Formation of massive stellar binaries in the early universe

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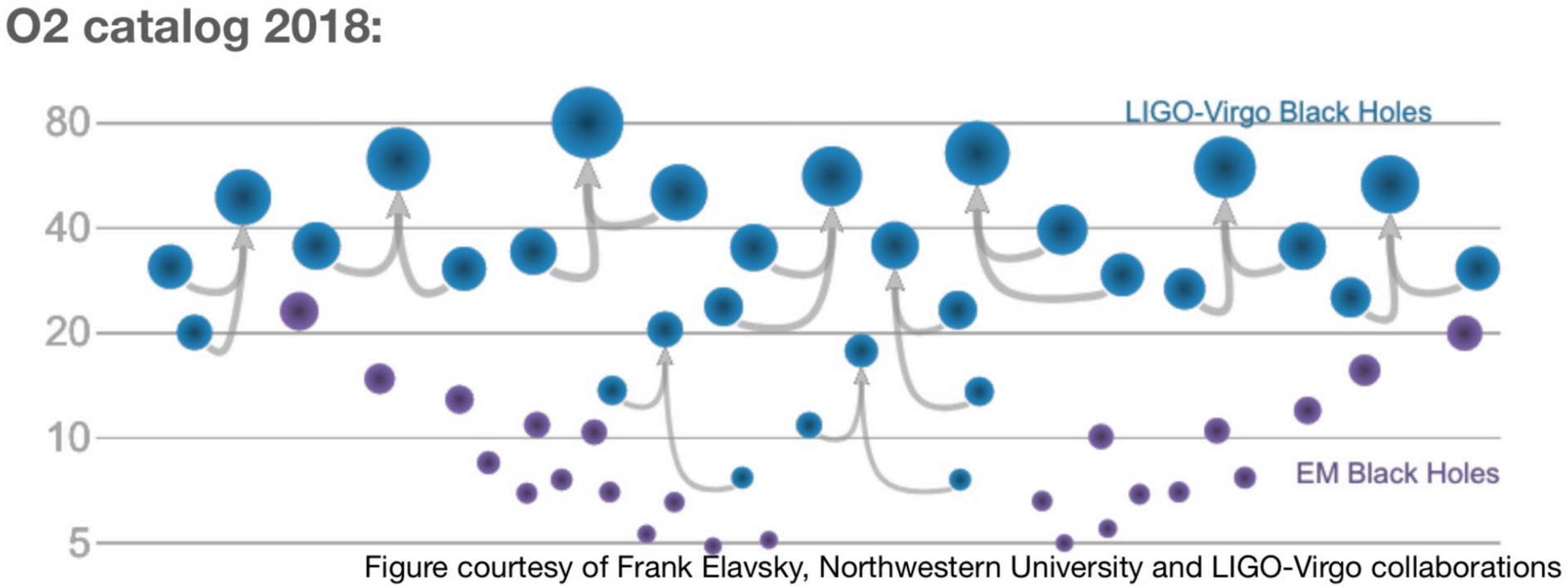
17.Oct.2019 Multi-messenger workshop in GW era @ YITP

Advent of GW Era

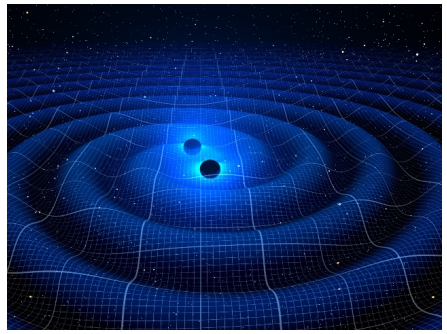


What are the origins of such massive BH-BH binaries?

massive stellar binaries $\Rightarrow$ binary evolution (e.g., common envelope)
$\Rightarrow$ BH-BH binary (w/ $\sim$0.1AU separation)

Consider the first stage of the formation of massive stellar binaries

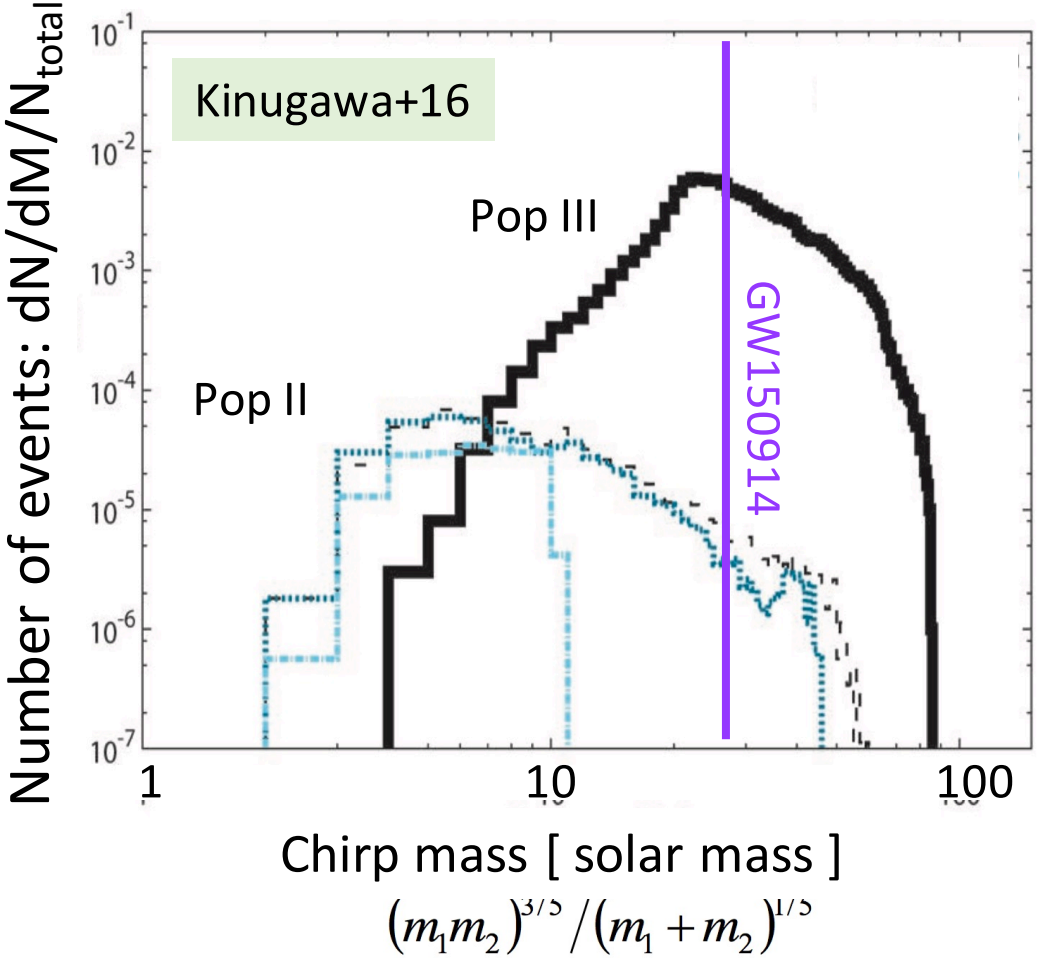
Pop III Origin?



