Formation of zero- and low-metallicity stars

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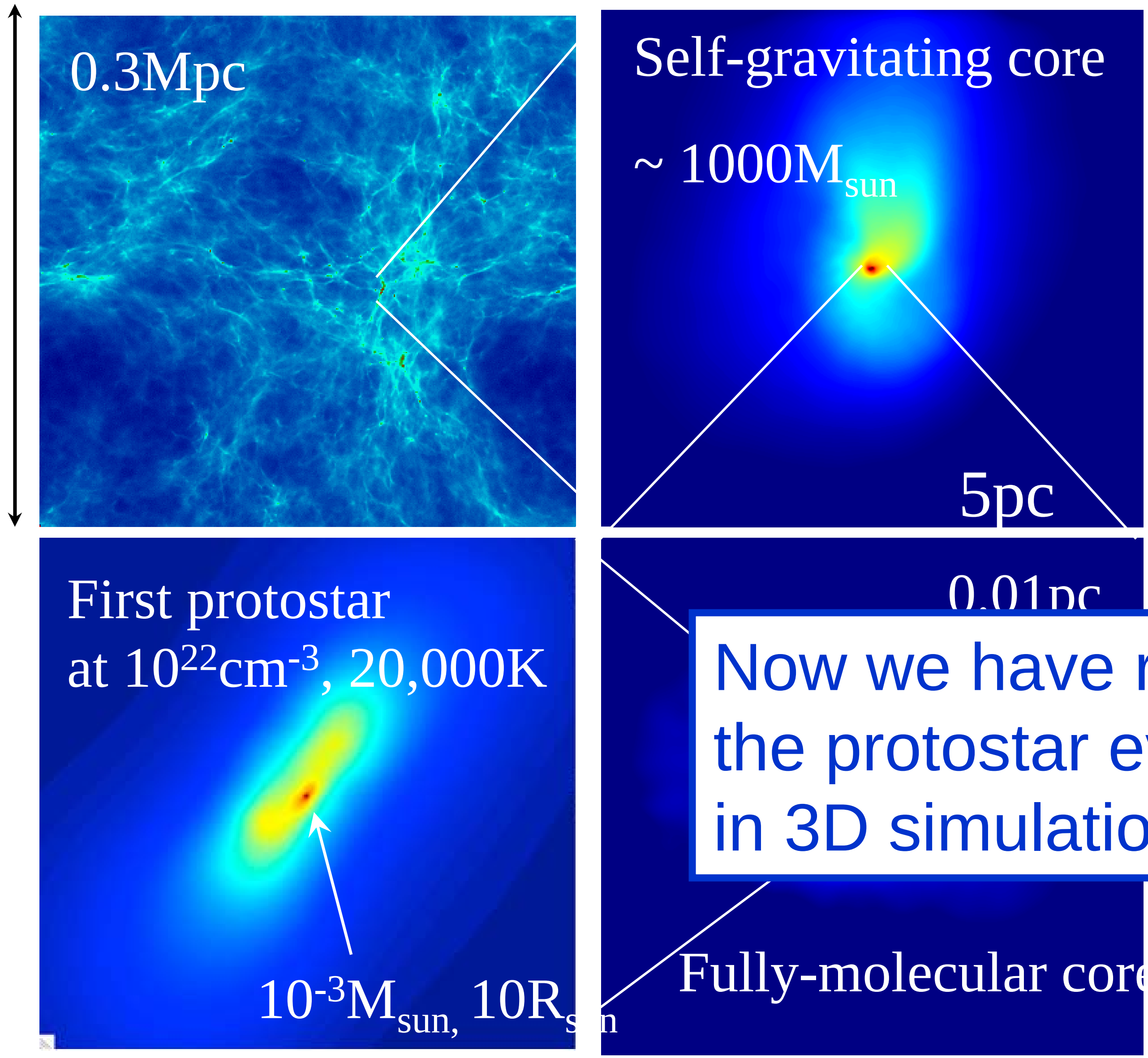
CONTENTS

I) Zero-metallicity star formation

- first-generation stars
  - Pop III.1: (H_2 cooling)
- second-generation stars
  - Pop III.2:
    1) Star formation in ionized regions (HD cooling)
    2) Star formation in extremely strong UV field (atomic cooling)

