Simulations of early structure formation: Properties of halos that host primordial star formation

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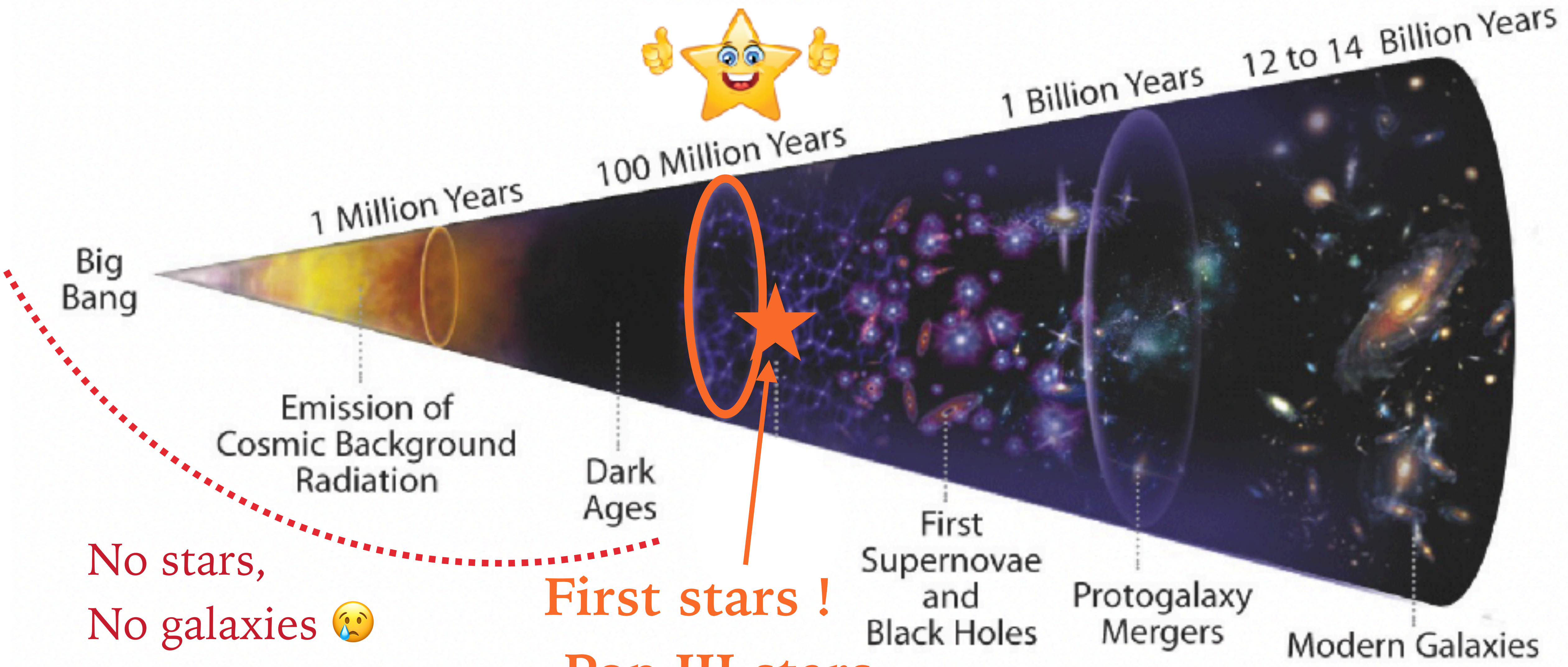
POP III STAR FORMATION



No stars,
No galaxies 😢

First stars !
= Pop III stars

z ~ 20-30
~ 100 millions years after Big Bang

- Formed in the **first bounded objects** of the universe → link cosmology to star formation
- **No dust - metal-free gas → only coolants H_2 and HD**
  - Big Bang nucleosynthesis species (76% H, 24% He, $\sim 10^{-5}$ D) → Only coolants : H_2 and HD

MOTIVATION

Big question: What is the **initial mass function** of pop III stars?

- No observation yet → rely on **numerical simulation and theory**
- Were they massive, as suggested by early first 3D simulations ?
- Or low-mass stars were also formed ?

- Do **initial conditions** of the host halo play a role?
  - Yes → *Hirano+2014, Hirano+2015*
  - To run isolated collapse → need to know precisely the initial conditions

I. NUMERICAL SET-UP : INITIAL CONDITION

What are the **physical and chemical properties** of halos leading to pop III formation ?

- Running a **cosmological simulation** with **primordial non-equilibrium chemistry**

L_{box} (cMpc/h)	Δx_{max} at $z = 18.16$	Δx_{min} at $z = 18.16$	m_{DM} ($M_\odot$)	z_{ini}	z_{end}	$M_{halo, lim}$
1	150 pc	0.14 pc	813	100	18.16	$8.1 \times 10^4 M_\odot$

Parameters of the simulation

PSMN
PÔLE SCIENTIFIQUE DE MODÉLISATION NUMÉRIQUE

~1 M CPUh

RAMSES, *Teyssier+2002*

- N-body and hydrodynamical code
- AMR technique

Coupling physics & chemistry on the fly

Cost : $\times 2 - 3$ in cpu time

KROME, *Grassi+2014*

- Solve non-equilibrium chemistry
- Include H_2 and HD in our chemical network
- 11 species : e^-, H, H^+, H^-, D, D^+, He, H_2, H_2^+, HD, and HeH^+

$$\frac{dT_{gas}}{dt} = -2T_{gas}\frac{\dot{a}}{a} + \frac{2}{3kn}\left[(\Gamma - \Lambda)_{Compton} + (\Gamma - \Lambda)_{mol} + (\Gamma - \Lambda)_{chem}\right]$$

