Formation of the First-star Binaries

KS, Matsumoto, Hosokawa, Hirano, Omukai, 2020 ApJL
(+ more)

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  - first stars, first-star binaries
- Methods
  - new code "SFUMATO-RT", simulation set-up
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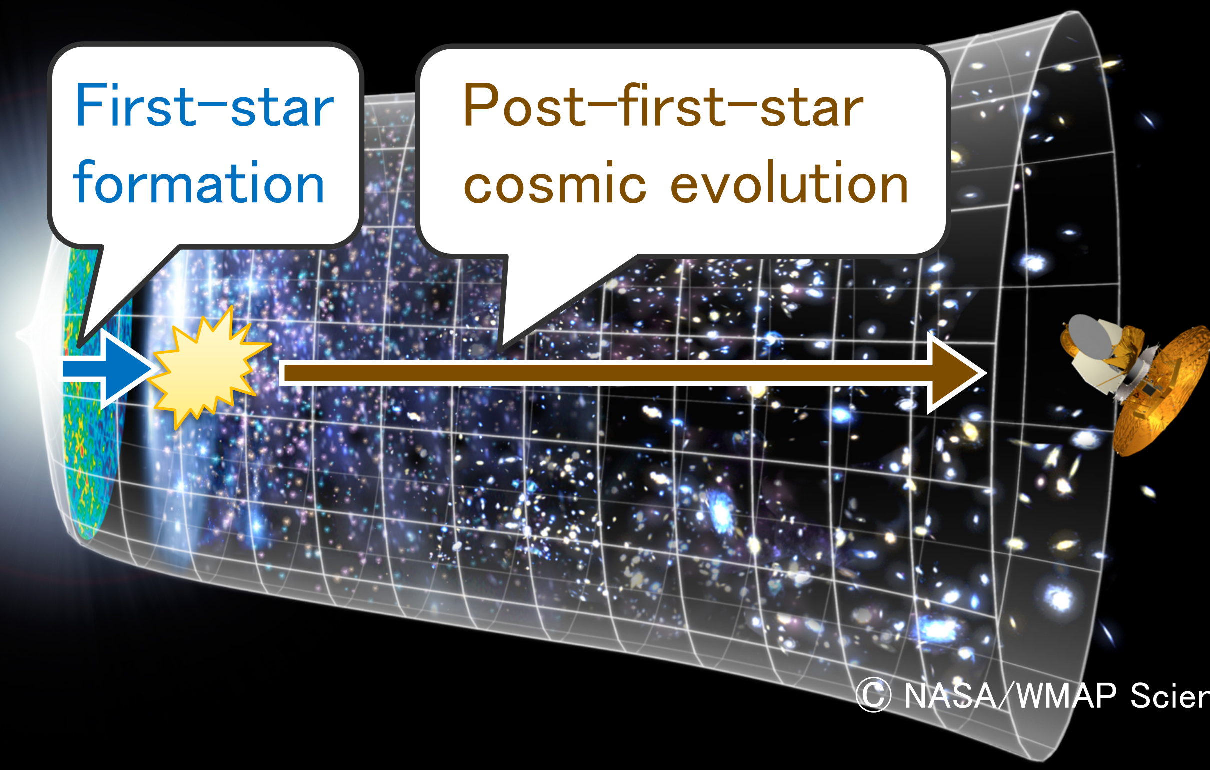
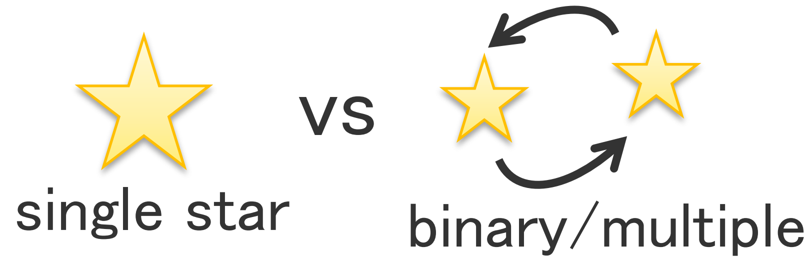
INTRODUCTION

