Radiative feedback from the first stars and the formation of the second-generation stars

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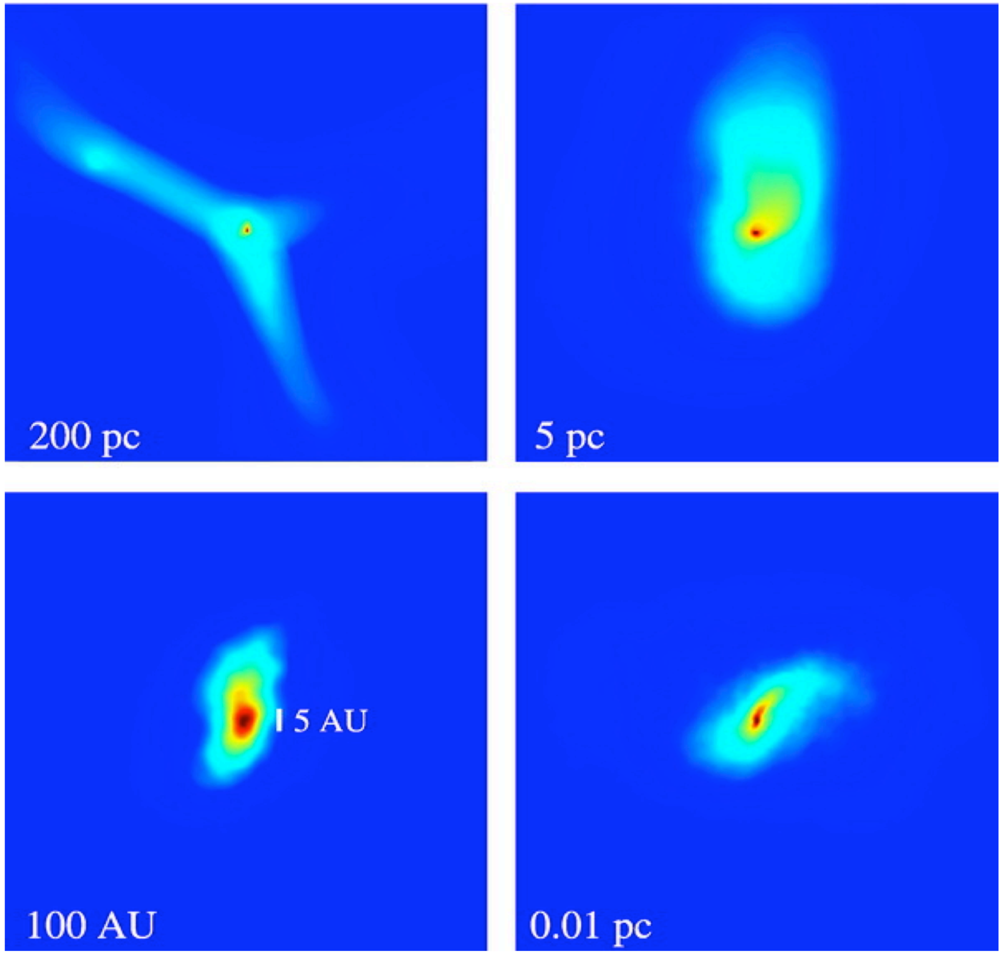
Contents

Three modes of primordial star formation

- First-generation stars (H_2 mode)
- Second-generation stars
  - Star formation in fossil HII regions (HD mode)
  - Star formation in extremely strong UV field (atomic mode)

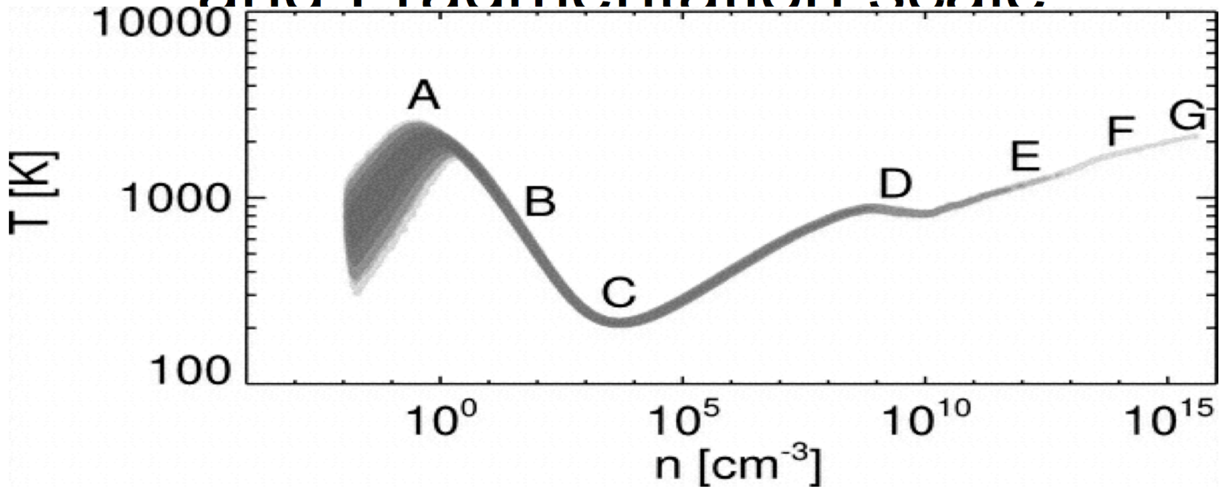
First Stars



Yoshida, K.O., Hernquist, Abel (2006)