Variation of the Temperature

I. NUMERICAL SET-UP : INITIAL CONDITION

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Parameters of the simulation

INITIAL CONDITION AT $z = 10^2$

- **Matter and DM field :**
  - MUSIC, *Hahn+2011*
  - No relative velocity between DM and baryons

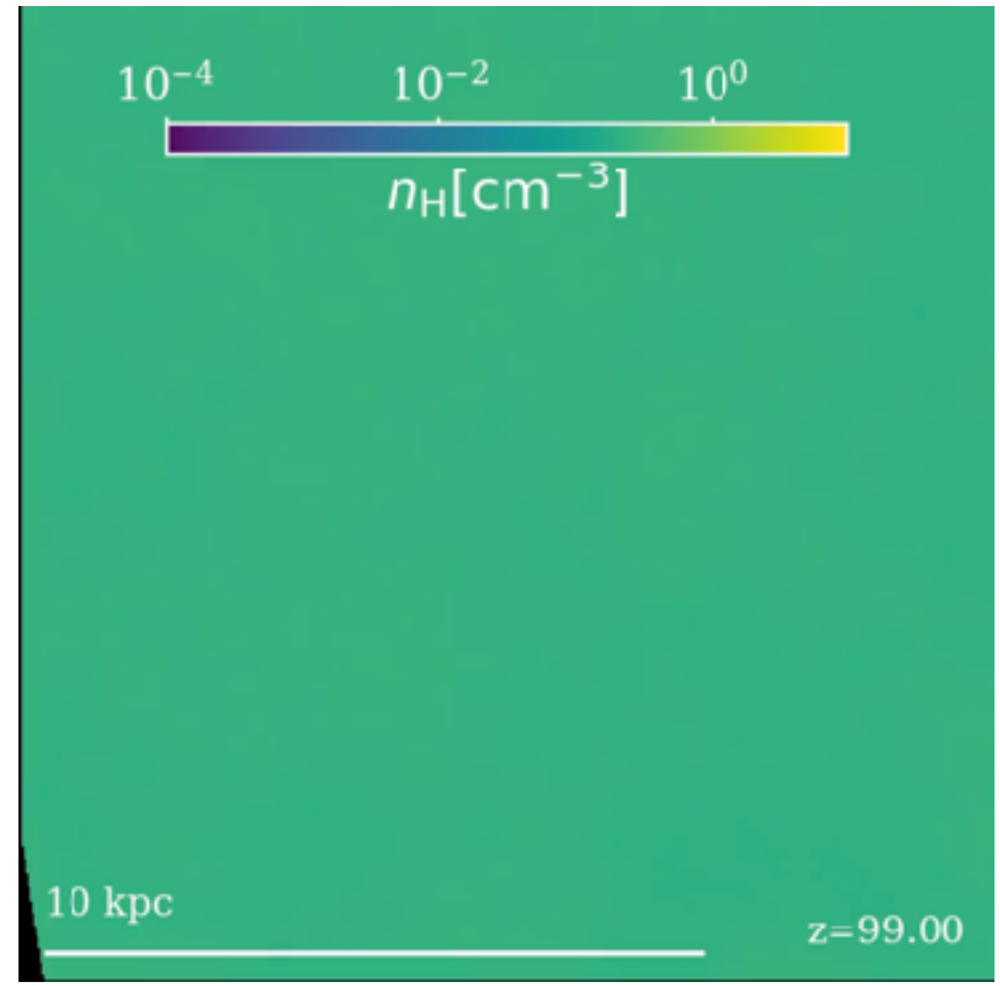
- **Chemical initial abundances :**
  - Computed from a one-zone model from the Universe from $z = 10^4$ to $z = 10^2$

I. NUMERICAL SET-UP : ANALYSIS TOOLS

What are the **physical and chemical properties** of halos leading to pop III formation ?

ANALYSIS TOOLS :

- Identify **DM halo** → Adapthop algorithm, *Aubert+2004*
- Identify **cold and dense gas clouds** → HOP algorithm,
  - Over-densities in the baryonic field *Eisenstein+1998*
  - Once **cloud gas starts to cool** → **molecular gas** grow rapidly → rapidly exceed characteristic **Jeans mass** → active sites of **star formation**
  - Check : **gravitationally unstable,** $\alpha_{vir} \leq 1$



