Introduction to Chemistry in HAeBE (outer) disks

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What we like to know

- Ideally, we would like to know when and how disks form, evolve and dissipate.
  - We want to understand what physical mecanisms regulate their dissipation, in particular planetary formation vs e.g. photoevaporation.
  - For that we need to measure their content and distribution, i.e. surface density or even better volumic density.
- What about chemistry then ?

Introduction to the introduction

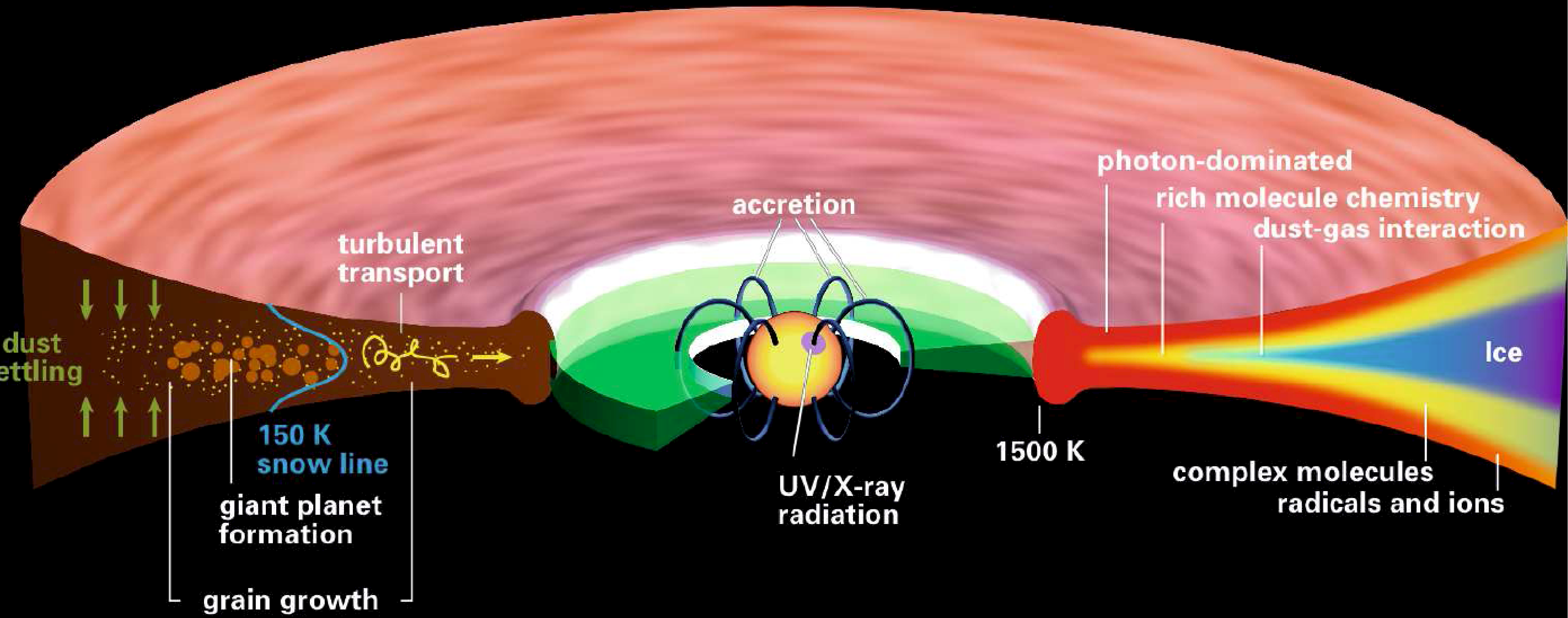
- What is chemistry ?

  “Chemistry, a branch of physical science, is the study of the composition, structure, properties and change of matter.” (Wikipedia)

- Why does chemistry matter ?
  - (Putative) disk composition: 99% gas, 1% dust
  - (Putative) gas composition: 99.99% H_2, 0.01% CO
  - First reason: if we are interested in the distribution of the matter in disks, we should understand its composition
  - Second reason: disks are supposed to be the birthplace of planets

Disks: gradients

- Radial gradient of:
  - Velocity (with Keplerian velocities)
  - Temperature (irradiation by the central star)
  - Surface density (viscous evolution)
- Vertical gradient of:
  - Temperature (irradiation by the central star)
  - Density (hydrostatic equilibrium)
- HAeBe means
  - Hotter stars, hotter disks ?
  - More uv, less X-rays



Henning & Semenov 2013

Table 2: Chemical reactions active in disks

Process	Example	Midplane $r > 20$ AU	Molecular layer $r > 20$ AU	Atmosphere $r > 20$ AU	Inner zone $r < 20$ AU
Bond formation					
Radiative association	$C^+ + H_2 \rightarrow CH_2^+ + h\nu$	X	X	X	X
Surface formation	$H + H\|gr \rightarrow H_2 + gr$	X	X	0	0
Three-body	$H + H + H \rightarrow H_2 + H$	0	0	0	X
Bond destruction					
Photodissociation	$CO + h\nu \rightarrow C + O$	0	X	X	X
Dissociation by CRP	$H_2 + CRP \rightarrow H + H$	X	X	0	0
Dissociation by X-rays	—	0	X	X	X
Dissociative recombination	$H_3O^+ + e^- \rightarrow H_2O + H$	X	X	X	X
Bond restructuring					
Neutral-neutral	$O + CH_3 \rightarrow H_2CO + H$	X	X	0	X
Ion-molecule	$H_3^+ + CO \rightarrow HCO^+ + H_2$	X	X	X	X
Charge transfer	$He^+ + H_2O \rightarrow He + H_2O^+$	X	X	X	X
Unchanged bond					
Photoionization	$C + h\nu \rightarrow C^+ + e^-$	0	X	X	X
Ionization by CRP	$C + CRP \rightarrow C^+ + e^-$	X	X	0	0
Ionization by X-rays	—	0	X	X	X

Henning & Semenov 2013

Outline

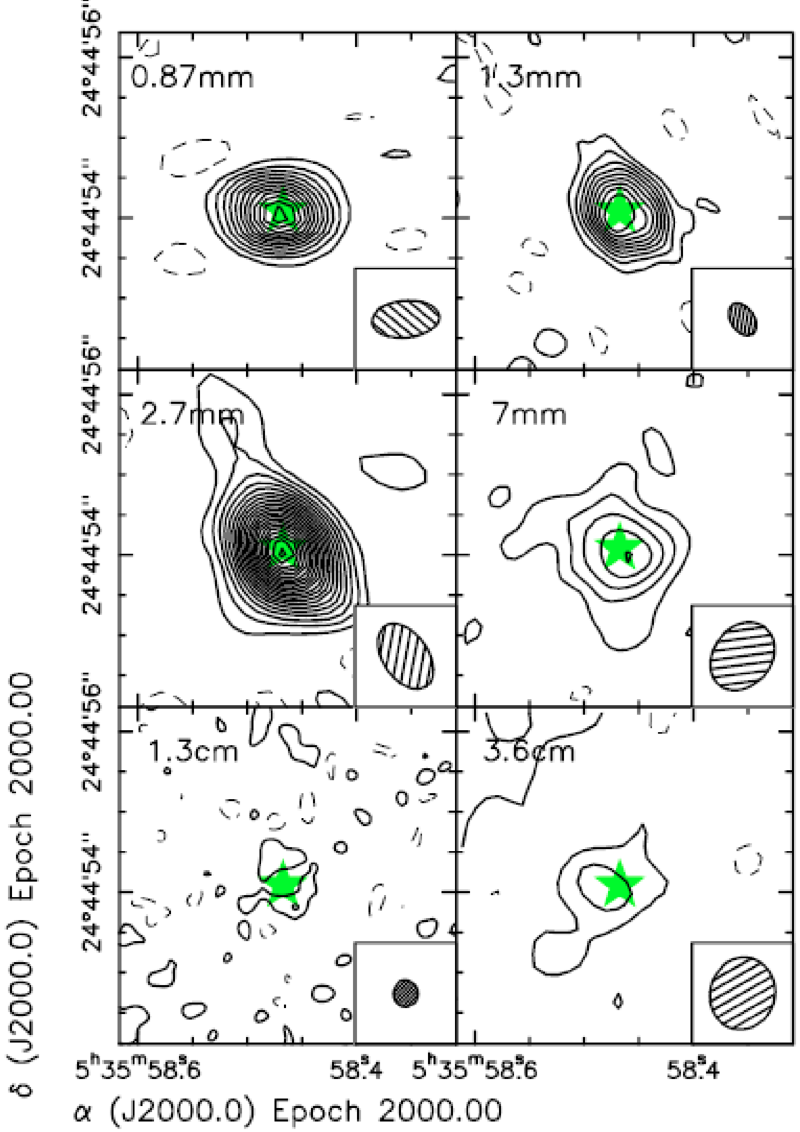
- A word about dust
- Line formation in disks
- What can we learn from CO isotopes
- Towards molecular complexity
- Conclusions

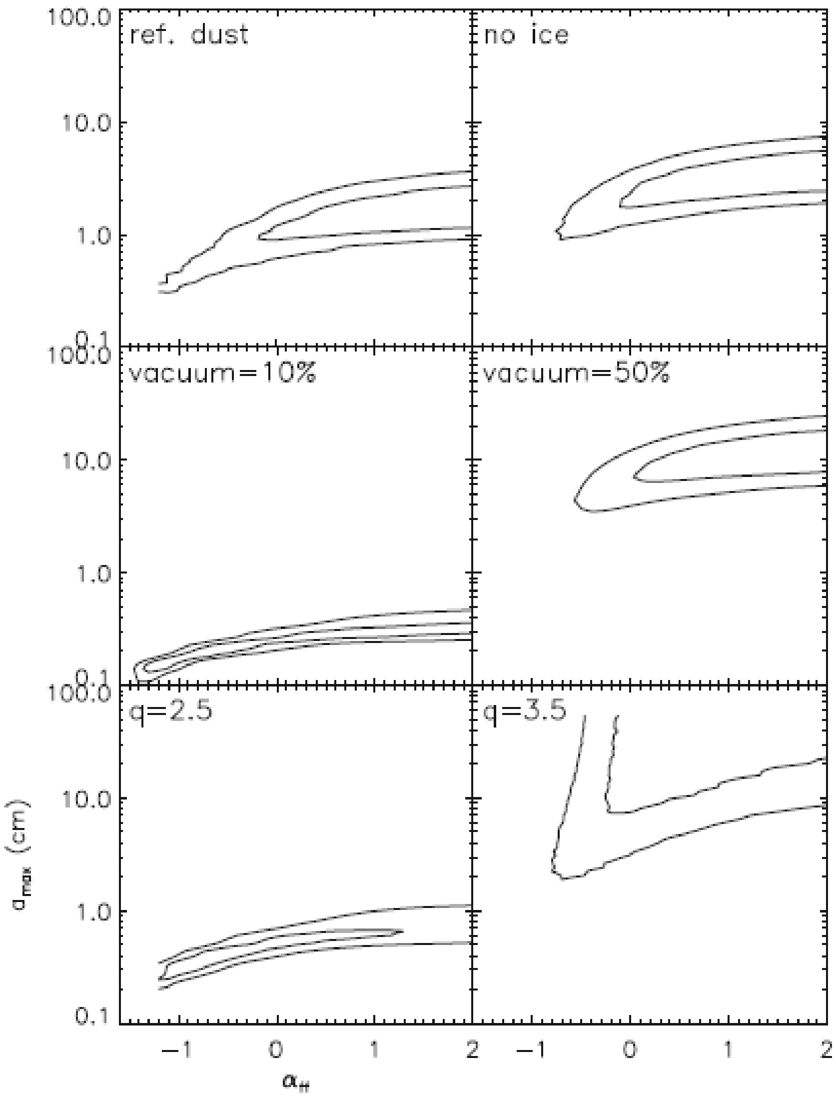
I. A word about dust

Dust is a concern to chemistry

- Dust is used as tracer too. Getting the right emissivity is very important (but this will be covered elsewhere).
- Dust evolves: grain growth/dust settling through friction
- This modifies:
  - The penetration of stellar/interstellar radiation, especially uv
  - The total available surface for sticking
  - The large grain may be thermally decoupled and lock their ice mantles.

