Application of 3D-RSPH Scheme to the Radiative Feedback by Population III Stars

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Outline

Introduction

- ✓ Population (Pop) III stars
- ✓ Radiative feedback

Methodologies

- ✓ Simulation code
- ✓ Setup

Results

Summary

Research interests

Numerical Scheme

Gas Dynamics: SPH

Gravity :Tree-GRAPE

$$\frac{d\rho}{dt} = -\rho\nabla\cdot v$$

$$\frac{d^2 r}{dt^2} = -\frac{1}{\rho}\nabla P - \nabla\phi + f_{\mathrm{rad}}$$

$$\frac{du}{dt} = \frac{P}{\rho}\nabla\cdot v + \frac{\Gamma - \Lambda}{\rho}$$

$$P = (\gamma - 1)\rho u = \frac{k_{\mathrm{B}}\rho_{\mathrm{b}} T}{\mu m_{\mathrm{p}}}$$

Radiative transfer (Susa 2006)

$$\frac{dI_\nu}{d\tau_\nu} = I_\nu + \cancel{S_\nu}$$

On the spot approximation

Photoionization rate $$k_{ion} = \int_{\nu_L}^{\infty} d\nu \int d\Omega \frac{a_\nu I_\nu}{h\nu}$$

Photoheating rate $$\Gamma_{ion} = \int_{\nu_L}^{\infty} d\nu \int d\Omega \frac{(h\nu - h\nu_L) a_\nu I_\nu}{h\nu}$$

Photodissociation rate: $k_{\mathrm{H2dis}} = 1.13 \times 10^8 F_{\mathrm{LW0}} f_{\mathrm{sh}} [\mathrm{s}^{-1}]$

$f_{\mathrm{sh}} = \min[1, (N_{\mathrm{H2}}/10^{14})^{-0.75}]$

Draine & Bertoldi (1996)

Non equilibrium chemistry (Kitayama et al.2001)

$$\frac{dn_i}{dt} = \sum_j^6 \sum_k^6 k_{jk} n_j n_k + \sum_l^6 \sum_m^6 \sum_n^6 k_{lmn} n_l n_m n_n$$

For e, p, H, H_2, H_2^+, H^-,

$\Rightarrow$determines **fractions of species** and **radiative cooling rate**

Radiative Feedback by Population III stars

Using RSPH code, the radiative feedback by Pop III stars on neighboring gas clumps have been explored.

We derive the critical distance below which the neighboring clumps cannot collapse.

$$D_{\mathrm{cr}} = 78.8\mathrm{pc} \times f_{\mathrm{dyn}} \left(\frac{L_{\mathrm{LW}}}{5 \times 10^{23} \mathrm{erg\ s^{-1}}} \right)^{2} \left(\frac{N_{\mathrm{ion}}}{10^{50} s^{-1}} \right)^{-2/3} \left(\frac{n_{\mathrm{c}}}{10^{3} \mathrm{cm^{-3}}} \right)^{-7/16} \left(\frac{T_{c}}{300\mathrm{K}} \right)^{-3/4}$$

f_{dyn}:a factor depending on U/W

T_{c}: core temperature

n_{c}: core number density

N_{ion}: number of ionizing photons emitted per second

L_{LW}: Lyman-Werner (LW) band luminosity

Masses of Pop III stars

- **Very Massive Stars of >100M$_\odot$**

e.g., Abel, Bryan & Norman 2000;Bromm, Coppi & Larson 2001;Nakamura & Umemura 2001;Yoshida et al. 2006

$\boxed{H_2 \text{ cooling} \rightarrow T \sim 100\text{K}}$

- **Less Massive Star ~10M$_\odot$-100M$_\odot$**

Variation of cosmological density fluctuation **(O'Shea & Norman 2007)**

Enhanced H_2 cooling (via virial shock with T_{vir}>10^4K)

(eg.,Shapiro & Kang 1987; Susa et al. 1998; Oh & Haiman 2002)

HD cooling in fossil HII region (often called Pop III.2 star)

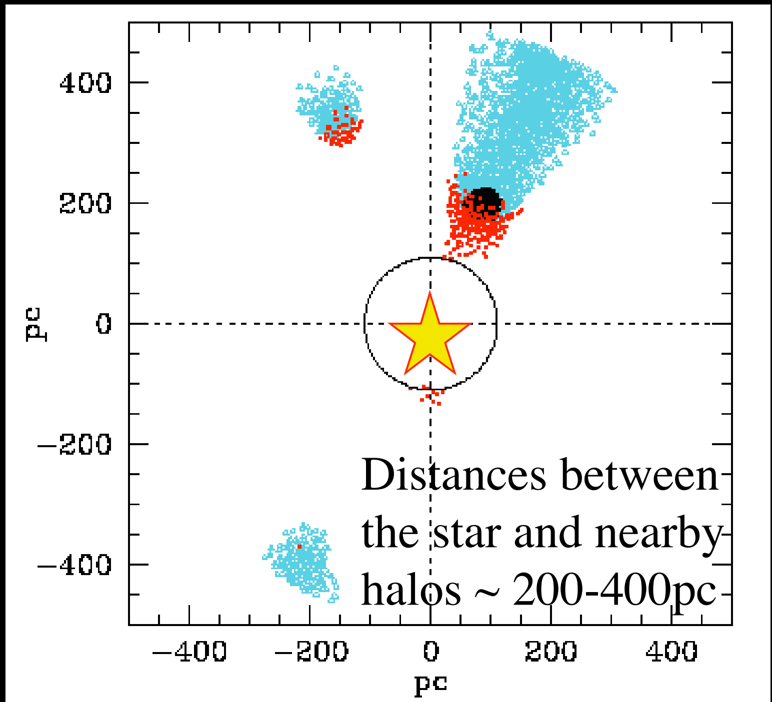
(eg.,Nkamura & Umemura 2002; Ngakura & Omukai 2005; Grief & Bromm 2006; Yoshida, Omukai & Hernquist 2007)