The first stars: a trigger for the phase transition of the Universe



First stars (Pop III) → Stellar radiation, Supernovae, X-ray binaries → Radiation, Metals, Energies

The first-star binaries/multiples



- First-star binaries/multiples …

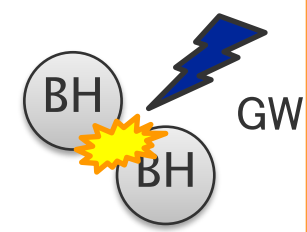
1. can be the dominant population of the first stars
   - massive stars are often in multiple systems in the local Universe

(e.g., Duchene and Kraus 2013)

2. can modify the later evolution of the Universe
   - the physics leading to binary formation closely related to the mass of first stars and the abundance of X-ray binaries

3. can be the progenitors of observed BH mergers

(e.g., Kinugawa+ 2014, Hartwig+ 2016; but also see Belczynski+ 2017)



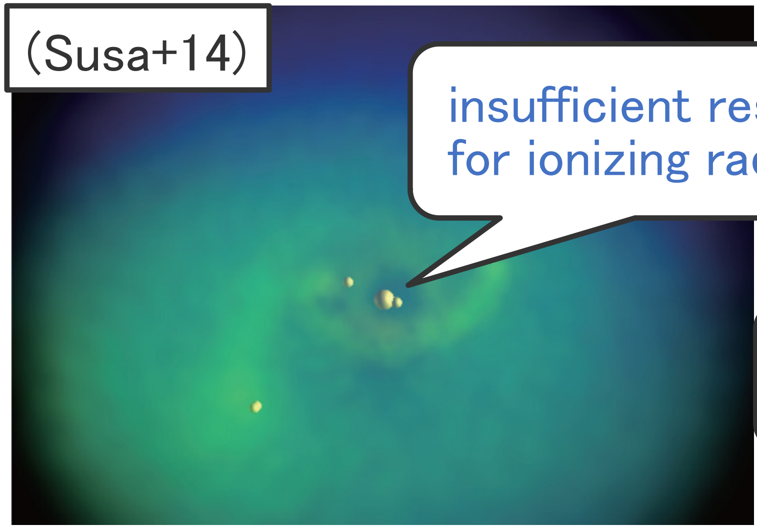
4. are suggested by simulations focusing on the early phase
   - initial fragmentation leads to multiple protostar formation

(e.g., Turk+09; Stacy+10,12,16; Clark+11; Greif+11,12; Smith+11; Hirano&Bromm17; Sharda+19)

Former 3D simulations for the entire formation process of the first stars

- SPH (particle-type) simulations
- Spherical-grid simulations

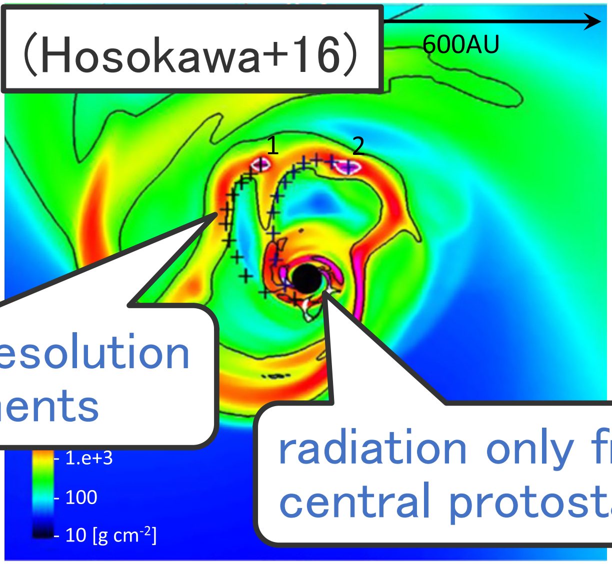
(Susa+14)



insufficient resolution for ionizing radiation

(see Stacy+16 for a semi-analytical method to deal with this problem)

(Hosokawa+16)



insufficient resolution around fragments

radiation only from central protostar

No former simulations could properly follow Pop III binary formation

New simulations with a new code!!

