Early phases of Solar System formation: 3D physical & chemical modeling of the collapse of a prestellar dense core.

Ugo Hincelin

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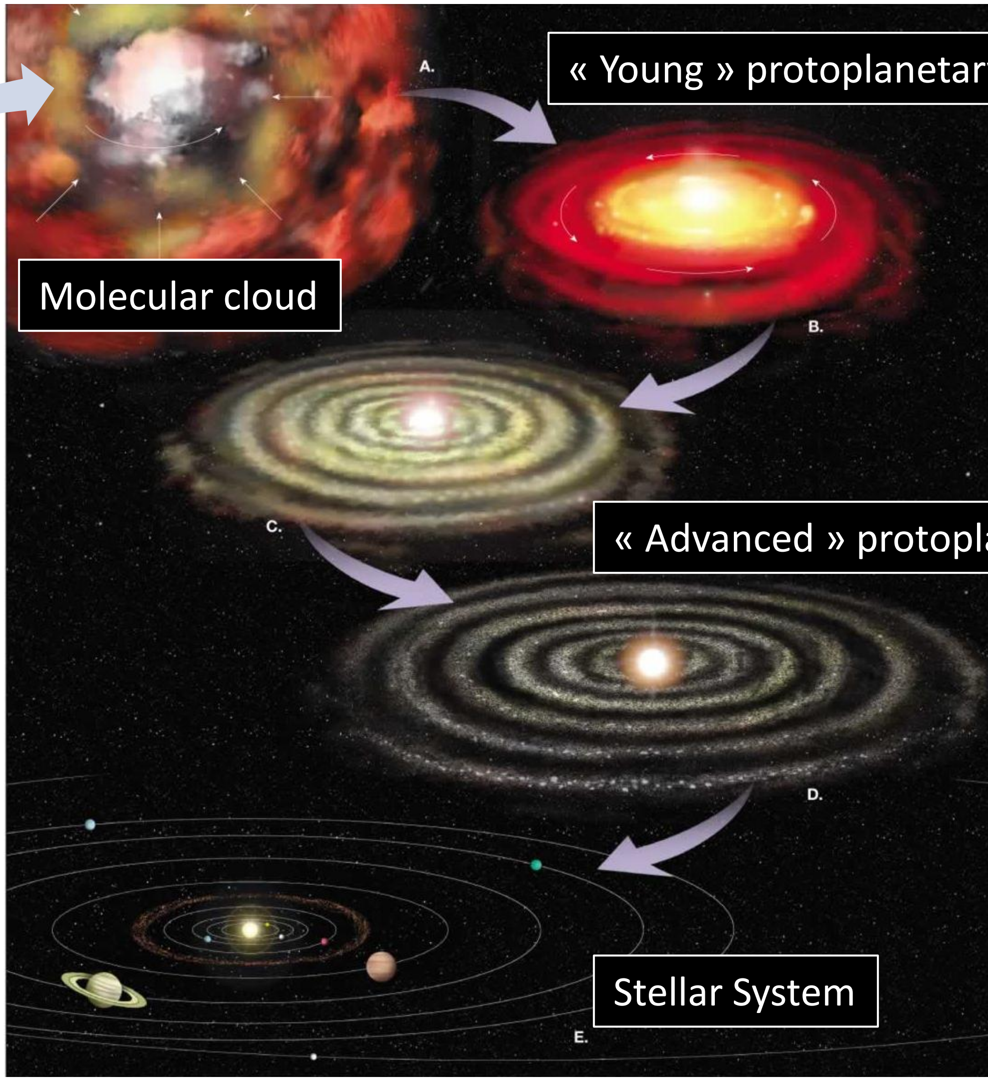
Benoit Commerçon & François Levrier (LERMA/ENS, Paris)
Equipe COMEX (ISM, Bordeaux)
Yuri Aikawa & Kenji Furuya (Kobe University, Japan)

Funding: Région Aquitaine, LAB

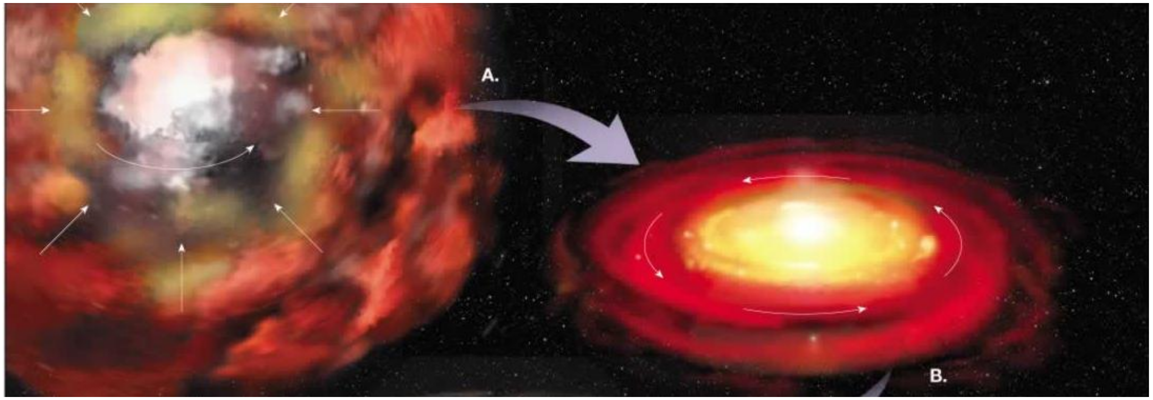
Low mass star formation ($<8M_{sol}$)

Main phases



Scientific objectives

Chemical evolution of gas & ice (from cloud to « young » disk)



Issue

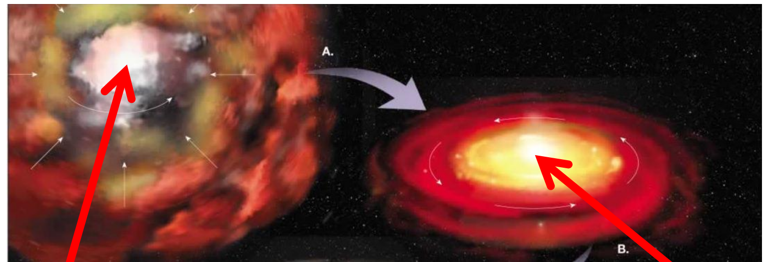
- ➢Link between : Chemical composition of Interstellar medium & Matter of the disk
- Influence of initial conditions
- Influence of physical history (T, n) of the medium
- Survival of interstellar molecules to the formation of disks

Study using numerical simulation :

- Compute chemical composition/evolution
- Prepare observation

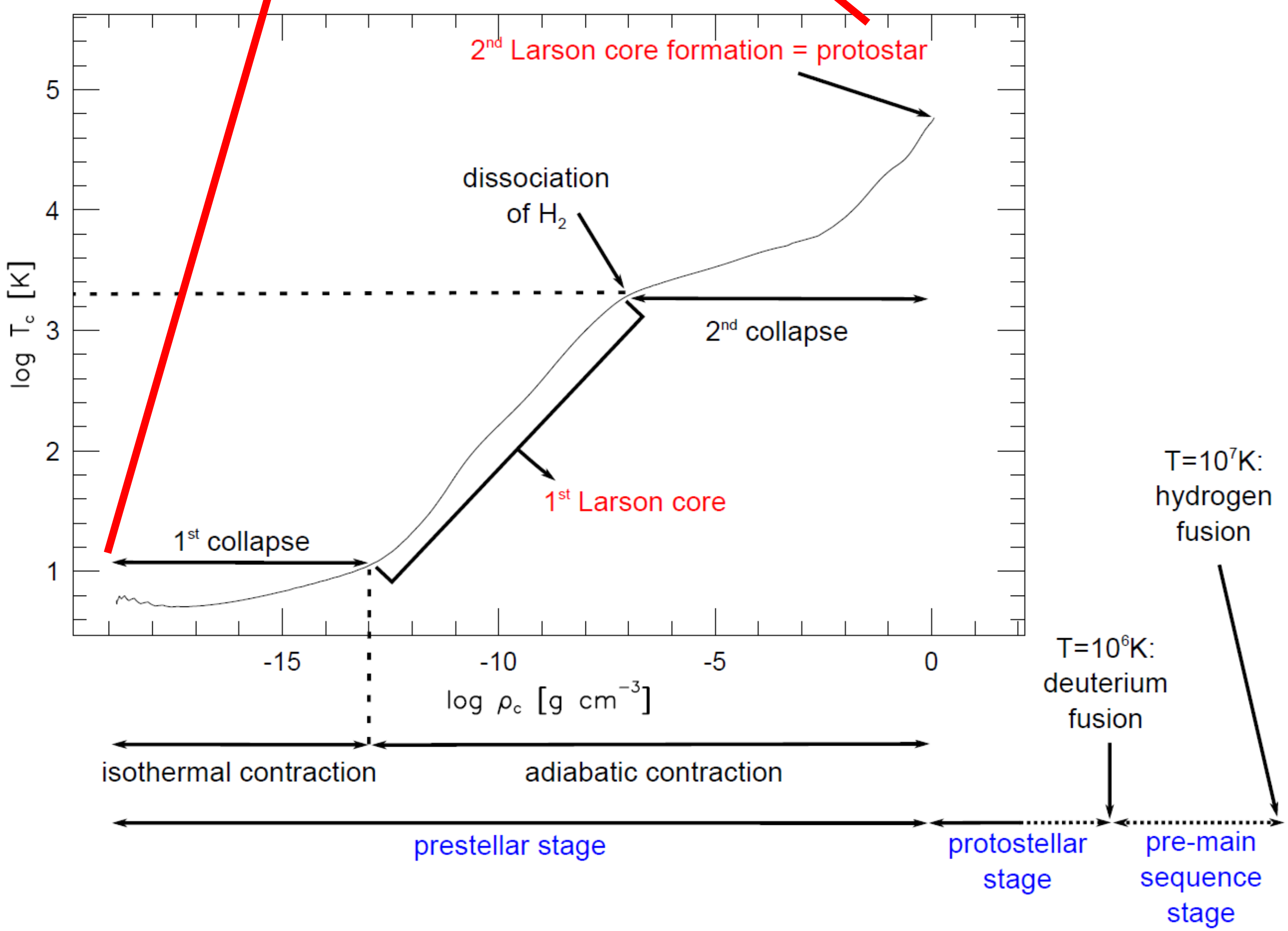
1^{st} Larson core *(Larson 1969)*

Dense core within a molecular cloud



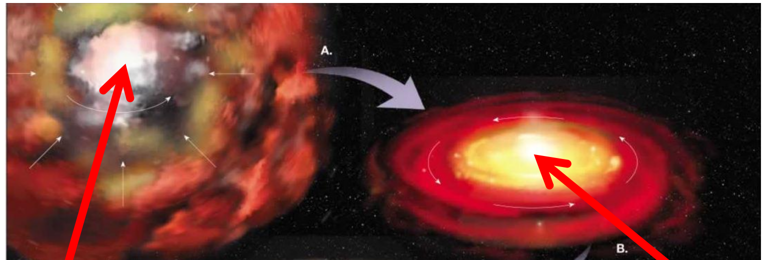
« Young » protoplanetary disk (10^4yr)