Mass scale
of dense cores
(Fragmentation
scale)
~$1000M_{sun}$

Thermal evolution of primordial gas and Fragmentation scale



Temperature minimum at critical density for LTE (n_{cr}~10^4cm^{-3}; C)

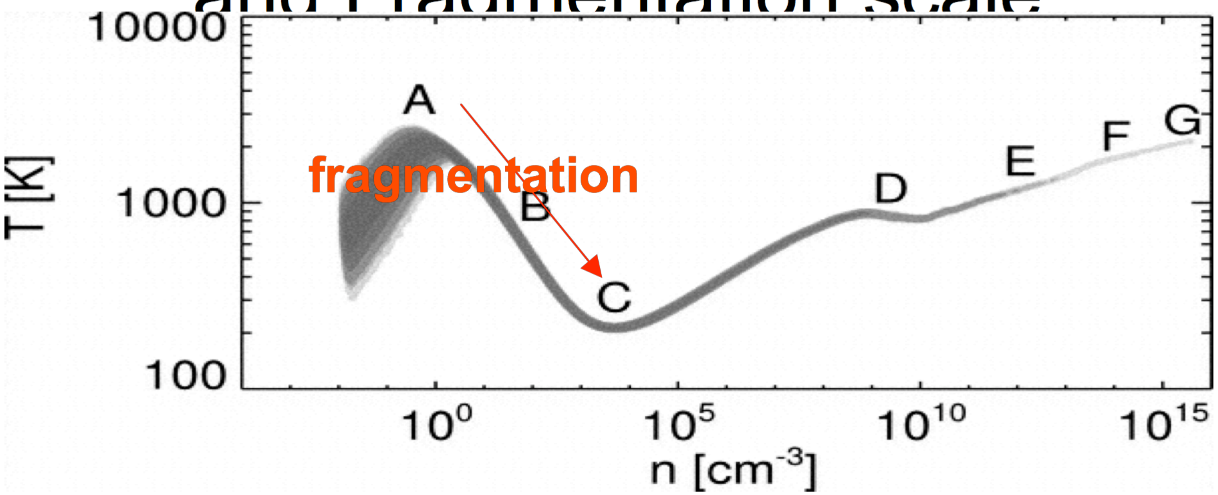
- Λ : Cooling rate (per unit mass)
  $\propto$ n ($n < n_{cr}$)
  ~ const. ($n > n_{cr}$)
- Γ : Compressional heating rate
  $\propto$(free-fall time) $^{-1}$
  $\propto n^{1/2}$

For $n > n_{cr}$ Γ dominates Λ
➔ T increases

Fragmentation

T decreases→ Easily fragment
T increases→ Hardly fragment
➔Mass scale of fragmentation
~Jeans mass
at C(**3000/cc, 200K)**
~1000M_{sun}

Thermal evolution of primordial gas and Fragmentation scale



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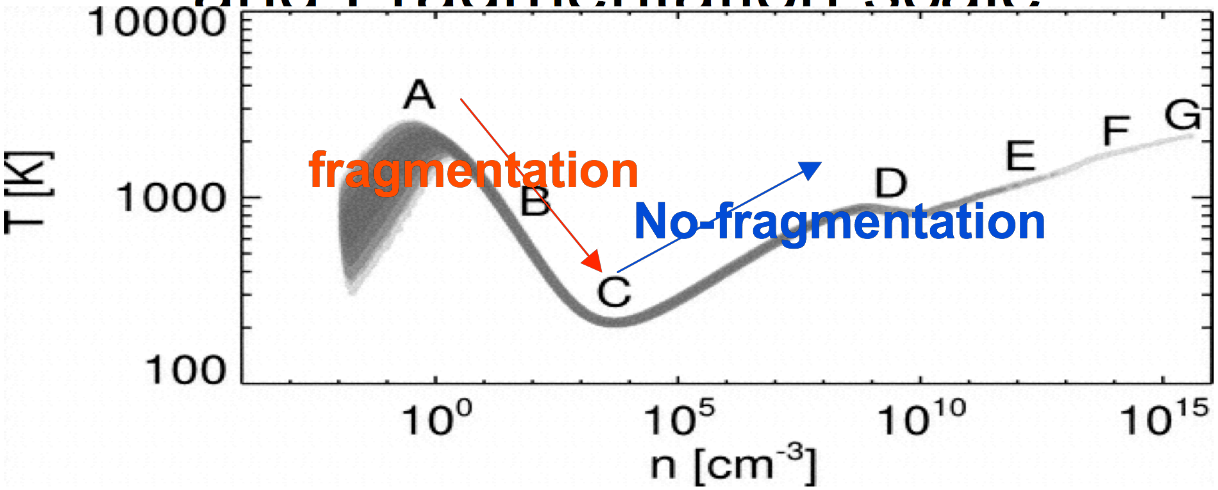

