

# 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

O2 catalog 2018:

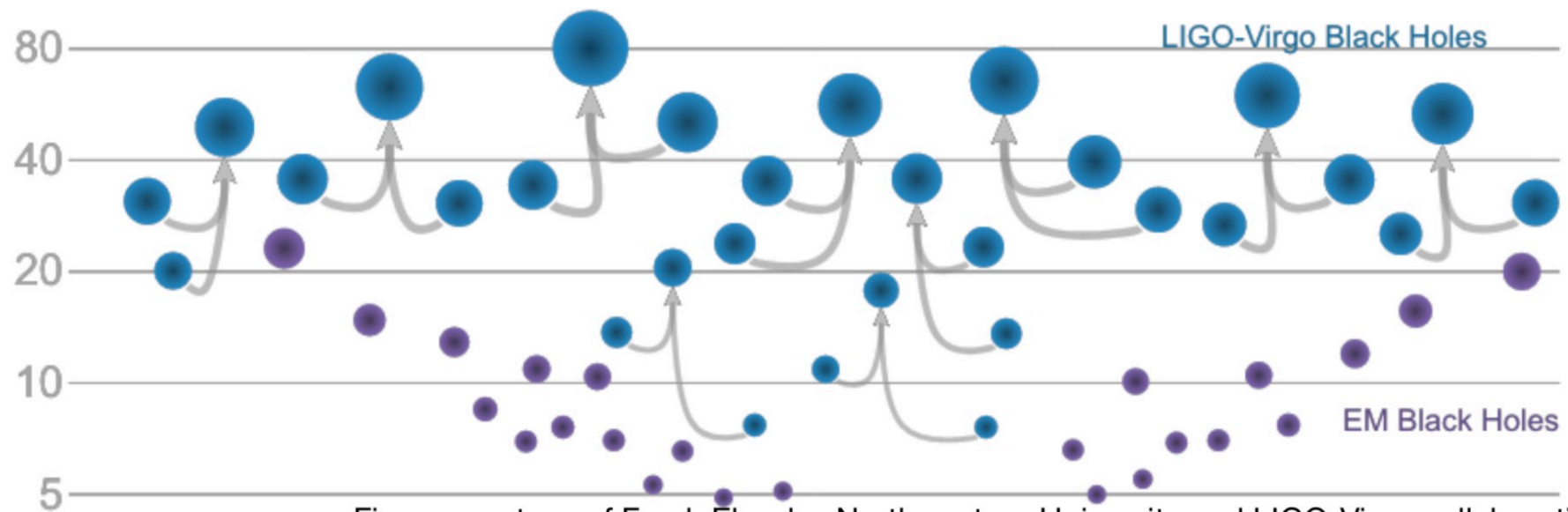


Figure courtesy of Frank Elavsky, Northwestern University and LIGO-Virgo collaborations

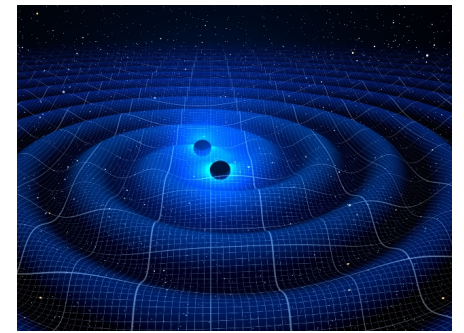
What are the origins of such massive BH-BH binaries?

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

Consider the first stage of the formation of massive stellar binaries

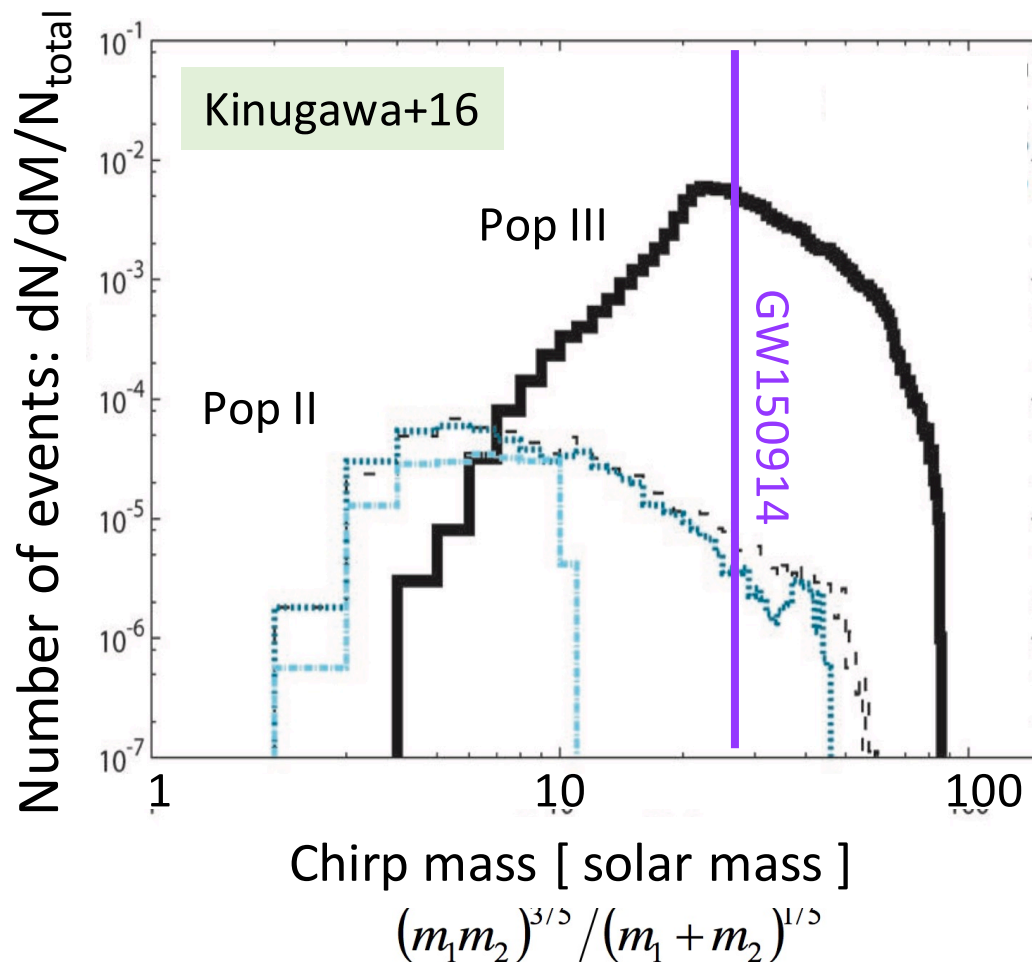
# Pop III Origin?