(Adapted from Masunaga & Inutsuka 2000)



3D physical & chemical model : RAMSES + NAUTILUS

Dense core within a molecular cloud



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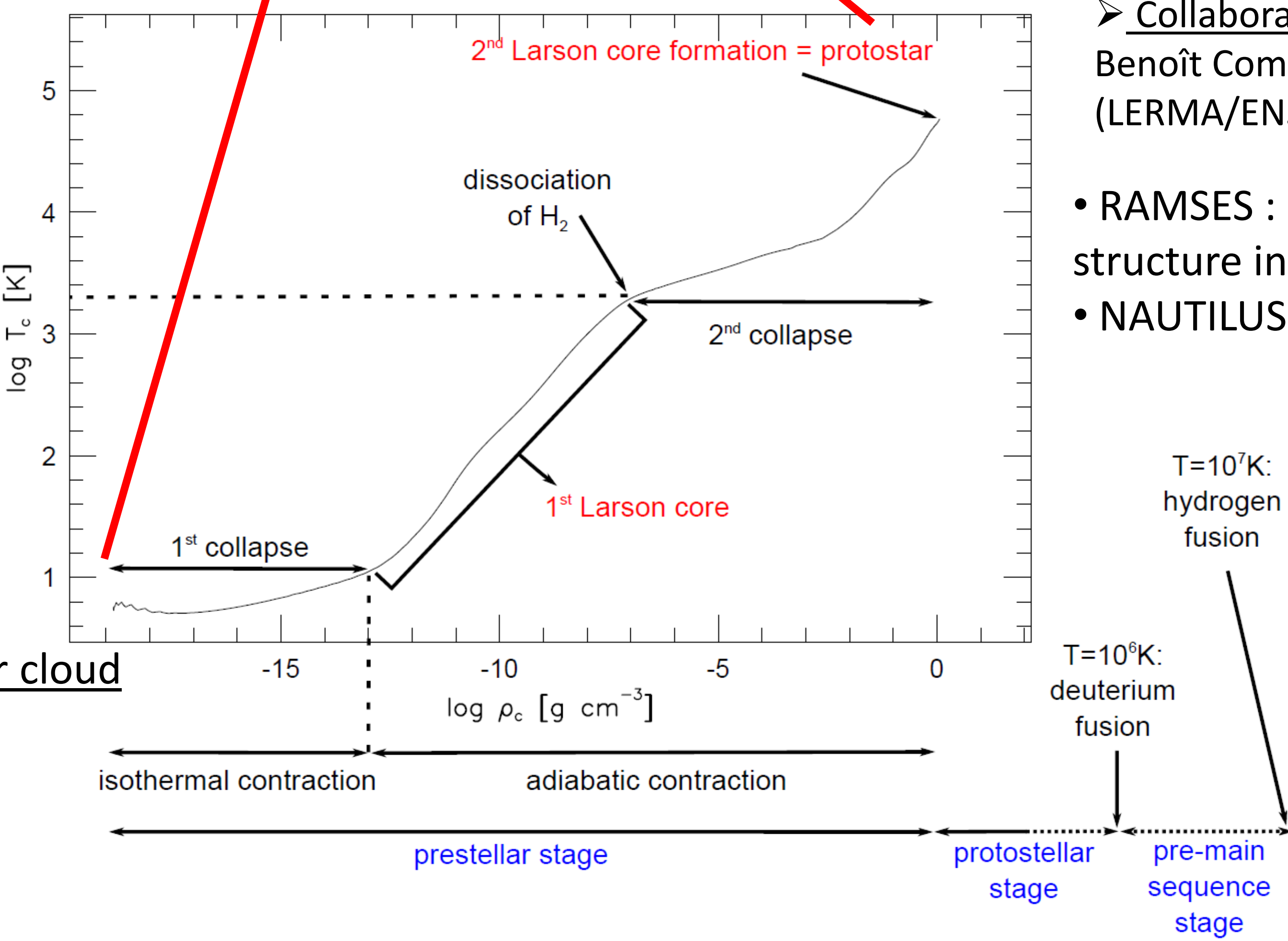


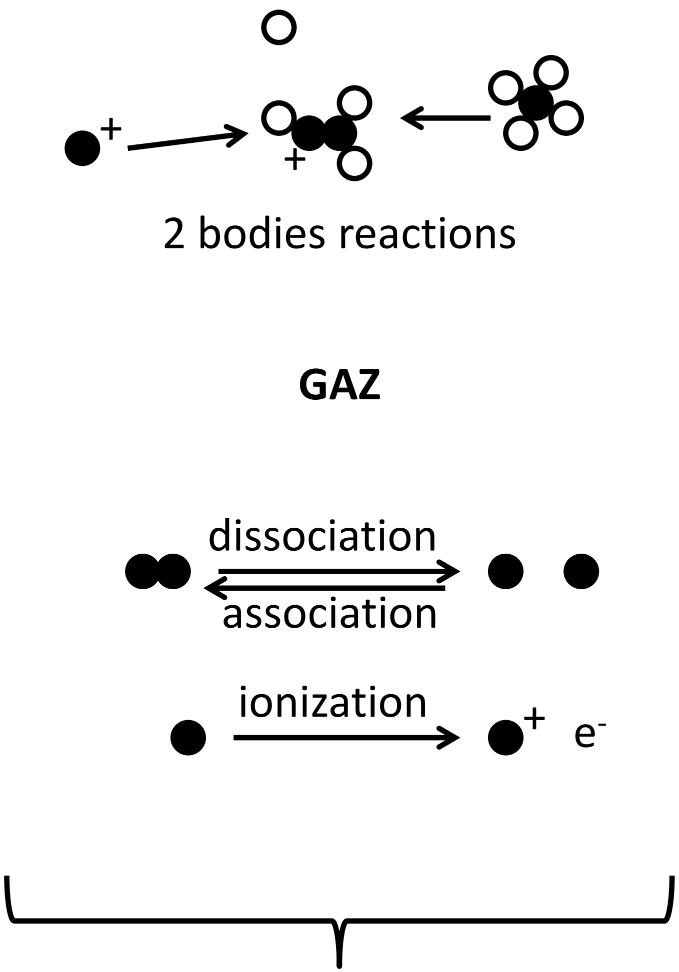
(Adapted from Masunaga & Inutsuka 2000)

Start: molecular cloud

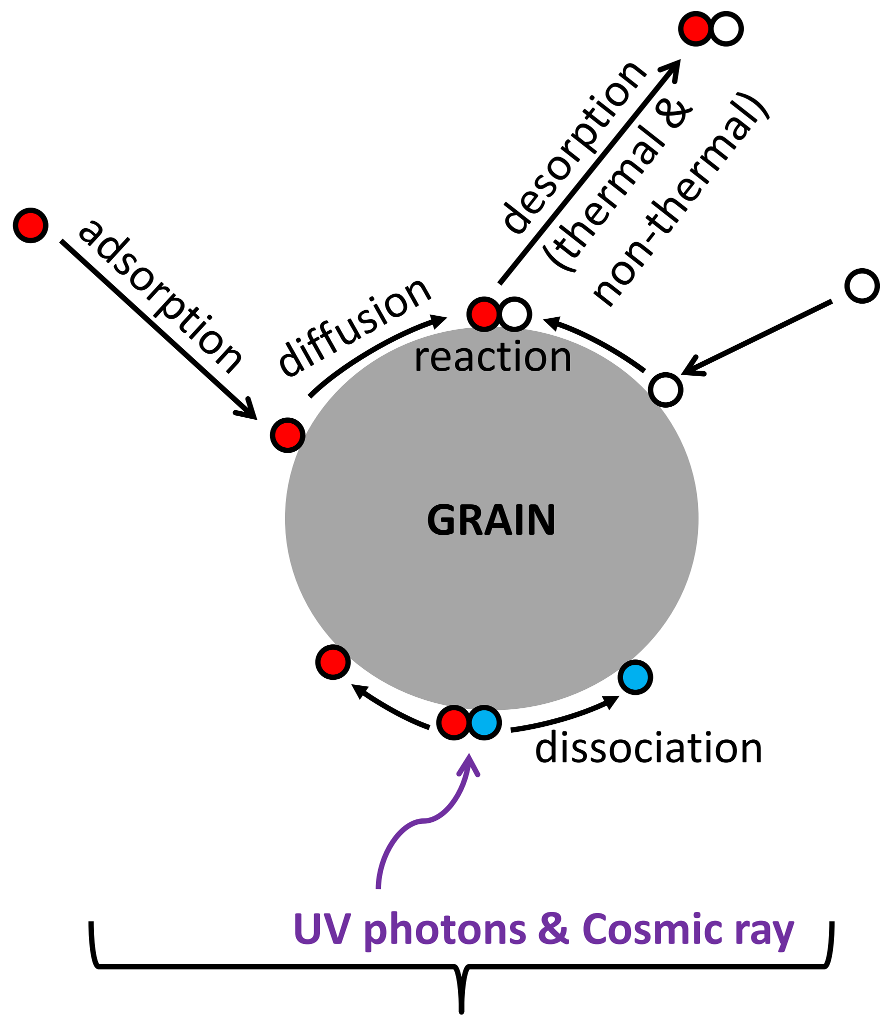
➢ Collaboration:
Benoît Commerçon (LERMA/ENS Paris)

