Molecular Lines and thermal Dust Emission as Tools to investigate the physical Structure of Disks

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TTauri Disks: Many Pending Issues ?

Planet Formation: when and how ?

- Geometry (inner, outer sizes ? flaring? tilt?)
- Kinematics (keplerian .. yes BUT ...)
  - ➔ Stellar masses if Keplerian
  - ➔ Direct measurement of the Turbulence (MRI) ?
- Molecular lines
  - Gas temperature ?
  - → As function of r and z (multi-isotopes, multi-transition)
  - Molecular abundances ?
  - H_2 density ? (from line excitation ?)
- Thermal dust emission
  - Dust properties (K_ν , size distribution in r,z ? G/D?)
  - T Dust ?
  - H_2 density ? (assuming G/D known and uniform)

Current observations: 0.3″ - 0.5″ resolution ~ 50 – 70 AU

Modelling: State of the Art

Easy

- LTE conditions: Dutrey et al 1994, approach
- Power law parametrization of a passive disk in hydrostatic equilibrium
- *unbiased* Model independent
- *errorbars* Yields errorbars (Guilloteau & Dutrey 1998)

- Non-LTE conditions:
- Fast approximate radiative transfer tool still allowing χ^2 minimization (Pietu Ph.D thesis) & 2-D Monte-Carlo radiative transfer modelling (eg Semenov et al., 2004, Qi et al 2005)
- Need density, Tk distributions…
- Benchmark: Pavluchenkov et al., 2007 (2-D Monte-Carlo & fast methods)

- *ALMA ?* Global: outer passive + inner active disk with non-LTE conditions where the temperature is "self-consistently" calculated from assumed grains properties and distribution in disk → model dependent

Difficult

In common to all models: power law distributions

Today: UV plane analysis

ALMA → More sophisticated distributions than power laws (hydrodynamics)

CO Line Distribution

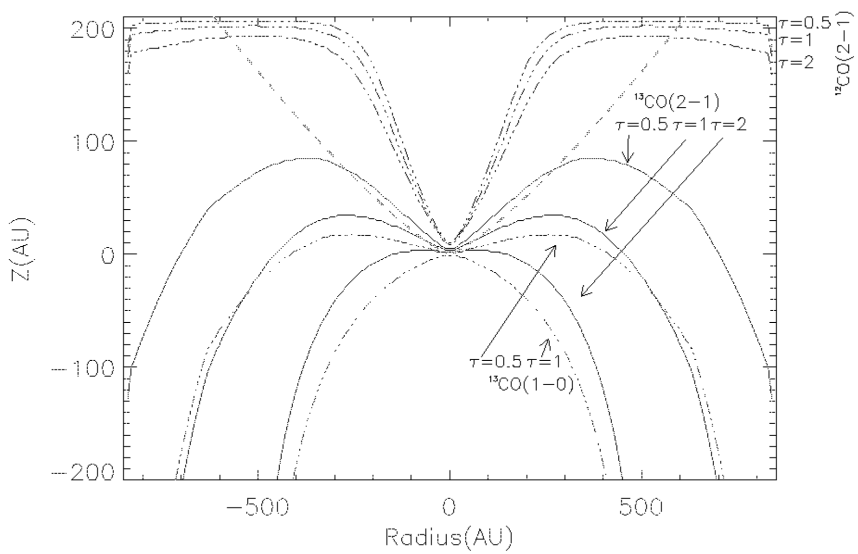
- If optically thick thermalized lines
  → $T_b(r) = T_k(r)$
- If optically thin thermalized lines
  → $T_b(r) \sim T_k/\Sigma(mol)(r)$ for J=1-0
  → $T_b(r) \sim \Sigma(r)$ for J=2-1
- $\Sigma(mol) = \Sigma(H_2) \times X(mol)$
  → X(mol) diffcult to constrain
  (usually referenced to dust)

