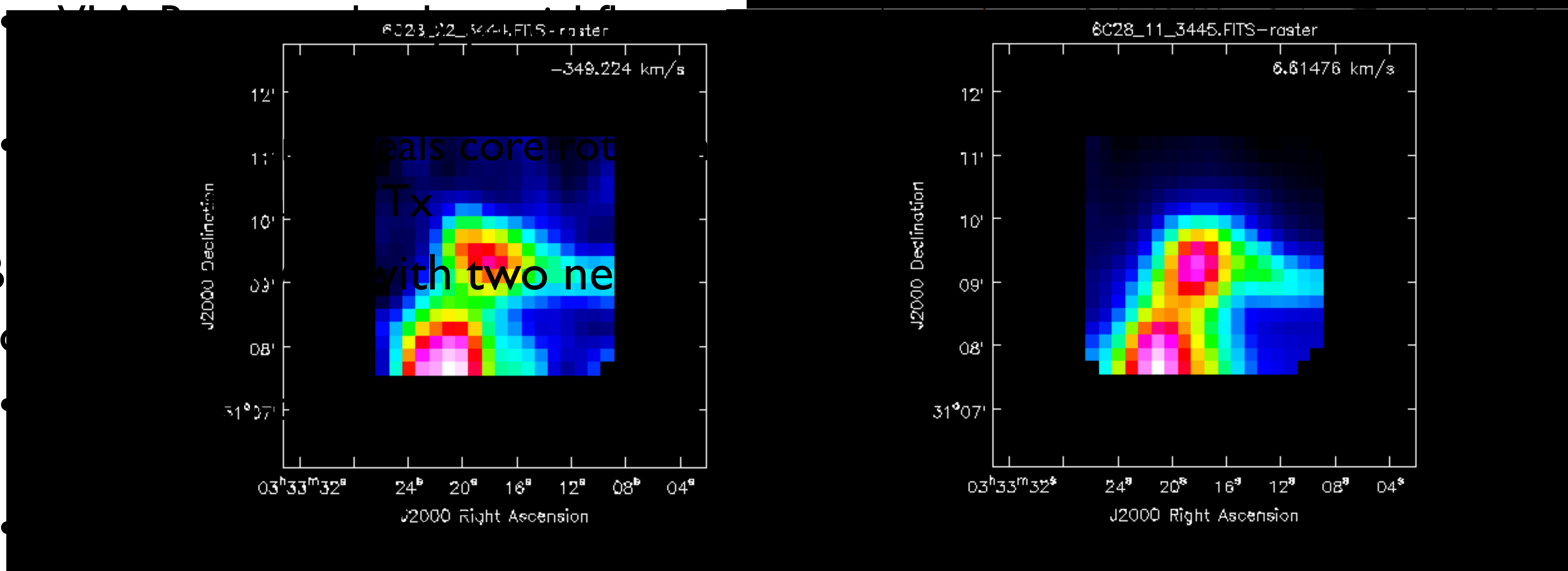
# Example: Perseus Barnard 1



# The Star-forming B1 Core

- Multiple sites of Star formation (IRAM image)
- Focus on three;
- B1c: Class 0, well developed flow, core
  - GBT NH3 images: clearly separated core in an elongated NS structure

