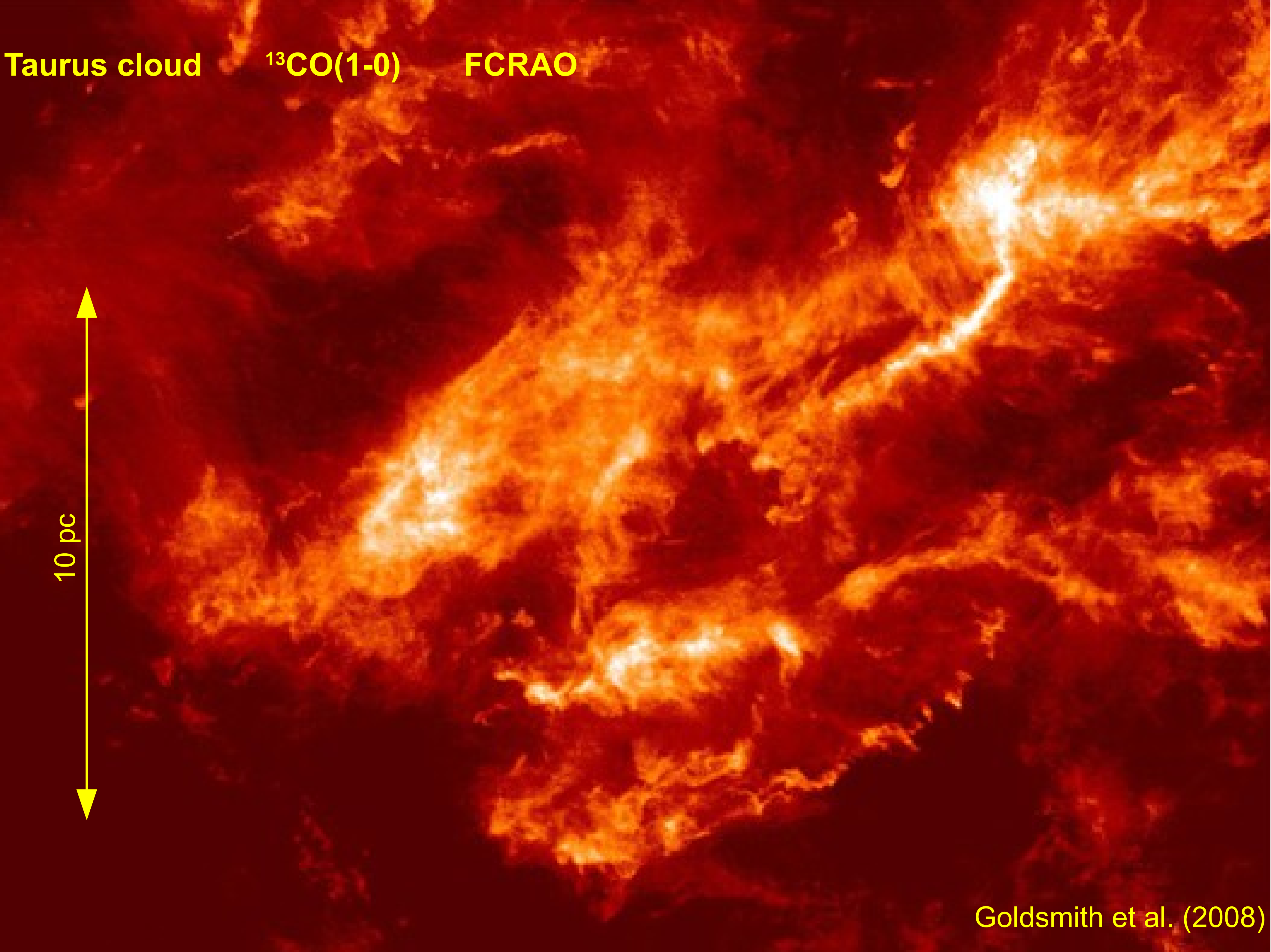
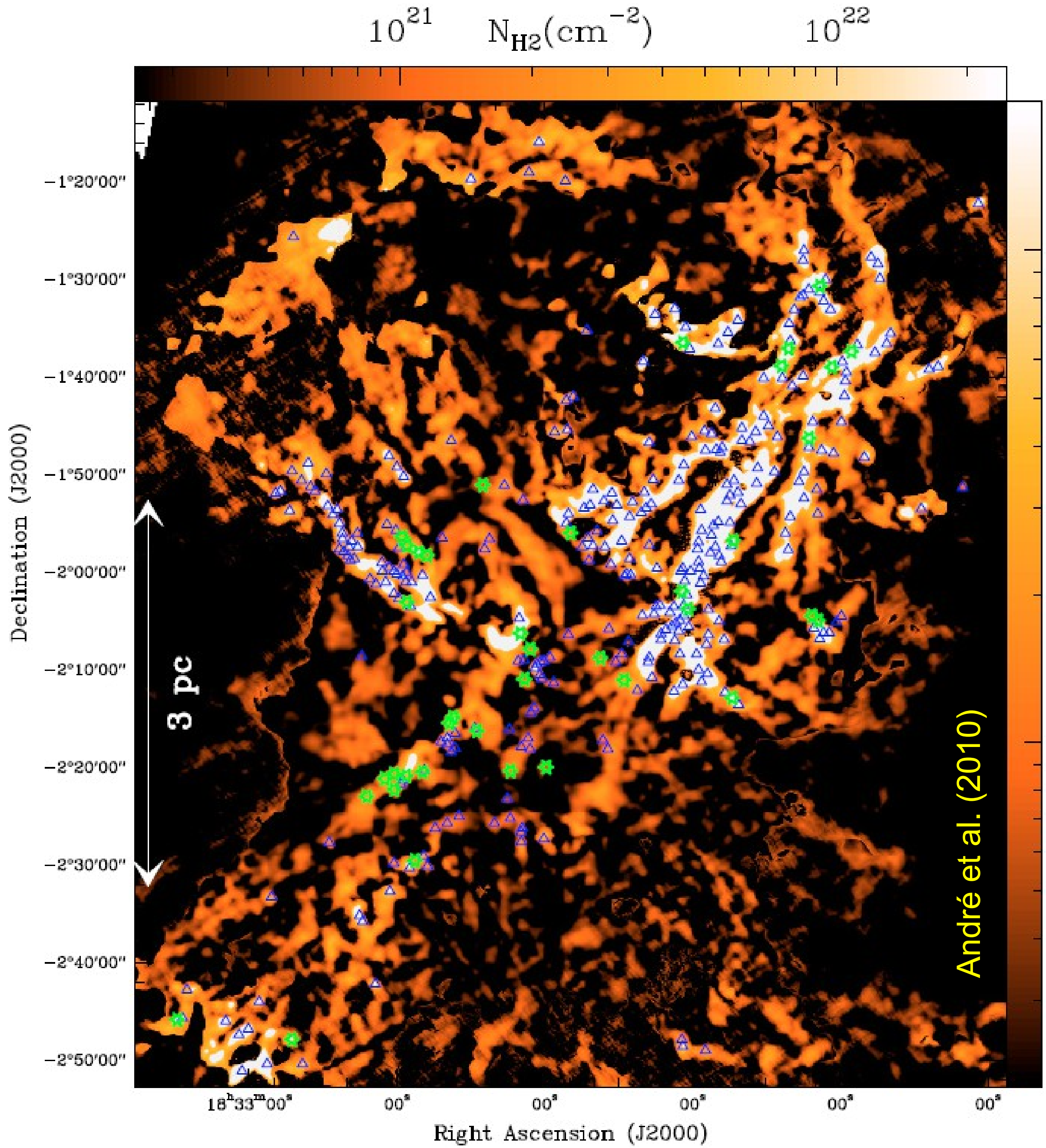
Low-mass star formation: current status and future progress with ALMA

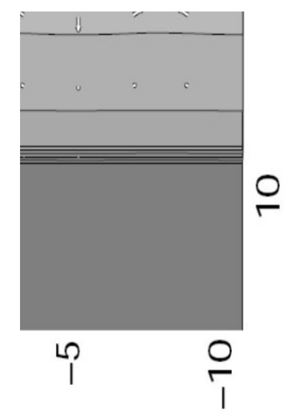
Mario Tafalla (OAN-IGN, Spain)


Taurus cloud
^{13}CO(1-0)
FCRAO
10 pc
Goldsmith et al. (2008)

Core formation occurs along filaments



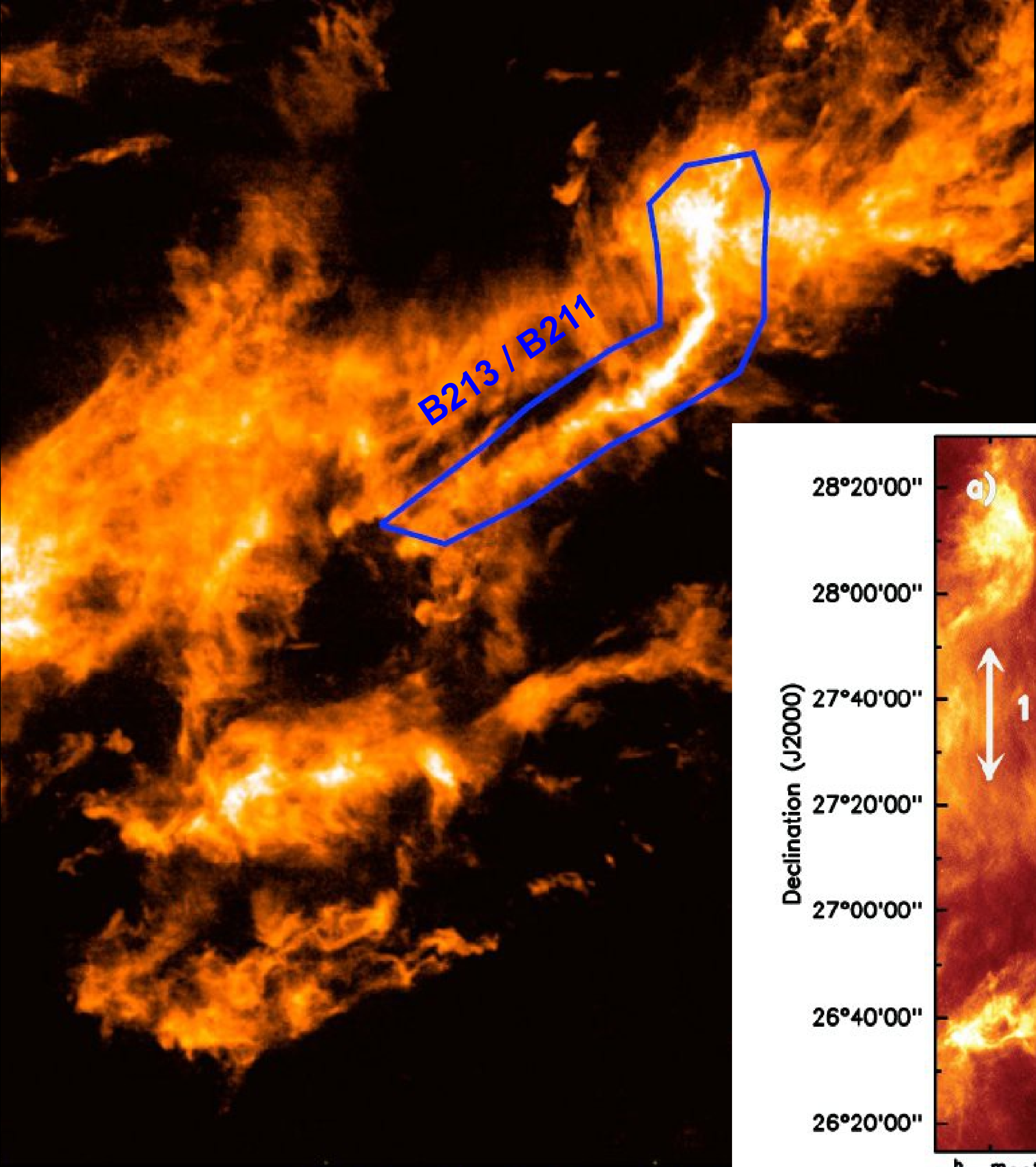
- Herschel Gould Belt Survey (André et al. 2010)
- > 70% of prestellar cores lie in filaments

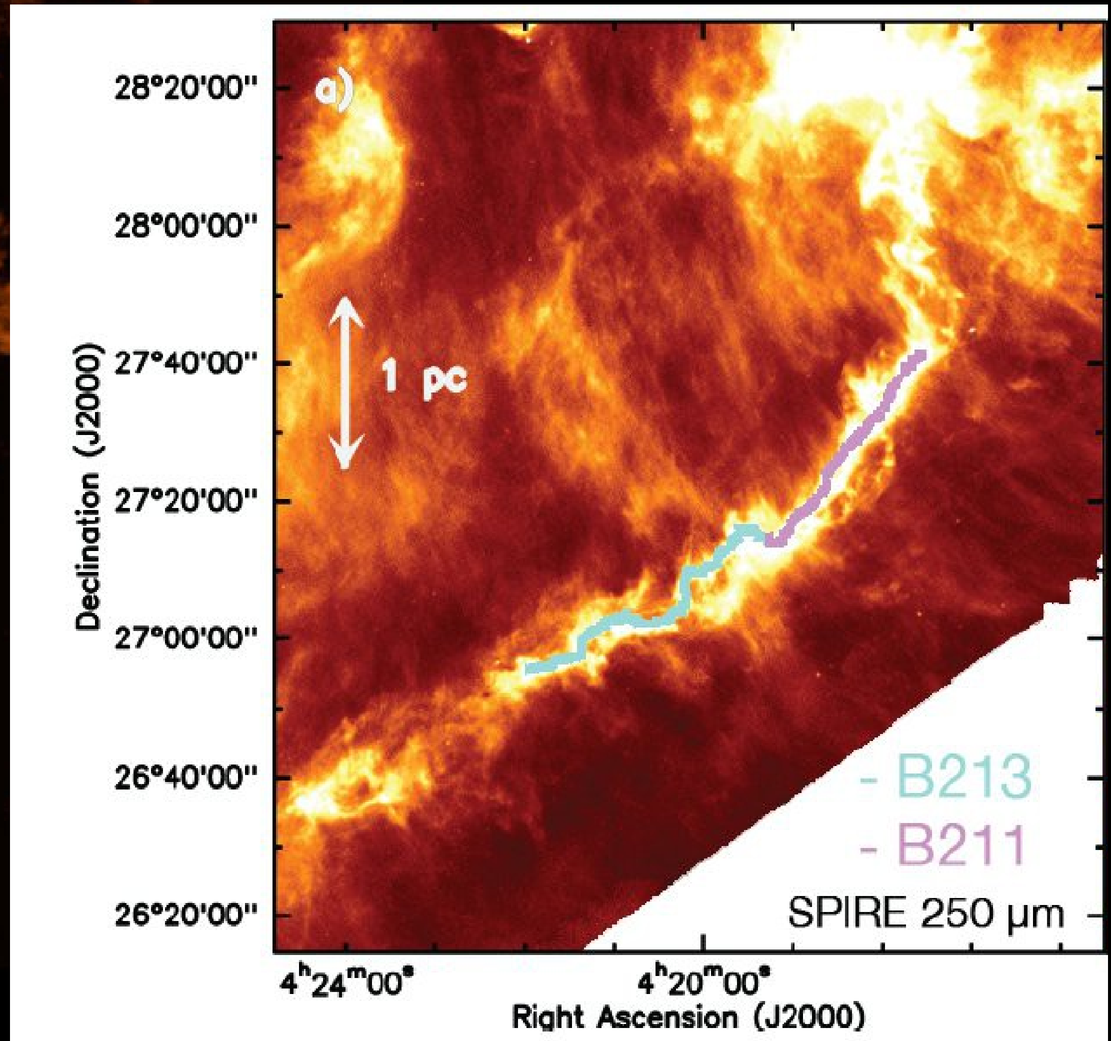


Fiege & Pudritz (2000)

"Beads in a string"