II) Low-metallicity star formation

First Protostar Formation

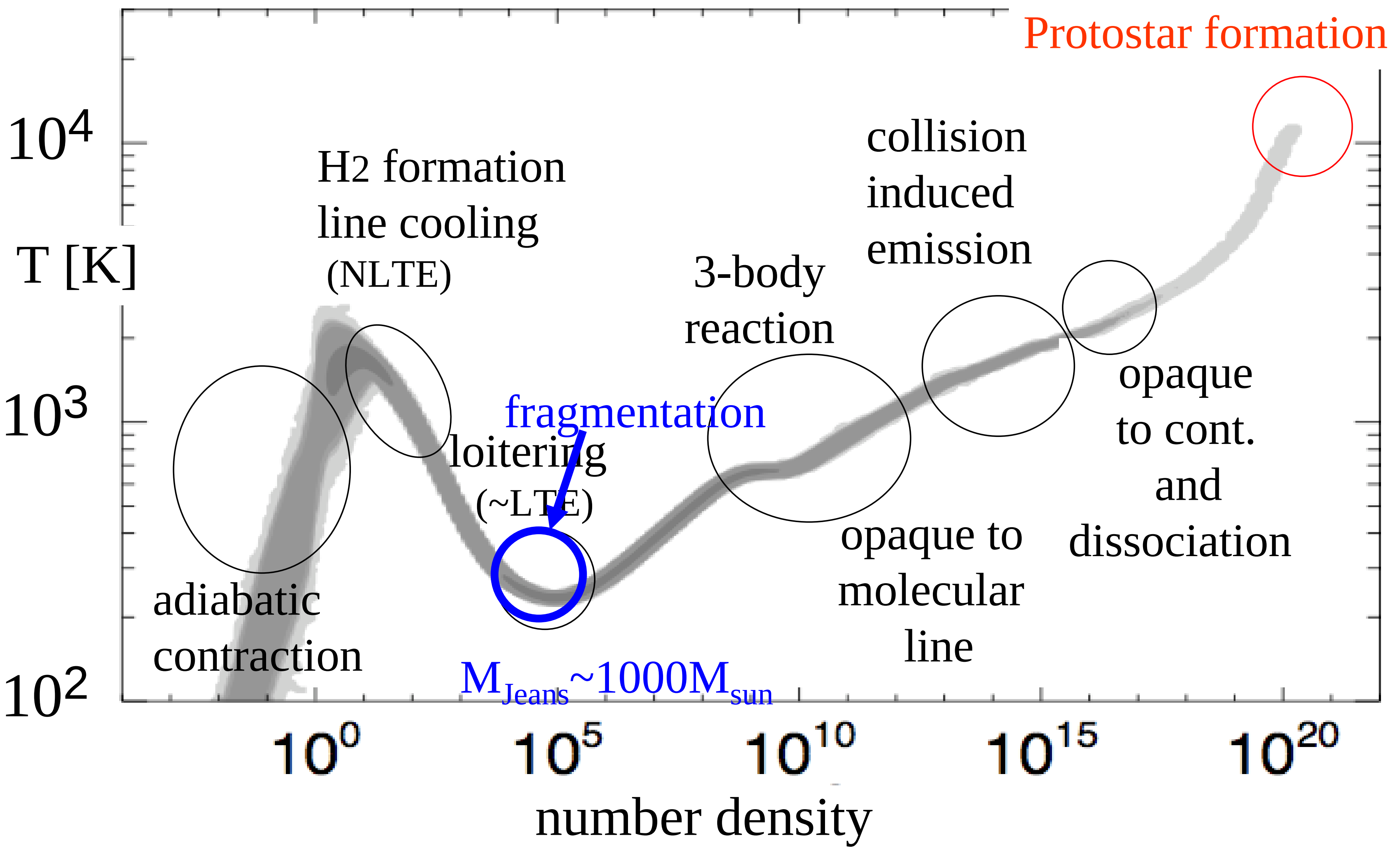


Now we have reached the protostar even in 3D simulation.

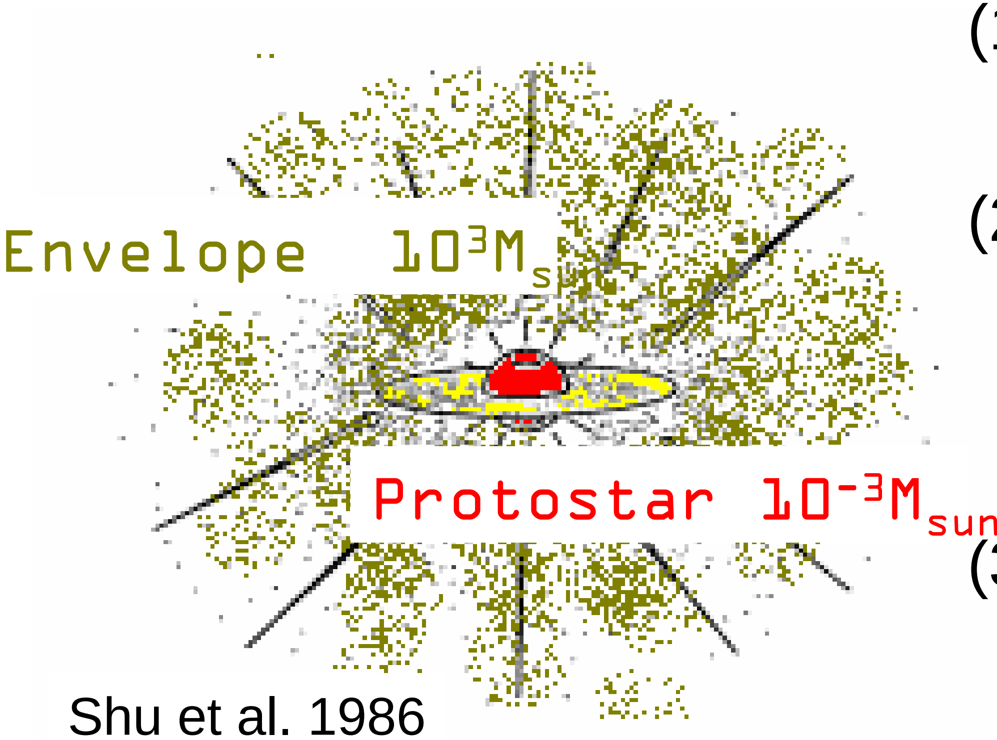
1D:
Omukai & Nishi 1998
3D:
Abel et al. 2002
Bromm & Loeb 2004
O'Shea & Norman 2006

Yoshida et al. 2007

Thermal evolution of a primordial gas



Accretion Phase



Shu et al. 1986

(1) Massive Envelope
~a few $100M_{sun}$

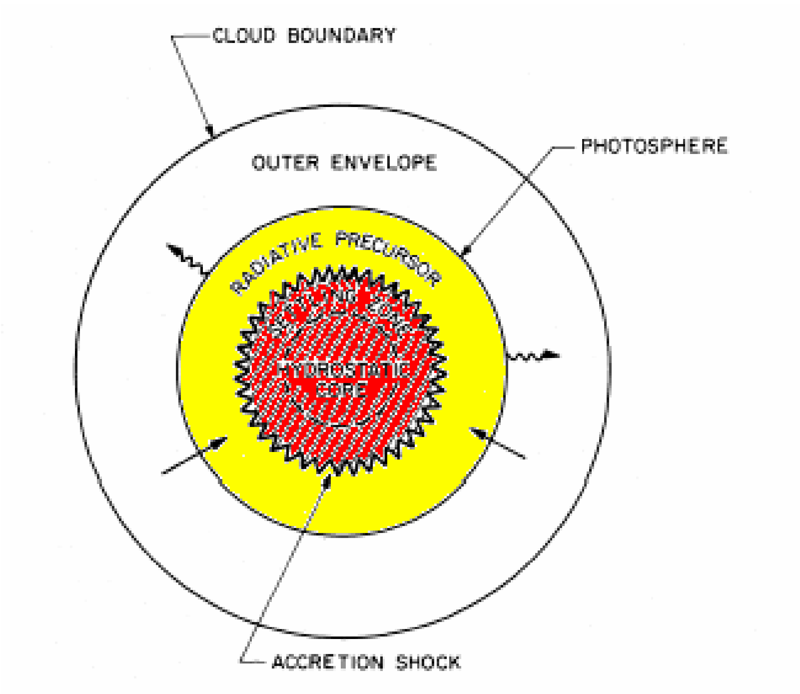
(2) High accretion rate
$dM/dt \sim c_s^3/G \sim T^{3/2}$ (~300K)
$=10^{-3..-2}M_{sun}/yr$
(contemporary: 10^{-6}-$10^{-5}M_{sun}/yr$)

