初代星形成
an overview

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Review of Reviews…

Most of the previous review slides are still available on the web.
First visit a summary site at Konan, http://tpweb2.phys.konan-u.ac.jp/~shodai/

2018.11 @ 水戸 “初期宇宙構造形成シミュレーション”by 吉田さん
“連星形成” by 町田さん

2018.2 @ 呉 “初代星形成理論の現状” by 須佐さん
“連星の形成について” by 釣部さん

2016.10 @ 金沢 “初代星形成: an overview” by 細川

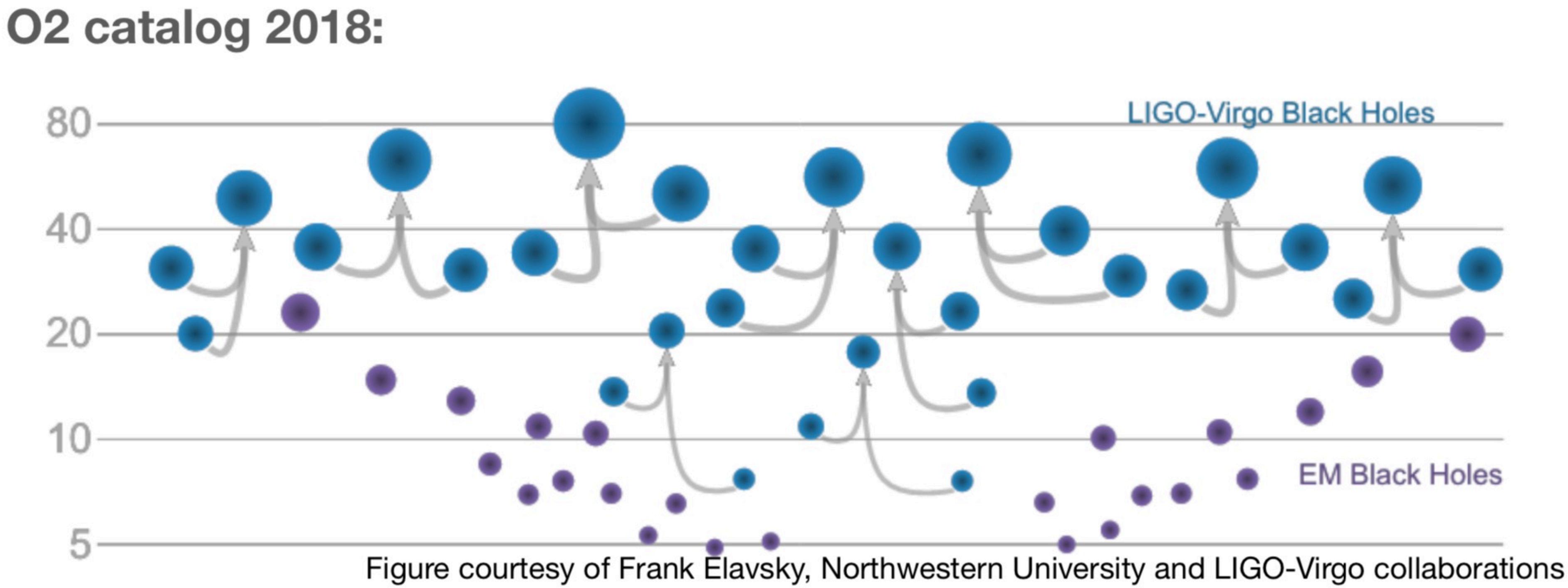
2015.12 @ 草津温泉 “初代星の形成” by 大向さん

2015.1 @ 仙台 “初代星形成過程の理論的研究” by 平野くん

…and more!

Binary formation is a recent ”hot topic”!

Advent of GW Era



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

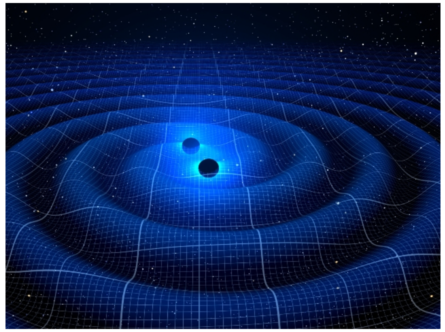
massive stellar binaries ⇒ binary evolution (e.g., common envelope)

⇒ BH-BH binary (w/ ∼0.1AU separation)

Consider the first stage of the formation of massive stellar binaries

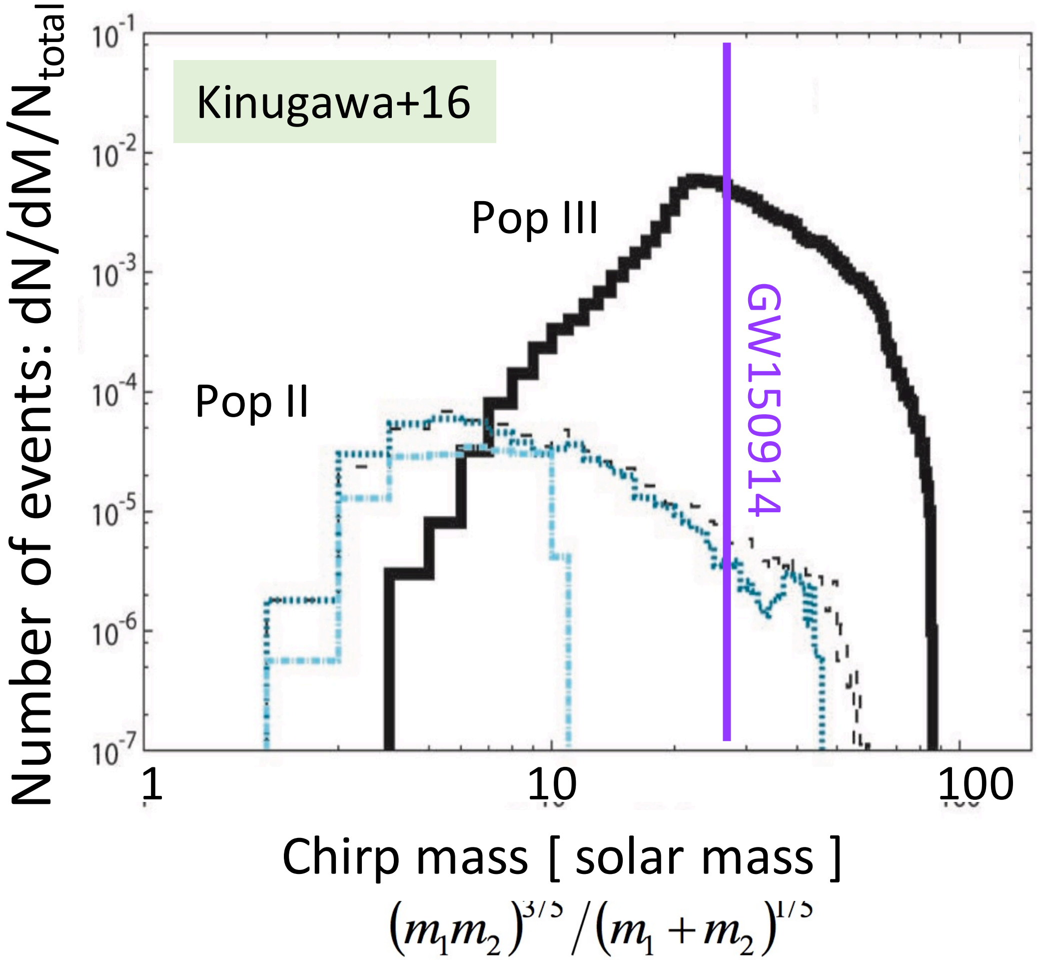
Pop III Origin?

