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Low-metallicity star formation

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CONTENTS

- Prestellar collapse of low-metallicity clouds
  thermal evolution and fragmentation properties
- Protostellar evolution by accretion:
  Upper limit on the stellar mass by stellar feedback

Pop III-II transition

✓First stars (Pop III stars)

theoretically predicted to be very massive(>100M_{sun})

✓Stars in the solar neighborhood (Pop I)

typically low-mass(0.1-1M_{sun})

Low−mass Pop II stars exist in the halo.

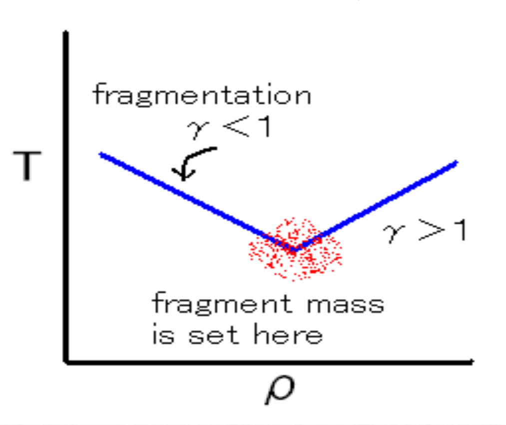
●transition of characteristic stellar mass in the early universe from very massive to low-mass (Pop III−II transition)

●This transition is probably caused by accumulation of a certain amount of metals and dusts in ISM (critical metallicity)

Fragmentation and thermal evolution

Effective ratio of specific heat

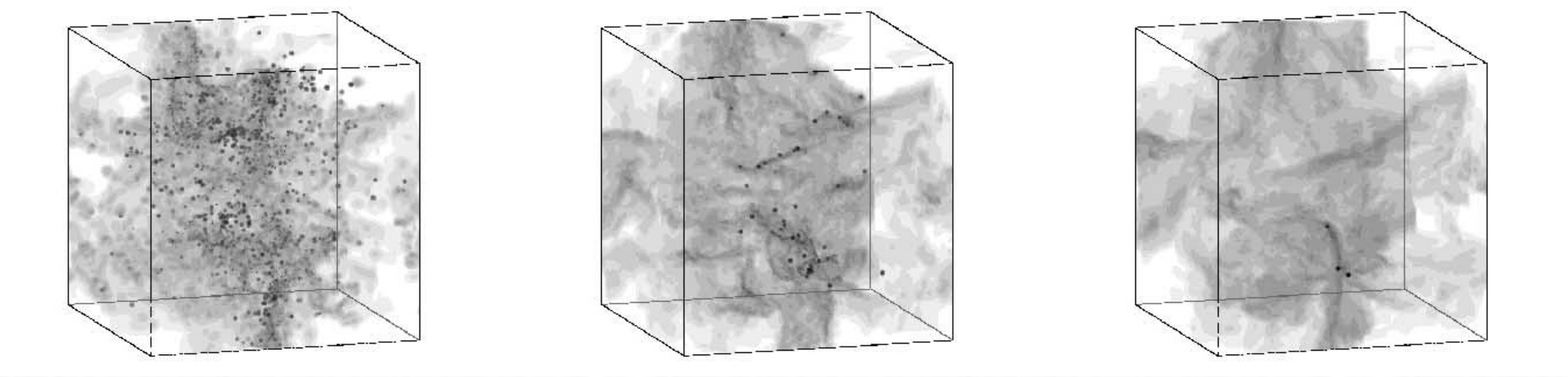
$\gamma := d\log p / d\log \rho$



- $\gamma<1$ vigorous fragmentation, $\gamma>1$ fragmentation suppressed
- The Jeans mass at $\gamma \sim 1$ (T minimum) gives the fragmentation scale.