→H_2 mass is not yet well constrained even if distribution ~ known

Non-LTE → replace Tk by Tex …

CO J=3-2 and higher lines are not thermalized everywhere

Dartois et al 2003



DM Tau: the prototype

CO isotopes

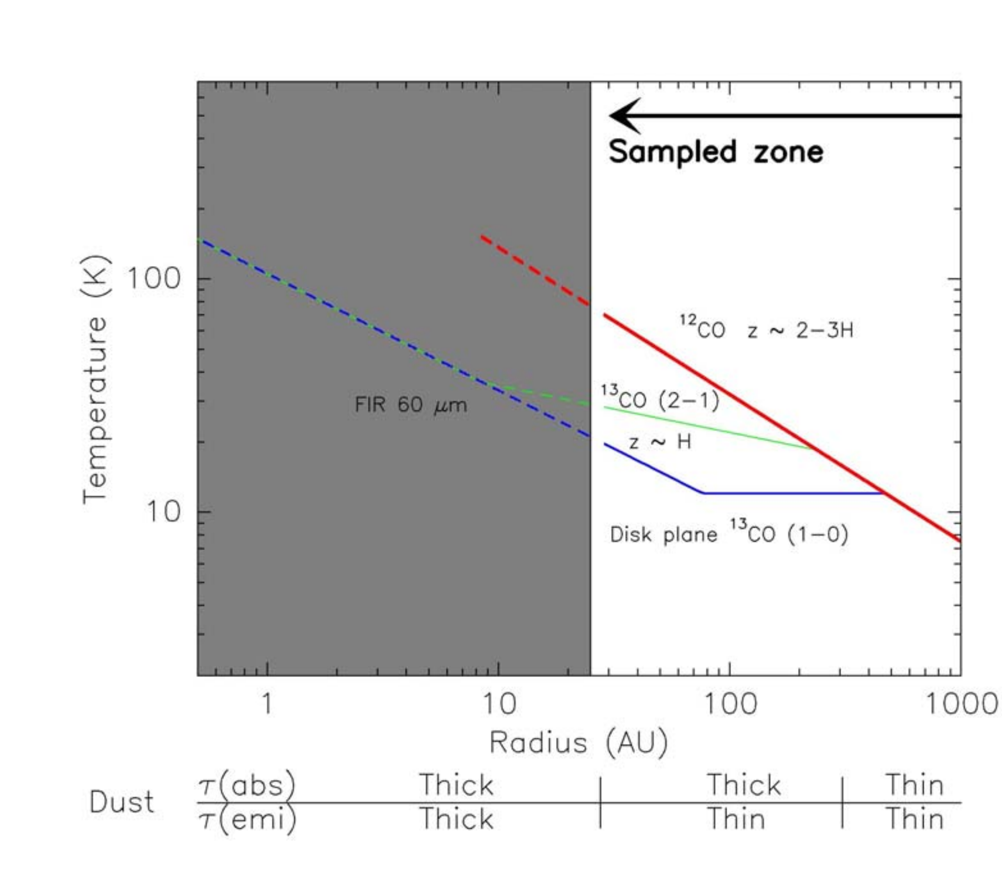
First observational evidence for a vertical temperature gradient.

	T	q
^{12}CO	32	0.63
$^{13}CO(2-1)$	22	0.30
$^{13}CO(1-0)$	14	0

Consistent with passively heated flared disk

& selective photodissociation

	Rout
^{12}CO	800 +/-10
$^{13}CO(2-1)$	640 +/-15
$^{13}CO(1-0)$	650 +/-20
$C^{18}O(1-0)$	600 +/-50