- RAMSES : physical structure in 3D
- NAUTILUS : chemistry

Nautilus = Gas grain chemical model, developed in Bordeaux (V. Wakelam & F. Hersant)



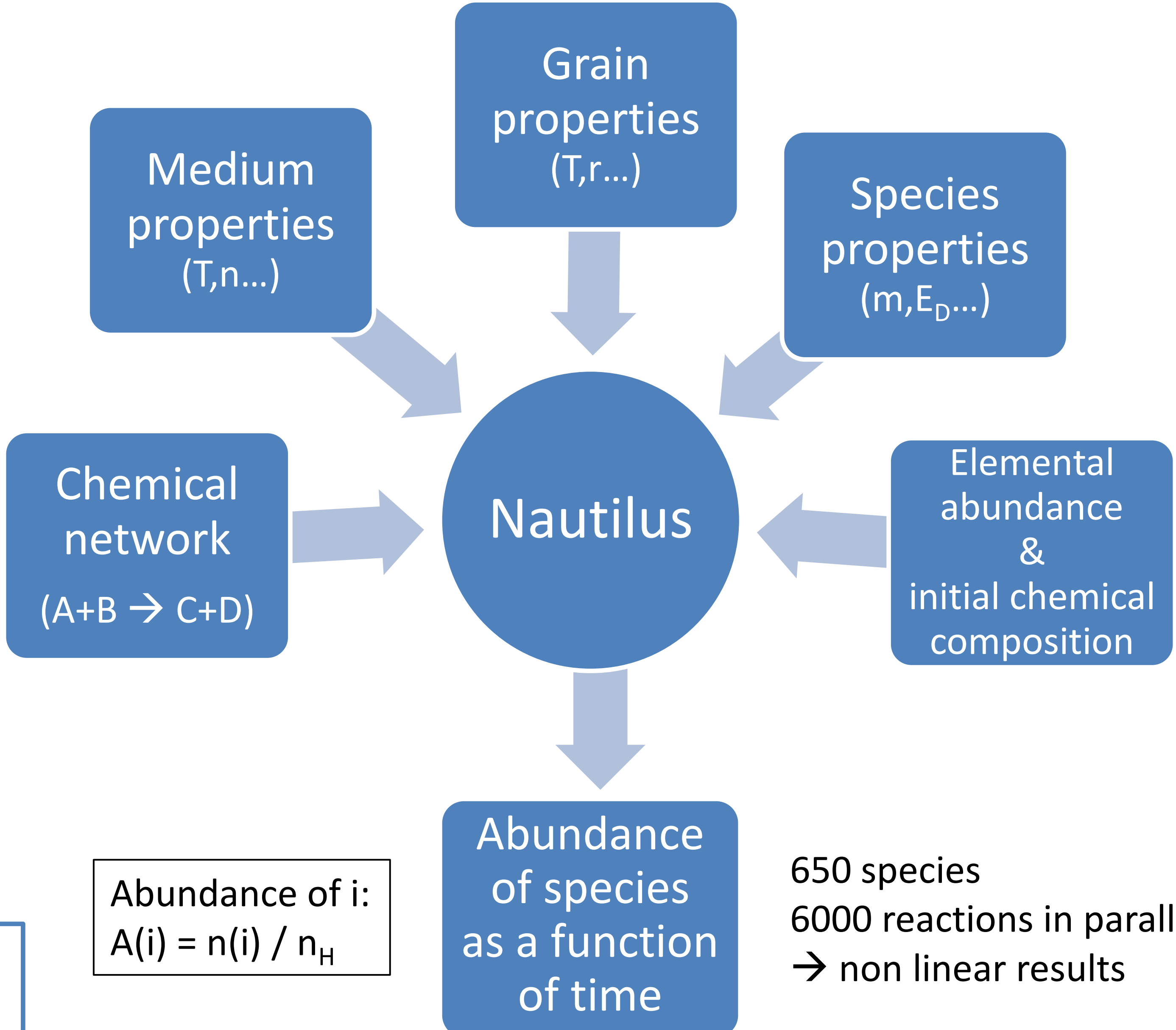
460 species
4400 reactions



200 species
1700 reactions

Chemical modeling : NAUTILUS

Functional diagram

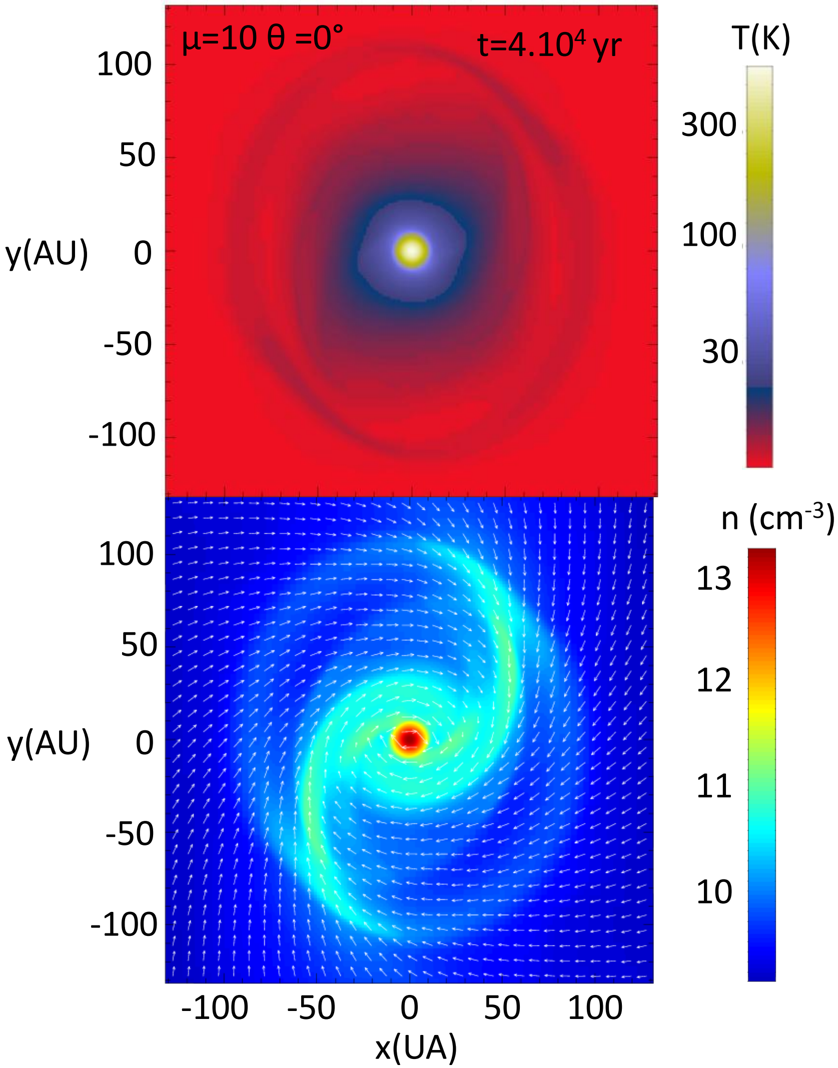


Abundance of i:
$A(i) = n(i) / n_H$

650 species
6000 reactions in parallel
→ non linear results

Poster n°47
H. Mokrane

Physical modeling : RAMSES | Radiation-Magneto-HydroDynamic (RMHD)



- Hydrodynamic model *(Teyssier 2002)*
- \+ Magnetic solver *(Fromang et al. 2006)*
- \+ Radiative solver *(Commerçon et al. 2011)*

} RMHD model

- Eulerian approach (grid)

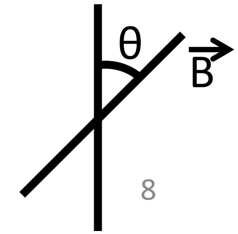
- Gravity leads to collapse → 1st Larson core

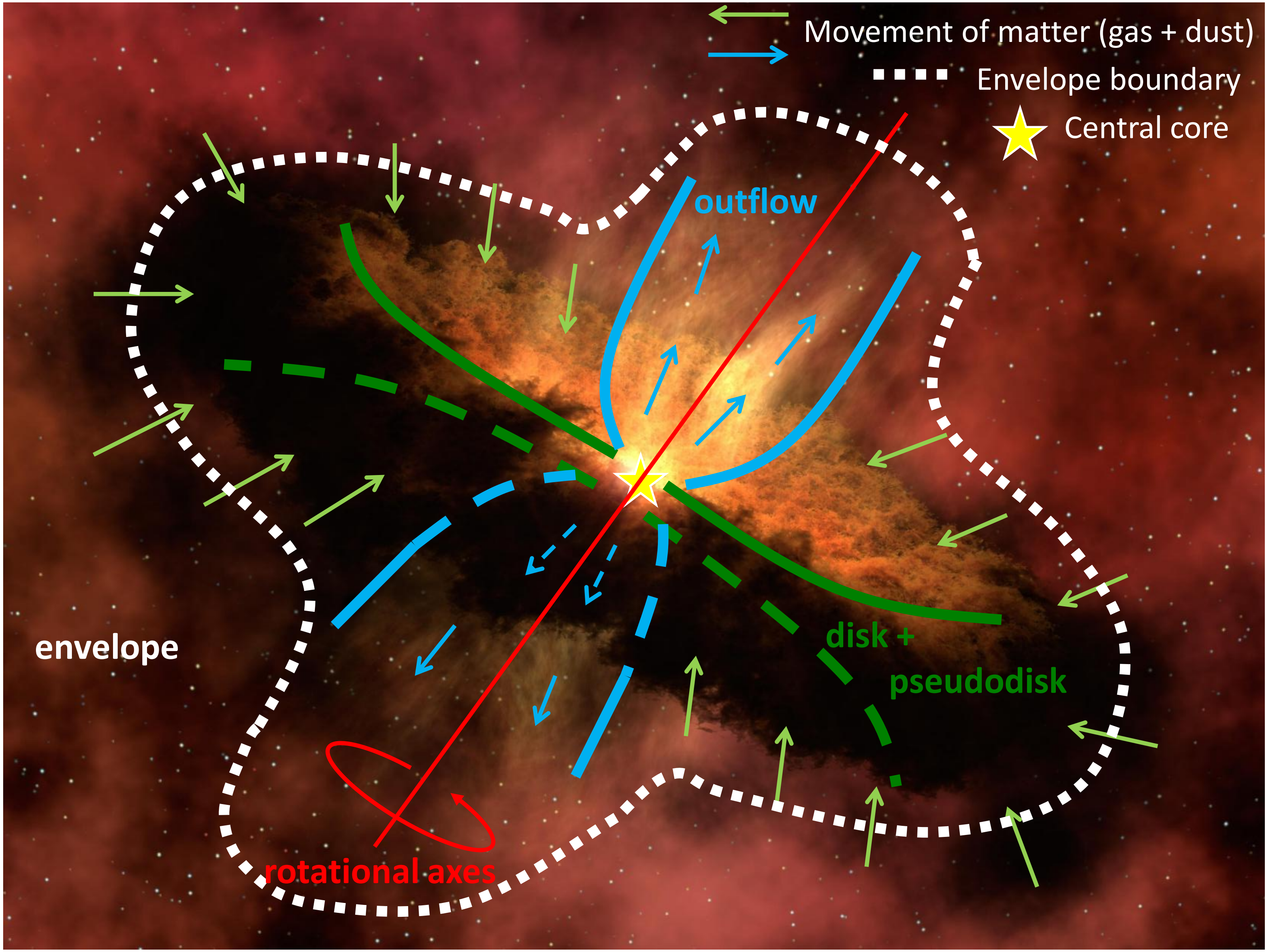
➢ Physical structure (T,n) of the collapse as a function of time