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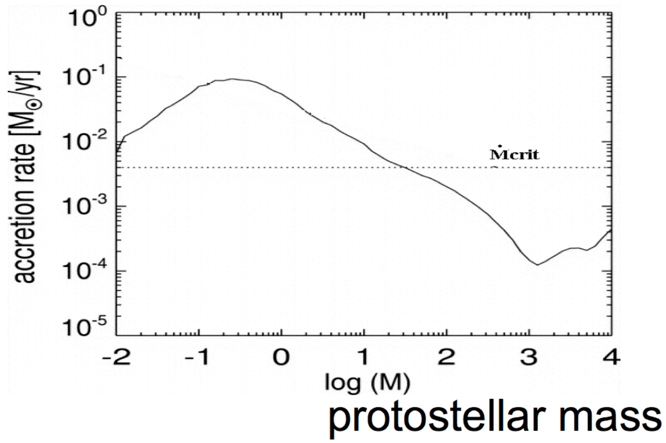
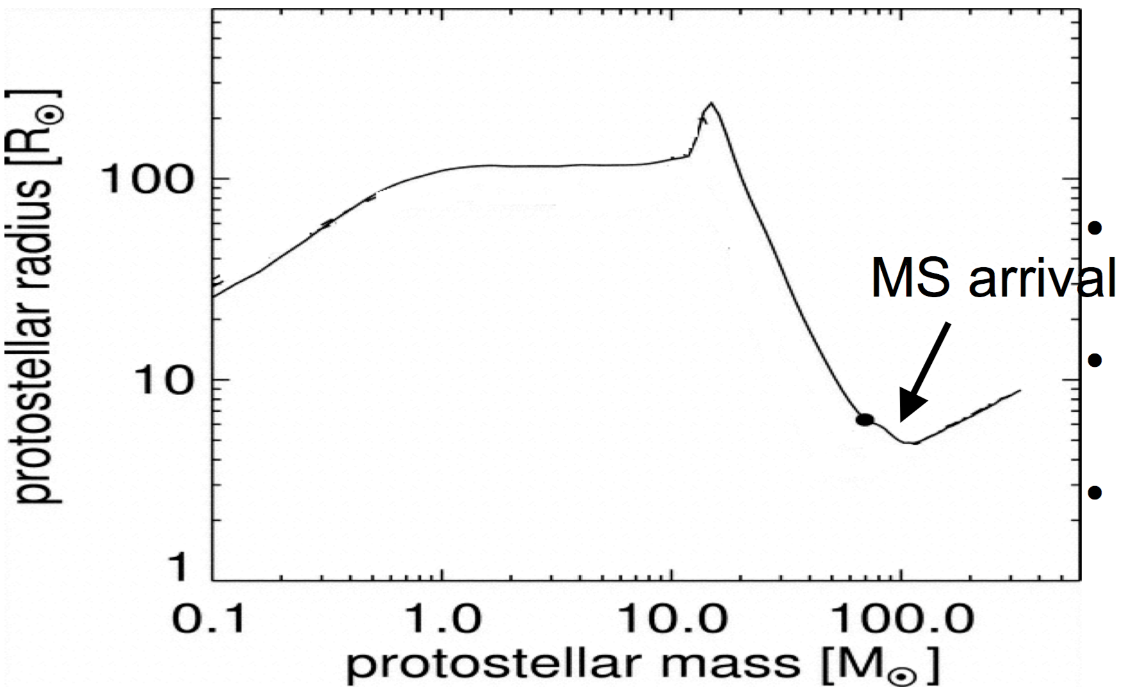
Growth of a protostar by accretion



