Simulating the formation of the first stars

Shingo Hirano

Kyushu Univ. (JSPS Research Fellow)

九州大学 KYUSHU UNIVERSITY

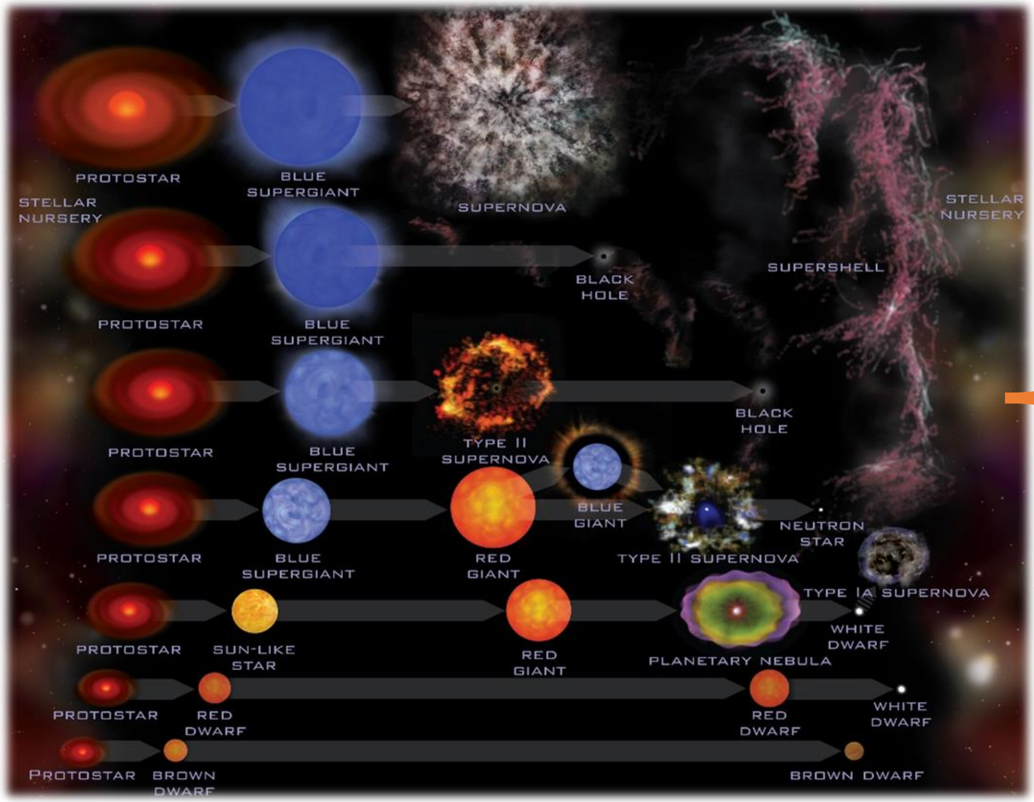
科研費 KAKENHI

Stellar Archaeology as a Time Machine to the First Stars @ Kavli IPMU (Dec 3-7, 2018)

Vital player in the early universe

First Stars (1^{st}-generation, Population III stars)

formed from the primordial gas (H, He, light atoms)



Massive First Stars : Why?

"1st-generation" (Population III) stars

formed from the **primordial, metal-free gas.**

(Big Bang nucleosynthesis species; 76% H, 24% He, 10^{-5}% D, little Li)

High-temperature cloud due to the limited coolants

H at >8000 [K] : T → 8000 [K]

H_2 at ~200-1000 [K]: T → 200 [K]

(fully H_2 at 10^8 [cm^{-3}] via 3-body reaction)

HD at <150 [K] : T → T_{CMB} ~ 50 [K] (at z~20)

Vary weak seed magnetic field

10^{-9} [G] at 10^{10} [cm^{-3}] in the host minihalo (Xu+'08)

(reconsidering recently; see details later)

Reason-1 : Rapid mass growth

Jeans mass

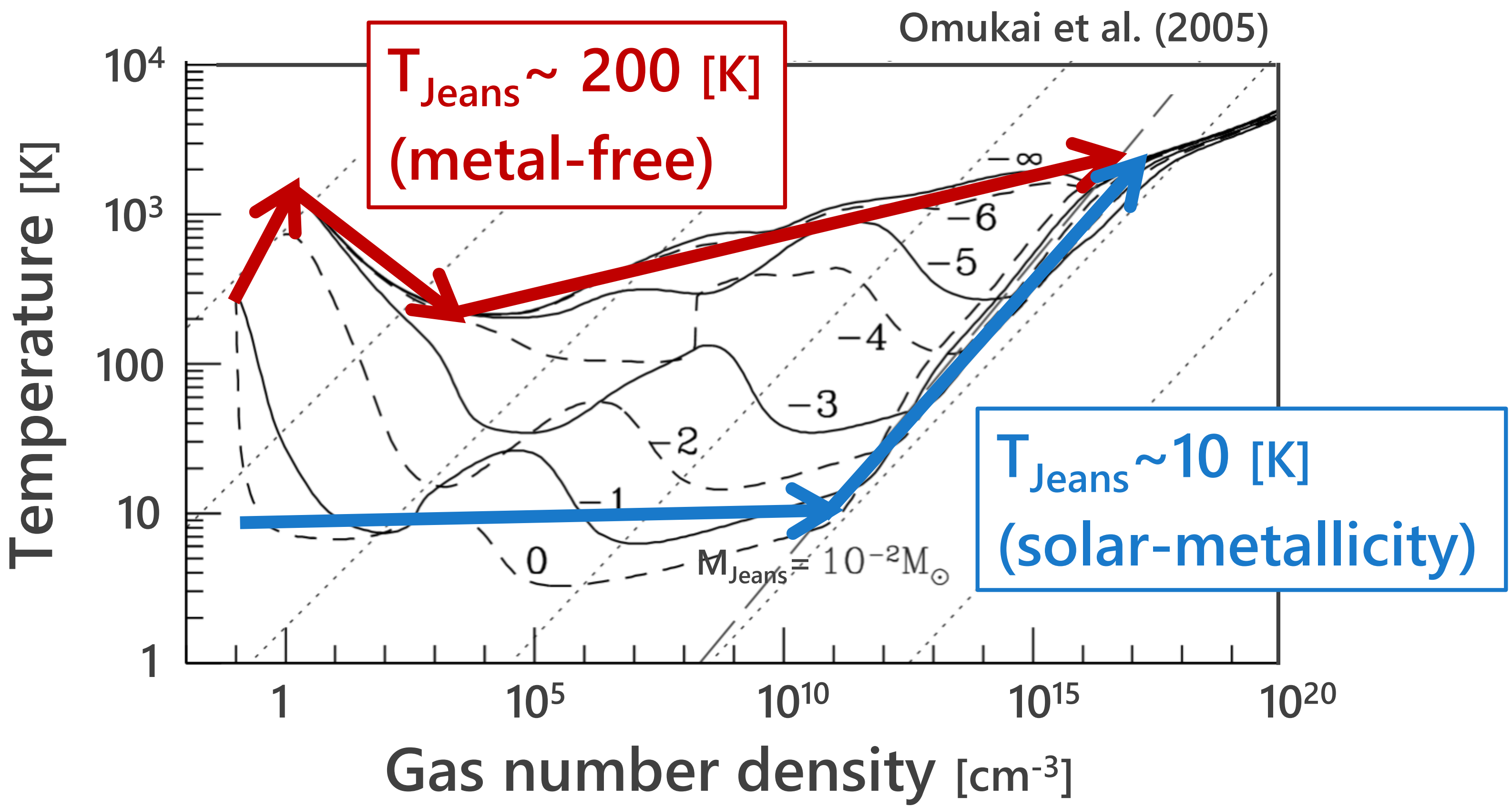
$$M_{\rm Jeans} = 1000 \left(\frac{T_{\rm Jeans}}{200\ [\rm K]}\right)^{1.5} \left(\frac{n_{\rm H}}{10^4\ [\rm cm^{-3}]}\right)^{-0.5} [\rm M_\odot]$$

$$= 0.01 \left(\frac{T_{\rm Jeans}}{10\ [\rm K]}\right)^{1.5} \left(\frac{n_{\rm H}}{10^{10}\ [\rm cm^{-3}]}\right)^{-0.5} [\rm M_\odot]$$