(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

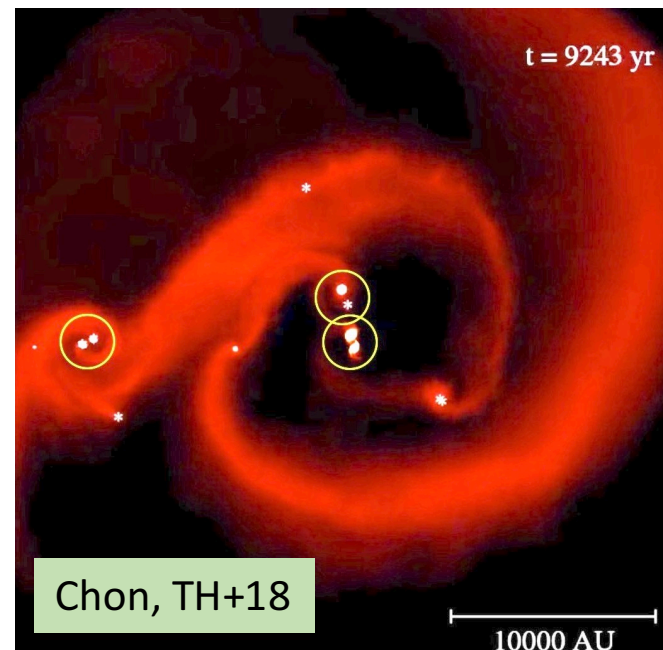
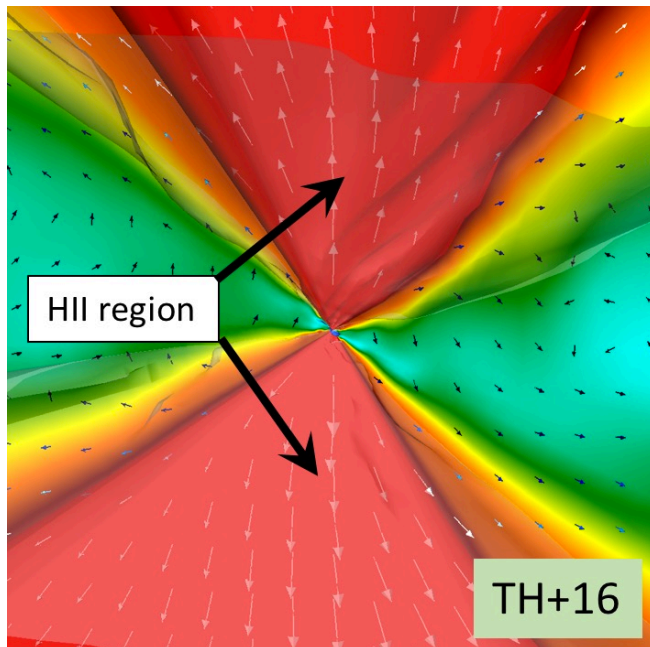
It was predicted in 2014,  
*before* the GW detection

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?**

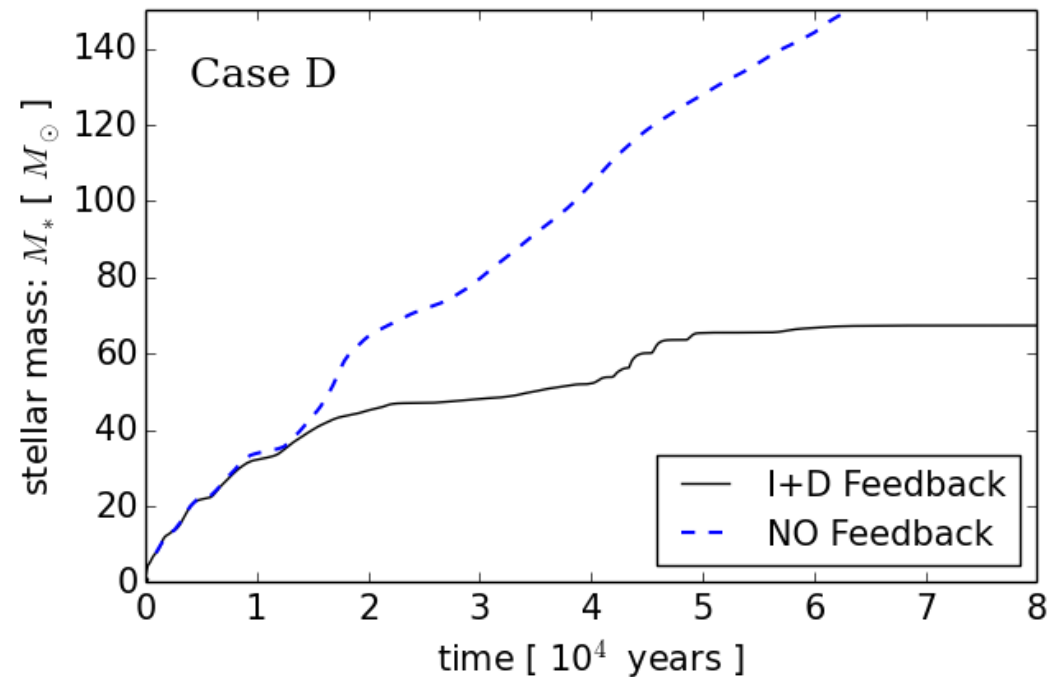
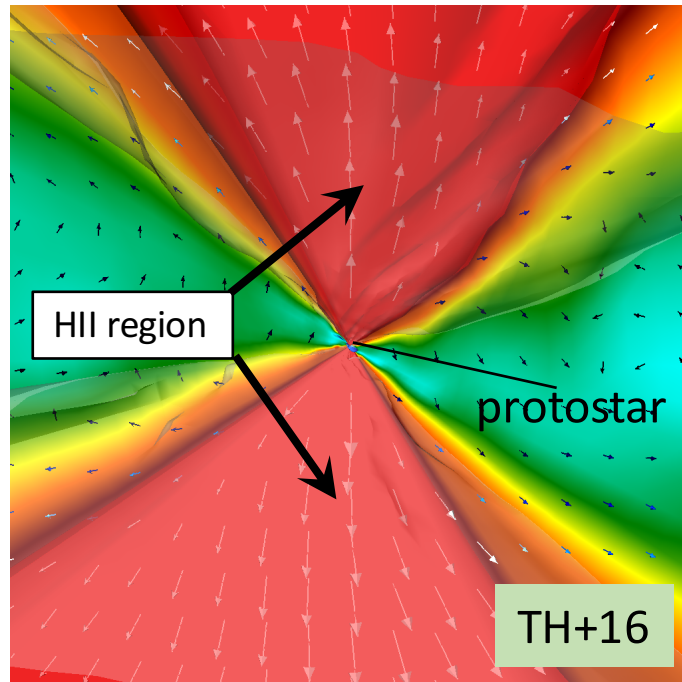
To answer these, we understand the key processes:  
(I) stellar radiative feedback + (II) fragmentation



