

Formation and Dynamical Evolution of Globular Cluster

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*Elucidation on the Origin of FIRST Generation Objects by HMCS-E
Specially Promoted Research
in Grants-in-Aid for Scientific Research by MEXT*

14Gyr

1Gyr

0.1Gyr

0.5Myr

Dark Age

1st Part

2nd Part

**Globular
Cluster
Formation**

**Dynamical
Evolution
(~10Gyr)**

Present Day
GC

Big Bang
ビッグバン

CMB

Pop III

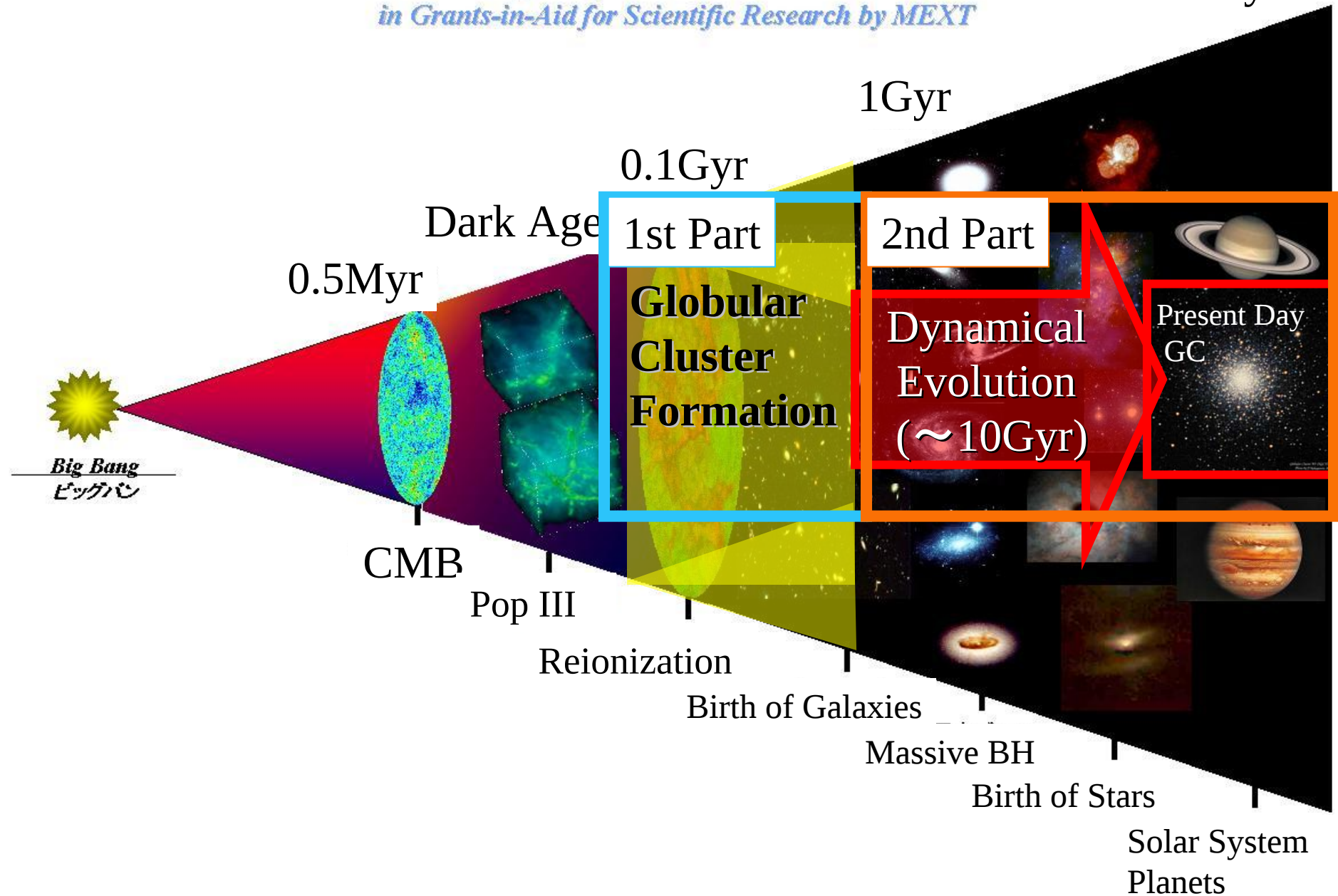
Reionization

Birth of Galaxies

Massive BH

Birth of Stars

Solar System
Planets



1st PART

Formation of Globular Cluster within UV Radiation Field

Collaborators

Masayuki Umemura (U. Tsukub)

Tetsu Kitayama (U. Toho)

Reionization and GC Formation Epoch

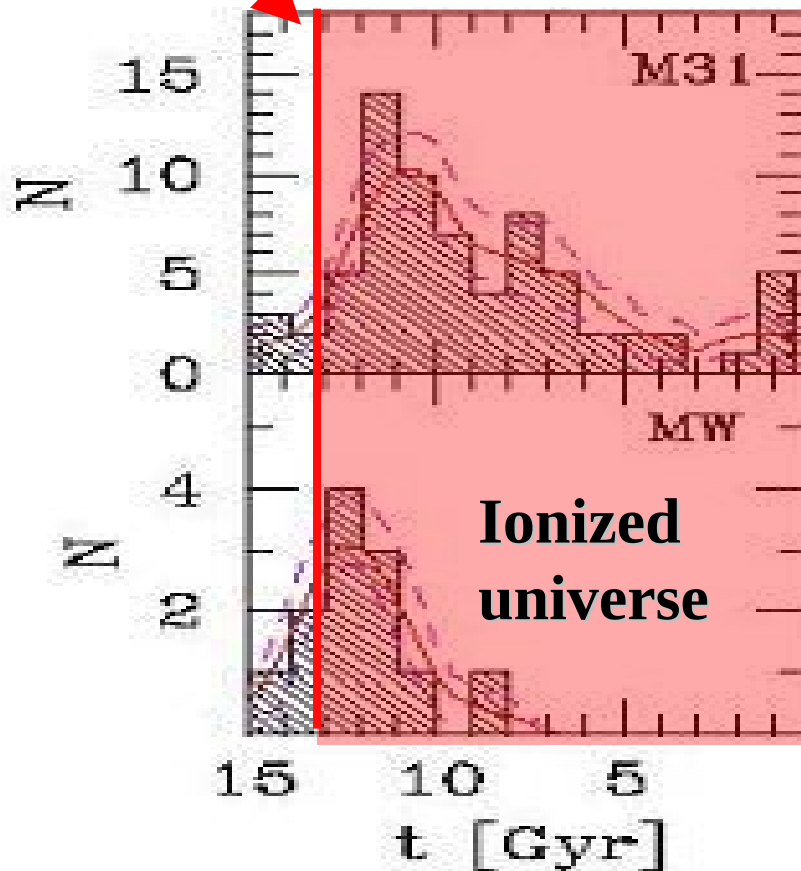
WMAP 3year (Page et al. 2006)

Reionization epoch ~ 13 Gyr ago

v.s

The age distribution of GCs

Mean age of GCs ~ 12 Gyr



Puzia et al. (2005)

It indicates that **many**
GCs formed after
cosmic reionization !!

GCs could form within
UV radiation field ?

Importance of UV Radiation

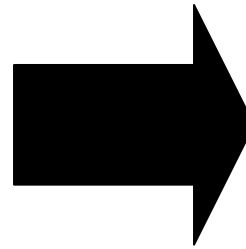
negative

✓ Photoheating

➡ Gas temperature $\sim 10^4\text{K}$

✓ Photodissociation(H_2)

➡ Gas clouds can not cool
below 10^4K



UV radiation might
suppress the
formations of GCs?

★ OBJECTIVE ★

We explore the possibility that GCs
form within UV radiation field !!