Dartois et al 2003

Temperature gradient

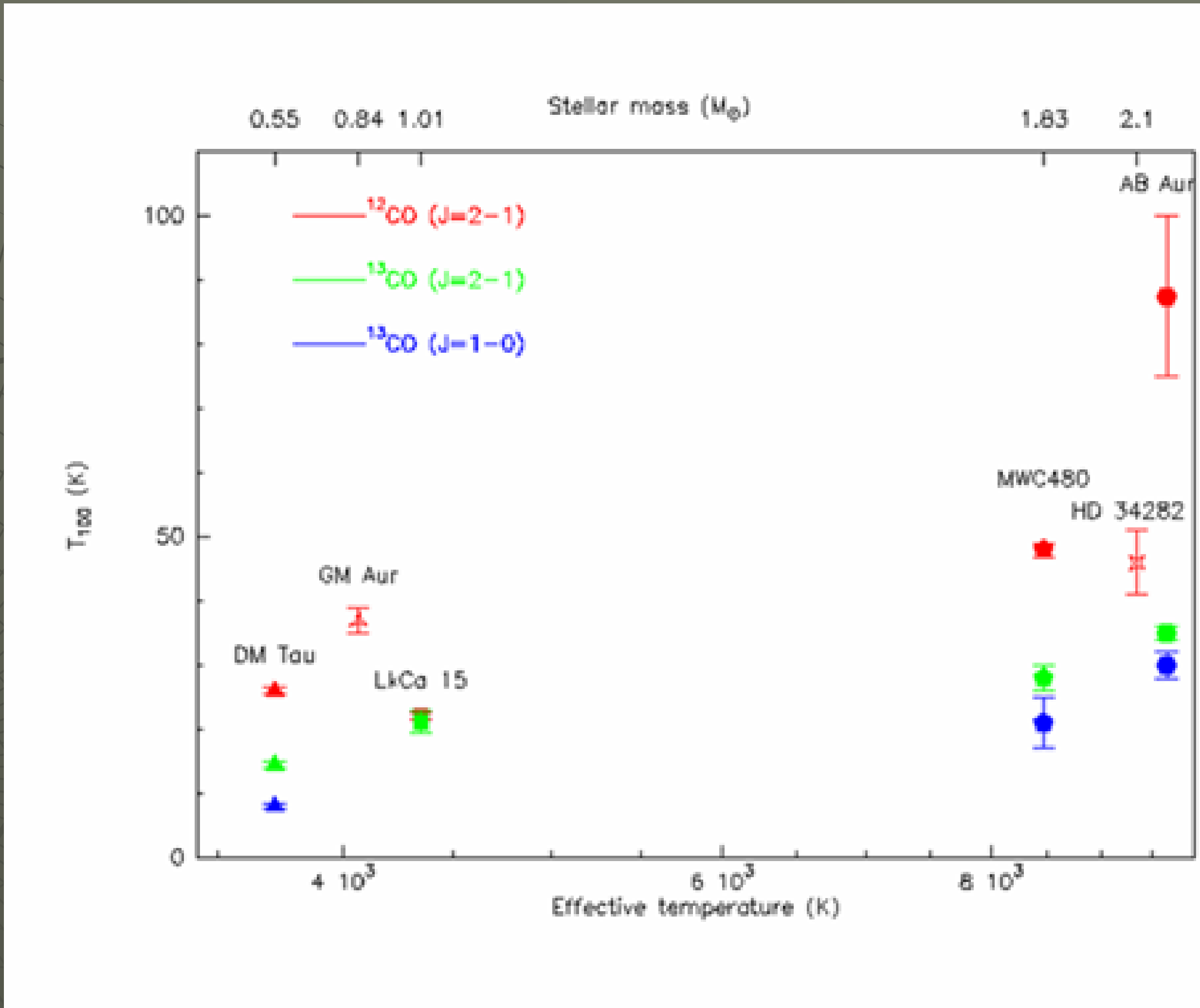
CO isotopes

Same trend for other TTauri & Herbig Ae stars as for DM Tau

- Vertical temperature gradient
- Selective photodissociation
- Varying depletion
- Cold CO for TTauri stars