# 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



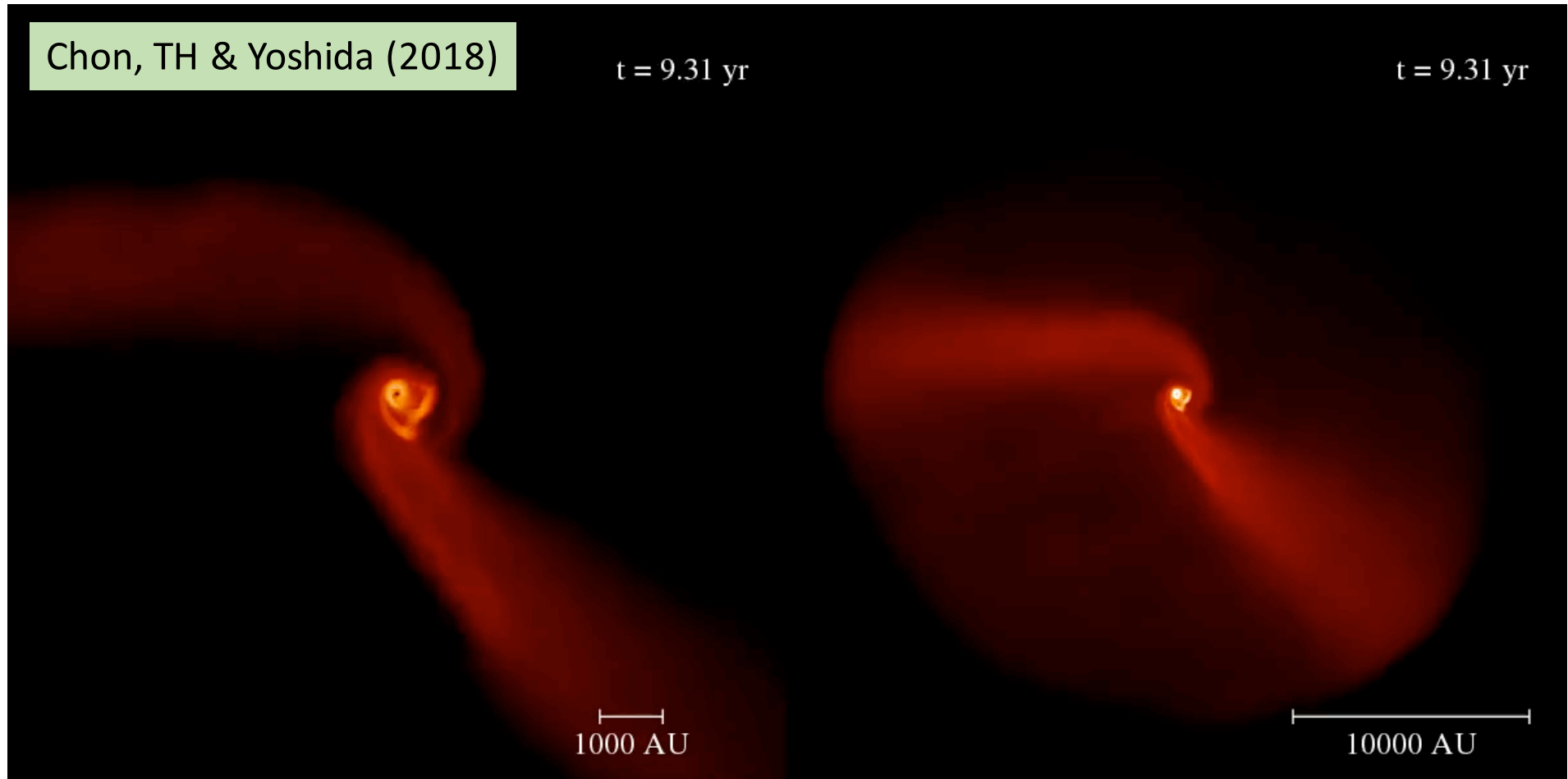
The mass accretion onto the star is shut off by the UV feedback

→ 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  $\Rightarrow$  binary formation?



## Desperately complex evolution?

The fragmentation is often followed by *merger* events.

