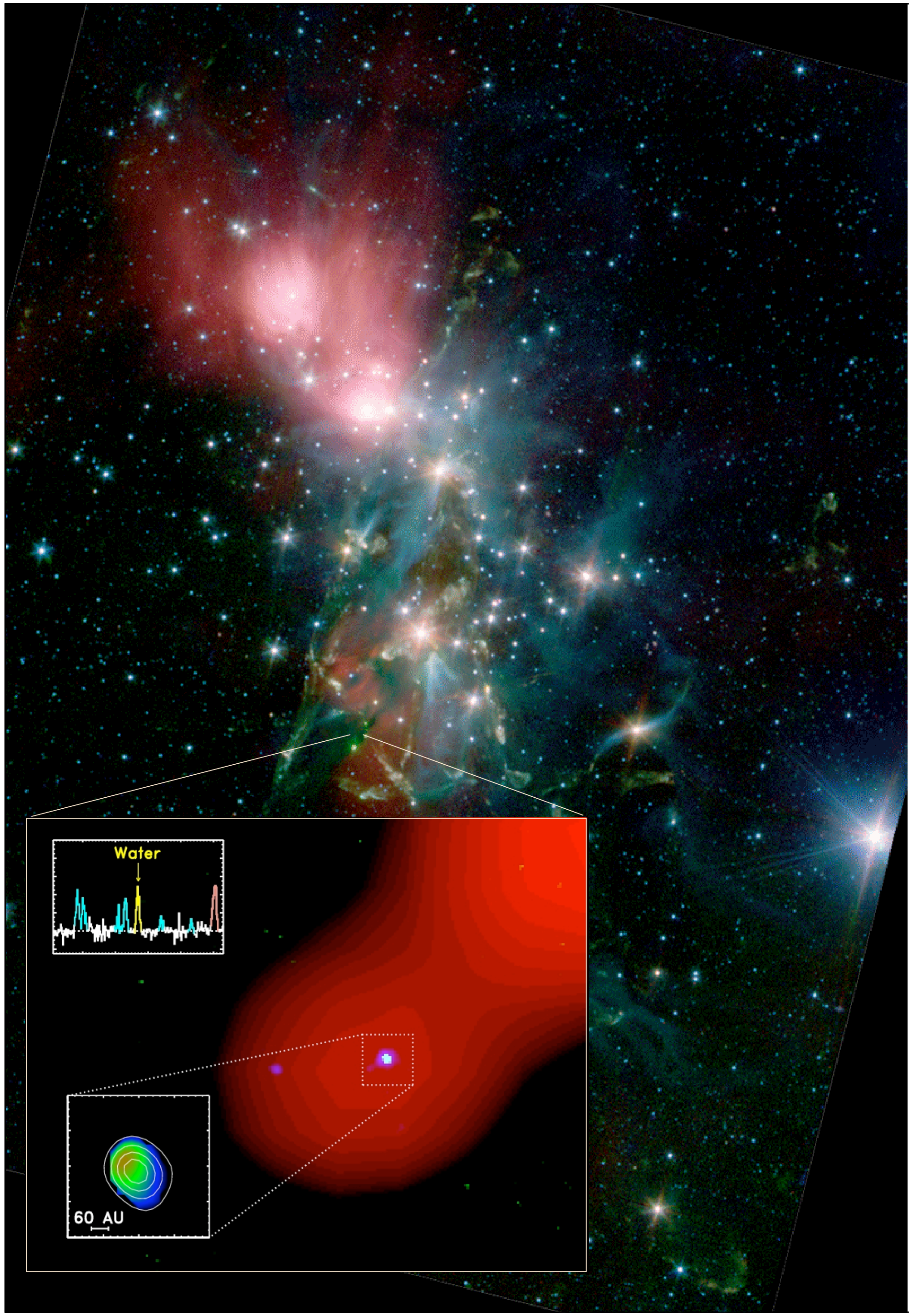

Interferometric studies of low-mass protostars

...while we are waiting for ALMA...

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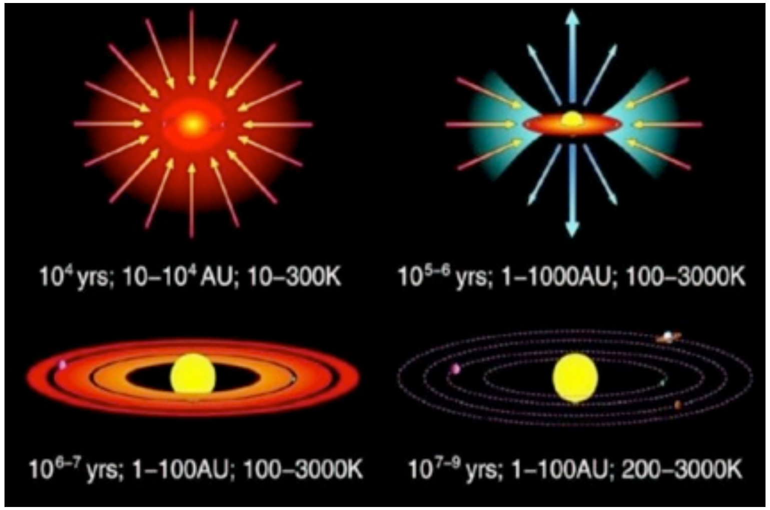
University of Copenhagen

Our basic picture of low-mass star formation

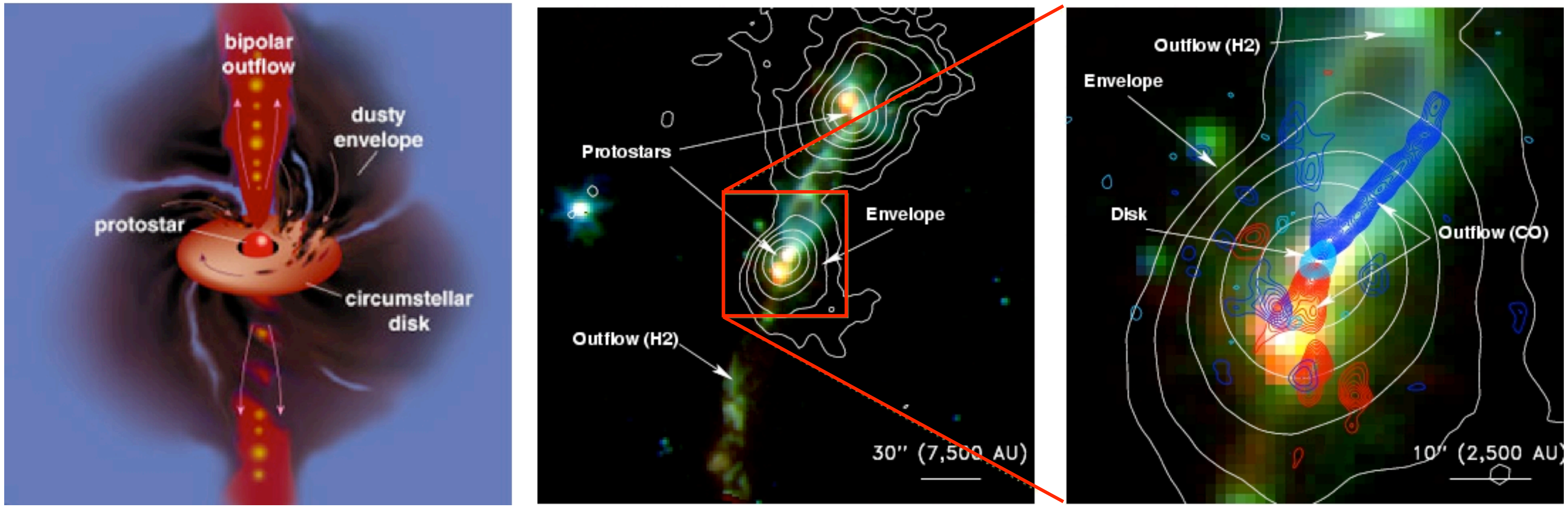


after Shu et al. 1987

Low-mass stars formed from gravitational collapse of dense cloud cores.