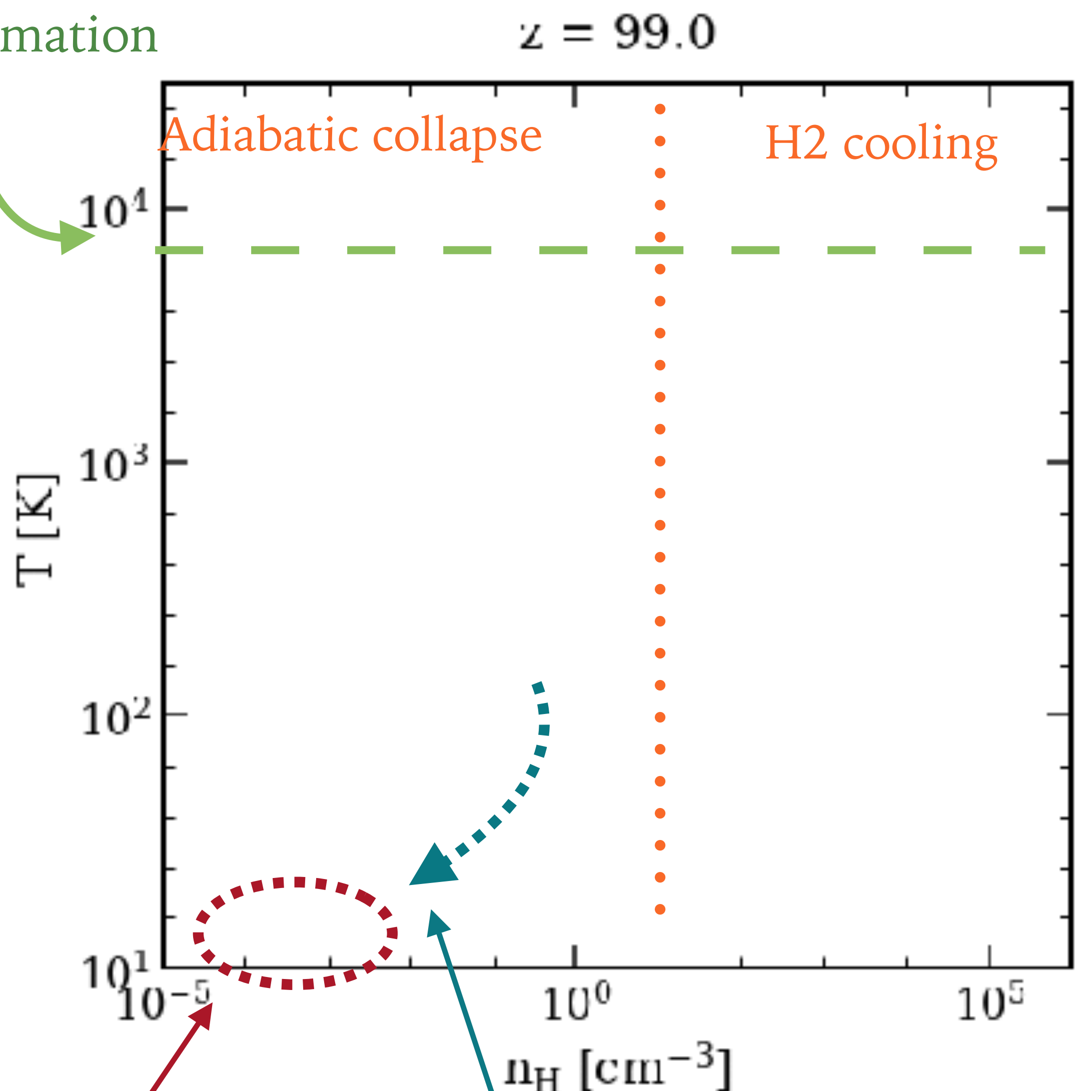
Evolution of density in our simulation

- **Properties of the hosting halo :** mass, chemical abundance, …
- **Properties of the dense gas :** cooling species, accretion rate, …