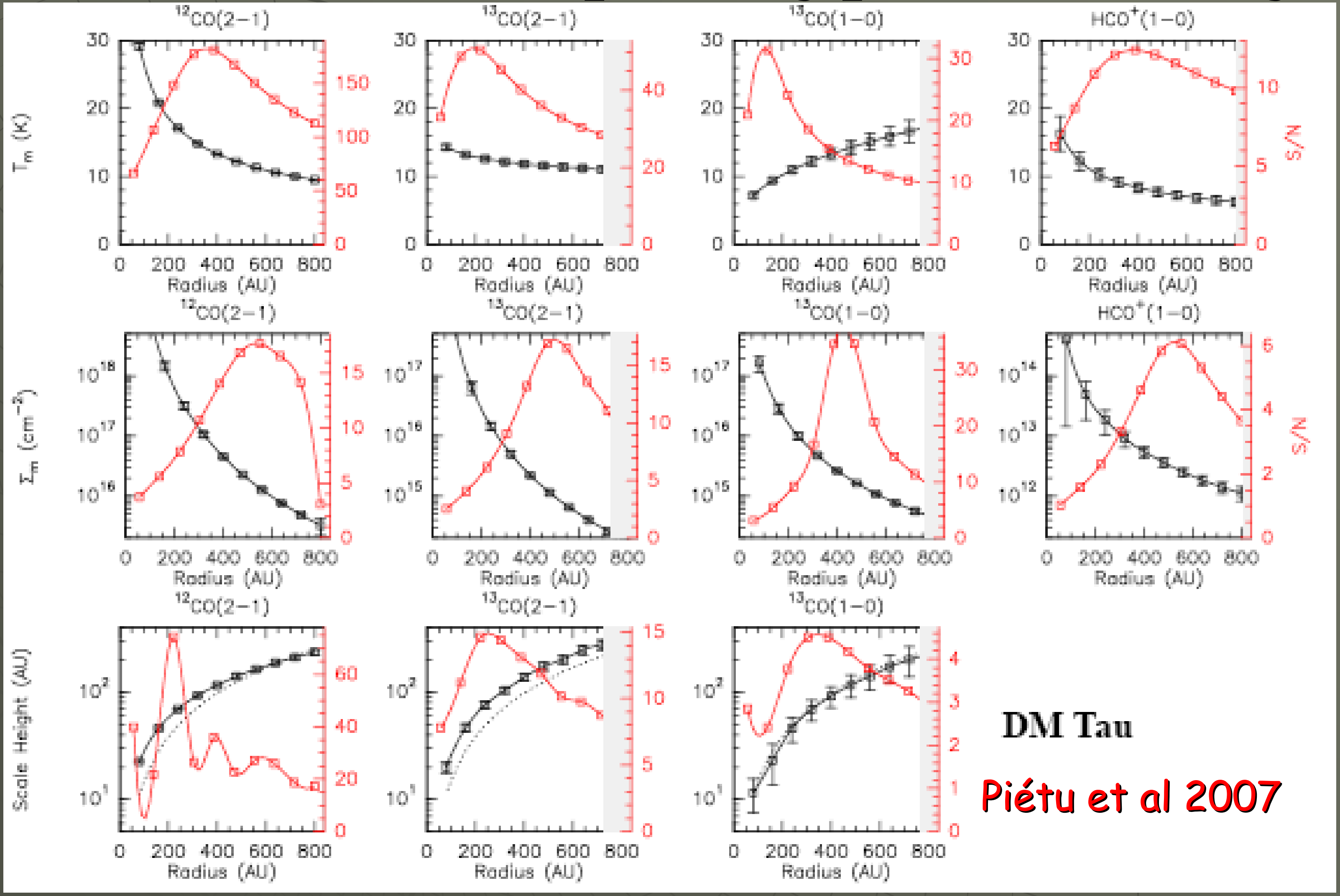
→Role of vertical mixing

See: Semenov et al, 2006 & Aikawa 2007 …



Piétu et al 2007

DM Tau: the prototype: CO analysis



ALMA sensitivity (band6): res = 0.3″ (~40 AU) – dv = 0.1 km/s
➔ 3 K at 3σ in 2hours ➔ time consuming even for ALMA

"Apparent" Scale Height

Phase referencing between velocity channels

+ known velocity law

➔Super-resolution

➔can constrain the scale height

Piétu et al 2007

$$\delta r = 2r\frac{\delta v}{v} \simeq 10 \text{ AU at } r = 100 \text{ AU}$$

$$\delta v = 0.15 \,\mathrm{km.s^{-1}}$$

Fits to the data

➔ $H(r) = H_{100} \times (r/100\ \mathrm{AU})^{1.25}$
where 1.25: hydrostatic value when $q = 0.5$

In DM Tau:	12CO	13CO 2-1	1-0	HCO+ 1-0
Scale Height at 100 AU, (AU)	30 ± 1.1	28 ± 4	28 ± 5	(19 ± 8)

Expected hydrostatic scale heights at 100 AU → H(r) ~ 15 AU

→ "Apparent" scale heights (…depending on the thickness of the CO layer…)

Thermal Dust Emission

- Dust properties ?
  - K_ν (cm^2/g) ? (K_0, β ?)
  - size distribution in r,z ?

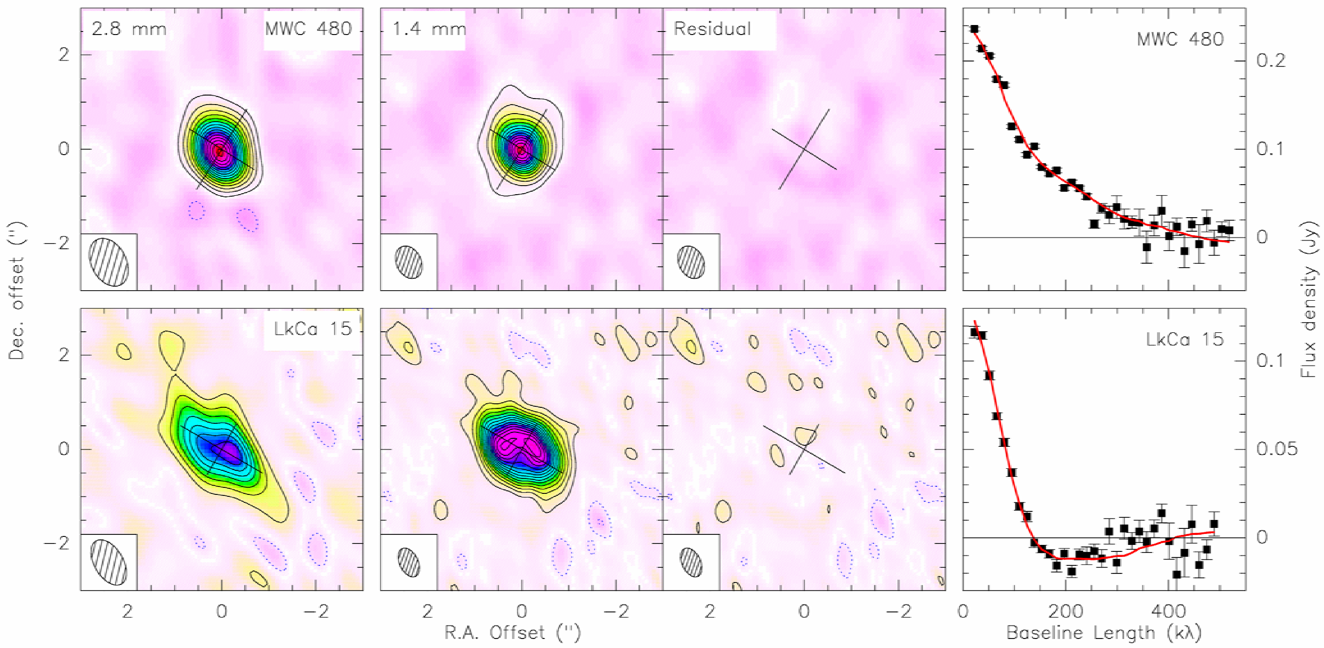
- If centrally peaked, the dust emission is partially optically thick
  → Need to measure the size of the optically thick core
  → Allow us to estimate T(dust)
  → Then extrapolate to estimate Σ(dust)
  (& $\Sigma(H_2)$) taking gas/dust-ratio =100 ?)
  Tb(dust)(r) α κ_ν(dust) x dust/gas-ratio x $\Sigma(H_2)$(r) x T(dust)
  → gas/dust-ratio, κ_ν(dust) not well known

  But this assumes a single power law distribution – Is this true ?
  Gas/Dust ratio poorly known

- MWC480 and LkCa15 ?