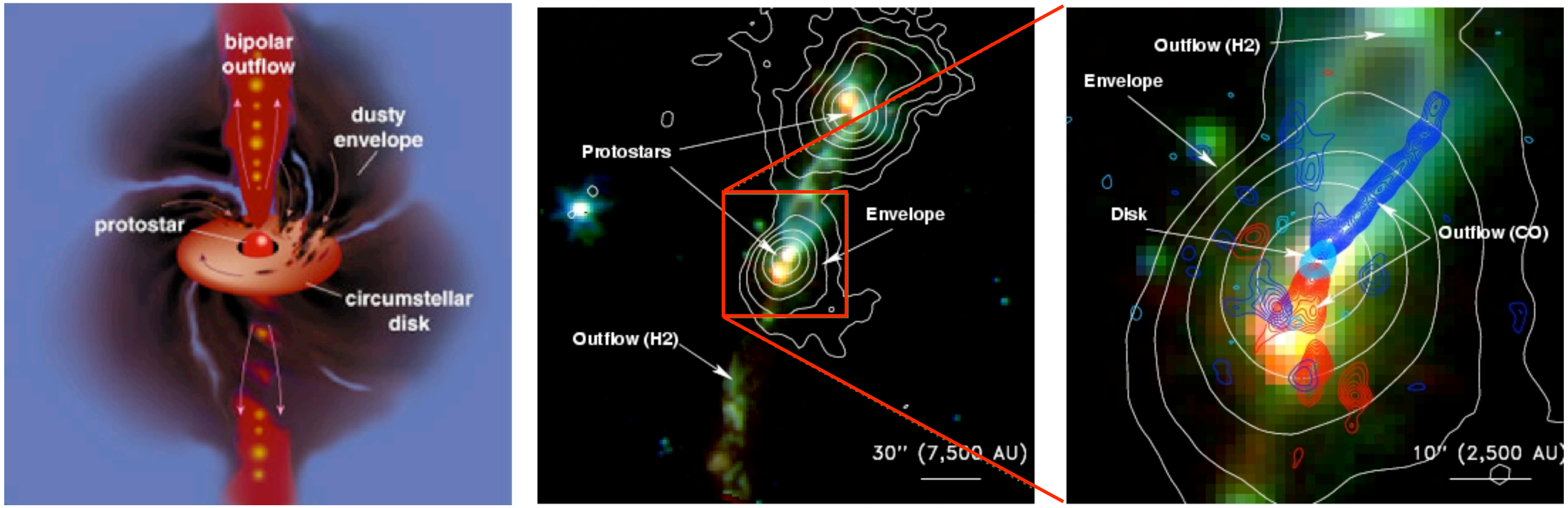
Gradual dispersal of protostellar envelope (disk accretion; outflow action).

The earliest stages of young stars



Data: Large SMA survey, "PROSAC", of 20 embedded Class 0/I protostars in a wide range of submm lines and continuum (Jørgensen et al. 2007, 2009). Cartoon from Greene (2001), Spitzer data (Jørgensen et al. 2006) compared to SMA and JCMT/SCUBA data (Jørgensen et al. 2007).

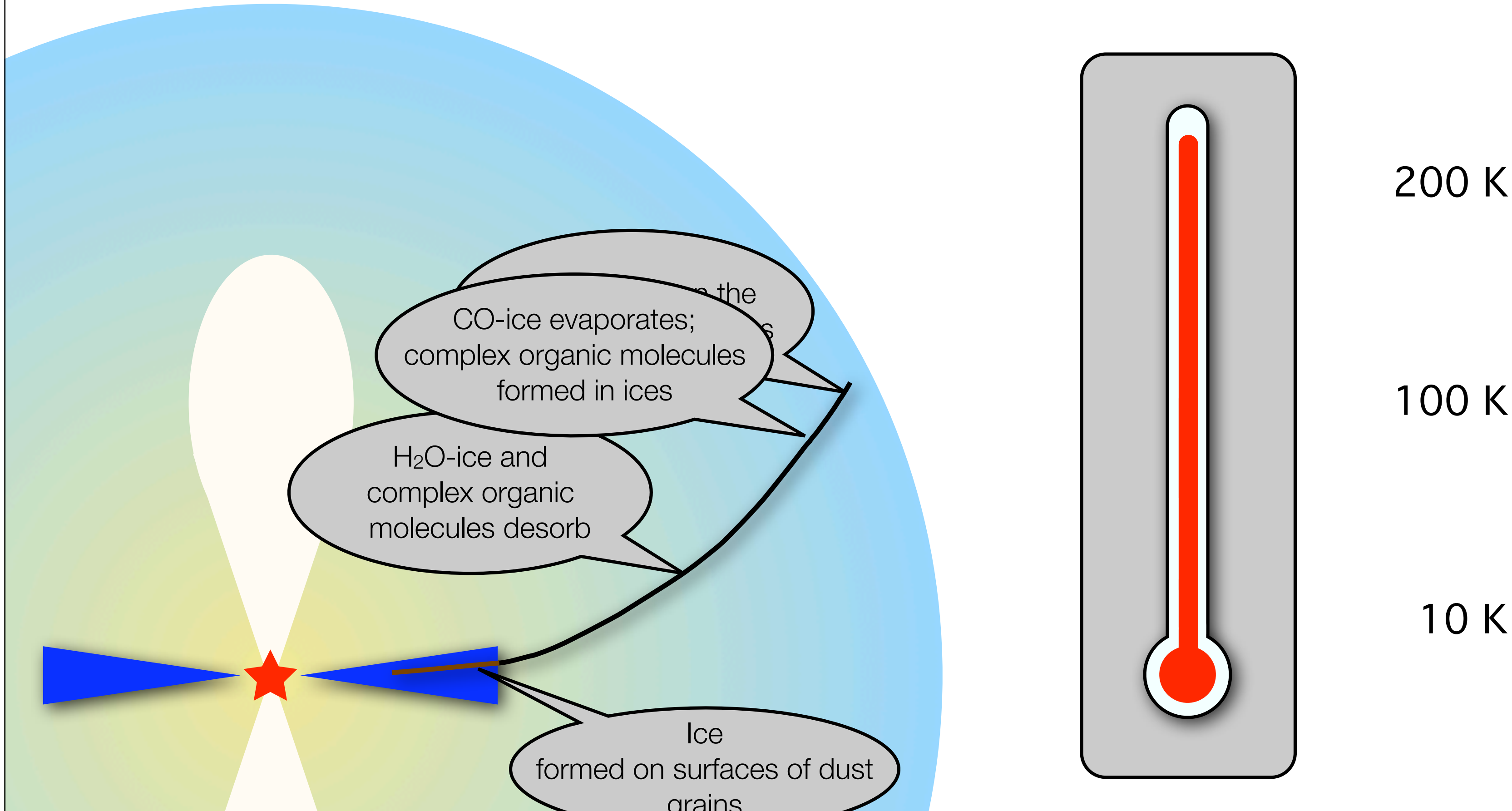
The earliest stages of young stars



Early embedded stages provide the link to the parental molecular cloud/pre-stellar stages - and set the initial conditions for the later evolution of the young star and, in particular, potential protoplanetary disk.

High angular resolution (sub)mm wavelength observations critical tool to study chemical structure of protostars from envelope to disk scales.