- 4 models (**μ2θ0**, **μ10θ0**, **μ200θ0**, **μ10θ45**)

3 magnetization levels (μ=2, 10, 200)

2 initial configurations (θ=0°, 45°)

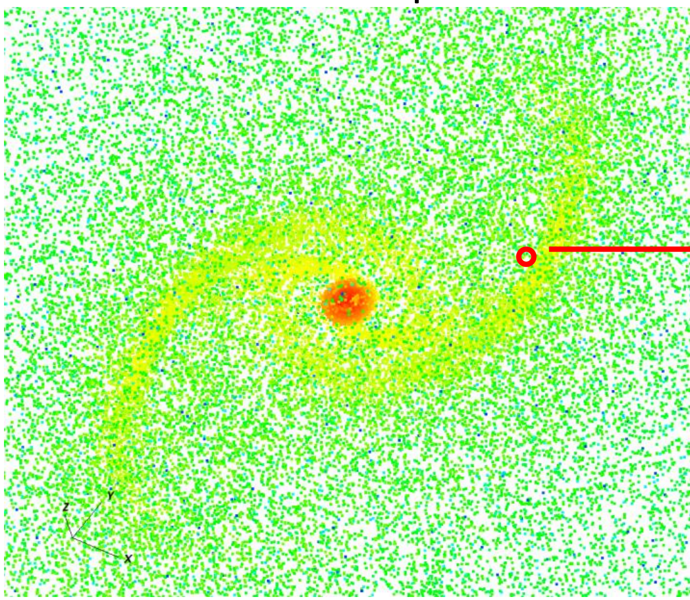



Movement of matter (gas + dust)
Envelope boundary
Central core
outflow
envelope
disk +
pseudodisk
rotational axes

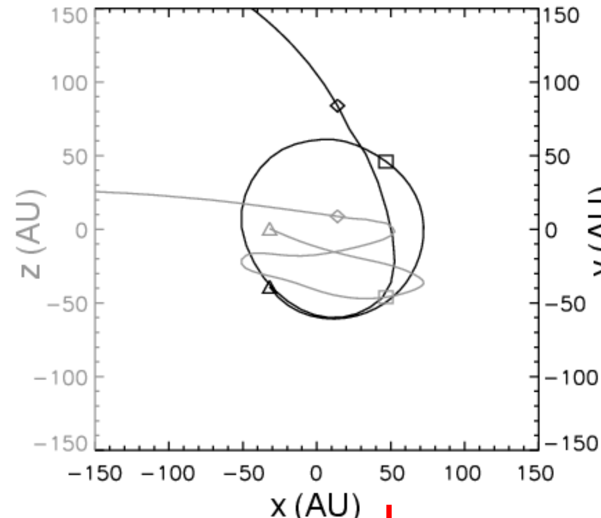
Interface between RAMSES & NAUTILUS

method: Lagrangian approach

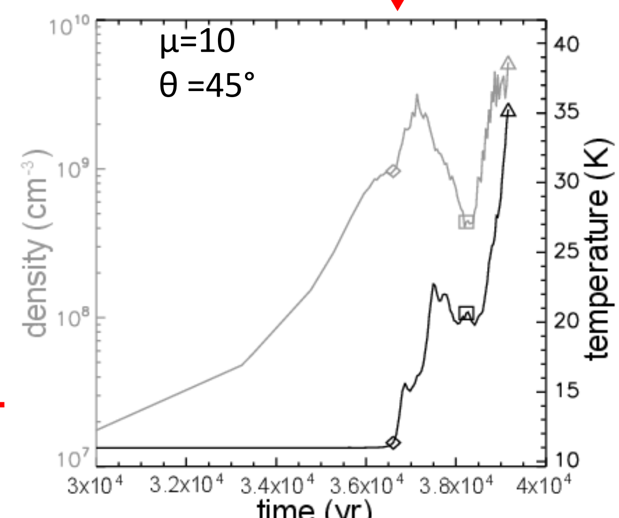
Introduce 10^6 tracer particles in RAMSES



each particle follows the fluid in movement



probes T & n along the trajectory



- ➢T & n = inputs for **Nautilus**
- ➢ compute chemical evolution on the particle

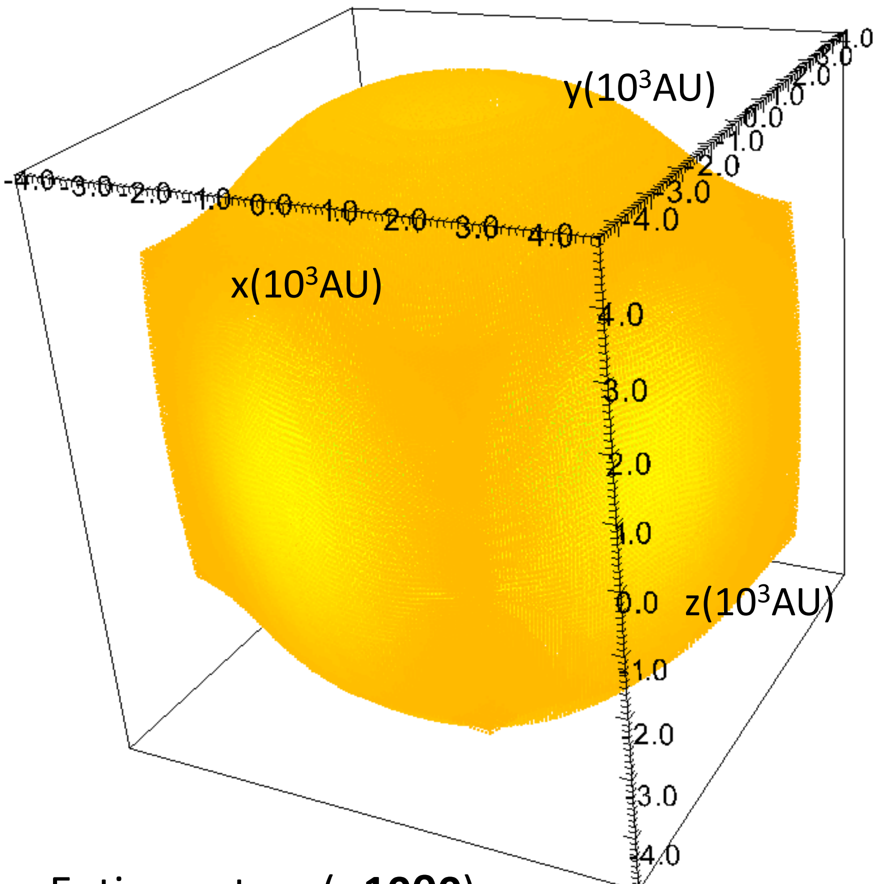
Hincelin, Wakelam, Commerçon, Hersant & Guilloteau, submitted to ApJ
Hincelin, Commerçon, Wakelam, Hersant & Guilloteau, in preparation

Outputs

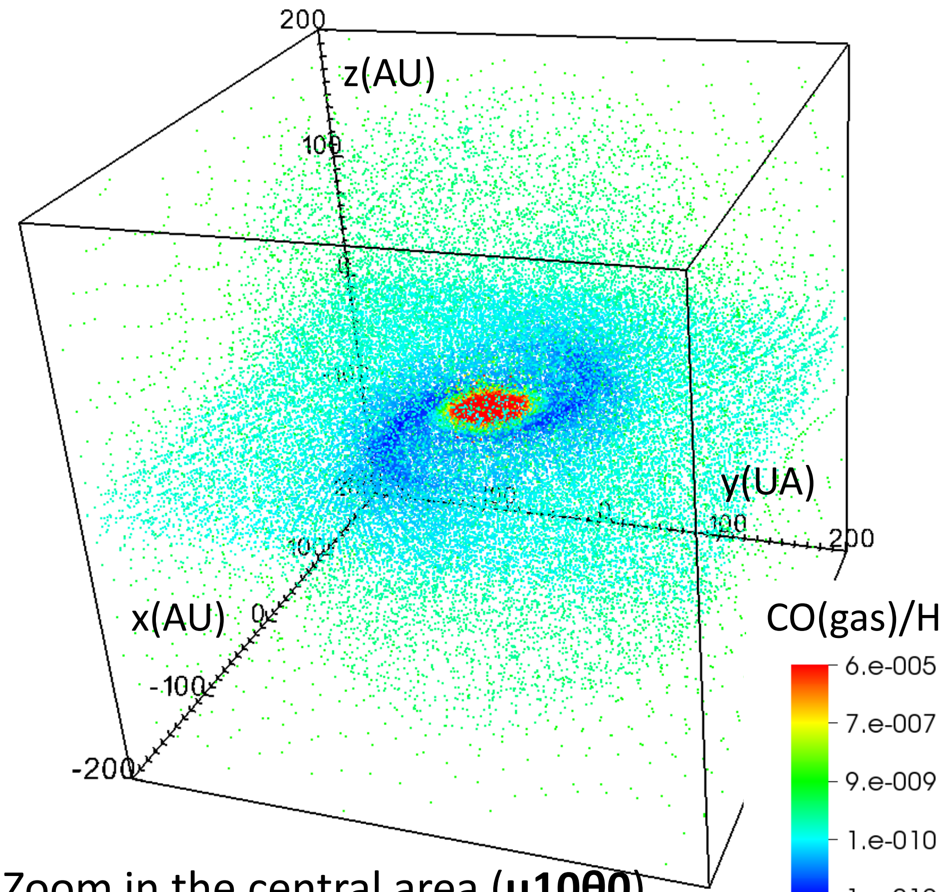
- Chemical composition as a function of time in a 3D space for 4 models

