On the mass of first stars

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First star formation

- Very massive ?
  - ✓ High gas temperature (inefficient H_2 cooling)
  - ✓ High mass accretion rate
  - ✓ little evidence for fragmentation in run-away phase

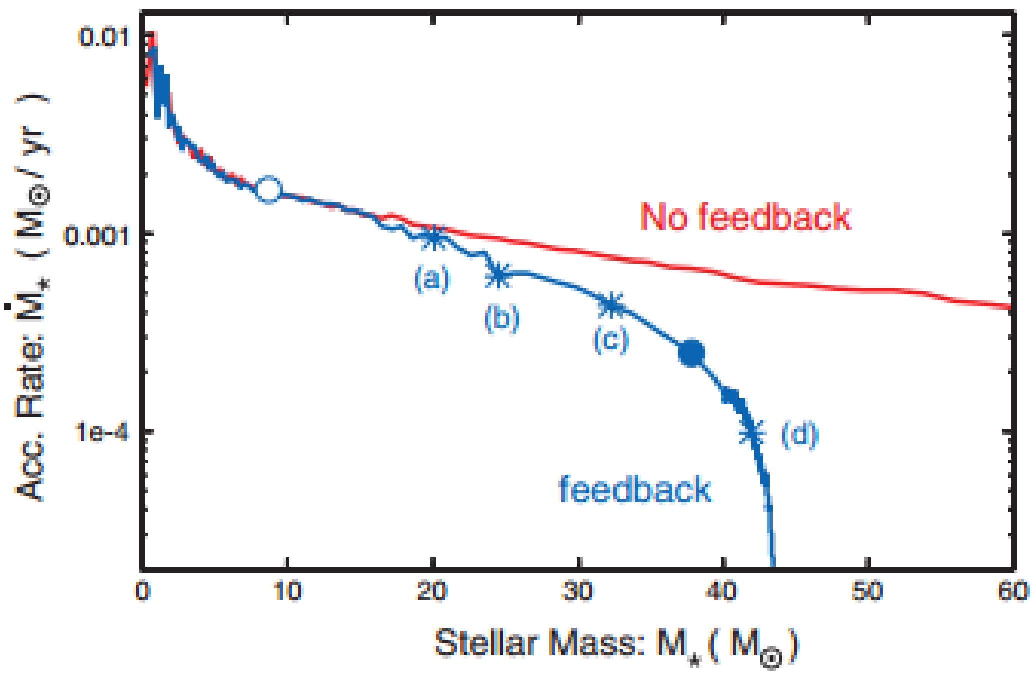
※ But no evidence found for Pair Instability SN

- Massive, sub-solar, Very massive ?
  - ✓ Heavy disk formed and fragment into multiple stars in accretion phase
  - ✓ Strong radiative feedback from protostars

Feedback from protostar(s)

Hosokawa+2011

2D RHD



Stacy+2012

3D RHD

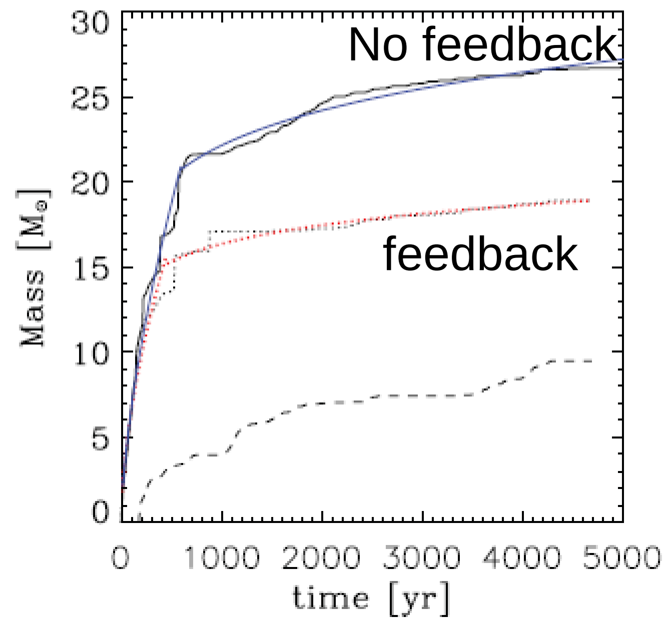


Figure 10. Effect of radiative feedback on protostellar accretion. Black solid line shows mass growth with no radiative feedback, while black dotted

∼43Msun 10^5 yrs after the formation of protostar.

∼20-30Msun at 10^5 yrs estimated by extraporation

'with feedback' case the main sink does not grow beyond ∼20 $M_\odot$ in the

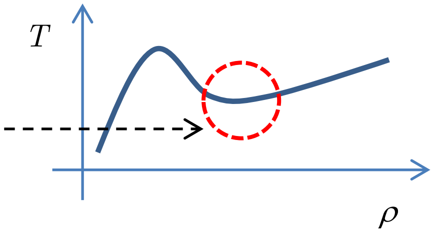
Long term 3D calculation needed.

RSPH code

Susa 2006 (http://ads.nao.ac.jp/abs/2006PASJ...58..445S)

- Parallel BH Tree (mpi)
- SPH
- Domain decomposition : ORB
- RT solver (Ray-Tracing , mpi)
- Implicit solver for reactions and energy equation
- H2
- On-the-Spot approximation (Case B recom.)
- Multiple sources (～< 10）
- Any Spectrum

Setup



- 200K, 10^4 cm^{-3} Bonner-Ebert Sphere (motivated by the cosmological simulations)
- + rotation Ω = 2x 10^{-14} rad/s (comparable to Yoshida+06)
- Sink conditions: $n_{max}=3\times10^{13}$ cm^{-3} r_{acc}=30AU
- Accretion conditions:

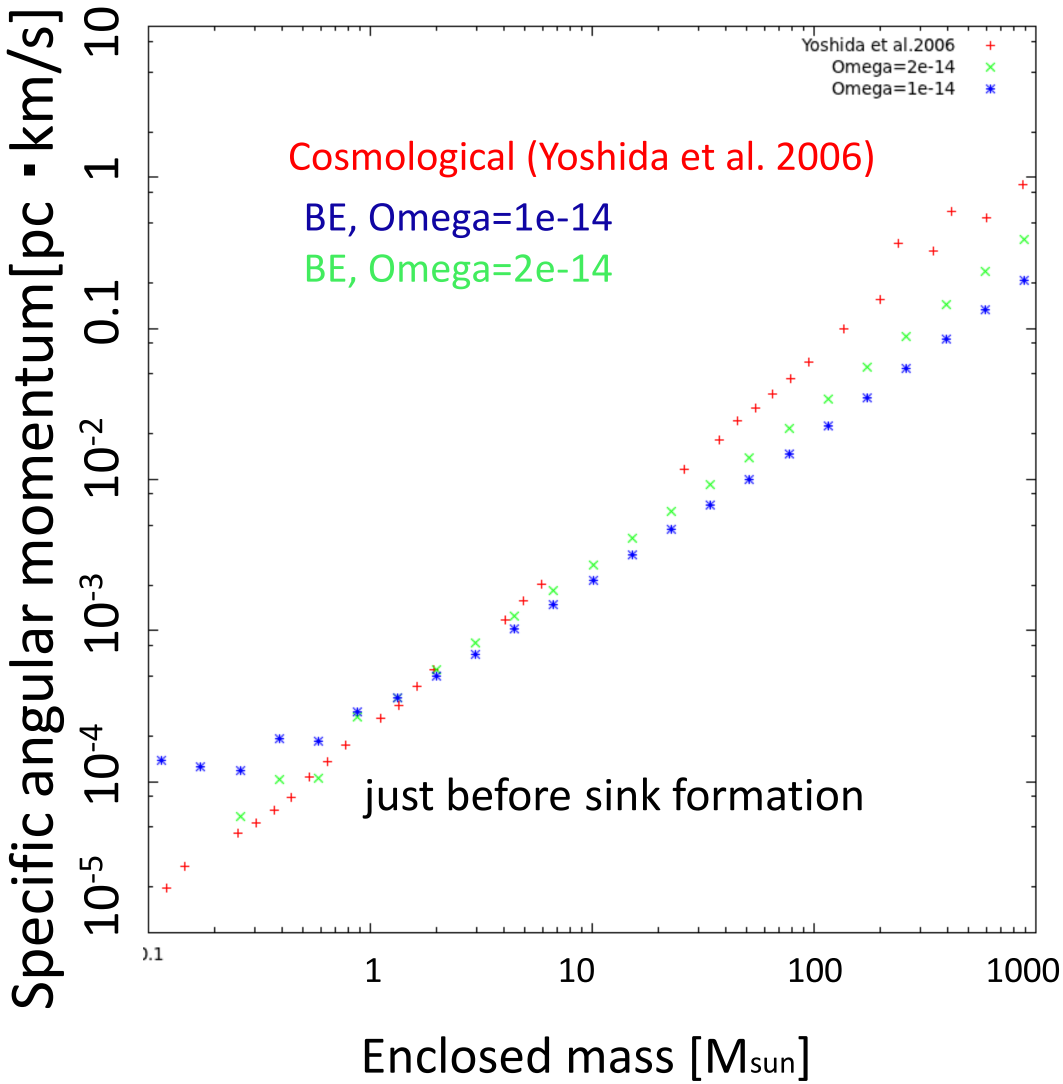
  $r < r_{acc}$ + energetically bounded with each other
- Sinks do not have own pressure (like BHs).
- Sinks do not merge with each other
- $M_{sph} = 5\times10^{-3} M_{sun}$ → $M_{res} = 2N_{neib}M_{sph}=0.5M_{sun}$
- Radiative Feedback (Dissociation, Ionization)
- Model of protostars:

  Function of M and dM/dt (Hosokawa model)

Distribution of Angular mom.

$\Omega = 2\text{x } 10^{-14} s^{-1}$

Comparable to Cosmological simulations



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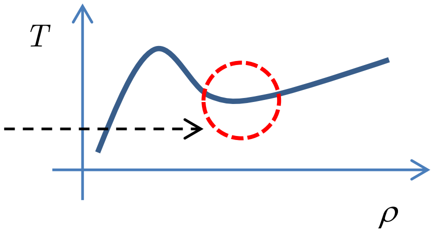