(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

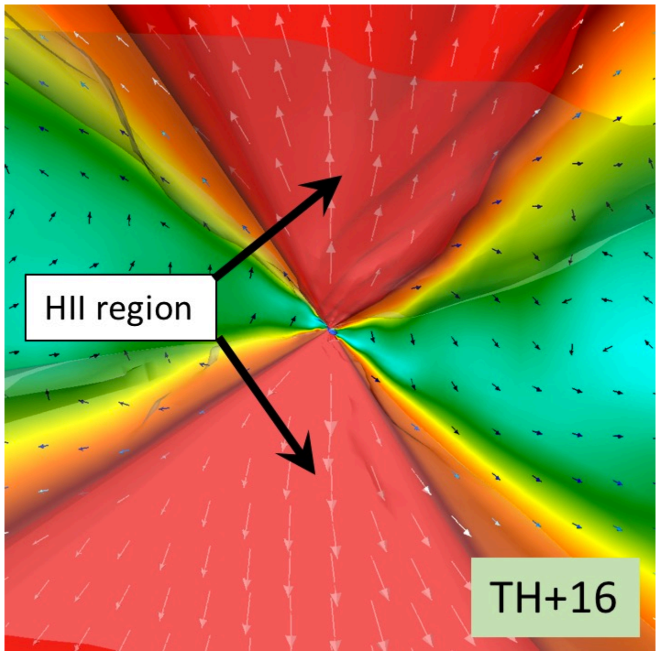
And then GW150914 came just on the peak...