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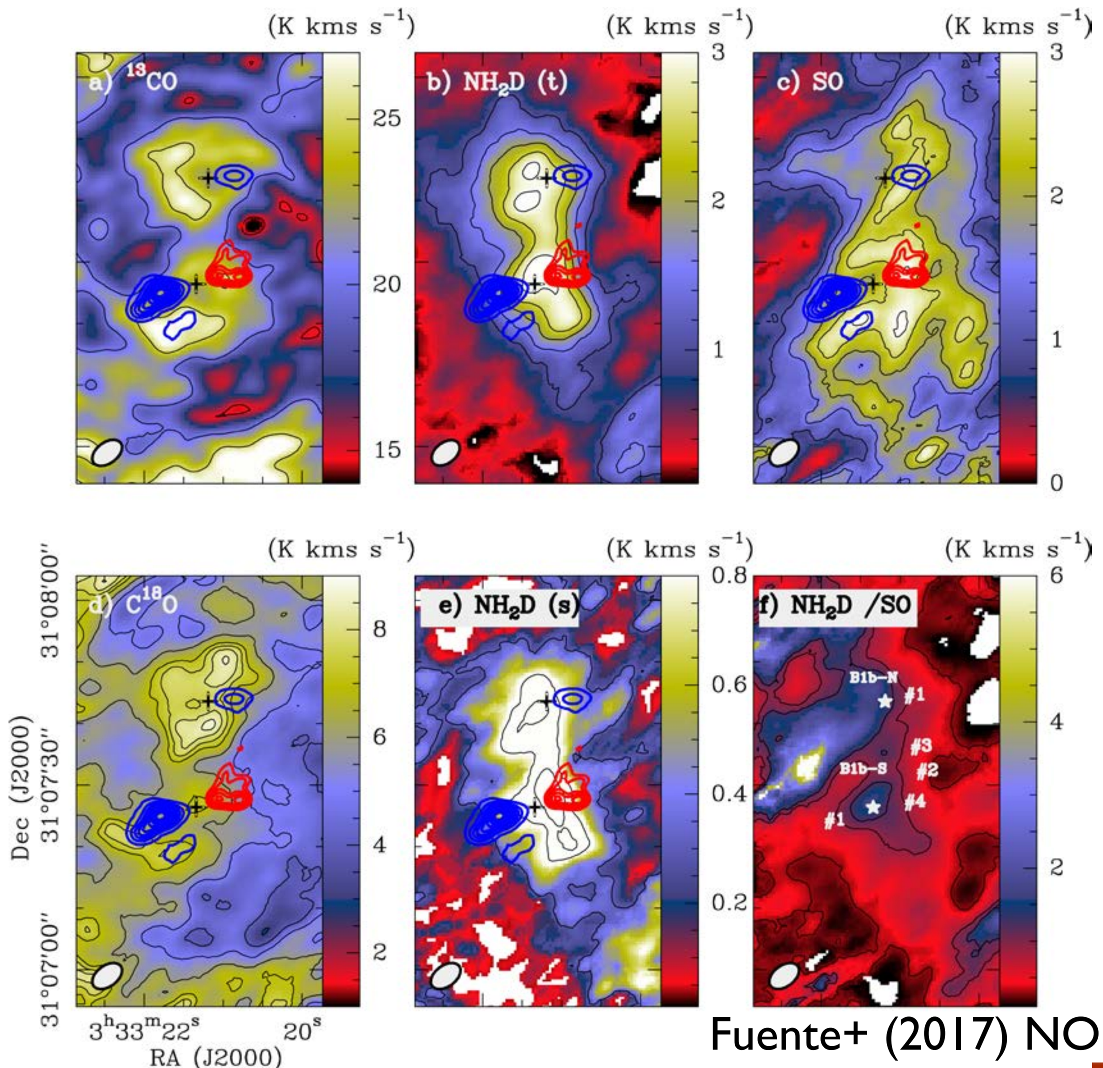
Hydrostatic Core

