Molecular and continuum surveys as tools to determine the structure of protoplanetary disks - part I

by Anne Dutrey (LAB, France)

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With inputs from

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Circumstellar Disks around low-mass PMS Stars

- Disks: r ~ 100-900 AU, M ~ 0.001 – 0.1 Msun (of H_2 gas)
  - Nearest star forming regions at ~ 150 pc, 1'' = 150 AU
  - Planet formation: 1 gap (~5 AU) = 0.03"
  - High angular resolution required

- Mostly cold gas and dust: T_k 10 to 30 K
  - High sensitivity required
  - (sub)-mm domain well matched (rotation lines, dust emission)

- For M_* = 1 Mo, rotation velocities around 2 km/s.
- Turbulence only around 0.2 km/s.
  - High spectral resolution required

➢ Large mm and sub-mm arrays are the ideal tools …

… Geometry, dynamics, temperature, mass distribution …

→Thermal Dust emission
→Molecular Rotation Lines such as those of CO (no « easy » detection of H_2)

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

Circumstellar Disks around low-mass PMS Stars

c),d) Proto-planetary Disks

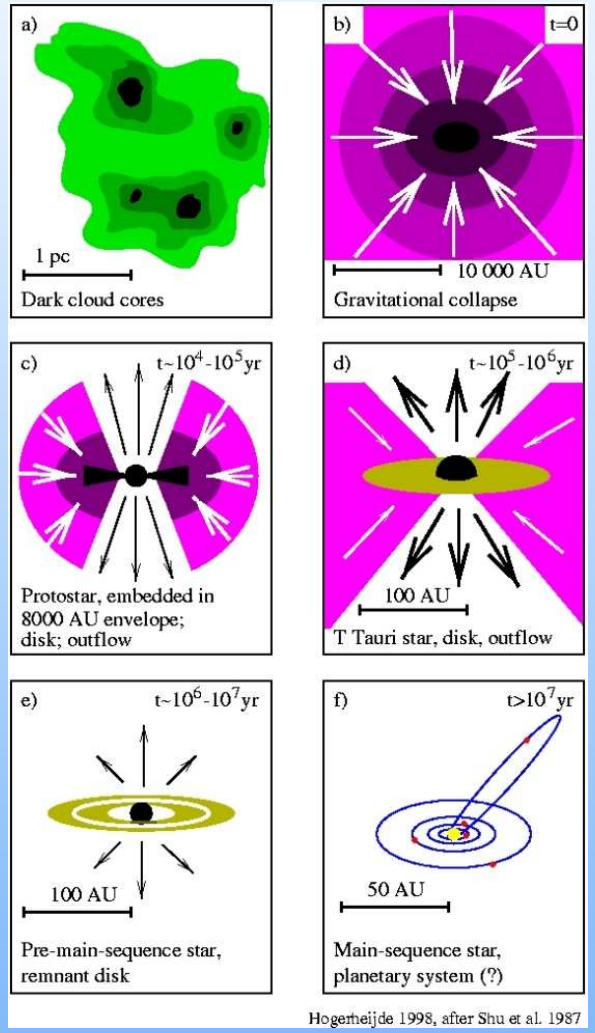
→ Dust emission opt. thick at λ= 1 μm

→Should contain enough gas to form a “proto-Jupiter”
Total disk mass ~ a few 0.01 Msun

→ Most of the disk mass in gas phase - G/D ~ 100 (?)
H_2 not easy to detect (rot. lines in the IR, where the dust is optically thick)

→Age ~ a few Myrs

TTauri stars 0.5 to 2 Msun



Hogerheijde 1998, after Shu et al. 1987

Towards Planet Formation

- Molecular Gas Properties
→CO as « cold »gas tracer

-Morphology/Kinematics
(disks in Keplerian rotation)

- Gas Density / Temperature
(excitation should be known)

- Turbulence ?

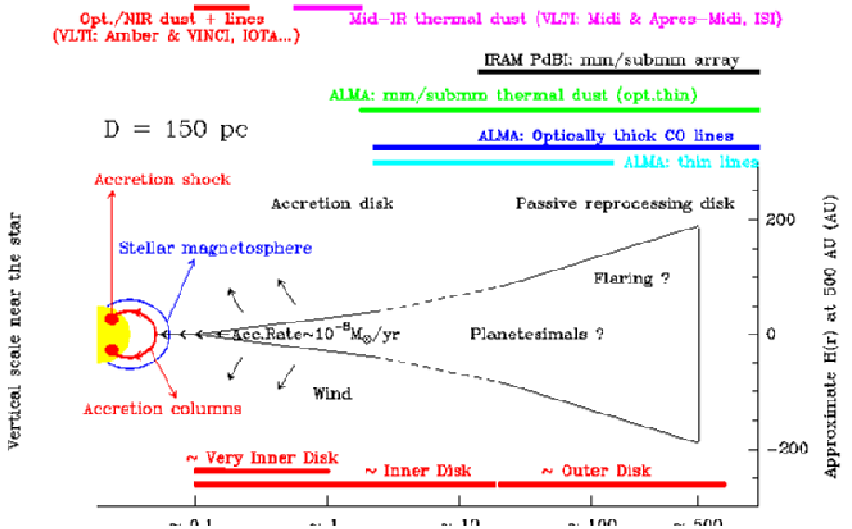
- Ionisation ?

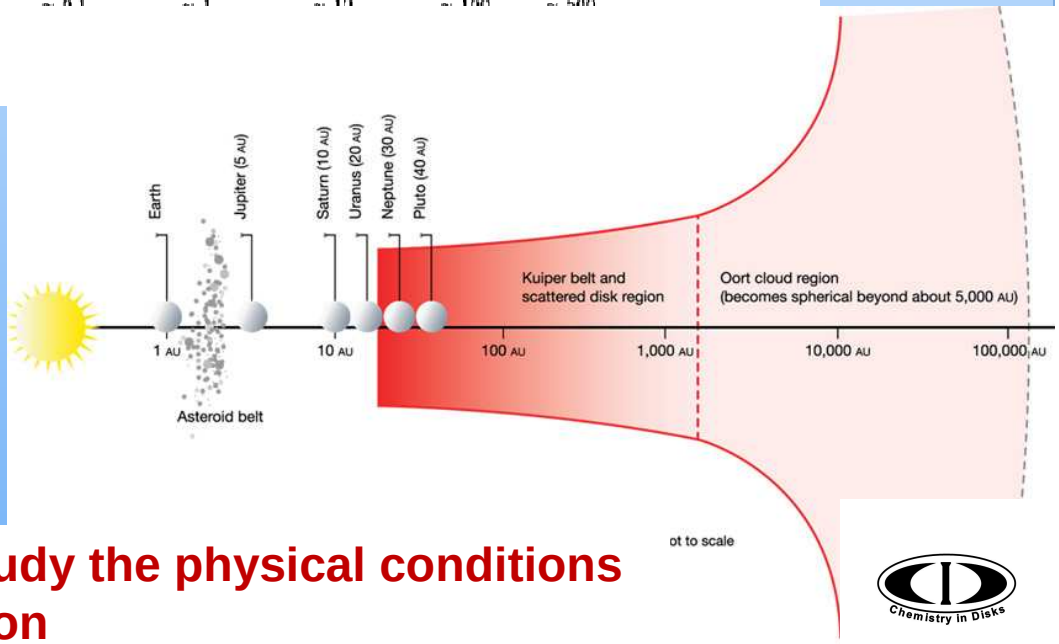
-Deuteration ?

-Molecular Complexity ?

-Gas/Dust ratio ?

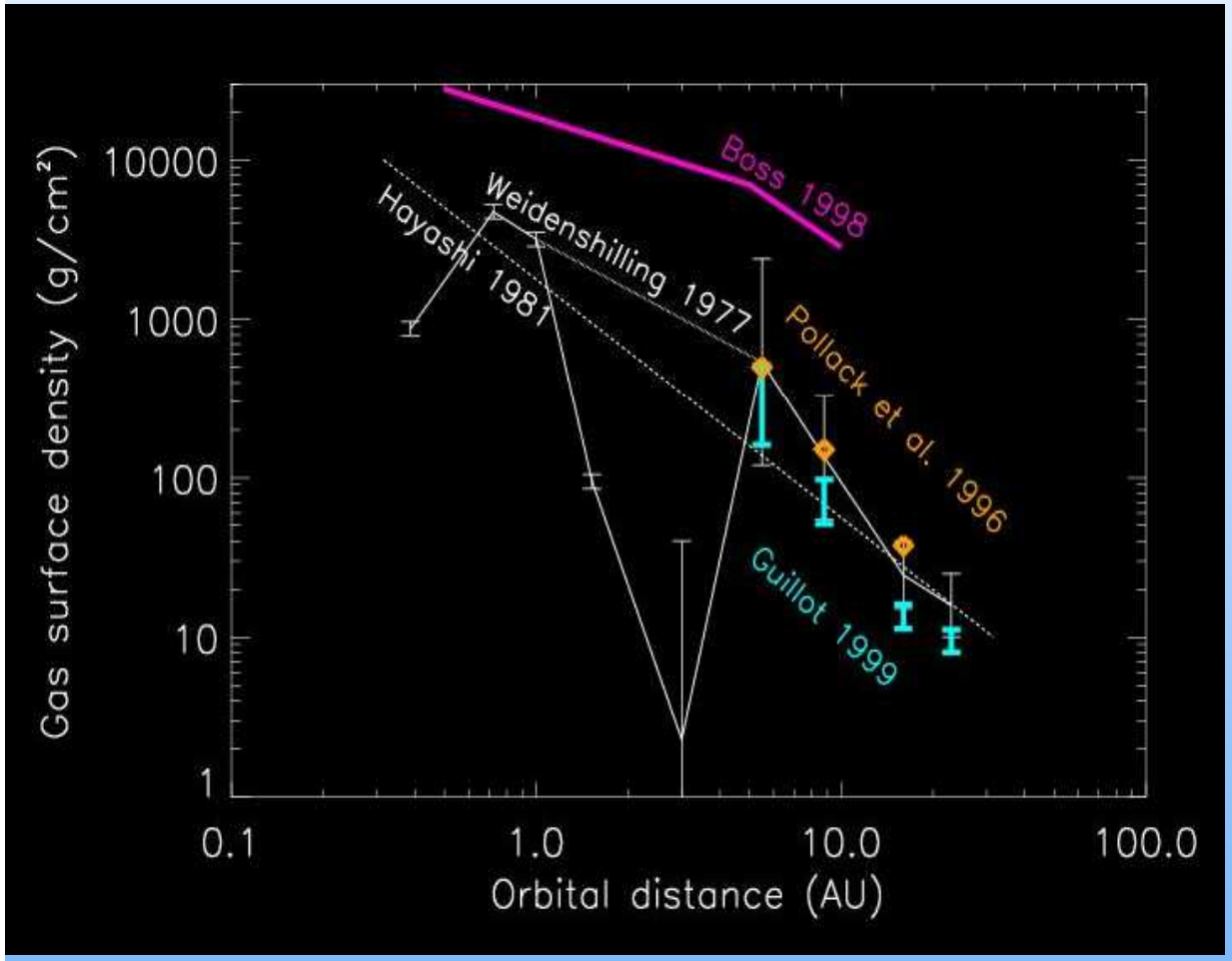
- Impact of Grain properties ?





Chemistry as a tool to study the physical conditions leading to planet formation

Towards Planet Formation



Σ(r): a key parameter!

↓

From classes O to III …

Various Gas Σ(r) (G/D = 100) to form our planetary system (from Guillot 2000)
High-mass and low-mass Proto-solar Nebulae

Outline part-I & part-II

PART I (Anne's talk)

→What can we learn from CO ?
- Tgas
-Gas Surface Density **(Diskfit)**
- Inner Geometry

→Chemistry & Molecular Surveys:
-IRAM 30-m
- CiD project **(Nautilus,KIDA)**
- Interferometric mapping
  (Tgas – ionisation – deuteration)

→Molecular Complexity:
- H_2CO…
- What else ?

→What about dust ?
- Disk structure
- Dust Settling

PART II (Stephane's talk)

→ Dust disks
- Geometry of inner/outer dust disks
- Tdust versus Tgas
- Surface density
- Dust radial and vertical variations
- Alpha prescription & turbulence

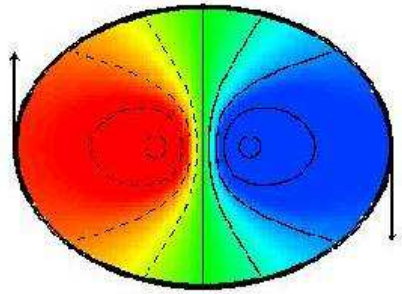
→ Impact on Gas Disks
- Grain growth & UV penetration
- Role Mixing /turbulence
- Impact on chemistry & G/D ?

→ How to measure turbulence ?