Mass accretion rate

$$\dot{M} \cong \frac{M_{\rm Jeans}}{t_{\rm freefall}} = 2\times10^{-3} \left(\frac{T_{\rm Jeans}}{200\ [\rm K]}\right)^{1.5} [\rm M_\odot\ yr^{-1}]$$

$$= 2\times10^{-5} \left(\frac{T_{\rm Jeans}}{10\ [\rm K]}\right)^{1.5} [\rm M_\odot\ yr^{-1}]$$



Reason-2: Limited feedback process

In the metal-free cloud with the tiny B-field,

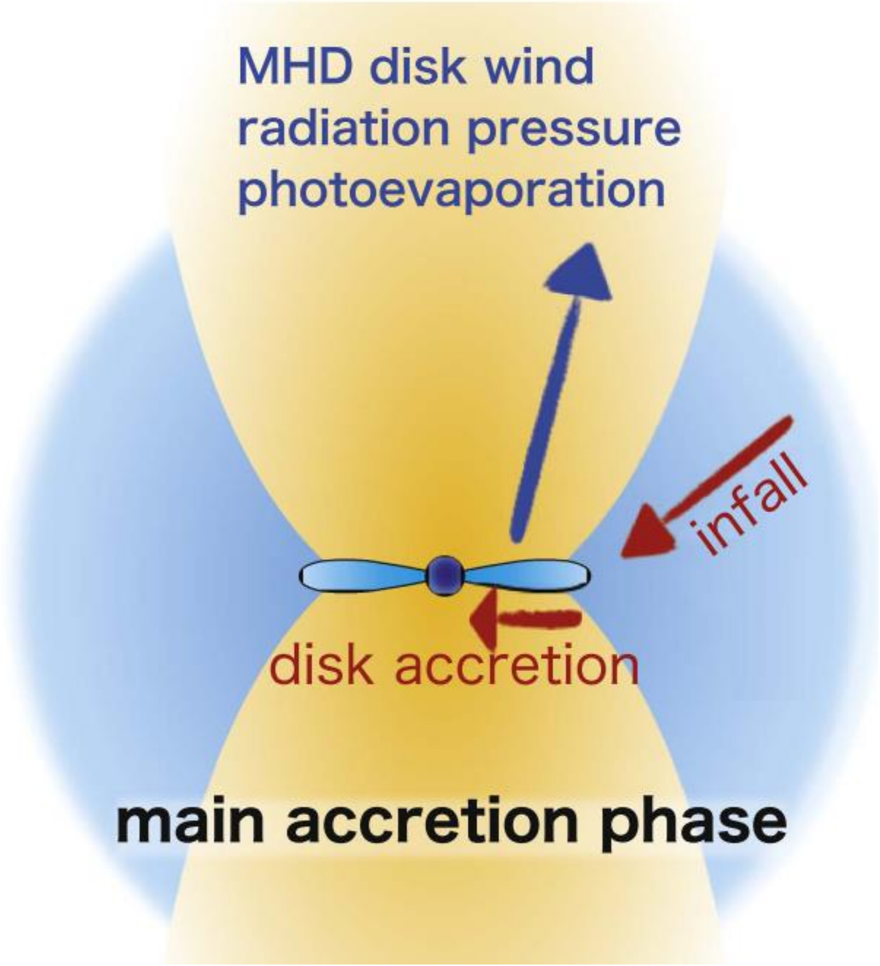
✖ Radiation pressure

✖ MHD disk wind

〇 **UV photo-evapolation**

(McKee & Tan 2008)

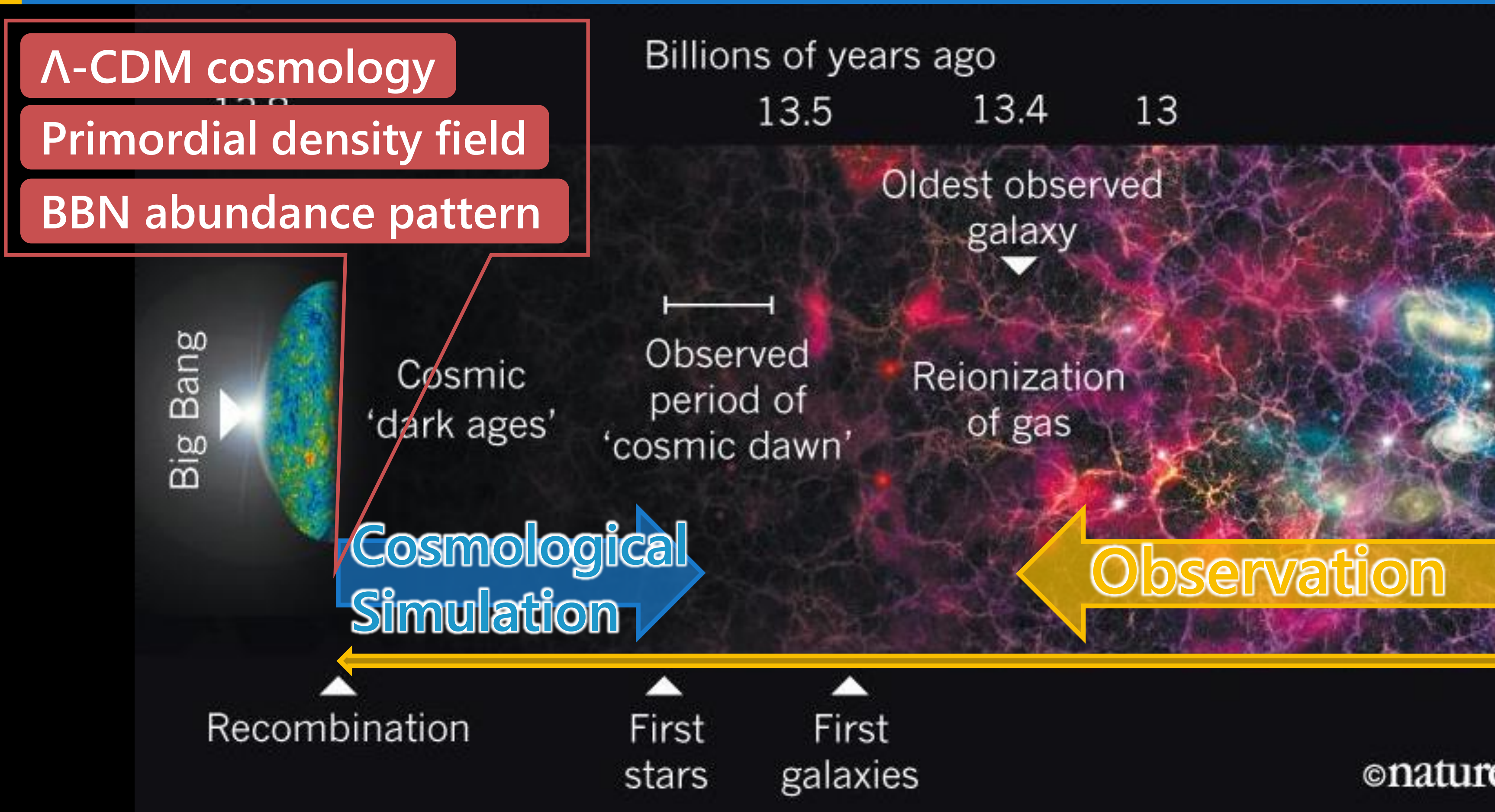
With $\dot{M} \geq 4 \times 10^{-3}$ [M$_\odot$/yr],
the expanded protostar cannot emit UV photons from the low-T surface ($T_{eff} \propto R^{-2}$).
➔ UV feedback is inefficient!
(Omukai&Palla 2003)