# B1b: Larger Scale Structure Star-Forming Cores in a Filament

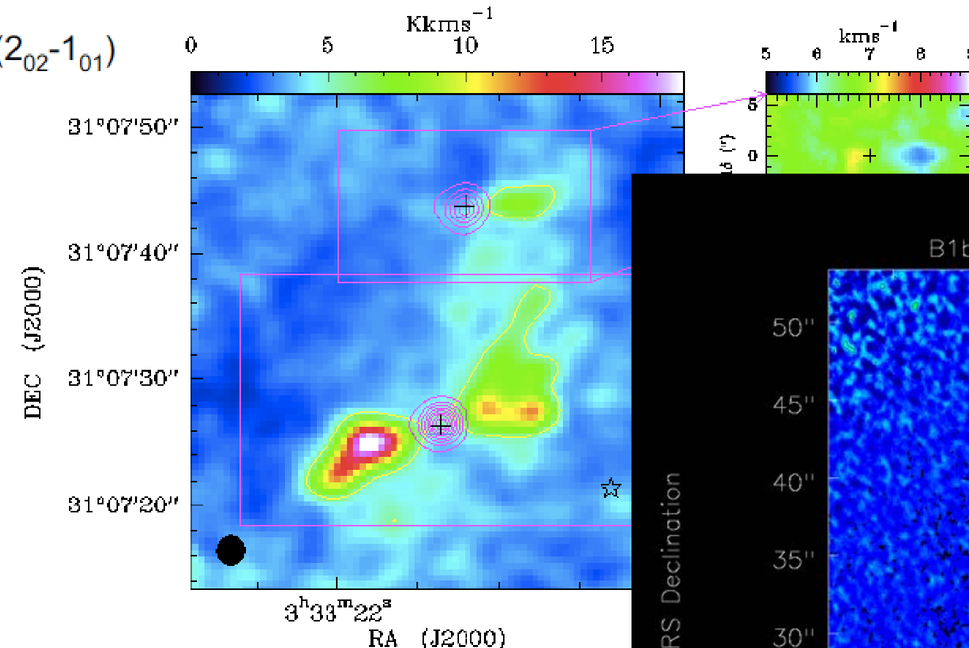
Argus+ could image at similar resolution (6" vs 2.5") with GBT alone.




Fuente+ (2017) NOEMA+30m

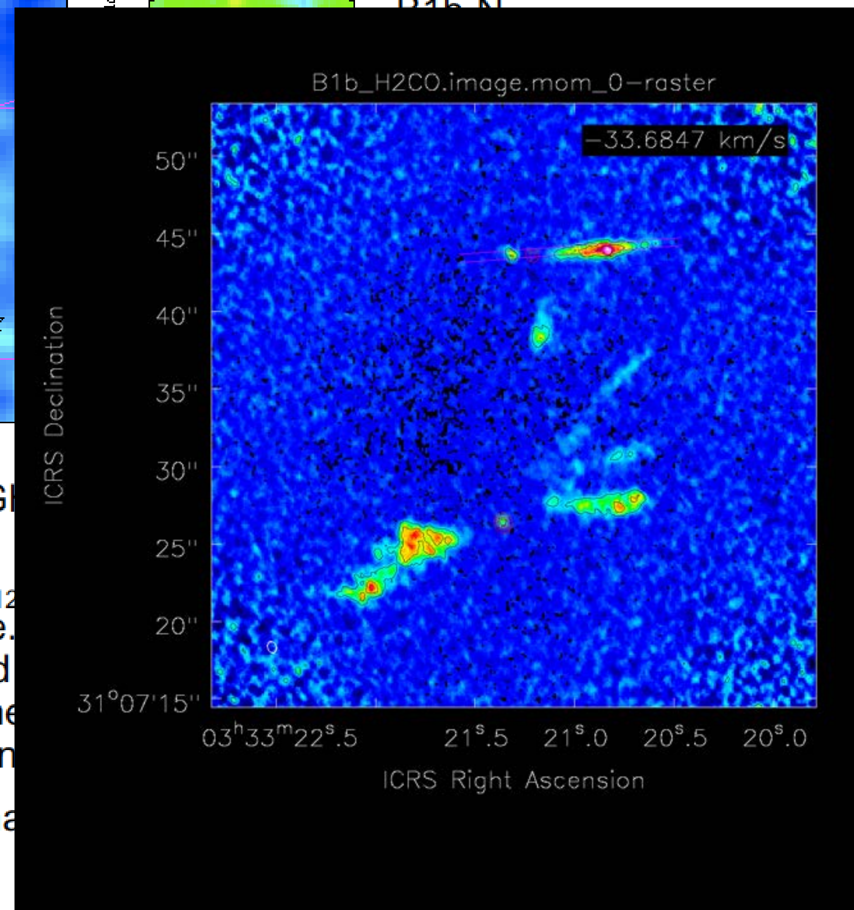
# NOEMA Observations

$H_2CO$ ($2_{02}$-$1_{01}$)