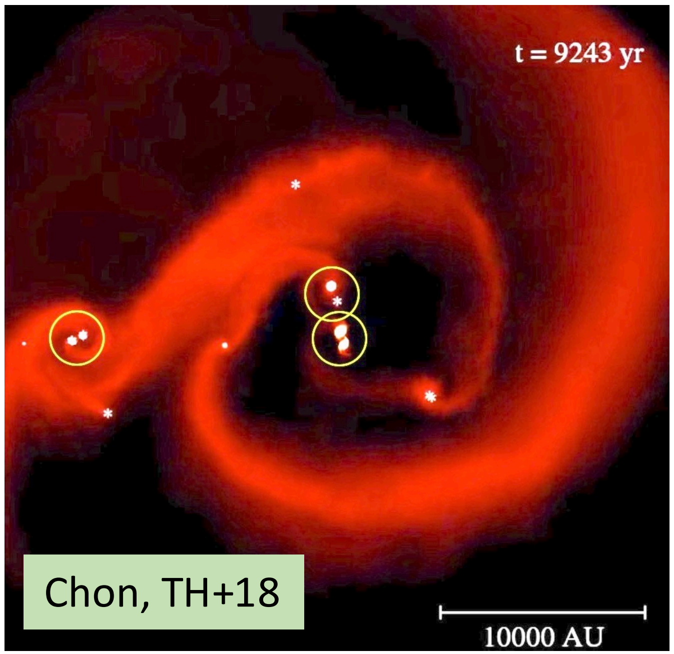
Key Questions

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

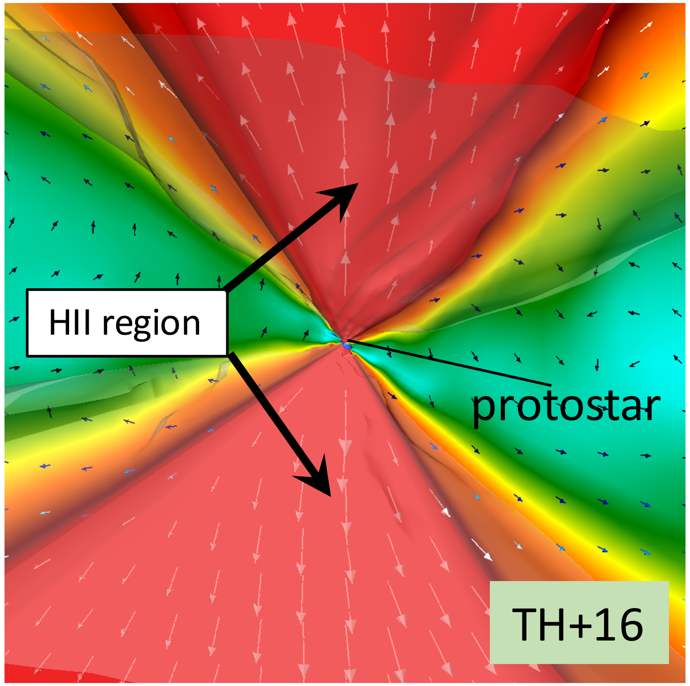


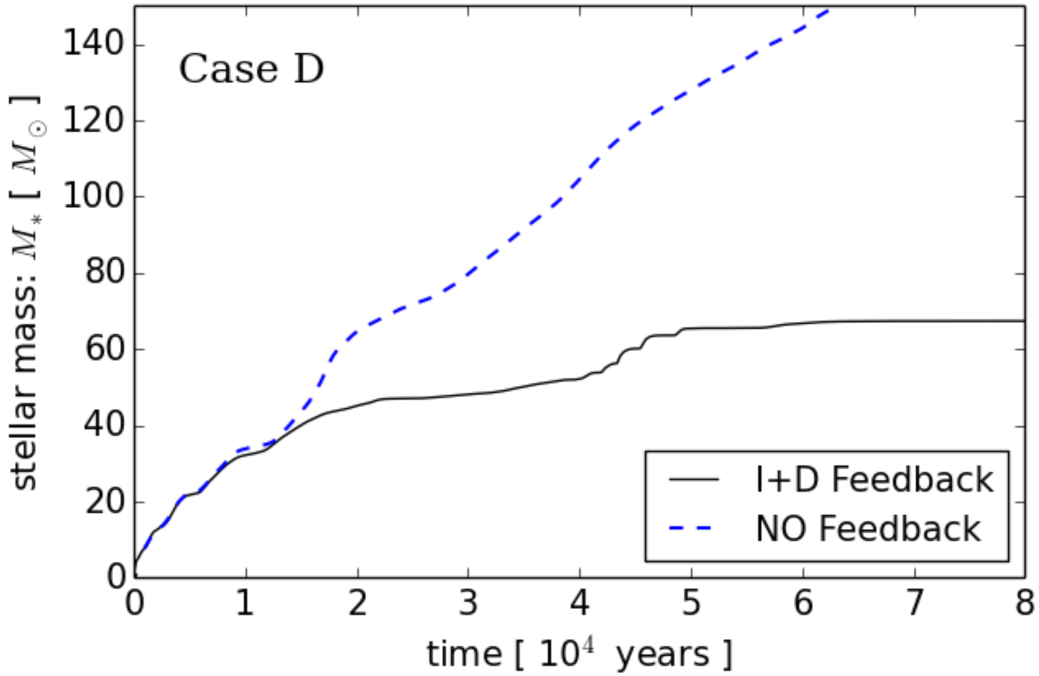


Pop III UV feedback

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

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





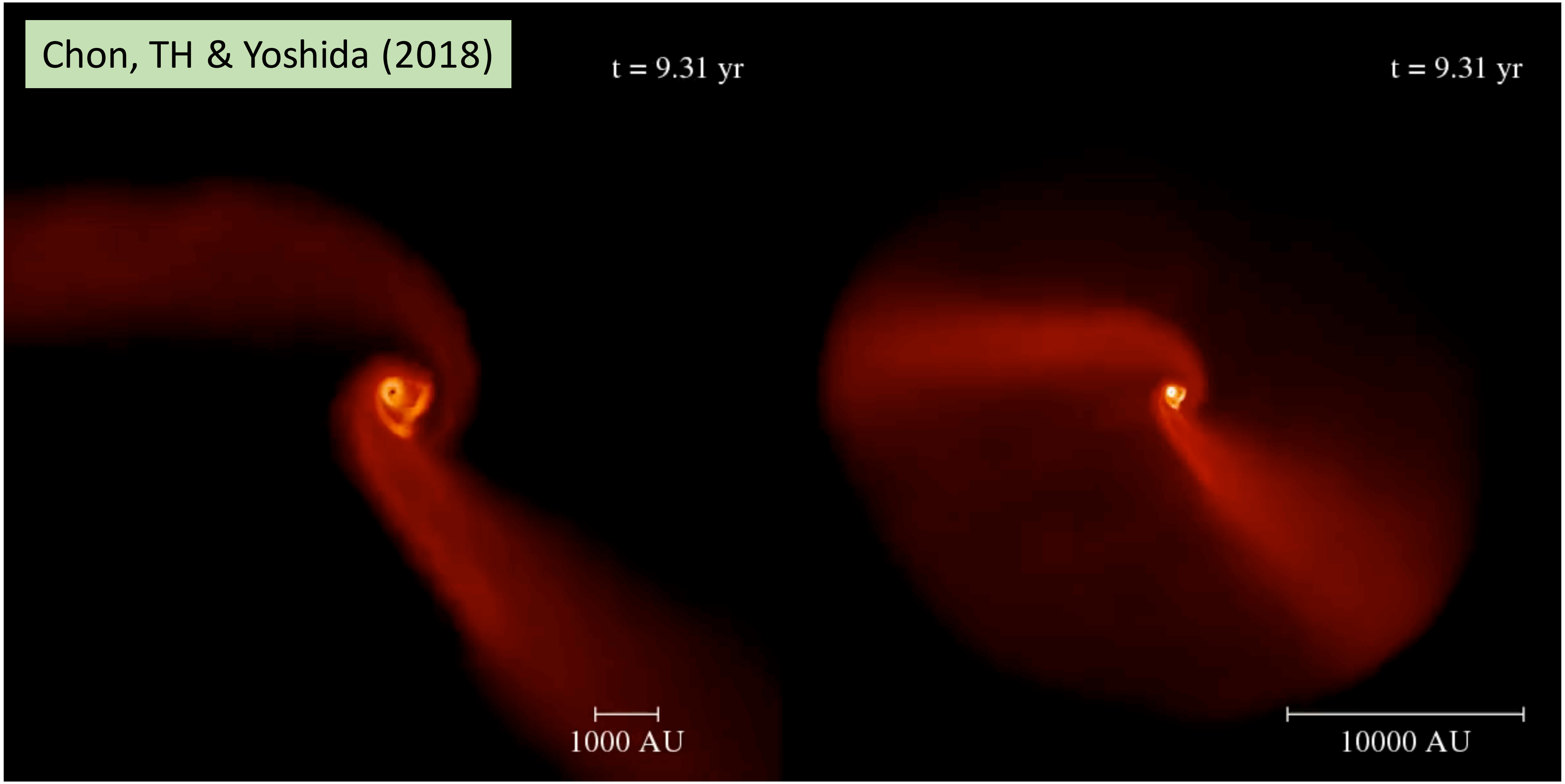
The mass accretion onto the star is shut off by the UV feedback

→ 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.

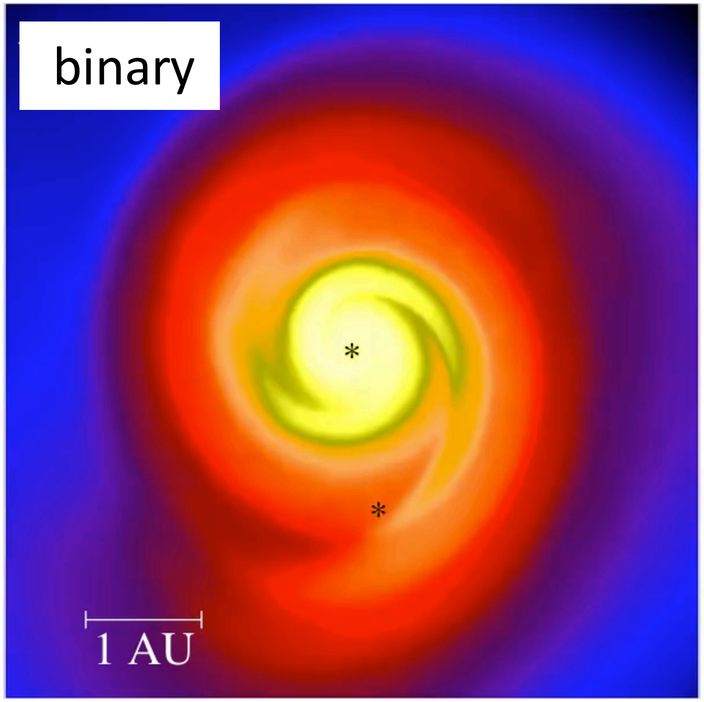
But not for all. Some fragments evolve into ***binary*** systems, and survive.

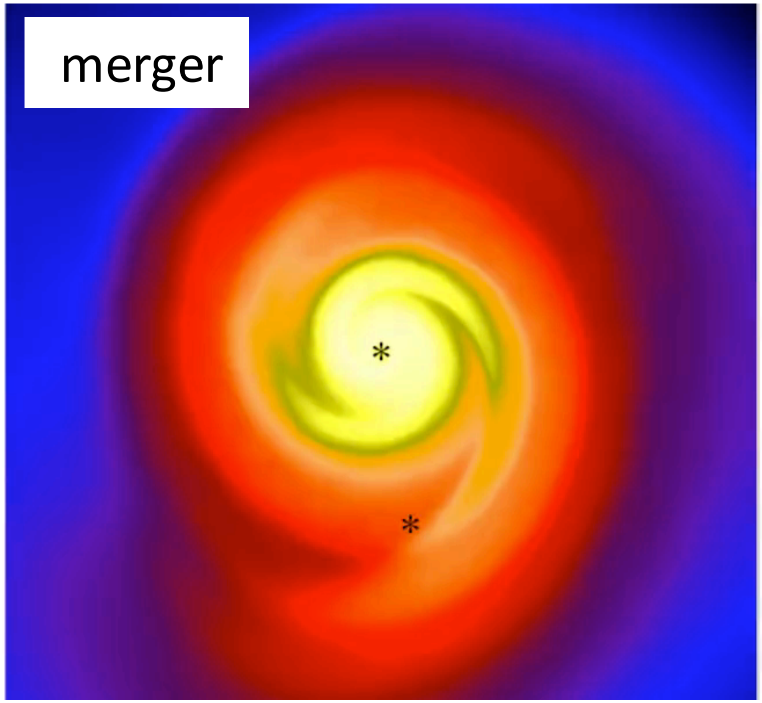
Binary *v.s.* Merger

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)





