Simulating the formation of Supermassive Stars and their Binaries

Takashi Hosokawa (Kyoto Univ.)

+ Sunmyon Chon (Univ. of Tokyo),
Naoki Yoshida (Univ. of Tokyo), Shingo Hirano (Texas) et al.

Ref) Chon et al. (2016) ApJ; (2017) in prep.

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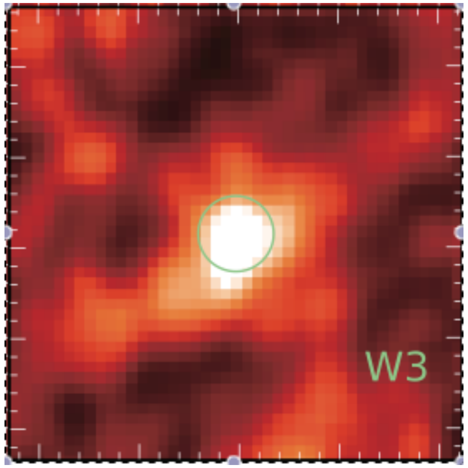
The first SMBHs?

A number (∼10) of very bright QSOs have been found beyond redshift 6



+ $M_{BH} \sim 2 \times 10^9 M_\odot$ @ z= 7.085 (Mortlock et al. 2011, Nature)
+ $M_{BH} \sim 1.2 \times 10^{10} M_\odot$ @ z=6.3 (Wu et al. 2015, Nature):

Age of the universe@z∼7: 0.77Gyr. Get them quickly before this

If a Pop III remnant BH (∼$100M_\odot$) grows via Eddington accretion…

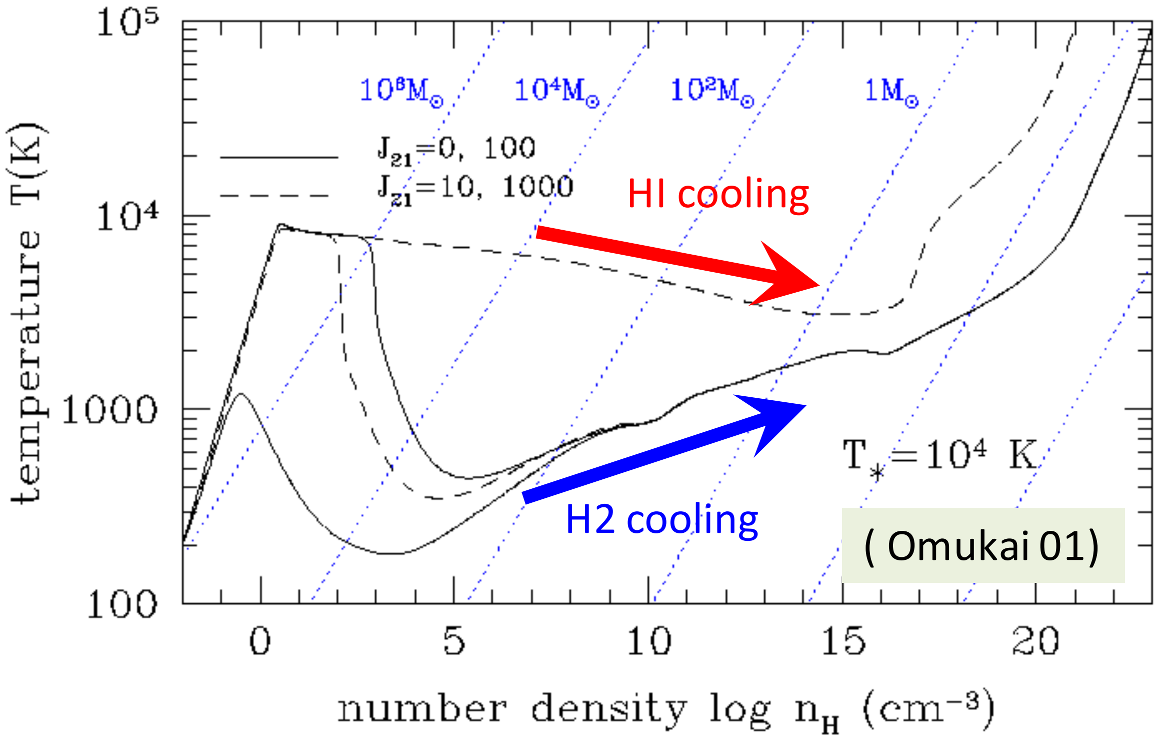
$$t_{\rm grow} = 0.05 \log \left(\frac{10^9 \ M_\odot}{10^2 \ M_\odot} \right) \simeq 0.8 \rm Gyr$$

But 100% of the duty cycle is needed (feedback prohibits this)

Supermassive (～$10^5 M_\odot$) Stars?

Direct Collapse (DC):

a special case of Pop III star formation



①cloud exposed by strong UV radiation from nearby galaxy (destroying H2 molecules）

↓

②nearly isothermal collapse via H atomic cooling with higher T

↓

③very rapid accretion (> $0.1 M_\odot$/yr) onto the protostar

$$\dot{M} \sim \frac{M_J}{t_{ff}} = \frac{c_s^3}{G} \propto T^{1.5}$$

↓

④collapse of supermassive star via GR instability →$10^5 M_\odot$ BH

Key Questions

+ Is this really possible in a full cosmological context?

※People normally study the DC scenario with artificial setting:
put a strong UV radiation field *by hand* with an arbitrary
H atomic-cooling halo…

BUT nobody knows if such situations are realized or not.
Environments which allows the DC should not be normal…