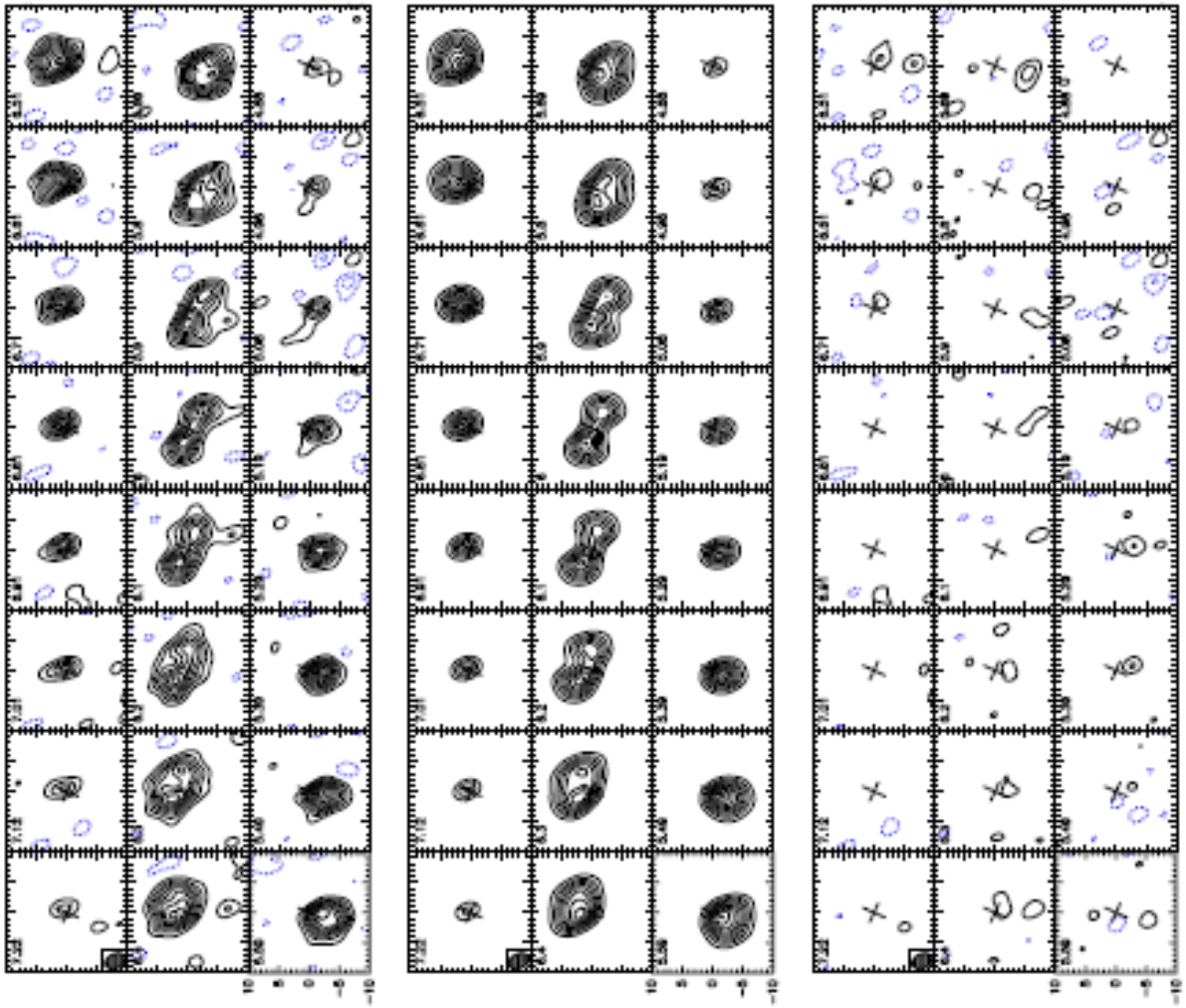
→ Stellar Masses ?

→Challenges for ALMA
- A long list …

CO as gas tracer
power of spectro-imaging



Data Best Model Difference



DM Tau:
0.5 Msol, Age ~ 5 Myrs

CO J=1-0,
pdBI data

Guilloteau & Dutrey 1998

➔ Keplerian Rotation
(stellar mass measurement: see Part II)

➔ Determination of the physical parameters (eg temperature, density, turbulence…) versus r and z.

Dust and Gas Modeling – Diskfit

Dutrey et al., 1994 – Guilloteau et Dutrey 1998 – Piétu et al., 2007

- Power law distributions (or viscous law – see Stephane's talk) :
  - $T(r) = T_0 \cdot (r/r_0)^{-q}$
  - $\Sigma(r) = \Sigma_0 \cdot (r/r_0)^{-p}$
  - $h(r) = h_0 \cdot (R/r_0)^{h}$, - or - $h(r) = \sqrt{(2kT(r)/(\mu m_H))}r/v(r)$
  - $n(r,z) = n(r,0) \cdot \exp[-(z/h)^2]$
  - $\text{Kappa}(\nu) = K_0(\nu/10^{12}\ \text{Hz})^{\beta}$ (Beckwith prescription, Boehler et al 2012...)

$$\Sigma(r) = \Sigma_0 \left(\frac{R_0}{r}\right)^{\gamma} \exp\left(-(r/R_c)^{2-\gamma}\right)$$

- Rotation: $v(r) = v_0 \cdot (r/r_0)^{-v}$
  - Keplerian case : $v = 0.5$, $v_0 = (G.M/r_0)^{1/2}$ (V is measured)
- Line-width: thermal + turbulent
- LTE / non-LTE
- Prédiction of Tb(r) - "ray tracing"

- Minimization in the Fourier plane (not necessary with ALMA)

$$\chi^2 = \Sigma_n \Sigma_i (Re(mod_{i,n} - Re(obs_{i,n}))^2 \times W_i + \Sigma_n \Sigma_i (Im(mod_{i,n} - Im(obs_{i,n}))^2 \times W_i \quad (1)$$

Benchmark of Diskfit (CiD): **Pavlyuchenkov et al.,2007**

Chemistry in Disks

CO line distributions

- **If disks are resolved → Tb(r)**
- **If optically thick thermalized lines**
  → Tb(r) = Tk(r)
- **If optically thin thermalized lines**
  → Tb(r) ~ Σ_{mol}(r)/Tk(r) for J=1-0
- **$\Sigma(H_2) = \Sigma_{mol}$ / X(mol)**
  → X(mol) difficult to constrain

($\Sigma(H_2) = \Sigma_{dust}$ x G/D)

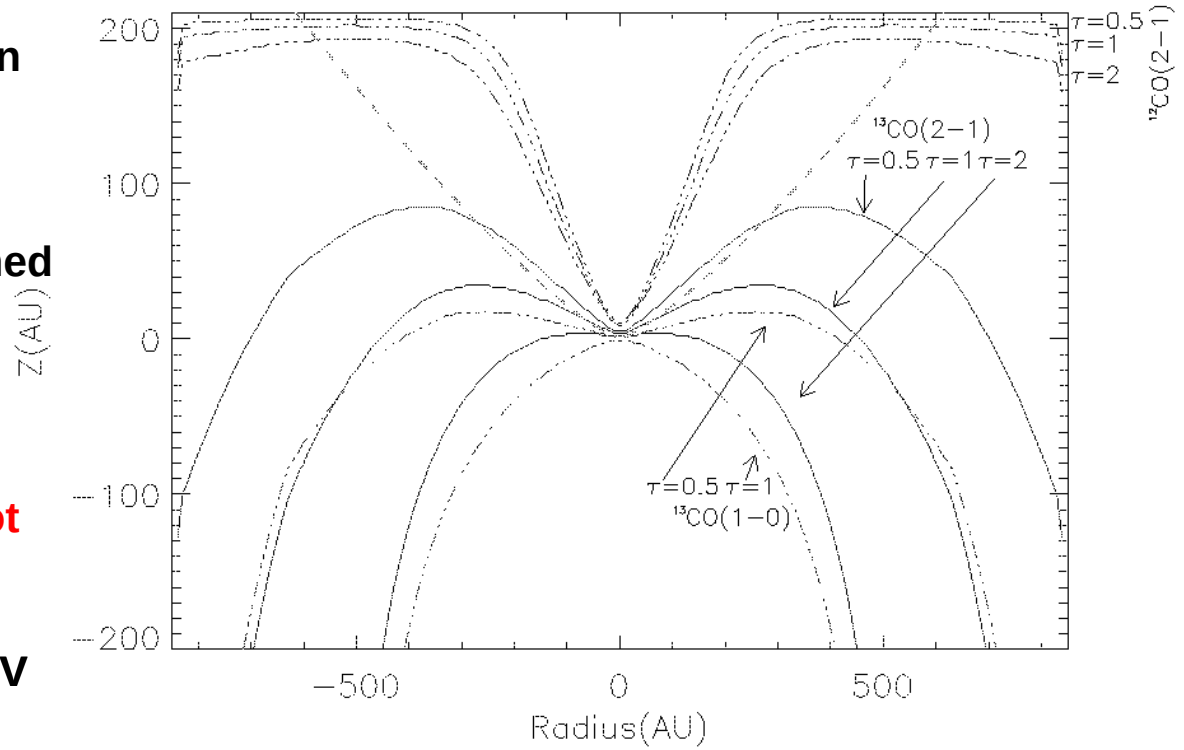
H_2 mass is not yet well constrained even if distribution ~ known

Non-LTE → replace Tk by Tex …

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

Dutrey, Guilloteau, Ho, 2007 - PPV

DM TAU PdBI data Dartois et al 2003



DM Tau: the case study - CO analysis

Increasing opacity

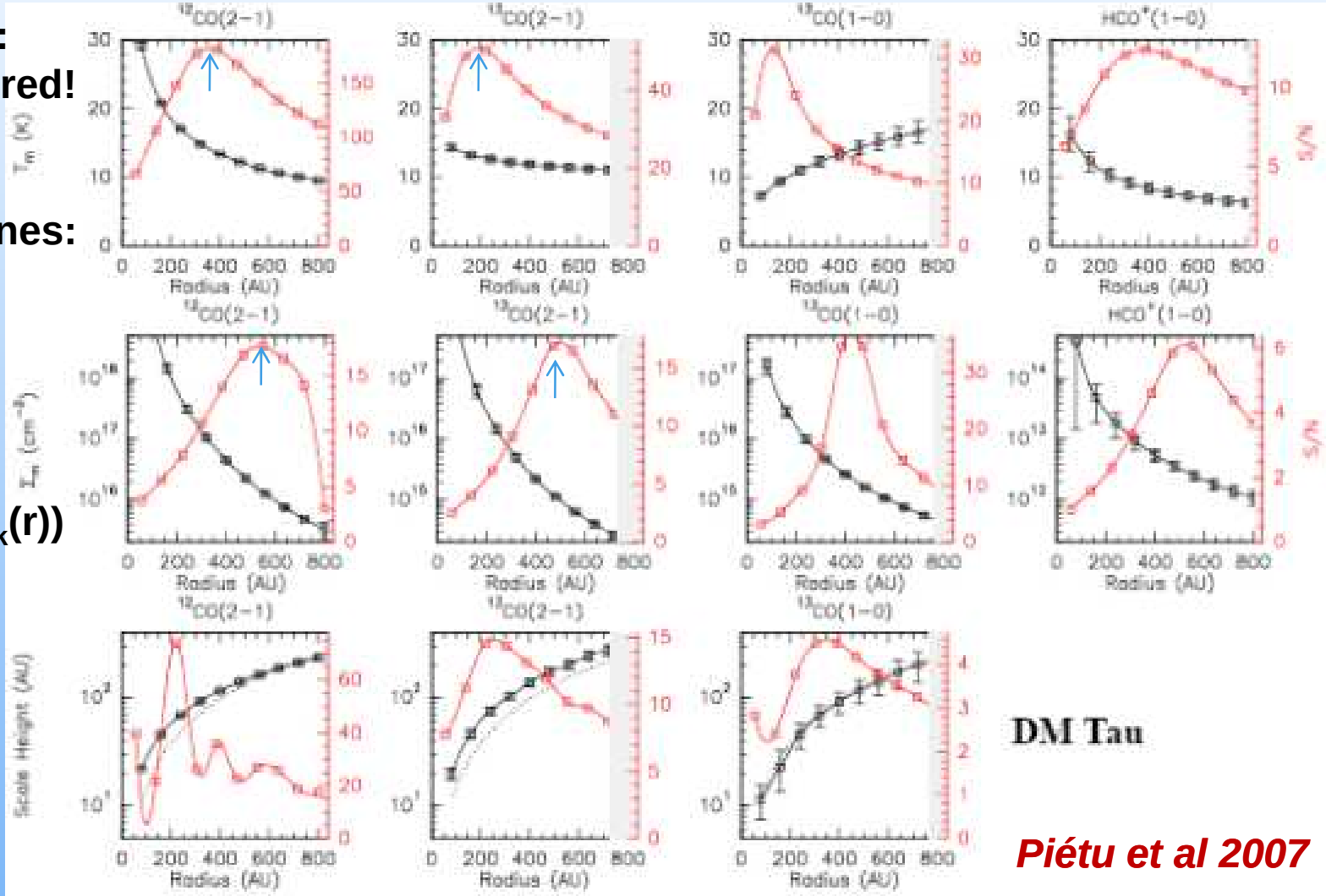
Interferometry:
T_B (r) is measured!