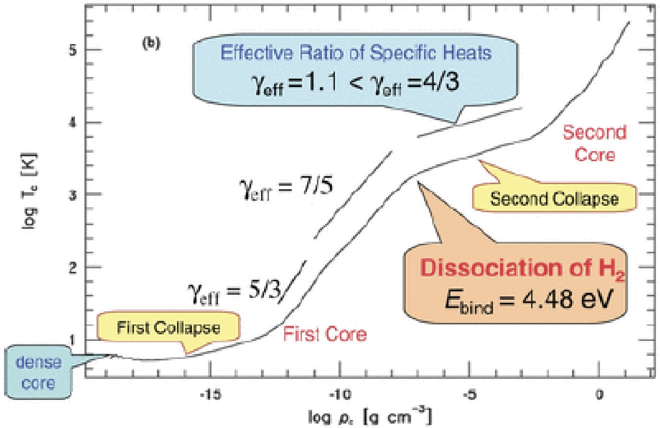

*Gerin et al. 2015, A&A*

B1b-N




7-field mosaic in C+D configurations at 145G
Beam : 2.2 x 2.3" (500 AU), PA = 108°
$H_2CO$ ($2_{02}$-$1_{01}$) ; $CH_3OH$ ($3_K$ - $2_K$) ; c-$C_3H_2$ ($3_{12}$
Slow molecular outflows around each source.
The outflows are not parallel, and not aligned

- B1b - S : outflow inclination constraine angle between outflow axis and magn
- B1b – N : β > 36° and likely larger tha



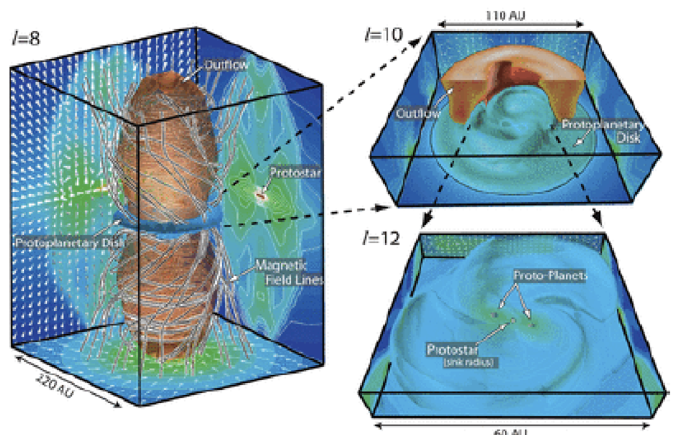

*Masunaga & Inutsuka 2000 ApJ 531, 350*

# Dense core Collapse

Pre-stellar core ~ isothermal sphere

1st Collapse
First HydroStatic Core (FHSC)
(500 – $10^3$ yrs)

2nd Collapse & $H_2$ dissociation
2nd hydrostatic core &
(few days)