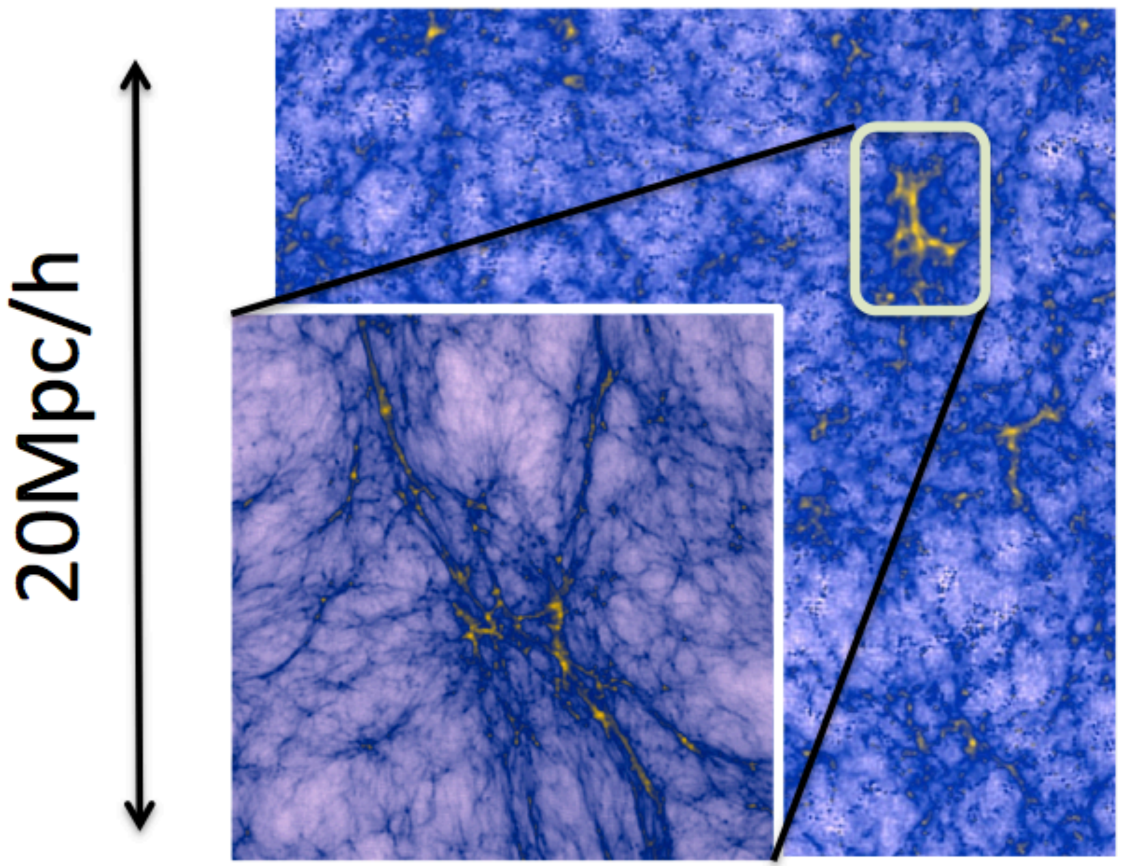
+ What kind of star(s) emerge after the evolution considering
such environmental effects?

Answer the above with direct cosmological simulations

Look for potential sites of DC

3 necessary conditions for the direct collapse

+ Nearby strong UV source to destroy H2 molecules
+ Halo is massive enough to turn on H atomic cooling
+ Zero (or very low) metallicity



Locate DC candidate clouds in cosmological simulations;

N-body

+

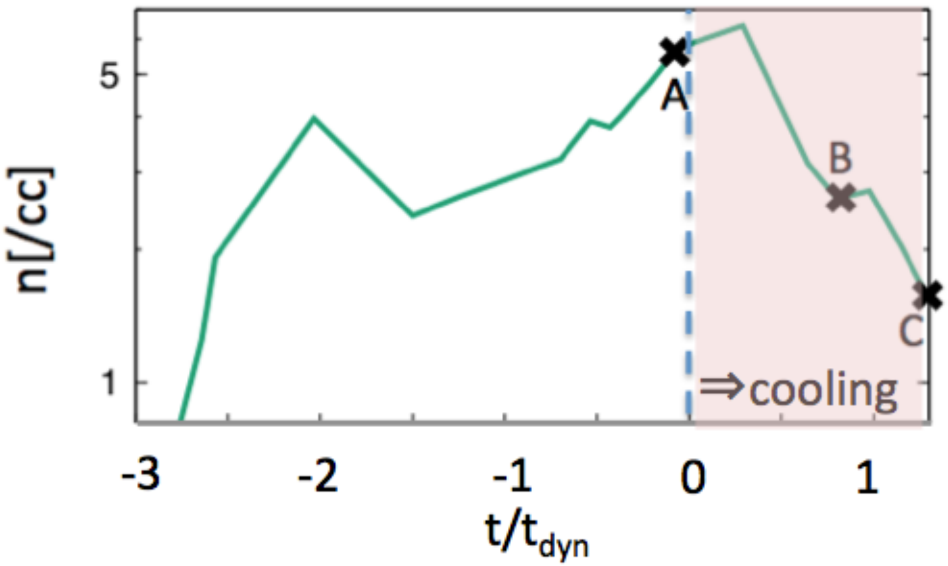
star/galaxy formation semi-analytic models