$M_{frag} = M_{Jeans}@T_{minimum}$

$\gamma=0.2$ $\gamma=1$ (isothermal) $\gamma=1.3$

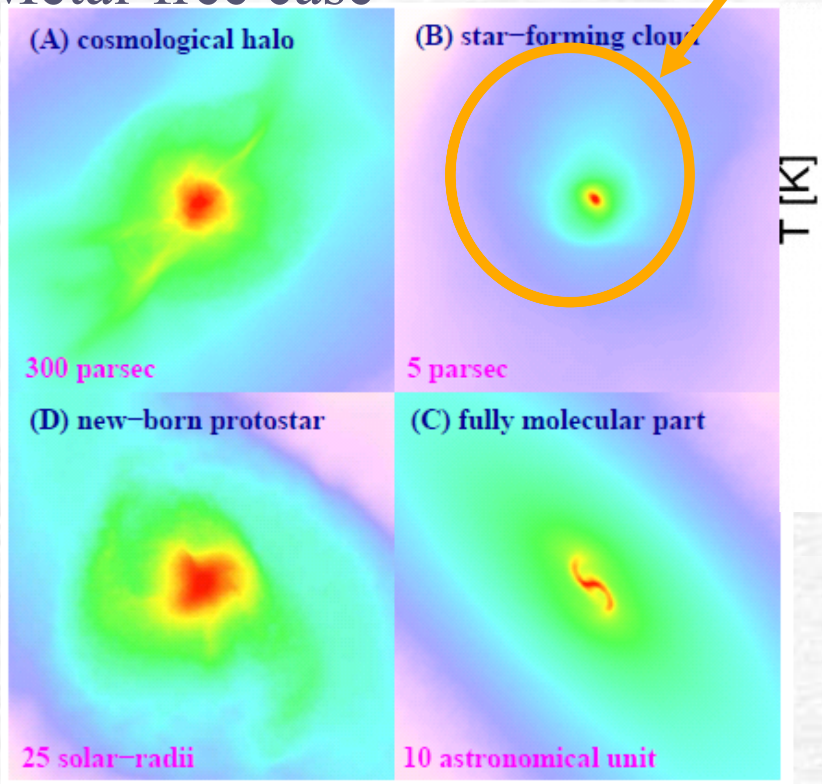


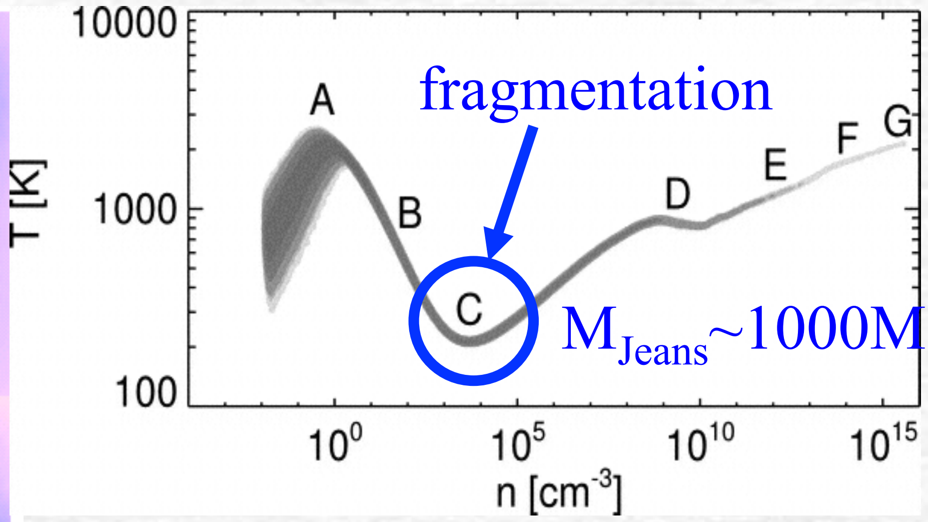
Li et al. 2003

First stars

dense core (fragment) ~1000M_{sun}

Metal-free case





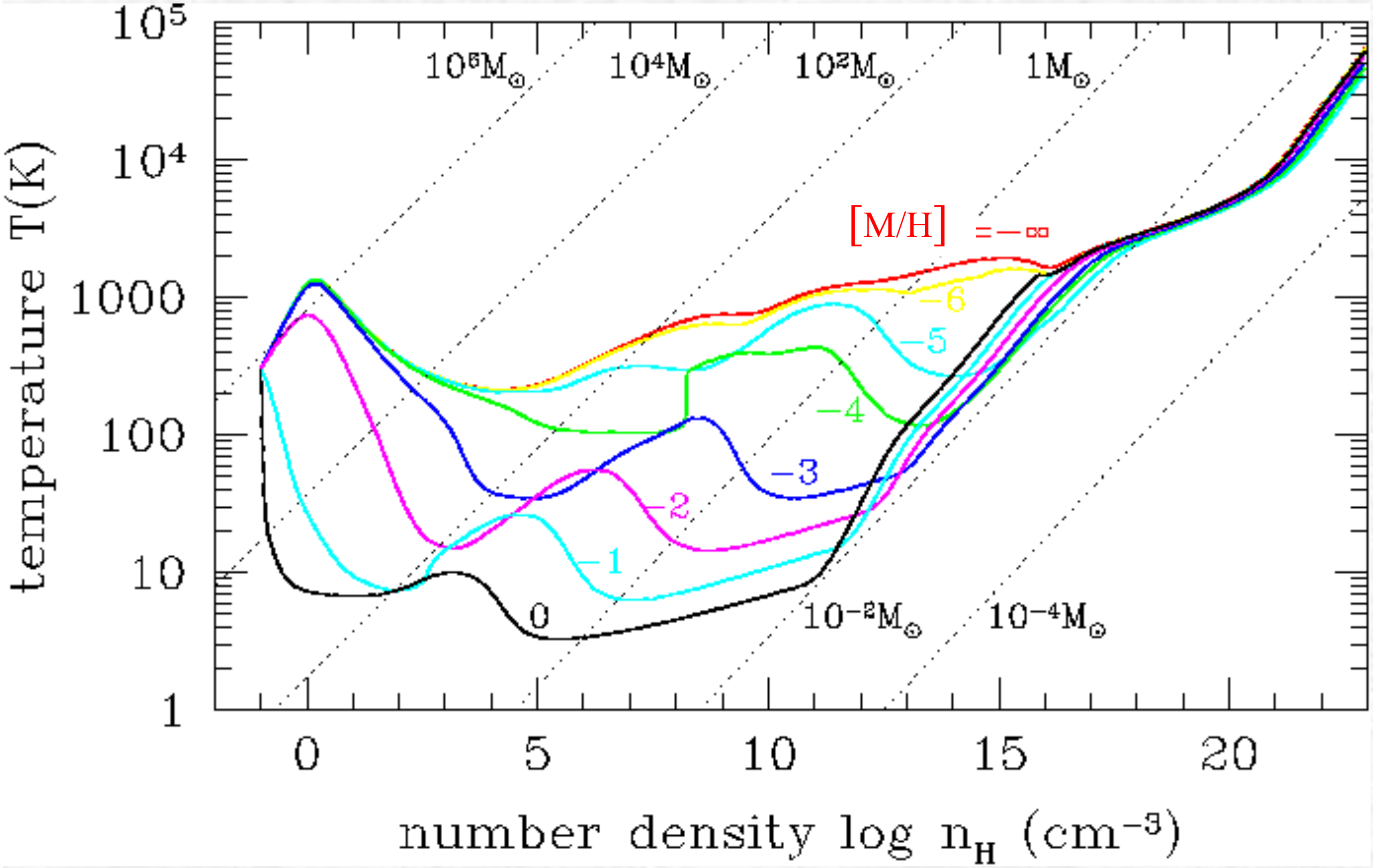
fragmentation

M_{Jeans}~1000M_{sun}

M_{frag}~ M_{jeans}
@T minimum
(Bromm et al. 1999)

Yoshida, KO, Hernquist 2008

Thermal Evolution of clouds with different Z



[M/H]
$:= \log_{10}(Z/Z_{sun})$

one-zone model

- collapses in the free-fall timescale

$t_{dyn}=d\rho/(d\rho/dt) = t_{ff}$

- core size ~ the Jeans length
- dust/metal ratio same as local ISM

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

1D Hydrodynamics

KO, Hosokawa & Yoshida 2010

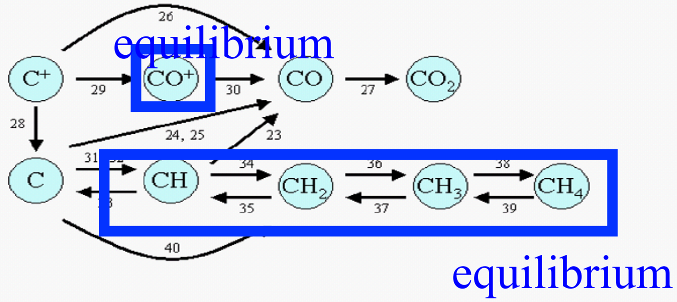
- Spherical symmetry
- Radiative processes
  - Line: CII, CI, OI, H_2, HD, CO, OH, H_2O
    escape probability method
  - Continuum: dust、gas（e.g., H_2 CIA）
    variable Eddington factor method
    gray approximation
- Chemical reactions

  reduced H, D, C, O network

Reduced chemical network

C network

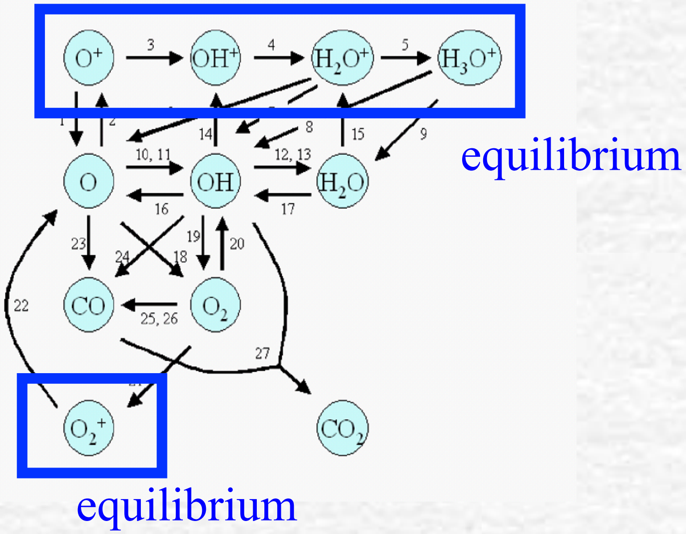
$CII \rightarrow CI \rightarrow CO \rightarrow CO_2$



non-equilbrium chemistry among 15 species : H, H_2, H^+, e, D, HD, D^+, C, CO, CO_2, C^+, O, OH, H_2O, O_2