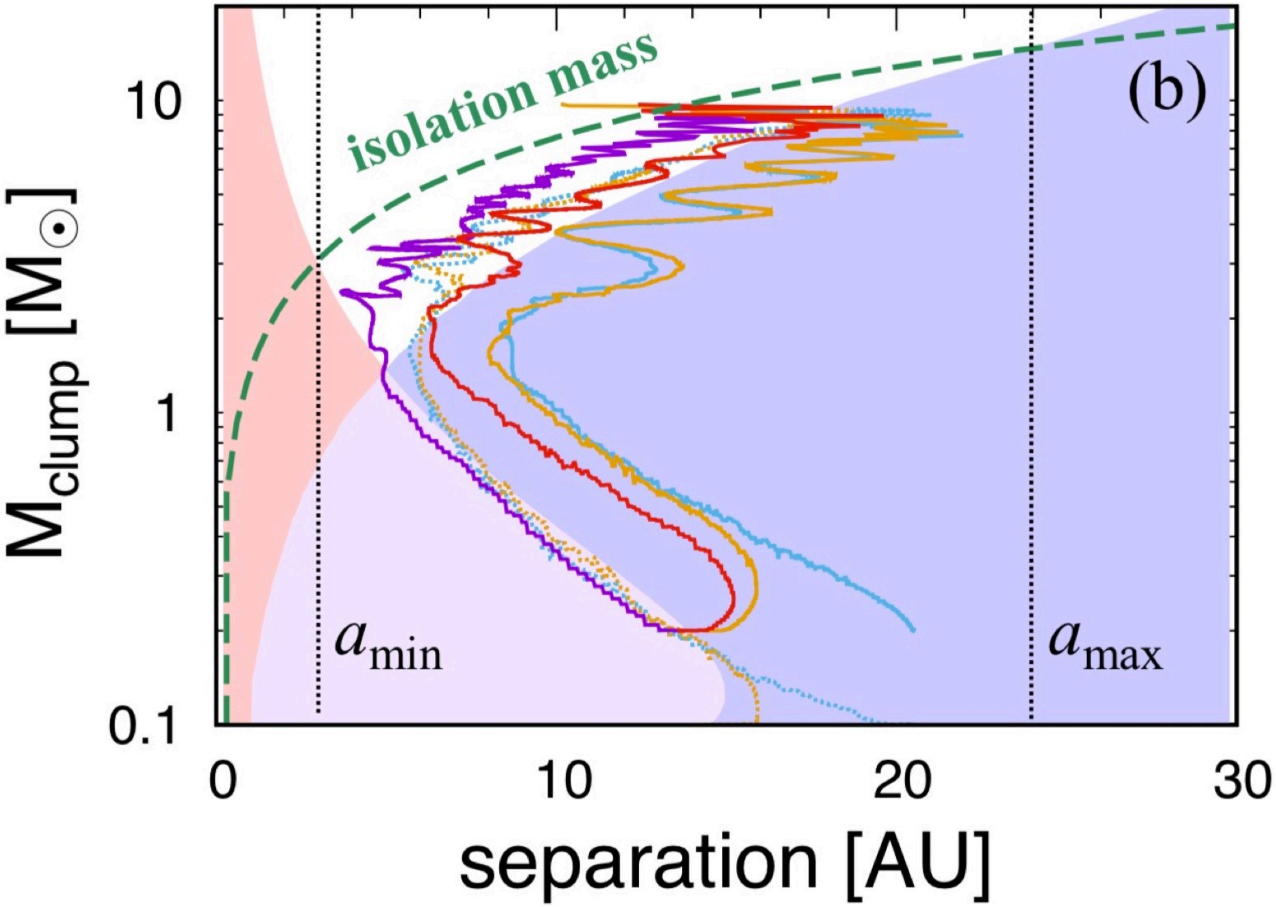
Evolution is diverse: it sensitively depends on the parameter choice