Simulation of GC Formation within UV Radiation

1D spherical symmetric Lagrangian scheme
(Kitayama et al. 2001)

Gas dynamics

$$\frac{dm_b}{dr_b} = 4\pi r_b^2 \rho_b$$

$$\frac{d^2 r_b}{dt^2} = -4\pi r_b^2 \frac{dP}{dm_b} - \frac{GM(< r_b)}{r_b^2} + \Lambda_0 H_0^2 r_b + f_{\text{rad}}$$

$$\frac{du}{dt} = \frac{P}{\rho_b^2} \frac{d\rho_b}{dt} + \frac{\Gamma - \Lambda}{\rho_b}$$

$$P = (\gamma - 1)\rho_b u = \frac{k_B \rho_b T}{\mu m_p}$$

$$T < 2000 \text{ K}$$

$$V_r < 0$$

$$\frac{d\rho}{dt} > 0$$

$$\frac{dT}{dt} < 0$$

SF criteria

Λ CDM universe:

$$\Omega_0 = 0.3, \Omega_b = 0.05, \Lambda_0 = 0.7, h = 0.7$$

DM dynamics

$$\frac{d^2 r_d}{dt^2} = -\frac{GM(< r_d)}{r_d^2} + \Lambda_0 H_0^2 r_d$$

Star dynamics

$$\frac{d^2 r_s}{dt^2} = -\frac{GM(< r_s)}{r_s^2}$$

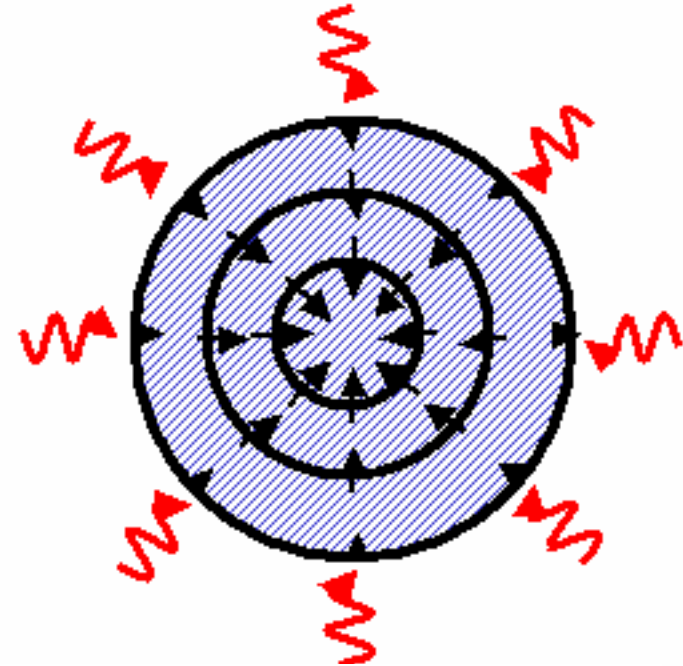
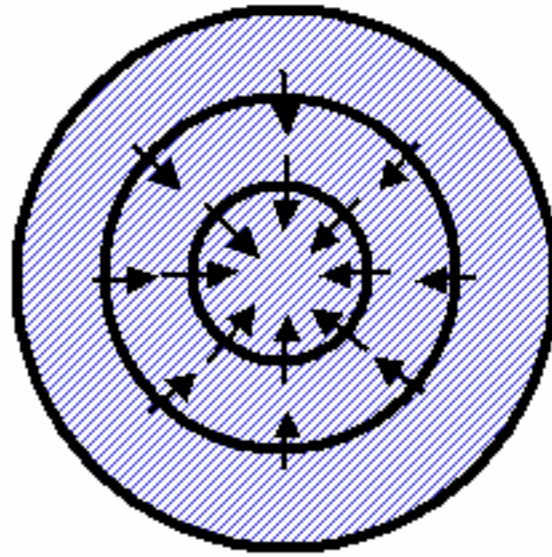
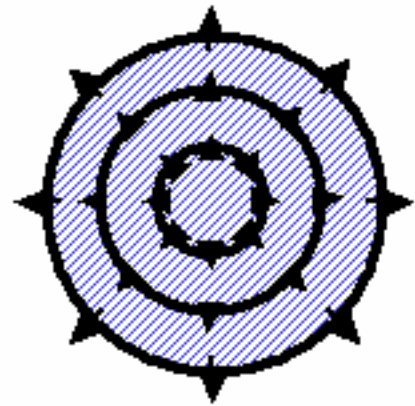
- RT of UV photons $\Rightarrow$ **Determine the heating and the chemical reaction rate**
- Non-equilibrium of chemistry $\Rightarrow$ **Determine the cooling rate (H2)**

Calculation Procedure

The cloud expands
on the Hubble flow

The cloud turnaround.

The contracting cloud is
exposed by UV radiation!!



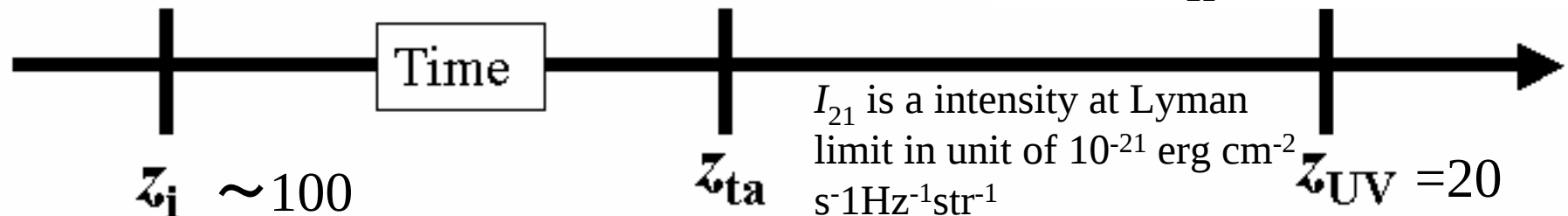
START

The cloud is still
in linear regime.

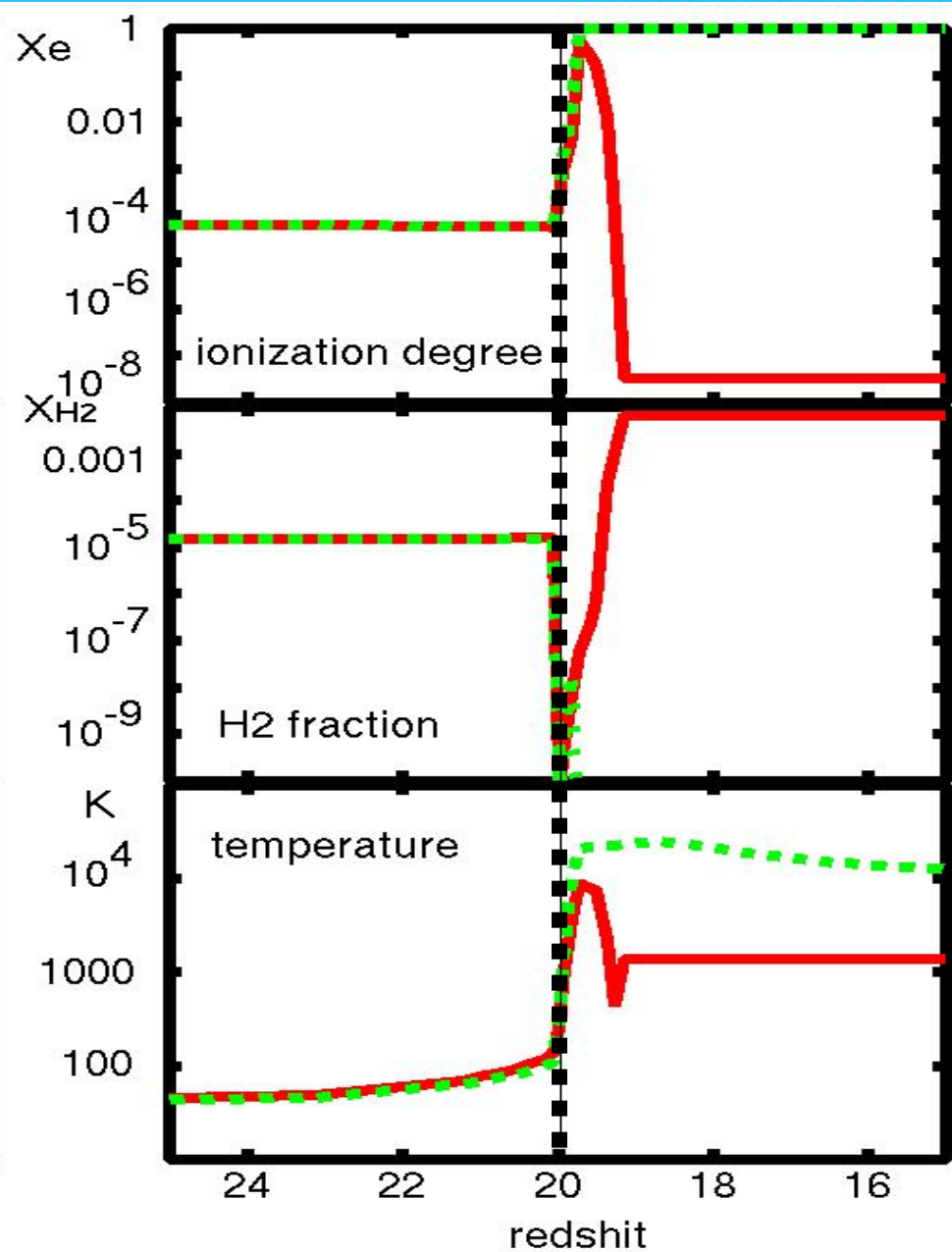
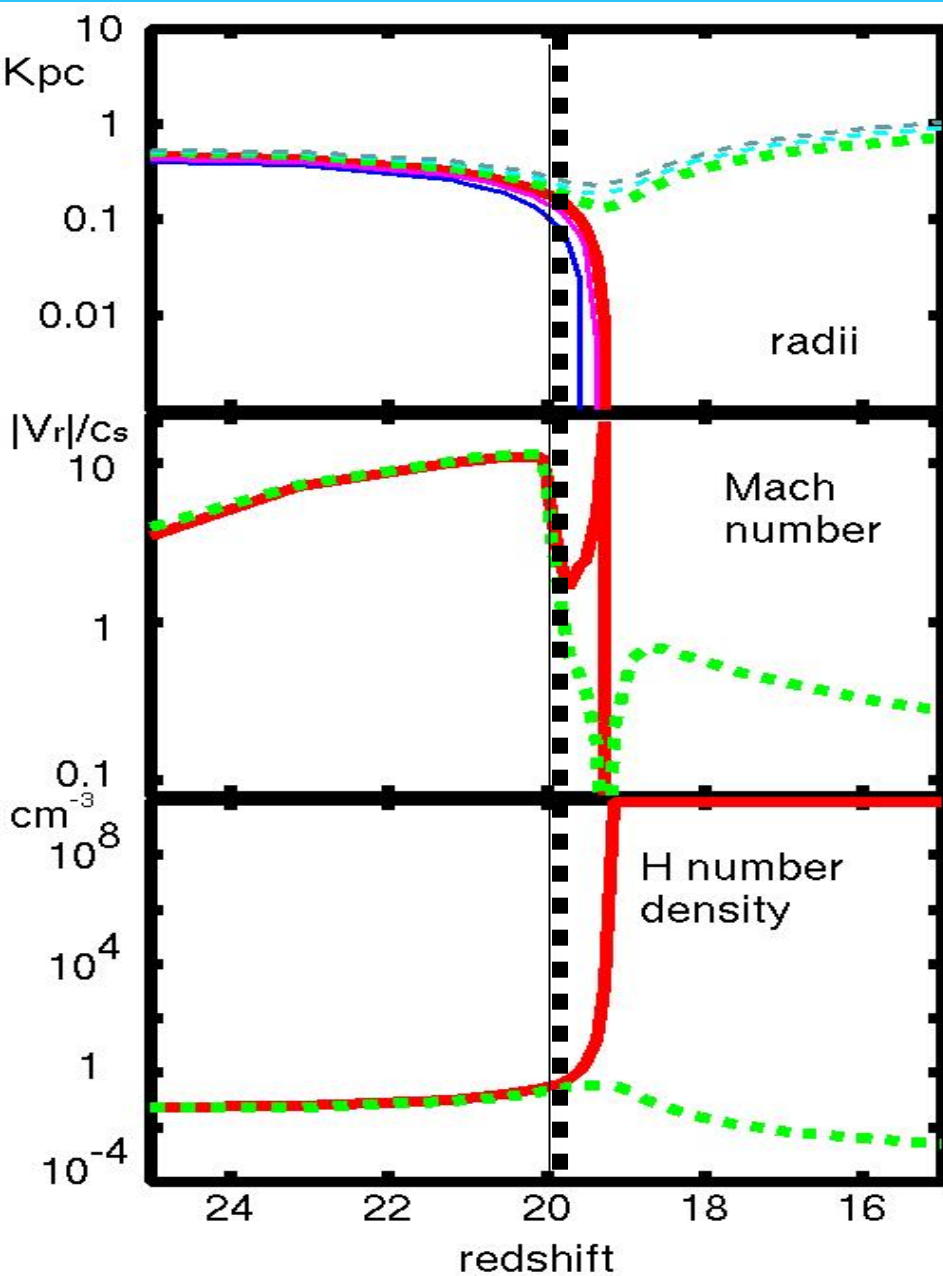
UV radiation on !!