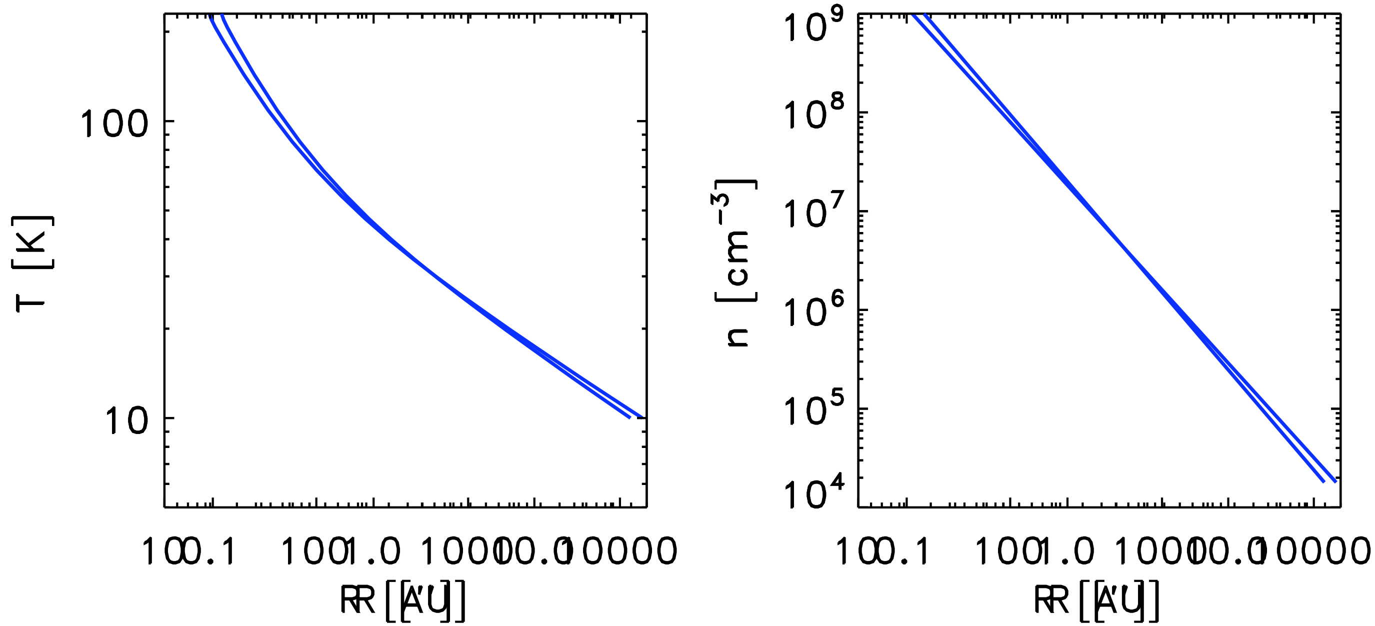
Chemical evolution of dust and gas in protostars



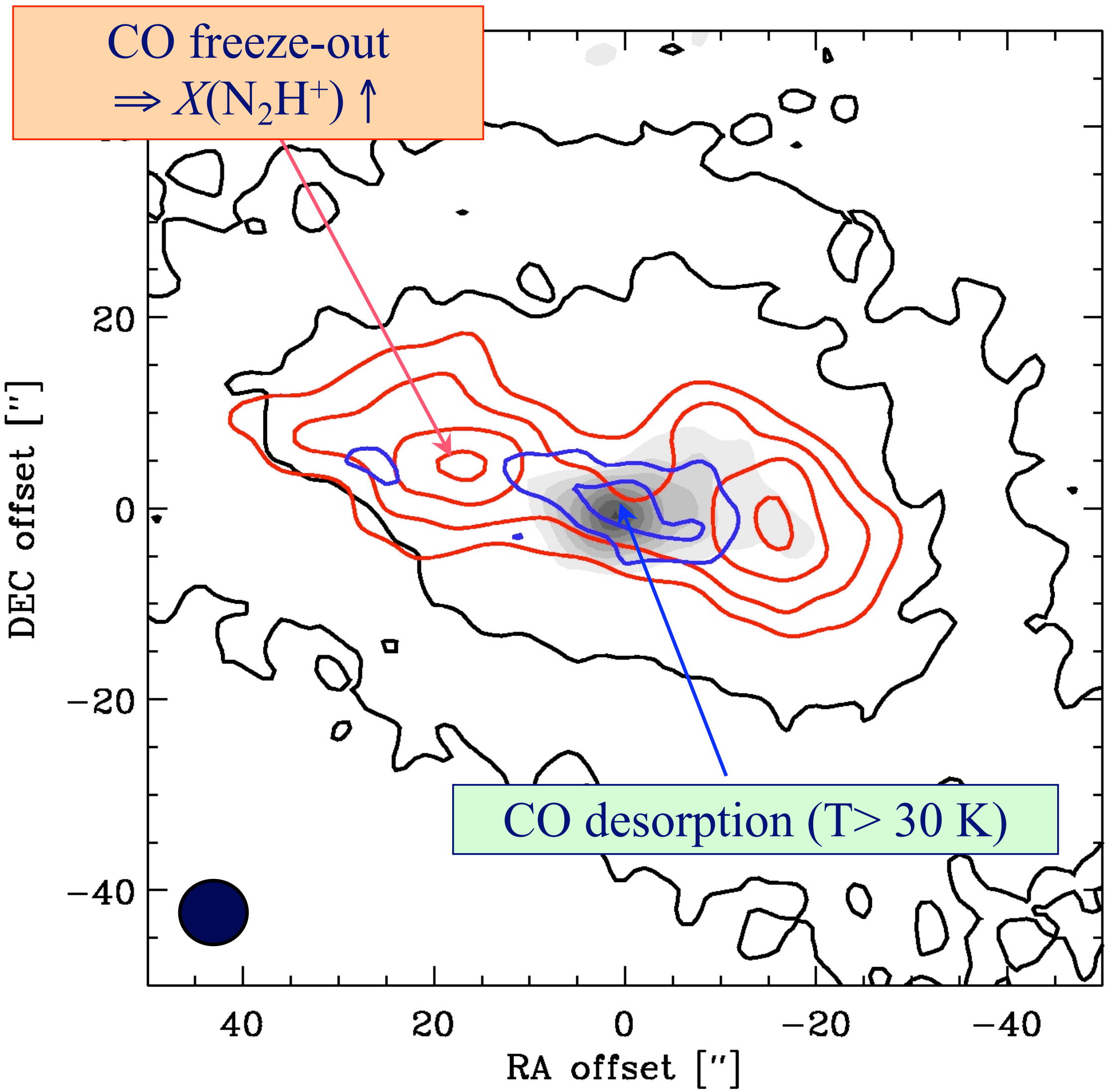
Based on figure by R. Visser / review by Herbst & van Dishoeck 2009

Typical YSO structure

NGC1333-IRAS2A in Perseus (Class 0 YSO - 20 $L_{\odot}$; 250 pc)



- Example of freeze-out and gas-phase chemistry from interferometric observations of L483 core (450 μm continuum in black contours).
- $C^{18}O$ (blue contours) localized at centre but disappearing at radii > 2000 AU (where T < 30 K).
- N_2H^+ (red contours) enhanced there as its main destruction agent (CO) depletes.