Evolution of protostellar radius

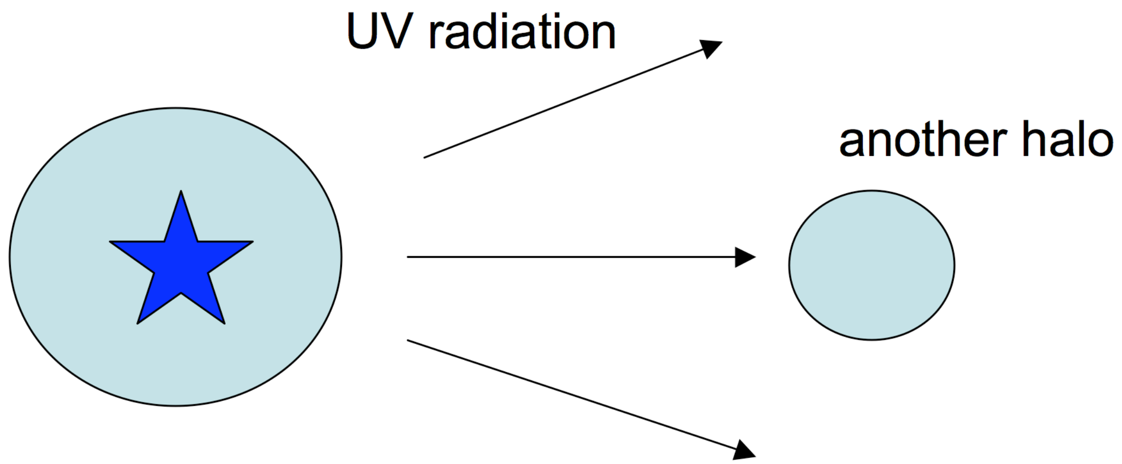


Omukai & Palla 2001, 2003;
Yoshida, K.O., Hernquist, Abel 2006

- The protostar reaches MS at ~100Msun
- The accretion continues unimpeded.
- Since (MS lifetime~3×10^6yr) > (core free-falltime~3×10^5yr), most of the core material can accrete within stellar lifetime.
- Very massive star (~ a few 100Msun) is formed

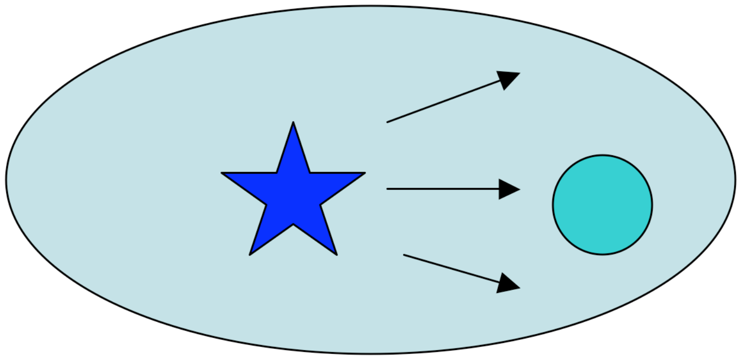
Photodissociation feedback

- **External feedback** (Haiman, Rees, & Loeb 1997)
  ➔ previous talks
  - feedback to neighboring halos
  - Not as strong as originally proclaimed (Anh & Shapiro 2007)

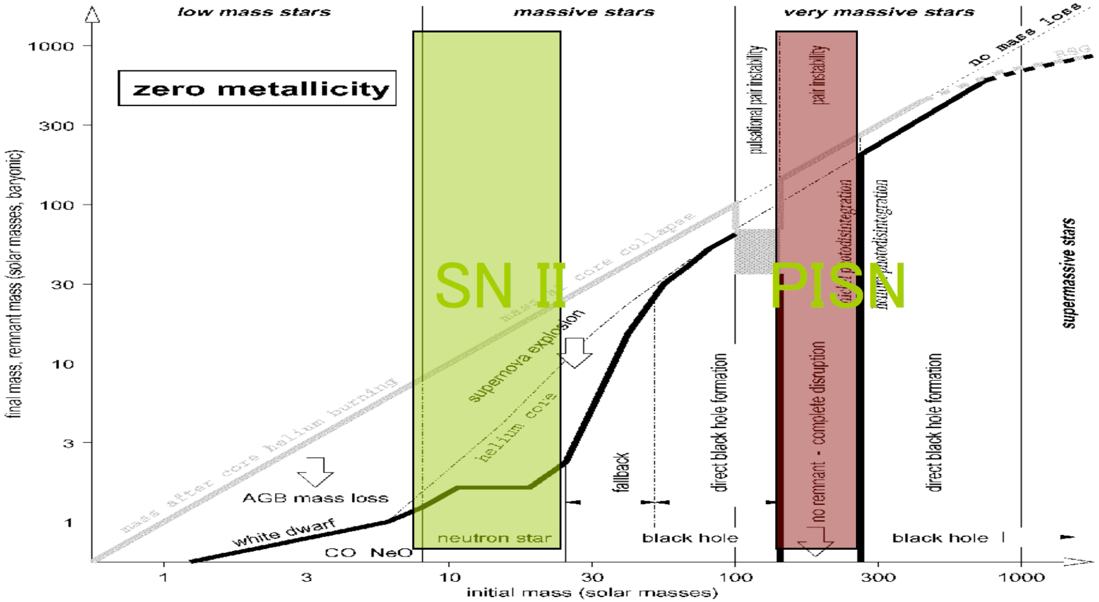


Photodissociation feedback

- **Internal feedback** (K.O. & Nishi 1999)
  - feedback within the same halo
  - Even an ordinary O star photodissociates H_2 in the entire halo and prohibits subsequent star formation
  - Low SF efficiency of the first stars
    (one star per halo: $\varepsilon_* \sim 10^{-3}$-$10^{-2}$)
    consistent with the late reionization scenario
    (e.g., Haiman & Bryan 2006; Choudhury & Ferrara 2006)