Schematic view from Tanaka+'18

Simulation

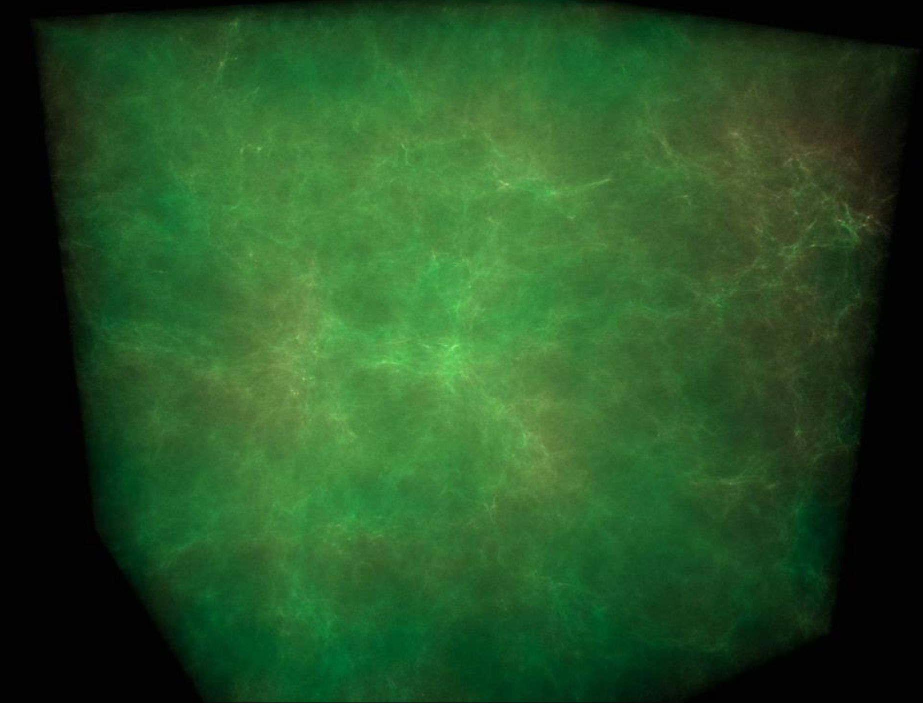
Ab initio cosmological simulation



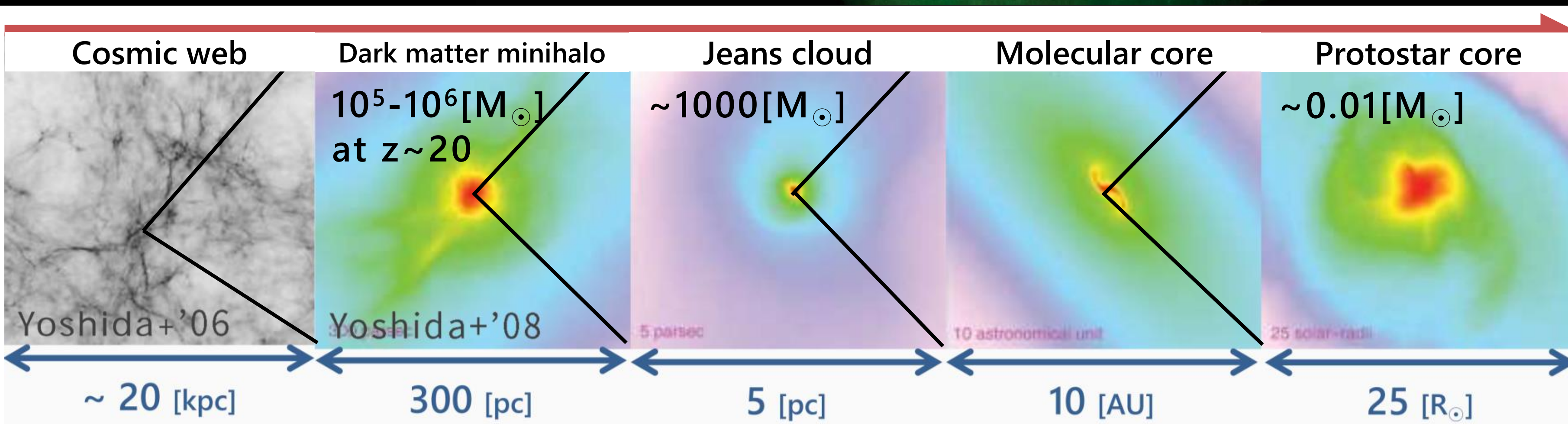
Physical properties of the primordial star-forming cloud can be reproduced theoretically & numerically by performing the cosmological simulation

Simulation of the first star formation

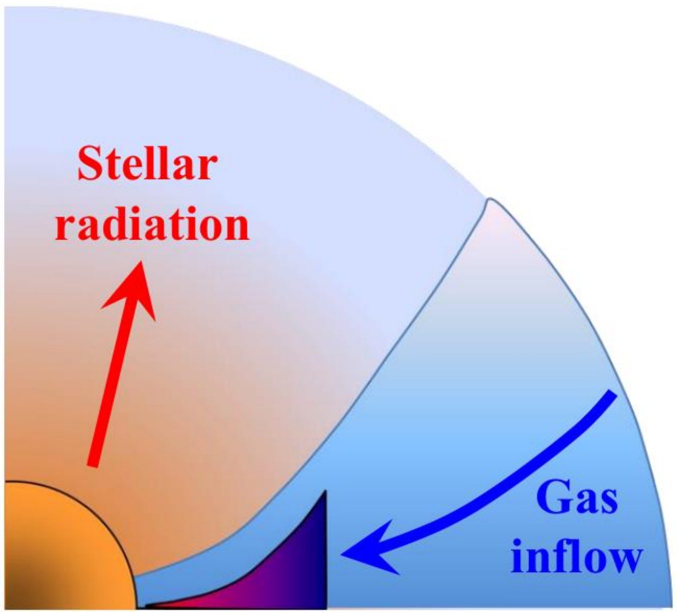
Cosmological hydro simulation
by Gadget-3 (Springel'05)
N-body (DM) + SPH (Gas)
+Primordial chemistry
+Hierarchical zoom-in
+Particle splitting (L_{Jeans}/L_{sph} > 15)



Simulation by SH
Visualization by Takaaki Takeda (VASA)