Not only very massive Pop III stars but also less massive Pop III stars are expected to form

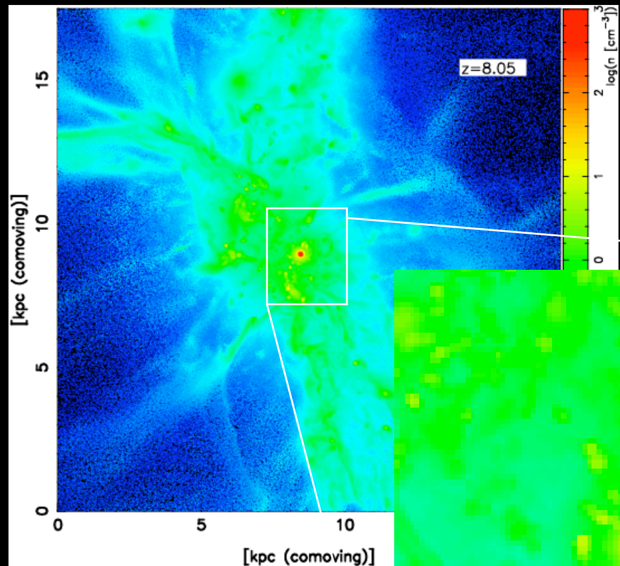
Pop III stars are Massive

UV radiation from the stars affects surrounding medium!!

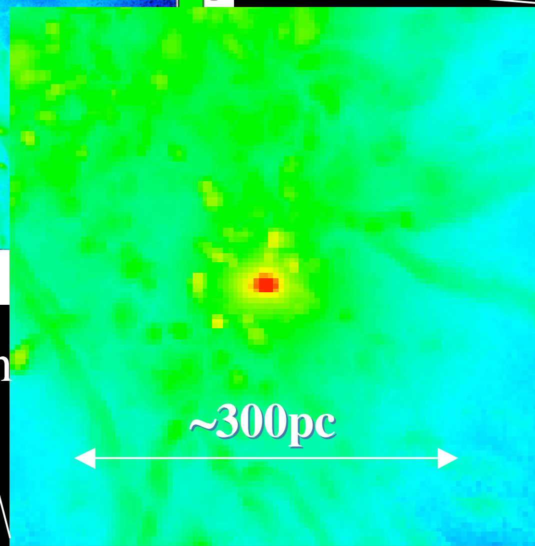
Alvarez, Bromm & Shapiro 2006



Suwa, Umemura & Susa in prep.



Separation between peaks ~70-80pc

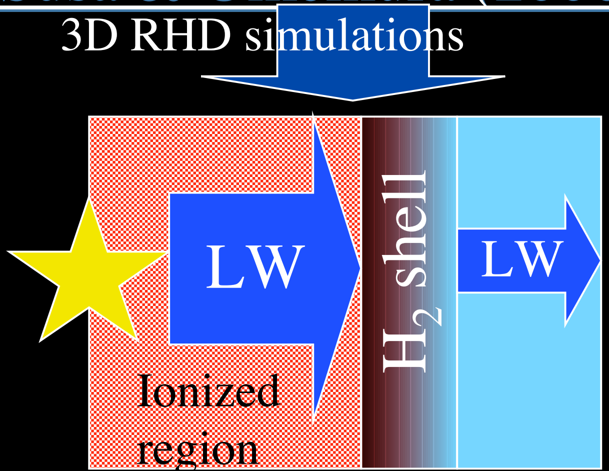


To know the final fate of the cores, we should carry out Radiation-Hydrodynamic (RHD) simulations involving H_2 chemistry.

UV feedback by PopIII stars

✓**RHD simulations**

Susa & Umemura (2006), Ahn & Shapiro (2007), Whalen + (2008)



I-front

$$H + e^- \rightarrow H^- + \gamma$$
$$H^- + H \rightarrow H_2 + e^-$$

The H_2 shell can shield the cloud core from the LW radiation emitted by the source star.

Ionizing radiation alleviates the negative effect by LW radiation.

These studies focus on the radiative feedback from a very massive Pop III star with $M_* = 120 M_\odot$.

Purpose

Radiative feedback from less massive PopIII stars on neighboring cores have not been investigated in detail so far...

→ **The feedback tends to be more negative ?**

We perform 3D RHD simulations in order to

✓Investigate the radiative feedback effects from less massive Pop III stars.
✓Clarify what mechanisms determine the condition for the collapse of a neighboring primordial cloud.