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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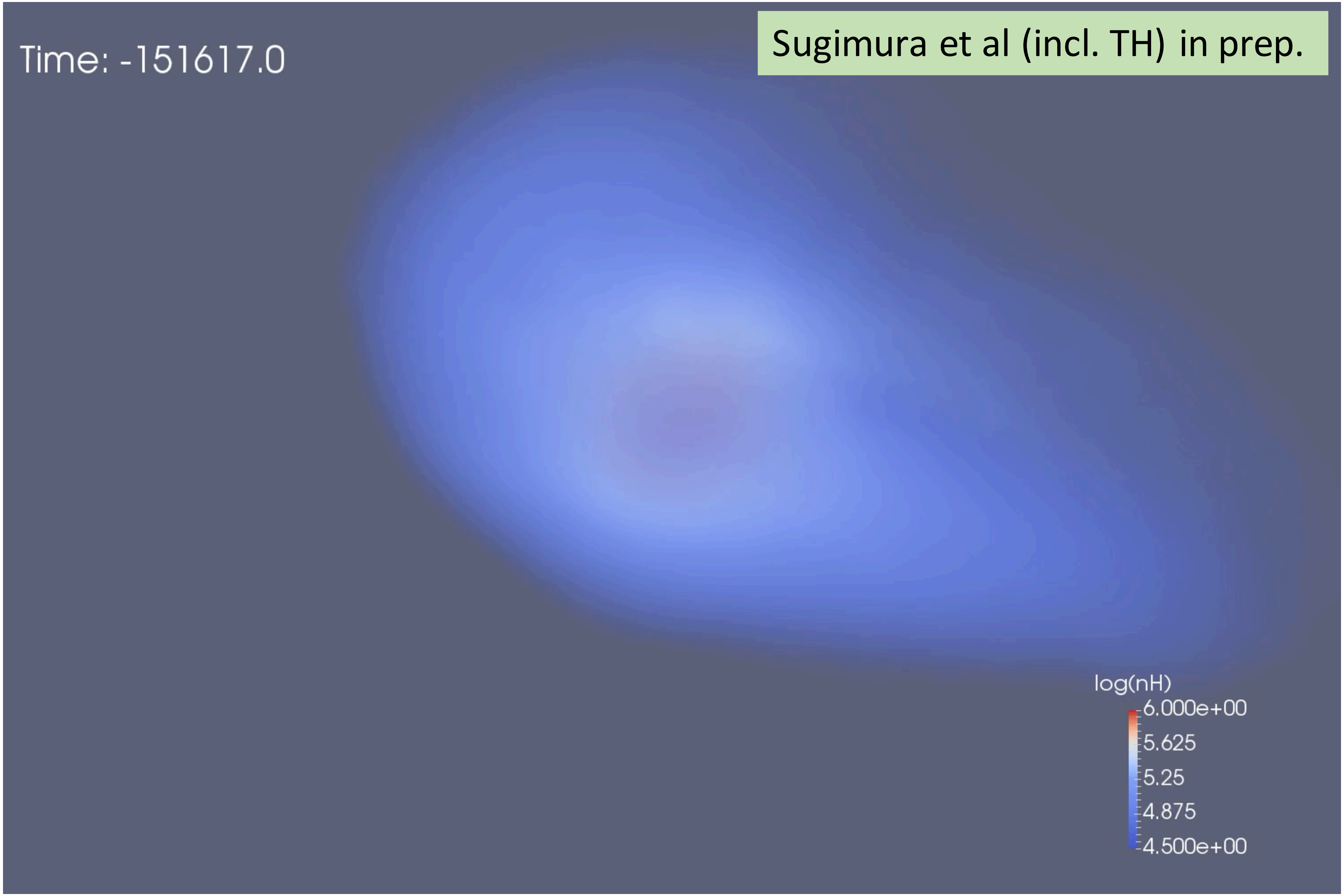
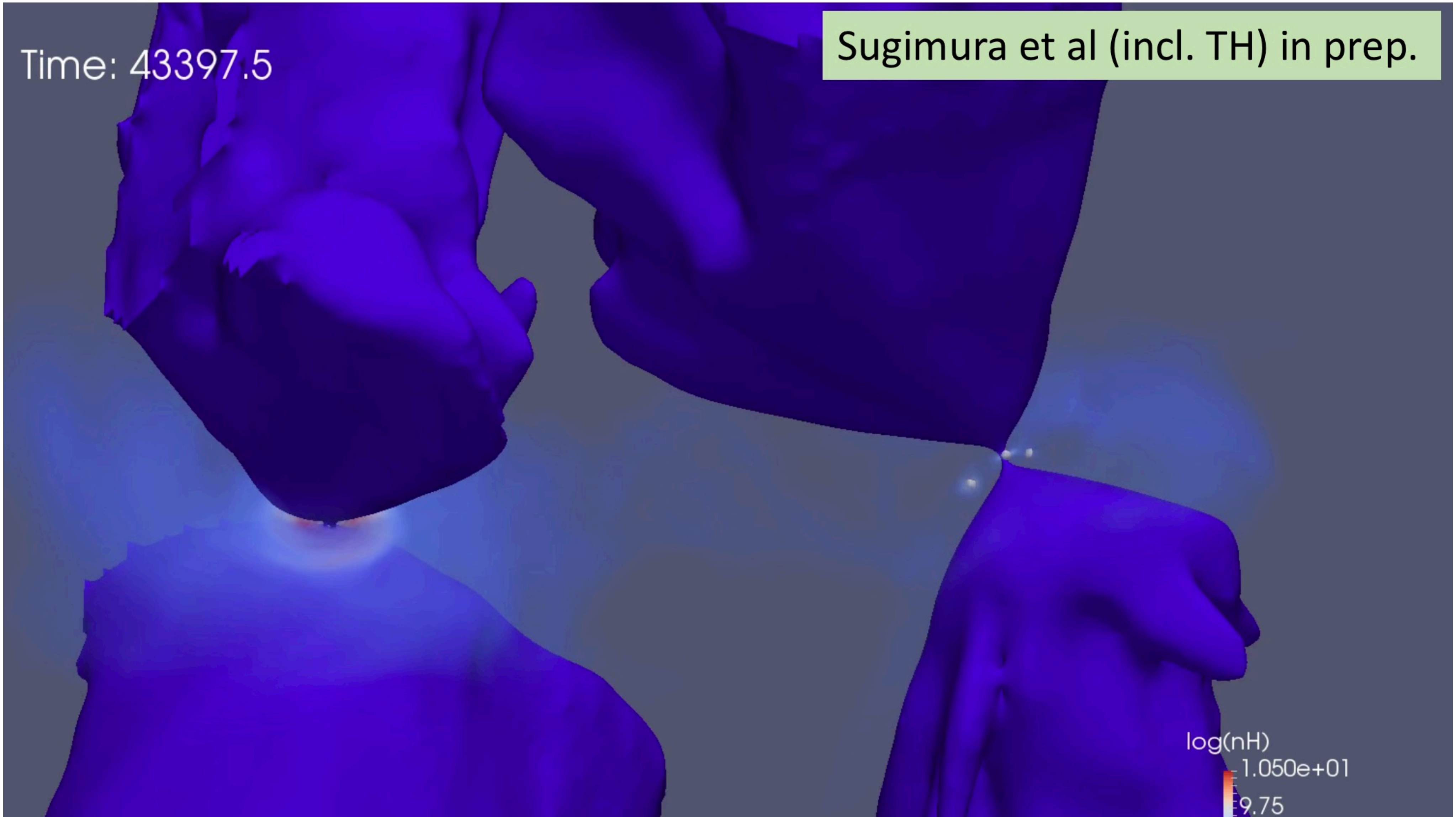
We can explain the divergent evolution with the above ansatz.

The binaries generally *expand* while accreting the gas.