(Kinugawa+14,16; Nakamura+16; Inayoshi+17 etc)

Assume millions of stellar binaries, and then derive the chirp-mass distribution of merger events that occur within the cosmic age…

(Monte-Carlo simulations)



Peak around $30M_{\odot}$ only for Pop III case

It was predicted in 2014, *before* the GW detection

And then GW150914 came just on the peak…

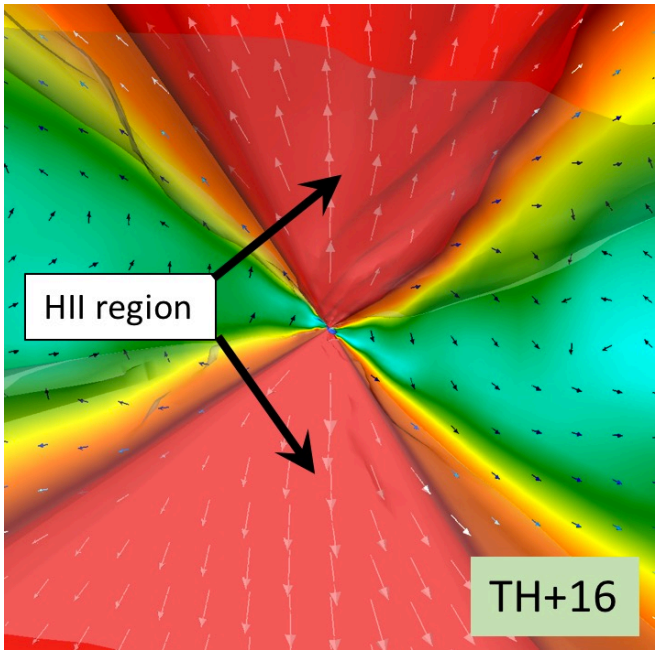
Key Questions

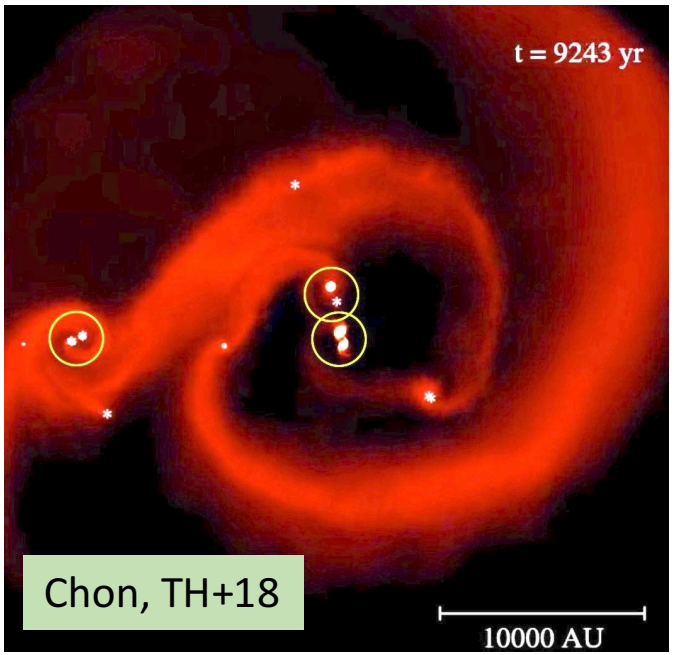
Stars in the earliest universe: What is their

typical mass? / mass distribution? /

binarity and multiplicity?

To answer these, we understand the key processes:
(I) stellar radiative feedback + (II) fragmentation

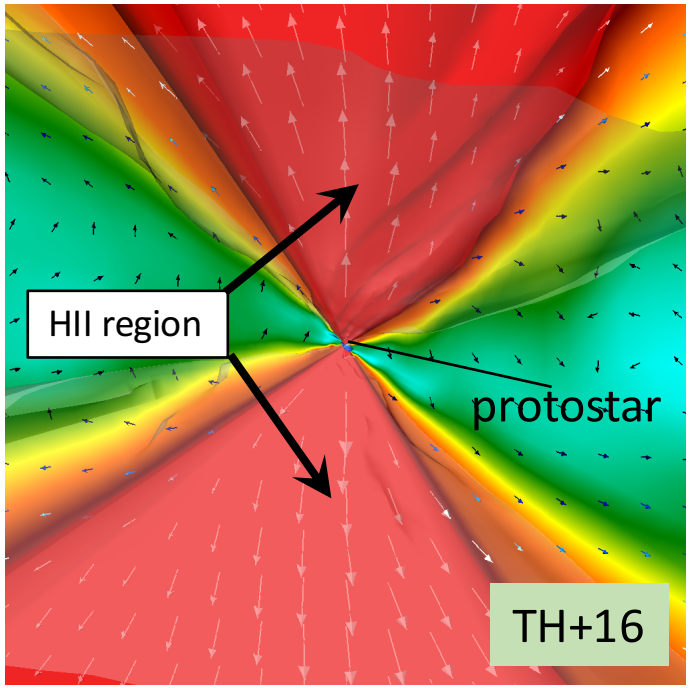


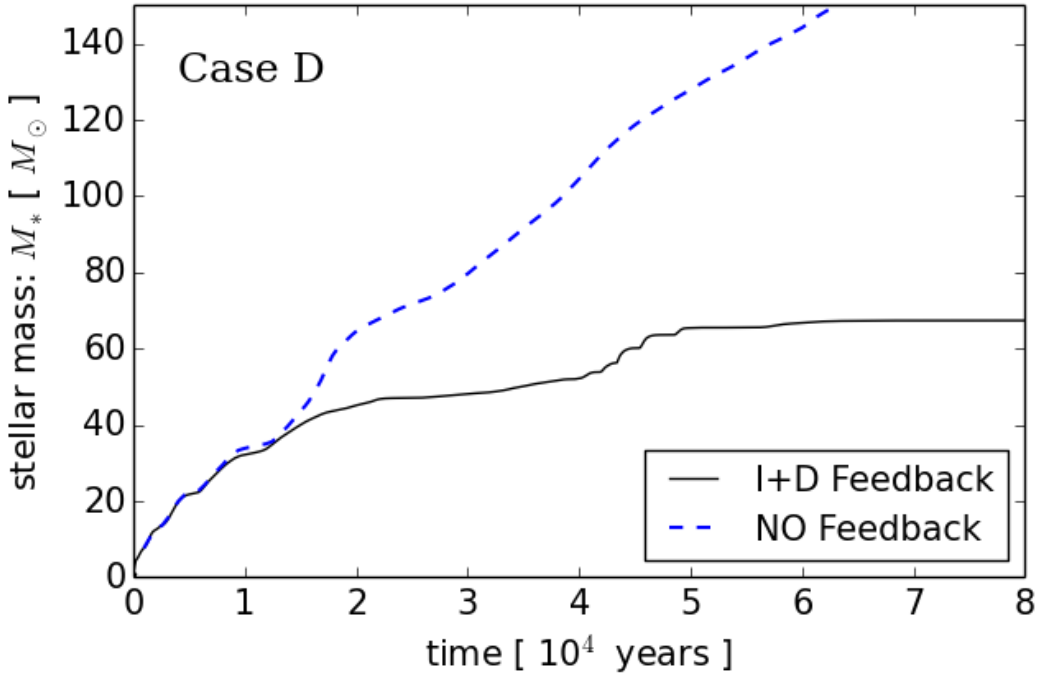


Pop III UV feedback

(TH+16, 11; Stacy+16, 12; Susa+14, 13 etc)