Initial mass of first star at the ZAMS



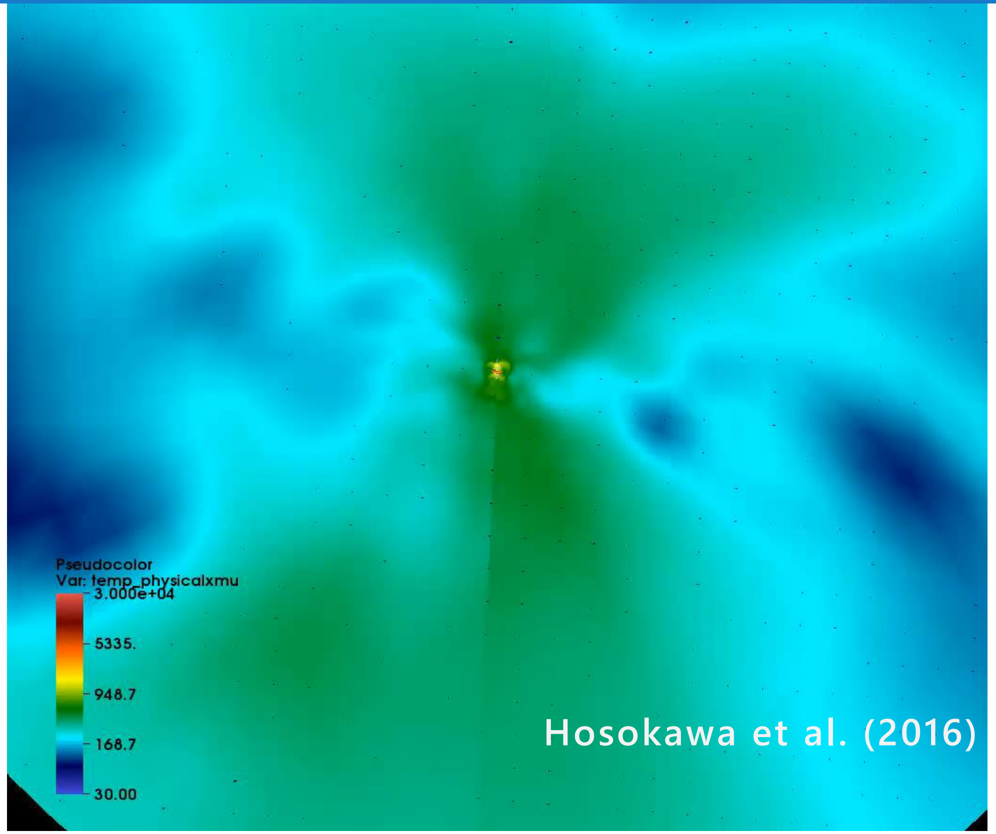
RHD simulation

Self-gravity, hydrodynamic,
primordial chemistry,
radiation transfer

Stellar Radiation ↑ ↓ **Gas Inflow**

Stellar evolution

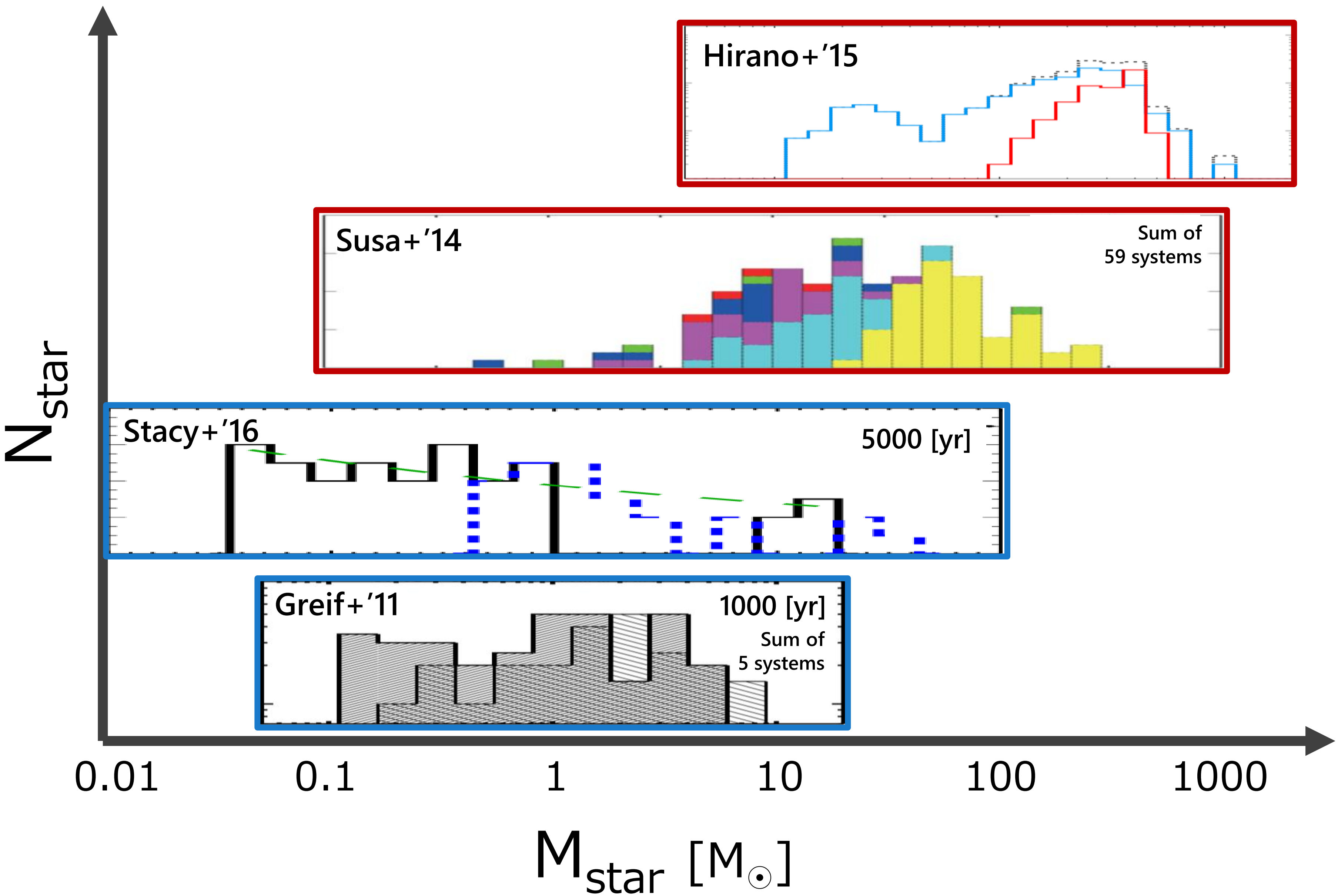
Equation system
of the protostar



UV stellar radiative feedback finally ceases the mass accretion onto the protostar.

(Hosokawa+'11; Stacy+'12; Susa+'13)

We haven't finished our "Homework" yet.