II. PRIMORDIAL HALO POPULATION : GROWTH OF PERTURBATIONS IN MATTER FIELD

Collapse of the baryonic field

Critical temperature for H2 formation

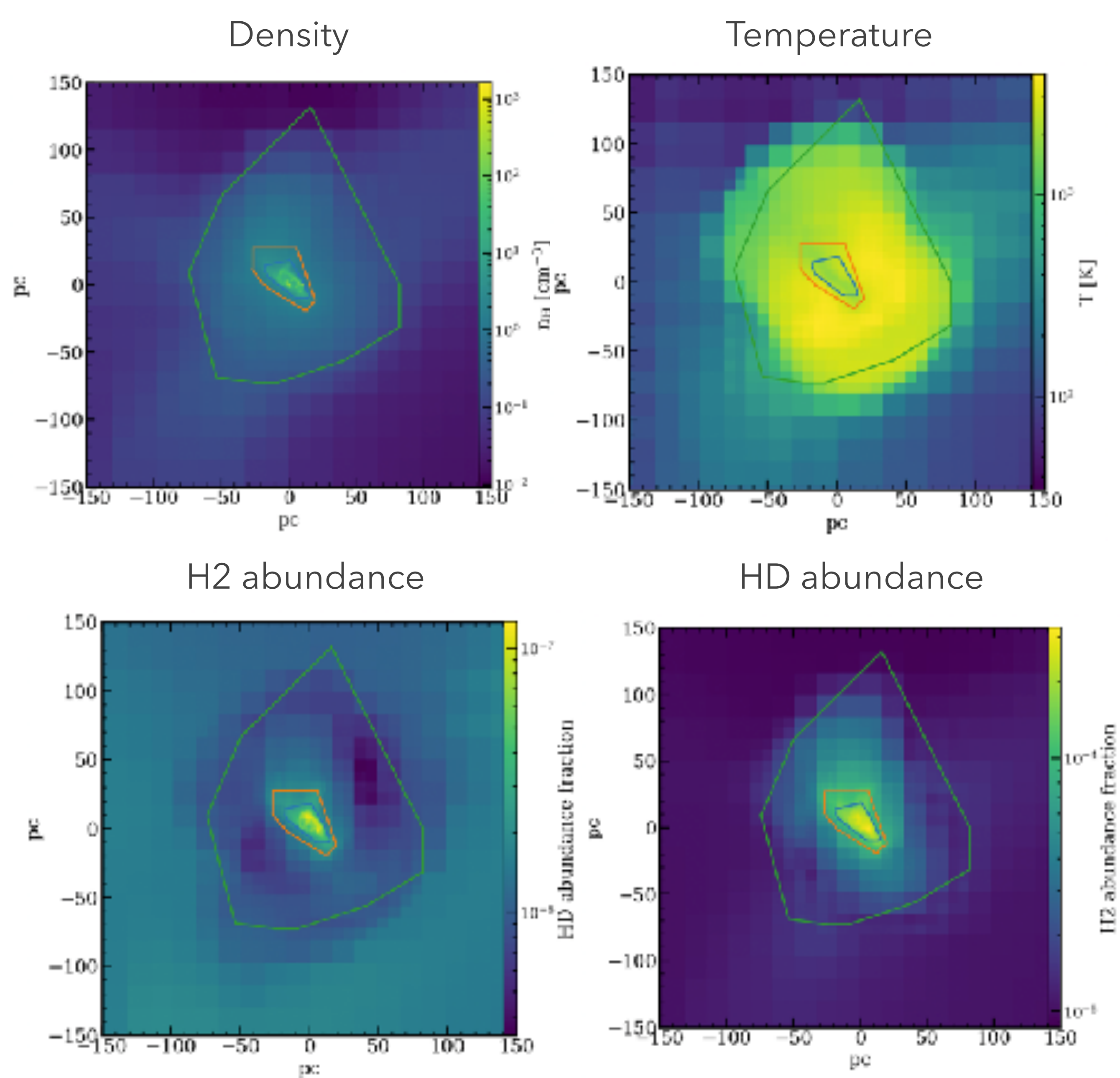


T_{floor}

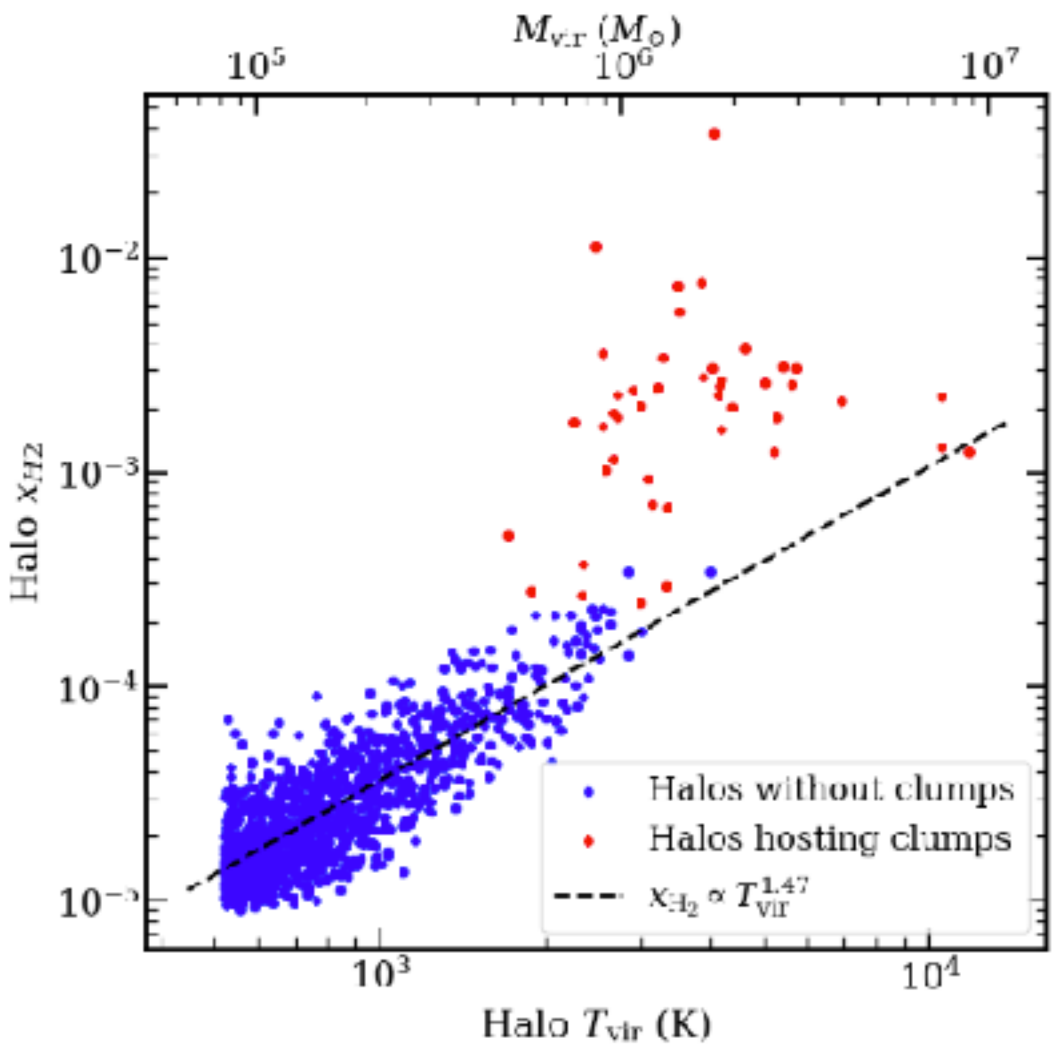
Adiabatic expansion from the universe : T_{gas} ↘