LkCa 15 and MWC 480 dust Disks

PdBI data, Pietu et al., 2006 – Resol ~ 40 AU or 0.3"



➔MWC480: emission is centrally peaked

➔VERY COLD DUST: T_d ~ 20 K at 20 AU

To compare with T_{13CO} ~ 35 K, T_{CO} ~ 150 K (strong Tk gradient)

➔ LkCa15: cavity of R ~ 50 AU

➔Planet formation or very-low-mass companion ? (M < 5-10 Mjup)

ALMA: High Resolution = Big Surprise!

What do we know today ?

- Outer disk mid-planes colder than the surface - in agreement with passive disk model heated by the central star (inner disk?)
- Outer disks are in Keplerian rotation (but what about AB Aur ?)
- H(r) … first estimates ~ roughly hydrostatic
- Sub-sonic turbulence in outer Disk (integrated value…)
- Cold "mm" dust (vertical location ?)
- Inner cavity in some proto-planetary disks (most of them ?)

Not yet statistically significant → large surveys with ALMA

Evolution of disks ?

Large Surveys are needed …

CO multi-transitions & multi-isotopes → a robust basis

→ Tk (r,z)

→ H(r)

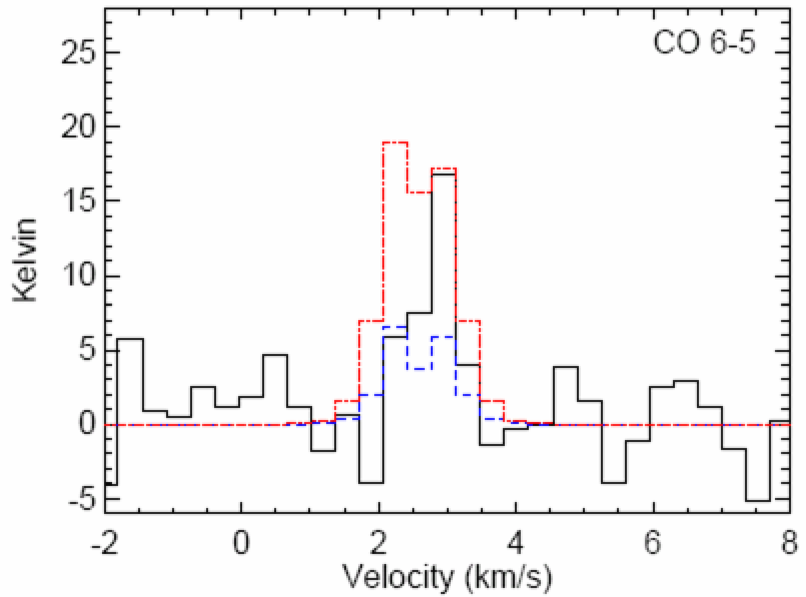
→ large/small departure from Keplerian rotation (role of self gravity?)

→ Direct measurement of DV: turbulence (r,z)

$$\Delta V = \sqrt{\frac{2kT}{m} + v_{\mathrm{turb}}^2}$$

High transitions needed to better constrain the disk physics (eg X ray heating)