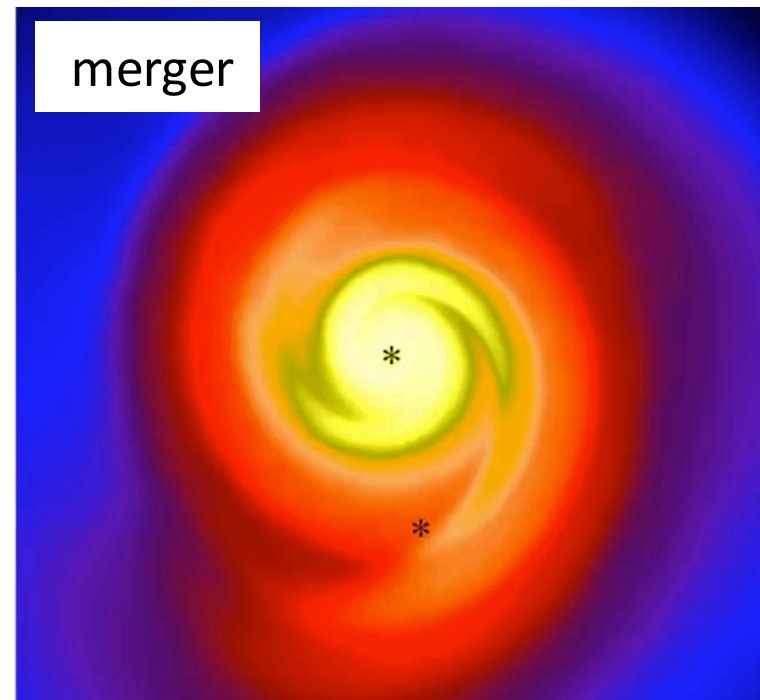
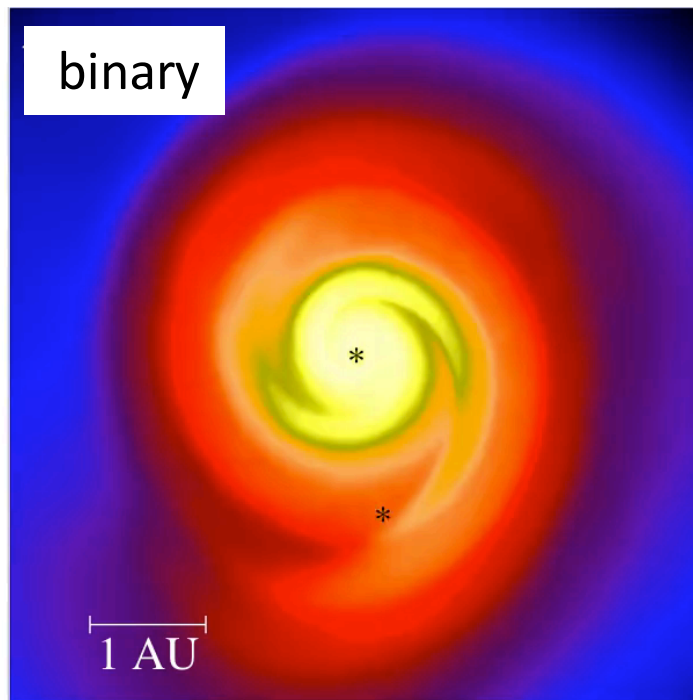
**But not for all.** Some fragments evolve into *binary* systems, and survive.

# 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

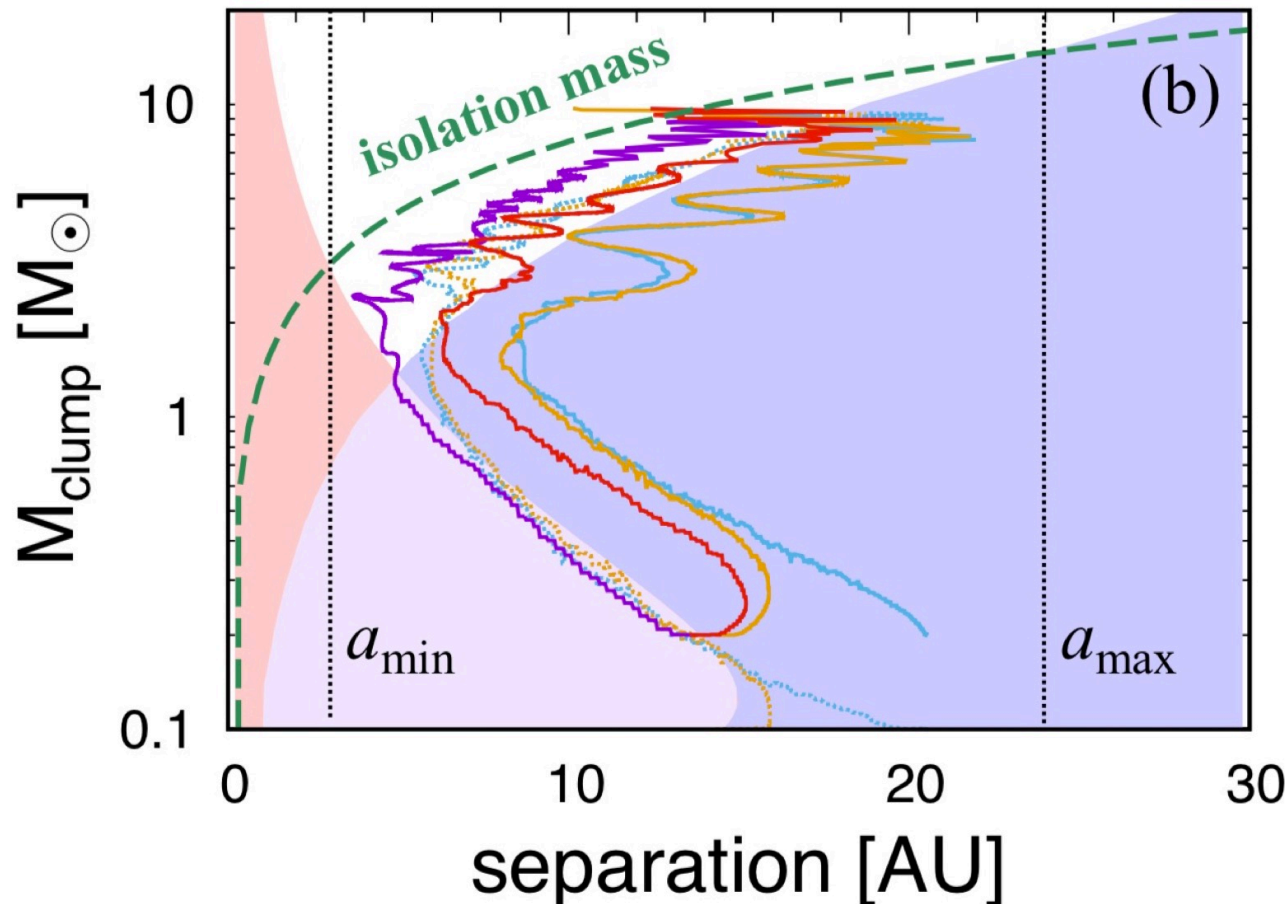


# Extract Key Physics

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



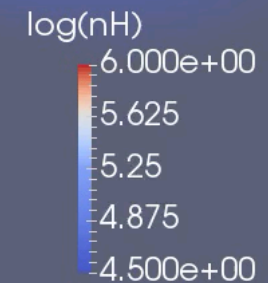
We can explain the divergent evolution with the above ansatz.