caused by the stellar ionizing radiation, which heats up the accreting gas



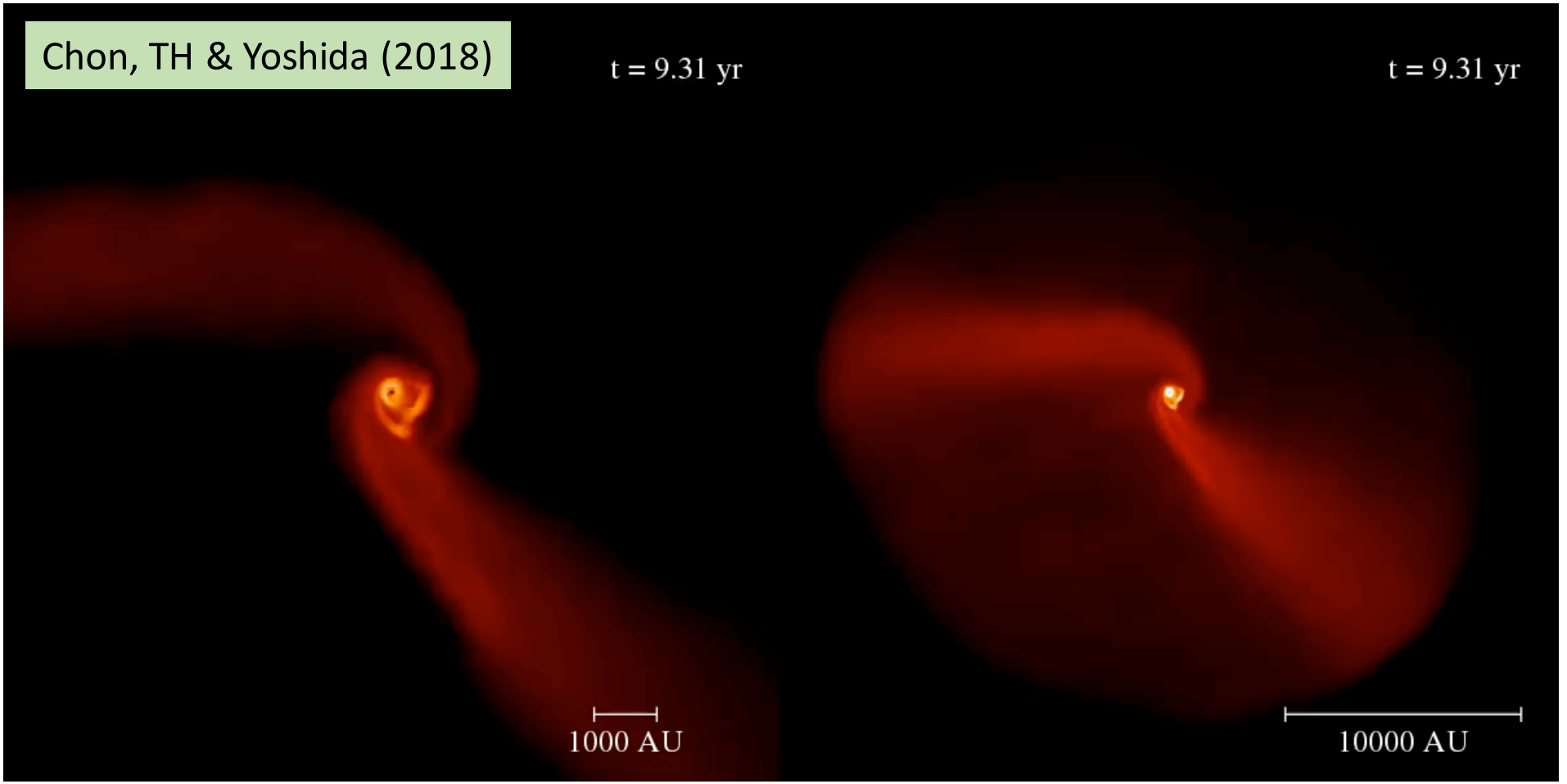


The mass accretion onto the star is shut off by the UV feedback

→ it determines how massive star is finally formed.

※**Gas pressure** effect (UV radiation enhances the gas pressure)

Fragmentation



The grav. fragmentation yield multiple star-disk systems ⇒ binary formation?

Desperately complex evolution?

The fragmentation is often followed by ***merger*** events.

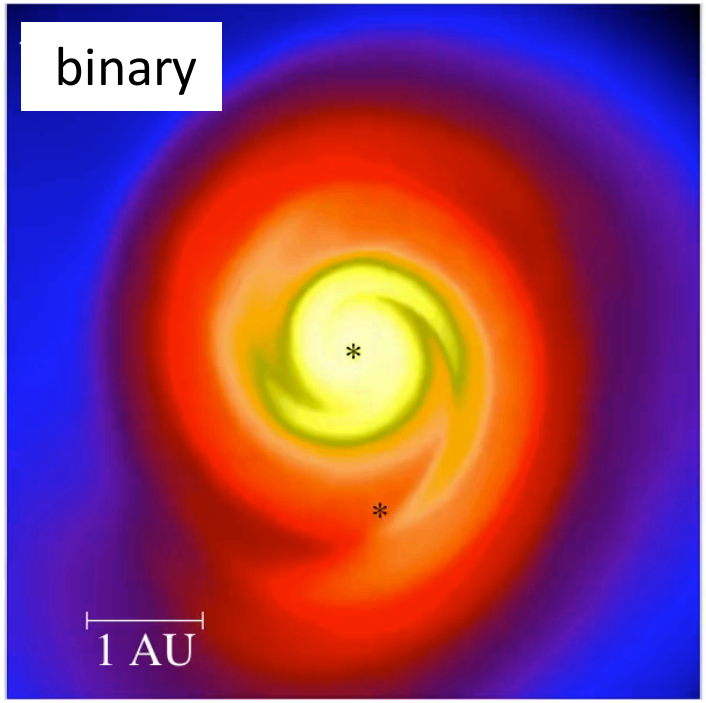
But not for all. Some fragments evolve into ***binary*** systems, and survive.

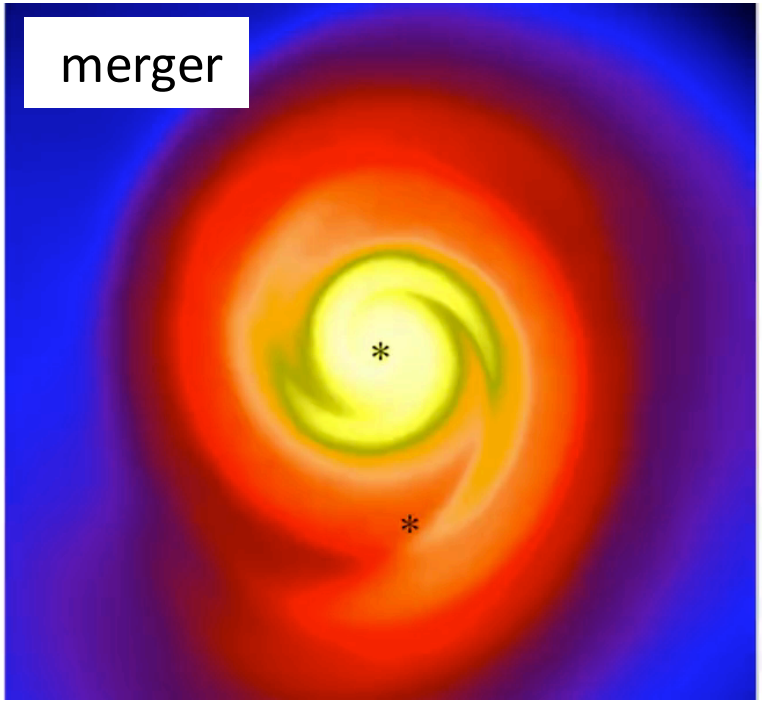
Binary *v.s.* Merger

What determines such different fates? Chon & TH (2019)

numerical experiments

Artificially put a clump in a rapidly accreting disk,
and then follow the orbital evolution
(initial positions and clump masses are free parameters)