X-ray Heating is Needed to Explain Strong CO 6-5 Line

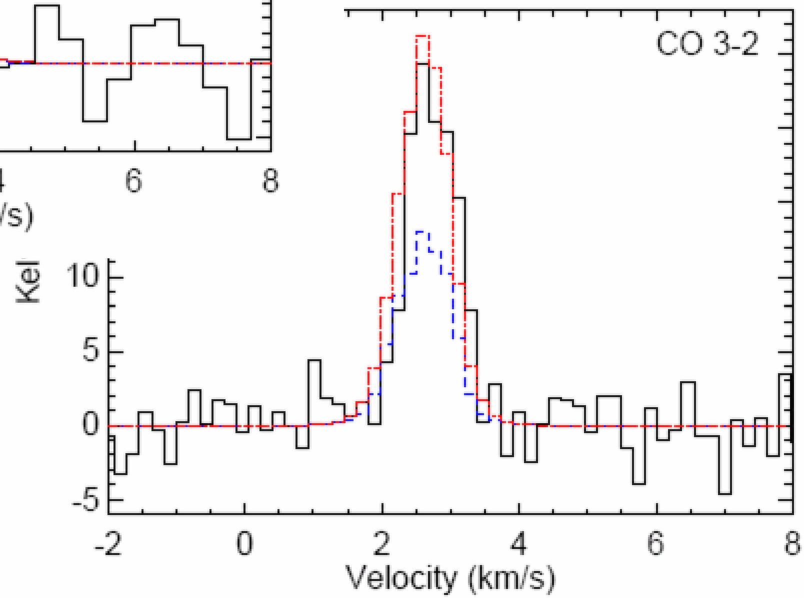


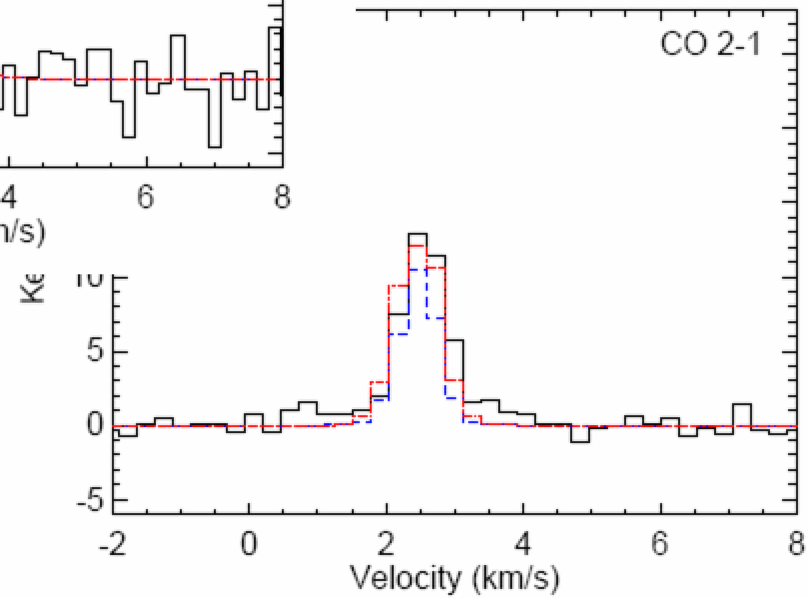
Blue: Canonical Model

(Calvet et al. 2002, Qi et al. 2004)

Red: Model with X ray heating

Black: SMA data





TW Hya

QI et al., 2004, 2006

Large Surveys are needed …

CO multi-transitions & multi-isotopes → a robust basis

→ Tk (r,z)
→ H(r)
→ large/small departure from Keplerian rotation (role of self gravity?)
→ direct measurement of Dv: turbulence (r,z)

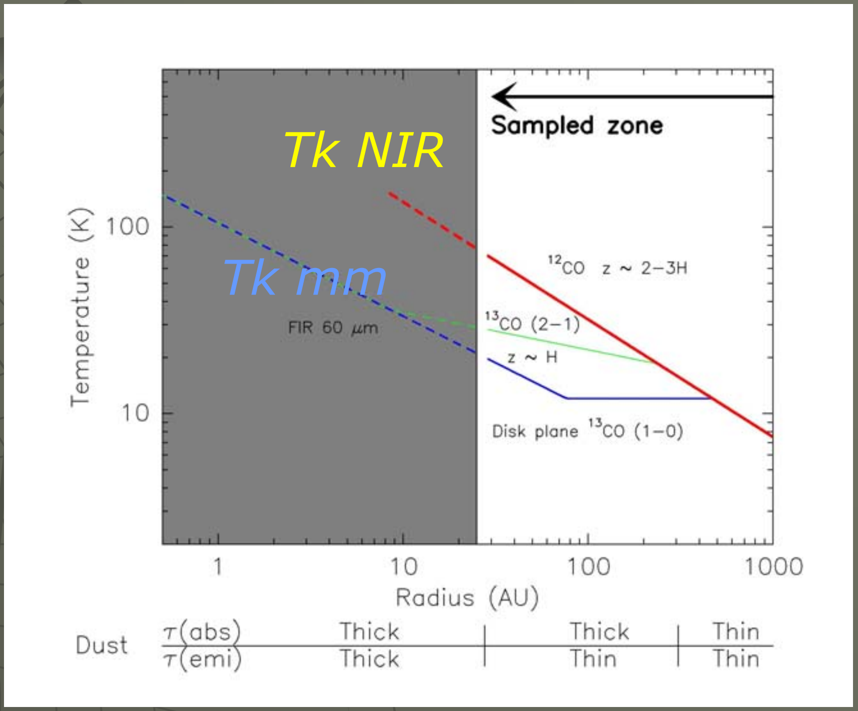
Multi-frequency continuum survey:
→ dust properties: K_ν ? (K_0, β ?)
→ Distribution in (r,z) & mass

- Inner cavity in some proto-planetary disks (most of them ?)