↓

～50 potential sites of DC

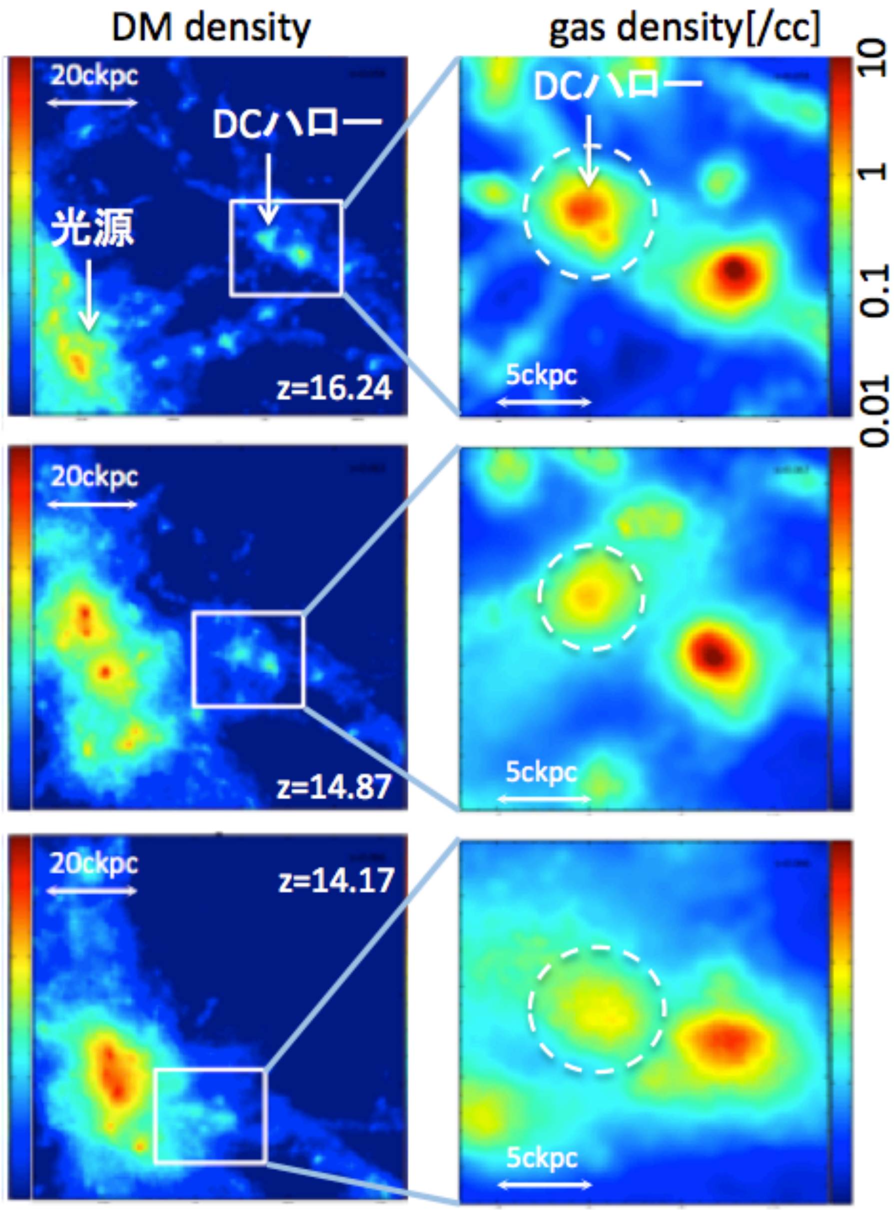
DC prevented by tidal effect

Follow the evolution of each cloud with N-body+SPH simulations



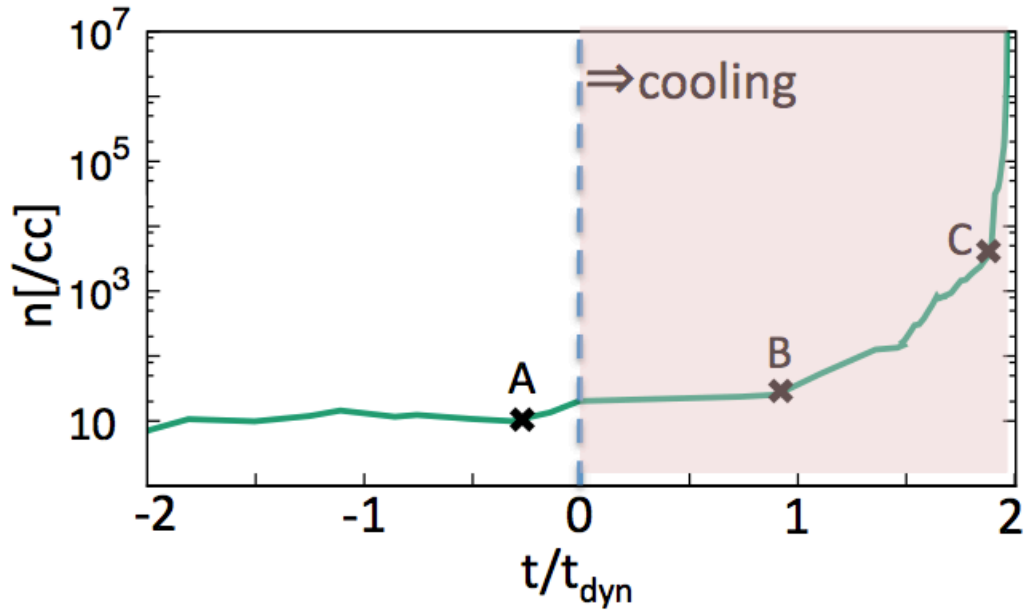
Density actually turns to decrease at some point in 40/42 cases.

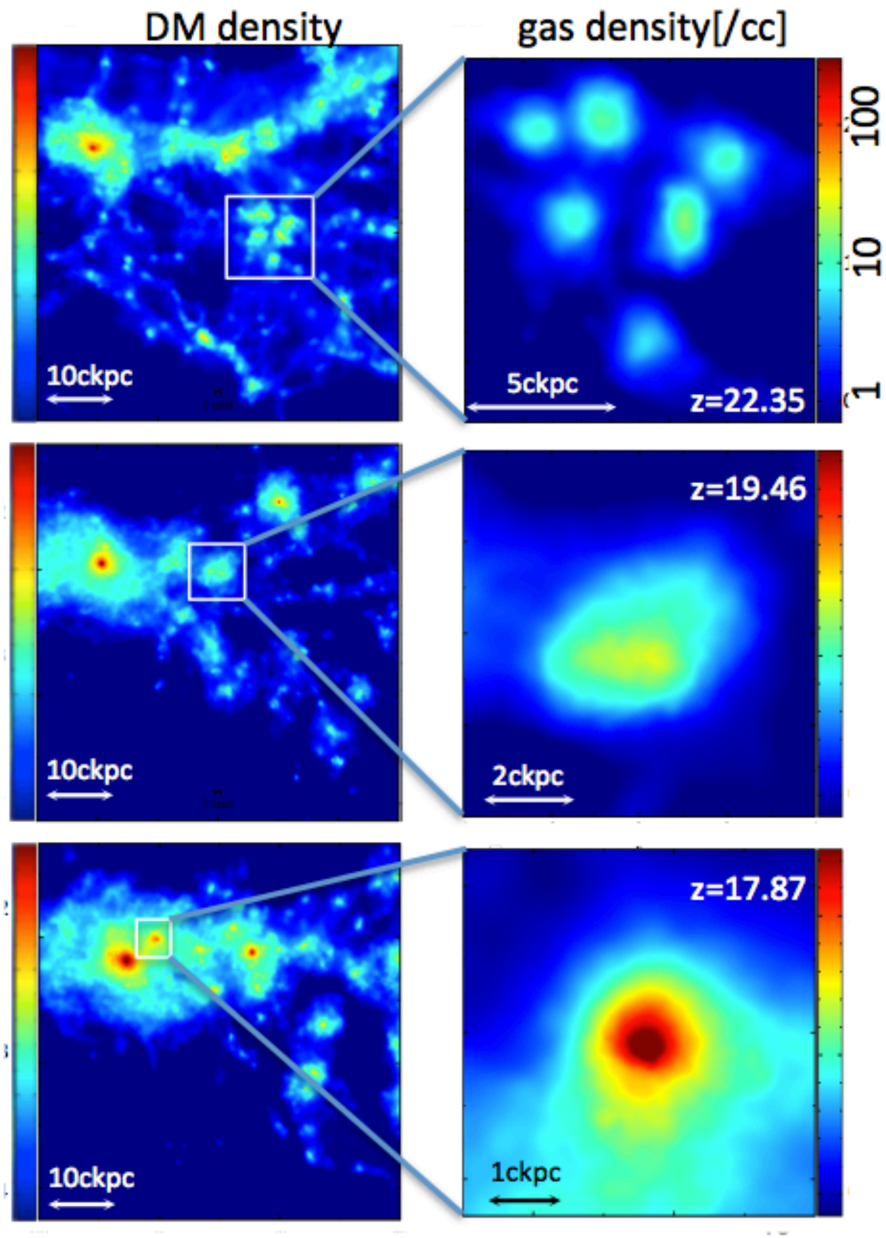
Because of the strong tidal field created by nearby massive halos that have UV-emitting galaxies



Collapse aided by halo mergers

But collapse does occur for 2/42 cases, where the density continues to increase.