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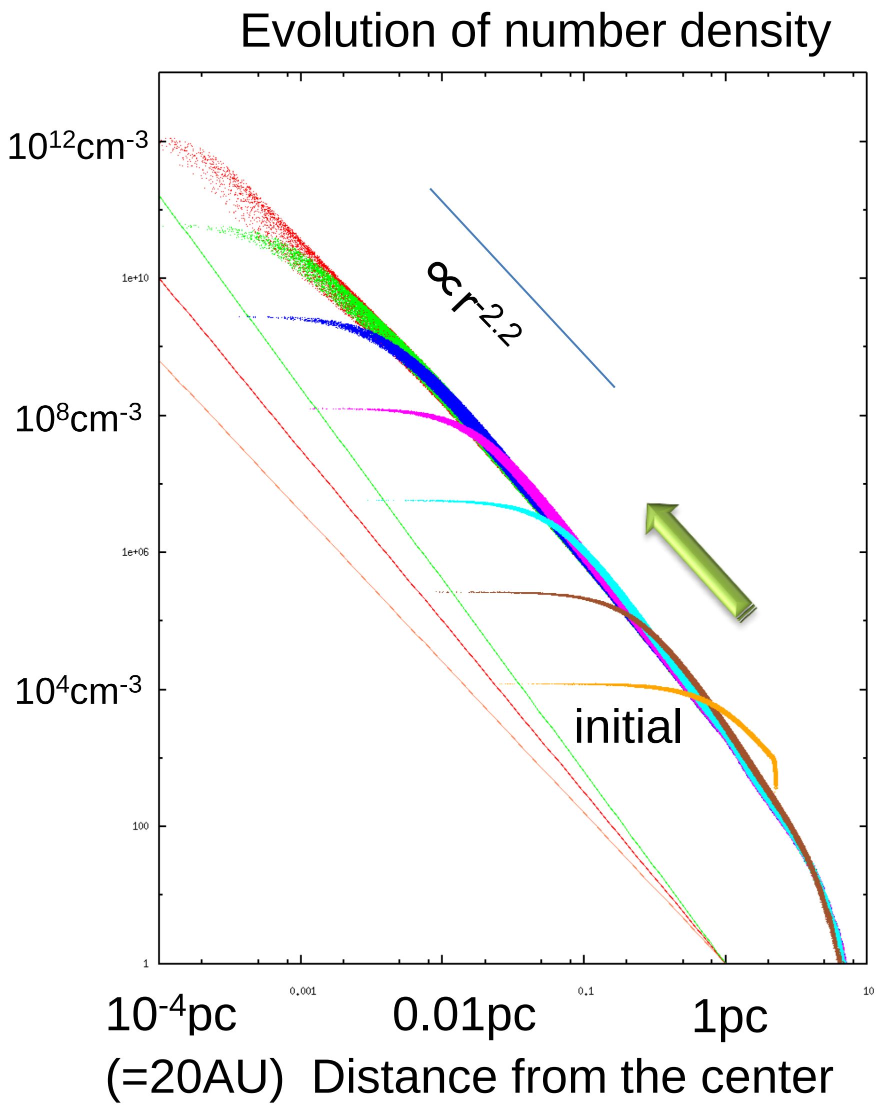
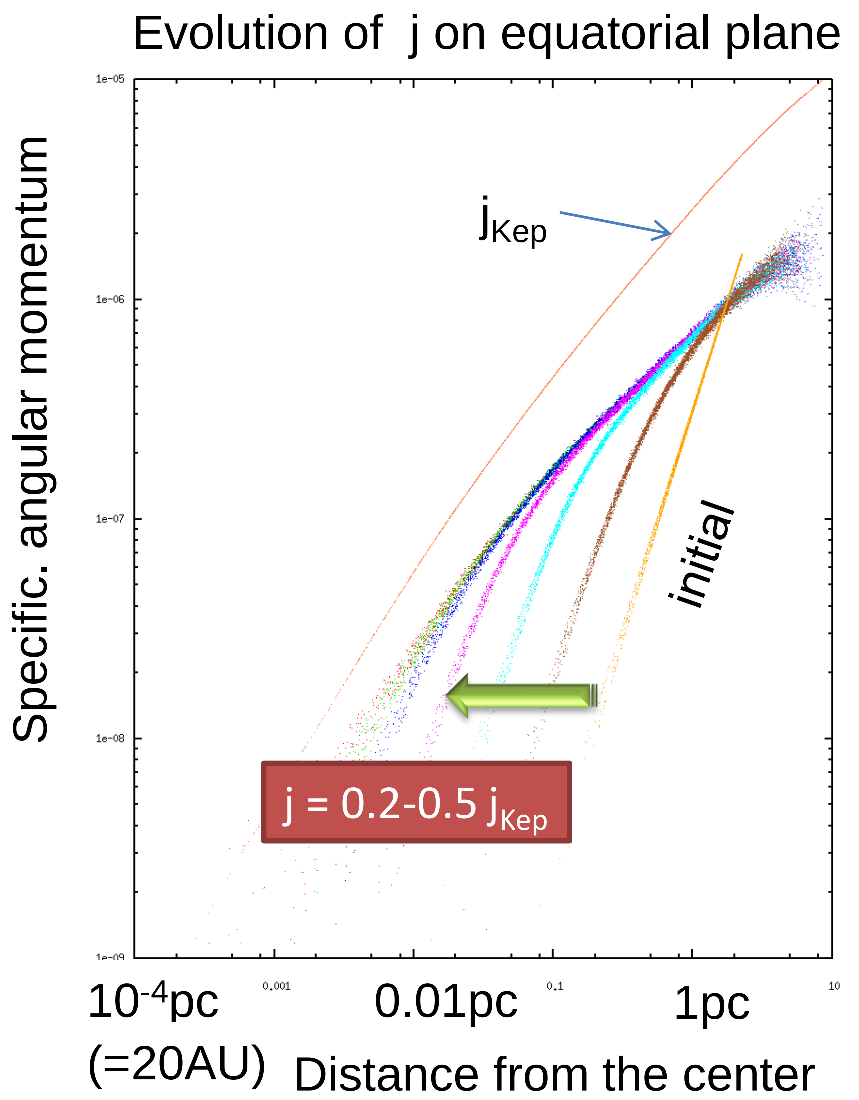
run-away collapse (Ω=2x10^{-14} rad/s)





Radius of the accretion disk

Definition of j of Kepler rot.

$$\frac{j_{Kep}^2}{r_c^3} = \frac{GM}{r_c^2}$$

Balance between the gravity and the centrifugal force with given **j**

$$\frac{j^2}{r_d^3} = \frac{GM}{r_d^2}$$

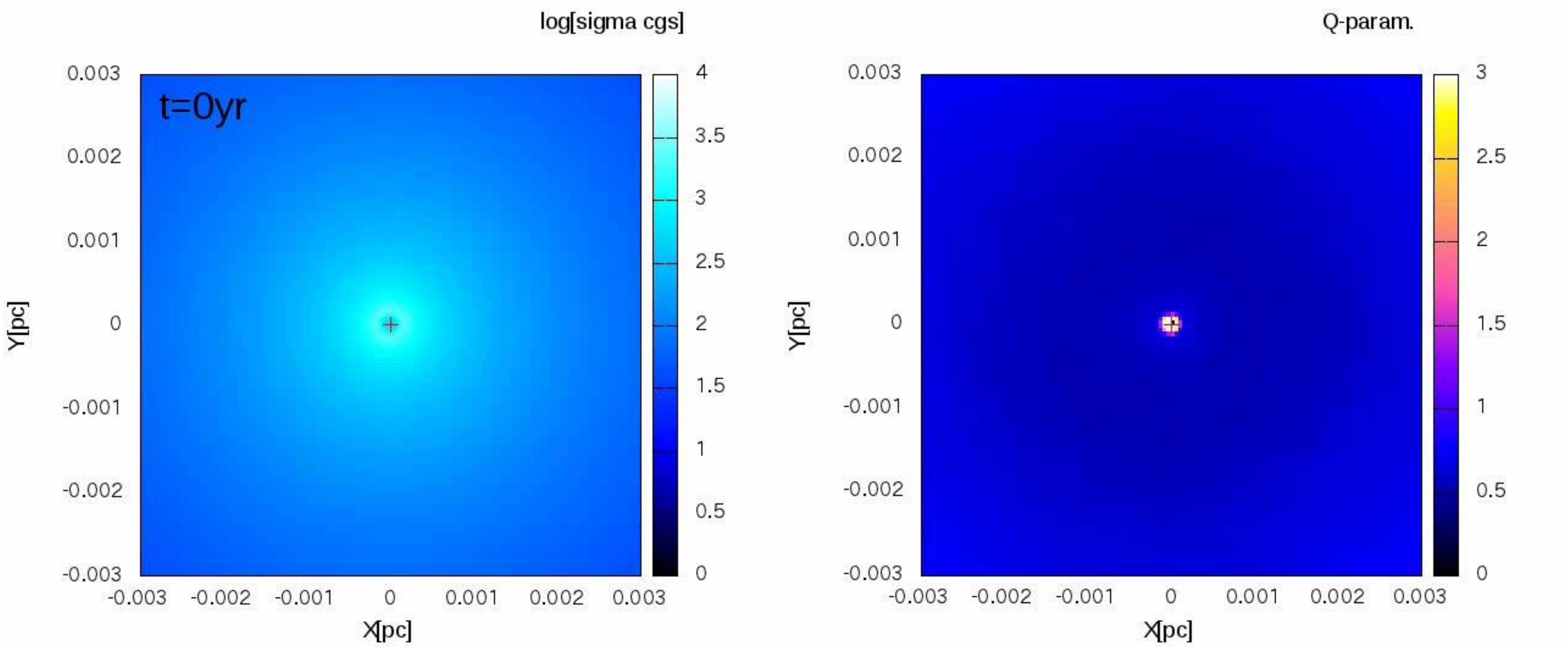
Specific ang.mom. of Run-away collapsing core