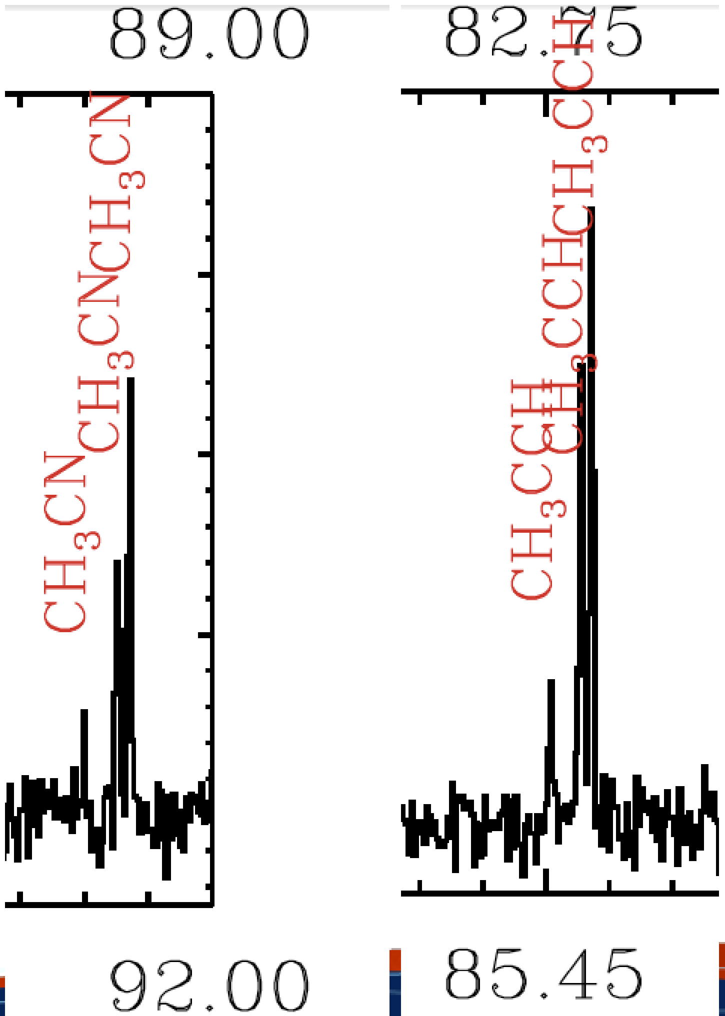

*Inutsuka, Machida & Matsumoto 2010 ApJ 718, L58*

Coupling rotation, collapse with a magnetic field
→ slow outflows at the FHSC stage
→ jets at the 2nd core stage

Gerin, IAU332

# High Frequency T, n

- Marcelino et al Survey of the B1b core shows emission from $CH_3CN$ and $CH_3CCH$ 80 GHz lines at tenth K level. Temperature fit suggests ~15K, agrees with $NH_3$
- J=5-4 and J=4-3 can be observed simultaneously with other lines with broadband receivers
- Relative intensities of different J lines provide a measure of density over a range $10^4$ to $10^6$ $cm^{-3}$; they lie near excitation peak



# Flexibility

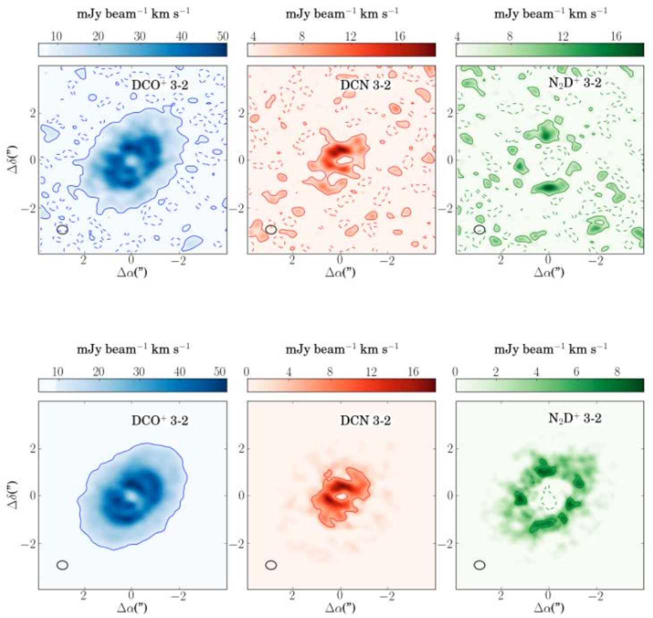
- Ability to confirm a cornerstone molecule with a difficult spectrum: $CH_2D^+$ the cornerstone molecule of carbon chemistry and key to warm deuterium chemistry