Thermalised lines:

Opt.Thick:
$T_B(r) \propto T_k(r)$

Opt.Thin:
$T_B(r) \propto F(\Sigma(r), T_k(r))$

Subthermal:
$T_k(r) \longrightarrow T_{ex}(r)$



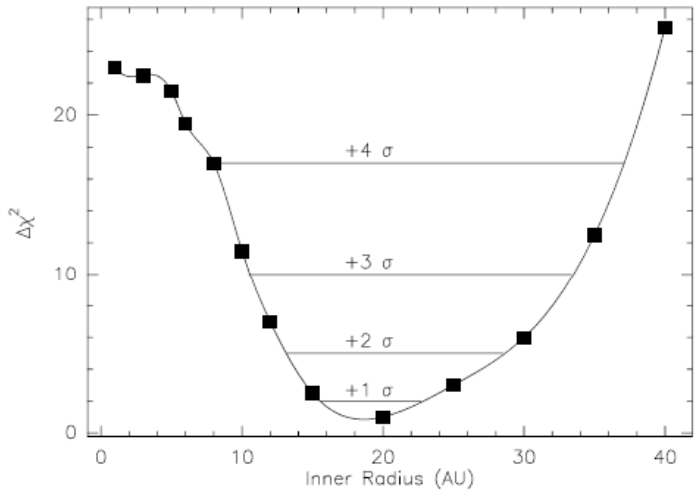
Piétu et al 2007

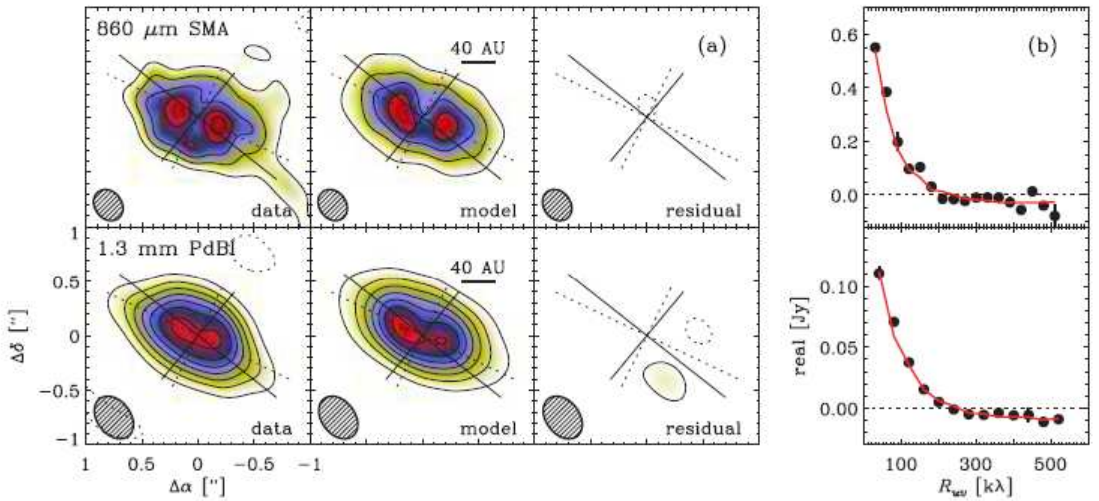
➔ **Compromise angular resol./line opacity: still true with ALMA**

CO: Inner Cavities … GM Aur case

Dutrey et al., 2008 (CID) → **Rin = 20 AU**
Spectroscopic detection

Hughes et al., 2009 **– same dust inner radius**





Analysis 12CO, 13CO, C18O 1-0, 2-1
PdBI data

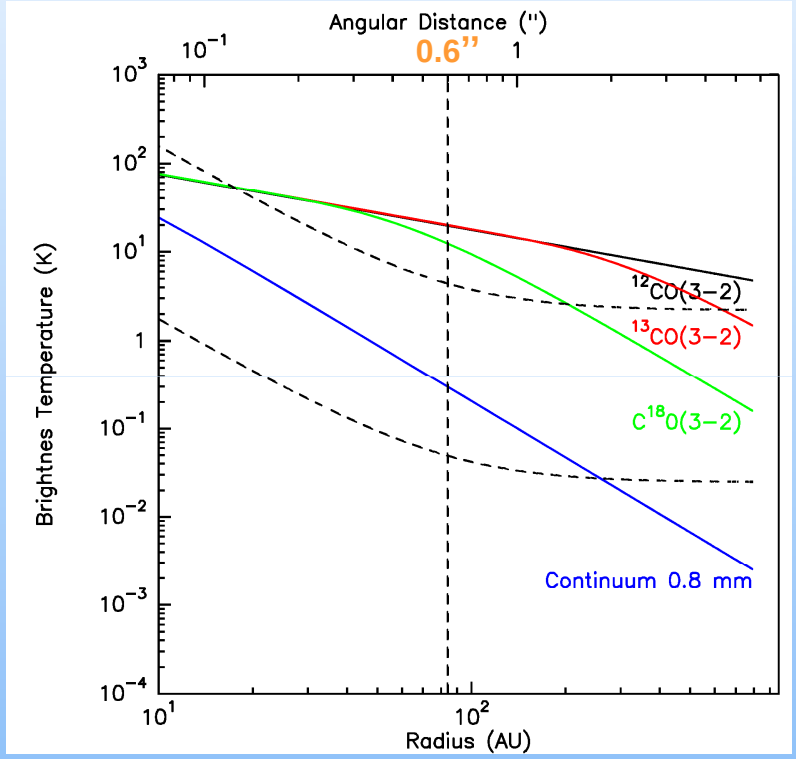
The cavity is «devoid » of dust and gas

CO line wings are tidally truncated « super resolution »
→companion: is this a planet ? (mass ~ 5 – 10 Mjup)

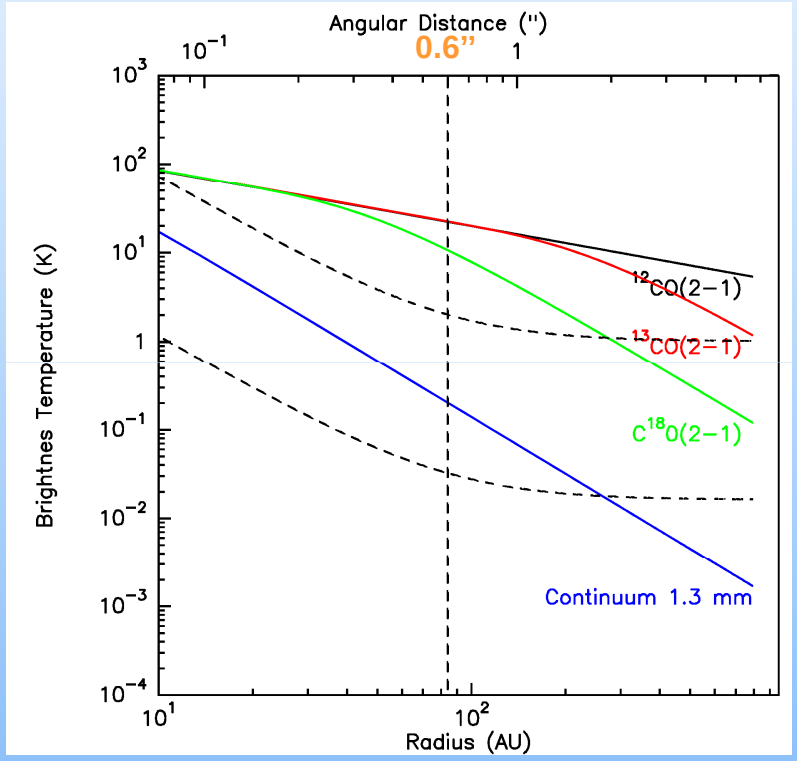
Cavity Radius < Pluto's Orbit

Current arrays are for 50-100 AU resolution

- For SMA J=3-2

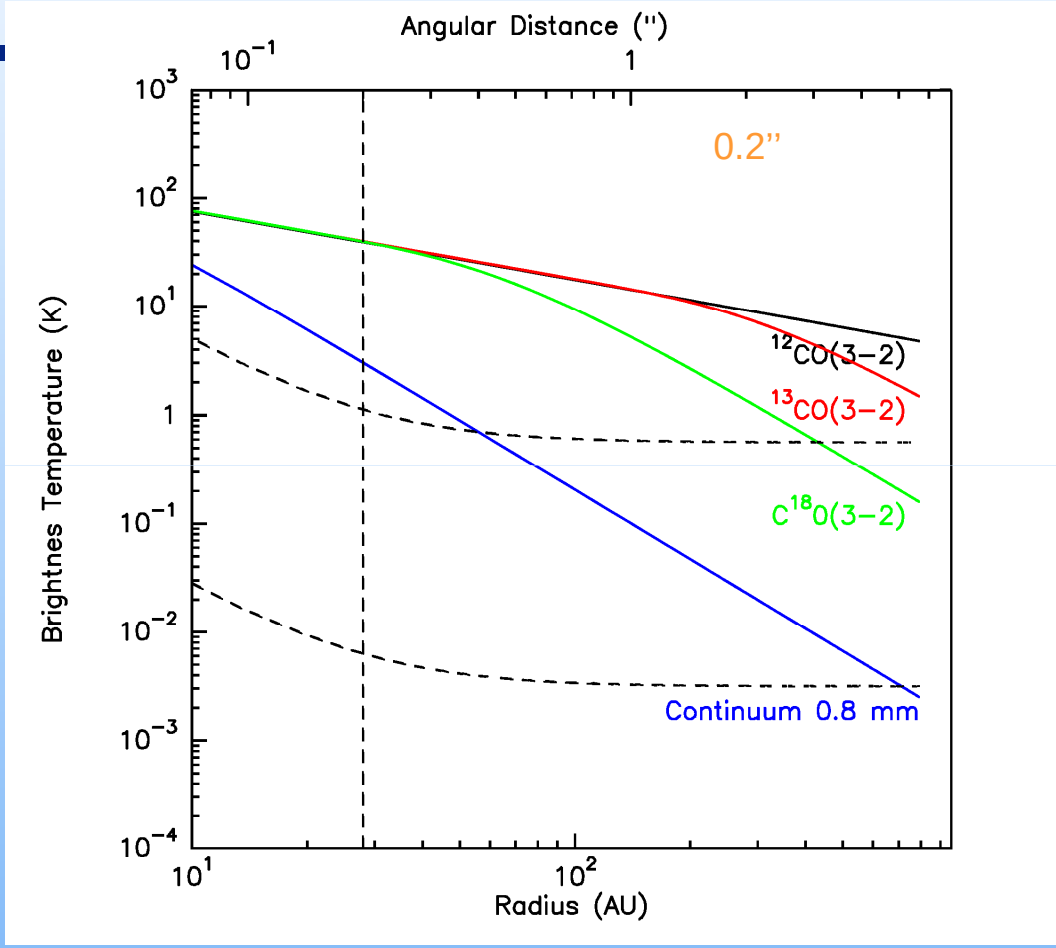


- For PdBI J=2-1



Only outer disks (> 30 AU) studied so far…

ALMA sensitivity for disks



Making predictions is not enough

Inversion mandatory

with a step by step approach to remove at best degeneracies. Otherwise, you don't prove anything…

CO in the ALMA era → Disk Gas Structure

Molecular abundances referenced to CO ?

Chemistry & molecular Surveys

- **Detection**

  CO, ^{13}CO, $C^{18}O$ (many papers)

  HCO^+, CN, HCN, HNC, CS, H_2CO and C_2H (Dutrey et al 1997: DM Tau & GG Tau, Henning et al 2010, **CID**, Chapillon et al 2011, **CID**: MWC480, DM Tau, LkCa15)

  DCO^+ (van Dishoeck et al 2004: TW Hya, Guilloteau et al 2006, DM Tau)

  N_2H^+ (Dutrey et al 2007, DM Tau, LkCa 15, **CID**)

  DCN (Qi et al 2008: TW Hya)

  $H^{13}CO+$ (Qi et al 2008: TW Hya)

  H_2O (Herschel, Bergin et al 2010, Hogerheijde et al 2011)

- **Deep Search**

  H_2D^+ (Chapillon et al 2011 in DM Tau & TW Hya) - no detection
  Sulfur-bearing molecules (Dutrey et al 2011, **CID**) – only CS
  HC_3N, CCS (Chapillon et al 2012 in DM Tau, GO Tau, MWC480 and LkCa15, **CID**)

Chemistry & molec

- **CiD: Chemistry In Disks**

A french-german collaboration
→ started in 2004,
co-leaders: A.Dutrey & Th.Henning

PdBI:
Best angular resolution → 0,35'' ≡ 50 AU @ D=140 pc

ALMA: International collab. in 2010
« cycle 0 » Chapillon et al., CN proposal

→ 7 papers written + several satellites

Let's discuss the CN paradigm , first ...

→ Need for a chemical model including the disk physics

Molecular Disk "Ingredients"

What we need to mimick a disk :

- Surface chemistry (on grains)
(need for a realistic size distribution)
- Neutral-neutral (low and high T)
- Ion-neutral
- 3 body reactions (?)