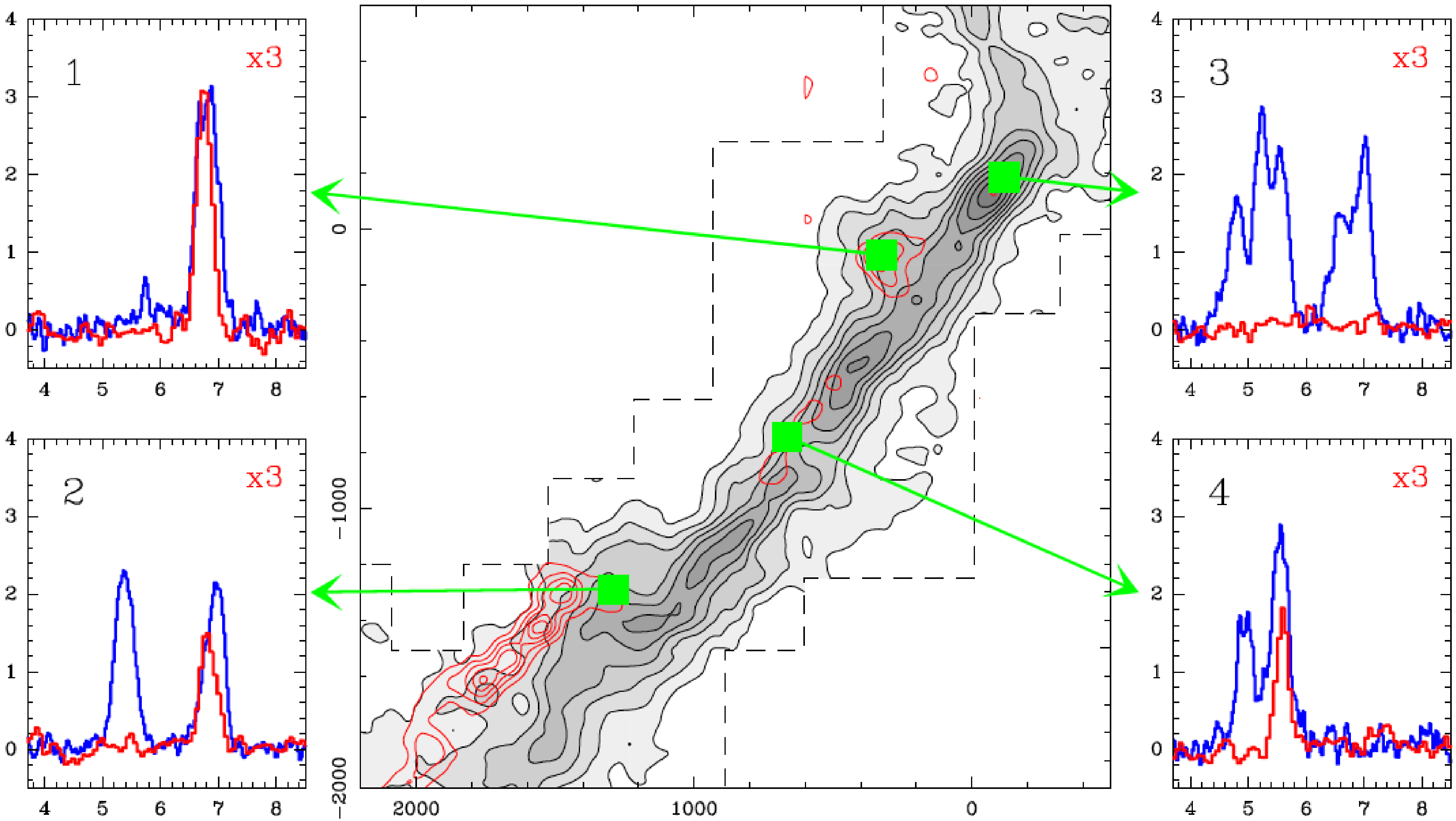
Internal structure of filaments





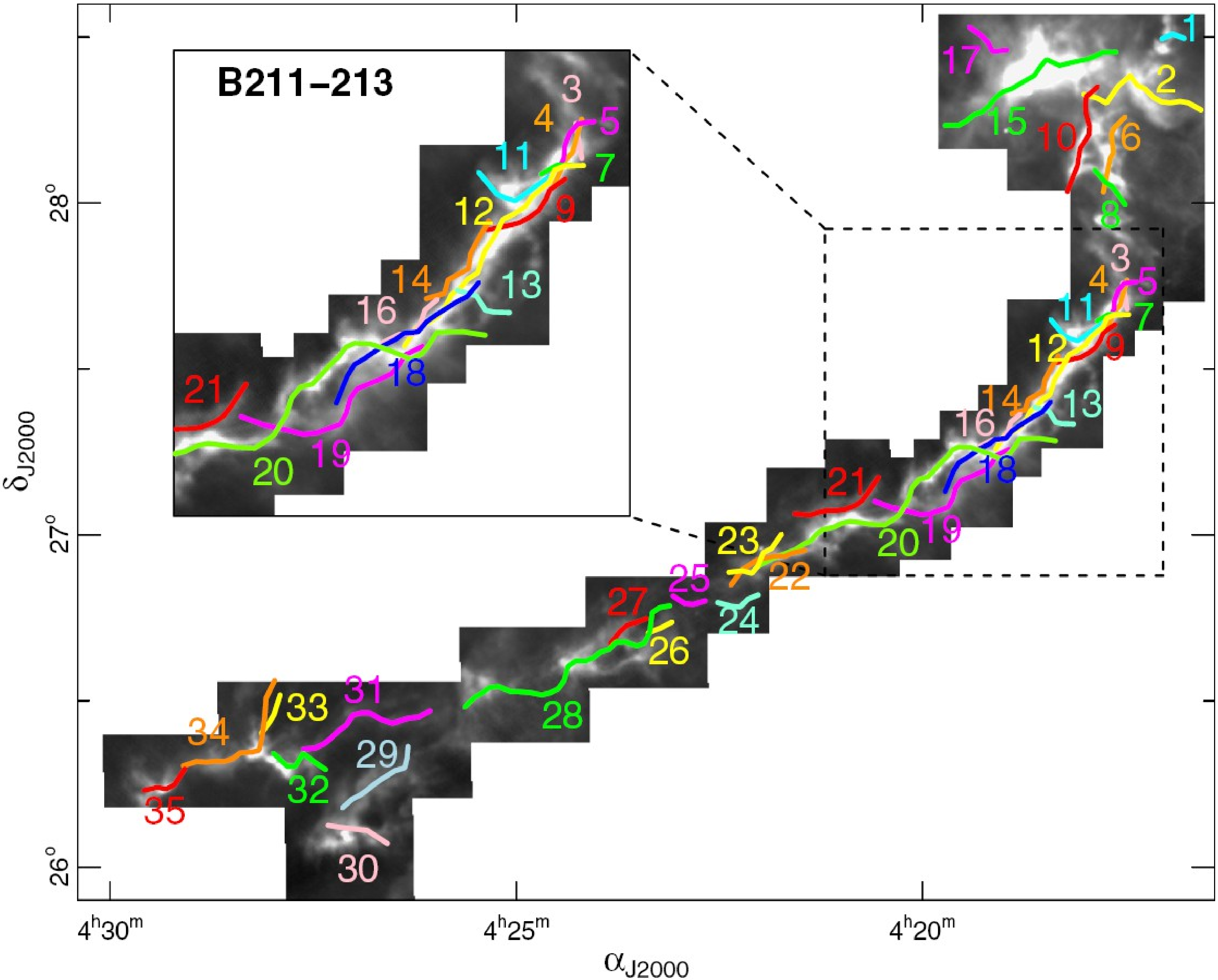
Palmeirim et al. (2013)

Multiple velocity components in a "single" filament



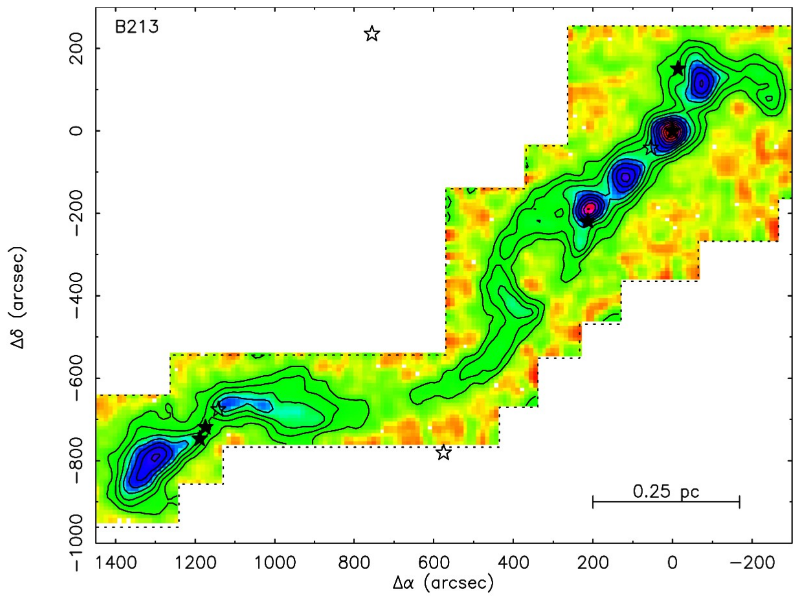
Hacar et al. (2013)

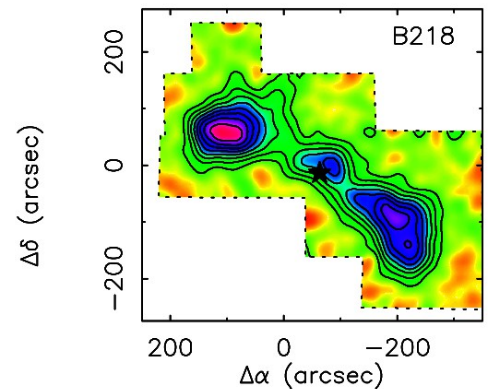
Filaments made out of fibers

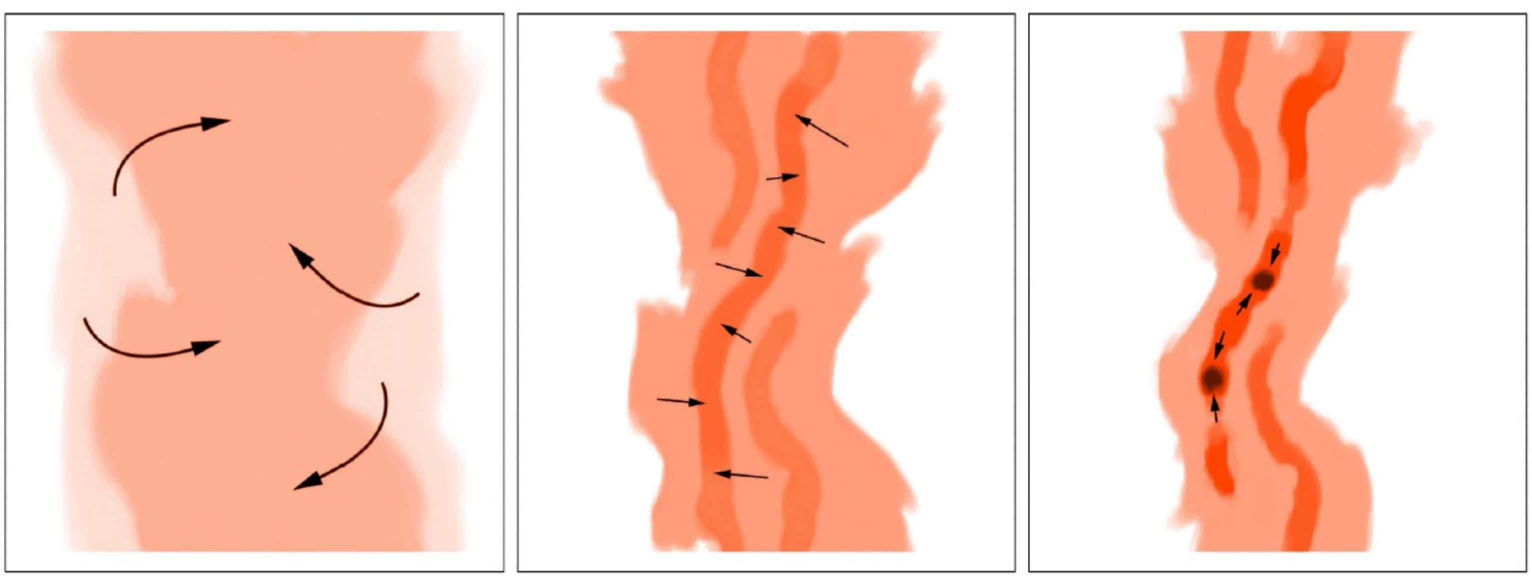


$C^{18}O$ fibers from Hacar et al. (2013)
SPIRE map from Palmeirim et al. (2013)

Filaments → fibers → cores

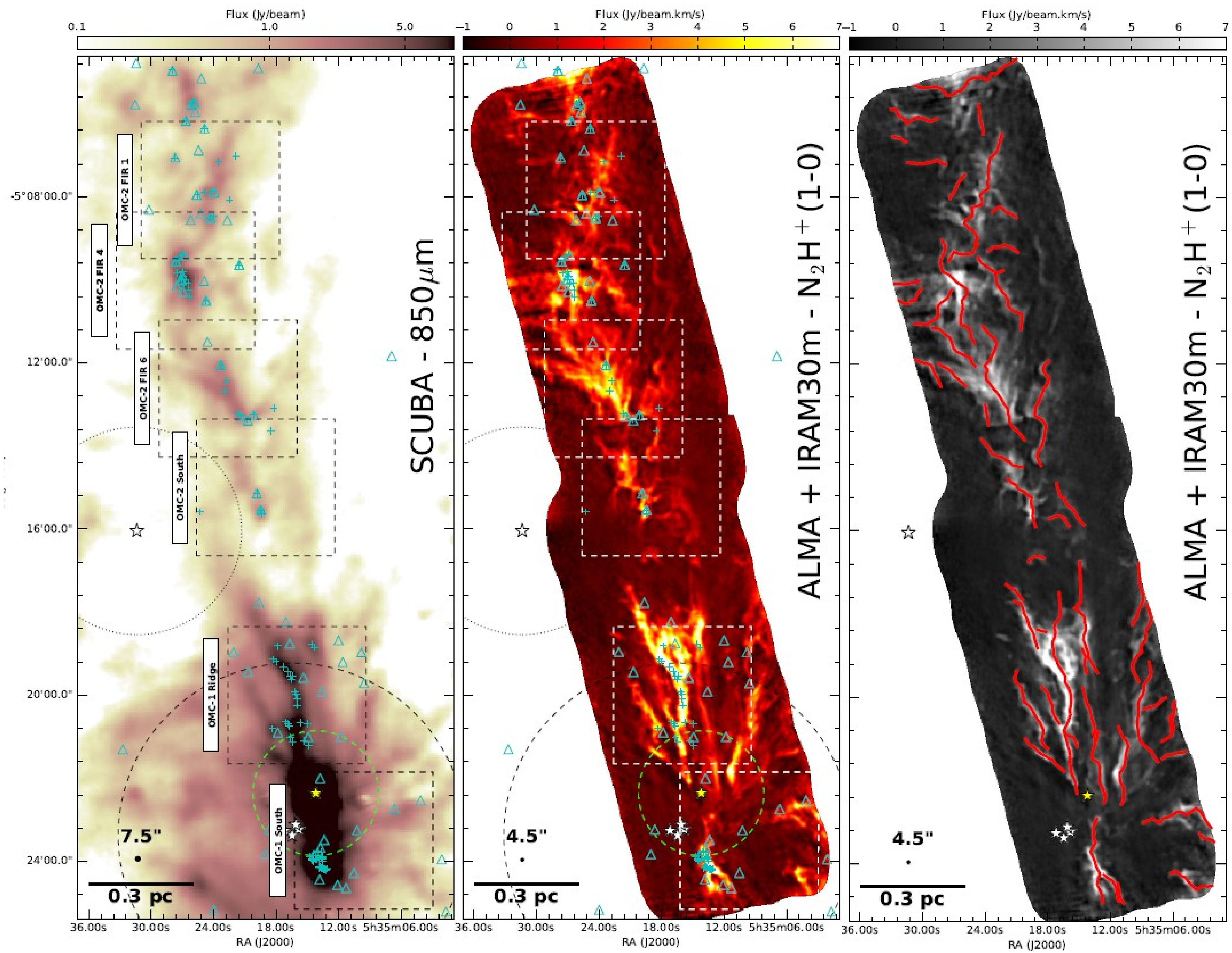






Tafalla & Hacar (2015)

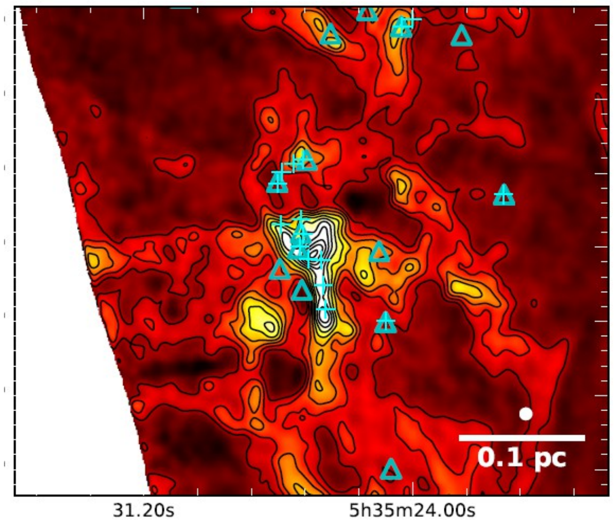
Fibers in Orion with ALMA



Hacar, Tafalla, et al. (A&A submitted)

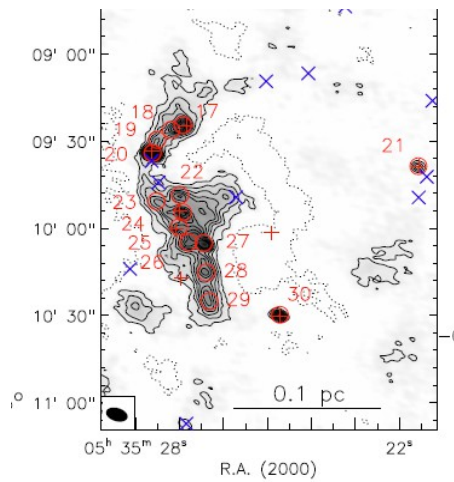
Filaments → fibers → cores with ALMA

N_2H^+ (1-0)



Hacar, Tafalla, et al. (A&A submitted)

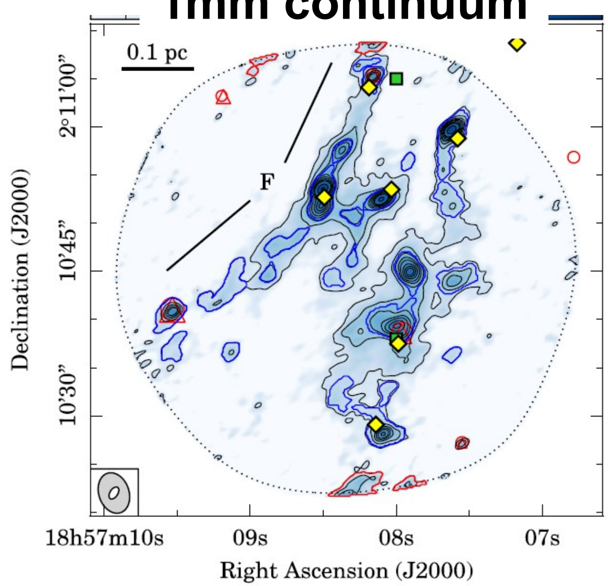
3mm continuum

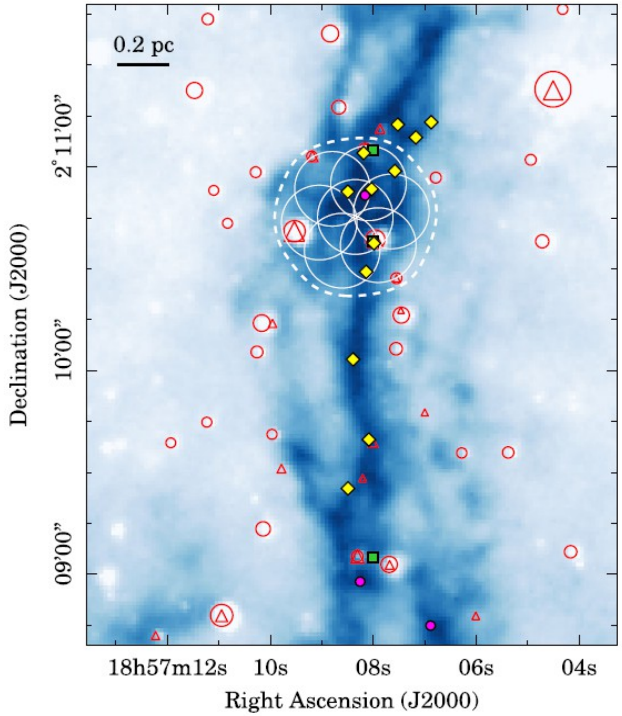


Kainulainen et al. (2017)

→ Orion (OMC2)

1mm continuum

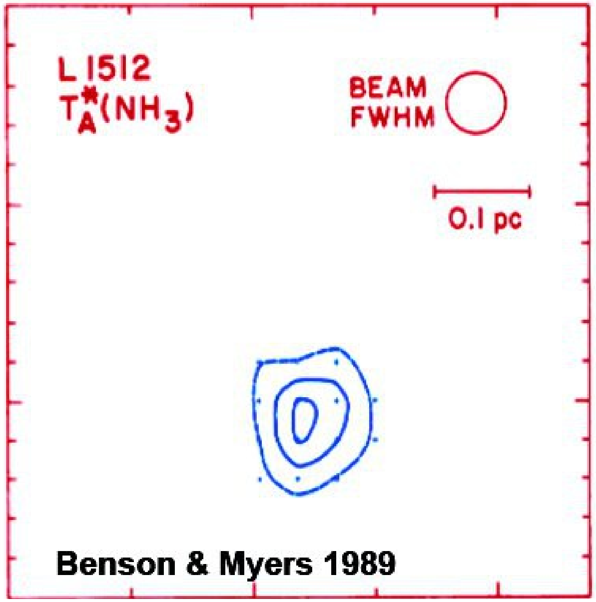


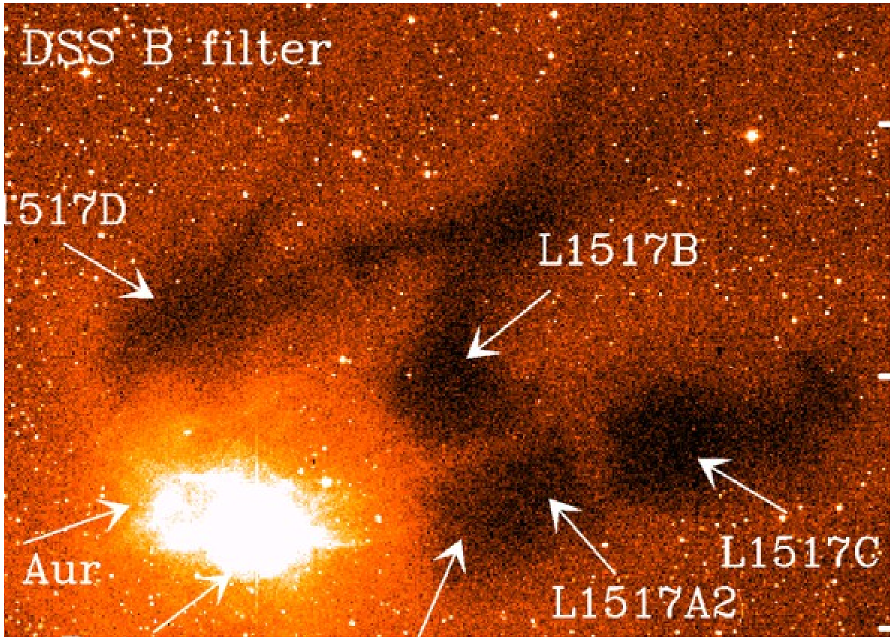


G035.39-00.33 ←

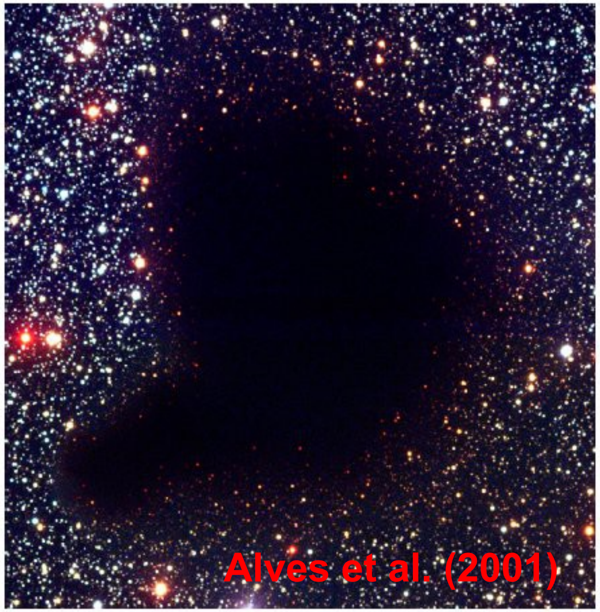
Henshaw et al. (2017)