O network

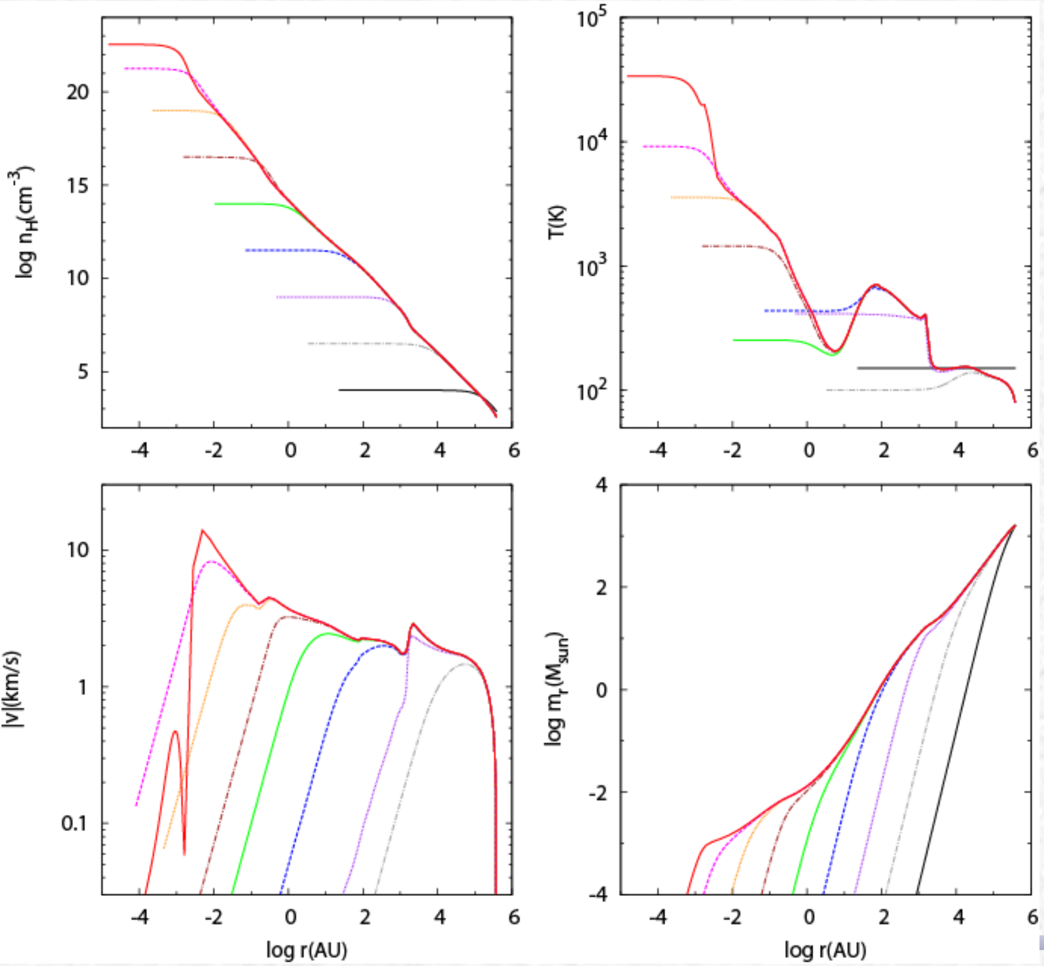
$O \rightarrow OH \rightarrow H_2O$
$\rightarrow O_2$
$\rightarrow CO \rightarrow CO_2$



Evolution until protostar formation

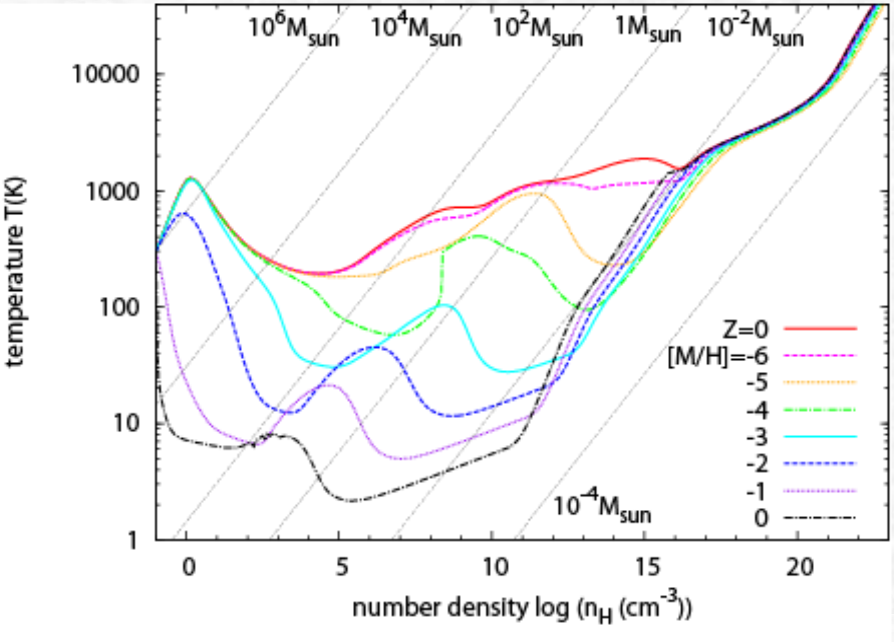
ex. [M/H]=-4

Initial model : Temperature , chemical abundances
from one-zone result at $10^4 \mathrm{cm}^{-3}$
Density distribution : critical BE sphere x 1.2