✓ Black Body with $T_{\text{eff}} = 10^5 \text{K}$

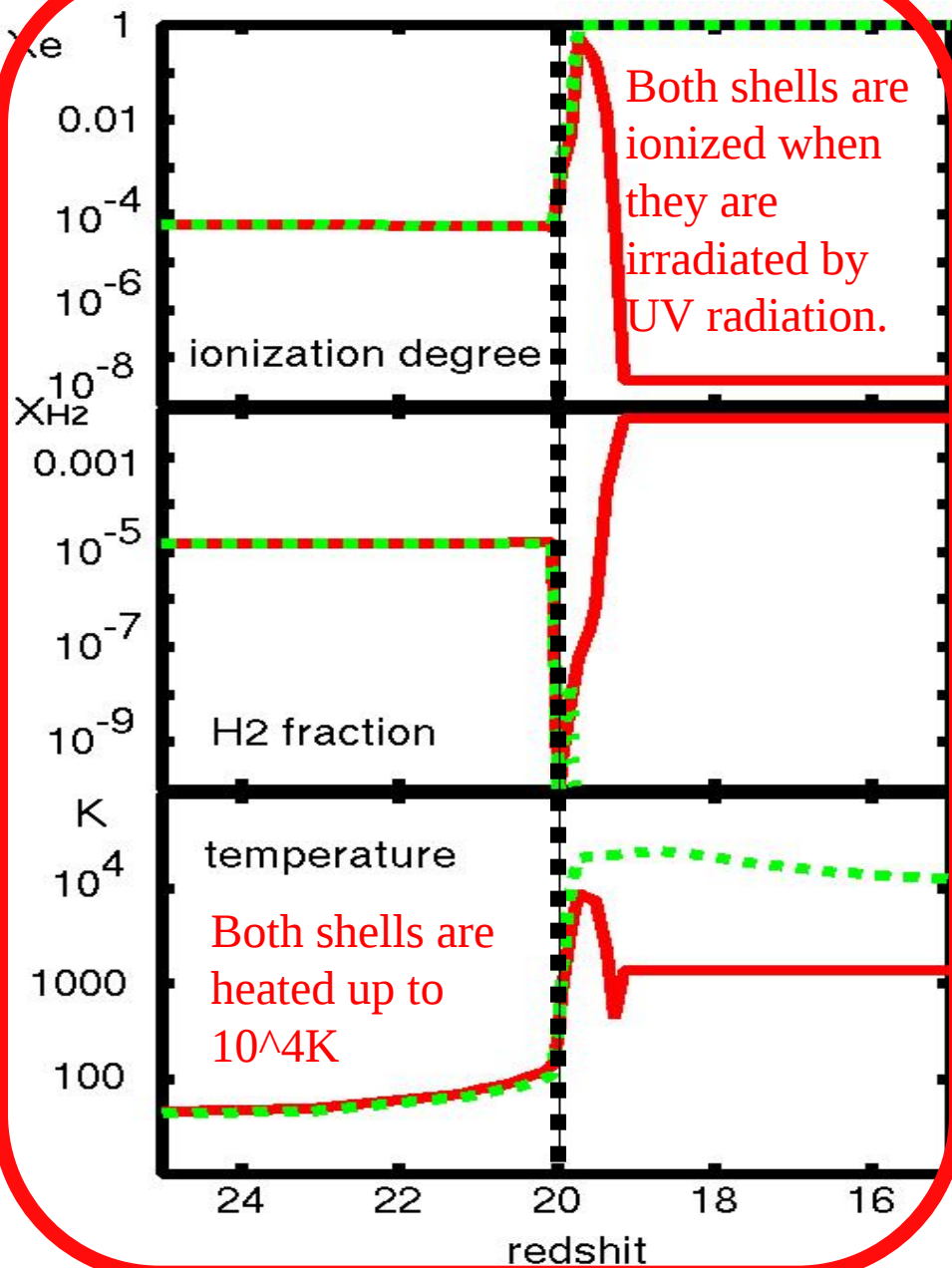
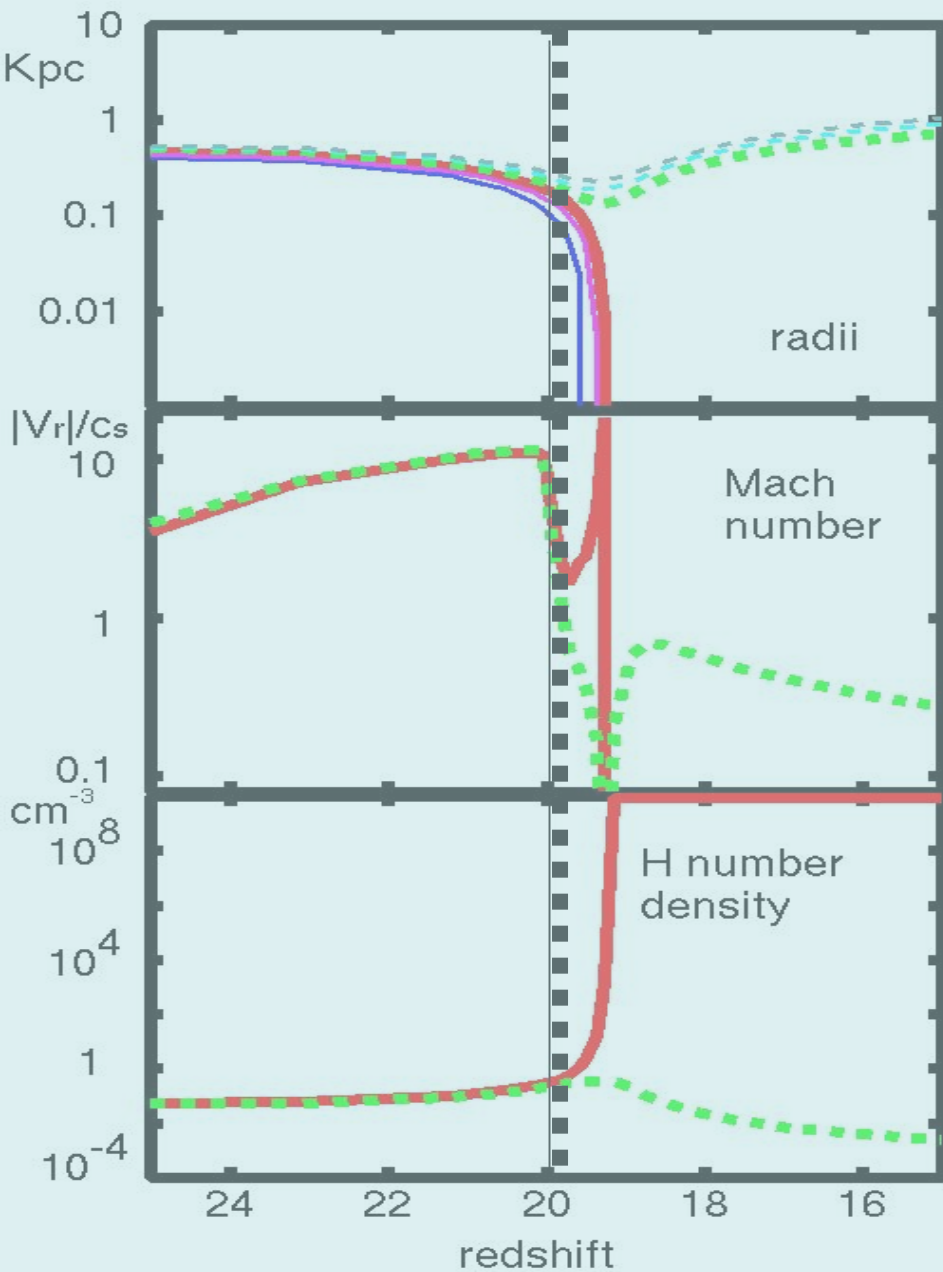
✓ $10^{-3} < I_{21} < 10^3$