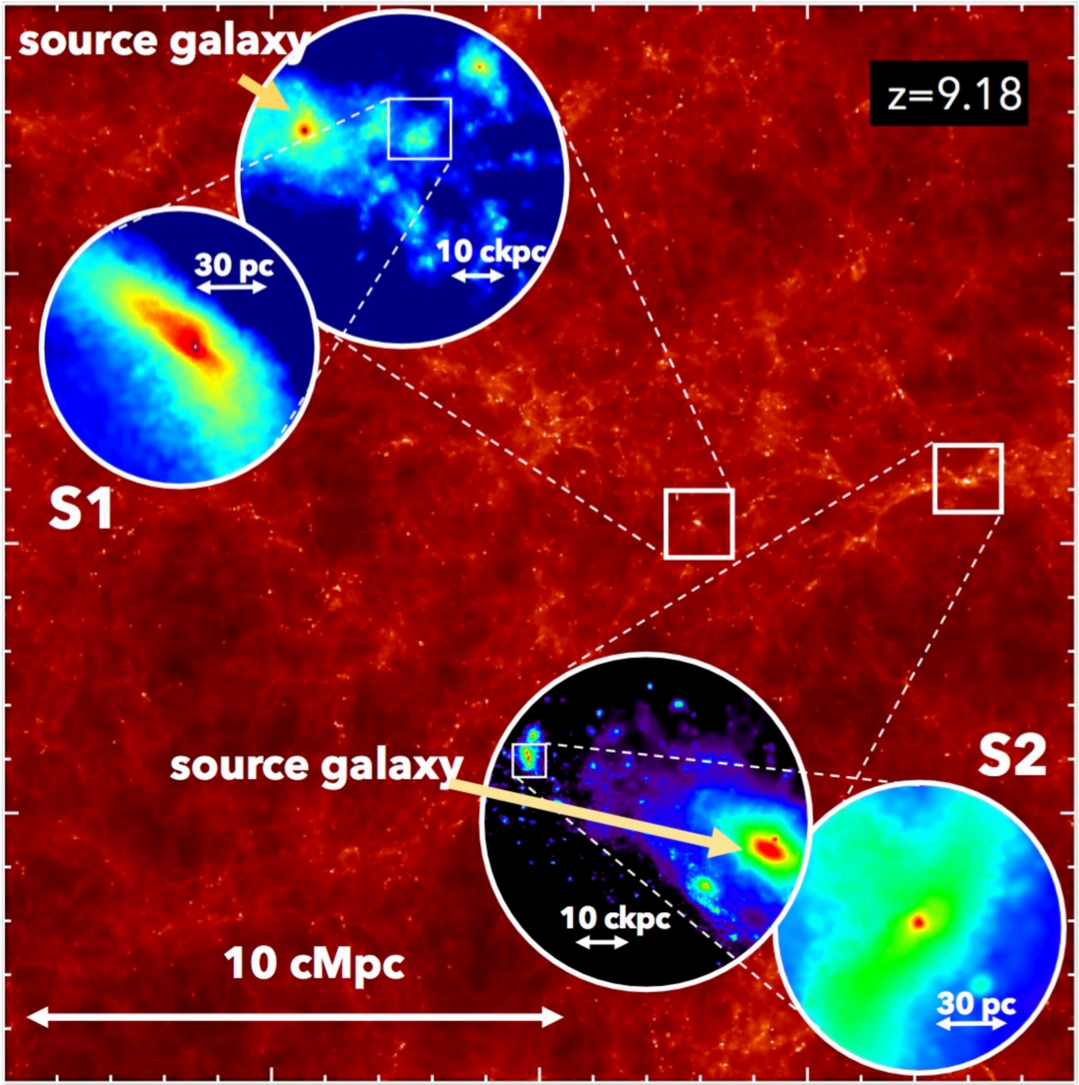


The rapid halo mergers carry a large mount of gas toward the cloud center, which accelerates the collapse.

Collapse with 2 different clouds

Different strength of the tidal field results in different cloud morphology

“filamentary” case (strong tidal field)

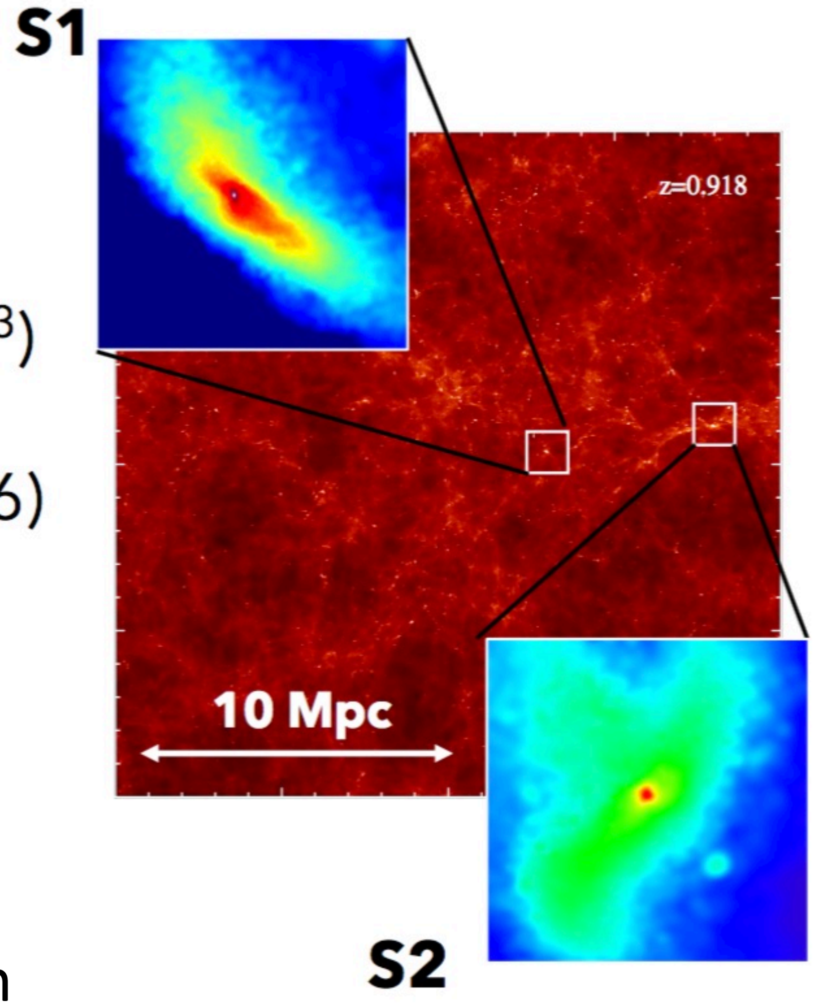


“spherical” case (weak tidal field)