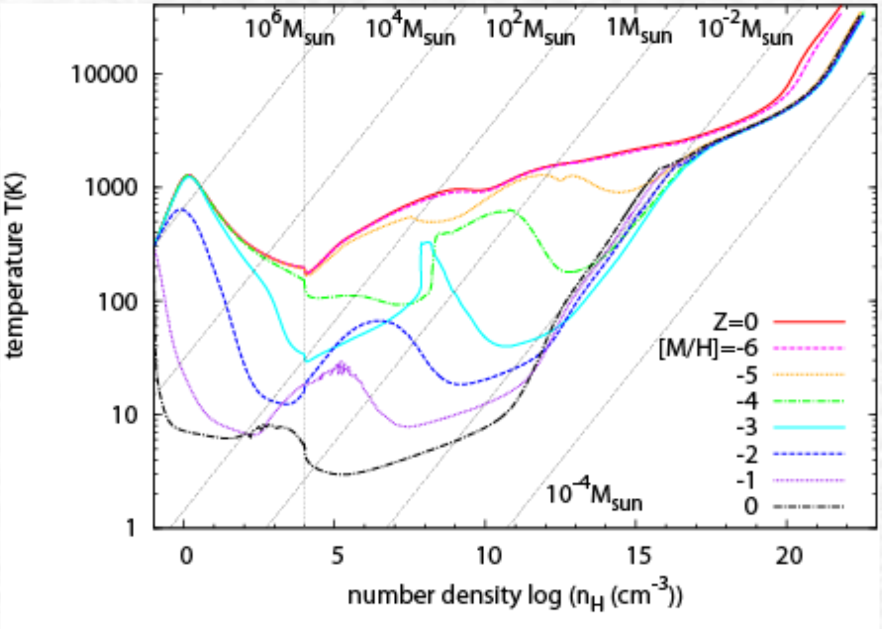


Comparison between 1-D and 1-zone models

1zone model



1D hydro; spherical collapse

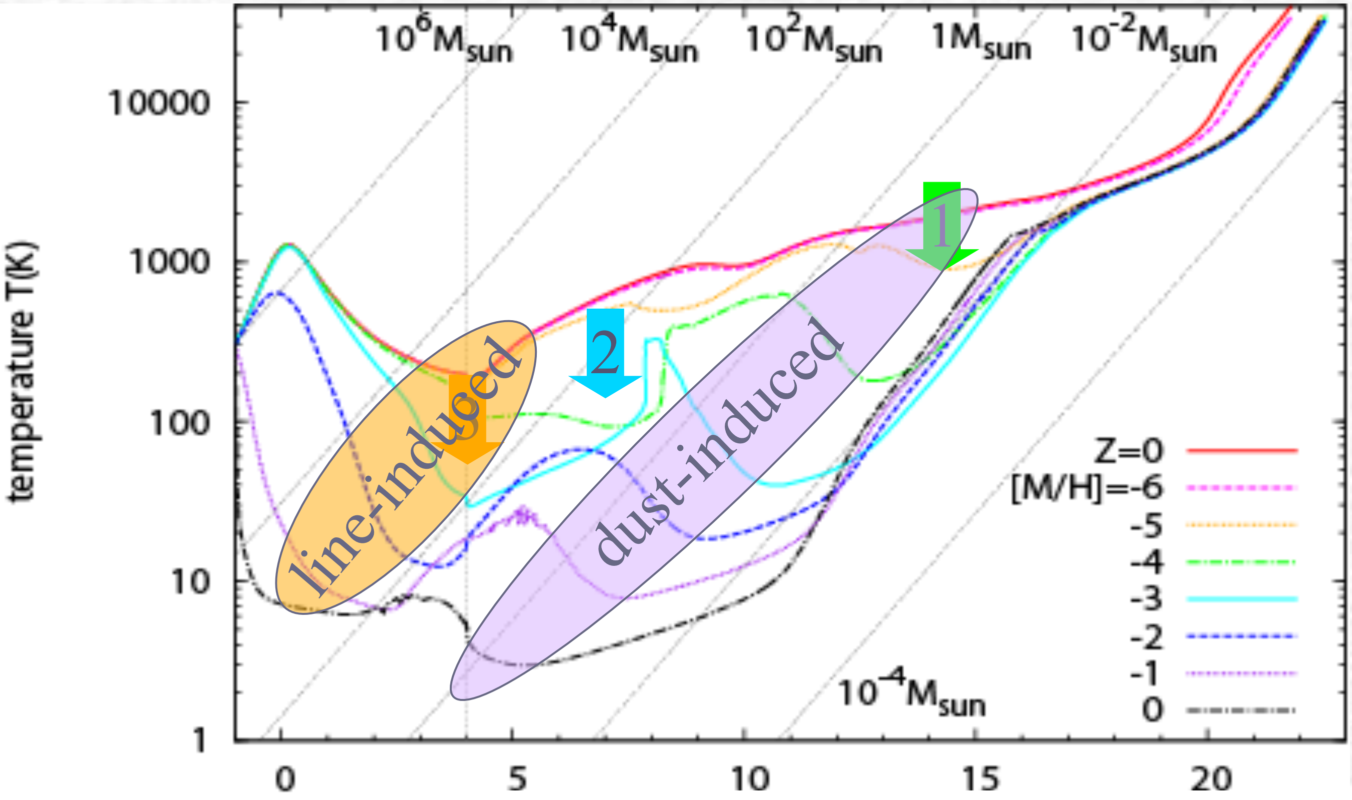


Agreement is fairly well.
But small differences in low-Z and high density
due to higher collapse rate in 1D model.
e.g., $t_{dyn} := \rho/(d\rho/dt) \sim t_{ff}/3$ in LP collapse

Thermal Evolution of clouds with different Z

1) Cooling by dust thermal emission: [M/H] > -5
2) H_2 formation on dust : [M/H] > -4
3) Cooling by fine-str. lines (C and O): [M/H] > -3

[M/H] := $\log_{10}(Z/Z_{sun})$

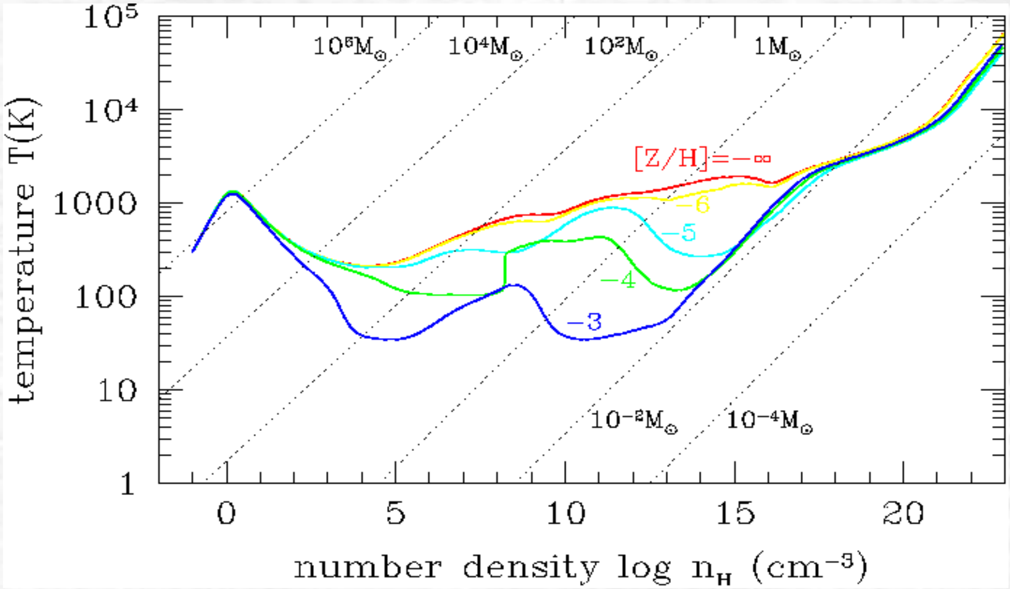


- 1D hydro (spherical)
- dust/metal ratio same as local ISM

Low-mass fragments are formed only in the dust-induced mode.