$$j = f\, j_{Kep}$$

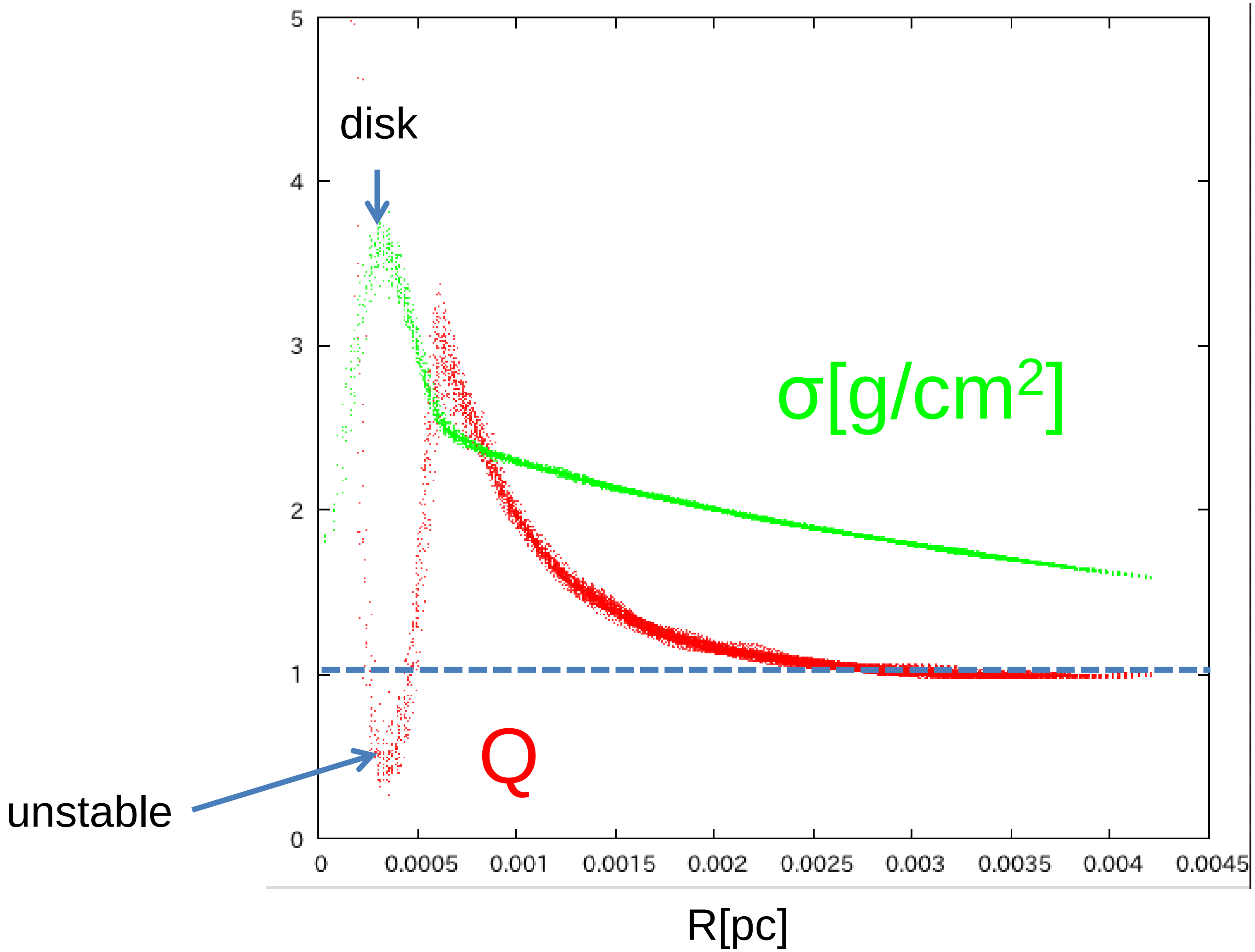
$$\boxed{r_d = f^2 r_c}$$

f= 0.5
→ disk radius is 25% of core radius

Fragmentaion of the disk (t <2000yr)