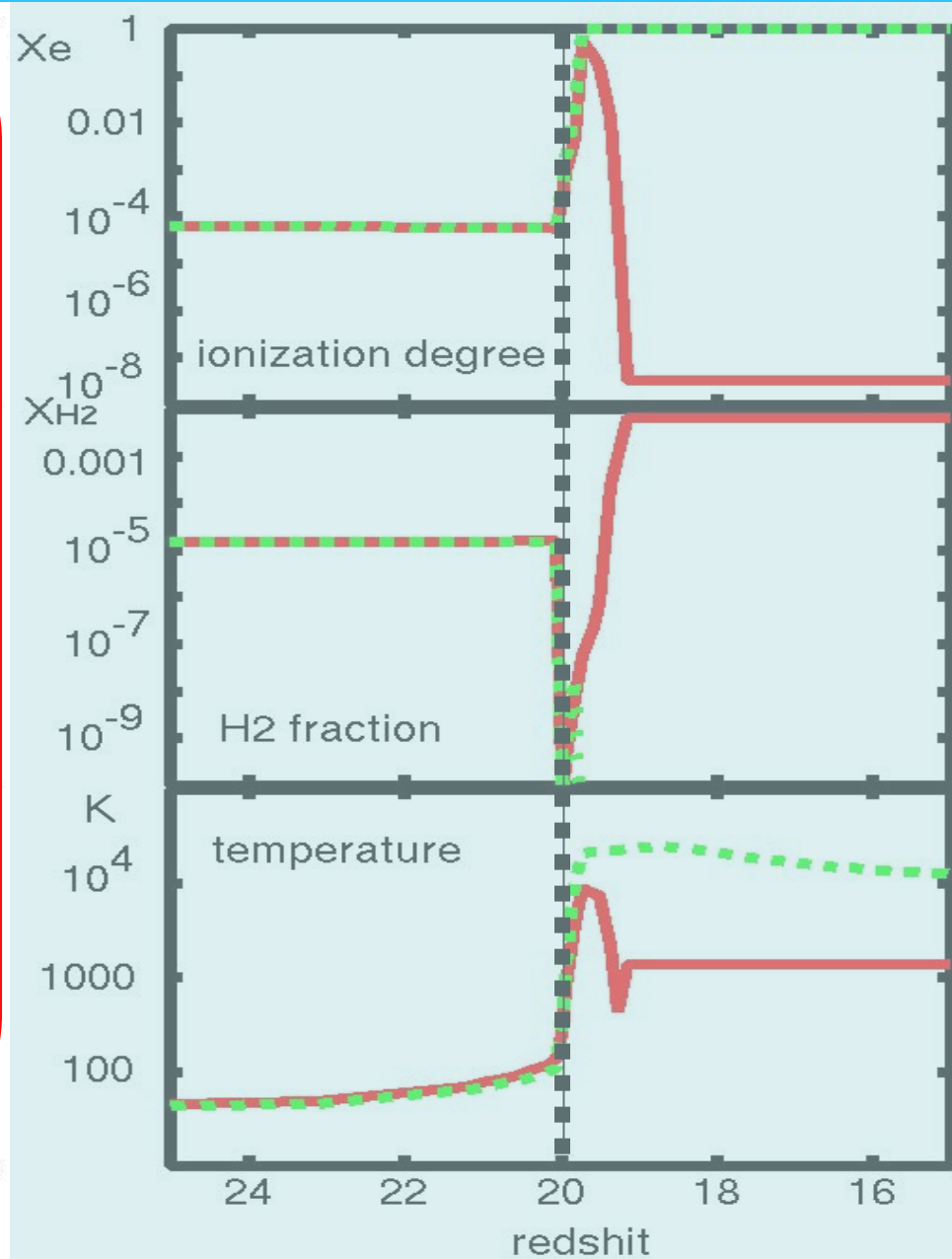
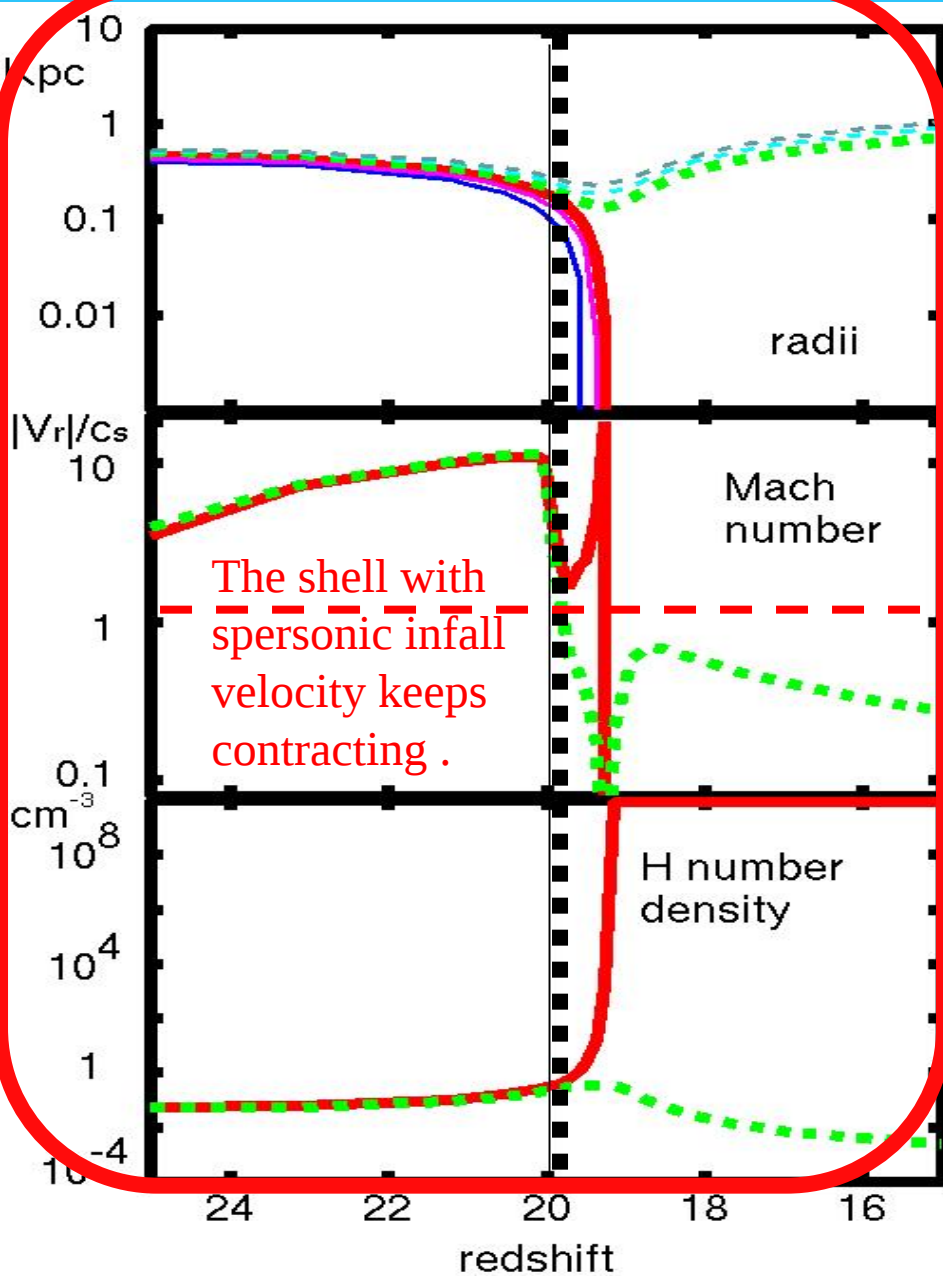
Evolution of the Cloud