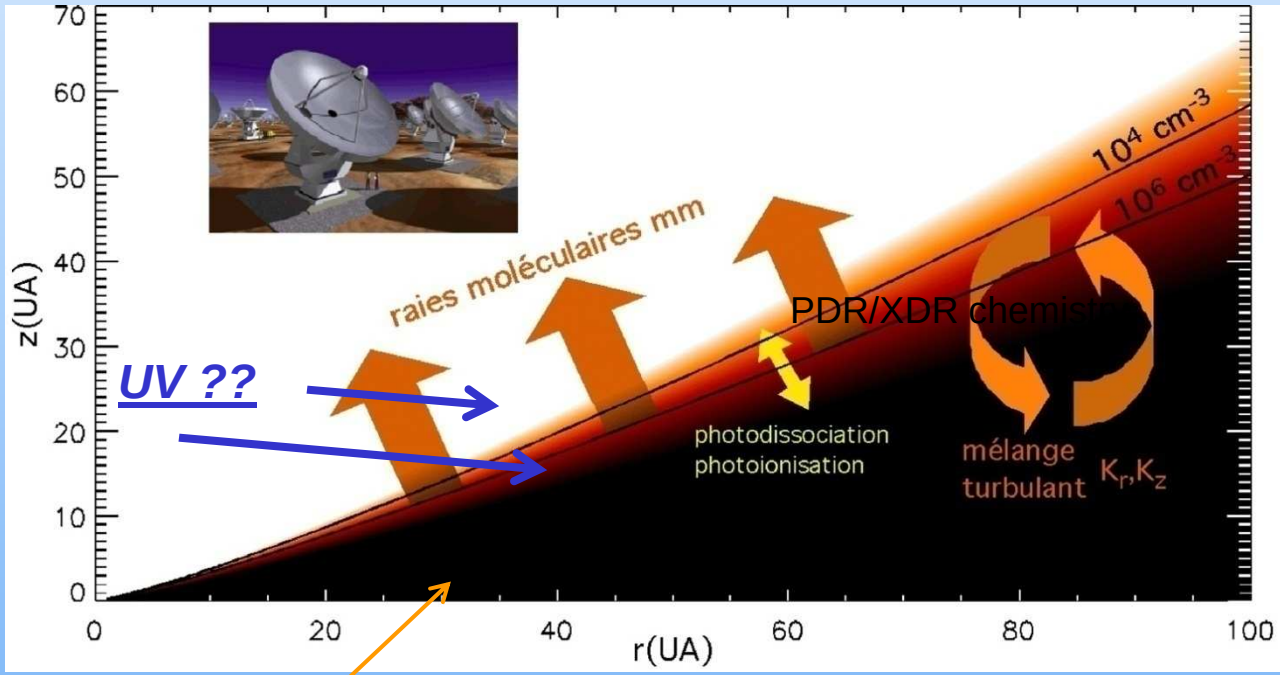
- Photodissociation, photoionization by UV
- Interactions with X rays
- Interactions with cosmic rays

z

-Surface(3-5H): XDR/PDR Chemistry

-Molecular layer (1-3H)

- Mid-plane (0-1H) with a cold dense cloud chemistry



molecules also observed in the mid-plane or at very cold T~7 K !!!

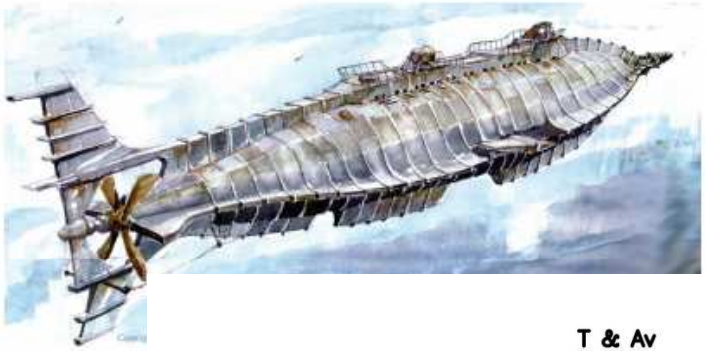
NAUTILUS – developed in LAB / AMOR

Hersant et al., 2009

1D code developed in Bordeaux by F. Hersant and V. Wakelam (originally from the Eric Herbst's team, Ohio State University)

Chemistry:
- full gas-phase network (~4000 reactions, ~400 species): osu_03_2008
- surface chemistry (rate equation approach, ~2000 reactions, ~200 species)
- gas-grain interactions (sticking, thermic and non-thermic desorption, photo-processes)
- UV penetration (1D geometry)

Physics:
- 1D Vertical dimension (Av, T and n)
- z diffusion

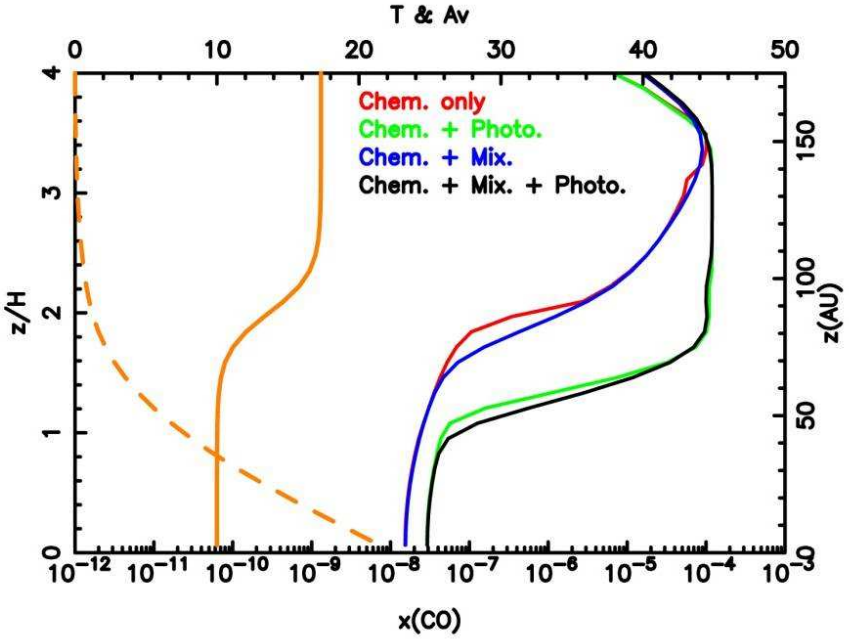


Future:
- improve gas-phase network for high temperature
- include 3-body reactions
- study the importance of grain size

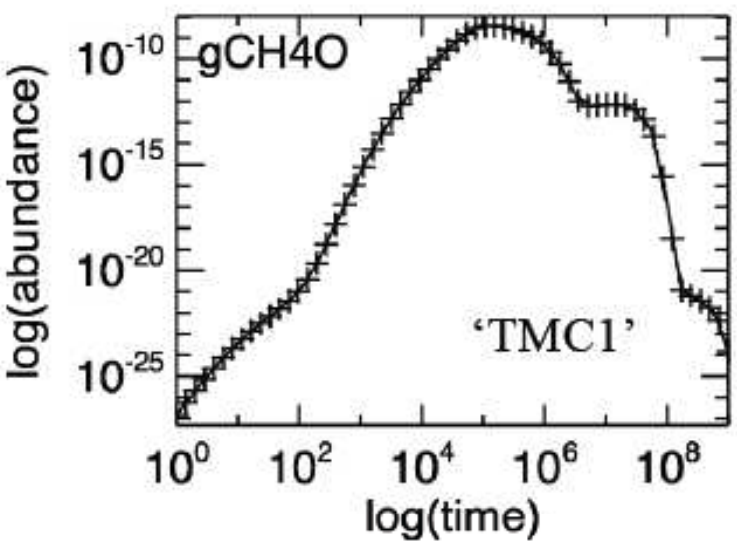
- DM Tau structure (Piétu et al., 2007)
- CO photo-desorption (Oberg et al., 2007)

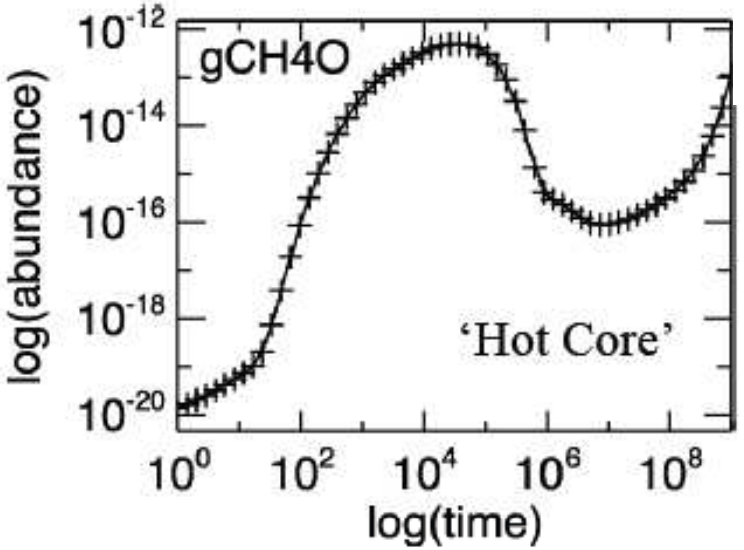
R=300 AU

(team AMOR = Astrochimie Moleculaire et ORigines des systemes planetaires)



Chemistry Benchmarks

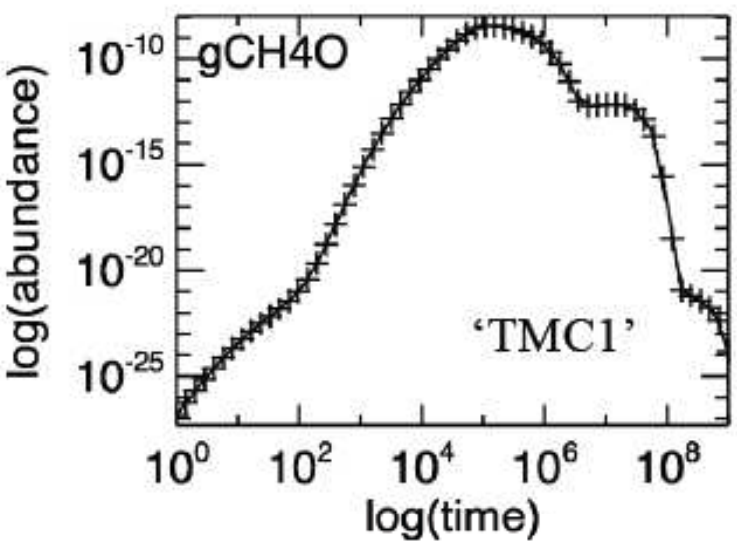


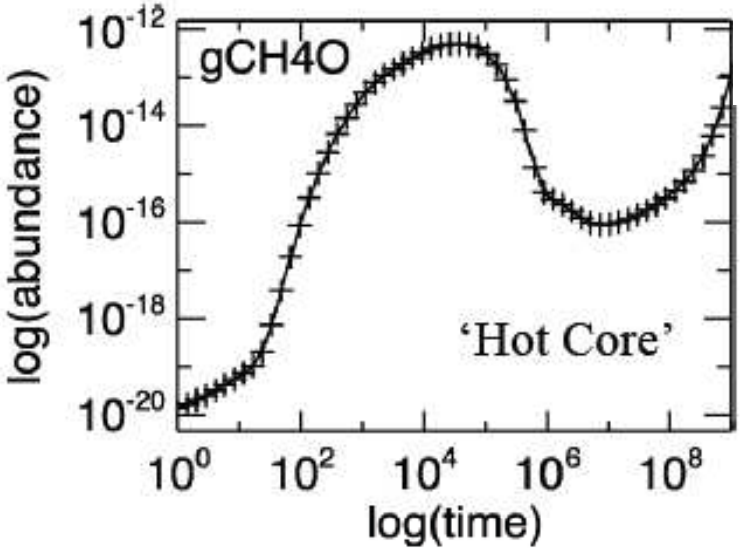


- Bordeaux versus Heidelberg chemical models
- osu_2008_03 ratefile
- Accretion / Desorption
- Surface Chemistry: Surface reactions on 0.1μm olivine grains
- 'TMC1', 'Hot core', 'DM Tau disk'