(3) No dust in envelope
➔ lower opacity and
radiation pressure

Protostars in Accretion Phase

Method

(Stahler et al. 1986)



Protostar

hydrostatic

Eq.s for Stellar Structure

▯ [radiative shock condition]

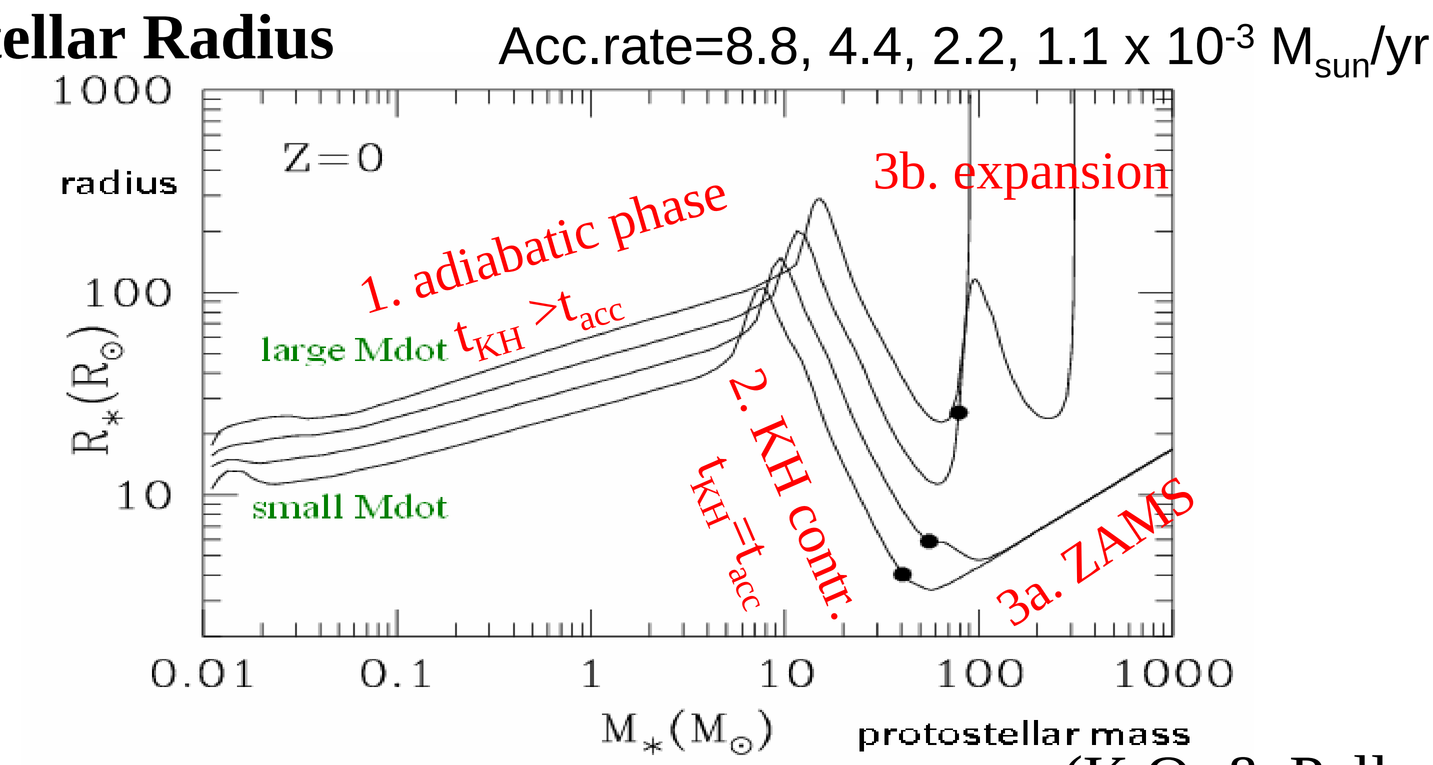
ENVELOPE

Stationary Accretion

radiative precursor(< R_{ph}) stationary hydro

outer envelope ($>R_{ph}$) free fall

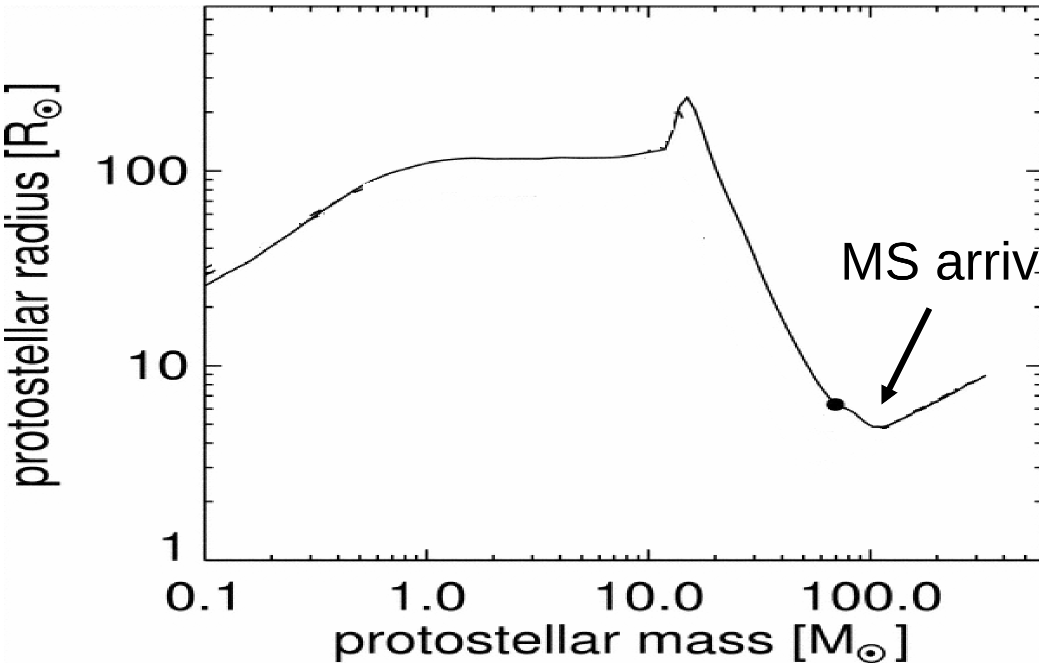
Accreting Metal-free Protostar



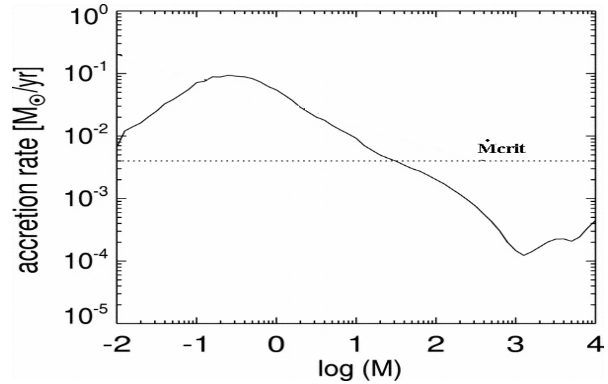
(K.O. & Palla 2003)

- Due to rapid accretion, stars become massive before the onset of H burning (at 40-100M_{sun}).
- Accretion continues if accretion rate $<M^{dot}_{crit}=4\ 10^{-3}M_{sun}$/yr
- Otherwise ($>M^{dot}_{crit}$) , no stationary solution at $>\sim100M_{sun}$

Using realistic accretion rate