Pop III IMF

Question-1: Low-mass end of IMF

Small-scale fragmentation of the accretion disk

[1] Merger

→ episodic accretion burst

[2] Survival

→ binary/multiple

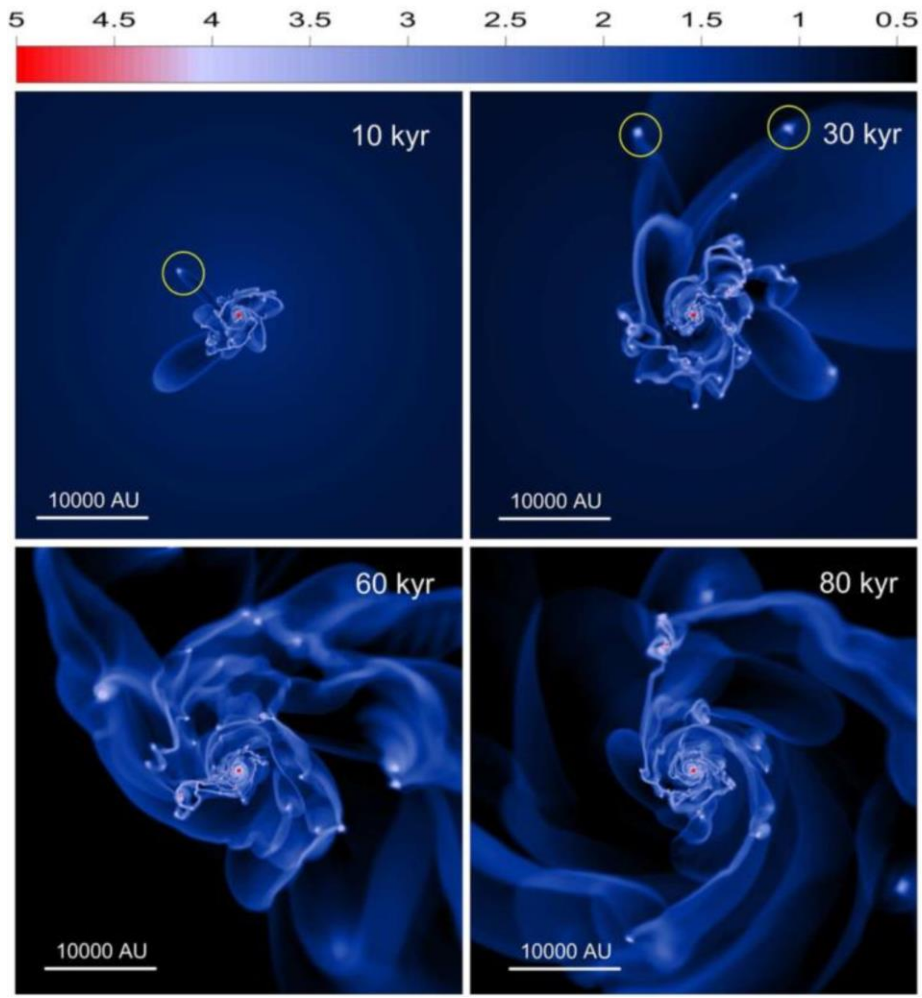
[3] Escape from the disk

→ surviving first stars

Depending on the

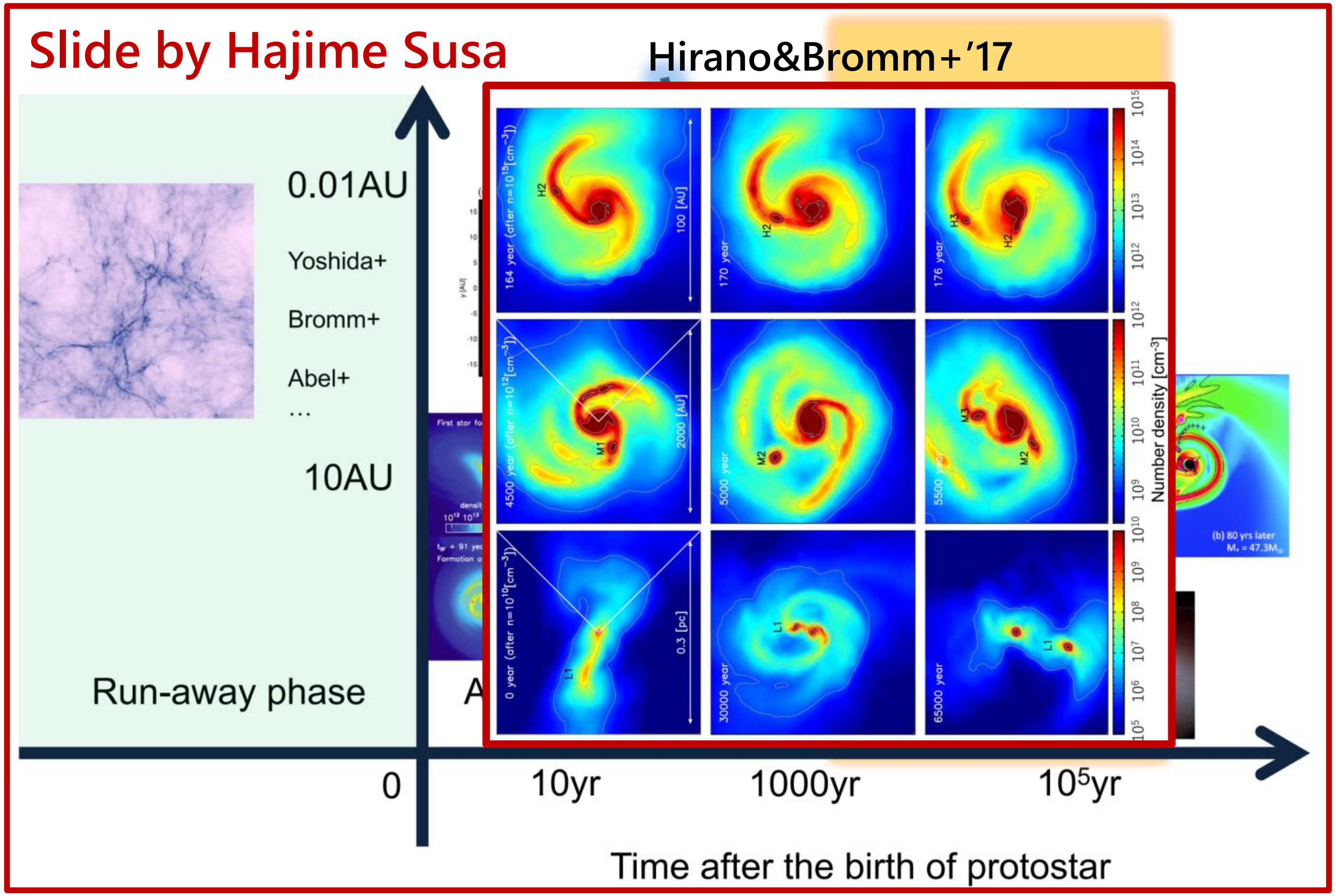
Calculation method:

△Sink particle technique



Sakurai+'16

Resolution ⇔ Calculation time



Restriction of the simulation scale by

- Sink particle technique → underestimates the scale
- Adiabatic core treatment → overestimates the scale

Question-2: High-mass end of IMF

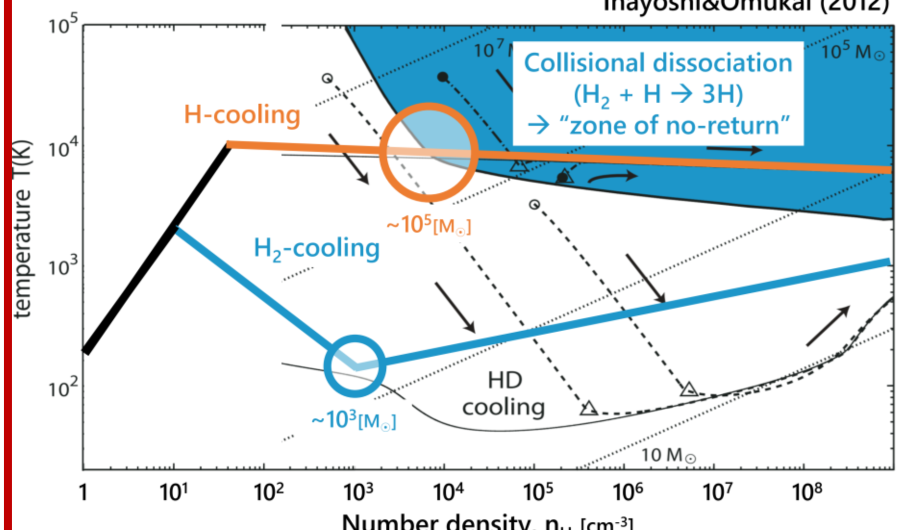
Higher-accretion rate than the critical value of the stellar feedback:

$$\dot{M} \cong \frac{M_{\rm Jeans}}{t_{\rm freefall}} \propto T_{\rm Jeans}^{\frac{3}{2}} \propto cs^3 \geq \dot{M}_{crit} = 4 \times 10^{-3}$$

Radiative origin

Processes for inefficient H_2-cooling
(a) Photo-dissociation
$H_2 + \gamma \rightarrow 2H$
(b) Collisional-dissociation
$H_2 + H \rightarrow 3H$

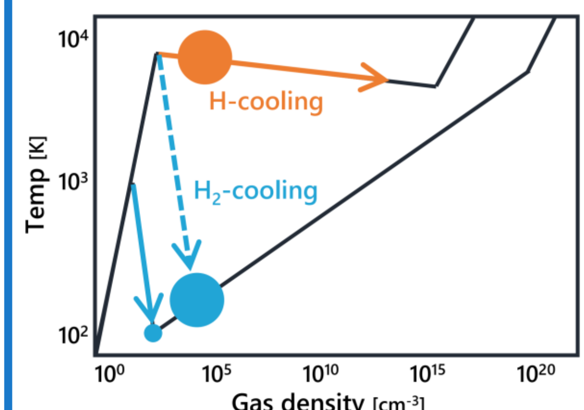
Inayoshi&Omukai (2012)