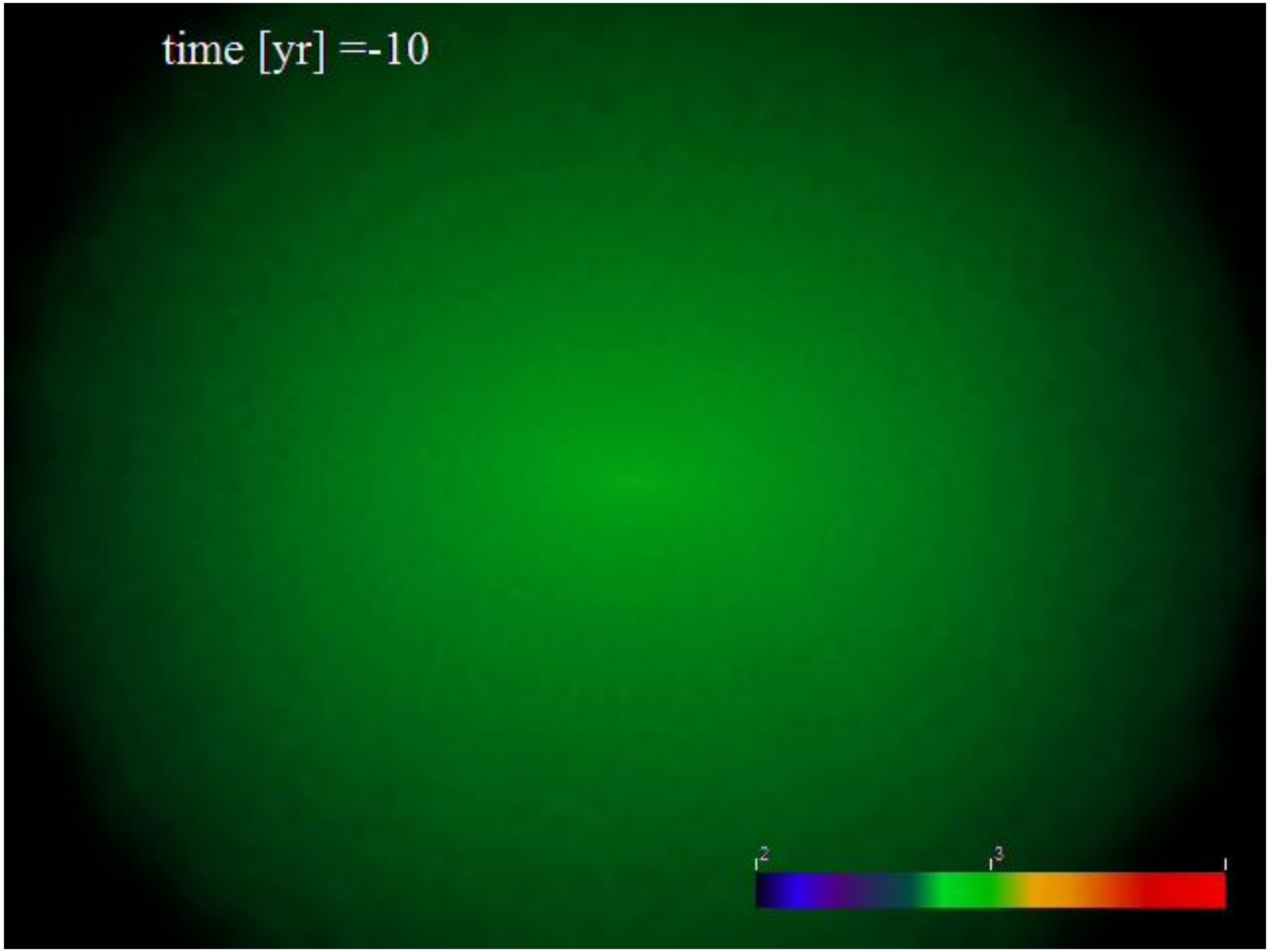


Q-parameter



5
4
3
2
1
0
disk
σ[g/cm2]
Q
unstable
0
0.0005
0.001
0.0015
0.002
0.0025
0.003
0.0035
0.004
0.0045
R[pc]