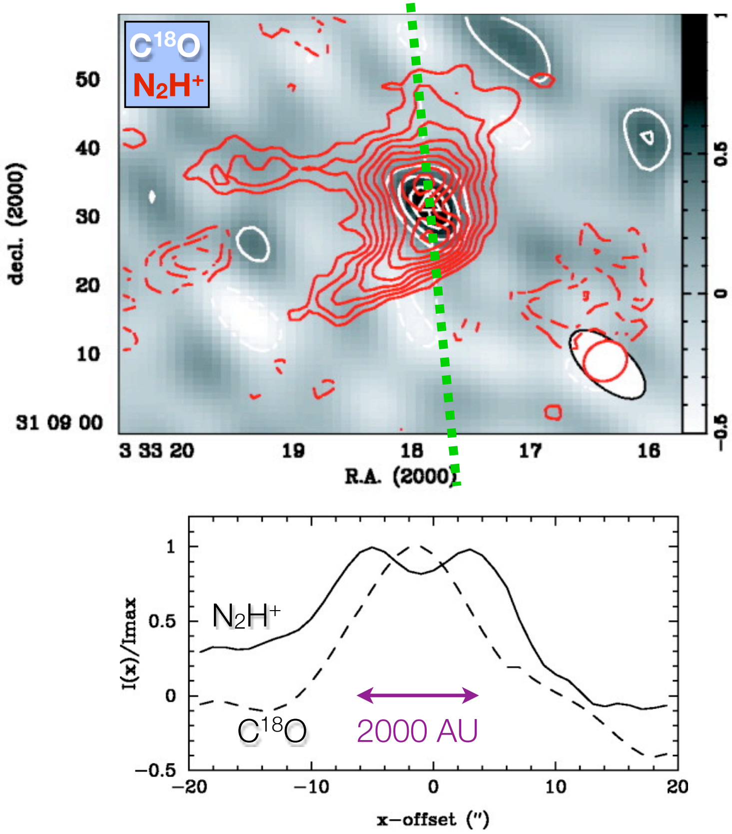


1” = 200 AU ≈ 3×10^{15} cm

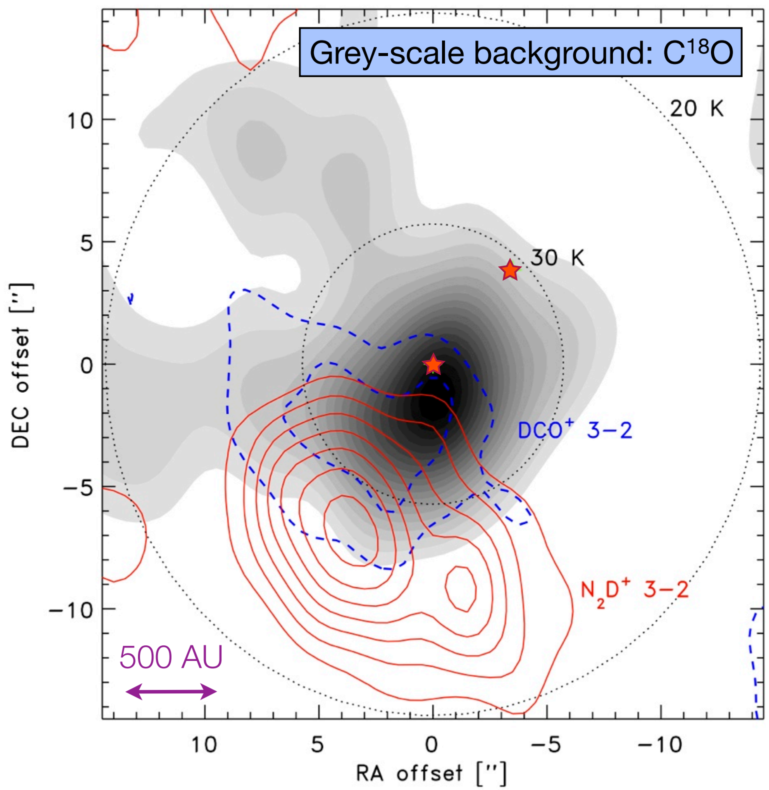
Jørgensen, 2004, A&A, 424, 589

Two other examples

Extent of CO emission/"N_2H^+ hole" depend on temperature luminosity/envelope mass

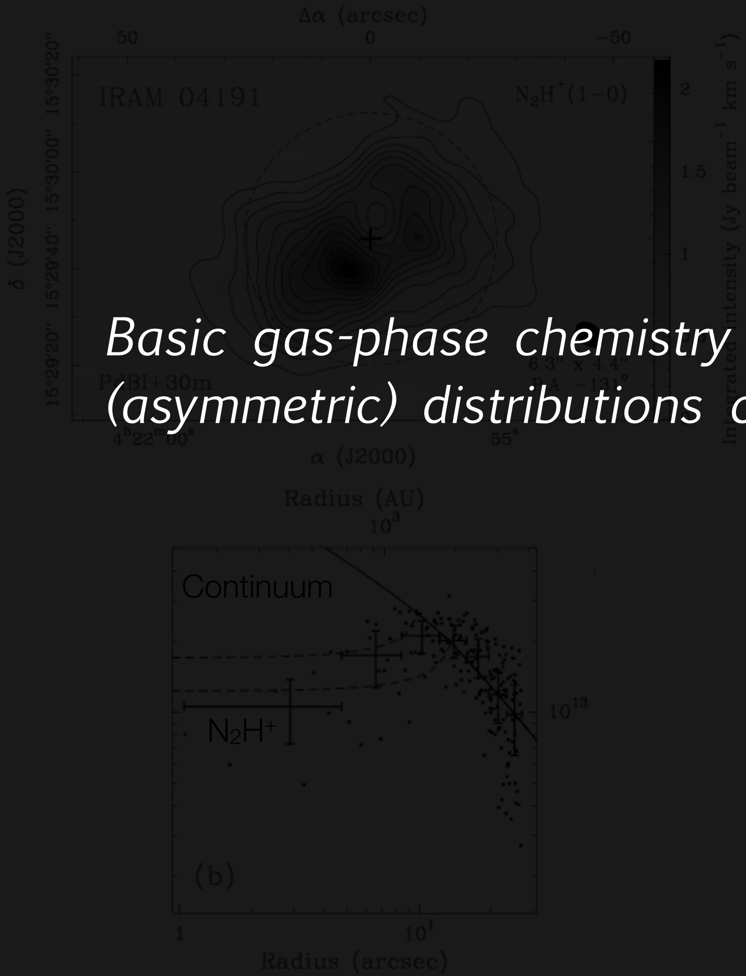


Barnard 1-c
Matthews et al., 2006, ApJ, 652, 1374



IRAS16293-2422
Jørgensen et al. 2011, A&A, submitted

Note: low luminosity sources



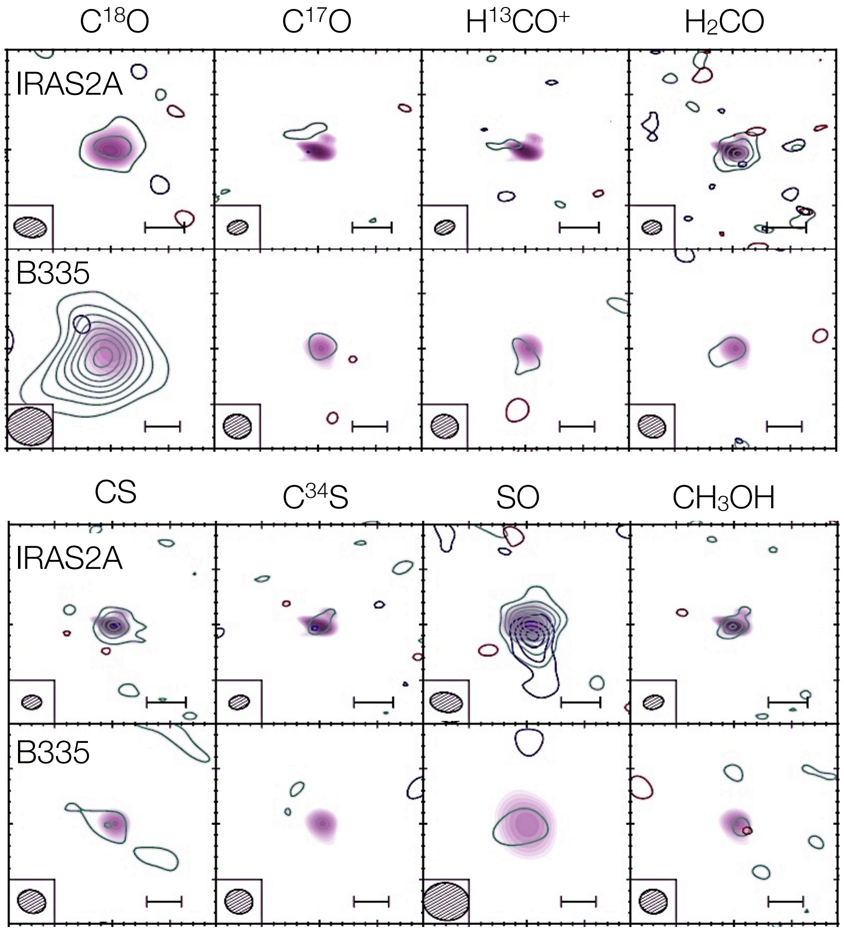
Basic gas-phase chemistry and molecular freeze-out reflected in (asymmetric) distributions of molecular emission.