Setup

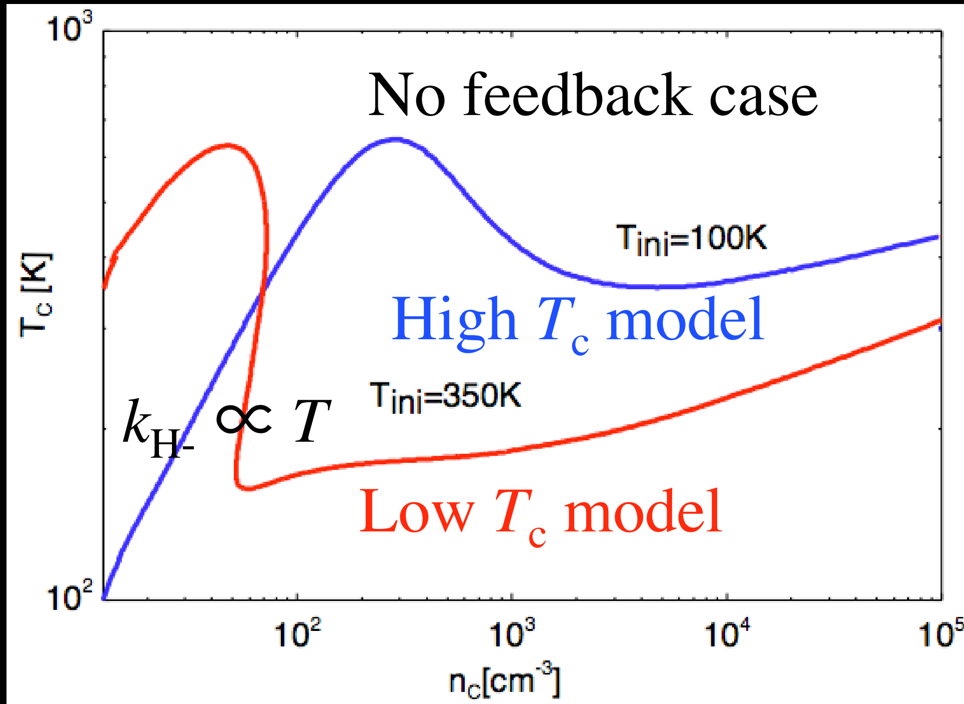
3D-RHD simulation

1. Purely baryonic primordial cloud

n_H=14cm^{-3} (uniform),

$M = 8.3 \times 10^4 M_\odot$, T_i = 100K,350K

Gravitational contraction



2. When the density of cloud core exceeds a certain value n_{on}, the core is irradiated by the source star with mass of M_*, which placed D pc away from the core.

Parameters

n_{on}: 30 - 10^4 cm^{-3}

D : 10-200pc

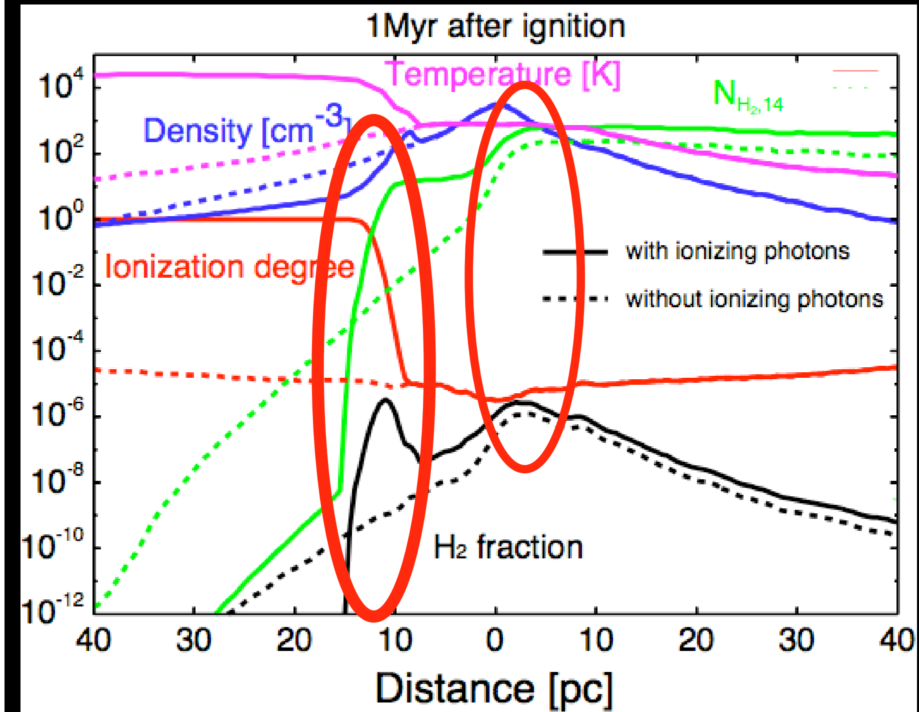
M_*: 25, 40, 80, 120$M_\odot$

We also perform simulations with NO ionizing radiation to investigate the effect of ionizing radiation.

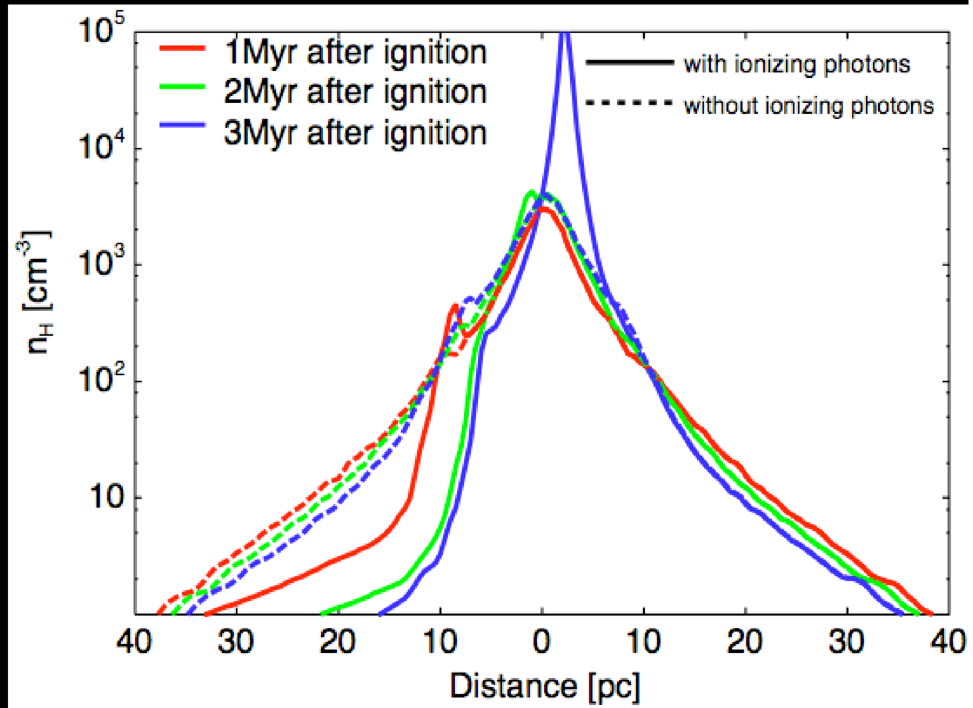
Result: $M_* = 80 M_\odot$, $D = 40$pc, $n_{on} = 10^3 \mathrm{cm}^{-3}$

