High-mass Star Formation across the Universe

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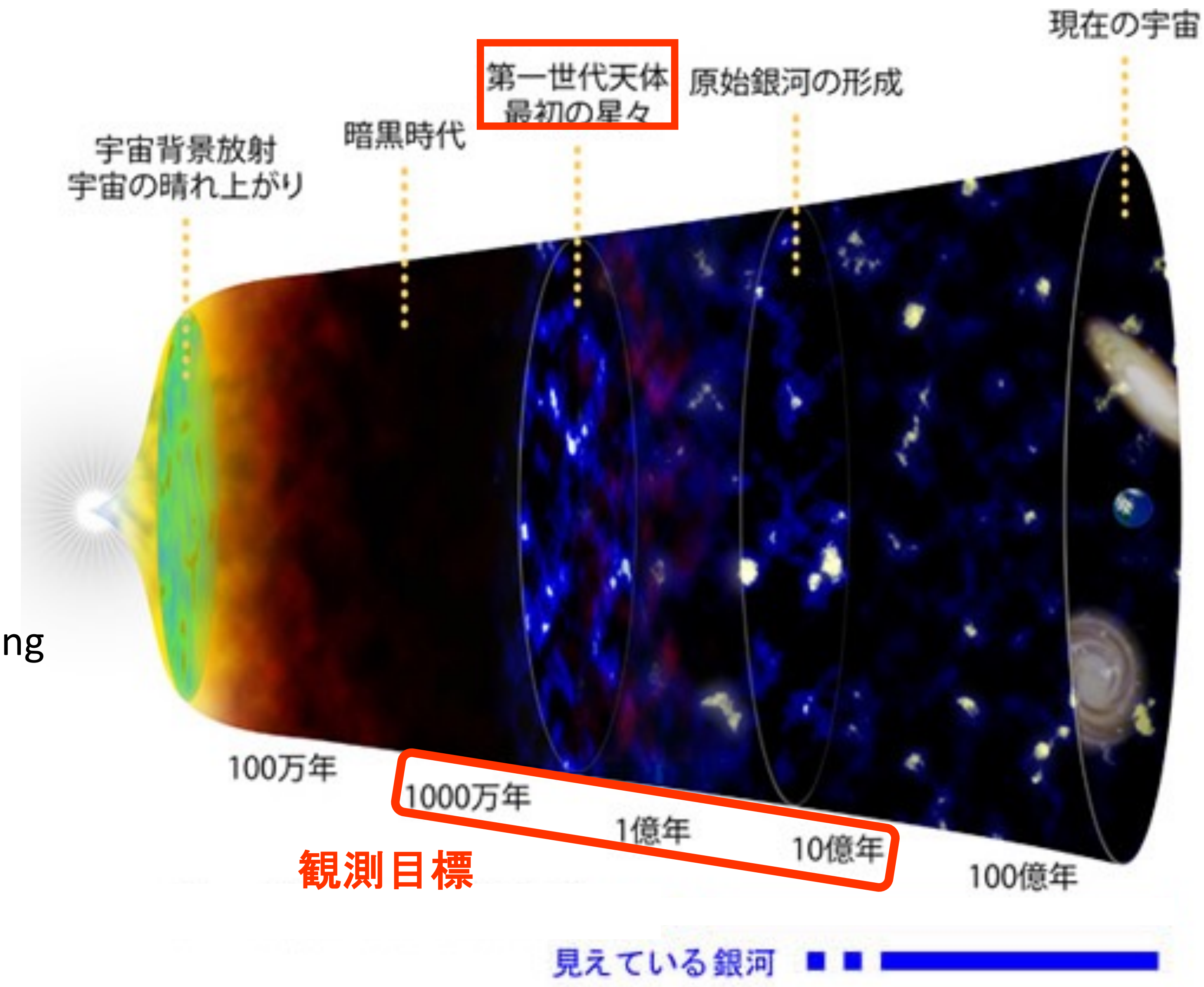
High-mass stars@present-day

The First (Pop III) Stars



They should have formed at some point… How did they form?

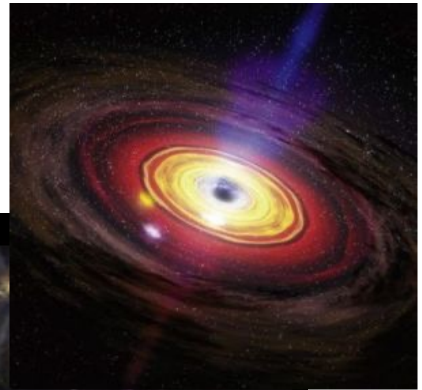
High-mass Stars @ early universe

- more popular than the present-day (suggested by theorists…)
- heavy-elements factory, cosmic reionization, SMBH seeds
- High-z observations see their emission

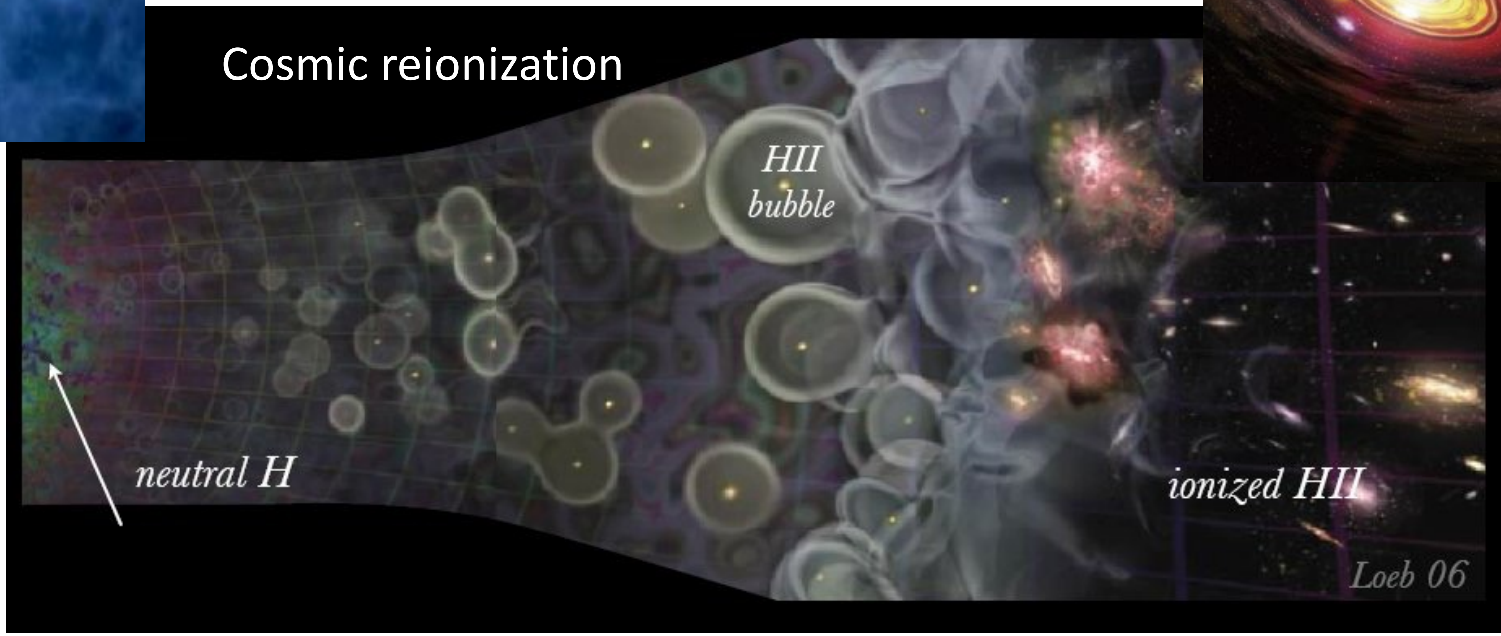
… How did they form?

First Stars (PopIII)

Seed BHs for SMBHs



Cosmic reionization



High-mass Star Formation across the Universe

Many generations of high-mass (>10$M_\odot$) stars have formed across cosmic history, including the present-day and early universe.

How do they form in different epochs of the cosmic history?

なぜこれを知りたいのか? 何が面白いのか?

+ feedback, big influences on the surrounding environments
+ factories of heavy elements (our origin)
+ origins of SMBHs
+ High-z observations see their emission

+ First (Pop III) stars … why not?

A Big Picture

Typical case | Rare case

$Z = Z_\odot$ (Pop I)

low-mass SF
$\sim 1 M_\odot$

high-mas SF
Up to $\sim 100\ M_\odot$

$Z = 0$ (Pop III)

The First Stars
$\sim 10 - 100\ M_\odot$
(?)

Supermassive Stars
Up to $\sim 10^5\ M_\odot$
(?)
"Direct Collapse"

A Big Picture

Typical case | Rare case

Z = $Z_\odot$
(Pop I)

low-mass SF
$\sim 1 M_\odot$

high-mas SF
Up to $\sim 100\ M_\odot$

same mass range

Z = 0
(Pop III)

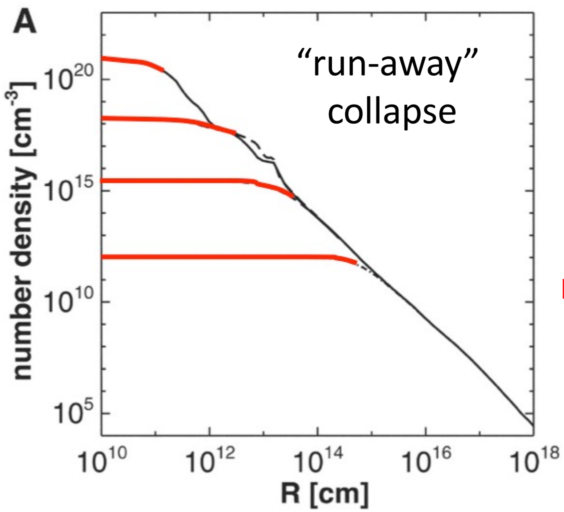
The First Stars
$\sim 10 - 100\ M_\odot$
(?)

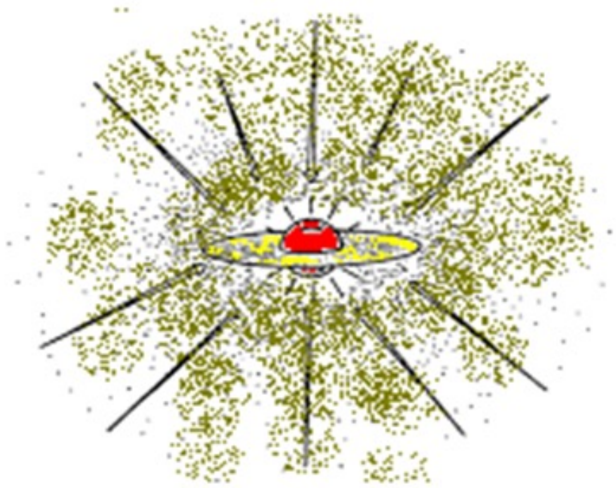
Supermassive Stars
Up to $\sim 10^5\ M_\odot$
(?)
"Direct Collapse"