(μ2θ0, μ10θ0, μ200θ0, μ10θ45)

(~65 000 h of computation at CINES)



Entire system (**μ10θ0**)



Zoom in the central area (**μ10θ0**)

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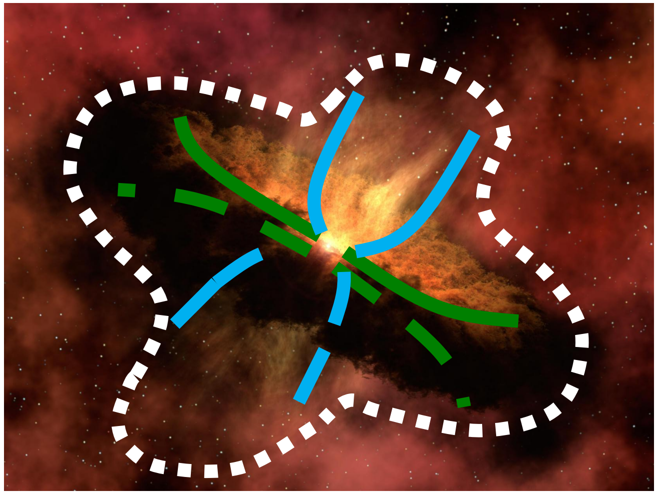
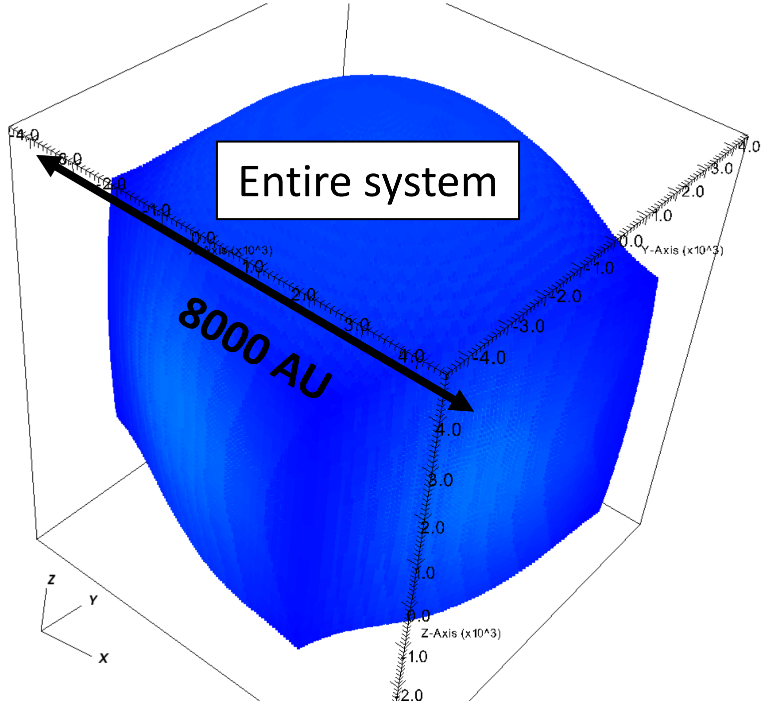
Extraction of the different components





Criteria based on velocity & energy *(Joos et al. 2012)*

Outflow

1. for $z > 0$: $v_z > v_{threshold}$
2. for $z < 0$: $v_z < v_{threshold}$

Disk

1. $v_\phi > f_{threshold}\, v_r$
2. $v_\phi > f_{threshold}\, v_z$
3. rotational support > $f_{threshold}$ thermal support
4. $n > 10^9 cm^{-3}$

Pseudodisk

3. of disk, but not 1. or 2., and 4. relaxed to $10^7 cm^{-3}$

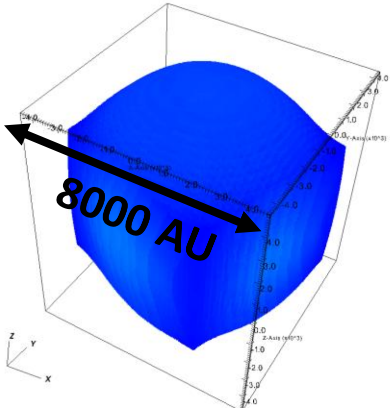
Central core

thermal support > $f_{threshold}$ rotational support

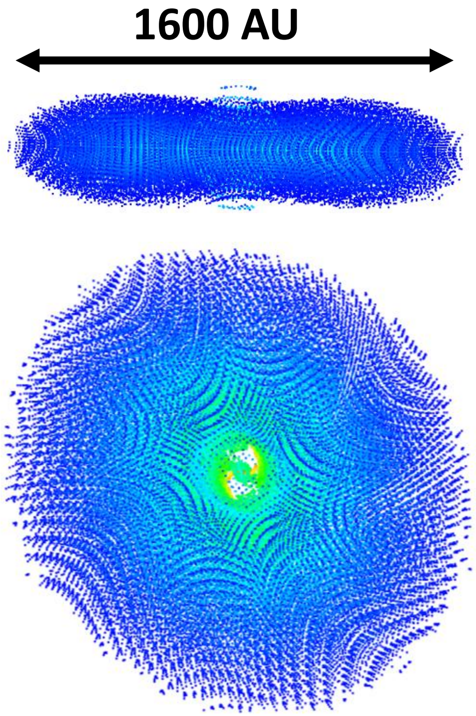
Envelope

what remains (with $n < 10^7 cm^{-3}$)