- Different from observations in starless cores or low luminosity protostars, where temperature becomes high enough for CO to desorb. Rather, depletion of N_2H^+ is likely related to N_2 freeze-out.

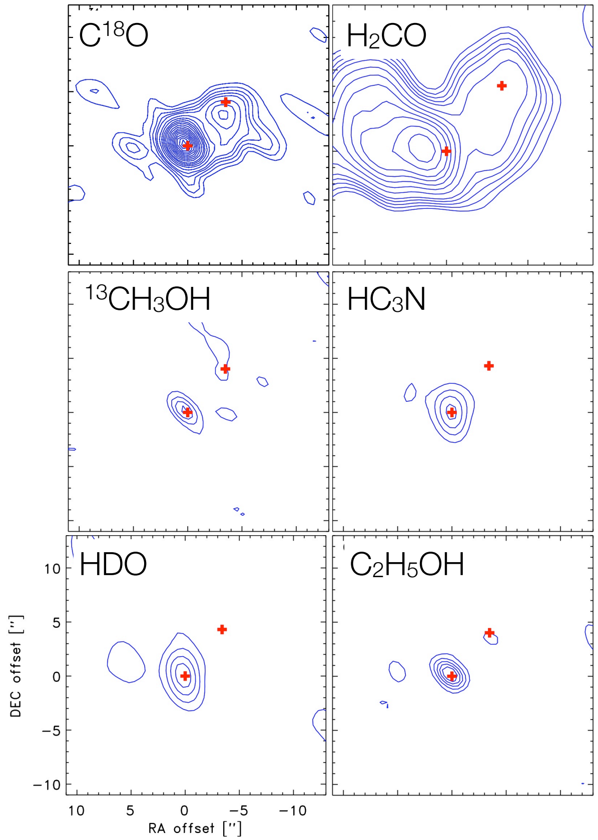
IRAM PdBI + 30m observations of N_2H^+ toward IRAM04191 VeLLO (L_{int} < 0.1 $L_\odot$ protostar) in Taurus.

Belloche et al. 2004, A&A, 419, L35

Molecular surveys



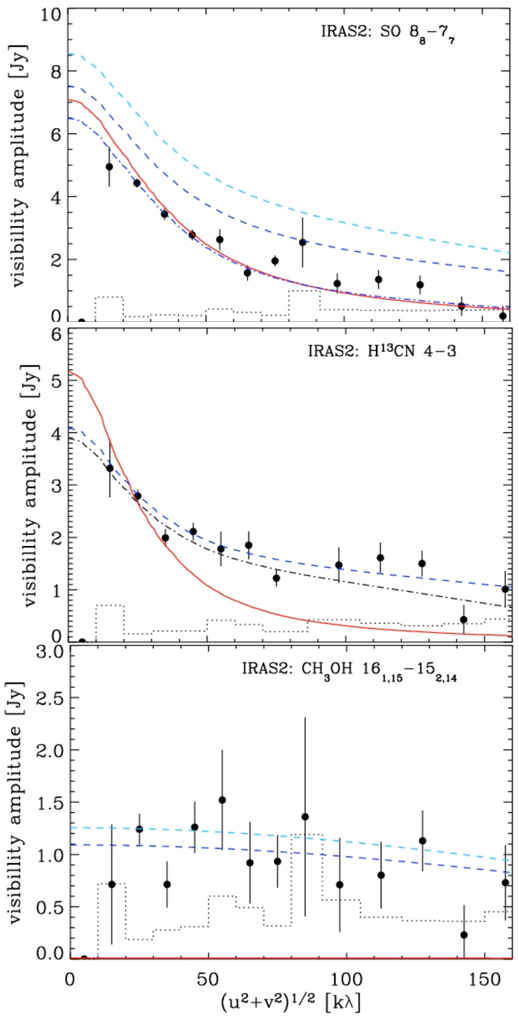
PROSAC survey: 8 protostellar cores, 10 common species (Jørgensen et al. 2007, ApJ, 659, 974)



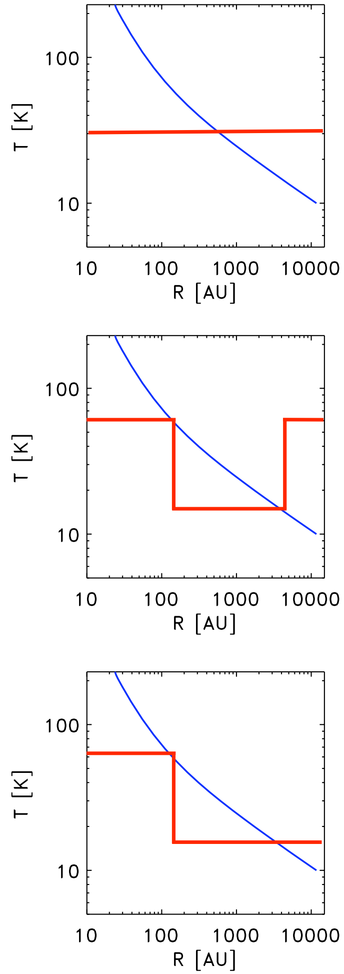
IRAS16293-2422 survey: 500+ transitions from 50+ species (including isotopologues)
Jørgensen et al. 2011, A&A, submitted

Radial abundance variations

Extended emission



Small scales



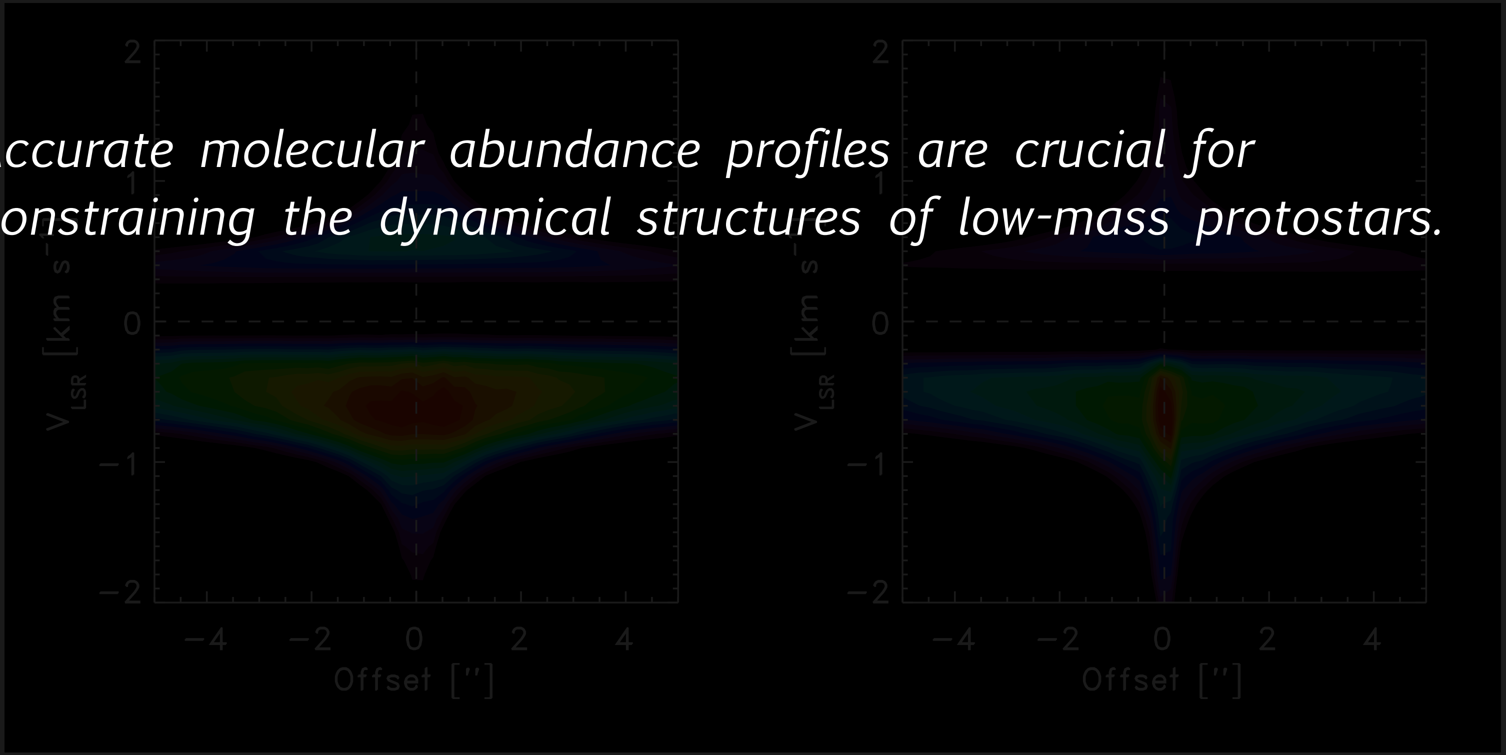
Molecular emission profiles from SMA observations. In all cases, red indicates envelope profile (for CH_3OH with an abundance jump) from single-dish observations.