星形成の基本シナリオ

前期段階
ガス雲の重力崩壊

後期段階
原始星へのガス降着



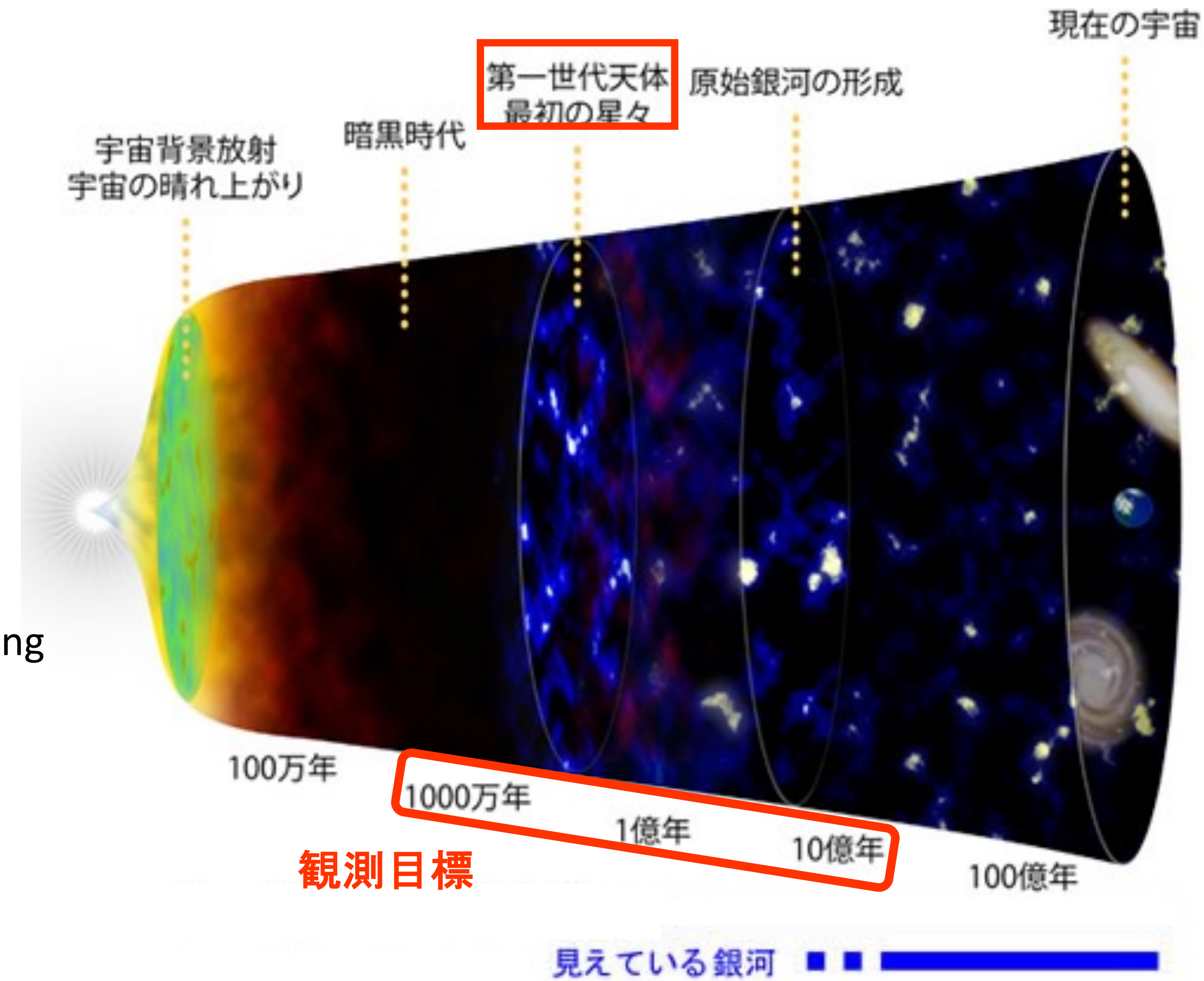


何らかの冷却過程で
$\gamma\_{eff} < 4/3$ である限り続く

$\gamma\_{eff} > 4/3$ になったら原始星誕生
(原始星質量) << (ガス雲質量)
↓
ガス降着で原始星質量増

初期宇宙/現在の宇宙の星形成、ともに共通の基本描像
大質量星形成の研究 ＝ 後期段階の研究

The First (Pop III) Stars

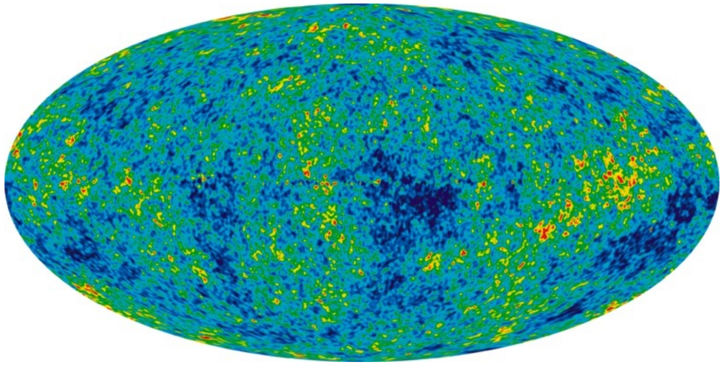


Our Galaxy

BigBang

How, When, and Where did they form?
What kind of stars were they? Can we observe them?

コンピューターで
宇宙最初の星を作ろう



Matter distribution just after the Big Bang

＋

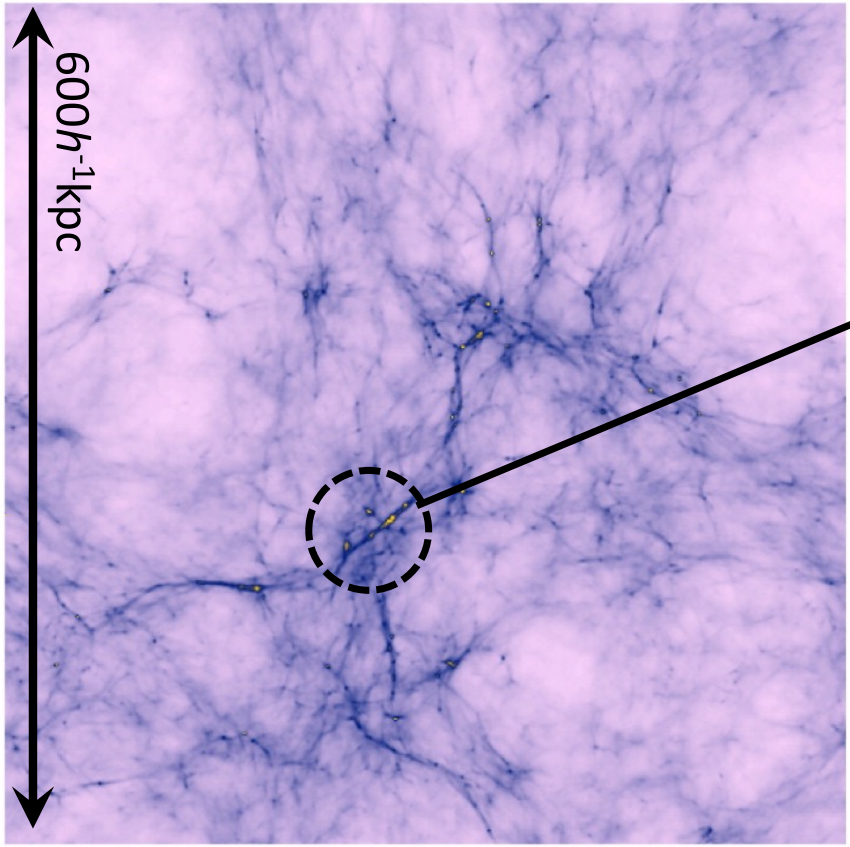
Basic physical laws
(gravity, gas dynamics, radiation)

NAOJ super-computer: ATERUI

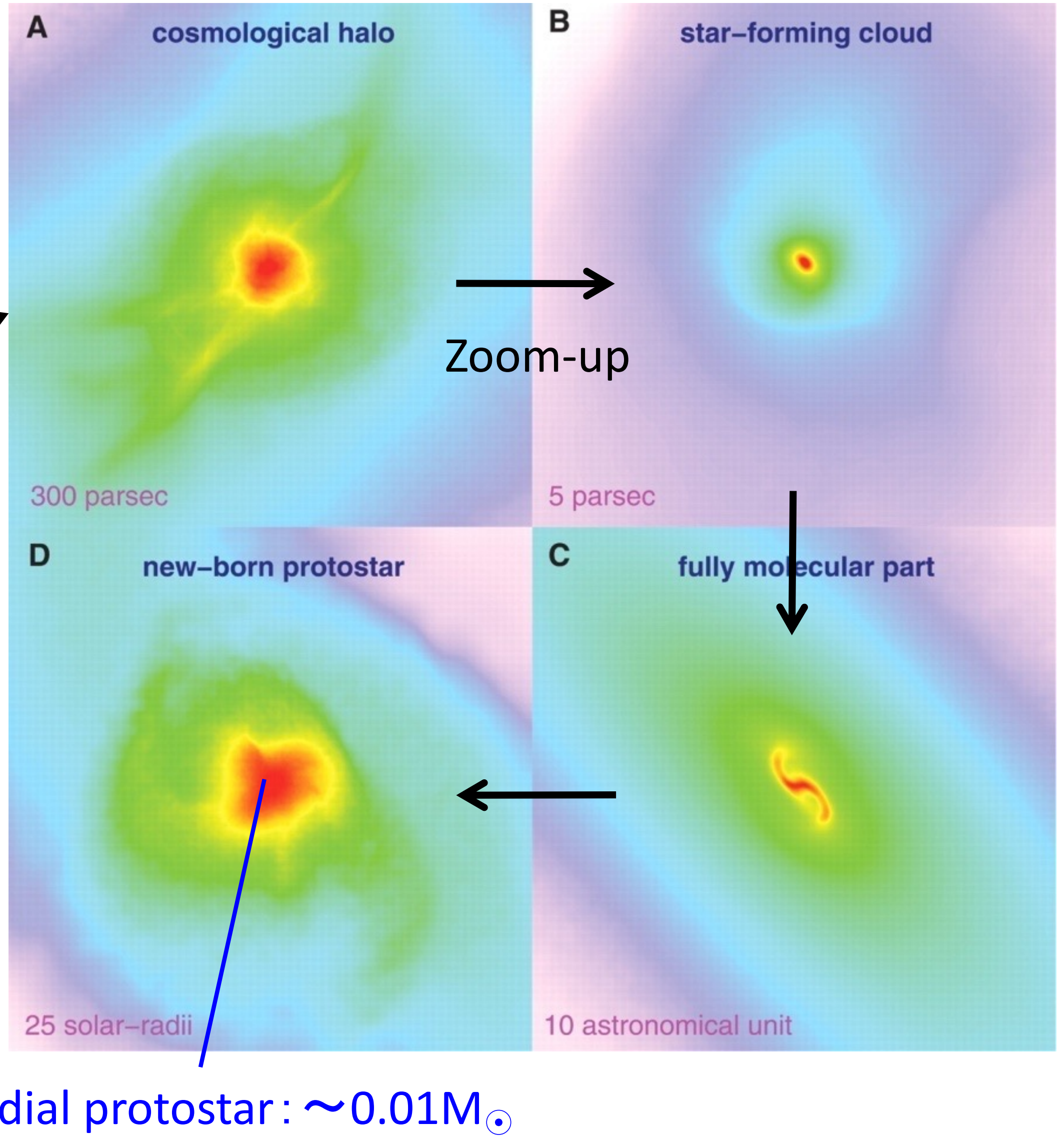
With the well-defined initial condition, it is straightforward to follow the evolution from the Big Bang to the birth of the first stars.

Collapse stage in 3D

Yoshida et al. 03



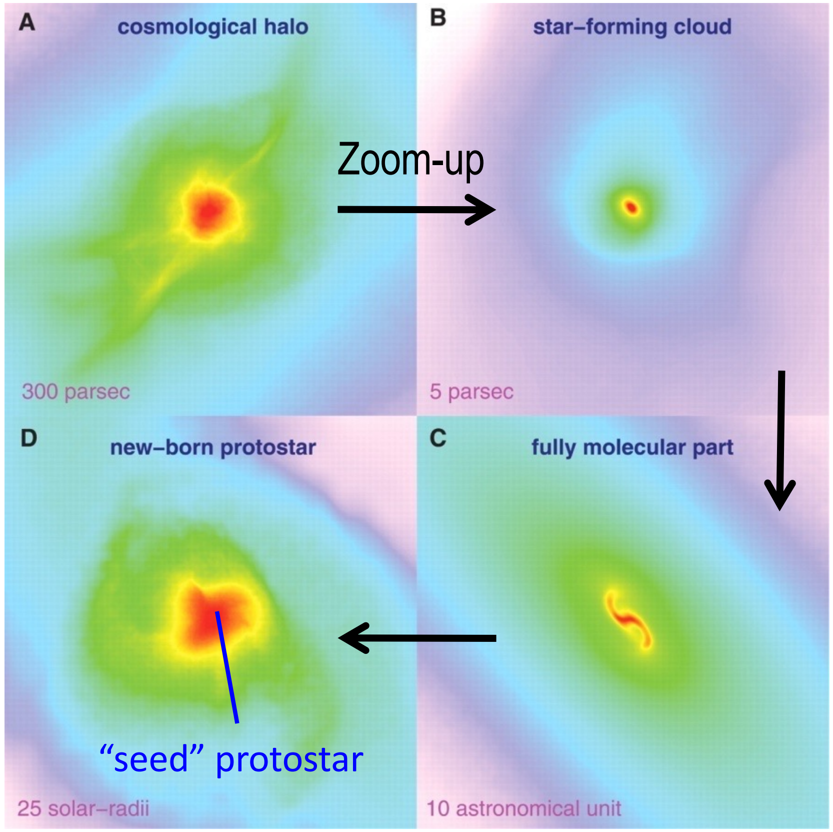
Yoshida et al. 08



How massive were they?