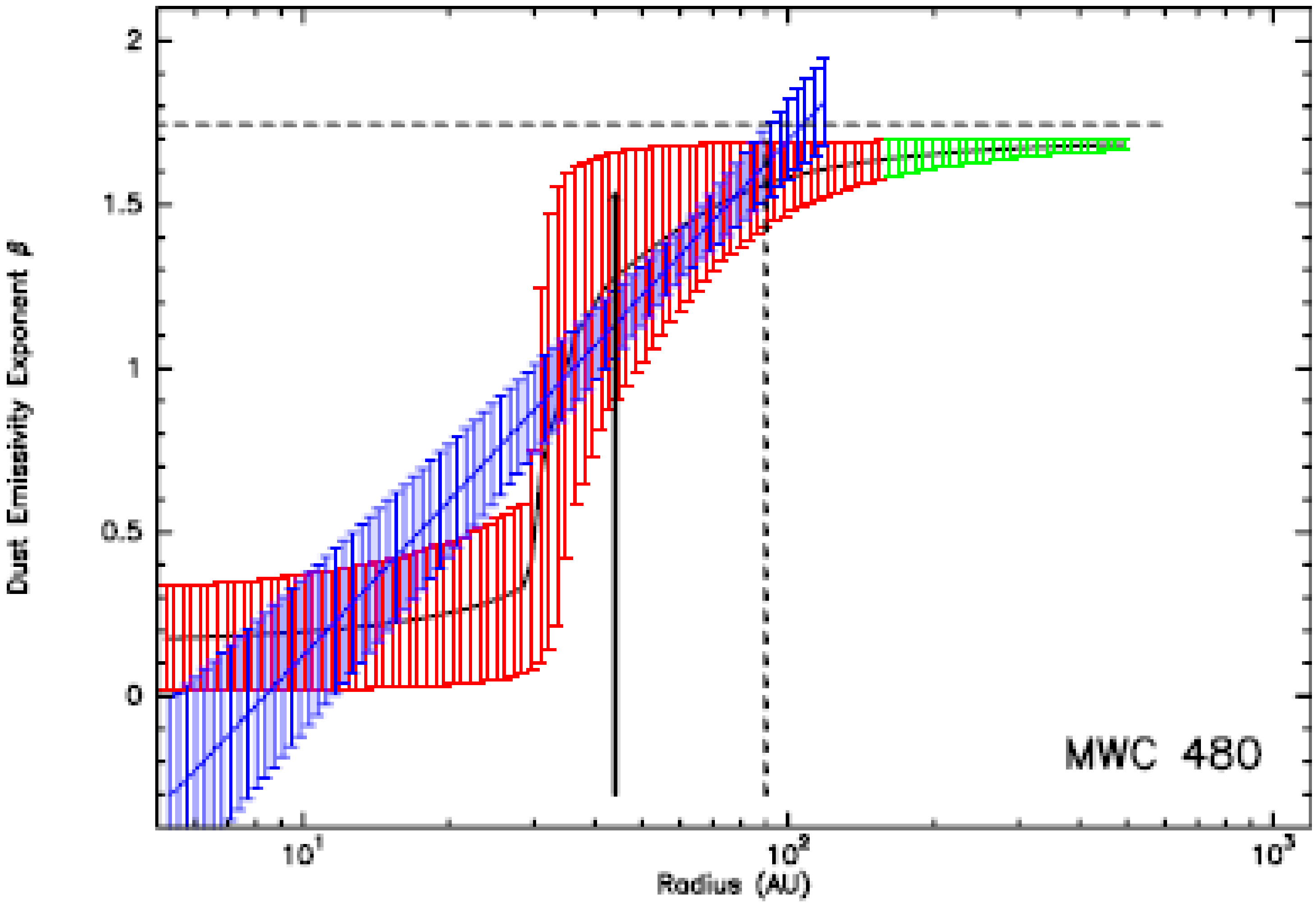
Evidence for grain growth





Banzatti et al. 2011

Varial radiation of grain properties

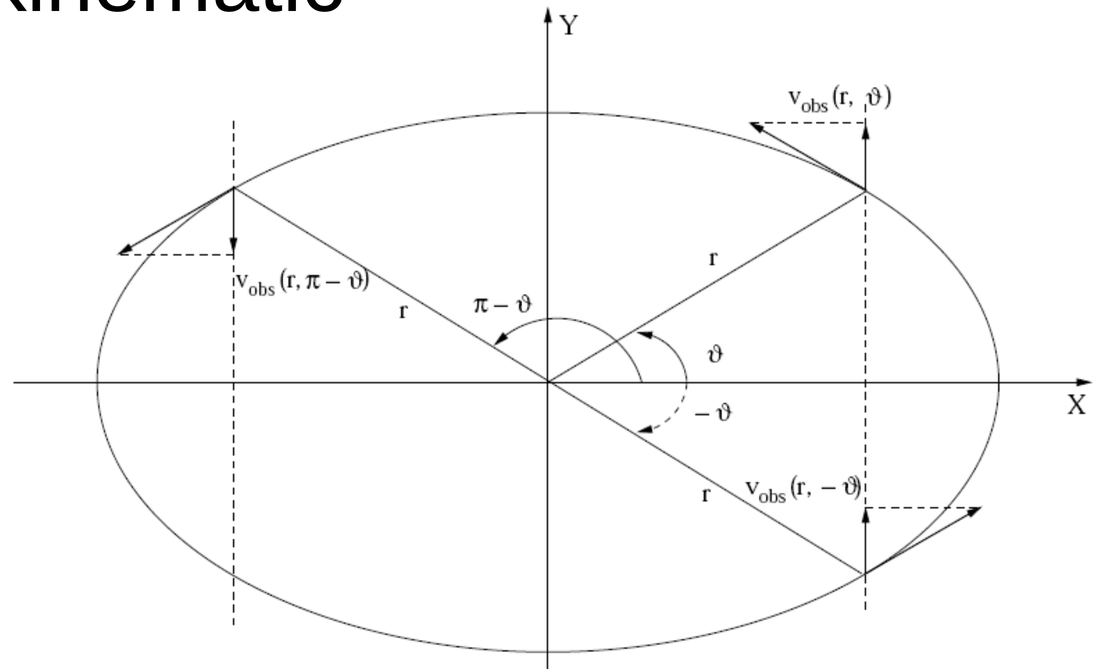


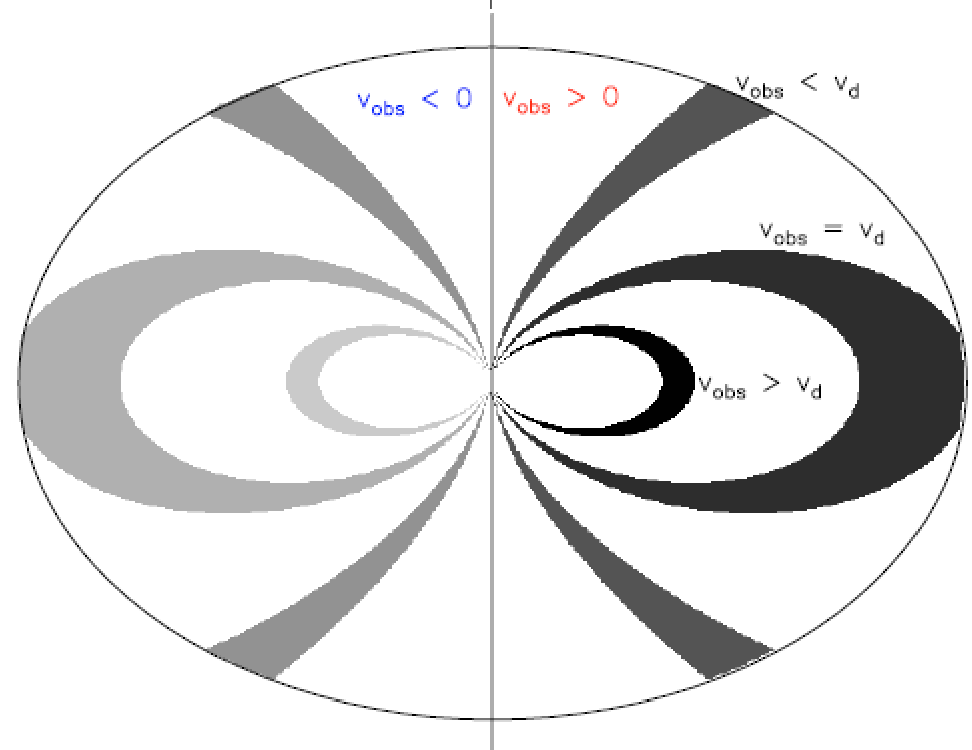
Guilloteau et al. 2011

II. Line formation in disks

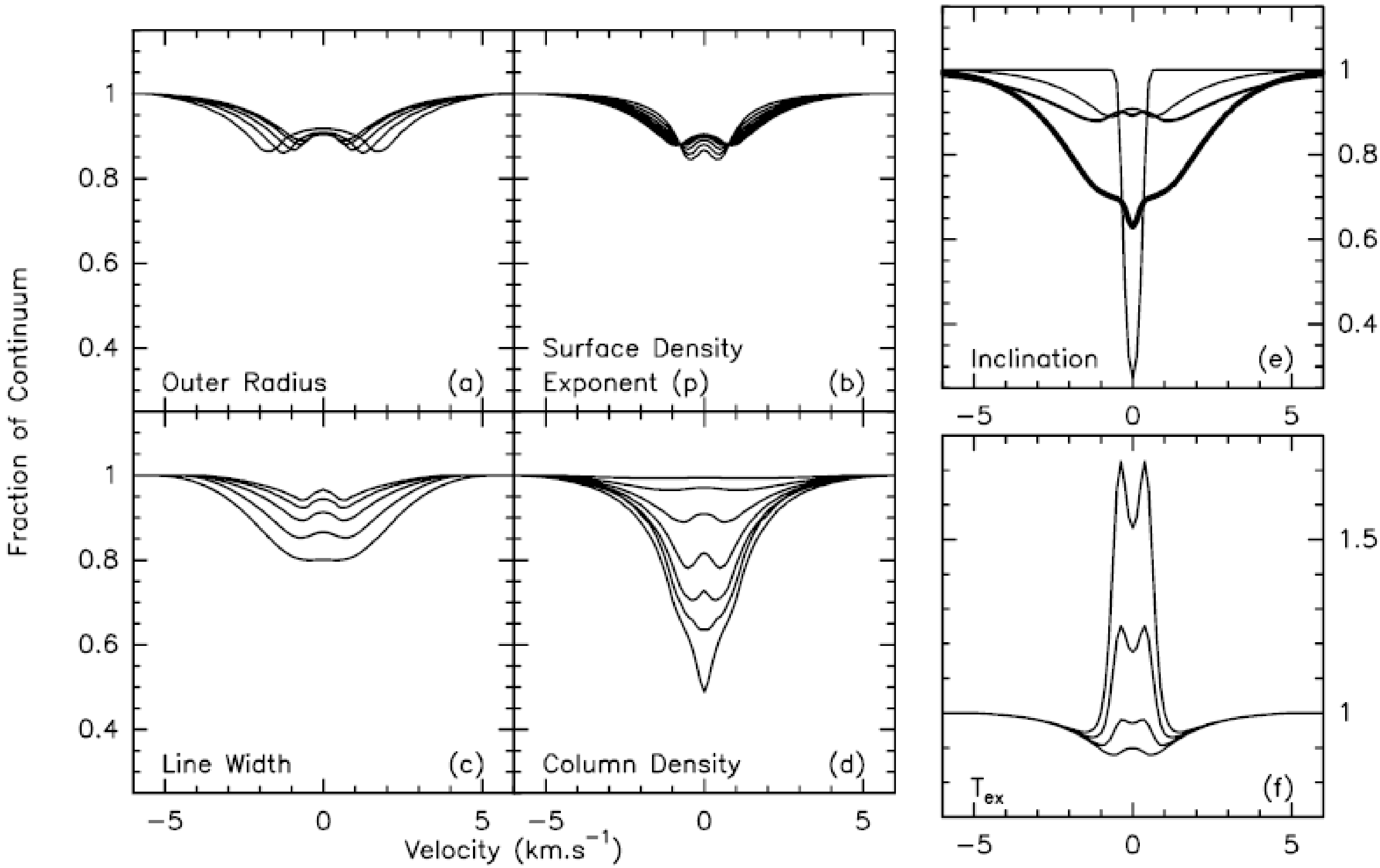
Disk kinematic

- If one consider a geometrically thin disk
- Axisymetric
- In Keplerian rotation
- One obtains the typical shape for the channels.



