Simulating Pop III multiple formation under radiation feedback

Kazuyuki Sugimura
(Univ. of Maryland, Tohoku Univ.)

Collaborators: T. Matsumoto (Hosei., Princeton)
T. Hosokawa (Kyoto), K. Omukai (Tohoku)
S. Hirano (Kyushu)

Contents

Introduction
- Pop III (binary/multiple) formation

Methods
- code, simulation set-up

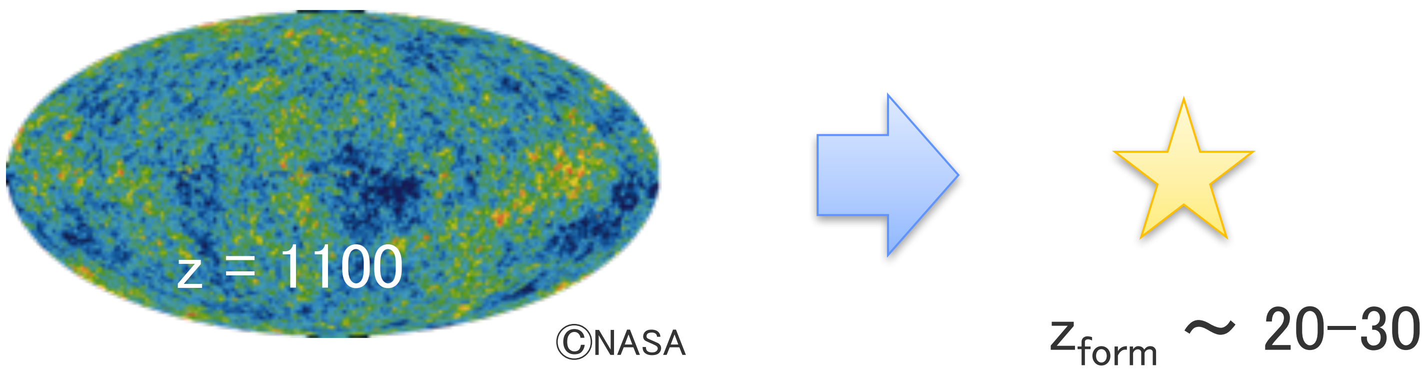
Results
- simulations of multiple Pop III star formation

Conclusions

INTRODUCTION

Formation of Pop III stars

- From Big Bang to first objects (= Pop III stars)



- Well-established initial condition and relevant physics make first principle study possible
- Former analytical/numerical works have revealed the outline
- A next important step is to properly follow binary/multiple formation

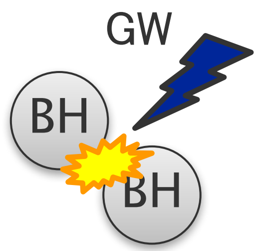
Why Pop III binaries/multiples?

1. They can be of dominant population of Pop III stars

- most of present-day massive stars found in binaries/multiples

  > 80% of O stars are in multiple systems (Duchene and Kraus 2013)

2. They are also interesting because...



- they can be progenitors of observed GW events

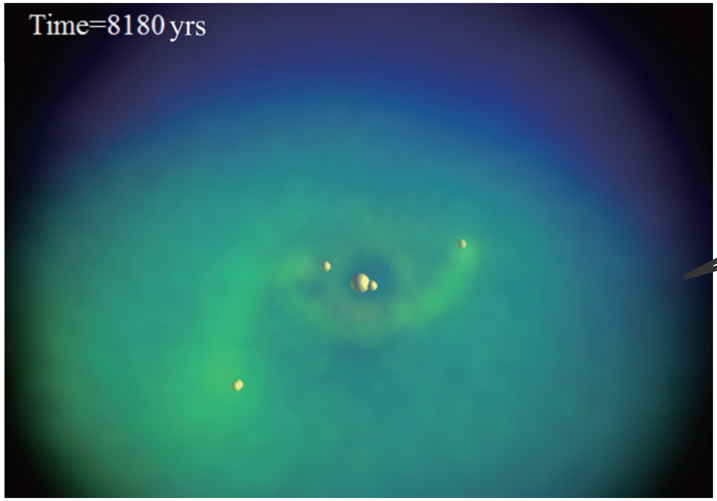
- their contribution to the cosmic evolution is likely quite different from that of single Pop III stars

  (reionization, first galaxy formation, Pop III to Pop II transition, ...)

Pop III multiple formation in former 3D simulations

(see also Stacy+16)

- SPH simulation (Susa+14)

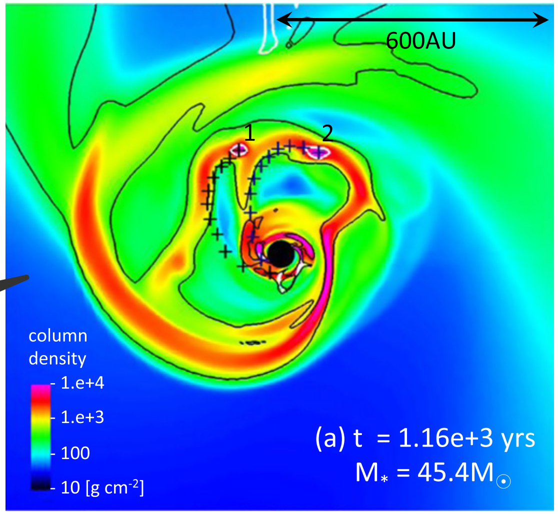


→ multiple stars

- effectively NO feedback by ionizing photons

(Hosokawa+16)

- Spherical grid simulation



→ single star

- fragmentation not well resolved
- radiation only from central star

All former simulations miss at least one of the essential processes in Pop III multiple formation

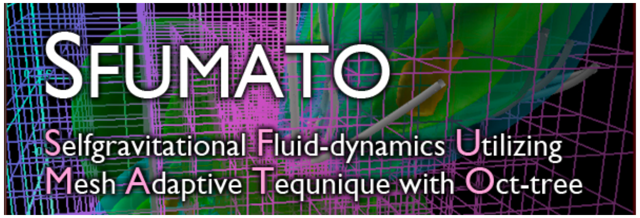
New simulations with new code!!