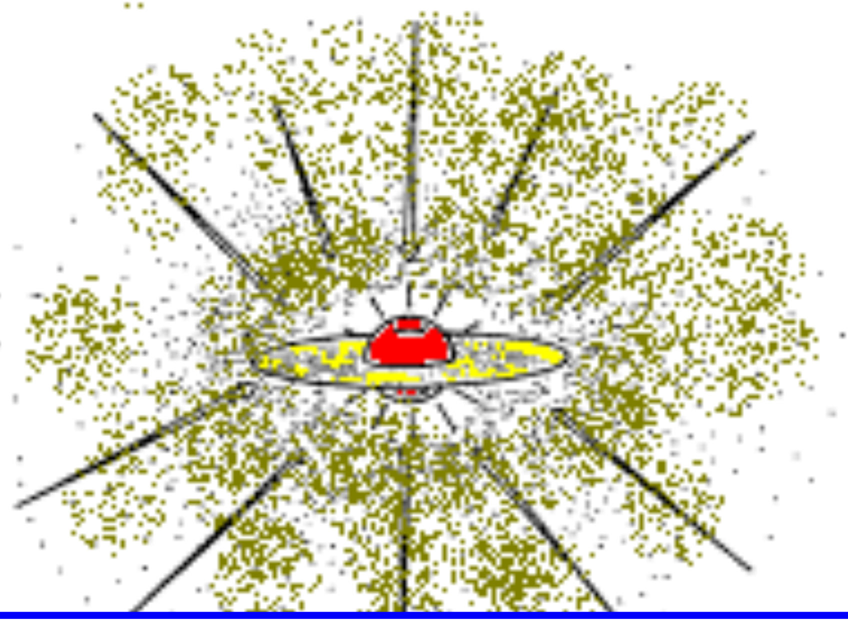
early collapse stage ⇒ late accretion stage

Yoshida, Omukai & Hernquist (2008)



$10^{-2}\,M_\odot$ protostar

surrounded by $>10^{3}\,M_\odot$ gas envelope

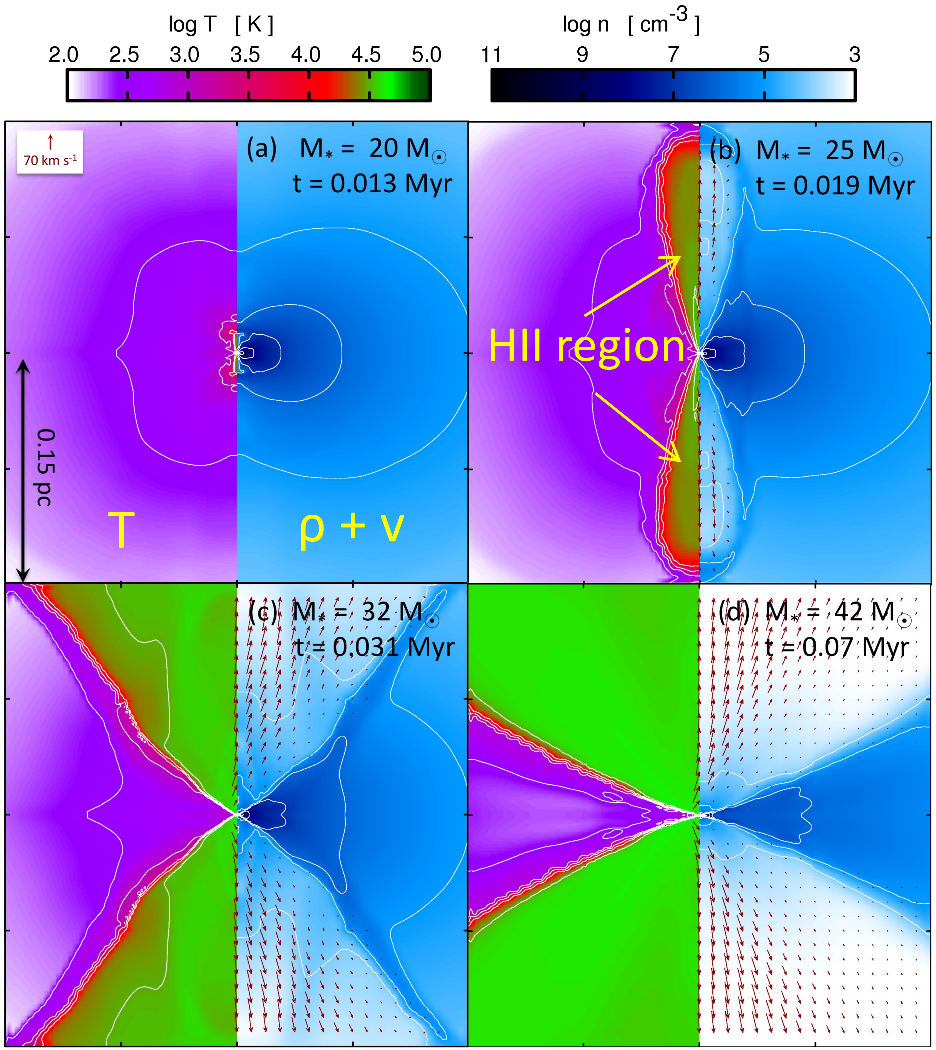


$$\dot{M} \sim \frac{M_J}{t_{ff}} = \frac{c_s^3}{G} \sim 7 \times 10^{-4} M_\odot/\mathrm{yr} \left(\frac{T}{300\ \mathrm{K}} \right)^{3/2}$$

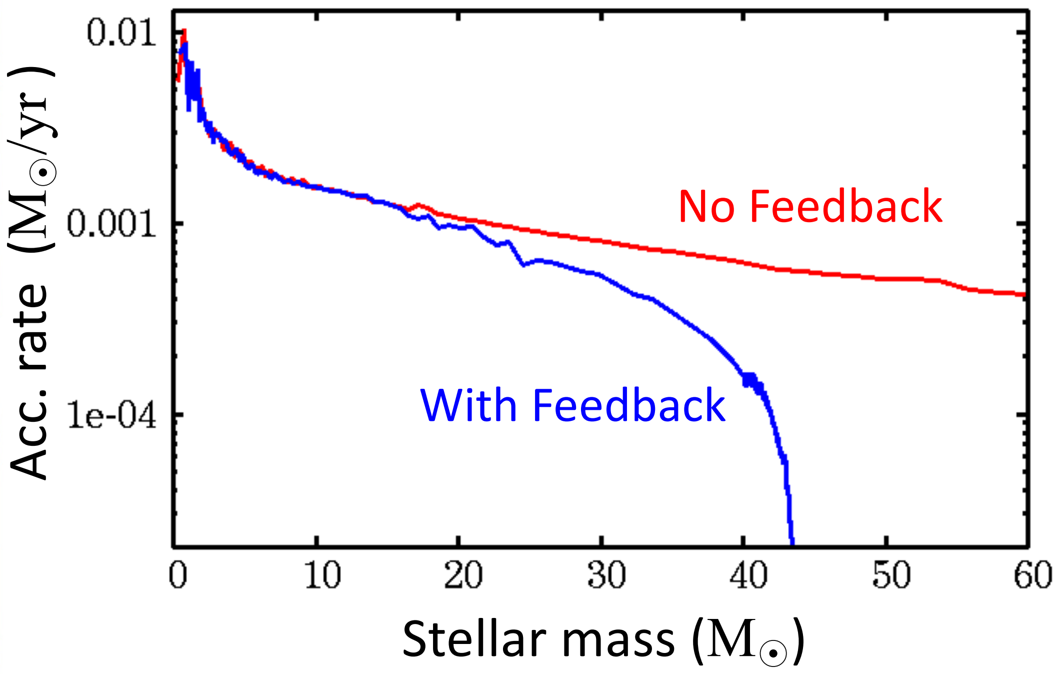
for stellar lifetime (～Myr) → ～$1000M_\odot$ star

本当は何が起こるか?

2D numerical simulations



TH+11, 12; Hirano, TH et al. 14



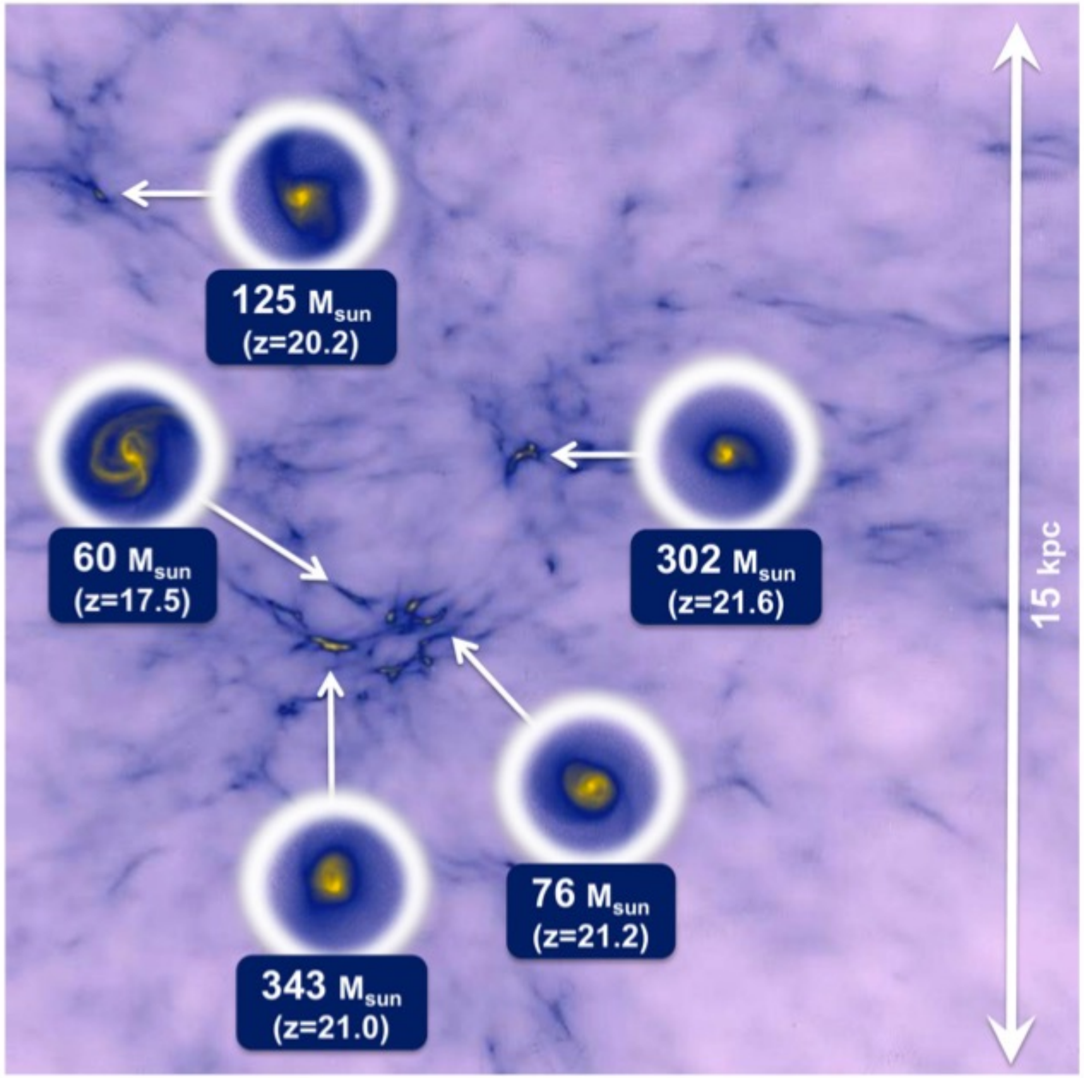
Stellar UV feedback halts the accretion at $M_* \sim 43\ M_\odot$

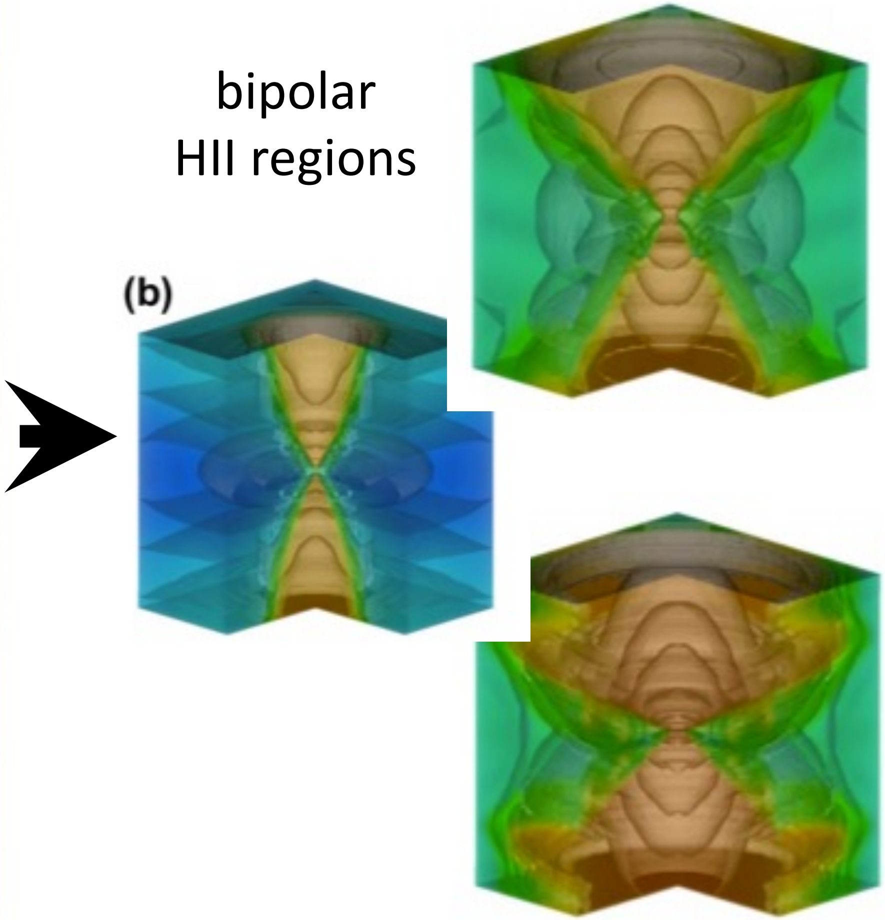
"Ordinary massive" Pop III star

Forming >100 Pop III Stars

Pick up > 100 of the star-forming clouds found in cosmological simulations. The later evolution until the stellar mass is fixed is followed by 2D RHD simulations