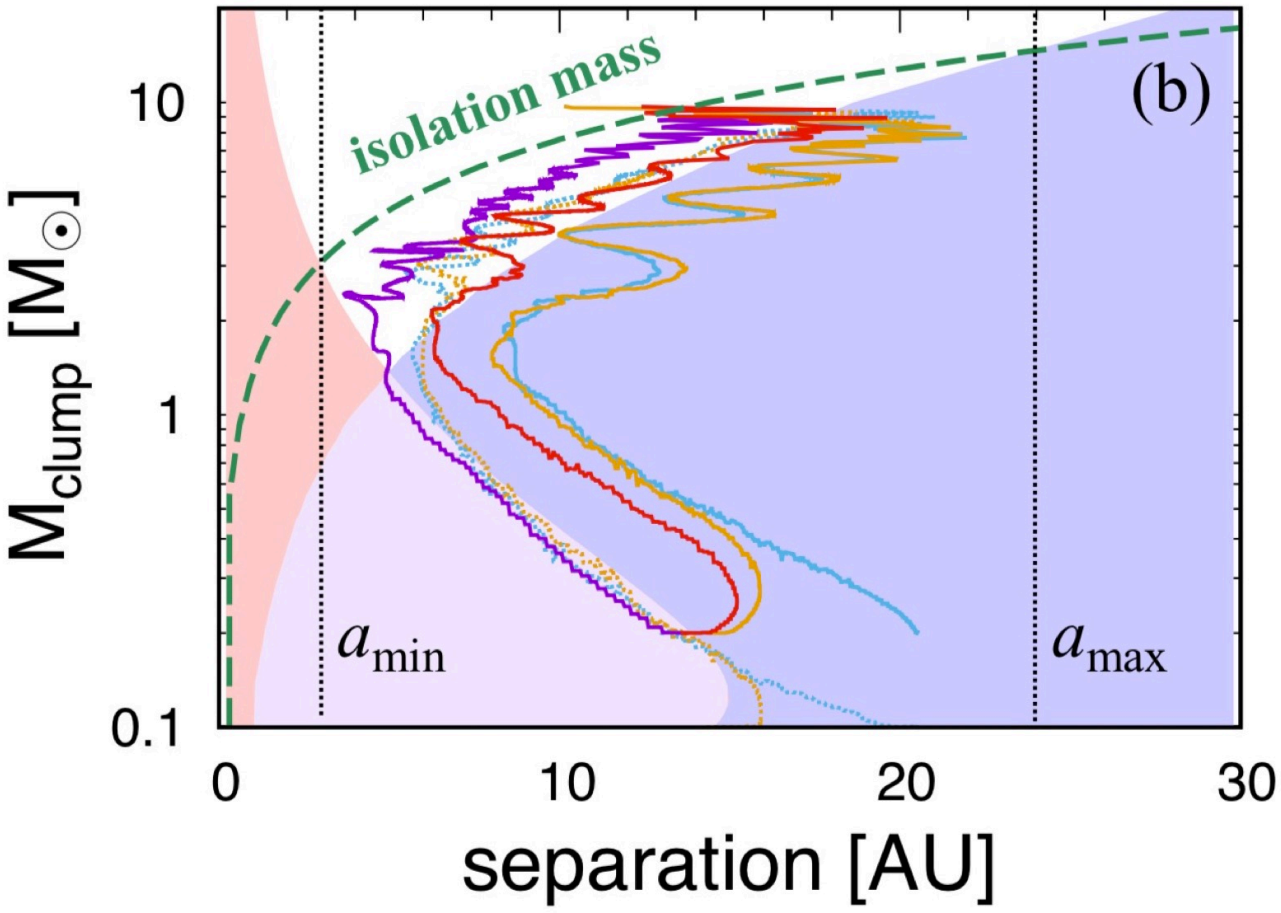
Evolution is diverse: it sensitively depends on the parameter choice

Extract Key Physics

Planet formation theories help us (though the situation is so different!)

Ansatz

1. orbital ang. momentum is lost by (I) type-I migration, (II) tidal disruption
2. the binary formation occurs when gap/cavity is cleared in the disk



Analytic evaluations

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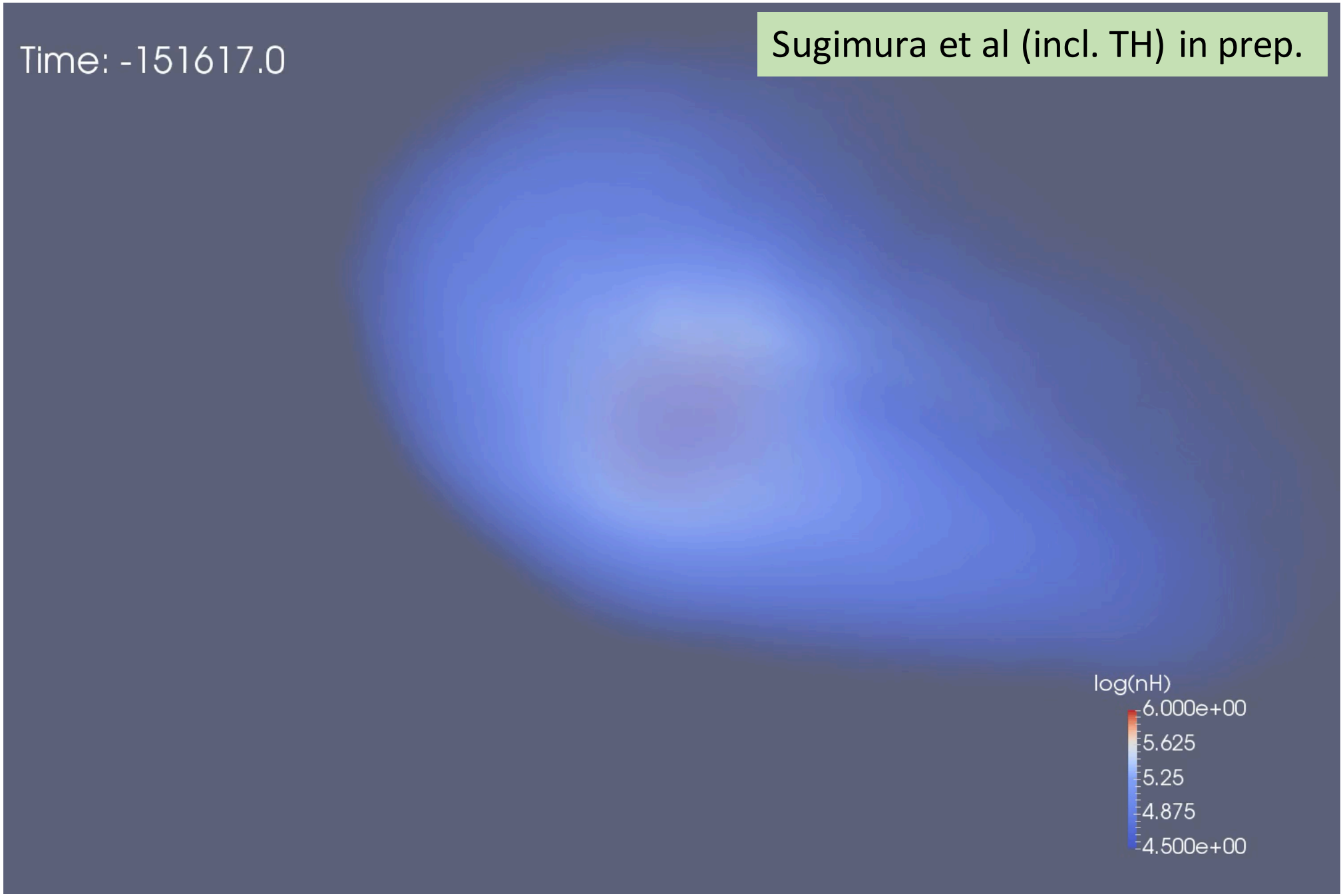
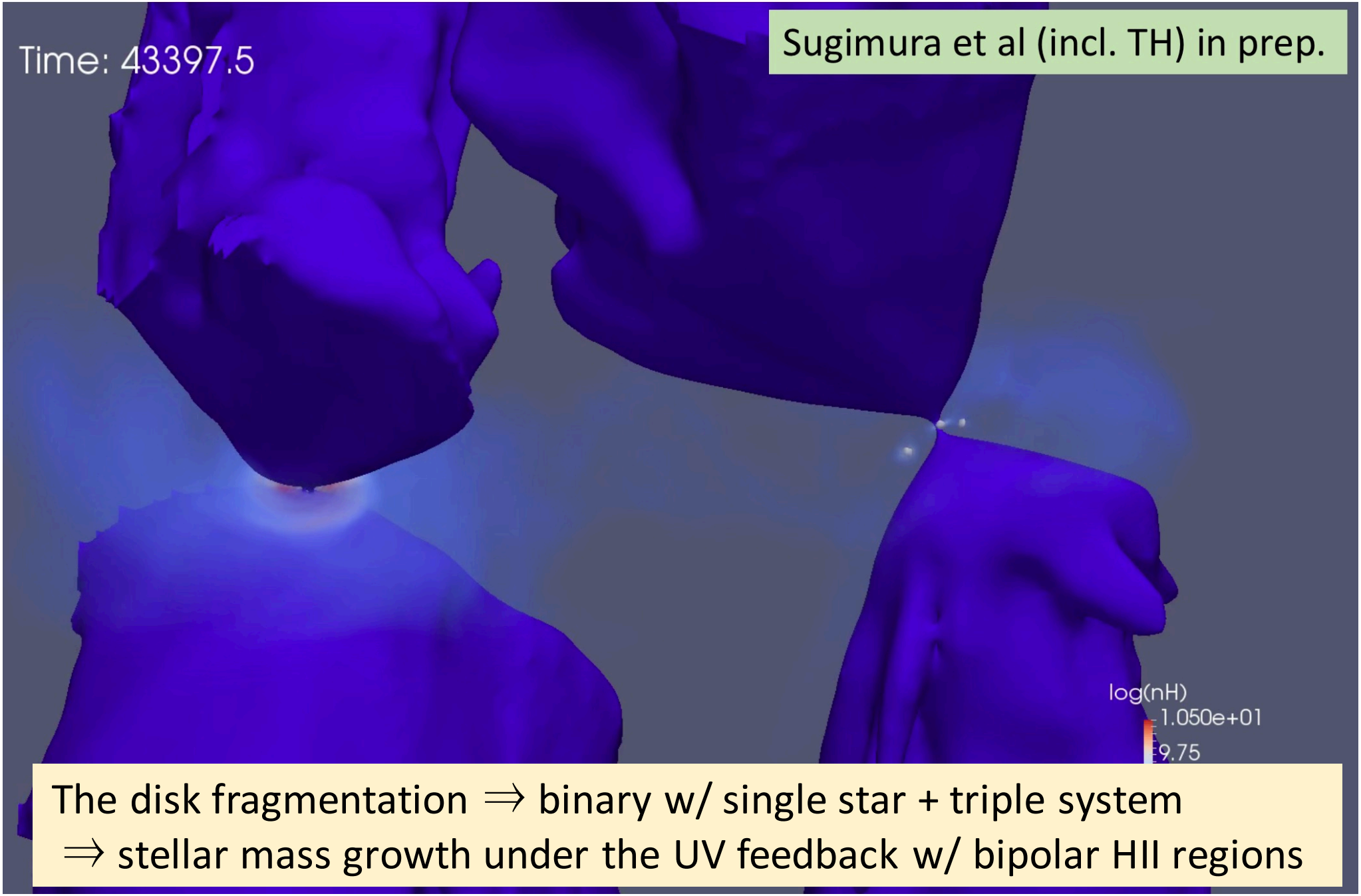
We can explain the divergent evolution with the above ansatz.