METHODS

Simulation code & setup

Recipe for new code

- ✓ self-gravitational (M)HD
- ✓ AMR
- ✓ sink particle



(Matsumoto 2007)

+

✓ Ray tracing of
EUV, FUV photons

Adaptive Ray-Tracing

(Abel&Wandelt 2002)

+

- ✓ prim. chem./thermodynamics
- ✓ protostellar radiation

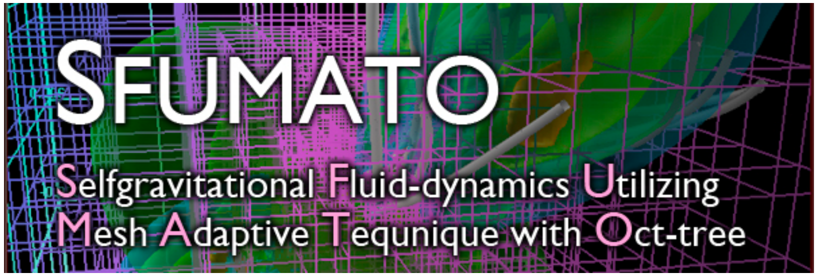
Pop III physics

(Hosokawa+ 2016)

= **New code for Pop III binary formation!!**

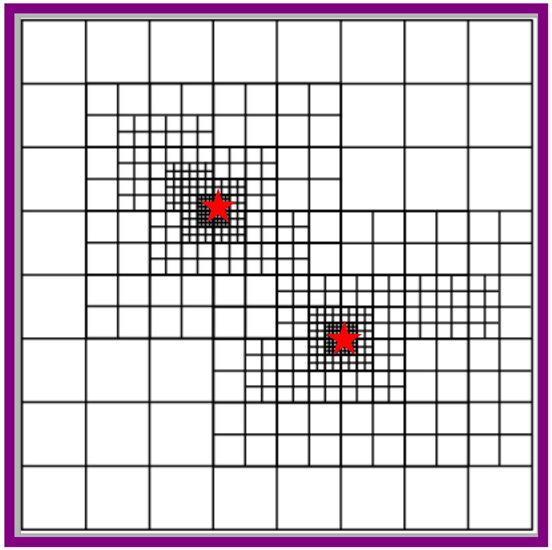
SFUMATO

(Matsumoto 2007)



- **MHD (AMR)**

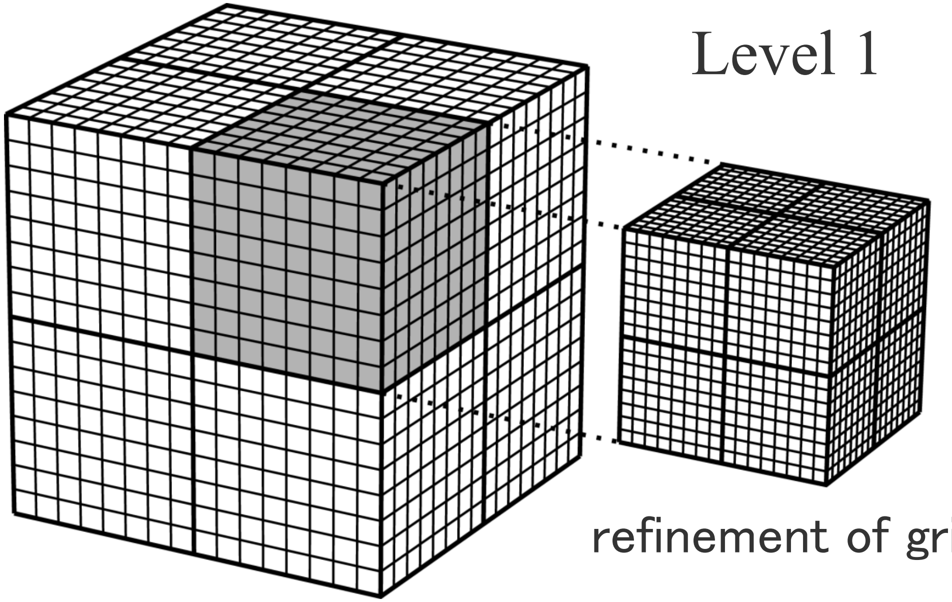
  Adaptive Mesh Refinement
  = high resolution where you need it



minimum unit = cell
grid = collection of cells

Level 0

Level 1



refinement of grid

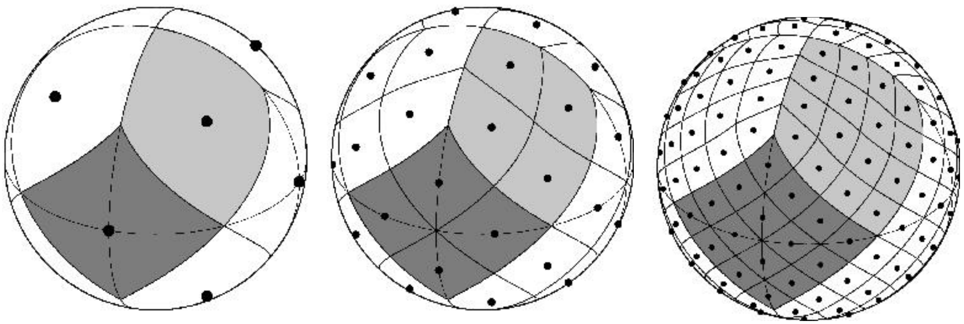
Oct-tree type block structure

- **Selfgravity**
- **Sink particle**

Adaptive Ray Tracing (ART) Method

HEALPix (Górski+ 2005)

- ✓ Library originally for CMB analysis
- ✓ Split sphere into 12 x 4^{level} patches