Hirano, TH, Yoshida et al. (2014)

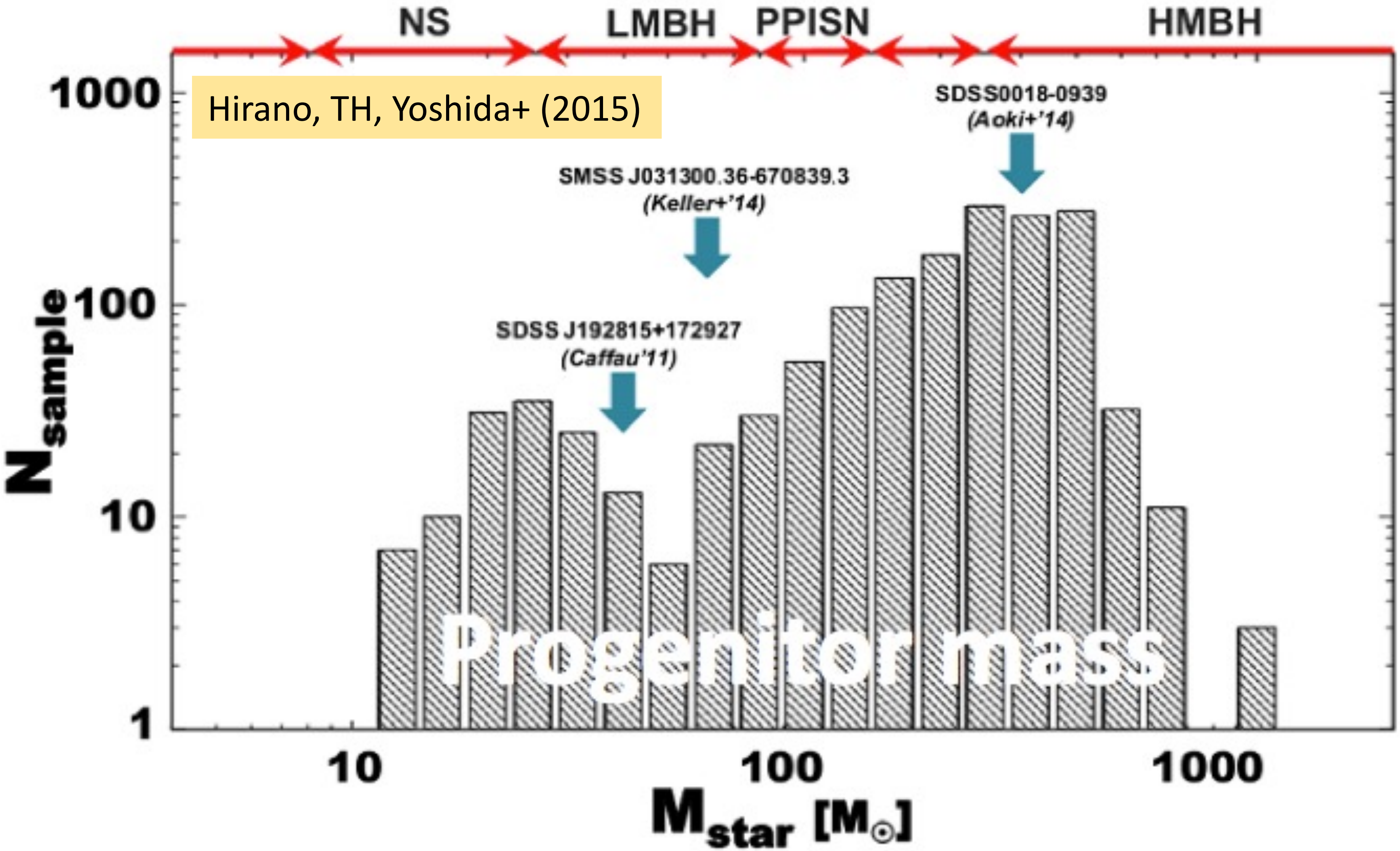




The UV feedback finally shuts off the mass accretion in all the cases

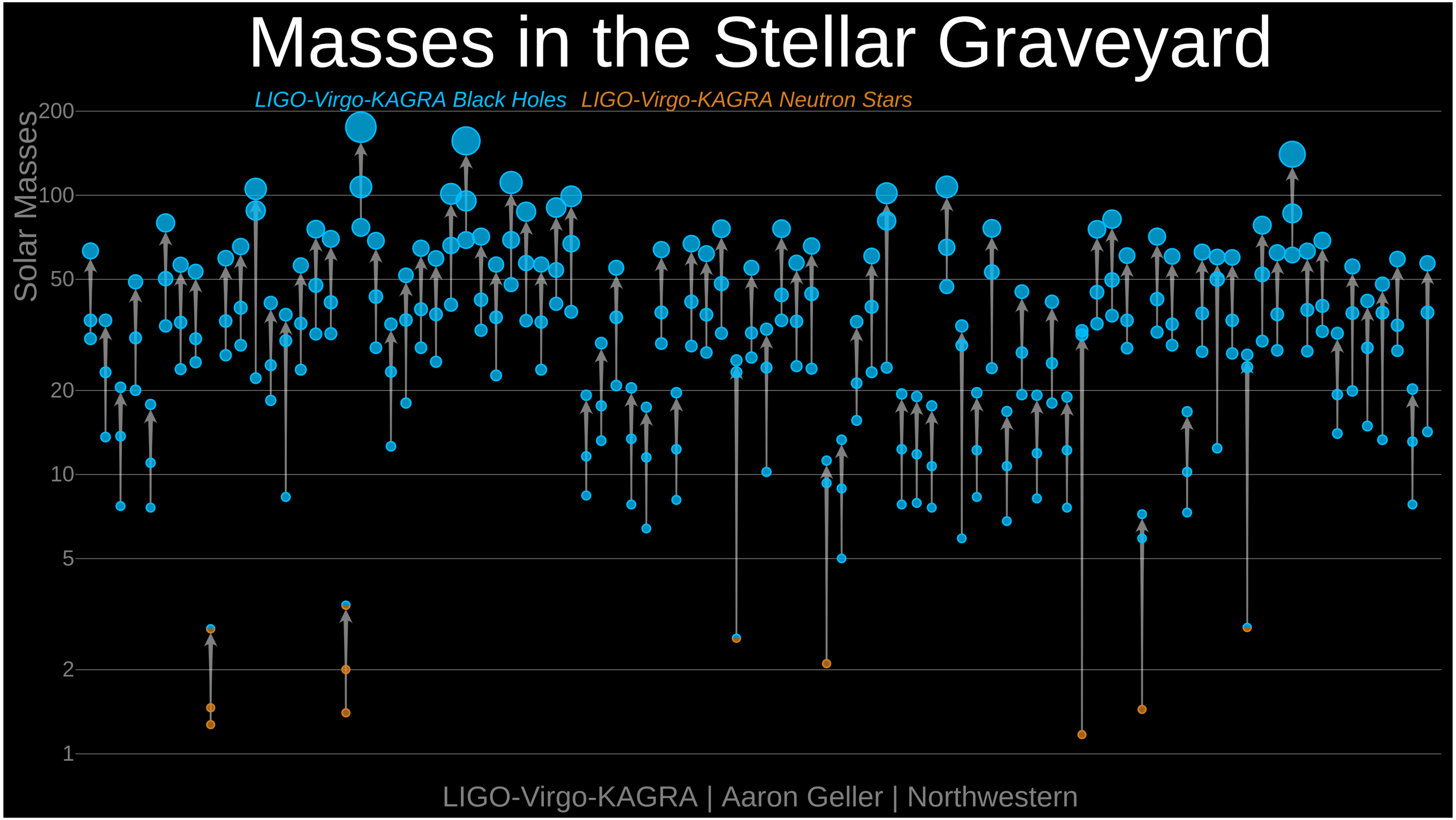
The "Mass Spectrum"