What happens after the death of the first stars



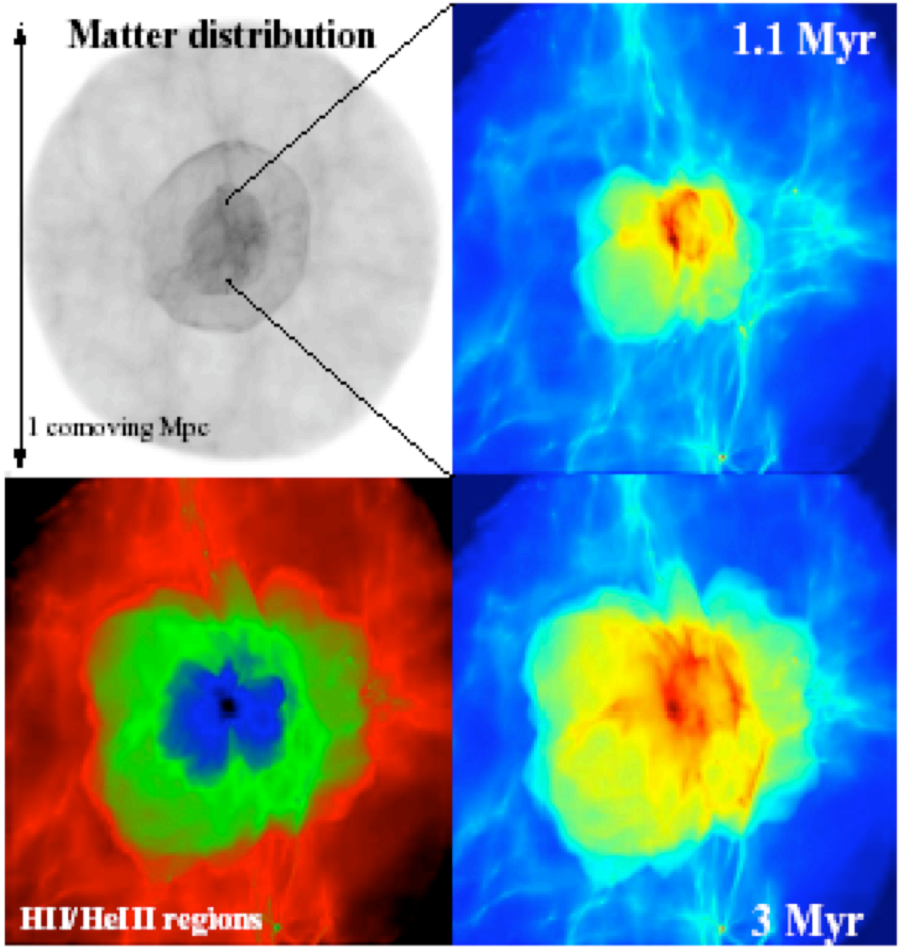
Heger, Baraffe, Woosley
2001

Two windows for SNe

- Type II SN
  8-25M_{sun}
- Pair-instability SN
  150-250M_{sun}

Outside these windows,
the star shrinks without explosic
➔primordial SF continues

SF in a fossil HII region

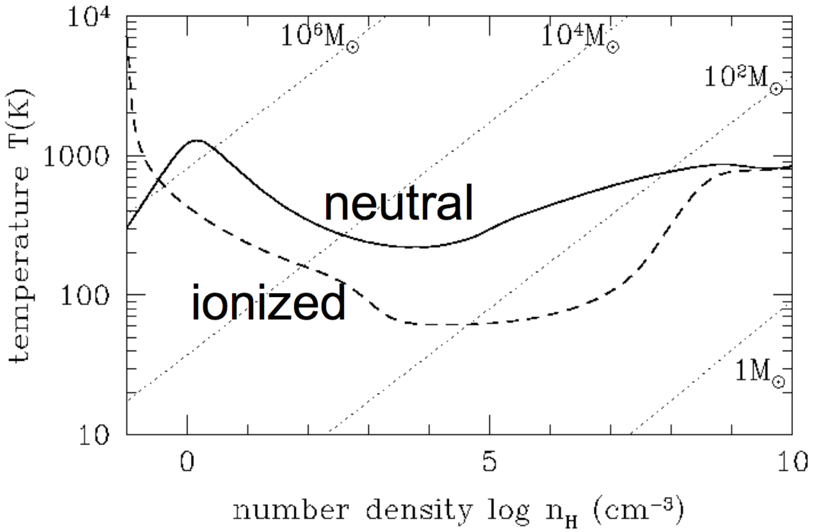


Yoshida, Oh, Kitayama, & Hernquist (2007)