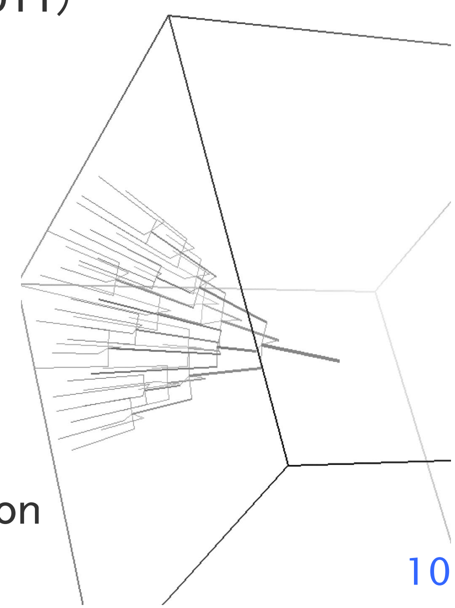


level 0 level 1 level 2

Adaptive Ray Tracing method

(Abel&Wandelt 2002, Wise&Abel 2011)

- ✓ Rays are split with HEALPix to ensure the minimum # of rays penetrating each cell surface
- ✓ Tracing direct EUV/FUV photons from protostars



EUV (>13.6eV) → H photo-ionization

FUV (11.2-13.6eV) → H_2 photo-dissociation

protostar

Physics model of Pop III formation

(basically same as Hosokawa+ 2016)

- **Prim. chemistry** (H, H_2, e, H^+, H^-, H_2^+, (He))
  - chemical reactions

    H photo-ion., H_2 photo-dis., H^- photo-det., H^+ rec., H^-/H_2^+-channel & 3-body H_2 formation, etc.
  - cooling/heating processes

    H photo-ion heat., H^+ rec. cool., Lyα cool, free-free cool., H_2 line cool (w/ f_{esc}), chemical heat/cool, etc.

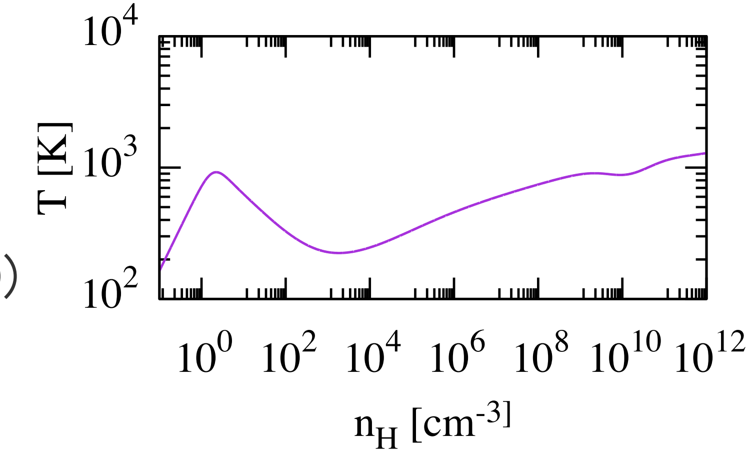
- **Pop III proto-stellar radiation**

  pre-calculated table from stellar evolution code

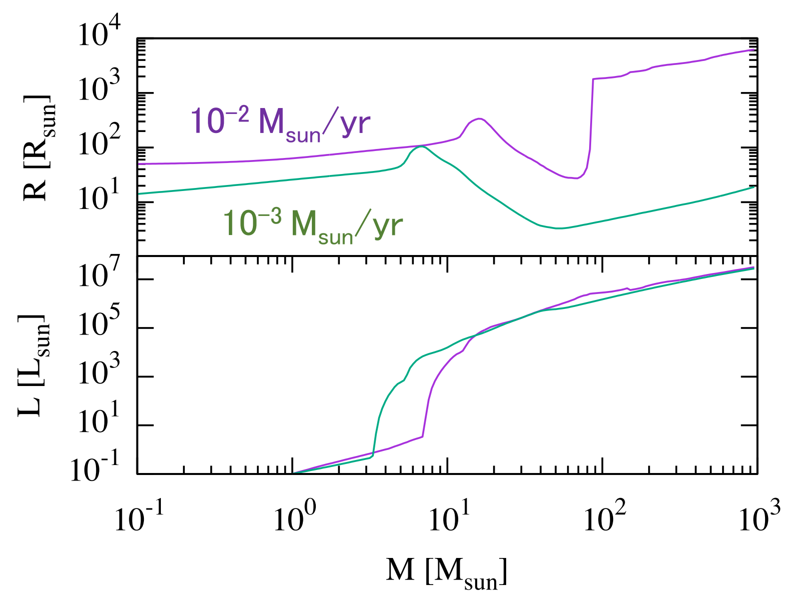
  (M_*: 10^{-1}–10^3 M_{sun}, $\dot{M}$: 10^{-5}–10^{-1} M_{sun}/yr)