# Focus on Particular Molecules: Deuterium ices, Snow lines

## Disk Deuteration regimes in the Herbig Ae star HD163296

Salinas et al A&A in press

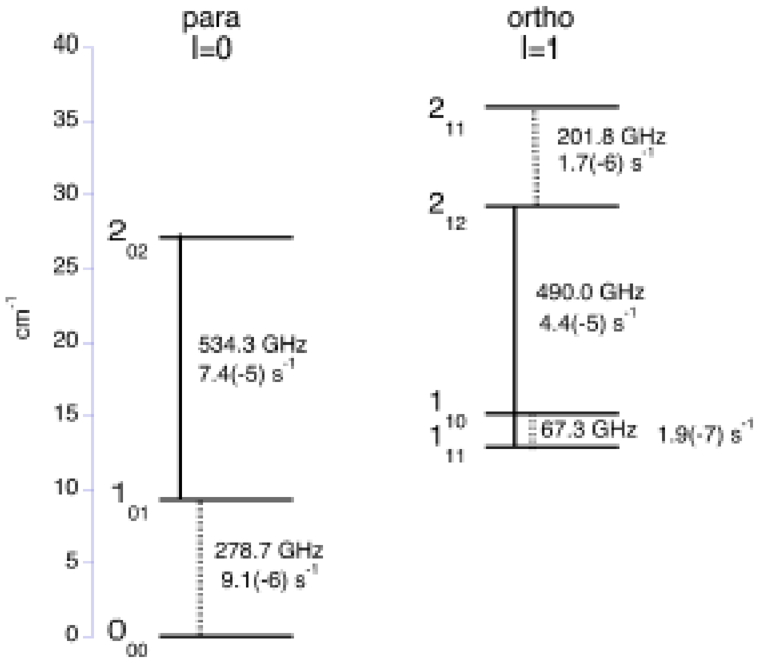
- HD163296 is a well-placed disk showing a multi-ring structure in dust (
- Central planes of circumstellar disks are cold, well-traced by D-bearing isotopologues
  - These offer temperature probes, as different chemistries enhance D at different temperatures
  - Also probe 'snow lines', where molecules freeze out of the gas, at different temperatures
- Different chemistries determine distributions
  - 'Warm' deuterium chemistry dominates DCN production through $CH_2D^+$ reactions which may also form some $DCO^+$
  - 'Cold' deuterium chemistry dominates $N_2D^+$ and much $DCO^+$ chemistry originating with $H_2D^+$
- Conclusions
  - CO snowline is at r~100AU
  - Inner depression of DCO+, DCN arises from dust opacity, not warm deuteration pathway
  - Three ring DCO+ may relate to small grain structures
    - 70 AU and 150 AU rings may link to differing deuteration pathways
    - Outer ring at 260 AU may reflect lowering UV opacity, desorption of CO



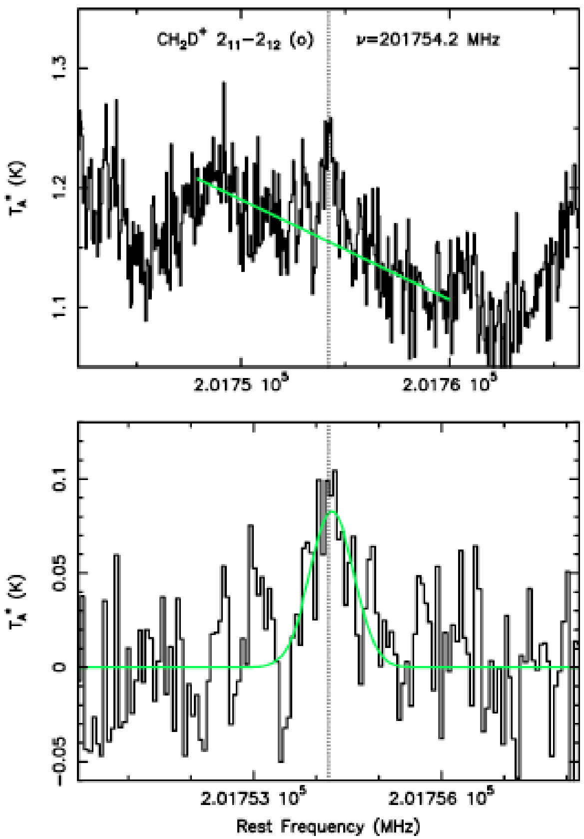

Above: Integrated intensity maps of deuterated molecular emission with (lower panels) and without (upper panels) a Keplerian mask as explained in the Appendix of the paper.