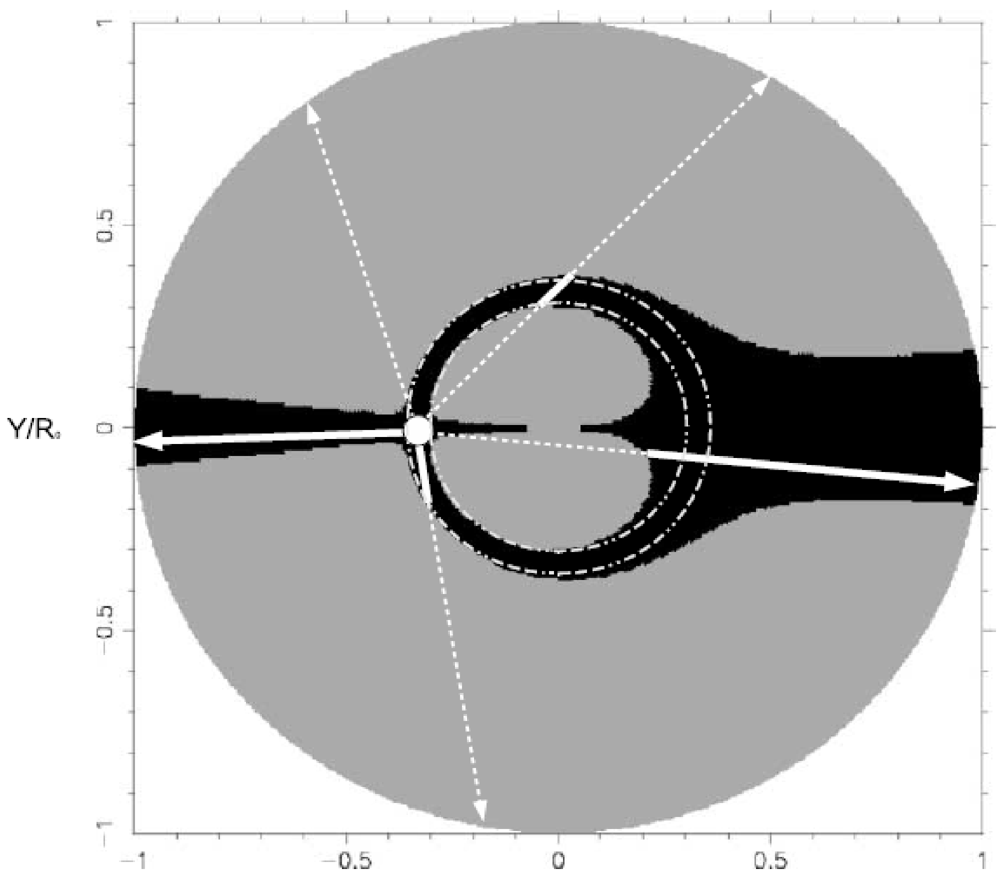


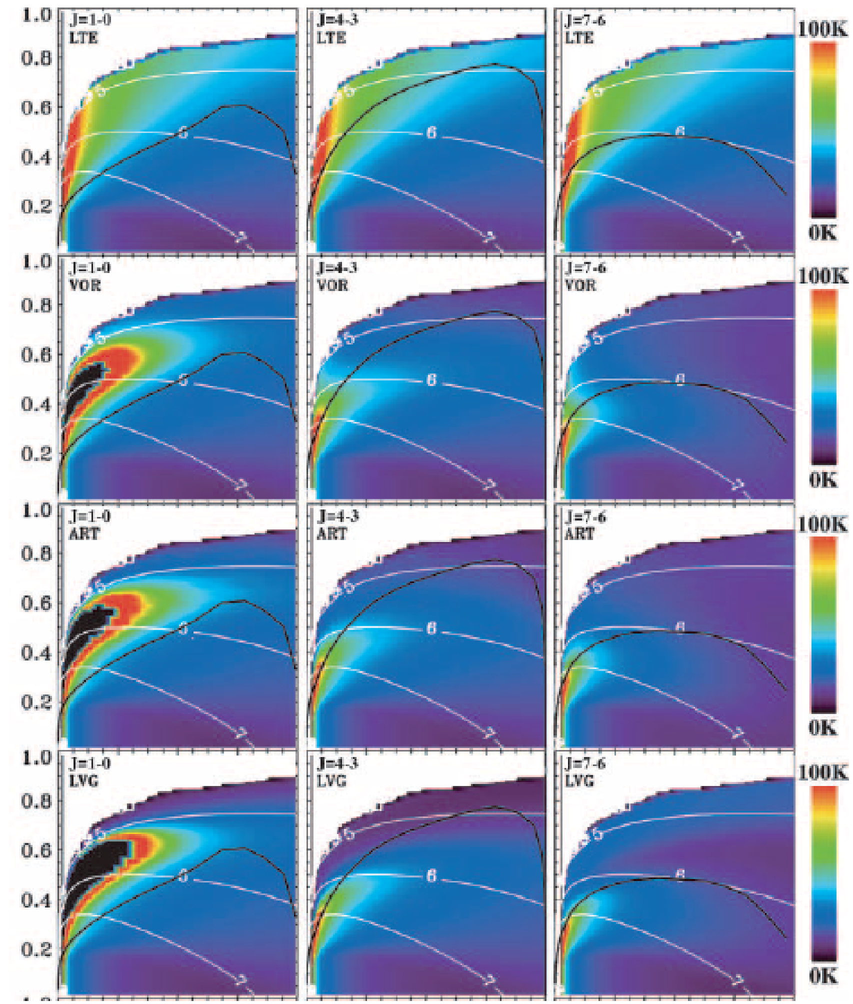
Example: absorption lines

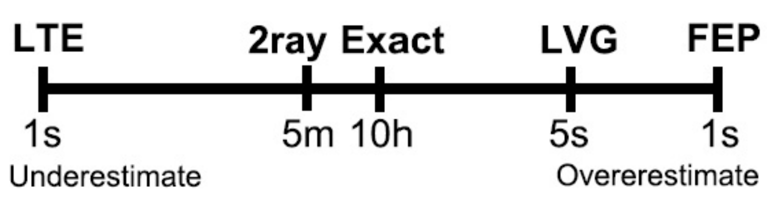


Guilloteau et al. 2006

Non Local Thermodynamic Equilibrium

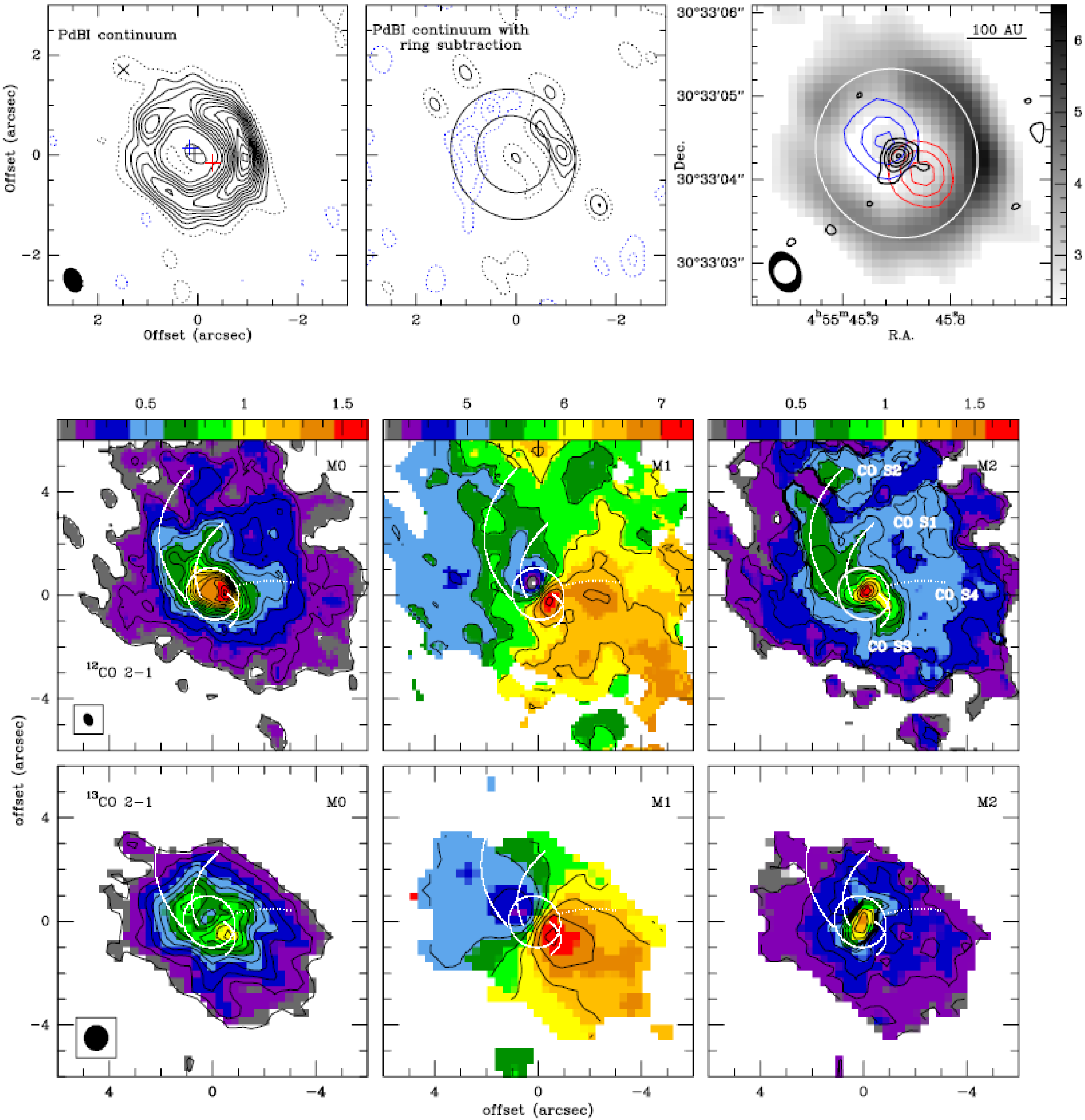






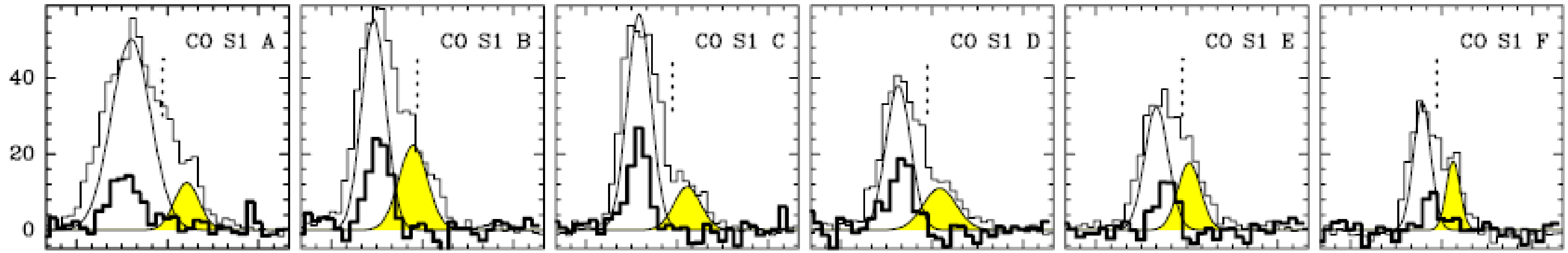
Pavlyuchenkov et al. 2007

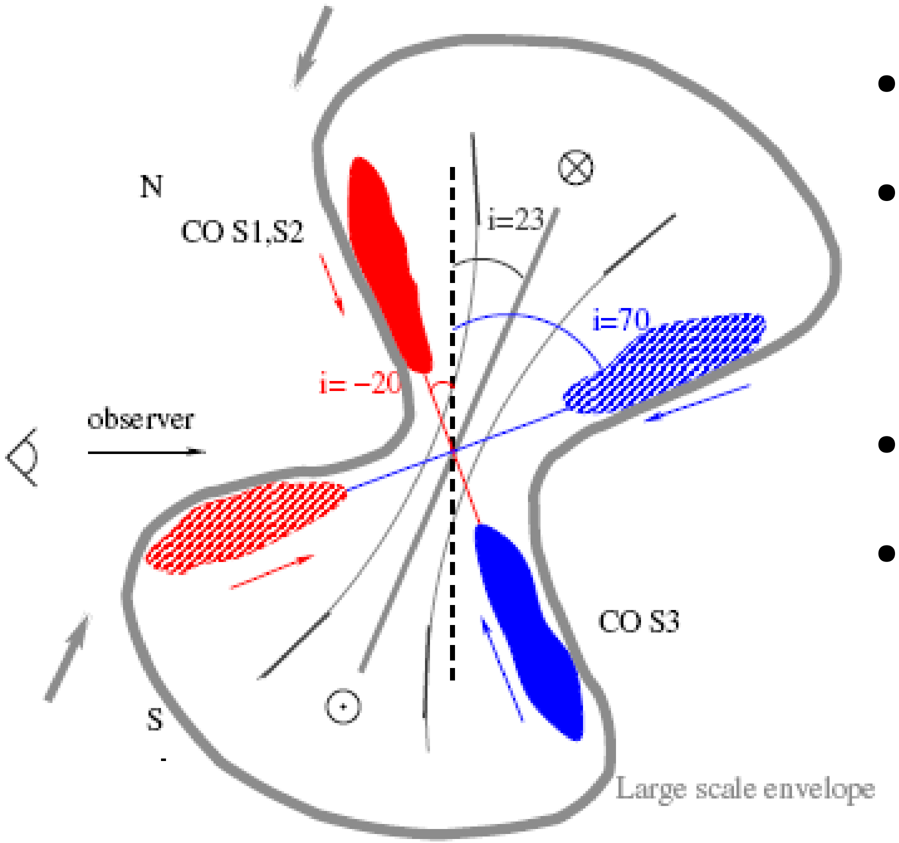
II. CO and isotopes



- AB Aur
- Inner cavity in dust continuum
- Spiral structure seen in CO
- But spirals are apparently counter-rotating !