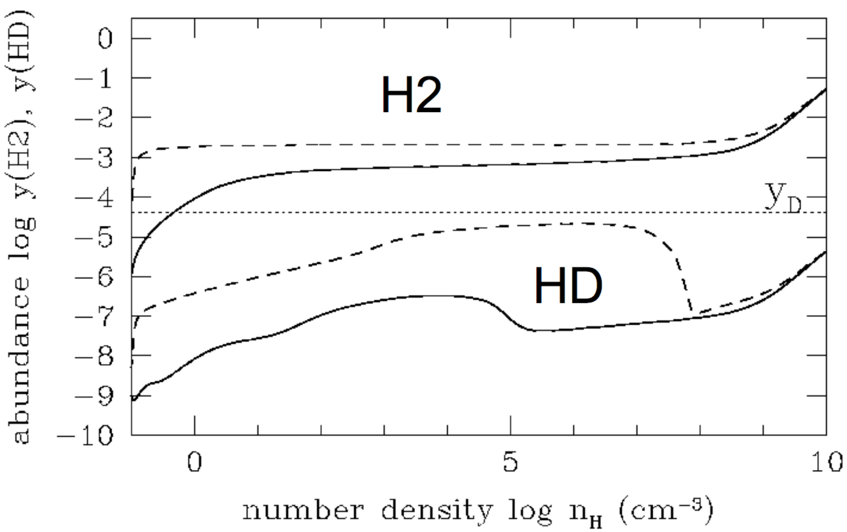
- After the death of the first star, recombination proceeds in the fossil HII region
- Another episode of star formation commences

Initial ionization and molecule formation: HD mode

Temperature evolution



H_2,HD fraction

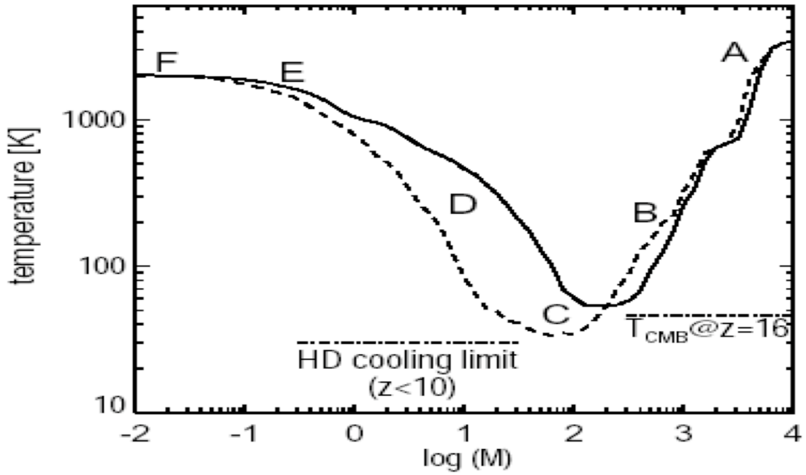


- Ionized environments e.g., fossil HII region, SN blast wave, structure formation shock
- In initially ionized gas, H_2 formation is enhanced [y(H2)>10^{-3}]. This causes low temperature, and as a result HD forms abundantly (Uehara & Inutsuka 2001).
- Further temperature decrease by HD cooling