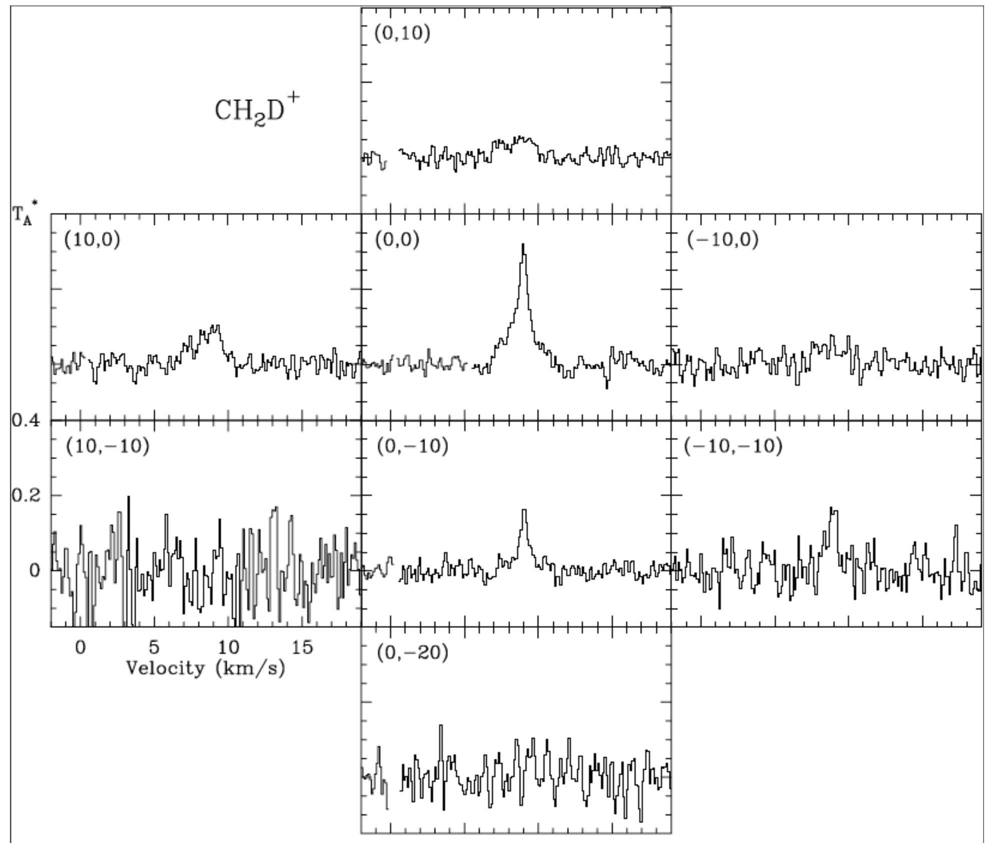
# Fundamental Molecules: $CH_2D^+$

- Light molecule, widely spaced levels, sparse lines
- Inconveniently placed
- Four low-lying millimeter lines
- Two reasonable ones in 1mm band with predicted ν