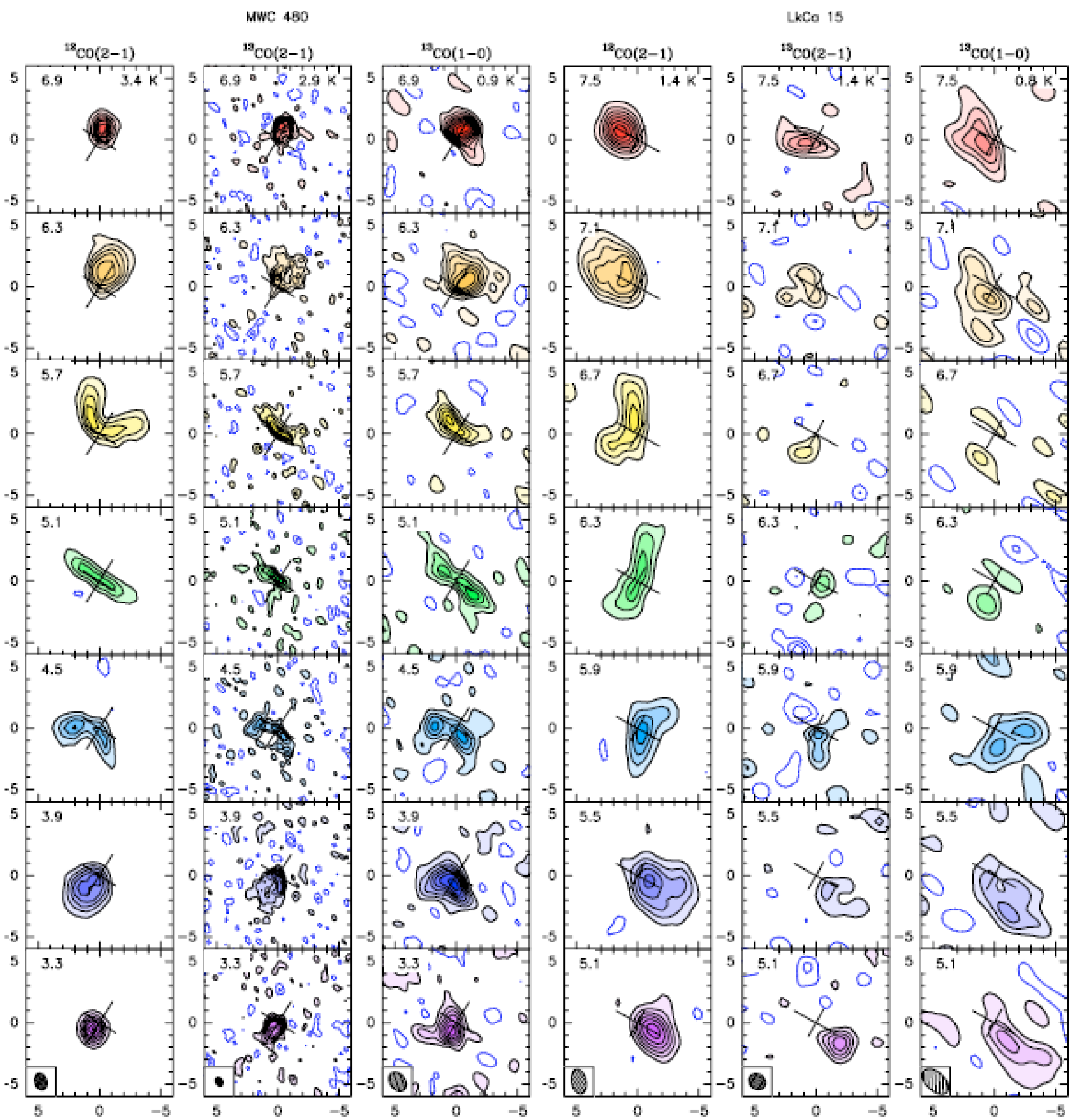
Tang et al 2012





- Counter-rotating spirals
- Possibly tracing accretion from the enveloppe onto the star
- In a 3 Myr system ?
- Might also explain the discrepant inclinations and non-Keplerian velocities

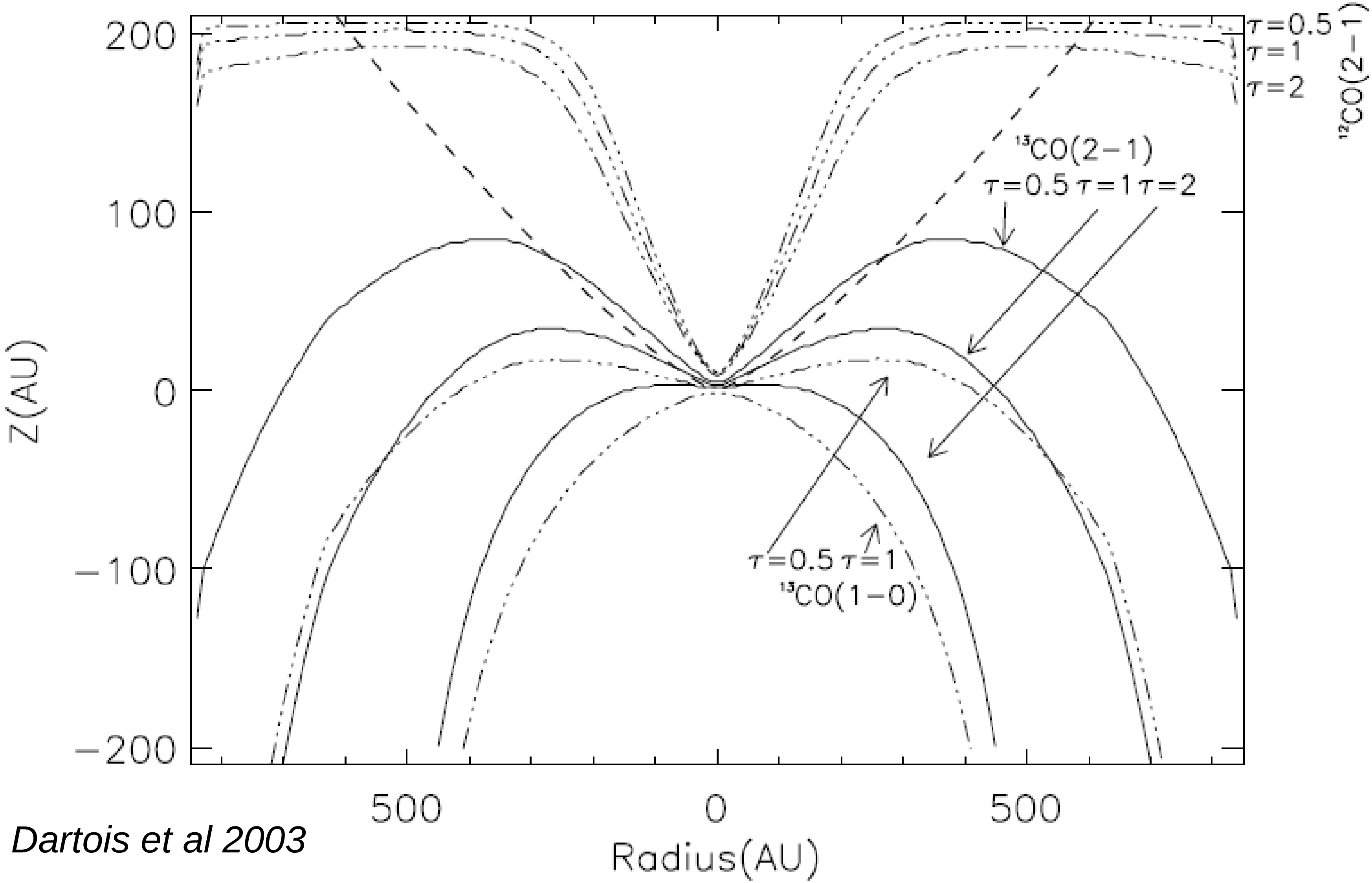
Measuring the temperature



Pietu et al 2007

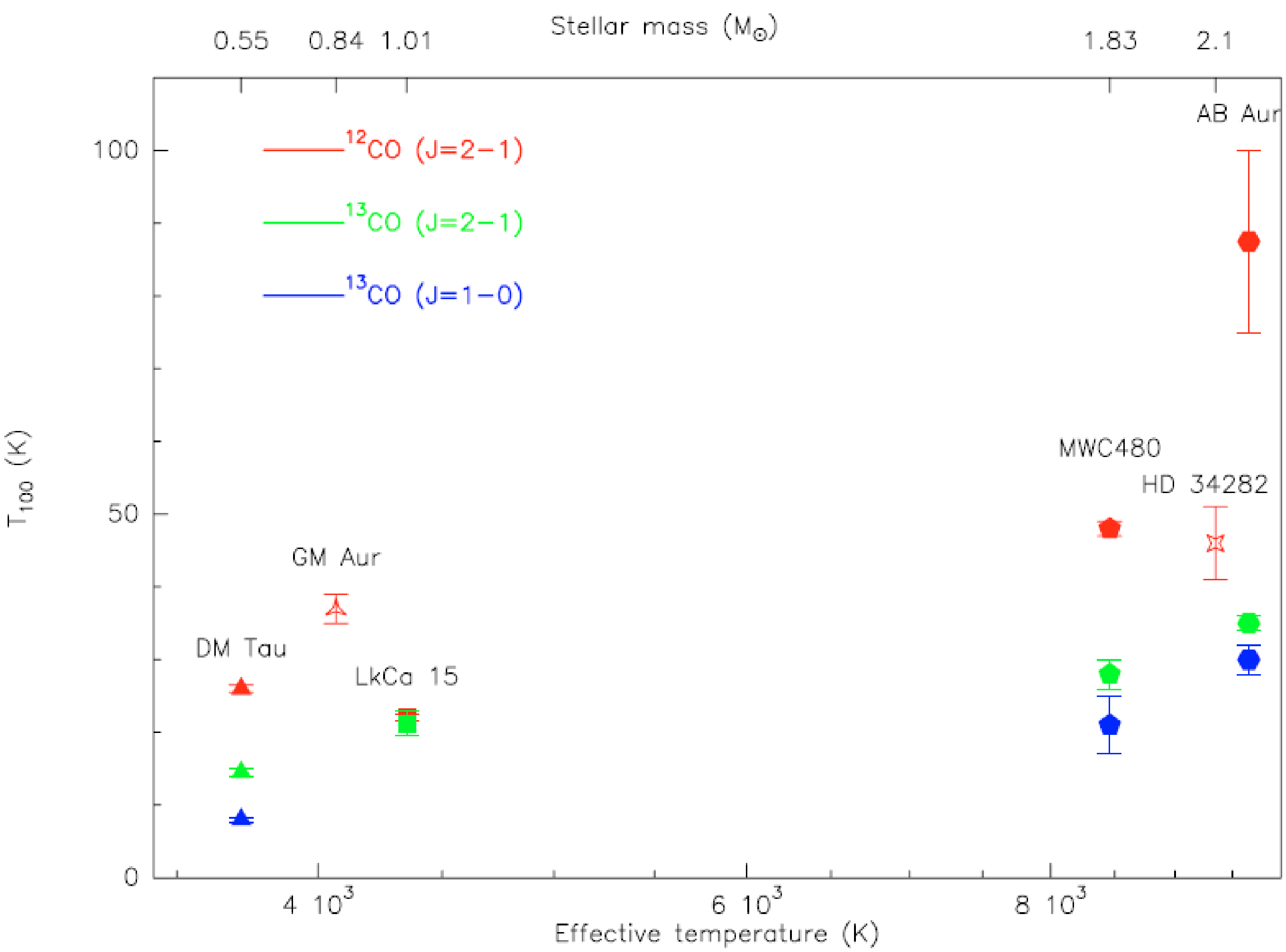
- The brightness temperature of an optically thick line is equal to the kinetic temperature
- Adding the opacity effects allowing to probe more or less deeply within the disk, one can retrieve the vertical temperature gradient