Evolution of the phase diagram T vs ρ of the entire simulation box

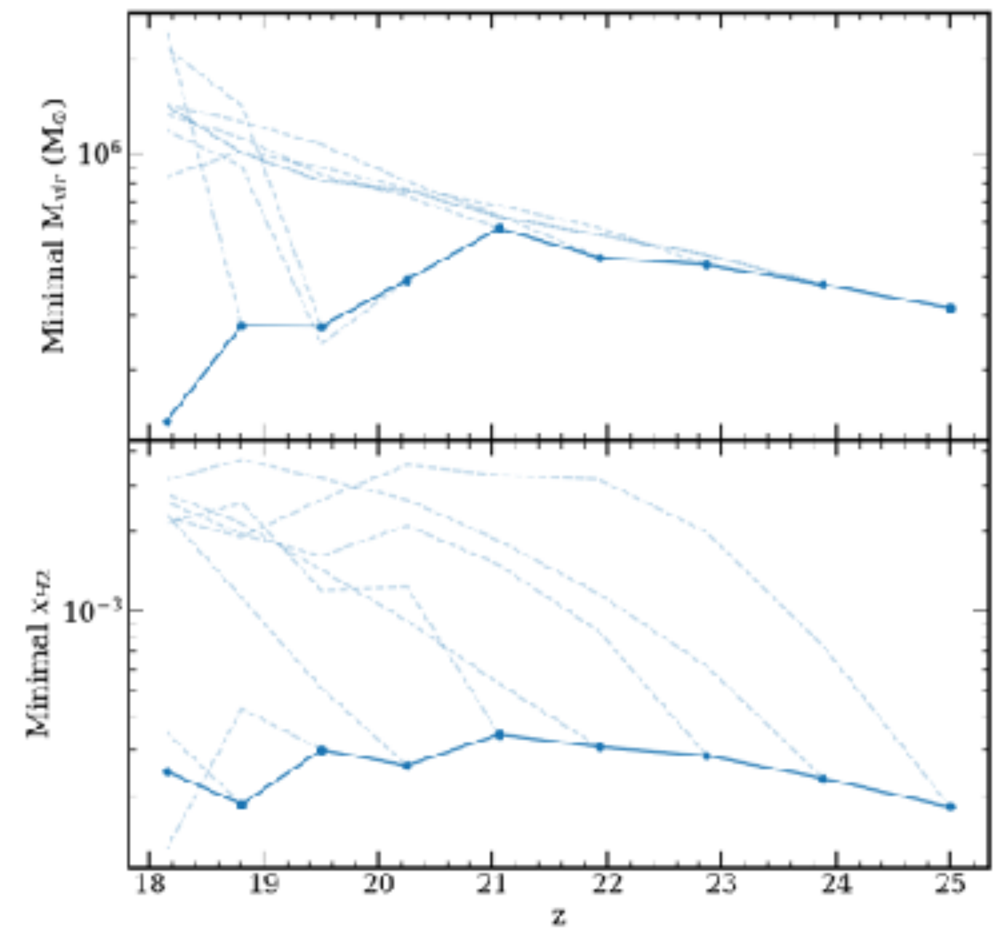
Map on one halo starting to collapse



Can we link the presence of a **cold gas clump to the halo properties** ?



The mass weighted H_2 fraction versus virial temperature from every detected halos.