Semenov, Hersant, Wakelam, Dutrey et al 2010

Chemistry Benchmarks





ALMA next steps: channel per channel molecular maps

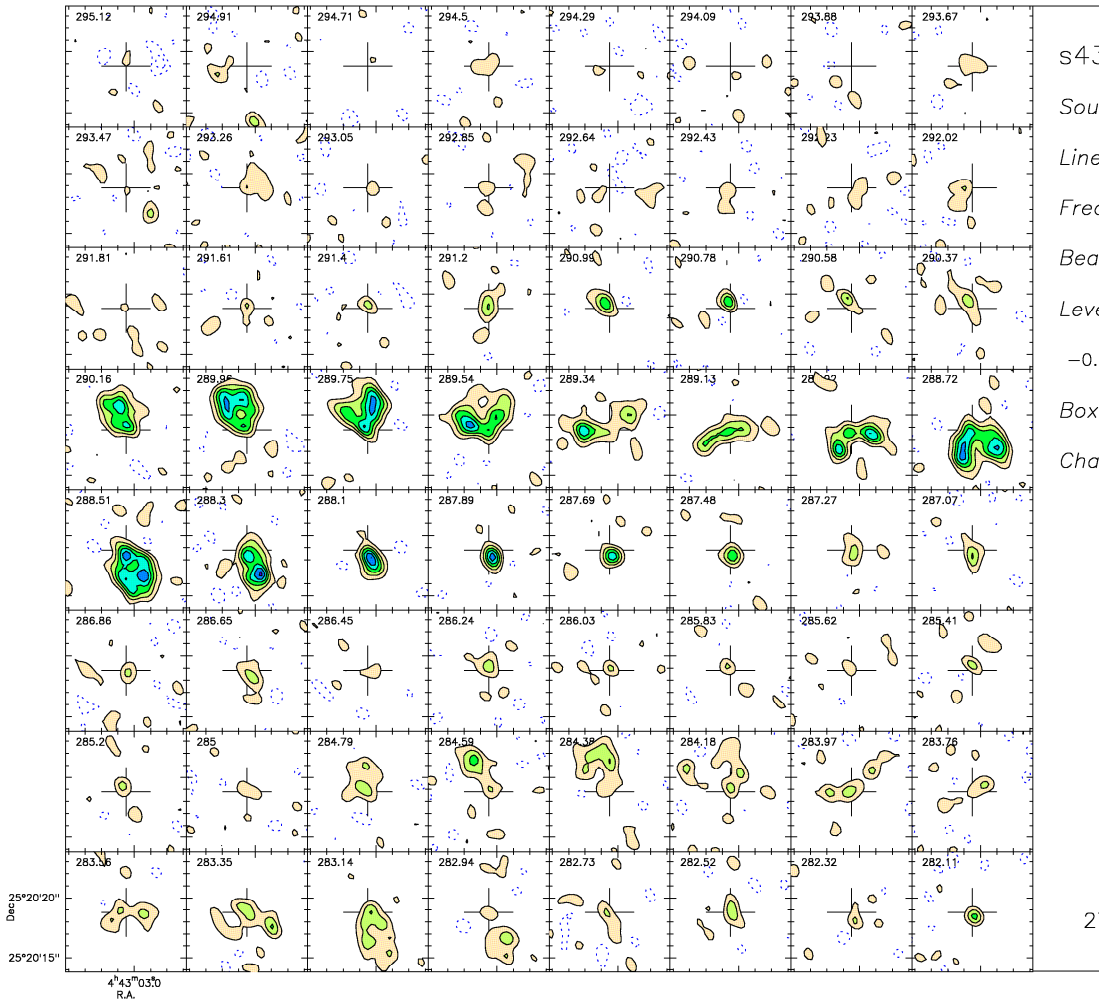
On going …

- Accretion / Desorption
- Surface Chemistry: Surface reactions on 0.1μm olivine grains
- 'TMC1', 'Hot core', 'DM Tau disk'

Semenov, Hersant, Wakelam, Dutrey et al 2010

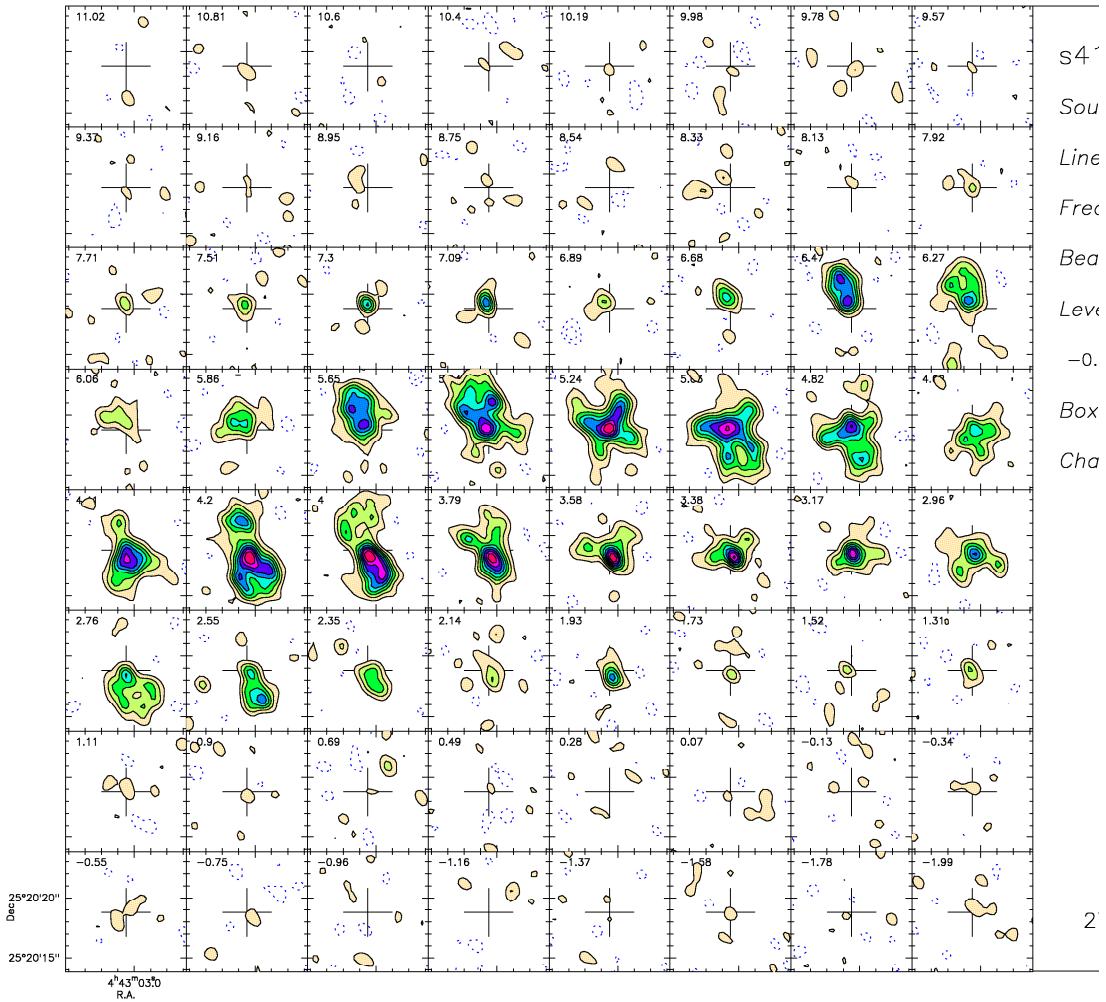
CN at PdBI

PdBI CN J=2-1 data in GO Tau (DM Tau -like)
One hyperfine component - dv = 0.2 km/s, res~ 1”



CN at PdBI

PdBI CN J=2-1 data in GO Tau (DM Tau -like)
Main hyperfine component dv = 0.2 km/s , res~ 1”



Gas temperature around mid-plane: towards a (partly) cold molecular layer ?

- **CO/^{13}CO PdBI data:** ***Dartois et al 2003***

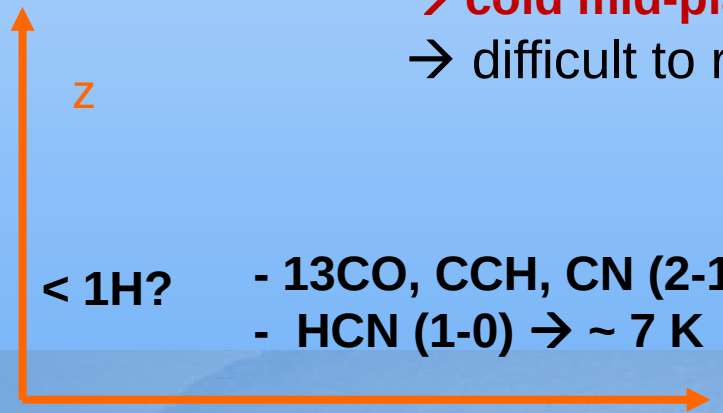
→ the outer disk is cold, r ~ 100 AU, Tk~ 10 K, confirmed by ***Pietu et al 2007***

- Vertical/Radial mixing: ***Semenov et al., 2006, Aikawa 2007, Hersant 2009***

- **CCH (CID):** ***Henning et al 2010*** → ~ 8-10K at 100 AU
- **CN/HCN (CID):** ***Chapillon et al., 2011*** PdBI data

HAe: MWC 480 – warm (~ 30 K)
TTauri: LkCa15 (as cold as DM Tau)

→ cold mid-plane or cold molecules
→ difficult to reconcile with models



< 1H?

- 13CO, CCH, CN (2-1) → ~ 9 K
- HCN (1-0) → ~ 7 K

Gas temperature around mid-plane: towards a cold molecular layer ?

Chapillon et al.,: CN and HCN in proto-planetary disks

Chapillon et al 2011

Table 2. Results of analysis

Source	Molecule	Σ 10^{12} cm^{-2}	p	R_{out} (AU)	δV (km s^{-1})	T_k (K)	q	R_{int} (AU)	α_d
MWC 480	HCN 1-0	1.1 ± 0.4	2.4 ± 0.4	[550]	0.3 ± 0.2	[30]	[0]		0.0 ± 0.7
	CN 2-1 (high)	11 ± 1	2.1 ± 0.1	540 ± 40	0.25 ± 0.04	33 ± 6	[0]		0.0 ± 0.3
	CN 2-1 (low)	11 ± 1.2	2.1 ± 0.15	550 ± 70	0.26 ± 0.07	33 ± 6	[0]		–
	CN 2-1 (all)	10.4 ± 0.9	2.1 ± 0.1	545 ± 35	0.25 ± 0.04	30 ± 4	[0]		–
LkCa 15	HCN 1-0	10.6 ± 1.5	1.1 ± 0.2	600 ± 40	0.20 ± 0.03	7.0 ± 0.6	0.55 ± 0.25	[30]	0.0 ± 0.8
	CN 2-1 (high)	38 ± 4	2.3 ± 0.2	570 ± 20	0.18 ± 0.02	10.8 ± 0.7	0.20 ± 0.07	[30]	0.15 ± 0.17
	CN 2-1 (low)	115 ± 18	0.2 ± 0.2	690 ± 20	0.26 ± 0.03	6.6 ± 0.3	0.80 ± 0.07	[30]	–
	CN 2-1 (all)	58 ± 5	0.8 ± 0.1	630 ± 35	0.18 ± 0.01	8.8 ± 0.3	0.95 ± 0.05	[30]	–
DM Tau	HCN 1-0	6.5 ± 0.9	1.0 ± 0.3	660 ± 20	0.18 ± 0.01	6.0 ± 0.4	0.00 ± 0.12		0.0 ± 0.5
	CN 2-1 (high)	26 ± 4	2.1 ± 0.15	650 ± 20	0.16 ± 0.01	8.6 ± 0.5	0.05 ± 0.05		0.0 ± 0.3
	CN 2-1 (low)	46 ± 9	0.7 ± 0.15	550 ± 25	0.20 ± 0.01	6.5 ± 0.5	0.50 ± 0.08		0.0 ± 0.3
	CN 2-1 (all)	35 ± 9	0.6 ± 0.06	620 ± 15	0.17 ± 0.01	7.5 ± 0.3	0.60 ± 0.05		0.0 ± 0.3

α_d is the depletion scale height (see text). All values are referred to 300 AU.

- **Should be thermalised (n ~ a few 10^6 cm^{-3})**
- **T = 8 K for DM Tau & LkCa 15, 30 K for MWC 480**
- **But CN is expected mostly close to the warm PDR**

PDR: HCN + hv → CN + H (high amount of HCN)

N + CH → CN + H (upper in the disk)
N + C2 → CN + C

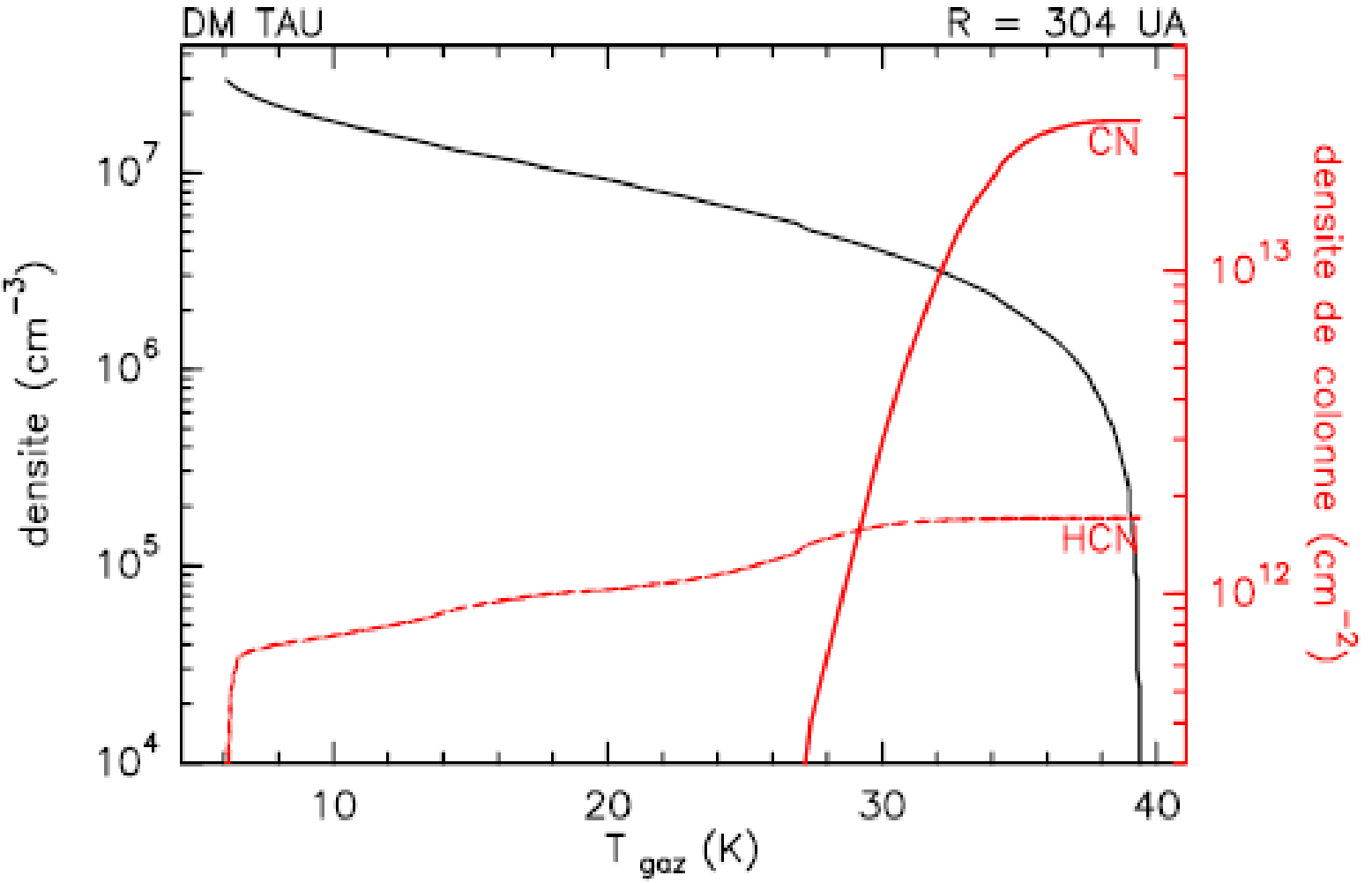
Gas temperature around mid-plane: towards a (partly) cold molecular layer ?