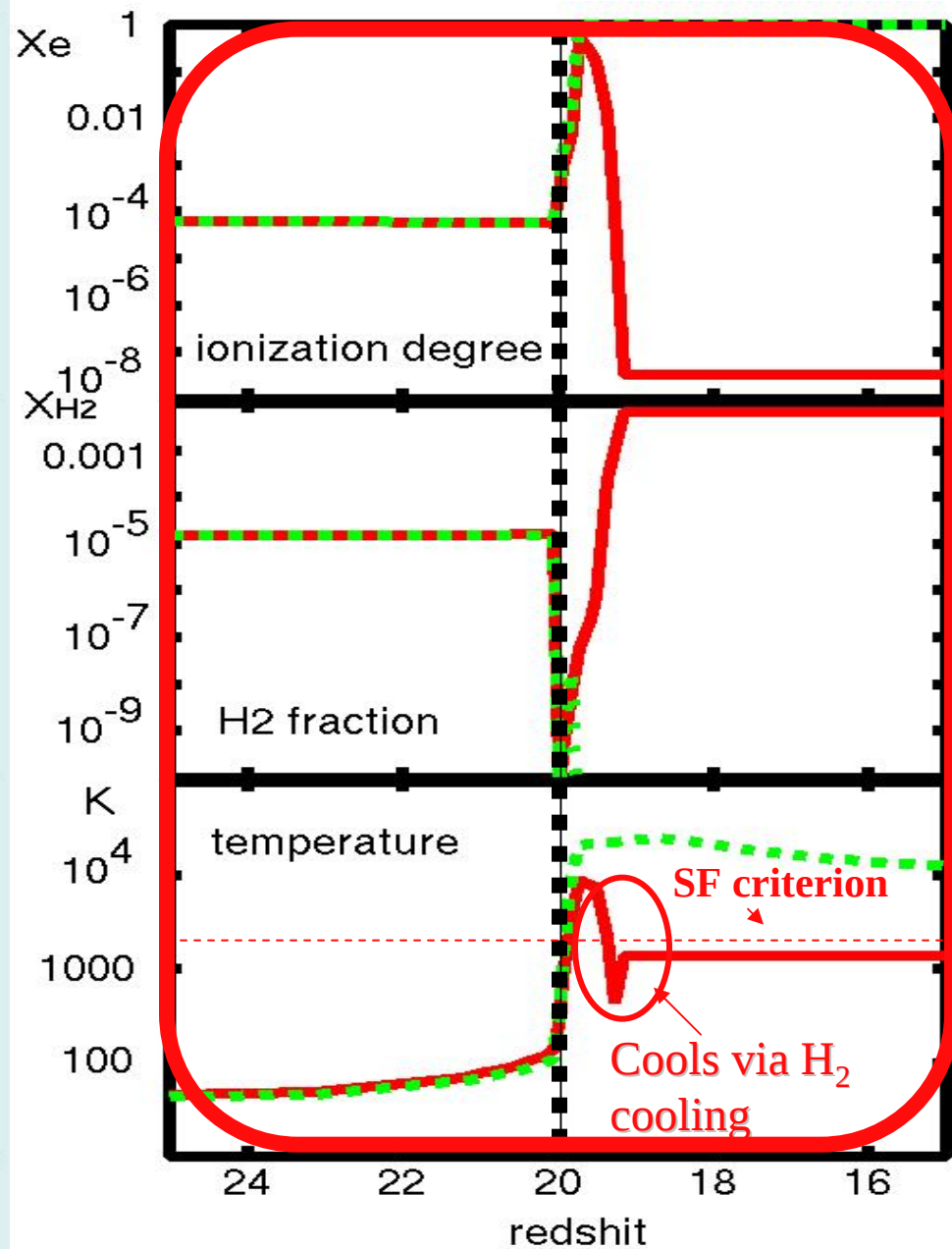
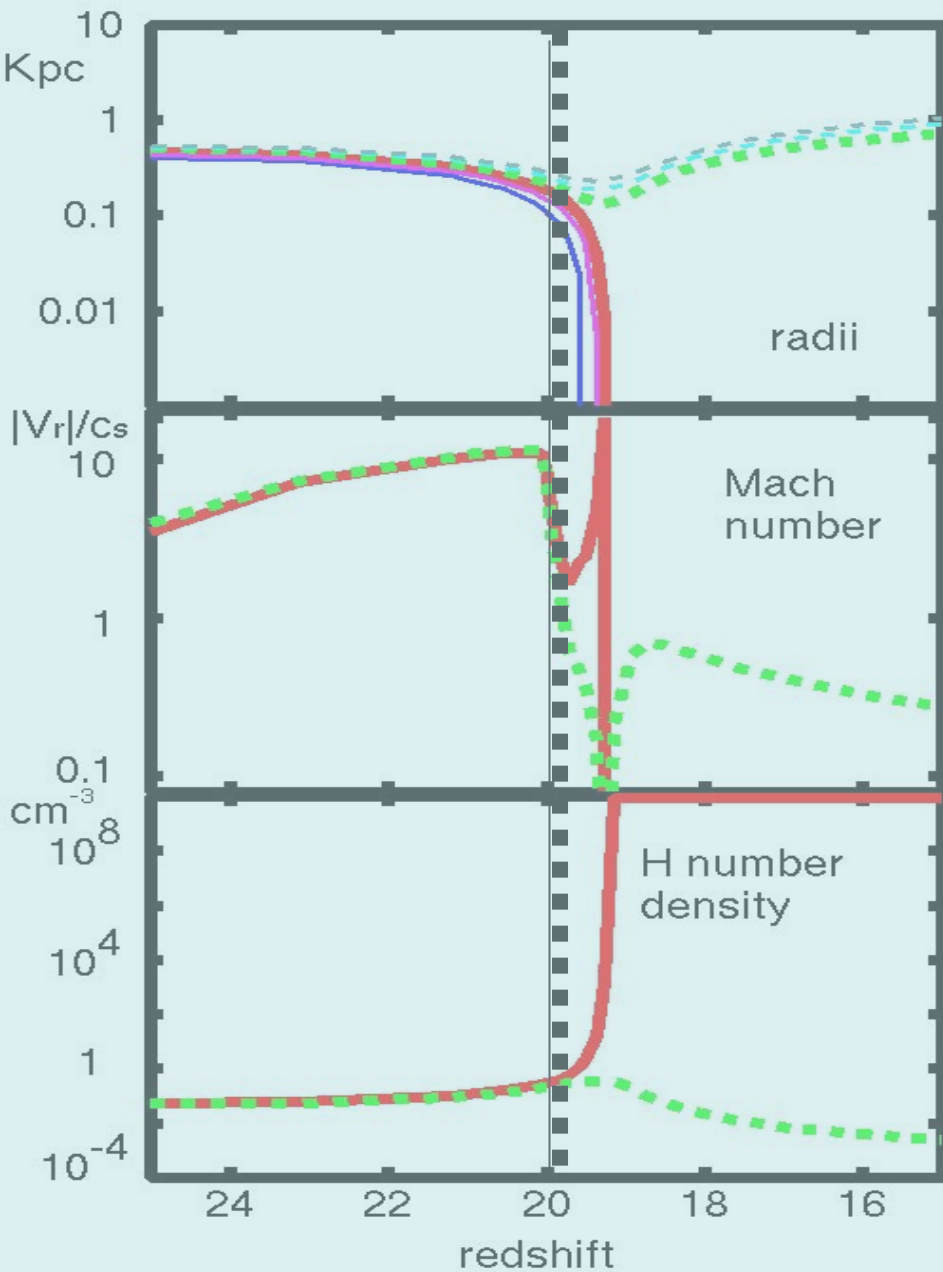
Evolution of the Cloud