Dotted LW only   **Solid** LW + ION

Various physical quantities along the symmetry axis at 1Myr after the ignition



Time variations of density profiles



LW : Self-shielding by the core is not effective → Fails to collapse (a hydrostatic core is formed)

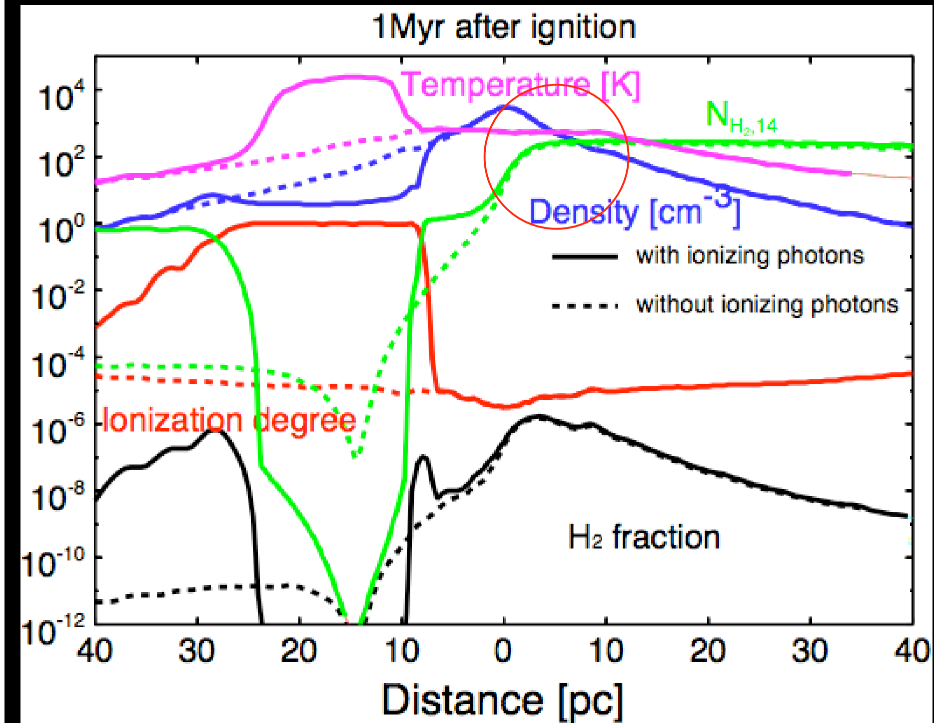
LW + ION :The H_2 shell enhances N_{H2} → The cloud is able to collapse

Result: $M_* = 25M_\odot$, D=14pc, $n_{on}=10^3 cm^{-3}$

The LW flux is the same as that in the previous case.