With more than 1000 (!) star-forming clouds taken from cosmological simulations

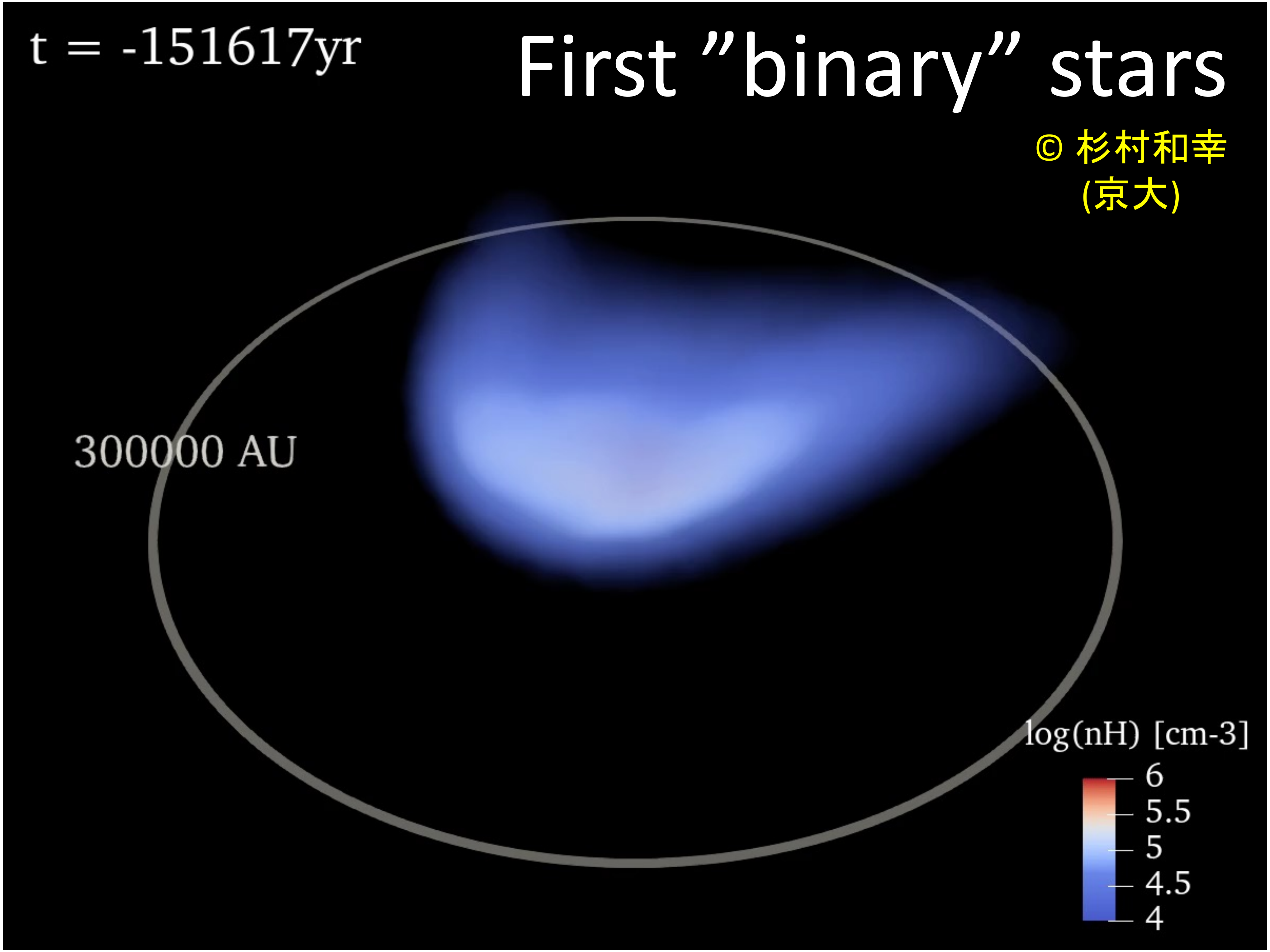


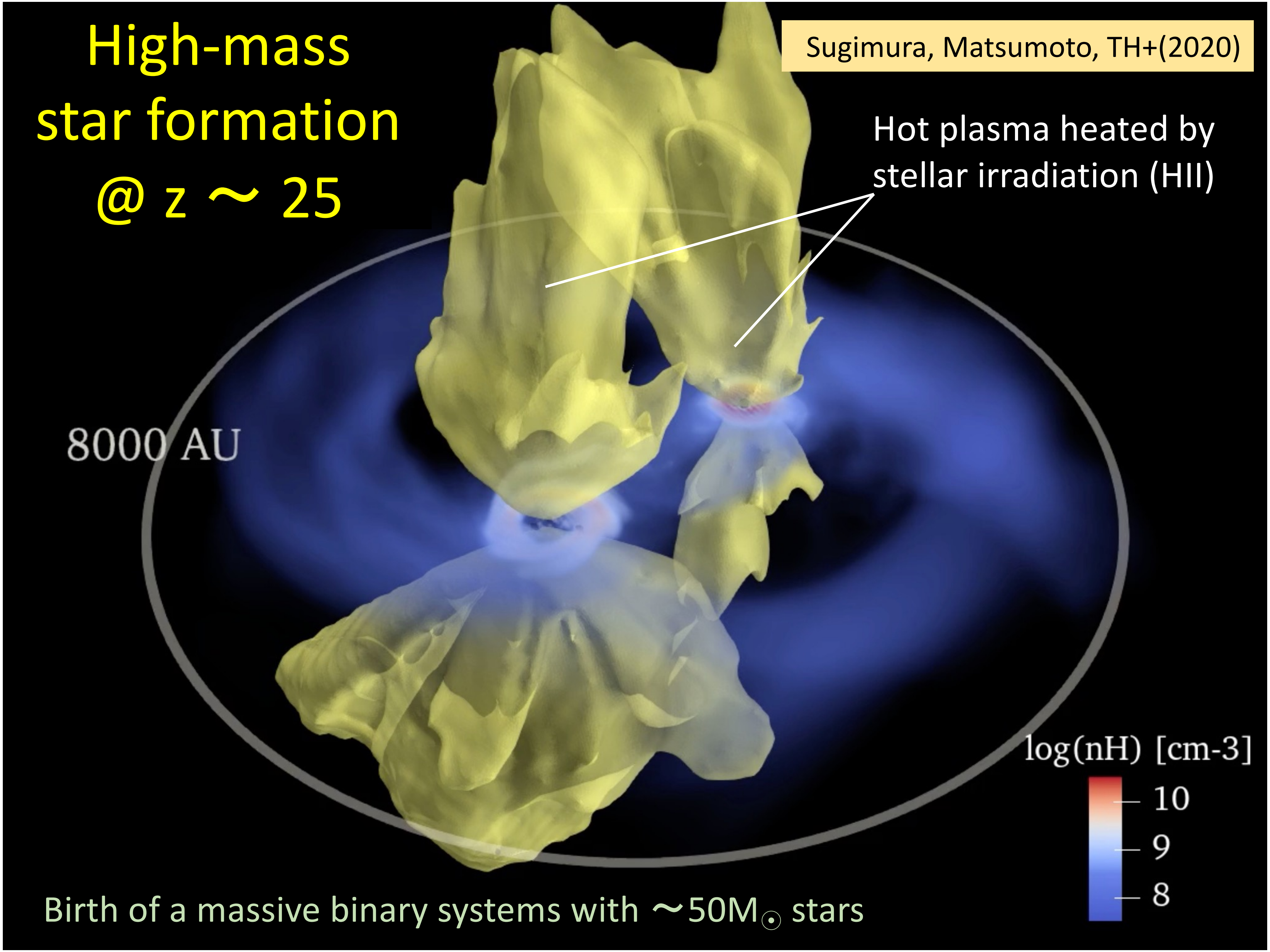
Diversity is originally created through the cosmological structure formation.

Era of Gravitational Wave



Pop III stars are possible progenitors of merging BH-BH binaries!


t = -151617yr
First ”binary” stars
© 杉村和幸
(京大)
300000 AU
log(nH) [cm-3]
6
5.5
5
4.5
4


High-mass
star formation
@ z ～ 25
Sugimura, Matsumoto, TH+(2020)
Hot plasma heated by
stellar irradiation (HII)
8000 AU
log(nH) [cm-3]
10
9
8
Birth of a massive binary systems with ～50M⊙ stars

Advent of JWST

JAMES WEBB SPACE TELESCOPE
GODDARD SPACE FLIGHT CENTER

Webb will be a powerful time machine with infrared vision that will peer back over 13.5 billion years to see the first stars and galaxies forming out of the darkness of the early universe.

SCIENCE

Early Universe

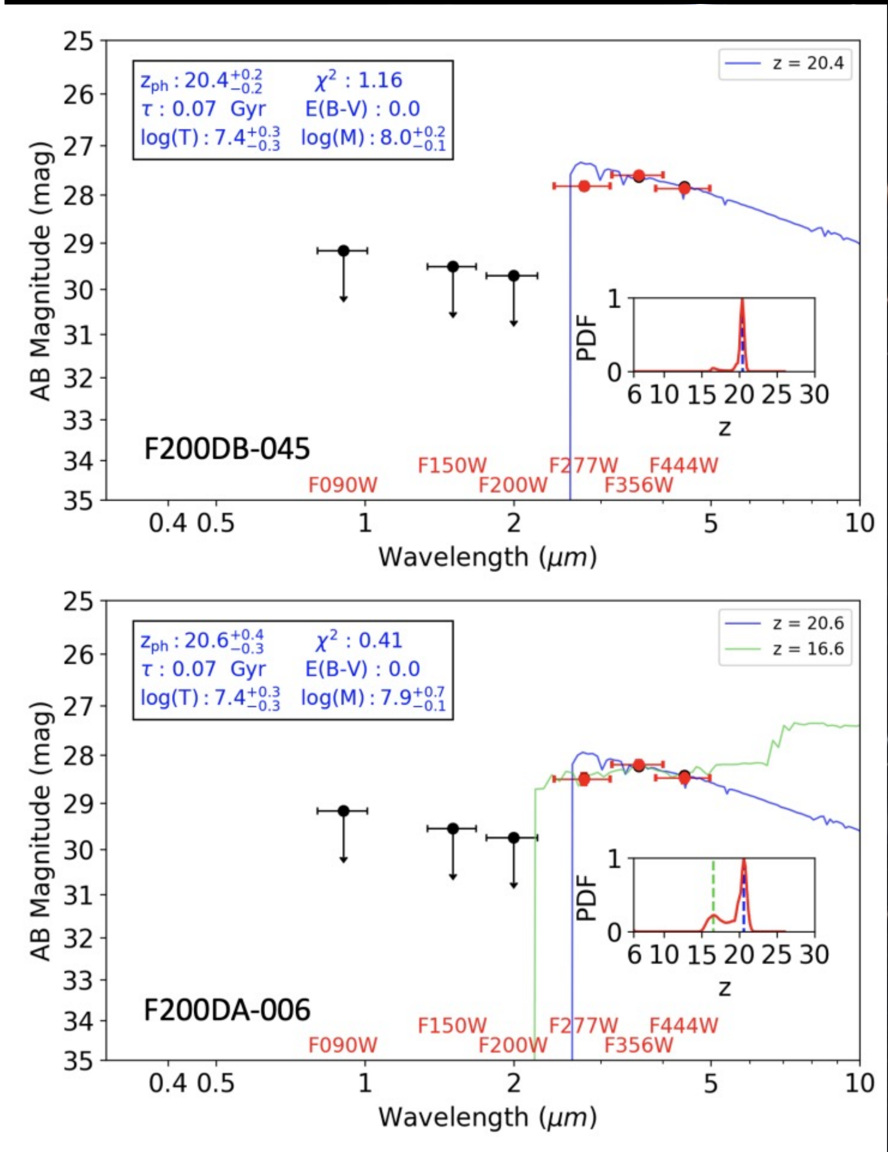
https://webb.nasa.gov/content/science/firstLight.html

BUT expected to be impossible to detect individual ～1000$M_\odot$ stars at z～10
(common knowledge in the community)

Realistic targets are larger high-z galaxies / star clusters
that may contain some stellar component of Pop III stars.

⇒ 極めて金属量の少ない大質量星団の形成過程が面白いだろう
(like young version of globular clusters)

JWST + grav. lensing

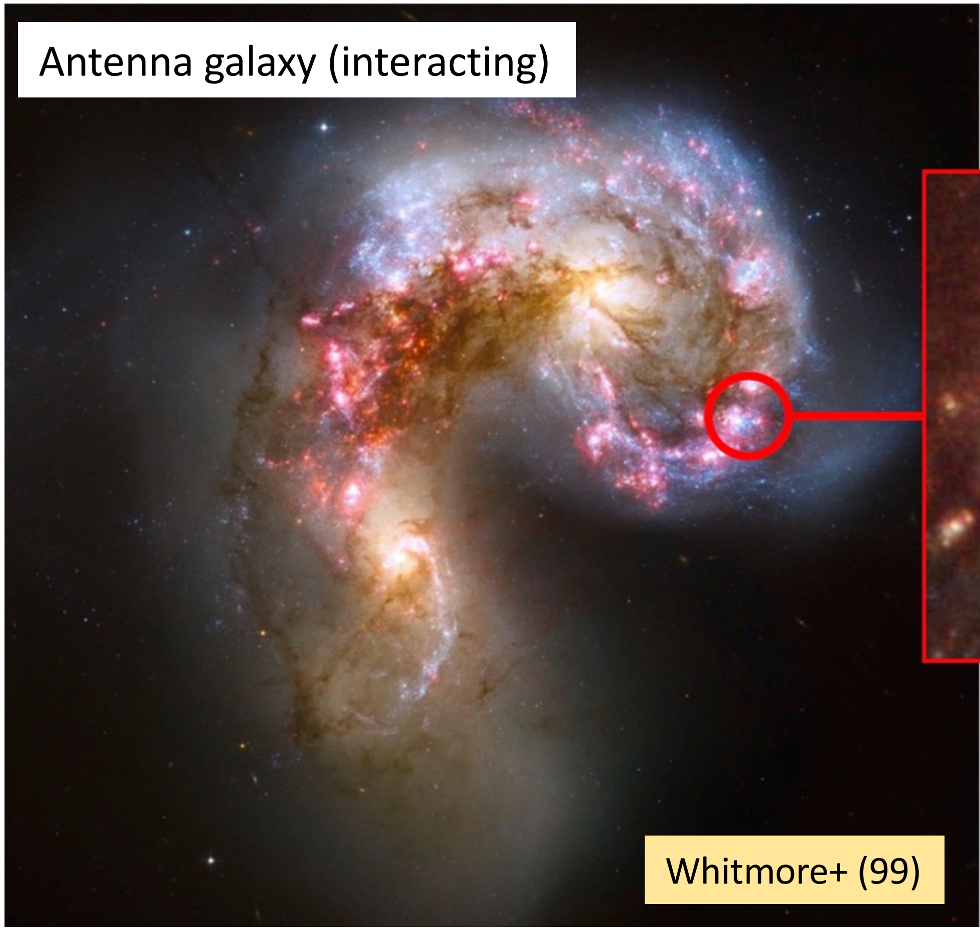


z～20 candidates!?