METHODS

code & simulation set-up

New code: SFUMATO-RT

- ✓ self-gravitational (M)HD
- ✓ Adaptive mesh refinement
- ✓ sink particle

(Matsumoto 2007)

+

New!

- ✓ Multiple-source radiation transfer
- ✓ ionizing/dissociating photons

Adaptive Ray-Tracing

(Abel&Wandelt 2002)

+

New!

- ✓ chemical/thermal evolution
- ✓ protostellar evolution

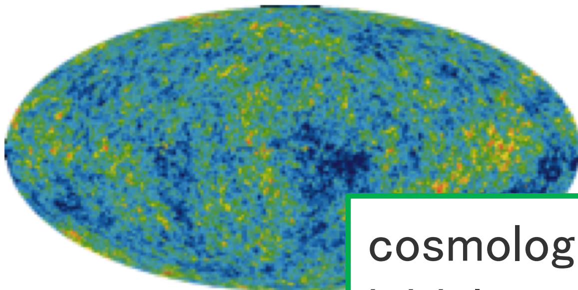
Pop III physics

(Hosokawa+ 2016)

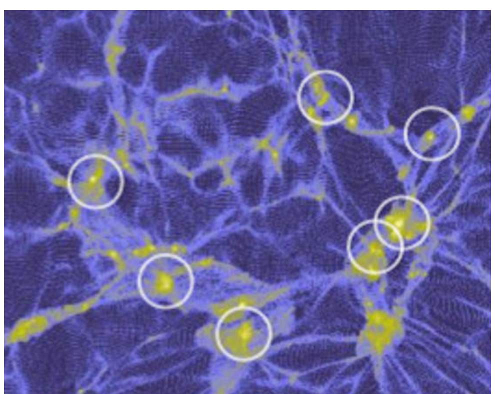
=

Code for Pop III binary formation!!

Initial conditions

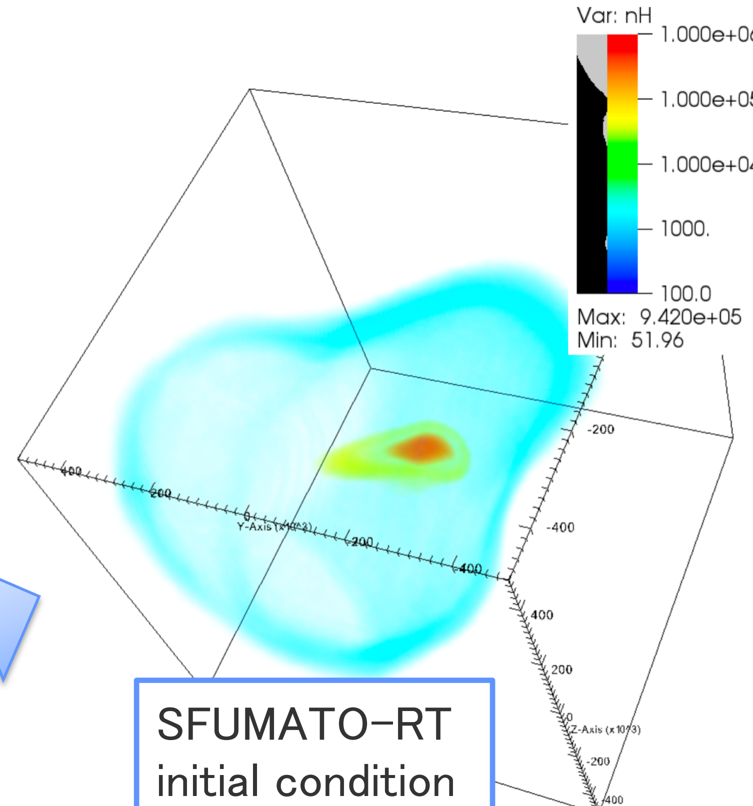


cosmological initial condition



cosmological simulations with Gadget (Hirano+15)