Dense Cores



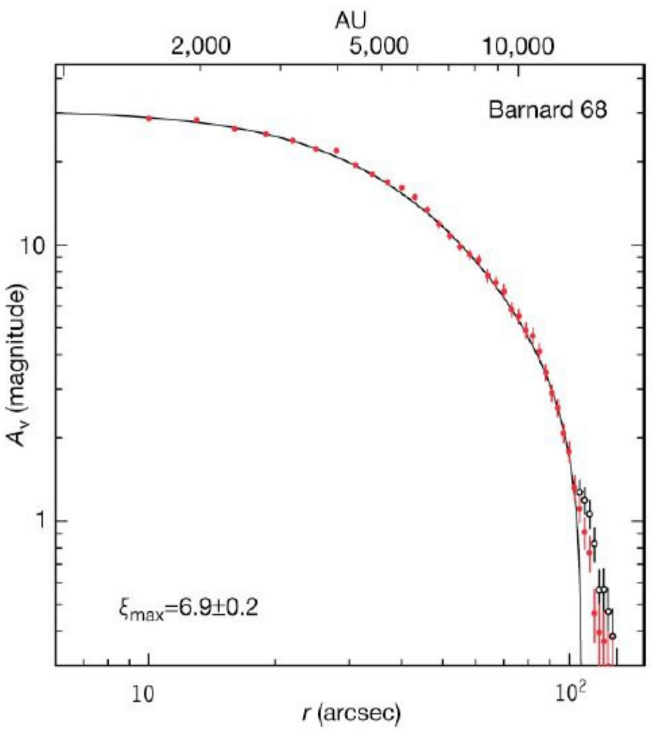


Hacar & Tafalla (2011)

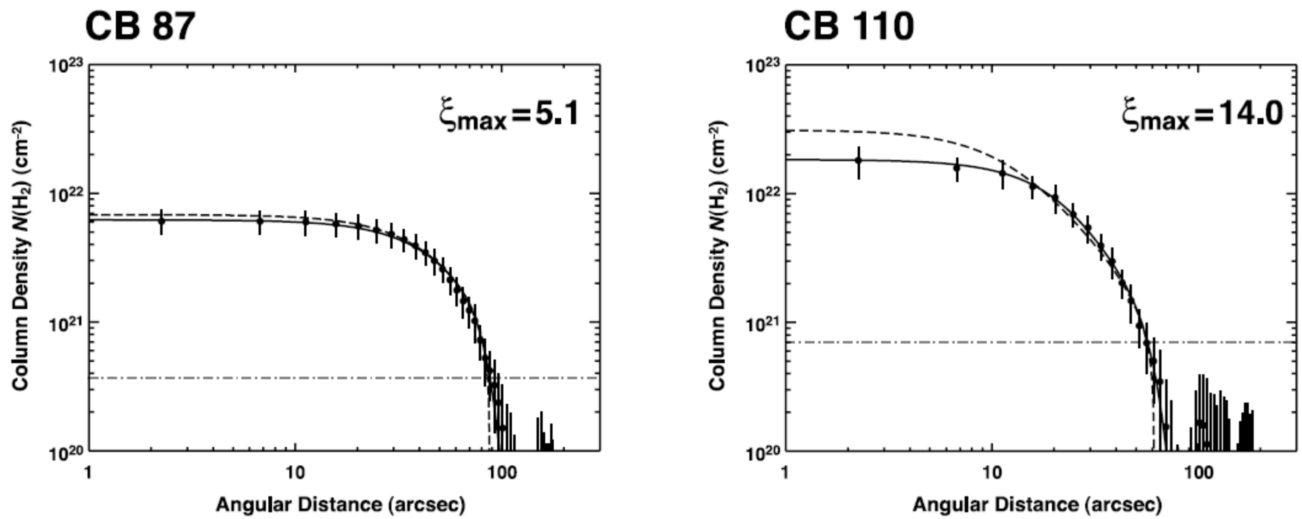


- Simplest low-mass star-formation sites
- Found in Taurus, Perseus, Oph,...
- Identified by obscuration, NH_3, N_2H^+
- Size ~ 0.1 pc, typically ~ 1 $M_{o,}$, subsonic
- ~ 50% starless and 50% with embedded YSO

Density structure of starless cores



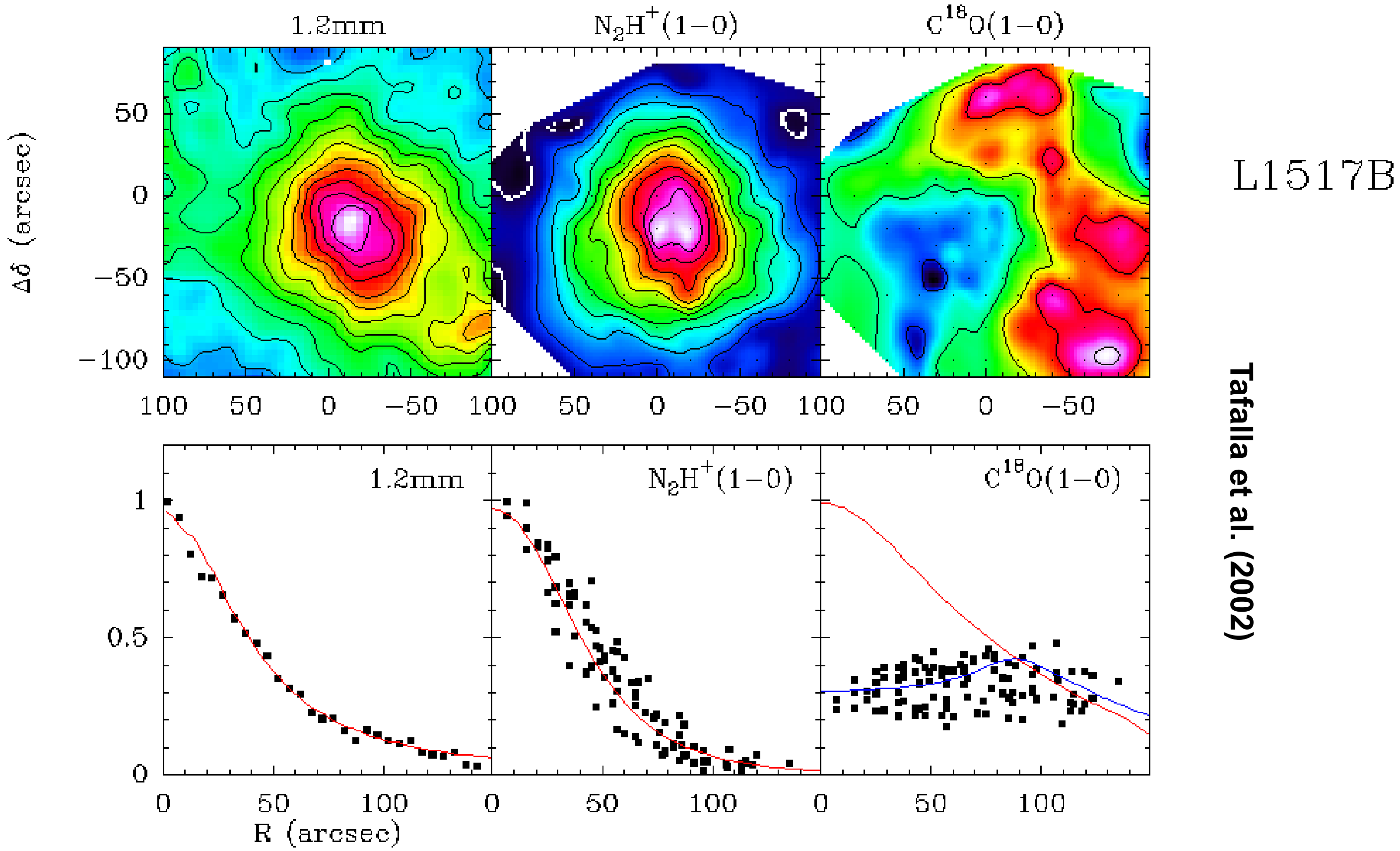
Alves et al. (2001)



Kandori et al. (2005)

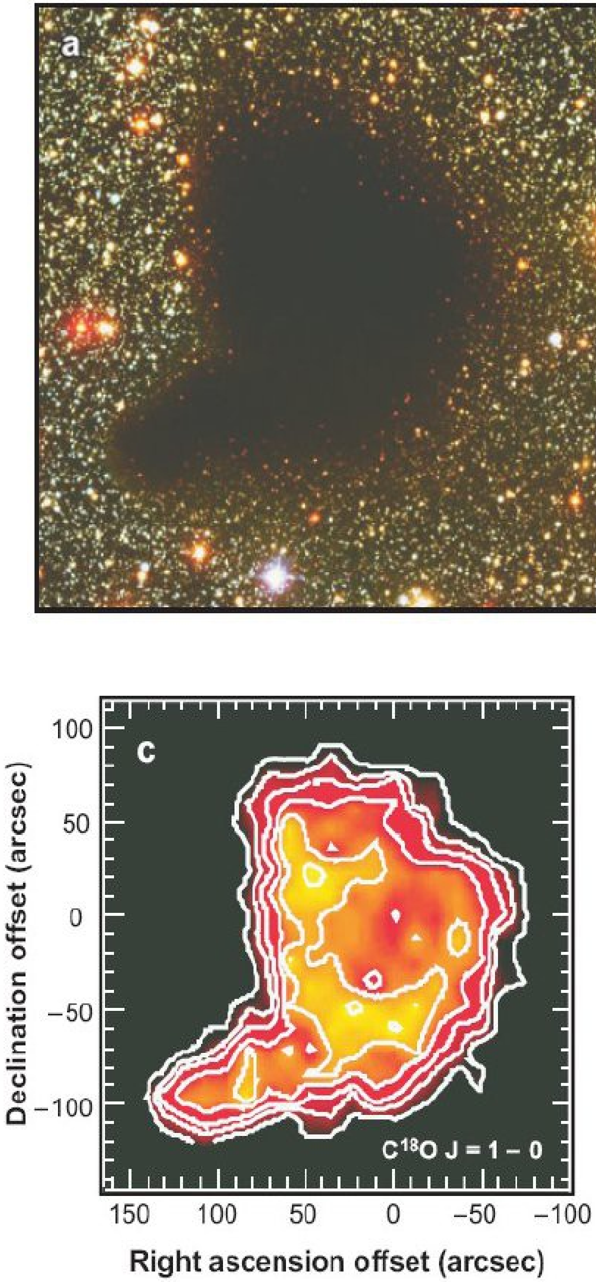
- Original expectation was $1/r^2$ profile (singular isothermal sphere)
- Consistent result from extintion and emission measurements
  - Radial density profiles are systematically flat toward center of core
- Flattening generally consistent with isothermal (Bonnor-Ebert) model
- Often profiles are unstable

Chemical composition



- Most molecular tracers freeze out onto dust grains in the core interior
- Only few species seem to remain in the gas phase (N_2H^+, NH_3)

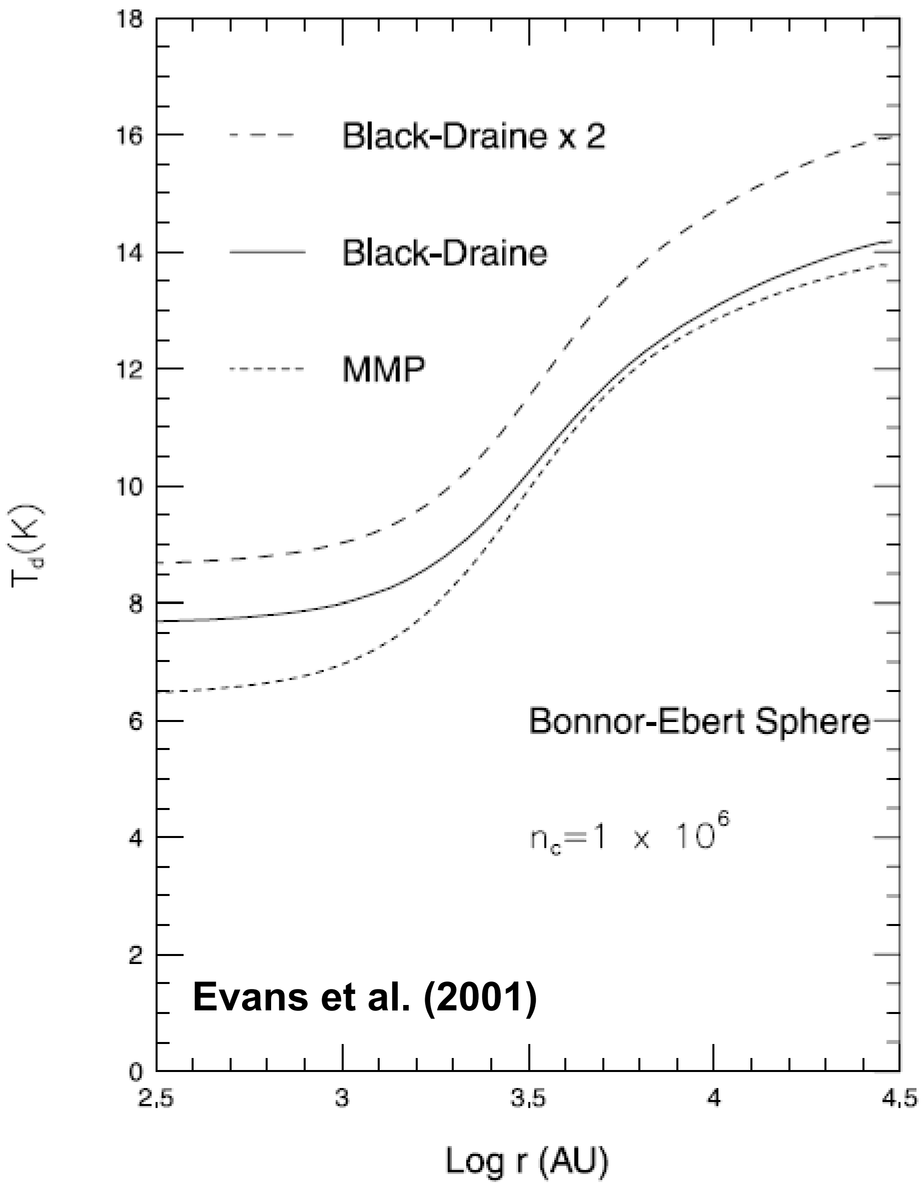
Chemical composition

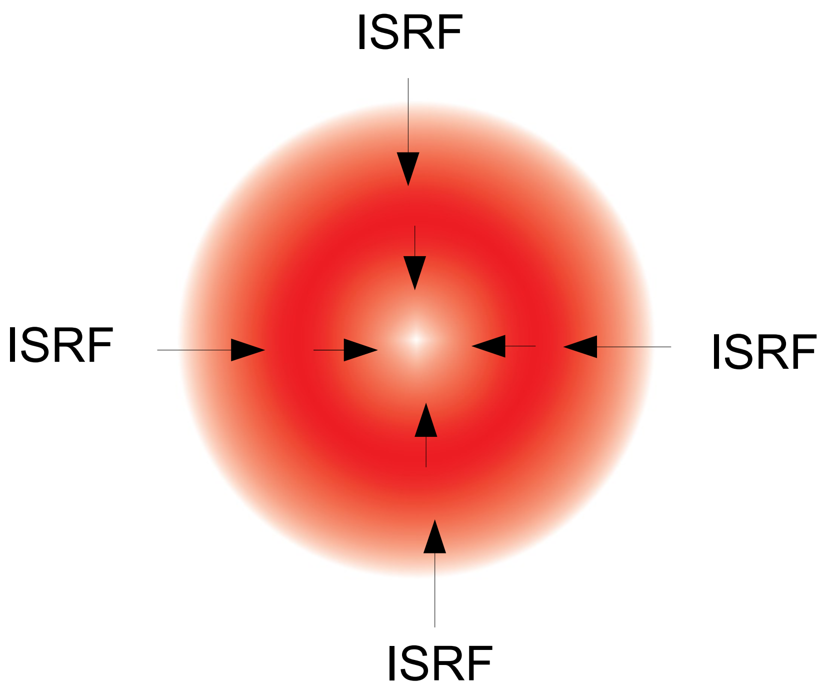


B68

Bergin et al. (2002)

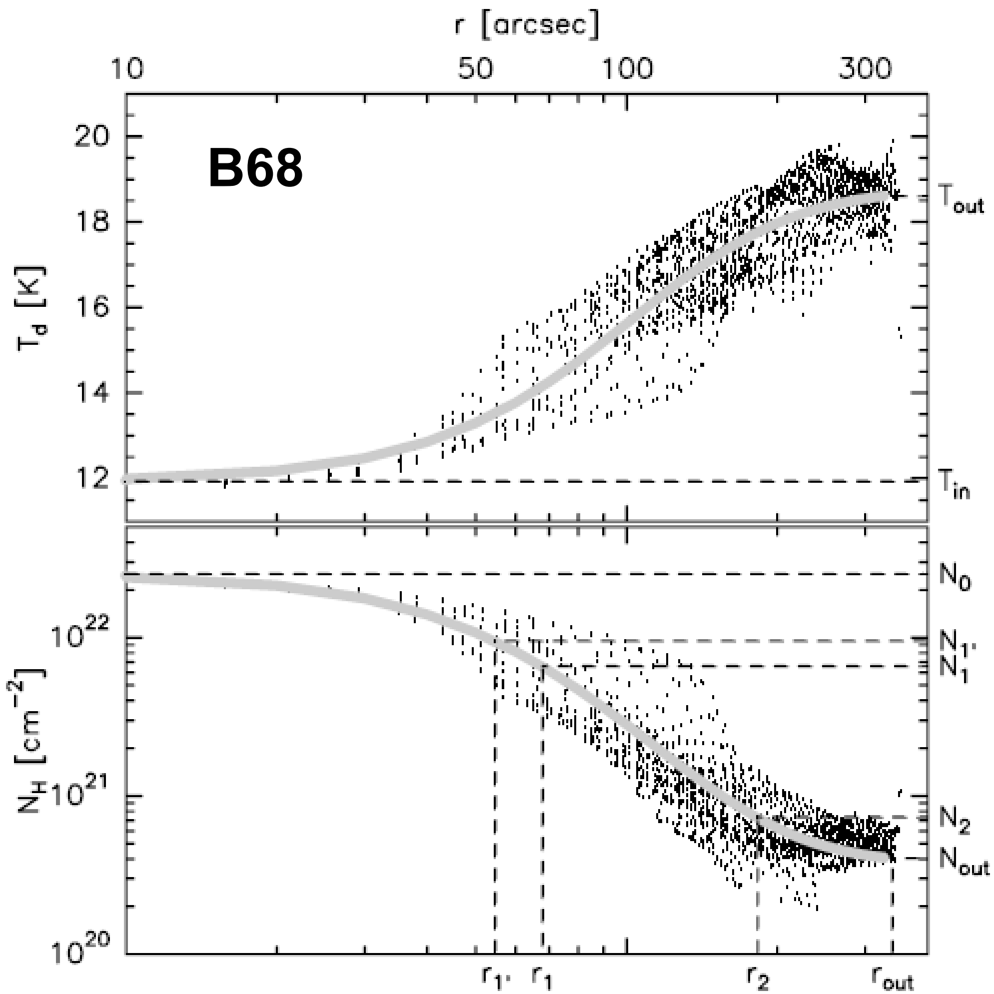
Temperature profile (dust + gas)