Opacity effects



Dartois et al 2003

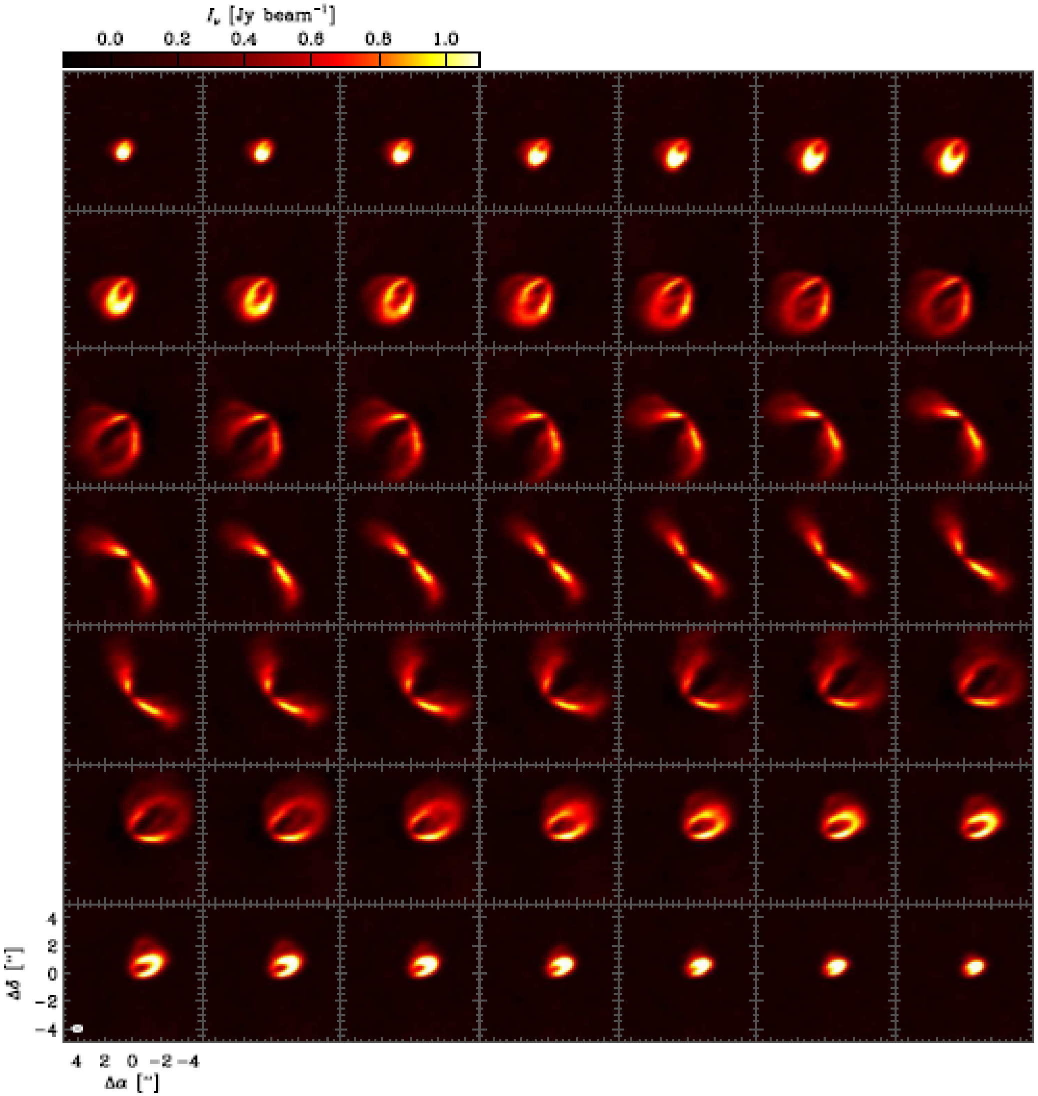
Herbig Hae stars have hotter disks



- Hotter surface
- But also hotter interior
- Also evidenced by less CO depletion due to freeze-out

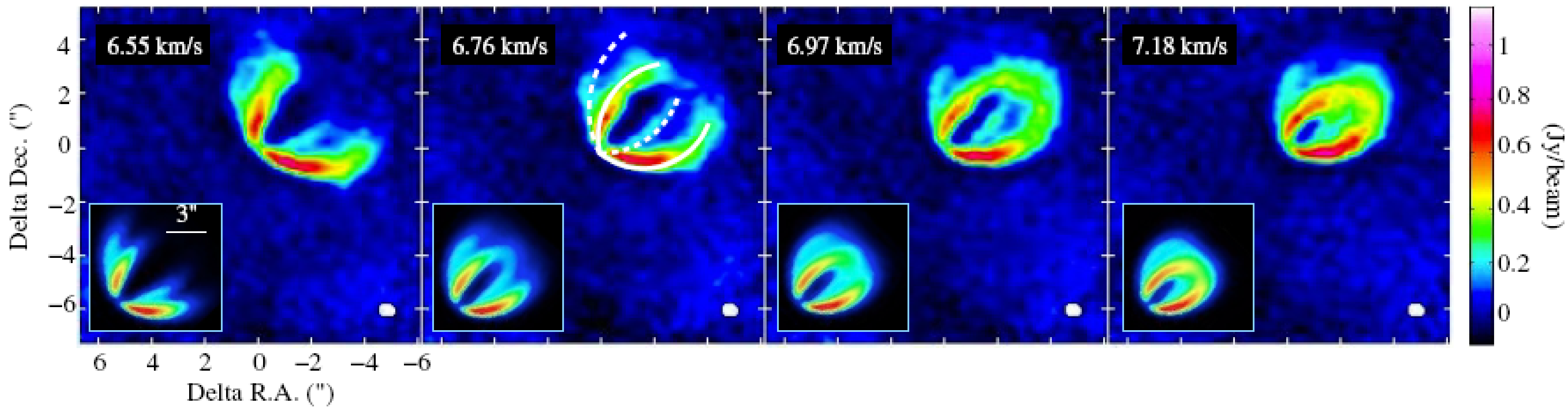
Pietu et al 2007

Well, some

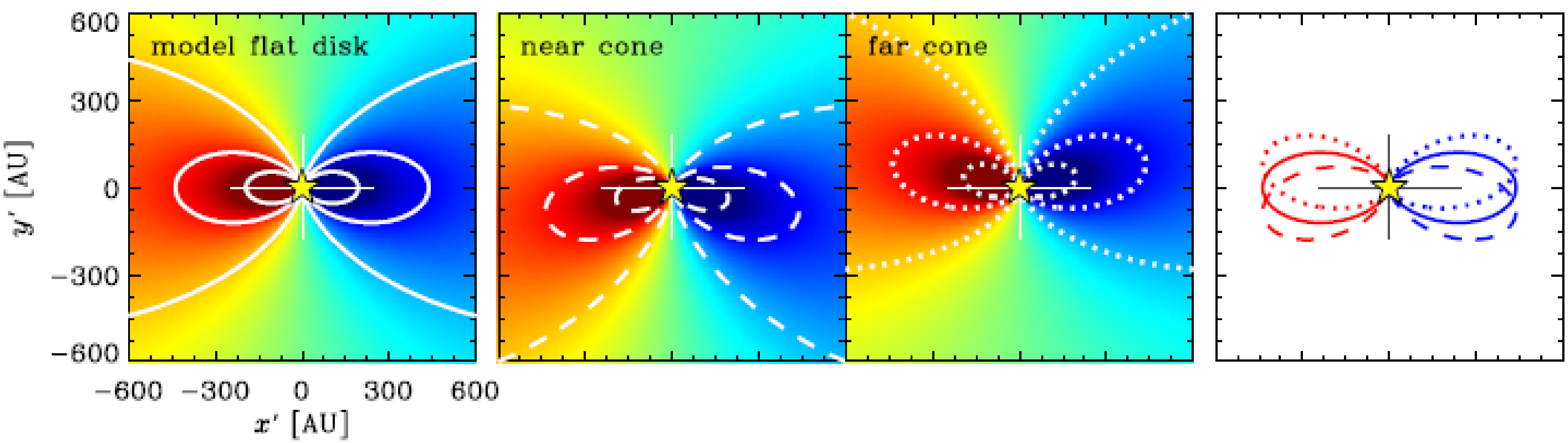


- HD163296 (we already heard of this one)
- ALMA Science Verification data
- One sees two disks