- **CO/^{13}C**

→ the oute

- Vertical

- **CCH (**
- **CN/HC**



z

r

< 1H? - 13CO, CCH, CN (2-1) → ~ 9 K

- HCN (1-0) → ~ 7 K

→ cold mid-plane or cold molecules

→ difficult to reconcile with models

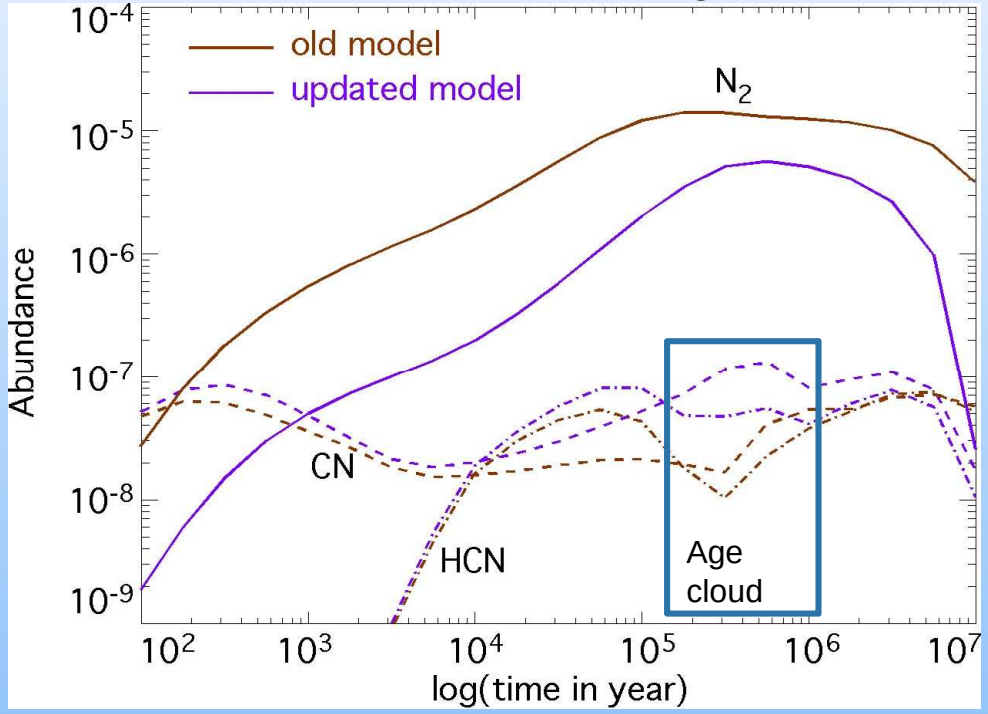
Revisiting the gas-phase kinetic of Nitrogen-bearing species

- New experiments for the measurements of N + NO (Bergeat et al. 2009), N + OH (Daranlot et al. 2011) and N + CN reactions (Daranlot et al. submitted)

-Update of gas-phase reactions involving N-bearing species from KIDA experts (Wakelam et al. in prep)

-Less N_2, more NH_3 on grains

Simulations of the chemical evolution of a cold dense cloud using Nautilus



http://kida.obs.u-bordeaux1.fr
Administrator : V. Wakelam (kida@obs.u-bordeaux1.fr)
→ Subscribe to the newsletter

Nautilus: grains of 0.1µm, No UV, Tk = 10K, $n(H_2) = 10^4$ cm^{-3}

How to trace the disk mid-plane ?

→ Wait for CN 3-2 from ALMA …

•H_2D^+ formed in gas phase only at low temperature, easily destroyed by CO, N_2

$H_3^+ + HD \rightarrow H_2D^+ + H_2$ // $H_2D^+ + CO \rightarrow DCO^+ + H_2$ - $H_2D^+ + CO \rightarrow HCO^+ + HD$

→should be abundant in the cold depleted mid-plane

• No detection , so far …

Chapillon et al 2011

→JCMT (10hrs) - DM Tau
→ APEX (4hrs) - TW Hya O - H_2D^+ ($1_{1,1}$-$1_{1,0}$) at 372 GHz

• 3x more sensitive than previous data → H_2D^+ still not detected !

• Analysis: chemical model from Parise et al 2011

Mid-plane: is H_2D^+ a good tracer ?

Chapillon et al 2011 - JCMT/ APEX data on DM Tau & TW Hya

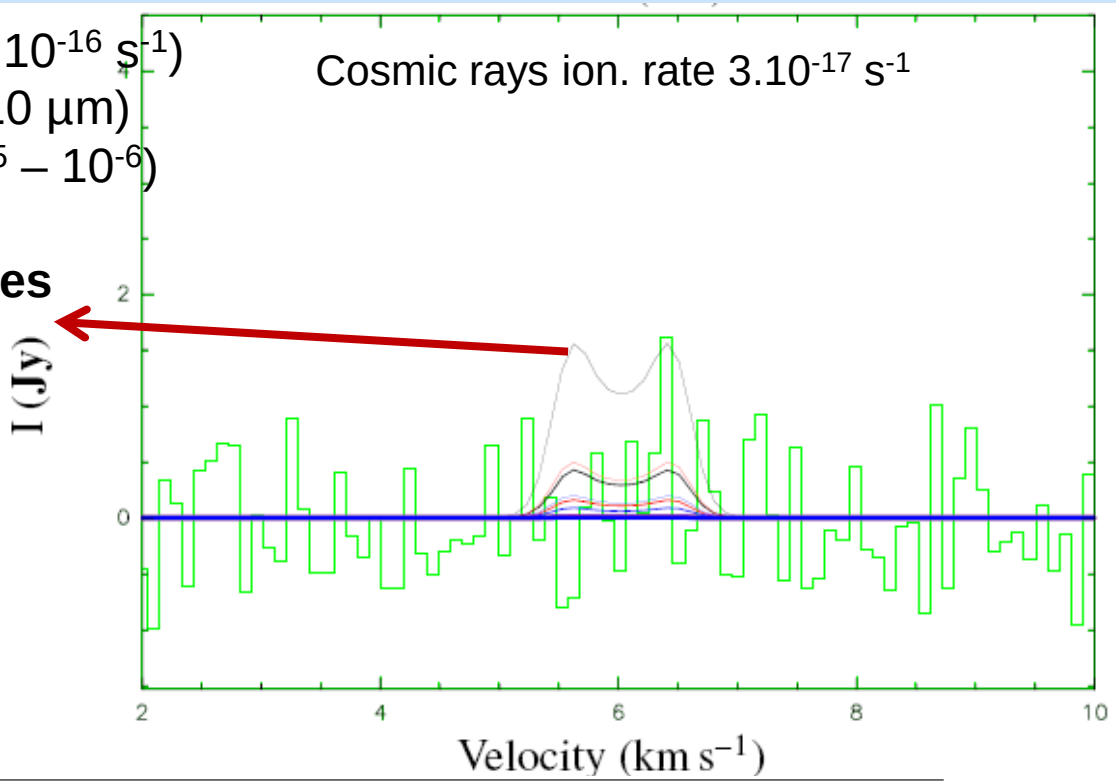
O - H_2D^+ ($1_{1,1}$-$1_{1,0}$) 372 GHz

→ **Check several disk structures (Σ, Tk, R_{out})**

- No UV (mid-plane)
- Several CR rates (10^{-17} – 3.10^{-17} – 10^{-16} s^{-1})
- Several grain sizes (a = 0.1 – 1 – 10 µm)
- Several CO abundance (10^{-4} – 10^{-5} – 10^{-6})

• **Results on DM Tau: only excludes**
- X(CO) = 10^{-6} and a = 0.1 µm
- If X(CO) = 10^{-5} , all grain sizes ok

ALMA detection may be not so easy



	H_2 density								Temperature			
	Model 1				Model 2				Case L		Case H	
	$\Sigma_0^{H_2}$ (cm^{-2})	p	R_0 (AU)	R_{out} (AU)	$\Sigma_0^{H_2}$ (cm^{-2})	p	R_0 (AU)	R_c (AU)	T_{100} (K)	q	T_{100} (K)	q
DM Tau	8.4×10^{23}	0.85	45	700	9.6×10^{23}	0.45	45	180	15	0.4	30	0.63
TW Hya	4.3×10^{23}	1.0	45	200	3.3×10^{23}	0.7	45	30	30	0.5	40	0.2

Ionisation in Disks

- N_2H^+ has been observed at PdBI CID , ***Dutrey et al., 2007***

5σ detection LkCa15 and DM Tau, upper limit on MWC480

- **Main results:**

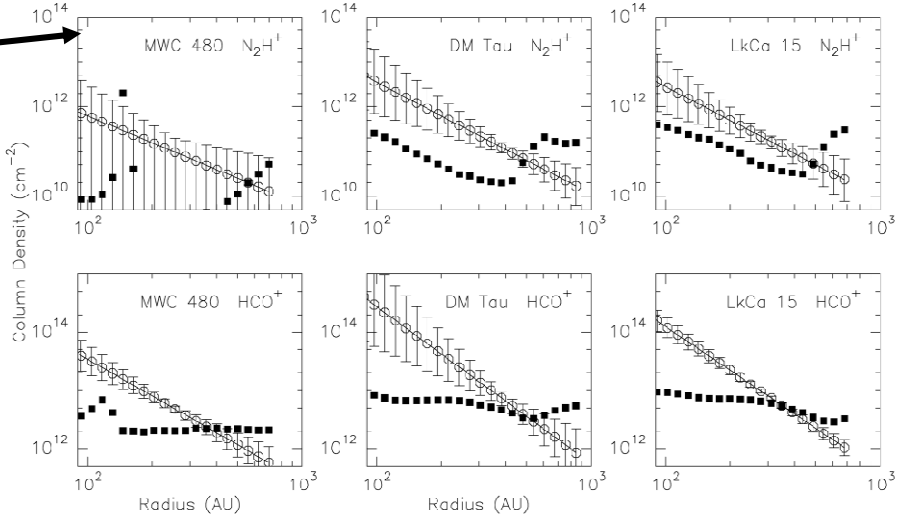
HCO^+ remains the most abundant molecular ion in disk

$[N_2H^+]/[HCO^+]$ ~ 0.02- 0.05 (similar to dense cores)

- **DCO^+/HCO^+** in TW Hya
  Qi et al., 2008

[e] = n(e)/n(H_2) ~ 10^{-7} in the disk layer where the molecules are present (following Caselli 2002)

HCO^+ and N_2H^+



~Good agreement, but the slope p is not yet properly reproduced !