Jørgensen et al. 2005, ApJ, 632, 973

Chemistry vs. dynamics

Position-velocity diagrams from model of $H^{13}CN$ toward NGC1333-IRAS2A (free-falling envelope; little rotation).

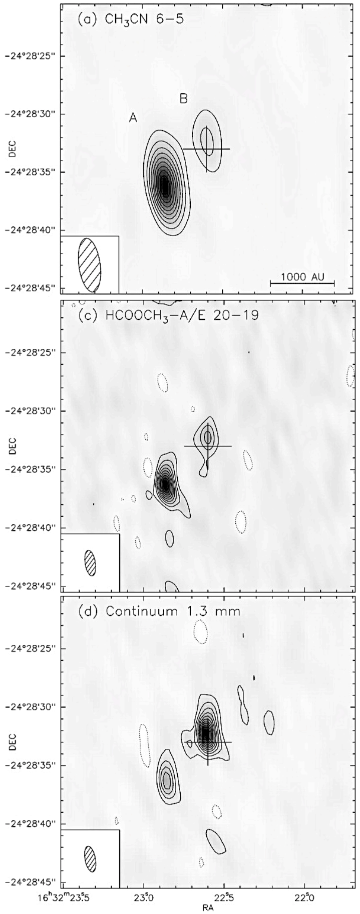
Constant abundance *"Drop" abundance*



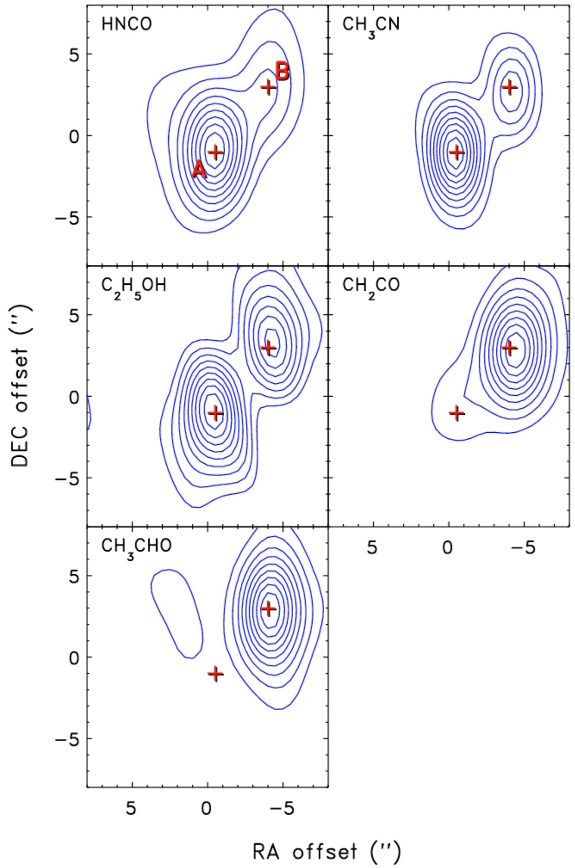
Accurate molecular abundance profiles are crucial for constraining the dynamical structures of low-mass protostars.

Brinch et al. (2009)

Complex organic molecules on small scales...1



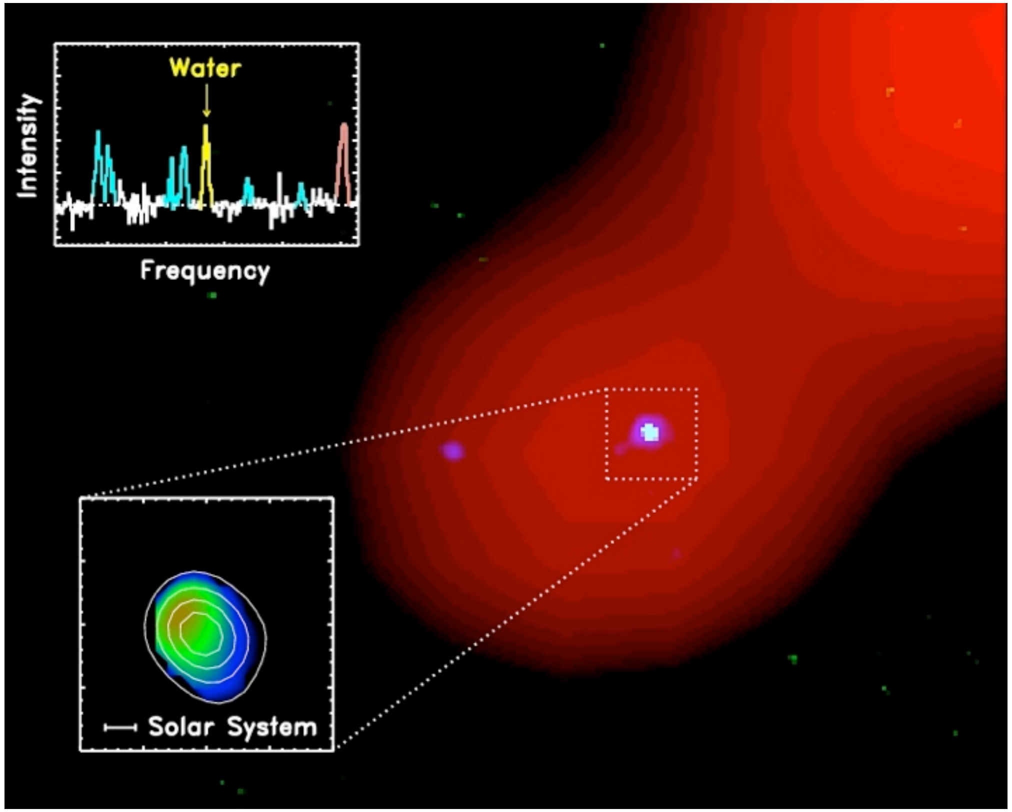
IRAM PdBI (Bottinelli et al. 2004)



SMA obs. (Bisschop et al. 2008)

- Complex organic molecules observed on small scales toward centers of four protostellar cores *(Bottinelli et al. 2004; Kuan et al. 2004; Chandler et al. 2005; Huang et al. 2005; Jørgensen et al. 2005, 2010; Remijan & Hollis 2006; Bisschop et al. 2008).*
- Significant differences in relative abundances of complex organics observed in IRAS16293-2422.