minihalo@n_{cen}=10^6 cm^{-3}



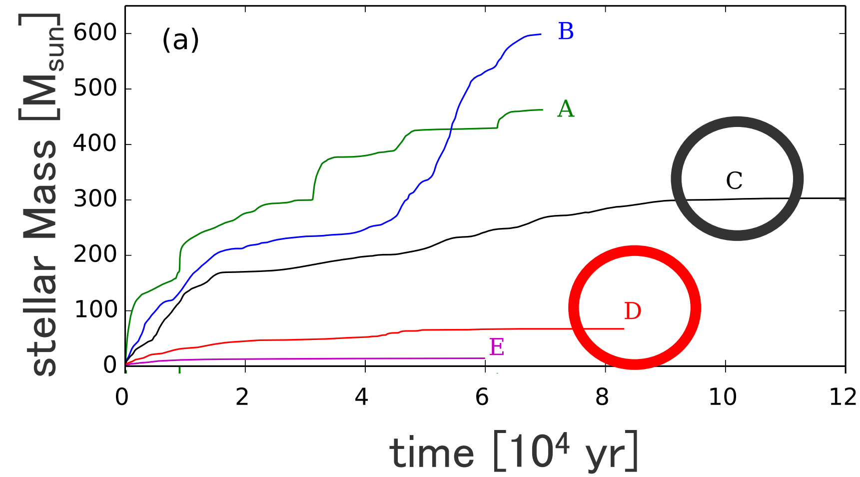
SFUMATO-RT initial condition

We pick up 2 minihalos for this work

Simulation set-up

- Initial conditions
  typical low-mass
  Minihalos "C" and "D" in H16
- box size ~10^5 au
- sink radius/minimum cell size
  64 au/4 au
- refinement condition for AMR
  >16 cells per Jeans length
- computational cost ~ 8 months x 512 cores

Hosokawa+16 (H16)



What's new?