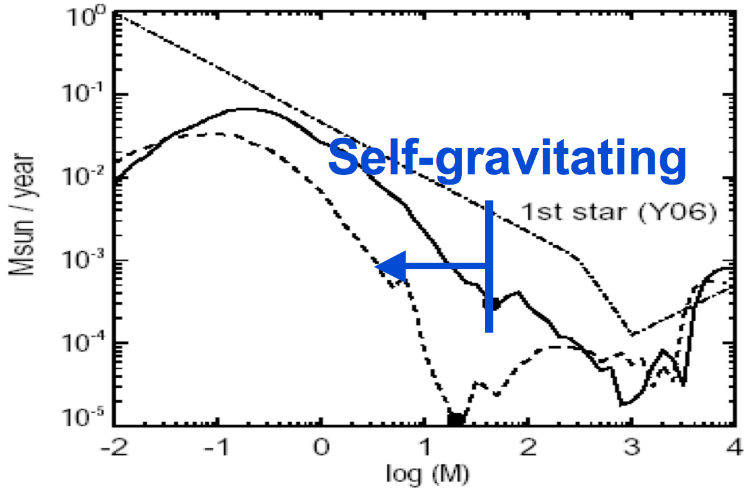
mass accretion rate in HD mode

Yoshida, KO & Hernquist 2007

Temperature distribution

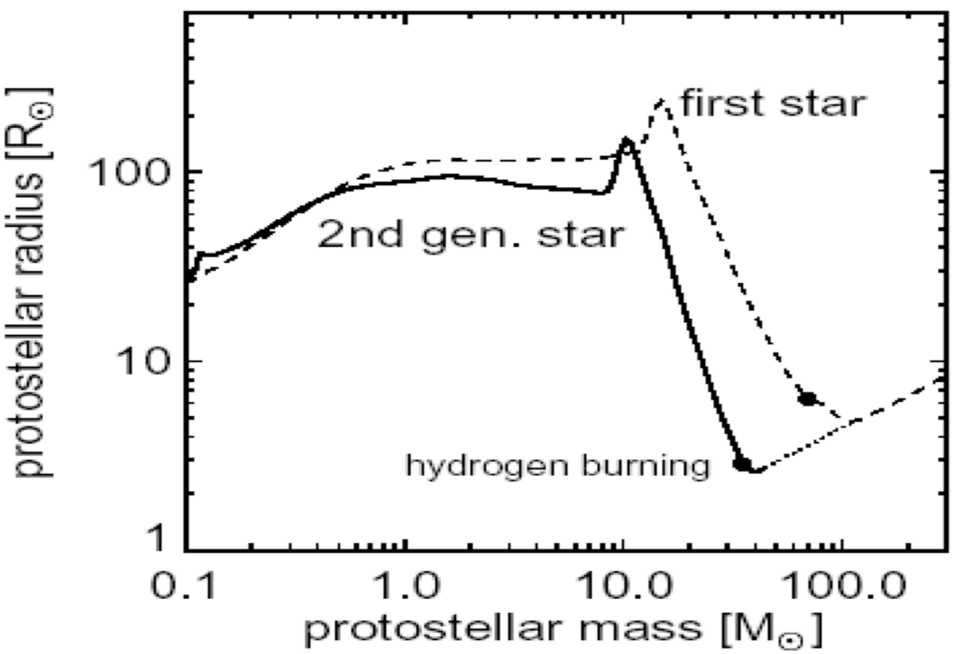


Accretion rate



- Self-gravitating mass ~ a few 10M_{sun}
- Lower temperature (~100K) than in the H_2 mode (~several 100K)
  ➔ lower accretion rate ~10^{-4}-$10^{-3}M_{sun}$/yr (~10^{-3}-$10^{-2}M_{sun}$/yr in the H_2 mode)

Stellar Mass by HD mode



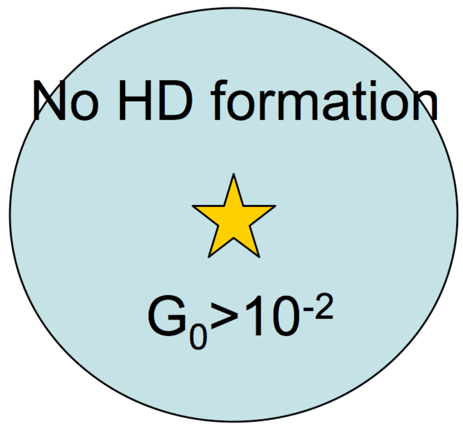
- Arrival to the MS at ~a few $10M_{sun}$
- Self-gravitating core mass is also ~ a few $10M_{sun}$

➔ the final mass of the star ~ a few $10M_{sun}$

Photodissociation feedback to HD mode star formation

- Vulnerable to FUV
- G_0>~10^{-2}
  no HD cooling
- This is due to H2 photodissociation
  (Not due to HD photodissociation)

G_0: strength of FUV
~1 in our Galactic disk



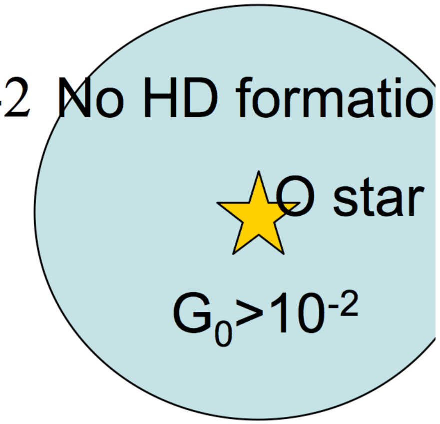
Preliminary

No-HD region

- No HD cooling if radiation $G_0>\sim 10^{-2}$ ($J_{LW}\sim 3\text{x}10^{-22}$)

  $J_{LW}=L_{LW}/(16\pi^2 r^2)\ f_{shield}$

  $f_{shield}=(N_{H2}/10^{14}\text{cm}^{-2})^{-3/4}$; $N_{H2}=n_H\ y(H2)\ r$



- Size of no-HD region

  e.g., $L_{LW}\sim 10^{24}$ ergs/s/Hz (ordinary massive stars; O5)