Water at high angular resolution

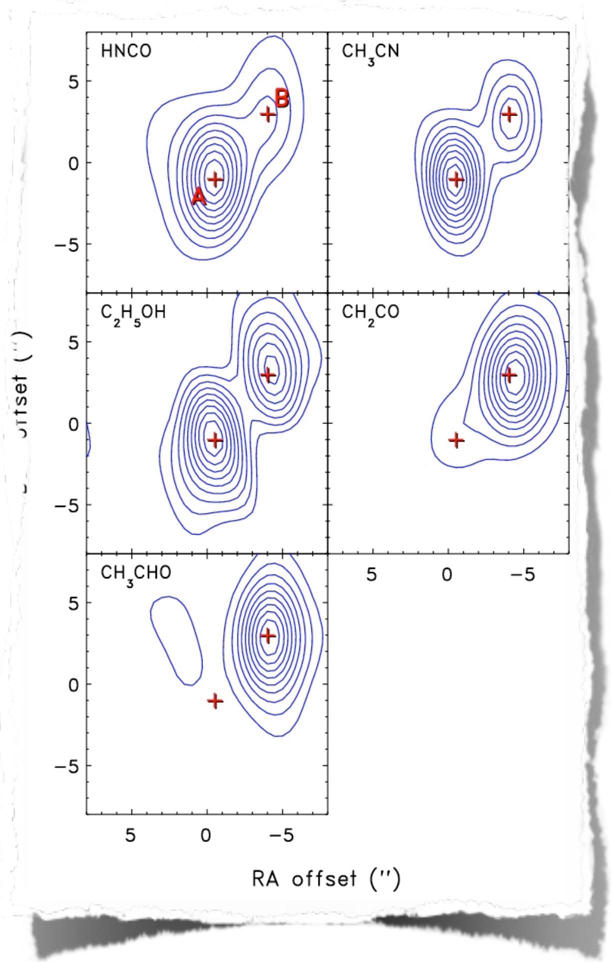


The first spatially and spectrally resolved image of water vapor around a young solar-type star.

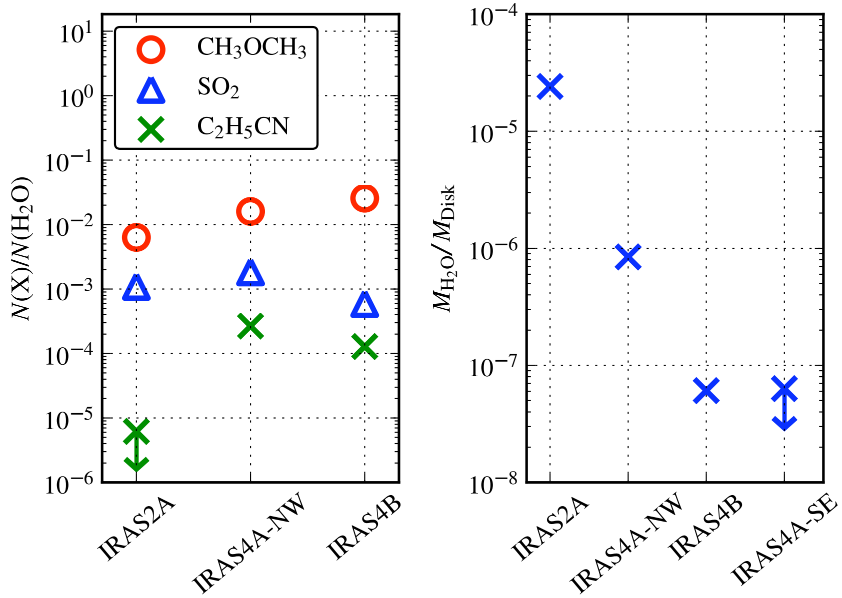
Now detections for four of four sources where we searched for $H_2{}^{18}O$ using mm interferometry.

Red background: cold dust (SCUBA); insert $H_2{}^{18}O$ 203.4 GHz spectrum and moment-0/1 maps.
Jørgensen & van Dishoeck, 2010; Persson, et al. in prep.

When you got a hammer... (1)



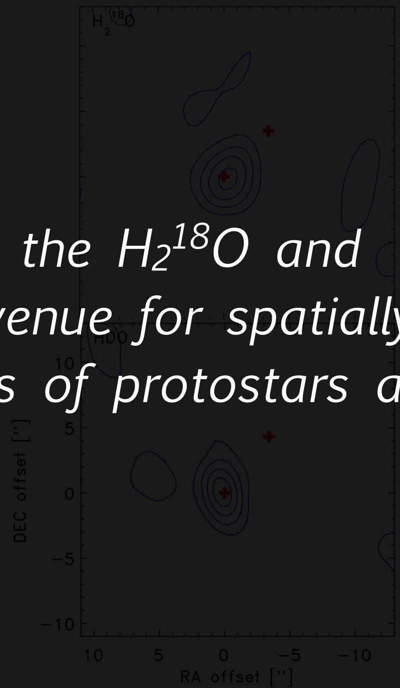
SMA obs. (Bisschop et al. 2008)



Abundances of complex organics relative to water, reflect the grain mantle composition or warm gas-phase chemistry on small scales of the protostars (Persson et al., in prep.; see also poster).

When you got a hammer... (2)

- Is the HDO / H_2O ratio (enhanced in comets & Earth's oceans compared to cosmic D/H ratio) established in the protostellar core phase or due to ion-molecule reactions in the disk?
- Some indications of varying ratios in protostellar cores [illegible] column densities on comparable scales.
- HDO [illegible] conditions as $H_2{}^{18}O$ $3_{1,3}$-$2_{2,0}$ @ 203.4 GHz.
- *HDO non-detection in SMA observations for IRAS4B suggests HDO/H_2O ratio in warm gas < 6×10^{-4} (Jørgensen & van Dishoeck 2010b). Detection of both in IRAS16293A suggest a ratio there of ~1.5×10^{-3}.*
- *For comparison van der Tak et al. (2006) finds ratios of 1×10^{-4} to 3×10^{-3} for high-mass YSOs.*

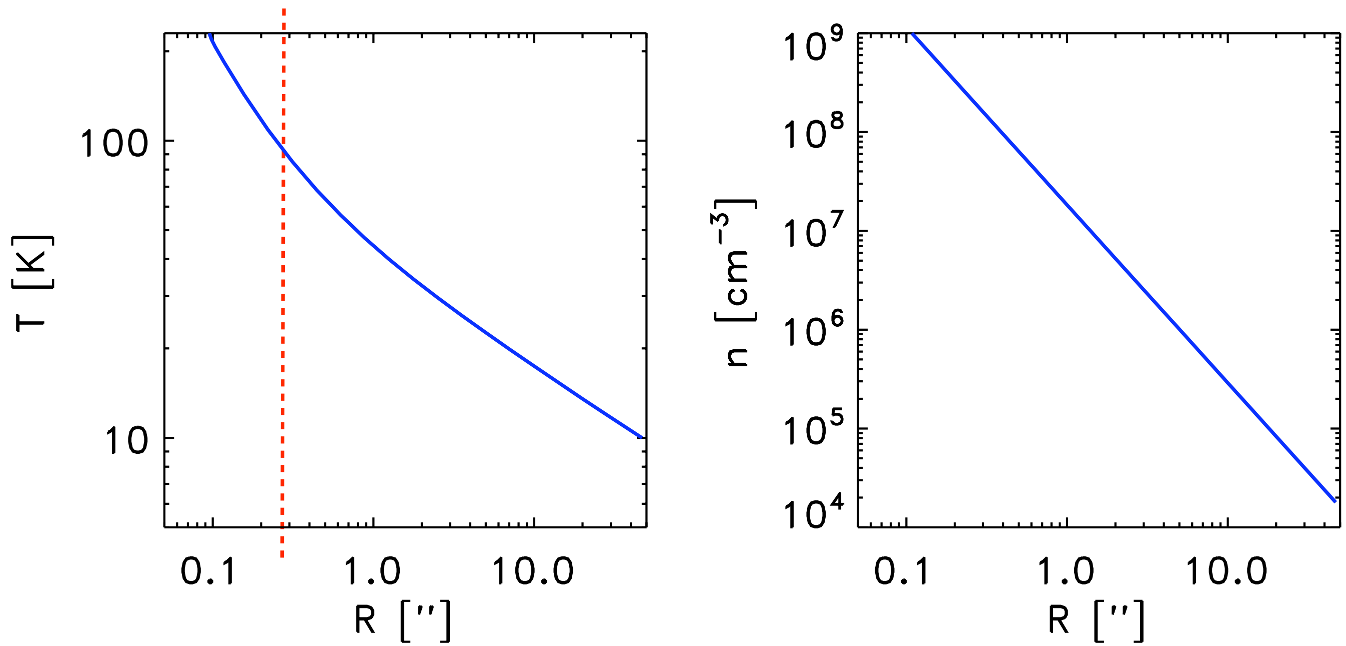


(Persson et al., in prep.; see also posters by Persson et al., Coutens et al.).