Dotted LW only **Solid** LW + ION

Various physical quantities along the symmetry axis at 1Myr after the ignition



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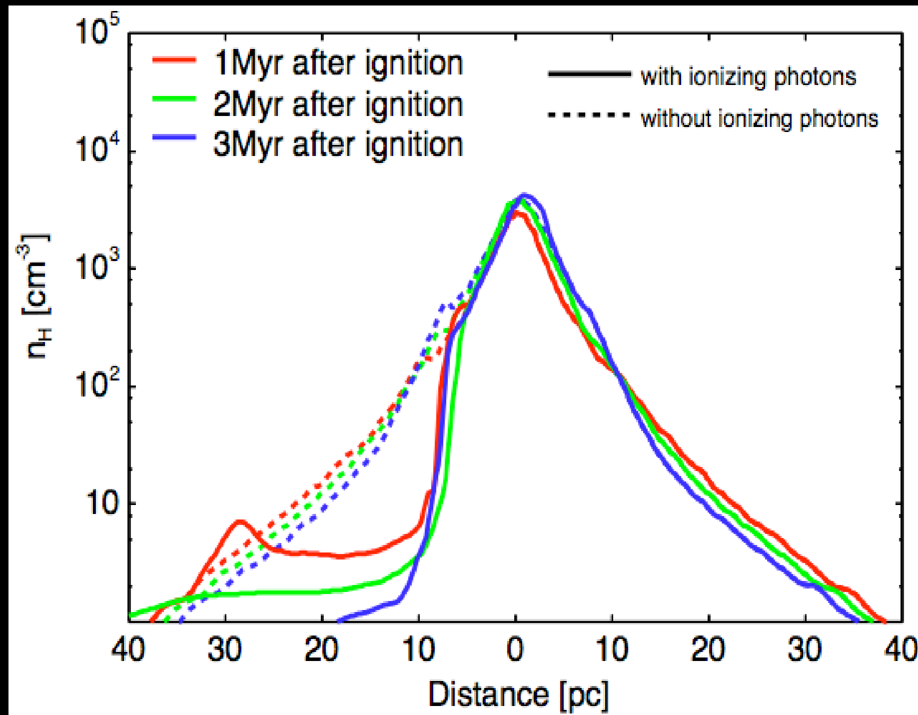
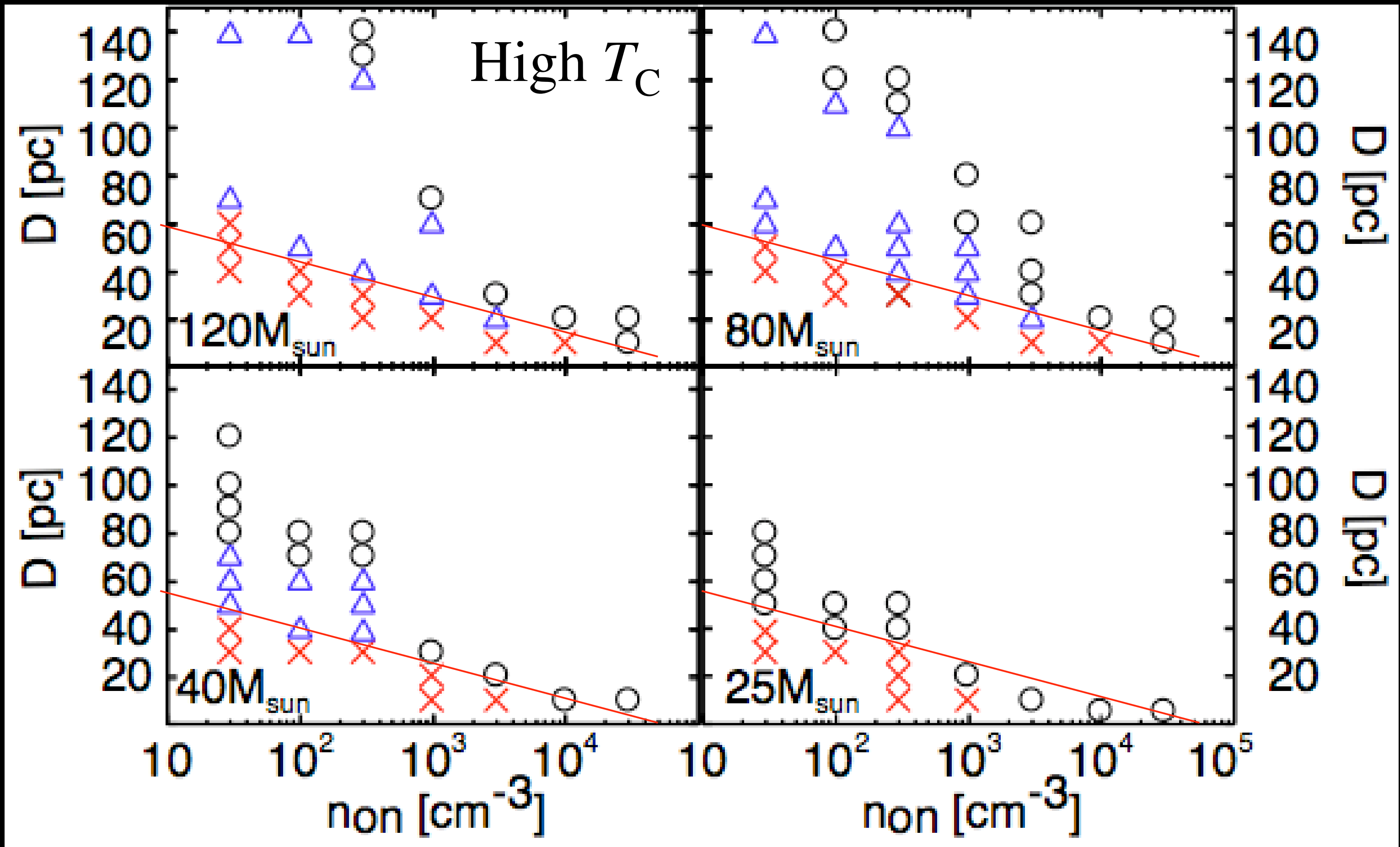


Ionizing radiation **cannot** alleviates the negative feedback of photodissociation.

Summary of Numerical Runs

○ **Collapses,** △**Collapses with the aid of ionizing radiation,** ×**failed collapse**



☆The shielding effect by H_2 shell becomes weak as the source star becomes less massive.

☆Resultant critical distance, below which the cloud cannot collapse, does not so strongly depend on the mass of source star.

Analytic Estimation (1)

Susa (2007) explored the feedback of LW radiation on nearby collapsing cores.

A condition for the collapse of the cores is determined by $t_{dis} = t_{ff}$

Photodissociation timescale

$$t_{dis} = 1/k_{dis} = \frac{1}{1.13 \times 10^{8} F_{LW0} \boxed{f_{s,c}}} \text{ s}$$

Self-shielding by the core

$$f_{s,c} = \min\{1, (N_{H2,core}/10^{14}\,\mathrm{cm}^{-2})^{-0.75}\}$$

Shielding function (Draine & Bertoldi 1996)

Free-fall timescale

$$t_{ff} = \sqrt{\frac{3\pi}{32 G\rho}}$$

F_{LW0}: LW flux at the core (without shielding)

L_{LW}: the luminosity of star in LW band

$r_c \propto T_c^{1/2}$, $k_{H-} \propto T_c$

Critical distance below which a cloud cannot collapse (Susa 2007)

$$D_{cr,d} = 147\,\mathrm{pc} \left(\frac{L_{Lw}}{5 \times 10^{23}\,\mathrm{erg\ s^{-1}}} \right)^{1/2} \left(\frac{n_c}{10^{3}\,\mathrm{cm^{-3}}} \right)^{-7/16} \left(\frac{T_c}{300\mathrm{K}} \right)^{-3/4}$$

Since the estimation does not include the effect of ionizing radiation, we should derive a new criterion.

Analytic Estimation (2)

Effect of ionizing radiation ⇨ The H_2 shell shields the core form the LW radiation !!