(Yan+22, arXiv:2207.11558)

Young Massive Clusters (YMCs)

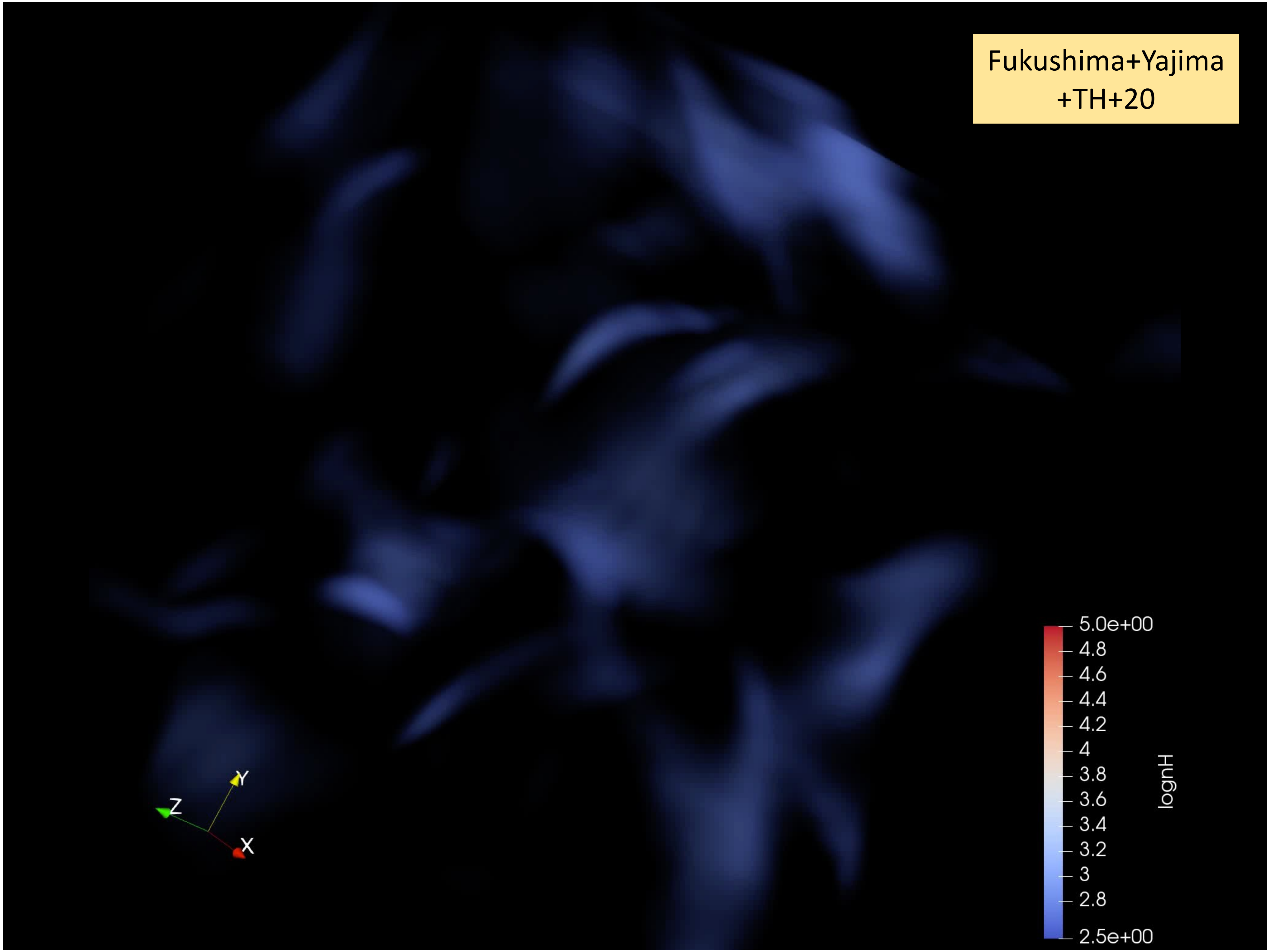
Young analogues of globular clusters?



few $\times\ 10^6\ M_\odot$
$\sim$7 Myr

Such massive clusters rarely form in nearby starburst galaxies.

What physical conditions are necessary for their formation?
Cloud-Cloud collisions prepare such conditions... (e.g., Tsuge+21; Enokiya+21)



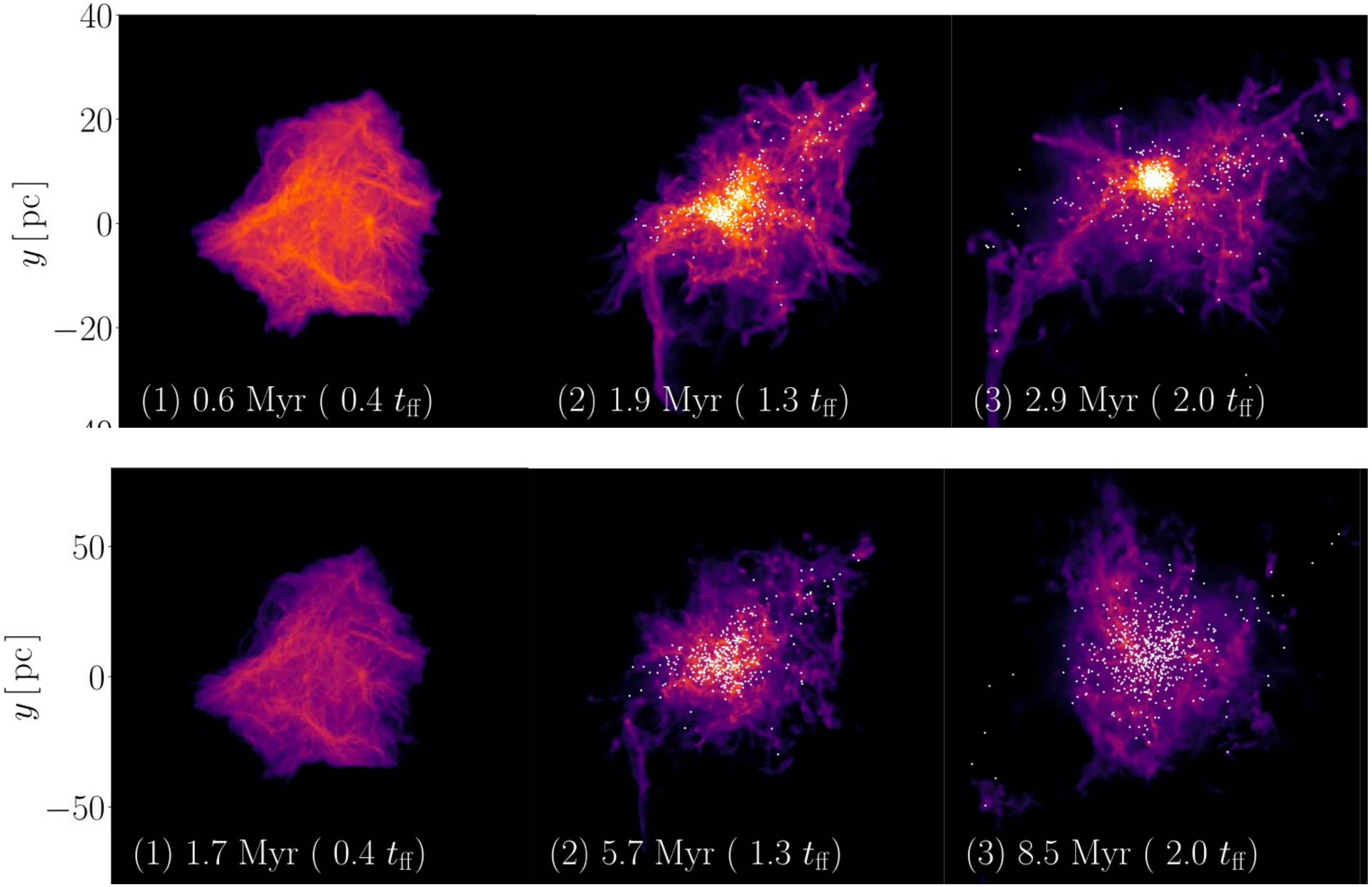
Fukushima+Yajima
+TH+20
Y
Z
X
5.0e+00
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
2.5e+00
lognH

Fukushima & Yajima (2021)

RHD simulations following the star cluster formation, including YMCs (w/ SFUMATO).
YMC formation occurs if the surface density of a cloud Σ exceeds a threshold value.

Cloud mass:
$10^6 M_\odot$,
+
Cloud radius:
20pc

Cloud mass:
$10^6 M_\odot$,
+
Cloud radius:
40pc



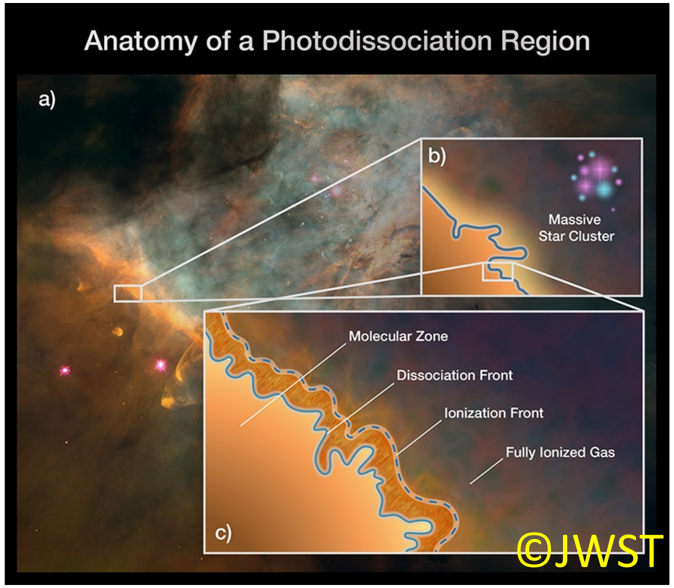
電離バブル膨張より十分早く、電離ガスをtrapできるだけ星団がmassiveになるか否か

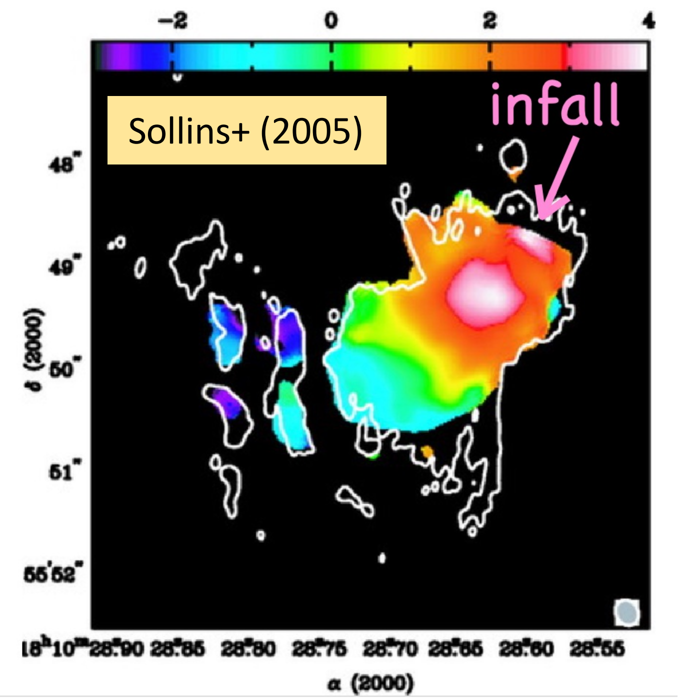
Observational Signatures?

Particularly, YMCs in the formation stage (when the stellar mass increases)

+ Photodissociation region (PDR)
  clouds irradiated by stellar FUV photons

  tracer: CII (158μm), OI (63μm) …
  line emission, warm dust etc.





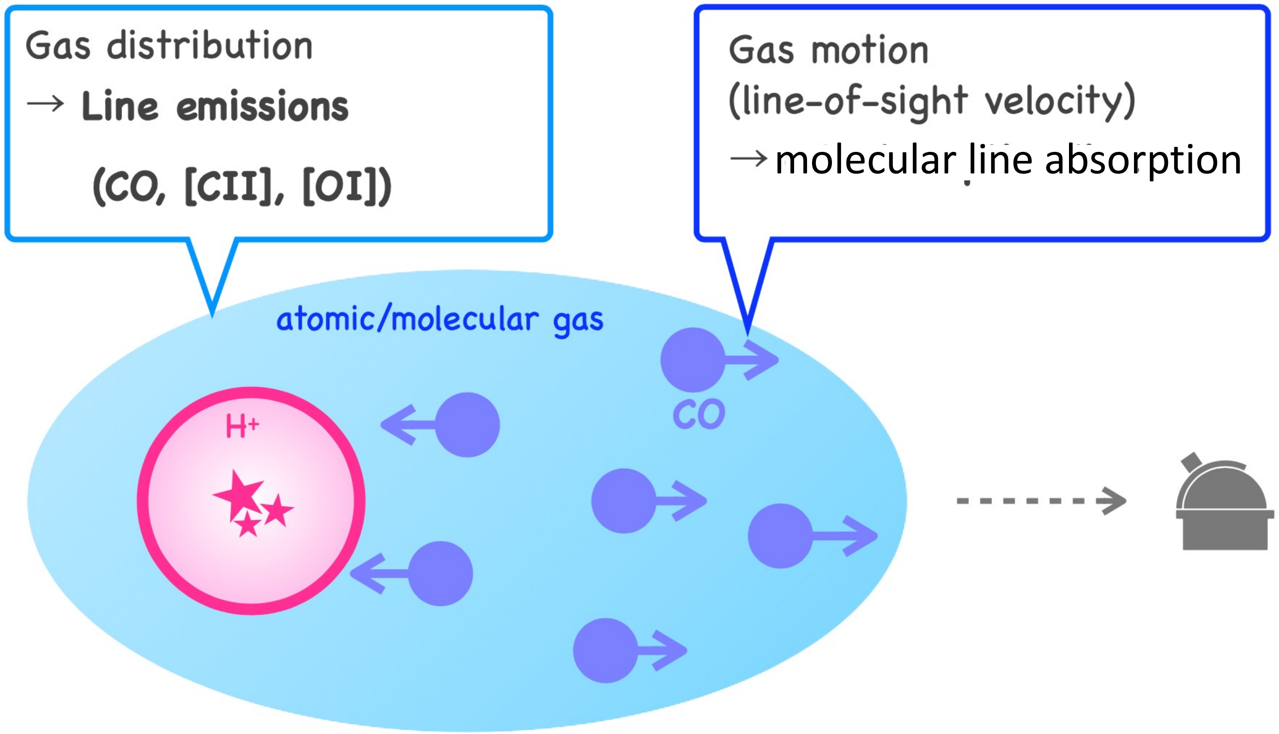
+ gas infall motion toward the forming cluster

← motion detected by the molecular (NH_3) absorption line against the background free-free emission

Molecular gas infalling toward the central HII region

Aim

What are observational signatures of forming YMCs?