Evolution of the Cloud

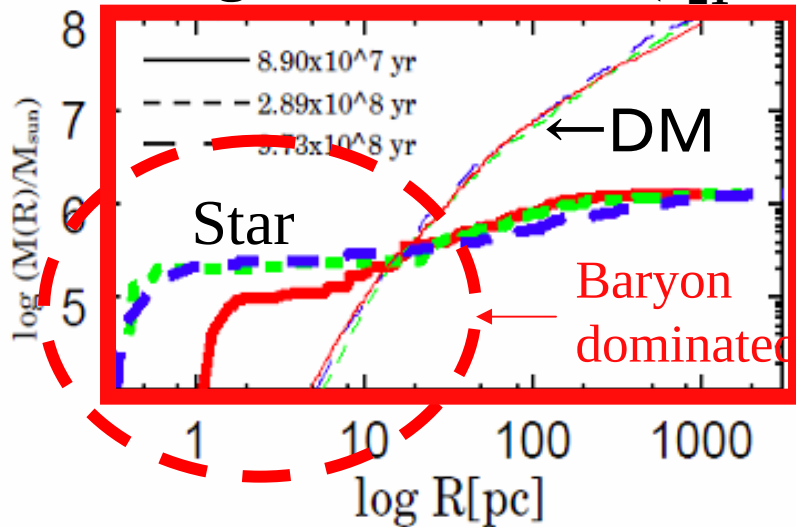


Evolution of the Cloud

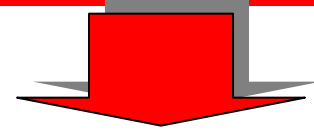


Mass Distribution

Strong UV radiation ($I_{21} > 1$)



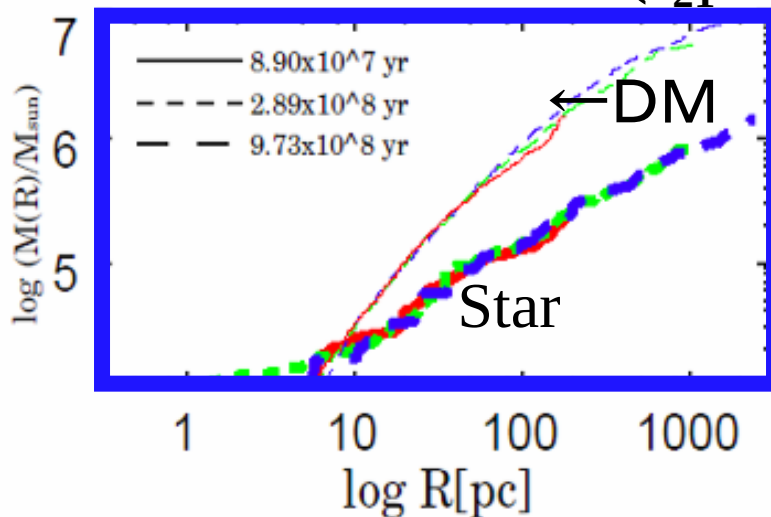
Stars are born at inner region of the cloud. The energy dissipation is strong !!



Compact star cluster forms !!

⇒ **GC like** (with DM halo)

Weak UV radiation ($I_{21} < 0.1$)



Stars are born at earlier dynamical stage.



DM dominated and low density star cluster forms ! ⇒ **dSphs like**

2nd PART

Dynamical Evolution of Globular Cluster

Collaborator

Masayuki Umemura (Tsukuba University)

FIRST Project Team

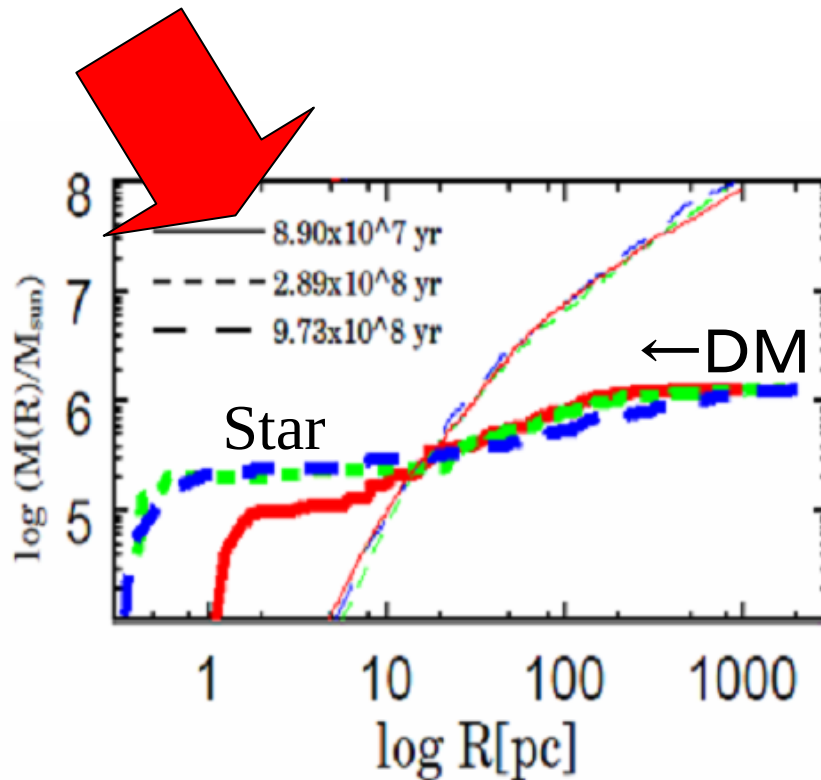
Setup for the Simulation

➤ Number of particle : $N_*=2^{14}$, $N_{\text{DM}}=2^{18}$ ($m_*/m_{\text{DM}}=10.39$)

➤ External tidal field

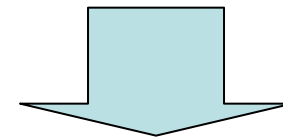
*NFW type potential (with $M_{\text{gal}}=10^9 M_{\odot}$, $R_{\text{vir}}=294\text{pc}$, $c=10$)

➤ Initial condition : Obtained by our simulation of GC formation.



★ Two-body relaxation (Spitzer & Hart 1971)

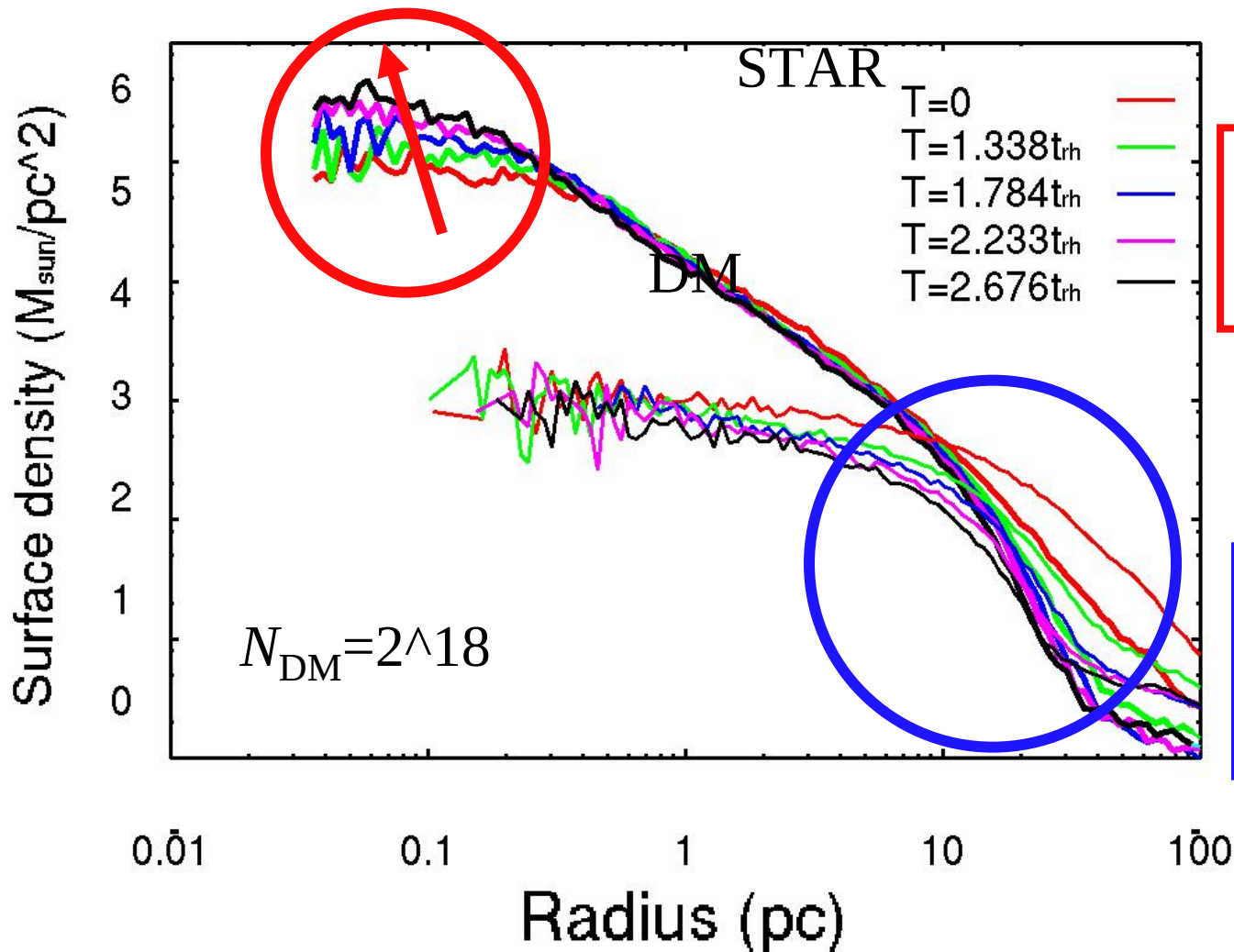
$$t_{\text{rh}} \approx 5.76 \times 10^9 \left(\frac{M}{10^6 M_{\text{sun}}} \right)^{1/2} \left(\frac{1 M_{\text{sun}}}{m} \right) \left(\frac{r_h}{10 \text{pc}} \right)^{3/2}$$



Cosmic age($\sim 14\text{Gyr}$)
corresponds to $\underline{2.6 t_{\text{rh}}}$.