Evolutionary status – class 0/I to Class III
→ Dust around Class 0 is more evolved than in the ISM (L1157)

Continuum Surveys

Disk "TK"



- Pietu et al, 2006 (MWC480) have shown that the dust emitting at 1.3mm is significantly colder than that emitting in the NIR
  - → Avoid to take the NIR "temperature" to analyse unresolved mm data
  - → Vertical stratification ?
  - → Not yet sure …

ALMA:
→ 0.1" = 15 AU ~ H(r) at 100 AU
→precise β measurements (several bands)
→SURVEYS (accuracy of the relative calibration?)

Gaps, Cavities and other Holes …

- 1994: GG Tau: CB disk of inner radius ~ 180 AU
- 2005: AB Aur: an inner cavity of ~ 100 AU
- 2006: LkCa15: 40 AU, a very low-mass companion?
- 2007: HH30: an inner cavity of radius ~ 40 AU

→ Accretion disks …

Only the hole of GG Tau is clearly detected in NIR
Low density contrast only detectable in mm/submm (opacity)

Mm arrays → 1994: R ~ 2″
2007: R ~ 0.3″

ALMA: Base ~ 15km - D =150 pc
~ 0.02″ (~ 3 AU) at 1.3mm - 0.01″ (~ 1 AU) at 0.45mm
-Origins of the cavities ?
-Planet or very-low-mass companion?
-Photoevaporation ?
→ Specific ALMA observations required

AB Aurigae

Circumstellar Spiral Arms ! and non Keplerian Motions

- Spiral arms…
- Non keplerian motions

$V(r) = V_0 \, (r/r_0)^{-0.41+/-0.01}$

- Dust not very evolved

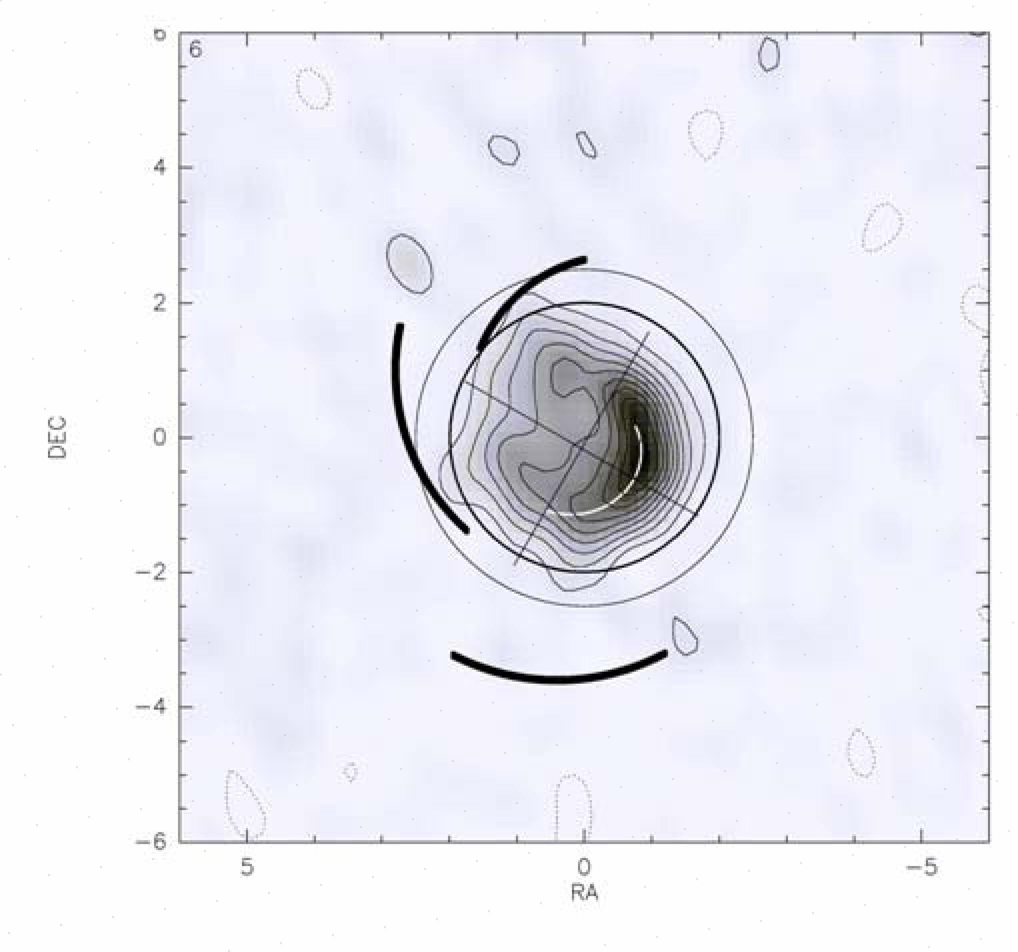
$\beta = 1.4 +/- 0.2$

- Warm disk (> 30 K)
- Little CO depletion
- An external envelope (Semenov et al 2004)

-a low mass companion ?

-a young disk

→ stellar age ?