Yoshida, K.O., Hernquist, Abel 2006



protostellar mass

The protostar reaches MS at ~100Msun

The accretion continues unimpeded.

Since (MS lifetime~$3x10^6$yr) > (core free-falltime~$3x10^5$yr), most of the core material can accrete within stellar lifetime.

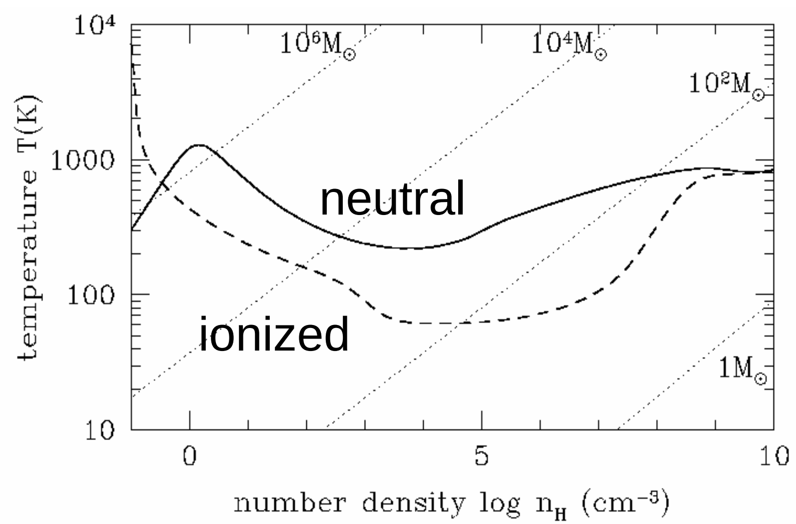
Very massive star (~ a few 100Msun) is formed

Second-Generation Stars

- Different Initial Condition
  - Ionization by the first stars
  - Density fluctuation by SN blast wave, or HII region
- Different Environment
  - External Radiation (UV, X, Cosmic Ray)
- Different Composition
  - Metal Enrichment
  - Dust formation

Pop III.2:
Star formation in an initially ionized gas

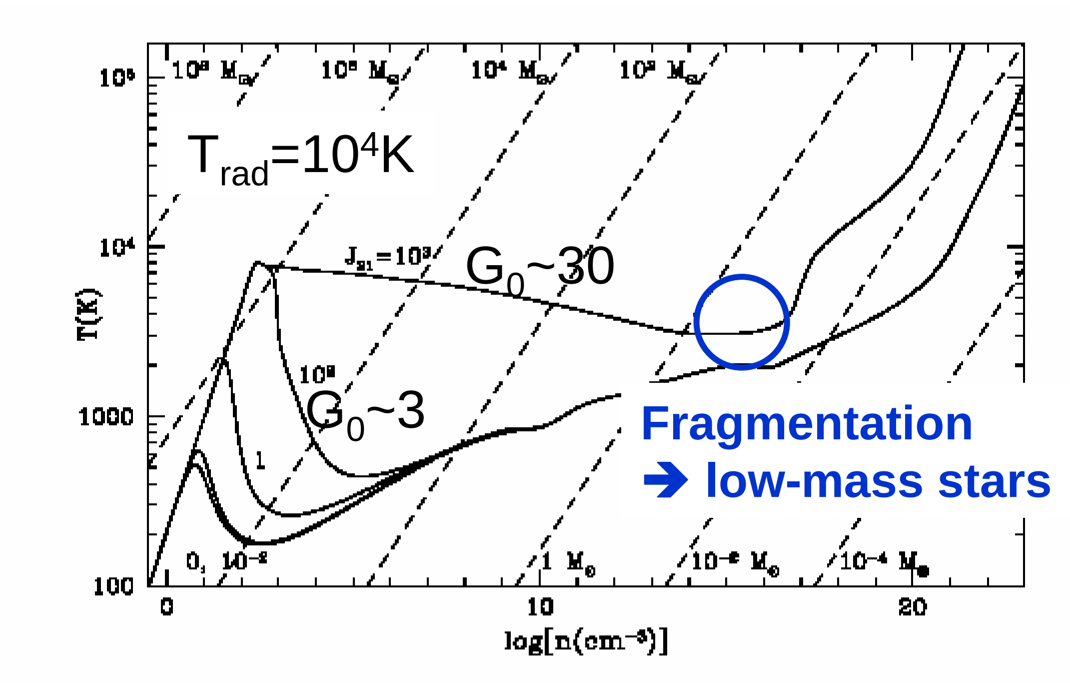
Uehara & Inutsuka 2002
Nagakura & KO 2005
Yoshida, KO, Hernquist 2007