$N_2H^+ + CO \rightarrow HCO^+ + N_2$

- **Less HCO^+ in Herbig Ae Disks ?**

-AB Auriga: ***Schreyer et al 2009 (CID)***
-MWC480: ***Dutrey et al 2007 (CID)***

Towards more complex molecules ?
Sulfur-bearing molecules in TTauri Disks

→ So far, molecules observed in disks are the most abundant seen in cold clouds

Dutrey et al 2011 (CID) – IRAM 30-m - DM Tau, LkCa15 & MWC480

•**Deep search** for Sulfur-bearing molecules: **CS, SO, H_2S**

•CS detected, significant upper limits on SO, H_2S (~7x better than in Dutrey et al 2000)

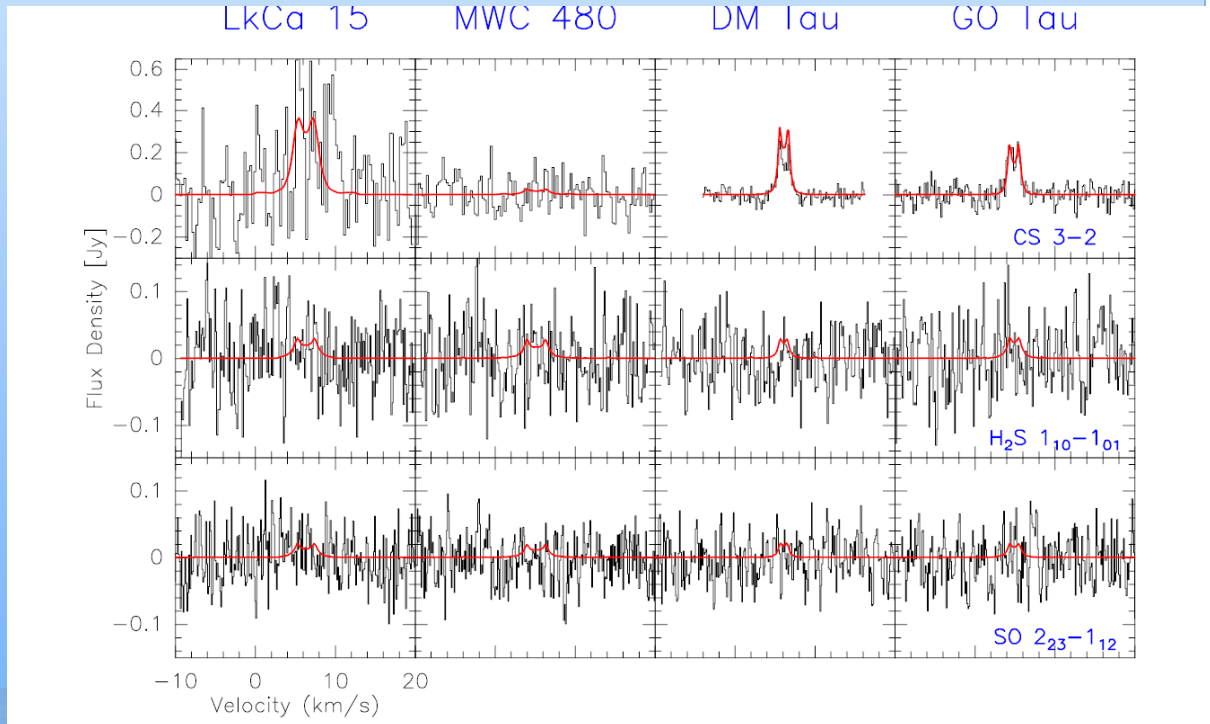


Fig. 1. Observations of SO $2_{23} - 1_{12}$, H_2S $1_{10} - 1_{01}$ and CS 3-2 in the four disks. For CS J=3-2, the best models have been superimposed for al sources. For SO and H_2S, the models always correspond to the 3σ upper limits.

Towards more complex molecules ?
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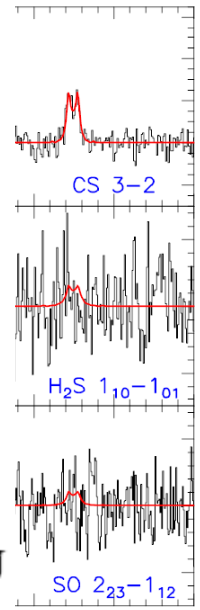
Table 3. Sulfur-bearing Molecules: detections and 3σ upper limits.

Sources	Σ_{300} (cm^{-2}) SO	H_2S	CS
DM Tau	$\leq 7.5 \cdot 10^{11}$	$\leq 1.4 \cdot 10^{11}$	$3.5 \pm 0.1 \cdot 10^{12}$
LkCa15	$\leq 1.9 \cdot 10^{12}$	$\leq 3.6 \cdot 10^{11}$	$8.7 \pm 1.6 \cdot 10^{12}$
MWC480	$\leq 2.5 \cdot 10^{12}$	$\leq 4.1 \cdot 10^{11}$	$\leq 8.4 \cdot 10^{11}$
GO Tau	$\leq 8.9 \cdot 10^{11}$	$\leq 1.8 \cdot 10^{11}$	$2.0 \pm 0.16 \cdot 10^{12}$

Notes. Sulfur-bearing molecules surface densities (cm^{-2}) at 300 AU (modeled as $\Sigma(r) = \Sigma_{300}(r/300\mathrm{AU})^{-1.5}$). The surface densities are derived from the 30-m data (except for CS 3-2 in DM Tau) and the model DISKFIT. See text for details.

GO Tau



have been superimposed for al

Towards more complex molecules ?
Sulfur-bearing molecules in TTauri Disks

Dutrey et al 2011 (CID)

•**Results:** (outer) disk chemical modeling (Nautilus, Hersant et al 2009)
- Grains 0.1µm
- full network, inc. surface chemistry

→ **H_2S modeling incompatible with upper limit …**
locked onto grains, form other species → no desorption

Experiments from Garozzo et al 2010: sulfur mostly in the form of a rich residuum (polymers, aggregates).

→ **Need for a proper chemistry at grain surface**
Large temperature gradients (10-100 K) on small spatial scales (H ~ 20 AU at r= 20-50 AU)

→ **Importance of the physical structure (current observations not accurate enough), inc. UV field**

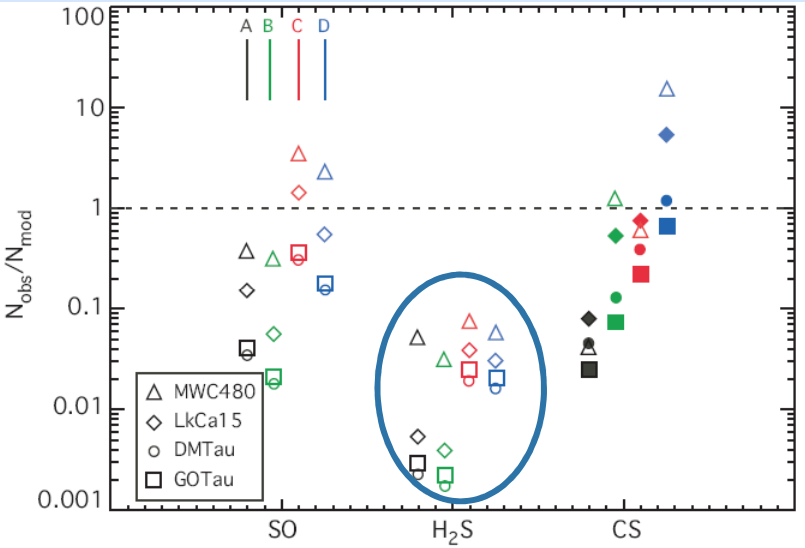


Fig. 3. Ratio between the column densities of SO, CS and H_2S observed in the four protoplanetary disks at 300 AU from the central star and the values computed with NAUTILUS. For SO and H_2S, they corresponds to upper limits. The four models (A, B, C and D) correspond to the elemental abundances given in Table 4 and to the prameters given in Table 5.

→ **Weakness (surface chemistry) of current chemical models!**

→ **Must be solved for ALMA data interpretation!**

What Else ?
CCS & HC_3N in Disks

Chapillon et al 2012 (CID)

– IRAM 30-m – (EMIR+FTS)

DM Tau, LkCa15, MWC480 & GO Tau

→So far, molecules observed in disks are the most abundant seen in cold clouds

•**Deep search** for heavier molecules in disk
• CCS, HC_3N …

•**Results:** see future Edwige's talk …

- Our 3σ upper limits on CCS are in very good agreement with the best modeling of sulfur-bearing molecules from Dutrey et al 2011 and rejects the other models.

Molecular Disk "Ingredients"

What we need to mimick a **gas** disk : **We need Grains .**

- **Disk temperature governed by grains**: dust absorbs the UV & visible light
In most of the disk (< 3-4 Hgas): Tgas = Tdust, by collisions

- **Surface chemistry (on grains)**, need for a realistic (vertical, radial) size distribution

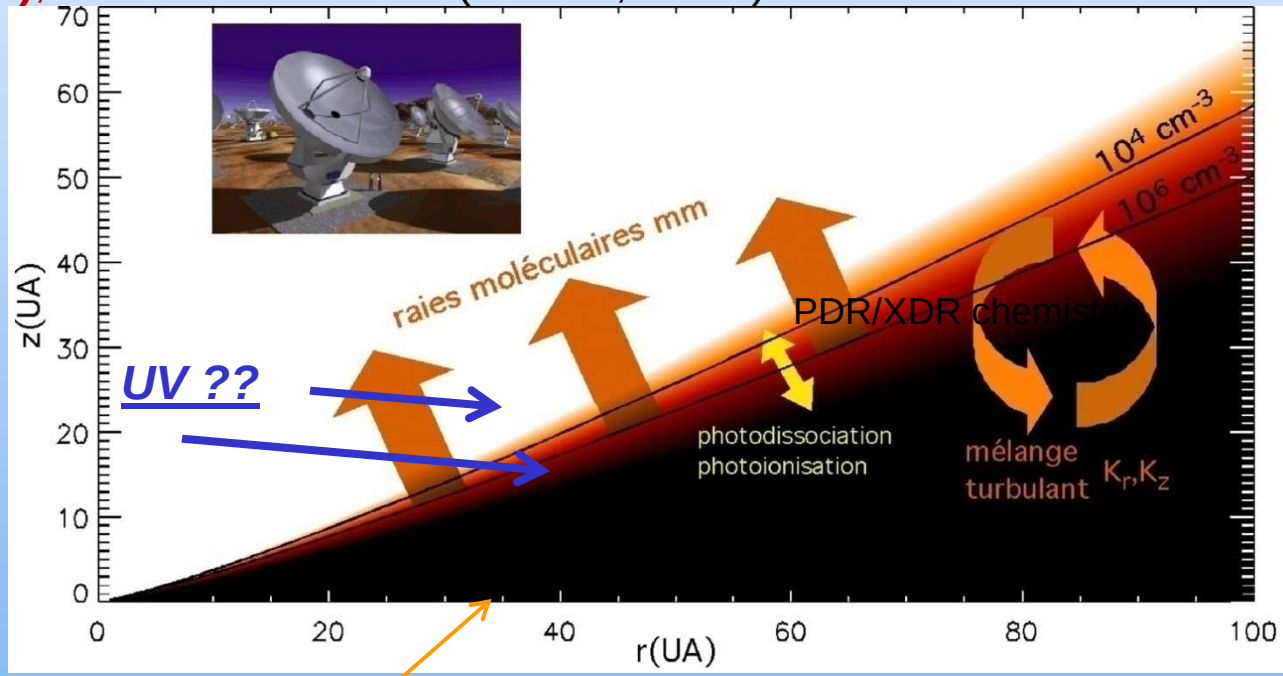
Impact on
G/D(z), UV penetration…

z

-Surface(3-5H): XDR/PDR Chemistry

-Molecular layer (1-3H)

- Mid-plane (0-1H) with a cold -dense cloud chemistry
→ **Most of the dust << 1H**



Dust settling & grain growth – a major ingredient of disk physics and chemistry
First steps: ALMA predictions and inversion of dust vertical structure…

Dust Settling seen by ALMA

Boehler PhD thesis, dec. 2011, Boehler et al 2012

Settling controled by the product:

'angular velocity Ω' x 'dust stopping time τ'

($\tau = (\rho_d a)/(\rho C_s)$)