De Gregorio et al. 2013, Rosenfeld et al 2013

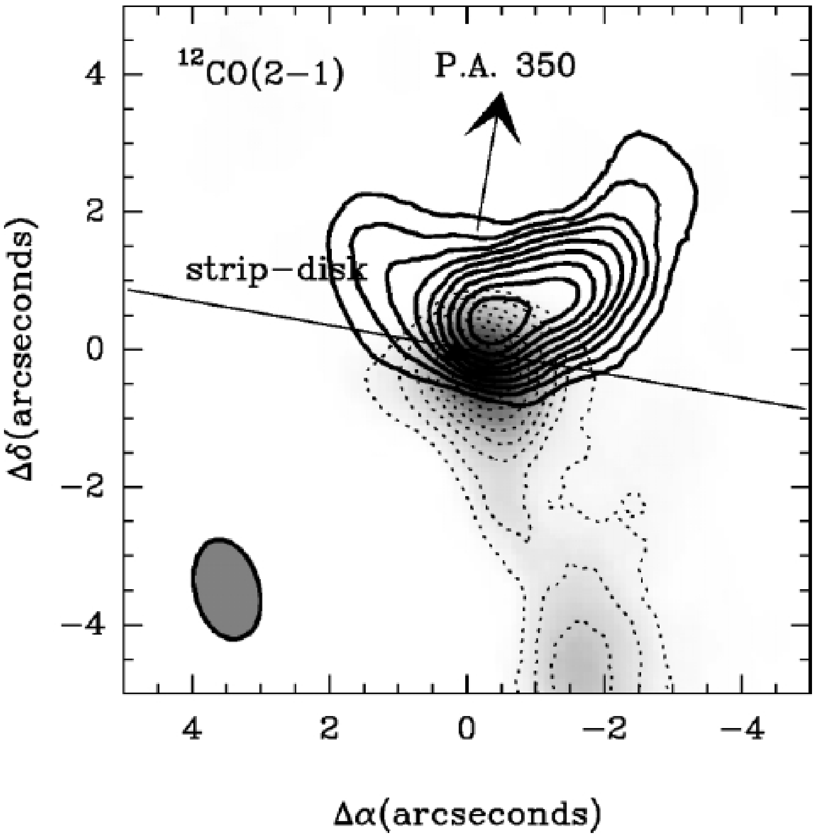


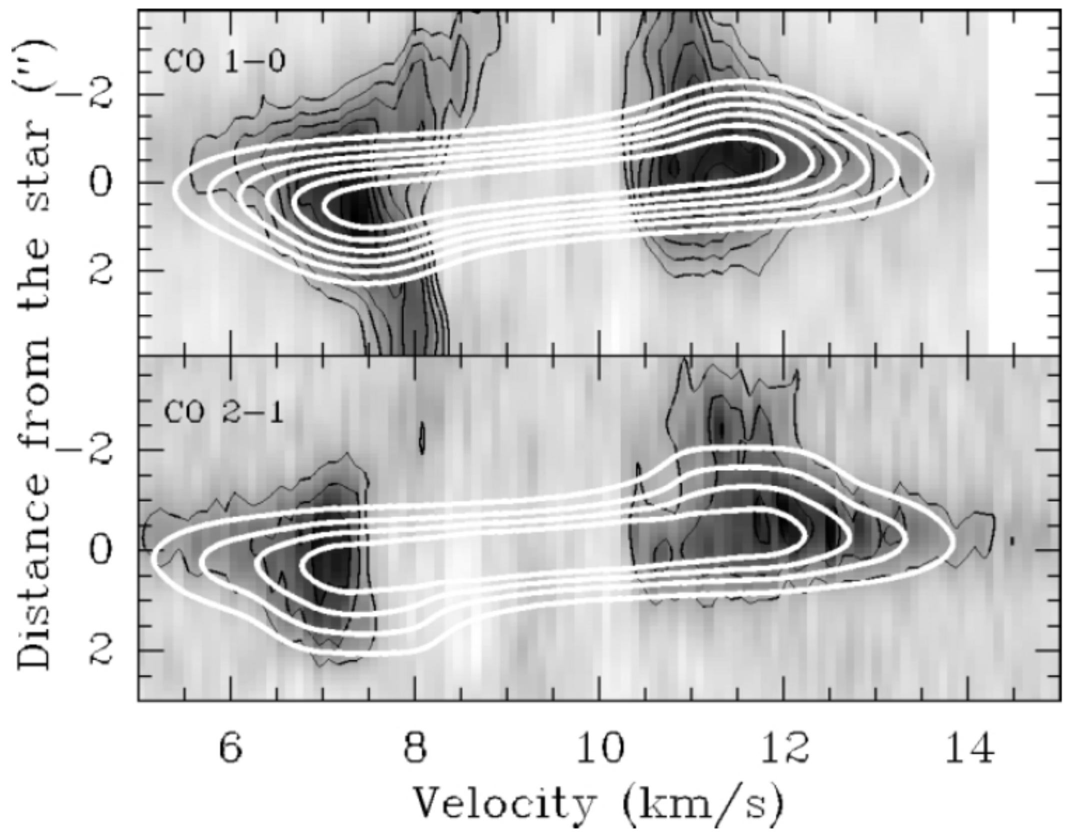
De Gregorio et al 2013



Rosenfeld et al 2013

The Be molecular line: R Mon



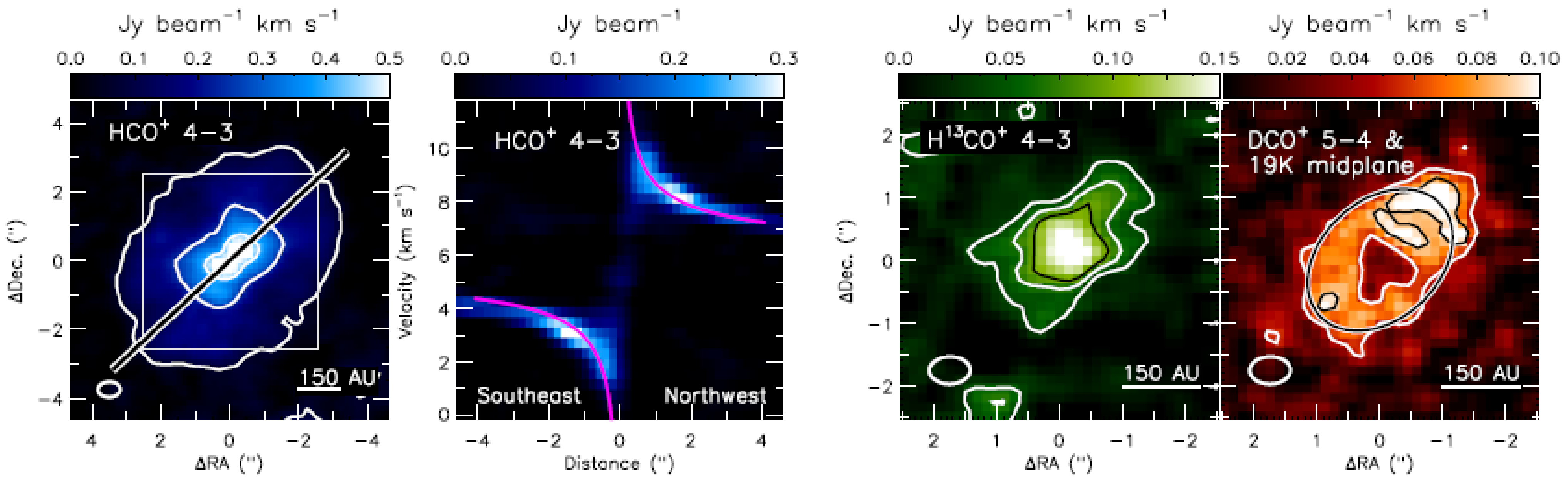


Fuente et al 2006 but see also *Sandell et al 2011*

III. Towards molecular complexity

CO snowline

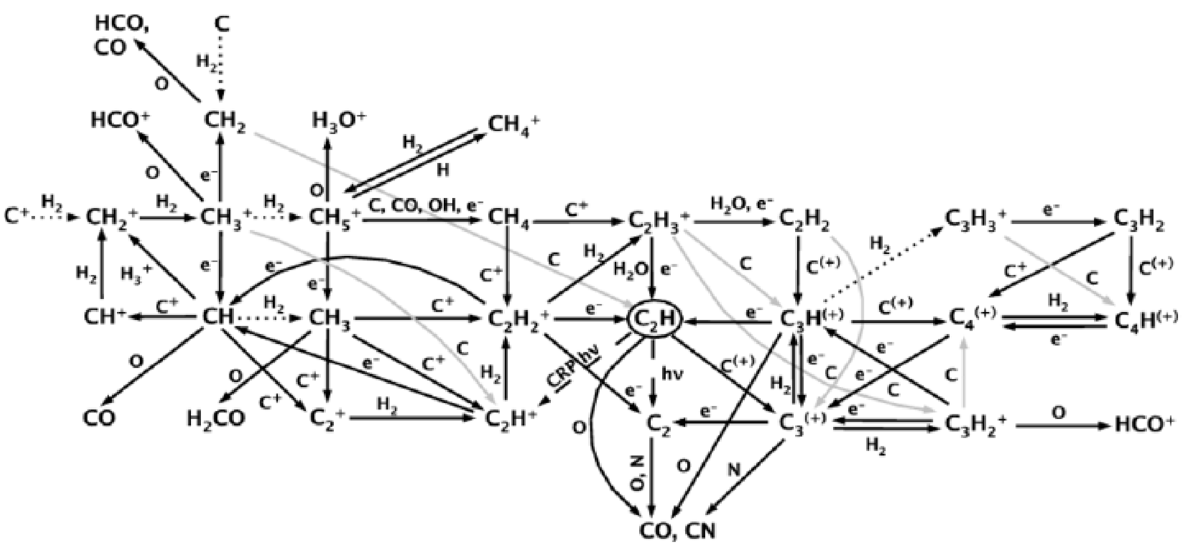
- Snowline corresponds to the region below which water condensates
- Found using $^{13}CO(2\text{-}1)$ by *Qi et al 2011*.
- DCO^+ confined in a ring where temperature 19< T < 21 K. (no H_2D^+ if hotter, no CO if colder).



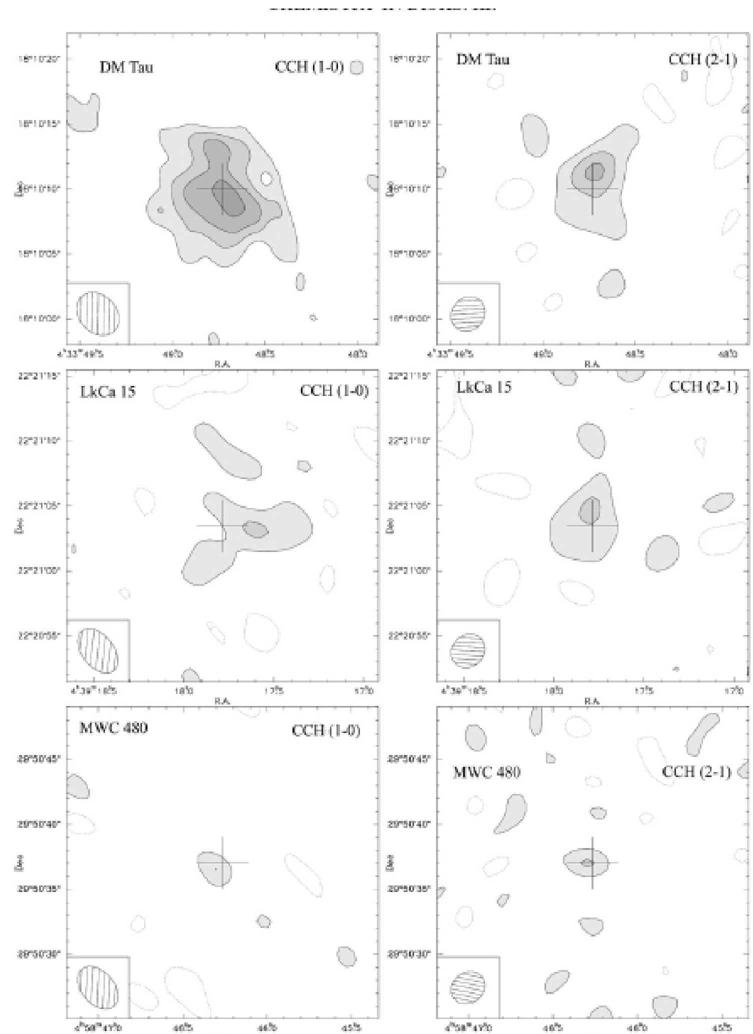
Matthews et al. 2013

CID (Chemistry In Disks)

- Observations with PdBI.
- C_2H^+ (*Henning et al 2010*): found in T Tauri stars, not in Hae star (MWC480).
- N_2H^+ (*Dutrey et al 2007*): idem
- CS (*Dutrey et al 2011*): idem



Henning et al. 2010



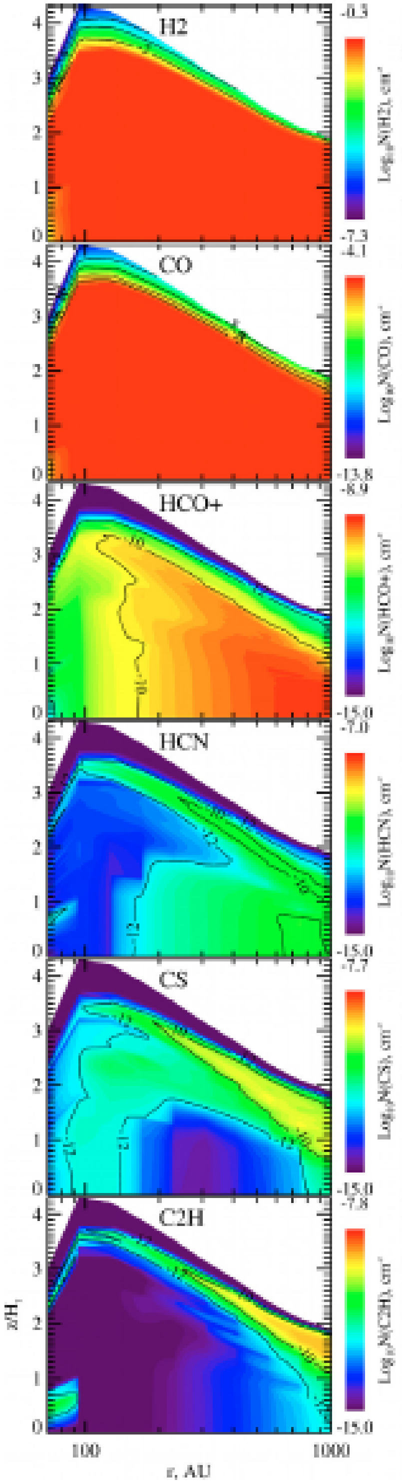
Molecules in AB Aur

Molecule	χ^2-minimization method			Chemical model		DM Tau
	N [cm^{-2}]	1 σ error	$N/N(^{13}CO)$[1]	N [cm^{-2}]	$N/N(^{13}CO)$[2]	$N/N(^{13}CO)$[1]
H_2	6×10^{22}	1×10^{22}	1.5×10^6	5×10^{22}	1.3×10^6	1×10^7
^{13}CO(*3)	4×10^{16}	5×10^{15}	1	4×10^{16}	1	1
HCO^+	6×10^{12}	3×10^{11}	1.5×10^{-4}	1.5×10^{13}	4×10^{-4}	2×10^{-3}
HCN	5×10^{11}	3×10^{11}	1.3×10^{-5}	4×10^{11}	10^{-5}	7×10^{-4}
CS	3×10^{12}	3×10^{12}	$<8 \times 10^{-5}$	2×10^{11}	5×10^{-6}	3×10^{-4}
C_2H	2×10^{13}	2×10^{13}	$<5 \times 10^{-4}$	10^{10}	2.5×10^{-7}	10^{-3}
CH_3OH	0	7×10^{15}	$<2 \times 10^{-1}$	0	0	0

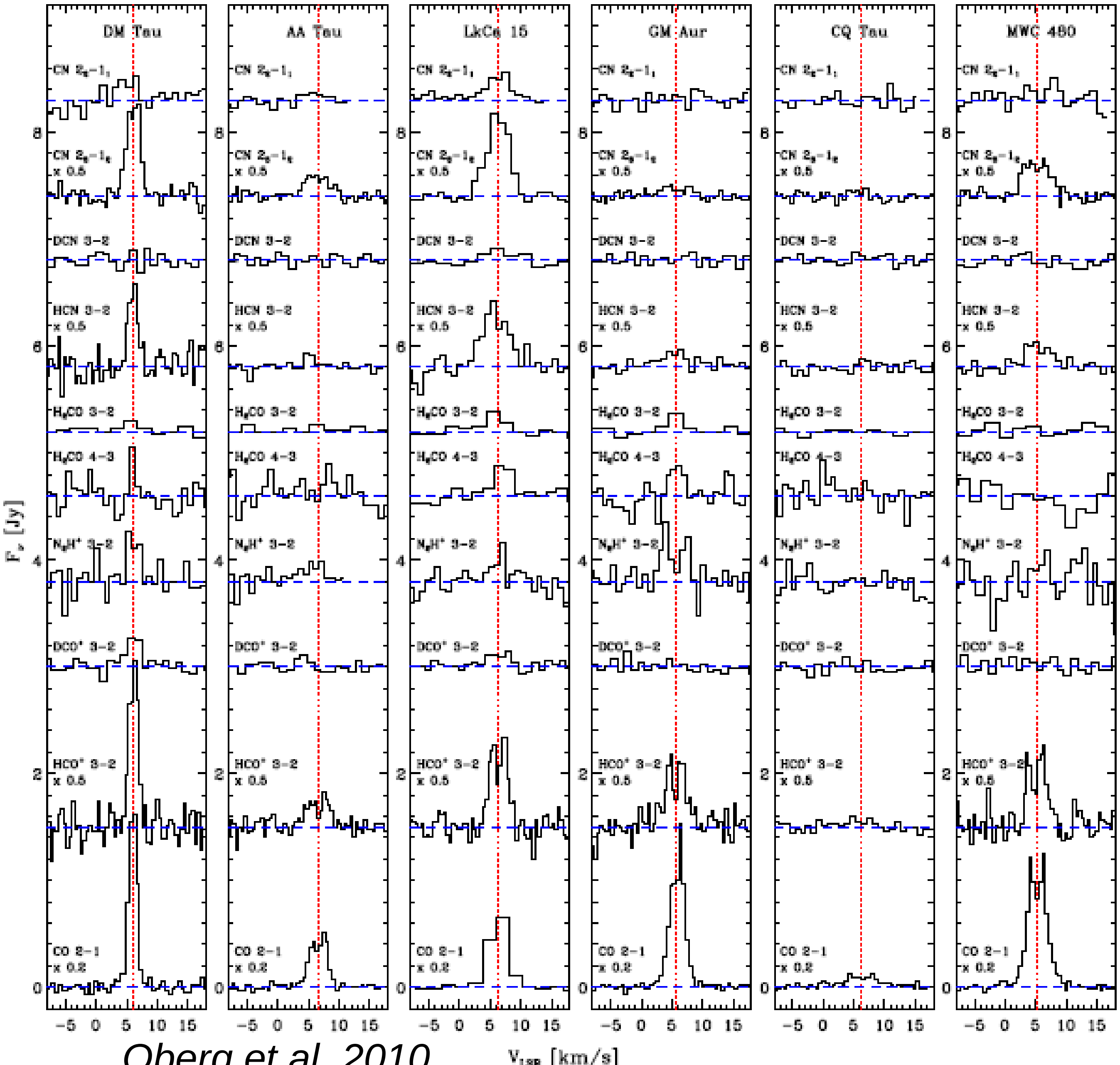
[1] Relative to the ^{13}CO column density at 250 AU obtained by the χ^2-minimization method.
[2] Relative to the ^{13}CO column density at 250 AU obtained by the chemical modeling.
[3] See results reported by Pietu et al. (2005).