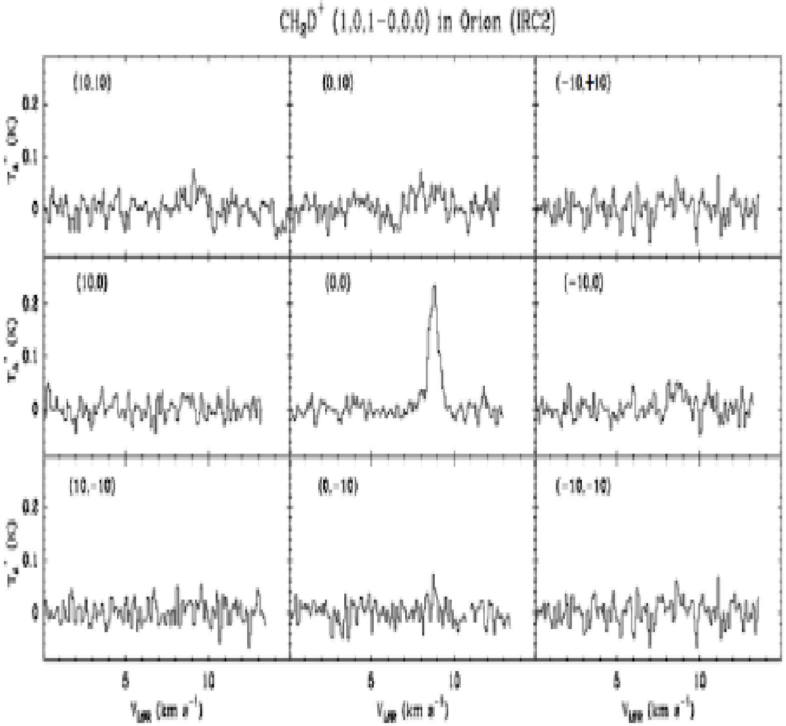
# The 201.7 GHz Line

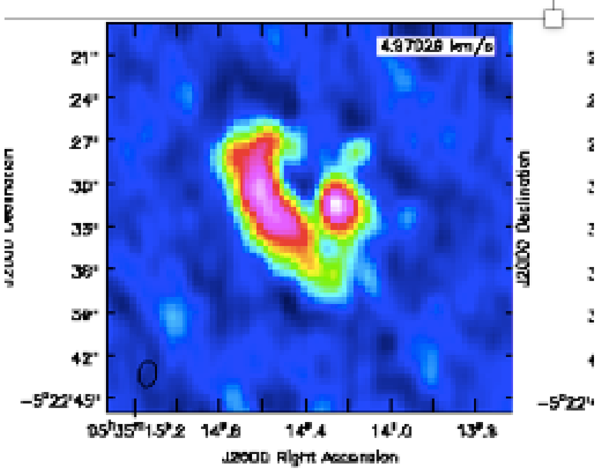



N.B. Could be blended with high excitation Methyl Formate line

# The 278.7 GHz Line




Left: $CH_2D^+$ at 278.7 GHz (IRAM 30m)

Right: DCN J=3-2 (color) (ALMA)

# SF/ISM on the GBT

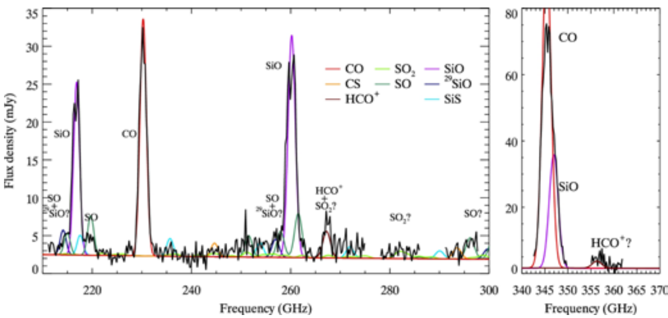
- Flexibility: sensitively covers full spectral range; provides access to critical emission
- Widefield coverage to provide context for star formation
- Sensitivity needed for complete flux recovery of VLA, ALMA, NOEMA images

# Unexpected Chemistries

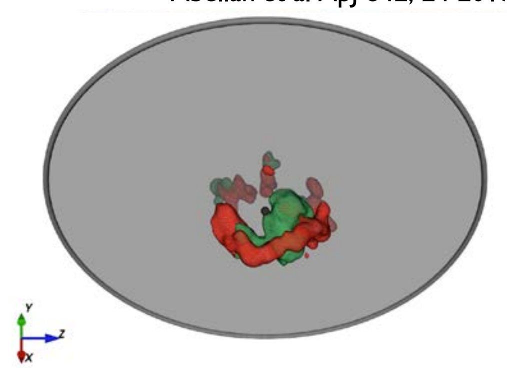
## Molecular Emission from SN1987A

- ALMA spectral survey shows:
  - Cold (20–170 K) CO, $^{28}SiO$, $HCO^+$ and SO, with weaker lines of $^{29}SiO$ from ejecta.
  - Low $^{29}Si$ and $^{30}Si$ abundances are consistent with nucleosynthesis models that show inefficient formation of neutron-rich isotopes in a low-metallicity environment, such as the Large Magellanic Cloud
- ALMA image shows:
  - Central molecular void, possible owing to heating by radioactive nickel
  - Cold molecular gas whose 3D distributions differ
    - Clumpy mixed structure seen, expected from asymmetric explosion but previously unseen
    - Molecules form torus or shell perpendicular to equatorial ring (blue on right)
    - SiO has greater extent than CO from the center, therefore non-spherical instabilities occurred

Matsuura et al. 2017 MNRAS 469, 3347




Abellan et al ApJ 842, 24 2017



Molecular Emission
Blue ring is HST Hα
Red/Green CO/ SiO