✓Thickness of the shell is determined by the amount of ionized gas ▷

$$N_{H_2,sh} = y_{H_2,sh} n_c^{\frac{1}{3}} r_c^{\frac{2}{3}} \left(\frac{N_{ion}}{8\pi\alpha_B} \right)^{\frac{1}{3}}$$

✓H_2 fraction at the shell is in chemical equilibrium

$$y_{H2,sh} = \frac{n_{sh} y_{e,sh} k_{H^-}}{k_{dis}}$$

N_{ion}: ionizing photon number emitted by the source star, $y_{e,sh}$:electron fraction at the shell

$$N_{H_2,sh} = 5.8 \times 10^{14} \boxed{\left(\frac{N_{ion}}{10^{50}\,s^{-1}} \right)^4 \left(\frac{L_{LW}}{5 \times 10^{23}\,ergs^{-1}} \right)^{-4}}$$

strongly depends on N_{ion}/L_{LW} !!

$$f_{s,sh} = \min\{1, (N_{H2,sh}/10^{14}\,cm^{-2})^{-0.75}\}$$

$$\boxed{D_{cr,sh} = 147\,pc \left(\frac{L_{LW} f_{s,sh}}{5 \times 10^{23}\,erg\ s^{-1}} \right)^{1/2} \left(\frac{n_c}{10^3\,cm^{-3}} \right)^{-7/16} \left(\frac{T_c}{300K} \right)^{-3/4}}$$

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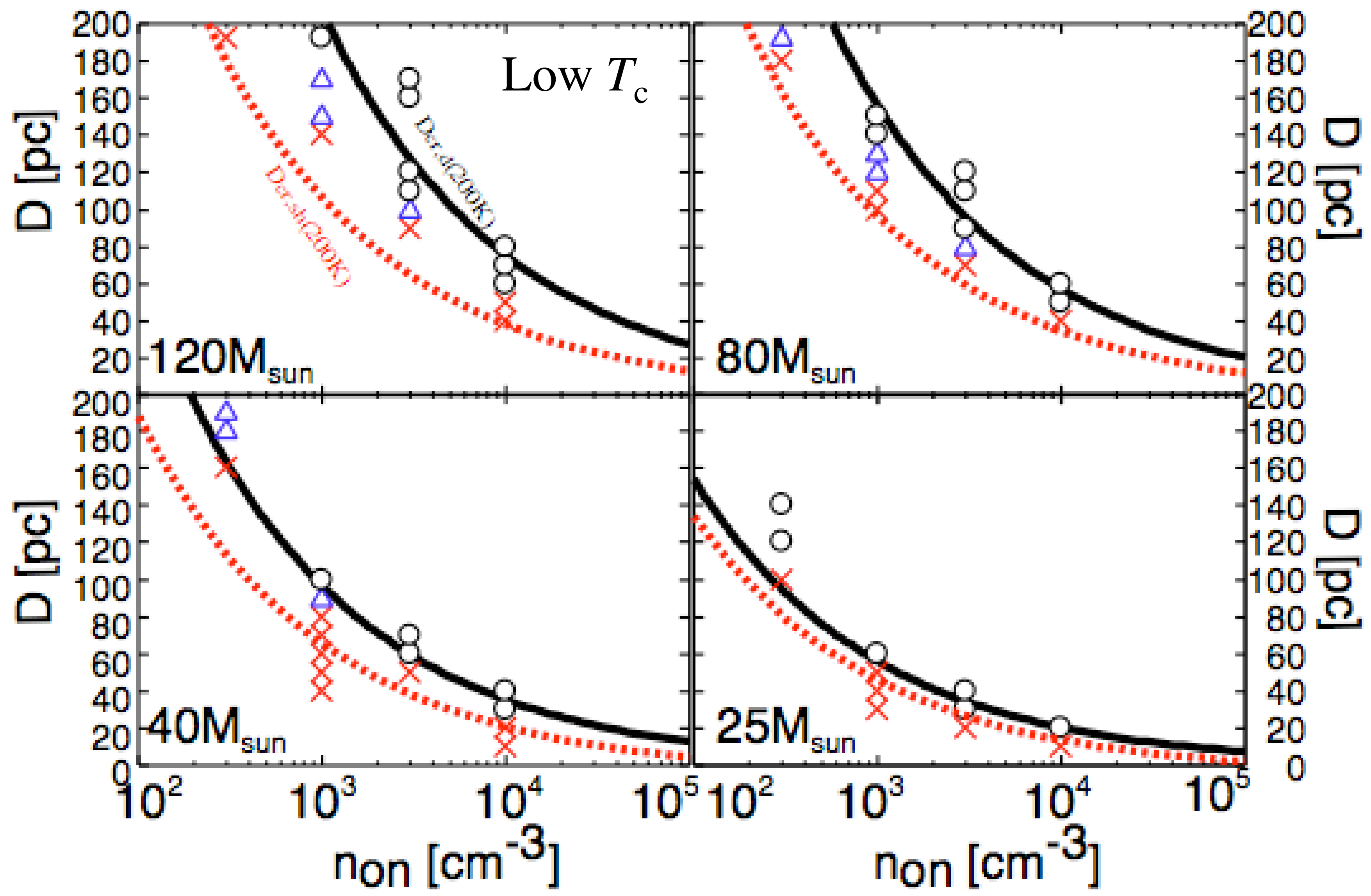