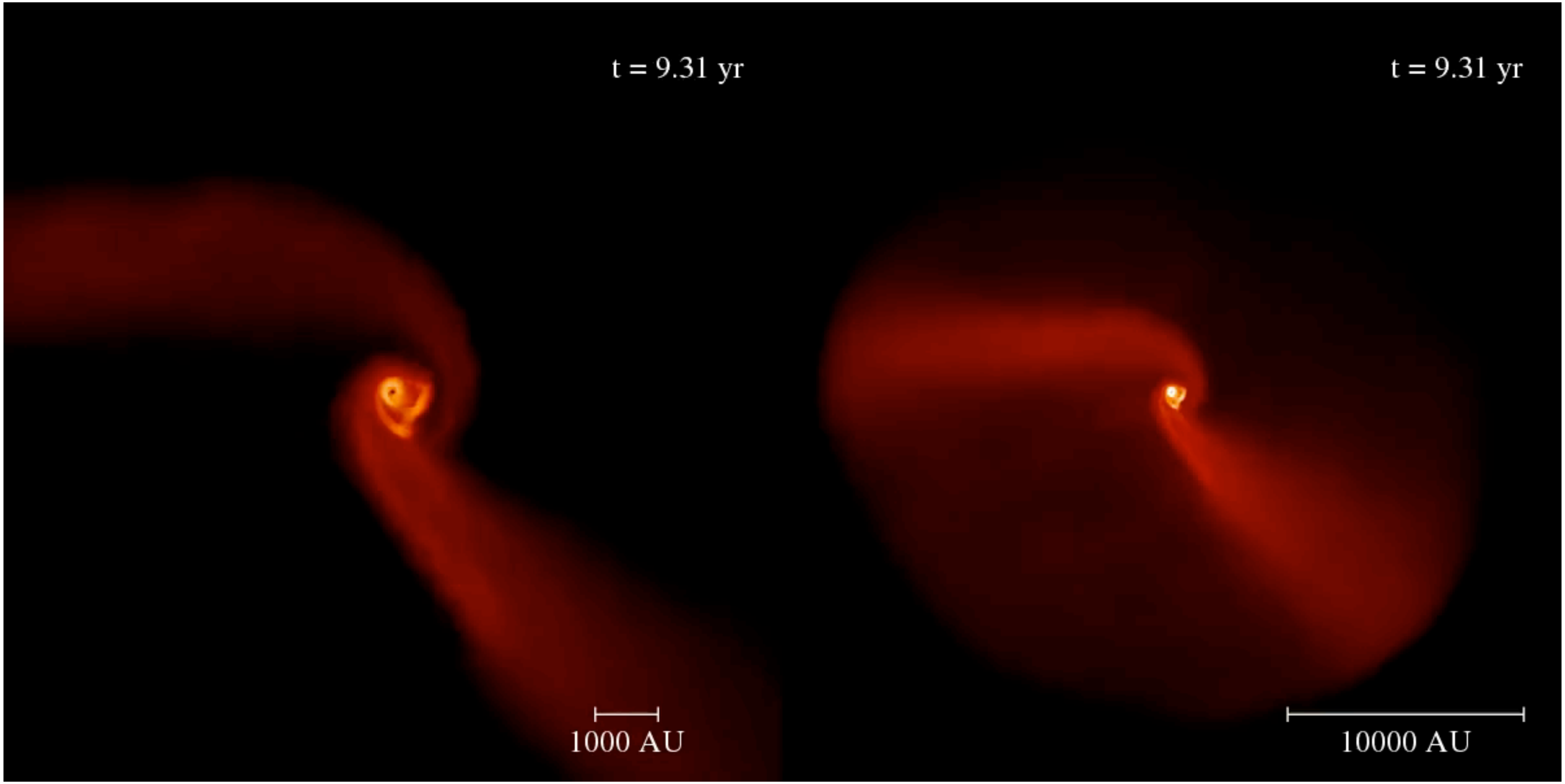
Follow next accretion stage

- Gadget3 (SPH + N-body)
- Primordial chemistry
- Multiple sink w/ mergers
  (created at $n > 10^{14}\ cm^{-3}$)
- Sink radius = 20 AU
- UV feedback from sinks (Susa, 2006)
- Luminosity of the sink
  → fitting of Hosokawa+2012
- Optically thin Lya cooling

- Initial Condition
  → taken from cosmological simulation



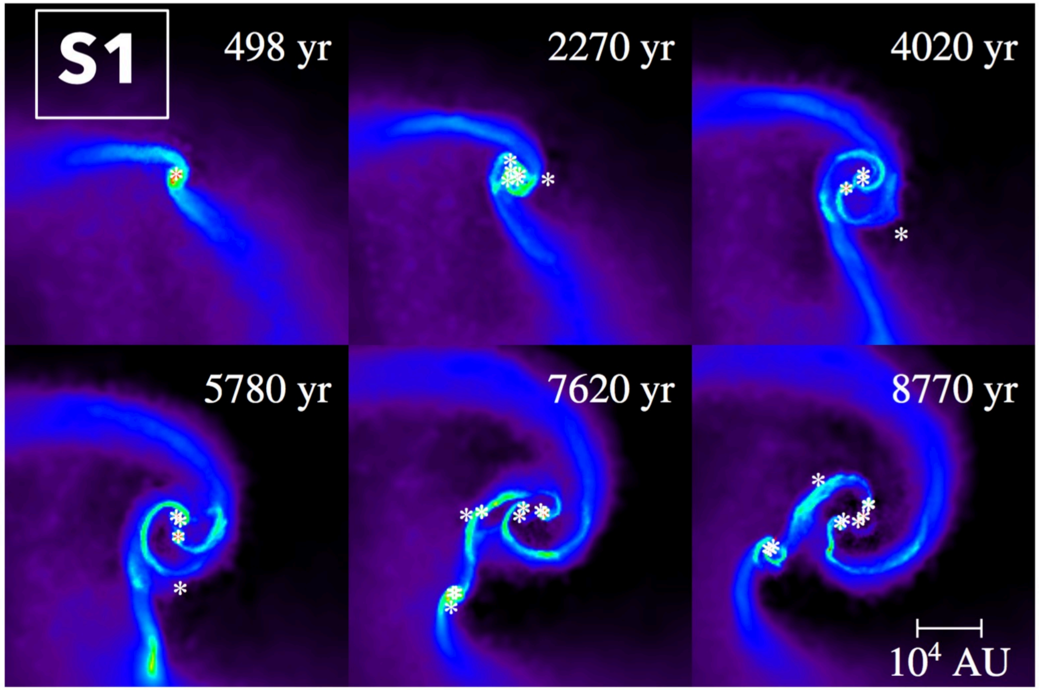
Multiples w/ filamentary cloud



The filamentary cloud easily fragments via gravitational instability, which produce multiple star-disk systems → cluster of very massive stars (w/ some binaries)

“Filamentary” Cloud

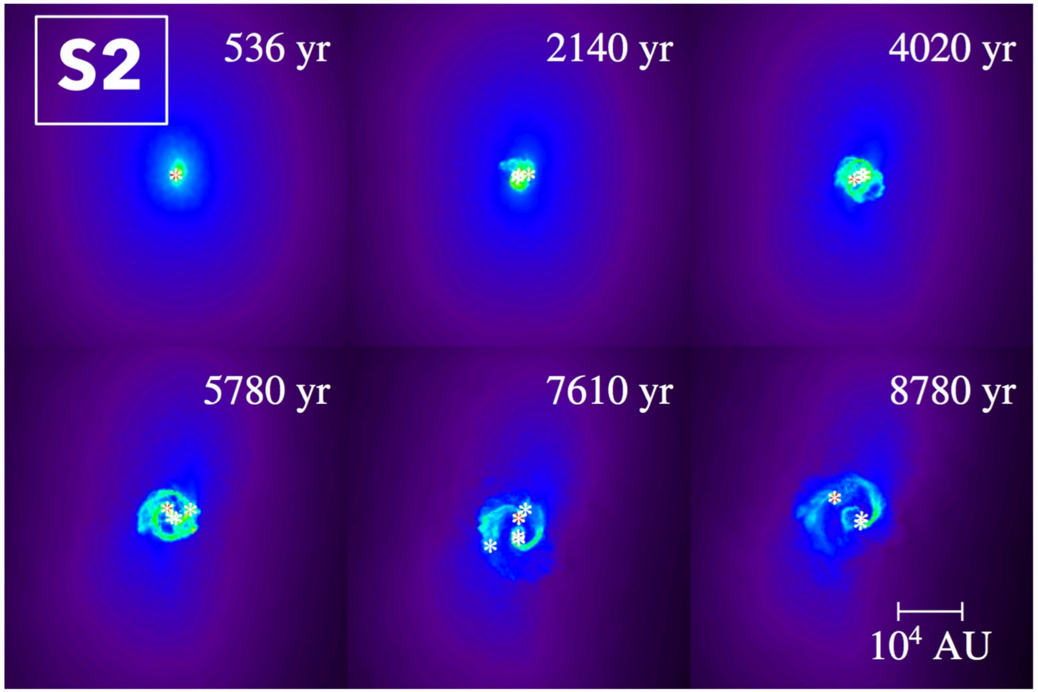
Multiple, large
Star-disk system



v.s.