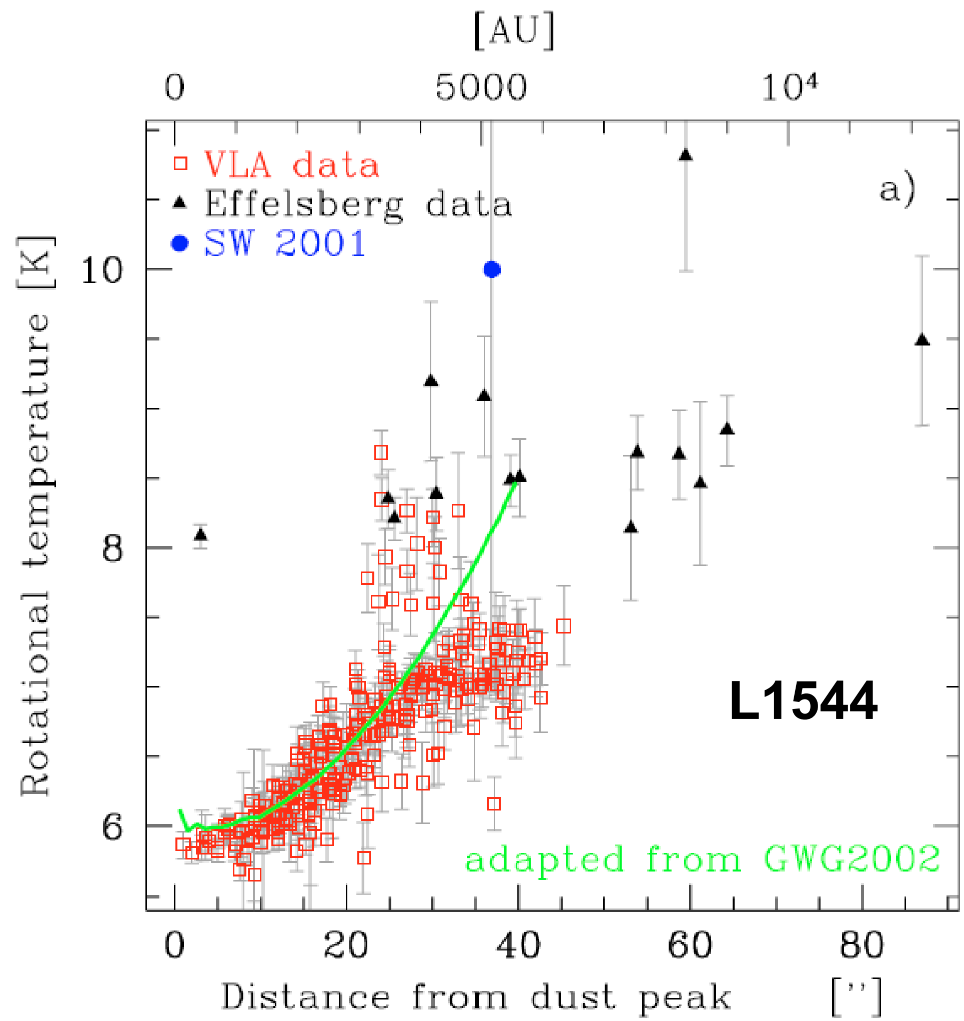


- Dust heating by ISRF decreases toward core center
  - T(dust) decreases inward
- If $n(H_2) > 10^5$ cm^{-3}
  - Dust and gas are thermally coupled

Temperature profile (dust + gas)

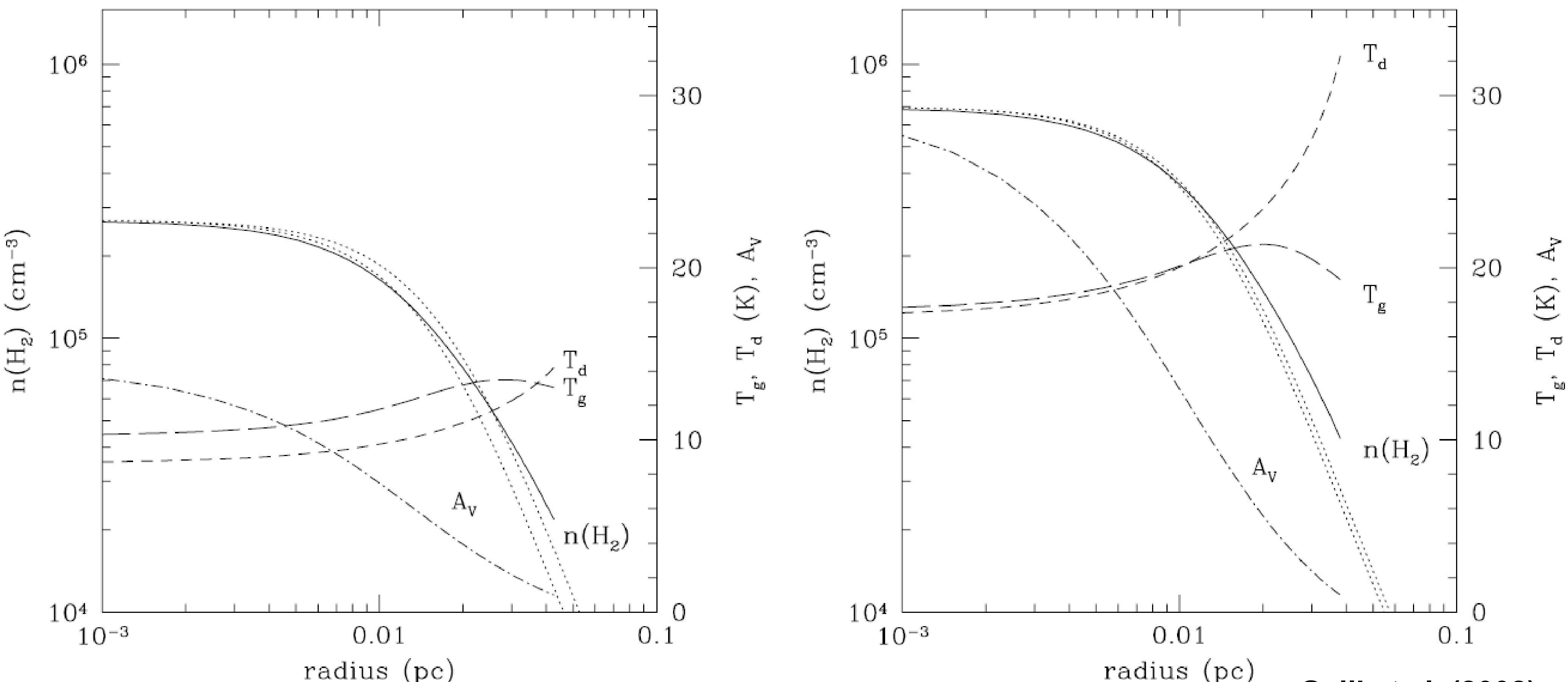


Launhardt et al. (2013)



Crapsi et al. (2007)

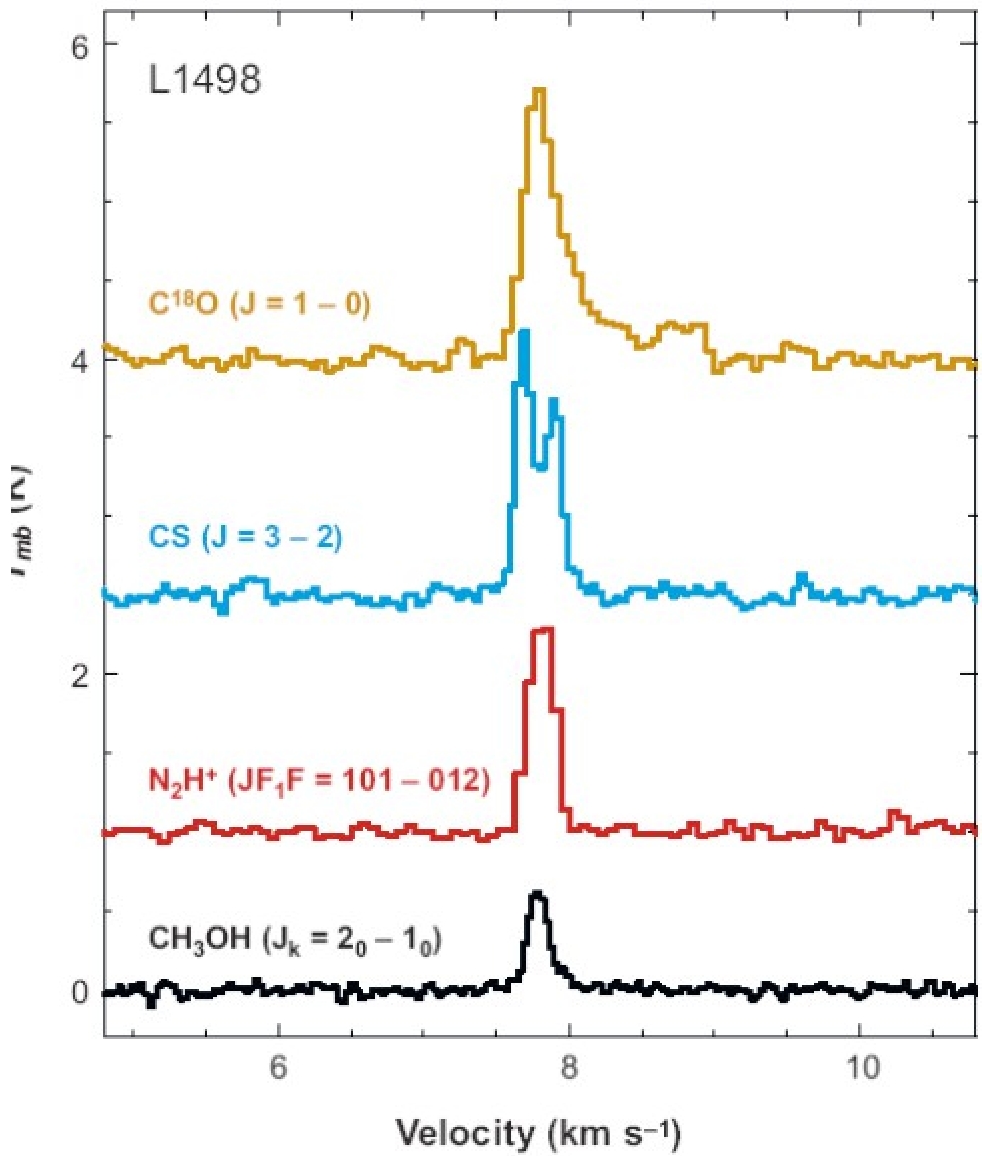
Effect on equilibrium structure

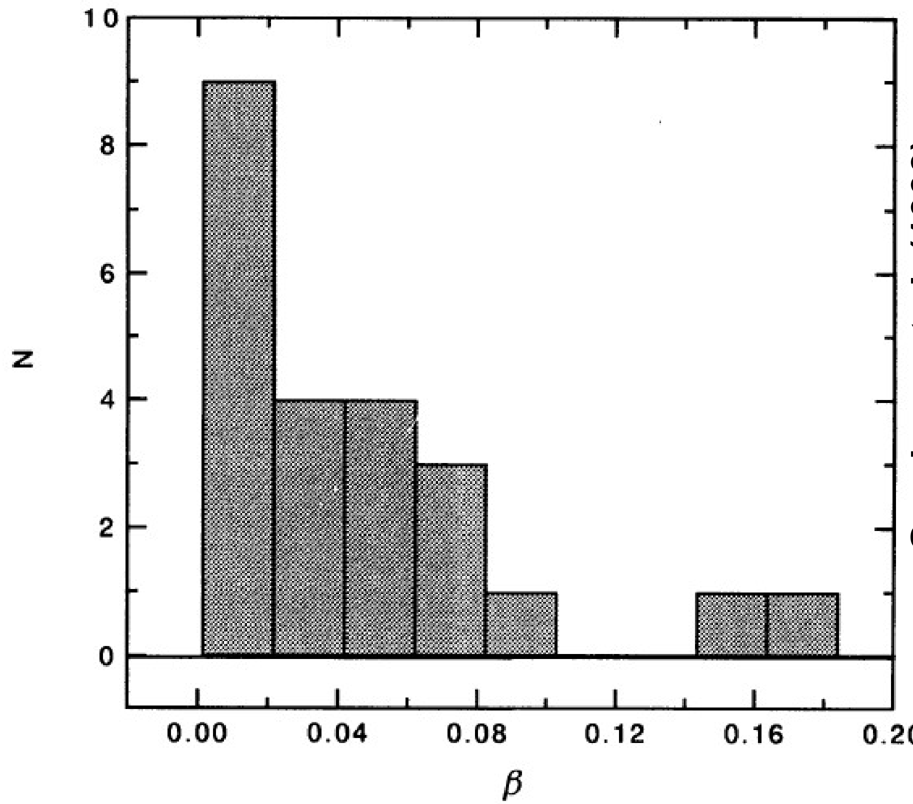


Galli et al. (2002)

- Temperature gradient has little effect on density profile
  - Bonnor-Ebert profile still good fit

Gas kinematics

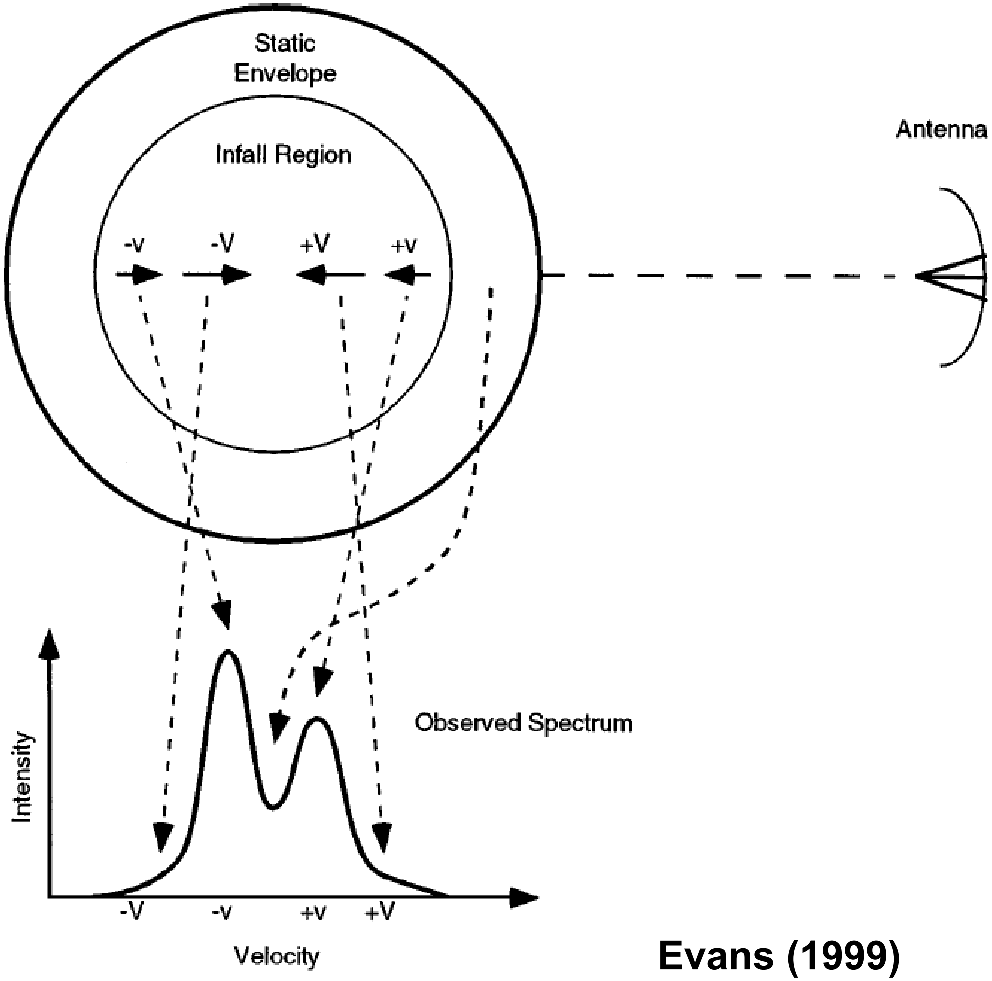




Goodman et al. (1993)

- Narrow spectra lines: < 0.5 km/s
  - Subsonic internal motions
- Rotation is unimportant for stability

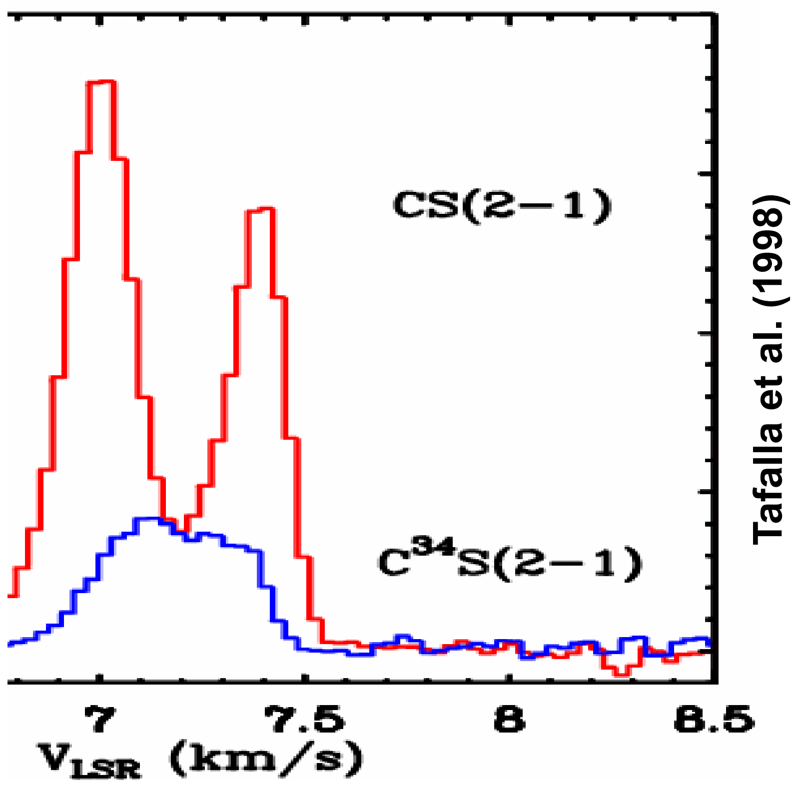
Gas kinematics. Inward motions

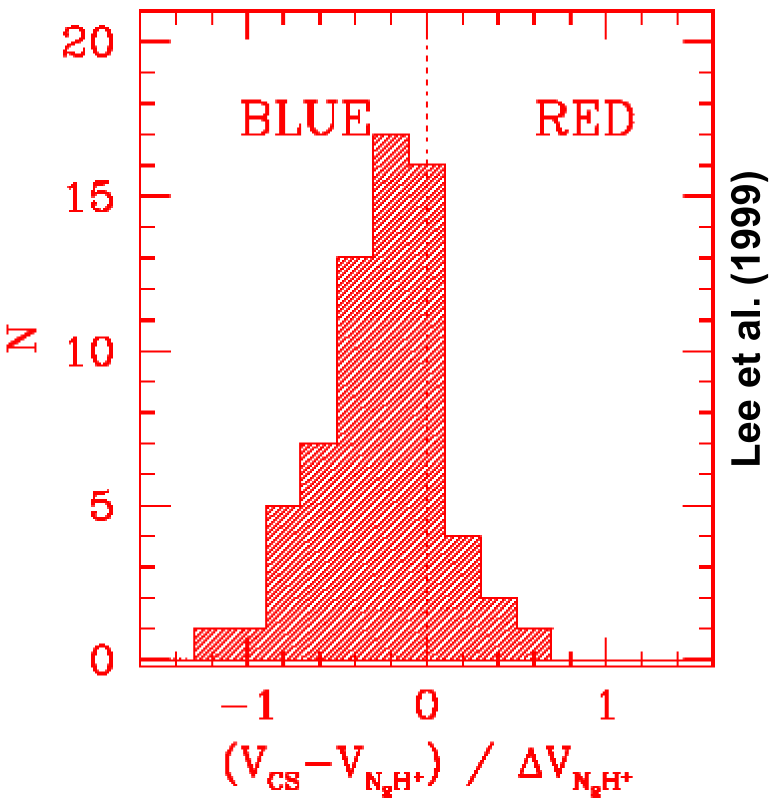


Evans (1999)