$$(M_*, \dot{M}) \rightarrow (R_*, L_*)$$

$$\rightarrow (\dot{N}_{EUV}, \dot{N}_{FUV}) \quad \text{(blackbody)}$$

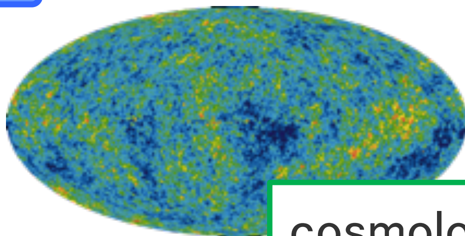


chemistry module check by 1-zone evolution calculation

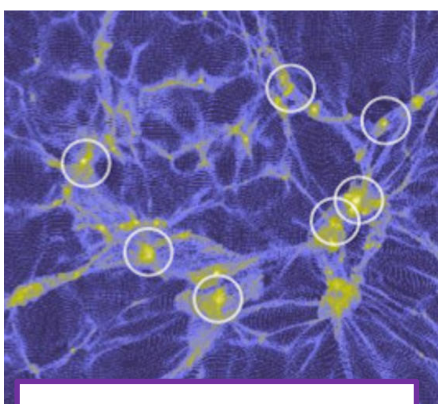


pre-calc. Pop III star model

Initial conditions for SFUMATO

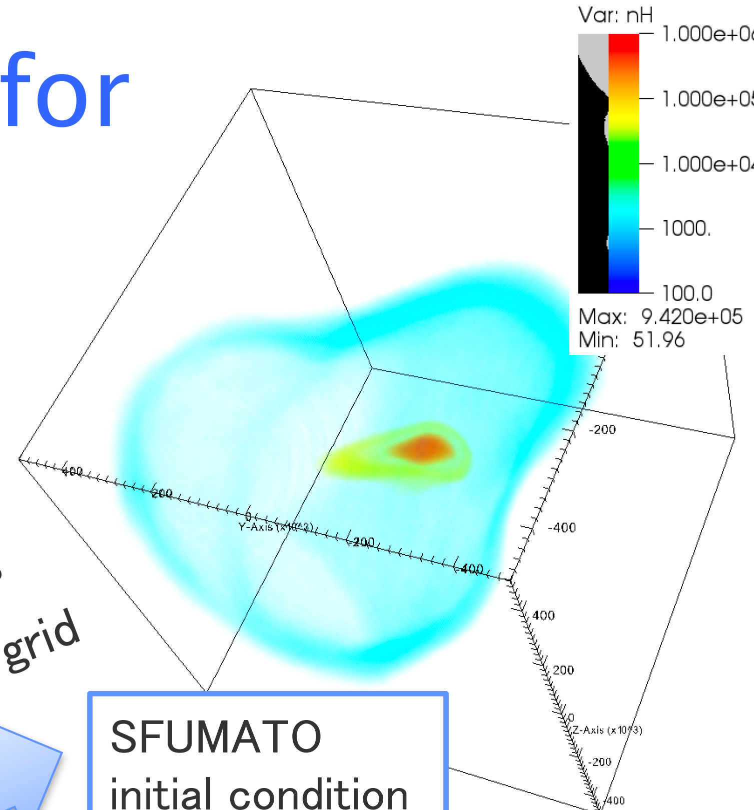


cosmological initial condition

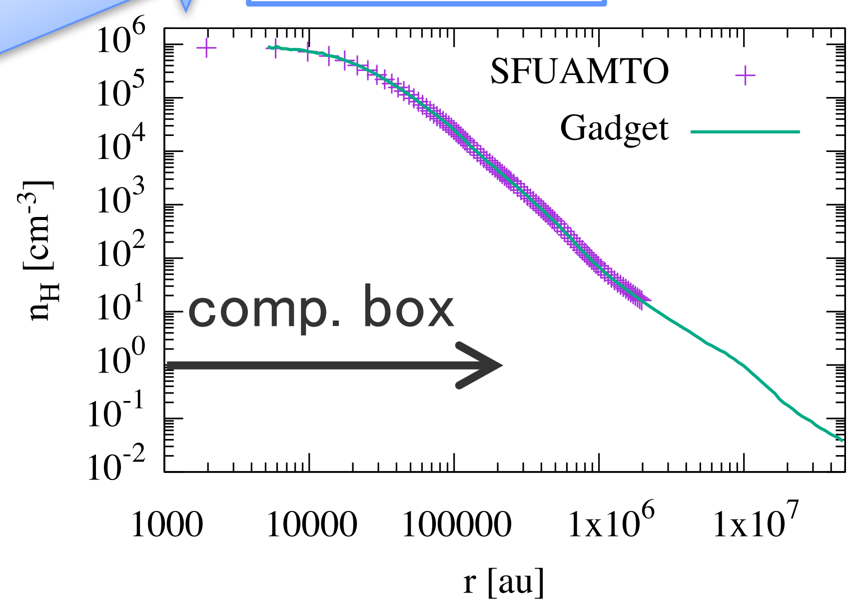


Gadget cosmo. sim. (Hirano+15)

take a minihalo@$n_{cen}=10^6 cm^{-3}$
Gadget SPH → SFUMATO grid



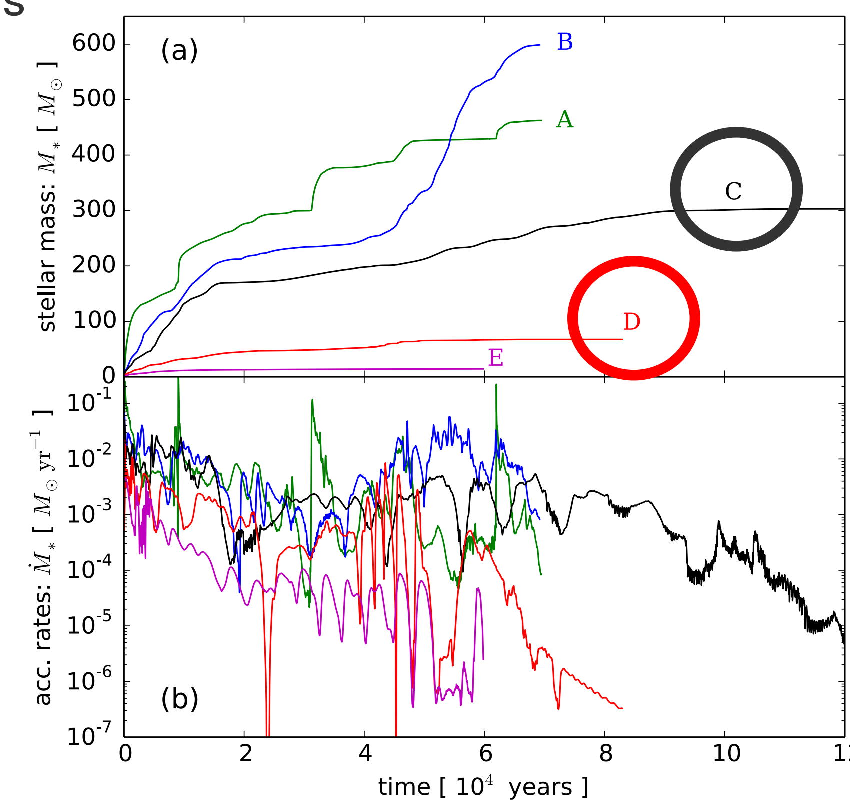
SFUMATO initial condition



Simulation Parameters

- Initial conditions
  typical low-mass
  Minihalos "C" and "D" in H16
- box size $\sim 10^5$ au
- sink radius/minimum cell size
  64 au/4 au
- refinement condition for AMR
  >16 cells per λ_J
- computational cost
  ~ 512 cores x 6 months

Hosokawa+16 (H16)



What's new?