Ground-based observations of water (through the $H_2{}^{18}O$ and HDO isotopologues) provide an interesting avenue for spatially resolving water on the few hundred AU scales of protostars and study the grain mantle composition.

Typical YSO structure

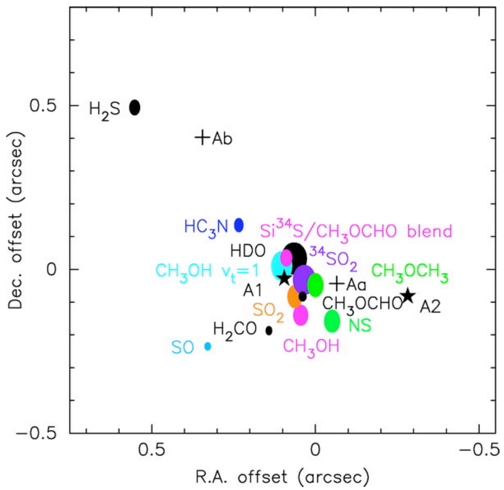
NGC1333-IRAS2A in Perseus (Class 0 YSO - 20 $L_\odot$; 250 pc)



- For typical low-mass YSOs the regions where molecules like H_2O would come off dust grains are smaller than ~0.5-1" (diameter; 100-200 AU)... also the regions where non-spherical collapsing protostellar cores will result in the formation of circumstellar disks sometime during the collapse of protostars.

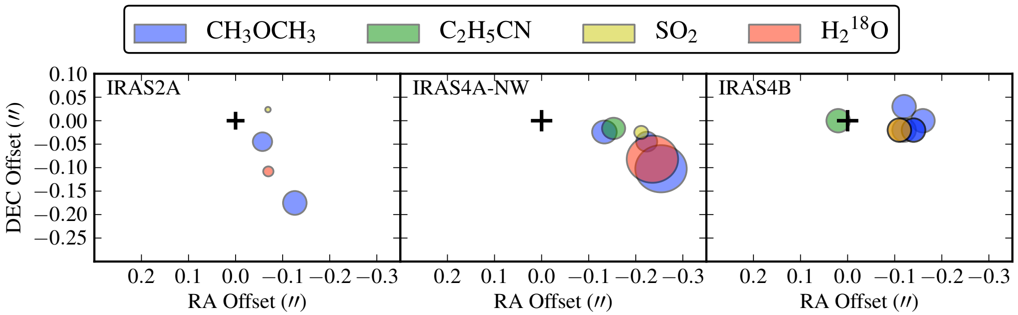
Complex organic molecules on small scales...2

Positions relative to continuum peaks in four Class 0 YSOs from subarcsecond resolution observations.



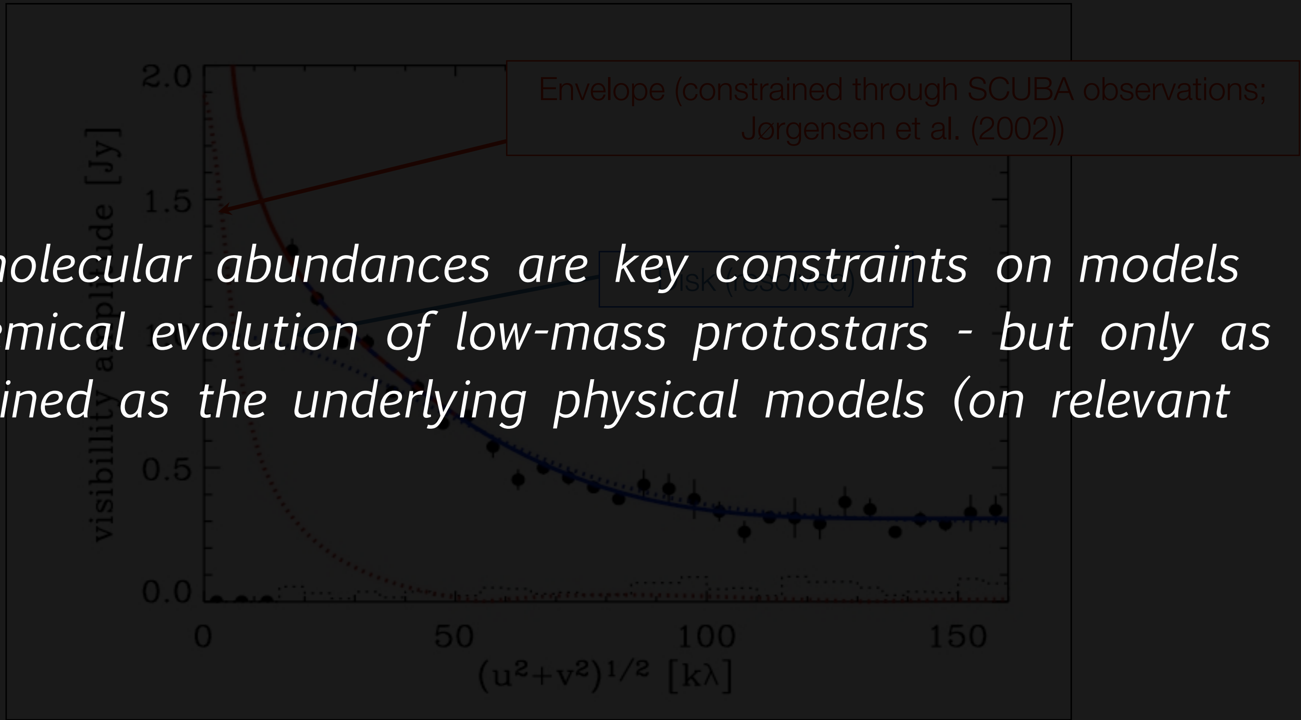
IRAS16293-2422 (SMA)
(Chandler et al. 2005)

- Physical environments still not completely understood.



NGC1333-IRAS2A, IRAS4A, IRAS4B (IRAM PdBI)
(Persson et al., in prep.)

Models based on dust continuum observations



Accurate molecular abundances are key constraints on models for the chemical evolution of low-mass protostars - but only as well-determined as the underlying physical models (on relevant scales).

Power-law-like envelope models valid to scales of about 500 AU; thereafter significantly more emission than expected *(e.g. Hogerheijde & Sandell 2000, Harvey et al. 2003, Jørgensen et al. 2004, 2005, 2009; Enoch et al. 2010, Chiang et al. 2008)*.

The bright future of ALMA - key themes:

Grain mantle composition, complex organics and deuteration
Statistical surveys: evolution and environment (surface brightness)
Physical structure on small scales (disk formation)

Credit: ALMA (ESO/NAOJ/NRAO), Carlos Padilla

"The universe is full of magical things, patiently waiting for our wits to grow sharper."

Eden Phillpotts (1862-1960)

Summary

- Basic gas-phase chemistry and molecular freeze-out reflected in (asymmetric) distributions of molecular emission.
- Accurate molecular abundances are key constraints on models for the chemical evolution of low-mass protostars - but only as well-determined as the underlying physical models (on relevant scales).
- Accurate molecular abundance profiles are crucial for constraining the dynamical structures of low-mass protostars.
- Ground-based observations of water (through the $H_2^{18}O$ and HDO isotopologues) provide an interesting avenue for spatially resolving water on the few hundred AU scales of protostars and directly constrain the grain mantle composition/warm gas-phase chemistry.