“Spherical” Cloud

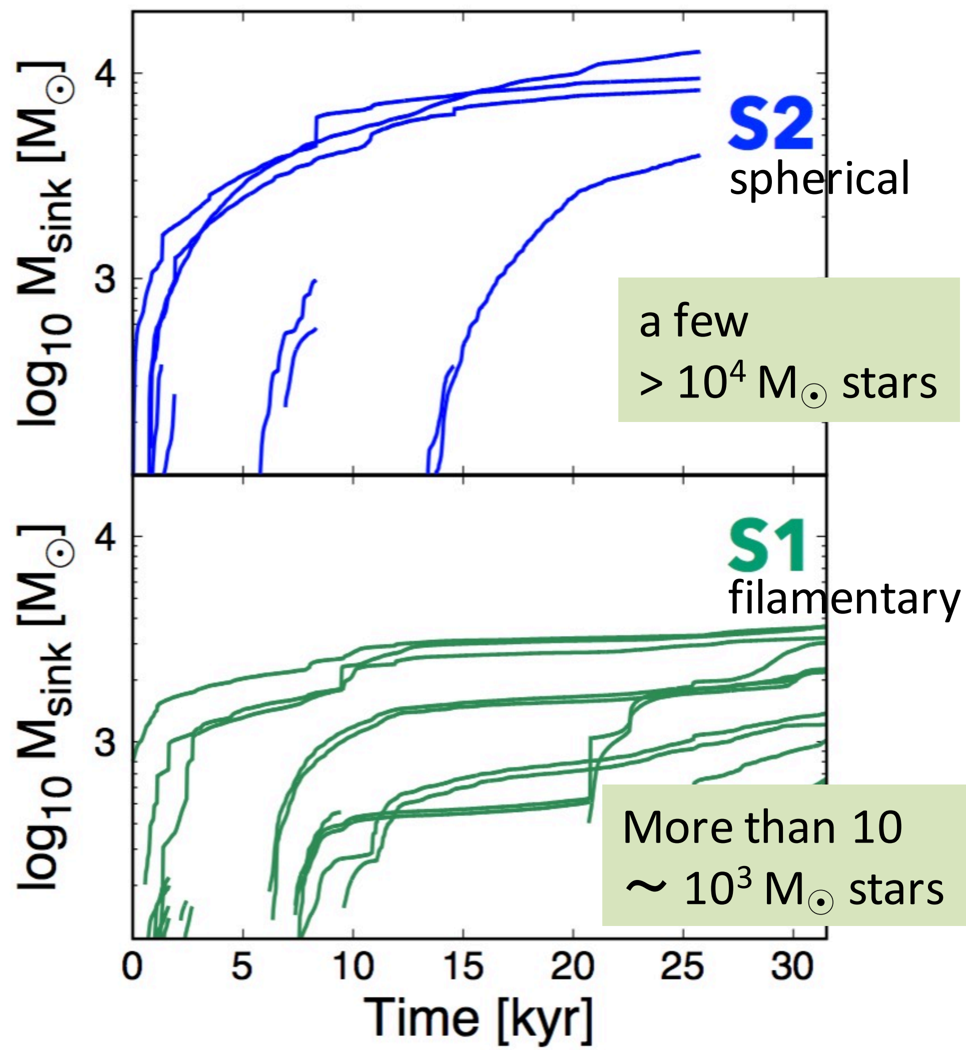
Single, compact
Star-disk system



Mass Evolution, and Binarities

Binary in the simulation

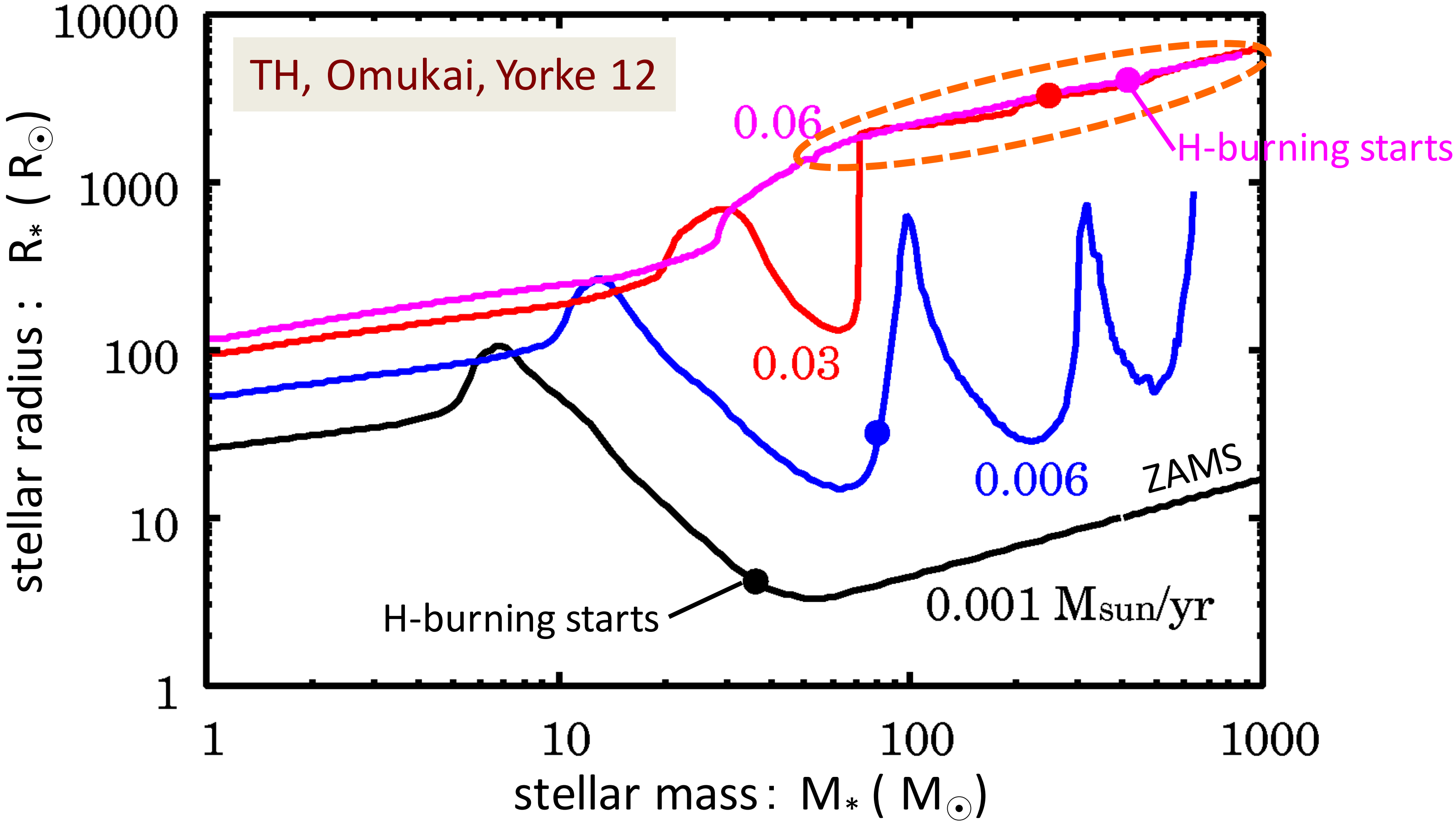
	ID		Mass [$M_\odot$]	
S2	0	2	9276.63	8102.17
	2	8	8102.17	3564.67
S1	0	1	3266.96	2877.49
	0	2	3266.96	3178.68
	7	10	15.3697	1780.07
	10	11	1780.07	1698.32
	10	12	1780.07	939.39
	10	16	1780.07	869.668
	10	18	1780.07	472.122
	11	16	1698.32	869.668
	14	17	1750.76	1652.44
	16	18	869.668	472.122