✓ AMR makes it possible to achieve 10 times better resolution compared with H16 in the outer part of disks where fragmentation is most active

✓ ART makes it possible to treat radiation from multiple proto-Pop III stars

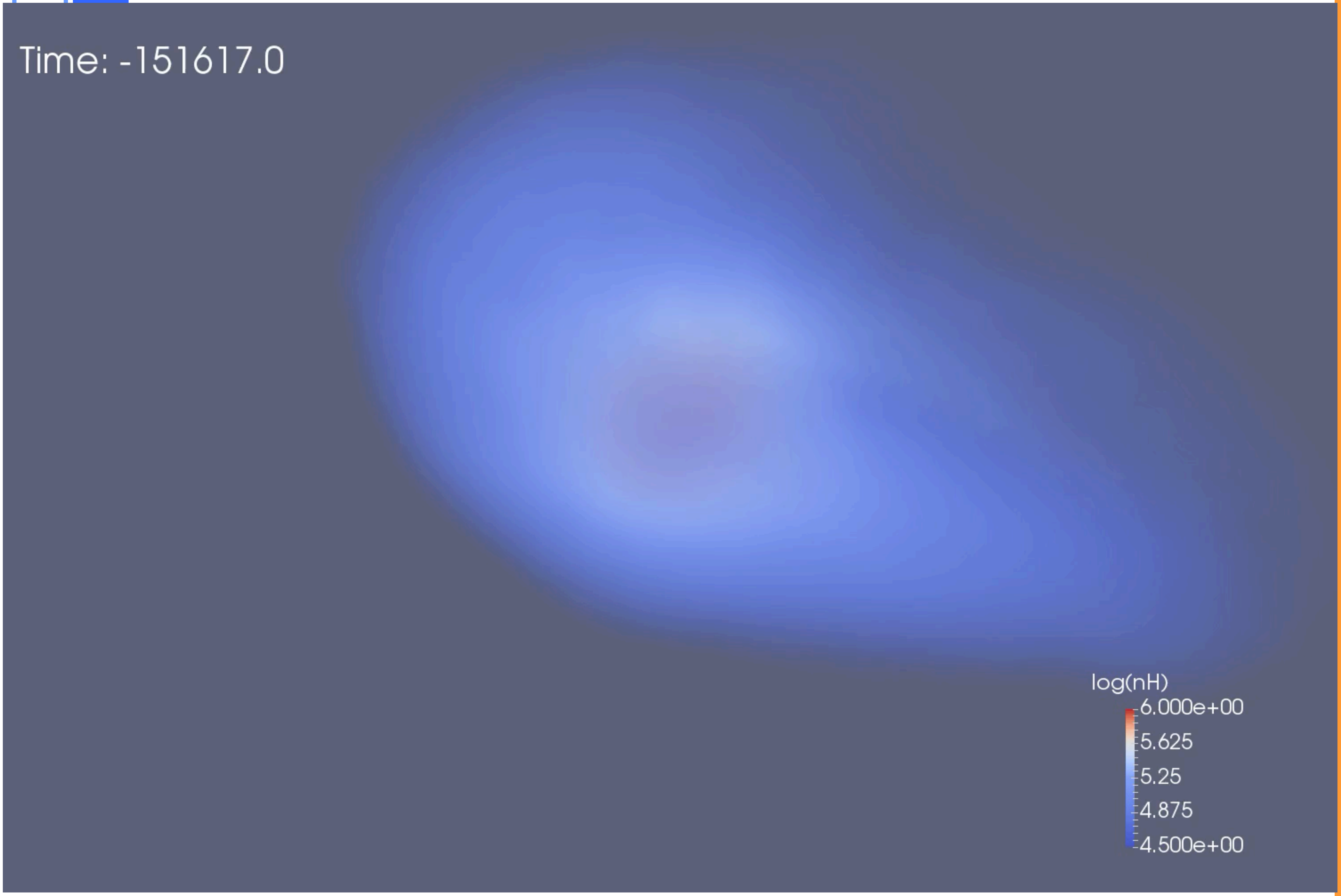
RESULTS

a typical pop III formation site

CASE OF MINIHALO “C”

3D movie

halo C (typical Pop III formation site)