Kinetic origin

Supersonic coherent flow between DM and gas fluids left over the Big Bang suppresses the abundance of the first objects **(Tseliakhovich & Hirata 2010)**

➔ Massive halo, dense cloud

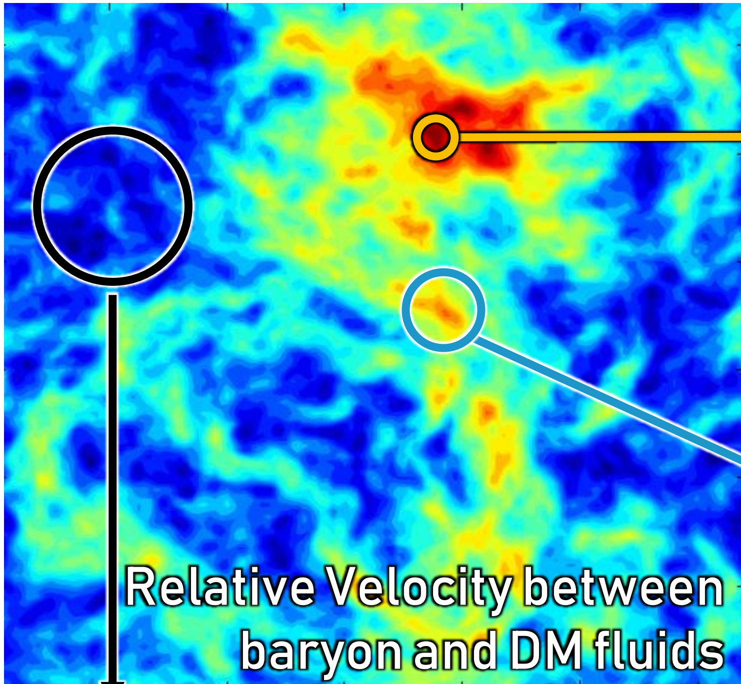


$$\dot{M} \simeq M_{\rm Jeans}/t_{\rm ff} \propto T_{\rm Jeans}^{3/2}$$

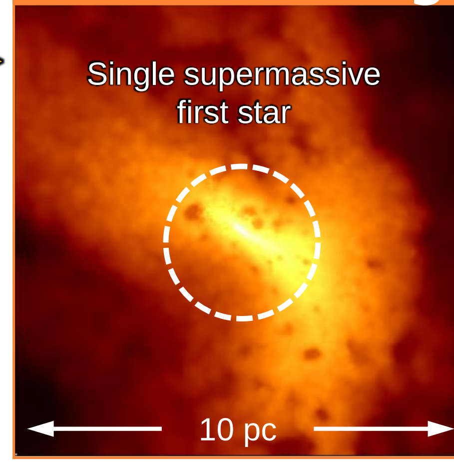
Streaming Motion

$$\dot{M} \propto v_{\rm eff}^3 \sim (c_s^2 + v_{\rm bc}^2)^{3/2}$$

Supermassive / Massive binary



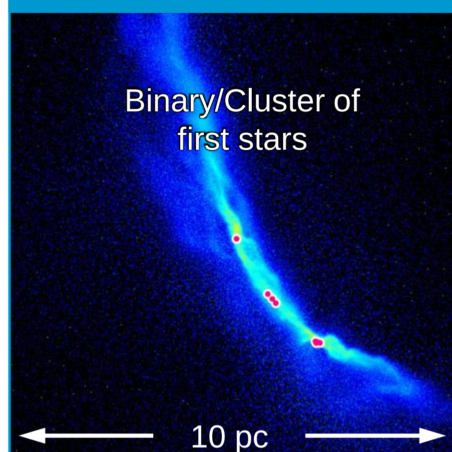
Strong wind



10^4-10^5[$M_\odot$] Pop III star at z~30

Seed of high-z quasars with 10^9[$M_\odot$] at z>7

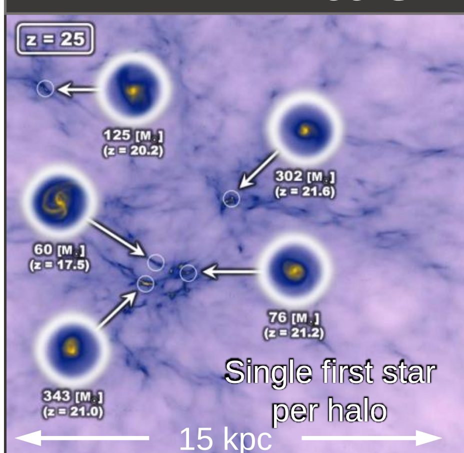
Weak wind



~10 Pop III stars with 100[$M_\odot$] at z~15

Massive BH binary (GW progenitor)