- Ionized environments e.g., fossil HII region, SN blast wave, structure formation shock
- HD formation and cooling
- Lower (~a few 10Msun)-mass star formation

➔Naoki Yoshida's talk

Pop III.2: In strong FUV environment

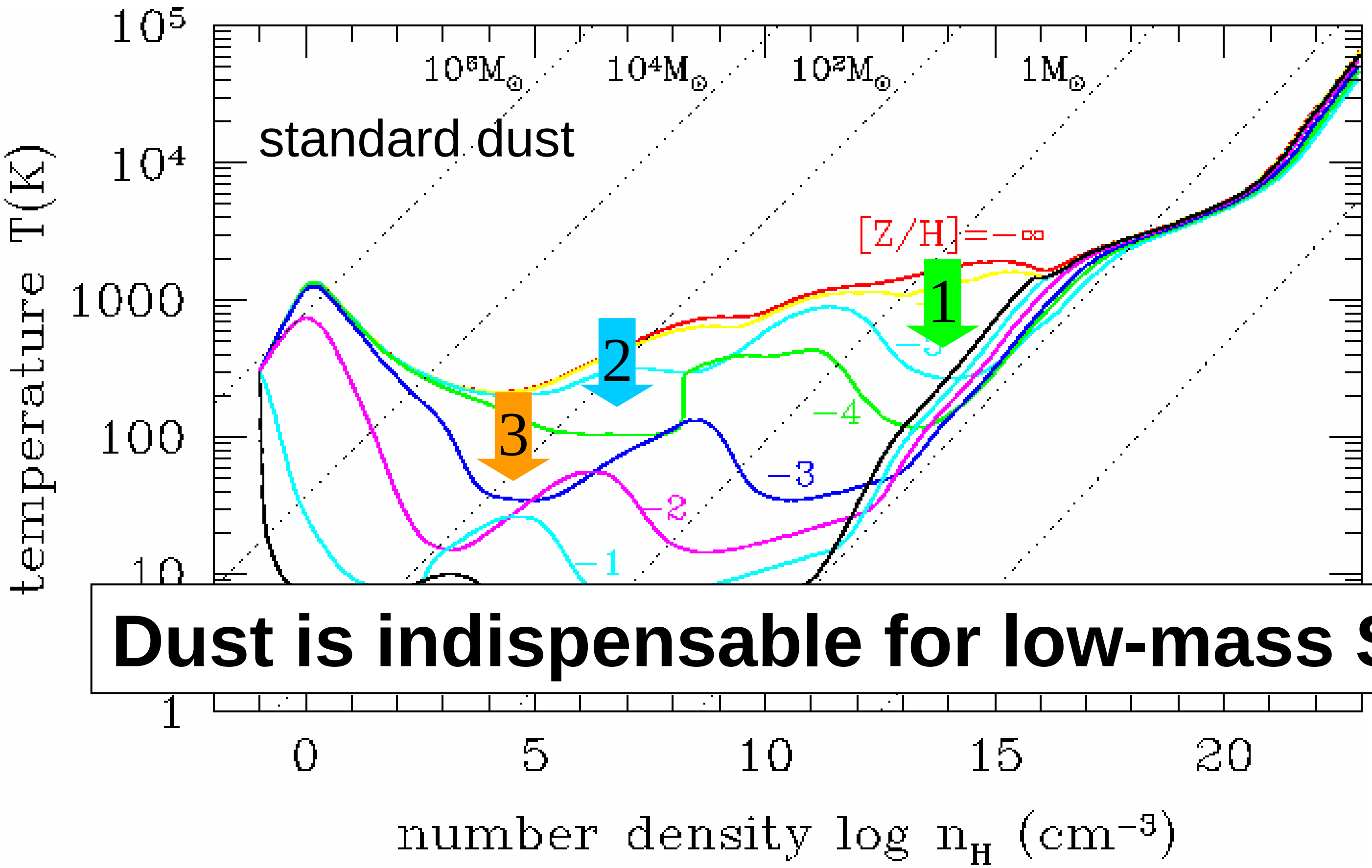


Omukai 2001

- Under very strong FUV field $G_0>30$ ($J_{21}>10^3$), no H2 formation
- New pathway to stars open "atomic mode"
  Lyα→ H^- f-b cooling
- Jeans mass at T minimum $<1M_{sun}$