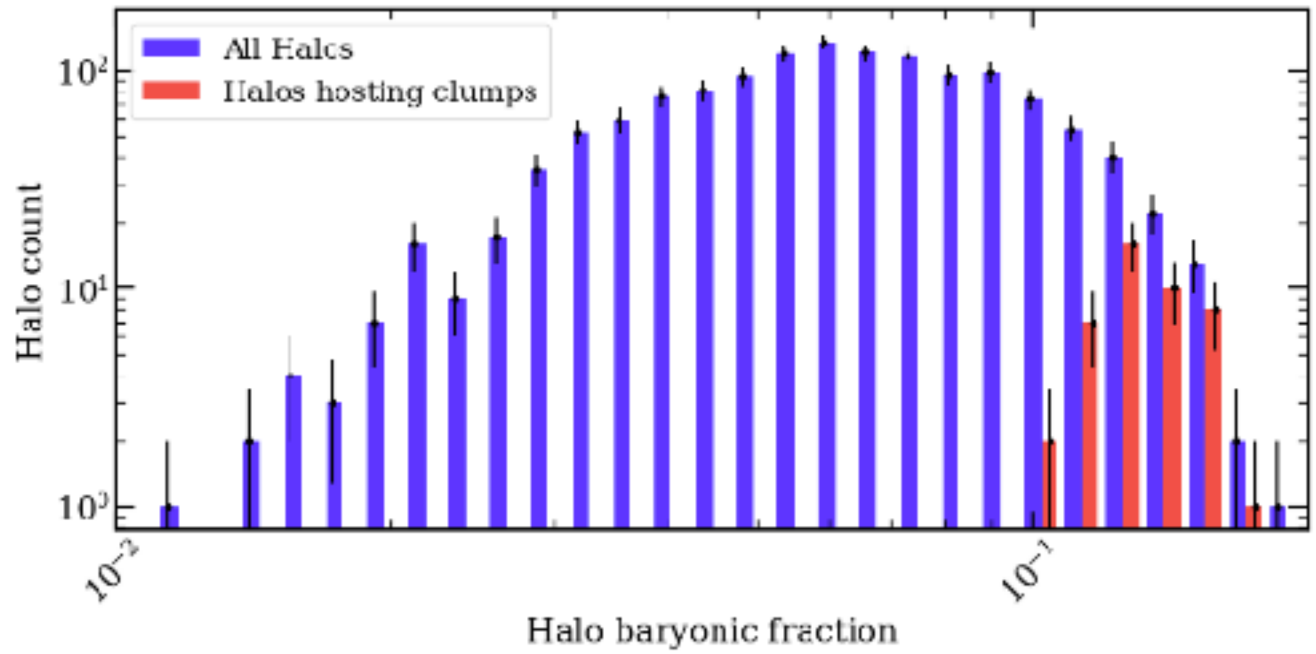


The minimum mass of halos hosting gas clumps detected with our algorithm.

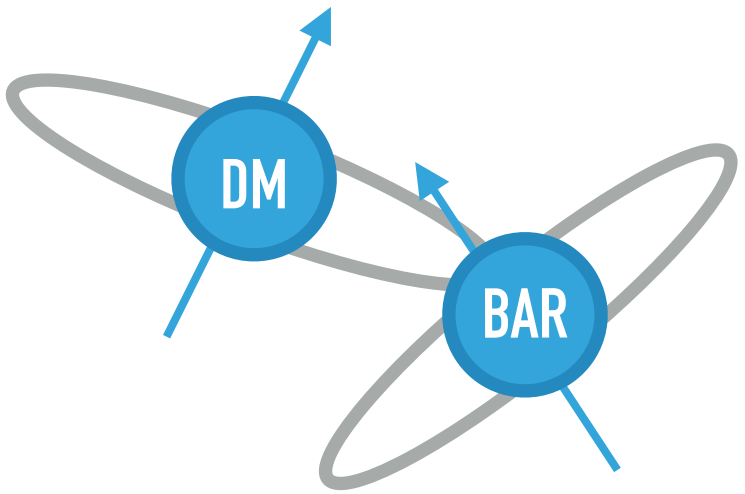
Lenoble+2024

- Presence of a **cold gas clump** → $x_{H_2, halo} \geq 3 \times 10^{-4}$
- **Minimum halo mass** hosting a cold gas clump $\sim 4 \times 10^5 M_\odot$ and weakly depend on z

What are the baryonic and DM properties of theses halos ?



Histogram of the probability density of the baryonic fraction for the all population of halos (blue bars) and those hosting clumps (red bars).



- The baryonic fraction follow **2 different distributions,** $f_{\rm b,crit} = 10^{-1}$
- DM and baryons **velocity fields are not aligned**

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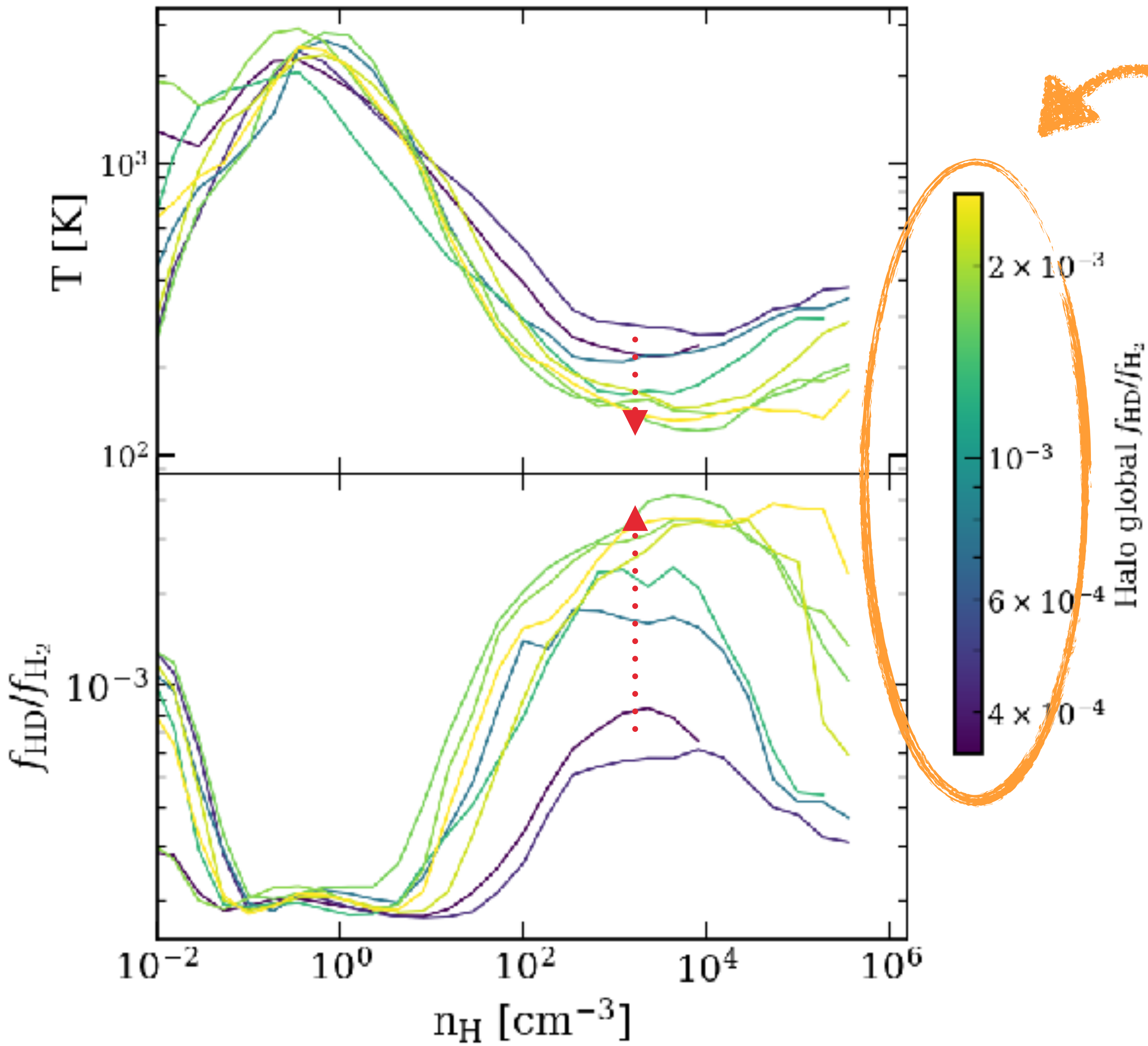
III. THE COOLING SPECIES