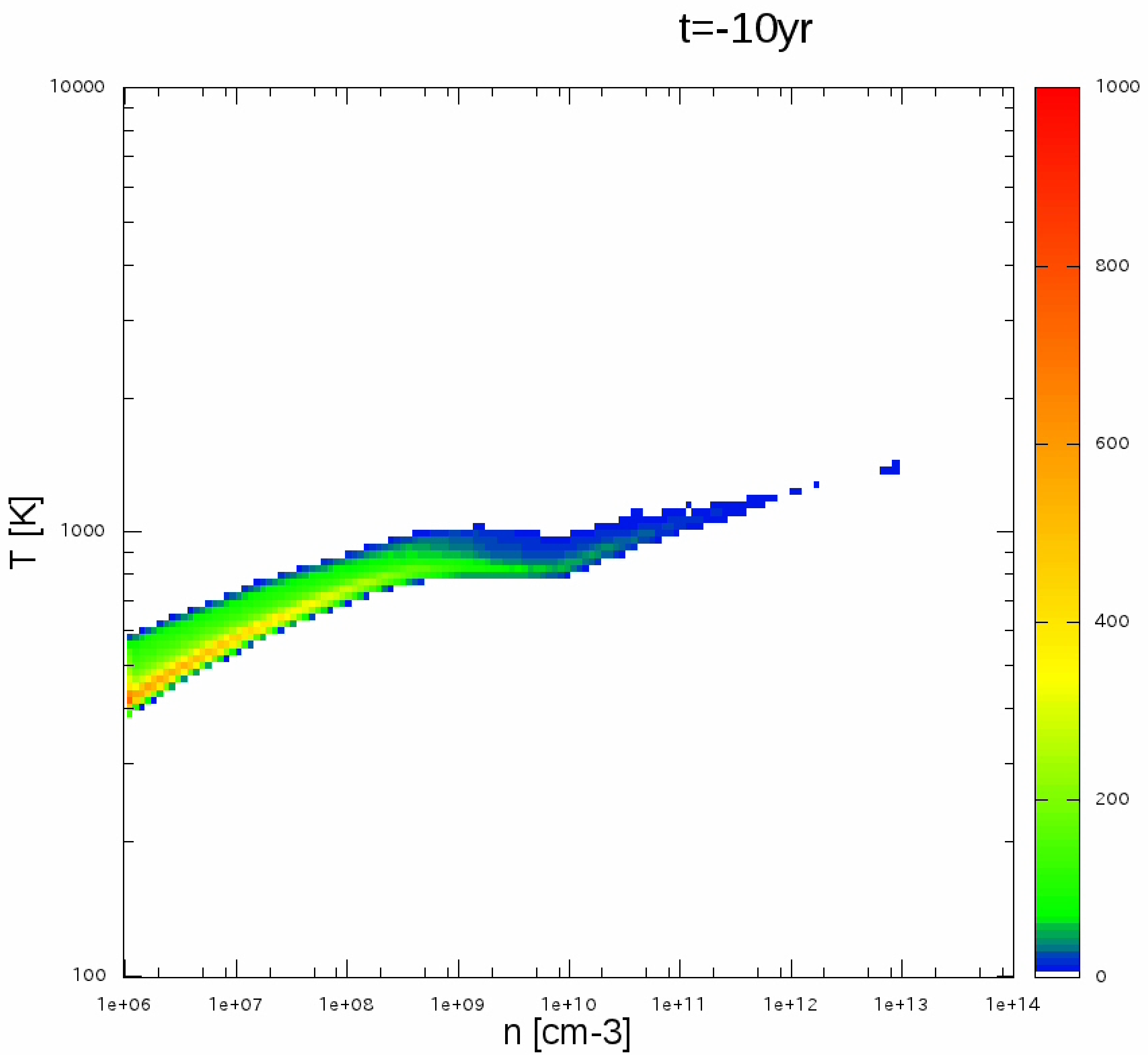
Gas distribution < 0.05pc = 10000AU



Color : Temperature 10^2 10^3 10^4

Powered by Zindaiji

Evolution on n-T plane



Heating by Photodissociation

- H_2 dissociation → no coolant
- Chemical Heating/cooling

$3H \rightarrow H_2 + H$, $H + H^- \rightarrow H_2 + e^-$: Heating

$H_2 + H$ (or H_2) $\rightarrow 3H$ or $(2H + H_2)$: Cooling

$3H \rightarrow H_2 + H$, $H + H^- \rightarrow H_2 + e^-$: Heating

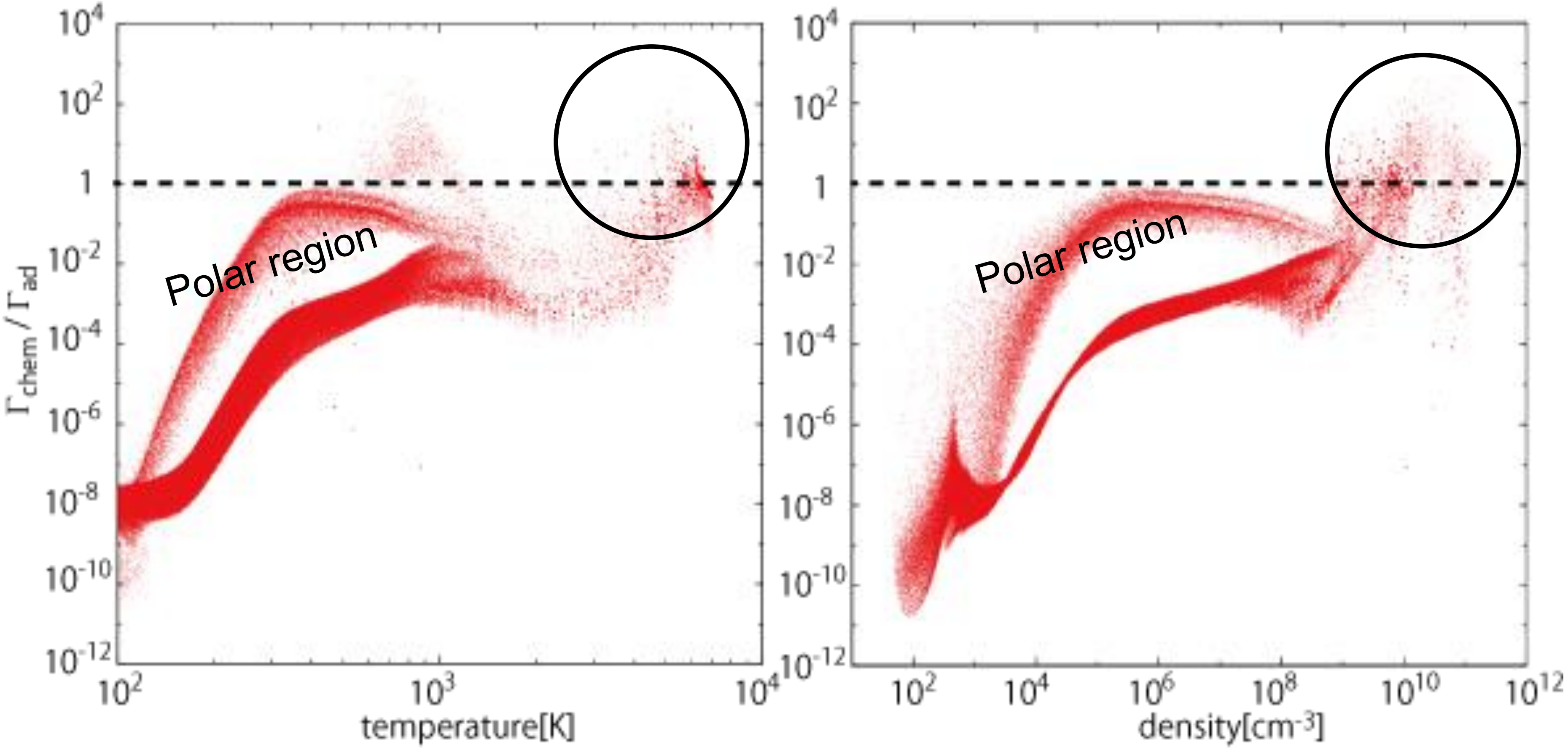
$H_2 + \gamma_{LW} \rightarrow 2H$: Thermal energy is not consumed