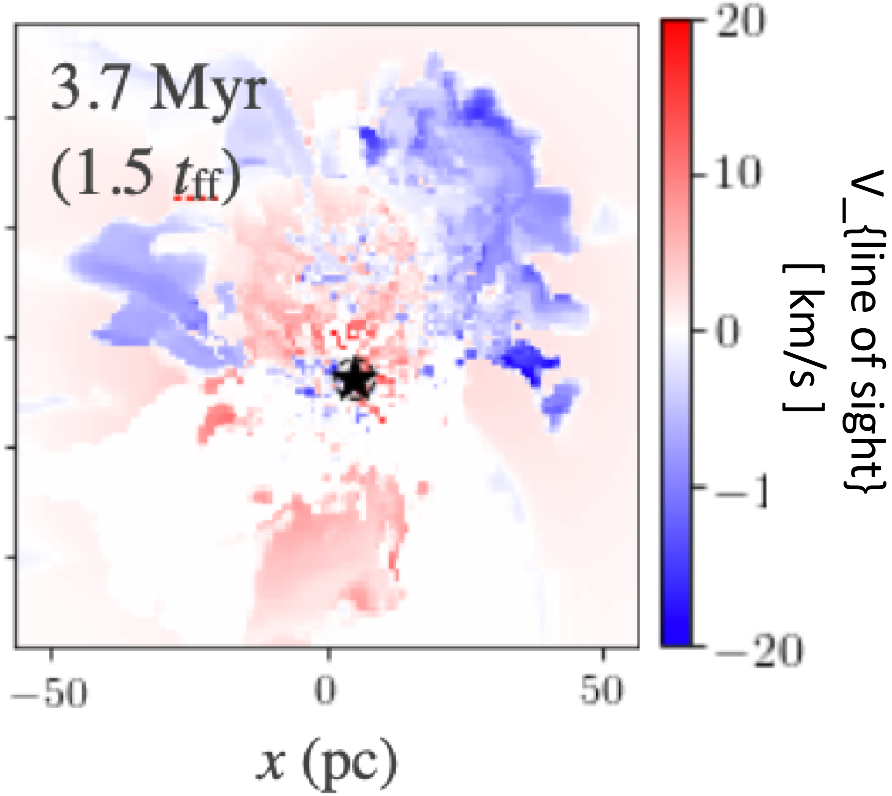
Method: Post-process calculation (synthetic observation)

Line emission
- level population calculations solving the detailed balance (local)
- ↓
- radiation transfer (integration along lines of sight)

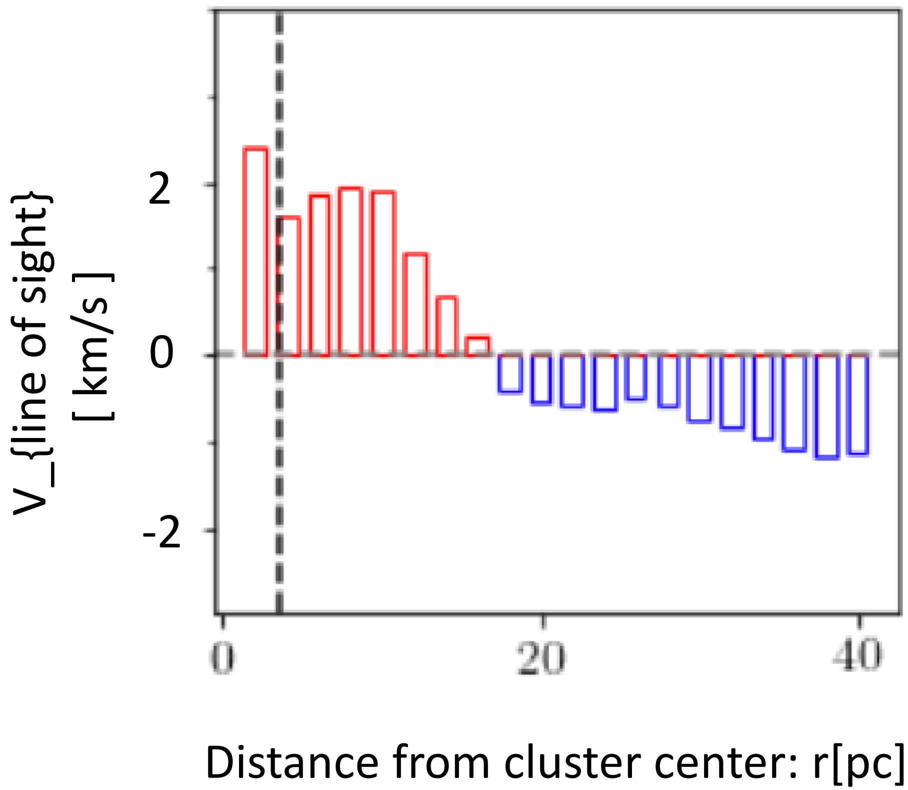
molecular absorption: 2D velocity distributions weighted by foreground CO column densities

Motion of Molecular Gas

Case of YMC formation



averaged over 6 lines of sight



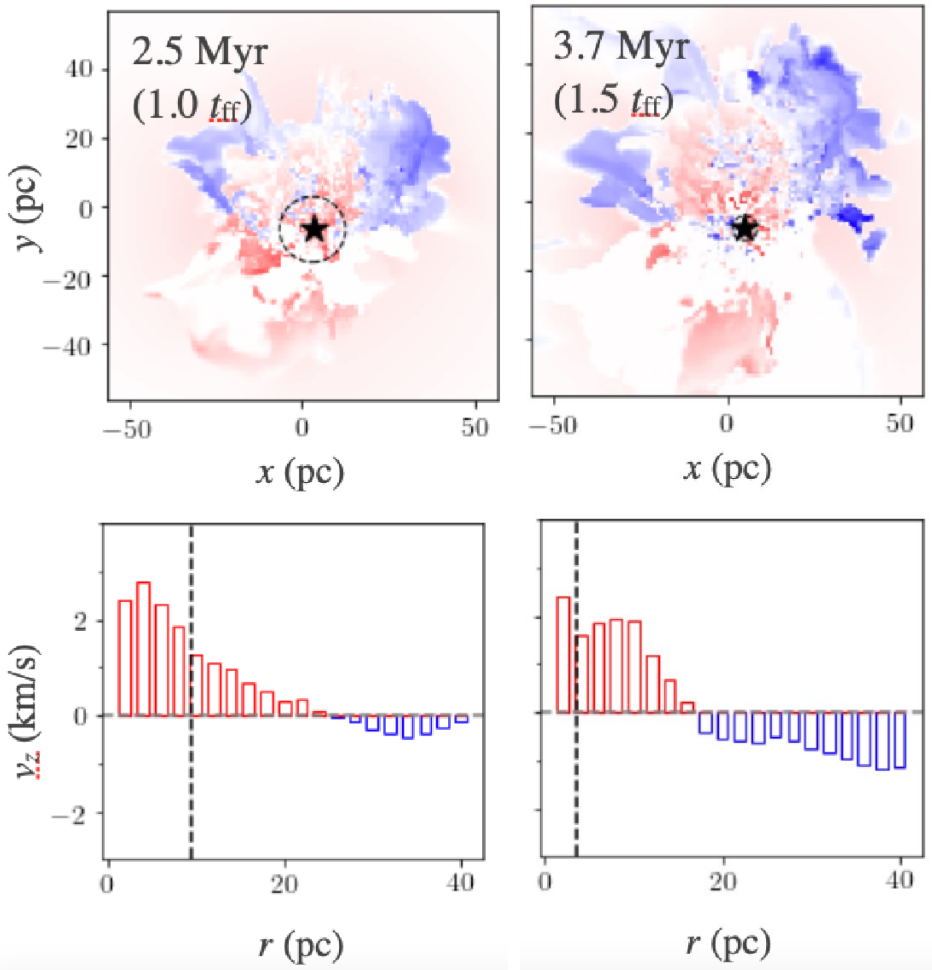
Inner infall motion (infalling molecular gas trapped by the cluster's gravity)

+

Outer outflow motion (molecular gas blown away by escaping ionizing photons)

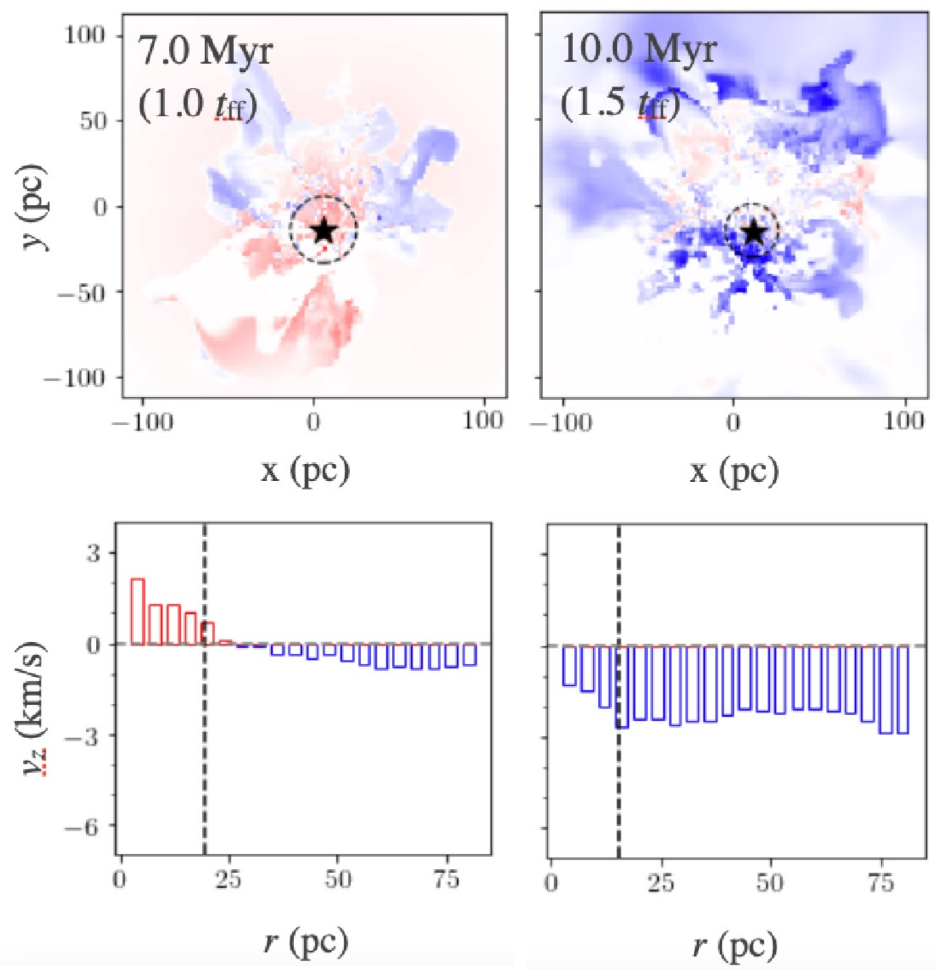
Comparing time evolution

YMC formation



Inner infall motion continues long
(normalized by t_ff)