But in both cases, the minimum binary separation is 〜100AU

※ we assume that the stars merge with the smaller separation because…

“Supergiant Protostar”



+ This is the reason why the UV feedback does not stop the stellar mass growth until the stellar mass exceeds $1000 M_{\odot}$
+ ”common-envelope”-like evolution may occur in the protostellar phase…
  ← future studies needed

Summary

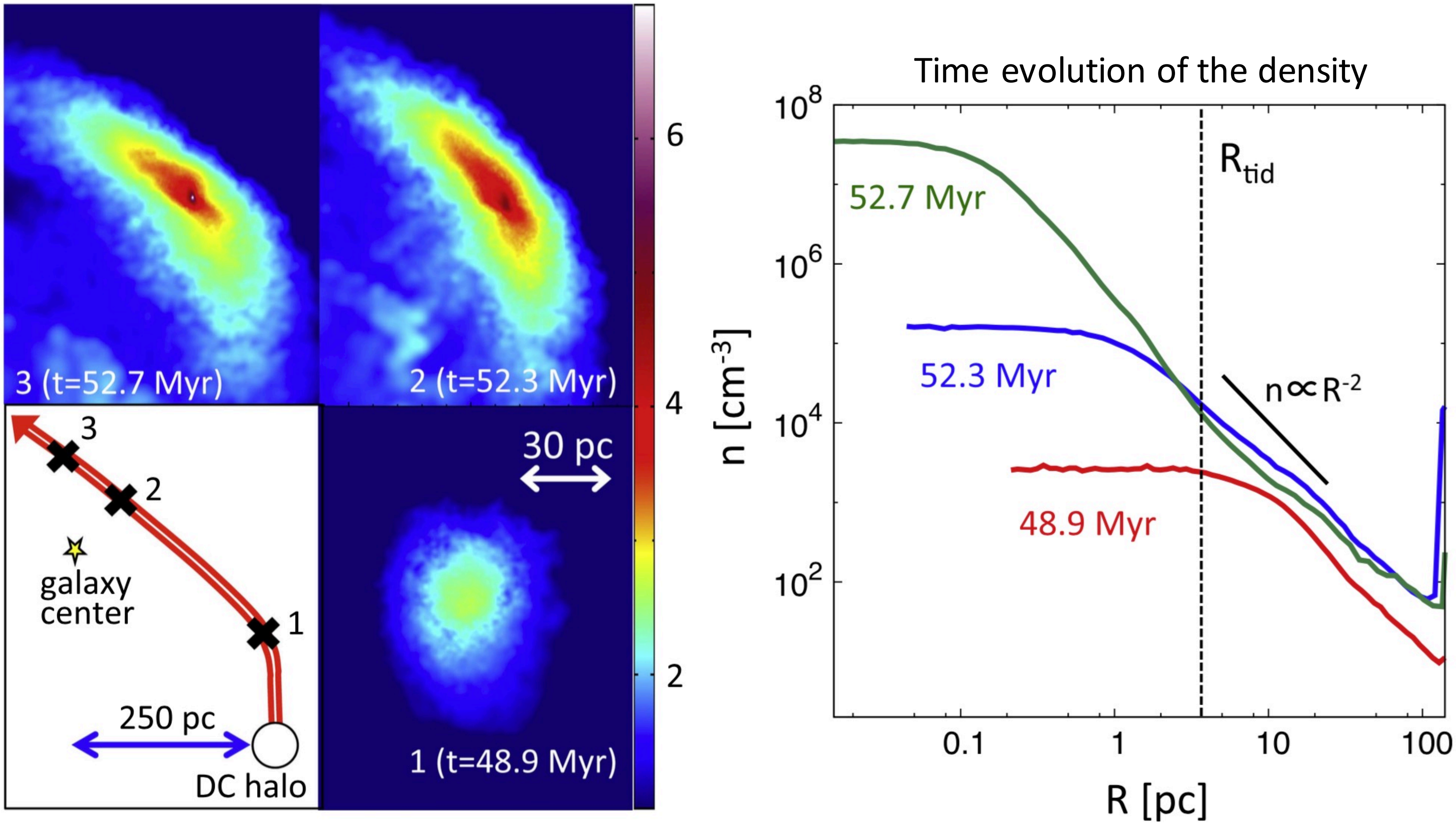
Formation of supermassive stars and their binaries
in a full cosmological context, with direct numerical simulations