UV feedback + Fragmentation

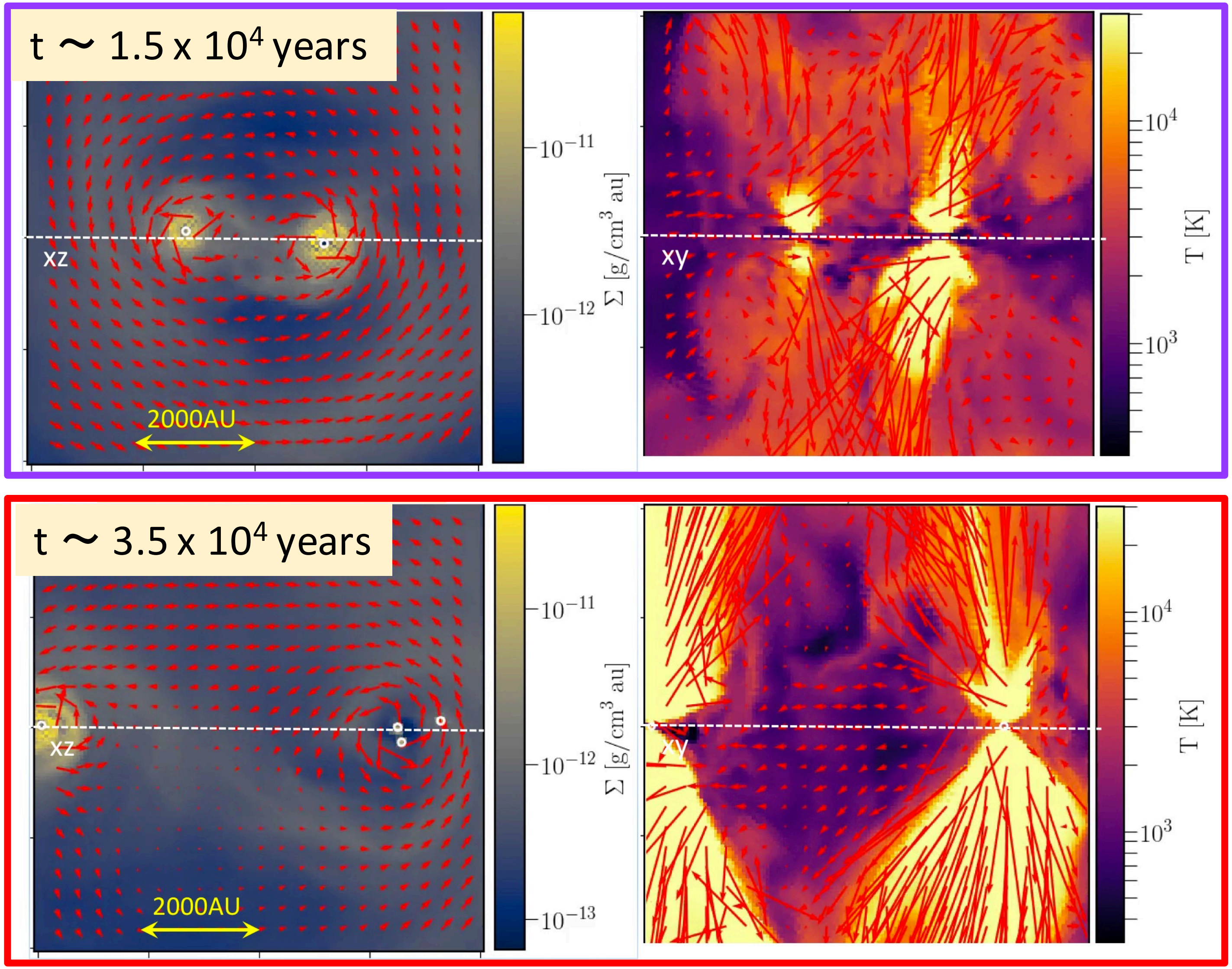


UV feedback + Fragmentation



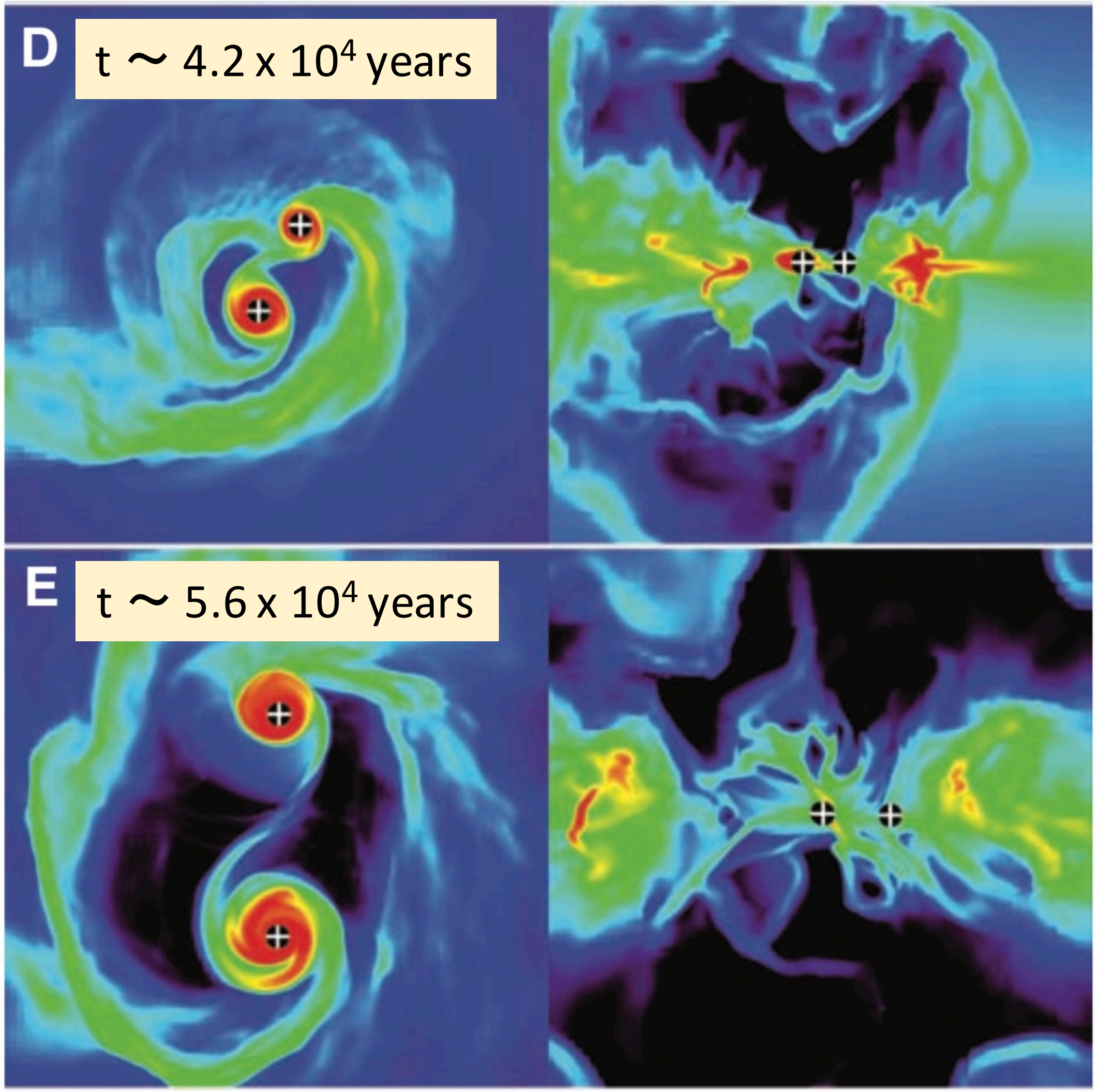
The disk fragmentation ⇒ binary w/ single star + triple system
⇒ stellar mass growth under the UV feedback w/ bipolar HII regions

Binary Separation



The massive binary expands while accreting the gas! (c.f. Chon & TH 19)

Pop I Massive Star Formation



Krumholz+09

The similar binary expansion has been also reported
in the context of the present-day high-mass star formation

Massive Binaries Expand?

※ 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

↓

As time goes by, the gas with the larger specific angular momentum starts to accrete