↓

2step heating

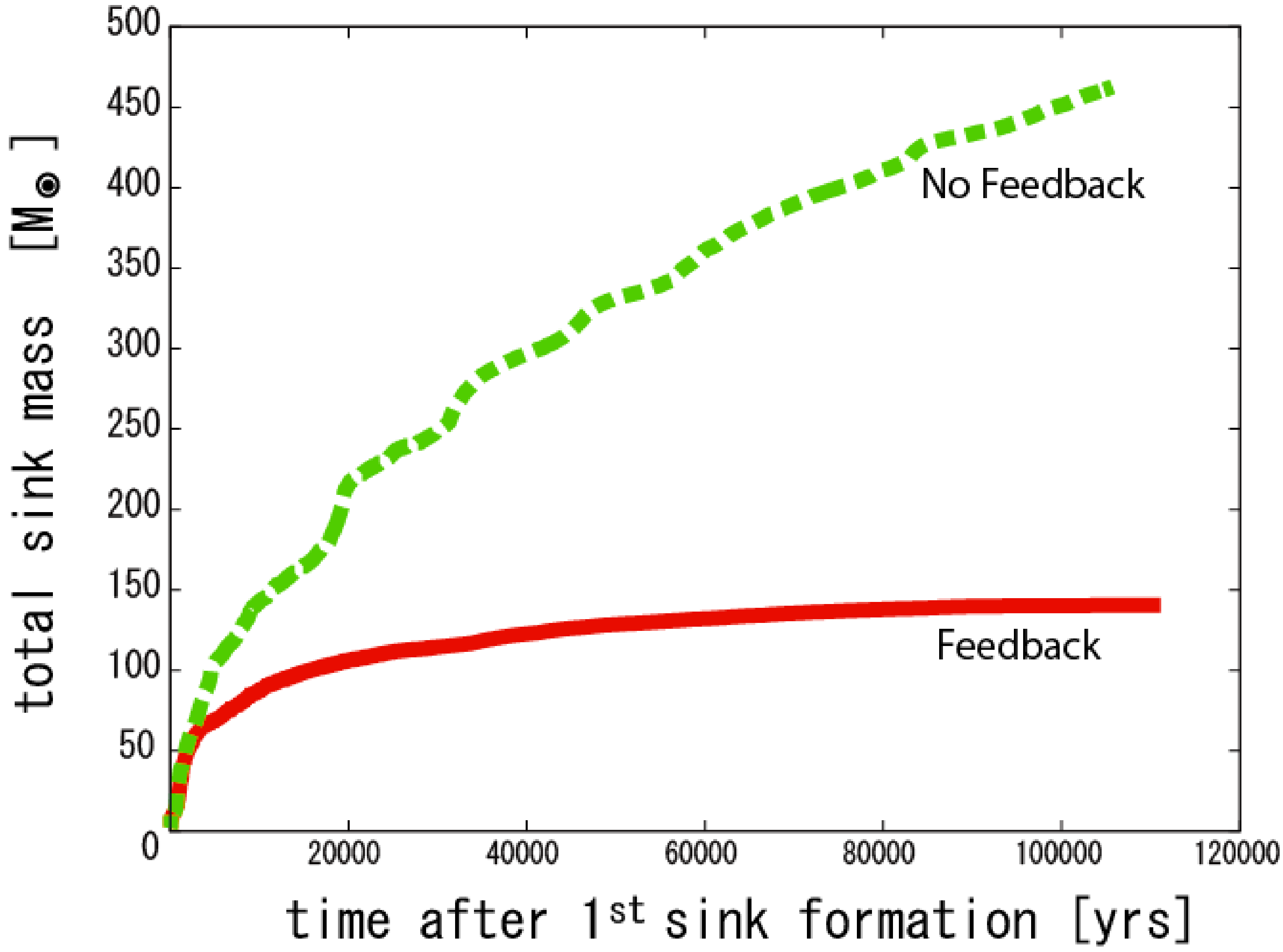
Chemical Heating Rate

t=2030 yr

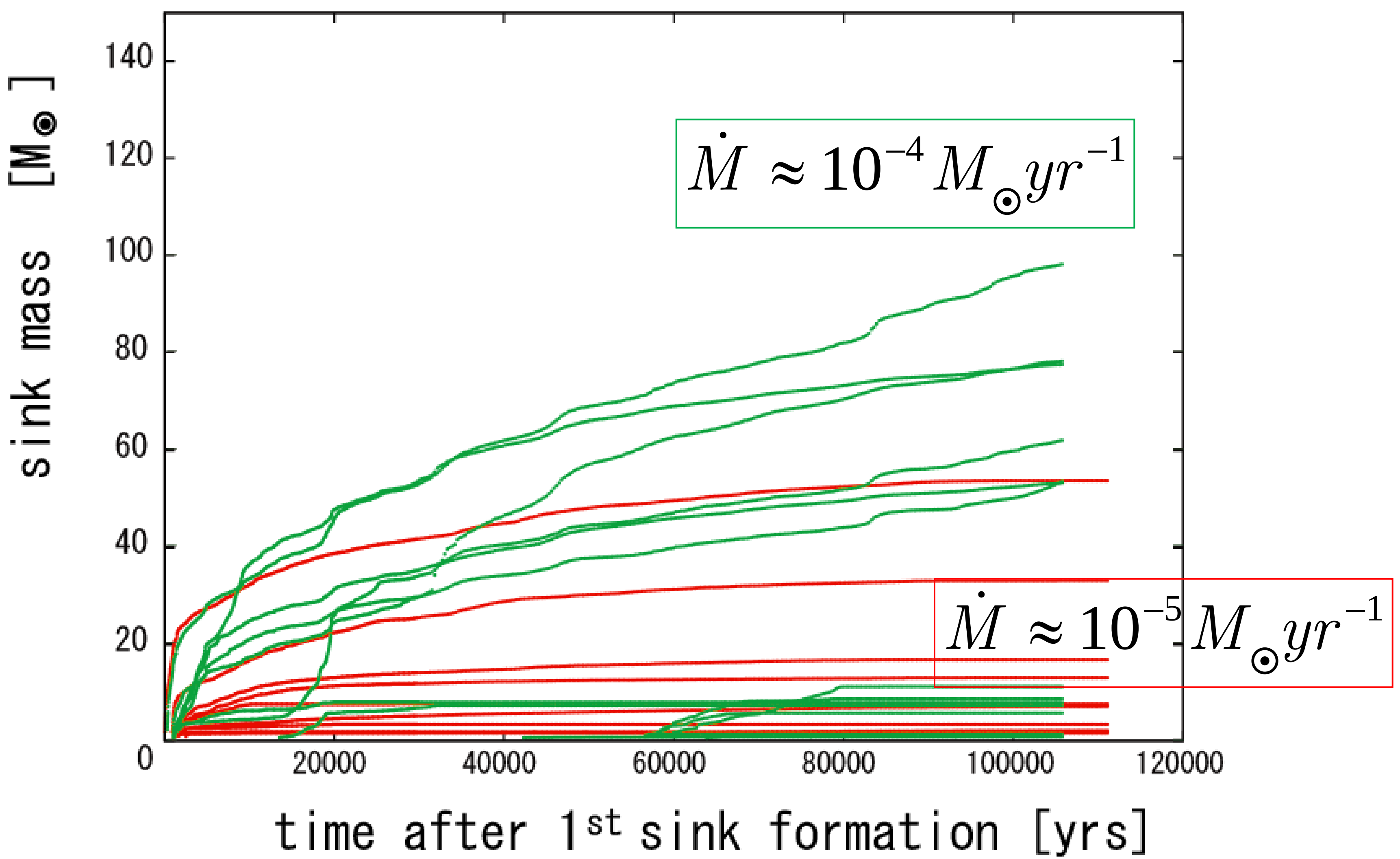


Photodissociation process is an important source of gas heating.