The critical metallicity

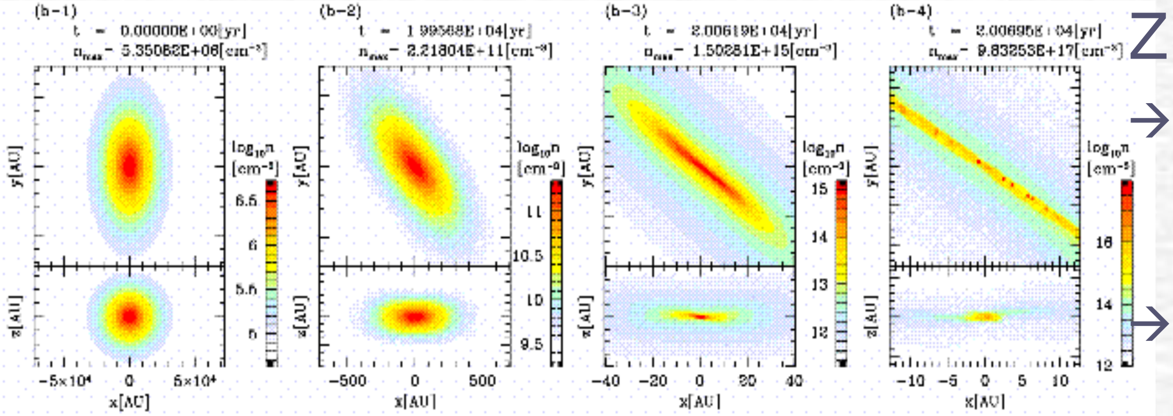
How much metallicity (dust) is needed for the low-mass star formation ?



Dust-induced fragmentation

Tsuribe & K.O. (2006; 2008)

[M/H]=-5.5 ($Z=3\times10^{-6}Z_{sun}$)