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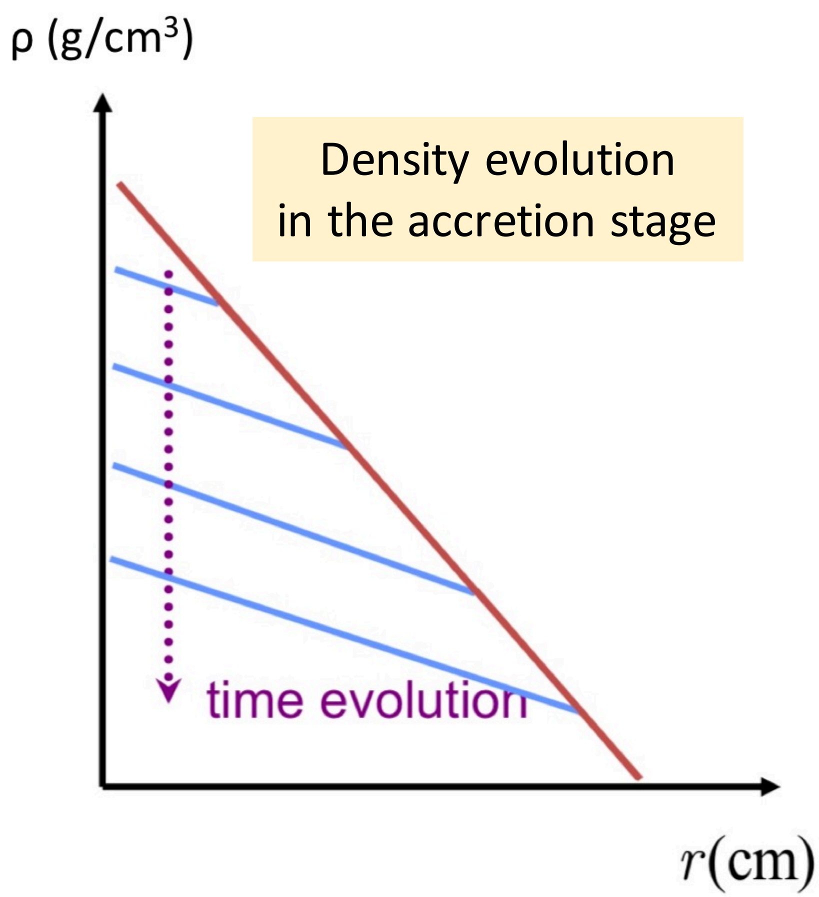
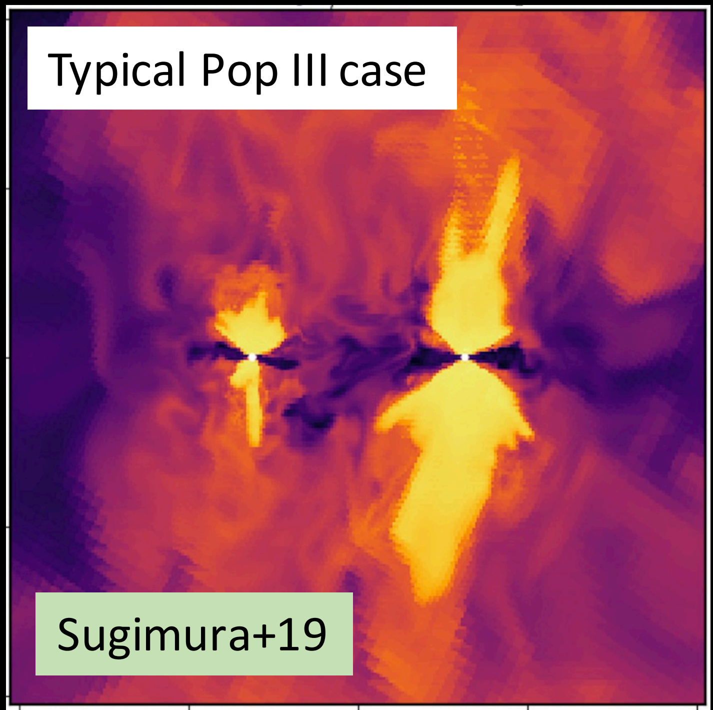
The binary mass increases, but the binary separation also increases

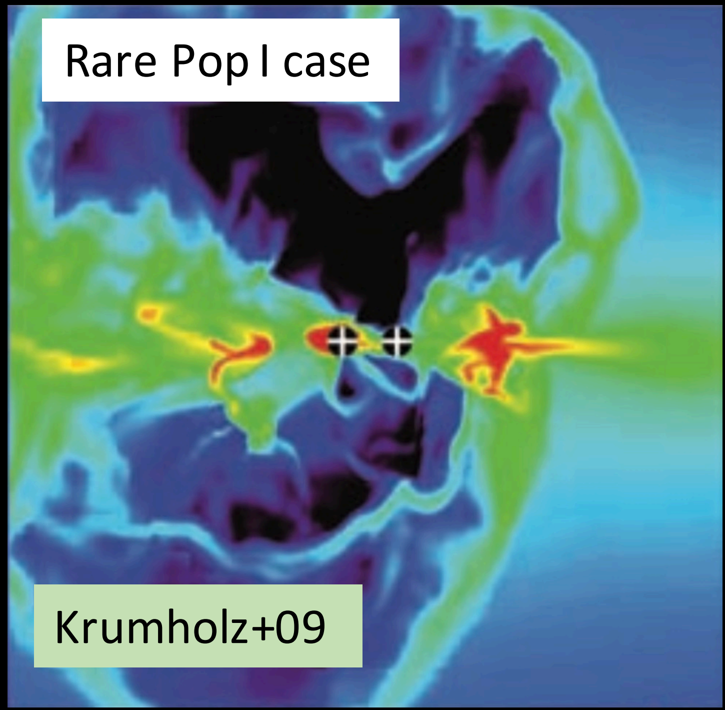
Magnetic fields may change the story…
⇒ see Eric-san + Harada-san's talks



Pop III v.s. Pop I
High-mass Star Formation

～100$M_\odot$ star formation is considered for the both cases…





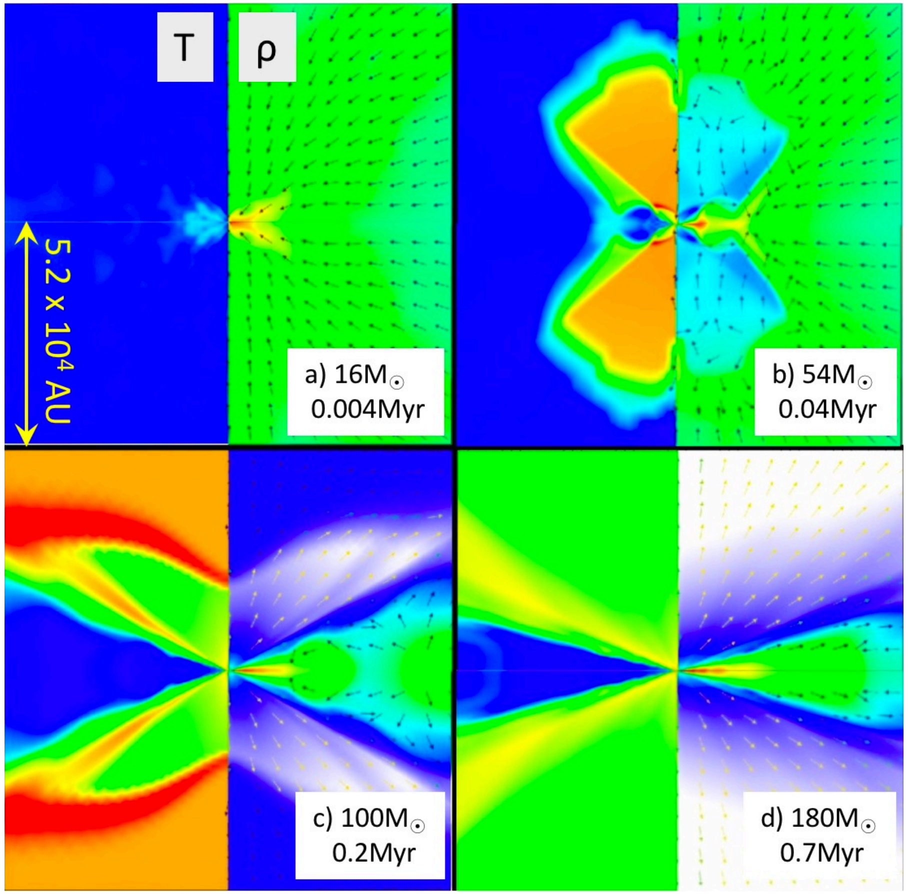
Photoionization feedback
(gas pressure effect)