The binaries generally *expand* while accreting the gas.

# UV feedback + Fragmentation

Time: -151617.0

Sugimura et al (incl. TH) in prep.



# UV feedback + Fragmentation

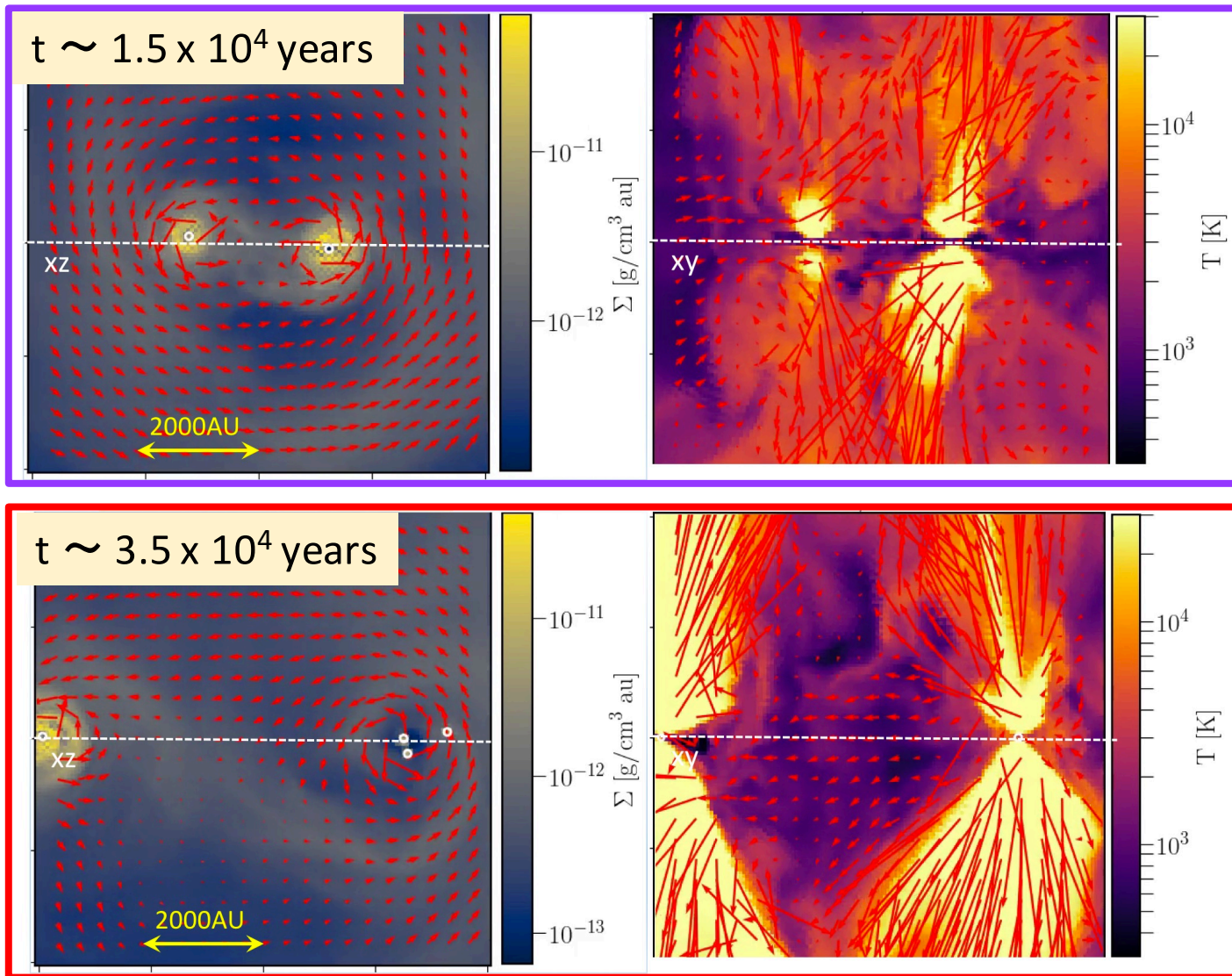
Time: 43397.5

Sugimura et al (incl. TH) in prep.