$Z>\sim10^{-6}Z_{sun}$

→ long filament forms during dust-cooling phase

→ fragmentation into low-mass (0.1-1M_{sun}) objects

Using T evolution given
by 1-zone model

Standard dust

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

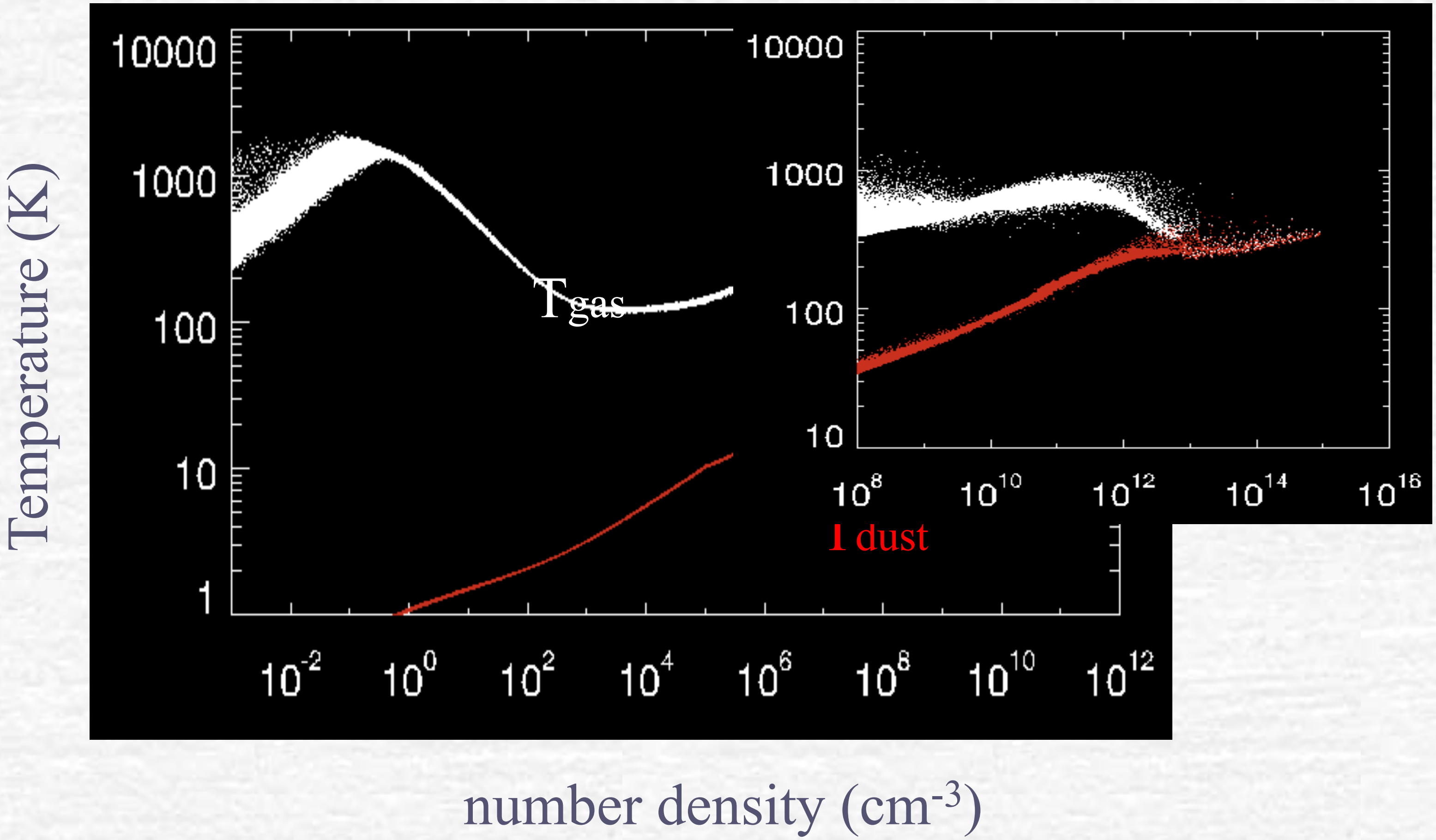
First dust

3D simulation with self-consisitent thermal evolution

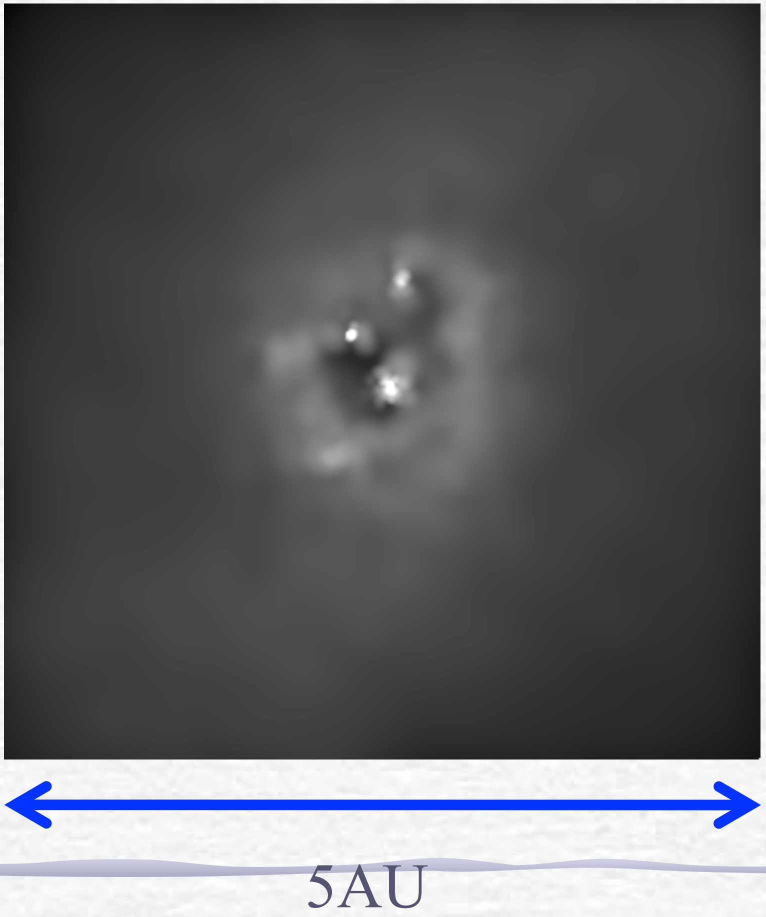
Yoshida & KO in prep.

Simulation set-up
A NFW sphere (static potential)
5 x 10^6 Msun @ z=10; Tvir ~ 2000 K
1 million gas particles
Mass resolution at the center
~ 0.004 Msun
dust-to-gas ratio scaled by metallicity Z

Results: [M/H]=-5

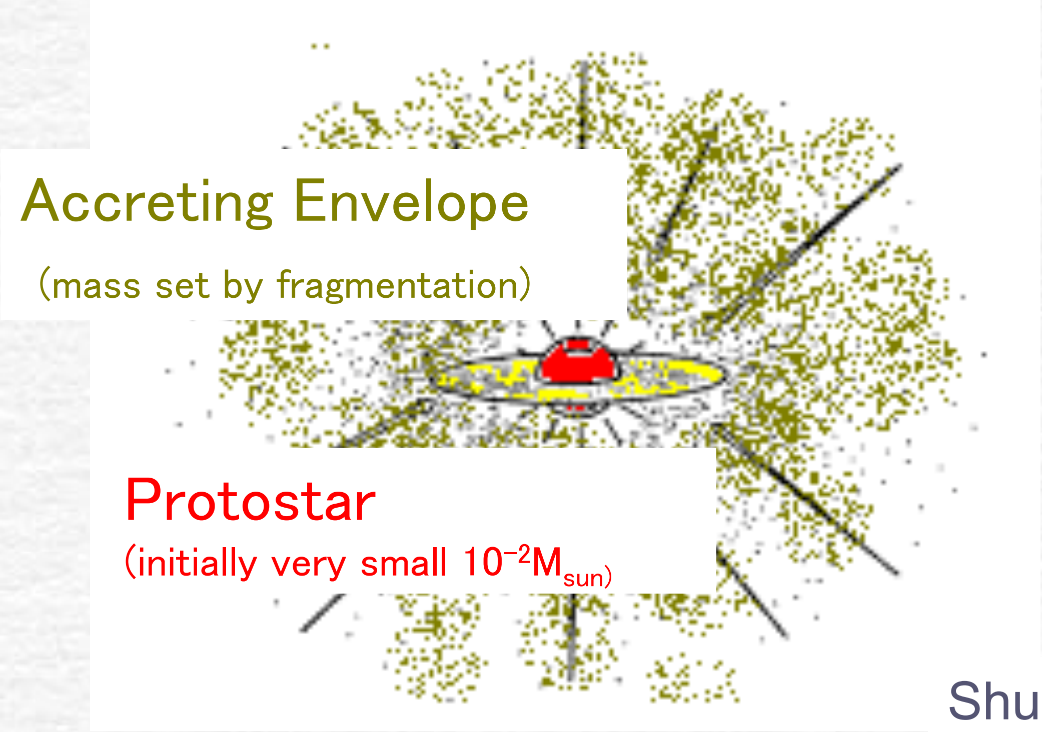

Temperature (K)
10000
1000
100
10
1
10000
1000
100
10
Tgas
Tdust
10^-2
10^0
10^2
10^4
10^6
10^8
10^10
10^12
10^8
10^10
10^12
10^14
10^16
number density (cm^-3)

Dust-induced fragmentation



For [M/H]=-5,
Rapid cooling by dust
at high density ($n \sim 10^{14} cm^{-3}$)
leads to core
fragmentation.
Fragment mass ~ 0.1 Msun

Protostellar Evolution in the Accretion Phase



Accreting Envelope

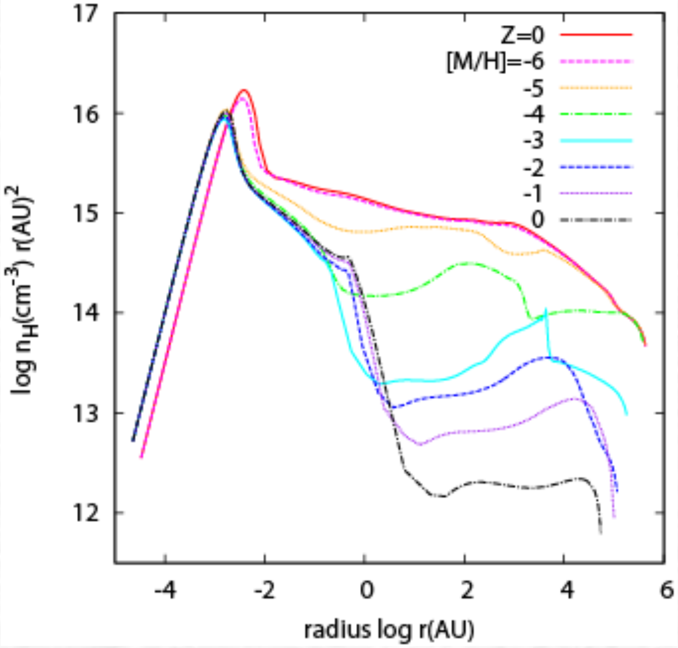
(mass set by fragmentation)