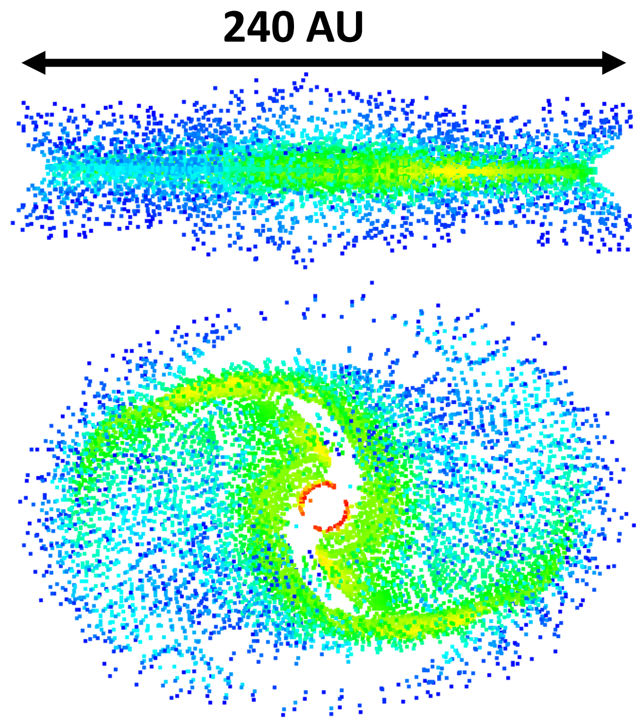
Extraction of the different components



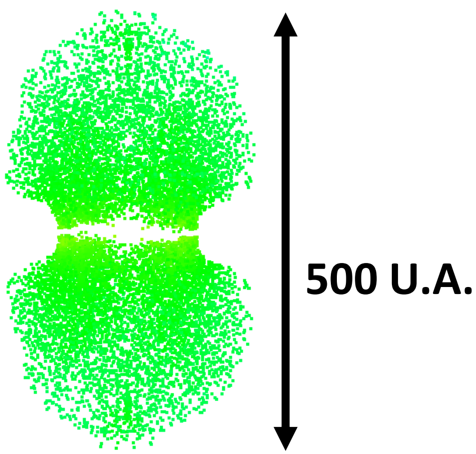
Envelope



Pseudodisk

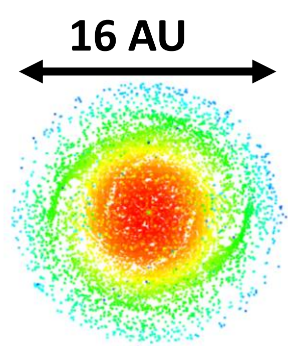


Disk



Bipolar outflow

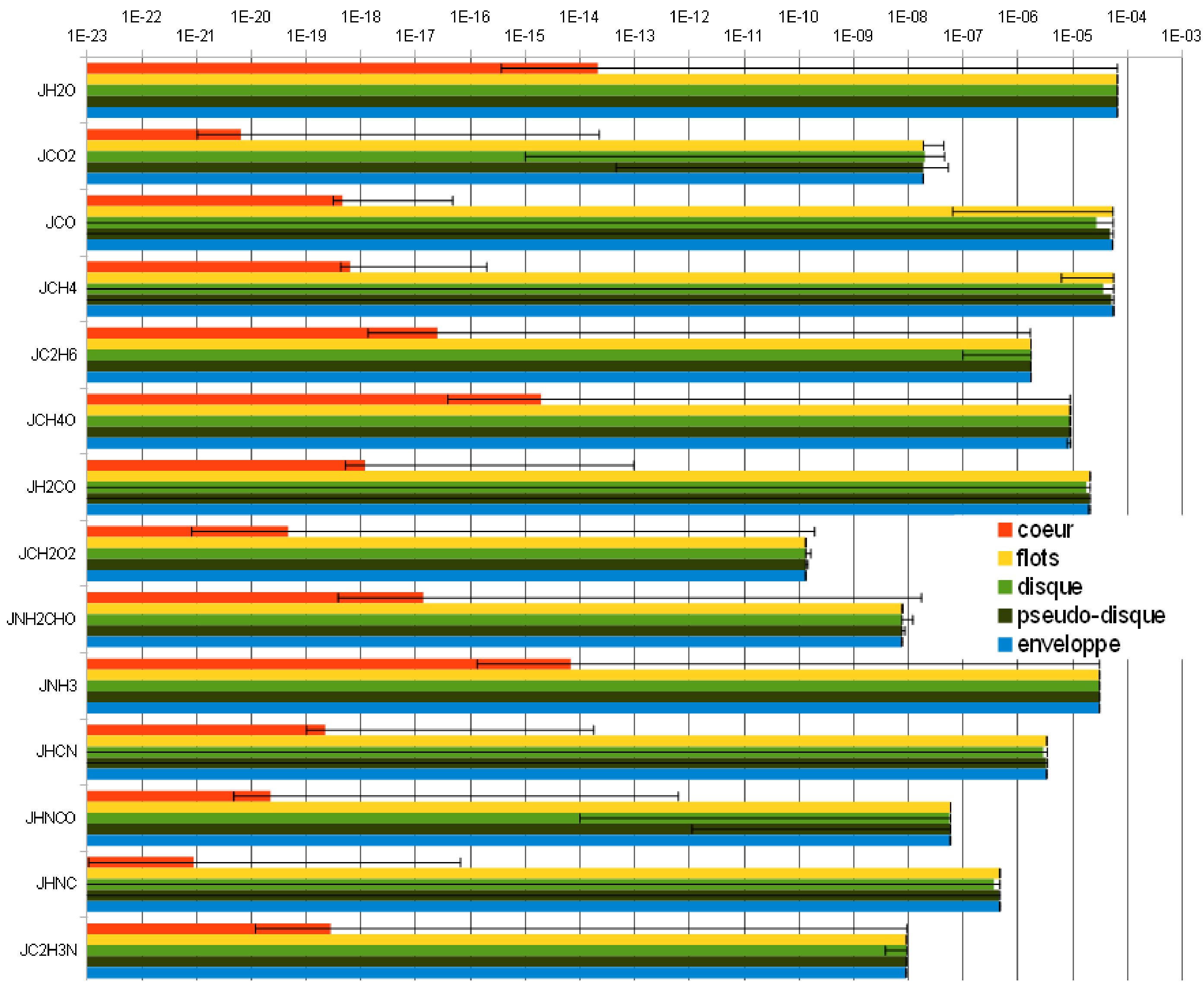
Central core



μ10θ0 model

µ1000 model

abundance of ices (/n_H)



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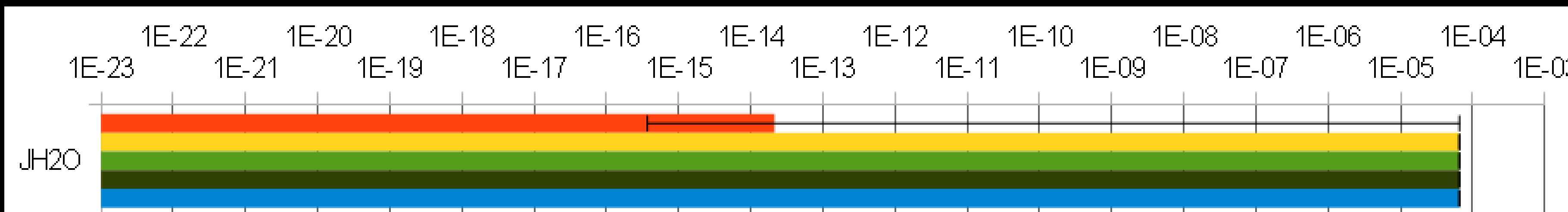
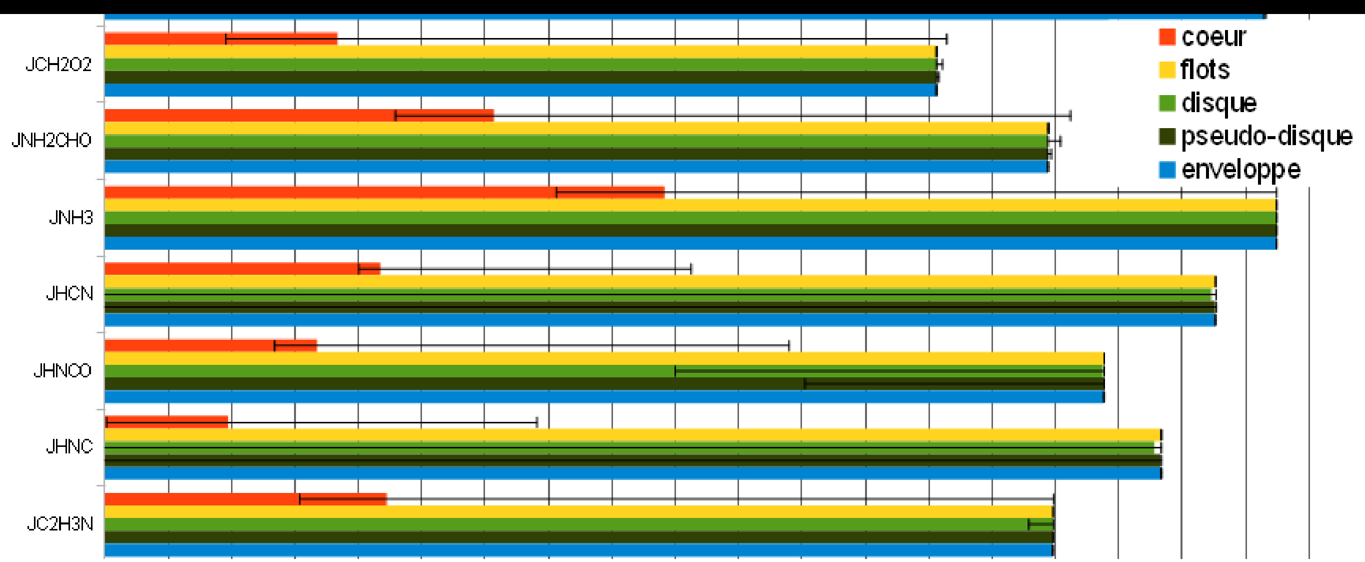
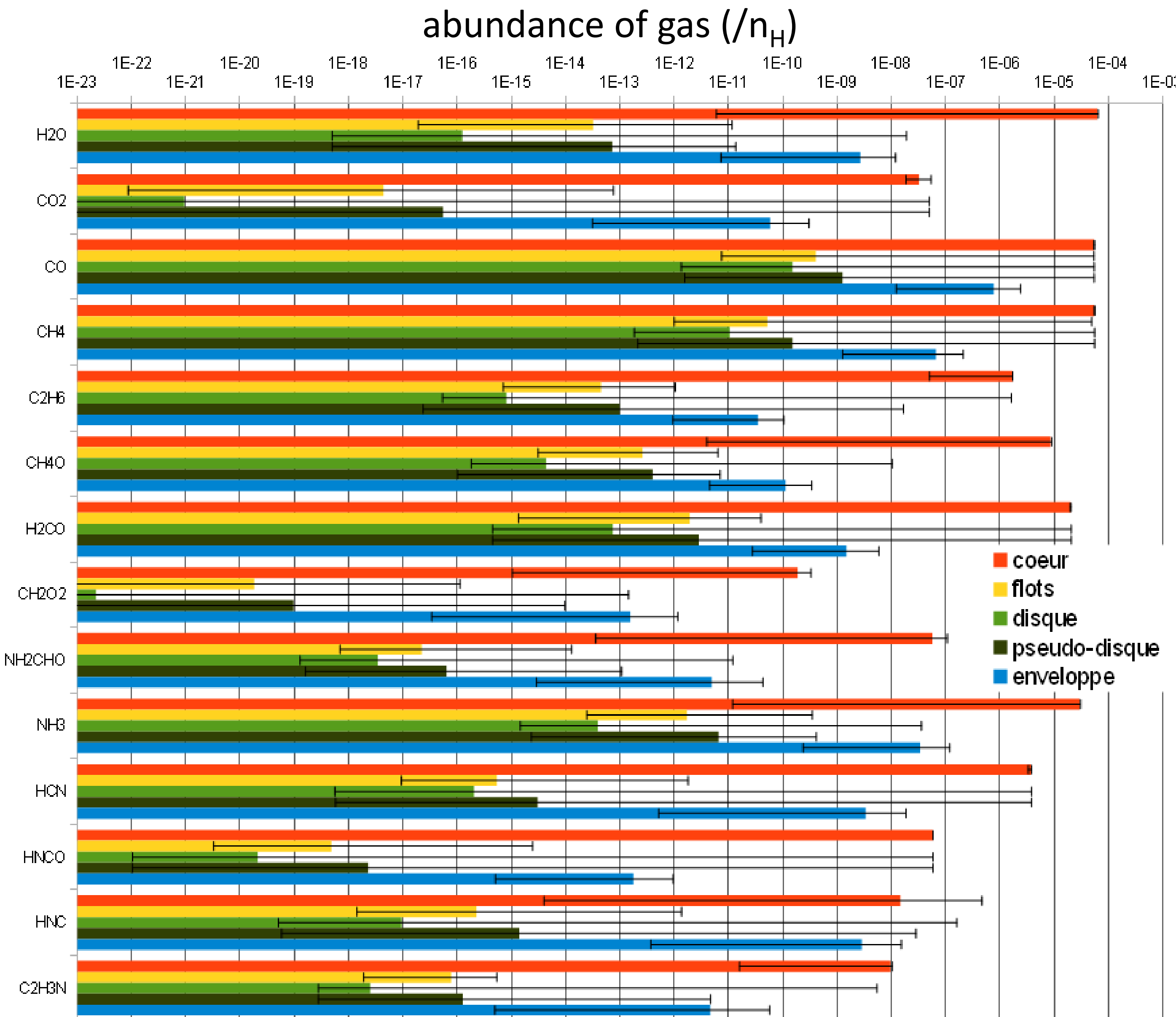