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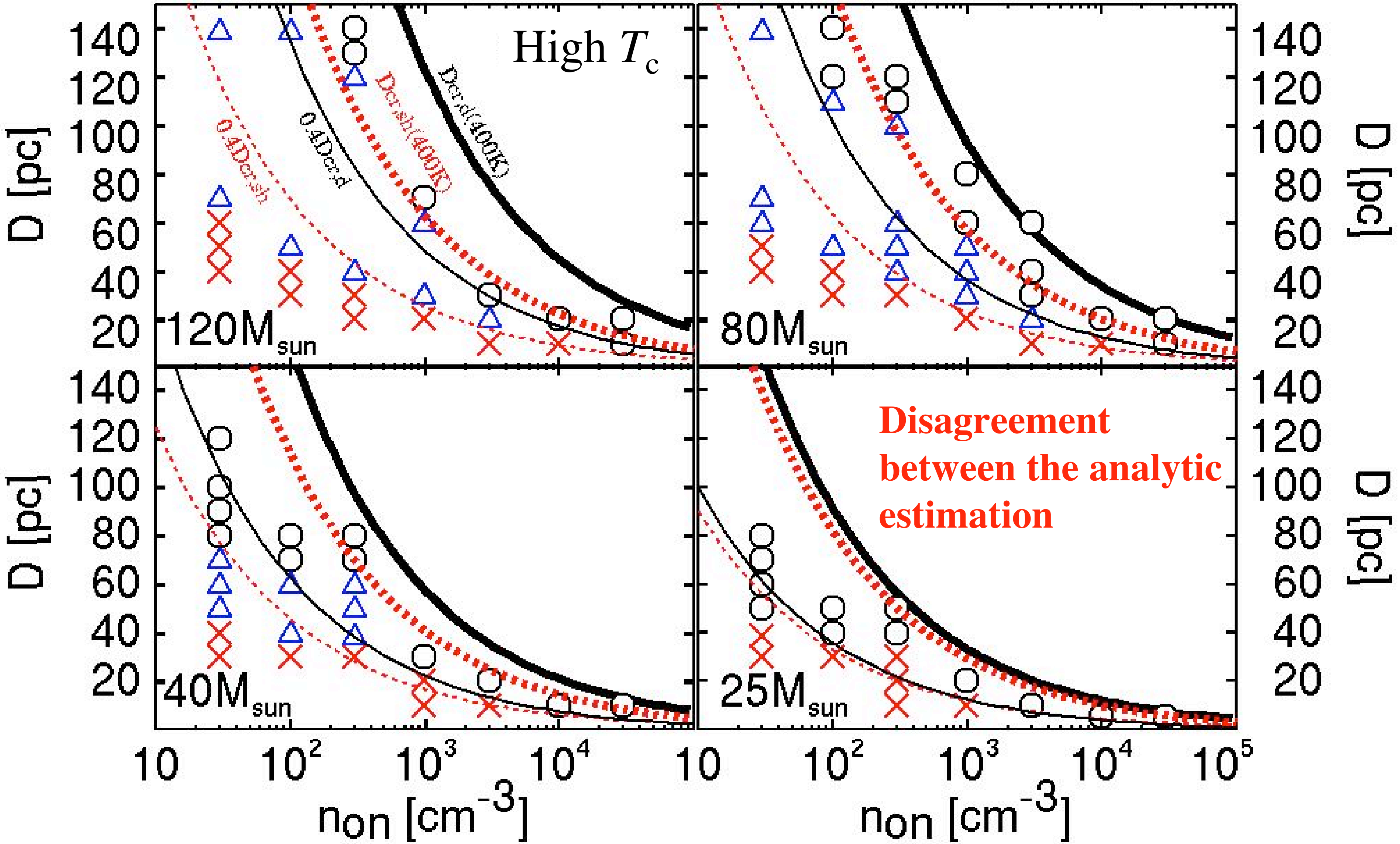


Dynamical Effect

$M_* = 80 M_\odot$, D=40pc, $n_{on} = 10^3 cm^{-3}$

H_2 fraction at the core (Susa 2007)

$$y_{H_2} = 2.33 \times 10^{-5} \left(\frac{F_{\rm LW}}{2 \times 10^{-17} \,\rm cgs} \right)^4 \left(\frac{n_c}{10^4 \,\rm cm^{-3}} \right)^{7/2} \left(\frac{T_c}{10^3 \,\rm K} \right)^{15/2}$$