Total sink mass evolution



Individual sink mass evolution



Final accretion rate

Hoyle-Lyttleton Accretion

$$\dot{M}_{HL} = \pi R_{HL}^2 \rho_\infty v_\infty = \pi \left(\frac{2GM}{v_\infty^2} \right)^2 \rho_\infty v_\infty$$

$$\approx 3 \times 10^{-4} M_\odot \mathrm{yr}^{-1} \left(\frac{M}{50 M_\odot} \right)^2 \left(\frac{n_\infty}{10^7 \mathrm{cm}^{-1}} \right) \left(\frac{v_\infty}{10 \mathrm{km\,s}^{-1}} \right)^{-3}$$

Geometrical cross section

$$\dot{M}_{acc} = \pi R_{\mathrm{acc}}^2 \rho_\infty v_\infty$$

$$\approx 1.5 \times 10^{-7} M_\odot \mathrm{yr}^{-1} \left(\frac{R_{\mathrm{acc}}}{30 \mathrm{AU}} \right)^2 \left(\frac{n_\infty}{10^7 \mathrm{cm}^{-1}} \right) \left(\frac{v_\infty}{10 \mathrm{km\,s}^{-1}} \right)$$

10^{-5} Msun /yr falls between these two estimates.

→ Cs^3/G is not appropriate to describe the mass accretion at later phase.

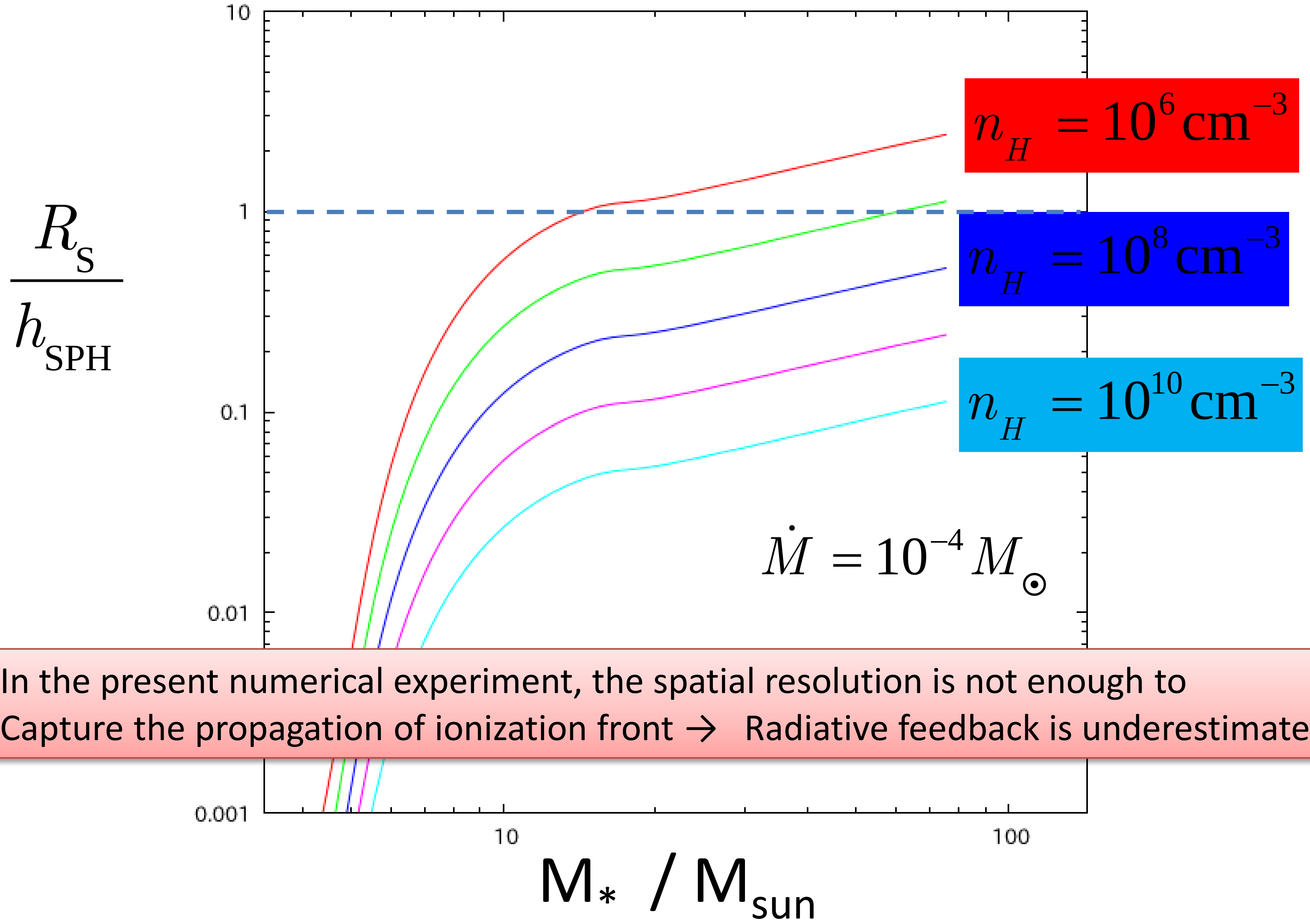
Sink mass v.s. Stellar mass

1. According to the employed accretion condition onto sinks, the accretion rate is overestimated (large r_{acc}, no pressure).
2. Spacial resolution is not enough to capture the propagation of I-front. In fact, fully ionized region do not emerge until the very late epoch. Thus, we underestimate the feedback effects in this simulation.

Both of two limitations enhance the mass of sink particles.
→ Obtained mass of sinks are regarded as an upper limit.

But this is the result of a realization of simplified initial condition,
we need more statistical argument by the cosmological simulations

Strömgren radius v.s. h_{SPH}



In the present numerical experiment, the spatial resolution is not enough to Capture the propagation of ionization front → Radiative feedback is underestimated.

Summary

- We perform 3D RHD simulations on the formation of first stars, especially focusing on the effects of radiative feedback from protostars.
- The accretion disk formed around the primary proto-first-star, fragment into O(10) protostars.
- Due to the gas heating associated to photodissociation process, hot bubble is formed around the protostars, and it expand to reduce the central density of the cloud.
- Because of the reduced density in the central region, the mass accretion onto protostars are strongly suppressed.
- After long-term time integration(t～0.1Myrs), the mass of the sinks < 50-60 Msun, and the mass accretion rates reduce to ～10^{-5}Msun/yr. But cosmological many halos are necessary for statistical arguments.
- In any case, very massive first stars unlikely to form from present setup.

Future: Cosmological minihalos as initial conditions

Ionization: 10 times better mass resolution ?