The binaries generally *expand* while accreting the gas.

UV feedback + Fragmentation

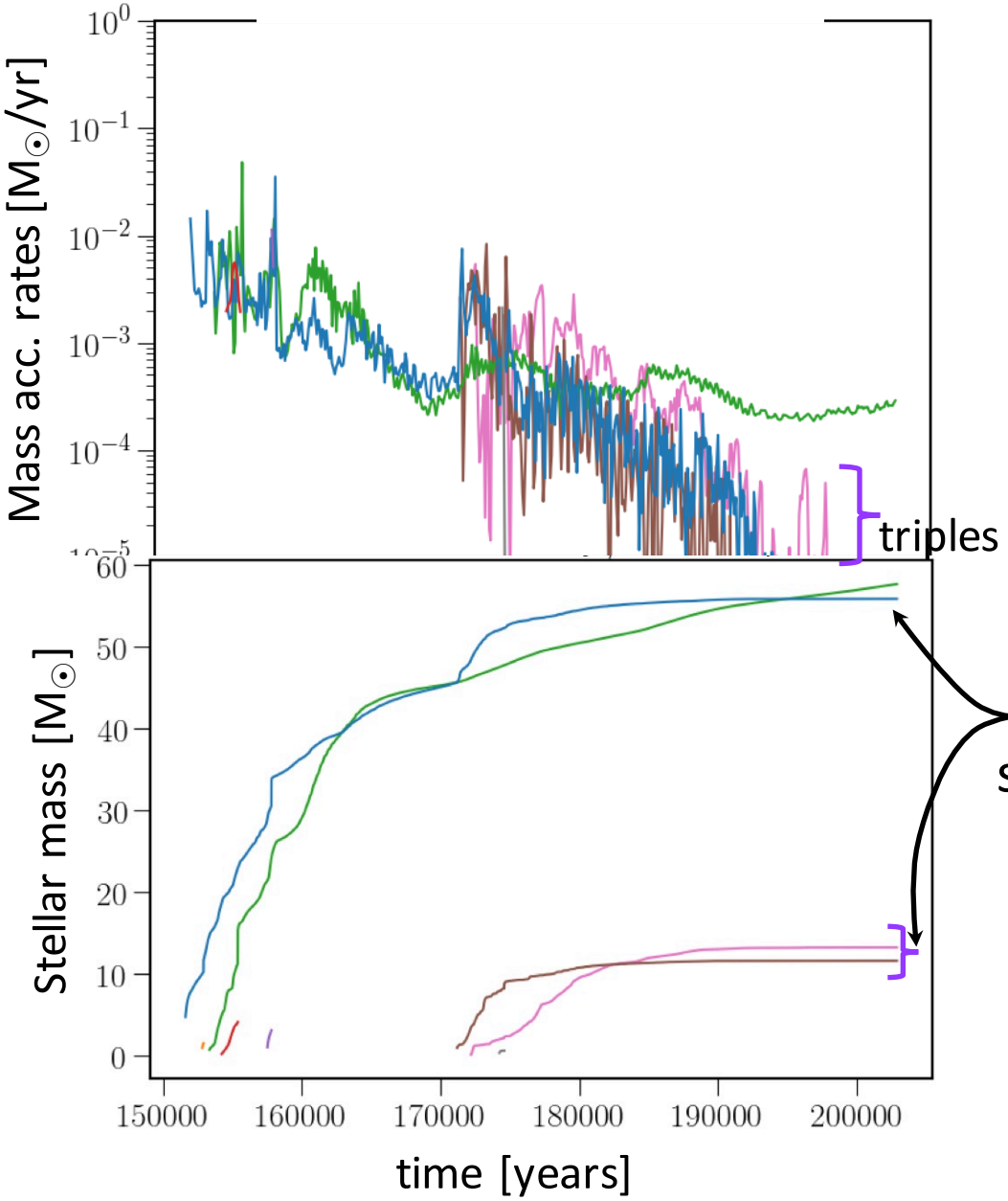


UV feedback + Fragmentation



The disk fragmentation ⇒ binary w/ single star + triple system
⇒ stellar mass growth under the UV feedback w/ bipolar HII regions