Sink particle evolution

5 Evolutionary phases

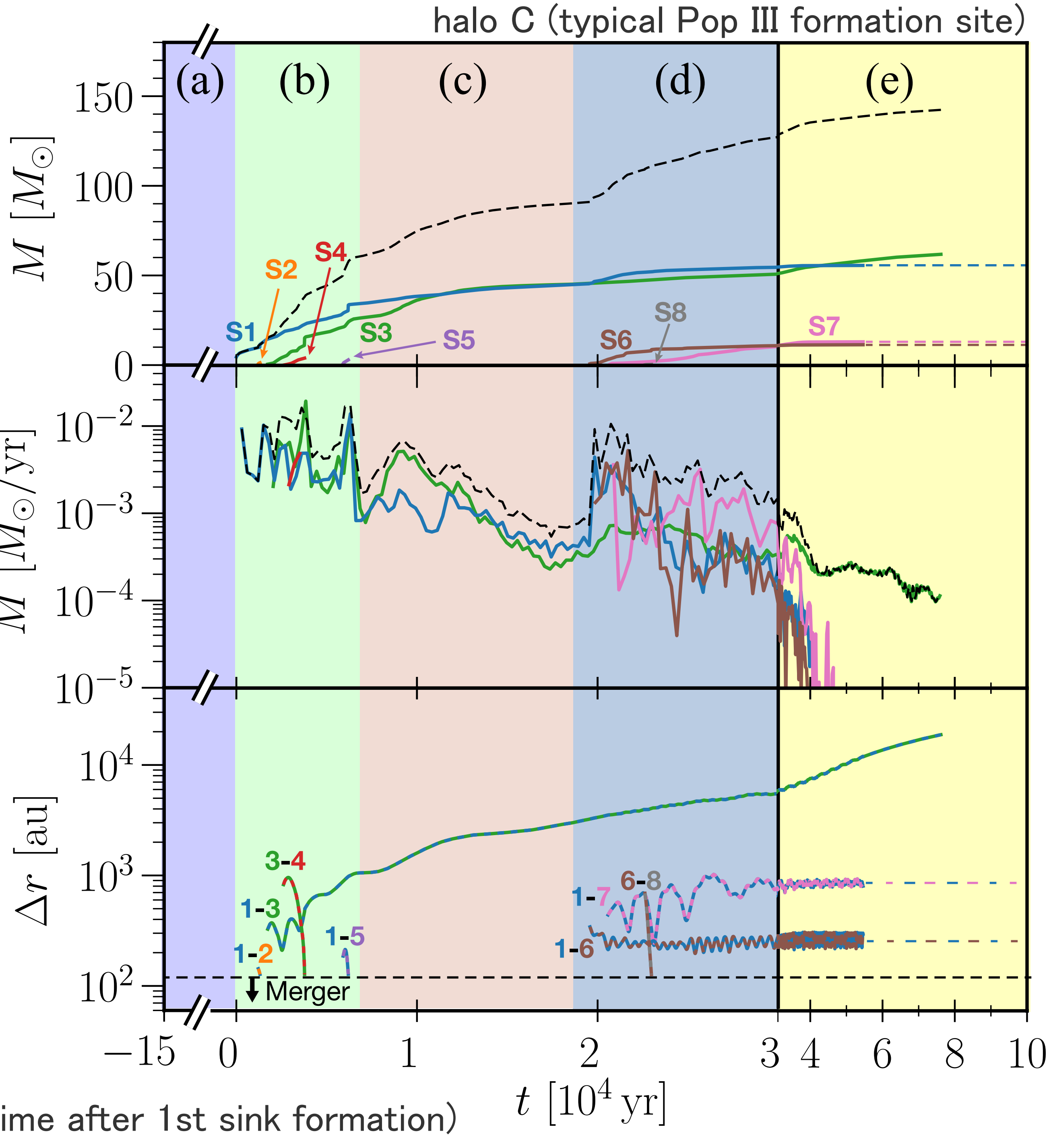
(a) grav. collapse

(b) initial frag.

(c) binary evl. via acc.

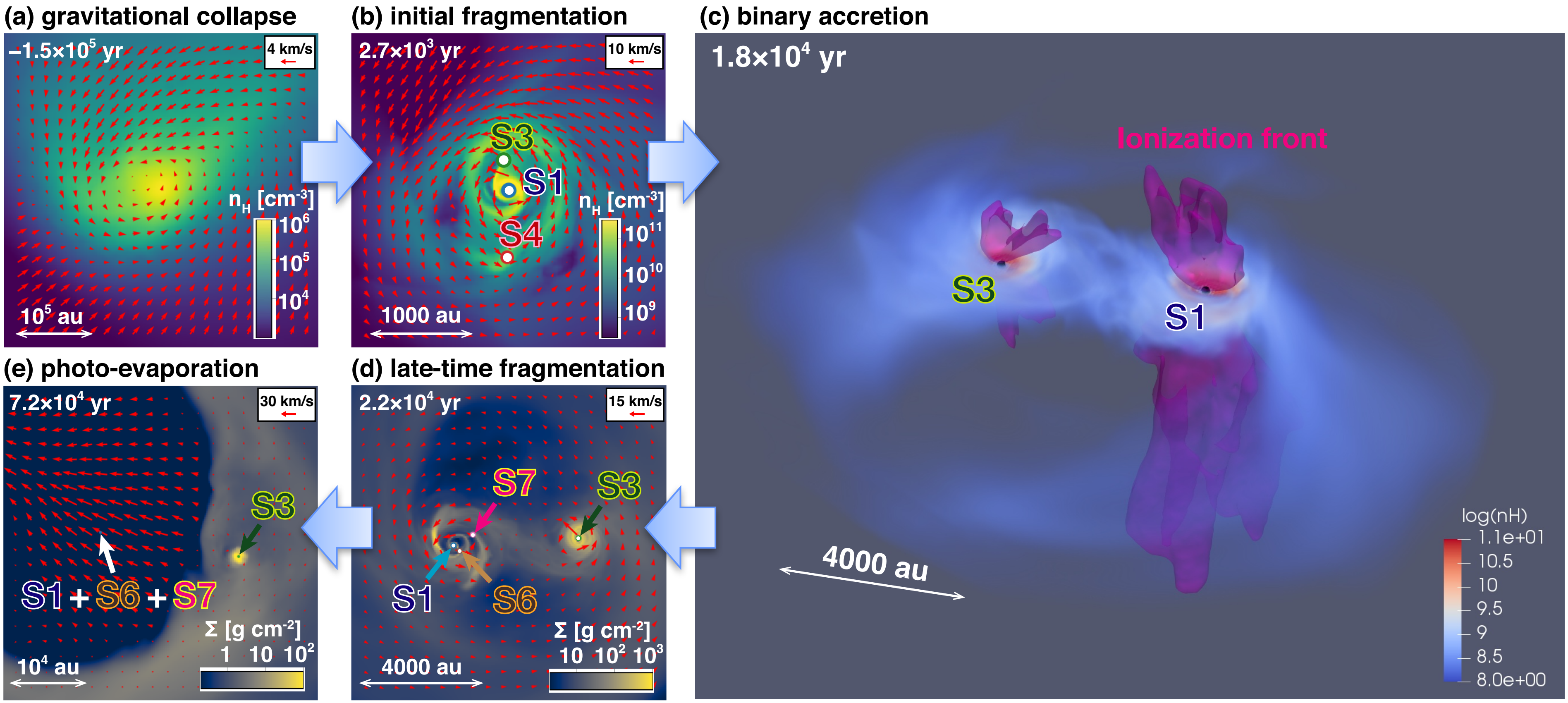
(d) late-time frag.