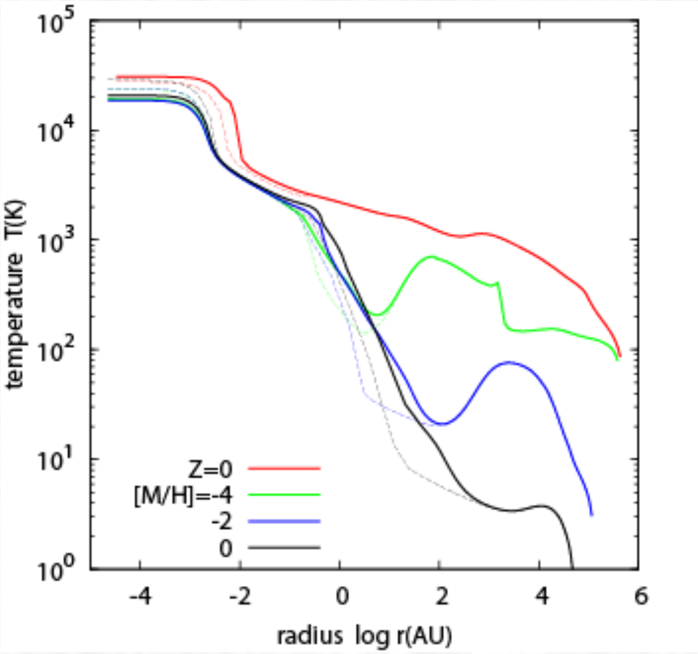
Protostar

(initially very small $10^{-2}M_{sun}$)

Shu et al. 1986

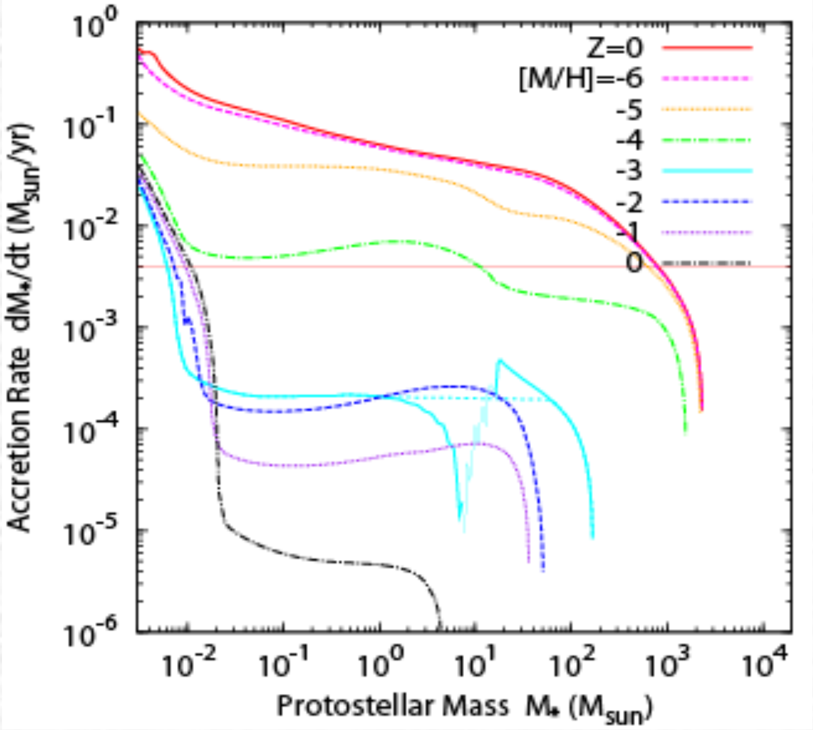
Envelope structure at protostar formation





at >AU scale ---- higher Temperature and density for lower-Z

Mass accretion rate

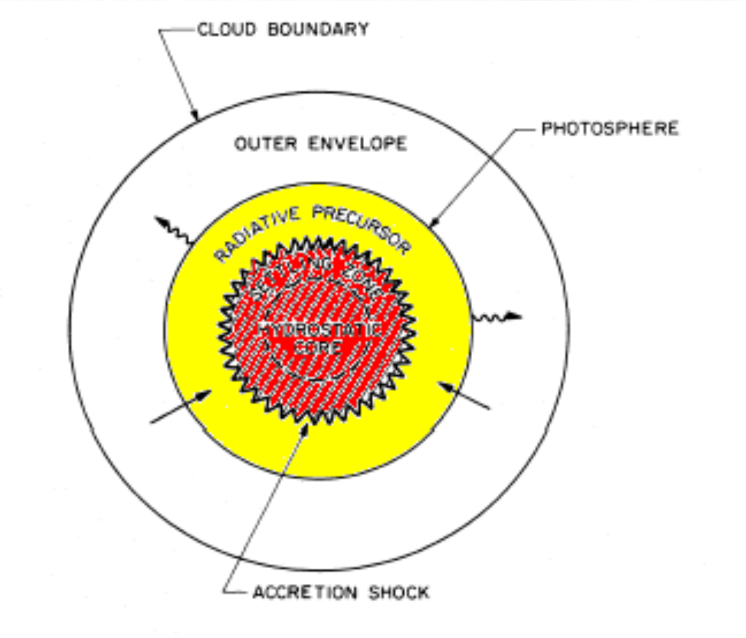


- Lower metallicity → Higher density → Higher accretion rate
- Mass accetion rate $dM_*/dt \sim 10c_s^3/G$

Protostars in Accretion Phase

Method

(Stahler et al. 1986)



Protostar **hydrostatic**

Eq.s for Stellar Structure

＋ [radiative shock condition]