- Lower abundances in the AB Aur disk explained by the higher uv flux of the Herbig A0/B9 star.

Schreyer et al. 2008



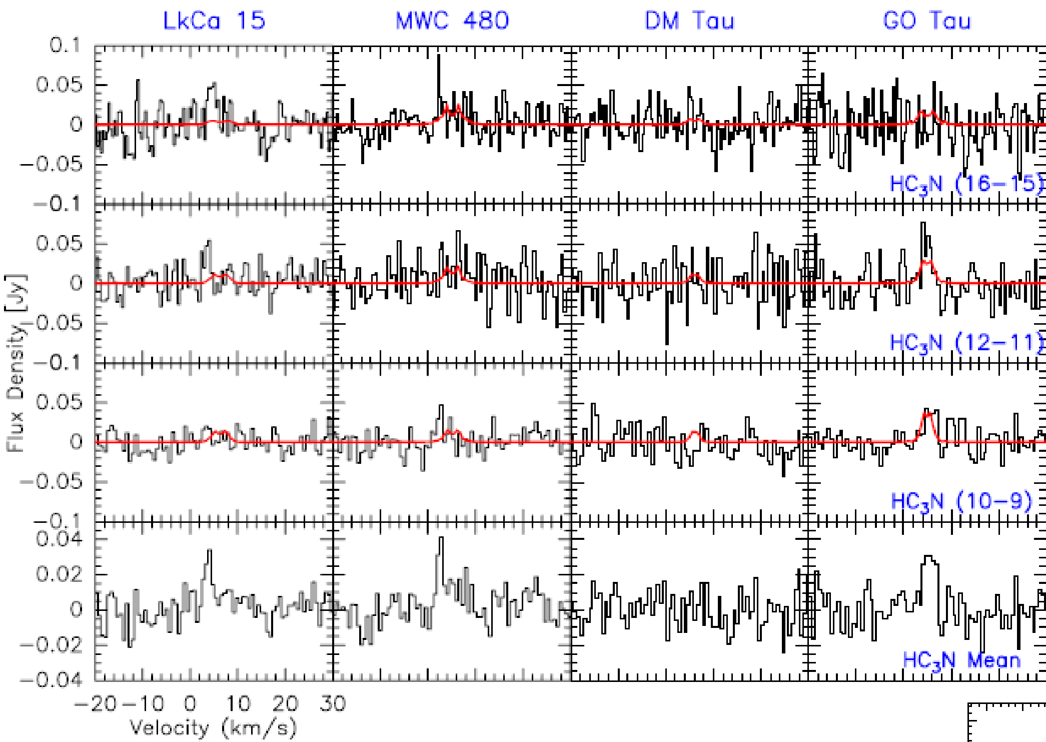
DISCS (Disks Imaging Survey of Chemistry with SMA)

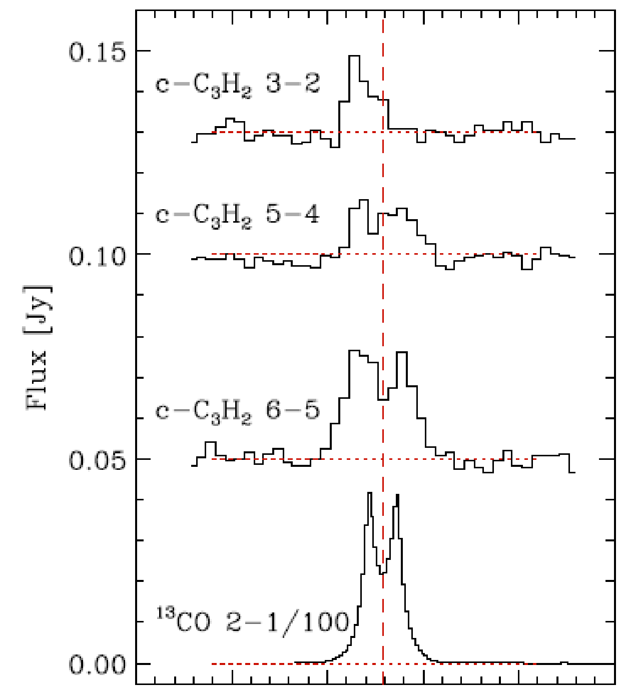


Oberg et al. 2010

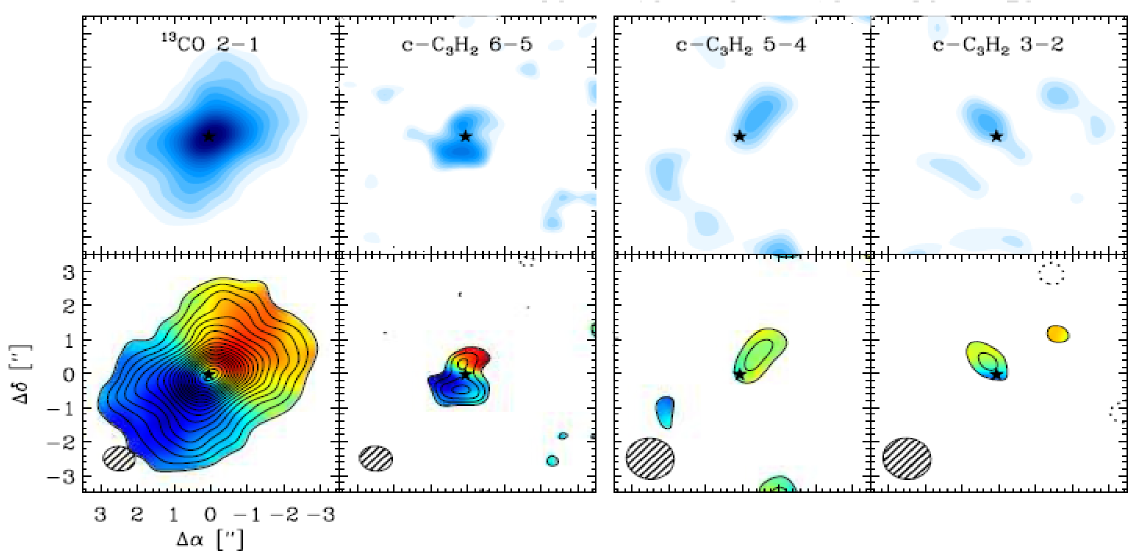
- *Oberg et al. 2010, Oberg et al 2011*
- Small sample of 12 disks, 6 in Taurus, 6 in the South.
- Much less detections around Herbig Ae stars