- Inward motions: line of tick tracer has self absorption with brighter blue peak
- Reversed shape for outward motions

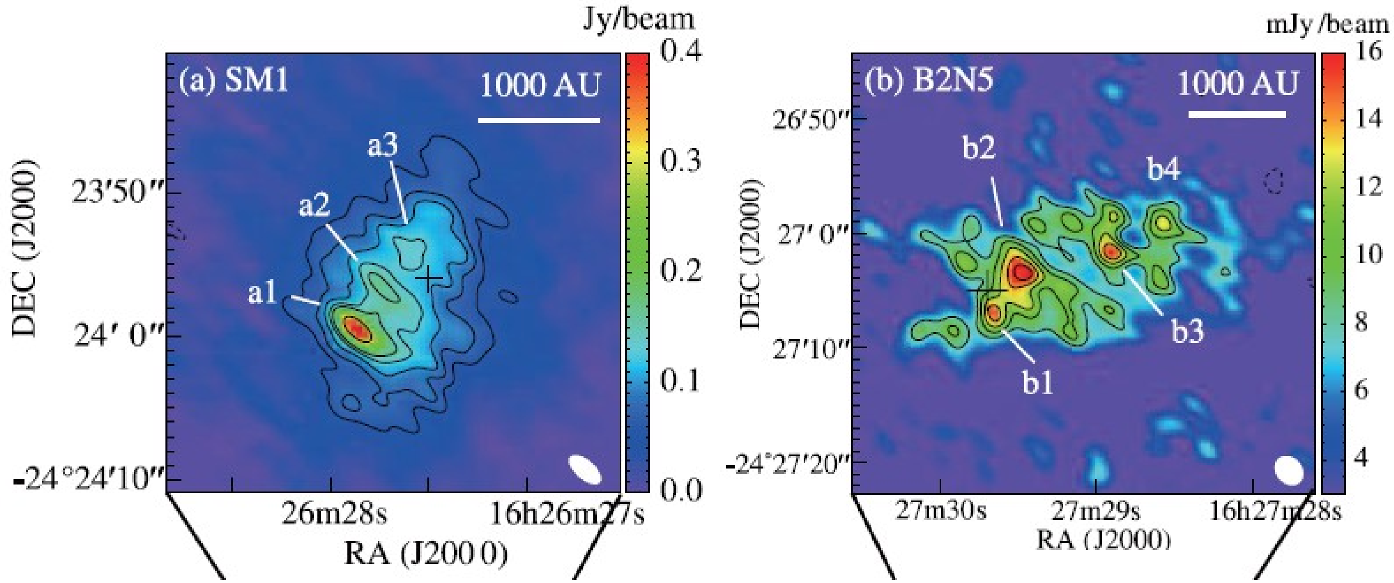
Gas kinematics. Inward motions





- Distinguish from two velocity components: compare optically thick and thin tracers
  - $\delta V = (V_{thick} - V_{thin})/\Delta V_{thin}$
- Prevalence of blue-asymmetric profiles: statistical evidence for contraction

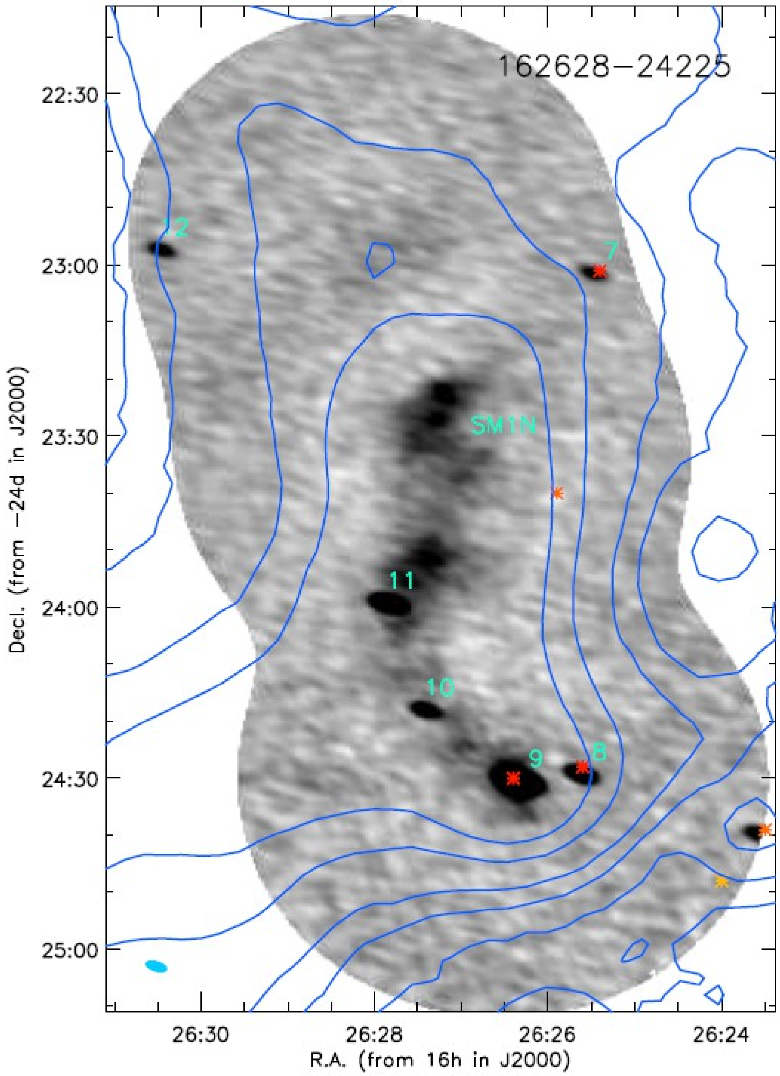
Searches for substructure



Nakamura et al. (2012)

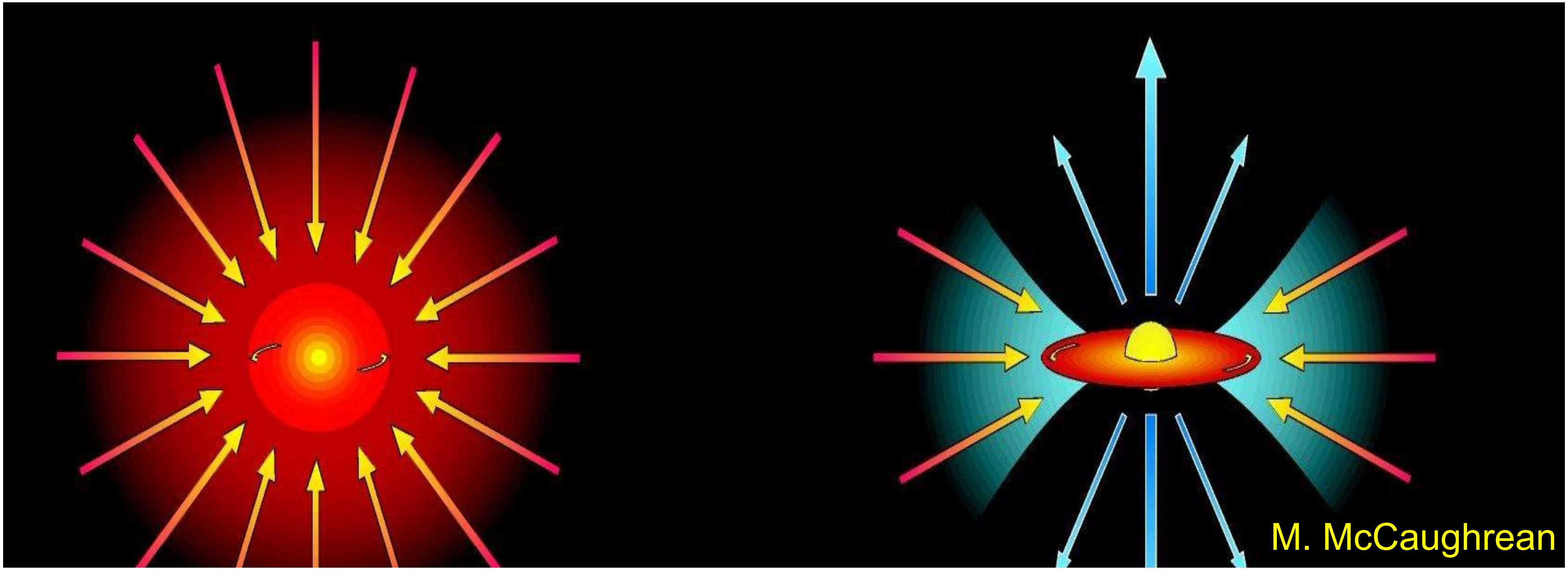
- Substructure in starless cores may indicate early stages of fragmentation
  - ~ 50% of young stars are binary/multiple
- Searches for substructure towards starless cores mostly negative
  - Schnee et al. (2010, 2012): SMA + CARMA Pers & Oph
- Nakamura et al. (2012) [SMA]: SM1 & B2N5

The ALMA contribution



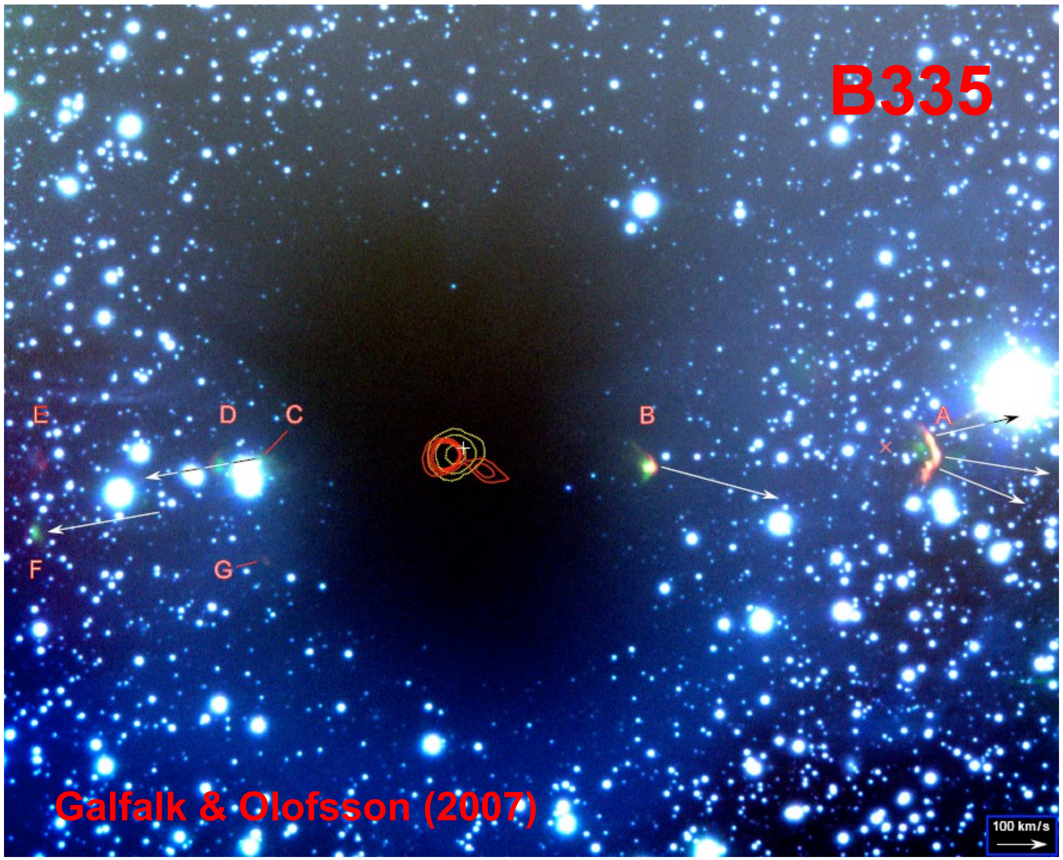
- Few studies of starless cores so far with ALMA
- No substructure in 56 starless cores of Chamaeleon I
  - Dunham et al. (2017)
- 2 cores with substructure in Ophiuchus (out of ~ 60)
  - Kirk et al. (2017)
- Differences between clouds?
  - Surveys are still shallow
- More work on starless cores with ALMA needed
  - Some in progress

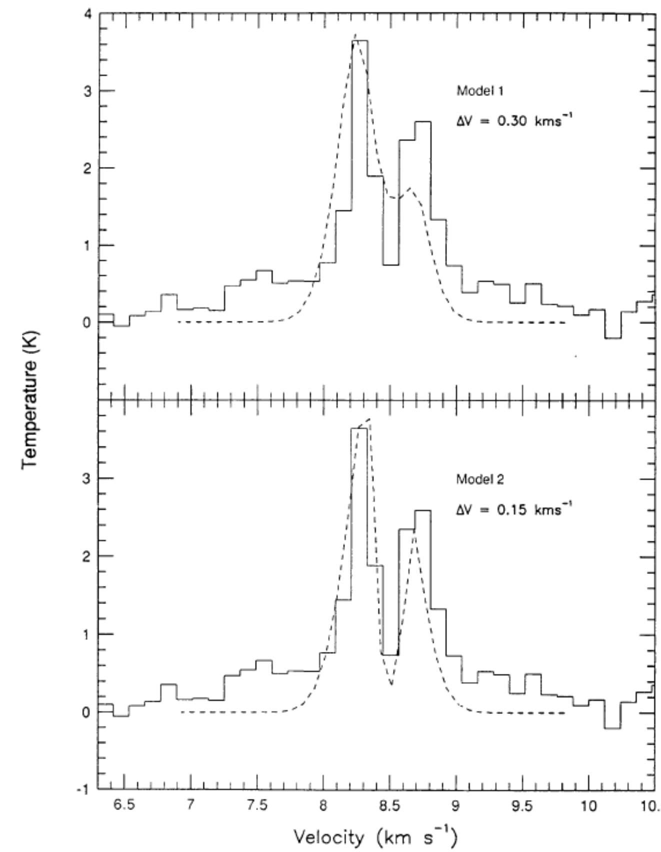
Protostar formation



- Formation of compact source at the center
  - Infall
  - Outflow
  - Disk
- Ideal target for ALMA observations

Infall toward protostars

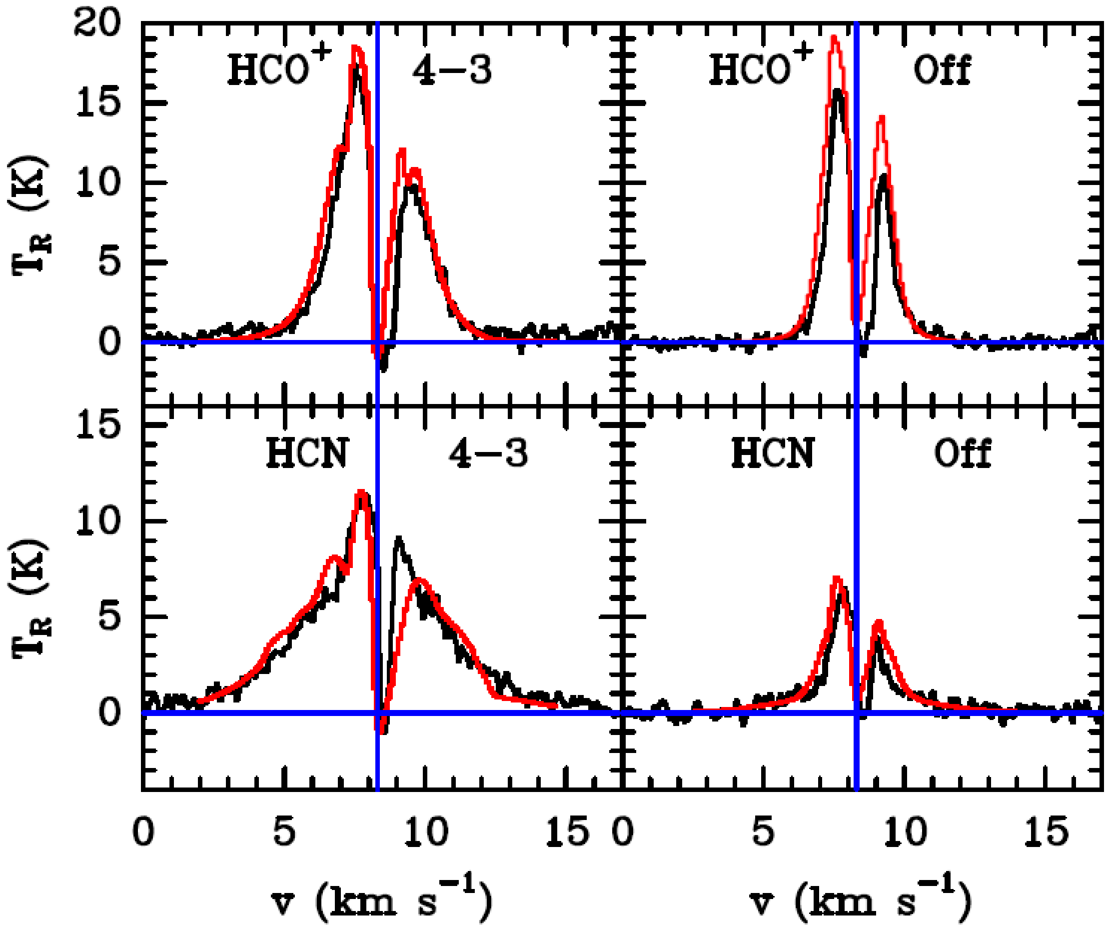




Zhou et al. (1993)

- B335: isolated globule, YSO + outflow
- Evidence for infall motions from single dish obs. (Zhou et al. 1993, Choi et al. 1995)
  - Good fit with gravitational collapse SIS sphere (Shu 1977)