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

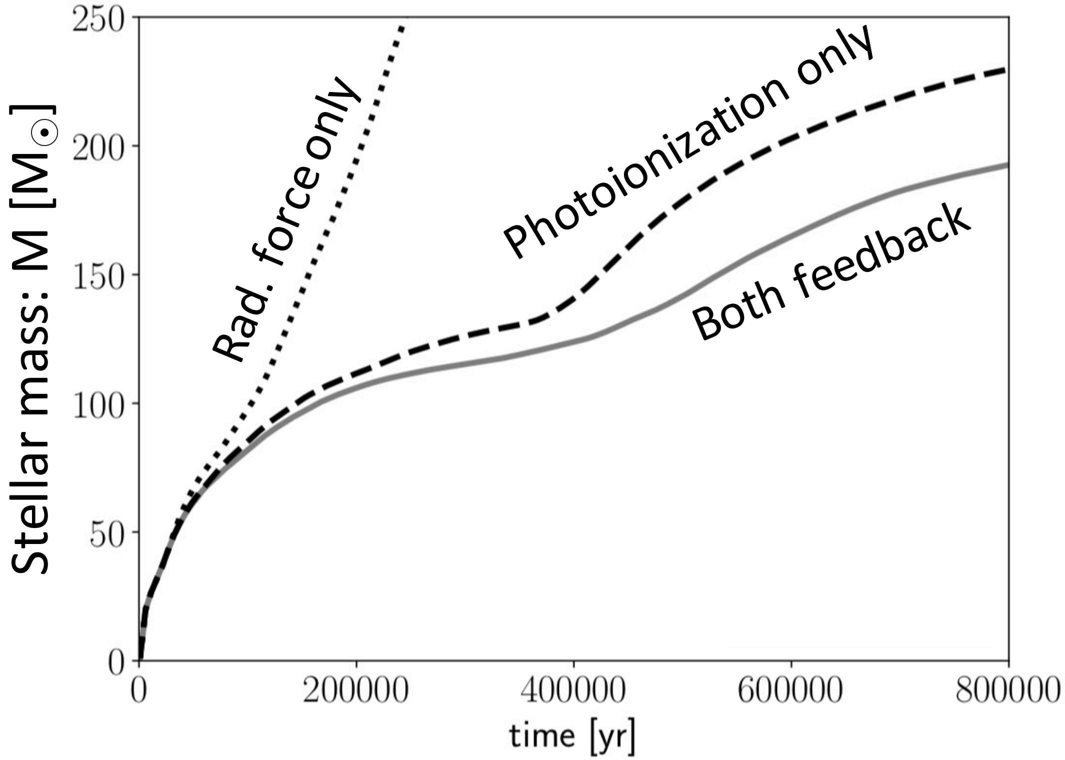
"Bridge the gap" btw Pop I and III high-mass star formation

$10^{-2}Z_\odot$ Massive Star Formation

Fukushima + TH+ in prep. 19

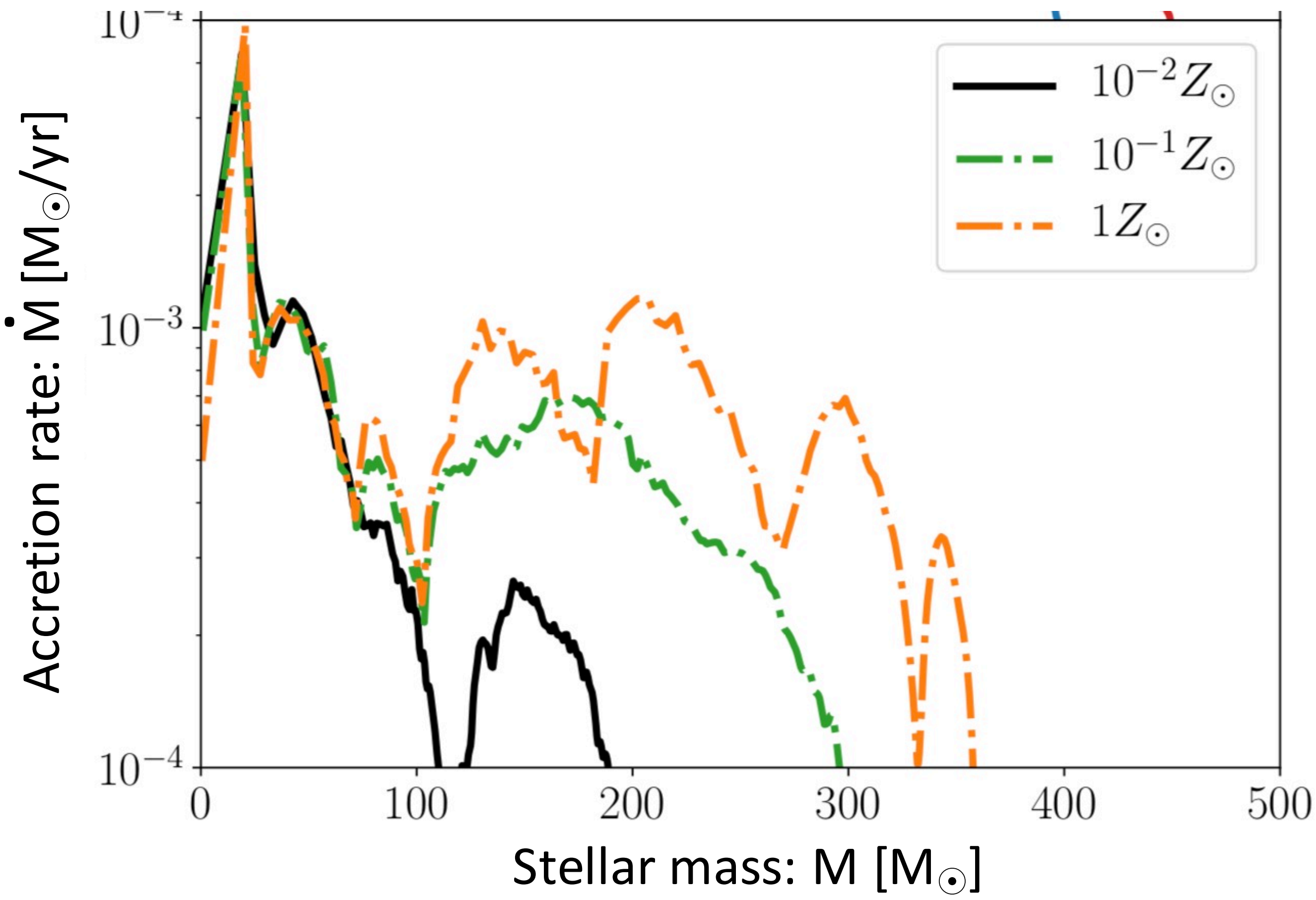


~Myr evolution of the protostellar acc., with a cosmological halo (H2) studied in Chiaki+



The net feedback is dominated by the photo-ionization, as in Pop III cases.

Feedback and Metallicity



In comparison to ~$1Z_\odot$ case, the net feedback is actually *stronger*

Weaker Rad.-force feedback ⇔ *Stronger* Photoionization feedback

The latter effect dominates the metallicity-dependence.

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