Detection of HC_3N and c-C_3H_2



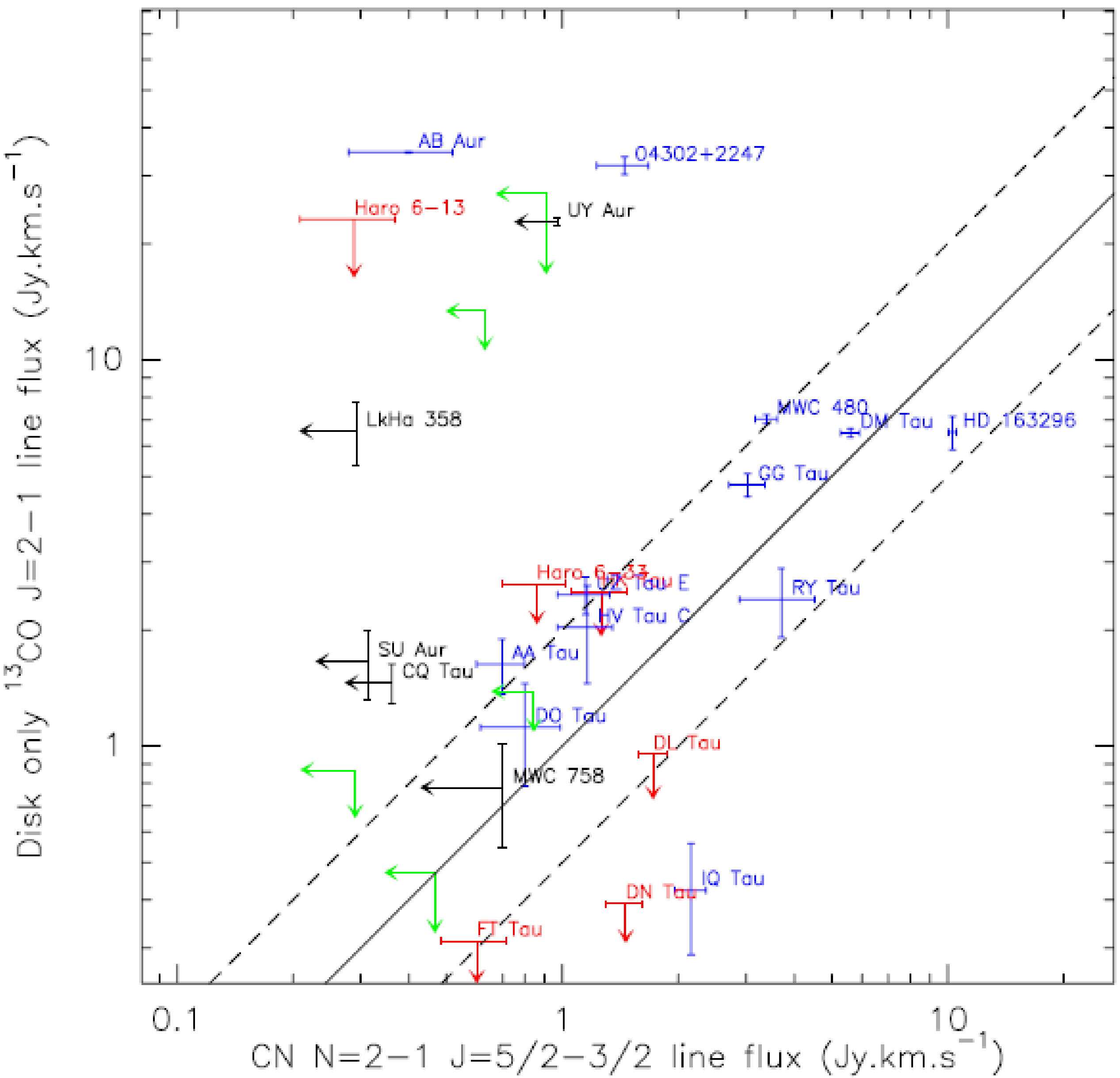


Chapillon et al. 2012

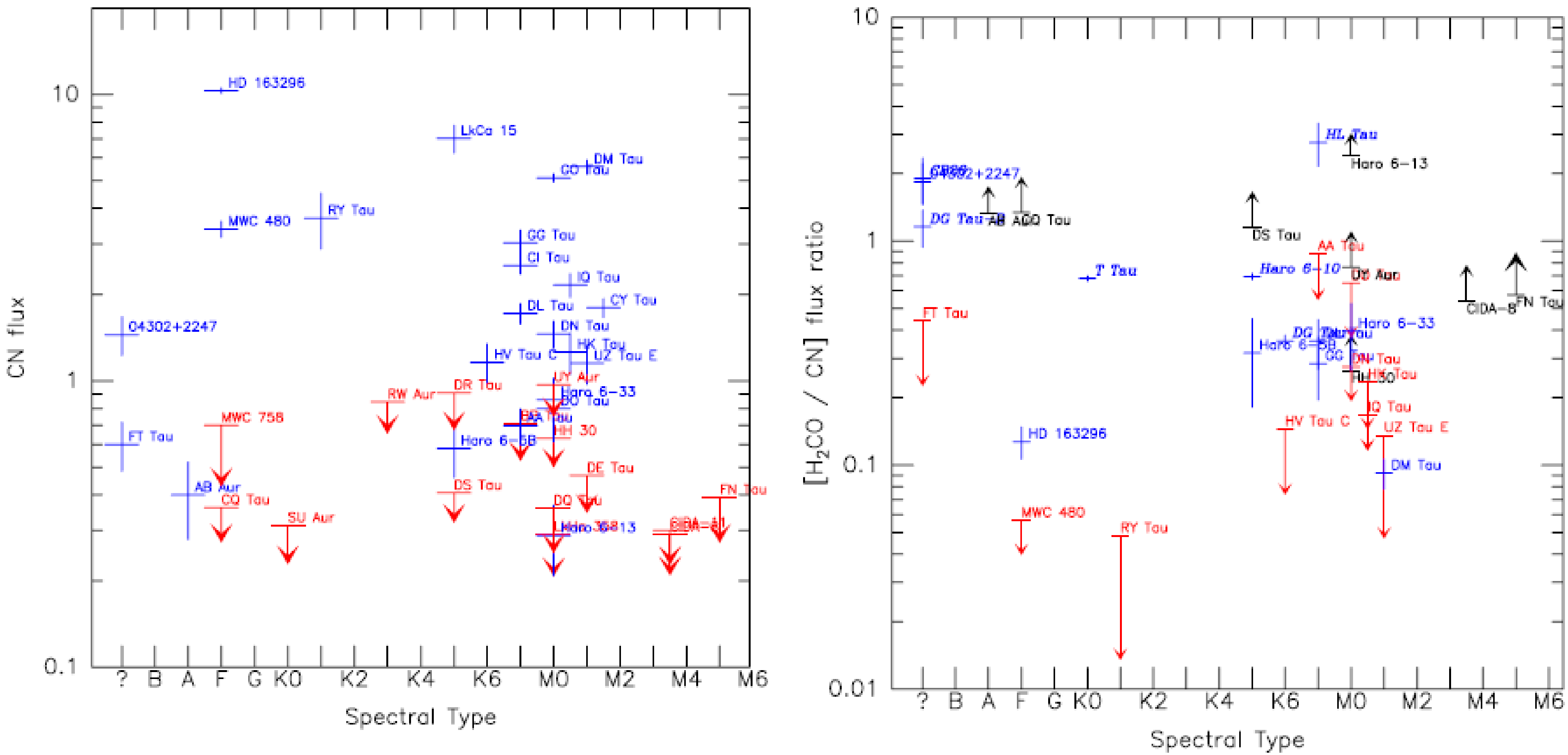


Qi et al. 2013

30m single-dish survey



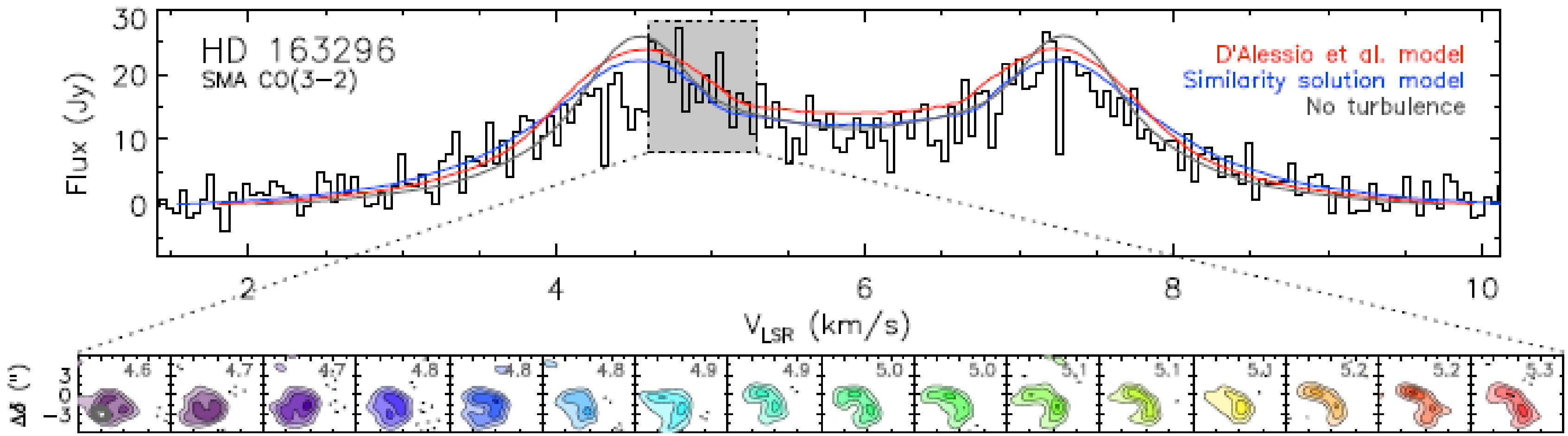
- CN not detected in AB Aur (detection from the envelope), MWC758 (Type I objects), detected in MWC480, HD163269 (Type II objects).
- H_2CO detected in sources w/o detected CN. Might be a tracer of temperature (see also *Van der Marel et al. 2014* in IRS 48).



Guilloteau et al. 2013

Measuring the turbulence

- Local line width: $$\Delta V(r) = \sqrt{\frac{2kT(r)}{\mu m_H} + \delta V_{\mathrm{tu}}(r)^2}$$
- More precise if using a heavy molecule
- Requires a good knowledge of the temperature structure and a good spectral resolution.
- 0.3 km/s (0.4 Mach number)

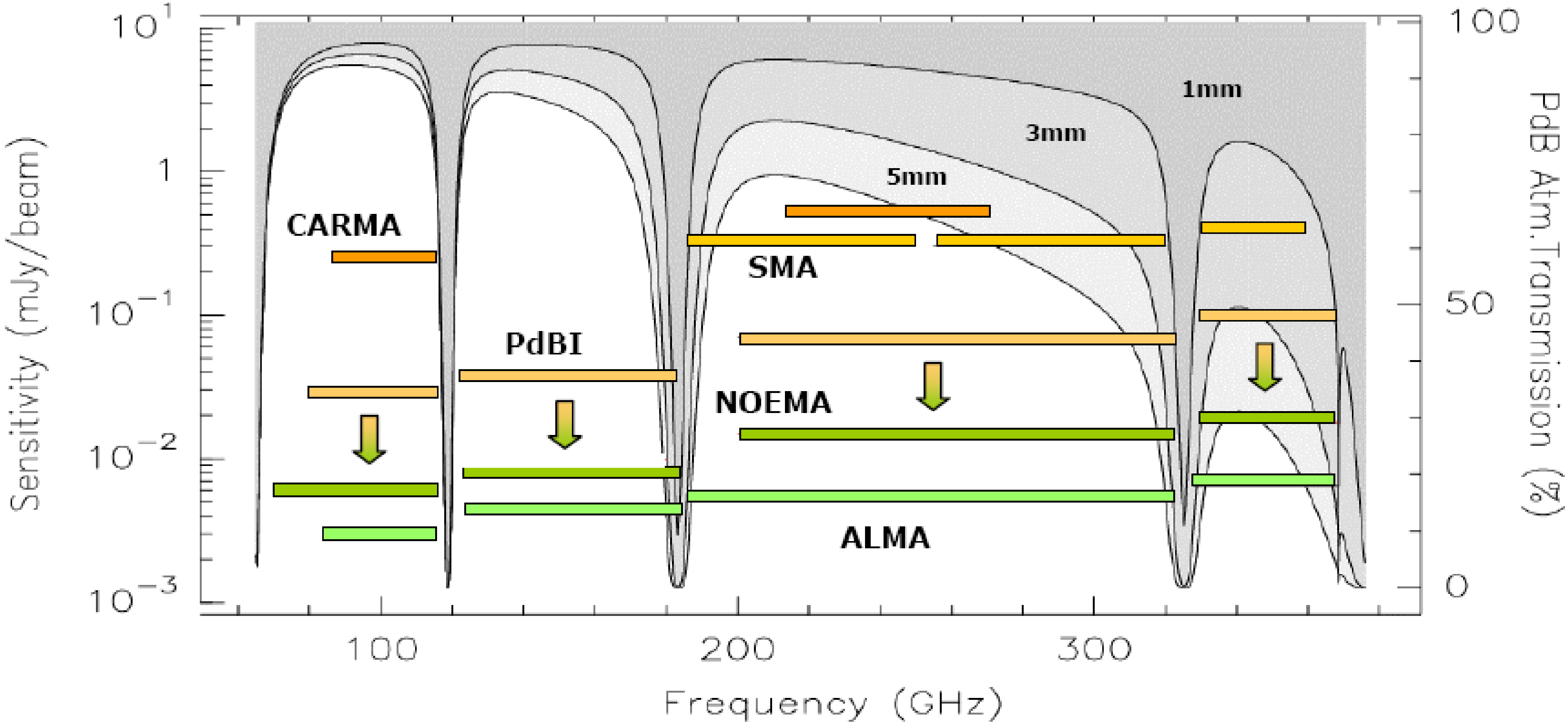


Hughes et al. 2011

Conclusions

- CO found in many HAe star, maybe up to B8 or so, but HBe star do not show any cold molecular content.
- In HAe, difference in opacities allow to sample temperature gradient.
- Less depletion in HAe stars (than T Tauri), but see HD163296.
- Is even detected in some transition and debris disks (see e.g. Beta Pictoris, *Dent et al 2013*, A3 star HD21997 *Kospal et al 2013, Moor et al. 2013*).
- Molecular inventory is very scarce: CO, HCO^+, HCN, CN, H_2CO, HC_3N, c-C_3H_2
- Molecular content of Class II sources more important than of Class I sources (but very limited sample)
- ALMA/NOEMA will provide answers to these questions

NOEMA sensitivity



Baseline extension

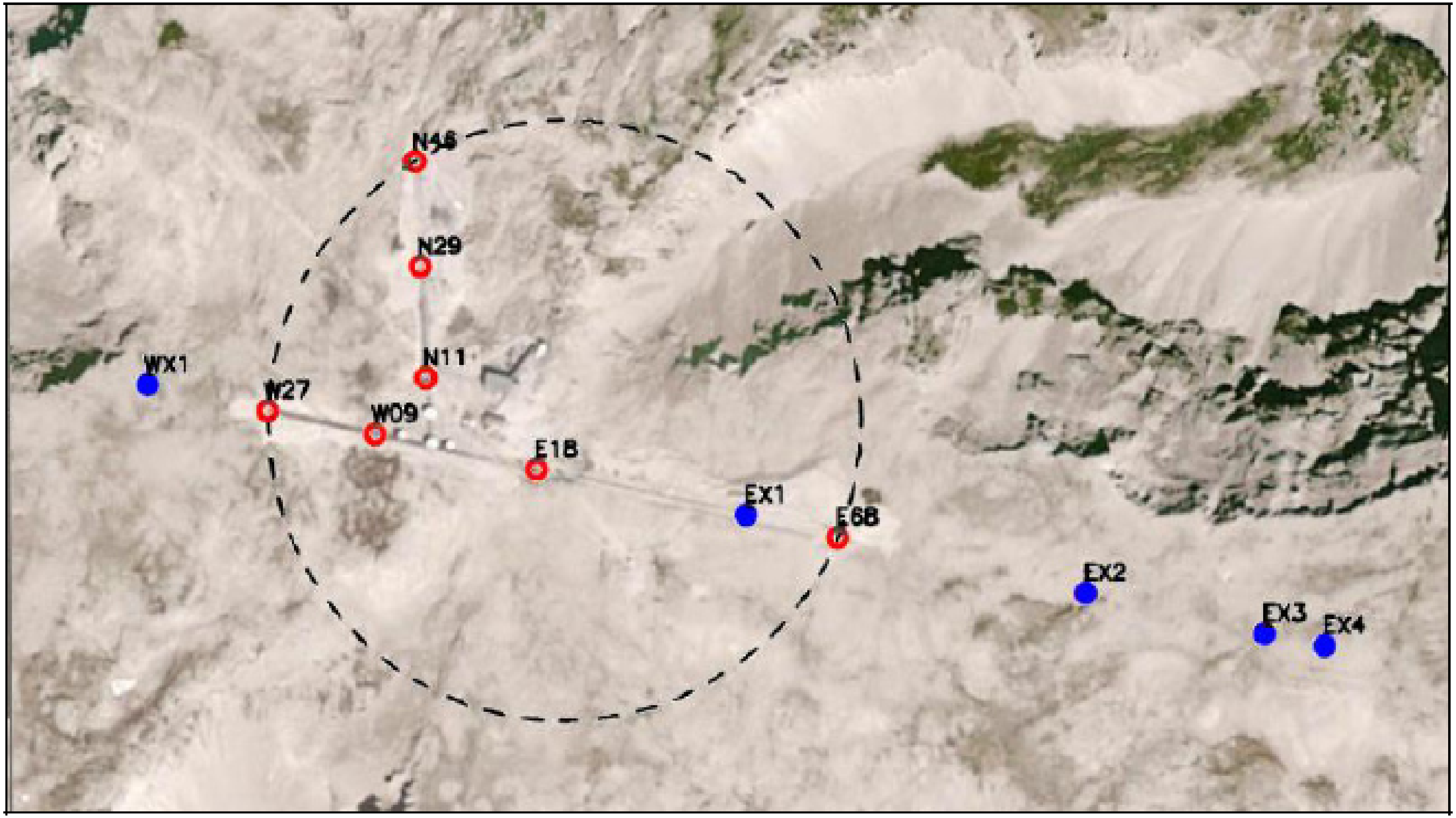


Fig. 11: The 12 locations of the A configuration pads (red: existing stations, blue: planned stations) overlayed on an aerial view of the Plateau de Bure Observatory (E is right, N is top). The tracks of the current PdB array are confined within a circle (dashed) of ~760 m diameter.

Thank you for your attention