- Central core: low abundance (high temperature → desorption)
- Other components: similar



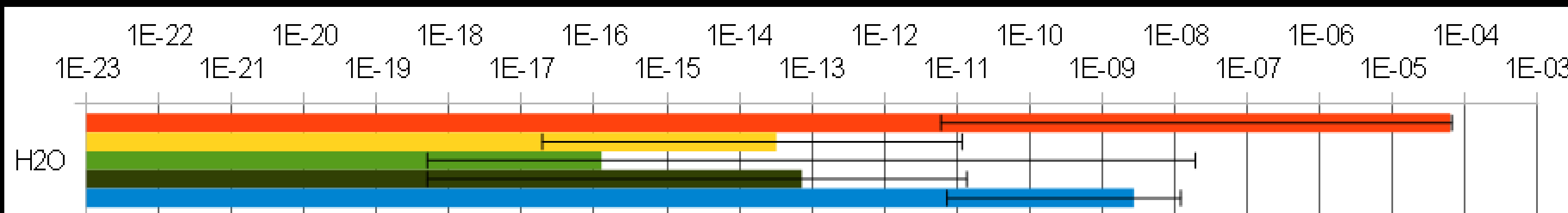
µ1000 model


abundance of gas (/n_H)
1E-23
1E-22
1E-21
1E-20
1E-19
1E-18
1E-17
1E-16
1E-15
1E-14
1E-13
1E-12
1E-11
1E-10
1E-09
1E-08
1E-07
1E-06
1E-05
1E-04
1E-03
H2O
CO2
CO
CH4
C2H6
CH4O
H2CO
CH2O2
NH2CHO
NH3
HCN
HNCO
HNC
C2H3N
coeur
flots
disque
pseudo-disque
enveloppe

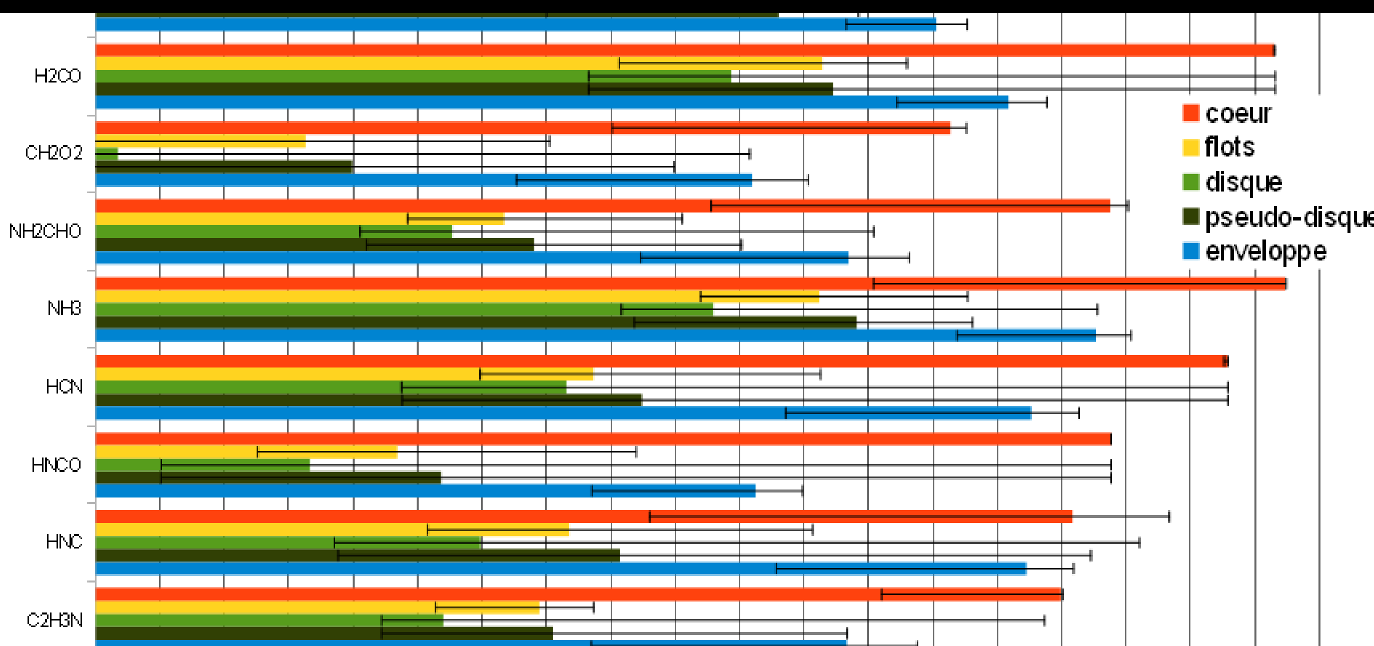
Chemical composition of the different components | Gas

µ1000 model

abundance of gas (/n_H)



- ➢ Central core: high abundance (high temperature → desorption)
- ➢ Other components: differences (density variation → adsorption)



µ1000 model

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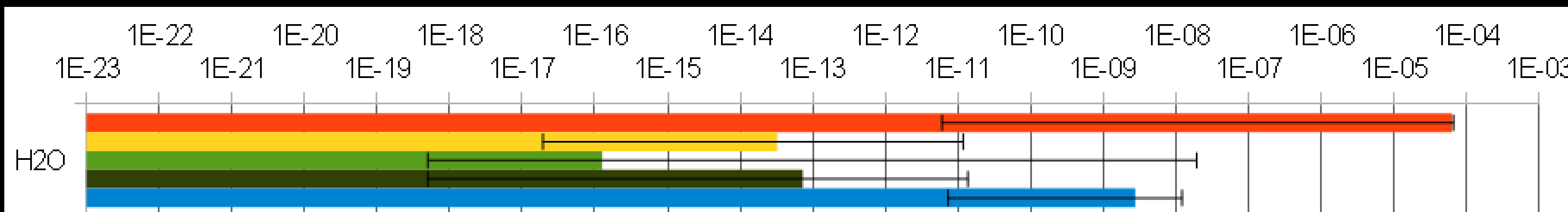

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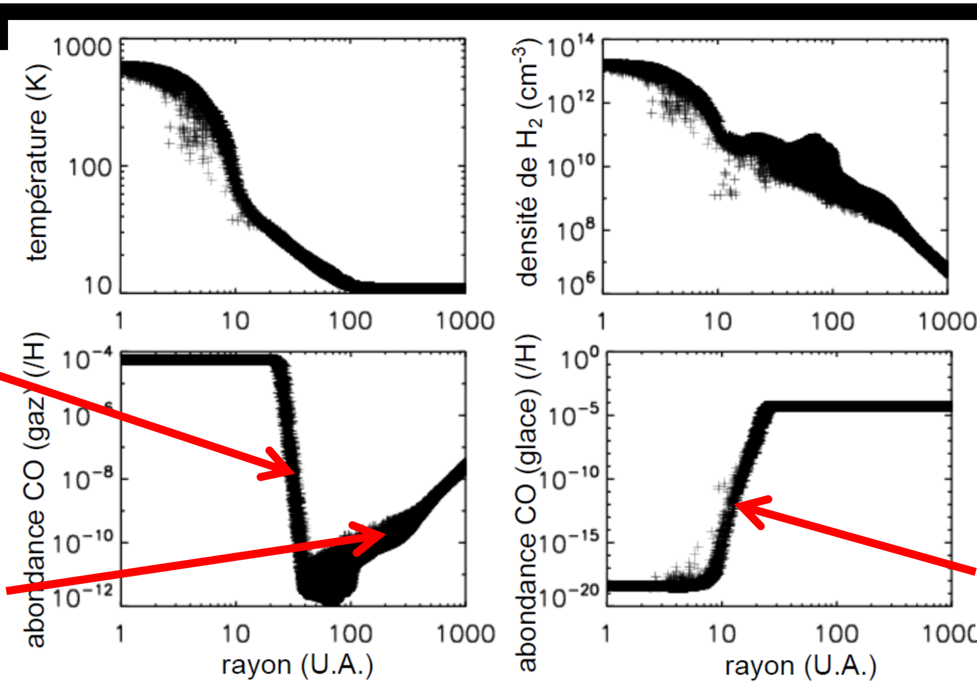


<u>End of simulation</u>
Equatorial plan
Thickness: 20 AU (|z|<10 AU)