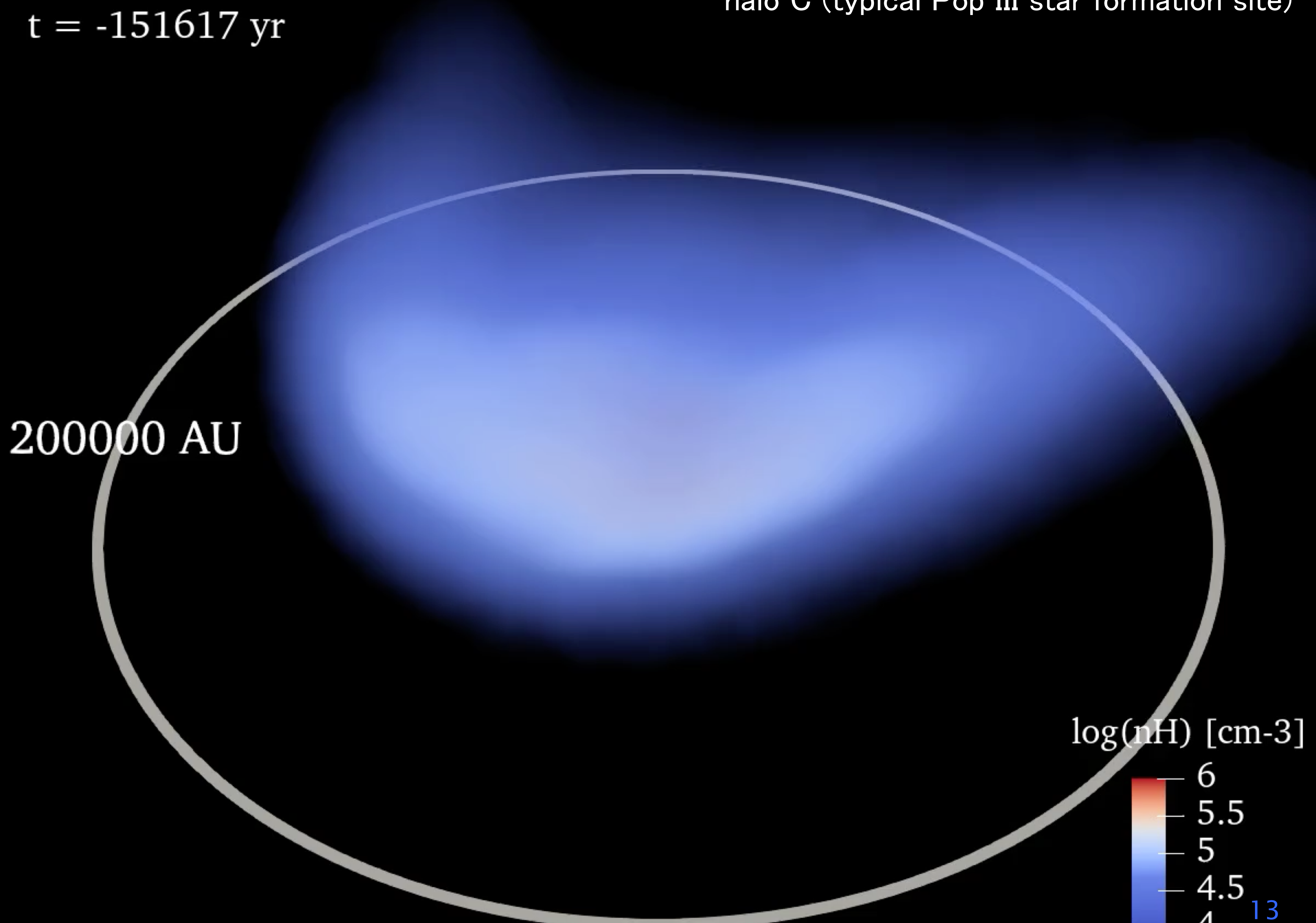
1. Adaptive ray tracing makes it possible to treat radiation from multiple protostars
2. Adaptive mesh refinement makes it possible to achieve much higher (x10) resolution around off-center protostars

RESULTS

a typical pop III star formation site

CASE OF MINIHALO C

halo C (typical Pop III star formation site)



(https://www.youtube.com/watch?v=794O0yGWGp0)