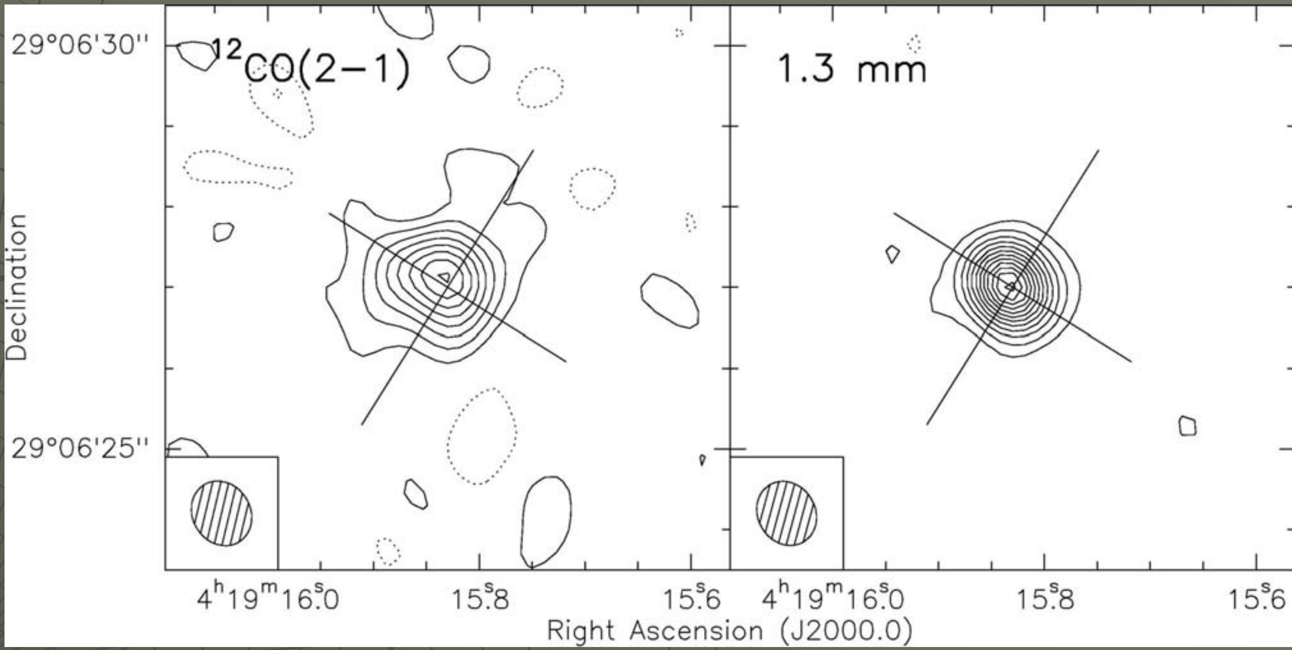
Piétu et al 2005

ALMA: Explicit the dynamics ? The dust properties ? …

Transition Disks - BP Tau

- Small radius: 120 AU
- Strong continuum
- Weak (τ~ 1) , warm CO
- CO depleted by a factor 160

→ Dissipation process ?



Dutrey et al 2003

➔ Starting gas dispersal ?

ALMA → Is this object typical of a new class of "evolved" disks ?

Evolutionary Status ?

A wide range of observed properties (from dust & CO)

- AB Auriga – a younger object ?
- BP Tau – a transition disk ?
- Too few objects known today …

Planet Formation:

- Time-scale → from dust to planetesimals
- Time-scale → giant planet formation?

ALMA: gas and dust relative distribution
→ from Class 0/I to class III

What about the Mass Content ?

➔ M(r,z) in H_2 & dust
– distribution (relative)
- Total mass (absolute)

- The more difficult parameter to determine, even with ALMA
  ➔ still need of complementary approaches

- n(dust) → K_ν , size distribution…
- n(CO) → X(CO)

- n(mol) → X(mol)
- From multi-line analysis and study of the excitation conditions (linked to chemistry → see poster by Semenov et al.)

- → M(r, z) and even G/D (r,z)

The ALMA ERA → inner disk

Geometry, vertical and radial structure (Tk, n, X, DV) → planet formation

→ CO multi-transitions & multi-isotopes analysis are mandatory
- → Tk (r,z)
- → H(r)
- → large/small departure from Keplerian rotation (role of self gravity?)
- → direct measurement of DV: turbulence (r,z)

→ Multi-frequency continuum survey:
- → dust properties: K_ν ? (K_0, β ?)
- → Distribution in (r,z)
- → Images of inner cavity in proto-planetary disks (most of them ?)

→ Evolutionary status – class 0/I to Class III
- → Dust around Classes 0 is more evolved than in the ISM (L1157)

ALMA sensitivity (Bd 6): res = 0.3'' (~40 AU) – dv = 0.1 km/s ➔ 3 K at 3σ in 2hours

➔ Require large surveys of disks: statistics with an homogenous data quality