Mass Growth Histories



Accretion onto the triple system is shut off by the UV feedback

But the single star is still accreting

Mass

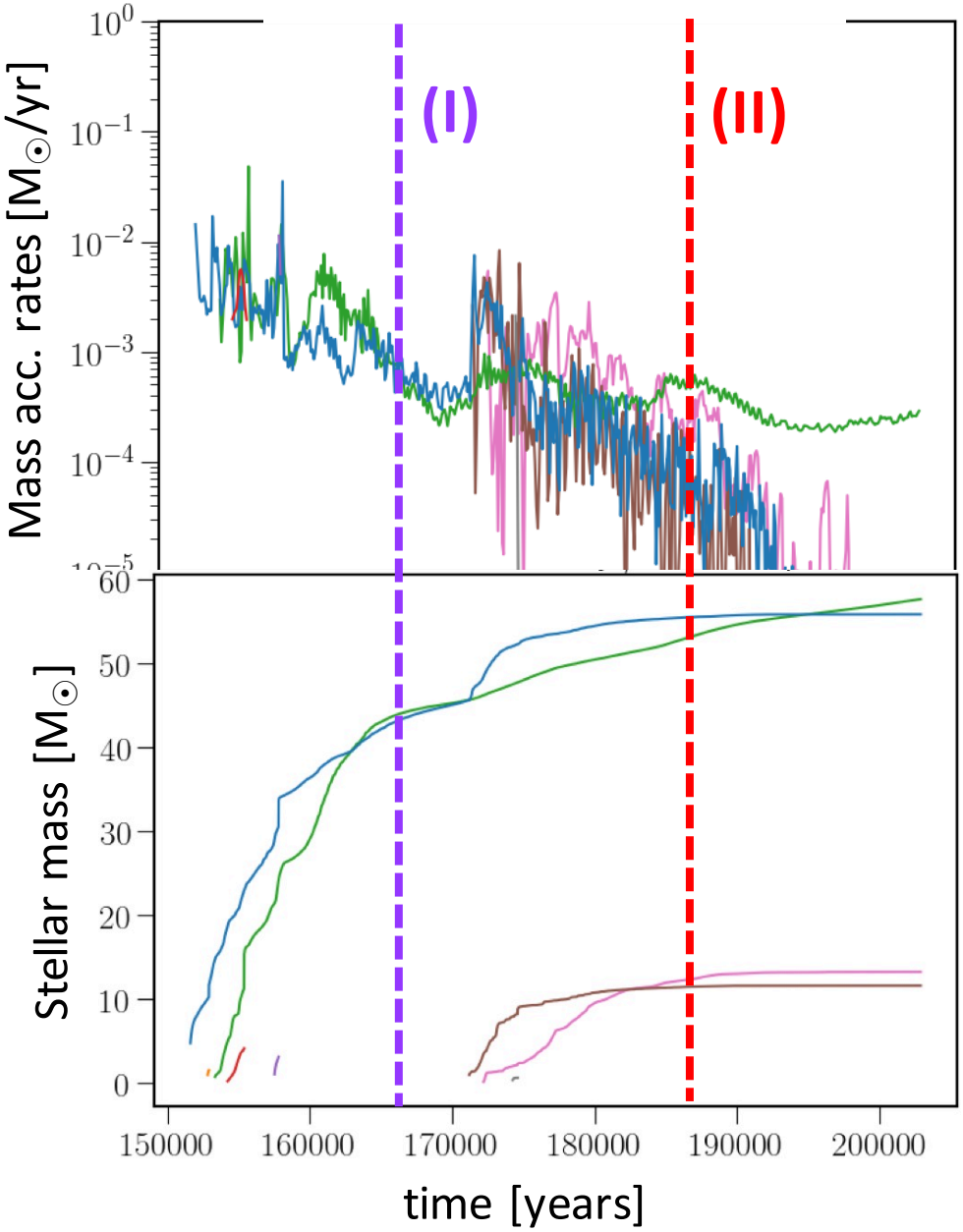
triples : $55M_\odot$, $10M_\odot$+$10M_\odot$

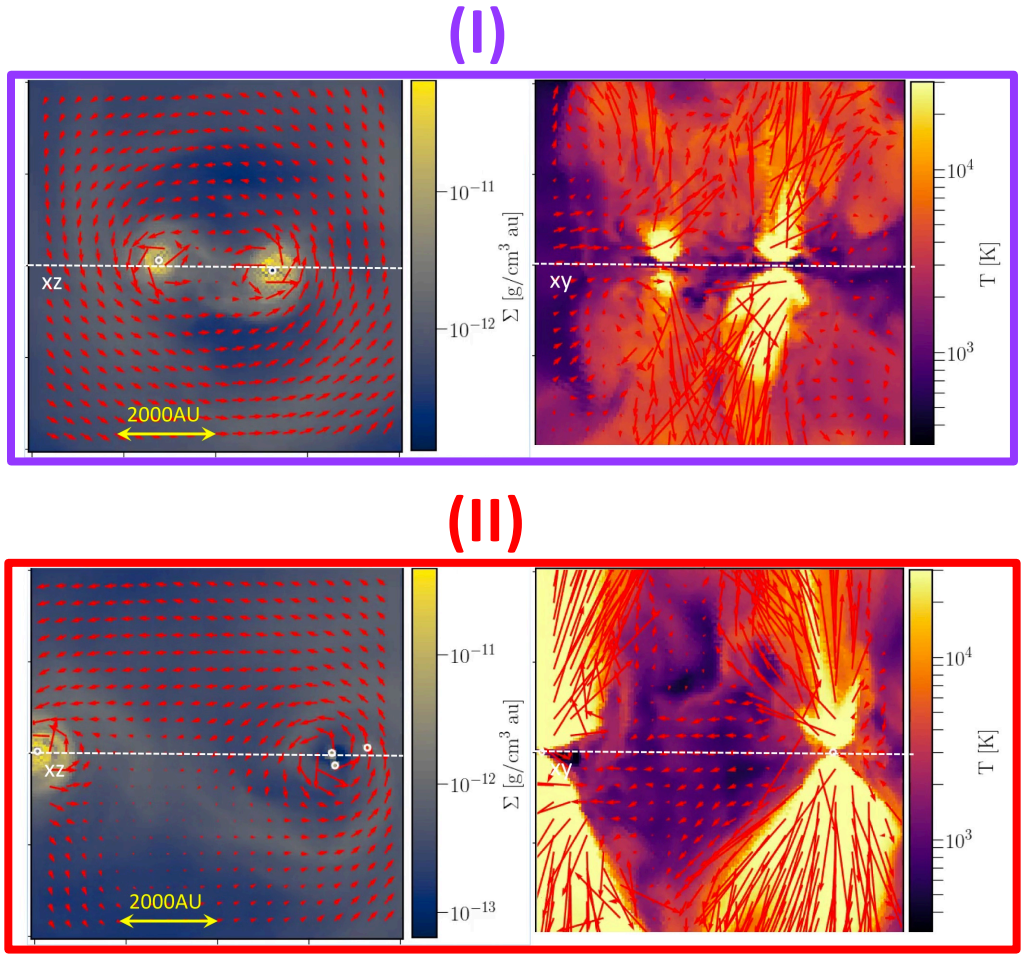
single : $>55M_\odot$ + circumstellar disk

Massive (～ several x $10M_\odot$)

Pop III binary is forming!

Binary Separation





Triple-single separation increases…

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Massive *wide* binary

NO tight massive binaries?

※ BH-BH binary separation must be <∼ 0.1AU
for the merger to occur within the Hubble time

Why?