log(nH)  
1.050e+01  
9.75

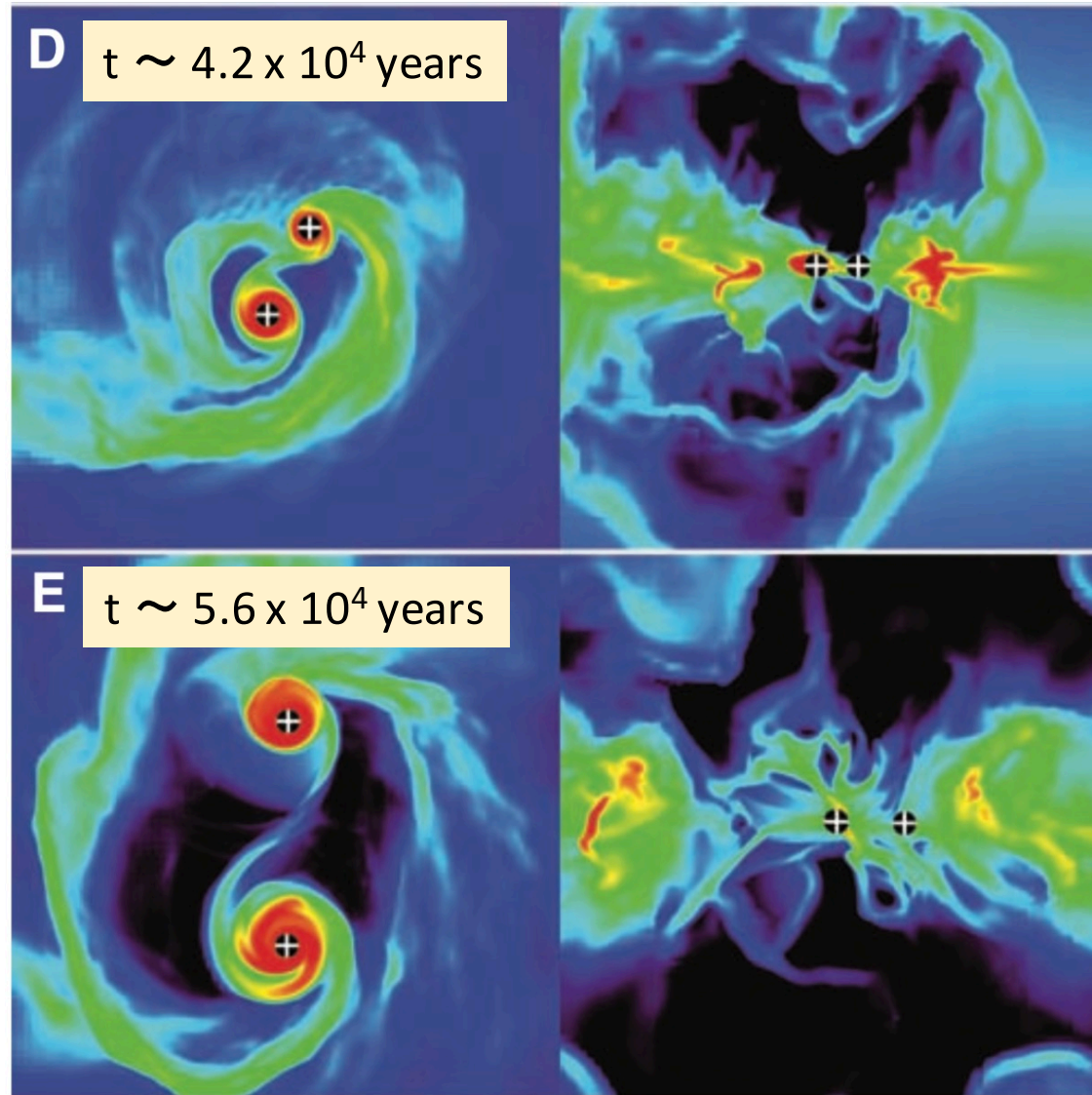
The disk fragmentation  $\Rightarrow$  binary w/ single star + triple system  
 $\Rightarrow$  stellar mass growth under the UV feedback w/ bipolar HII regions

# 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  $< \sim 0.1\text{AU}$   
for the merger to occur within the Hubble time

Why?

“Inside-Out Accretion” onto stars

The gas near the star accretes first

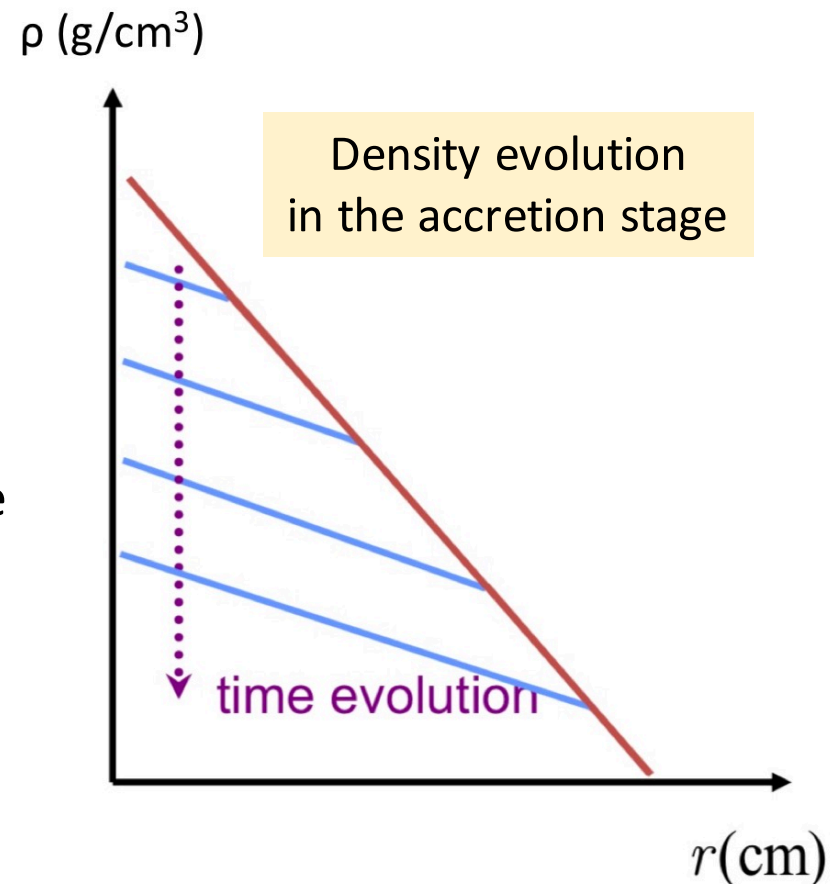


As time goes by, the gas with the larger  
specific angular momentum starts to accrete