Metallicity effects: thermal evolution

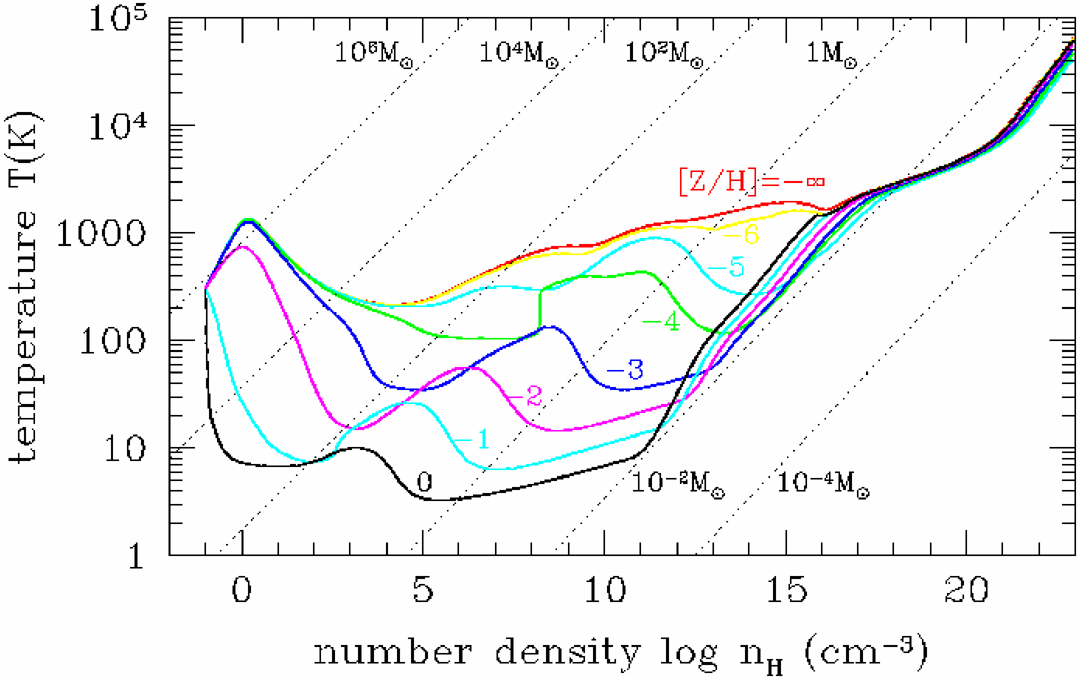
1) Cooling by dust thermal emission: [Z/H] > -5
2) H_2 formation on dust : [Z/H] > -4
3) Cooling by metal lines: [Z/H] > -3



Dust is indispensable for low-mass SF

K.O., Tsuribe, Schneider & Ferrara (2005)

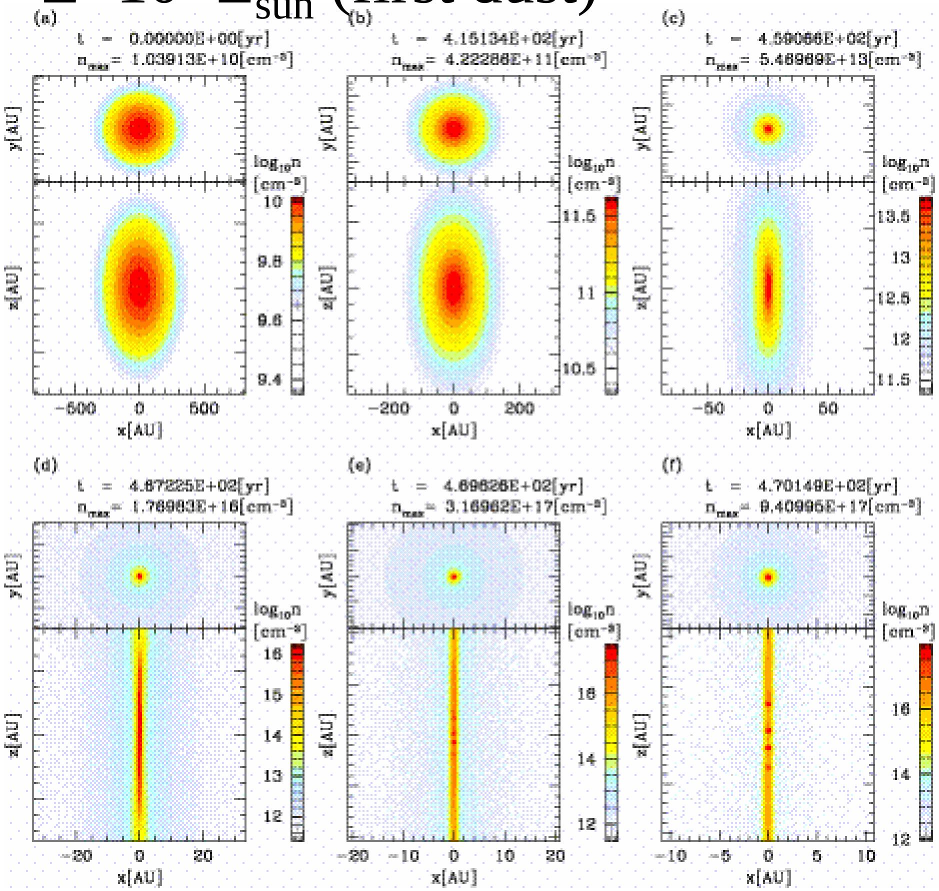
How much is the critical metallicity (gas-dust ratio) for low-mass SF by dust cooling ?



Dust-induced fragmentation

Tsuribe & K.O. (2006)

$Z=10^{-5}Z_{sun}$ (first dust)



- With gas-dust ratio $Z>\sim10^{-6}Z_{sun}$ (first dust: smaller grains)
  ➔low-mass fragments by dust cooling

Standard dust

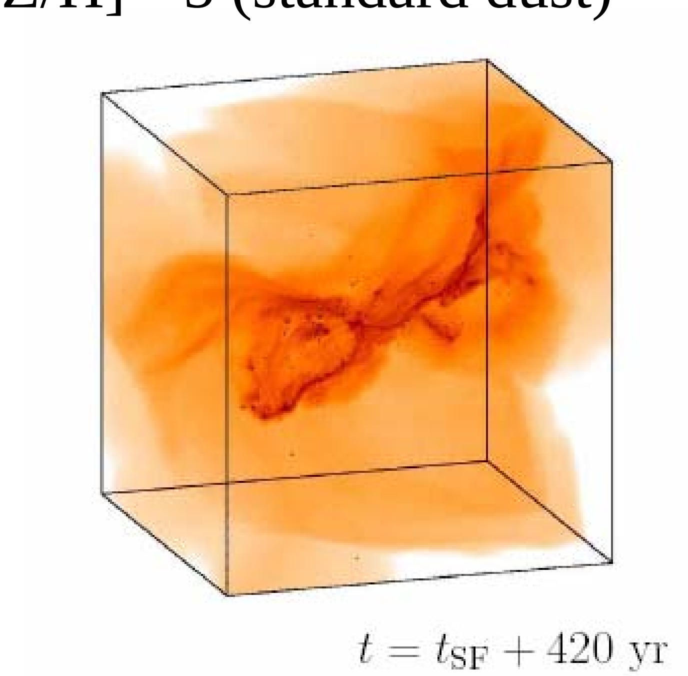
$$Z_{cr}\sim10^{-6}\text{-}10^{-5}\ Z_{sun}$$