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- **HD abundance** is not the same in all halos
  - $\sim$10% of halos with $f_{HD}/f_{H_2} \geq 10^{-3}$ at $z = 19$
- **HD cooling** can cool the gas to the CMB floor, *(Ripamonti+2007)*
  - Theses halos are **colder**
  - Temperature in the range $10^2 - 10^5\,\mathrm{cm}^{-3}$ depends a lot on the HD abundance.

III. THE COOLING SPECIES

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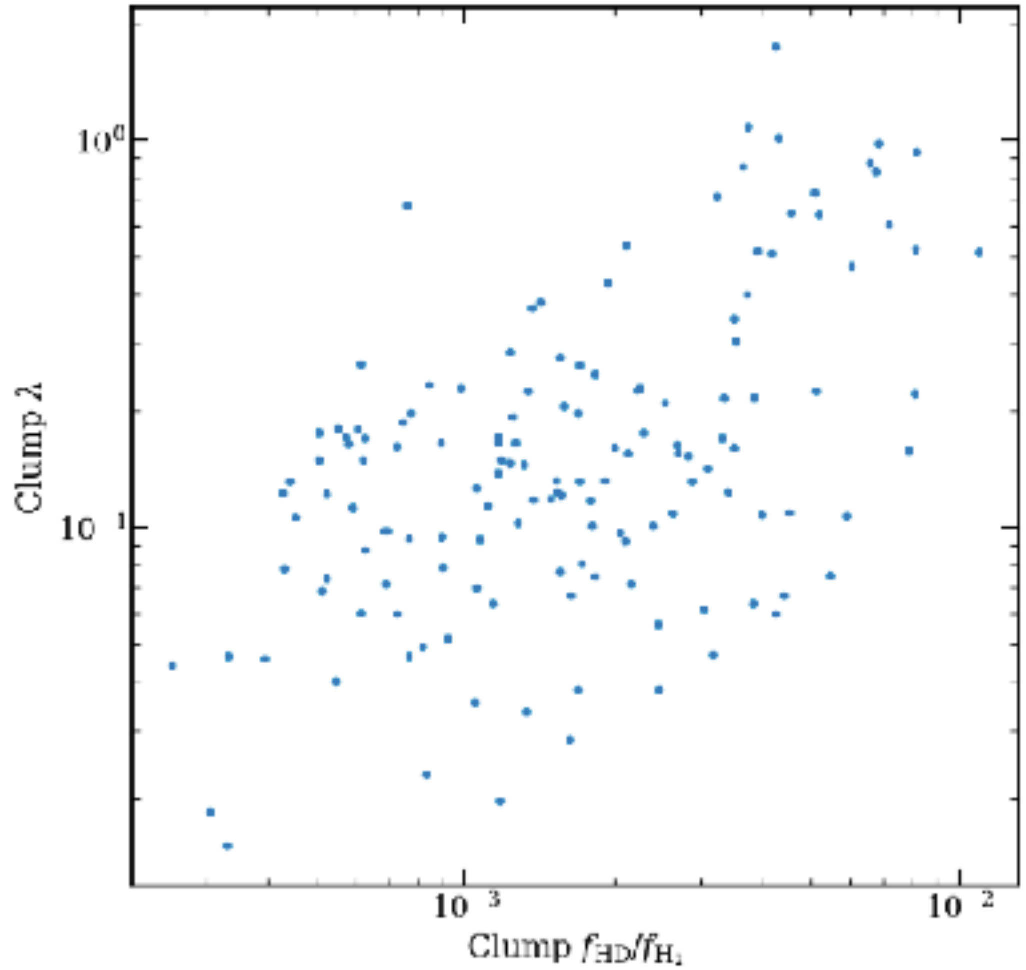
Spin parameter = Degree of rotation of a halo



x_{HD}/x_{H_2}

Spin parameter vs H2 fraction in our gas clump at z = 19.8

- Trend between f_{HD}/f_{H_2} and the **spin parameter** :
  - Higher spin parameter → longer collapse → Higher f_{HD}/f_{H_2} fraction