Evolution of Protostars

5 Evolutionary phases

(a) gravitational collapse

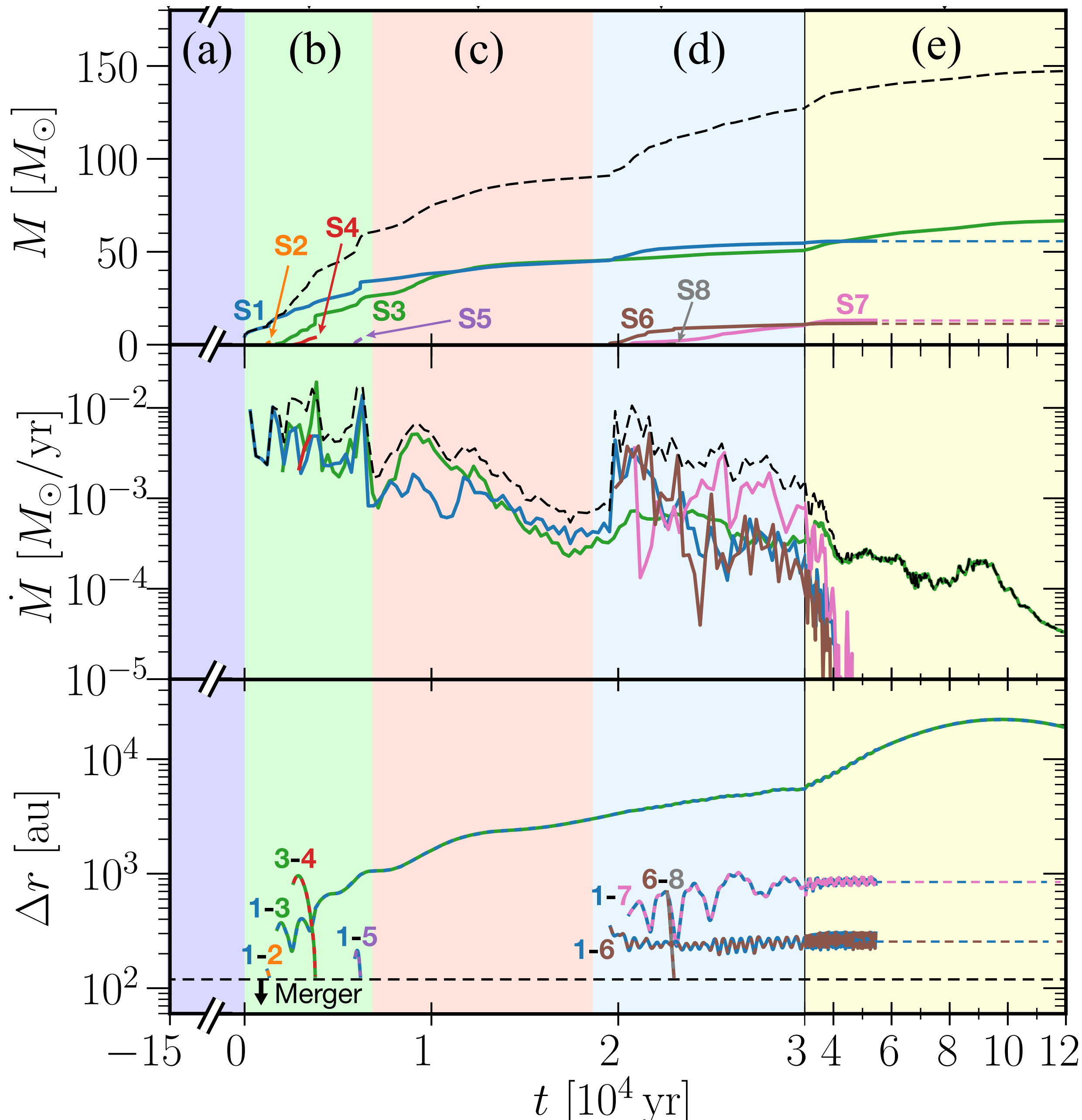
(b) initial fragmentation

(c) binary accretion

(d) late-time fragmentation

(e) photo-evaporation

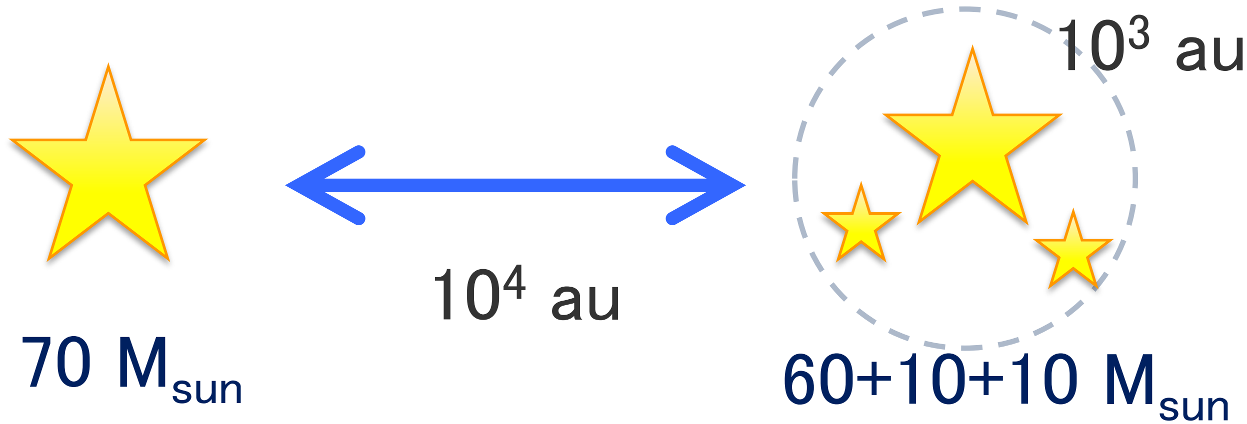
halo C (typical Pop III star formation site)



(t: time after 1st sink formation)

typical Pop III star formation site

The resulting stellar system in Case C



A wide binary of massive single and mini–triplet systems

(↔ single 300 M_{sun} star in the previous simulation by Hosokawa+16) a formation site of low-mass Pop III star(s)