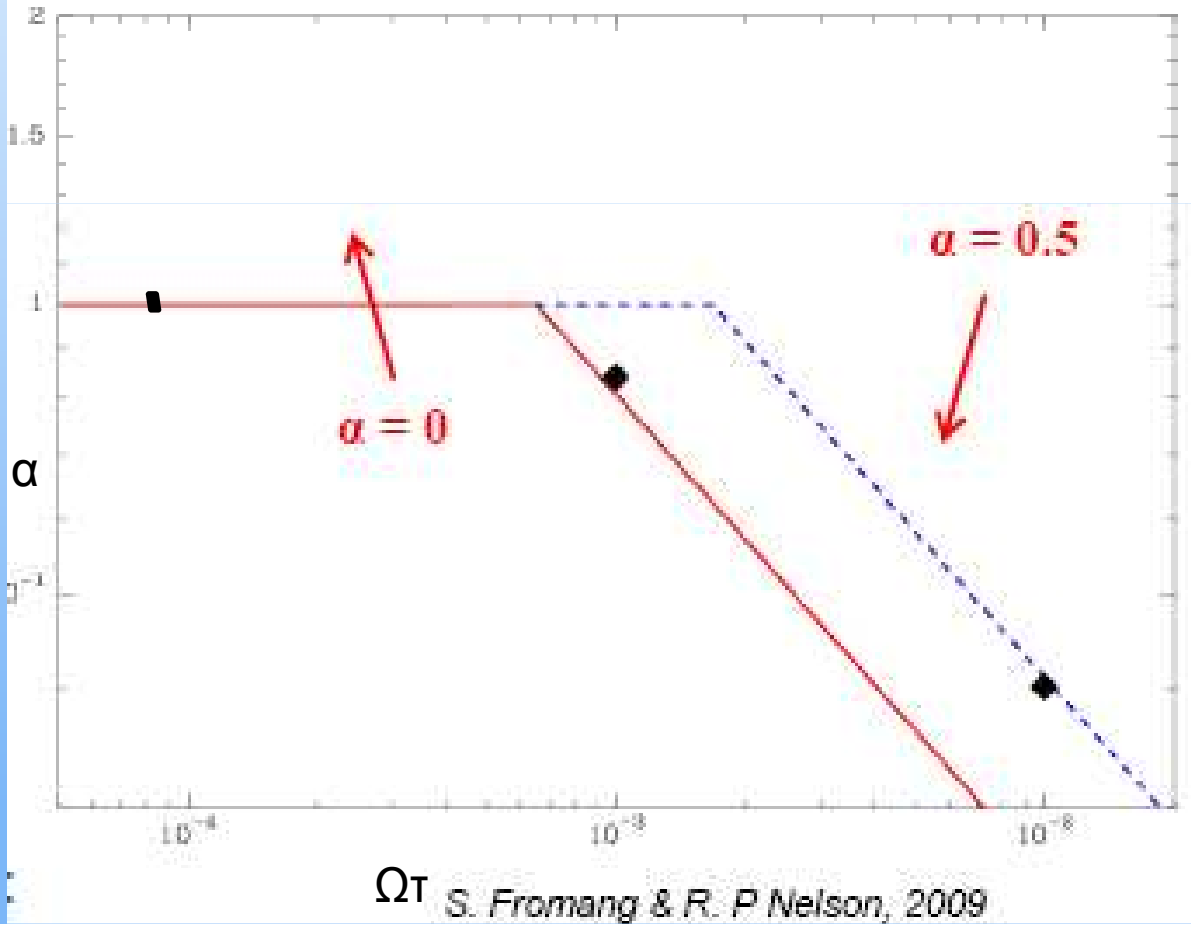
- $\Omega\tau < 1$ dust coupled to gas
- $\Omega\tau > 1$ dust settles toward mid-plane

$$\frac{H_d}{H} \alpha ((\Omega\tau)_0)^{-\alpha}$$

Small grains: **α = 0** - α = 0.05 (Pinte et al., 2008)

Big grains: Dubrulle et al., 1995, Cabadillo et al., 2006
α = 0.5

MRI induced MHD turbulence
(from Fromang et Nelson 2009 simulations)
used to parametrize Ωτ



Dust Settling seen by ALMA

Boehler PhD these, dec. 2011, Boehler et al 2012

- Some Diskfit improvements

$$\frac{H_d}{H} \alpha ((\Omega\tau)_0)^{-\alpha}$$

- Realistic dust properties
- a_{min} = 0.01 µm
- a_{max} = 3mm, a_{max} = 10cm

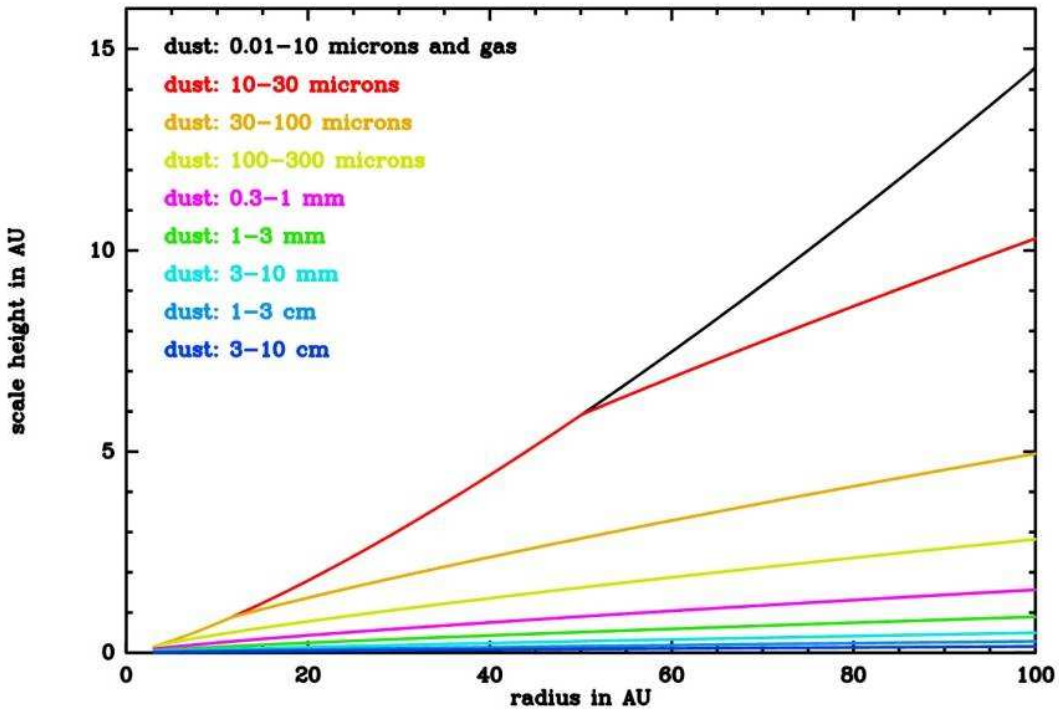
→ H(dust) << H(gas)

z

-Surface(3-5H):
-XDR/PDR Chemistry

-Molecular layer (1-3H)

-Mid-plane (0-1H) with a cold dense cloud chemistry →
Most of the dust << 1H



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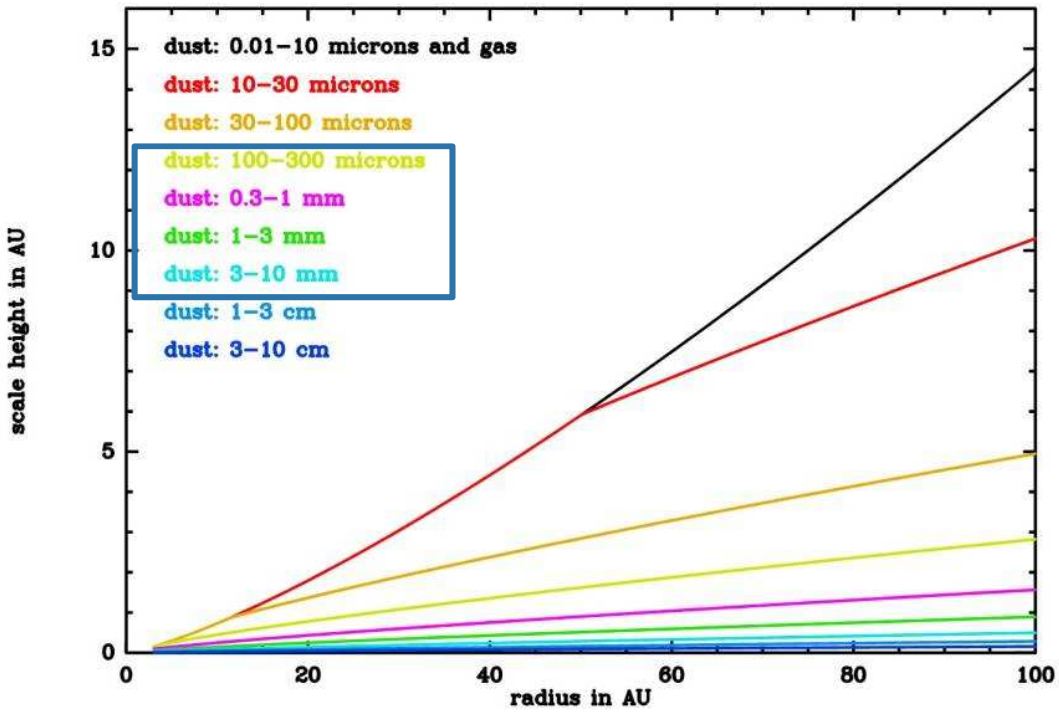


ALMA

Dust Settling: methodology

Inversion is mandatory to estimate the accuracy on derived parameters

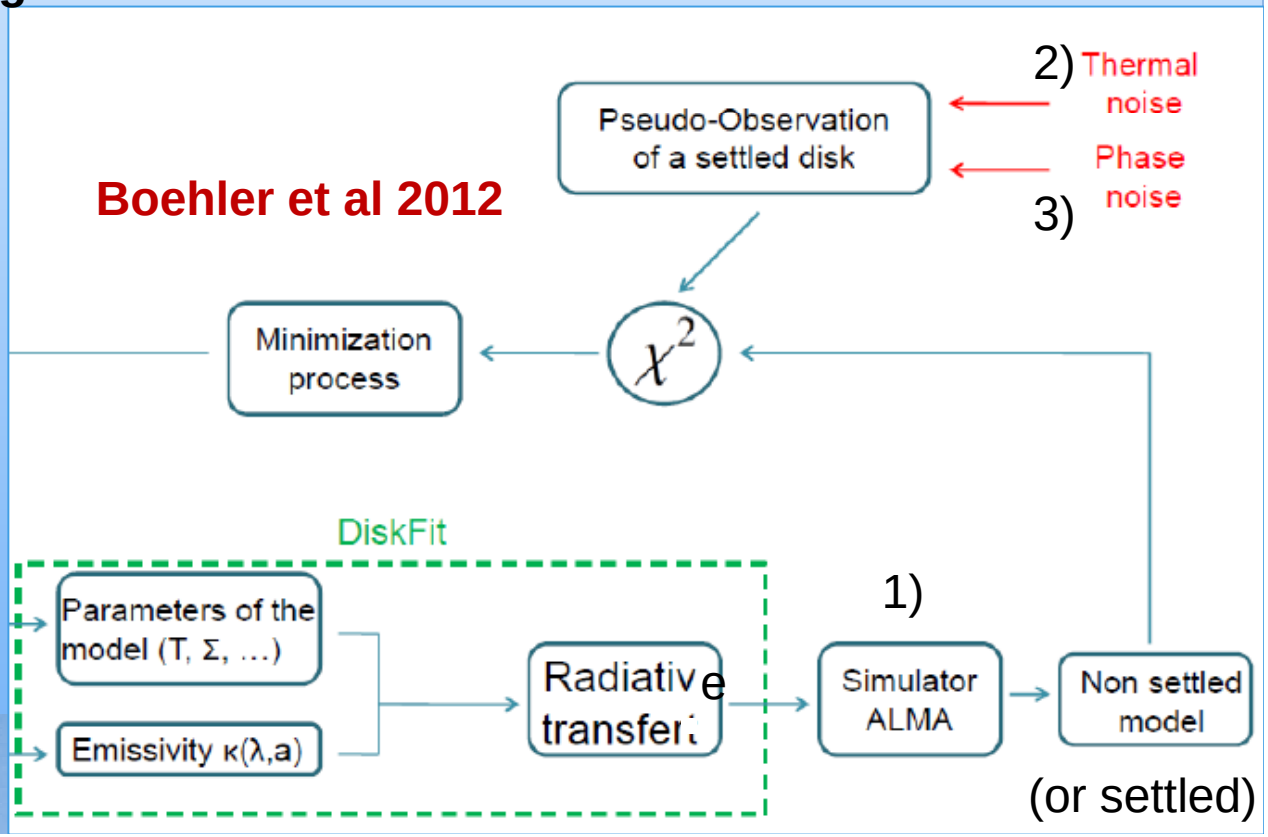
Several steps:

-1) Make both homogeneous & settled disk pseudo observations

-2) Inversion by an homogeneous one with realistic thermal noise

-3) Add phase noise

Boehler et al 2012



Dust Settling

Disks: DM Tau-like with Rout = 100 AU
 - sharp Rout

homogeneous & settled disk models
have the same dust mass

- ALMA simulation at 0.5mm (670 GHz)
with Bmax = 2.5km

→Dust settling visible up to 75 degrees

Next steps:

- Several wavelengths: 3mm, 1.3mm,
0.8mm and 0.5mm

-Inversion with noise (inc. Phase noise)

Dust Settling

-**Results of the inversion by an homogenous model of grains when adding thermal + phase noises**

→ Tdust is properly recovered & Hdust is low <<< Hgas(Tdust=Tgas)

→ Phase noise < 40 degrees

Errorbars increase but it does not prevent to observe settling !

→NEXT STEPS:

→**Define the optimum ALMA observational strategy and quantify settling with ALMA**

Boehler et al 2012

Many pending questions

1) **Temperature determination** → where is the molecular layer , warm versus cold ?
- Large temperature/density changes within a few AU - impact on chemistry?
- How to trace the **« cold » mid-plane** ?

→ **H_2D^+ detection not as easy as expected** (emission should be resolved by ALMA)

2) **Density distribution** → absolute value of the gas mass ?
- No direct tracer of H_2, X(mol)?

→CO and isotopologues remain robust to determine the temperature and density gradients detailed excitation conditions needed

3**) Molecular complexity ?**
Which level of complexity can be reached ? **depends on** ALMA final characteristics

4) **Dust settling** should be observable by ALMA !
Need to be properly incorporated in disk models (thermal eq. & chemistry)

5) **Roles of grains → See stephane's talk next week …**
- Grain size varies with (r,z) – radial and vertical evolution
- UV extinction & G/D variable in (r,z)
- Surface chemistry needed - temperature gradients, vertical mixing…

→ Should be incorporated in chemical models

KIDA Kinetic Database for Astrochemistry

Chemistry in Disks