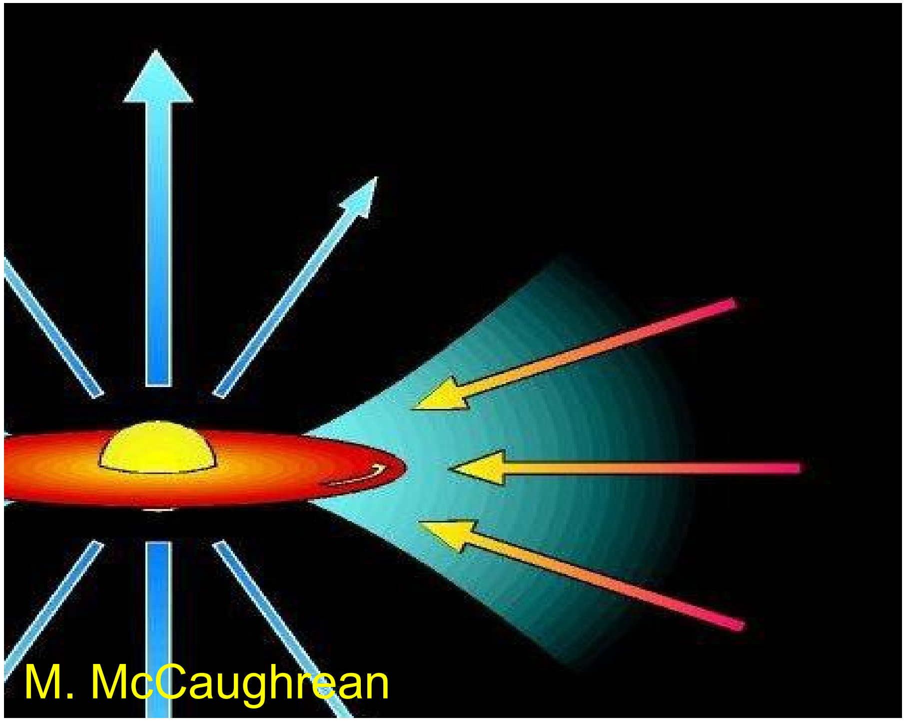
ALMA observations of B335

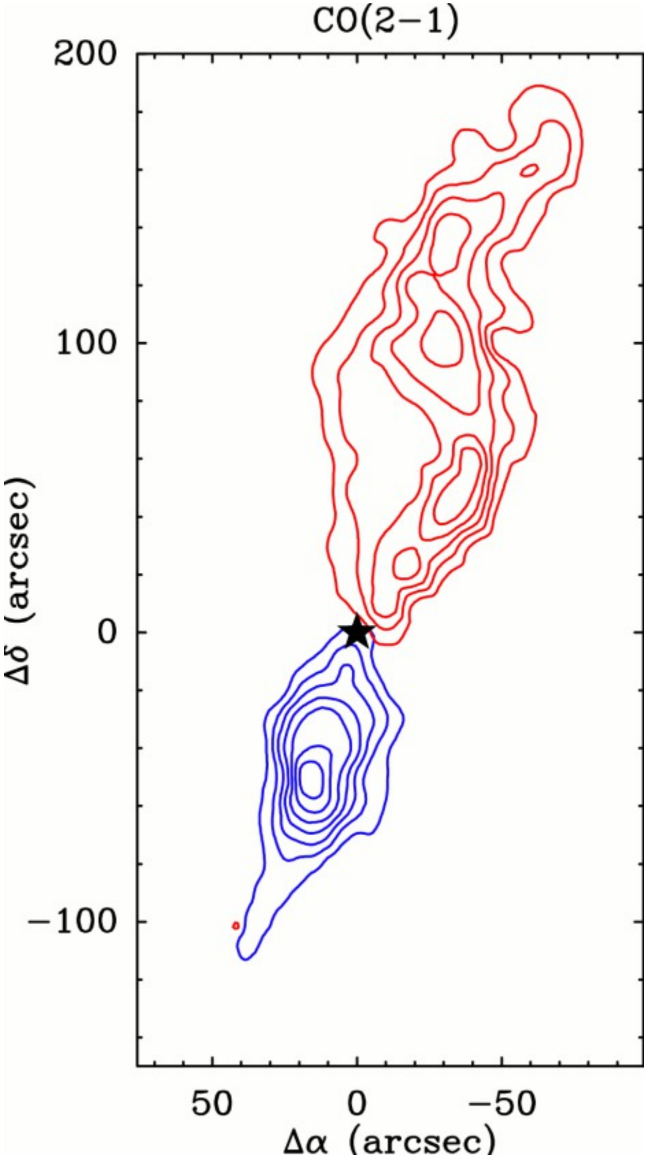


Evans et al. (2015)

- Infall signature in optically thick tracers (HCO^+ & HCN), 0.5'' resol
- Good fit with SIS model (new distance of 100 pc)
  - 3×10^{-6} M_o/yr & 5×10^4 yr

Bipolar outflows

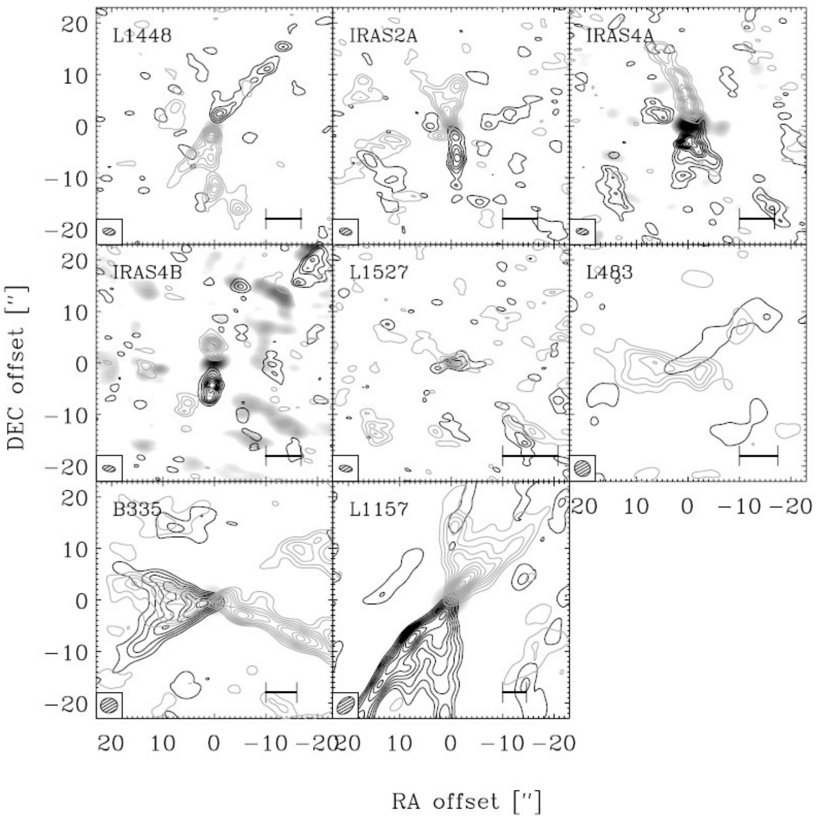




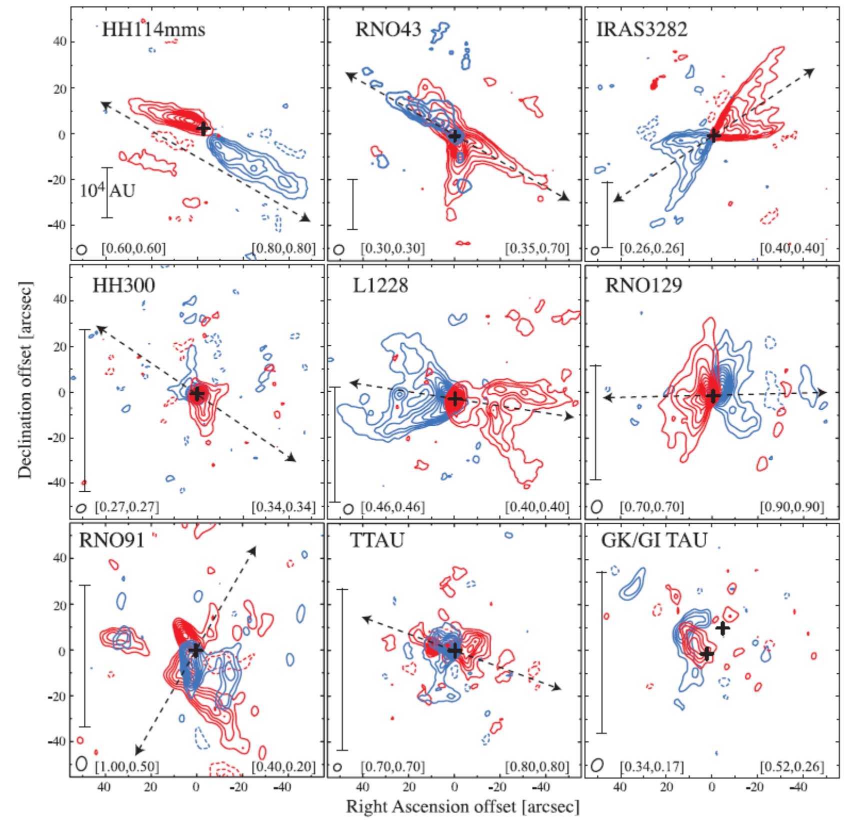
Bachiller et al. (2001)

- Infall is compact and subsonic: challenging detection
- Outflow is extended, supersonic, and bipolar: easily detected

Bipolar outflows pre-ALMA



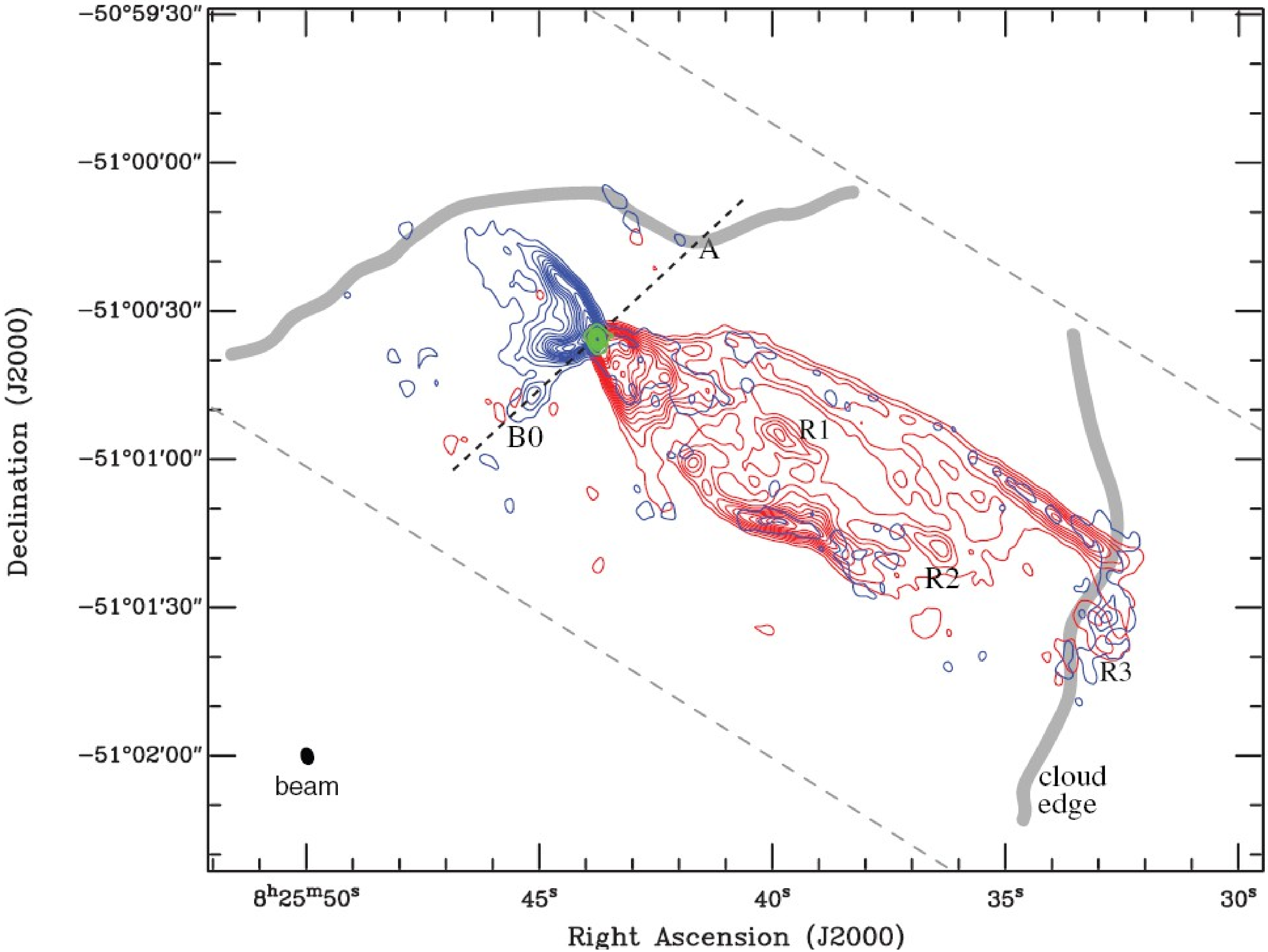
Joergensen et al. (2007)



Arce & Sargent (2006)

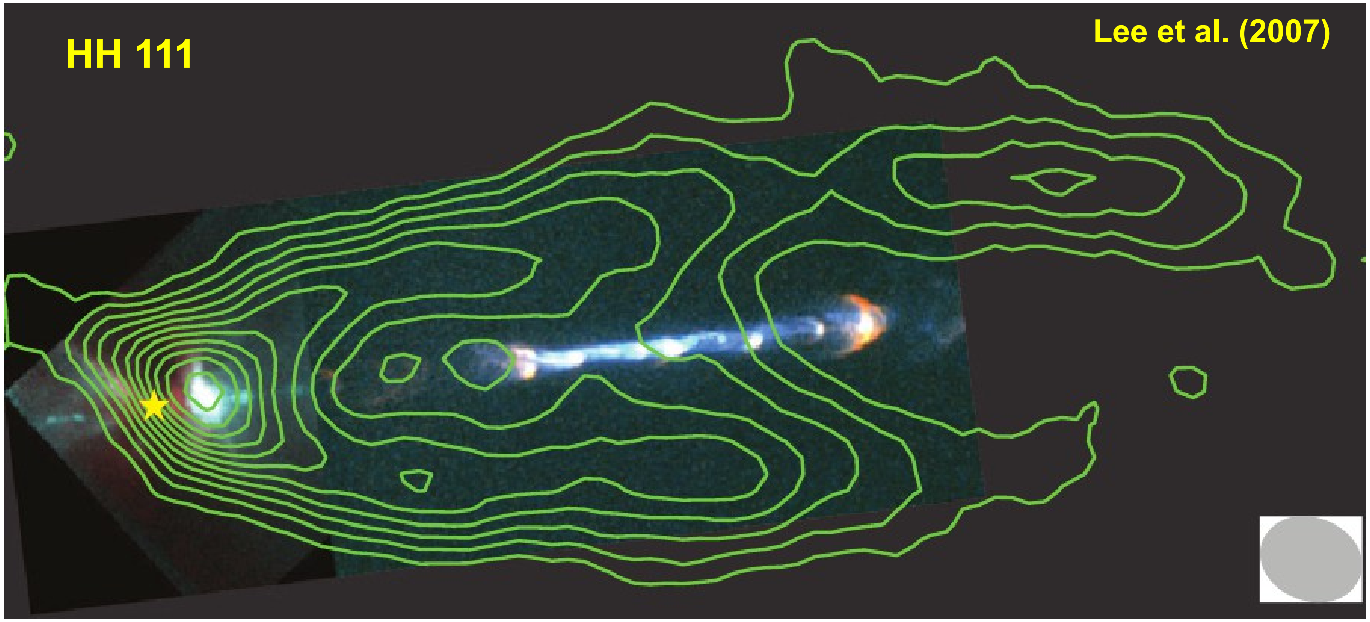
- Previous surveys with SMA, OVRO
- Variety of geometries, but common presence of shells near YSO
  - Sometimes jet component

Shells in HH 46/47 with ALMA



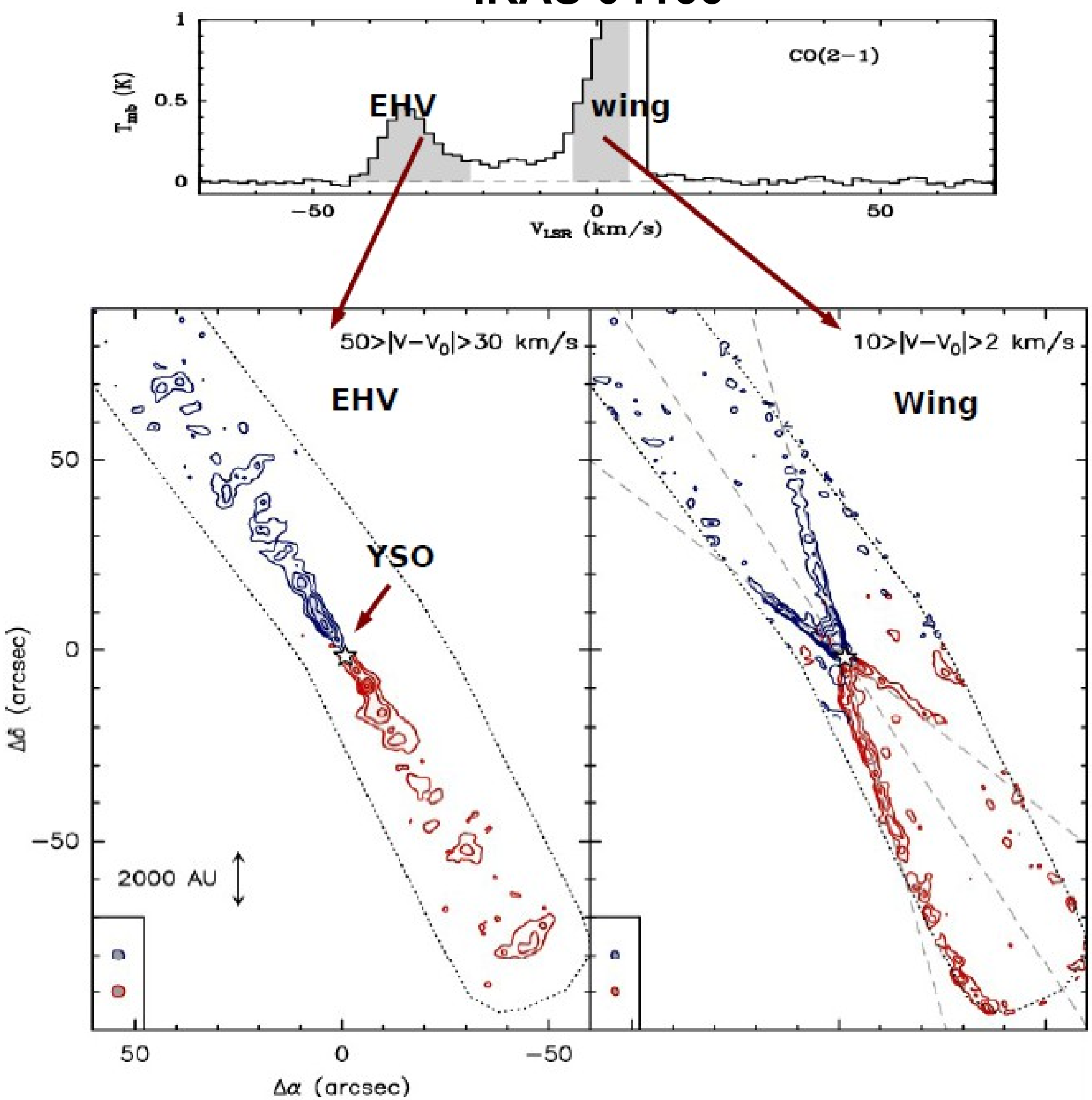
Arce et al. (2013)

What drives bipolar outflows ?