”Inside-Out Accretion” onto stars

The gas near the star accretes first
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As time goes by, the gas with the larger specific angular momentum starts to accrete
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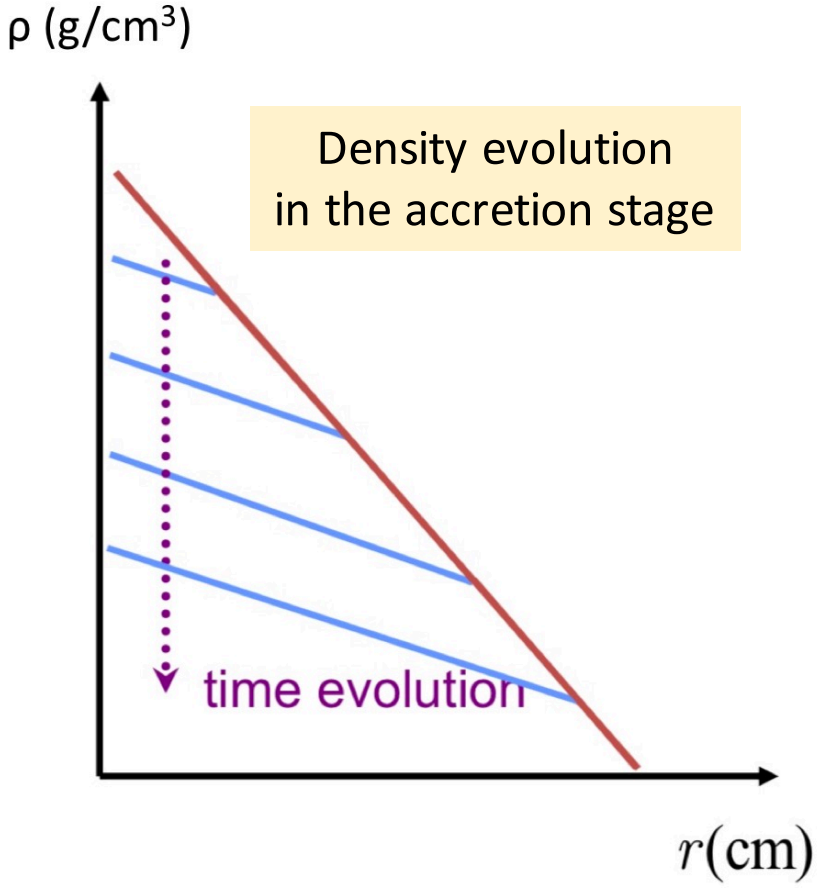
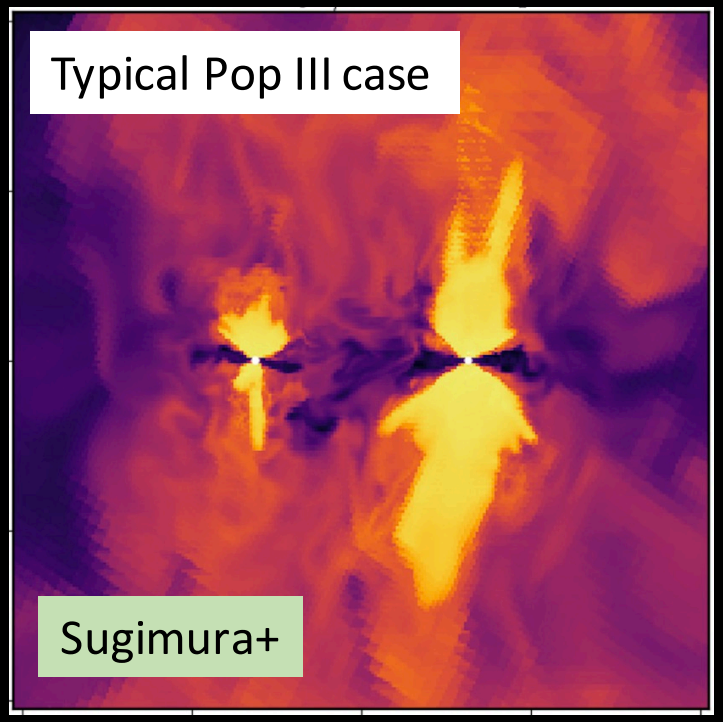
The binary mass increases, but
the binary separation also increases

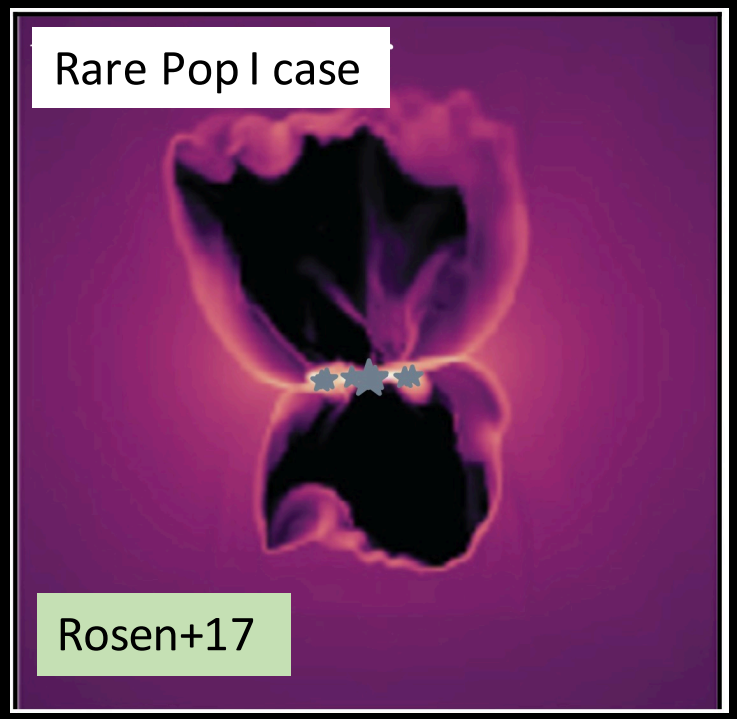


Magnetic fields may change the story…

"Bridge the Gap" between Pop III and I SF



Photoionization feedback
(gas pressure effect)



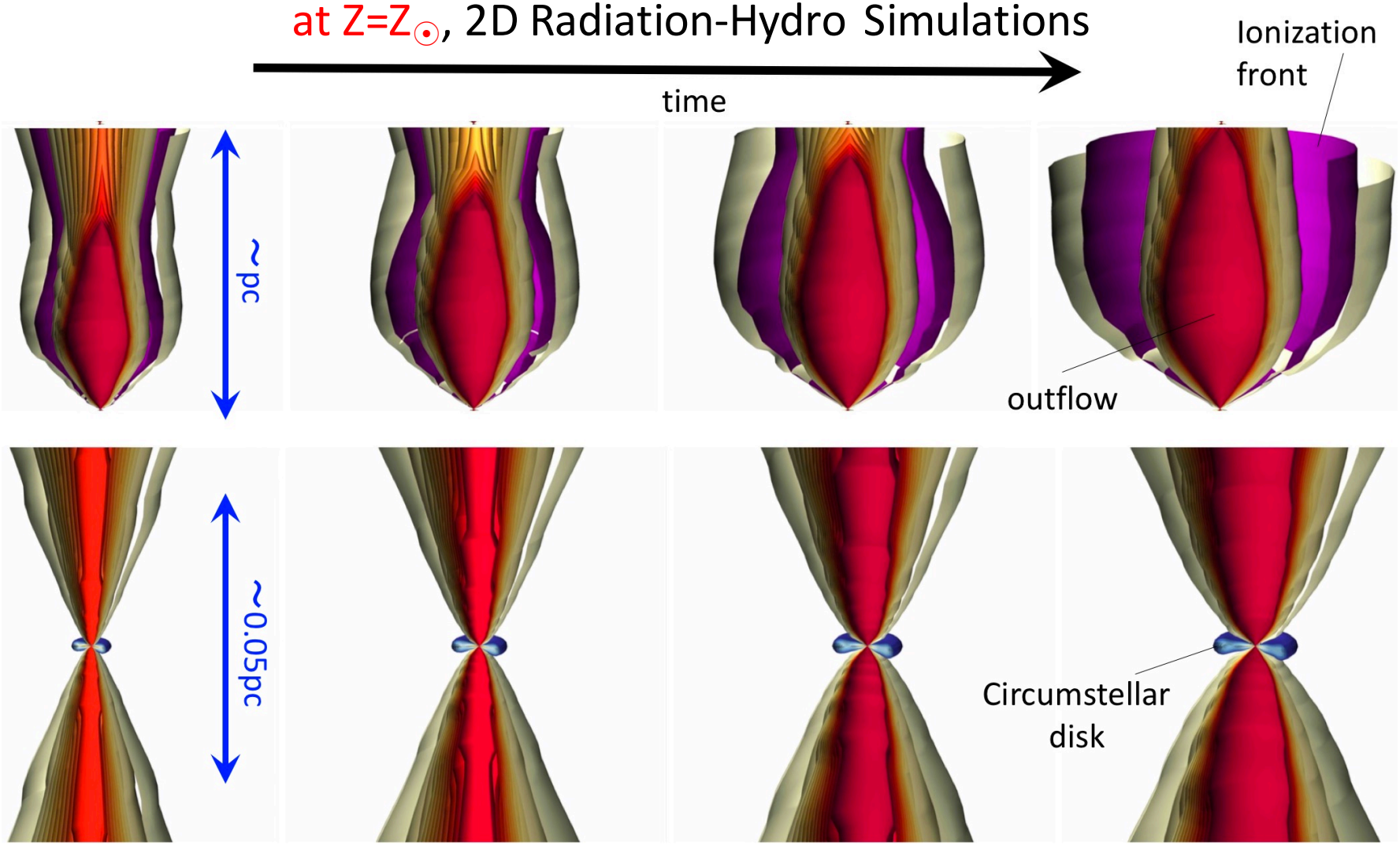
Radiation force feedback
(rad. pressure effect w/ dust)

What is the interplay btw these feedback in Pop I high-mass SF?