Evolution of Observable Profile

✓ The profile changes as the star cluster evolves !!



Inner part

The core shrinks
via two-body
relaxation.

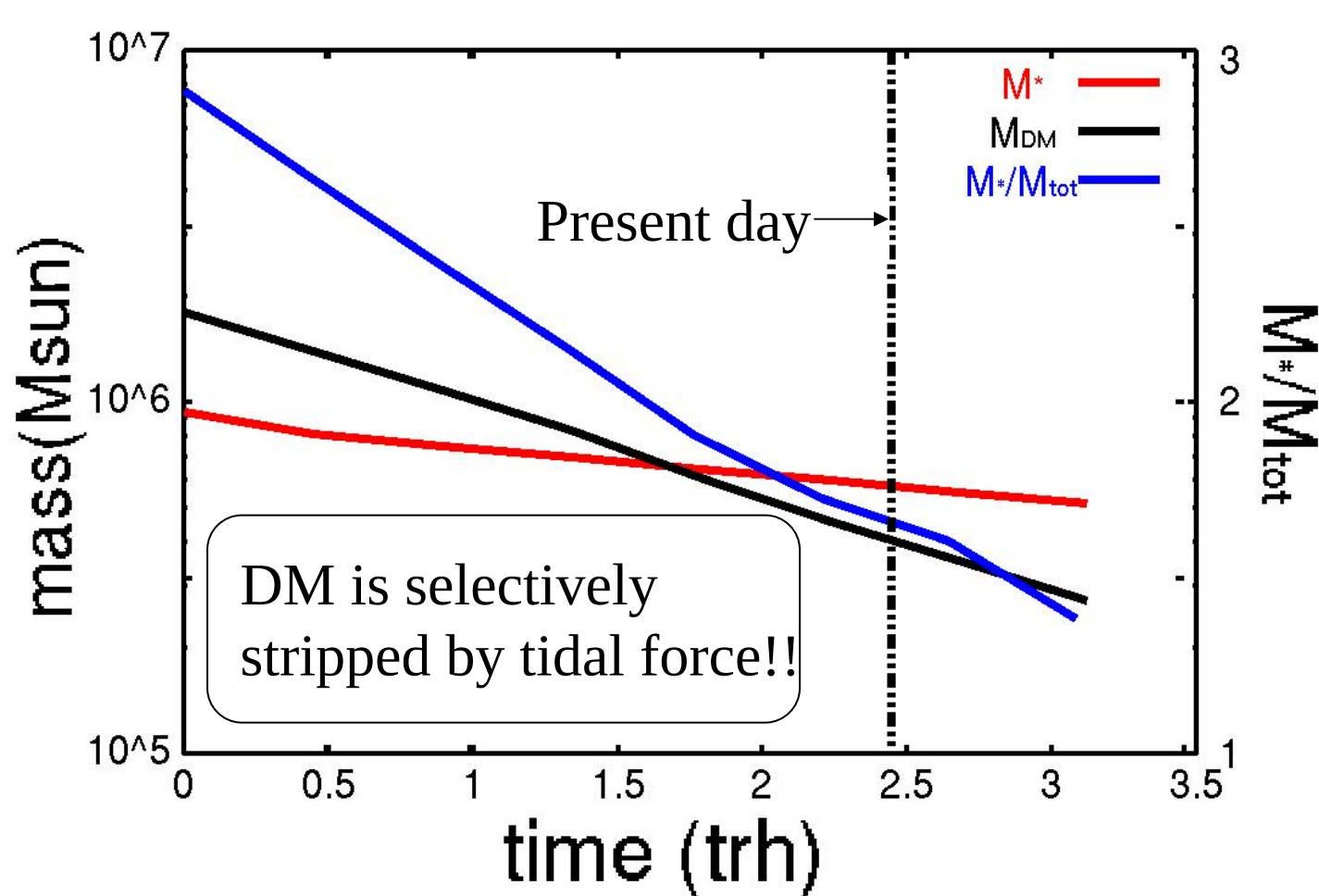
Outer part

Tidal stripping

⇒ The cluster
mass decreases !!

Evolution of the Cluster Mass

We assume a mass within 50pc from the center as the cluster mass.



Simulation

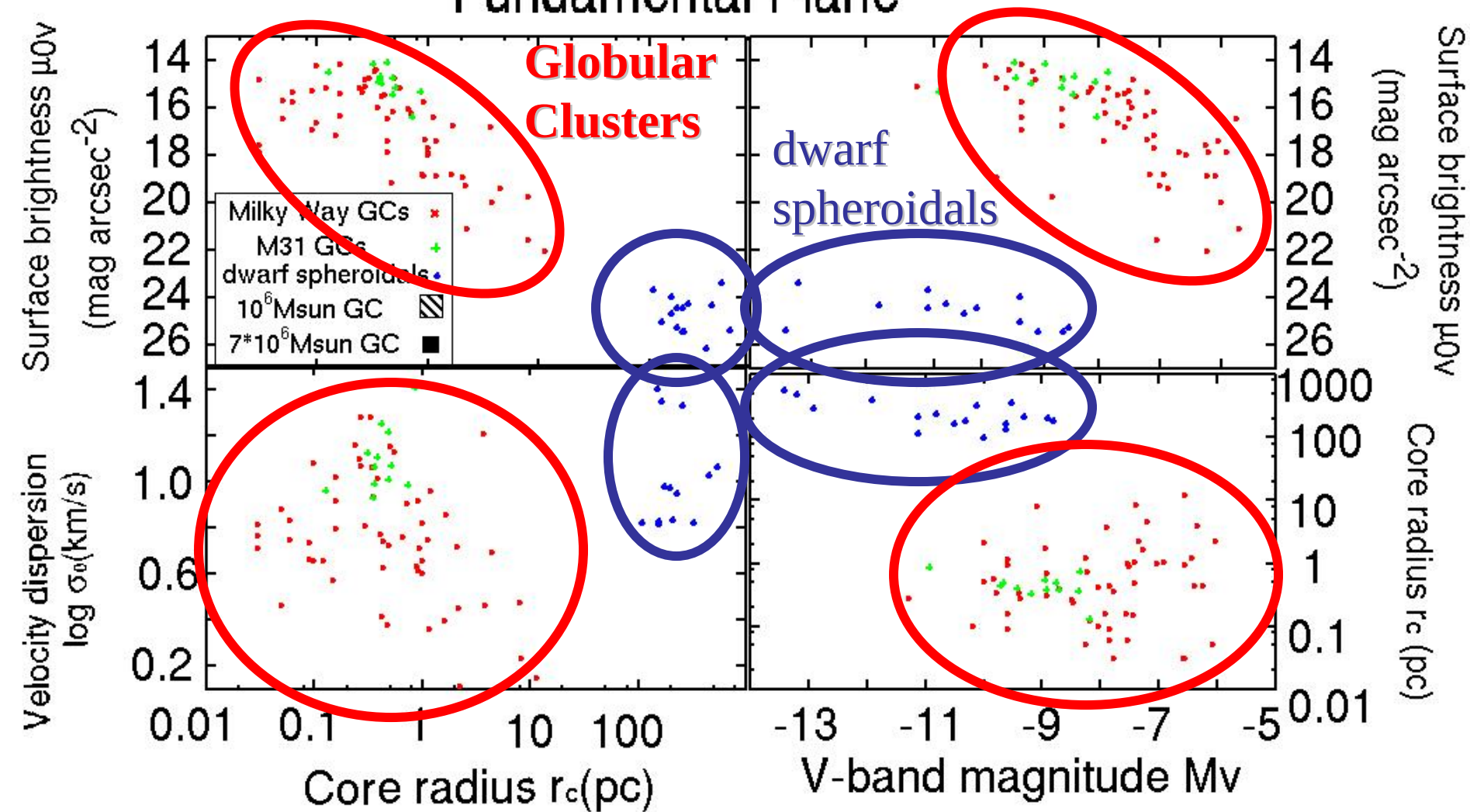
The star cluster with a small amount of DM survive !!