- Jet-driven models: jet responsible for all acceleration
  - Needs to widen action: precession, wandering, entrainment
  - Raga & Cabrit (1993), Masson & Chernin (1993), Stahler (1993)
- Wind-driven models: driving agent is wider than jet
  - Jet is central part of a wider component
  - Shang et al. (2006)

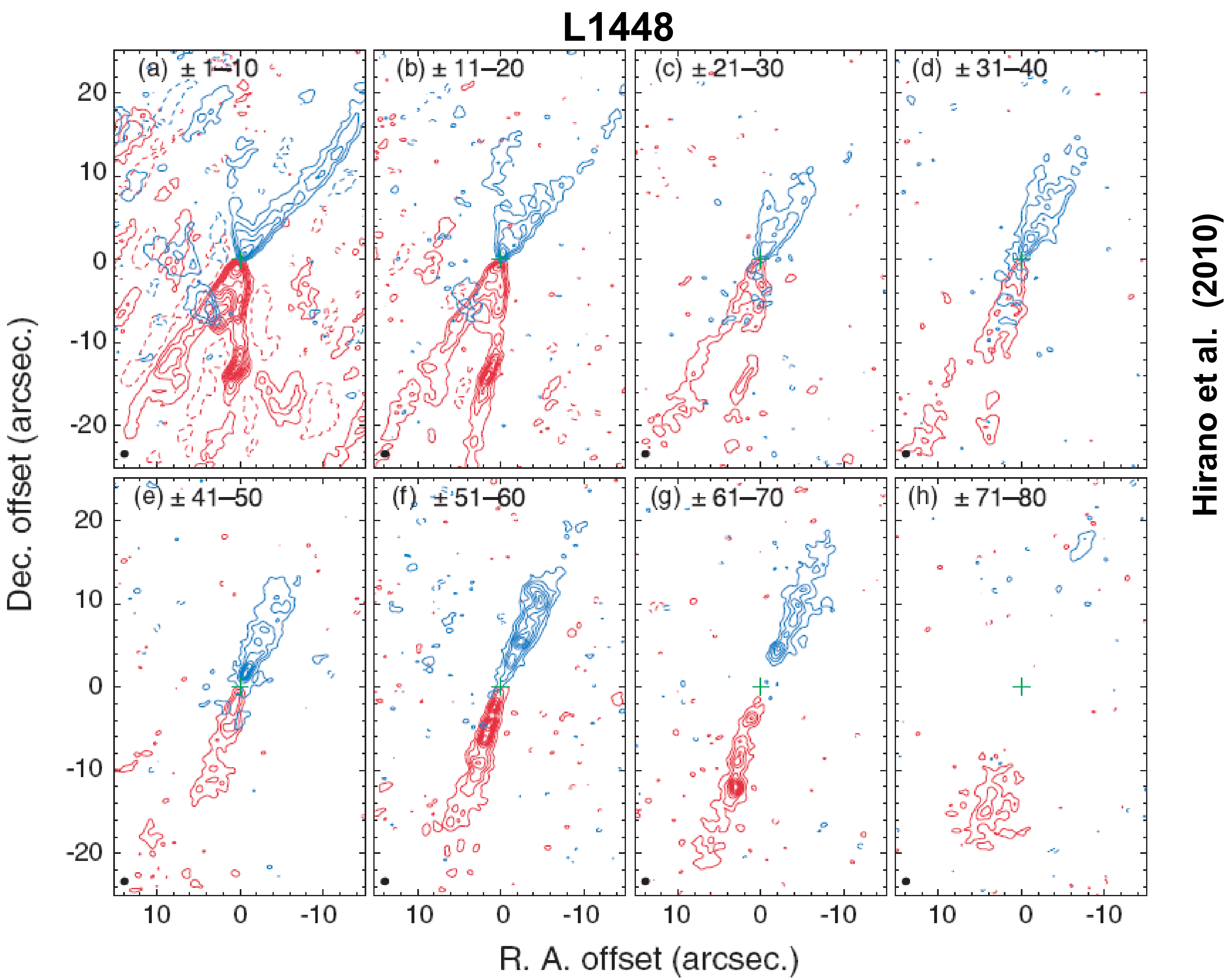
Extremely high velocity (EHV) jets



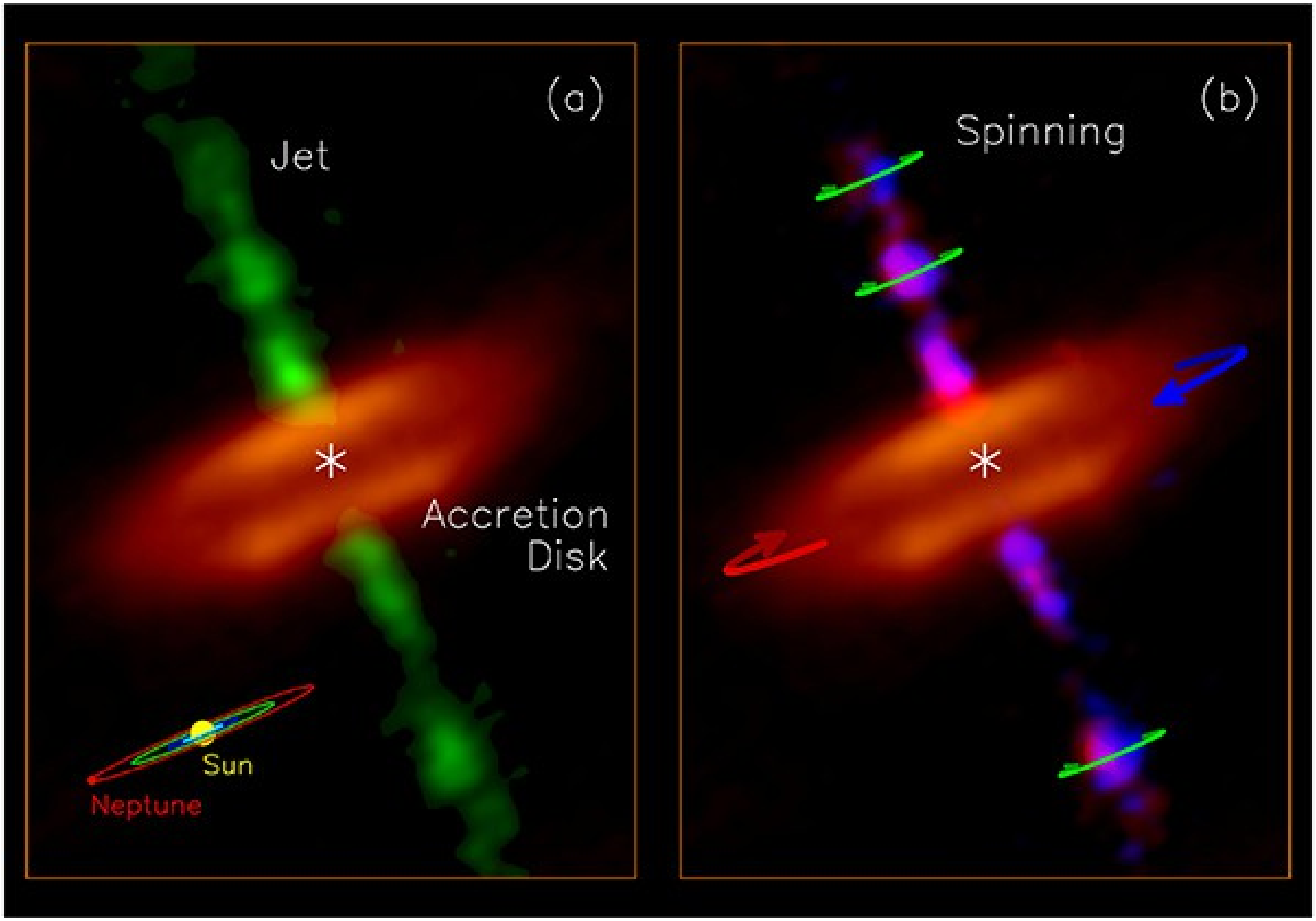
Santiago-Garcia et al. (2009)

- Small group of outflows
  - Shells
  - Jet
- Shell: low velocity gas
- Jet: Extremely High Velocity (EHV) component
- Best targets to investigate jet-shell connection

Extremely high velocity (EHV) jets



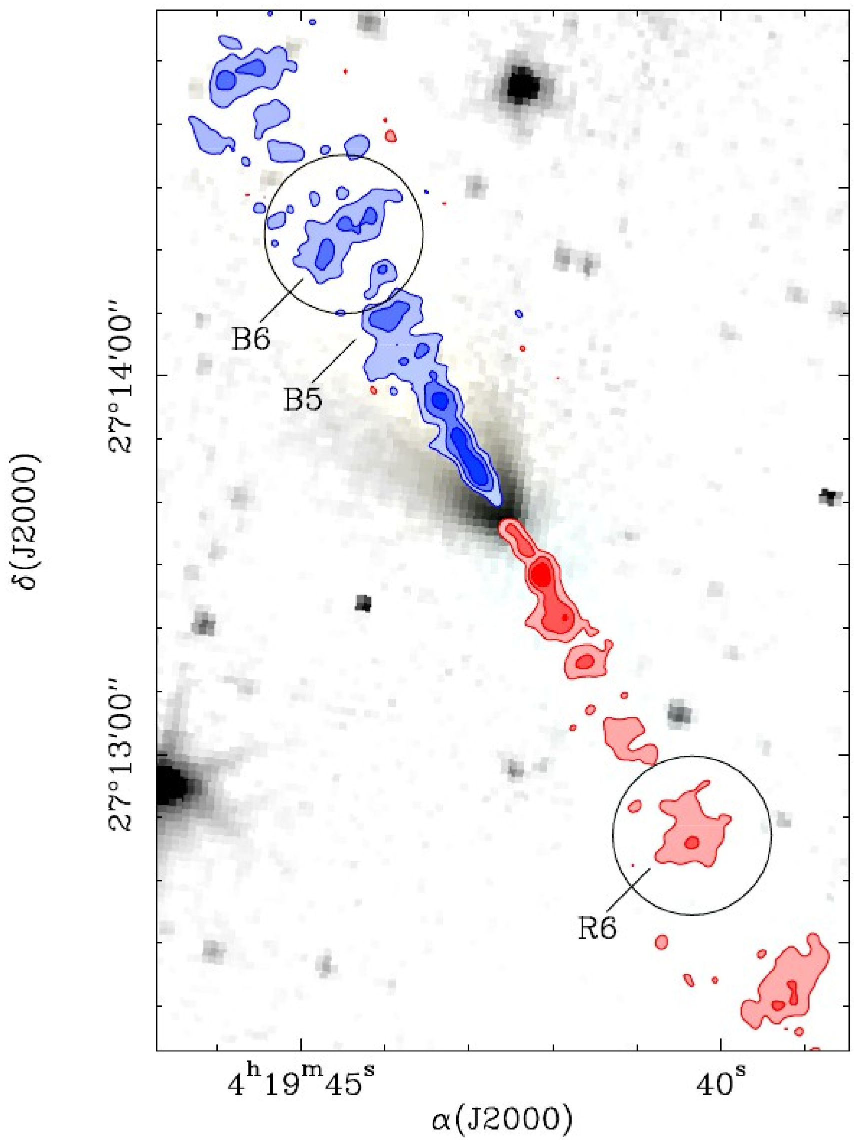
Jets with ALMA: HH 212

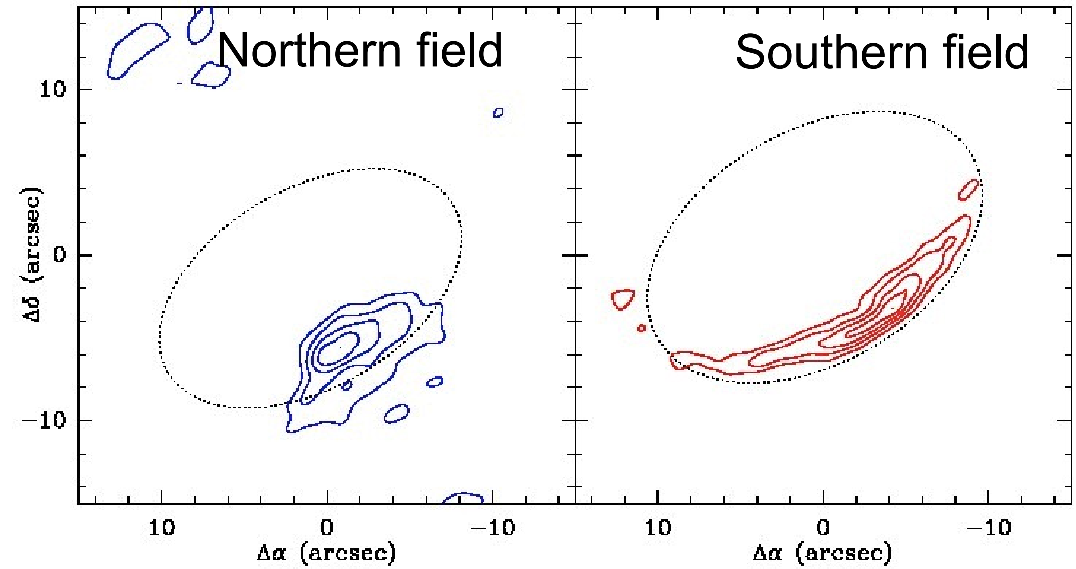


Lee et al. (2017)

- See talk by C-F Lee tomorrow (Galactic parallel session)

Jets with ALMA: IRAS 04166

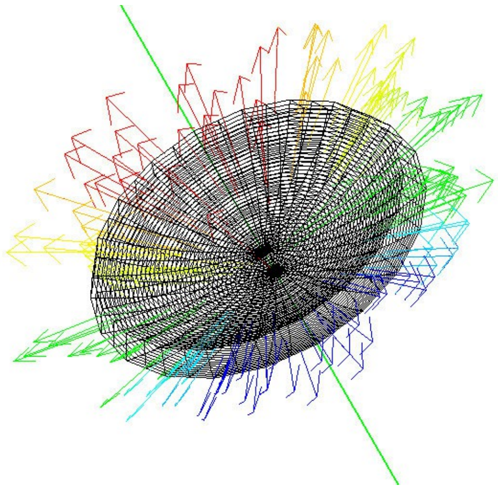




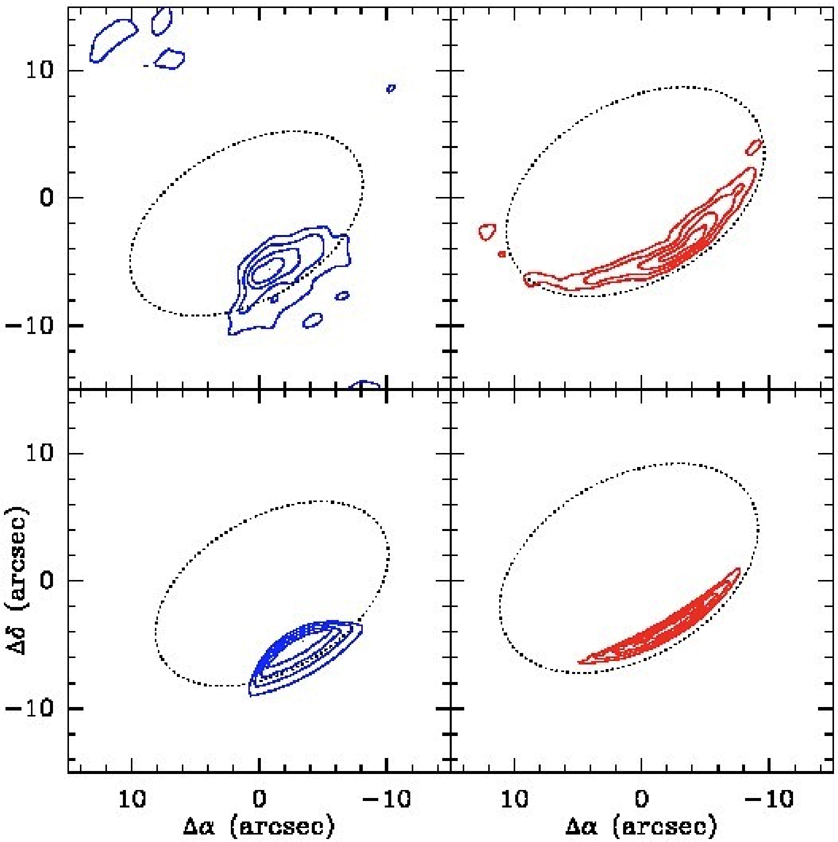
Tafalla et al. (2017)

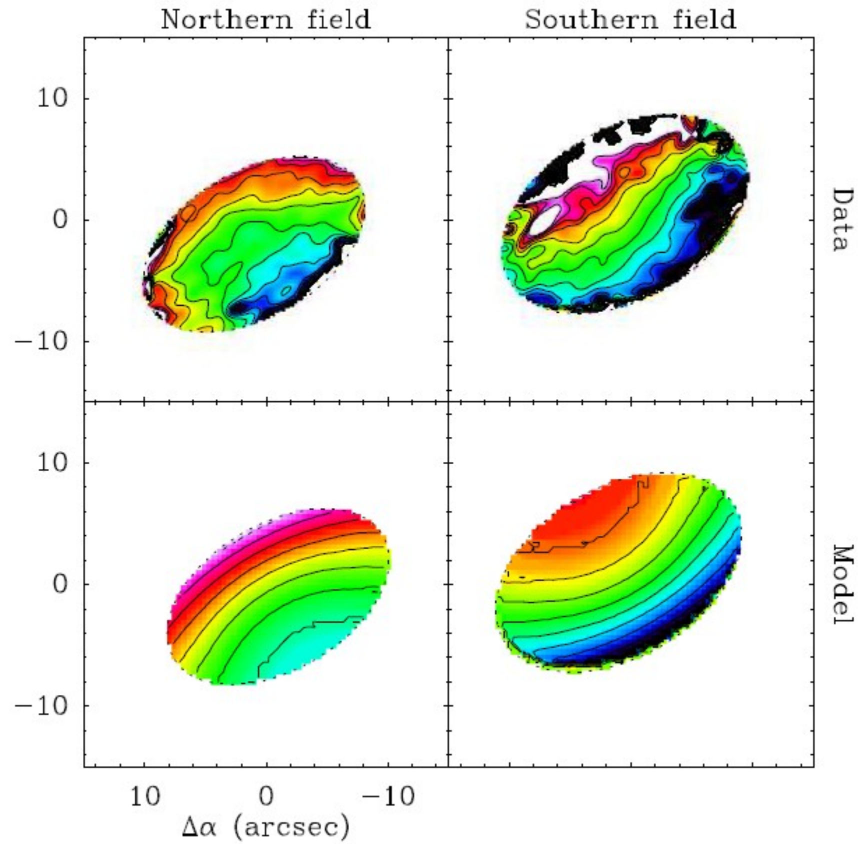
- CO(2-1), 1.3" resolution
- Systematic velocity pattern
  - Emission moves SE to NW
  - Emission restricted to ellipse
  - Full range is ~ 20 km/s

Jets with ALMA: IRAS 04166

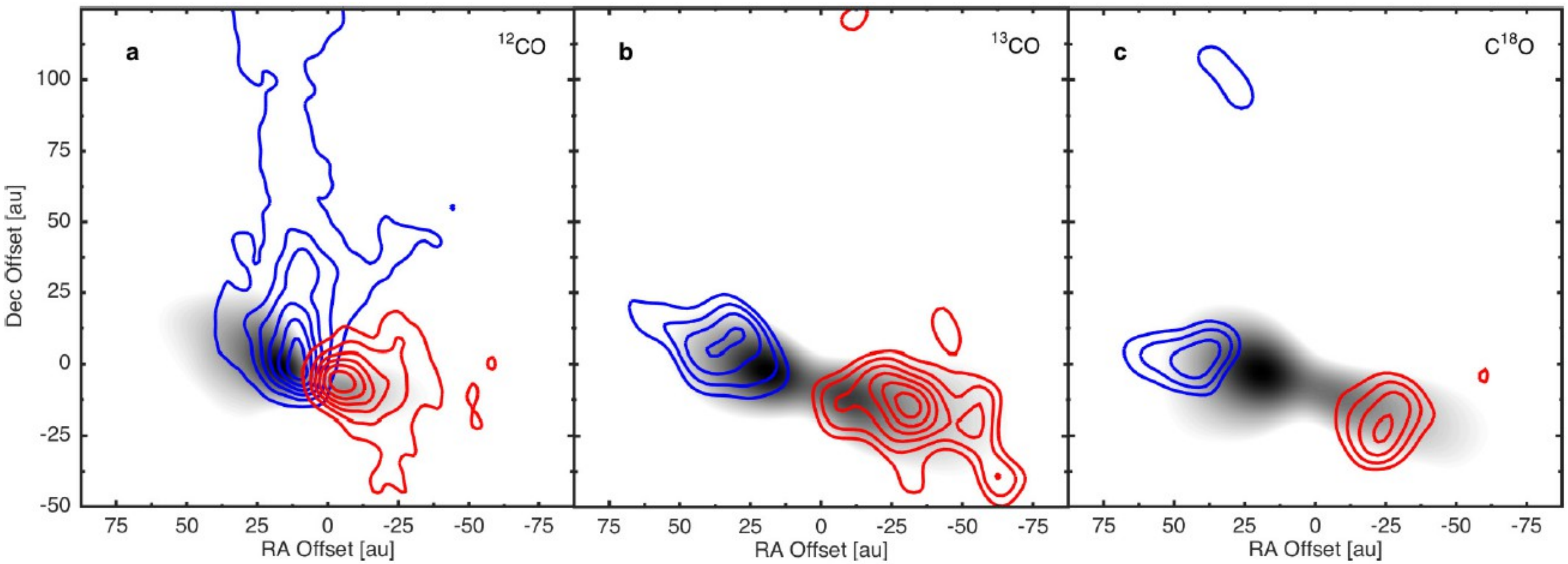


- Simple geometric model: expanding bowshock caused internal jet shock
- Sideways momentum of the gas can potentially accelerate wide outflow shell
- Consistent with jet-driven models