(e) photo-evaporation



halo C (typical Pop III formation site)

Five Evolutionary Phases

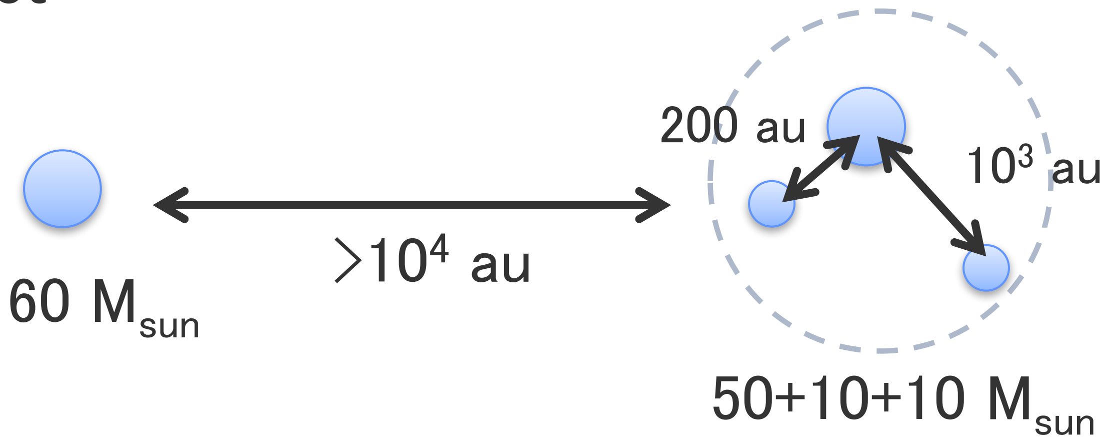


Summary of simulation for Case C

- We use the initial condition from which a single 300 M_{sun} Pop III star was formed in Hosokawa+16

- Although we are still running the simulation, the main accretion phase has (hopefully) ended

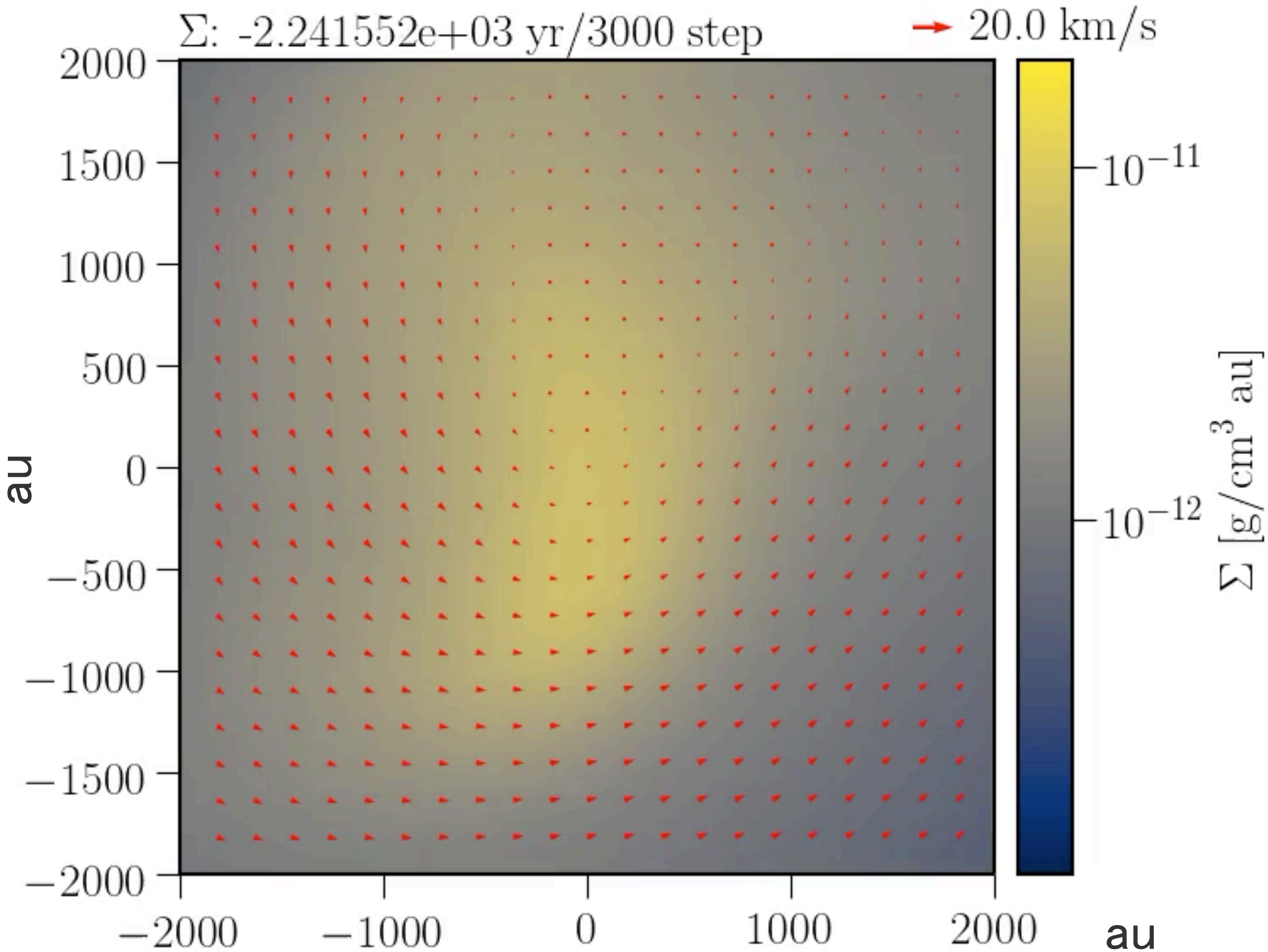
- The final(?) product is a massive wide binary of single and close triplet



a formation site of small Pop III star(s)