Observation

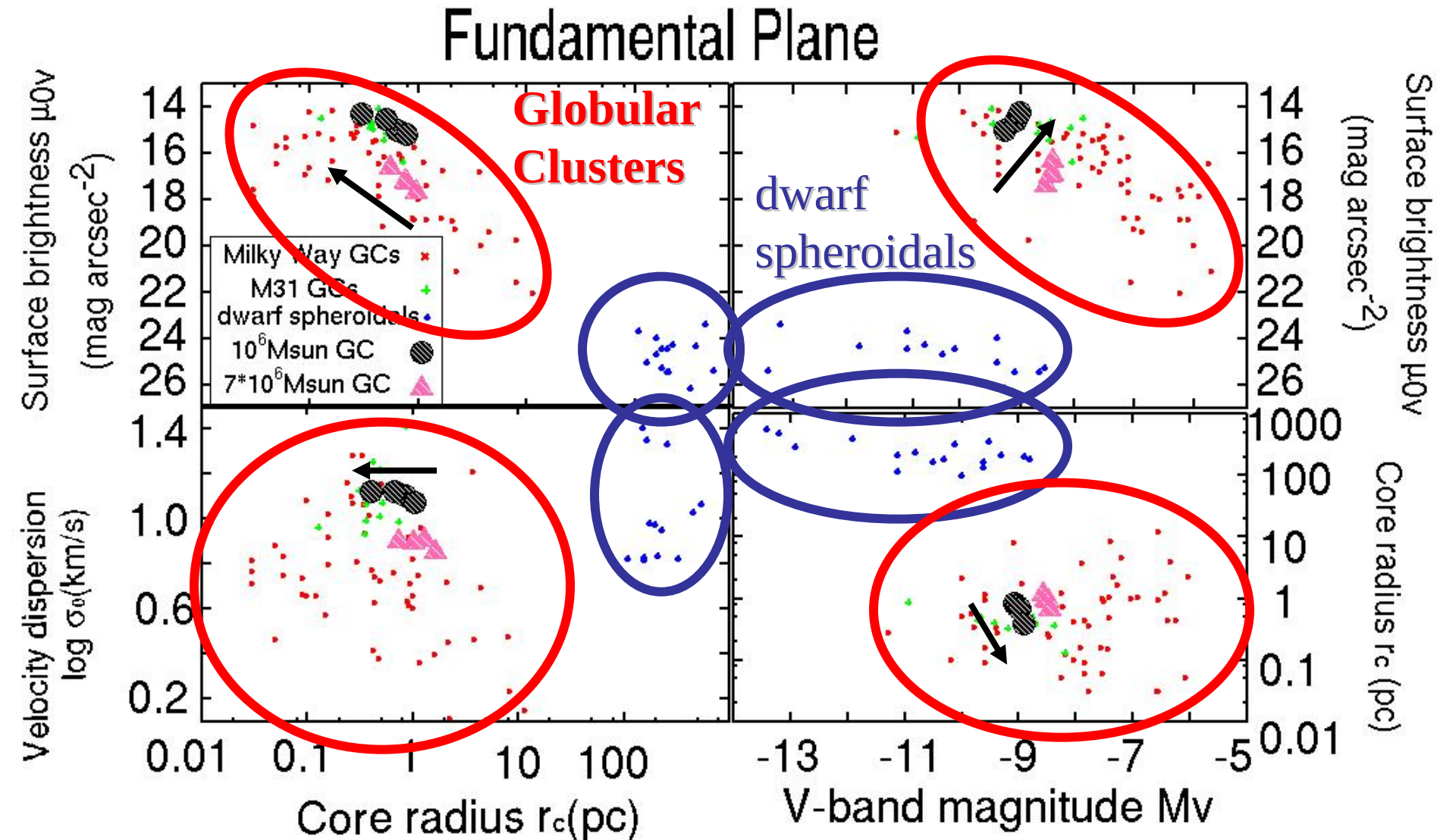
GCs have low mass-to-light ratio $M/L \sim 2$

Comparison with observations

Fundamental Plane



Comparison with observations



$T = 1.338, 1.784, 2.233, 2.676 t_{\text{rh}}$ are shown

Summary

★ Globular Cluster Formation within UV radiation Field

Strong UV radiation → **The cloud is ionized !!**

If the cloud has supersonic infall velocity, the cloud keeps contracting.

→ Star formation is delayed and stars are born at inner region of the cloud

Compact star cluster forms

Weak UV radiation → **Shielding effect works well !!**

→ Stars are born at earlier dynamical stage.

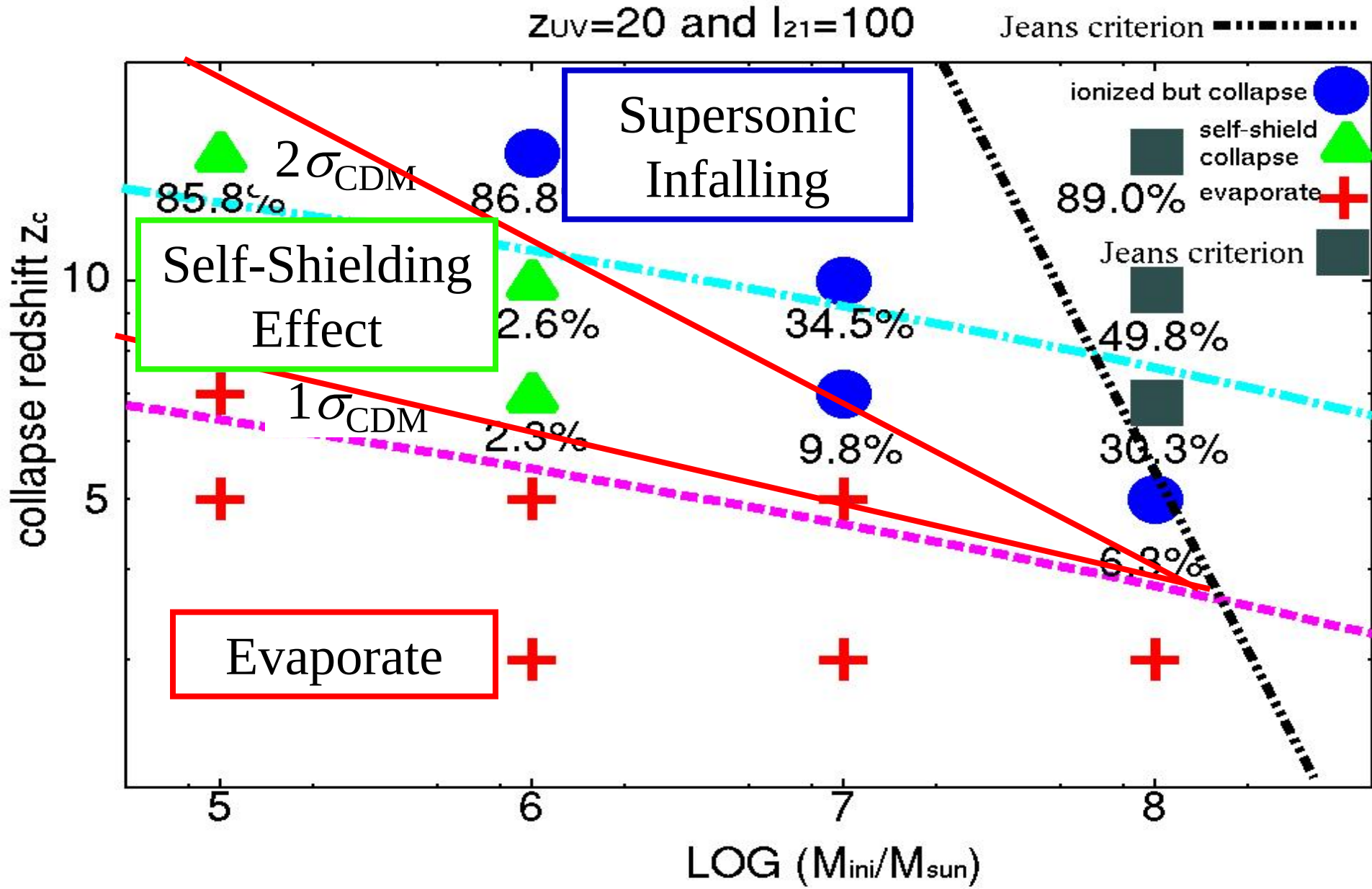
Diffuse star cluster forms

★ Dynamical Evolution of Globular Cluster

- ✓ Observable profiles change as the cluster evolves.
- ✓ DM halo is stripped by tidal interaction with the host galaxy. → Low mass-to-light ratio.
- ✓ Simulation results are well consistent with observations.

Our GC formation scenario is plausible to explain the observed GCs

Result: Strong UV case



Result: Weak UV Case