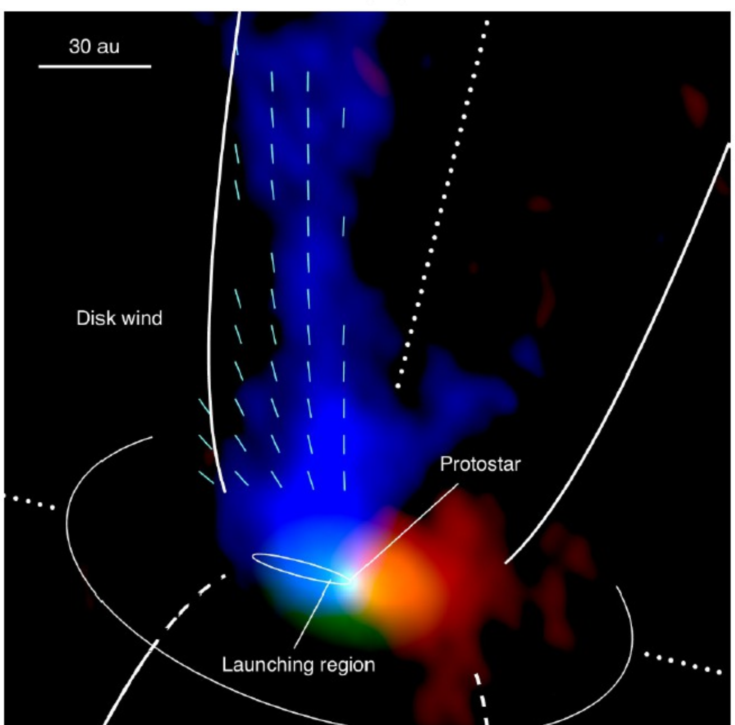




Disk wind in TMC1A

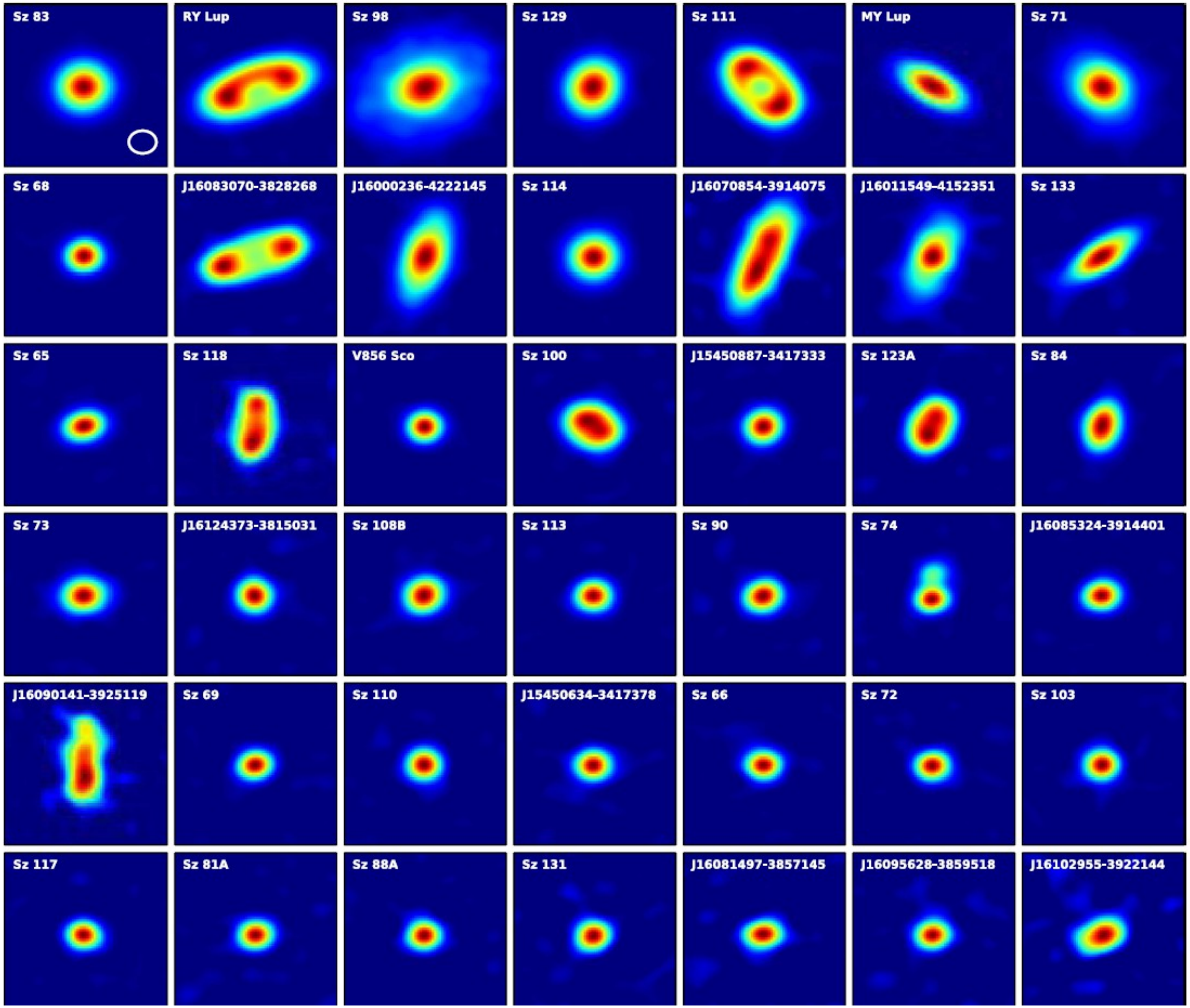


Bjerkeli et al. (2017)



- CO (1.3mm)
- CO isotopologues trace a rotating disk
- Main CO isotopologue shows evidence for wind emerging from disk

Disks with ALMA



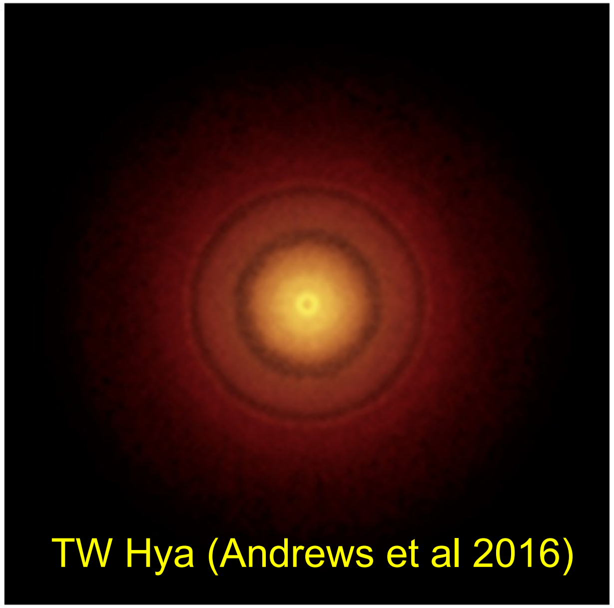
Ansdell et al. (2016)

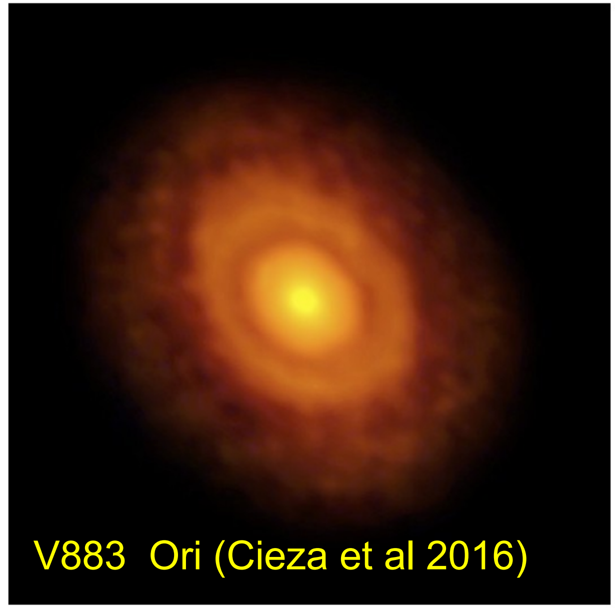
- ALMA optimized for disk studies
  - < 1" beam
  - High sensitivity
- Allows systematic searches
- Lupus (Ansdell et al. 2016)
  - 62 continuum, 36 ^{13}CO

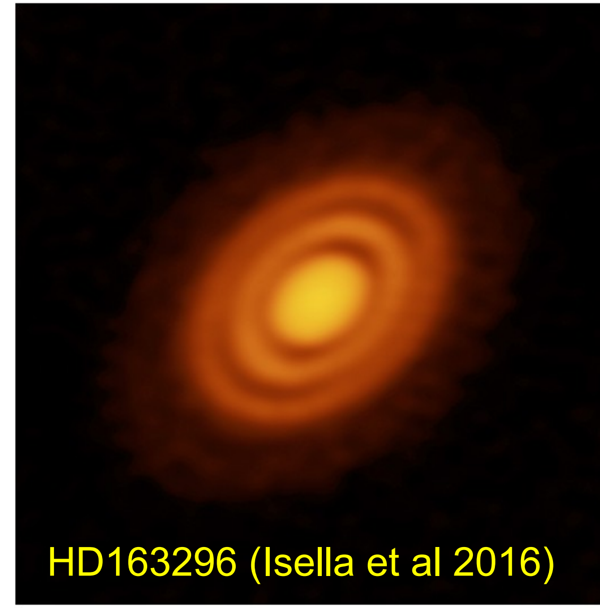
Disks with ALMA

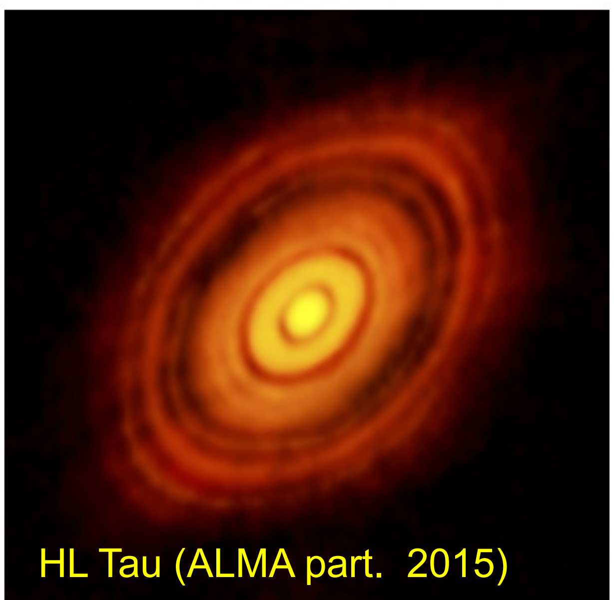
	Galactic Parallel Session 1	
	- Chair: Jungyeon Cho	
14:00 - 14:30	• ALMA polarization of HL Tau - investigating planet formation (Akimasa Kataoka, invited talk)	14:00 -
14:30 - 14:50	• Spinning dust emission from disks around T-Tauri and Herbig Ae/Be stars (Thiem Hoang)	14:30 -
14:50 - 15:10	• The Synthetic ALMA Multi-band Analysis of Dust Properties of the TW Hya Protoplanetary Disk (Seongjoong Kim)	14:50 -
15:10 - 15:30	• Young protostellar discs and their role in planet formation and evolution (Dimitris Stamatellos)	15:10 -
15:30 - 16:00	♦ Break	15:30 -
	- Chair: Chin-Fei Lee	
16:00 - 16:30	• Formation of Protostellar Binary system (Seokho Lee, invited talk)	16:00 -
16:30 - 16:50	• ALMA Cycle 2 Observations of the Class I Protostar L1489 IRS: Misaligned Disk Structure (Jinshi Sai)	16:30 -
16:50 - 17:10	• Evolutional phases of three Class 0 protostars in Serpens Main (Yusuke Aso)	16:50 -
17:10 - 17:30	• Spatially resolved study of the CO selective dissociation in the Oph-A region (Mitsuyoshi Yamagishi)	17:10 -
17:30 - 18:00	♦ Move to banquet	17:30 -
18:00 -	♦ Banquet	18:00 -

From disks to planets ?

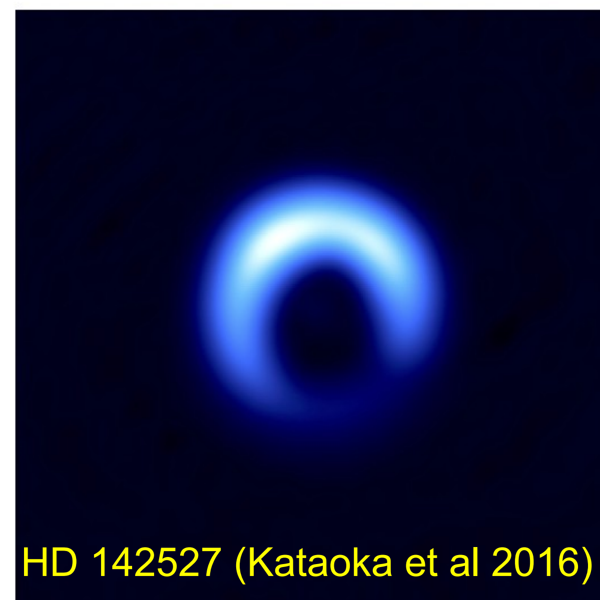

TW Hya (Andrews et al 2016)


V883 Ori (Cieza et al 2016)

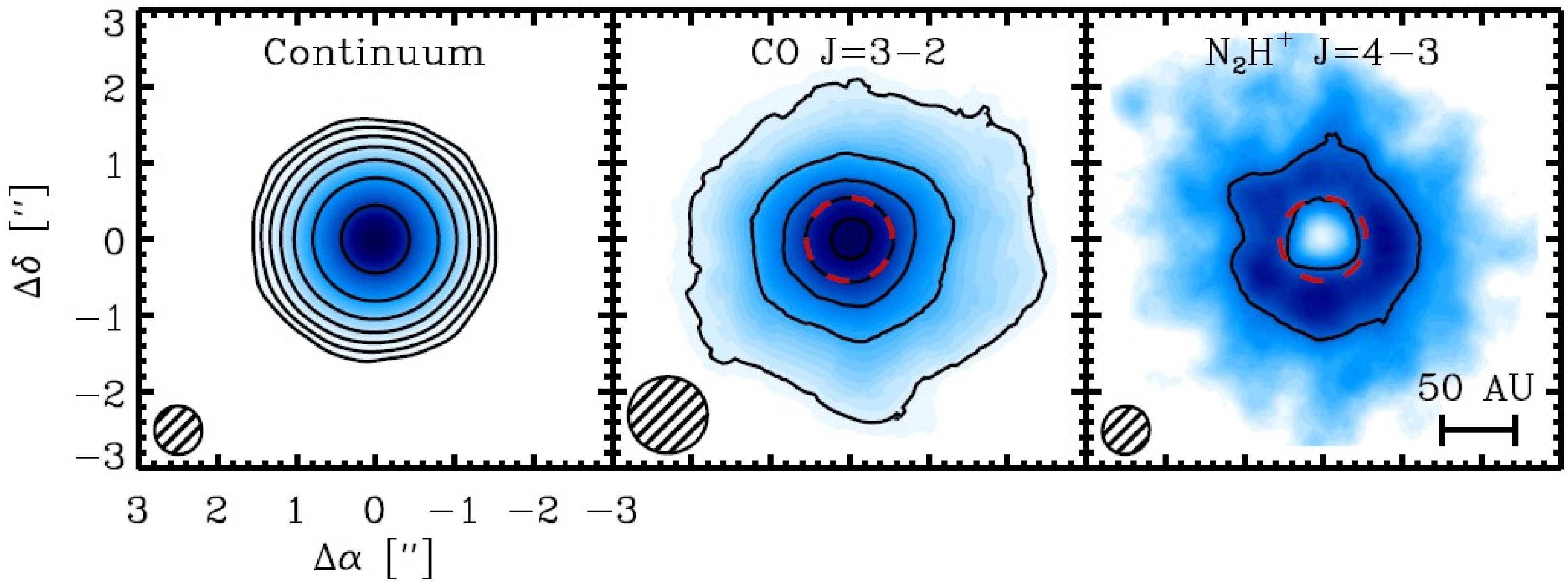

HD163296 (Isella et al 2016)


HL Tau (ALMA part. 2015)

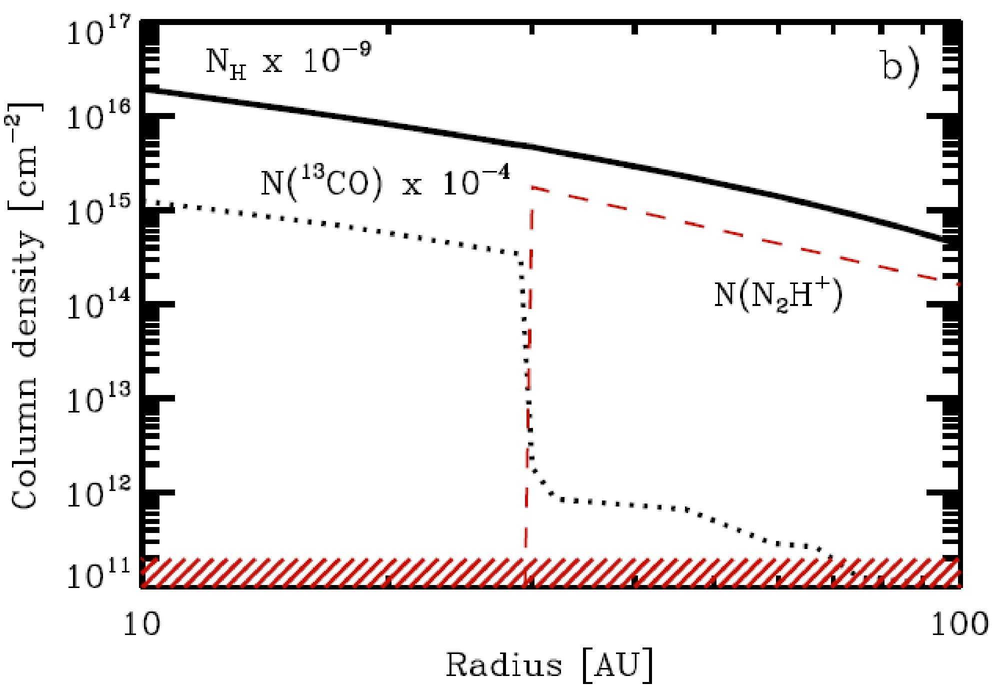

Elias 2-27 (Perez et al 2016)


HD 142527 (Kataoka et al 2016)

Disk chemistry



Qi et al. (2013)



- Snowline
-

Summary

Our view of low-mass star formation now covers from ~10pc to ~ 20 AU (5 orders of magnitude):

- ~ 10 pc: clouds appear structured in filaments
- ~ 1pc: filaments often contain velocity coherent fibers
- ~ 0.1 pc: dense cores fragment out of fibers
- ~ 0.01 pc: dense-core profiles present central flattening
- ~ 0.001 pc (200 AU): matter organizes in disks
- ~ 0.0001 pc (20 AU): disks present gaps,asymmetries, and highly collimated jets

ALMA challenge:

keep high resolution progression
&
connect all scales