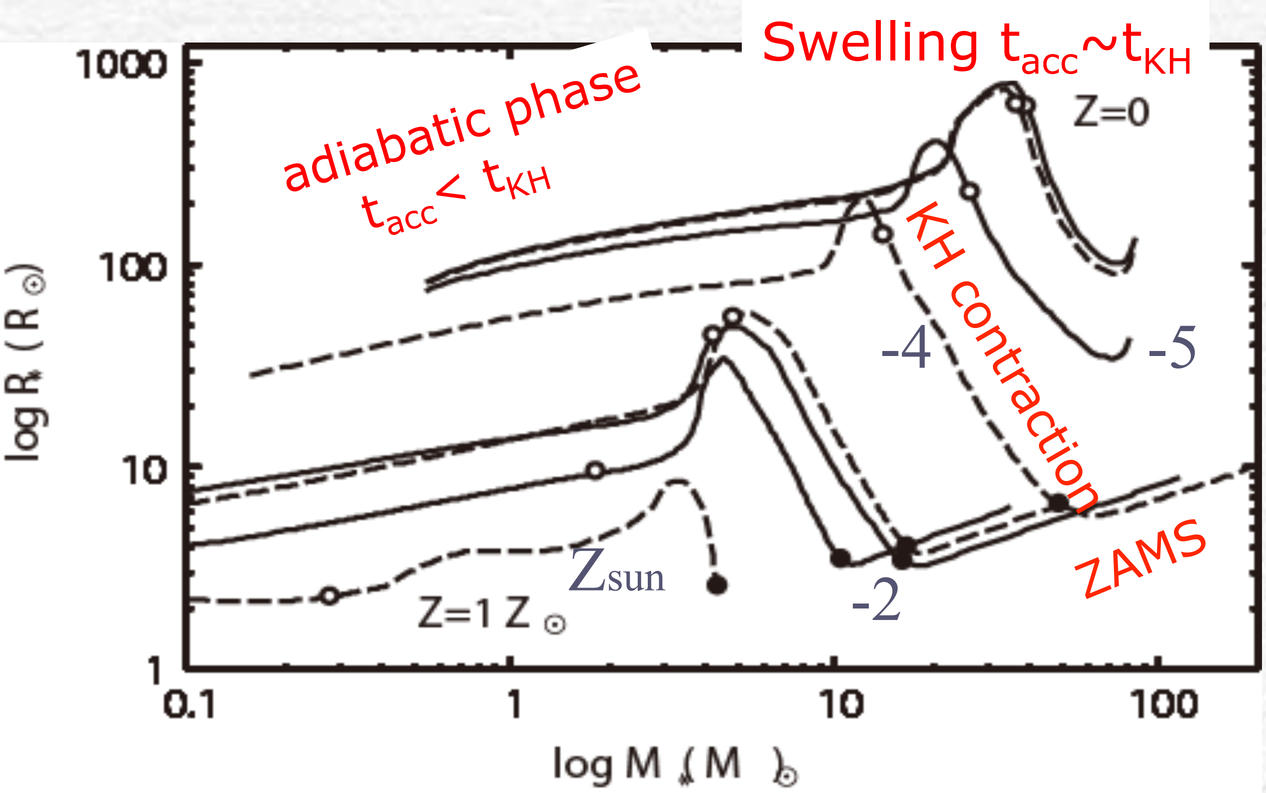
ENVELOPE

Stationary Accretion

radiative precursor($< R_{ph}$) stationary hydro

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

Growth of protostars by accretion



Four Evolutionary Phases:

1. Adiabatic phase
2. Swelling
3. KH contraction
4. Zero-Age Main Sequence (ZAMS)

Accretion time

$t_{acc}=M_*/(dM_*/dt)$

KH timescale

$t_{KH}=(GM_*^2/R_*)/L_*$

For lower metallicities (= higher accretion rate):

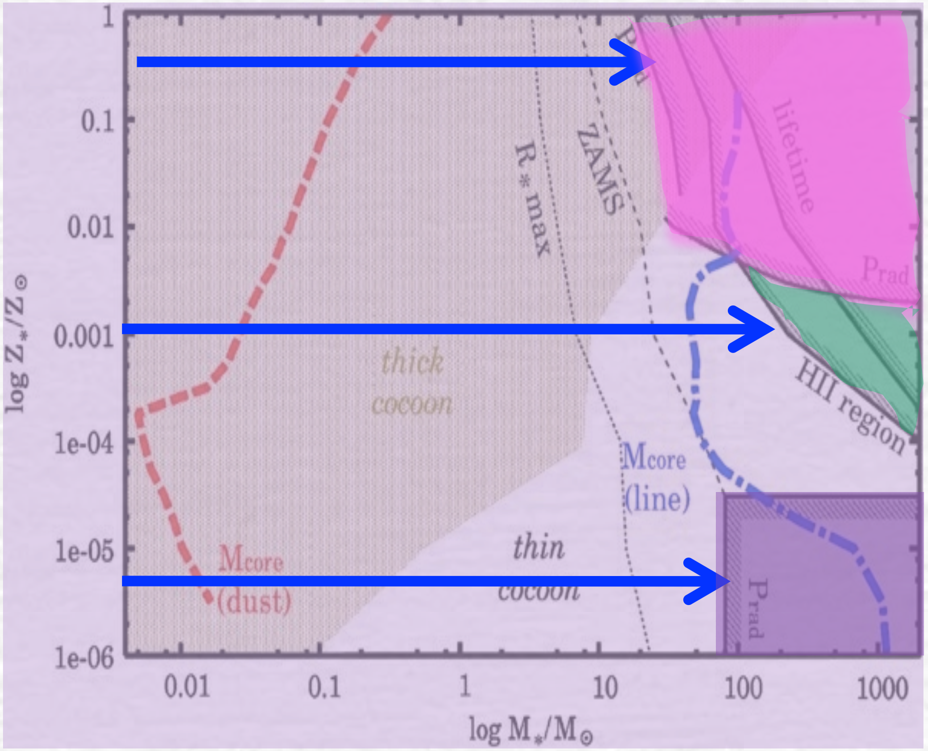
✓Protostars have larger radii

✓Protostars are more massive at the onset of H burning.

✓No stationary solution during KH contraction for [M/H]<-5

Upper Limit on the stellar mass

Case for mass accetion rate $dM_*/dt \sim 10c_s^3/G$ by one-zone model



Low metallicity gas

Higher accretion rate

Lower opacity

➔Weaker feedback,

Higher upper mass limit

- Limit by Radiation force
  > $0.01Z_{sun}$; $20\text{-}100M_{sun}$
- Limit by HII region expansion
  $10^{-4}\text{-}0.01Z_{sun}$; a few $100M_{sun}$
- No stationary accretion
  $<10^{-4}\ Z_{sun}$; $100M_{sun}$

Hosokawa & KO 2009

SUMMARY (1)

Prestellar evolution of low-Z gas
and its fragmentation properties.

- Line cooling affects the thermal evolution only at low densities where the Jeans mass is still high (>10-$100M_{sun}$).
- Dust cooling causes a sudden temperature drop at high density where M_{Jeans}~$0.1M_{sun}$, which induces low-mass fragmentation.
- The critical metallicity for dust-induced fragmentation is $[Z/H]_{cr}$~-5

SUMMARY (2)

evolution of low-Z protostars and the upper limit on the mass by stellar feedback

- In low metallicity gas, high temperature in star forming cores results in high accretion rate.
- Lower Z protostars become more massive before the arrival to the MS owing to higher accretion.
- The upper limit on the stellar mass is 20-100M_{sun} set by radiation pressure feedback for >0.01Z_{sun}, while it is a few 100M_{sun} set by expansion of HII regions <0.01Z_{sun}.