T ↗ : desorption
$A(i)_{gas}$ ↗

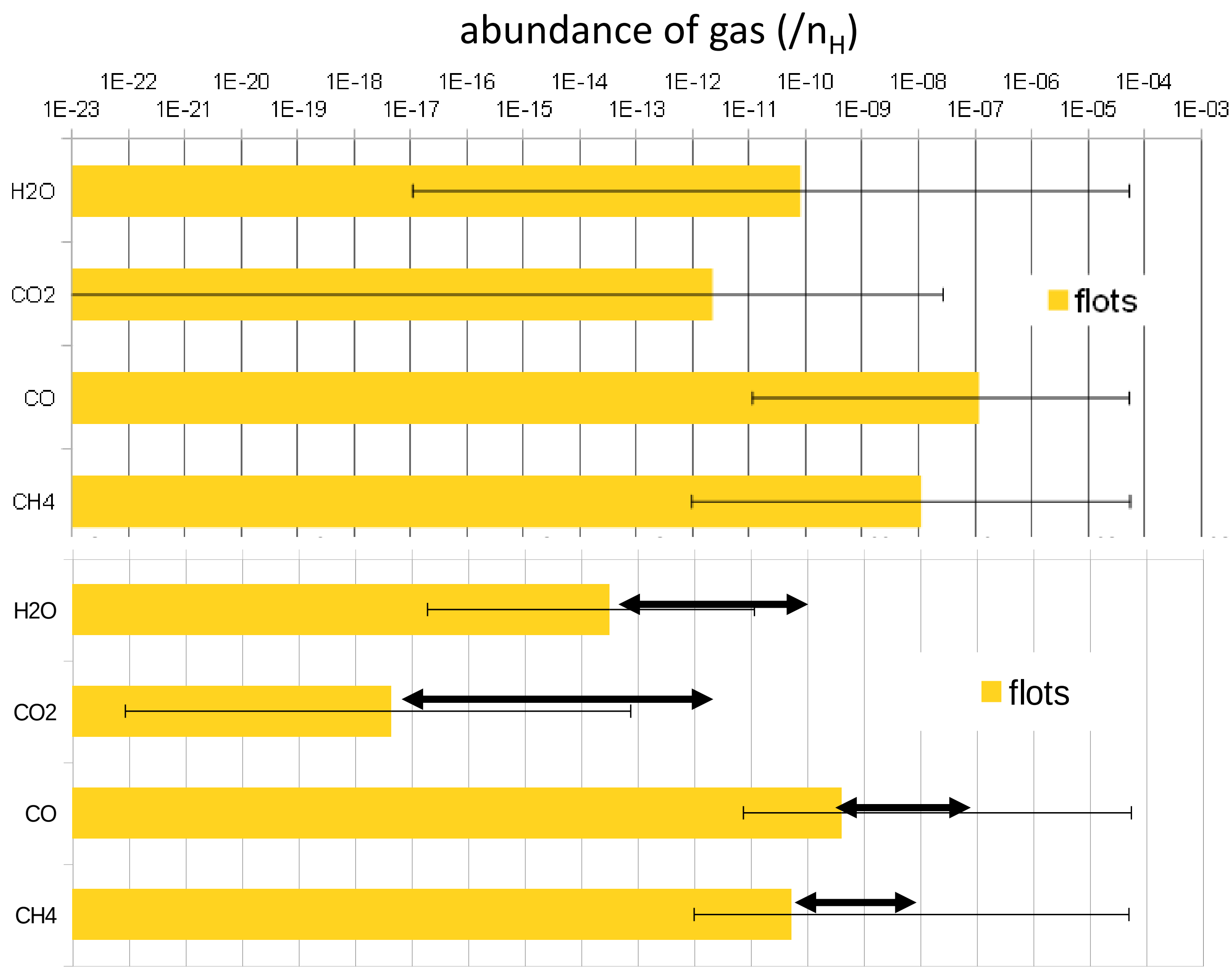
n ↗ : adsorption
$A(i)_{gas}$ ↘

- Main mechanisms at play: adsorption & desorption

T ↗ : desorption
$A(i)_{ice}$ ↘

μ2θ0 model

μ10θ0 model



- differences = 2 to 5 order of magnitude
- Why? outflow of **μ2θ0** warmer (some K) & less dense (/40) than outflow of **μ10θ0**

(Hincelin, Wakelam, Commerçon, Hersant & Guilloteau, submitted to ApJ)

- Abundance Gas + Ice (global view)

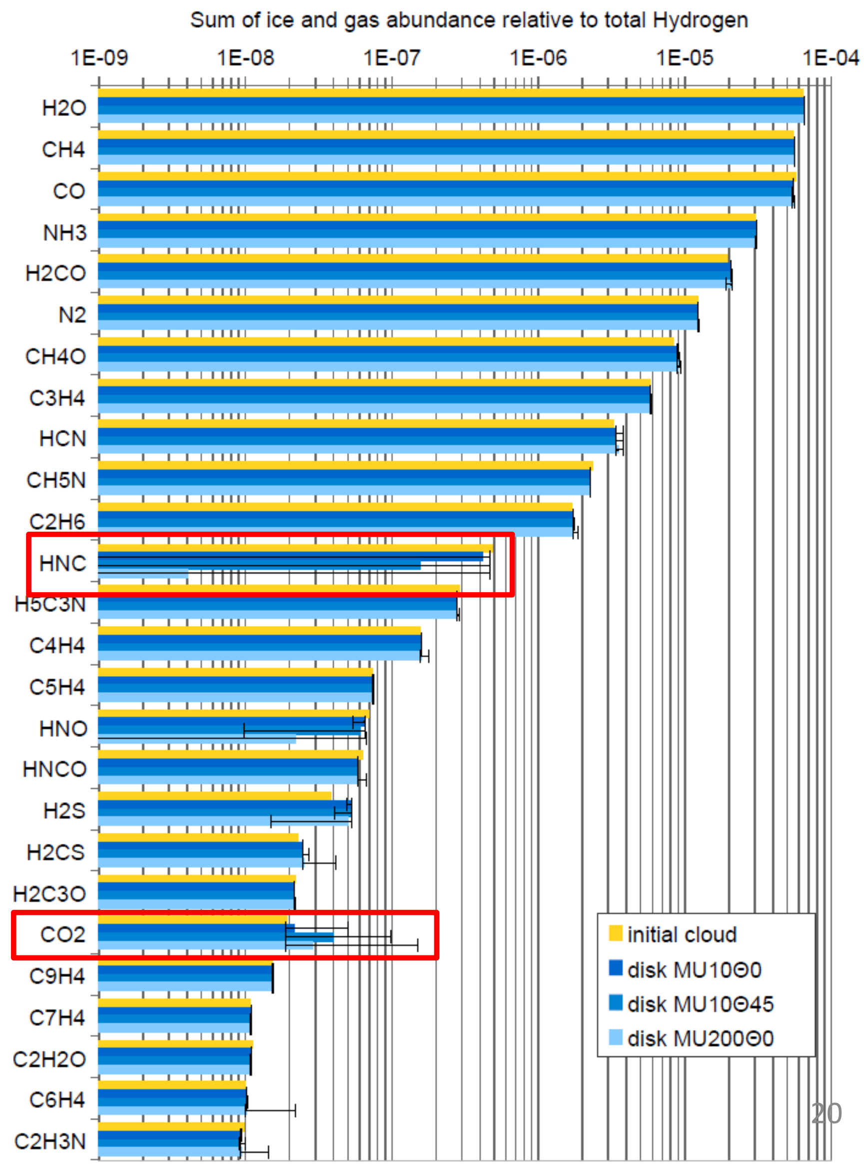
  3 models: **μ10θ0**, **μ10θ45**, **μ20θ0**

- Differences between chemical composition:
  1) Initial molecular cloud
  2) Disk

➢ Similar abundances for disk & cloud except for:

➢ HNC destruction
(desorption followed by destruction in the gas phase when T > 50K)

➢ CO_2 formation
(High T promotes OH + CO → CO_2 + H on the grain surface *(Ruffle & Herbst 2001)*)



- ❑ Early phases of Solar System formation:
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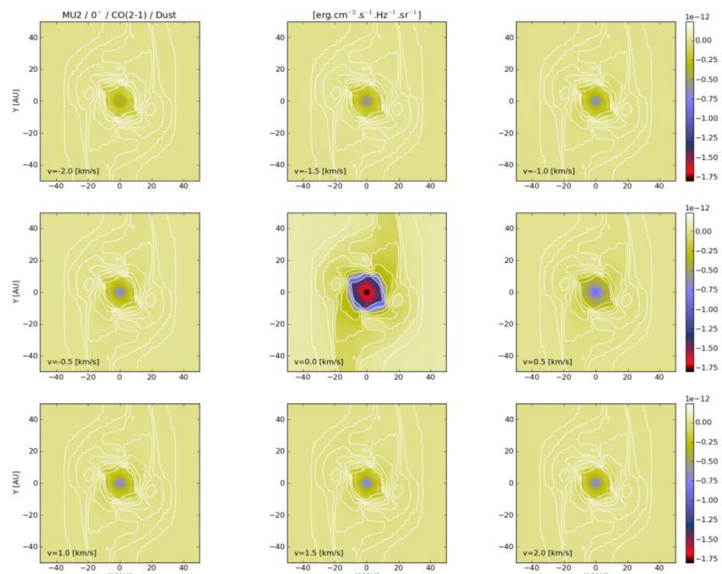
- ➢ Globally, few chemical modifications of the matter during the collapse
  ➔ initial chemical conditions are important
- ➢ Chemical distinction between components (disk, outflow…) and between cores (high B versus intermediate B) theoretically possible

- ❑ Synthetic observations of 1st Larson core

  on-going work
  (B. Commerçon, F. Levrier, LERMA ENS Paris
  A. Dutrey, S. Guilloteau, LAB Bordeaux)

  ➔ 3D model + radiative transfer
  ➔ synthetic observations of molecules
  (ALMA cycle 2)



µ2θ0 CO(2-1)
Example of computed synthetic observations

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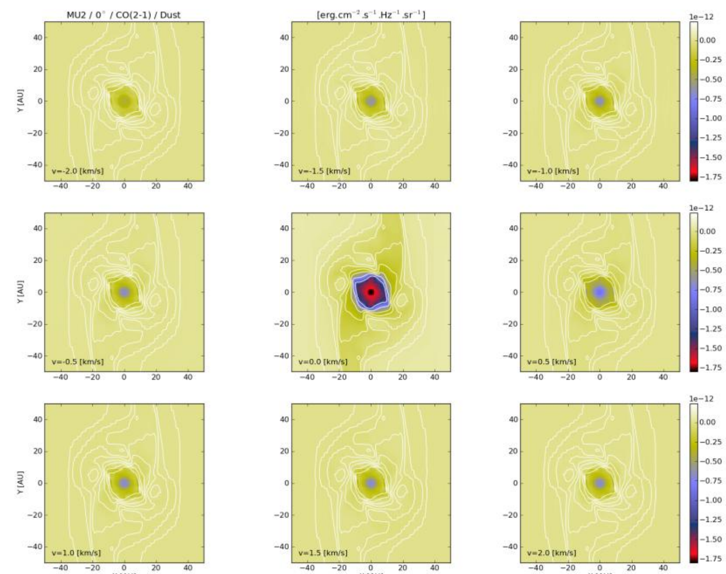
Thank you for your attention ☺
Ugo HINCELIN, LAB, Bordeaux



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