CASE OF MINIHALO D

Evolution of Protostars

4 Evolutionary phases

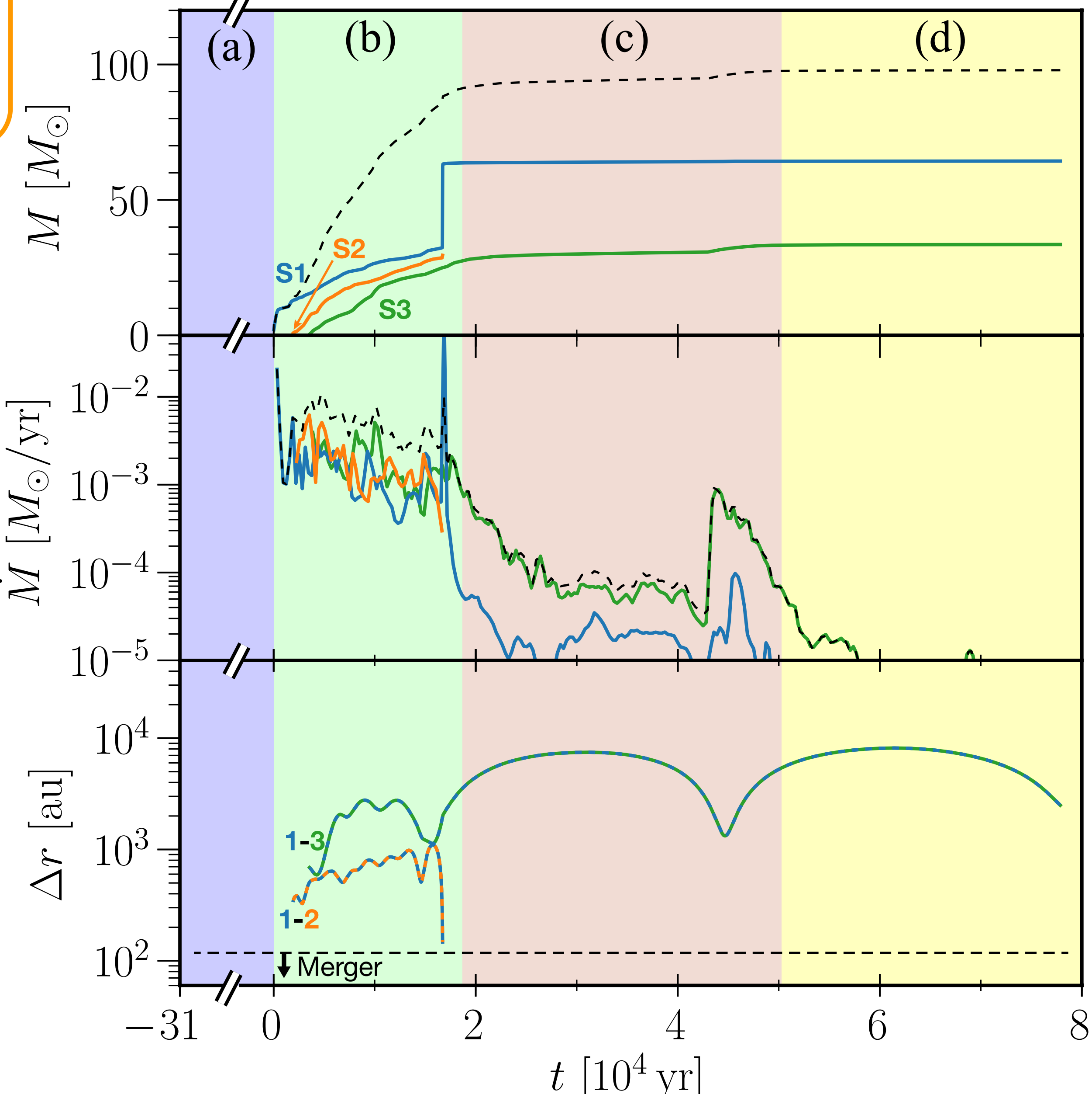
(a) gravitational collapse

(b) initial fragmentation

(c) binary accretion

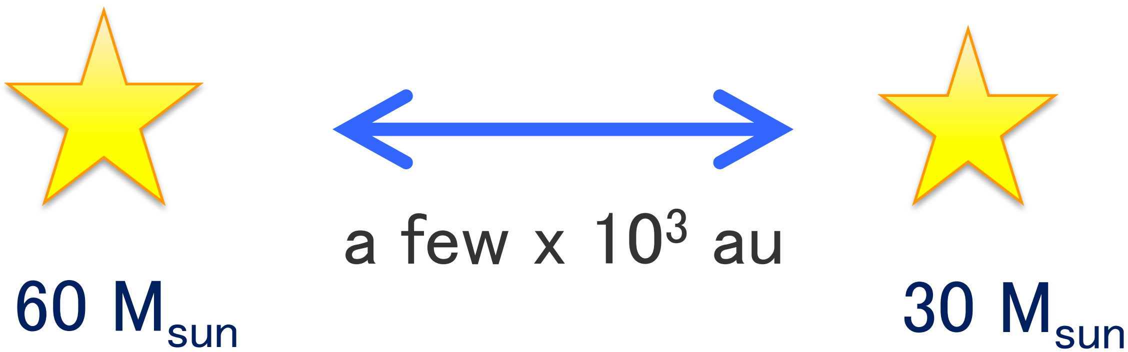
(d) photo-evaporation

halo D (formation site of low-mass Pop III stars)



(t: time after 1st sink formation)

The resulting stellar system in Case D



A wide binary of unequal-mass massive stars

(↔ single 80 M_{sun} star in the previous simulation by Hosokawa+16)

CONCLUSIONS

Summary

- We have performed simulations of the entire formation process of the first stars from cosmological initial conditions to the end of accretion phase
- We have developed and used a new code SFUMATO-RT, capable of following the formation of multiple protostars with ionizing/dissociating radiation feedback
- Massive binary/multiple stars form in both of two examined cases

⇒ The first stars form as massive binary/multiple stars!

Discussion

- While our simulations have shown that the physics leading to binary formation is essential for first star formation, larger sample is needed to reveal the statistical properties of the first stars, such as masses, binarities and binary separations
- The binaries in our simulations are massive enough but too distant to be the progenitors of recently observed binary BHs, partly due to the limited resolution

⇒ Future directions: larger sample, higher resolution