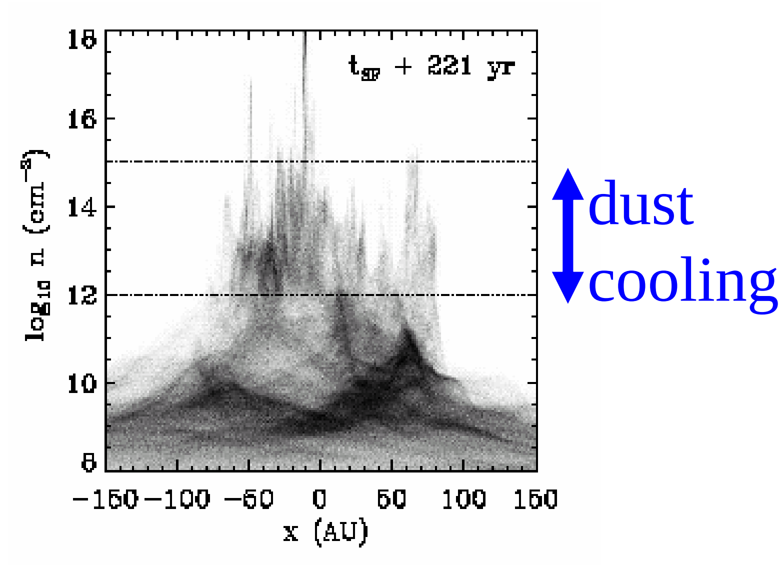
First dust

In more realistic setting

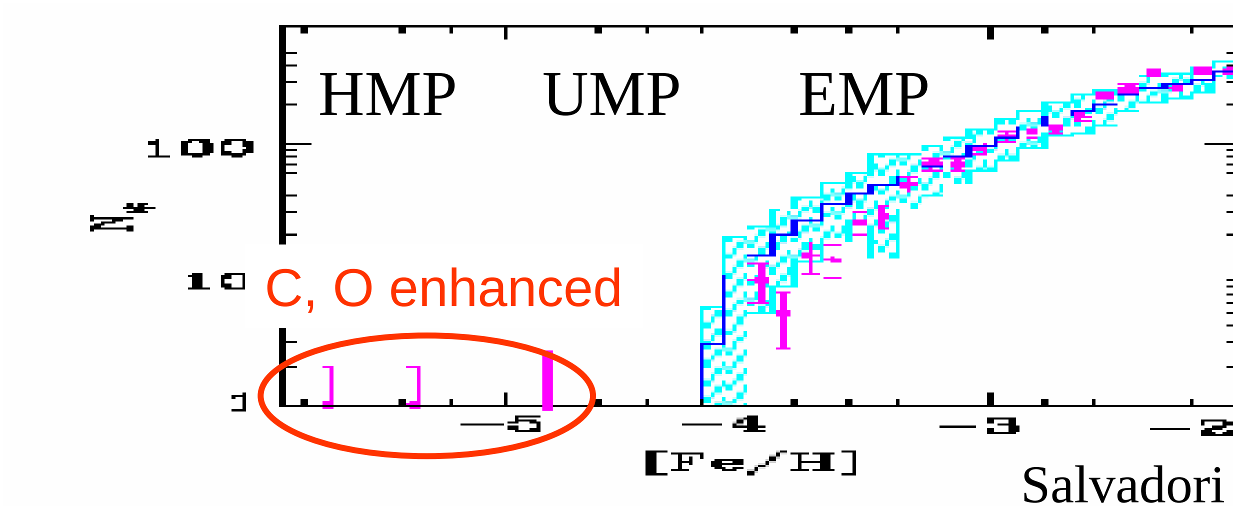
Clark, Glover, & Klessen (2007) confirmed fragmentation during the dust-cooling phase.

[Z/H]=-5 (standard dust)