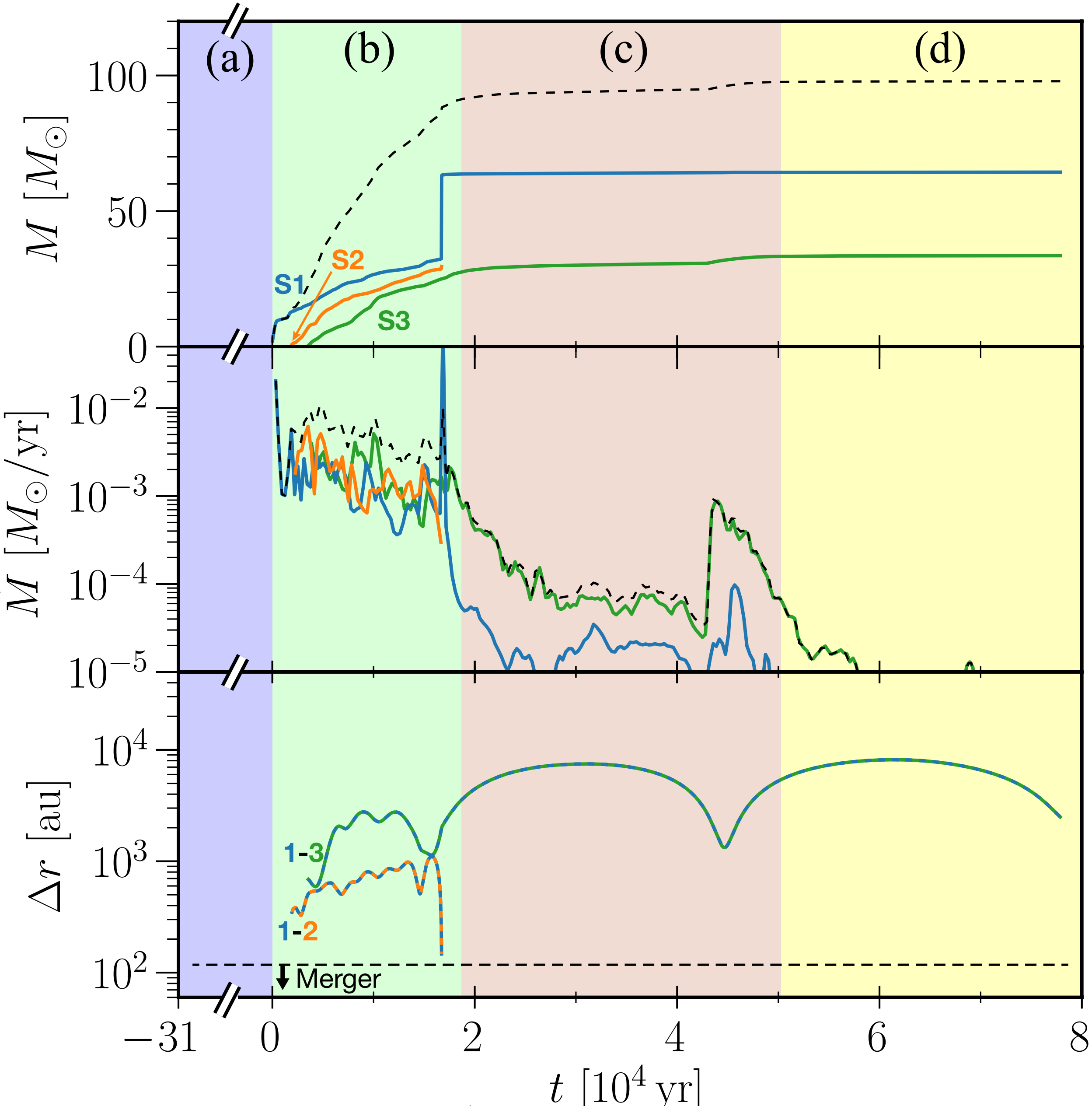
CASE OF MINIHALO “D”

Surface density (face-on)



Sink particle evolution

halo D (formation site of small Pop III)



(t: time after 1st sink formation)

4 Evolutionary phases

(a) grav. collapse

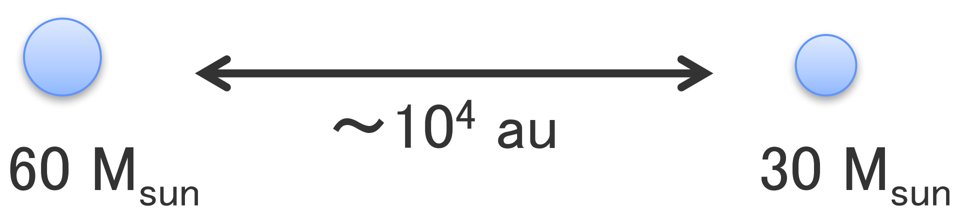
(b) initial frag.

(c) binary accretion

(d) photo-evaporation

Summary of simulation for Case D

- We use the initial condition from which a single 80 M_{sun} Pop III star was formed in Hosokawa+16
- The entire formation process has been followed in the simulation (accretion rate of each star reaches zero)
- The final product is a massive wide binary



CONCLUSIONS

Summary

- We have performed simulations of entire Pop III multiple formation: from cosmological initial conditions to the end of accretion phase

- We have developed a new code with AMR + Pop III phys. + ART, capable of following both fragmentation and ionization feedback

- In two out of two different halos studied in this work, the final products are massive Pop III binaries/multiples

Pop III stars typically form as massive multiple stars!