CONCLUSION

- **Properties of halos that host primordial star formation**
  - The **minimal halo mass** for halo hosting pop III star formation : $\sim 7 \times 10^5 M_\odot$
  - The **minimum** H_2 abundance for a halo of $x_{H_2} = 2 \times 10^{-4}$
  - The **HD abundance is not uniform among the halo population**.
    - Higher HD abundance $\rightarrow$ gas colder in the density range $10^2 - 10^5\ \mathrm{cm}^{-3}$
    - The higher fraction of HD $\leftrightarrow$ higher spin parameter of the dense gas.
- Current work : **sample the IMF with sinks particles**
  - **Zoom-in simulation** $\rightarrow$ much higher resolution until sink formation
  - **Isolated collapse** $\rightarrow$ distribution of initial condition to sample pop III IMF

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I. POP III FORMATION : EVOLUTIONARY SEQUENCE

Adiabatic collapse to the virial temperature

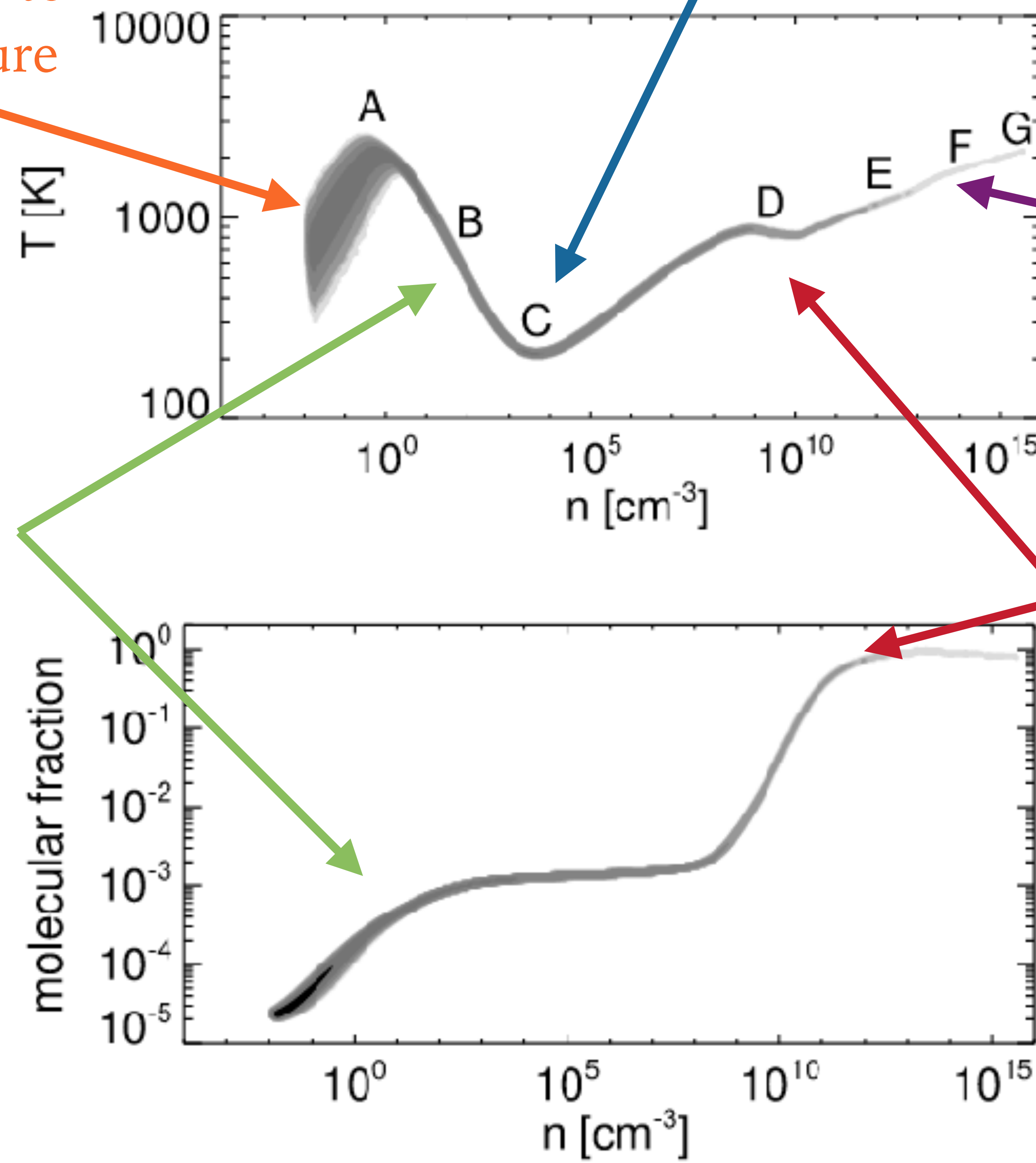
H2 cooling saturates

E. Gas optically thick to **H2 line cooling** rate decreases.

F. Cooling by collision-induced emission

G. H2 dissociation.

H2 formation by two-body reactions + H2 cooling



H2 formation by **three-body reactions**. Gas fully molecular.

Yoshida+2006