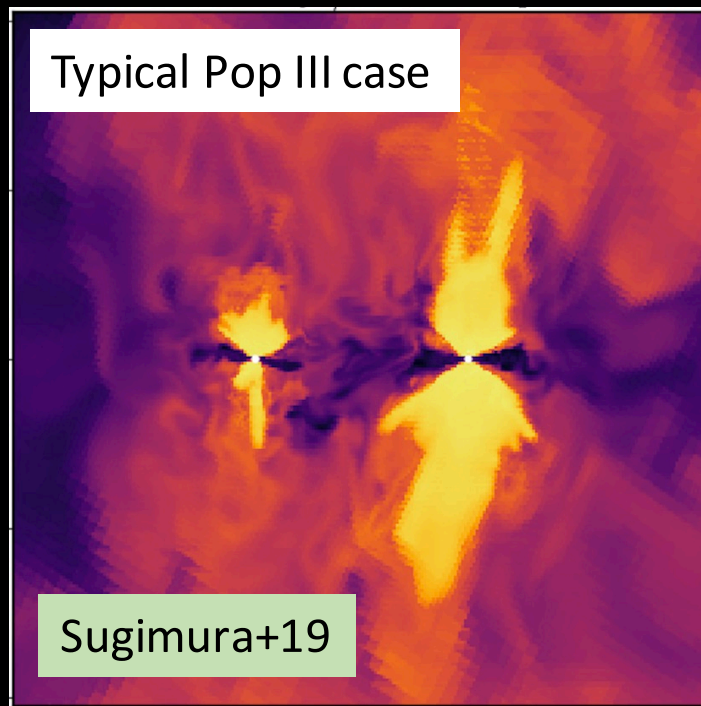
The binary mass increases, but  
the binary separation also increases

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

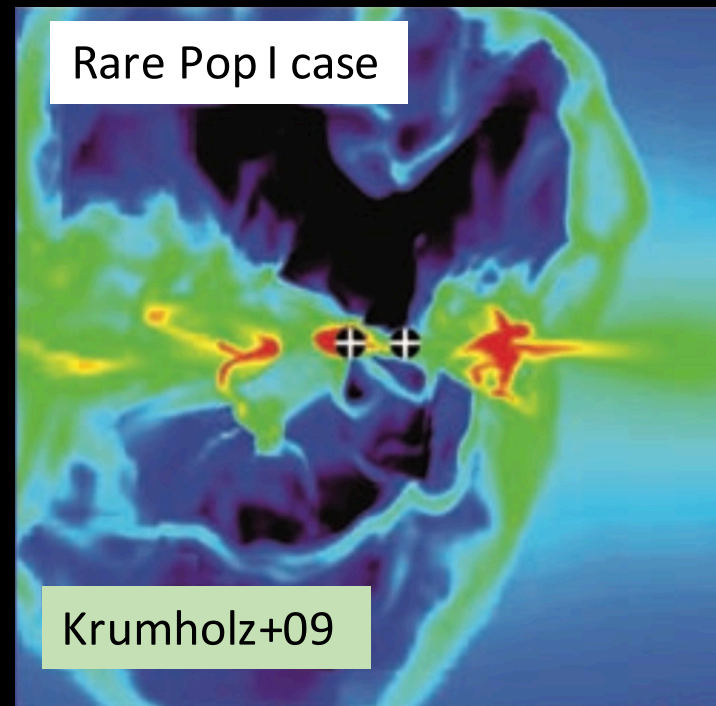


# Pop III v.s. Pop I High-mass Star Formation

~100M<sub>☉</sub> star formation is considered for the both cases...



Photoionization feedback  
(gas pressure effect)

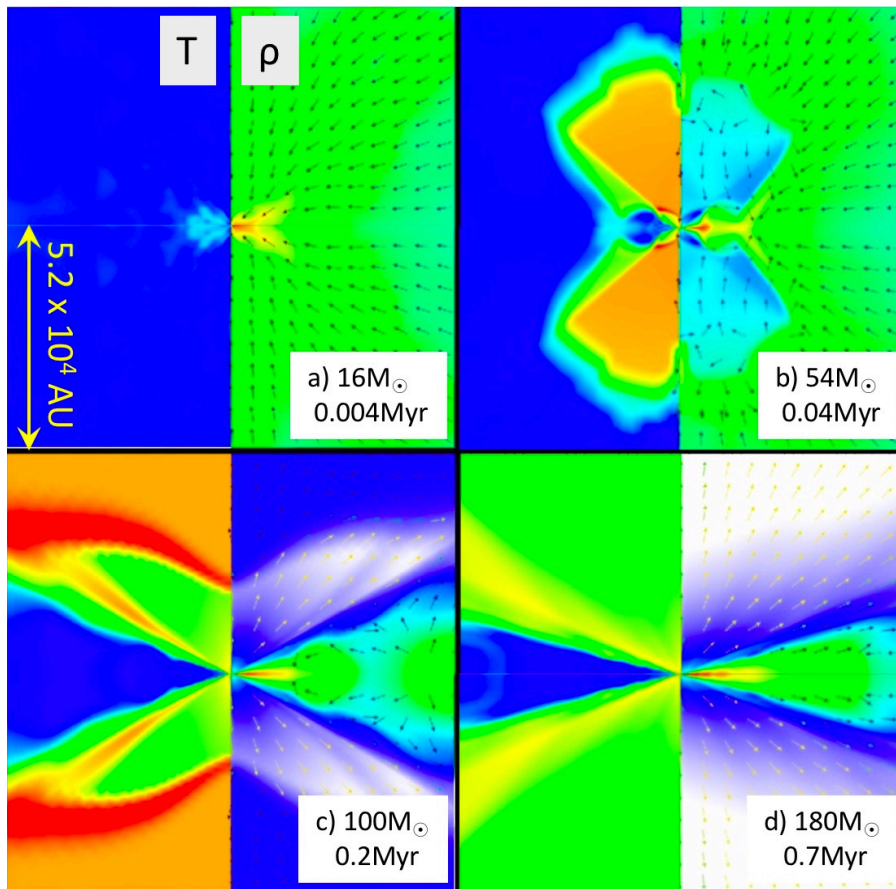


Radiation force feedback  
(rad. pressure effect w/ dust)