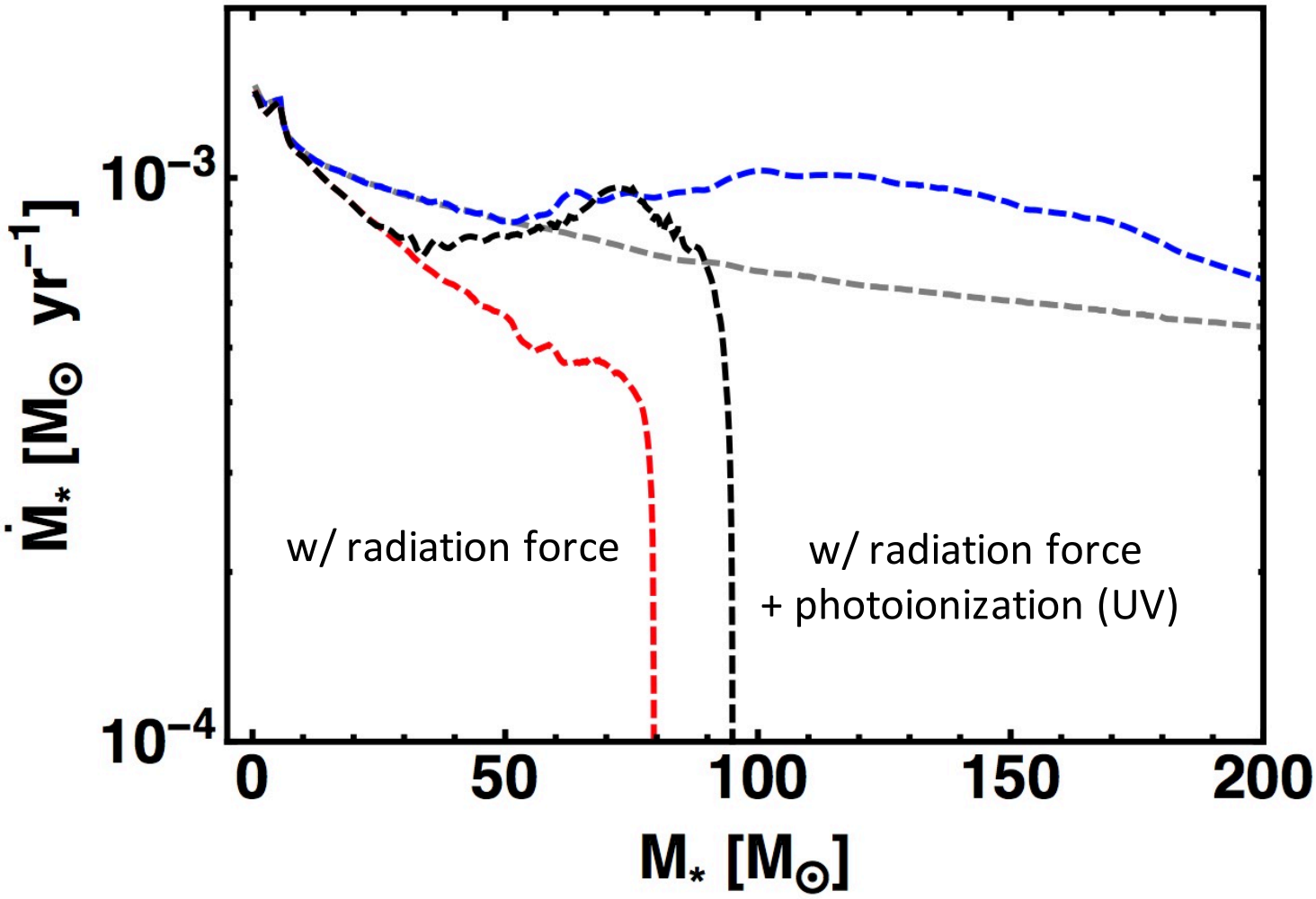
First Hydrodynamics Simulations of Radiation Forces and Photoionization Feedback in Massive Star Formation

Kuiper + TH 18, A&A

at $Z=Z_{\odot}$, 2D Radiation-Hydro Simulations



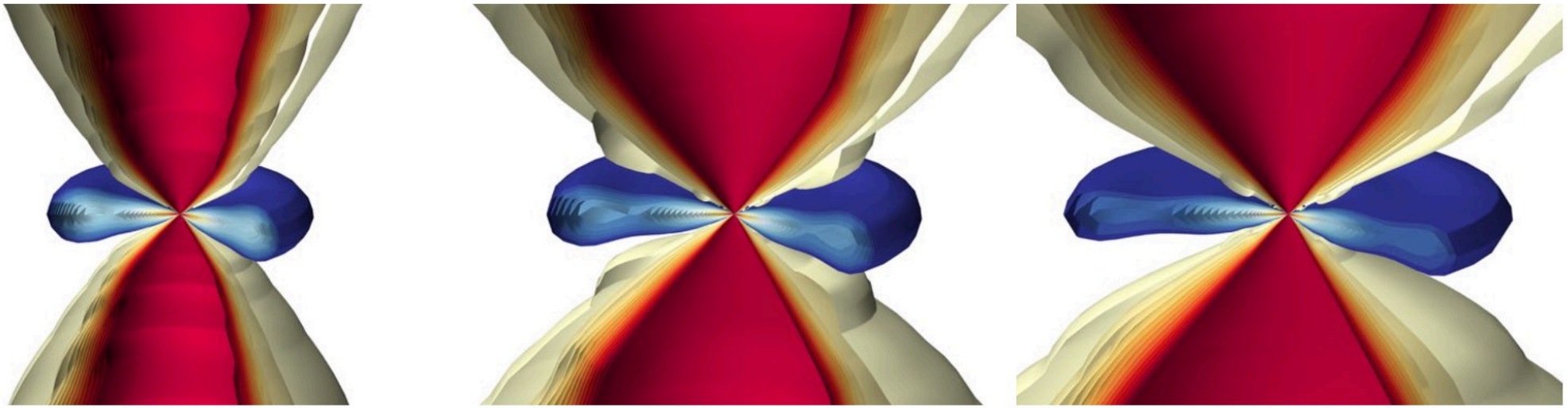
Accretion Histories



Photoionization feedback rather increases the final mass
(opposite to Pop III case)

What's happening?

The expansion of an HII regions pushes the gas in the envelope toward the shade of the disk, where the irradiation from the central star is blocked ⇒ it weakens "rad.-force" feedback



Unlike in the Pop III case, UV feedback does not halt the mass accretion, but rather promotes the mass accretion

→ ***Metallicity dependence of radiative feedback!***

(see also, TH & Omukai 09, Fukushima (TH) et al. 18, Tanaka (TH) et al. 18)

Summary

+ PopIII binaries: possible origin of BH-BH merger?

A large number of Pop III stars may be in binaries.
BUT no one answers how massive and tight binaries could form
(actually it is also the same for Pop I and II cases)

+ We shall bridge the gap btw Pop I and III massive star formation