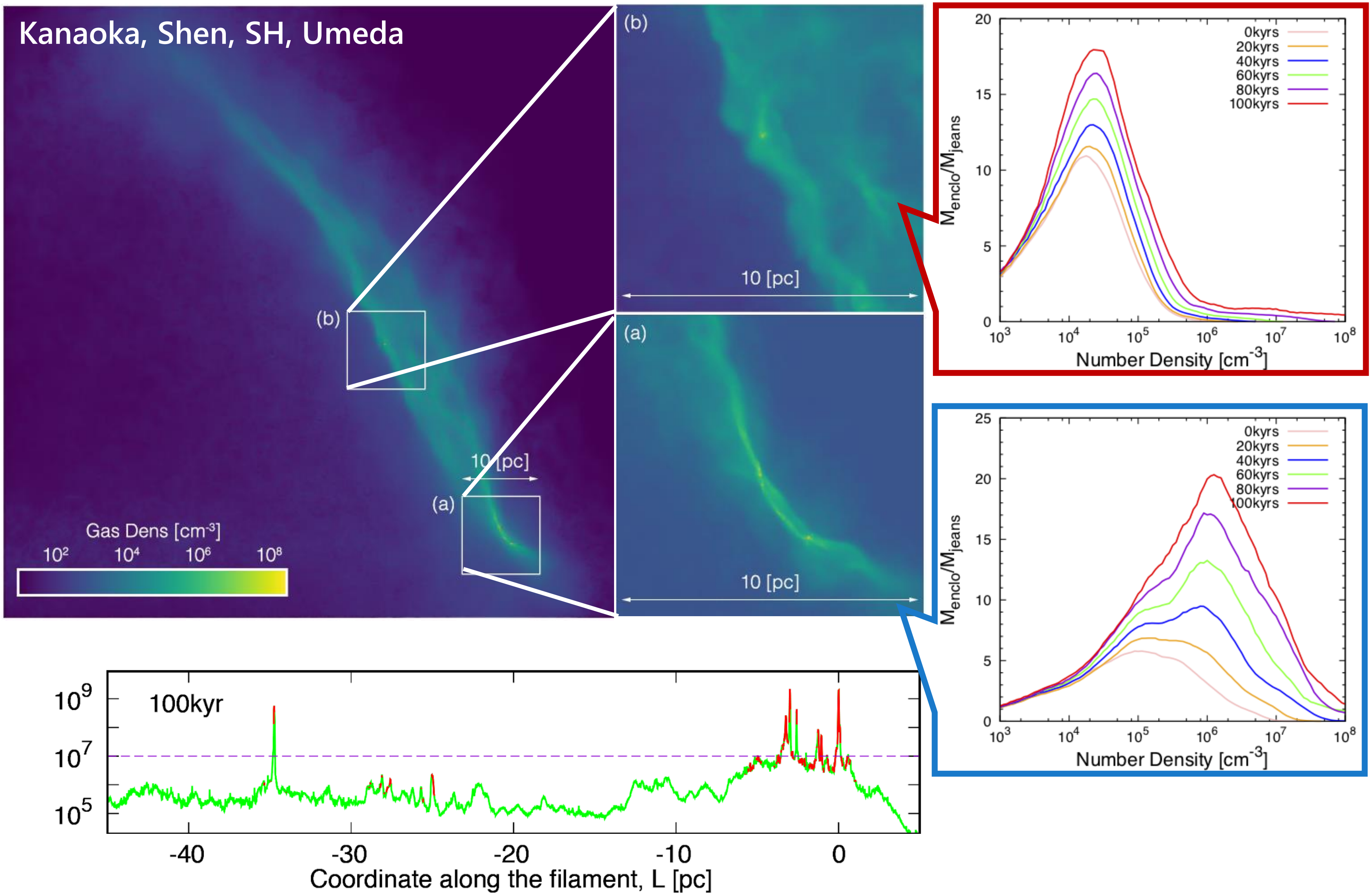
Little wind



Pop III stars with 10-1000[$M_\odot$] around z~15-25

Parent stars of observed EMPs

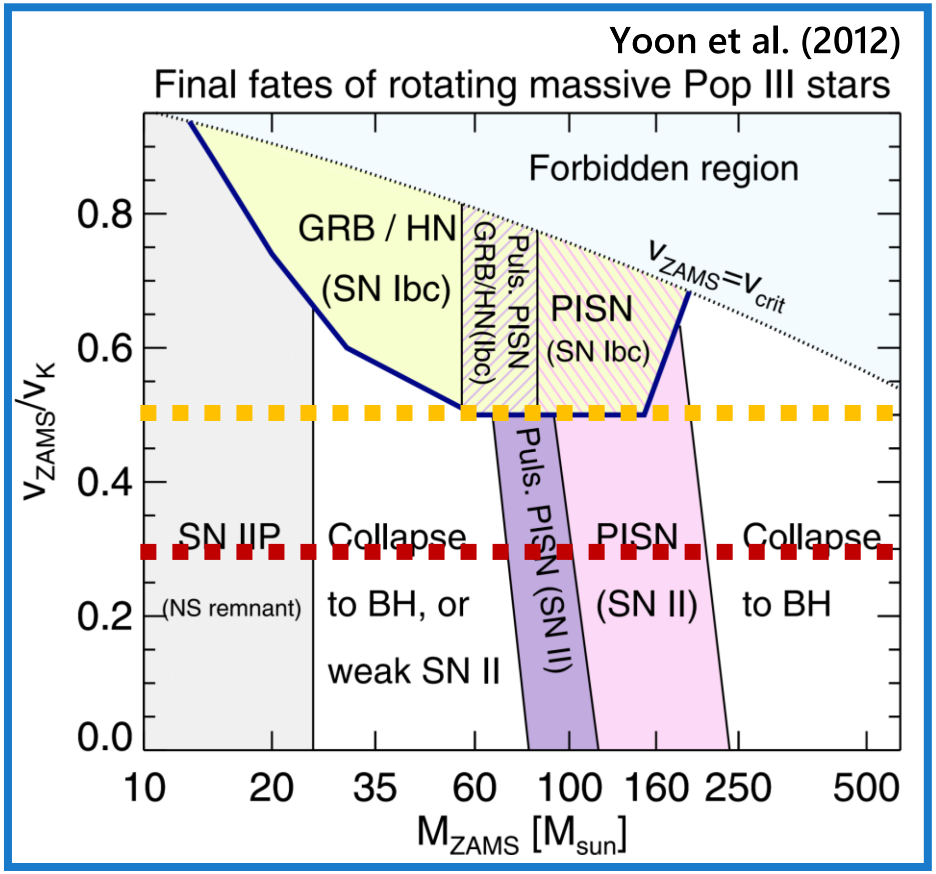
Fragmentation of massive filament

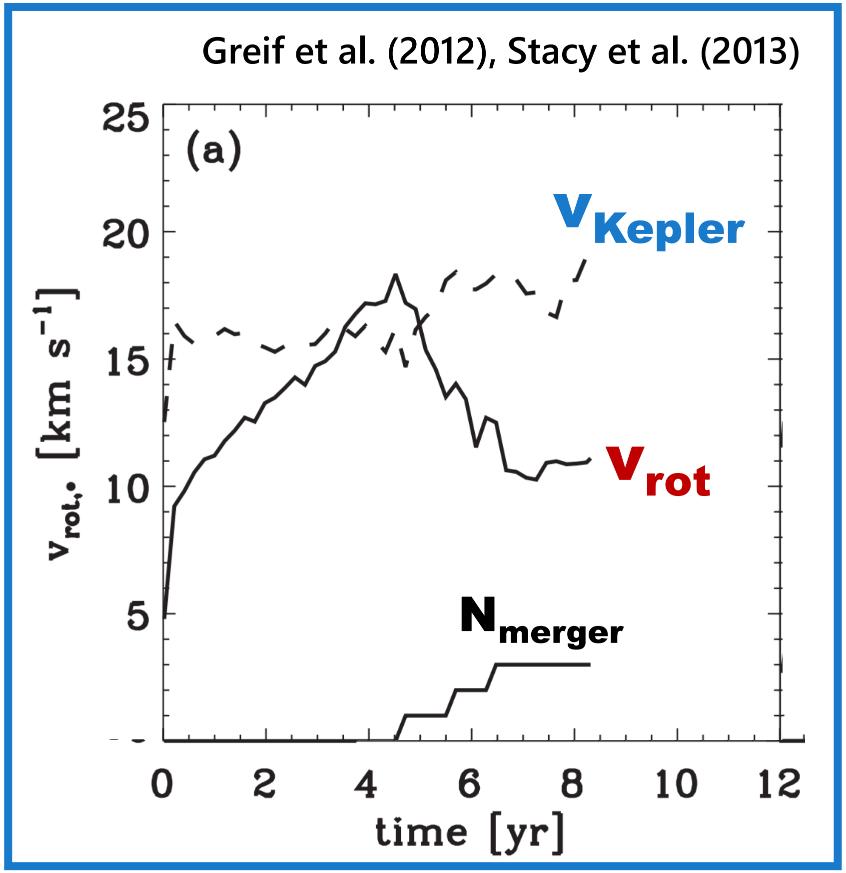


Question-3: Spin

Evolution and death of first stars depends on

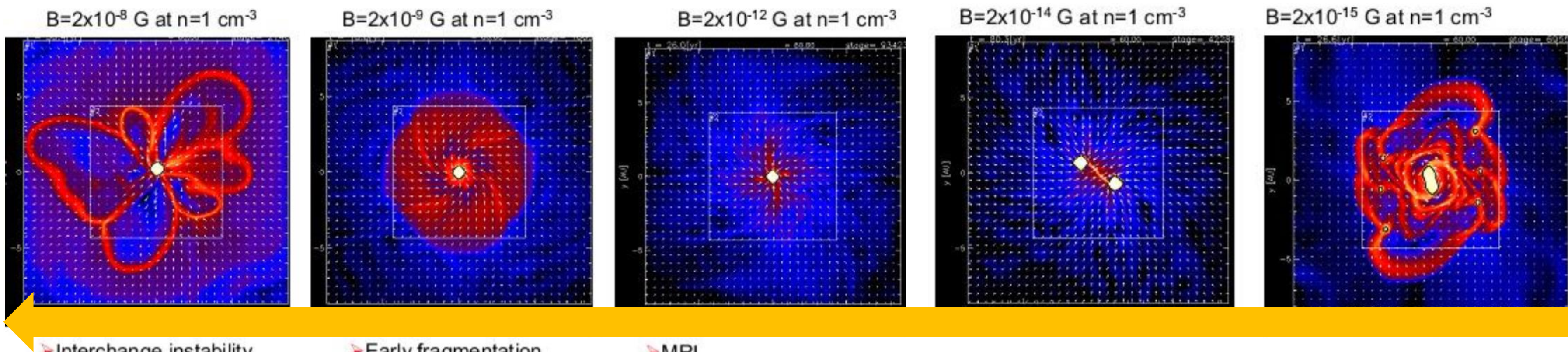
1. Stellar mass (e.g. Heger & Woosley'02; Heger+'03)
2. **Stellar rotation** (e.g. Chiappini+'11; Chatzopoulos&Wheeler'12)