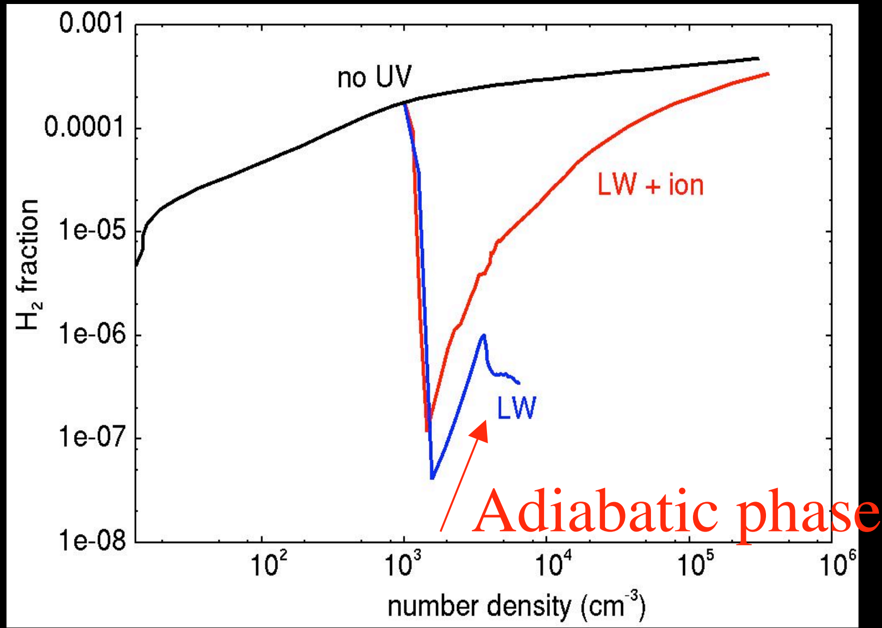
Intense LW radiation

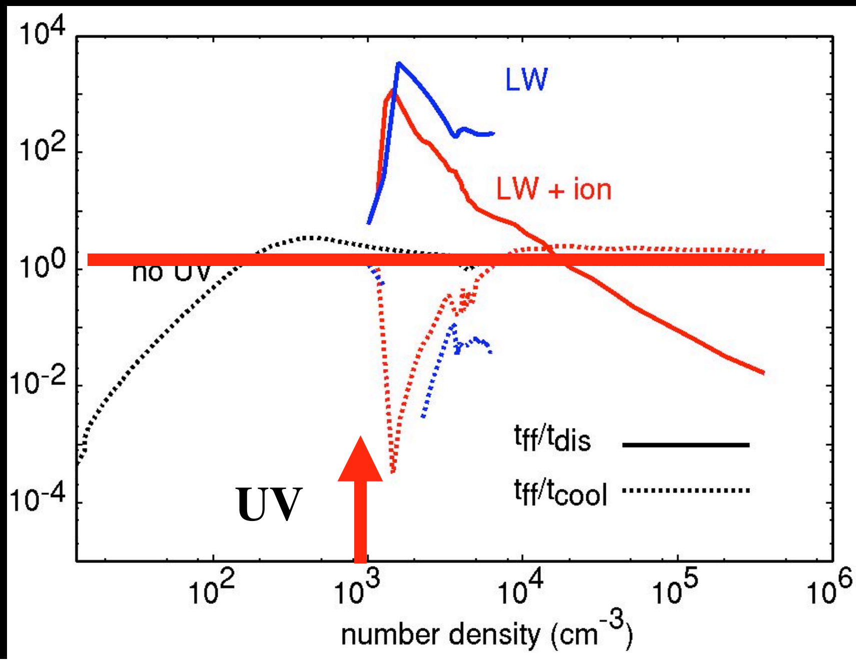
⇨adiabatic evolution

$T_c \propto n_c^{2/3}$ and $\mathbf{y_{H2} \propto n_c^{17/2}}$

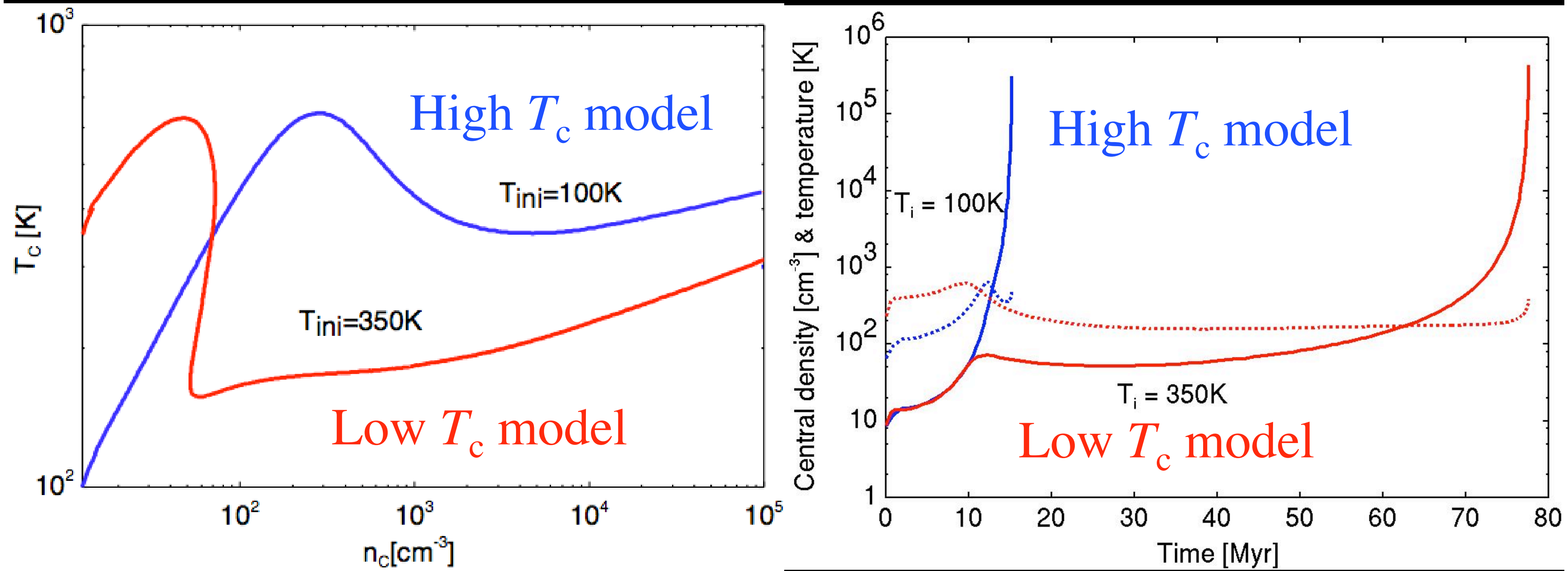
H_2 fraction is quickly recovered, and H_2 column density becomes large.

Finally, $t_{ff} < t_{dis}$ is satisfied





Evolution of Clouds without Radiative Feedback



Low T_c model: high initial temperature ⇨ high U/W

High T_c model: low initial temperature ⇨ low U/W

Summary of my talk

We have found

i) The critical distance below which a neighboring cloud cannot collapse does not so strongly depend on the mass of source star.

ii) H_2 column density of the H_2 shell sensitively depends on the relative intensity of the ionizing radiation to LW radiation $\{\propto (N_{\rm ion}/L_{\rm LW})^4\}$.

⇒ **If M_* is less than ~25$M_\odot$, ionizing radiation cannot extinguish the negative feedback of LW radiation.**

iii) The feedback criterion is well expressed as

$$\boxed{D_{\rm cr} = f_{\rm dyn} D_{\rm cr,sh} = 59{\rm pc}\left(\frac{f_{\rm dyn}}{0.4}\right)\left(\frac{L_{\rm LW} f_{\rm s,sh}}{5\times 10^{23}{\rm erg\ s^{-1}}}\right)^{1/2}\left(\frac{n_{\rm c}}{10^3{\rm cm^{-3}}}\right)^{-7/16}\left(\frac{T_c}{300{\rm K}}\right)^{-3/4}}$$

$f_{\rm dyn}$ =0.4 for the high $T_{\rm c}$ model, while $f_{\rm dyn}$ =1 for the low $T_{\rm c}$ model.

Spectrum for source Pop III stars

Base on Schaerer 2002