NO YMC formation

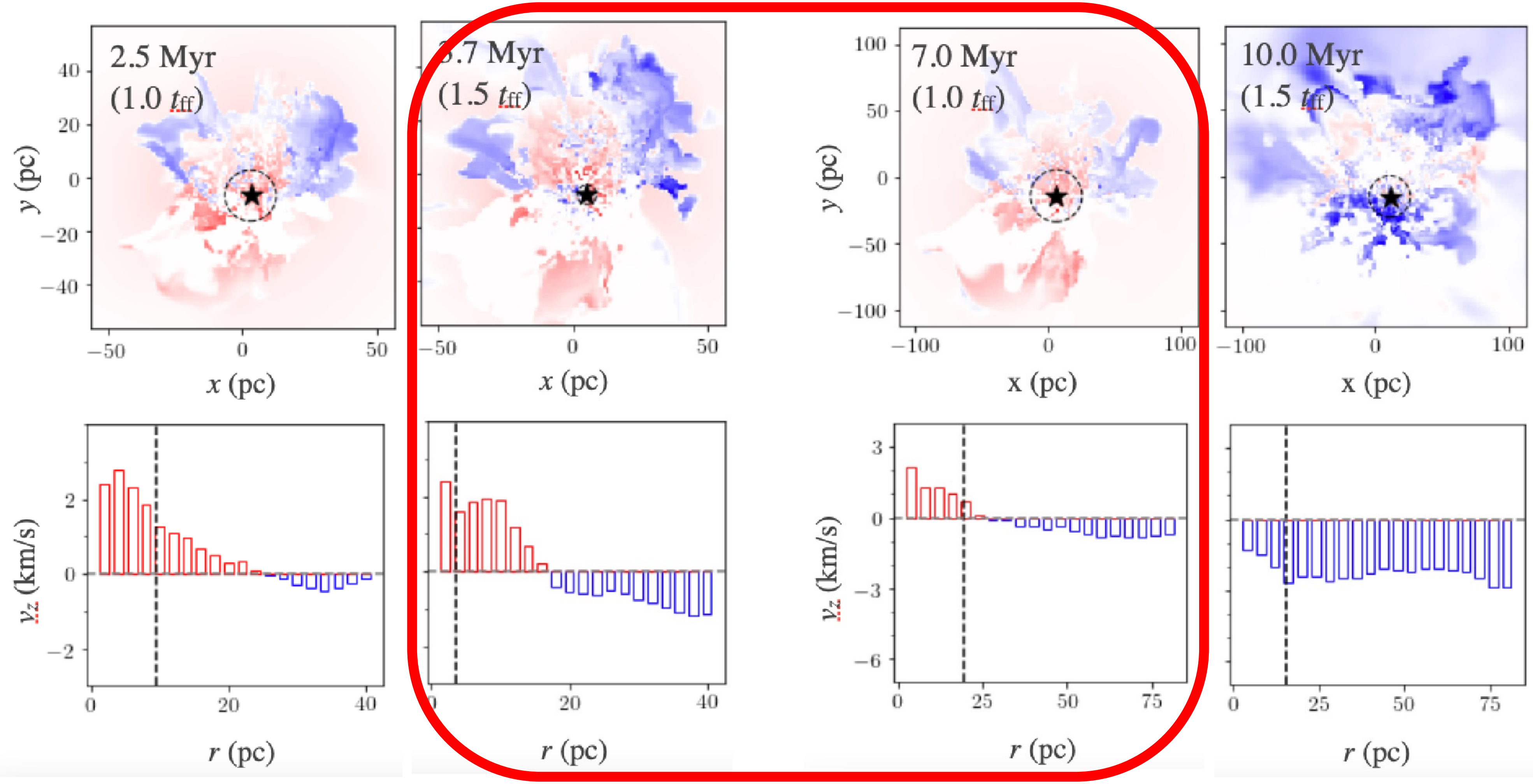


Inner infall motion only in an early stage
→ outflow motion dominates everywhere

Comparing time evolution

YMC formation

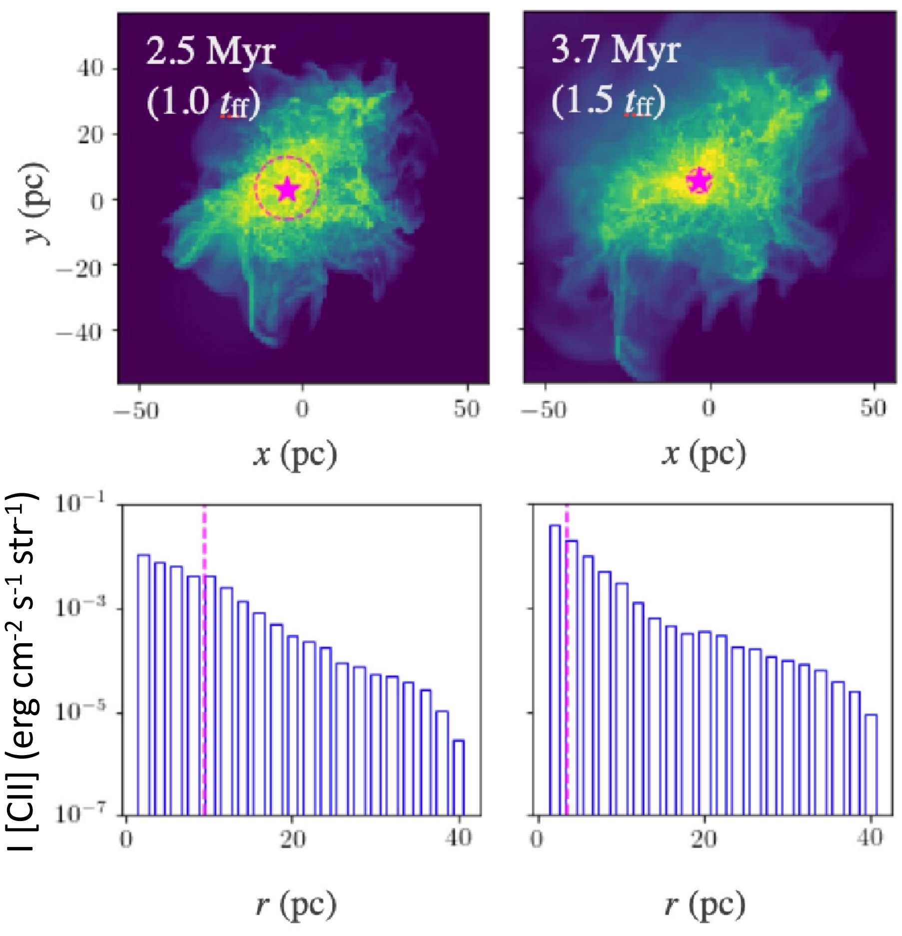
NO YMC formation



How to distinguish these cases?

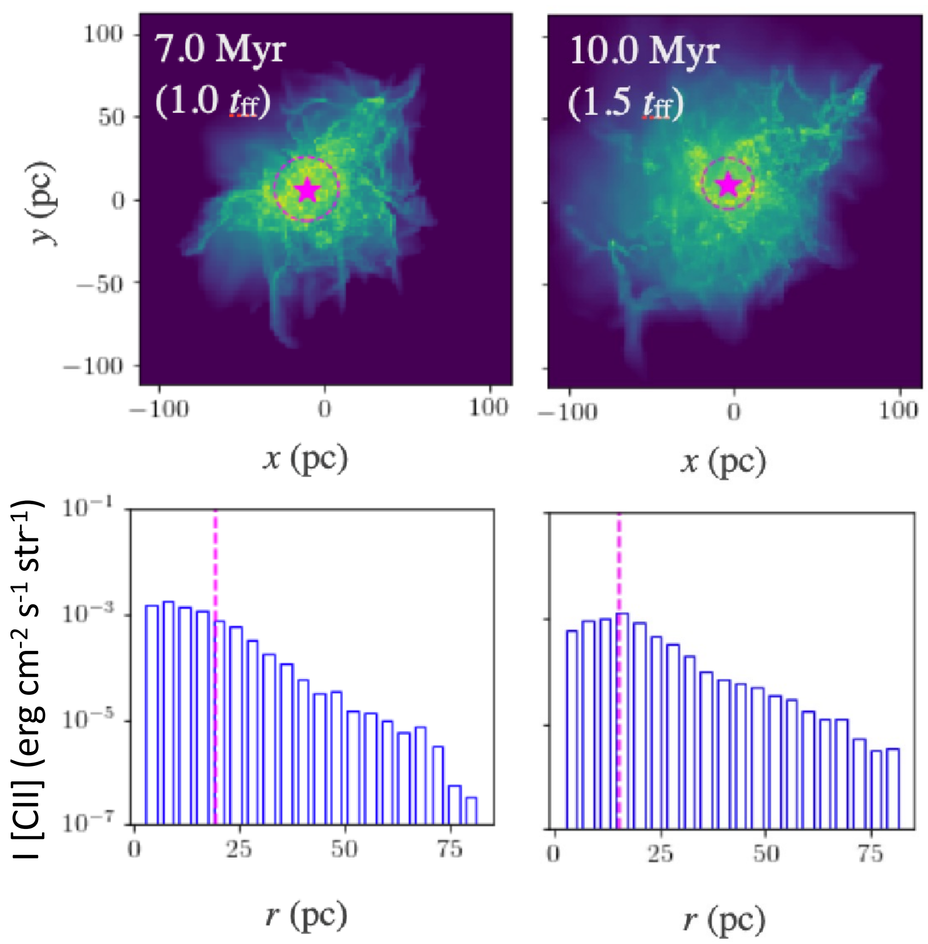
CII emission map

YMC formation



Very strong emission at the center
Centrally-condensed distribution

NO YMC formation

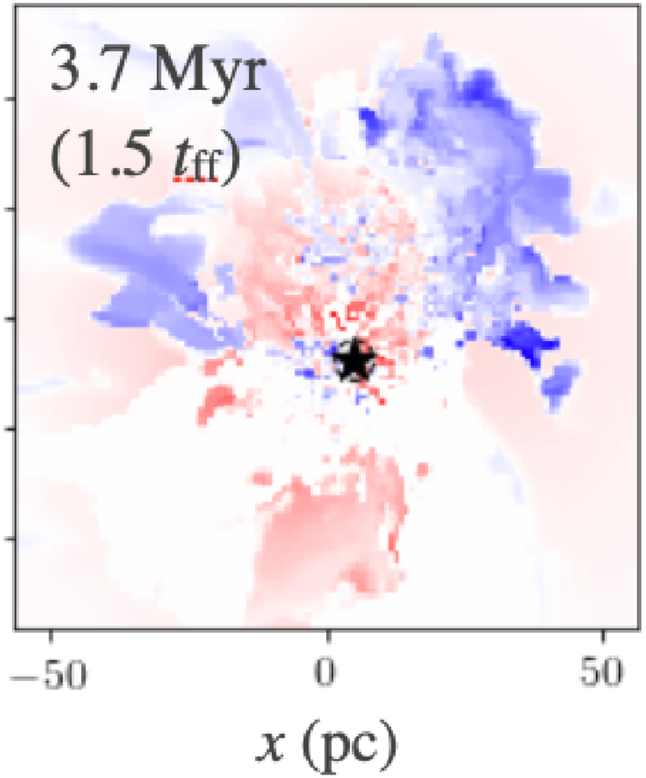


Weaker emission at the center
Less centrally-condensed distribution

Obs. Signatures of YMC formation

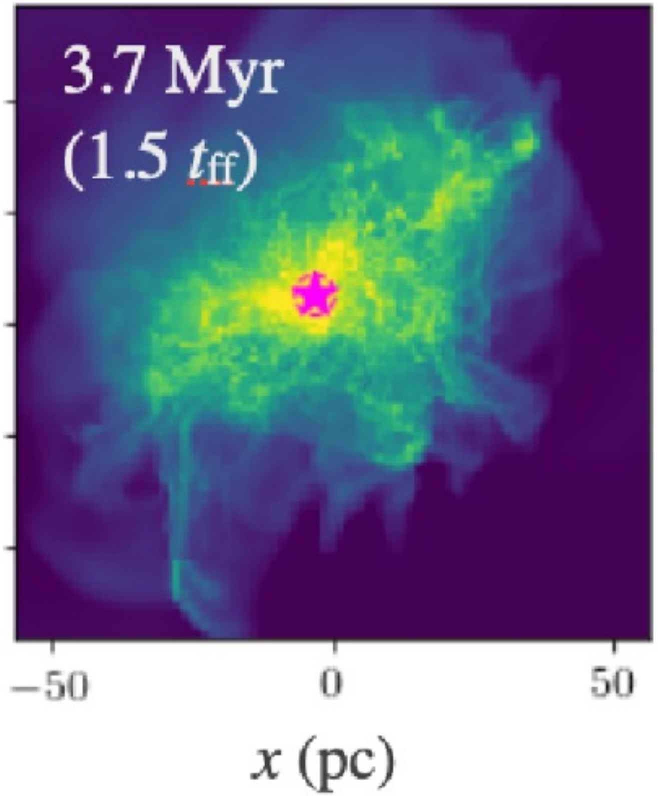
As far as we have explored…

Molecular gas infalling toward the central HII region



Centrally-condensed, very strong CII emission (+ OI, CO, H2, and dust)

+



These features co-exist only during the YMC formation stage

Currently only at $Z \sim Z_{\odot}$ and to be extended for low-metallicity cases

Summary

+ Pop III star formation as a challenge of the computational astrophysics

3D simulations reveal great details of their formation process,
e.g., mass distributions, binality, etc.

技術的には詳細観測と比較している銀河系の星形成研究と遜色なし

+ Observational signatures of their on-going formation process?

Low-metallicity massive clusters may provide some chance