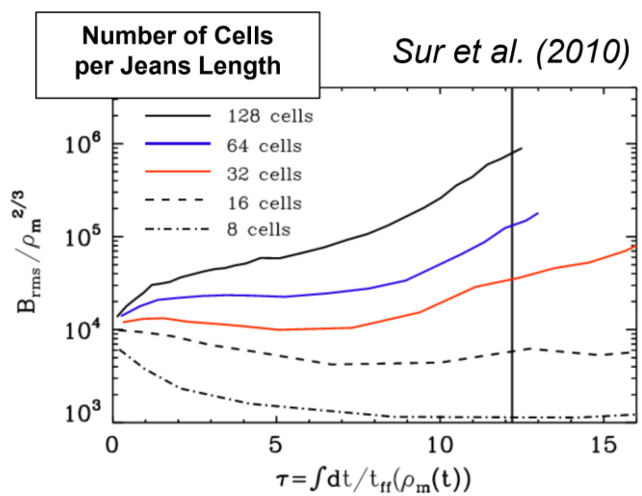
Problem: Magnetic effect

e.g. 3D non-ideal MHD **(Machida&Doi 2013)**



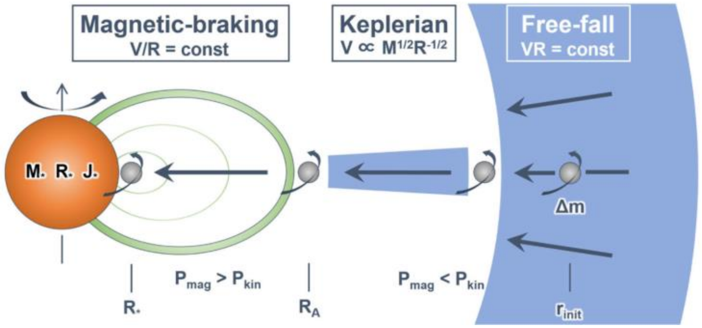
- Interchange instability
  B ~ 10 nano G
  Single star
- Early fragmentation
- MRI
  B ~ nano G
  Single star
- MRI
  B ~ pico G
  Single star
- MRI
  B ~ 10 femto G
  Binary star
- Multiple fragmentation
  B ~ femto G
  Multiple stars

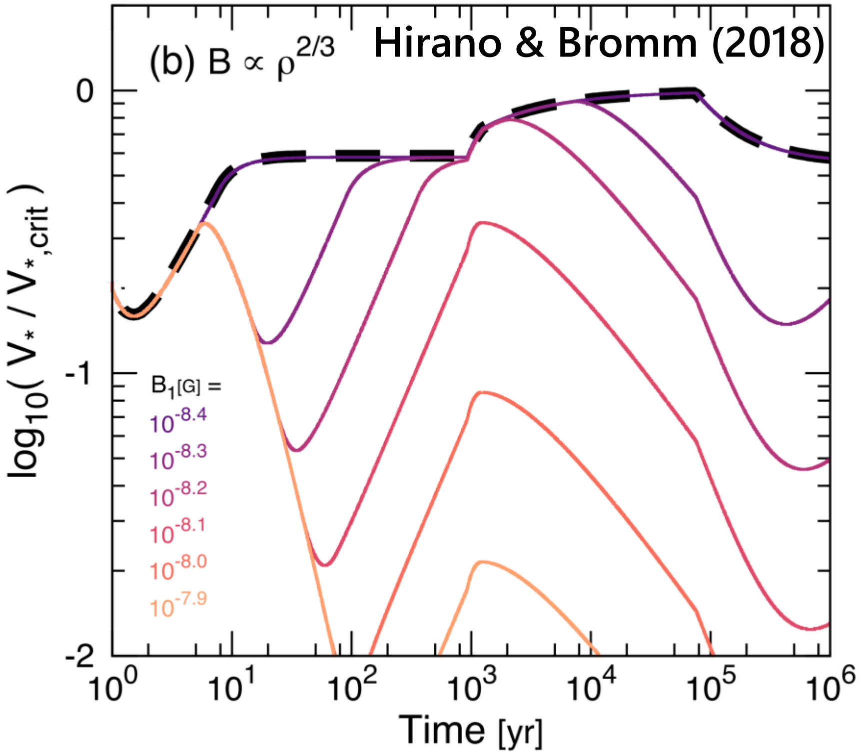
Q. B-field amplification by
the small-scale dynamo
in the turbulent cloud



On-going: Magnetic effect

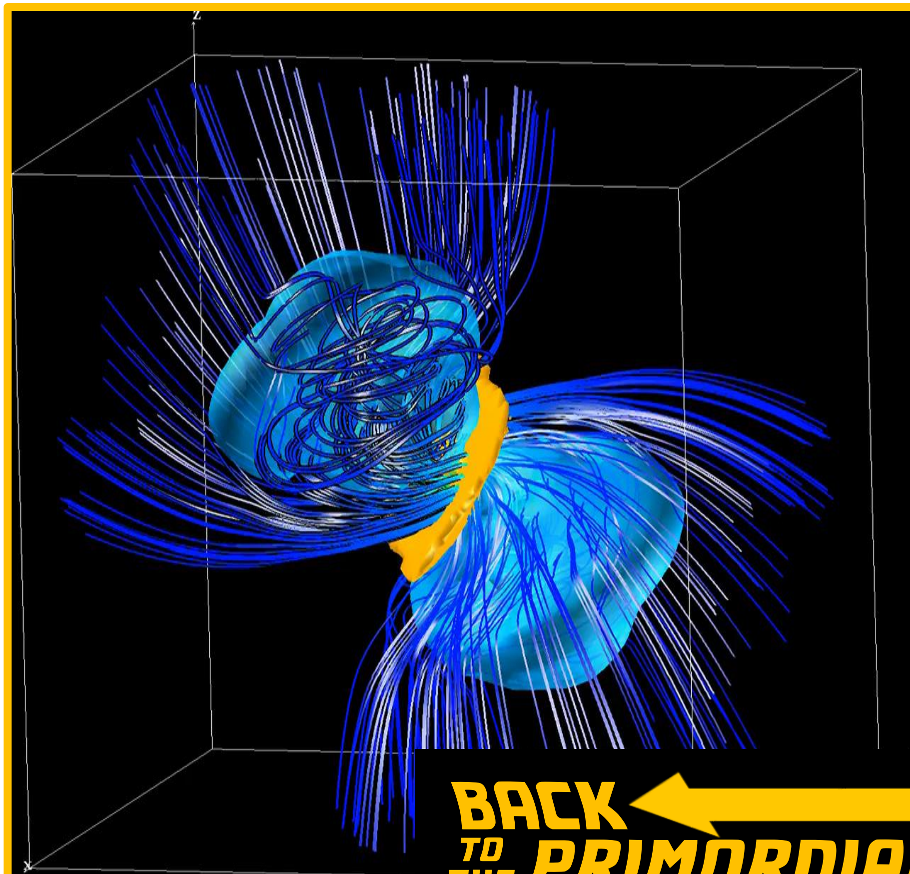
Analytic evaluation





Numerical simulation

- 3D non-ideal MHD
  (but for present-day case now)



BACK TO THE PRIMORDIAL

Summary

"Simulating the formation of the first stars"

1. DM Structure formation (~2000; e.g. Abel et al. 1997)
2. Collapse phase (~2010; e.g. Yoshida et al. 2008)
3. Accretion phase (~2020; **who?**)
4. Pop III IMF (~2030; **who?**)
   - ✓ We found important physical mechanisms, but there are still unresolved problems: fragmentation, magnetic effect.
   - ✓ Dependence on the formation environment.