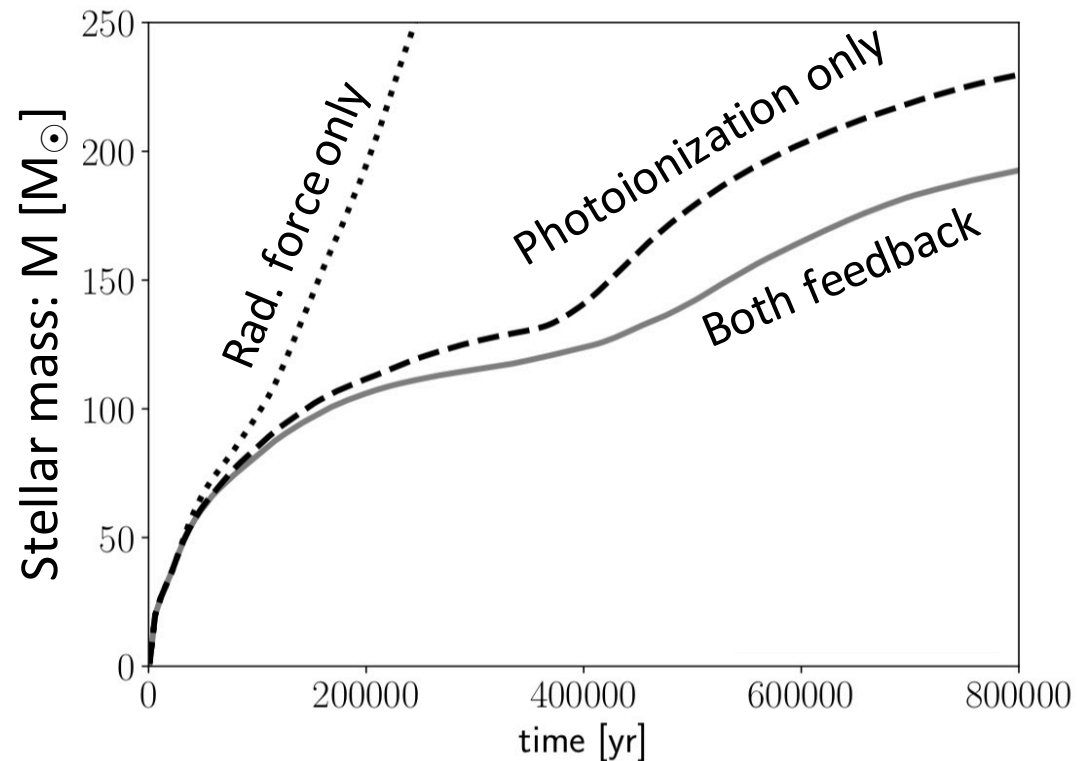
“Bridge the gap” btw Pop I and III high-mass star formation

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

Fukushima + TH in prep. 19



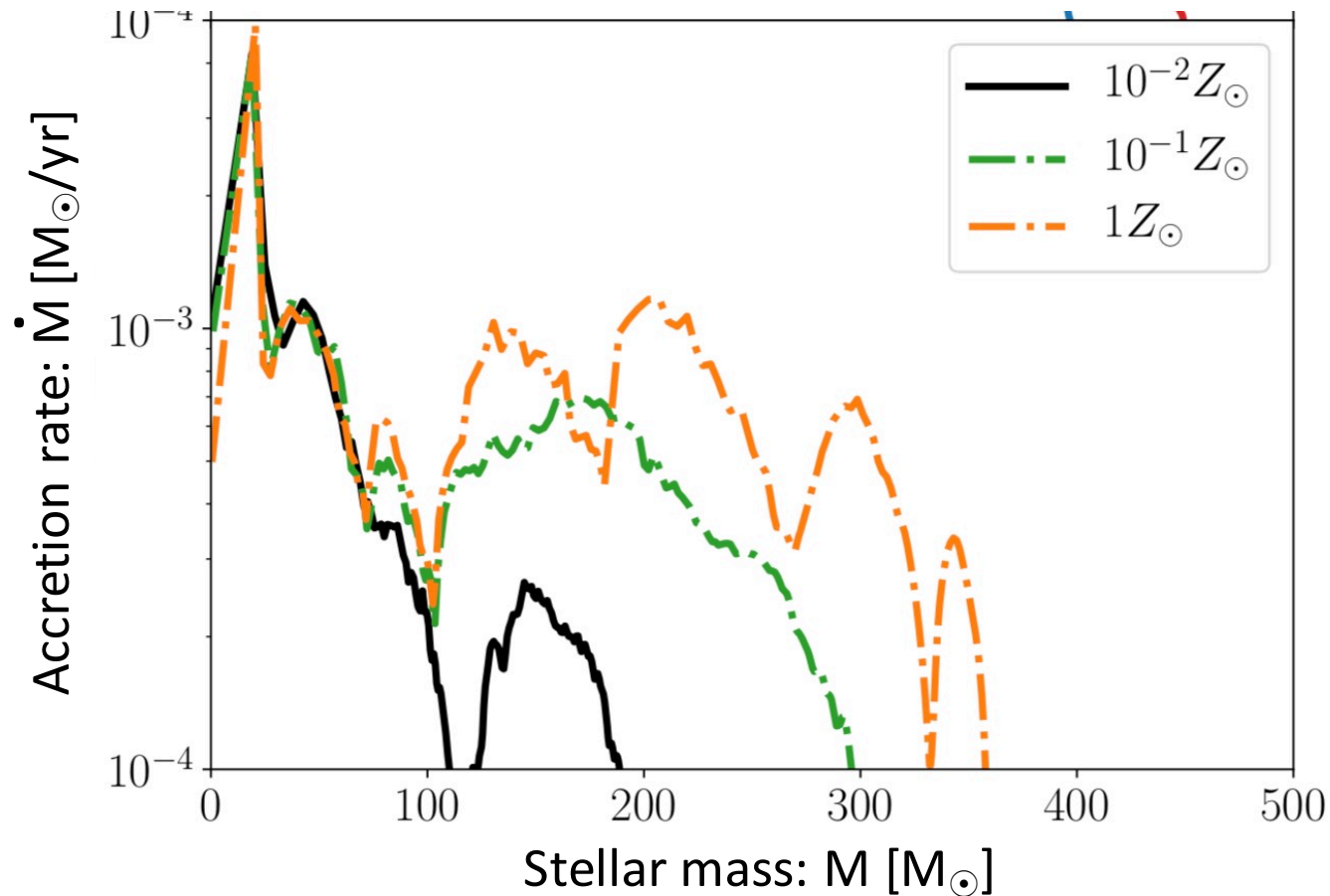
$\sim$  Myr evolution of the protostellar acc.,  
with a cosmological halo ( $H_2$ )  
studied in Chiaki+



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



# Feedback and Metallicity



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

*Weaker* Rad.-force feedback  $\Leftrightarrow$  *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