+ Environmental effects (e.g., tidal field) are obviously important

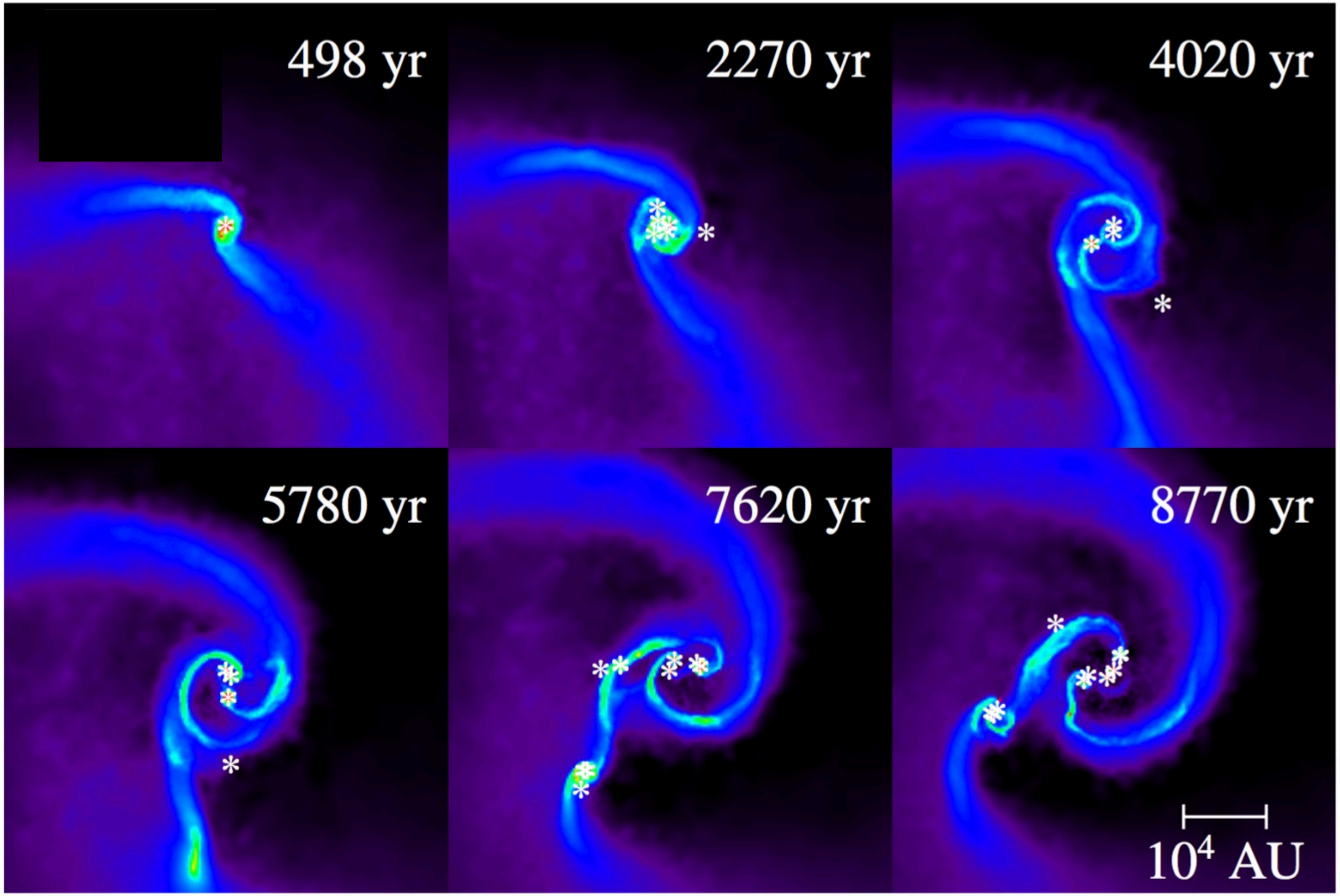
Strong tidal force stretches the cloud to make it filamentary,
causing the gravitational fragmentation

+ a number of massive binaries
Regarding tightest massive binaries, the protostellar evolution
becomes critical; "common-envelope"-like evolution ?

Additional pages

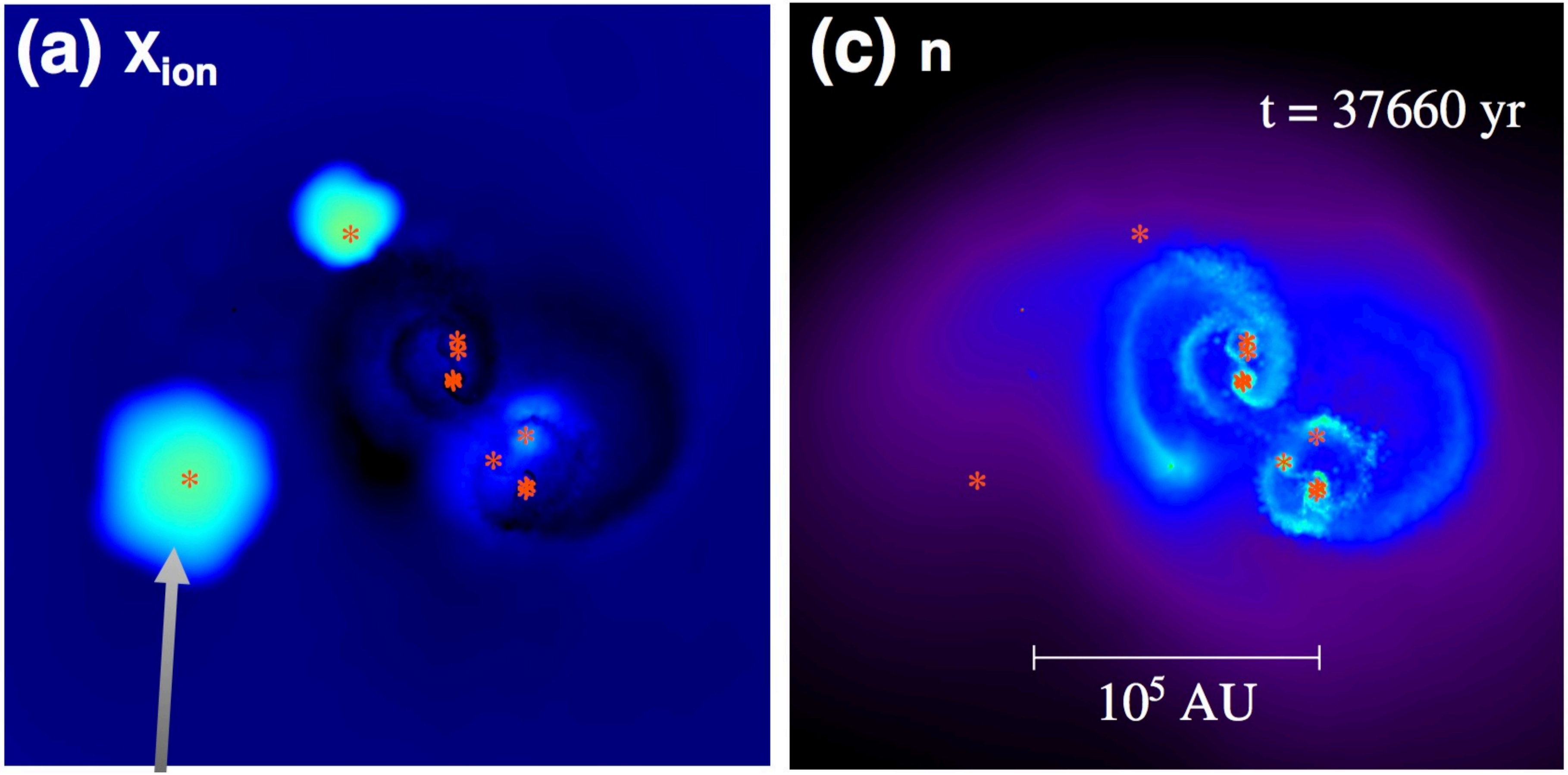


Gravitational collapse proceeds, but the cloud is largely stretched by the strong tidal force



$\sim$10 stars with $\sim$1000$M_{\odot}$ from in 3 x 10^4 years,
and some of them are in binary systems
(minimum separation $\sim$ 100 AU)

Emergence of HII regions



HII region