Cutoff at [Z/H]~-4 in stellar metallicity distribution function



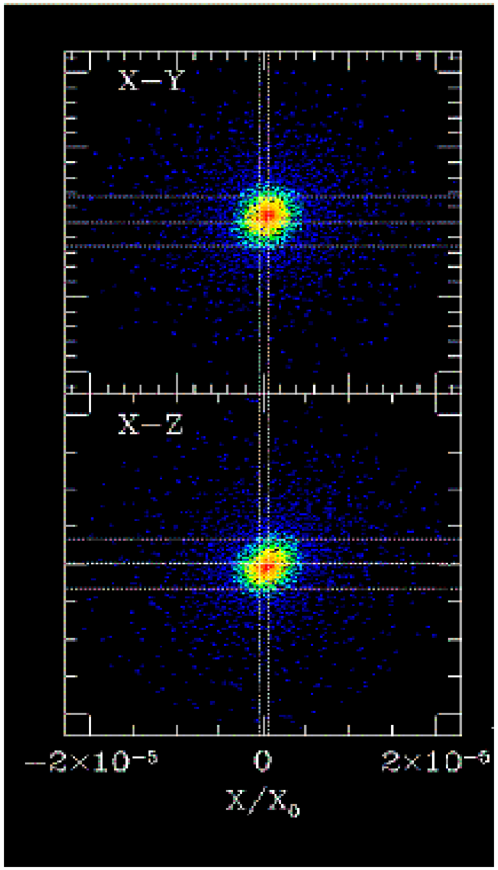
Salvadori et al. 2006

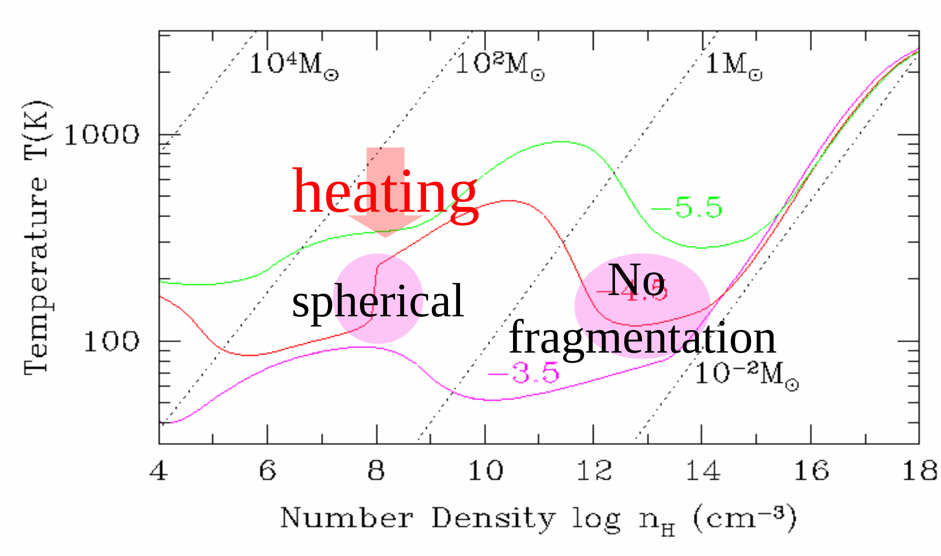
- Several 100 of EMP stars
- Only three HMP or UMP stars:
  all C, O enhanced with [Z/H]>-4
  ➔Sharp cutoff at [Z/H]~-4
- Even if C,O in HMP stars are *a posteriori* (e.g., accretion from a binary companion), scarcity of UMP stars remains a mystery.
  (“metallicity desert”)

Case of [Z/H]~-5…-4

Tsuribe & K.O. (2007) in prep.

[Z/H]=-4.5, first dust

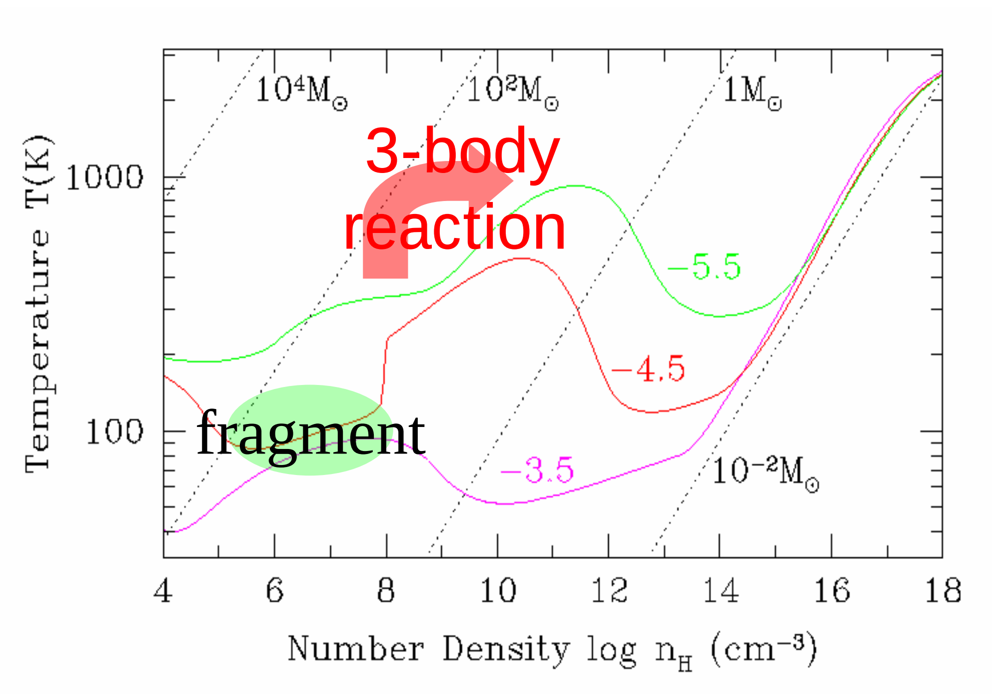




- Sudden H_2 formation heating ➔ very spherical hydrostatic core
- No fragmentation in the dust-cooling phase

Why sudden heating only in [Z/H]~-5..-4 ?

Temperature evolution



- In [Z/H]<~-5, temperature is already high and heating is not so remarkable.
- In [Z/H]>~-4, H_2 formation is almost completed by dust reaction before 3 body reaction starts.
- in [Z/H]~-5..-4, 3-body reaction starts at low-temperature.
  This results in sudden heating.

➔fragment mass
~10-100M_{sun}
No low-mass stars

Summary 1: zero-metallicity SF

- **First generation**

  1) Pop III.1 in small halos, H_2 cooling

  ---- 100-1000M_{sun}

  Up to protostar formation: theoretically converged

  Accretion phase: only simple modeling available

- **Second generation (and later)**

  2) Pop III.2(1) in ionized gas, HD cooling

  ---- 10-100M_{sun}

  Only the case of the fossil HII region explored in some details.

  Other cases (large halos, SN shells, etc.) not yet studied well.

  3) Pop III.2(2) in strong FUV, atomic cooling

  Fragmentation mass-scale controversial ----1M_{sun} or $10^5 M_{sun}$?

Summary 2: low-metallicity SF

- Dust is indispensable for low mass SF
- Critical metallicity for low-mass SF
  $Z_{cr} \sim 10^{-6} Z_{sun}$ (first dust)
- H_2 formation heating prevents low-mass SF in [Z/H]=-5..-4

Dust nature in the early universe is quite uncertain.