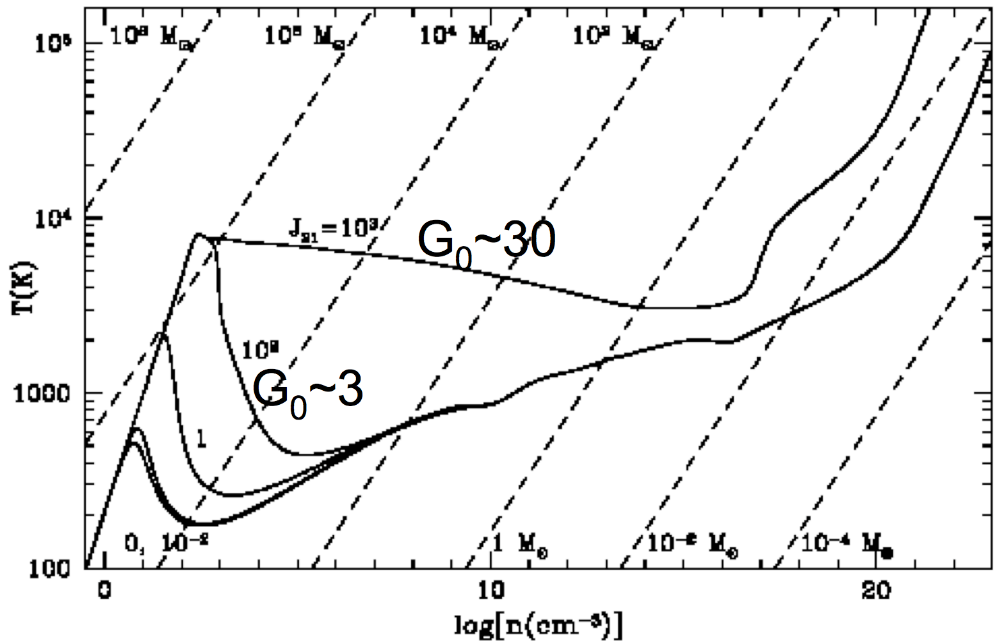
  $r_{noHD}\sim 80$pc [for $y(H2)\sim 10^{-3}$]

  if no shielding, $r_{noHD}\sim 2$kpc

- Star formation strongly regulated

  ➔SF efficiency in the HD mode is low

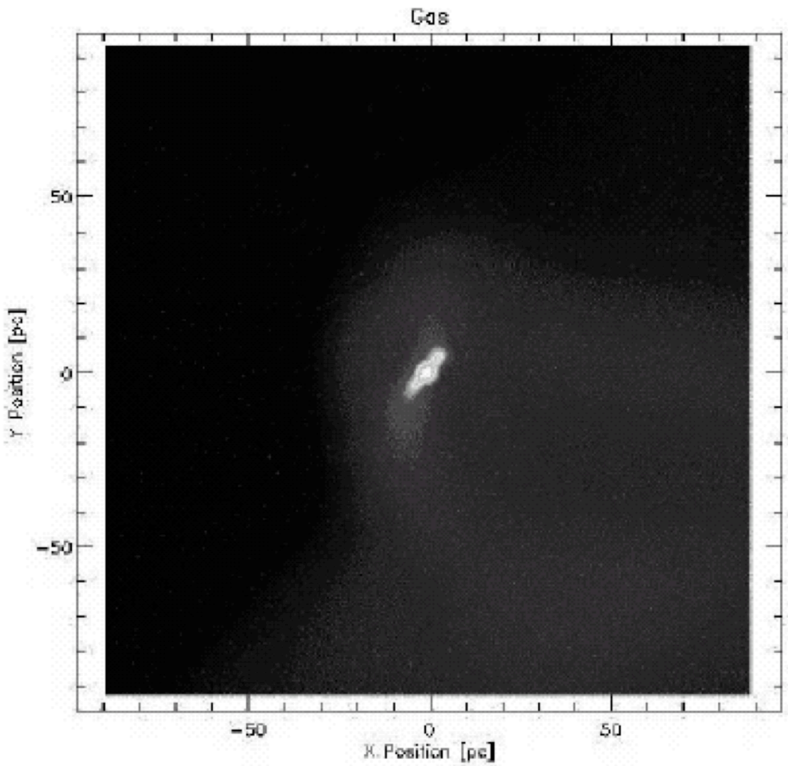
In strong FUV environment: atomic mode



Omukai 2001

- Under very strong FUV field G_0>30 (J_{LW}>10^{-18}), no H2 formation
- New pathway to stars opens "atomic mode"
- Lya→ H- cooling
- Jeans mass at T minimum~0.1Msun

What's the end product of the atomic mode ?



Bromm & Loeb 2001

Two controversial views

Low-mass stars ?

Super massive star ($\sim 10^5 M_{sun}$)?

Summary

- Three modes of primordial star formation depending on the strength of FUV field

  1) H_2 mode ---- 100-1000M_{sun}

  2) HD mode (initially ionized & $G_0<10^{-2}$)
  ---- 10-100M_{sun}

  3) Atomic mode ($G_0>30$)----- controversial
  1M_{sun} or 10^5M_{sun} ?